SIDIS Program at the EIC

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Research Supported by

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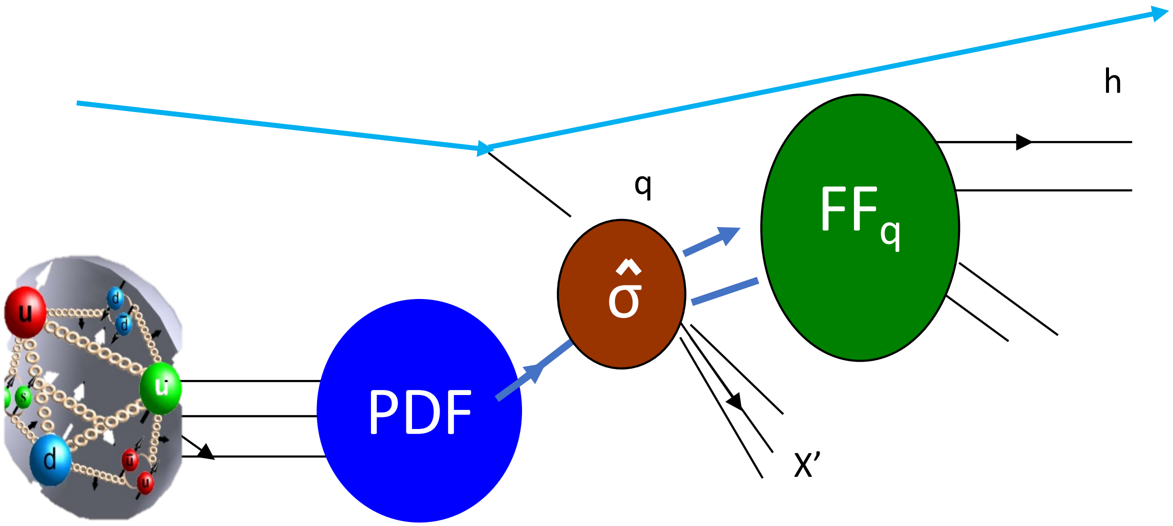
20+5

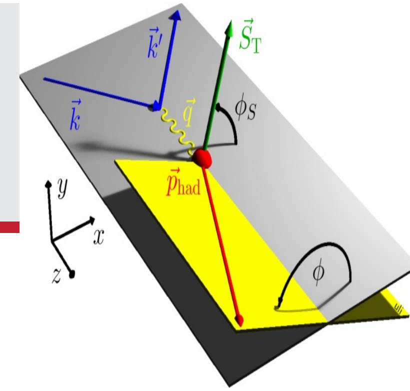
SIDIS is a premier tool to probe the quark and gluon degrees of freedom



- 3D Spin-Momentum Structure
- Sea Quark Polarization
- Saturation Effects

- Fragmentation Functions
- Passage of color through nuclear matter (nFFs)

SIDIS cross-section



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

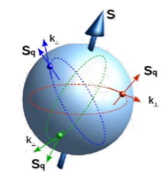
- Disentangling the different contributions is not trivial
- Ratio of T to L flux
  - At fixed x e.g. change Q

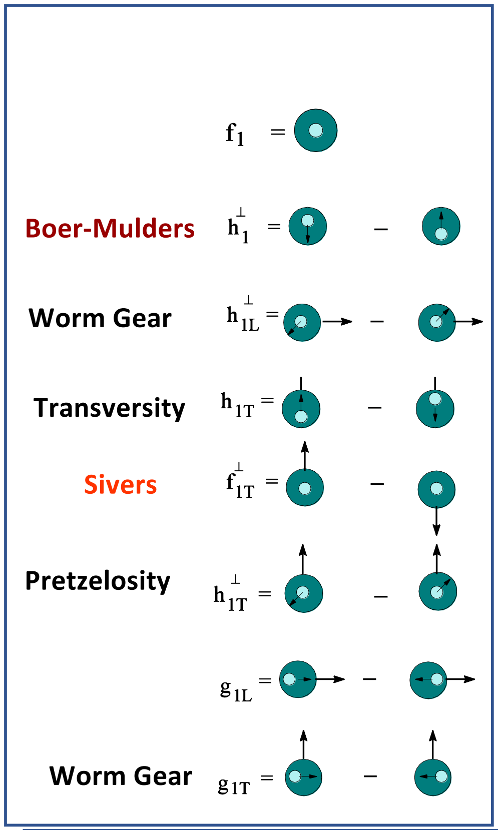
$$
\varepsilon = \frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2}, \qquad \gamma = \frac{2Mx}{Q}.
$$

SIDIS X-section in the Parton Model

- Massive simplification, Nontrivial assumptions for validity
  - Power corrections, decays, targetFF, …
  - Open questions
    - transverse momentum spectrum
    - TMD evolution
    - …

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 $h_{1T}^\perp$





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

Unpolarized

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

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

Polarized target

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

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

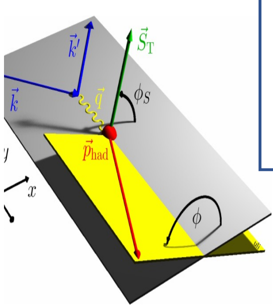
$$+|S_T|(1-y+\frac{1}{2}y^2)\frac{P_{h\perp}}{zM_N}\sin(\phi_h^l-\phi_S^l)\sum_{q,\bar q} e_q^2 f_{1T}^{\perp(1)q}(x) D_1^q(z,P_{h\perp}^2)$$

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

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

Polarzied beam and target

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



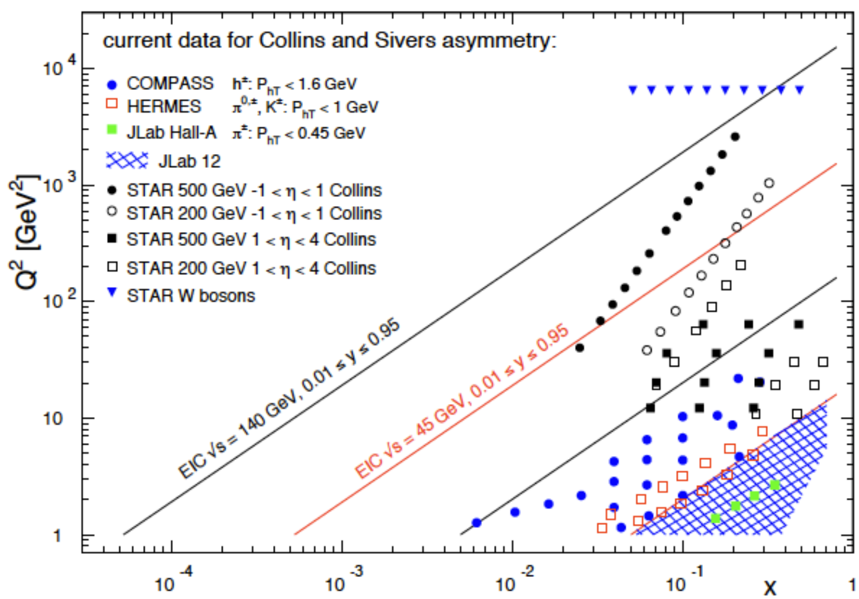
S_L and S_T: Target Polarizations; λe: Beam Polarization

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

SIDIS physics at an EIC: Coverage

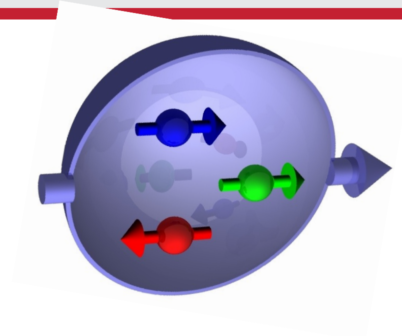
- Common theme on EIC impact
  - Extended kinematic coverage and precision, along with polarization and possible beam charge degrees of freedom allow multi-pronged approach →needed to extract multidimensional objects
  - TMD factorization is valid

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

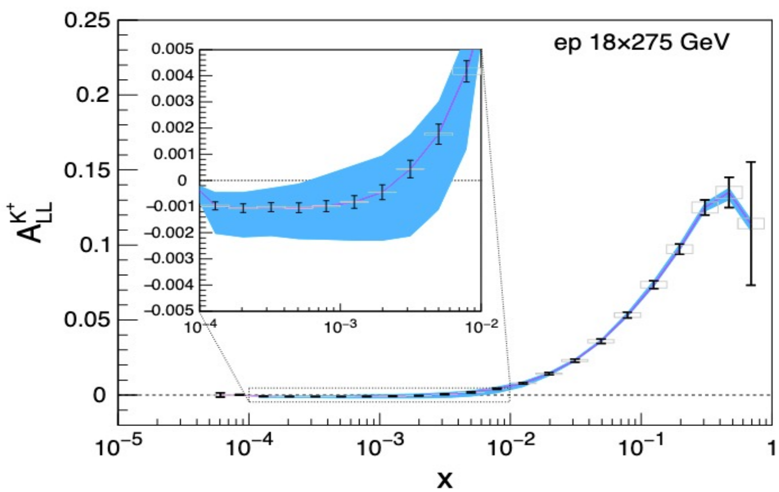


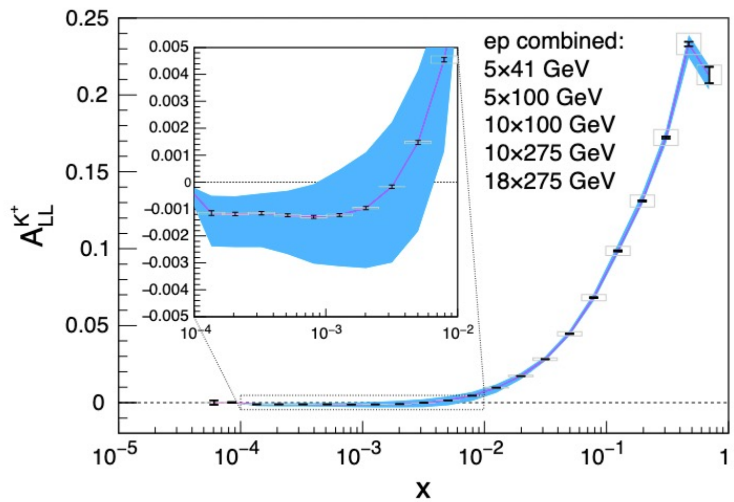
Coverage to low x: access sea and gluon distributions

Longitudinal double spin asymmetries



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



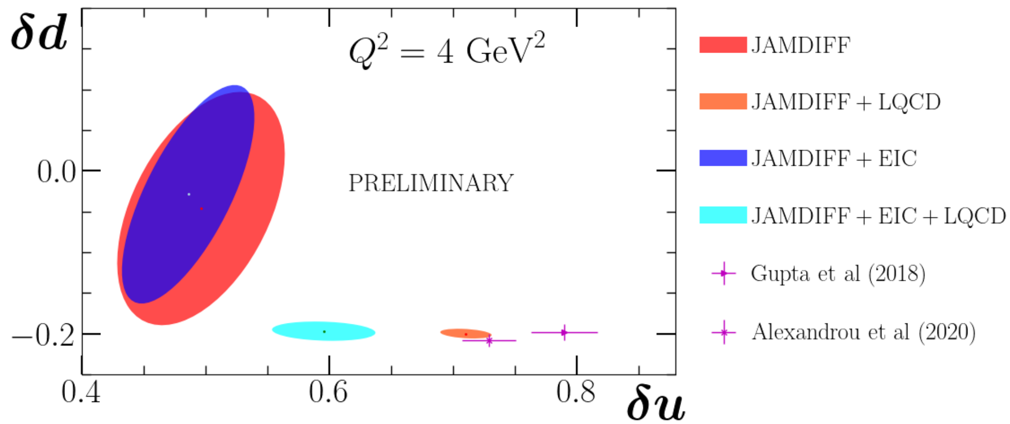


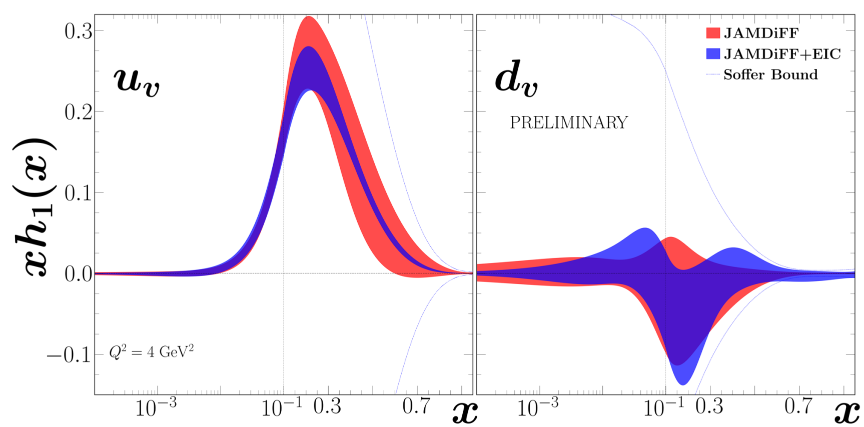
- Projections for Athena (2022 *JINST* **17** P10019)
- 3% point-to-point, 2% scale uncertainties (from Hera experience)
- $z > 0.2$
- $15.5\ fb^{-1}$ at $18x275$, other datasets scaled accordingly

