SoLID in the Jlab 12 GeV Program

P. A. Souder, Syracuse University

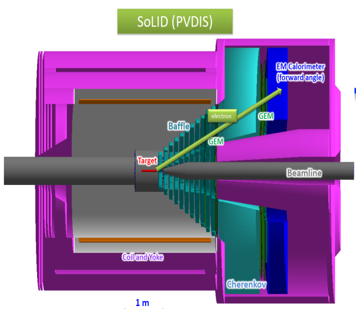
Outline

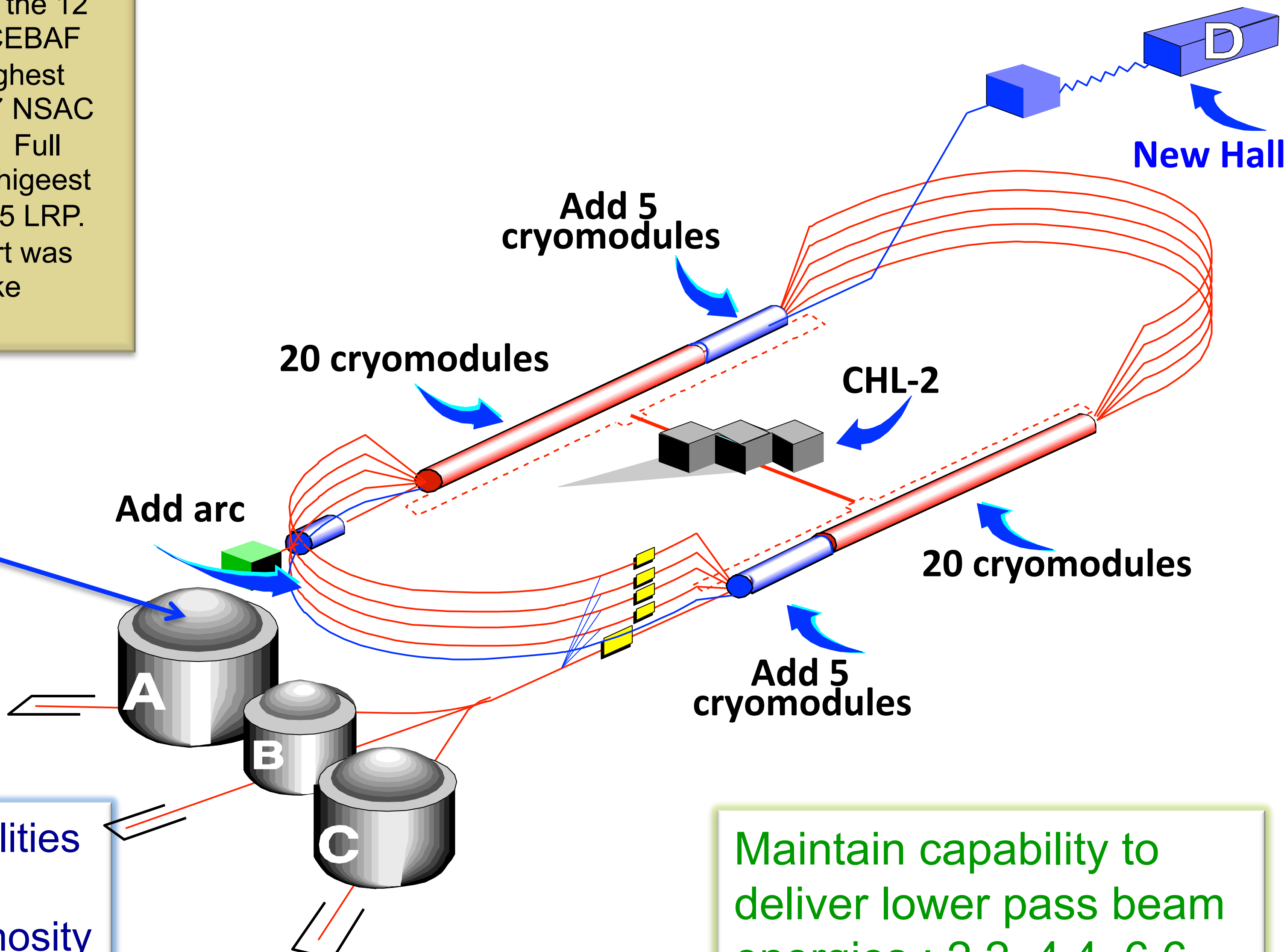
- Overview of program
- Introduction to SIDIS
- * J/psi
- * PVDIS
- Instrumentation details

Jlab 12 GeV Upgrade

The completion of the 12 GeV Upgrade of CEBAF was ranked the highest priority in the 2007 NSAC Long Range Plan. Full use of upgrade is higeest priority for the 2015 LRP. In addition, support was given for MRE's like SoLID.

SoLID





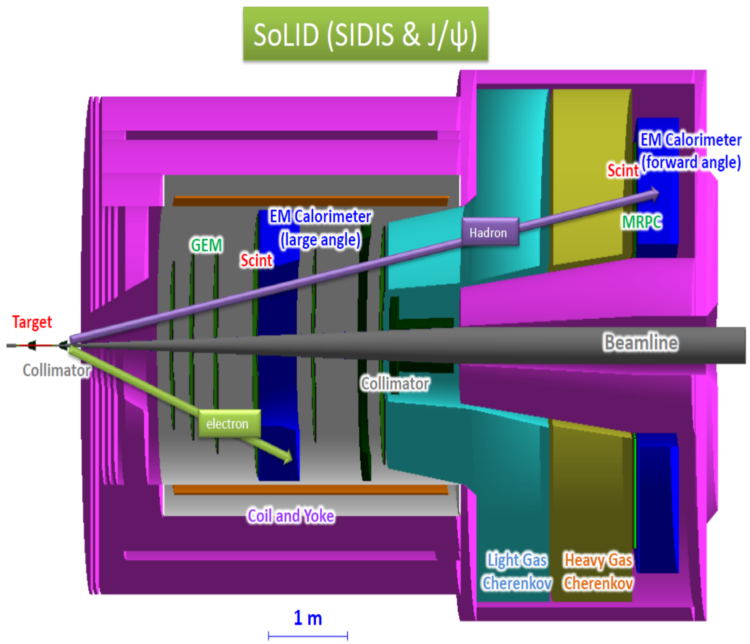
- Enhanced capabilities in existing Halls
- Increase of Luminosity 10^{35} - ~10^{39} $cm^{-2}s^{-1}$

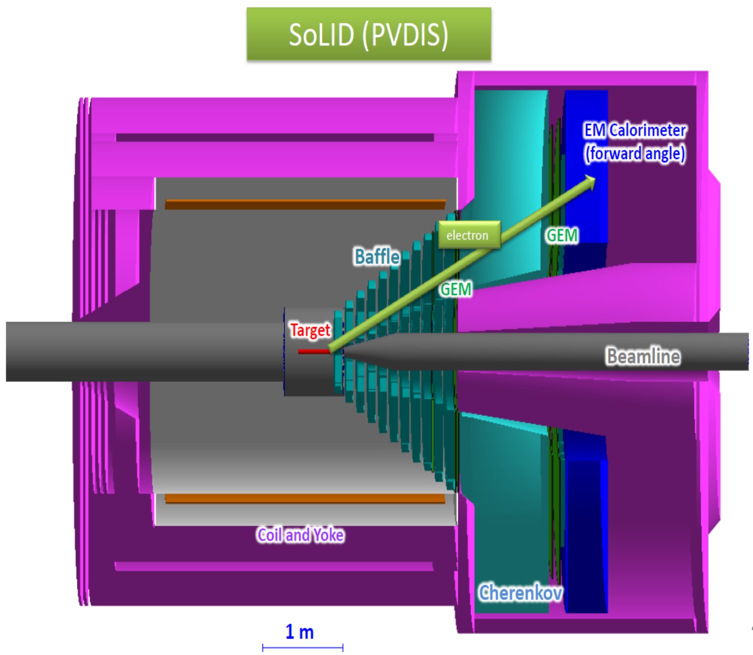
Maintain capability to deliver lower pass beam energies : 2.2, 4.4, 6.6, ….

Overview of SoLID in Hall A

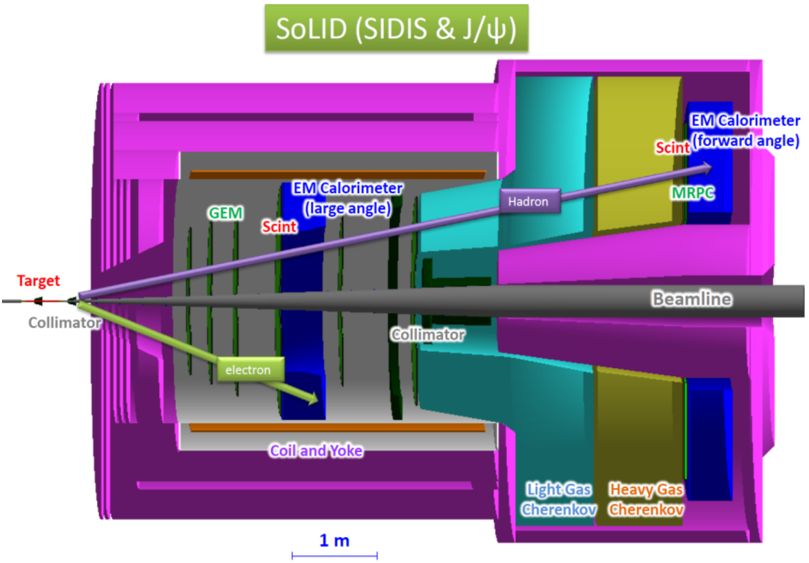
Solenoidal Large Intensity Device

- 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 and threshold J/ψ
- 5 highly rated experiments approved
  Three SIDIS experiments, one PVDIS, one J/ψ production (+ 3 run group experiments)
- Strong collaboration (250+ collaborators from 70+ institutes, 13 countries)
  Significant international contributions (Chinese collaboration)





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

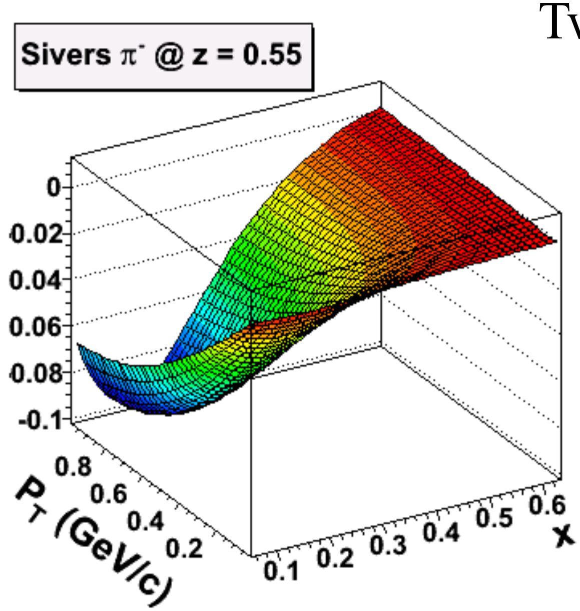


E12-10-006: Single Spin Asymmetry on Transverse ^{3}He, **rating A**

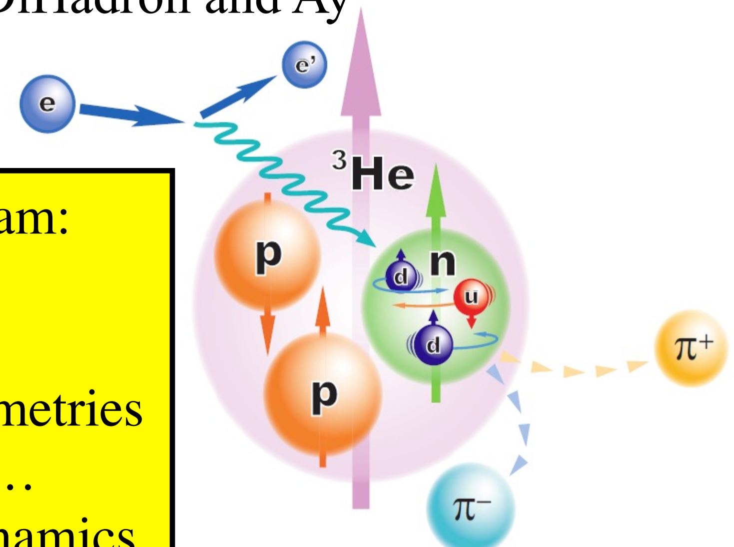
E12-11-007: Single and Double Spin Asymmetries on ^{3}He, **rating A**

