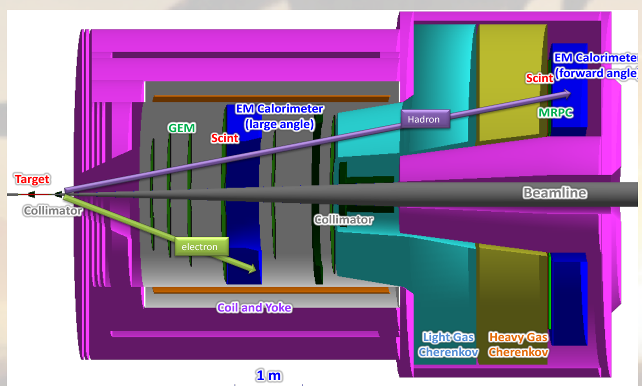
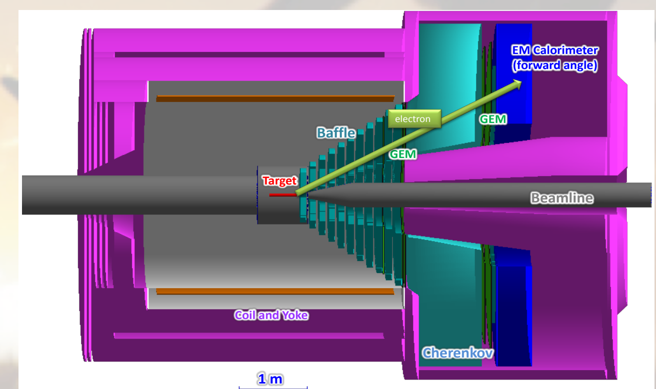
Inpc 2016

International Nuclear Physics Conference
Adelaide Convention Centre, Australia
11-16 September 2016

# SoLID @ Jefferson Laboratory

## Solenoidal Large Intensity Device



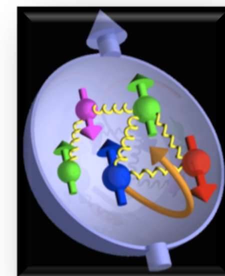

Acknowledgement:
J. P. Chen, H. Gao, K. Kumar, Z.-E. Meziani, J. Qiu, S. Riordan, P. Souder

Stony Brook University

Abhay Deshpande

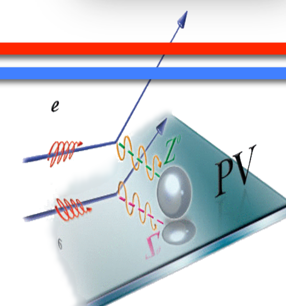
# SoLID Science Program

- Proton SPIN: Where is the missing spin in the nucleon? Role of quark transverse momentum and their orbital angular momentum?



- Proton's MASS through threshold production of J/Ψ: Can we understand fully the gluon's role origin of the mass?

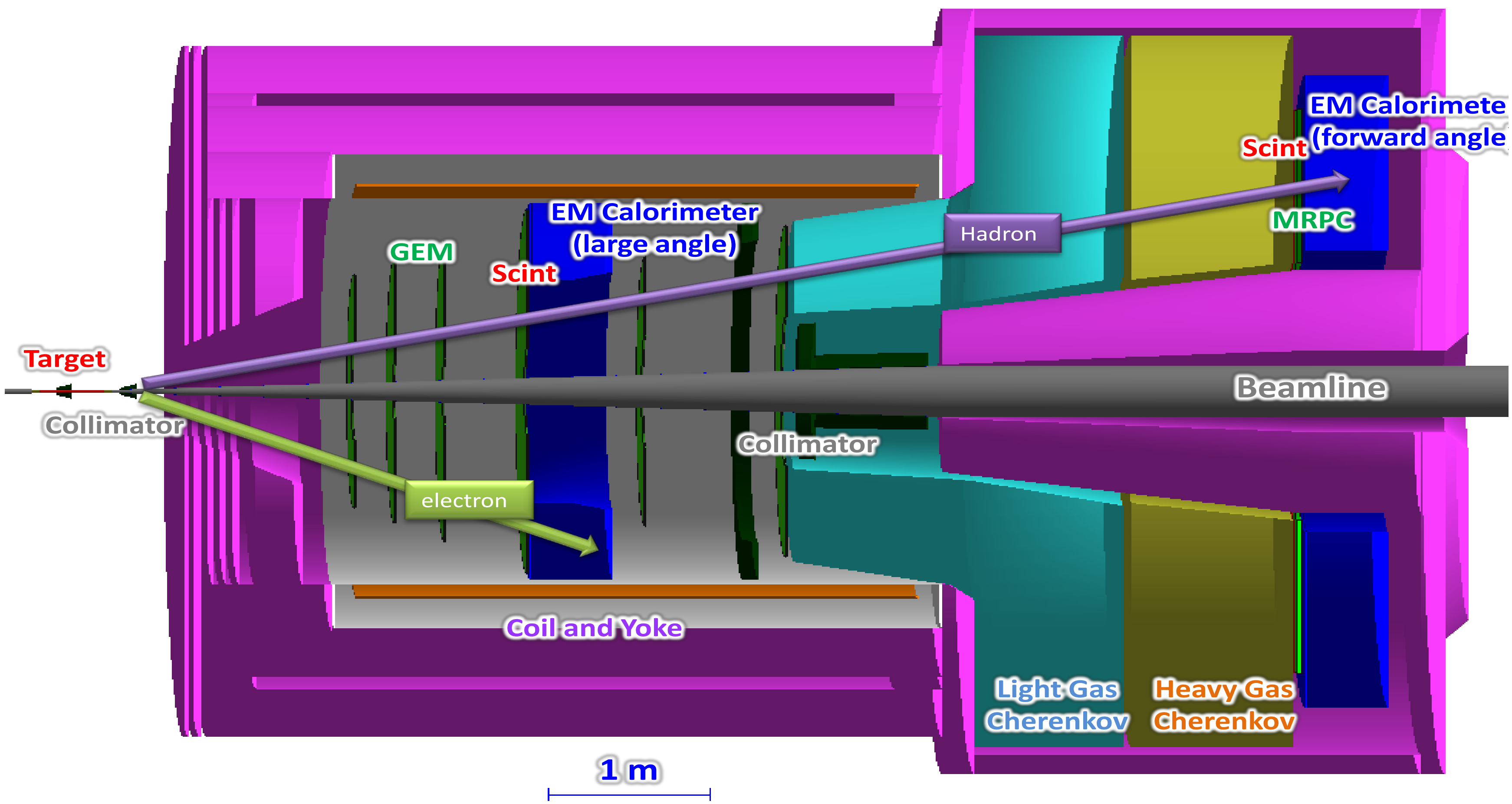
- Can we discover evidence for physics beyond the Standard Model with high intensity electron beam of the CEBAF?

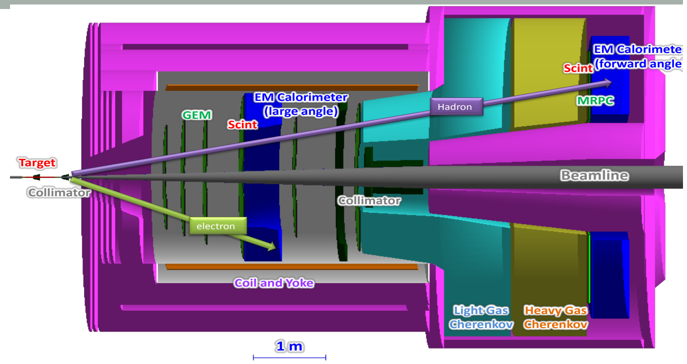



- **Not covered today**: Large acceptance detector with capability for high luminosity also makes possible many other investigations: such as Polarized/EMC effect, PVDIS D/DVCS, Polarized PDF, Charge Symmetry Violation p/n….

# SoLID In Hall-A

Solenoidcal Large Intensity Device






# SoLID In Hall-A

## Solenoidcal Large Intensity Device

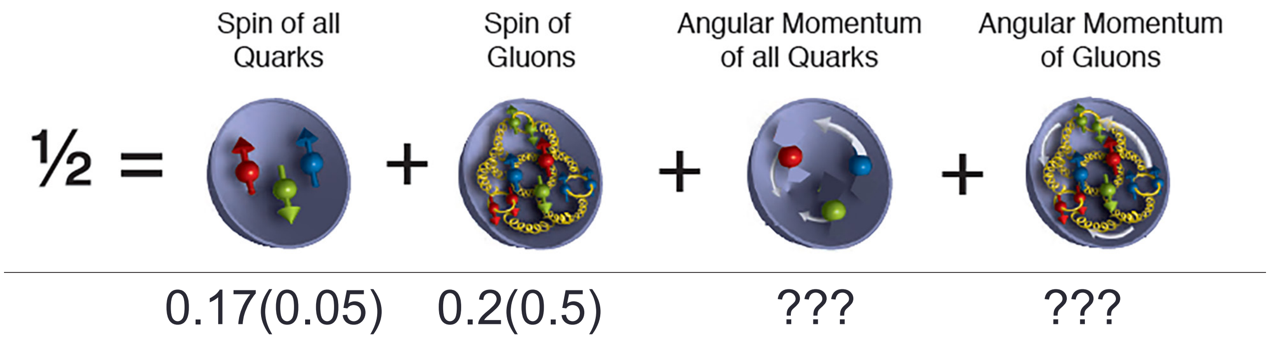
- Large acceptance
  - Full azimuthal coverage
- High luminosity ($10^{37\text{-}39}$ $cm^{-2}sec^{-1}$)
- Latest detector technology in detector & data acquisition

- World wide interest in the science at SoLID evidenced by:
  - 250+ collaborators, 50 institutions and 13 countries
  - Significant international contributions and commitment
  - Strong theoretical interest and support

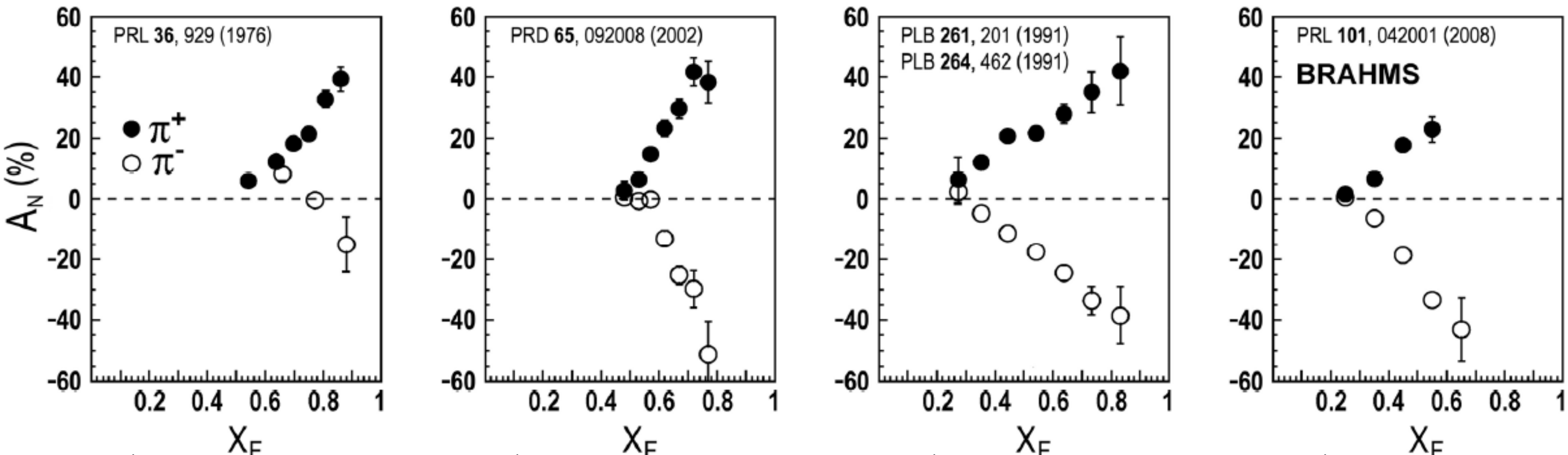
- 500+ days of science already been reviwed and approved by the JLab Physics Advisory Committee (PAC)