➔See also double tagged A_1 (D. Nguyen's talk)

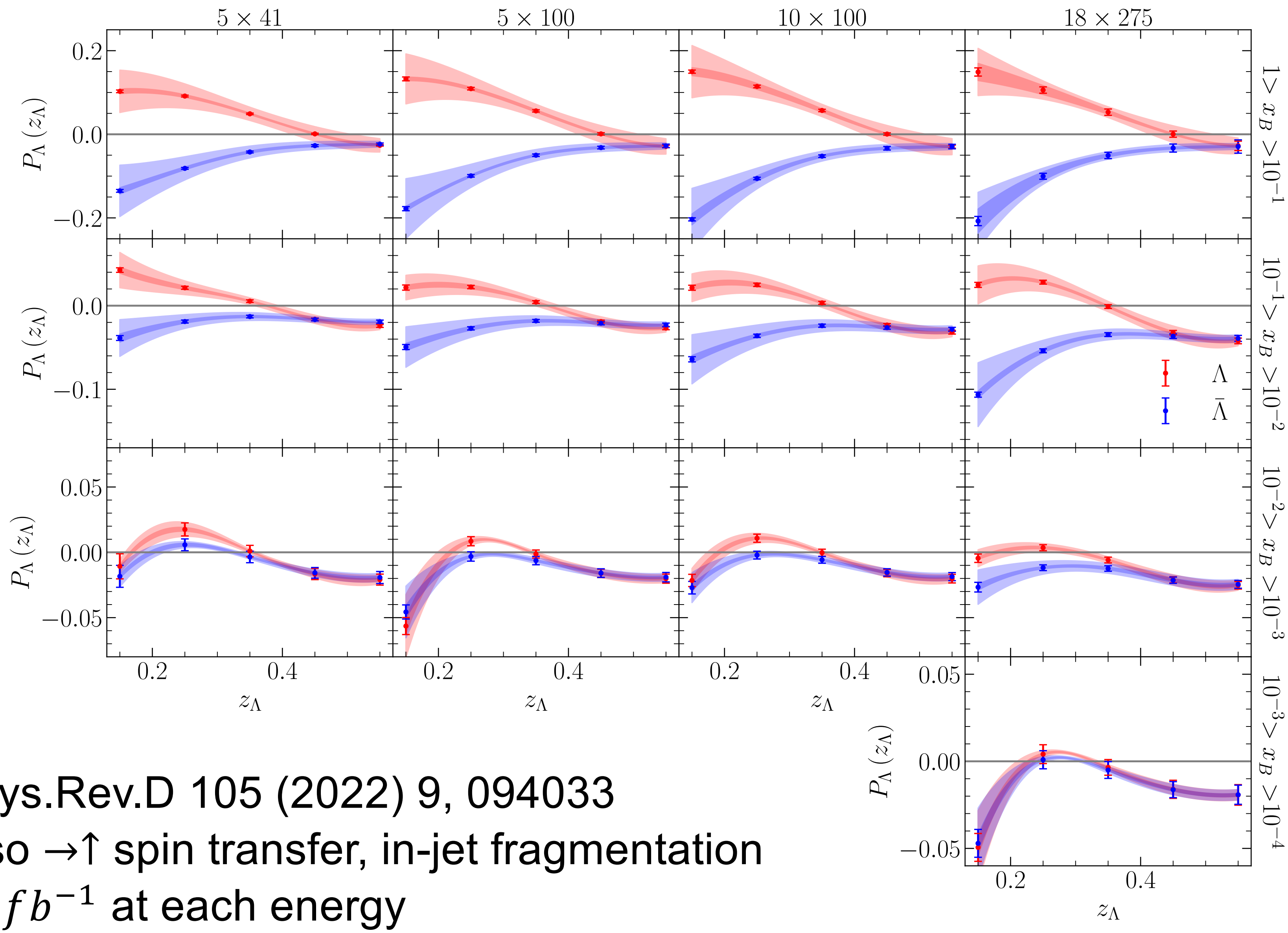
Example: Transversity Extraction from Di-hadrons

- Only proton data
- No small-x constraint
- See also *Phys.Lett.B* 816 (2021) 136255 for single hadrons
- Projected to be able to distinguish between lattice and phenomenology



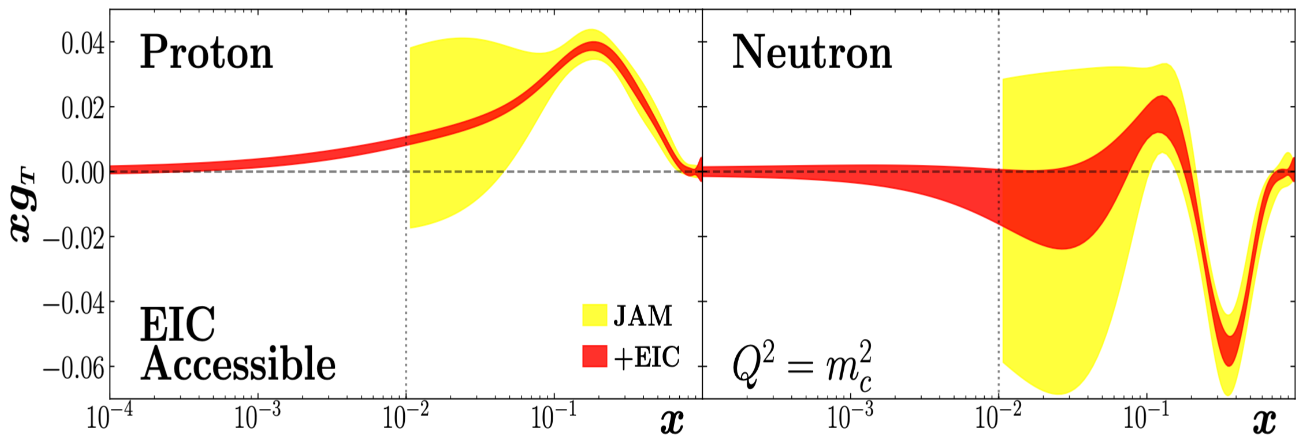


Precision Λ physics at the EIC



- 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

Impact Twist-3 PDF g_T



- A_{LT} (here projection with $100\ fb^{-1}$)

EIC kinematic leverarm provides Insight into Evolution

- CS kernel sensitive to vacuum structure [Vladimirov 2020]
- Significant uncertainties on extractions
- Disagreement in different extractions and with lattice

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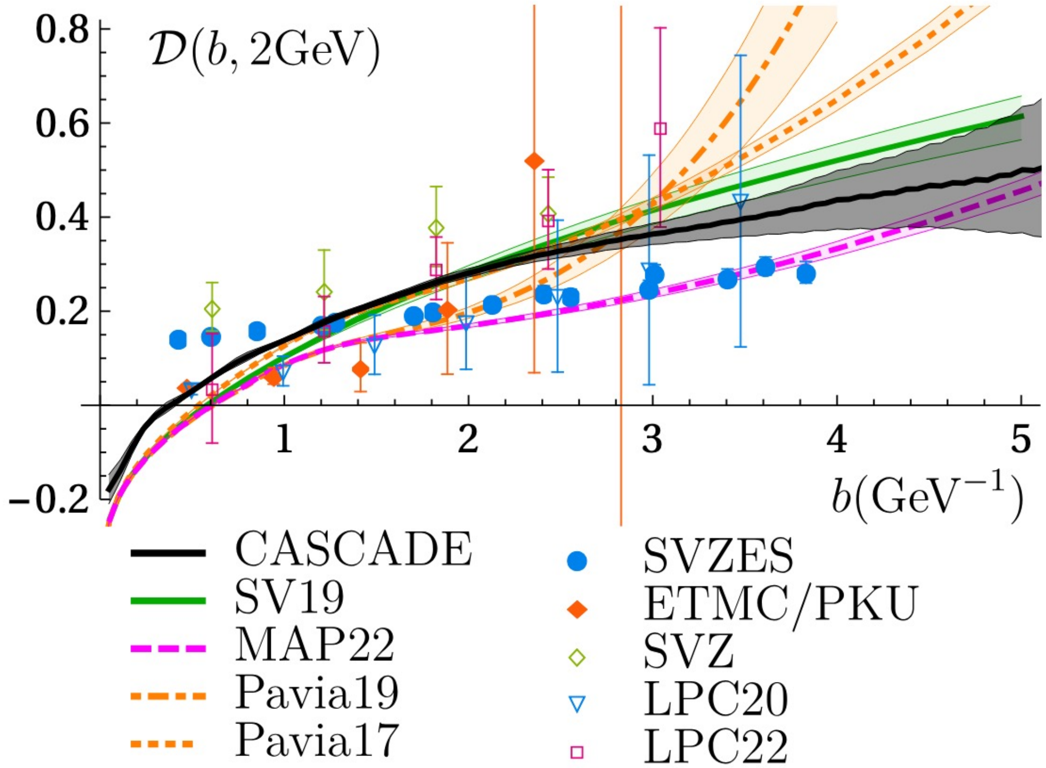
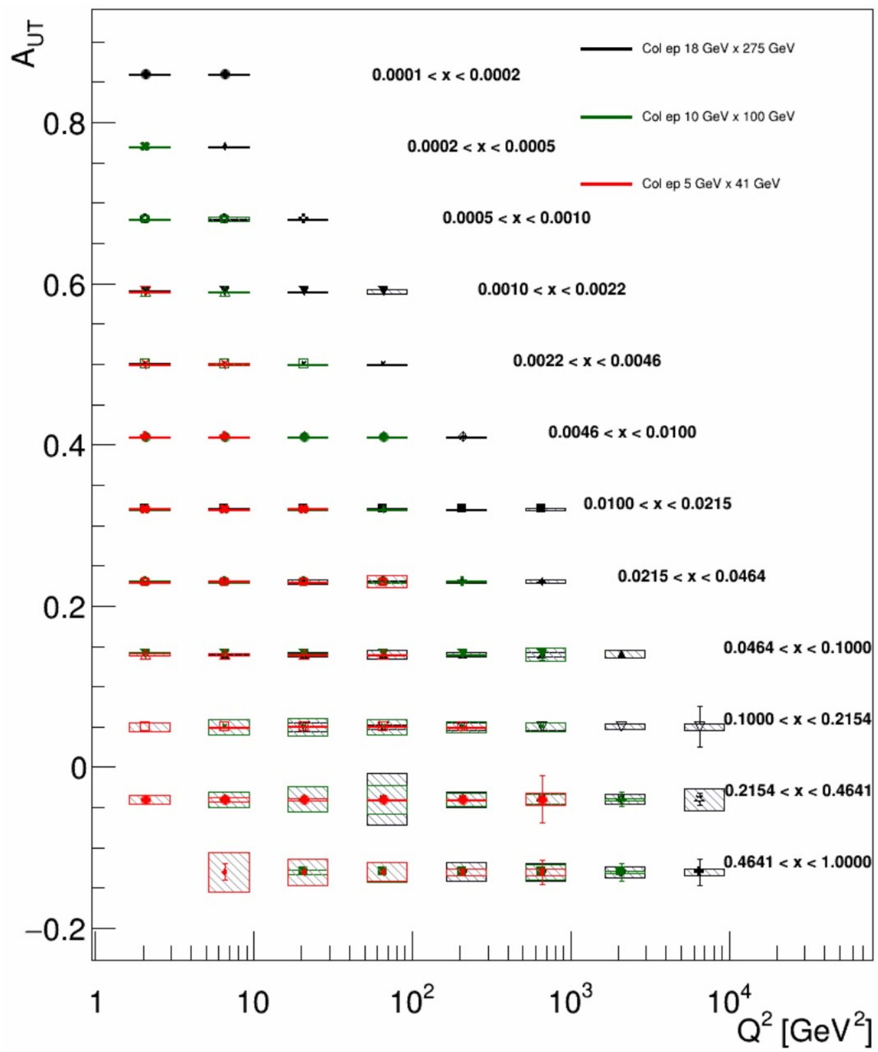
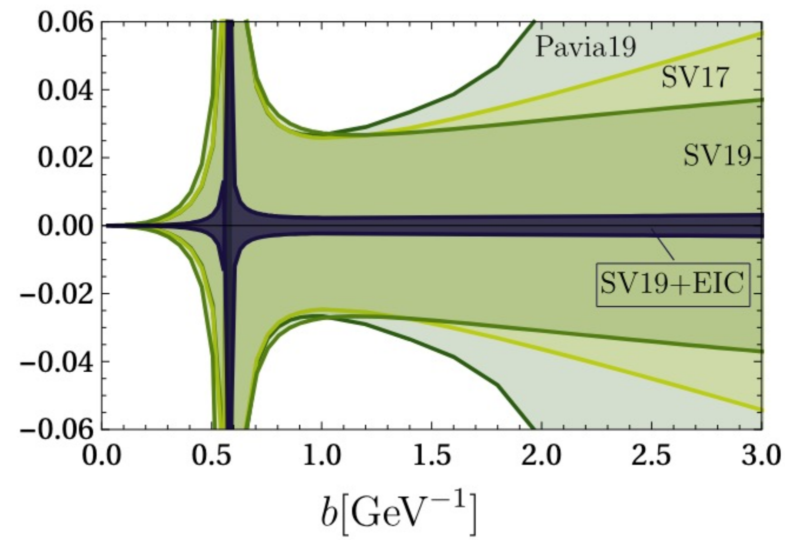


