MC4EIC -- SIDIS

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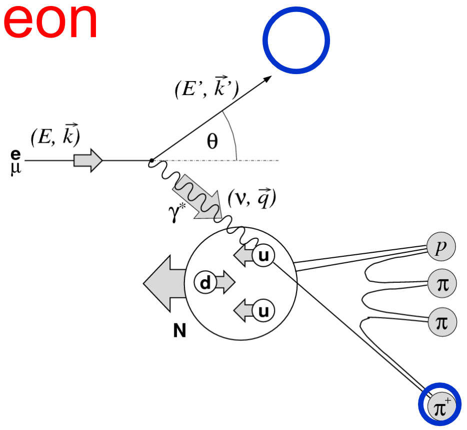
Research supported by the
U.S. DEPARTMENT OF ENERGY | Office of Science

Duke UNIVERSITY

Jefferson Lab

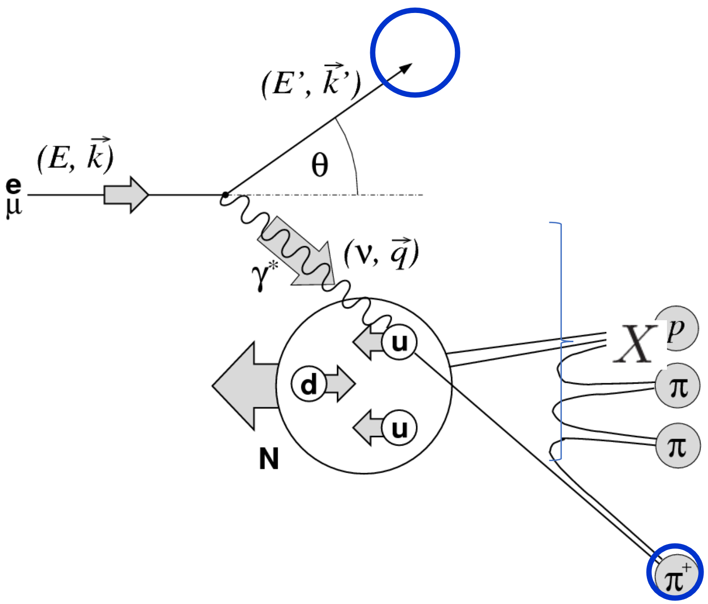
SIDIS measurements 'bread and butter' of the EIC

- Role of sea quarks in spin spin structure
- Access to TMD PDFs →3D structure of the nucleon
- Search for saturation effects
- Nuclear modification of (TMD) PDFs and FFs



SIDIS Observables

Semi-inclusive DIS (SIDIS)



LO parton picture valid at high Q^2>>1 GeV^2

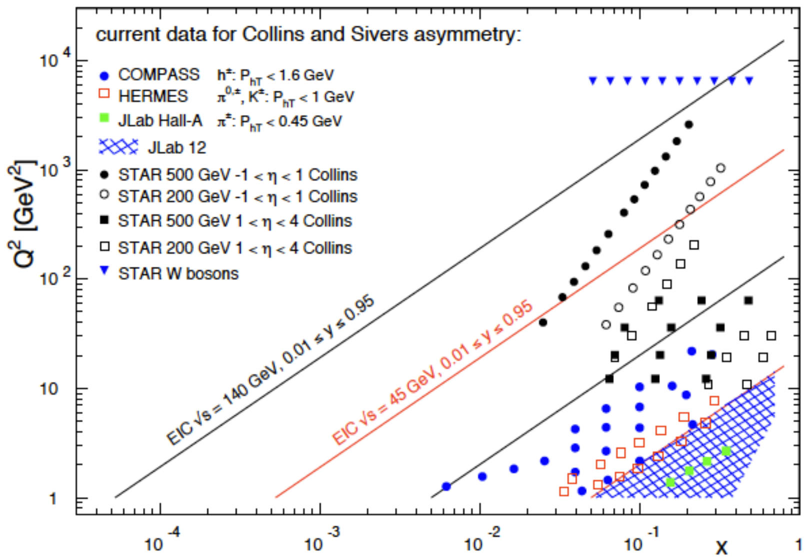
Identified particles in final state

- Q^2:"hard scale" of the probe
- $x =$: bjorken **scaling variable**, in partonic picture momentum fraction of the struck parton
- $z = E_h/E_q(lab)$: fractional energy the hadron is carrying
- p_T: transverse momentum of hadron with respect to γ^*