# Evidence of transverse momenta of quarks in polarized proton:

From Polarized DIS and Polarized RHIC Experiments



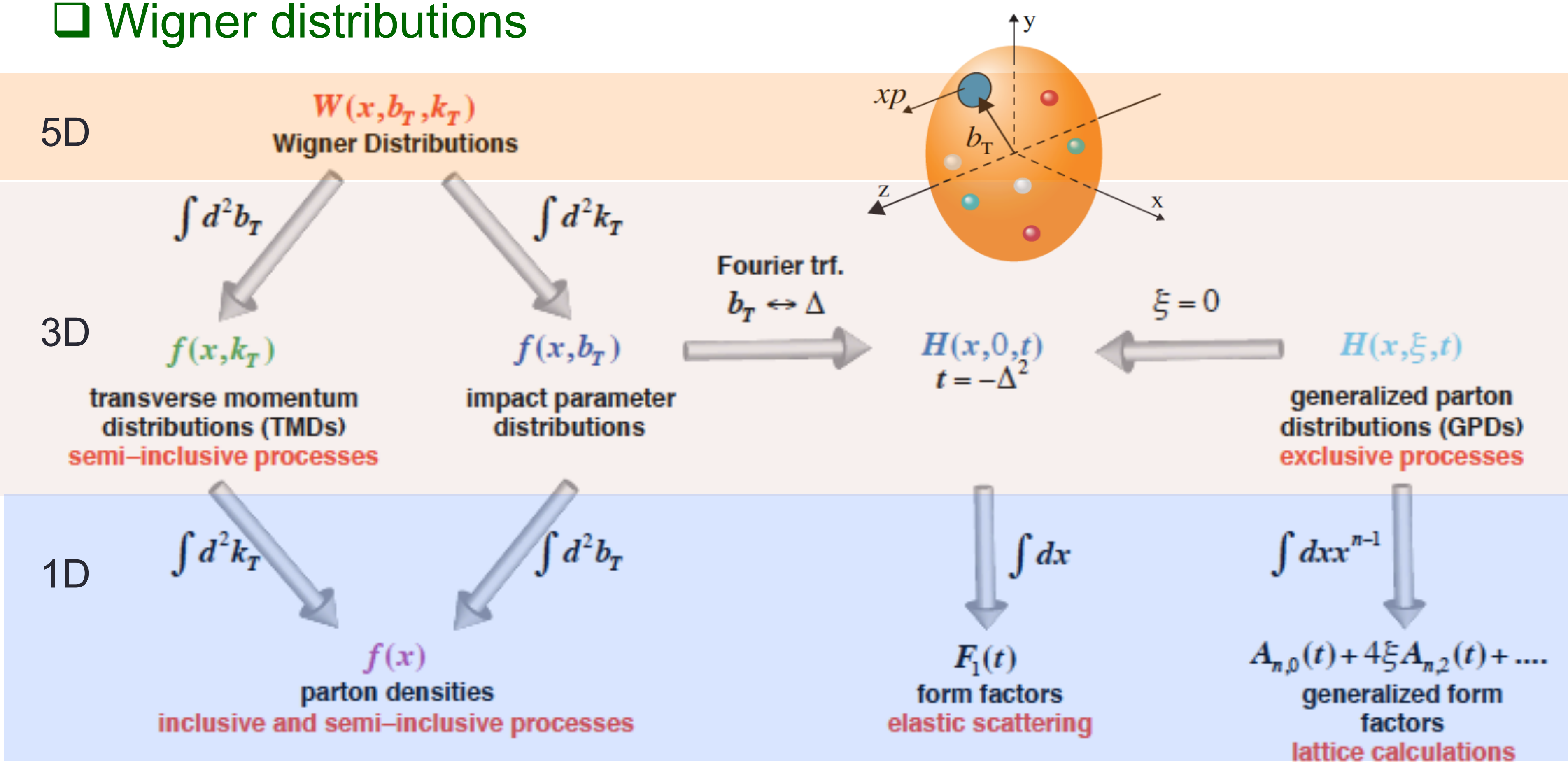

Transvers Single Spin Asymmetry in $\pi^{+/-}$ production → p+p scattering




$\sqrt{s}$=4.9 GeV $\sqrt{s}$=6.9 GeV $\sqrt{s}$=19.4 GeV $\sqrt{s}$=62.4 GeV

# Unified view of the Nucleon Structure

- Wigner distributions



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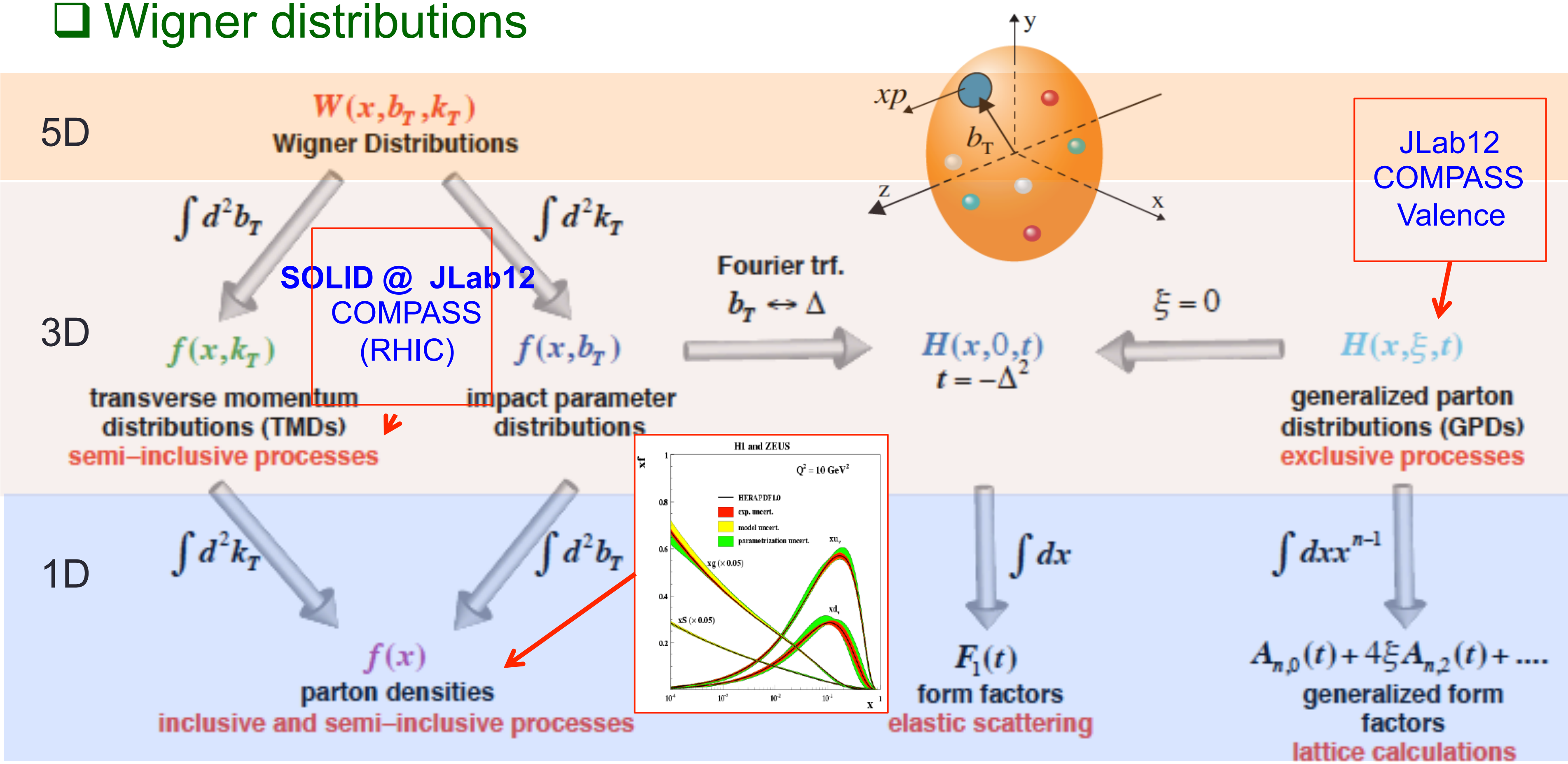
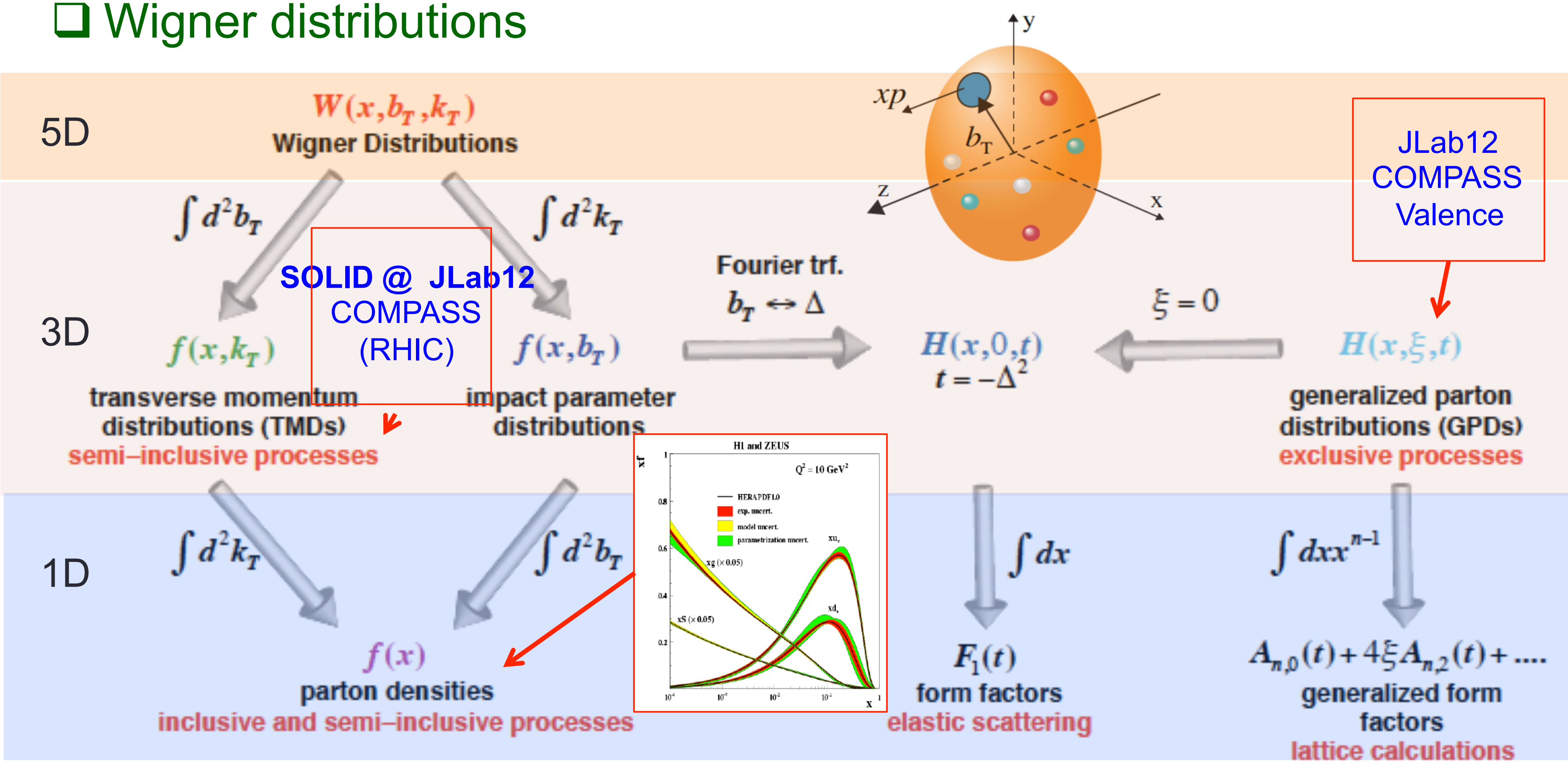


