TOWARDS TRANSVERSE MOMENTUM DEPENDENCE IN DISTRIBUTIONS AND FRAGMENTATION

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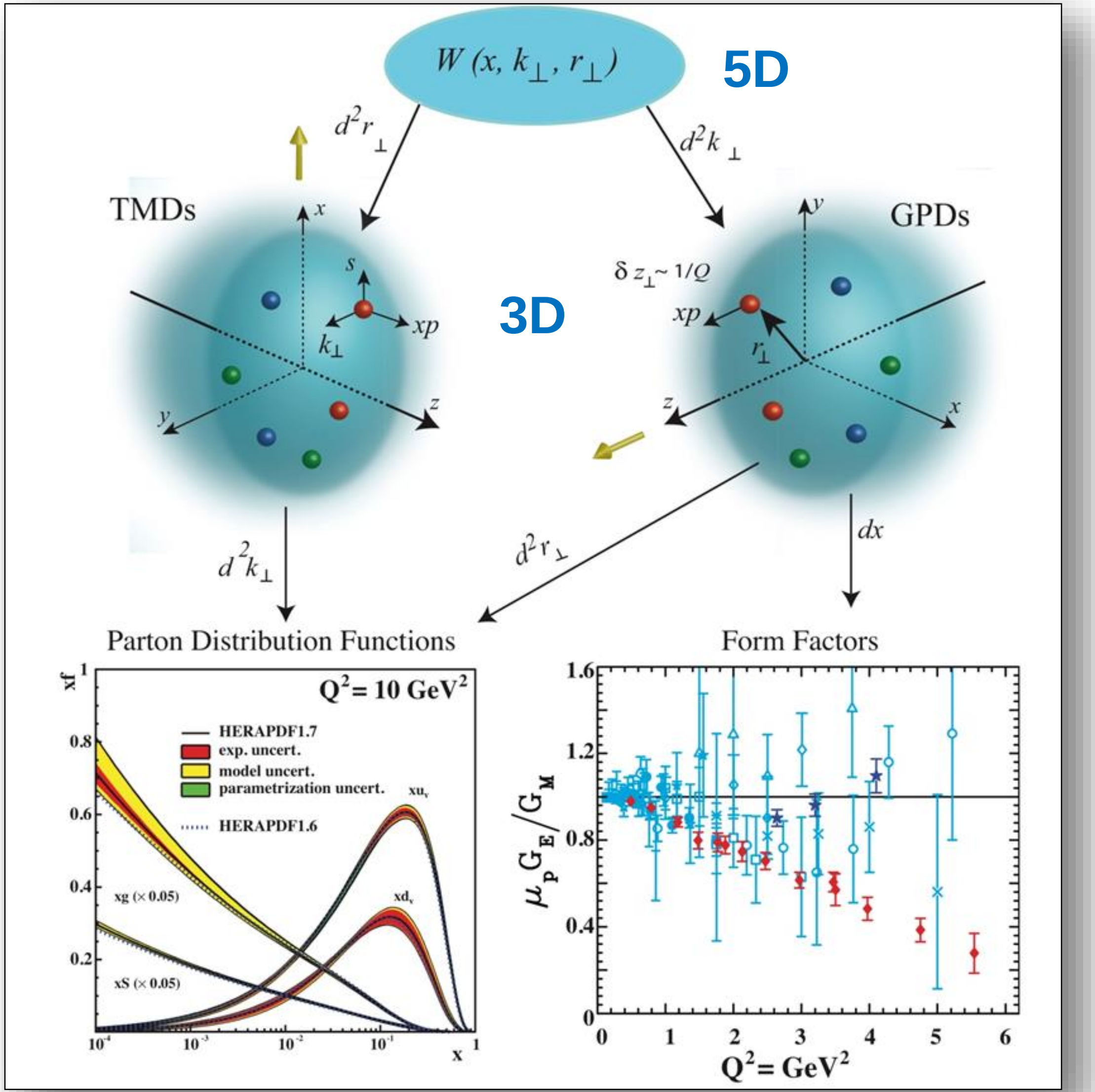
Jefferson Lab

INT-17-3, Spatial and Momentum Tomography of Hadrons and Nuclei, Seattle, Washington, August 31, 2017

Outline

- New 3D Paradigm for Nucleon Structure
- Semi-Inclusive Deep Inelastic Scattering and TMDs
- Transverse Momentum Dependence: 3D Distributions
  - validate basic reaction mechanism of SIDIS at “our” energies
  - spin and flavor dependence of quark transverse momentum distributions
- Transverse Momentum Dependence: 3D Fragmentation
  - The emergence of hadrons
    - Lessons from the 70’s
    - To disembroil the Lund string
  - Towards a QM description of the final state
    - Balancing the transverse momentum – candles of space-time
    - The Collins Function – candle of DχSB
    - Balancing the spin
    - Creating polarization from nothing
- Summary

New Paradigm for Nucleon Structure



- ◆ TMDs
  - – Confined motion in a nucleon (semi-inclusive DIS)
- ◆ GPDs
  - – Spatial imaging (exclusive DIS)
- ◆ Requires
  - − High luminosity
  - − Polarized beams and targets

Major new capability with JLab12

JLab: 21st Century Science Questions

- What is the role of gluonic excitations in the spectroscopy of light mesons? Can these excitations elucidate the origin of quark confinement?

- Where is the missing spin in the nucleon? Is there a significant contribution from valence quark orbital angular momentum?

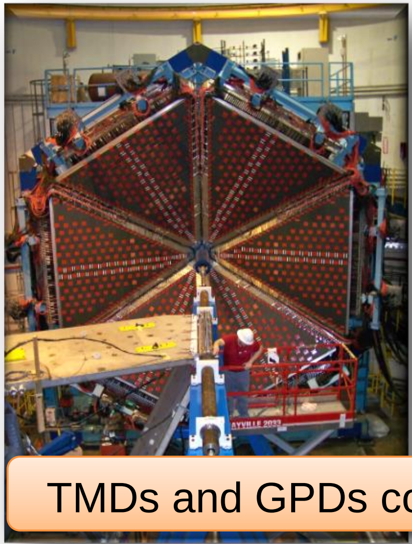
- Can we reveal a novel landscape of nucleon substructure through measurements of new multidimensional distribution functions?

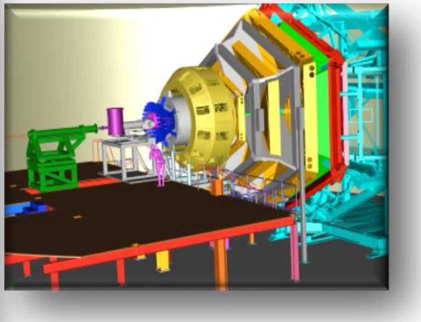
- What is the relation between short-range N-N correlations, the partonic structure of nuclei, and the nature of the nuclear force?

- Can we discover evidence for physics beyond the standard model of particle physics?

12 GeV (GPD/TMD) Scientific Capabilities

Hall B **– understanding nucleon structure via generalized parton distributions**

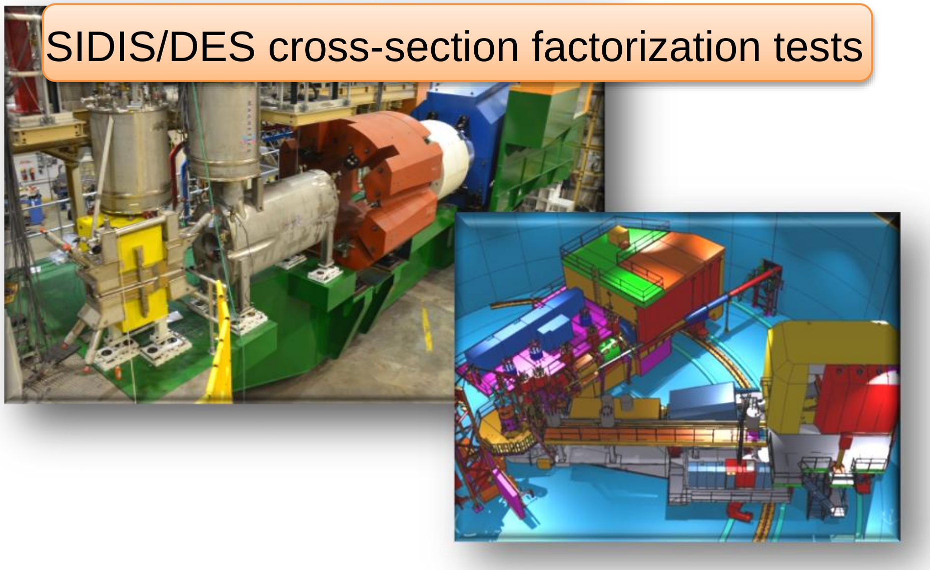




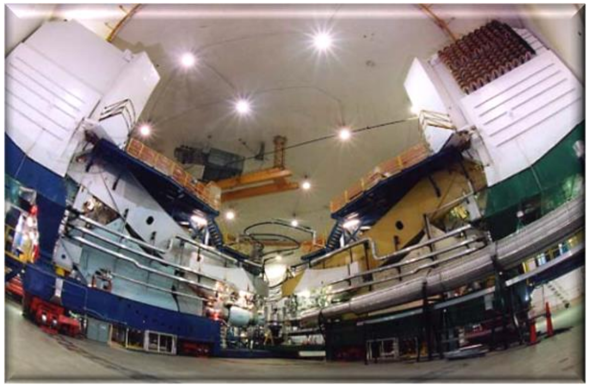
TMDs and GPDs comprehensive study

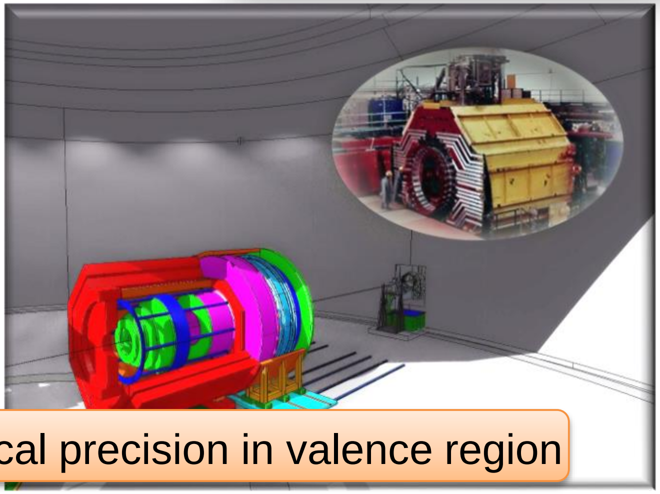
Hall C **– precision determination of valence quark properties in nucleons/nuclei**

SIDIS/DES cross-section factorization tests



Hall A **– polarized 3He, future new experiments (e.g., SBS, MOLLER and SoLID)**





Ultimate TMD statistical precision in valence region

12 GeV Approved Experiments by Physics Topics

Topic	Hall A	Hall B	Hall C	Hall D	Other	Total
The Hadron spectra as probes of QCD	0	3	1	3	0	**7**
The transverse structure of the hadrons	6	4	3	1	0	**14**
The longitudinal structure of the hadrons	2	3	6	0	0	**11**
The 3D structure of the hadrons	5	9	6	0	0	**20**
Hadrons and cold nuclear matter	8	4	7	0	1	**20**
Low-energy tests of the Standard Model and Fundamental Symmetries	3	1	0	1	1	**6**
Total	**24**	**24**	**23**	**5**	**2**	**78**
Total Experiments Completed	**2.5**	**1.1**	**0**	**0.4**	**0**	**4.0**
Total Experiments Remaining	**21.5**	**22.9**	**23.0**	**4.6**	**2.0**	**74.0**

1D-3D nucleon structure science in Hall B (CLAS12 + ancillary equipment), Hall C (HMS, SHMS, NPS) and Hall A (SBS + SoLID)

12 GeV Approved Experiments by PAC Days

Topic	Hall A	Hall B	Hall C	Hall D	Other	Total
The Hadron spectra as probes of QCD	0	319	11	540	0	**870**
The transverse structure of the hadrons	150.5	185	110	25	0	**470.5**
The longitudinal structure of the hadrons	65	230	165	0	0	**460**
The 3D structure of the hadrons	409	872	197	0	0	**1478**
Hadrons and cold nuclear matter	220	230	205	0	14	**669**
Low-energy tests of the Standard Model and Fundamental Symmetries	547	180	0	79	60	**866**
Total Days	**1392**	**2016**	**688**	**644**	**74**	**4813.5**
Total Days - Without MIE Days	**574**	**2016**	**688**	**644**	**28**	**3950**
Total Approved Run Group Days (includes MIE)	**1392**	**981**	**645**	**444**	**74**	**3536**
Total Approved Run Group Days (without MIE)	**573.5**	**981**	**645**	**444**	**28**	**2672**
Total Days Completed	**83**	**30**	**0**	**48**	**0**	**161**
Total Days Remaining	**491**	**951**	**645**	**396**	**28**	**2511**

1D-3D nucleon structure = half of approved 12-GeV science program

Exploring the 3D Nucleon Structure

- After decades of study of the partonic structure of the nucleon we finally have the experimental and theoretical tools to systematically move beyond a 1D momentum fraction (x_{Bj}) picture of the nucleon.
    - High luminosity, large acceptance experiments with polarized beams and targets.
    - Theoretical description of the nucleon in terms of a 5D Wigner distribution that can be used to encode both 3D momentum and transverse spatial distributions.

- Deep Exclusive Scattering (DES) cross sections give sensitivity to electron-quark scattering off quarks with longitudinal momentum fraction (Bjorken) x at a transverse location b.

- Semi-Inclusive Deep Inelastic Scattering (SIDIS) cross sections depend on transverse momentum of hadron, $P_{h\perp}$, but this arises from both intrinsic transverse momentum (k_T) of a parton and transverse momentum (p_T) created during the [parton → hadron] fragmentation process.

Generalized Parton Distributions

(Quantum phase-space quark distribution in the nucleon)

5D

$$W_\Gamma(\mathbf{r},k) = \frac{1}{2M_N}\int \frac{d^3\mathbf{q}}{(2\pi)^3} e^{-i\mathbf{q}\cdot\mathbf{r}} \left\langle \mathbf{q}/2 \left| \hat{W}_\Gamma(0,k) \right| -\mathbf{q}/2 \right\rangle \ ,$$

$$W_\Gamma(\mathbf{r},\mathbf{k}) = \int \frac{dk^-}{(2\pi)^2} W_\Gamma(\mathbf{r},k)$$

Integrate over transverse ***momentum*** space

Generalized Parton Distributions (GPD) ***H***, ***$\tilde{H}$***, ***E***, ***$\tilde{E}$***

3D

3D nucleon imaging in transverse coordinate and longitudinal momentum space

Polarized DVCS directly probes GPDs

Nucleon polarization		Sensitivity to GPD
	UP	***H***, ***$\tilde{H}$***, ***E***
	LP	***$\tilde{H}$***, ***H***, ***E***
	TP	***E***, ***H***

DVMP is required for flavor separation

Transverse Momentum Structure of Nucleon – TMDs

(Quantum phase-space quark distribution in the nucleon)

5D

$$W_\Gamma(\mathbf{r},k) = \frac{1}{2M_N}\int \frac{d^3\mathbf{q}}{(2\pi)^3} \mathrm{e}^{-i\mathbf{q}\cdot\mathbf{r}} \left\langle \mathbf{q}/2 \left| \hat{\mathcal{W}}_\Gamma(0,k) \right| -\mathbf{q}/2 \right\rangle$$

$$\boxed{W_\Gamma(\mathbf{r},\mathbf{k}) = \int \frac{dk^-}{(2\pi)^2} W_\Gamma(\mathbf{r},k)}$$

Integrate over ***spatial*** dimensions

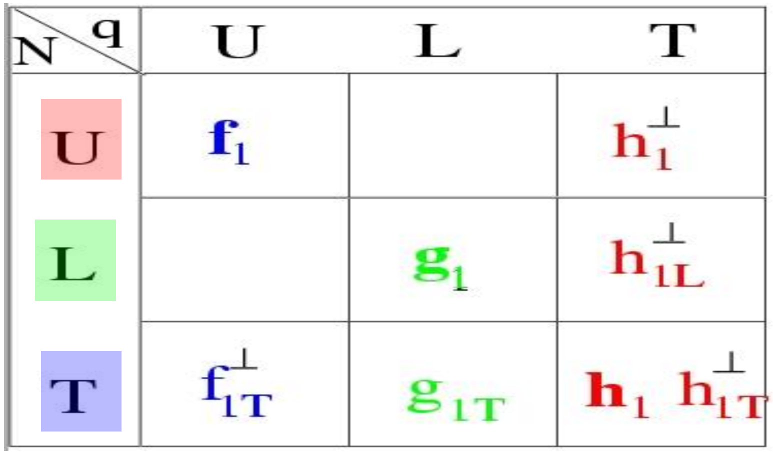
Transverse Momentum-dependent Distributions (TMD)

3D

3D imaging of the nucleon in momentum space

Quark spin polarization

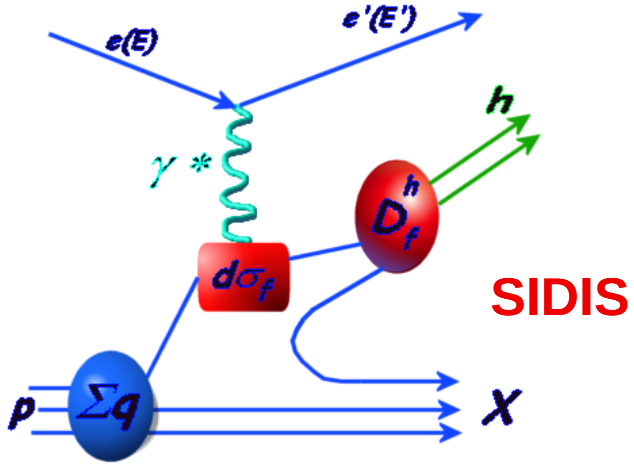
Nucleon polarization



N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

JLab has planned a complete SIDIS program with π/K to access quark TMDs

SIDIS – Flavor Decomposition



DIS probes only the sum of quarks and anti-quarks → requires assumptions on the role of sea quarks $\sum e_q^2(q+\bar{q})$

Solution: Detect a final state hadron in addition to scattered electron

→ Can 'tag' the flavor of the struck quark by measuring the hadrons produced: 'flavor tagging'

$M_x^2 = W'^2 \sim M^2 + Q^2 (1/x - 1)(1 - z)$

$Z = E_h/\nu$

$$\frac{1}{\sigma_{(e,e')}} \frac{d\sigma}{dz}(ep \to hX) = \frac{\sum_q e_q^2 f_q(x) D_q^h(z)}{\sum_q e_q^2(x) f_q(x)}$$

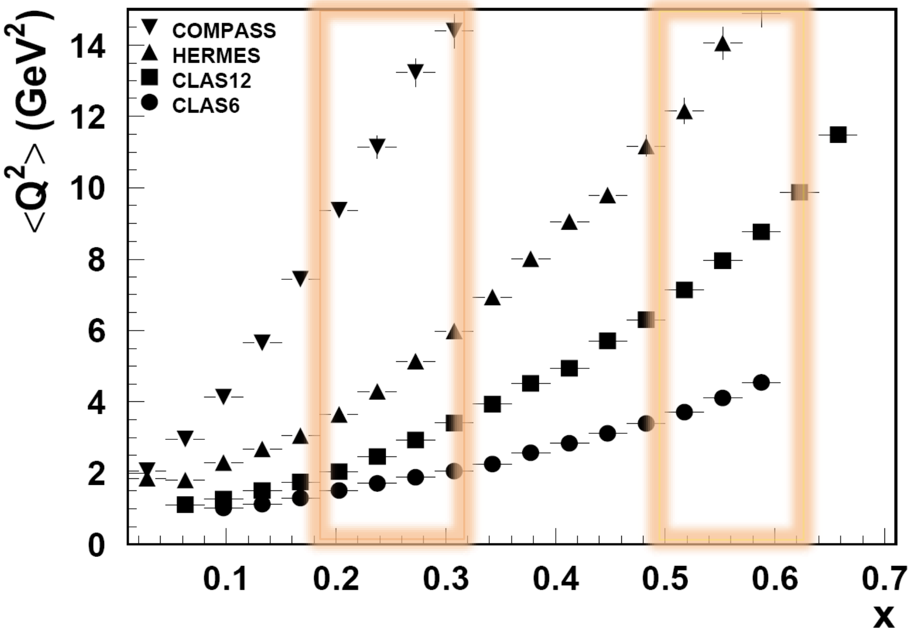
$f_q(x)$: parton distribution function

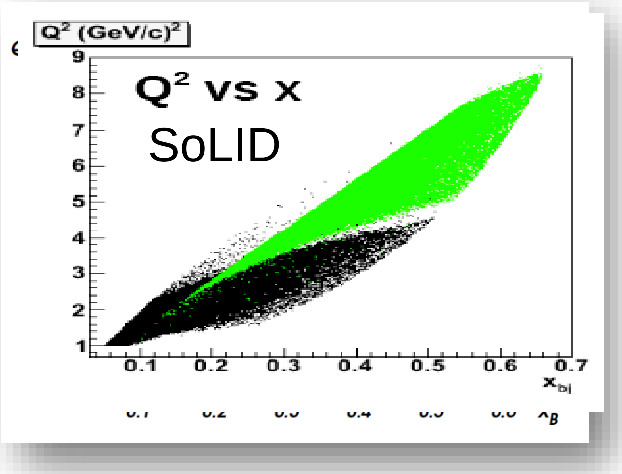
$D_q^h(z)$: fragmentation function

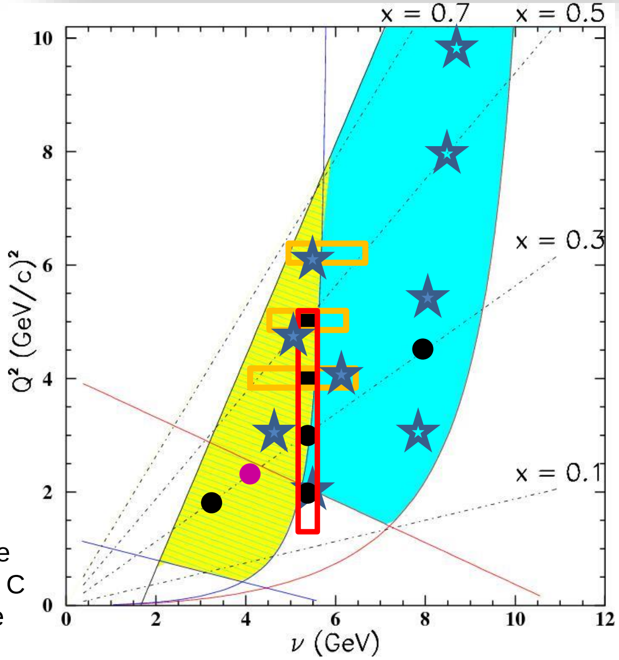
Measure inclusive (e,e') at same time as (e,e'h)

- Leading-Order (LO) QCD
- after integration over p_T and ϕ
- NLO: gluon radiation mixes x and z dependences
- Target-Mass corrections at large z
- ln(1-z) corrections at large z

Need precision over range in Q^2 @ fixed x







$$\frac{d\sigma(ep \rightarrow e'hX)}{dxdy\;dzdP_{h\perp}} \propto \sum_q e_q^2 C\left[q(x,k_T)D_q^h(z,p_T)\right]$$

Still many complications:

