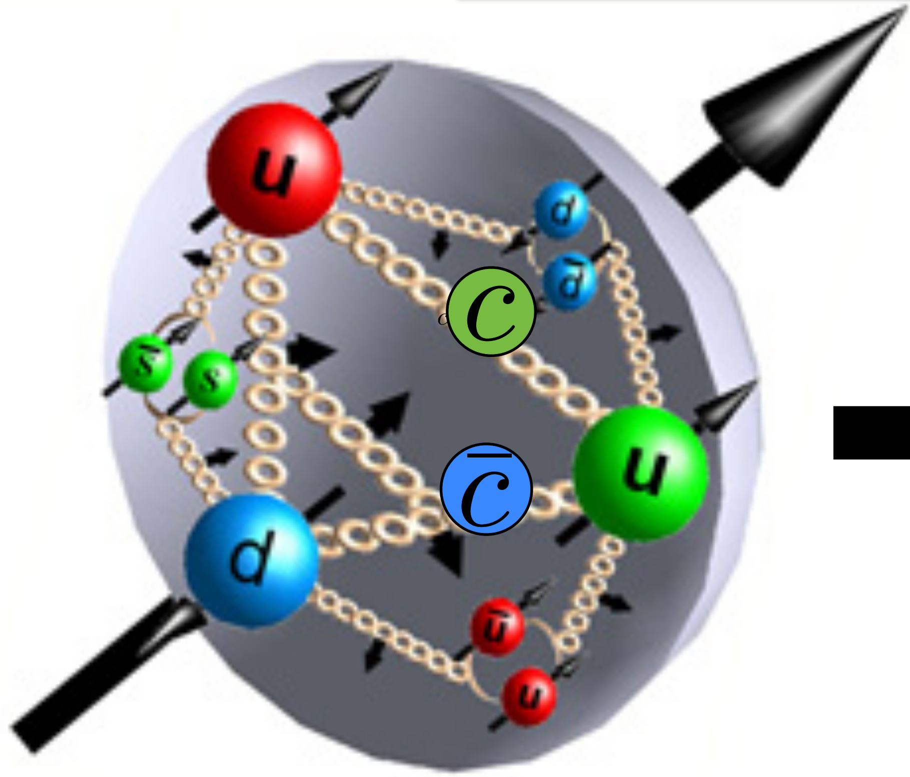
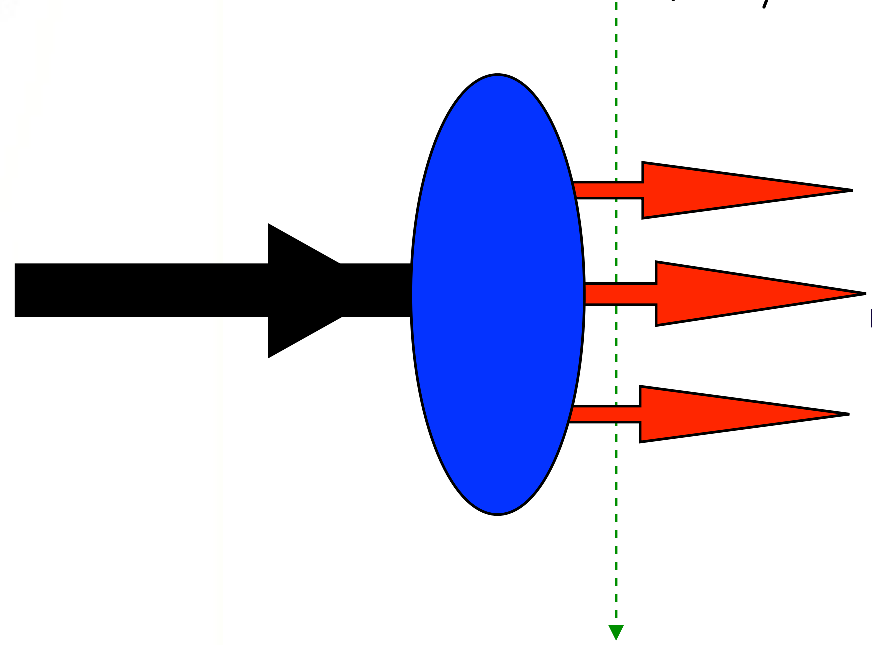
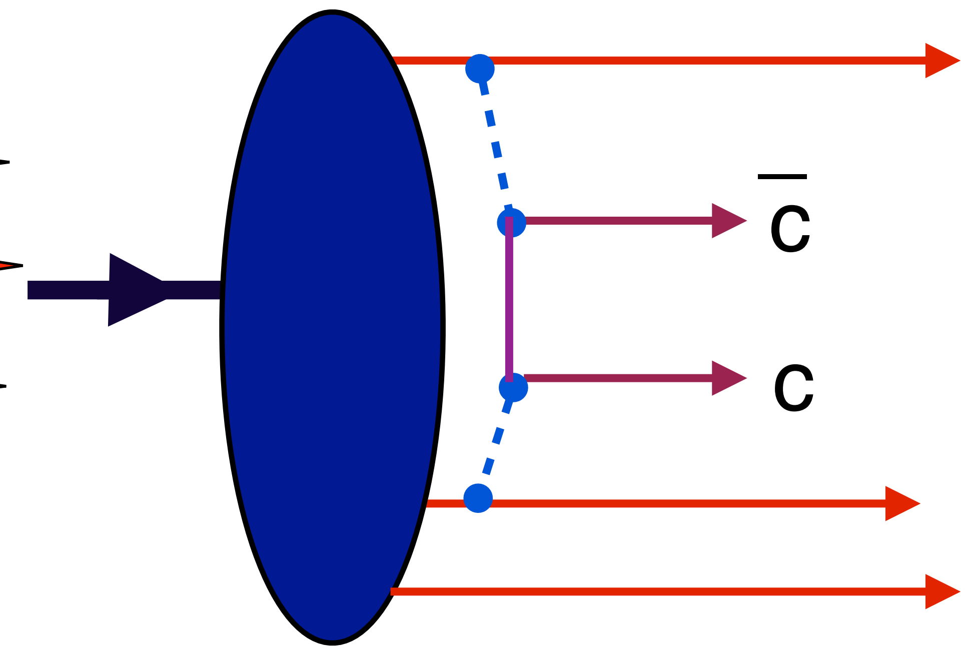
Intrinsic Heavy Quarks and other Novel QCD Phenomena







Stan Brodsky

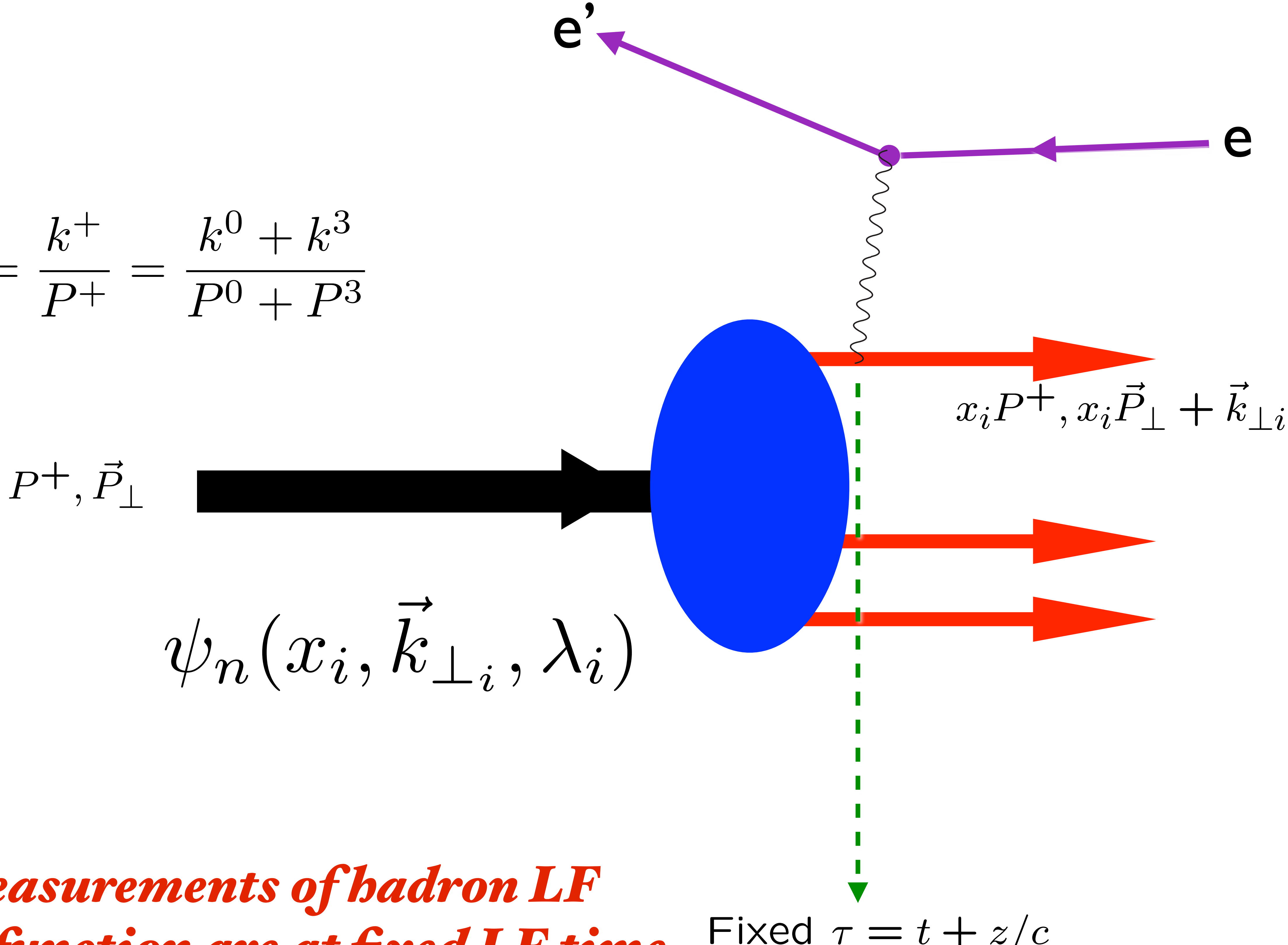
SLAC NATIONAL ACCELERATOR LABORATORY

INSTITUTE FOR NUCLEAR THEORY

Intersections of BSM Phenomenology and QCD for New Physics Searches (INT-15-3)

October 20, 2015, INT, University of Washington

$$x = \frac{k^+}{P^+} = \frac{k^0 + k^3}{P^0 + P^3}$$



$$\psi_n(x_i, \vec{k}_{\perp_i}, \lambda_i)$$

Measurements of hadron LF wavefunction are at fixed LF time

Like a flash photograph

$$x_{bj} = x = \frac{k^+}{P^+}$$

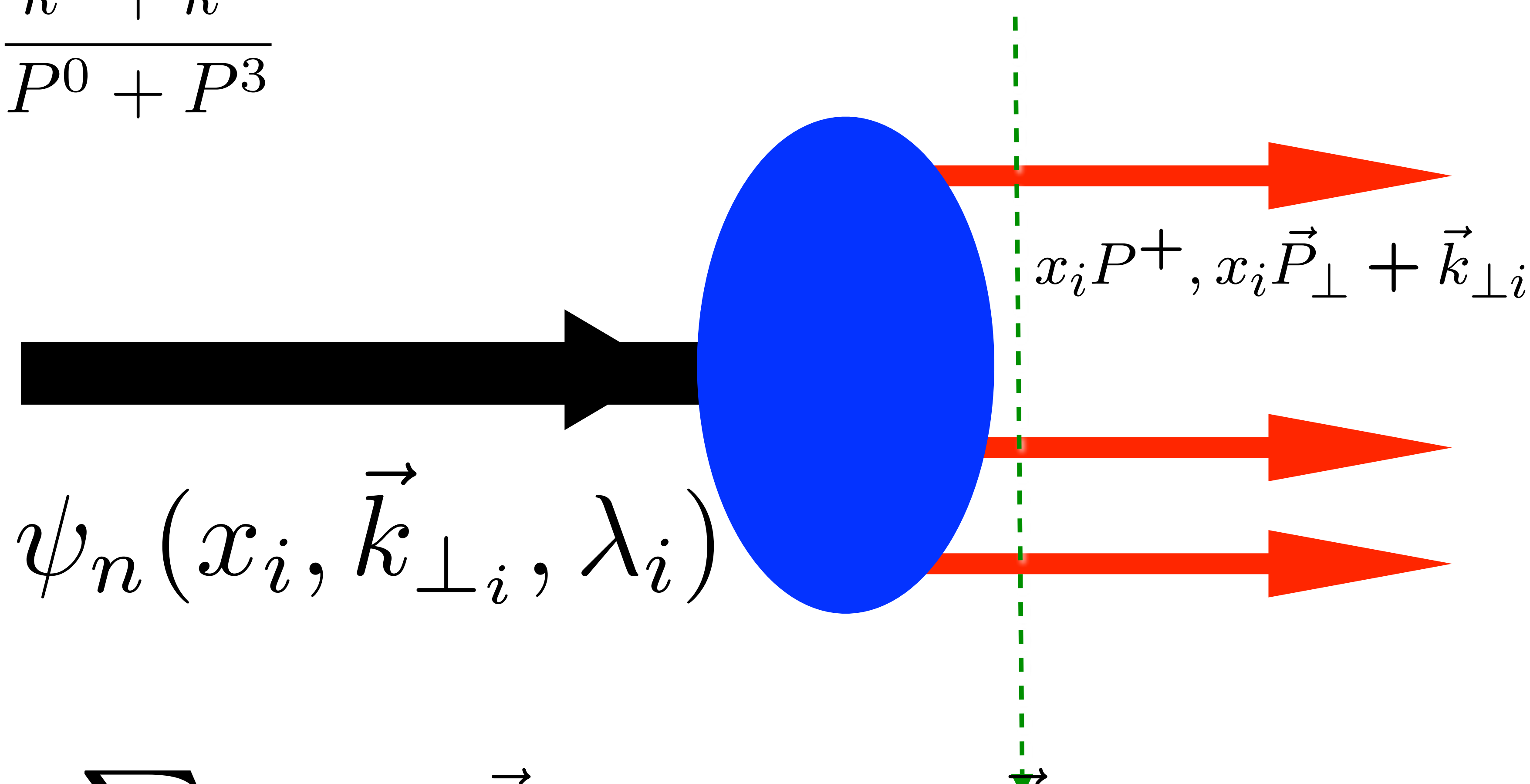
Light-Front Wavefunctions: rigorous representation of composite systems in quantum field theory

Eigenstate of LF Hamiltonian

$$x = \frac{k^+}{P^+} = \frac{k^0 + k^3}{P^0 + P^3}$$

Fixed $\tau = t + z/c$

$P^+, \vec{P}_\perp$



$$|p, J_z> = \sum_{n=3} \psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)|n; x_i, \vec{k}_{\perp i}, \lambda_i>$$

$\sum_i^n x_i = 1$

$\sum_i^n \vec{k}_{\perp i} = \vec{0}_\perp$

$\psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$ invariant under boosts! Independent of $P^+, \vec{P}_\perp$

Causal, Frame-independent. Creation Operators on Simple Vacuum, Current Matrix Elements are Overlaps of LFWFS

Angular Momentum on the Light-Front

$$J^z = \sum_{i=1}^{n} s_i^z + \sum_{j=1}^{n-1} l_j^z.$$

Conserved
LF Fock state by Fock State!

LF Spin Sum Rule

$$l_j^z = -\mathrm{i}\left(k_j^1 \frac{\partial}{\partial k_j^2} - k_j^2 \frac{\partial}{\partial k_j^1}\right)$$

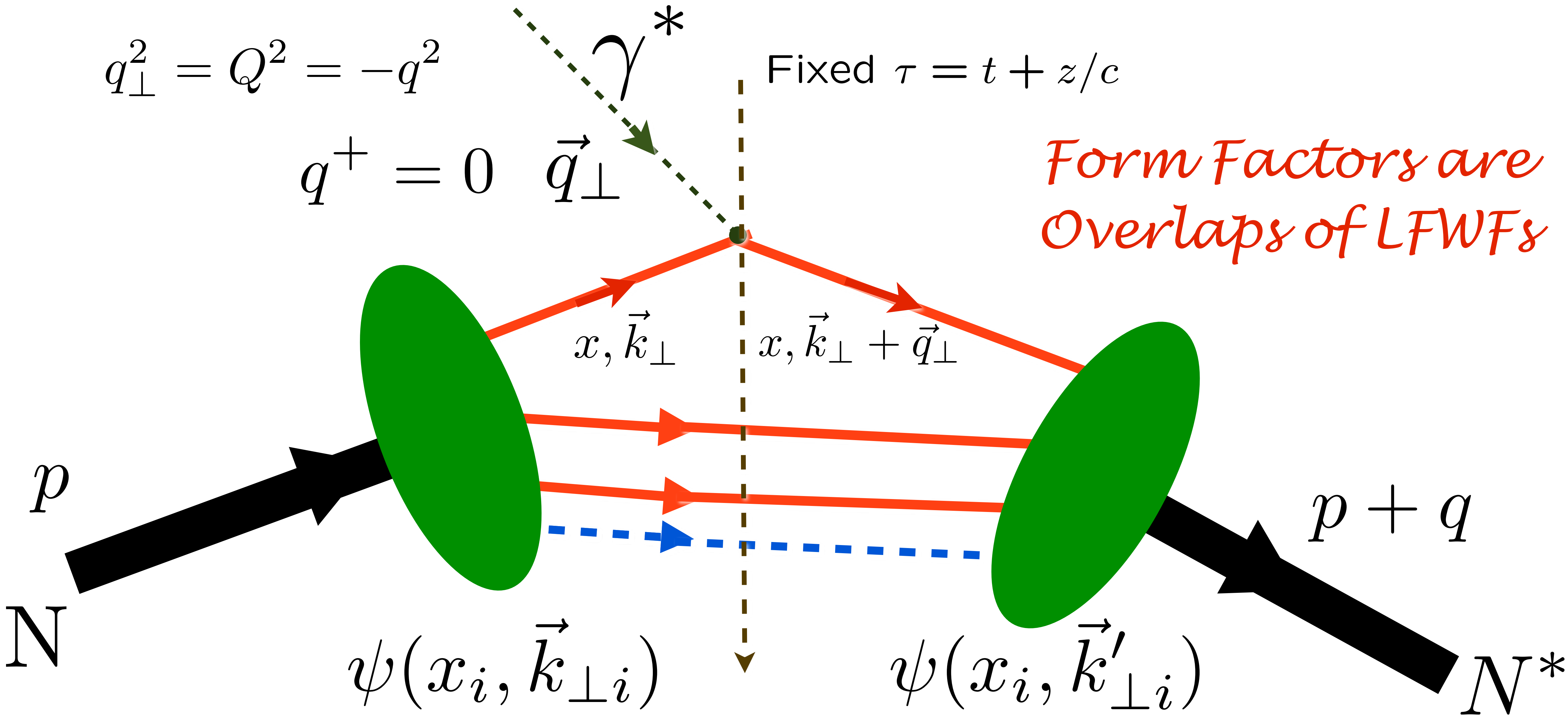
n-1 orbital angular momenta

Orbital angular momentum is a property of Light-Front Wavefunctions

Nonzero Anomalous Moment -->Nonzero orbital angular momentum

$$< p+q|j^+(0)|p >= 2p^+F(q^2)$$

Interaction picture



struck $\vec{k}'_{\perp i} = \vec{k}_{\perp i} + (1 - x_i)\vec{q}_\perp$

spectators $\vec{k}'_{\perp i} = \vec{k}_{\perp i} - x_i\vec{q}_\perp$

Drell &Yan, West
Drell, sjb
Exact LF formula

Sum over Fock states

Exact LF Formula for Pauli Form Factor

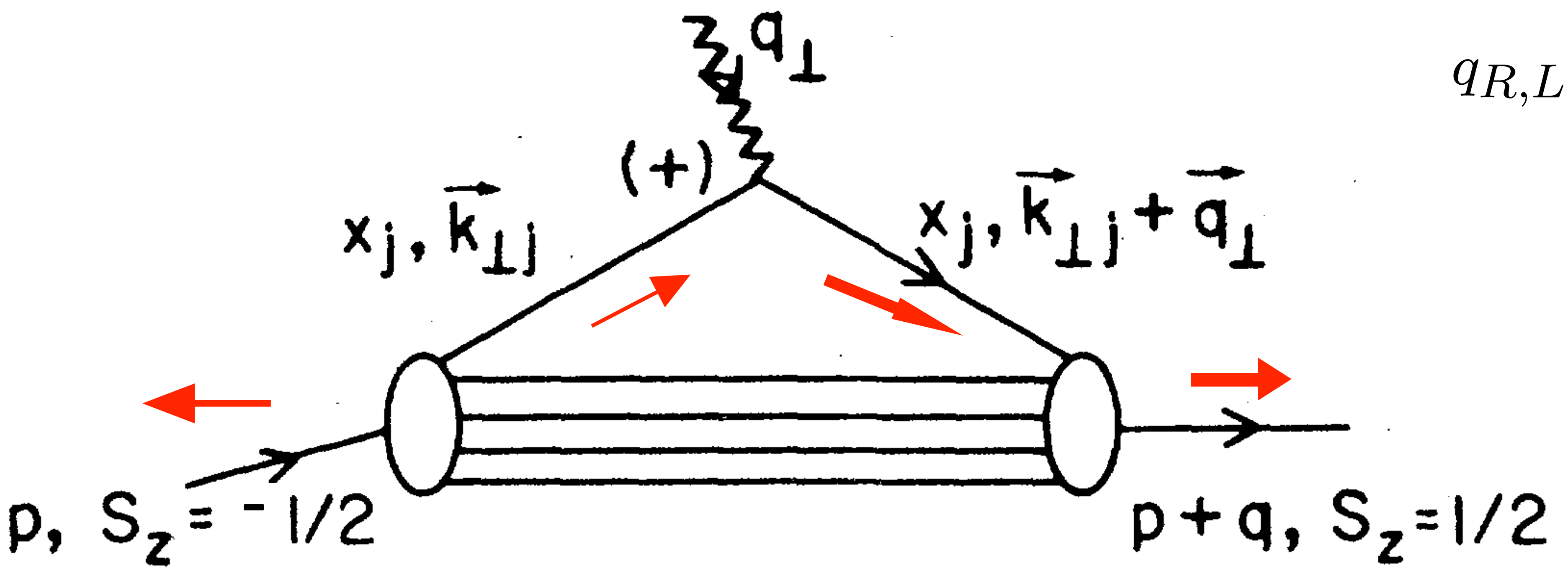
$$\frac{F_2(q^2)}{2M} = \sum_a \int [\mathrm{d}x][\mathrm{d}^2\mathbf{k}_\perp] \sum_j e_j \, \frac{1}{2} \times$$

Drell, sjb

$$\left[-\frac{1}{q^L}\psi_a^{\uparrow *}(x_i, \mathbf{k}'_{\perp i}, \lambda_i)\, \psi_a^{\downarrow}(x_i, \mathbf{k}_{\perp i}, \lambda_i) + \frac{1}{q^R}\psi_a^{\downarrow *}(x_i, \mathbf{k}'_{\perp i}, \lambda_i)\, \psi_a^{\uparrow}(x_i, \mathbf{k}_{\perp i}, \lambda_i) \right]$$

$$\mathbf{k}'_{\perp i} = \mathbf{k}_{\perp i} - x_i \mathbf{q}_\perp \qquad \mathbf{k}'_{\perp j} = \mathbf{k}_{\perp j} + (1 - x_j)\mathbf{q}_\perp$$

$$q_{R,L} = q^x \pm i q^y$$

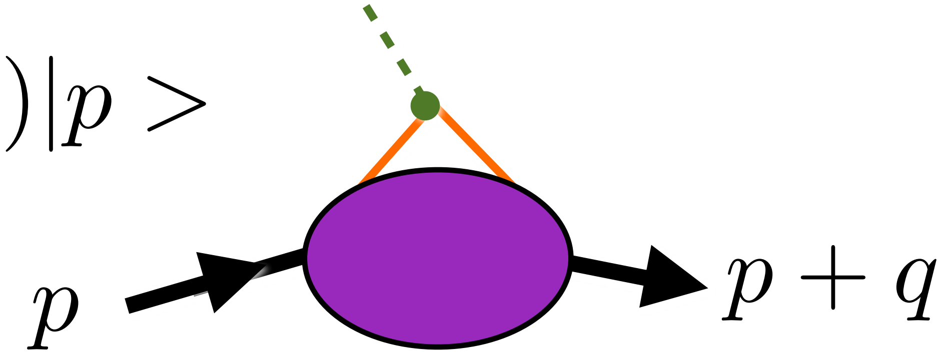


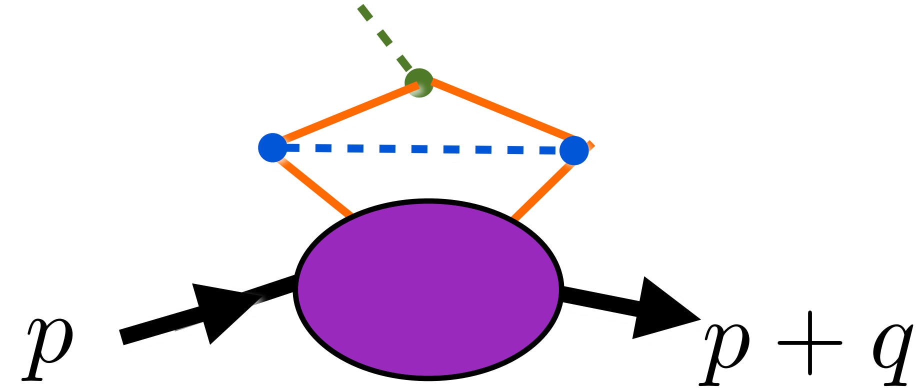
Must have $\Delta \ell_z = \pm 1$ to have nonzero $F_2(q^2)$

Nonzero Proton Anomalous Moment -->
Nonzero orbital quark angular momentum

Calculation of proton form factor in Instant Form

$$< p+q|J^\mu(0)|p >$$





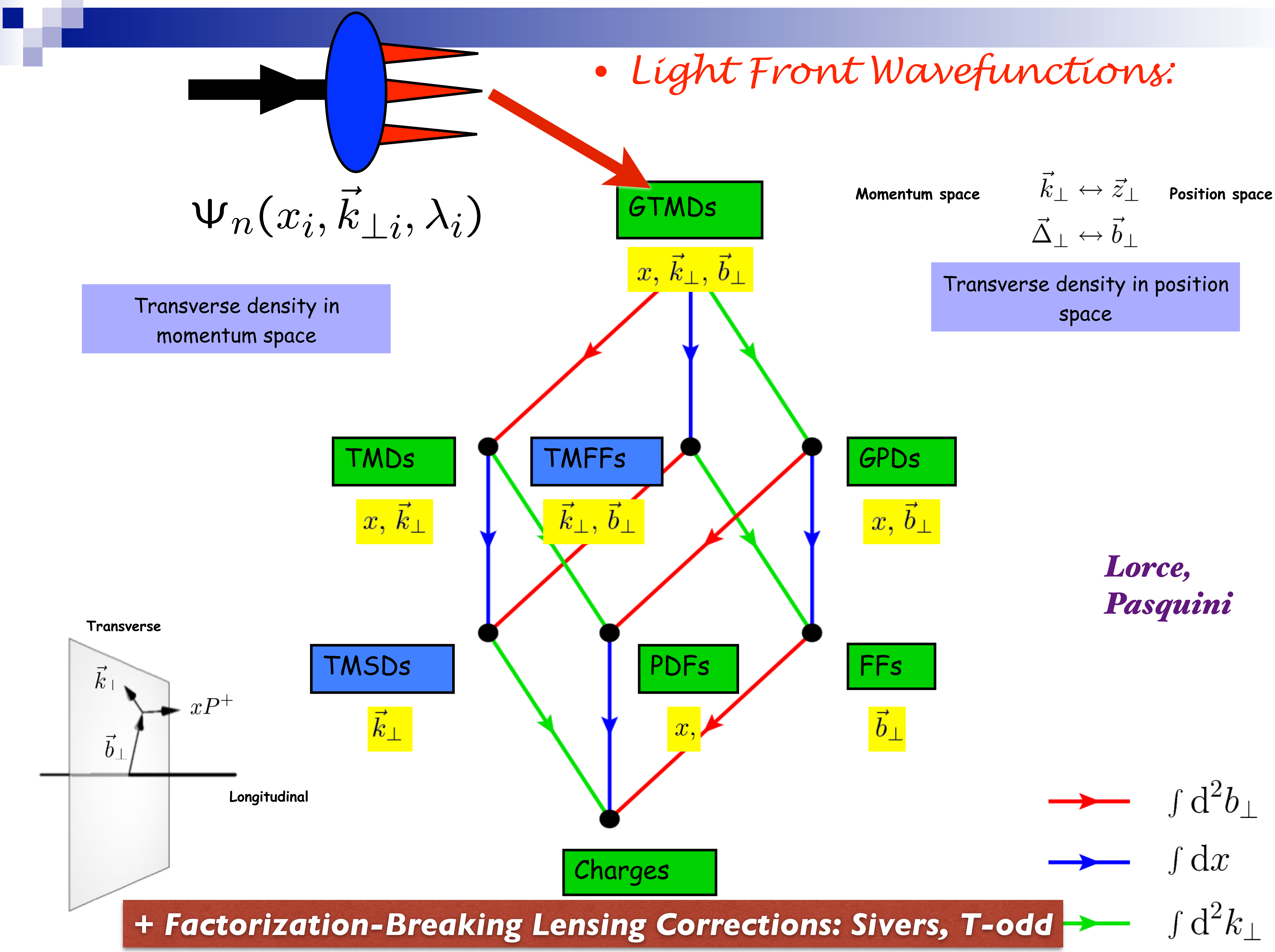
- **Need to boost proton wavefunction: p to p+q.**
  Extremely complicated dynamical problem.
  Particle number changes

- **Need to couple to all currents arising from vacuum!!**
  Remain even after normal-ordering

- **Instant-form WFs insufficient to calculate form factors**

- **Each time-ordered contribution is frame-dependent**

- **Normal order; Divide by disconnected vacuum diagrams**


• Light Front Wavefunctions:
$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$
GTMDs
$x, \vec{k}_\perp, \vec{b}_\perp$
Momentum space
$\vec{k}_\perp \leftrightarrow \vec{z}_\perp$
Position space
$\vec{\Delta}_\perp \leftrightarrow \vec{b}_\perp$
Transverse density in momentum space
Transverse density in position space
TMDs
$x, \vec{k}_\perp$
TMFFs
$\vec{k}_\perp, \vec{b}_\perp$
GPDs
$x, \vec{b}_\perp$
Lorce, Pasquini
Transverse
$\vec{k}_\perp$
xP^+
$\vec{b}_\perp$
Longitudinal
TMSDs
$\vec{k}_\perp$
PDFs
$x,$
FFs
$\vec{b}_\perp$
Charges
$\int d^2 b_\perp$
$\int dx$
$\int d^2 k_\perp$
+ Factorization-Breaking Lensing Corrections: Sivers, T-odd

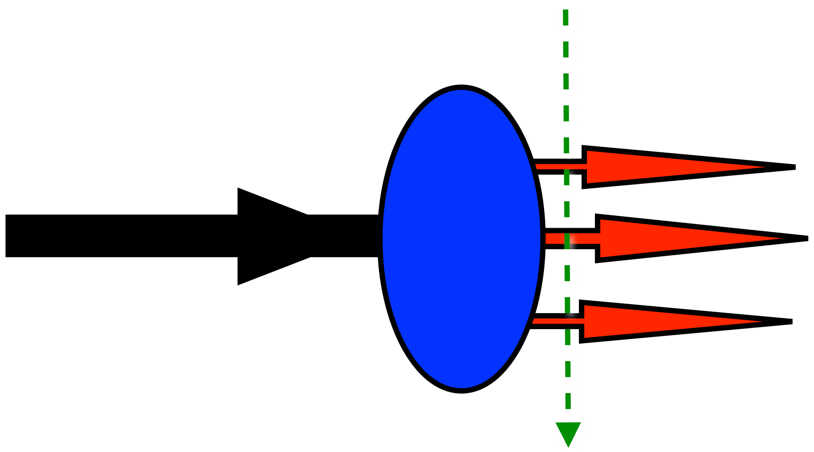
Advantages of the Dirac's Front Form for Hadron Physics

- **Measurements are made at fixed τ**
- **Causality is automatic**
- **Structure Functions are squares of LFWFs**
- **Form Factors are overlap of LFWFs**
- **LFWFs are frame-independent -- no boosts!**
- **No dependence on observer's frame**
- **LF Holography: Dual to AdS space**
- **LF Vacuum trivial -- no condensates!**
- **Profound implications for Cosmological Constant**

Bound States in Relativistic Quantum Field Theory:

Light-Front Wavefunctions

Dirac's Front Form: Fixed $\tau = t + z/c$



$$\psi(x_i, \vec{k}_{\perp i}, \lambda_i)$$

$$x_i = \frac{k_i^+}{P^+}$$

Invariant under boosts. Independent of P^μ

$$\mathrm{H}_{LF}^{QCD} |\psi> = M^2 |\psi>$$

Direct connection to QCD Lagrangian

Remarkable new insights from AdS/CFT, the duality between conformal field theory and Anti-de Sitter Space

Light-Front QCD

Physical gauge: $A^{+} = 0$

Exact frame-independent formulation of nonperturbative QCD!

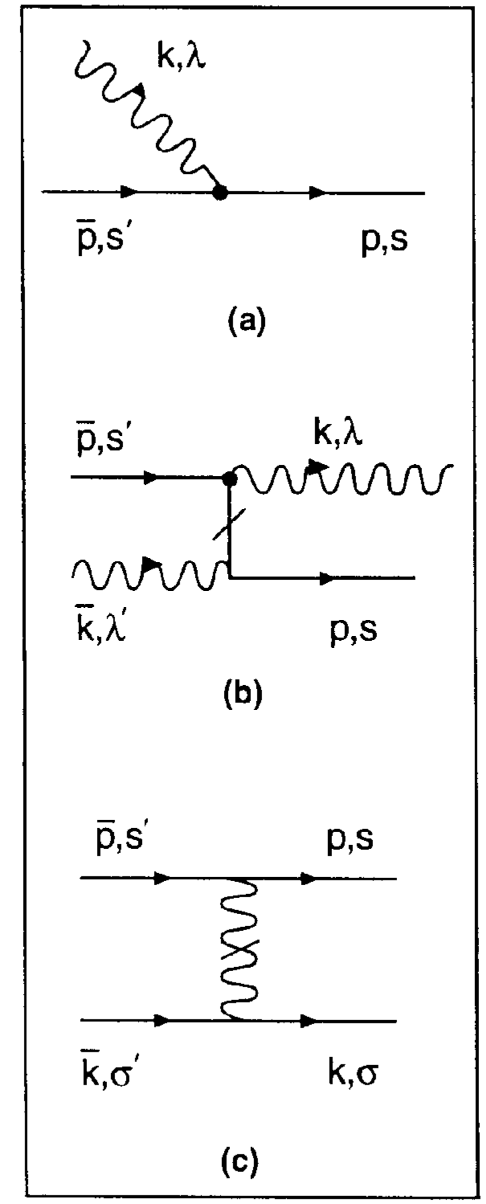
$$L^{QCD} \rightarrow H^{QCD}_{LF}$$

$$H^{QCD}_{LF} = \sum_i \left[\frac{m^2 + k^2_{\perp}}{x}\right]_i + H^{int}_{LF}$$

H^{int}_{LF}: Matrix in Fock Space

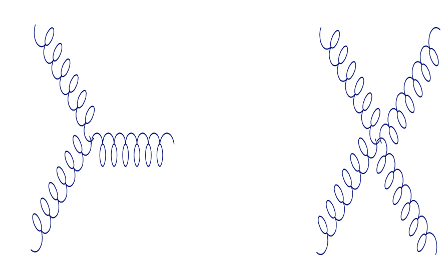
$$H^{QCD}_{LF}|\Psi_h> = \mathcal{M}^2_h|\Psi_h>$$

$$|p, J_z> = \sum_{n=3} \psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)|n; x_i, \vec{k}_{\perp i}, \lambda_i>$$



Eigenvalues and Eigensolutions give Hadronic Spectrum and Light-Front wavefunctions

LFWFs: Off-shell in P- and invariant mass

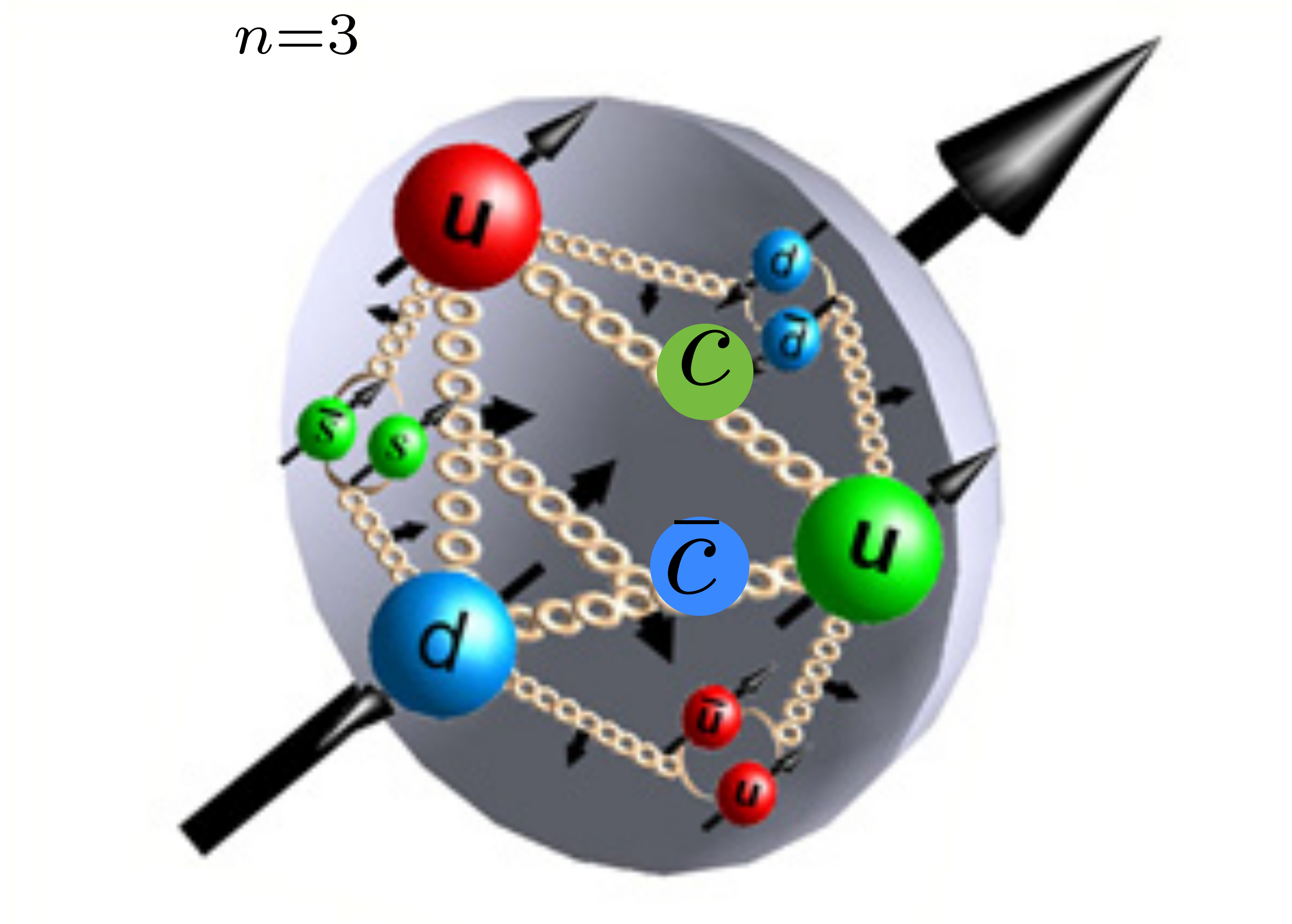


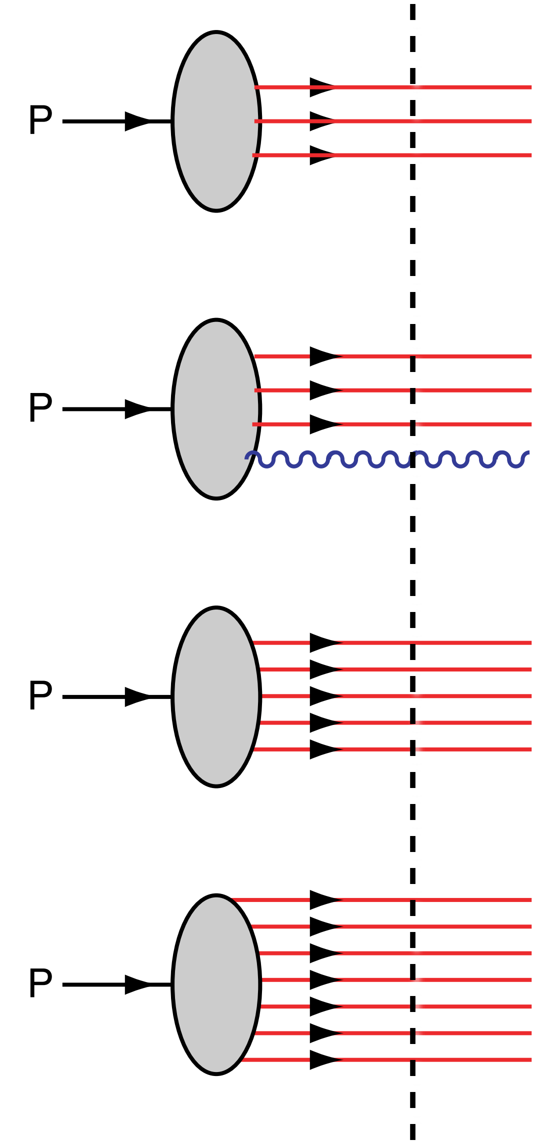
$$H^{int}_{LF}$$

Wavefunction at fixed LF time: Arbitrarily Off-Shell in Invariant Mass

Eigenstate of LF Hamiltonian : all Fock states contribute

$$|p, J_z> = \sum_{n=3} \psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)|n; x_i, \vec{k}_{\perp i}, \lambda_i>$$





Higher Fock States of the Proton

Fixed LF time

$$|p, S_z> = \sum_{n=3} \Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) |n; \vec{k}_{\perp_i}, \lambda_i>$$

sum over states with n=3, 4, ...constituents

The Light Front Fock State Wavefunctions

$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

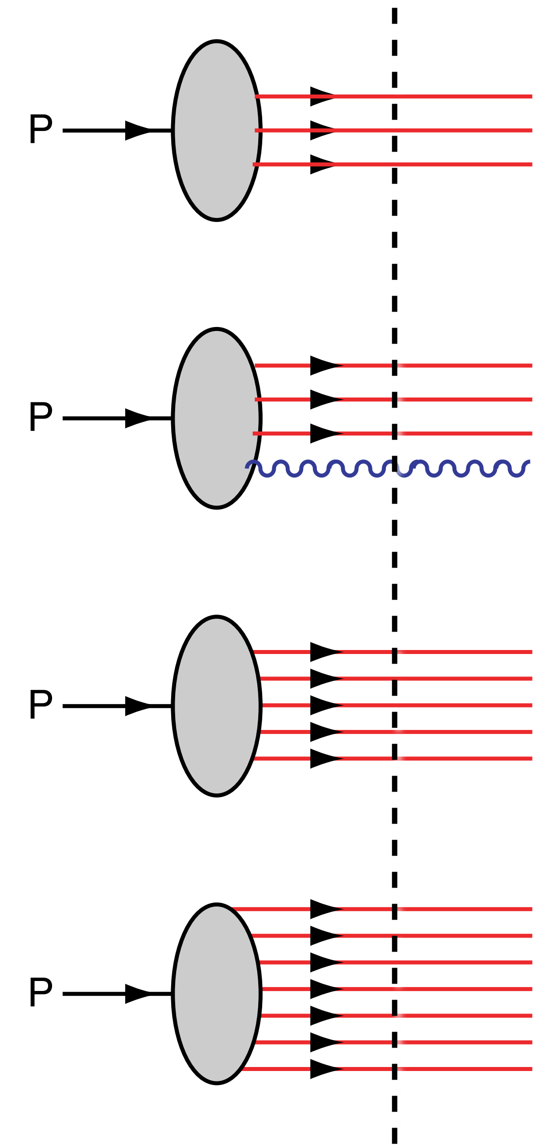
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

The light-cone momentum fraction

$$x_i = \frac{k_i^+}{p^+} = \frac{k_i^0 + k_i^z}{P^0 + P^z}$$

are boost invariant.

$$\sum_i^n k_i^+ = P^+, \ \sum_i^n x_i = 1, \ \sum_i^n \vec{k}_i^\perp = \vec{0}^\perp.$$



Fixed LF time

Intrinsic heavy quarks

s(x), c(x), b(x) at high x !

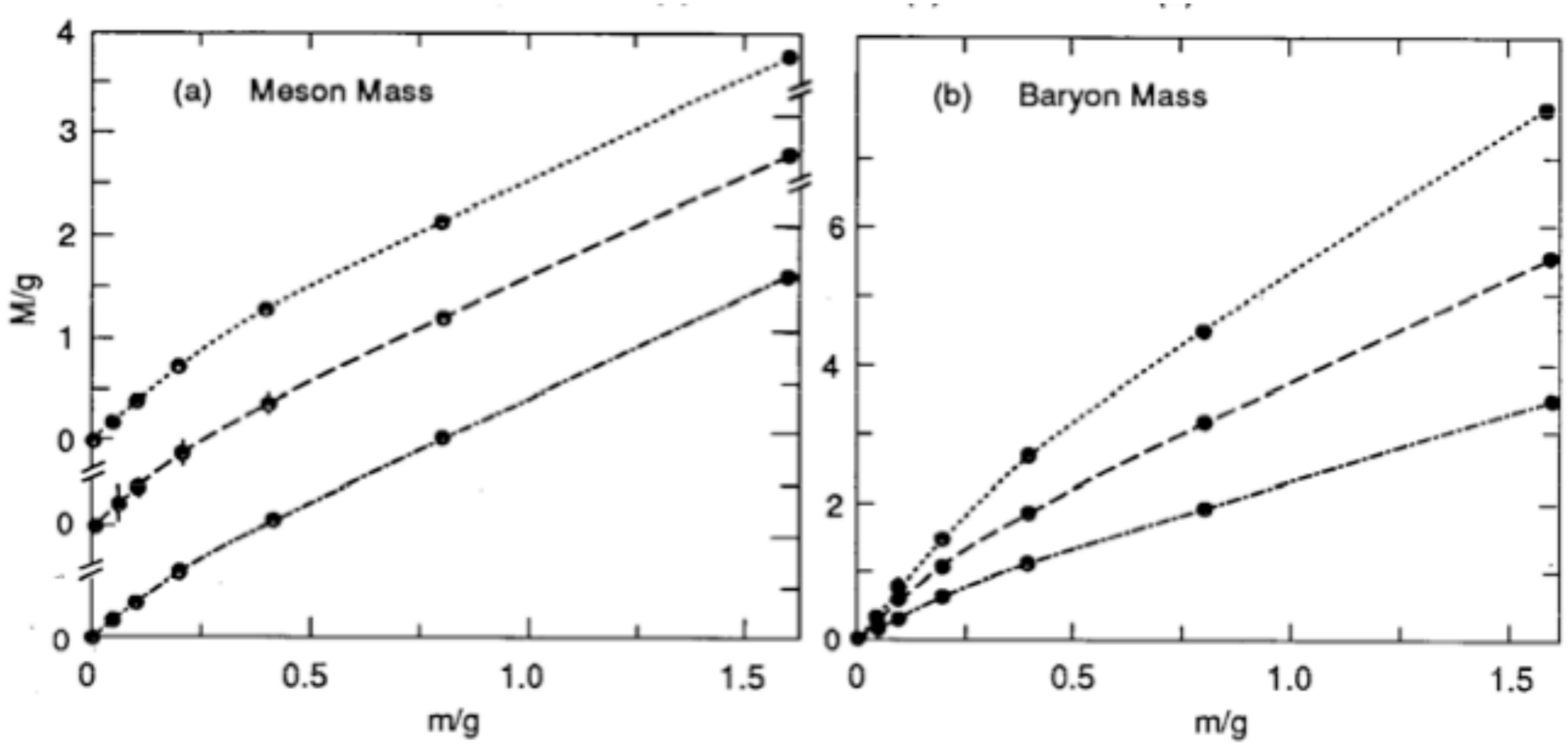
$\bar{s}(x) \neq s(x)$

$\bar{u}(x) \neq \bar{d}(x)$

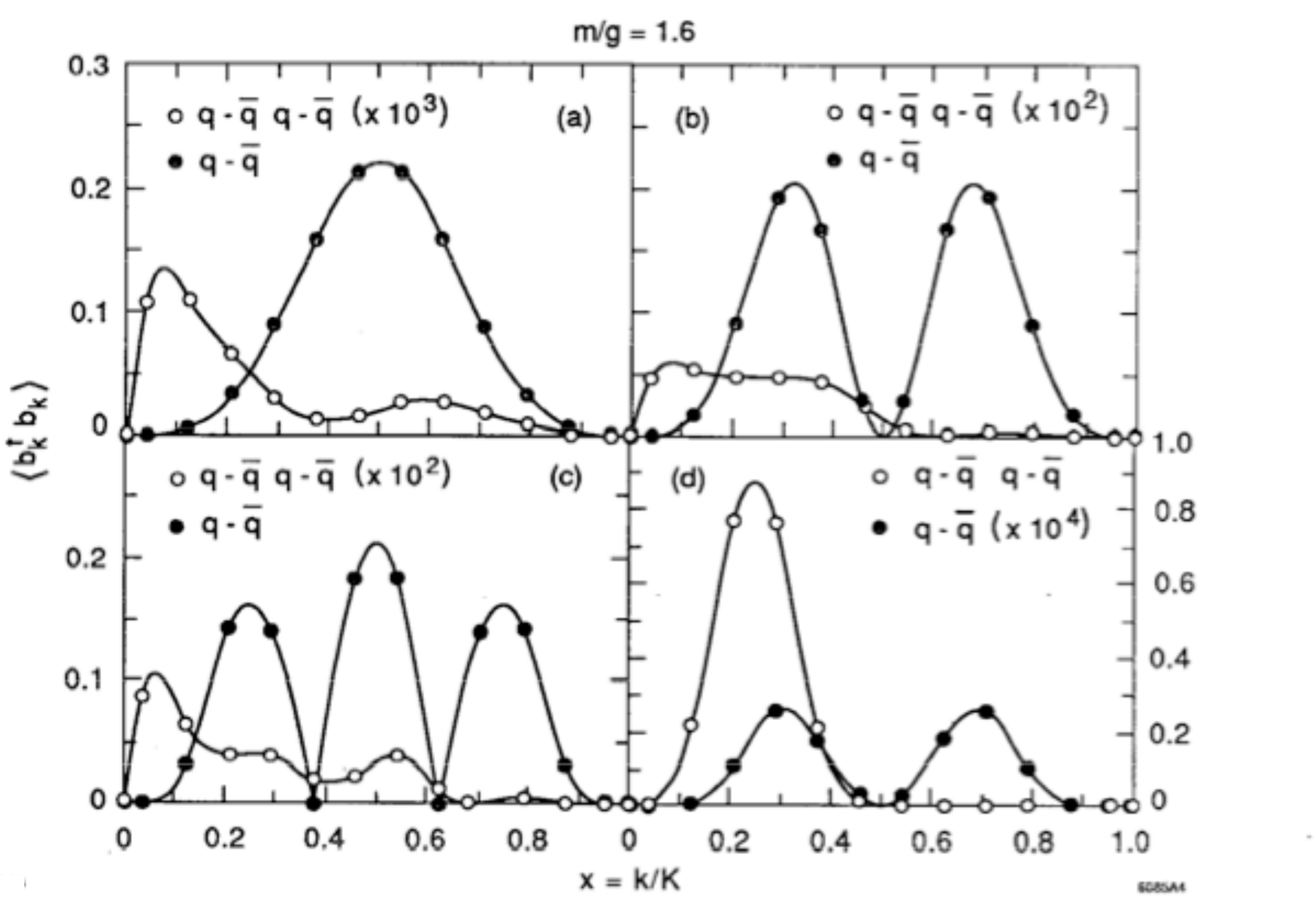
Mueller: gluon Fock states BFKL Pomeron

Hidden Color

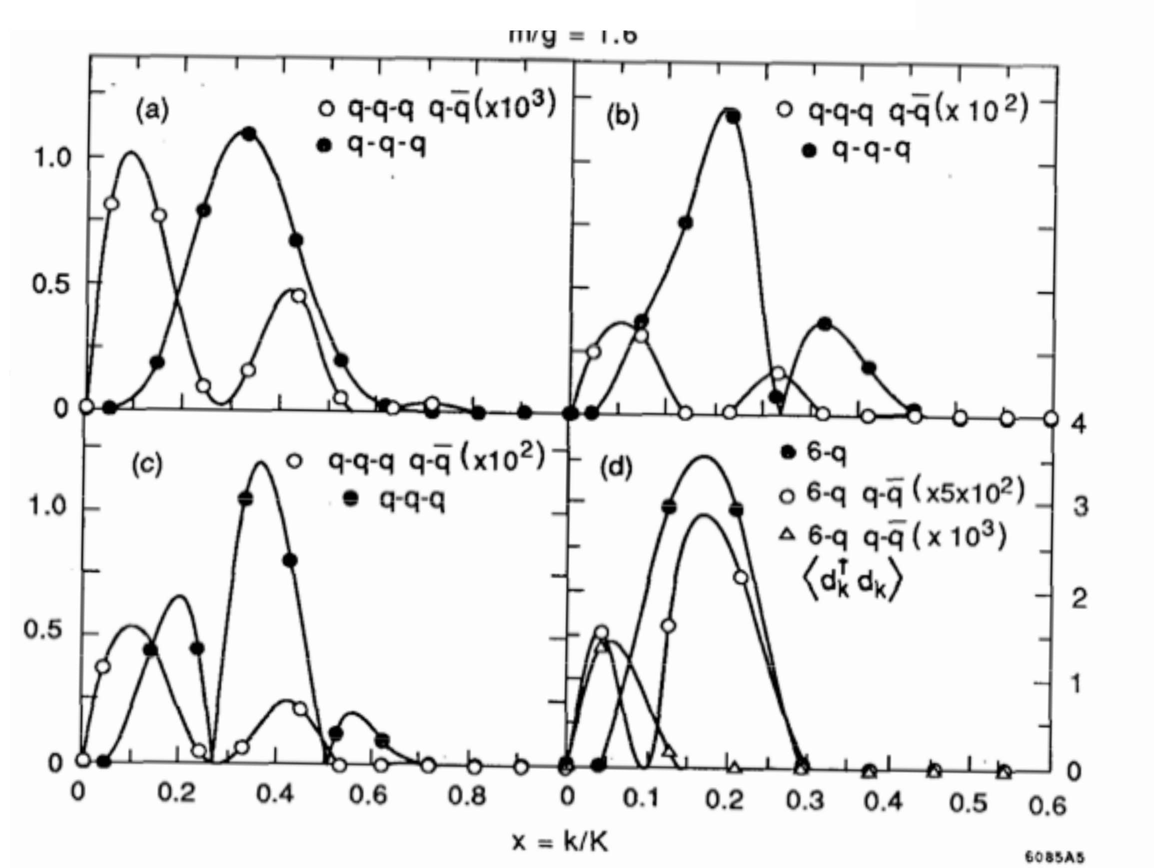
DLCQ: Solve QCD(1+1) for any quark mass and flavors



Extrapolated masses for $N = 2, 3$ and 4 meson and baryon.



a-c) First three states in $N = 3$ meson spectrum for $m/g = 1.6$, 2K=24. d) Eleventh state.



a-c) First three states in $N = 3$ baryon spectrum, 2K=21. d) First $B = 2$ state.

Hornbostel, Pauli, sjb

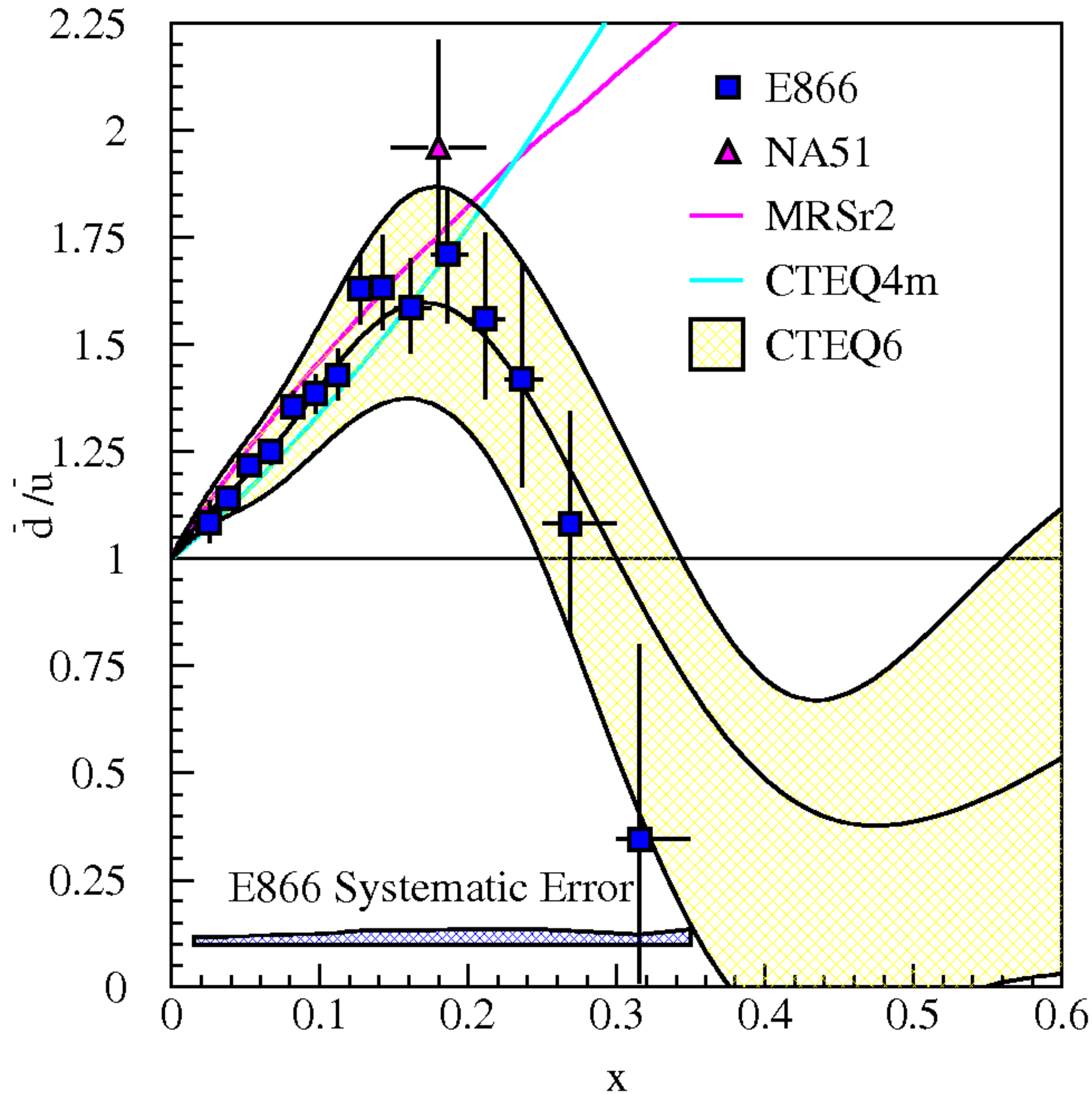
- E866/NuSea (Drell-Yan)

$$\bar{d}(x) \neq \bar{u}(x)$$

$$s(x) \neq \bar{s}(x)$$

Intrinsic glue, sea, heavy quarks

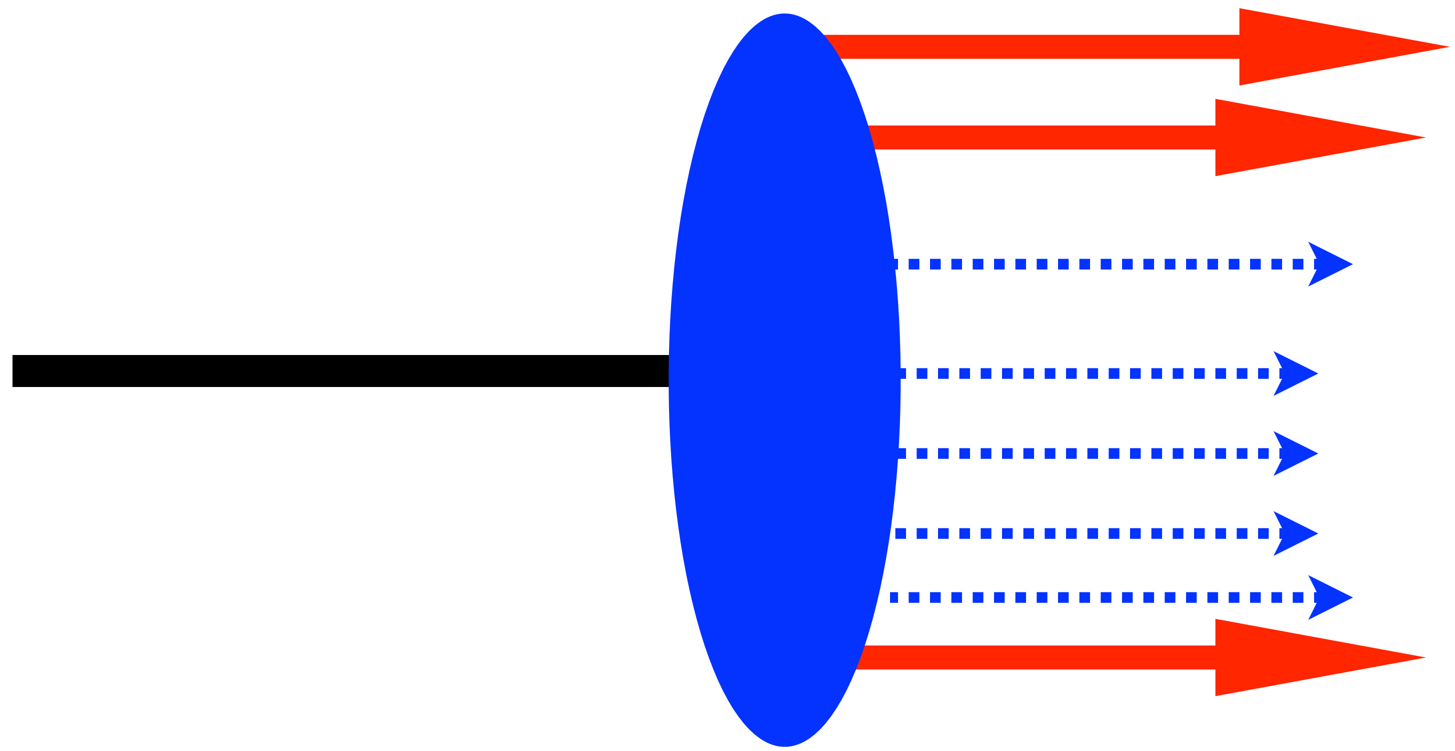
$\bar{d}(x)/\bar{u}(x)$ for $0.015 \leq x \leq 0.35$



Soft gluons in the infinite momentum wave function and the BFKL **pomeron.**
Alfred H. Mueller (SLAC & Columbia U.) . SLAC-PUB-10047, CU-TP-609, Aug 1993. 12pp.
Published in **Nucl.Phys.B415:373-385,1994**.