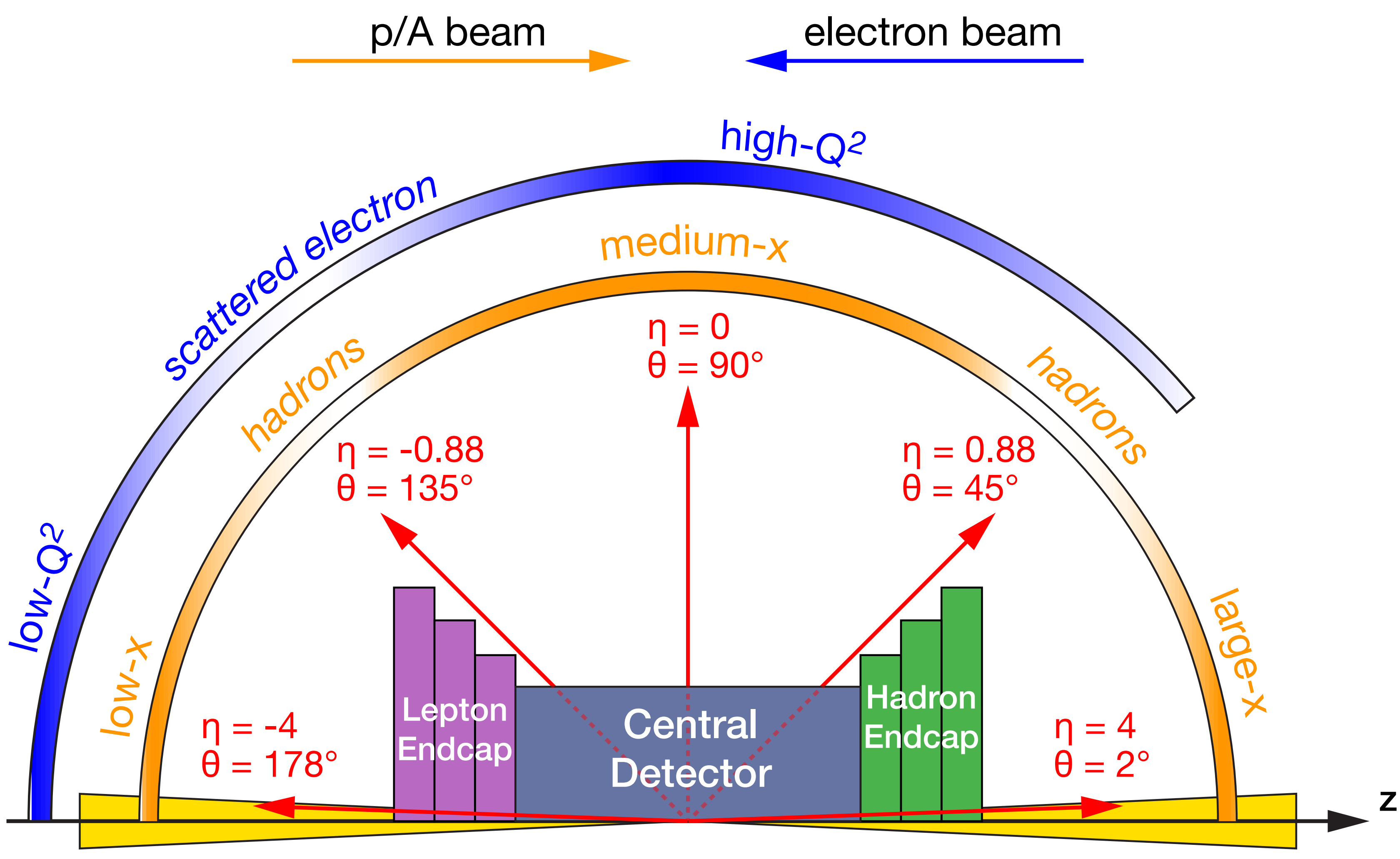
SIDIS physics at an EIC: Coverage

- 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

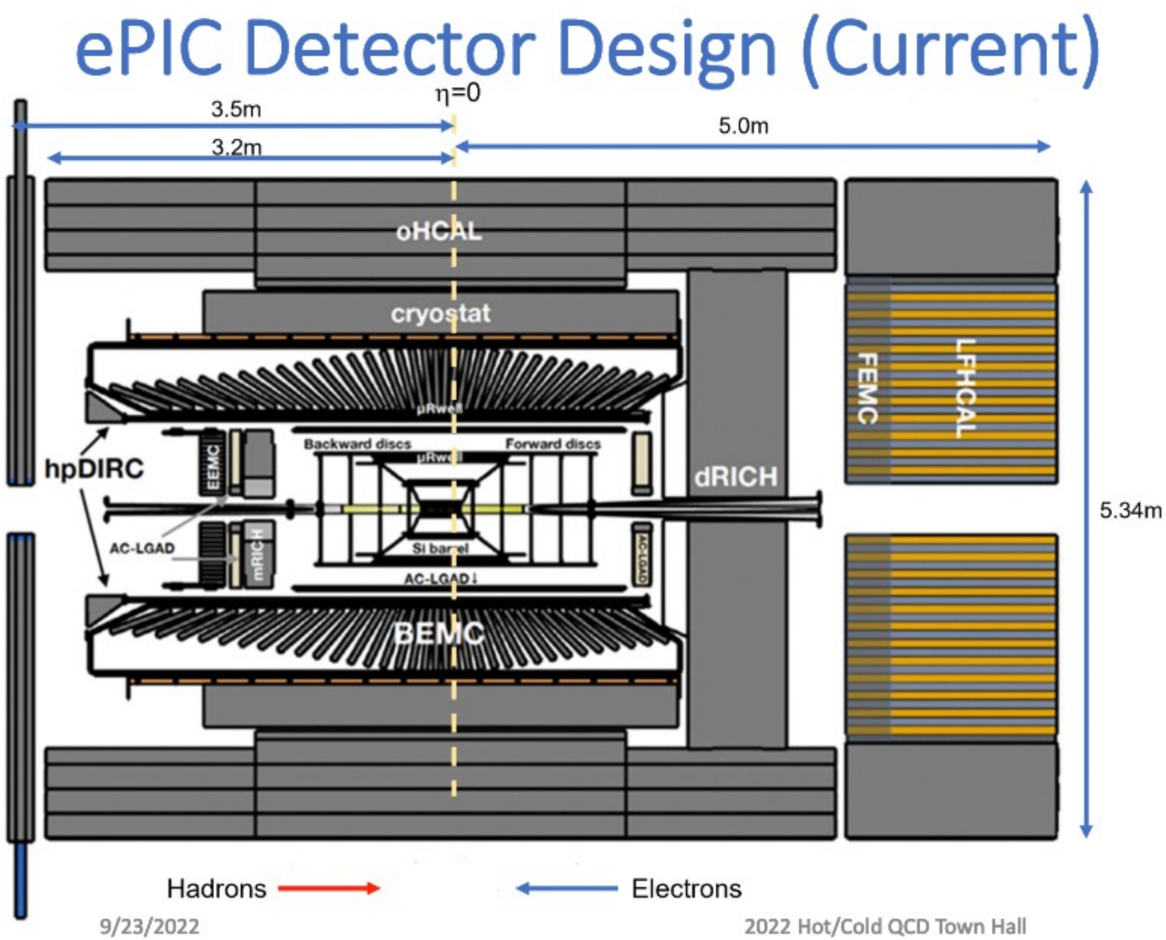


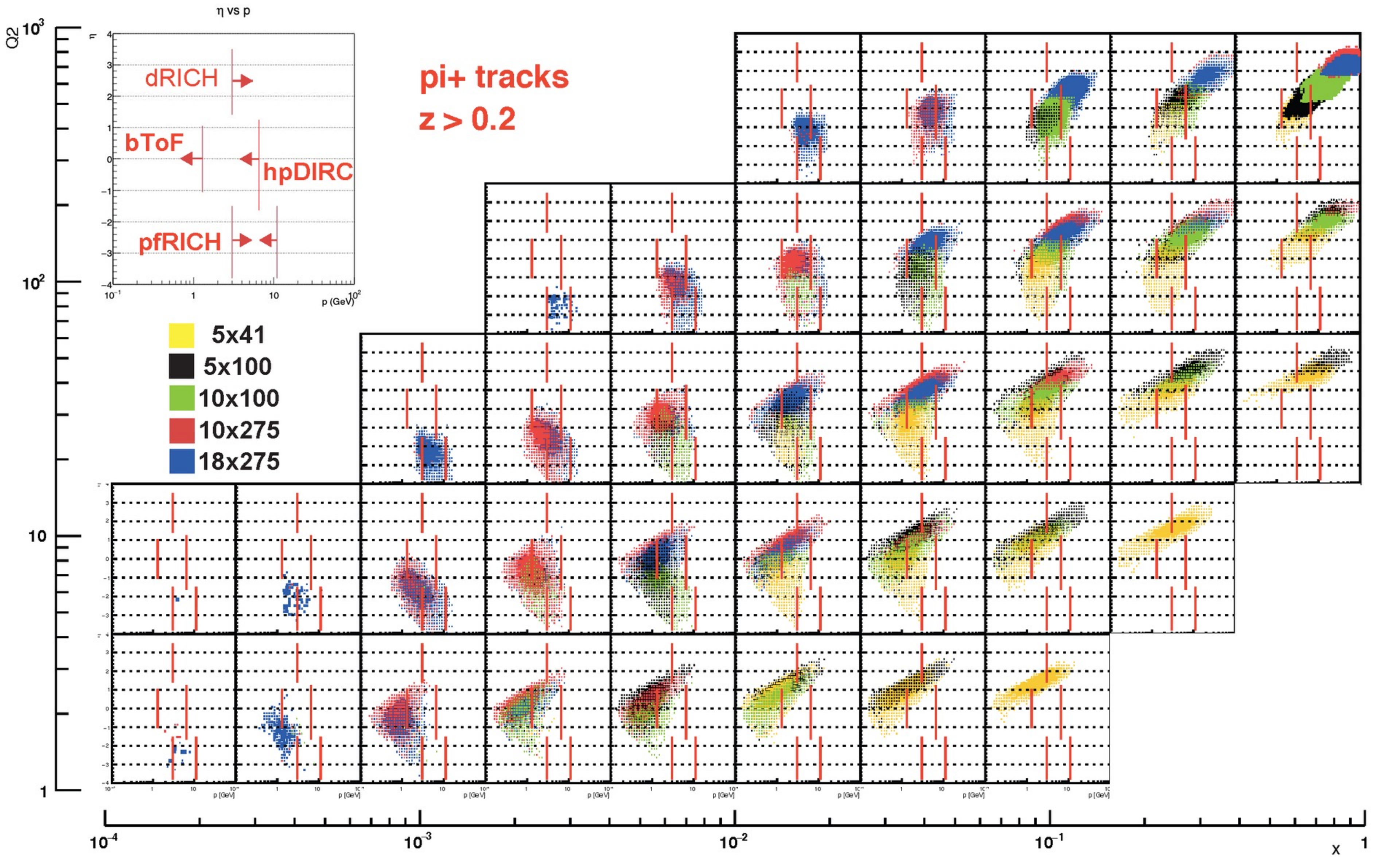
Coverage to low x: access sea and gluon distributions


p/A beam
electron beam
high-Q^2
scattered electron
low-Q^2
medium-x
hadrons
hadrons
low-x
large-x
$\eta = 0$
$\theta = 90°$
$\eta = -0.88$
$\theta = 135°$
$\eta = 0.88$
$\theta = 45°$
$\eta = -4$
$\theta = 178°$
$\eta = 4$
$\theta = 2°$
Lepton Endcap
Central Detector
Hadron Endcap
z

EIC Project Detector

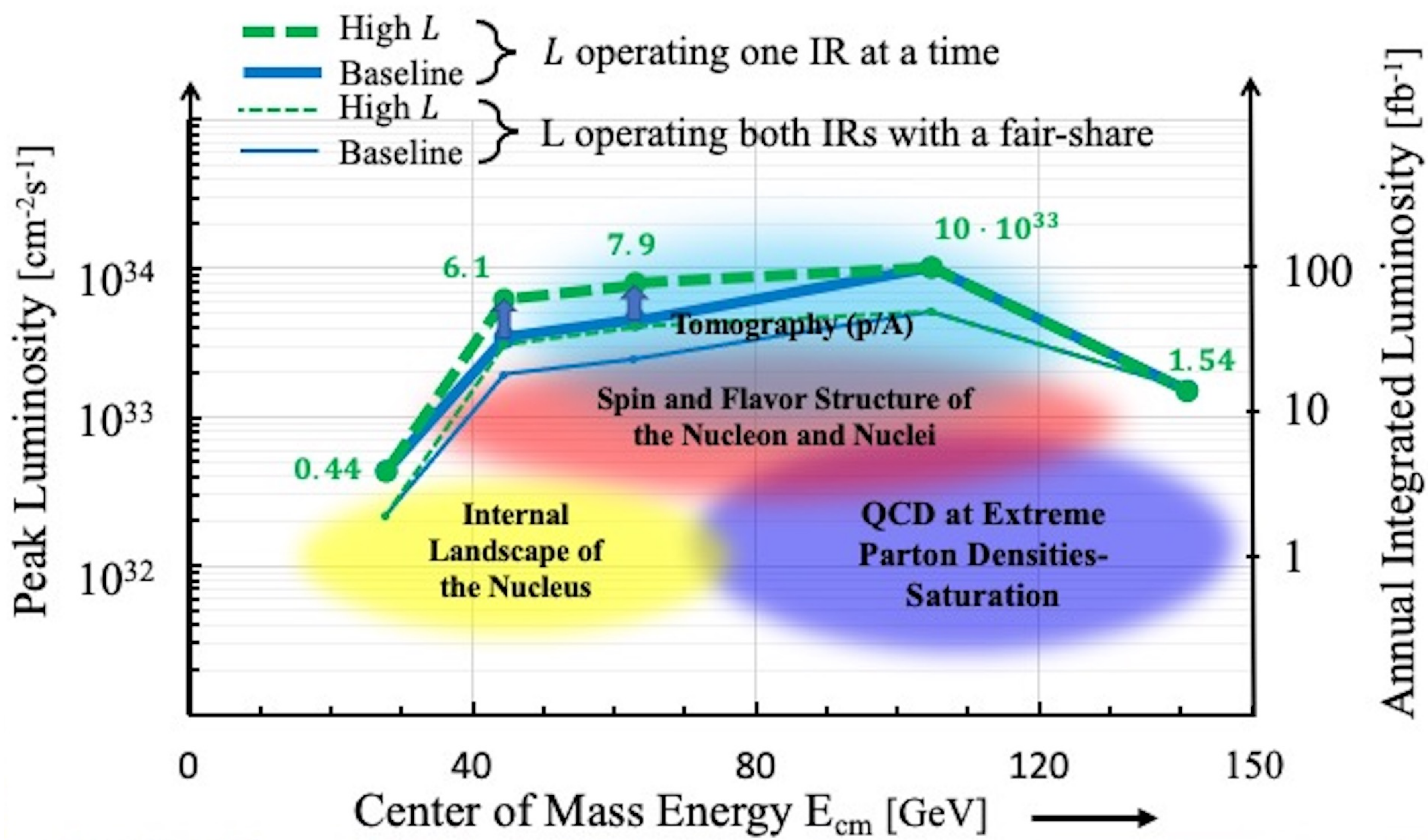
- Based on ECCE design
- New 1.7 T magnet
- Fulfills Yellow report requirements with excellent tracking and PID
- Hermetic
- Currently working towards pre-TDR and CD 2(A)





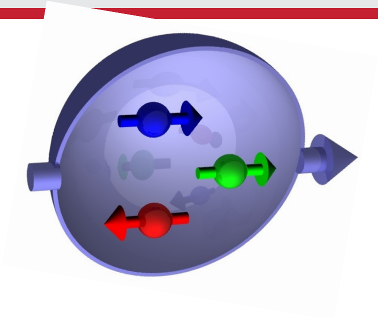
pi+ tracks
z > 0.2
η vs p
dRICH
bToF
hpDIRC
pfRICH
p (GeV)
5x41
5x100
10x100
10x275
18x275
Q2
x

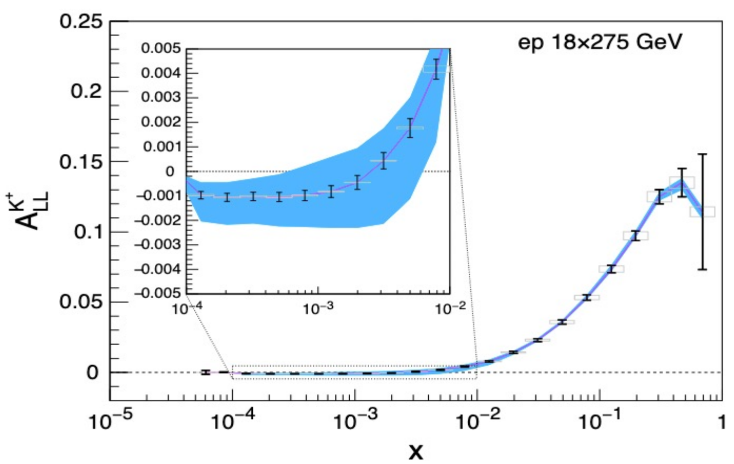
Order of magnitude in luminosity depending on $\sqrt{s}$ (beware of projections with fixed $\int L$)

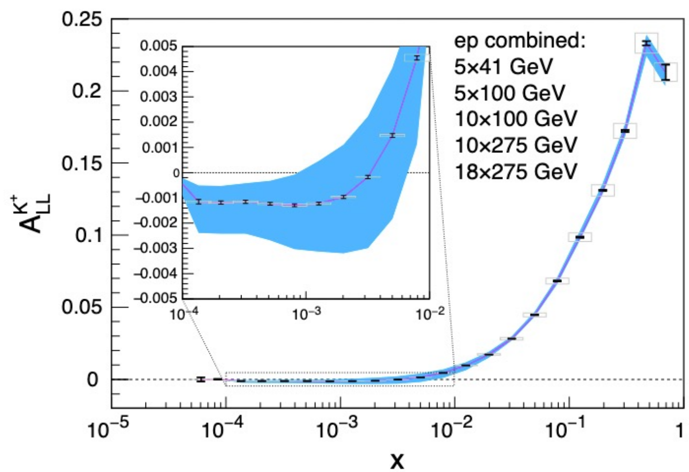


Longitudinal double spin asymmetries

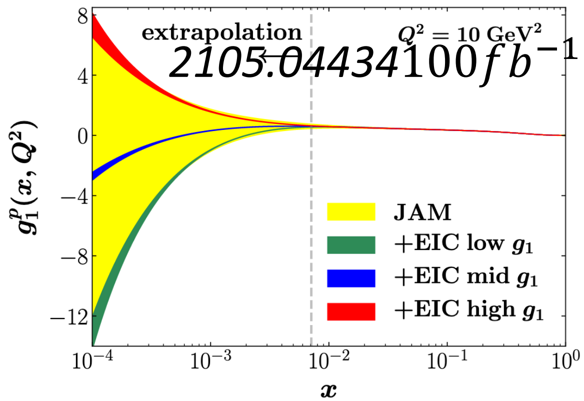
- $A_{LL} = \frac{\sigma^{\uparrow\Uparrow} - \sigma^{\uparrow\Downarrow}}{\sigma^{\uparrow\Uparrow} + \sigma^{\uparrow\Downarrow}} \propto g_1$







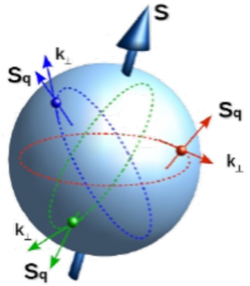
- Projections for Athena (2022 *JINST* **17** P10019)
- 3% point-to-point, 2% scale uncertainties (from Hera experience)
- $z > 0.2$
- $15.5\ fb^{-1}$ at $18x275$, other datasets scaled accordingly



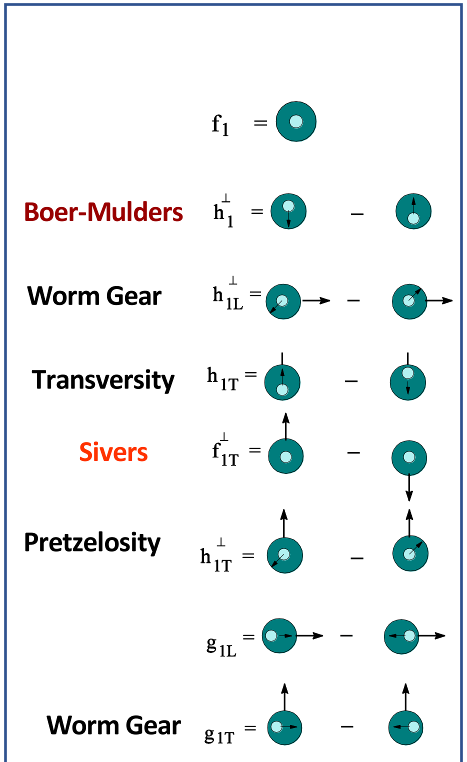
Transverse momentum dependent distributions (TMDs)

