ECCE
kinematic reco, Sivers, Collins and unpol TMD studies

Project detector SIDIS meeting

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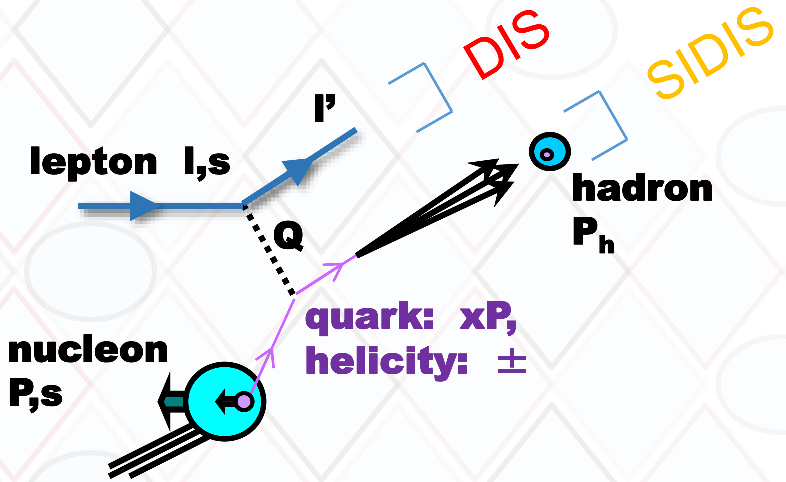
Exp.Physics analysis strategy

- For any (SI)DIS analysis:

1. Find DIS kinematics: easiest case via scattered lepton l' (other methods include hadronic final state)
2. Calculate DIS variables: x,y,Q^2, W^2, ϕ_S (around virtual photon in proton rest frame, wrt to scattering plane)
3. Select DIS events (typically $Q^2>1$ GeV^2, $W^2>10GeV^2$,$0.01<y<0.95$)
4. Search for final state hadrons →SIDIS
5. Calculate SIDIS variables: z, P_{hT} (wrt to virtual photon in proton rest frame), ϕ_h (around virtual photon in proton rest frame, wrt to scattering plane)



$$q = l - l'$$
$$Q^2 = -q^\mu q_\mu$$

Momentum transfer

$$x = \frac{Q^2}{2p\cdot q}$$

Parton momentum fraction*

$$y = \frac{q\cdot p}{l\cdot p}$$

Inelasticity

$$W^2 = M_p^2 + (1-x)Q^2/x$$

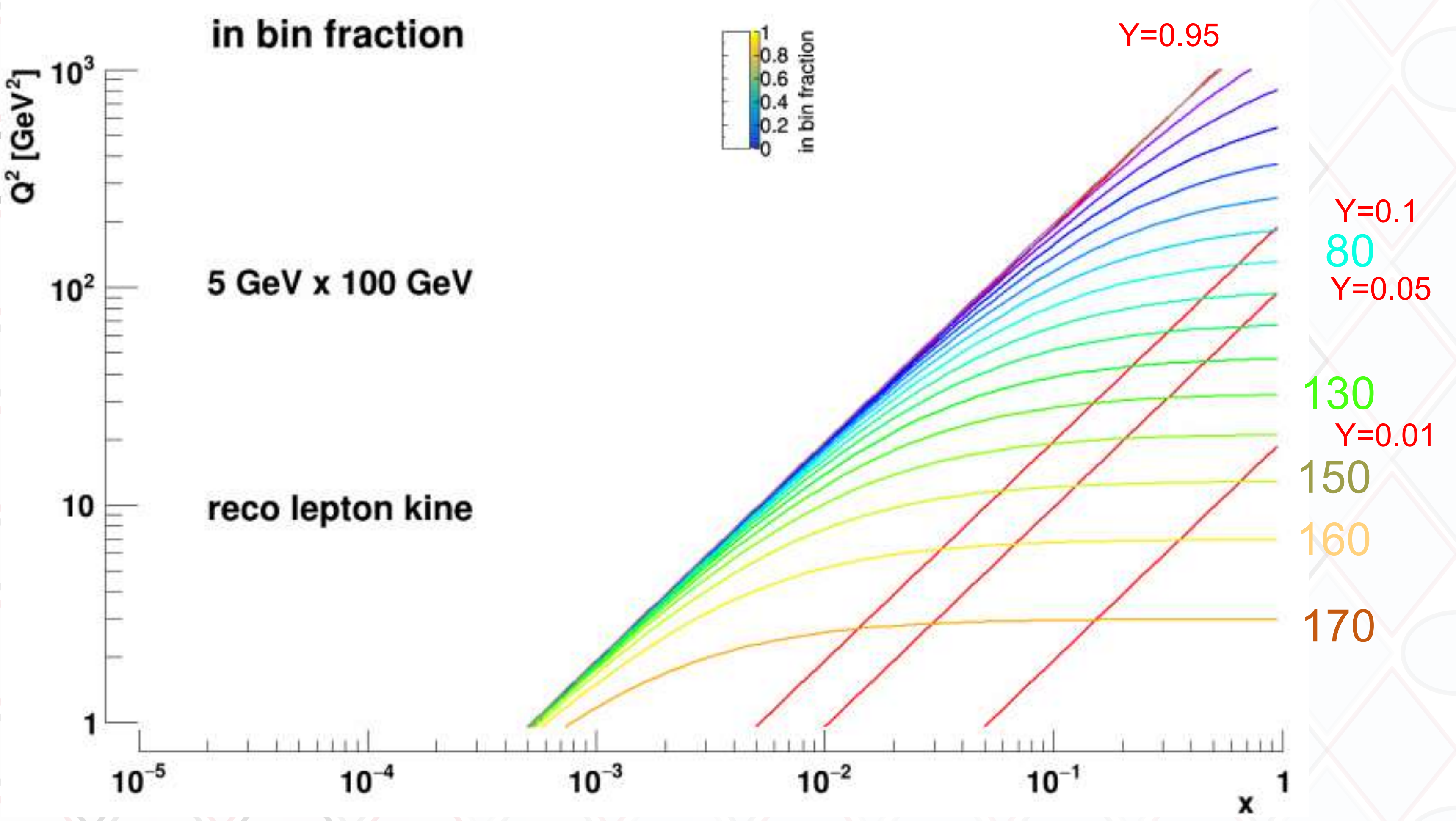
Mass of had final state

$$z = \frac{p\cdot P_h}{p\cdot q}$$

SIDIS hadron momentum fraction

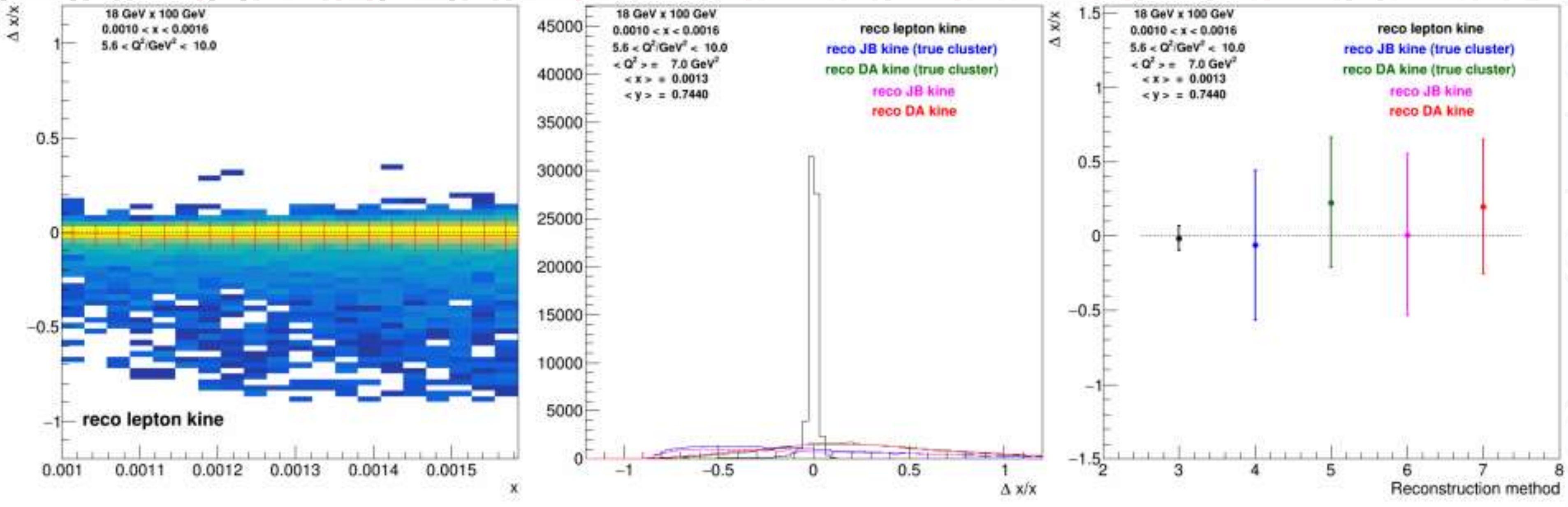
DIS kinematic regions

Inelasticity
$y = 1 - E'/E \sin^2 \theta/2$



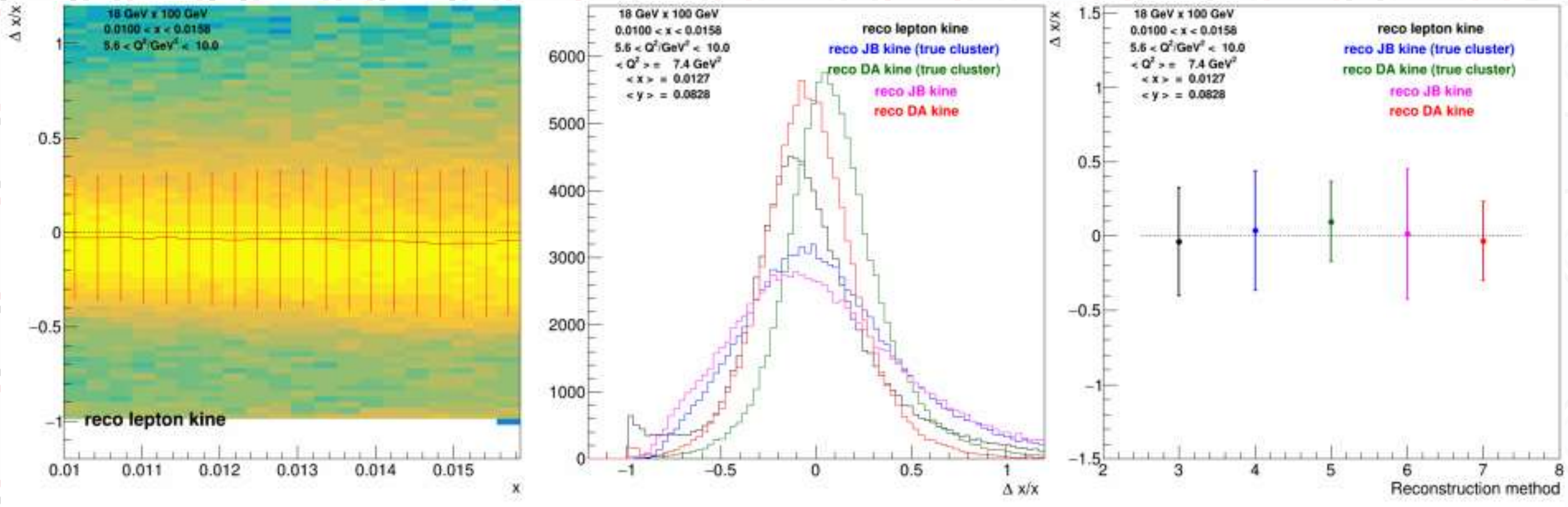
Lepton scattering angle θ

Kinematic reco example plots (x, high y)



