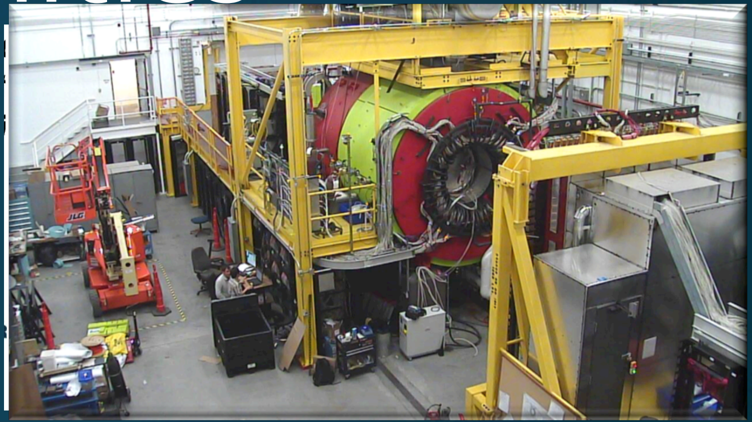
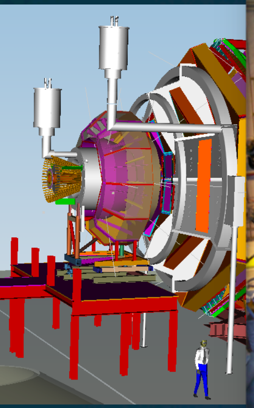
Solenoidal Large Acceptance Device (SoLID) Science Update

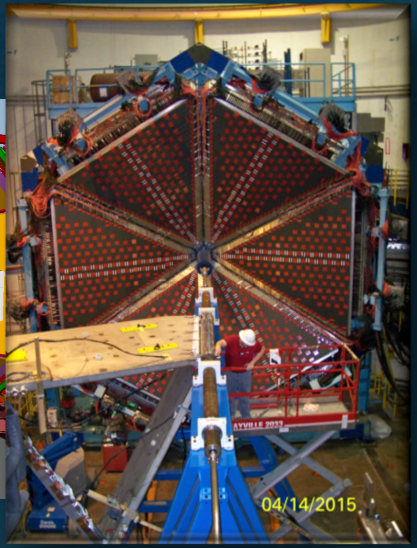
- JLab 12 GeV scientific capabilities
- SoLID; the tool for a full exploitation of the 12 GeV upgrade
- Physics Overview
  - Semi-Inclusive Deep Inelastic Scattering (New studies)
  - Parity Violation in Deep Inelastic Scattering
  - Threshold Electro- and Photo-Production of J/Psi (New data and studies)
- Summary

12 GeV Scientific Capabilities

Hall D – exploring origin of confinement by studying exotic mesons

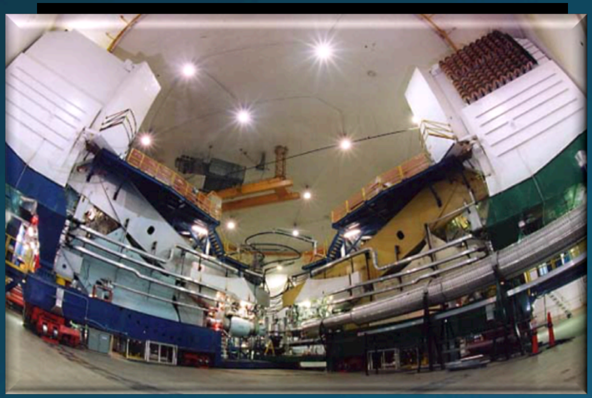






Hall B – understanding nucleon structure via generalized parton distributions and transverse momentum distributions

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



Hall A – short range correlations, form factors, hyper-nuclear physics, future new experiments (e.g., SoLID and MOLLER)

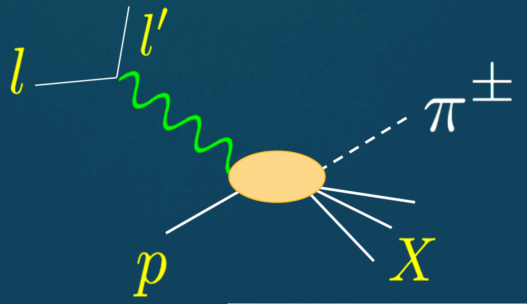
SoLID

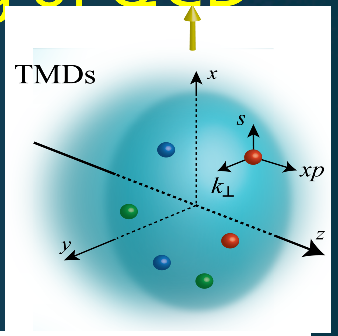
A key tool for a full exploitation of the 12 GeV upgrade

- SoLID is unique in that it provides equipment that combines - The capability to handle high luminosity ($10^{37\text{-}39}$ cm^{-1} s^{-1}) - A large acceptance detector with full ϕ coverage
- SoLID takes advantage of the latest developments in detector and data acquisition technologies
- SoLID is unique as evidenced by the approval of already 5 highly rated experiments, covering a wide range of important science topics:
  - Nucleon structure: transverse momentum imaging of valence quarks
  - Fundamental symmetries: new physics in the 10-20 TeV region
  - QCD: constraining the conformal (trace) anomaly/Origin of proton mass
  - ...including spatial imaging
- There is wide interest in SoLID science as manifested by:
  - More than 250 collaborators over 50 institutions and 13 countries - Already quite significant international contributions and potential
- further commitments, particularly from China - strong theoretical support

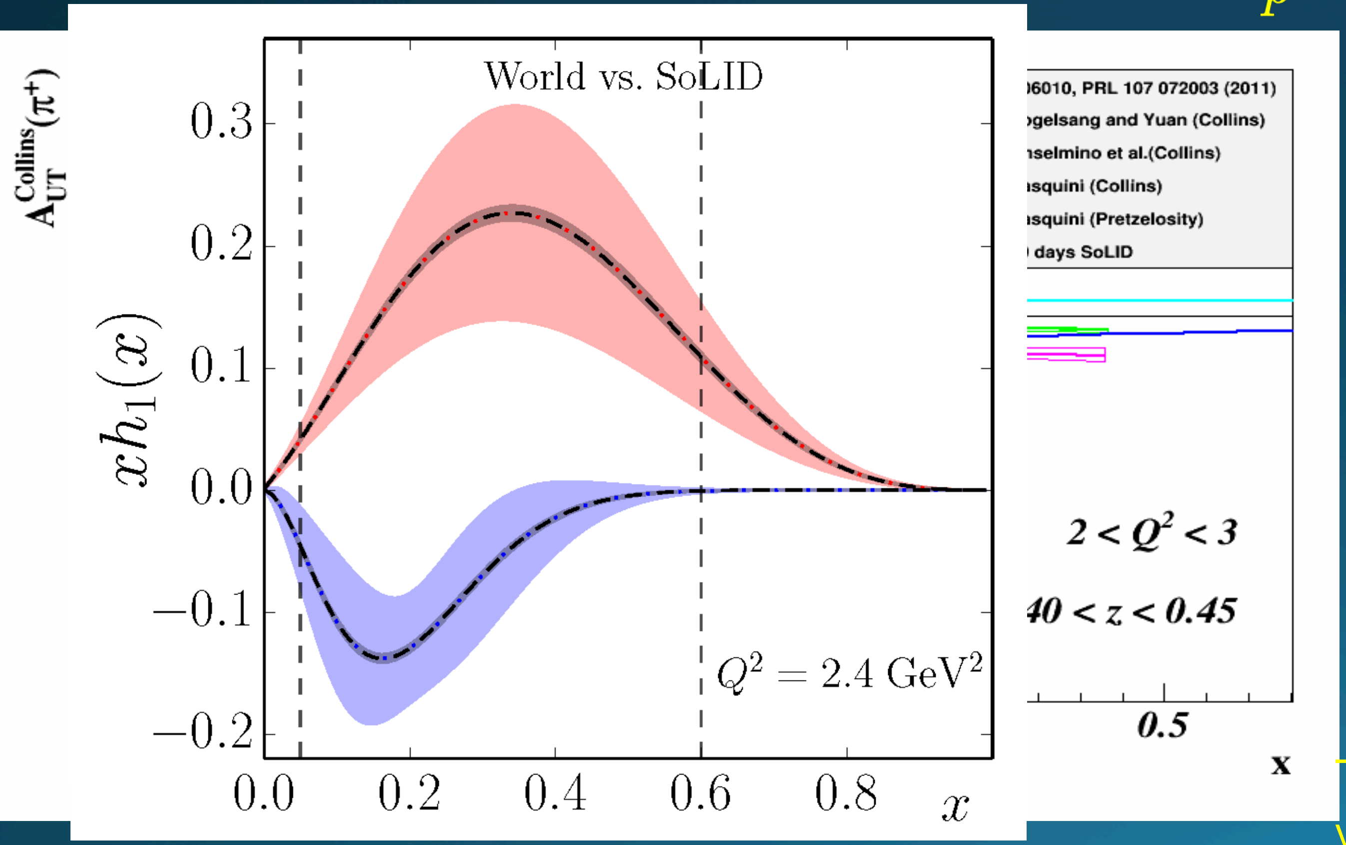
SIDIS @ SoLID:

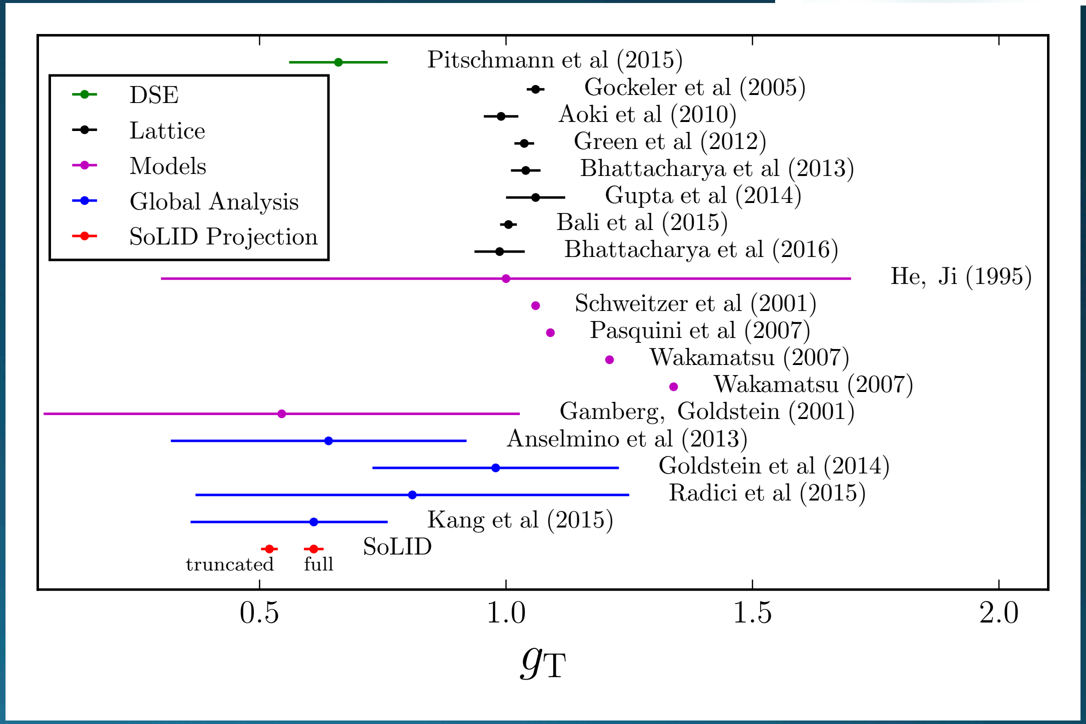
An unprecedented tool to unravel the rich structure and dynamics of nucleon structure in the valence region and the inner working of QCD





Impact of SoLID on our knowledge of the Transversity distributions





Tensor Charge, an intrinsic property as important axial vector charge, charge and magnetic moment of the nucleon

New Studies

Slides from TMDs at JLab Present and Future, Pavia 19-20 December 2018

Marco Radici

- https://agenda.infn.it/event/17379/#0-overview-of-jlab-activities

- M. Radici and A. Bacchetta, ``First Extraction of Transversity from a Global Analysis of Electron-Proton and Proton-Proton Data,"
  Phys. Rev. Lett.120, no. 19, 192001 (2018)

why transversity (PDF / TMD) ?

1st Mellin moment of transversity $\Rightarrow$ tensor "charge"

$$\delta q \equiv g_T^q = \int_0^1 dx \; \left[h_1^q(x,Q^2) - h_1^{\bar{q}}(x,Q^2) \right]$$

tensor charge connected to tensor operator

$$\begin{aligned} \langle p, S_p | \, \bar{q} \, \sigma^{\mu\nu} \, q \, | p, S_p \rangle &= \left(P^\mu S_p^\nu - P^\nu S_p^\mu \right) \; g_T^q(Q^2) \\ &= \left(P^\mu S_p^\nu - P^\nu S_p^\mu \right) \; \int dx \; h_1^{q-\bar{q}}(x,Q^2) \end{aligned}$$

tensor operator not accessible in tree-level Standard Model
low-energy footprint of new physics at higher scales ?

results

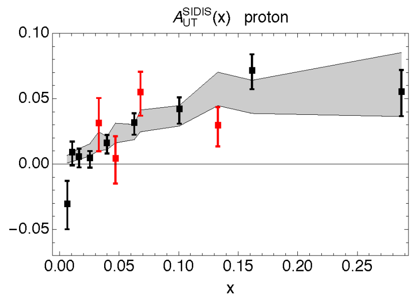
global fit published in

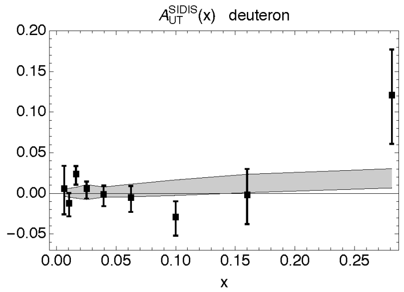
Radici and Bacchetta, P.R.L. ***120*** *(18) 192001*

SIDIS

Adolph et al., P.L. ***B713*** *(12)*

Airapetian et al.,
JHEP ***0806*** *(08) 017*



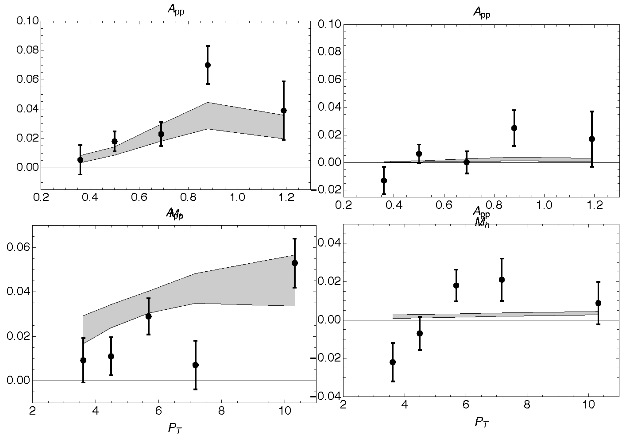


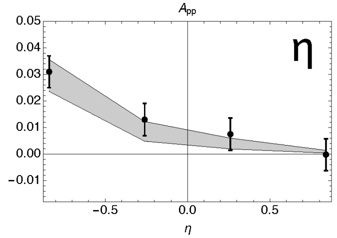
pp collisions

Adamczyk et al.,
P.R.L. ***115*** *(2015) 242501*

M_h, $\eta<0$

M_h, $\eta>0$



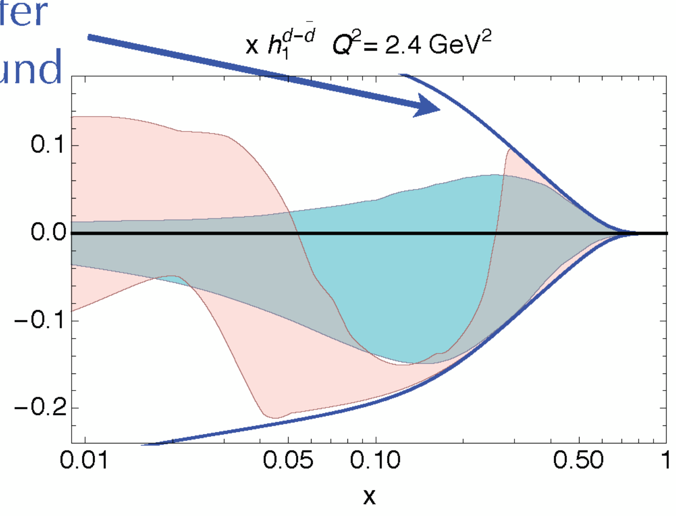


p_T, $\eta<0$

p_T, $\eta>0$

comparison with previous fit

Soffer bound



Radici & Bacchetta, P.R.L. ***120*** *(18) 192001*

down

global fit

p-p: up~down , gluon @LO
but
SIDIS: up~(8x)down , gluon @NLO

old fit

Radici et al., JHEP ***1505*** *(15)*

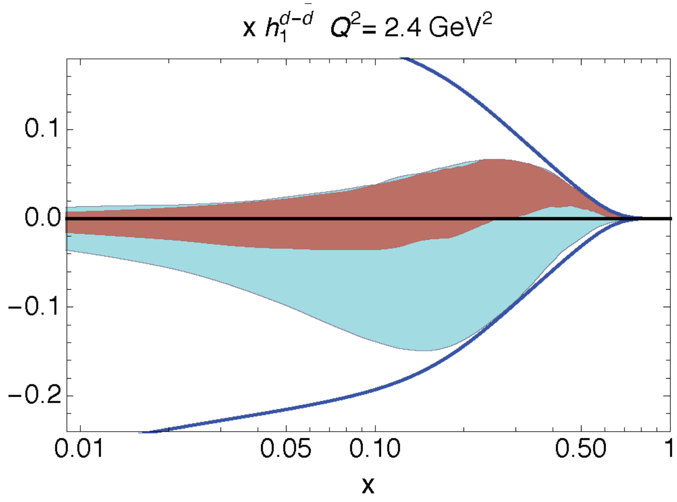
need data from target more sensitive to down : deuteron, ^{3}He …

