Perspectives of SIDIS

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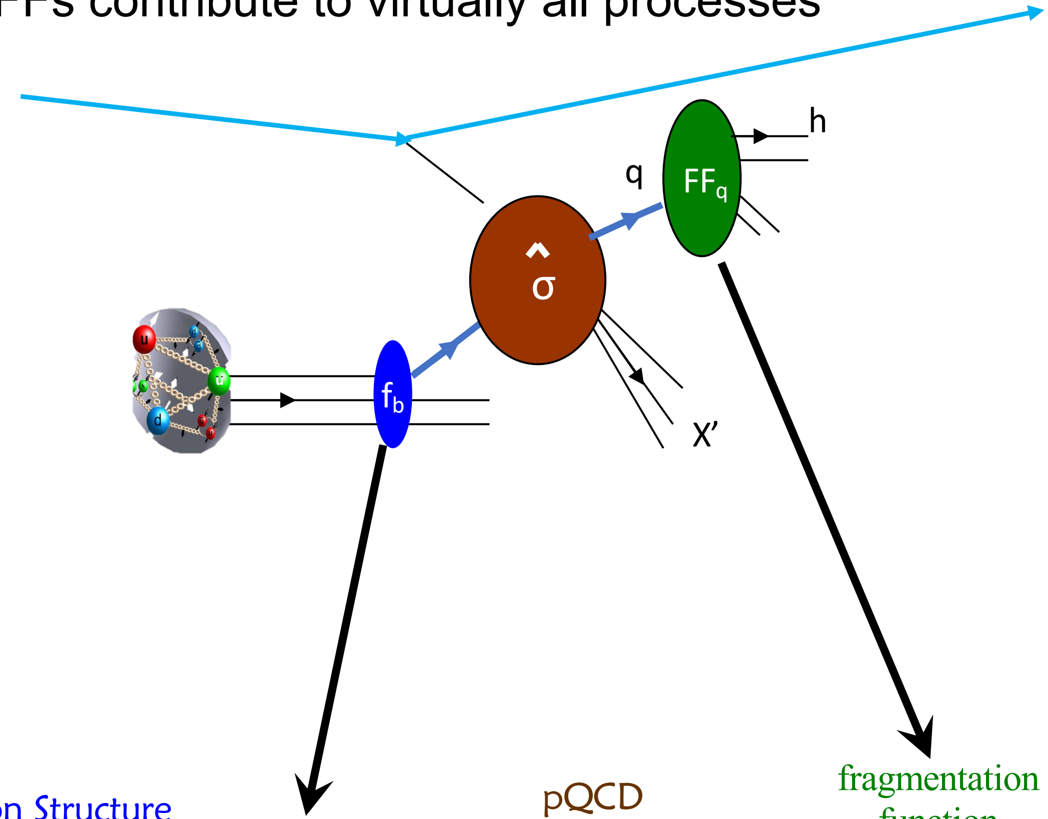
Thanks to content shown at SPIN 2023

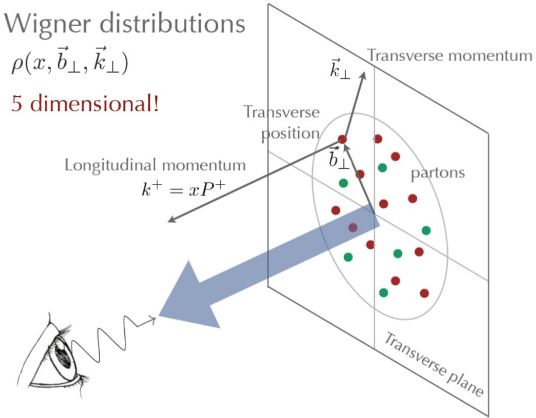
Duke UNIVERSITY

Jefferson Lab

Hard Scattering is a premier tool to probe the quark and gluon degrees of freedom

- Proton Structure extracted using QCD factorization theorem
- FFs contribute to virtually all processes





- Q^2 "scale" of the probe, "resolution"
- x: bjorken **scaling variable**, in partonic picture momentum fraction of the struck parton, "shutter speed"
- z fractional quark momentum carried by hadron
- p_T

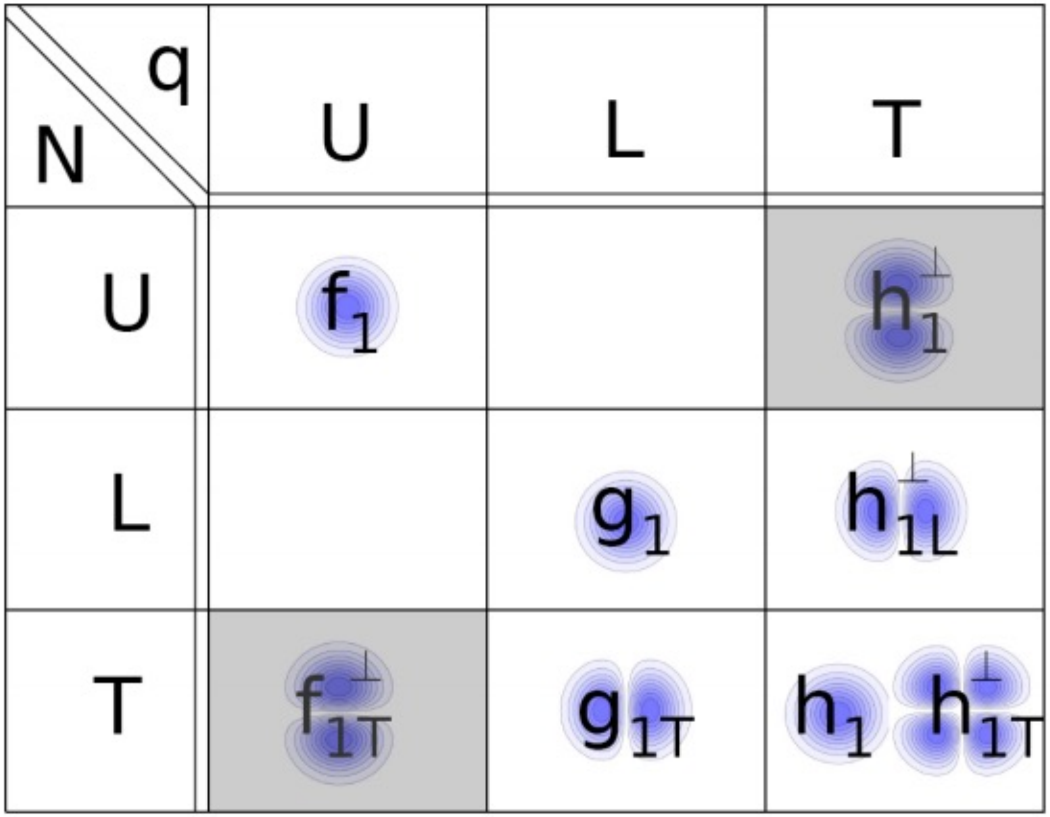
Proton Structure

pQCD

fragmentation function

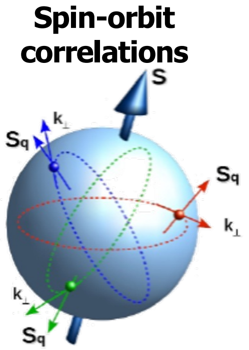
$$\frac{d^2\sigma(ep \to \pi X)}{dx\, dz\, p_{hT}} \propto q(x, k_T) \times \frac{d\sigma^2(e\, q \to e' q')}{dx} \times FF(z, p_T)\delta(p_{hT} - (k_T + p_T)$$

Momentum structure in the parton model parametrized by TMDs (spin ½)



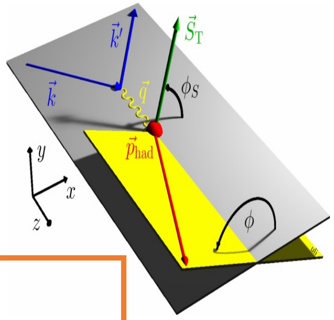
N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

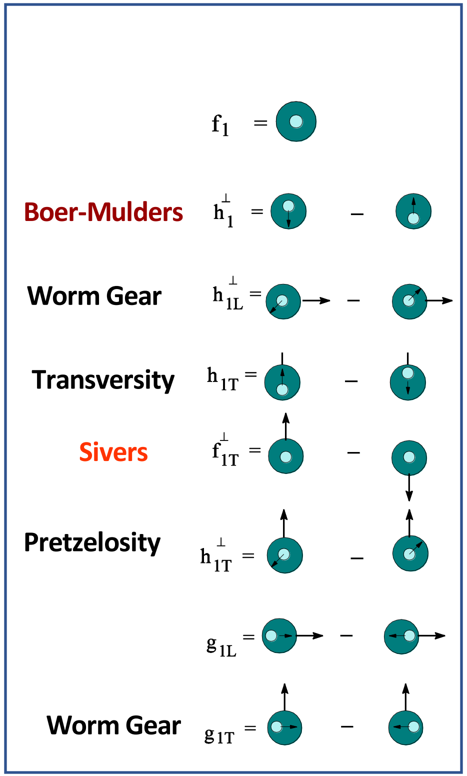
- In addition to the spin-spin correlations can have spin momentum correlations!



Spin-orbit correlations

SIDIS X-section in the Parton Model





f_1 =

Boer-Mulders $h_1^\perp$ = −

Worm Gear $h_{1L}^\perp$ = −

Transversity h_{1T} = −

Sivers $f_{1T}^\perp$ = −

Pretzelosity $h_{1T}^\perp$ = −

g_{1L} = −

Worm Gear g_{1T} = −

$$d^6\sigma = \frac{4\pi\alpha^2 sx}{Q^4}\times$$

$$\{[1+(1-y)^2]\sum_{q,\bar{q}} e_q^2 f_1^q(x) D_1^q(z,P_{h\perp}^2)$$

$$+(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\cos(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_1^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

Unpolarized

$$-|S_L|(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\sin(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_{1L}^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

$$+|S_T|(1-y)\frac{P_{h\perp}}{zM_h}\sin(\phi_h^l+\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_1^q(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

$$+|S_T|(1-y+\frac{1}{2}y^2)\frac{P_{h\perp}}{zM_N}\sin(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 f_{1T}^{\perp(1)q}(x) D_1^q(z,P_{h\perp}^2)$$

$$+|S_T|(1-y)\frac{P_{h\perp}^3}{6z^3 M_N^2 M_h}\sin(3\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_{1T}^{\perp(2)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

$$+\lambda_e|S_L|y(1-\frac{1}{2}y)\sum_{q,\bar{q}} e_q^2 g_1^q(x) D_1^q(z,P_{h\perp}^2)$$

Polarized target

$$+\lambda_e|S_T|y(1-\frac{1}{2}y)\frac{P_{h\perp}}{zM_N}\cos(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 g_{1T}^{(1)q}(x) D_1^q(z,P_{h\perp}^2)\}$$

Polarzied beam and target

S_L and S_T: Target Polarizations; λe: Beam Polarization

x: momentum fraction carried by struck quark, z: fractional energy of hadron

SIDIS cross-section

$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} \\
&= \frac{\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\Bigg\{ F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} \\
&\quad + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + S_L\Bigg[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\Bigg] \\
&\quad + S_L\,\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\Bigg] \\
&\quad + S_T\Bigg[\sin(\phi_h-\phi_S)\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big) + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} \\
&\qquad + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} \\
&\qquad + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg] + S_T\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} \\
&\qquad + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Bigg]\Bigg\}
\end{aligned}
$$

- Disentangling the different contributions is not trivial
- Ratio of T to L flux
  - At fixed x e.g. change Q

$$
\varepsilon = \frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2}, \qquad \gamma = \frac{2Mx}{Q}.
$$

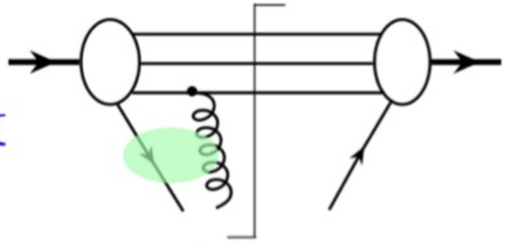
Beyond the parton picture

- Higher Twist Contributions
- Overlap of regions that are not captured by factorized TMD picture
- VM Meson decays
- Radiative corrections
- Assumption of suppressed long photon contributions

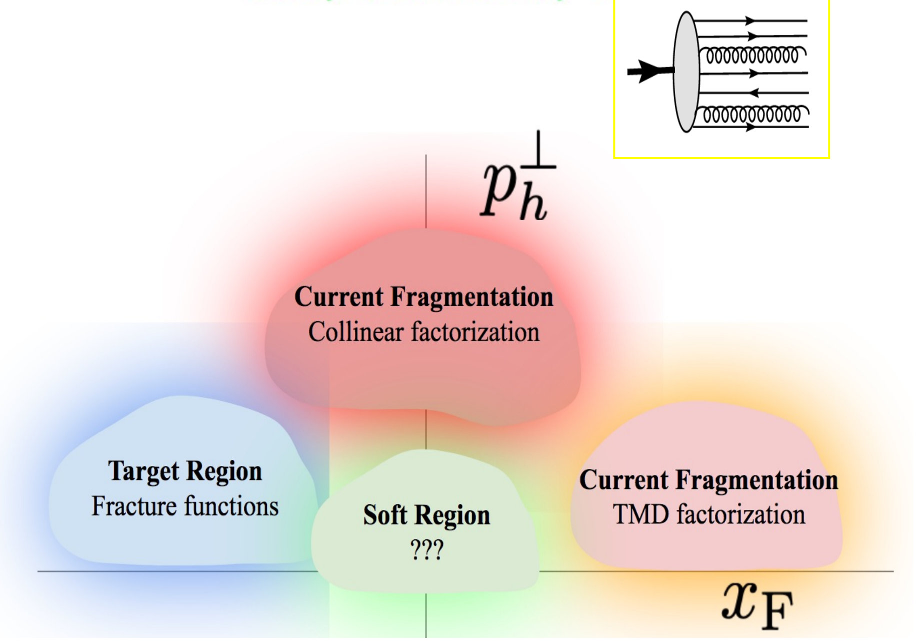
One persons ‘complication’ is another person's signal…

➔Need high lumi, leverarm in kinematics to disentangle various contributions

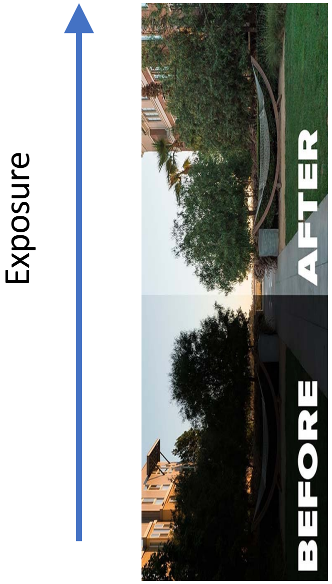
$T^{(3)}(x, x) \propto$

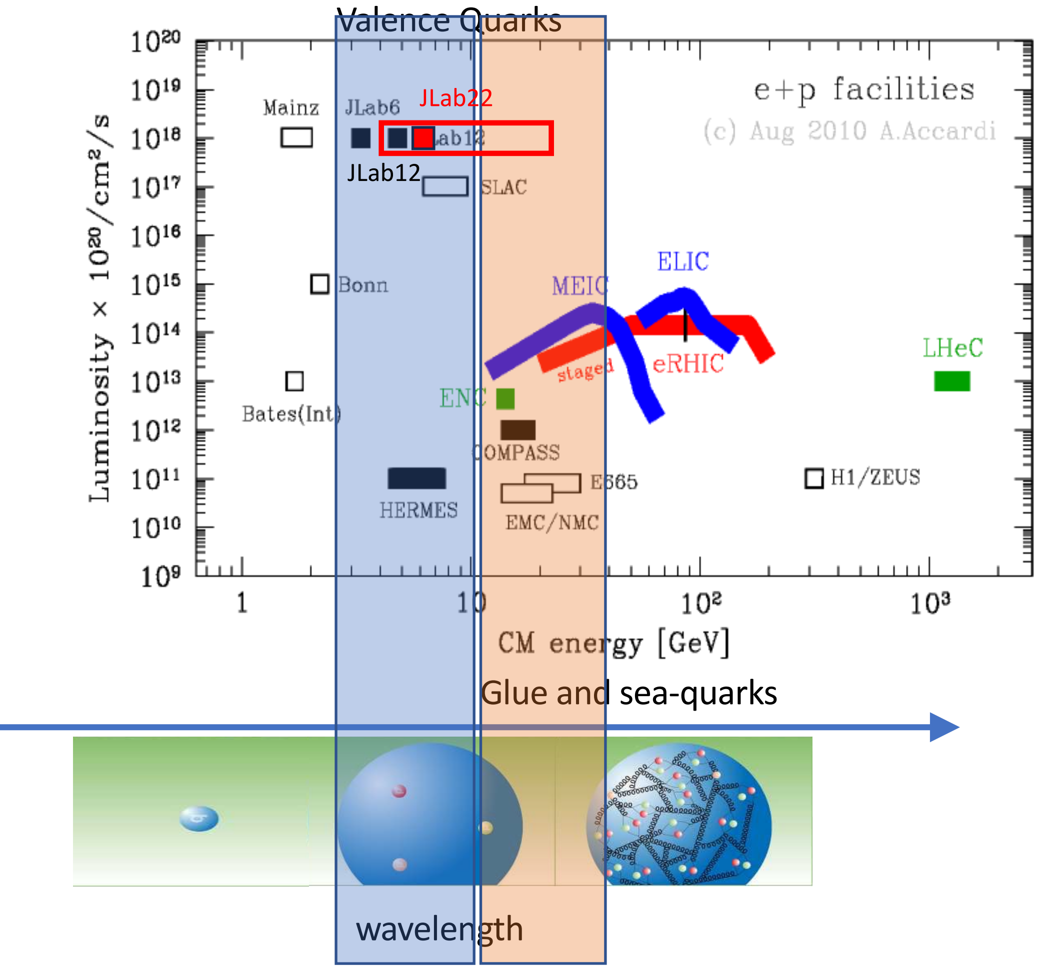


Qiu, Sterman, 1991, ...



Landscape

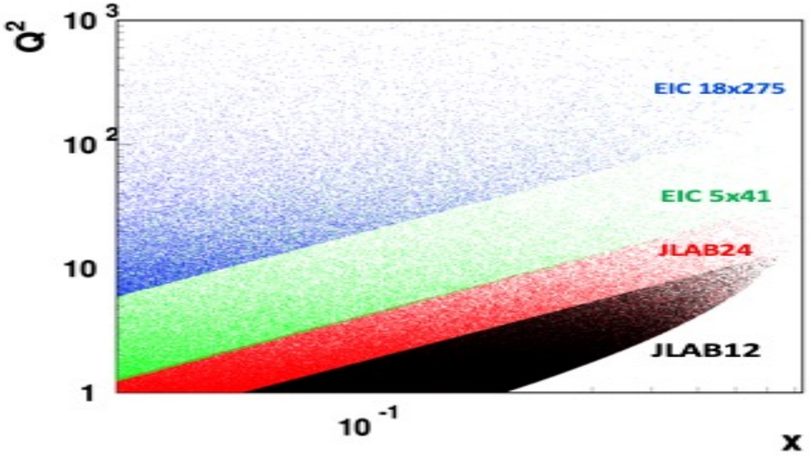


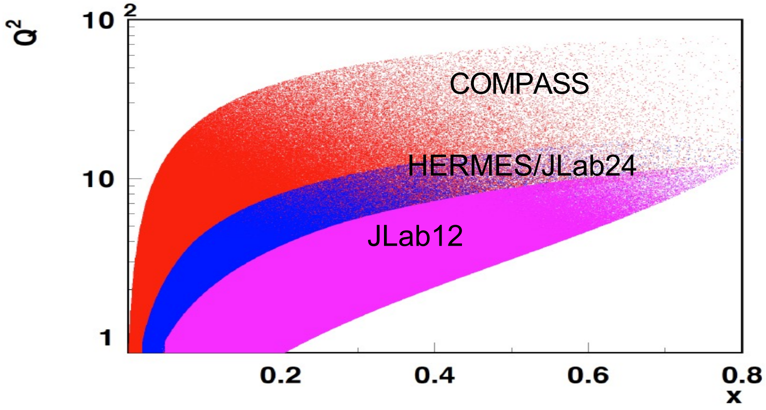


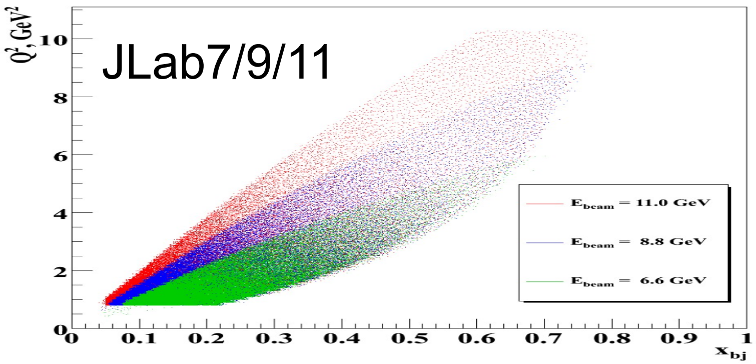
To extract 3D structure
Need luminosity

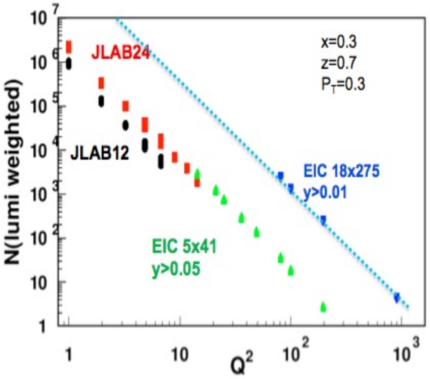
- Jlab12: 2018+
- JLab22:

Kinematic comparisons



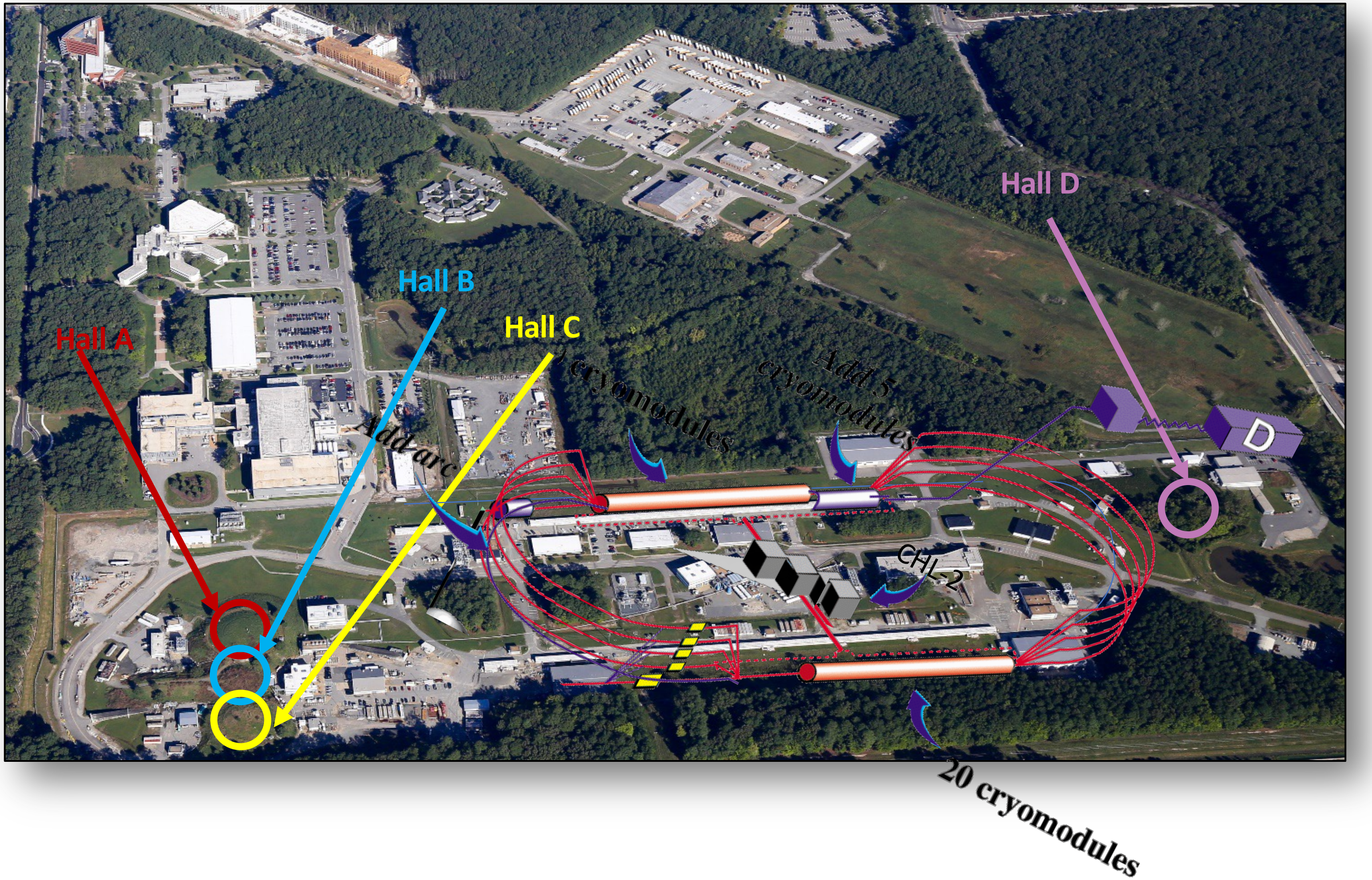




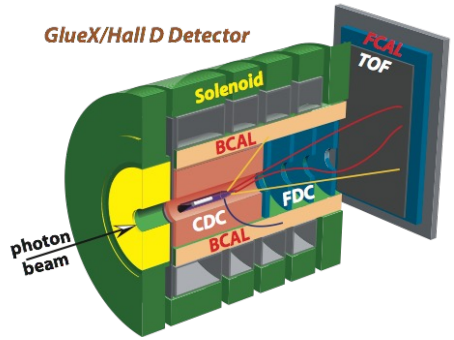


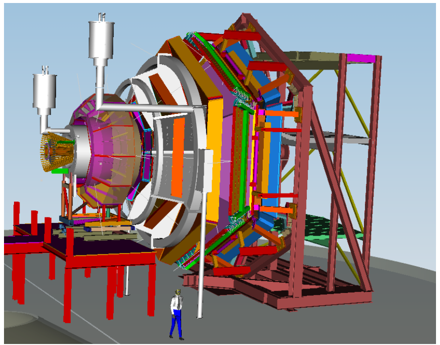
NB: Kinematic slice heavily biased towards Jlab

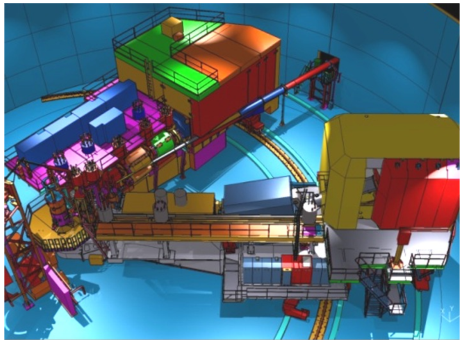
Jefferson Lab with CEBAF at 12 GeV

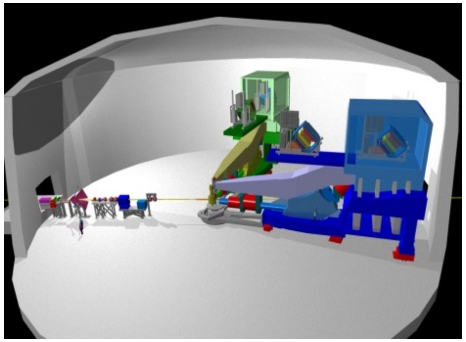


Detector Requirements: Complementarity



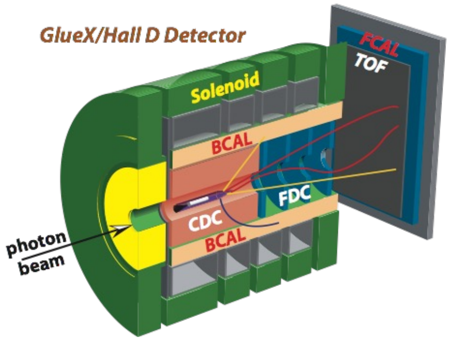


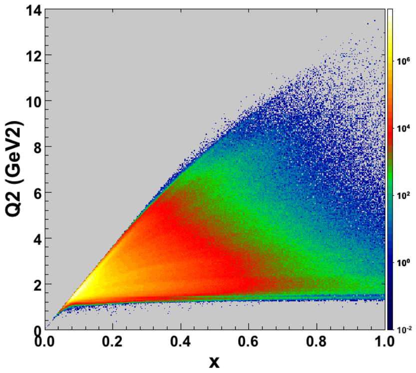


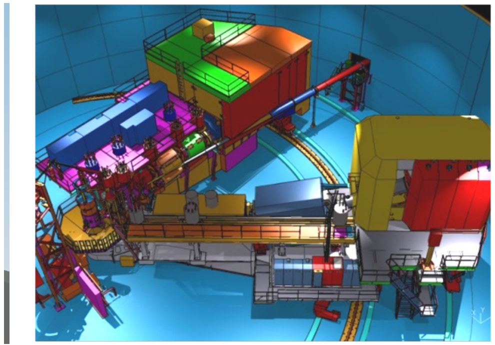


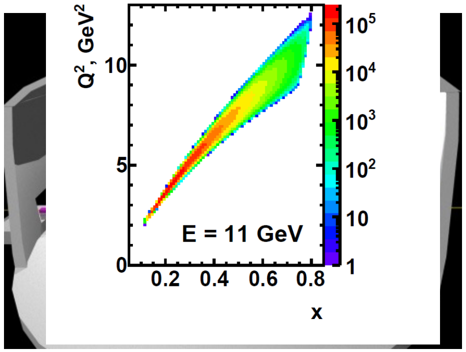
Hall D	Hall B	Hall C	Hall A
excellent hermeticity	luminosity 10^{35}	energy reach	custom installations
polarized photons	Hermeticity	precision	
E_γ~8.5-9 GeV	11 GeV beamline		
10^8 photons/s	target flexibility		
good momentum/angle resolution		excellent momentum resolution	
high multiplicity reconstruction		luminosity up to 10^{38}	
particle ID			