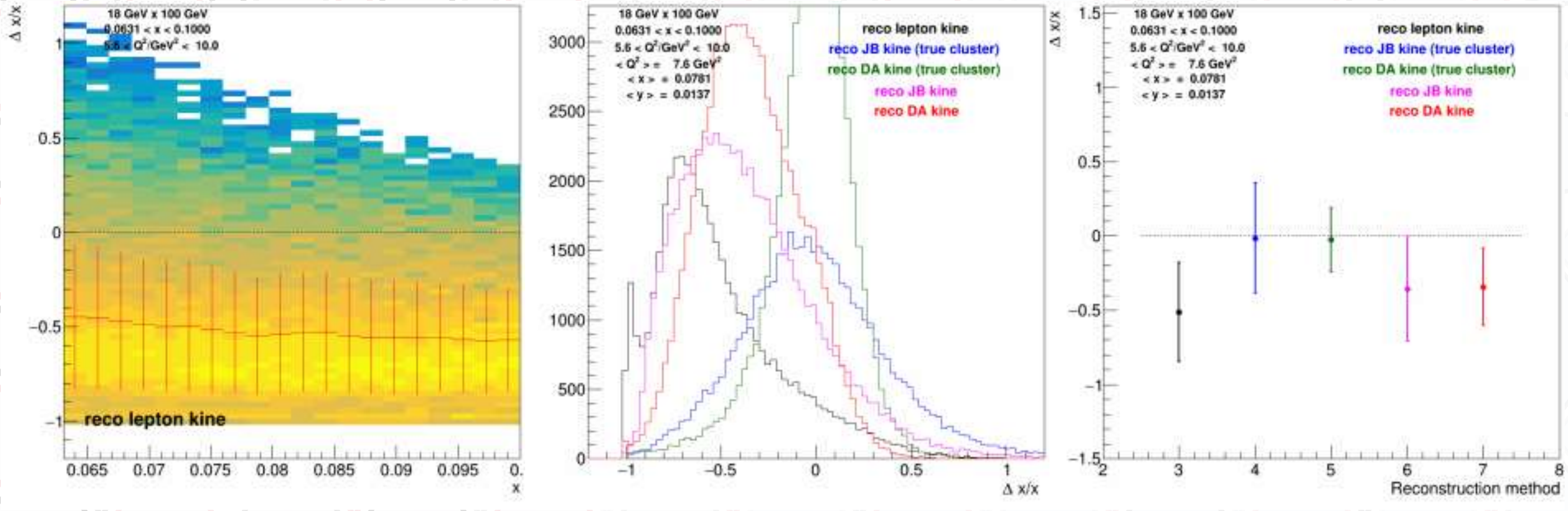
1. (var_{reco} – var_{true} / var_{true}) distributions as a function of variable/x/z in one x-Q2 bin
2. (var_{reco} – var_{true} / var_{true}) distribution in one x-Q2 bin
3. Mean and width for various reconstruction methods

Kinematic reco example plots (x, med y)



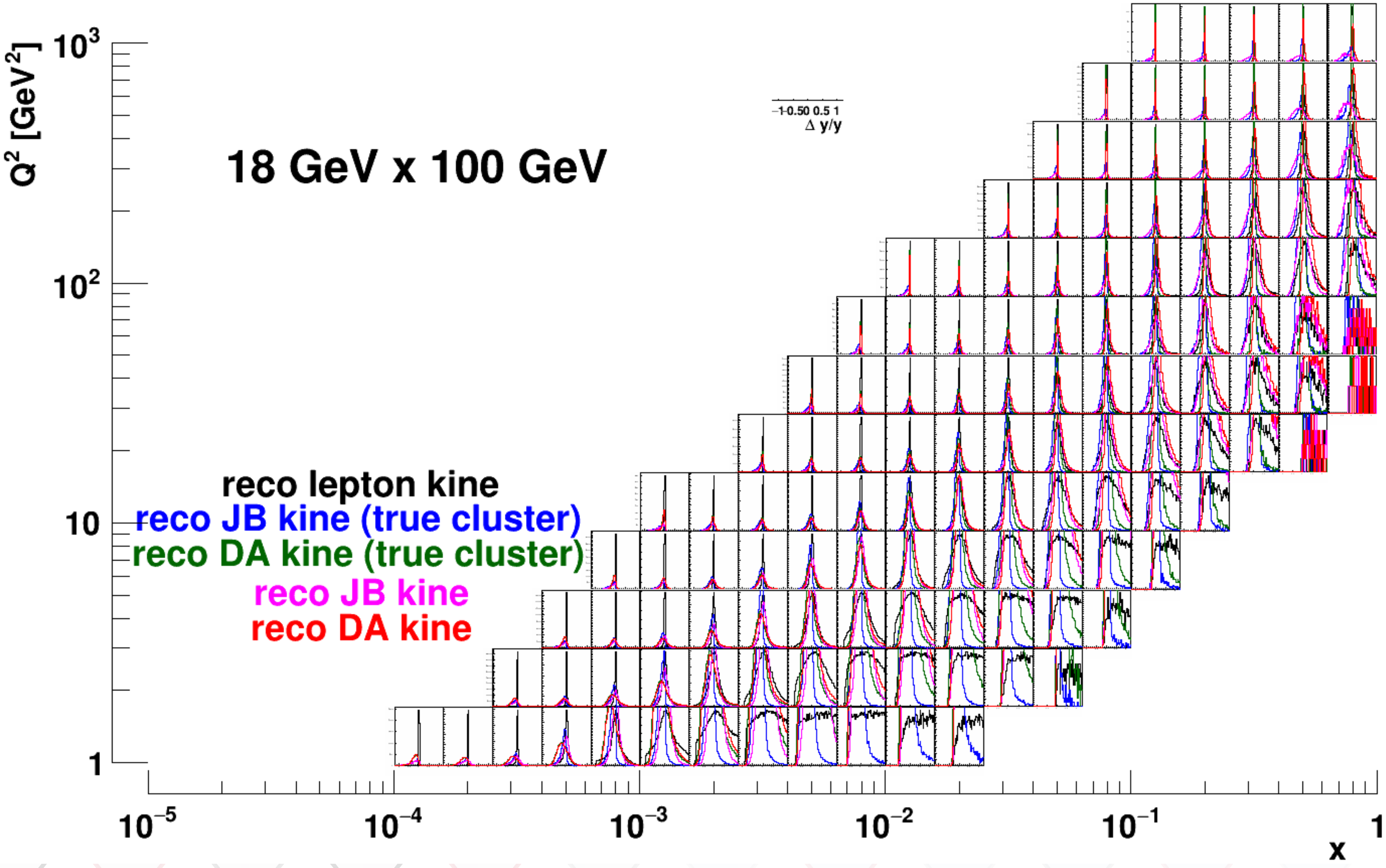
- At medium y all resolutions similar,

Kinematic reco example plots (x, low y)

