Overview of SoLID Program

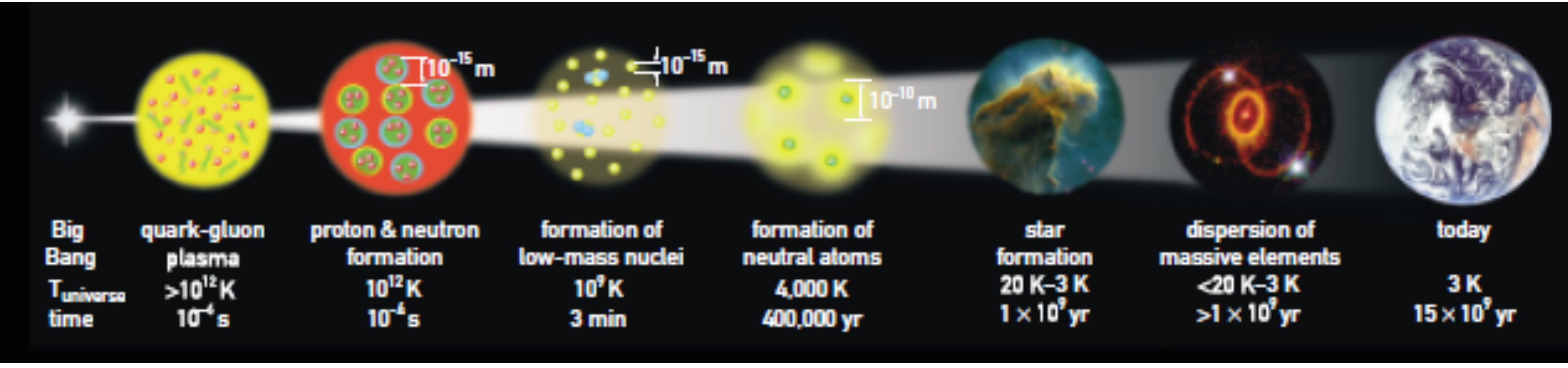
Jian-ping Chen, Jefferson Lab

INT-17-3, Seattle, Washington, Sept. 11, 2017

- Introduction: Nucleon Structure and Interactions
  Global Properties (Mass, Spin, …) and Internal Structure
- Jefferson Lab, 12 GeV Energy Upgrade and Physics Program
- SoLID Program
  - 3-d Structure of the Nucleon
    - **TMDs** and GPDs
  - Nucleon Mass and **J/ψ** Threshold Production
  - Test Standard Model: PVDIS
- SoLID Status
- Summary

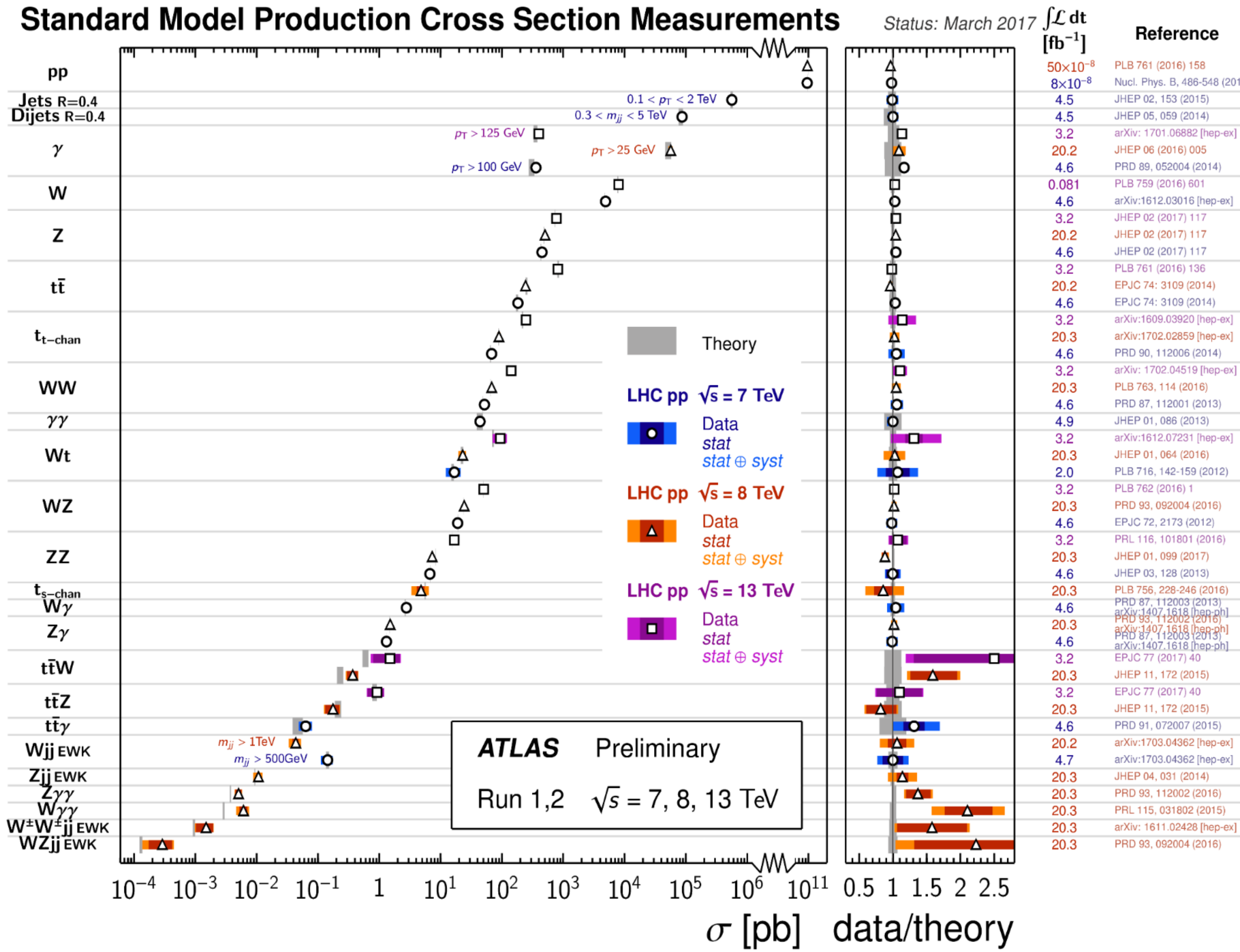
Introduction

Nucleon Structure and Strong Interaction (QCD)



Successes of the Standard Model

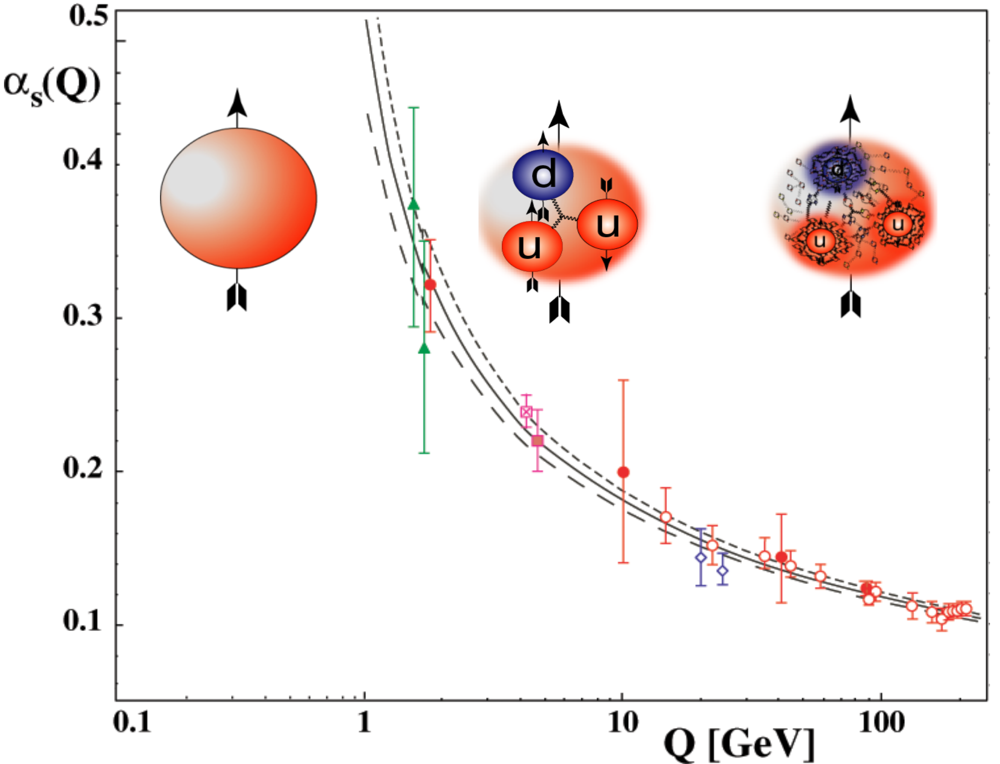
- **EW tested to high precision**
- **LHC:** *Higgs found*
  no evidence of BSM so far!
- **QCD tested at high energy**
  perturbative region
  pQCD works
  over a large range
  for many channels



Last Frontier in SM: QCD in Nonperturbative Region

- *2004 Nobel prize for ``asymptotic freedom''*
- *Non-perturbative regime QCD*
  Confinement ←→ dynamical chiral symmetry breaking ?
- *Nature's only known truly nonperturbative fundamental theory*
- *One of the top 10 challenges for physics!*
- *QCD: Important for discovering new physics beyond SM*
- *QCD vacuum*
- *Nucleon: stable lab to study QCD*

running coupling "constant"



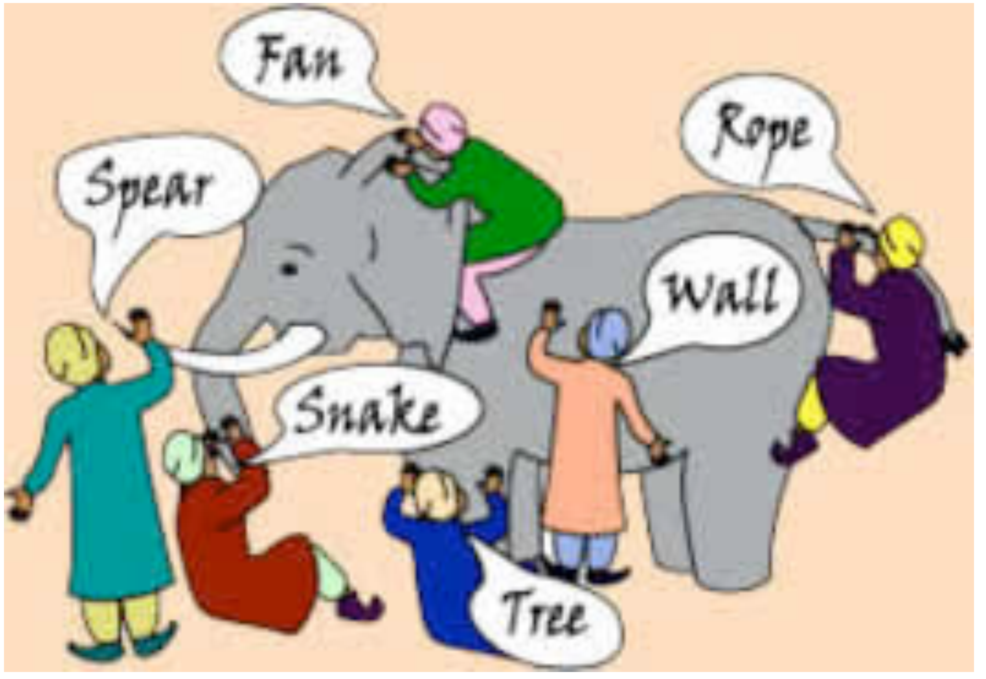
Nucleon Structure Study: Blind Men Touch Elephant

- *With the complexity of non-perturbative QCD, nucleon structure study is very challenging*
- *Precise 1d unpolarized PDF not enough*
- *1d spin shows surprise*
- *precision 3d (or multi-d) tomography needed*
- *But even that, it's not enough*

→ Need to ask good questions

→ Need good theory guidance

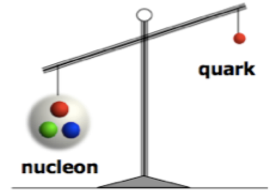
Turn on LIGHTS



Nucleon Structure: A Universe Inside

- Nucleon: proton =(uud) , neutron=(udd) *+ sea quarks + gluons (**QCD vacuum**)*
- Nucleon: ***99% of the visible mass in universe***

➢ **Proton mass "puzzle":**



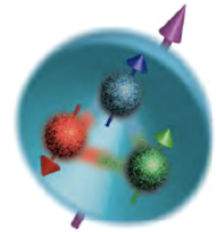
$m_q \sim 10$ MeV

$m_N \sim 1000$ MeV

Quarks carry $\sim 1\%$? of proton's mass

How does glue dynamics generate the energy for nucleon mass?

➢ **Proton spin "puzzle":**



Quarks carry $\sim 30\%$ of proton's spin

How does quark and gluon dynamics generate the rest of the proton spin?

➢ **3D structure of nucleon: 3D in momentum or (2D space +1 in momentum)**

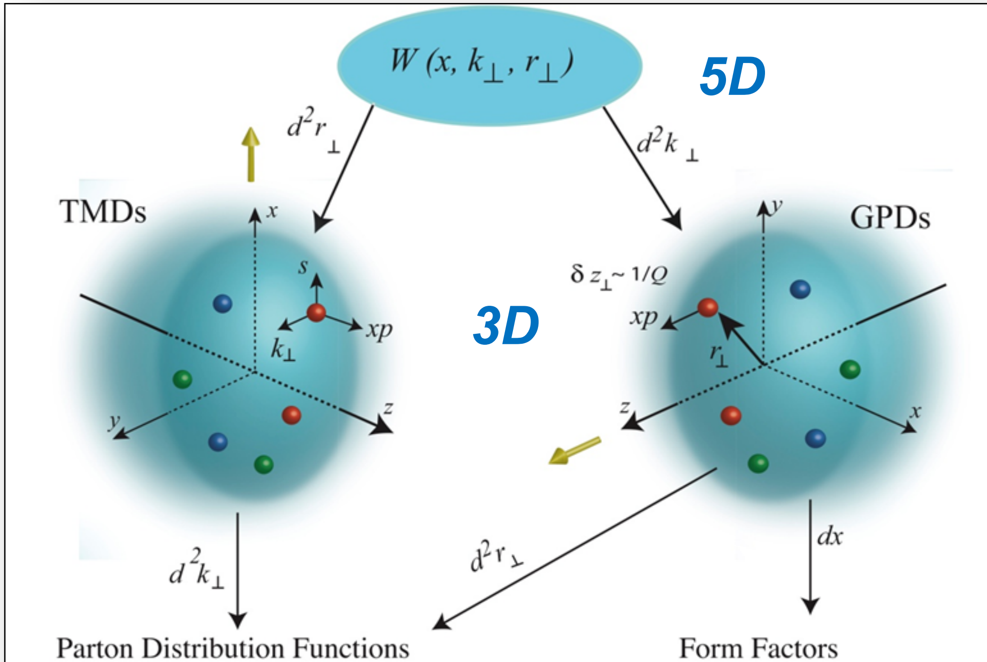
Color Confinement — Asymptotic freedom

200 MeV (1 fm) — 2 GeV (1/10) — Q (GeV)

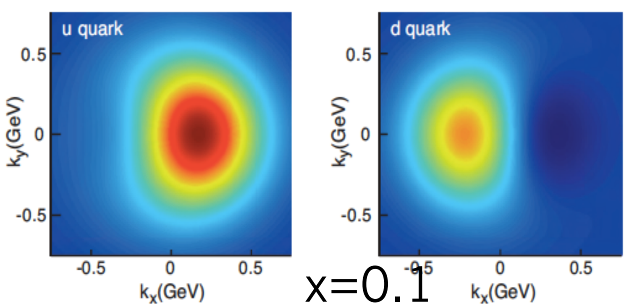
Probing momentum

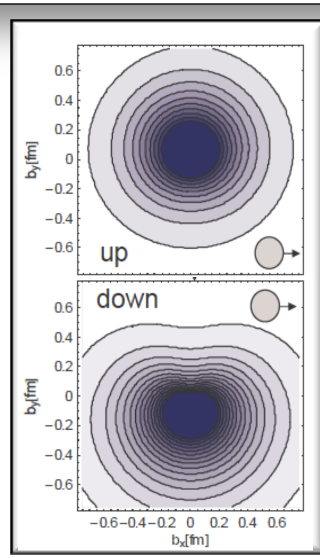
How does the glue bind quarks and itself into a proton and nuclei?
Can we scan the nucleon to reveal its 3D structure?

Nucleon Landscape (Tomography)



- ***Transverse Momentum Dist. (TMD)***
  - ***Confined motion in a nucleon (semi-inclusive DIS)***
- ***Generalized Parton Dist. (GPD)***
  - ***Spatial imaging (exclusive DIS)***
- ***Requires***
  - ***High luminosity***
  - ***Polarized beams and targets***
  - ***Sophisticated detector systems***





Major new capability with JLab @ 12 GeV COMPASS, … and EIC

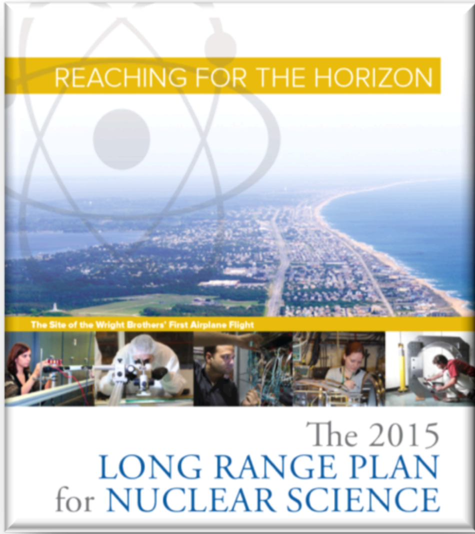
JLab and 12 GeV Energy Upgrade

12 GeV Physics Program

SoLID: Large Acceptance and High Luminosity

Cut-edge detectors/DAQ/Simulations/Reconstructions

Jefferson Lab is an Integral Part of the NSAC Long Range Plan



RECOMMENDATION I

The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to capitalize on the investments made.

- *With the imminent completion of the CEBAF 12-GeV Upgrade, its forefront program of using electrons to unfold the quark and gluon structure of hadrons and nuclei and to probe the Standard Model must be realized.* ***→ Operate 12 GeV CEBAF***

RECOMMENDATION II

We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

RECOMMENDATION III

We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.