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

Two run group experiments DiHadron and Ay



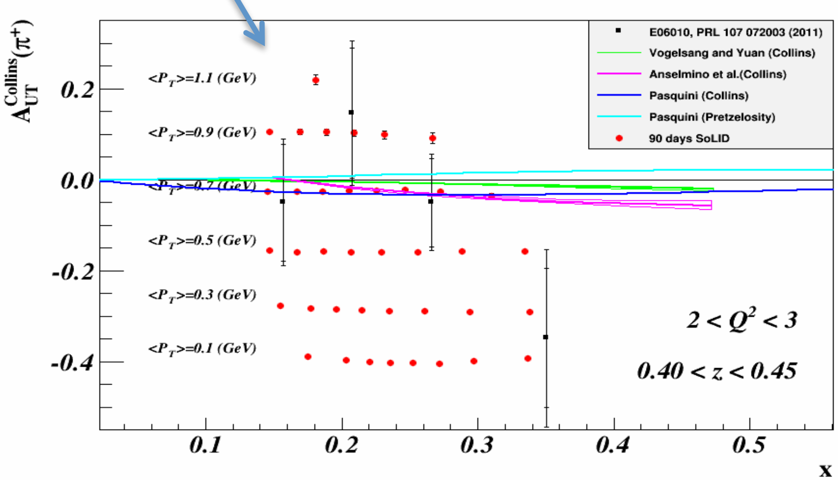
Key of SoLID-Spin program:
Large Acceptance
+ High Luminosity
→ 4-D mapping of asymmetries
→ Tensor charge, TMDs …
→Lattice QCD, QCD Dynamics, Models.



Features of SoLID for SIDIS

- **Uses new high-rate technology; GEM trackers, Sashlyk calormimeters, MRPC for timing and K identification, deadtimeless electronics.**
- **Can accommodate longitudinal and transversely polarized 3He and H targets. Can measure TMD's for p and n.**
- **Solenoidal geometry avoids gaps in the acceptance: Can measure double asymmetry to reduce systematic errors to below the large statisitcs:**
- **Excellent statistics.**

Collins Asymmetries



$$A_{UT}^{h}(\phi_h,\phi_T) = \frac{2}{P_T^1 + P_T^2}\,\frac{\sqrt{N_1 N_2^+} - \sqrt{N_1^+ N_2}}{\sqrt{N_1 N_2^+} + \sqrt{N_1^+ N_2}}$$

$$N_1 = N_1(\phi_h,\phi_T) \qquad N_1^+ = N_1(\phi_h,\phi_T + \pi)$$

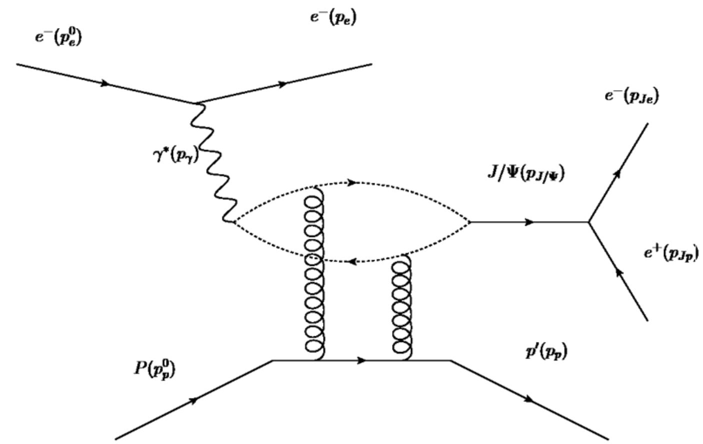
See talk by H. Gao on TMD's with SoLID

Threshold J/ψ Production

Gluon Dynamics, Proton Mass, Conformal Anomaly

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

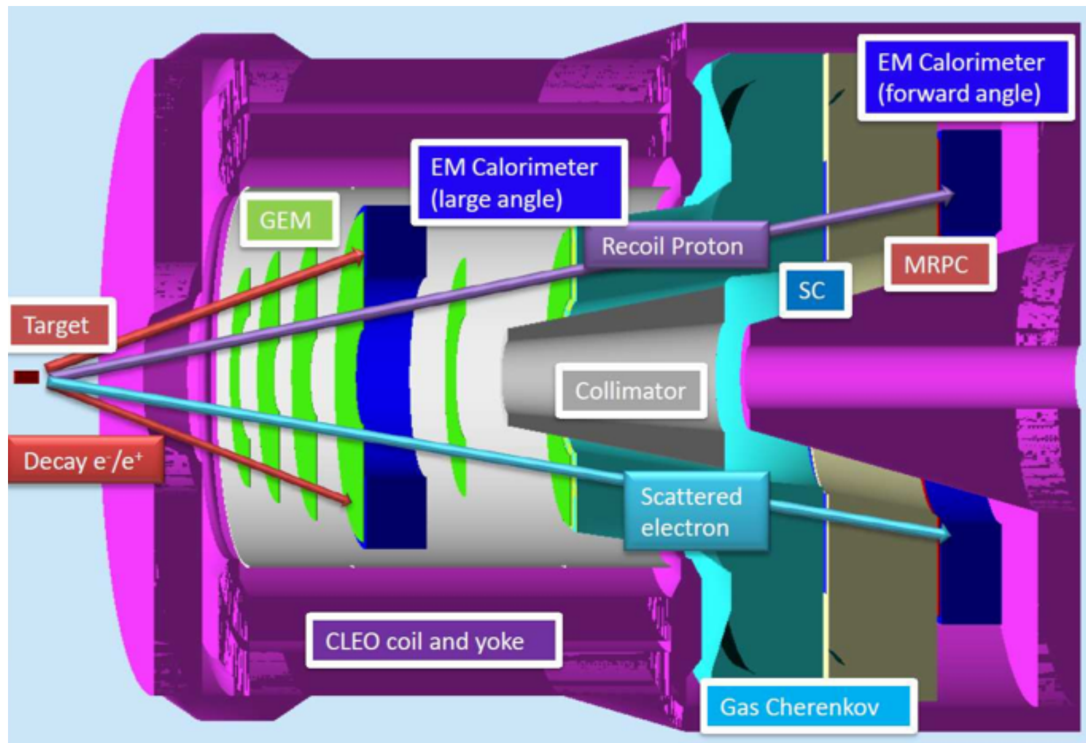
$$\gamma^* + N \rightarrow N + J/\psi$$



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

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

Real part (dominant at the lowest energies): contains the conformal (trace) anomaly



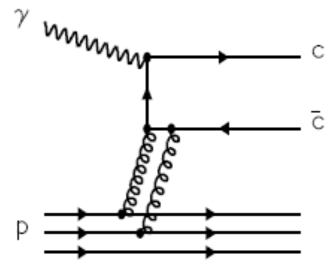
Reaction mechanism for J/Ψ production

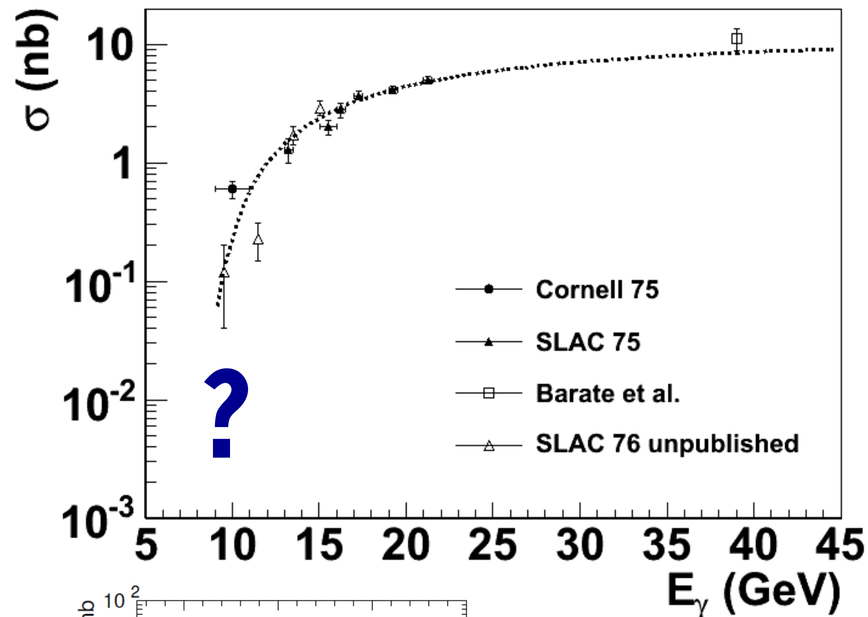
Models-I: Hard scattering mechanism (Brodsky, Chudakov, Hoyer, Laget 2001)

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

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

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



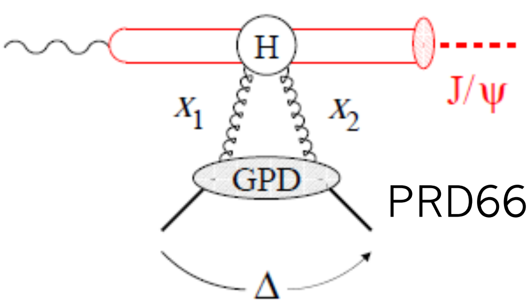


Models -II: Partonic soft mechanism

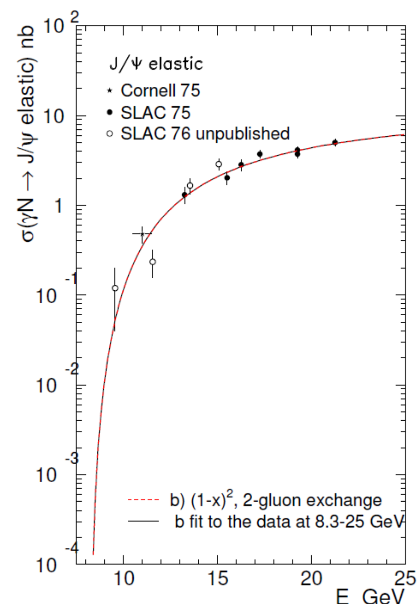
(Frankfurt and Strikman 2002)