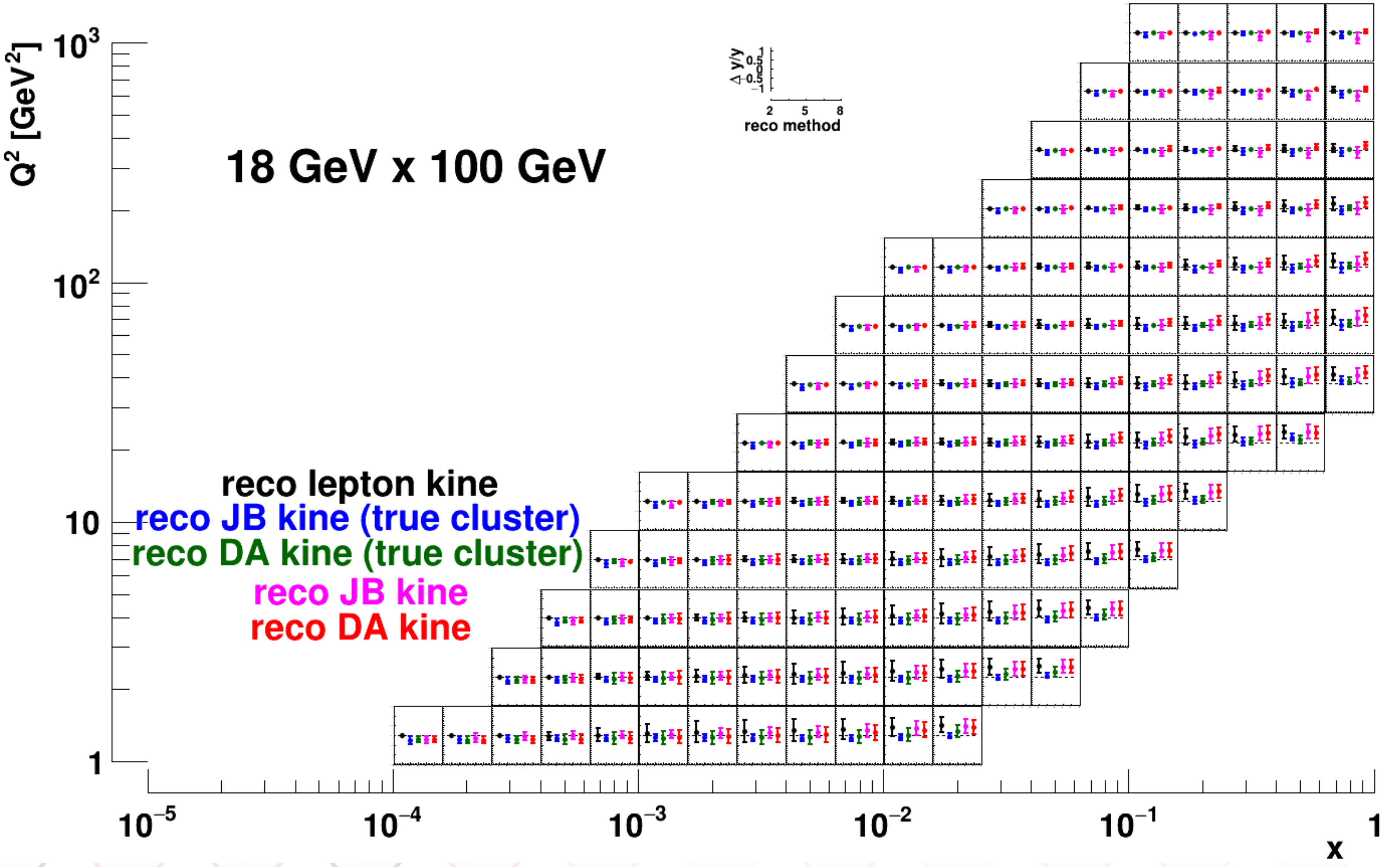


- Low y, lepton shifted and wide, hadronic methods better

Accumulated resolutions

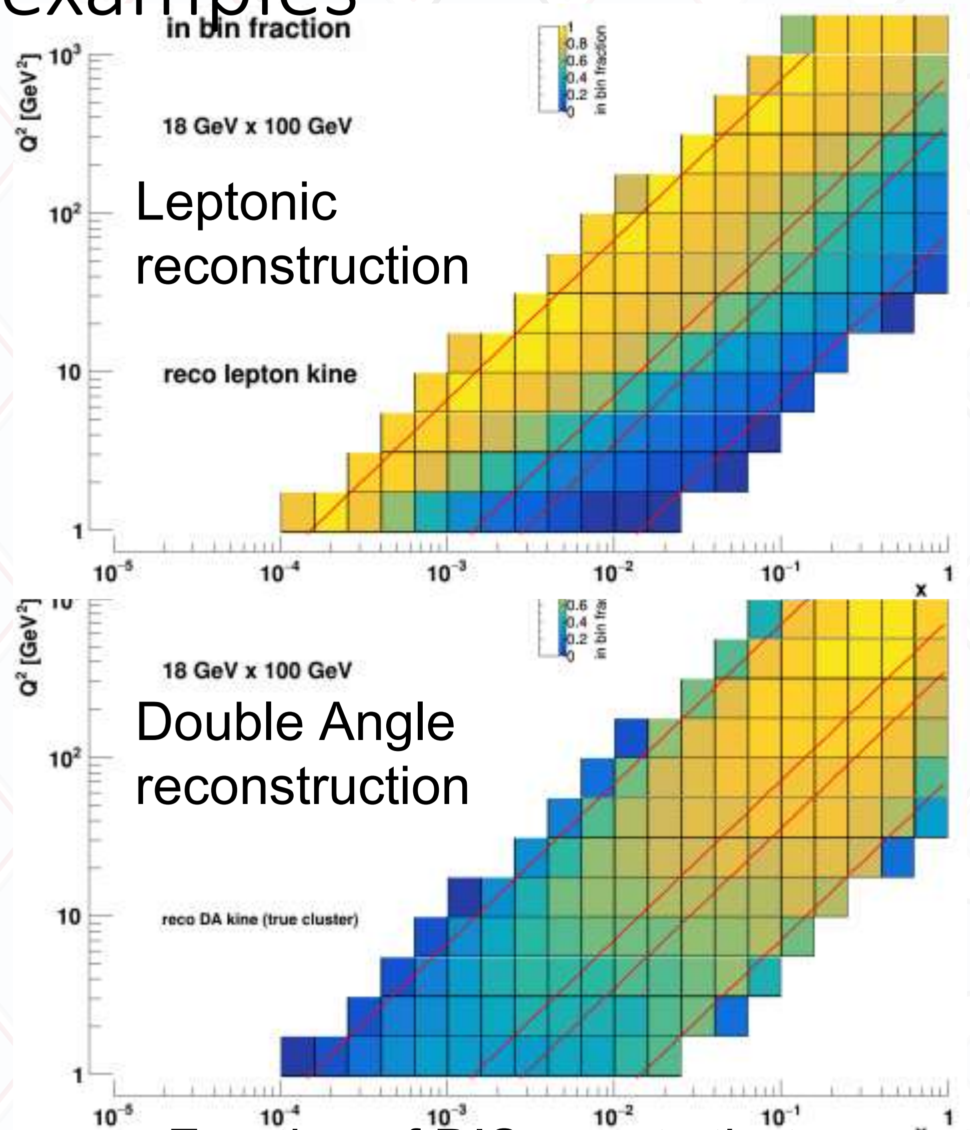


All y resolution widths and means



DIS kinematic reconstruction examples

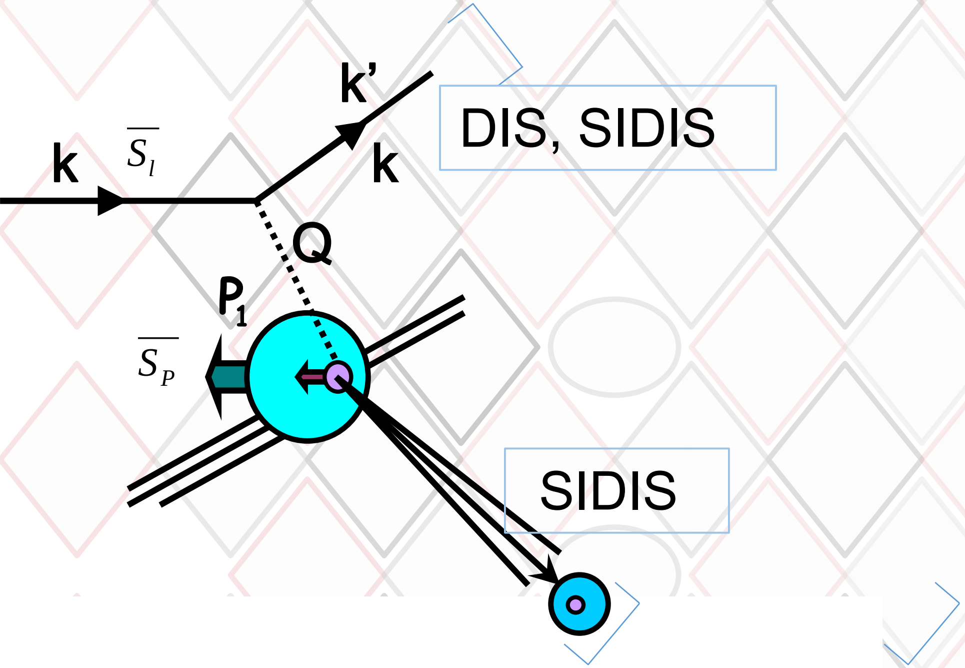
- Full Pythia6+GEANT simulations of the ECCE detector used for various (SI)DIS kinematic resolutions and for various reconstruction methods (lepton, Jaquet-Blondel, Double Angle, etc)
- x and y resolutions suffer from lepton method at lower y, partially recoverable in double angle method(hybrid of scattered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



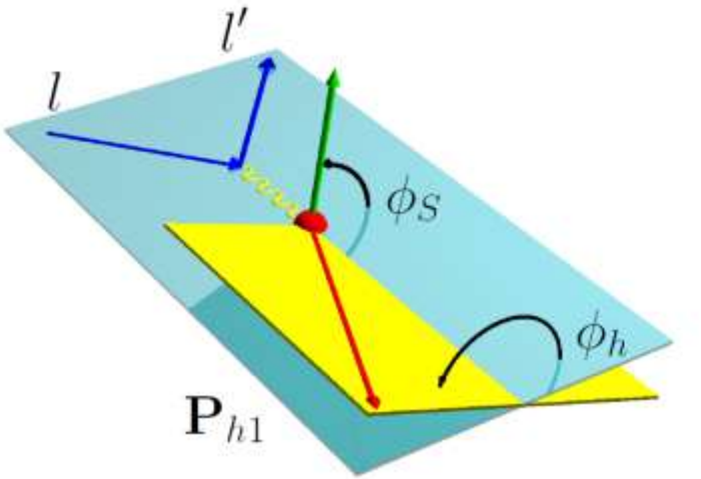
Fraction of DIS events that stay in their x-Q^2 bins

SIDIS Kinematics

Detect also final-state hadron(s) and make use of flavor, etc. sensitivity of Fragmentation functions