→Jefferson Lab EIC (JLEIC) development

RECOMMENDATION IV

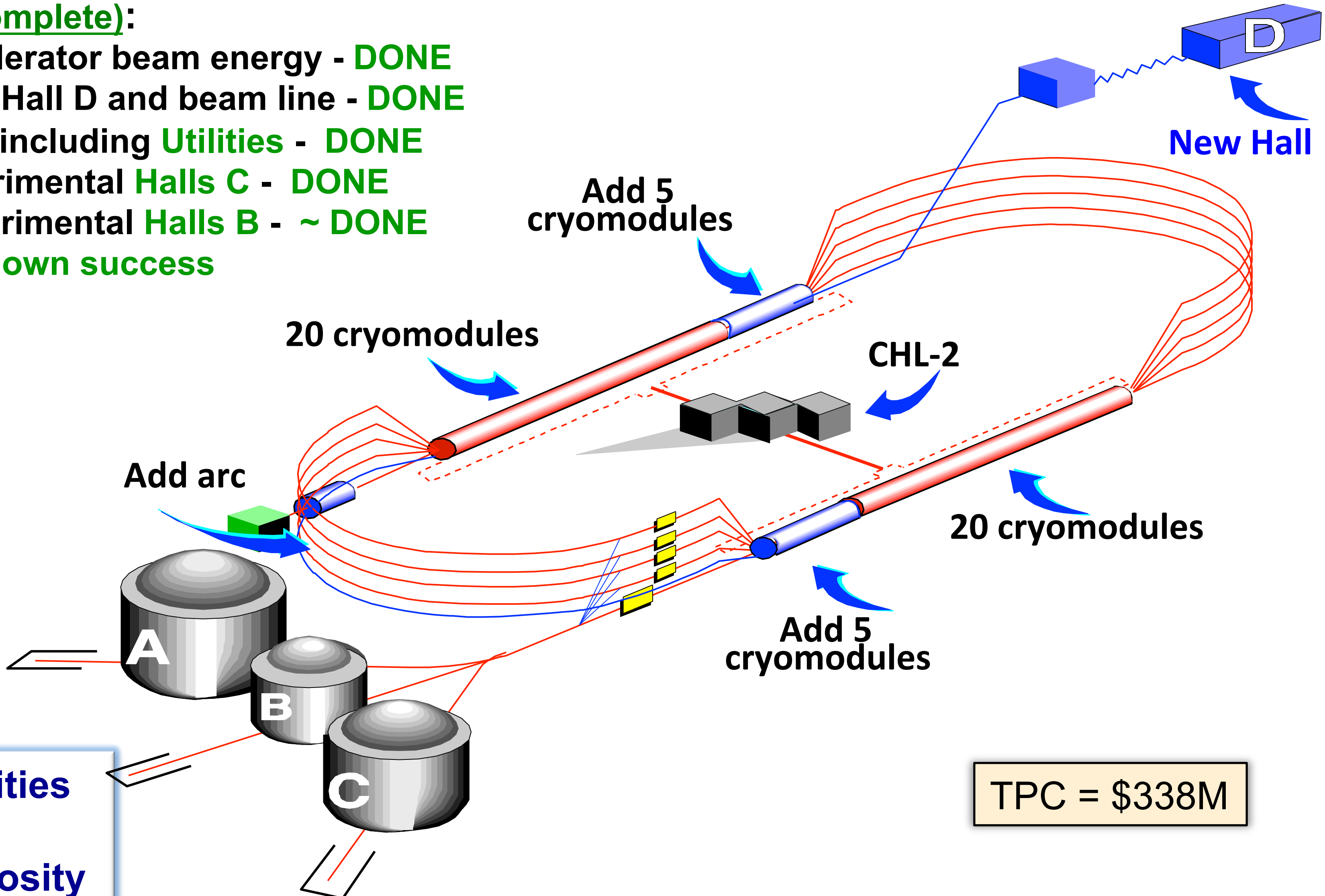
We recommend increasing investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories.

→ SoLID, MOLLER

12 GeV Upgrade Project

Project Scope (~ complete):

- Doubling the accelerator beam energy - DONE
- New experimental Hall D and beam line - DONE
- Civil construction including Utilities - DONE
- Upgrades to Experimental Halls C - DONE
- Upgrades to Experimental Halls B - ~ DONE
  - Solenoid cool-down success

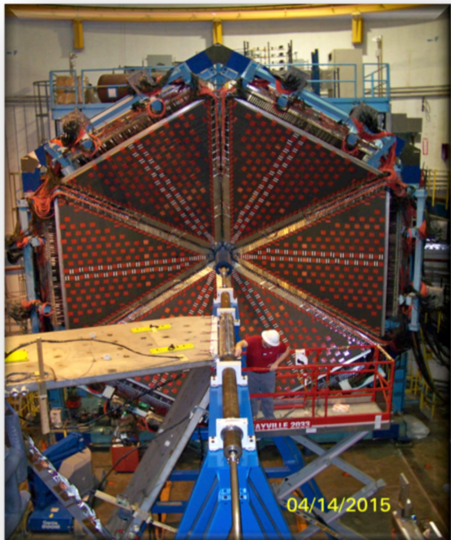


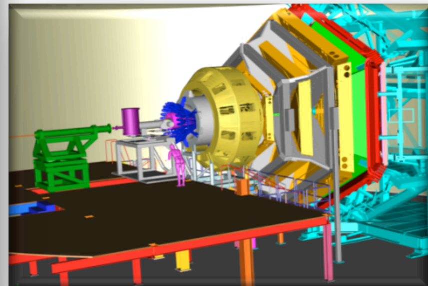
- Enhanced capabilities in existing Halls
- Increase of Luminosity 10^{35} - ~10^{39} $cm^{-2}s^{-1}$

TPC = $338M

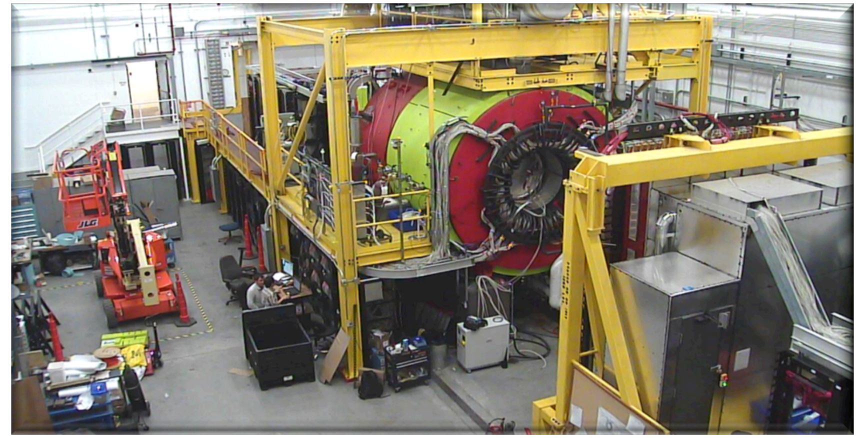
12 GeV Scientific Capabilities

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

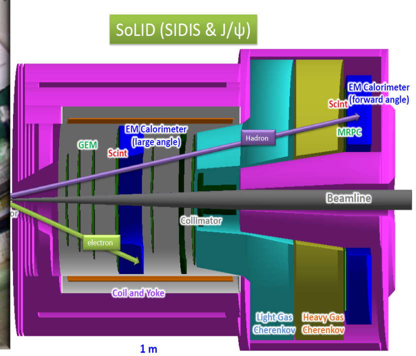




Hall D – exploring origin of *confinement* by studying *exotic mesons*



Hall A – form factors, future new experiments (e.g., SoLID and MOLLER)



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

Why SoLID

- **JLab 6 GeV: precision measurements**

  high luminosity (10^{39}) but small acceptance (HRS/HMS: < 10 msr)

  or large acceptance but low luminosity (CLAS6: 10^{34})

- **JLab 12 GeV upgrade opens up a window of opportunities (DIS, SIDIS, Deep Exclusive Processes) to study valence quark (3-d) structure of the nucleon and other high impact physics (PVDIS, J/ψ, …)**
- **High precision in multi-dimension or rare processes requires very high statistics → large acceptance and high luminosity**
- **CLAS12: luminosity upgrade (one order of magnitude) to 10^{35}**
- **To fully exploit the potential of 12 GeV, taking advantage of the latest technical (detectors, DAQ, simulations, …) development**

→ **SoLID: large acceptance detector can handle 10^{37} luminosity (no baffles)**

10^{39} with baffles

Overview of SoLID

Solenoidal **L**arge **I**ntensity **D**evice

- **Full exploitation of JLab 12 GeV Upgrade**

  → A **Large Acceptance** Detector **AND** Can Handle **High Luminosity** (10^{37}-10^{39})

  Take advantage of latest development in detectors , data acquisitions and simulations

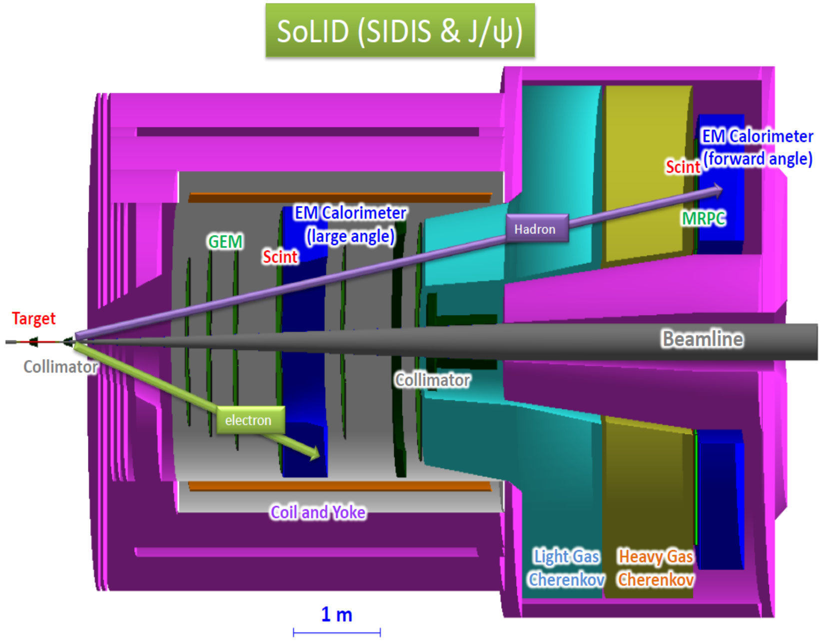
  Reach ultimate precision for SIDIS (TMDs), PVDIS in high-*x* region, threshold J/ψ and GPDs

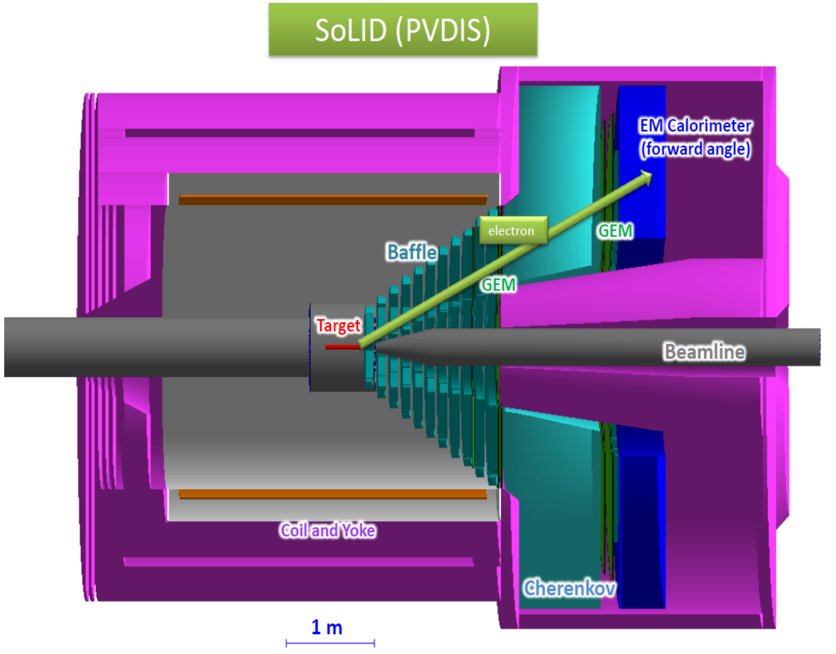
- **5 highly rated experiments approved**

  Three SIDIS experiments, one PVDIS, one J/ψ (+ 4 run group experiments, TMDs/GPDs)

- **Strong collaboration** (250+ collaborators from 70+ institutes, 13 countries)

  Significant international contributions (Chinese collaboration)





SoLID Experiments

- **Approved experiments (5):**

3 TMDs: unpolarized/polarized e on Transverse Pol. ^{3}He (n), detect e and pion (or kaon)
(H. Gao, JPC, …) Longitudinal Pol. ^{3}He (n)
Transverse Pol. Proton

PVDIS: unpolarized LD2 and LH2, detect only e (P. Souder)

Threshold J/ψ: unpolarized LH2, detect e-e-e+ ((e-production) and e-e+ (γ-production)
(Z. Meziani, Z. Zhao,…)

- **Run group experiments (4):**

TMDs, Dihadron: detect e and two hadrons (J. Zhang, JPC, …)
Ay: detect only e (T. Averett, …)

GPDs, TSC: detect e-e+ (Z. Zhao, …)
DVMP: detect e and pion (G. Huber, Z. Ye, Z. Ahmed)

- **Proposed or to-be-proposed:**

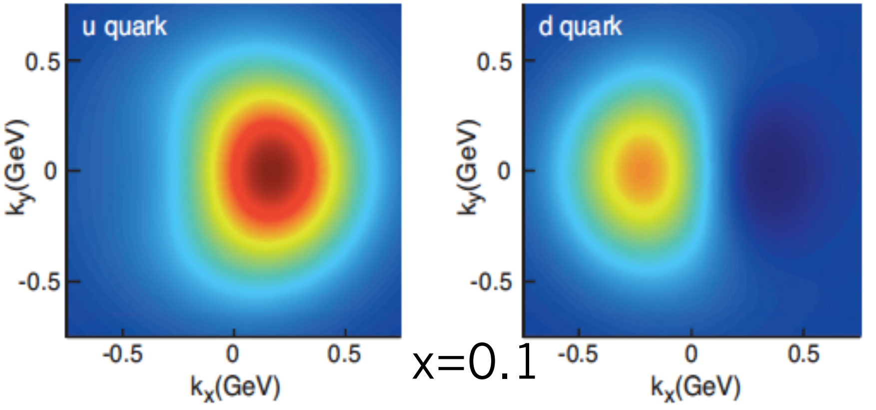
GPD Program: DVCS-pol.^{3}He, detect e and γ (to be proposed, Z. Ye,…)
DDVCS-LH2, detect e-e-e+ or e-μ-μ+ (LOI, A. Camsonne,…)

PVDIS-EMC: on ^{40}Ca (proposed, R. Beminiwattha, S. Riordan, J. Arrington)

PVDIS-Spin: on pol.^{3}He, spin-flavor (LOI, Y. Zhao, X. Zheng, …)

Transverse Spin and 3-D Structure

Transverse Momentum-Dependent Distributions



Nucleon Spin Structure Study

- 1980s: EMC (CERN) + early SLAC
  quark contribution to proton spin is very small
  $\Delta\Sigma = (12 +- 9 +- 14)\%$! 'spin crisis' (spin puzzle)

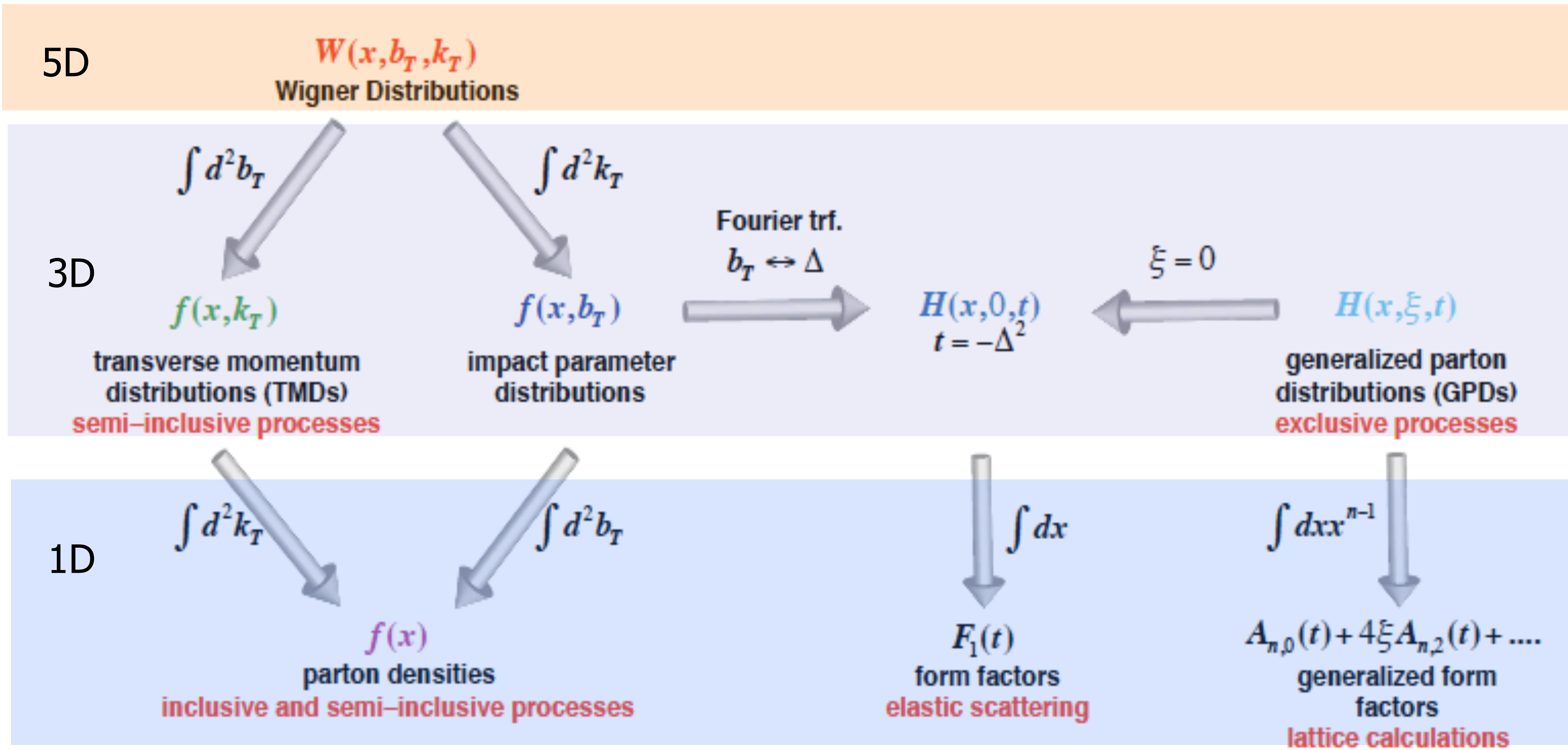
- 1990s: SLAC, SMC (CERN), HERMES (DESY)
  $\Delta\Sigma = 20\text{–}30\%$, the rest: gluon and quark orbital angular momentum
  $(½)\Delta\Sigma + L_q + \Delta G + L_G = 1/2$
  gauge invariant $(½)\Delta\Sigma + \mathcal{L}_q + J_G = 1/2$

- 2000s: COMPASS (CERN), HERMES, RHIC-Spin, JLab, … :
  $\Delta\Sigma \sim 30\%$; ΔG contributes, orbital angular momentum significant

- 2010s: RHIC-Spin/Global Fit $\Delta G \sim 0.2$ @ 10 GeV^2
  study spin decomposition and orbital angular momentum
  Needs precision 3-d structure information
  both GPDs and TMDs
  → Wigner distributions (GTMDs)