down

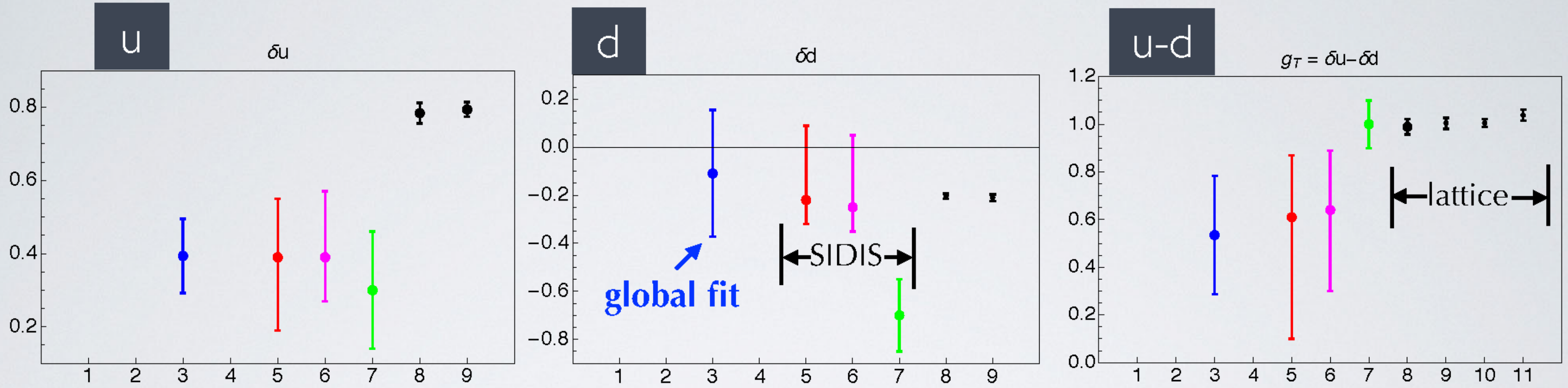
sensitive to uncertainty on gluon D_1

$$D_1{}^g(Q_0) = 0$$

$$D_1{}^g(Q_0) = \begin{cases} 0 \\ D_1{}^u/4 \\ D_1{}^u \end{cases}$$



tensor charge



no simultaneous compatibility between lattice and phenomenology

Q^2=4 GeV^2 *

JAM includes "lattice data"

Radici & Bacchetta, P.R.L. ***120*** *(18) 192001* 3) **global fit '17**

*Kang et al., P.R. D****93*** *(16) 014009* 5) **"TMD fit" * Q^2=10**

*Anselmino et al., P.R. D****87*** *(13) 094019* 6) **Torino fit * Q^2=1**

Lin et al., P.R.L. ***120*** *(18) 152502* 7) **JAM fit '17 * Q_0^2=2**

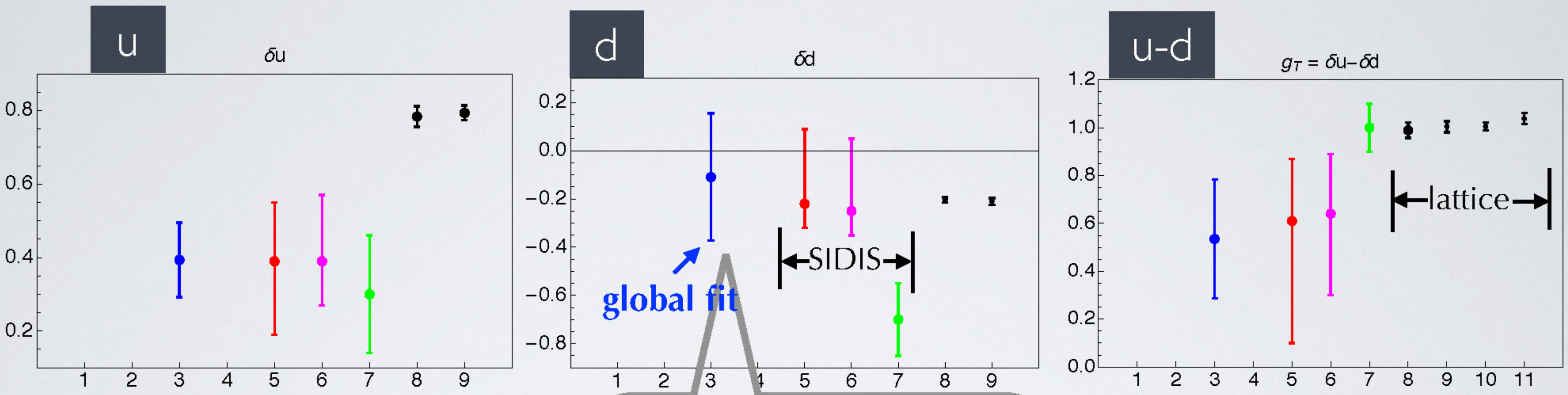
8) **PNDME '18** *Gupta et al., P.R. D****98*** *(18) 034503*

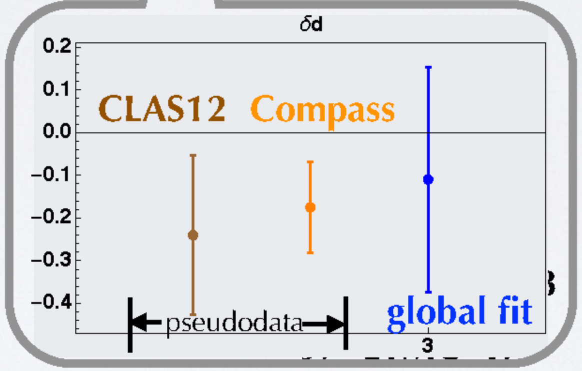
9) **ETMC '17** *Alexandrou et al., P.R. D****95*** *(17) 114514; E P.R. D****96*** *(17) 099906*

10) **RQCD '14** *Bali et al., P.R. D****91*** *(15)*

11) **LHPC '12** *Green et al., P.R. D****86*** *(12)*

tensor charge





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Radici & Bacchetta, P.R.L. ***120*** *(18) 192001* — **3) global fit '17**

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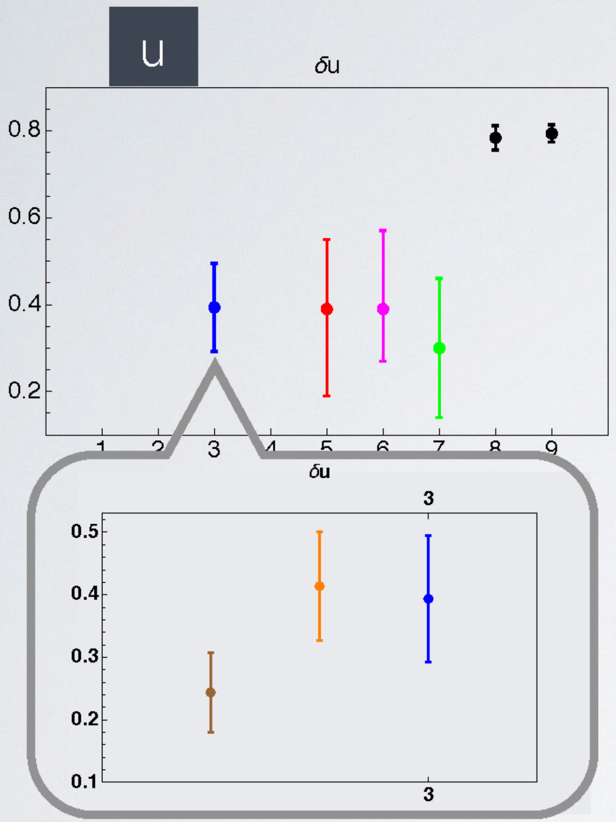
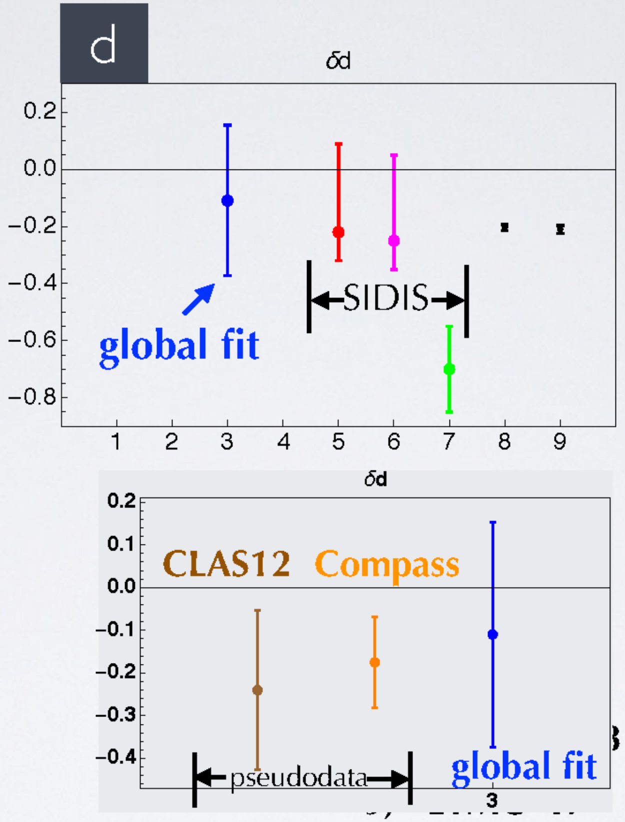
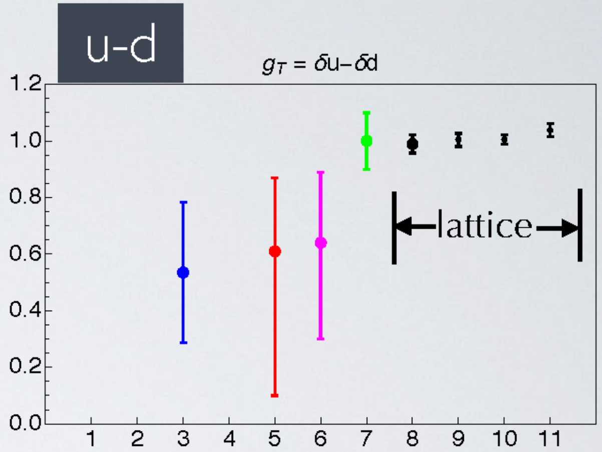
11) LHPC '12 — *Green et al., P.R. D**86** (12)*

