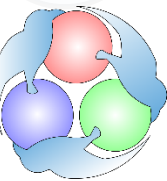


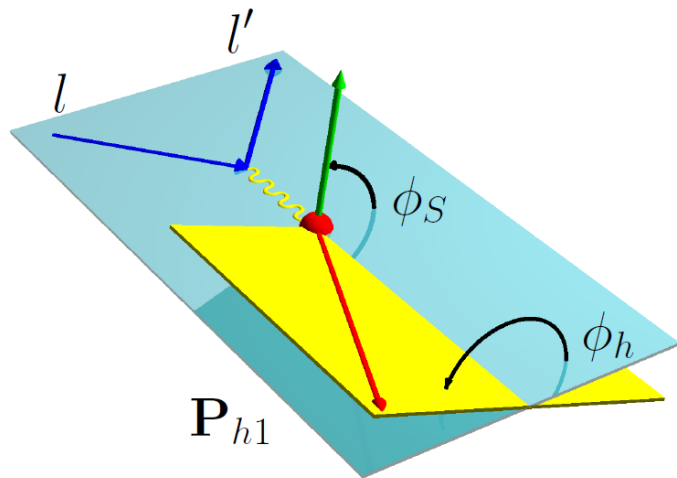
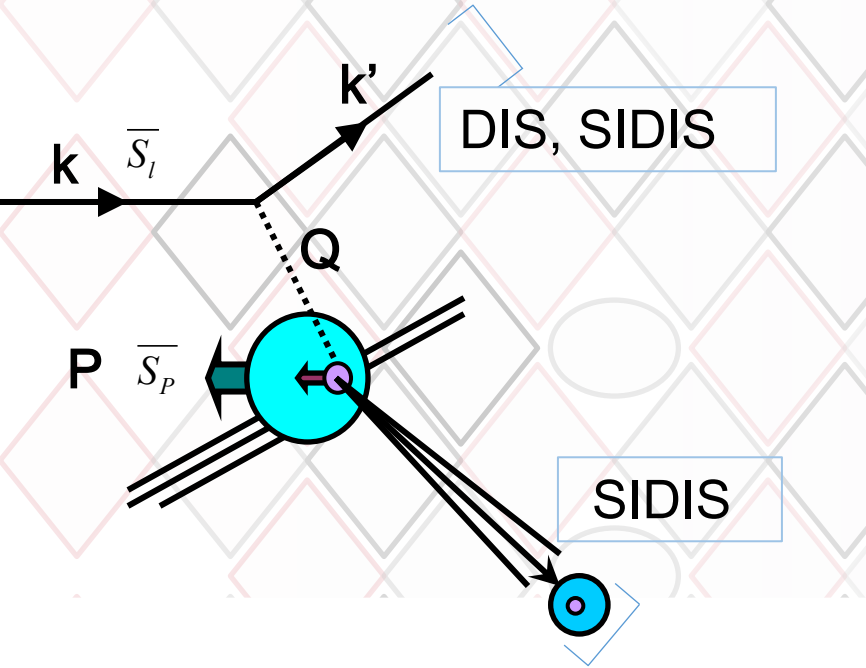
Sivers/Collins pseudo- data and figures

6/2/2026

Ralf Seidl (University of Tokyo QNSI)



SIDIS Kinematics

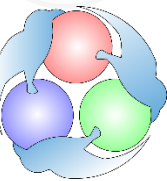


Detect also final-state hadron(s): Additional benefit of **flavor, spin and transverse momentum sensitivity** via Fragmentation functions

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

- z : Fractional hadron momentum wrt to parton momentum ($0 < z < 1$)
- P_{hT} : transverse hadron momentum wrt to virtual photon (convolution over intrinsic transverse momenta of PDFs and FFs)
- 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 $u \rightarrow \pi^+$, $d \rightarrow \pi^-$, $s \rightarrow K^-$, etc)
- Transverse momentum and angles rely also on correct boost to hadron rest system



Transverse Spin and TMDs

TMD: transverse momentum dependent distribution and fragmentation functions, all except f_1, g_1 and h_1 cancel upon integration over k_T

		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 = \odot$		$h_1^\perp = \uparrow \ominus - \downarrow \ominus$
	L		$g_1 = \odot \rightarrow - \ominus \rightarrow$	$h_{1L}^\perp = \uparrow \rightarrow - \downarrow \rightarrow$
	T	$f_{1T}^\perp = \uparrow \odot - \downarrow \ominus$	$g_{1T} = \uparrow \rightarrow - \downarrow \rightarrow$	$h_1 = \uparrow \uparrow - \downarrow \uparrow$ $h_{1T}^\perp = \uparrow \odot - \downarrow \odot$

- Transversity

$$h_{1,q}(x)$$



- Sivers Function

$$f_{1T,q}^\perp(x, k_T)$$



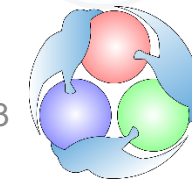
- Boer Mulders function

$$h_{1T,q}^\perp(x, k_T)$$



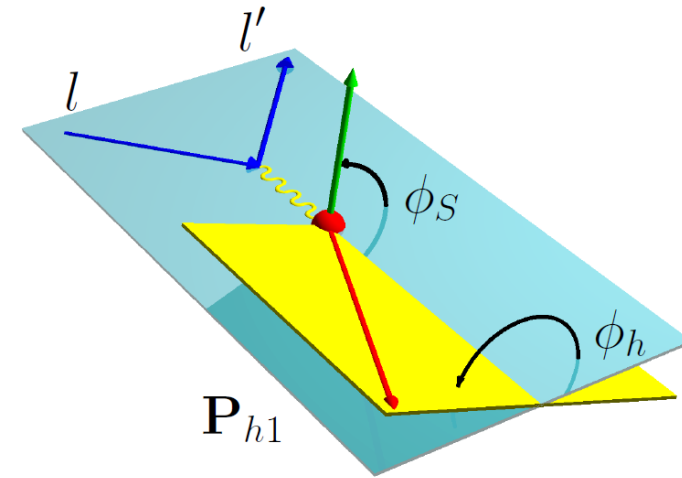
Closely related:

- Higher Twist correlations (TMD moments) $T_F(x, x)$
- TMD FFs (Collins, polarizing FFs, etc) $H_{1,q}^{\perp(1)}(z)$



Experimental access to Transversity/tensor charge and Sivers function

- Both functions are accessible as different azimuthal modulations in transversely polarized SIDIS of single hadrons
- Reweight events according to true parton flavor q , hadron h , x , z , Q^2 , P_{hT} , azimuthal angles and random spin orientation
- Input structure functions (Collins, Sivers and unpolarized) from Torino global fits (arXiv:0812.4366, arXiv:0805.2677) as in <https://github.com/prokudin/tmd-parametrizations/>
- Currently no partonic event record for $e^+{}^3\text{He}$ → all weights are unity (zero asymmetries) → will be fixed for with next simulations
- For $e^+{}^3\text{He}$ currently only tagging on the truth level → need to implement reconstructed tagging (but effi+purity high accd to W.Lin's study)



$$A_{UT}^{\sin(\phi_h + \phi_S)}(x, z, P_T) \propto \mathbf{S}_T \frac{\sum_{q, \bar{q}} e_q^2 \delta q(x, k_t) \otimes H_1^\perp(z, p_t)}{\sum_{q, \bar{q}} e_q^2 q(x, k_t) \otimes D_1(z, p_t)}$$