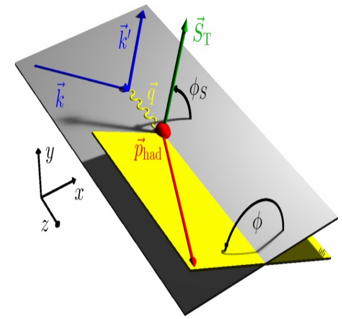
N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Spin-orbit correlations



SIDIS X-section in the Parton Model





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

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

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

Unpolarized

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

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

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

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

Polarized target

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

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

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

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

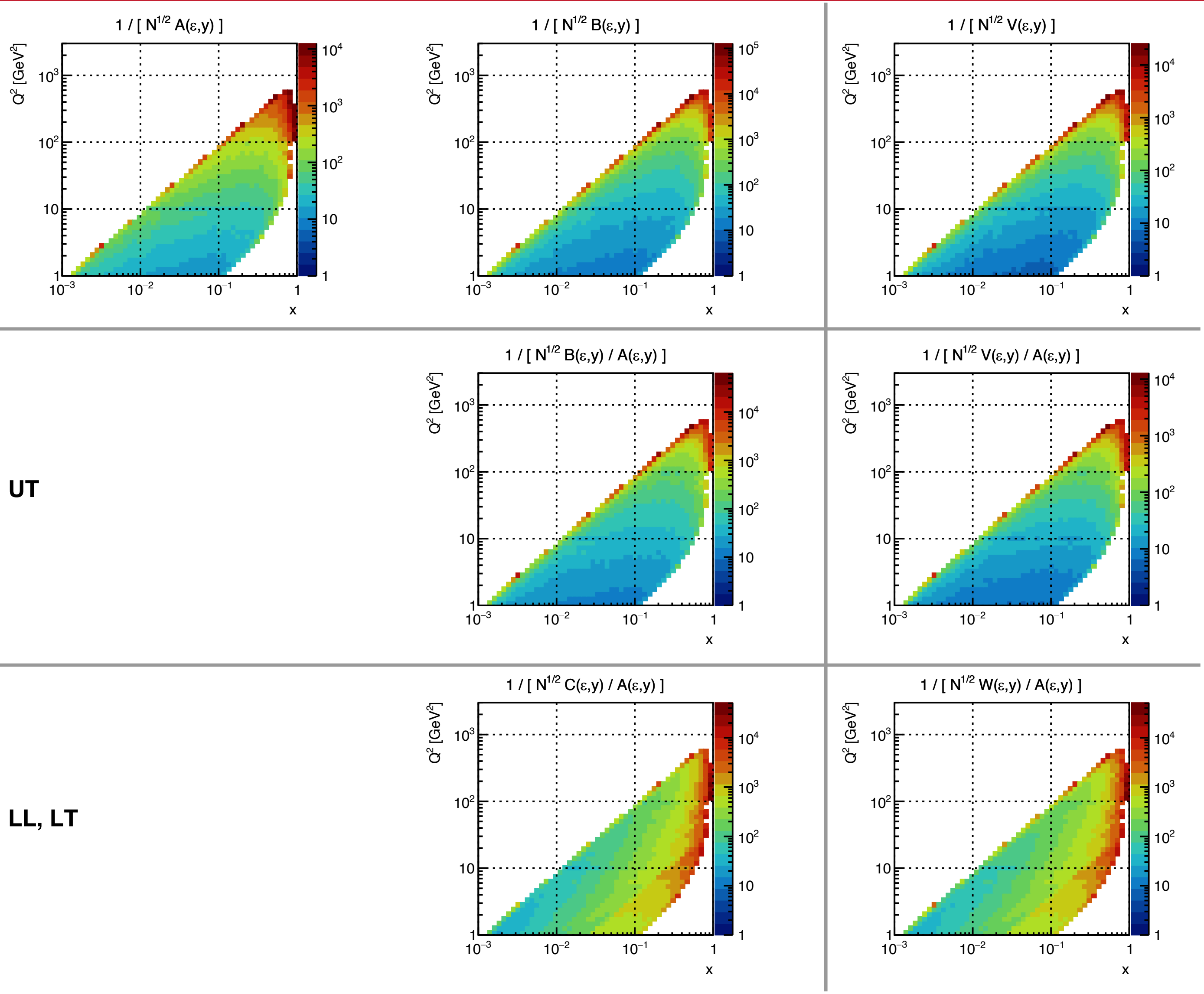
Slide from C. Dilks

Statistical uncertainty scaling factor for $5x41$

UU

UL, UT

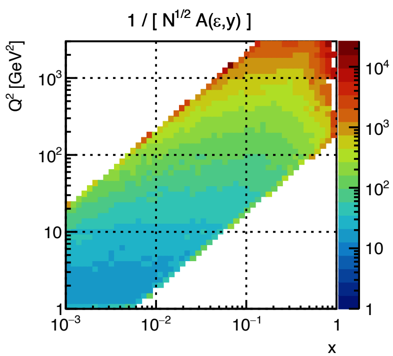
LU, LL, LT

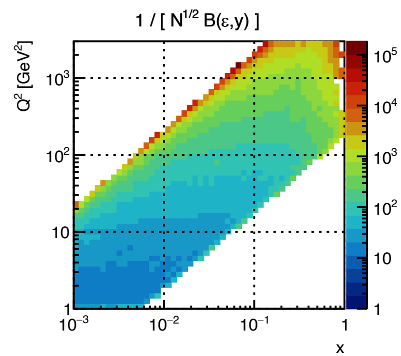


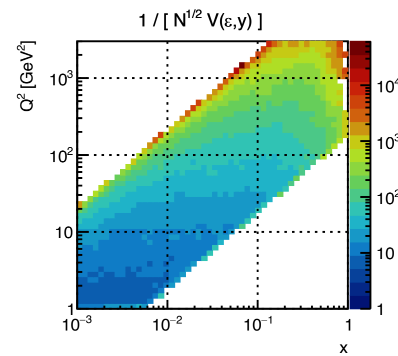
Slide from C. Dilks

Statistical uncertainty scaling factor for $18x275$

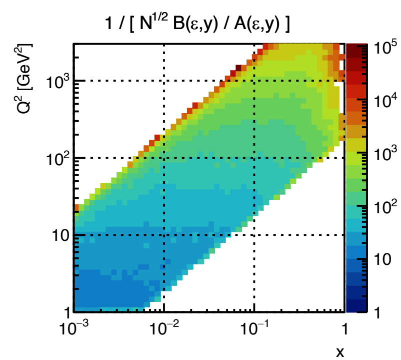
UU

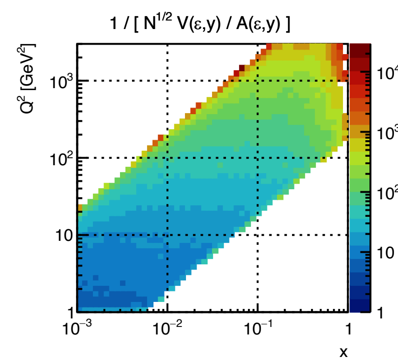




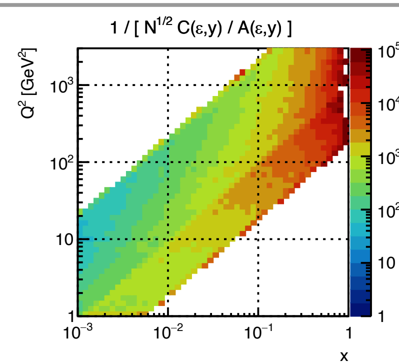


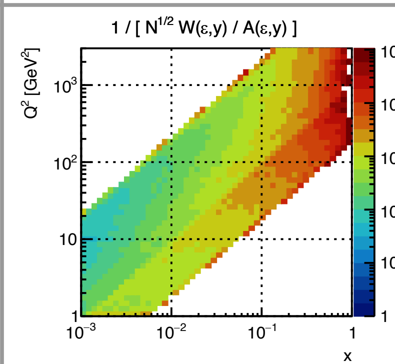
UL, UT





LU, LL, LT





Slide from C. Dilks

Depolarization Factors

	Polarization	Depolarization
Boer-Mulders	UU	B
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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 2

Twist 3

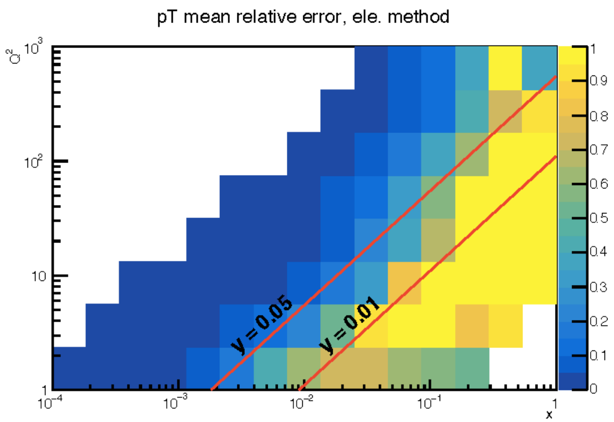
Suppressed at EIC

Slide from C. Dilks

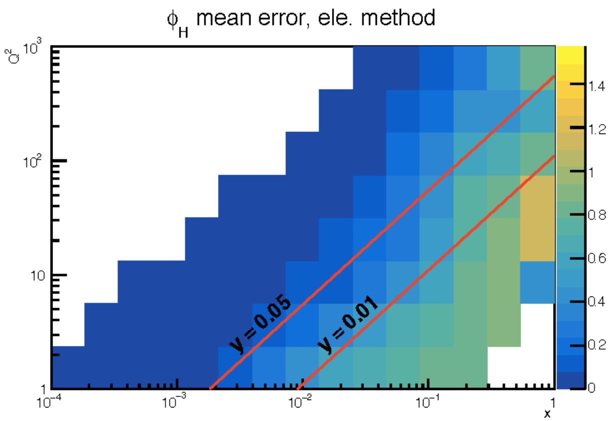
Kinematic reconstructions

Electron method

$$\frac{p_T - p_{T,true}}{p_{T,true}}$$

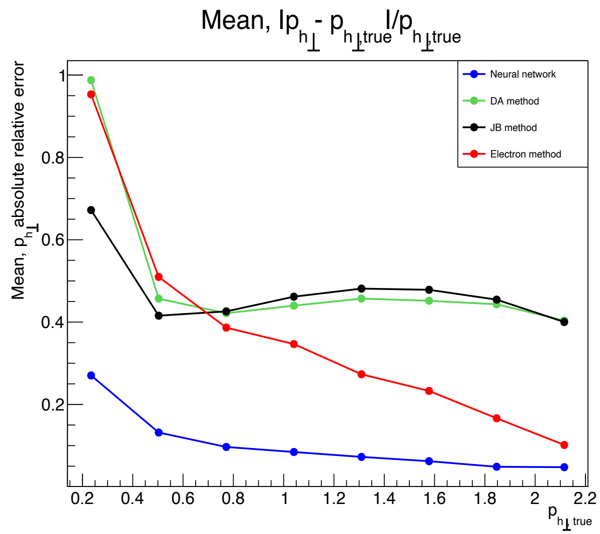


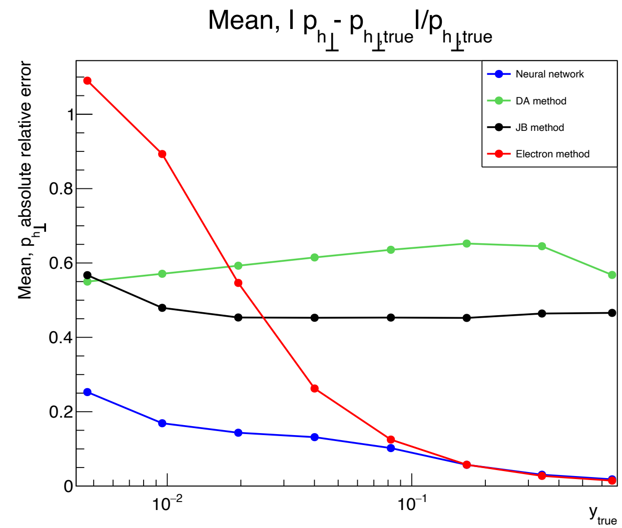
$$\phi_H - \phi_{H,true}$$



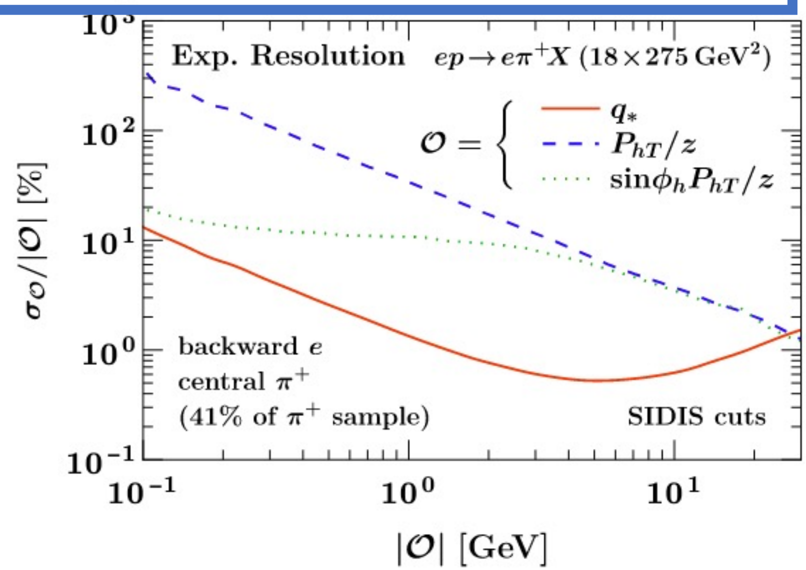
Progress in kinematic reconstruction

ML Method using
full hadronic final state
Connor Pecar, Duke
arXiv:2209.14489





Reconstruction of relevant TMD quantities
in the lab frame
Gao, Michel, Stewart, Sun [2209.1121]