2-gluon Form Factor

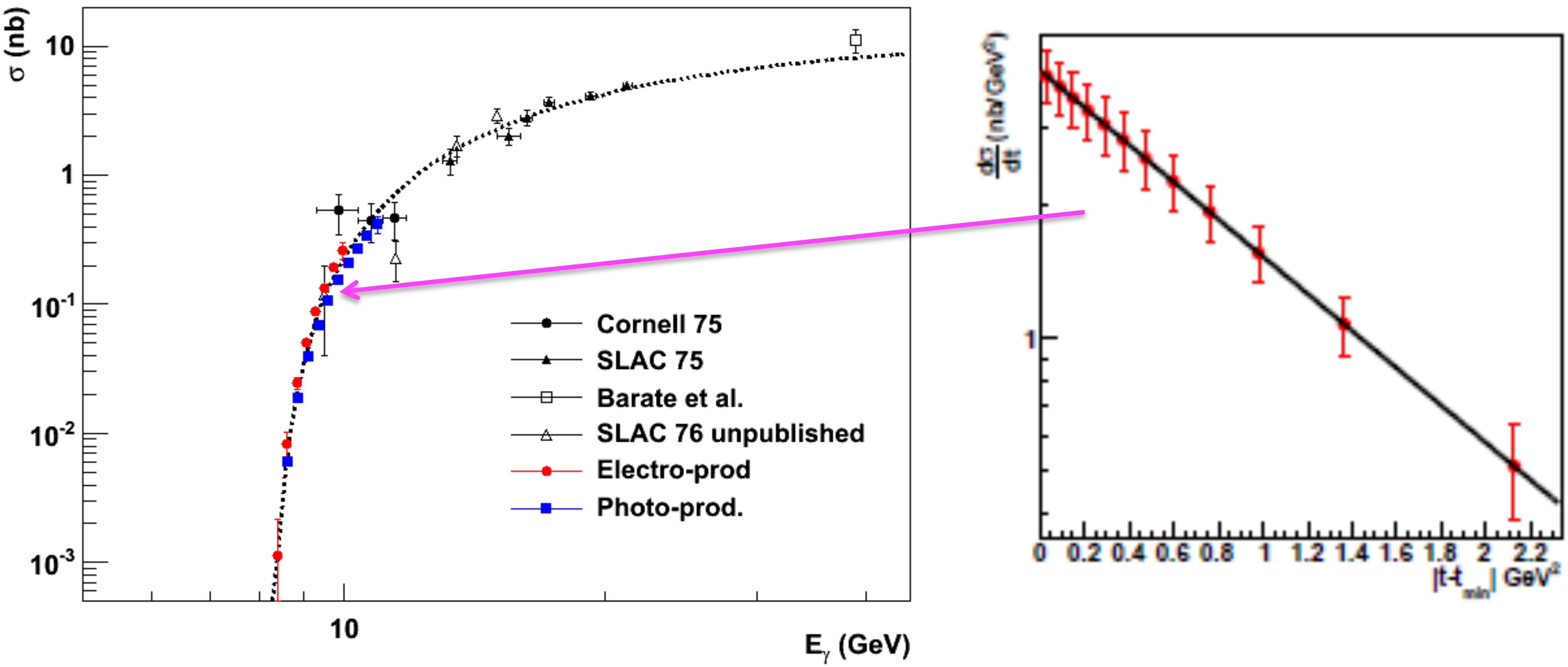
$$F.F. \propto (1 - t/1.0\ \mathrm{GeV}^2)^{-4}$$



PRD66, 031502 (2002)



Projection of Differential and Total Cross Section



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

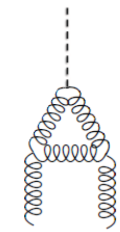
No competition in statistics

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

Nucleon Mass Decomposition and the Trace Anomaly

X. Ji PRL 74 1071 (1995)

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



$$H_{QCD} = \int d^3x \; T^{00}(0, \mathbf{x})$$

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

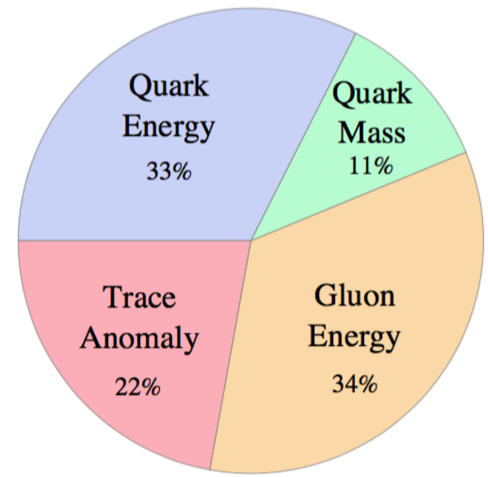
$$H_q = \int d^3x \; \psi^\dagger \left(-i\mathbf{D} \cdot \alpha\right) \psi$$

$$H_m = \int d^3x \; \bar{\psi} m \psi$$

$$H_g = \int d^3x \; \frac{1}{2} \left(\mathbf{E^2} + \mathbf{B^2}\right)$$

$$H_a = \int d^3x \; \frac{9\alpha_s}{16\pi} \left(\mathbf{E^2} - \mathbf{B^2}\right)$$

Proton Mass budget



CM Frame
MS at 2 GeV^2

- **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

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays

R. Aaij *et al.*[*]
(LHCb Collaboration)
(Received 13 July 2015; published 12 August 2015)

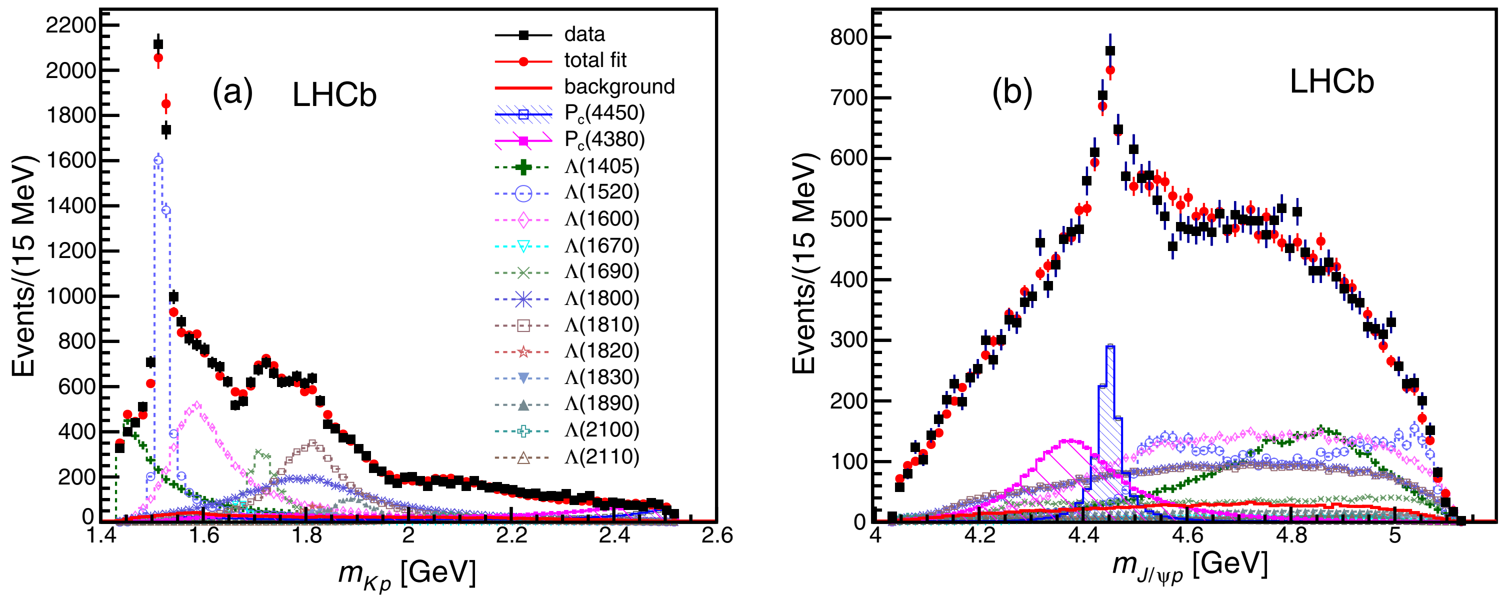
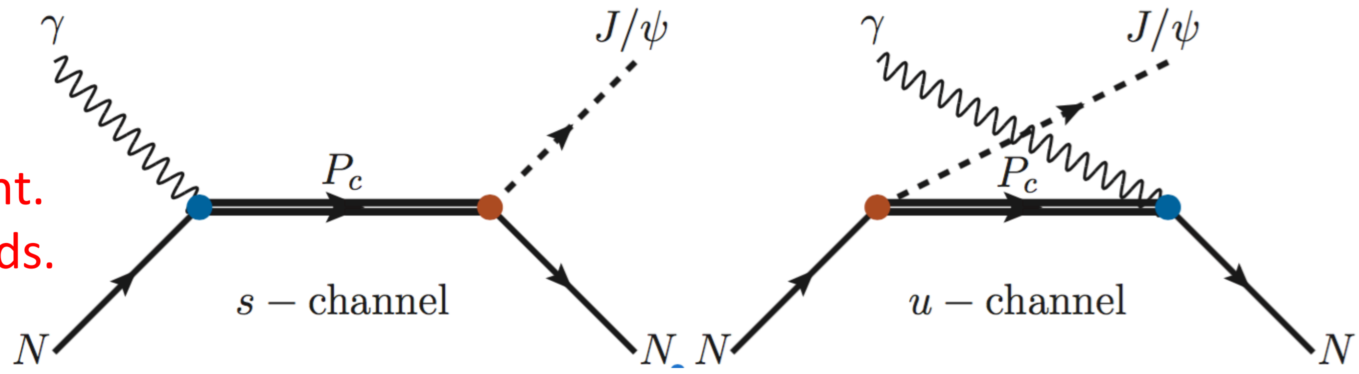


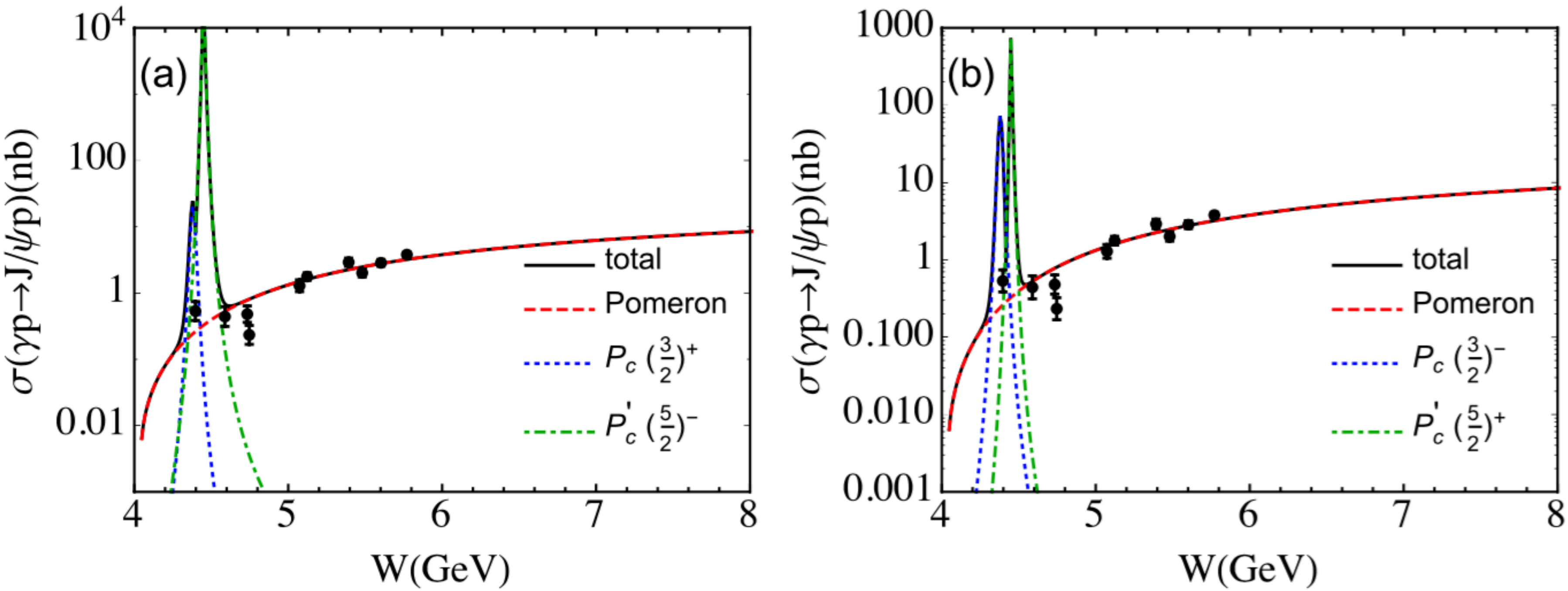
FIG. 3 (color online). Fit projections for (a) m_{Kp} and (b) $m_{J/\psi p}$ for the reduced Λ^* model with two P_c^+ states (see Table I). The data are shown as solid (black) squares, while the solid (red) points show the results of the fit. The solid (red) histogram shows the background distribution. The (blue) open squares with the shaded histogram represent the $P_c(4450)^+$ state, and the shaded histogram topped with (purple) filled squares represents the $P_c(4380)^+$ state. Each Λ^* component is also shown. The error bars on the points showing the fit results are due to simulation statistics.

Charm Pentaquark

Size is model-dependent.
Shown are upper bounds.