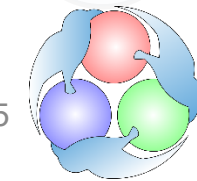
$$A_{UT}^{\sin(\phi_h - \phi_S)}(x, z, P_T) \propto \mathbf{S}_T \frac{\sum_{q, \bar{q}} e_q^2 f_{1T}^{\perp, q}(x, k_t) \otimes D_1(z, p_t)}{\sum_{q, \bar{q}} e_q^2 q(x, k_t) \otimes D_1(z, p_t)}$$

Binning and data

Species	Energy	Q^2 range	M events	Luminosity (fb^{-1})	ES Luminosity (fb^{-1})
e+p	10x250	1 - 10	4.97	0.007	1.25
e+p	10x250	10 - 100	4.97	0.083	
e+p	10x250	100 - 1000	4.99	2.256	
e+p	10x250	1000 - 10000	0.50	18.975	
e+p	10x130	1 - 10	4.96	0.008	0.5
e+p	10x130	10 - 100	4.98	0.105	
e+p	10x130	100 - 1000	4.97	3.425	
e+p	10x130	1000 - 10000	0.50	62.686	
e+ ³ He	10x166	2 - 10	4.94	0.024	0.75
e+ ³ He	10x166	10 - 100	4.96	0.116	
e+ ³ He	10x166	100 - 10000	4.98	3.138	

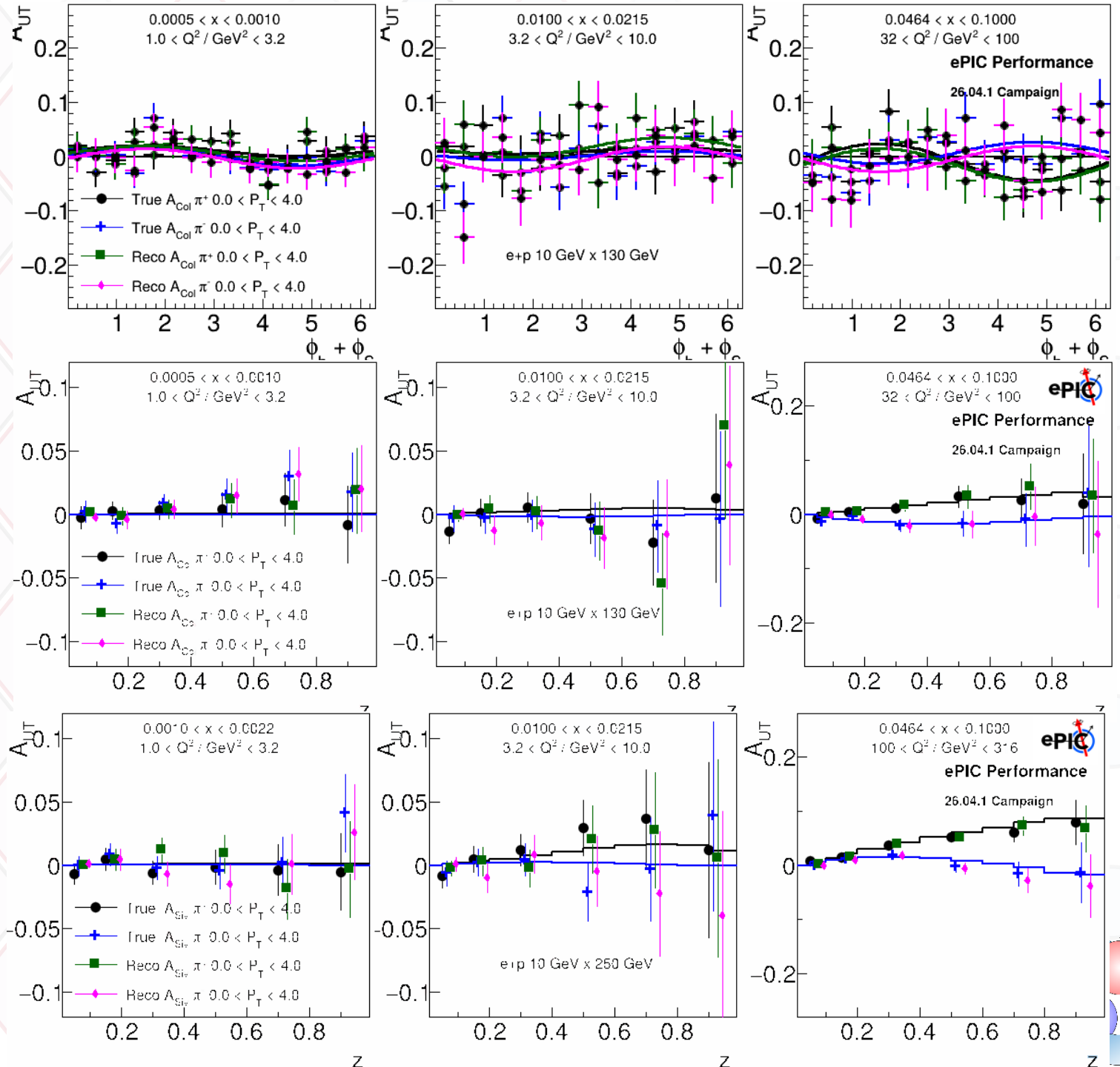
- 26.04.1 Campaign
- Pythia6/BeAGLE simulations
- InclusiveKinematicsElectron method used/or calculated from ScatteredElectronAssociations
- DIS Cuts:
 - $Q^2 > 1 \text{ GeV}^2$
 - $W^2 > 10 \text{ GeV}^2$
 - $0.01 < y < 0.95$
- True pions and Kaons used, assuming that PID can be sufficiently unfolded

	Kinematic variable	Bin boundaries
12, 3 per decade	x	$1.0 \times 10^{-4}, 2.154 \times 10^{-4}, 4.641 \times 10^{-4}, 1.0 \times 10^{-3}, 2.154 \times 10^{-3}, 4.641 \times 10^{-3}, 1.0 \times 10^{-2}, 2.154 \times 10^{-2}, 4.641 \times 10^{-2}, 1.0 \times 10^{-1}, 2.154 \times 10^{-1}, 4.641 \times 10^{-1}, 1.0 \times 10^0$
8, 2 per decade	Q^2	$1.0 \times 10^0, 3.162 \times 10^0, 1.0 \times 10^1, 3.162 \times 10^1, 1.0 \times 10^2, 3.162 \times 10^2, 1.0 \times 10^3, 3.162 \times 10^3, 1.0 \times 10^4$
12	z	0,0.05,0.1,0.15,0.2,0.3,0.4,0.5,0.6,0.7,0.8,0.9,1.0
12	P_T	0,0.05,0.1,0.2,0.3,0.5,0.7,0.9,1.2,1.5,1.8,2.4,4.0