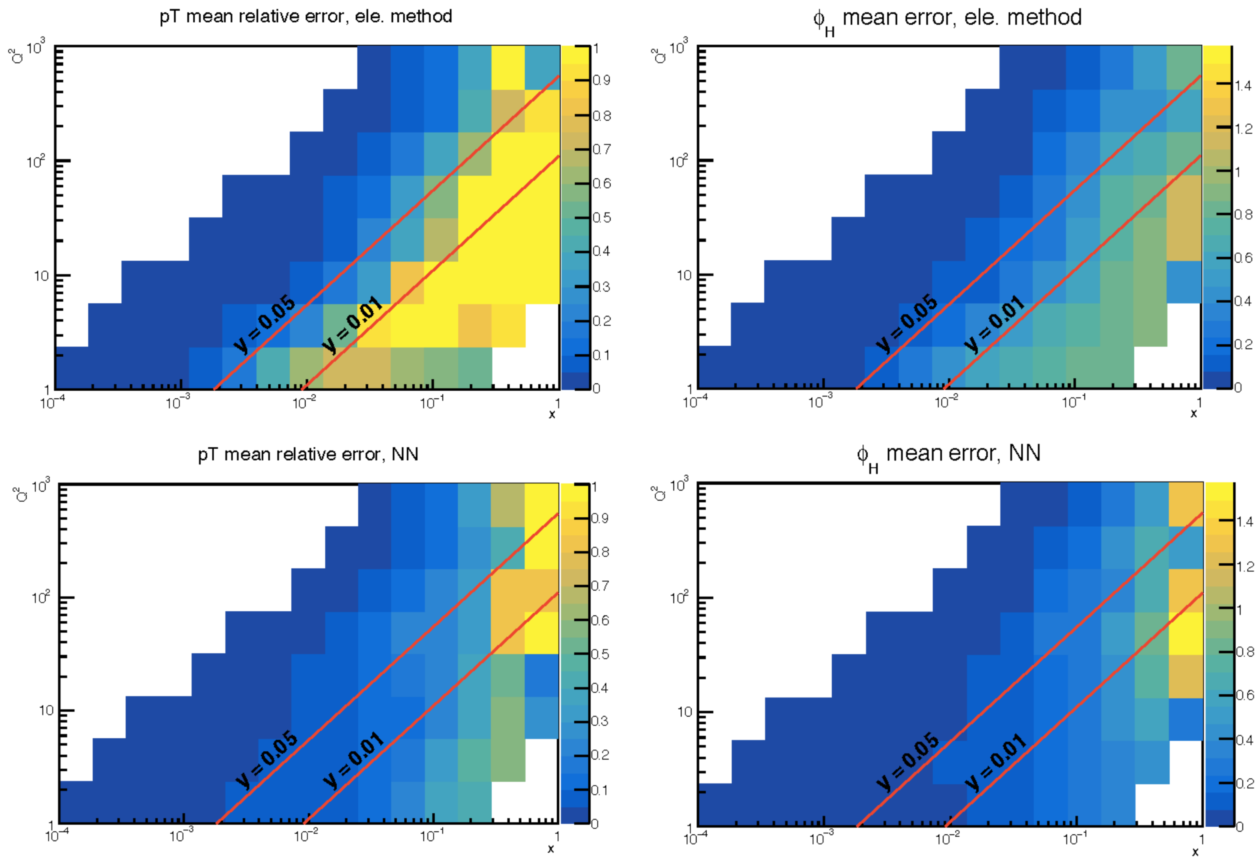
$$q^* = -\sin\phi_h P_{hT}/z$$

$$\frac{p_T - p_{T,true}}{p_{T,true}}$$

$$\phi_H - \phi_{H,true}$$

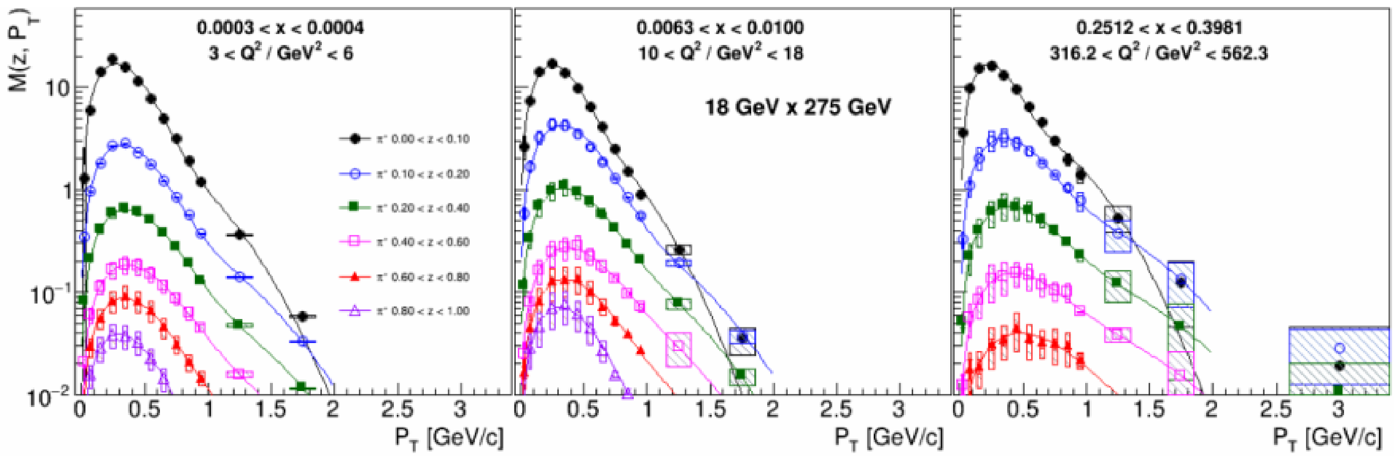
Electron method

Particle flow network + electron

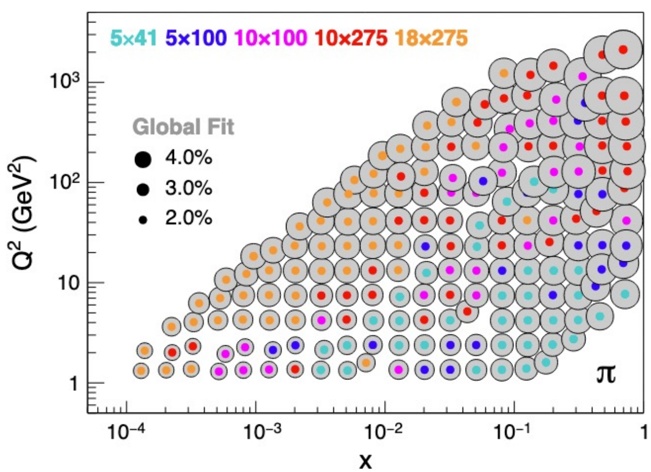


Unpolarized TMDs

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

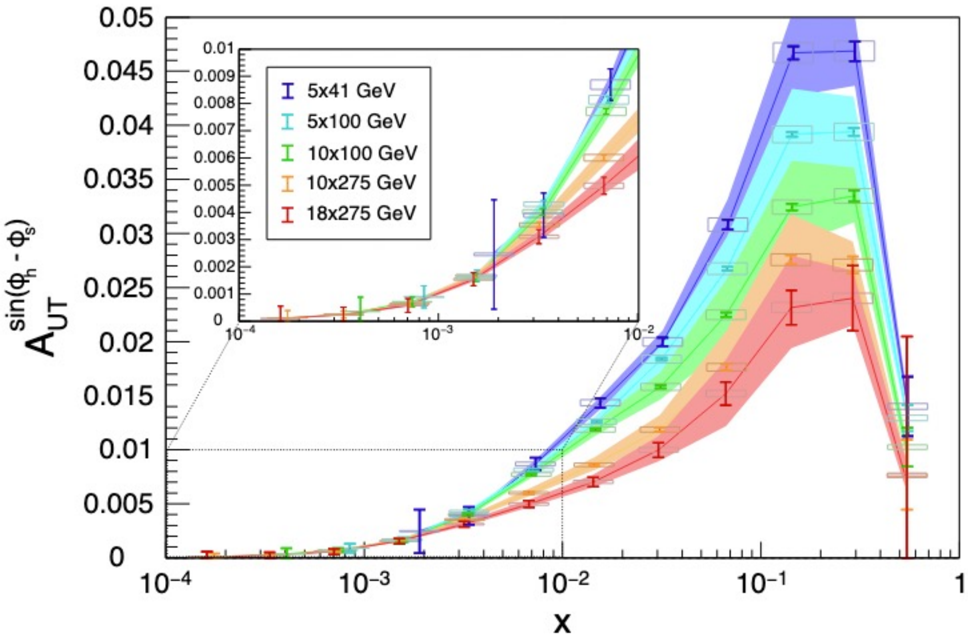


hep-ex:2207.10893



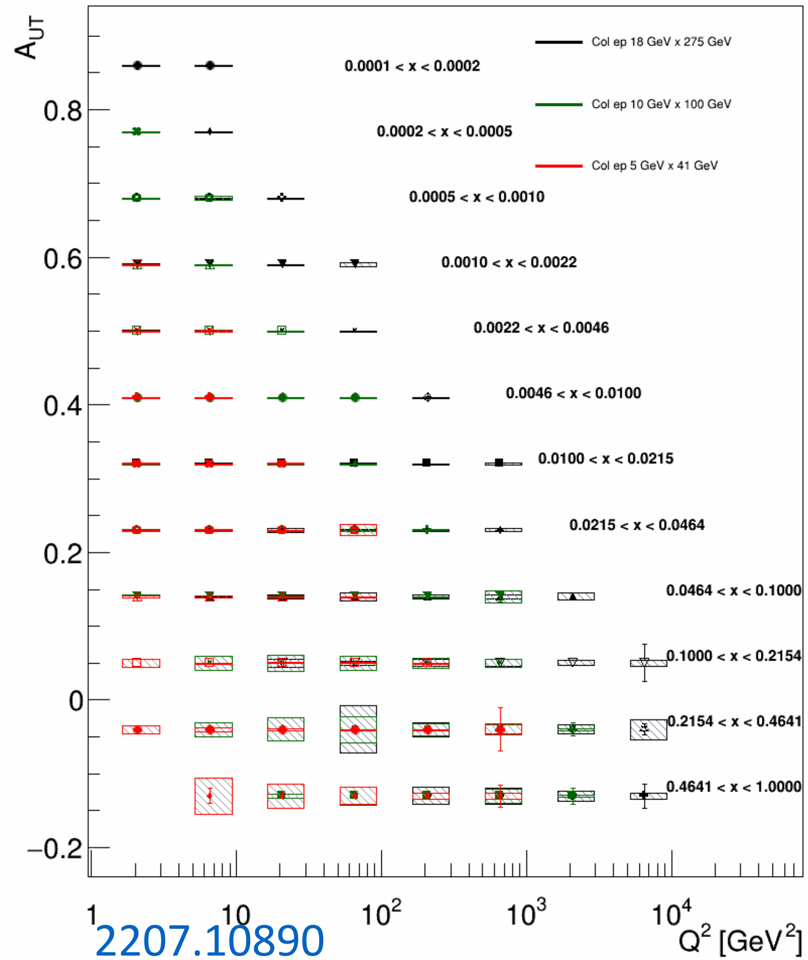
- Impact on $f(x, k_T)$ from Athena proposal
- $\frac{q_T}{Q} < 1.0, y > 0.01$
- Experimental uncertainties dominated by 2% $p2p$, 3% scale, theoretical uncertainties driven by uncertainties on evolution