From Bermudez-Martinez, Vladimirov , arxiv:2206.01105

EIC kinematic leverarm provides Insight into Evolution

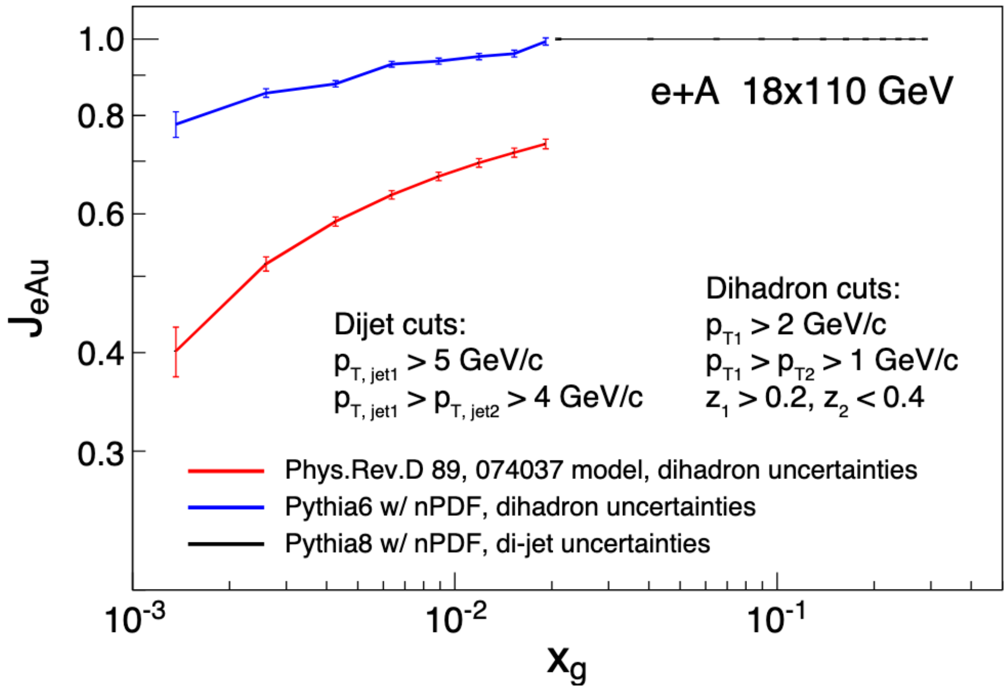


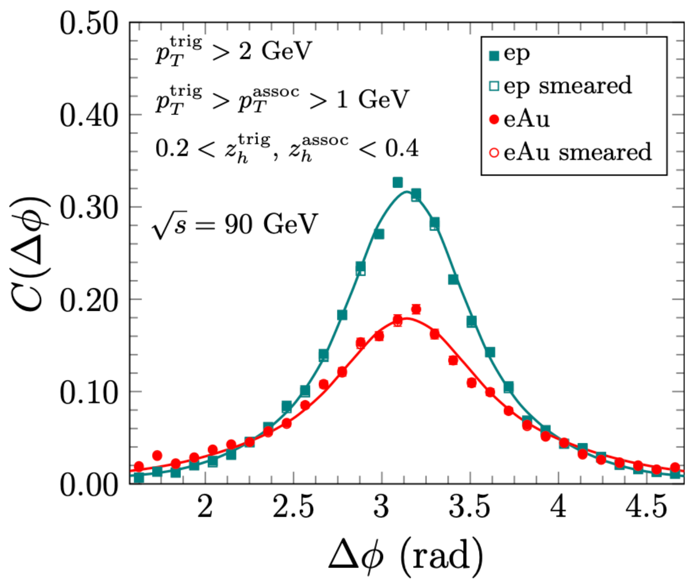


EIC Yellow Report

Ecce projections for Collins asymmetries for $10\ fb^{-1}$ at each energy
(NIMA 1049 (2023) 168017)

Di-hadrons to access saturation





• Signals in di-hadron correlation and broadening large (projections here for $10\ fb^{-1}$)

Early Running Constraints

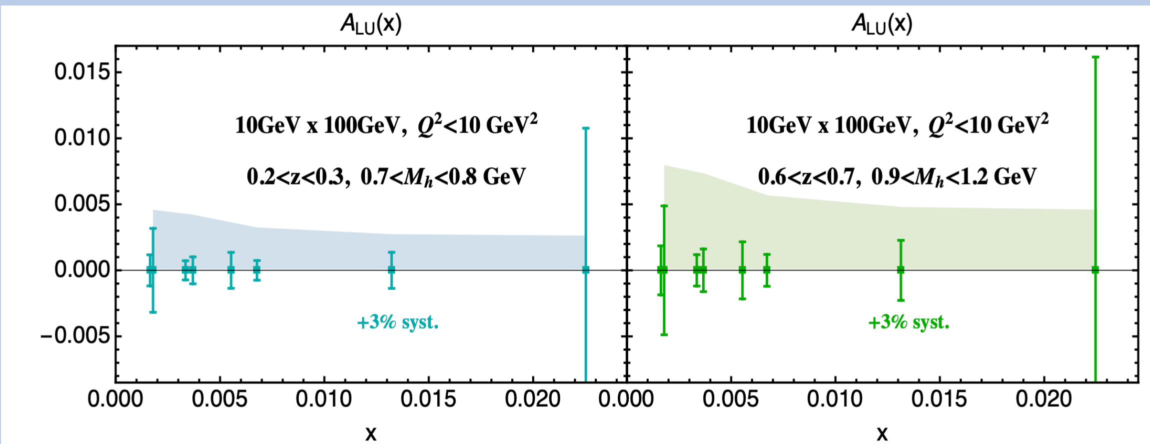
Year	Species	Energy	Luminosity (fb^{-1})	p/A polarization
Year 1	$e + Ru/Cu$	10×115	1	N/A
Year 2	$e + d$	10×130	10	N/A
Year 2	$e + p$	10×130	1	trans
Year 3	$e + p$	10×130	5	trans&long
Year 4	$e + Au$	10×100	0.5	N/A
Year 4	$e + p$	10×250	4	trans&long
Year 5	$e + Au$	10×100	0.5	N/A
Year 5	$e + {}^3He$	10×166	4	trans& long

- $O(10\%)$ of YR projection data
- Early HI data
- top energy in Year 4

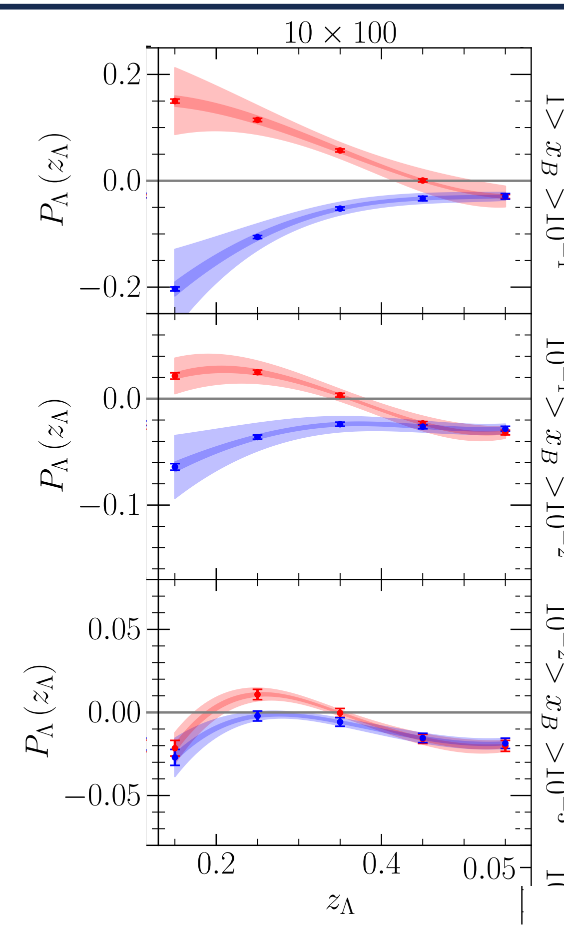
- Cross-section measurements ((n)PDF, (n)FFs, are not luminosity hungry but need good understanding of detector

- BSAs a good start but kinematically suppressed
- Also consider asymmetries in species, final state, charge..

BSAs and Lambdas with early data



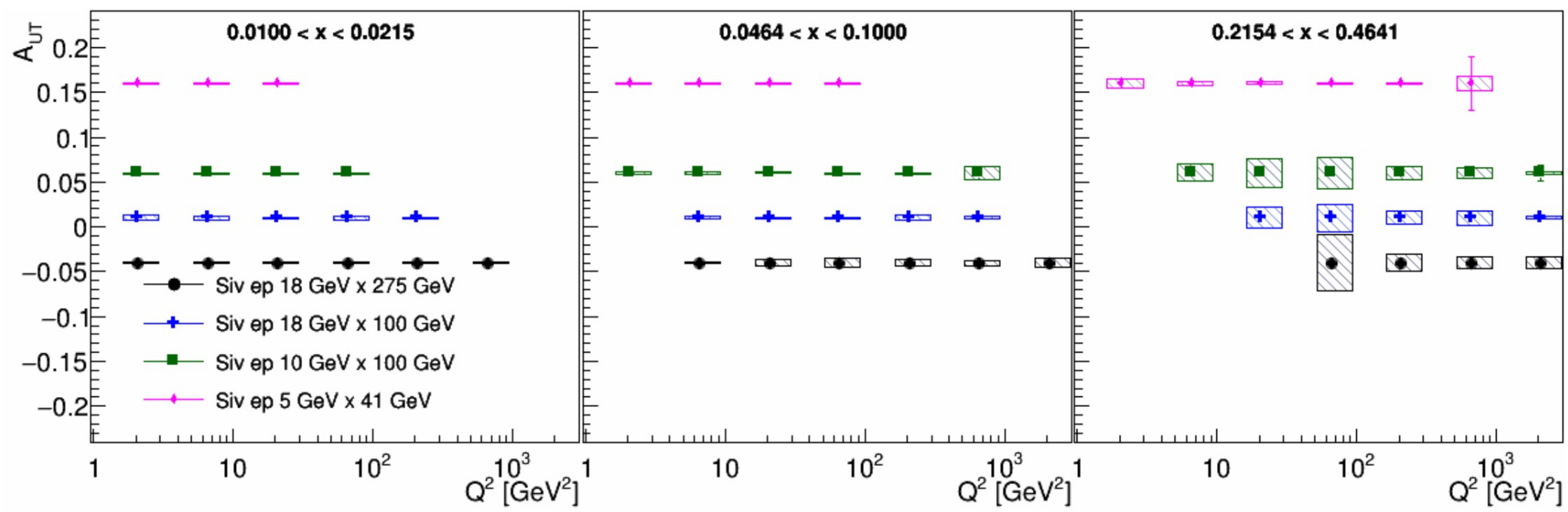
- A_{LU} for dihadrons(here projection with $10\ fb^{-1}$)
- Also: $g^{\perp}$ in jet A_{LU} , A_{LU}^{h} (but interpretation difficult)