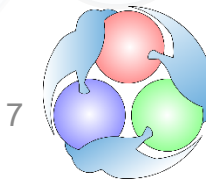
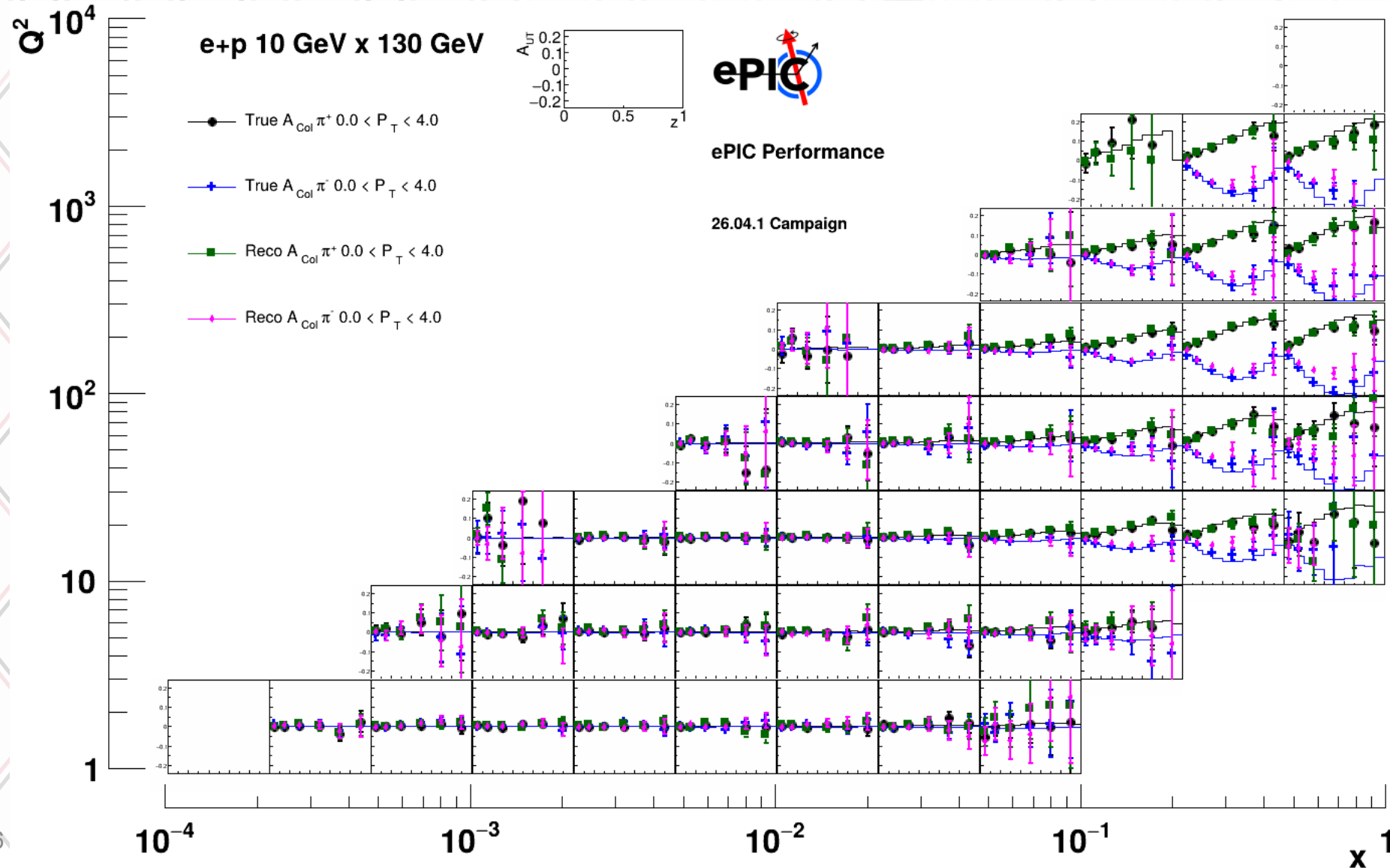


Example Asymmetries

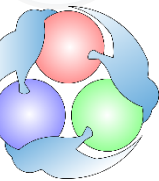
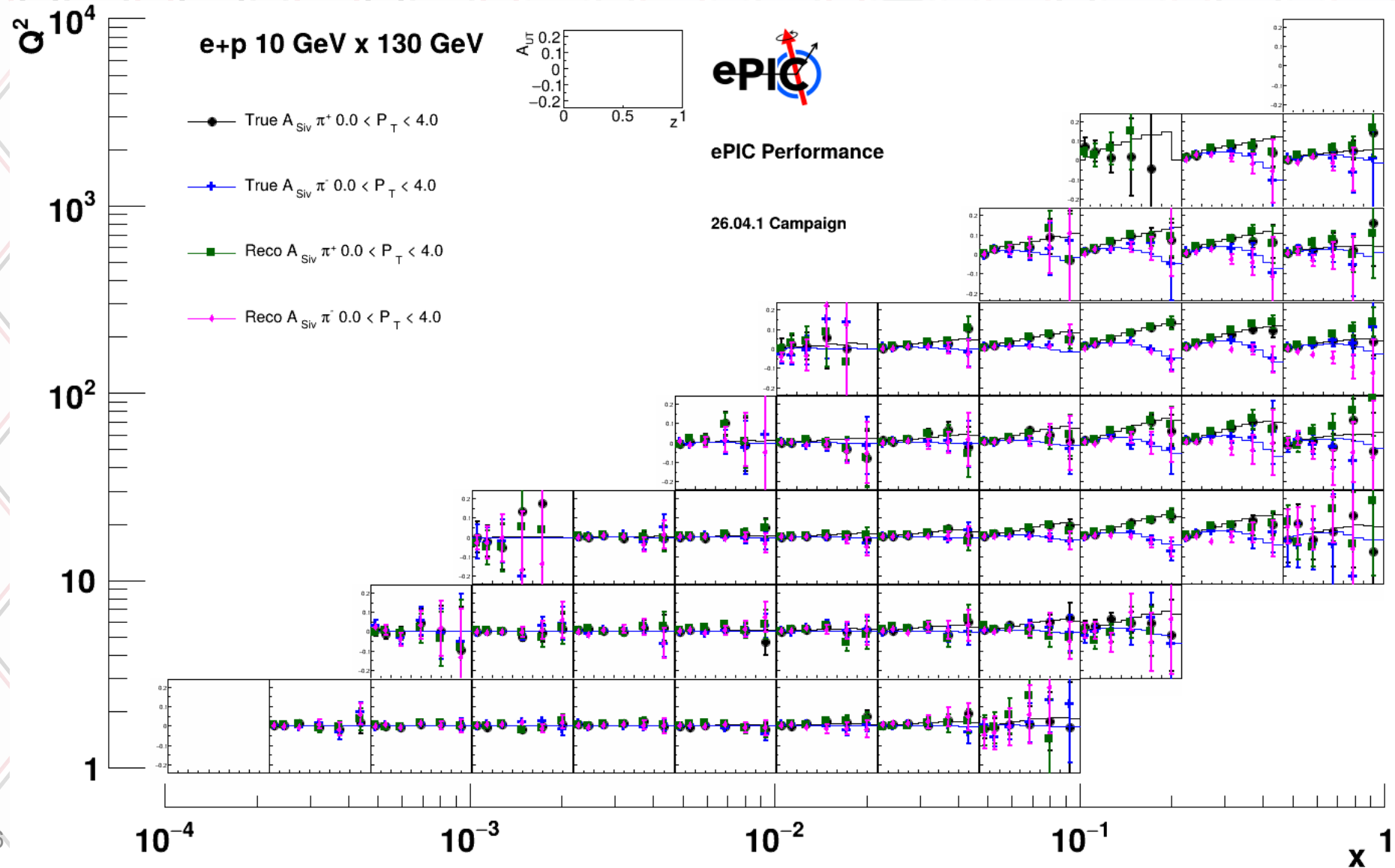
- Examples in 3 x and Q^2 bins: on top for the Collins angular combination for charged pions true and reconstructed in an intermediate z bin
- Lower figures: Collins, Sivers projected vs z (integrated over P_{hT} bins)
- Histograms: nominal true weights