Projection of transverse TSSAs



Athena projections for the measurement of Sivers asymmetries

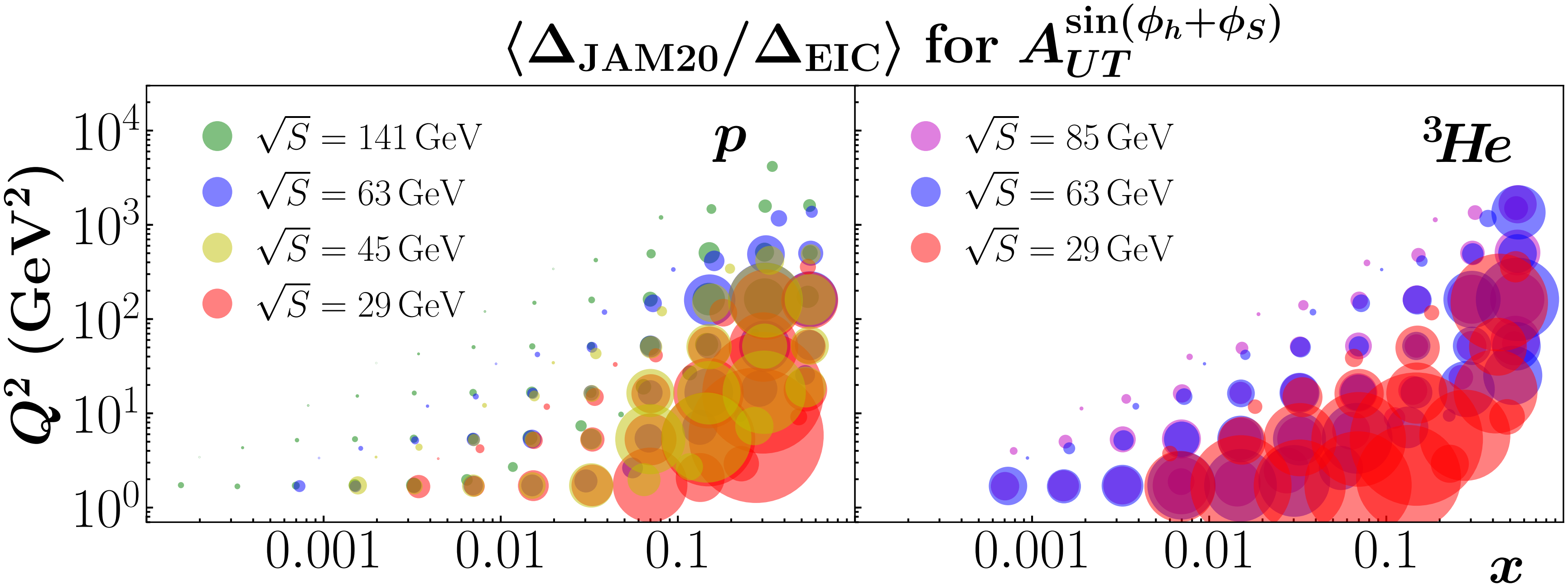
$$0.2 < z < 0.7, Q^2 > 1.0, y > 0.05, \frac{qT}{Q} < 1.0$$



[2207.10890](https://arxiv.org/abs/2207.10890)

Projected uncertainties on Collins Asymmetries by ECCE

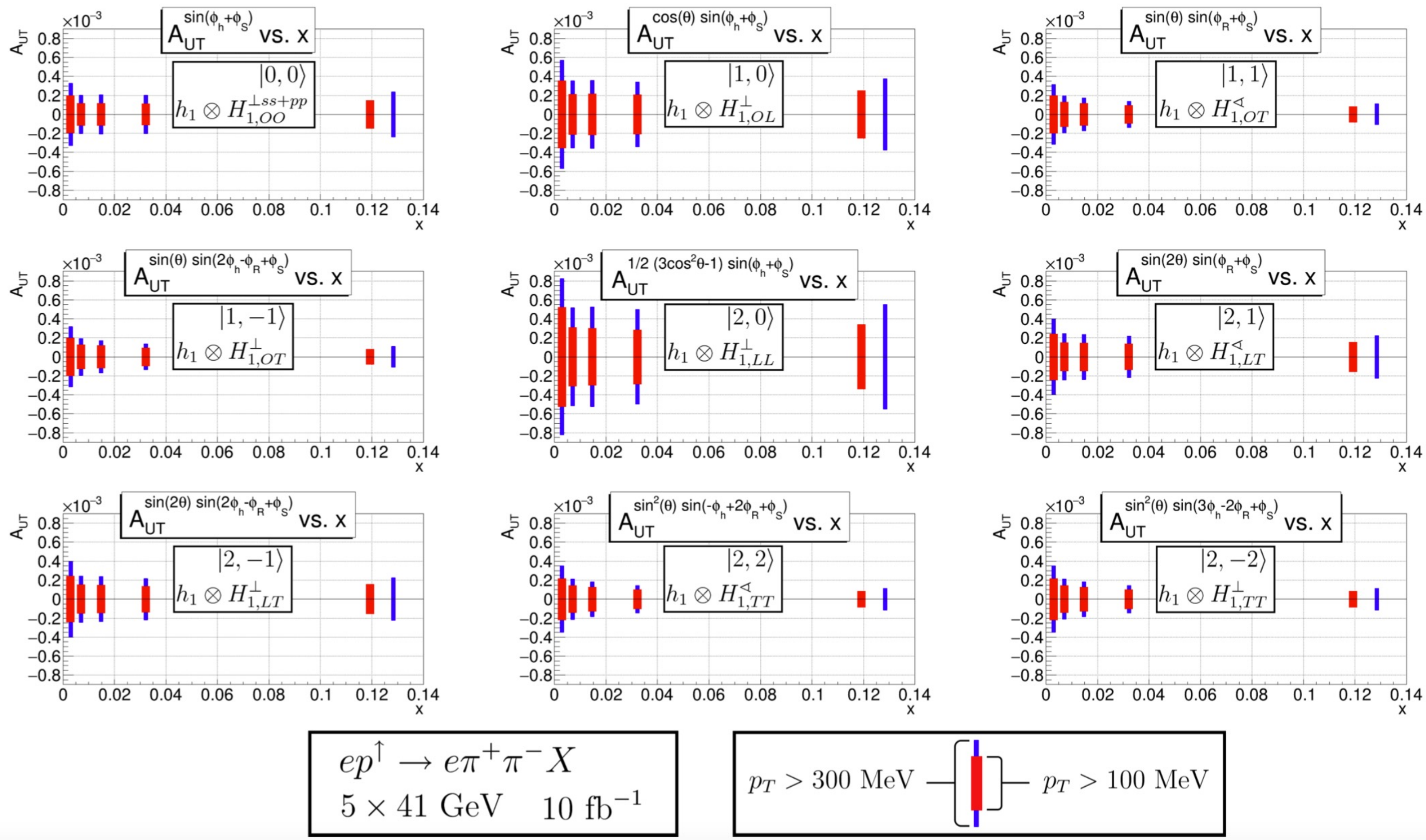
Example: transverity extraction from Jlab and the EIC



But careful with parametrization bias…

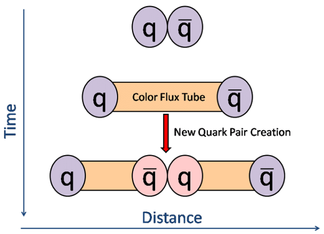
Phys.Lett.B 816 (2021) 136255

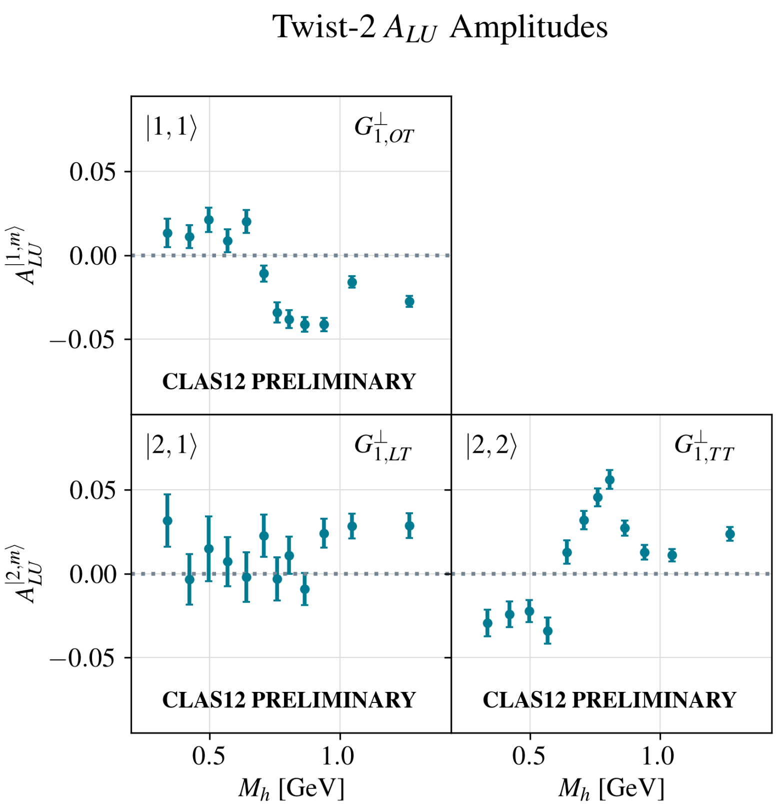
Partial Wave decomposition of di-hadron asymmetries up to $L = 2$