4) SoLID — *Ye et al., P.L. B**767** (17) 91*

tensor charge







JAM includes "lattice data"

Gupta et al., P.R. D ***98*** *(18) 034503*

Alexandrou et al., P.R. D ***95*** *(17) 114514; E P.R. D* ***96*** *(17) 099906*

Radici & Bacchetta, P.R.L. ***120*** *(18) 192001* — 3) global fit '17

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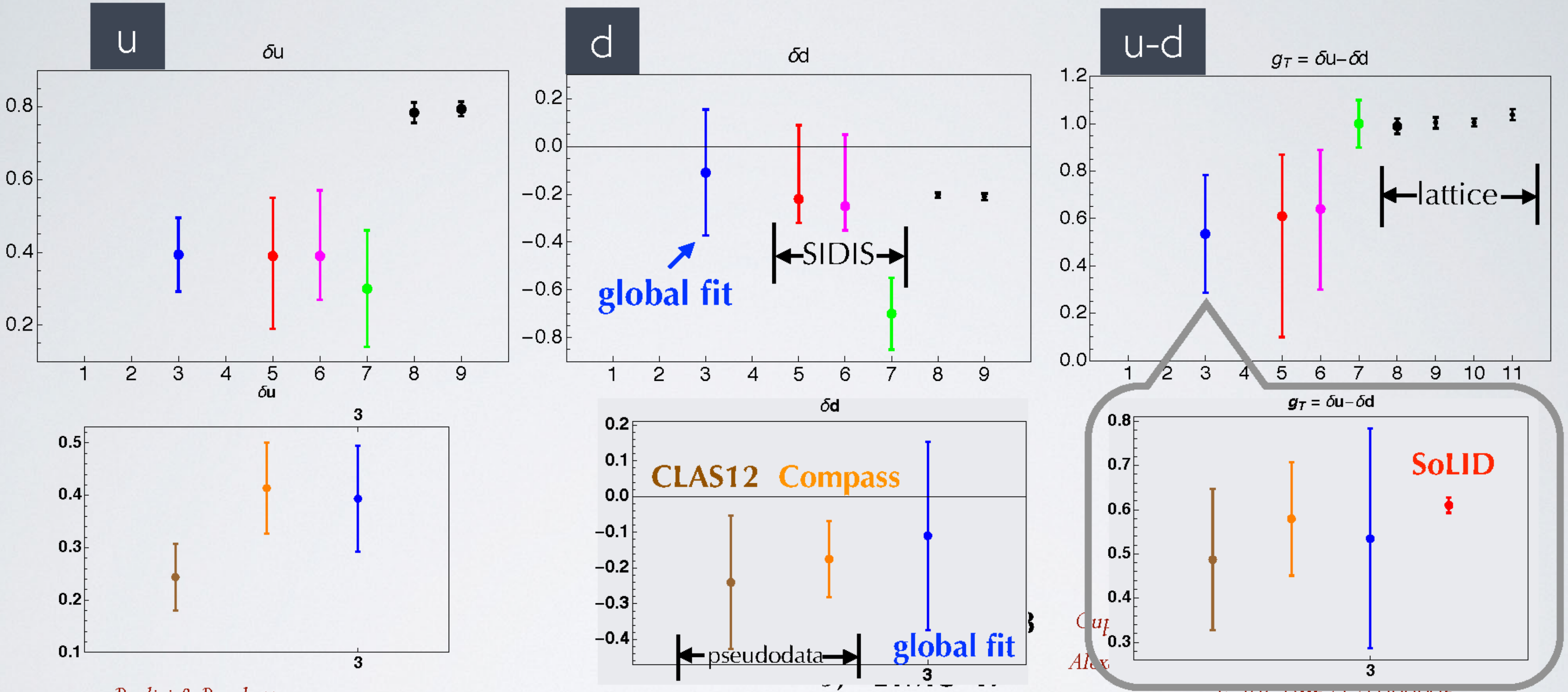
Lin et al., P.R.L. ***120*** *(18) 152502* — 7) JAM fit '17 * Q_0^2=2

tensor charge



Radici & Bacchetta, P.R.L. ***120*** *(18) 192001* — 3) global fit '17

*Kang et al., P.R. D****93*** *(16) 014009* — 5) "TMD fit" * $Q^2=10$

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Lin et al., P.R.L. ***120*** *(18) 152502* — 7) JAM fit '17 * $Q_0^2=2$

10) RQCD '14 — *Bali et al., P.R. D****91*** *(15)*

11) LHPC '12 — *Green et al., P.R. D****86*** *(12)*

4) SoLID — *Ye et al., P.L. B****767*** *(17) 91*

Conclusions / Open Problems

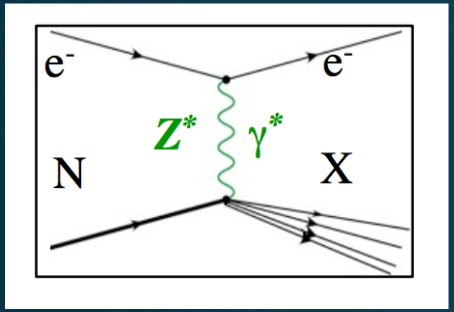
- First global fit of di-hadron inclusive data leading to extraction of **transversity as a PDF** in collinear framework
- inclusion of STAR p-p$^{\uparrow}$ data increases precision of up channel; **large uncertainty on down** due to unconstrained gluon unpolarized di-hadron fragmentation function → **need more/better "neutron target" data**
- **NO** apparent simultaneous **compatibility with lattice** for tensor charge in up, down, and isovector channels
- adding **Compass** SIDIS **pseudo-data for deuteron** increases precision of down, but leaves this scenario unaltered
- adding **CLAS12** SIDIS **pseudo-data for proton** affects large x (error of up tensor charge reduced by ~2x), but tension with lattice even increased
- it is possible to force replicas to be **compatible with data and**

enlarging the covered x-range is crucial → (target)$^{\uparrow}$ program at JLab12 !

