SIDIS
at the Electron Ion Collider

Taiwan EIC workshop, NCU,

December 9, 2022,

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SIDIS Measurements

Spin of the nucleon:

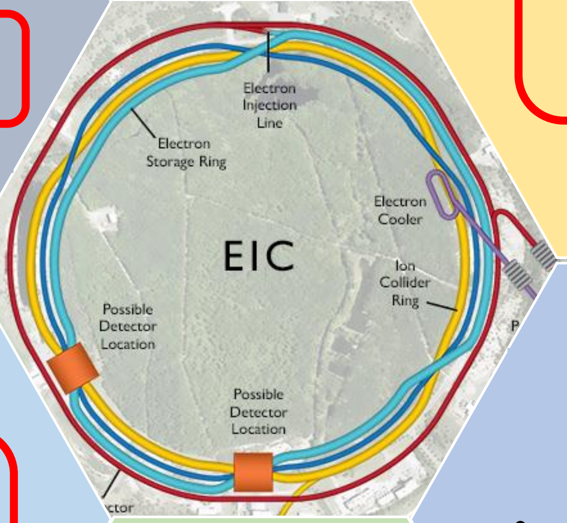
- Gluon spin
- Role of Sea quarks

QCD at high gluon densities

- Saturation effects

Tomography :

- 3D momentum structure (q, g Sivers, Tensor charge, TMD Evolution)
- 3D spatial structure



Nucelar effects

- Nuclear PDFs
- Passage of color through nuclear matter (nFFs, pT broadening)

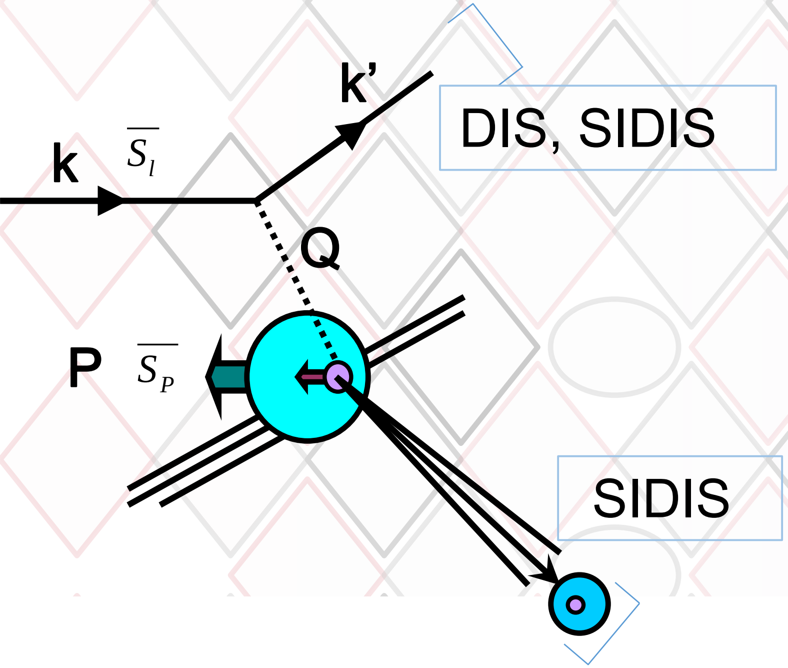
Origin of the Mass

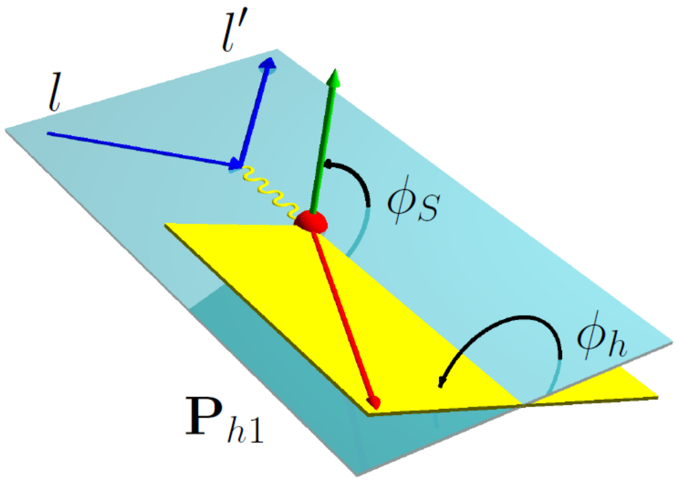
- Axial anomaly contributions
- Hadron structure

Other

- Spectroscopy (XYZ)
- EW physics
- Fragmentation
- Unpol PDFs

SIDIS Kinematics





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

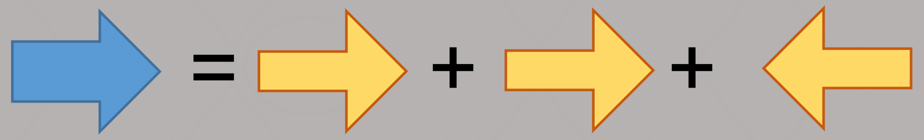
$$\frac{d^6\sigma}{dx dQ^2 dz dP_{hT} d\phi_S d\phi_h} \overset{LO}{\propto} \sum_{q,\bar{q}} e_q^2 q(x, Q^2, k_t) \otimes D_{1,q}^h(z, Q^2, p_t)$$

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→π^+ , d→π^-, s→K^- , etc)
- Transverse momentum and angles rely also on correct boost to hadron rest system

The Spin sum rule

Naïve Quark Model picture: 3 valence quarks make up the spin of the nucleon:



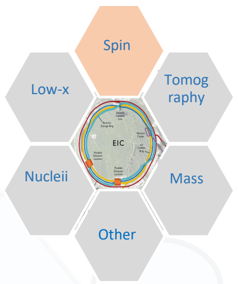
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$ Jaffe, Manohar

Quark spin — Gluon spin — Orbital angular momentum

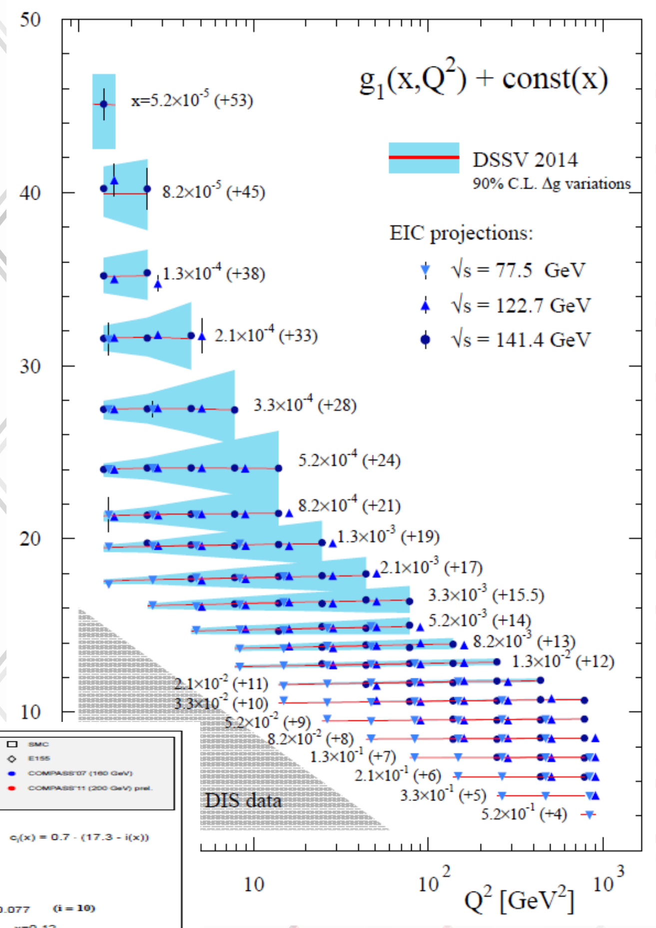
$$\Delta\Sigma = \int dx \left[(\Delta u(x) + \Delta\bar{u}(x)) + (\Delta d(x) + \Delta\bar{d}(x)) + (\Delta s(x) + \Delta\bar{s}(x))\right]$$

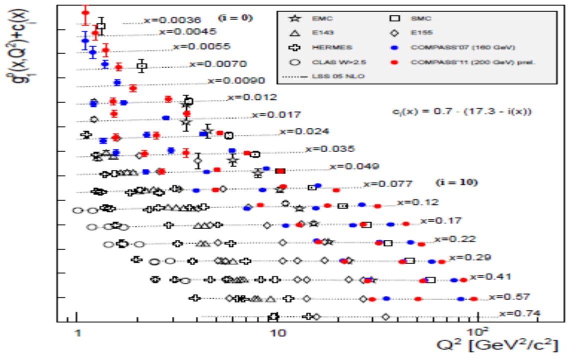
- Spin Crisis (1980s): Quark spin contributes only little
- $\Delta\Sigma$ and ΔG can be accessed in longitudinally polarized (SI)DIS and pp collisions (currently for x>0.01)
- Where is the rest of the spin? Gluons? Lower momentum fractions? Orbital angular momentum?

Inclusive DIS and $\Delta g(x)$

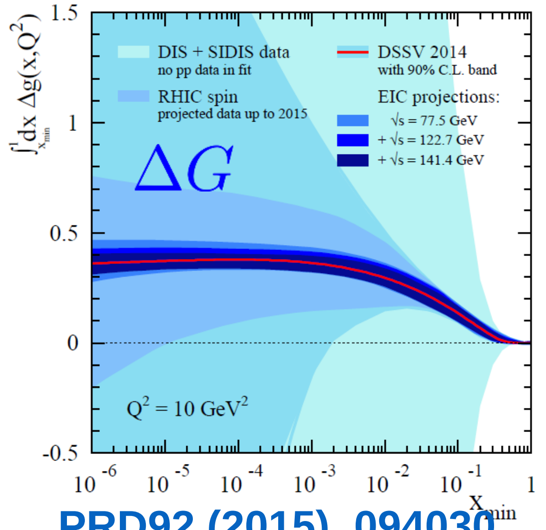


- Currently no lever arm to access gluon helicities via DIS (lepton-proton scattering)
- Nonzero gluon polarization found from 200/510 GeV RHIC data
- EIC: Several orders of magnitude of Q^2 at same x allows to determine gluon helicity via DGLAP (scale) evolution





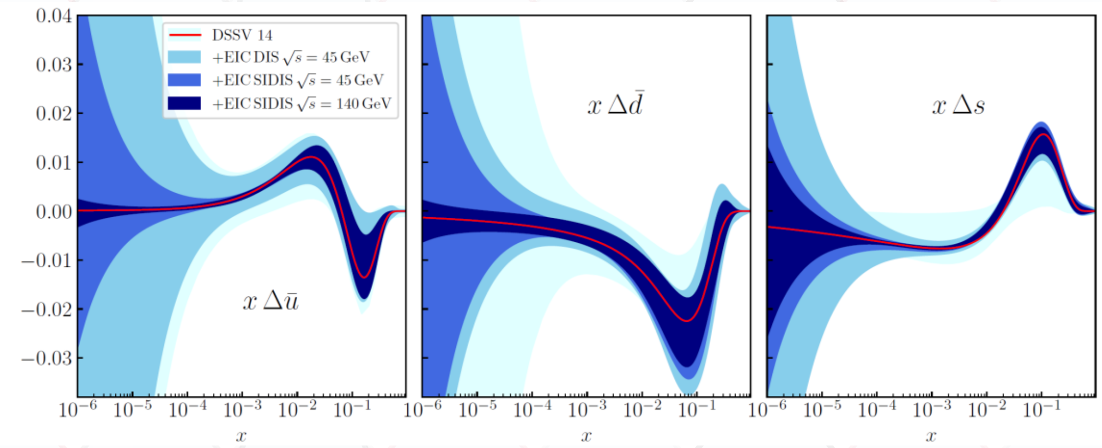
PRD92 (2015), 094030

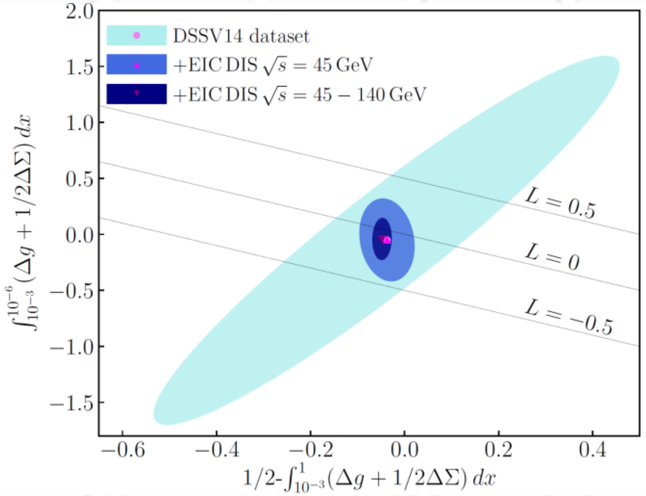


PRD92 (2015), 094030

Gluon and sea polarization

- 1 year of EIC running will pin down gluon polarization
- Using SIDIS:
  - precise determination of sea quark helicities via pion and kaon asymmetries
  - especially strange contribution of interest
- Indirect determination of orbital angular momentum via sum rule
- Also interesting access to flavor via charged current reactions