Detector Requirements: Complementarity









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Tentative Timelines relevant for TMD program shown here

CLAS12 in Hall B

- 2018-2020: unpolarized proton/deuterium target – long. polarized beam

- 2022/23 longitudinally polarized proton/deuterium long target → ≈ 5 % produced

- Future Polarized He3 (long/trans)

Hall A

- 2028 SoLID with He3/proton target (long/transverse)

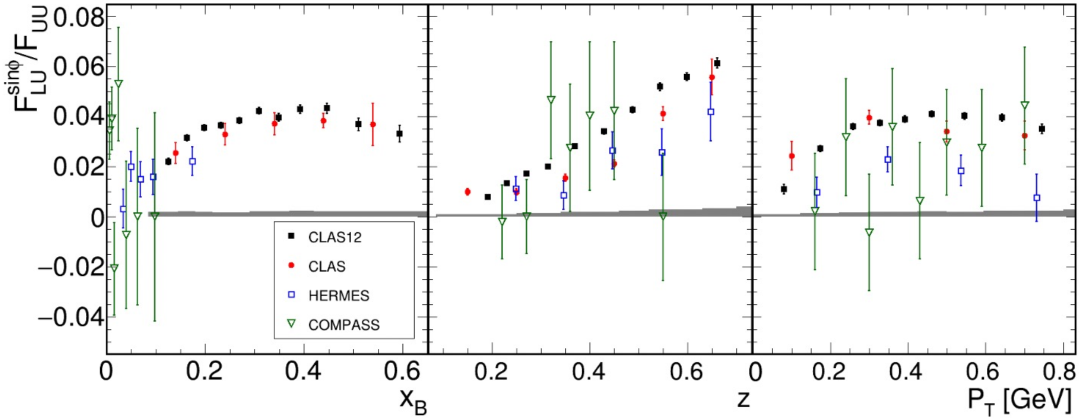
See talk by Chao Peng

CLAS12 pion BSAs

Higher Twist PDFs

N/q	U	L	T
U	$f^{\perp}$	$g^{\perp}$	h, e
L	$f_L^{\perp}$	$g_L^{\perp}$	h_L, e_L
T	$f_T, f_T^{\perp}$	$g_T, g_T^{\perp}$	$h_T, e_T, h_T^{\perp}, e_T^{\perp}$

Phys.Rev.Lett. 128 (2022) 6, 062005



twist-3 pdf

unpolarized PDF

twist-3 t-odd PDF

Boer-Mulders

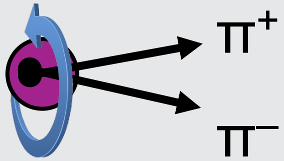
$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\mathcal{C}\left[-\frac{\hat{h}\cdot k_T}{M_h}\left(x\boxed{e}\boxed{H_1^{\perp}} + \frac{M_h}{M}\boxed{f_1}\frac{\boxed{\tilde{G}^{\perp}}}{z}\right) + \frac{\hat{h}\cdot p_T}{M}\left(x\boxed{g^{\perp}}\boxed{D_1} + \frac{M_h}{M}\boxed{h_1^{\perp}}\frac{\boxed{\tilde{E}}}{z}\right)\right]$$

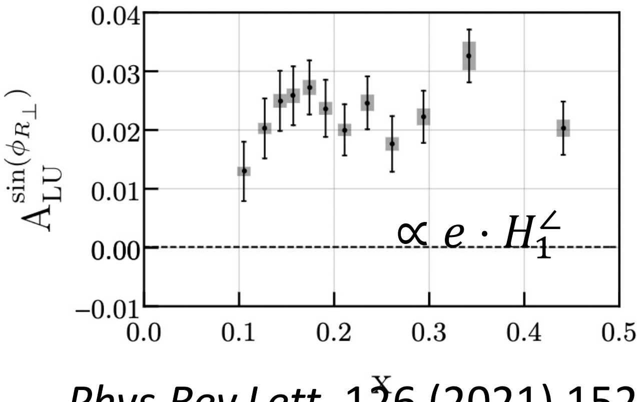
Collins FF

twist-3 FF

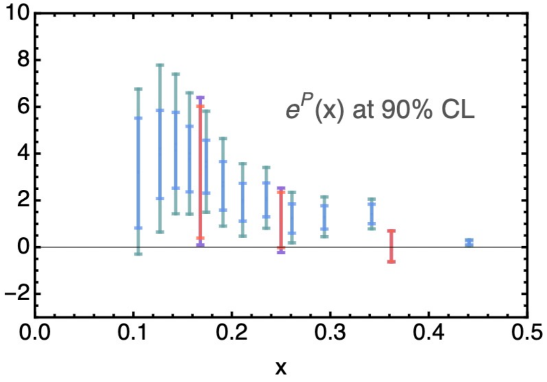
unpolarized FF

Better: di-hadrons

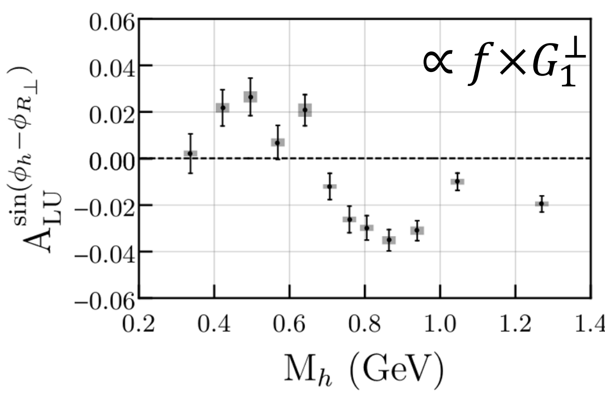




Phys.Rev.Lett. 126 (2021) 152501



Phys.Rev.D 106 (2022) 1, 014027

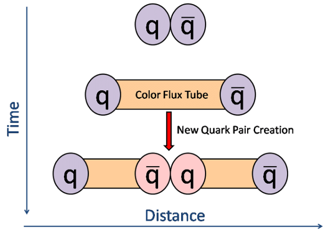


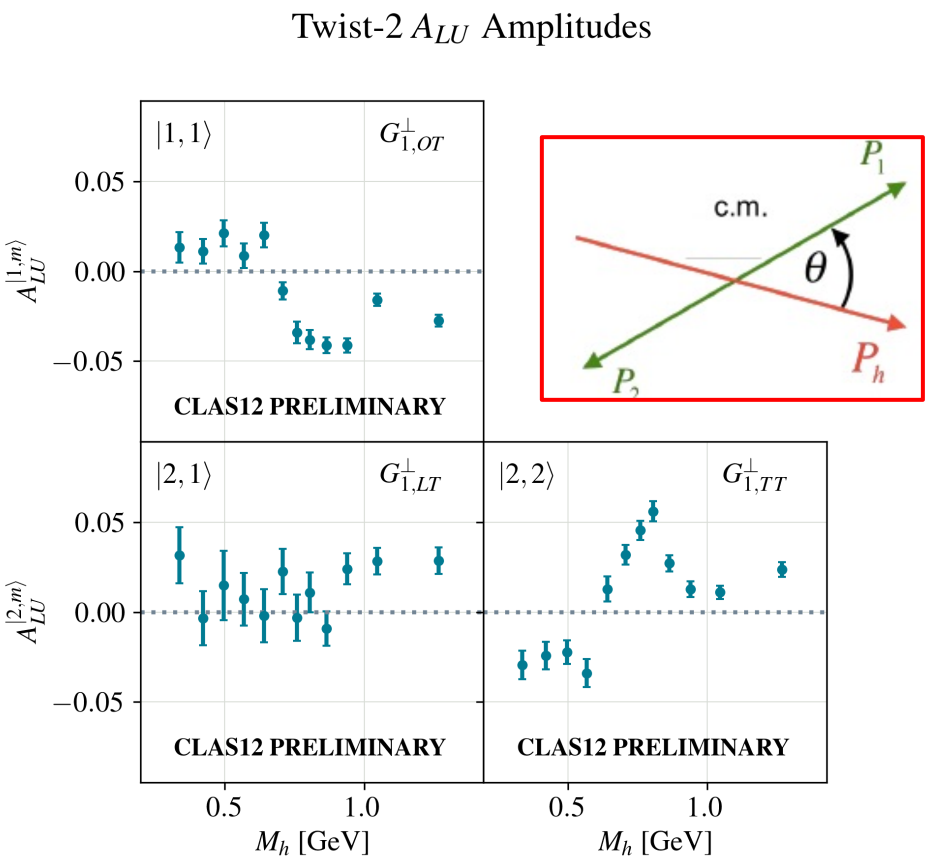
$$F_{LU}^{\sin\phi_R} = -x\frac{|\boldsymbol{R}|\sin\theta}{Q}\left[\frac{M}{m_{hh}}\,x\,e^q(x)\,H_1^{\sphericalangle q}(z,\cos\theta,m_{hh}) + \frac{1}{z}\,f_1^q(x)\,\widetilde{G}^{\sphericalangle q}(z,\cos\theta,m_{hh})\right],$$

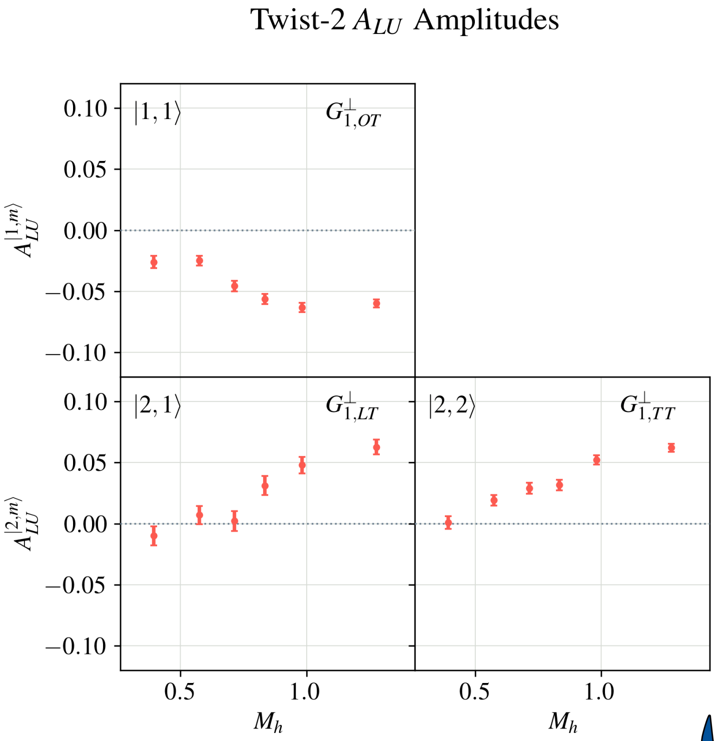
- First extraction of $e(x)$
- Further constrains from F_{UL} and F_{LL}

Compare Partial Wave Decomposition in MC and Data

- Comparing to Polarized Lund model here (StringSpinner, A. al, *Comput.Phys.Commun.* 272 (2022))



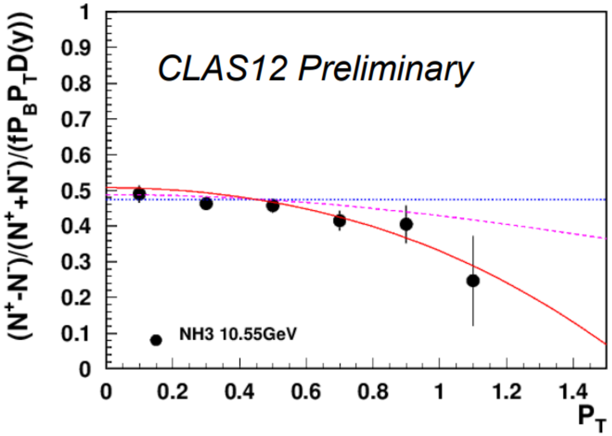




- New version of string+$3P_0$ model shown at SPIN (Kerbizi) with improved VM treatment

Longitudinal target results

- Results represent 5% proton target



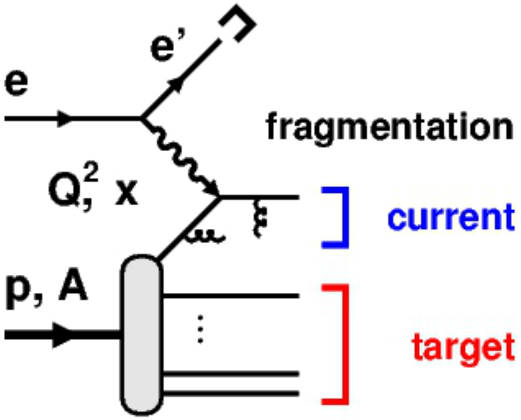
Harut Avakian at

$$F_{LL} \propto g_1(x, k_T) \otimes D_1(z, p_T)$$

Convolution over transverse momentum space

- Rich program underway

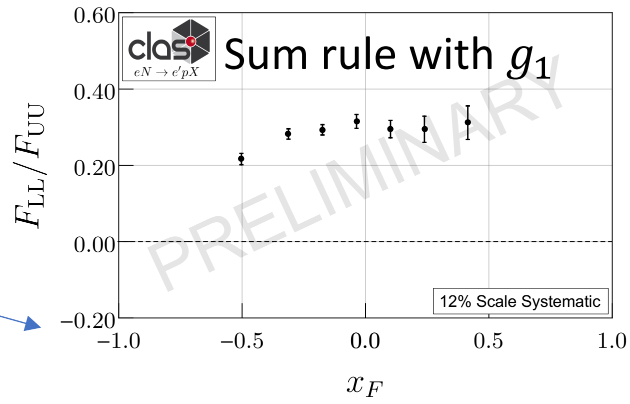
Target Fragmentation → Fracture Functions



Quark polarization

Nucleon polarization	U	L	T
U	$\hat{u}_1$	$\hat{l}_1^{\perp h}$	$\hat{t}_1^h, \hat{t}_1^\perp$
L	$\hat{u}_{1L}^{\perp h}$	$\hat{l}_{1L}$	$\hat{t}_{1L}^h, \hat{t}_{1L}^\perp$
T	$\hat{u}_{1T}^h, \hat{u}_{1T}^\perp$	$\hat{l}_{1T}^h, \hat{l}_{1T}^\perp$	$\hat{t}_{1T}, \hat{t}_{1T}^{hh}$ $\hat{t}_{1T}^{\perp\perp}, \hat{t}_{1T}^{\perp h}$

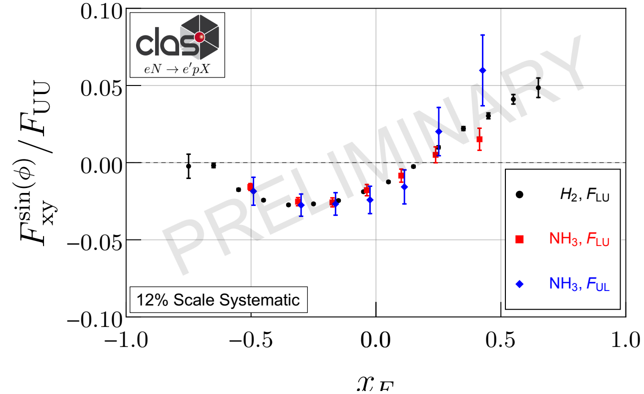
M. Anselmino et al., Phys. Lett. B. 706 (2011), 46-52, [hep-ph] 1109.1132



Quark polarization

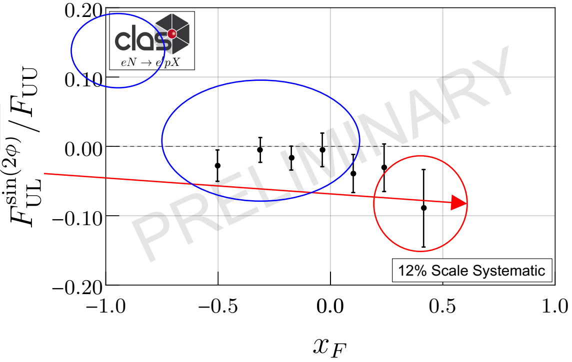
Nucleon polarization	U	L
U	u^h	l^h
L	u_L^h	l_L^h

Twist-3 Collinear terms;
Chen, K. B., Ma, J. P. and Tong, X. B., [hep-ph] 2308.11251



- Correlations between CFR-TFR allows to extract fracture functions coupled to FFs

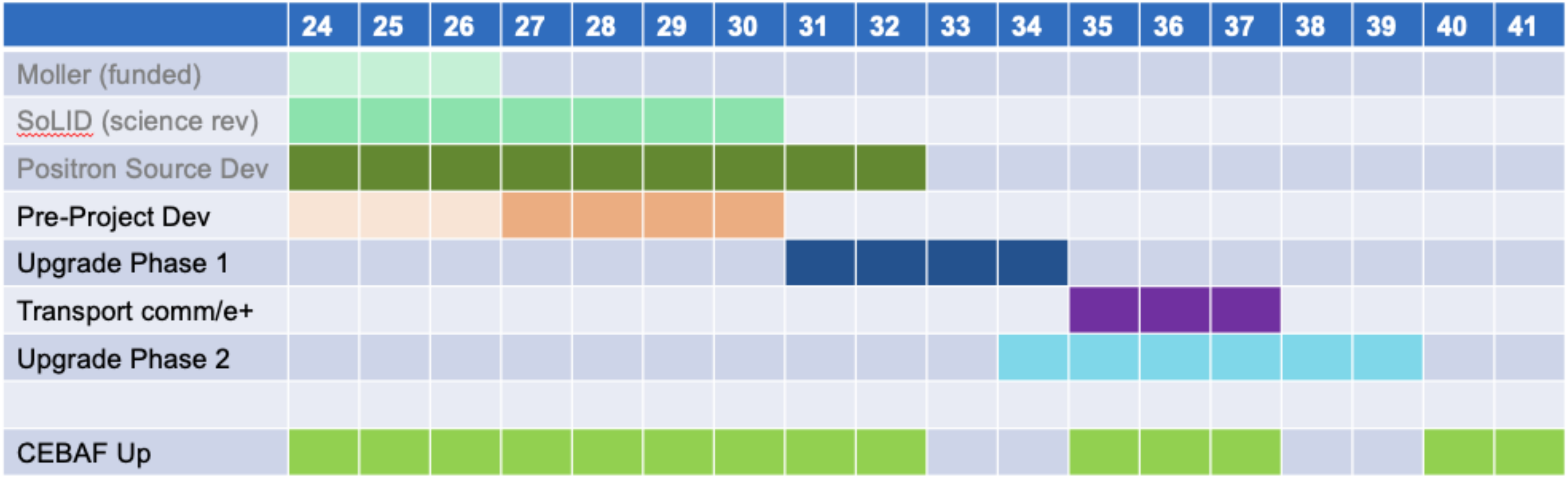
$$F_{UL}^{\sin 2\phi_h} = \mathcal{C}\left[-\frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right)-\boldsymbol{k}_T\cdot\boldsymbol{p}_T}{M M_h} h_{1L}^{\perp} H_1^{\perp}\right]$$



T. Hayward at S

Notional CEBAF & upgrade schedule (FY24 – FY42)

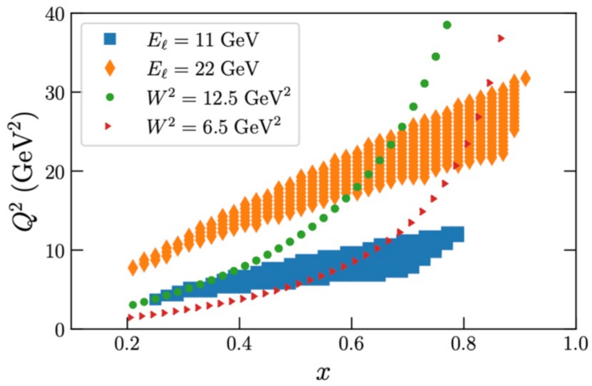
- Accelerator and engineering team have worked up an early schedule and cost estimate
  - Schedule assumptions based on a notional timing of when funds might be available (near EIC ramp down based on EIC V3 profile)
  - For completeness, Moller and SoLID (part of 12 GeV program) are shown; positron source development also shown

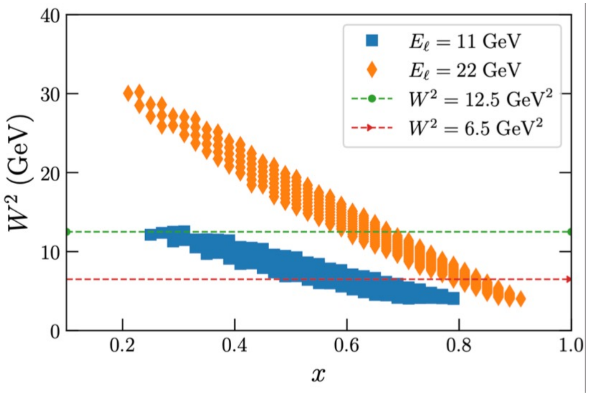


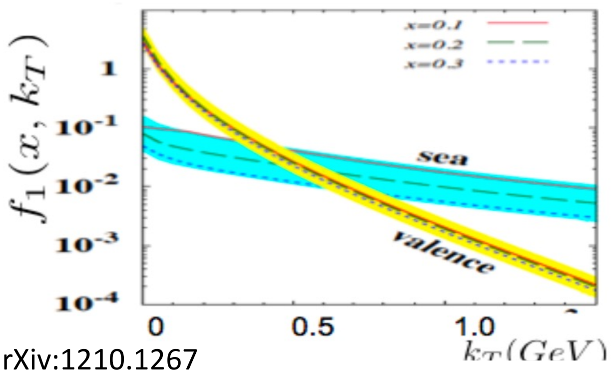
	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41
Moller (funded)	🟩	🟩	🟩															
SoLID (science rev)	🟩	🟩	🟩	🟩	🟩	🟩	🟩											
Positron Source Dev	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩									
Pre-Project Dev	🟧	🟧	🟧	🟧	🟧	🟧	🟧											
Upgrade Phase 1								🟦	🟦	🟦	🟦							
Transport comm/e+												🟪	🟪	🟪				
Upgrade Phase 2											🟦	🟦	🟦	🟦	🟦	🟦		
CEBAF Up	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩			🟩	🟩	🟩			🟩	🟩

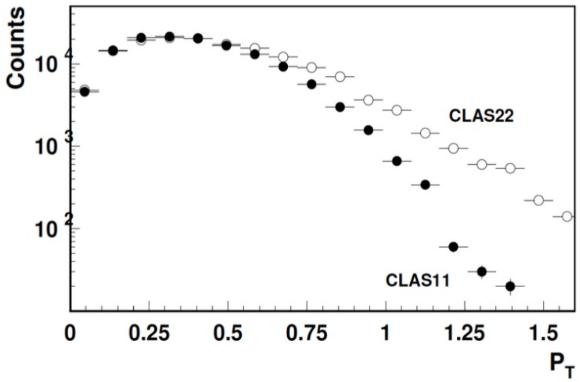
Tia Keppel at SPIN 2023

High x at Jlab 22









P.Schweitzer et al. arXiv:1210.1267

Strong Interaction Physics at the Luminosity Frontier
with 22 GeV Electrons at Jefferson Lab

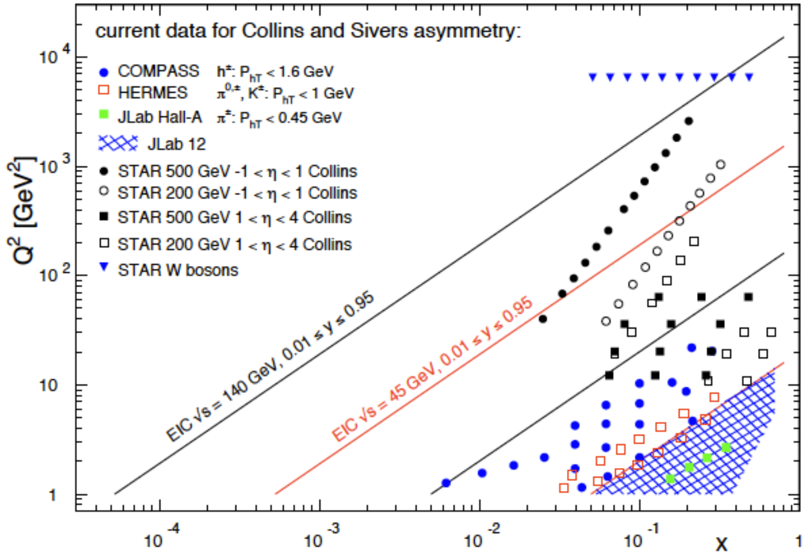
t: 2306.09360 [nucl-ex]

- ≈doubling beam energy significantly increases phase space
- Pin down valence structure of the proton
- Integration in global analyses (e.g. strange distributions, CS Kernel)
- See M. Battaglieri's talk

SIDIS physics at an EIC: Coverage

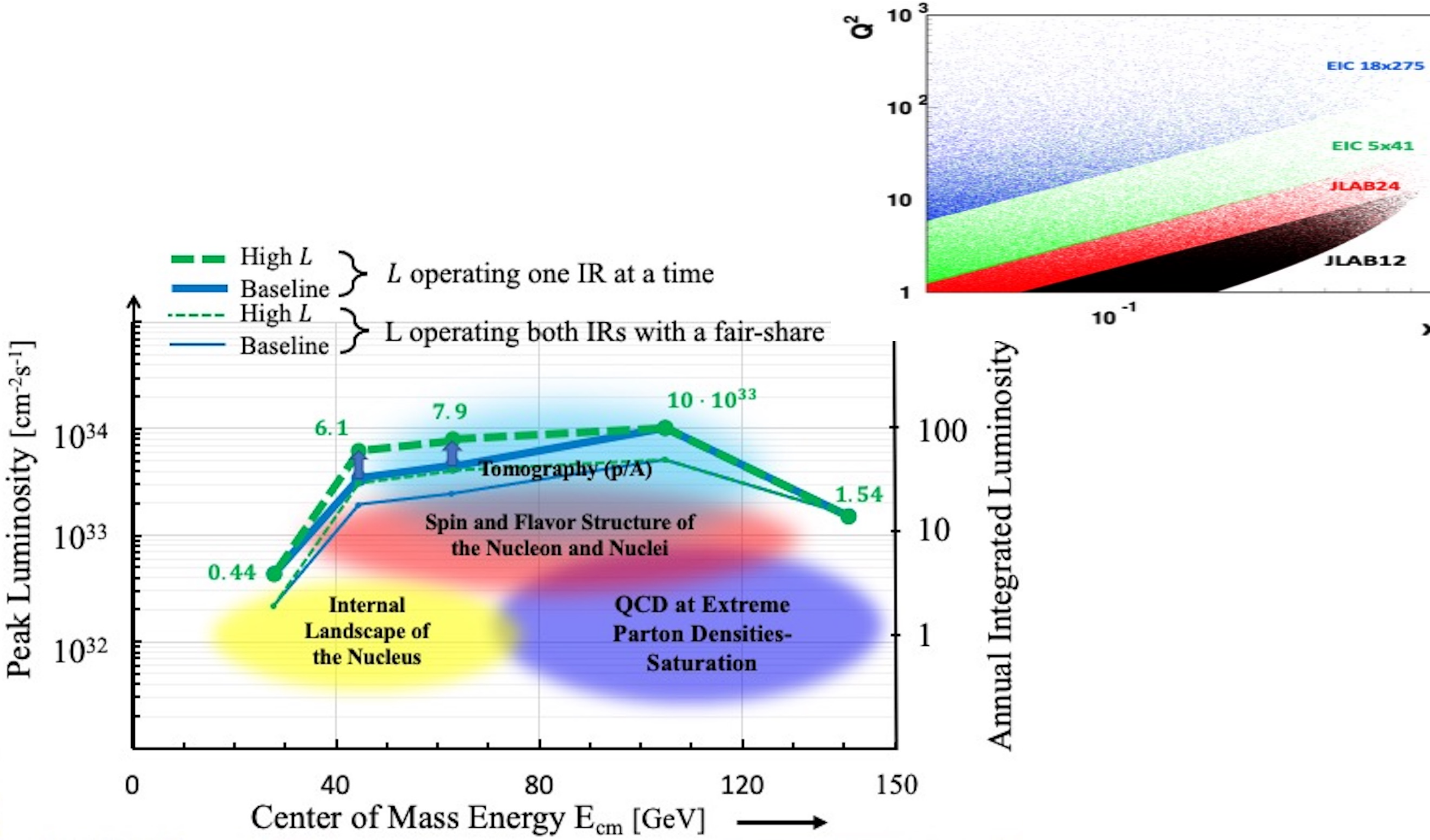
- Common theme on EIC impact
  - Extended kinematic coverage and precision, along with polarization and possible beam charge degrees of freedom allow multi-pronged approach →needed to extract multidimensional objects
  - TMD factorization is valid