PVDIS

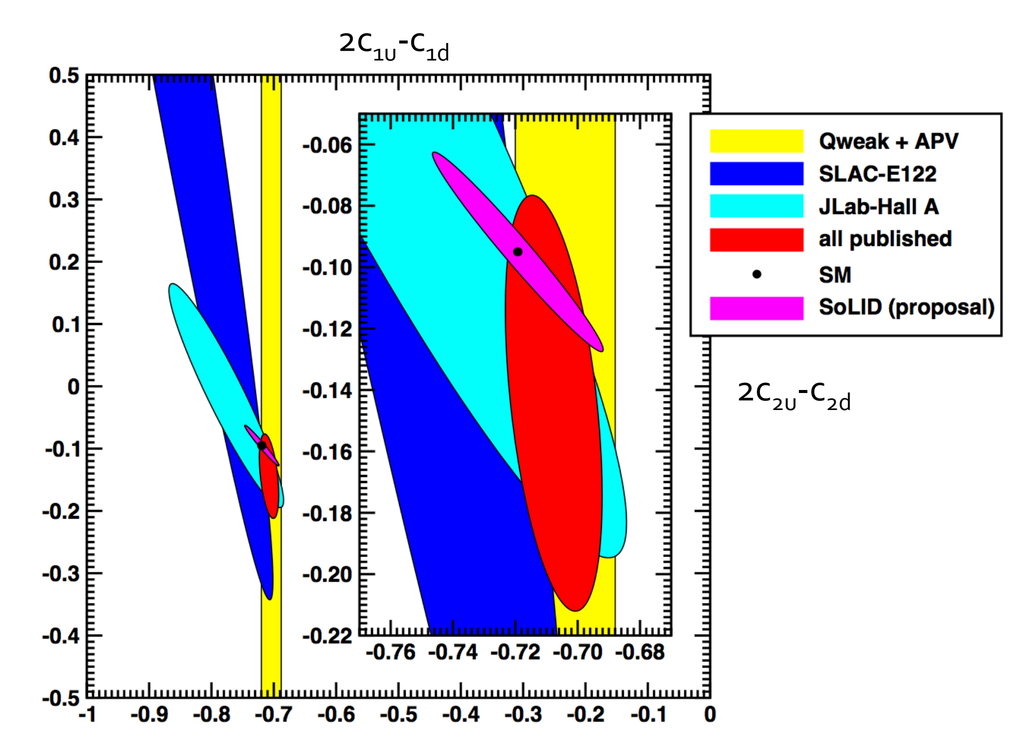
- Last update given at the previous SoLID collaboration meeting by Paul Souder

PVDIS@SoLID: Ultimate PVDIS measurement

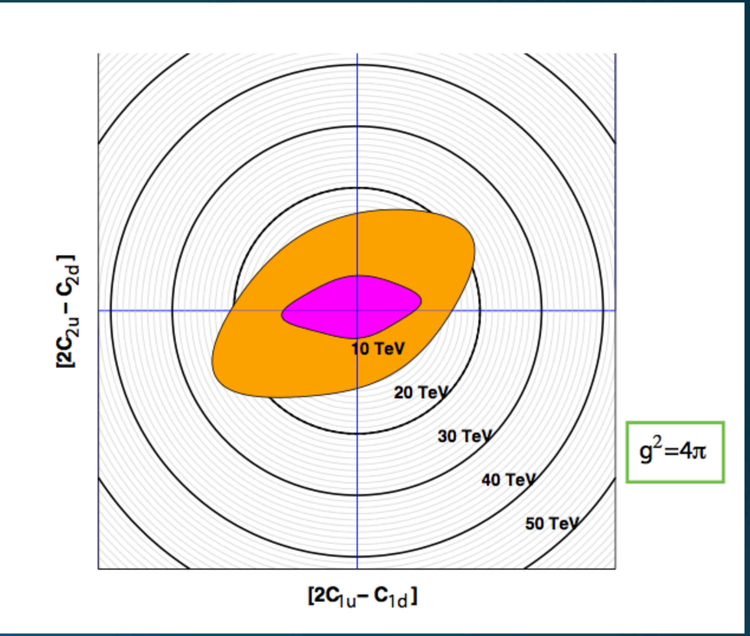


Searching for Physics Beyond the Standard Model

An asymmetry is measured: $$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$



- Sensitive to fundamental couplings $2C_{2U}$-C_{2d}
- Charge symmetry violation in the parton distribution functions
- Clean measurement of d/u ratio in the valence region



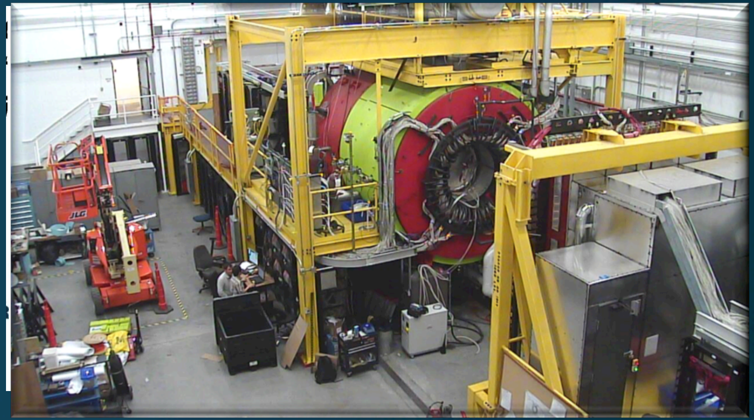
Results from the PVDIS experiment, Wang et al., Nature 506 No. 7486, 67 (2014) together with projected results from PVDIS@SoLID

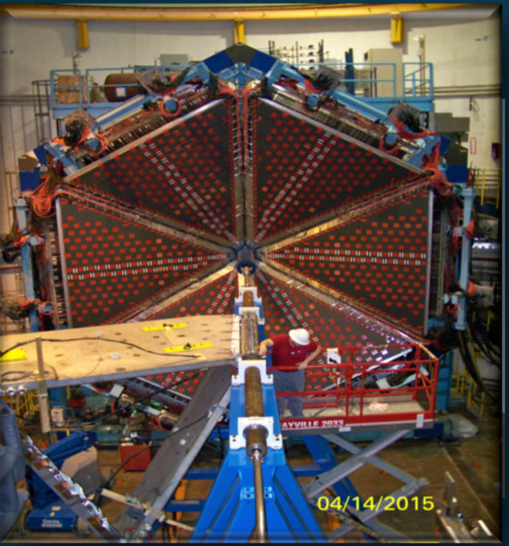
Projected mass limits for composite models.
Purple region is excluded by published data
Orange region is the projected reach with SoLID and final Qweak result

Sensitive to new physics, example: Leptophobic Z’

12 GeV J/Ψ experiments at JLab Overview

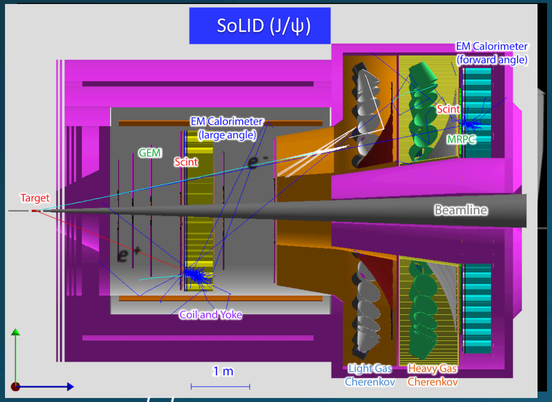
Hall D – GlueX has observed the first J/ψs at Jlab





*Hall B – Has an approved proposal to measure TCS + J/psi in phot-production **E12-12-001***

*Hall C – has an approved proposal **to search for the LHCb pentaquark E12-16-007***



*Hall A-has an approved proposal involving a future detector of high luminosity capabilities -**SoLID** **E12-12-006***

Proton Mass Decomposition useful to find the role the constituents but not unique

- Trace decomposition
  - see, e.g., [M. Shifman et al., Phys. Lett. 78B (1978), D. Kharzeev, Proc. Int. Sch. Phys. Fermi 130 (1996)]
- Rest frame decomposition
- [X.D. Ji, Phys. Rev. Lett. 74, 1071 (1995), X. D. Ji, Phys. Rev. D 52, 271 (1995)]
- Decomposition with Pressure effects
  - [C. Lorce´, Eur. Phys. J. C78 (2018) 2, arXiv:1706.05853]

More recent references

- Y. Hatta, A. Rajan and K. Tanaka, ``Quark and gluon contributions to the QCD trace anomaly,'' JHEP 1812, 008 (2018)

- Y. Hatta and D. L. Yang, ``Holographic J/psi production near threshold and the proton mass problem,'' Phys. Rev. D 98, no. 7, 074003 (2018)

- C. Lorcé, H. Moutarde and A. P. Trawiński, ``Revisiting the mechanical properties of the nucleon,'' arXiv:1810.09837 [hep-ph]

- S. Liuti, A. Rajan and K. Yagi, ``Bounds on the Equation of State of Neutron Stars from High Energy Deeply Virtual Exclusive Experiments,'' arXiv:1812.01479 [hep-ph].
- T. F. Caramés, C. E. Fontoura, G. Krein, J. Vijande and A. Valcarce, ``Charmed baryons in nuclear matter,'' Phys. Rev. D 98, no. 11, 114019 (2018)

Scale Anomaly in QCD; Trace Decomposition

D. Kharzeev Proc. Int. Sch. Phys. Fermi 130 (1996)

$$T^{\mu}_{\mu} = +\frac{\beta(g)}{2g} G^{\alpha\beta a} G^{a}_{\alpha\beta} + \sum_{l=u,d,s} m_l (1+\gamma_{m_l}) \bar{q}_l q_l + \sum_{h=c,b,t} m_h (1+\gamma_{m_h}) \bar{q}_h q_h$$

with

$$\beta(g) = -b \frac{g^3}{16\pi^2} + \ldots, \quad b = 9 - \frac{2}{3} n_h$$

At small momentum transfer, heavy quarks decouple:

$$\sum_h \bar{q}_h q_h \to -\frac{2}{3} n_h \frac{g^2}{32\pi^2} G^{\alpha\beta a} G^{a}{}_{\alpha\beta} + \ldots$$