PRD 102 (2020), 094018

Transverse Spin

S.Pisano, Transversity 14

Nucleon Polarization		Quark polarization: Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
	U	$f_1 =$		$h_1^\perp =$
	L		$g_1 =$	$h_{1L}^\perp =$
	T	$f_{1T}^\perp =$	$g_{1T} =$	$h_1 =$ $h_{1T}^\perp =$

- Transversity

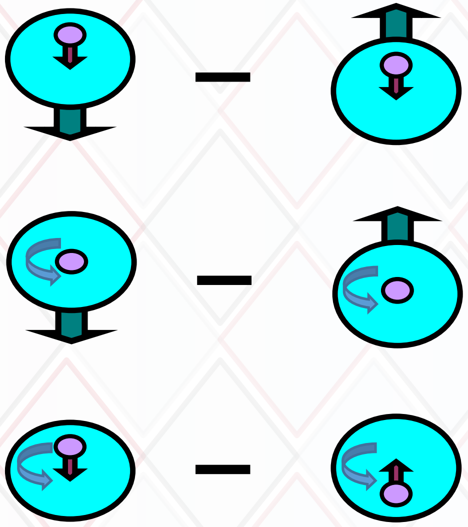
$h_{1,q}(x)$

- Sivers Function

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

- Boer Mulders function

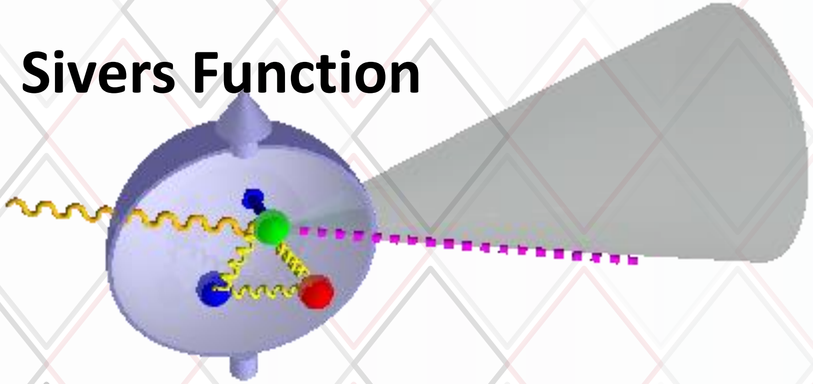
$h_{1T,q}^\perp(x, k_T)$



Closely related:

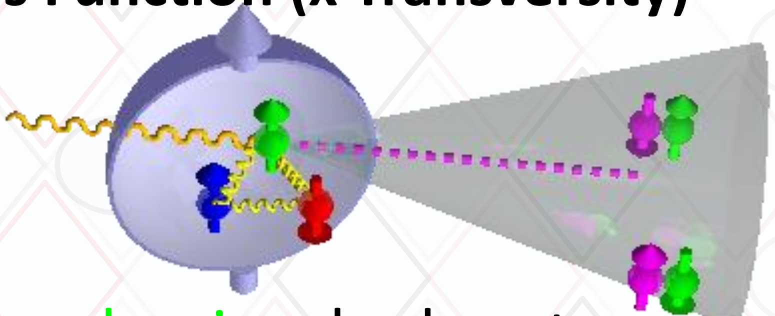
- Higher Twist correlations (TMD moments) $T_F(x,x)$
- TMD FFs (Collins, polarizing FFs, etc) $H_{1,q}^{\perp(1)}(z)$

Sivers Function

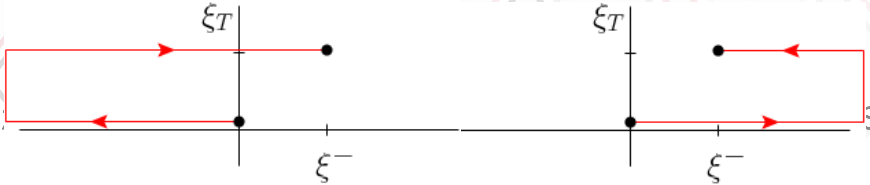


- Proton–spin – quark orbit (k_T) correlation
- Suggested in '93 – dead due to time reversal
- Brodsky-Hwang-Schmid '02 model example of Sivers function using gauge links
- Belitsky-Yuan '02 → gauge links generally needed
- Collins → function can exist, but modified universality (the SIGN change)

Collins Function (x Transversity)



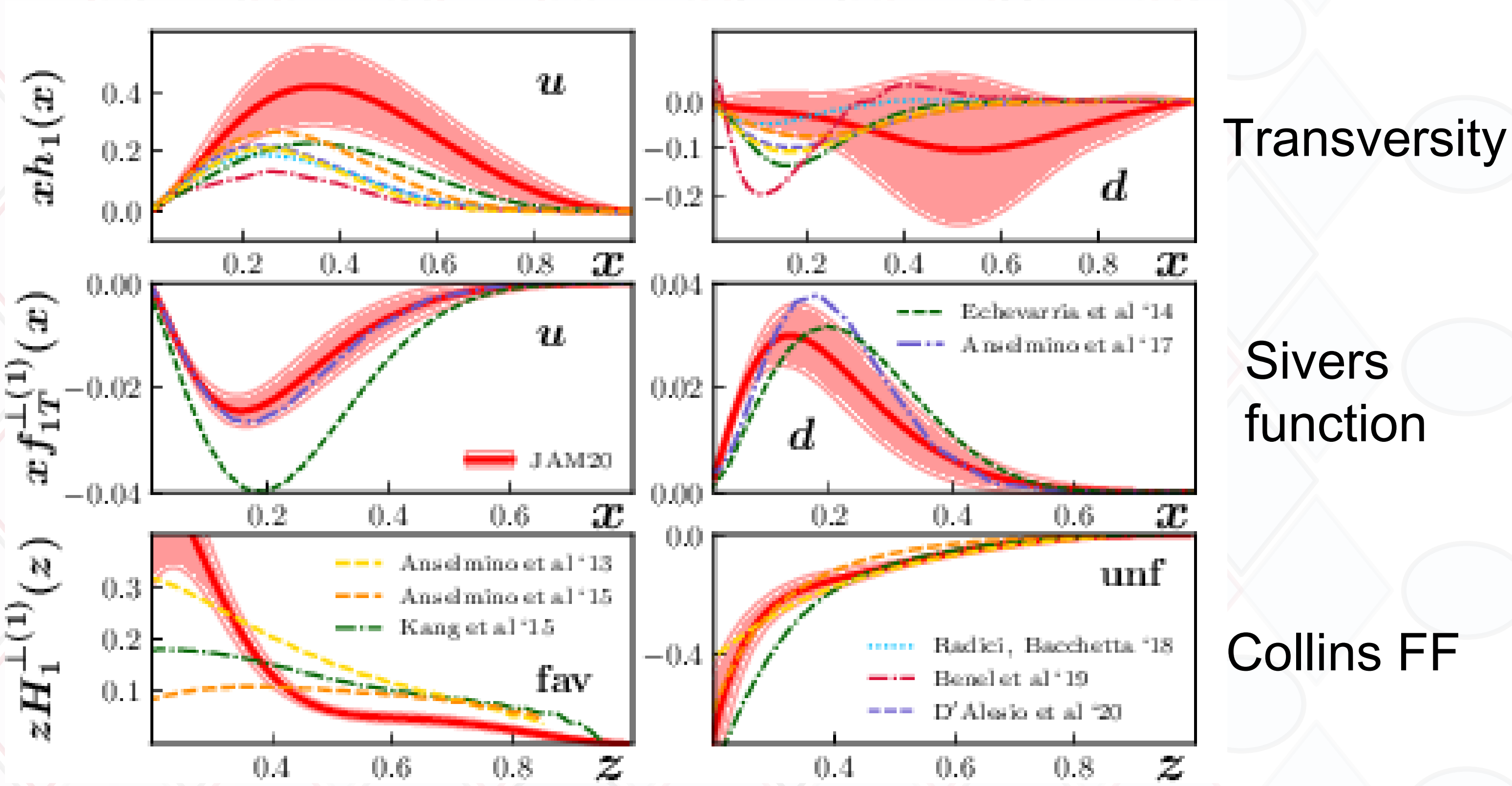
- Quark spin – hadron transverse momentum correlation (in fragmentation)
- Analyzer for quark transversity → access to tensor charge (Lattice, BSM?)
- A polarized (ie signed) fragmentation function
- Transverse momentum conservation requires some compensation (Terayev-Schaefer)



Figs from Buffing et al. : PRD 86 (2012) 074030

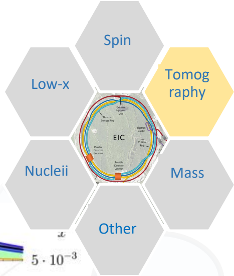
Current knowledge on these functions

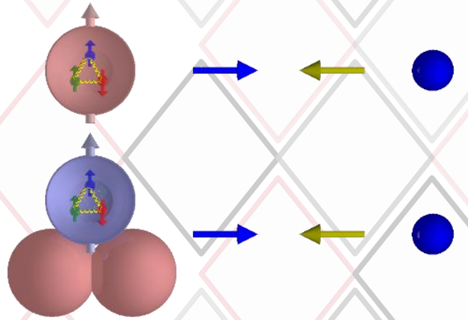
- Only valence quark Sivers and Transversity functions known at this time with substantial uncertainties
- Experimentally covered range 0.01 < x < 0.3
- So far no sensitivity to sea quarks and gluons* and lower x



Cammarota et al, PRD 102 (2020) 054002

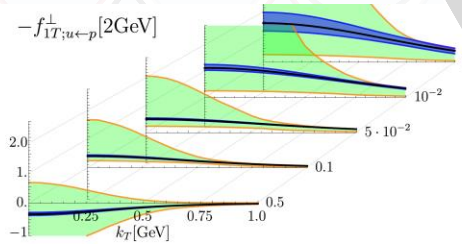
Motivation: 3D Transverse spin and momentum structure

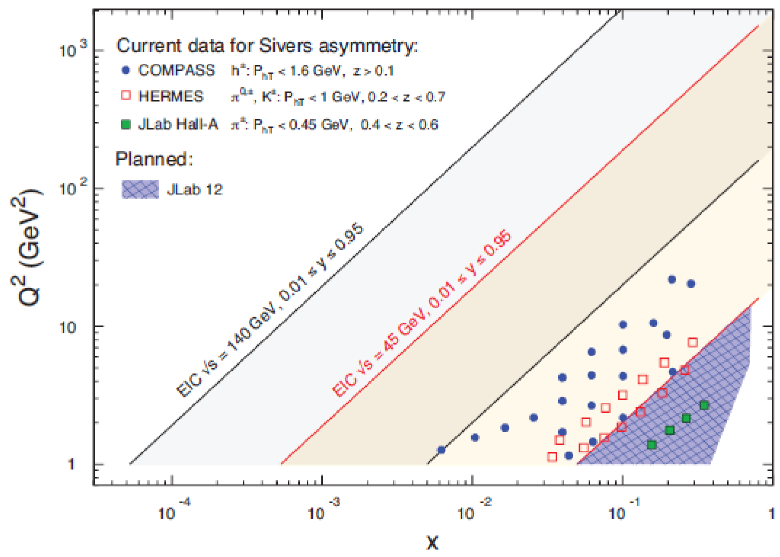




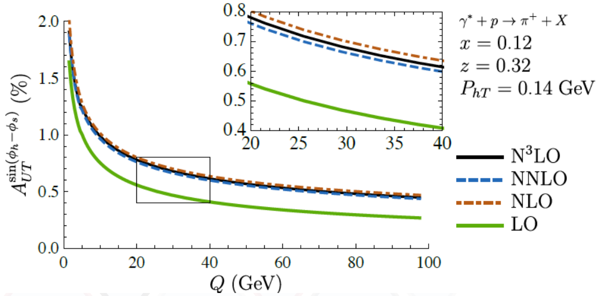
Deliverables	Observables	What we learn	Stage I	Stage II
Sivers & unpolarized TMD quarks and gluon	SIDIS with Transverse polarization; di-hadron (di-jet)	Quantum Interference & Spin-Orbital correlations	3D Imaging of quarks valence+sea	3D Imaging of quarks & gluon; Q^2 (P_{hT}) range QCD dynamics
Chiral-odd functions: Transversity; Boer-Mulders	SIDIS with Transverse polarization	3^{rd} basic quark PDF; novel hadronization effects	valence+sea quarks	Q^2 (P_{hT}) range for detailed QCD dynamics