Unified View of Nucleon Structure

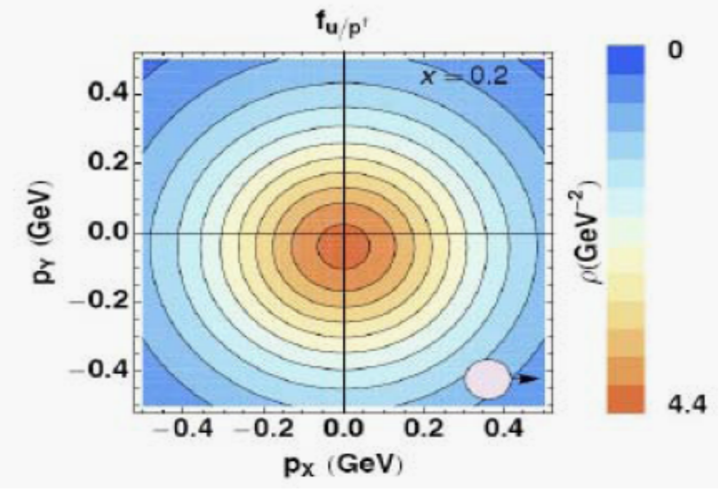
- ❑ **Wigner distributions**



Towards Imaging - Two Approaches

TMDs

2+1 D picture in **momentum space**

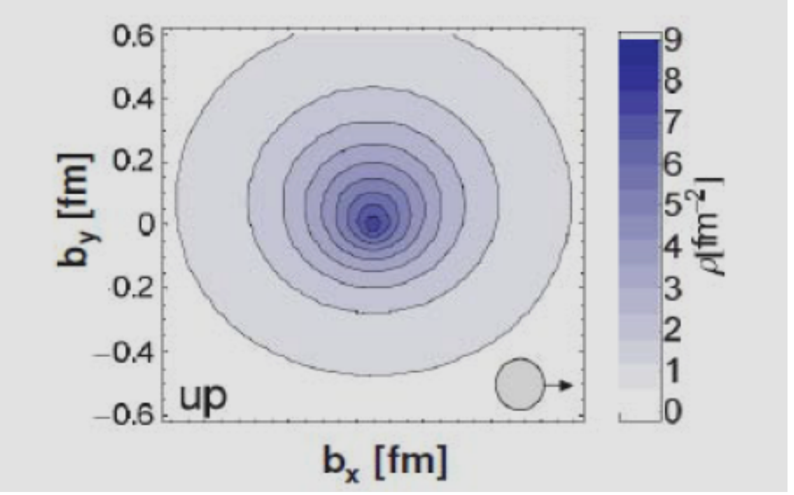


Bacchetta, Conti, Radici

- intrinsic transverse motion
- spin-orbit correlations- relate to OAM
- non-trivial factorization
- accessible in SIDIS (and Drell-Yan)

GPDs

2+1 D picture in **impact-parameter space**



QCDSF collaboration

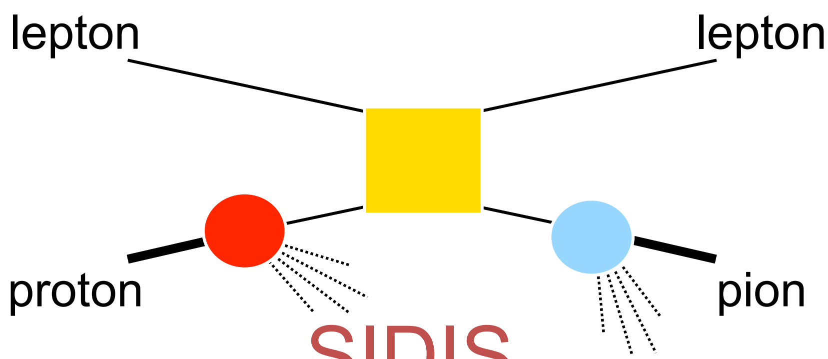
- collinear but long. momentum transfer
- indicator of OAM; access to Ji's total $J_{q,g}$
- existing factorization proofs
- DVCS, exclusive vector-meson production

Leading-Twist TMD PDFs

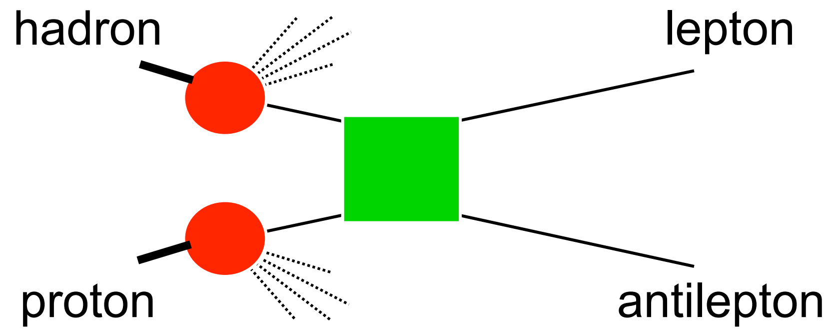
Nucleon Spin
Quark Spin

Nucleon Polarization	Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)
U	f_1		$h_1^{\perp}$ Boer-Mulders
L		g_1 Helicity	$h_{1L}^{\perp}$ Long-Transversity
T	$f_{1T}^{\perp}$ Sivers	g_{1T} Trans-Helicity	h_1 Transversity $h_{1T}^{\perp}$ Pretzelosity

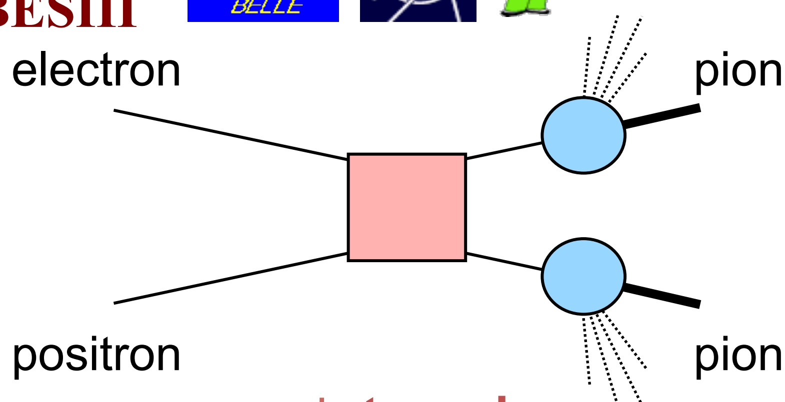
Access TMDs through Hard Processes



SIDIS



Drell-Yan

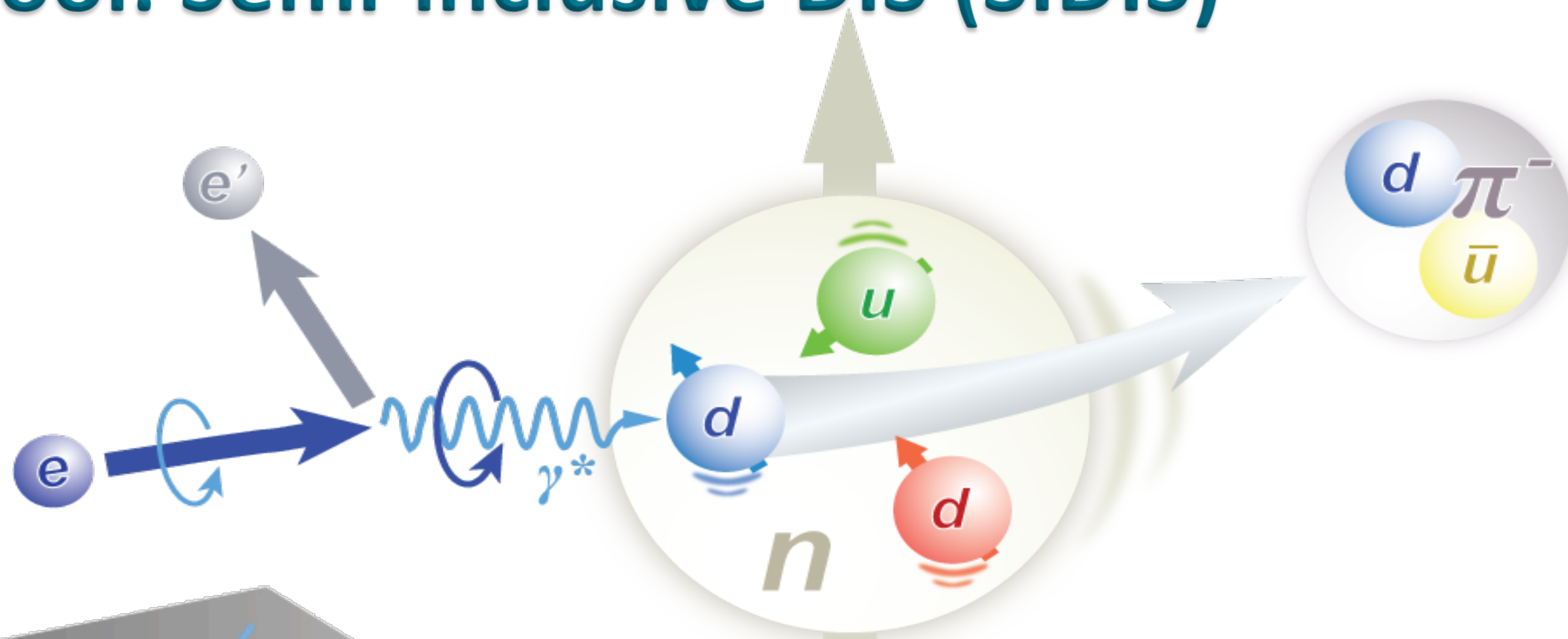


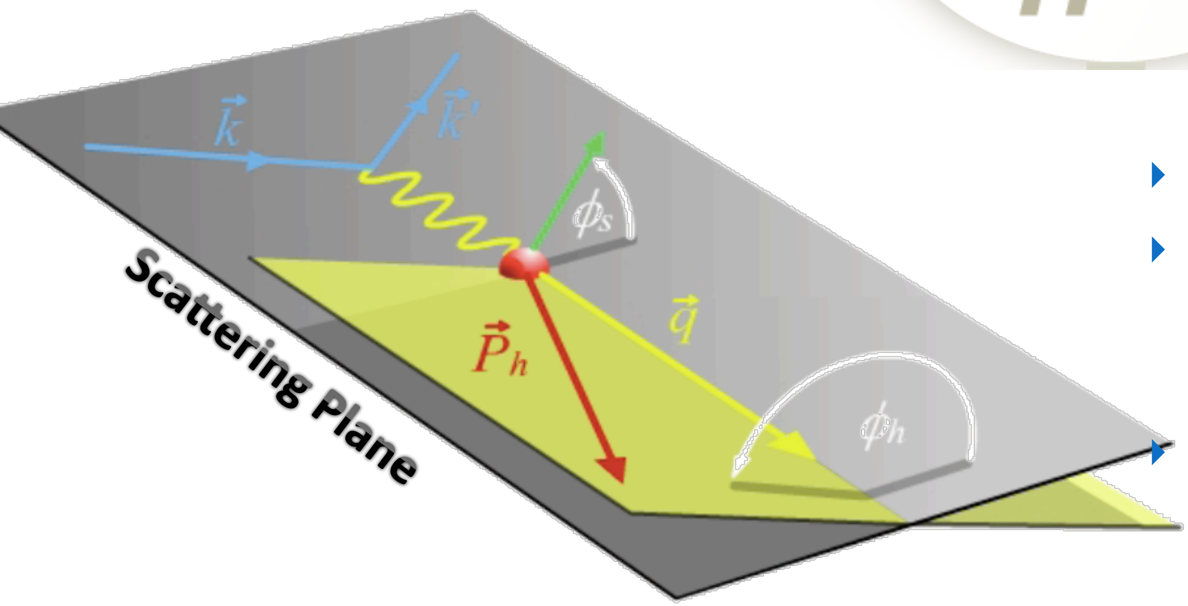
$e^{-}e^{+}$ to pions

- Partonic scattering amplitude
- Fragmentation amplitude
- Distribution amplitude

$$f_{1T}^{\perp q}(\text{SIDIS}) = -f_{1T}^{\perp q}(\text{DY})$$

Tool: Semi-inclusive DIS (SIDIS)

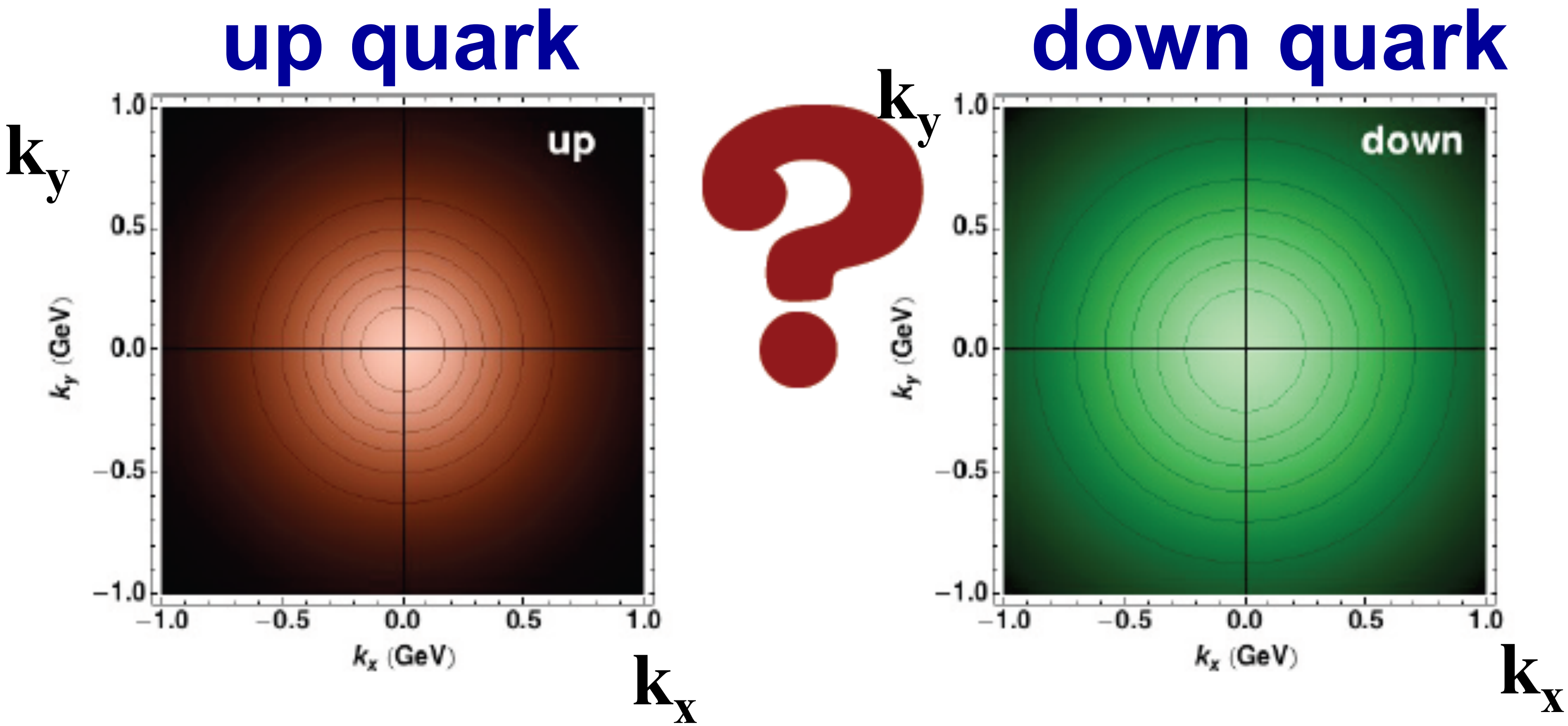




- Gold mine for TMDs
- Access all eight leading-twist TMDs through spin-comb. & azimuthal-modulations
- Tagging quark flavor/kinematics

Unpolarized TMD: Flavor P_T Dependence?

Flavor in transverse-momentum space



Is the up distribution wider or narrower than the down?

And the sea?

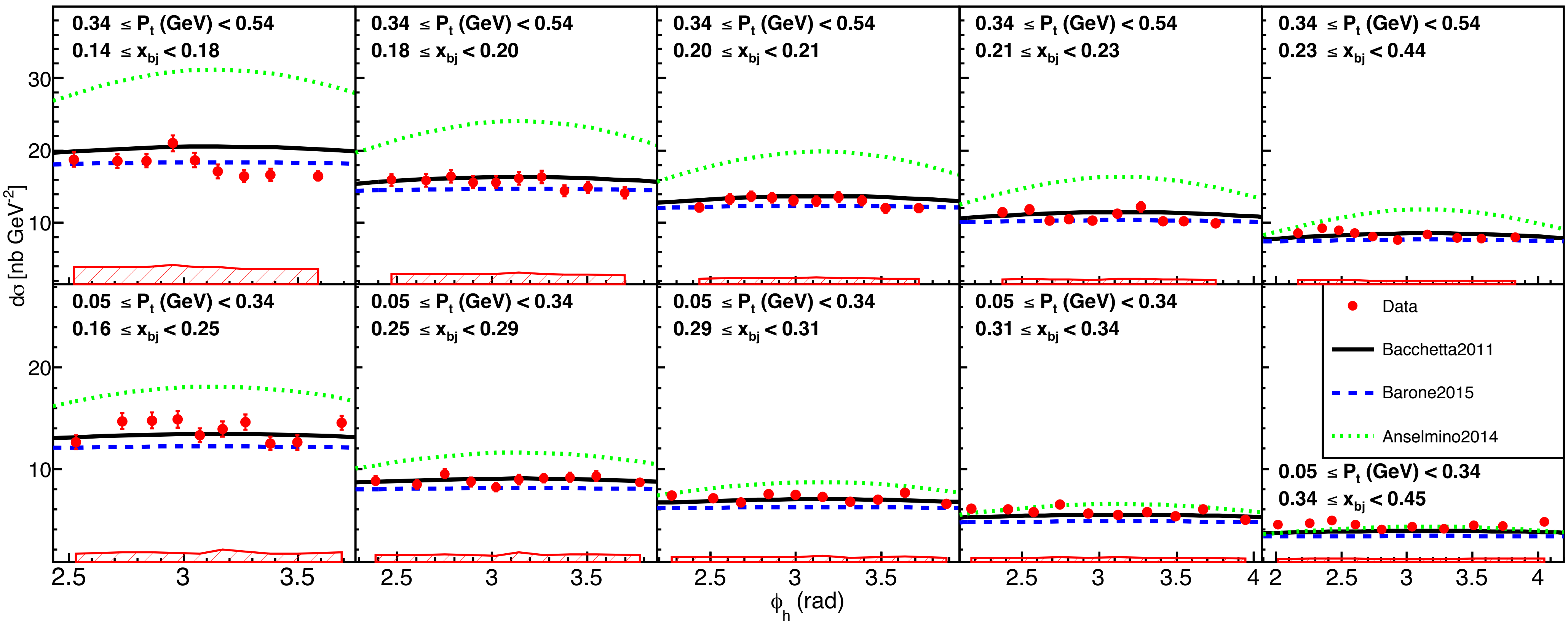
How wide are the distributions?