Light cone wave functions at small x.
F. Antonuccio (Heidelberg, Max Planck Inst. & Heidelberg U.) , S.J. Brodsky (SLAC) , S. Dalley (CERN) .
Phys.Lett.B412:104-110,1997.
e-Print: **hep-ph/9705413**

Mueller: BFKL derived from multi-gluon Fock State



Antonuccio, Dalley, sjb: Ladder Relations

Static	Dynamic
Square of Target LFWFs	Modified by Rescattering: ISI & FSI
No Wilson Line	Contains Wilson Line, Phases
Probability Distributions	No Probabilistic Interpretation
Process-Independent	Process-Dependent - From Collision
T-even Observables	T-Odd (Sivers, Boer-Mulders, etc.)
No Shadowing, Anti-Shadowing	Shadowing, Anti-Shadowing, Saturation
Sum Rules: Momentum and J^z	Sum Rules Not Proven
DGLAP Evolution; mod. at large x	DGLAP Evolution
No Diffractive DIS	Hard Pomeron and Odderon Diffractive DIS

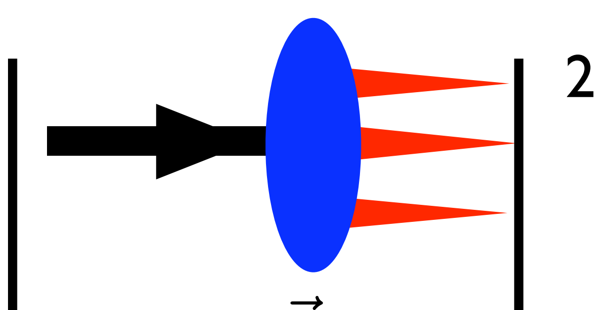
Hwang, Schmidt, sjb,

Mulders, Boer

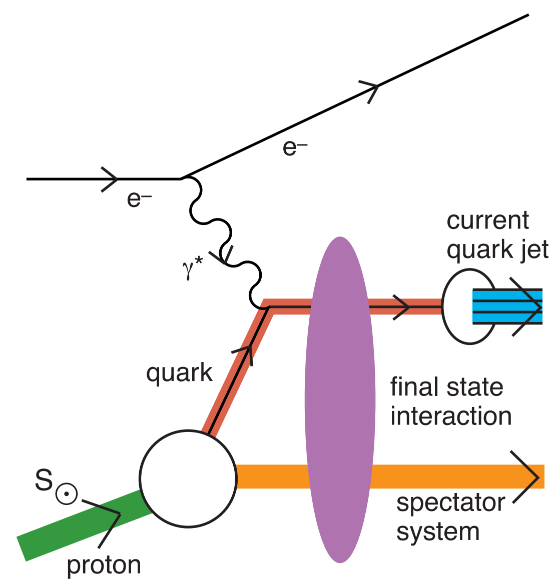
Qiu, Sterman

Collins, Qiu

Pasquini, Xiao, Yuan, sjb



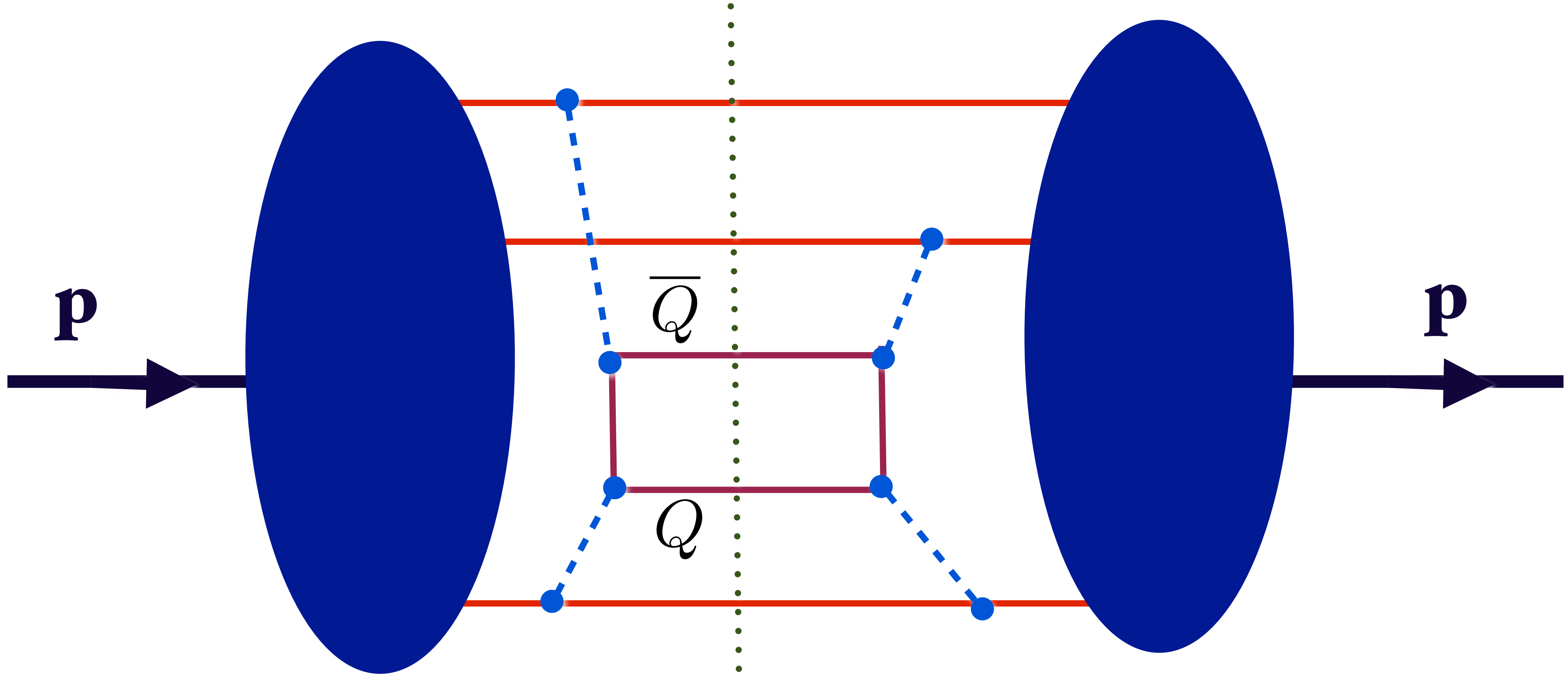
$$\left|\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)\right|^2$$



Fixed LF time

Proton Self Energy
Intrinsic Heavy Quarks

$$x_Q \propto (m_Q^2 + k_\perp^2)^{1/2}$$

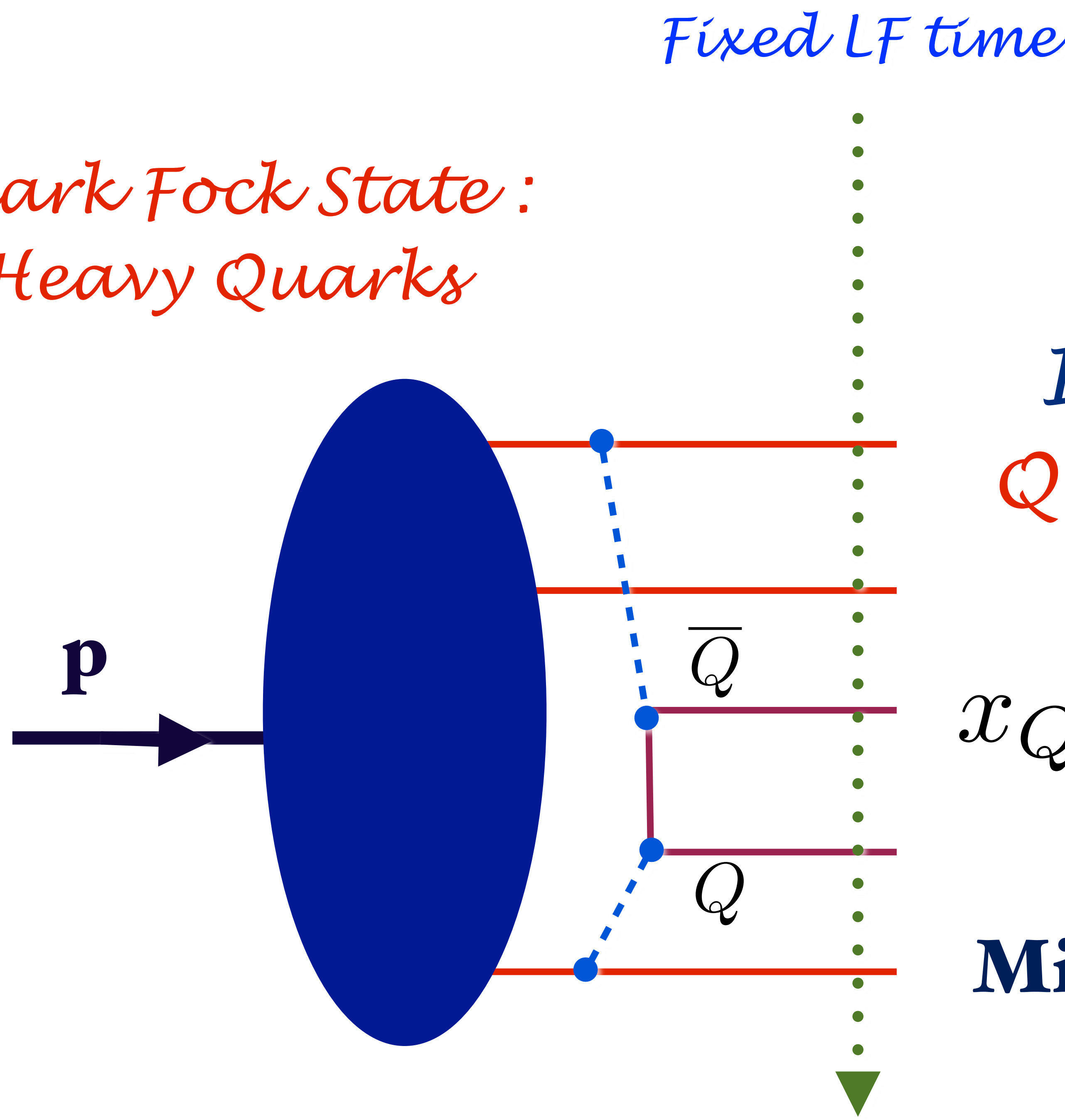


Probability (QED) $\propto \frac{1}{M_\ell^4}$

Probability (QCD) $\propto \frac{1}{M_Q^2}$

Collins, Ellis, Gunion, Mueller, sjb
M. Polyakov, et al.

Proton 5-quark Fock State :
Intrinsic Heavy Quarks



QCD predicts Intrinsic Heavy Quarks at high x!

$$x_Q \propto (m_Q^2 + k_\perp^2)^{1/}$$

Minimal off-shellness

$$\text{Probability (QED)} \propto \frac{1}{M_\ell^4} \qquad \text{Probability (QCD)} \propto \frac{1}{M_Q^2}$$

Collins, Ellis, Gunion, Mueller, sjb
M. Polyakov, et al.

Aug 1984. 10 pp.
DOE/ER/40048-21 P4, C84/06/23
C84-06-23 (Snowmass Summer Study 1984:0227)

INTRINSIC CHEVROLETS AT THE SSC

DE85

Stanley J. Brodsky

Stanford Linear Accelerator Center, Stanford University, Stanford CA 94305

John C. Collins

Department of Physics, Illinois Institute of Technology, Chicago IL 60616
and
High Energy Physics Division, Argonne National Laboratory, Argonne IL 60439

Stephen D. Ellis

Department of Physics, FM-15, University of Washington, Seattle WA 98195

John F. Gunion

Department of Physics, University of California, Davis CA 95616

Alfred H. Mueller

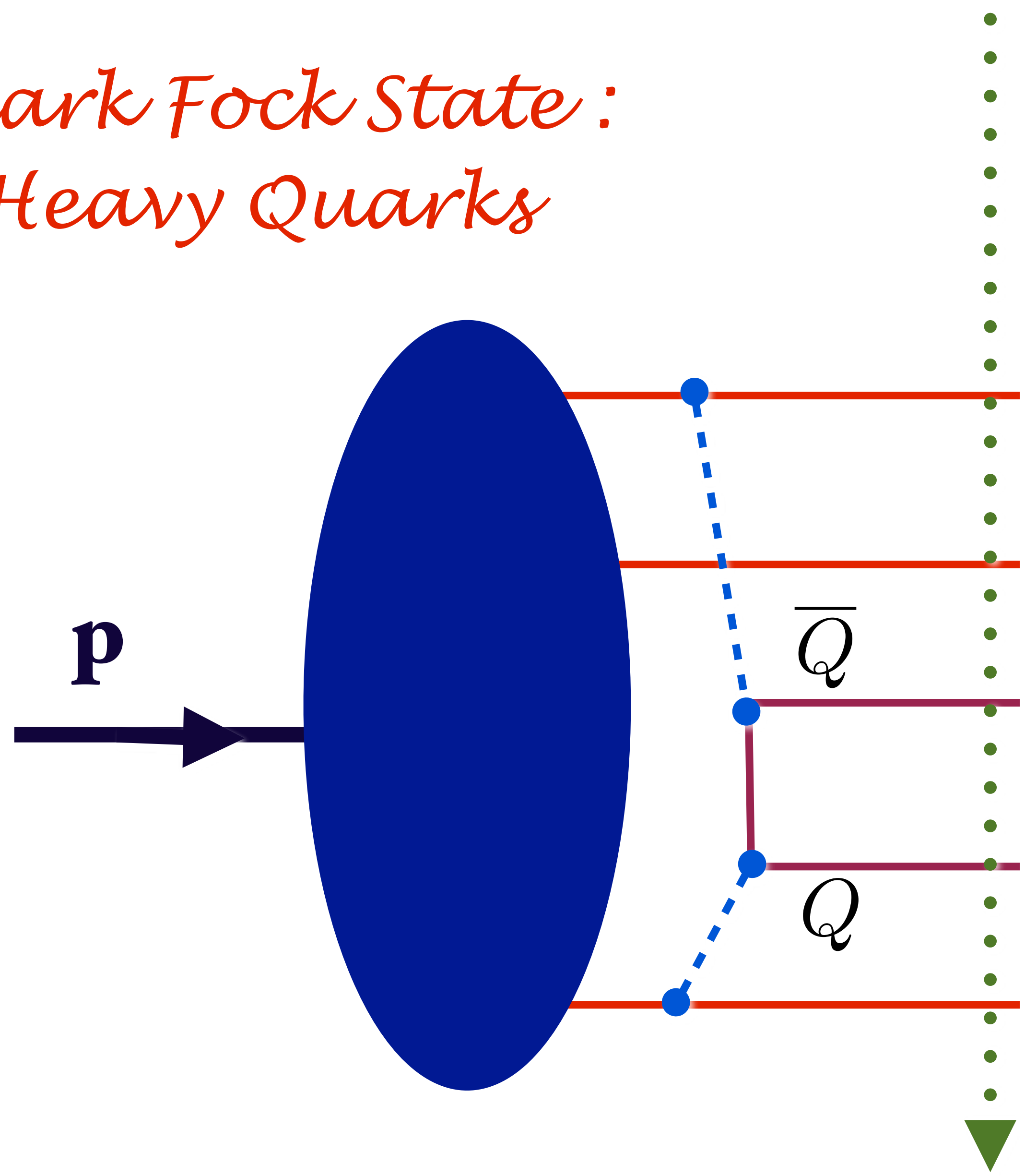
Department of Physics, Columbia University, New York NY 10027

$$\mathcal{L}^{eff}_{QCD} = -\frac{1}{4} F_{\mu\nu a} F^{\mu\nu a} - \frac{g^2}{120\pi^2 M_Q^2} D_\alpha F_{\mu\nu a} D^\alpha F^{\mu\nu a} + C \frac{g^3}{\pi^2 M_Q^2} F_\mu^{a\nu} F_\nu^{b\tau} F_\tau^{c\mu} f_{abc} + \mathcal{O}(\frac{1}{M_Q^4})$$

QCD predicts ***Intrinsic Heavy Quarks at high x!***

Proton 5-quark Fock State: Intrinsic Heavy Quarks

Fixed LF time



Minimal off-shellness

$$x_Q \propto (m_Q^2 + k_\perp^2)^{1/2}$$

Equal rapidity
all at rest in hadron frame
maximum coalescence

$$\frac{dP_{uud\bar{Q}Q}}{d\mathcal{M}^2} \propto \frac{1}{\mathcal{M}^4}$$

$$\text{Probability (QCD)} \propto \frac{1}{M_Q^2}$$

Collins, Ellis, Gunion, Mueller, sjb
M. Polyakov, et al.

THE INTRINSIC CHARM OF THE PROTON

S.J. BRODSKY [1]
Stanford Linear Accelerator Center,
Stanford, California 94305, USA

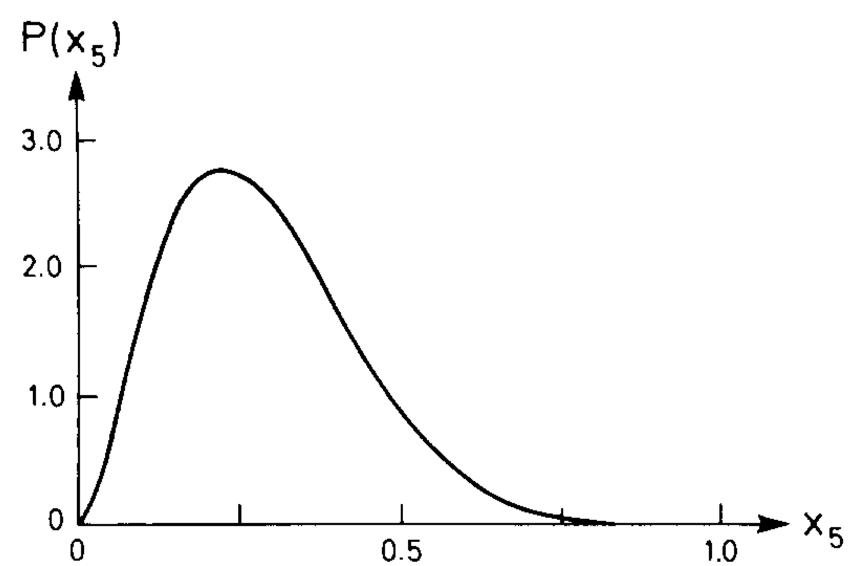
and

P. HOYER, C. PETERSON and N. SAKAI [2]
NORDITA, Copenhagen, Denmark

Received 22 April 1980

$$P(x_4, x_5) = \tfrac{1}{2} N \frac{x_4^2 x_5^2}{(x_4 + x_5)^2} (1 - x_4 - x_5)^2 \,.$$

$$P(x_5) = \tfrac{1}{2} N x_5^2 \left[\tfrac{1}{3}(1 - x_5) \times (1 + 10x_5 + x_5^2) - 2x_5(1 + x_5)\ln 1/x_5\right]$$



PHYSICAL REVIEW D, VOLUME 62, 074024

Heavy quark mass expansion and intrinsic charm in light hadrons

M. Franz
Institut für Theoretische Physik II, Ruhr-Universität Bochum, D-44780 Bochum, Germany

M. V. Polyakov
Institut für Theoretische Physik II, Ruhr-Universität Bochum, D-44780 Bochum, Germany and Petersburg Nuclear Physics Institute, 188350 Gatchina, Russia

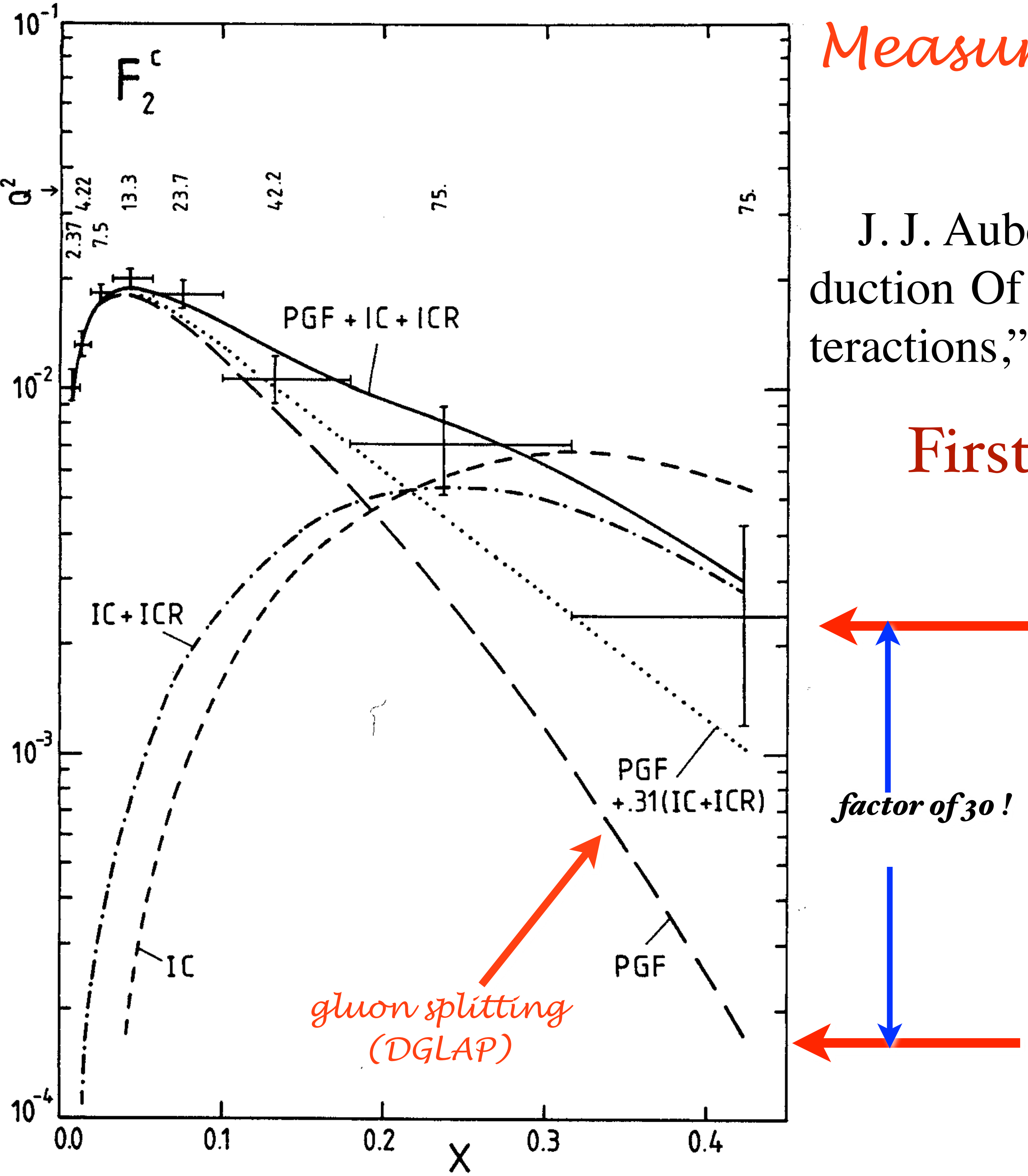
K. Goeke
Institut für Theoretische Physik II, Ruhr-Universität Bochum, D-44780 Bochum, Germany
(Received 17 April 2000; published 12 September 2000)

We review the technique of heavy quark mass expansion of various operators made of heavy quark fields using a semiclassical approximation. It corresponds to an operator product expansion in the form of a series in the inverse heavy quark mass. This technique applied recently to the axial vector current is used to estimate the charm content of the η, η' mesons and the intrinsic charm contribution to the proton spin. The derivation of heavy quark mass expansion for $\langle \bar{Q}\gamma_5 Q\rangle$ is given here in detail and the expansions of the scalar, vector and tensor current and of $\langle \bar{Q}\nabla_\mu \gamma_\nu Q\rangle$ (a contribution to the energy-momentum tensor) are presented as well. The obtained results are used to estimate the intrinsic charm contribution to various observables.

Heavy quark mass expansion of vector and tensor currents and intrinsic charm in nucleon form factors
1 M.V. Polyakov (Ruhr U., Bochum & St. Petersburg, INP), J. Sieverding (Ruhr U., Bochum).
May 26, 2015. 52 pp.
e-Print: **arXiv:1505.06942 [hep-ph] | PDF**

Heavy quark mass expansion and intrinsic charm in light hadrons
M. Franz (Ruhr U., Bochum), Maxim V. Polyakov (Ruhr U., Bochum & St. Petersburg, INP), K. Goeke (Ruhr U., Bochum). Feb 2000. 20 pp.
2 Published in **Phys.Rev. D62 (2000) 074024**
RUB-TP2-03-00, RUB-TPII-03-00
DOI: 10.1103/PhysRevD.62.074024
e-Print: **hep-ph/0002240 | PDF**

The Intrinsic charm contribution to the proton spin
Maxim V. Polyakov (St. Petersburg, INP & Ruhr U., Bochum), A. Schafer (Regensburg U.), O.V. Teryaev (Dubna, JINR). Dec 1998. 6 pp.
3 Published in **Phys.Rev. D60 (1999) 051502**
RUB-TPII-22-98, TPR-98-38
DOI: 10.1103/PhysRevD.60.051502
e-Print: **hep-ph/9812393 | PDF**

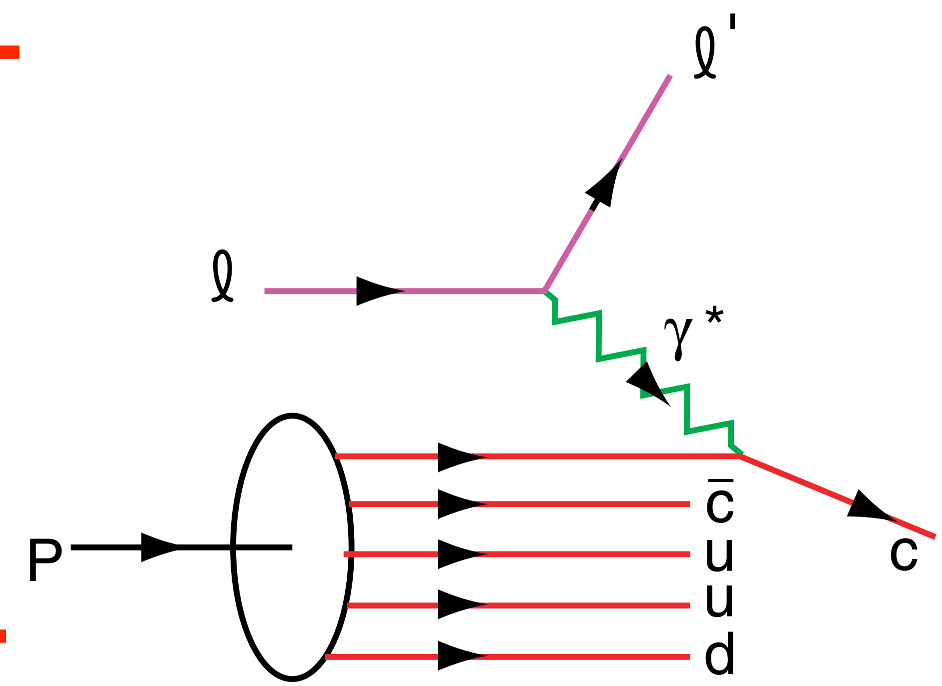


Measurement of Charm Structure Function!

J. J. Aubert et al. [European Muon Collaboration], "Production Of Charmed Particles In 250-Gev Mu+ - Iron Interactions," Nucl. Phys. B 213, 31 (1983).

First Evidence for Intrinsic Charm

Hoyer, Peterson, Sakai, sjb



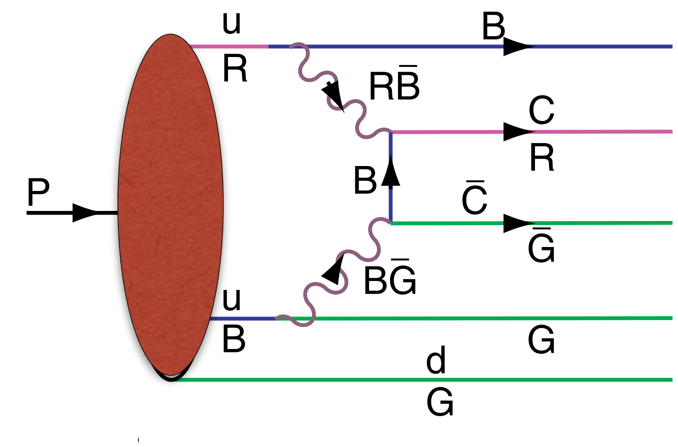
DGLAP / Photon-Gluon Fusion: factor of 30 too small

Two Components (separate evolution):

$$c(x, Q^2) = c(x, Q^2)_{\text{extrinsic}} + c(x, Q^2)_{\text{intrinsic}}$$

Hoyer, Peterson, Sakai, sjb

Intrinsic Heavy-Quark Fock



- **Rigorous prediction of QCD, OPE**
- **Color-Octet Color-Octet Fock State**
- **Probability** $P_{Q\bar{Q}} \propto \frac{1}{M_Q^2}$ $P_{Q\bar{Q}Q\bar{Q}} \sim \alpha_s^2 P_{Q\bar{Q}}$ $P_{c\bar{c}/p} \simeq 1\%$
- **Large Effect at high x**
- **Greatly increases kinematics of colliders such as Higgs production (Kopeliovich, Schmidt, Soffer, sjb)**
- **Underestimated in conventional parameterizations of heavy quark distributions (Pumplin, Tung)**

Do heavy quarks exist in the proton at high x?

Conventional wisdom:

Heavy quarks generated only at low x
via DGLAP evolution
from gluon splitting

Maximally off-shell - requires high W^2

$$s(x, \mu_F^2) = c(x, \mu_F^2) = b(x, \mu_F^2) \equiv 0$$

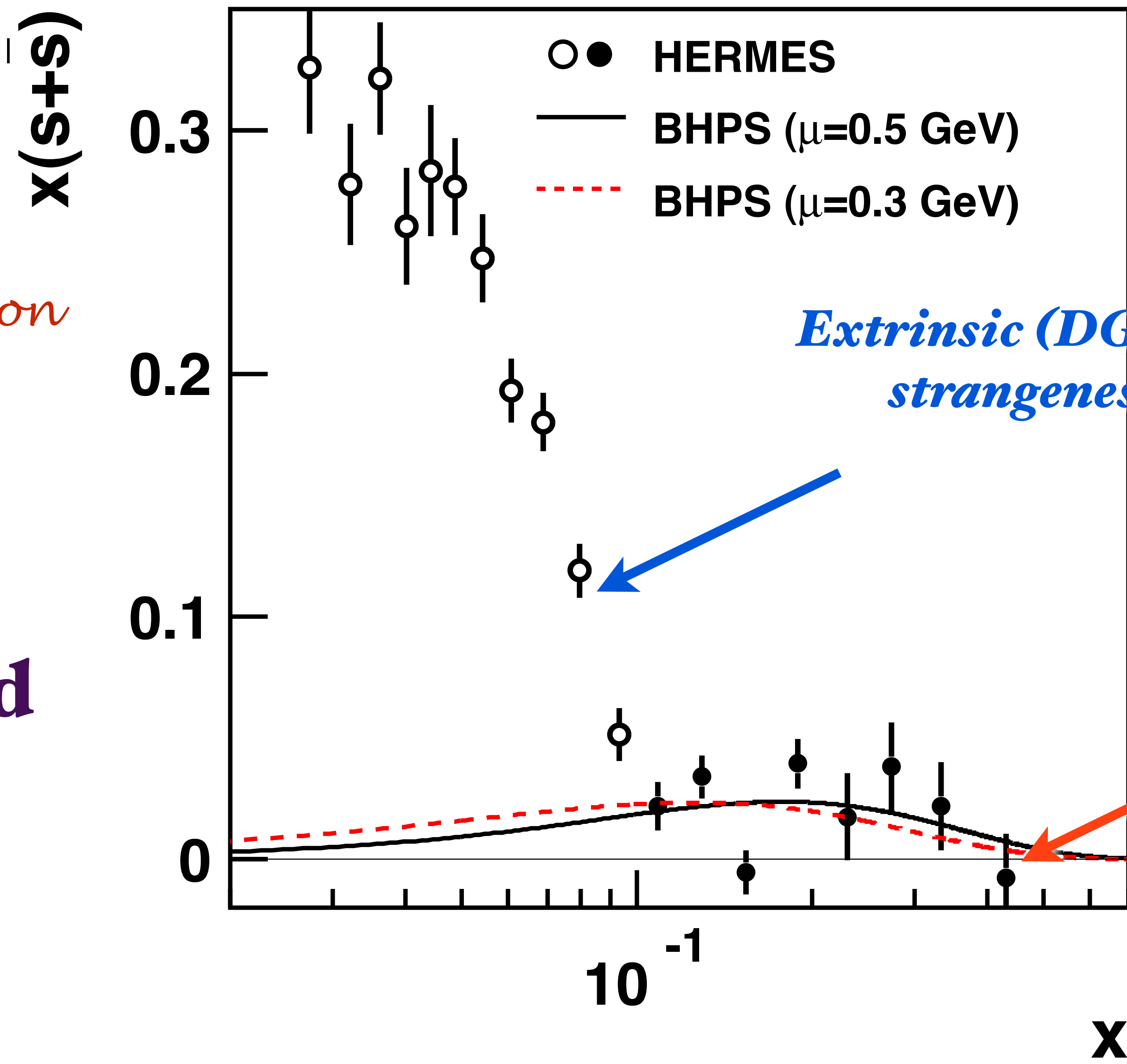
$$\text{at starting scale } Q_0^2 = \mu_F^2$$

Conventional wisdom is wrong even in QED!

HERMES: Two components to s(x,Q²)!

BHPS: Hoyer, Sakai, Peterson, sjb

Sensitive to Fragmentation Function



Extrinsic (DGLAP) strangeness!

Intrinsic strangeness!

W. C. Chang and J.-C. Peng

arXiv:1105.2381

Consistent with intrinsic charm data

QCD: $\frac{1}{M_Q^2}$ scaling

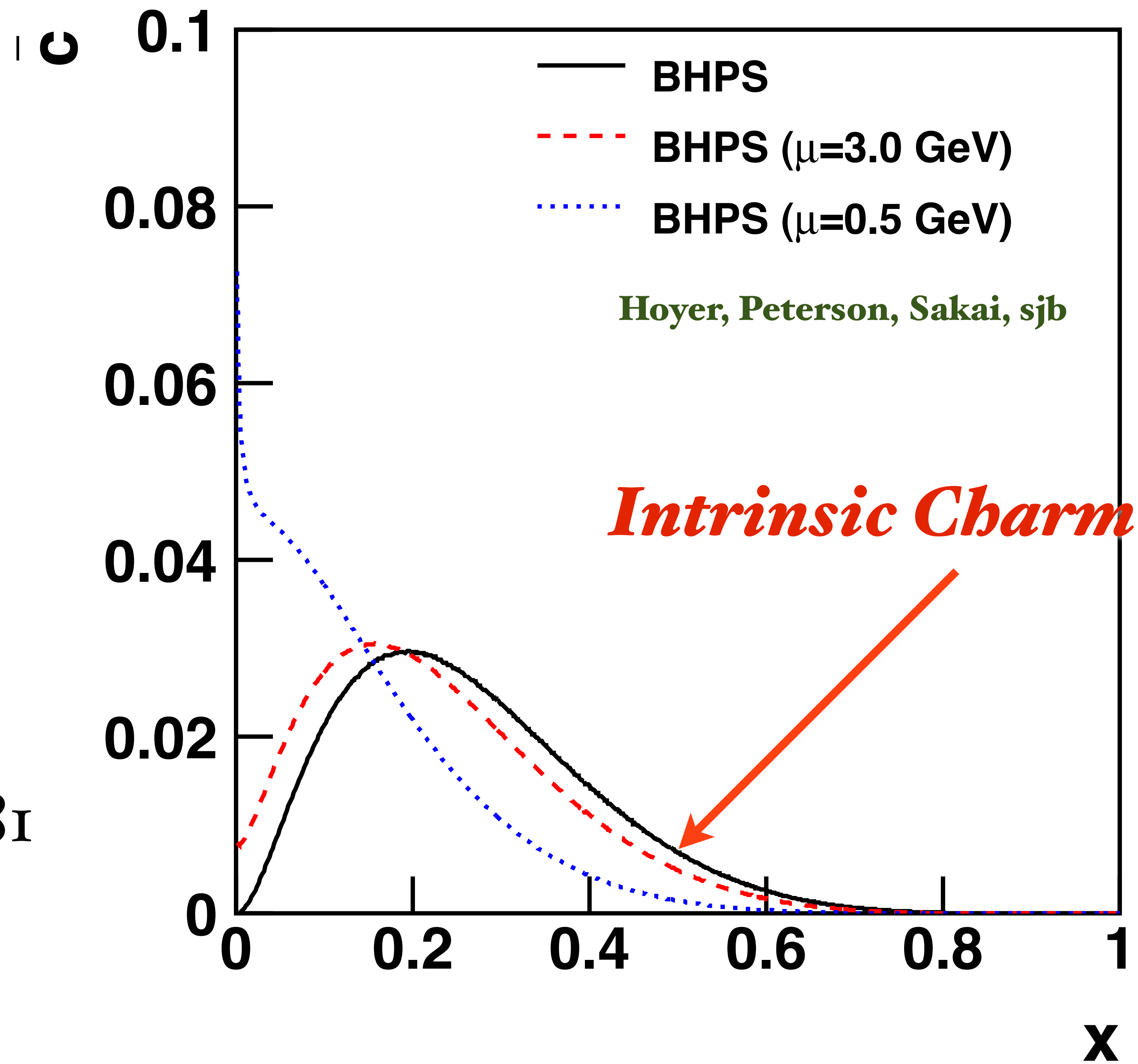
Comparison of the HERMES $x(s(x)+\bar{s}(x))$ data with the calculations based on the BHPS model. The solid and dashed curves are obtained by evolving the BHPS result to $Q^2 = 2.5$ GeV^2 using $\mu = 0.5$ GeV and $\mu = 0.3$ GeV, respectively. The normalizations of the calculations are adjusted to fit the data at $x > 0.1$ with statistical errors only, denoted by solid circles.

$$s(x,Q^2) = s(x,Q^2)_{\rm extrinsic} + s(x,Q^2)_{\rm intrinsic}$$

QCD ($1/m_Q^2$) scaling: predict IC !

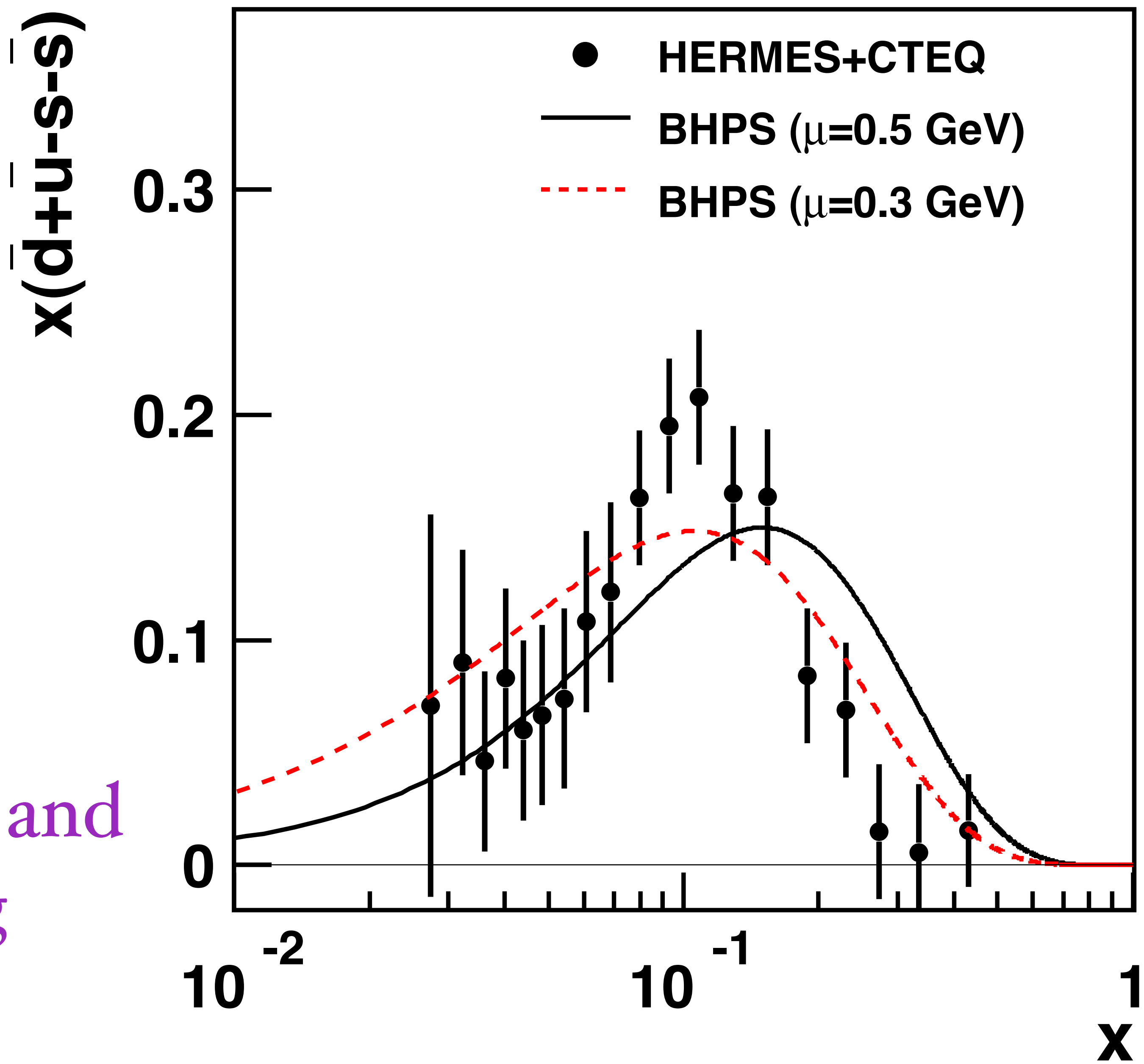
W. C. Chang and J.-C. Peng

arXiv:1105.2381



Calculations of the $\bar{c}(x)$ distributions based on the BHPS model. The solid curve corresponds to the calculation using Eq. 1 and the dashed and dotted curves are obtained by evolving the BHPS result to $Q^2 = 75$ GeV^2 using $\mu = 3.0$ GeV, and $\mu = 0.5$ GeV, respectively. The normalization is set at $\mathcal{P}_5^{c\bar{c}} = 0.01$.

Consistent with EMC



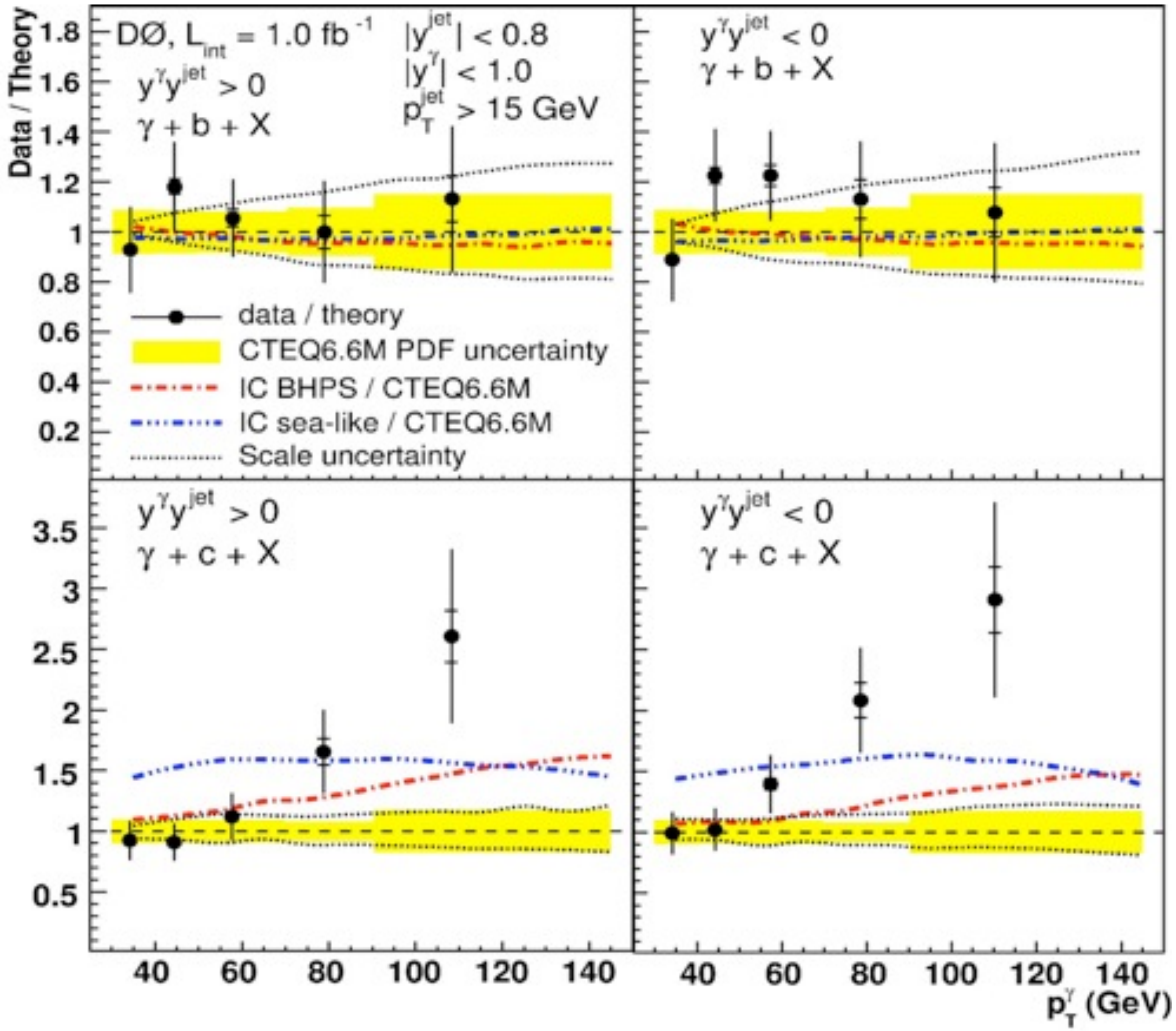
W. C. Chang and J.-C. Peng

Comparison of the $x(\bar{d}(x)+\bar{u}(x)-s(x)-\bar{s}(x))$ data with the calculations based on the BHPS model. The values of $x(s(x)+\bar{s}(x))$ are from the HERMES experiment [6], and those of $x(\bar{d}(x)+\bar{u}(x))$ are obtained from the PDF set CTEQ6.6 [11]. The solid and dashed curves are obtained by evolving the BHPS result to $Q^2 = 2.5$ GeV^2 using $\mu = 0.5$ GeV and $\mu = 0.3$ GeV, respectively. The normalization of the calculations are adjusted to fit the data.

D0

Measurement of $\gamma + b + X$ and $\gamma + c + X$ Production Cross Sections in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

$$p\bar{p} \to \gamma + Q + X$$



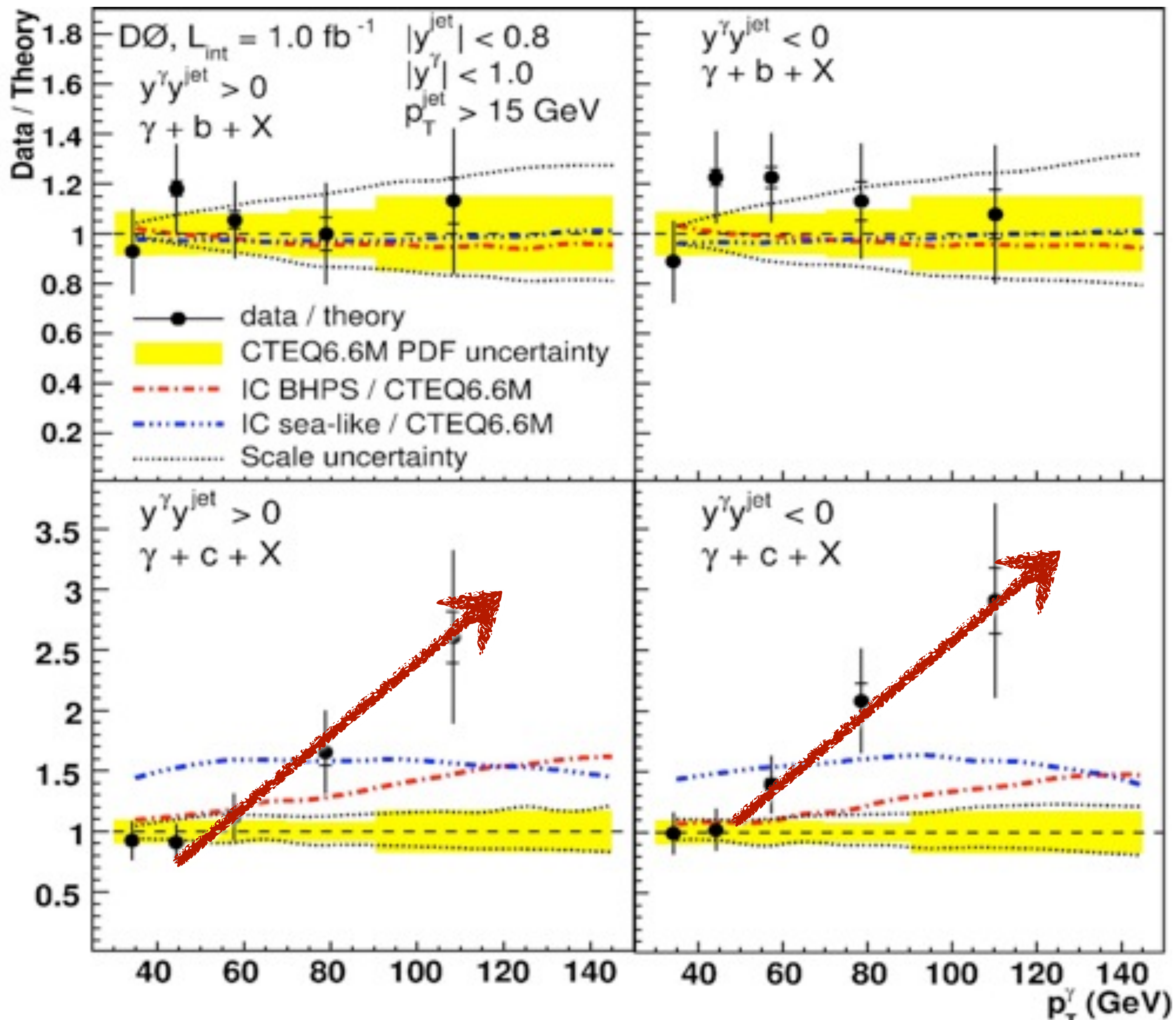
$$\frac{\Delta\sigma(\bar{p}p \to \gamma c X)}{\Delta\sigma(\bar{p}p \to \gamma b X)}$$

Ratio is insensitive to gluon PDF, scales

D0

Measurement of $\gamma + b + X$ and $\gamma + c + X$ Production Cross Sections in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

$$p\bar{p} \to \gamma + Q + X$$



$$\frac{\Delta\sigma(\bar{p}p \to \gamma c X)}{\Delta\sigma(\bar{p}p \to \gamma b X)}$$

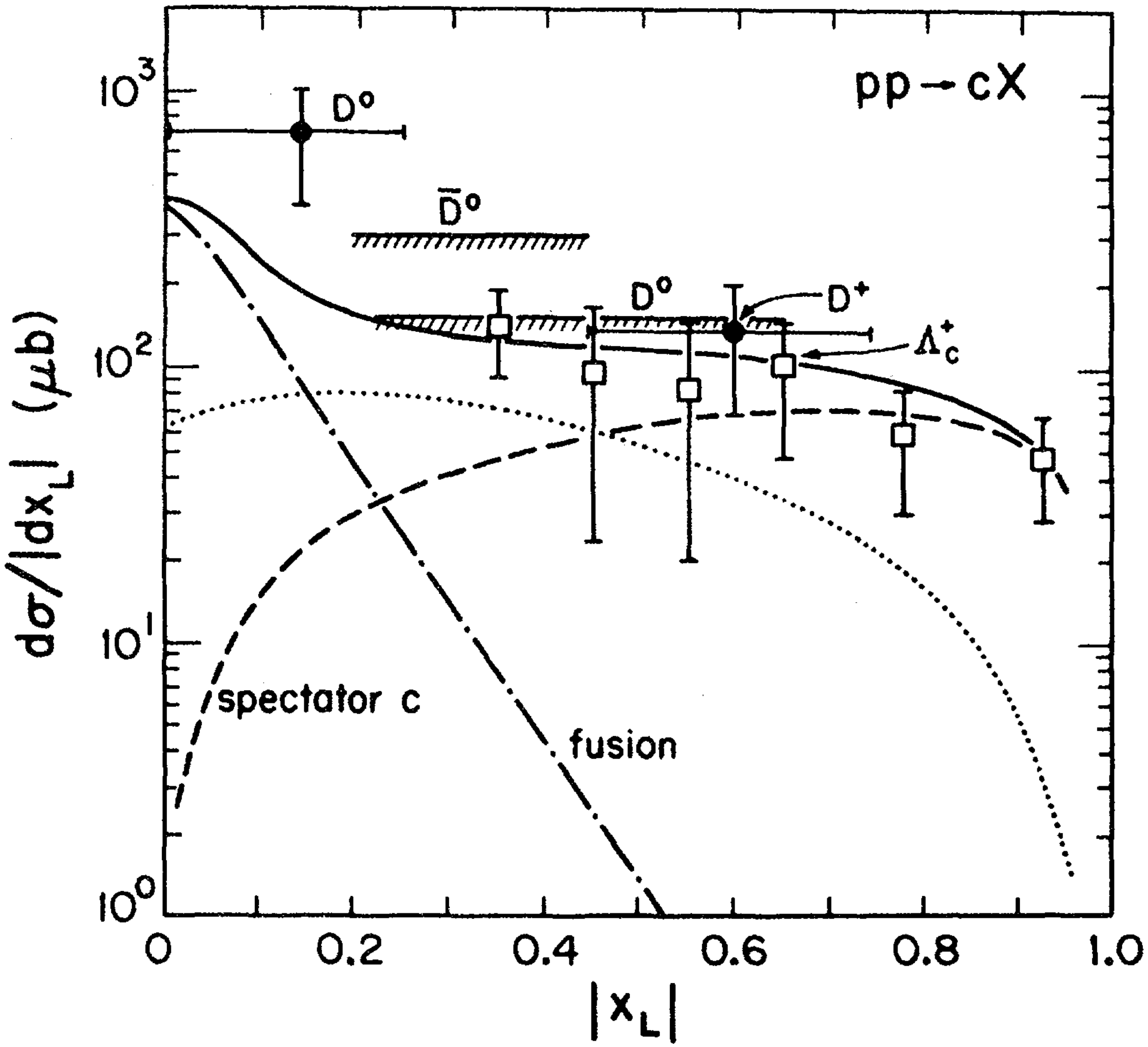
Ratio is insensitive to gluon PDF, scales

$$gc \to \gamma c$$

Signal for significant intrinsic charm at x > 0.1 ?

Two Components (separate evolution):

$$c(x, Q^2) = c(x, Q^2)_{\text{extrinsic}} + c(x, Q^2)_{\text{intrinsic}}$$



Barger, Halzen, Keung

Evidence for charm at large x

- EMC data: $c(x, Q^2) > 30 \times$ DGLAP
  $Q^2 = 75$ GeV^2, $x = 0.42$

- High x_F $pp \to J/\psi X$

- High x_F $pp \to J/\psi J/\psi X$

- High x_F $pp \to \Lambda_c X$

- High x_F $pp \to \Lambda_b X$

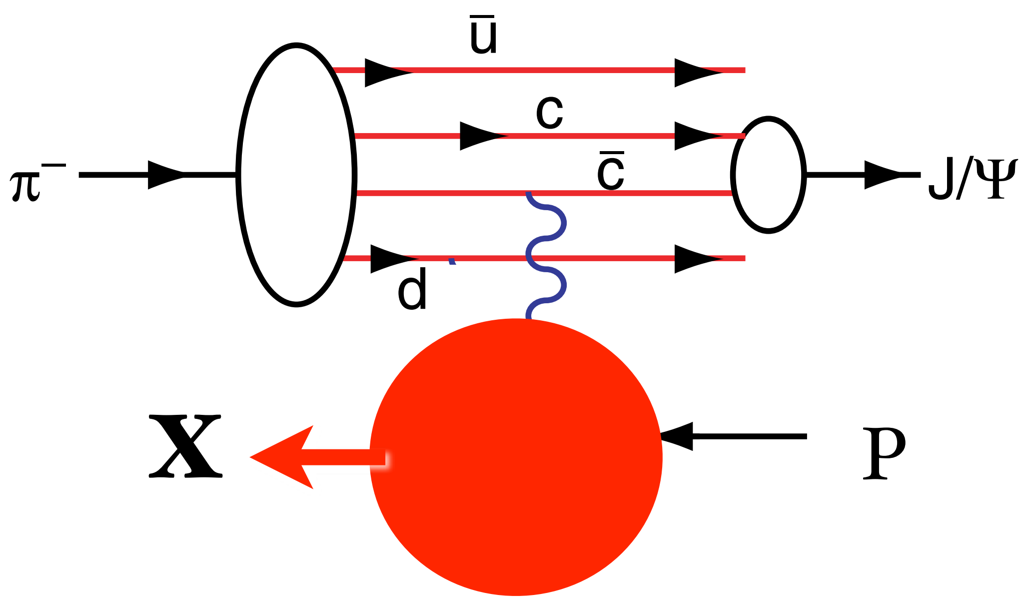
- High x_F $pp \to \Xi(ccd) X$ (SELEX)

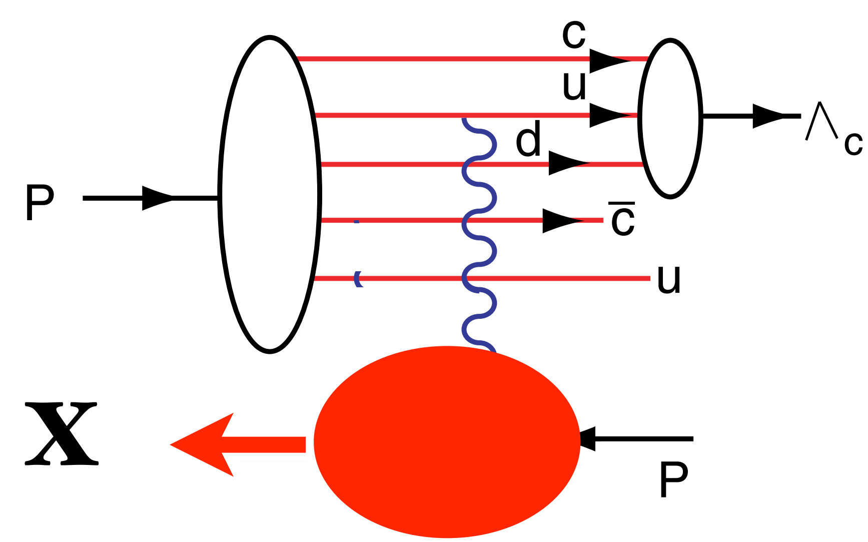
Explain Tevatron anomalies: $p\bar{p} \to \gamma c X, Z c X$

Interesting spin, charge asymmetry, threshold, spectator effects

Important corrections to B decays; Quarkonium decays

Gardner, Karliner, sjb





Spectator counting rules

$$\frac{dN}{dx_F} \propto (1 - x_F)^{2n_{spect}-1}$$

Coalescence of Comoving Charm and Valence Quarks
Produce J/ψ, Λ_c and other Charm Hadrons at High x_F

- EMC data: $c(x, Q^2) > 30 \times$ DGLAP
  $Q^2 = 75$ GeV^2, $x = 0.42$

- High x_F $pp \to J/\psi X$

- High x_F $pp \to J/\psi J/\psi X$

- High x_F $pp \to \Lambda_c X$

- High x_F $pp \to \Lambda_b X$

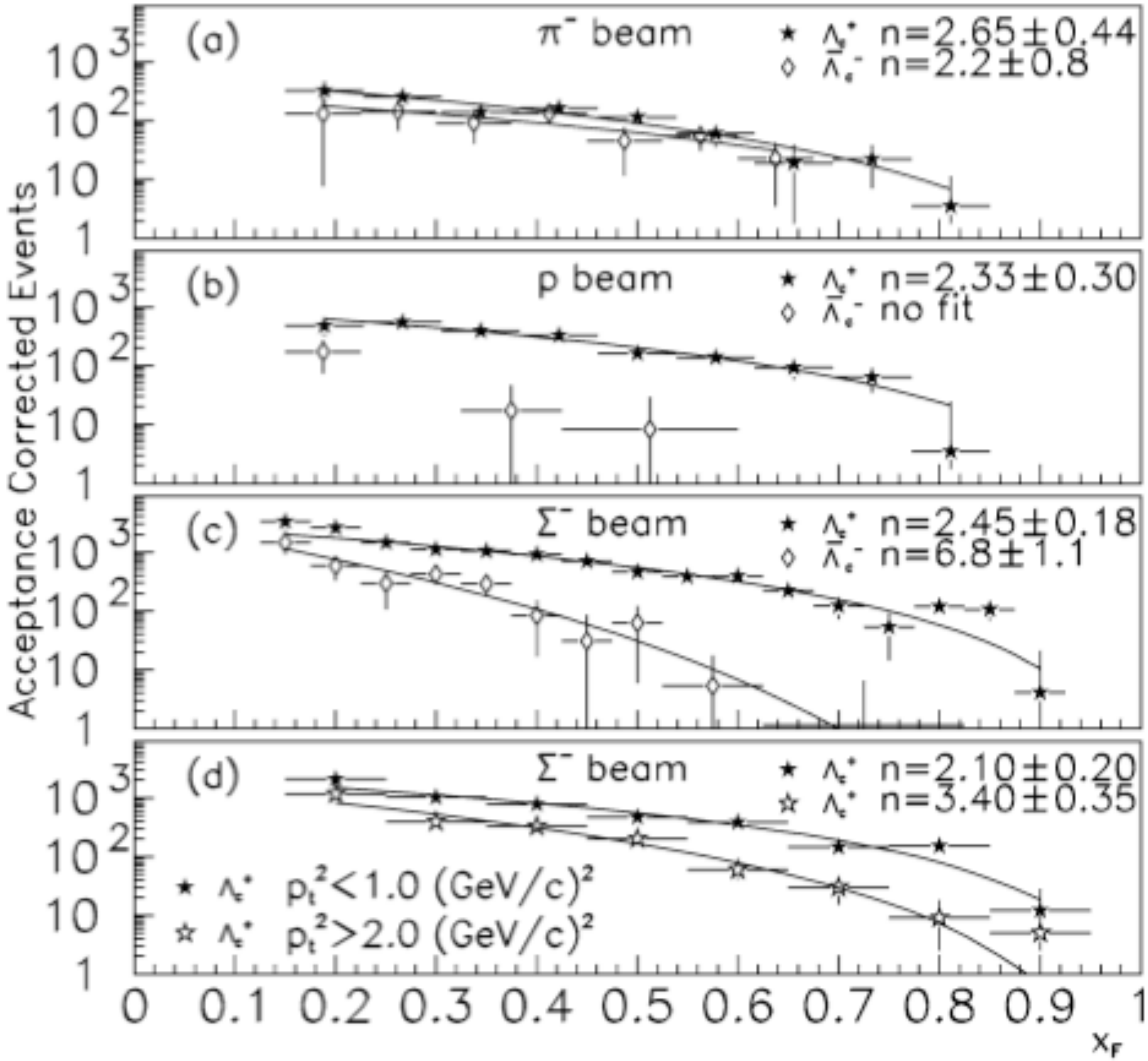
- High x_F $pp \to \Xi(ccd) X$ (SELEX)

Critical Measurements at threshold: JLab, PANDA

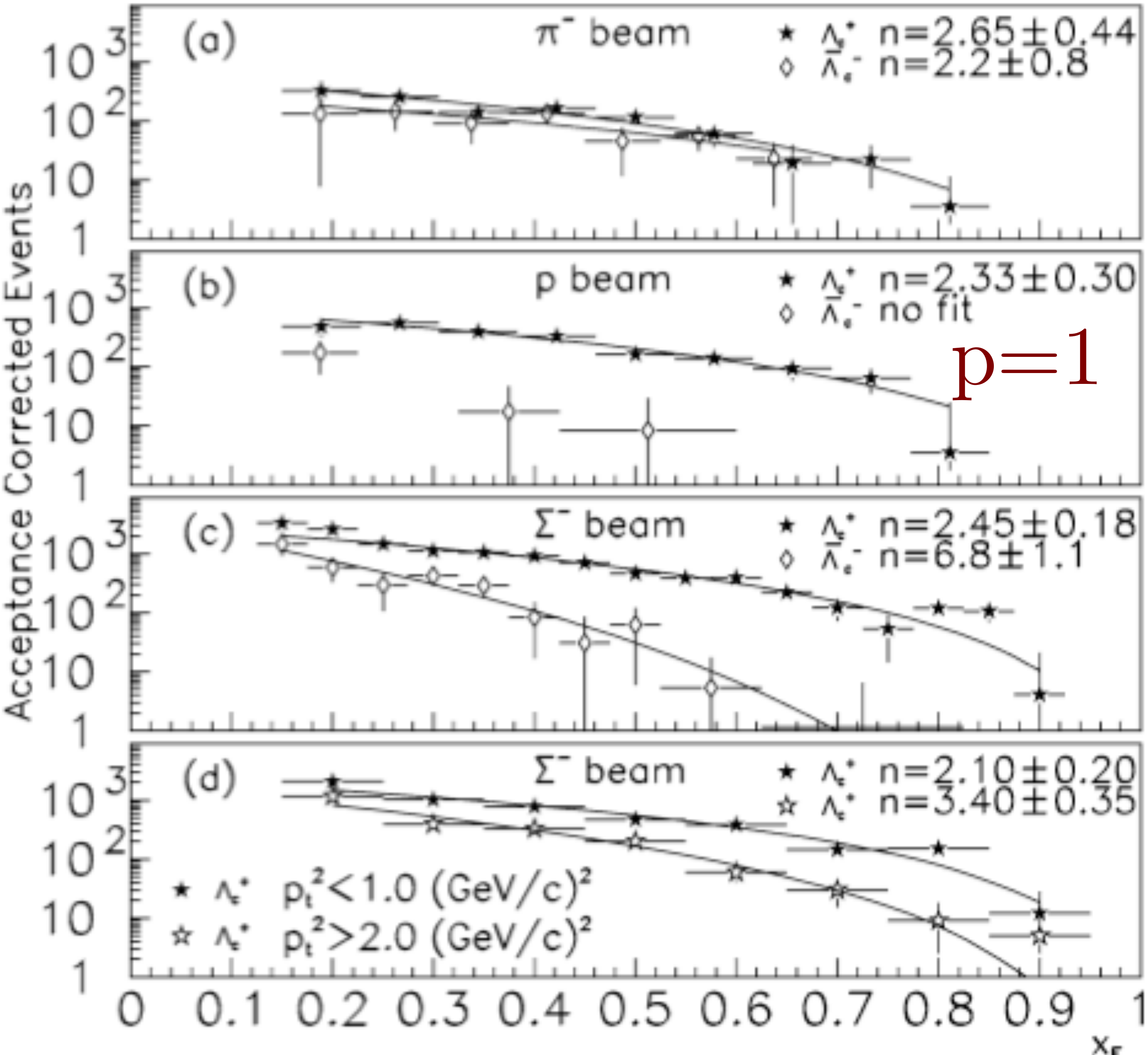
Interesting spin, charge asymmetry, threshold, spectator effects

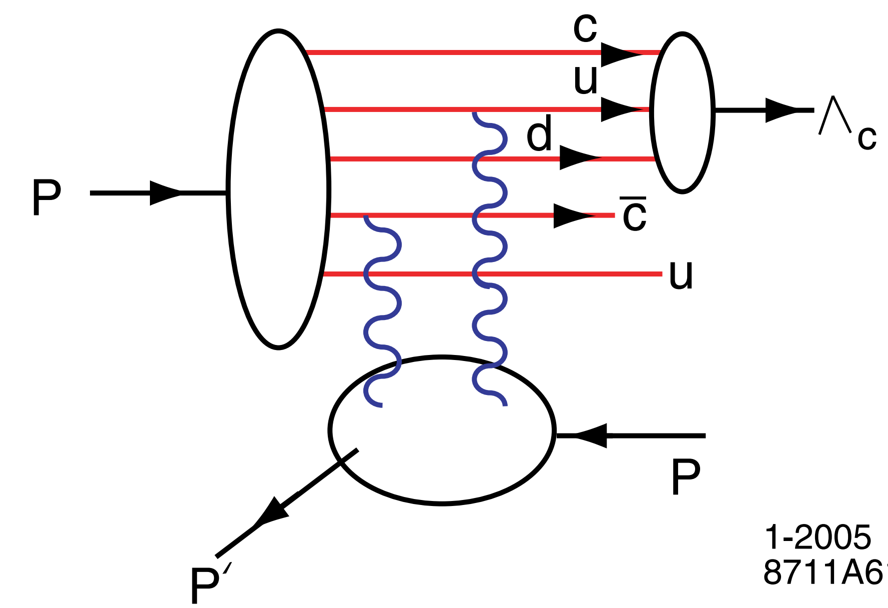
Important corrections to B decays; Quarkonium decays

Gardner, Karliner, sjb



Large xF production close to the maximum allowed by phase space!





$$p(uudc\bar{c})$$

$$\rightarrow \Lambda_c(cud)$$

$$n_s = 2$$

Phase space gives minimum power p

$$(1 - x_F)^p, p = n_s - 1$$

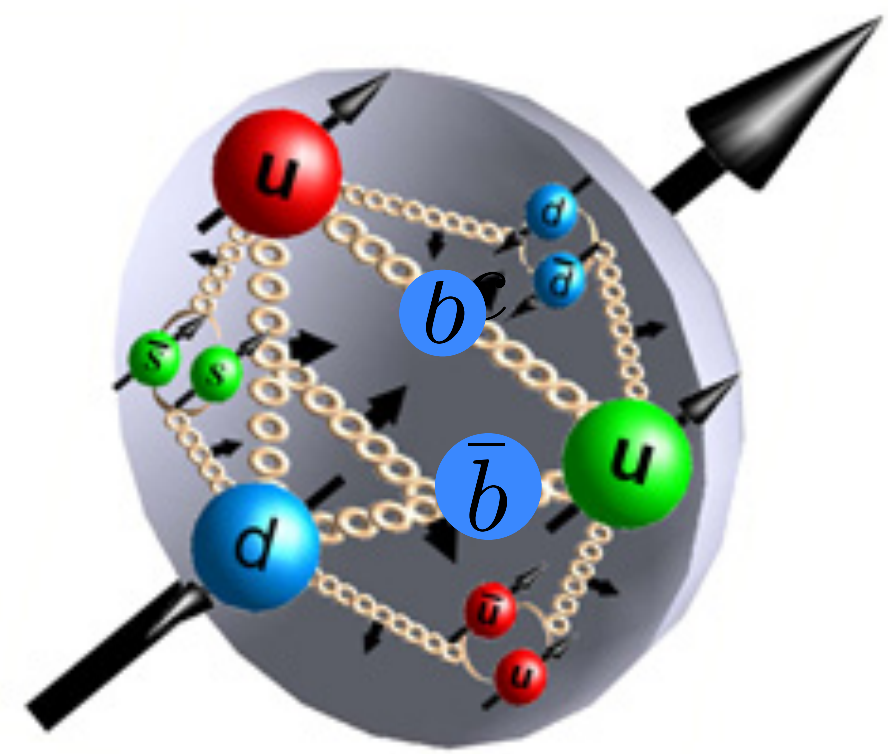
27 May 1991

CM-P00063074

THE Λ_b^o BEAUTY BARYON PRODUCTION IN PROTON-PROTON INTERACTIONS AT $\sqrt{s}$=62 GeV: A SECOND OBSERVATION

G. Bari, M. Basile, G. Bruni, G. Cara Romeo, R. Casaccia, L. Cifarelli, F. Cindolo, A. Contin, G. D'Alì, C. Del Papa, S. De Pasquale, P. Giusti, G. Iacobucci, G. Maccarrone, T. Massam, R. Nania, F. Palmonari, G. Sartorelli, G. Susinno, L. Votano and A. Zichichi

CERN, Geneva, Switzerland
Dipartimento di Fisica dell'Università, Bologna, Italy
Dipartimento di Fisica dell'Università, Cosenza, Italy
Istituto di Fisica dell'Università, Palermo, Italy
Istituto Nazionale di Fisica Nucleare, Bologna, Italy
Istituto Nazionale di Fisica Nucleare, LNF, Frascati, Italy



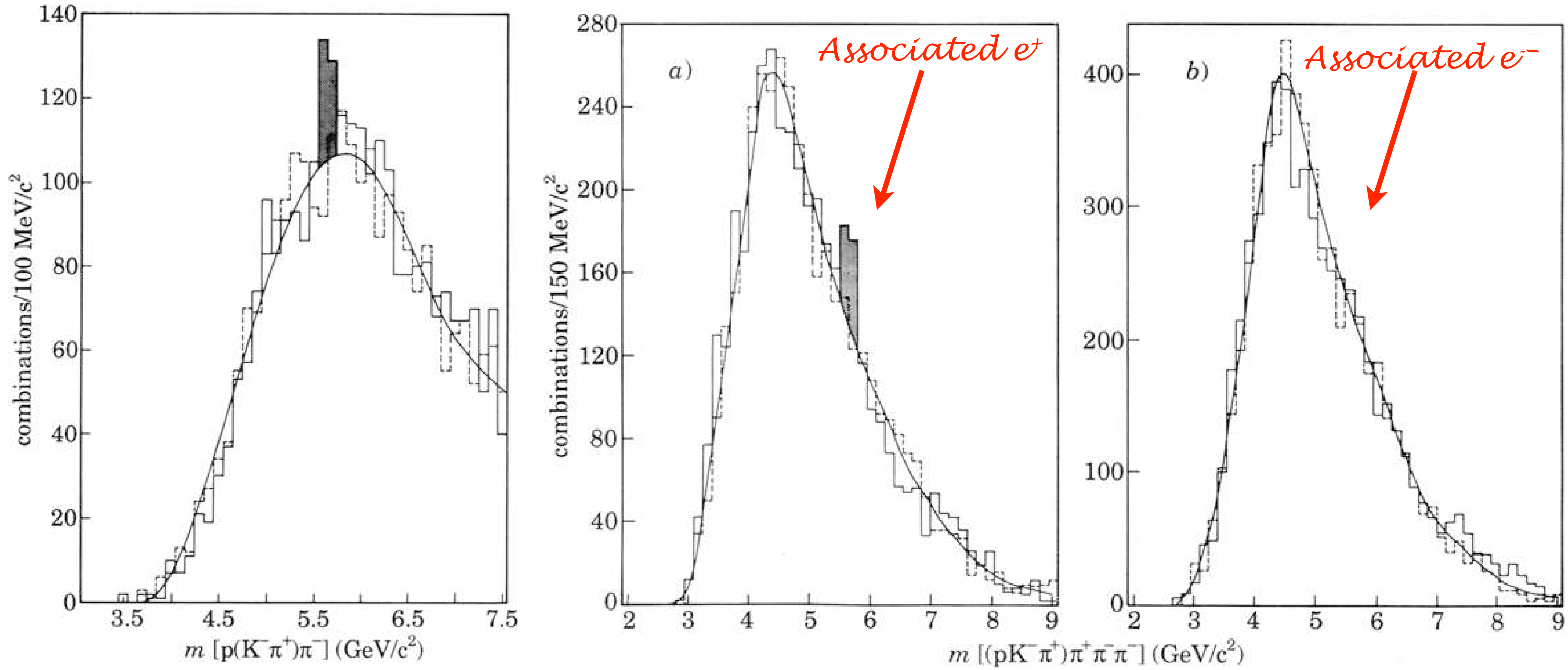
Abstract

Another decay mode of the Λ_b^o (open-beauty baryon) state has been observed: $\Lambda_b^o \to \Lambda_c^+\pi^+\pi^-\pi^-$. In addition, new results on the previously observed decay channel, $\Lambda_b^o \to pD^o\pi^-$, are reported. These results confirm our previous findings on Λ_b^o production at the ISR. The mass value (5.6 GeV/c^2) is found to be in good agreement with theoretical predictions. The production mechanism is found to be "leading".

