Summary of Pre-town Meeting on SPIN Physics at future Electron Ion Collider

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Zhongbo Kang

September 13, 2014

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Pre-town meeting at Jefferson Lab

- ## Meeting

  August 13 - 15, 2014
  Thomas Jefferson National Accelerator Facility

- ## Goals

  The goal of this meeting was to have a critical number of scientists from the Spin physics community gathered with the purpose to update and sharpen our message as it relates to the case for the Electron Ion Collider in the USA

- ## Participants

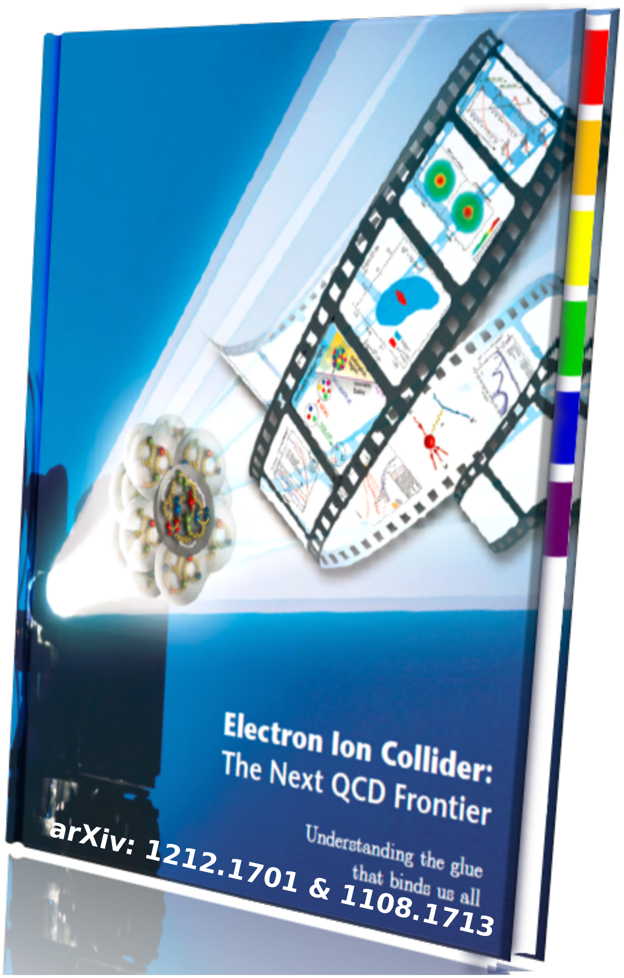
  44 scientists from JLab, BNL, LBNL, LANL, SLAC and other labs and universities including 6 remote participants from Europe

- ## Results

  http://www.jlab.org/conferences/pretownjlab2014/

Electron Ion Collider in the USA

Broad agreement of the Spin physics community that the next facility should be Electron Ion Collider



Explore "sea" quark and gluon dominated region.

From the White Paper:

– High luminosity up to

$$L \sim 10^{34}\ (\mathrm{cm}^{-2}\mathrm{s}^{-1})$$

– Variable energy range

$$\sqrt{s} = \sim 20 \text{ to } \sim 100\ (\mathrm{GeV})$$

– Polarized, longitudinally and transversely, for the proton and light-ions

– Unpolarized heavy-ion beams

– wide acceptance detector and good PID

EIC White Paper (2012) is an excellent summary of EIC physics

The goal of the meeting was to review progress in the last 2 years in SPIN physics and “3-D” structure of the nucleon

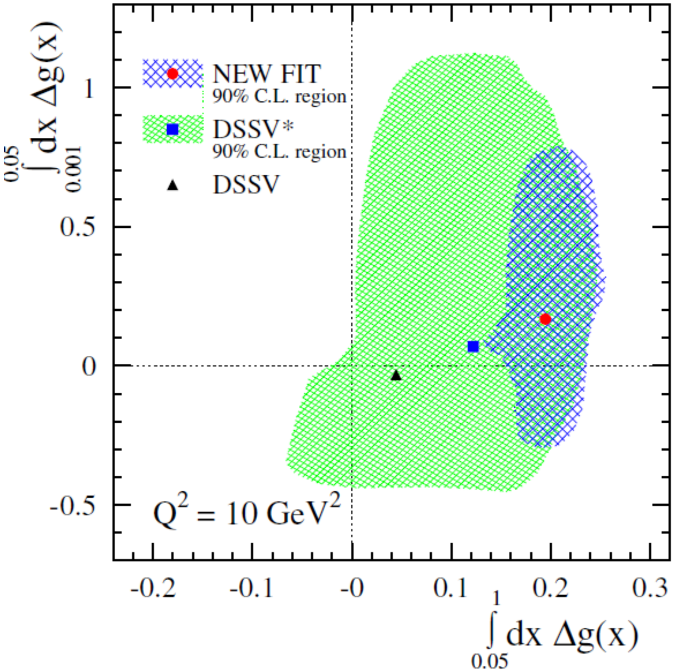
Helicity structure at EIC

W. Vogelsang
E. Aschenauer
W. Melnitchouk
E. Sichtermann
J. Qiu
Many others

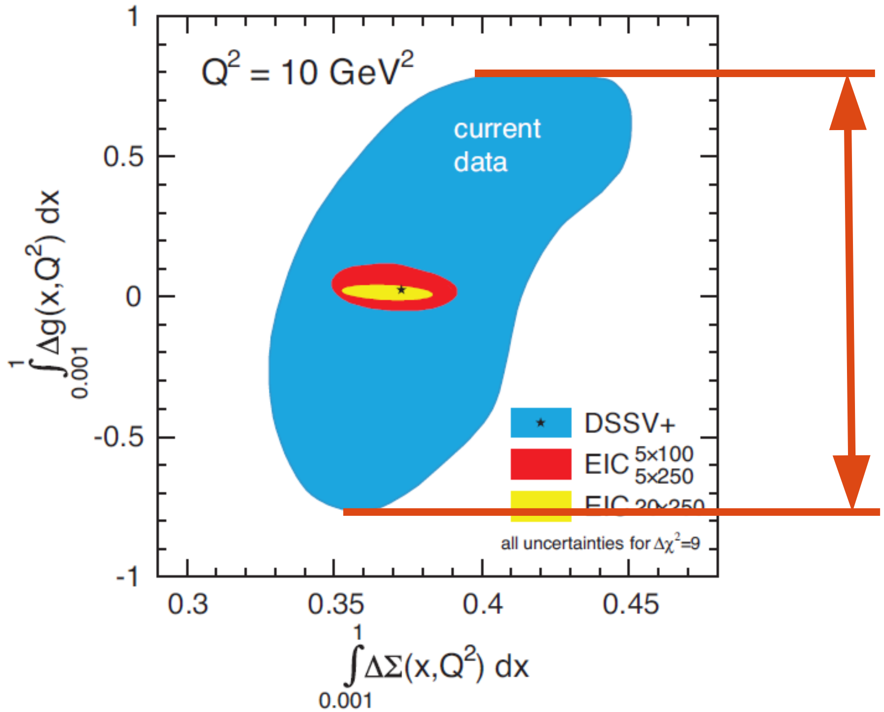
Without EIC we will never have a good quantitative knowledge of Spin decomposition of the nucleon

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

Current knowledge



PRL 113, 012001 (2014)



EIC White Paper

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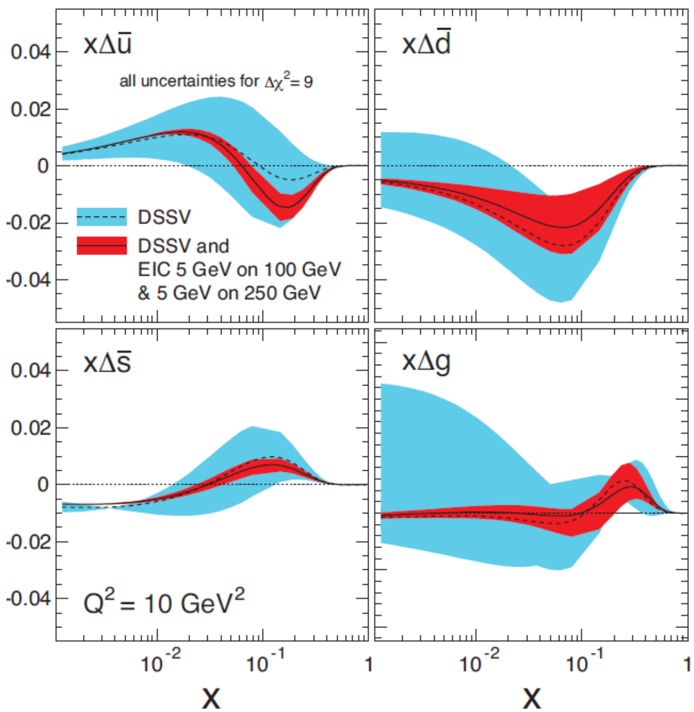
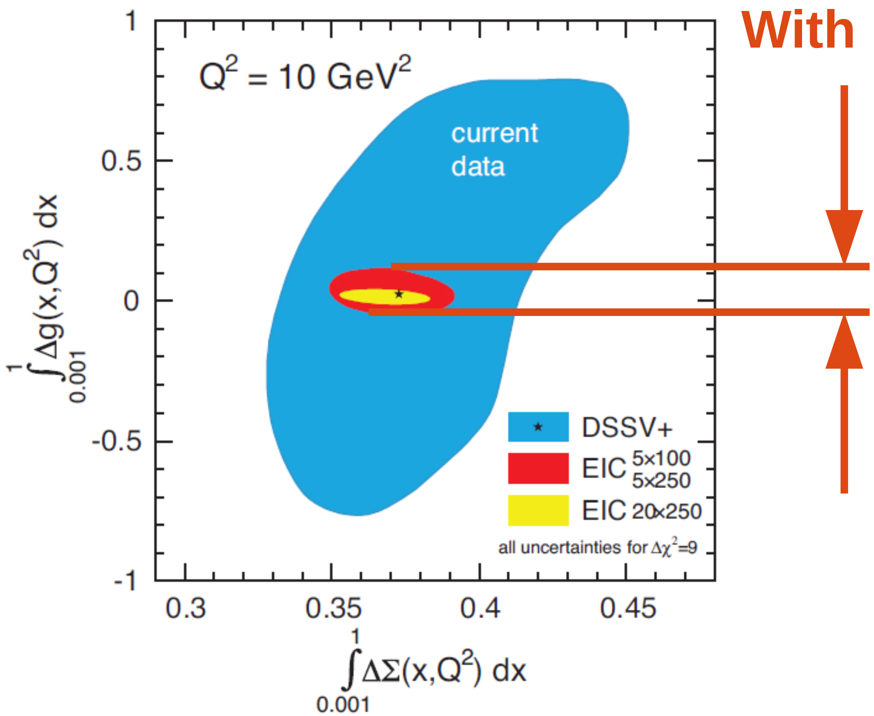


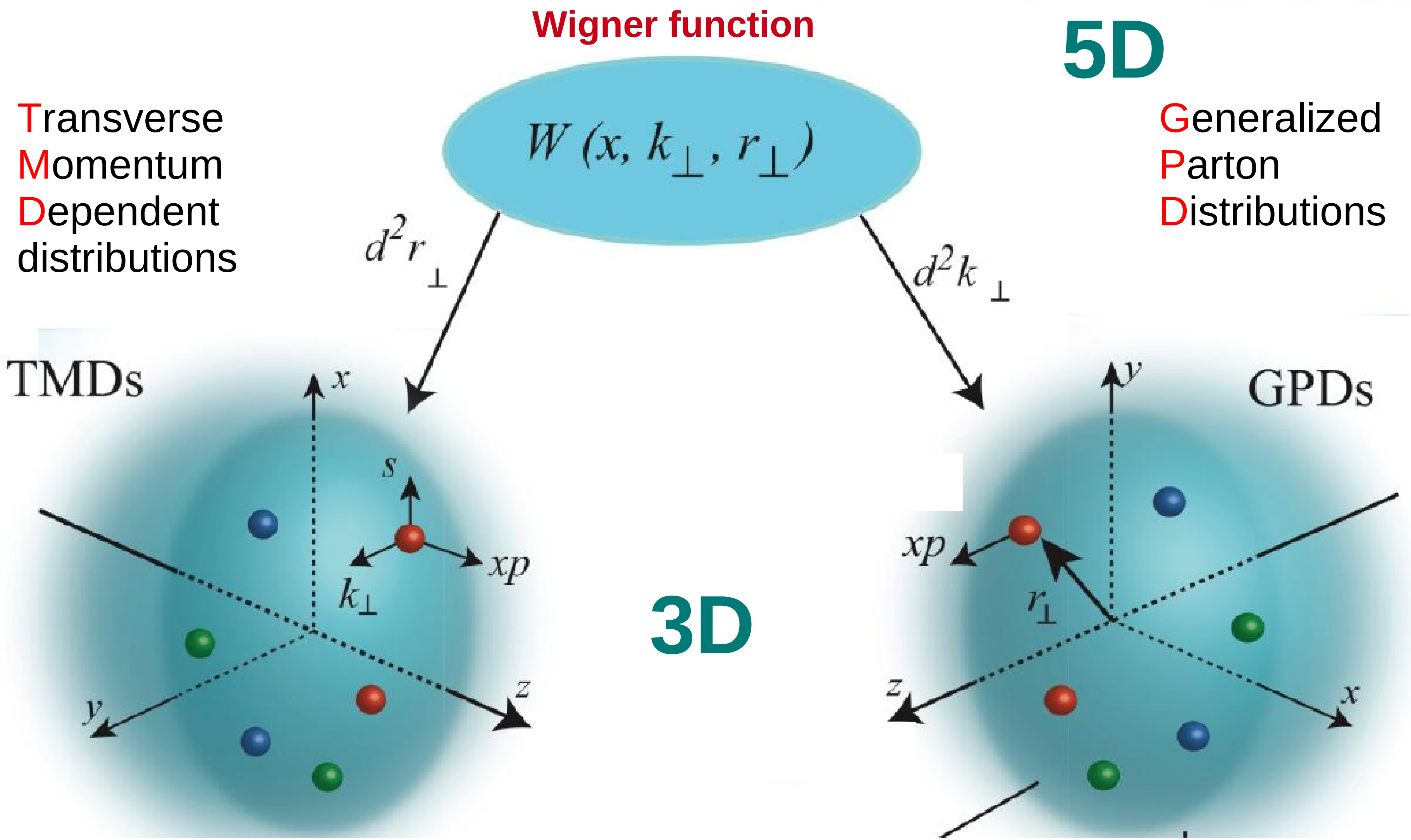


With EIC

Also functions, not only integrated quantities
No other facility in the World can do it!

3D structure of the nucleon

F. Yuan
C. Weiss
M. Burkardt
X. Ji
A. Radyushkin
Many others



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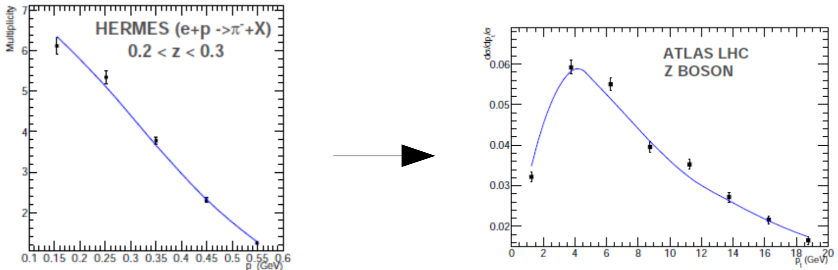
TMDs

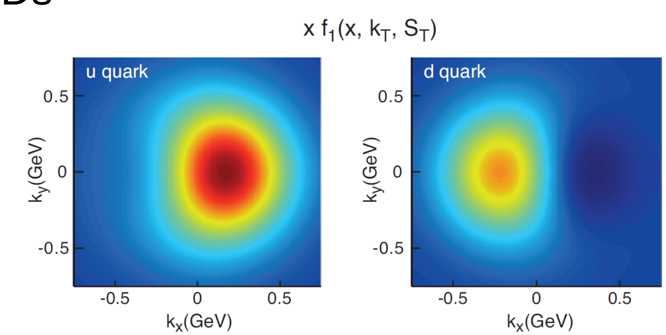
Enormous progress of understanding of evolution. We are able to span energies of JLab 6 GeV up to LHC

$$\sqrt{s} \sim 7 \text{ GeV} \qquad \sqrt{s} \sim 7 \text{ TeV}$$



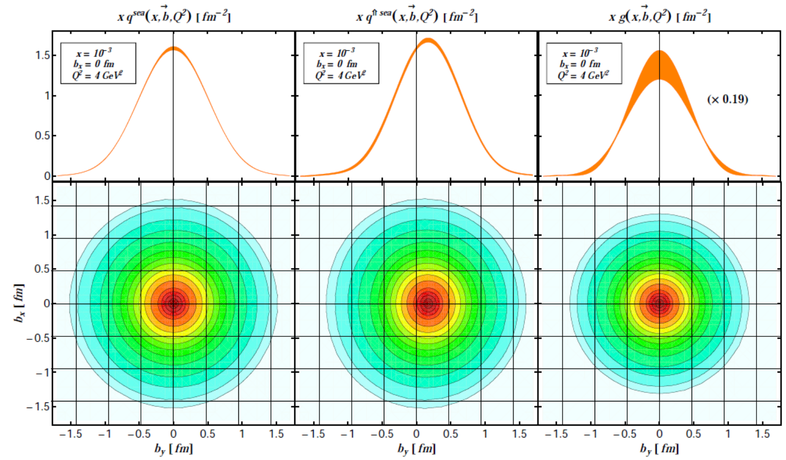
arXiv:1406.3073

Publication by JLab, HERMES, COMPASS data on multiplicities is an essential step forward towards better understanding of TMDs



GPDs

Important progress of analysis of EIC impact



JHEP 1309 (2013) 093

3D structure of the nucleon

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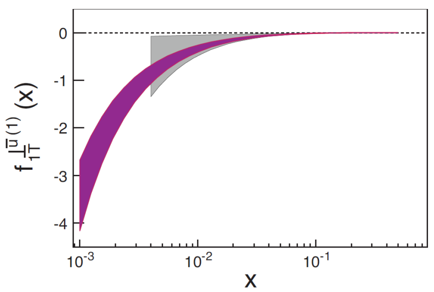
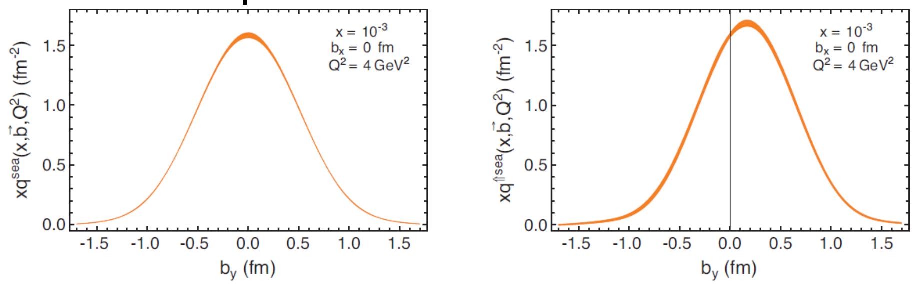
Data of EIC is essential for our understanding of hadron structure in the regime dominated by “sea” quarks and gluons

$\bar{u}$ TMD Sivers function at EIC



Sea quark GPD functions at EIC



Progress of lattice QCD and other non-perturbative methods is very encouraging and is complementary to our experimental goals of EIC

We are going to discover new phenomena and new structures associated with hadron dynamics

Spin physics community is thrilled about the prospect of building an Electron Ion Collider in the USA

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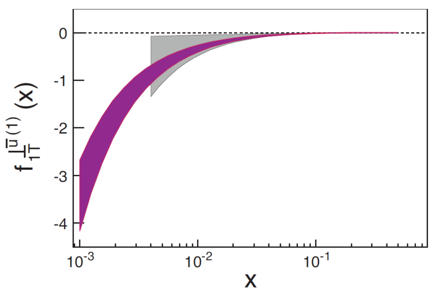

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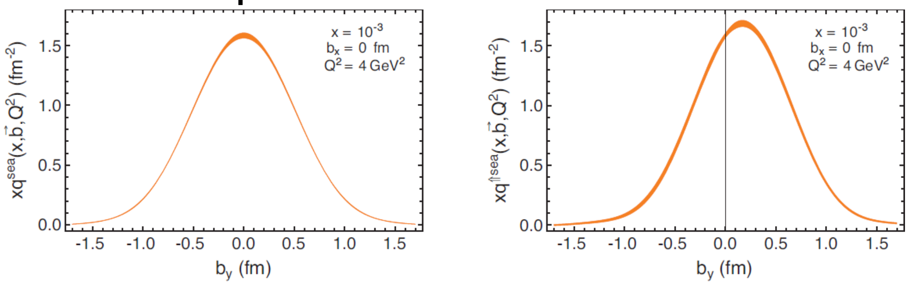

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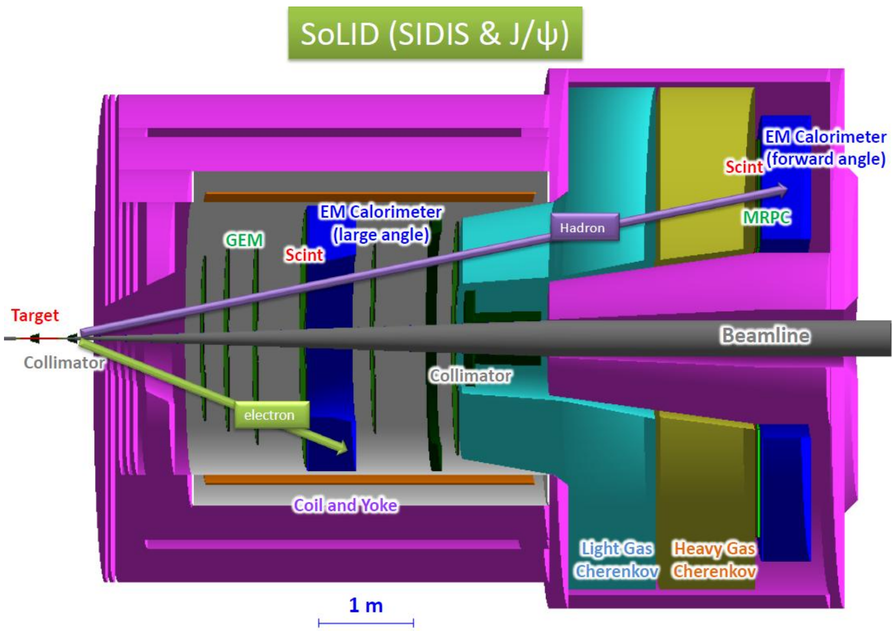
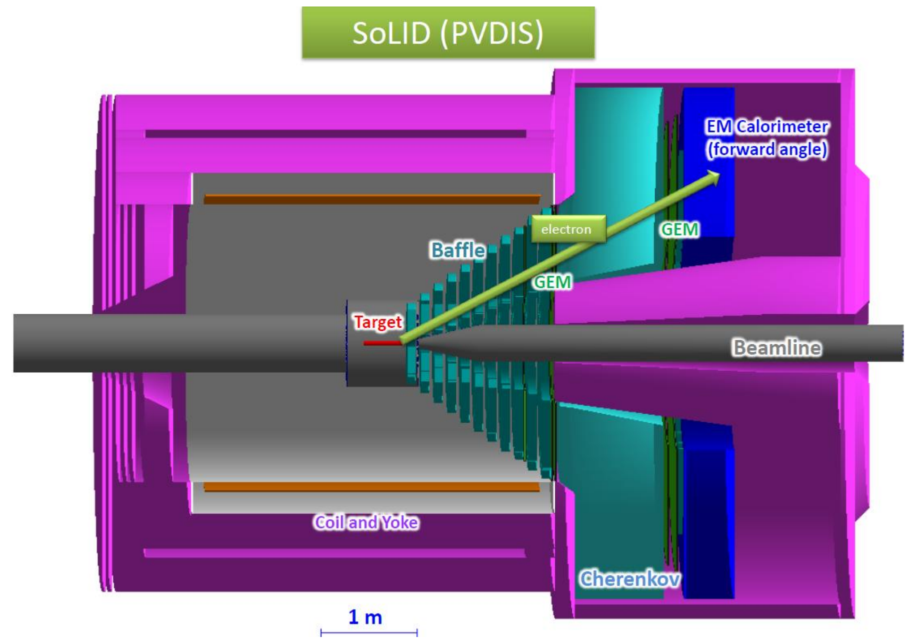
THANK YOU!