Large Q^2 lever arm: probe evolution, disentangle contributions to σ



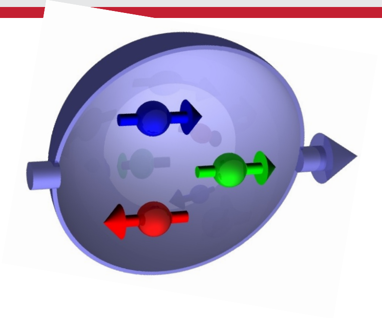
Coverage to low x: access sea and gluon distributions

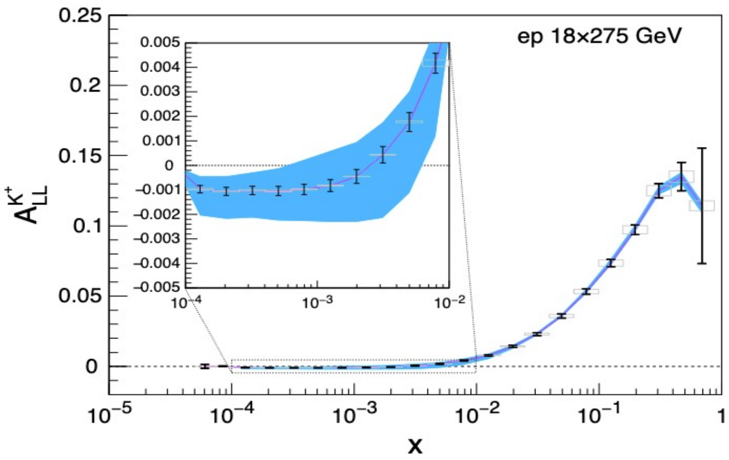
Order of magnitude in luminosity depending on $\sqrt{s}$ (beware of projections with fixed $\int L$)

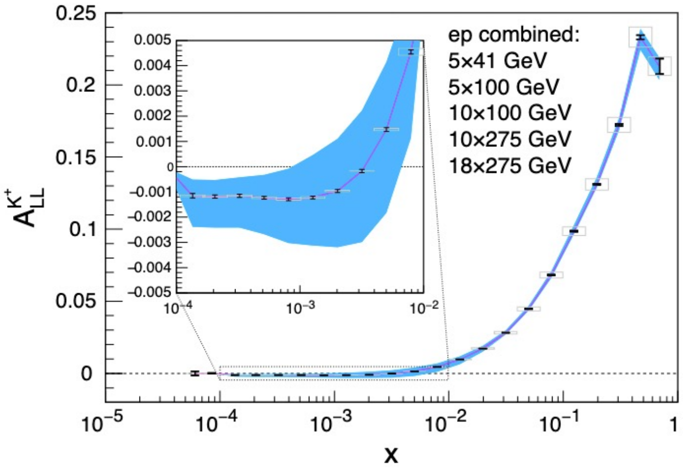


Longitudinal double spin asymmetries

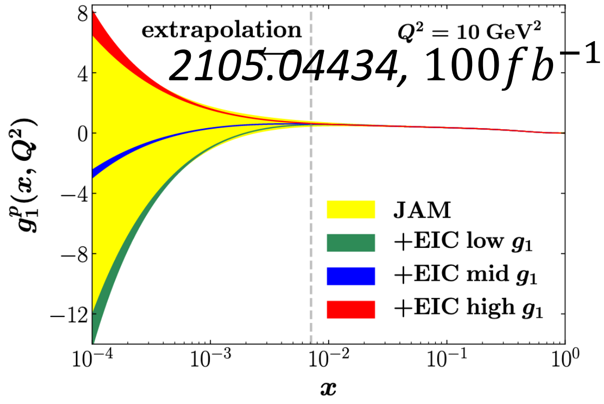
- $A_{LL} = \frac{\sigma^{\uparrow\Uparrow}-\sigma^{\uparrow\Downarrow}}{\sigma^{\uparrow\Uparrow}+\sigma^{\uparrow\Downarrow}} \propto g_1$







- Projections for Athena (2022 *JINST* **17** P10019)
- 3% point-to-point, 2% scale uncertainties (from Hera experience)
- $z > 0.2$
- $15.5\ fb^{-1}$ at $18x275$, other datasets scaled accordingly

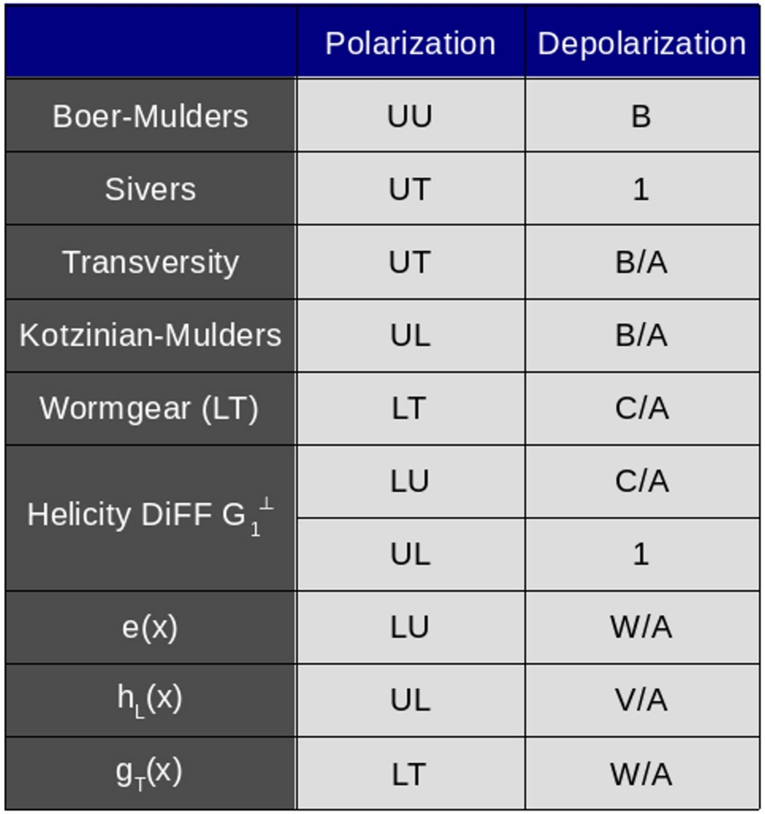


2105.04434, $100 fb^{-1}$

Access to TMDs: Kinematic factors

Twist 2

Twist 3

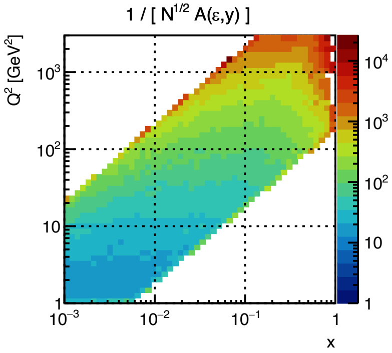


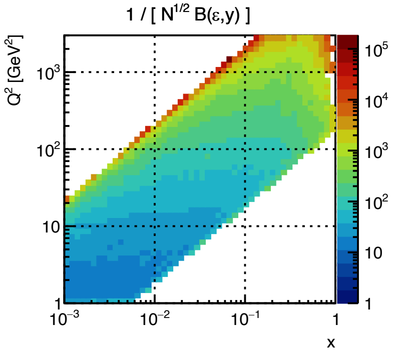
	Polarization	Depolarization
Boer-Mulders	UU	B
Sivers	UT	1
Transversity	UT	B/A
Kotzinian-Mulders	UL	B/A
Wormgear (LT)	LT	C/A
Helicity DiFF $G_1^{\perp}$	LU	C/A
	UL	1
$e(x)$	LU	W/A
$h_L(x)$	UL	V/A
$g_T(x)$	LT	W/A

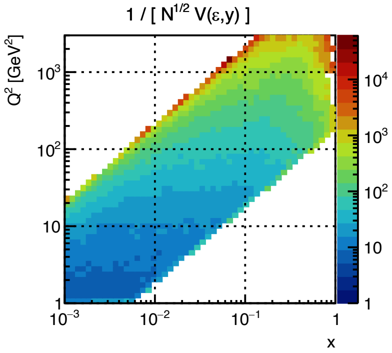
Slide from C. Dilks

Statistical uncertainty scaling factor for $18x275$

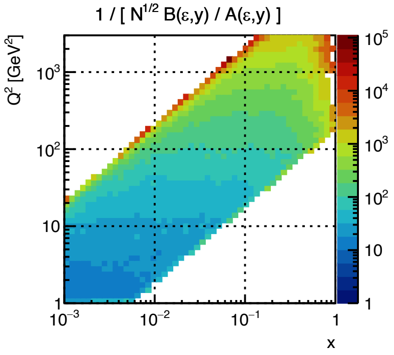
UU

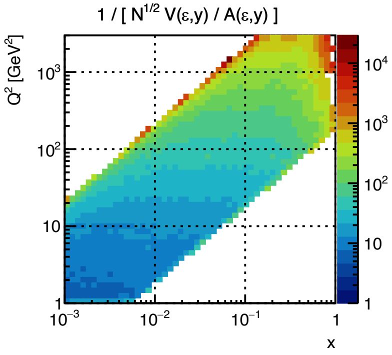




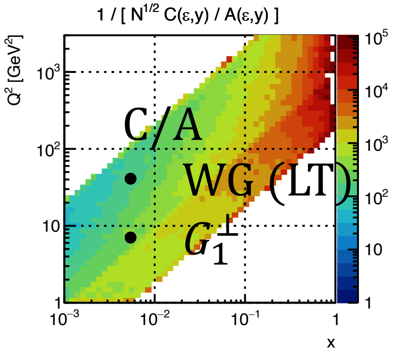


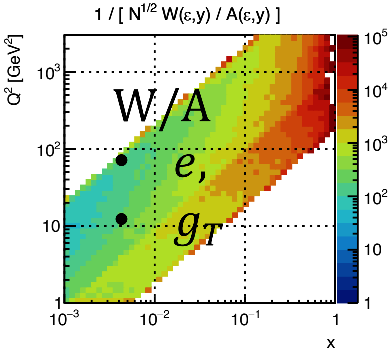
UL, UT





LU, LL, LT





Slide from C. Dilks

Depolarization Factors

Twist 2

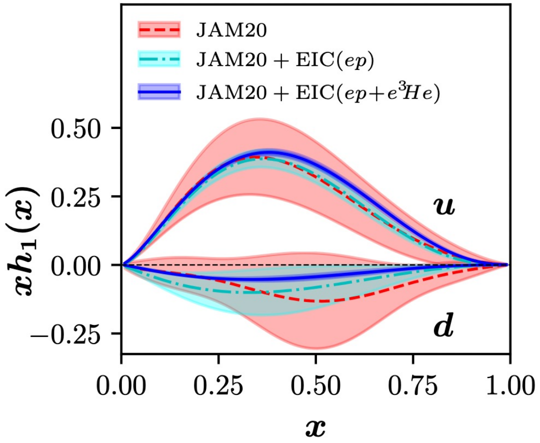
Twist 3

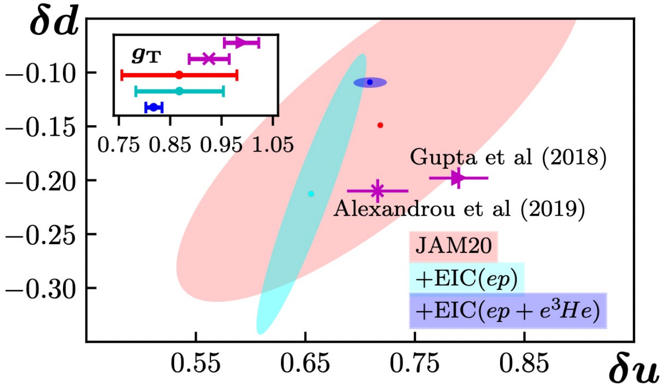
	Polarization	Depolarization
Boer-Mulders	UU	B
Sivers	UT	1
Transversity	UT	B/A
Kotzinian-Mulders	UL	B/A
Wormgear (LT)	LT	C/A
Helicity DiFF $G_1^\perp$	LU	C/A
	UL	1
$e(x)$	LU	W/A
$h_L(x)$	UL	V/A
$g_T(x)$	LT	W/A

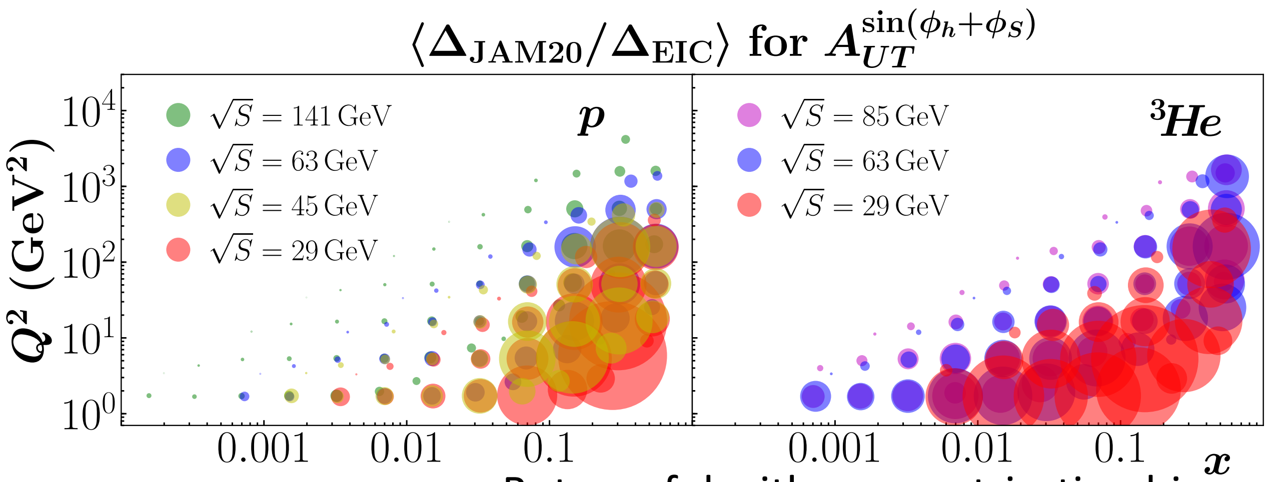
Suppressed at EIC

Slide from C. Dilks

Example: transversity extraction from Jlab and the EIC





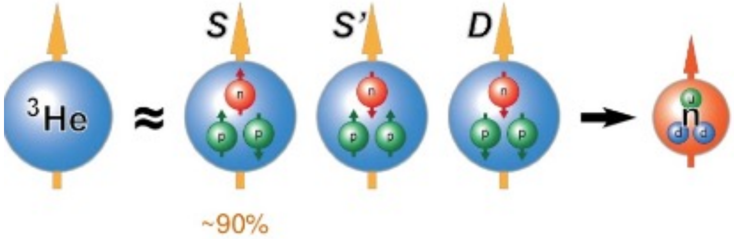


But careful with parametrization bias…

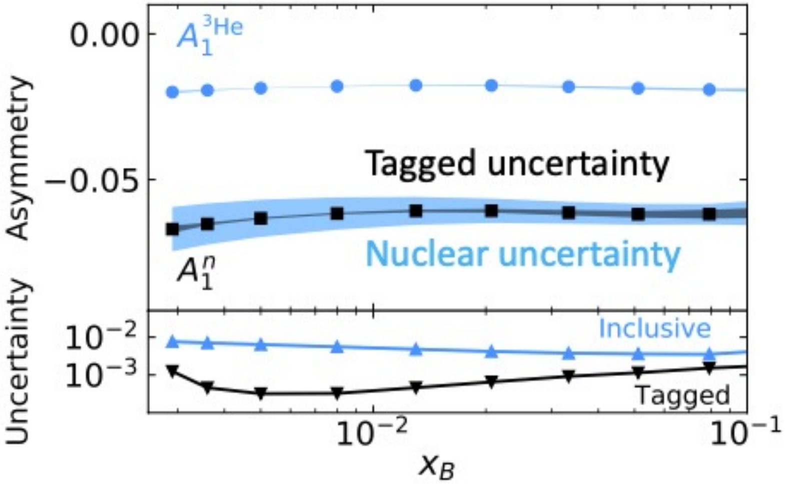
Phys.Lett.B 816 (2021) 136255

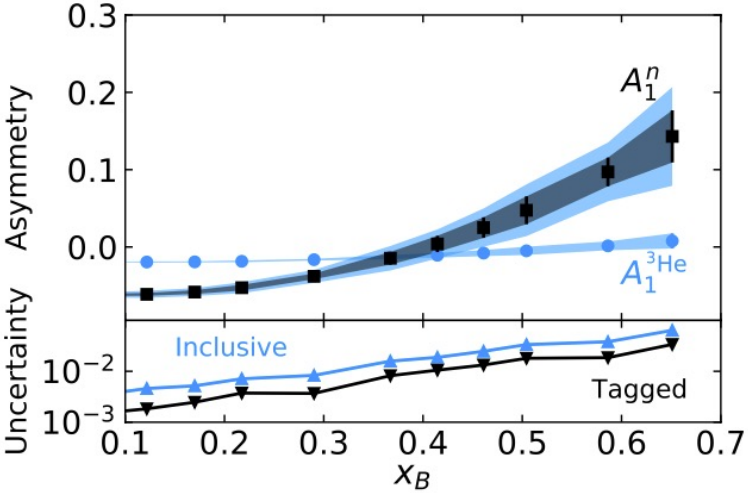
He^3 Double Tagging at the EIC allows clean neutron measurement

- Neutron is to 87% polarized
- Double tagged events thus provide access to polarized neutron beam



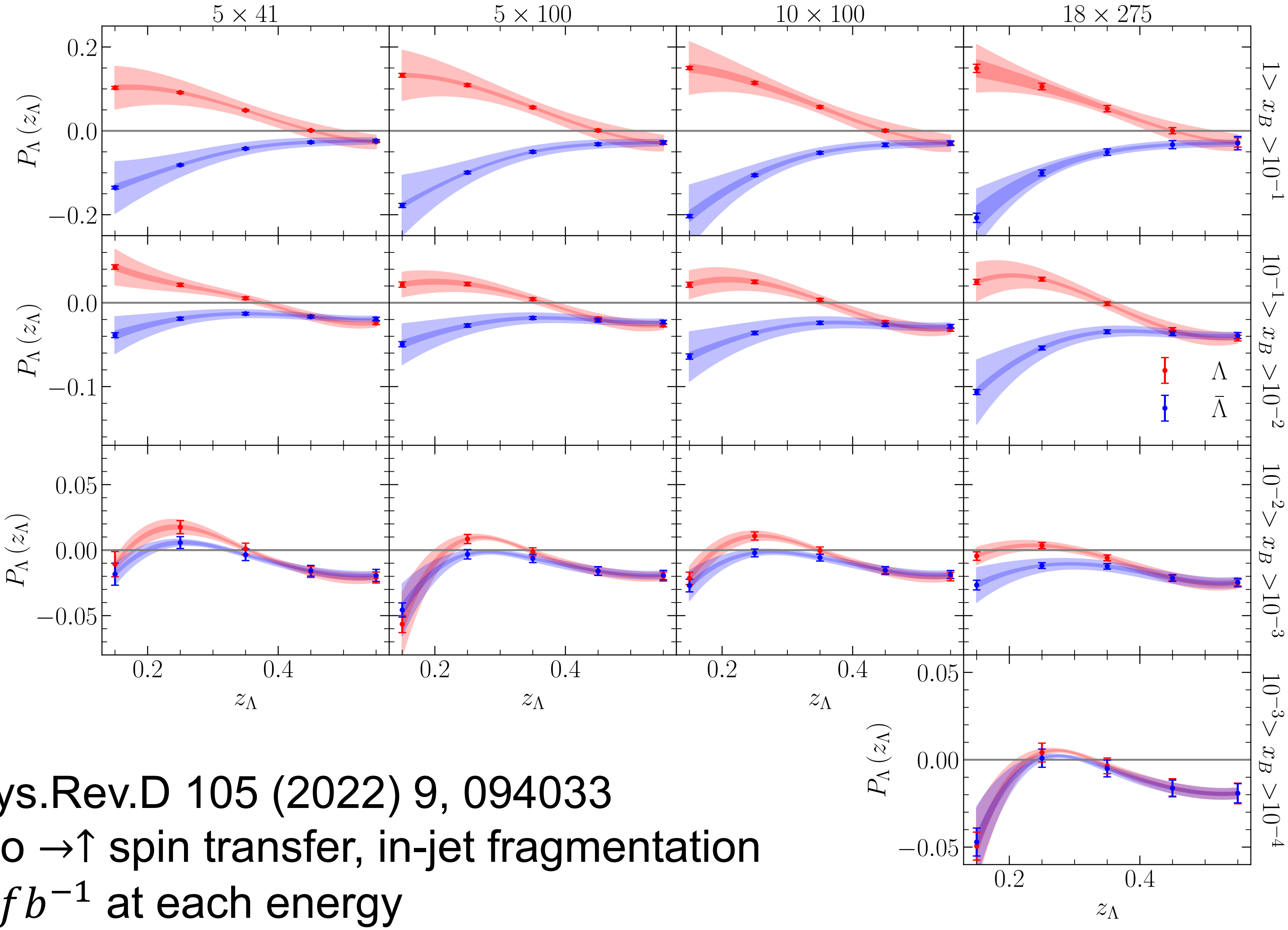
- Reconstruction of initial neutron momentum from tagged protons allows reduction of uncertainties from nuclear corrections





Friščić, I, Nguyen, D, Pybus, JR, Jentsch et al

Precision Λ physics at the EIC

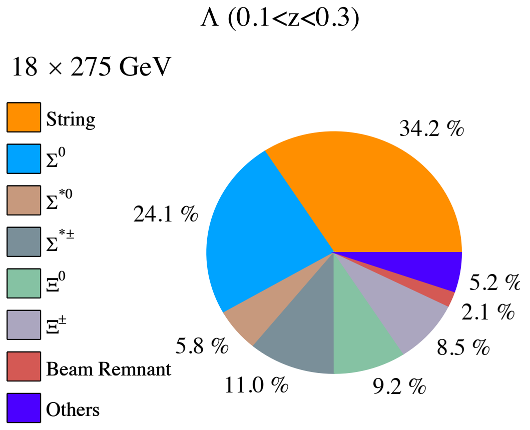


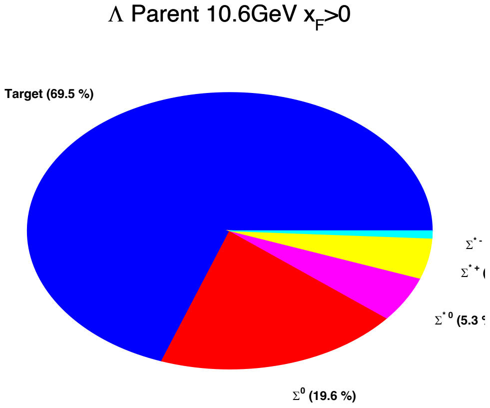
- Phys.Rev.D 105 (2022) 9, 094033
- Also →↑ spin transfer, in-jet fragmentation
- 40 fb^{-1} at each energy
- Significant impact of low $\sqrt{s}$ data

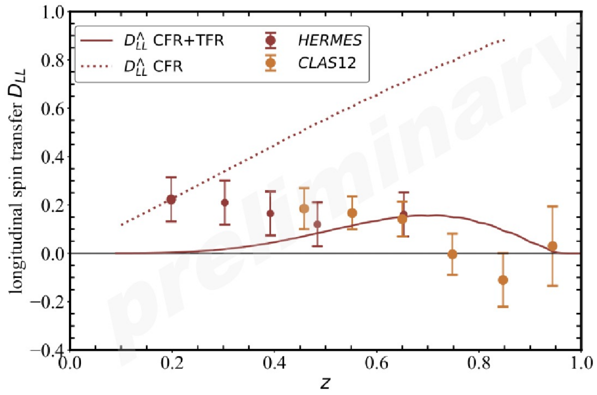
Lambda feed-down composition vs JLab20

EIC

JLAB12







Xiaoyan Zhao at S

- Possible to unfold at the EIC (not so much at Jlab)
- ML methods might help

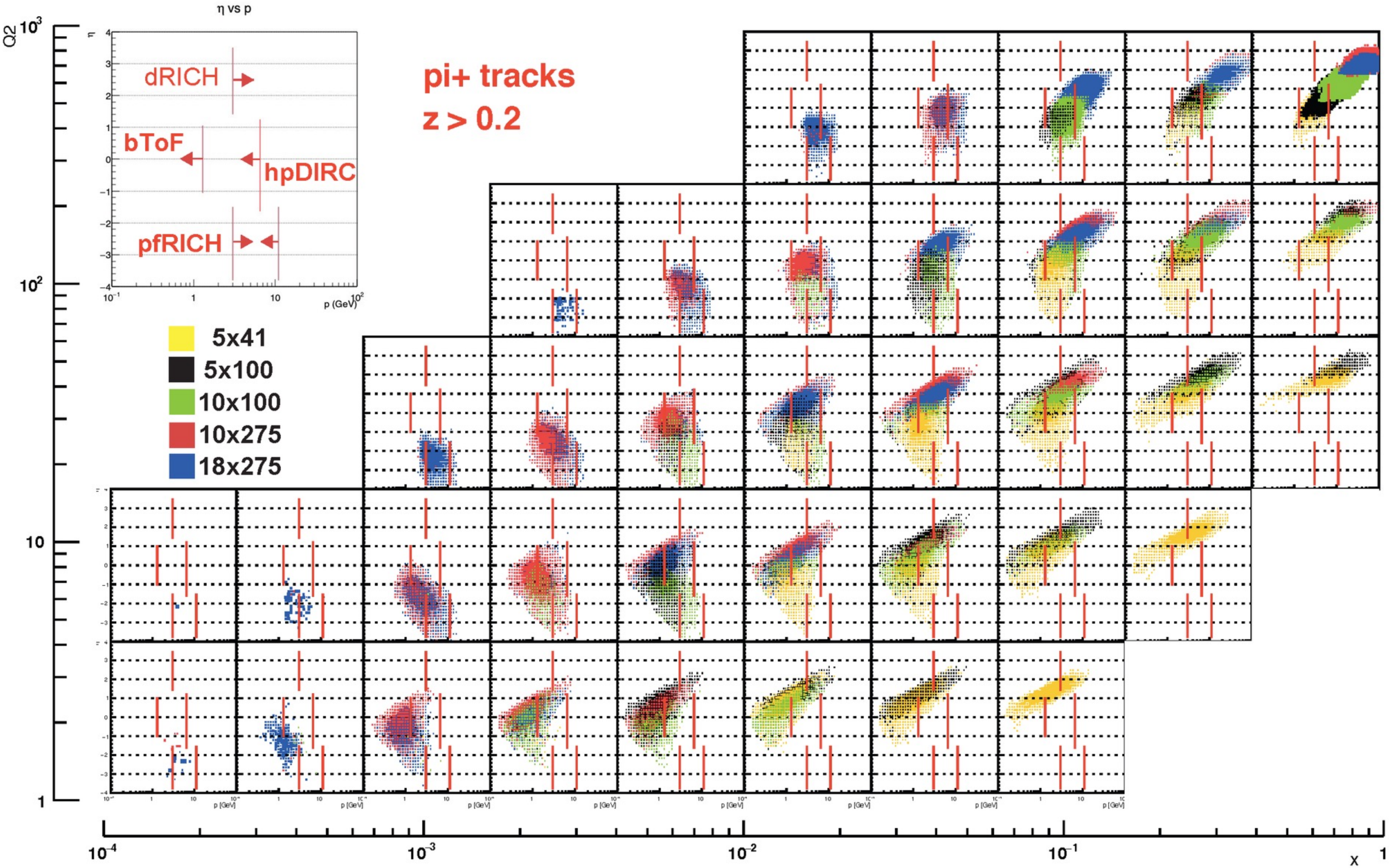
Study by M. McEneaney(Duke)
JLab22 similar