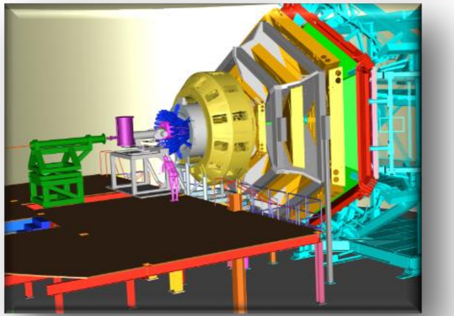
- Description valid? At what energies?
- TMD evolution
- Target-Mass effects
- ln(1-z) resummation

Symbols and rectangles indicate the kinematics of approved Hall C experiments within the available phase space

12 GeV SIDIS/TMD Scientific Capabilities

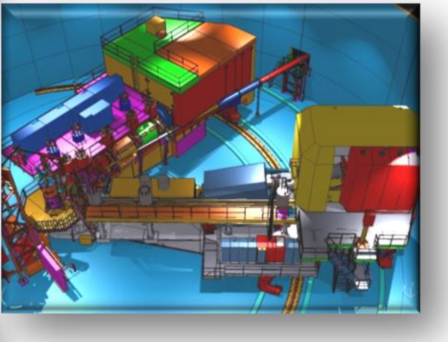
- **CLAS12 in Hall B**

  General survey, medium lumi



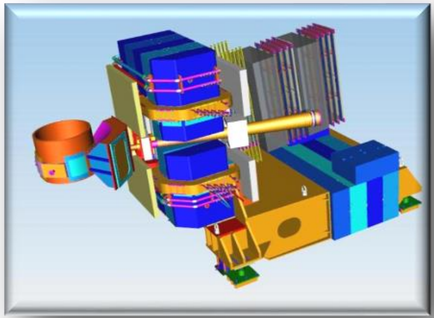
- **SHMS, HMS, NPS in Hall C**

  L-T studies, precise $\pi^+/\pi^-/\pi^0$ ratios



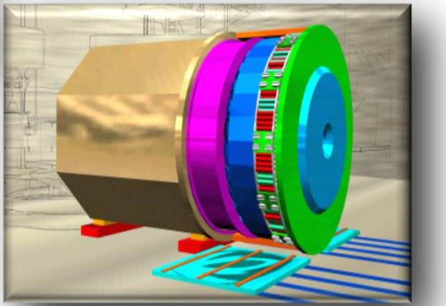
- **SBS in Hall A**

  High x, High Q^2, 2-3D



- **SOLID in Hall A**

  High lumi and acceptance – 4D



Overall Goal of SIDIS Program

validate basic reaction mechanism of SIDIS at “our” energies

and then

spin and flavor dependence of quark transverse momentum distributions

There are indications from both theory (lattice, chiral constituent quark model) and experimental data of different k_T dependences of quark flavor distributions

… but, keep in mind overall goal of 3D nucleon structure…

TMDs and SIDIS – General Formalism

General formalism for (e,e'h) coincidence reaction w. polarized beam: [A. Bacchetta et al., JHEP 0702 (2007) 093]

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h,t}^2} = \frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\left\{\boxed{F_{UU,T}+\varepsilon F_{UU,L}}+\right.$$

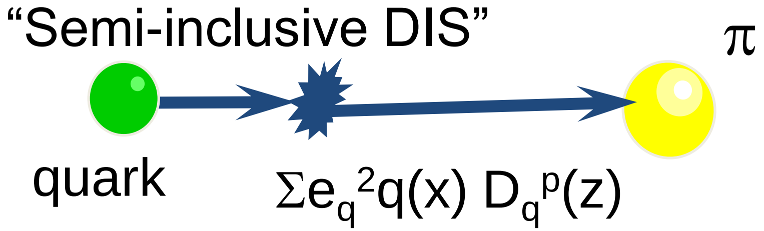
$$\left.\sqrt{2\varepsilon(1+\varepsilon)}\,\underline{\cos\phi_h F_{UU}^{\cos\phi_h}}+\varepsilon\,\underline{\cos(2\phi_h)F_{UU}^{\cos(2\phi_h)}}+\boxed{\lambda_e}\sqrt{2\varepsilon(1+\varepsilon)}\,\underline{\sin\phi_h F_{LU}^{\sin\phi_h}}\right\}$$

(Ψ = azimuthal angle of e' around the electron beam axis w.r.t. an arbitrary fixed direction)

If beam is unpolarized, and the (e,e'h) measurements are fully integrated over ϕ, only the **$F_{UU,T}$** and **$F_{UU,L}$** responses, or the usual transverse (σ_T) and longitudinal (σ_L) cross section pieces, survive.

$R = \sigma_L/\sigma_T$ in SIDIS (ep → $e'\pi^{+/-}X$)

Knowledge on $R = \sigma_L/\sigma_T$ in SIDIS is essentially non-existing!

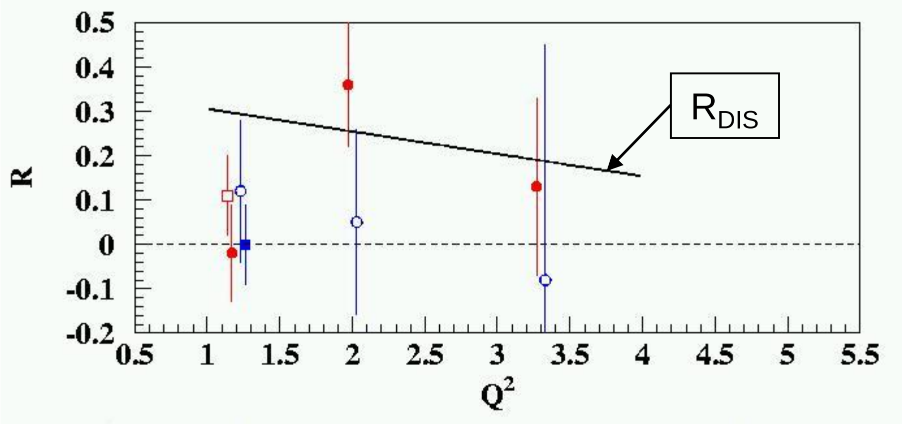


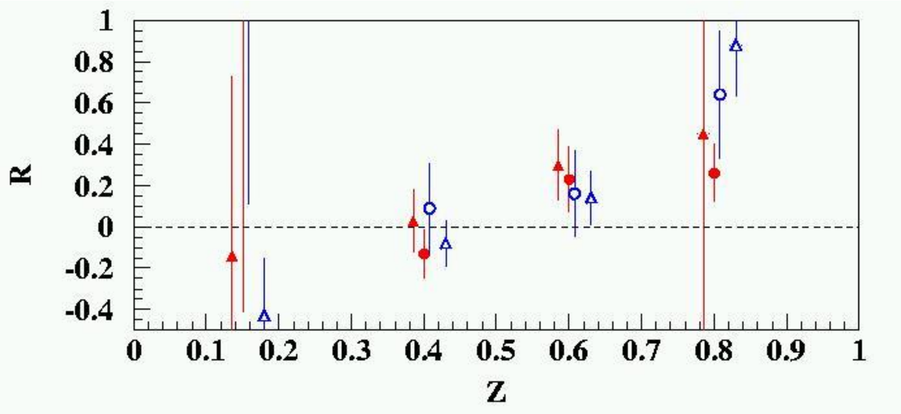
"Deep exclusive scattering" is the z → 1 limit of this "semi-inclusive DIS" process

Here, $R_{SIDIS} \rightarrow R_{DIS}$ disappears with Q^2

Here, $R = \sigma_L/\sigma_T \sim Q^2$ (at fixed x)

Only existing data: Cornell 70's data (H and D, π^+ and π^-)



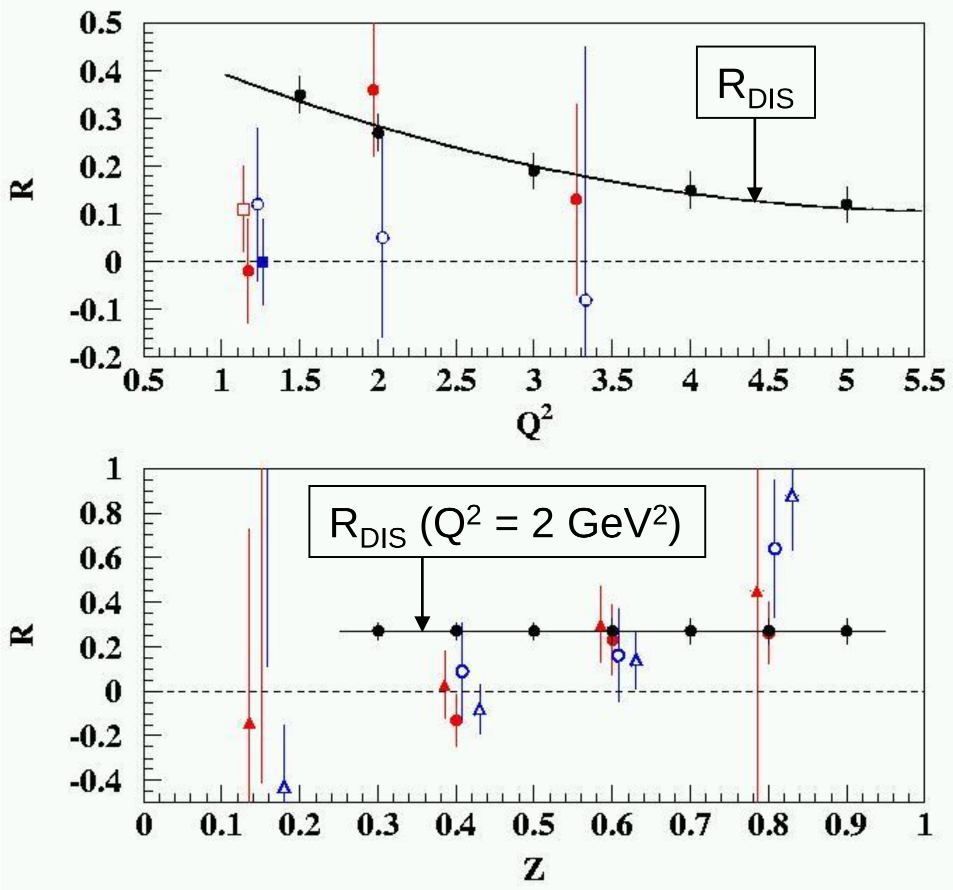


Conclusion: "data consistent with both R = 0 and $R = R_{DIS}$"

Some hint of large R at **large z** in Cornell data?

Longitudinal Cross Section: $R = \sigma_L/\sigma_T$ in SIDIS

- R_{DIS} is in the naïve parton model related to the parton's transverse momentum:
  $R = 4(M^2x^2 + \langle k_T^2\rangle)/(Q^2 + 2\langle k_T^2\rangle)$.
- $R_{DIS} \rightarrow 0$ at $Q^2 \rightarrow \infty$ is a consequence of scattering from free spin-½ constituents



Only existing SIDIS data:
Cornell 70's (H and D, π^+ and π^-)

- Knowledge on R_{SIDIS} is non-existing
- R_{SIDIS} may (will!) vary with z, and with p_T
  (JLab E12-06-104 will scan versus p_T too)
- Knowledge on R_{SIDIS} needed for any TMD-related asymmetry
- Even if one can relate R_{SIDIS} to a flavor-dependent average transverse momentum in a naïve parton model (W. Melnitchouk *et al*, in progress), R_{SIDIS} can not easily be integrated in a global TMD analysis as it is sensitive to gluon and HT effects.

TMDs and SIDIS – General Formalism

General formalism for (e,e'h) coincidence reaction w. polarized beam: [A. Bacchetta et al., JHEP 0702 (2007) 093]

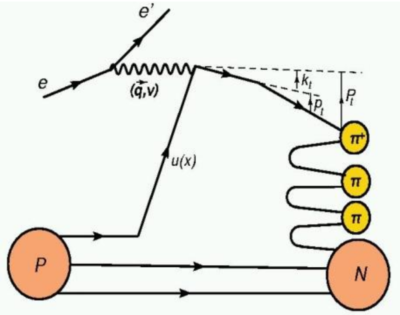
$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h,t}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\left\{\boxed{F_{UU,T}+\varepsilon F_{UU,L}}+\right.$$

$$\left.\underline{\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h}} + \underline{\varepsilon\cos(2\phi_h)F_{UU}^{\cos(2\phi_h)}} + \lambda_e\sqrt{2\varepsilon(1+\varepsilon)}\,\underline{\sin\phi_h F_{LU}^{\sin\phi_h}}\right\}$$

(Ψ = azimuthal angle of e' around the electron beam axis w.r.t. an arbitrary fixed direction)

If beam is unpolarized, and the (e,e'h) measurements are fully integrated over ϕ, only the $F_{UU,T}$ and $F_{UU,L}$ responses, or the usual transverse (σ_T) and longitudinal (σ_L) cross section pieces, survive.

Unpolarized k_T-dependent SIDIS: $F_{UU}^{\cos(\phi)}$ and $F_{UU}^{\cos(2\phi)}$, in framework of Anselmino et al. described in terms of *convolution of quark distributions f and (one or more) fragmentation functions D*, each with own characteristic (Gaussian) width. Transverse momentum widths of quarks with **different flavor (and polarization)** can be different.



Final transverse momentum of the detected pion $\mathbf{P}_t$ arises from convolution of the struck quark transverse momentum $\mathbf{k}_t$ with the transverse momentum generated during the fragmentation $\mathbf{p}_t$.

$P_t = p_t + z\,k_t + O(k_t^2/Q^2)$

TMDs and 3D FFs

Functions surviving on integration over Transverse Momentum

The **others** are sensitive to ***intrinsic* k_T** in the nucleon & in the fragmentation process

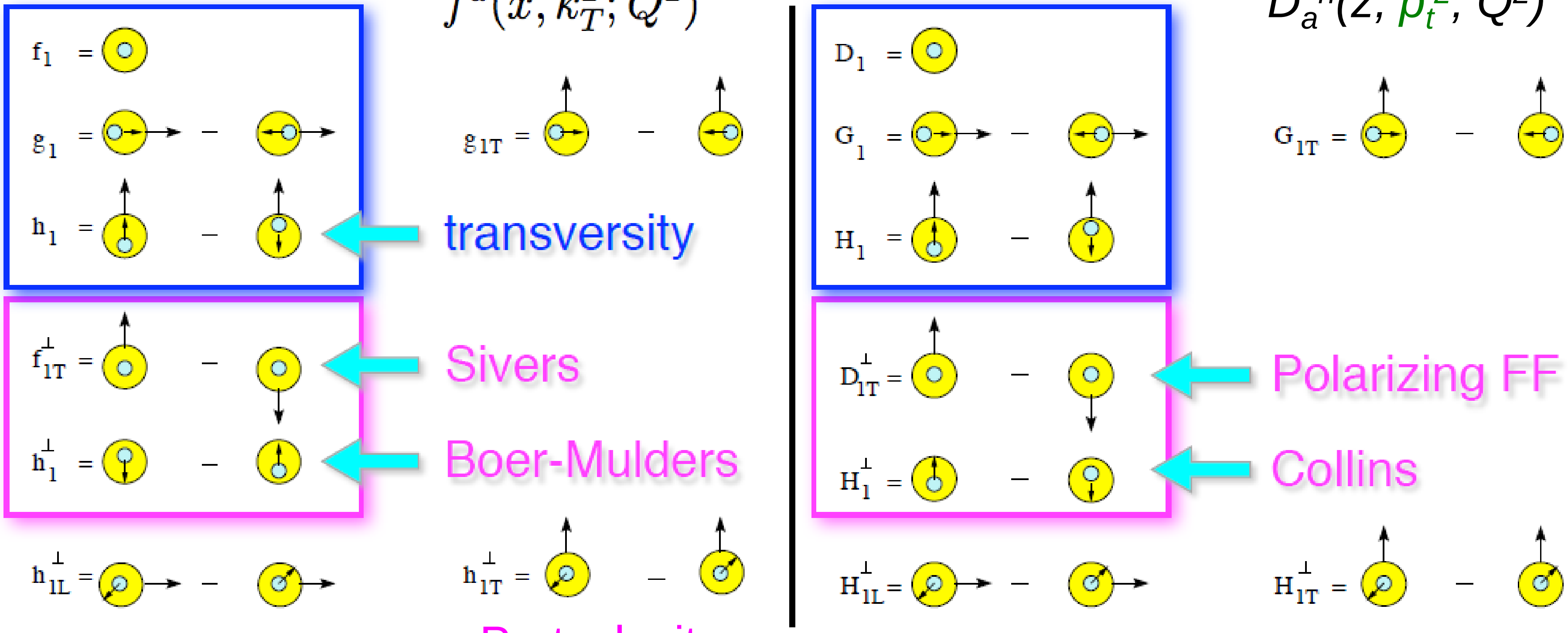
Mulders & Tangerman, NPB 461 (1996) 197

Distribution Functions

$f^a(x, k_T^2; Q^2)$

Fragmentation Functions

$D_a^h(z, p_t^2; Q^2)$



transversity

Sivers

Boer-Mulders

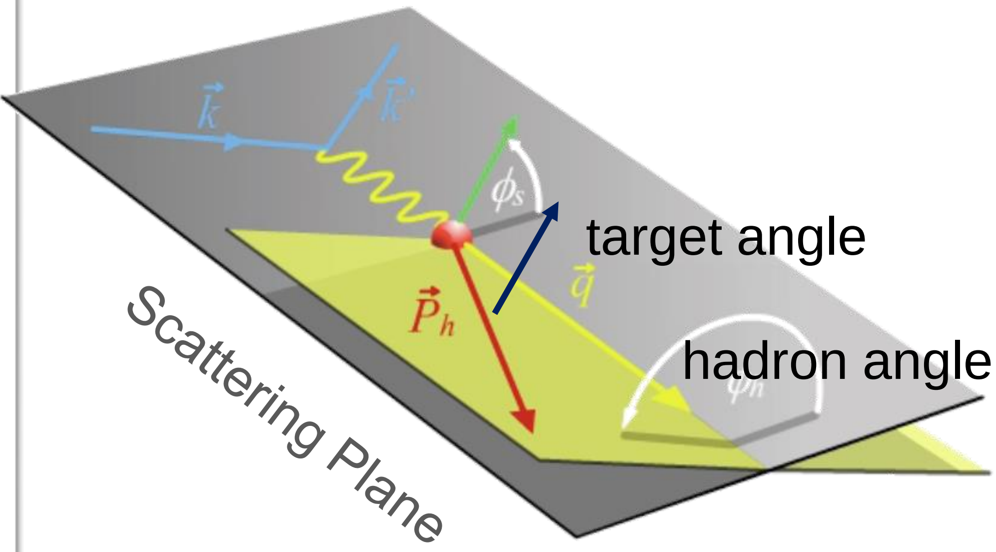
Pretzelosity

Polarizing FF

Collins

TMDs Accessible through Semi-Inclusive Physics

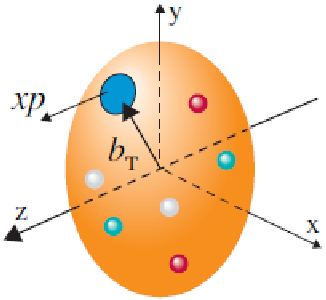
- Separate Sivers and Collins effects



Naturally, two scales:

- High Q: localized probe to “see” quarks and gluons
- Low P_T: sensitive to confining scale to “see” their confined motion

+ Theory input: TMD QCD factorization
TMD QCD evolution



- **Sivers** angle, effect in distribution function: $(\phi_h-\phi_s)$

  Or other combinations: Pretzelosity: $(3\phi_h-\phi_s)$

- **Collins** angle, effect in fragmentation function: $(\phi_h+\phi_s)$

  Pay attention to this one!

- *Kaons enabled by Hall B RICH (INFN/DOE) and Hall C Aerogel (NSF)*

Features of 3D Distributions/TMDs

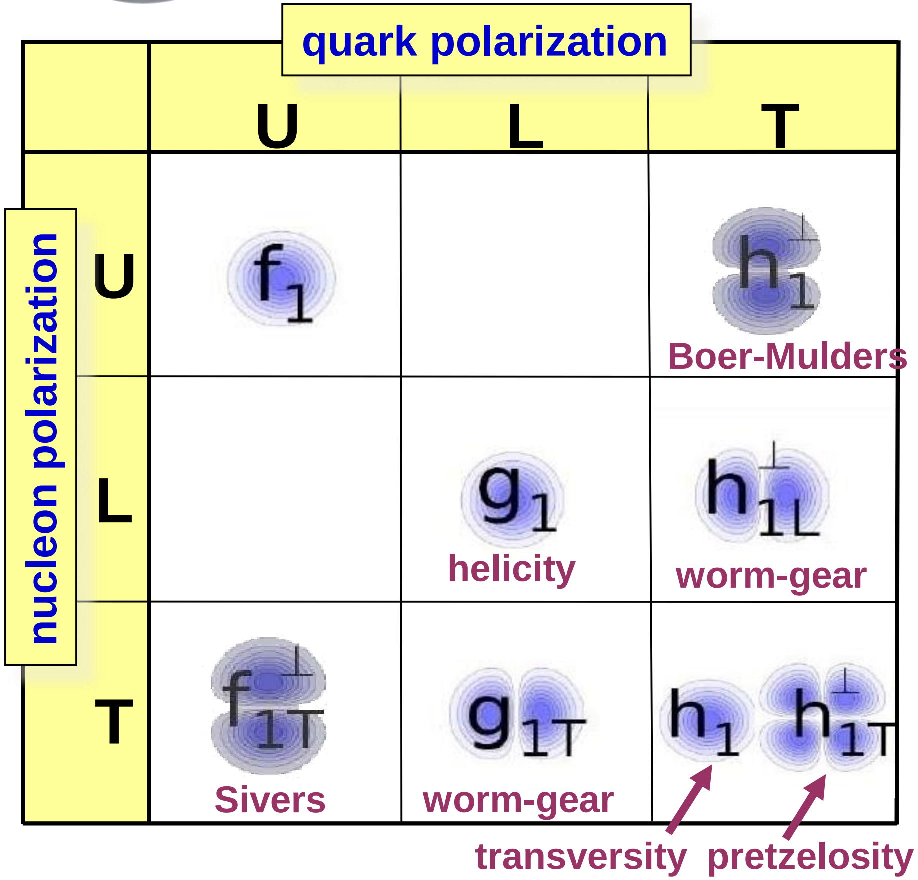
$$f^a(x, k_T^2; Q^2)$$

Ex. TMD PDF for a given combination of parton and nucleon spins

$$\boxed{\sigma = \sum_q e_q^2 f(x) \otimes D(z)}$$

$$\downarrow$$

$$f^a(x, k_T^2; Q^2)$$



nucleon polarization \ quark polarization	U	L	T
U	f_1		$h_1^\perp$ Boer-Mulders
L		g_1 helicity	$h_{1L}^\perp$ worm-gear
T	$f_{1T}^\perp$ Sivers	g_{1T} worm-gear	h_1 transversity $h_{1T}^\perp$ pretzelosity

- transverse position and momentum of partons are correlated with the spin orientations of the parent hadron and the spin of the parton itself
- transverse position and momentum of partons depend on their flavor
- transverse position and momentum of partons are correlated with their longitudinal momentum
- spin and momentum of struck quarks are correlated with remnant
- quark-gluon interaction play a crucial role in kinematical distributions of final state hadrons, both in semi-inclusive and exclusive processes

Hall C SIDIS Program (typ. x/Q^2 ~ constant)

HMS + SHMS (or NPS) Accessible Phase Space for SIDIS; w. typical z range 0.3-0.65

Accurate cross sections for validation of SIDIS factorization framework and for L/T separations