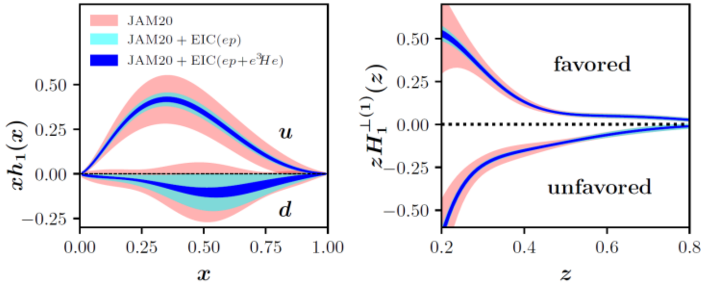
Tables from original EIC white paper





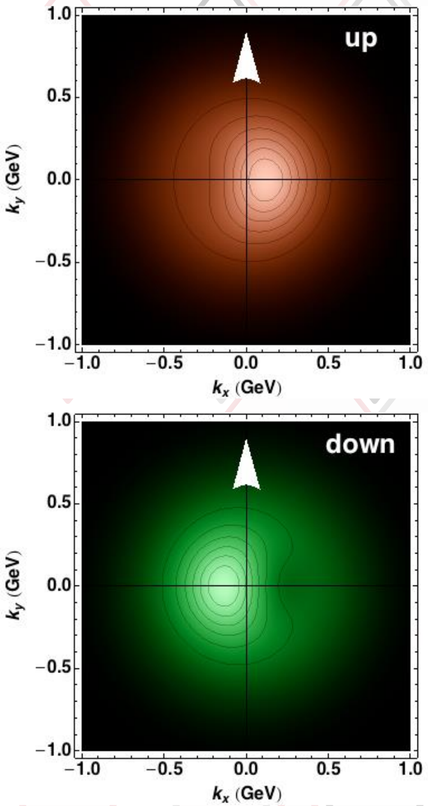
Current coverage for transverse spin related measurements



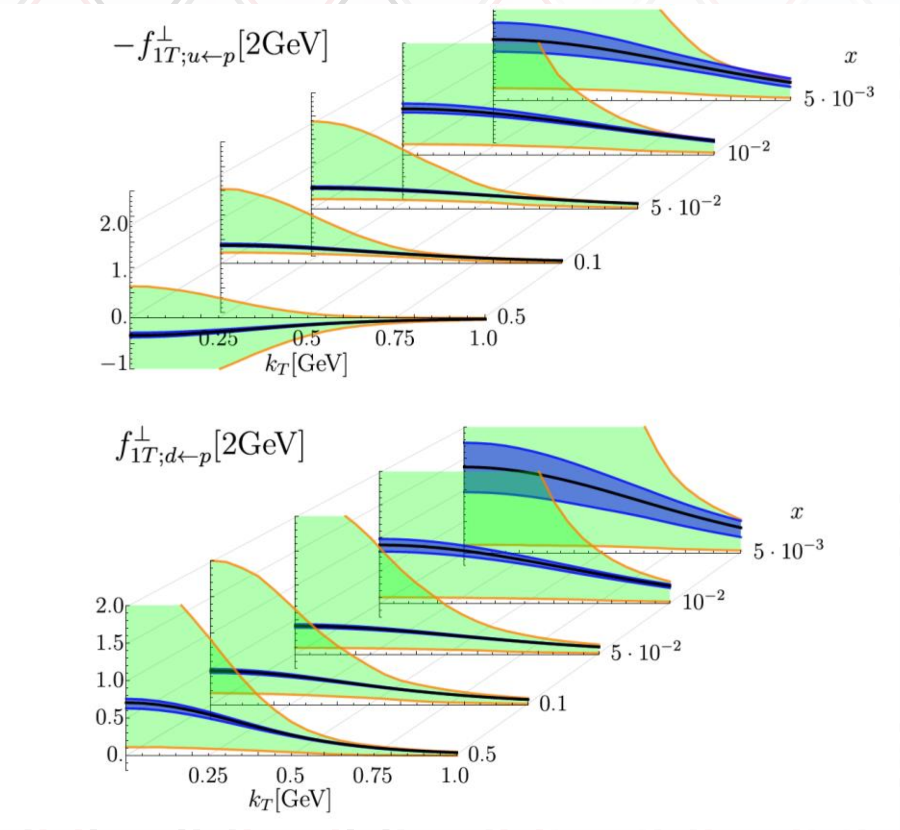


EIC impact for Sivers Functions

Transverse momentum imbalance of unpolarized partons in a transversely polarized nucleon <-> model dependent relation to orgbital angular momentum

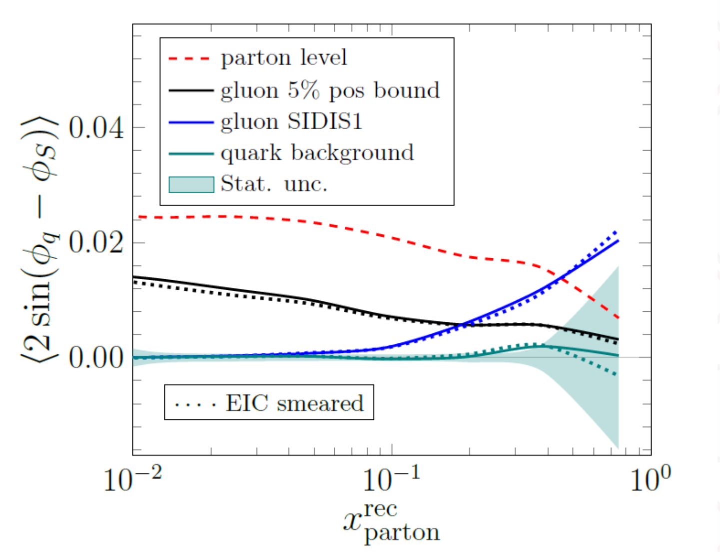


Bacchetta, Radici,
PRL 107 (2011) 212001



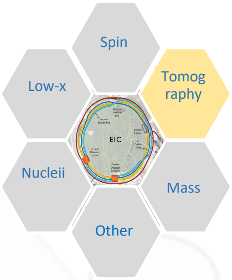
YR: Fig 7.53
Vladimirov, et al

- Precise nucleon image in momentum space for quarks, sea-quarks and gluons



YR Fig 7.55
Xiao, et al

EIC access to TMD evolution

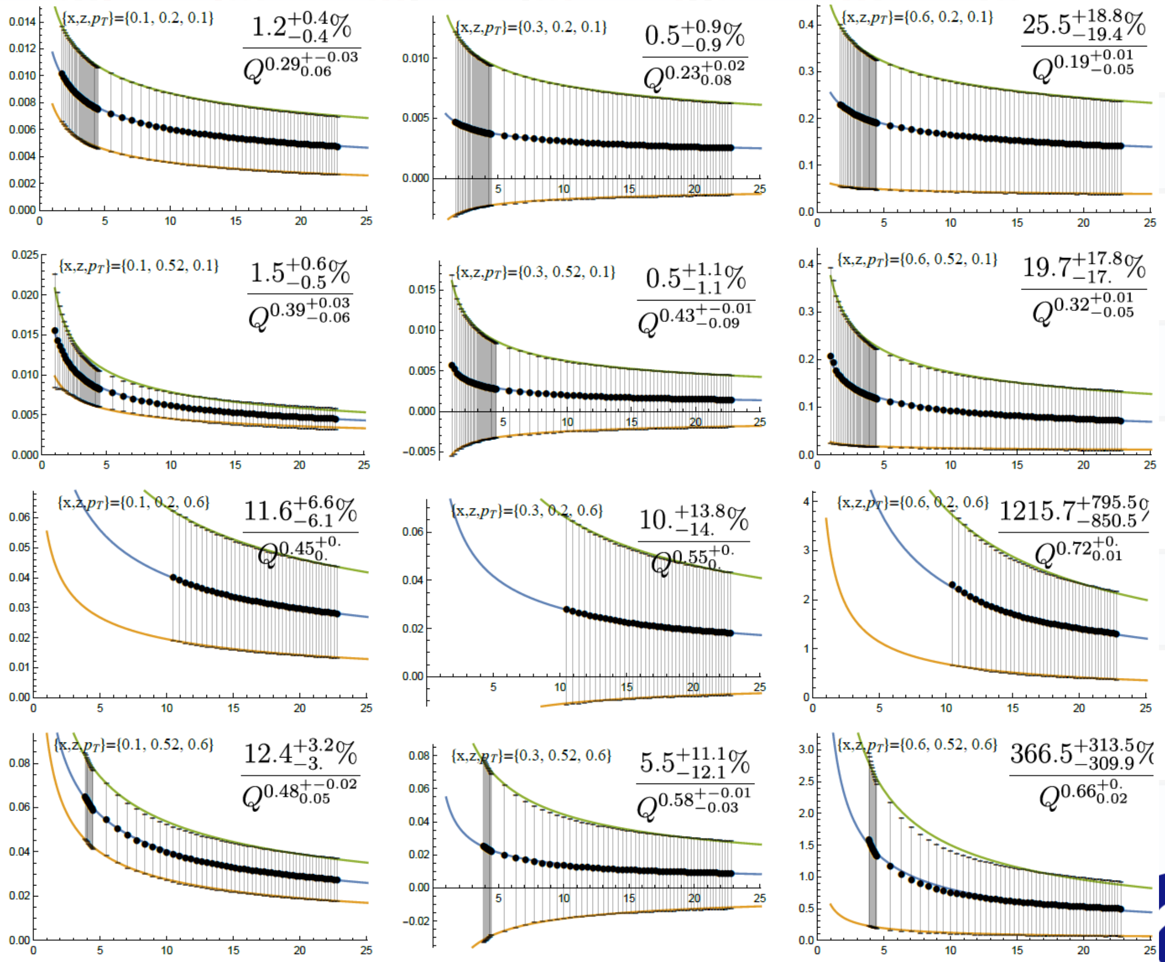


- Very important aspect is the study of TMD evolution
- Sivers asymmetries are expected to decrease at higher scales, but only logarithmically (ie they do NOT "disappear")
- At higher x Asymmetries of several % expected

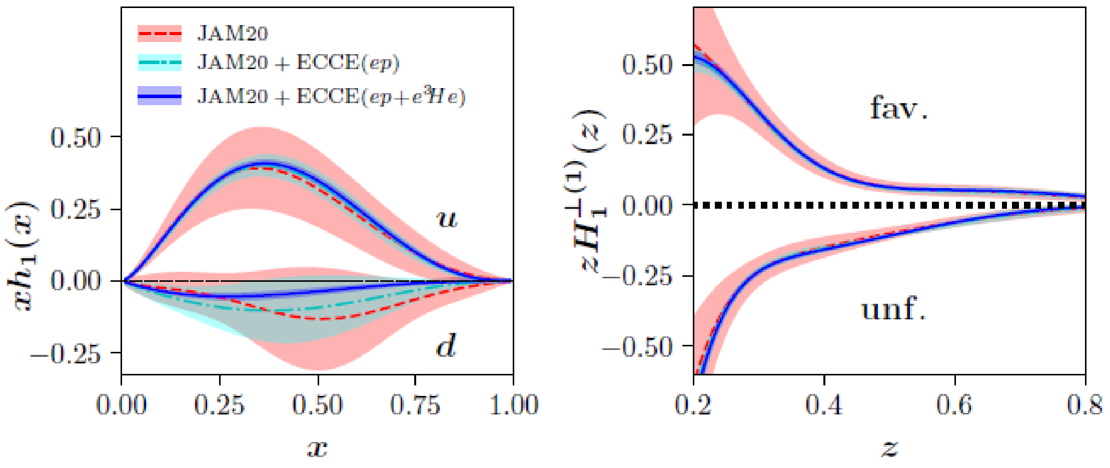
➔Well accessible with EIC over wide range in x and Q^2

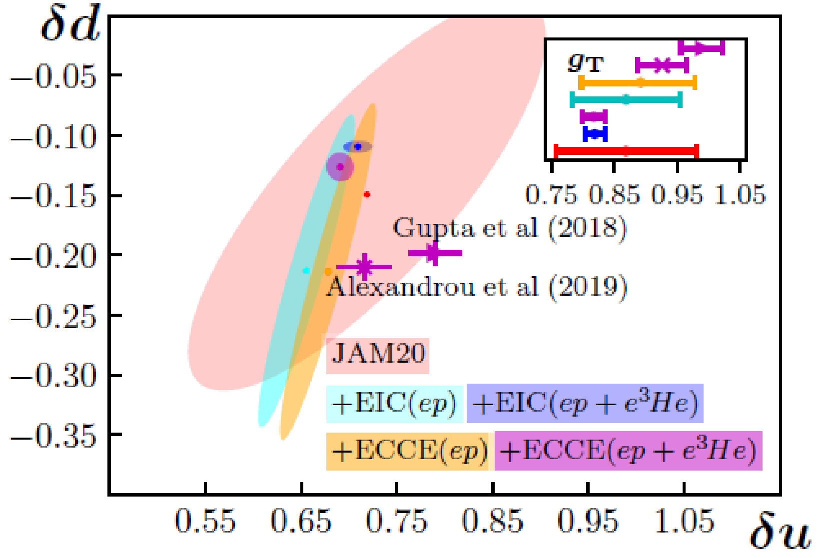
➔Lower x to study sea and glue (both mostly unknown)

Vladimirov et al.