M. Shifman et al., Phys. Lett. 78B (1978),

Only light quarks enter the expression

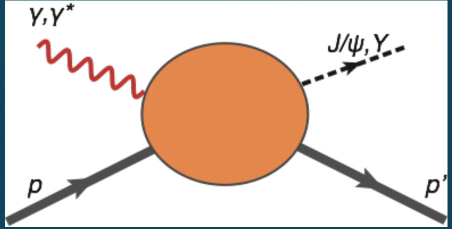
$$T^{\mu}_{\mu} = +\frac{\tilde{\beta}(g)}{2g} G^{\alpha\beta a} G^{a}_{\alpha\beta} + \sum_{l=u,d,s} m_l (1+\gamma_{m_l}) \bar{q}_l q_l$$

From the Cross section to the Trace Anomaly

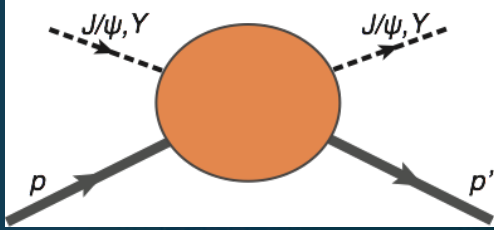
D. Kharzeev. Quarkonium interactions in QCD, 1995
D. Kharzeev, H. Satz, A. Syamtomov, and G. Zinovjev, Eur.Phys.J., C9:459–462, 1999

$$\frac{d\sigma_{\gamma N\to\psi N}}{dt}(s,t=0)=\frac{3\Gamma(\psi\to e^+e^-)}{\alpha m_\psi}\left(\frac{k_{\psi N}}{k_{\gamma N}}\right)^2\frac{d\sigma_{\psi N\to\psi N}}{dt}(s,t=0)$$

$$\frac{d\sigma_{\psi N\to\psi N}}{dt}(s,t=0)=\frac{1}{64\pi}\frac{1}{m_\psi^2(\lambda^2-m_N^2)}|\mathcal{M}_{\psi N}(s,t=0)|^2$$

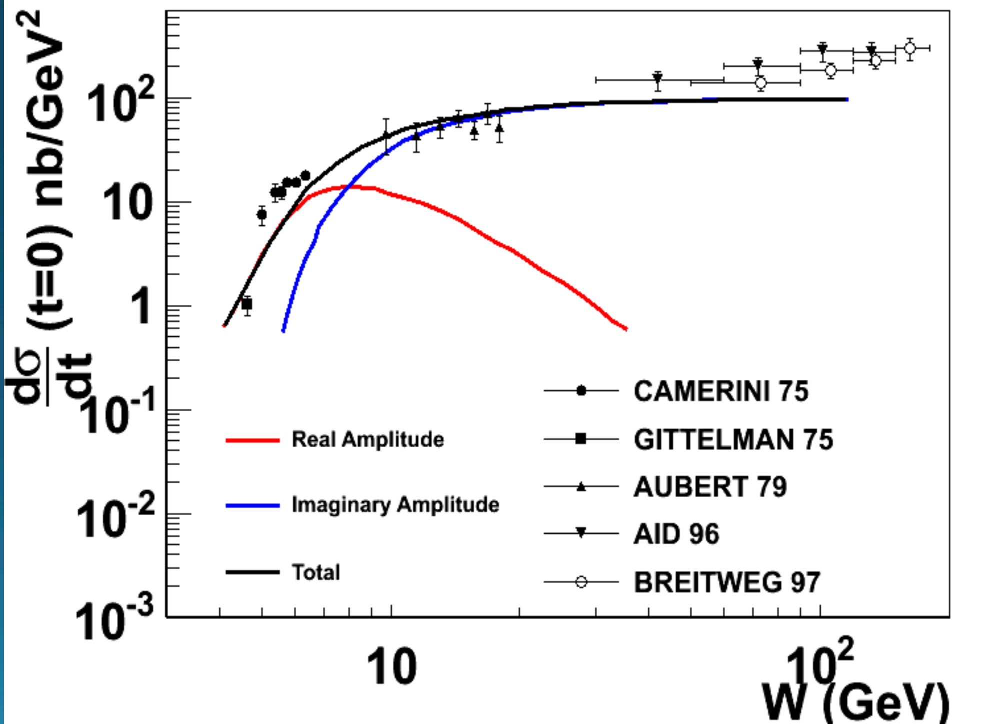


VDM



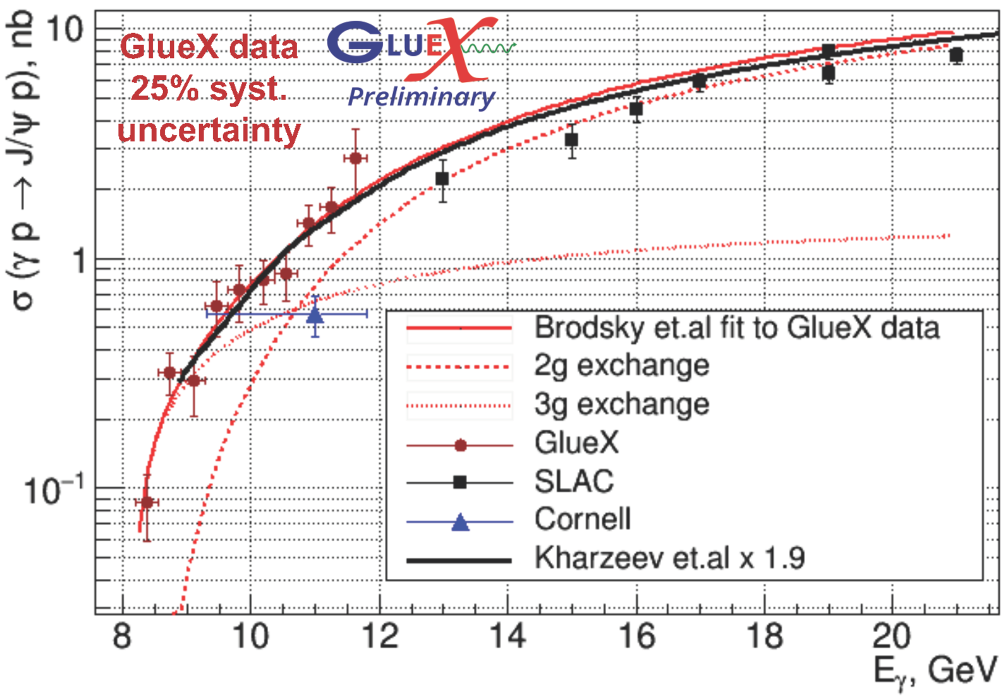
- VMD relates photo-production cross section to quarkonium-nucleon scattering amplitude $M_{\psi p}$
- **Imaginary part** is related to the total cross section through optical theorem
- **Real part contains the conformal (trace) anomaly**
  - Dominate the near threshold region and constrained through dispersion relation

A measurement near threshold could allow access to the trace anomaly



Hall D results at threshold

Preliminary results: comparison to theory

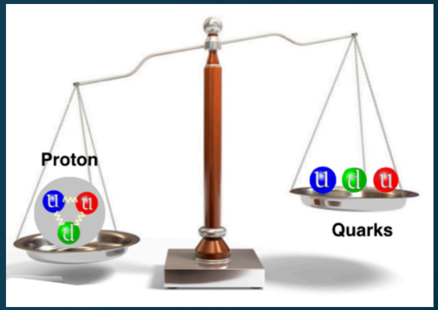


Brodsky at.al (2001)
fit of the GlueX data ONLY, with 2g and 3g shapes using F(t) as t-dependence