Summary/Conclusion/Outlook

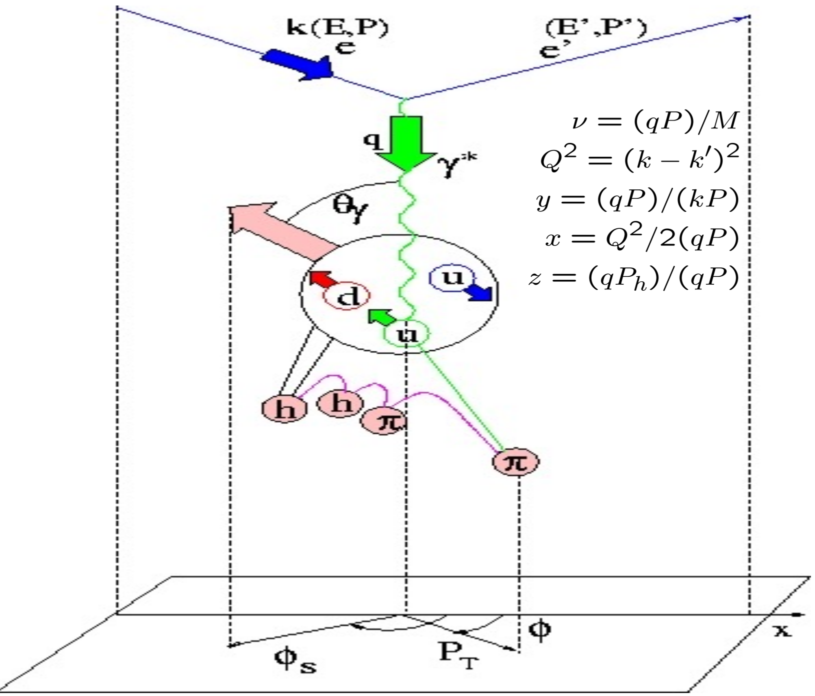
- Broad and diverse SIDIS program
  - Present: JLab12, COMPASS
  - Future: JLab22, EIC
- Wide kinematic reach enabling us to understand the full QCD picture
- Jlab: unprecendented precision in valence quark regime
- EIC: new frontiers

- What is missing in this talk:
  - COMPASS
    - Deuterium target: Statistics now similar to proton target
    - Work on radiative corrections: RADGEN→DJANGOH
    - Exciting/large datasets still to be analyzed
  - Exclusive limit
  - TMDs in medium
  - Charged current at the EIC
  - Details on JLab12, 22 and EIC programs can be found in review papers and detector proposals
    - Yellow Report, Athena, ECCE, CORE proposals, PSQ report…
  - …(and a lot more)

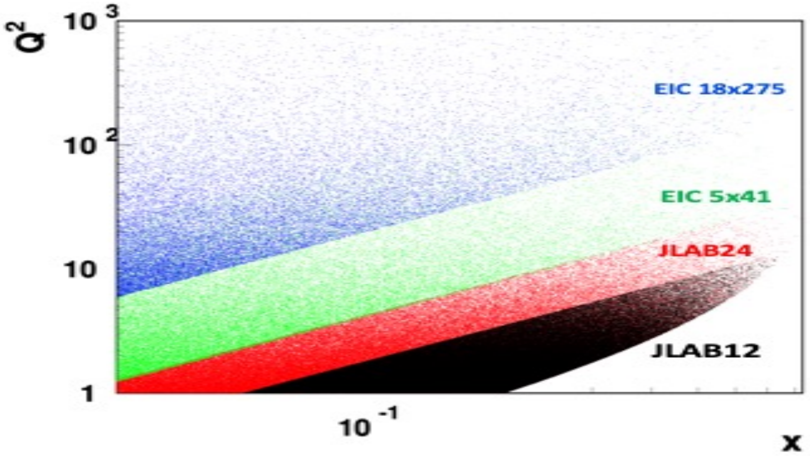
Wide Coverage

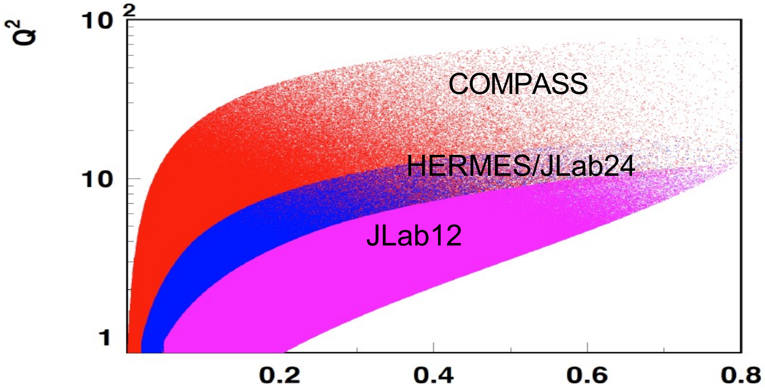


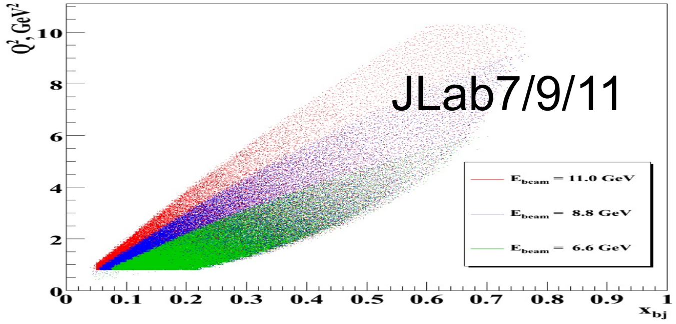
Electroproduction kinematics



EIC



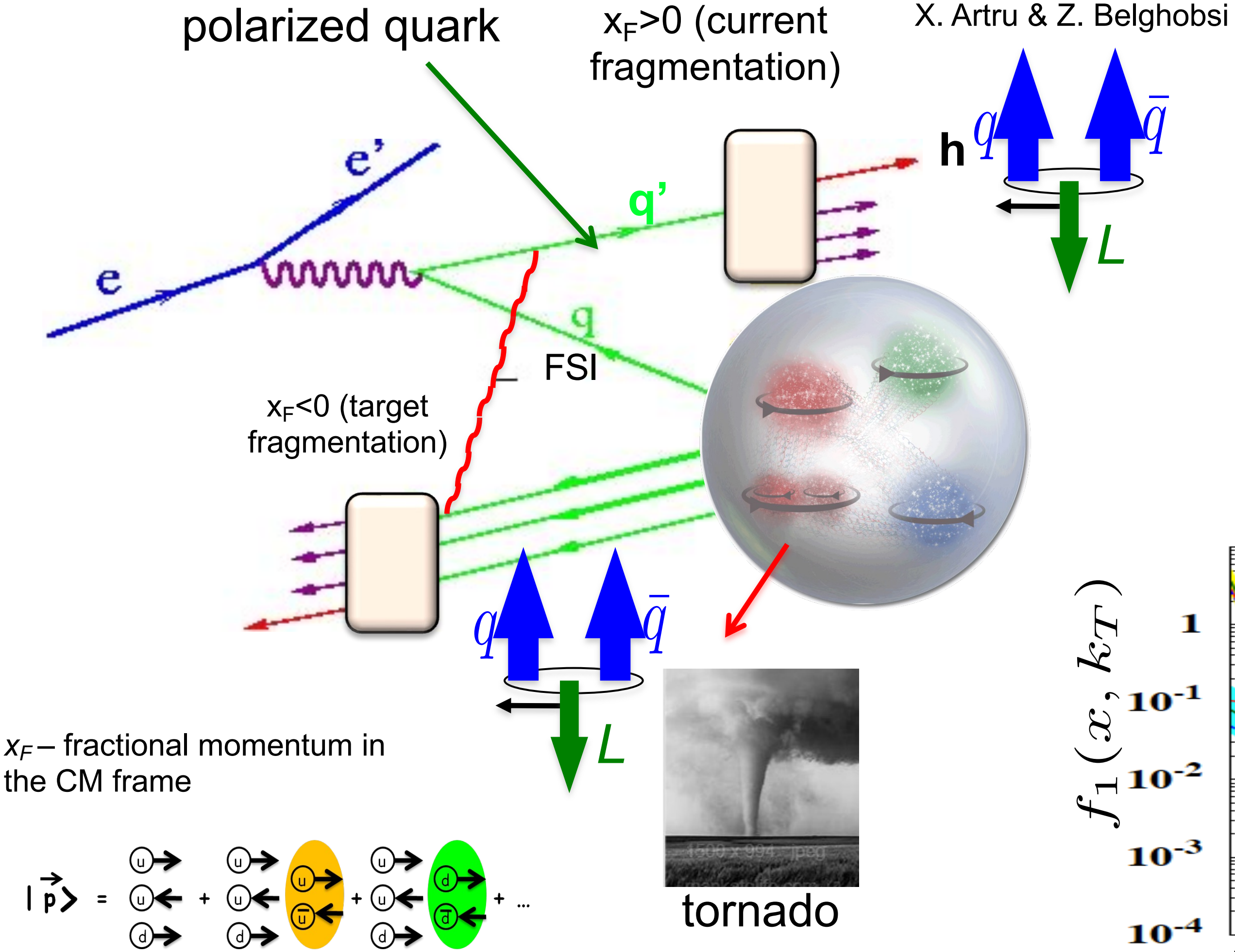




Experiments measure azimuthal dependence of the cross section as a function of x,Q^2,z,P_T

- Studies of azimuthal modulations give access to underlying dynamics (3D partonic distributions,…)
- QCD predicts the Q^2-dependence of 3D PDFs

Hadron production in hard scattering



polarized quark

x_F>0 (current fragmentation)

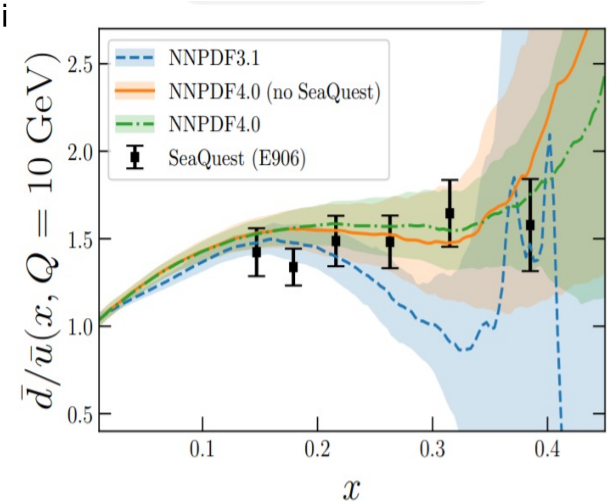
X. Artru & Z. Belghobsi

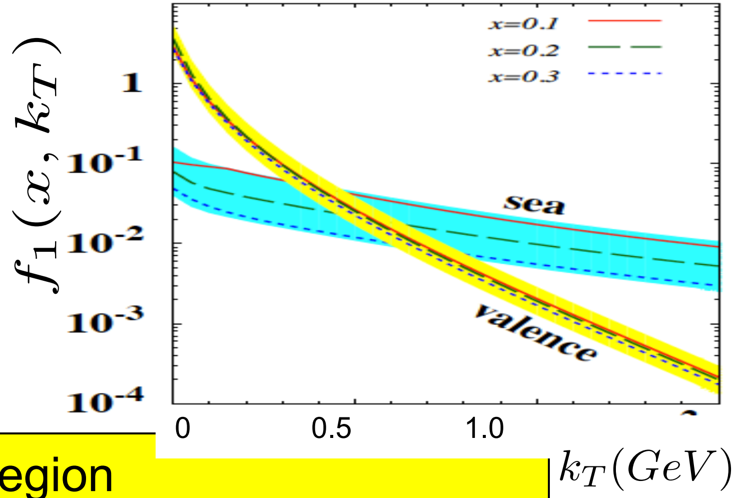
FSI

x_F<0 (target fragmentation)

x_F – fractional momentum in the CM frame

tornado

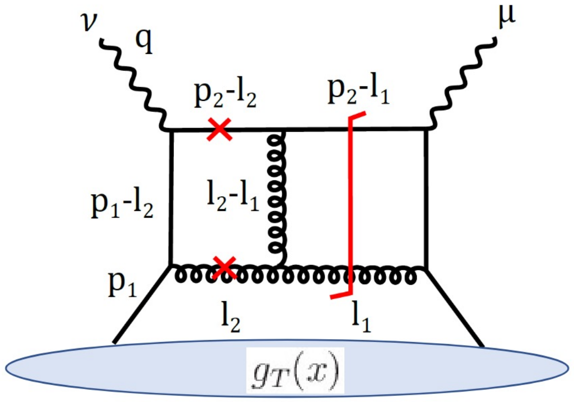


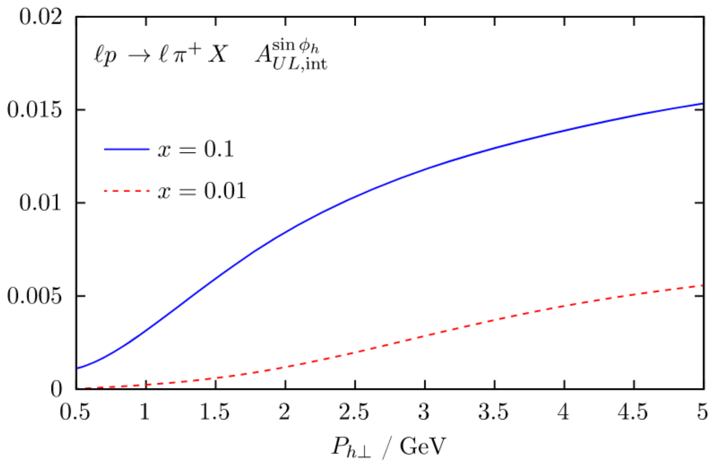


Non-perturbative sea is significant in the valence region
It contribute in spin-orbit correlations, more at large transverse momenta

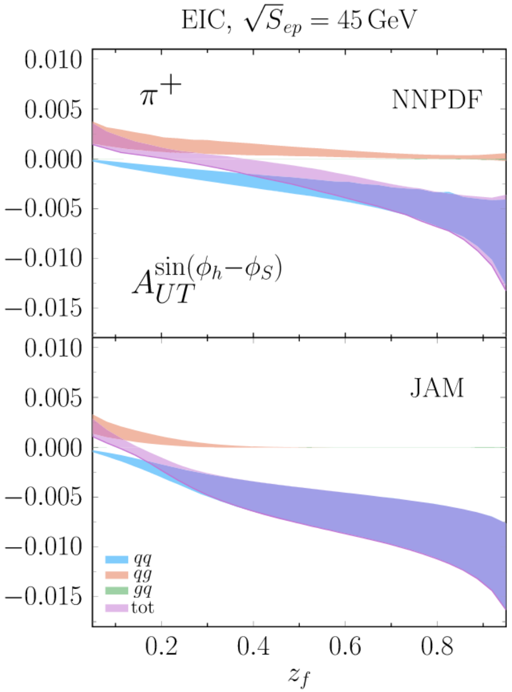
Appearance of perturbative asymmetries

- Additionally: perturbative generation of asymmetries from g_T
- What about di-hadron correlations?





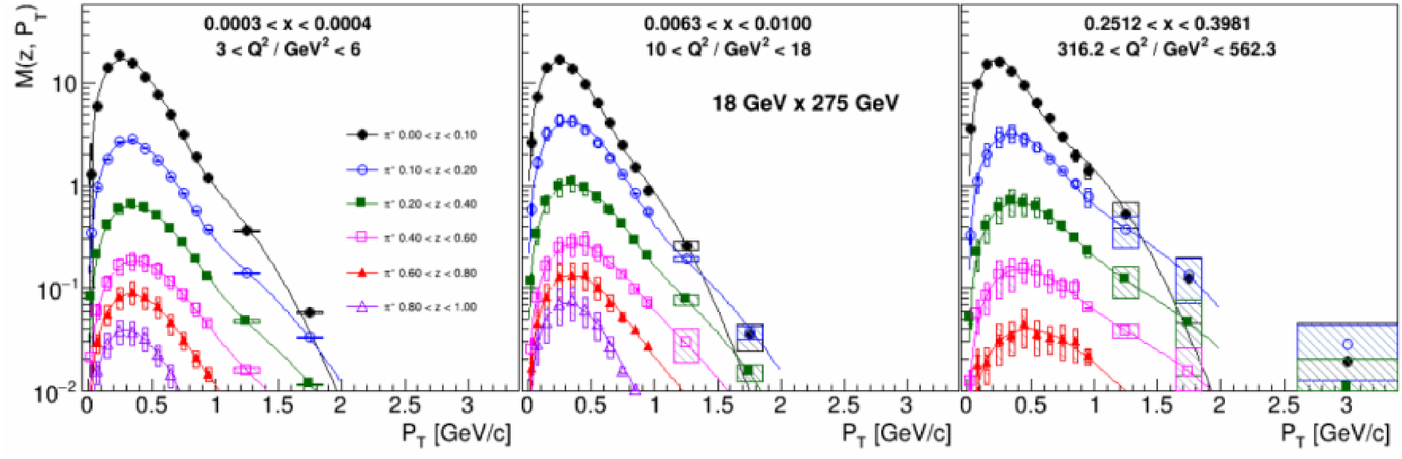
Abele, Aicher, Piacenza, Schafer, Vogelsang (2022)



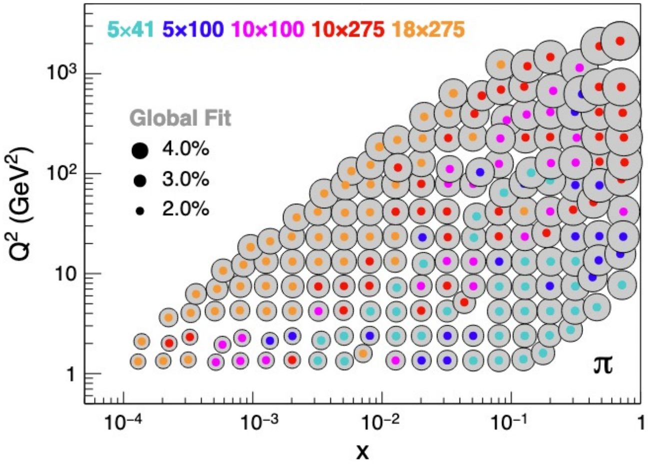
Benic et al. Phys. Rev. D 104, 094027

Unpolarized TMDs

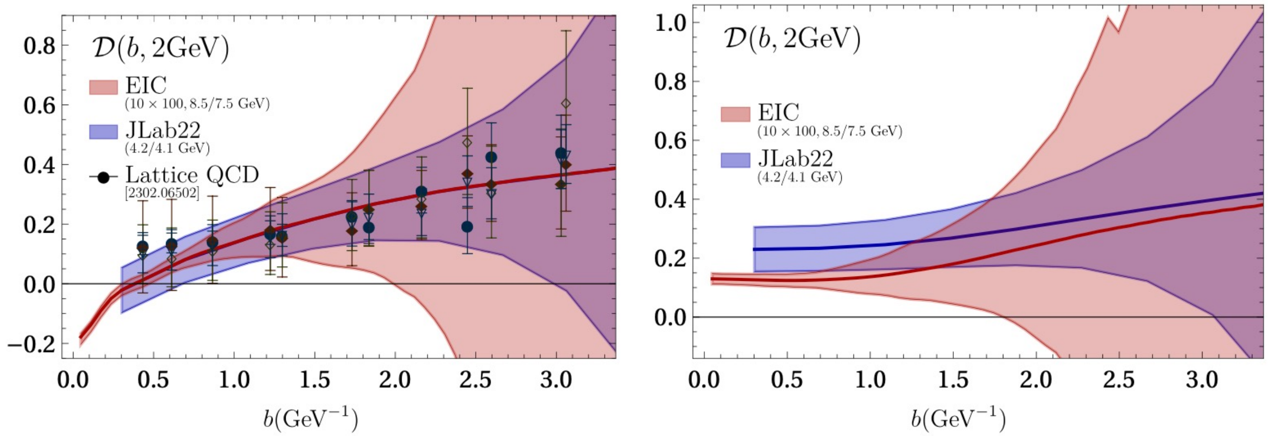
- Top: Explicit z dependence of select pion multiplicities in 3 x-Q^2 bins, including the double-Gaussian fits



hep-ex:2207.10893



- Impact on $f(x, k_T)$ from Athena proposal
- $\frac{q_T}{Q} < 1.0, y > 0.01$
- Experimental uncertainties dominated by $2\%\ p2p$, 3% scale, theoretical uncertainties driven by uncertainties on evolution



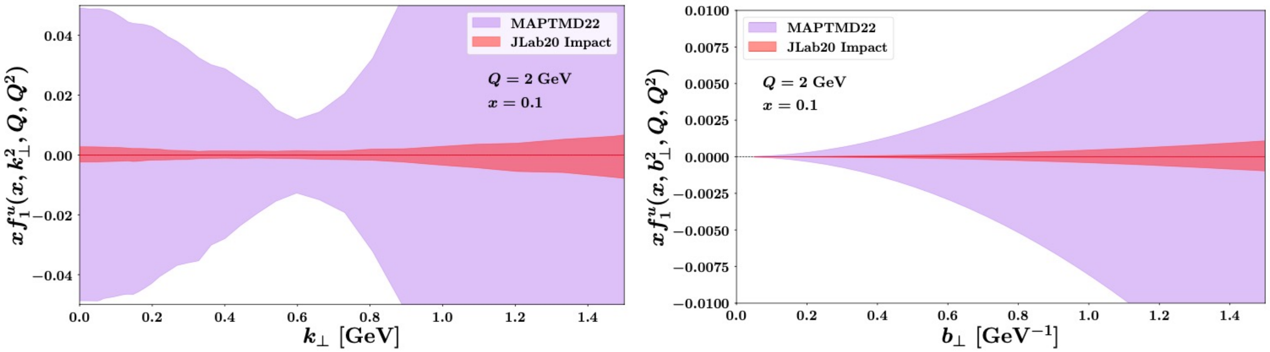
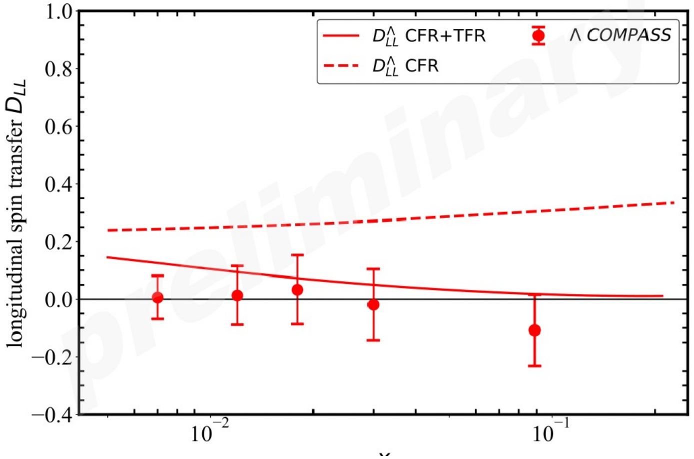


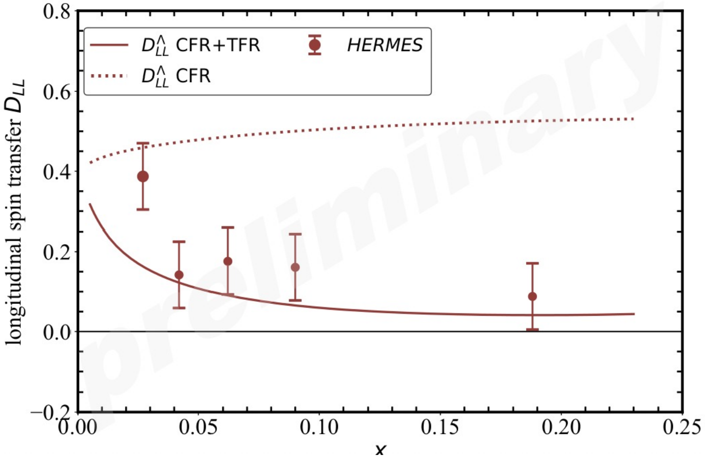
Figure 25: Impact on the error bands of the TMD in $k_\perp$ space (left) and its Fourier-conjugate $b_\perp$ (right) at two values of x and at $Q = 2$ GeV, based on the MAP22TMD analysis [132]. Purple bands: current situation. Red bands: after the inclusion of JLab22 data.

Lambda

$$\zeta = \frac{2x_B(M_h^2 + P_{h\perp}^2)}{z_hQ^2 + \sqrt{z_h^2Q^4 - 4x_B^2M^2(M_h^2}}$$

D_{LL}^{Λ} in CFR (dashed line) and CFR+TFR (real line):



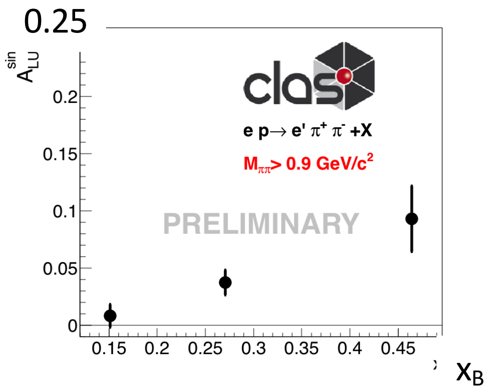


Example, Access of e(x) in SIDIS x-section

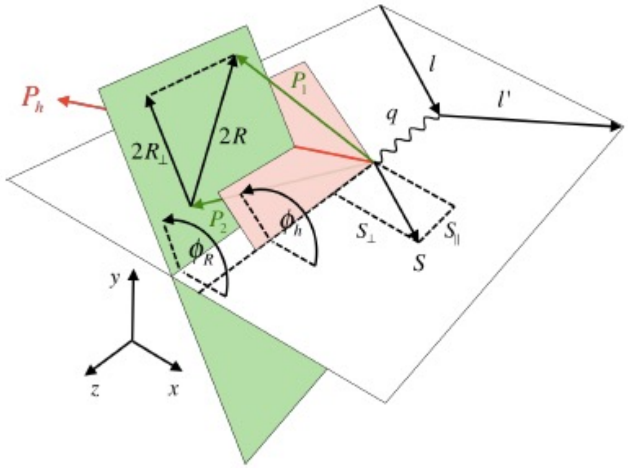
- Di-hadron cross section: Clean access to e(x)

$$F_{LU}^{\sin\phi_R} = -x\frac{|\boldsymbol{R}|\sin\theta}{Q}\left[\frac{M}{m_{hh}}\,x\,e^q(x)\,H_1^{\sphericalangle q}(z,\cos\theta,m_{hh}) + \frac{1}{z}\,f_1^q(x)\,\widetilde{G}^{\sphericalangle q}(z,\cos\theta,m_{hh})\right],$$

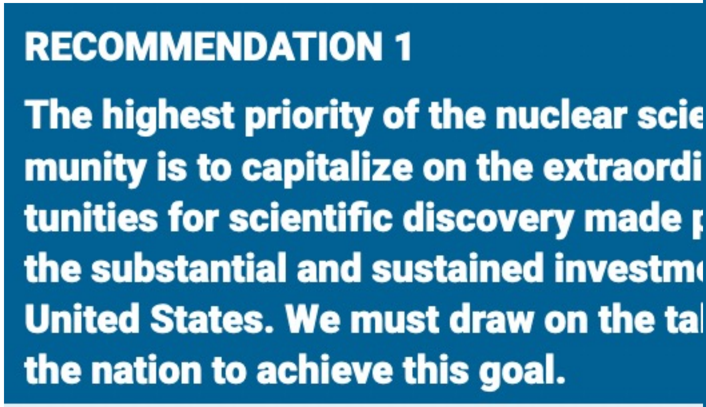
- See e.g. Aurore Courtoy, arXiv:1405.7659



AV, DNP 2018

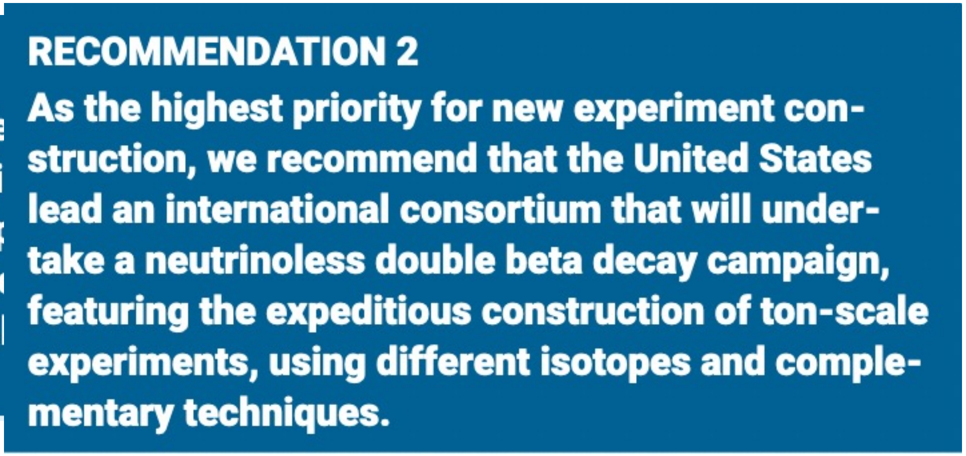


- f



RECOMMENDATION 1

The highest priority of the nuclear scie
munity is to capitalize on the extraordi
tunities for scientific discovery made p
the substantial and sustained investm
United States. We must draw on the ta
the nation to achieve this goal.