A. Bacchetta, Seminar @ JLab, JHEP 1311 (2013) 194

Hall A SIDIS Cross Section Results From E06-010 (Transversity):

pi+ and pi- production on He3

X. Yan *et al.*, Hall A Collaboration, PRC 95, 035209 (2017)

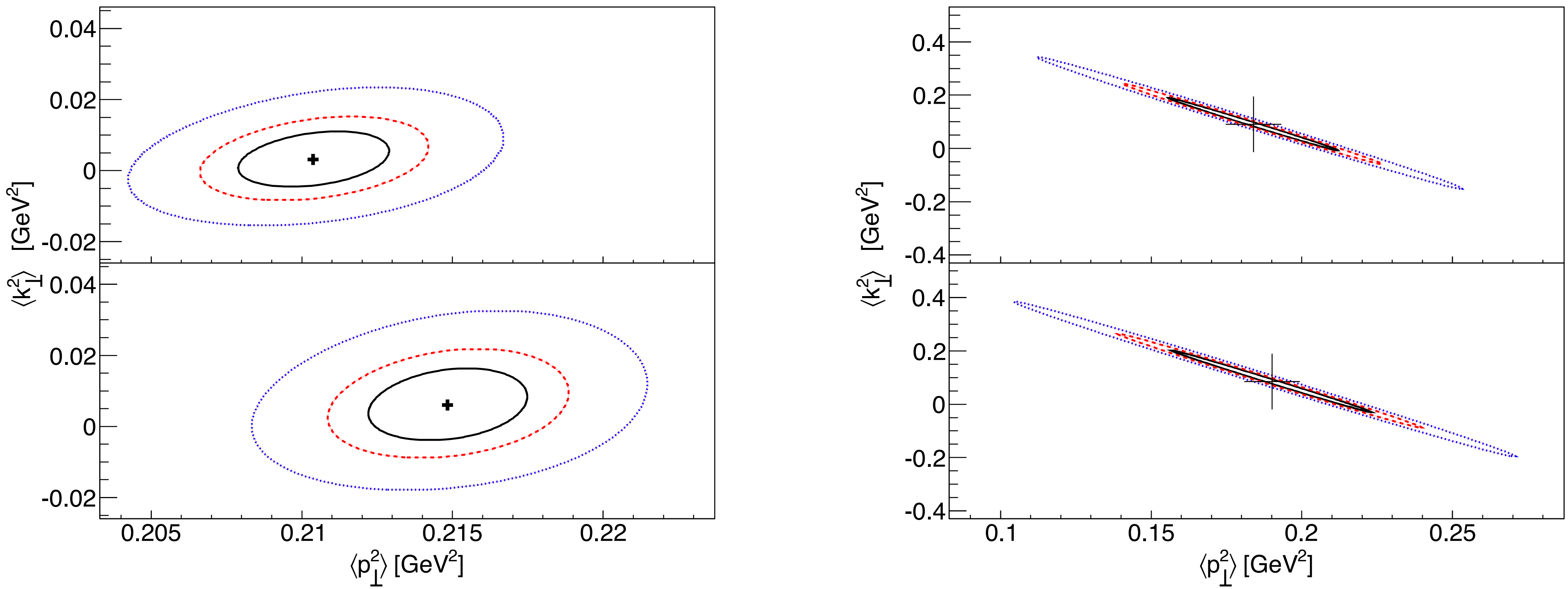


pi+ results Φ_h **(rad)**

Hall A Results: Transverse Momentum dependence

average quark transverse momentum distribution squared
vs. average quark transverse momentum in fragmentation squared

with modulation **no modulation**



Collins Asymmetry and Sivers Asymmetry:

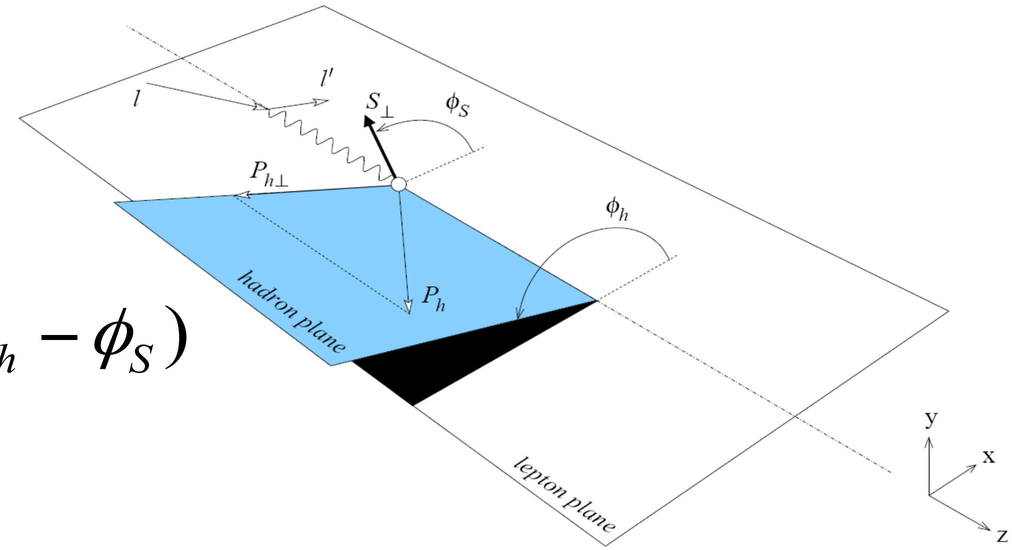
Transversity and Tensor Charge
3-d Imaging

Separation of Collins, Sivers and pretzelocity effects through angular dependence

$$A_{UT}(\varphi_h^l, \varphi_S^l) = \frac{1}{P}\frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

$$= A_{UT}^{Collins}\sin(\phi_h + \phi_S) + A_{UT}^{Sivers}\sin(\phi_h - \phi_S)$$

$$+ A_{UT}^{Pretzelosity}\sin(3\phi_h - \phi_S)$$

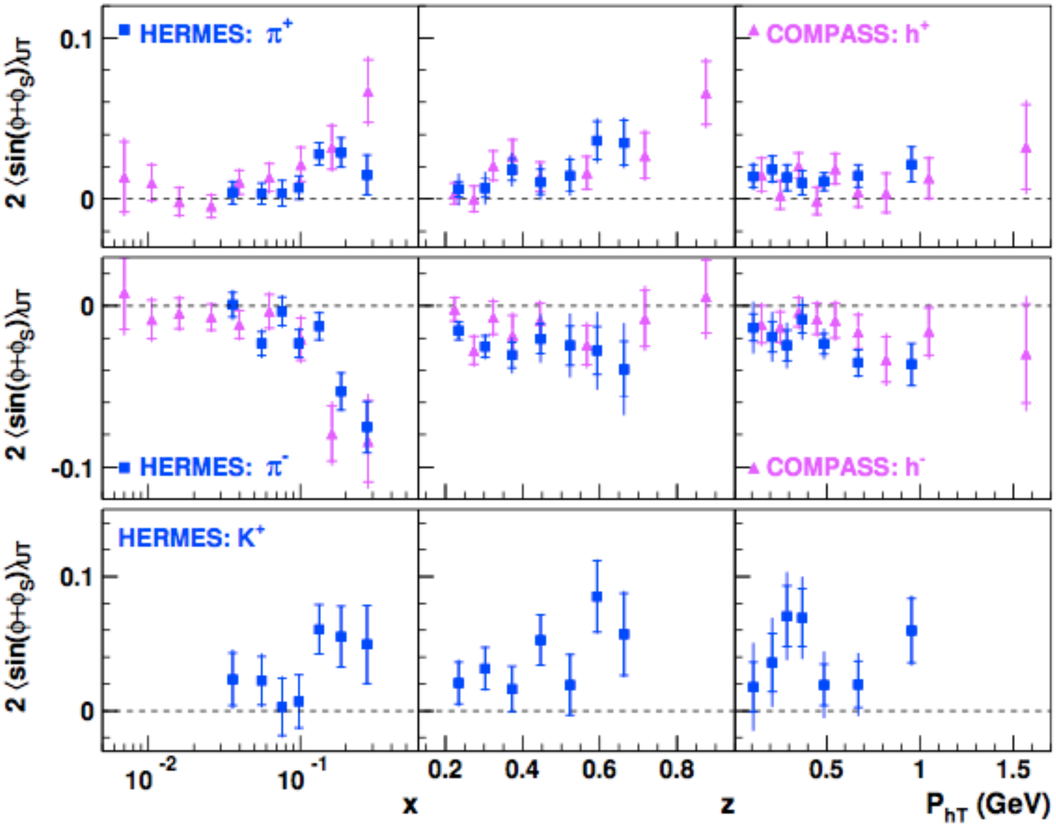


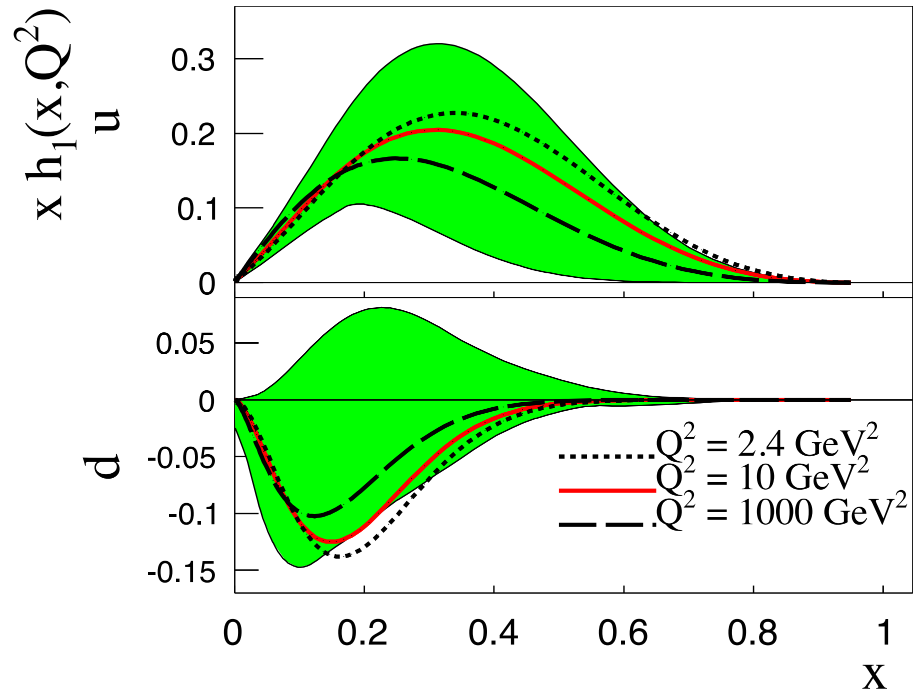
$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^{\perp}$$

$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^{\perp} \otimes D_1$$

$$A_{UT}^{Pretzelosity} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T}^{\perp} \otimes H_1^{\perp}$$

HERMES/COMPASS: *Collin Asymmetries and Extraction of Transversity*



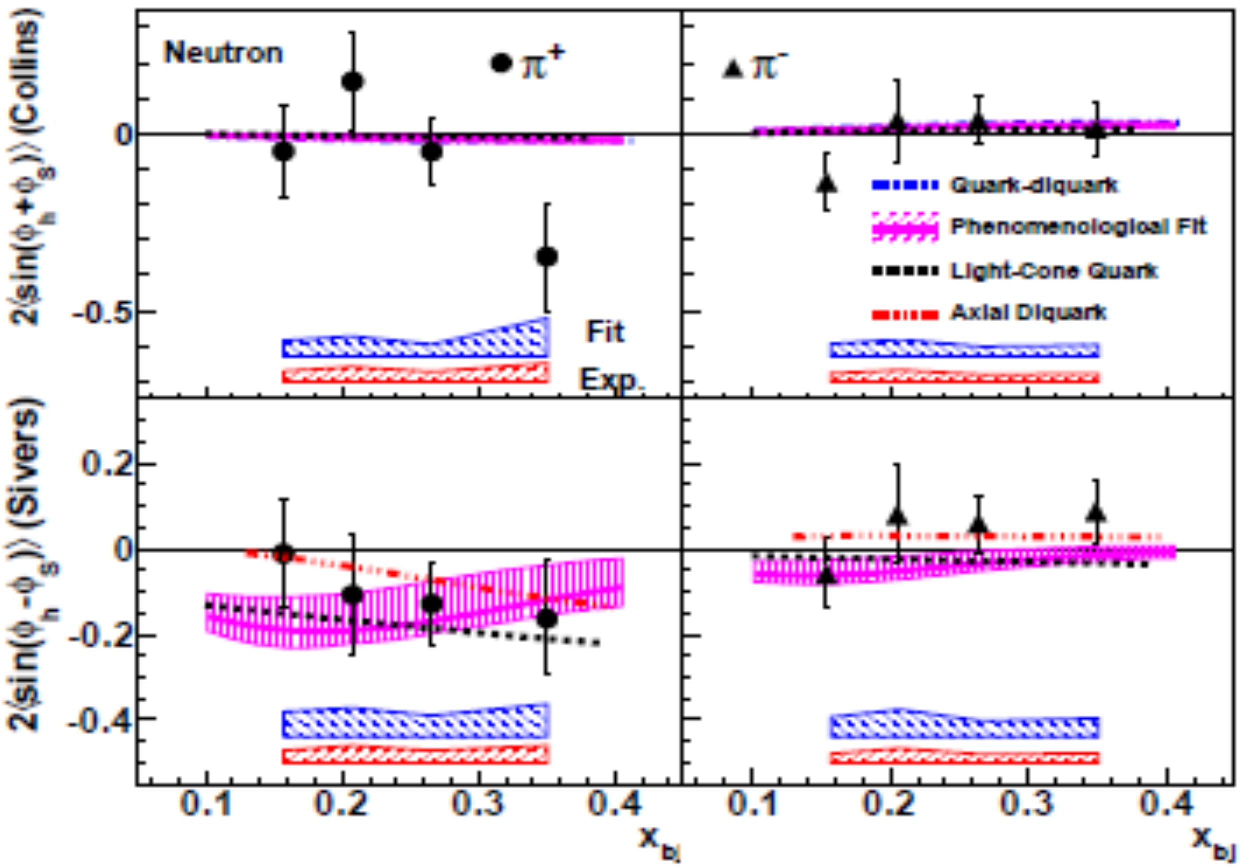


Z. Kang, *et al.*
arXiv:1505.05589 (2015)

^{3}He (n) Target Single-Spin Asymmetry in SIDIS

E06-010 collaboration, X. Qian at al., **PRL 107:072003(2011)**

$$n^{\uparrow}(e,e'h), h = \pi^+, \pi^-$$



neutron Collins SSA small
Non-zero at highest x for π+

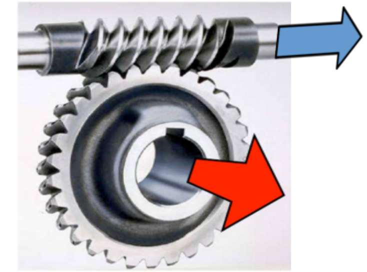
N \ q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

neutron Sivers SSA:
negative for π^+,
Agree with Torino Fit

Blue band: model (fitting) uncertainties
Red band: other systematic uncertainties

Asymmetry A_{LT} Result

E06-010 Collaboration, J. Huang et al., **PRL. 108, 052001 (2012).**



Worm-Gear
Trans helicity

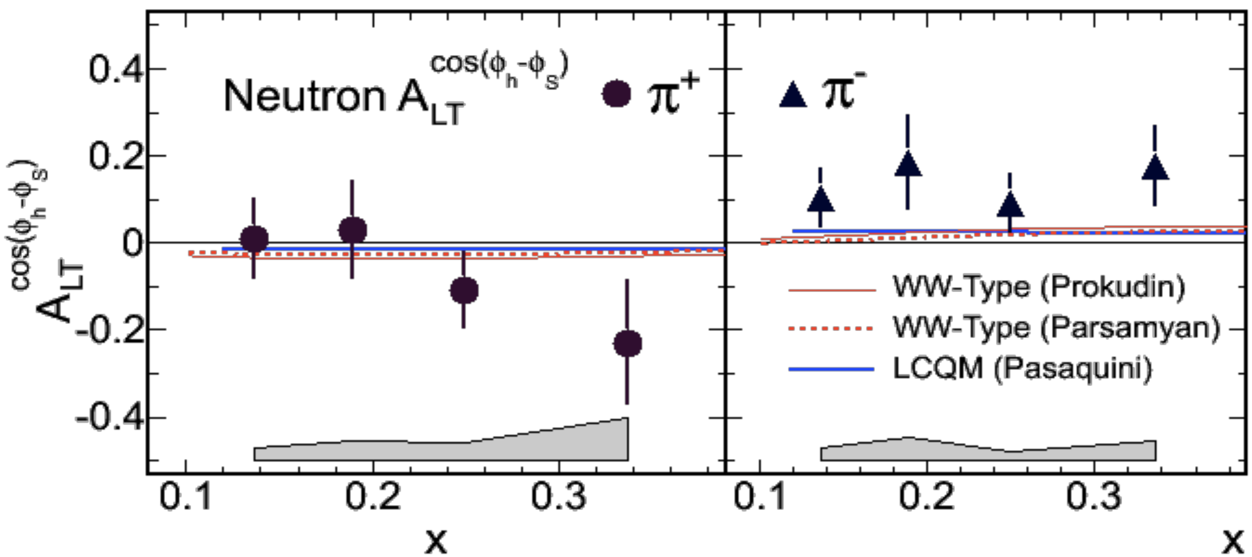
To leading twist:

$$A_{LT}^{\cos(\phi_h-\phi_s)} \propto F_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^{q} \otimes D_{1q}^{h}$$

Dominated by L=0 (S) and L=1 (P) interference

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 $h_{1T}^{\perp}$

- **neutron A_{LT} : Positive for π-**
- **Consist w/ model in signs, suggest larger asymmetry**

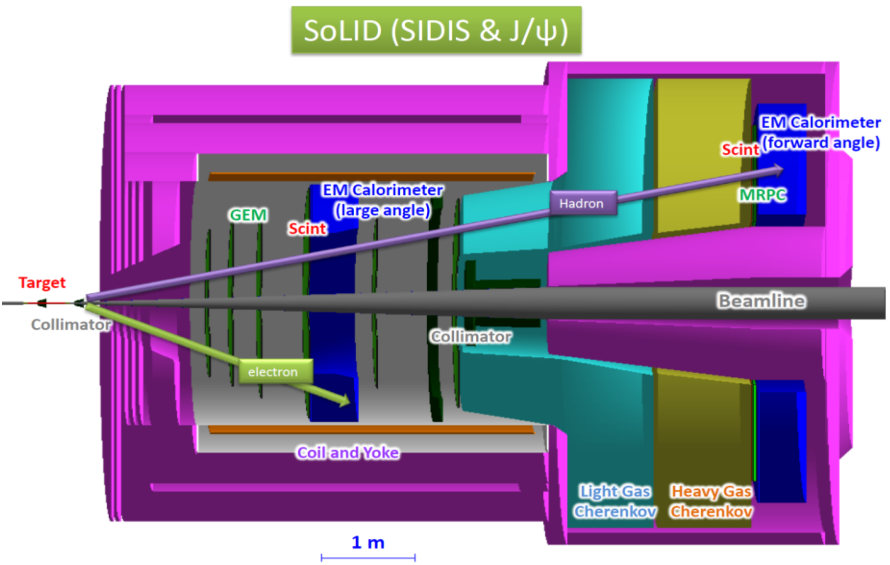


Precision Study of TMDs: JLab 12 GeV, EIC

- Explorations: HERMES, COMPASS, RHIC-spin, JLab6,…
- From exploration to precision study

  JLab12: valence region; EIC: sea and gluons
- Transversity: fundamental *PDF*s, tensor charge, LQCD
- *TMD*s: 3-d momentum structure of the nucleon
  - information on quark orbital angular momentum
  - information on QCD dynamics
- Multi-dimensional mapping of *TMD*s
  - 4-d ($x,z,P_\perp,Q^2$)
  - Multi-facilities, global effort
- Precision → high statistics
  - high luminosity and large acceptance