First Evidence for Intrinsic Bottom!

$pp \to \Lambda_b(bud)B(\bar{b}q)X$ at large x_F

CERN-ISR R422 (Split Field Magnet), 1988/1991



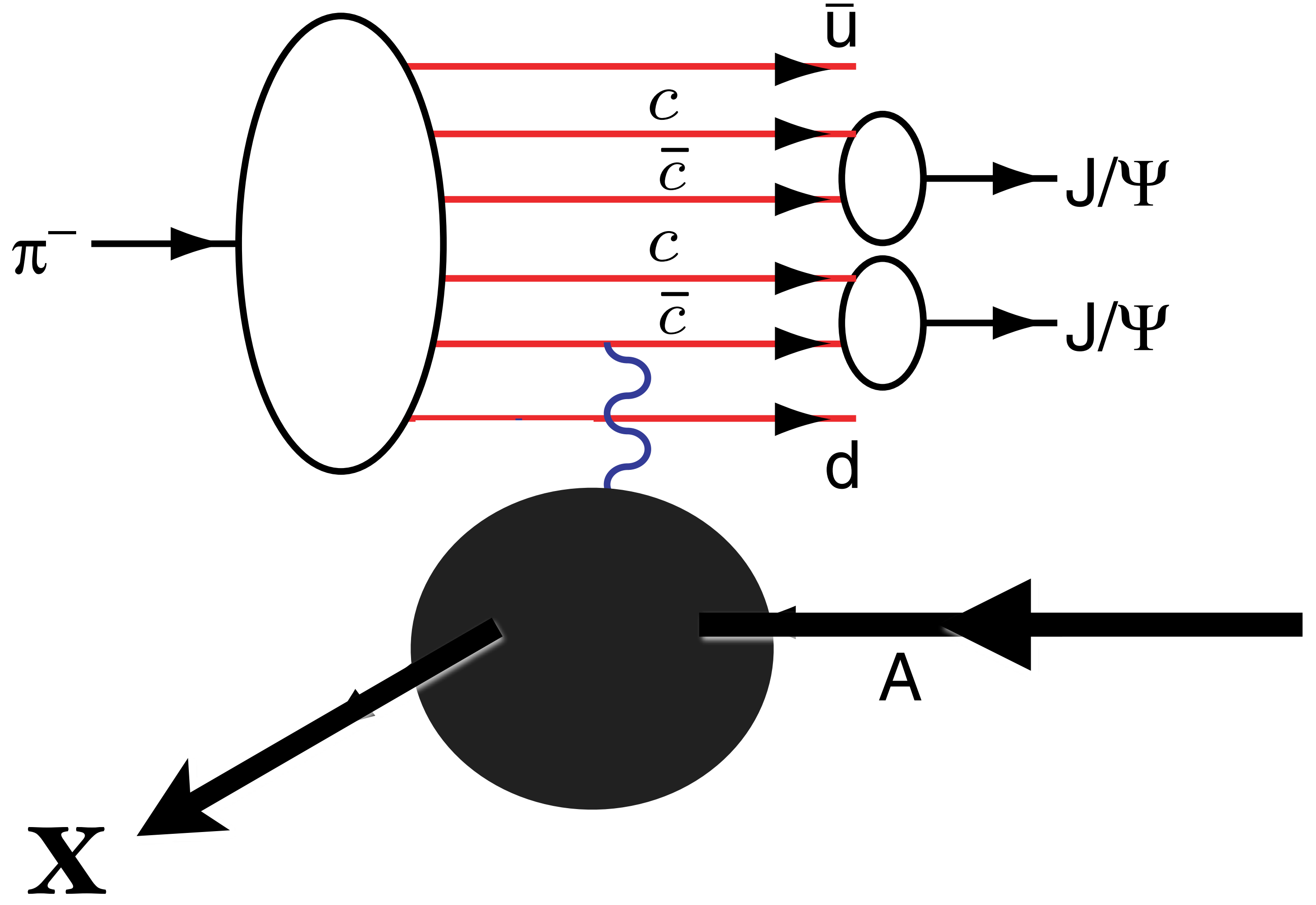
$\Lambda_b^0 \to pD^0\pi^-$

$\Lambda_b^0 \to \Lambda_c^+\pi^+\pi^-\pi^-$

Il Nuovo Cimento 104, 1787

First Evidence for Intrinsic Bottom!

Production of Two Charmonia at High x_F



Excludes PYTHIA 'color drag' model

All events have $x^F_{\psi\psi} > 0.4$!

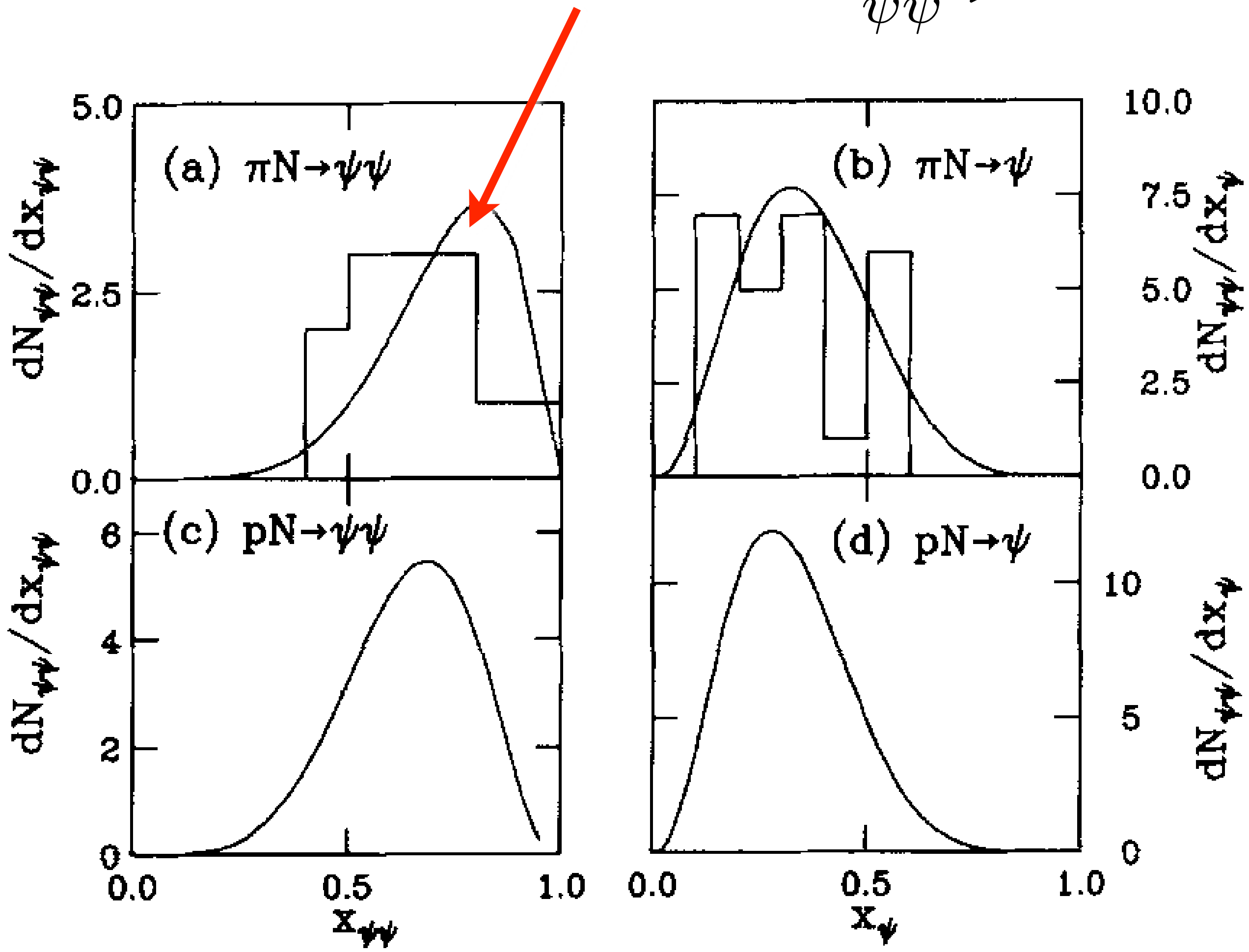


Fig. 3. The $\psi\psi$ pair distributions are shown in (a) and (c) for the pion and proton projectiles. Similarly, the distributions of J/ψ's from the pairs are shown in (b) and (d). Our calculations are compared with the $\pi^- N$ data at 150 and 280 GeV/c [1]. The $x_{\psi\psi}$ distributions are normalized to the number of pairs from both pion beams (a) and the number of pairs from the 400 GeV proton measurement (c). The number of single J/ψ's is twice the number of pairs.

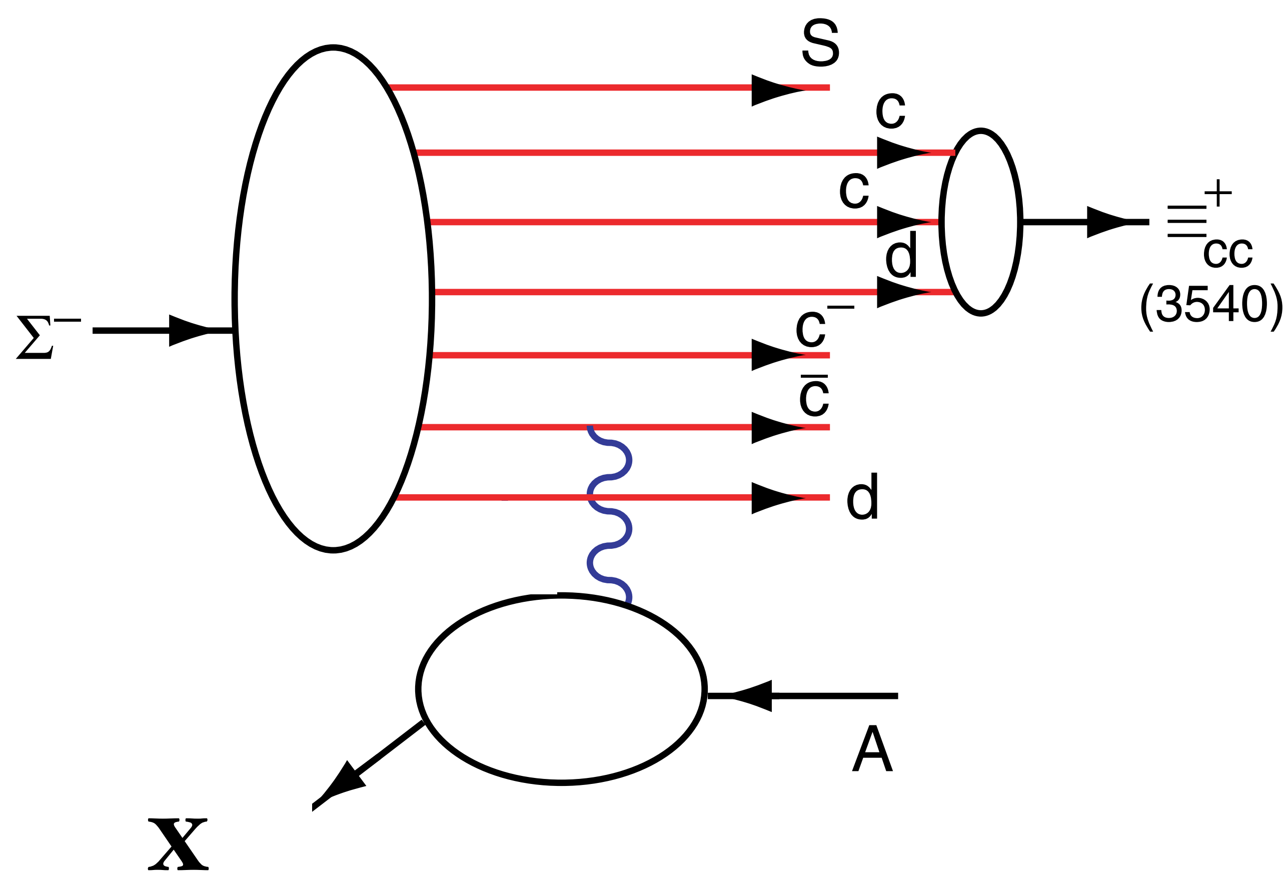
NA3 Data

$$\pi A \to J/\psi J/\psi X$$

R. Vogt, sjb

The probability distribution for a general n-particle intrinsic $c\bar{c}$ Fock state as a function of x and $\boldsymbol{k}_T$ is written as

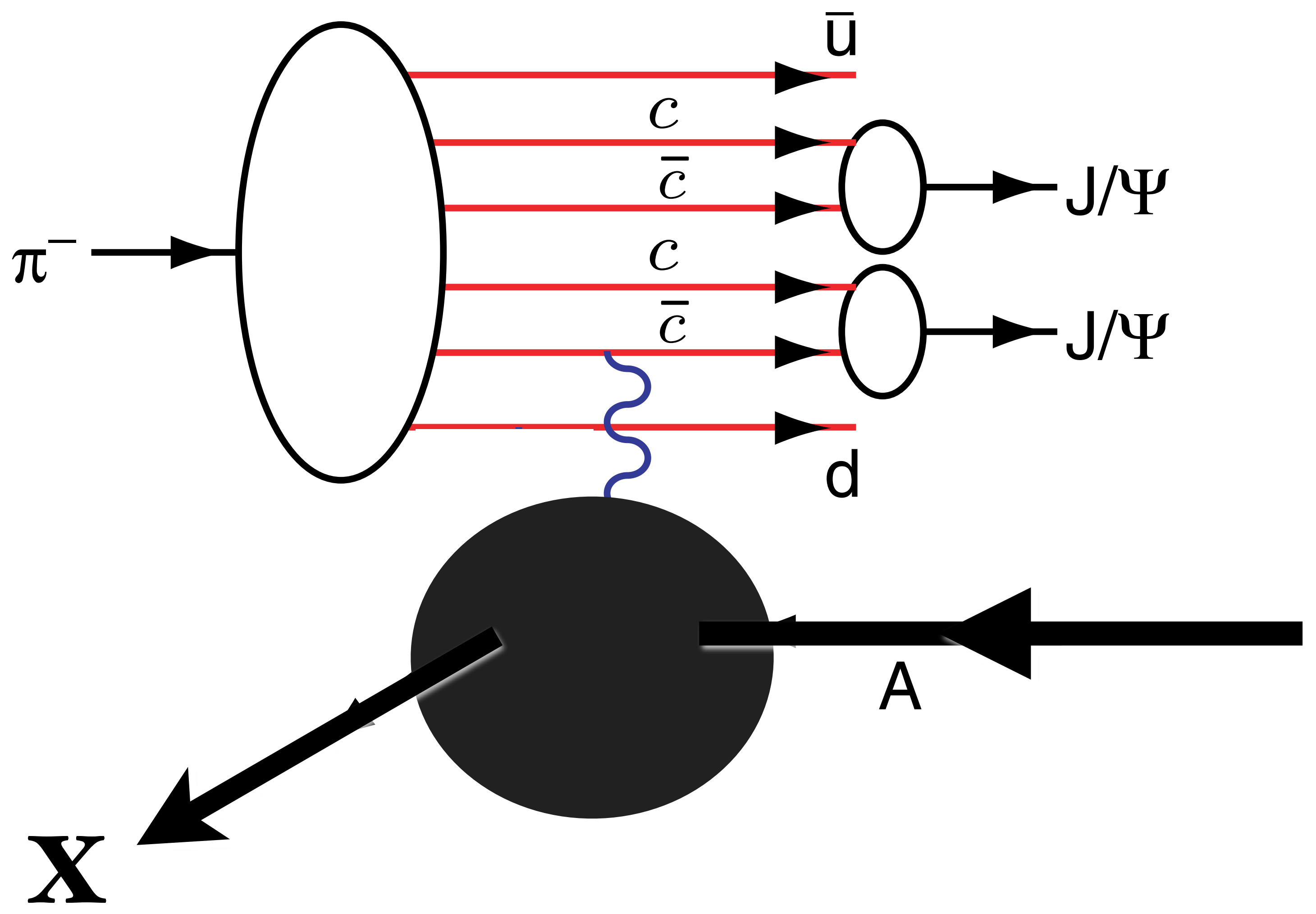
$$\frac{dP_{\rm ic}}{\prod_{i=1}^n dx_i d^2k_{T,i}} = N_n \alpha_s^4(M_{c\bar{c}}) \frac{\delta(\sum_{i=1}^n \boldsymbol{k}_{T,i})\delta(1-\sum_{i=1}^n x_i)}{(m_h^2 - \sum_{i=1}^n (m_{T,i}^2/x_i))^2},$$



Production of a Double-Charm Baryon

SELEX high x_F $<x_F>= 0.33$

Production of Two Charmonia at High x_F



All events have $x^F_{\psi\psi} > 0.4$!

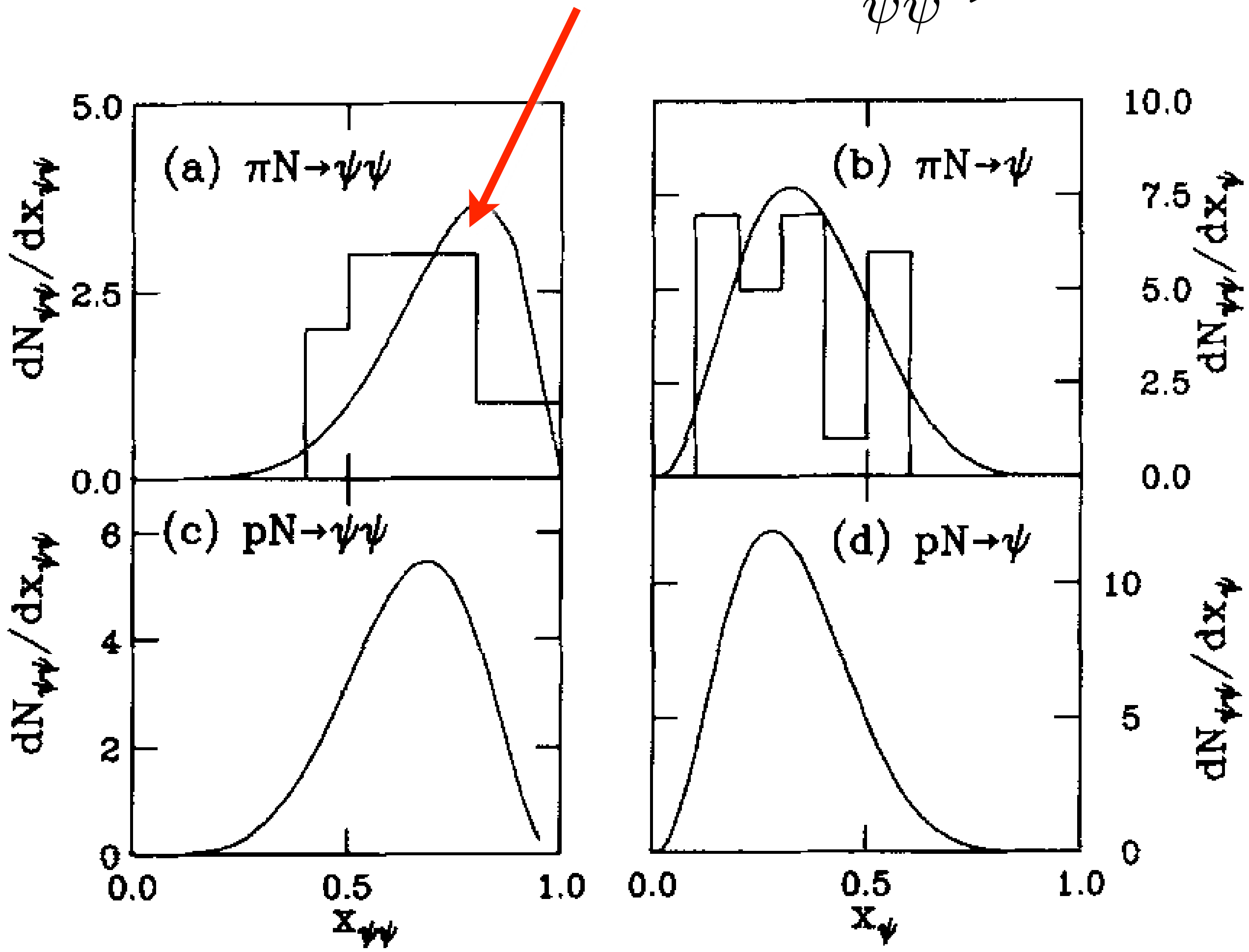


Fig. 3. The $\psi\psi$ pair distributions are shown in (a) and (c) for the pion and proton projectiles. Similarly, the distributions of J/ψ's from the pairs are shown in (b) and (d). Our calculations are compared with the $\pi^- N$ data at 150 and 280 GeV/c [1]. The $x_{\psi\psi}$ distributions are normalized to the number of pairs from both pion beams (a) and the number of pairs from the 400 GeV proton measurement (c). The number of single J/ψ's is twice the number of pairs.

NA3 Data

Excludes PYTHIA 'color drag' model

$$\pi A \rightarrow J/\psi J/\psi X$$

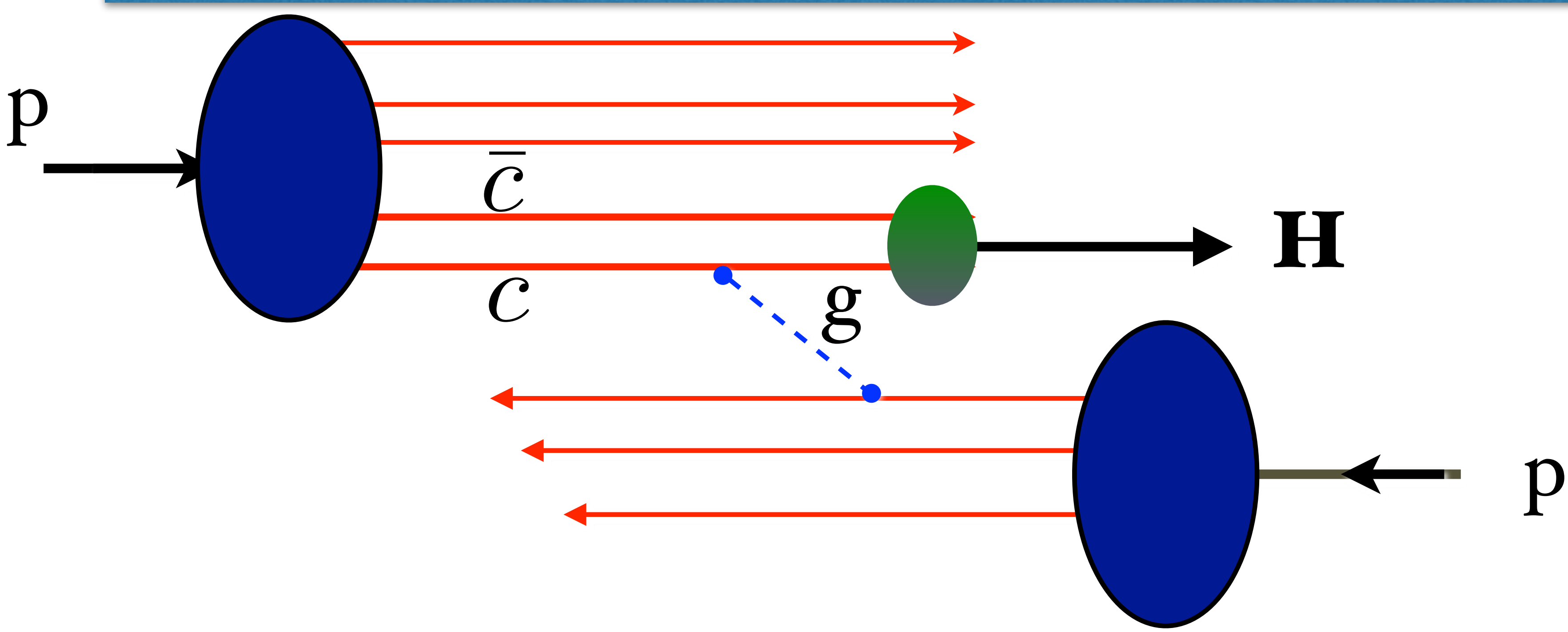
R. Vogt, sjb

The probability distribution for a general n-particle intrinsic $c\bar{c}$ Fock state as a function of x and $\boldsymbol{k}_T$ is written as

$$\frac{dP_{\rm ic}}{\prod_{i=1}^{n} dx_i d^2k_{T,i}} = N_n \alpha_s^4(M_{c\bar{c}}) \frac{\delta(\sum_{i=1}^{n} \boldsymbol{k}_{T,i})\delta(1-\sum_{i=1}^{n} x_i)}{(m_h^2 - \sum_{i=1}^{n}(m_{T,i}^2/x_i))^2},$$

Goldhaber, Kopeliovich, Schmidt, Soffer, sjb

Intrinsic Heavy Quark Contribution to Inclusive Higgs Production



$pp \rightarrow HX$

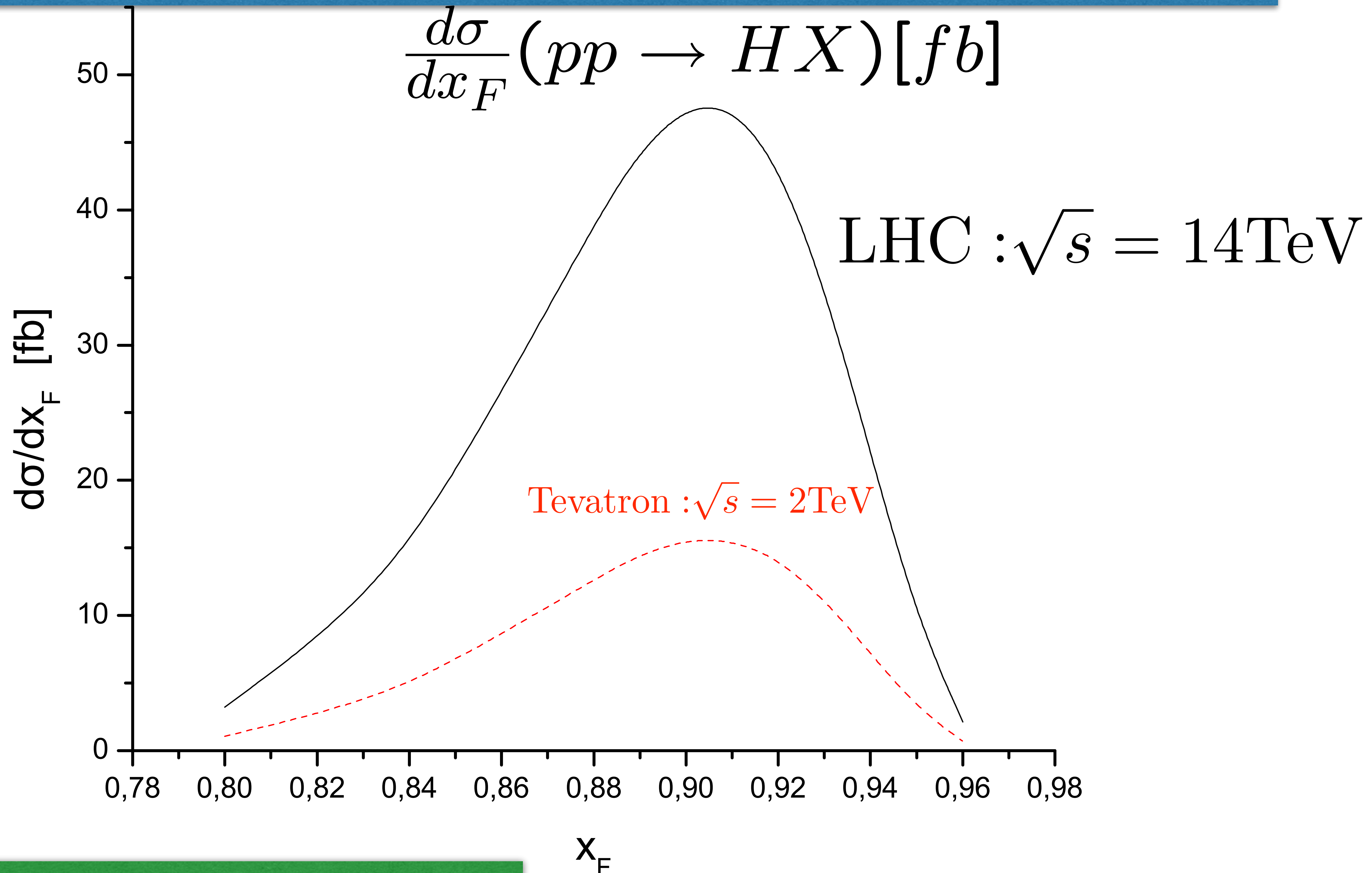
Also: intrinsic strangeness, bottom, top

Higgs can have > 80% of Proton Momentum!

New production mechanism for Higgs at the LHC

AFTER: Higgs production at threshold!

Intrinsic Heavy Quark Contribution to High x_F Inclusive Higgs Production



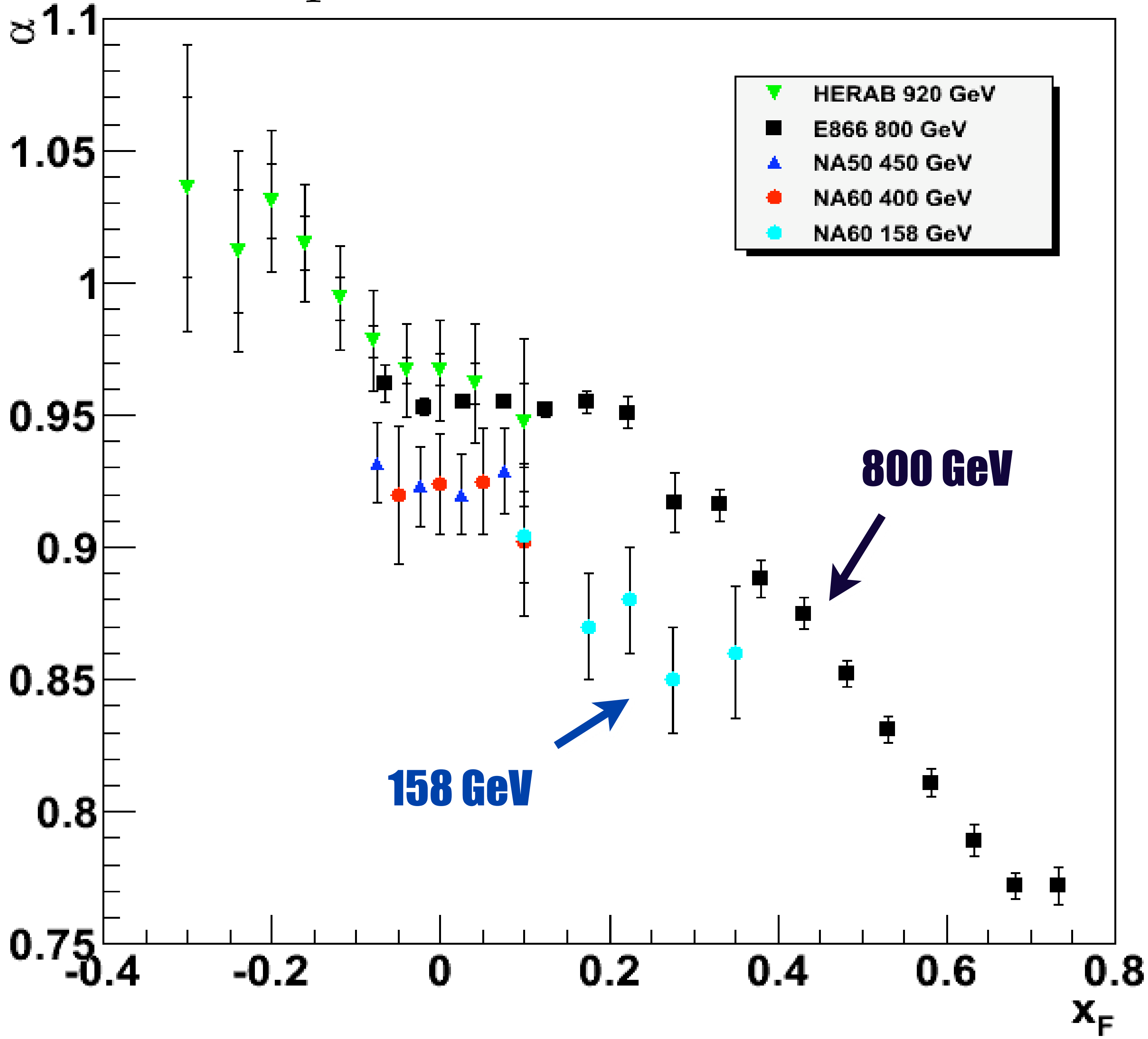
Need High x_F Acceptance

Most practical: Higgs to 4 muons

Goldhaber, Kopeliovich, Schmidt, Soffer, sjb

NA60 pA data @ 158GeV

$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) \propto A^{\alpha}$$



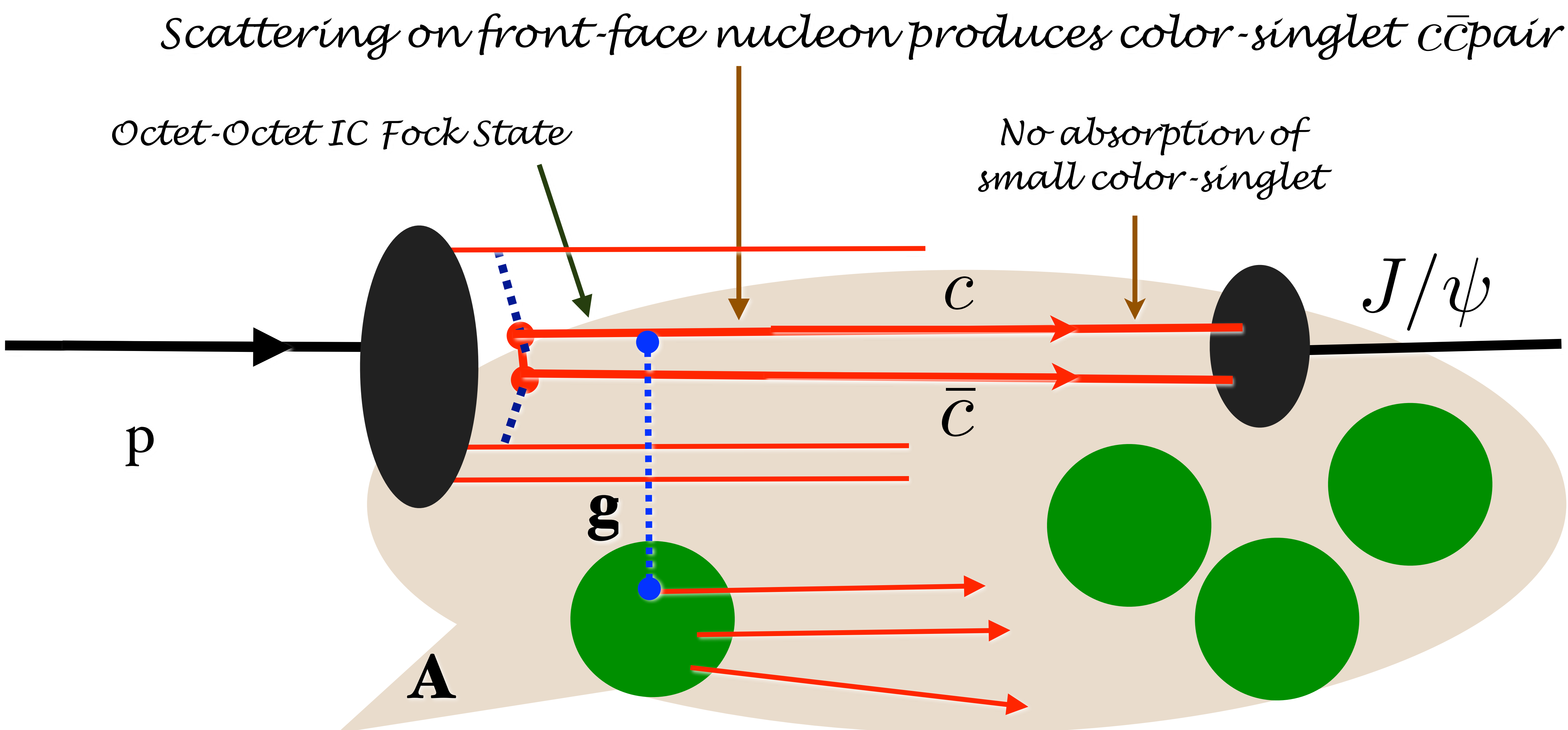
Clear dependence on x_F and beam energy

Remarkably strong nuclear suppression at high x_F

High x_F

Color-Opaque IC Fock state interacts on nuclear front surface

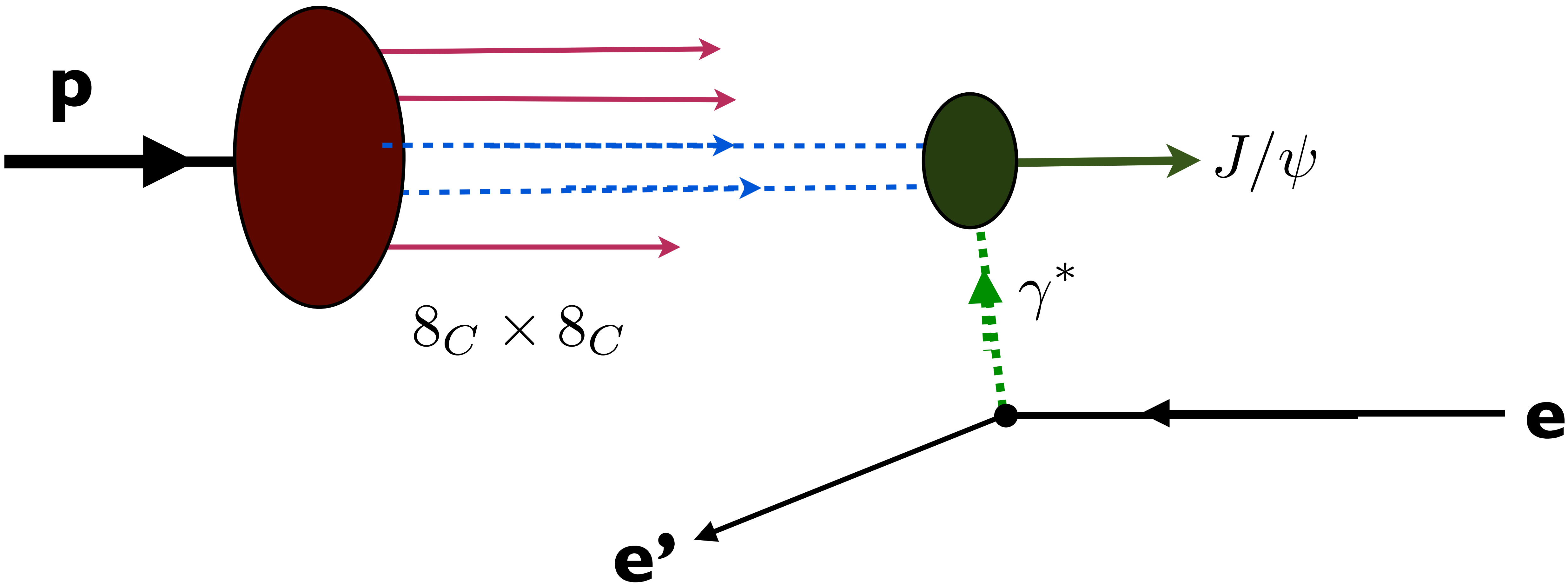
Kopeliovich, Schmidt, Soffer, sjb



$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^{2/3} \times \frac{d\sigma}{dx_F}(pN \to J/\psi X)$$

$$\gamma^* p \to J/\psi X$$

$$(gg)_{1C} + \gamma^* \to J/\psi$$

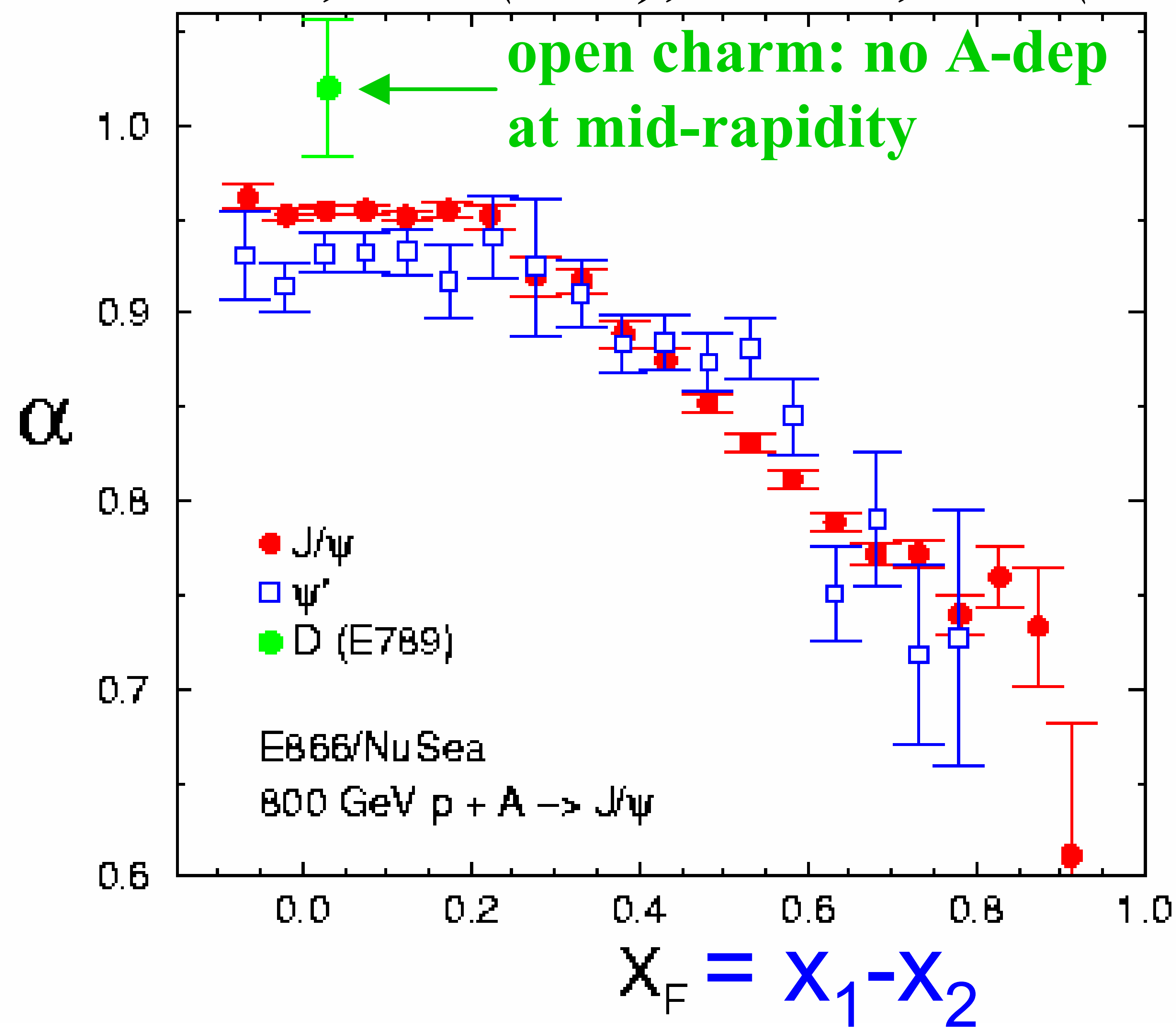


Digluon-initiated subprocess at an ep collider

M. Leitch

800 GeV p-A (FNAL) $\sigma_A = \sigma_p * A^{\alpha}$

PRL 84, 3256 (2000); PRL 72, 2542 (1994)



$$\frac{d\sigma}{dx_F}(pA \to J/\psi X)$$

Remarkably Strong Nuclear Dependence for Fast Charmonium

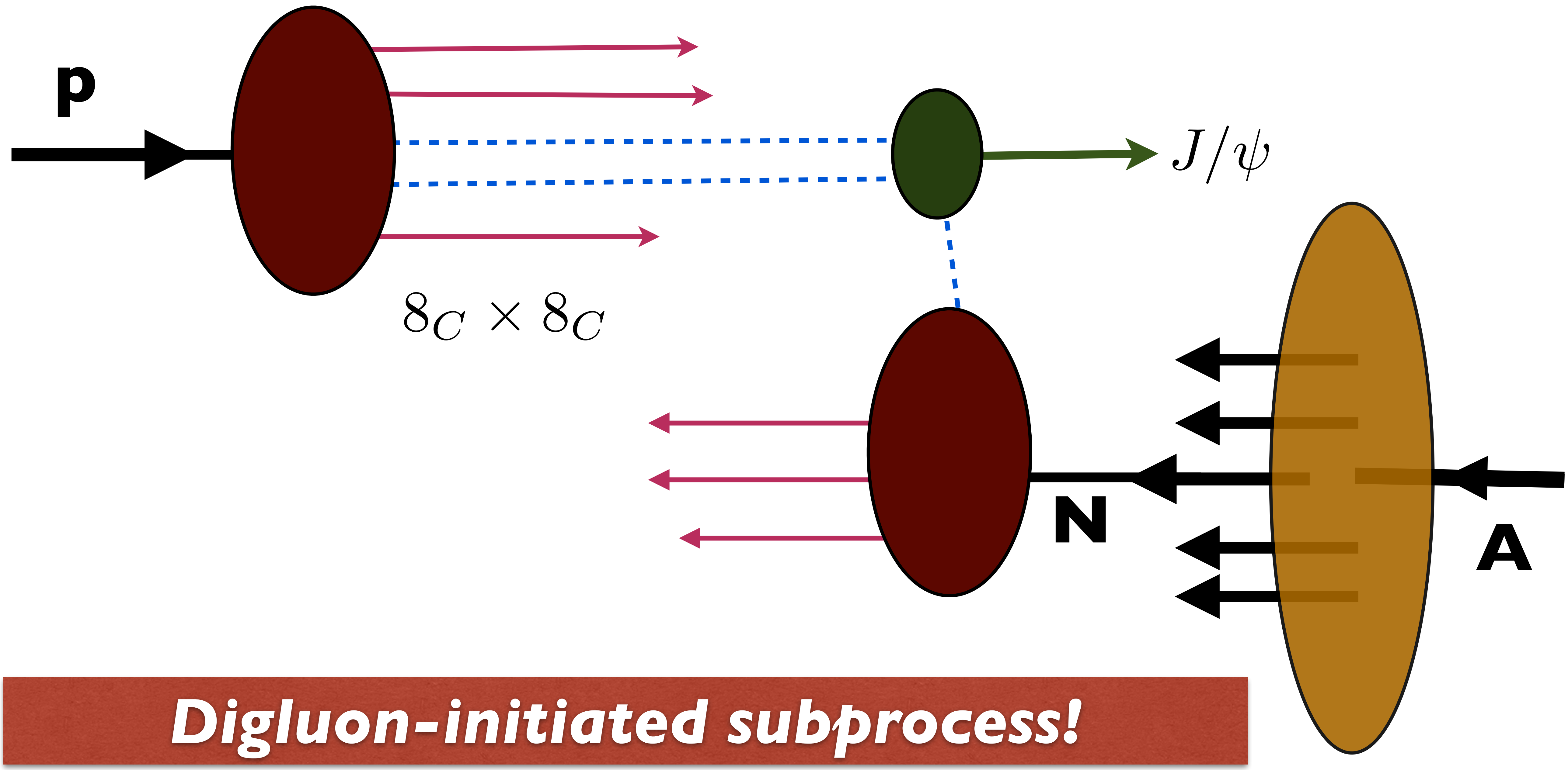
Violation of PQCD Factorization!

Violation of factorization in charm hadroproduction.
P. Hoyer, M. Vanttinen (Helsinki U.) , U. Sukhatme (Illinois U., Chicago) . HU-TFT-90-14, May 1990. 7pp.
Published in Phys.Lett.B246:217-220,1990

IC Explains large excess of quarkonia at large x_F, A-dependence

$$pA \to J/\psi X$$

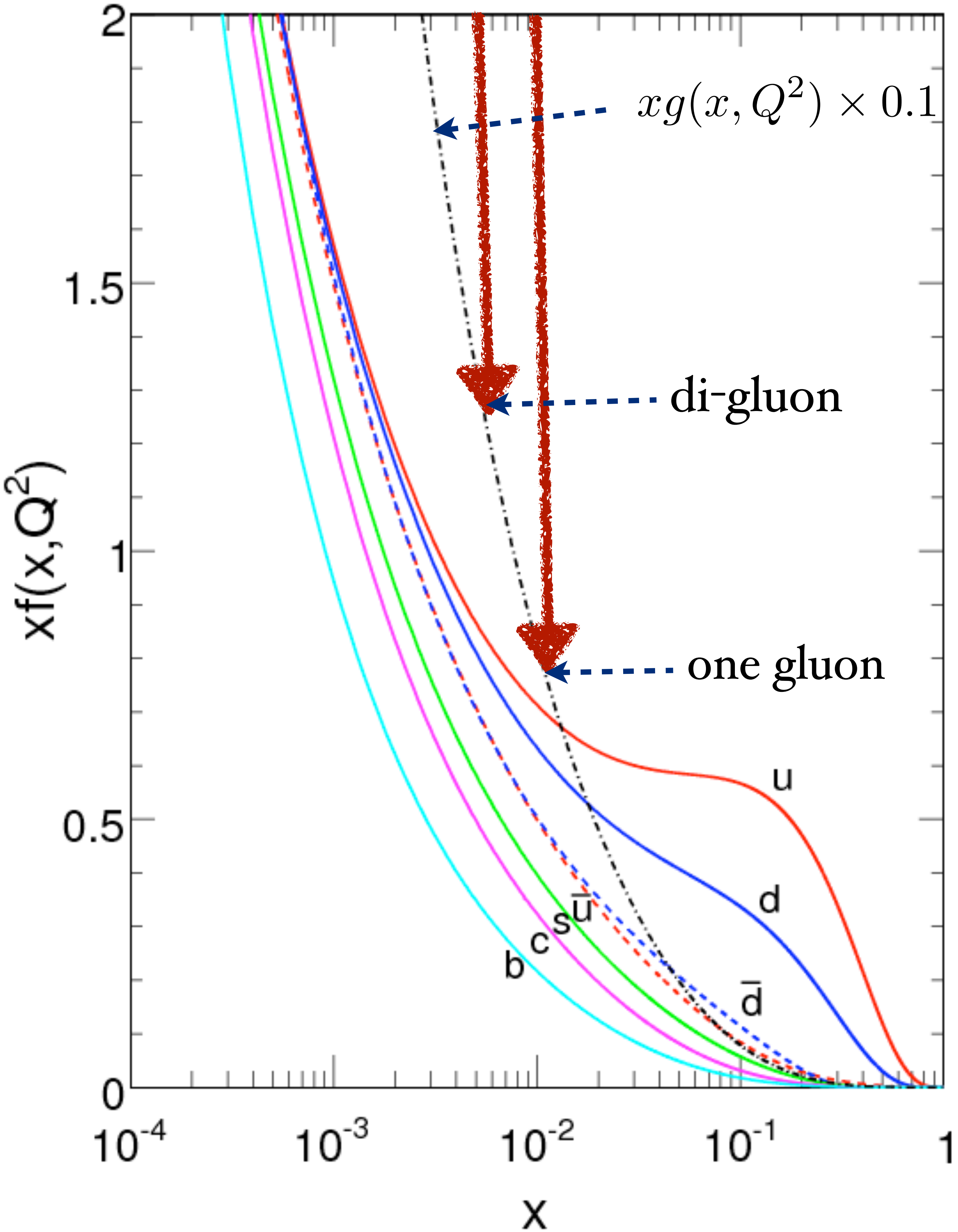
$$(gg)_{8_C} + g_{8_C} \to J/\psi$$



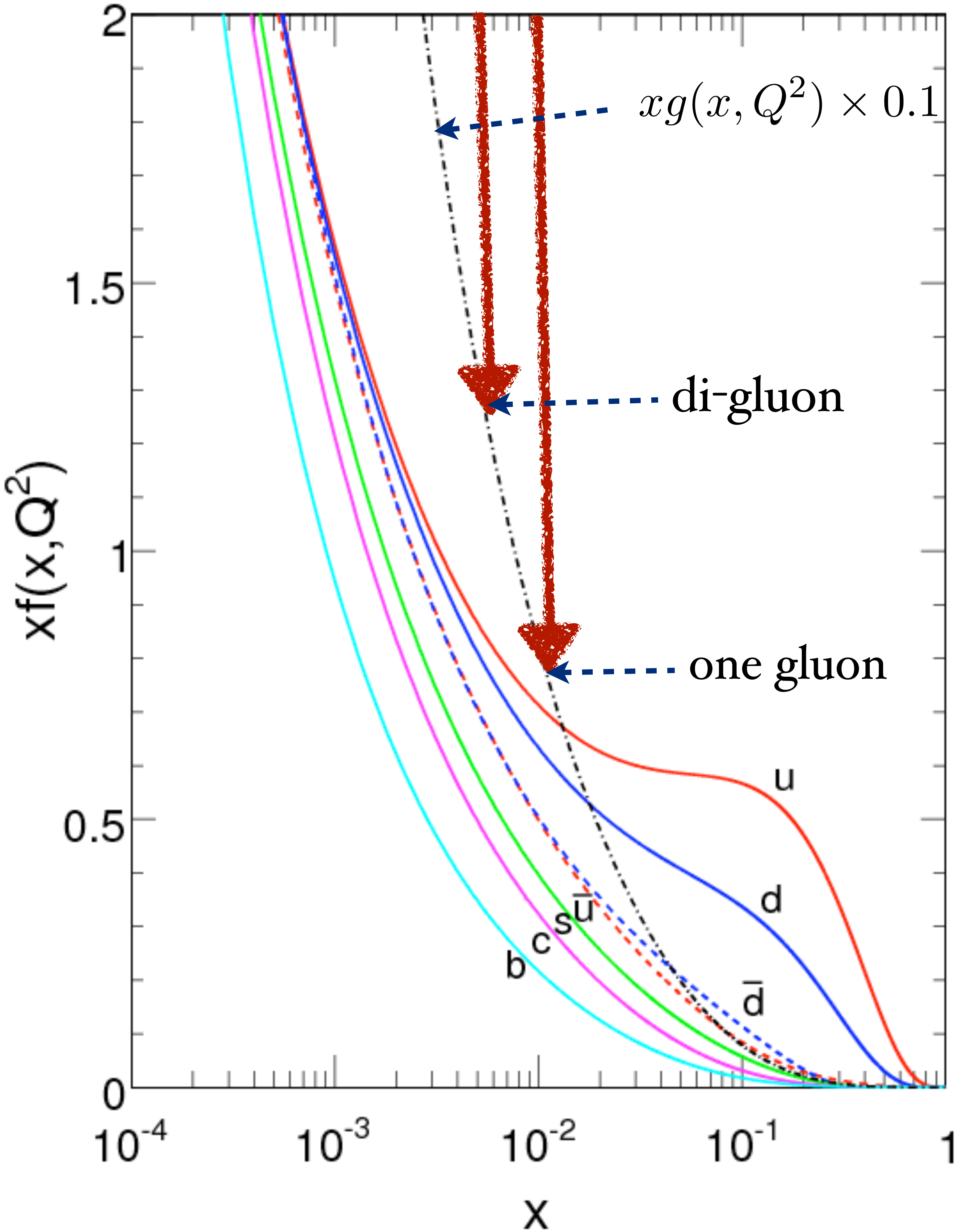
Digluon-initiated subprocess!

Higher-Twist but can dominate at forward rapidity, small p_T

Two gluons at $g(0.005) \sim \frac{13}{0.005} = 2600$ vs. one gluon at $g(0.01) \sim \frac{8}{0.01} = 800$



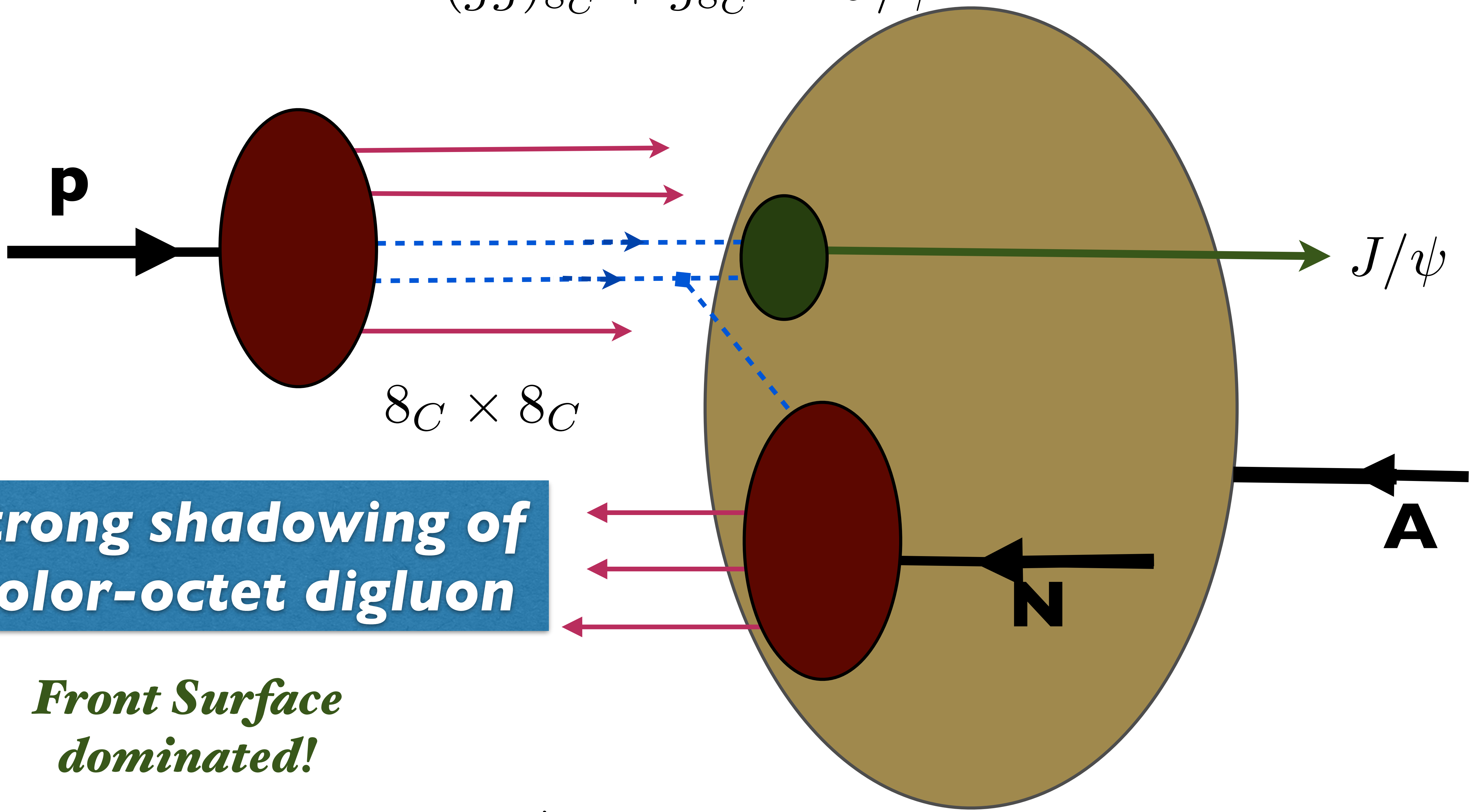
Two gluons at $g(0.005) \sim \frac{13}{0.005} = 2600$ vs. one gluon at $g(0.01) \sim \frac{8}{0.01} = 800$



Forward rapidity y ~4

$pA \to J/\psi X$

$$(gg)_{8_C} + g_{8_C} \to J/\psi$$



Strong shadowing of color-octet digluon

Front Surface dominated!

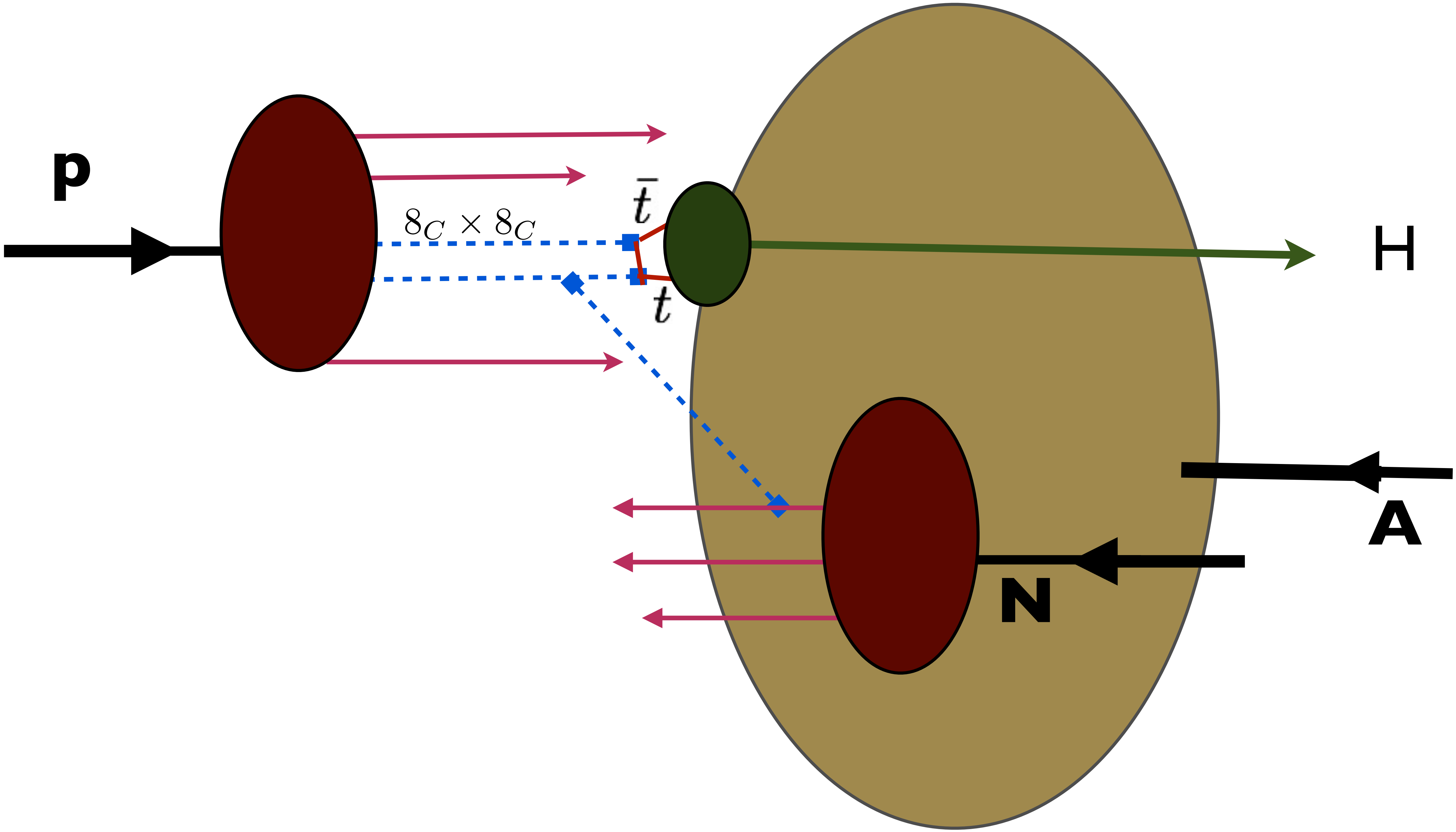
ψ' suppressed as it propagates through the nucleus

Digluon-initiated subprocess!