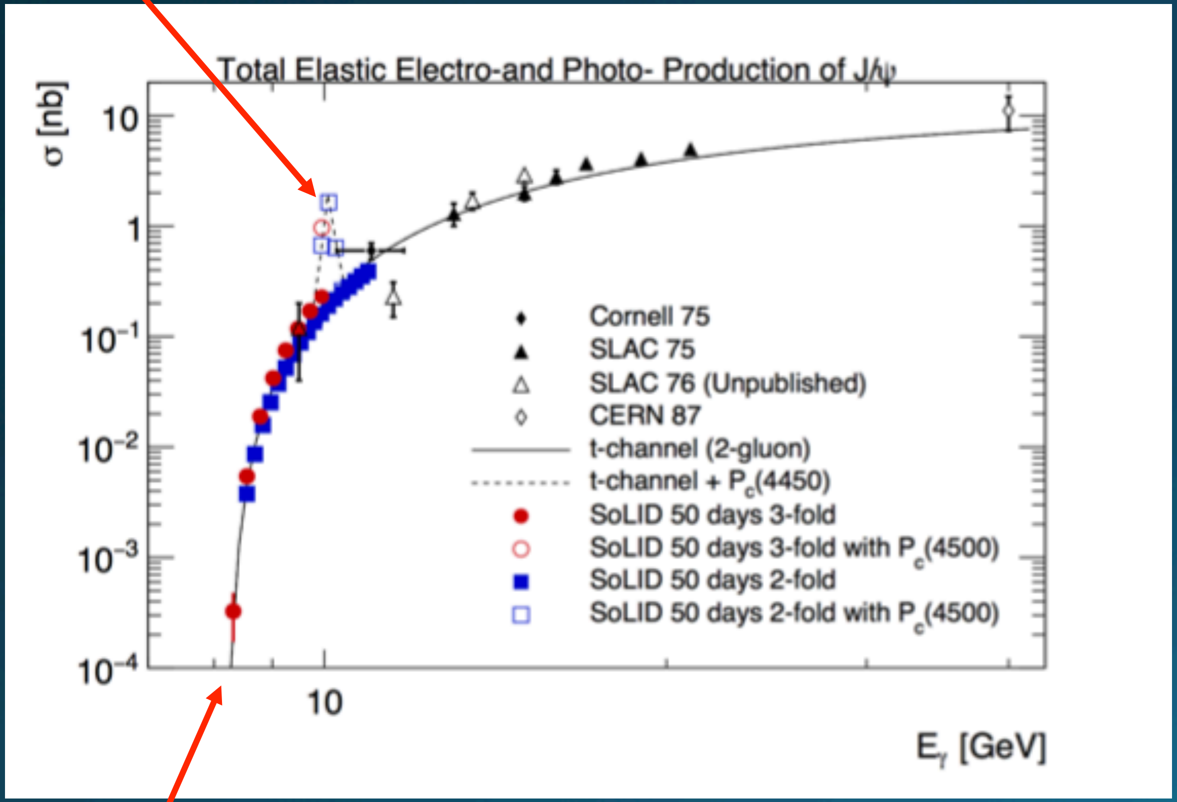
Kharzeev et.al (1999)
absolute (factor 2-3 uncertainty) perturbative calculations using PDFs - related to the gluonic contribution to the mass of the proton

J/Psi@ SoLID; The threshold region, the mass of the proton and the LHCb charmed pentaquark

- Measure the contribution of the gluons to the mass of the proton directly.
- Poduce and determine the quantum numbers of the LHCb pentaquark if it exist.



LHCb Pentaquark production



Threshold

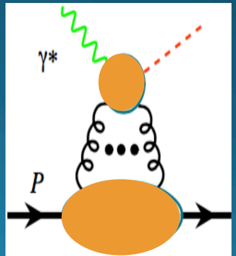
How does QCD generate the mass of the proton?

- Trace of the QCD energy-momentum tensor:

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

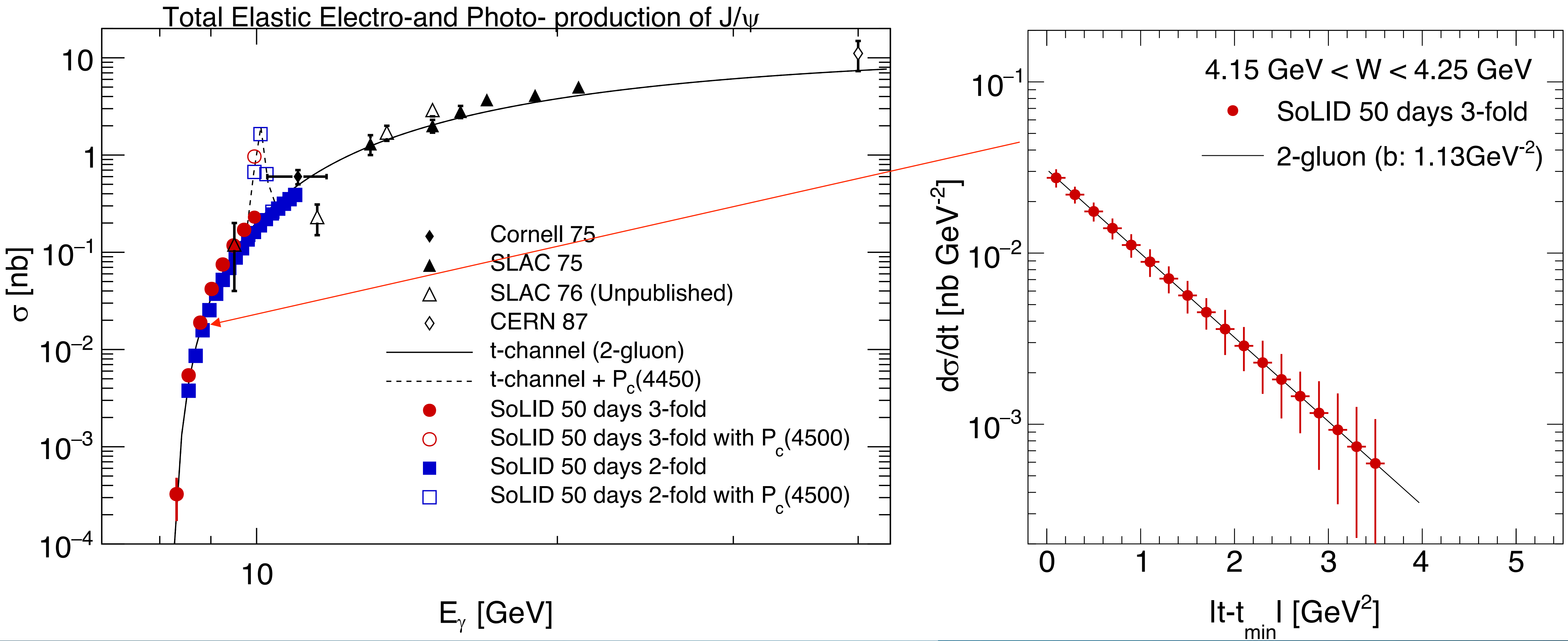
$$\beta(g) = -(11 - 2n_f/3) g^3/(4\pi)^2 + \ldots$$

J/Ψ , Υ, ...



Heavy quarkonium production near the threshold, from JLab12 to EIC

J/Psi Experiment E12-12-006 @ SoLID



Sensitivity below 10^{-3} nb!

Binding energy of the J/ψ - nucleon potential

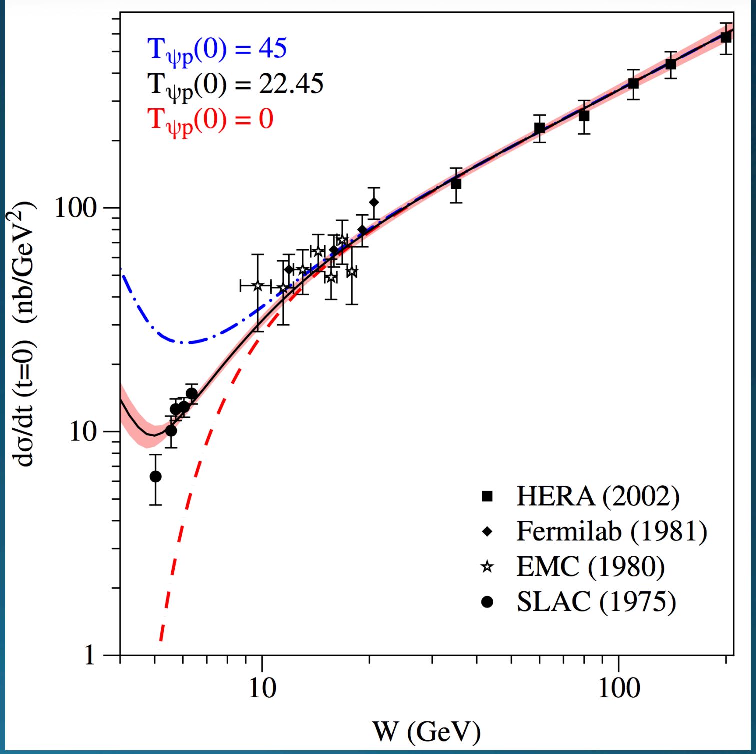
- Color neutral objects:
  gluonic Van der Waals force
  - At threshold, spin-averaged scattering amplitude related to s-wave scattering length $a_{\psi p}$
  - Binding $B_{\psi p}$ can be derived from $a_{\psi p}$

$$T_{\psi p} = 8\pi(M + M_\psi)a_{\psi p}$$

  - Estimates between 0.05-0.30 fm, corresponding to $B_{\psi p}$ < 20 MeV
  - LQCD: $B_{\psi p}$ < 40 MeV S. R. Beane *et al.*, Phys. Rev. D 91, 114503 (2015)
  - Recent fit to existing data in a dispersive framework:
    - $a_{\psi p}$ ~ 0.05 fm ($B_{\psi p}$ ~ 3 MeV in nuclear matter)