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 and threshold J/ψ
- **5 highly rated experiments approved**
  Three SIDIS experiments, one PVDIS, one J/ψ production
  Bonus: di-hadron, Inclusive-SSA, and much more …
- **Strong collaboration** (200+ collaborators from 50+ institutes, 11 countries)
  Significant international contributions

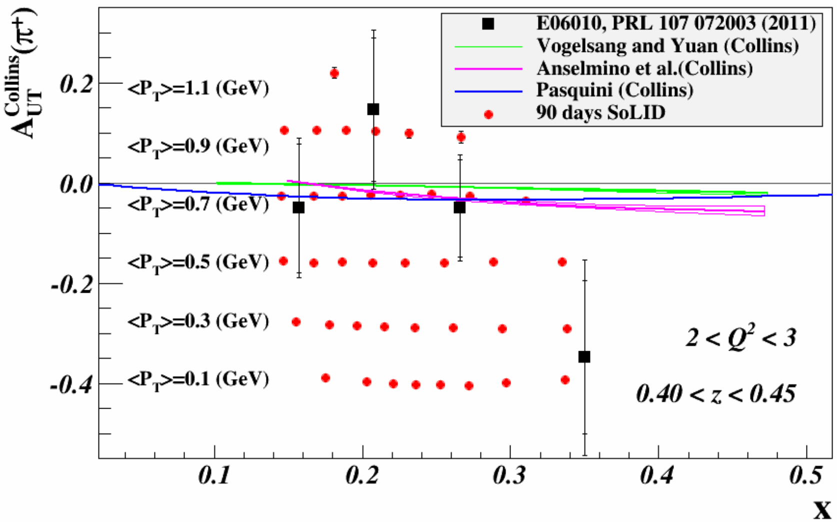




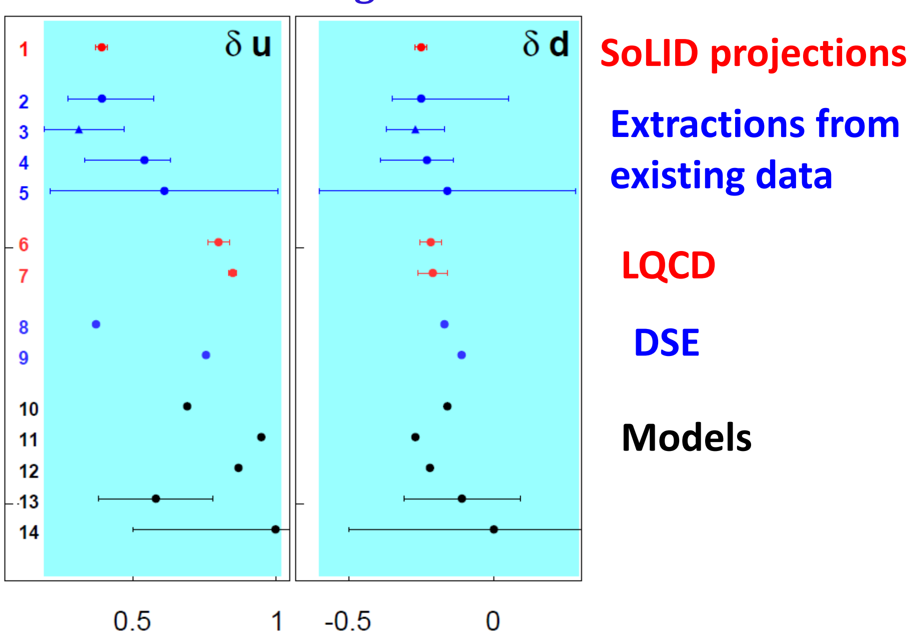
Nucleon Structure with SoLID-SIDIS

Semi-inclusive Deep Inelastic Scattering *program*:
Large Acceptance + High Luminosity
+ Polarized targets
→ **4-D** mapping of **Collins**, Sivers, and pretzelocity asymmetries,…
→ Tensor charge of quarks, **transversity** distributions, **TMDs**…
→Benchmark test of Lattice QCD, probe QCD Dynamics and quark orbital motion

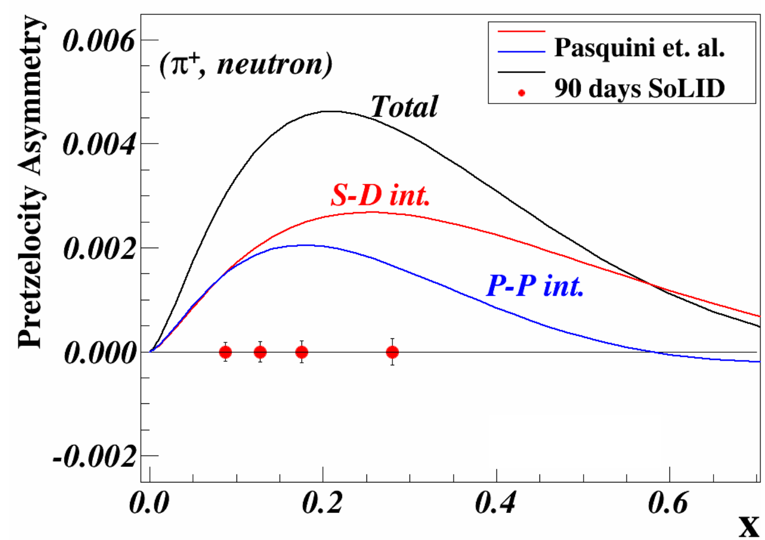
Collins Asymmetry *Total > 1400 points*



Tensor Charges



Pretzelosity → information on OAM

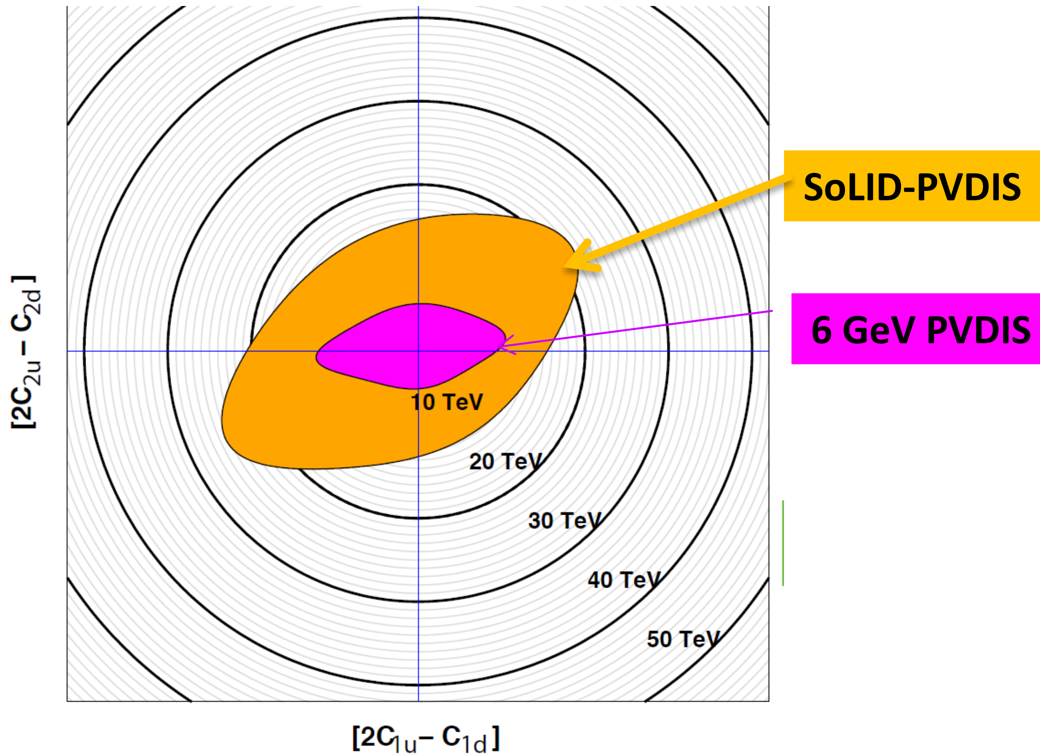


Parity Violation with SoLID

Parity-violating Deep Inelastic Scattering:

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

Presentation by P. Souder and K. Kumar



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 (LHC scale)

SoLID-J/ψ: Study Non-Perturbative Gluons

Presentation by Z. Zhao

J/ψ: ideal probe of non-perturbative gluon

The high luminosity & large acceptance capability of SoLID enables a unique "precision" measurement near threshold

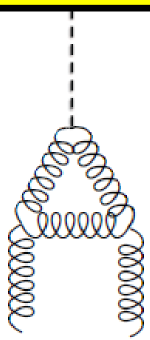
- **Shed light on the low energy J/ψ-nucleon interaction (color Van der Waals force)**
- **Shed light on the 'conformal anomaly' an important piece in the proton mass budget:**

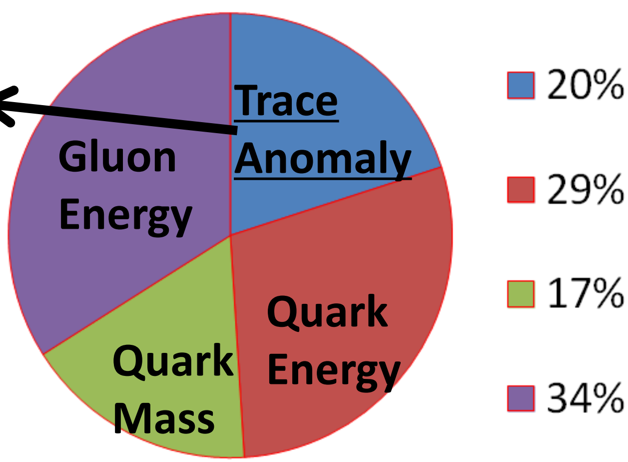
Models relate J/ψ enhancement to trace anomaly

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

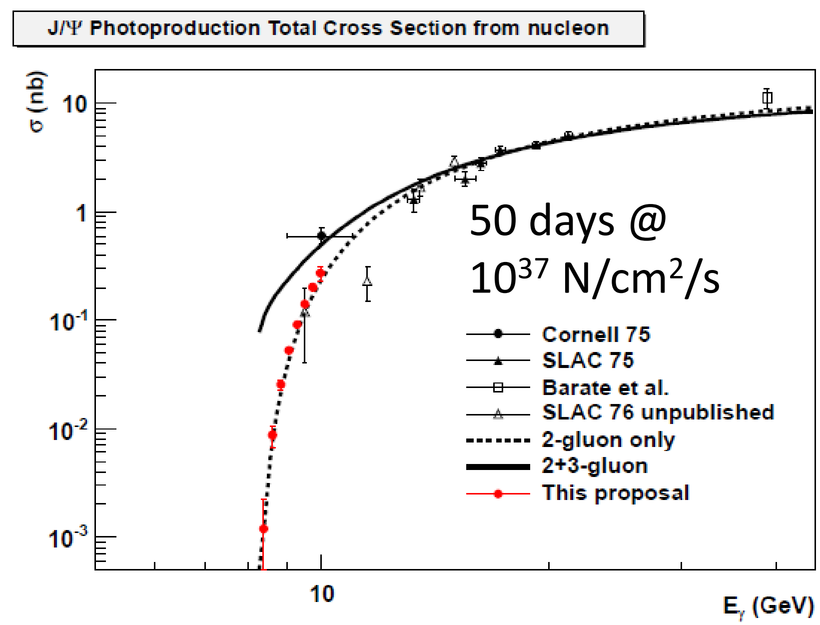
Proton Mass Budget

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





X. Ji PRL 74 1071 (1995)



SoLID Timeline and Status

- 2010-2012 Five SoLID experiments approved by PAC (4 A, 1 A- rating)

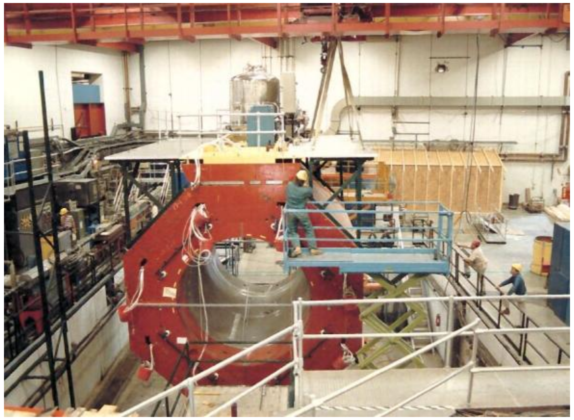
    3 SIDIS with polarized ^{3}He/p target, 1 **PVDIS**, 1 **threshold J/ψ**

- 2013: **CLEO-II magnet formally requested and agreed**
- 2014: Site visit, plan transportation to JLab (2016)

2010-2014: Progress

- **Spectrometer magnet, modifications**
- **Detailed simulations**
- **Detector pre-R&D**
- **DAQ**

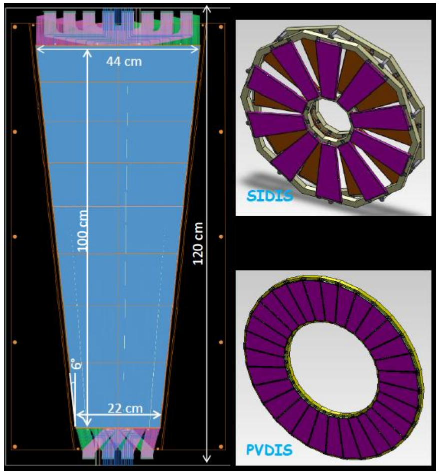
✓ 2014: **pre-CDR submitted** for JLab Director's Review



CLEO-II magnet

Active collaboration,
200+ physicists from 50+ international institutions

Draft funding profile includes significant international contributions (China)



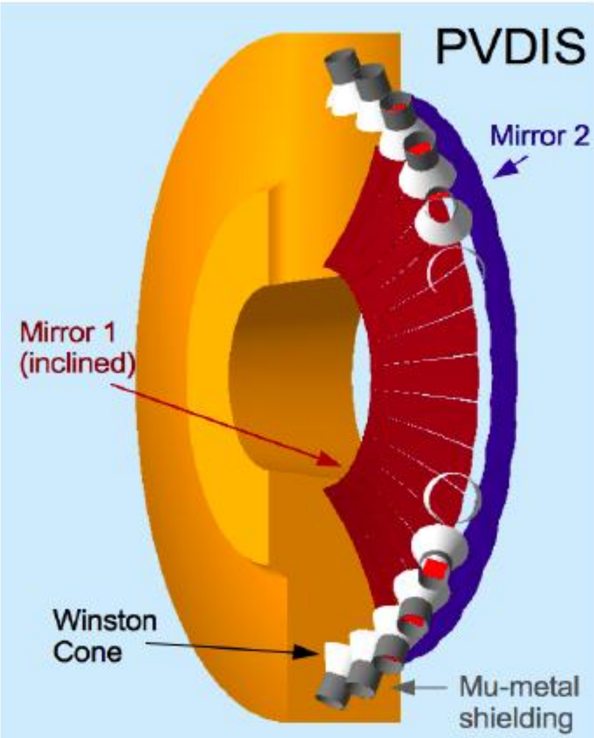
GEM R&D
China/UVa

Backup

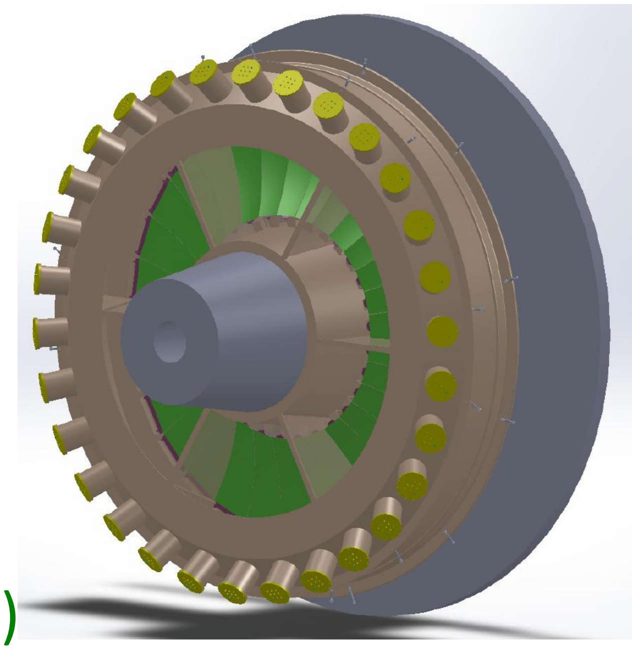
Progress in Detectors
SIDIS/TMD Program

SoLID Detector Development

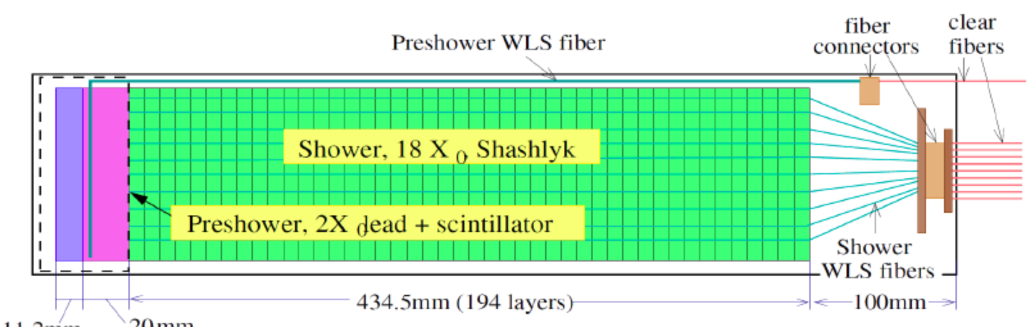
Simulations now with realistic backgrounds



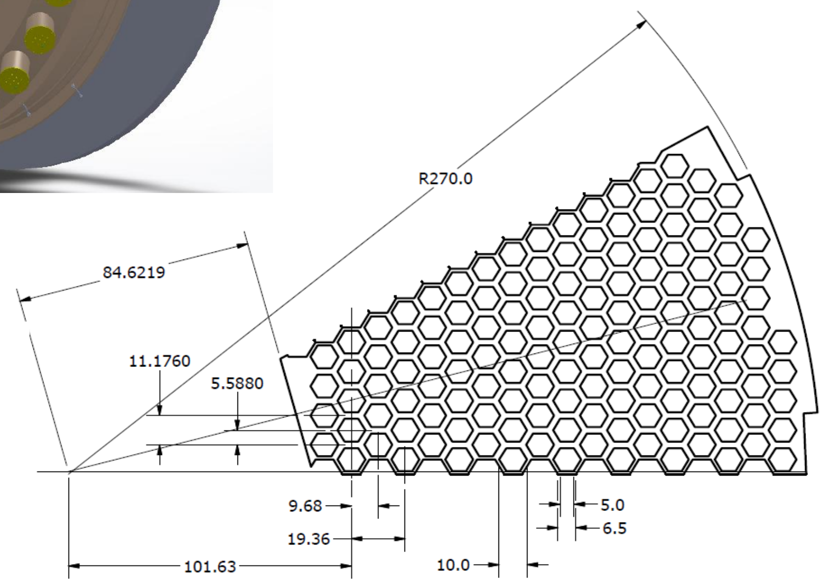
Light Gas Cerenkov (Temple)



Heavy Gas Cerenkov (Duke)



ECal Module (UVA, W&M, Shandong)

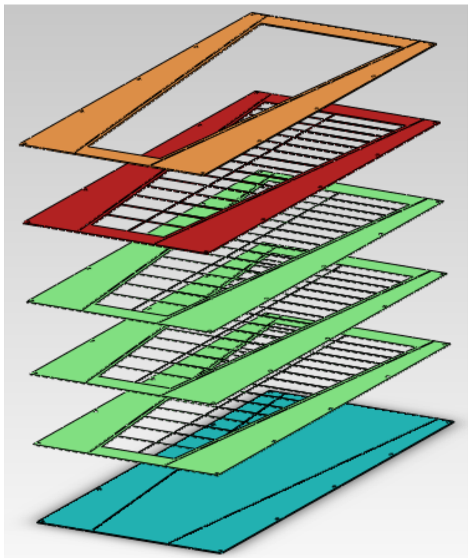


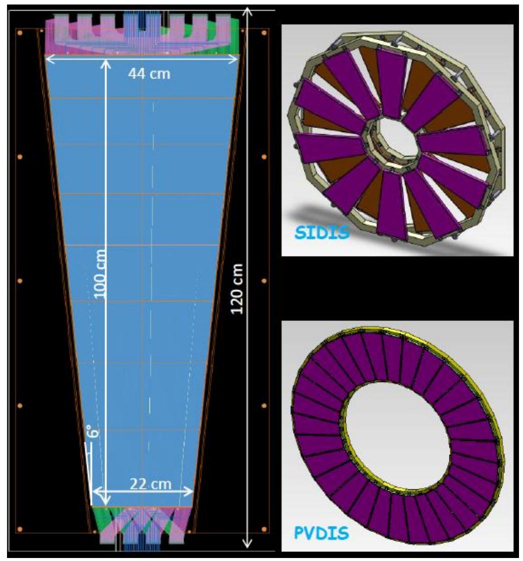
ECal Mounting Design (ANL)

GEM Progress

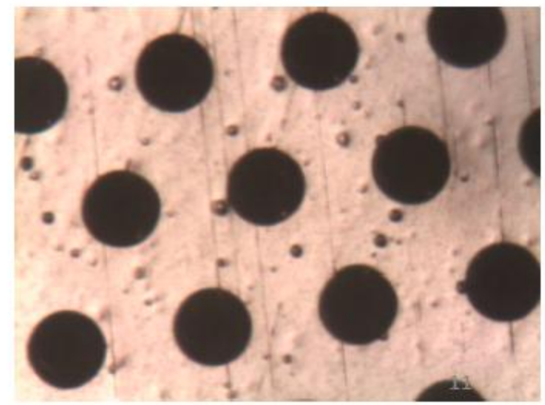
Chinese Collaboration

- 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)





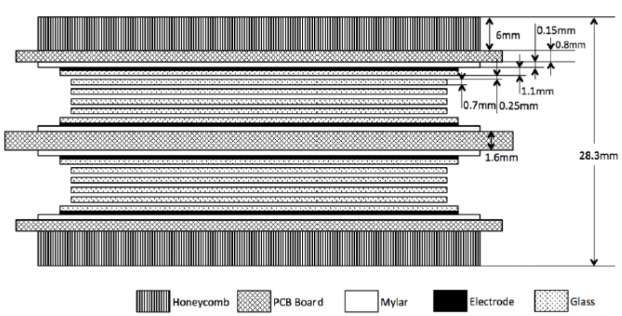
GEM foils made at CIAE

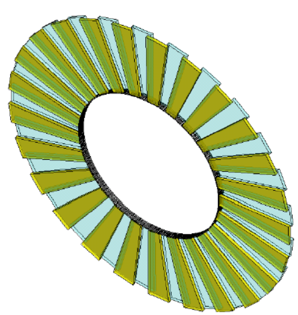


MRPC – High Resolution TOF

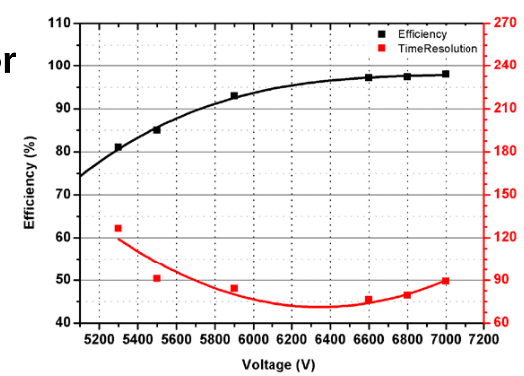
> 95 % efficiency

Timing resolution ~ 85 ps





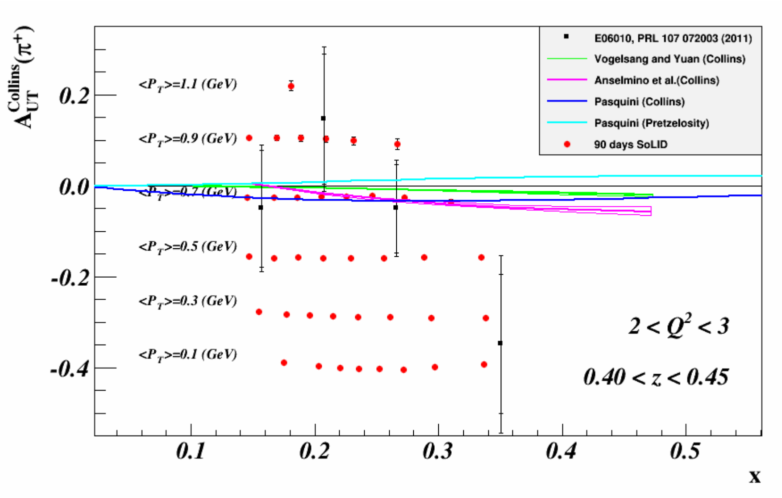
A MRPC prototype for SOLID-TOF in JLab
Y. Wang, *et al.* **JINST 8 (2013) P03003**
(Tsinghua)



Transversity and Tensor Charge

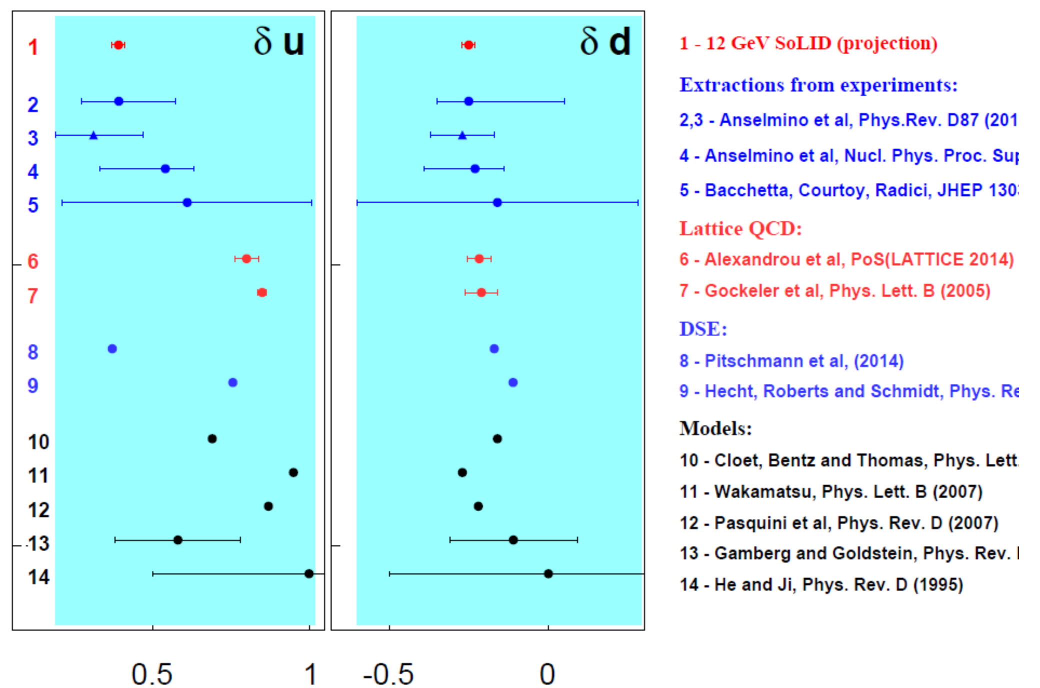
- Collins Asymmetries ~ Transversity (x) Collin Function
- **Transversity**: chiral-odd, not couple to gluons, **valence behavior**, largely unknown
- **Tensor charge (0th moment of transversity): fundamental property**
  Lattice QCD, Bound-State QCD (Dyson-Schwinger) , Light-cone Quark Models, …
- Global model fits to experiments (SIDIS and e+e-)
- SoLID with **trans polarized n & p** → determination of tensor charges for **d & u**

Collins Asymmetries



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

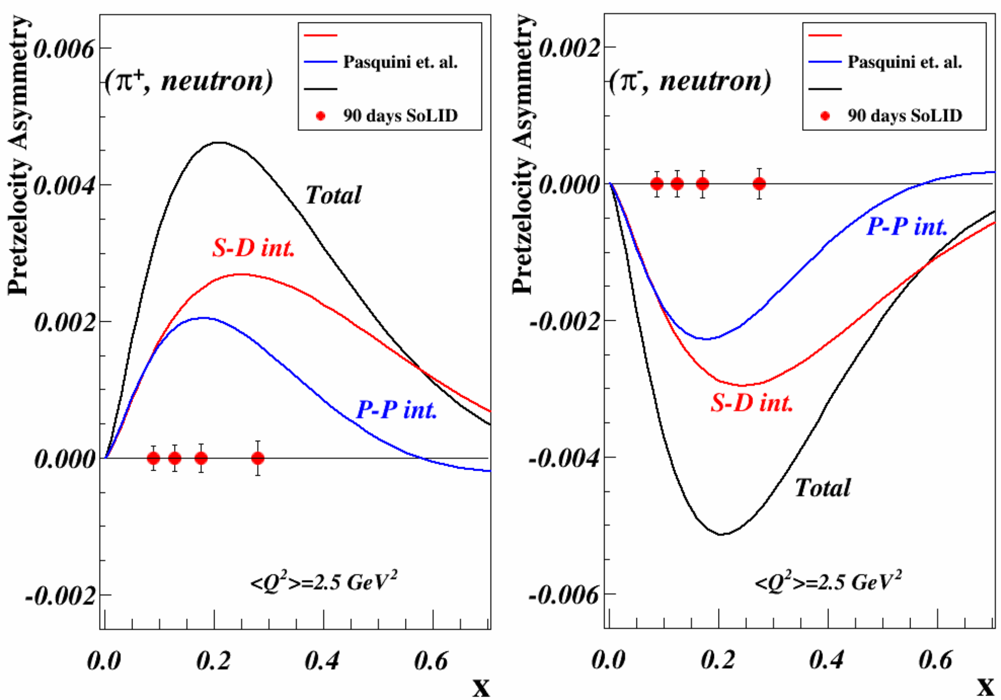
Tensor Charges



- *Projections with a model*
- *There are un-measured regions*
- *QCD evolutions being worked*

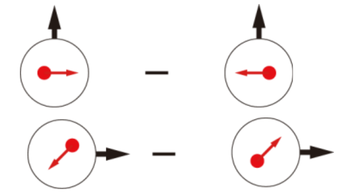
TMDs: 3-d Structure, Quark Orbital Motion