Crossing: Diffractive & pomeron exchange

$$pA \to HX$$

$$(gg)_{8_C} + g_{8_C} \to H$$



Double-gluon subprocess for Higgs production at forward rapidity

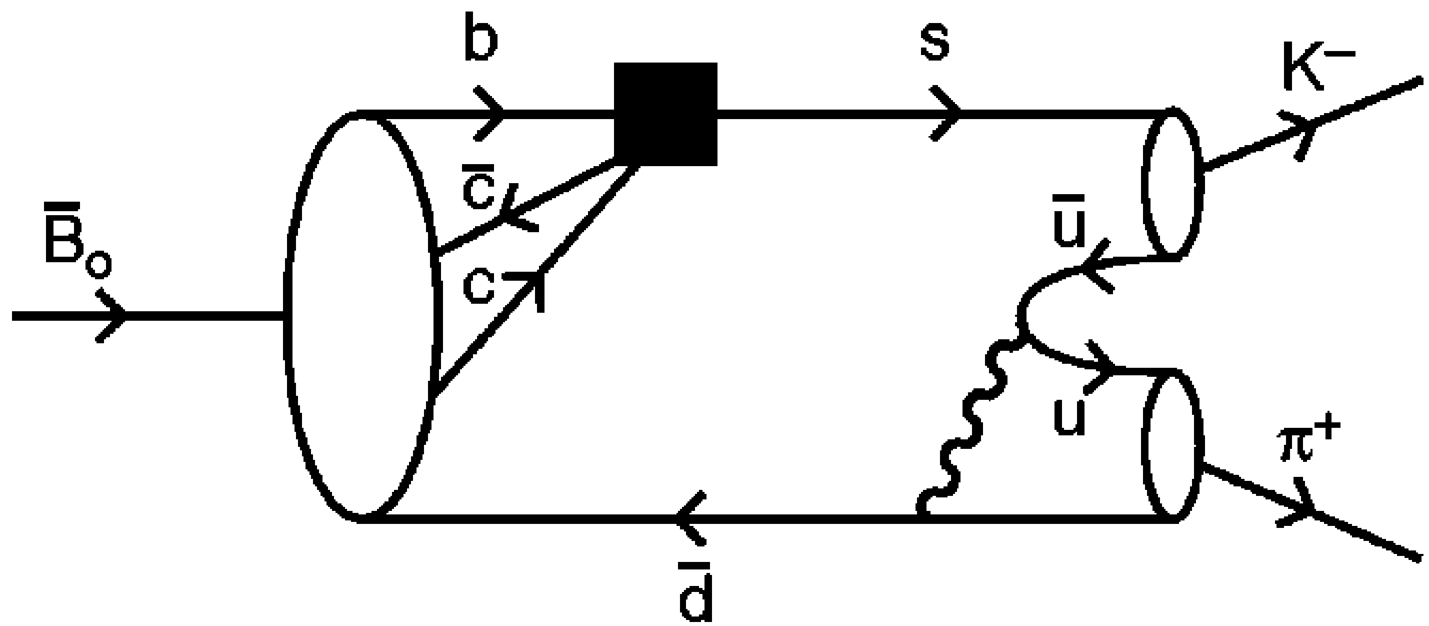
PHYSICAL REVIEW D, VOLUME 65, 054016

Evading the CKM hierarchy: Intrinsic charm in *B* decays

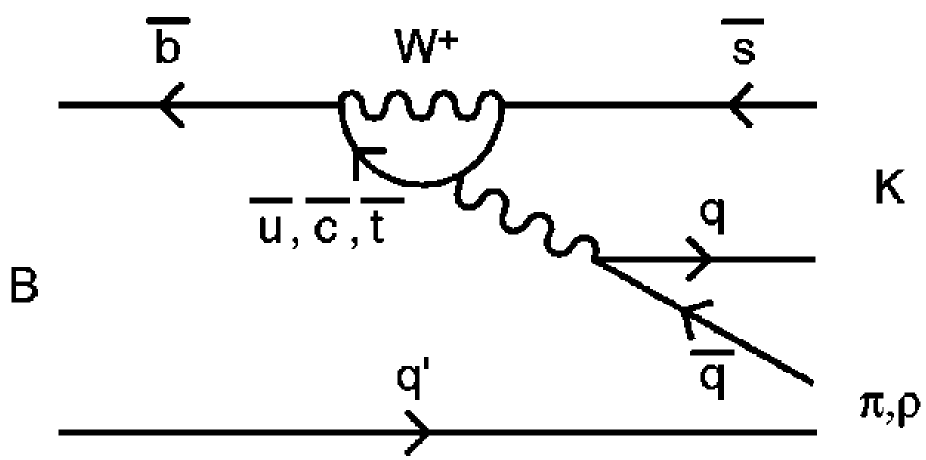
S. J. Brodsky*
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309

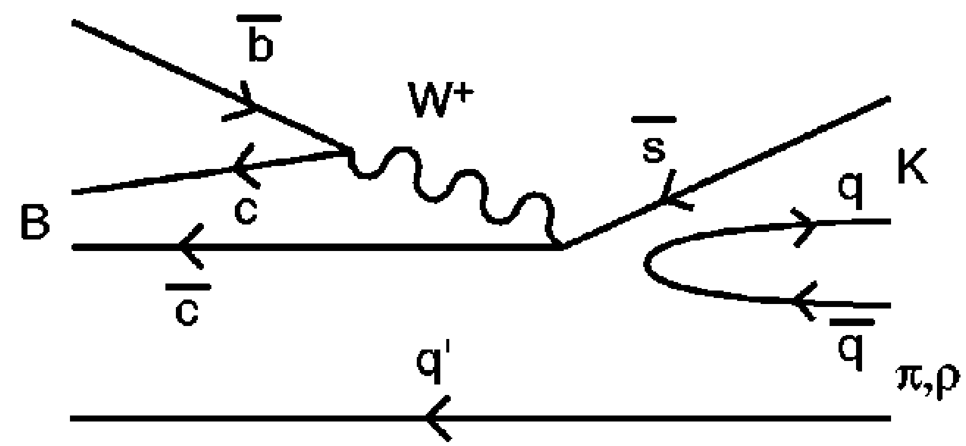
S. Gardner†
Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky 40506-0055
(Received 17 August 2001; published 5 February 2002)

We show that the presence of intrinsic charm in the hadrons' light-cone wave functions, even at a few percent level, provides new, competitive decay mechanisms for B decays which are nominally CKM suppressed. For example, the weak decays of the B-meson to two-body exclusive states consisting of strange plus light hadrons, such as $B\to\pi K$, are expected to be dominated by penguin contributions since the tree-level $b\to su\bar{u}$ decay is CKM suppressed. However, higher Fock states in the B wave function containing charm quark pairs can mediate the decay via a CKM-favored $b\to sc\bar{c}$ tree-level transition. Such intrinsic charm contributions can be phenomenologically significant. Since they mimic the amplitude structure of "charming" penguin contributions, the latter need not be penguin contributions at all.



Intrinsic charm in the B meson can mediate the decay to a strange, charmless final state via the weak transition $b \rightarrow s c \bar{c}$. The square box denotes the weak transition operator.





SLAC-PUB-14828

The Impact of Intrinsic Heavy Quark Distributions in the Proton on New Physics Searches at the High Intensity Frontier

Stanley J. Brodsky[1] and Susan Gardner[2]

[1] *SLAC National Accelerator Laboratory, Stanford University, Stanford, CA 94309*
[2] *Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506-0055*

The existence of intrinsic heavy quarks in the proton have important consequences for collider physics. They contribute to QCD background studies. For example, they are important to the interpretation of high p_T lepton and photon signals, as recently illustrated by a Tevatron study of inclusive photon production in association with b and c quarks [14] — the data reveal an excess at large p_T^γ which require an amendment of the charm quark distribution at large x. Intrinsic heavy quarks also mediate the materialization of novel heavy particles at high x_F, since most of the proton's momentum is transferred to its intrinsic heavy quarks. In fact, it even makes Higgs hadroproduction at large x_F possible [15, 16].

Heavy intrinsic quarks also play a role in indirect searches for new physics. In the context of studies of CP violation in weak decays, their flavor content is key because the CKM matrix is strongly hierarchical [17]. For example, the presence of intrinsic charm, e.g., in the hadrons' light-front wave functions, even at a few percent level, provides new, competitive decay mechanisms for B decays which are nominally CKM-suppressed. This can be important in the context of $B \to \pi K$ decays because the tree-level $b \to su\bar{u}$ decay is CKM suppressed, whereas the presence of intrinsic charm in the B-meson LFWF can mediate the decay via a CKM-favored $b \to sc\bar{c}$ tree-level transition [17]. More recently, the role of intrinsic charm quarks in semi-leptonic processes has been studied [18–20] with regard to their impact on the value of $V_{\rm cb}$.

Heavy quarks in the proton are also important to searches for dark-matter candidates within the context of supersymmetry — for so-called "WIMPs". Previous work has focussed on the role of strangeness in the proton for WIMP searches [21, 22]. Heavier flavors also play a significant role in mediating the gluon coupling to the Higgs, and hence to the neutralino, and the leading contribution in the heavy-quark limit is well-known [23, 24] — this may describe elastic scattering sufficiently well. Recently, interpreting the tangle of possible dark-matter signatures has led to the suggestion of composite dark-matter candidates [25]; intrinsic heavy quarks could play a role in mediating transitions to excited dark-matter states in scattering experiments. These issues merit further study.

Excitation of Intrinsic Heavy Quarks in Proton

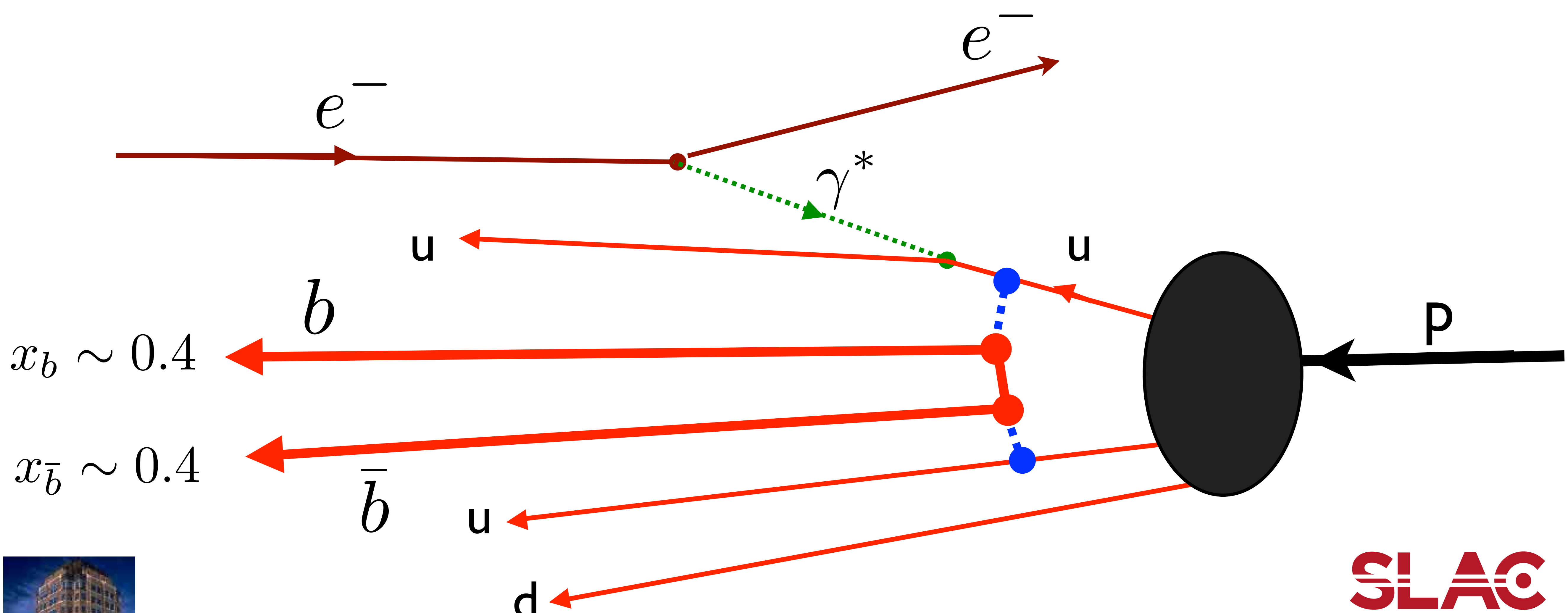
Amplitude maximal at small invariant mass, equal rapidity

$$x_i \sim \frac{m_{\perp i}}{\sum_j^n m_{\perp j}}$$

Produce forward, high x_F

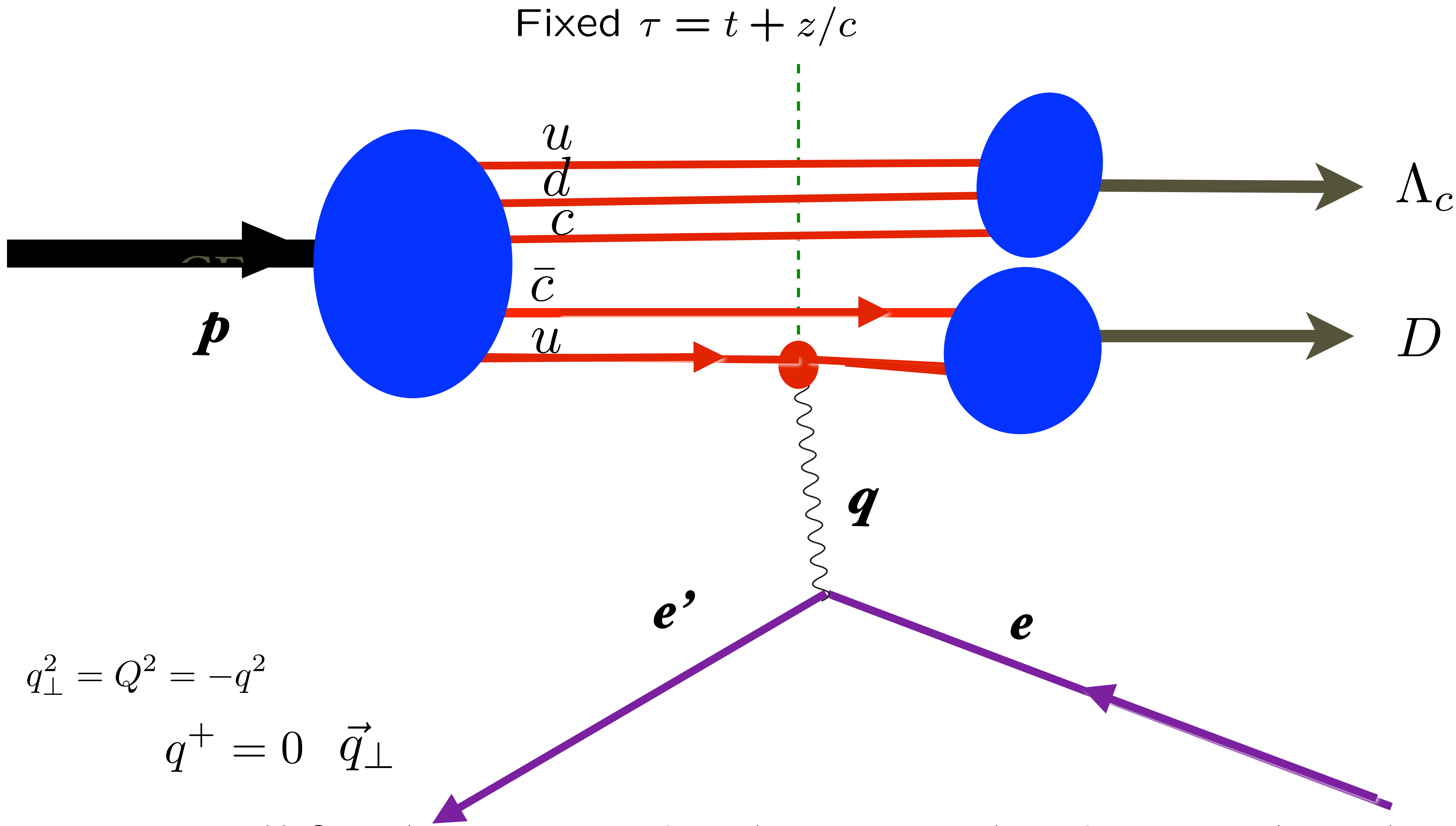
$\Upsilon(b\bar{b}), \Lambda_b(bud), B^+(\bar{b}u), B^0(\bar{b}d)$

Need Forward Small Angle Detection



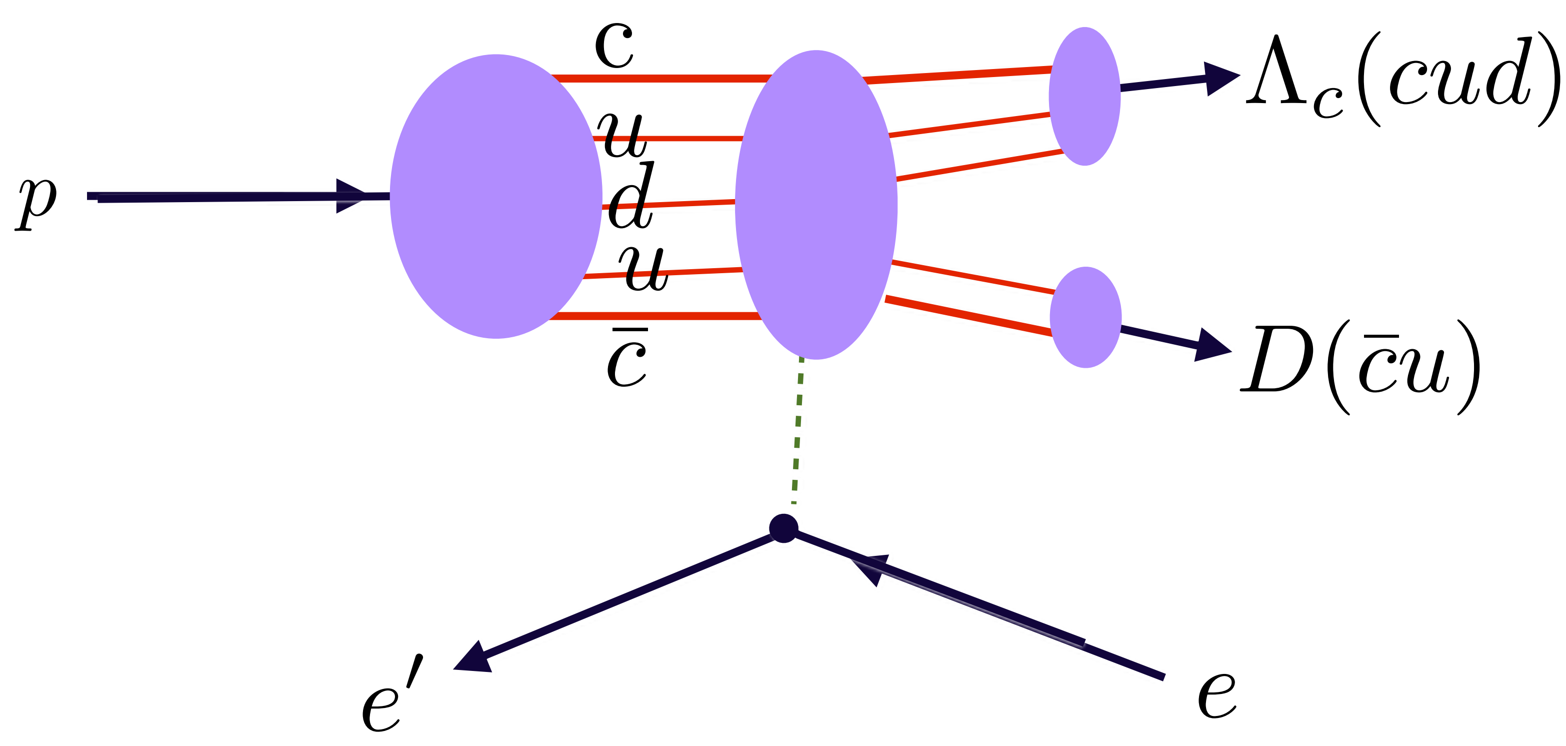
SLAC
NATIONAL ACCELERATOR LABORATORY

Light-Front Wavefunctions and Electron-Proton Collisions



All final states |F> in electroproduction produced from n to n' overlap of LFWFs

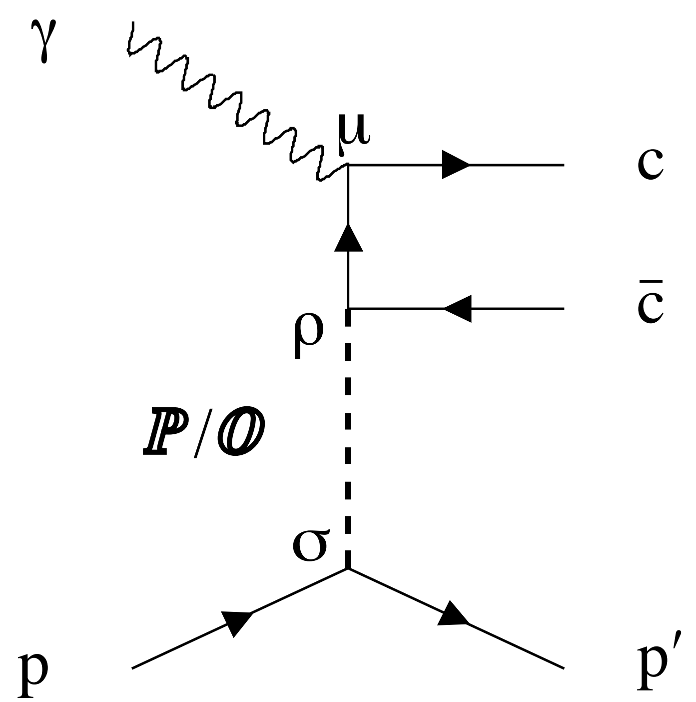
Coalescence of comovers produces $|F> = |\Lambda_c D>$ final state



Dissociate proton to high x_F heavy-quark pair

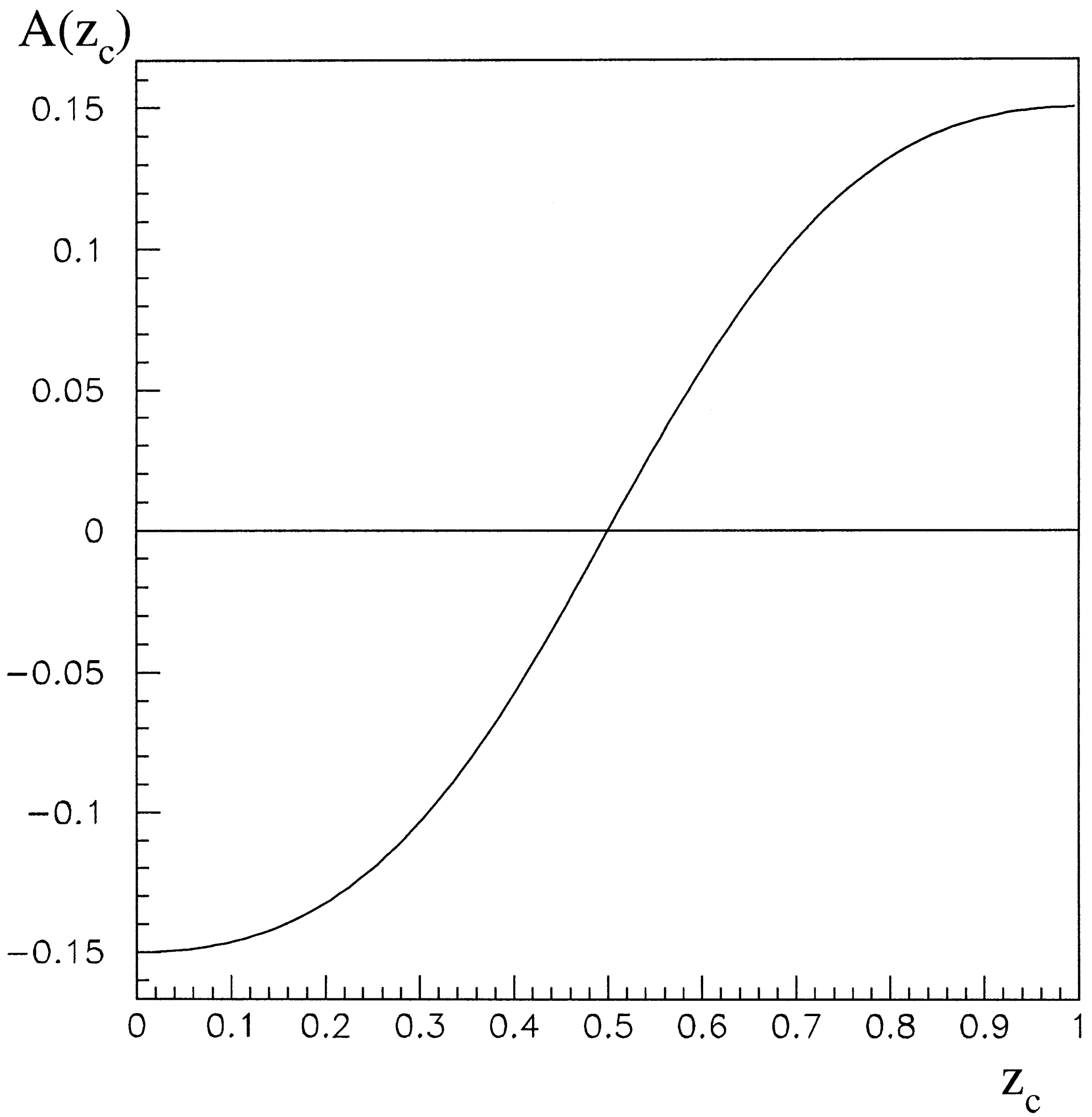
$$\gamma^* p \to \Lambda_c(cdd) + D(\bar{c}u), \gamma^* p \to \Lambda_b(bud) B^+(\bar{b}u)$$

Produce Charm near Threshold at JLab!



$$\gamma^* p \to c\bar{c}p$$

Odderon-Pomeron Interference!

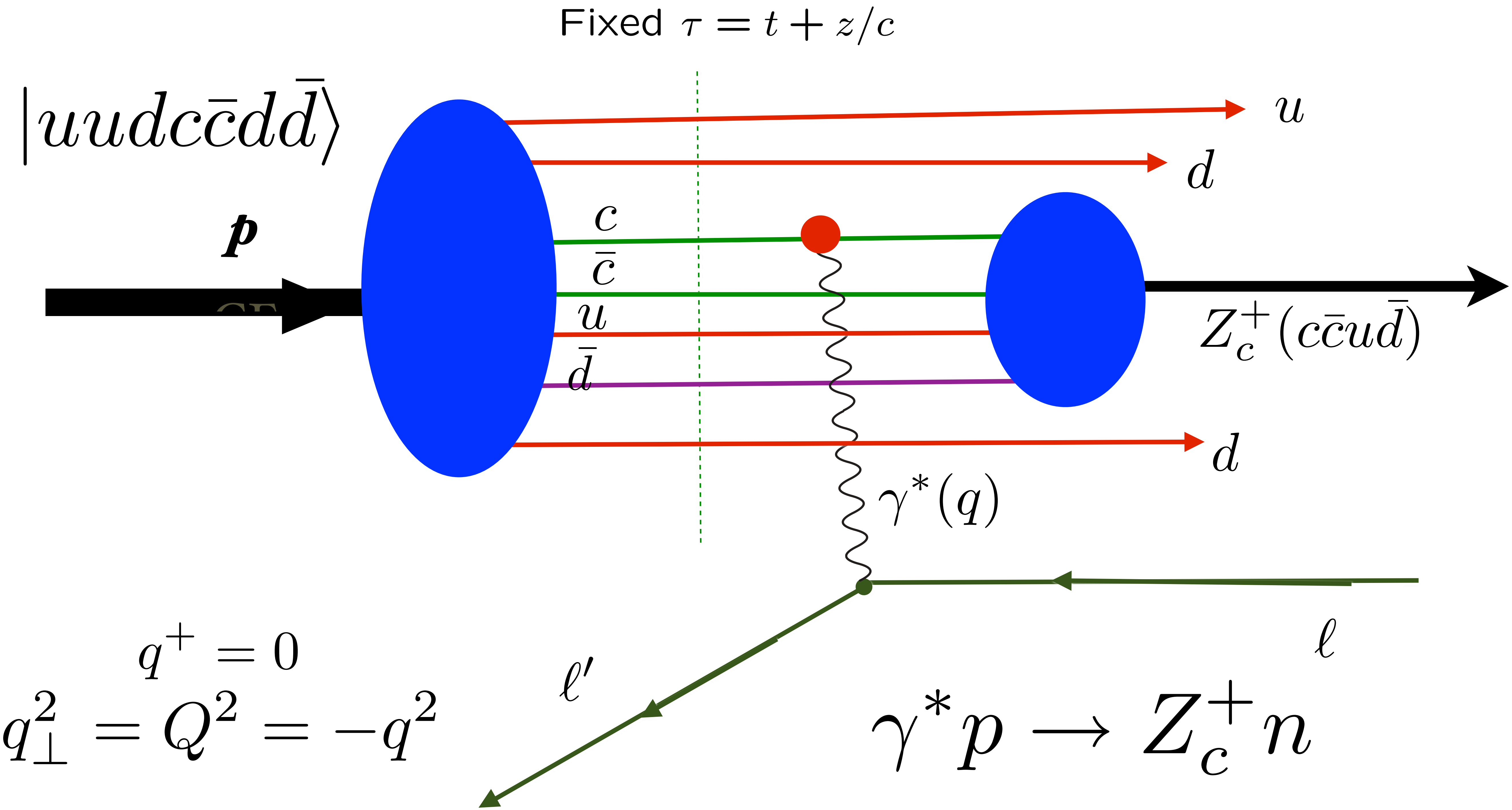


$$\mathscr{A}\left(t \simeq 0, M_X^2, z_c\right) \simeq 0.45 \left(\frac{s_{\gamma p}}{M_X^2}\right)^{-0.25} \frac{2 z_c - 1}{z_c^2 + (1 - z_c)^2}$$

Measure charm asymmetry in photon fragmentation region

Merino, Rathsman, sjb

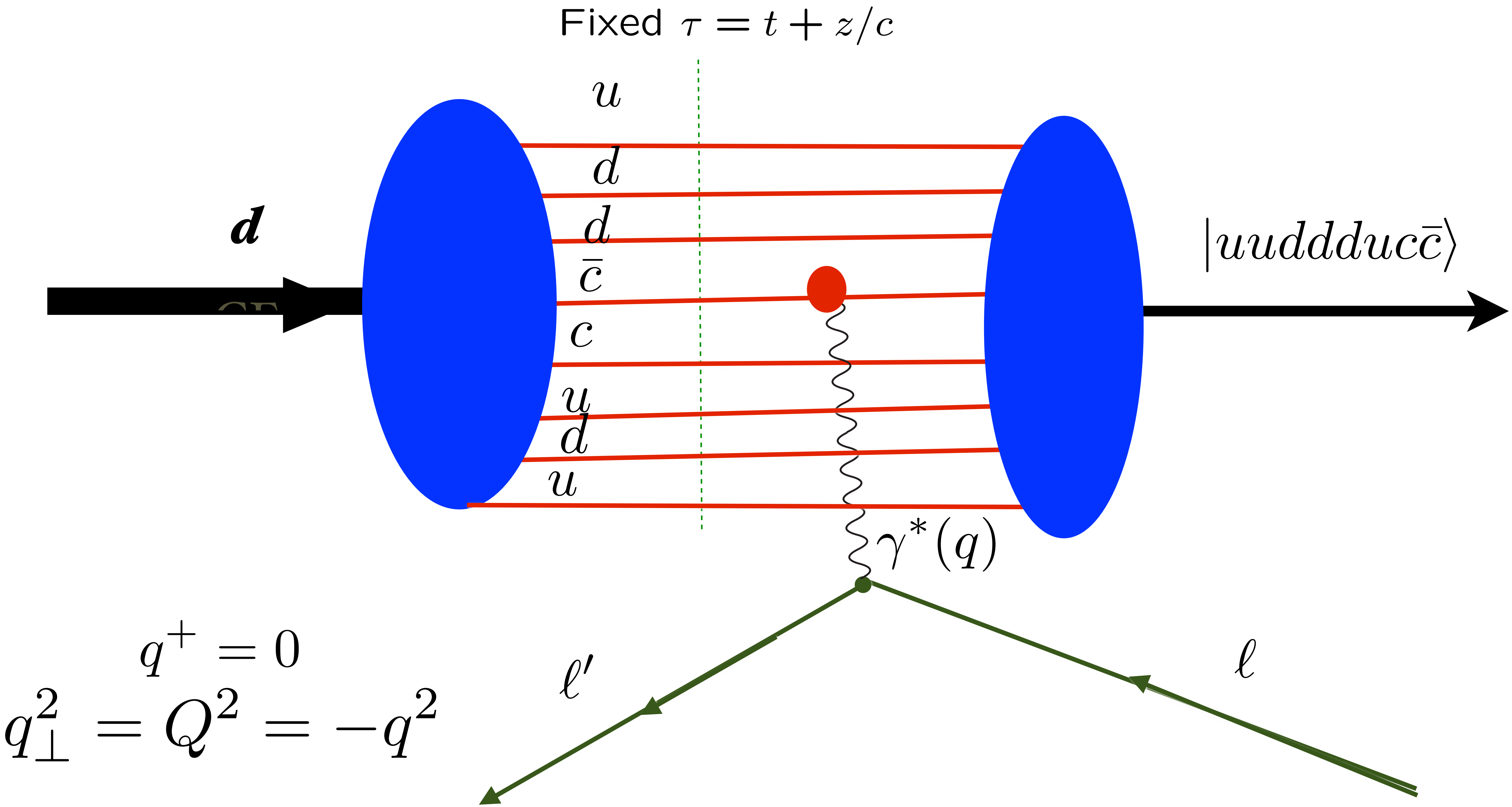
Light-Front Wavefunctions and Heavy-Quark Electroproduction



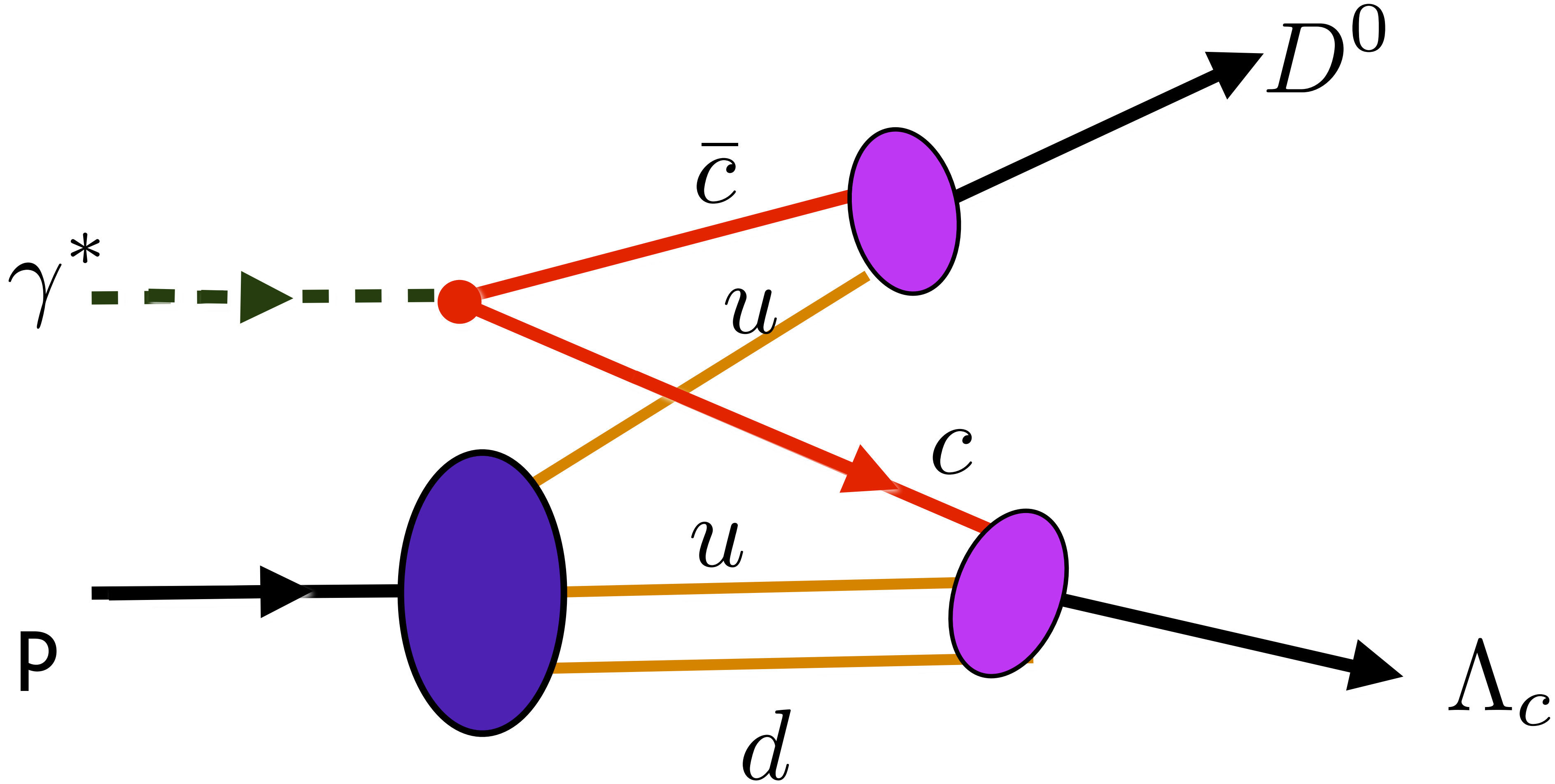
Coalescence of comovers at threshold produces
Z_c^+ tetraquark resonance

Bottom Tetraquarks

Octoquarks and Heavy-Quark Electroproduction



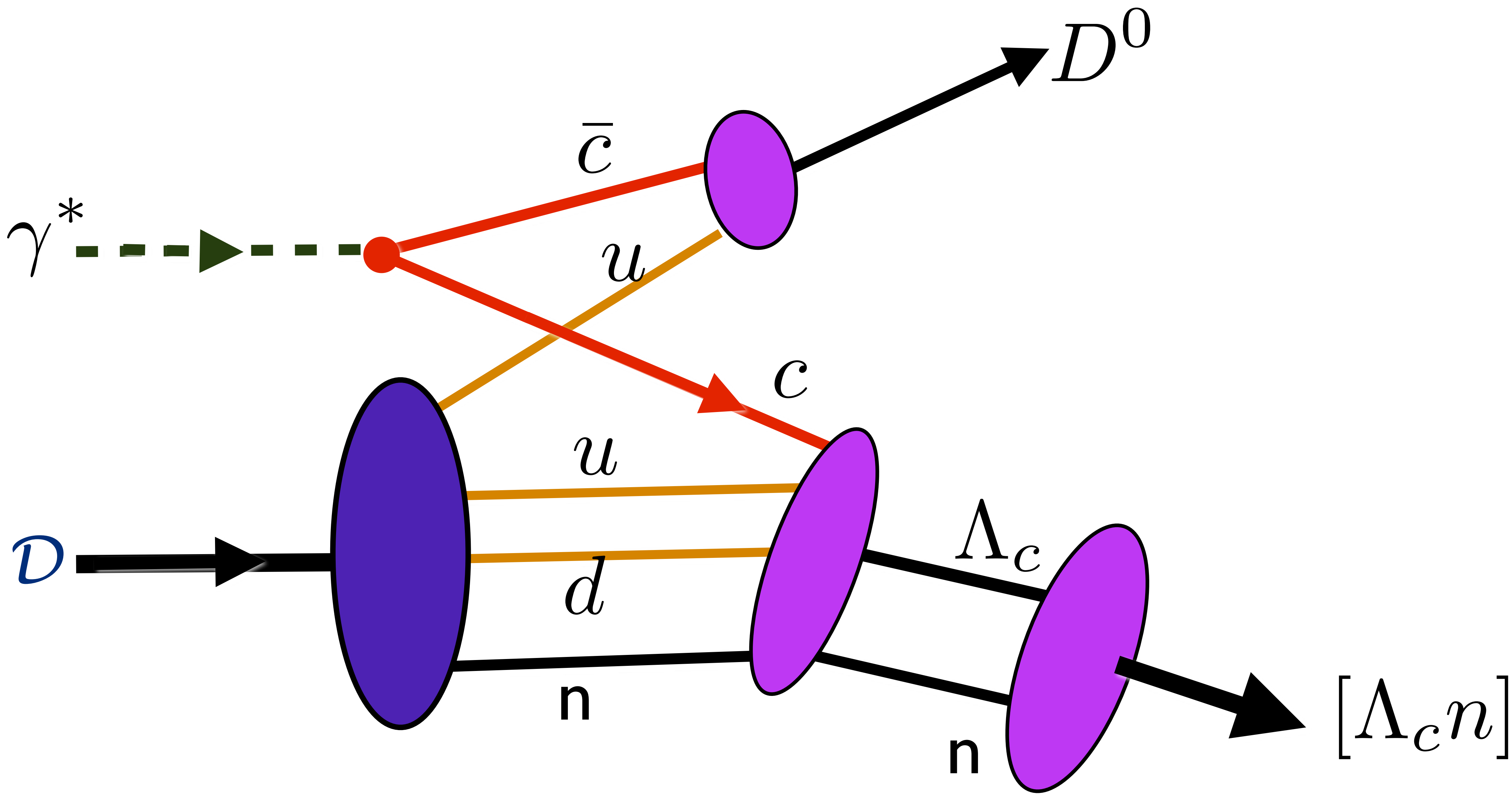
Coalescence of comovers can produce the $B = +2$ $Q = +1$ isospin partner of the $B = +2$ $Q = +2$ resonance $|uuduudc\bar{c}\rangle$ which produces the large R_{NN} in p p elastic scattering



$$\gamma^* p \to \overline{D}^0(\bar{c}u)\Lambda_c(cud)$$

c and u quark interchange

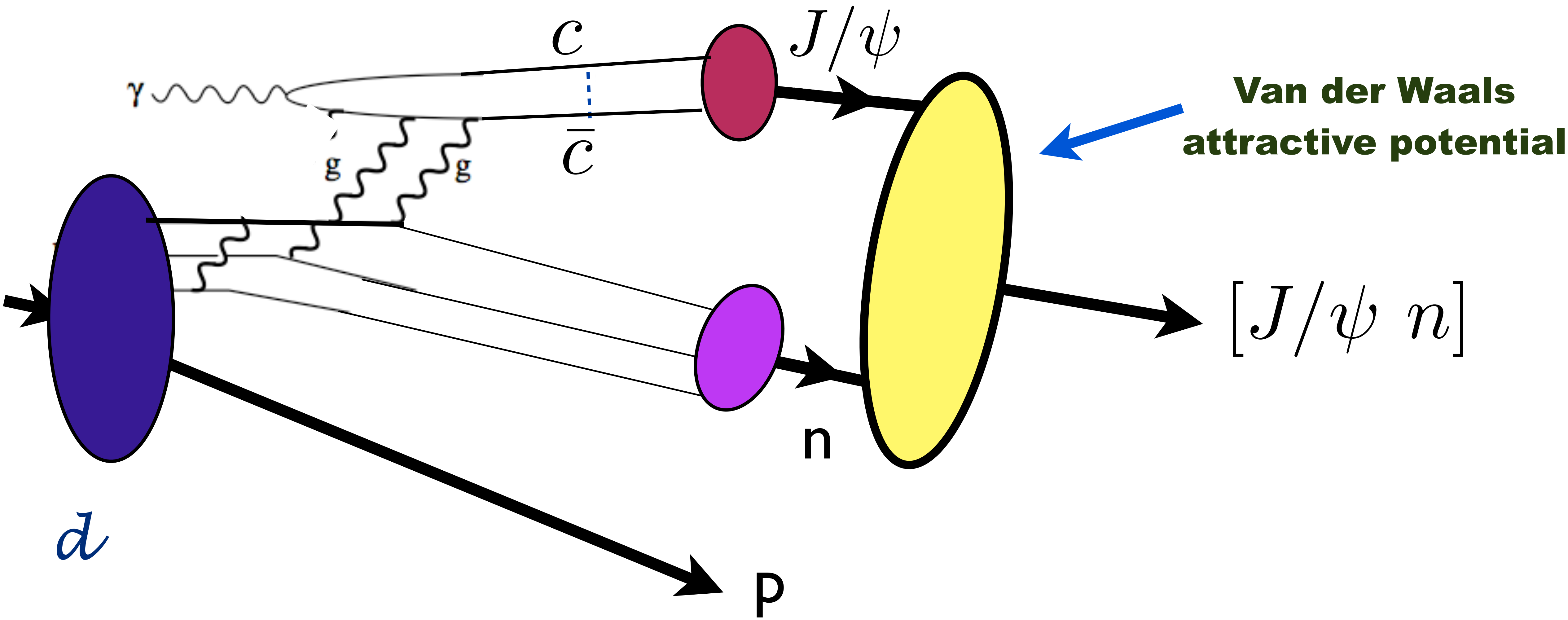
Nuclear binding at low relative velocity



$$\gamma^* d \to \overline{D}^0(\bar{c}u)[\Lambda_c n](cududd)$$

Possible charmed B= 2 nucleus

Charmonium Production at Threshold

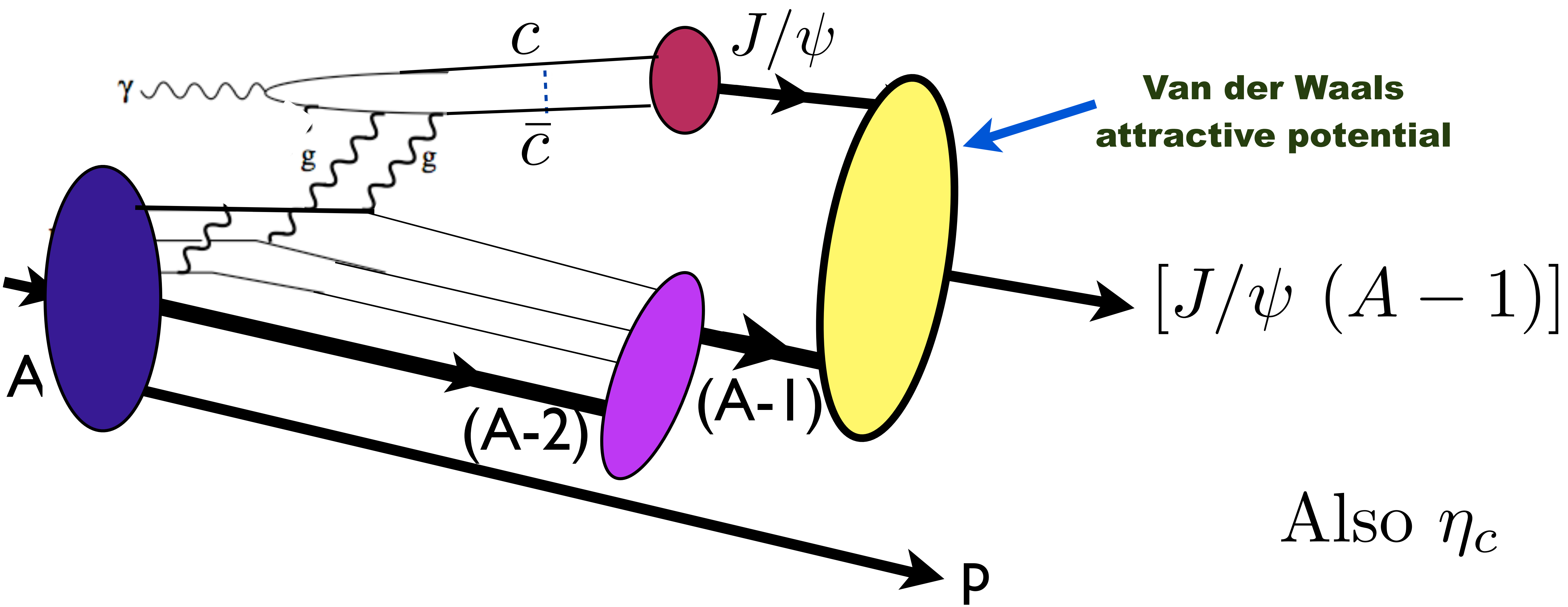


$$\gamma \ d \rightarrow [J/\psi \ n] \ p$$

$$\gamma \ d \rightarrow [J/\psi \ p] \ n$$

Form nucleon-charmonium bound state! $|uudc\bar{c}>$

Charmonium Production at Threshold

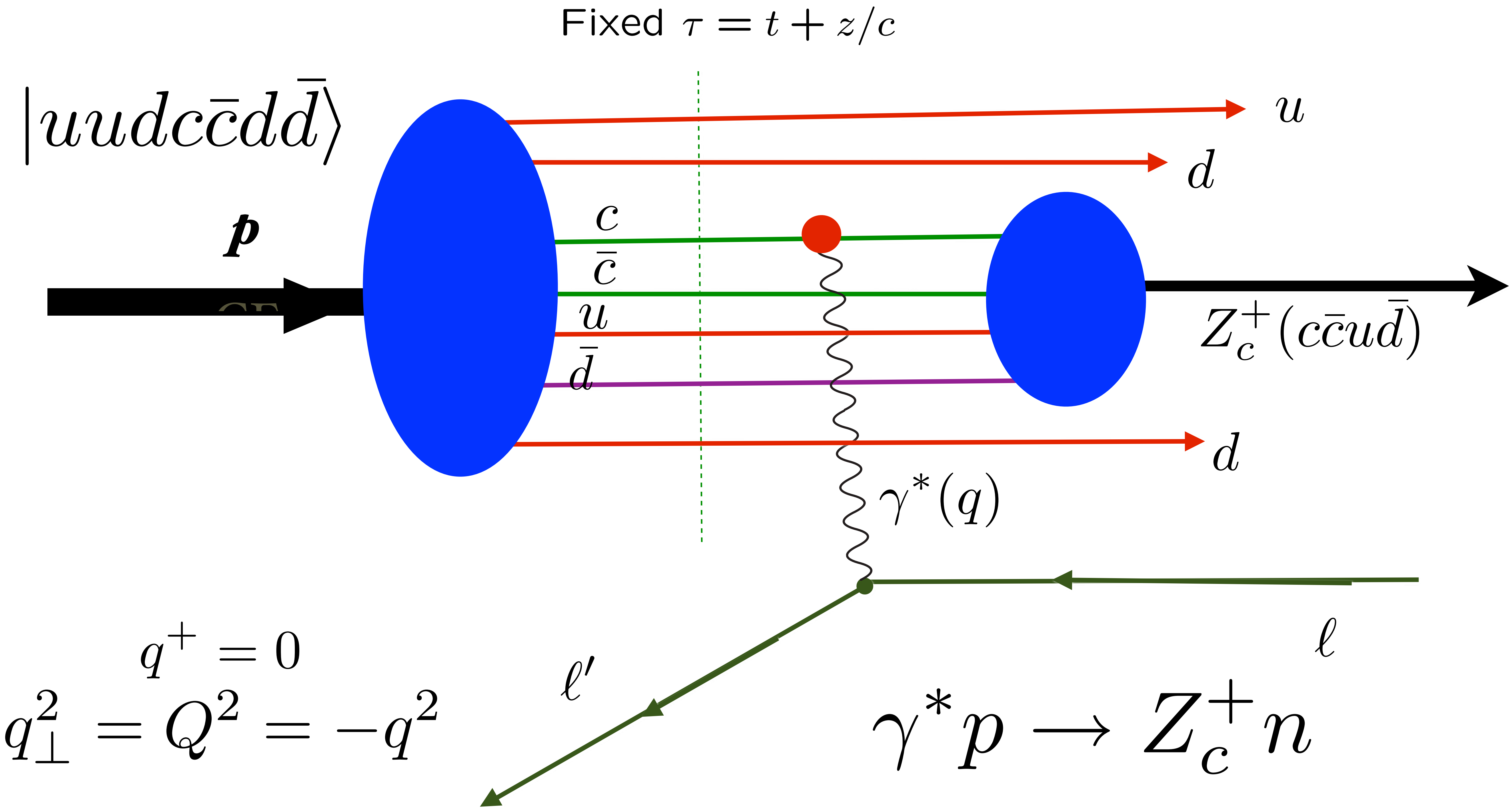


Also η_c

$$\gamma\ A \rightarrow [J/\psi\ (A-1)]\ p$$

Form nuclear bound-charmonium bound state!

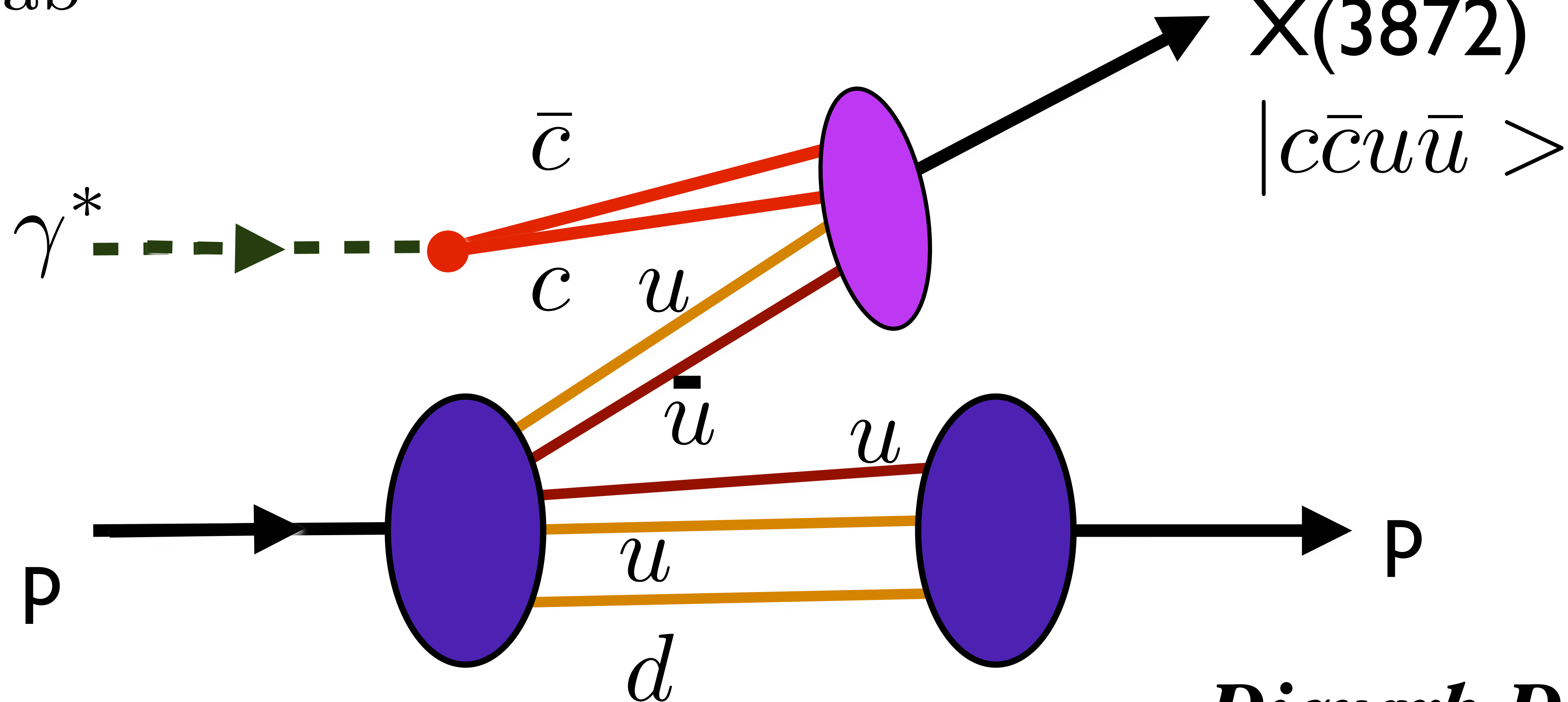
Light-Front Wavefunctions and Heavy-Quark Electroproduction



Produce Charged Tetraquarks at JLab!

Coalescence of comovers at threshold produces Z_c^+ tetraquark resonance

$$E^{\gamma}_{\text{lab}} > 11.9 \text{ GeV}$$



Diquark-Diquark vs Molecular State?

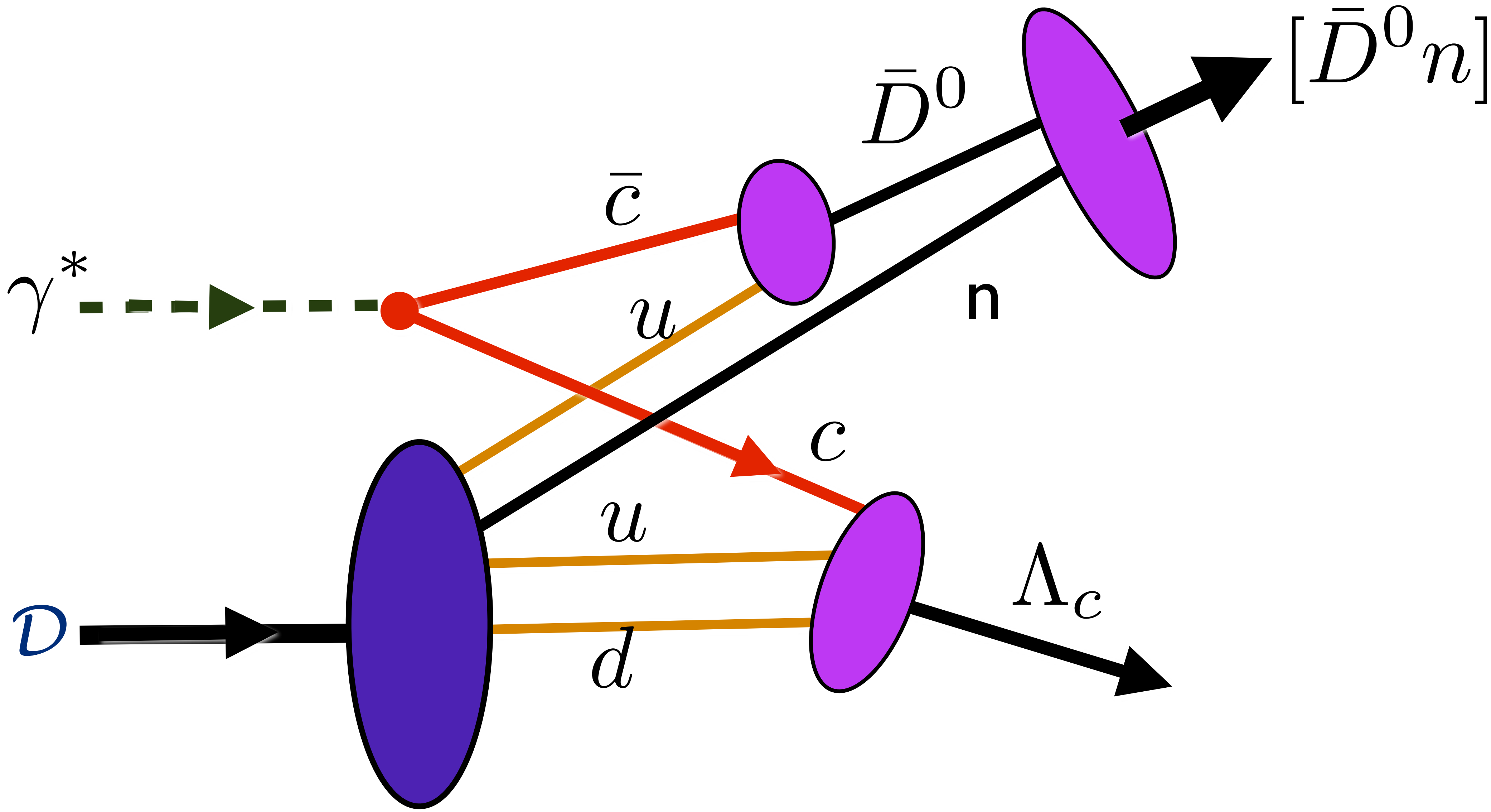
$$\gamma^* p \to X(3872) + p'$$

$$|c\bar{c}q\bar{q} >$$

New approach to hadronic decays

Dominance of Ψ' vs J/Ψ decays

Lebed, Hwang, sjb



$$\gamma^* d \to \Lambda_c + [\overline{D}^0(\bar{c}u)n](\bar{c}uudd)$$

Create pentaquark on deuteron at low relative velocity

JLab 12 GeV: An Exotic Charm Factory!

$$\gamma^* p \to J/\psi + p \text{ threshold}$$
$$\text{at } \sqrt{s} \simeq 4 \text{ GeV}, \; E_{\text{lab}}^{\gamma^*} \simeq 7.5 \text{ GeV}.$$

Produce $[J/\psi + p]$ bound state

$$|uudc\bar{c} >$$

$$\gamma^* d \to J/\psi + d \text{ threshold}$$
$$\text{at } \sqrt{s} \simeq 5 \text{ GeV}, \; E_{\text{lab}}^{\gamma^*} \simeq 6 \text{ GeV}.$$

Produce $[J/\psi + d]$ nuclear-bound quarkonium state

$$|uudduc\bar{c} >$$

JLab 12 GeV: An Exotic Charm Factory!

Electroproduce open charm at threshold

$$\gamma^* p \to D^0(u\bar{c})\Lambda_c(udc)$$

Use deuteron or light nuclear target

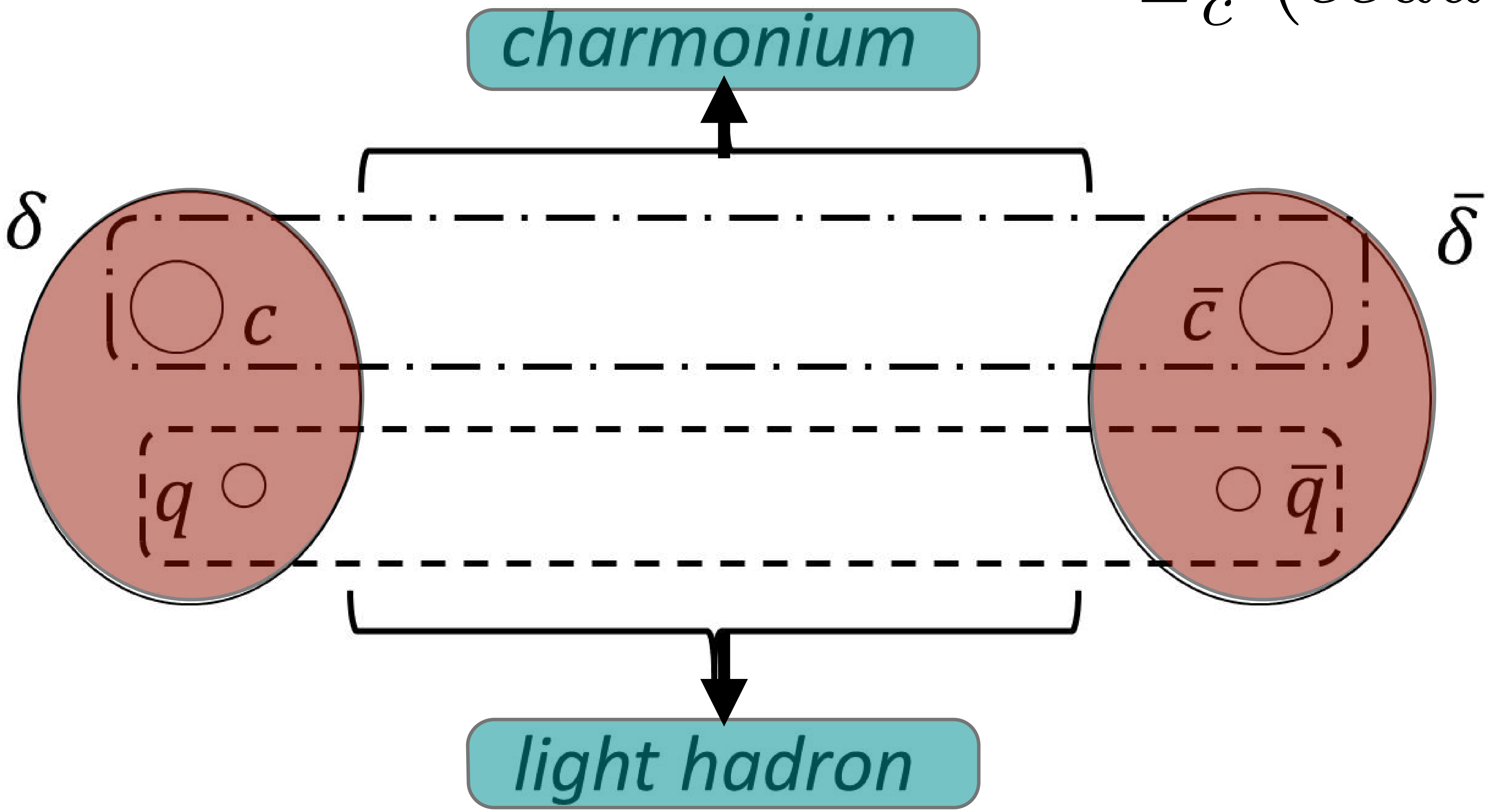
$$\gamma^* d \to D + [\Lambda_c n]$$ ***New baryonic state***

$$\gamma^* d \to \Lambda_c + [D^0 n]$$ ***Pentaquark***

Binding at threshold: covalent bonds from quark interchange

Also: Dramatic Spin Effects Possible at Threshold!

