Nuclear Measurements in SoLID?

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- The SoLID physics program in Hall A at JLab uses nuclear targets to study nucleon structure however nuclear targets are being considered
  - PVDIS uses a deuterium target (inclusive)
  - SIDIS uses a polarized ^{3}He to a probe neutron TMDs (semi-inclusive)
  - Exclusive production of vector mesons as a probe to gluons uses a hydrogen target but we also want to consider nuclear targets

Why SoLID?

- Pursuit of multidimensional observables and rare processes not easily accessible due to luminosity and acceptance demands

The driving science program encompasses

- 3-Dimensional Imaging in Momentum Space
- Parity Violation Deep Inelastic Scattering
- J/Psi Electroproduction at Threshold
- Time-like Compton Scattering
- Di-Hadrons
- SSA
- .....

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 and data acquisitions

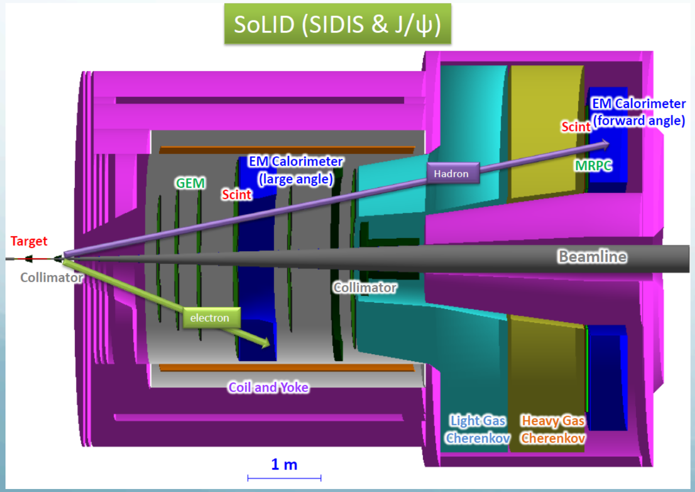
- Reach ultimate precision for SIDIS (TMDs), providing three-dimensional imaging of nucleon in momentum space
- PVDIS in high-*x* region providing sensitivity to new physics at 10-20 TeV, and QCD
- Threshold J/ψ, probing strong color field in the nucleon, trace anomaly

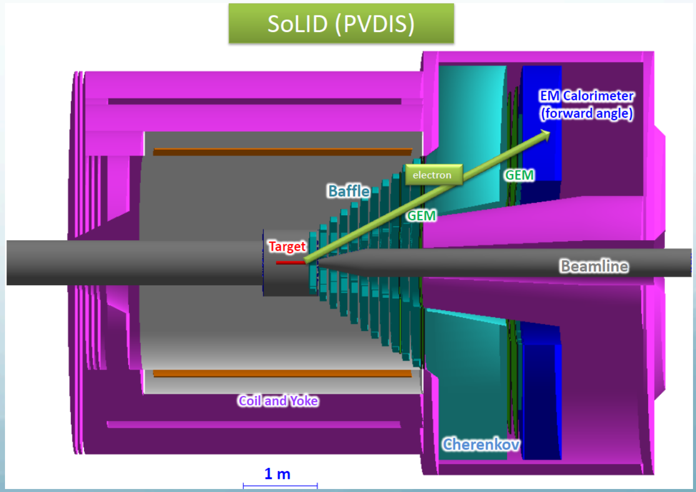
- **5 highly rated experiments approved**

  Three SIDIS experiments, one PVDIS, one J/ψ production

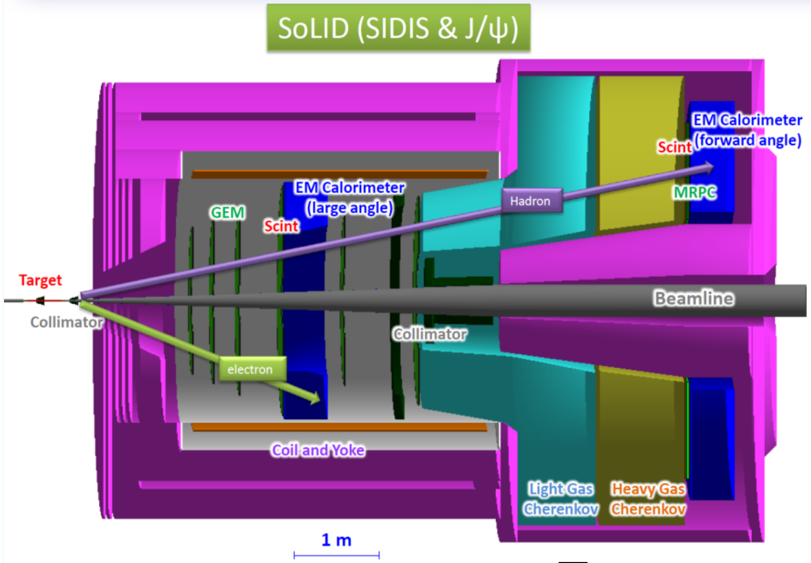
  Run group experiments: di-hadron, Inclusive-SSA, TCS and more coming…

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





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

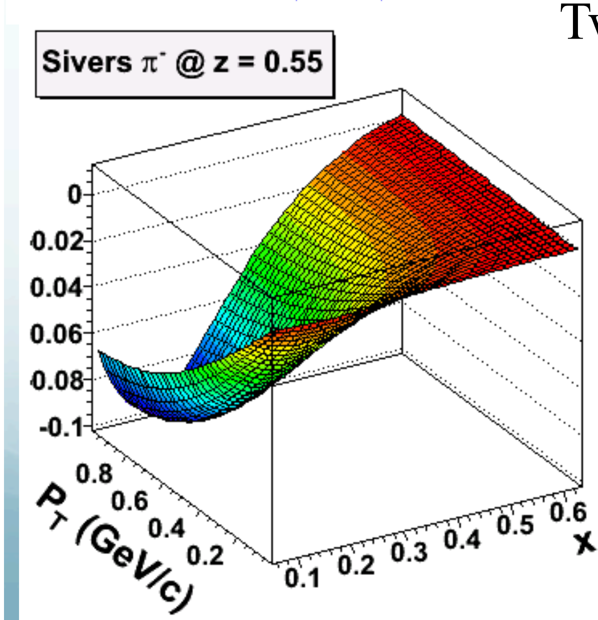


E12-10-006: Single Spin Asymmetry on Transverse ^{3}He, **rating A**

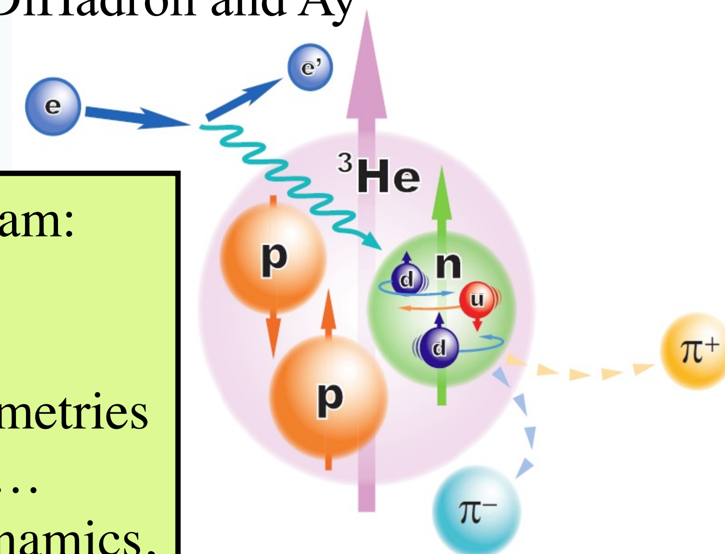
E12-11-007: Single and Double Spin Asymmetries on ^{3}He, **rating A**