- 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**



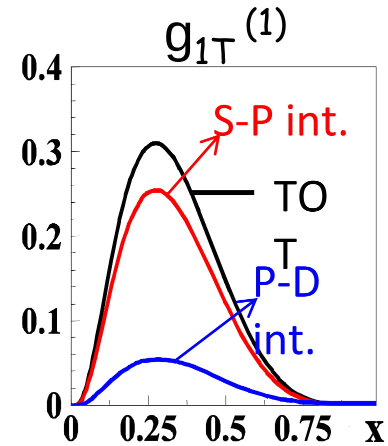
Pretzelosity

Worm-gear Functions

g_{1T} = 

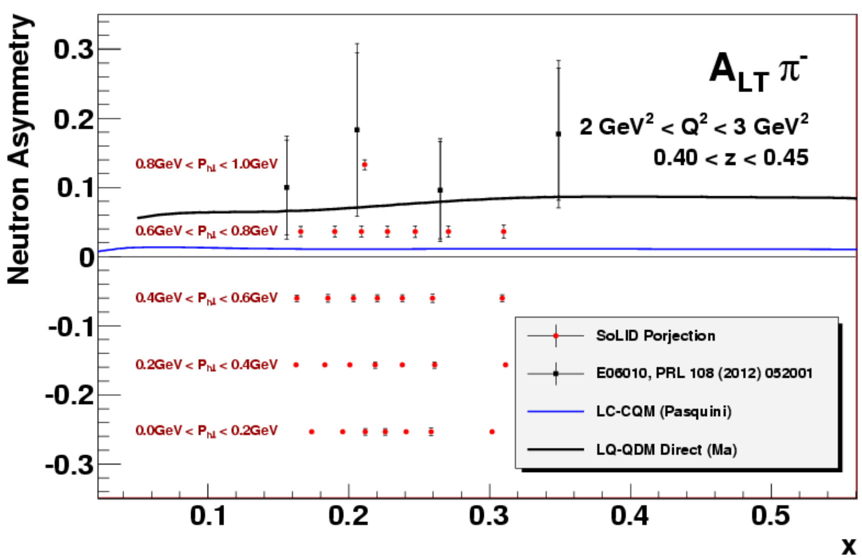
$h_{1L}^{\perp}$ =

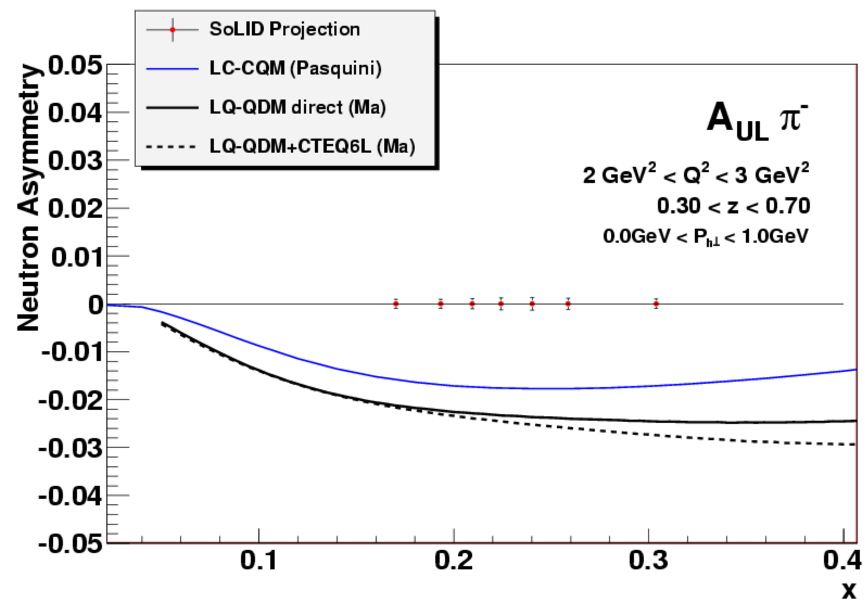
- Dominated by real part of interference between L=0 (S) and L=1 (P) states
- No GPD correspondence
- Exploratory lattice QCD calculation:
  Ph. Hägler et al, EPL 88, 61001 (2009)



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

Neutron Projections,





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

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

Polarized Dell-Yan at Fermilab

APS LRP:
Joint Town Meetings on QCD

(13-September, 2014)

Wolfgang Lorenzon
University of Michigan

- Unpolarized Drell-Yan at Fermilab: (~70 collaborators)
  - → **SeaQuest [E-906]:** (USA, Japan, Taiwan)
  - → **science run**: Feb 2014 — spring/summer 2016
- **Polarized Drell-Yan** at Fermilab: (USA, Japan, Taiwan, Spain) (~80 collaborators)
  - → polarized **Target** [**E-1039**]: 2016 (for 2 yrs) **Stage 1 approval: July-2013**
  - → polarized **Beam** [**E-1027**]: >2018 (for 2 yrs) **Stage 1 approval: Nov-2012**
- **Present status & needs**

Planned Polarized Drell-Yan Experiments

Experiment	Particles	Energy (GeV)	x_b or x_t	Luminosity ($cm^{-2}\,s^{-1}$)	$A_T^{\sin\phi_S}$	P_b or P_t (f)	rFOM#	Timeline
COMPASS (CERN)	$\pi^{\pm} + p^{\uparrow}$	160 GeV $\sqrt{s} = 17$	$x_t = 0.1 - 0.3$	2×10^{33}	0.14	$P_t = 90\%$ f = 0.22	1.1×10^{-3}	2014, 2018
PANDA (GSI)	$\bar{p} + p^{\uparrow}$	15 GeV $\sqrt{s} = 5.5$	$x_t = 0.2 - 0.4$	2×10^{32}	0.07	$P_t = 90\%$ f = 0.22	1.1×10^{-4}	>2018
PAX (GSI)	$p^{\uparrow} + \bar{p}$	collider $\sqrt{s} = 14$	$x_b = 0.1 - 0.9$	2×10^{30}	0.06	$P_b = 90\%$	2.3×10^{-5}	>2020?
NICA (JINR)	$p^{\uparrow} + p$	collider $\sqrt{s} = 26$	$x_b = 0.1 - 0.8$	1×10^{31}	0.04	$P_b = 70\%$	6.8×10^{-5}	>2018
PHENIX/STAR (RHIC)	$p^{\uparrow} + p^{\uparrow}$	collider $\sqrt{s} = 510$	$x_b = 0.05 - 0.1$	2×10^{32}	0.08	$P_b = 60\%$	1.0×10^{-3}	>2018
fsPHENIX (RHIC)	$p^{\uparrow} + p^{\uparrow}$	$\sqrt{s} = 200$ $\sqrt{s} = 510$	$x_b = 0.1 - 0.5$ $x_b = 0.05 - 0.6$	8×10^{31} 6×10^{32}	0.08	$P_b = 60\%$ $P_b = 50\%$	4.0×10^{-4} 2.1×10^{-3}	>2021
SeaQuest (FNAL: E-906)	$p + p$	120 GeV $\sqrt{s} = 15$	$x_b = 0.35 - 0.9$ $x_t = 0.1 - 0.45$	3.4×10^{35}	---	---	---	2012 - 2015
Pol tgt DY‡ (FNAL: E-1039)	$p + p^{\uparrow}$	120 GeV $\sqrt{s} = 15$	$x_t = 0.1 - 0.45$	4.4×10^{35}	0 – 0.2*	$P_t = 88\%$ f = 0.176	0.15	2016
Pol beam DY§ (FNAL: E-1027)	$p^{\uparrow} + p$	120 GeV $\sqrt{s} = 15$	$x_b = 0.35 - 0.9$	2×10^{35}	0.04	$P_b = 60\%$	1	>2018

‡ 8 cm NH_3 target / § L= 1×10^{36} $cm^{-2}\,s^{-1}$ (LH_2 tgt limited) / L= 2×10^{35} $cm^{-2}\,s^{-1}$ (10% of MI beam limited)

**not constrained by SIDIS data* / # rFOM = relative lumi * P^2 * f^2 wrt E-1027 (f=1 for pol p beams, f=0.22 for π^- beam on NH_3)

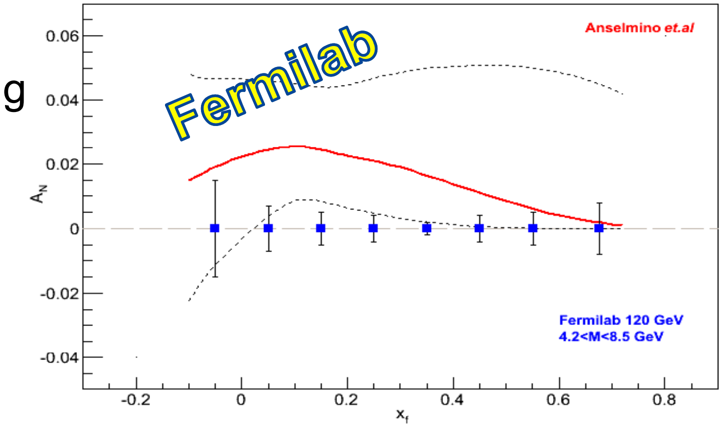
W. Lorenzon (U-Michigan) 9/10/2014

Polarized Beam Drell-Yan at Fermilab (E-1027)

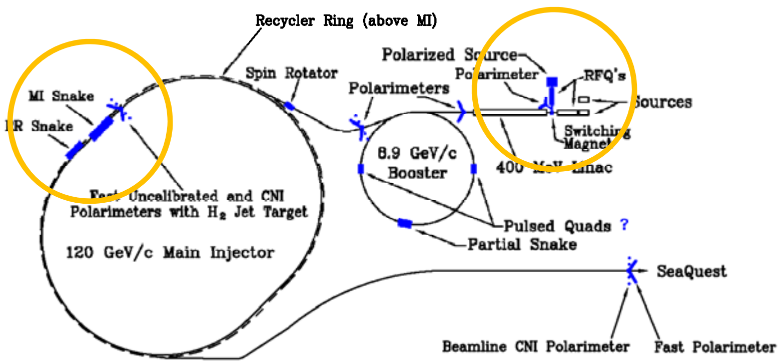
- Polarized Drell-Yan:
  - ⟶ QCD (and factorization) require sign change
  - ⟶ major milestone in hadronic physics (HP13)

$$f_{1T}^{\perp}\Big|_{SIDIS} = -f_{1T}^{\perp}\Big|_{DY}$$

- Extraordinary opportunity at Fermilab (best place for polarized DY) :
  - ⟶ high luminosity, large x-coverage
  - ⟶ (SeaQuest) spectrometer already setup and running
  - ⟶ run alongside neutrino program (w/ 10% of beam)
  - ⟶ experimental sensitivity:
    - › 2 yrs at 50% eff, P_b = 60%, I_{av} = 15 nA
    - › luminosity: $L_{av} = 2 \times 10^{35}$ /cm²/s



- Path to polarized proton beam at Main Injector
  - ⟶ perform detailed design studies
- Cost estimate to polarize Main Injector $10M (total)
  - ⟶ includes M&S, labor, 15% project management & 50% contingency
- Measure DY with both Beam or/and Target polarized
  - ⟶ broad spin physics program possible

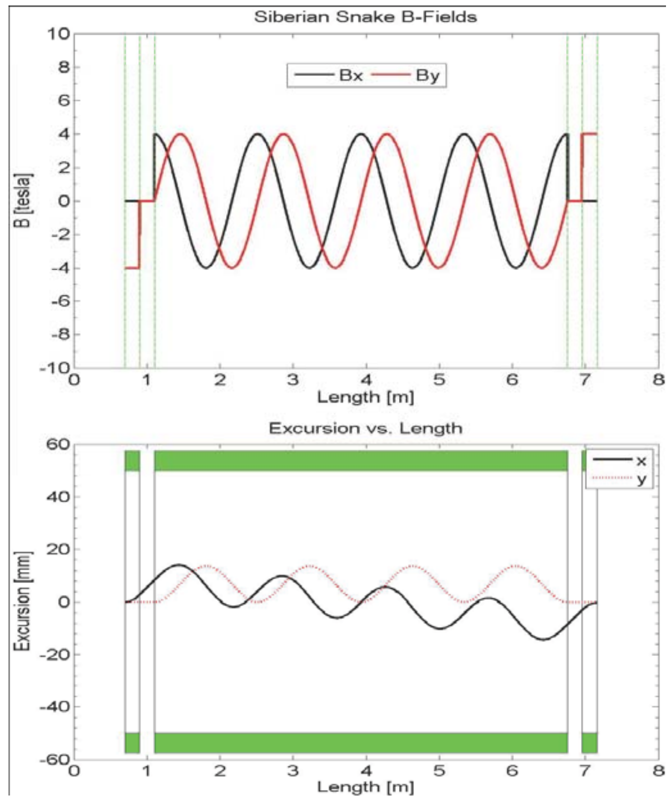


A Novel, Compact Siberian Snake for the Main Injector

Single snake design (6.4m long):

- 1 helical dipole + 2 conv. dipoles
    - helix: 4T / 5.6 m / 4” ID
    - dipoles: 4T / 0.2 m / 4” ID
- use one 4-twist helical magnet
    - 8π rotation of B field
- never done before in a high energy ring
    - RHIC uses snake pairs
    - 4 single-twist magnets (2π rotation ea)

initial design studies



Path to polarized proton beam at MI

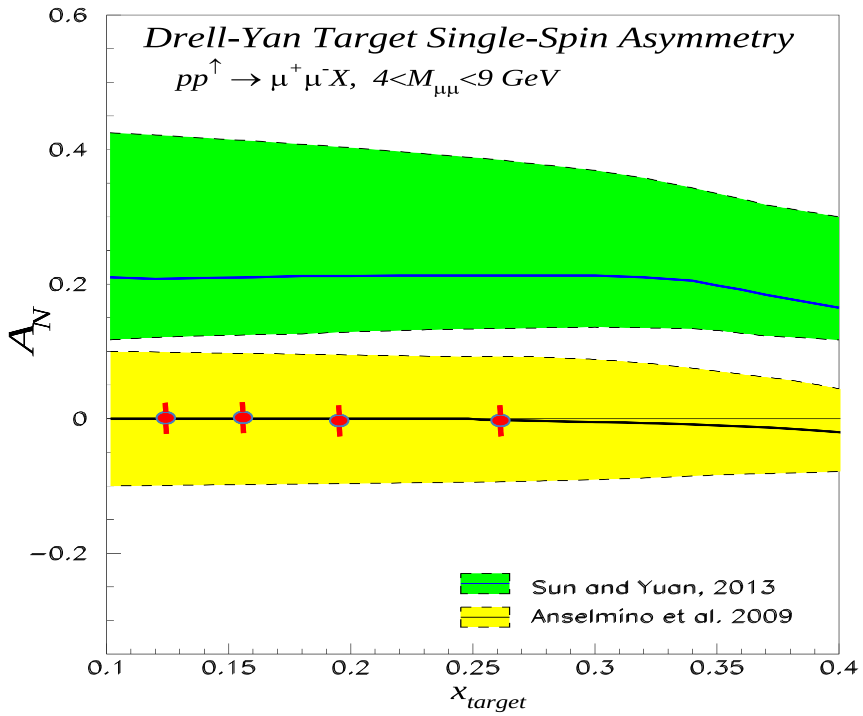
- detailed design studies: \$300k (short-term)
- implement modifications to MI \$10M (longer-term)

Needs

- endorsement in LRP document

Polarized Beam Drell-Yan at Fermilab (E-1039)

- Probe **Sea-quark Sivers Asymmetry**
  with a polarized proton target at SeaQuest



- Statistics shown for one calendar year of running:
- L = 7.2 *10^{42} /cm^2 ↔ POT = 2.8*10^{18}
- Running will be two calendar years of beam time

– existing SIDIS data poorly constrain sea-quark Sivers function

– significant Sivers asymmetry expected from meson-cloud model

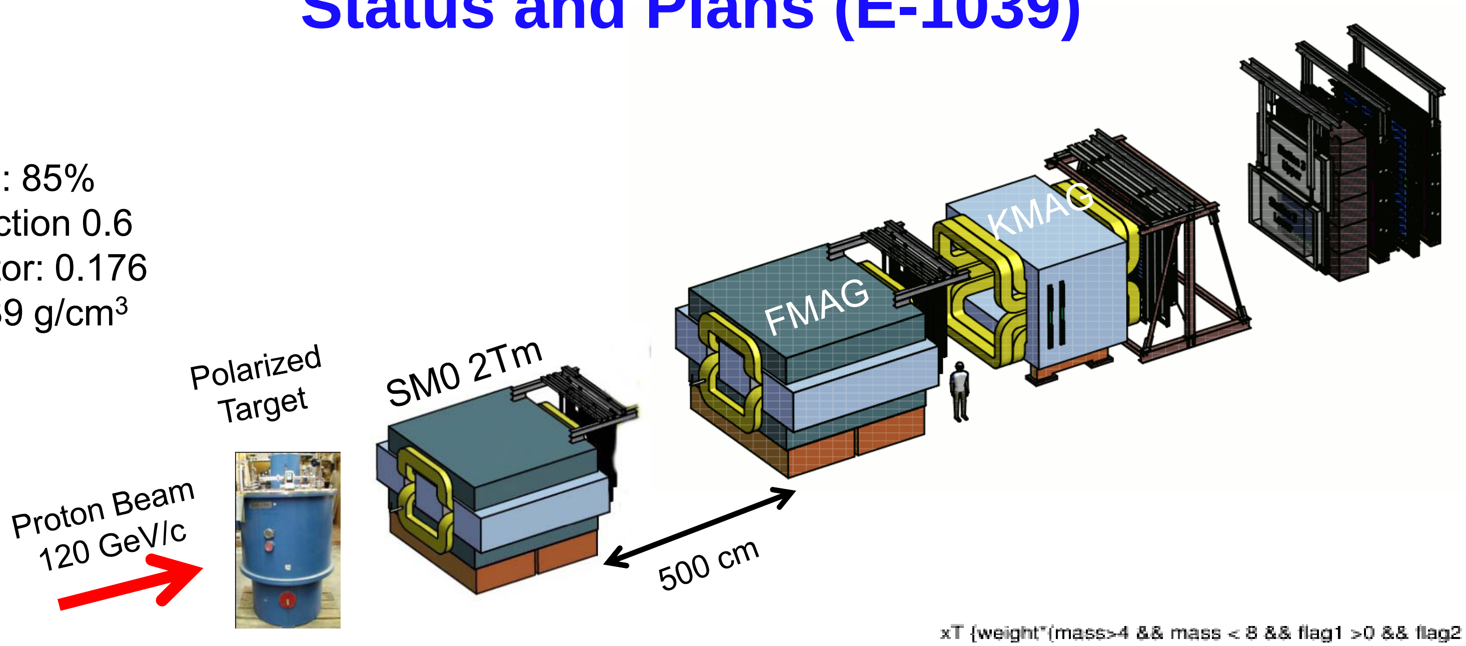
– **first Sea Quark Sivers Measurement**

– **determine sign and value of $\bar{u}$ Sivers distribution**

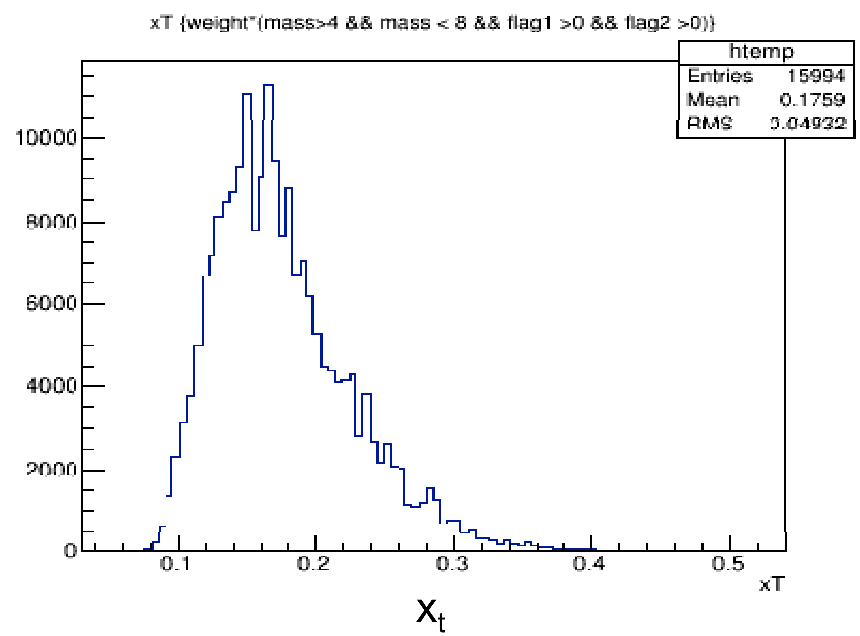
If $A_N \neq 0$, **major discovery**:
"Smoking Gun" evidence for $L_{\bar{u}} \neq 0$

Status and Plans (E-1039)

Target
Polarization: 85%
Packing fraction 0.6
Dilution factor: 0.176
Density: 0.89 g/cm^3



- use current SeaQuest setup, a polarized proton target, unpolarized beam
- add third magnet SM0 ~5m upstream
- improves dump-target separation
- moves $\langle x_t \rangle$ from 0.21 to 0.176
- reduces overall acceptance
- adds shielding challenges



COMPASS, E-1027, E-1039 (and Beyond)

	Beam Pol.	Target Pol.	Favored Quarks	Physics Goals			
				(Sivers Function)			L_{sea}
				sign change	size	shape	
COMPASS $\pi^- p^\uparrow \to \mu^+ \mu^- X$	✗	✓	valence	✓	✗	✗	✗
E-1027 $p^\uparrow p \to \mu^+ \mu^- X$	✓	✗	valence	✓	✓	✓	✗
E-1039 $p\, p^\uparrow \to \mu^+ \mu^- X$	✗	✓	sea	✗	✓	✓	✓
E-10XX $p^\uparrow p^\uparrow \to \mu^+ \mu^- X$ $\vec{p}\, \vec{p} \to \mu^+ \mu^- X$	✓	✓	sea & valence	Transversity, Helicity, Other TMDs ...			

Polarized Drell-Yan Recommendation Text for the QCD Town Meeting

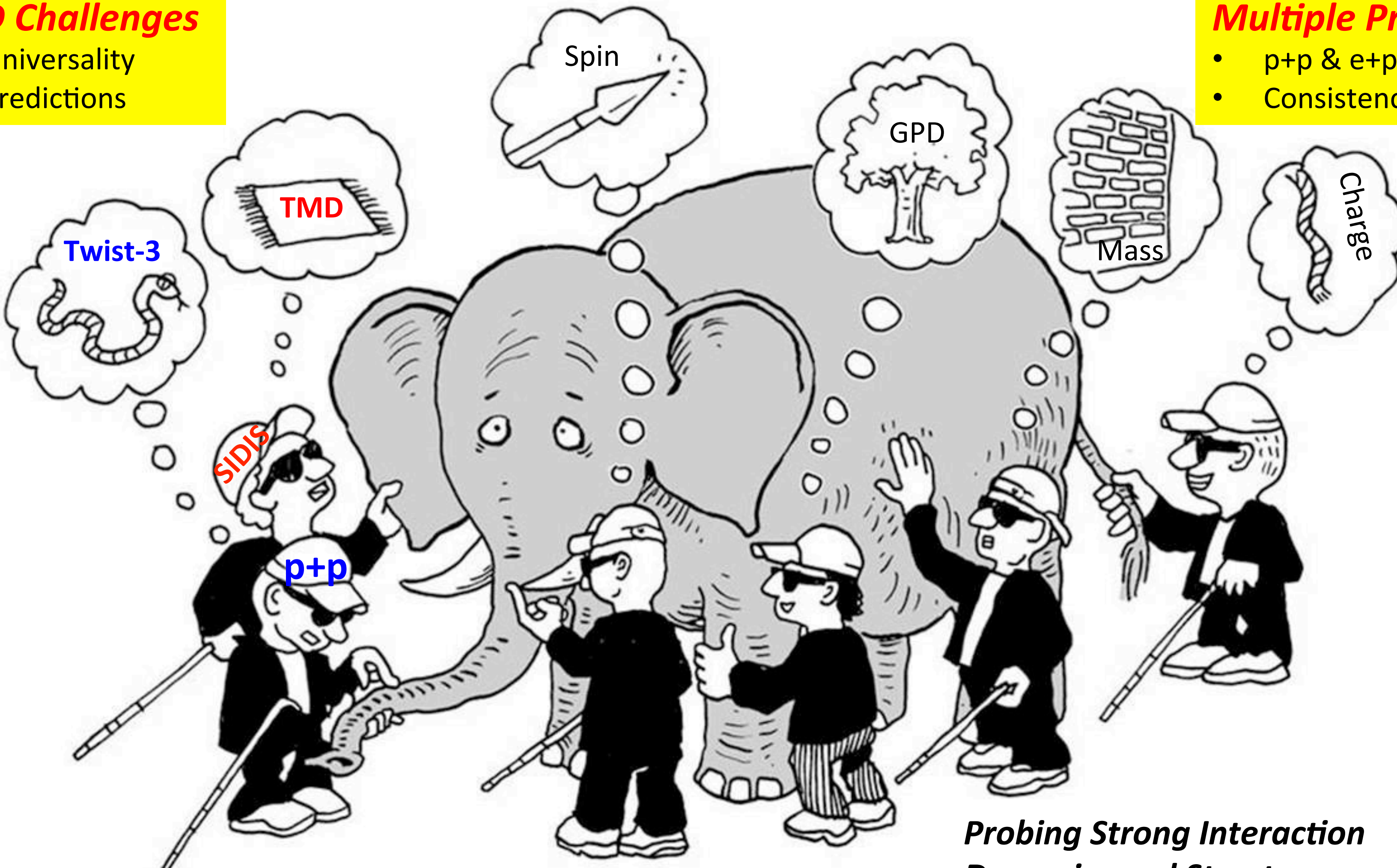
- A high-luminosity polarized Drell-Yan program at the Fermilab Main Injector with both polarized beams and targets is endorsed by the U.S. QCD community.

The Importance of a New Transverse Spin Program at RHIC and Its Impacts on Future e+p Physics

Ming Liu (Los Alamos)

QCD Challenges
- Universality
- Predictions

Multiple Probes
- p+p & e+p
- Consistency



Probing Strong Interaction Dynamics and Structures

When "pp" and "DIS" Confront Each Other: ***A Surprise!***

First attempt to test the universal QCD descriptions of TSSA in p+p and e+p

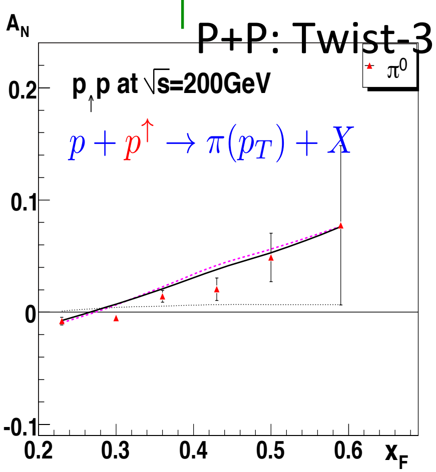
- What are the sources of the large TSSA in p+p?
  - Long-standing puzzle ~40 years!
  - Sivers and Collins effects observed in SIDIS
- Are they universal?
  - p+p vs SIDIS

$$gT_{q,F}(x,x) \stackrel{?}{=} -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\text{SIDIS}}$$

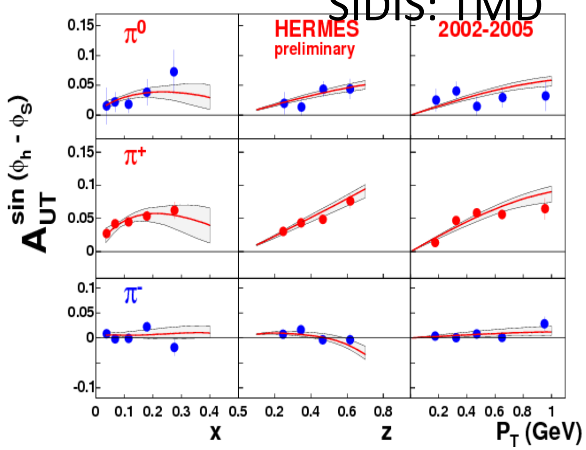
Urgency: Experimental resolution!

- SIDIS:
  - Sivers and Collins separated
  - Limited to "small" (x,Q^2)
  - Need EIC to help!
- p+p:
  - Inclusive TSSA, mix of effects
  - Limited to "large" (x, Q^2)
  - Need new data to overlap SIDIS!