- Transverse Λ polarization with $40\ fb^{-1}$

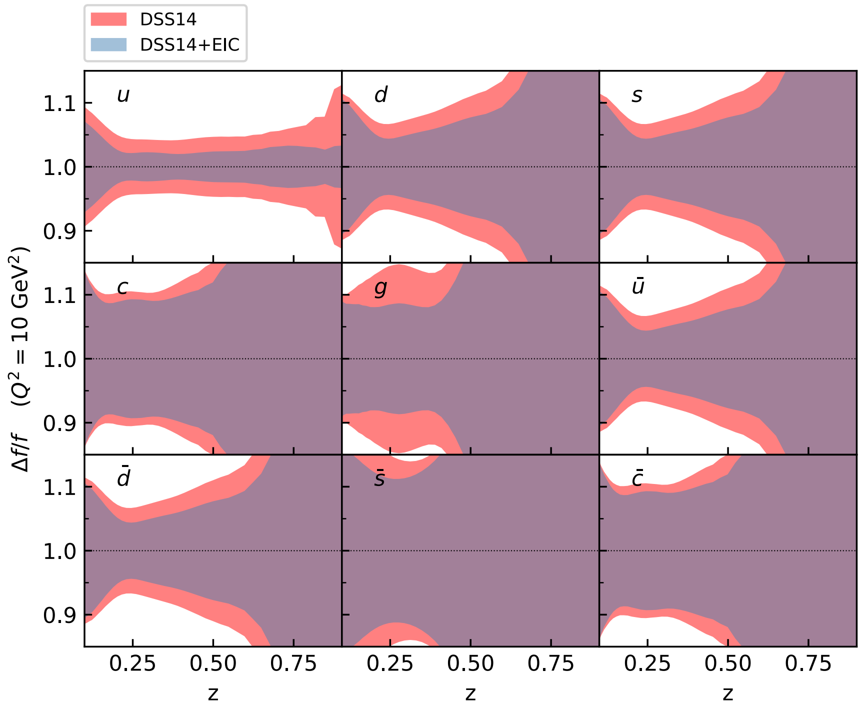
Transverse Single Spin Asymmetries at $10\ fb^{-1}$

- Uncertainties ≪ then expected asymmetries
- Insights into TMD framework

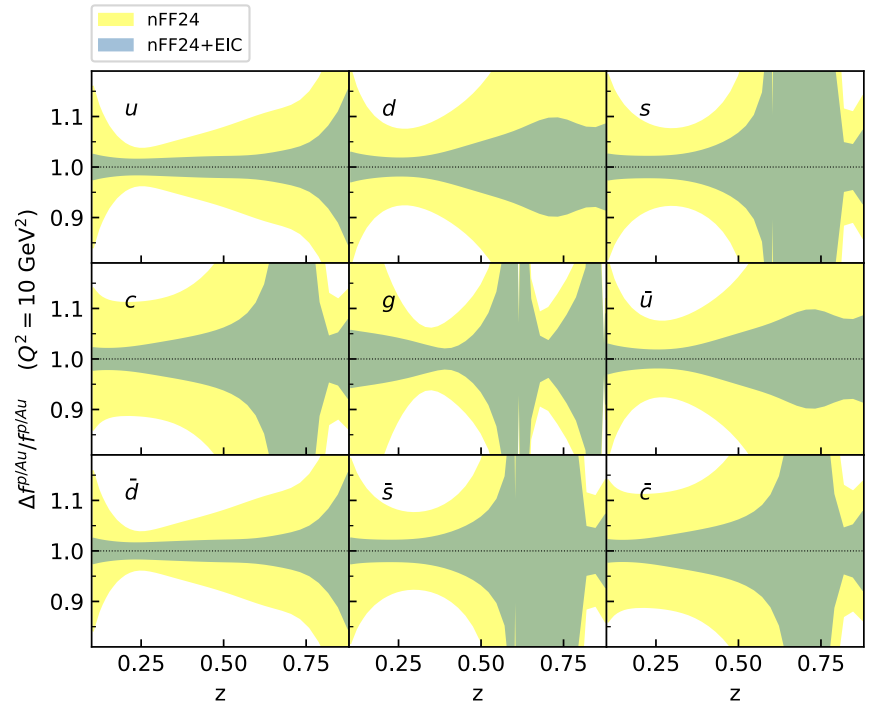


Ecce projections for Sivers asymmetries
(NIMA 1049 (2023) 168017)

(nFF)



DSS14

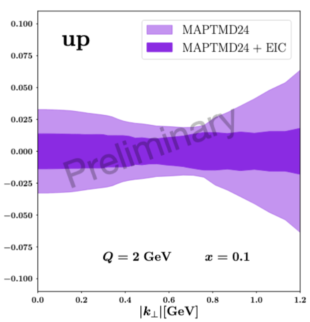


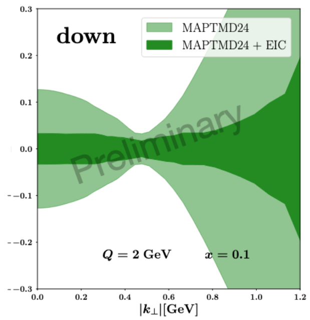
nFF24

- Plots by P. Zurita with $10/\ 1\ fb^{-1}$ for p/A
- Larger impact on nFFs, remaining questions with interpolation to intermediate A
- Beyond impact on individual FF set, need to probe consistency and compatibility with other datasets

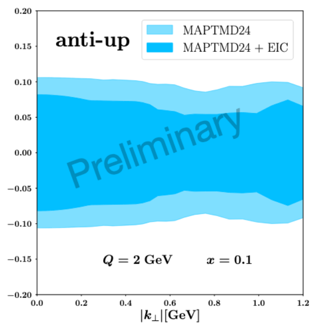
Unpolarized TMDs

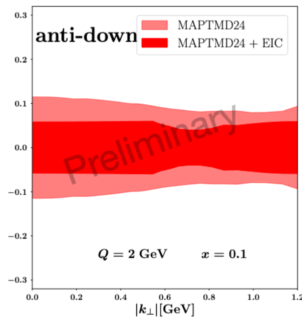
$x = 0.1$

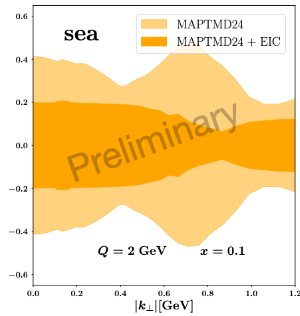


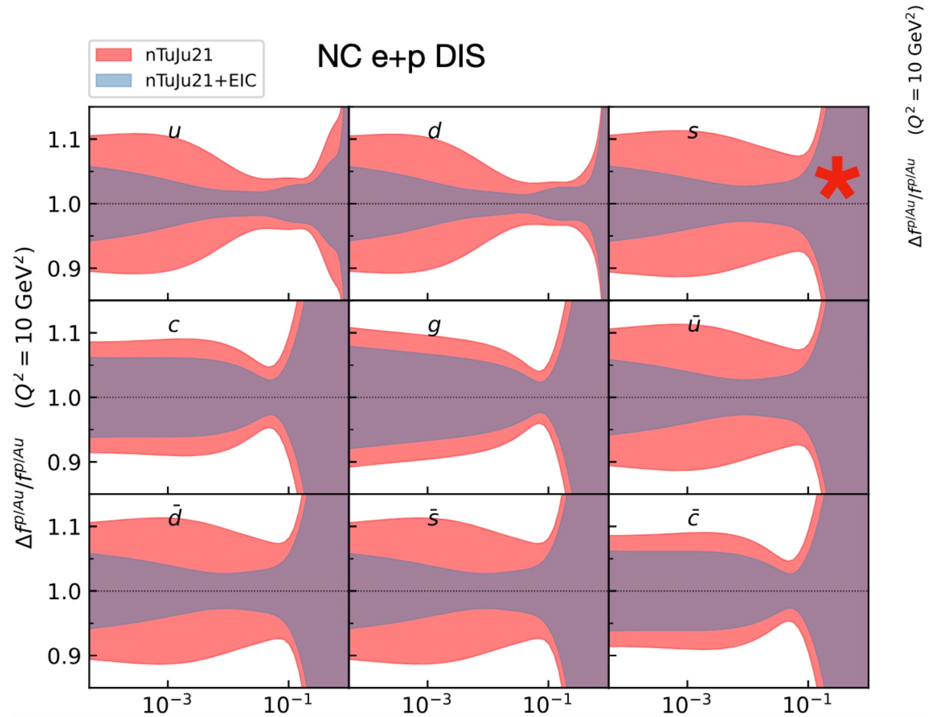


Energy	Lumi
5x41	2.85
10x100	5.13
18x275	10







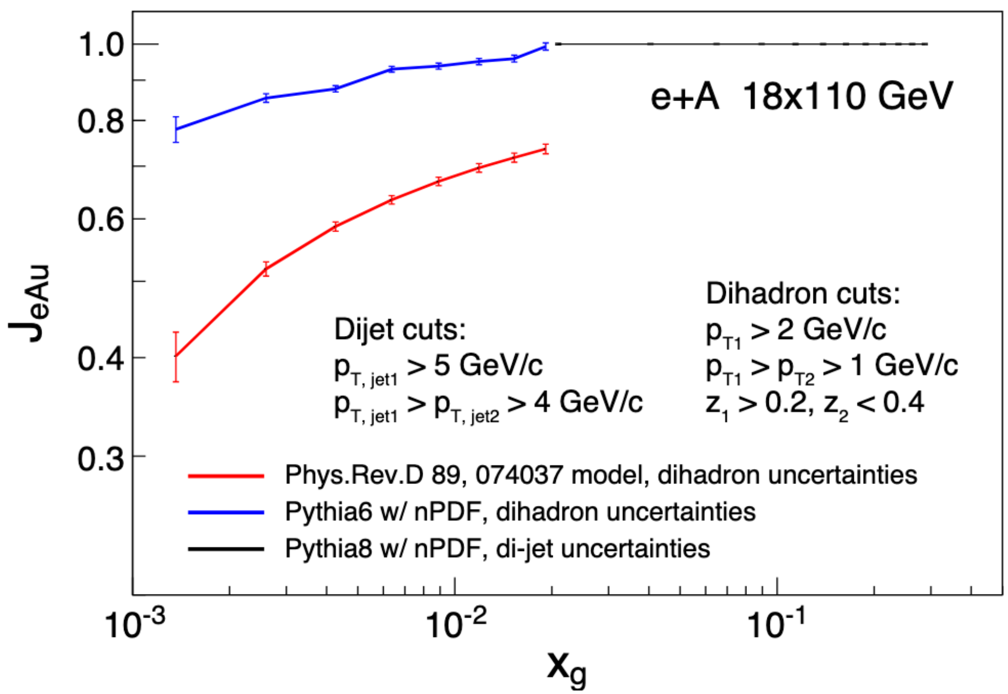


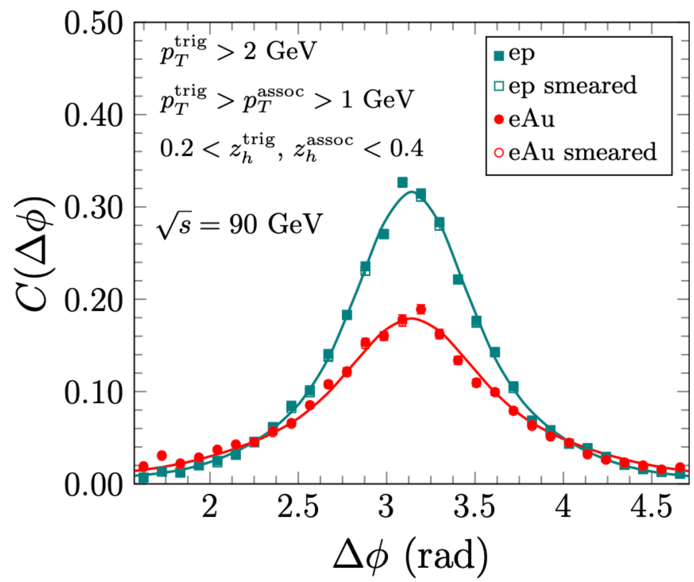
- MAP analysis (Bacchetta at ePIC collaboration meeting),
- Simulated data by G. Matousek (Duke)

- Significant impact, even with limited data
- Absolute cross-sections will be challenging in the beginning
- Nuclear PDFs/FF can also be measured as ratios to p/d

Impact of $1 fb^{-1}$ DIS on nTuJu21 nPDFs (P. Zurita)
SIDIS Impact?