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

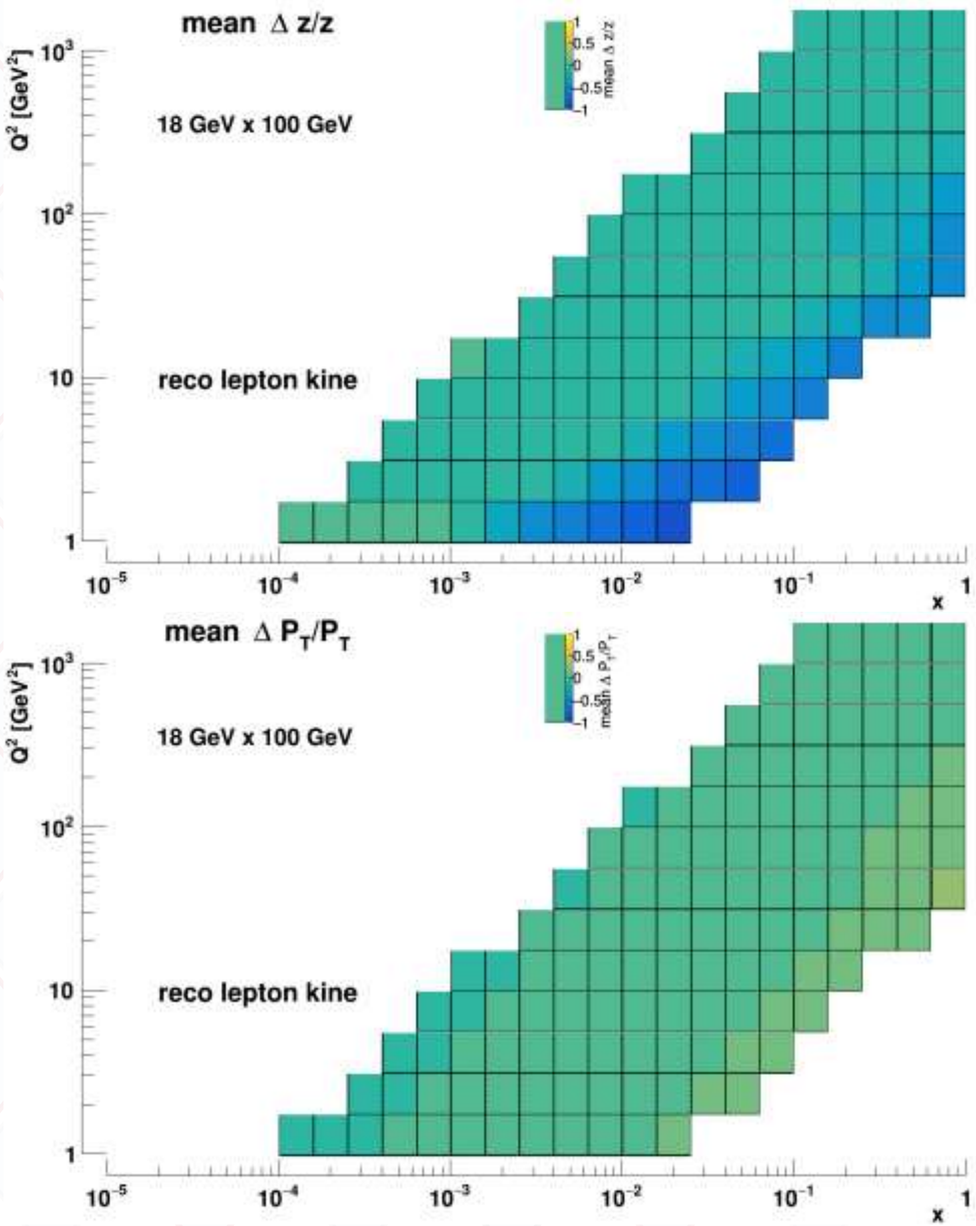


$$\frac{d^6\sigma}{dx\,dQ^2\,dz\,dP_{hT}\,d\phi_S\,d\phi_h} \overset{LO}{\propto} \sum_{q,\bar{q}} e_q^2\, q(x,Q^2,k_t) \otimes D^h_{1,q}(z,Q^2,p_t)$$

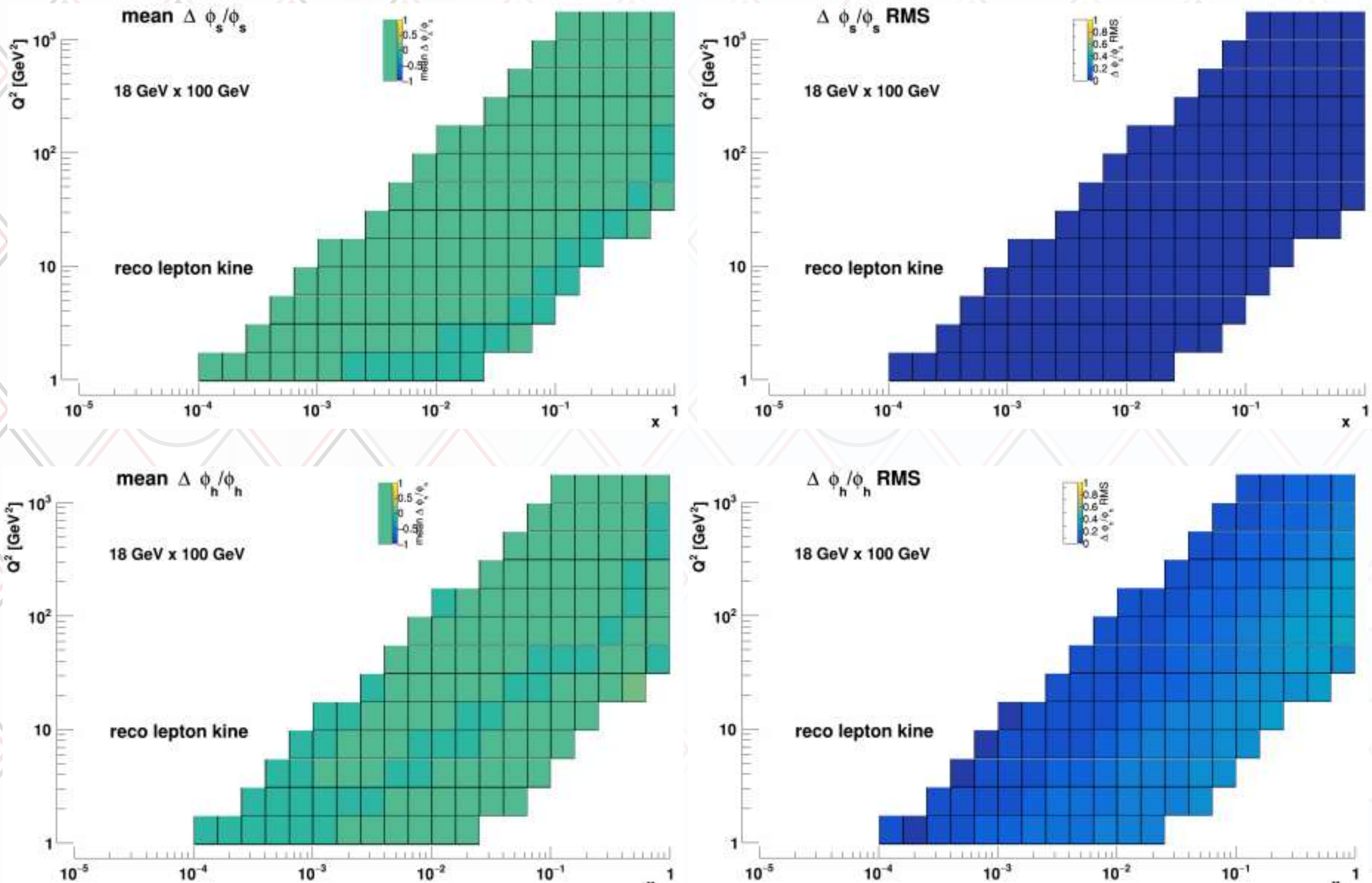
- Transverse momentum and angles rely also on correct boost to hadron rest system
- Current fragmentation: related to struck quark
- Target fragmentation: related to nucleon remnant

Example of resolutions studies

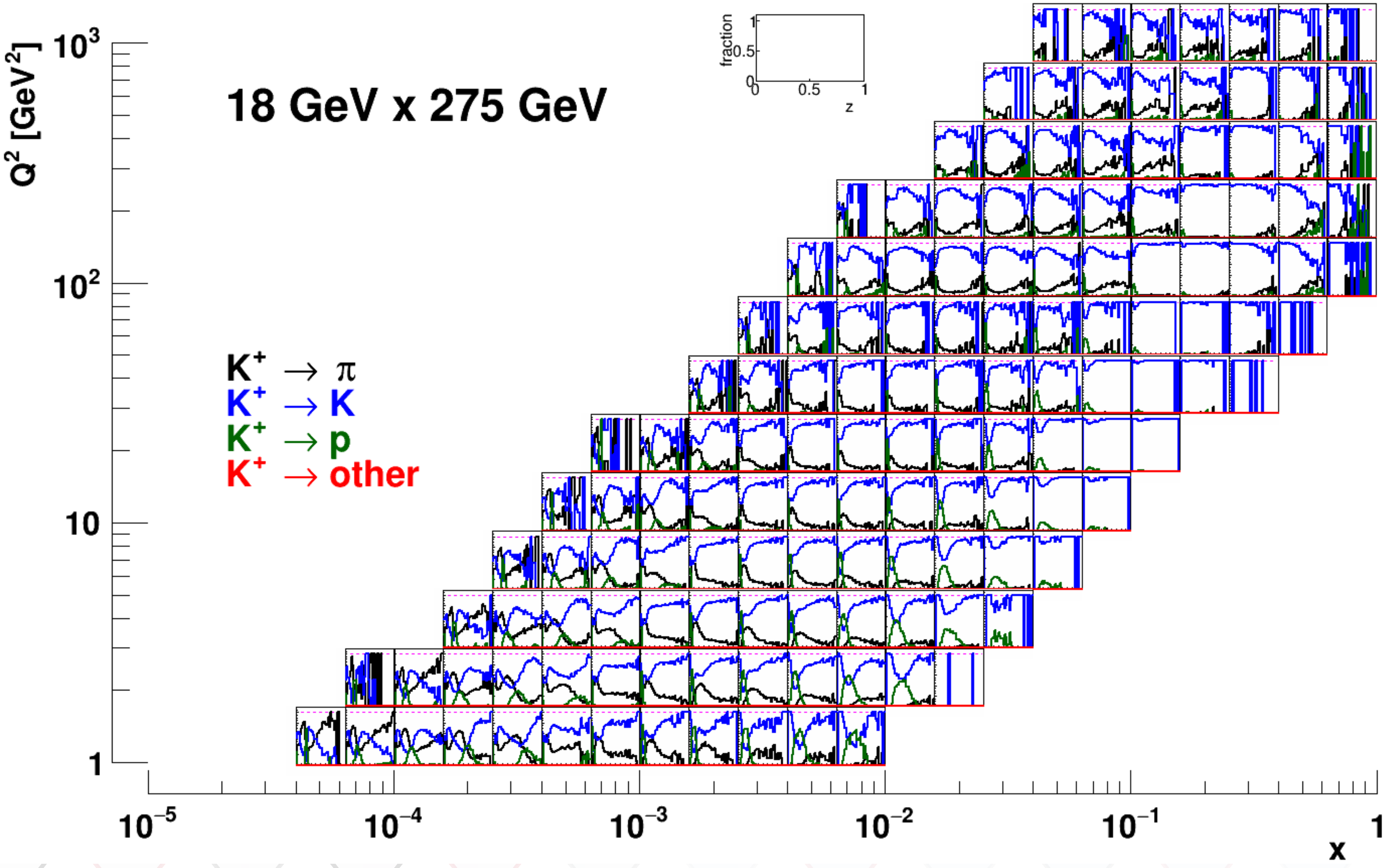
- Full Pythia6+GEANT simulations of the ECCE detector for various (SI)DIS kinematic resolution and reconstruction methods:
  - z resolution suffers in lepton method at lower y, partially recoverable in double angle method
  - p_T and azimuthal angles ϕ_h, ϕ_S very robust