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

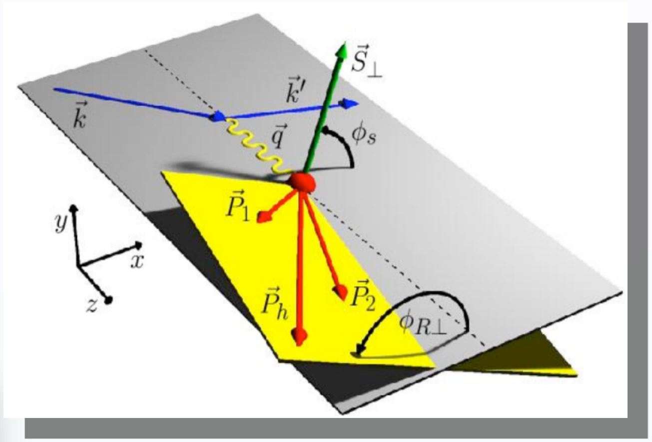
Two run group experiments DiHadron and Ay



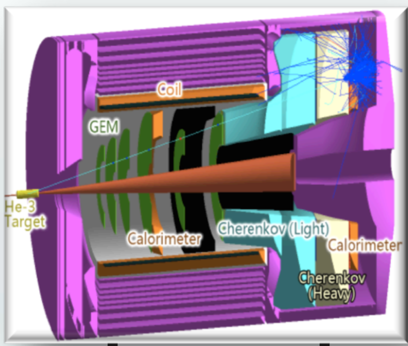
Key of SoLID-Spin program:
Large Acceptance
+ High Luminosity
→ 4-D mapping of asymmetries
→ Tensor charge, TMDs …
→Lattice QCD, QCD Dynamics, Models.



JLab 12: Multi-Halls TMD Program



Hall A/SoLID
High Lumi and acceptance – 4D



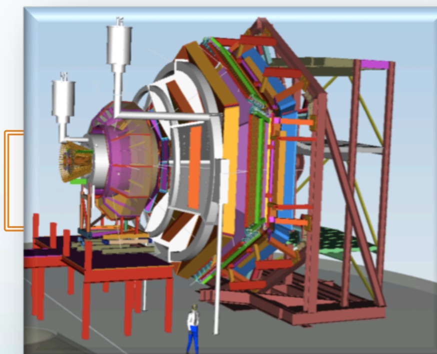
^3He, NH_3

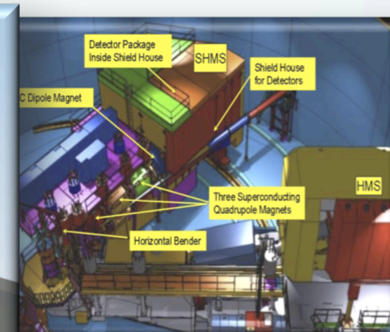
Hall A/SBS
High x - Q^2, 2-3D

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 $h_{1T}^\perp$

Hall B/CLAS12
General survey, medium luminosity

Hall C/SHMS
L-T studies, precise π^+/π^- ratios



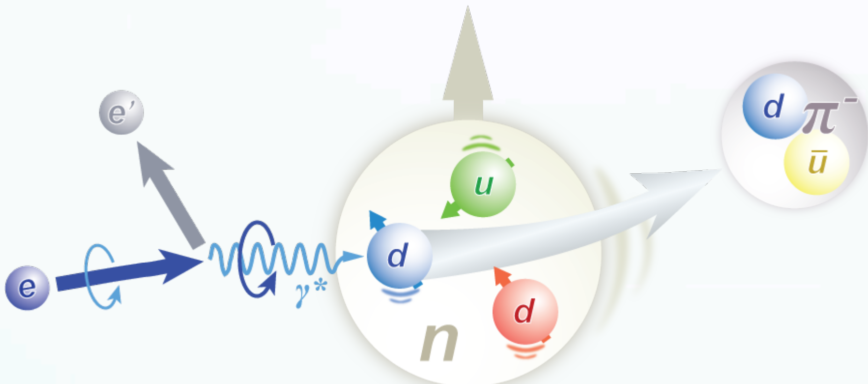


H_2/D_2, NH_3/ND_3, HD

H_2 D_2

Semi-Inclusive DIS (SIDIS)

- **TMDs - rich quantum correlations:**

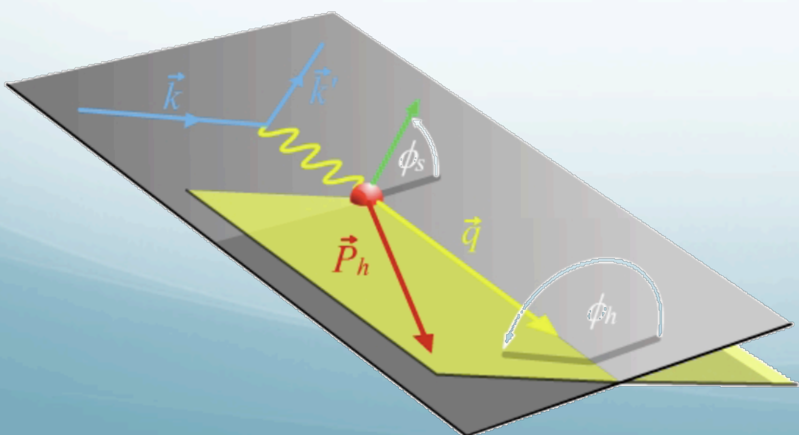


- **Two scales, two planes and flavor tagging:**
  - Two scales (theory-QCD TMD factorization):
    high Q - localized probe
    Low p_T - sensitive to confining scale
  - Two planes:
    angular modulation to separate TMDs

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

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

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



Leading-Twist TMD PDFs

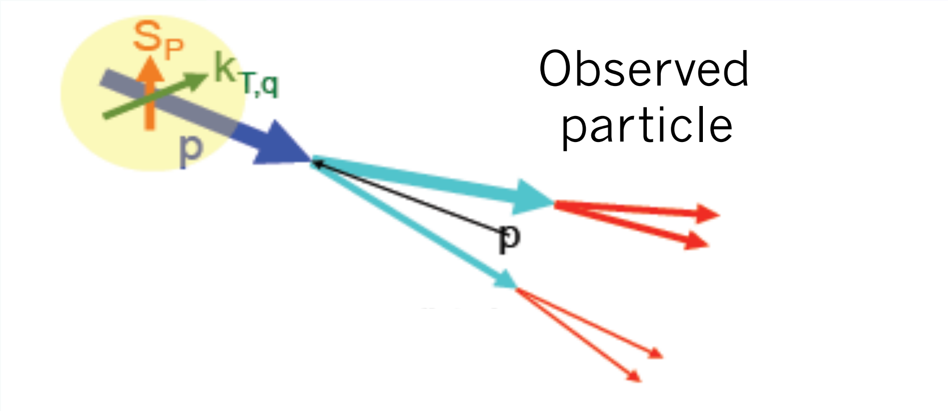
Nucleon Spin

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

Confined motion in a polarized nucleon

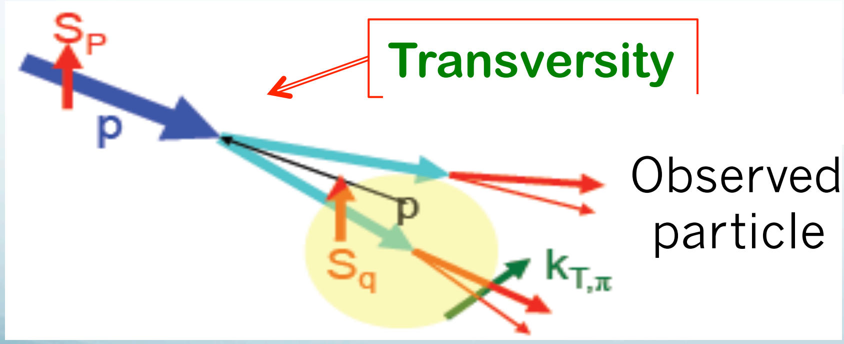
- **Quantum correlation between hadron spin and parton motion:**



Sivers effect – Sivers function

Hadron spin influences parton's transverse motion

- **Quantum correlation between parton spin and hadronization:**



Collins effect – Collins function

Parton's transverse spin influence its hadronization

JLab12 and COMPASS for valence, EIC covers the sea and gluon!