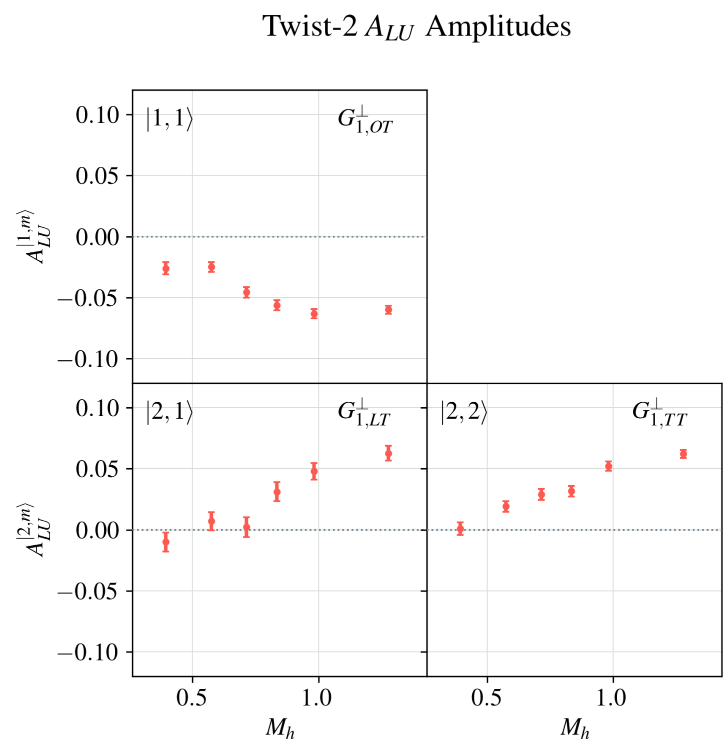


Compare Partial Wave Decomposition in MC and Data

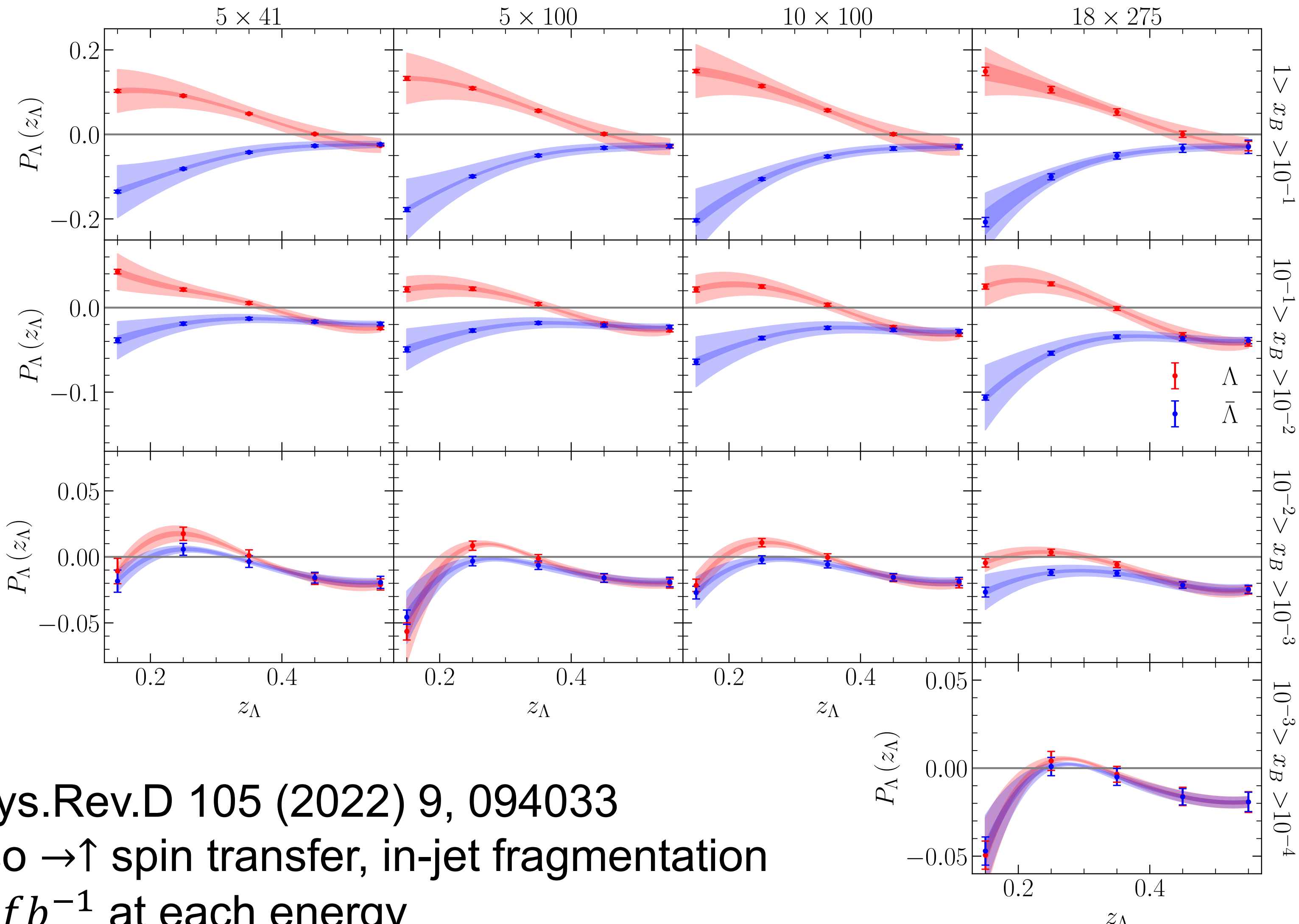
- Comparing to Polarized Lund model here (StringSpinner, A. Kerbizi et al, *Comput.Phys.Commun.* 272 (2022))







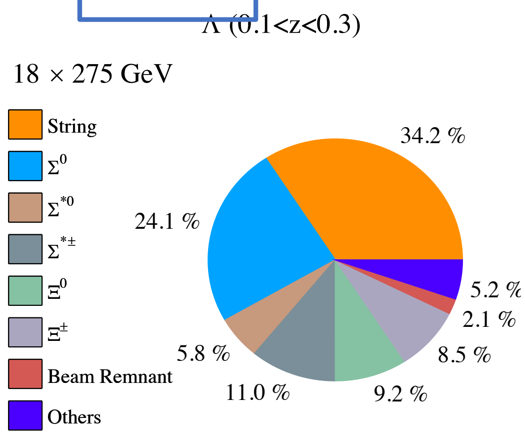
Precision Λ physics at the EIC

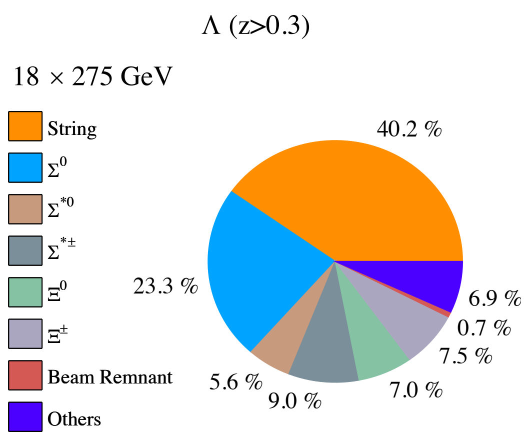


- Phys.Rev.D 105 (2022) 9, 094033
- Also →↑ spin transfer, in-jet fragmentation
- 40 fb^{-1} at each energy
- Significant impact of low $\sqrt{s}$ data

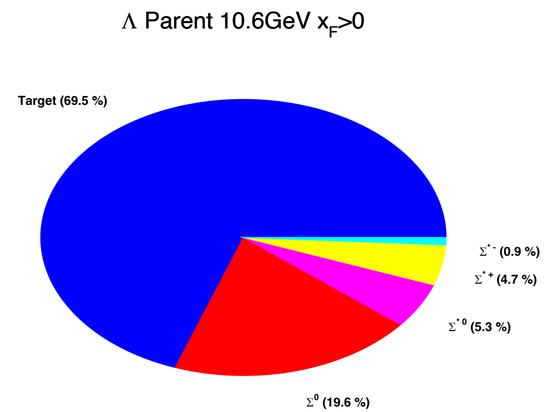
Lambda feed-down composition vs JLab20

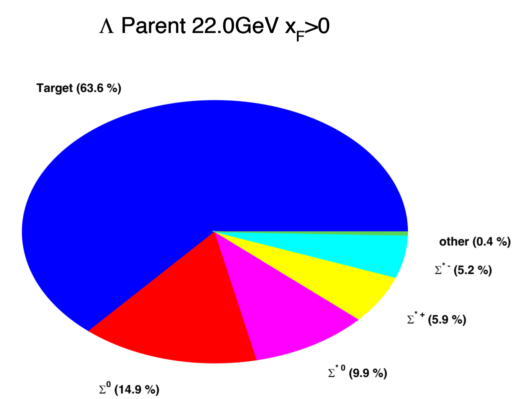
EIC





JLAB12, 20



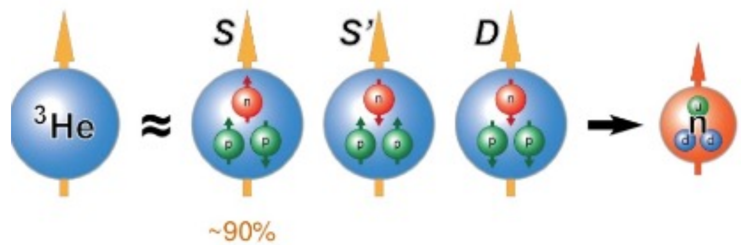


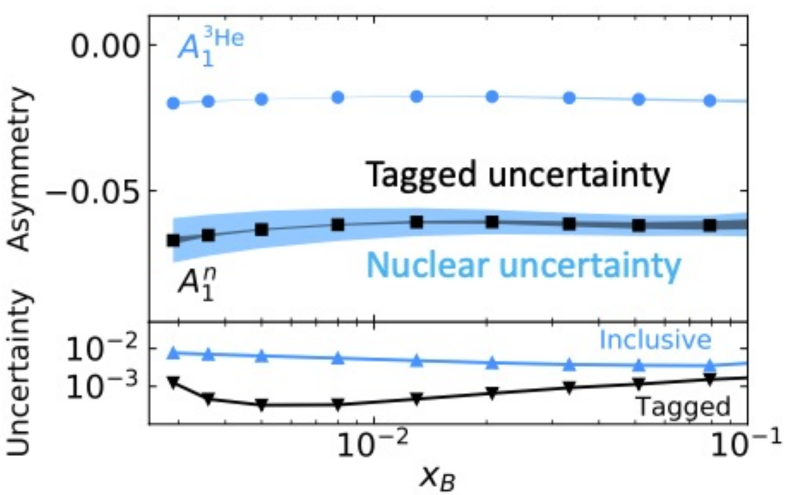
- Possible to unfold at the EIC (not so much at Jlab)
- ML methods might help

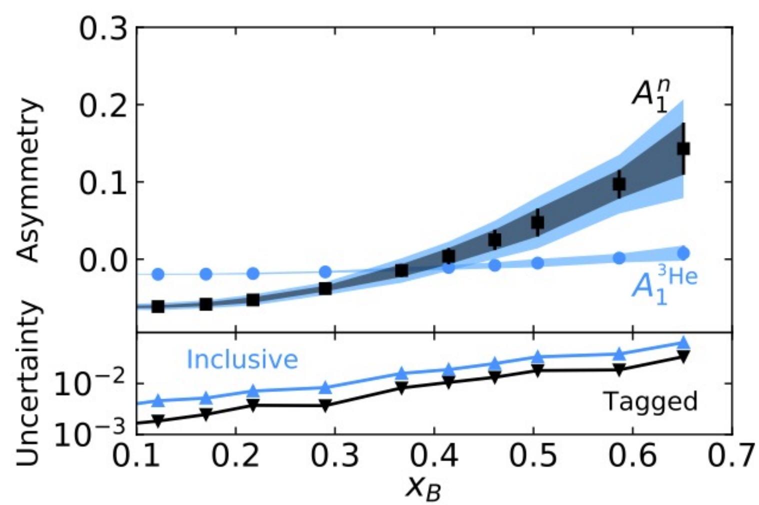
Study by M. McEneaney(Duke)
JLab12 similar