$Z_c^+(c\bar{c}u\bar{d})$



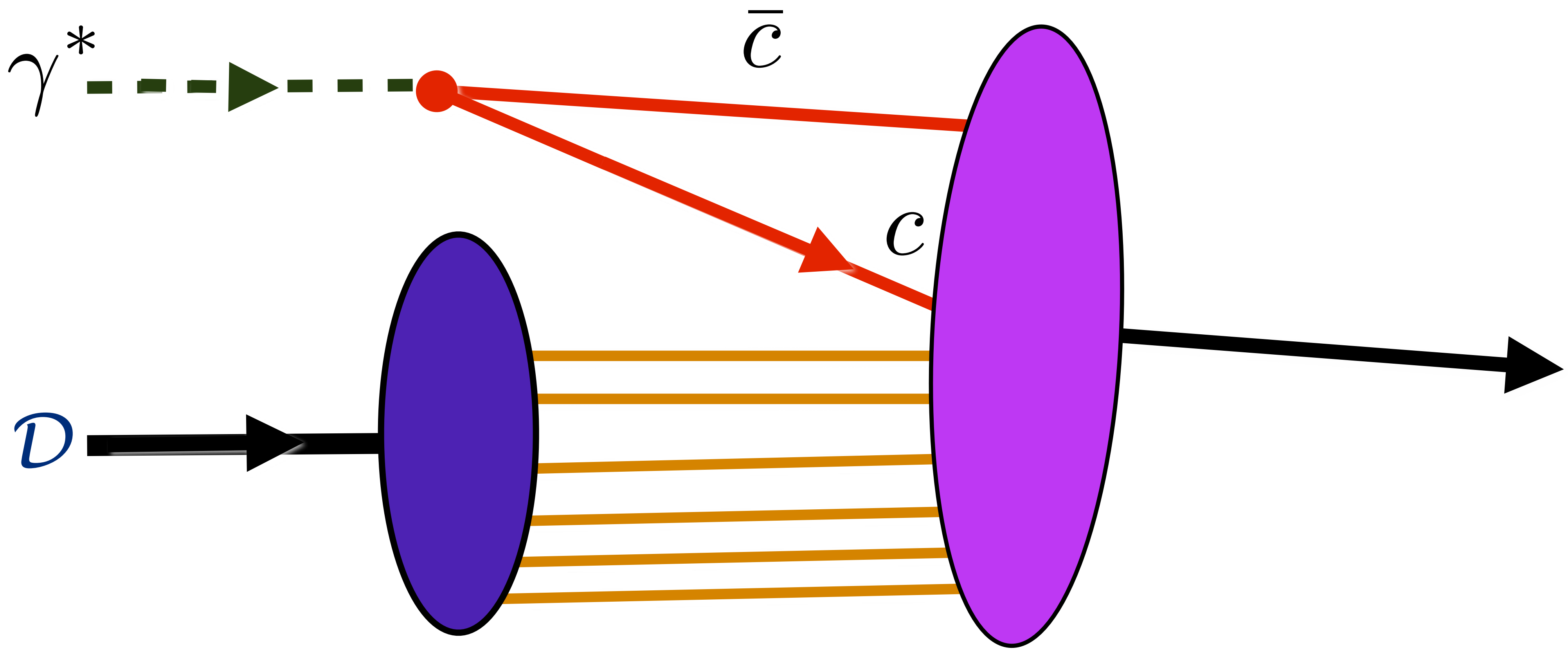
$Z_c^+([cu][\bar{c}\bar{d}]) \to \pi^+ \psi'$

Diquark-Diquark

Dominance of large size Ψ' vs J/Ψ decays

Lebed, Hwang, sjb

$$M_{\rm octoquark} \sim 5 \text{ GeV}$$

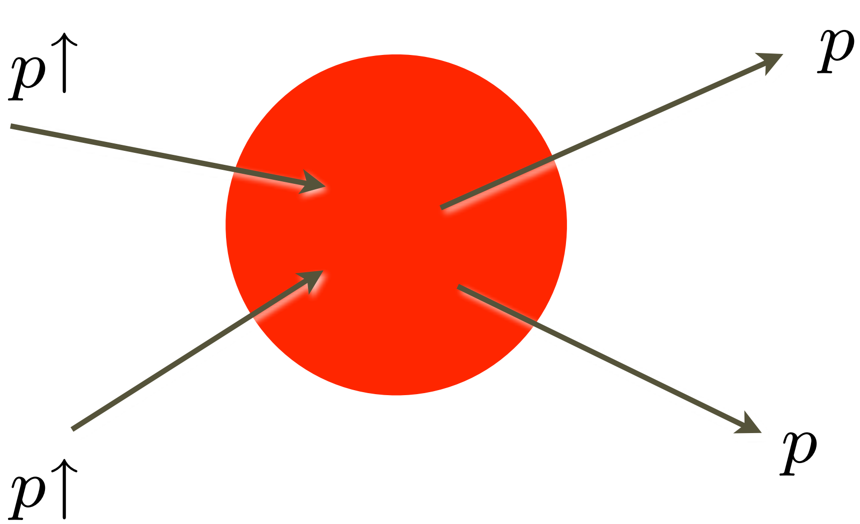


$$\gamma^* D \to |uuduudc\bar{c} >$$

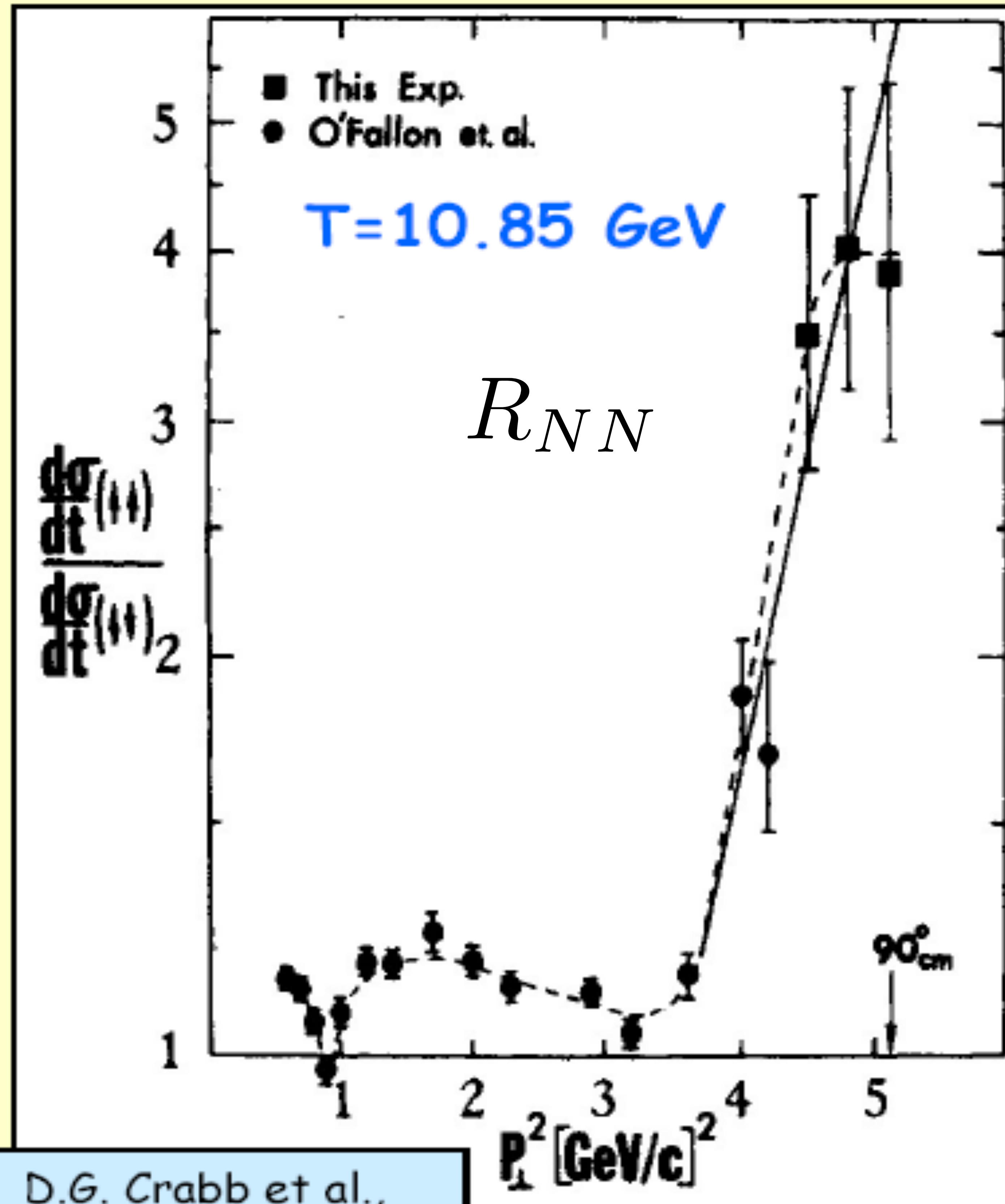
Explains Krisch Effect!

Krisch, Crabb, et al

Unexpected spin-spin correlation in pp elastic scattering

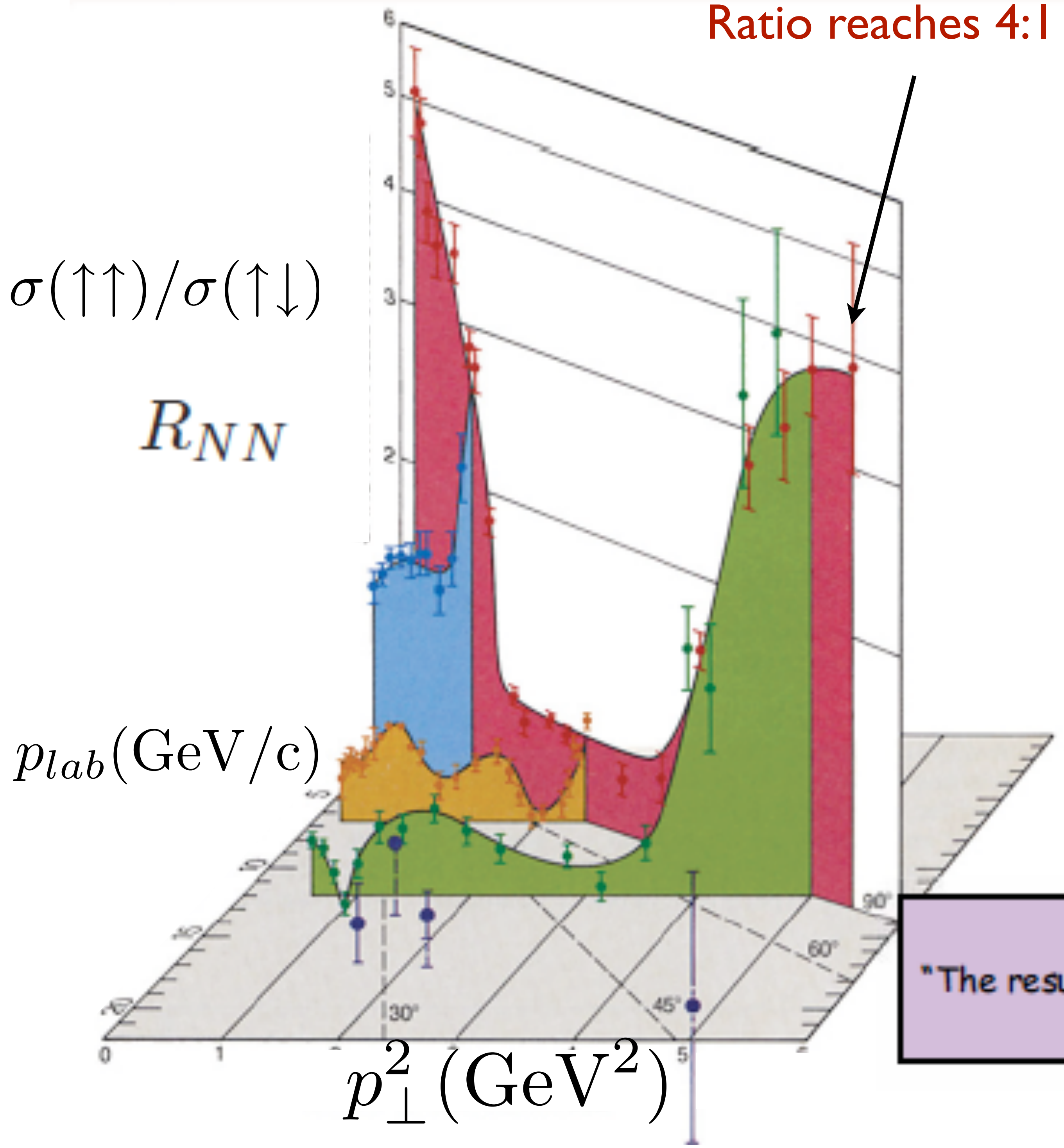


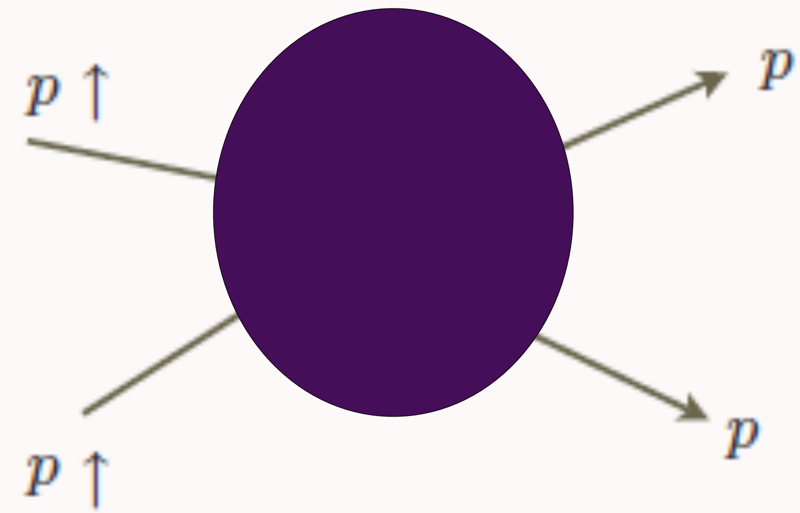
polarizations normal to scattering plane



D.G. Crabb et al.,
PRL 41, 1257 (1978)

Spin Correlations in Elastic $p-p$ Scattering





polarization normal to scattering plane

$$|uud\ uud\ c\bar{c}\rangle$$

Dibaryon resonance?

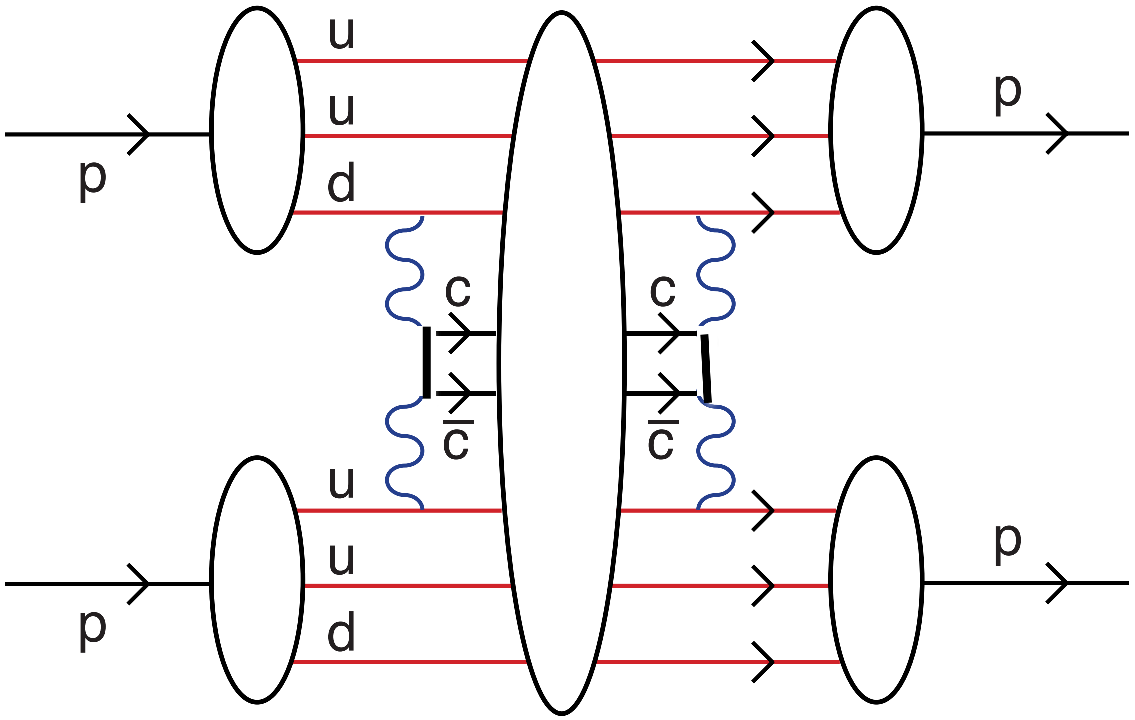
A. Krisch, Sci. Am. 257 (1987)
"The results challenge the prevailing theory that describes the proton's structure and forces"

de Teramond and sjb

Large R_{NN} in $pp \to pp$ explained by
$B=2, J=L=1\ |uuduudc\bar{c}>$ resonance
at $\sqrt{s} \sim 5$ GeV

Alternative: Ralston

$$A_{nn} = 1!$$



Production of
uud c̄ c uud
octoquark resonance

J=L=S=1, C=-, P=- state

QCD Schwinger-Sommerfeld Enhancement at Heavy Quark Threshold

Hebecker, Kuhn, sjb

8 quarks in S-wave: odd parity

S. J. Brodsky and G. F. de Teramond, "Spin Correlations, QCD Color Transparency And Heavy Quark Thresholds In Proton Proton Scattering," Phys. Rev. Lett. **60**, 1924 (1988).

$$\sigma(pp \to c\bar{c}X) \simeq 1\ \mu b \text{ at threshold} \qquad \sigma(\gamma p \to c\bar{c}X) \simeq 1\ nb \text{ at threshold}$$

Charm at Threshold

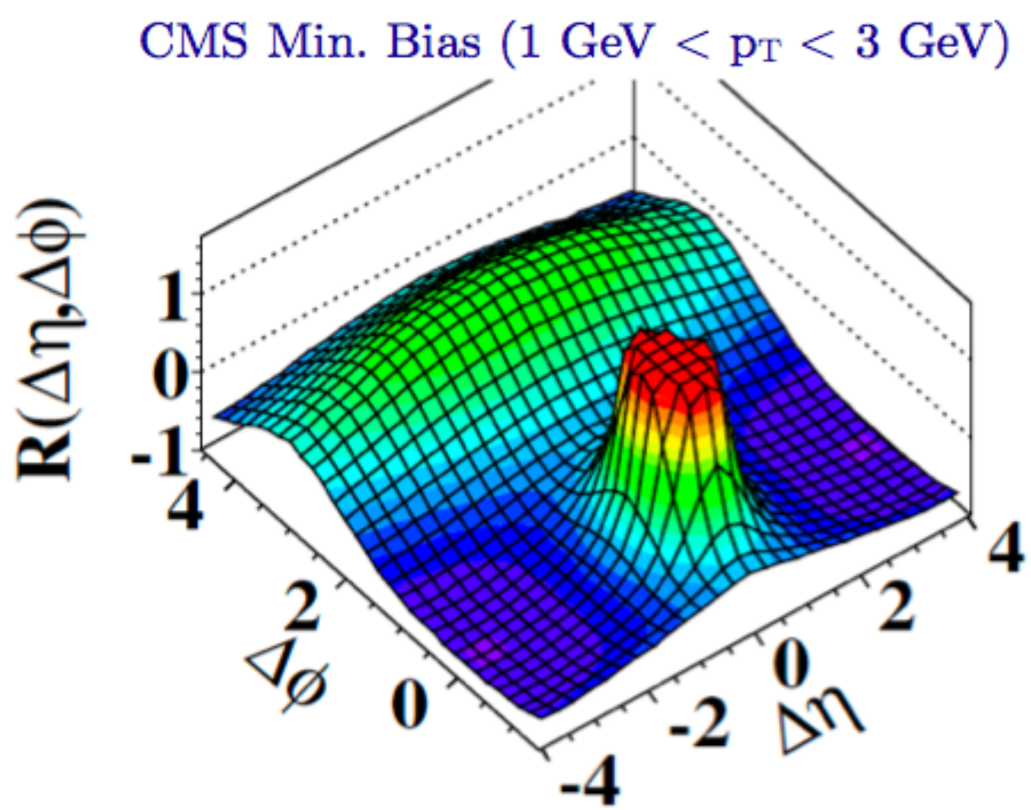
- Intrinsic charm Fock state puts 80% of the proton momentum into the electroproduction process
- 1/velocity enhancement from FSI
- CLEO data for quarkonium production at threshold
- Krisch effect shows B=2 resonance
- all particles produced at small relative rapidity-- resonance production
- Many exotic hidden and open charm resonances will be produced at JLab (12 GeV)

Key QCD Issues in Electroproduction

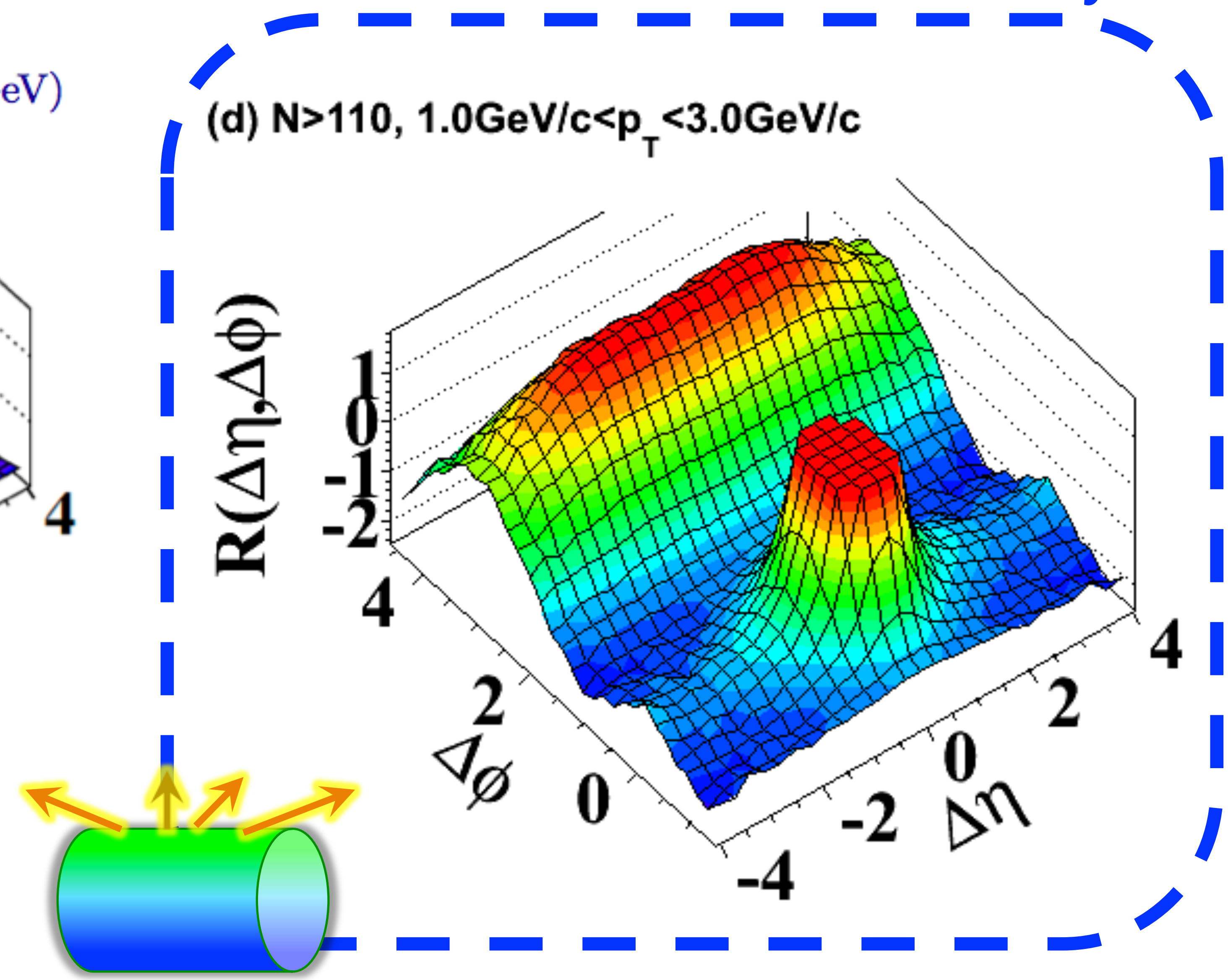
- **Intrinsic Heavy Quarks**
- **Role of Color Confinement in DIS**
- **Hadronization at the Amplitude Level**
- **Leading-Twist Lensing: Sivers Effect**
- **Diffractive DIS**
- **Static versus Dynamic Structure Functions**
- **Origin of Shadowing and Anti-Shadowing**
- **Is Anti-Shadowing Non-Universal: Flavor Specific?**
- **Nature of Nuclear Correlations**
- $1 < x < A$

Ridge in high-multiplicity p p collisions

Two-particle correlations: CMS results



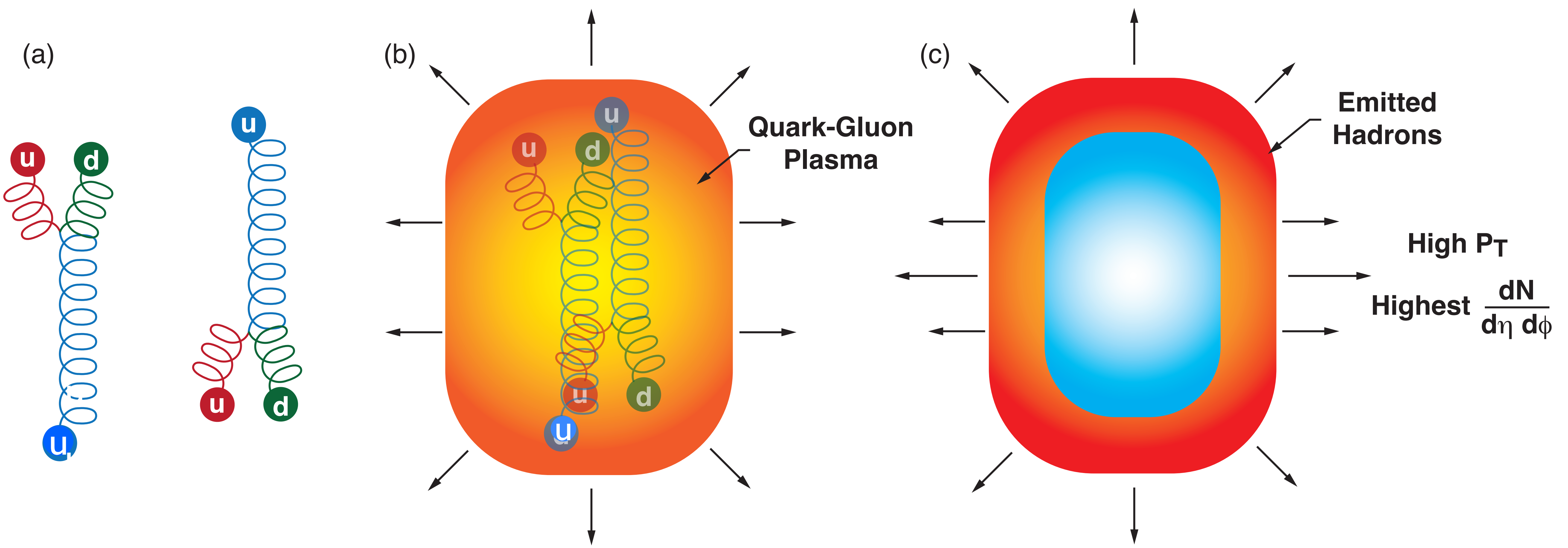
"Discovery"



- **Ridge: Distinct long range correlation in η collimated around ΔΦ≈ 0 for two hadrons in the intermediate 1 < p_T, q_T < 3 GeV**

Raju Venugopalan

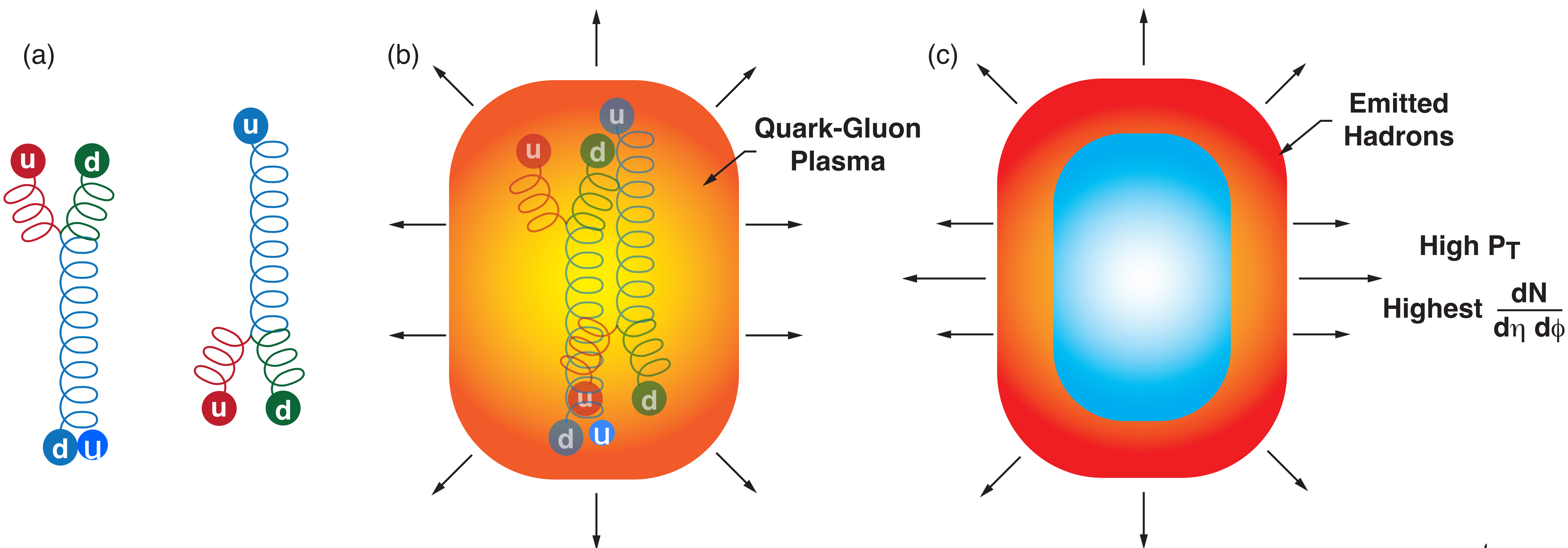
Ridge may reflect collision of aligned flux tubes



Bjorken, Goldhaber, sjb

Possible origin of same-side CMS ridge in p p collisions

Bjorken, Goldhaber, sjb



$$\vec{V} = \sum_{i=1}^{N} [\cos 2\phi_i \hat{x} + \sin 2\phi_i \hat{y}]$$

v_3 from collisions of Y junctions

Multiparticle ridge-like correlations in very high multiplicity proton-proton collisions

Bjorken, Goldhaber, sjb

We suggest that this "ridge"-like correlation may be a reflection of the rare events generated by the collision of aligned flux tubes connecting the valence quarks in the wave functions of the colliding protons.

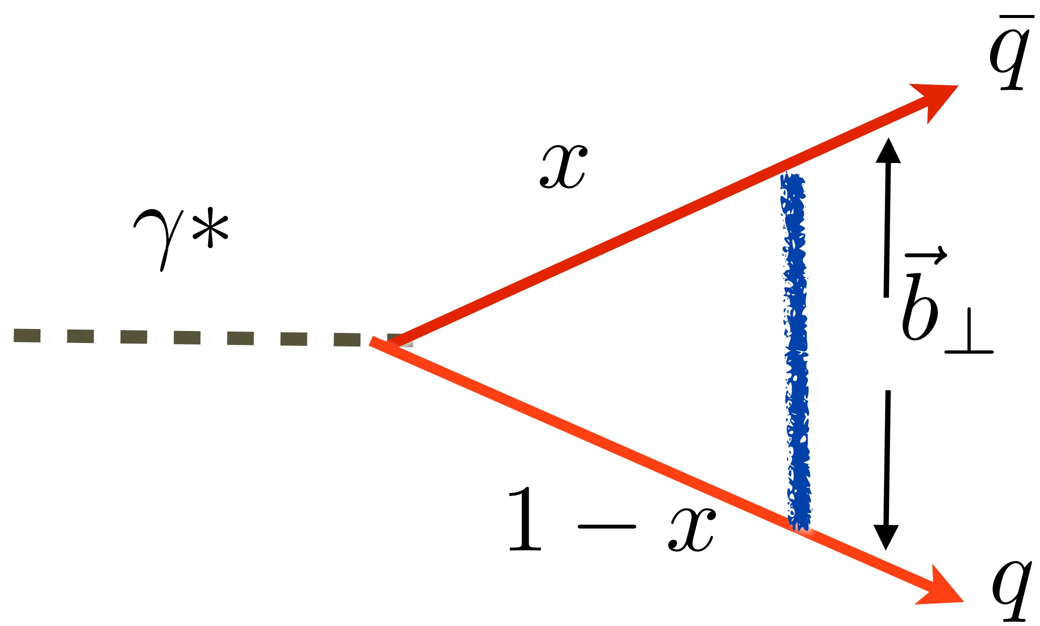
The "spray" of particles resulting from the approximate line source produced in such inelastic collisions then gives rise to events with a strong correlation between particles produced over a large range of both positive and negative rapidity.

Two-Dimensional Confinement

Interesting feature from AdS/QCD

$$U(\zeta) = \kappa^4 \zeta^2 + 2\kappa^2 (L + S - 1)$$

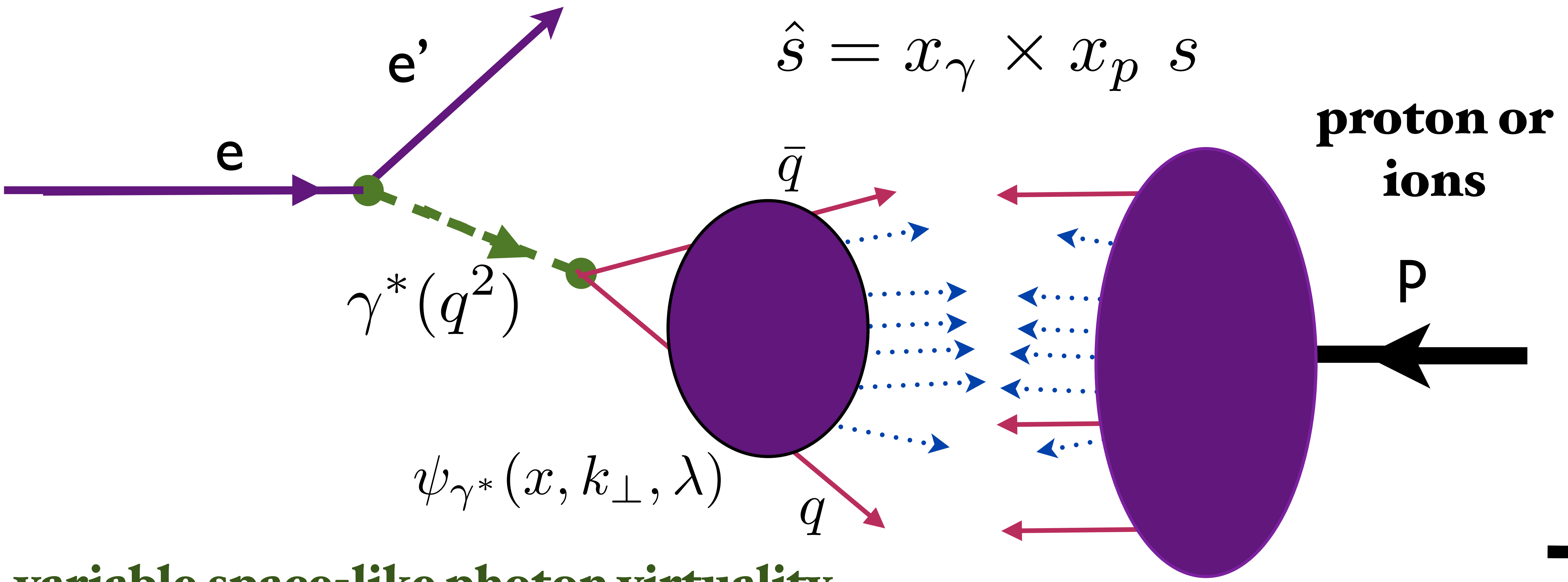
$$\vec{\zeta}_\perp = \vec{b}_\perp \sqrt{x(1-x)}$$



confinement in plane of pair

Electron-Ion Colliders: Virtual Photon-Ion Collider

Perspective from the e-p collider frame



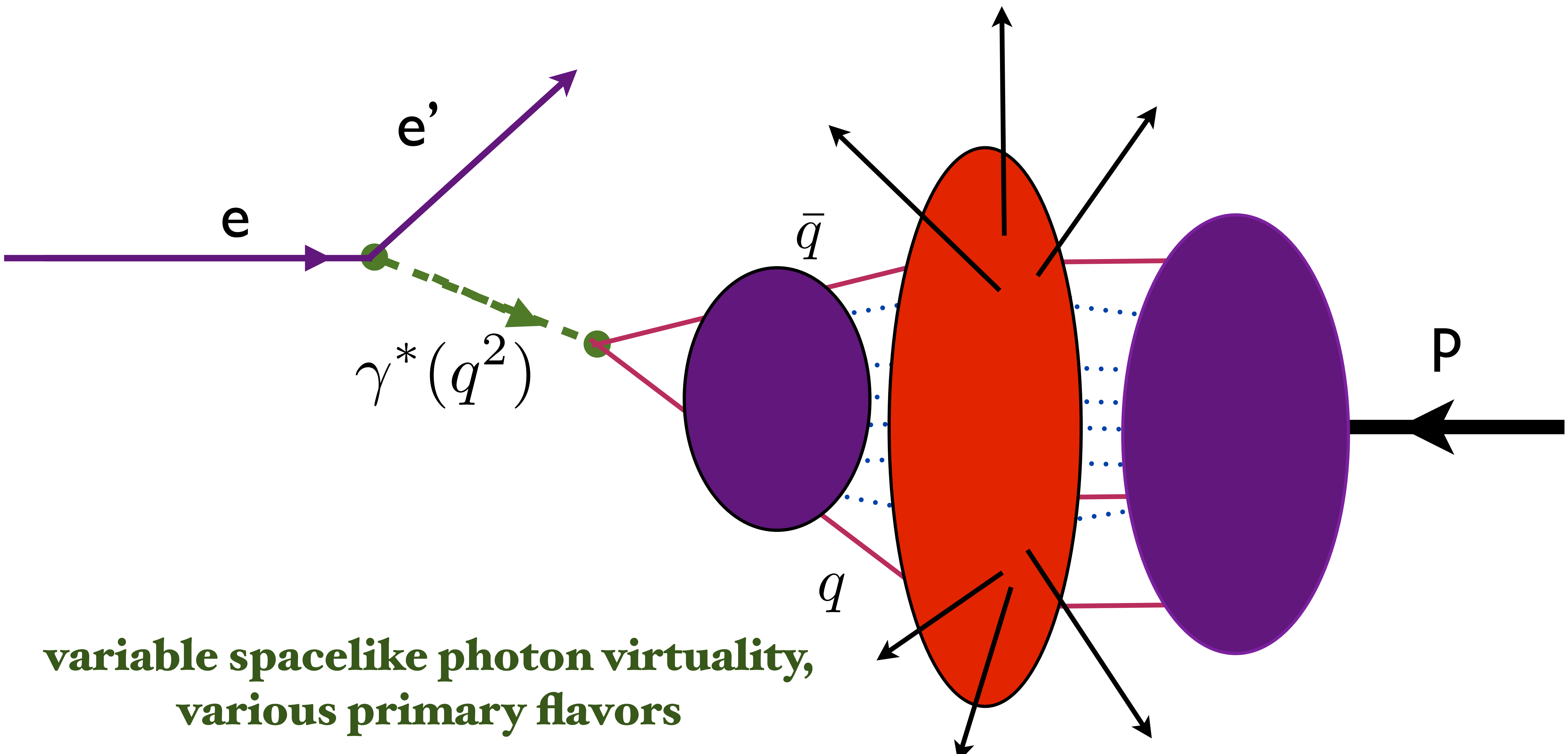
variable space-like photon virtuality, various primary flavors

$\bar{q}\, q$ plane aligned with lepton scattering plane ~ $\cos^2\phi$

Front-surface dynamics: shadowing/antishadowing

LHeC: Virtual Photon-Proton Collider

Perspective from the e-p collider frame



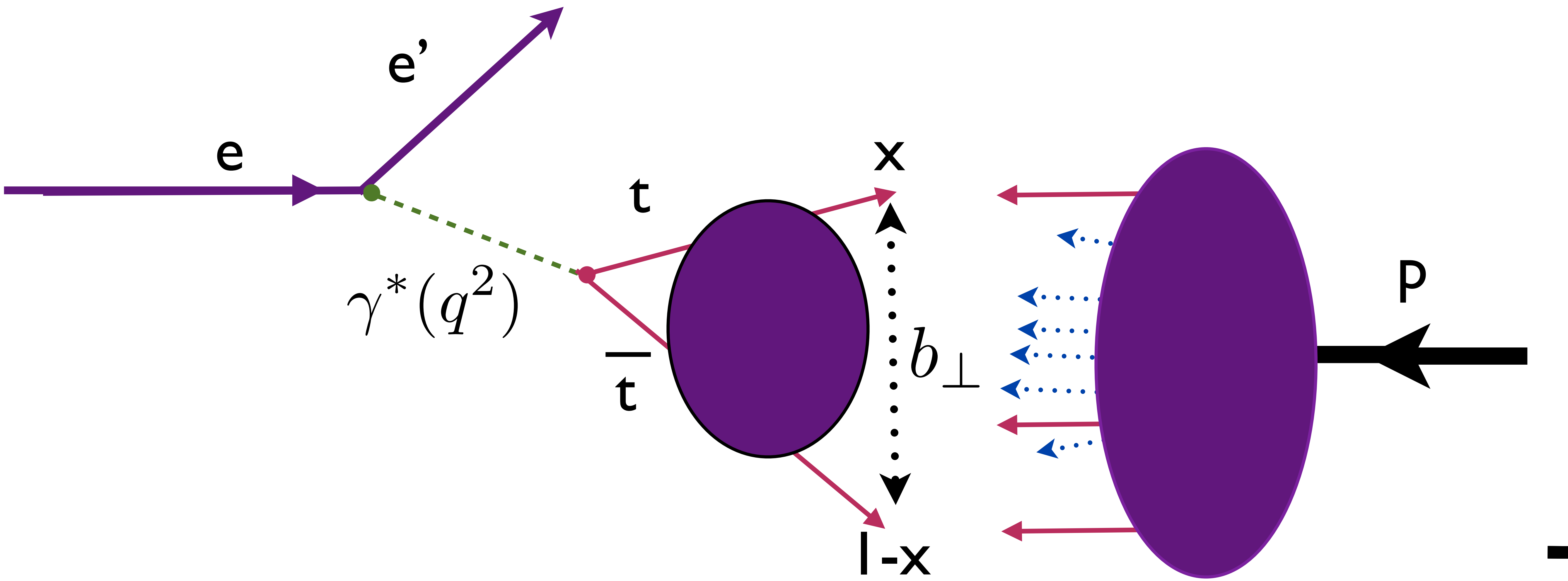
variable spacelike photon virtuality, various primary flavors

photon and proton fragmentation vs. central regions

Saturation, nuclear shadowing, antishadowing

$\bar{t}\,t$ acts as a 'drill'

$$\langle b_\perp^2 \rangle \sim \frac{1}{Q^2 x(1-x) + M_t^2}$$



High Q^2, high M^2_Q virtual photon at LHeC acts as a precision, small bore, linearly oriented, flavor-dependent probe acting on a proton or nuclear target.

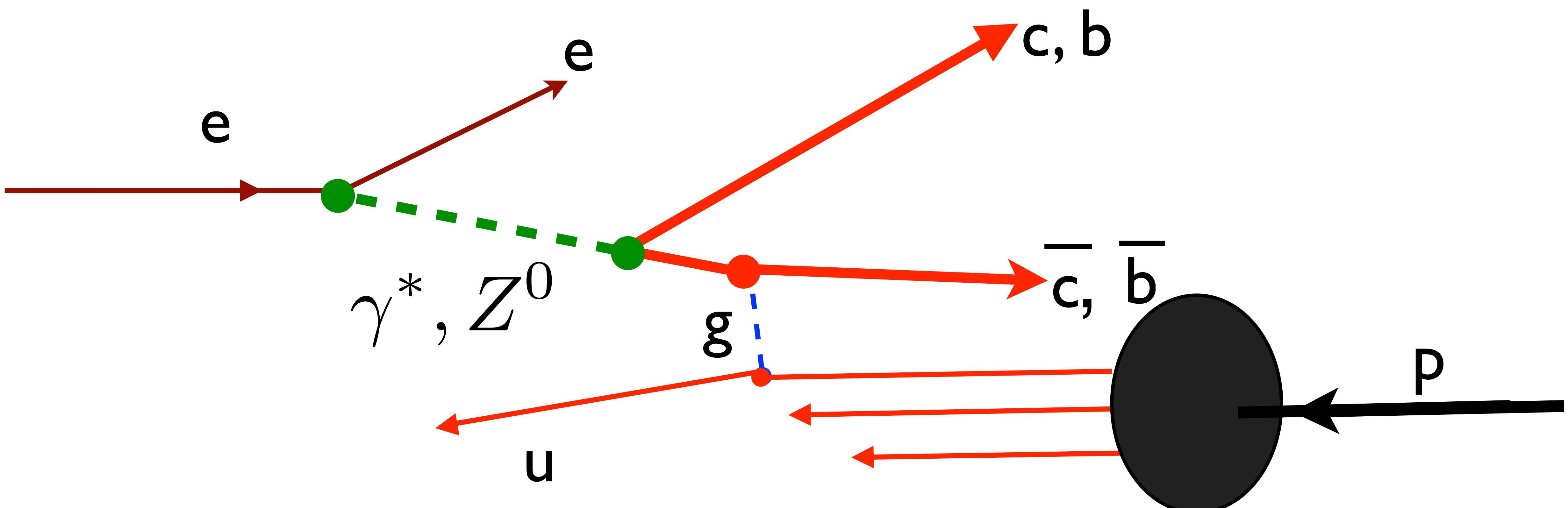
Study final-state hadron multiplicity distributions, ridges, nuclear dependence, etc.

EIC: Virtual-Photon—Ion Collider

Inclusive c,b Electroproduction at the EIC

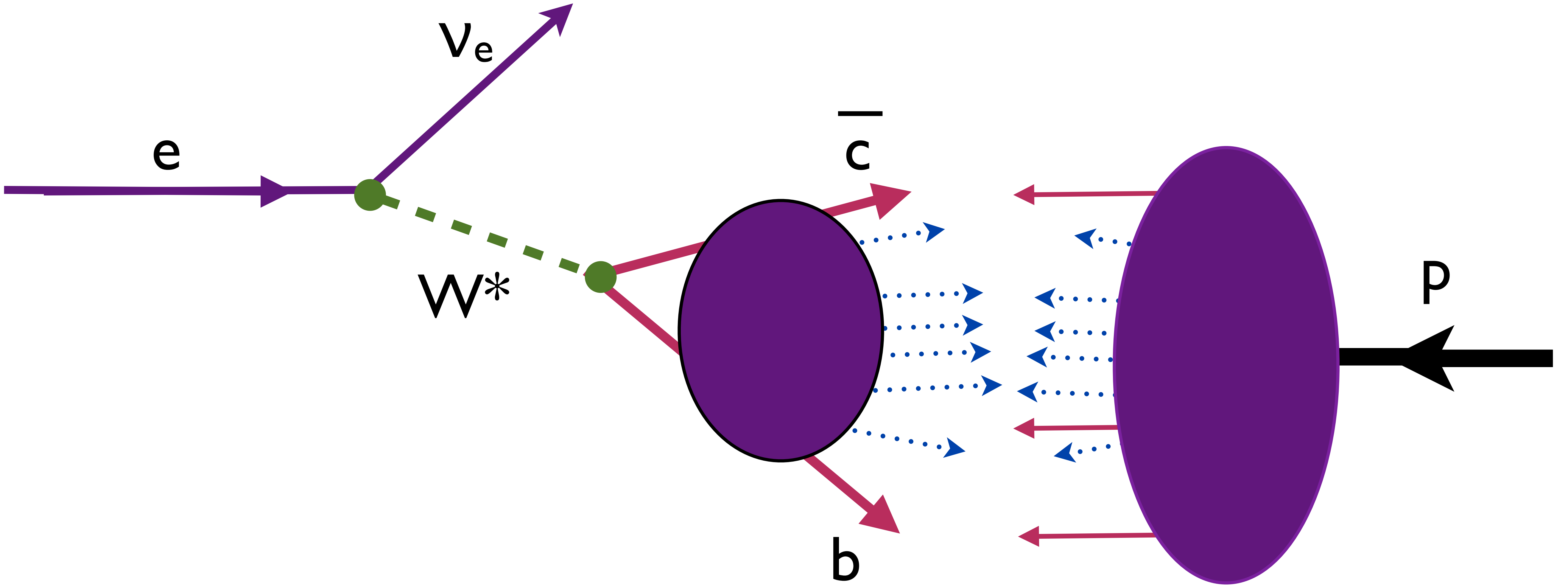
$c - \bar{c}$ asymmetry from $\gamma^* - Z^*$ or pomeron/odderon interference

Interpretation: Charm quark in photon vs. heavy sea quark in proton?



$Q\ \bar{Q}$ Plane correlated with Electron Scattering Plane

EIC: Virtual Weak Boson-Proton Collider



variable W* virtuality, variable flavors

proton or ions

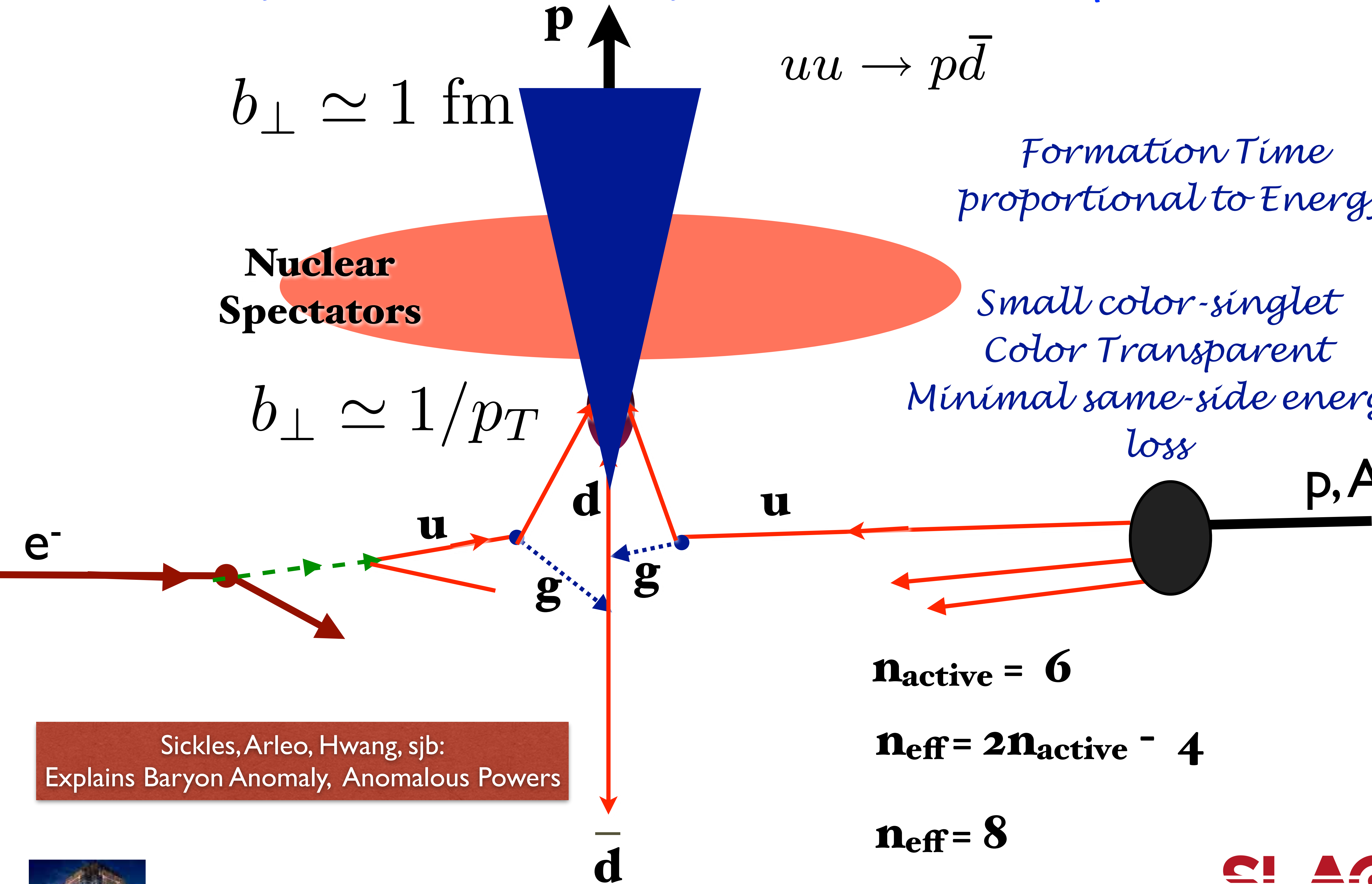
Novel QCD Physics at the EIC

- Control Collisions of Flux Tubes and Ridge Phenomena
- Study Flavor-Dependence of Anti-Shadowing
- Heavy Quarks at Large x; Exotic States
- Direct, color-transparent hard subprocesses and the baryon anomaly
- Tri-Jet Production and the proton's LFWF
- Odderon-Pomeron Interference
- Digluon-initiated subprocesses and anomalous nuclear dependence of quarkonium production
- Factorization-Breaking Lensing Corrections

QCD Myths

- Anti-Shadowing is Universal
- ISI and FSI are higher twist effects and universal
- High transverse momentum hadrons arise only from jet fragmentation -- baryon anomaly!
- Heavy quarks only from gluon splitting
- Renormalization scale cannot be fixed
- QCD condensates are vacuum effects
- QCD gives 10^{42} to the cosmological constant
- QCD Confinement and Mass Scale from $\Lambda_{\overline{MS}}$

Baryon made directly within hard subprocess



$uu \rightarrow p\bar{d}$

Formation Time proportional to Energy

Small color-singlet Color Transparent Minimal same-side energy loss

$n_{active} = 6$

$n_{eff} = 2n_{active} - 4$

$n_{eff} = 8$

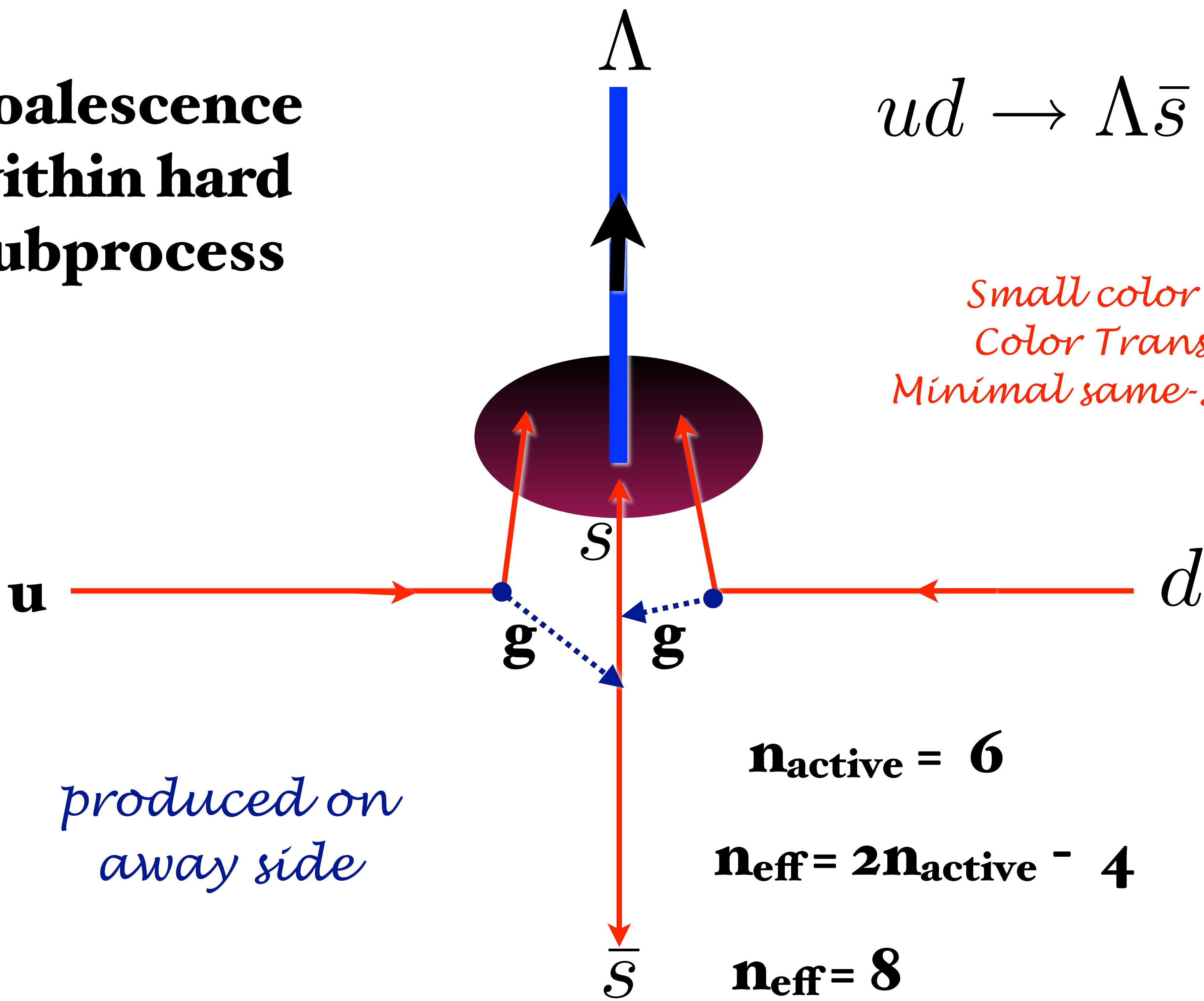
Sickles, Arleo, Hwang, sjb:
Explains Baryon Anomaly, Anomalous Powers

Lambda can be made directly within hard subprocess

Coalescence within hard subprocess

$$ud \rightarrow \Lambda \bar{s}$$

Small color-singlet
Color Transparent
Minimal same-side energy



$\bar{s}$ *produced on away side*

$n_{active} = 6$

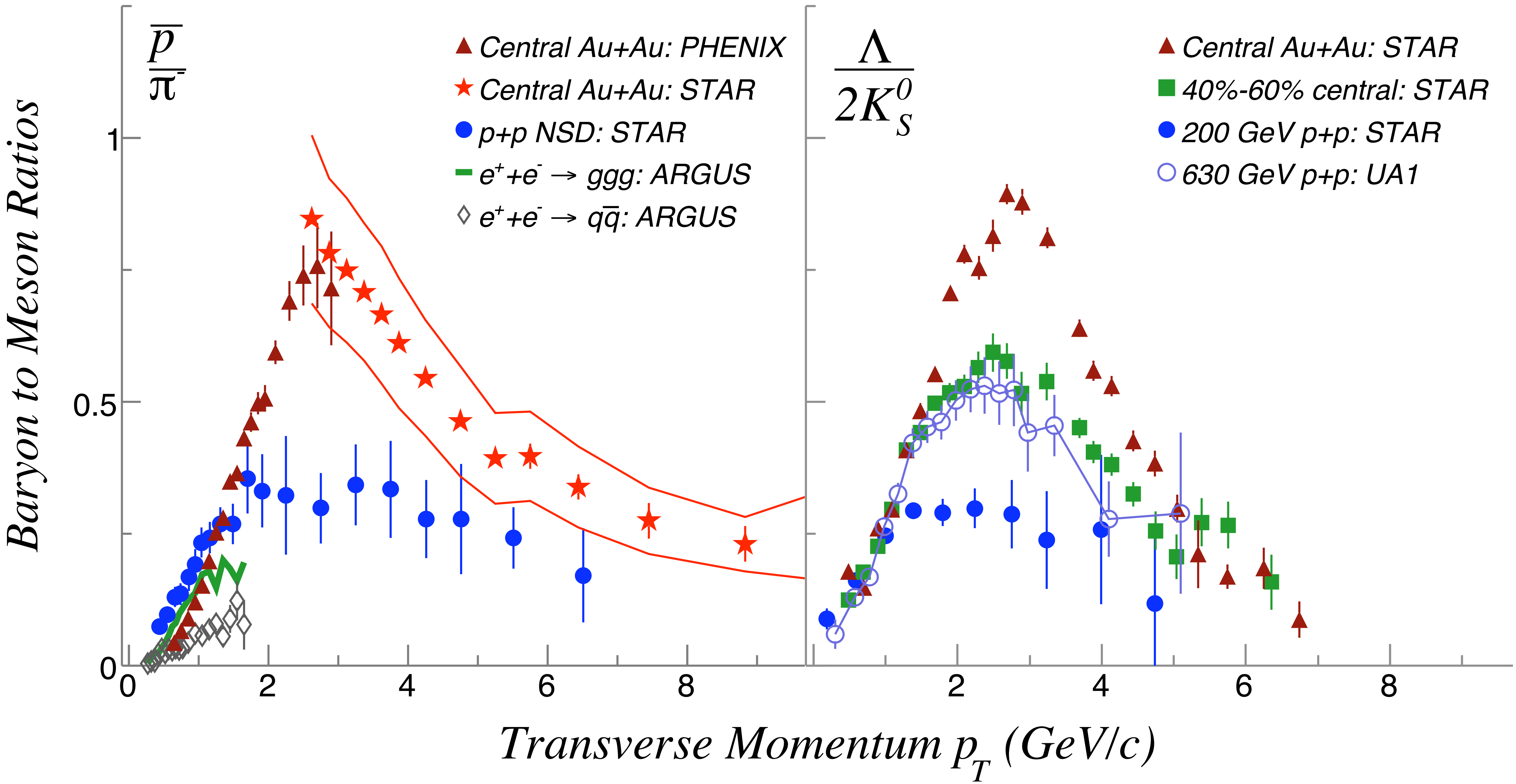
$n_{eff} = 2n_{active} - 4$

$n_{eff} = 8$

Evidence for Direct, Higher-

- Anomalous power behavior at fixed x_T
- Protons more likely to come from direct subprocess than pions
- Protons less absorbed than pions in central nuclear collisions because of color transparency
- Predicts increasing proton to pion ratio in central collisions
- Exclusive-inclusive connection at $x_T = 1$

Paul Sorensen



Goals

- Test QCD to maximum precision at the LHC
- Maximize sensitivity to new physics
- High precision determination of fundamental parameters
- Determine renormalizations scales without ambiguity
- Eliminate scheme dependence

Predictions for physical observables cannot depend on theoretical conventions such as the renormalization scheme

Myths concerning scale setting

- Renormalization scale "unphysical": No optimal physical scale
- Can ignore possibility of multiple physical scales
- Accuracy of PQCD prediction can be judged by taking arbitrary guess $\mu_R = Q$ with an arbitrary range $Q/2 < \mu_R < 2Q$
- Factorization scale should be taken equal to renormalization scale $\mu_F = \mu_R$

These assumptions are untrue in QED and thus they cannot be true for QCD

Clearly heuristic. Wrong in QED. Scheme dependent!

Goals

- Test QCD to maximum precision
- High precision determination of $\alpha_s(Q^2)$ at all scales
- Relate observable to observable --no scheme or scale ambiguity
- Eliminate renormalization scale ambiguity in a scheme-independent manner
- Relate renormalization schemes without ambiguity
- Maximize sensitivity to new physics at the colliders

Electron-Electron Scattering in QED

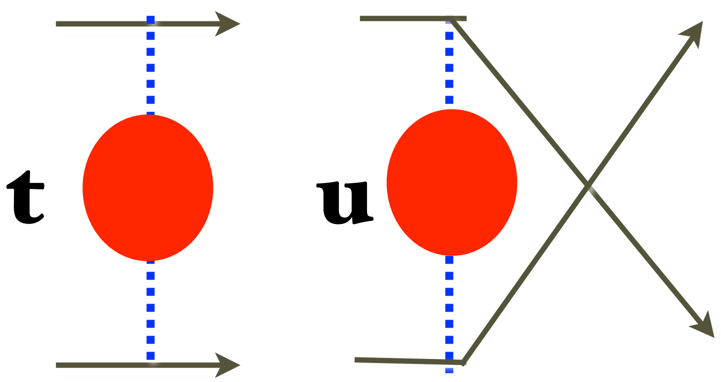
$$\mathcal{M}_{ee\to ee}(++;++) = \frac{8\pi s}{t}\,\alpha(t) + \frac{8\pi s}{u}\,\alpha(u)$$

$$\alpha(t) = \frac{\alpha(0)}{1 - \Pi(t)}$$

Gell-Mann--Low Effective Charge

Electron-Electron Scattering in QED

$$\mathcal{M}_{ee\to ee}(++;++) = \frac{8\pi s}{t}\,\alpha(t) + \frac{8\pi s}{u}\,\alpha(u)$$



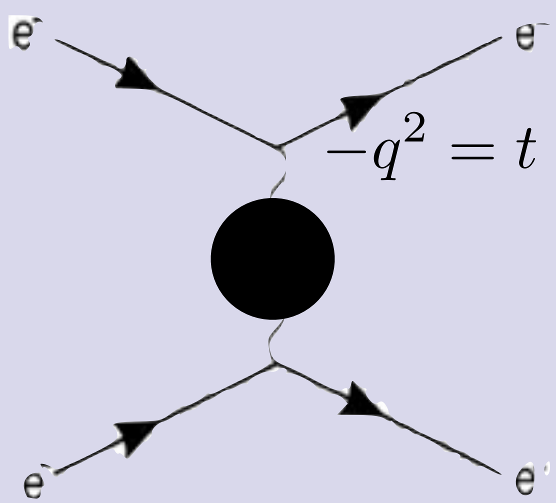
- **Two separate physical scales: t, u = photon virtuality**
- **Gauge Invariant. Dressed photon propagator**
- **Sums all vacuum polarization, non-zero beta terms into running coupling. This is the purpose of the running coupling!**
- **If one chooses a different initial scale, one must sum an infinite number of graphs -- but always recover same result!**
- **Number of active leptons correctly set**
- **Analytic: reproduces correct behavior at lepton mass thresholds**
- **No renormalization scale ambiguity!**

Lessons from QED

In the (physical) Gell Mann-Low scheme, the momentum scale of the running coupling is the virtuality of the exchanged photon; independent of initial scale.

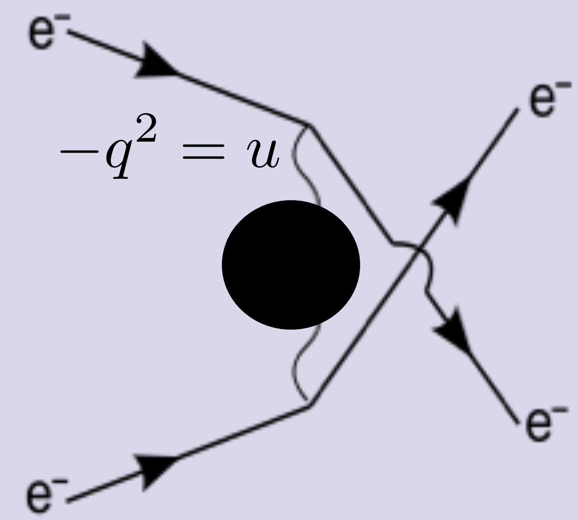
$$\alpha(t) = \frac{\alpha(t_0)}{1-\Pi(t,t_0)} \qquad \Pi(t,t_0) = \frac{\Pi(t)-\Pi(t_0)}{1-\Pi(t_0)}$$

Example: ee-scattering



$$\mathcal{M}_{ee\to ee} = \frac{8\pi s}{t}\alpha(t) + \frac{8\pi s}{u}\alpha(u)$$

Two separate scales;
one for each skeleton graph.



For any other scale choice an infinite set of diagrams must be taken into account to obtain the correct result!

In any other scheme, the correct scale displacement must be used

$$\log\frac{\mu^2_{\overline{MS}}}{m^2_\ell} = 6\int_0^1 dx\, x(1-x)\log\frac{m^2_\ell + Q^2 x(1-x)}{m^2_\ell}, \quad \xrightarrow{Q^2 \gg m^2_\ell} \log\frac{Q^2}{m^2_\ell} - \frac{5}{3}$$

$$\boxed{\alpha_{\overline{MS}}(e^{-5/3}q^2) = \alpha_{GM-L}(q^2).}$$

PRL **110,** 192001 (2013) PHYSICAL REVIEW LETTERS week ending 10 MAY 2013

Systematic All-Orders Method to Eliminate Renormalization-Scale and Scheme Ambiguities in Perturbative QCD

Matin Mojaza*
CP3-Origins, Danish Institute for Advanced Studies, University of Southern Denmark, DK-5230 Odense, Denmark and SLAC National Accelerator Laboratory, Stanford University, Stanford, California 94039, USA

Stanley J. Brodsky†
SLAC National Accelerator Laboratory, Stanford University, Stanford, California 94039, USA

Xing-Gang Wu‡
Department of Physics, Chongqing University, Chongqing 401331, People's Republic of China

(Received 13 January 2013; published 10 May 2013)

We introduce a generalization of the conventional renormalization schemes used in dimensional regularization, which illuminates the renormalization scheme and scale ambiguities of perturbative QCD predictions, exposes the general pattern of nonconformal $\{\beta_i\}$ terms, and reveals a special degeneracy of the terms in the perturbative coefficients. It allows us to systematically determine the argument of the running coupling order by order in perturbative QCD in a form which can be readily automatized. The new method satisfies all of the principles of the renormalization group and eliminates an unnecessary source of systematic error.