# Unified view of the Nucleon Structure

- ❑ Wigner distributions




- ❑ (2+1)D imaging **Quarks (SOLID@JLAB12)** , Gluons (EIC)
  - ✧ **TMDs – confined motion in a nucleon (semi-inclusive DIS)**
  - ✧ GPDs – Spatial imaging of quarks and gluons (exclusive DIS & diffraction)

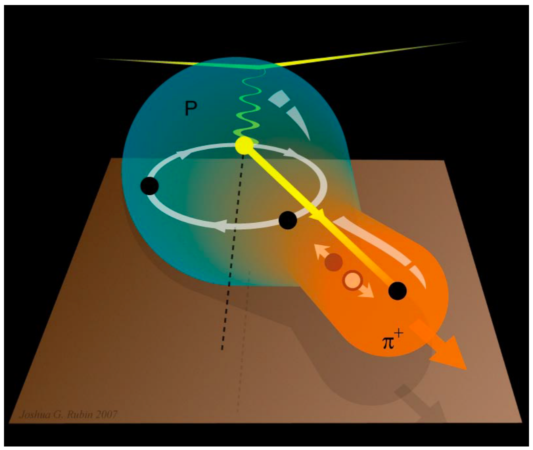
# Possible Origins of TMDs

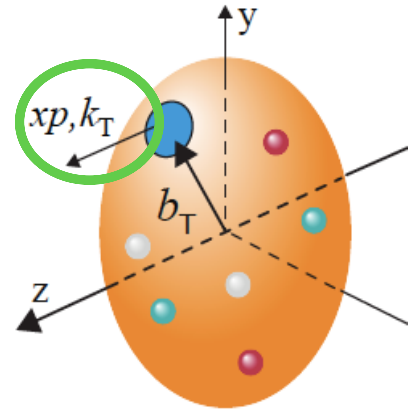
(Leading twist Transverse Momentum Diistributions)

→ Nucleon Spin
→ Quark Spin

| | | Quark polarization | | |
|---|---|---|---|---|
| | | Un-Polarized | Longitudinally Polarized | Transversely Polarized |
| Nucleon Polarization | U | $f_1 =$ | | $h_1^{\perp} =$ − <br> Boer-Mulder |
| | L | | $g_1 =$ − <br> Helicity | $h_{1L}^{\perp} =$ − |
| | T | $f_{1T}^{\perp} =$ − <br> Sivers | $g_{1T}^{\perp} =$ − | $h_{1T} =$ − <br> Transversity <br> $h_{1T}^{\perp} =$ − <br> Pretzelosity |

# SIDIS → Ideal for measuring Transverse Momentum Distribution (TMDs)



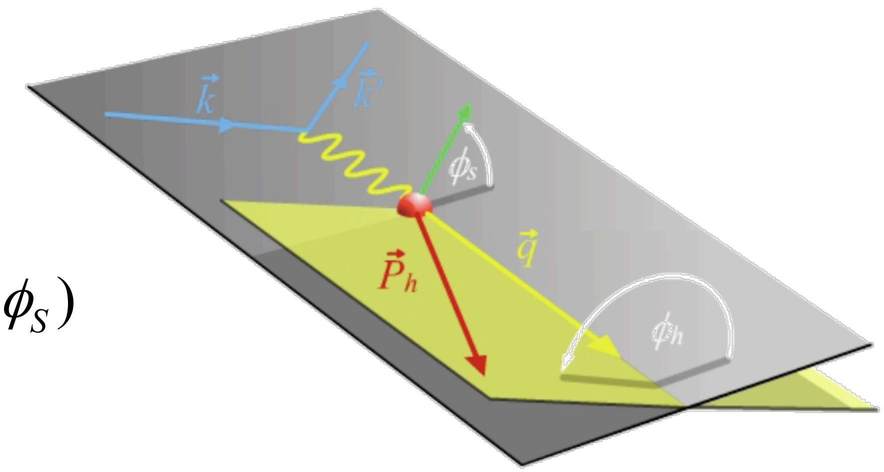

- ❑ Naturally, two scales:
  - ✧ high Q – localized probe
    To “see” quarks and gluons
  - ✧ Low $p_T$ – sensitive to confining scale
    To “see” their confined motion
  - ✧ *Theory – QCD TMD factorization*

- ❑ Naturally, two planes:

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

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

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

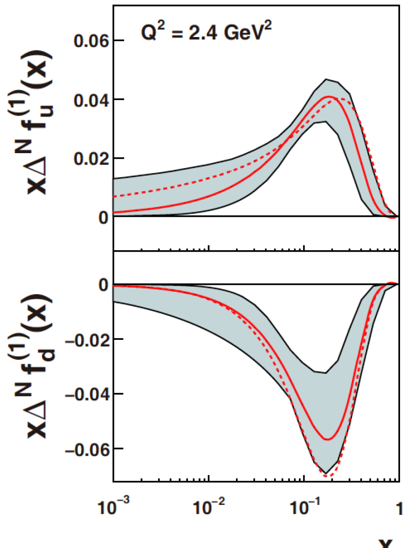



❑ Experimental Issue: High Luminosity, Large Acceptance & particle ID

# Current Status of TMD Extraction

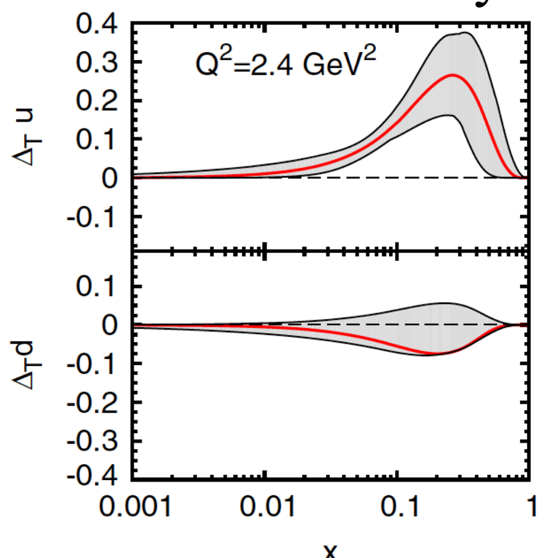
**Theoretical extraction based on limited data sets in e-p/n, e-e, and p-p measurements**

Sivers



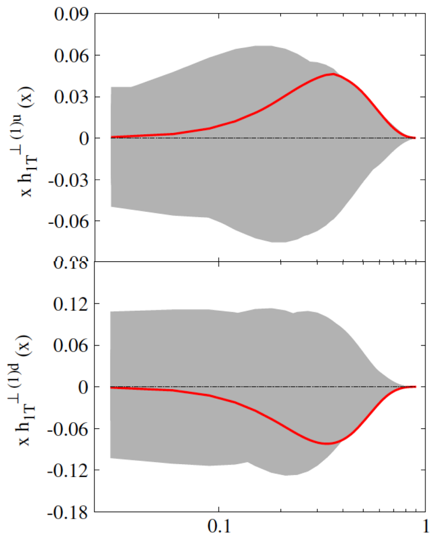

Anselmino et al, EPJA39, 89 (2009)

Transversity




Anselmino et al, PRD92, 114023 (2015)

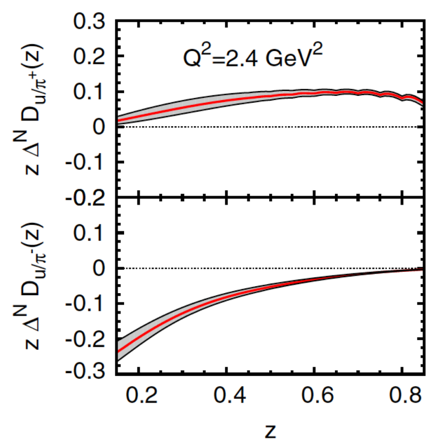
Pretzelosity

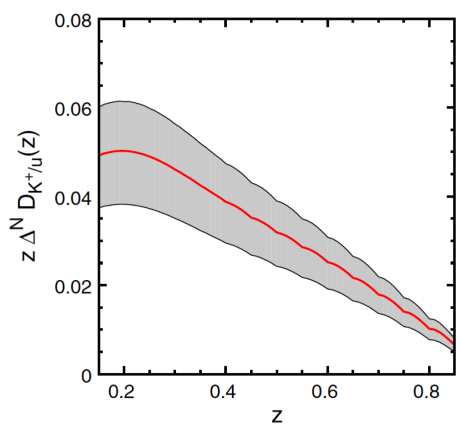


Lefky et al, PRD91, 034010 (2015)

Collins fragmentation

Anselmino et al, PRD92, 114023 (2015)
PRD93, 034025 (2016)

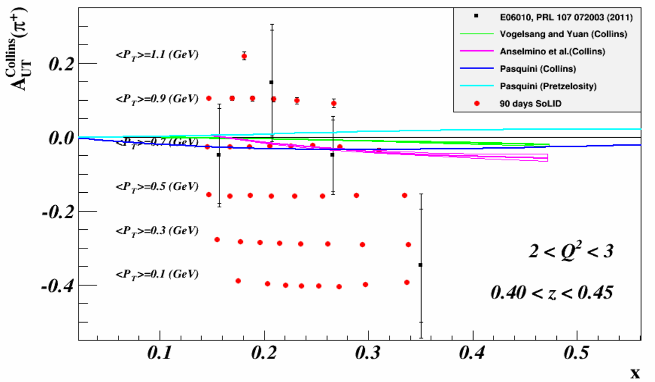


# SoLID Impact: Luminosity & Precision

(Selected examples….) Impact Plots: Grey Band is Current 95% CL **vs with SoliD**

E12-10-006: e-transverse ($^3$He), *Chen et al*



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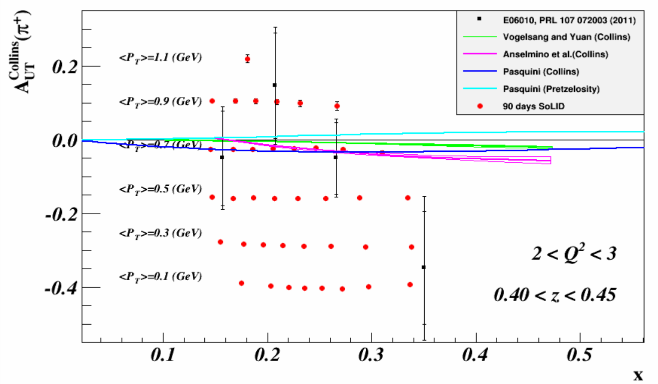
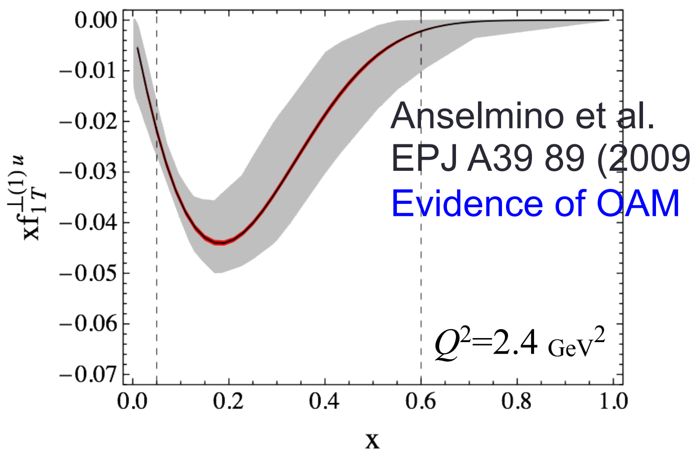



Sivers Distribution for u quarks,:



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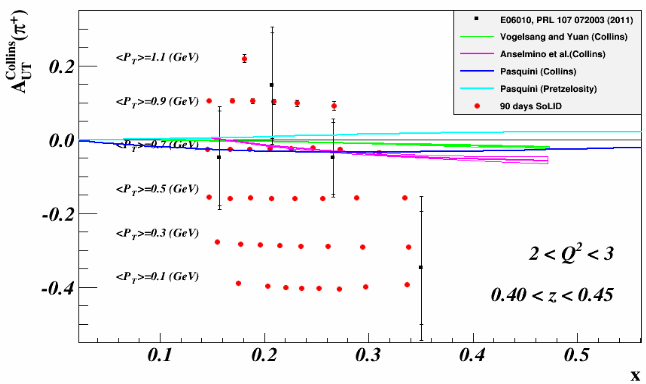


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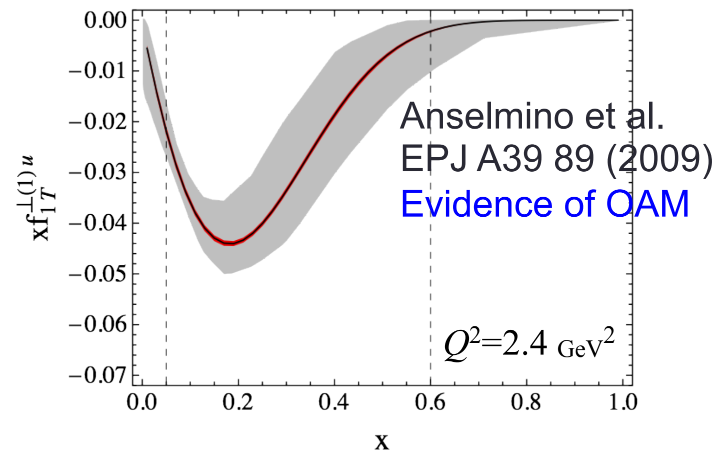
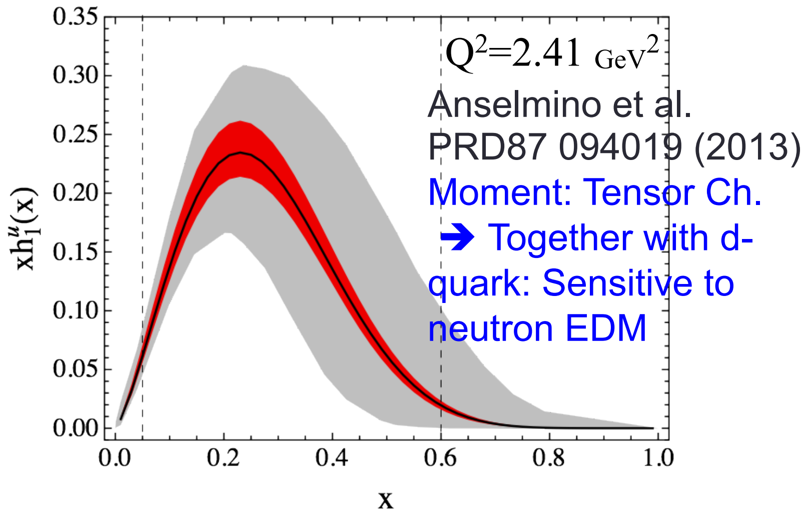



Transversity Distribution for u quarks,:



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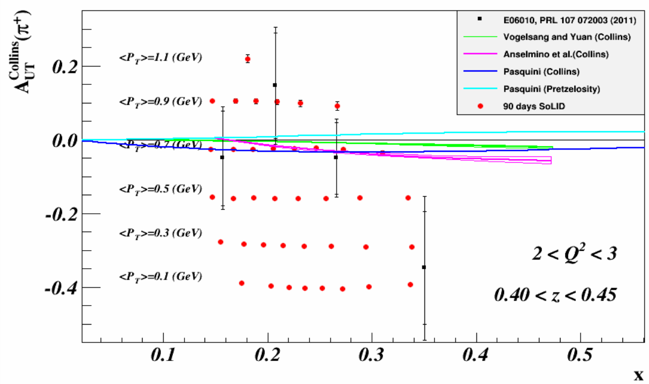


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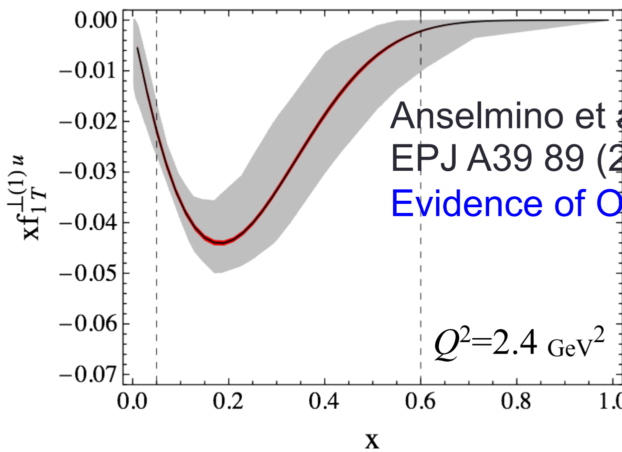
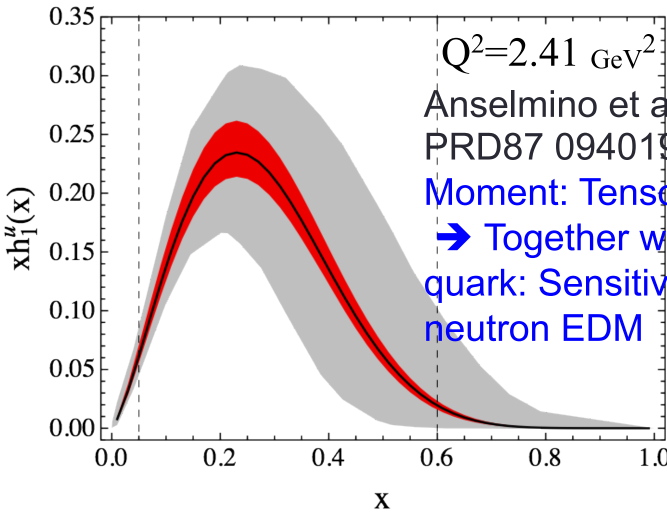


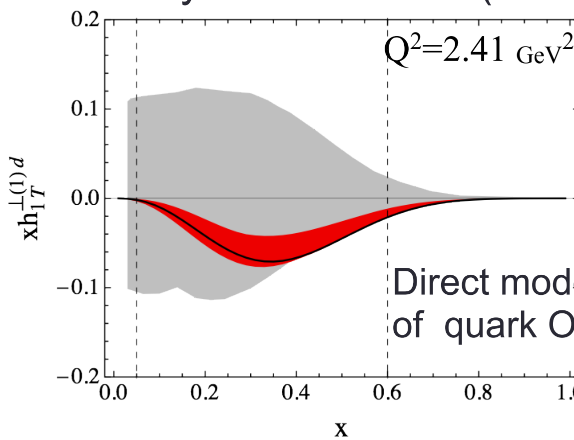

Anselmino et al.
EPJ A39 89 (2009)
Evidence of OAM

Transversity Distribution for u quarks,:




Anselmino et al.
PRD87 094019 (2013)
Moment: Tensor Ch.
➔ Together with d-quark: Sensitive to neutron EDM

Pretzelosity Distribution for d quarks,
C. Leftky et al. PRD 91 (034010) 2015




Direct model dep. calculation
of quark OAM

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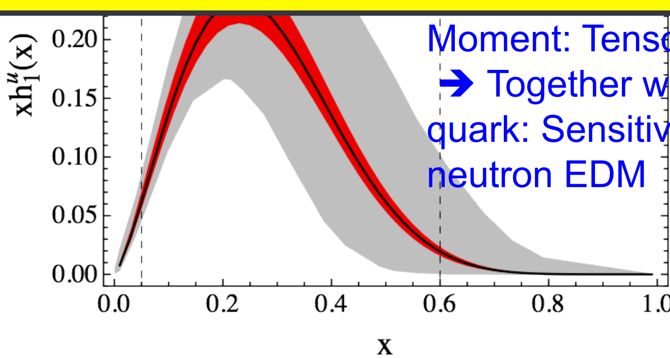
E12-10-006: e-transverse ($^3$He), *Chen et al*

Sivers Distribution for u quarks,:

Spin Physics with SoLID Experiment's
Large Acceptance and High Luminosity allows:

→ **4-D** mapping of asymmetries
→ Tensor charge, TMDs …
→ Direct comparison with Lattice QCD, QCD Dynamics & Models

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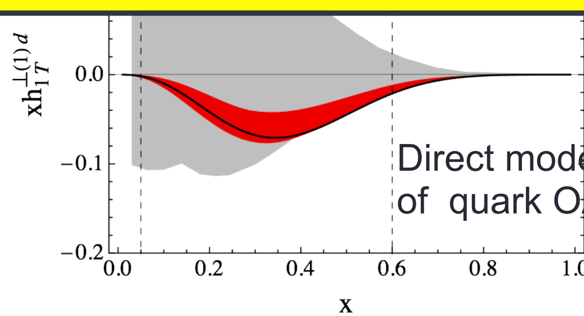



Direct model dep. calculation of quark OAM

# Understanding Glue interactions in non-perturbative QCD

# Understanding Glue interactions in non-perturbative QCD

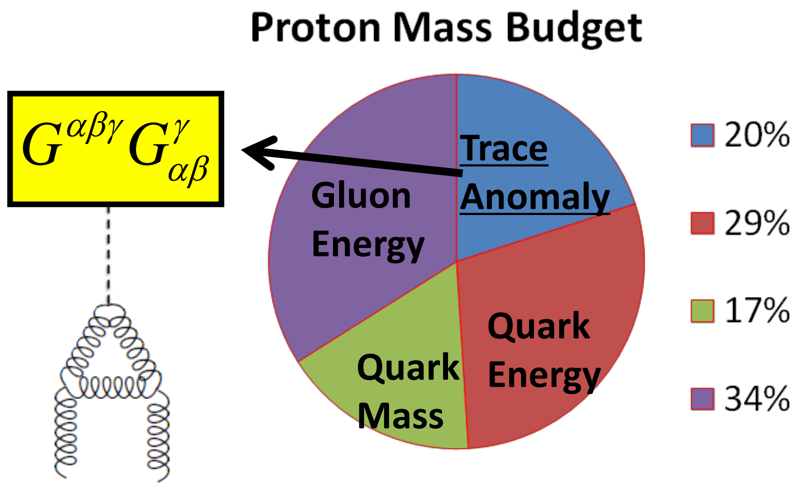
$$H_{QCD} = H_q + H_m + H_g + H_a$$

$$H_q = Quark\ \ Energy = \int d^3x \psi^* (-iD \cdot \alpha)\psi$$

$$H_m = Quark\ \ Mass = \int d^3x \overline{\psi} m \psi$$

$$H_g = Gluon\ \ Energy = \int d^3x \frac{1}{2}(E^2 + B^2)$$

$$H_a = Trace\ \ Anomaly = \int d^3x \frac{9\alpha}{16\pi}(E^2 - B^2)$$




X. Ji PRL 74 1071 (1995)

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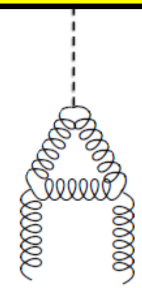
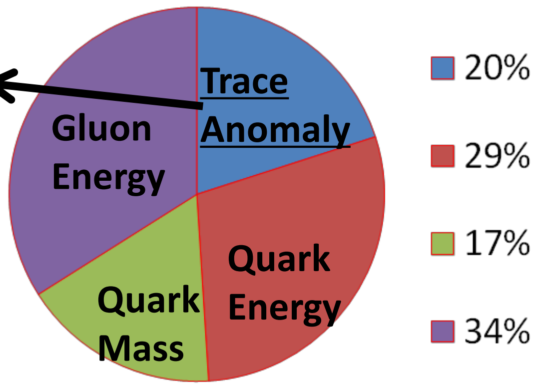
$$\boxed{G^{\alpha\beta\gamma} G^{\gamma}_{\alpha\beta}}$$