Tensor charges





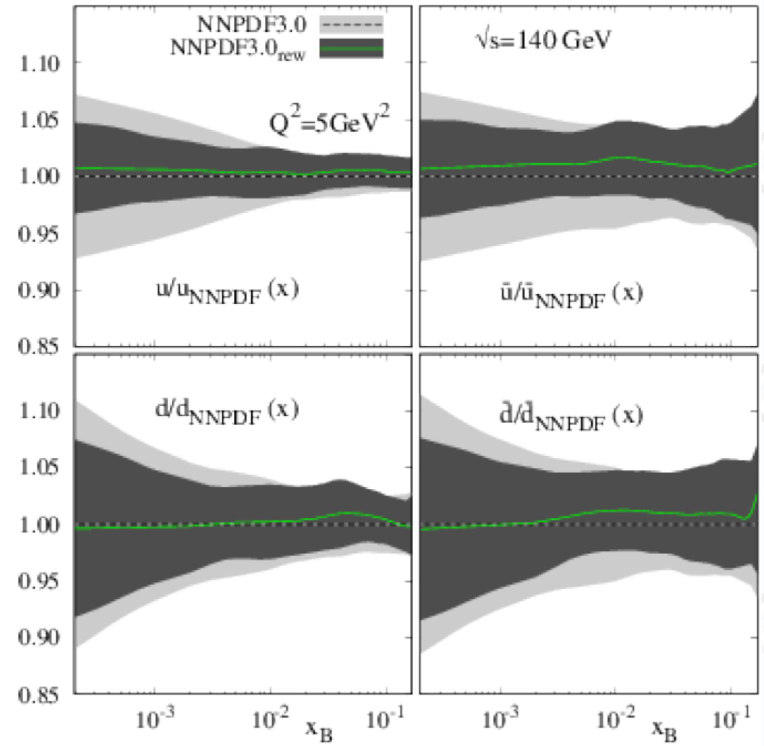
hep-ex:2207.10890

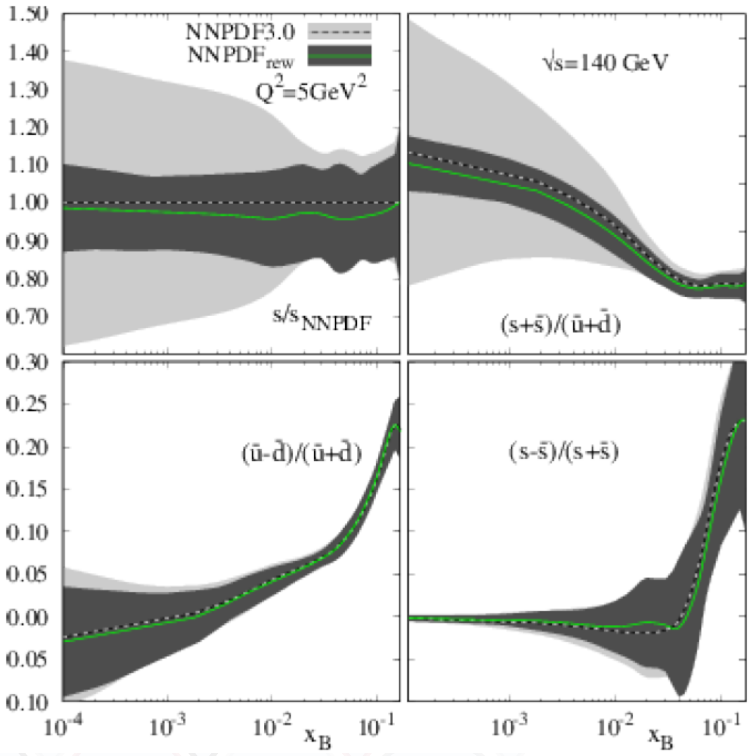
- Precise determination of tensor charges via Collins and di-hadron channels
- Better precision than lattice → potential access to BSM physics in case of discrepancies
- Preform full integrals, study role of sea quark transversity

Similarly:
Single hadron channel (YR : Fig 7.54 Gamberg et al *Phys.Lett.B* 816 (2021) 136255)
Di-hadron channel (YR : Fig 7.56, Radici)

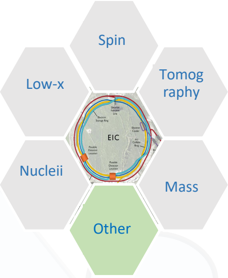
Unpolarized PDFs

- Impact on unpolarized PDFs from plain (NC) DIS, PV (CC) DIS and SIDIS
- SIDIS (flavor sensitivity)→Sea quarks, especially strangeness suppression
- Also potential access to intrinsic charm?



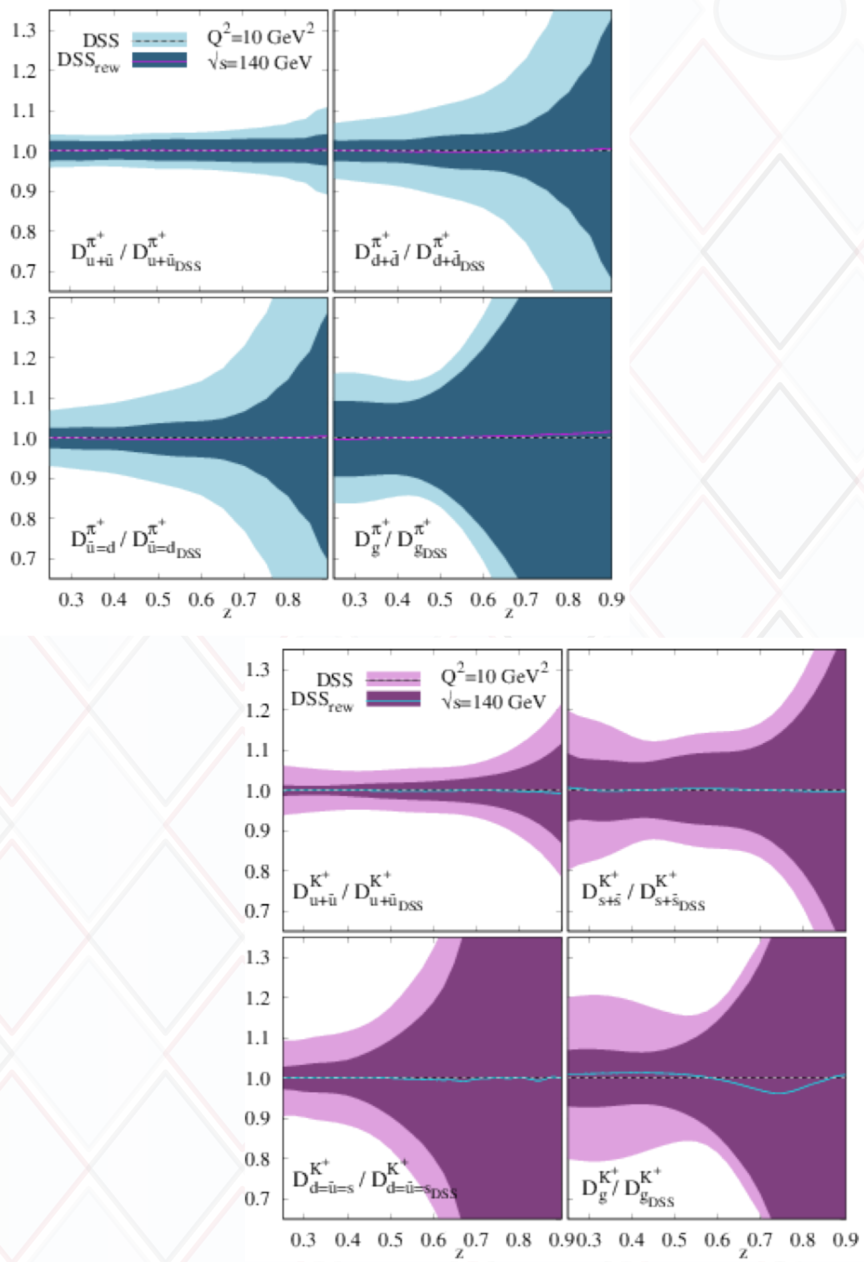


YR Figs 7.8, Aschenauer

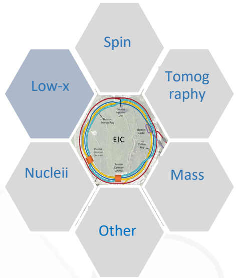


FFs

- Fragmentation functions provide information on struck parton, its flavor and spin
- They are a staple of all SIDIS measurements
- Also their understanding will improve further with the EIC