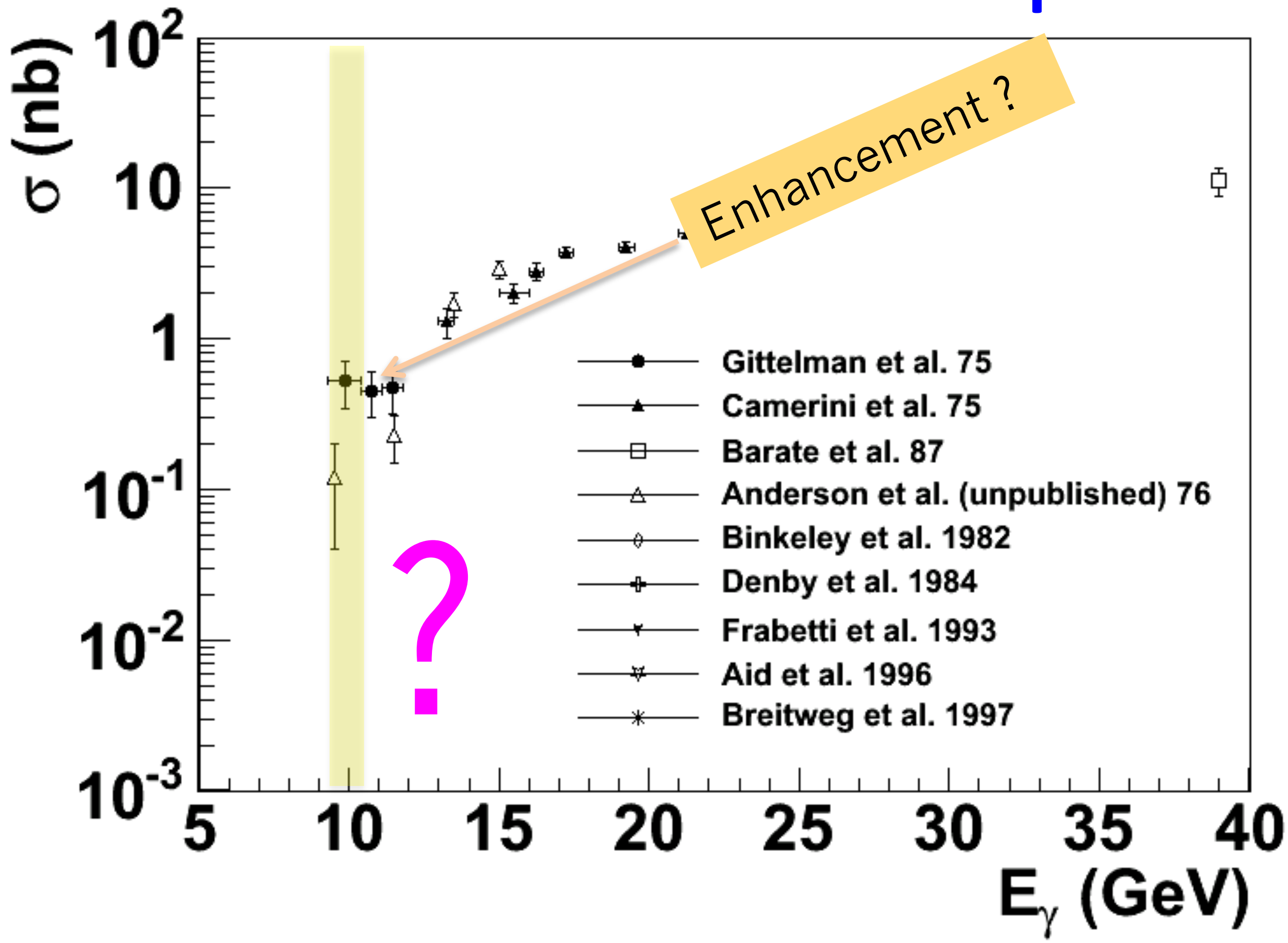


Qian Wang , Xiao-Hai Liu , and Qiang Zhao Phys. Rev. D 92, 034022 (2015)



If the pentaquark can be seen in photoproduction, it would be as important as the original discovery: T. Swarnicki, (LHCb & SU).

Evidence for the Pentaquark???



Intense experimental effort (SLAC, Cornell ...) shortly after the discovery of J/ψ

But near threshold not much since (**~40 years till now**)

J/Ψ Summary

- SoLID can observe J/Ψ production near threshold with unprecidented statisitcs.
- Measure both E and t dependence.
- Sensitive to multi-gloun exchanges and the conformal anomaly.
- Charmed Pentaquark can be probed at Jlab with SoLID

Parity Violating Deep-Inelastic Scattering

Precision Test of Standard Model
Unique Information on Nucleon Structure

Signature of Neutral Weak Interaction in Electron Scattering - Parity Violation Asymmetry

- In the Standard Model,
  - weak interaction current = V(vector) minus A(axial-vector)

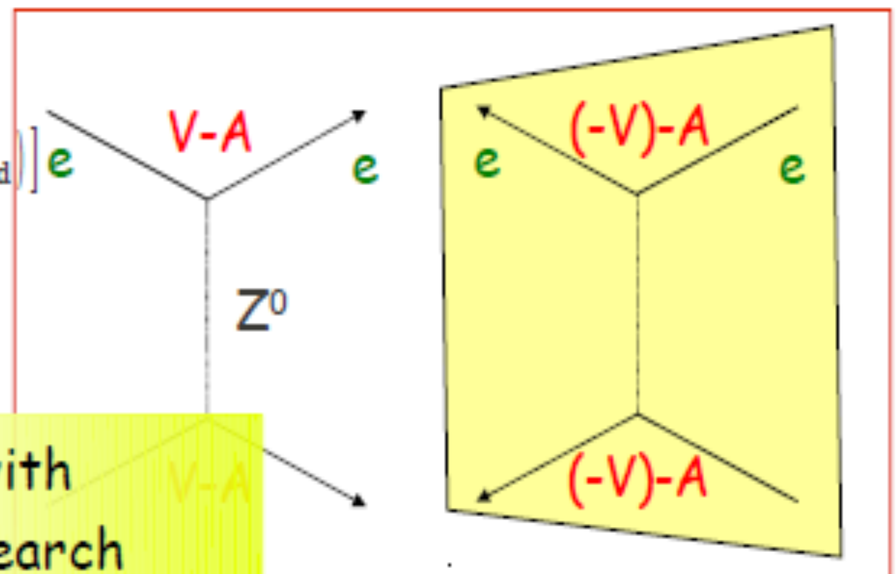
fermions	$g_A^f = I_3$	$g_V^f = I_3 - 2Q\sin^2\theta_W$
ν_e, ν_μ	$\frac{1}{2}$	$\frac{1}{2}$
$e-, \mu-$	$-\frac{1}{2}$	$-\frac{1}{2}+2\sin^2\theta_W$
u, c	$\frac{1}{2}$	$\frac{1}{2} - \frac{4}{3}\sin^2\theta_W$
d, s	$-\frac{1}{2}$	$-\frac{1}{2}+\frac{2}{3}\sin^2\theta_W$

- PV comes from the product V×A
- In DIS: $A_{PV} = -\left(\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\right)\left[a_1 Y_1 + a_3 Y_3\right]$
- In the valence quark region:

$$a_1 = \frac{6}{5}\left[2C_{1u} - C_{1d}\right] \qquad a_3 = \frac{6}{5}\left[\left(2C_{2u} - C_{2d}\right)\right]$$

$$C_{1q} = 2 g_A^e g_V^q, \quad C_{2q} = 2 g_V^e g_A^q$$

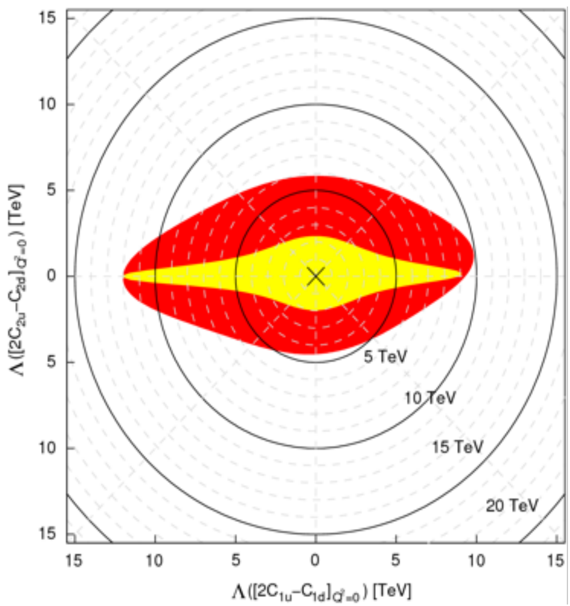
e-q contact terms, both with potential in new physics search