Collins Asymmetries vs z (integrated over P_{hT})

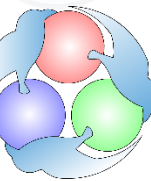
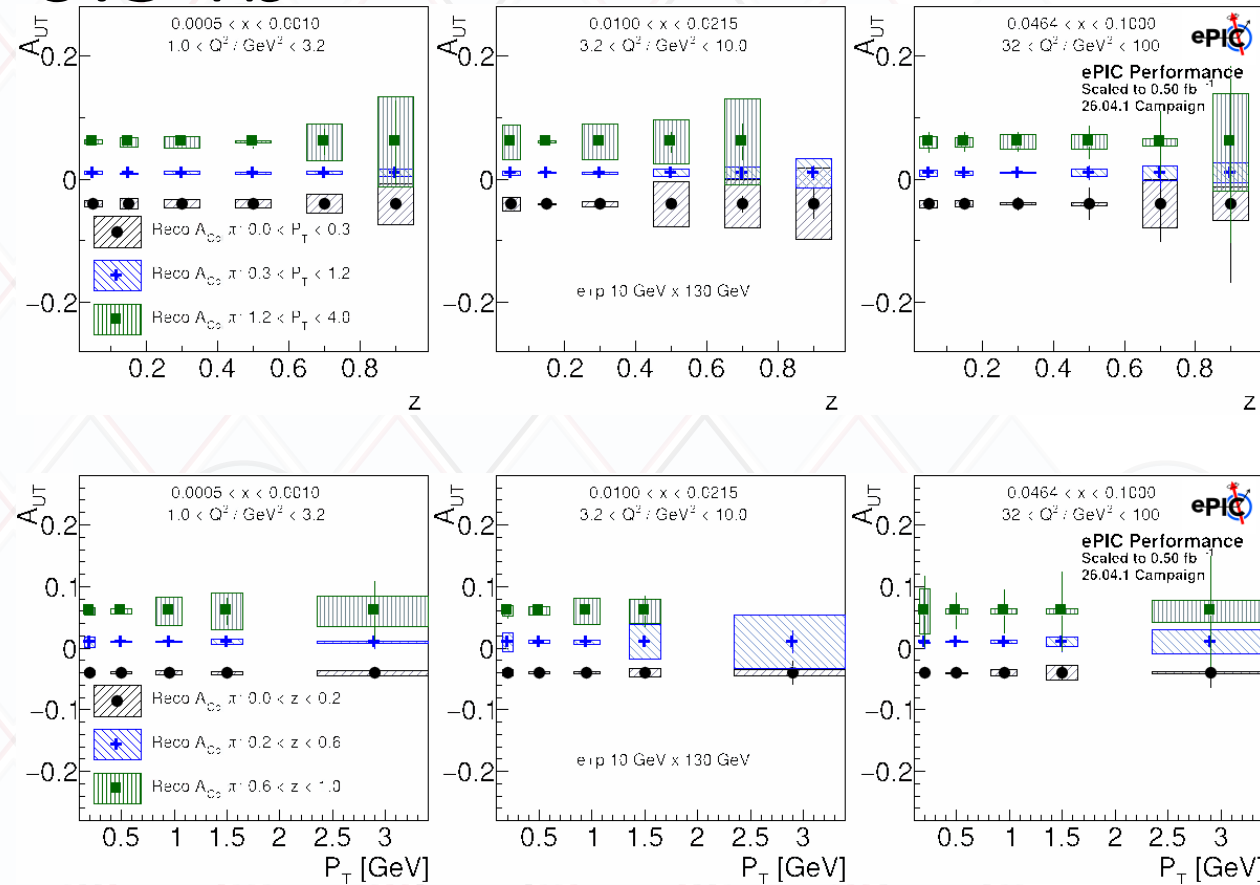


Sivers asymmetries



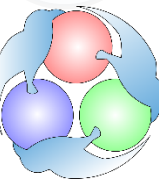
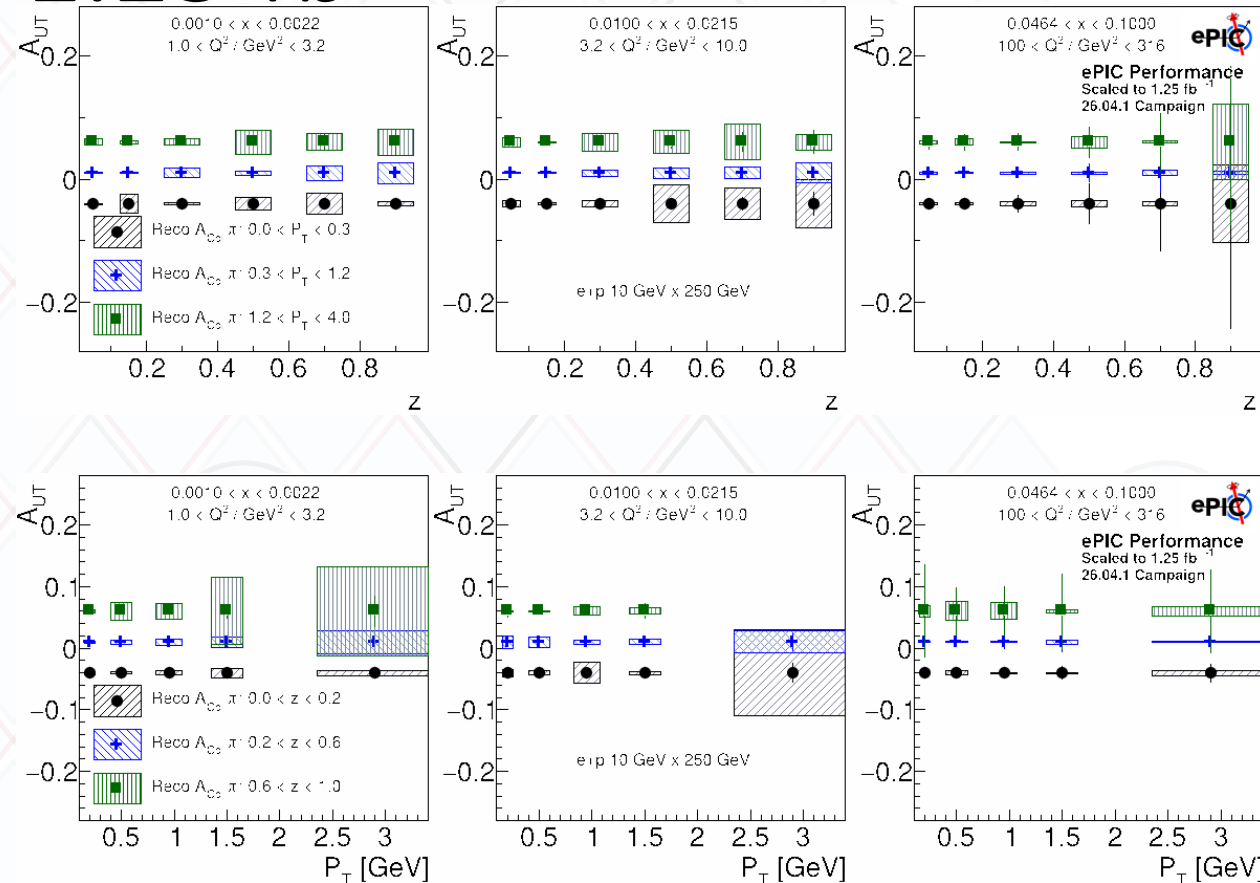
Projections (10x130) to 0.5 fb^{-1}