RECOMMENDATION 2

As the highest priority for new experiment construction, we recommend that the United States lead an international consortium that will undertake a neutrinoless double beta decay campaign, featuring the expeditious construction of ton-scale experiments, using different isotopes and complementary techniques.

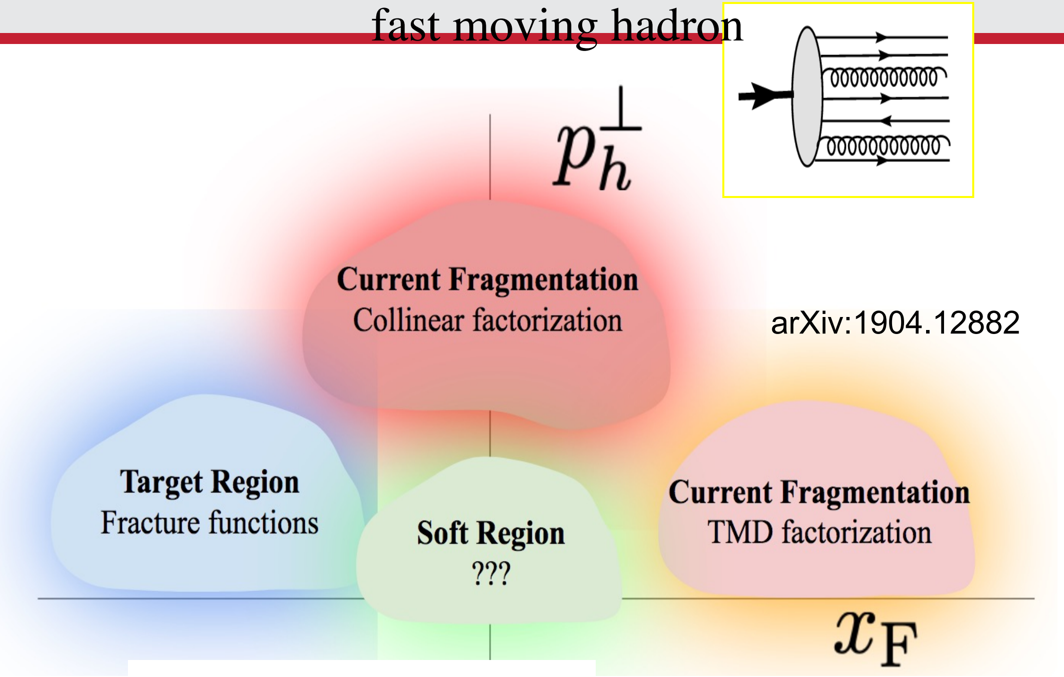
RECOMMENDATION 3

We recommend the expeditious completion of the EIC as the highest priority for facility construction.

RECOMMENDATION 4

We recommend capitalizing on the unique ways in which nuclear physics can advance discovery science and applications for society by investing in additional projects and new strategic opportunities.

Structure functions and depolarization factors in SIDIS



arXiv:1904.12882

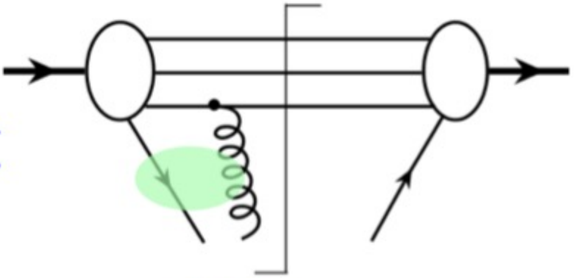
x_F – fractional momentum in the CM frame

1) Theory works well for $P_T/Q<0.25$,
2) Kinematic regions not trivial to separate at lower energies
3) Multi-dimensional measurements critical, requiring high lumi
4) Decays can lead to additional contamination

Maybe not the full picture

- Twist-3

$$T^{(3)}(x,x) \propto$$

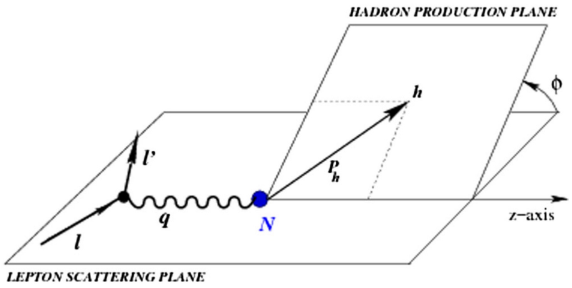


Qiu, Sterman, 1991, ...

- Regions
- Mesons
- Decays
- Rad corr
- Some projections from the EIC
- Jlab 22

e(x) in single hadrons

- The 3D nucleon structure in momentum space can be described by TMDs
- SIDIS provides an effective tool to probe the transverse momentum dependent partonic structure of the nucleon



SIDIS cross section for an unpolarized target:

→ Contains model independent structure functions

$$\frac{d\sigma}{dx_B\,dQ^2\,dz\,d\phi_h\,dp_{h\perp}^2} = K(x,y,Q^2)\Big\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)F_{UU}^{\cos 2\phi_h} + \lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\sin\phi_h \underline{F_{LU}^{\sin\phi_h}}\Big\}$$

$$F_{LU}^{\sin\phi} = \frac{2M}{Q}\mathcal{C}\left(-\frac{\hat{\mathbf{h}}\cdot\mathbf{k_T}}{M_h}\left(xeH_1^\perp + \frac{M_h}{M}f_1\frac{\tilde{G}^\perp}{z}\right) + \frac{\hat{\mathbf{h}}\cdot\mathbf{p_T}}{M}\left(xg^\perp D_1 + \frac{M_h}{M}h_1^\perp\frac{\tilde{E}}{z}\right)\right)$$

twist-3 pdf

Collins FF

unpolarized dist. function

twist-3 FF

twist-3 t-odd dist. funcion

Boer-Mulders

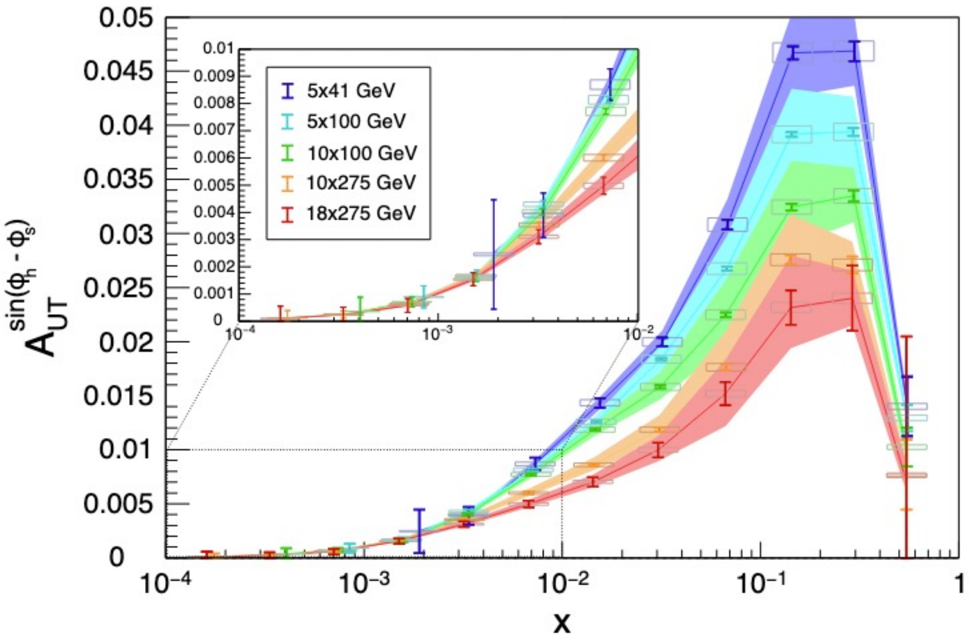
twist-3 FF

➔ A convolution of 4 TMDs and 4 fragmentation functions

➔ The results can be used in a global fit to constrain the TMDs and FF

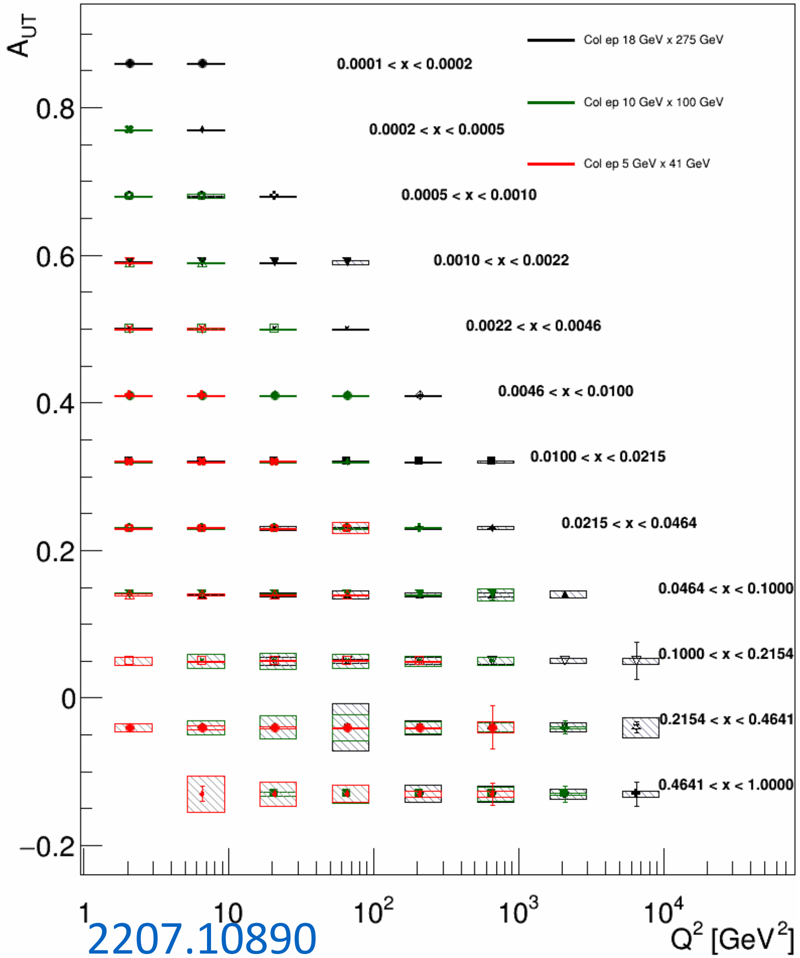
See talk by Stefan Diehl

Projection of transverse TSSAs



Athena projections for the measurement of Sivers asymmetries

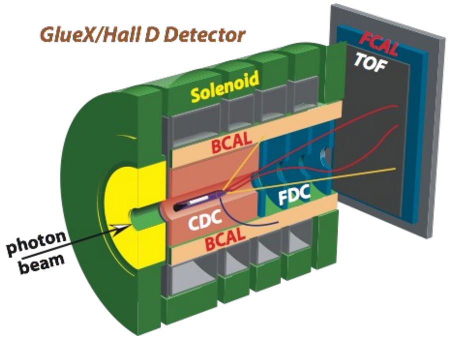
$$0.2 < z < 0.7, Q^2 > 1.0, y > 0.05, \frac{qT}{Q} < 1.0$$

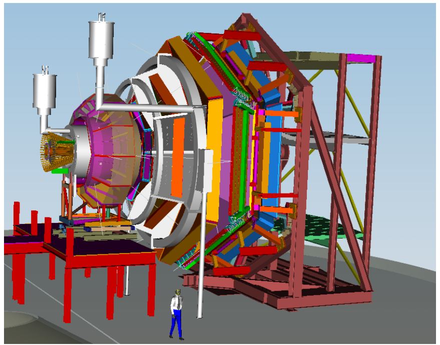


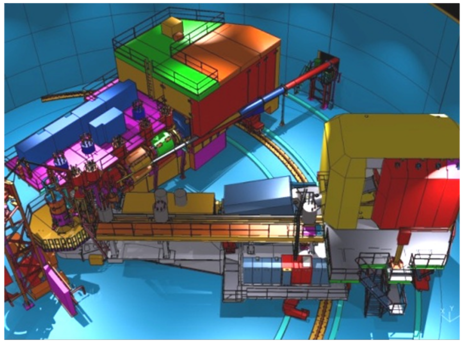
2207.10890

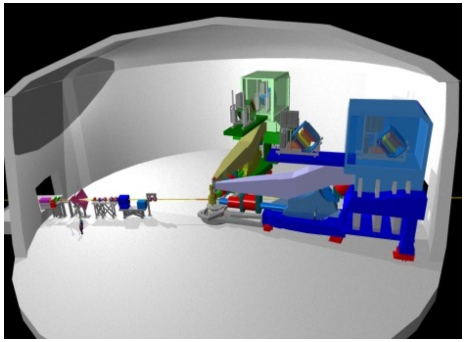
Projected uncertainties on Collins Asymmetries by ECCE

Detector Requirements: Complementarity



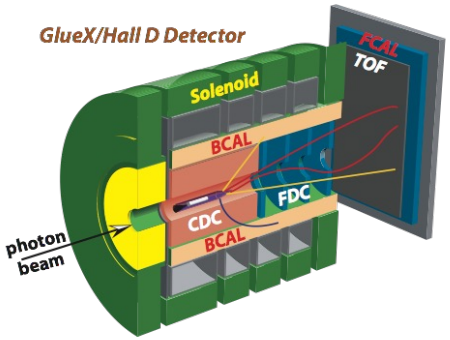


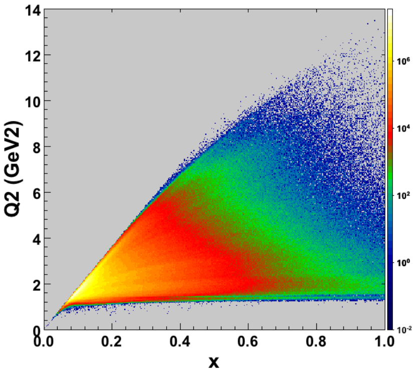


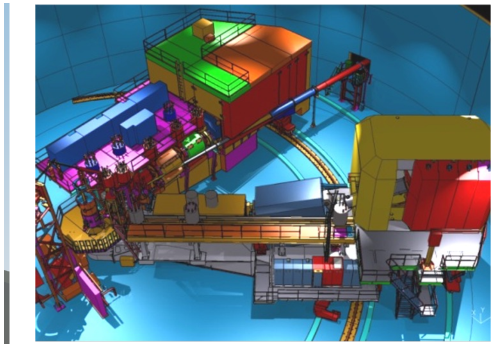


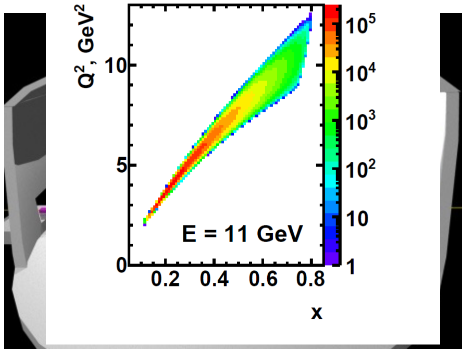
Hall D	Hall B	Hall C	Hall A
excellent hermeticity	luminosity 10^{35}	energy reach	custom installations
polarized photons	hermeticity	precision	
E_γ~8.5-9 GeV	11 GeV beamline		
10^8 photons/s	target flexibility		
good momentum/angle resolution		excellent moment	
high multiplicity reconstruction		luminosity up to 10^{38}	
particle ID			

Detector Requirements: Complementarity









<table>
<tr><th>Hall D</th><th>Hall B</th><th>Hall C</th><th>Hall A</th></tr>
<tr><td>excellent hermeticity</td><td>luminosity 10^{35}</td><td>energy reach</td><td>custom installations</td></tr>
<tr><td>polarized photons</td><td>hermeticity</td><td>precision</td><td></td></tr>
<tr><td>E_γ~8.5-9 GeV</td><td colspan="3">11 GeV beamline</td></tr>
<tr><td>10^8 photons/s</td><td colspan="3">target flexibility</td></tr>
<tr><td colspan="2">good momentum/angle resolution</td><td colspan="2">excellent momentum resolution</td></tr>
<tr><td colspan="2">high multiplicity reconstruction</td><td colspan="2">luminosity up to 10^{38}</td></tr>
<tr><td colspan="4">particle ID</td></tr>
</table>

Tentative Timelines relevant for TMD program shown here

CLAS12 in Hall B

- 2018-2020: unpolarized proton/deuterium target – long. polarized beam
- 2022+ polarized long target?
- Future Polarized He3 (long/trans)
- Polarized transverse HD

Hall A

- 2023 Transverse single spin asymmetries on He3 (64 beam days)
- 2028 SoLID with He3/proton target (long/transverse)

Accessing e(x) in the TMD framework

- The PDF e can be measured in the F_{LU} structure function of the cross section for the production of a pion on an unpolarized target.

$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\mathcal{C}\left[-\frac{\hat{h}\cdot k_T}{M_h}\left(x\overset{\text{twist-3 pdf}}{\boxed{e}}\underset{\text{Collins FF}}{\boxed{H_1^\perp}} + \frac{M_h}{M}\overset{\text{unpolarized PDF}}{\boxed{f_1}}\frac{\boxed{\tilde{G}^\perp}}{\underset{\text{twist-3 FF}}{z}}\right) + \frac{\hat{h}\cdot p_T}{M}\left(x\overset{\text{twist-3 t-odd PDF}}{\boxed{g^\perp}}\underset{\text{unpolarized FF}}{\boxed{D_1}} + \frac{M_h}{M}\overset{\text{Boer-Mulders}}{\boxed{h_1^\perp}}\frac{\boxed{\tilde{E}}}{\underset{\text{twist-3 FF}}{z}}\right)\right]$$

- Complicated combination of four terms in the structure function.
- TMD factorization at twist-3 not yet proven!

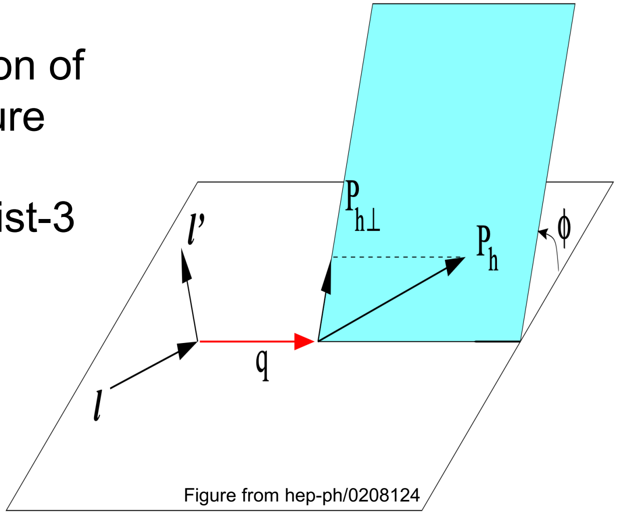
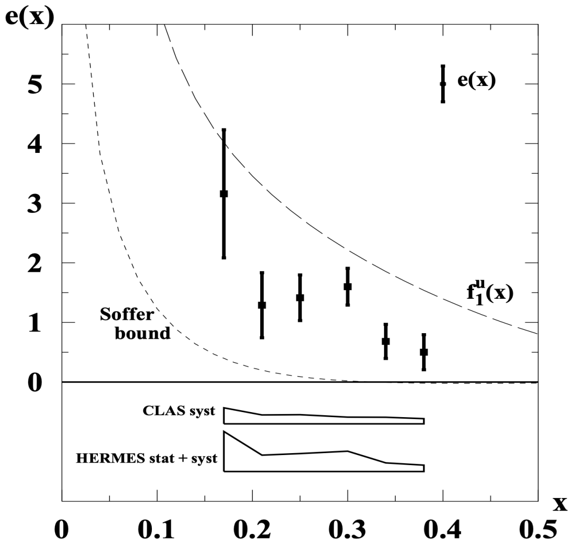


Figure from hep-ph/0208124



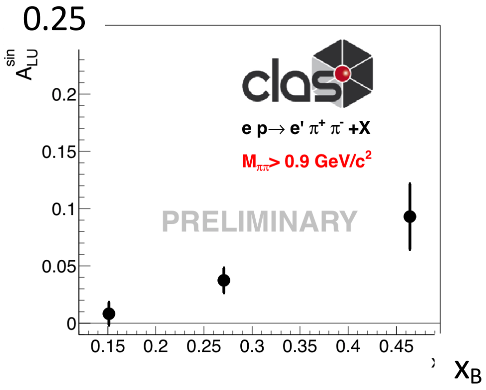
A. Efremov, K. Goeke, and P. Schweitzer, Phys.Rev. D67, 114014 (2003)

Example, Access of e(x) in SIDIS x-section

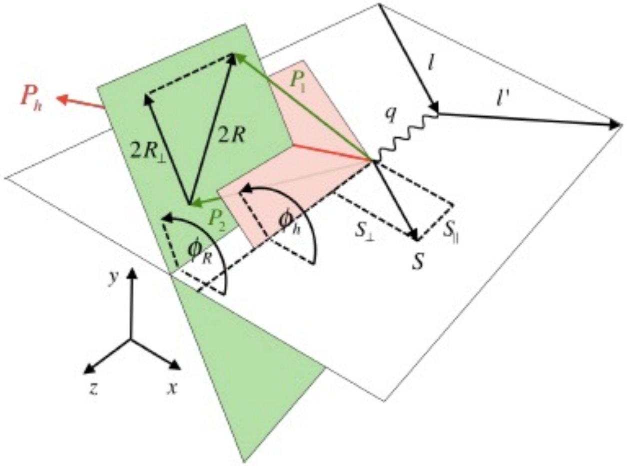
- Di-hadron cross section: Clean access to e(x)

$$F_{LU}^{\sin\phi_R} = -x\frac{|\boldsymbol{R}|\sin\theta}{Q}\left[\frac{M}{m_{hh}}\,x\,e^q(x)\,H_1^{\triangleleft q}(z,\cos\theta,m_{hh}) + \frac{1}{z}\,f_1^q(x)\,\widetilde{G}^{\triangleleft q}(z,\cos\theta,m_{hh})\right],$$

- See e.g. Aurore Courtoy, arXiv:1405.7659



AV, DNP 2018



Partial Wave, Model comparisions, VM, stringspinner string-P03 model

Analog to PDFs; Momentum Sum Rules

- A direct relationship exists to the eight leading twist PDFs after the fracture functions are integrated over the fractional longitudinal nucleon momentum, ζ.

$$\sum_h \int_0^{1-x} d\zeta \zeta M_a(x,\zeta) = (1-x) f_a(x)$$

M. Anselmino et al., Phys. Lett. B. 699 (2011), 108, [hep-ph] 1102.4214

Quark polarization

Nucleon polarization

	U	L	T
U	f_1		$h_1^{\perp}$
L		g_{1L}	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	$h_1, h_{1T}^{\perp}$

Unpolarized PDF analog

helicity PDF analog

etc. etc.

Quark polarization

Nucleon polarization

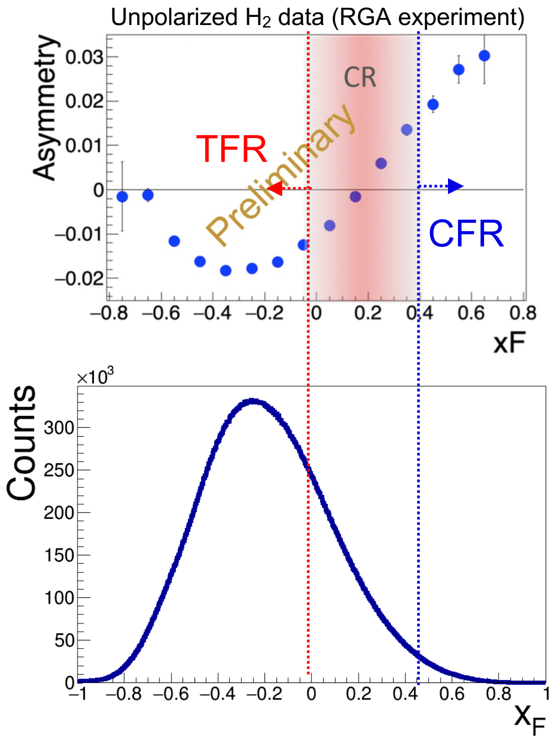
	U	L	T
U	$\hat{u}_1$	$\hat{l}_1^{\perp h}$	$\hat{t}_1^h, \hat{t}_1^{\perp}$
L	$\hat{u}_{1L}^{\perp h}$	$\hat{l}_{1L}$	$\hat{t}_{1L}^h, \hat{t}_{1L}^{\perp}$
T	$\hat{u}_{1T}^h, \hat{u}_{1T}^{\perp}$	$\hat{l}_{1T}^h, \hat{l}_{1T}^{\perp}$	$\hat{t}_{1T}, \hat{t}_{1T}^{hh}$ $\hat{t}_{1T}^{\perp\perp}, \hat{t}_{1T}^{\perp h}$

M. Anselmino et al., Phys. Lett. B. 706 (2011), 46-52, [hep-ph] 1109.1132

CFR ⟷ TFR

Can We Separate Target and Current?

ep → e'pX



Feynman variable

$$x_F = \frac{p_h^z}{p_h^z(\text{max})}$$ in CM frame $\mathbf{p} = -\mathbf{q}$, $-1 < x_F < 1$

Rapidity

$$y_h = \frac{1}{2}\log\frac{p_h^+}{p_h^-} = \frac{1}{2}\log\frac{E_h + p_h^z}{E_h - p_h^z}$$

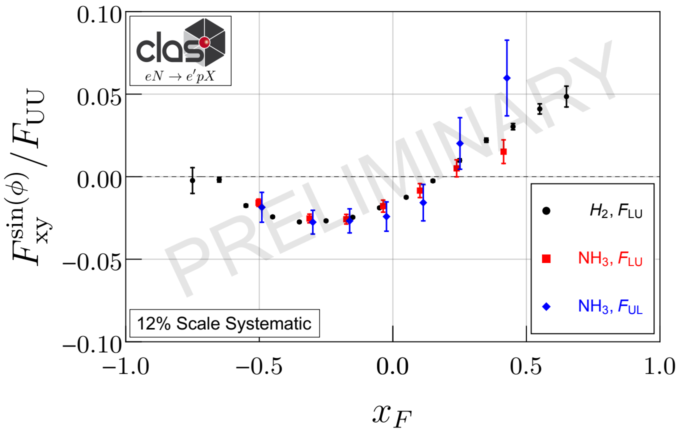
- No clear *experimental* definition of what constitutes current production versus target production.
- Odd structure functions, with different production mechanisms in both regions, give a possible clue.
- Protons (as opposed to mesons) at CLAS12 kinematics give a unique opportunity because they have extensive coverage in both regions.