E12-13-007

★ Neutral pions:

Scan in (x,z,P_T)

Overlap with

E12-09-017 &

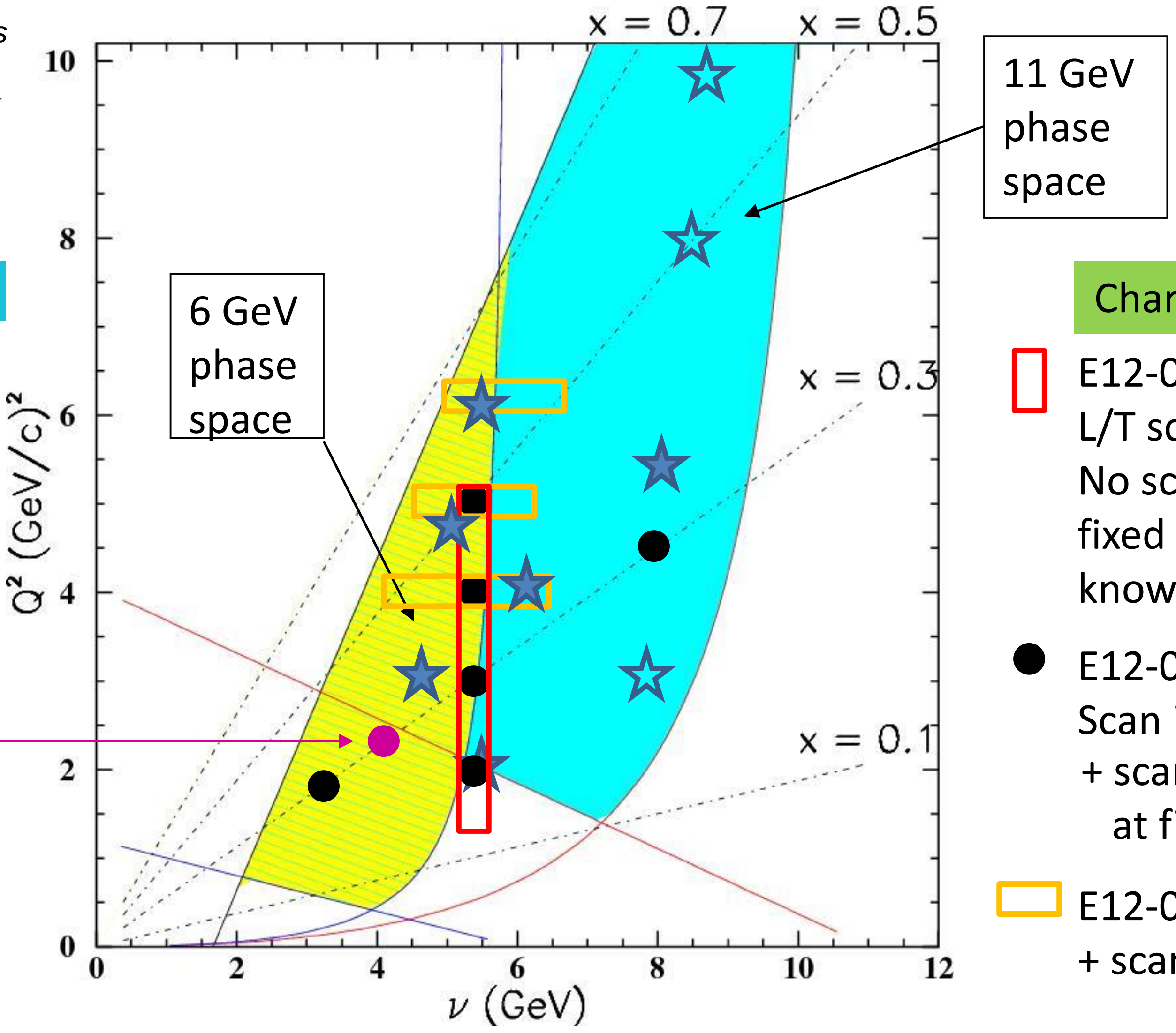
E12-09-002

☆ Parasitic with

E12-13-010

E00-108

(6 GeV)



Charged pions:

☐ E12-06-104

L/T scan in (z,P_T)

No scan in Q^2 at fixed x: $R_{DIS}(Q^2)$ known

● E12-09-017

Scan in (x,z,P_T)

+ scan in Q^2

at fixed x

☐ E12-09-002

+ scans in z

Hall C SIDIS Program – basic (e,e'π) cross sections

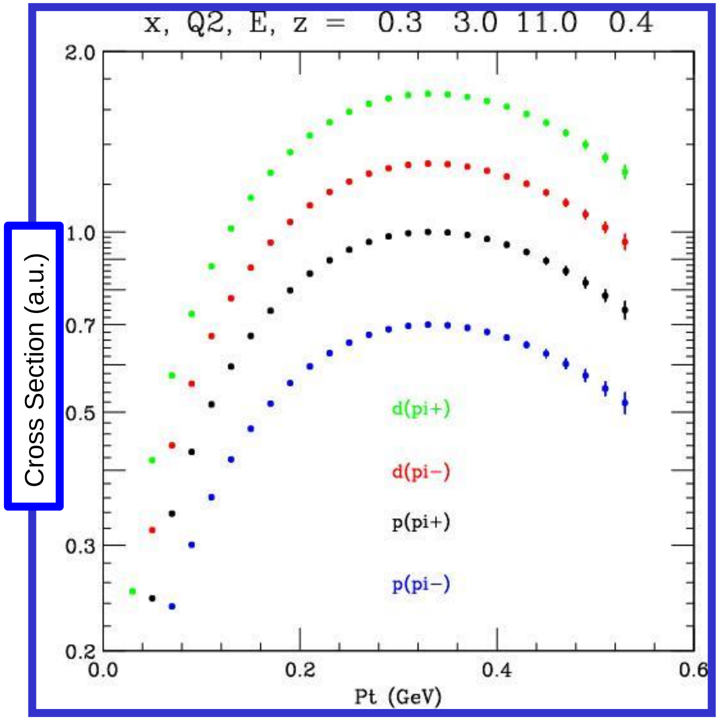
Goal: Measure the basic SIDIS cross sections of **π^+, π^-, π^0 (and K^+)** production off the proton (and deuteron), including a map of the P_T dependence ($P_T \sim \Lambda < 0.5$ GeV), to validate(*) a flavor decomposition and the k_T dependence of (unpolarized) up and down quarks

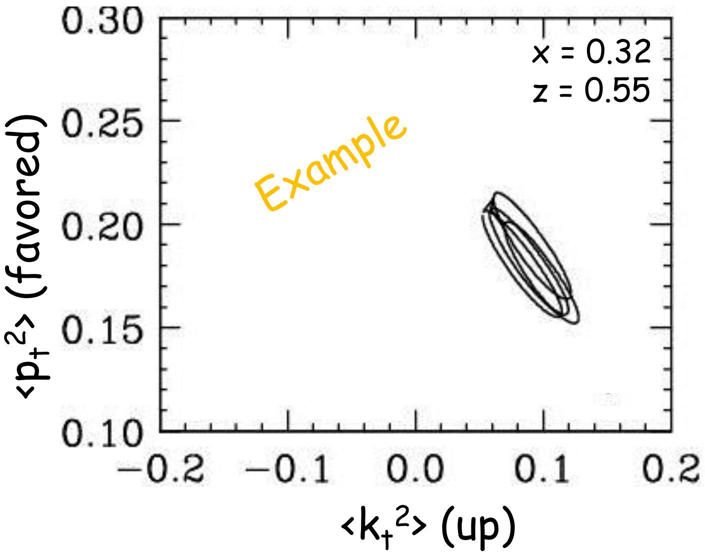
$$\sigma = \sum_q e_q^2 f(x) \otimes D(z)$$

(*) Can only be done using spectrometer setup capable of %-type measurements (an essential ingredient of the global SIDIS program!)

$\pi^{+/-}$

(Kinematics II, z = 0.4 bin only)





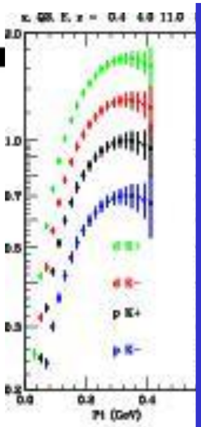
Basic precision cross section measurements:

- Crucial information to validate theoretical understanding
  - Convolution framework requires validation for most future SIDIS experiments and their interpretation
  - Can constrain Q^2 dependence & TMD evolution
  - Questions on target-mass corrections and ln(1-z) re-summations require precision large-z data

π^0 with Neutral-Particle Spectrometer (NPS)

Hall C Projected Results – Kaons

III



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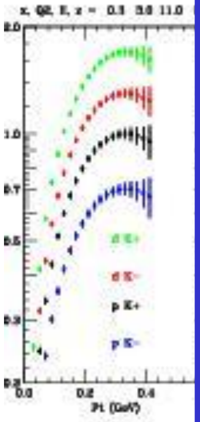

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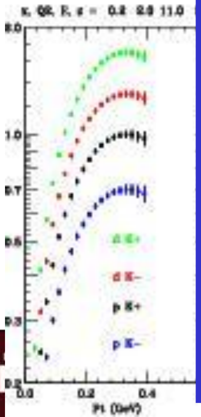

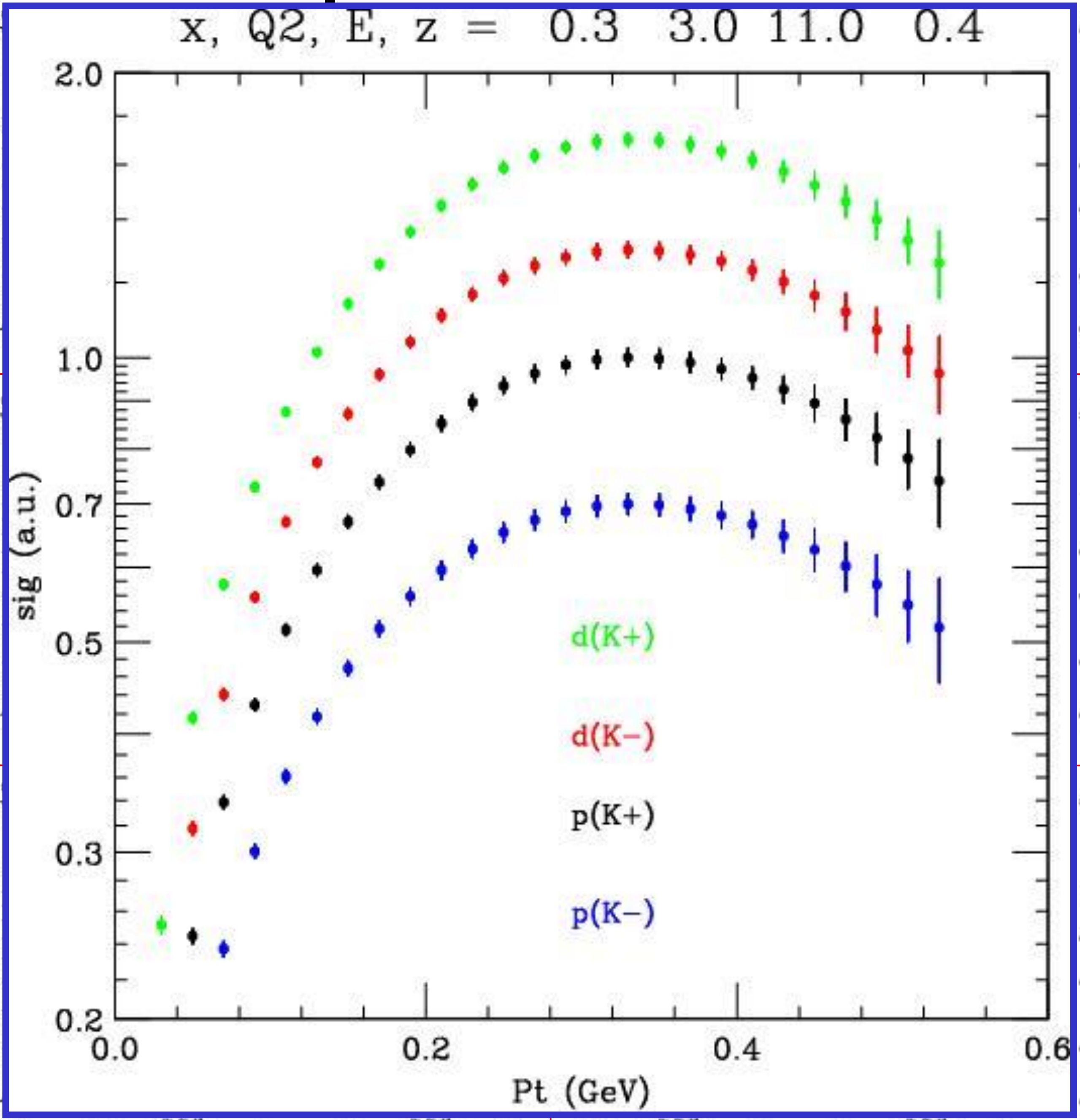

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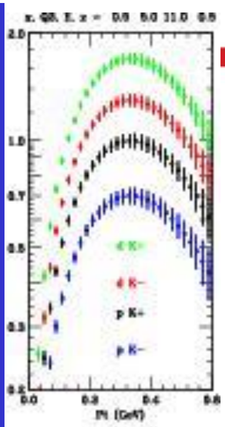

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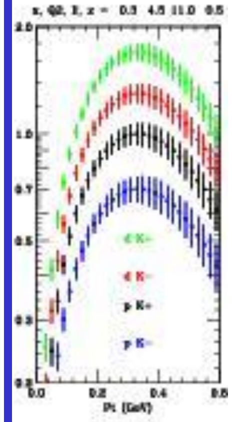
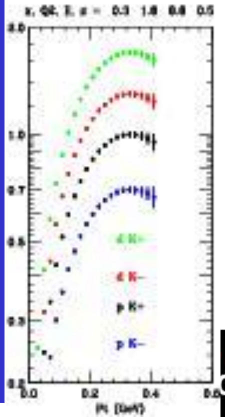


V



Hall C SIDIS Program – basic (e,e’π) cross sections

(Hall C’s basic SIDIS cross section data at a 6-GeV JLab showed agreement with partonic expectations laying the foundation for a vigorous 12-GeV SIDIS program. PRL 98 (2007) 022001; PL B665 (2008) 20; PRC 85 (2012) 015202. At a 12-GeV JLab, Hall C’s role will be again to provide basis SIDIS cross sections, furthering our understanding.)

Low-energy (x,z) factorization, or possible *convolution in terms of quark distribution and fragmentation functions*, at JLab-12 GeV <u>must be</u> well validated to substantiate the SIDIS science output. Many questions remain at intermediate-large z (~0.2-1) and low-intermediate Q^2 (~2-10 GeV^2).

<u>Why need for (e,e’π^0) beyond (e,e’$\pi^{+/-}$)?</u>

(e,e’π^0) experimental advantages:

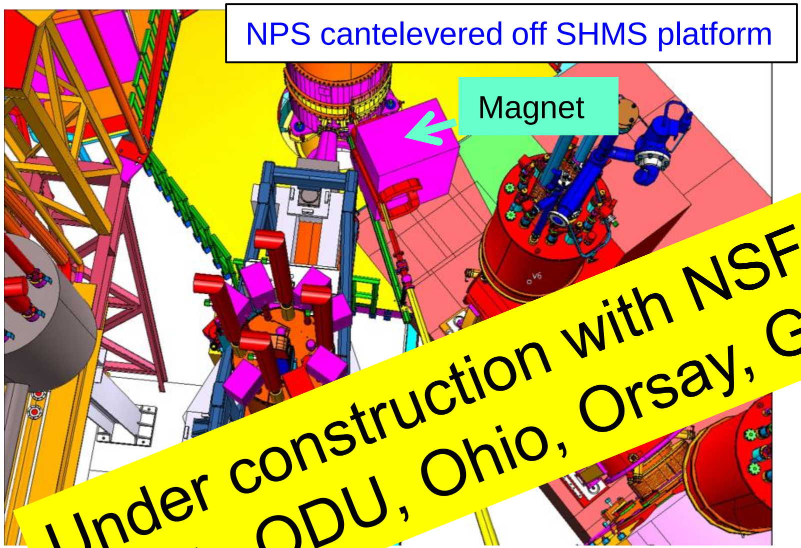
☺ no diffractive ρ contributions
☺ no exclusive pole contributions
☺ reduced resonance contributions
☺ proportional to average D

Further advantages:

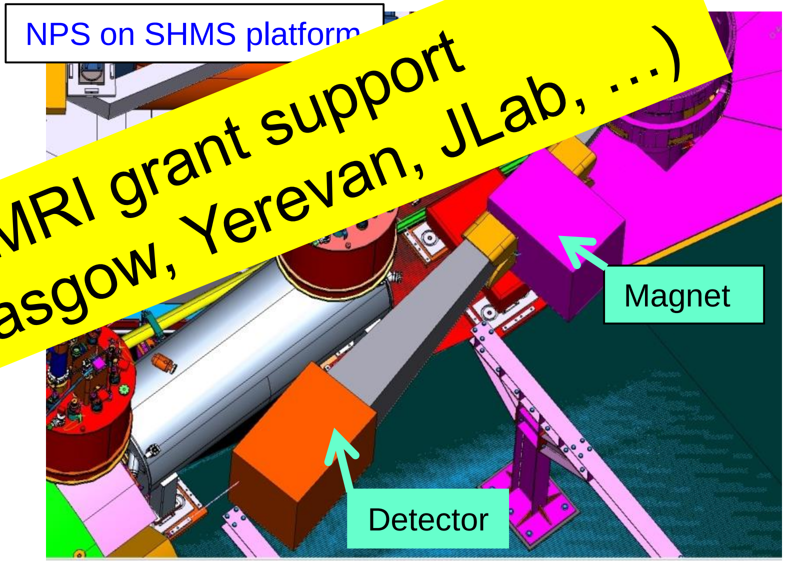
- Can verify: $\sigma^{\pi^0}(x,z) = \frac{1}{2}\,(\sigma^{\pi^+}(x,z) + \sigma^{\pi^-}(x,z))$
- Confirms understanding of flavor decomposition & of k_T dependence

The Neutral-Particle Spectrometer (NPS)

The NPS is envisioned as a facility in Hall C, utilizing the well-understood HMS and the SHMS infrastructure, to allow for precision (coincidence) cross section measurements of neutral particles (γ and π^0). The NPS will be remotely rotatable off the SHMS platform.



N ange: 5.5 – 30 degrees



NPS angle range: 25 – 60 degrees

Under construction with NSF/MRI grant support (CUA, ODU, Ohio, Orsay, Glasgow, Yerevan, JLab, …)

The large interest for such a device can be exemplified by the PAC-approved science program:

E12-13-007 – Measurement of Semi-inclusive π^0 production as Validation of Factorization

E12-13-010 – Exclusive Deeply Virtual Compton and Neutral Pion Cross Section Measurements in Hall C

(E12-13-007 & E12-13-010 runs as one run group – first run group in Hall C)

E12-14-003 – Wide-angle Compton Scattering at 8 and 10 GeV Photon Energies

E12-14-005 – Wide Angle Exclusive Photoproduction of π^0 Mesons **(runs as run group with E12-14-003)**

E12-17-008 – Polarization Observables in Wide-Angle Compton Scattering at large s, t and u (Cond. Approved)

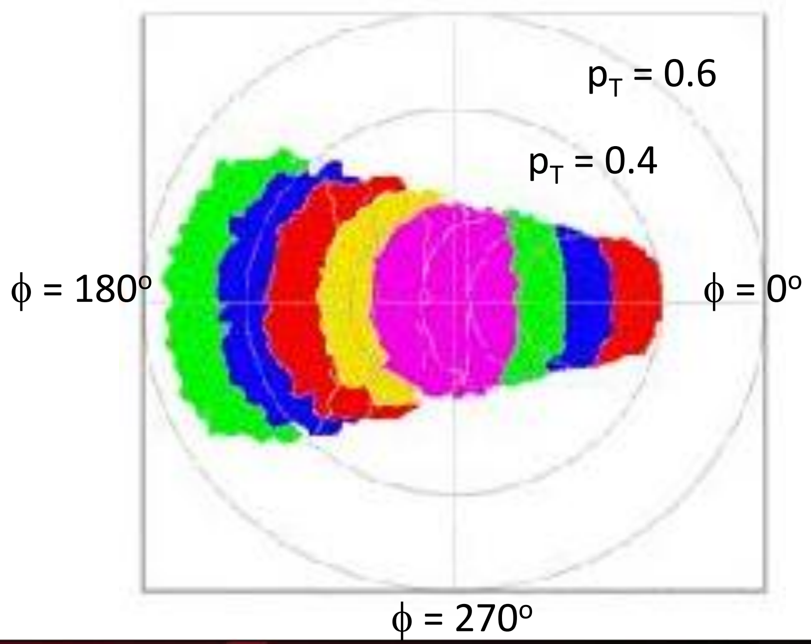
HMS + SHMS: P_T coverage

E12-09-017

Can do meaningful $\pi^{+/-}$ measurements at low p_T (<u>down to 0.05 GeV</u>) due to excellent momentum and angle resolutions!

- Excellent ϕ coverage
  up to P_T = 0.2 GeV
- Sufficient up to P_T = 0.4 GeV
  → coverage at $\phi = 0, \pi$
- Limited up to P_T = 0.5 GeV
  → use $f(\phi)$ from CLAS12

$\pi^{+/-}$



HMS + NPS: P_T coverage

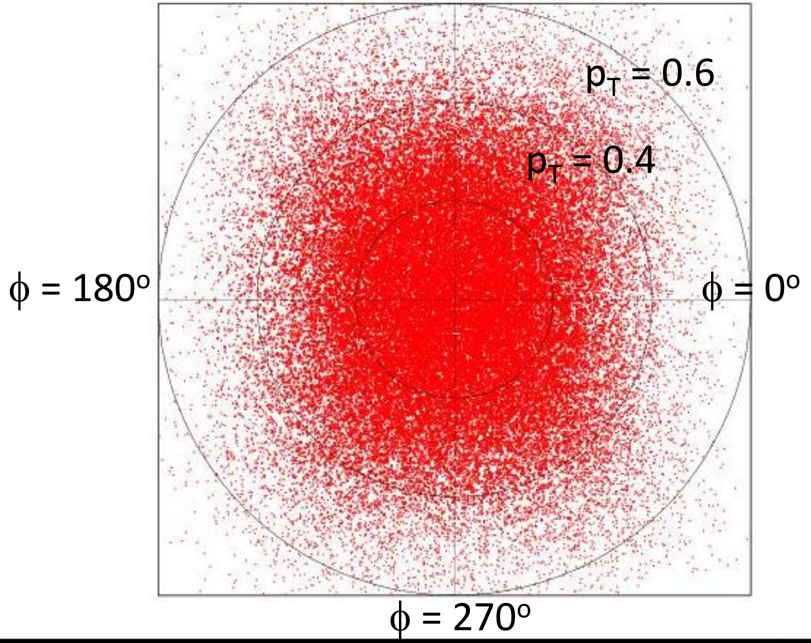
E12-13-007

Basic π^0 SIDIS cross sections with excellent precision, and very good momentum and angle resolutions!