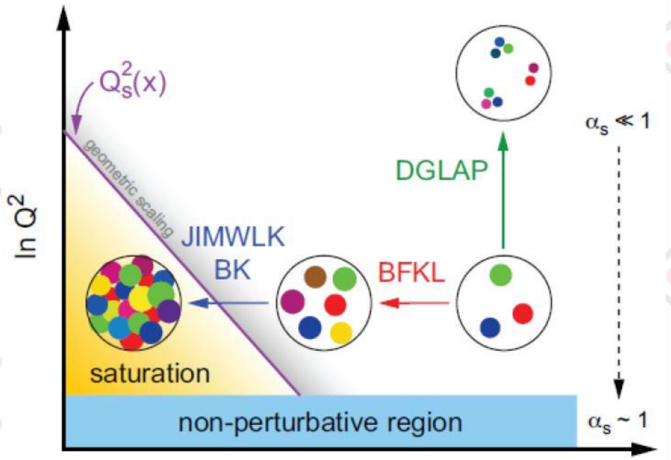


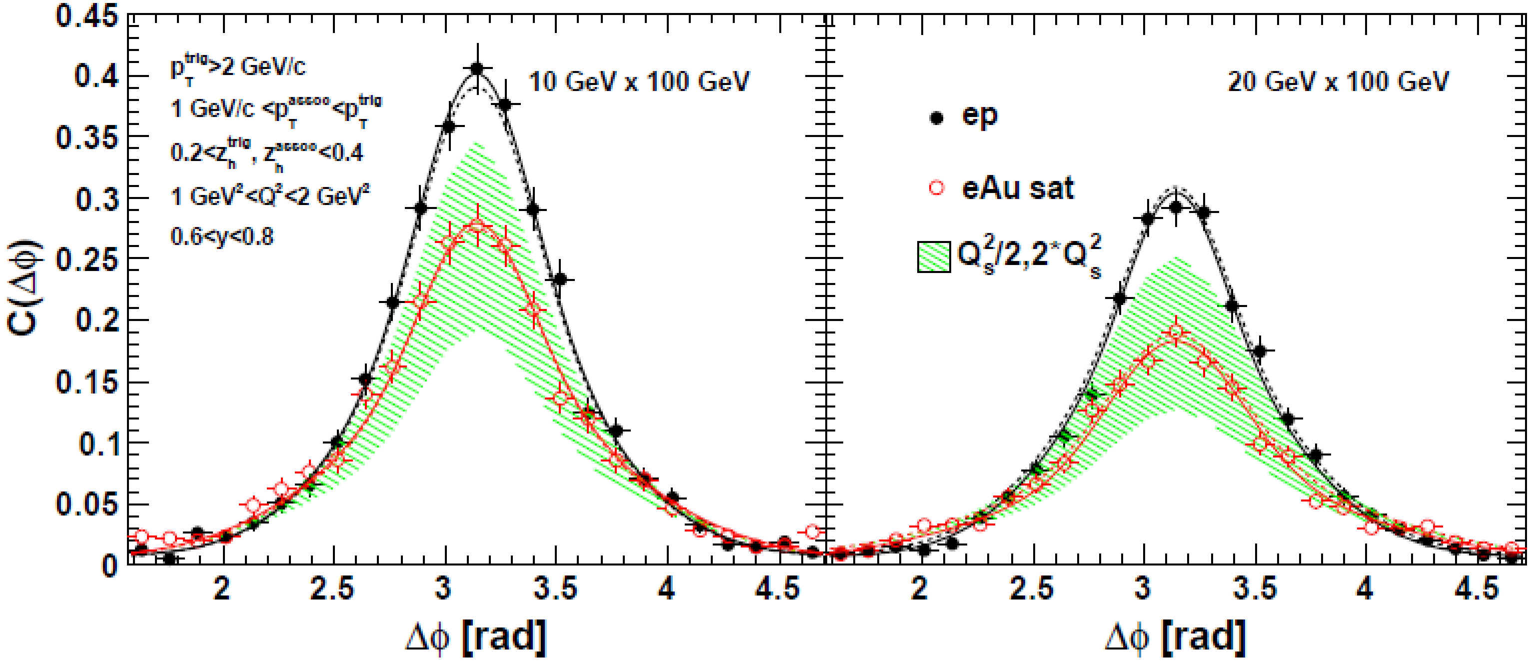
YR Fig 7.84, Aschenauer



Di-hadron de-correlations to cleanly probe saturation

[PRD89 (2014) 074037]

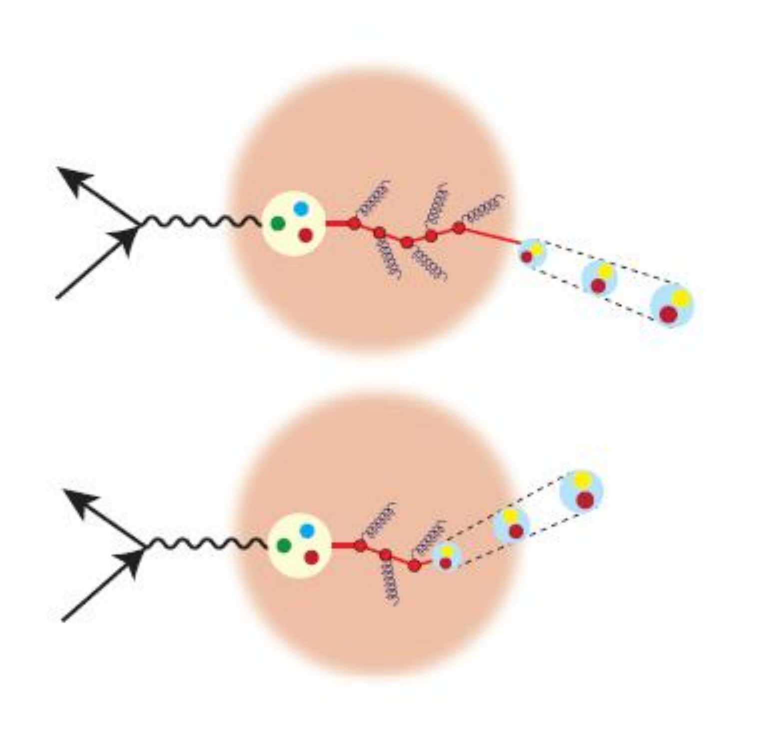


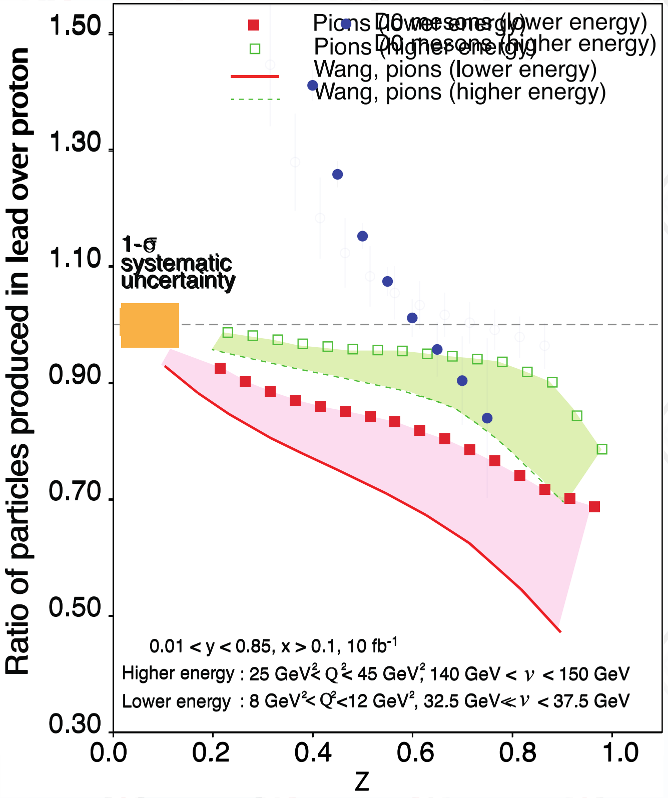


- Measure back-to-back hadron(jet) - hadron or hadron(jet) - photon correlations
- Suppression of away peak as indication for saturation
- Different probes to access different low-x gluon TMDs

Fragmentation in the nucleus

Does the it affect hadron/quark mass?

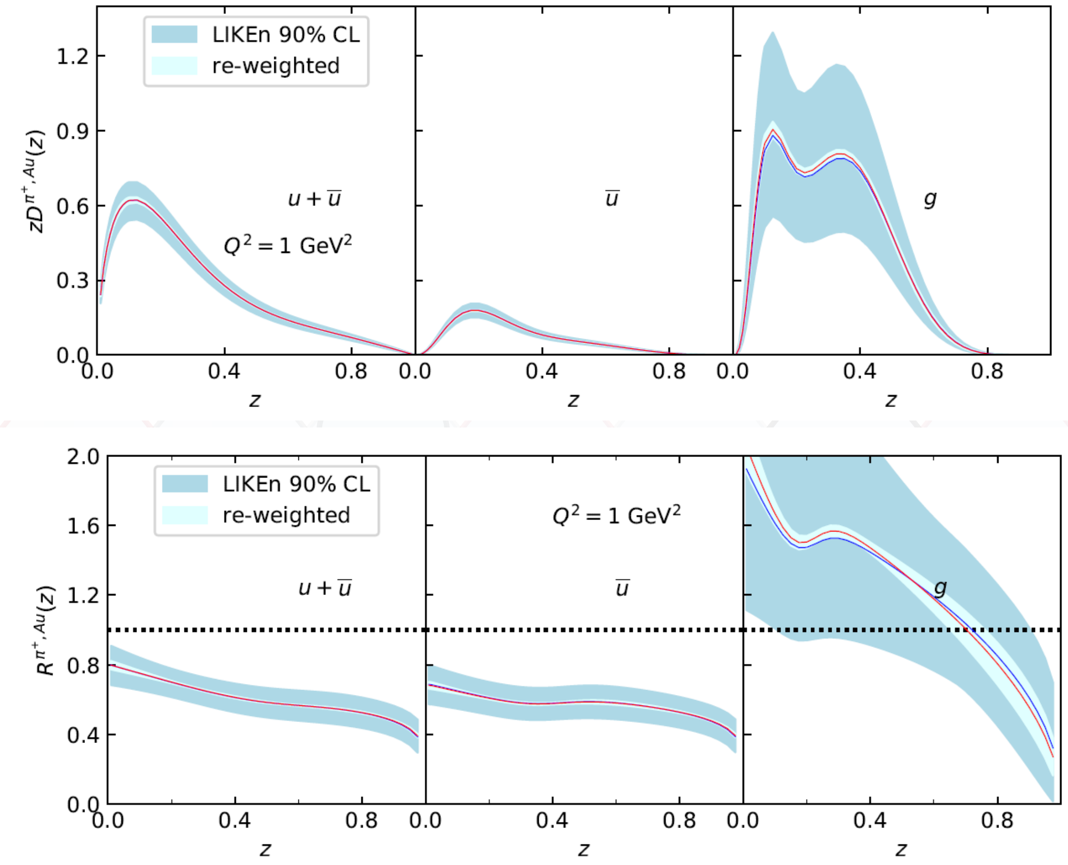




Comparison of Multiplicity ratios for light and heavy hadrons and various parton energies ν

nFFs

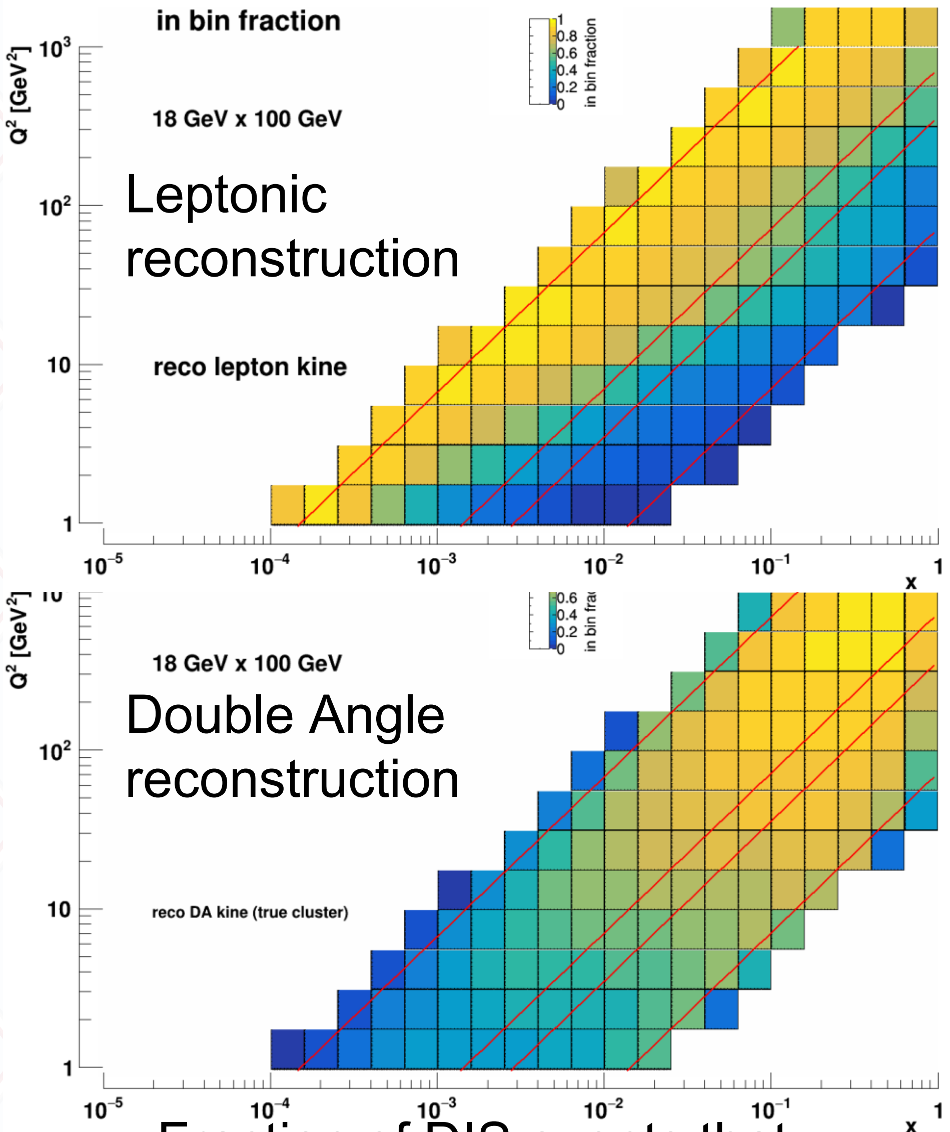
- Expected impact from EIC on light hadron nuclear FFs
- Also more sophisticated studies ongoing (transverse momentum broadening, nu dependence, etc)
- Similar studies for heavy flavor