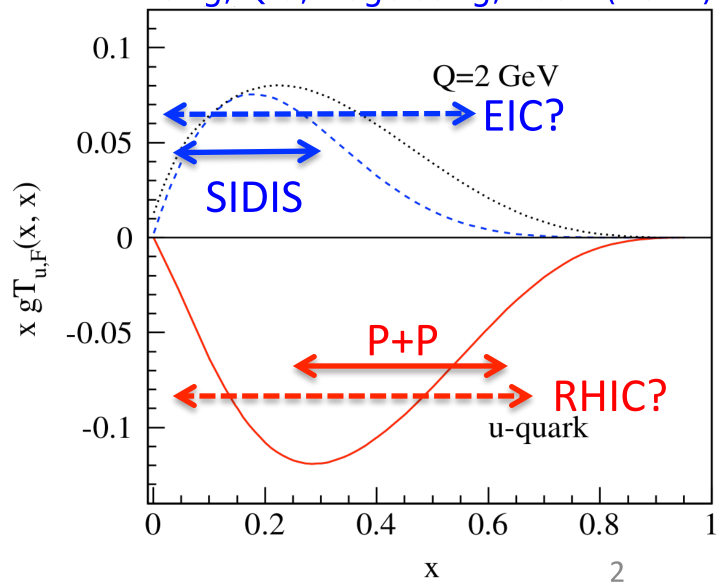
P+P: Twist-3



SIDIS: TMD



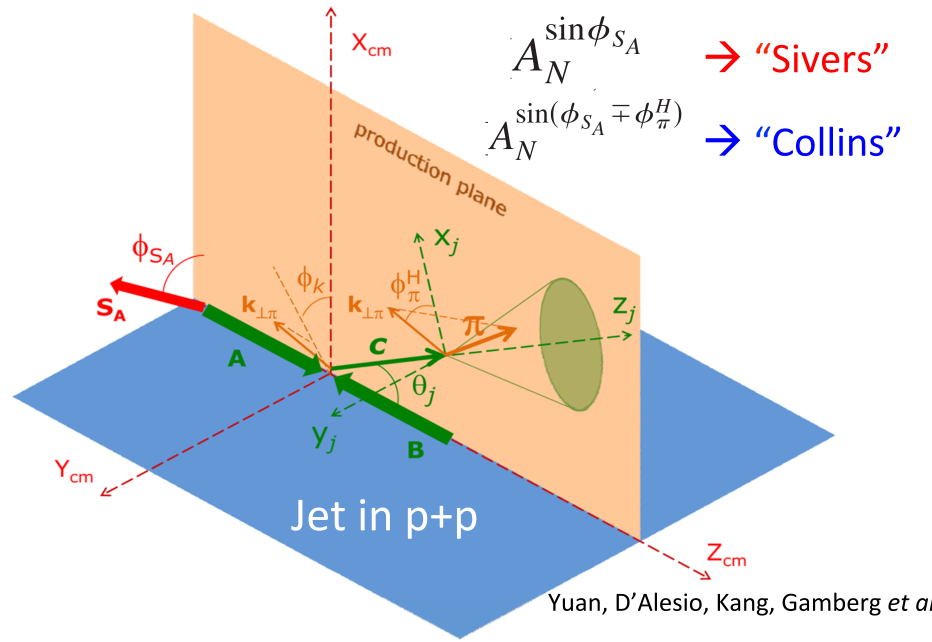
Kang, Qiu, Vogelsang, Yuan (2011)



Proposal: New Transverse Spin/TMD Physics at RHIC

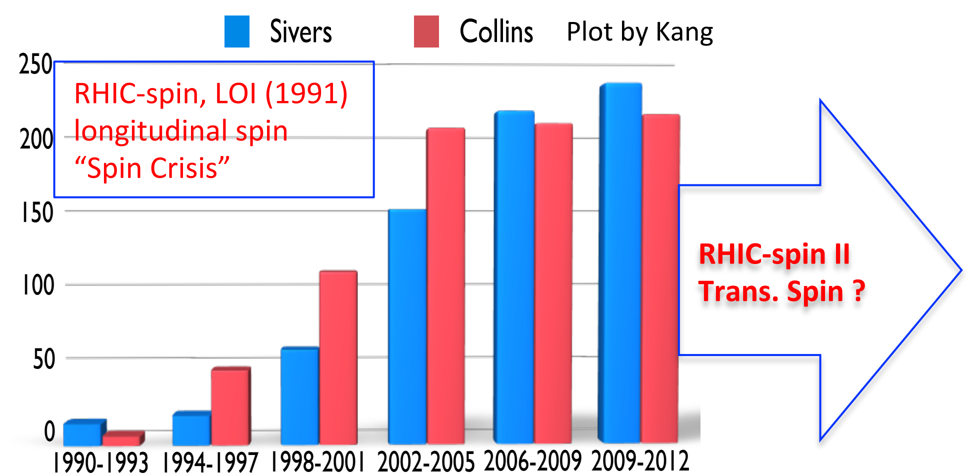
Discover Novel QCD Structures and Dynamics at RHIC

- New Opportunity at RHIC - the world only polarized p+p Collider
  - First unambiguous measurements of initial and final state spin asymmetries in p+p
    - Jet “Sivers” asymmetry
    - Intra-Jet “Collins” asymmetry
    - Direct comparison with SIDIS
  - Access new **quark** and **gluon** TMDs
    - Boer-Mulders, Warm-Gear etc
  - Requires new experimental capabilities
    - Full jet, forward rapidity
    - Drell-Yan and other probes possible



Yuan, D’Alesio, Kang, Gamberg *et al*

- Recent revolution in “TMD physics”
  - Universal QCD descriptions being developed
  - EIC physics focus
- Unique opportunity, discovery physics!
  - Harvest early investment with moderate detector upgrade (also EIC ready)
  - Critical for EIC physics interpretation

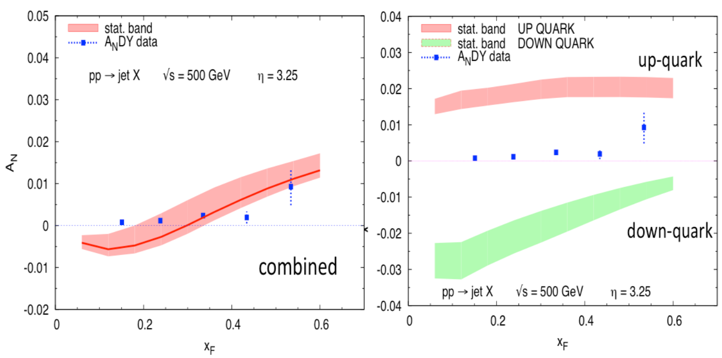


Backup Slides

Jet “Sivers” and “Collins” Measurements

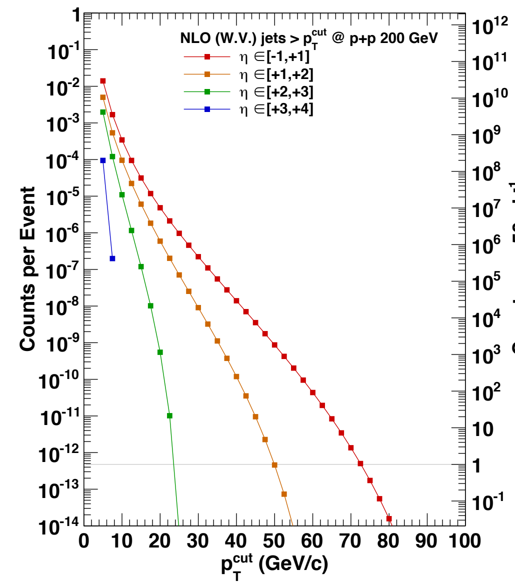
A Proposed EIC Detector, eta={-1, +4}

- Jet “Sivers” Asymmetry

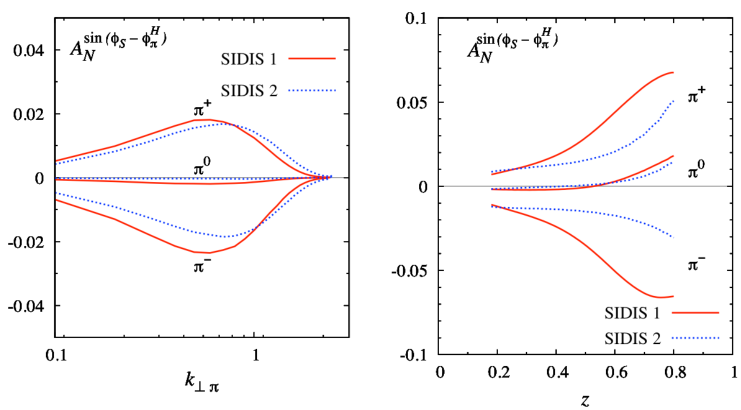


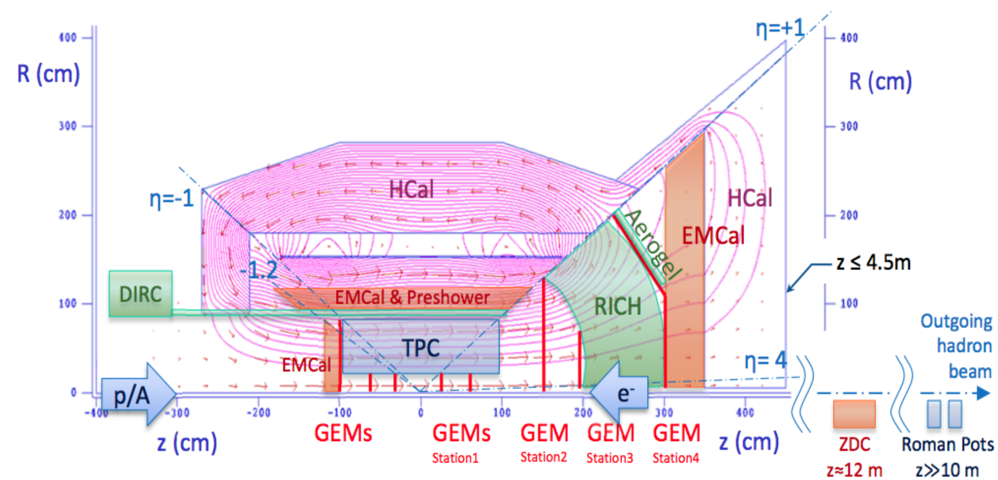
Jet Kinematic:

X = 0.1 ~ 0.6
Q^2 = 16 ~ 1000
Huge statistics for precision



- Intra-Jet “Collins” Asymmetry





Gluons are Important at Large x Too!
incoming parton flavors

- CTEQ 10, NLO
- Q^2 = 10 GeV^2

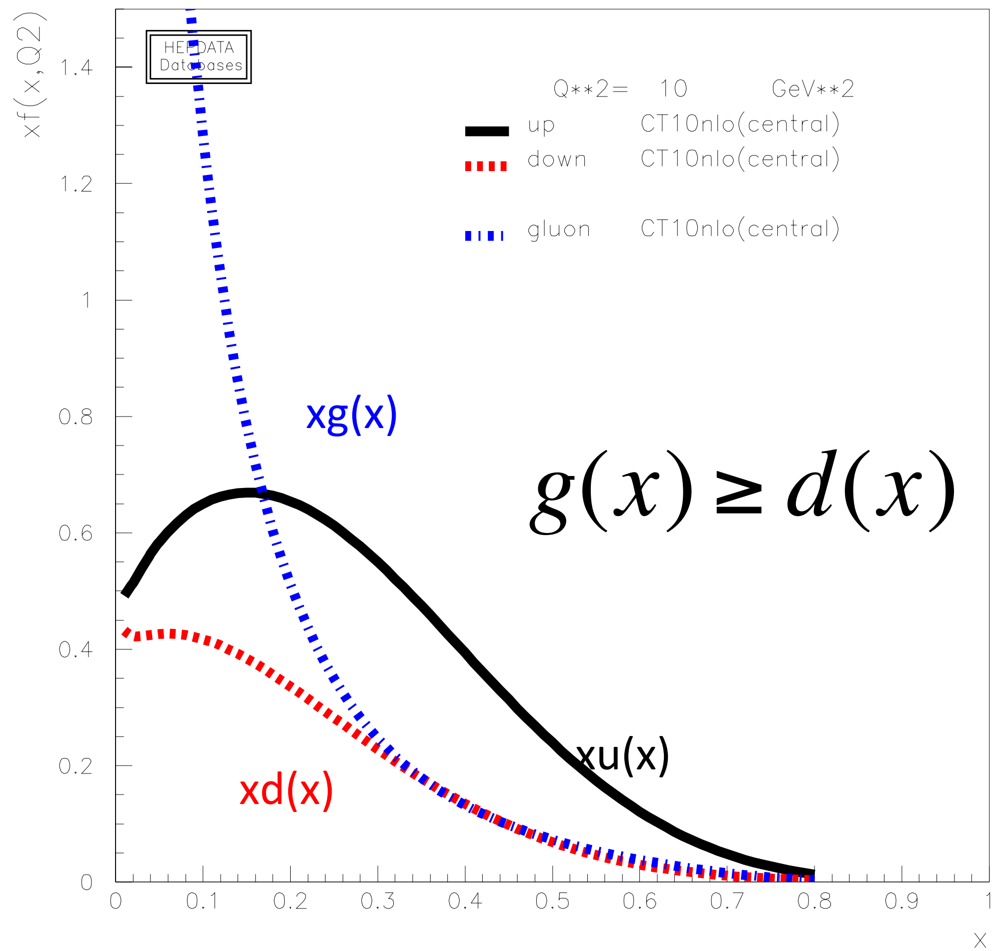
There are a lot of gluons at X1 > 0.1

Access gluon TMDs in p+p in leading order processes

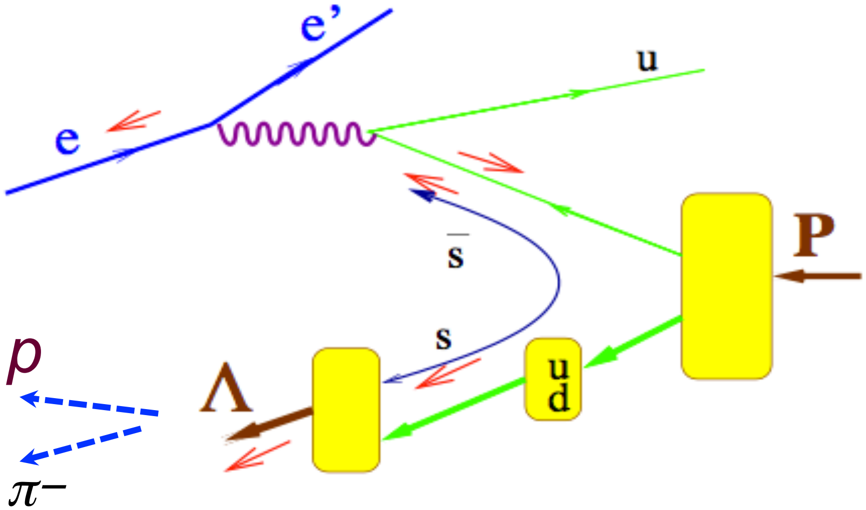
Forward jets: x1 >> x2

u(x1) + g(x2) -> jets
g(x1) + g(x2) –> jets
d(x1) + g(x2) -> jets

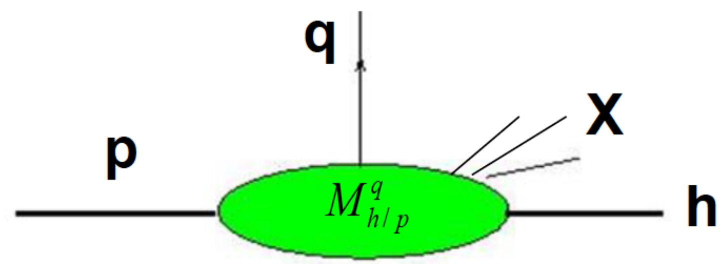
g(x1) + q_sea(x2) -> jets
q(x1) + q_sea(x2) -> jets



Target fragmentation region and fracture functions



Large acceptance of CLAS12 and EIC provide a unique possibility to study the nucleon structure simultaneously in current and target fragmentation regions in SIDIS



probability to produce the hadron h when a quark q is struck in a proton target

M. Anselmino, V. Barone and A. Kotzinian, Phys. Lett. B 699 (2011) 108

$$\frac{d\sigma^{TFR}}{dx_B dy d\zeta d\phi_S d\phi} = \frac{\alpha_{em}^2}{\pi Q^2 y}\sum_a e_a^2 \times$$

$$\Big\{\Big(1-y+\frac{y^2}{2}\Big)\Big[M(x_B,\zeta)+S_{N\parallel}S_\parallel M_L^L(x_B,\zeta)+|\mathbf{S}_{N\perp}|\,|\mathbf{S}_\perp|\,M_T^T(x_B,\zeta)\cos(\phi-\phi_S)\Big]$$

$$+hy\Big(1-\frac{y}{2}\Big)\Big[S_{N\parallel}\Delta M_L(x_B,\zeta)+S_\parallel \Delta M^L(x_B,\zeta)+$$

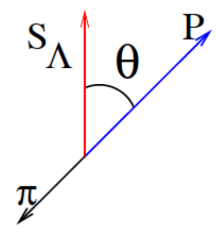
$$+|\mathbf{S}_{N\perp}|\,|\mathbf{S}_\perp|\,\Delta M_T^T(x_B,\zeta)\sin(\phi-\phi_S)\Big]\Big\}$$

Measurements of hadrons produced in the target fragmentation region (fracture functions) opens a new avenue in studies of the structure of the nucleon in general and correlations between current and target fragmentation in particular

Λ production in the target fragmentation region

Λ – unique tool for polarization study due to self-analyzing parity violating decay

$$\frac{dN}{d\cos\theta_p^*} \propto 1 + \alpha P_\Lambda \cos\theta_p^*$$

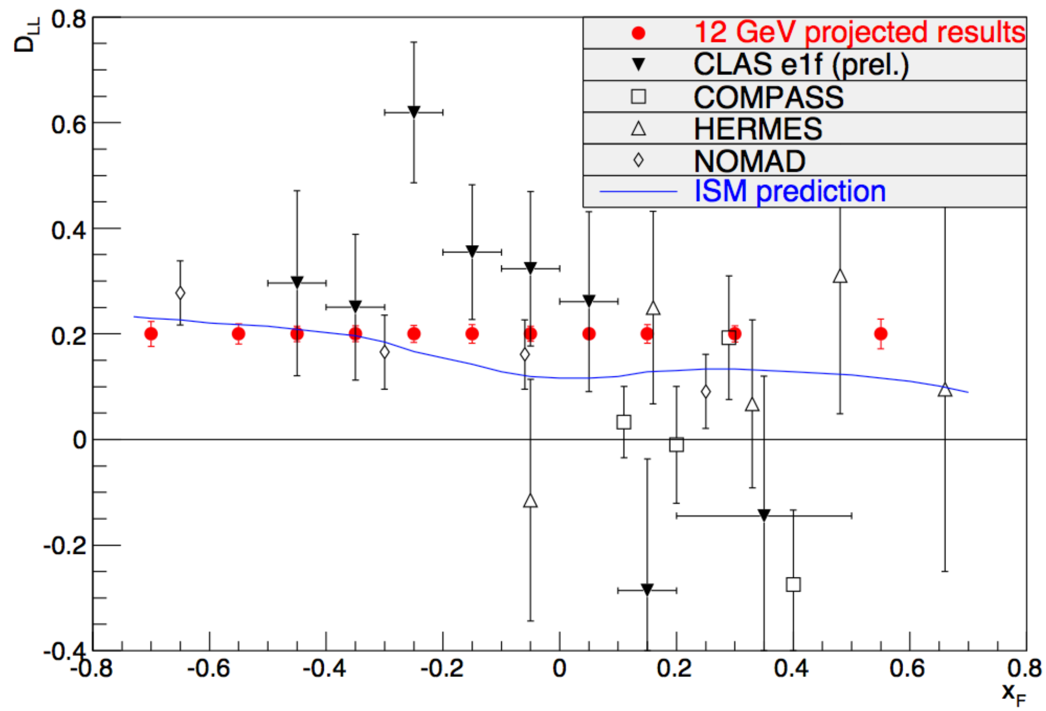


$$A_{LUL}^{TFR} = hS_\parallel \frac{y\left(1-\frac{y}{2}\right)\sum_a e_a^2 \Delta M^L}{\left(1-y+\frac{y^2}{2}\right)\sum_a e_a^2 M}$$

polarization tranfer coefficient

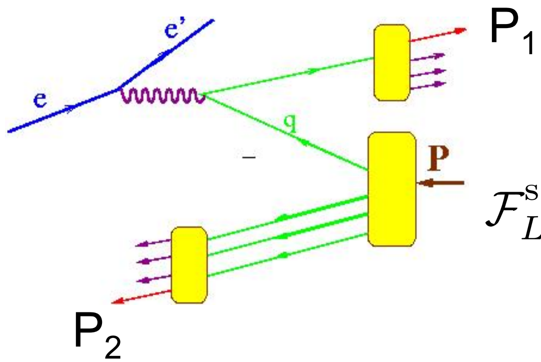
$$D^{LL} = \frac{\sum_a e_a^2 \Delta M^L}{\sum_a e_a^2 M}$$

30 days of CLAS12 data taking



Projected results of the longitudinal spin transfer as a function of $\mathbf{x}_F$ (red full circles) compared with the CLAS preliminary data and the ISM prediction

Back-to-back hadron (b2b) production in SIDIS

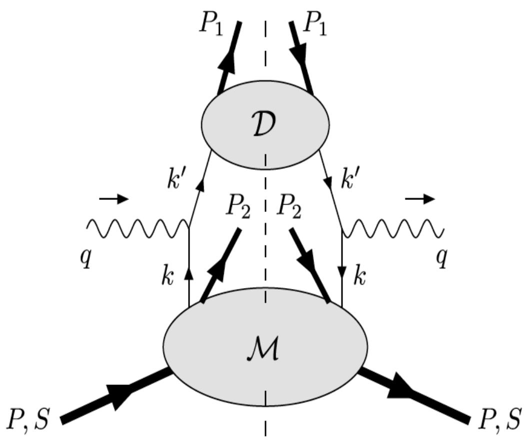


M. Anselmino, V. Barone and A. Kotzinian, Physics Letters B 713 (2012)

$$\mathcal{F}_{LU}^{\sin(\phi_1-\phi_2)} = \frac{|\vec{P}_{1\perp}\vec{P}_{2\perp}|}{m_N m_2}\mathcal{C}[w_5 M_L^{\perp,h} D_1]$$

	U	L	T
U	M	$M_L^{\perp,h}$	$M_T^h, M_T^\perp$
L	$\Delta M^{\perp,h}$	ΔM_L	$\Delta M_T^h, \Delta M_T^\perp$
T	$\Delta_T M_T^h, \Delta_T M_T^\perp$	$\Delta_T M_L^h$ $\Delta_T M_L^\perp$	$\Delta_T M_T, \Delta_T M_T^{hh}$ $\Delta_T M_T^{\perp\perp}, \Delta_T M_T^{\perp h}$

The beam–spin asymmetry appears, at leading twist and low transverse momenta, in the deep inelastic inclusive lepto-production of two hadrons, one in the target fragmentation region and one in the current fragmentation region.



$$A_{LU} = -\frac{y(1-\frac{y}{2})}{(1-y+\frac{y^2}{2})}\frac{\mathcal{F}_{LU}^{\sin\Delta\phi}}{\mathcal{F}_{UU}}\sin\Delta\phi$$

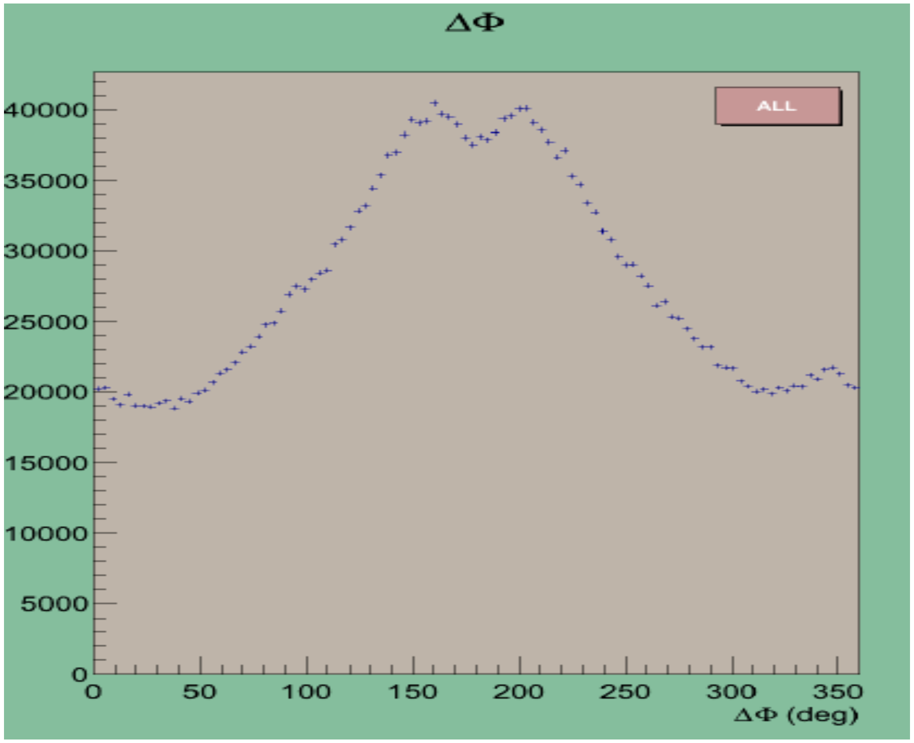
$$= -\frac{|\boldsymbol{P}_{1\perp}||\boldsymbol{P}_{2\perp}|}{m_N m_2}\frac{y(1-\frac{y}{2})}{(1-y+\frac{y^2}{2})}\frac{\mathcal{C}[w_5 M_L^{\perp,h} D_1]}{\mathcal{C}[M D_1]}\sin\Delta\phi$$

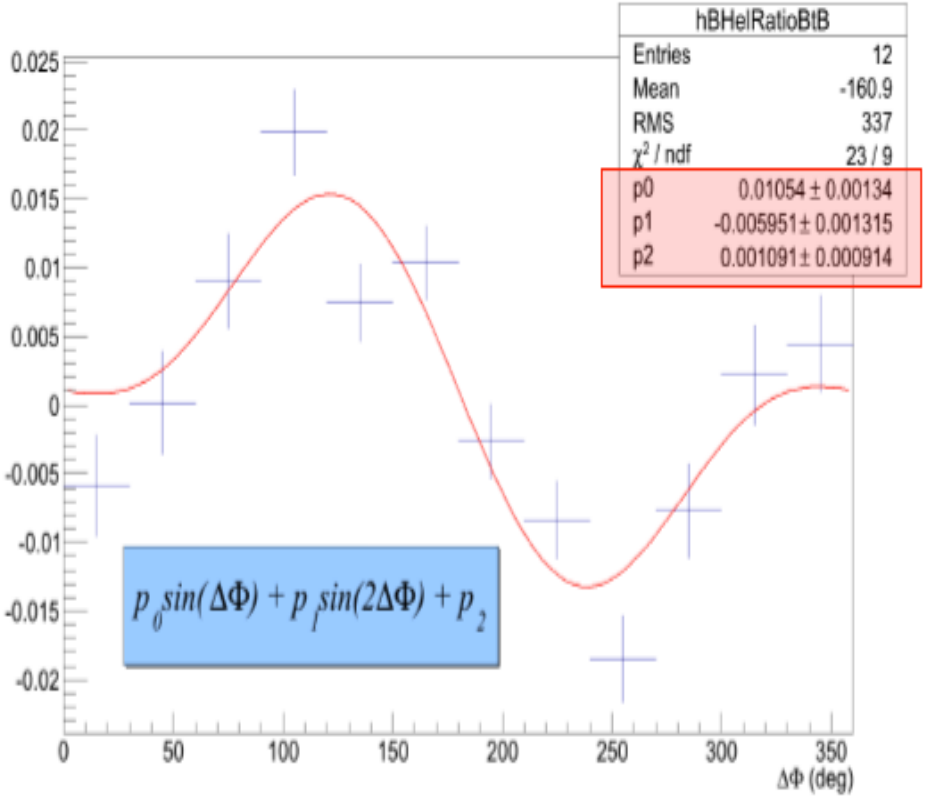
Back-to-back hadron production in SIDIS would allow:

- study SSAs not accessible in SIDIS at leading twist
- measure fracture functions
- control the flavor content of the final state hadron in current fragmentation (detecting the target hadron)
- study correlations in target vs current and access factorization breaking effects (similar to pp case)
- access quark short-range correlations and χSB (Schweitzer et al)
- ...

Support slides….