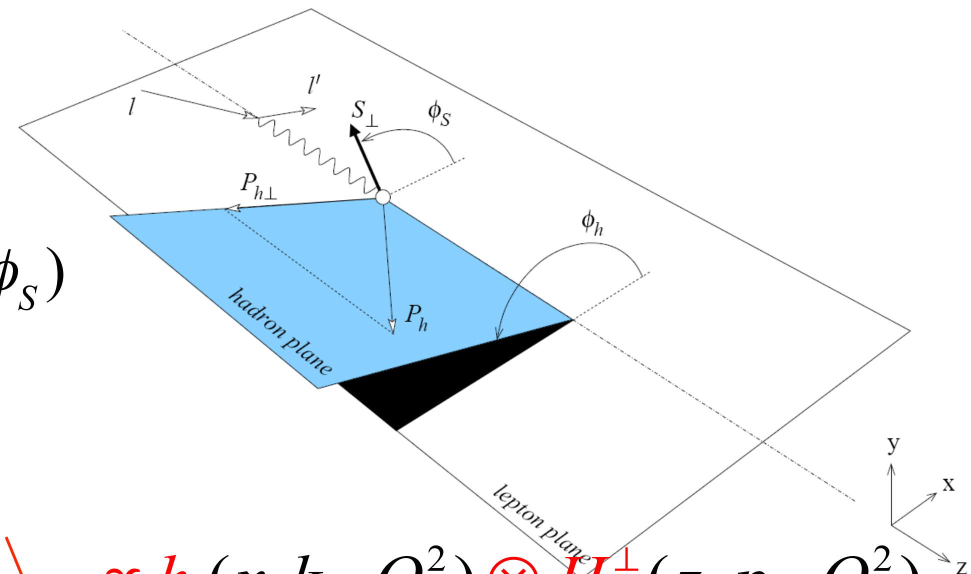
Separation of Collins, Sivers and pretzelocity Asymmetries through Polarization/Angular Dependence

At Leading twist:

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

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

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



$$A_{UT}^{Collins}(x,z,P_h,Q^2) \propto \left\langle \sin(\phi_h+\phi_S)\right\rangle_{UT} \propto h_1(x,k_T,Q^2)\otimes H_1^\perp(z,p_T,Q^2)$$

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

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

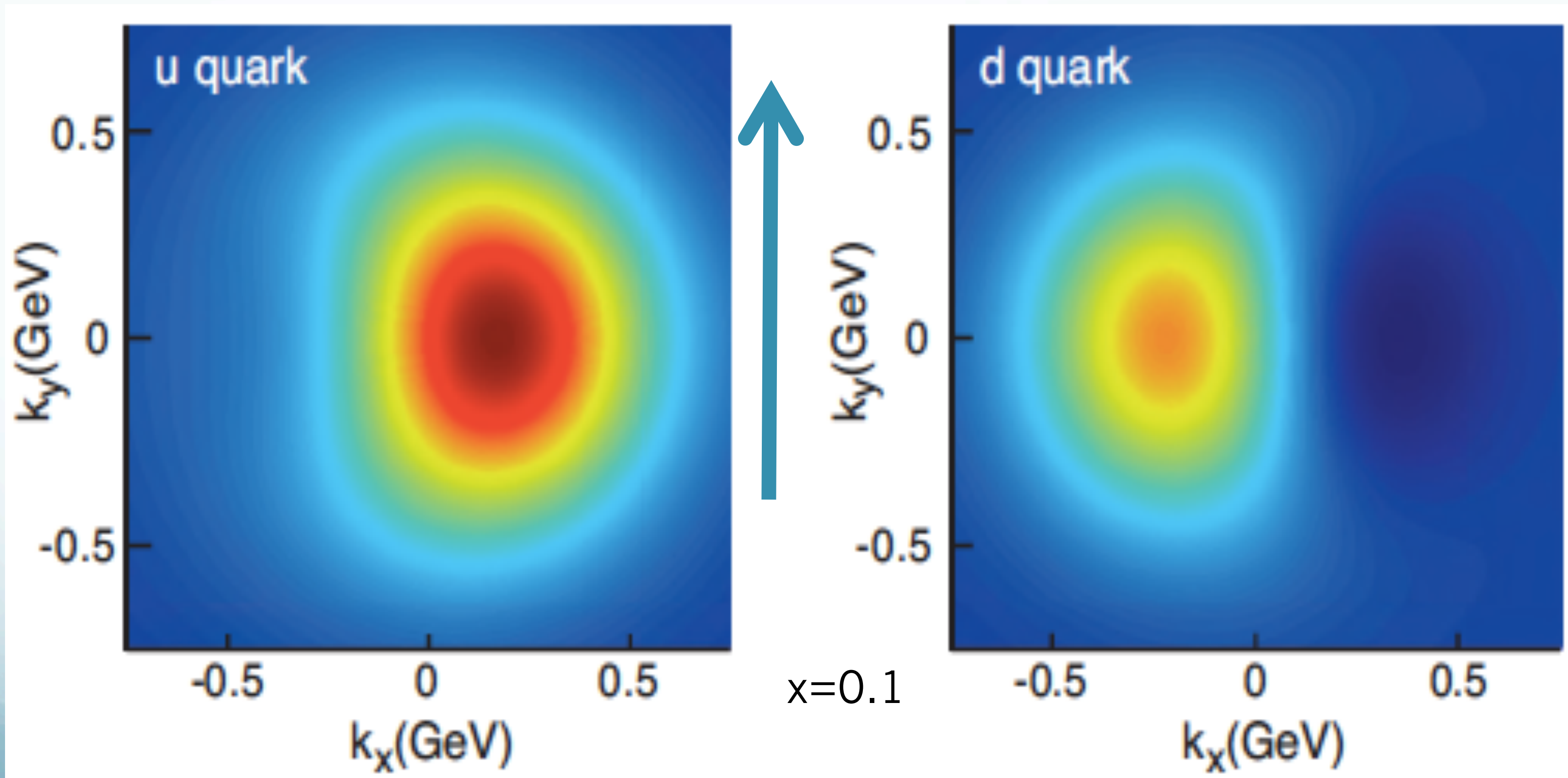
High precision multi-dimension mapping (x,Q^2,z and P_T) → very high statistics needed