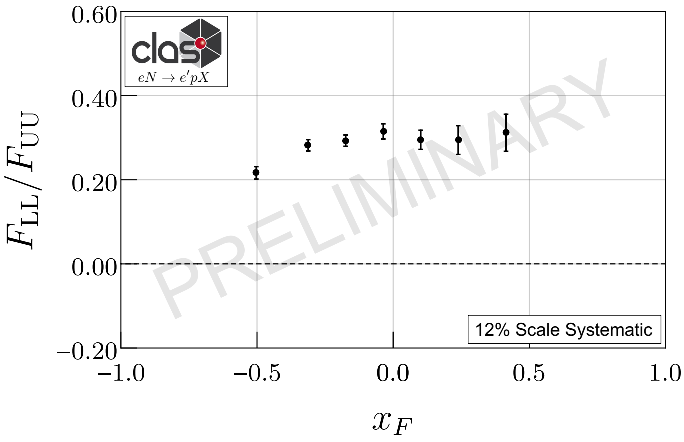
Current and Target Separation

Quark polarization

Nucleon polarization	U	L
U	u^h	l^h
L	u_L^h	l_L^h

Twist-3 Collinear terms;
Chen, K. B., Ma, J. P. and Tong, X. B., [hep-ph] 2308.11251





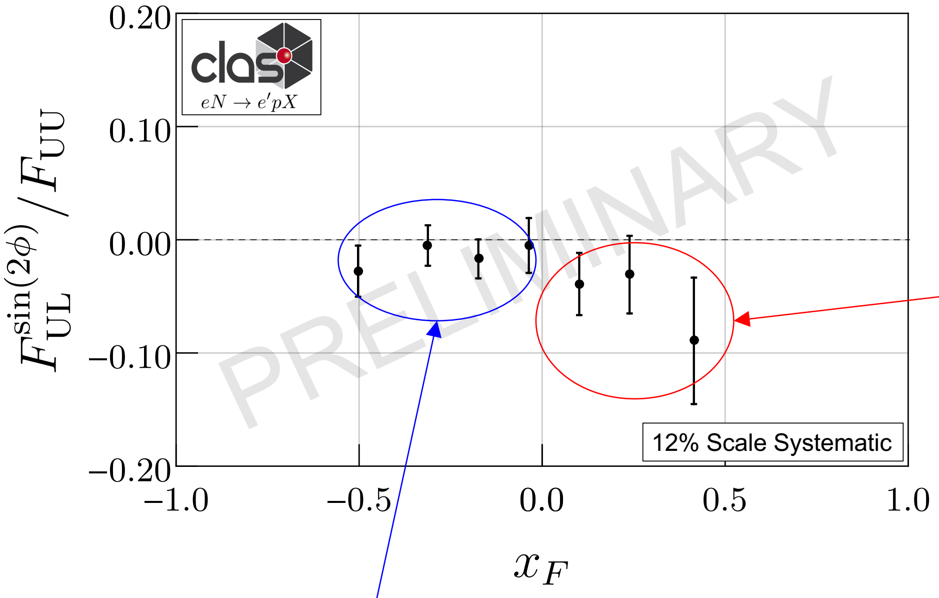
Quark polarization

Nucleon polarization	U	L
U	$\hat{u}_1$	$\hat{l}_1^{\perp h}$
L	$\hat{u}_{1L}^{\perp h}$	$\hat{l}_{1L}$

M. Anselmino et al., Phys. Lett. B. 706 (2011), 46-52, [hep-ph] 1109.1132

- Odd-function (sine) modulations exhibit a sign flip around the transition from target to current fragmentation. Interestingly, we observe F_{LU} ~ F_{UL}.
- Even-function (cosine) behavior of double-spin asymmetry does not show a sign flip; possible signs decreasing F_{LL} as $x_F \to \pm 1$ (x_B decreasing but likely not the only cause).
- Consistent beam-spin asymmetries in unpolarized H_2 and polarized NH_3 indicates minimal nuclear medium modification.

Kotzinian-Mulders Asymmetry



$$F_{UL}^{\sin 2\phi_h} = \mathcal{C}\left[-\frac{2\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T) - \boldsymbol{k}_T\cdot\boldsymbol{p}_T}{M M_h} h_{1L}^{\perp} H_1^{\perp} \right]$$

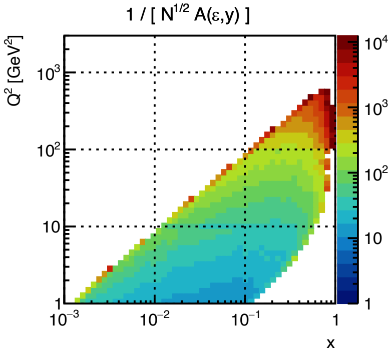
- The $F_{UL}^{\sin2\varphi}$ asymmetry is purely generated by the Collins mechanism – whereby a transversely polarized quark flips orientation during hadronization and produces an asymmetric distribution in the transverse plane.
- Hadronization in the TFR is more isotropic – there is no additional chiral-odd quantity like the Collins function to pair with the Kotzinian-Mulders TMD because factorization into separate soft and hard scale processes does not hold.

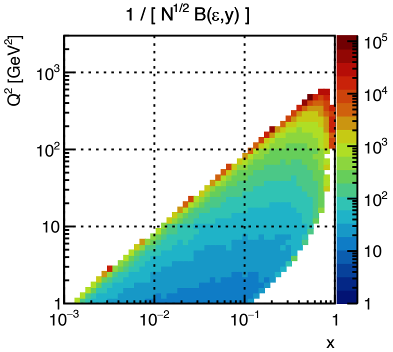
- No Collins mechanism in the TFR so $F_{UL}^{\sin2\varphi}$ (and $F_{UU}^{\cos2\varphi}$) are pure twist-4. We would expect small magnitude at $-x_F$.

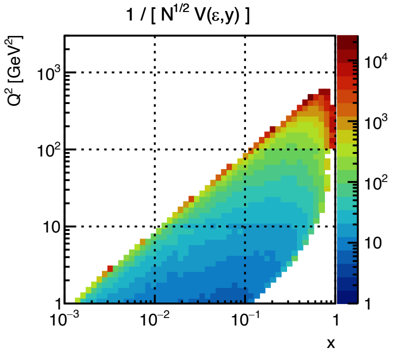
Early signs give a *possible* hint but need more statistics!

Statistical uncertainty scaling factor for $5x41$

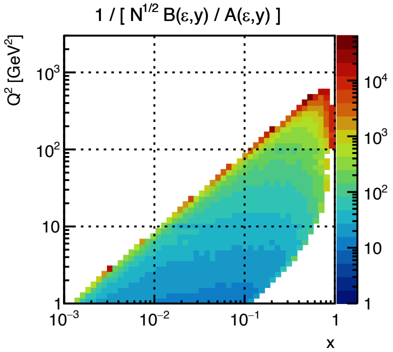
UU

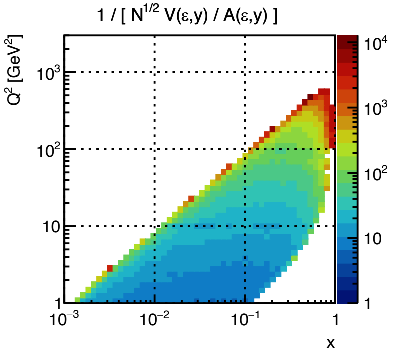

1 / [N$^{1/2}$ A(ε,y)]


1 / [N$^{1/2}$ B(ε,y)]

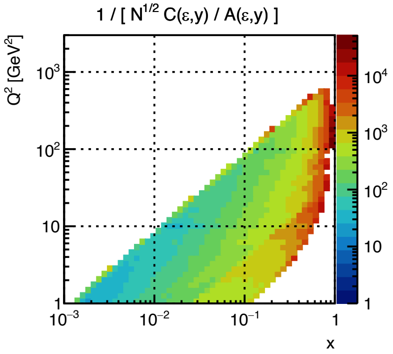

1 / [N$^{1/2}$ V(ε,y)]

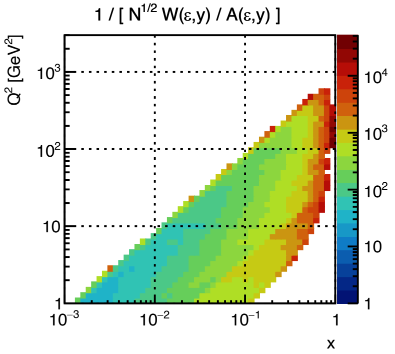
UL, UT


1 / [N$^{1/2}$ B(ε,y) / A(ε,y)]


1 / [N$^{1/2}$ V(ε,y) / A(ε,y)]

LU, LL, LT


1 / [N$^{1/2}$ C(ε,y) / A(ε,y)]


1 / [N$^{1/2}$ W(ε,y) / A(ε,y)]

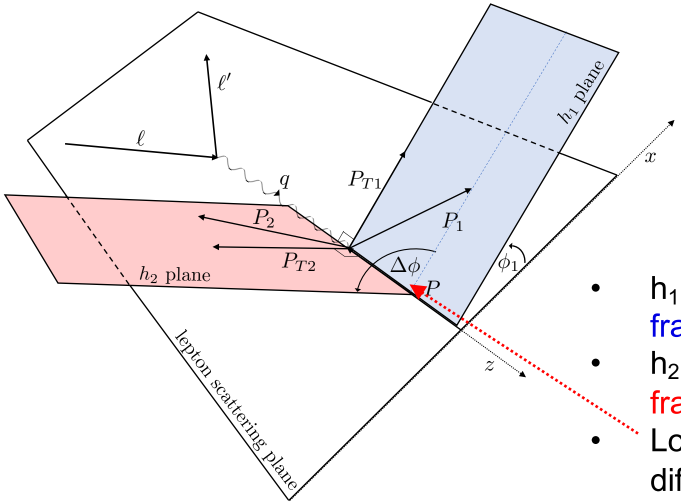
Slide from C. Dilks

Back-to-back (dSIDIS) Formalism

- When two hadrons are produced “back-to-back”[1,2] with one in the CFR and one in the TFR the structure function contains a convolution of a fracture function and a fragmentation function.
- Leading twist beam(target)-spin asymmetry.

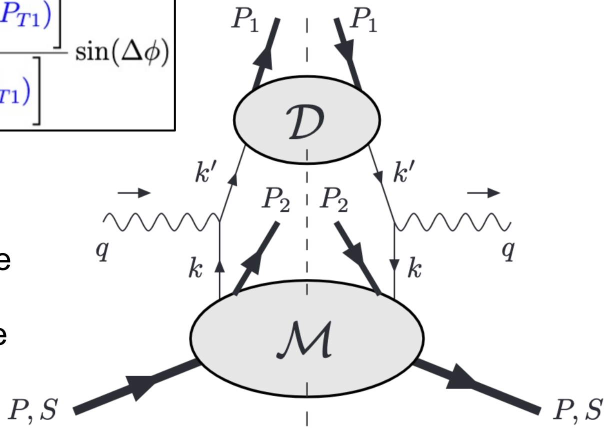
$\hat{l}_1^{\perp h}$ Unique access to longitudinally polarized quarks in unpolarized nucleon… no corresponding PDF!

$$A_{LU} = -k(\epsilon)\frac{P_{T1}P_{T2}}{m_1 m_2}\frac{\mathcal{C}\left[w_5 \hat{l}_1^{\perp h}(x,\zeta_2,P_{T2})D_1(z_1,P_{T1})\right]}{\mathcal{C}\left[\hat{u}_1(x,\zeta_2,P_{T2})D_1(z_1,P_{T1})\right]}\sin(\Delta\phi)$$



Kinematic plane for b2b dihadron production.

- h_1 in the CFR with production dictated by the fragmentation function
- h_2 in the TFR with production dictated by the fracture function
- Long range correlation depends on the difference in azimuthal angles of both hadrons



Handbag diagram for dihadron production; lower blob contains FrFs and upper blob contains the FFs.

1. M. Anselmino et al., Phys. Lett. B. 706 (2011), 46-52, [hep-ph] 1109.1132
2. M. Anselmino et al., Phys. Lett. B. 713 (2012), 317-320, [hep-ph] 1112.2604

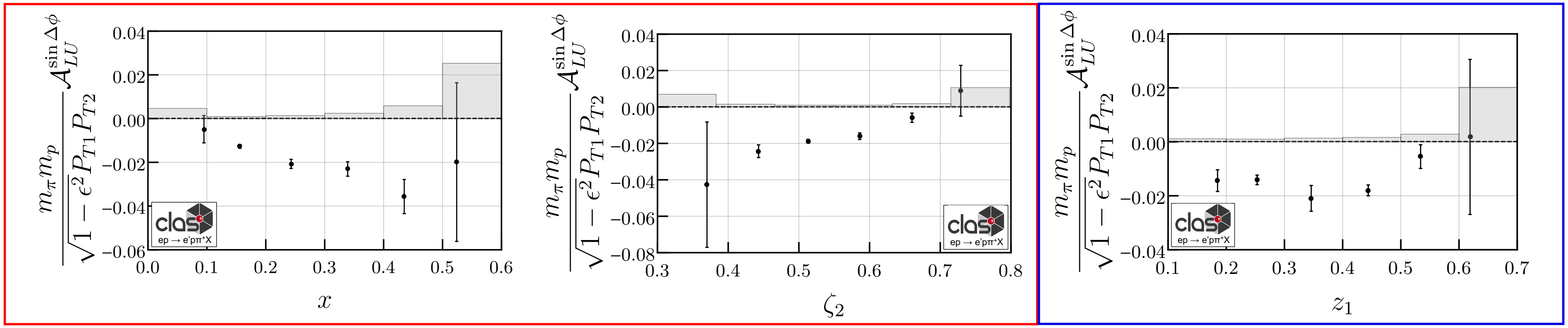
Access to unmeasured fracture functions

- x-dependence increases in magnitude in the valance quark region.
- ζ_2-dependence shows decreasing amplitude with increasing momenta. Possibly due to correlations with x.
- Relatively flat as a function of z_1, possibly due to cancellation of fragmentation functions.
- First observation of TMD fracture functions and long-range correlations between current and target. Already working on follow up (negative pion, deuteron target, more statistics etc.)

$ep \rightarrow e'p\pi^+X$

$$A_{LU} \propto \frac{\mathcal{C}\left[w_5 \hat{l}_1^{\perp h}(x,\zeta_2,P_{T2}) D_1(z_1,P_{T1})\right]}{\mathcal{C}\left[\hat{u}_1(x,\zeta_2,P_{T2}) D_1(z_1,P_{T1})\right]}$$

H. Avakian, T.B. Hayward et al., Phys. Rev. Lett. 130 (2023), [hep-ex] 2208.05086



Target-Current

Ex mesons

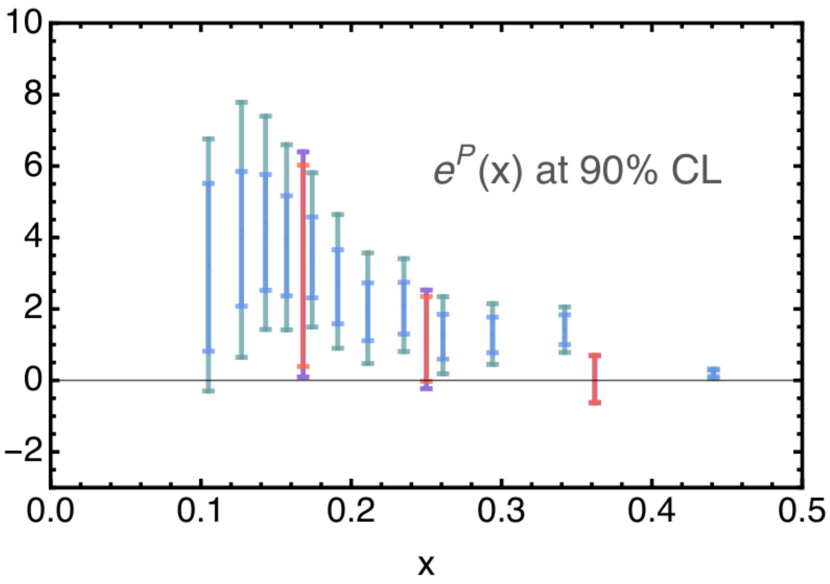
Long target

Compass rad corrections

New e(x) Extraction – Proton Flavor Combination

$$A_{LU}^{\sin\phi_R} \propto \frac{M}{Q}\frac{\sum_q e_q^2\left[x e^q(x)\, H_{1,sp}^{\sphericalangle,q}(z,m_{\pi\pi}) + \frac{m_{\pi\pi}}{zM}\, f_1^q(x)\, \tilde{G}_{sp}^{\sphericalangle,q}(z,m_{\pi\pi})\right]}{\sum_q e_q^2\, f_1^q(x)\, D_{1,ss+pp}^q(z,m_{\pi\pi})}$$

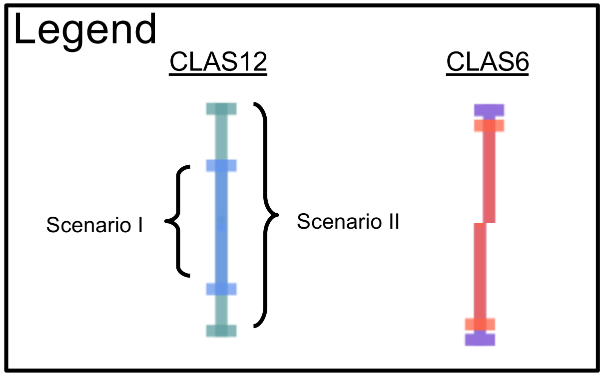
twist-3 DiFF



Courtoy, Aurore, et al. *Phys.Rev.D* 106 (2022)

Courtoy, Aurore – CPHI 2022

- **Scenario I: Wandzura-Wilczek (WW) Approximation**
  - Drop twist-3 DiFF
- **Scenario II: Beyond WW approximation**
  - Estimate max integrated twist-3 DiFF from COMPASS A_{UL} and A_{LL}



Future

- Timeline
- LRP

Physics with Jlab 22

- High X phasespace-->seaquarks (e.g. strange)
- Lambda/charm
- Collins Soper Kernel

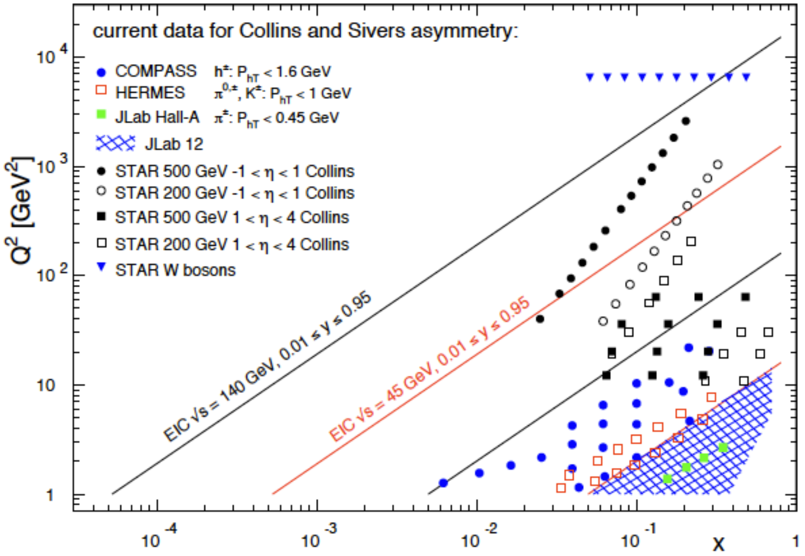
EIC

- See slides from MC for EIC workshop, summer school

SIDIS physics at an EIC: Coverage

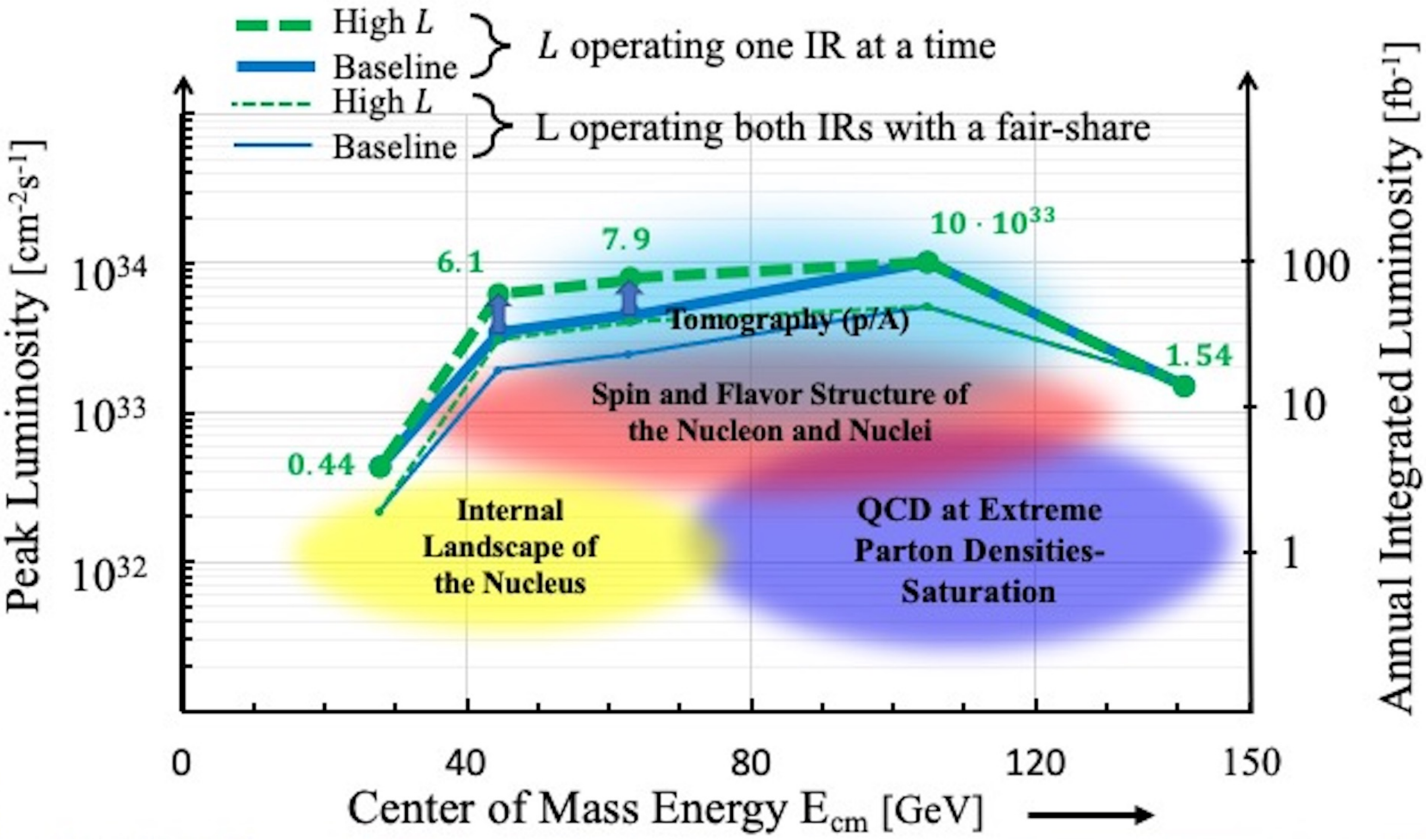
- Common theme on EIC impact
  - Extended kinematic coverage and precision, along with polarization and possible beam charge degrees of freedom allow multi-pronged approach →needed to extract multidimensional objects
  - TMD factorization is valid

Large Q^2 lever arm: probe evolution, disentangle contributions to σ

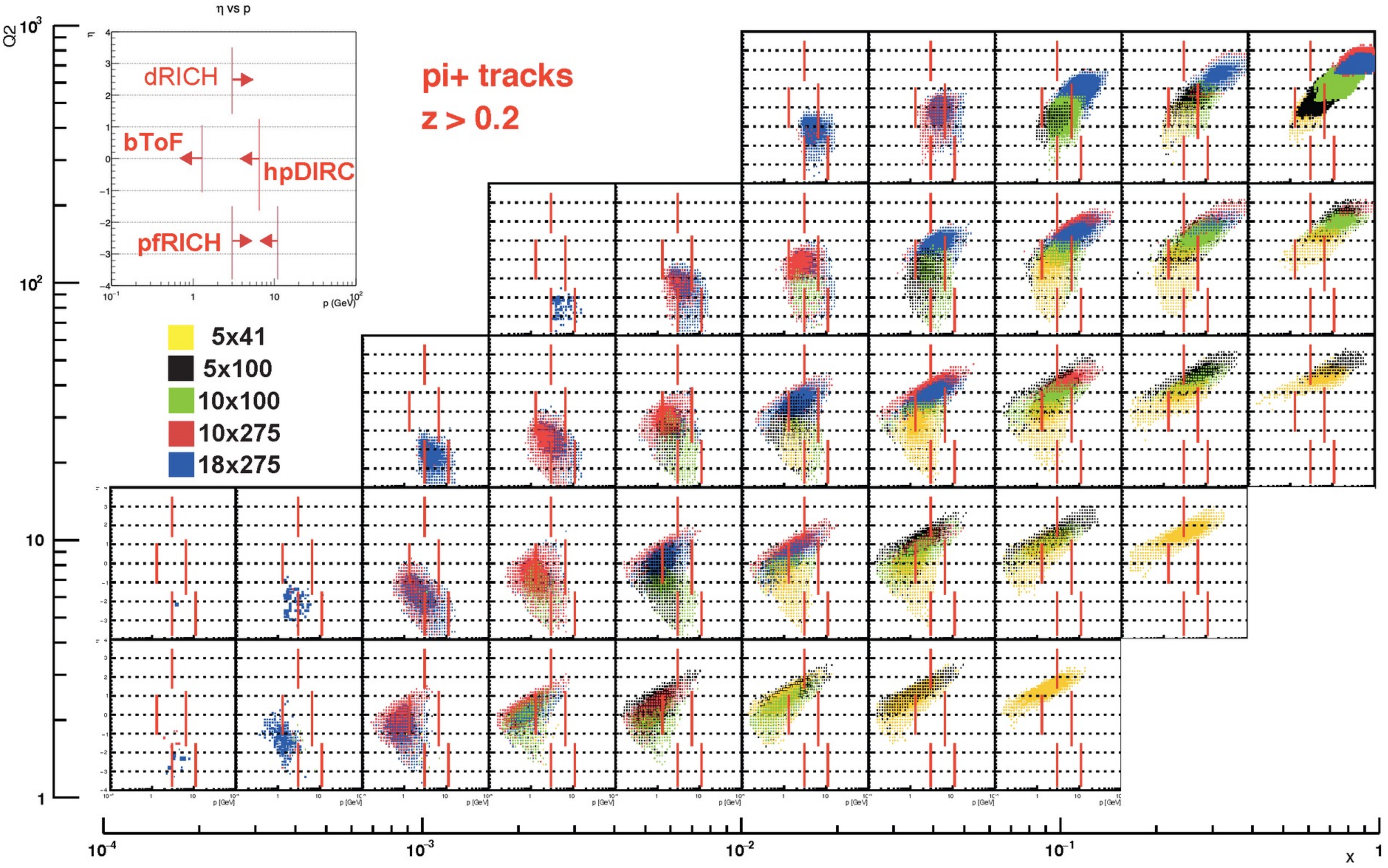


Coverage to low x: access sea and gluon distributions

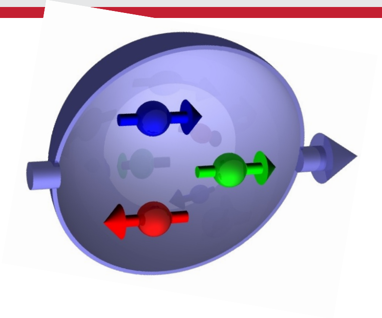
Order of magnitude in luminosity depending on $\sqrt{s}$ (beware of projections with fixed $\int L$)



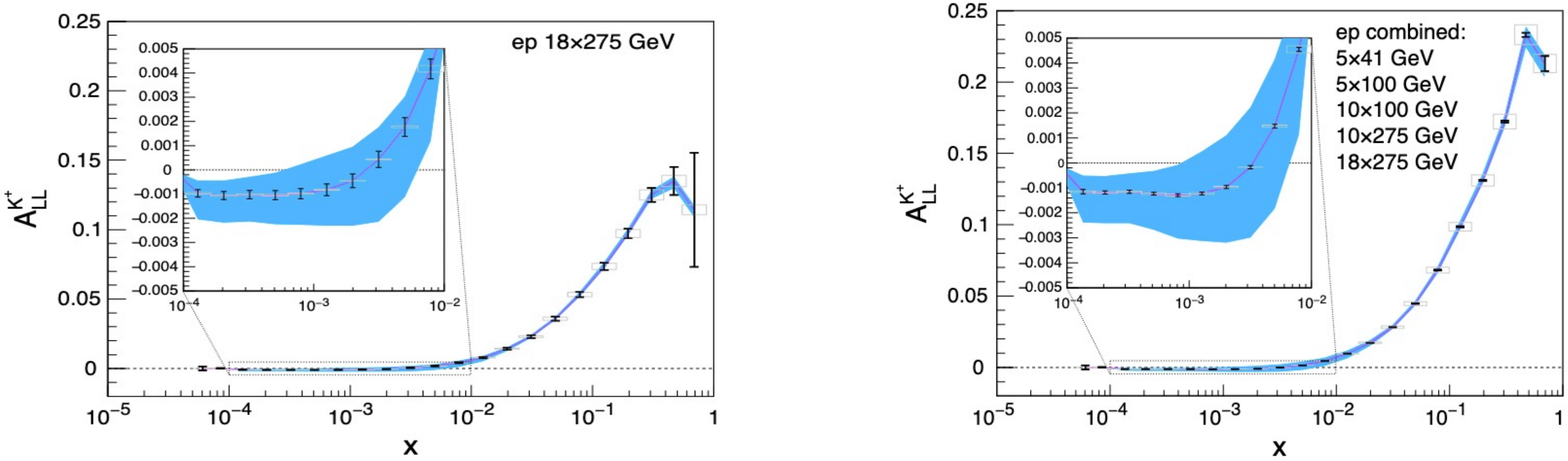
Wide Coverage



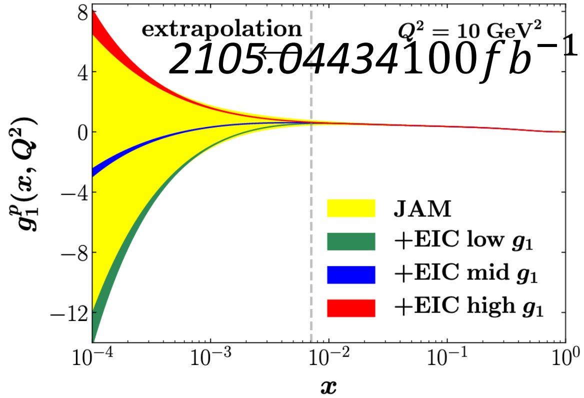
Longitudinal double spin asymmetries



- $A_{LL} = \frac{\sigma^{\uparrow\Uparrow} - \sigma^{\uparrow\Downarrow}}{\sigma^{\uparrow\Uparrow} + \sigma^{\uparrow\Downarrow}} \propto g_1$