SLAC NATIONAL ACCELERATOR LABORATORY

δ-$\mathcal{R}$enormalization Scheme ($\mathcal{R}_\delta$ scheme)

In dim. reg. $1/\epsilon$ poles come in powers of [Bollini & Gambiagi, ‘t Hooft & Veltman, ’72]

$$\ln \frac{\mu^2}{\Lambda^2} + \frac{1}{\epsilon} + c$$

In the modified minimal subtraction scheme (MS-bar) one subtracts together with the pole a constant [Bardeen, Buras, Duke, Muta (1978) on DIS results]:

$$\ln(4\pi) - \gamma_E$$

This corresponds to a shift in the scale:

$$\mu^2_{\overline{\rm MS}} = \mu^2 \exp(\ln 4\pi - \gamma_E)$$

A finite subtraction from infinity is arbitrary. *Let’s make use of this!*

Subtract an arbitrary constant and keep it in your calculation: $\mathcal{R}_\delta$-scheme

$$\ln(4\pi) - \gamma_E - \delta,$$

$$\mu^2_\delta = \mu^2_{\overline{\rm MS}} \exp(-\delta) = \mu^2 \exp(\ln 4\pi - \gamma_E - \delta)$$

Exposing the Renormalization Scheme Dependence

Observable in the $\mathcal{R}_\delta$-scheme:

$$\rho_\delta(Q^2) = r_0 + r_1 a(\mu) + [r_2 + \beta_0 r_1 \delta] a(\mu)^2 + [r_3 + \beta_1 r_1 \delta + 2\beta_0 r_2 \delta + \beta_0^2 r_1 \delta^2] a(\mu)^3 + \cdots$$

$$\mathcal{R}_0 = \overline{\mathrm{MS}}\ , \quad \mathcal{R}_{\ln 4\pi - \gamma_E} = \mathrm{MS} \qquad \mu^2 = \mu^2_{\overline{\mathrm{MS}}} \ \exp(\ln 4\pi - \gamma_E)\ , \quad \mu^2_{\delta_2} = \mu^2_{\delta_1} \ \exp(\delta_2 - \delta_1)$$

Note the divergent 'renormalon series' $n!\beta^n \alpha_s^n$

Renormalization Scheme Equation

$$\frac{d\rho}{d\delta} = -\beta(a)\frac{d\rho}{da} \stackrel{!}{=} 0 \quad \longrightarrow \mathrm{PMC}$$

$$\rho_\delta(Q^2) = r_0 + r_1 a_1(\mu_1) + (r_2 + \beta_0 r_1 \delta_1) a_2(\mu_2)^2 + [r_3 + \beta_1 r_1 \delta_1 + 2\beta_0 r_2 \delta_2 + \beta_0^2 r_1 \delta_1^2] a_3(\mu_3)^3$$

The $\delta_k^p a^n$-term indicates the term associated to a diagram with $1/\epsilon^{n-k}$ divergence for any p. Grouping the different δ_k-terms, one recovers in the $N_c \to 0$ Abelian limit the dressed skeleton expansion.

Special Degeneracy in PQCD

There is nothing special about a particular value for δ, thus for any δ

$$\rho(Q^2) = r_{0,0} + r_{1,0}a(Q) + [r_{2,0} + \beta_0 r_{2,1}]a(Q)^2 + [r_{3,0} + \beta_1 r_{2,1} + 2\beta_0 r_{3,1} + \beta_0^2 r_{3,2}]a(Q)^3$$
$$+ [r_{4,0} + \beta_2 r_{2,1} + 2\beta_1 r_{3,1} + \frac{5}{2}\beta_1\beta_0 r_{3,2} + 3\beta_0 r_{4,1} + 3\beta_0^2 r_{4,2} + \beta_0^3 r_{4,3}]a(Q)^4$$

According to the principal of maximum conformality we must set the scales such to absorb all 'renormalon-terms', i.e. non-conformal terms

$$\rho(Q^2) = r_{0,0} + r_{1,0}a(Q) + (\beta_0 a(Q)^2 + \beta_1 a(Q)^3 + \beta_2 a(Q)^4 + \cdots)r_{2,1}$$
$$+ (\beta_0^2 a(Q)^3 + \frac{5}{2}\beta_1\beta_0 a(Q)^4 + \cdots)r_{3,2} + (\beta_0^3 + \cdots)r_{4,3}$$
$$+ r_{2,0}a(Q)^2 + 2a(Q)(\beta_0 a(Q)^2 + \beta_1 a(Q)^3 + \cdots)r_{3,1}$$
$$+ \cdots$$

$$r_{1,0}a(Q_1) = r_{1,0}a(Q) - \beta(a)r_{2,1} + \frac{1}{2}\beta(a)\frac{\partial\beta}{\partial a}r_{3,2} + \cdots + \frac{(-1)^n}{n!}\frac{d^{n-1}\beta}{(d\ln\mu^2)^{n-1}}r_{n+1,n}$$

$$r_{2,0}a(Q_2)^2 = r_{2,0}a(Q)^2 - 2a(Q)\beta(a)r_{3,1} + \cdots$$

M. Mojaza, Xing-Gang Wu, sjb

General result for an observable in any $\mathcal{R}_\delta$ renormalization scheme:

$$\begin{aligned}\rho(Q^2) =& r_{0,0} + r_{1,0}a(Q) + [r_{2,0} + \beta_0 r_{2,1}]a(Q)^2 \\ &+ [r_{3,0} + \beta_1 r_{2,1} + 2\beta_0 r_{3,1} + \beta_0^2 r_{3,2}]a(Q)^3 \\ &+ [r_{4,0} + \beta_2 r_{2,1} + 2\beta_1 r_{3,1} + \frac{5}{2}\beta_1\beta_0 r_{3,2} + 3\beta_0 r_{4,1} \\ &+ 3\beta_0^2 r_{4,2} + \beta_0^3 r_{4,3}]a(Q)^4 + \mathcal{O}(a^5)\end{aligned}$$

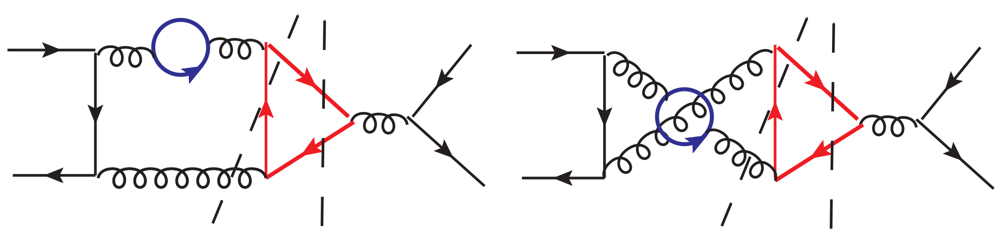
PMC scales thus satisfy

$$\begin{aligned} r_{1,0}a(Q_1) &= r_{1,0}a(Q) - \beta(a) r_{2,1} \\ r_{2,0}a(Q_2)^2 &= r_{2,0}a(Q)^2 - 2a(Q)\beta(a) r_{3,1} \\ r_{3,0}a(Q_3)^3 &= r_{3,0}a(Q)^3 - 3a(Q)^2\beta(a) r_{4,1} \\ &\vdots \\ r_{k,0}a(Q_k)^k &= r_{k,0}a(Q)^2 - k\ a(Q)^{k-1}\beta(a) r_{k+1,1} \end{aligned}$$

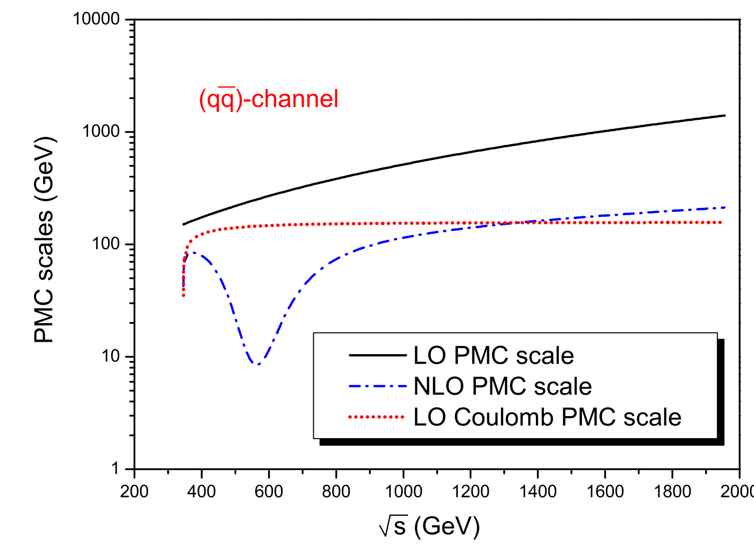
Important Example: Top-Quark FB Asymmetry

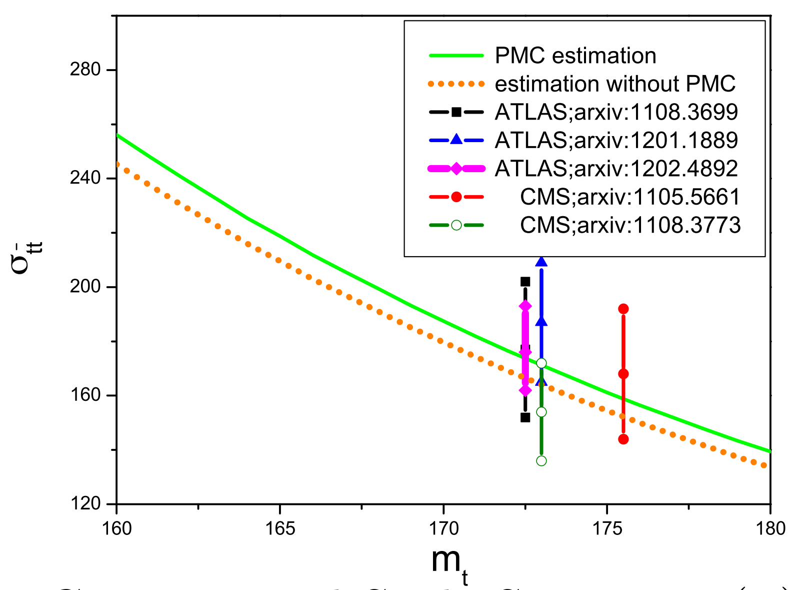
Brodsky, Wu, **Phys.Rev.Lett. 109**, [arXiv:1203.5312]

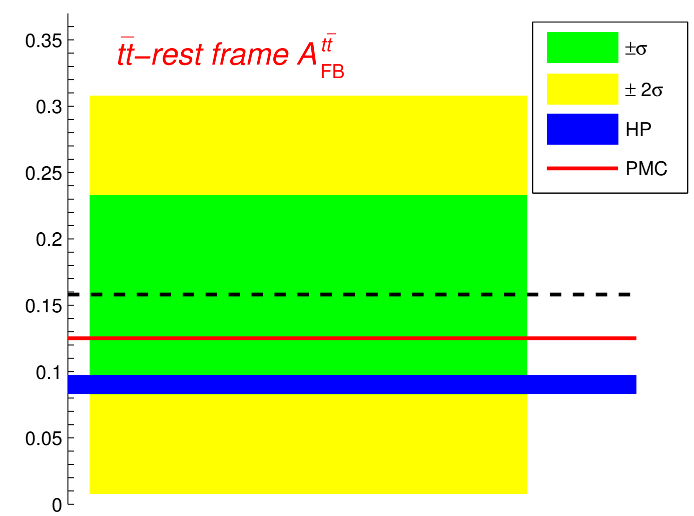
$$A_{FB}^{t\bar{t}} = \frac{\sigma(y_t^{t\bar{t}} > 0) - \sigma(y_t^{t\bar{t}} < 0)}{\sigma(y_t^{t\bar{t}} > 0) + \sigma(y_t^{t\bar{t}} < 0)}$$

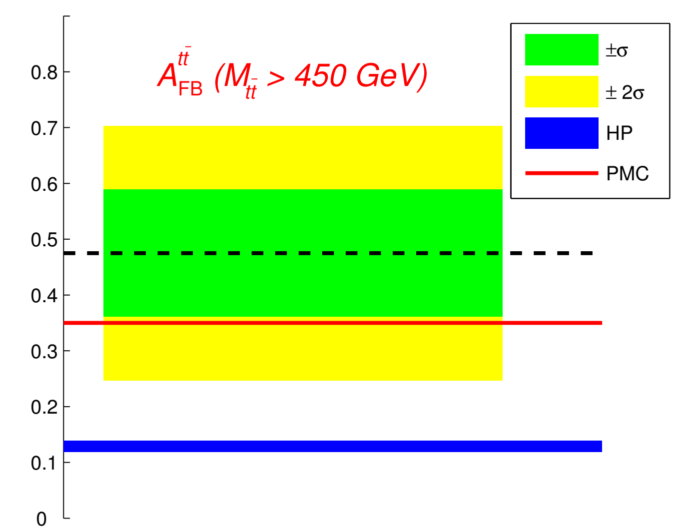


$$\mu_r \neq \mu_f \;\; (!)$$









Conventional Scale Setting: $\alpha(\mu) = \alpha_{\overline{MS}}(\mu)$ and $\mu = [\frac{1}{2}Q, 2Q]$

HP: Hollik, Pagani, **Phys.Rev. D84**(2011)

Conventional 'uncertainty estimate' can be misleading

(see also Blumlein & van Neerven, Phys.Lett. B450, 417[1999])

Improving pQCD precision important for exposing new physics correctly!

What is PMC ?

Principle of Maximum Conformality

Choose renormalization scheme; e.g. $\alpha_s^R(\mu_R^{\rm init})$

↓

Choose μ_R^{init}*; arbitrary initial renormalization scale*

↓

Identify $\{\beta_i^R\}$ *− terms using* n_f *− terms*

through the PMC − BLM correspondence principle

↓ order-by-order

Shift scale of α_s *to* $\mu_R^{\rm PMC}$ *to eliminate* $\{\beta_i^R\}$ *− terms*

↓

Conformal Series

Result is independent of $\mu_R^{\rm init}$ *and scheme at fixed order*

Xing-Gang Wu, Matin Mojaza
Leonardo di Giustino, SJB

PMC−BLM − one

Phys. Rev. Lett. **109**, 042002 (2012)

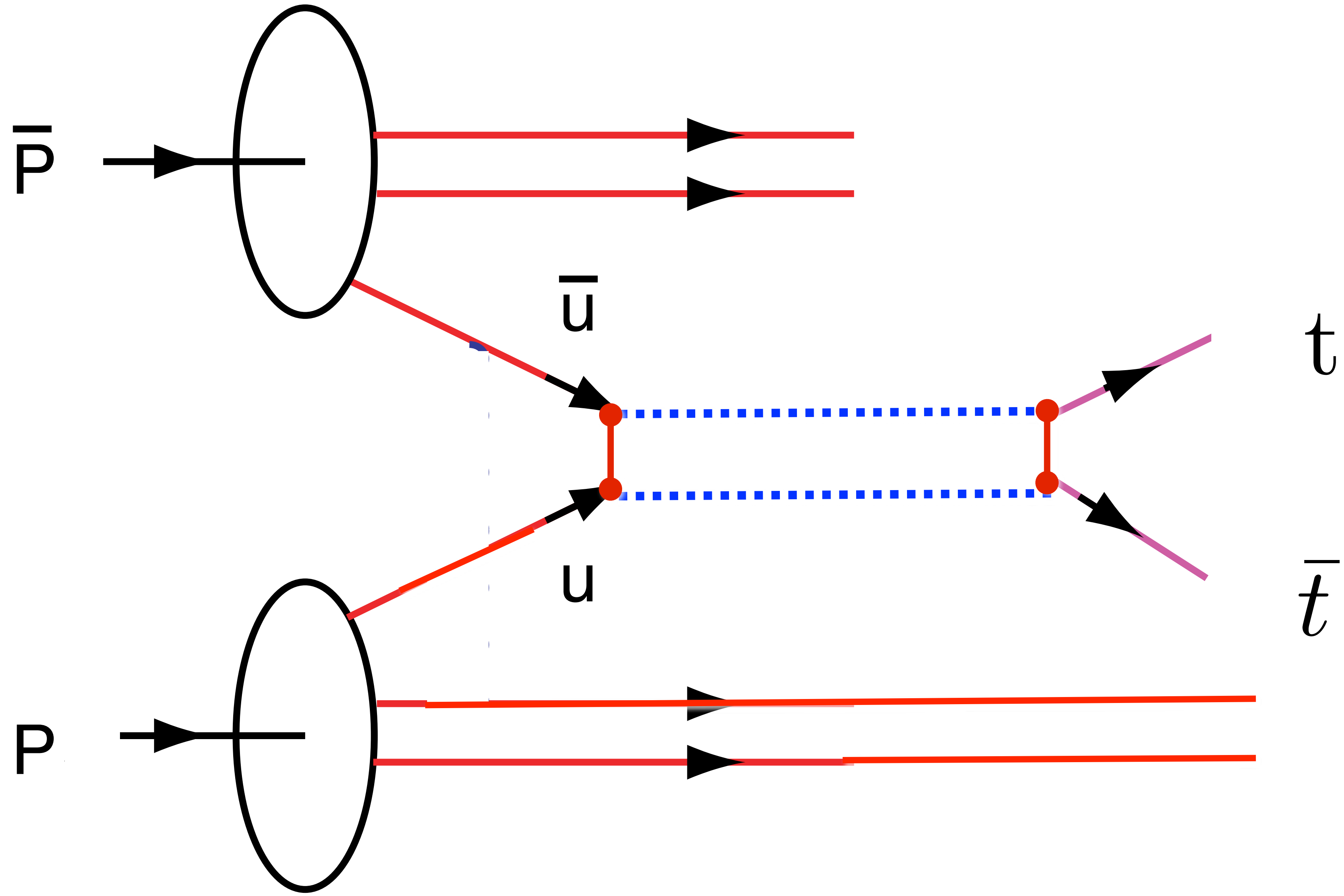
R_δ−scheme − two

Phys. Rev. Lett. **110**, 192001 (2013)

Eliminate β−terms

n_f dependence of pQCD series does not uniquely identify the β terms

Implications for the $\bar{p}p \to t\bar{t}X$ asymmetry at the Tevatron



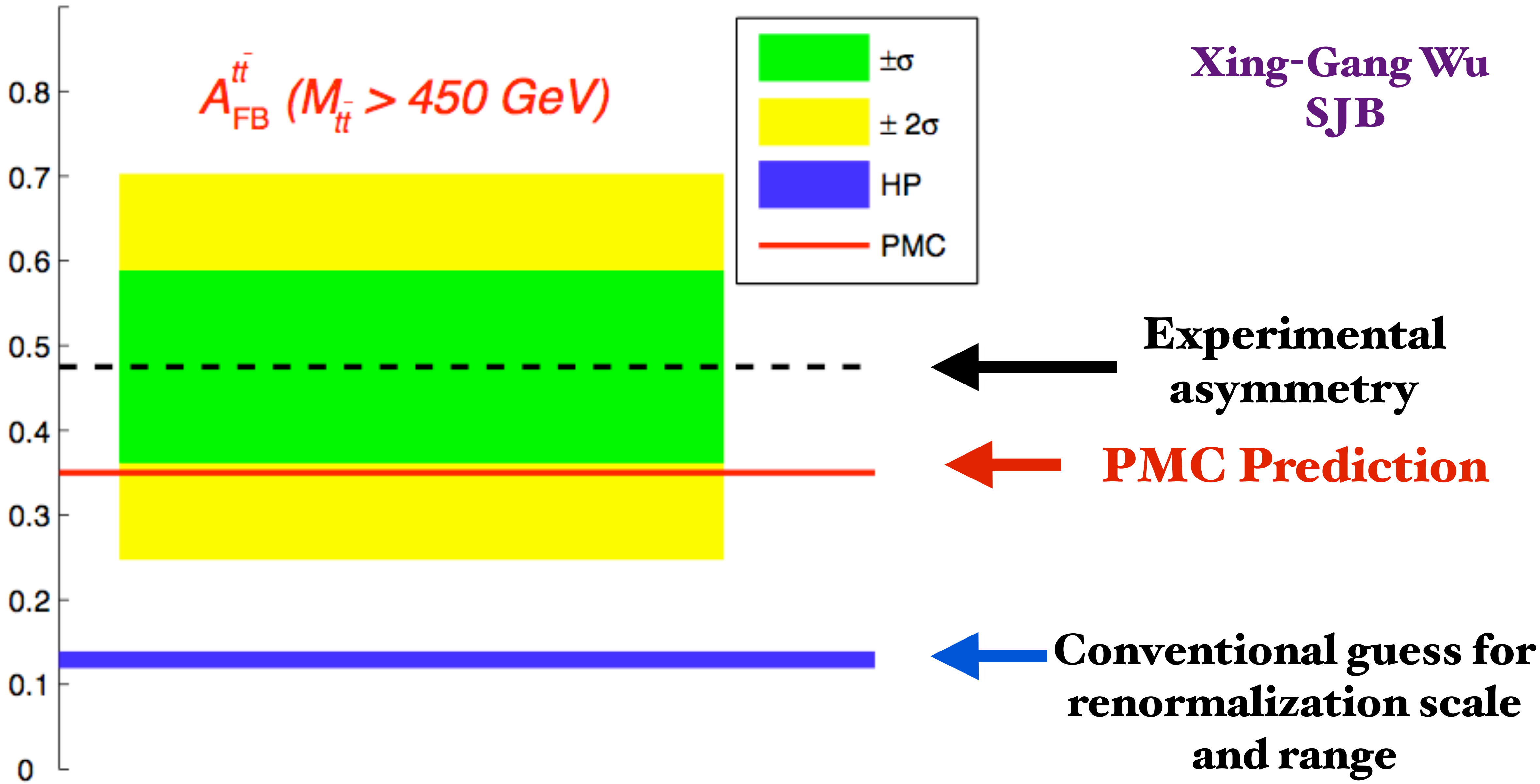
Interferes with Born term.

Small value of renormalization scale increases asymmetry, just as in QED

Xing-Gang Wu, sjb

The Renormalization Scale Ambiguity for Top-Pair Production Eliminated Using the 'Principle of Maximum Conformality' (PMC)

Xing-Gang Wu
SJB

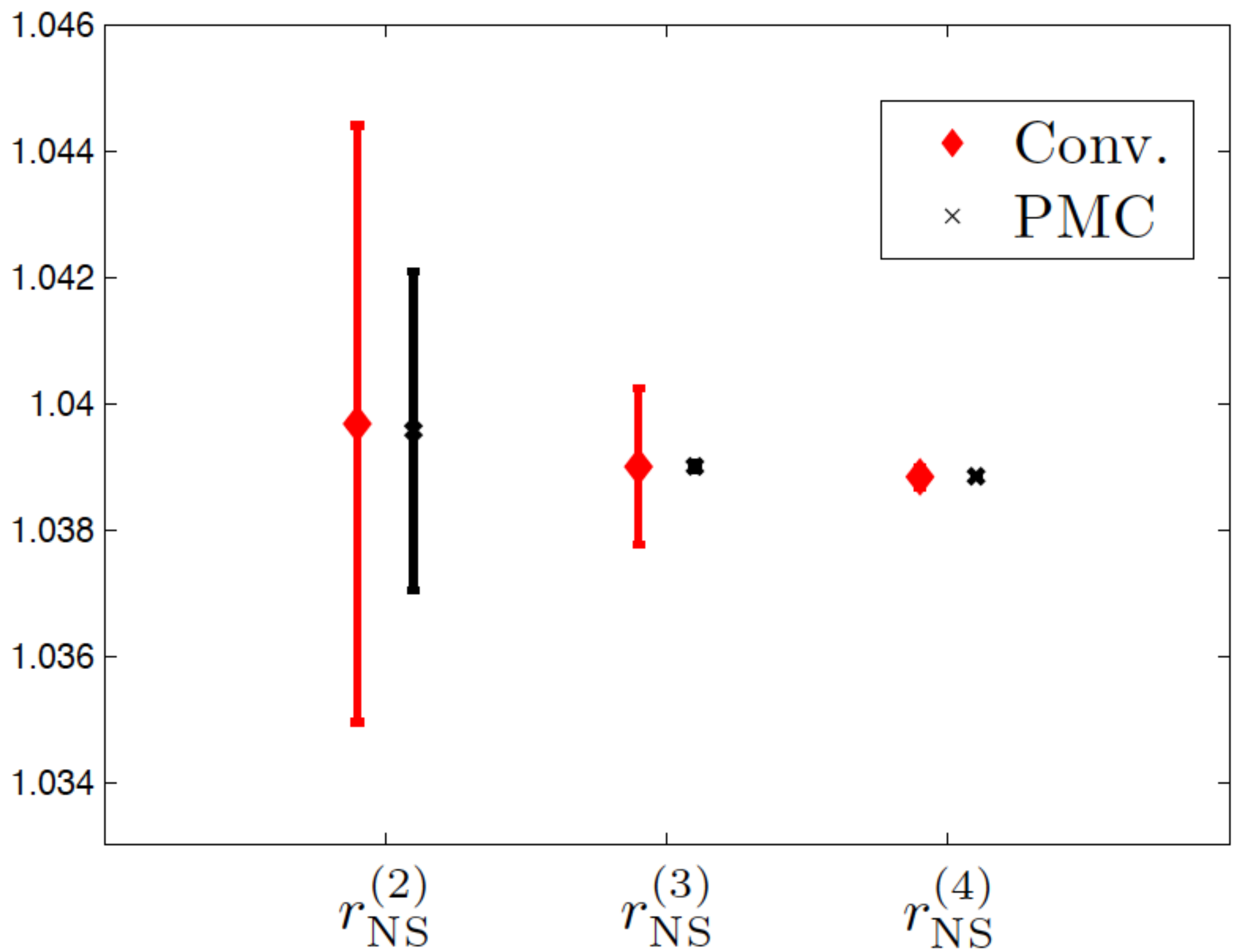


Top quark forward-backward asymmetry predicted by pQCD NNLO within 1 σ of CDF/D0 measurements using PMC/BLM scale setting

Reanalysis of the Higher Order Perturbative QCD corrections to Hadronic Z Decays using the Principle of Maximum Conformality

S-Q Wang, X-G Wu, sjb

P.A. Baikov, K.G. Chetyrkin, J.H. Kuhn, and J. Rittinger, Phys. Rev. Lett. 108, 222003 (2012).



The values of $r_{\rm NS}^{(n)} = 1 + \sum_{i=1}^{n} C_i^{\rm NS} a_s^i$ and their errors $\pm|C_n^{\rm NS} a_s^n|_{\rm MAX}$. The diamonds and the crosses are for conventional (Conv.) and PMC scale settings, respectively. The central values assume the initial scale choice $\mu_r^{\rm init} = M_Z$.

Set multiple renormalization scales -- Lensing, DGLAP, ERBL Evolution ...

$Choose\ renormalization\ scheme;\ e.g.\ \alpha_s^R(\mu_R^{\rm init})$

↓

$Choose\ \mu_R^{init};\ arbitrary\ initial\ renormalization\ scale$

↓

$Identify\ \{\beta_i^R\} - terms\ using\ n_f - terms$

$through\ the\ PMC - BLM\ correspondence\ principle$

↓

$Shift\ scale\ of\ \alpha_s\ to\ \mu_R^{\rm PMC}\ to\ eliminate\ \{\beta_i^R\} - terms$

↓

$Conformal\ Series$

$Result\ is\ independent\ of\ \mu_R^{\rm init}\ and\ scheme\ at\ fixed\ order$

PMC/BLM

No renormalization scale ambiguity!

Result is independent of Renormalization scheme and initial scale!

QED Scale Setting at N_C=0

Eliminates unnecessary systematic uncertainty

Scale fixed at each order

δ-Scheme automatically identifies β-terms!

Principle of Maximum Conformality

Xing-Gang Wu, Matin Mojaza
Leonardo di Giustino, SJB

Features of BLM/PMC

- ***Predictions are scheme-independent***
- ***Matches conformal series***
- ***Commensurate Scale Relations between observables: Generalized Crewther Relation (*Kataev, Lu, Rathsman, sjb*)***
- ***No n! Renormalon growth***
- ***New scale at each order; n_F determined at each order***
- ***Multiple Physical Scales Incorporated***
- ***Rigorous: Satisfies all Renormalization Group Principles***
- ***Realistic Estimate of Higher-Order Terms***
- ***Eliminates unnecessary theory error***

Novel QCD Physics

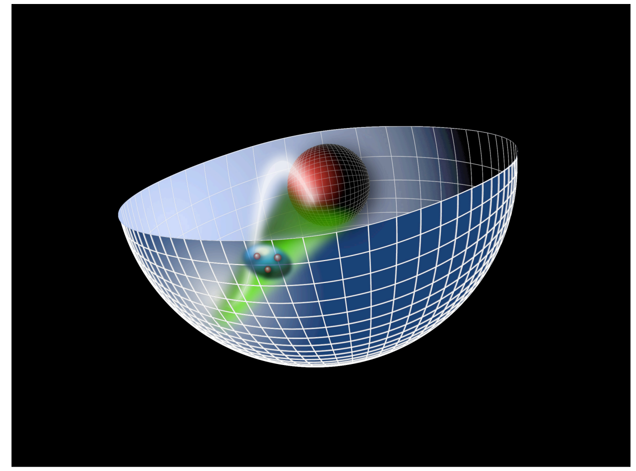
- Collisions of Flux Tubes and the Ridge
- Factorization-Breaking Lensing Corrections
- Digluon initiated subprocesses and anomalous nuclear dependence of quarkonium production
- Higgs Production at high x_F from Intrinsic Heavy Quarks
- Direct, color-transparent hard subprocesses and the baryon anomaly
- PMC eliminates renormalization scale ambiguity order by order; increased top/anti-top asymmetry; scheme independent
- Light-Front Schrödinger Equation: New approach to confinement, origin of QCD mass scale

SLAC NATIONAL ACCELERATOR LABORATORY

de Tèramond, Dosch, sjb

AdS/QCD
Soft-Wall Model

Single scheme-independent fundamental mass scale κ



Light-Front Holography

$$\zeta^2 = x(1-x)\mathrm{b}^2_\perp .$$

$$\Big[-\frac{d^2}{d\zeta^2} + \frac{1-4L^2}{4\zeta^2} + U(\zeta)\Big]\psi(\zeta) = \mathcal{M}^2\psi(\zeta)$$

Light-Front Schrödinger Equation

$$U(\zeta) = \kappa^4\zeta^2 + 2\kappa^2(L+S-1)$$

Unique Confinement Potential!

Conformal Symmetry of the action

Confinement scale:

(m_q=0)

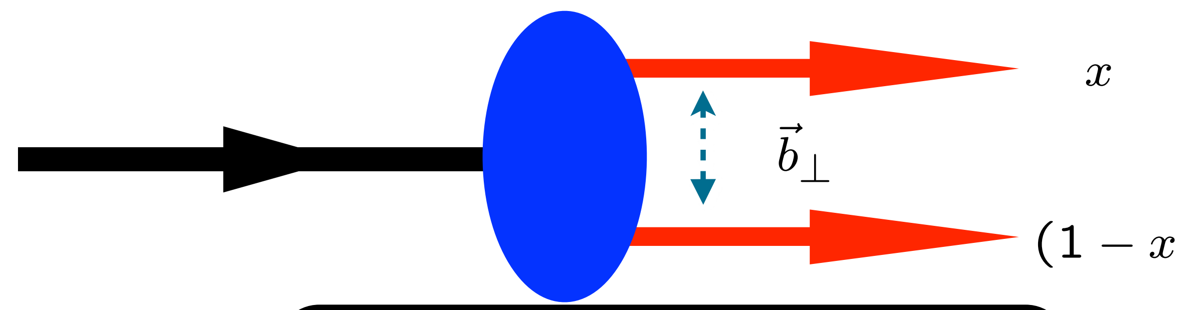
$$\kappa \simeq 0.6\ GeV$$

$$1/\kappa \simeq 1/3\ fm$$

- **de Alfaro, Fubini, Furlan:** ***Scale can appear in Hamiltonian and EQM without affecting conformal invariance of action!***

Light-Front QCD

Fixed $\tau = t + z/c$



$$\zeta^2 = x(1-x) b_\perp^2$$

$\mathcal{L}_{QCD} \rightarrow H^{LF}_{QCD}$

$$(H^0_{LF} + H^I_{LF})|\Psi> = M^2|\Psi>$$

Coupled Fock states

Eliminate higher Fock states and retarded interactions

$$[\frac{\vec{k}^2_\perp + m^2}{x(1-x)} + V^{LF}_{\rm eff}]\ \psi_{LF}(x,\vec{k}_\perp) = M^2\ \psi_{LF}(x,\vec{k}_\perp)$$

Effective two-particle equation

$$[-\frac{d^2}{d\zeta^2} + \frac{m^2}{x(1-x)} + \frac{-1+4L^2}{4\zeta^2} + U(\zeta,S,L)]\ \psi_{LF}(\zeta) = M^2\ \psi_{LF}(\zeta)$$

Azimuthal Basis

ζ, ϕ

AdS/QCD:

$$U(\zeta) = \kappa^4\zeta^2 + 2\kappa^2(L+S-1)$$

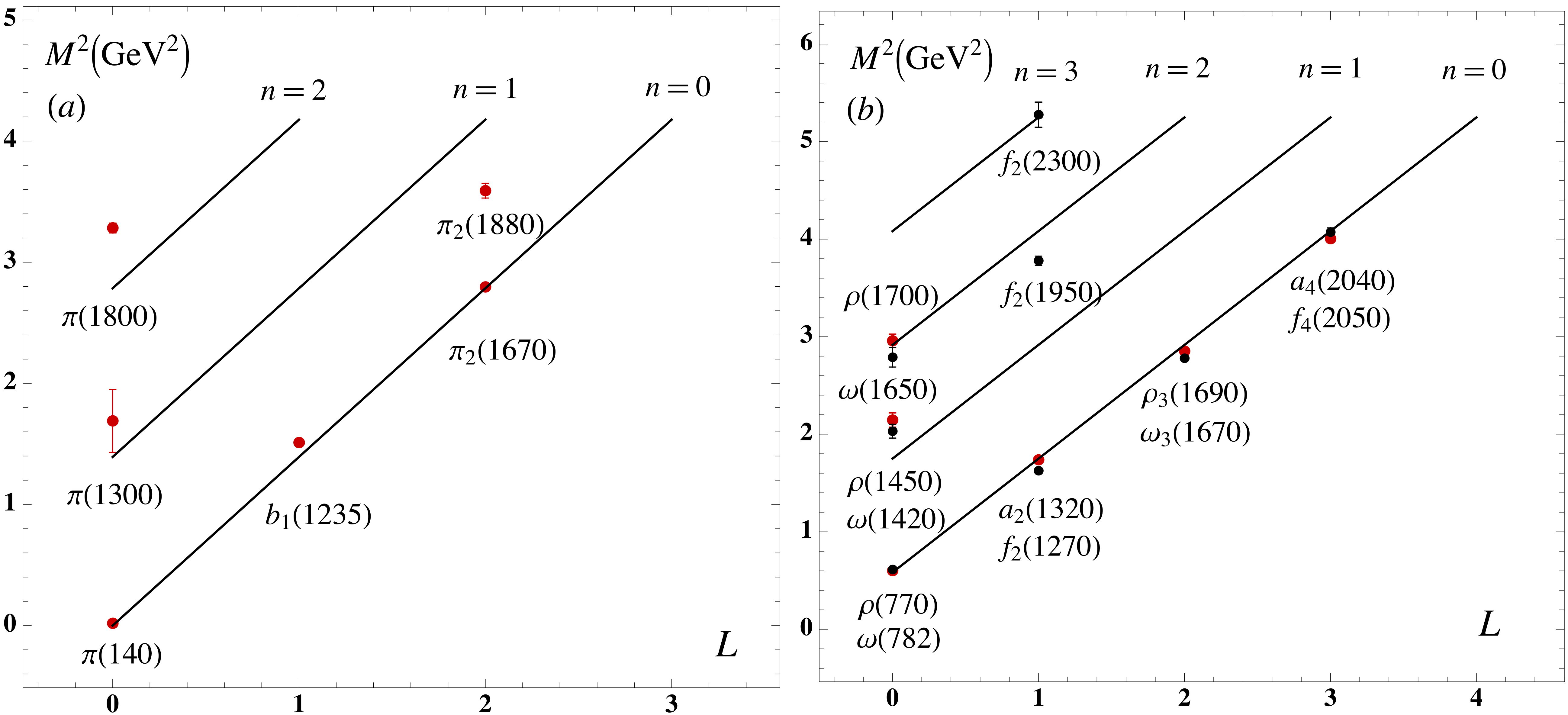
Confining AdS/QCD potential!

Sums an infinite # diagrams

Semiclassical first approximation to QCD

$$m_u = m_d = 0$$

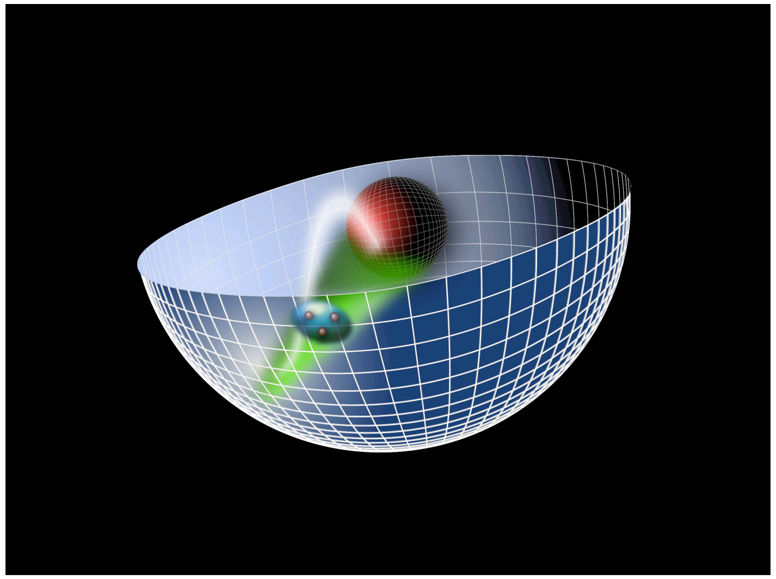
de Tèramond, Dosch, sjb



$$M^2(n, L, S) = 4\kappa^2(n + L + S/2)$$

AdS5: Conformal Template for QCD

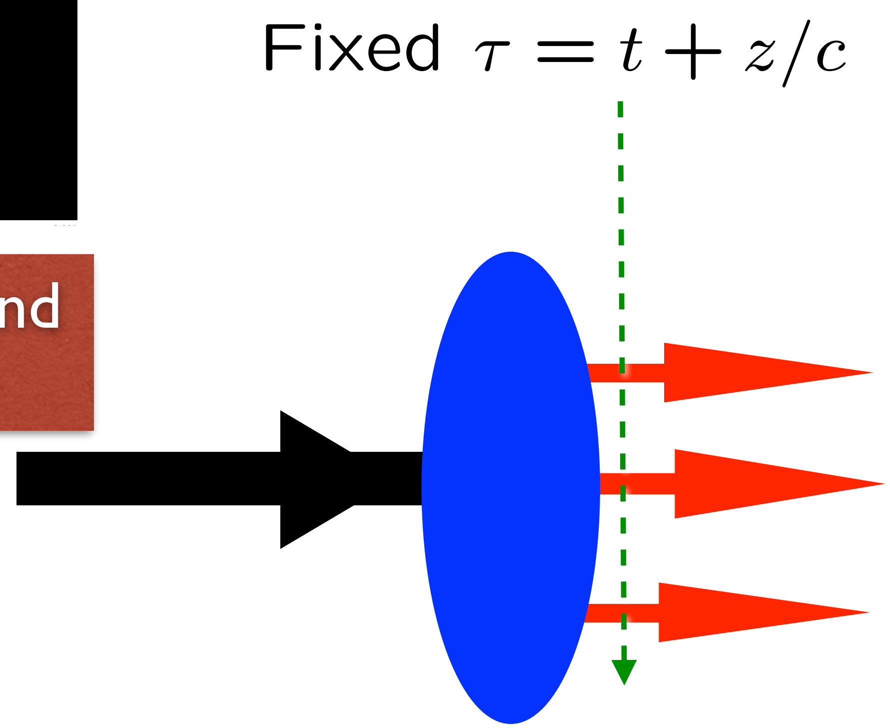
$\phi(z)$



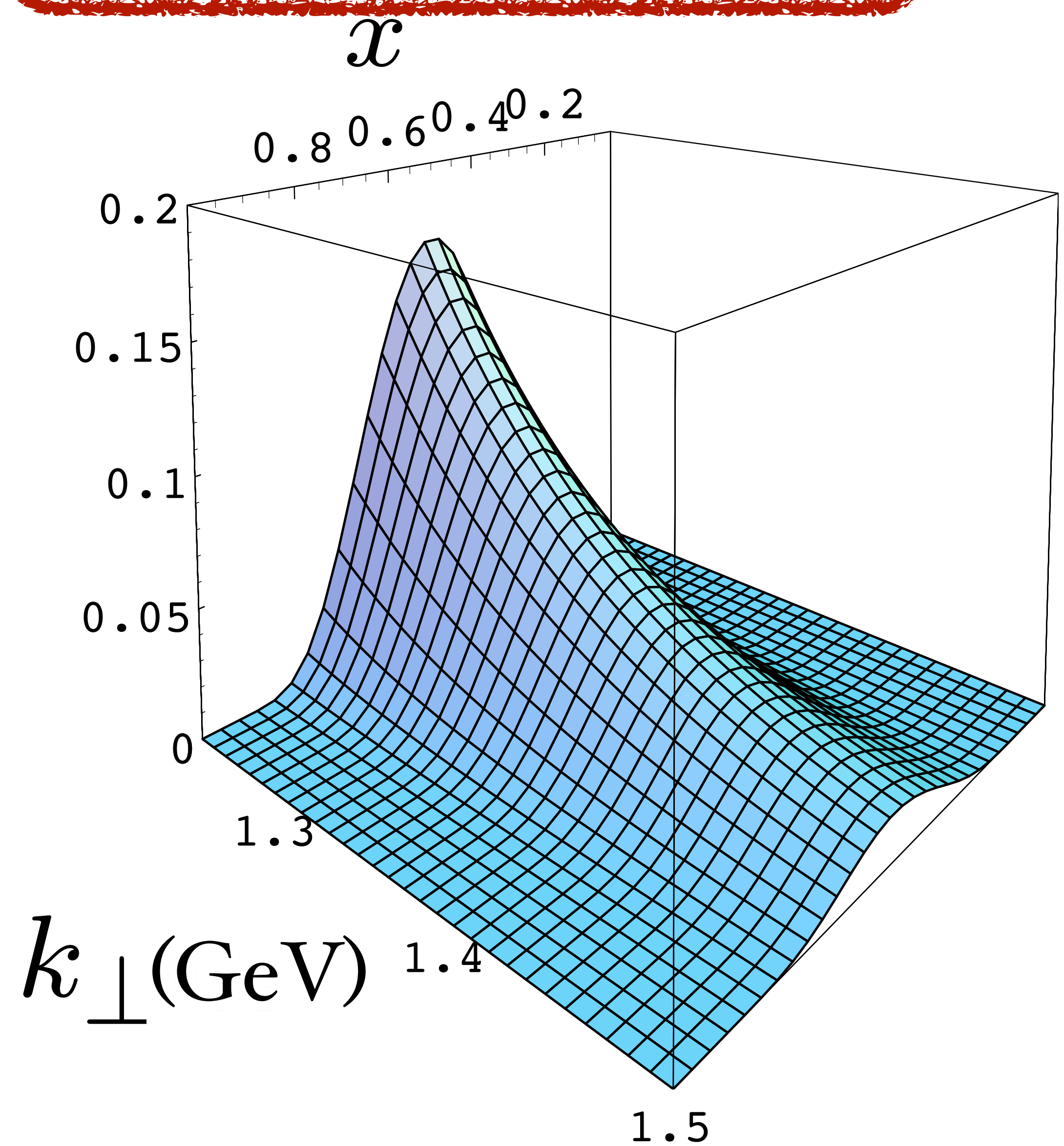
with Guy de Teramond and Hans Guenter Dosch

- *Light-Front Holography*

Duality of AdS_5 with LF Hamiltonian Theory



$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$



- *Light Front Wavefunctions:*

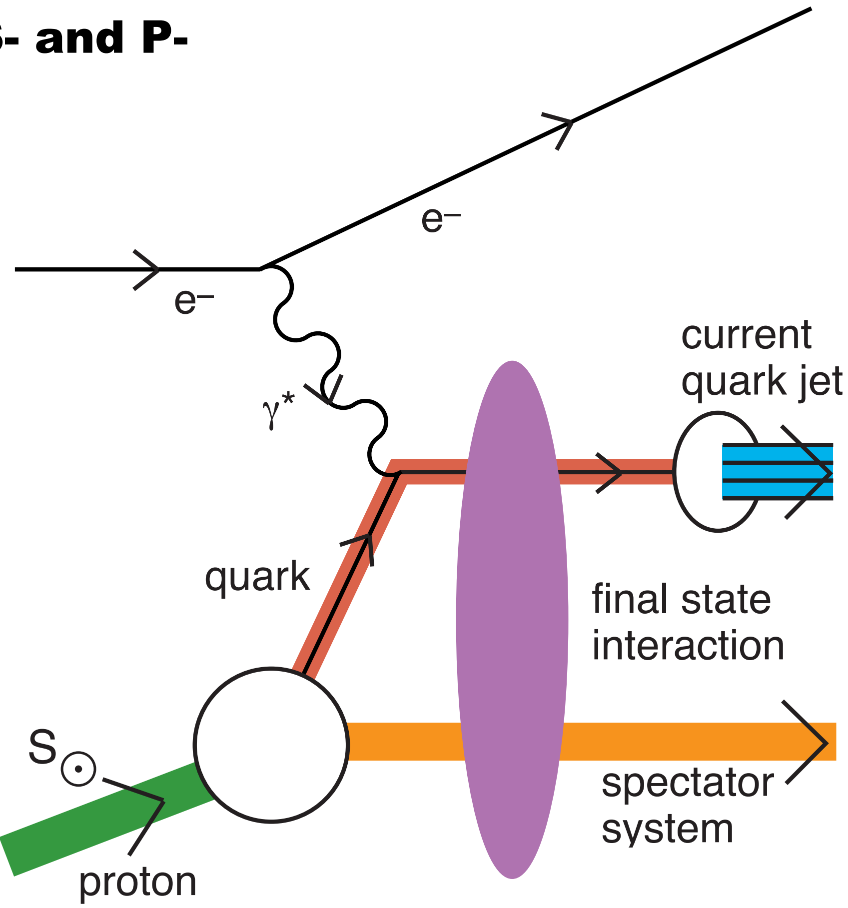
Light-Front Schrödinger Equation
Spectroscopy and Dynamics

Final-State Interactions Produce Pseudo T-Odd (Sivers Effect)

Hwang, Schmidt, sjb
Collins

$$\mathbf{i}\ \vec{S}\cdot\vec{p}_{jet}\times\vec{q}$$

- **Leading-Twist Bjorken Scaling!**
- **Requires nonzero orbital angular momentum of quark**
- **Arises from the interference of Final-State QCD Coulomb phases in S- and P-waves;**
- **Wilson line effect -- lc gauge prescription**
- **Relate to the quark contribution to the target proton anomalous magnetic moment and final-state QCD phases**
- **QCD phase at soft scale!**
- **New window to QCD coupling and running gluon mass in the IR**
- **QED S and P Coulomb phases infinite -- difference of phases finite!**
- **Alternate: Retarded and Advanced Gauge: Augmented LFWFs**



Dae Sung Hwang, Yuri V. Kovchegov, Ivan Schmidt, Matthew D. Sievert, sjb

Mulders, Boer   Qiu, Sterman

Pasquini, Xiao, Yuan, sjb

AdS/QCD and Light-Front Holography

$$\mathcal{M}^2_{n,J,L} = 4\kappa^2 (n + \frac{J+L}{2})$$

- **Zero mass pion for $m_q = 0$ (n=J=L=0)**
- **Regge trajectories: equal slope in n and L**
- **Form Factors at high Q^2: Dimensional counting** $[Q^2]^{n-1} F(Q^2) \to \text{const}$
- **Space-like and Time-like Meson and Baryon Form Factors**
- **Running Coupling for NPQCD** $\alpha_s(Q^2) \propto e^{-\frac{Q^2}{4\kappa^2}}$
- **Meson Distribution Amplitude** $\phi_\pi(x) \propto f_\pi \sqrt{x(1-x)}$

Bjorken sum rule defines effective charge

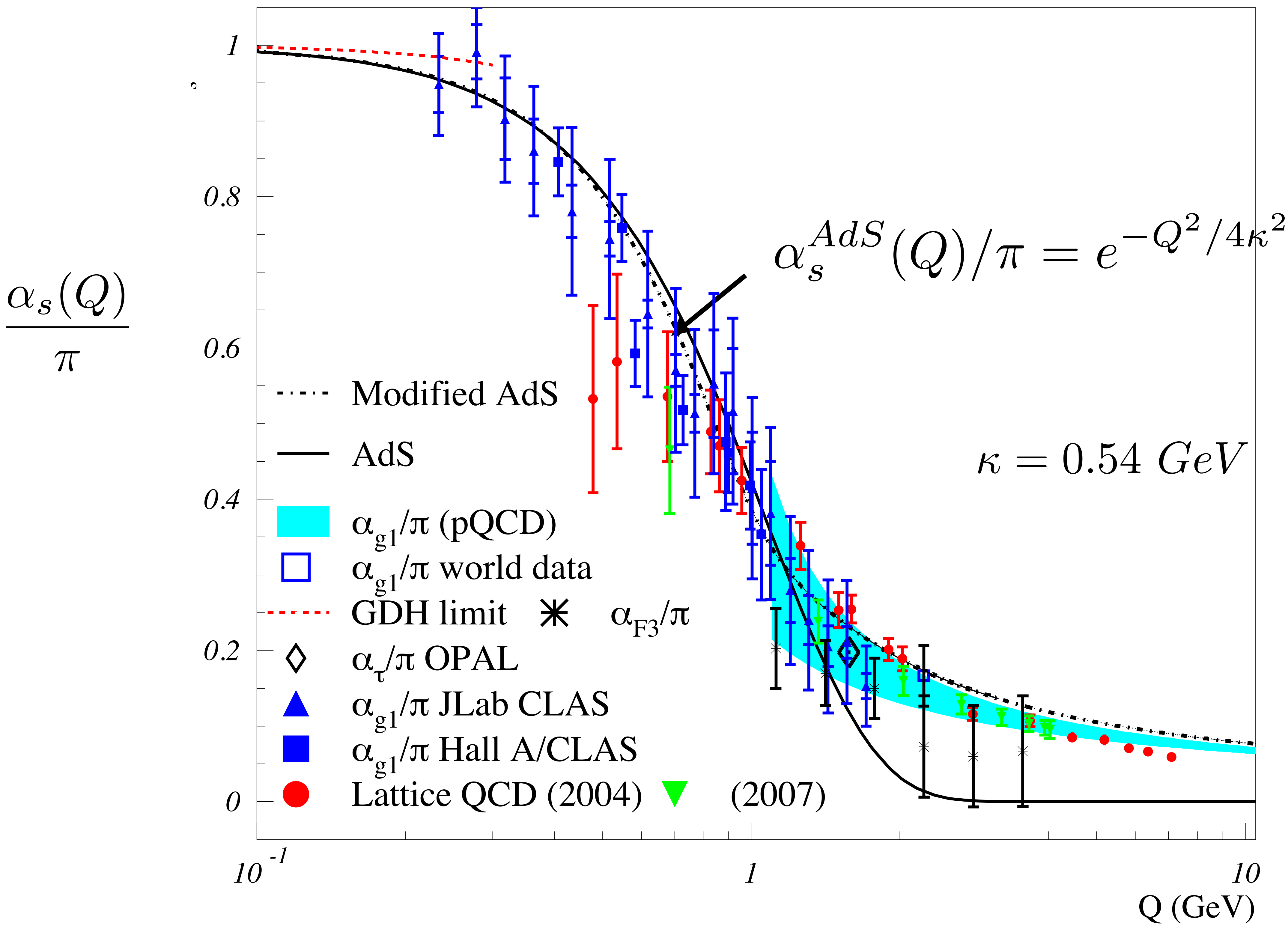
$$\int_0^1 dx[g_1^{ep}(x,Q^2) - g_1^{en}(x,Q^2)] \equiv \frac{g_a}{6}[1 - \frac{\alpha_{g1}(Q^2)}{\pi}]$$

$\alpha_{g1}(Q^2)$

- Can be used as standard QCD coupling
- Well measured
- Asymptotic freedom at large Q^2
- Computable at large Q^2 in any pQCD scheme
- Universal β_0, β_1

Running Coupling from Light-Front Holography and AdS/QCD

Analytic, defined at all scales, IR Fixed Point



AdS/QCD dilaton captures the higher twist corrections to effective charges for Q < 1 GeV

$$e^{\varphi} = e^{+\kappa^2 z^2}$$

Deur, de Teramond, sjb

Running Coupling from Modified AdS/QCD

Deur, de Teramond, sjb

- Consider five-dim gauge fields propagating in AdS$_5$ space in dilaton background $\varphi(z) = \kappa^2 z^2$

$$S = -\frac{1}{4} \int d^4x \, dz \, \sqrt{g} \, e^{\varphi(z)} \, \frac{1}{g_5^2} \, G^2$$

- Flow equation

$$\frac{1}{g_5^2(z)} = e^{\varphi(z)} \frac{1}{g_5^2(0)} \quad \text{or} \quad g_5^2(z) = e^{-\kappa^2 z^2} g_5^2(0)$$

where the coupling $g_5(z)$ incorporates the non-conformal dynamics of confinement

- YM coupling $\alpha_s(\zeta) = g_{YM}^2(\zeta)/4\pi$ is the five dim coupling up to a factor: $g_5(z) \to g_{YM}(\zeta)$
- Coupling measured at momentum scale Q

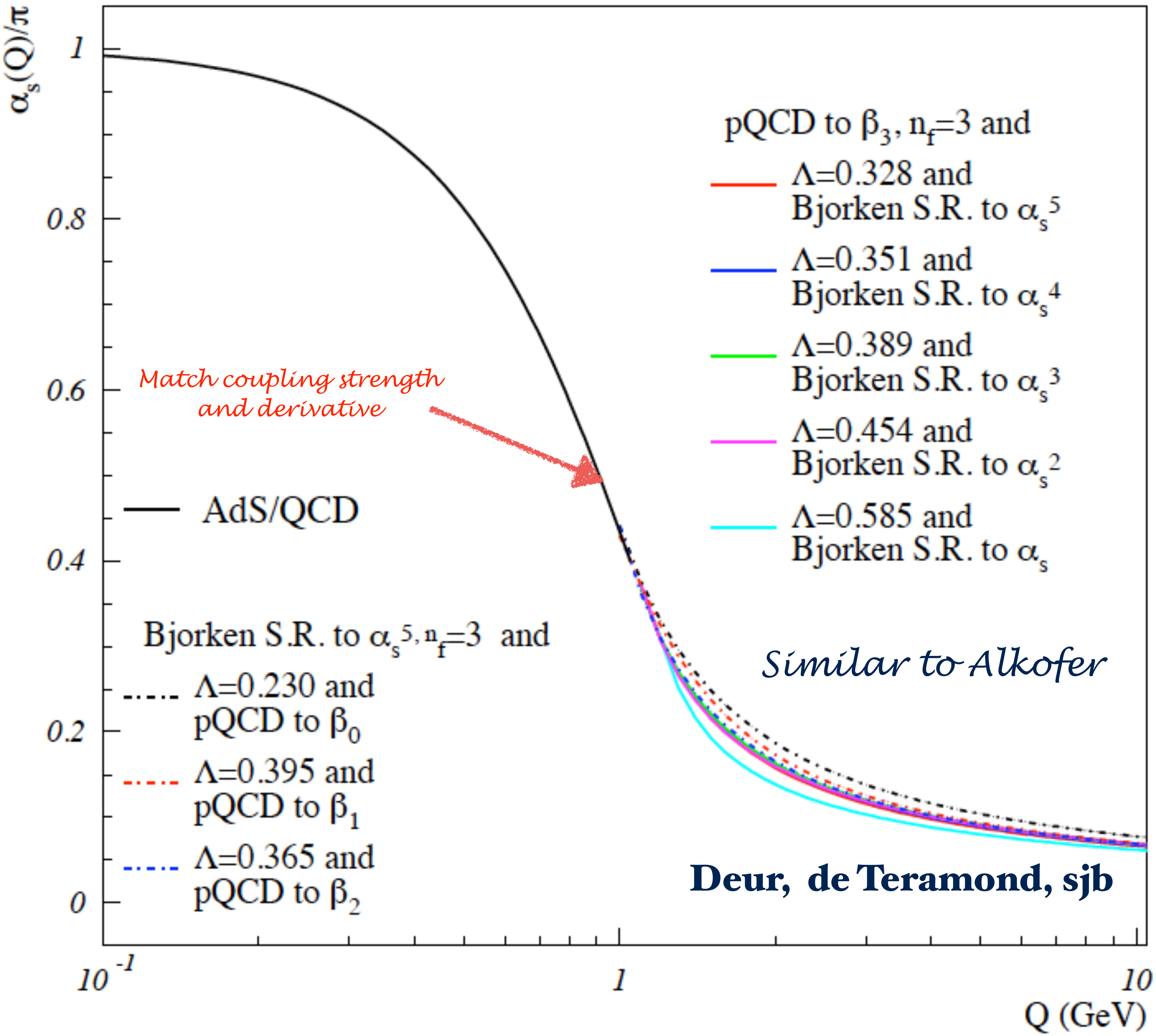
$$\alpha_s^{AdS}(Q) \sim \int_0^\infty \zeta d\zeta \, J_0(\zeta Q) \, \alpha_s^{AdS}(\zeta)$$

- Solution

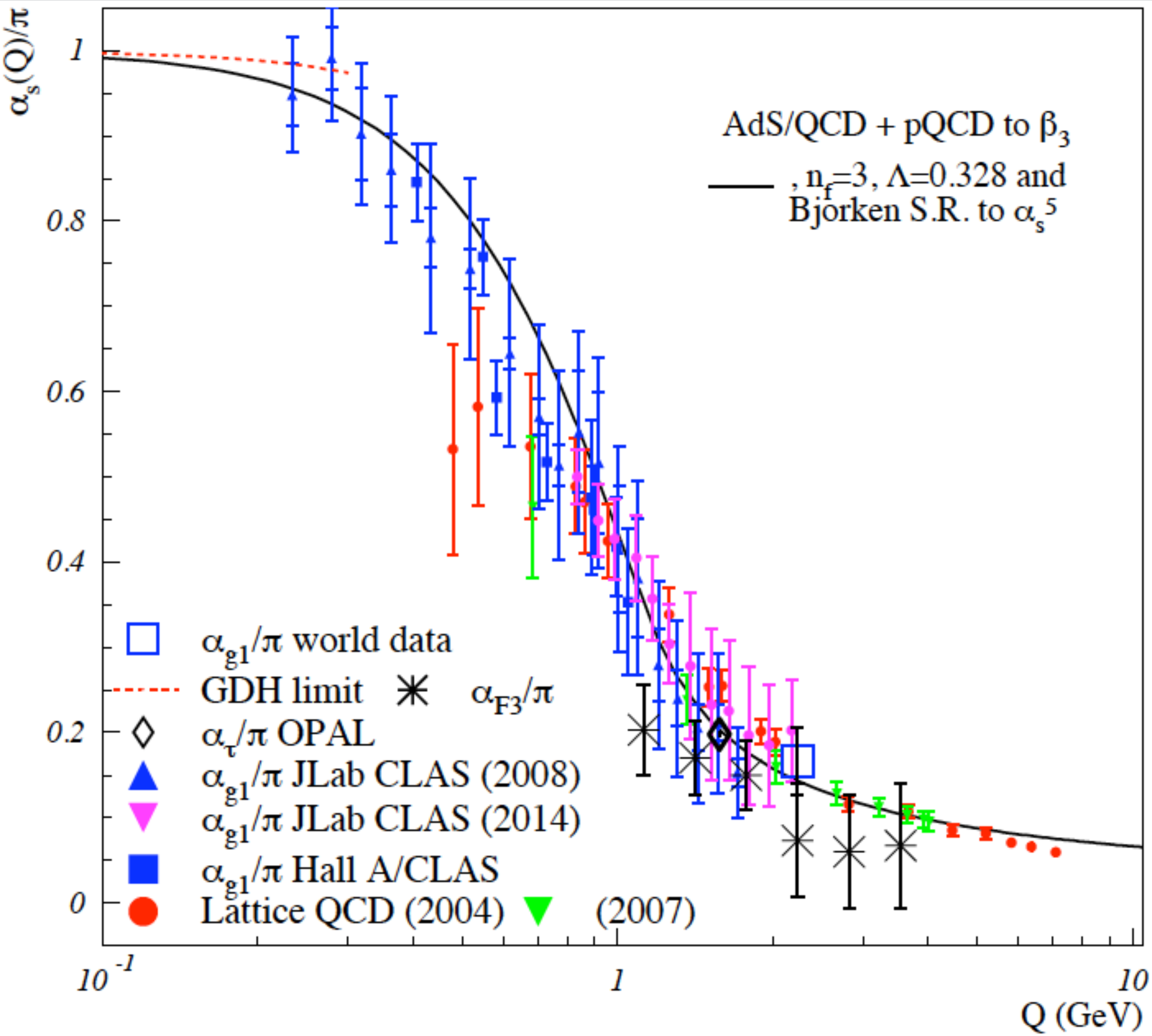
$$\alpha_s^{AdS}(Q^2) = \alpha_s^{AdS}(0) \, e^{-Q^2/4\kappa^2}.$$

where the coupling α_s^{AdS} incorporates the non-conformal dynamics of confinement

$$\Lambda_{\overline{MS}} = 0.5983\kappa = 0.5983\frac{m_\rho}{\sqrt{2}} = 0.4231 m_\rho = 0.328\ GeV$$

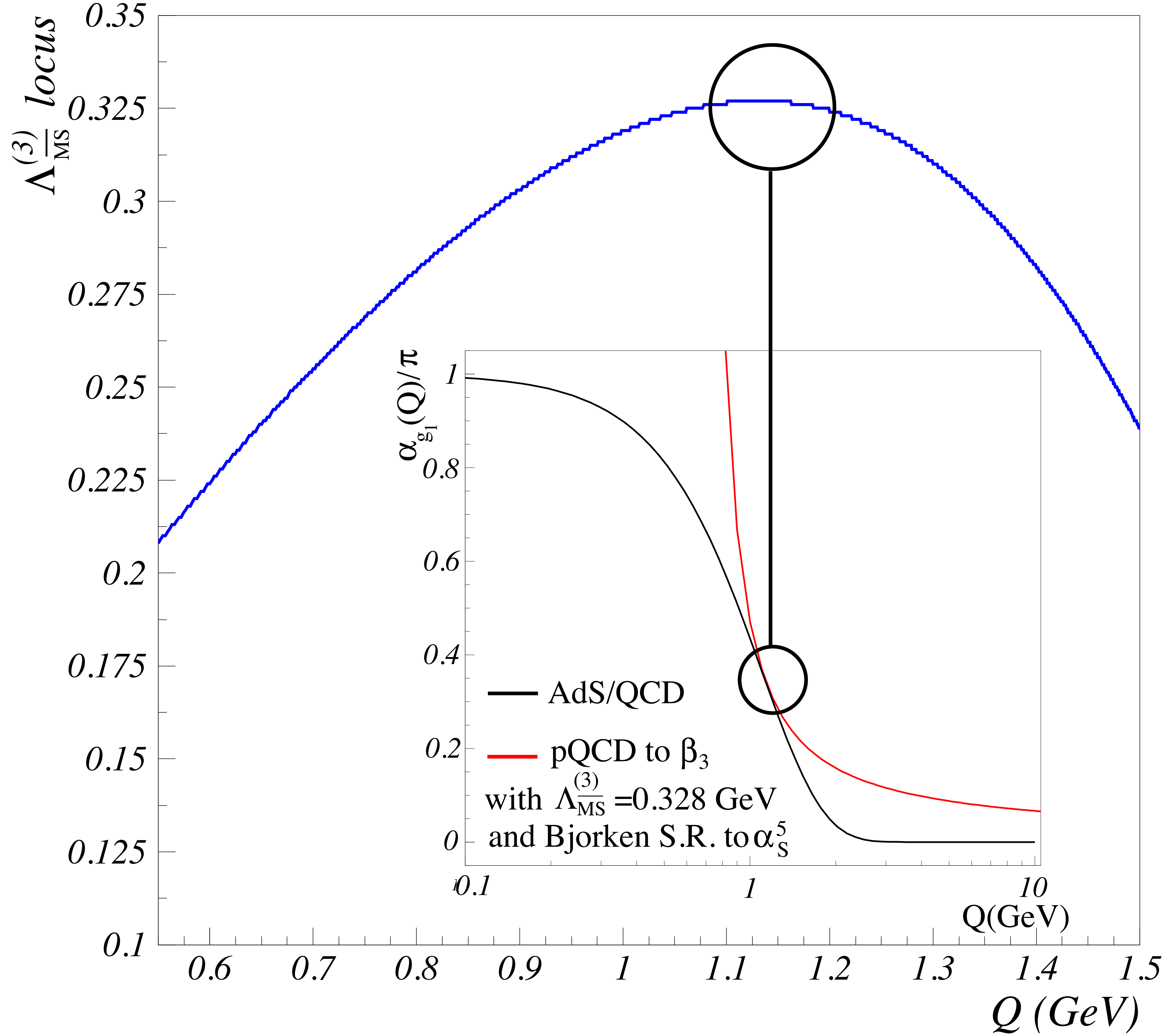


$$\Lambda_{\overline{MS}} = (0.598 \pm 0.044)\,\kappa = (0.423 \pm 0.031)\,M_\rho.$$

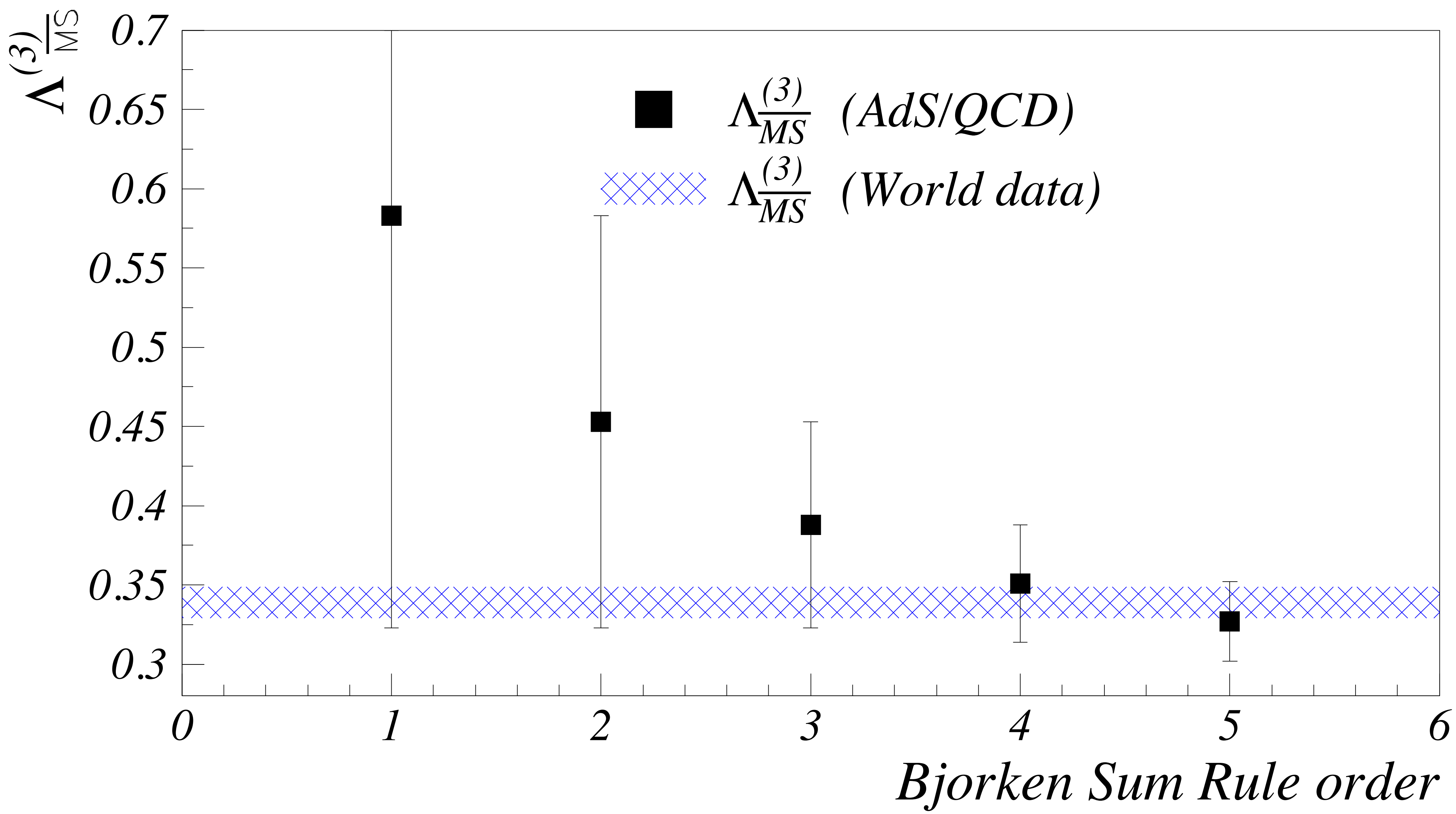


Deur,
de Teramond, sjb

Deur, de Teramond, sjb



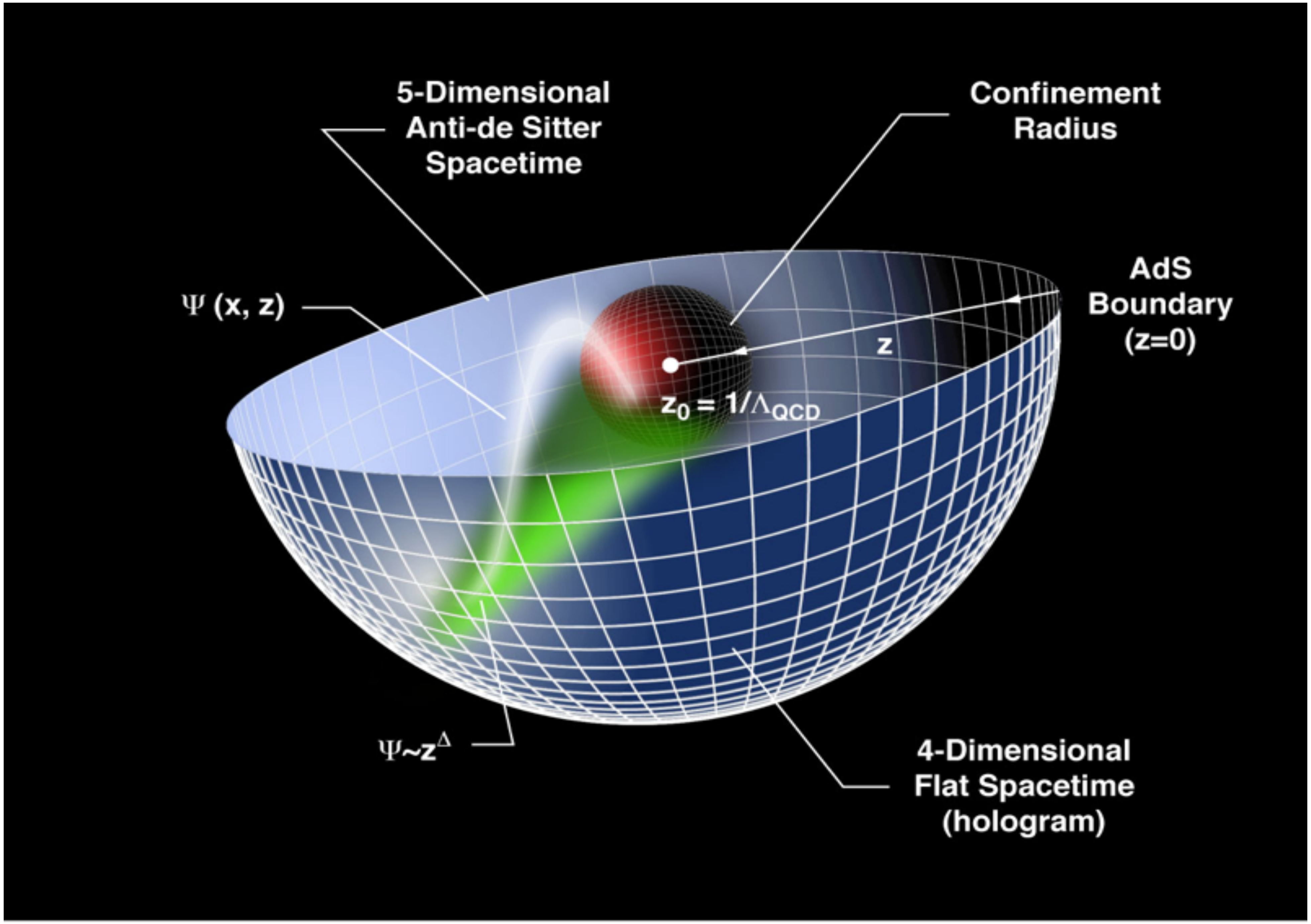
Deur, de Teramond, sjb



$$\Lambda_{\overline{MS}} = 0.5983\kappa = 0.5983\frac{m_\rho}{\sqrt{2}} = 0.4231 m_\rho = 0.328\ GeV$$

Connect $\Lambda_{\overline{MS}}$ to hadron masses!