SoLID-Spin: SIDIS on ^{3}He/Proton @ 11 GeV

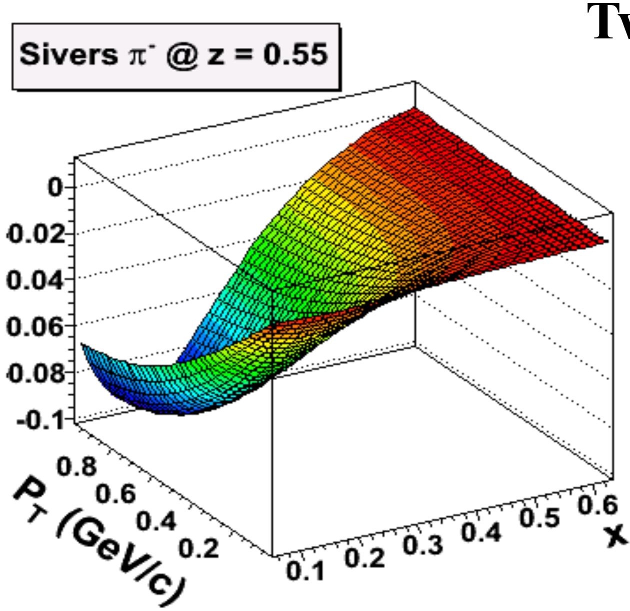


E12-10-006: Single Spin Asymmetry on Transverse ^{3}He, **rating A**

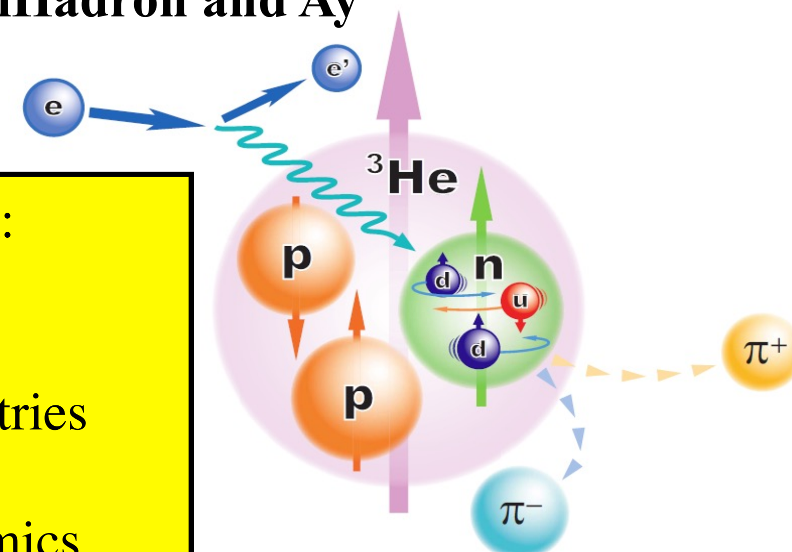
E12-11-007: Single and Double Spin Asymmetries on ^{3}He, **rating A**

E12-11-108: Single and Double Spin Asymmetries on Transverse Proton, **rating A**

Two run group experiments DiHadron and Ay



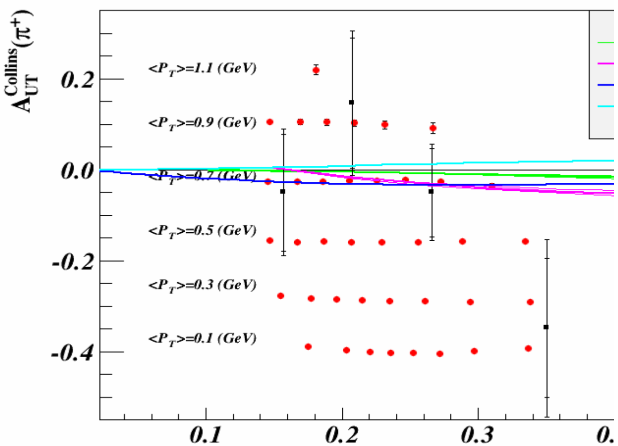
Key of SoLID-Spin program:
Large Acceptance
+ High Luminosity
→ **4-D** mapping of asymmetries
→ Tensor charge, TMDs …
→Lattice QCD, QCD Dynamics, Models.



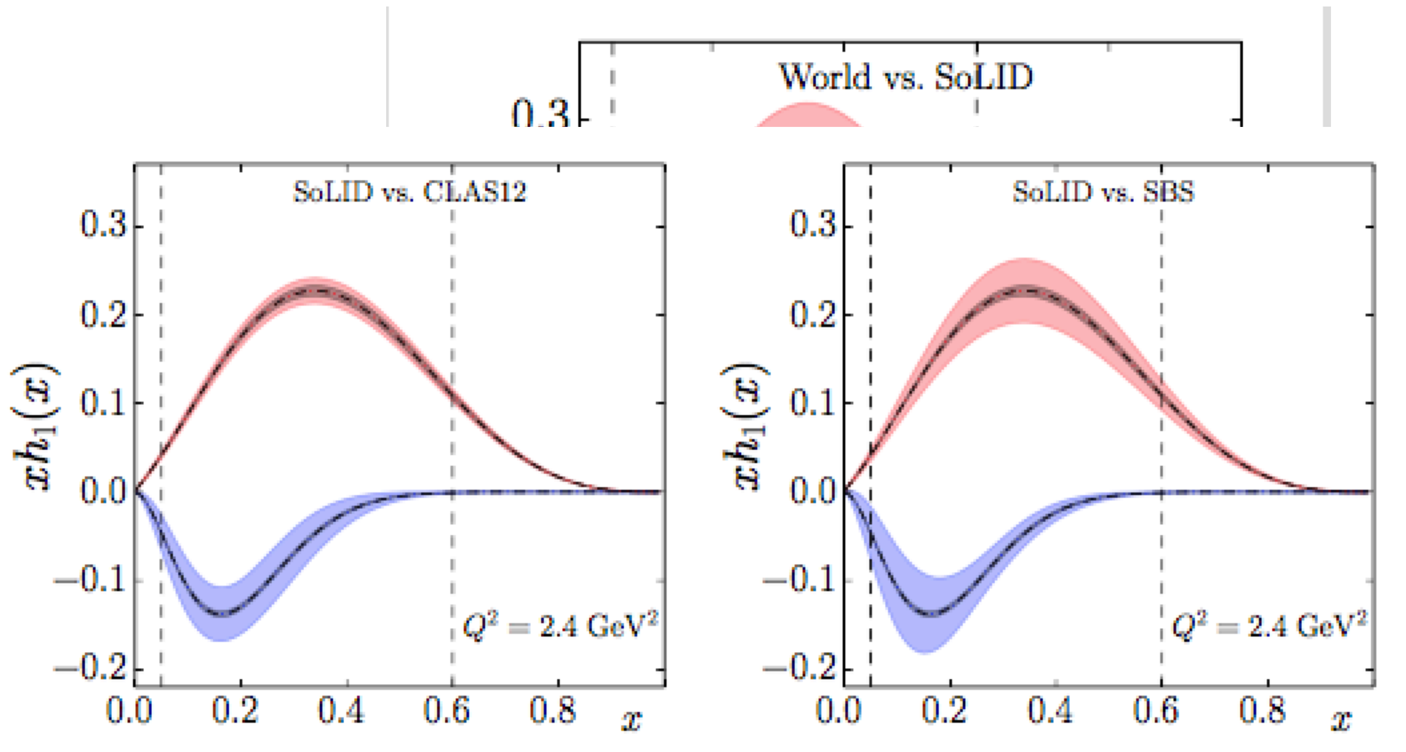
Transversity from SoLID

- Collins Asymmetries ~ Transversity (x) Collin Function
- **Transversity**: chiral-odd, not couple to gluons, **valence behavior**, largely unknown
- Global model fits to experiments (SIDIS and e+e-)
- SoLID with **trans polarized n & p** → Precision extraction of u/d quark transversity
- Collaborating with theory group (N. Sato, A. Prokudin, …) on impact study

Collins Asymmetries



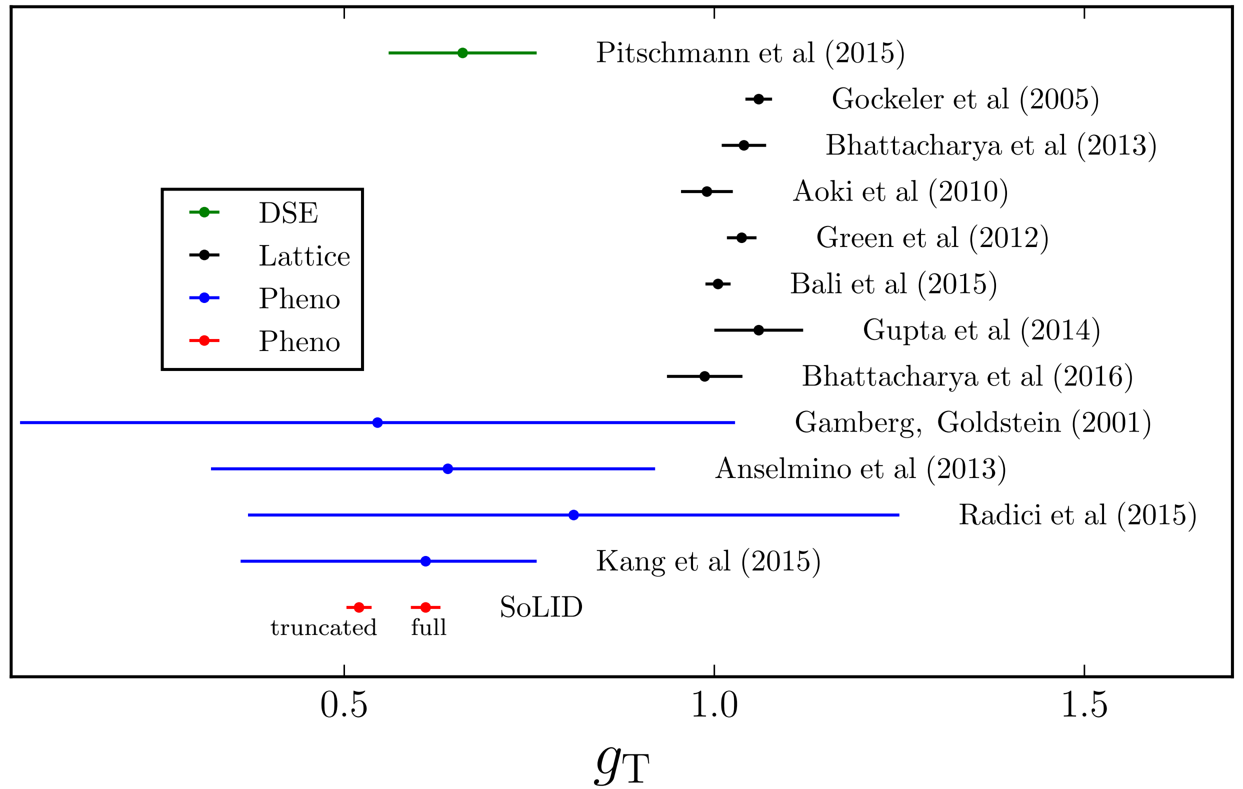
P_T vs. x for one (Q^2, z) bin
Total > 1400 data points



Z. Ye *et al.*, PLB 767, 91 (2017)

Tensor Charge from SoLID

- **Tensor charge (0th moment of transversity): fundamental property**
  Lattice QCD, Bound-State QCD (Dyson-Schwinger) , …
- SoLID with **trans polarized n & p** → determination of tensor charge



DSE

LQCD

Extractions from existing data

SoLID projections

Tensor Charges

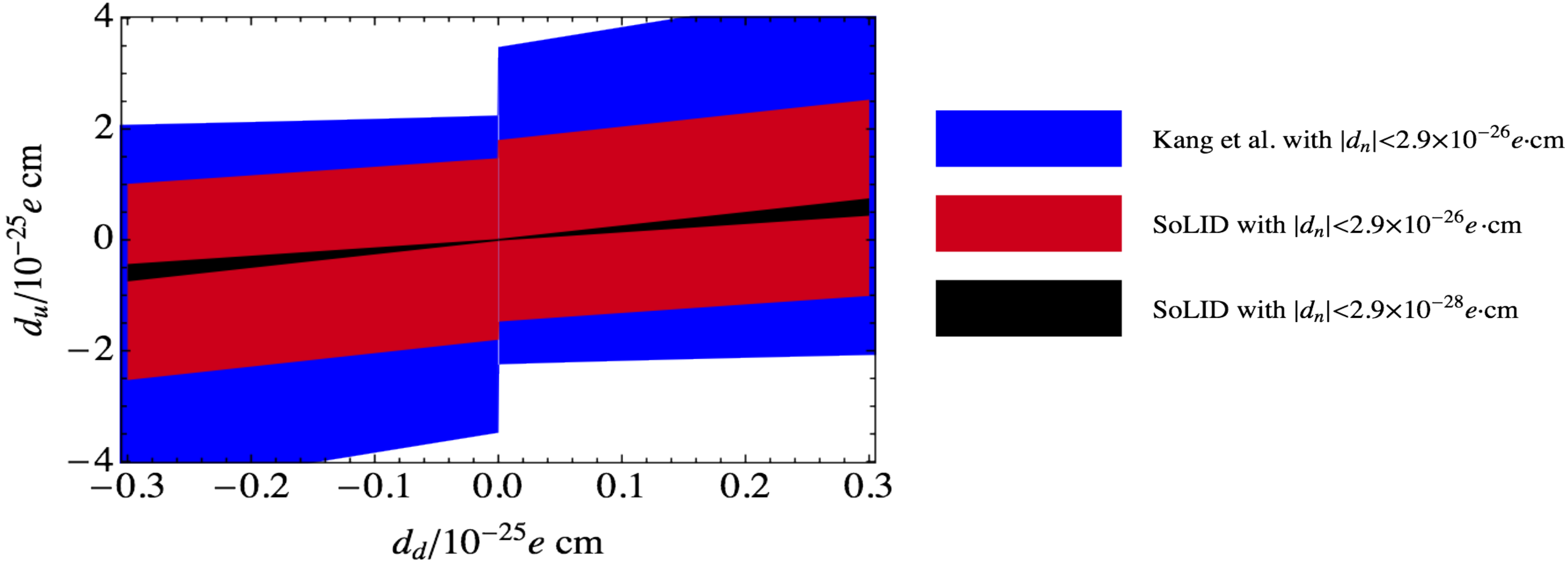
Projections with a model QCD evolutions included

Tensor Charge and Neutron EDM

Electric Dipole Moment

Tensor charge and EDM

$$d_n = \delta_T u \, d_u + \delta_T d \, d_d + \delta_T s \, d_s$$



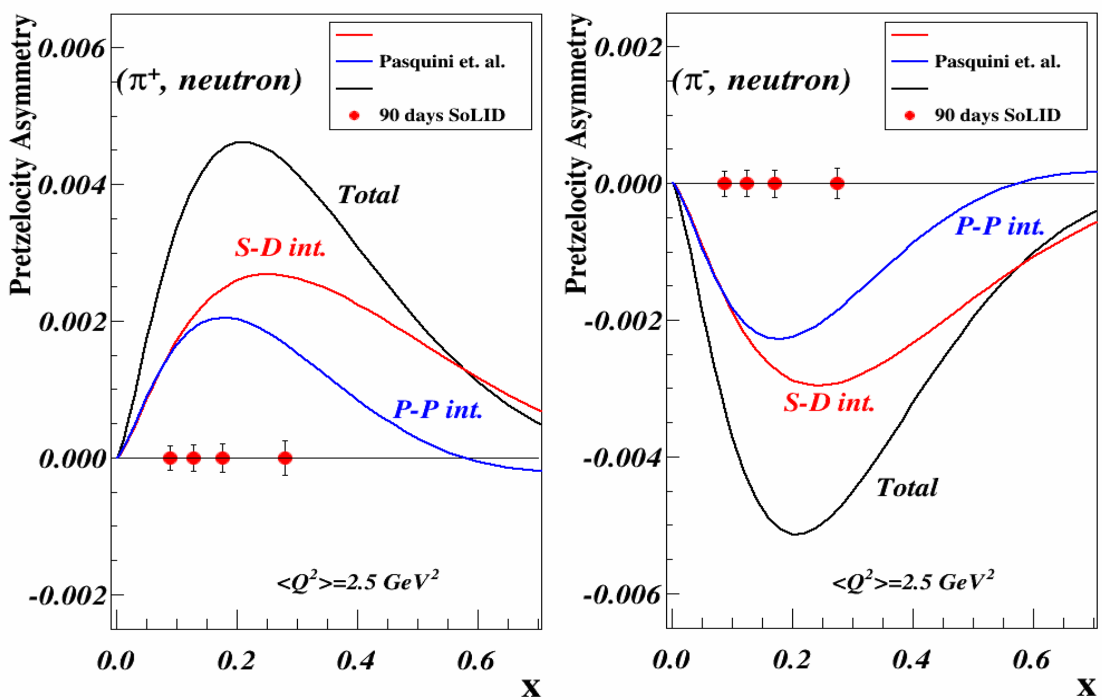
current neutron EDM limit $\quad |d_n| < 2.9 \times 10^{-26} \, e \cdot \mathrm{cm}$

TMDs and Orbital Angular Momentum

Pretzelosity ($\Delta L=2$), Worm-Gear ($\Delta L=1$),
Sivers: Related to GPD E through Lensing Function

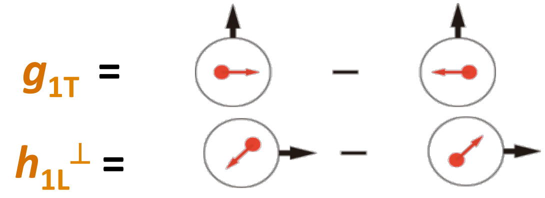
TMDs: Access Quark Orbital Angular Momentum

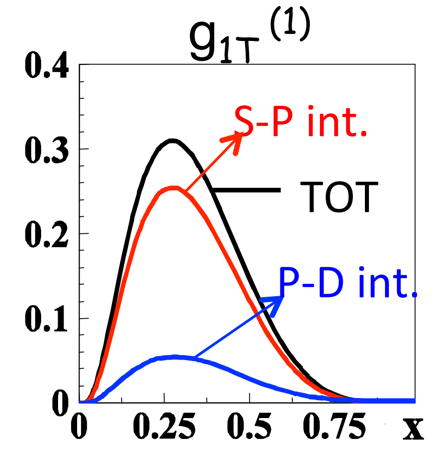
- TMDs : Correlations of transverse motion with quark spin and orbital motion
- **Without OAM, off-diagonal TMDs=0,**
  no direct model-independent relation to the OAM in spin sum rule yet
- Sivers Function: QCD lensing effects
- In a large class of models, such as light-cone quark models
  Pretzelosity: ΔL=2 (L=0 and L=2 interference , L=1 and -1 interference)
  Worm-Gear: ΔL=1 (L=0 and L=1 interference)
- **SoLID with trans polarized n/p → quantitative knowledge of OAM**