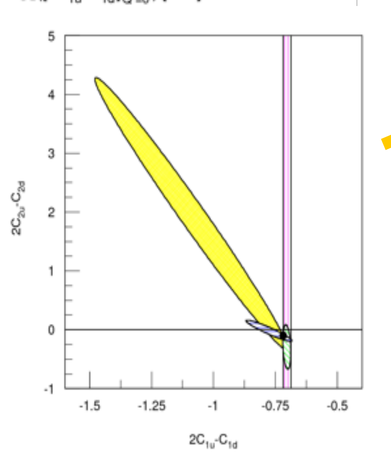


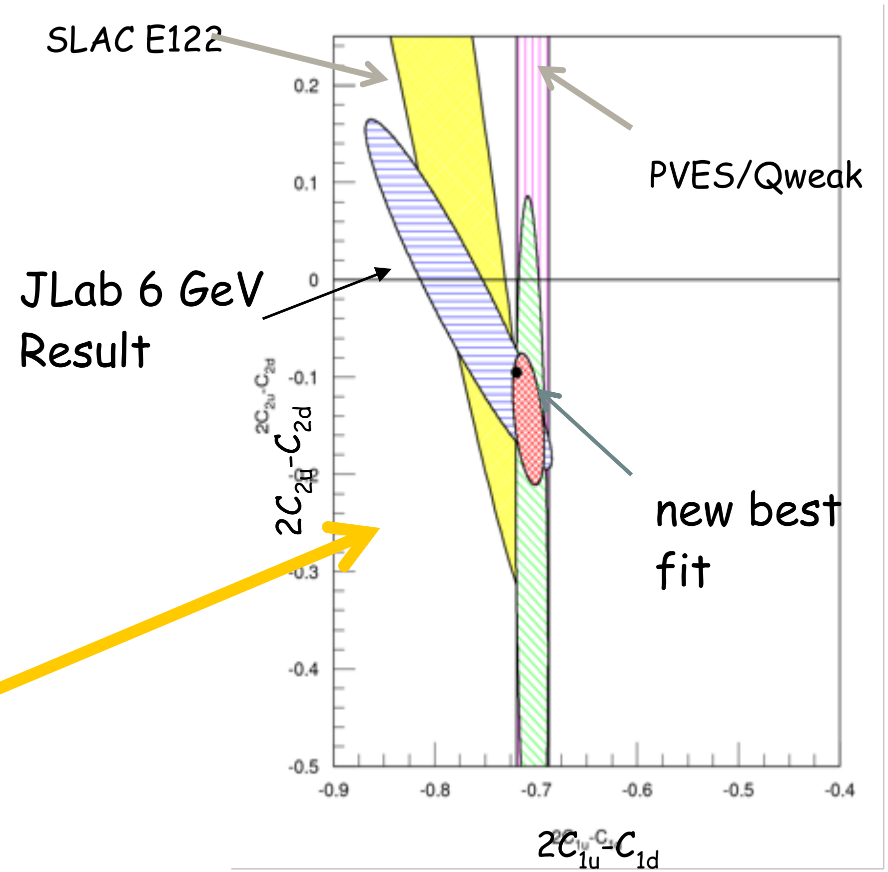
JLab 6 GeV PVDIS Results

nature International weekly journal of science

D. Wang et al., Nature 506, no. 7486, 67 (2014)

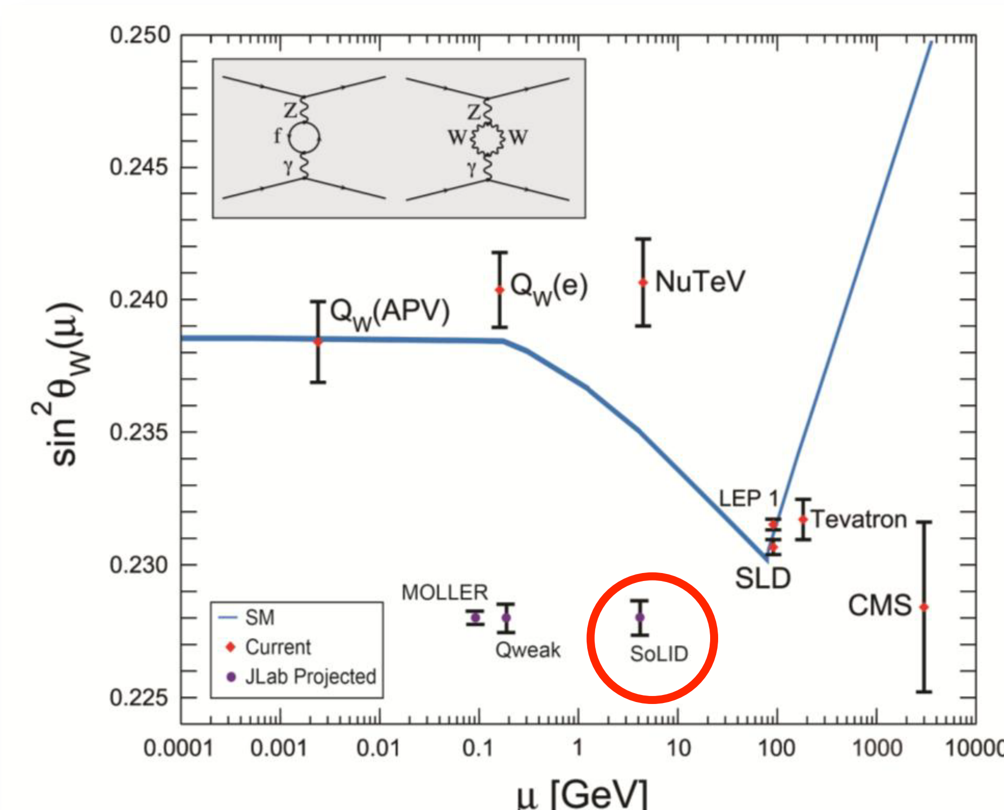


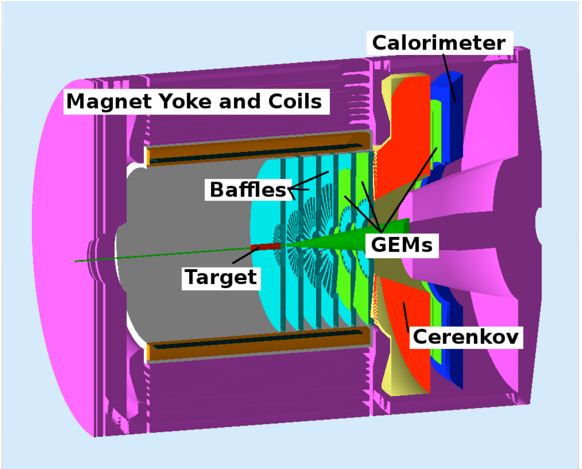




first experimental determination that an axial quark coupling combination is non-zero (as predicted)

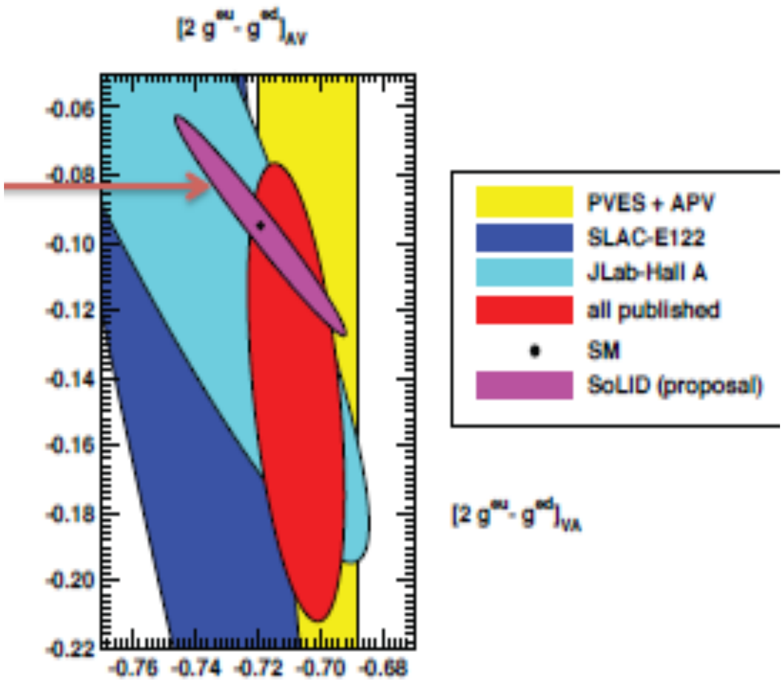
PVDIS with SoLID @ JLab12

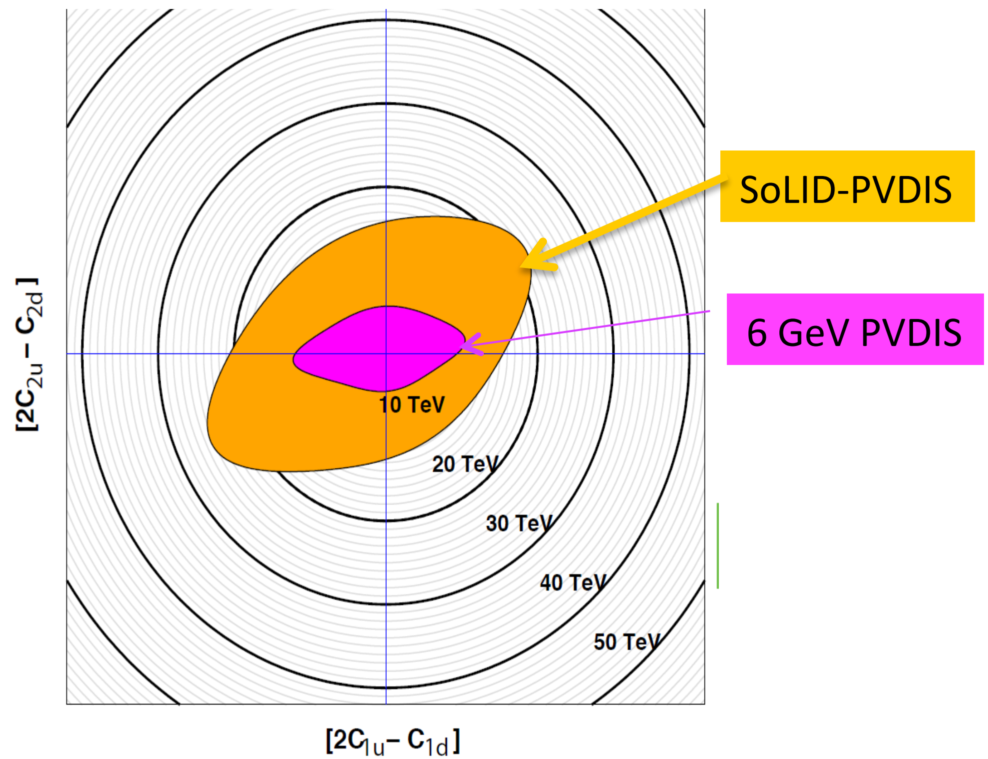




- High Luminosity on LD2 and LH2
- Better than 1% errors for small bins over large range kinematics
- Test of Standard Model
- Quark structure:
  - charge symmetry violation
  - quark-gluon correlations
  - d/u at large-x

Parity Violation with SoLID





PVDIS asymmetry has two terms:

1) 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

New Physics and c_2's

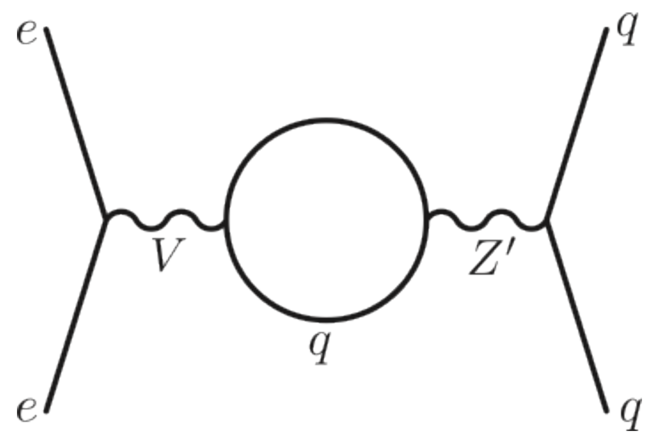
Leptophobic Z'

- ***Virtually all GUT models predict new Z's***
- ***LHC reach ~ 5 TeV, but….***
- ***Little sensitivity if Z' doesnt couple to leptons***
- ***Leptophobic Z' as light as 120 GeV could have escaped detection***

*Since electron vertex must be vector, the Z' cannot couple to the C_{1q}'s if there is no electron coupling: can only affect **C_{2q}'s***

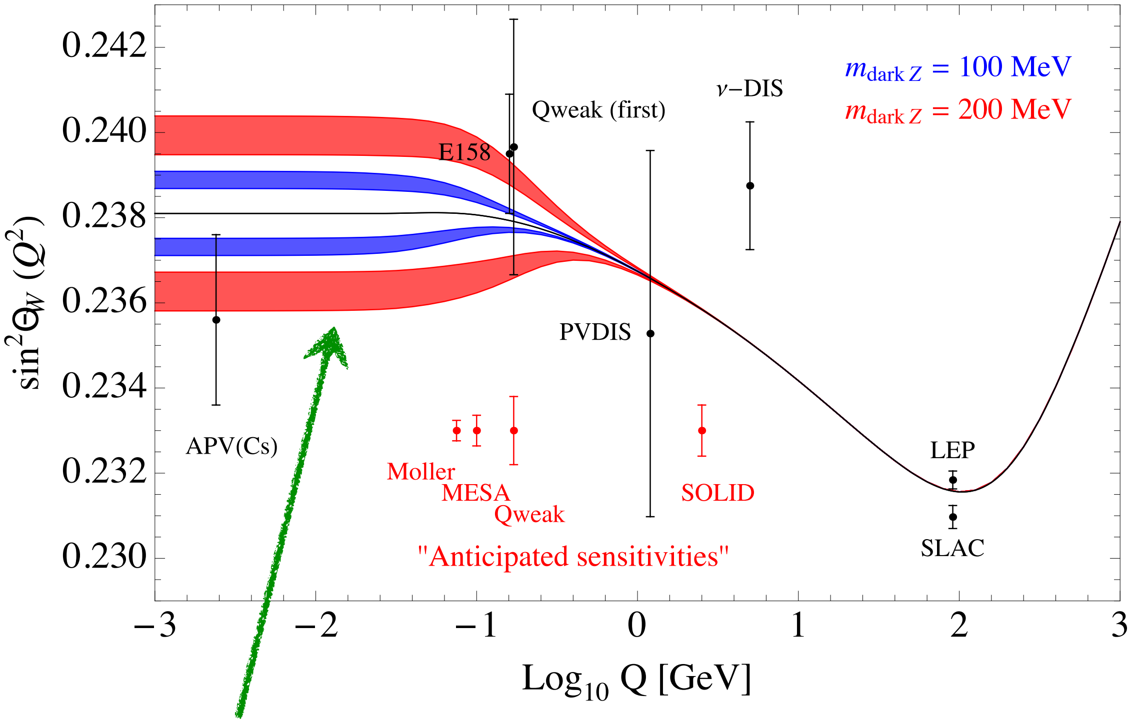
SOLID can improve sensitivity: 100-200 GeV range

arXiv:1203.1102v1
Buckley and Ramsey-Musolf



Weak angle shift for Low Q^2 due to Dark Z′

[Davoudiasl, Lee, Marciano (2014)]



Invisibly-decaying Dark Z.