YR Figs 7.90, 7.91, Zurita

DIS kinematic reconstruction examples

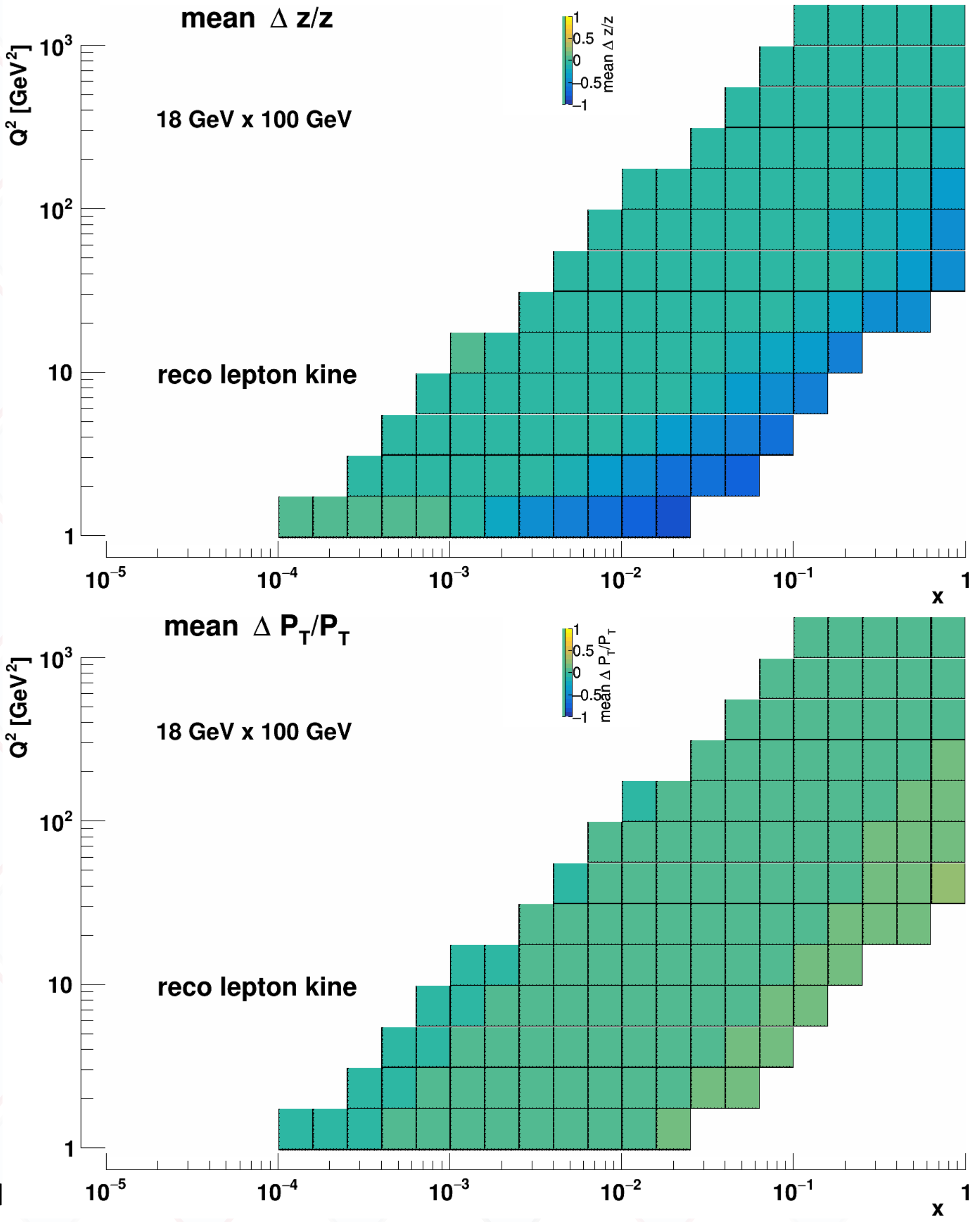
- Full Pythia6+GEANT simulations of the ECCE detector used for various (SI)DIS kinematic resolutions and for various reconstruction methods (lepton, Jaquet-Blondel, Double Angle, etc)
- x and y resolutions suffer from lepton method at lower y, partially recoverable in double angle method(hybrid of scattered lepton + hadronic final state)



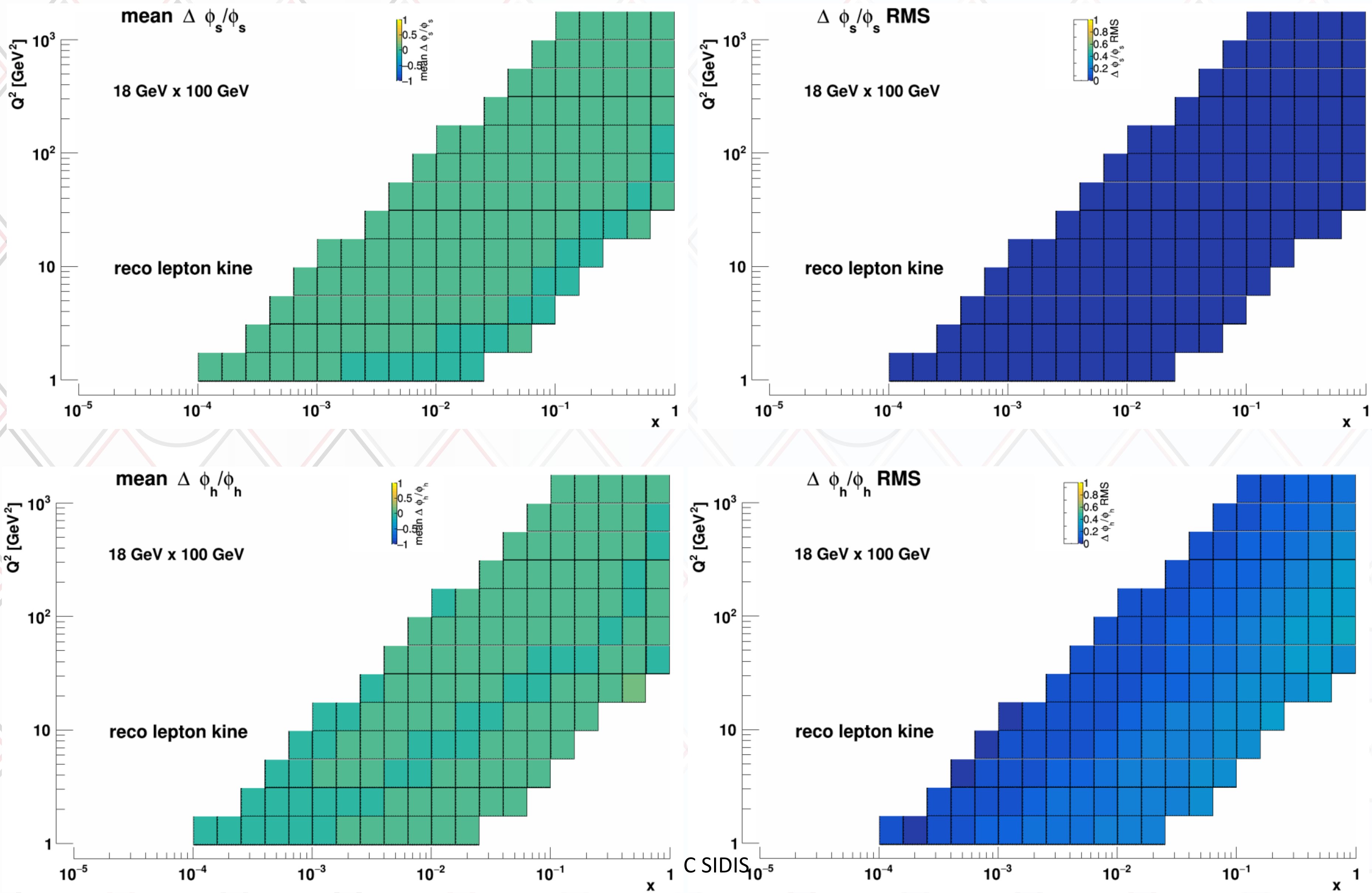
Fraction of DIS events that stay in their x-Q^2 bins

Example of SIDIS resolutions studies

- Full Pythia6+GEANT simulations of the ECCE detector for various (SI)DIS kinematic resolution and reconstruction methods:
  - z resolution suffers in lepton method at lower y, partially recoverable in double angle method
  - p_T and azimuthal angles ϕ_h, ϕ_S very robust

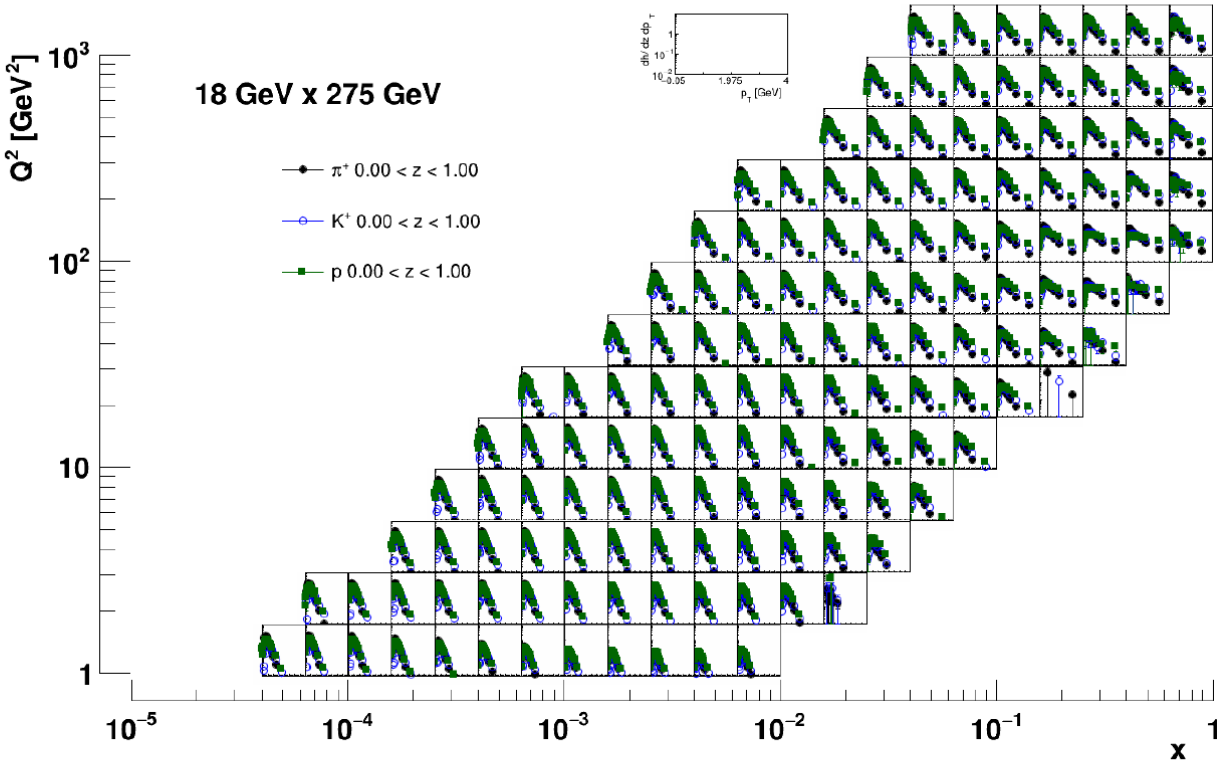


Azimuthal angles



ECCE simulation setup, unpolarized TMD studies

- pythiaeRHIC (Pythia 6) simulations for e+p collisions at 4 energies similar to YR
- Generator output simulated through GEANT4
- Scattered lepton (|η|<3.5) DIS kinematic reconstruction using reco track momenta (assuming perfect eID)
- DIS cuts: $0.01<y<0.95$, $Q^2>1$, $W^2>10 GeV^2$
- SIDIS cuts: pions and kaons (|η|<3.5), using true PID (assuming successful unfolding)
- 25x13x12x12 kinematic bins (x,Q^2,z,P_T)
- Pion, kaon and proton multiplicities shown in all x-Q^2 bins as a function of P_T (integrated over z)