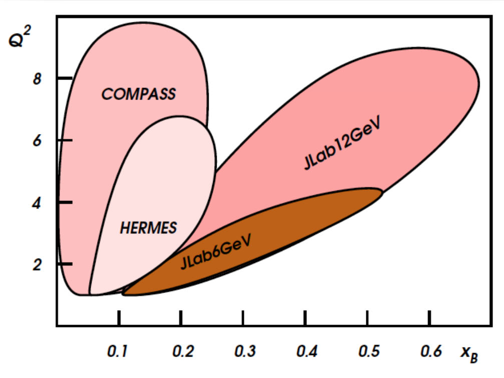
- Excellent ϕ coverage
  up to P_T = 0.3 GeV
- Good up to P_T = 0.4 GeV

- Limited up to P_T = 0.5 GeV
  → use $f(\phi)$ from CLAS12

π^0

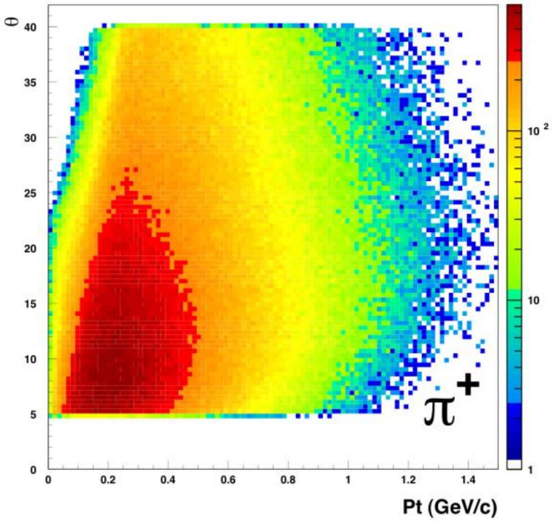


Towards the 3D Structure of the Proton

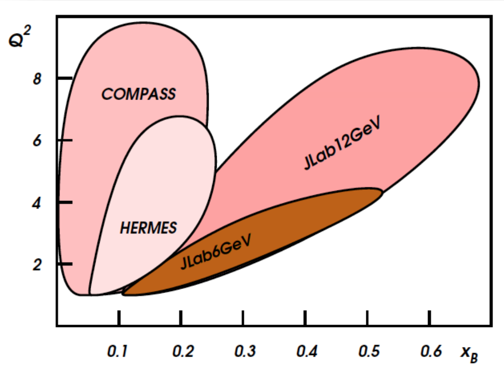


- **CLAS12** is expected to measure all the TMD observables accessible with a polarized beam, with a longitudinally polarized target, and (hopefully) a transversely polarized target.

CLAS12 lacks the precision of Hall C for basic cross section measurements, but does boast a (very) good coverage in (p_T,ϕ) relevant to access the general TMD observables.



Towards the 3D Structure of the Proton



- **CLAS12** **is expected to measure all the TMD observables accessible with a polarized beam, with a longitudinally polarized target, and (hopefully) a transversely polarized target.**

TMDs from unpolarised SIDIS data → p_T dependence of f_1, azimuthal aymmetries

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h,t}^2}=\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\left\{\boxed{F_{UU,T}+\varepsilon F_{UU,L}}+\right.$$

$$\left.\sqrt{2\varepsilon(1+\varepsilon)}\,\underline{\cos\phi_h F_{UU}^{\cos\phi_h}}+\underline{\varepsilon\cos(2\phi_h)F_{UU}^{\cos(2\phi_h)}}+\lambda_e\sqrt{2\varepsilon(1+\varepsilon)}\,\sin\phi_h\underline{F_{LU}^{\sin\phi_h}}\right\}$$

and Boer-Mulders $\boxed{F_{UU}^{\cos 2\varphi}\propto h_1^{\perp}H_1^{\perp}+[f_1D_1+\ldots]/Q^2}$

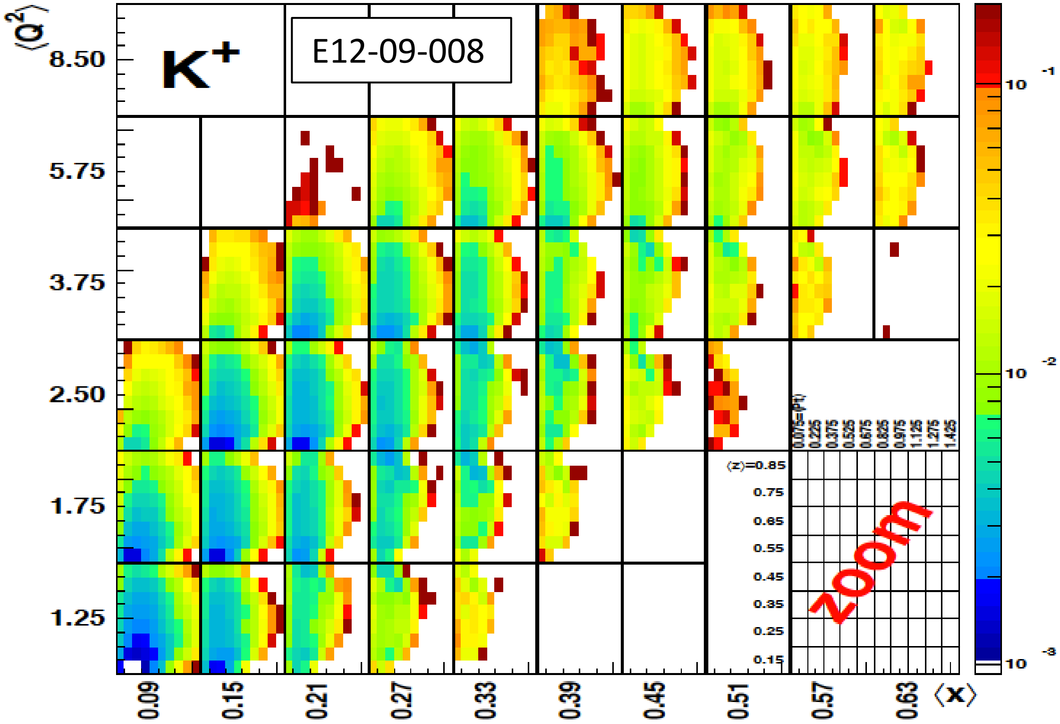
SIDIS π/K on unpolarized protons/deuterons

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

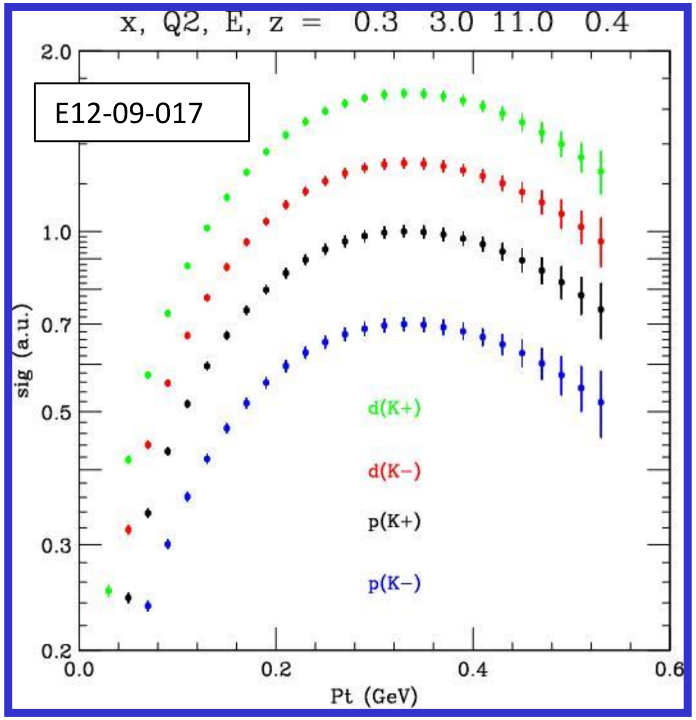
E12-06-112

$$\frac{d\sigma}{dx_B\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{x_B y Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x_B}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}\Big\},$$

Kaons



(CLAS12)



(Hall C, Kinematics II, z = 0.4 bin only)

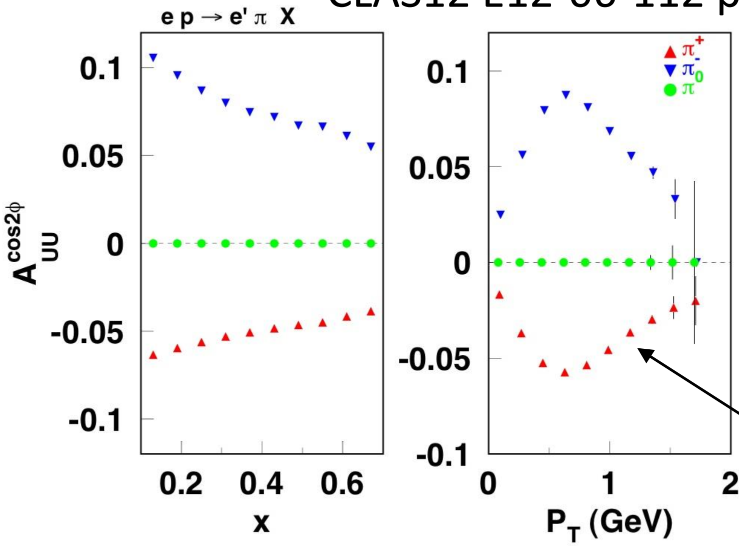
Towards the 3D Structure of the Proton

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h,t}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{\boxed{F_{UU,T}+\varepsilon F_{UU,L}}+$$

$$\underline{\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h}} + \underline{\varepsilon\cos(2\phi_h) F_{UU}^{\cos(2\phi_h)}} + \boxed{\lambda_e}\,\underline{\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi_h}}\Big\}$$

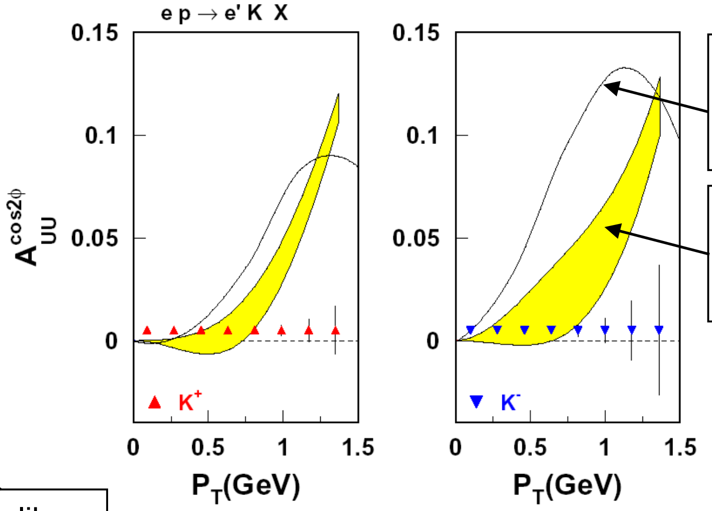
$$\boxed{F_{UU}^{\cos 2\varphi} \propto h_1^{\perp} H_1^{\perp} + [\,f_1 D_1 + \ldots]/Q^2}$$

CLAS12 E12-06-112 projections



Vanish like $1/p_T$ (Yuan)

CLAS12 E12-09-008 projections



Line: PRD78 045022
Boer-Mulders from Sivers
Collins from e+e- data

Band: PRD78 034035
Boer-Mulders from DY data
Collins from chiral limit

Overview of SoLID - Solenoidal Large Intensity Device

- SoLID is unique in that it provides equipment that combines
  - The capability to handle high luminosity ($10^{37\text{-}39}$)
  - A large acceptance detector with full ϕ coverage

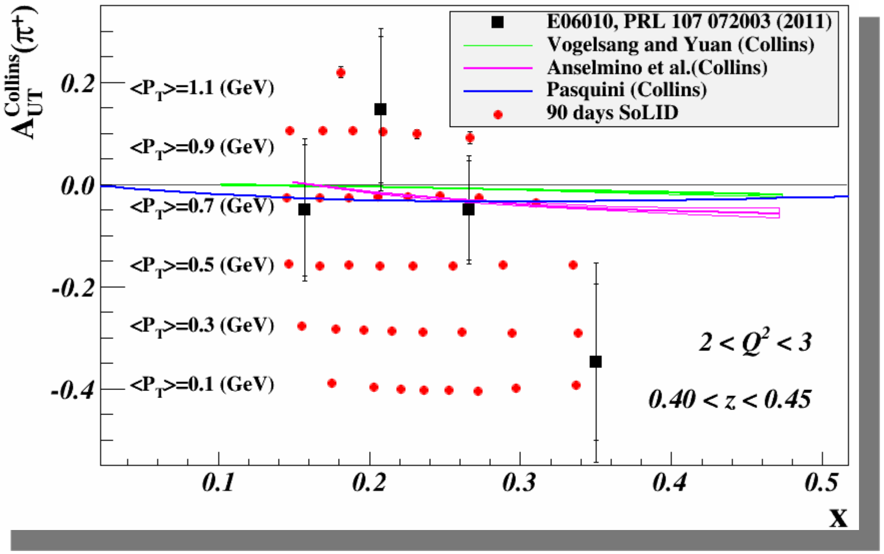
  → This allows a full exploitation of the JLab 12 GeV Upgrade

- SoLID Science Program:
  - Unprecedented precision in three-dimensional imaging of the nucleon in momentum space *in the valence quark region.*
  - A search for new physics in the 10-20 TeV region, complementary to the reach at LHC, for example uniquely improving sensitivity to a *lepto-phobic Z'* of 100-200 GeV.
  - Allowing access to a completely unexplored kinematic region near the threshold of J/ψ production, allowing access to the QCD conformal anomaly *without competition for its precision*

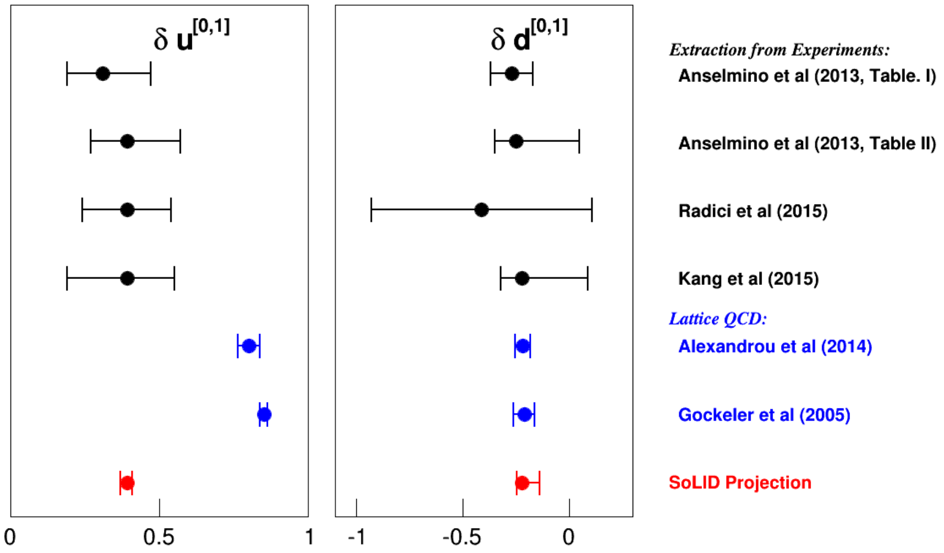
- There is wide interest in SoLID science as evidenced by:
  - More than 250 collaborators over 50 institutions and 13 countries
  - Already quite significant international contributions and potential further commitments, particularly from China
  - strong theoretical support

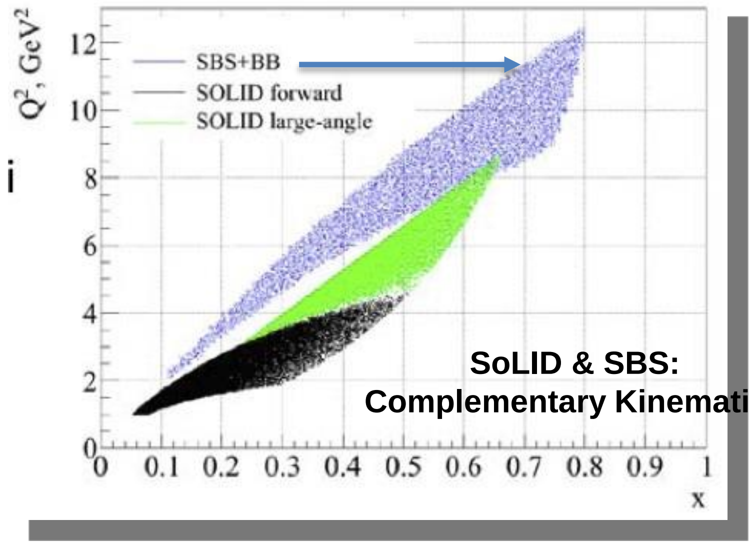
TMD Program in Hall A with SoLID & SBS

(match large acceptance devices at high luminosity to anticipated polarized 3He target performance)



Tensor Charges





SoLID & SBS: Complementary Kinematics

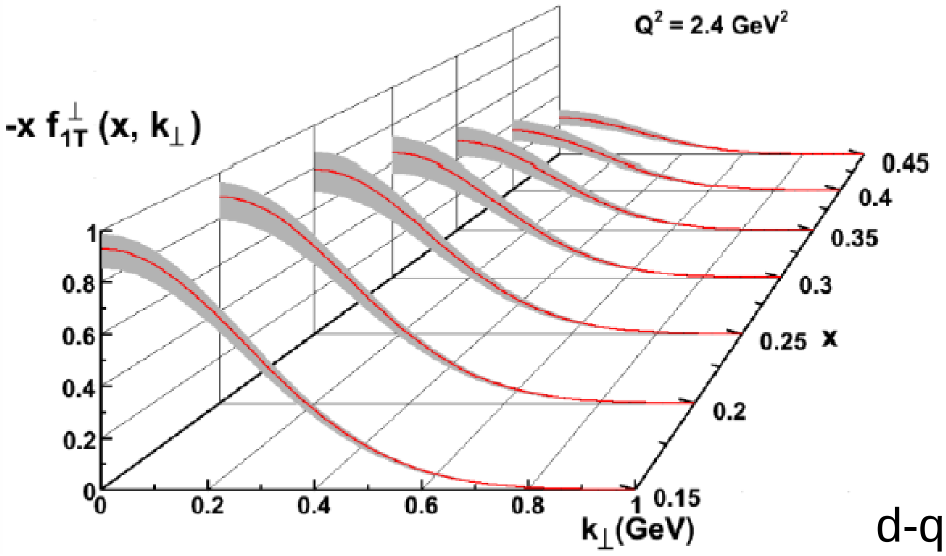
SoLID projection extraction by A. Prokudin using **only** statistical errors and based on:

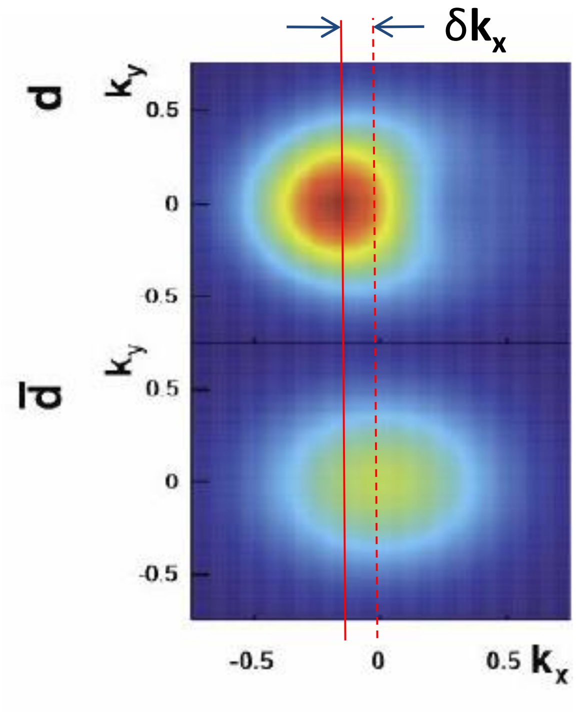
- a set of data with a limited range of x values
- the assumption of a negligible contribution from sea quarks
- assumption on Q^2 evolution
- model dependent assumptions on the shape of underlying TMD distributions

Momentum Tomography with TMDs

JLab/12 GeV Goal → Precision in 3D Momentum Imaging of the Nucleon!

Sivers function for d-quarks extracted from model simulations with a transverse polarized ^{3}He target.





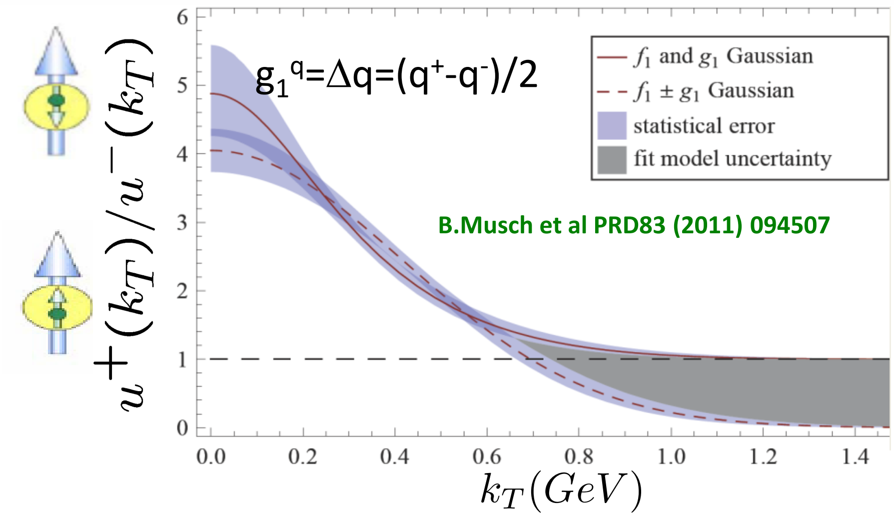
12 GeV ~ Valence Quark Region (x > 0.1)

d-quark momentum tomography for Sivers function. The d-quark momentum density shows a distortion and shift in $\mathbf{k}_x$. A non-zero $\delta \mathbf{k}_x$ value requires a non-zero orbital angular momentum.

spin and flavor dependence of quark transverse momentum distributions

Distributions of PDFs may (will) depend on flavor and spin
(lower fraction aligned with proton spin, and less u-quarks at large k_T,b_T)

CLAS12: K_T Helicity Dependence



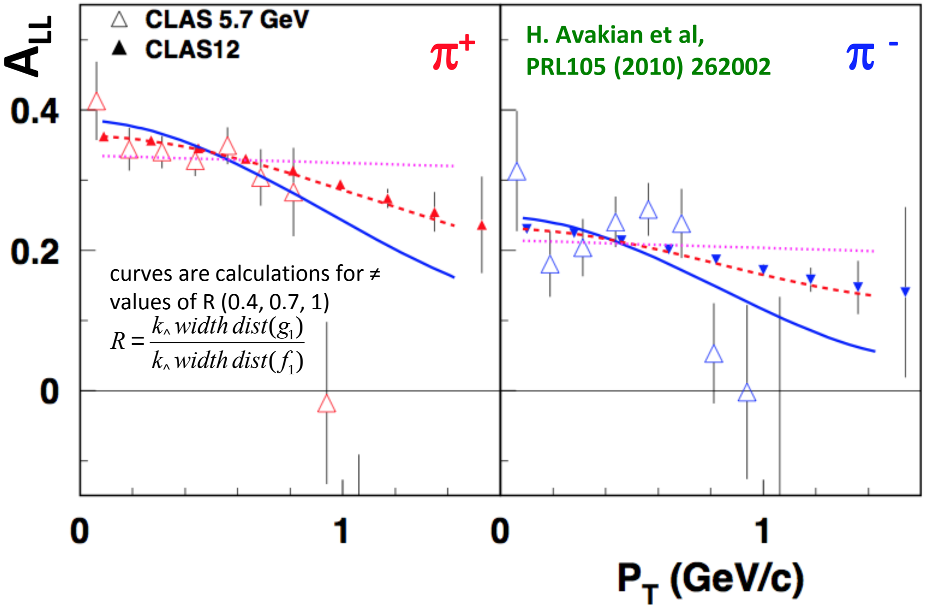
$g_1^q = \Delta q = (q^+ - q^-)/2$

B.Musch et al PRD83 (2011) 094507

- Higher probability to find a quark anti-aligned with proton spin at **large k_T**
- Important to have q^+ and q^- k_T-dependent distribution separately
- q^- sensitive to orbital motion:

$$q^-_{L=1} \sim (1-x)^5 log^2(1-x)$$

H. Avakian et al. PRL 99 (2007) 082001



H. Avakian et al, PRL105 (2010) 262002

curves are calculations for ≠ values of R (0.4, 0.7, 1)

$$R = \frac{k_\wedge \, width \, dist(g_1)}{k_\wedge \, width \, dist(f_1)}$$

- Double spin asymmetries from CLAS@JLab consistent with wider k_T distributions for f_1 than for g_1
- **Wider range in P_T from CLAS12 is crucial !**

Measurements of the P_T-dependence of A_{LL} ($\propto g_1/f_1$) provide access to transverse momentum distributions of quarks anti-aligned with the proton spin.