Colored regions are predictions for the Weak angle due to the g-2 Δa_μ shift.

$$\Delta\ \sin^2\theta_W\,(Q^2) \simeq -0.42\,\varepsilon\delta\,\frac{m_Z}{m_{Z'}}\,\frac{1}{1+Q^2/m_{Z'}^2}$$

Slide adapted from Lee, PAVI-14

Deviations from the SM prediction (due to Dark Z) can appear **"only" in the Low-E experiments.**

For the Low-Q^2 Parity Test (measuring Weak angle), we can use

(i) Atomic Parity Violation (Cs, …)

(ii) Low-Q^2 PVES (E158, Qweak, MESA P2, Moller, SoLID…)

independent of Z' decay BR (good for both visibly/invisibly decaying Z').

New Models Extend Q^2 Range

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*

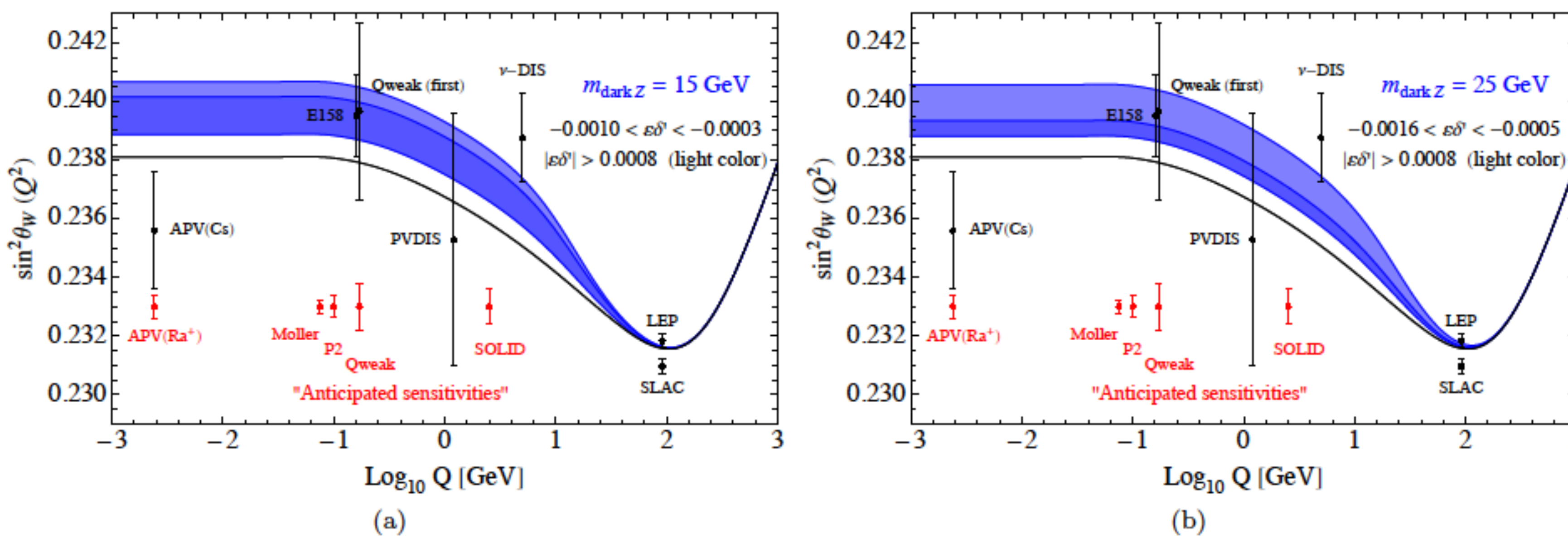


FIG. 3. Effective weak mixing angle running as a function of Q^2 shift (the blue band) due to an intermediate mass Z_d for (a) $m_{Z_d} = 15$ GeV and (b) $m_{Z_d} = 25$ GeV for 1 sigma fit to $\varepsilon\delta'$ in Eq. (12). The lightly shaded area in each band corresponds to choice of parameters that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

Charge Symmetry Violation

We already know CSV exists:

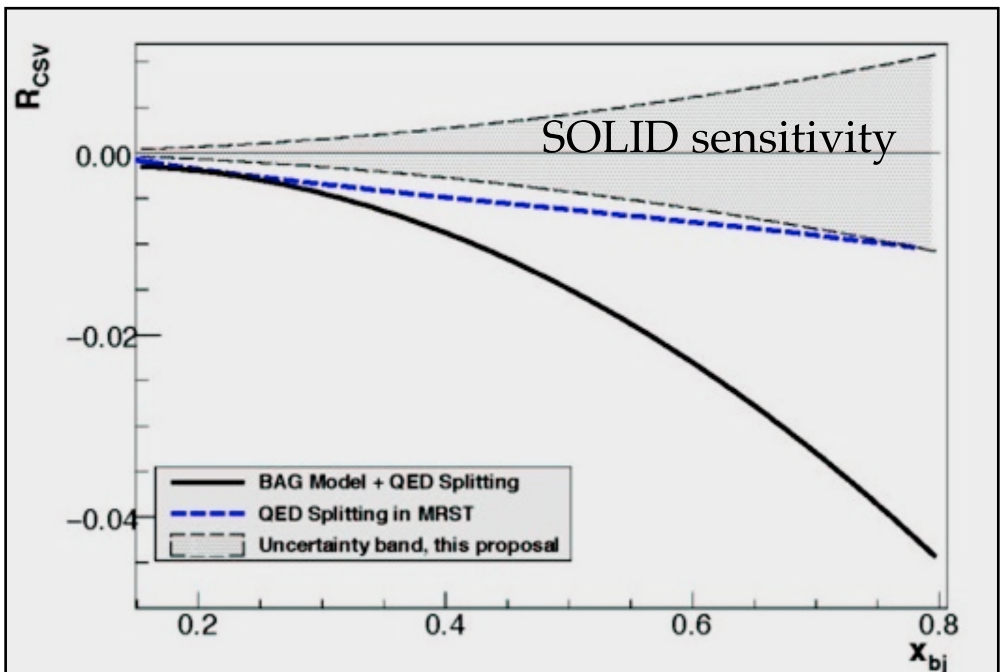
- u-d mass difference $\delta m = m_d - m_u \approx 4$ MeV
  $\delta M = M_n - M_p \approx 1.3$ MeV
- electromagnetic effects

$$u^p(x) \stackrel{?}{=} d^n(x) \quad \Rightarrow \quad \delta u(x) \equiv u^p(x) - d^n(x)$$
$$d^p(x) \stackrel{?}{=} u^n(x) \quad \Rightarrow \quad \delta d(x) \equiv d^p(x) - u^n(x)$$

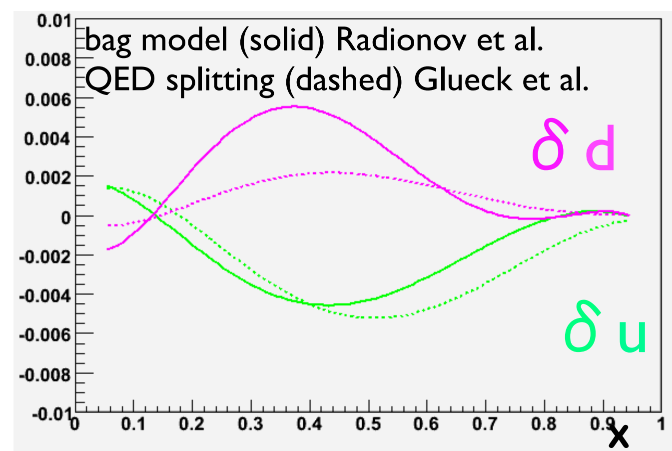
- Direct sensitivity to parton-level CSV
- Important implications for PDF's
- Could be partial explanation of the NuTeV anomaly

$$R_{CSV} = \frac{\delta A_{PV}}{A_{PV}} \approx 0.28 \frac{\delta u(x) - \delta d(x)}{u(x) + d(x)}$$

For A_{PV} in electron-^{2}H DIS



Sensitivity will be enhanced if u+d falls off more rapidly than δu-δd as x → 1



Significant effects are predicted at high x

Recent Predictions

M. Traini / Physics Letters B 707 (2012) 523–528

Progress in resolving charge symmetry violation in nucleon structure

R. D. Young*, P. E. Shanahan and A. W. Thomas

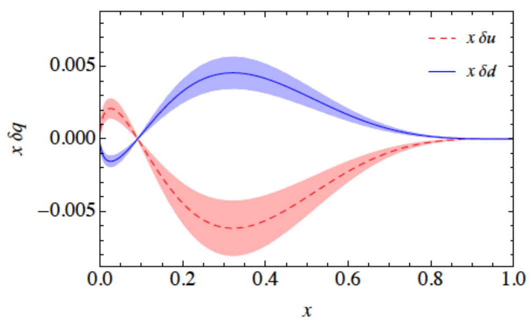


Fig. 3. Charge symmetry violating momentum fraction using simple phenomenological parameterisation $\delta q(x) = \kappa x^{-1/2}(1-x)^4(x-1/11)$ with normalisation determined from the lattice moment.[11]

Shape at large x is very different

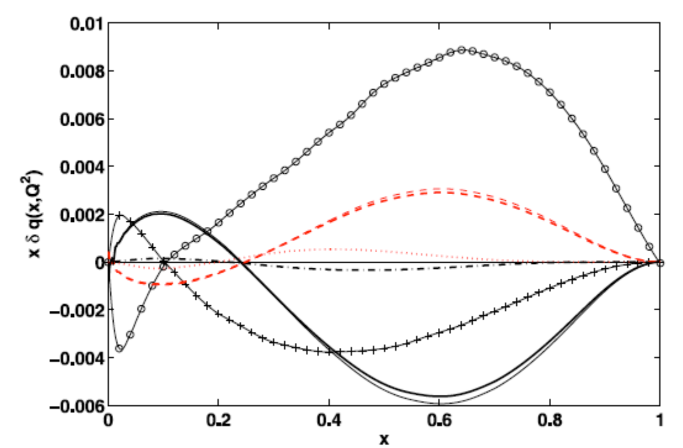
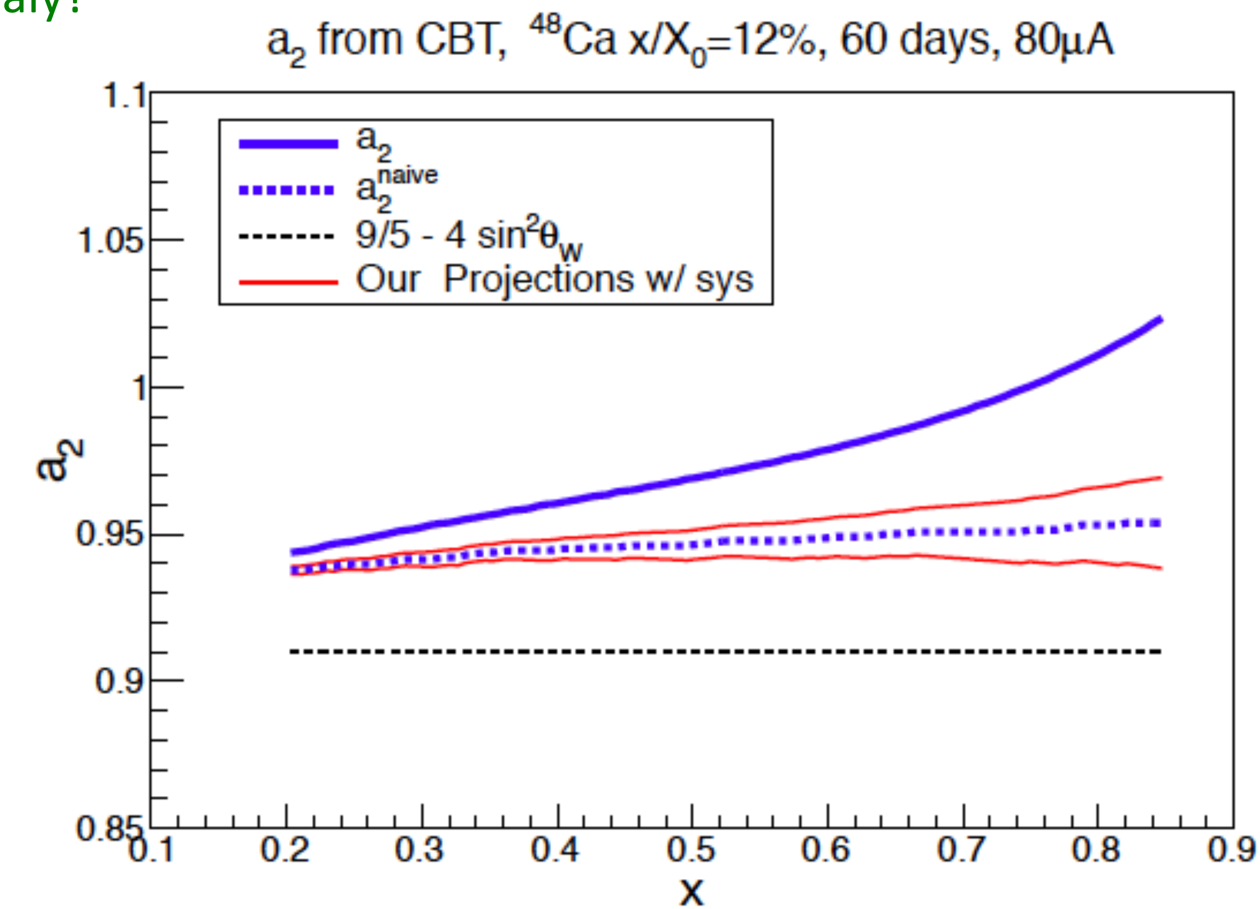