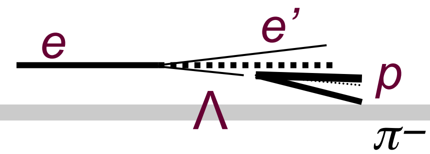
ALU in b2b SIDIS with CLAS @ 5.5 GeV

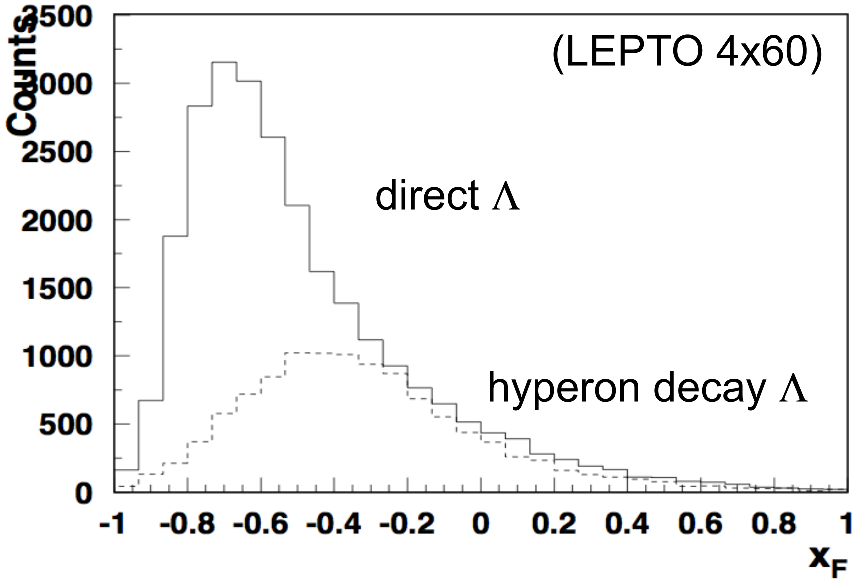


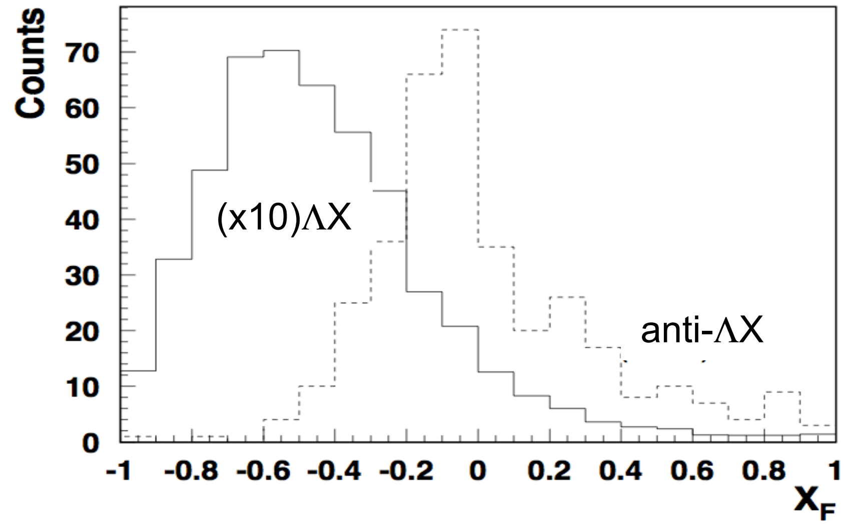


Preliminary results for a significant ALU asymmetry from CLAS with π+ produced in CFR and π− – in TFR.

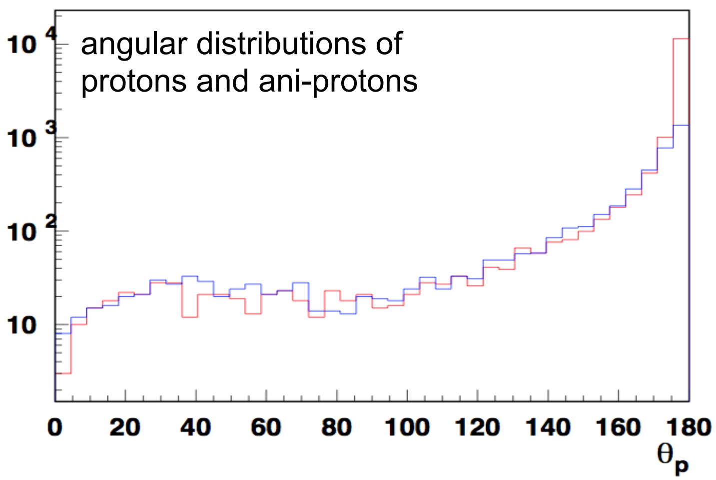
Λ production in the target fragmentation region

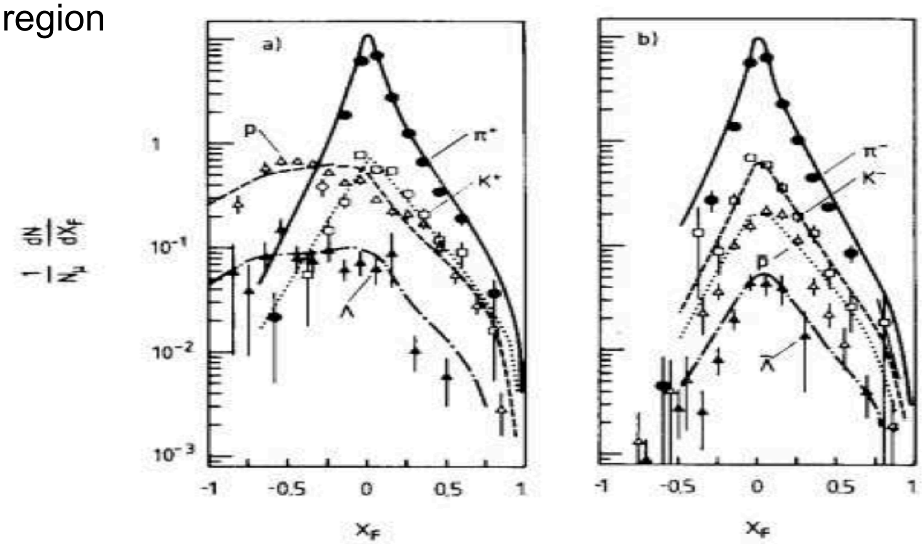




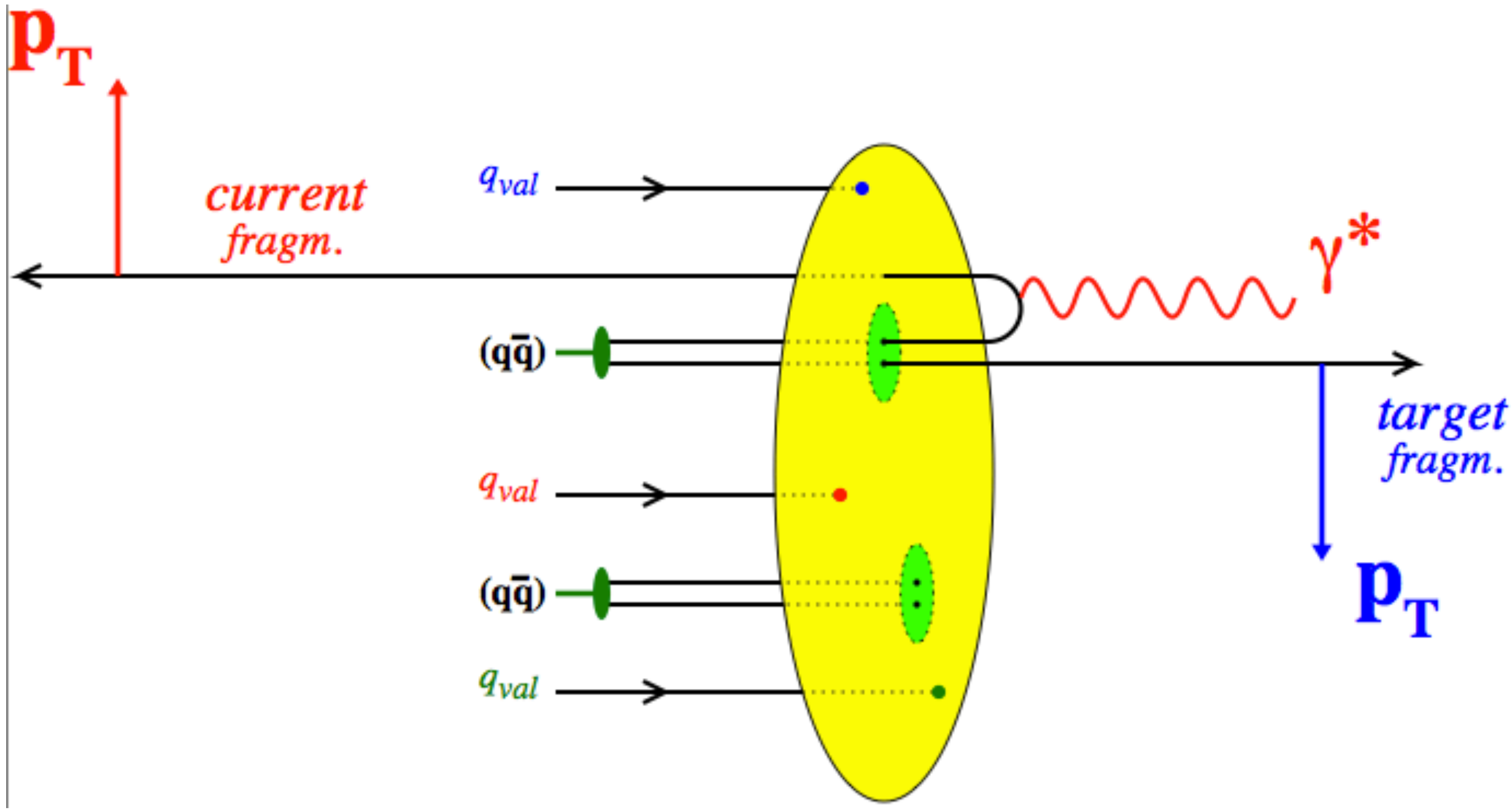


Most of the direct Lambdas in the target fragmenatation region



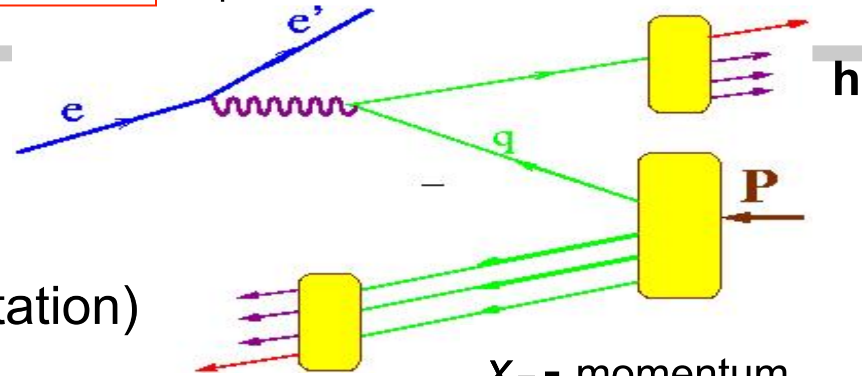


correlations between target and current



Single hadron production in hard scattering

$x_F > 0$ (current fragmentation)

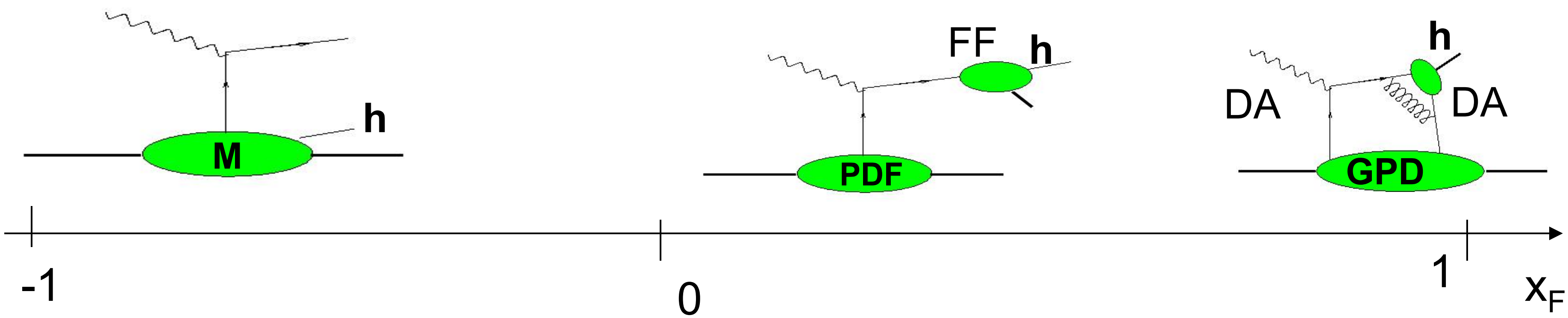


$x_F < 0$ (target fragmentation)

x_F - momentum in the CM frame

Target fragmentation **Current fragmentation**

semi-inclusive **exclusive**



Fracture Functions

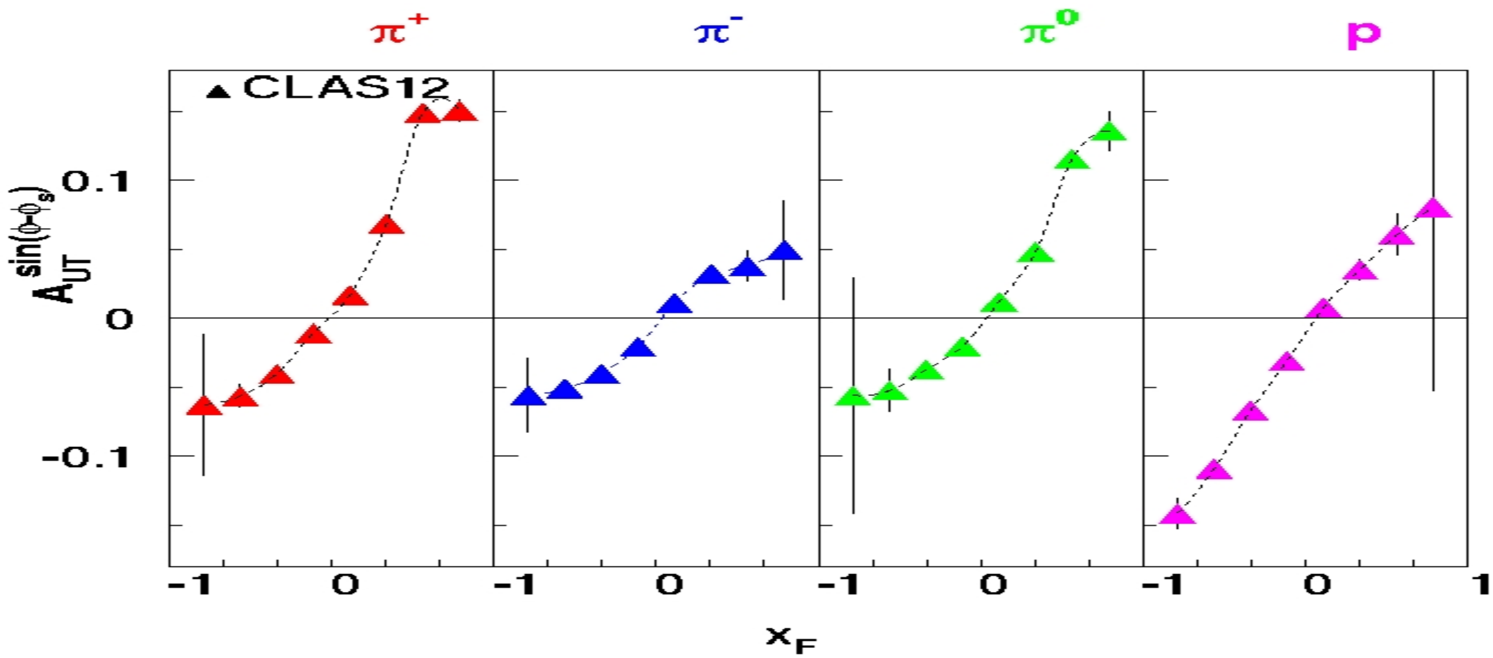
k_T-dependent PDFs

Generalized PDFs

Wide kinematic coverage of large acceptance detectors allows studies of hadronization both in the target and current fragmentation regions

Sivers effect in the target fragmentation

A.Kotzinian



High statistics of CLAS12 will allow studies of kinematic dependences of the Sivers effect in target fragmentation region

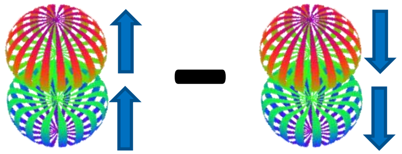
Tensor Spin Observables

Property of spin-1 nuclei

Tensor Spin Observables

Property of spin-1 nuclei

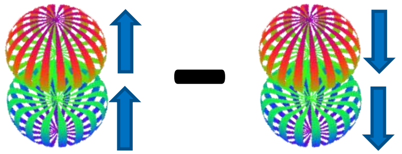
Vector $P_z = p_+ - p_-$



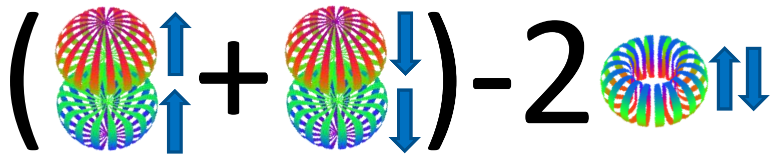
Tensor Spin Observables

Property of spin-1 nuclei

Vector $P_z = p_+ - p_-$



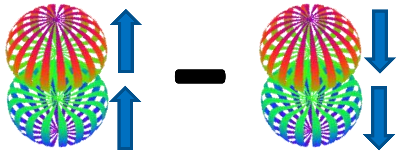
Tensor $P_{zz} = (p_+ + p_-) - 2p_0$



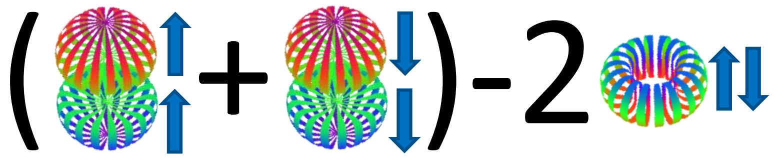
Tensor Spin Observables

Property of spin-1 nuclei

Vector $P_z = p_+ - p_-$



Tensor $P_{zz} = (p_+ + p_-) - 2p_0$



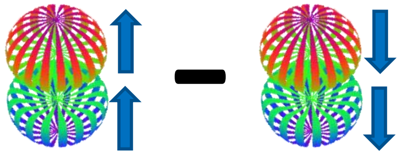
Development of a high luminosity, high tensor polarized target has promise as novel probe of nuclear physics

[1] IA Rachek *et al*, PRL **98,** 182303 (2007)

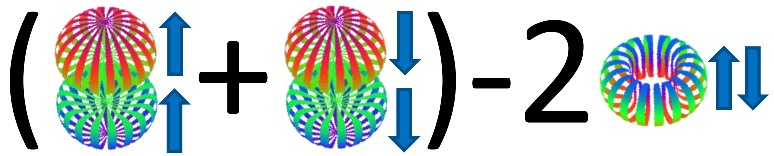
Tensor Spin Observables

Property of spin-1 nuclei

Vector $P_z = p_+ - p_-$



Tensor $P_{zz} = (p_+ + p_-) - 2p_0$



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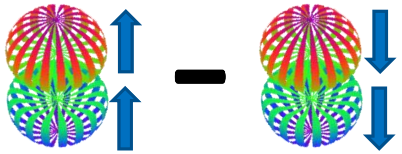

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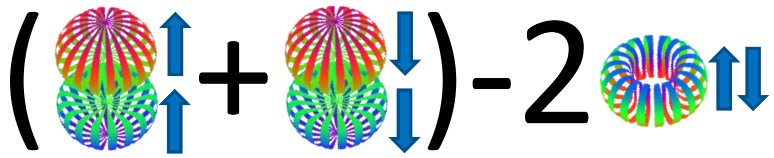

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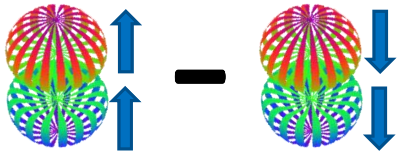

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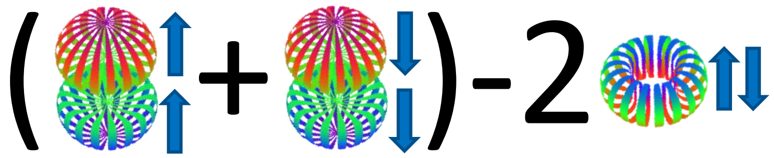

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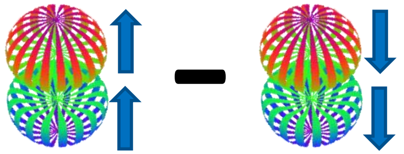

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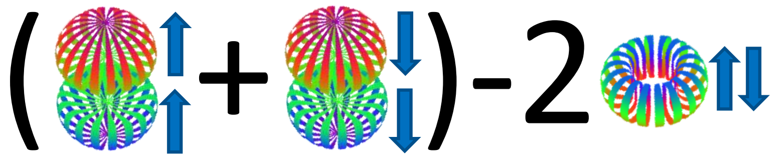

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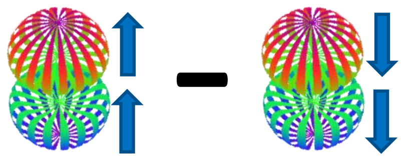

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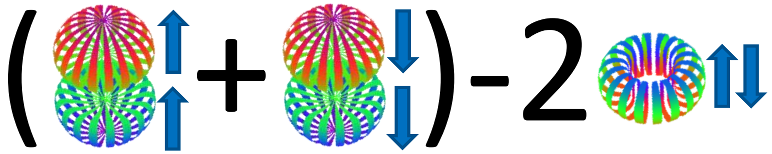

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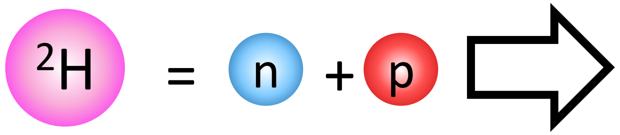

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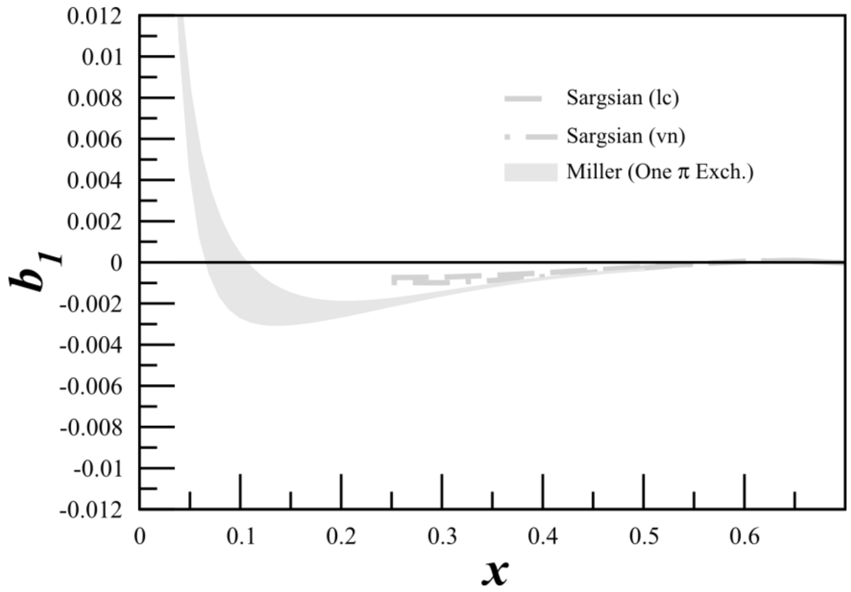

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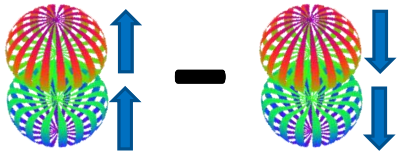

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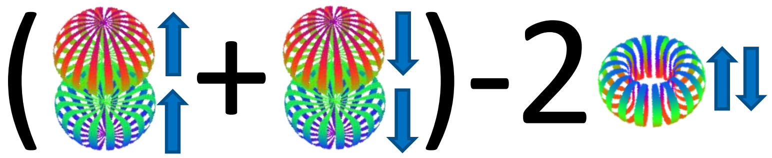

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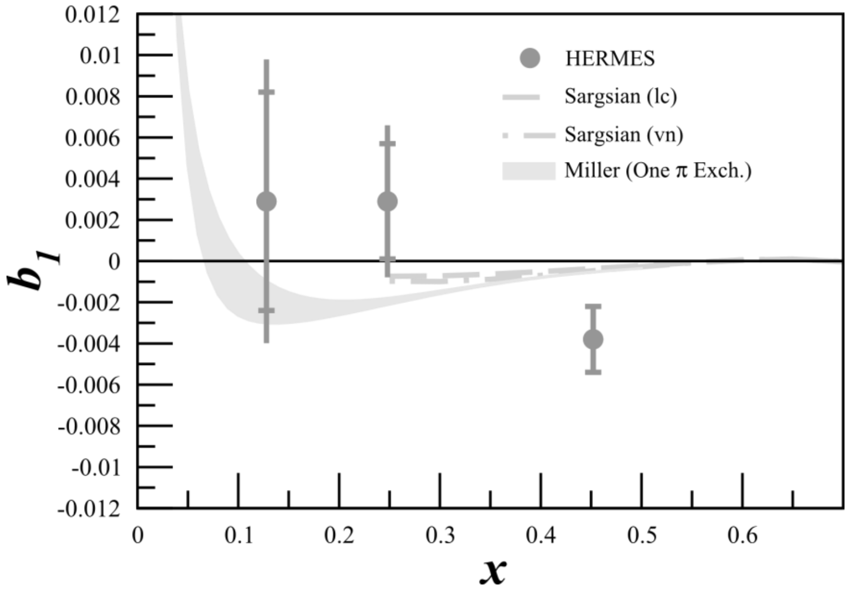

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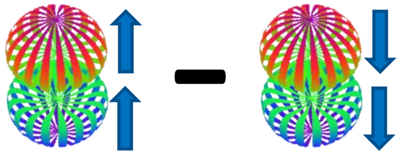

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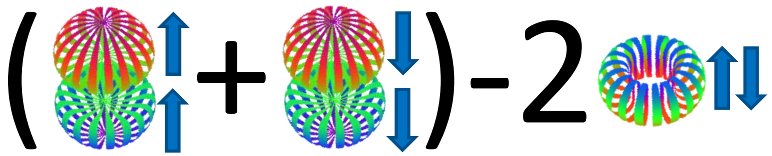

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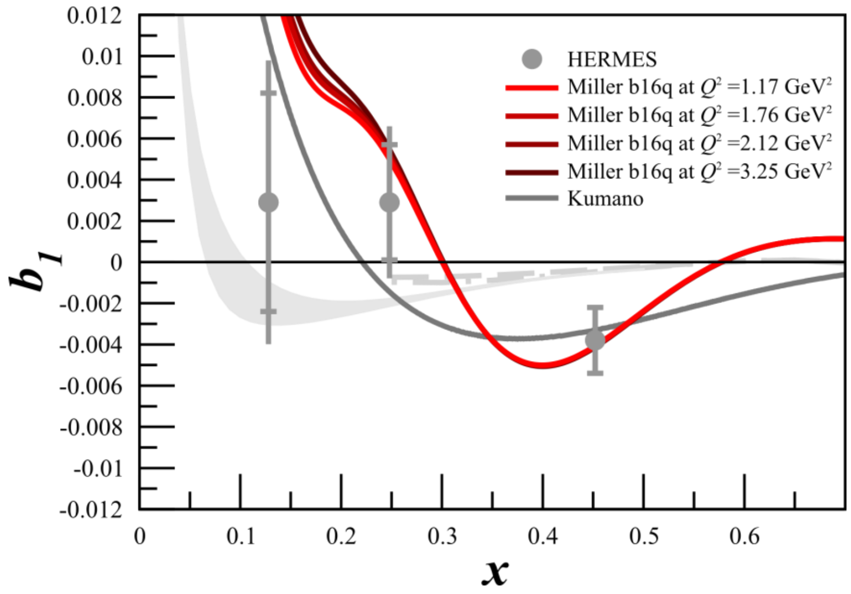

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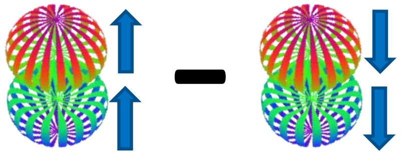