Large angular coverage and precision measurement is essential

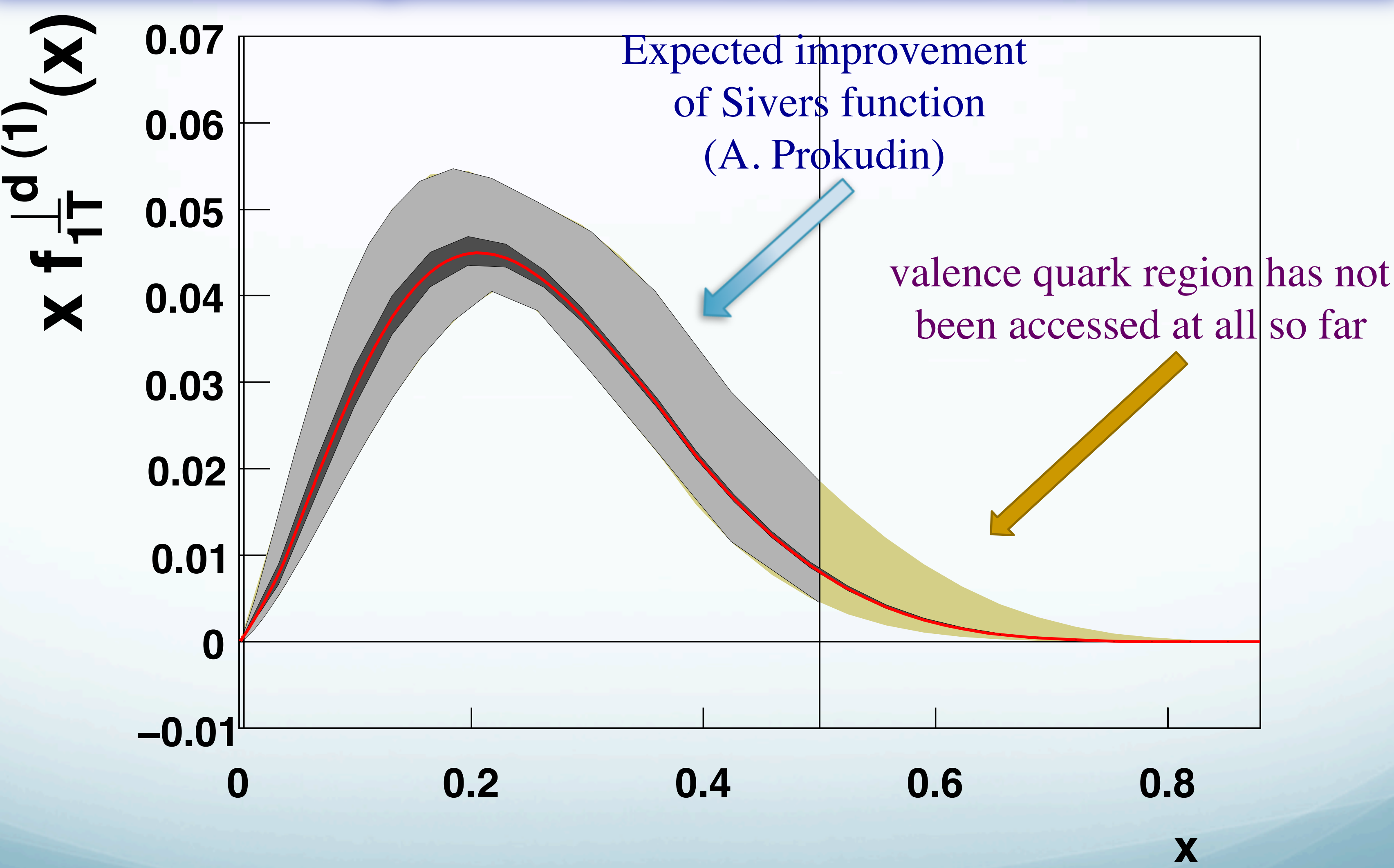
3-D imaging in momentum: Sivers Function

Alexei Prokudin

M. Anselmino et al. , J. Phys. Conf. Ser. 295 , 012062 (2011), arXiv: 1012.3565.

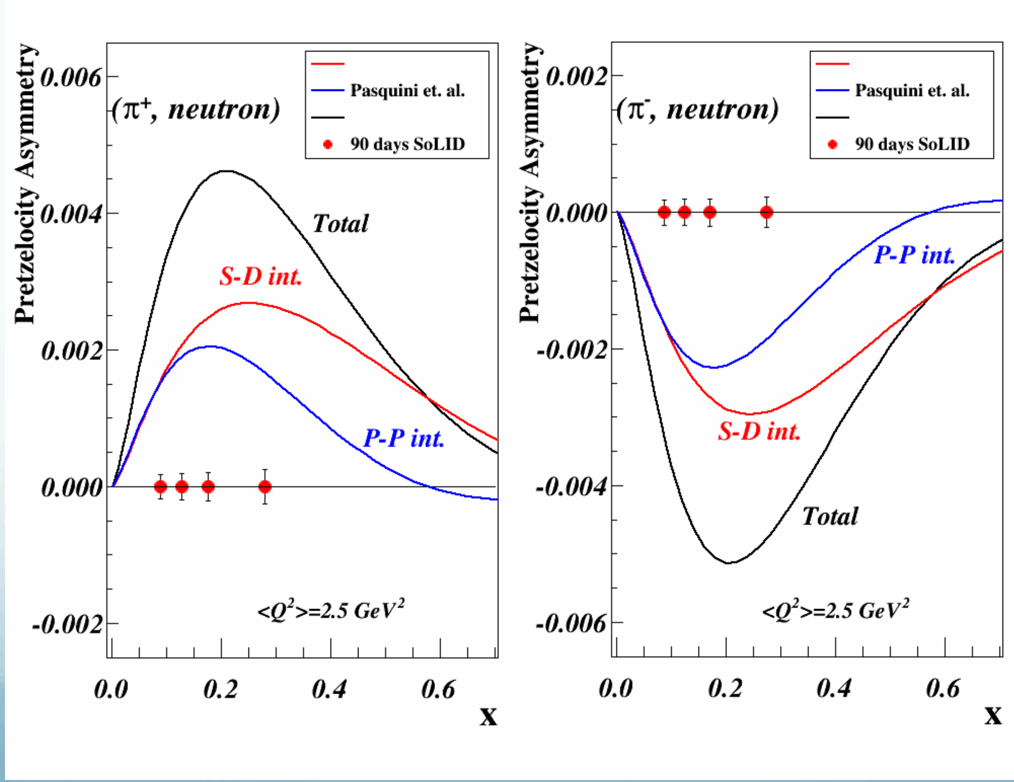


Projected Sivers Function



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: $\Delta L=2$ (L=0 and L=2 interference , L=1 and -1 interference)
  Worm-Gear: $\Delta L=1$ (L=0 and L=1 interference)
- SoLID with trans. polarized n/p → quantitative knowledge of OAM