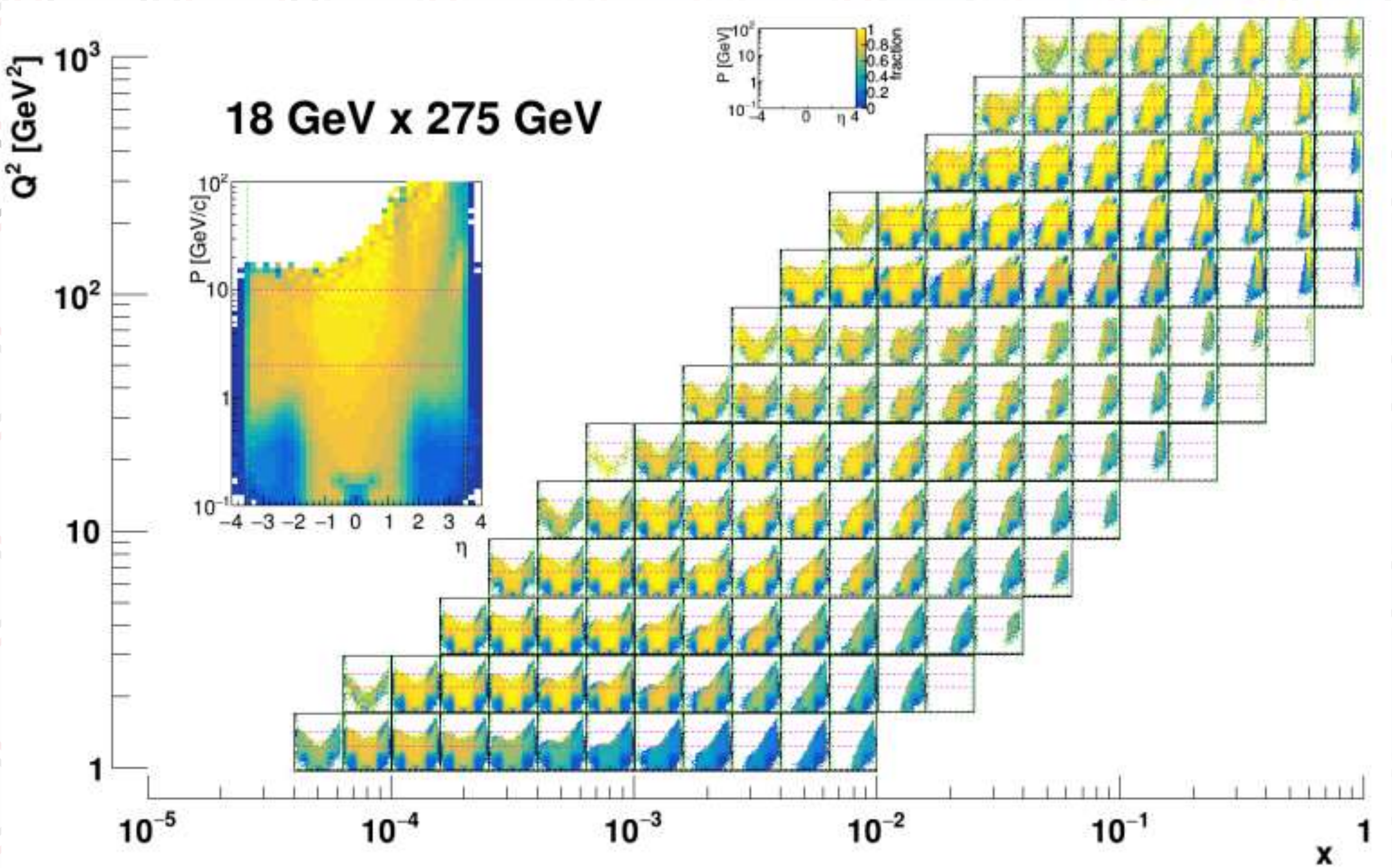
Azimuthal angles



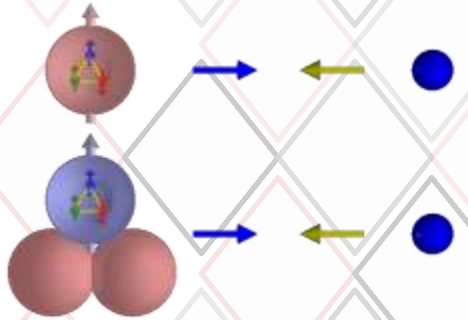
PID efficiencies
(fast PID based on dRICH, DIRC, and mRICH)



Hadron acceptance

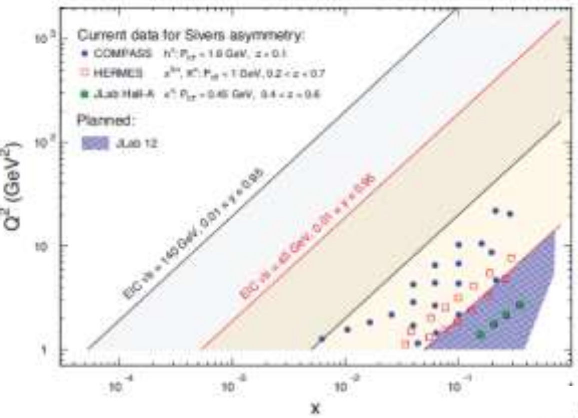


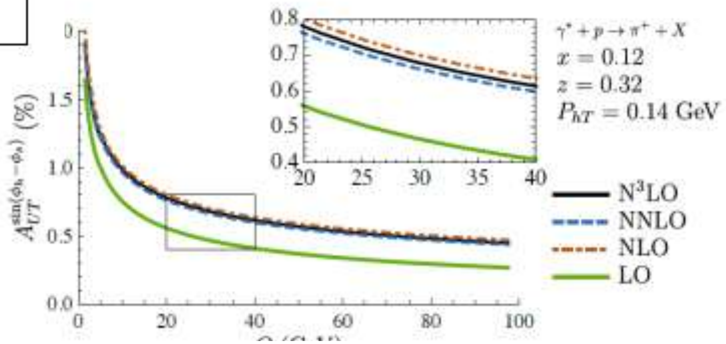
Motivation: 3D Transverse spin and momentum structure

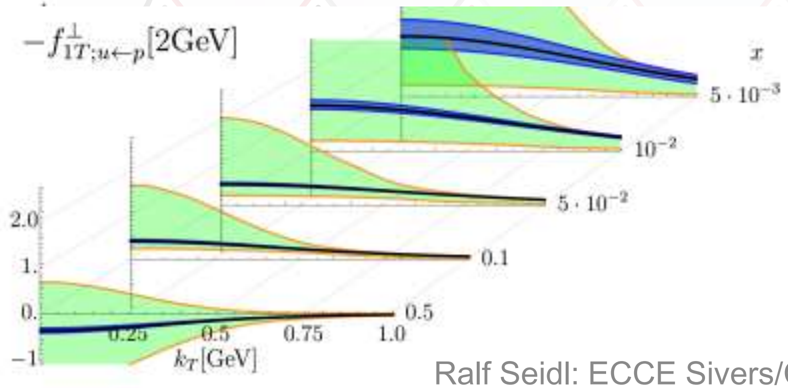


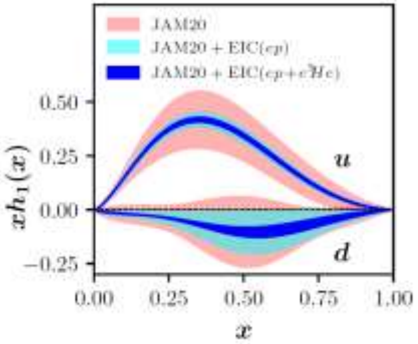
Deliverables	Observables	What we learn	Stage I	Stage II
Sivers & unpolarized TMD quarks and gluon	SIDIS with Transverse polarization; di-hadron (di-jet)	Quantum Interference & Spin-Orbital correlations	3D Imaging of quarks valence+sea	3D Imaging of quarks & gluon; Q^2 (P_{hT}) range QCD dynamics
Chiral-odd 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

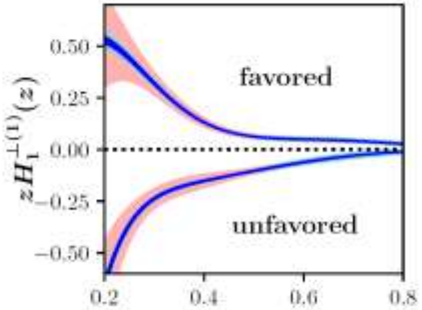
From EIC Yellow Report:







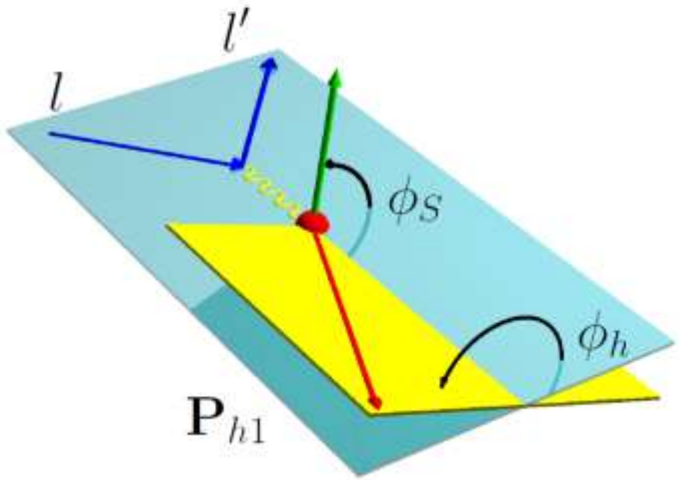




Gamberg et al *Phys.Lett.B* 816 (2021) 136255

Motivation

- Unpolarized TMD distribution and Fragmentation functions are the baseline for all polarized TMD measurements
- Relevant even to heavy boson production (H, W, Z) at LHC
- Also relevant to low-x physics
- Scale dependence in TMD regime still poorly known (as TMD evolution contains non-perturpartive parts)
- Understanding the regions of applicability between TMD, collinear frameworks and target fragmentation, etc



- SIDIS sensitive to convolution of intrinsic transverse momentua from PDF and FF
- Unlike jets (PDF only), detected SIDIS pions/kaons/etc provide flavor sensitivity