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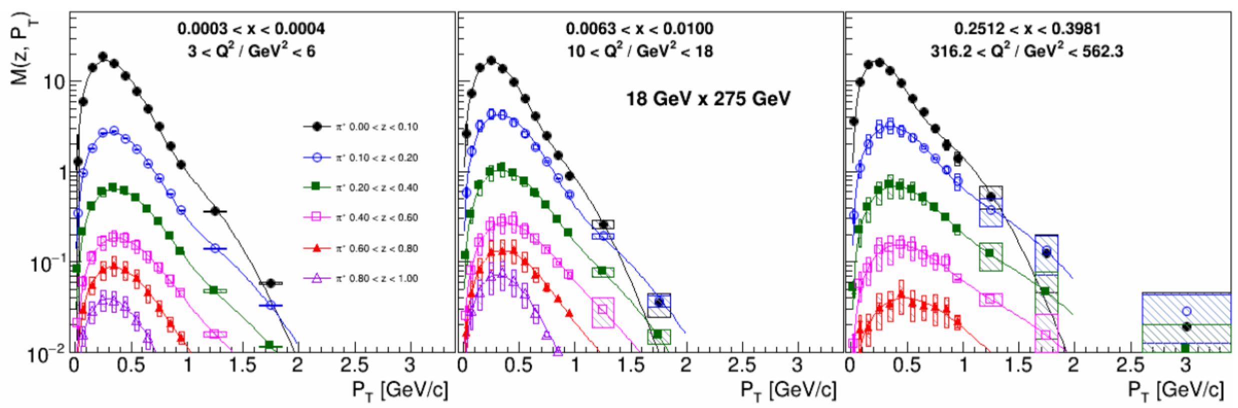
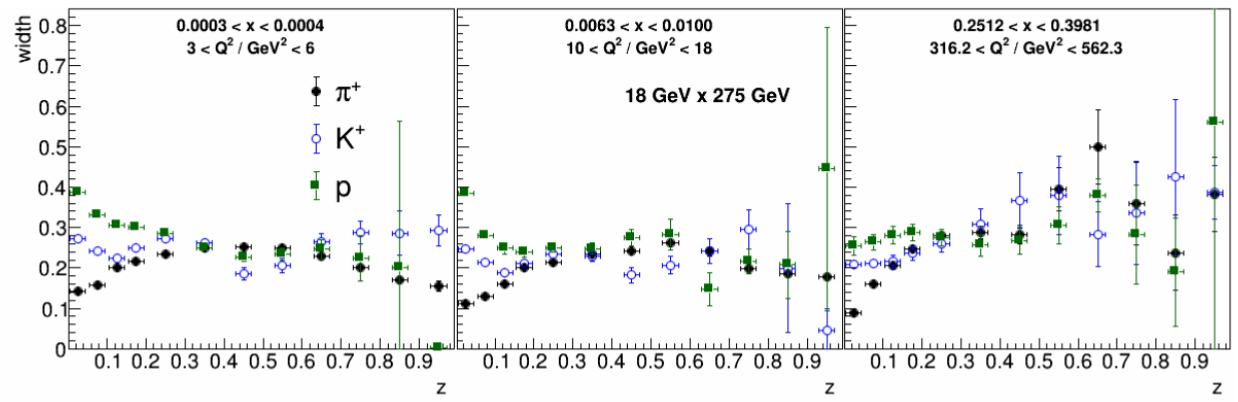
z-dependence of multiplicities and widths

- Top: Explicit z dependence of select pion multiplicities in 3 x-Q^2 bins, including the double-Gaussian fits
- Bottom: behavior of the narrow Gaussian widths vs z for pions, kaons and protons
- Small z discrepancies likely due to target fragmentation





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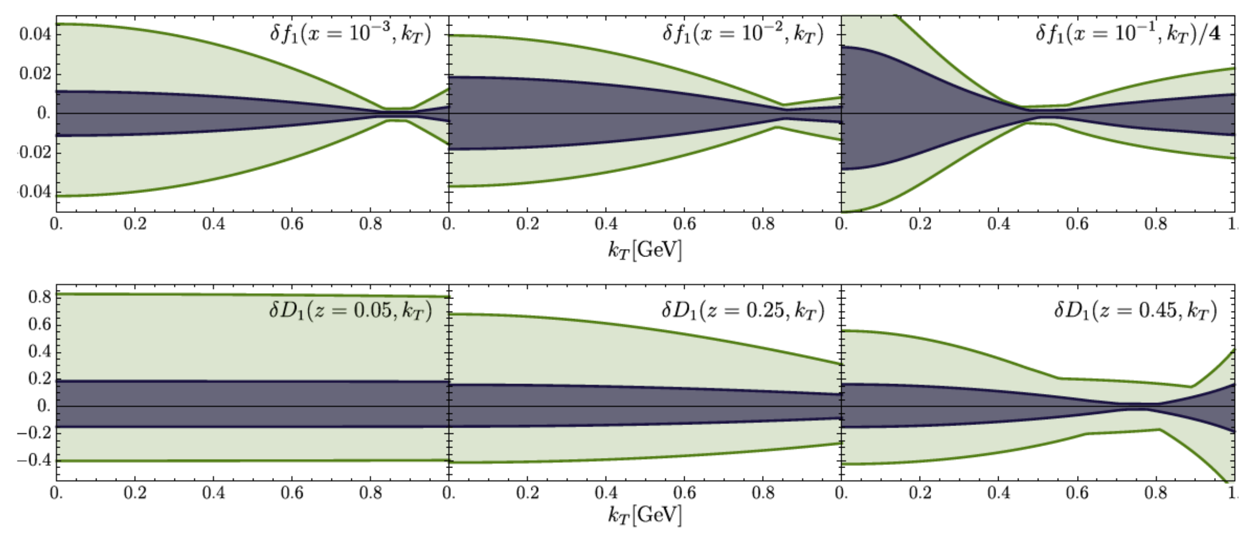
Impact for unpolarized TMD functions

- Similar to YR impact studies following the latest SV global fit (https://arxiv.org/abs/1912.06532) for the unpolarized TMDs based on the existing SIDIS +DY data
- Consistent with Yellow Report expected impact



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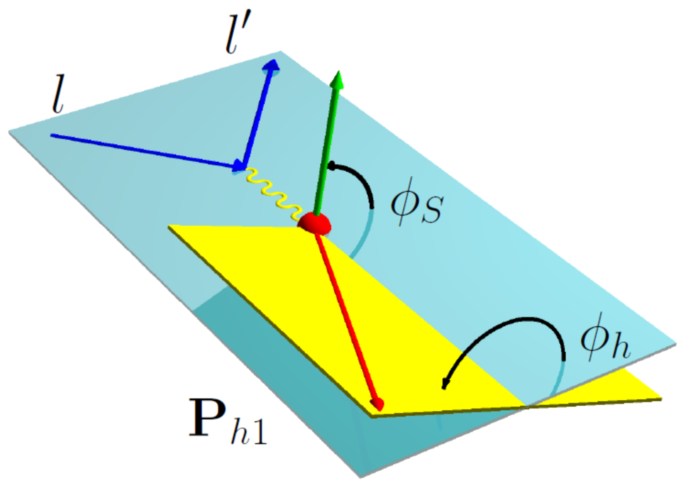
Experimental access to Transversity/tensor charge and Sivers function

- 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 orientiation
- Input structure functions (polarized and unpolarized) from Torino global fits (arXiv:0812.4366, arXiv:0805.2677) as in https://github.com/prokudin/tmd-parametrizations/
- Other TMD PDFs are similarly accessible via different modulations and spin orientations (though often higher twist effects present)
- Gluon Sivers via di-jet/di-HF TSSAs

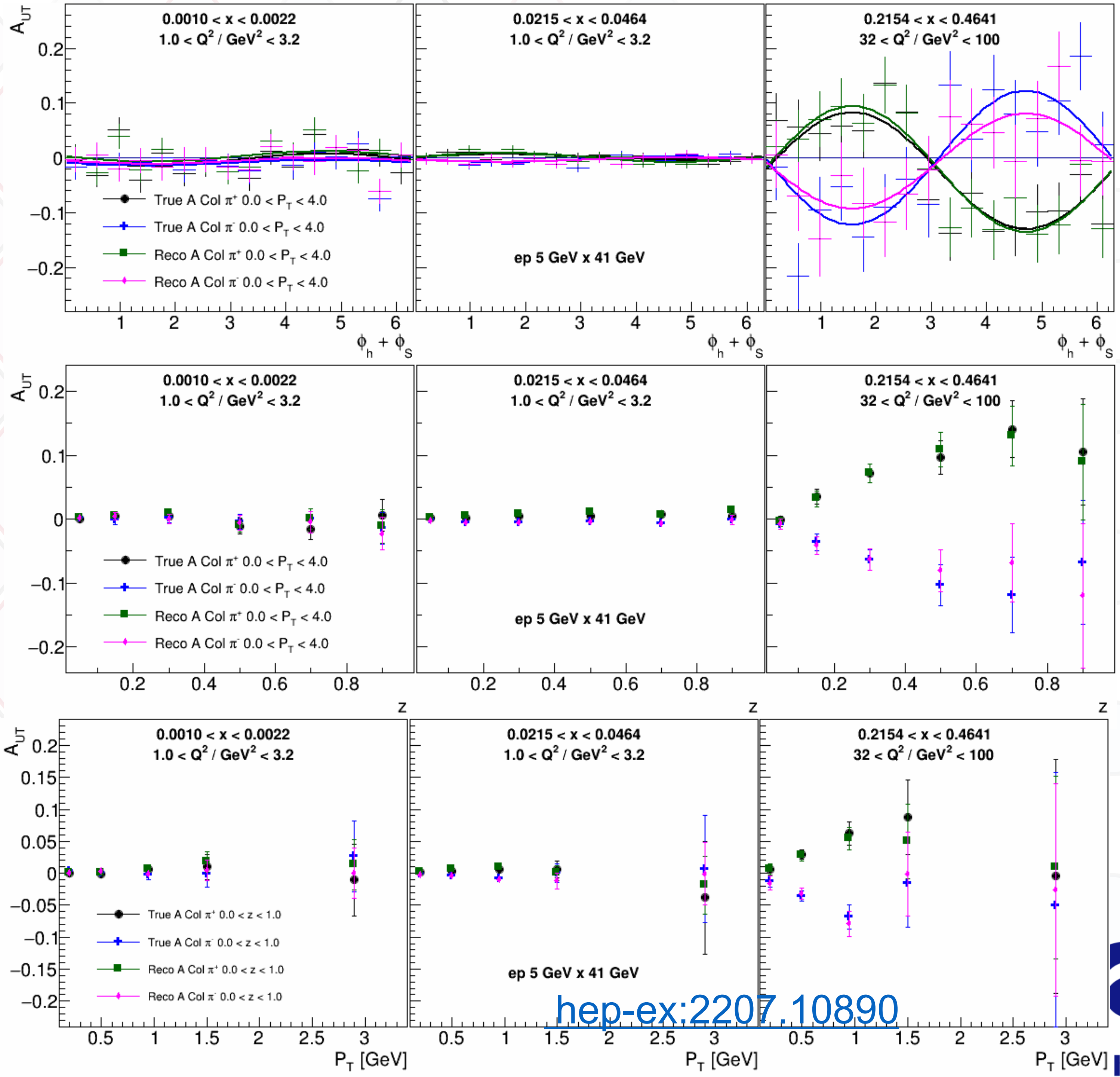


$$A_{UT}^{\sin(\phi_h+\phi_S)}(x,z,P_T) \propto \mathbf{S}_T \frac{\sum_{q,\bar{q}} e_q^2 \delta q(x,k_t) \otimes H_1^{\perp}(z,p_t)}{\sum_{q,\bar{q}} e_q^2 q(x,k_t) \otimes D_1(z,p_t)}$$

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

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: same, either projected vs z or vs Pt