SoLID Projections
Pretzelosity

Proton PVDIS: d/u at high x

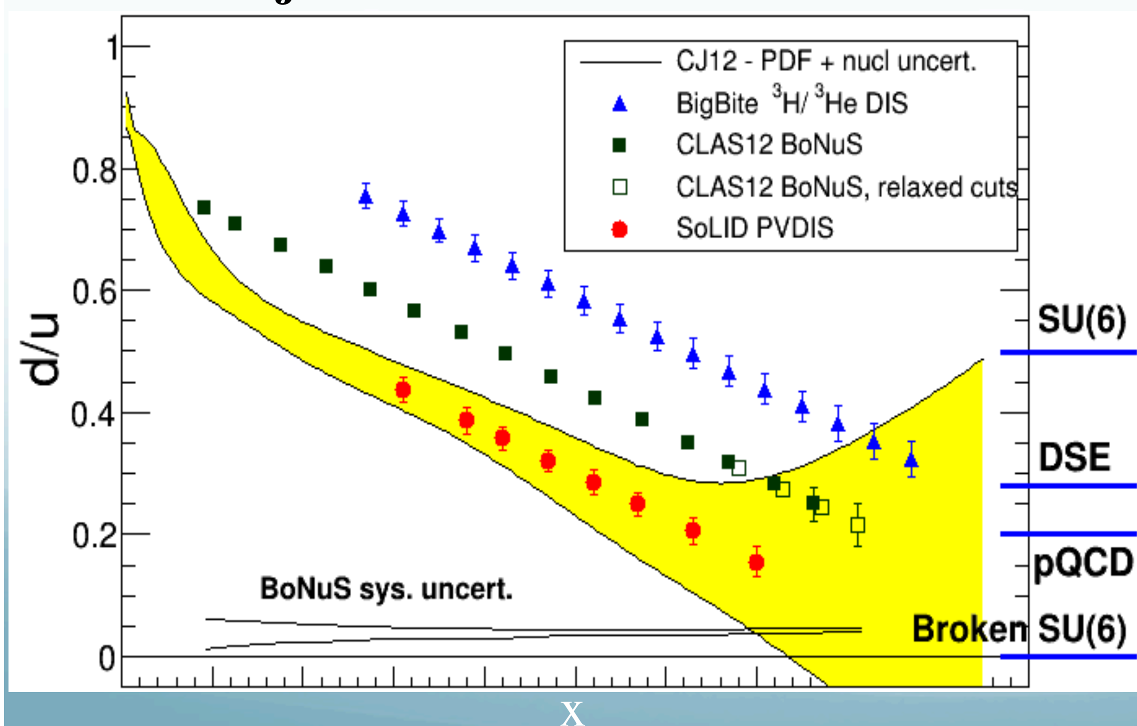
(high power liquid hydrogen target)

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

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



- <u>3 JLab 12 GeV experiments</u>:

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

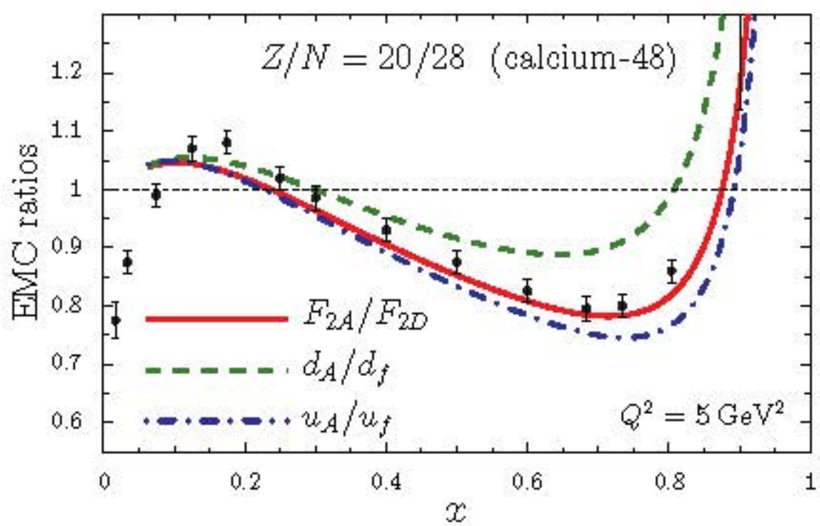
- **The SoLID extraction of *d/u* is directly from *ep* DIS:**

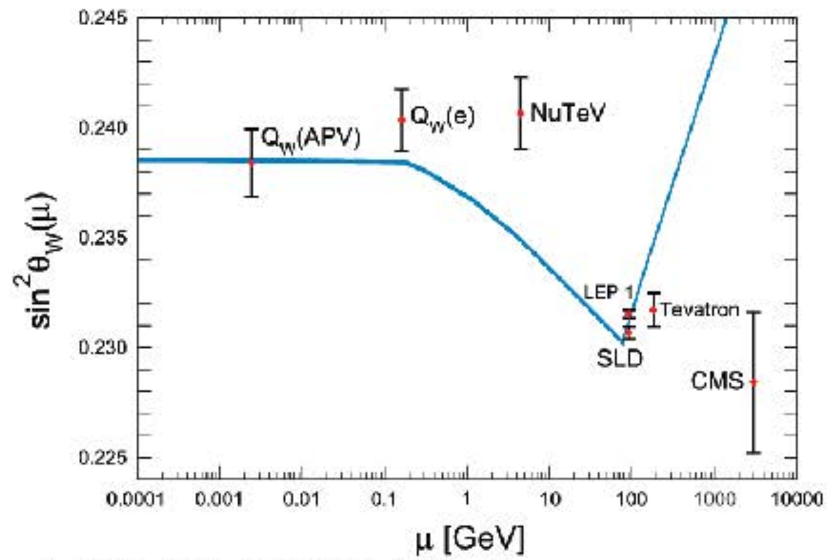
  - **No nuclear corrections**
  - **No assumption of charge symmetry**

Novel Isovector EMC Effect

u and *d* quarks can be modified differently in symmetric vs. asymmetric nuclei

- NuTeV sensitive to this effect - anomaly could be hinting new aspect of modification
- Cloet et *al.* make predictions based on mean field calculations which give reasonable reproductions of SFs
- PVDIS ^{48}Ca could also probe this - few percent effect in a_2, larger at larger x

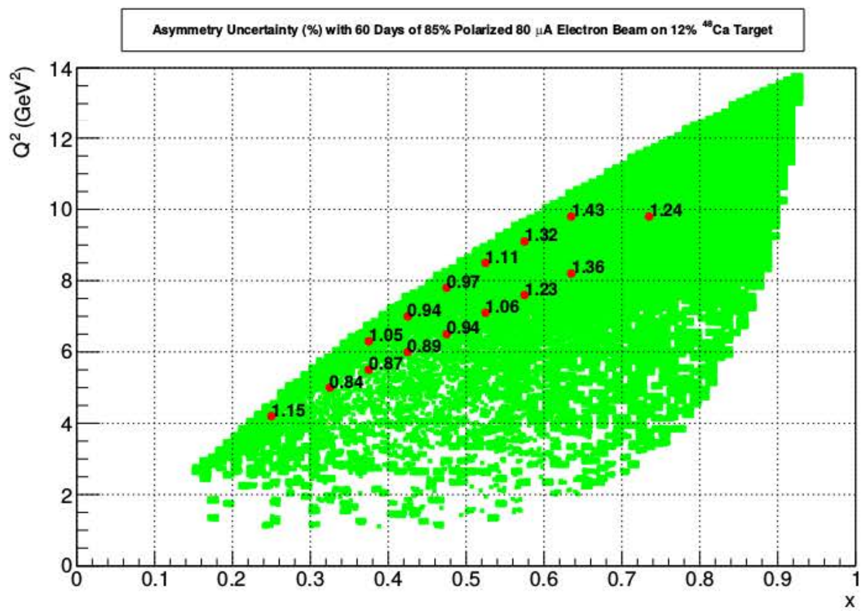




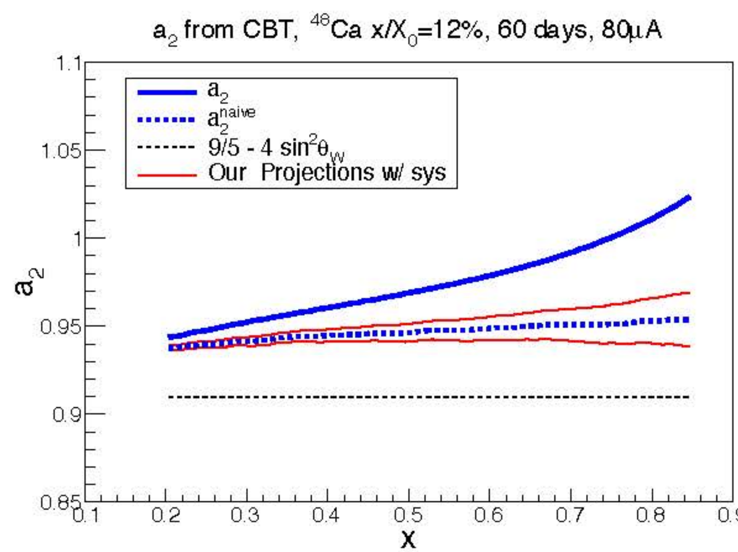
Cloet et *al.* PRL102 252301 (2009), Cloet et *al.* PRL109 182301 (2012)