A_1 P_T-dependence in SIDIS

$$A_1(\pi) \propto \frac{\sum_q e_q^2 g_1^q(x) D_1^{q\to\pi}(z)}{\sum_q e_q^2 f_1^q(x) D_1^{q\to\pi}(z)} \; e^{-z^2 P_T^2 \frac{(\mu_0^2-\mu_2^2)}{(\mu_D^2+z^2\mu_0^2)(\mu_D^2+z^2\mu_2^2)}}$$

M.Anselmino et al

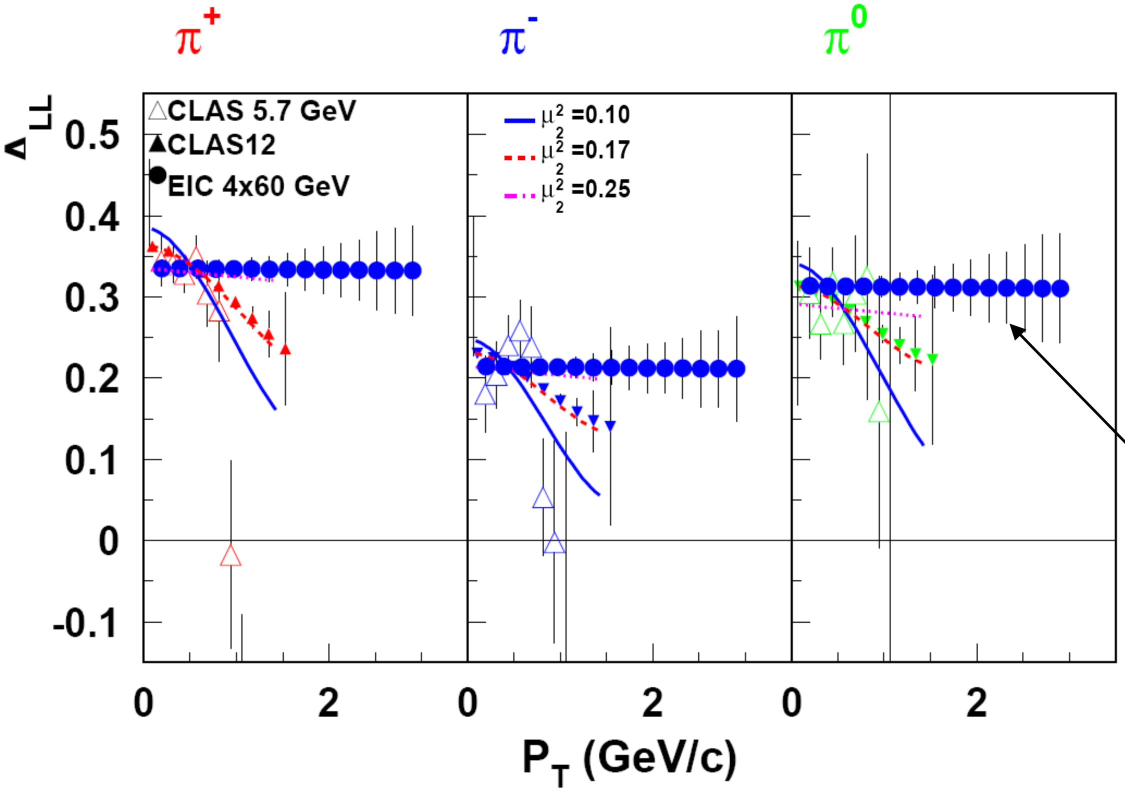
hep-ph/0608048

$$f_1^q(x,k_T) = f_1(x)\frac{1}{\pi\mu_0^2}\exp\left(-\frac{k_T^2}{\mu_0^2}\right)$$

$$g_1^q(x,k_T) = g_1(x)\frac{1}{\pi\mu_2^2}\exp\left(-\frac{k_T^2}{\mu_2^2}\right)$$

$$D_1^q(z,p_T) = D_1(z)\frac{1}{\pi\mu_D^2}\exp\left(-\frac{p_T^2}{\mu_D^2}\right)$$

μ_0^2=0.25GeV^2
μ_D^2=0.2GeV^2



Perturbative limit calculations available for : $g_1^q(x,k_T), f_1(x,k_T)$

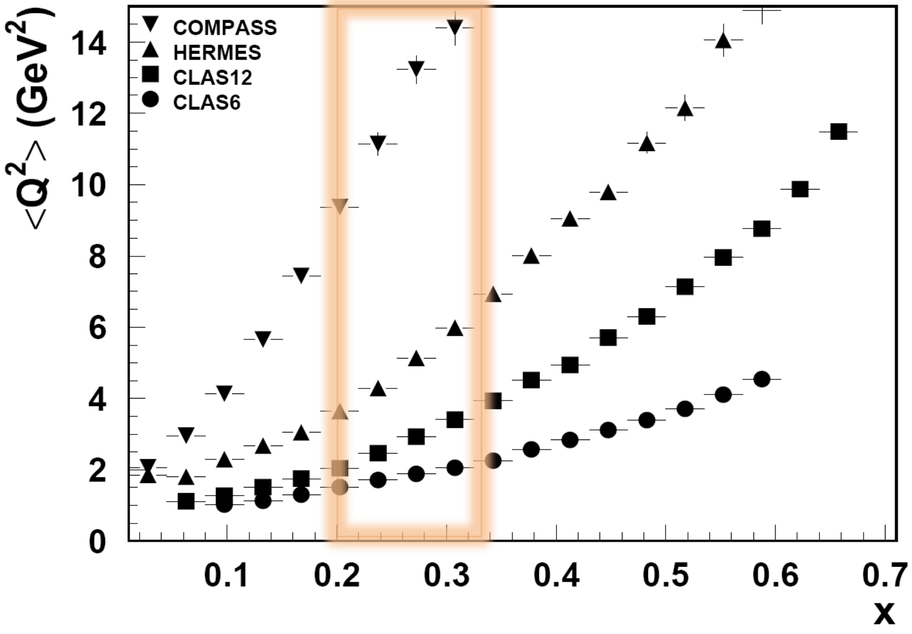
J.Zhou, F.Yuan, Z Liang: arXiv:0909.2238

- A_{LL} (π) sensitive to difference in k_T distributions for f_1 and g_1
- Wide range in P_T with EIC allows studies of transition from TMD to perturbative approach

The SIDIS Landscape

$$\frac{d\sigma(ep\to e'hX)}{dxdy\;dzdP_{h\perp}} \propto \sum_q e_q^2 C\left[q(x,k_T)D_q^h(z,p_T)\right]$$

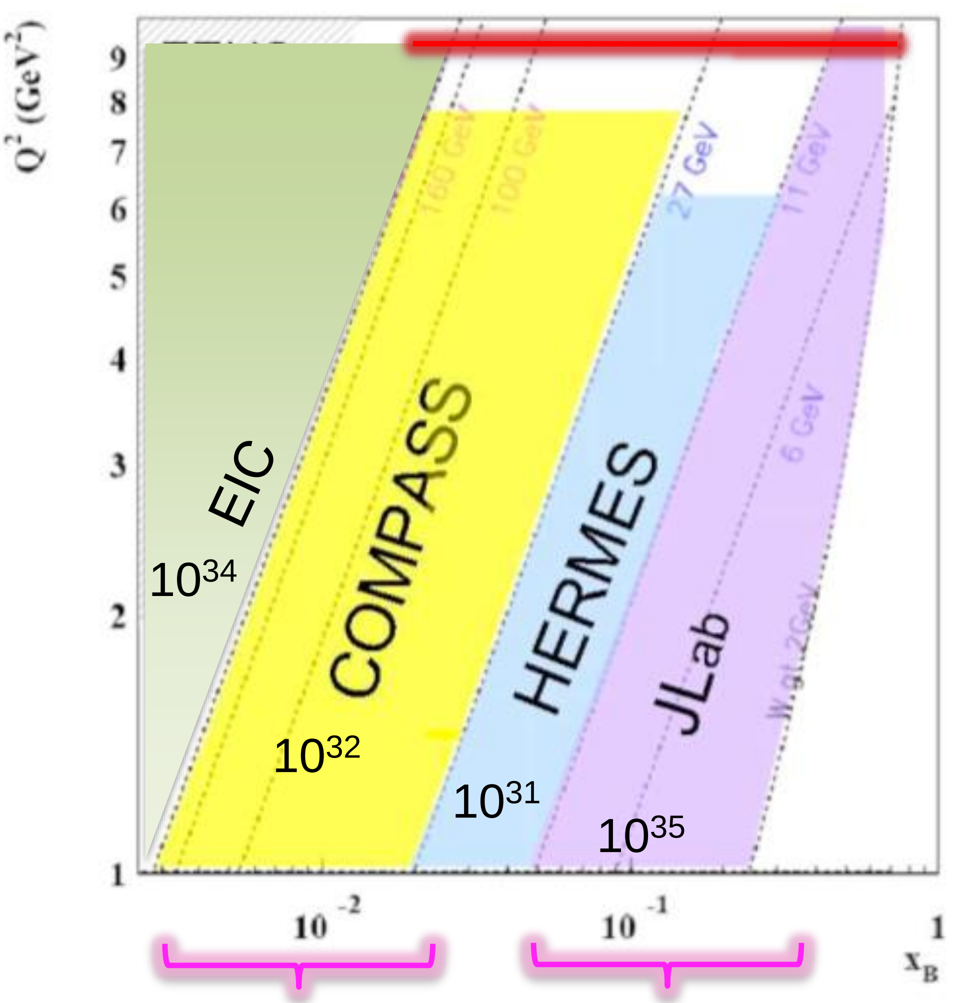
Different Q^2 for same x range



Complementary experiments

Adapted from Marco Contalbrigo

Limit defined by luminosity



Sea

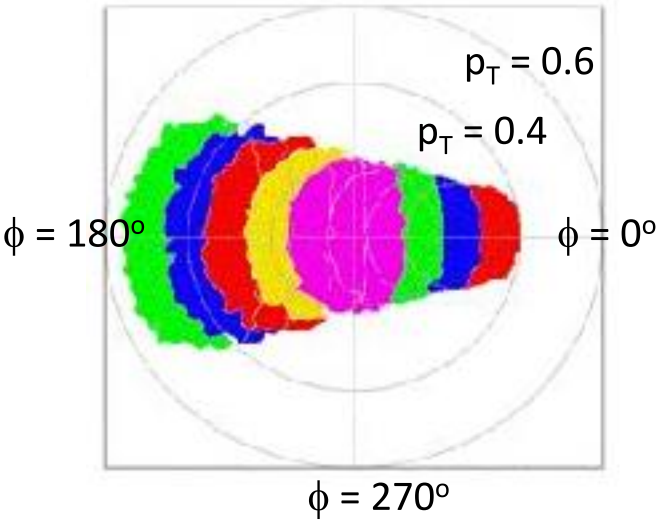
Valence

TMDs from SIDIS Analysis framework

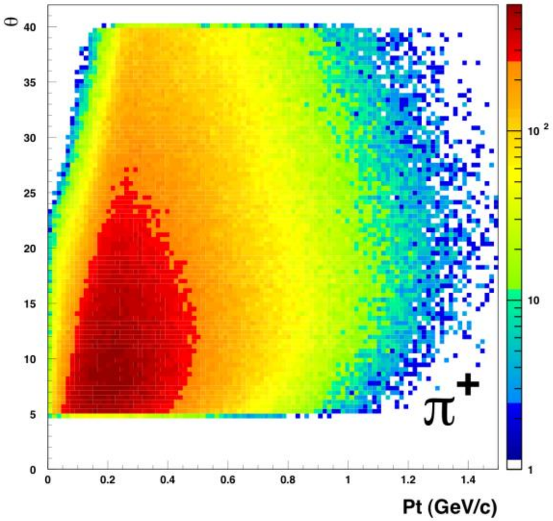
- Differential input (SIDIS):

M. Aghasyan et al arXiv:1409.0487 (JHEP)

bin#	x	Q^2	y	W	M_X	ϕ	z	P_T	λ	Λ	N(counts)	RC
1												
…												
N												



Need to combine precision experiments with more limited acceptance to broad-survey experiments with excellent acceptance



- Need a TMD extraction framework to define the input data info needed
- Define all the data from other experiments which may be needed (data preservation)

TMDs and **3D FFs**

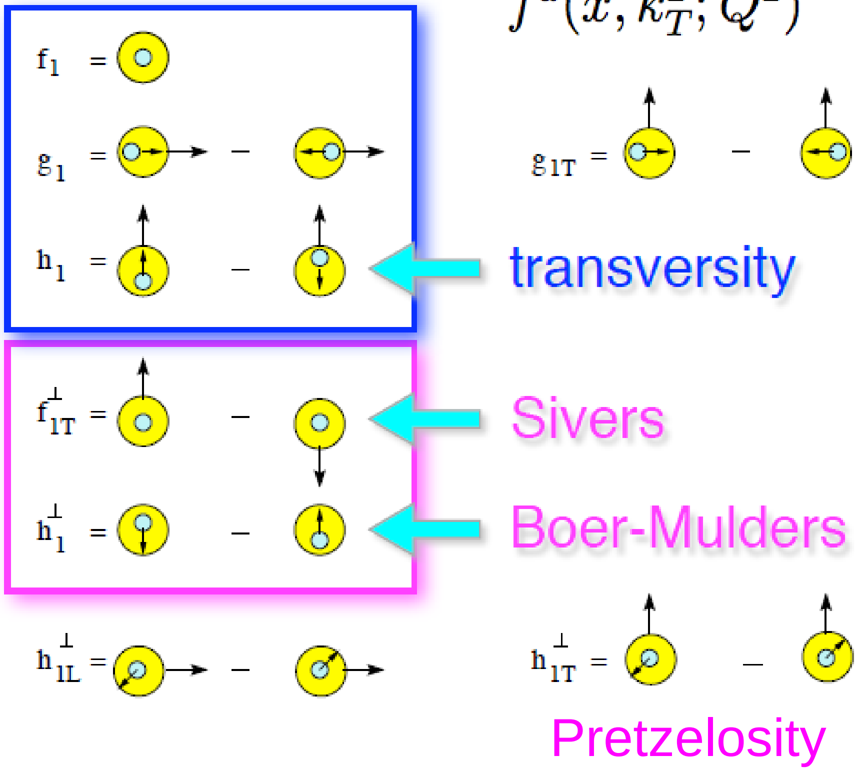
Functions surviving on integration over Transverse Momentum

The **others** are sensitive to ***intrinsic k_T*** in the nucleon & in the fragmentation process

Mulders & Tangerman, NPB 461 (1996) 197

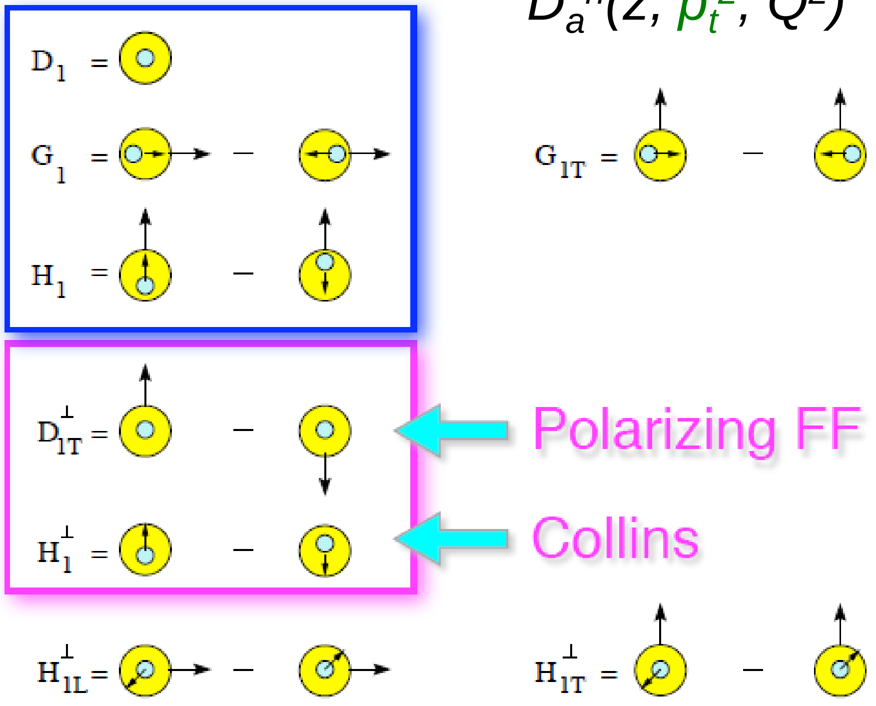
Distribution Functions

$f^a(x, k_T^2; Q^2)$

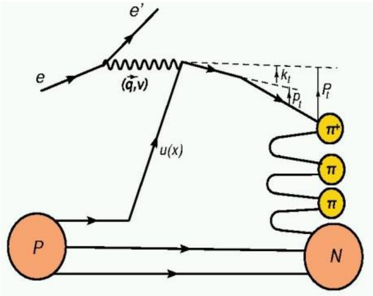


Fragmentation Functions

$D_a^h(z, p_t^2; Q^2)$



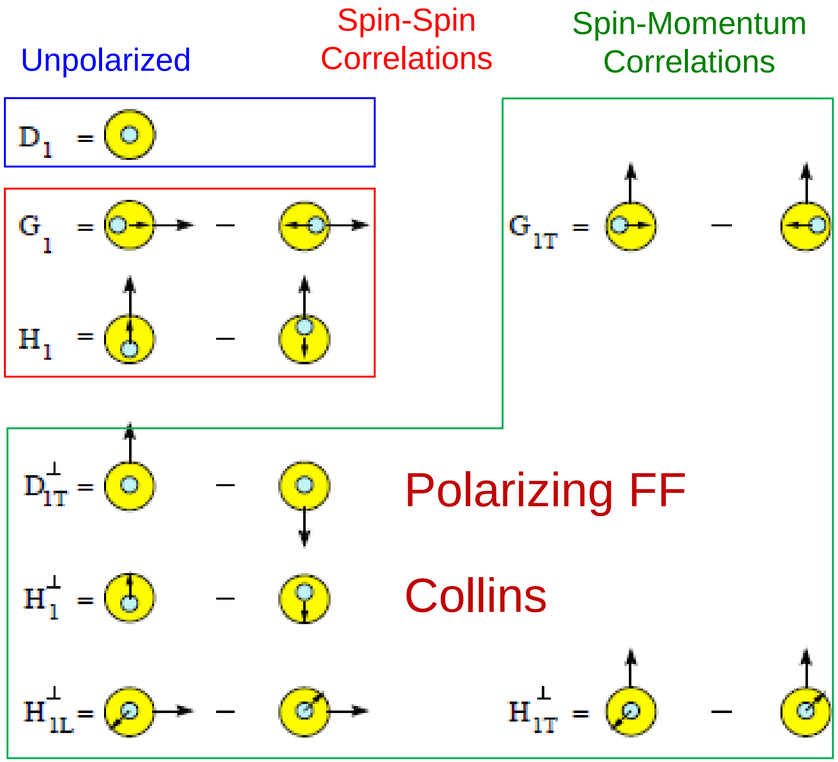
3D Fragmentation



$D_h^a(z, p_t^2; Q^2)$

Ex. p_t-dependent FF for a given combination of parton and hadron species

Final transverse momentum of the detected pion $\mathbf{P}_t$ arises from convolution of the struck quark transverse momentum $\mathbf{k}_t$ with the transverse momentum generated during the fragmentation $\mathbf{p}_t$.



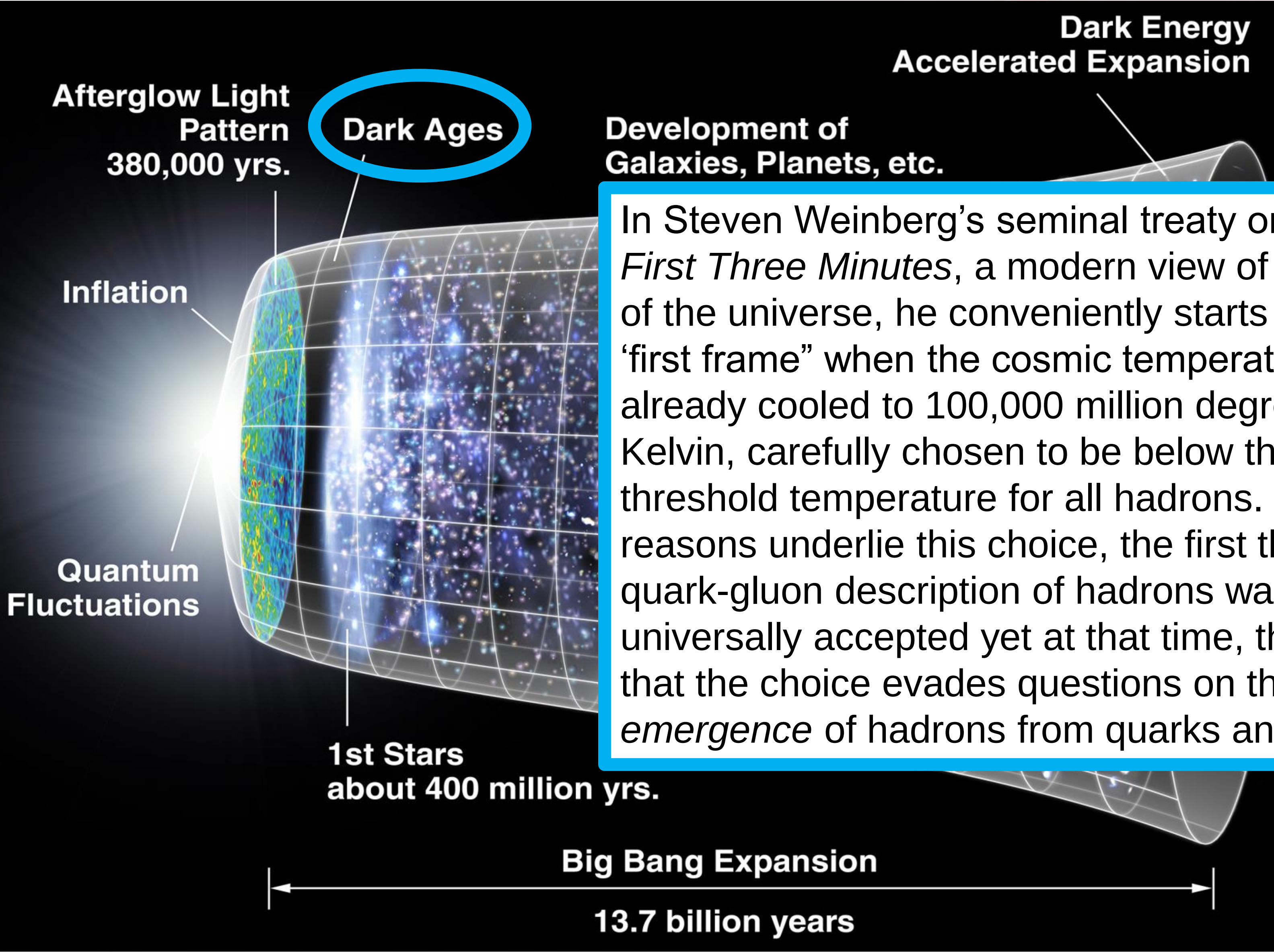
$$\boxed{\sigma = \sum_q e_q^2 f(x) \otimes D(z)}$$

$$f^a(x, k_T^2; Q^2)$$

$$D_a^h(z, p_t^2; Q^2)$$

Understanding of the 3D structure of fragmentation into a hadron requires studies of transverse momentum, spin and hadron species dependence

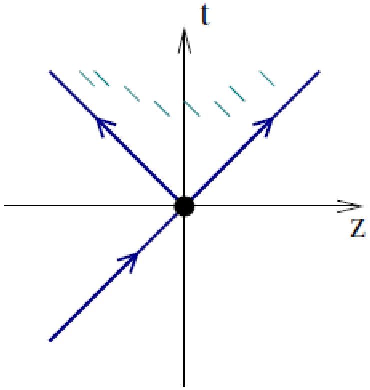
Timeline of the Universe



In Steven Weinberg’s seminal treaty on *The First Three Minutes*, a modern view of the origin of the universe, he conveniently starts with a ‘first frame” when the cosmic temperature has already cooled to 100,000 million degrees Kelvin, carefully chosen to be below the threshold temperature for all hadrons. Two reasons underlie this choice, the first that the quark-gluon description of hadrons was not universally accepted yet at that time, the second that the choice evades questions on the *emergence* of hadrons from quarks and gluons.