- Systematic uncertainties estimated from differences between true and reconstructed asymmetries \rightarrow they are likely largely overestimated since most of the kinematic smearing would be unfolded, but give a sense of where uncertainties still might be larger due to that unfolding



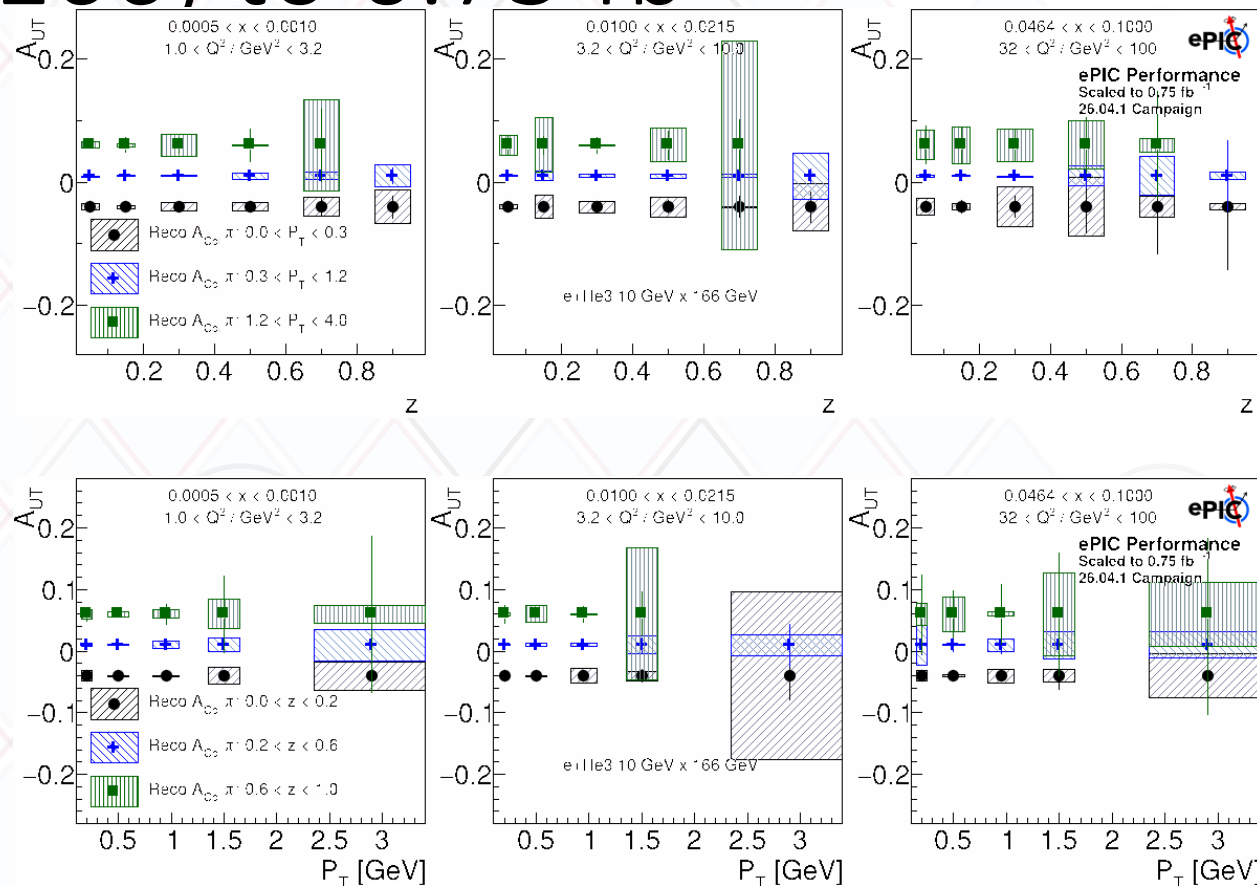
Projections (10x250) to 1.25 fb^{-1}

- Systematic uncertainties estimated from differences between true and reconstructed asymmetries \rightarrow they are likely largely overestimated since most of the kinematic smearing would be unfolded, but give a sense of where uncertainties still might be larger due to that unfolding

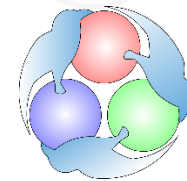


Projections (e+3He 10x166) to 0.75 fb⁻¹

- Systematic uncertainties estimated from differences between true and reconstructed asymmetries → they are likely largely overestimated since most of the kinematic smearing would be unfolded, but give a sense of where uncertainties still might be larger due to that unfolding