With SoLID - Arrington, Beminiwattha, Riordan

- 60 days at 80 μA 11 GeV get $\sim$1% stat uncertainties across a broad range of x - several sigma test of CBT model
- Planning for proposal going to next PAC
- *Provides direct, new ,and useful constraints in a sector where there is little data*
- Not accessible with EIC



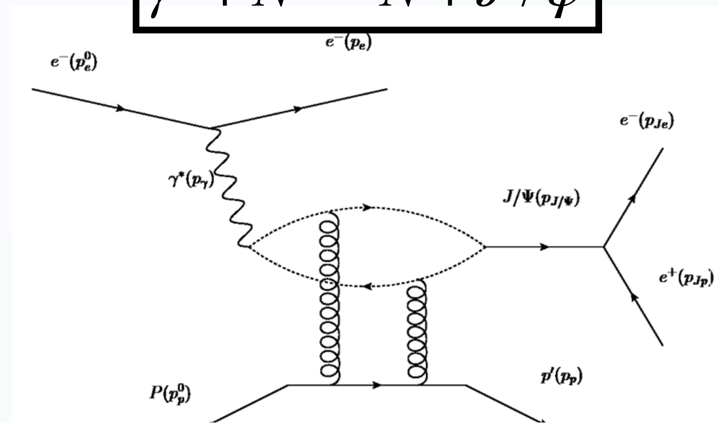
$$A = A_{\mathrm{naive}} + \alpha \Delta A_{\mathrm{CBT}}$$



J/ψ @ SoLID

$$\gamma^* + N \rightarrow N + J/\psi$$

Threshold J/Ψ production, probing strong color field in the nucleon, QCD trace anomaly (important to proton mass budget)

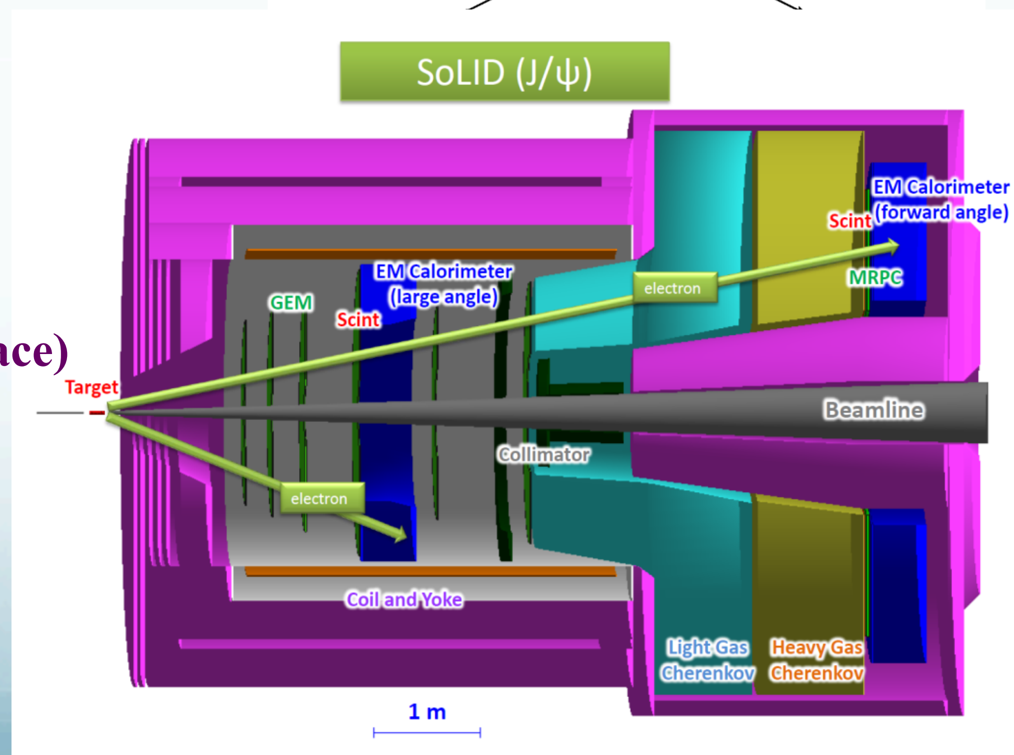


e p → e′ p′ J/ψ(e⁻ e⁺)

γ p → p′ J/ψ(e⁻ e⁺)

Imaginary part: related to the total cross section through optical theorem

Real part: contains the conformal (trace) anomaly



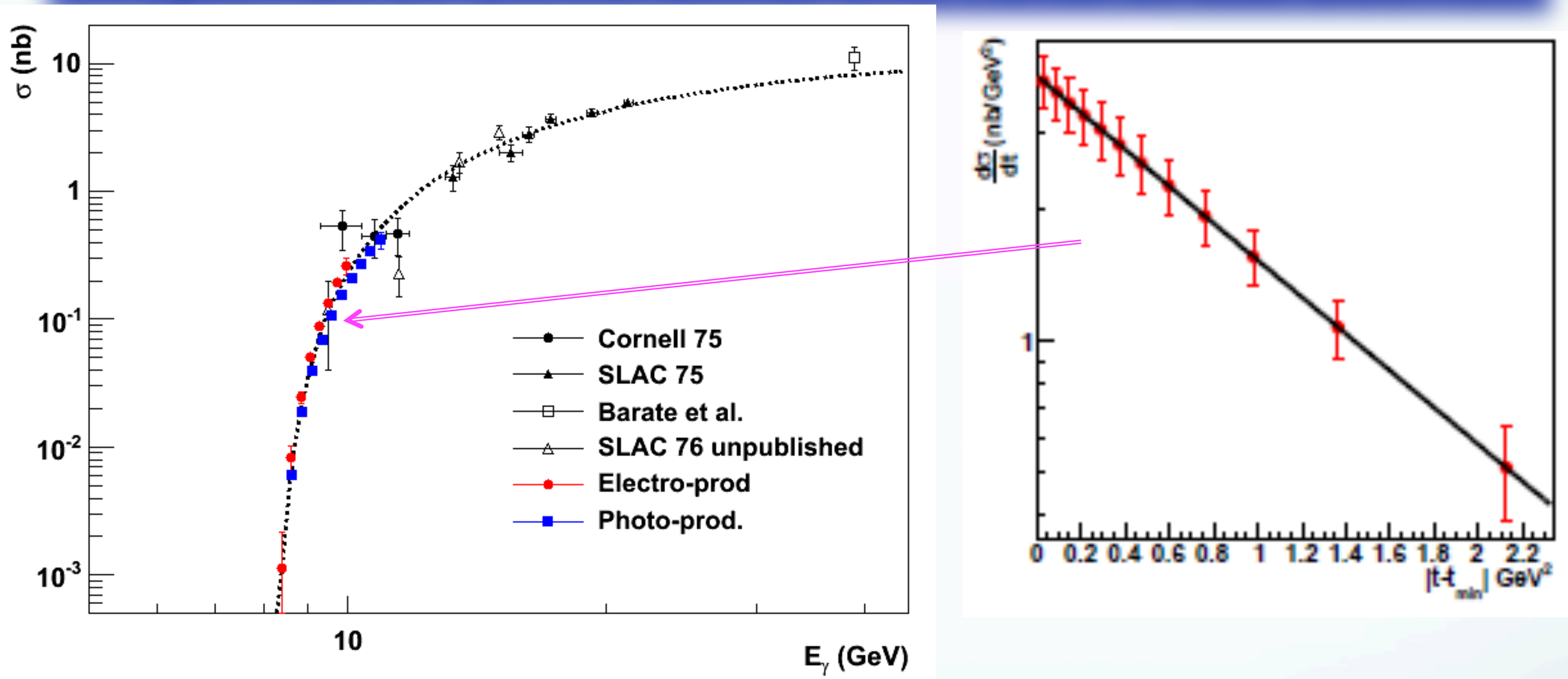
PR12-12-06: Near Threshold J/Ψ Electroproduction