Di-hadrons to access saturation





- Signals in di-hadron correlation and broadening large

→First hint with limited datasets? (projections here for $10\ fb^{-1}$)

Summary & Conclusion

- SIDIS measurements are central to the EIC physics program

- Early data has impact on (n)FFs, PDFs, potentially BSAs and more

- Projected reduction in uncertainties might not adequately reflect impact➔**Early EIC data will test our understanding of SIDIS**

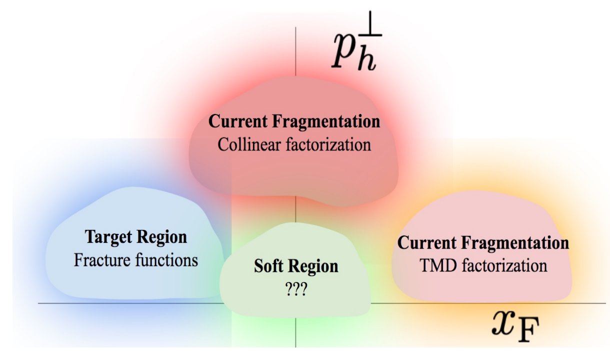
- Early analysis will be challenged by systematics/detector understanding
  - Luminosity non-hungry total cross-sections/multiplicities
  - Look for measurements where systematics cancel, e.g. ratios (p/d, p/A, n/d (tagged/untagged), π/K…

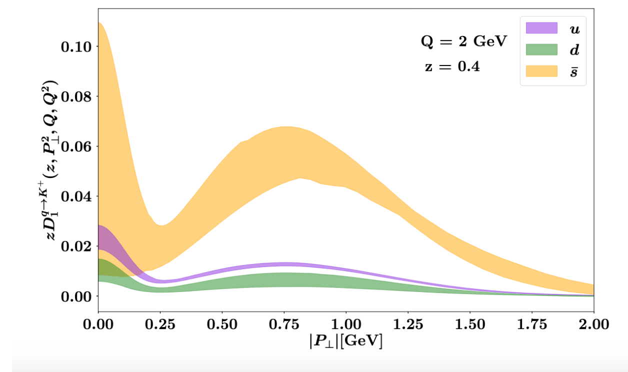
Backup

Validations of Theory Framework

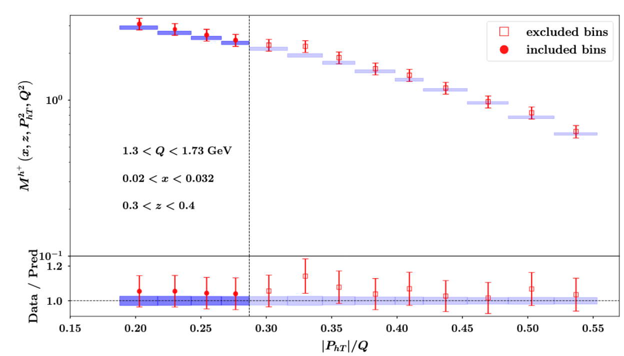
- TMD extraction is non-trivial
- Higher Twist Contributions
- Overlap of regions that are not captured by factorized TMD picture
- VM Meson decays
- Radiative corrections
- Evolution (CS Kernel)

➔EIC will be critical test of our understanding (high lumi, leverarm in kinematics to disentangle various contributions)





MAP extraction of FFs



Expect corrections in powers of $\delta \sim P_{hT}/z/Q$

Plots from A. Bacchetta's talk at ePIC Collaboration meeting

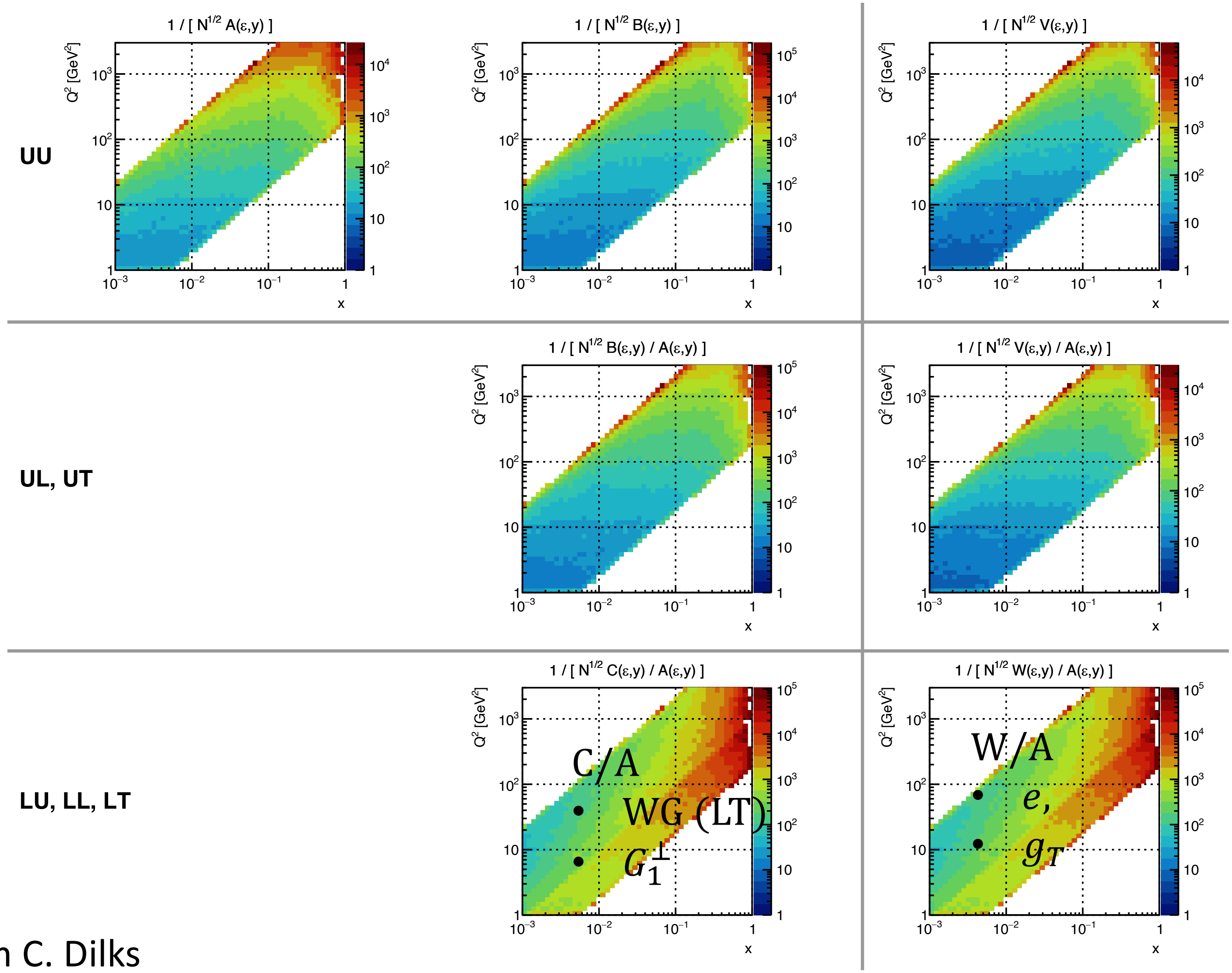
Access to TMDs: Kinematic factors

		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

Notation from *PRD*90 (2014) 11, 114027,

Slide from C. Dilks

Statistical uncertainty scaling factor for $18x275$



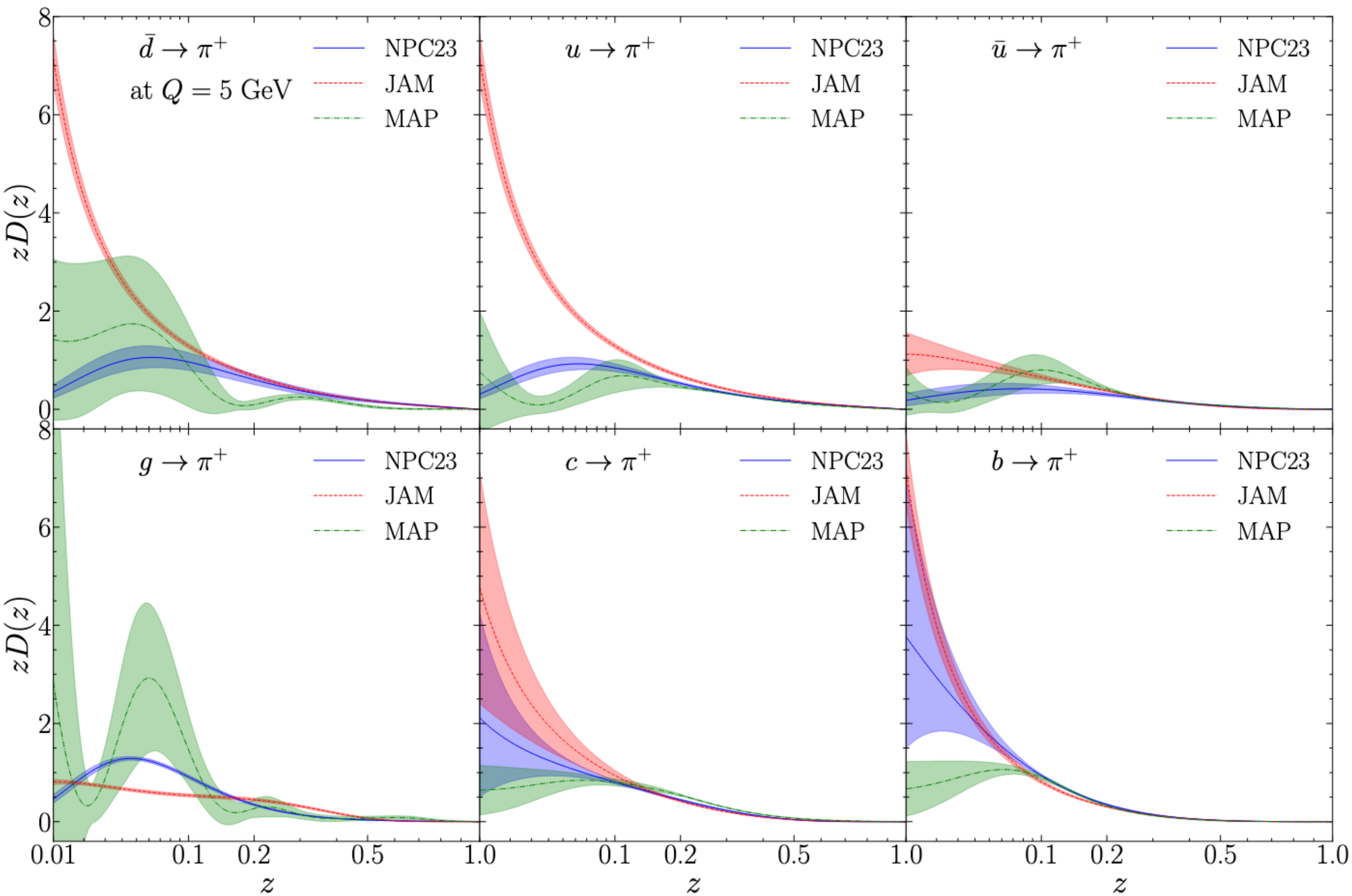
Slide from C. Dilks

Depolarization Factors

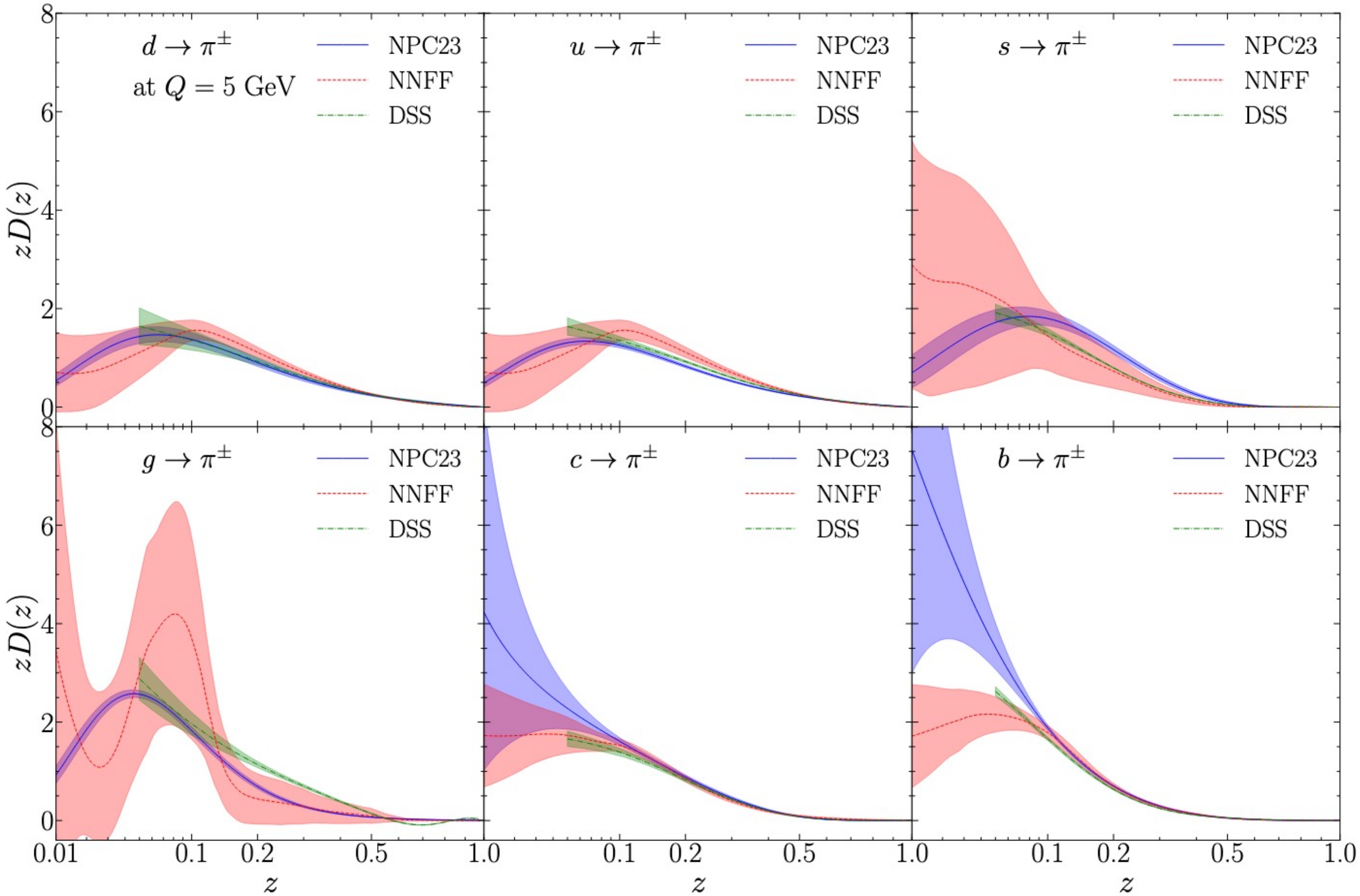
		Polarization	Depolarization
Twist 2	Boer-Mulders	UU	B
	Sivers	UT	1
	Transversity	UT	B/A
	Kotzinian-Mulders	UL	B/A
	Wormgear (LT)	LT	C/A
	Helicity DiFF $G_1^{\perp}$	LU	C/A
		UL	1
Twist 3	e(x)	LU	W/A
	$h_L(x)$	UL	V/A
	$g_T(x)$	LT	W/A