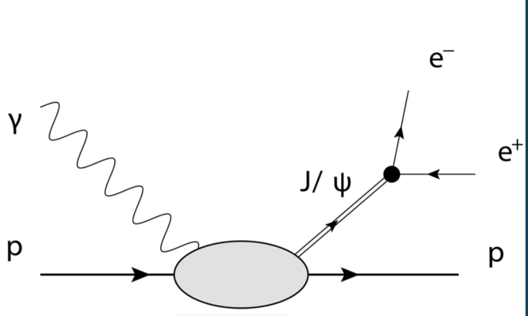
O. Gryniuk and M. Vanderhaeghen, Phys. Rev. D 94, 074001 (2016)

- Photo-production near threshold constrained through dispersion relations, not data
- **Threshold experiments needed!**

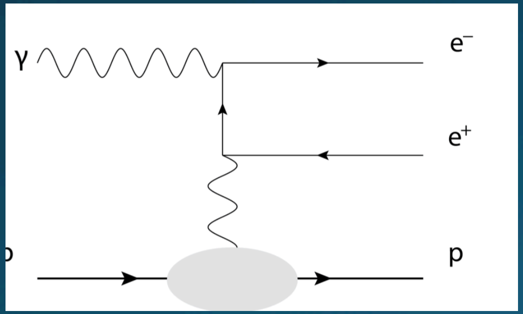


B-H asymmetry: access scattering length $a_{\psi p}$

- Interference between elastic J/ψ production near threshold and Bethe-Heitler
- Forward-backward asymmetry near the J/ψ invariant mass peak
- Sensitive to real part of the scattering amplitude, hence $a_{\psi p}$ and $B_{\psi p}$



J/ψ

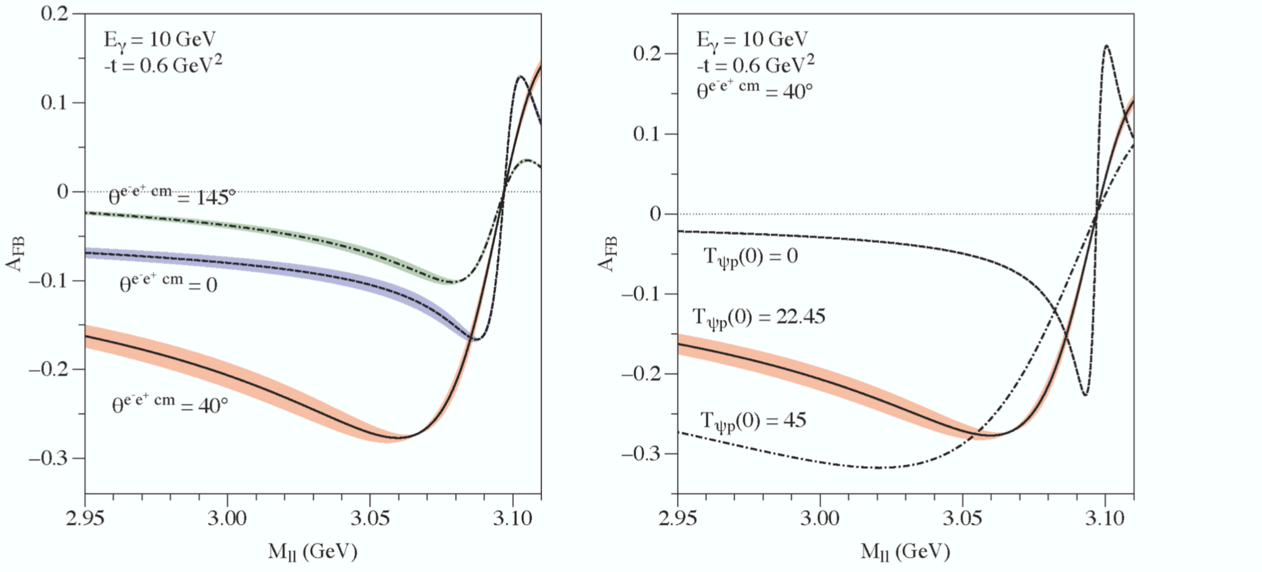


B-H

interference term

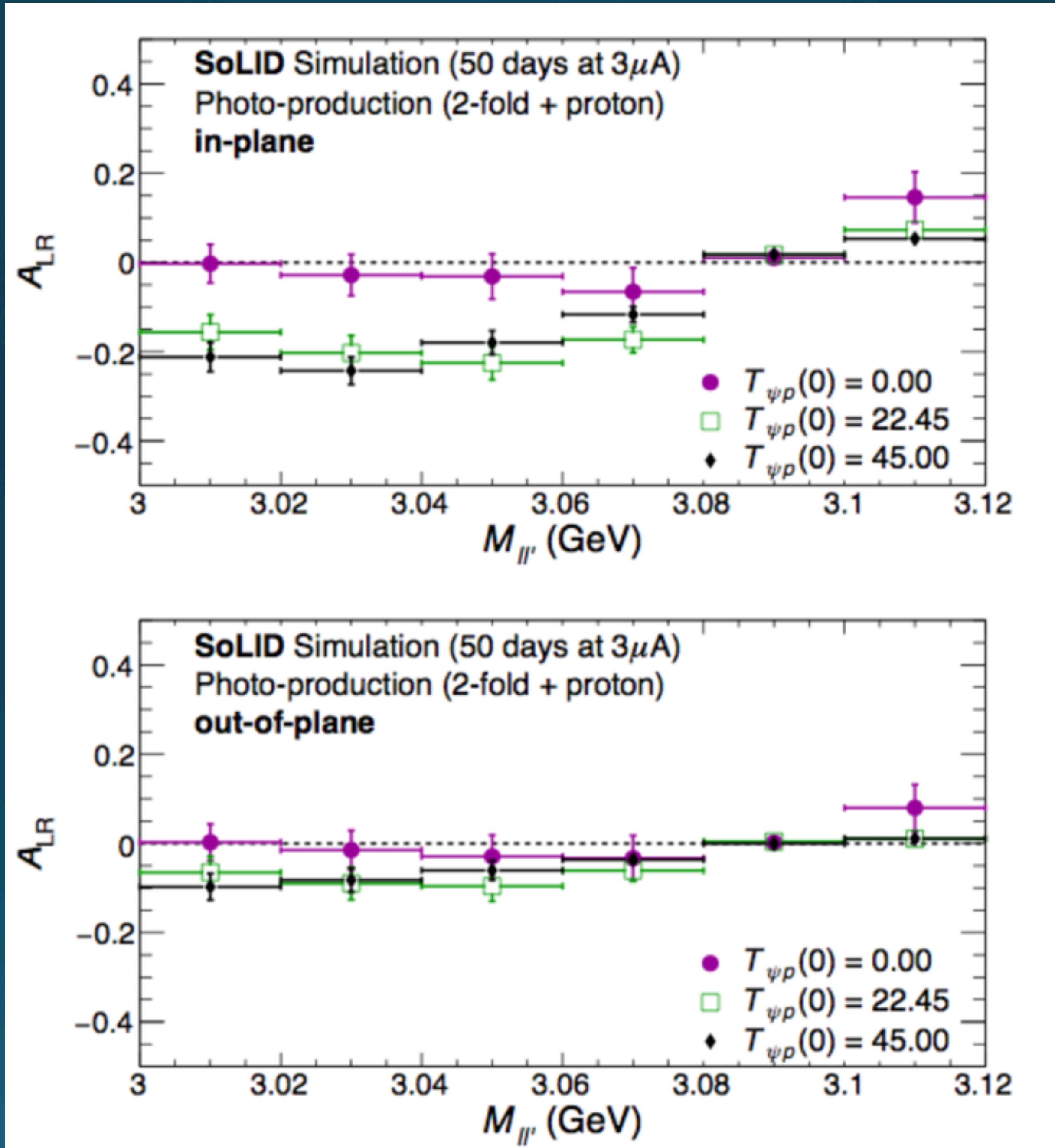
$$\boxed{A_{\mathrm{FB}} \equiv \frac{\frac{d\sigma}{d\Omega}(\theta_{cm}) - \frac{d\sigma}{d\Omega}(\theta_{cm}-\pi)}{\frac{d\sigma}{d\Omega}(\theta_{cm}) + \frac{d\sigma}{d\Omega}(\theta_{cm}-\pi)}} = \frac{\sum_s 2\,\mathrm{Re}T_\psi\, T_{BH}}{\sum_s |T_\psi|^2 + \sum_s |T_{BH}|^2}$$

θ_{cm} — scattering angle in a lepton pair CM frame



Slide from O. Gryniuk

LOI


SoLID Simulation (50 days at 3μA)
Photo-production (2-fold + proton)
in-plane
A_{LR}
0.4
0.2
0
−0.2
−0.4
3
3.02
3.04
3.06
3.08
3.1
3.12
$M_{ll'}$ (GeV)
$T_{\psi p}(0) = 0.00$
$T_{\psi p}(0) = 22.45$
$T_{\psi p}(0) = 45.00$
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Summary

- SoLID science program is rich and impactful and leads naturally to the EIC science program.
- SoLID complements well the 12 GeV existing science tools but takes advantage of the full potential the 12 GeV upgrade offers.
- The key factors are luminosity and acceptance.