ECCE simulation setup and binning

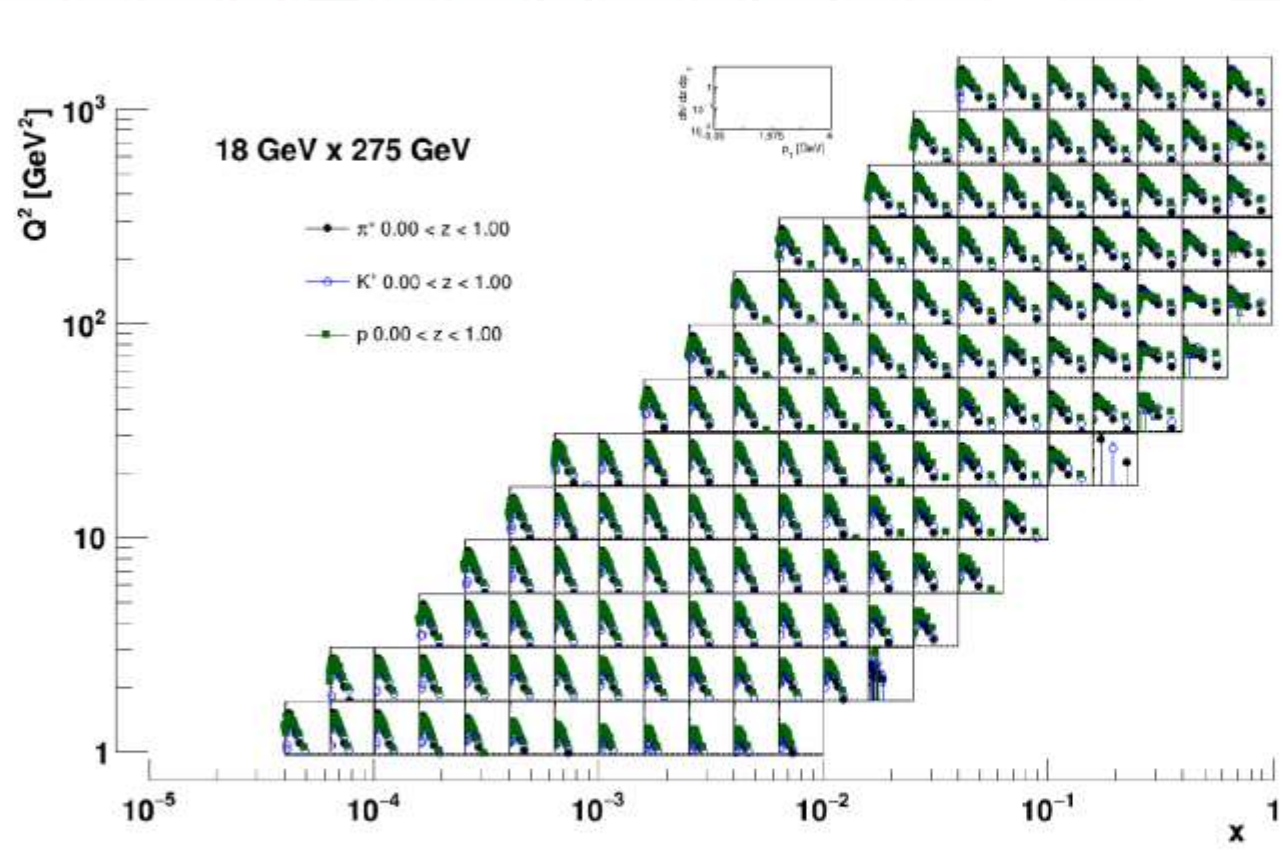
- pythiaeRHIC (Pythia 6) simulations for e+p collisions at 4 energies similar to YR
- Generator output simulated through GEANT4 (prop4)
- Analyzed via slightly modified EventEvaluator TTrees
- Scattered lepton (|η|<3.5) DIS kinematic reconstruction using reco track momenta (assuming perfect eID)
- DIS cuts: $0.01<y<0.95$, $Q^2>1$, $W^2>10\text{GeV}^2$
- SIDIS cuts: pions and kaons (|η|<3.5), using true PID (assuming successful unfolding)
- 25x13x12x12 kinematic bins (x,Q^2,z,P_T)

Energy	Q^2 range	events	Luminosity (fb^{-1})
18x275	1 - 100	38.71M	0.044
	> 100	3.81M	1.232
18x100	1 - 100	14.92M	0.022
	> 100	3.72M	2.147
10x100	1 - 100	39.02M	0.067
	> 100	1.89M	1.631
5x41	1 - 100	39.18M	0.123
	> 100	0.96M	5.944

Kinematic variable	Bin boundaries
x	$1.0x10^{-5}$, $1.59x10^{-5}$, $2.51x10^{-5}$, $3.98x10^{-5}$, $6.31x10^{-5}$, $1.0x10^{-4}$, $1.59x10^{-4}$, $2.51x10^{-4}$, $3.98x10^{-4}$, $6.31x10^{-4}$, $1.0x10^{-3}$, $1.59x10^{-3}$, $2.51x10^{-3}$, $3.98x10^{-3}$, $6.31x10^{-3}$, $1.0x10^{-2}$, $1.59x10^{-2}$, $2.51x10^{-2}$, $3.98x10^{-2}$, $6.31x10^{-2}$, $1.0x10^{-1}$, $1.59x10^{-1}$, $2.51x10^{-1}$, $3.98x10^{-1}$, $6.31x10^{-1}$, 1.0
Q^2	$1.0x10^0$, $1.78x10^0$, $3.16x10^0$, $5.62x10^0$, $1.0x10^1$, $1.78x10^1$, $3.16x10^1$, $5.62x10^1$, $1.0x10^2$, $1.78x10^2$, $3.16x10^2$, $5.62x10^2$, $1.0x10^3$, $1.0x10^4$
z	0., 0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0
P_T	0, 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.5, 2.0, 4.0

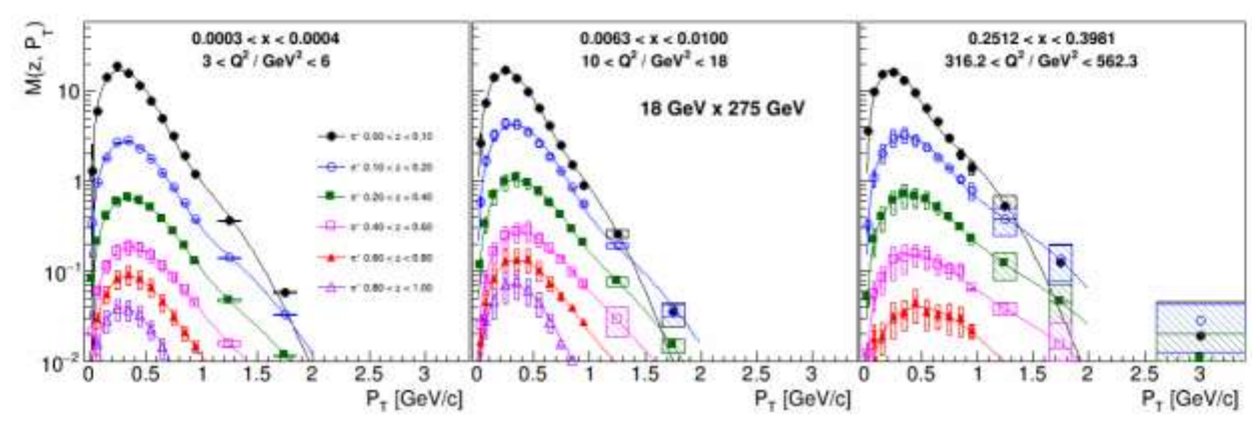
All Multiplicities at highest energies

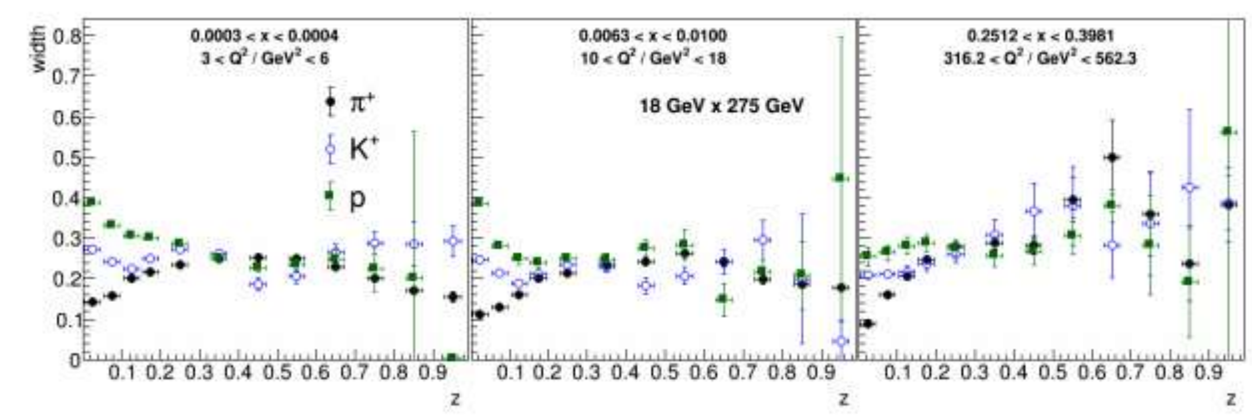
- Pion, kaon and proton multiplicities shown in all x-Q^2 bins as a function of P_T (integrated over z)