**Proton Mass Budget**




X. Ji PRL 74 1071 (1995)

There are models that **relate the trace anomaly** to the **J/Ψ production near threshold** (D. Kharzeev, EPJ C9 459 (1999), Int. Sch. Phys. Fermi 130, 105 (1996))

Past: Lack of statistics in the accessible phase space (near threshold). The 12GeV CEBAF provides two new possibilities:

- **Electro-production of J/Ψ in SOLID**
- Photoproduction of J/Ψ from Hall-D Gluex experiment

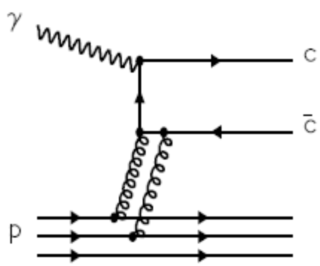
# Lack of knowledge of threshold behavior:

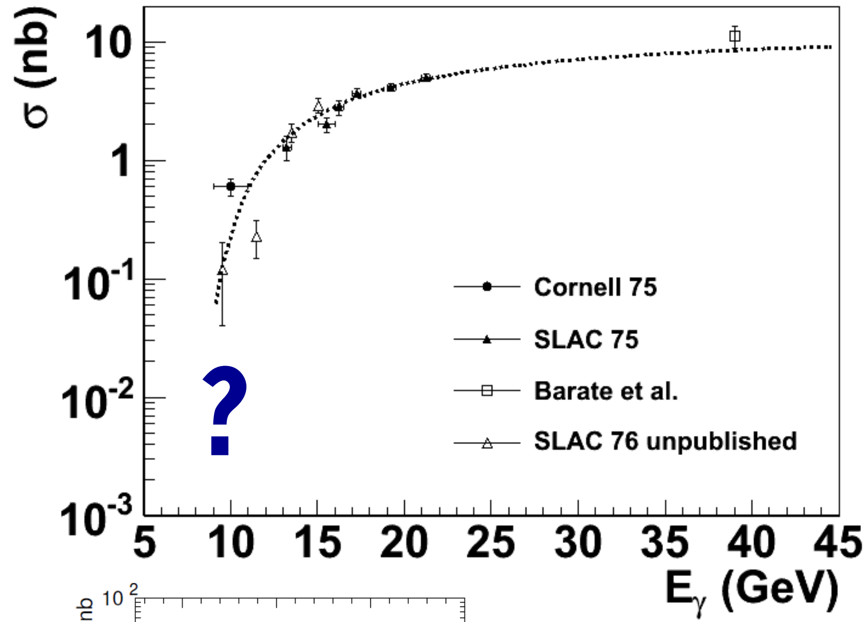
Models-I: Hard scattering mechanism (Brodsky, Chudakov, Hoyer, Laget 2001)

$$2-g:(1-x)^2 F(t)$$

$$F(t) \propto \exp(1.13t)$$

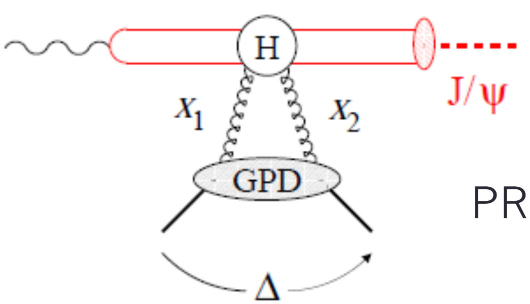
$$x = \frac{2M_p M_{J/\psi} + M_{J/\psi}^2}{2E_\gamma M_p}$$



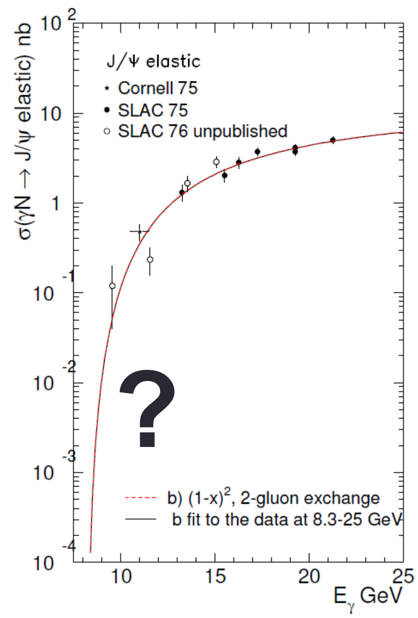




Models -II: Partonic soft mechanism
(Frankfurt and Strikman 2002)
2-gluon Form Factor

$$F.F. \propto (1 - t/1.0\ \mathrm{GeV}^2)^{-4}$$

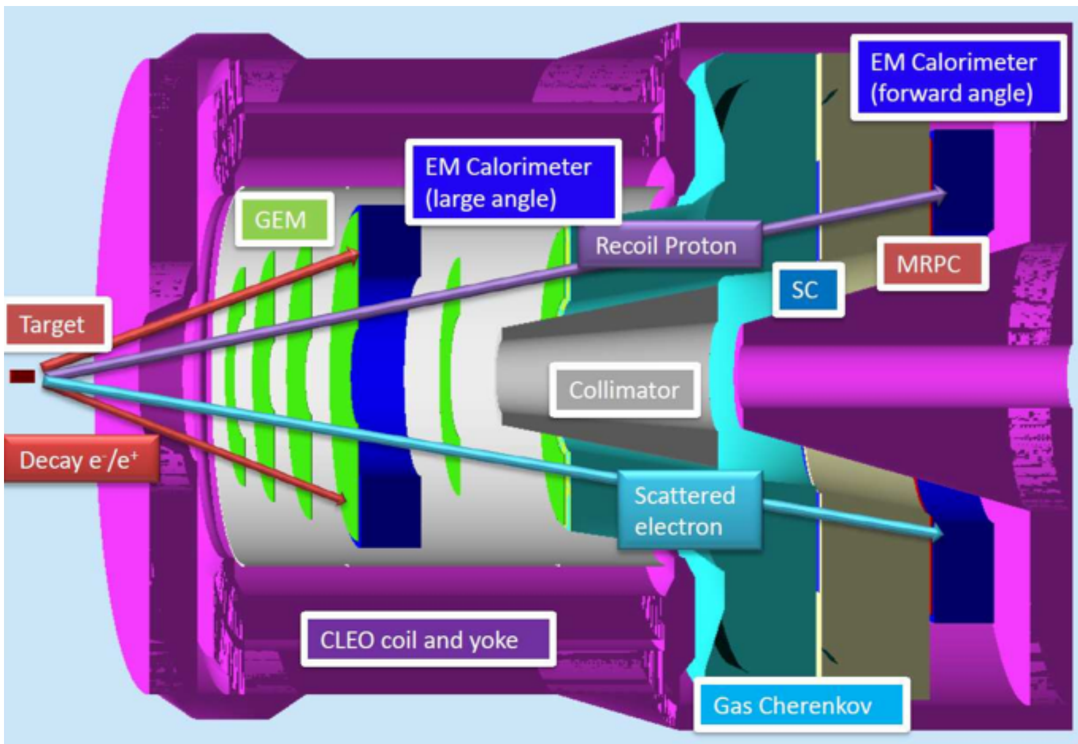


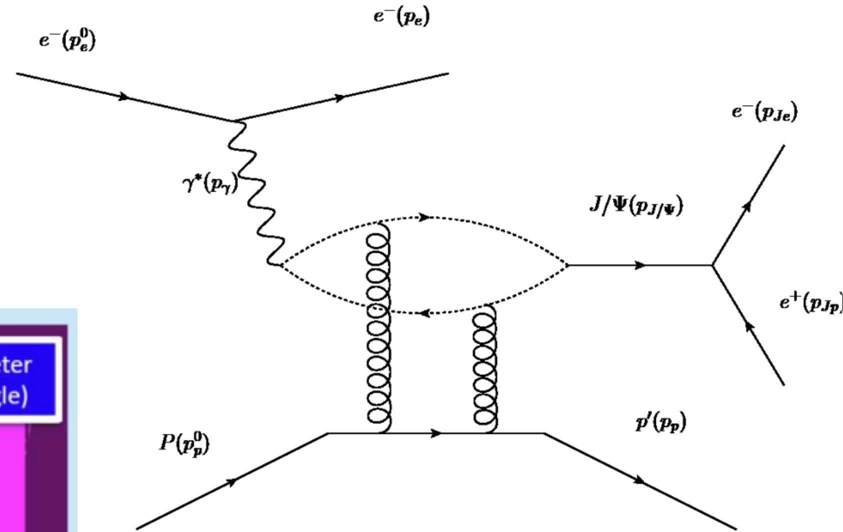

PRD66, 031502 (2002)



# Threshold J/Ψ production @ SoLID

$e\, p \rightarrow e'\, p'\, J/\psi(e^- e^+)$
$\gamma^*\, p \rightarrow p'\, J/\psi(e^- e^+)$

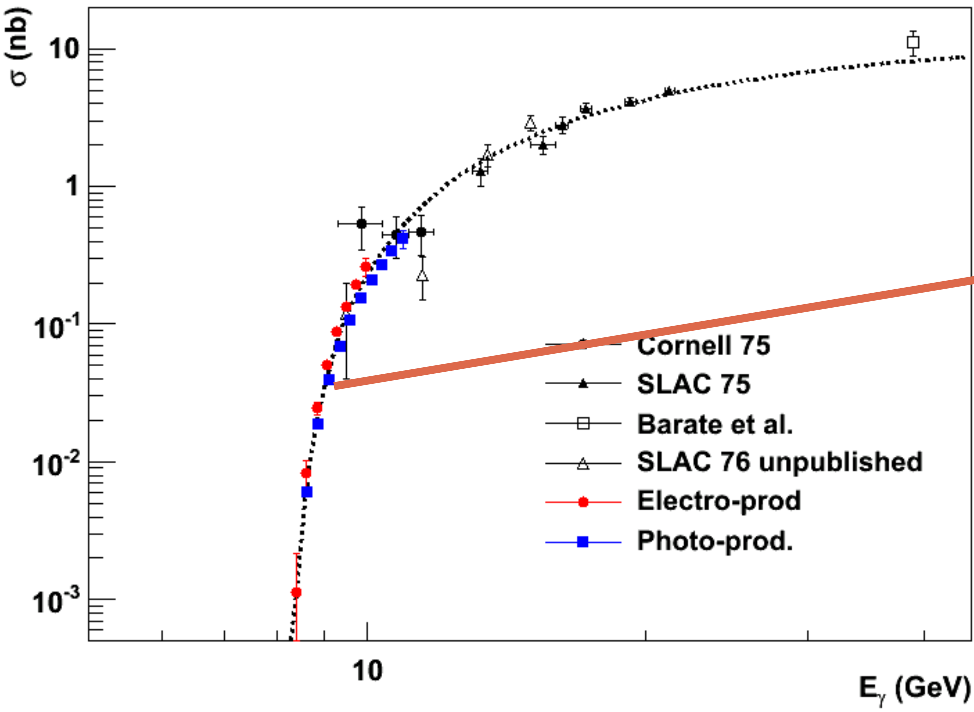


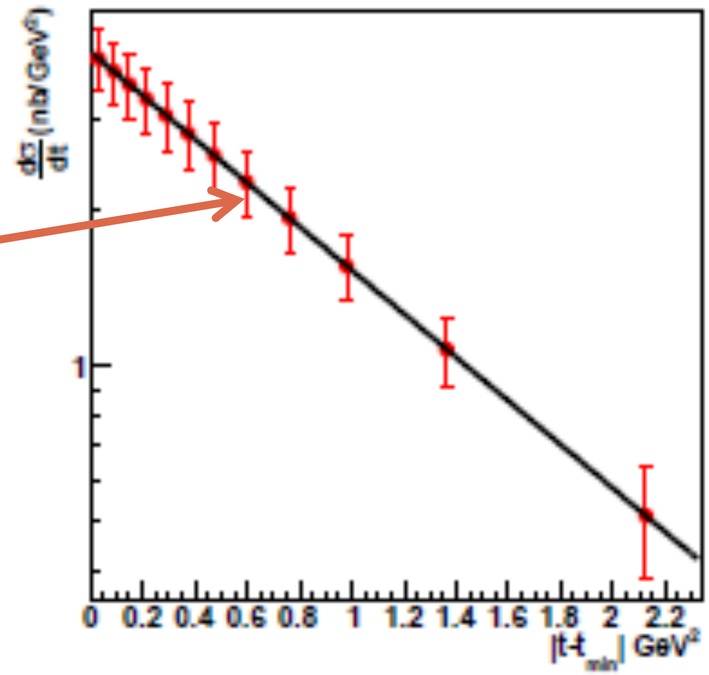




$$\boxed{\gamma^* + N \rightarrow N + J/\psi}$$

Real part ➔ total cross section
Imaginary part @ low energies
➔ conformal (trace) anomaly