Lessons from the 70s to Now

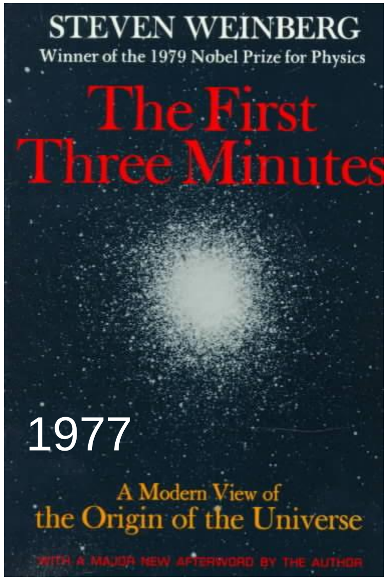
The emergence of hadrons – mass from massless gluons and nearly-massless quarks



Space-time view of parton model idea of hadronization (in γ^*p CM frame)

Basis on Parton Model Intuition:
- Localization in space-time & momentum
- Lorentz contraction, time dilation, causality
- Sharp separation of scales (…)
- Ideas about string-like hadronization

Issues: no direct connection with field theory
Sharp separation of scales?
Final state evolution in space-time??

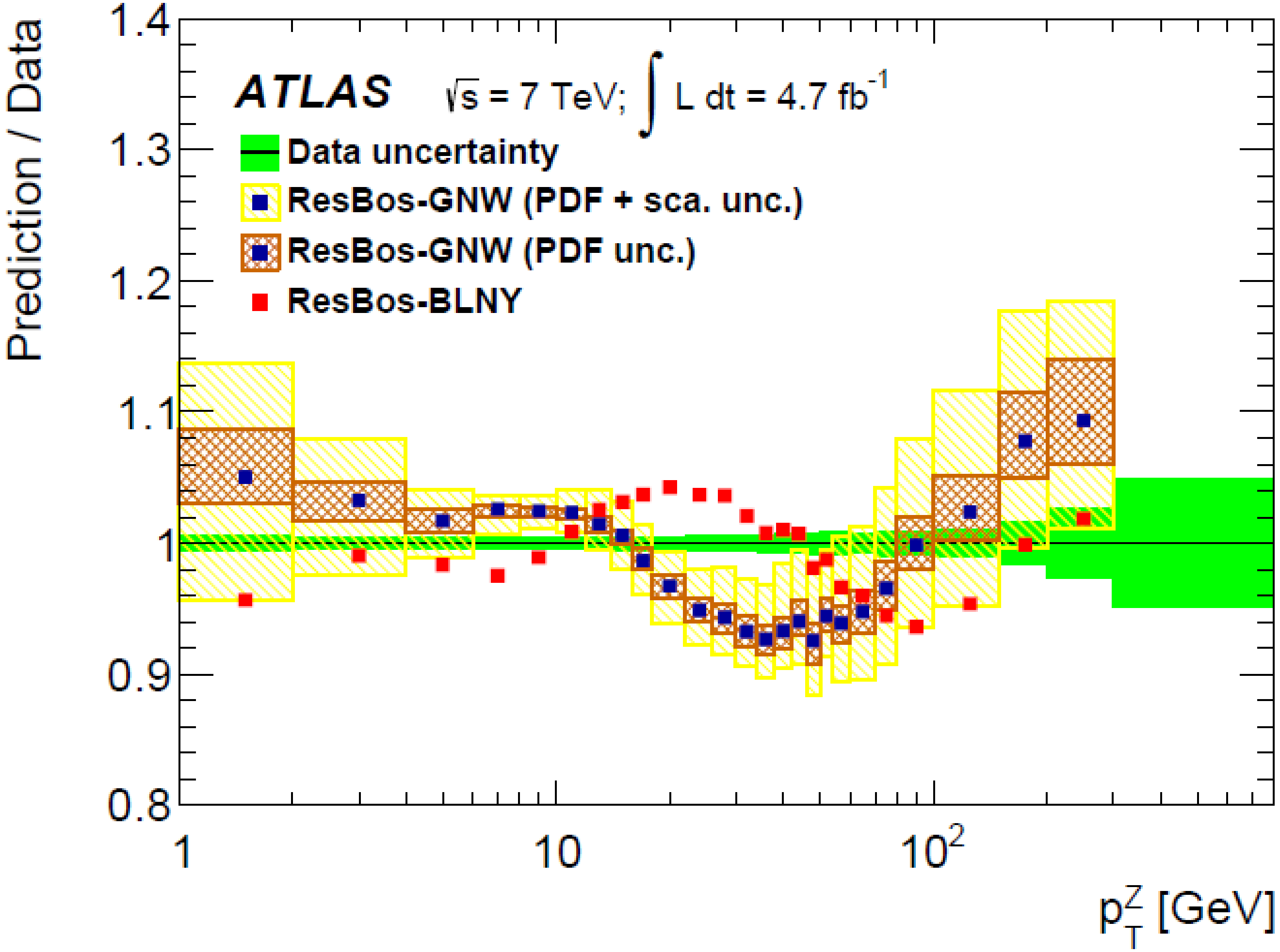


1977

History/timeline
- Late 60s/early 70s: Parton Model
- QCD ~ 1974
- Factorization ~ 1980
- ~2008 Transverse spin physics provokes new definition of pdfs (TMDs) - Back to need for separation of scales

Successful predictions at High E

Z production at the LHC



To Disembroil the Lund String

- Excellent description of high-energy transverse momentum spectra

  → Lund model must do something right…

- Started from best quantum mechanical insight of the time (Schwinger)
- Incorporates acquisition of mass and transverse momentum

$$\mathcal{P} \propto e^{-\frac{\pi m_{q\perp}^2}{\kappa}} = e^{-\frac{\pi m_q^2}{\kappa}} e^{-\frac{\pi p_\perp^2}{\kappa}}$$

- The transverse momentum acquired in the LUND string model a la Schwinger is about what we see from the (early stage) TMD analyses.
- Is there reciprocity between TMDs and fragmentation?

What does the Lund Model know that we don't know?

Successful at High E, but …

There have been important conceptual advances (. . .) to recent times.
One important area needing much further advance:

> How do we properly and accurately understand the space-time evolution from a state simply described in terms of a few partons of large relative rapidity to a measurable state of many hadrons?

→ Objects like correlation functions (fragmentation functions (TMD, collinear, dihadron, etc) need to be resolved and studied in terms of their underlying non-perturbative physics.

Connecting the NP and HEP Descriptions

LDRD Scope: Map the non-perturbative description of hadronization in the Pythia MCEG to the correlation functions of TMD factorization.

(**Diefenthaler**, Collins, Joosten, Lönnblad, Melnitchouk, Prestel, Rogers, Sato, Sjöstrand)

Hadronization / fragmentation:

- How do partonic degrees of freedom transform into the experimentally observed hadrons?

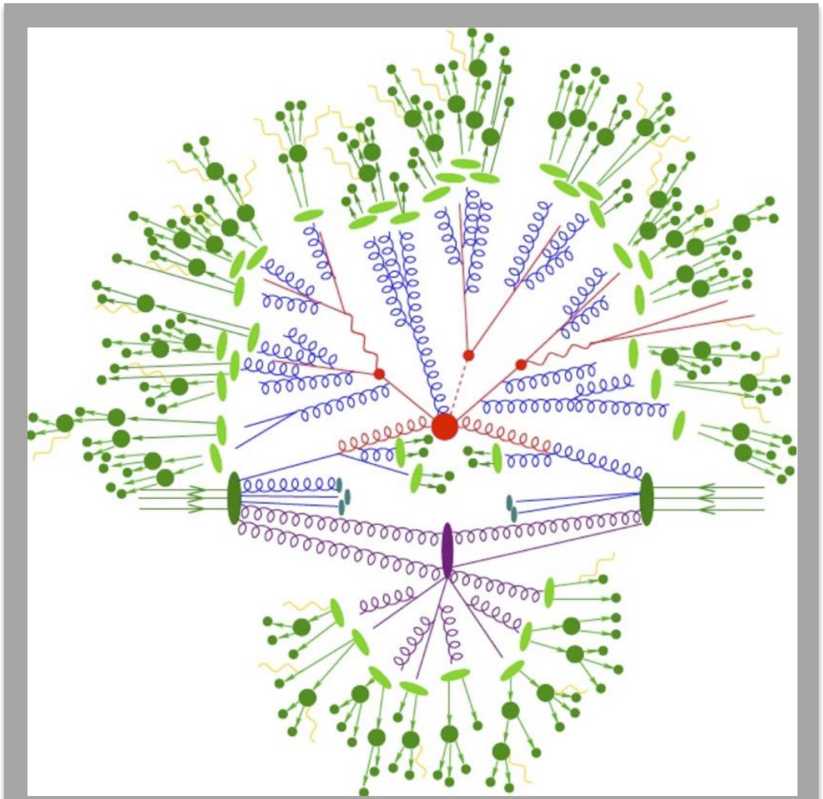
Pythia MCEG

- deal with the theory of final state hadronization in high-energy collisions.

QCD factorization theorems

- first principle QCD calculations of specific cross sections
- non-perturbative physics is contained in **universal** correlation functions

It is critical for the two to be combined if QCD studies of non-perturbative structure are to proceed.

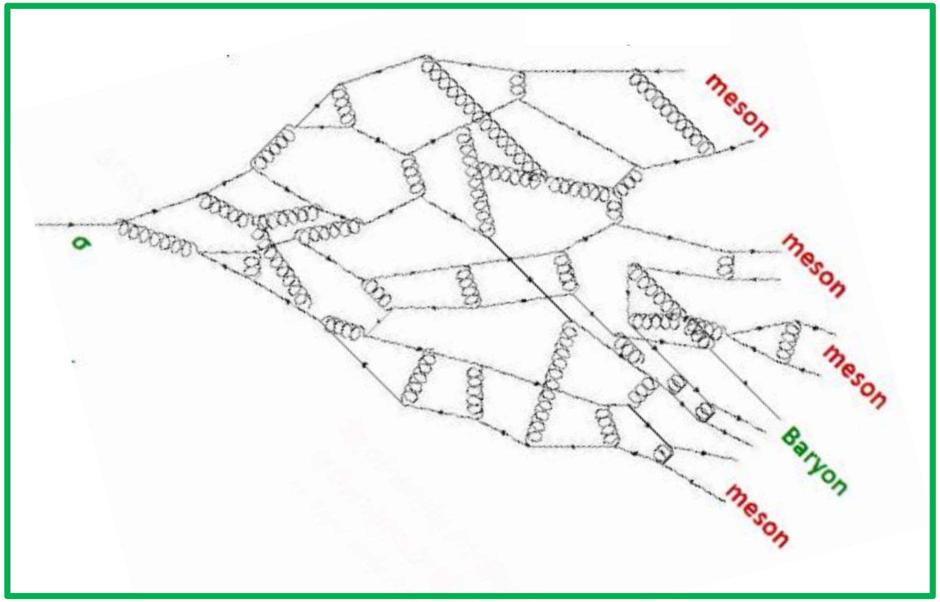


Theoretical description of a collision process

Fragmentation Process

- Colored object
- Nearly massless object
- Asymptotically free object

- Colorless objects
- Massive objects
- Confined objects



Color to colorless

→ loss of color? No, color of first parton always was balanced by another leg.

Characteristics of fragmentation process must be influenced by

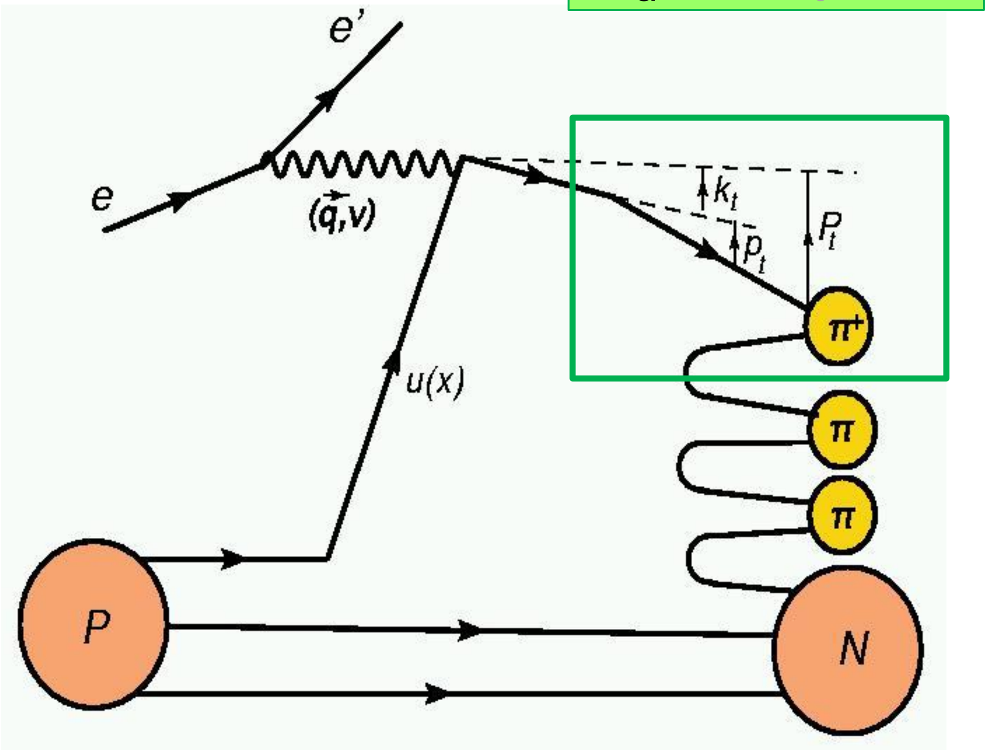
- Dynamical Chiral Symmetry Breaking
- Confinement

Color neutralization – it's a correlated 3D problem

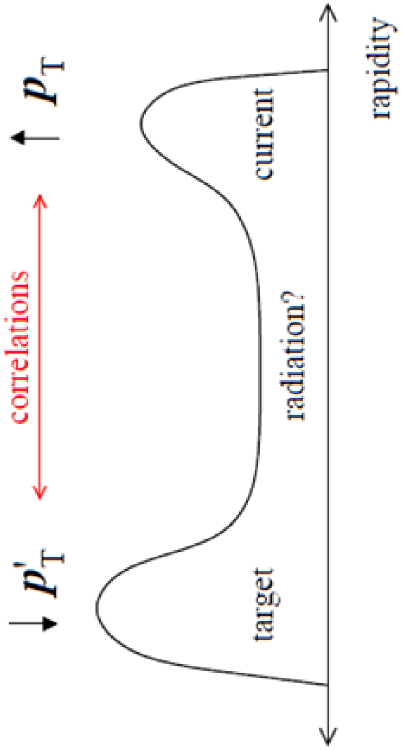
Final transverse momentum of the detected pion **P_t** arises from convolution of the struck quark transverse momentum **k_t** *with the transverse momentum generated during the fragmentation* **p_t**.

Can we learn more on how hadrons emerge from color charge by correlating one hadron with the residual system, and *track where it's momentum and spin originate*?

$D_u^{\pi^+}(z,p_t^2,Q^2)$

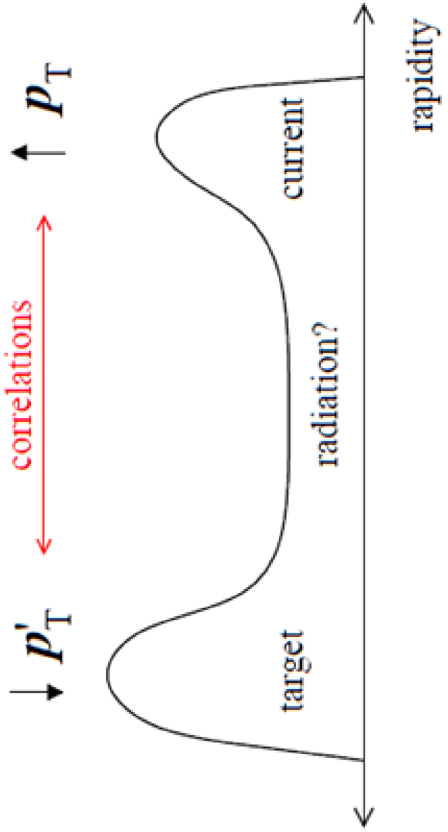


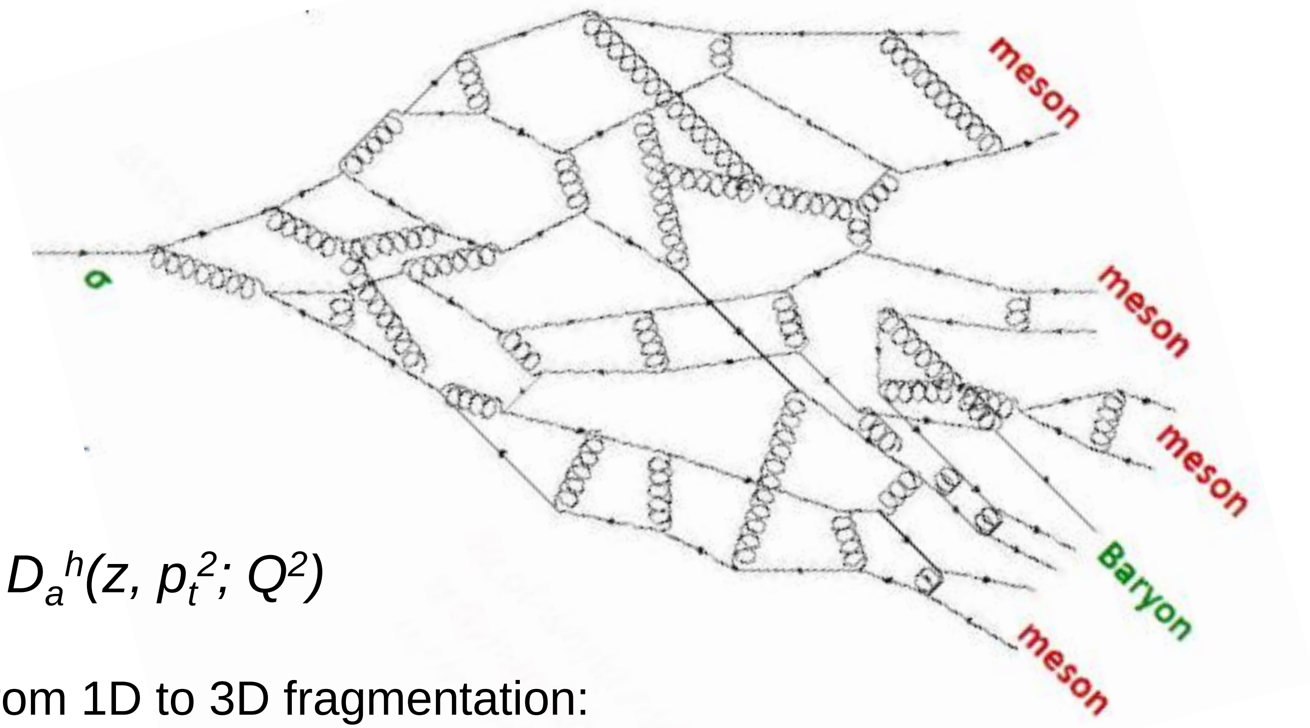
Mass of hadrons = E/c^2



Towards a QM Description of the Final State

Balancing the transverse momentum – candles of space-time





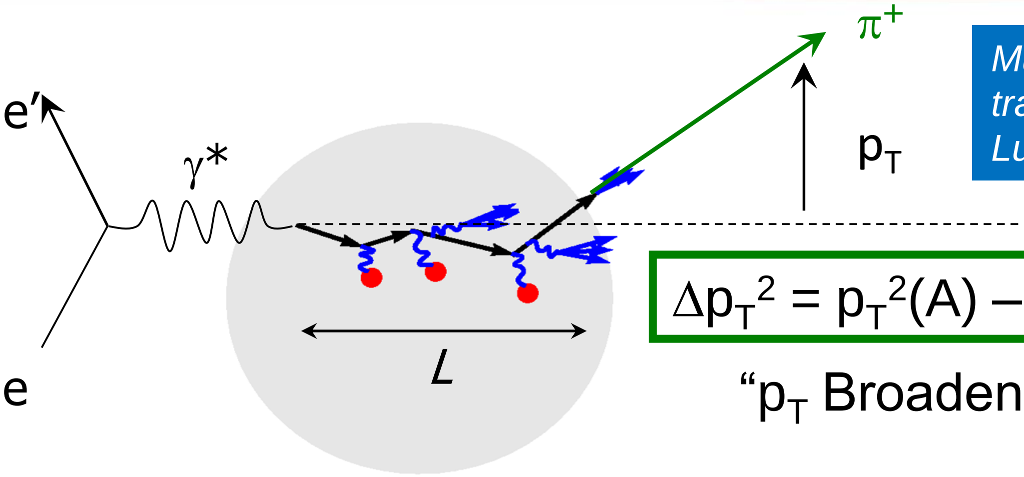
$D_a^h(z, p_t^2; Q^2)$

From 1D to 3D fragmentation:

- Many more variables,
  Many more angles
- Multi-dimensional data
- Fine binnings

First step is always unpolarized cross sections → JLab/12 GeV (but limited in kinematics)