z-dependence of multiplicities and widths

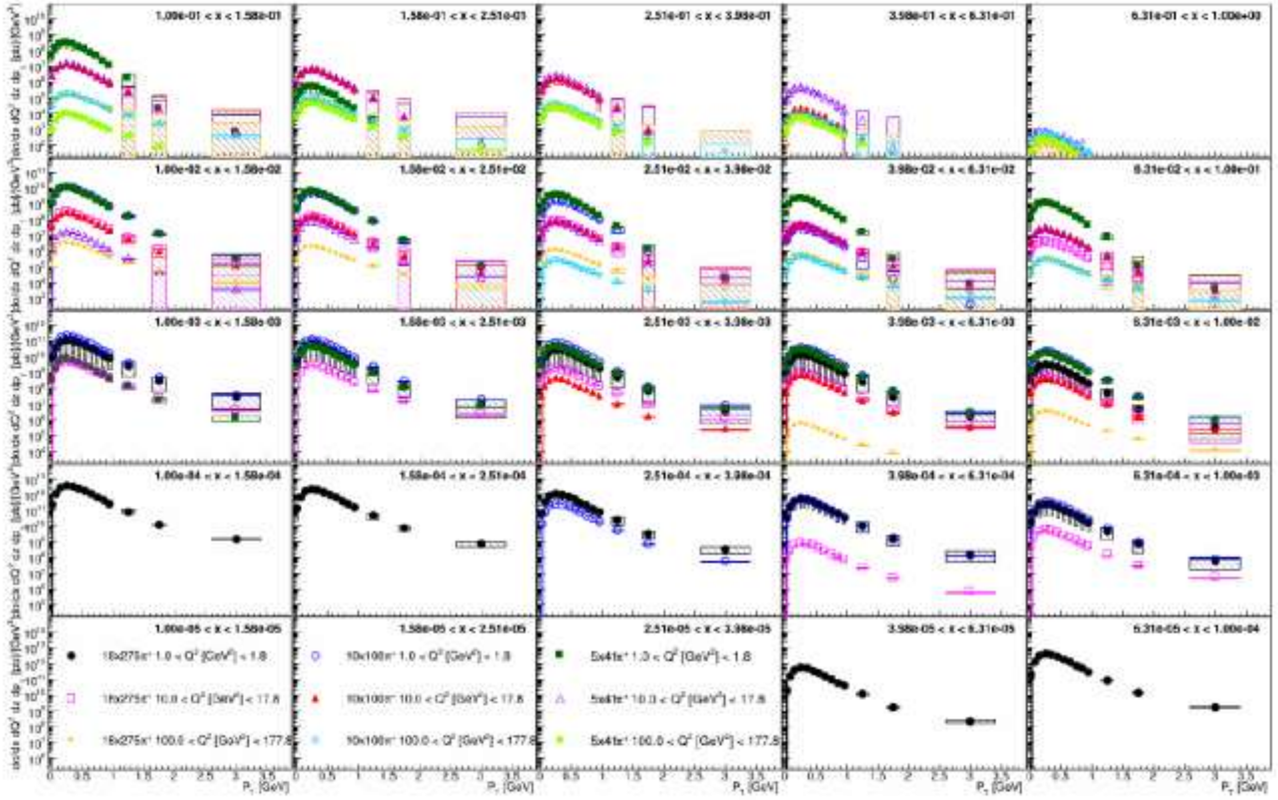
- Top: Explicit z dependence of select pion multiplicities in 3 x-Q^2 bins, including the double-Gaussian fits
- Bottom: behavior of the narrow Gaussian widths vs z for pions, kaons and protons
- Small z discrepancies likely due to target fragmentation





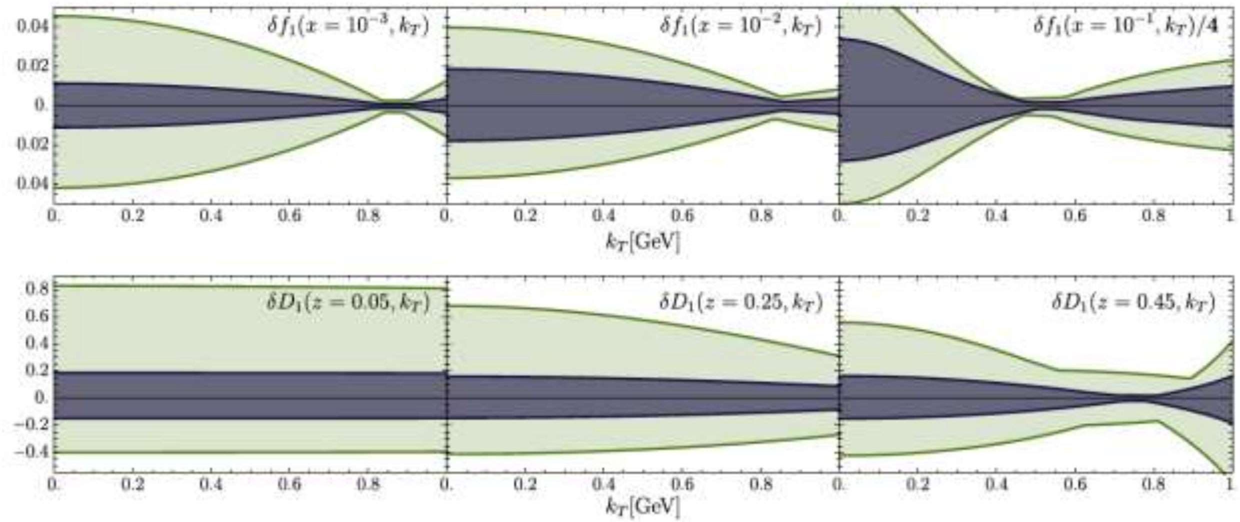
Combination of several collision energies

- Z-integrated PT dependent cross sections for several x and Q2 bins and various collision energies



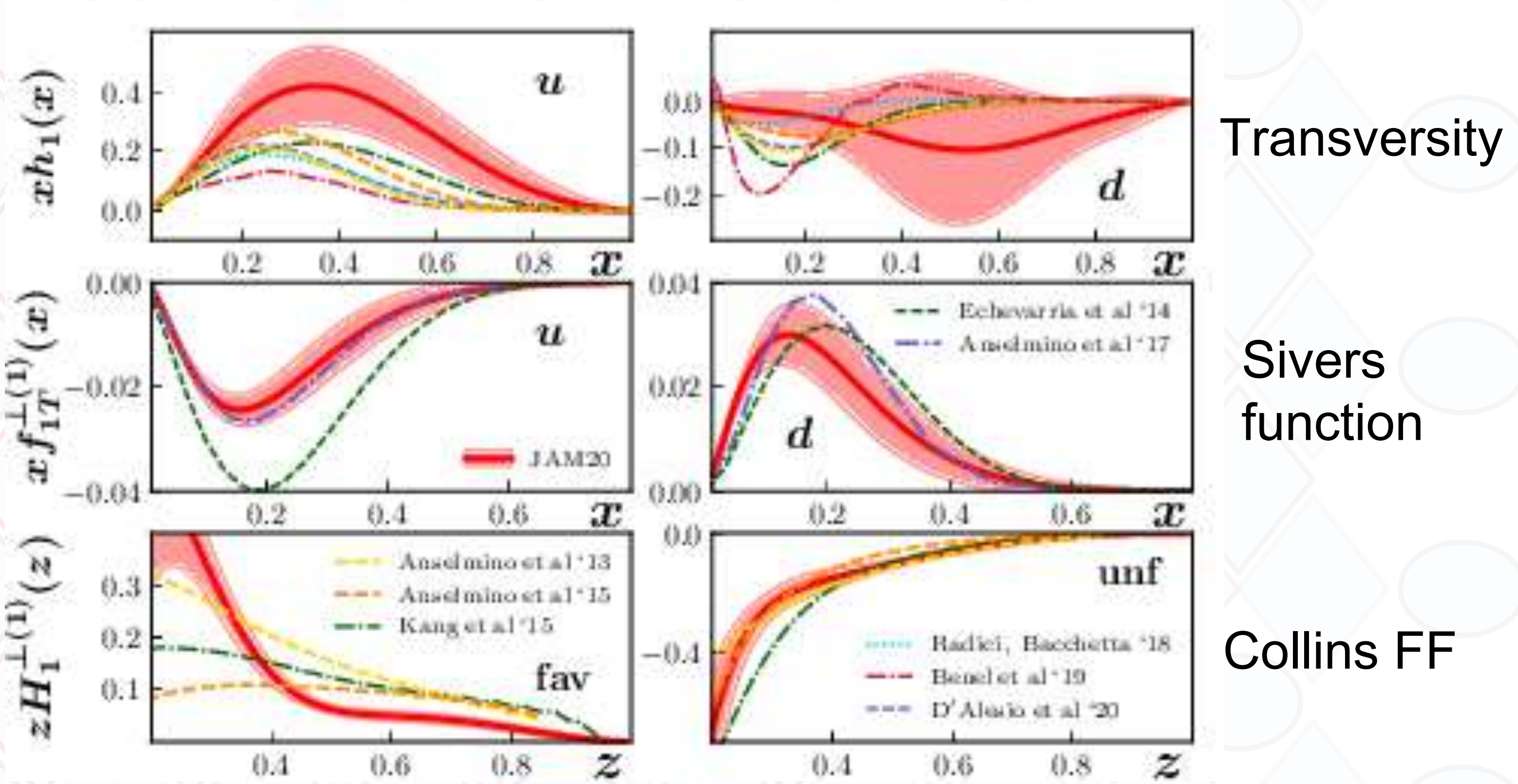
Impact for unpolarized TMD functions

- Similar to YR impact studies following the latest SV global fit (https://arxiv.org/abs/1912.0653 2) for the unpolarized TMDs based on the existing SIDIS +DY data
- Impact figure still that from YR, needs to be replaced (but little differences expected)



Current knowledge on these functions

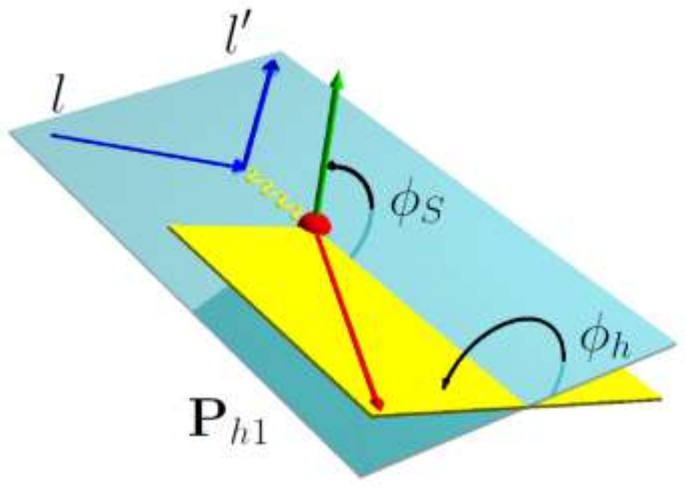
- Only valence quark Sivers and Transversity functions known at this time with substantial uncertainties
- Experimentally covered range 0.01 < x < 0.3
- So far no sensitivity to sea quarks and gluons* and lower x



Cammarota et al, PRD 102 (2020) 054002

Experimental access to transversity and Sivers function

- Both functions are accessible as different azimuthal modulations in transversely polarized SIDIS of single hadrons
- 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 (only partially studied in ECCE so far → needs to be addressed soon)



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

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

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- Analyzed via slightly modified EventEvaluator TTrees
- Scattered lepton (|η|<3.5) DIS kinematic reconstruction using reco track momenta (assuming perfect eID)
- DIS cuts: $0.01<y<0.95$, $Q^2>1$, $W^2>10\text{GeV}^2$
- SIDIS cuts: pions and kaons (|η|<3.5), using true PID (assuming successful unfolding)
- Initially 12x8x12x12 kinematic bins (x,Q^2,z,P_T) and 16x16 azimuthal bins