Suppressed at EIC

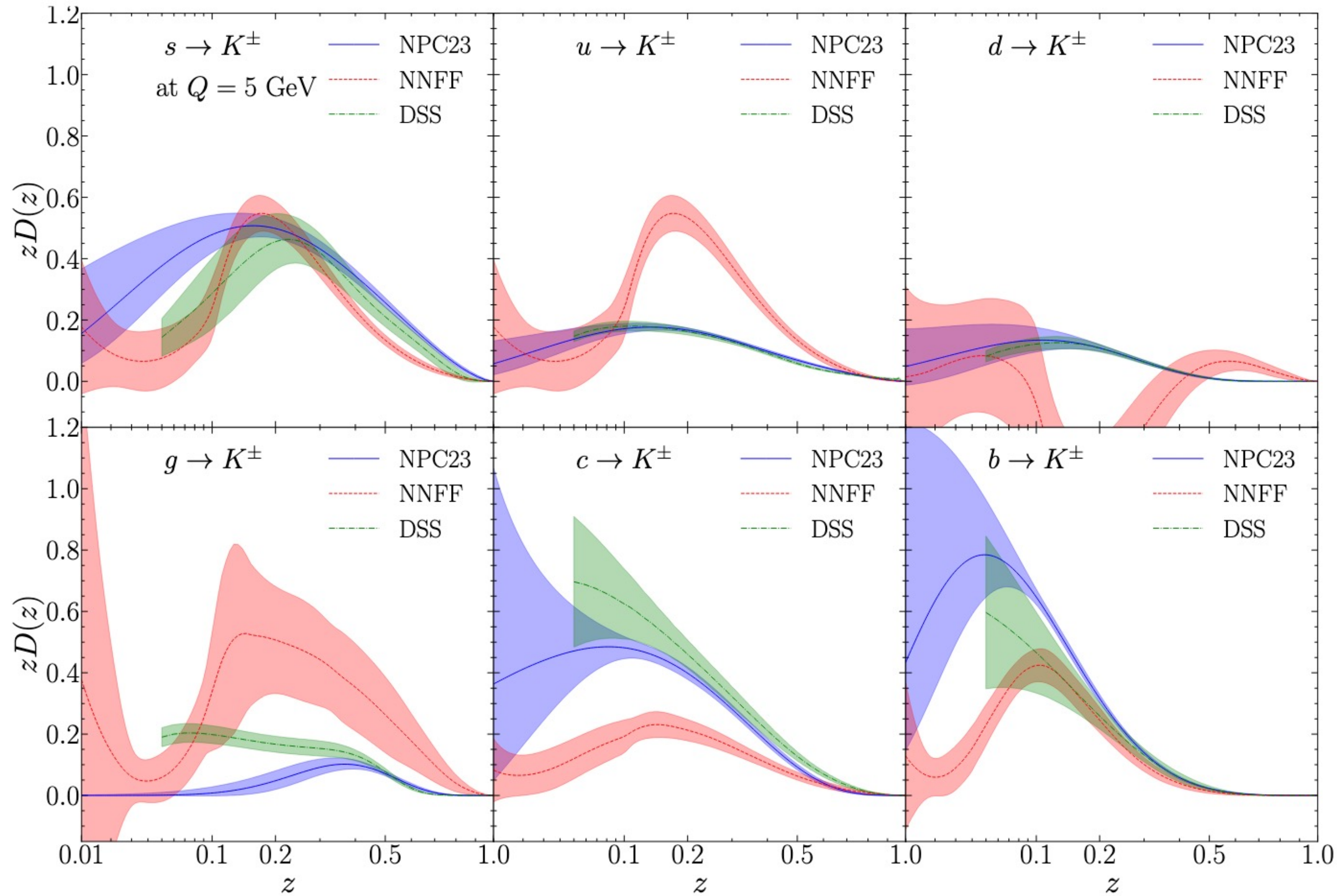
Slide from C. Dilks



$\bar{d} \to \pi^+$
at $Q = 5$ GeV
$u \to \pi^+$
$\bar{u} \to \pi^+$
$g \to \pi^+$
$c \to \pi^+$
$b \to \pi^+$
NPC23
JAM
MAP
$zD(z)$
z
0.01
0.1
0.2
0.5
1.0

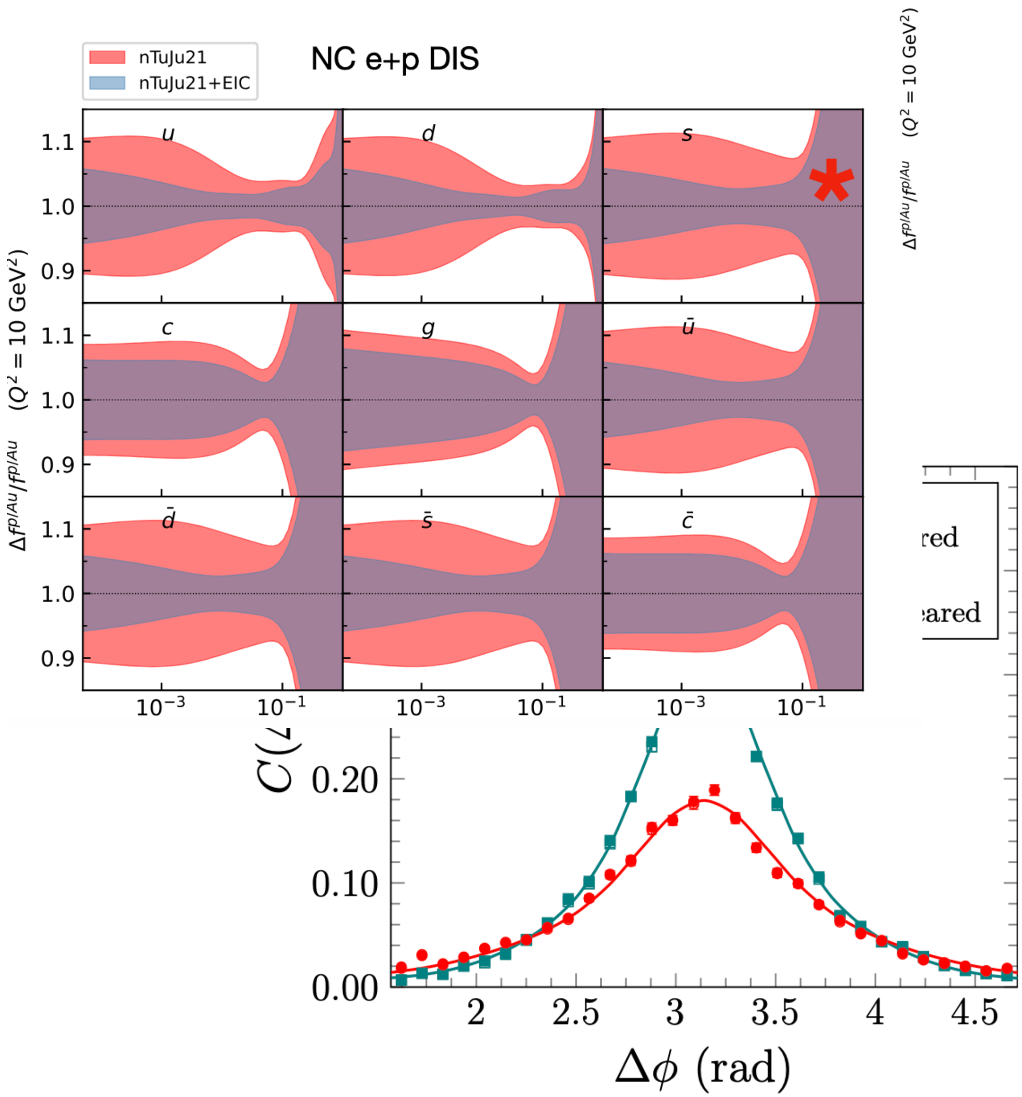


$d \to \pi^{\pm}$
at $Q = 5$ GeV
$u \to \pi^{\pm}$
$s \to \pi^{\pm}$
$g \to \pi^{\pm}$
$c \to \pi^{\pm}$
$b \to \pi^{\pm}$
NPC23
NNFF
DSS
$zD(z)$
z



From PR*D* 110 (2024) 11, 114019

Unpolarized PDFs



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	$f_T, f_T^{\perp}$	$g_T, g_T^{\perp}$	$h_T, e_T, h_T^{\perp}, e_T^{\perp}$

S. Diehl

twist-3 pdf, unpolarized PDF, twist-3 t-odd PDF, Boer-Mulders

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

Collins FF, twist-3 FF, unpolarized FF

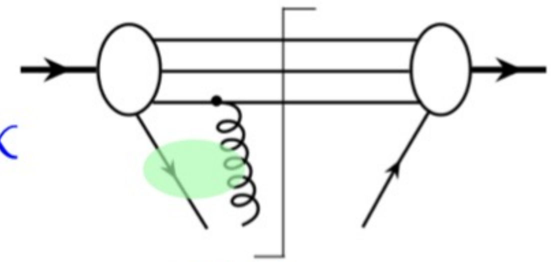
Beyond the parton picture

- 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

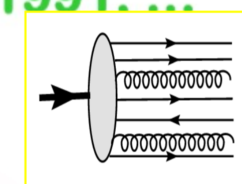
One persons ‘complication’ is another person's signal…

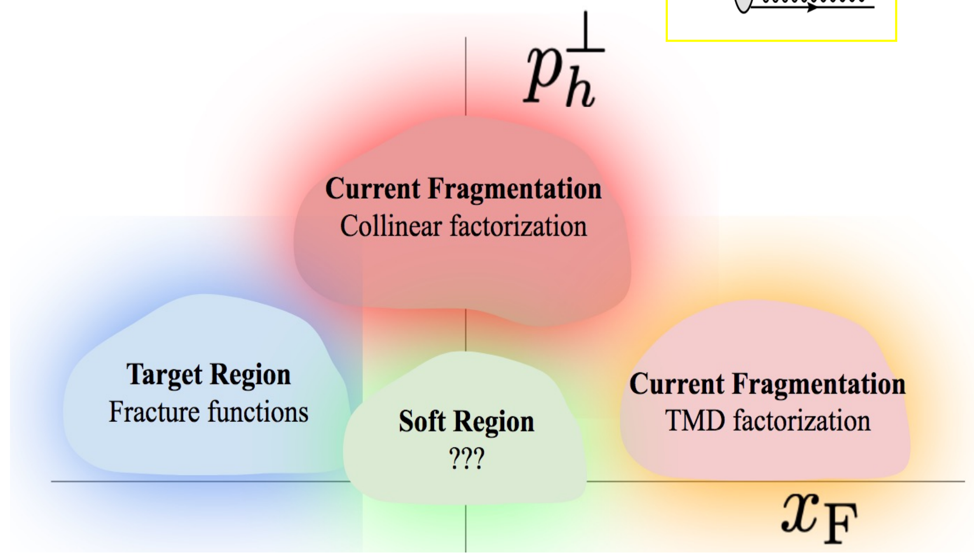
➔Need high lumi, leverarm in kinematics to disentangle various contributions