# SoLID's Projections: Precise σ and dσ/dt



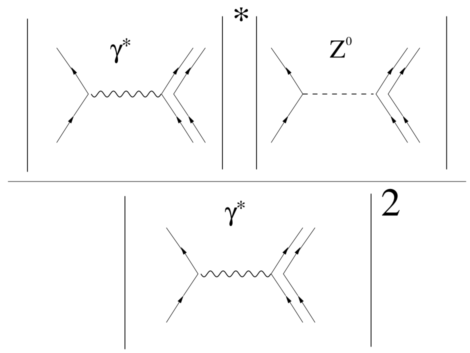

SoLID 11 GeV 3 μA e- on LH2 50 days ➔ 1.2 x $10^{37}$ cm$^{-2}$sec$^{-1}$
**Ample statistical sample in the region most crucial to this study**

Potentially very important contribution to the knowledge of the conformal anomaly can be measured directly with SoLID.

# Parity violating Deep Inelastic Scattering

Sensitive to different effective charge couplings

$A_{\mathrm{PV}} \sim$




$\sim 100 - 1000\ \mathrm{ppm}$

$$\approx -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[a_1(x) + \frac{1-(1-y)^2}{1+(1-y)^2}a_3(x)\right], y = 1 - \frac{E'}{E}$$

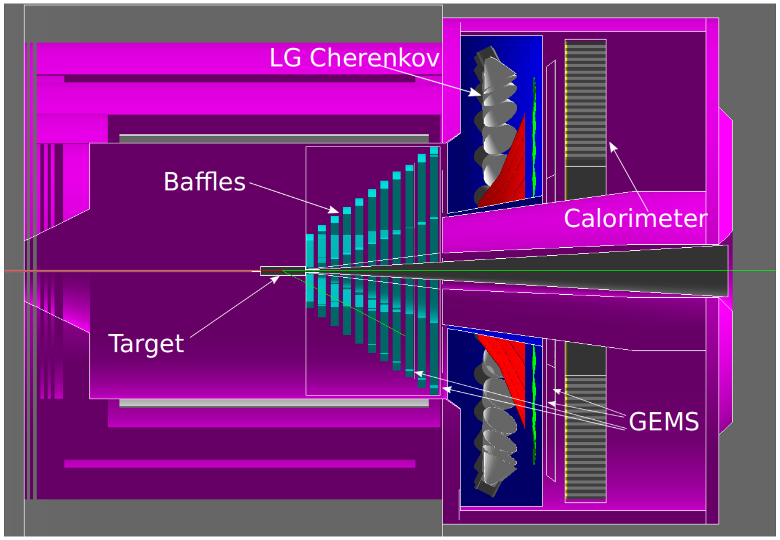
$$a_1(x) = 2\frac{\sum C_{1q}e_q(q+\bar{q})}{\sum e_q^2(q+\bar{q})}, a_3(x) = 2\frac{\sum C_{2q}e_q(q-\bar{q})}{\sum e_q^2(q+\bar{q})}$$

**New Effective Weak Couplings**

$$C_{1u} = -\tfrac{1}{2} + \tfrac{4}{3}\sin^2\theta_W = -0.19 \qquad C_{2u} = -\tfrac{1}{2} + 2\sin^2\theta_W = -0.03$$

$$C_{1d} = \tfrac{1}{2} - \tfrac{2}{3}\sin^2\theta_W = 0.34 \qquad C_{2d} = \tfrac{1}{2} - 2\sin^2\theta_W = 0.03$$

# SoLID proposed Setup for PVDIS:



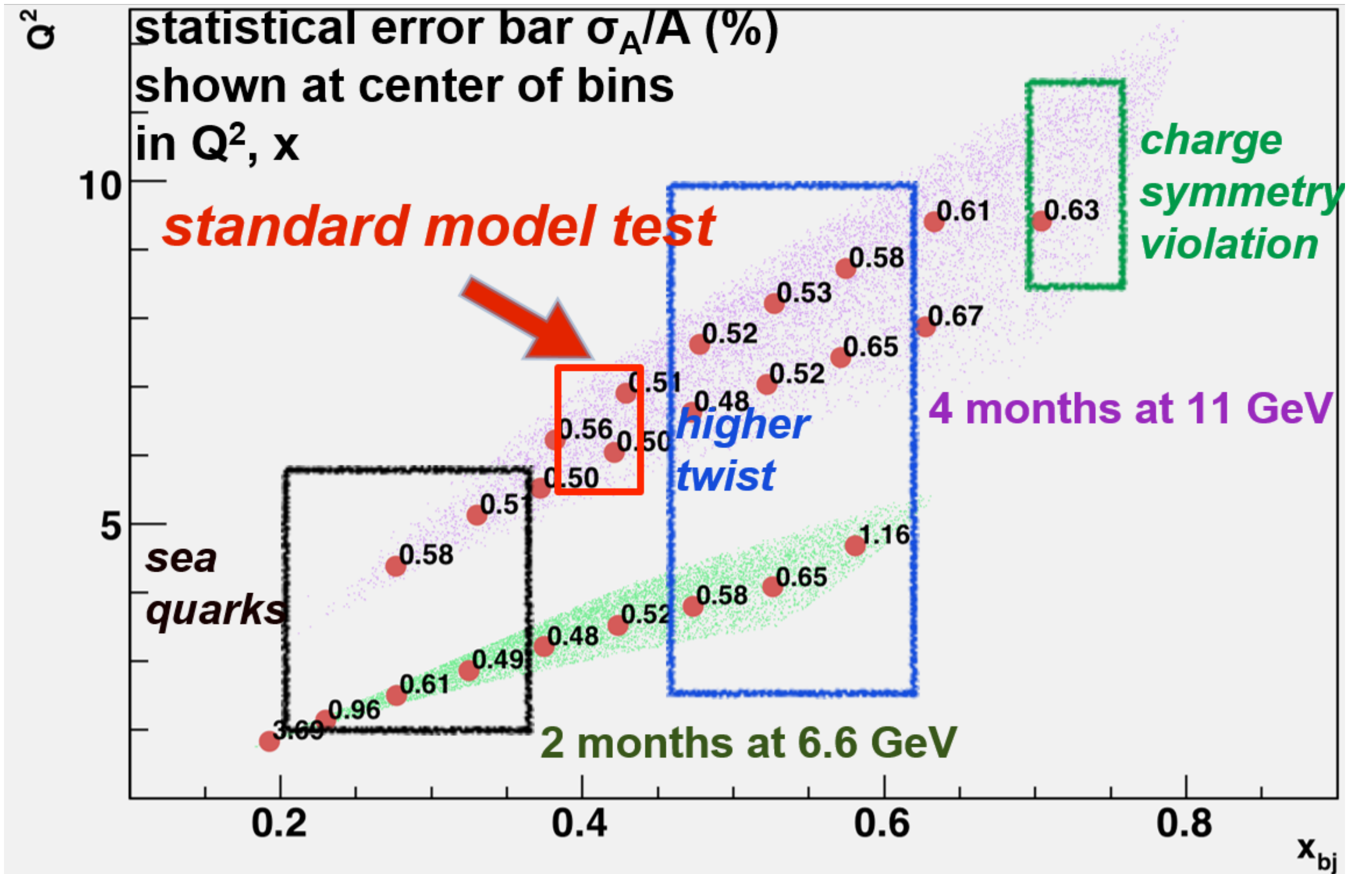

**SoLID Provides Large acceptance**

- ❖ $2 < p < 8$ GeV
- ❖ $2 < Q^2 < 8$ GeV$^2$
- ❖ $0.2 < X_{Bj} < 1$
- ❖ Acceptance 40% geometric
- ❖ Luminosity: $5 \times 10^{38}$ sec$^{-1}$ cm$^{-2}$

**Parity violation measurements need**

- ◆ Lots of statistics i.e. good to have high rate
- ◆ Broad kinematic range: largest possible acceptance
- ◆ A beam and detector that can accept the high rate with good systematic controls

# SoLID rate and kinematic acceptance

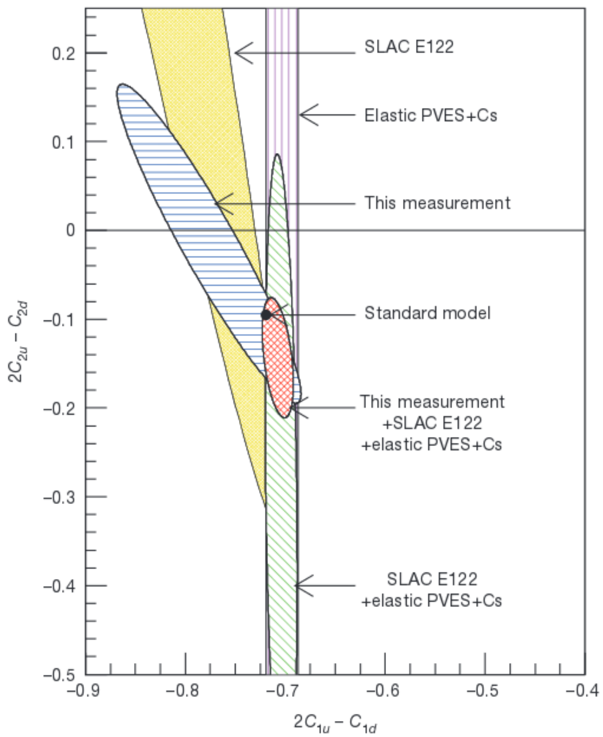



120 Days of $LD_2$ target (60 at 11 GeV and 60 at 6.6 GeV)
90 days with $LH_2$ 11 GeV
Sub 1% precision (modulo polarimetry advances)

# Precise determination of weak couplings

## Quark PDFs q(x) cancel at large x

$$a_1^D(x) \approx 2\frac{C_{1u}e_u[u(x)+d(x)] + C_{1d}e_d[u(x)+d(x)]}{e_u^2[u(x)+d(x)] + e_d^2[u(x)+d(x)]}$$



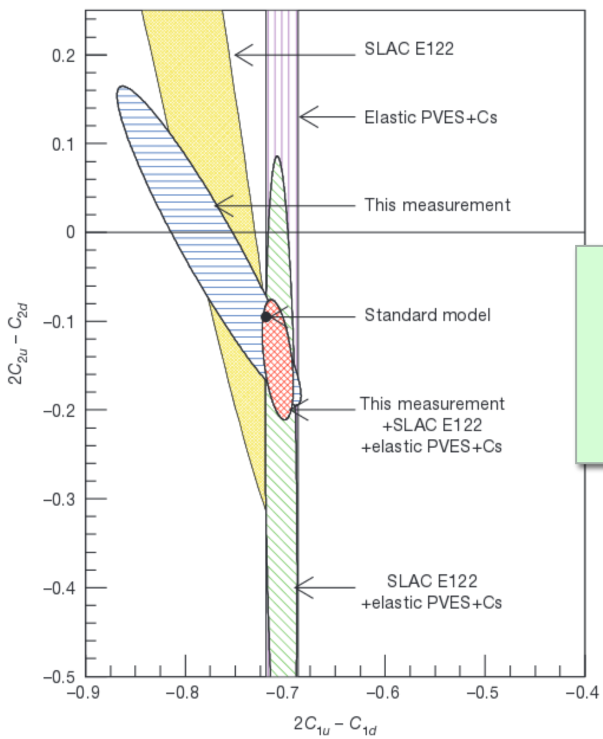

PVDIS Collaboration (w/ 6 GeV)