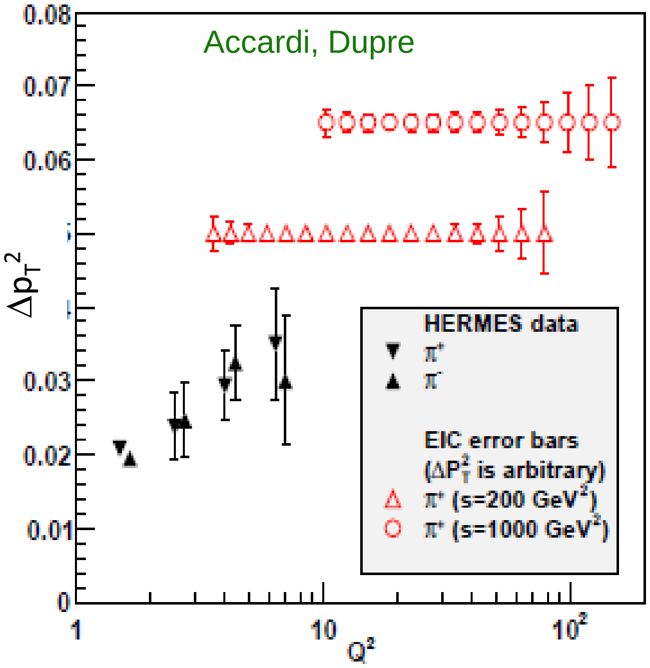
Hadronization – parton propagation in matter



Multiple gluon scattering making transverse momentum beyond the Lund string-breaking mechanism

$$\boxed{\Delta p_T^2 = p_T^2(A) - p_T^2(^2H)}$$

"p_T Broadening"



Comprehensive studies possible:

- wide range of energy ν = 10-1000 GeV
- wide range of Q^2: evolution
- Hadronization of charm, bottom
- High luminosity for 3D and correlations

EIC: Understand the conversion of color charge to hadrons through fragmentation and breakup

Towards a QM Description of the Final State

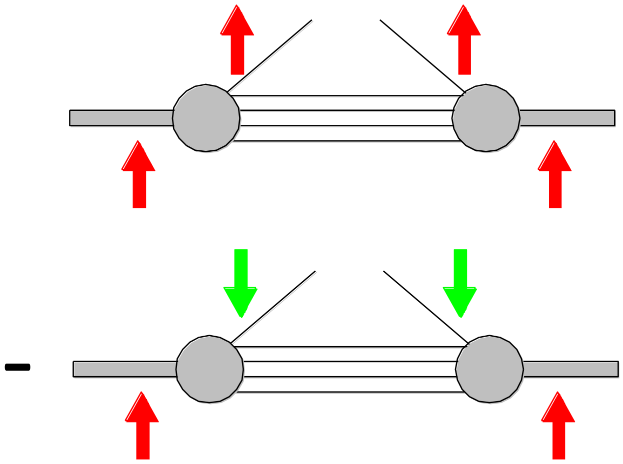
The Collins Function – candle of DχSB

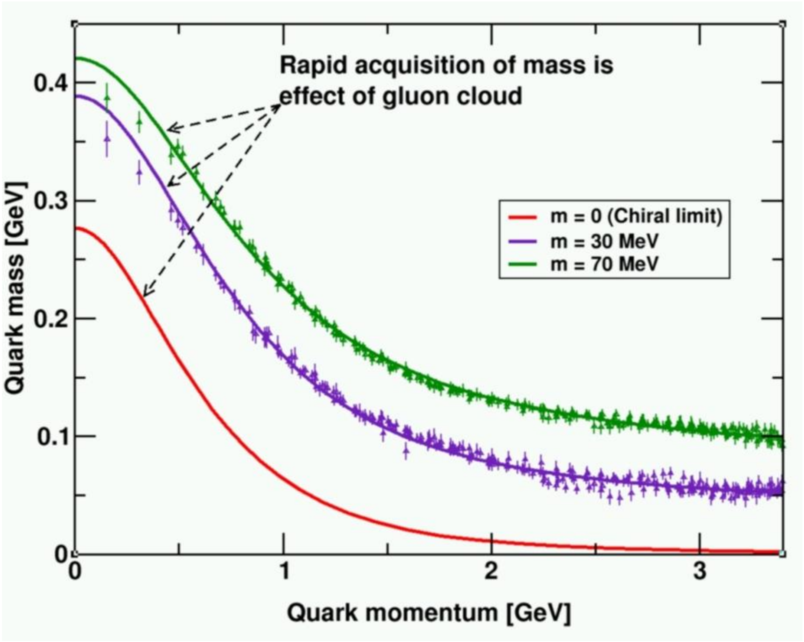
Recall the origin of the Collins function as motivated by forward π spin asymmetry. Requirements for non-zero effect:

1) Interference – helicity must be heavily broken. Can't be by small current quark mass as ~ m_q/Q. Chiral symmetry breaking (in dynamical situation) can do it.
2) Transverse momentum correlations.

$\delta q(x)$ ~

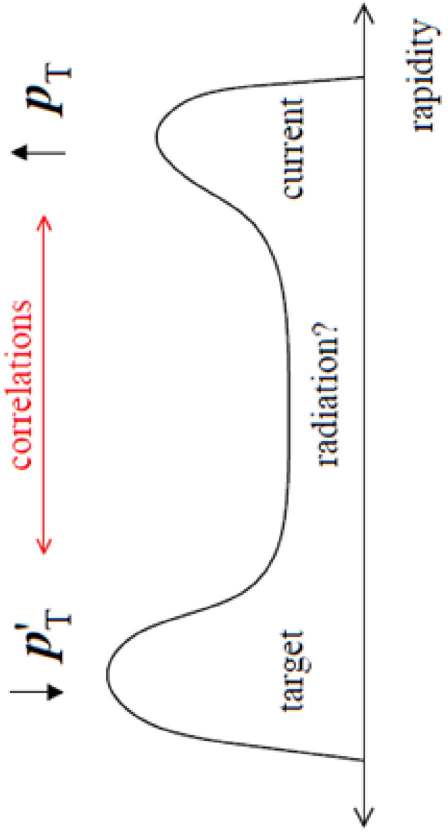
(in transverse basis)

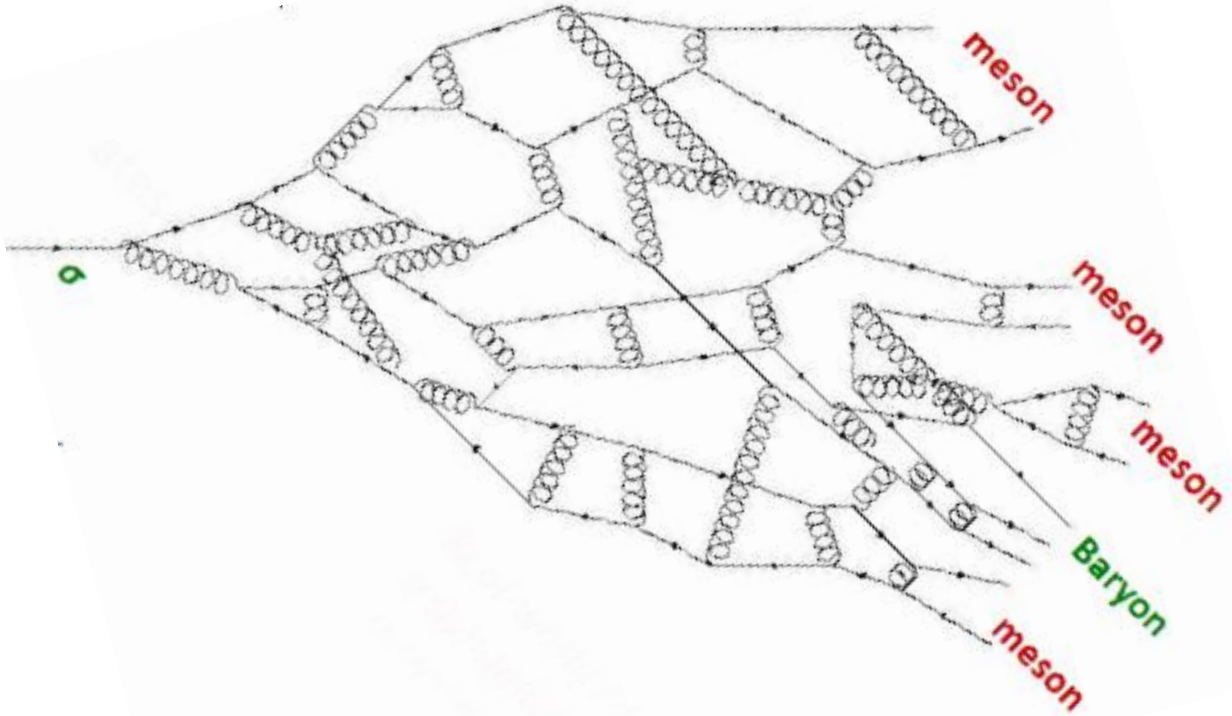



Rapid acquisition of mass is effect of gluon cloud

Towards a QM Description of the Final State

The Collins Function – candle of DχSB



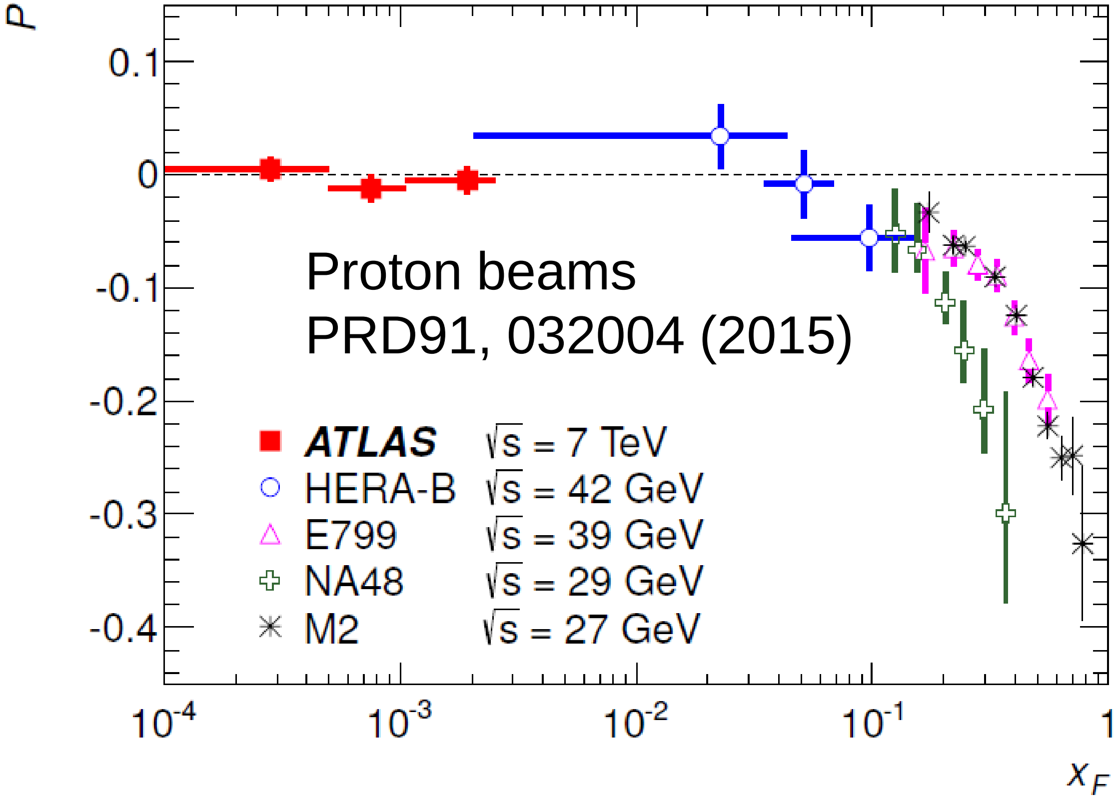


EIC: Map the Collins function over the regions of rapidity?

Towards a QM Description of the Final State

Balancing the Spin

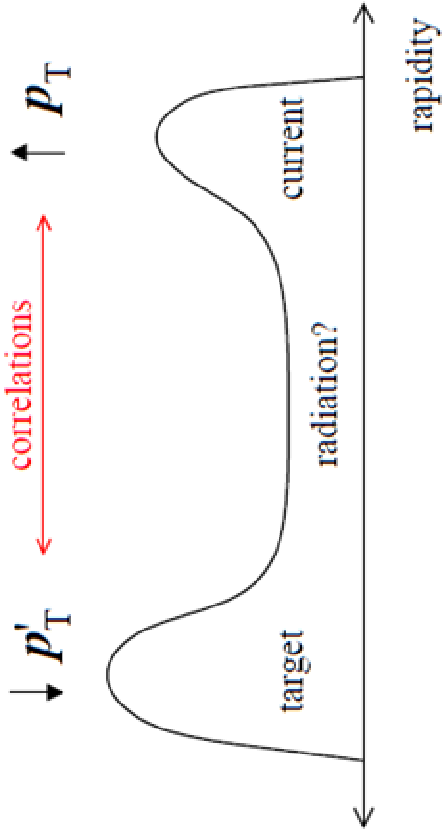
Feynman-x dependence of Λ Polarization in hadronic collisions

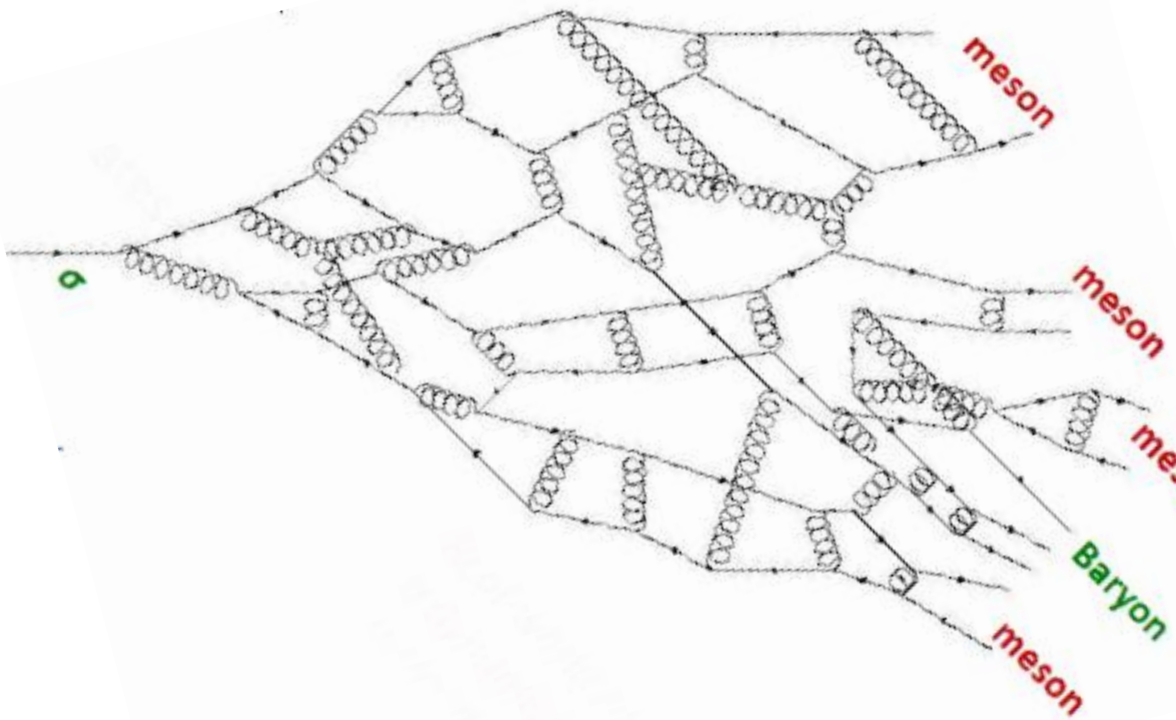


Proton beams
PRD91, 032004 (2015)

Towards a QM Description of the Final State

Balancing the Spin

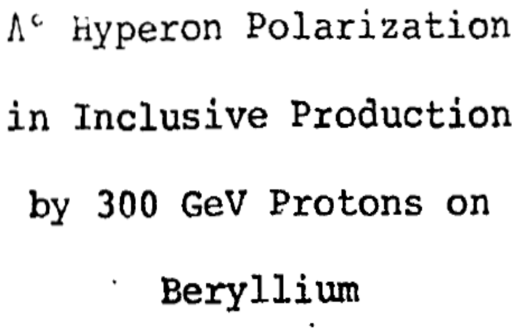




What happens with spin degrees of freedom over the regions of rapidity? Naively one would assume spin diffuses with a few quark-gluon scatterings. Or not …???

Towards a QM Description of the Final State

Creating Polarization from Nothing – the prototype example



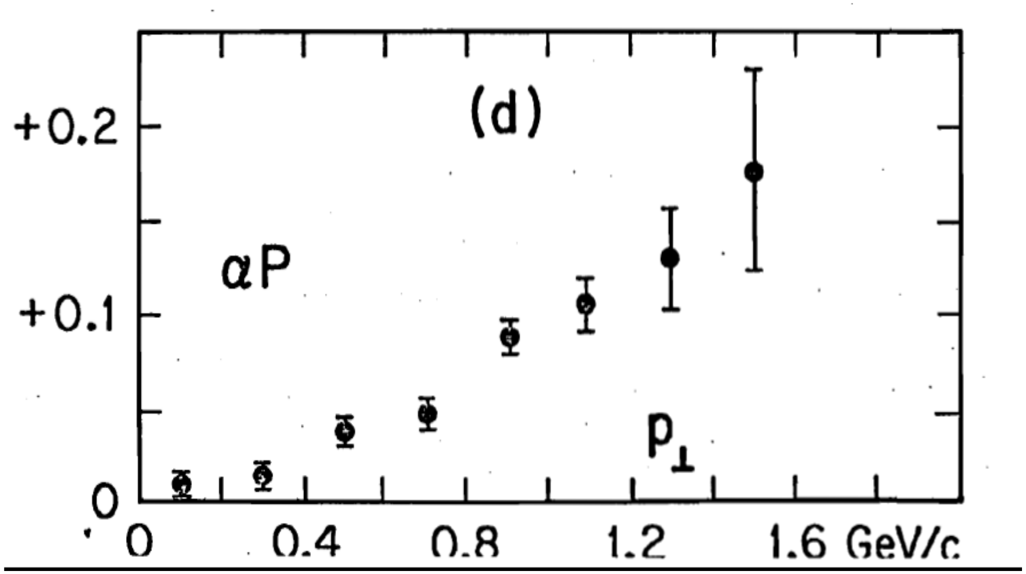
Λ^0 Hyperon Polarization

in Inclusive Production

by 300 GeV Protons on

Beryllium

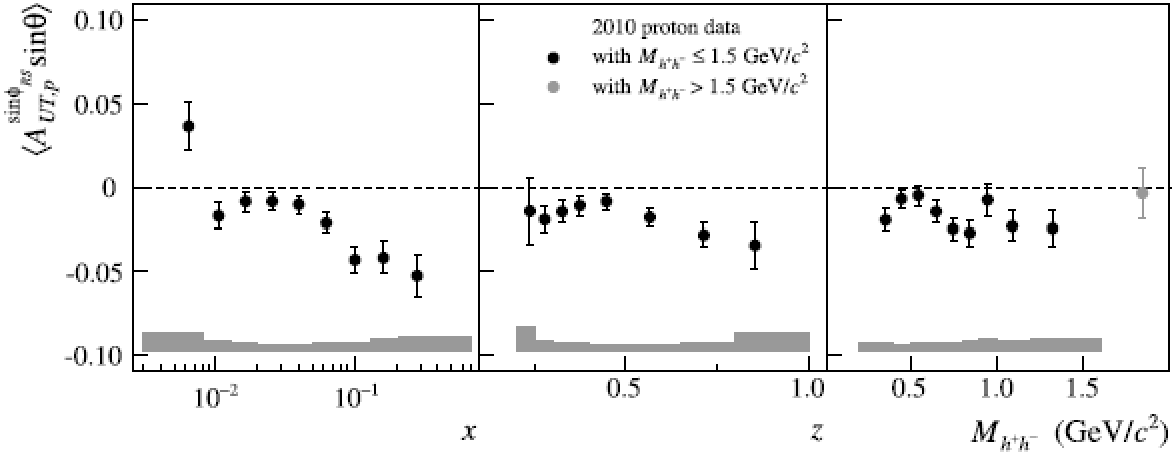
PRL36, 1113 (1976)



Towards a QM Description of the Final State

Creating Polarization from Nothing – some recent TMD examples

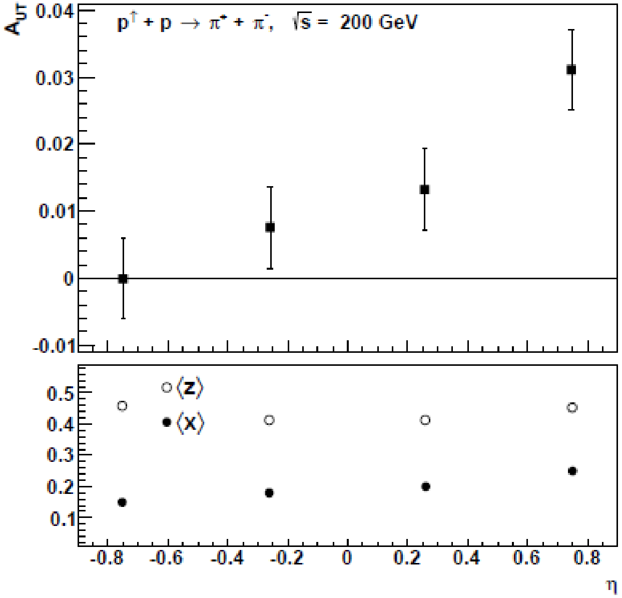
Di-hadron interference fragmentation function



COMPASS, PLB736, 124 (2014)

Transverse single-spin asymmetry in dihadron production, 200 GeV p+p

STAR, PRL 115, 242501 (2015)



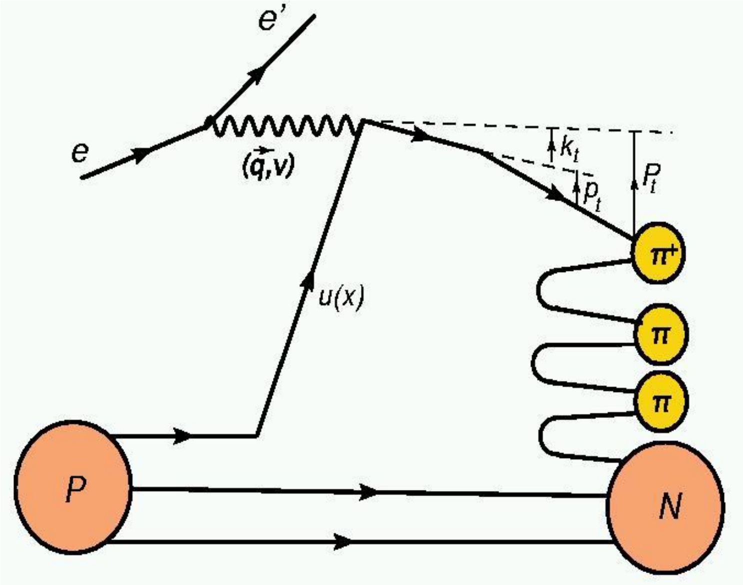
- Pion pair hadronizes from same quark
- correlation with quark transverse spin
- chiral-odd

- Clear nonzero asymmetry
- Pseudorapidity dependence
- Sensitive to transversity x IFF

Towards a QM Description of the Final State

Creating Polarization from Nothing

Boer-Mulders effect can create polarization due to spin-orbit correlations. Since spin in fragmentation process likely dilutes fast, maybe perhaps more a 12-GeV experiment.