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



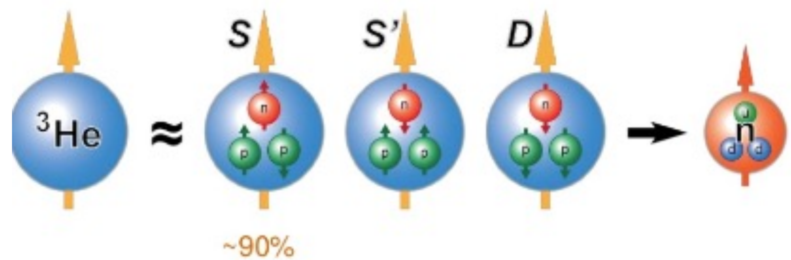
Qiu, Sterman, 1991, …

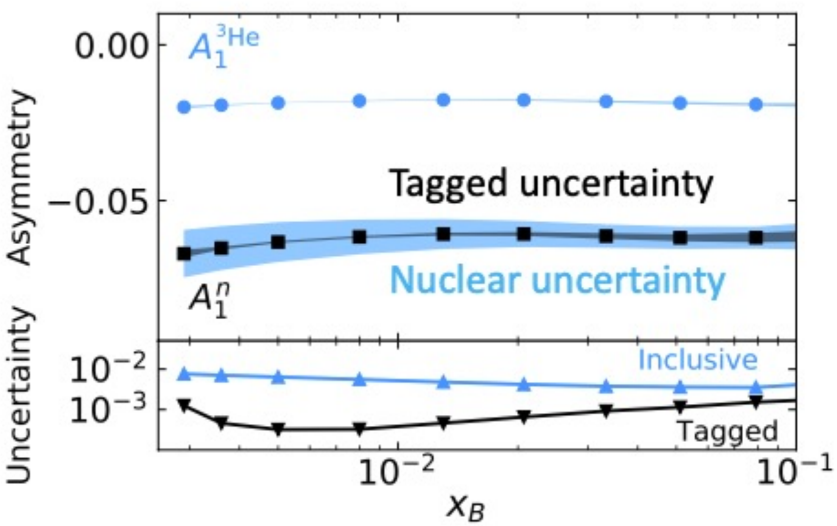


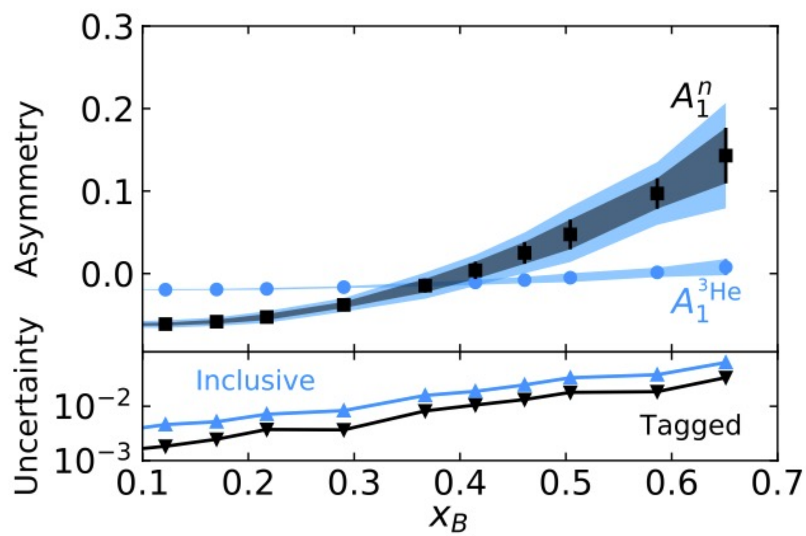


He^3 Double Tagging at the EIC allows clean neutron measurement

- 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

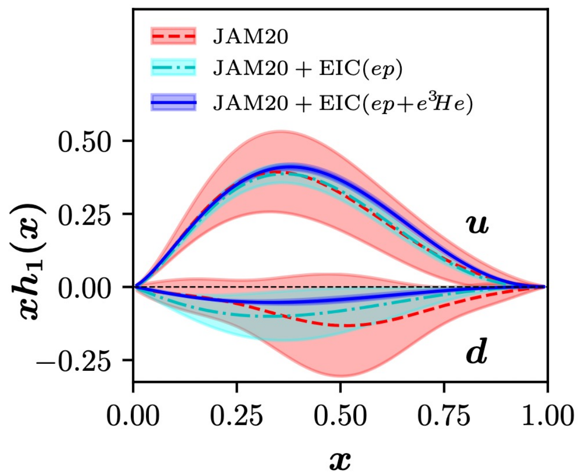


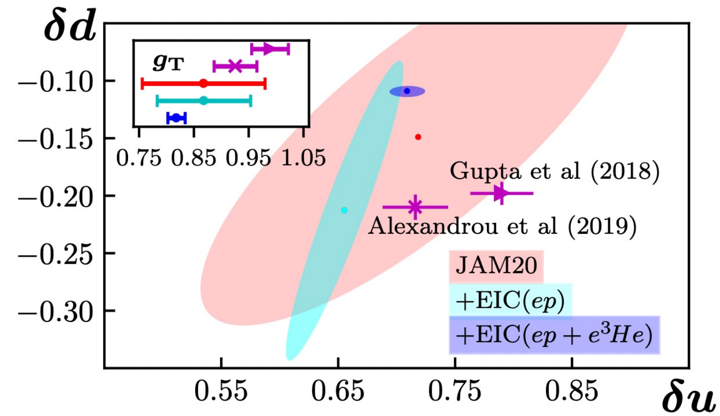


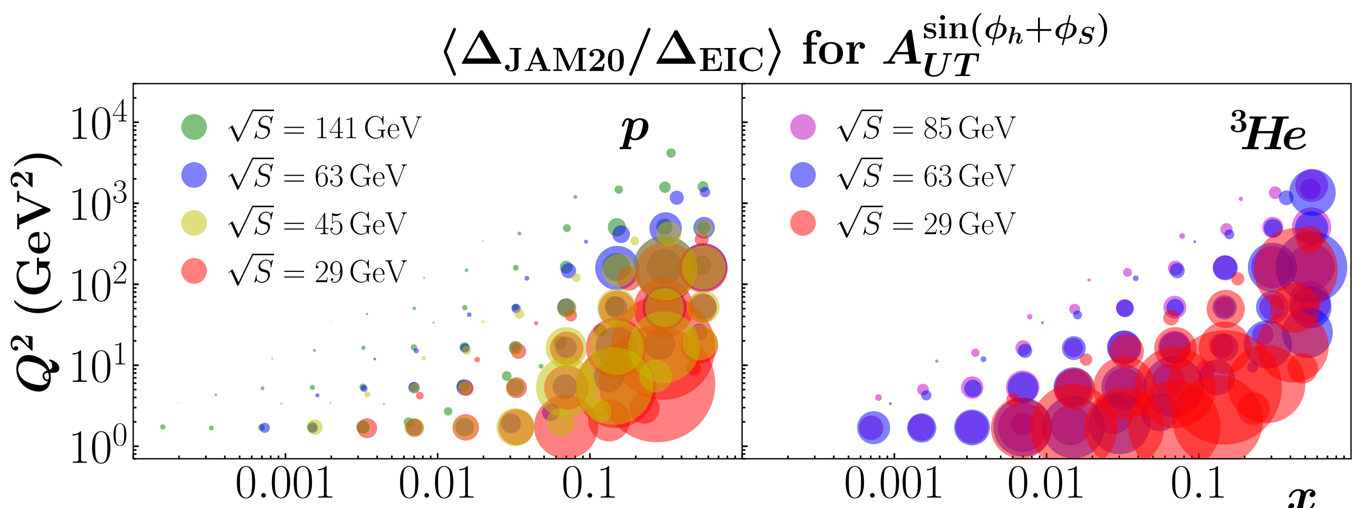


Friščić, I, Nguyen, D, Pybus, JR, Jentsch et al

Example: transversity extraction from Jlab and the EIC







But careful with parametrization bias…

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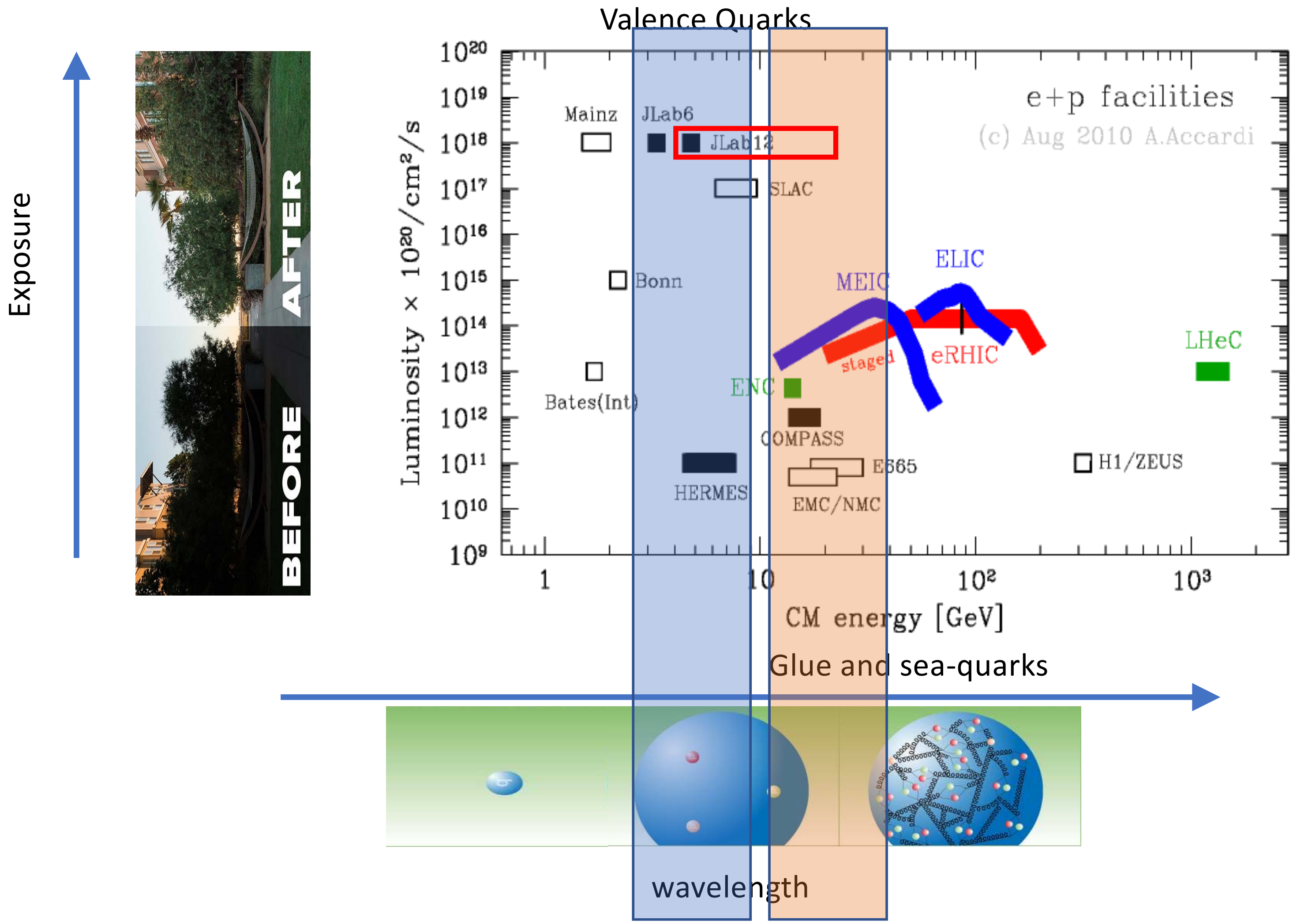
What makes the EIC era?