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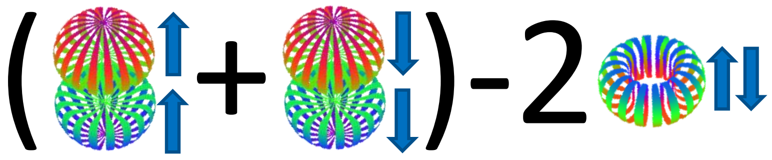

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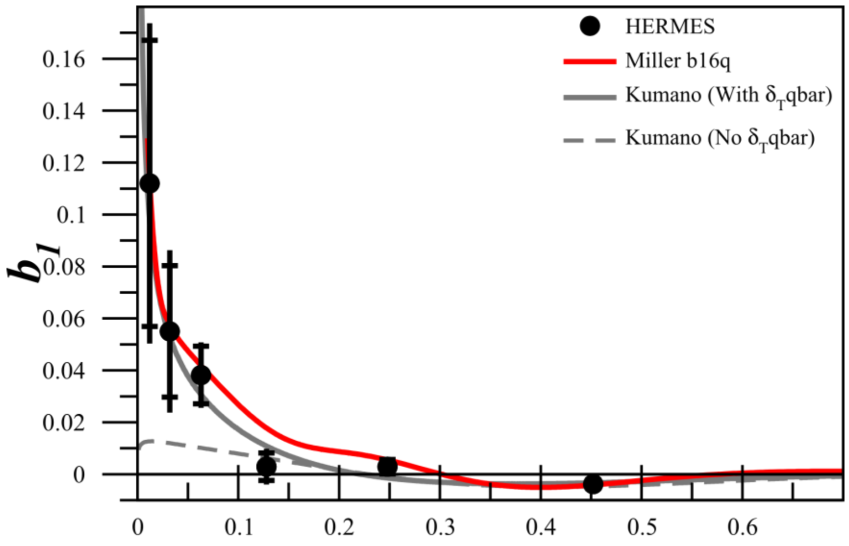

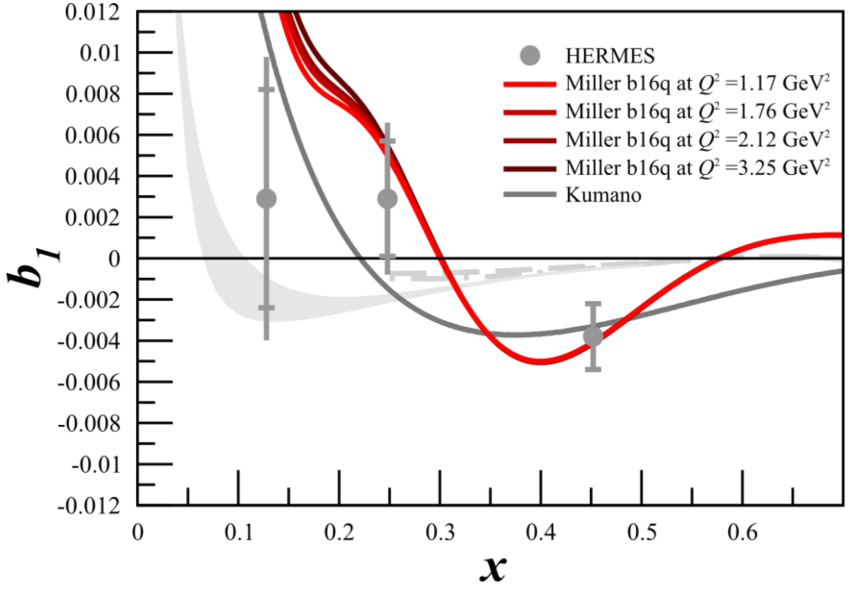

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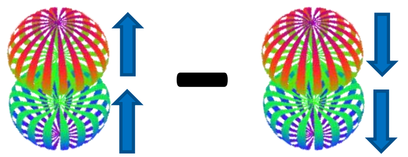

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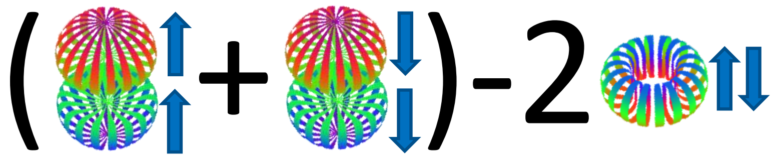

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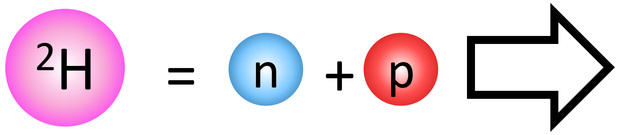

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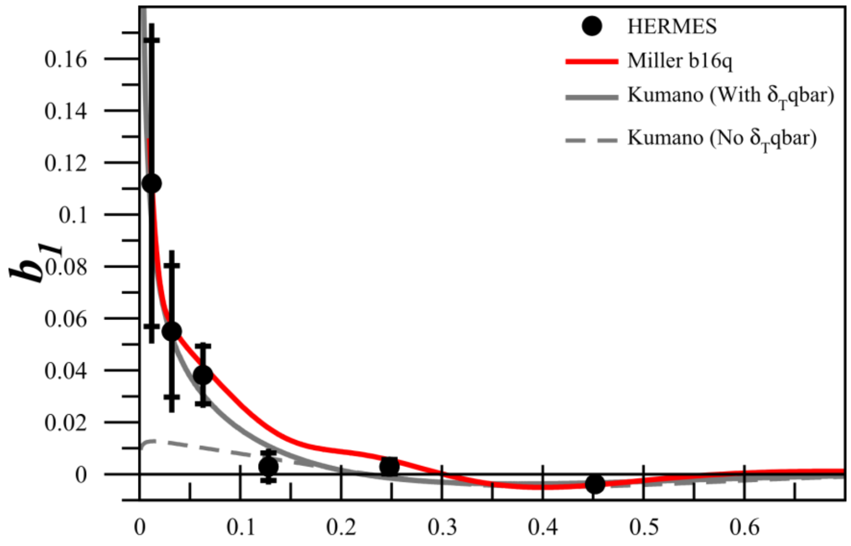

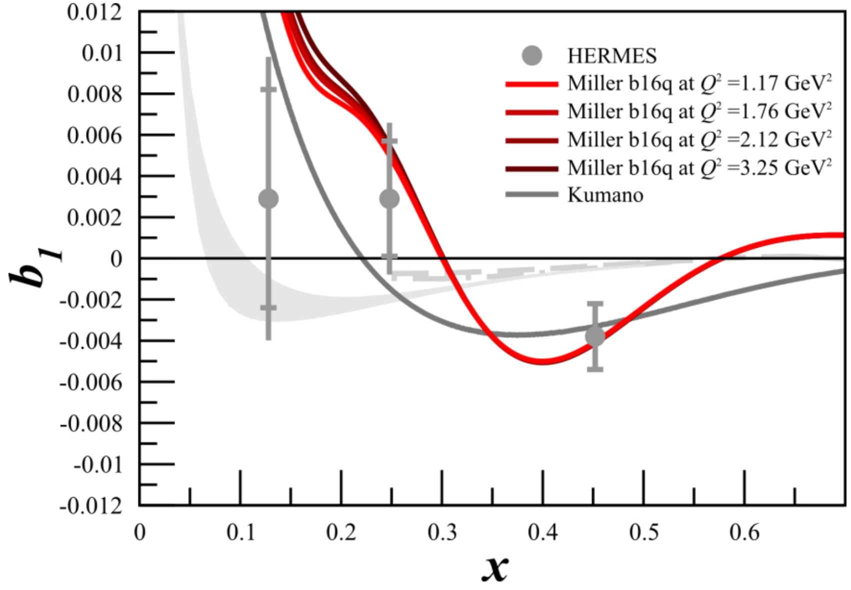

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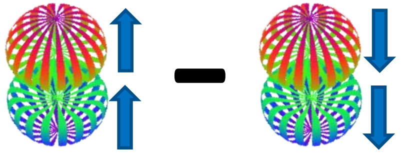

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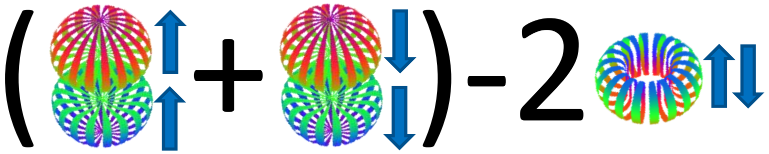

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JLab E12-13-011, A- Rating, C1 Approved

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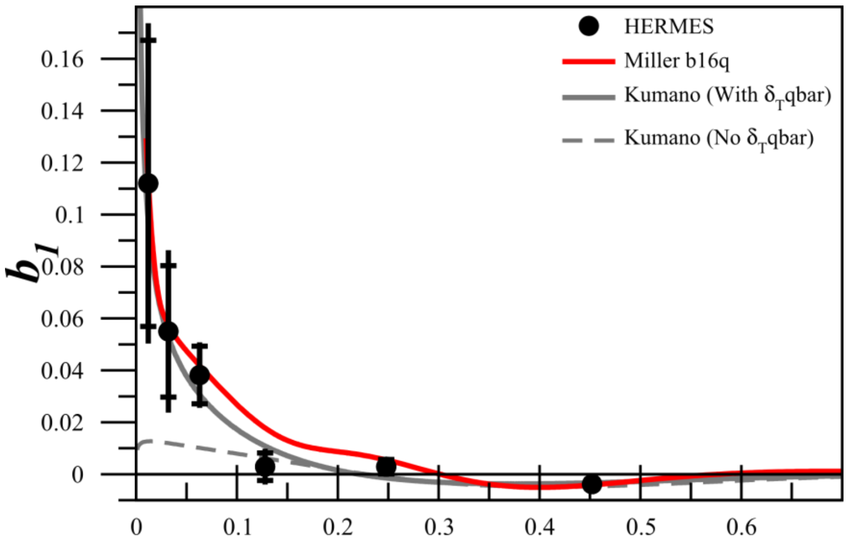

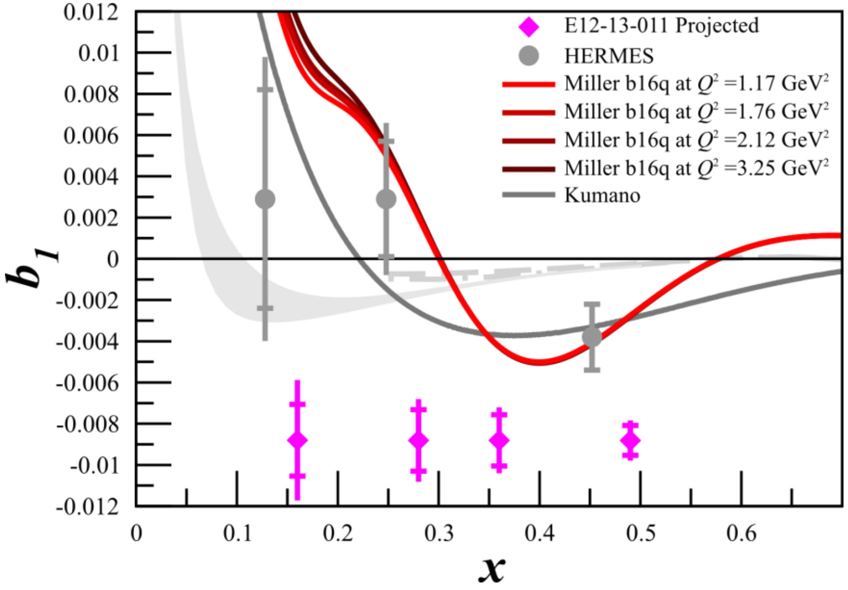

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JLab LOI12-14-002: Tensor Asymmetry
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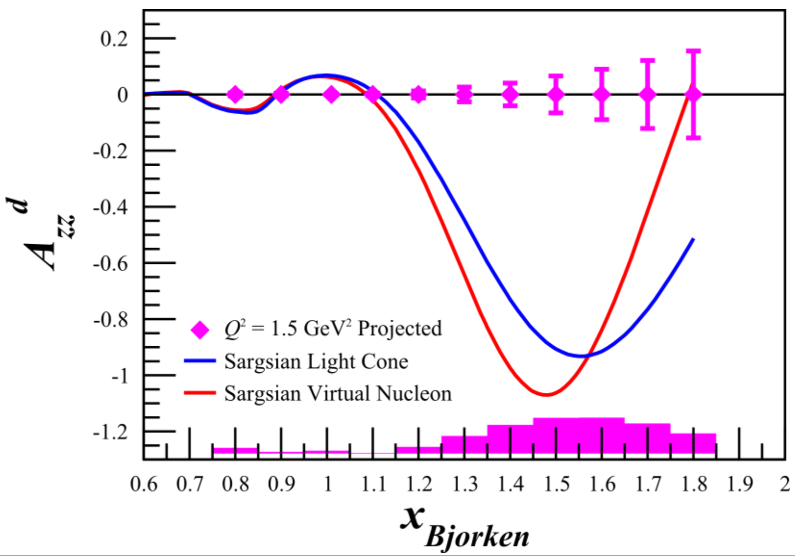

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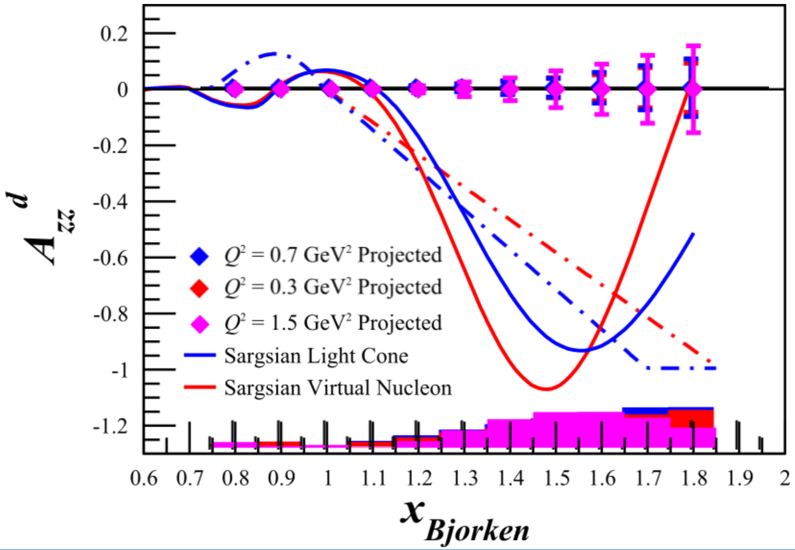

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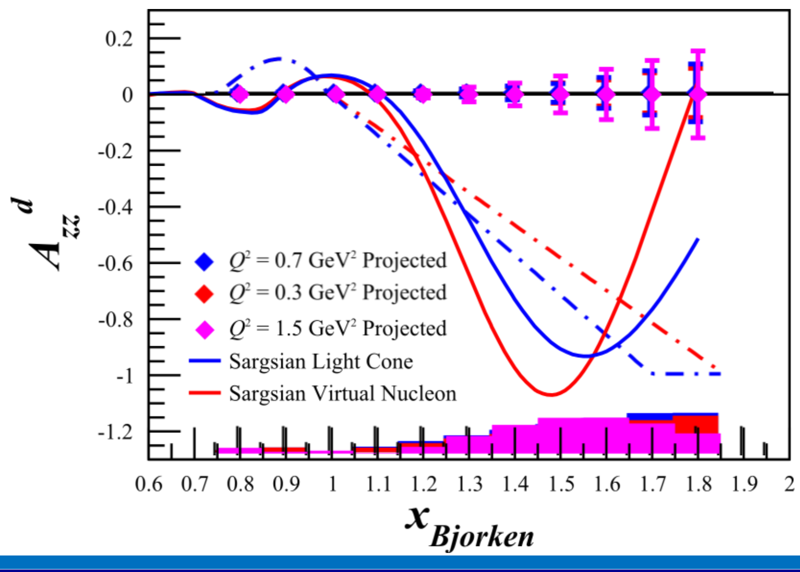

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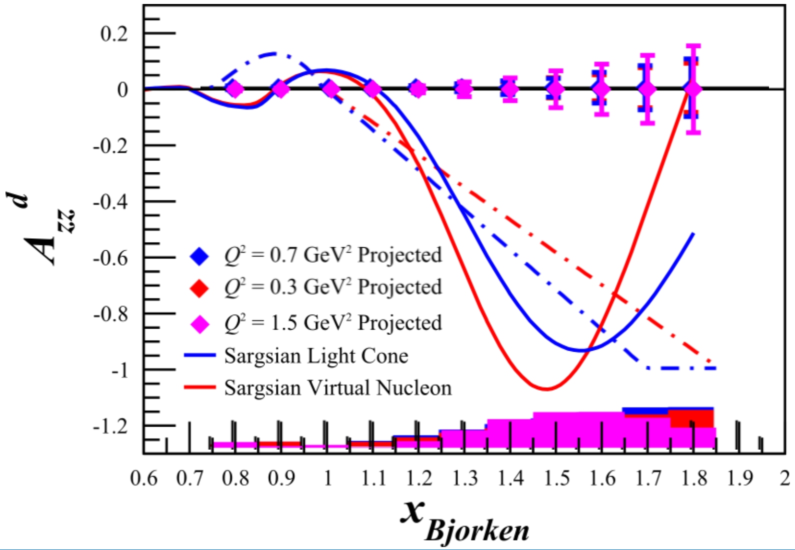

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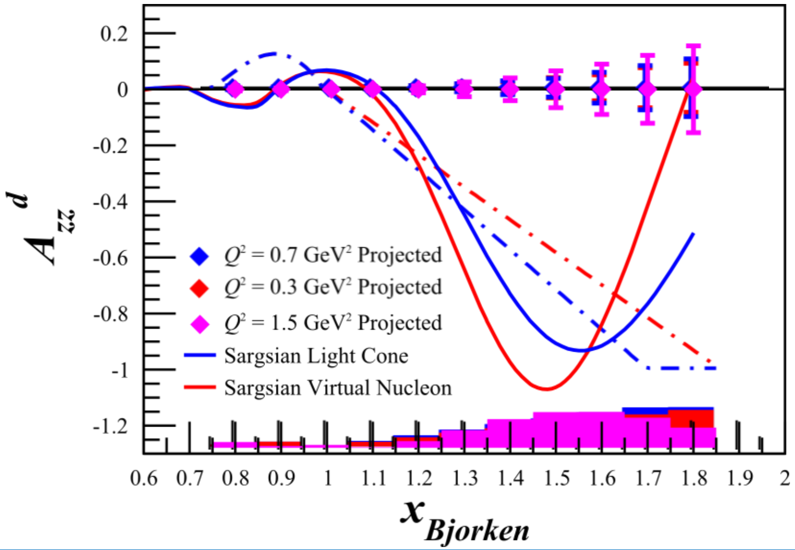

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JLab LOI12-14-001: Search for Exotic Gluonic States in the Nucleus

b_4 in $x < 0.3$ region

Insensitive to bound nucleons or pions[5]

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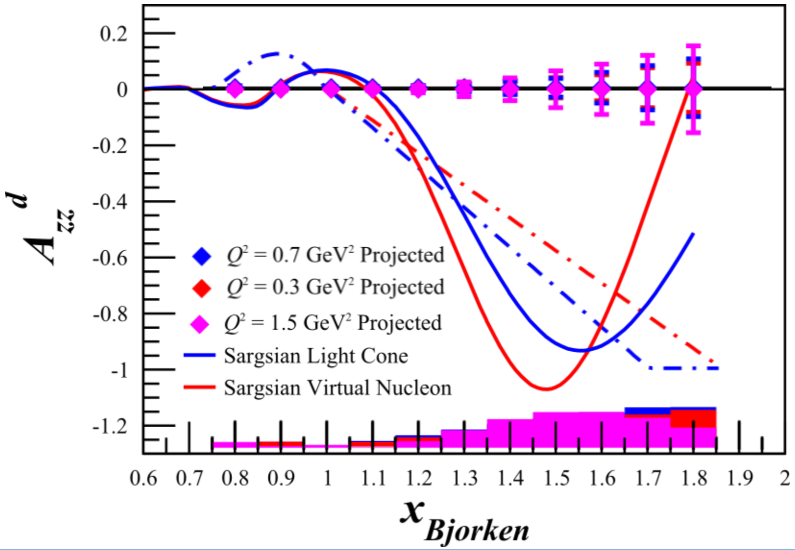

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Future of Tensor Measurements

Approved measurement of b_1

2 upcoming proposals

4 structure functions to explore

Many more ideas from Tensor Workshop

Ample opportunities for exploration

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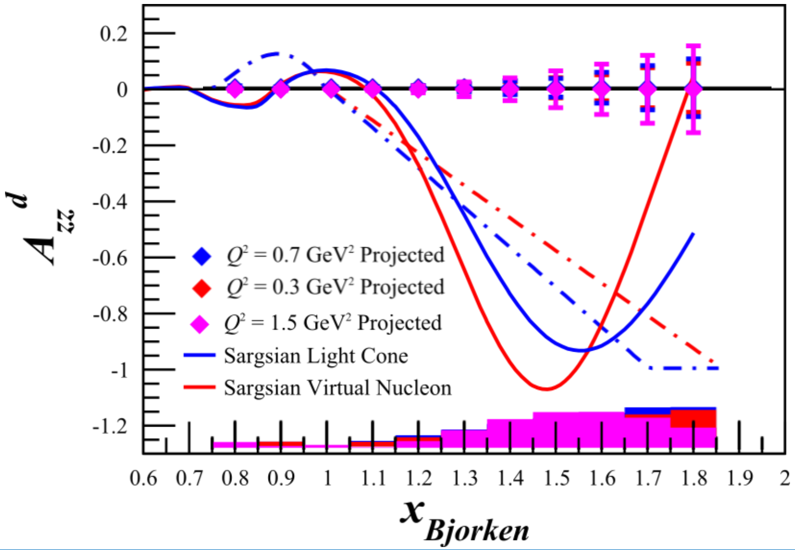
Similar to t_{20}, but in QE
SRCs & pn dominance[1]
Differentiate light cone and VN models[2]
Better understanding of s/d[3]
Final state interaction models[4]
Encouraged for full submission by PAC42

$$A_{zz} \propto \frac{\frac{1}{2}d^2 - sd}{s^2 + d^2}$$



"The measurement proposed here arises from a well-developed context, presents a clear objective, and enjoys strong theory support. It would further explore the nature of short-range *pn* correlations in nuclei, the discovery of which has been one of the most important results of the JLab 6 GeV nuclear program."
-JLab PAC42 Theory Advisory Committee

JLab LOI12-14-001: Search for Exotic Gluonic States in the Nucleus

b_4 in $x < 0.3$ region
Insensitive to bound nucleons or pions[5]
Any non-zero value indicates exotic gluonic components[5]
Encouraged for full submission by PAC42

[1] J Arrington *et al*, Prog. Part. Nucl. Phys. **67,** 898 (2012)
[2] M. Sargsian, private communication
[3] L Frankfurt, M Strikman, Phys. Rept. **160,** 235
[4] W Cosyn, M Sargsian, arXiv:1407.1653
[5] R Jaffe, A Manohar, Phys. Lett. **B223,** 218 (1989)

Future of Tensor Measurements

Approved measurement of b_1
2 upcoming proposals
4 structure functions to explore
Many more ideas from Tensor Workshop
Ample opportunities for exploration

Ideas to probe novel nuclear effects through tensor structure are growing rapidly. It is paramount that a high luminosity, high tensor polarization target be developed to make these experiments possible

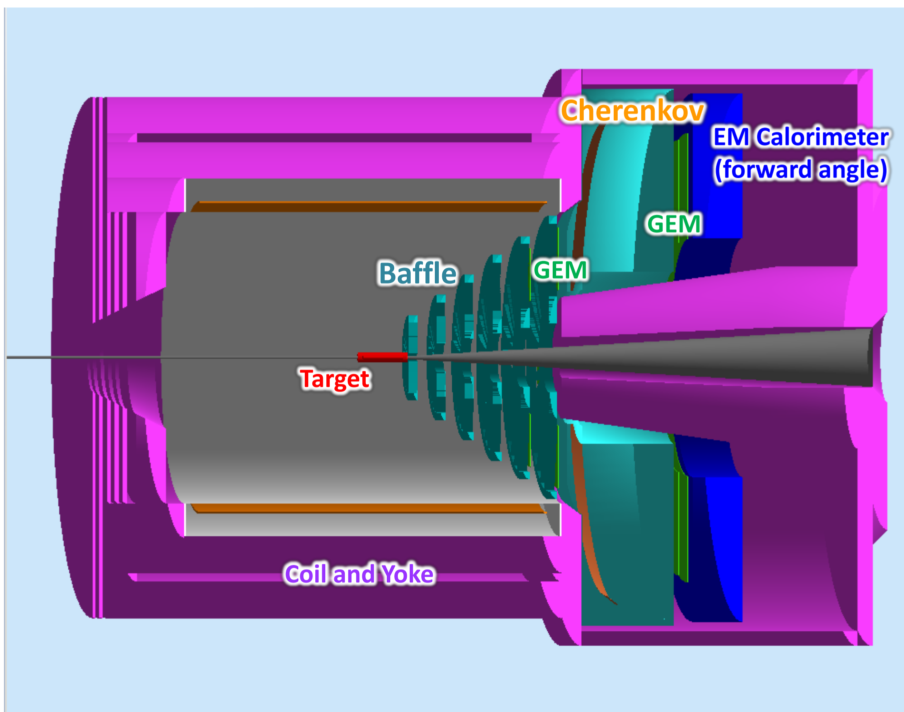
PVDIS with SoLID

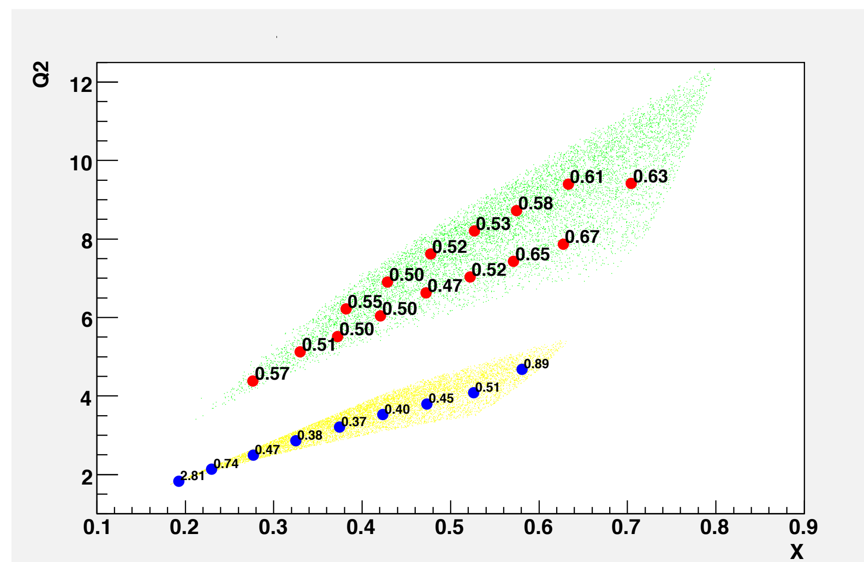
$$A_{\mathrm{PV}} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r} \approx \frac{\mathcal{M}^l_{Z^0} - \mathcal{M}^r_{Z^0}}{\mathcal{M}_\gamma}$$

$$\propto -\left(\frac{G_{\mathrm{F}} Q^2}{4\pi\alpha}\right)\left(g_A^e g_V^T + \beta g_V^e g_A^T\right)$$