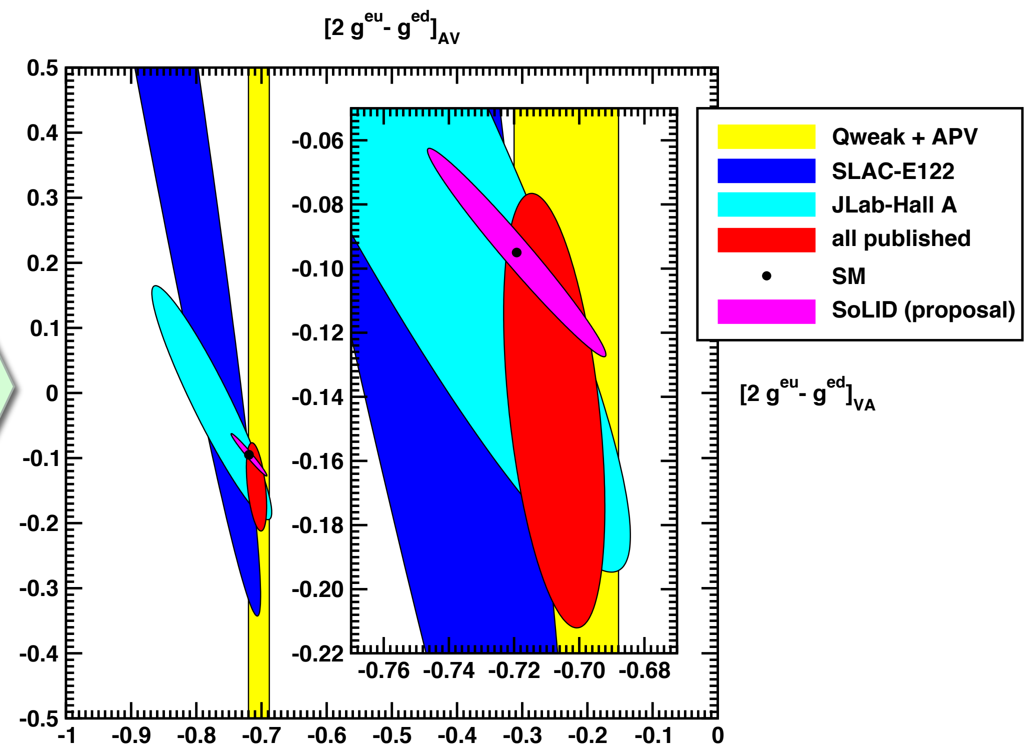
**Nature, 506, 67-70 (2014)**

# Precise determination of weak couplings

## Quark PDFs q(x) cancel at large x

$$a_1^D(x) \approx 2\frac{C_{1u}e_u[u(x)+d(x)]+C_{1d}e_d[u(x)+d(x)]}{e_u^2[u(x)+d(x)]+e_d^2[u(x)+d(x)]}$$




PVDIS Collaboration (w/ 6 GeV)
**Nature, 506, 67-70 (2014)**

**SoLID Projection**

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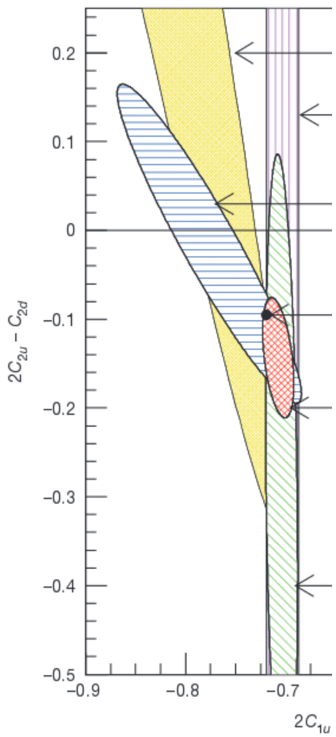
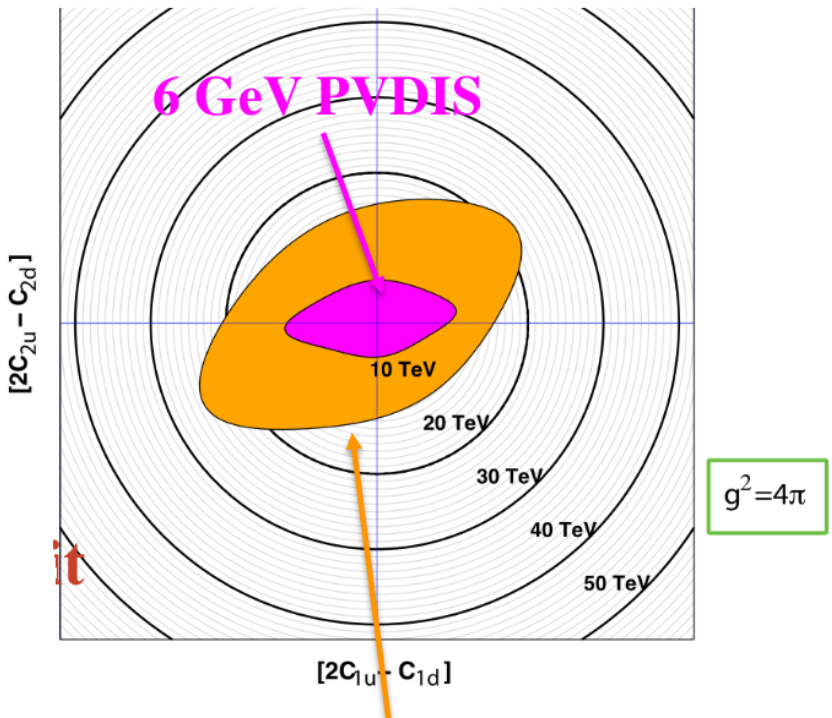
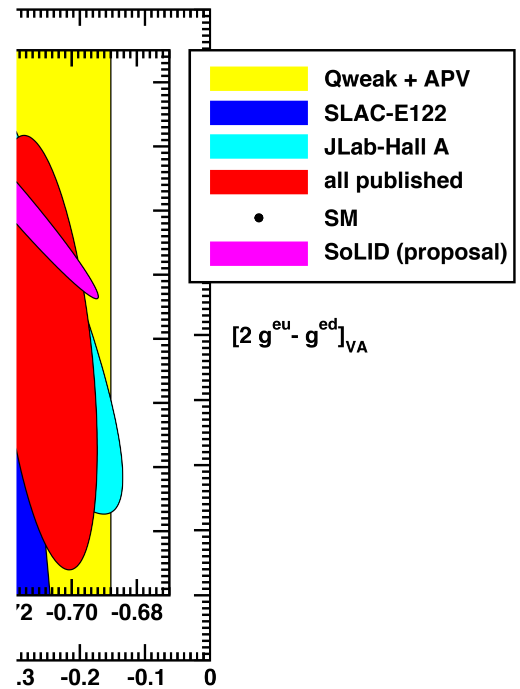



**Final Qweak result + projected SOLID**

PVDIS Collaboration (w/ 6 GeV)

**Nature, 506, 67-70 (2014)**

**SoLID Projection**

# Precision measurement of $Sin^2\Theta_W$

**Low $Q^2$ Weak Mixing Angle Measurements and Rare Higgs Decays**

Hooman Davoudiasl,[1] Hye-Sung Lee,[2] and William J. Marciano[1]

[1] *Department of Physics, Brookhaven National Laboratory, Upton, New York 11973, USA*
[2] *CERN, Theory Division, CH-1211 Geneva 23, Switzerland*



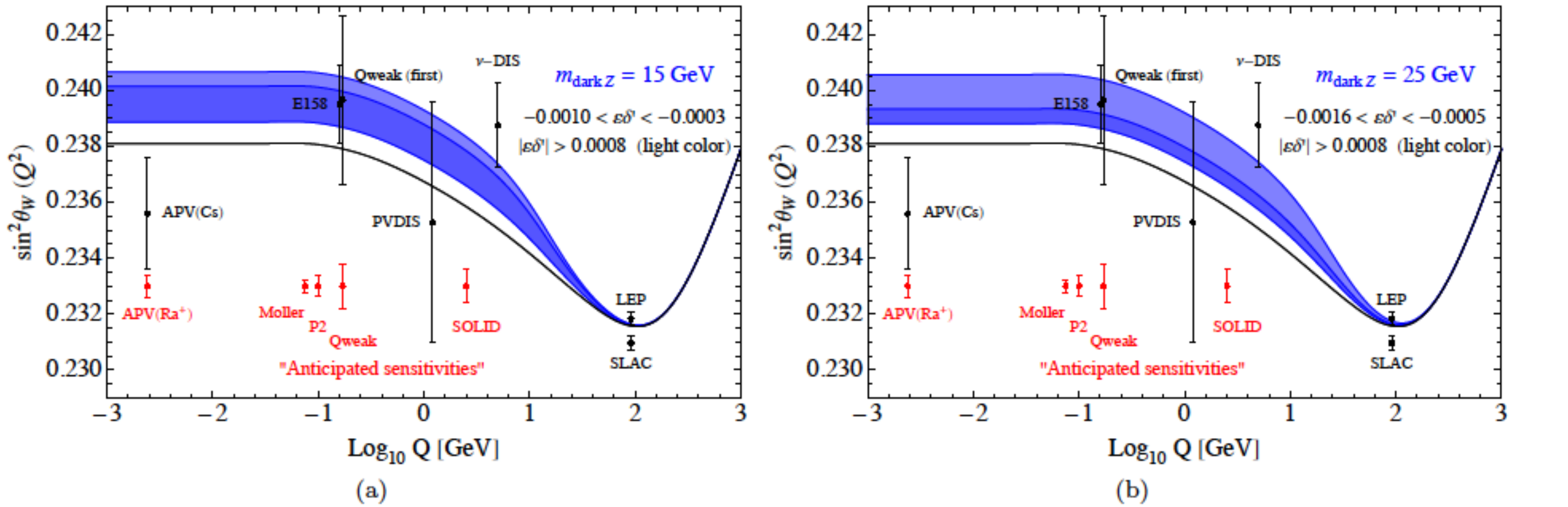
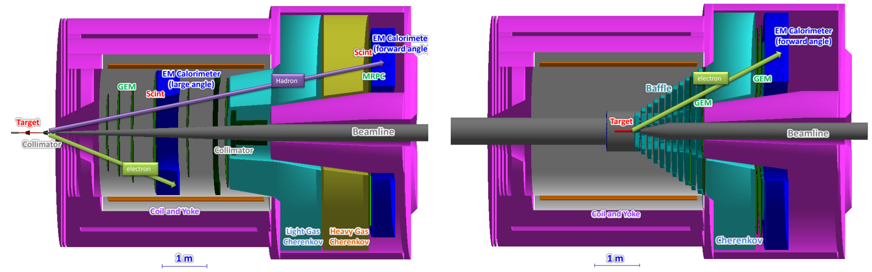



FIG. 3. Effective weak mixing angle running as a function of $Q^2$ shift (the blue band) due to an intermediate mass $Z_d$ for (a) $m_{Z_d} = 15$ GeV and (b) $m_{Z_d} = 25$ GeV for 1 sigma fit to $\varepsilon\delta'$ in Eq. (12). The lightly shaded area in each band corresponds to choice of parameters that is in some tension with precision constraints (see text for more details).