SoLID Projections Pretzelosity

Worm-gear Functions

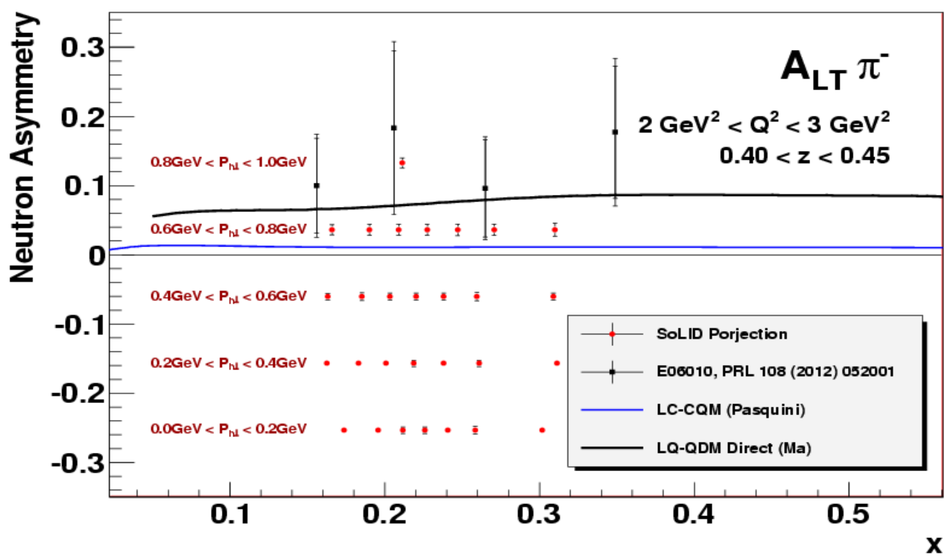


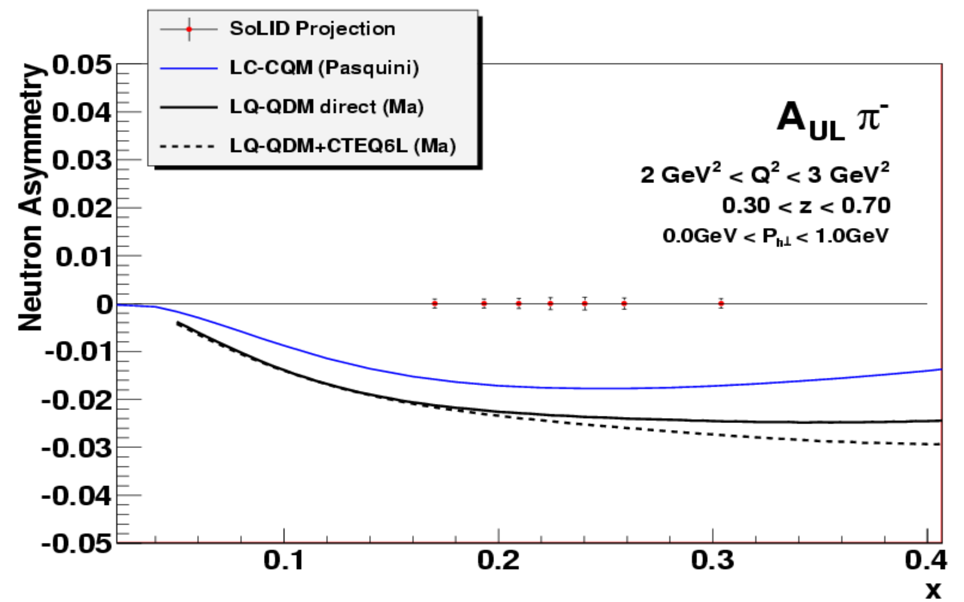


Light-Cone CQM by B. Pasquini
B.P., Cazzaniga, Boffi, PRD78, 2008

- Dominated by real part of interference between **L=0 (S) and L=1 (P) states**
- No GPD correspondence
- Exploratory lattice QCD calculation:
  Ph. Hägler et al, EPL 88, 61001 (2009)

Neutron Projections,





$$A_{LT} \sim g_{1T}(x) D_1(z)$$

$$A_{UL} \sim h_{1L}^{\perp}(x) \otimes H^{\perp}{}_1(z)$$

Angular Momentum

Sivers and GPD E:

model dependent

$$f_{1T}^{\perp(0)}(x, Q_0^2) = -L(\mathrm{x})\, E\left(x, 0, 0, Q_0^2\right)$$

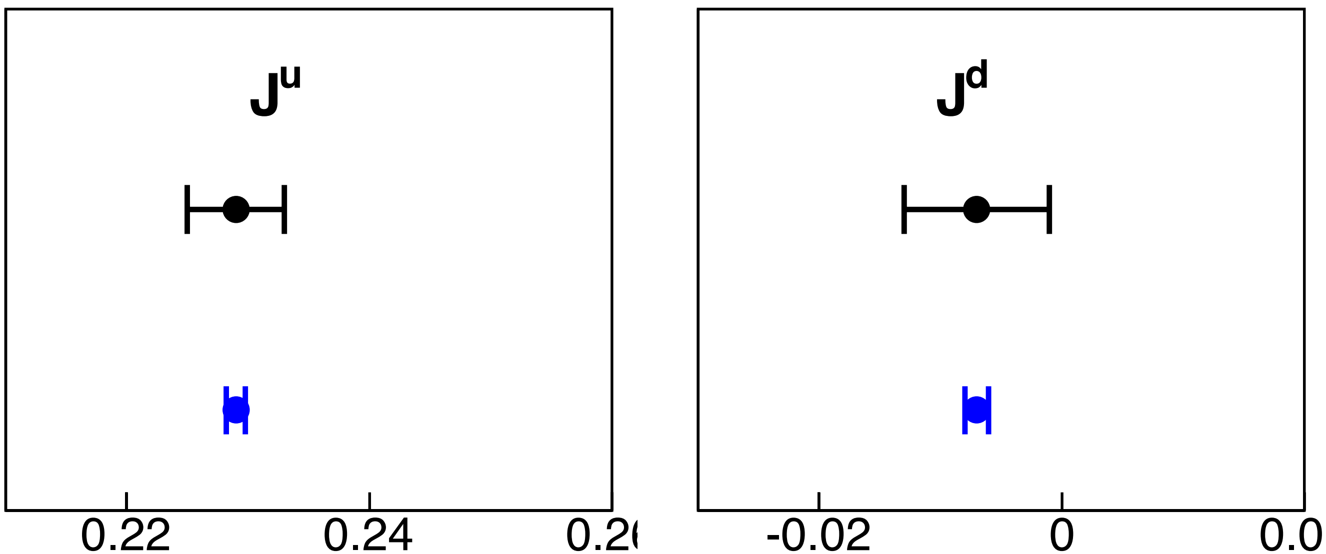
$$L(\mathrm{x}) = \frac{\mathrm{K}}{(1-x)^{\eta}}$$ lensing function

A. Bacchetta *et al.*, PR L 107, 212001 (2011).

K and η are fixed by anomalous magnetic moments κ^p and κ^n.

$$J = \frac{1}{2}\int dx\, x\, [\, H(x,0,0) + E(x,0,0)\,]$$

SoLID:



Summary on TMD Program

- Exploratory results from 6 GeV neutron experiment
- **Unprecedented precision *multi-d* mapping of SSA in valence quark region with SoLID at 12 GeV JLab**
- Both polarized n (^{3}He) and polarized proton

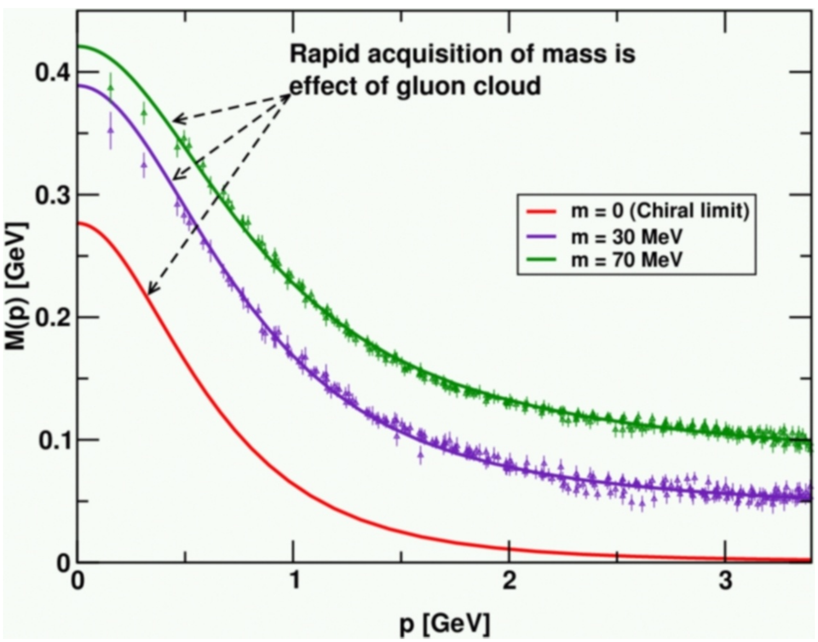
  Three "A" rated experiments approved

  \+ one run-group experiment on di-hadron

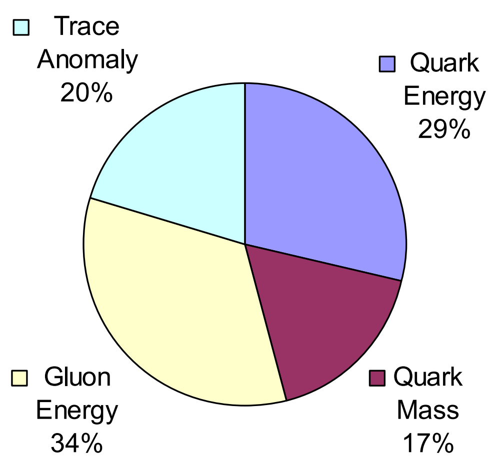
  \+ one run-group experiment on inclusive electron SSA
- Combining with the world data (fragmentation functions)
  - extract transversity for both *u* and *d* quarks
  - determine tensor charges
  - learn quark orbital motion and QCD dynamics
  - 3-d imaging
- Global efforts (experimentalists and theorists), global analysis
  - much better understanding of 3-d nucleon structure and QCD
- **Long-term future: EIC to map sea and gluon SSAs**

Proton Mass

Mass Generation

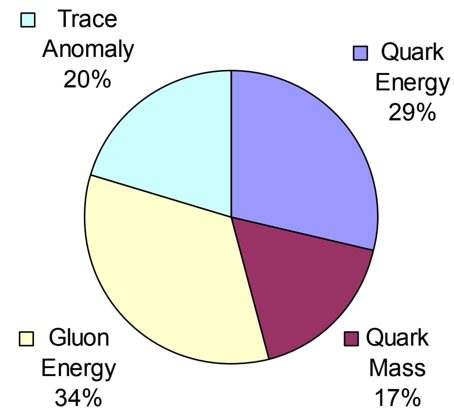


Mass Decomposition



Theoretical Developments

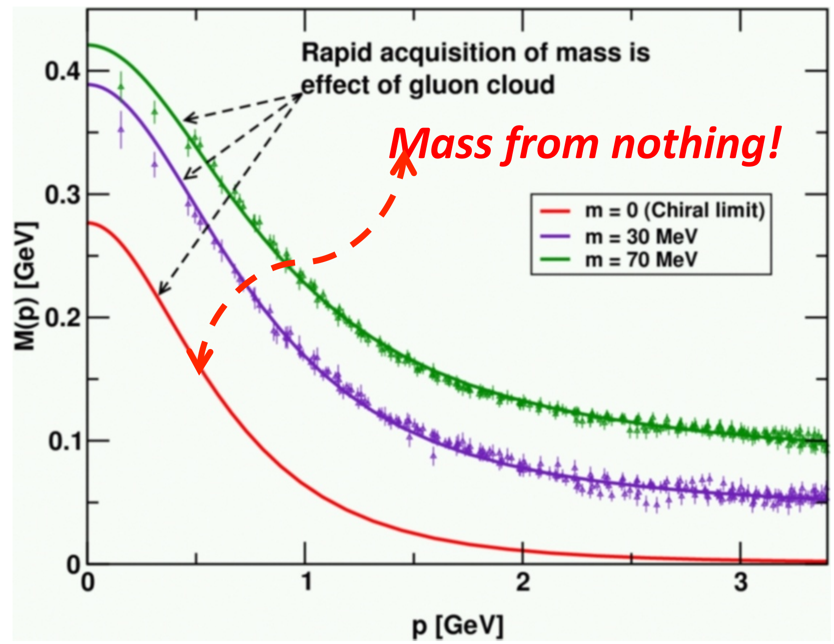
- **Dynamical Chiral Symmetry Breaking <-> Confinement**
  - Responsible for ~99%(?) of the nucleon mass
  - Higgs mechanism is (almost) irrelevant to light quarks
  - Understand proton mass (energy structure) can provide clue



Proton Mass Decomposition

- **Energy Momentum Tensor, $T^{\mu\nu}$**
  - Invariant: $m^2 = E^2 - P^2 \sim \langle p|\text{Trace}(T^{\mu\nu})|p\rangle$
  - Rest Frame: $m = E \sim \langle p|T^{00}|p\rangle$

- **Recent development in theory**
  - Lattice QCD
  - Bound State QCD: Dyson-Schwinger
  - Ads/CFT: Holographic QCD
  - ……



Proton Mass Generation

Decomposition – Sum Rules

❑ Roles of quarks and gluons?

✧ **QCD energy-momentum tensor:**

$$T^{\mu\nu} = \overline{T^{\mu\nu}} + \widehat{T^{\mu\nu}}$$

Traceless term: $\overline{T^{\mu\nu}} \equiv T^{\mu\nu} - \frac{1}{4} g^{\mu\nu} T^{\alpha}_{\alpha}$

Trace term: $\widehat{T^{\mu\nu}} \equiv \frac{1}{4} g^{\mu\nu} T^{\alpha}_{\alpha}$

Vacuum expectation breaks chiral symmetry

with $T^{\alpha}_{\alpha} = \frac{\beta(g)}{2g} F^{\mu\nu,a} F^{a}_{\mu\nu} + \sum_{q=u,d,s} m_q (1+\gamma_m) \overline{\psi}_q \psi_q$

QCD trace anomaly $\beta(g) = -(11 - 2n_f/3)\, g^3/(4\pi)^2 + \ldots$

✧ **Invariant hadron mass (in any frame):**

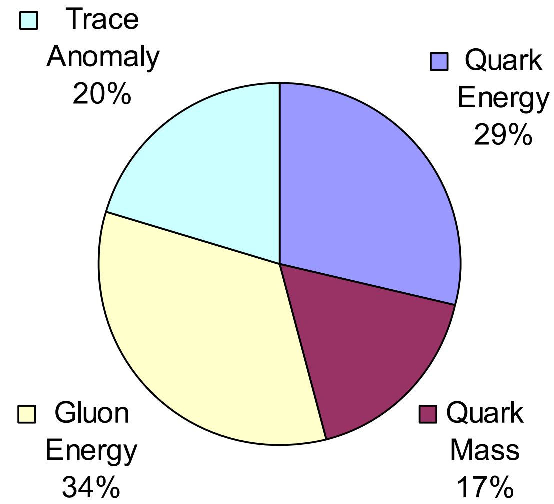
$\langle p | T^{\mu\nu} | p \rangle \propto p^{\mu} p^{\nu}$ ➡ $\langle p | T^{\mu\nu} | p \rangle (g_{\mu\nu}) \propto p^{\mu} p^{\nu} (g_{\mu\nu}) = m^2$

$m^2 \propto \langle p | T^{\alpha}_{\ \alpha} | p \rangle$ ➡ $\frac{\beta(g)}{2g} \langle p | F^2 | p \rangle$

➡ **At the chiral limit, the entire mass is from gluons!**

Proton Mass: QCD energy

X. Ji, PRL741071(1995)



- One can calculate the proton mass through the expectation value of the QCD Hamiltonian,

$$H_{\rm QCD} = H_q + H_m + H_g + H_a .$$

$$H_q = \int d^3\vec{x}\ \bar{\psi}(-i\mathbf{D}\cdot\alpha)\psi,$$ ← *Quark energy*

$$H_m = \int d^3\vec{x}\ \bar{\psi}m\psi,$$ ← *Quark mass*

$$H_g = \int d^3\vec{x}\ \frac{1}{2}(\mathbf{E}^2+\mathbf{B}^2),$$ ← *Gluon energy*

$$H_a = \int d^3\vec{x}\ \frac{9\alpha_s}{16\pi}(\mathbf{E}^2-\mathbf{B}^2).$$ ← *Trace anomaly* ***(Dark Energy)***

Relating to Measurements

- **Traceless part** at rest frame becomes ***quark kinetic energy and gluon energy***
  can be extracted from **parton distribution functions**
  scheme and scale dependent

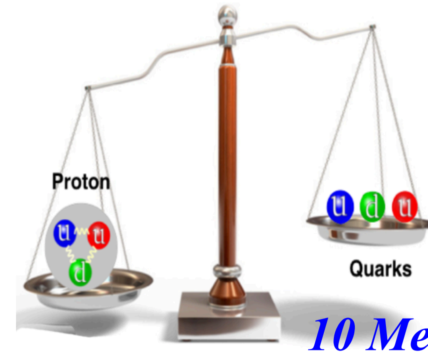
- ***Quark mass*****:** u and d quark contribution obtain from **pi-nucleon sigma term**
  s quark from **Chiral Purturbation Theory for baryon octet**
  or LQCD, …

- *Trace Anomaly*: **analogous to the cosmological constant (dark energy)!**
  J/ψ threshold production may provide access?

J/ψ@ SoLID

The threshold region, the mass of the proton and LHCb charmed pentaquark

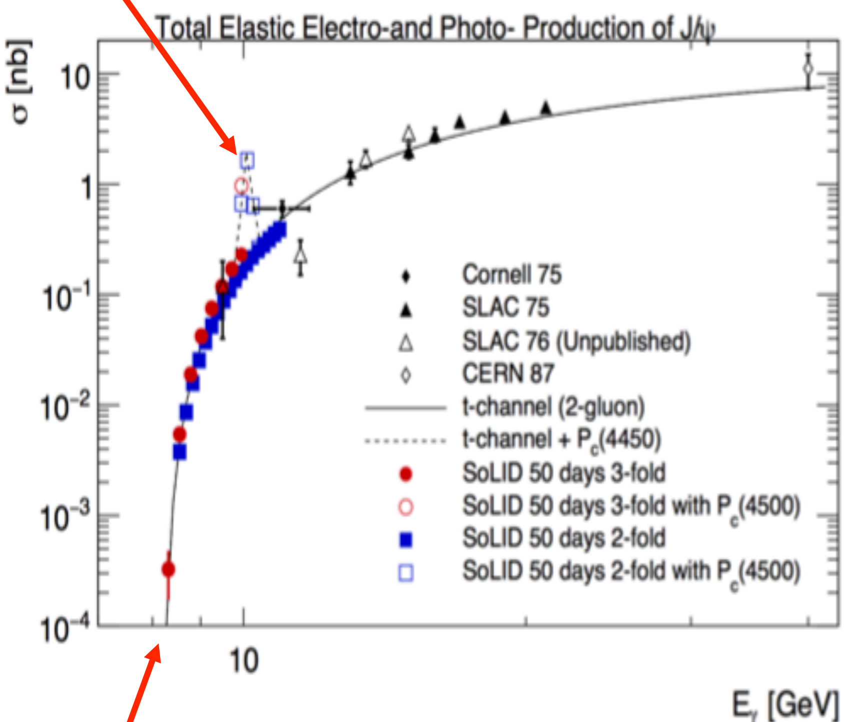
Measure contribution of gluons to mass of the proton
Produce and determine quantum numbers of pentaquark if exist



1 GeV

10 MeV

LHCb Pentaquark production

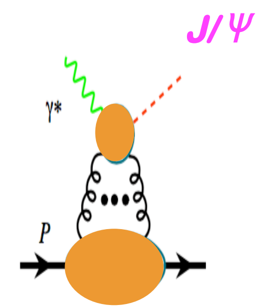


Threshold

How does QCD generate the mass of the proton?