Fig. 2. Isospin symmetry violations from radiative QED effects (from Eqs. (11) at $Q^2 = 10$ GeV^2) and mass effects (from the model (9) at Q_0^2). $x\delta u_V(x,Q^2)$ (continuous lines, the tiny line does not include strange sea at the static point $Q_0^2 = 0.149$ GeV^2) and $x\delta d_V(x,Q^2)$ (dashed lines, the tiny line does not include strange sea at the static point Q_0^2). $x\delta\bar{u}$ and $x\delta\bar{d}$ are represented by the dot-dashed and dotted lines respectively, they are calculated including strange sea at the static point. The effects due to the $u-d$ mass difference ($m_d - m_u = 4$ MeV according to Ref. [34]), are shown by line-circles ($x\delta d_V(x,Q_0^2)$) and by line-pluses ($x\delta u_V(x,Q_0^2)$).

Isovector EMC Effect (New Proposal)

Additional contribution to NuTeV anomaly?



A Special HT Effect

The observation of Higher Twist in PV-DIS would be exciting direct evidence for diquarks

following the approach of
Bjorken, PRD 18, 3239 (78),
Wolfenstein, NPB146, 477 (78)

$$V_\mu = \left(\bar{u}\gamma_\mu u - \bar{d}\gamma_\mu d\right) \Leftrightarrow S_\mu = \left(\bar{u}\gamma_\mu u + \bar{d}\gamma_\mu d\right)$$

Isospin decomposition before using PDF's

$$\langle VV \rangle = l_{\mu\nu} \int \langle D \,|\, V^\mu(x) V^\nu(0) \,|\, D \rangle e^{iqx} d^4x$$

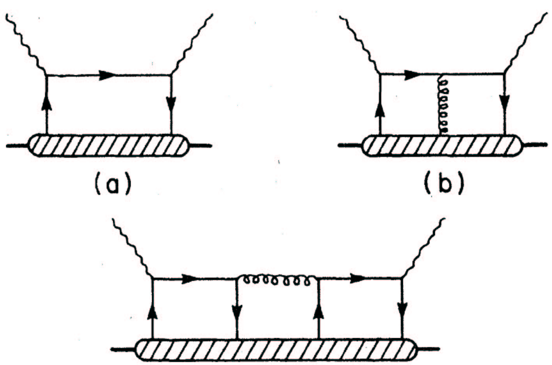
$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y) b(x)\right]$$

$$\delta = \frac{\langle VV \rangle - \langle SS \rangle}{\langle VV \rangle + \langle SS \rangle} \qquad a(x) \propto \frac{F_1^{\gamma Z}}{F_1^{\gamma}} \propto 1 - 0.3\delta$$

Higher-Twist valence quark-quark correlation

Zero in quark-parton model

$$\langle VV \rangle - \langle SS \rangle = \langle (V - S)(V + S) \rangle \propto l_{\mu\nu} \int \langle D \,|\, \bar{u}(x)\gamma^\mu u(x) \bar{d}(0)\gamma^\nu d(0) \rangle e^{iqx} d^4x$$



(c) Castorina & Mulders, '84

(c) type diagram is the only operator that can contribute to a(x) higher twist: theoretically very interesting!

σ_L contributions cancel

Use ν data for small b(x) term.

Coherent Program of PVDIS Study

Strategy: requires precise kinematics and broad range

Kinematic dependence of physics topics

	x	Y	Q^2
New Physics	none	yes	small
CSV	yes	small	small
Higher Twist	large?	no	large

- Measure A_d in **narrow** bins of *x*, Q^2 with *0.5%* precision
- Cover broad Q^2 range for *x* in *[0.3,0.6]* to constrain HT
- Search for CSV with *x* dependence of A_d at high *x*
- Use $x > 0.4$, high Q^2 to measure a combination of the C_{iq}'s

Fit data to:

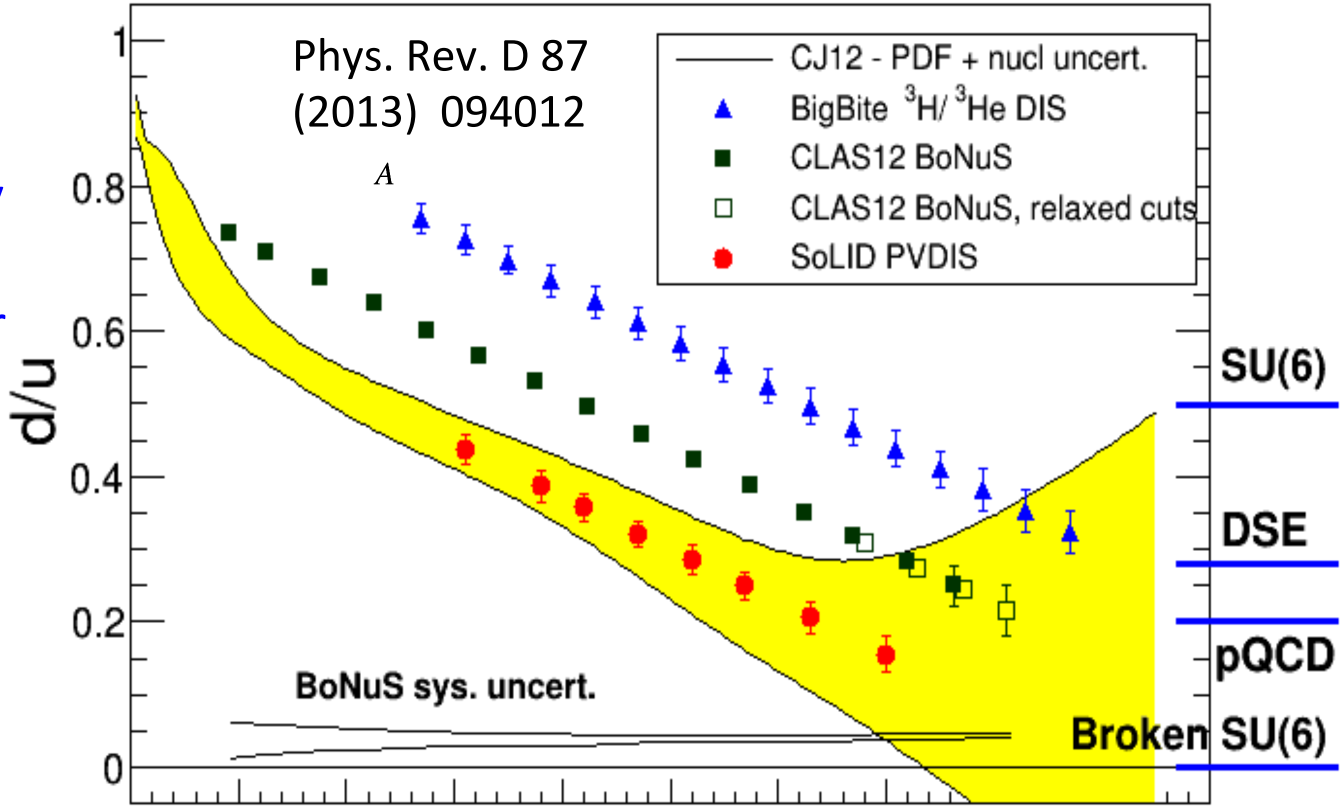
$$A_{\text{Meas.}} = A_{\text{SM}}\left[1 + \frac{\beta_{\text{HT}}}{(1-x)^3 Q^2} + \beta_{\text{CSV}} x^2\right]$$

PVIDS with the Proton

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

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

PVDIS is complementary to the rest of the JLAb d/u program: no nuclear effects



PVDIS Summary

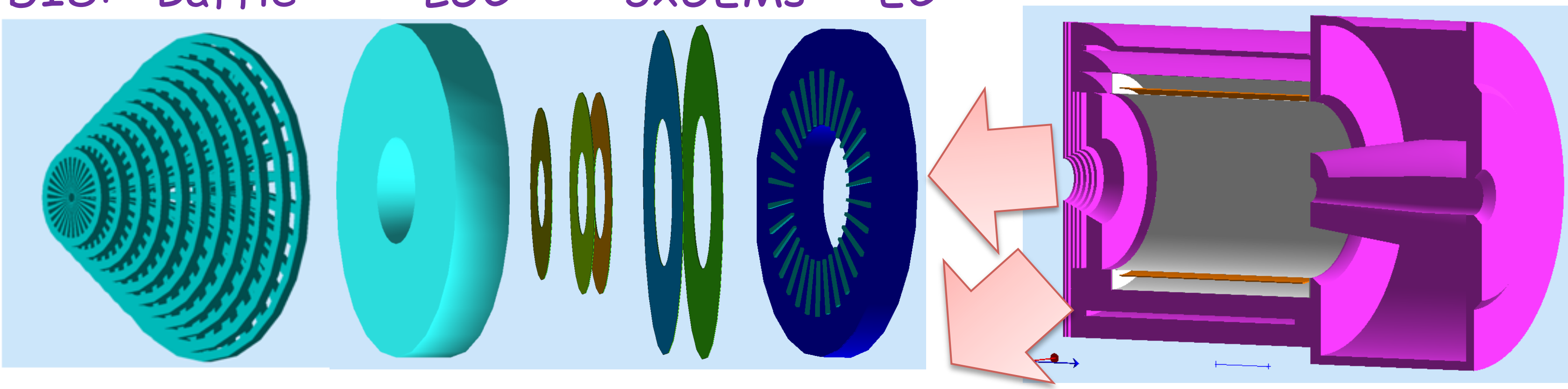
- SoLID can measure PVDIS in the large Bjorken x region with sub-percent statistcs.
- Sensitive to possible new weak interactions or compositeness scales.
- Can search for CVS at the quark level.
- Search for the isovector EMC effect.
- Search for di-quark higher twist effects.
- Measure d/u for the proton with no nuclear corrections.