# Summary




**SoLID Apparatus** with 12 GeV CEBAF an ideal detector for physics with high statistics, and large acceptance, with azimuthal symmetry, and excellent particle ID:

- Precision studies of transeverse momentum distributions of quarks, threshold production of J/Y ➔ non-perturbative gluon dynamics, precision parity violating DIS measurements ➔ access of physics beyond the SM complementary to high energy colliders
- Many other studies not covered today: Charge Symmetry Violation, D/DVCS, SIDIS possible, but not covered today

- **Status:**
  - Successful Director's review in February 2015
  - Pre-R&D requests being prepared now.
  - Expected to be considered for CD0 (2017/18)
  - FY2020 CD3 (Construction)

J. Qiu

# Mass vs. Spin

## ❑ Mass – intrinsic to a particle:

= Energy of the particle when it is at the rest

✧ QCD energy-momentum tensor in terms of quarks and gluons

$$T^{\mu\nu} = \frac{1}{2}\,\overline{\psi} i \overleftrightarrow{D}^{(\mu}\gamma^{\nu)}\psi + \frac{1}{4}\,g^{\mu\nu}F^2 - F^{\mu\alpha}F^{\nu}{}_{\alpha}$$

✧ Proton mass:

$$m = \frac{\langle p|\int d^3x\, T^{00}\,|p\rangle}{\langle p|p\rangle} \sim \mathrm{GeV}$$

X. Ji, PRL (1995)

## ❑ Spin – intrinsic to a particle:

= Angular momentum of the particle when it is at the rest

✧ QCD angular momentum density in terms of energy-momentum tensor

$$M^{\alpha\mu\nu} = T^{\alpha\nu}x^{\mu} - T^{\alpha\mu}x^{\nu} \qquad J^i = \frac{1}{2}\epsilon^{ijk}\int d^3x M^{0jk}$$

✧ Proton spin:

$$S(\mu) = \sum_f \langle P,S|\hat{J}^z_f(\mu)|P,S\rangle = \frac{1}{2}$$

# Access Trace Anomaly Experimentally

$$M_q = \frac{3}{4}(a-b)\,M$$
$$M_m = bM$$
$$M_g = \frac{3}{4}(1-a)M$$
$$M_a = \frac{1}{4}(1-b)M$$

quark momentum fraction

$$a(\mu^2) = \sum_q \int_0^1 dx[f^q(x) + f^{\bar{q}}(x)]$$

scalar charge

$$b(\mu^2) = \langle P|m_u\bar{u}u + m_d\bar{d}d + m_s\bar{s}s|P\rangle/M$$

$$\frac{d\sigma_{J/\psi N\to J/\psi N}}{dt} = \frac{1}{64\pi}\frac{1}{m^2_{J/\psi}(\lambda^2 - m_N^2)}F^2_{J/\psi N}$$

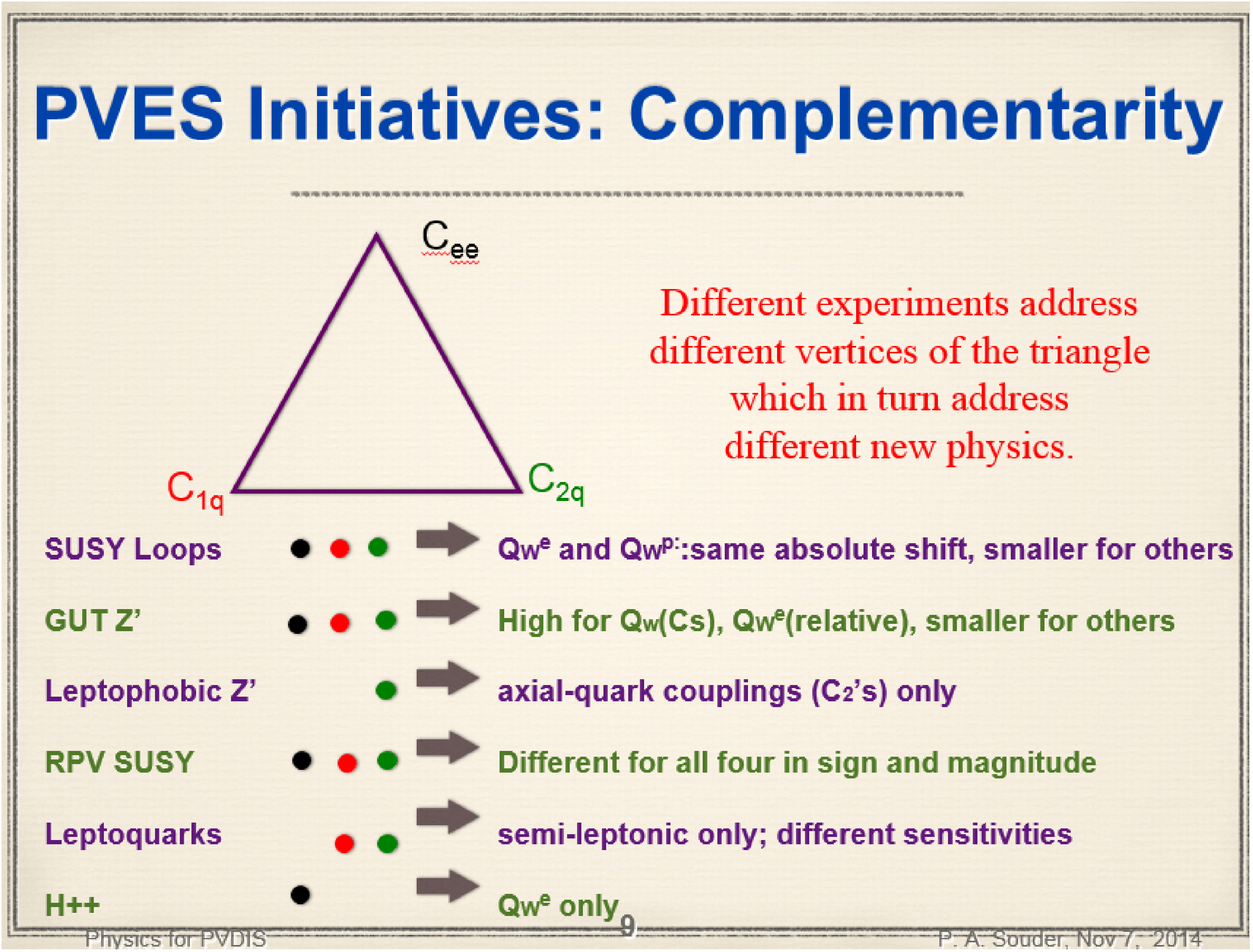
**J/ψ-N scattering**

$$F_{J/\psi N} = r_0^3 d_2 \frac{2\pi^2}{27}(2M^2 - bM)$$

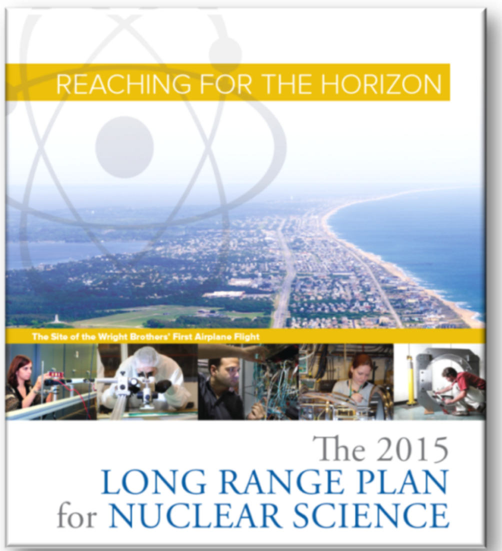
**J/ψ production on N**

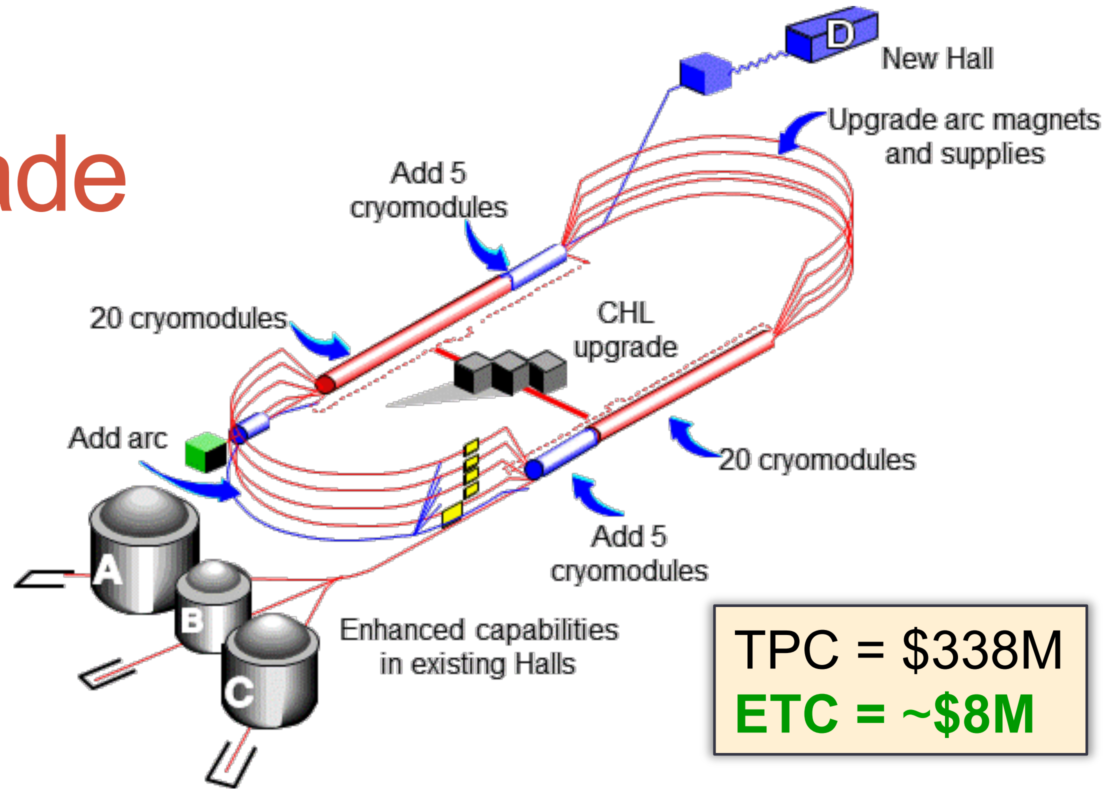
$$\frac{d\sigma_{\gamma N\to J/\psi N}}{dt} = \frac{3\Gamma(J/\psi\to e^+e^-)}{\alpha m_{J/\psi}}\left(\frac{k_{J/\psi N}}{k_{\gamma N}}\right)^2 \frac{d\sigma_{J/\psi N\to J/\psi N}}{dt}$$

D. Kharzeev et al Eur.Phys.J. C9 459 (1999), D. Kharzeev, Proc. Int. Sch. Phys. Fermi 130, 105 (1996)


PVES Initiatives: Complementarity
Cee
C1q
C2q
Different experiments address different vertices of the triangle which in turn address different new physics.
SUSY Loops
Qwe and Qwp:same absolute shift, smaller for others
GUT Z'
High for Qw(Cs), Qwe(relative), smaller for others
Leptophobic Z'
axial-quark couplings (C2's) only
RPV SUSY
Different for all four in sign and magnitude
Leptoquarks
semi-leptonic only; different sensitivities
H++
Qwe only
9
Physics for PVDIS
P. A. Souder, Nov 7, 2014

# CEBAF Upgrade




TPC = $338M
**ETC = ~$8M**

**"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"**

## Project Scope (~98% complete):

- **Doubling the accelerator beam energy - DONE**
- **New experimental Hall D and beam line - DONE**
- **Civil construction including utilities - DONE**
- **Upgrades to Experimental Halls B & C - ~96%**
  - **Halls B & C Detectors – DONE**