Involves both EW coupling and QCD Physics

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



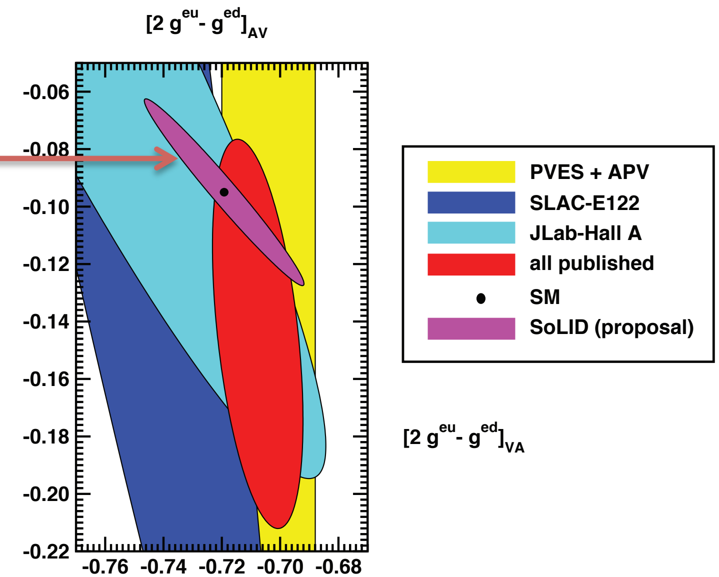


New Physics

SoLID projection

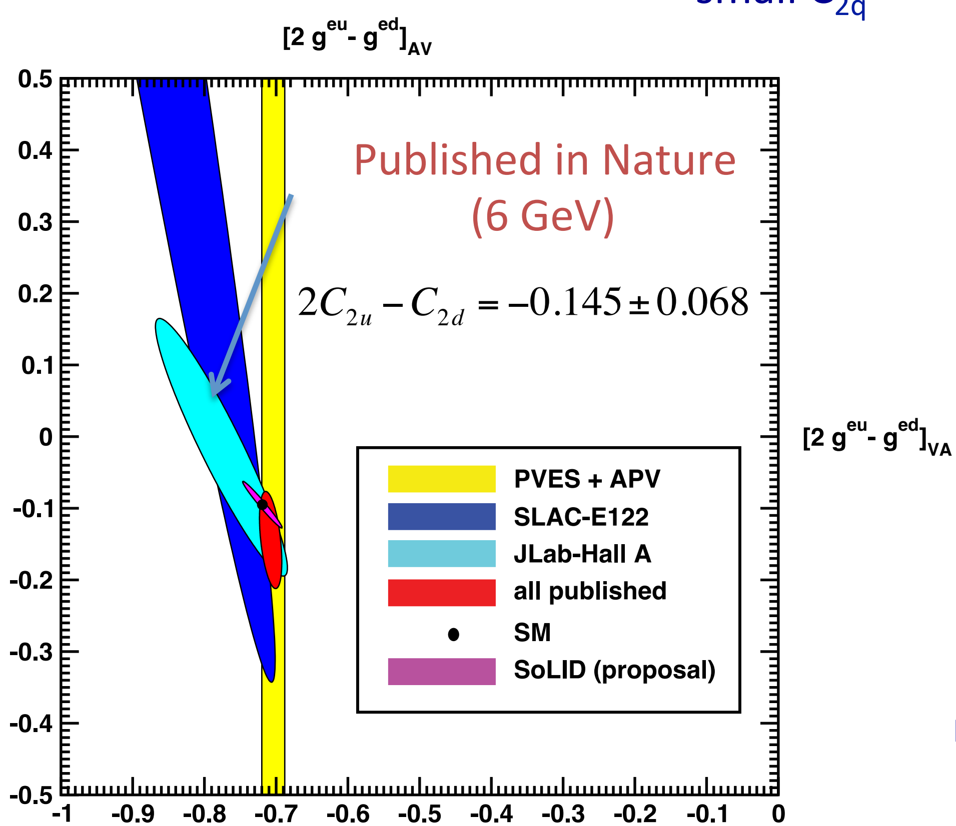
$$b(x) = \frac{\sum_i C_{2i} Q_i f_i^-(x)}{\sum_i Q_i^2 f_i^+(x)}$$

PVDIS is the only way to measure the small C_{2q}



Published in Nature (6 GeV)

$$2C_{2u} - C_{2d} = -0.145 \pm 0.068$$

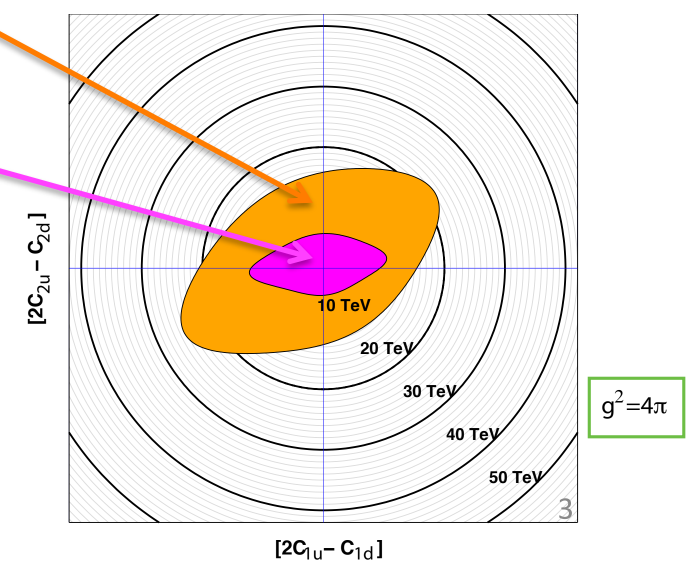


$$\mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{(g_{ij}^{12})^2}{\Lambda_{ij}^2} \bar{f}_{1i}\gamma_\mu f_{1i} \bar{f}_{2j}\gamma_\mu f_{2j}$$

SoLID

6 GeV

Composite model mass limits



QCD Physics with different targets

CSV at Quark Level

$$\delta u(x) = u^p(x) - d^n(x)$$

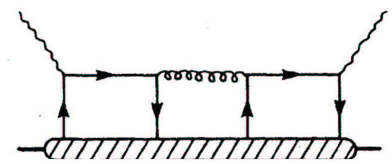
$$\delta d(x) = d^p(x) - u^n(x)$$

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

^{2}H (isoscalar)

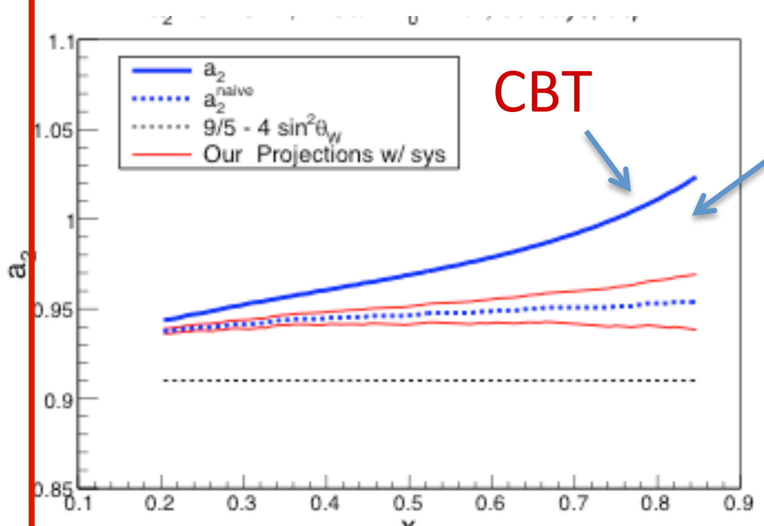
$$a(x) = \frac{\sum_i C_{1i} Q_i f_i^+(x)}{\sum_i Q_i^2 f_i^+(x)}$$

Di-quarks in the nucleon (Q^2 Dependence)



Explain NuTeV??

Isovector EMC effect

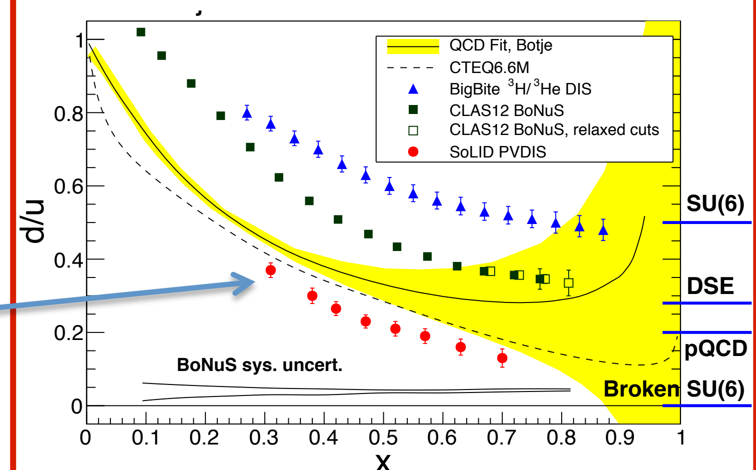


CBT

^{48}Ca

^{1}H

Measure d/u without nuclear effects



Backup

$$A = A\left[1 + \beta_{HT}\frac{1}{(1-x)^3 Q^2} + \beta_{CSV}x^2\right]$$

$ep \to ep\pi^0$: access to chiral-odd GPDs

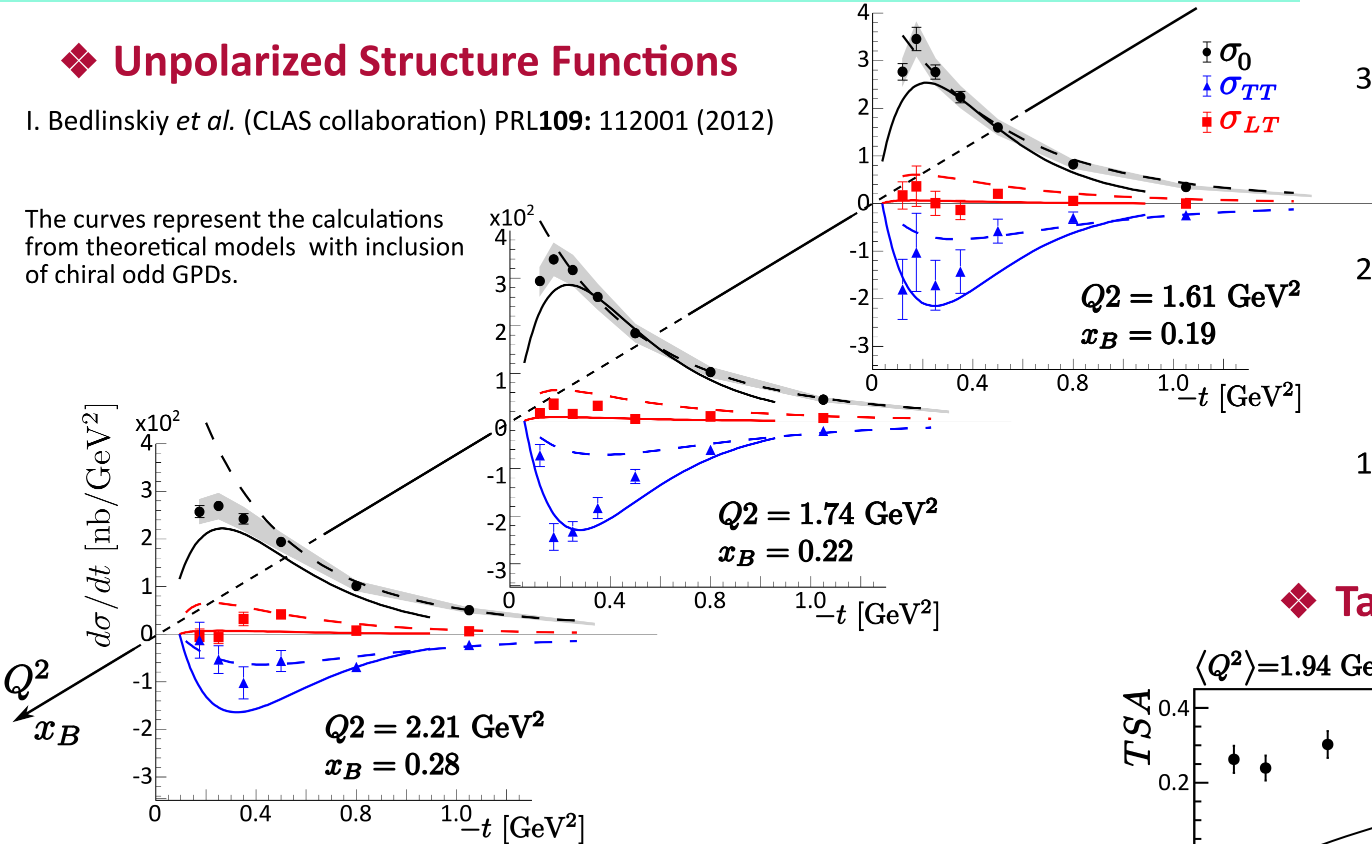
$$\sigma_T \sim (1-\xi^2)|\langle H_T\rangle|^2 - \frac{t'}{8m^2}|\langle \bar{E}_T\rangle|^2 \qquad A_{LU}^{\sin\phi}\sigma_0 \sim \mathrm{Im}\left[\langle H_T\rangle^* \langle \tilde{E}\rangle\right]$$

$$\sigma_{TT} \sim \frac{t'}{8m^2}|\langle \bar{E}_T\rangle|^2 \qquad A_{LL}^{const}\sigma_0 \sim |\langle H_T\rangle|^2$$

❖ Unpolarized Structure Functions

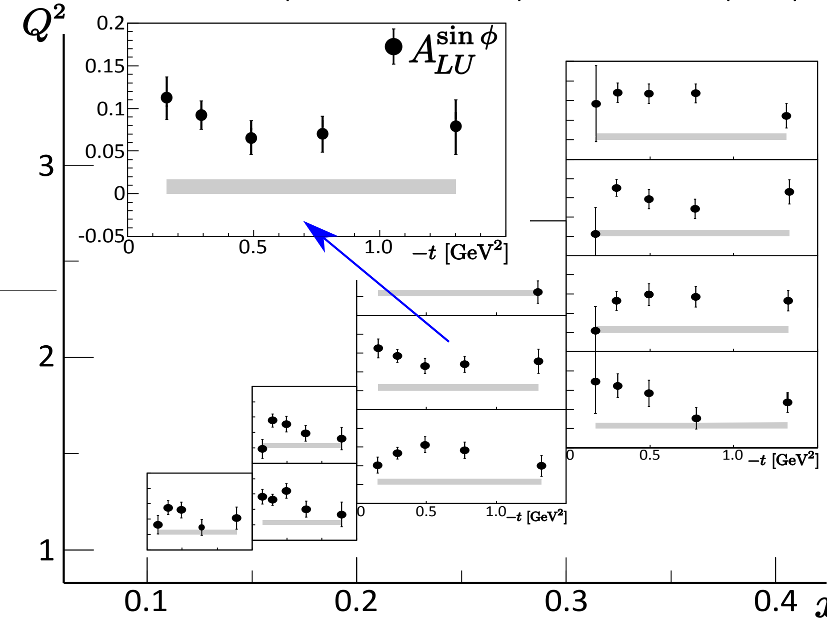
I. Bedlinskiy *et al.* (CLAS collaboration) PRL**109:** 112001 (2012)

The curves represent the calculations from theoretical models with inclusion of chiral odd GPDs.

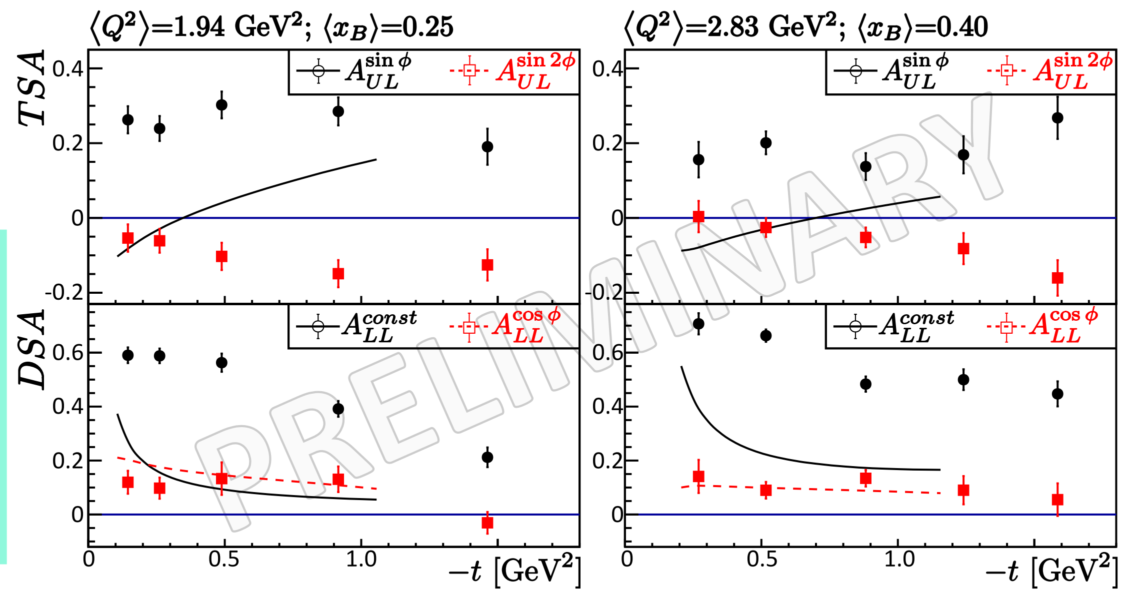


❖ Beam Spin Asymmetries

R. De Masi *et al.* (CLAS collaboration) PRC**77:** 042201 (2008)



❖ Target and Double Spin Asymmetries



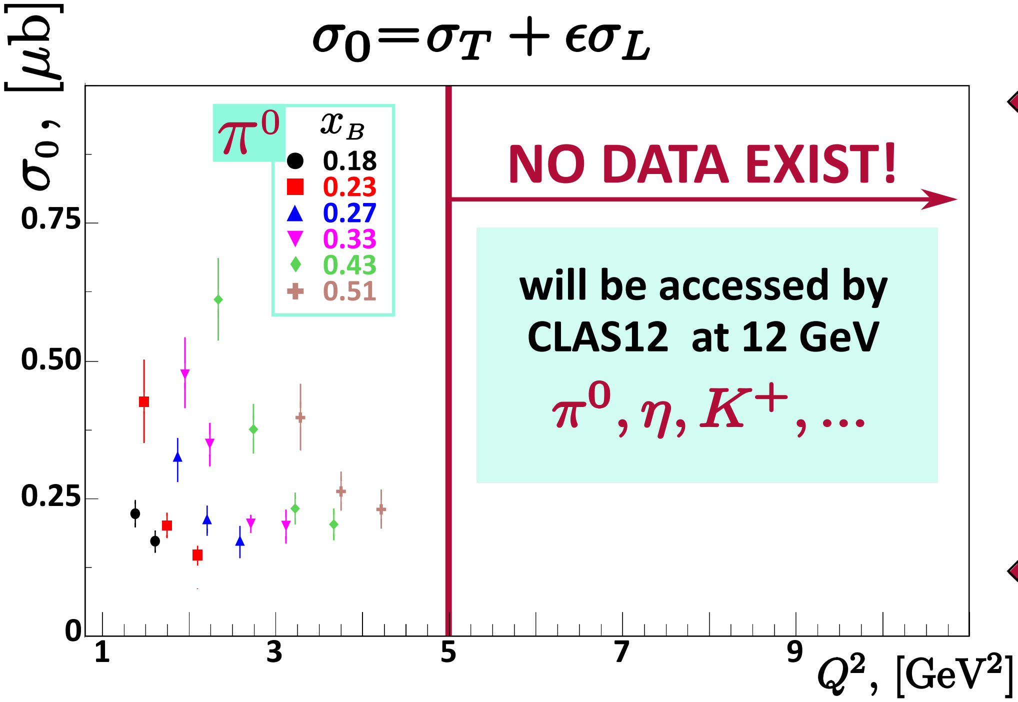
Dominated by transverse virtual photons contribution

⇓

Unique sensitivity

for constraining the chiral-odd GPDs

12 GeV Upgrade and Variety of Pseudoscalar Meson Production



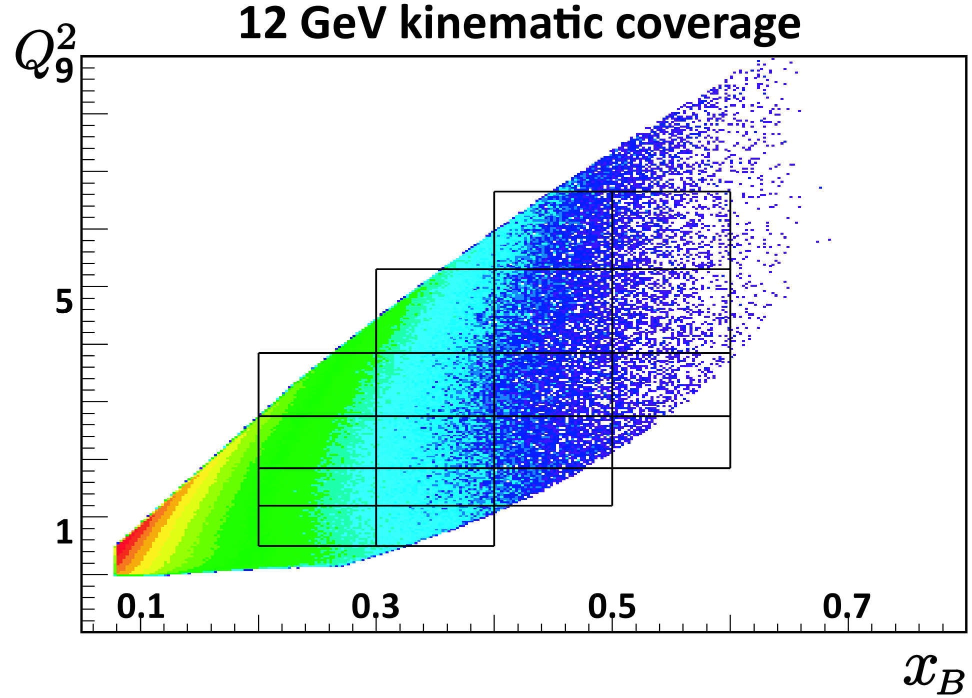
- Quark flavor decomposition:

$$F_i^{\pi^0} = \frac{(e_u F_i^u - e_d F_i^d)}{\sqrt{2}} \qquad F_{ip\to\Lambda} = -\frac{(2F_i^u - F_i^d)}{\sqrt{6}}$$

$$F_i^{\eta} = \frac{(e_u F_i^u + e_d F_i^d)}{\sqrt{6}} \qquad F_{ip\to\Sigma^0} = -\frac{F_i^d}{\sqrt{2}}$$

- Flavor ratios: cancellation of higher twist effects $\pi^0/\eta, \ldots$

12 GeV kinematic coverage



- The combination of high beam intensity with large acceptance detectors allows for precise measurements of "rare" processes such as deep exclusive reactions: CLAS12 is uniquely suited for simultaneous detection of various DVMP channels

- Expansion of the kinematic coverage provides the opportunity to test the mechanism of pseudoscalar meson electroproduction in great details and perform the separation of the contributions from the different chiral-odd GPDs

Projections for GPD H with CLAS12

Count rates
projections for 12 GeV
unpolarized
long. and transv.
polarized targets

$\Downarrow$ Acceptance, Binning, Resolutions

Observables, Uncertainties
σ, A_{LU}, A_{LL}, A_{UT} $\cdots$

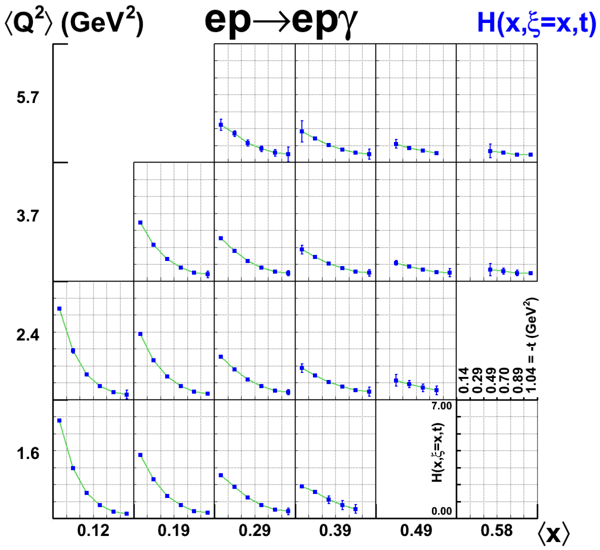
$\Downarrow$ Extraction procedures

Generalized Parton
Distributions
H, $\tilde{H}$, E, $\tilde{E}$

$\Downarrow$ Fourier Transform

Quark densities $q \ (x_B, p_\perp)$
Angular Momentum Sum Rule

related to E



Projections for GPD E with CLAS12

Count rates
projections for 12 GeV
unpolarized
long. and transv.
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$\Downarrow$ Acceptance, Binning, Resolutions

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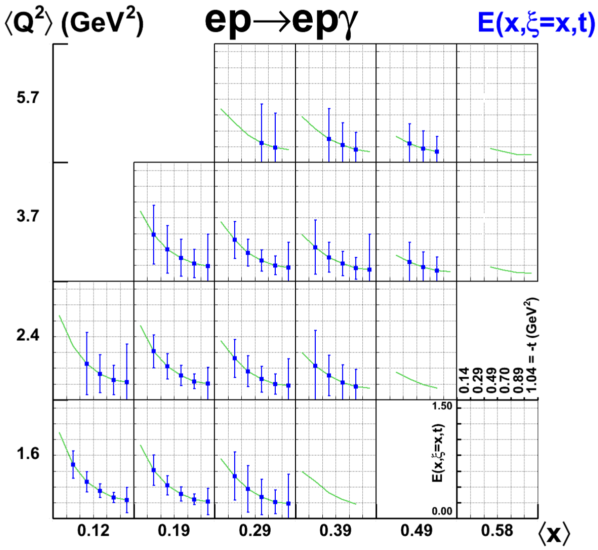
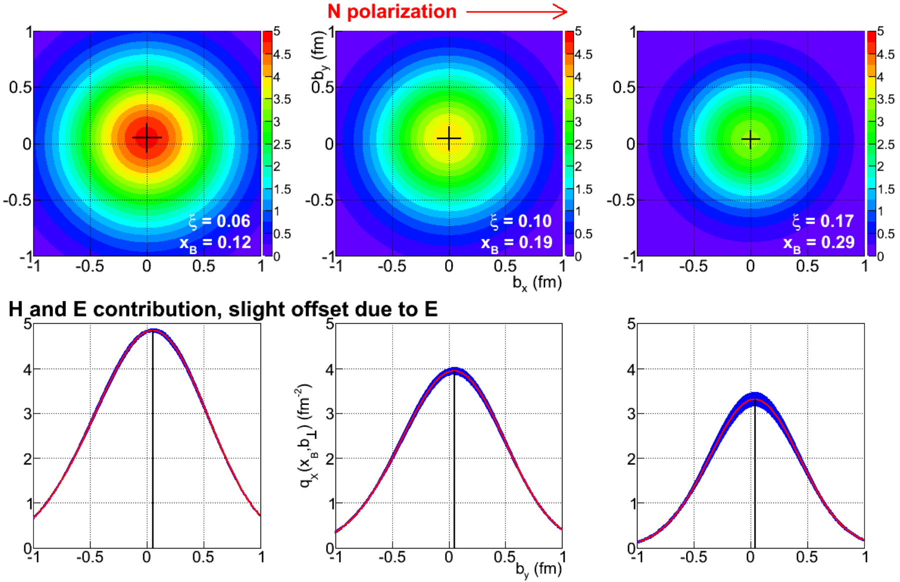
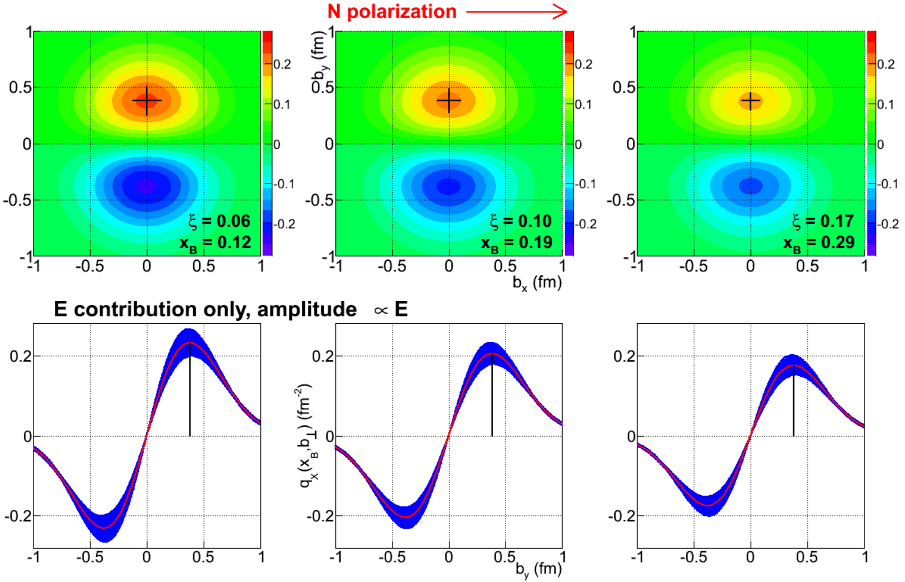
Quark densities $q_\perp(x_B, p_\perp)$
Angular Momentum Sum Rule
related to E