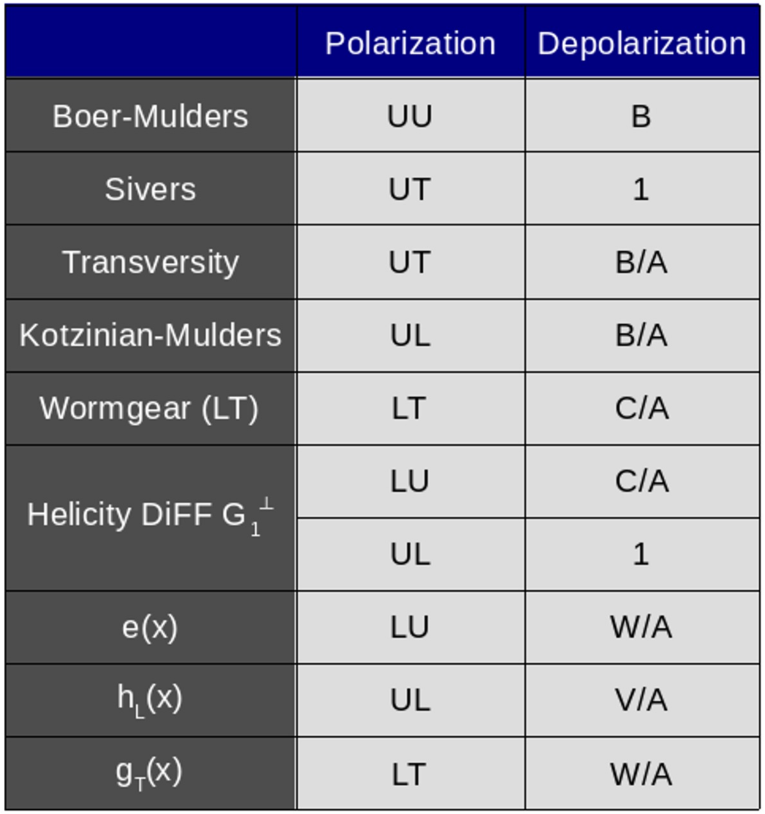


- Projections for Athena (2022 *JINST* **17** P10019)
- 3% point-to-point, 2% scale uncertainties (from Hera experience)
- $z > 0.2$
- $15.5\ fb^{-1}$ at $18x275$, other datasets scaled accordingly



2105.04434 $100\,fb^{-1}$

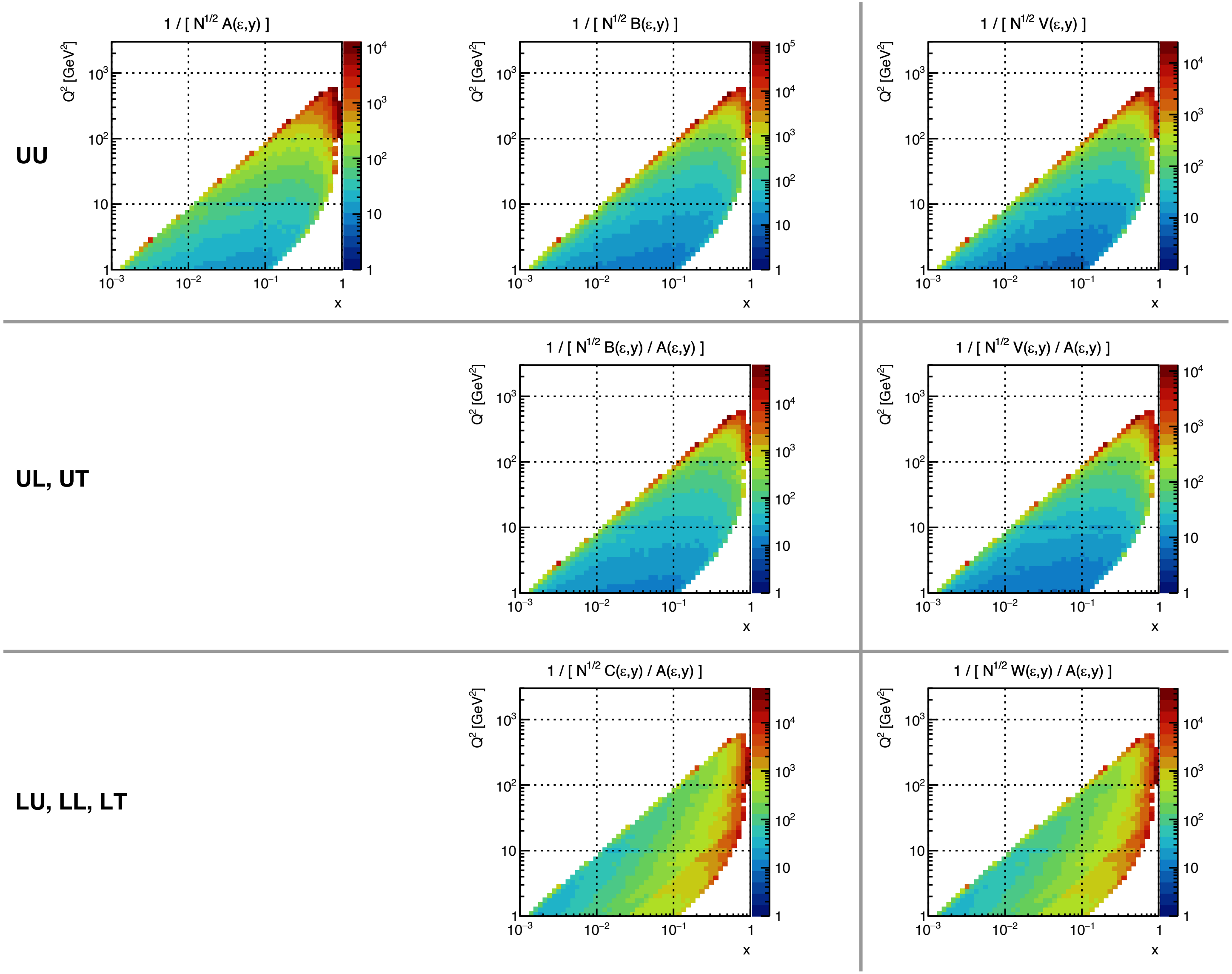
Depolarization Factors



		Polarization	Depolarization
Twist 2	Boer-Mulders	UU	B
	Sivers	UT	1
	Transversity	UT	B/A
	Kotzinian-Mulders	UL	B/A
	Wormgear (LT)	LT	C/A
	Helicity DiFF $G_1^\perp$	LU	C/A
		UL	1
Twist 3	e(x)	LU	W/A
	$h_L(x)$	UL	V/A
	$g_T(x)$	LT	W/A

Slide from C. Dilks

Statistical uncertainty scaling factor for $5x41$



Slide from C. Dilks

Depolarization Factors

Twist 2

	Polarization	Depolarization
Boer-Mulders	UU	B
Sivers	UT	1
Transversity	UT	B/A
Kotzinian-Mulders	UL	B/A
Wormgear (LT)	LT	C/A
Helicity DiFF $G_1^\perp$	LU	C/A
	UL	1
e(x)	LU	W/A
h_L(x)	UL	V/A
g_T(x)	LT	W/A

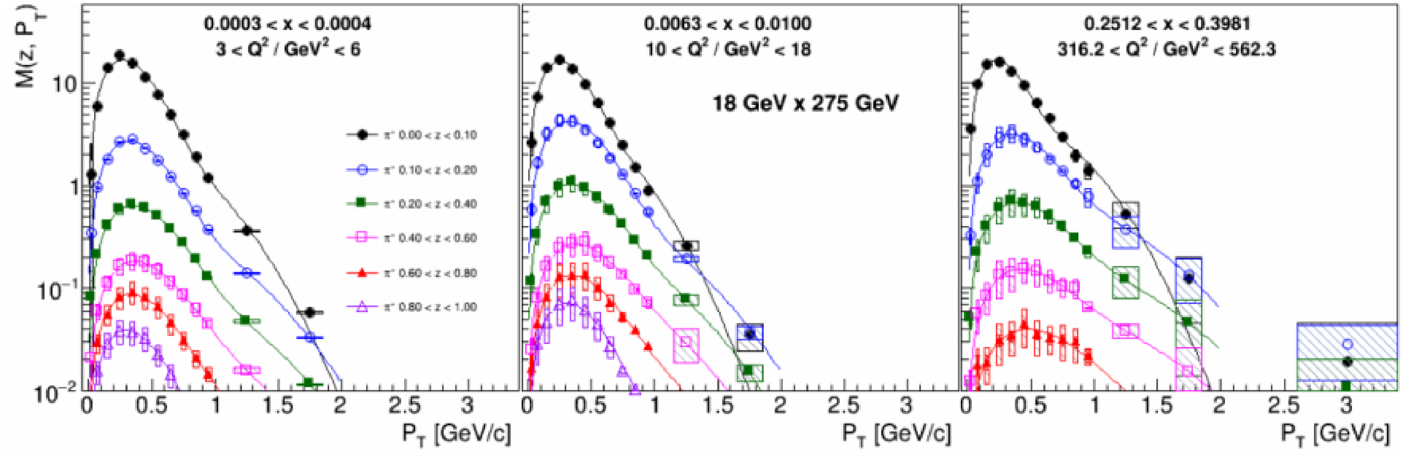
Twist 3

Suppressed at EIC

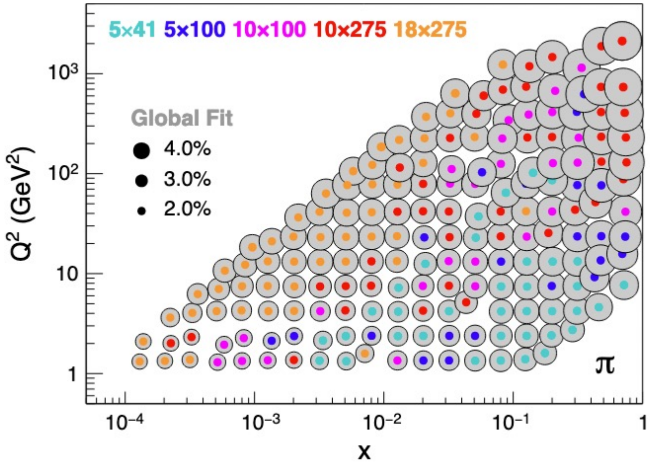
Slide from C. Dilks

Unpolarized TMDs

- Top: Explicit z dependence of select pion multiplicities in 3 x-Q^2 bins, including the double-Gaussian fits

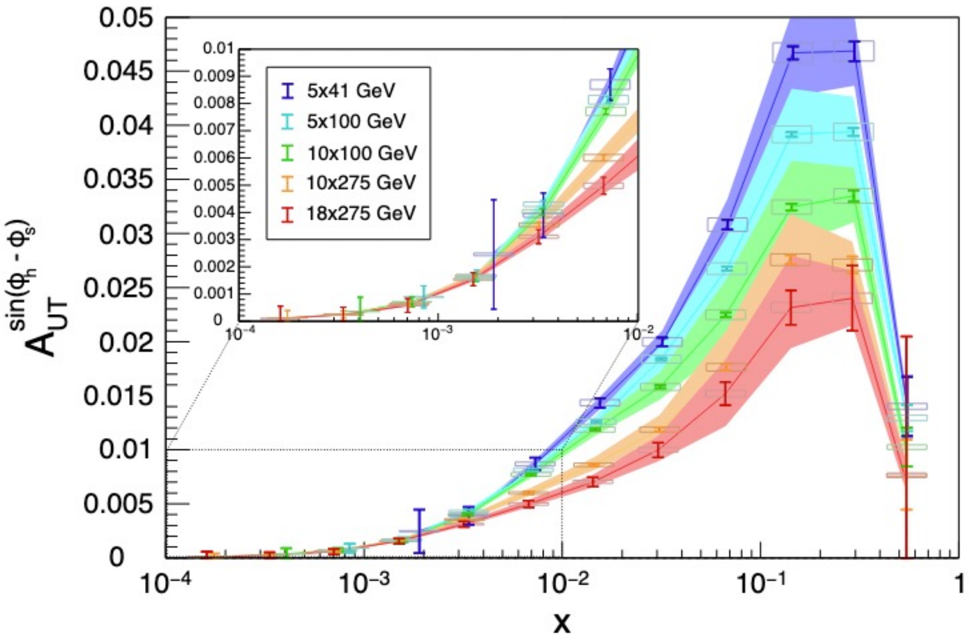


hep-ex:2207.10893



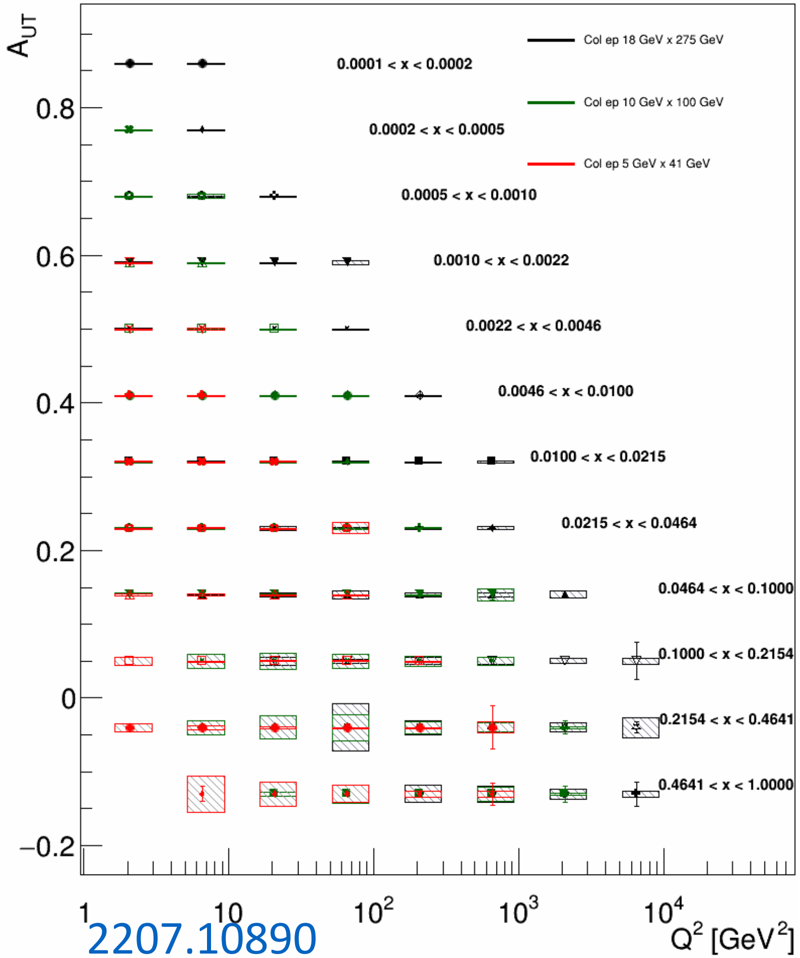
- Impact on $f(x, k_T)$ from Athena proposal
- $\frac{q_T}{Q} < 1.0, y > 0.01$
- Experimental uncertainties dominated by 2% $p2p$, 3% scale, theoretical uncertainties driven by uncertainties on evolution

Projection of transverse TSSAs



Athena projections for the measurement of Sivers asymmetries

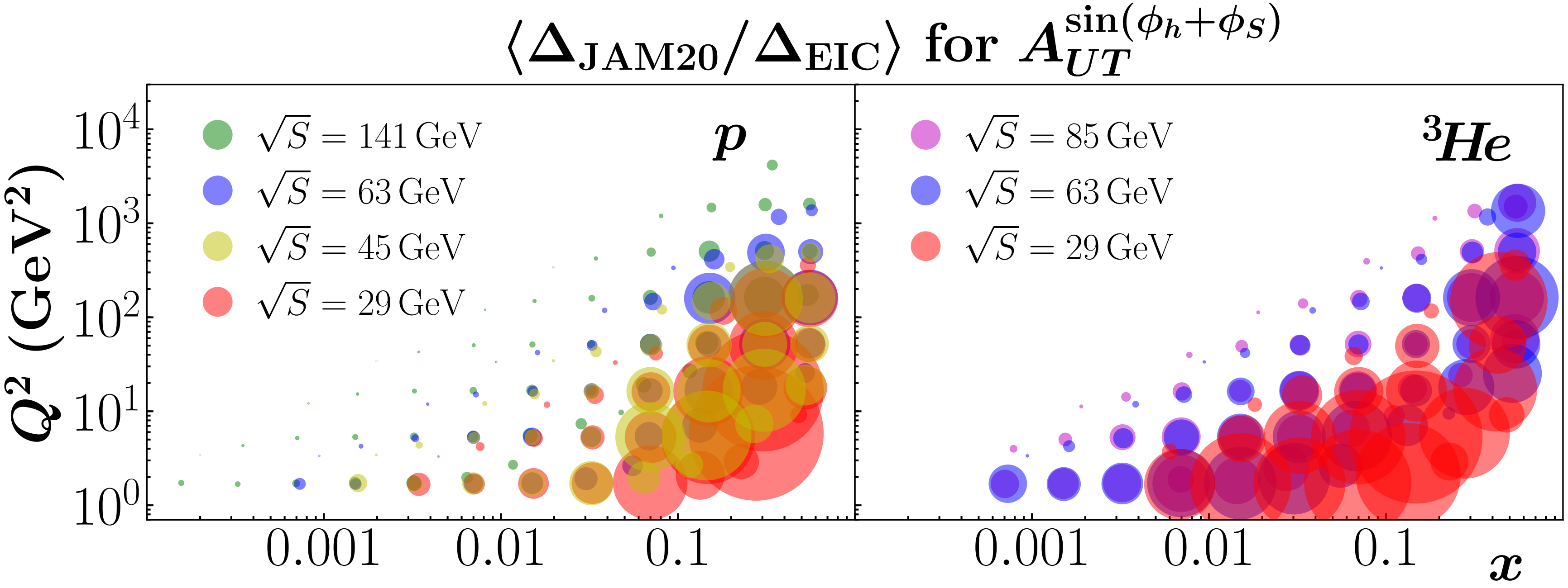
$$0.2 < z < 0.7, Q^2 > 1.0, y > 0.05, \frac{qT}{Q} < 1.0$$



2207.10890

Projected uncertainties on Collins Asymmetries by ECCE

Example: transversity extraction from Jlab and the EIC

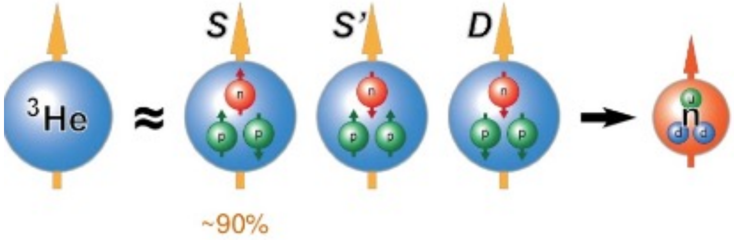


But careful with parametrization bias…

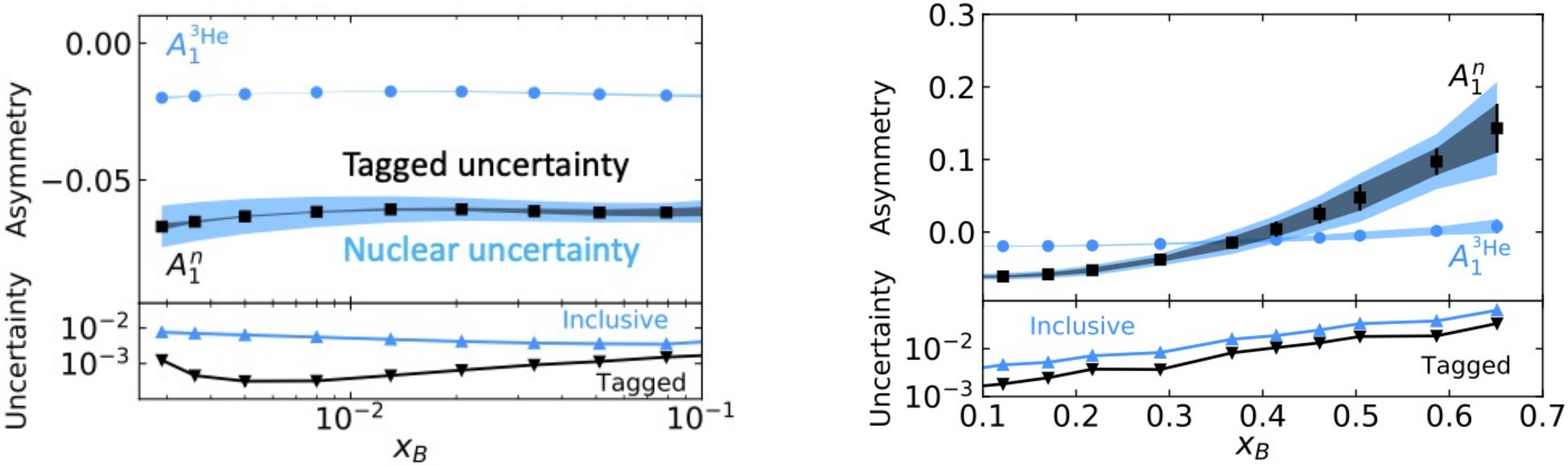
Phys.Lett.B 816 (2021) 136255

He^3 Double Tagging at the EIC allows clean neutron measurement

- Neutron is to 87% polarized
- Double tagged events thus provide access to polarized neutron beam



- Reconstruction of initial neutron momentum from tagged protons allows reduction of uncertainties from nuclear corrections



Friščić, I, Nguyen, D, Pybus, JR, Jentsch et al

- What has been discussed before

- Landscape of experiments, what can be done where… (case for Jlab, kinematics, twist3)
- See EIC, AMBER talks

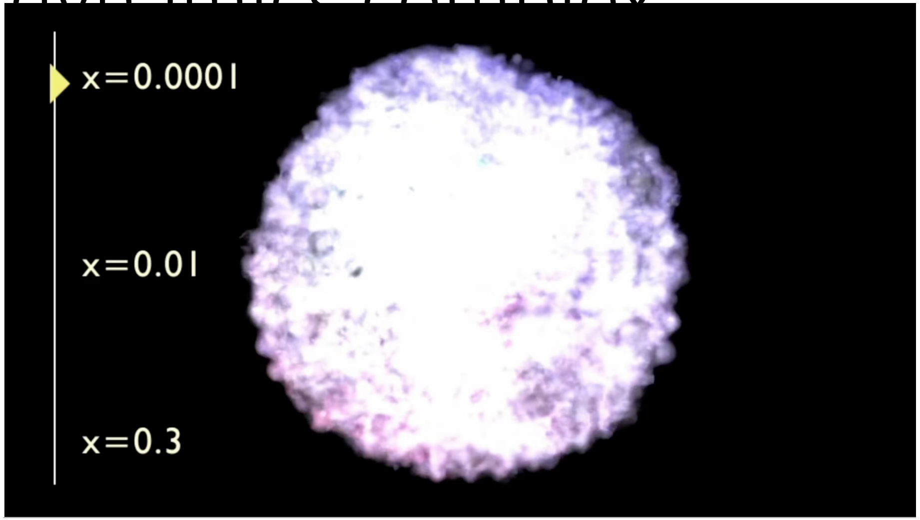
- (pick up ‘CT’ thing from Jianwei: CT needs lumi…

- Introduce HW

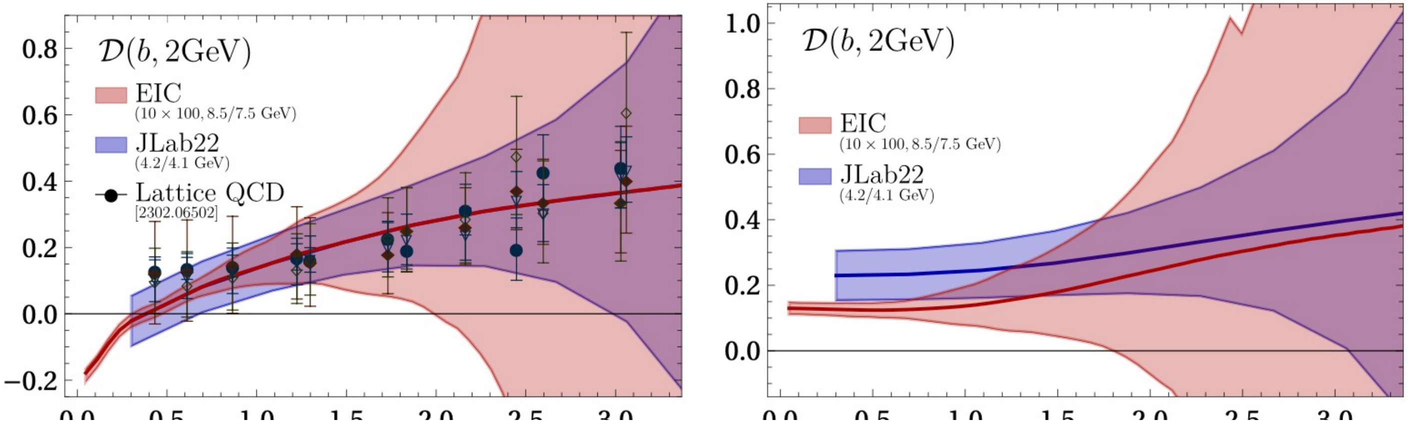
- New developments
  - Radcor: (how is that for di-hadrons)
- JLab22 (see cynthias talk)
- Compass deuterium

- Long range plan…

QCD dynamics complex



Clip from [2]



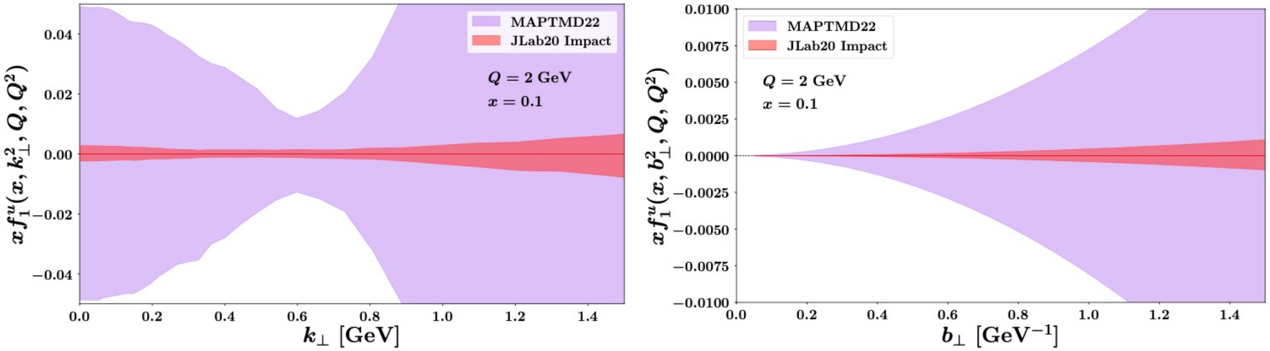


Figure 25: Impact on the error bands of the TMD in $k_\perp$ space (left) and its Fourier-conjugate $b_\perp$ (right)

RECOMMENDAT

The highest pri
munity is to cap
tunities for scie
the substantial and sustained investments of the
United S
the nati

RECOMMENDATION 2

As the highest priority for new experiment construction, we recommend that the United States lead an international consortium that will undertake a neutrinoless double beta decay campaign, featuring the expeditious construction of ton-scale experiments, using different isotopes and complementary techniques.