- **Measure the *t* dependence and energy dependence of *J/ψ* cross sections near threshold**
  - Probe the nucleon strong fields in a non-perturbative region
  - Search for a possible enhancement of the cross section close to threshold
  - Shed some light on the conformal/trace anomaly

Establish a baseline for *J/ψ* production in the JLab energy range!

- **Bonuses:**
  - Photoproduction data
  - Decay angular distribution of J/ψ
  - Interference with Bethe-Heitler term (real vs. imaginary)
- **Future Plans:**
  - Search for J/ψ-Nuclei bound states
  - J/ψ medium modification

Projection of Differential and Total Cross Section



Luminosity $1.2*10^{37}/cm^2/s$, 11GeV 3uA e- on 15cm LH2 50 Days

No competition in statistics

Study the threshold behavior of cross section with high precision **could shed light on the conformal anomaly**

Two goals to use coherent production of ϕ on ^{4}He

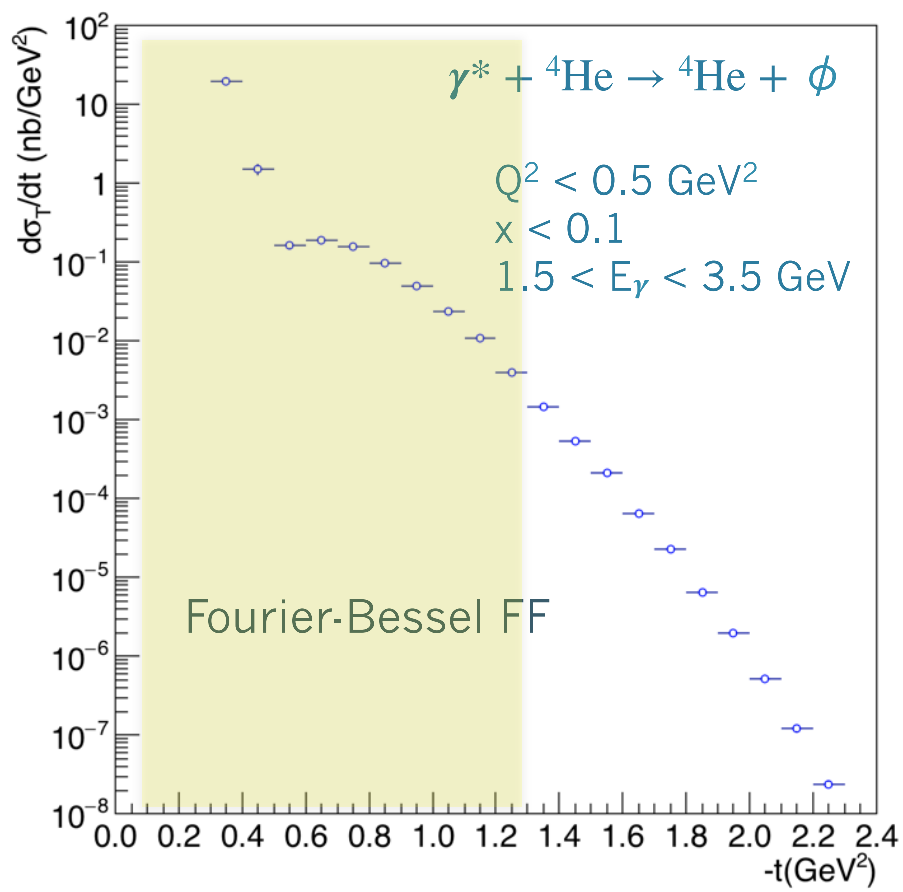
- Although the J/Ψ or Υ are better gluonic probes, we can use the ϕ to probe the gluon density in ^{4}He at JLab
  - Is the diffraction minimum for the charge and gluon distributions the same?
  - If we do not observe a diffraction minimum how is it filled, what are the mechanisms?
  - Are the exchanged gluons probing more then one nucleon at a time?

- Search for bound states near threshold, strong threshold interactions effects might be seen and studied.

Coherent ϕ electroproduction cross-section off ^{4}He

- **CLAS12:**
  - a new recoil nucleon/nuclei detector (ALERT detector) is being developed for use with a ^{4}He target.
  - Proposal in progress
- Cross-section goes like:

$$\frac{d\sigma_{^4He}}{dx_B dQ^2 dt} = \frac{d\sigma_p}{dx_B dQ^2 dt} \left| \frac{A\, F_C(t')_{^4He}}{F_C(t')_p} \right|^2$$

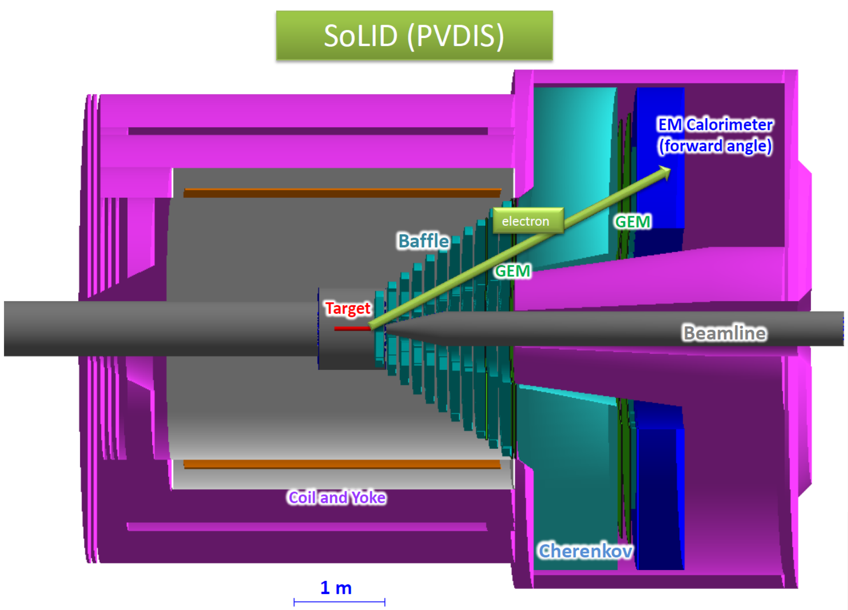


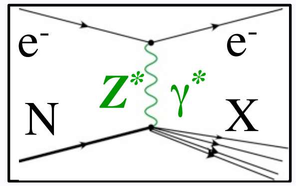
Summary

- SoLID has a robust science program which is growing beyond its original scope of TMDs, PVDIS and Threshold J/Ψ production.
- Ideas to use nuclei are emerging among them
  - Isovector EMC effect
  - Accessing nuclei gluon GPDs with phi and perhaps J/Ψ
  - Investigating possible quarkonium-nucleus bound states
  - Hadronization