To extract 3D structu
Need luminosity

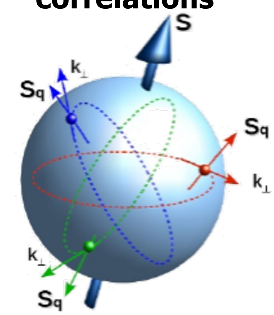
Luminosity + DIS Kinematics =
Precision tests of QCD, 3D structure of the nucleon

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

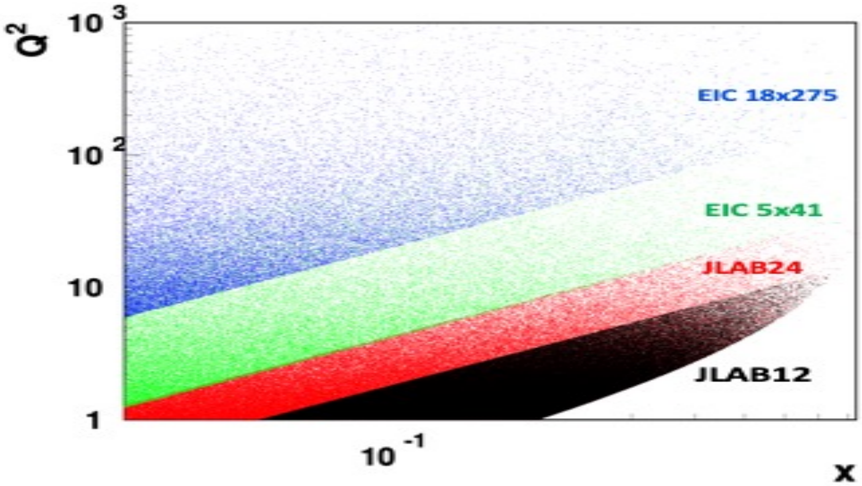
N \ q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

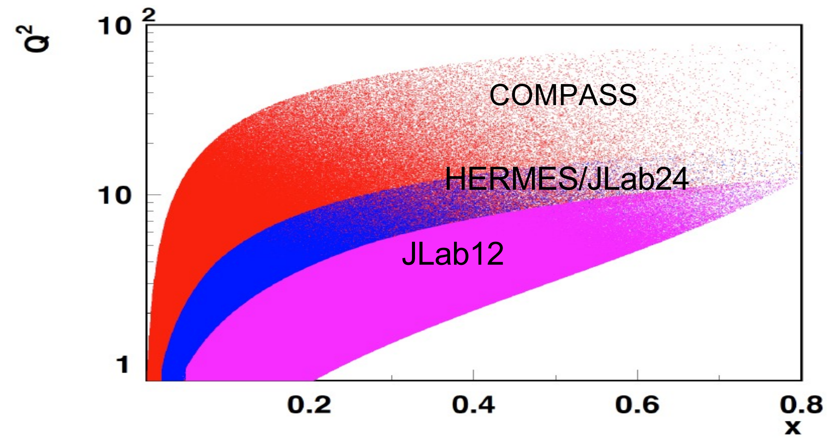
- In addition to the spin-spin correlations can have spin momentum correlations!

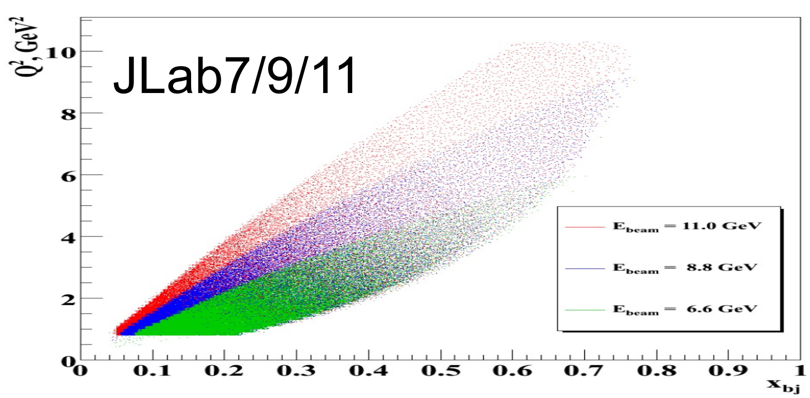
Spin-orbit correlations

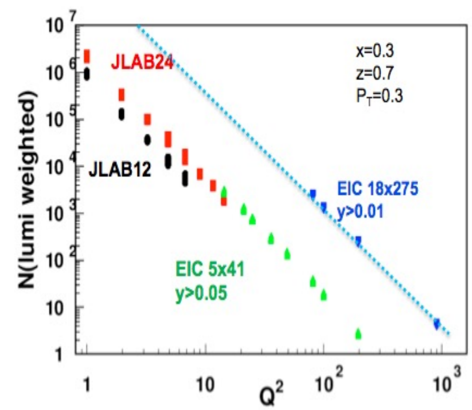


Kinematic comparisons





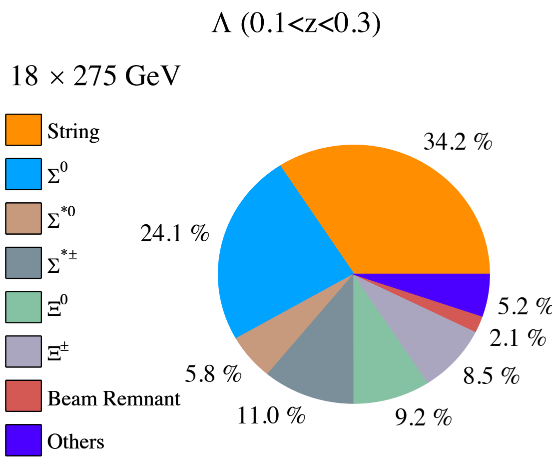




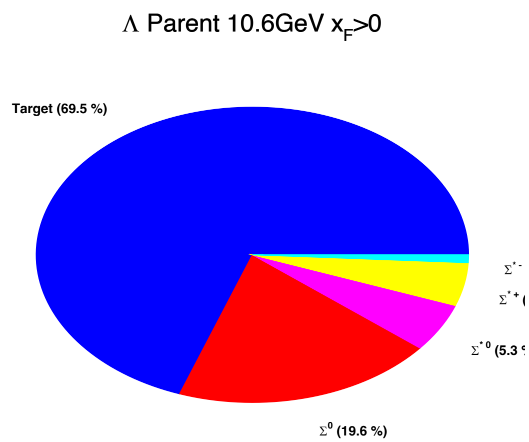
NB: Kinematic slice heavily biased towards Jlab

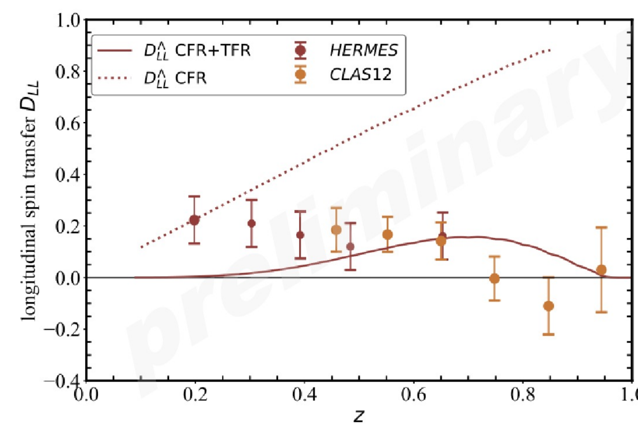
Lambda feed-down composition vs JLab20

EIC



JLAB12





Xiaoyan Zhao at S

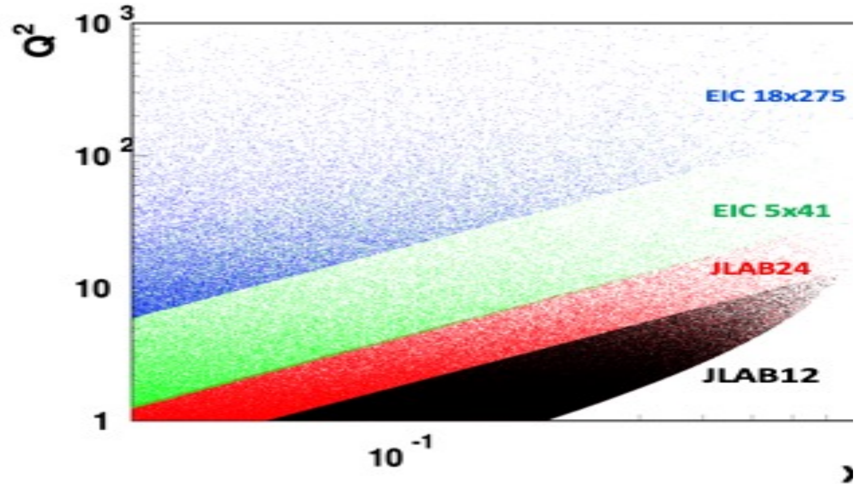
Study by M. McEneaney(Duke)
JLab22 similar

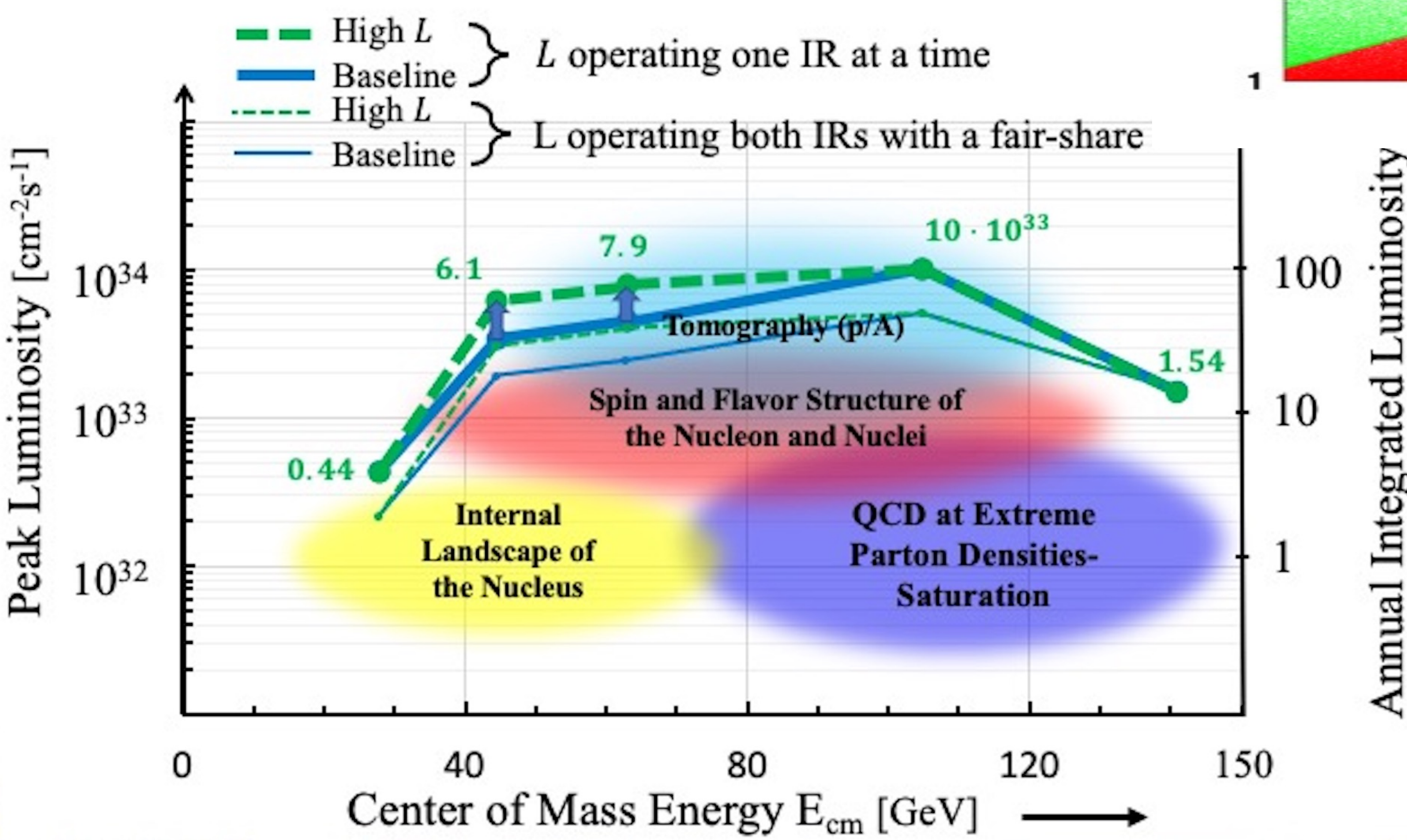
- Possible to unfold at the EIC (not so much at Jlab)
- ML methods might help

The TMD factorization formula receives corrections which enter in terms of powers of δ ~ PhT /z/Q.

$$\frac{d\sigma^{\rm SIDIS}}{dx_B dQ^2 d^2\mathbf{P}_{h_T}} \propto x \sum_i e_i^2 \int d^2\mathbf{p}_T\, d^2\mathbf{k}_T\, \delta^{(2)}(\mathbf{p}_T - \mathbf{k}_T - \mathbf{P}_{h_T}/z)\, \omega_i(\mathbf{p}_T, \mathbf{k}_T) f_i(x, p_T^2) D_{h/i}(z, k_T^2) \equiv \mathcal{C}\left[\omega f D\right] ,$$

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





Wide Coverage