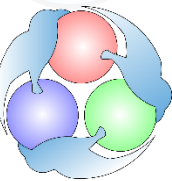
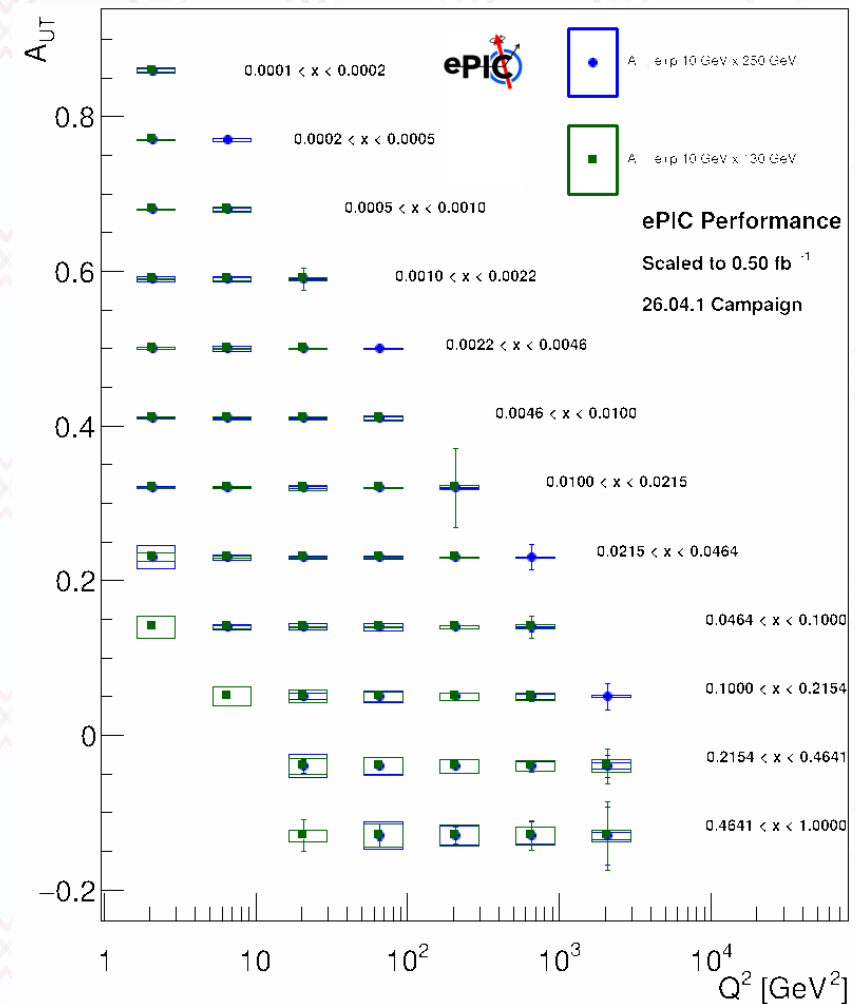


Due to tagging, essentially e+n

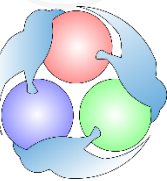
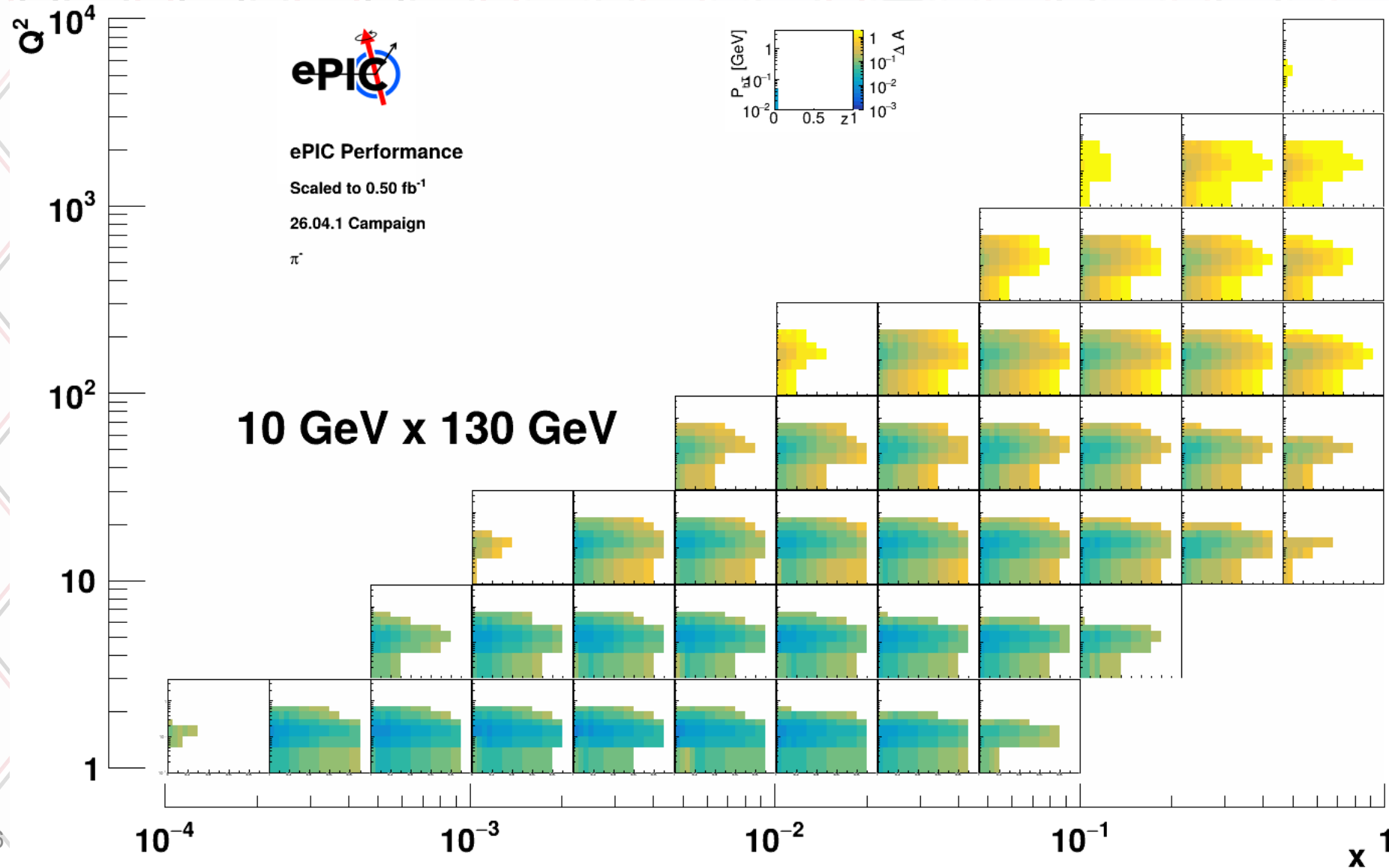


Scale dependence (and interplay of collision energies ESR)