Want only few pions produced

$$e + p \rightarrow e' + \overrightarrow{p} + X \text{ (few mesons only…)}$$

There could be measurable polarization of the proton in the final state in a fully unpolarized SIDIS process!
→ looking into possible JLab 12-GeV proposal.

Summary

- Overall goal of Jefferson Lab SIDIS Program (in x > 0.1 region):

  validate basic reaction mechanism of SIDIS at JLab energies

  and then

  spin and flavor dependence of quark transverse momentum distributions

- There are indications from both theory (lattice, chiral constituent quark model) and experimental data of different k_T dependences of quark flavor distributions

- The final hadron following the SIDIS process accumulates a momentum transverse to the beam direction by a convolution of the transverse momentum of the struck quark and the transverse momentum of the additional antiquark. This turns the understanding of fragmentation into a correlated 3D problem.

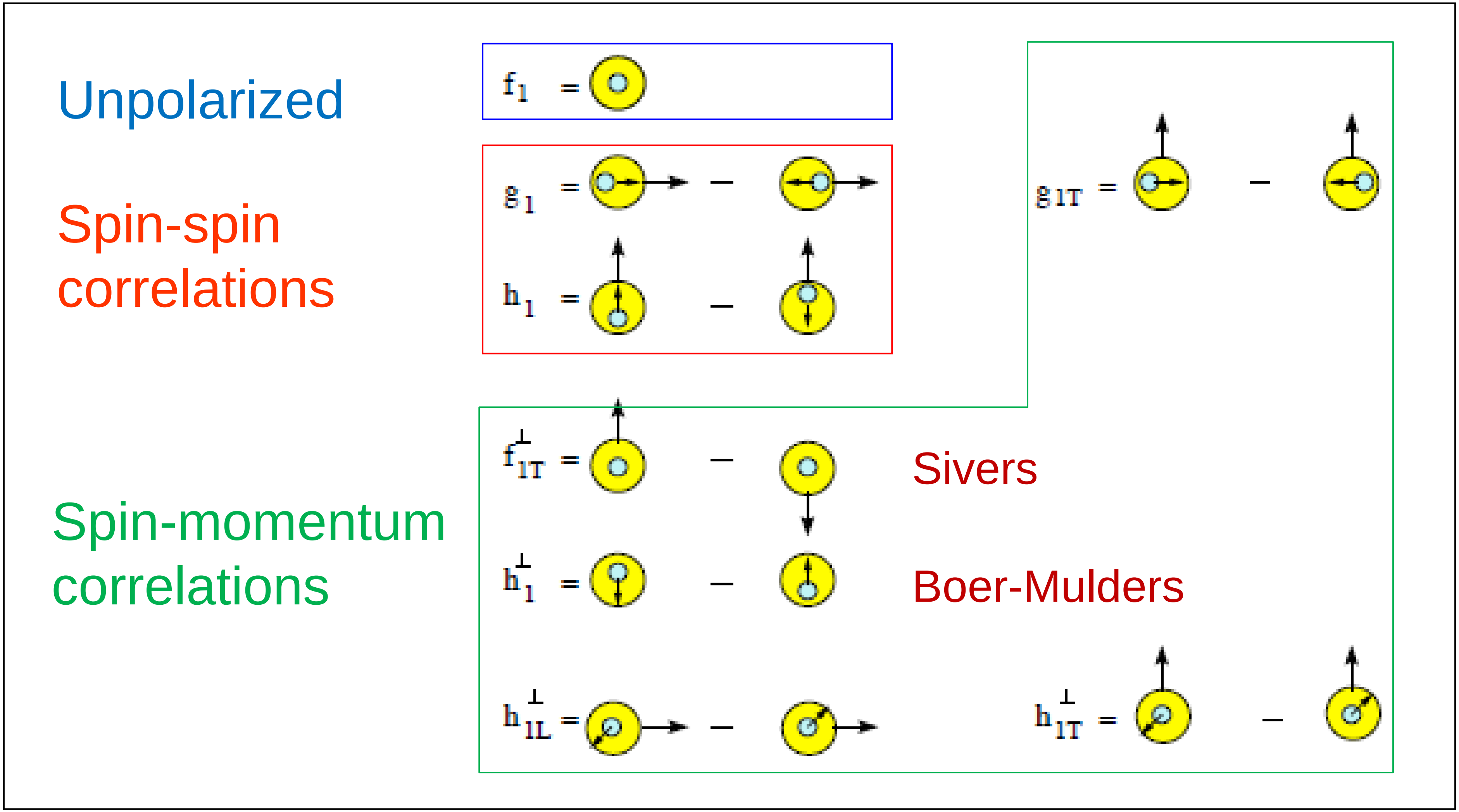
- Objects like correlation functions (fragmentation functions (TMD, collinear, dihadron, etc) need to be resolved and studied in terms of their underlying non-perturbative physics.

- Characteristics of fragmentation process must be influenced by
  - Dynamical Chiral Symmetry Breaking
  - Confinement

  We should isolate experimental signatures that are most likely to give insight

Twist-2 **3D** Distribution Functions

$f^a(x, k_T^2; Q^2)$



Unpolarized

Spin-spin correlations

Spin-momentum correlations

Sivers

Boer-Mulders

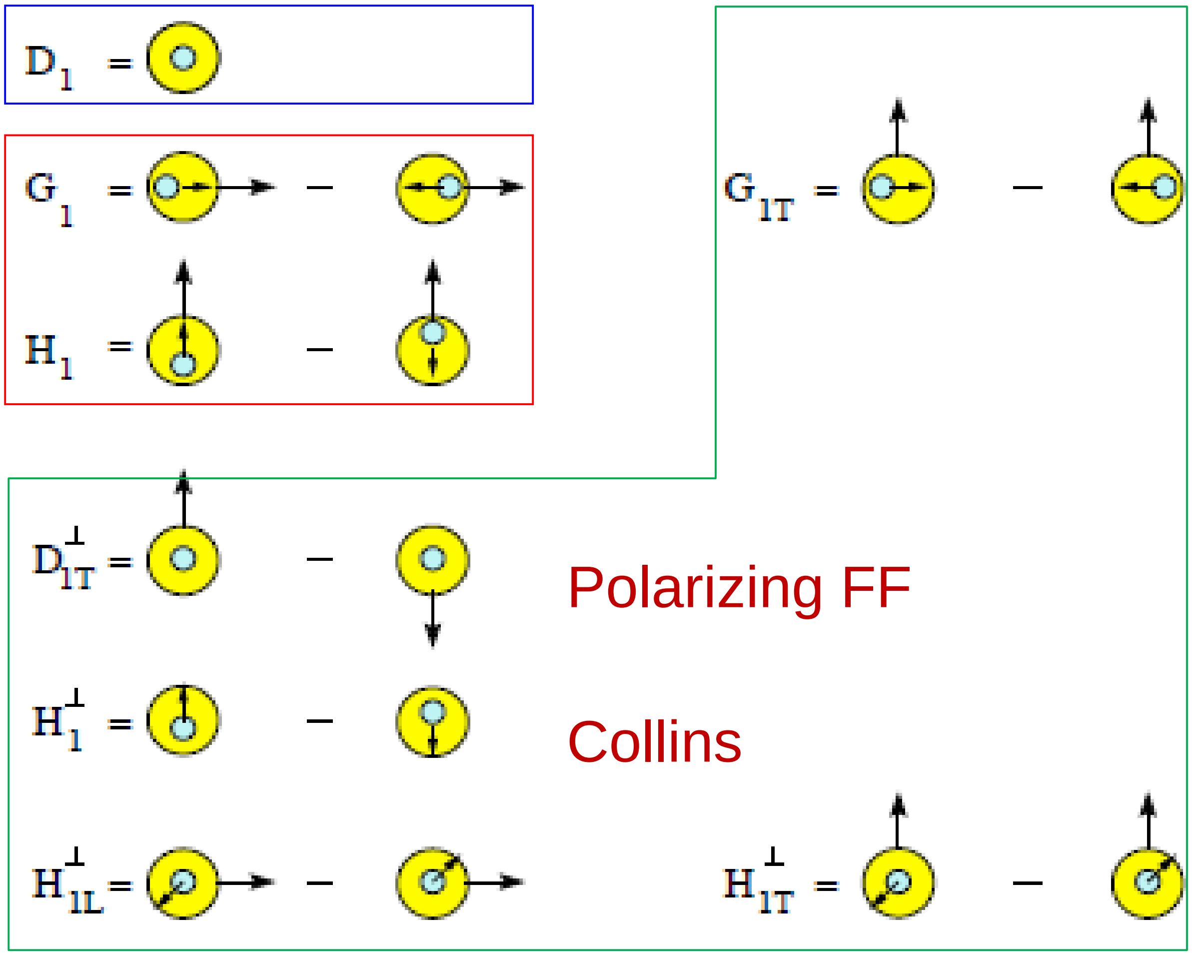
Twist-2 3D Fragmentation Functions

$D_a^h(z, p_t^2; Q^2)$

Unpolarized

Spin-spin correlations

Spin-momentum correlations



Polarizing FF

Collins

JLab Tentative Timeline

- Up to FY17: 12-GeV Upgrade Project ongoing
- FY16: ongoing program in
  - Hall A: Deeply-Virtual Compton Scattering &
    Proton Magnetic Form Factor
  - Hall B < 6 GeV science: Heavy Photon Search &
    Proton Radius Experiment
  - Hall C: Beam line/dump test
  - Hall D: GlueX engineering run
- FY17: completion of Halls C and B equipment upgrades
  official (DOE) start of 12 GeV science operations
- FY18: start of 4-Hall science operations
  (typical lifetime of facility science program ~ 15 years)

After few years:

- Precision Spatial and Momentum Imaging of Hadrons ←
  (note: flexibility as 12 GeV operations compatible with EIC operations)
- Somewhere beyond 2025: EIC construction complete

Hall C SIDIS Program – basic (e,e'π) cross sections

Why need for (e,e'π) cross sections?

PAC37 Report: "the **cross sections** are **such basic tests of the understanding of SIDIS** at 11 GeV kinematics that they will play a **critical role** in establishing the entire SIDIS program of studying the partonic structure of the nucleon. In particular they complement the CLAS12 measurements in areas where the precision of spectrometer experiments is essential, being able to separate P_T and ϕ-dependence for small P_T."

$$\boxed{\sigma = \sum_q e_q^2 f(x) \otimes D(z)}$$

Basic precision cross section measurements:

- Crucial information to validate theoretical understanding
  - Convolution framework requires validation for most future SIDIS experiments and their interpretation
  - Can constrain Q^2 dependence & TMD evolution
  - Questions on target-mass corrections and ln(1-z) re-summations require precision large-z data

Goal: Measure the basic SIDIS cross sections of **π^+, π^-, π^0 (and K^+)** production off the proton (and deuteron), including a map of the P_T dependence ($P_T \sim \Lambda < 0.5$ GeV), to validate$^{(*)}$ a flavor decomposition and the k_T dependence of (unpolarized) up and down quarks

$^{(*)}$ Can only be done using spectrometer setup capable of %-type measurements (an essential ingredient of the global SIDIS program!)

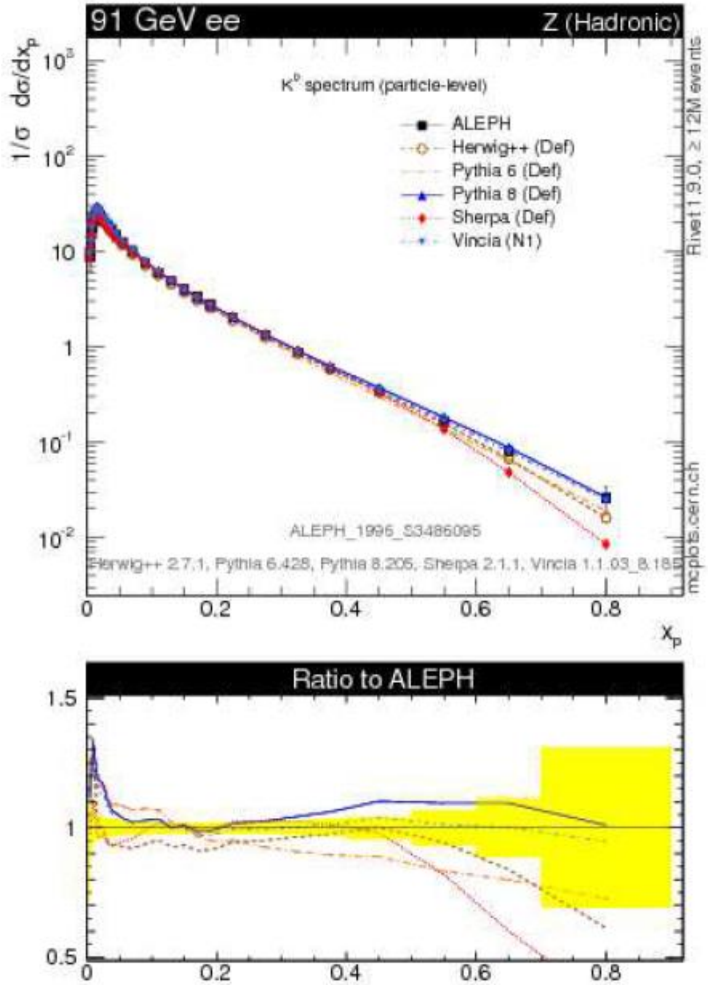
The Emergence of Hadrons

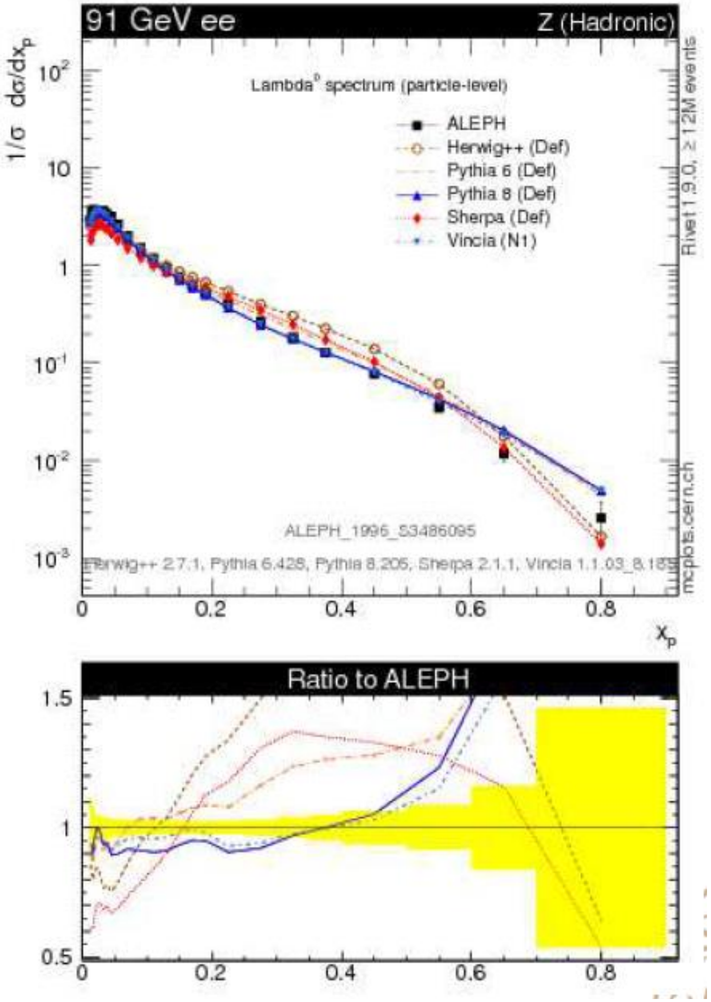
The emergence of hadrons – mass from massless gluons and nearly-massless quarks

Wikipedia – Emergence is a field of study, defined as:
In philosophy, systems theory, science, and art, emergence is conceived as a process whereby larger entities, patterns, and regularities arise through interactions among smaller or simpler entities that themselves do not exhibit such properties.

Sounds a bit like the larger baryons and mesons resulting through interactions from the smaller and simpler quarks and gluons, with different properties.

To Disembroil the Lund String

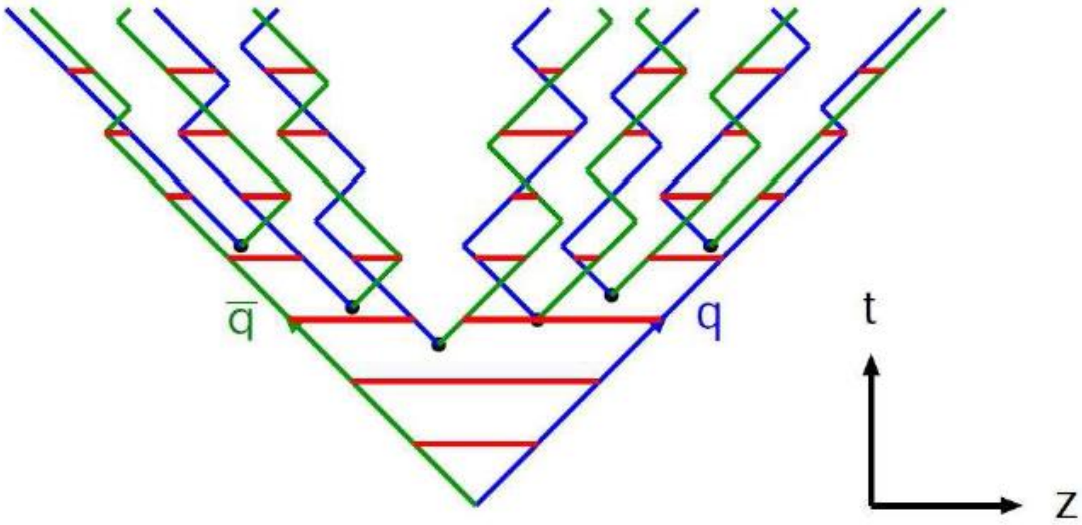




mcplots.cern.ch

Lund model must do something right…

To Disembroil the Lund String



The quarks obtain a mass and a transverse momentum in the breakup through a tunneling mechanism (à la Schwinger)

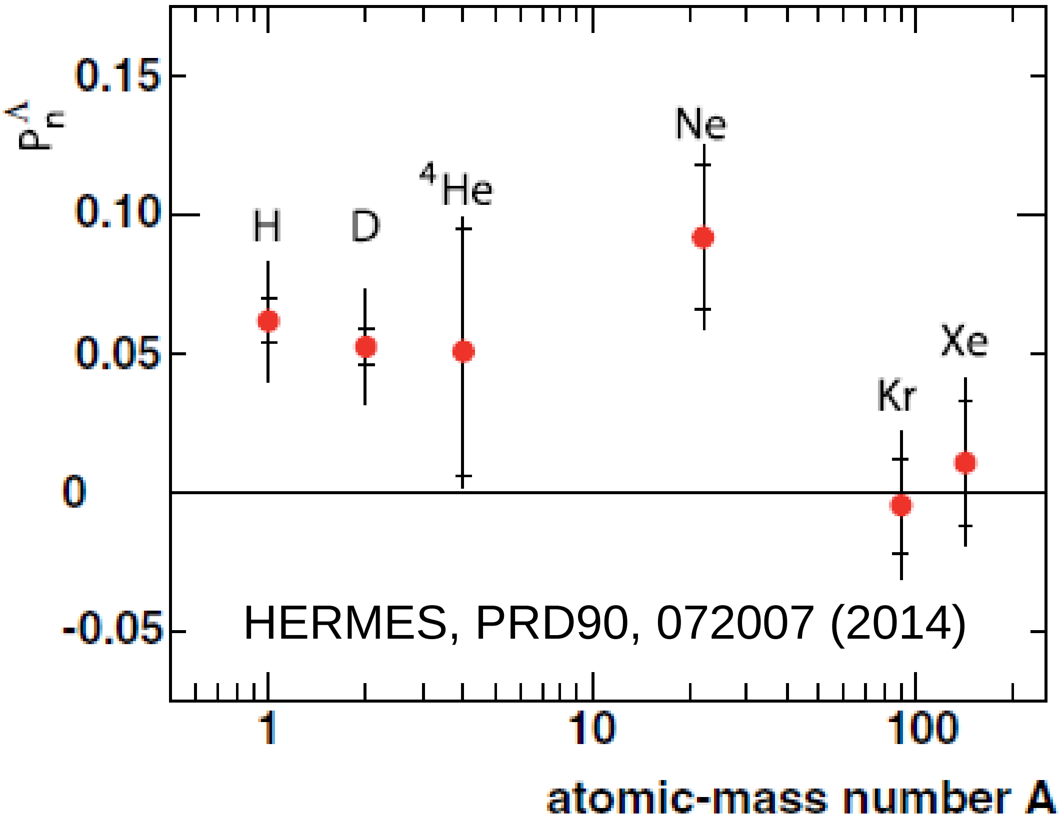
$$\mathcal{P} \propto e^{-\frac{\pi m_{q\perp}^2}{\kappa}} = e^{-\frac{\pi m_q^2}{\kappa}} e^{-\frac{\pi p_\perp^2}{\kappa}}$$

Gives a natural supression of heavy quarks

$d\bar{d} : u\bar{u} : s\bar{s} : c\bar{c} \approx 1 : 1 : 0.3 : 10^{-11}$

Towards a QM Description of the Final State

Creating Polarization from Nothing



HERMES, PRD90, 072007 (2014)

Lambda polarization maintained in the (light to medium-heavy) nuclear medium, as observed in semi-inclusive DIS

TMDs and SIDIS – General Formalism

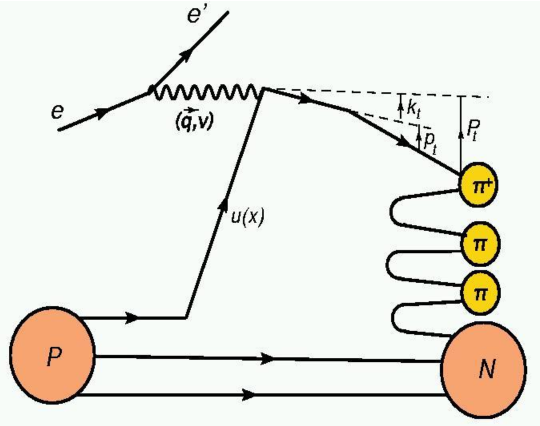
General formalism for (e,e'h) coincidence reaction w. polarized beam: [A. Bacchetta et al., JHEP 0702 (2007) 093]

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h,t}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\left\{\boxed{F_{UU,T}+\varepsilon F_{UU,L}}+\right.$$

$$\left.\underline{\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h}} + \underline{\varepsilon\cos(2\phi_h)F_{UU}^{\cos(2\phi_h)}} + \lambda_e\sqrt{2\varepsilon(1+\varepsilon)}\,\underline{\sin\phi_h F_{LU}^{\sin\phi_h}}\right\}$$

(Ψ = azimuthal angle of e' around the electron beam axis w.r.t. an arbitrary fixed direction)

If beam is unpolarized, and the (e,e'h) measurements are fully integrated over ϕ, only the $F_{UU,T}$ and $F_{UU,L}$ responses, or the usual transverse (σ_T) and longitudinal (σ_L) cross section pieces, survive.



$$\sigma = \sum_q e_q^2 f(x) \otimes D(z)$$

$P_T = p_t + z\,k_t + O(k_t^2/Q^2)$

Final transverse momentum of the detected pion $\mathbf{P_T}$ arises from convolution of the struck quark transverse momentum $\mathbf{k_t}$ with the transverse momentum generated during the fragmentation $\mathbf{p_t}$.