Applications of AdS/CFT to QCD



Changes in physical length scale mapped to evolution in the 5th dimension z

in collaboration with Guy de Teramond

AdS/CFT

- Isomorphism of $SO(4,2)$ of conformal QCD with the group of isometries of AdS space

invariant measure

$$ds^2 = \frac{R^2}{z^2}(\eta_{\mu\nu}dx^\mu dx^\nu - dz^2),$$

$x^\mu \to \lambda x^\mu, \; z \to \lambda z$, maps scale transformations into the holographic coordinate z.

- AdS mode in z is the extension of the hadron wf into the fifth dimension.

- Different values of z correspond to different scales at which the hadron is examined.

$$x^2 \to \lambda^2 x^2, \quad z \to \lambda z.$$

$x^2 = x_\mu x^\mu$: invariant separation between quarks

- The AdS boundary at $z \to 0$ correspond to the $Q \to \infty$, UV zero separation limit.

Dilaton-Modified AdS/QCD

$$ds^2 = e^{\varphi(z)} \frac{R^2}{z^2}(\eta_{\mu\nu} x^\mu x^\nu - dz^2)$$

- **Soft-wall dilaton profile breaks conformal invariance** $e^{\varphi(z)} = e^{+\kappa^2 z^2}$
- **Color Confinement**
- **Introduces confinement scale** κ
- **Uses AdS_5 as template for conformal theory**

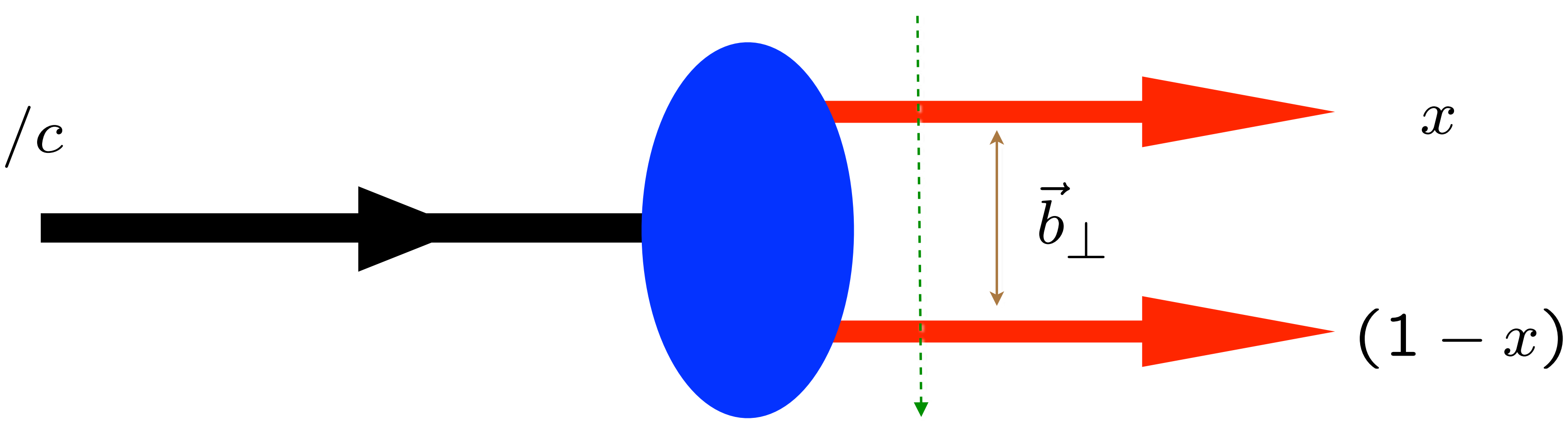
de Teramond, sjb

LF(3+1) ⟷ AdS_5

$$\psi(x, \vec{b}_\perp) \quad \longleftrightarrow \quad \phi(z)$$

$$\zeta = \sqrt{x(1-x)\vec{b}_\perp^2} \quad \longleftrightarrow \quad z$$

Fixed $\tau = t + z/c$



$$\psi(x, \zeta) = \sqrt{x(1-x)}\,\zeta^{-1/2}\phi(\zeta)$$

Light-Front Holography: *Unique mapping derived from equality of LF and AdS formula for EM and gravitational current matrix elements and identical equations of motion*

$$e^{\varphi(z)} = e^{+\kappa^2 z^2}$$

Positive-sign dilaton

- Dosch, de Teramond, sjb

AdS Soft-Wall Schrodinger Equation for bound state of two scalar constituents:

$$\left[-\frac{d^2}{dz^2} - \frac{1-4L^2}{4z^2} + U(z)\right]\Phi(z) = \mathcal{M}^2\Phi(z)$$

$$U(z) = \kappa^4 z^2 + 2\kappa^2(L+S-1)$$

Derived from variation of Action for Dilaton-Modified AdS_5

Identical to Light-Front Bound State Equation!

$$z \longleftrightarrow \zeta = \sqrt{x(1-x)\vec{b}_\perp^2}$$

- **de Alfaro, Fubini, Furlan**

$$G|\psi(\tau) >= i\frac{\partial}{\partial \tau}|\psi(\tau) >$$

New term

$$G = uH + vD + wK$$

$$G = H_\tau = \frac{1}{2}\left(-\frac{d^2}{dx^2} + \frac{g}{x^2} + \frac{4uw - v^2}{4}x^2\right)$$

Retains conformal invariance of action despite mass scale!

$$4uw - v^2 = \kappa^4 = [M]^4$$

Identical to LF Hamiltonian with unique potential and dilaton!

- **Dosch, de Teramond, sjb**

$$\left[-\frac{d^2}{d\zeta^2} + \frac{1-4L^2}{4\zeta^2} + U(\zeta)\right]\psi(\zeta) = \mathcal{M}^2\psi(\zeta)$$

$$U(\zeta) = \kappa^4\zeta^2 + 2\kappa^2(L + S - 1)$$

Remarkable Features of Light-Front Schrödinger Equation

- ***Relativistic, frame-independent***
- ***QCD scale appears - unique LF potential***
- ***Reproduces spectroscopy and dynamics of light-quark hadrons with one parameter***
- ***Zero-mass pion for zero mass quarks!***
- ***Regge slope same for n and L -- not usual HO***
- ***Splitting in L persists to high mass -- contradicts conventional wisdom based on breakdown of chiral symmetry***
- ***Phenomenology: LFWFs, Form factors, electroproduction***
- ***Extension to heavy quarks***

$$U(\zeta) = \kappa^4 \zeta^2 + 2\kappa^2(L + S - 1)$$

Meson Spectrum in Soft Wall Model

Pion: Negative term for J=0 cancels positive terms from LFKE and potential

- Effective potential: $U(\zeta^2) = \kappa^4\zeta^2 + 2\kappa^2(J-1)$
- LF WE

$$\left(-\frac{d^2}{d\zeta^2} - \frac{1-4L^2}{4\zeta^2} + \kappa^4\zeta^2 + 2\kappa^2(J-1)\right)\phi_J(\zeta) = M^2\phi_J(\zeta)$$

- Normalized eigenfunctions $\langle\phi|\phi\rangle = \int d\zeta\, \phi^2(z)^2 = 1$

$$\phi_{n,L}(\zeta) = \kappa^{1+L}\sqrt{\frac{2n!}{(n+L)!}}\,\zeta^{1/2+L}e^{-\kappa^2\zeta^2/2}L_n^L(\kappa^2\zeta^2)$$

- Eigenvalues

$$\mathcal{M}^2_{n,J,L} = 4\kappa^2\left(n + \frac{J+L}{2}\right)$$

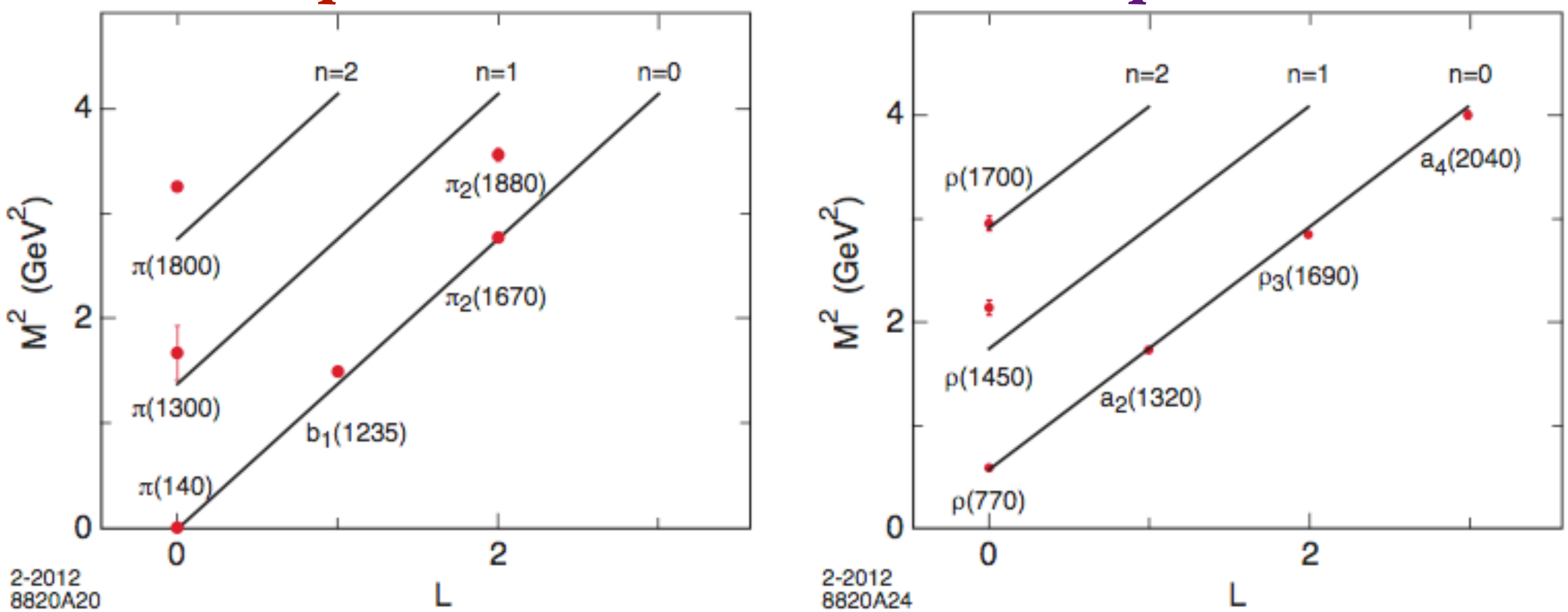
G. de Teramond, H. G. Dosch, sjb

- $J = L + S$, $I = 1$ meson families $\mathcal{M}^2_{n,L,S} = 4\kappa^2 \left(n + L + S/2\right)$

$4\kappa^2$ for $\Delta n = 1$
$4\kappa^2$ for $\Delta L = 1$
$2\kappa^2$ for $\Delta S = 1$

$m_q = 0$

Massless pion in Chiral Limit! ***Same slope in n and L!***



I=1 orbital and radial excitations for the π ($\kappa = 0.59$ GeV) and the ρ-meson families ($\kappa = 0.54$ GeV)

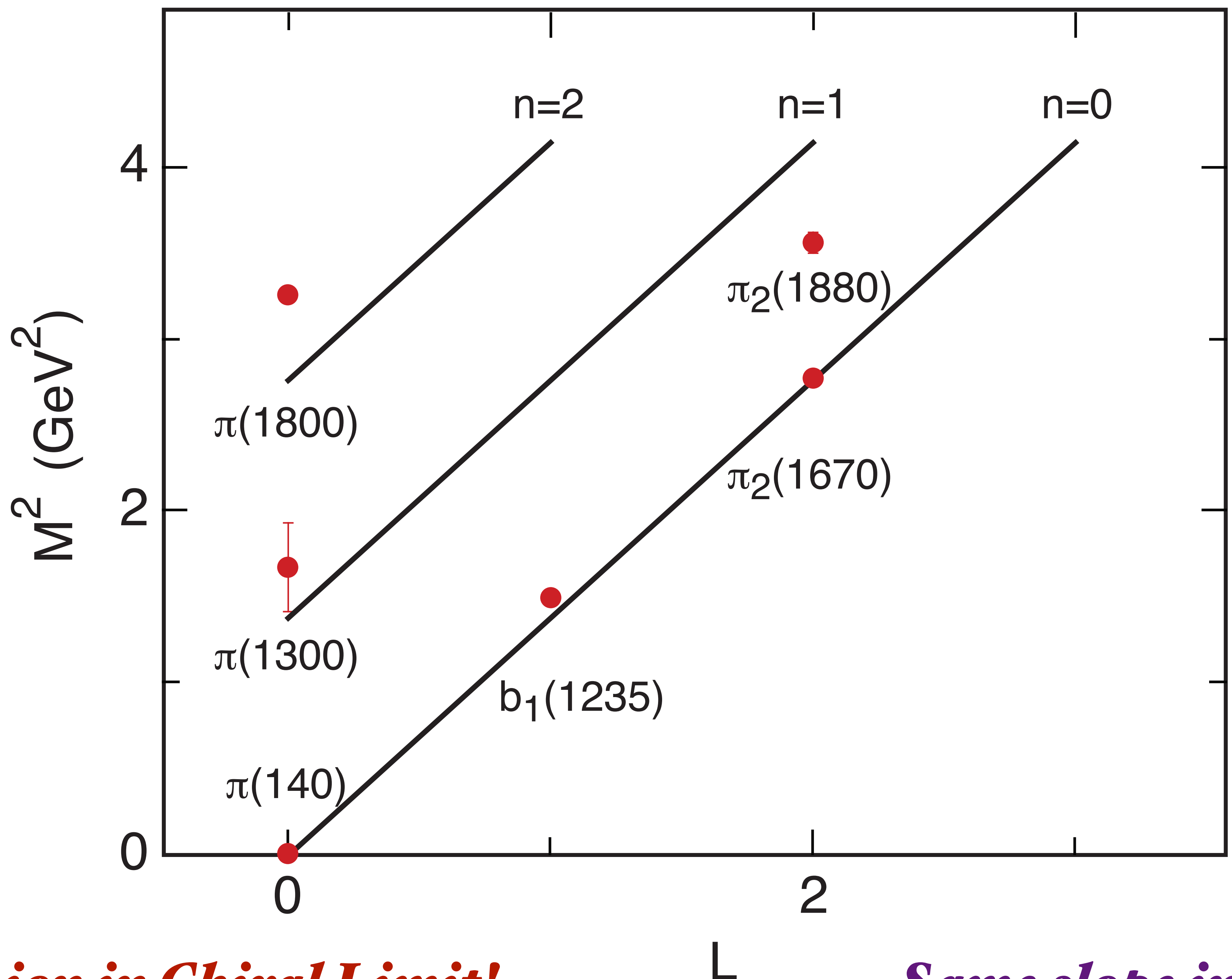
- Triplet splitting for the $I = 1$, $L = 1$, $J = 0, 1, 2$, vector meson a-states

$$\mathcal{M}_{a_2(1320)} > \mathcal{M}_{a_1(1260)} > \mathcal{M}_{a_0(980)}$$

Mass ratio of the ρ and the a_1 mesons: coincides with Weinberg sum rules

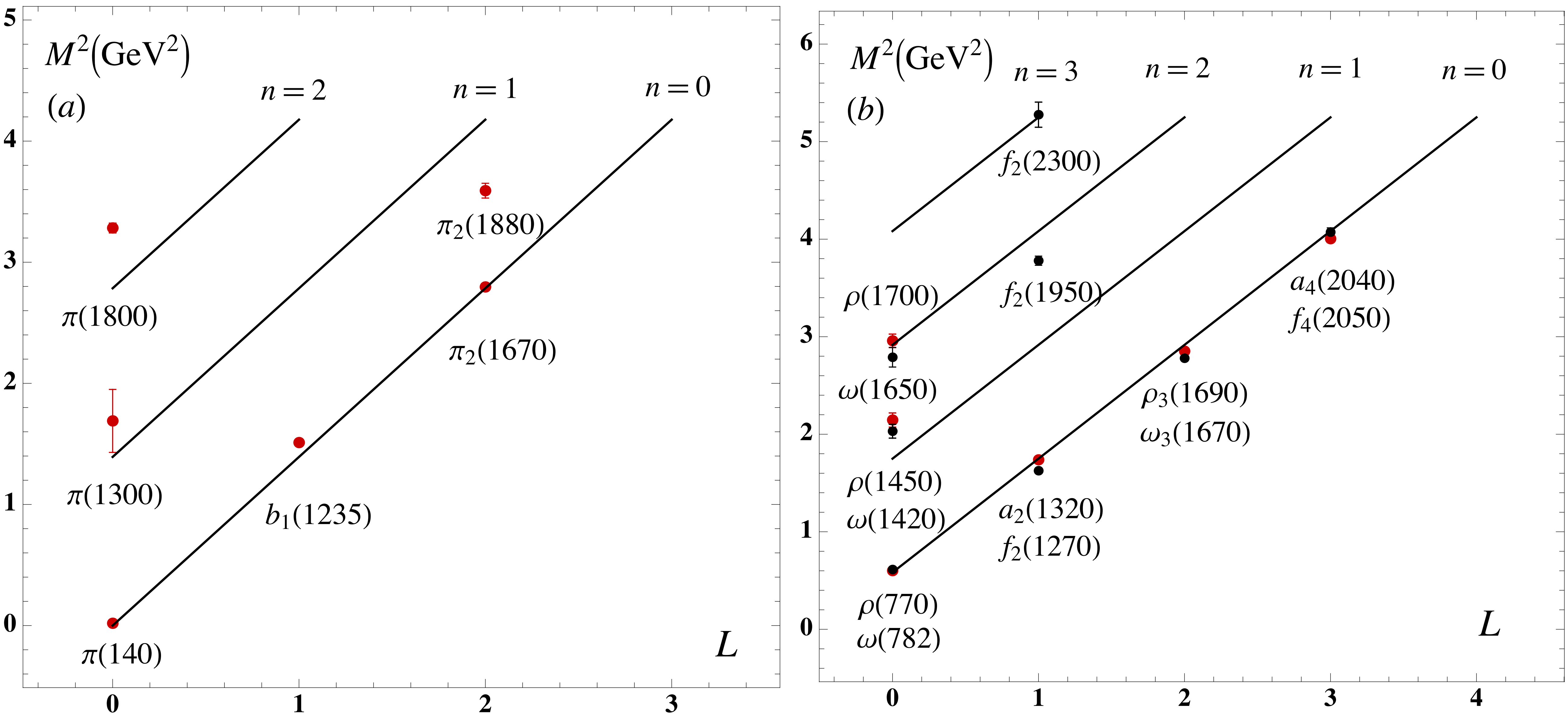
G. de Teramond, H. G. Dosch, sjb

$$\mathcal{M}^2_{n,L,S} = 4\kappa^2(n + L + S/2)$$



Massless pion in Chiral Limit!

Same slope in n and L!

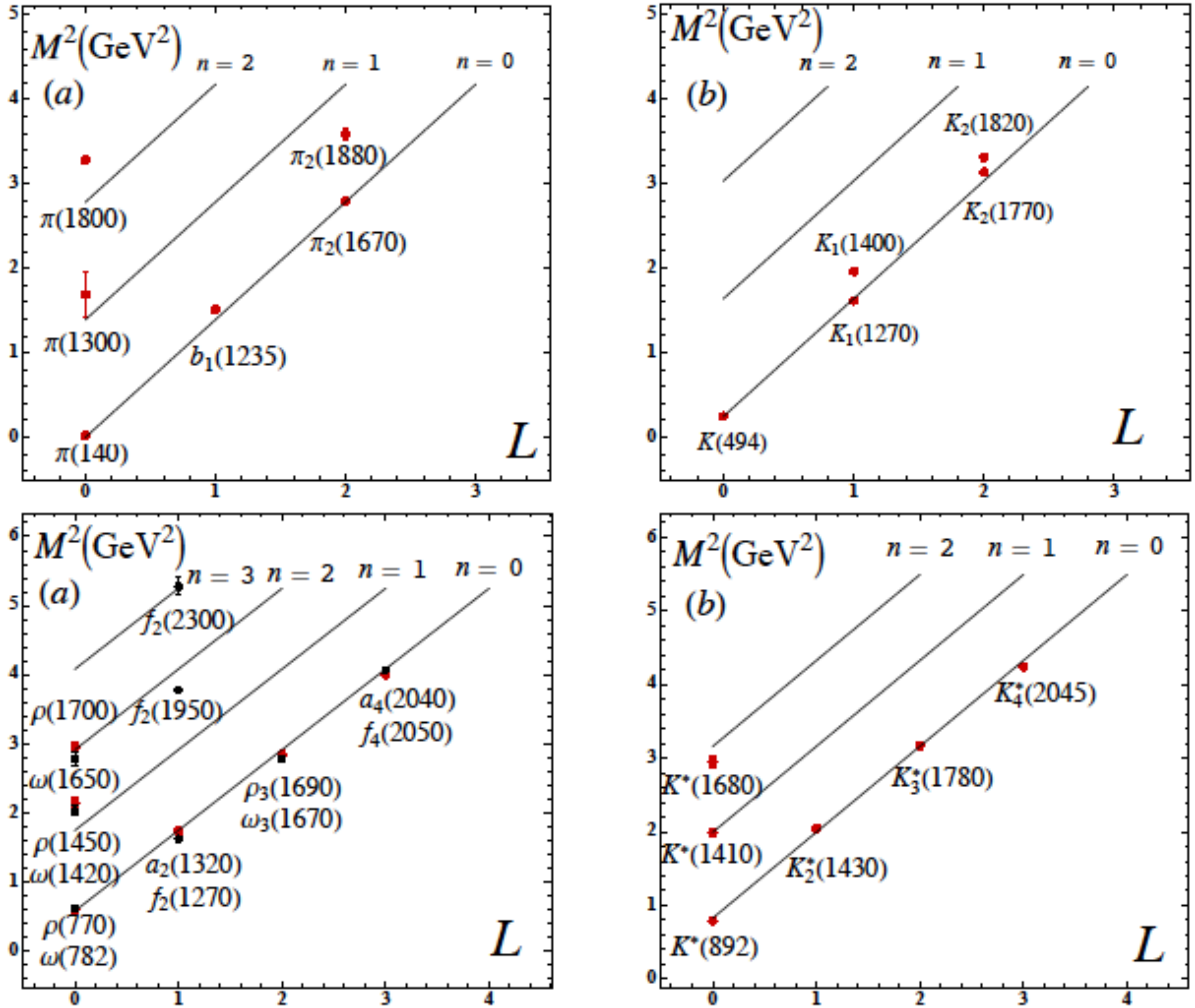


$M^2(\mathrm{GeV}^2)$
(a)
n = 2
n = 1
n = 0
π(1800)
π(1300)
π(140)
$b_1(1235)$
$\pi_2(1880)$
$\pi_2(1670)$
L
$M^2(\mathrm{GeV}^2)$
(b)
n = 3
n = 2
n = 1
n = 0
$f_2(2300)$
$f_2(1950)$
ρ(1700)
ω(1650)
ρ(1450)
ω(1420)
ρ(770)
ω(782)
$a_2(1320)$
$f_2(1270)$
$\rho_3(1690)$
$\omega_3(1670)$
$a_4(2040)$
$f_4(2050)$
L

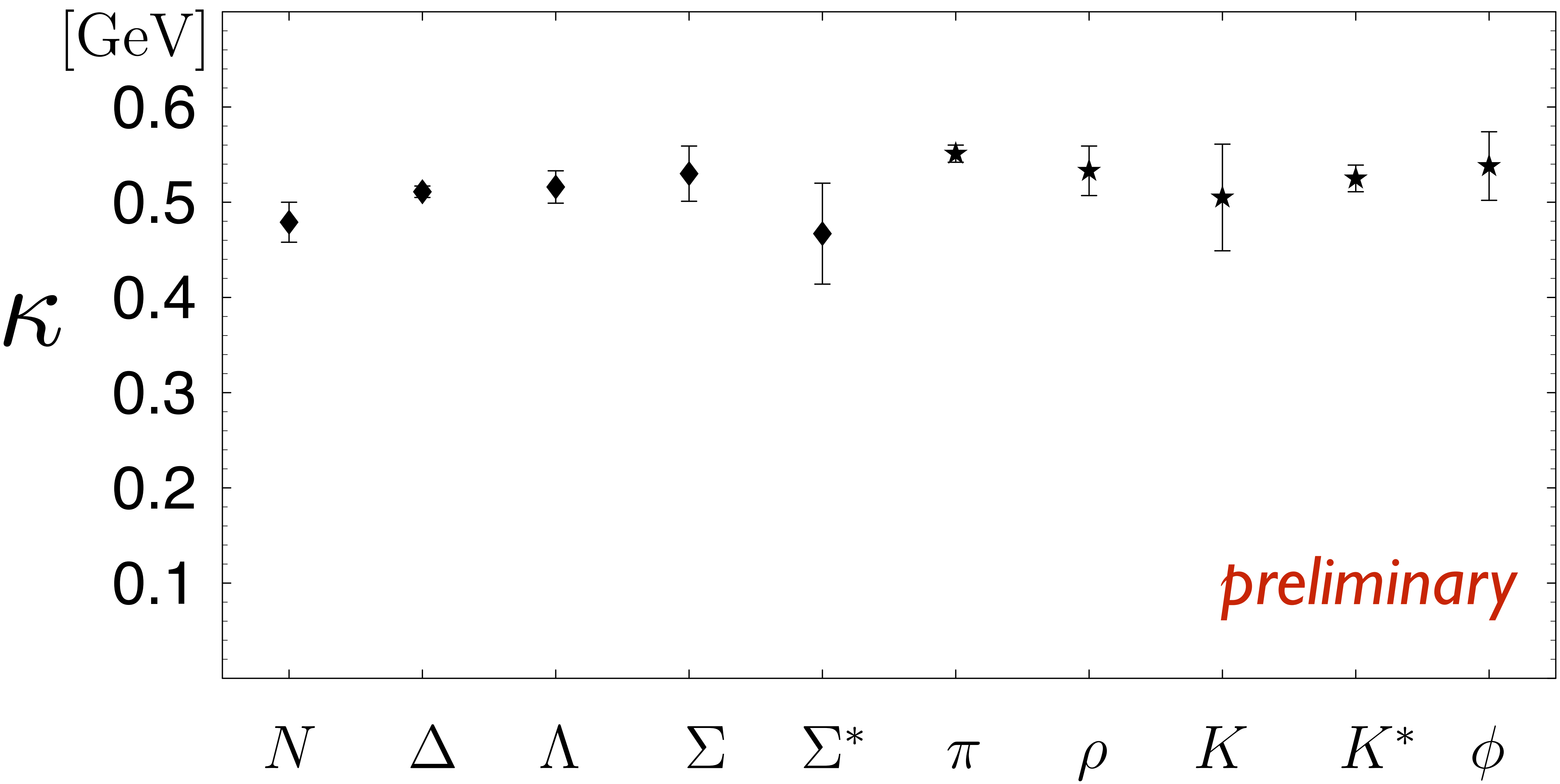
De Tèramond, Dosch, sjb

$m_u = m_d = 46 \text{ MeV}, \quad m_s = 357 \text{ MeV}$

$$M^2 = M_0^2 + \left\langle X \left| \frac{m_q^2}{x} \right| X \right\rangle + \left\langle X \left| \frac{m_{\bar{q}}^2}{1-x} \right| X \right\rangle$$



$$m_u = m_d = 46 \text{ MeV}, \; m_s = 357 \text{ MeV}$$



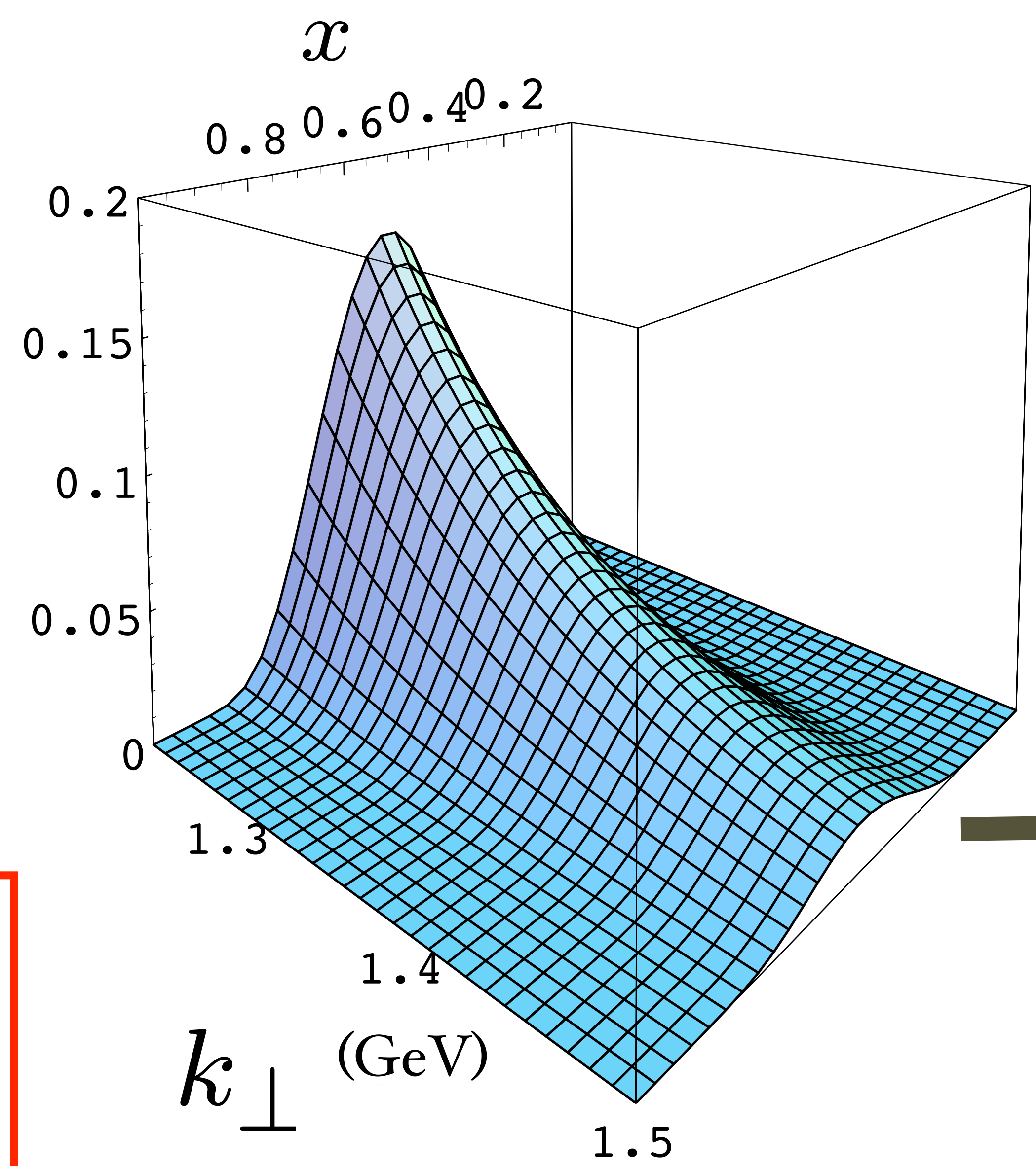
Fit to the slope of Regge trajectories, including radial excitations

Prediction from AdS/QCD: Meson LFWF

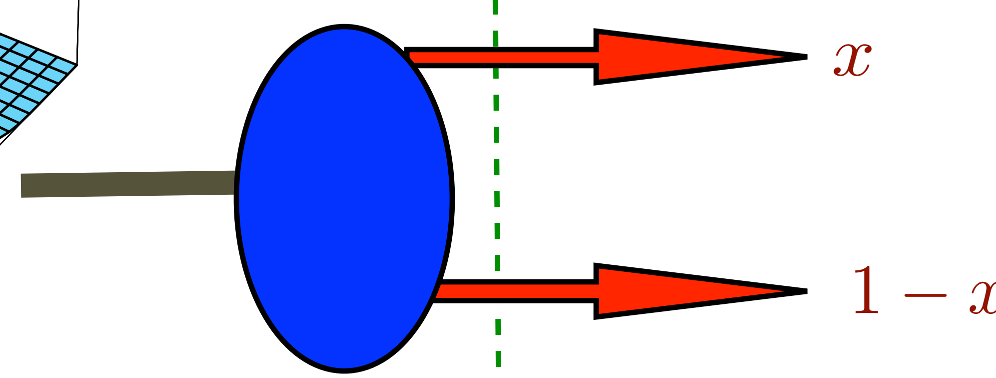
$$e^{\varphi(z)} = e^{+\kappa^2 z}$$

de Teramond, Cao, sjb

$$\psi_M(x, k_\perp^2)$$



"Soft Wall" model



massless quarks

Note coupling

$$k_\perp^2, x$$

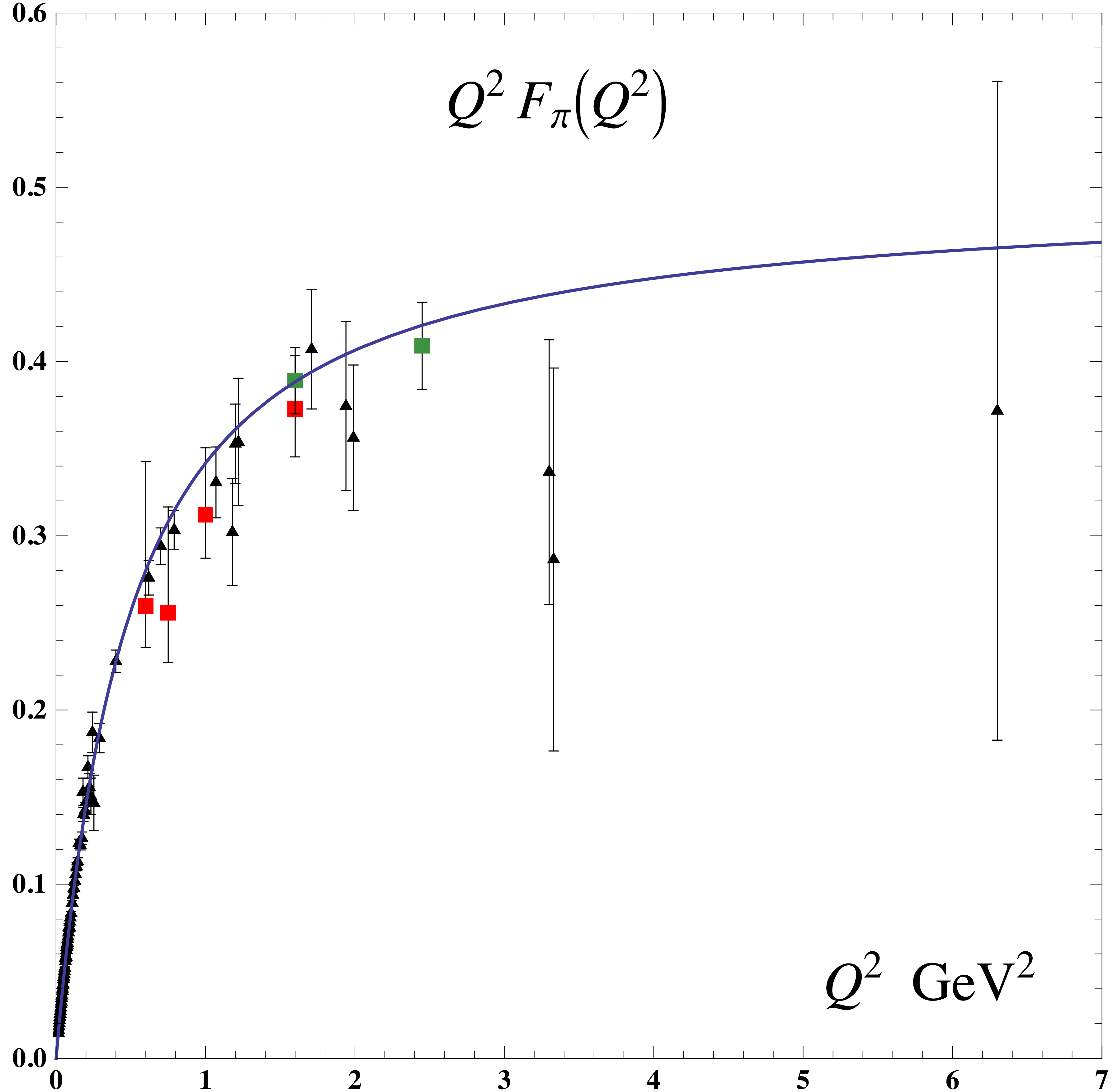
$$\psi_M(x, k_\perp) = \frac{4\pi}{\kappa\sqrt{x(1-x)}} e^{-\frac{k_\perp^2}{2\kappa^2 x(1-x)}}$$

$$\phi_\pi(x) = \frac{4}{\sqrt{3}\pi} f_\pi \sqrt{x(1-x)}$$

$$f_\pi = \sqrt{P_{q\bar{q}}}\frac{\sqrt{3}}{8}\kappa = 92.4 \text{ MeV}$$

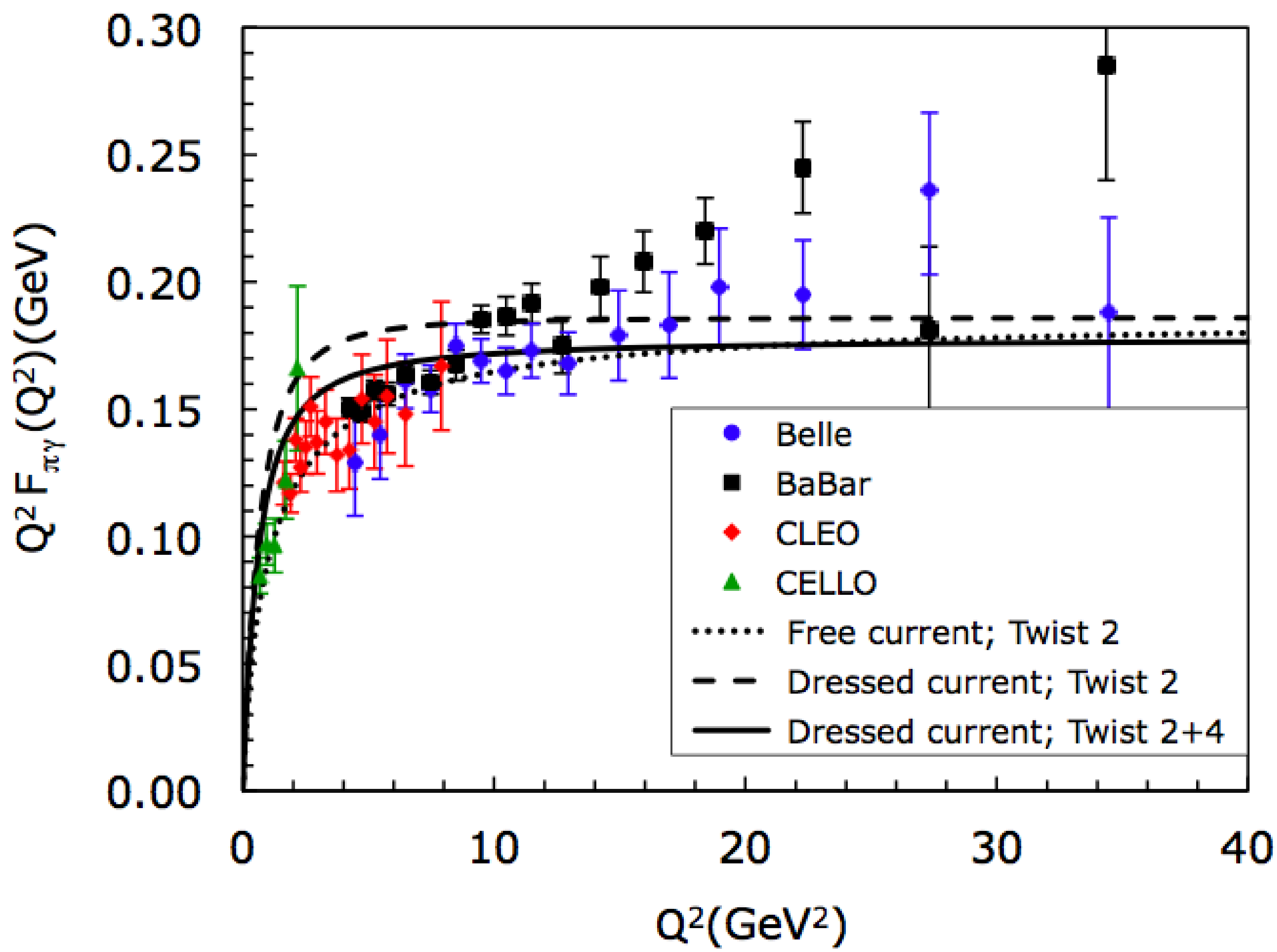
Same as DSE!

Provides Connection of Confinement to Hadron Structure



$Q^2 F_\pi(Q^2)$
Q^2 GeV^2
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
1
2
3
4
5
6
7

Pion-gamma transition form factor



$$\phi_\pi(x) = \frac{4}{\sqrt{3}\pi} f_\pi \sqrt{x(1-x)}$$

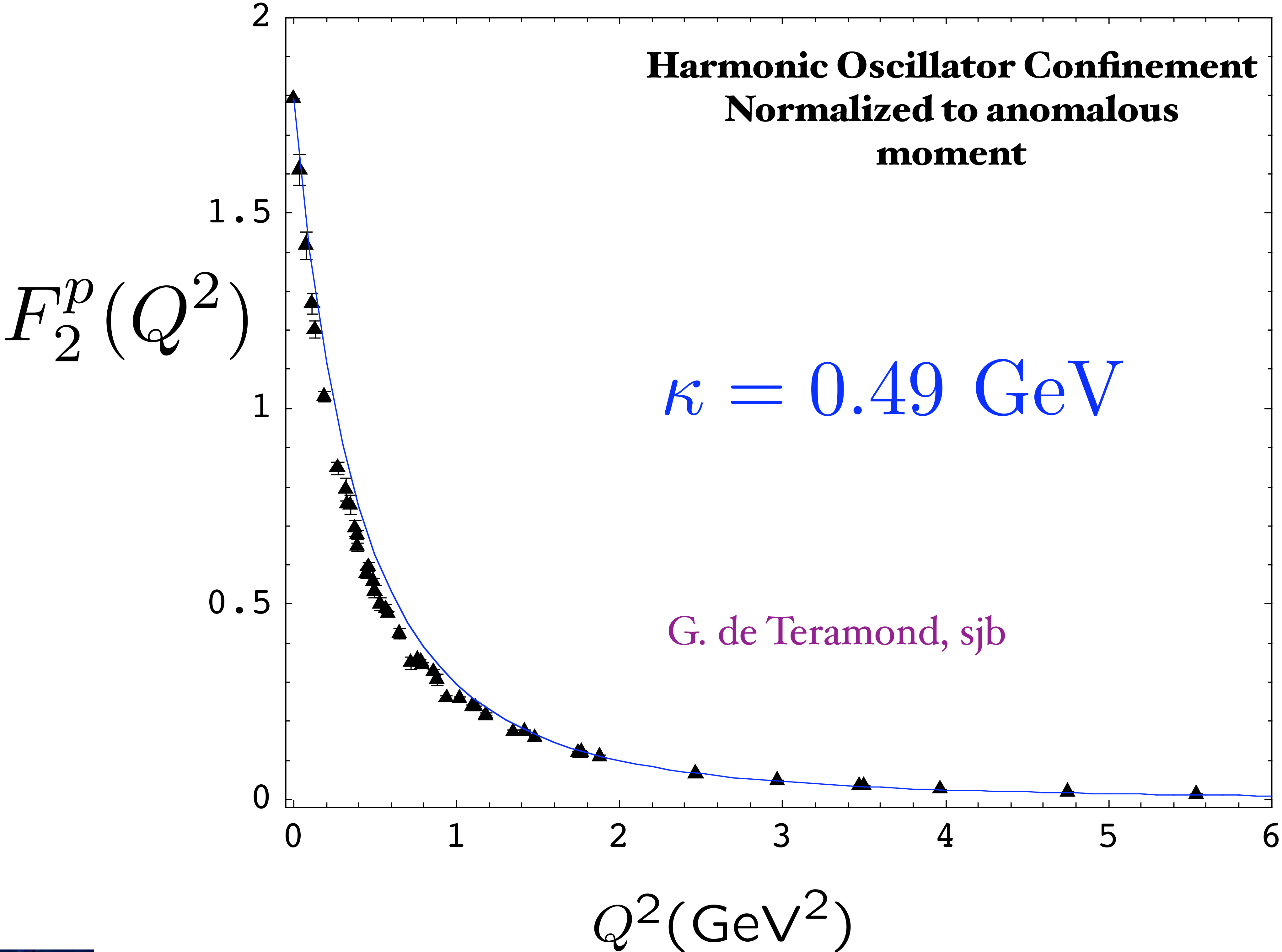
de Teramond, Cao, sjb

Stan Brodsky

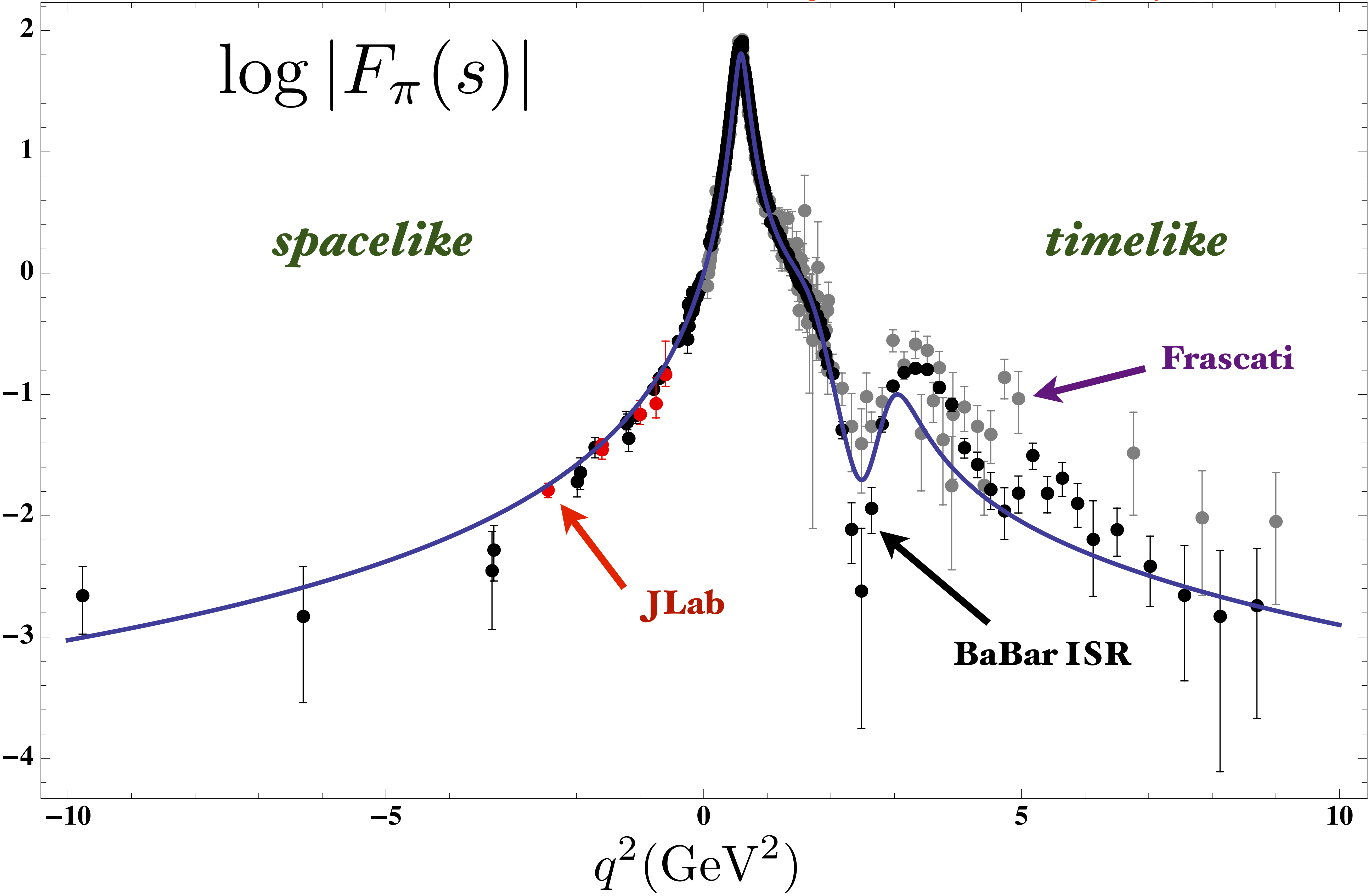
SLAC NATIONAL ACCELERATOR LABORATORY

Spacelike Pauli Form Factor

From overlap of $L = 1$ and $L = 0$ LFWFs

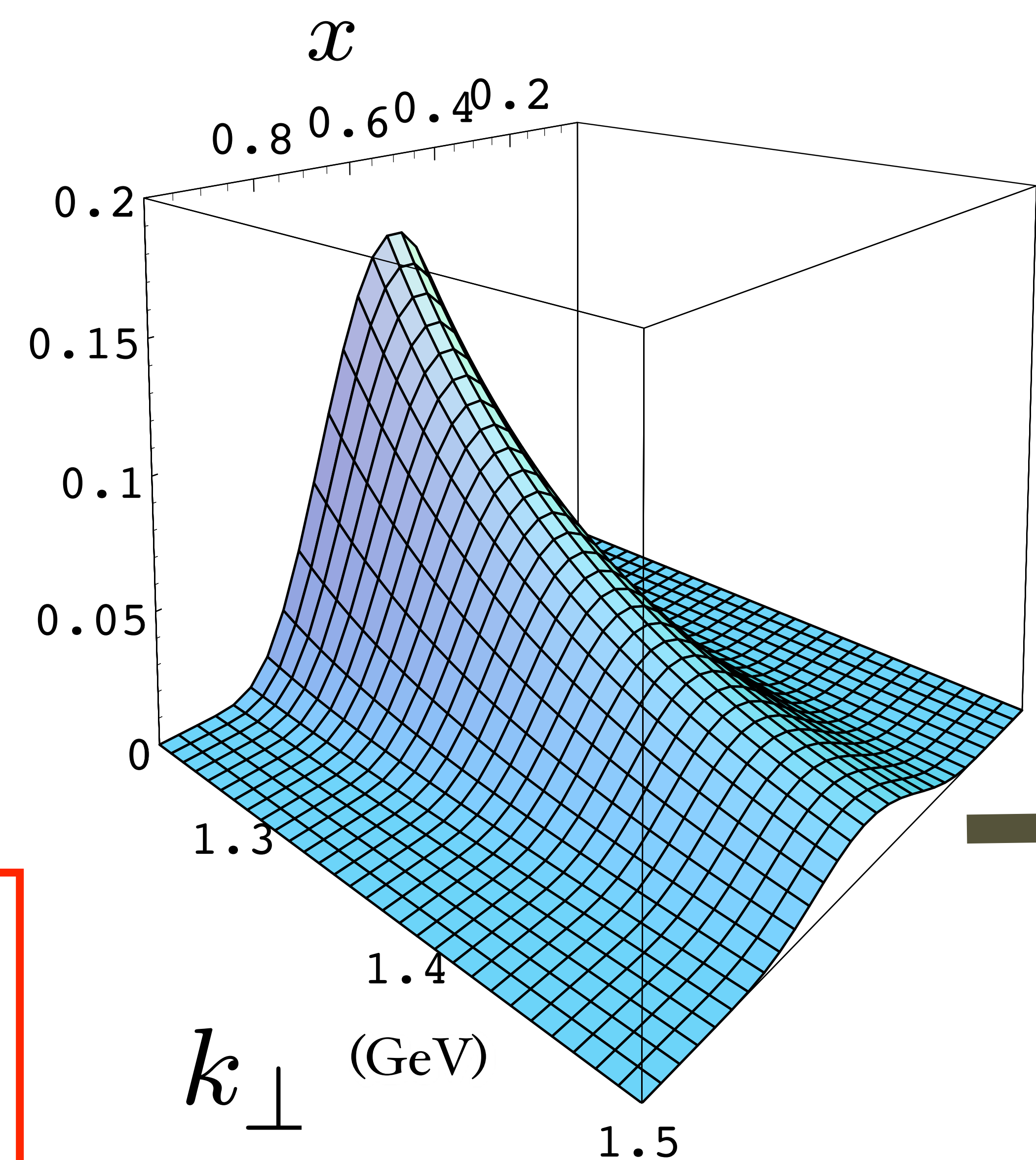


Pion Form Factor from AdS/QCD and Light-Front Holography



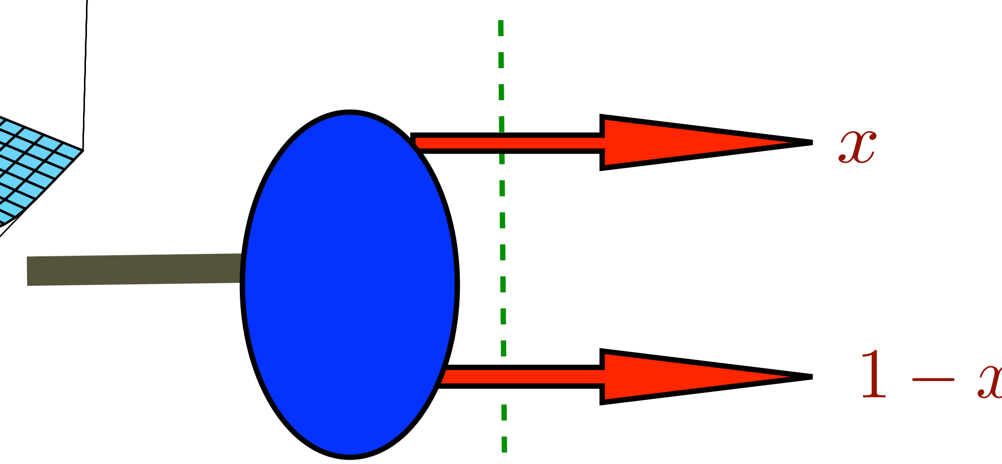
Prediction from AdS/QCD: Meson LFWF

$\psi_M(x, k_\perp^2)$



de Teramond, Cao, sjb

“Soft Wall” model



massless quarks

Note coupling

$k_\perp^2, x$

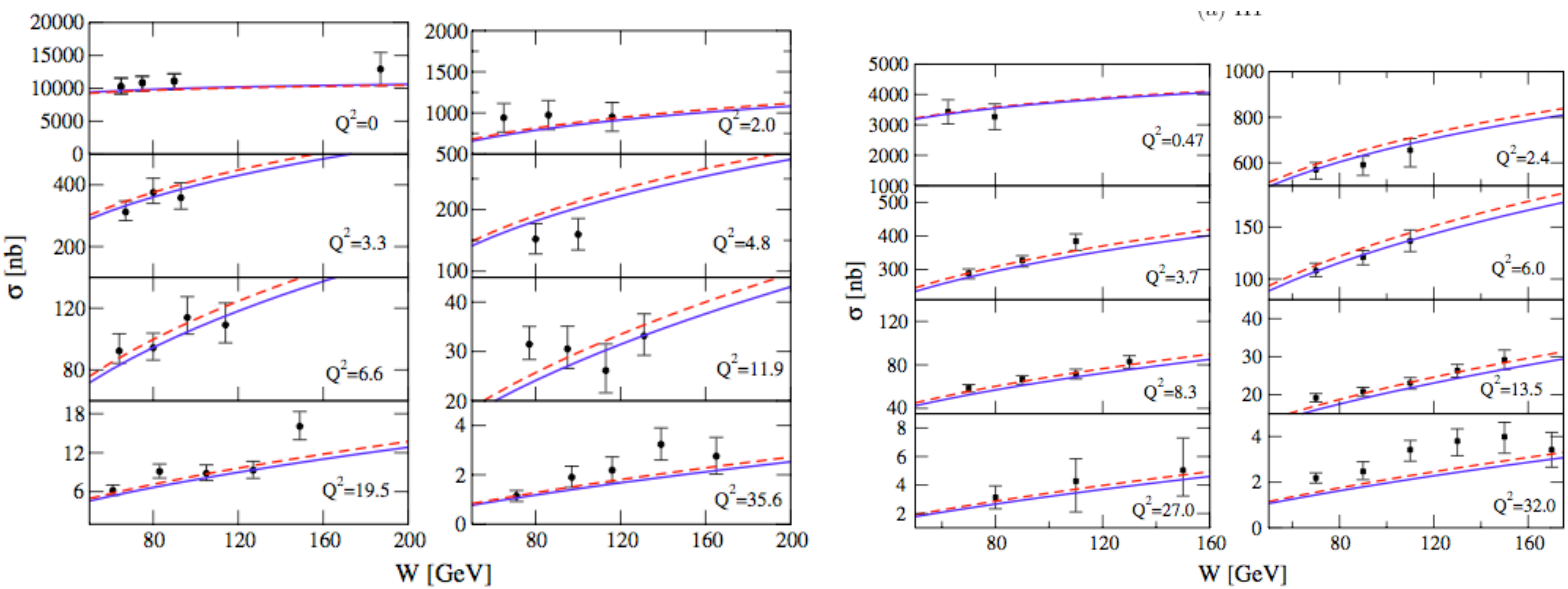
$$\psi_M(x, k_\perp) = \frac{4\pi}{\kappa\sqrt{x(1-x)}} e^{-\frac{k_\perp^2}{2\kappa^2 x(1-x)}}$$

$$\phi_\pi(x) = \frac{4}{\sqrt{3}\pi} f_\pi \sqrt{x(1-x)}$$

$$f_\pi = \sqrt{P_{q\bar{q}}}\frac{\sqrt{3}}{8}\kappa = 92.4 \text{ MeV}$$

Provides Connection of Confinement to Hadron Structure

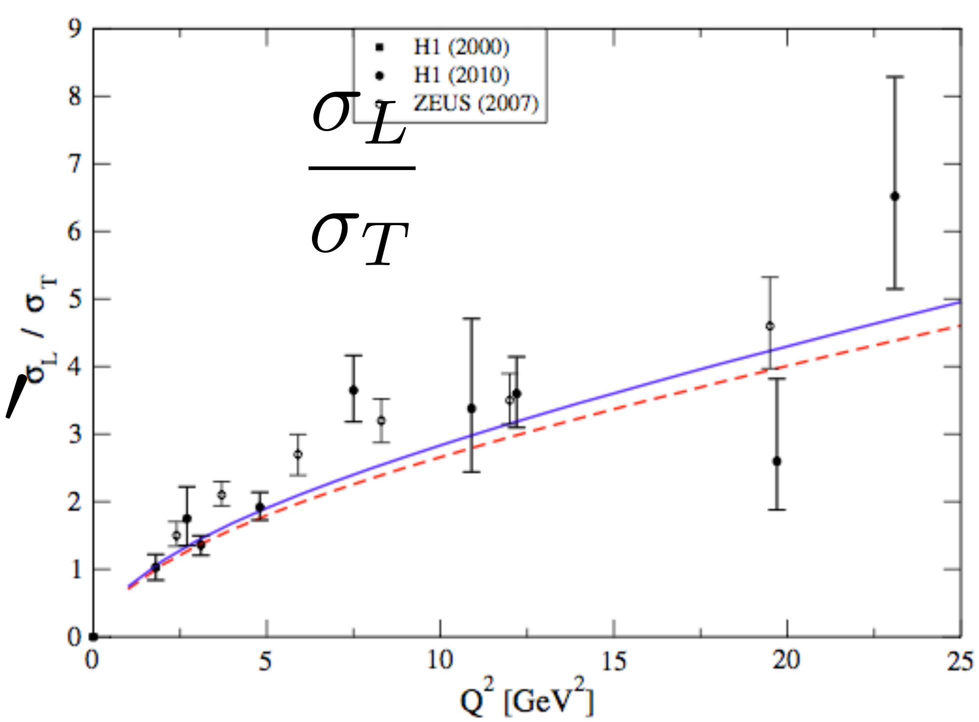
AdS/QCD Holographic Wave Function for the ρ Meson and Diffractive ρ Meson Electroproduction



(b) ZEUS

J. R. Forshaw, R. Sandapen

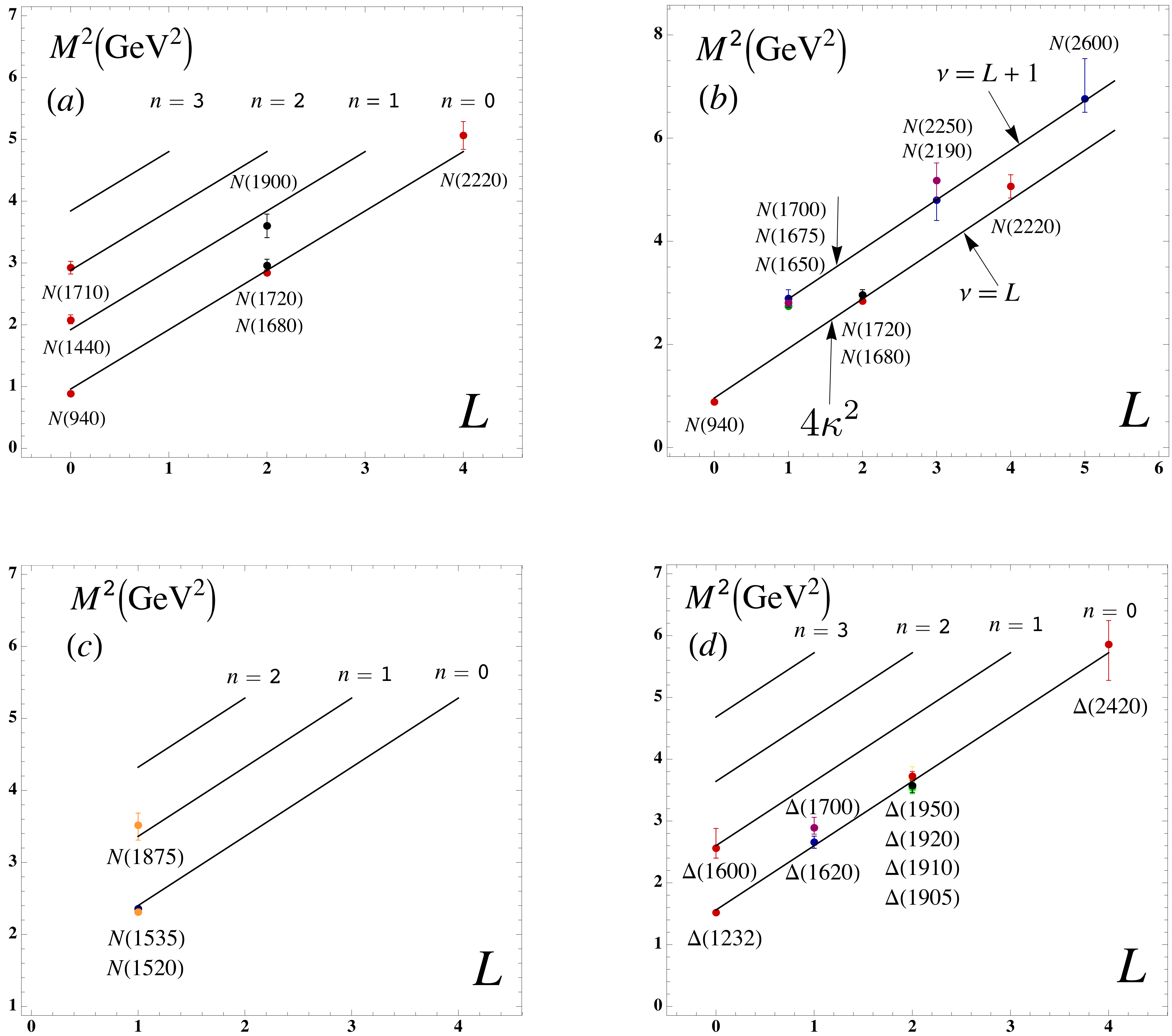
$$\gamma^* p \to \rho^0 p'$$



$$\frac{\sigma_L}{\sigma_T}$$

Prediction from Light-Front Holography

$$\psi_M(x, k_\perp) = \frac{4\pi}{\kappa\sqrt{x(1-x)}} e^{-\frac{k_\perp^2}{2\kappa^2 x(1-x)}}$$



$M^2(\mathrm{GeV}^2)$
(a)
n = 3
n = 2
n = 1
n = 0
N(1900)
N(2220)
N(1710)
N(1440)
N(1720)
N(1680)
N(940)
L
$M^2(\mathrm{GeV}^2)$
(b)
$\nu = L + 1$
N(2600)
N(2250)
N(2190)
N(1700)
N(1675)
N(1650)
N(2220)
$\nu = L$
N(1720)
N(1680)
N(940)
$4\kappa^2$
L
$M^2(\mathrm{GeV}^2)$
(c)
n = 2
n = 1
n = 0
N(1875)
N(1535)
N(1520)
L
$M^2(\mathrm{GeV}^2)$
(d)
n = 3
n = 2
n = 1
n = 0
Δ(2420)
Δ(1700)
Δ(1950)
Δ(1920)
Δ(1910)
Δ(1905)
Δ(1600)
Δ(1620)
Δ(1232)
L

Table 1: $SU(6)$ classification of confirmed baryons listed by the PDG. The labels S, L and n refer to the internal spin, orbital angular momentum and radial quantum number respectively. The $\Delta\frac{5}{2}^-(1930)$ does not fit the $SU(6)$ classification since its mass is too low compared to other members **70**-multiplet for $n = 0$, $L = 3$.