✧ *Trace of the QCD energy-momentum tensor*

Heavy quarkonium production near threshold:
→ access Trace Anomaly

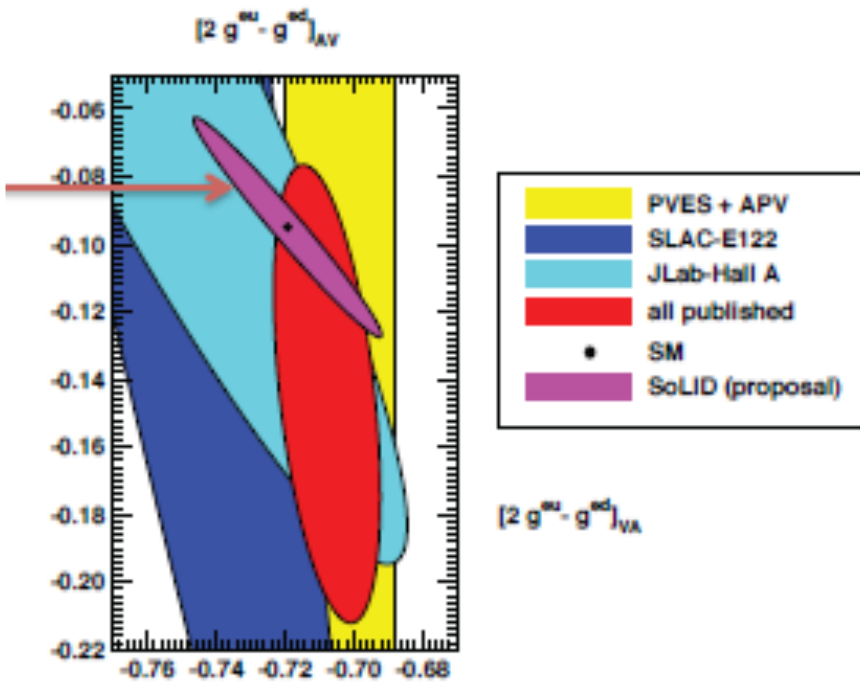


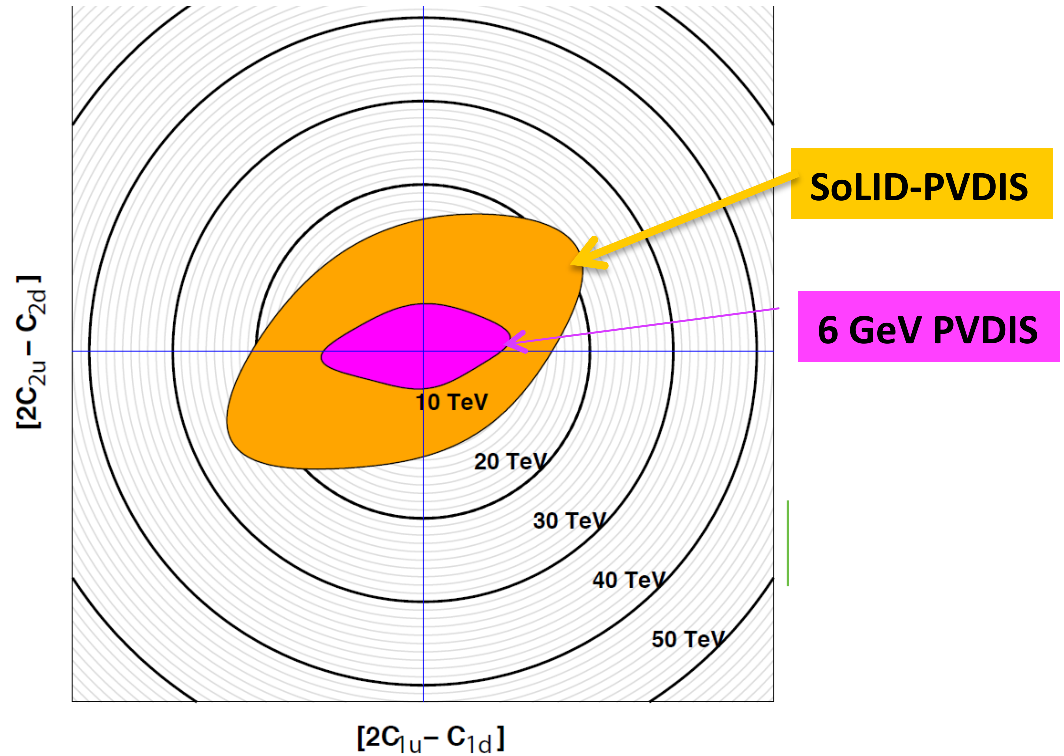
Other SoLID Program

PVDIS: Precision Test of Standard Model

Developing GPD Program

Parity Violation with SoLID





PVDIS asymmetry has two terms:

1) $\mathbf{C_{2q}}$ weak couplings, test of Standard Model

2) Unique precision information on **quark structure of nucleon**

Mass reach in a composite model, SoLID-PVDIS ~ 20 TeV, sensitivity match LHC reach with complementary Chiral and flavor combinations

6 GeV Results: D. Wang et al., Nature 506, no. 7486, 67 (2014)

Longstanding issue in proton structure

Proton PVDIS: d/u at high x

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}[a(x) + f(y)b(x)]$$

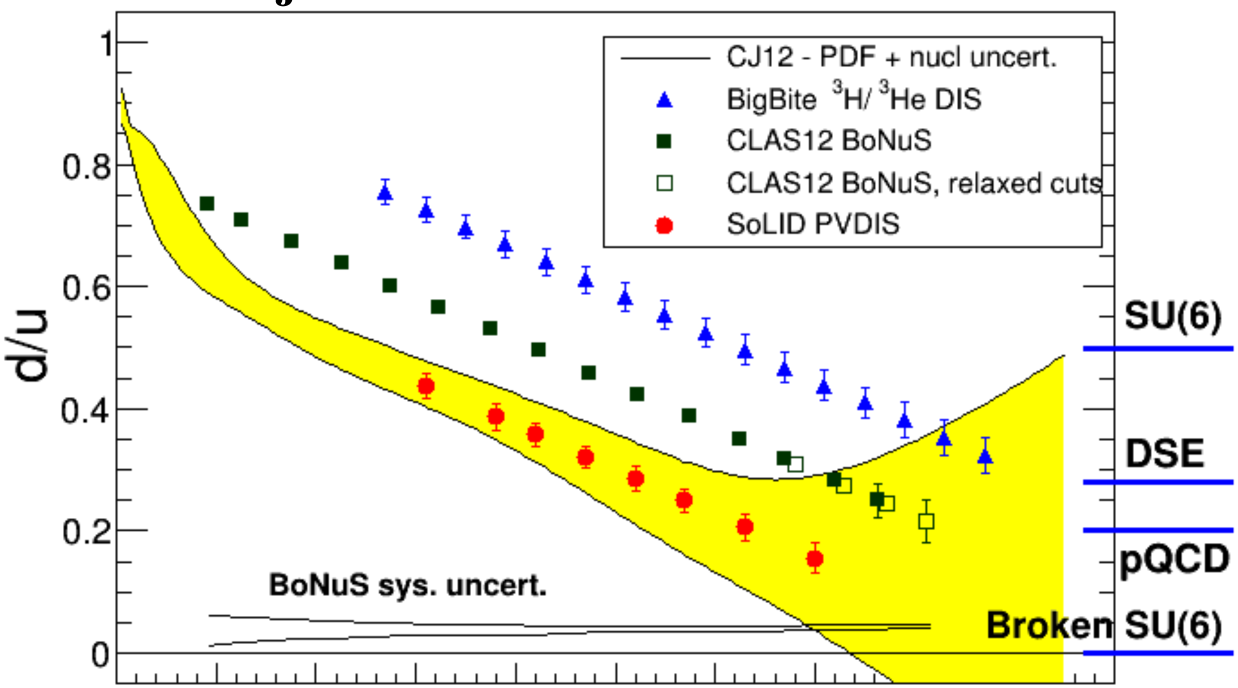
SU(6): d/u~1/2

Broken SU(6): d/u~0

Perturbative QCD: d/u~1/5

$$a^P(x) \approx \frac{u(x) + 0.91d(x)}{u(x) + 0.25d(x)}$$

Projected 12 GeV d/u extractions



- 3 JLab 12 GeV experiments:

- CLAS12 BoNuS spectator tagging
- BigBite – DIS $^3H/^3He$ ratio
- **SoLID – PVDIS *ep***

- **The SoLID extraction of *d/u* is directly from *ep* DIS:**

  - **No nuclear corrections**
  - **No assumption of charge symmetry**

3-D Structure II: GPD Study with SoLID

- A run-group proposal to PAC43: Time-like DVCS, Z. Zhao, *et al.*
  recently reviewed and approved by the SoLID collaboration

- A run-group proposal: Deep Exclusive Meson production,
  G. Huber, et al.
  recently reviewed and approved by the SoLID collaboration

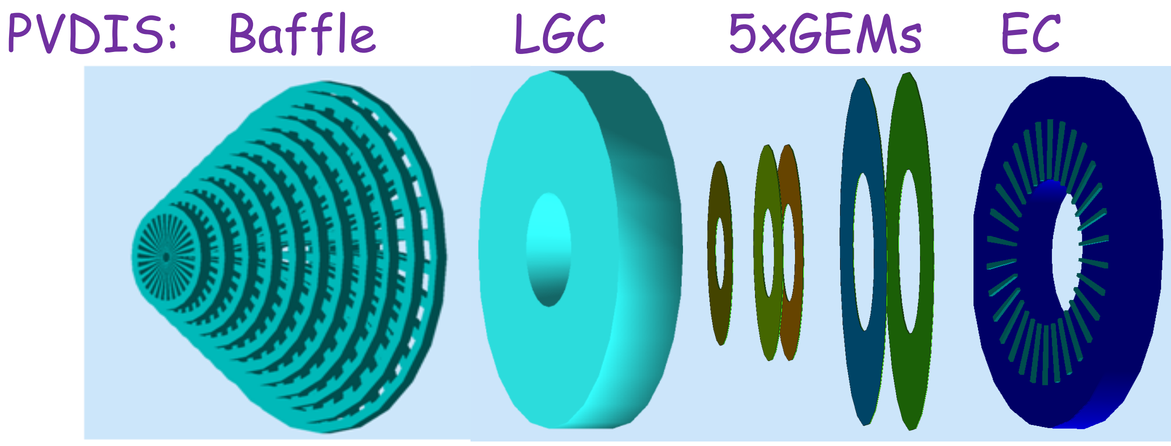
- A letter-of-intent to PAC43: Double-DVCS, A. Camsonne, *et al.*
  Encouraged by PAC. Work on-going. For a future PAC?

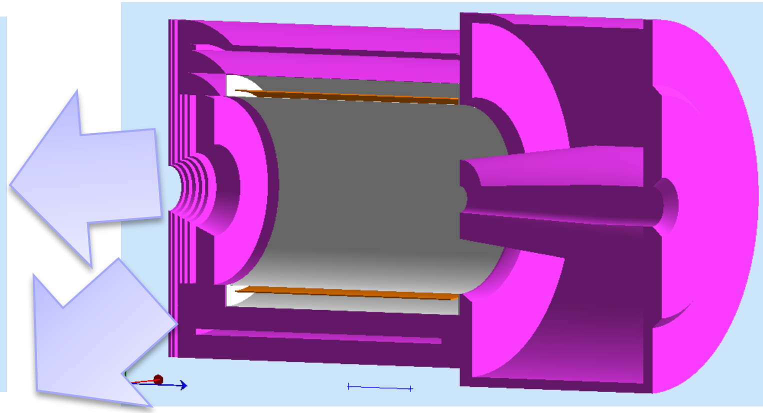
- A future proposal: DVCS with transversely polarized 3He,
  Z. Ye, et al.
  work on-going, presented at SoLID collaboration meeting,
  for a future PAC?

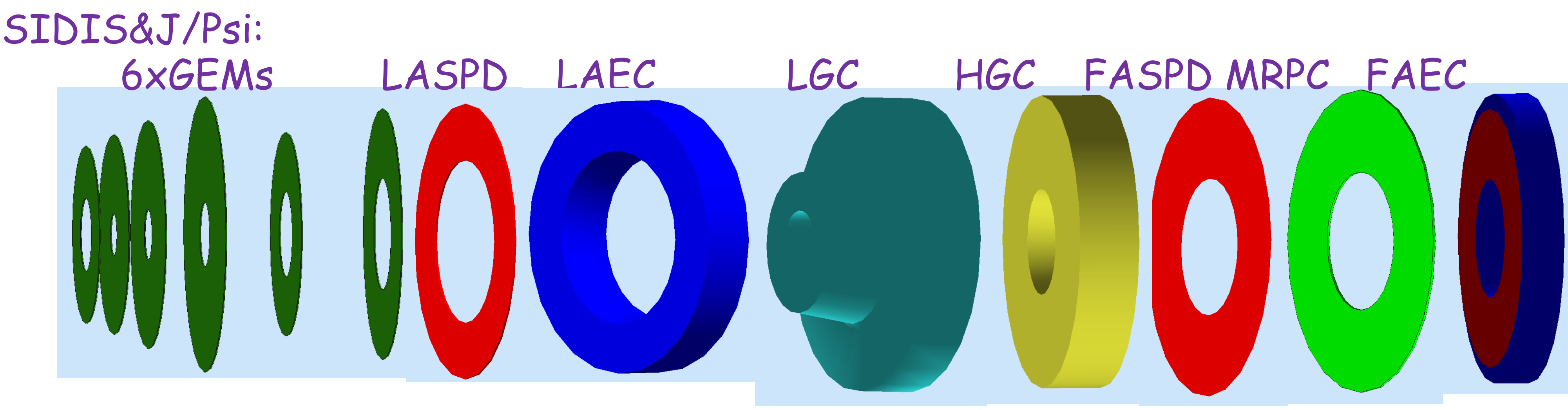
SoLID Status

Timeline and Organization

SoLID Detector Overview







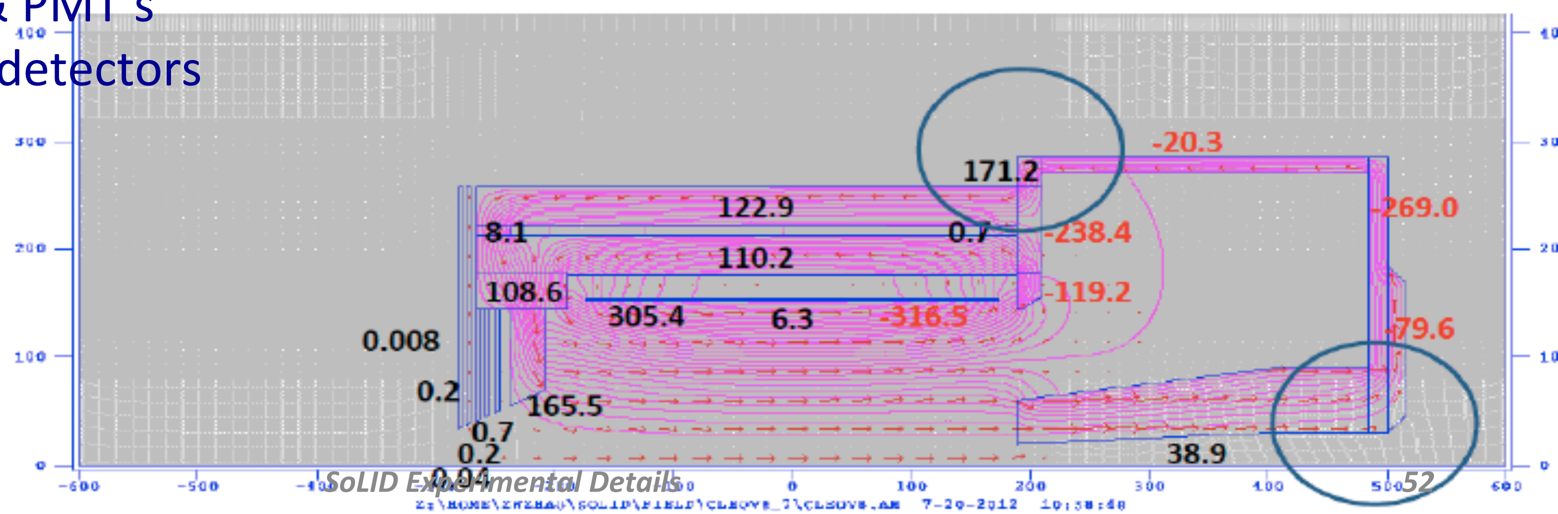
SoLID Solenoid: CLEO Magnet

Magnet transportation and testing

- Coils and cryostat were transported to JLab in 2016.
- Performance tests will be done at JLab.

Accurate 3D Field Map

1. Effects of saturation
2. Magnetic forces
3. Fields near target & PMT's
4. Final placement of detectors



SoLID Timeline, Status

- 2010-now: Five highly rated SoLID experiments approved by PAC + 4 run group
- 2013: CLEO-II magnet formally requested and agreed, site visits and planning

--2010-now: Progress

  - Spectrometer magnet study, modifications
  - Detailed simulations
  - Detector/DAQ design and pre-R&D
  - Strong International collaboration (Chinese, Canadian, …)

✓ 7/2014: pre-CDR submitted

✓ 2/2015: Director's Review, successful

✓ 2014-2015: Long Range Plan, SoLID strongly endorsed

✓ 2015: discussion with DOE on pre-R&D

✓ 2016: CLEO-II magnet transported JLab

✓ 2017: Responses to Director's Review Recommendations

SoLID Timeline, Status and Plan

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✓ 2016: CLEO-II magnet transported to JLab
✓ 2016-17: Responses to Director's Review Recommendations

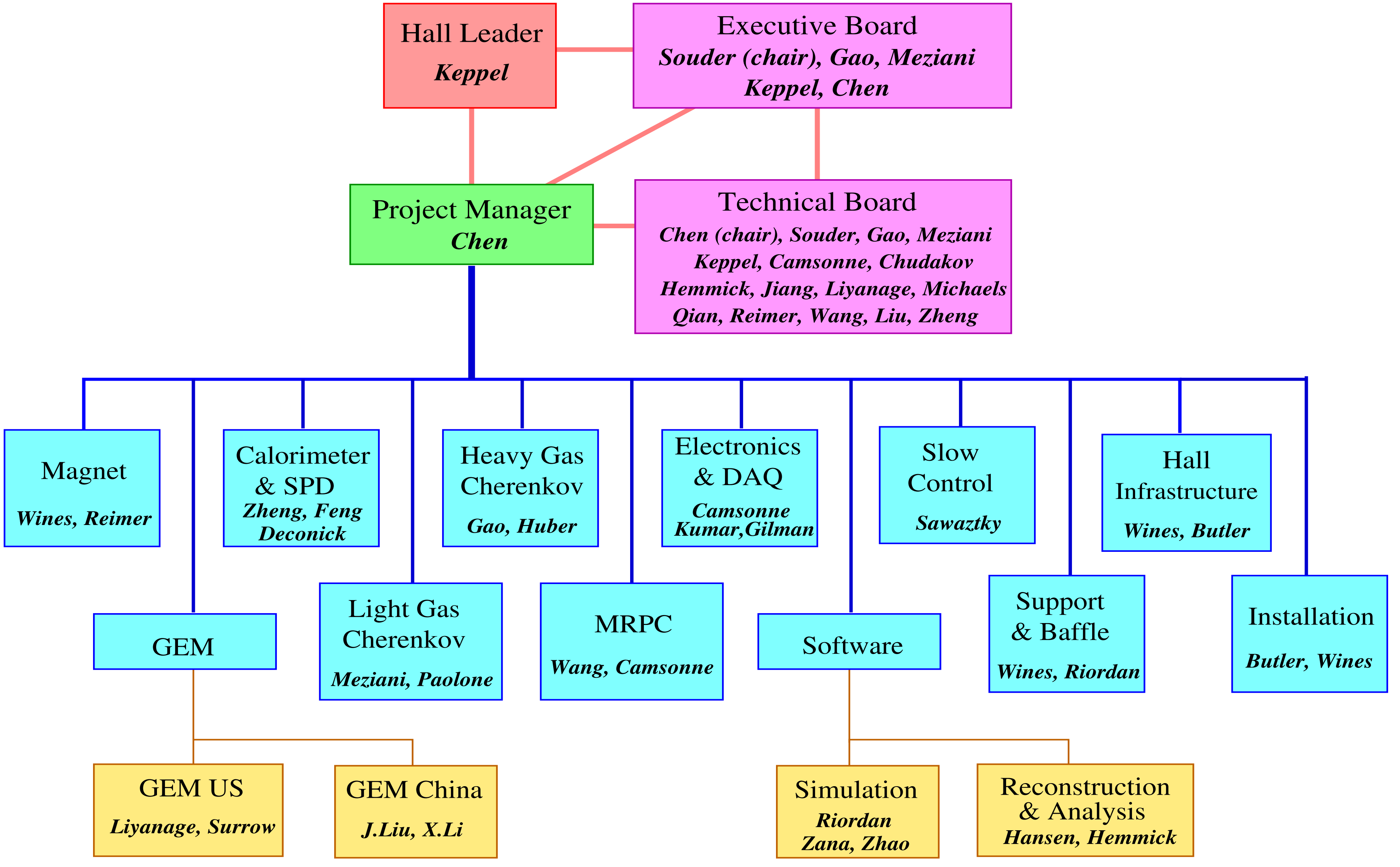
Plan:

○ 2017: Update pCDR (MIE) → DOE Science Review
○ CD processes/ PED/R&D (2017 – 2019)
○ Construction starts FY 2020

SoLID Collaboration and Organization

250+ collaborators from 70+ institutes, 13 countries, Strong Chinese Components

New Collaborators Welcome



Summary

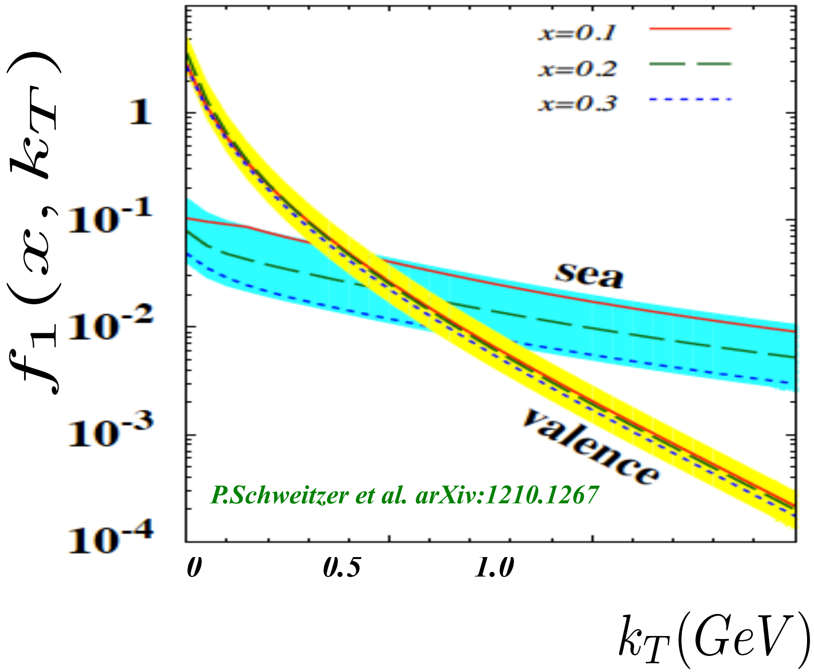
- **Full exploitation of JLab 12 GeV Upgrade**
  → **SOLID:** A **Large Acceptance** Detector that can handle **High Luminosity** (10^{37}-10^{39})
- **Rich, vibrant and important physics program to address some of the most fundamental questions in Nuclear Physics**
- **SoLID will provide the community with a large acceptance detector capable of operating at very high luminosities making high-precision JLab 12-GeV measurements in QCD (TMDs, J/ψ, d/u, GPDs), and electroweak physics.**
- **SoLID could be the 1st detector for future EIC.**
- **Strong International (Chinese) Collaboration.**
- **Excellent progress despite budget constraints, ready to move forward.**
- **Need work closely with theorists to plan and to be able to extract maximum information from SoLID program.**

Detailed information: see the SoLID whitepaper: arXiv:1409.7741;
and http://hallaweb.jlab.org/12GeV/SoLID/

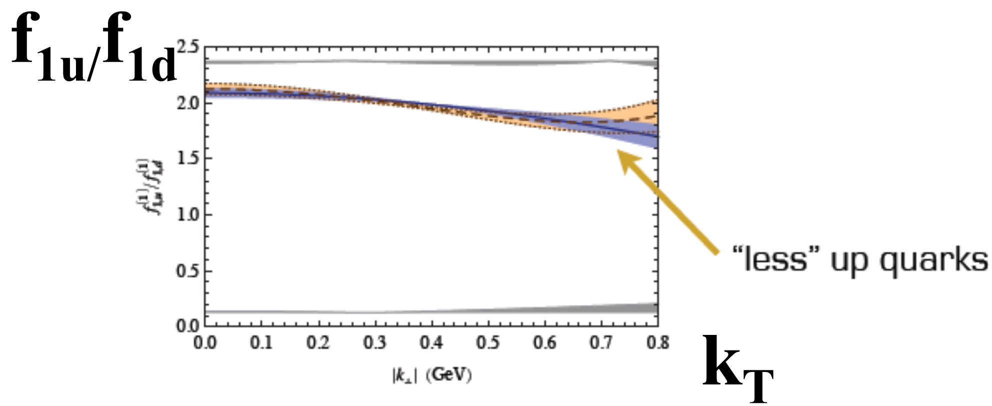
Backups

Flavor P_T Dependence from Theory

- **Chiral quark-soliton model (Schweitzer, Strikman, Weiss, JHEP, 1301 (2013)**
  → sea wider tail than valence



Indications from lattice QCD



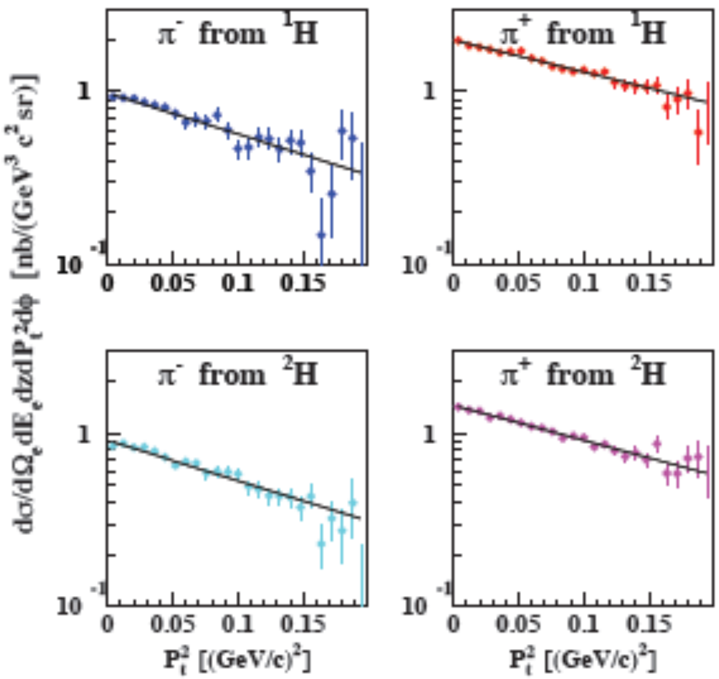
Musch, Hagler, Negele, Schafer, PRD 83 (11)

Pioneering lattice-QCD studies hint at a down distribution being wider than up

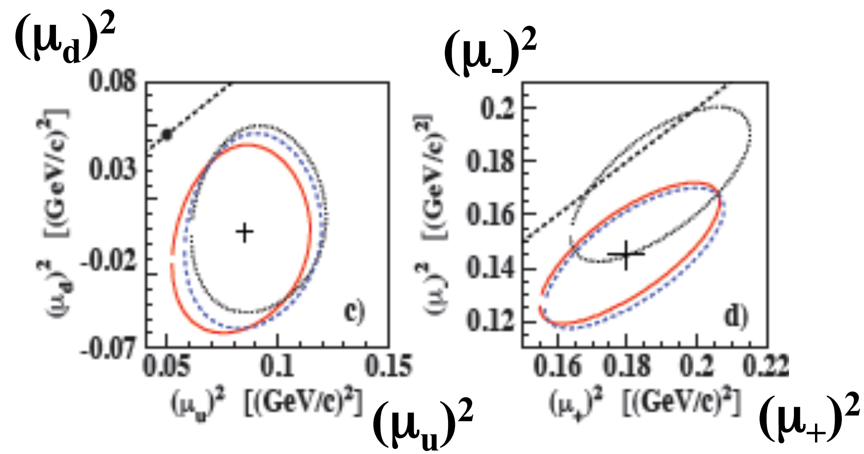
- **Flagmentation model, Matevosyan, Bentz, Cloet, Thomas, PRD85 (2012)**
  → unfavored pion and Kaon wider than favored pion

Hall C Results: Flavor P_T Dependence

First indications from experiments



no kaons, no sea,
no *x*-*z* dependence



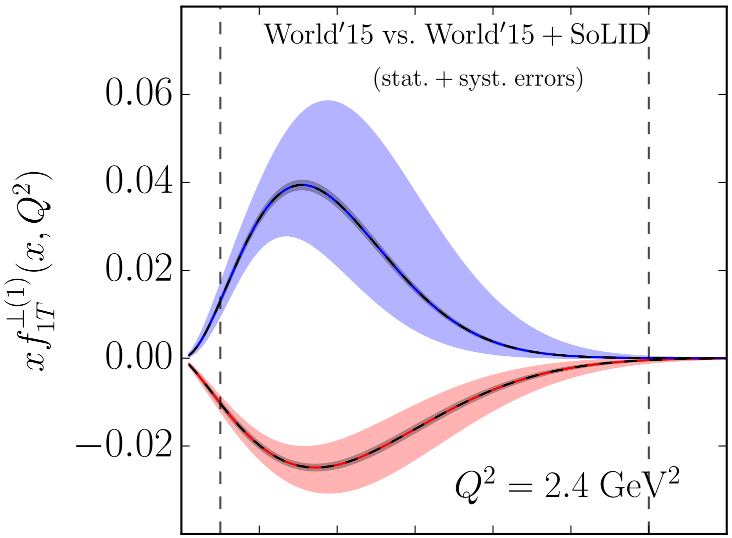
Asaturyan et al., E00-108, Hall C, PRC85 (2012)

Conclusion: up is wider than down and favored wider than unfavored

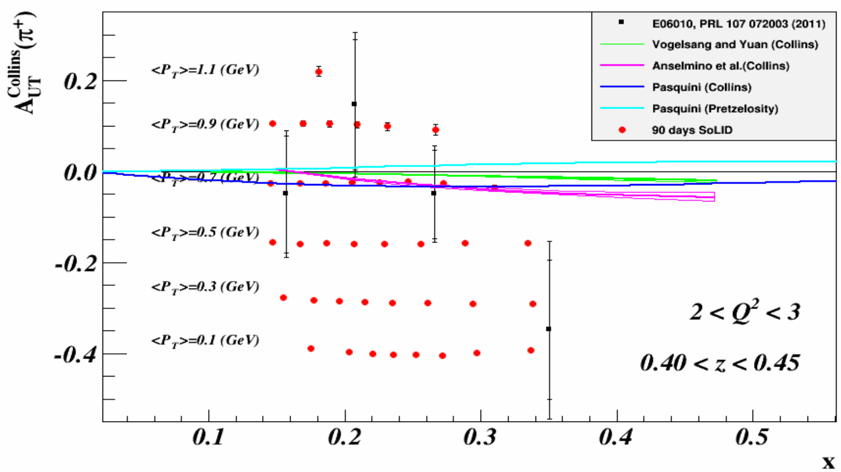
Jefferson Lab

Mapping Sivers Asymmetries with SoLID

- Sivers Asymmetries ~ Sivers Function (x, k_T, Q^2) (x) Fragmentation Function (z, p_T, Q^2)
- Leading-twist/not Q power suppressed: Gauge Link/ QCD Final State Interaction
- Transverse Imaging
- QCD evolutions
- **SoLID**: precision multi-d mapping
- Collaborating with theory group: impact study

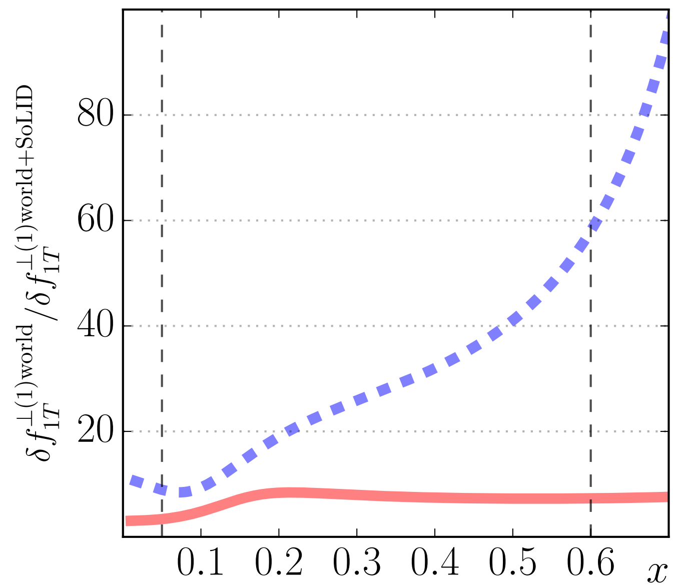


Sivers Asymmetries



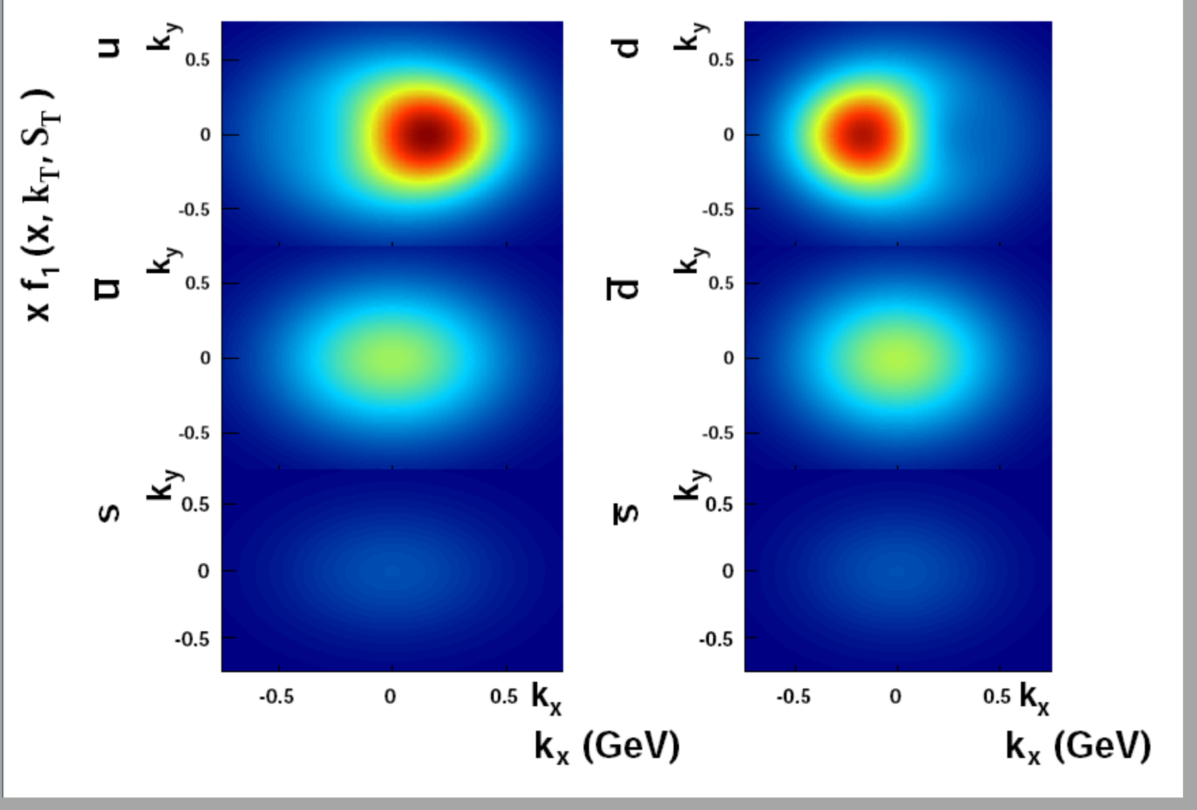
P_T vs. x for one (Q^2, z) bin
Total > 1400 data points

Liu, Sato, Prokudin,…



What do we learn from 3D distributions?

$$f(x, \mathbf{k_T}, \mathbf{S_T}) = f_1(x, \mathbf{k_T^2}) - f_{1T}^{\perp}(x, \mathbf{k_T^2}) \frac{\mathbf{k_{T1}}}{M}$$



The slice is at:

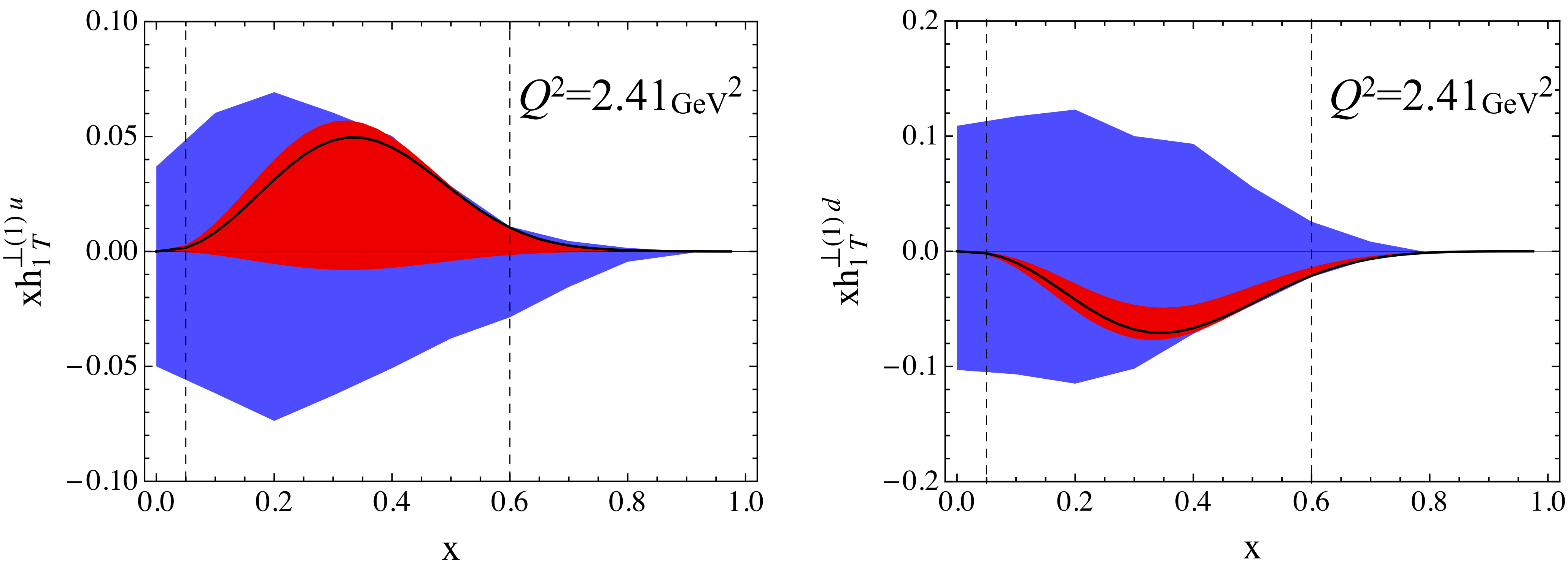
$x = 0.1$

Low-x and high-x region is uncertain
JLab 12 and EIC will contribute

No information on sea quarks

In future we will obtain much clearer picture

SoLID Impact on Pretzelosity



C. Lefky *et al.*, PR D 91, 034010 (2015).

SoLID transversely polarized ^{3}He, E12-10-006.

95% C.L.

Duke UNIVERSITY

by Tianbo Liu (Duke & DKU)

昆山杜克大学 DUKE KUNSHAN UNIVERSITY