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

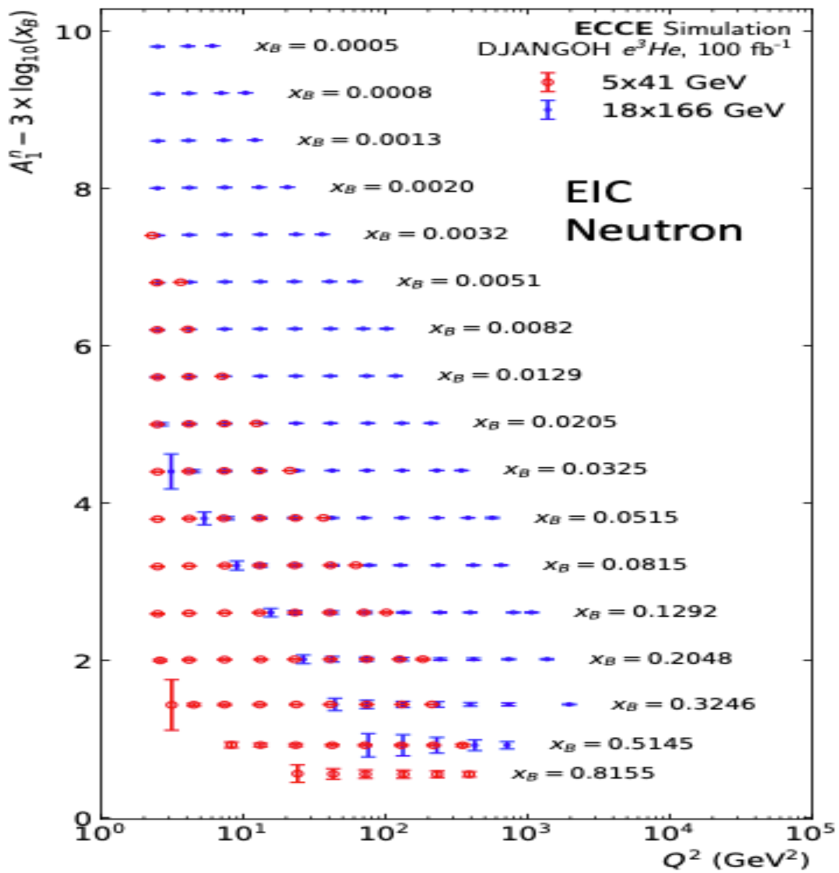


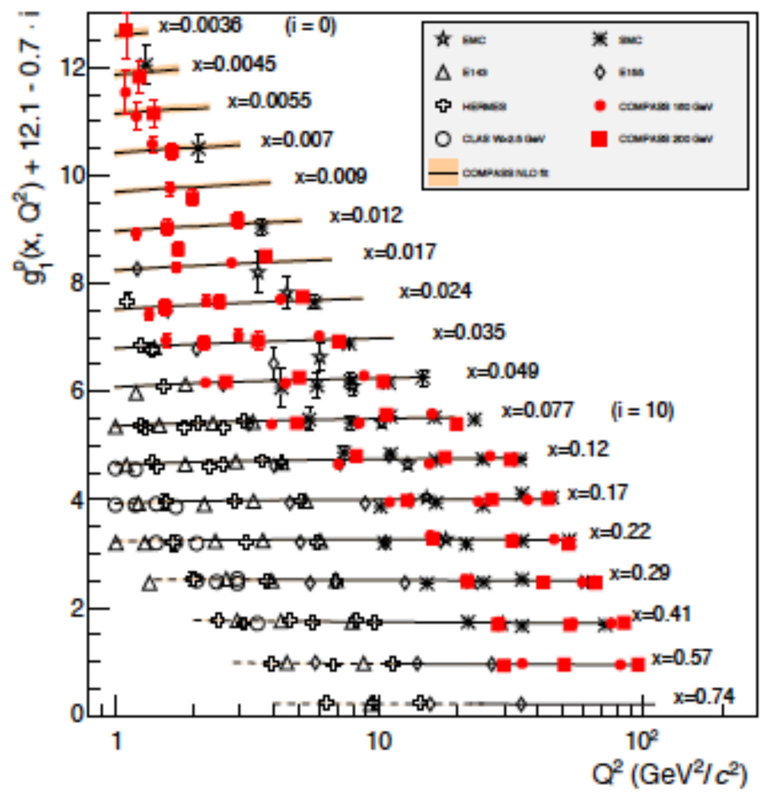




Friščić, I, Nguyen, D, Pybus, JR, Jentsch et al

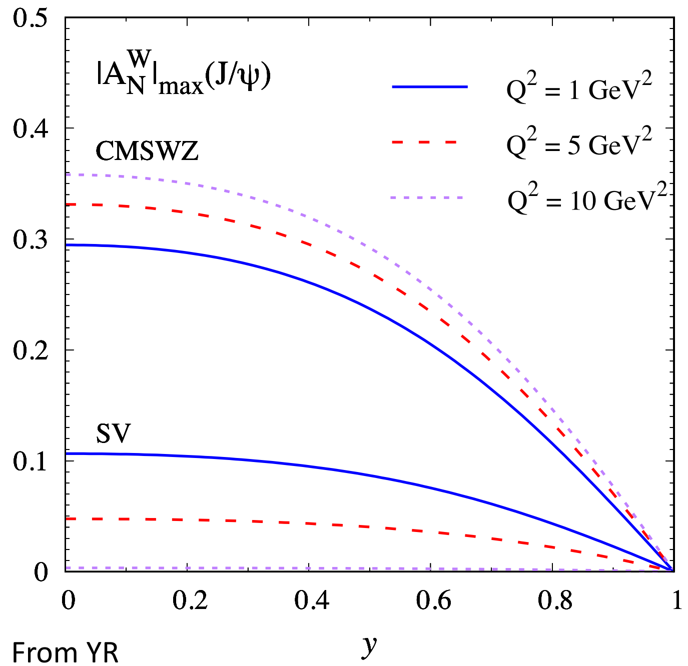
Projections for A_1

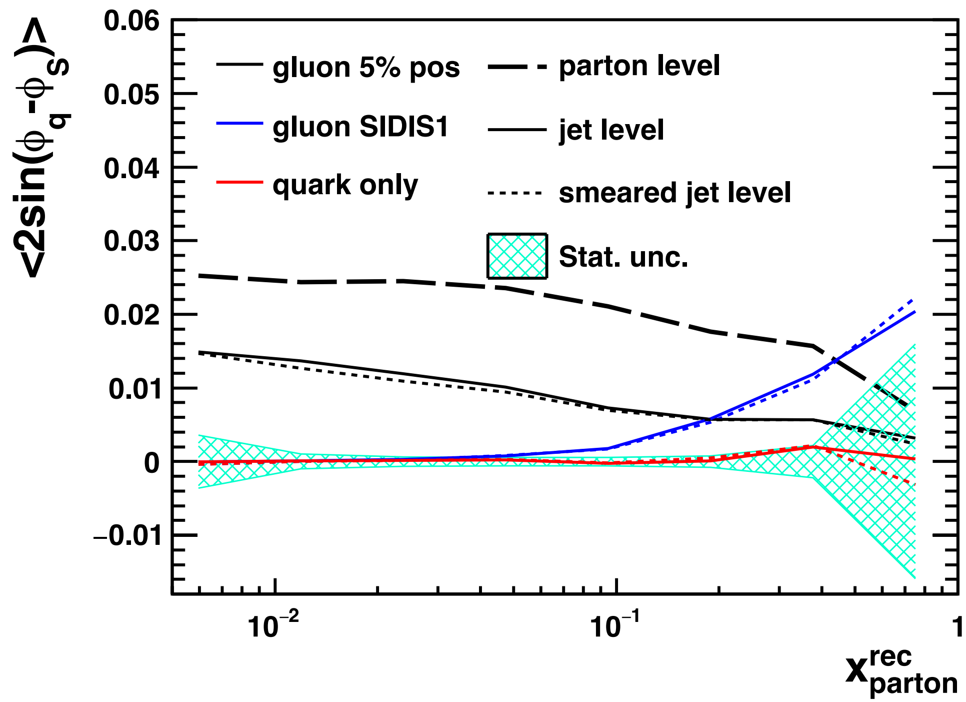




D. Nguyen@AGS User's meeting 2022

Gluon TMDs from J/Ψ and di-jets





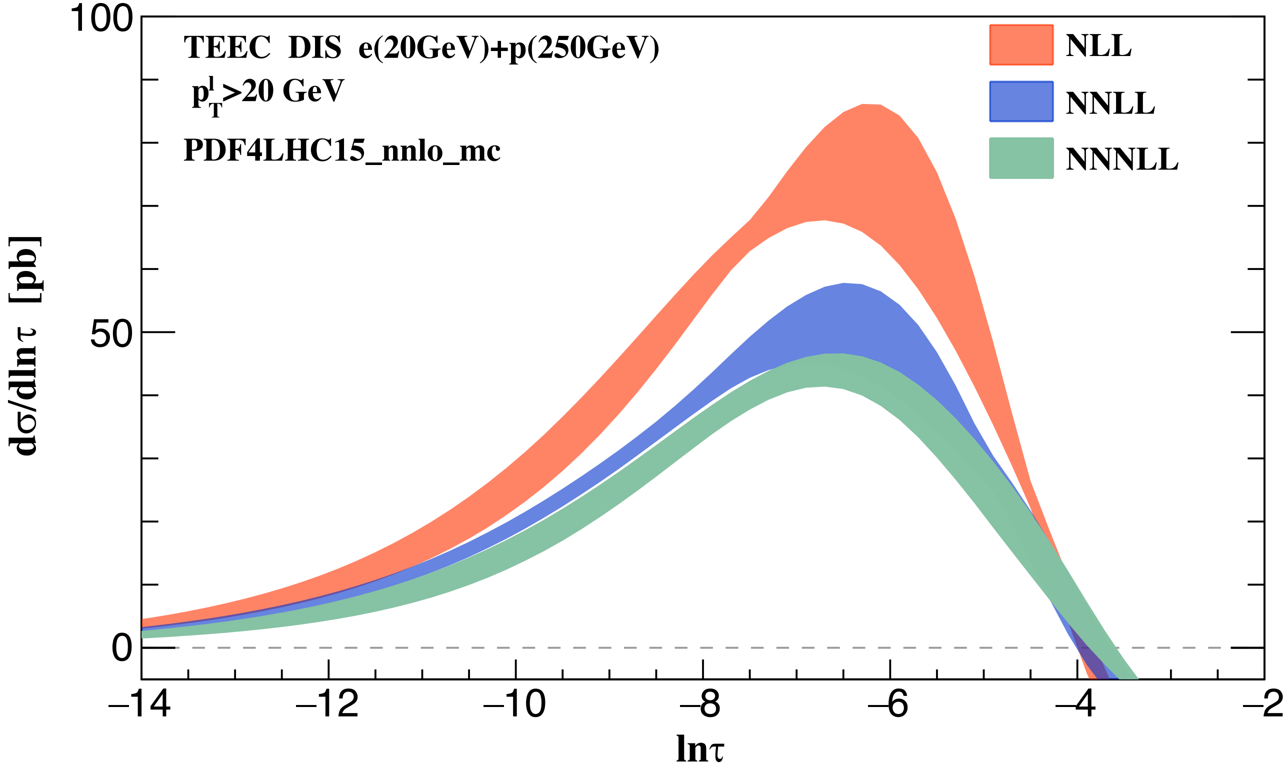
From YR
Max asymmetry corresponding to linearly polarized gluons in unpolarized and transversely polarized nucleon $h_1^{\perp g}, h_1^g, h_{1T}^{\perp g}$

From Yellow Report,
Study by L. Zhang, B. Xiao

- Transverse single spin asymmetries with J/Ψ have model uncertainties

Energy-Energy Correlations

- Precision calculations
- Close connection to TMD framework
- Here : transverse energy correlations between lepton and hadron

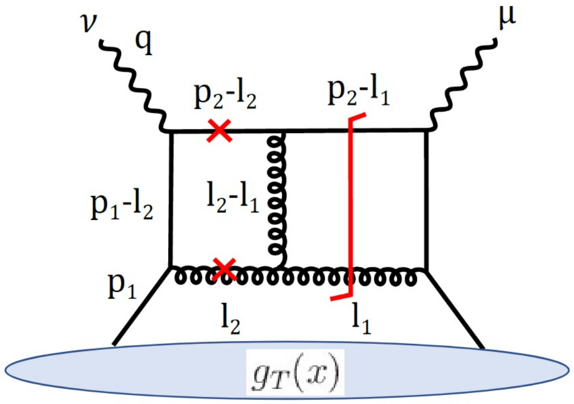


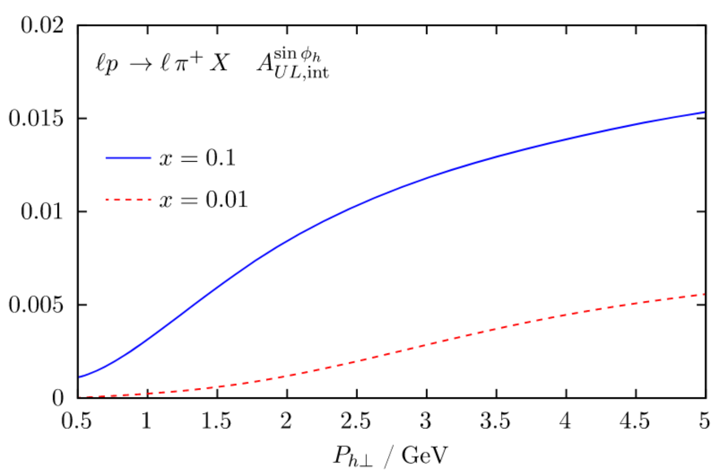
Yellow Report

$\tau = (1 + cos\phi)/2$:
sensitive to off back-to-backness

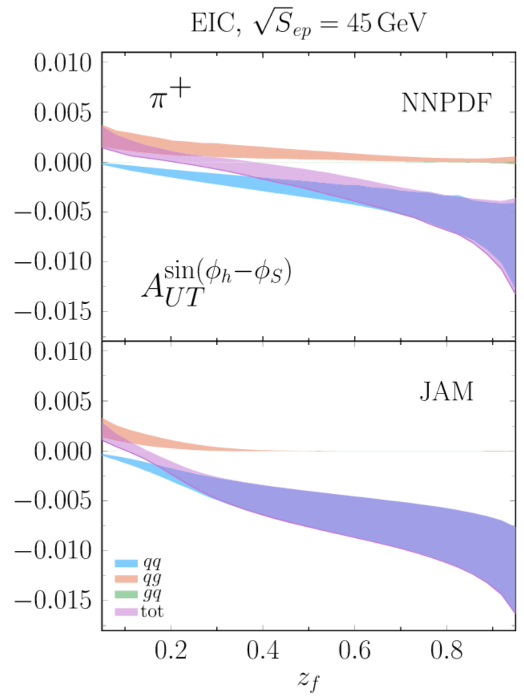
Appearance of perturbative asymmetries

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





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



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Remarks on radiative corrections

- Comprehensive studies of radiative corrections still at their infancy for SIDIS
- Preliminary studies indicate impact on kinematics, angles
- Hadronic methods might mitigate effects
- Experience from e^+e^-: strong interdependence between shape of spectra and radiative corrections

→Needs good MC description

Conclusion and Outlook

- EIC will enable a diverse set of SIDIS measurements
- EIC kinematic reach and precision in SIDIS measurements will have profound impact on our understanding of QCD and the 3D structure of the nucleon

- Measurements systematics dominated over a wide range
  - Detailed detector and physics simulations crucial

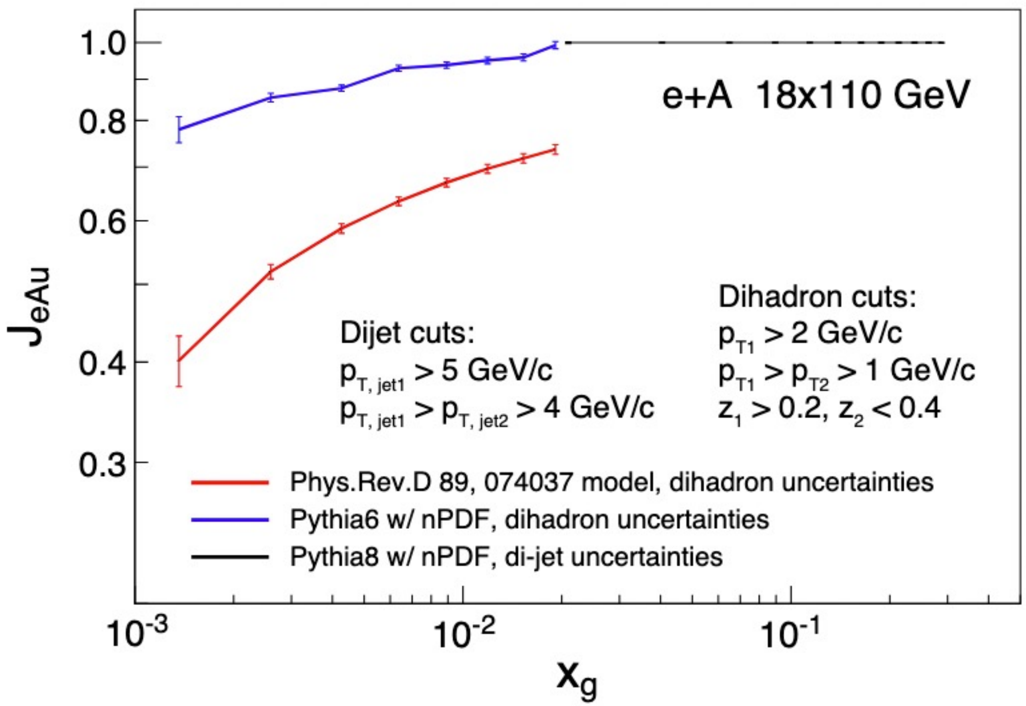
- Modern extraction schemes depend on detailed simulations
  - Folding/unfolding
  - Differentiable simulation chain?