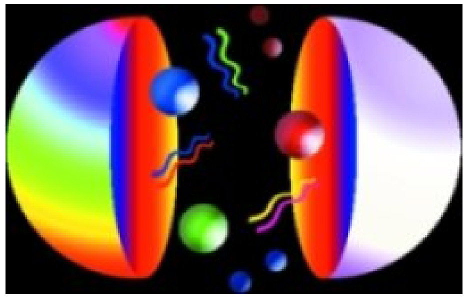
$SU(6)$	S	L	n	Baryon State
56	$\frac{1}{2}$	0	0	$N\frac{1}{2}^+(940)$
	$\frac{1}{2}$	0	1	$N\frac{1}{2}^+(1440)$
	$\frac{1}{2}$	0	2	$N\frac{1}{2}^+(1710)$
	$\frac{3}{2}$	0	0	$\Delta\frac{3}{2}^+(1232)$
	$\frac{3}{2}$	0	1	$\Delta\frac{3}{2}^+(1600)$
70	$\frac{1}{2}$	1	0	$N\frac{1}{2}^-(1535)$ $N\frac{3}{2}^-(1520)$
	$\frac{3}{2}$	1	0	$N\frac{1}{2}^-(1650)$ $N\frac{3}{2}^-(1700)$ $N\frac{5}{2}^-(1675)$
	$\frac{3}{2}$	1	1	$N\frac{1}{2}^-$ $N\frac{3}{2}^-(1875)$ $N\frac{5}{2}^-$
	$\frac{1}{2}$	1	0	$\Delta\frac{1}{2}^-(1620)$ $\Delta\frac{3}{2}^-(1700)$
56	$\frac{1}{2}$	2	0	$N\frac{3}{2}^+(1720)$ $N\frac{5}{2}^+(1680)$
	$\frac{1}{2}$	2	1	$N\frac{3}{2}^+(1900)$ $N\frac{5}{2}^+$
	$\frac{3}{2}$	2	0	$\Delta\frac{1}{2}^+(1910)$ $\Delta\frac{3}{2}^+(1920)$ $\Delta\frac{5}{2}^+(1905)$ $\Delta\frac{7}{2}^+(1950)$
70	$\frac{1}{2}$	3	0	$N\frac{5}{2}^-$ $N\frac{7}{2}^-$
	$\frac{3}{2}$	3	0	$N\frac{3}{2}^-$ $N\frac{5}{2}^-$ $N\frac{7}{2}^-(2190)$ $N\frac{9}{2}^-(2250)$
	$\frac{1}{2}$	3	0	$\Delta\frac{5}{2}^-$ $\Delta\frac{7}{2}^-$
56	$\frac{1}{2}$	4	0	$N\frac{7}{2}^+$ $N\frac{9}{2}^+(2220)$
	$\frac{3}{2}$	4	0	$\Delta\frac{5}{2}^+$ $\Delta\frac{7}{2}^+$ $\Delta\frac{9}{2}^+$ $\Delta\frac{11}{2}^+(2420)$
70	$\frac{1}{2}$	5	0	$N\frac{9}{2}^-$ $N\frac{11}{2}^-$
	$\frac{3}{2}$	5	0	$N\frac{7}{2}^-$ $N\frac{9}{2}^-$ $N\frac{11}{2}^-(2600)$ $N\frac{13}{2}^-$

PDG 2012

Fermionic Modes and Baryon Spectrum

[Hard wall model: GdT and S. J. Brodsky, PRL **94**, 201601 (2005)]

[Soft wall model: GdT and S. J. Brodsky, (2005), arXiv:1001.5193]



From Nick Evans

- Nucleon LF modes

$$\psi_+(\zeta)_{n,L} = \kappa^{2+L}\sqrt{\frac{2n!}{(n+L)!}}\,\zeta^{3/2+L}e^{-\kappa^2\zeta^2/2}L_n^{L+1}\left(\kappa^2\zeta^2\right)$$

$$\psi_-(\zeta)_{n,L} = \kappa^{3+L}\frac{1}{\sqrt{n+L+2}}\sqrt{\frac{2n!}{(n+L)!}}\,\zeta^{5/2+L}e^{-\kappa^2\zeta^2/2}L_n^{L+2}\left(\kappa^2\zeta^2\right)$$

- Normalization

$$\int d\zeta\,\psi_+^2(\zeta) = \int d\zeta\,\psi_-^2(\zeta) = 1$$

Chiral Symmetry of Eigenstate!

- Eigenvalues

$$\mathcal{M}^2_{n,L,S=1/2} = 4\kappa^2\left(n+L+1\right)$$

- "Chiral partners"

$$\frac{\mathcal{M}_{N(1535)}}{\mathcal{M}_{N(940)}} = \sqrt{2}$$

Chiral Features of Soft-Wall AdS/QCD Model

- **Boost Invariant**
- **Trivial LF vacuum! No condensates, but consistent with GMOR**
- **Massless Pion**
- **Hadron Eigenstates (even the pion) have LF Fock components of different L^z**
- **Proton: equal probability** $S^z = +1/2, L^z = 0; S^z = -1/2, L^z = +1$

$$J^z = +1/2 :< L^z >= 1/2, < S_q^z >= 0$$

- **Self-Dual Massive Eigenstates: Proton is its own chiral partner.**
- **Label State by minimum L as in Atomic Physics**
- **Minimum L dominates at short distances**
- **AdS/QCD Dictionary: Match to Interpolating Operator Twist at z=0.**

No mass -degenerate parity partners!

- Compute Dirac proton form factor using SU(6) flavor symmetry

$$F_1^p(Q^2) = R^4 \int \frac{dz}{z^4} V(Q,z) \Psi_+^2(z)$$

- Nucleon AdS wave function

$$\Psi_+(z) = \frac{\kappa^{2+L}}{R^2} \sqrt{\frac{2n!}{(n+L)!}} z^{7/2+L} L_n^{L+1}\left(\kappa^2 z^2\right) e^{-\kappa^2 z^2/2}$$

- Normalization $\quad (F_1{}^p(0) = 1, \quad V(Q=0,z) = 1)$

$$R^4 \int \frac{dz}{z^4} \Psi_+^2(z) = 1$$

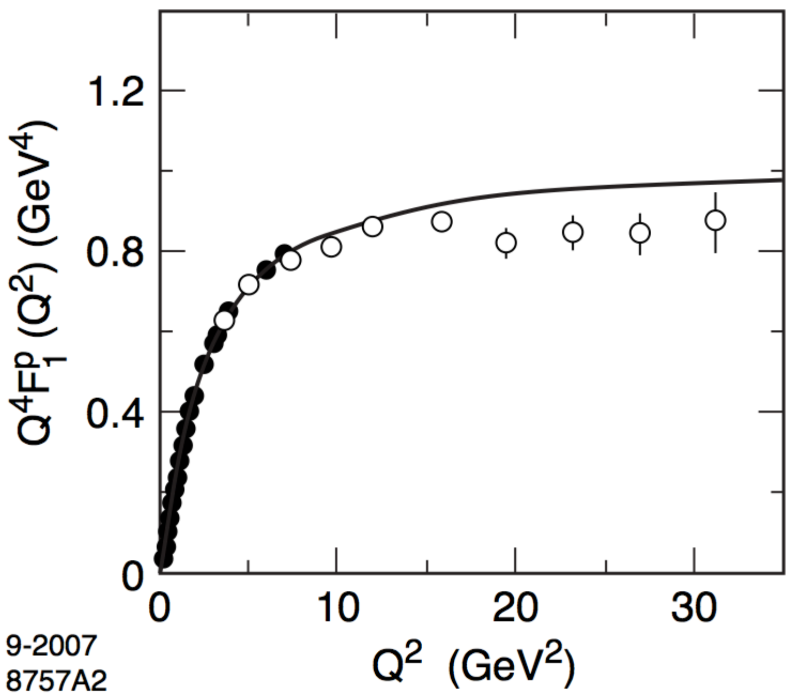
- Bulk-to-boundary propagator [Grigoryan and Radyushkin (2007)]

$$V(Q,z) = \kappa^2 z^2 \int_0^1 \frac{dx}{(1-x)^2} \, x^{\frac{Q^2}{4\kappa^2}} e^{-\kappa^2 z^2 x/(1-x)}$$

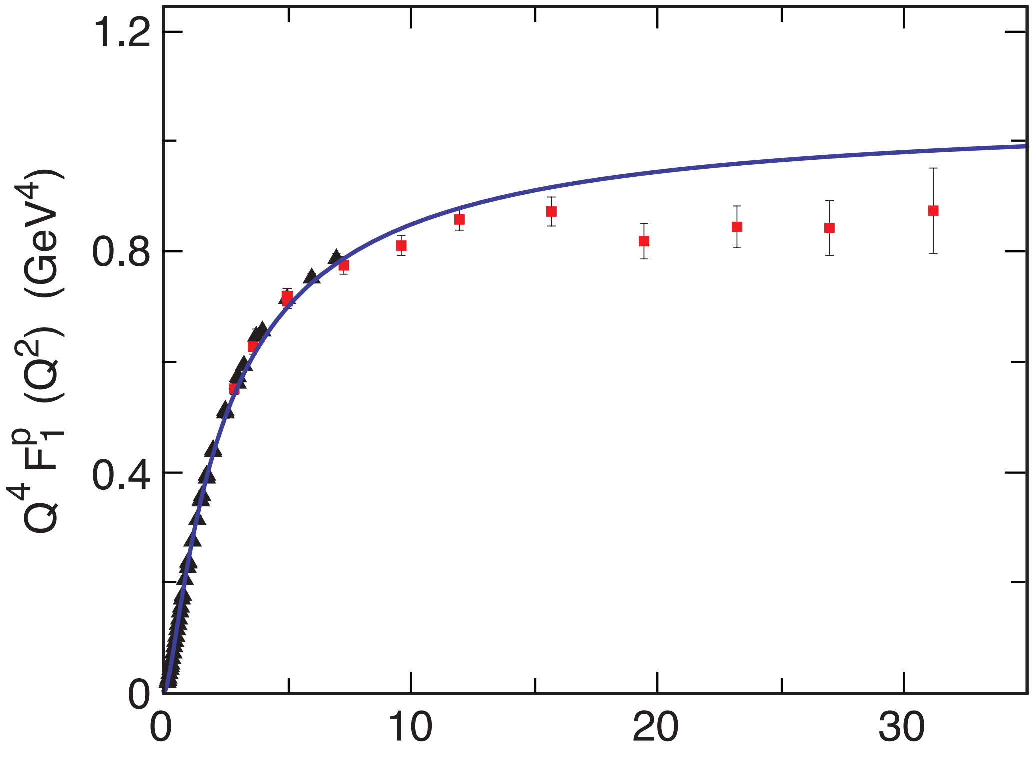
- Find

$$F_1^p(Q^2) = \frac{1}{\left(1 + \frac{Q^2}{\mathcal{M}_\rho^2}\right)\left(1 + \frac{Q^2}{\mathcal{M}_{\rho'}^2}\right)}$$

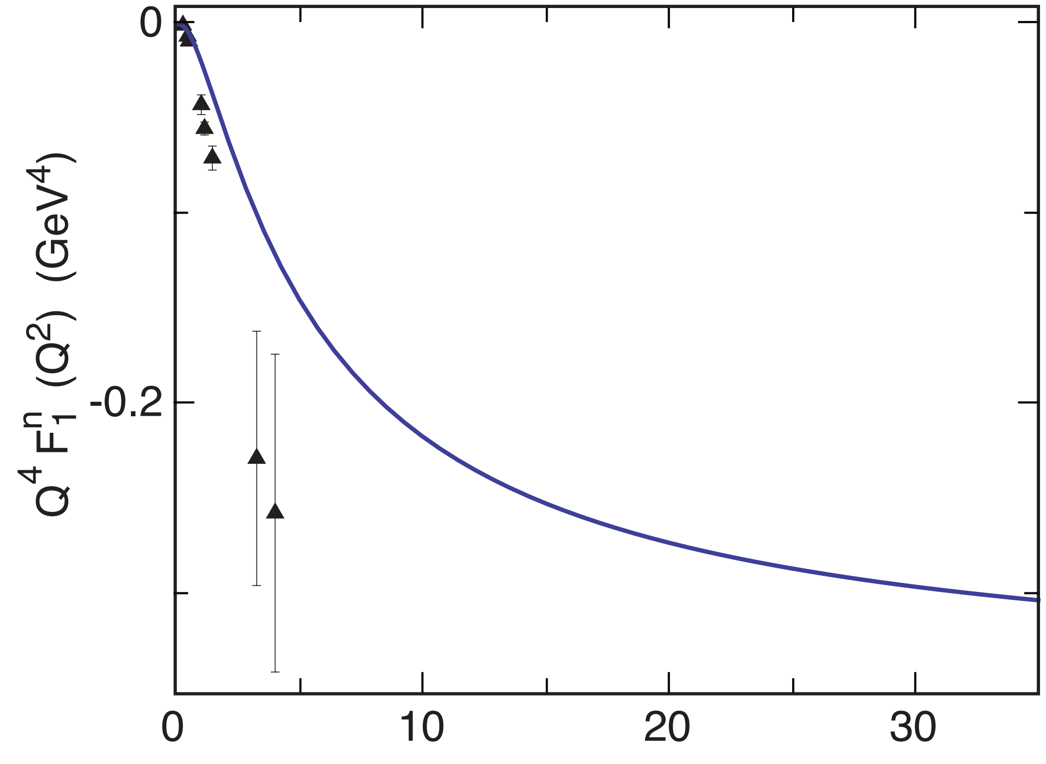
with $\mathcal{M}_{\rho_n}^2 \to 4\kappa^2(n+1/2)$



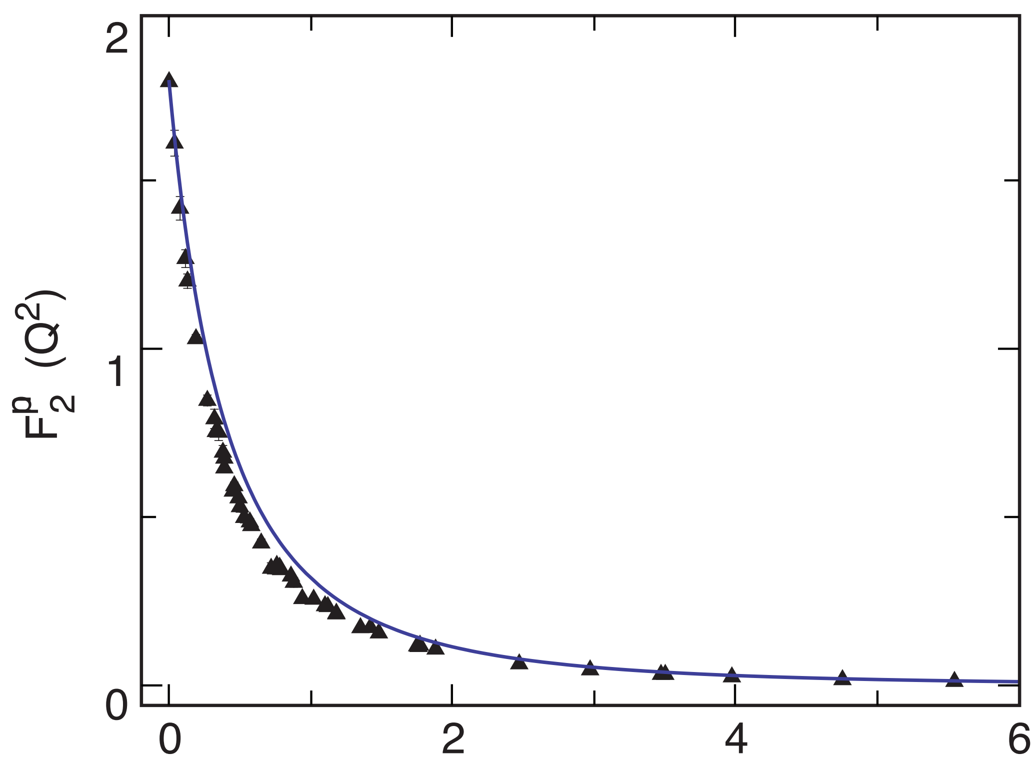
Using $SU(6)$ flavor symmetry and normalization to static quantities



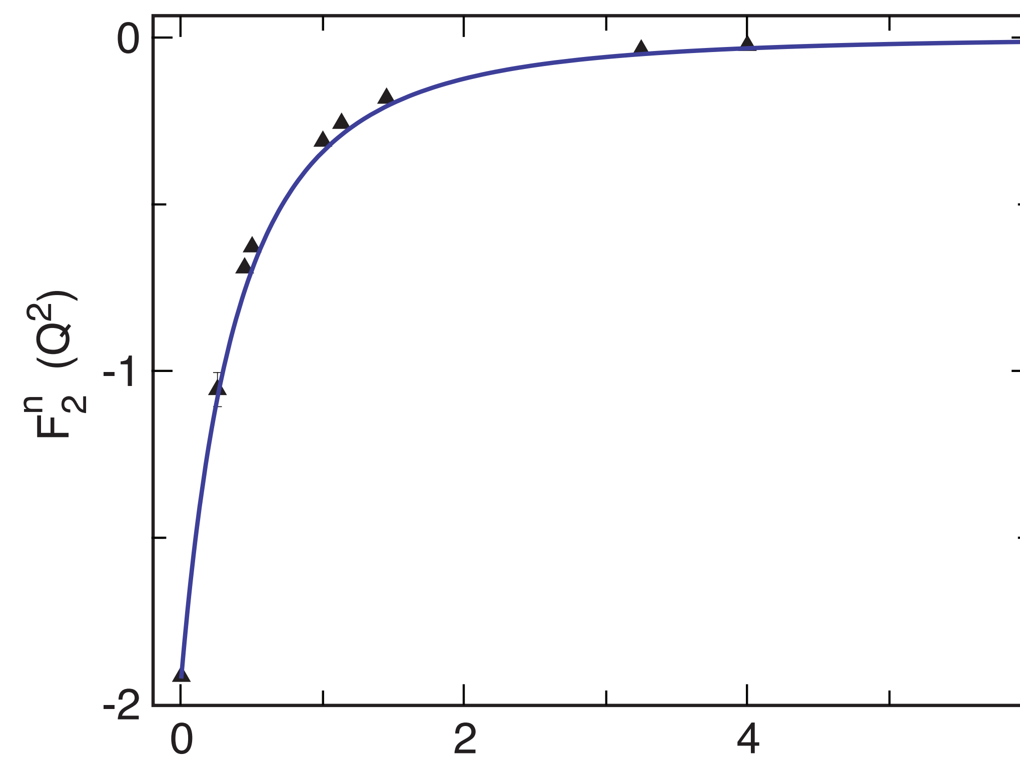
2-2012
8820A18



2-2012
8820A17



2-2012
8820A8



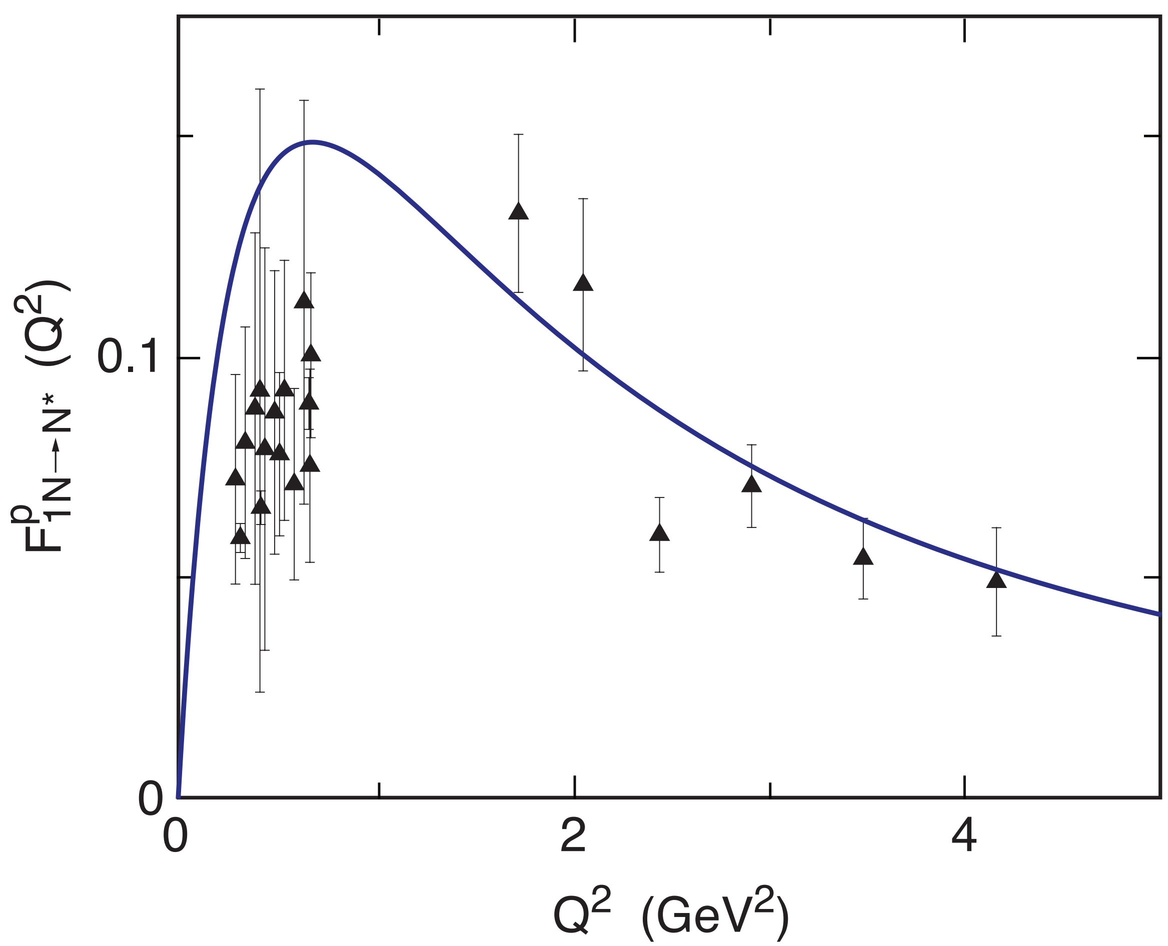
2-2012
8820A7

Nucleon Transition Form Factors

$$F_{1\,N\to N^*}^{p}(Q^2) = \frac{\sqrt{2}}{3} \frac{\frac{Q^2}{\mathcal{M}_\rho^2}}{\left(1+\frac{Q^2}{\mathcal{M}_\rho^2}\right)\left(1+\frac{Q^2}{\mathcal{M}_{\rho'}^2}\right)\left(1+\frac{Q^2}{\mathcal{M}_{\rho''}^2}\right)}.$$

AdS\QCD
Light-Front
Holography

G. de Teramond, sjb



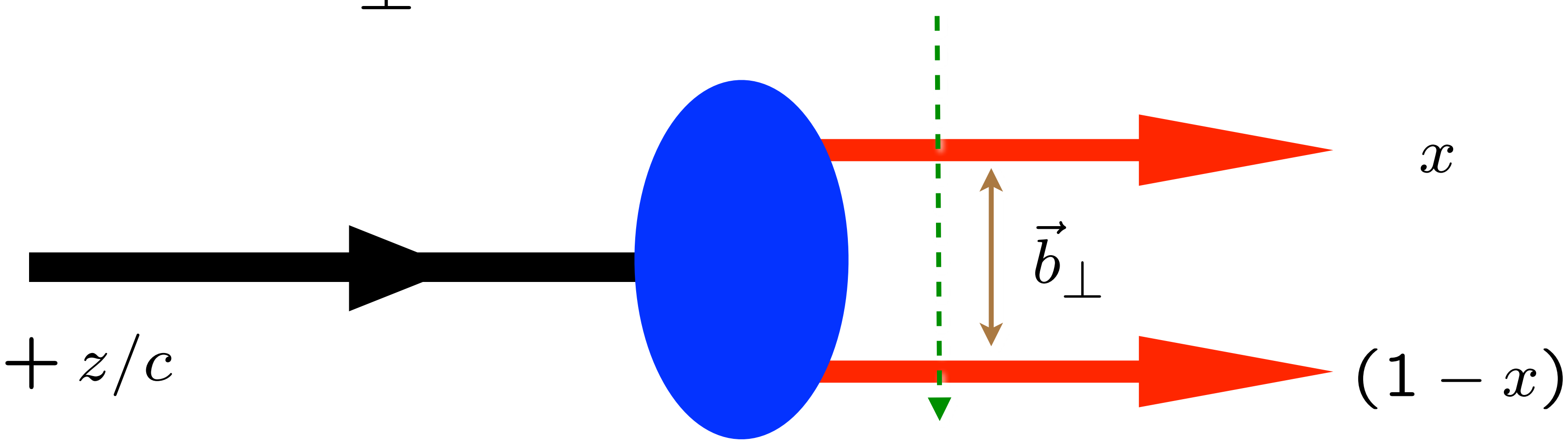
Proton transition form factor to the first radial excited state. Data from JLab

de Tèramond, Dosch, sjb

$LF(3+1) \longleftrightarrow AdS_5$

$$\psi(x, \vec{b}_\perp) \longleftrightarrow \phi(z)$$

$$\zeta = \sqrt{x(1-x)\vec{b}_\perp^2} \longleftrightarrow z$$



Fixed $\tau = t + z/c$

$$\psi(x,\zeta) = \sqrt{x(1-x)}\zeta^{-1/2}\phi(\zeta)$$

$$(\mu R)^2 = L^2 - (J-2)^2$$

Light-Front Holography: *Unique mapping derived from equality of LF and AdS formula for EM and gravitational current matrix elements and identical equations of motion*

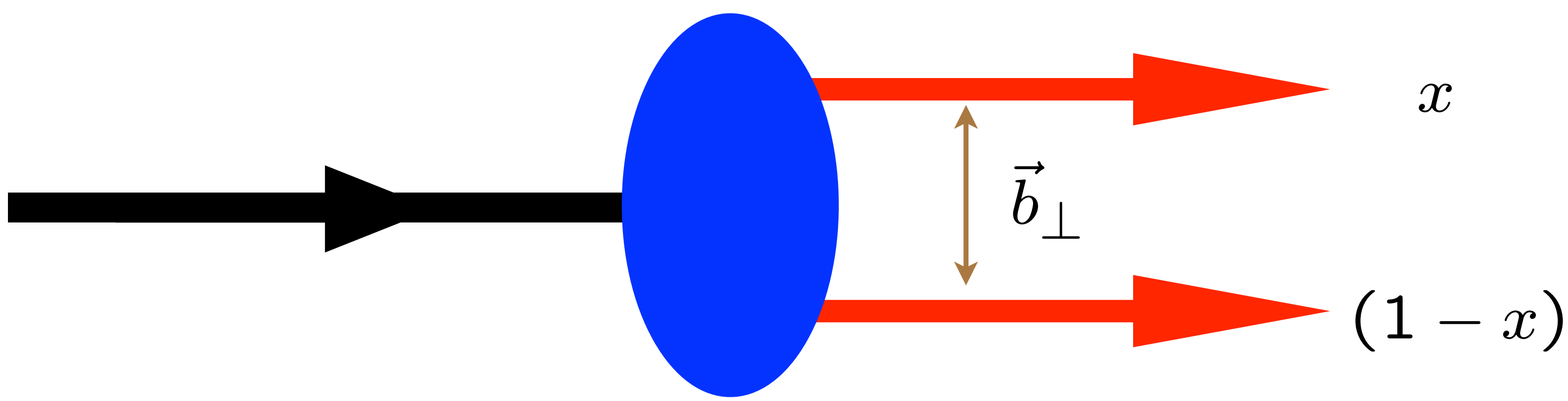
Light-Front Holography: Map AdS/CFT to 3+1 LF Theory

Relativistic LF radial equation

Frame Independent

$$\left[-\frac{d^2}{d\zeta^2}+\frac{1-4L^2}{4\zeta^2}+U(\zeta)\right]\psi(\zeta)=\mathcal{M}^2\psi(\zeta)$$

$$\zeta^2 = x(1-x)\mathbf{b}^2_\perp .$$



$$U(\zeta)=\kappa^4\zeta^2+2\kappa^2(L+S-1)$$

soft wall confining potential:

G. de Teramond, G. Dosch, sjb

LF Holography

Baryon Equation

Superconformal Algebra

$$\Big(- \partial_\zeta^2 + \kappa^4 \zeta^2 + 2\kappa^2 (L_B + 1) + \frac{4L_B^2 - 1}{4\zeta^2} \Big) \psi_J^+ = M^2 \psi_J^+$$

$$\Big(- \partial_\zeta^2 + \kappa^4 \zeta^2 + 2\kappa^2 L_B + \frac{4(L_B + 1)^2 - 1}{4\zeta^2} \Big) \psi_J^- = M^2 \psi_J^-$$

$$M^2(n, L_B) = 4\kappa^2 (n + L_B + 1)$$

S=1/2, P=+

both chiralities

Meson Equation

$$\Big(- \partial_\zeta^2 + \kappa^4 \zeta^2 + 2\kappa^2 (J - 1) + \frac{4L_M^2 - 1}{4\zeta^2} \Big) \phi_J = M^2 \phi_J$$

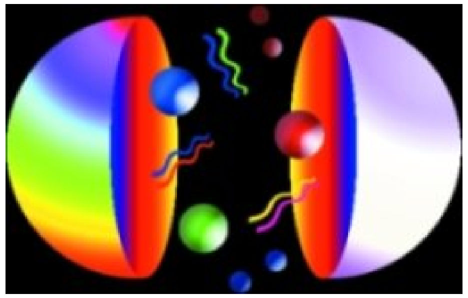
$$M^2(n, L_M) = 4\kappa^2 (n + L_M)$$

Same κ !

S=0, I=1 Meson is superpartner of S=1/2, I=1 Baryon

Meson-Baryon Degeneracy for $L_M = L_B + 1$

Fermionic Modes and Baryon Spectrum



From Nick Evans

- Nucleon LF modes

$$\psi_+(\zeta)_{n,L} = \kappa^{2+L}\sqrt{\frac{2n!}{(n+L)!}}\zeta^{3/2+L}e^{-\kappa^2\zeta^2/2}L_n^{L+1}\left(\kappa^2\zeta^2\right)$$

$$\psi_-(\zeta)_{n,L} = \kappa^{3+L}\frac{1}{\sqrt{n+L+2}}\sqrt{\frac{2n!}{(n+L)!}}\zeta^{5/2+L}e^{-\kappa^2\zeta^2/2}L_n^{L+2}\left(\kappa^2\zeta^2\right)$$

- Normalization

$$\int d\zeta\, \psi_+^2(\zeta) = \int d\zeta\, \psi_-^2(\zeta) = 1$$

Chiral Symmetry of Eigenstate!

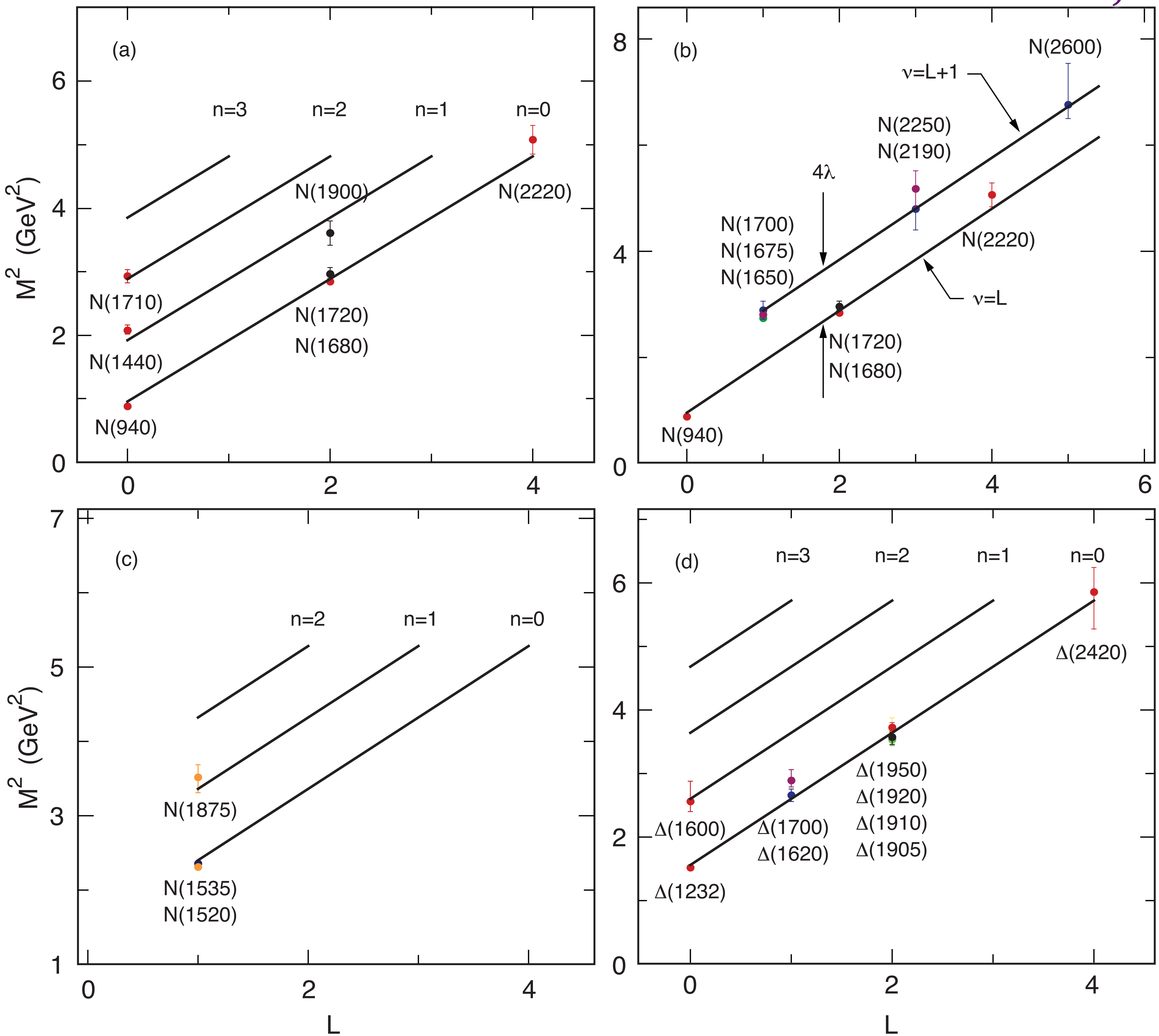
- Eigenvalues

$$\mathcal{M}^2_{n,L,S=1/2} = 4\kappa^2\left(n+L+1\right)$$

- "Chiral partners"

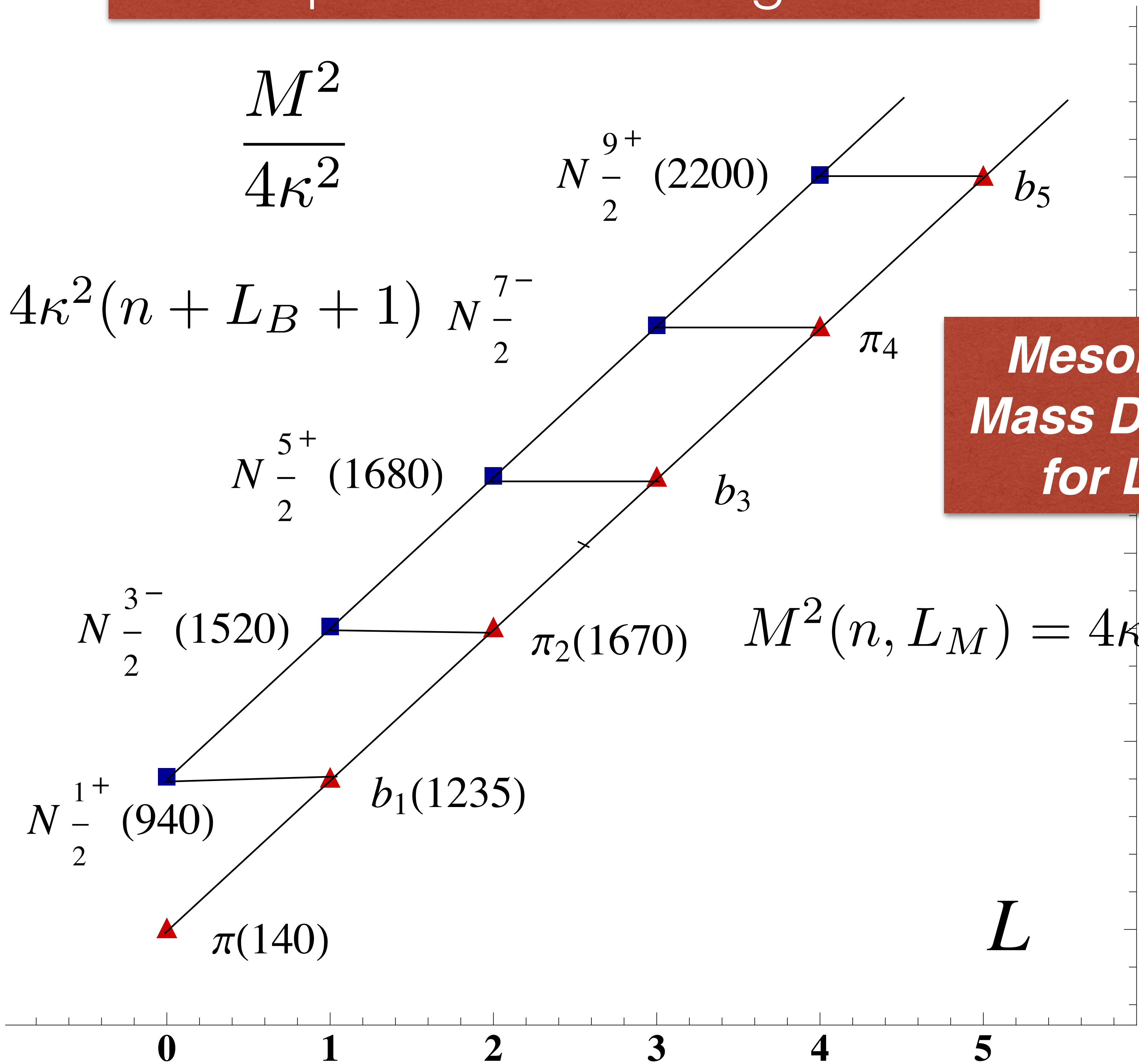
$$\frac{\mathcal{M}_{N(1535)}}{\mathcal{M}_{N(940)}} = \sqrt{2}$$

de Tèramond, Dosch, sjb



Baryon orbital and radial excitations for
$\kappa = 0.49$ GeV (nucleons) and 0.51 GeV (Deltas)

Superconformal Algebra



$$M^2(n, L_B) = 4\kappa^2(n + L_B + 1)$$

$$M^2(n, L_M) = 4\kappa^2(n + L_M)$$

Meson-Baryon Mass Degeneracy for $L_M = L_B + 1$

Same κ

$$\lambda = \kappa^2$$

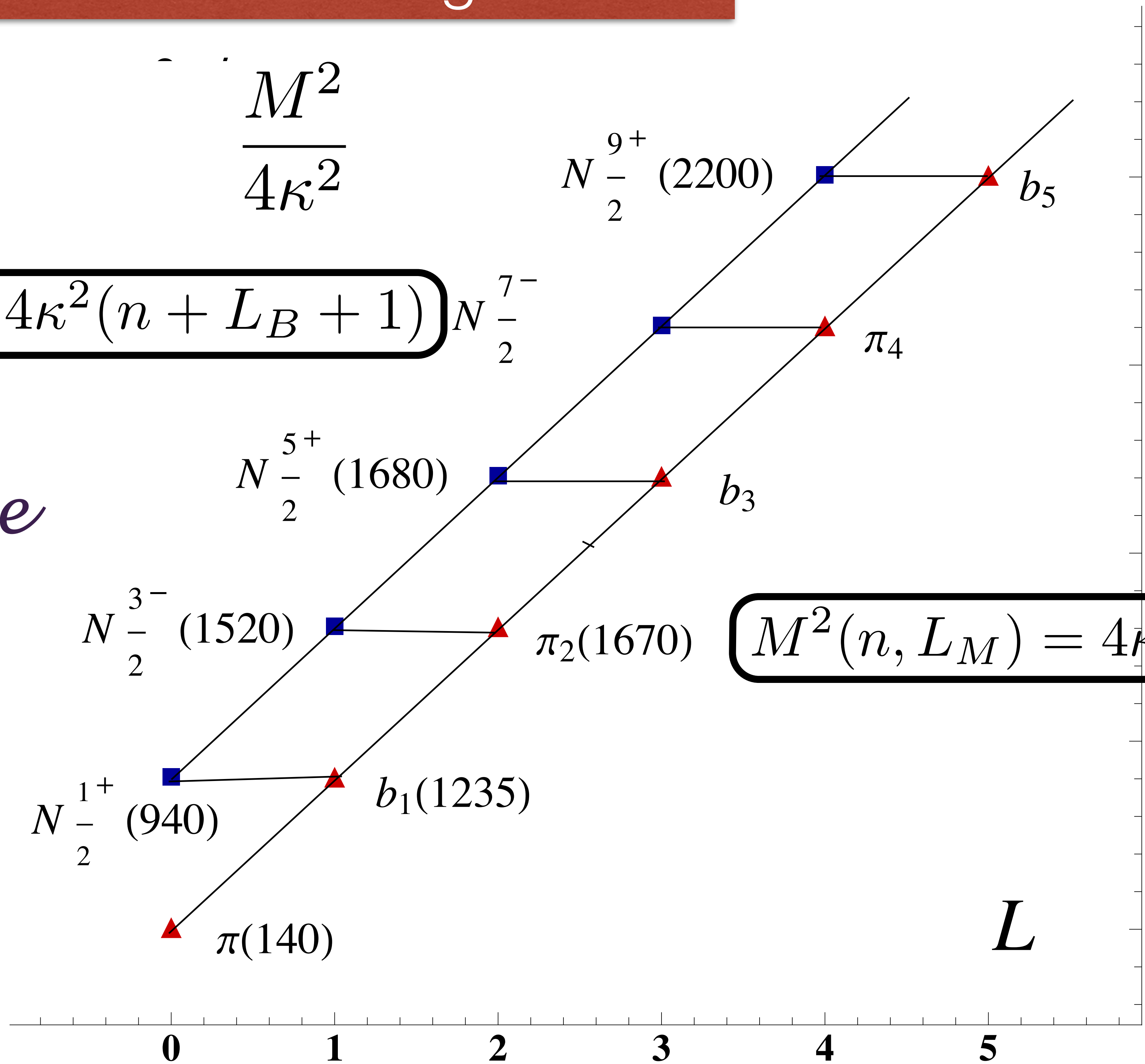
S=0, I=1 Meson is superpartner of S=1/2, I=1/2 Baryon

Superconformal Algebra

de Tèramond, Dosch, sjb

$$M^2(n, L_B) = 4\kappa^2(n + L_B + 1)$$

Same slope

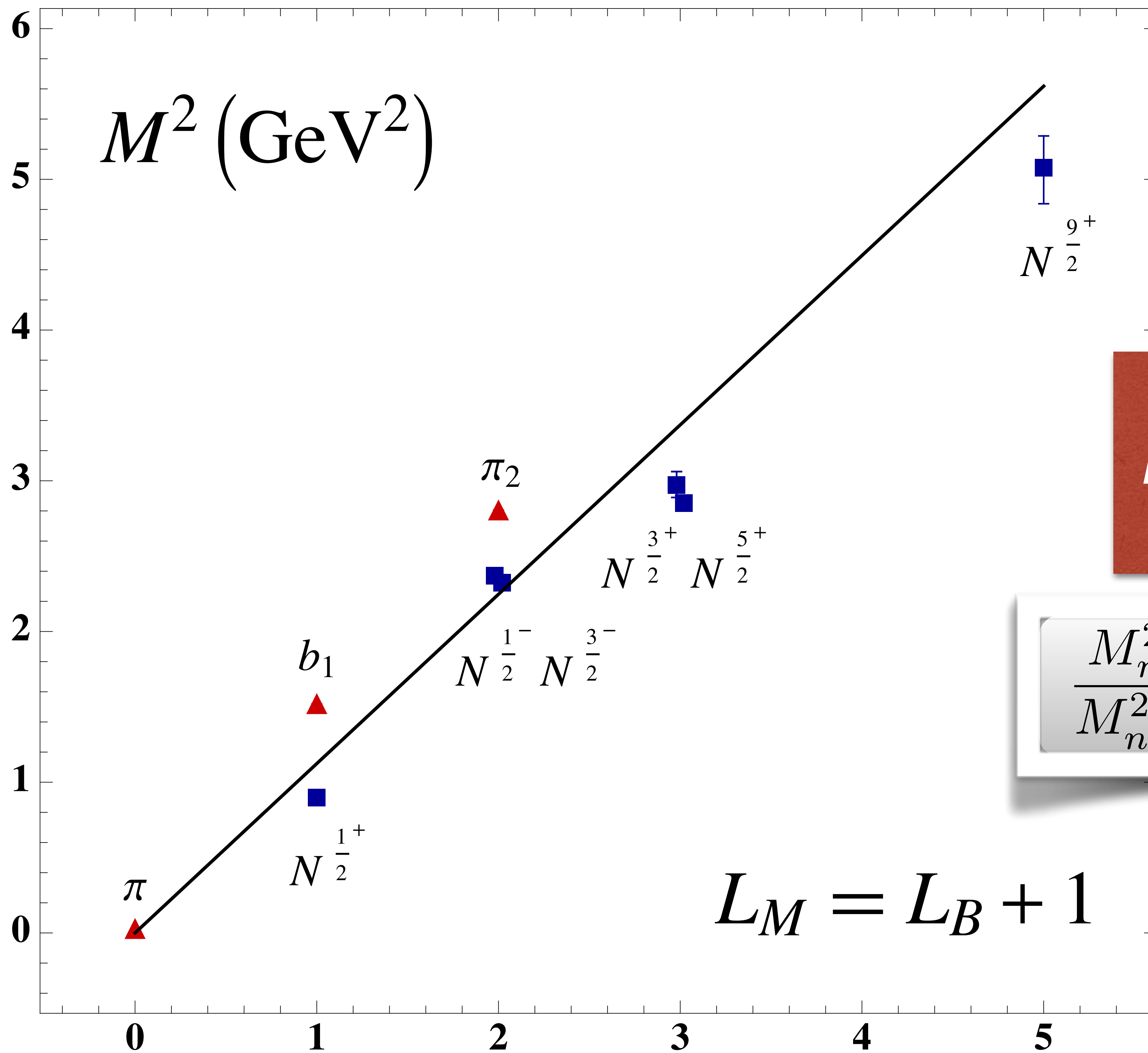


$$M^2(n, L_M) = 4\kappa^2(n + L_M)$$

$$\frac{M^2_{meson}}{M^2_{nucleon}} = \frac{n + L_M}{n + L_B + 1}$$

Meson-Baryon Mass Degeneracy for $L_M = L_B + 1$

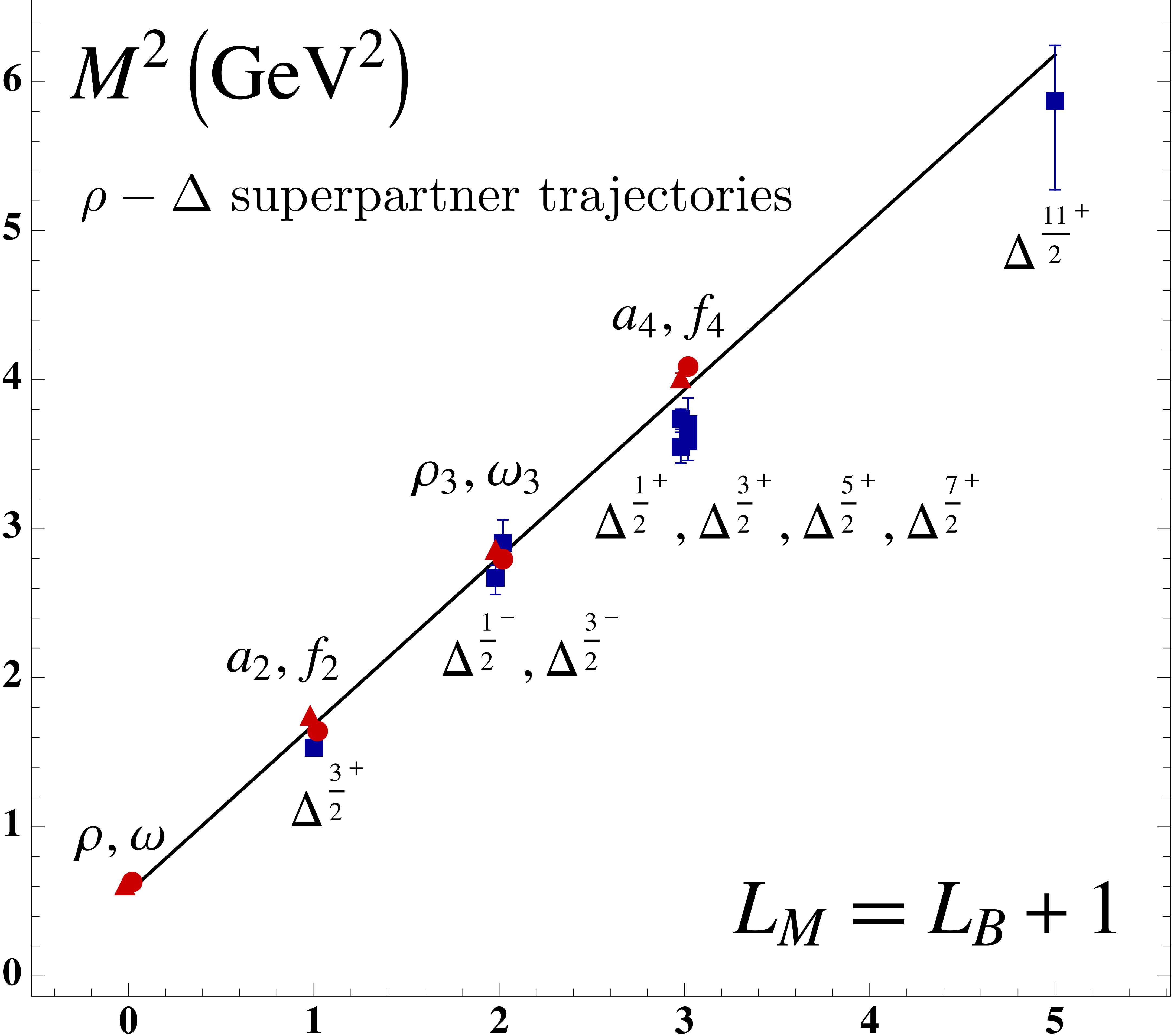
Superconformal AdS Light-Front Holographic QCD (LFHQCD): Identical meson and baryon spectra!



Meson-Baryon Mass Degeneracy for $L_M = L_B + 1$

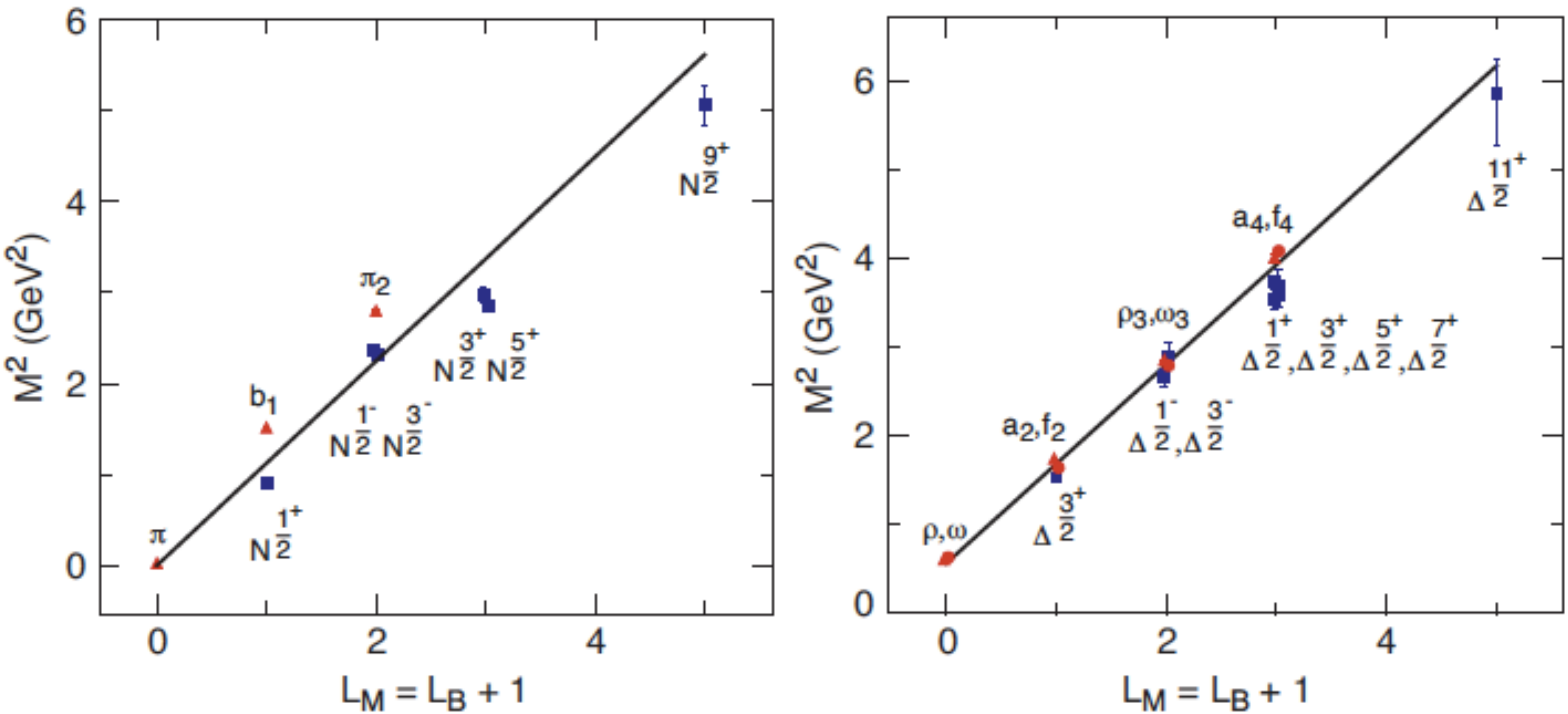
$$\frac{M^2_{meson}}{M^2_{nucleon}} = \frac{n + L_M}{n + L_B + 1}$$

S=0, I=1 Meson is superpartner of S=1/2, I=1/2 Baryon



Dosch, de Teramond, sjb

de Tèramond, Dosch, sjb



Superconformal Meson-Nucleon Partners

$$\kappa = 530 \text{ MeV}$$

Chiral Features of Soft-Wall AdS/QCD Model

- **Boost Invariant**
- **Trivial LF vacuum! No condensate, but consistent with GMOR**
- **Massless Pion**
- **Hadron Eigenstates (even the pion) have LF Fock components of different L^z**
- **Proton: equal probability** $S^z = +1/2, L^z = 0; S^z = -1/2, L^z = +1$

$$J^z = +1/2 : < L^z >= 1/2, < S_q^z >= 0$$

- **Self-Dual Massive Eigenstates: Proton is its own chiral partner.**
- **Label State by minimum L as in Atomic Physics**
- **Minimum L dominates at short distances**
- **AdS/QCD Dictionary: Match to Interpolating Operator Twist at z=0.**

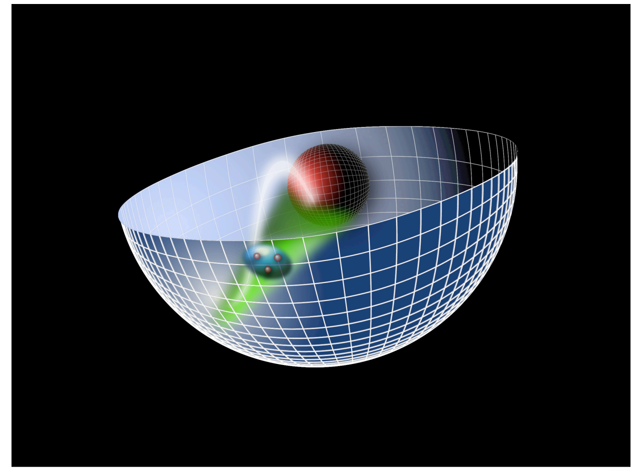
No mass -degenerate parity partners!

de Tèramond, Dosch, sjb

Interpretation of Mass Scale κ

- Does not affect conformal symmetry of QCD action
- Self-consistent regularization of IR divergences
- Determines all mass and length scales for zero quark mass
- Compute scheme-dependent $\Lambda_{\overline{MS}}$ determined in terms of κ
- Value of κ itself not determined -- place holder
- Need external constraint such as f_π

de Teramond, Dosch, sjb



AdS/QCD
Soft-Wall Model

Light-Front Holography

Semi-Classical Approximation to QCD

Relativistic, frame-independent
Unique color-confining potential
Zero mass pion for massless quarks
Regge trajectories with equal slopes in n and L
Light-Front Wavefunctions

Conformal Symmetry of the action

Light-Front Schrödinger Equation

NATIONAL ACCELERATOR LABORATORY

de Tèramond, Dosch, Lorce, sjb

Future Directions for AdS/QCD

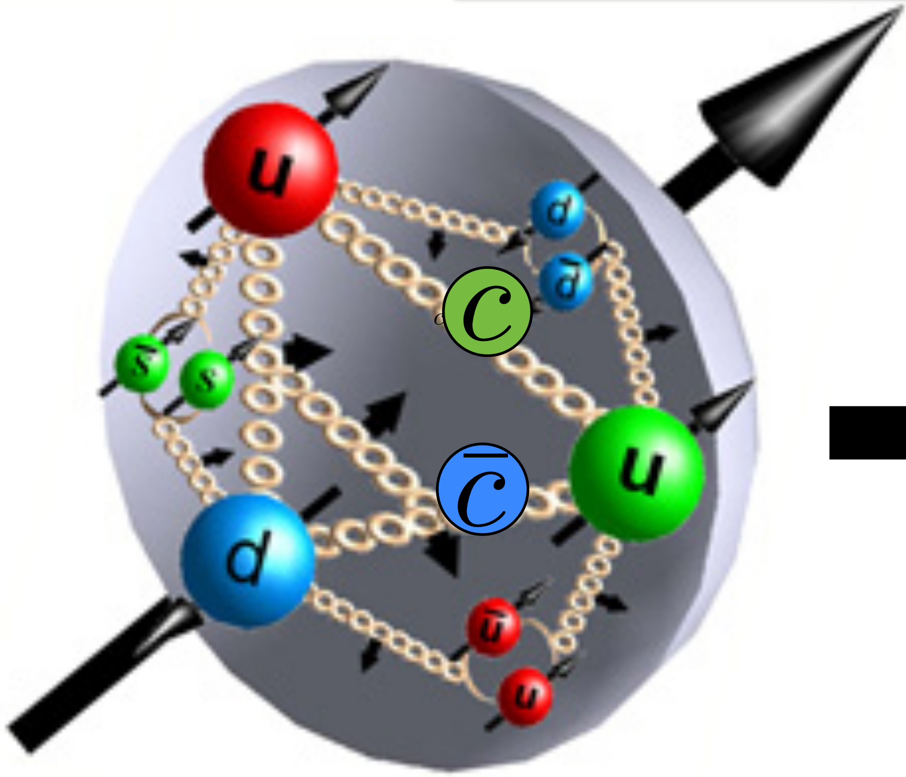
- **Hadronization at the Amplitude Level**
- **Diffractive dissociation of pion and proton to jets**
- **Identify the factorization Scale for ERBL, DGLAP evolution: Q_o**
- **Compute Tetraquark Spectroscopy Sequentially**
- **Update SU(6) spin-flavor symmetry**
- **Heavy Quark States: Supersymmetry, not conformal**
- **Compute higher Fock states; e.g. Intrinsic Heavy Quarks**
- **Nuclear States — Hidden Color**
- **Basis LF Quantization**

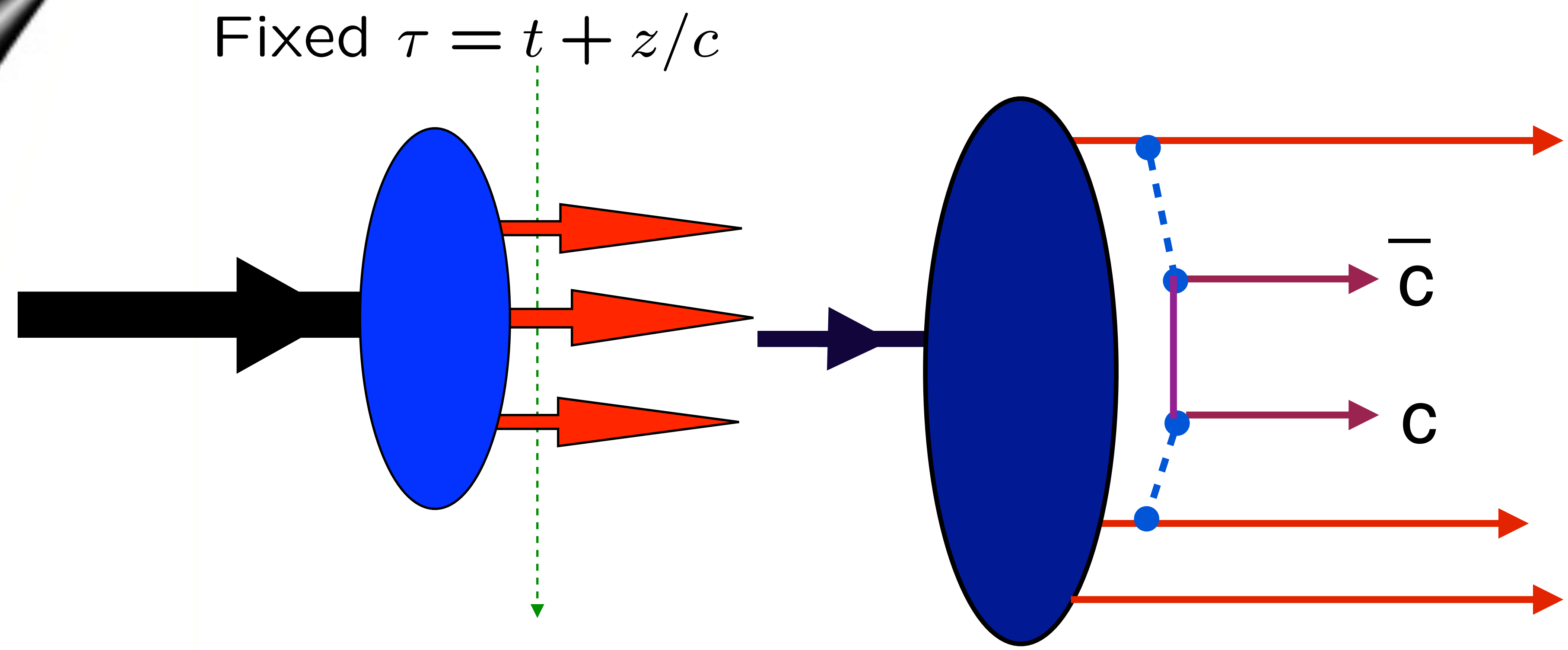
Vary, sjb, et al

Novel QCD Physics

- **Collisions of Flux Tubes and the Ridge**
- **Factorization-Breaking Lensing Corrections**
- **Digluon initiated subprocesses and anomalous nuclear dependence of quarkonium production**
- **Higgs Production at high x_F from Intrinsic Heavy Quarks**
- **Direct, color-transparent hard subprocesses and the baryon anomaly**
- **PMC eliminates renormalization scale ambiguity order by order; increased top/anti-top asymmetry; scheme independent**
- **Light-Front Schrödinger Equation: New approach to confinement, origin of QCD mass scale**

Intrinsic Heavy Quarks and other Novel QCD Phenomena





INSTITUTE FOR NUCLEAR THEORY

Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

Intersections of BSM Phenomenology and QCD for New Physics Searches (INT-15-3)

October 20, 2015, INT, University of Washington