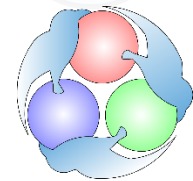
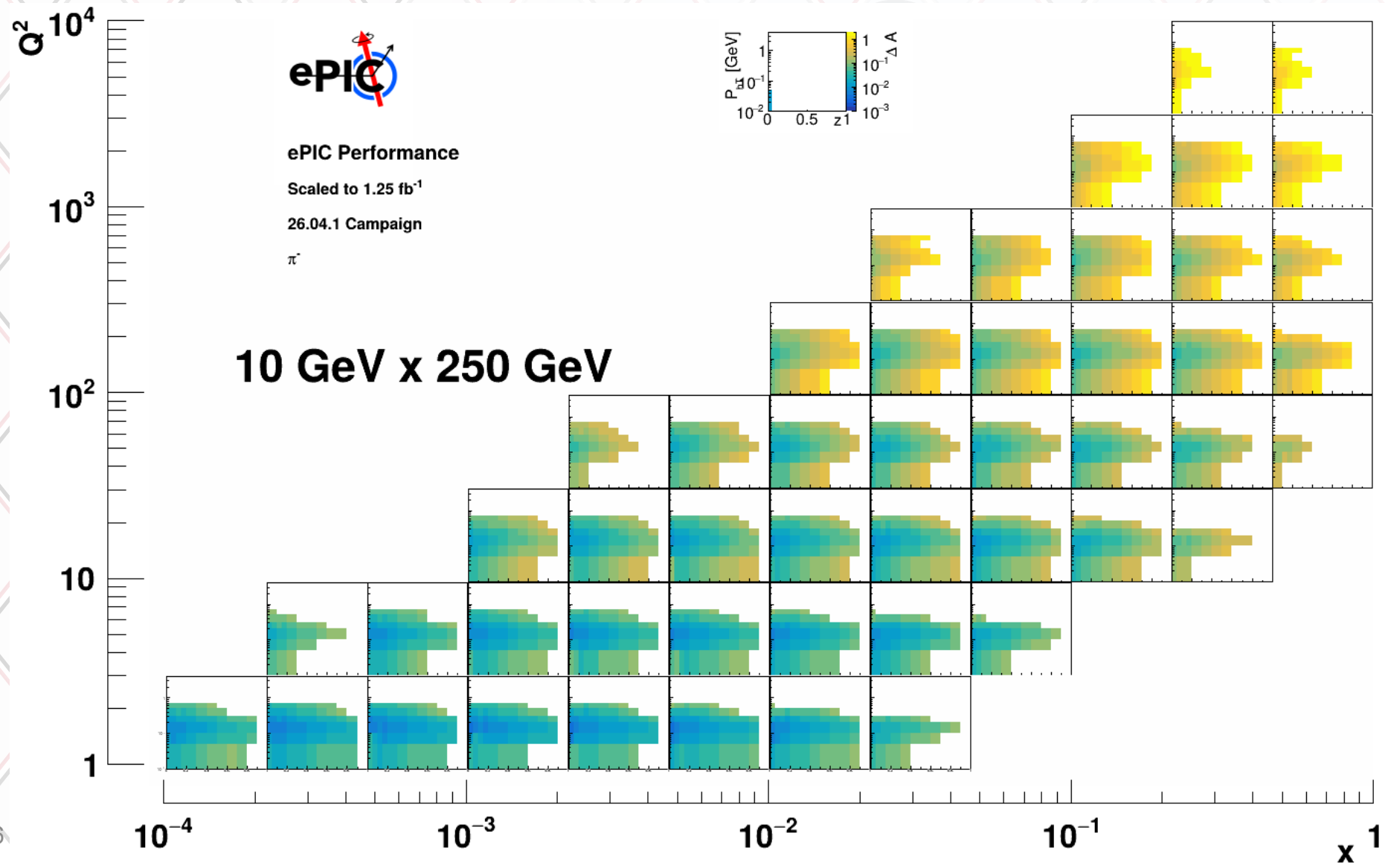
- An example of the expected uncertainties in x and Q^2 to study the scale dependence of the Sivers/Collins asymmetries (as TMD evolution is not very well known/contains other nonperturbative pieces)
- Even ESR energies show overlap and lever arm
- Note: in future evolution analysis likely more Q^2 bins and maybe not as fine x binning



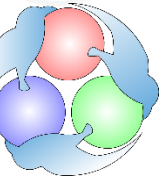
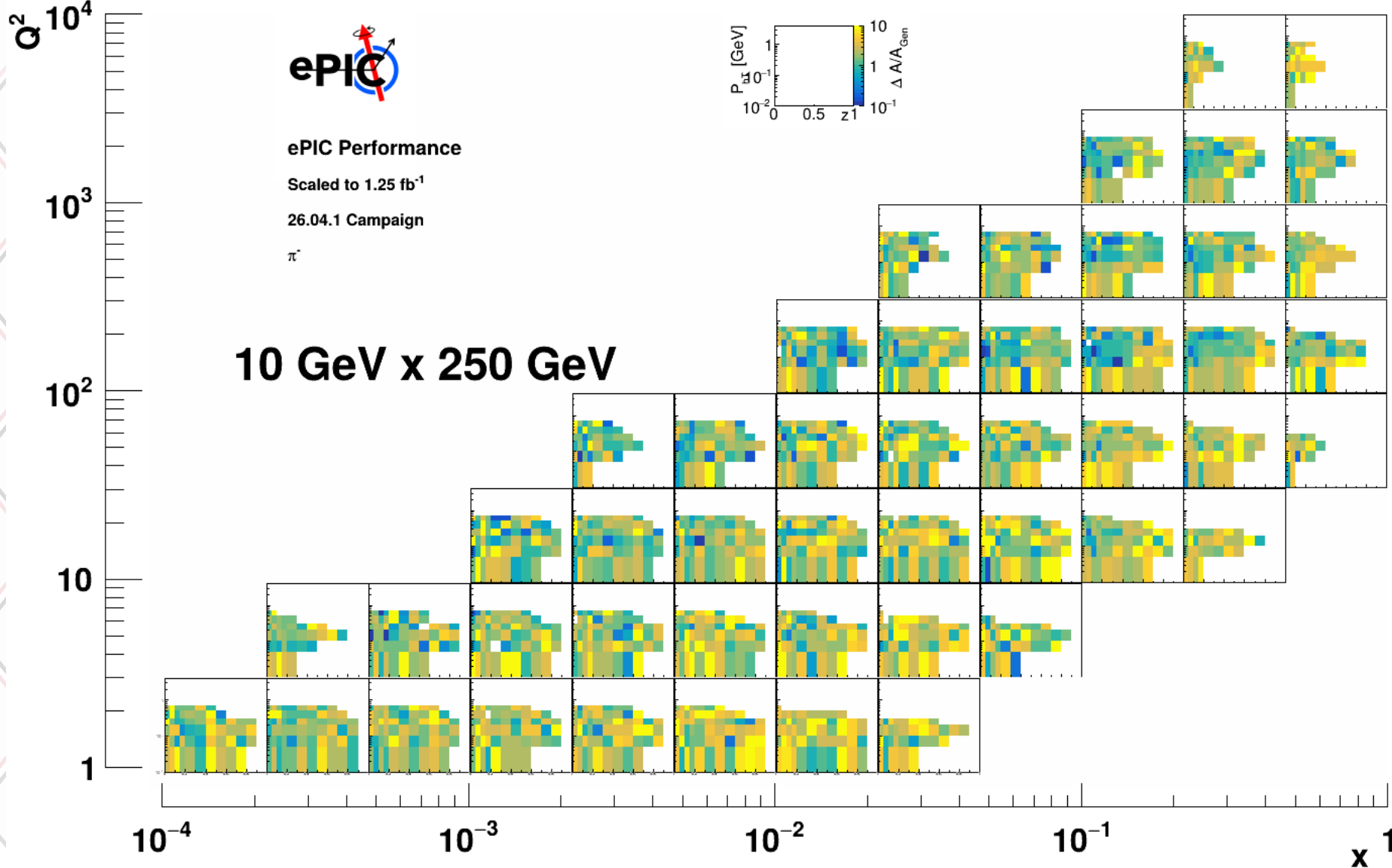
Statistical uncertainties as function of x, Q^2, z, P_{hT}