- EIC data will also be important as input to MC models (with e^+e^-)

SIDIS overview

- Depolarization factors

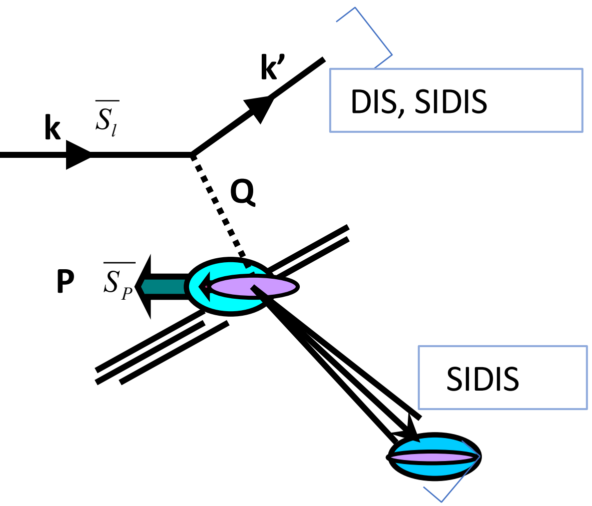
- See Ralf and Chris talk at Korea



e+A 18x110 GeV
Dijet cuts:
$p_{T,\,jet1} > 5$ GeV/c
$p_{T,\,jet1} > p_{T,\,jet2} > 4$ GeV/c
Dihadron cuts:
$p_{T1} > 2$ GeV/c
$p_{T1} > p_{T2} > 1$ GeV/c
$z_1 > 0.2$, $z_2 < 0.4$
Phys.Rev.D 89, 074037 model, dihadron uncertainties
Pythia6 w/ nPDF, dihadron uncertainties
Pythia8 w/ nPDF, di-jet uncertainties
J_{eAu}
x_g

SIDIS Kinematics

Detect also final-state hadron(s): Additional benefit of flavor, spin and transverse momentum sensitivity via Fragmentation functions



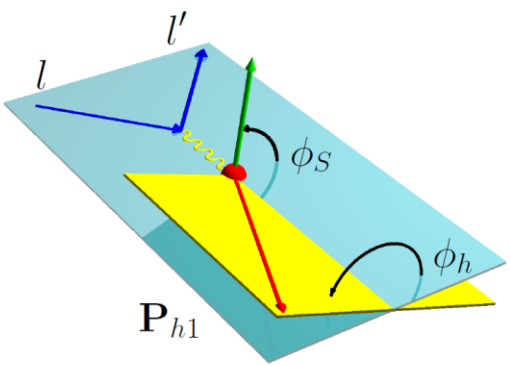
$$\frac{d^6\sigma}{dx\,dQ^2\,dz\,dP_{hT}\,d\phi_S\,d\phi_h} \stackrel{LO}{\propto} \sum_{q,\bar{q}} e_q^2\, q(x,Q^2,k_t) \otimes D^h_{1,q}(z,Q^2,p_t)$$

z: Fractional hadron momentum wrt to parton momentum ($0<z<1$)

P_{hT}: transverse hadron momentum wrt to virtual photon

ϕ_S: Azimuthal angle of nucleon (transverse) spin wrt to scattering plane, along virtual photon axis

ϕ_h: Azimuthal angle of hadron wrt to scattering plane, along virtual photon axis



- Current fragmentation: related to struck quark (favored fragmentation u→π^+ , d→π^-, s→K^- , etc)
- Transverse momentum and angles rely also on correct boost to hadron rest system

A_LL

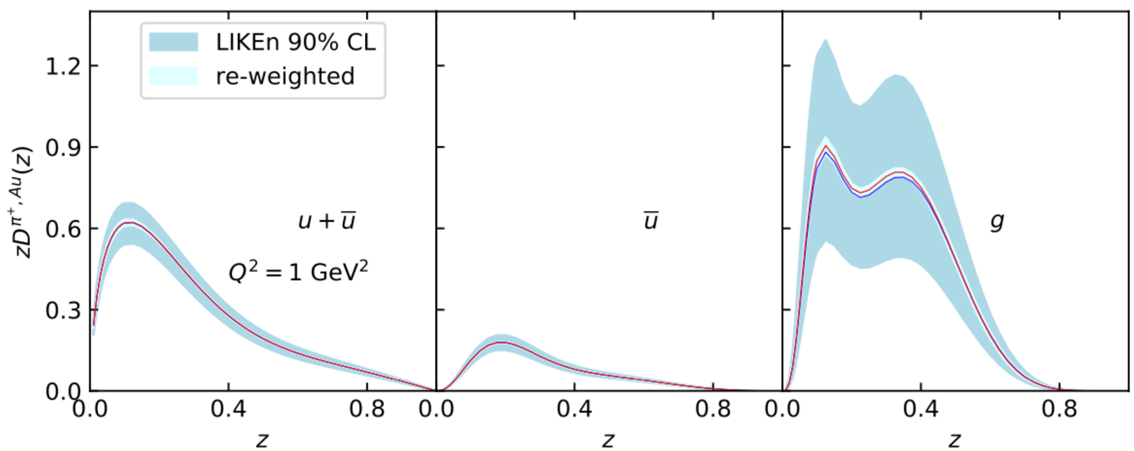


Figure 7.90: Nuclear FFs LIKEn21 for Au and impact of EIC pseudodata at $\sqrt{s} \sim 30$ GeV for $u + \bar{u}$ (left), $\bar{u}$ (center) and gluon (right). Similar results are found for higher $\sqrt{s}$.

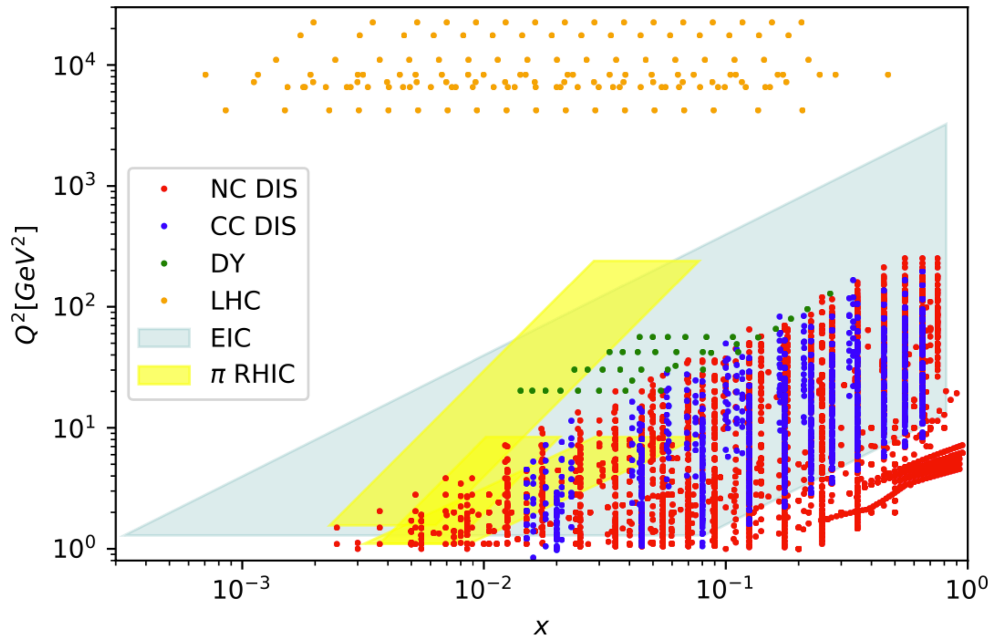


Figure 7.66: Kinematic coverage of experimental data and EIC pseudo data used in nPDFs fits. The coverage corresponds to all measured nuclei together. Each nPDFs set has extra cuts that further reduce the explored space.

TMDs

- Using heavy flavor

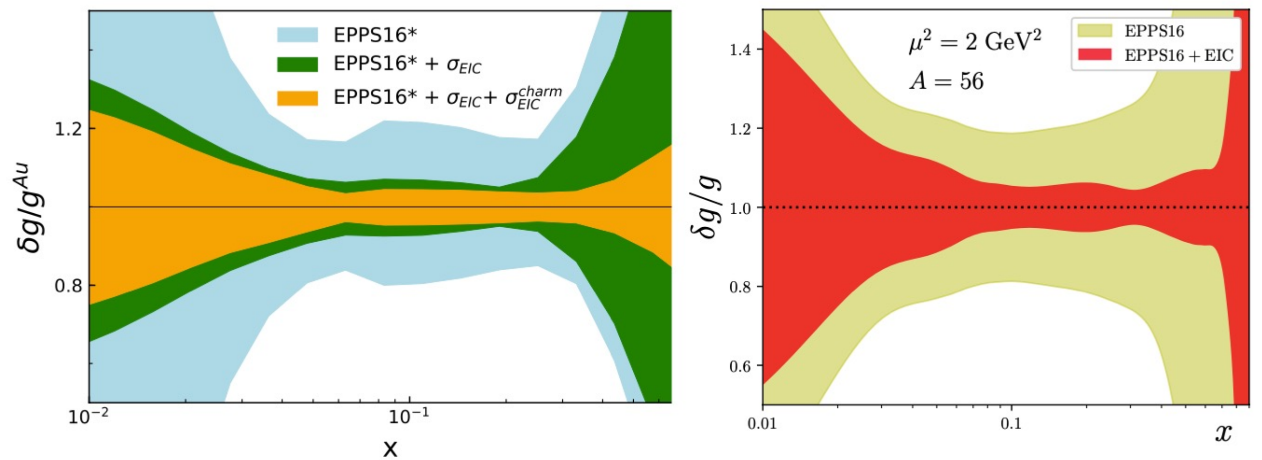


Figure 7.69: Left: Relative uncertainty bands of the gluon for Au at $Q^2 = 1.69$ GeV^2 for EPPS16* (light blue), EPPS16*+EIC σ (green) and EPPS16*+EIC σ^{charm} (orange). Right: same as left panel but for Fe at $Q^2 = 2$ GeV^2 for EPPS16 (yellow) and EPPS16+EIC σ^{charm} (red).

Main Channels

- Asymmetries,
- Cross-sections
- Nuclear? (what MC is needed here, ask Charlotte?)

Kinematics

- X,Q2 (what processes)
- Hera agreement?
- Reconstruction
  - ML →any preference what phase space is used?
  - Interplay with rad cor
  - New methods (MIT angle)

Detector requirements

- →i.e. what needs to be simulated correctly

Figure 31. Projected statistical and systematic uncertainties for A_{LL} for charged kaons. The curves are based on DSSV helicity PDFs [67] combined with DSS FFs [69]. The bands reflect only the helicity PDF uncertainties. Left: the expected results for $15.5\,\mathrm{fb}^{-1}$ of 18 GeV electrons colliding with 275 GeV protons. Right: results combining pseudodata from 5 GeV electrons colliding with 41 and 100 GeV protons, 10 GeV electrons colliding with 100 GeV and 275 GeV protons, and 18 GeV electrons colliding with 275 GeV protons. The uncertainties of the individual datasets were scaled to the dataset with 18 GeV electrons colliding with 275 GeV protons assuming equal data taking time for each center-of-mass-energy. Pseudodata with $Q^2 > 1\,\mathrm{GeV}^2$, $z > 0.2$, $y > 0.01$ and a depolarization factor $D(y) > 0.1$ were selected. Purities and efficiencies of the PID detectors have been taken into account. Systematic uncertainties were estimated to be 3% point-to-point and 2% scale uncertainty based on previous experience and the simulated PID performance of ATHENA. These results show a significant impact of the projected dataset, in particular, on the sea-quark helicity distributions and a constraining power over the entire x range (FastSim).

$100\ fb^{-1}$

Anticipated systematics

ML methods

- Infrared safety?

Unfolding

- (some statement from Belle uncertainties?)
- Tunes

- Saturation MC

Radiative Corrections

- ISR tunes…