12 GeV Upgrade: Extraordinary opportunity to do the ultimate PVDIS Measurement

SOLID with the 12 GeV Upgrade



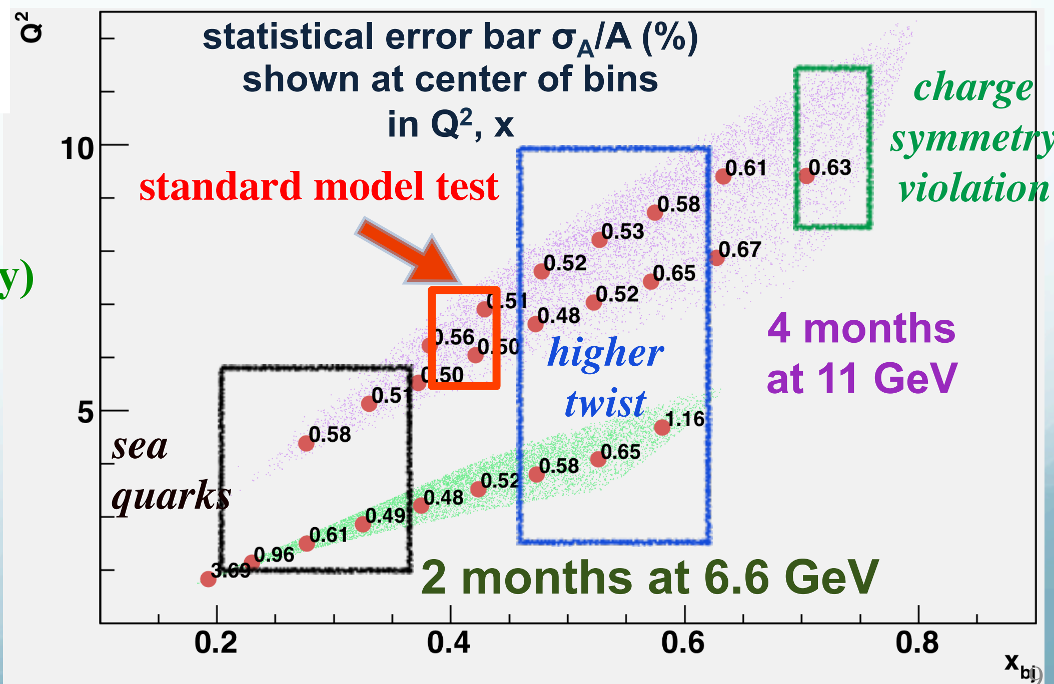


$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}[a(x) + f(y)b(x)]$$

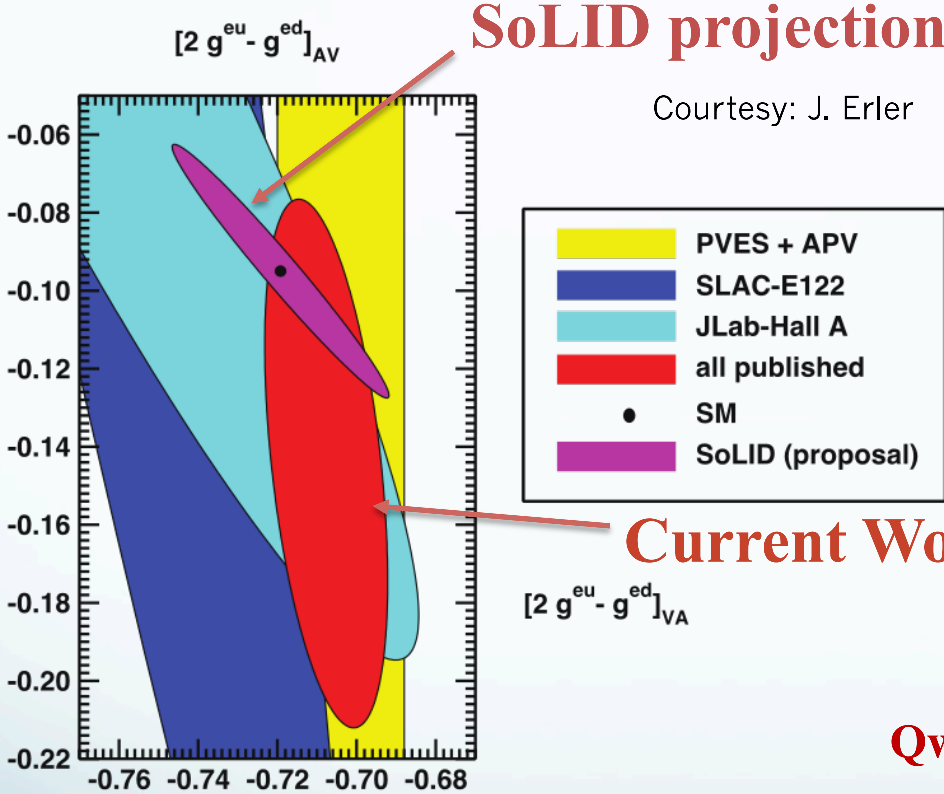
Strategy: **sub-1% precision** over broad kinematic range: **sensitive Standard Model test** *and* **detailed study of hadronic structure contributions**

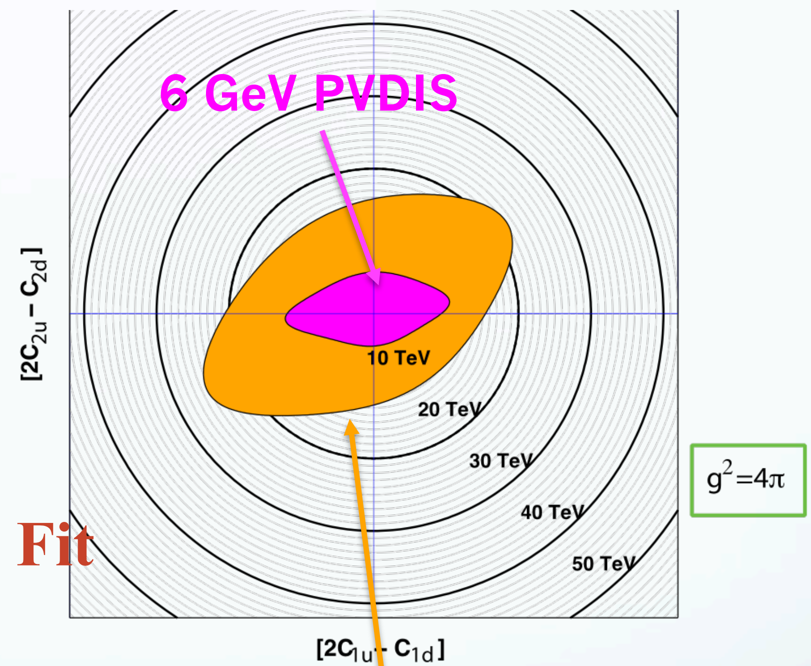
Requirements

- **High Luminosity with E > 10 GeV**
- **Large scattering angles (for high x & y)**
- **Better than 1% errors for small bins**
- **x-range 0.25-0.75**
- **$W^2 > 4$ GeV^2**
- **Q^2 range a factor of 2 for each x**
  – **(Except at very high x)**
- **Moderate running times**



SOLID New Physics Sensitivity





Qweak projected result + projected SOLID

Qweak and SOLID will expand sensitivity that will match high luminosity LHC reach with complementary chiral and flavor combinations

Jlab 6-GeV PVDIS results
Wang *et al.*, Nature 506, No. 7486, 67 (2014)

SoLID ~ 10 times improvement over 6 GeV result