Statistical uncertainties as function of x, Q^2, z, P_{hT}

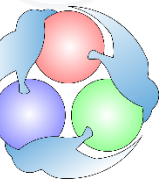
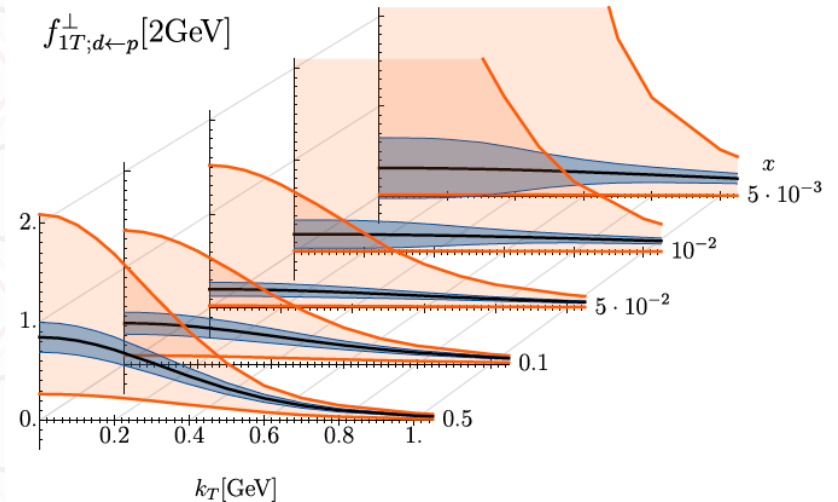
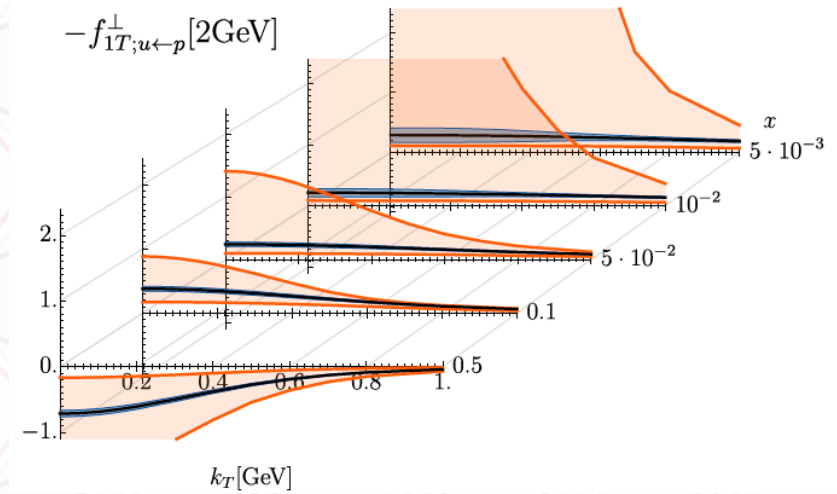


“systematics” for these measurements as function of x, Q^2, z, P_{hT}



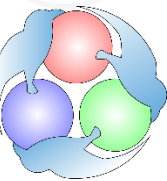
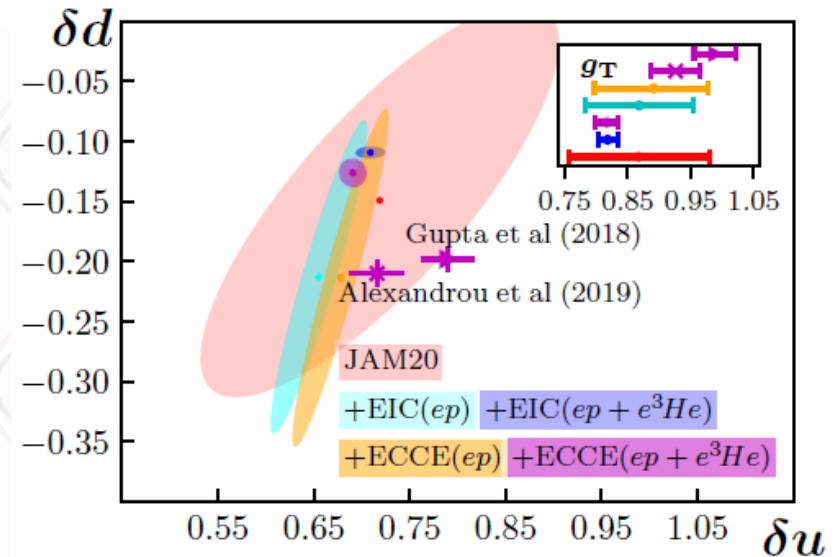
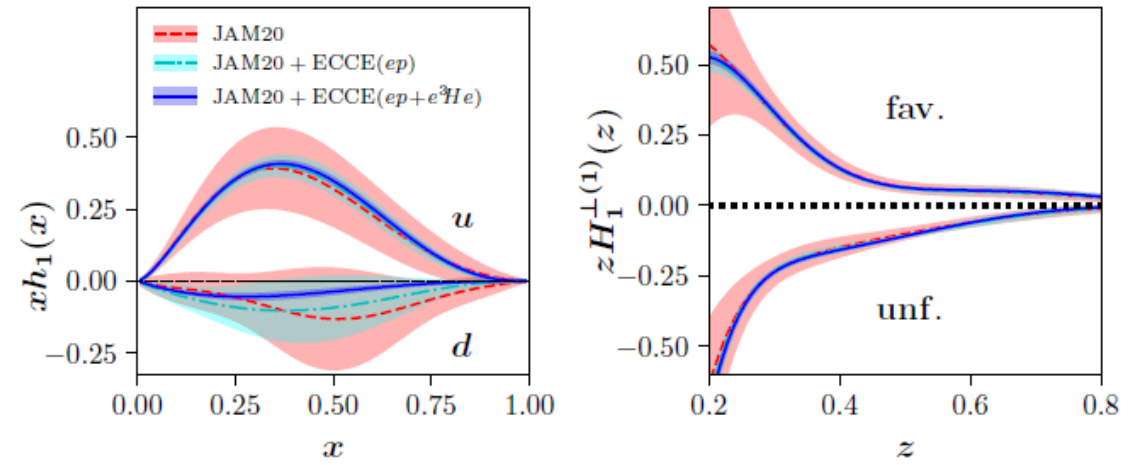
Need new Impact for Sivers functions

- Similar to YR impact studies following the latest BPV global fit (arXiv:2103.03270) for the Sivers function based on the existing SIDIS +DY data
- Uncertainties are shown for current level of knowledge on up/down Sivers functions at various x vs k_T and expected impact from ECCE



Need new impact for Tensor charges

- Similar to [Gamberg et al Phys.Lett.B 816 \(2021\) 136255](#) (for YR) use fitting code from latest global fit Cammarota et al arXiv:2002.08384 to extract impact on Transversity, Collins functions and tensor charges
- Together with projected JLAB12 data precision to compare with Lattice results (and check for possible discrepancies)



Outlook

- Provided the pseudo-data to JAM group (Pitonyak and Prokudin) and Alexey Vladimirov for impact studies
- Hope that A.Prokudin adds more parameterizations + uncertainties to code such that one can see impact already on asymmetry level
- Fix beam energies when available
- Fix ^3He asymmetry weighting when available
- Include reco tagging of ^3He , provide tagged/non-tagged comparison of weighted asymmetries