Projections for quark transverse profile



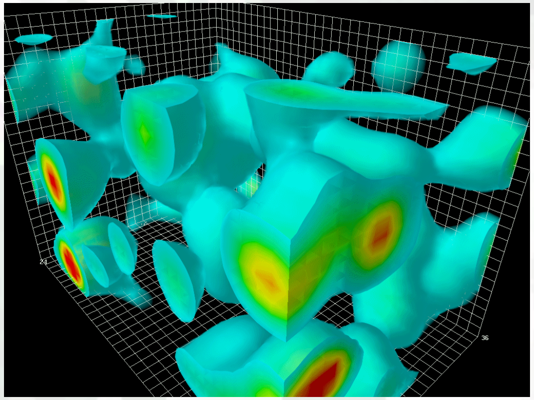
Projections for quark transverse profile



Future prospects of di-jet production at forward rapidity constraining $\Delta g(x)$ at low x in polarized p+p collisions at RHIC

Bernd Surrow

TEMPLE UNIVERSITY

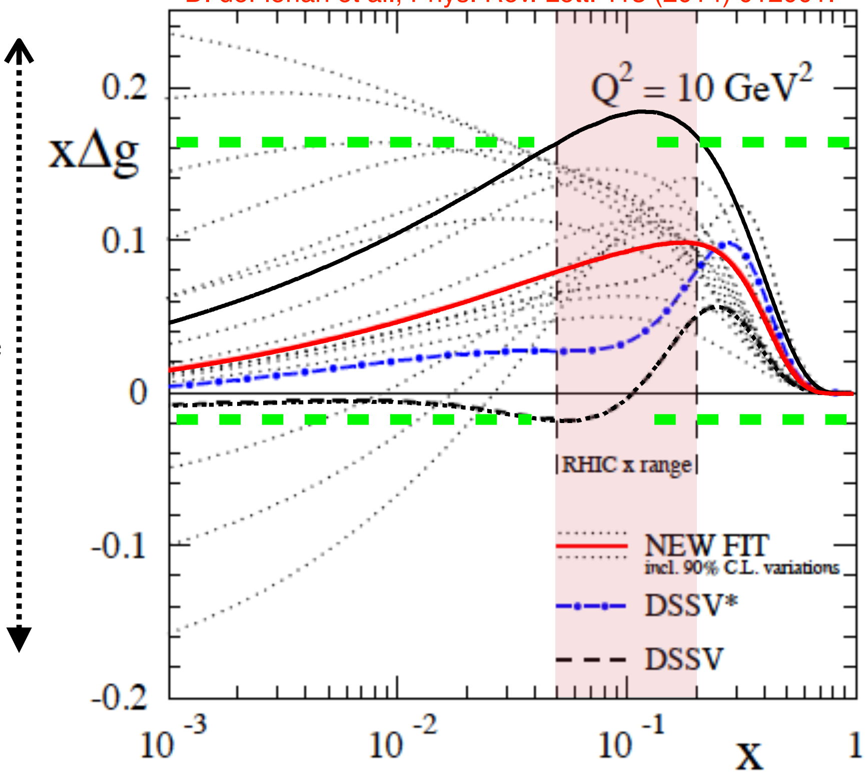


Results / Status - Gluon polarization program

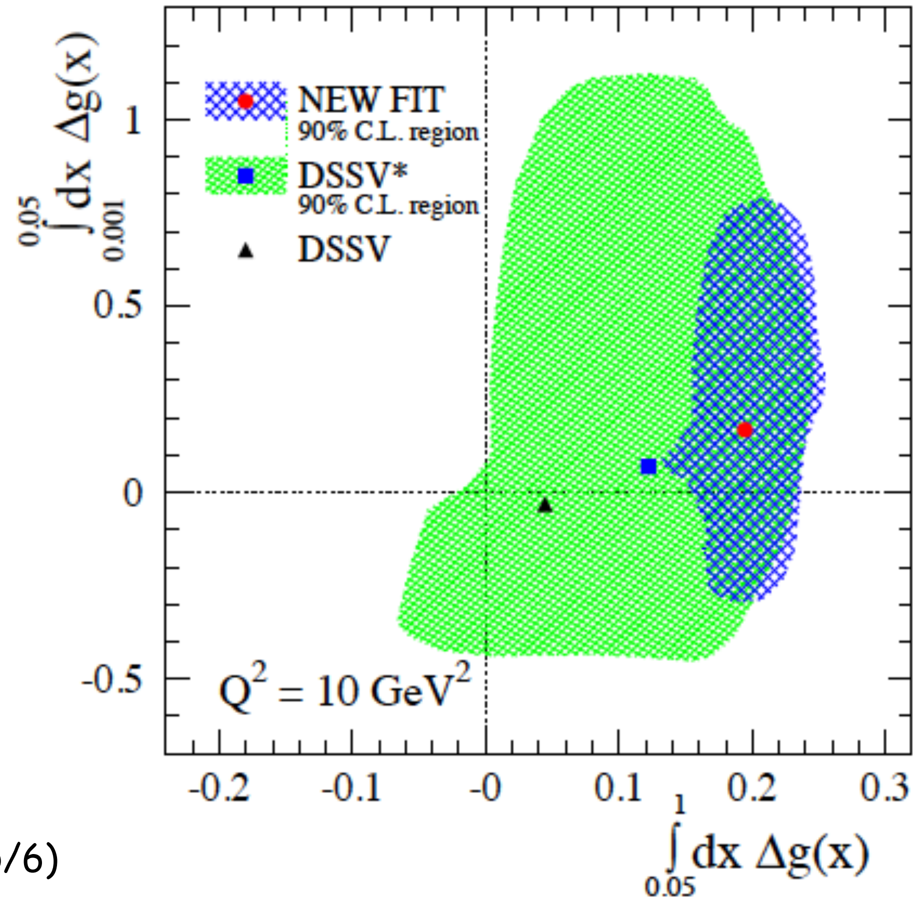
Impact on Δg from RHIC data

D. deFlorian et al., Phys. Rev. Lett. 113 (2014) 012001.

Wide spread at low x ($x<0.05$) of alternative fits consistent within 90% of C.L.



D. deFlorian et al., Phys. Rev. Lett. 113 (2014) 012001.



- DSSV: Original global analysis incl. first RHIC results (Run 5/6)
- DSSV*: New COMPASS inclusive and semi-inclusive results in addition to Run 5/6 RHIC updates
- DSSV - NEW FIT: Strong impact on $\Delta g(x)$ with RHIC run 9 results ⇒ Positive for $x > 0.05$!

"...better small-x probes are badly needed."

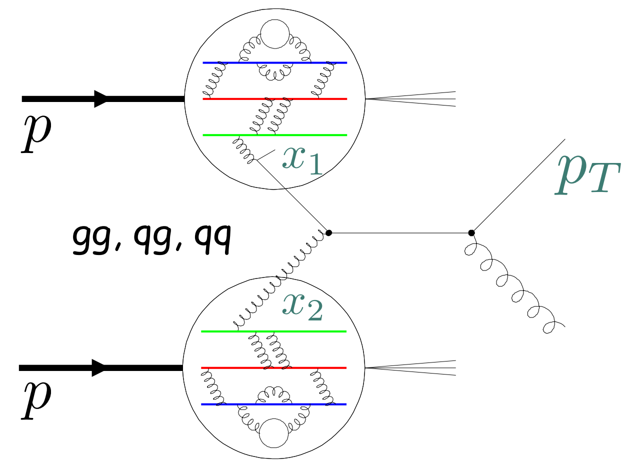
D. deFlorian et al., Phys. Rev. Lett. 113 (2014) 012001.

Results / Status - Gluon polarization program

RHIC Gluon polarization - Correlation Measurements

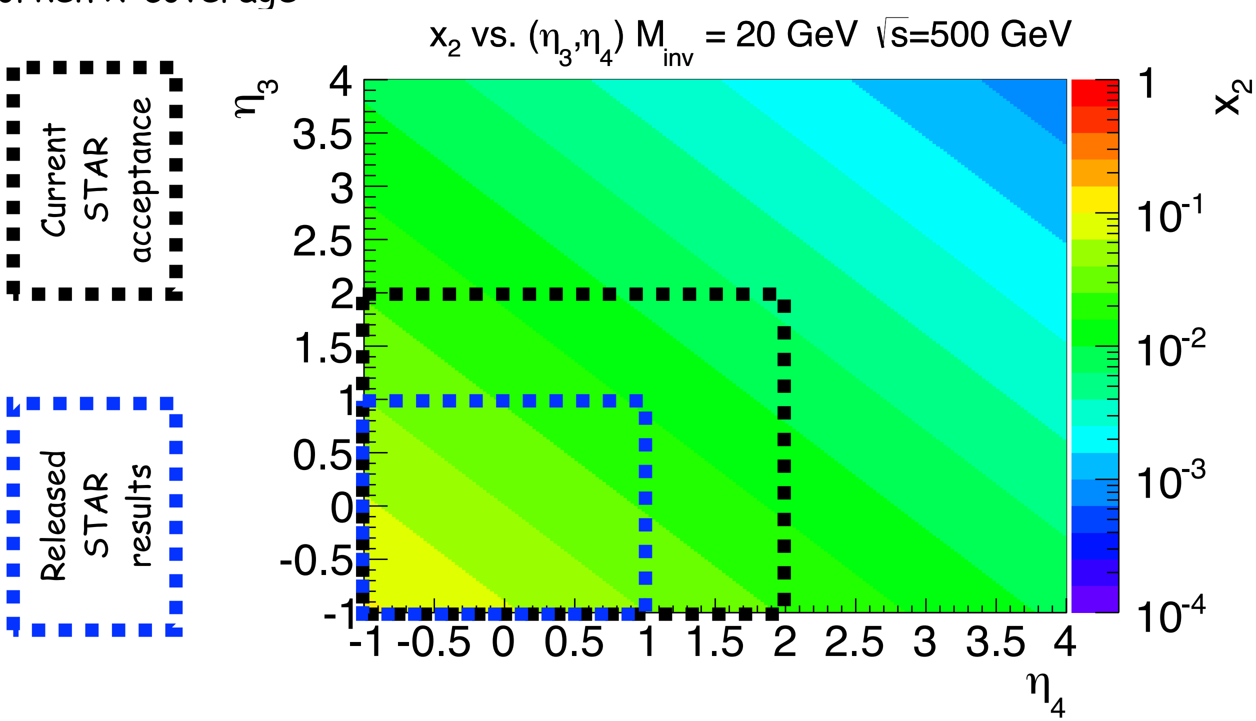
- Correlation measurements provide access to partonic kinematics through Di-Jet/Hadron production and Photon-Jet production:

$$x_{1\,(2)} = \frac{1}{\sqrt{s}} \left(p_{T_3} e^{\eta_3 (-\eta_3)} + p_{T_4} e^{\eta_4 (-\eta_4)} \right)$$



Di-Jet production

- Bjorken x-coverage:



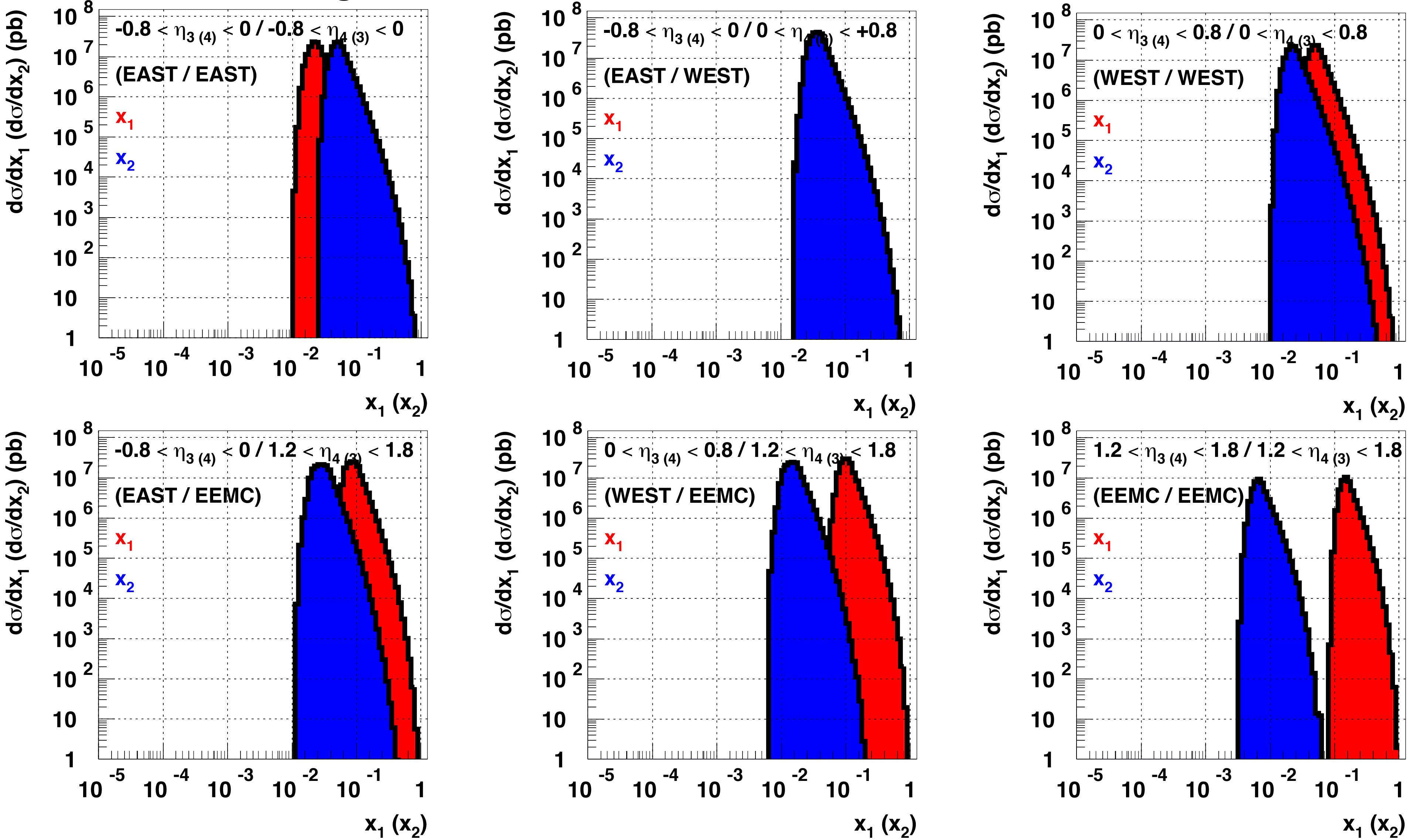
$$\eta_3 + \eta_4 = \ln \frac{x_1}{x_2}$$

$$M = \sqrt{s}\sqrt{x_1 x_2}$$

Future prospects - Gluon polarization program

- Kinematic coverage - Simulations / Central

Cone alg. (R=0.7) / E_{T3} > 5GeV E_{T4} > 8GeV



Bernd Surrow

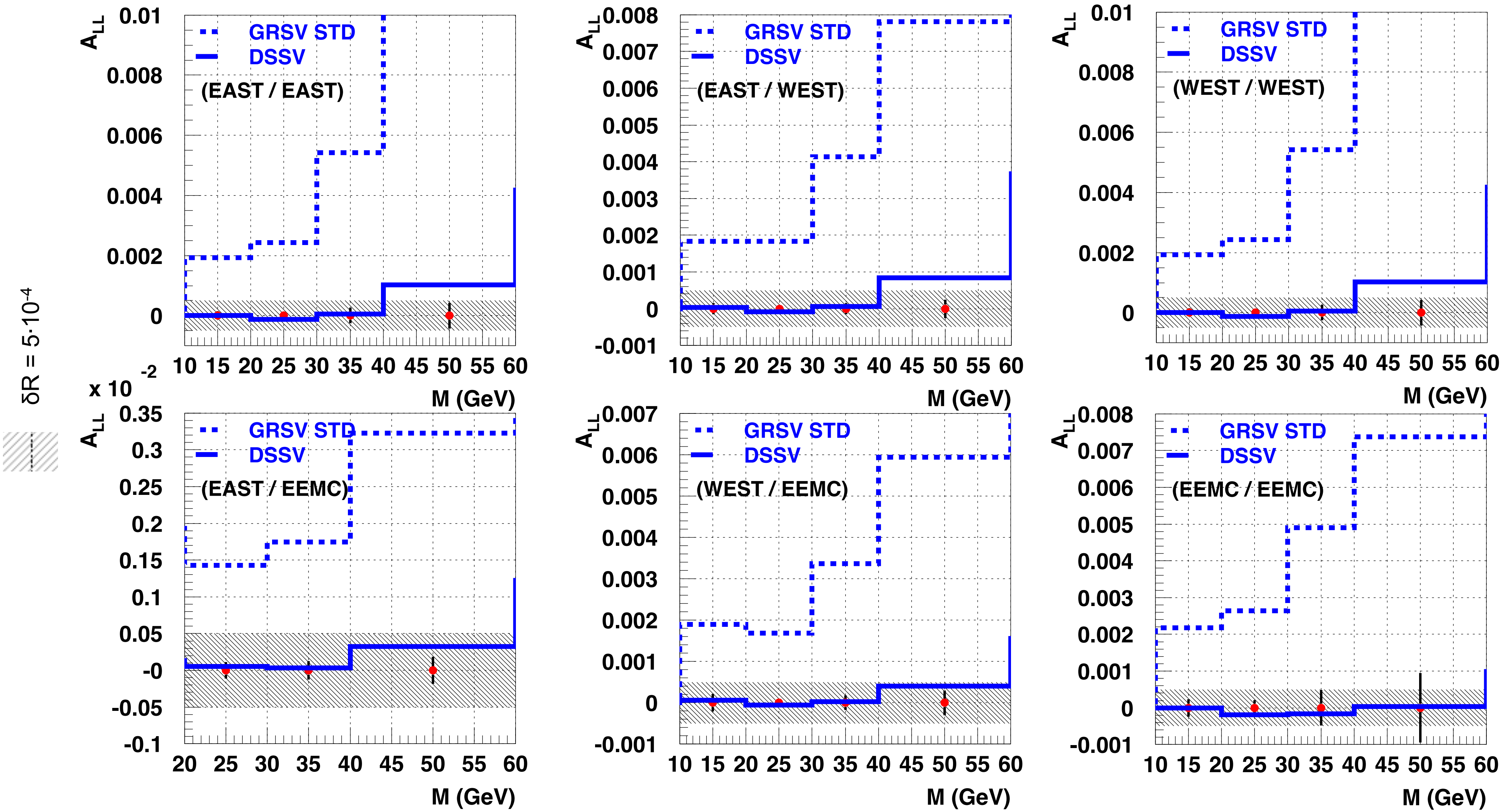
Future prospects - Gluon polarization program

- A_{LL} projections / Central

Cone alg. (R=0.7) / E_{T3} > 5GeV E_{T4} > 8GeV

Delivered Luminosity = $1000 pb^{-1}$

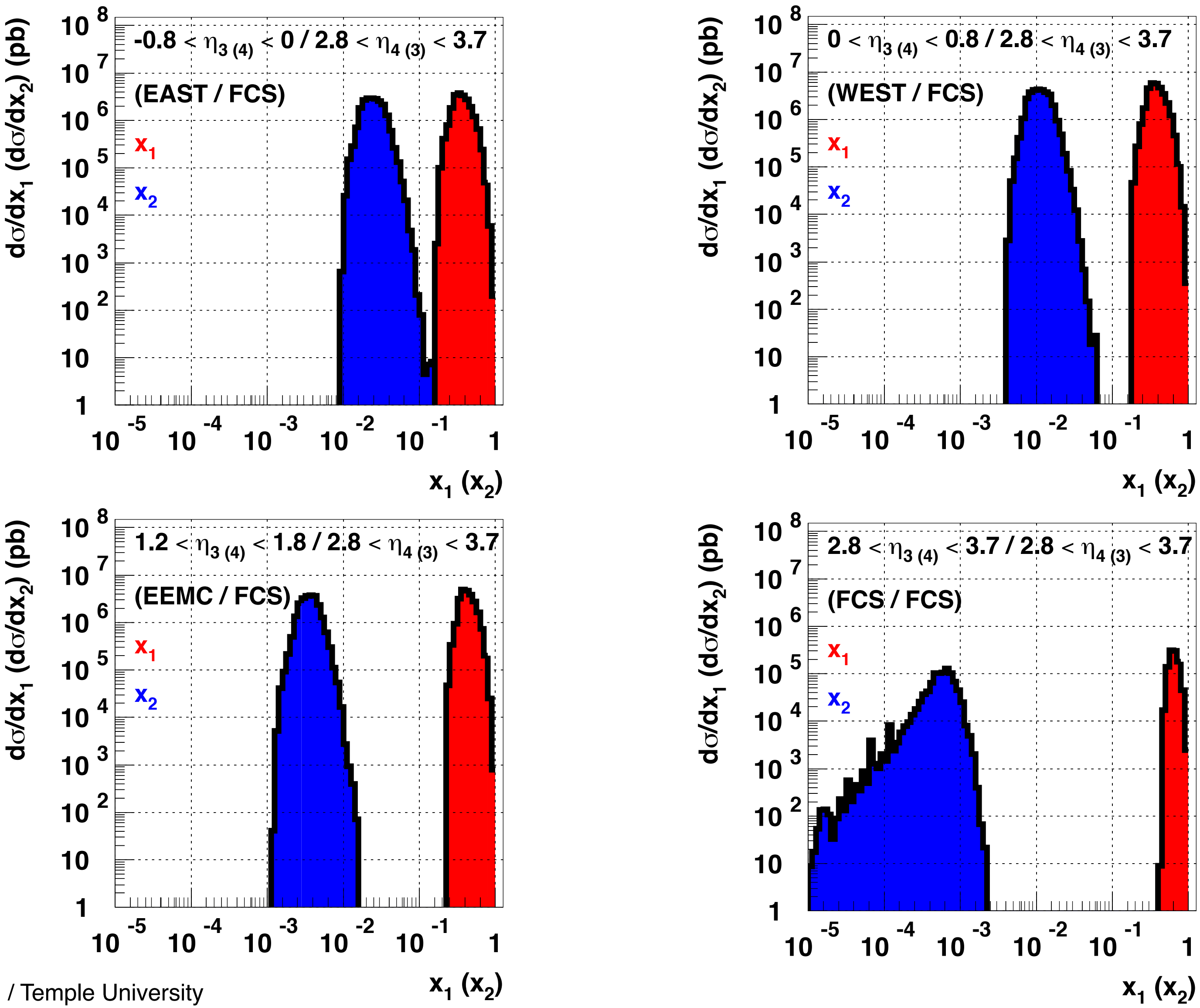
Polarization = 60%



Future prospects - Gluon polarization program

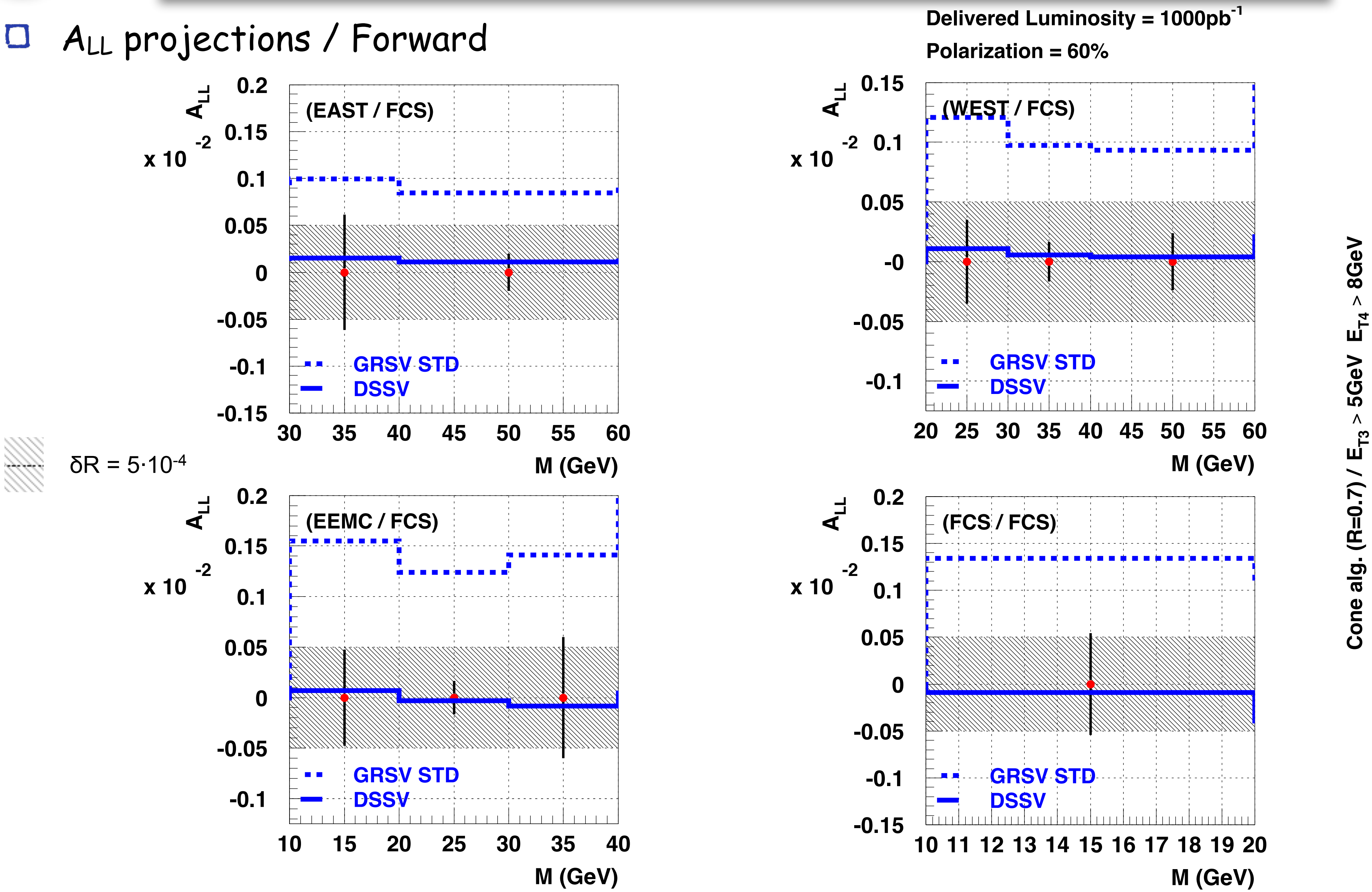
- Kinematic coverage - Simulations / Forward

Cone alg. (R=0.7) / E_{T3} > 5GeV E_{T4} > 8GeV



Future prospects - Gluon polarization program

- A_{LL} projections / Forward



Summary

- Status: Gluon polarization program:
  - First Di-Jet measurement opens the path to constrain the shape of Δg
  - Run 9 results: Precise A_{LL} measurement suggesting non-zero ΔG
- New global analysis by DSSV:
  - Non-zero $\Delta g(x)$ for $x > 0.05$
  - Larger uncertainties for $x < 0.05$, i.e. below current RHIC kinematic region!
- Run 14 STAR BUR request:
  - 6 weeks with $L_{delivered} = 75 pb^{-1}$ and 60%
- Forward jet production:
  - Extend jet measurements at forward rapidity probing $\Delta g(x)$ as low as 10^{-3} in x
  - Good control of sys. uncertainties important (Assume ~ 1 long RHIC run!)
  - Additional probes to be studied: π^0-jet correlations!
  - Important step prior to a future Electron-Ion Collider (EIC) ~2025!

STAR

LOI for forward STAR upgrade focusing on forward pp/pA program