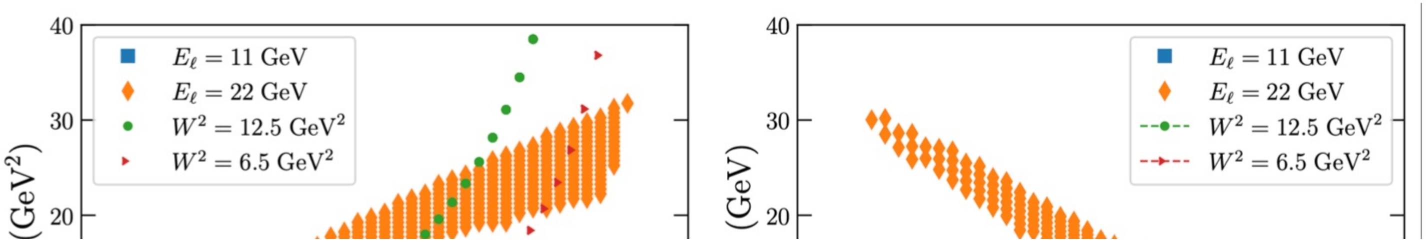
RECOMMENDATION 3

We recommend the expeditious completion of the
uction.

RECOMMENDATION 4

We recommend capitalizing on the unique ways in which nuclear physics can advance discovery science and applications for society by investing in additional projects and new strategic opportunities.

High x at Jlab 22



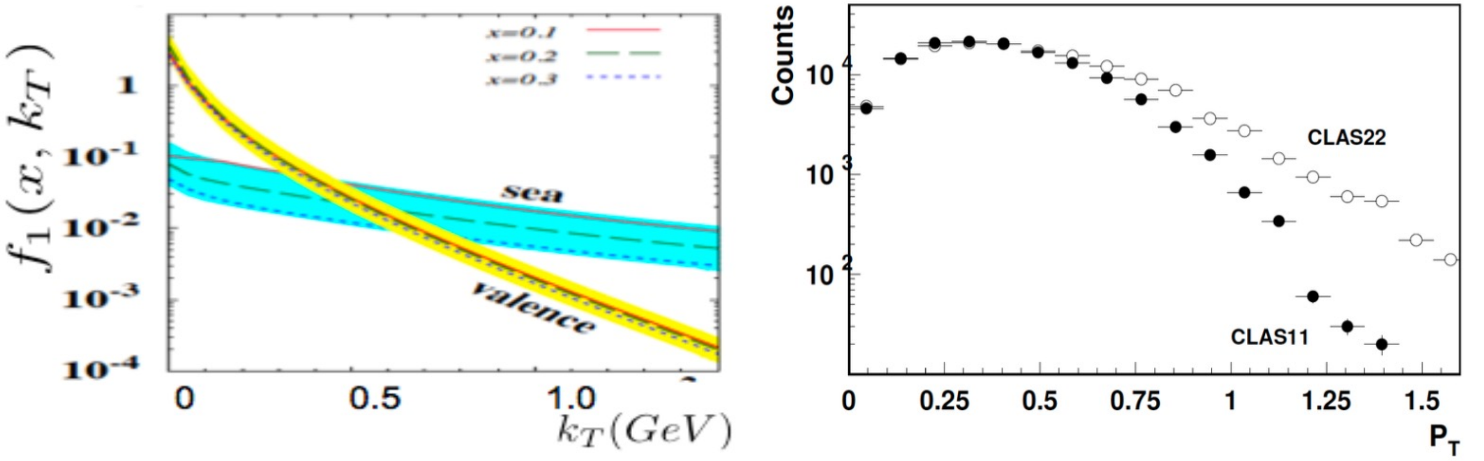
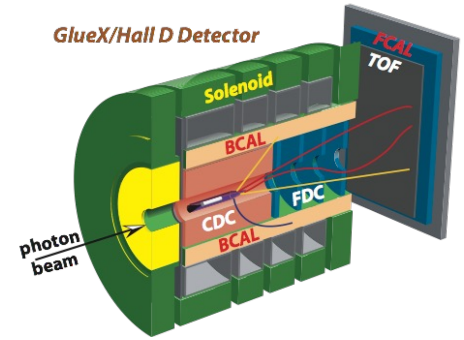
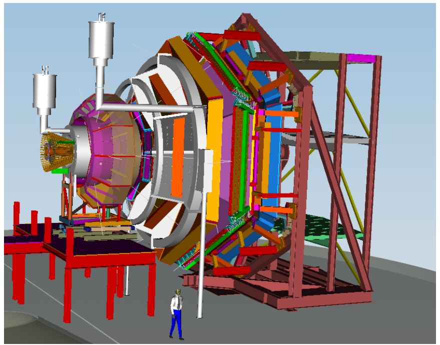
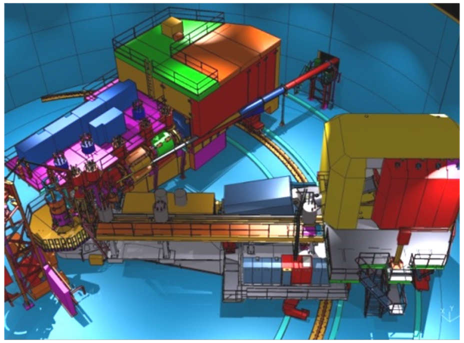


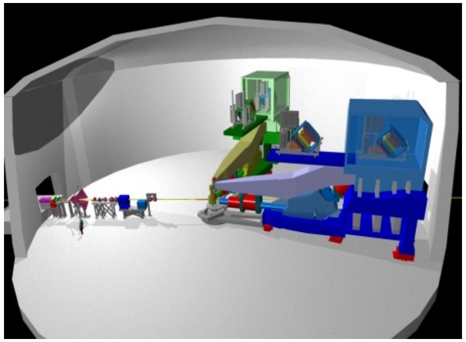
Figure 27: Transverse momentum dependence of sea and valence quarks [151] (left) and extension of the transverse momentum coverage with JLab22 (open circles) for a given bin in x and z ($0.25 < x < 0.3, 0.35 < z < 0.45$) at $Q^2 > 3$ GeV^2.

Detector Requirements: Complementarity



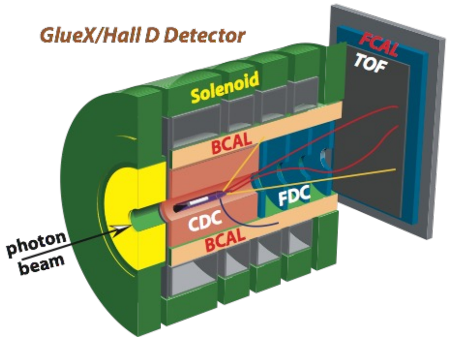


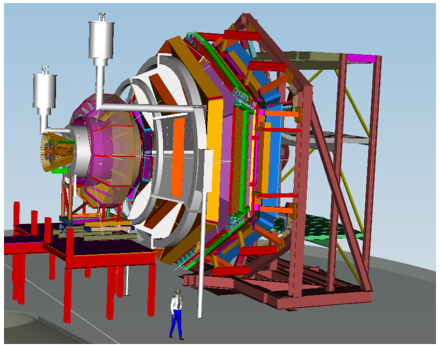


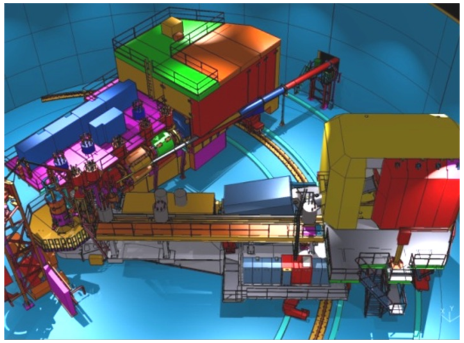


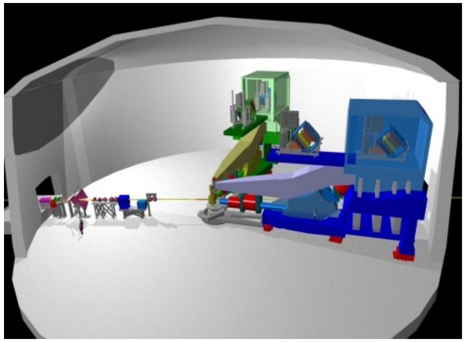
Hall D	Hall B	Hall C	Hall A
excellent hermeticity	luminosity 10^{35}	energy reach	custom installations
polarized photons	hermeticity	precision	
E_γ~8.5-9 GeV	11 GeV beamline		
10^8 photons/s	target flexibility		
good momentum/angle resolution		excellent momentum resolution	
high multiplicity reconstruction		luminosity up to 10^{38}	
particle ID			

Detector Requirements: Complementarity



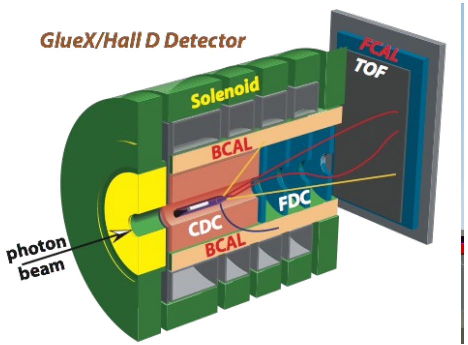


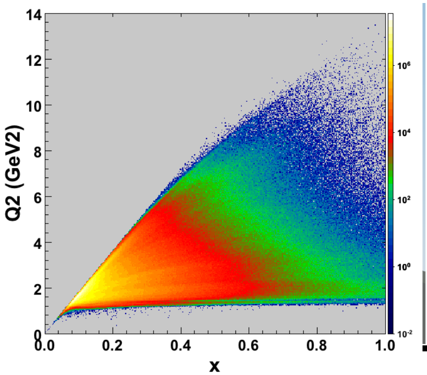


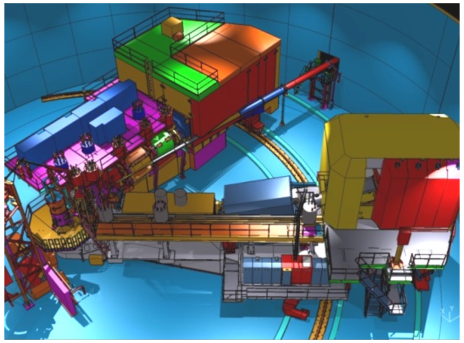


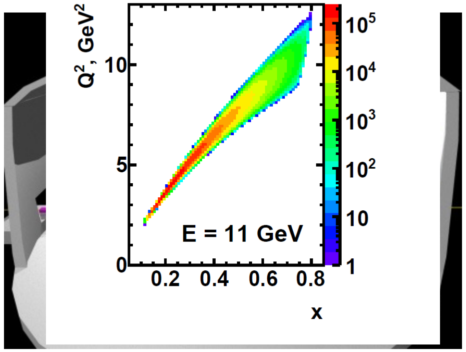
Hall D	Hall B	Hall C	Hall A
excellent hermeticity	luminosity 10^{35}	energy reach	custom installations
polarized photons	hermeticity	precision	
E_γ~8.5-9 GeV	11 GeV beamline		
10^8 photons/s	target flexibility		
good momentum/angle resolution		excellent moment	
high multiplicity reconstruction		luminosity up to 10^{38}	
particle ID			

Detector Requirements: Complementarity









Hall D	Hall B	Hall C	Hall A
excellent hermeticity	luminosity 10^{35}	energy reach	custom installations
polarized photons	hermeticity	precision	
E_γ~8.5-9 GeV	11 GeV beamline		
10^8 photons/s	target flexibility		
good momentum/angle resolution		excellent momentum resolution	
high multiplicity reconstruction		luminosity up to 10^{38}	
particle ID			

Tentative Timelines relevant for TMD program shown here

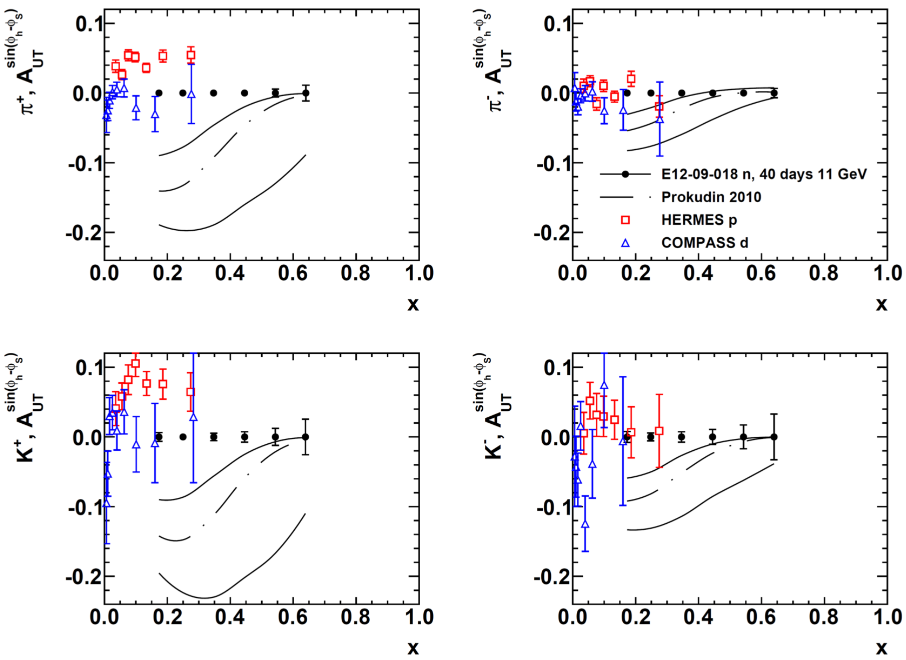
CLAS12 in Hall B

- 2018-2020: unpolarized proton/deuterium target – long. polarized beam
  - →Results shown here correspond to 15% of p-Data (120/90 beam days)
- FY22 polarized long target?
- Polarized He3 (long/trans)
- Polarized transverse HD

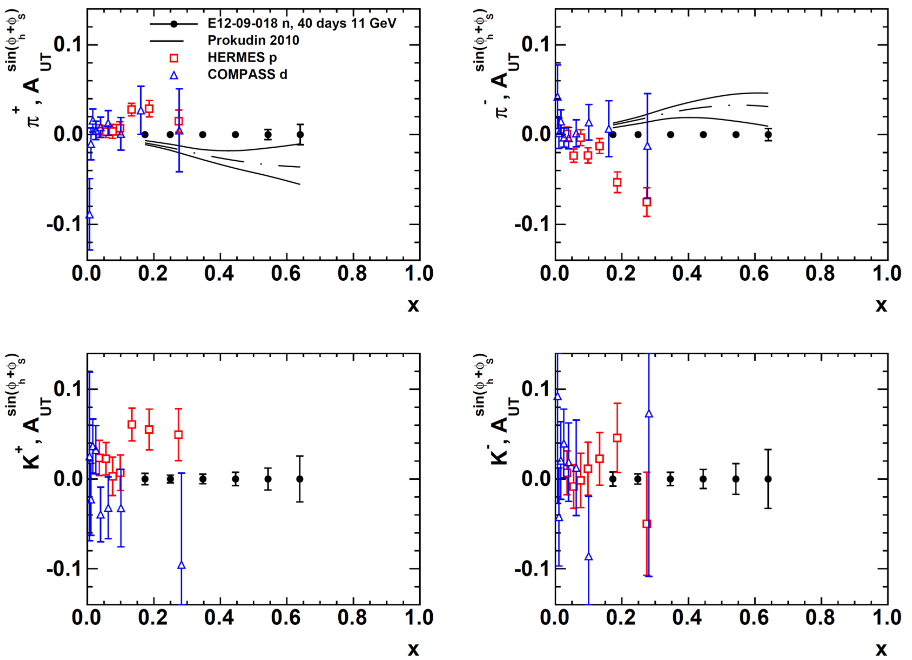
Hall A

- 2023 Transverse single spin asymmetries on He3 (64 beam days)
- 2028 SoLID with He3/proton target (long/transverse)

SBS+BB Projected Results: Collins and Sivers SSAs



Projected A_{UT}^{Sivers} vs. x (11 GeV data only)

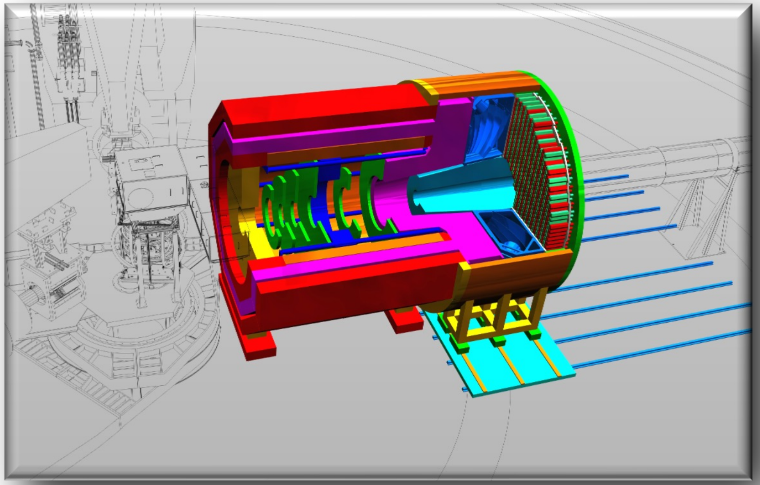


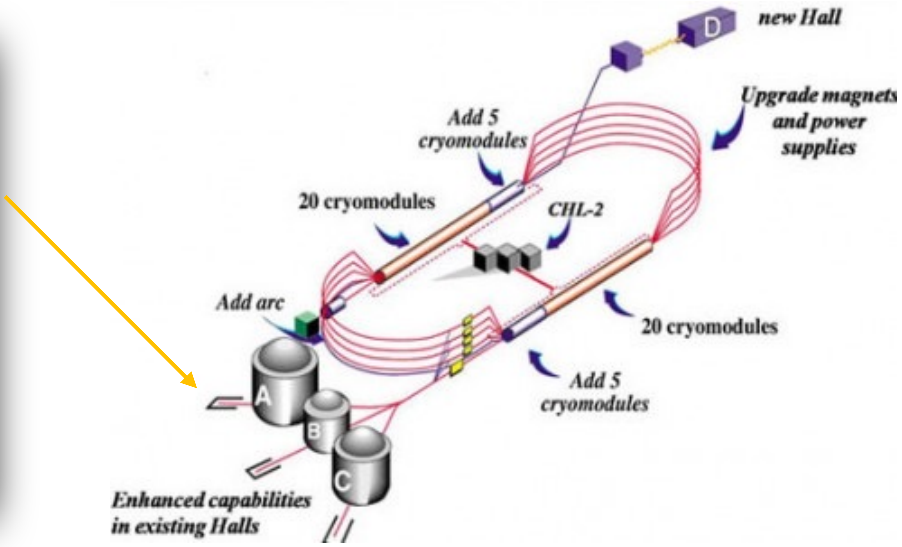
Projected $A_{UT}^{Collins}$ vs. x (11 GeV data only)

- E12-09-018 will achieve statistical FOM for the neutron ~100X better than HERMES proton data and ~1000X better than Hall A E06-010 neutron data. *Near-future more precise COMPASS deuteron data will sharpen expected impacts, urgency of E12-09-018*
- SBS installation starts 2020. E12-09-018 could run as early as 2022; 2023 more likely.

SoLID@12-GeV JLab: QCD at the intensity frontier

SoLID provides *unique* capability combining high luminosity (10^{37-39} /cm^2/s) (>100 of CLAS12; >1000 times of EIC) and **large acceptance** with full ϕ coverage to maximize the science return of the 12-GeV CEBAF upgrade





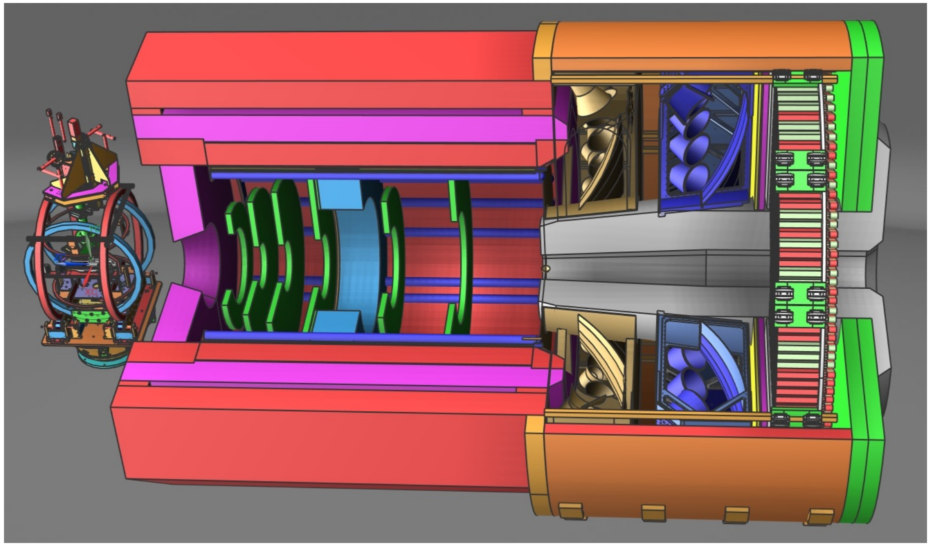
SoLID with unique capability for rich physics programs

- ✓ Pushing the phase space in the search of new physics and of hadronic physics
- ✓ 3D momentum imaging of a relativistic strongly interacting confined system (nucleon spin)
- ✓ Superior sensitivity to the differential electro- and photo- production cross section of J/ψ near threshold (proton mass)

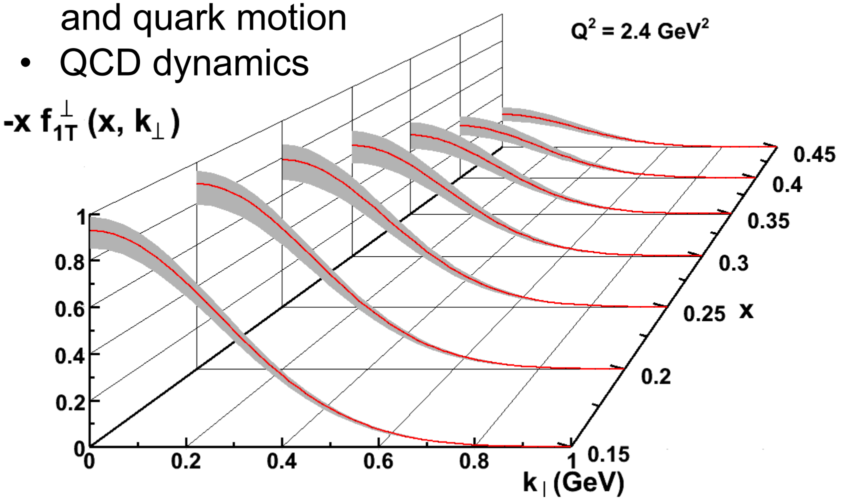
SoLID physics complementary and synergistic with the EIC science (proton spin and mass, two important EIC science questions) – high-luminosity SoLID unique for valence quark tomography (separation of structure from collision) and precision J/ψ production near the threshold

Nucleon momentum tomography and confined motion

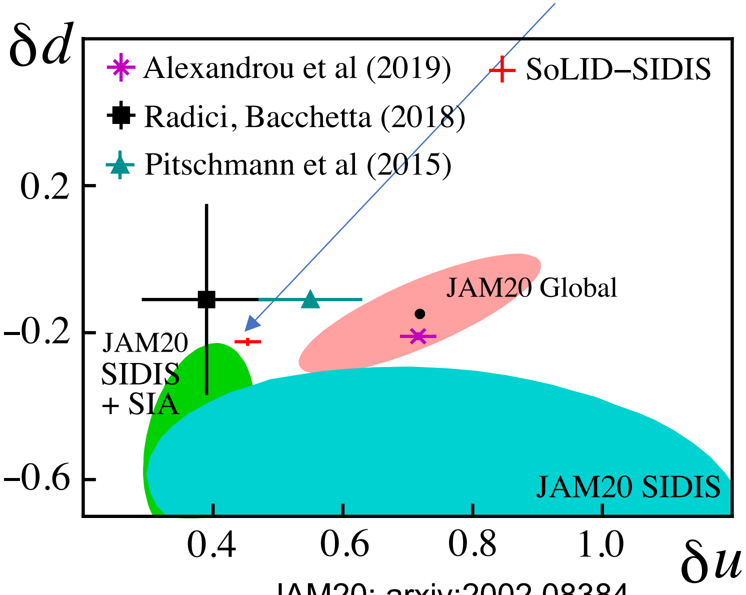
Polarized ^{3}He (``neutron”) @ SoLID



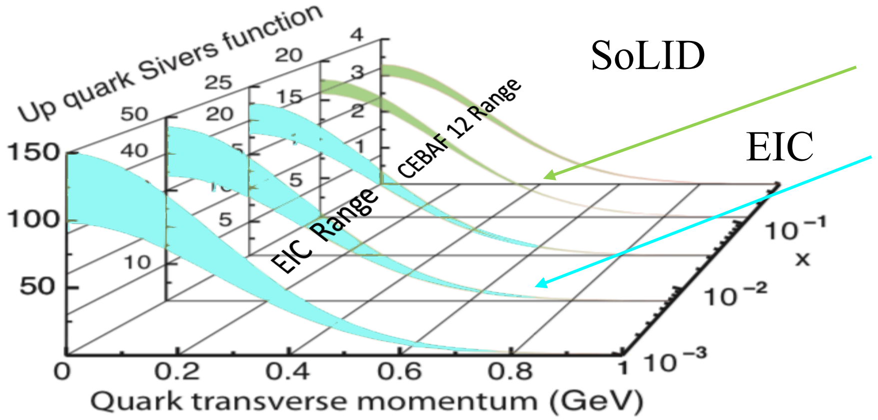
- Sivers: an example of TMDs
- Confined quark motion inside nucleon
- Quantum correlations between nucleon spin and quark motion
- QCD dynamics



SoLID impact on tensor charge



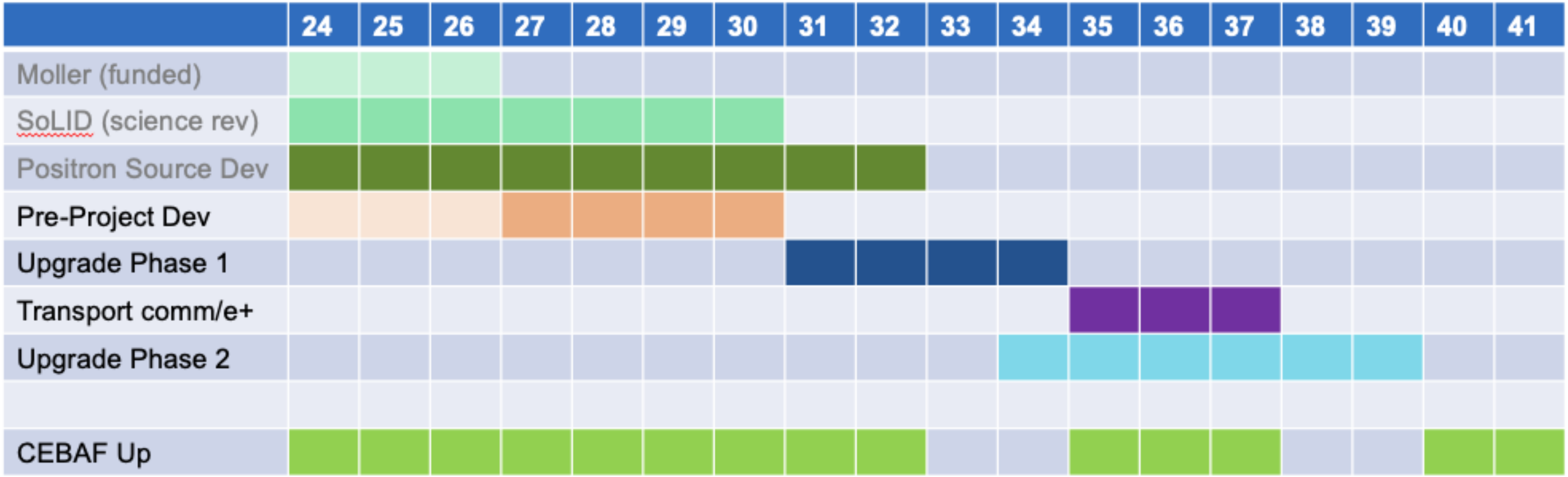
JAM20: arxiv:2002.08384



- Tensor charge: a fundamental QCD quantity to test lattice QCD
- Probe new physics combined with EDMs

Notional CEBAF & upgrade schedule (FY24 – FY42)

- Accelerator and engineering team have worked up an early schedule and cost estimate
  - Schedule assumptions based on a notional timing of when funds might be available (near EIC ramp down based on EIC V3 profile)
  - For completeness, Moller and SoLID (part of 12 GeV program) are shown; positron source development also shown



	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41
Moller (funded)	🟩	🟩	🟩															
SoLID (science rev)	🟩	🟩	🟩	🟩	🟩	🟩	🟩											
Positron Source Dev	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩									
Pre-Project Dev	🟧	🟧	🟧	🟧	🟧	🟧	🟧											
Upgrade Phase 1								🟦	🟦	🟦	🟦							
Transport comm/e+												🟪	🟪	🟪				
Upgrade Phase 2											🟦	🟦	🟦	🟦	🟦	🟦		
CEBAF Up	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩			🟩	🟩	🟩			🟩	🟩