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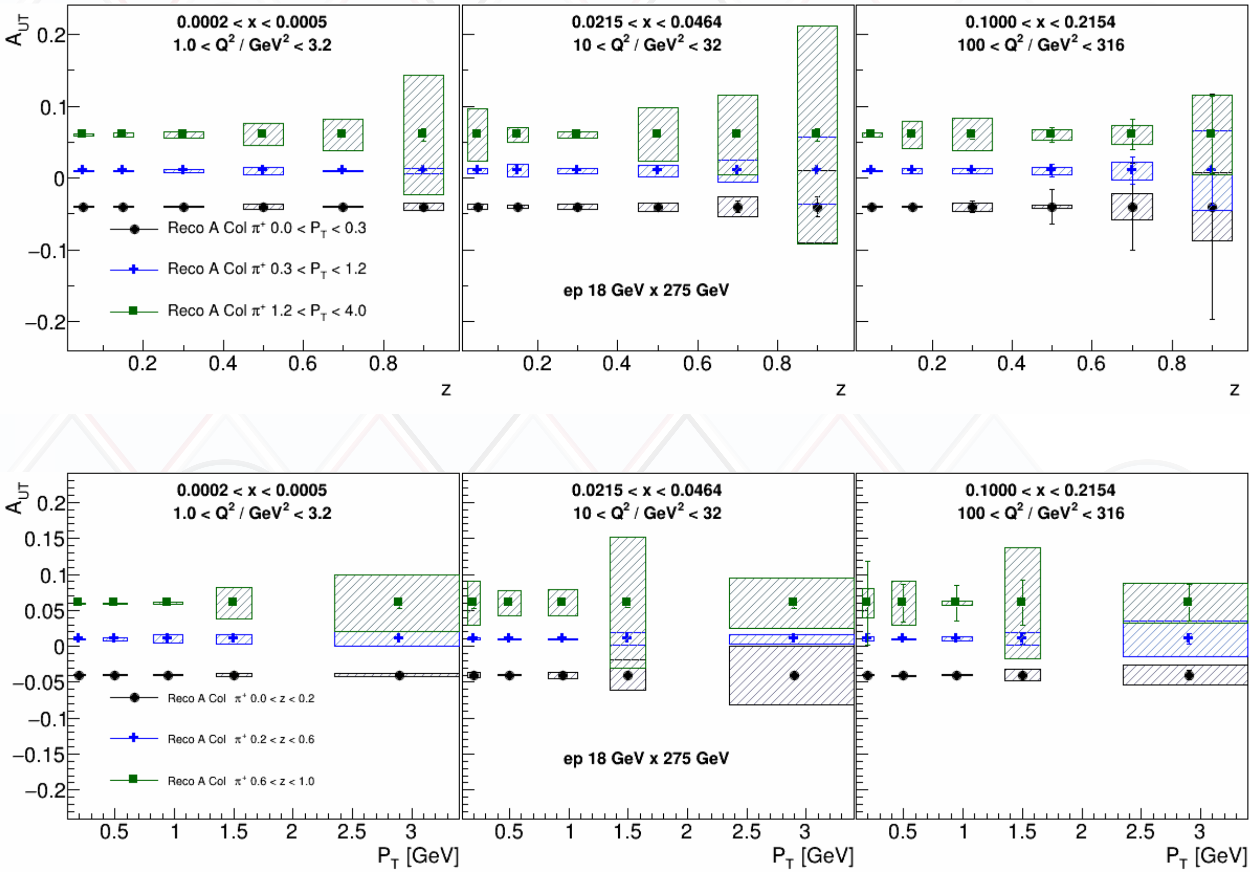
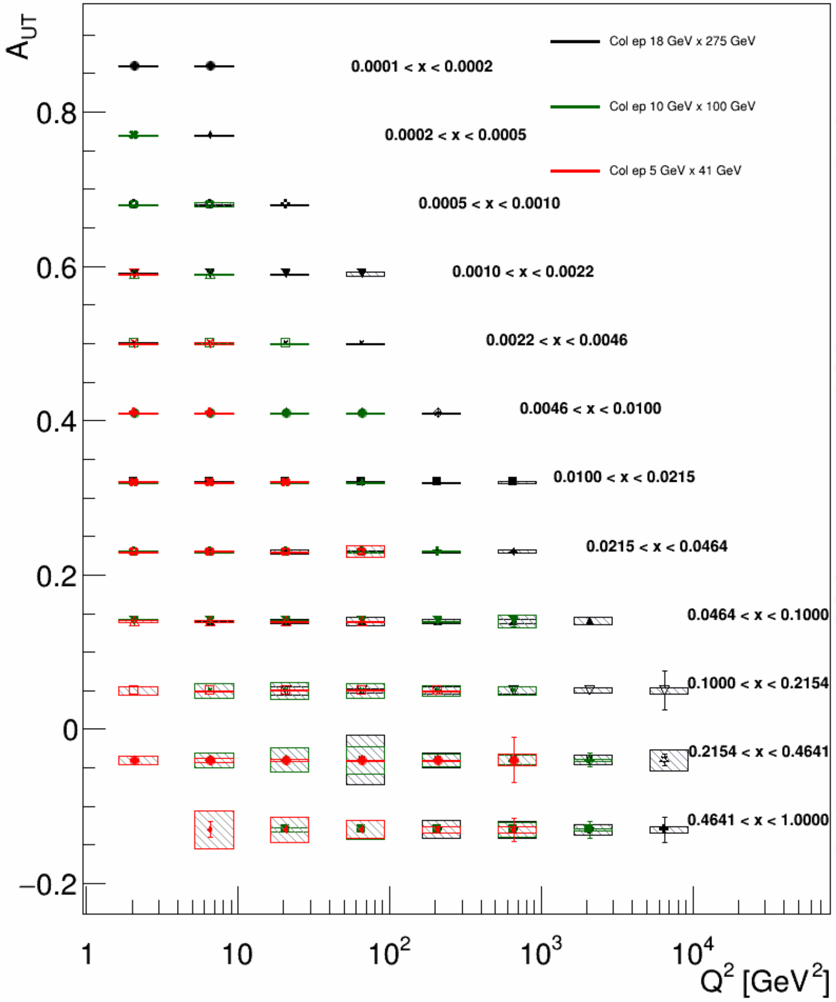
Projections to 10fb^{-1}

- 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



Scale dependence (and interplay of collision energies)

- 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)
- Overlap of the different energies shows how they increase the lever arm
- Note: in future evolution analysis likely more Q^2 bins and maybe not as fine x binning



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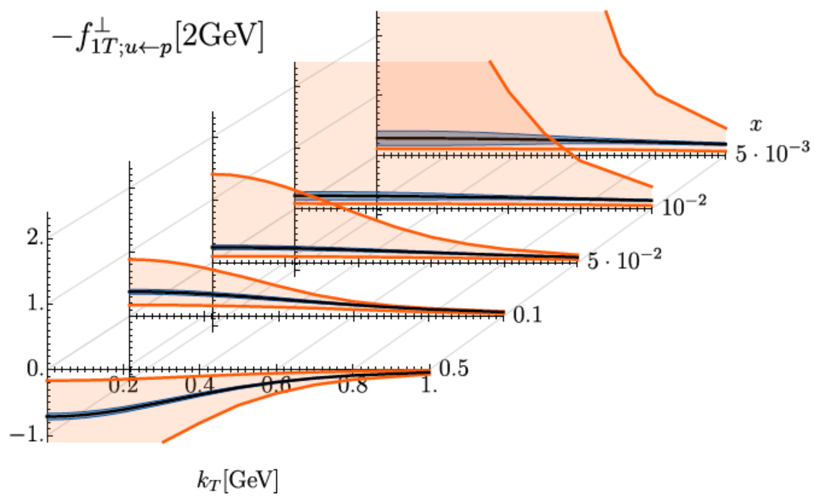
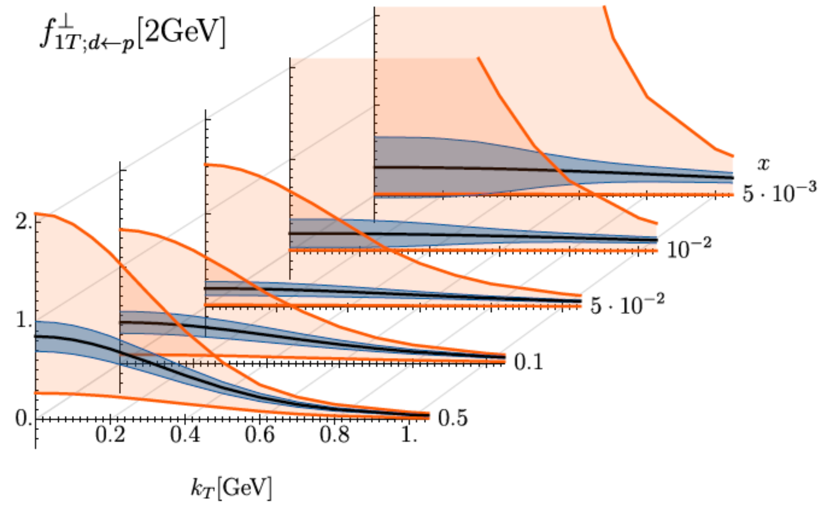
Impact for Sivers functions

- 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 kt and expected impact from ECCE





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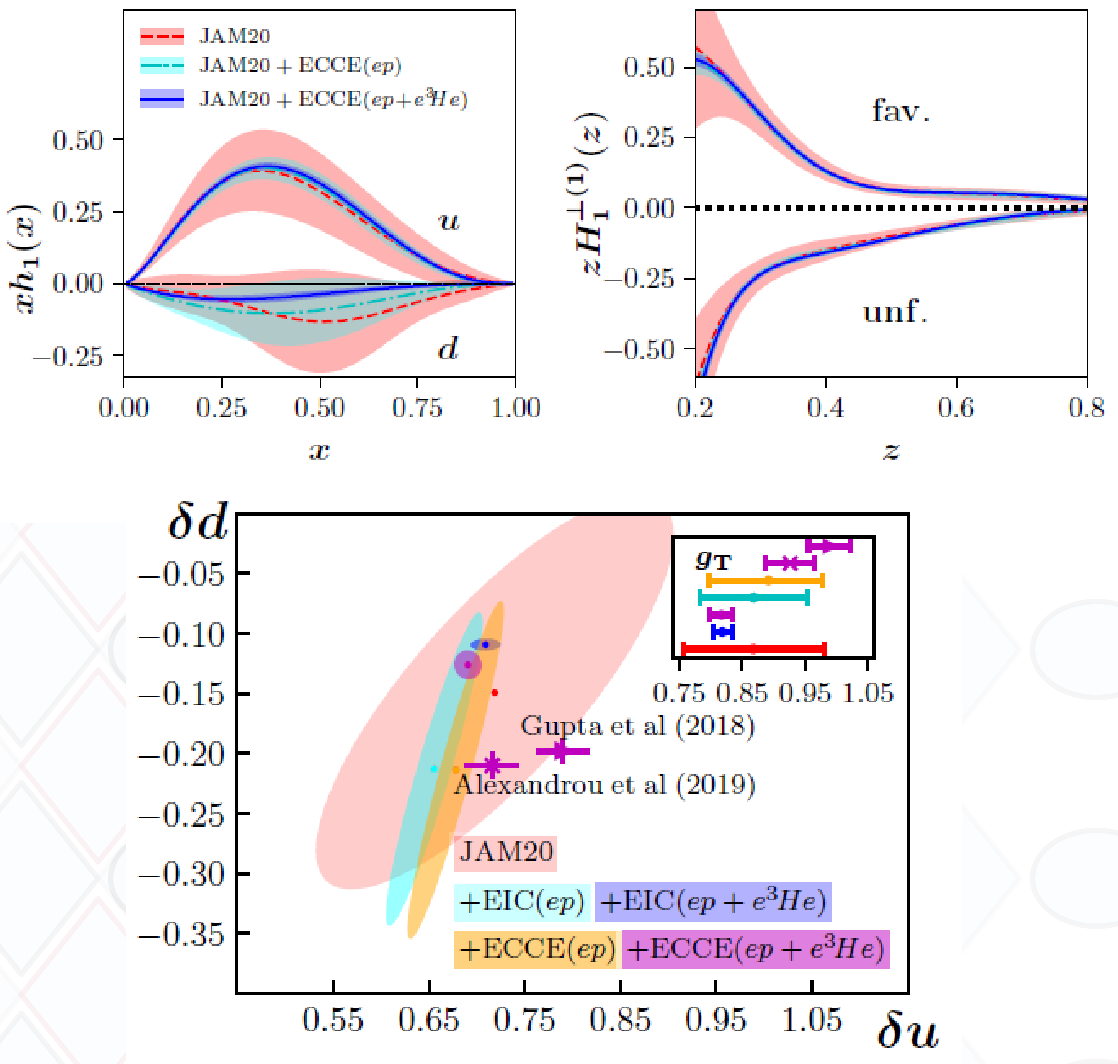
Tensor charge impact

- 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)



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Summary

- SIDIS gives access to the flavor of PDFs, helicities and TMDs
- Important piece in the spin puzzle to access sea quark helicities
- TMDs provide valuable input on the 3D momentum picture of the nucleon
- Closely related spin-spin (Transversity) and spin-orbit (Sivers function, Boer-Mulders function) effects
- Tensor charge as potential probe for BSM effects
- SIDIS also relevant to access low-x physics and nuclear PDF/FFs
- Full Geant studies show that ECCE/ePIC successfully addresses the TMD/SIDIS measurements of the EIC Yellow Report
- Continuation of evaluation as ePIC detector evolves, impact of kinematic reconstruction methods, prepare for unfolding (PID, tracking), understand radiative corrections, etc