Status of SoLID

Conceptual Design, pre-R&D,
Time Line, Organization

SoLID Detector Overview

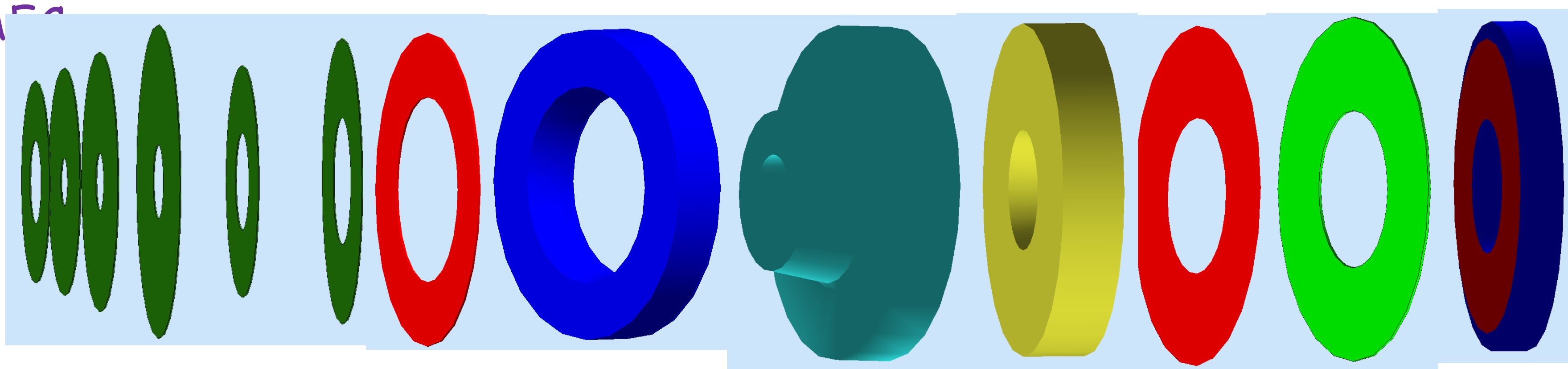
PVDIS: Baffle LGC 5xGEMs EC



SIDIS&J/Psi:

6xGEMs LASPD LAEC LGC HGC FASPD MRPC

FA

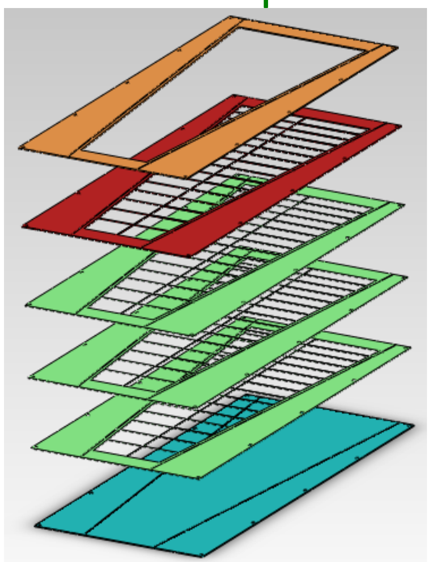


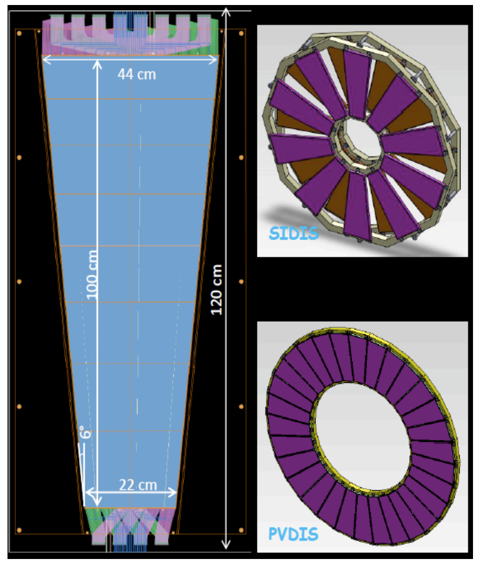
When the 12 GeV upgrade was proposed, much of this instrumentation was not fully developed.

GEM Progress

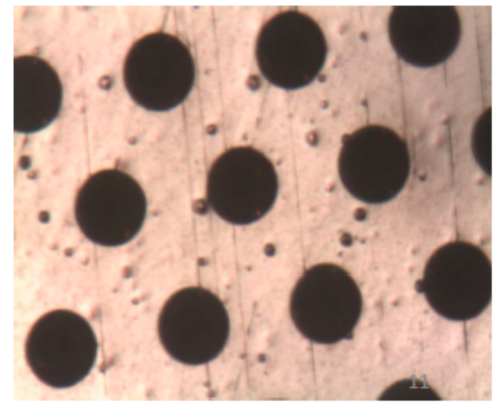
Chinese Collaboration

- First full size prototype assembled at UVA, tested in beam (Fermi Lab)
- 30x30 cm prototype constructed, readout tested (CIAE/USTC/Tsinghua/ Lanzhou)
- GEM foil production facility under development at CIAE (China)





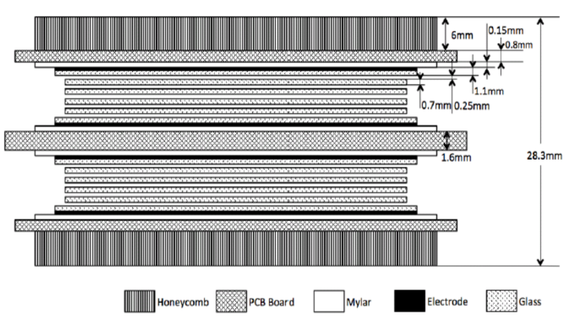
GEM foils made at CIAE

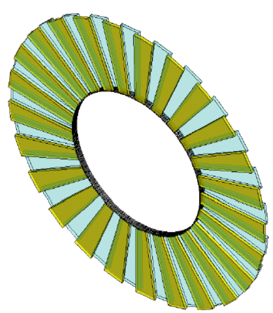


> 95 % efficiency

MRPC – High Resolution TOF

Timing resolution ~ 85 ps

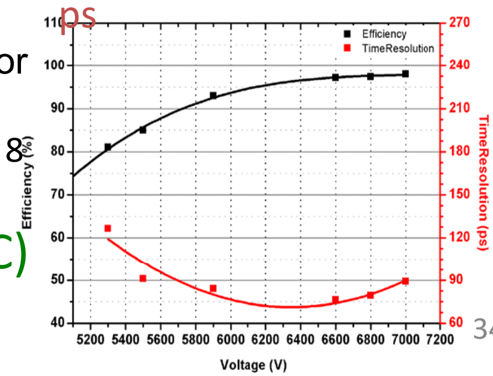




A MRPC prototype for SOLID-TOF in JLab

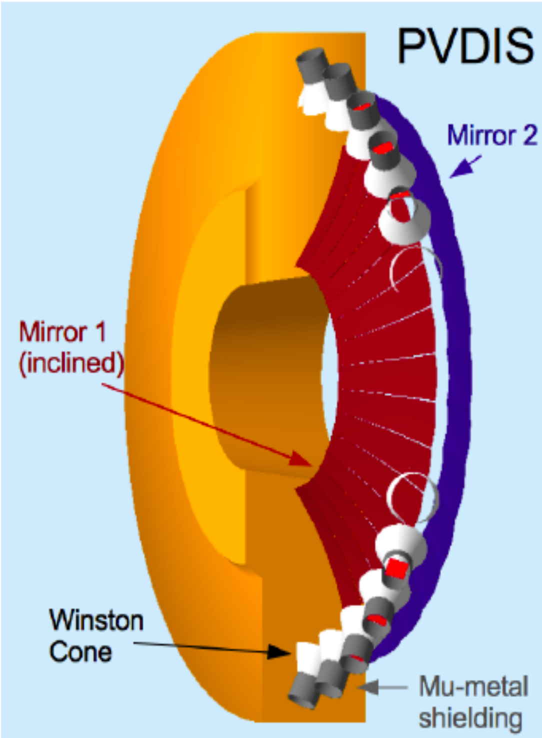
Y. Wang, et al. JINST 8 (2013) P03003

(Tsinghua, USTC)

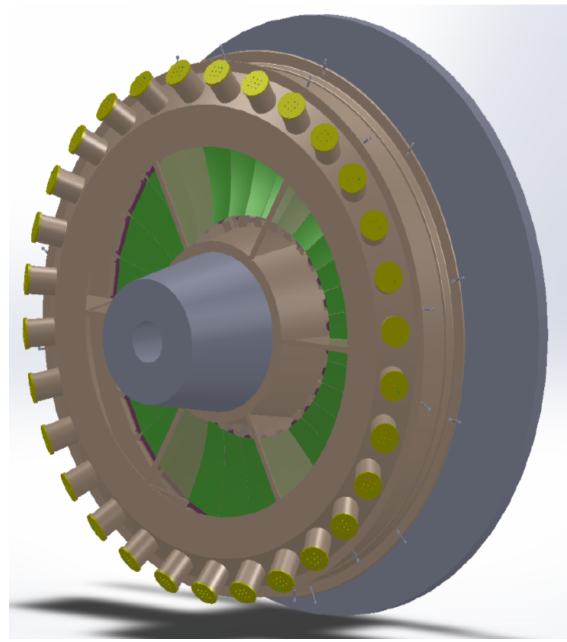


SoLID Detector Development

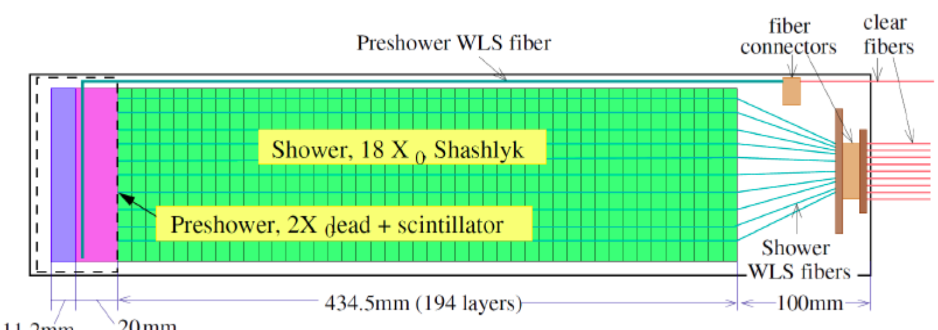
Simulations now with realistic backgrounds



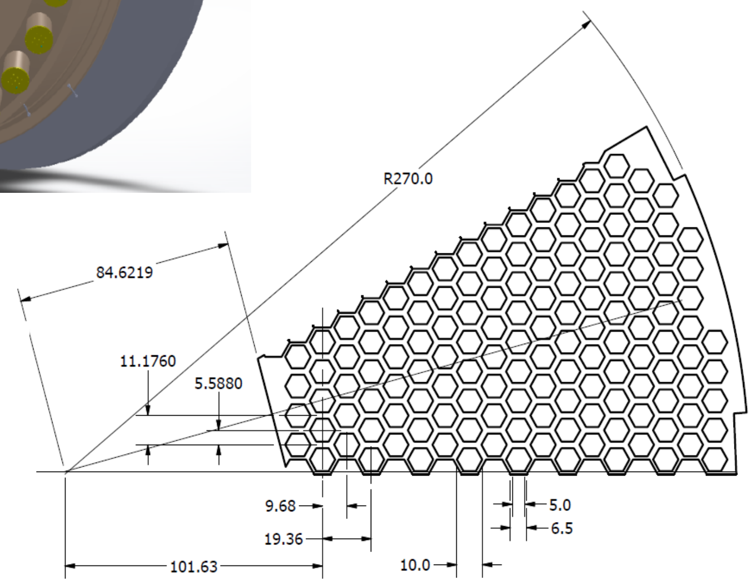
Light Gas Cerenkov (Temple)



Heavy Gas Cerenkov (Duke, Regina)



ECal (UVA, W&M, Shandong, Tsinghua)



ECal Mounting Design (ANL)

SoLID Timeline, Status and Plan

- 2010-now: Five highly rated SoLID experiments approved by PAC + 3 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

✓ 10/2015: Long Range Plan, SoLID strongly endorsed

✓ 11/2015: discussion with DOE, pre-R&D funding

Plan:

- Magnet transportation, initial tests and refurbish (2016)
- Detector, DAQ pre-R&D effort ramping up
- Science review (early 2017?)
- pCDR → TDR, MIE proposal (draft MIE in 2017)
- CD processes/ PED/R&D (2017 – 2019)
- Construction starts 2020

Summary

Full exploitation of JLab 12 GeV Upgrade

→ SOLID: A Large Acceptance Detector that can handle High Luminosity (10^{37}-10^{39})

Rich, important physics program to address some of the most fundamental questions in Nuclear Physics.

Vibrant program: For upcoming PAC, there will be 3 GPD proposals and 2 PVDIS proposals.

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 (TMD, GPD, J/ψ, d/u), and electroweak physics. It also provides access to a broad set of other reactions.

SoLID could be an initial detector for the future EIC.

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