Energy	Q^2 range	events	Luminosity (fb^{-1})
18x275	1 - 100	38.71M	0.044
	> 100	3.81M	1.232
18x100	1 - 100	14.92M	0.022
	> 100	3.72M	2.147
10x100	1 - 100	39.02M	0.067
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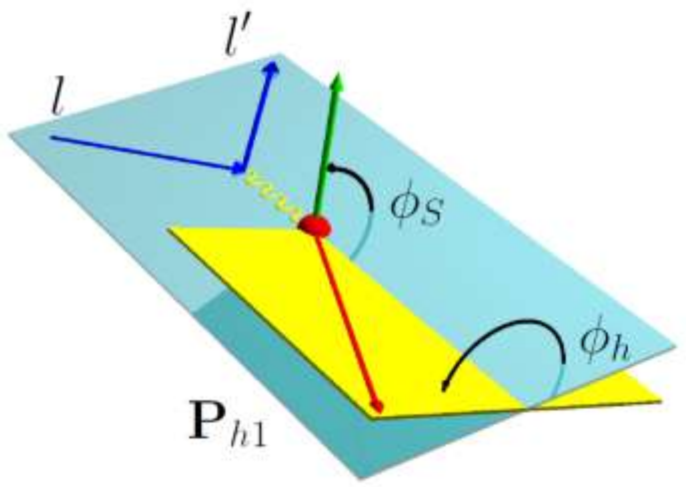
	> 100	0.96M	5.944

Kinematic variable	Bin boundaries
x	$1.0x10^{-4}$, $2.154x10^{-4}$, $4.641x10^{-4}$, $1.0x10^{-3}$, $2.154x10^{-3}$, $4.641x10^{-3}$, $1.0x10^{-2}$, $2.154x10^{-2}$, $4.641x10^{-2}$, $1.0x10^{-1}$, $2.154x10^{-1}$, $4.641x10^{-1}$, $1.0x10^{0}$
Q^2	$1.0x10^{0}$, $3.162x10^{0}$, $1.0x10^{1}$, $3.162x10^{1}$, $1.0x10^{2}$, $3.162x10^{2}$, $1.0x10^{3}$, $3.162x10^{3}$, $1.0x10^{4}$
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
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

Sivers/Collins measurements in SIDIS

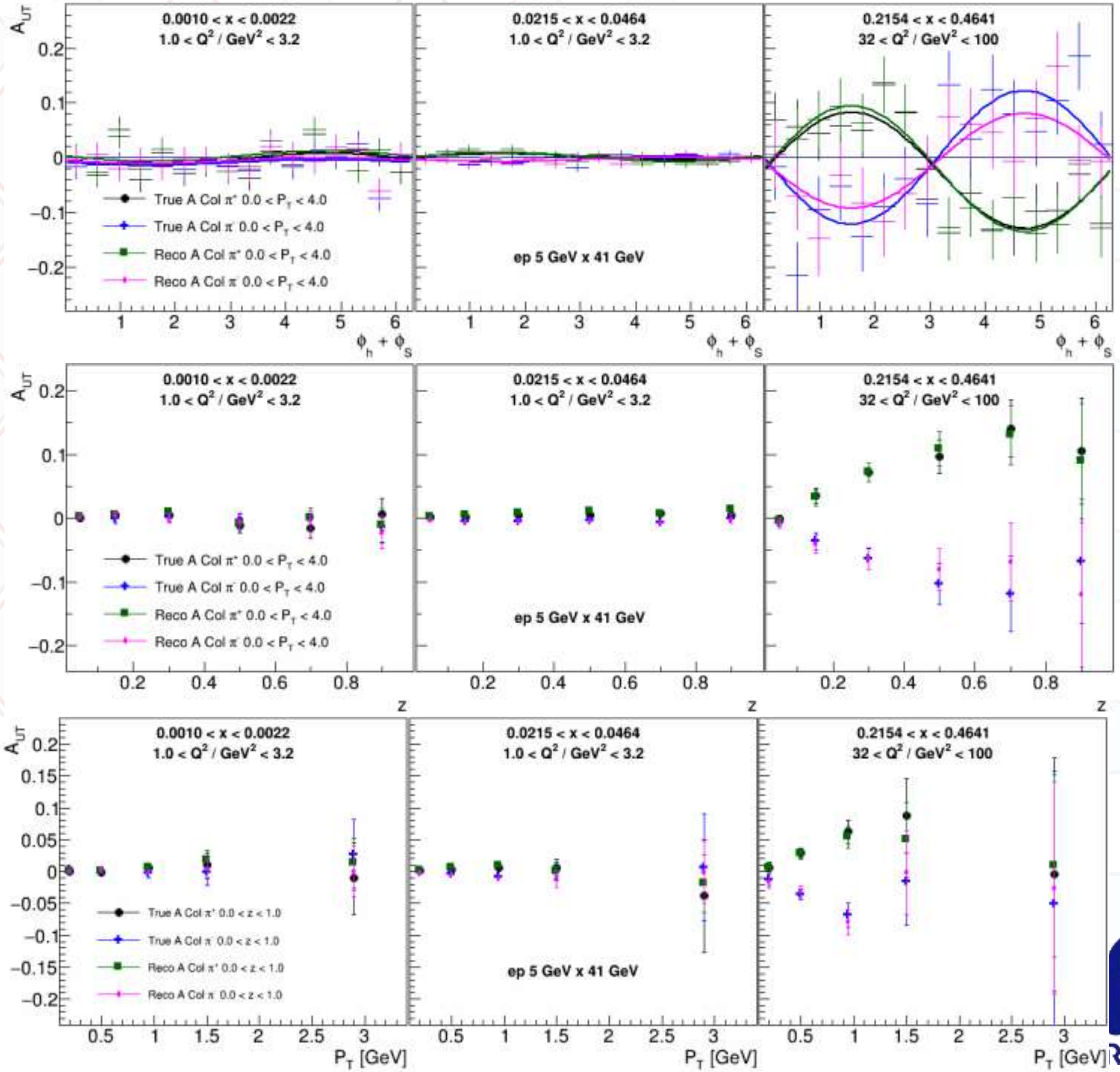
- Reweight events according to true parton flavor q, hadron h, x, z, Q^2, P_{hT}, azimuthal angles and random spin orientation
- $ep^{\uparrow} \rightarrow e'hX$
- A_{UT} asymmetries (Unpolarized lepton beam, Transversely polarized target)
- Different azimuthal modulations related to Sivers effect ($\sin(\phi-\phi_s)$) and Collins effect ($\sin(\phi+\phi_s)$)
- Fit simultaneously in the reconstructed events and calculate asymmetries



- Input structure functions (polarized and unpolarized) from Torino global fits (arXiv:0812.4366, arXiv:0805.2677) as in https://github.com/prokudin/tmd-parametrizations/

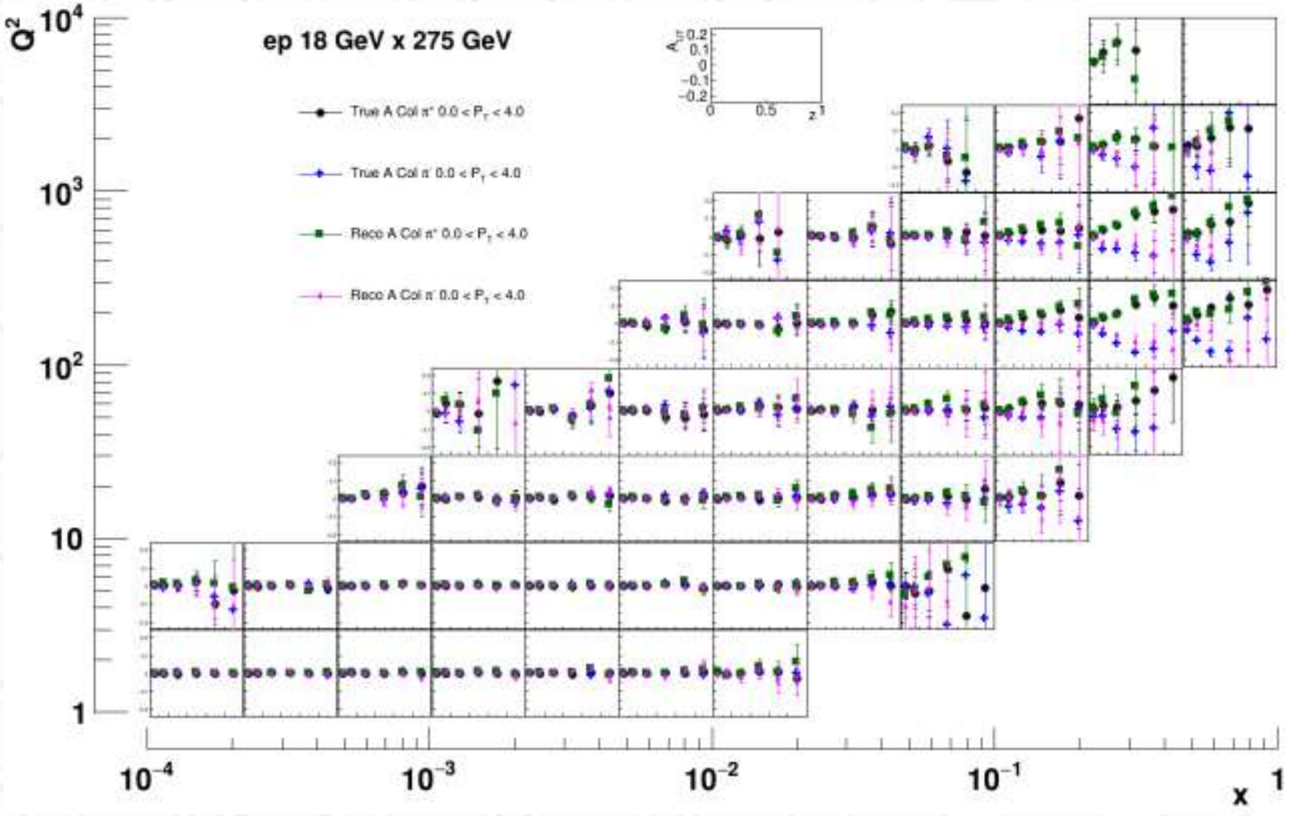
Example figures

- Examples in 3 x and Q2 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



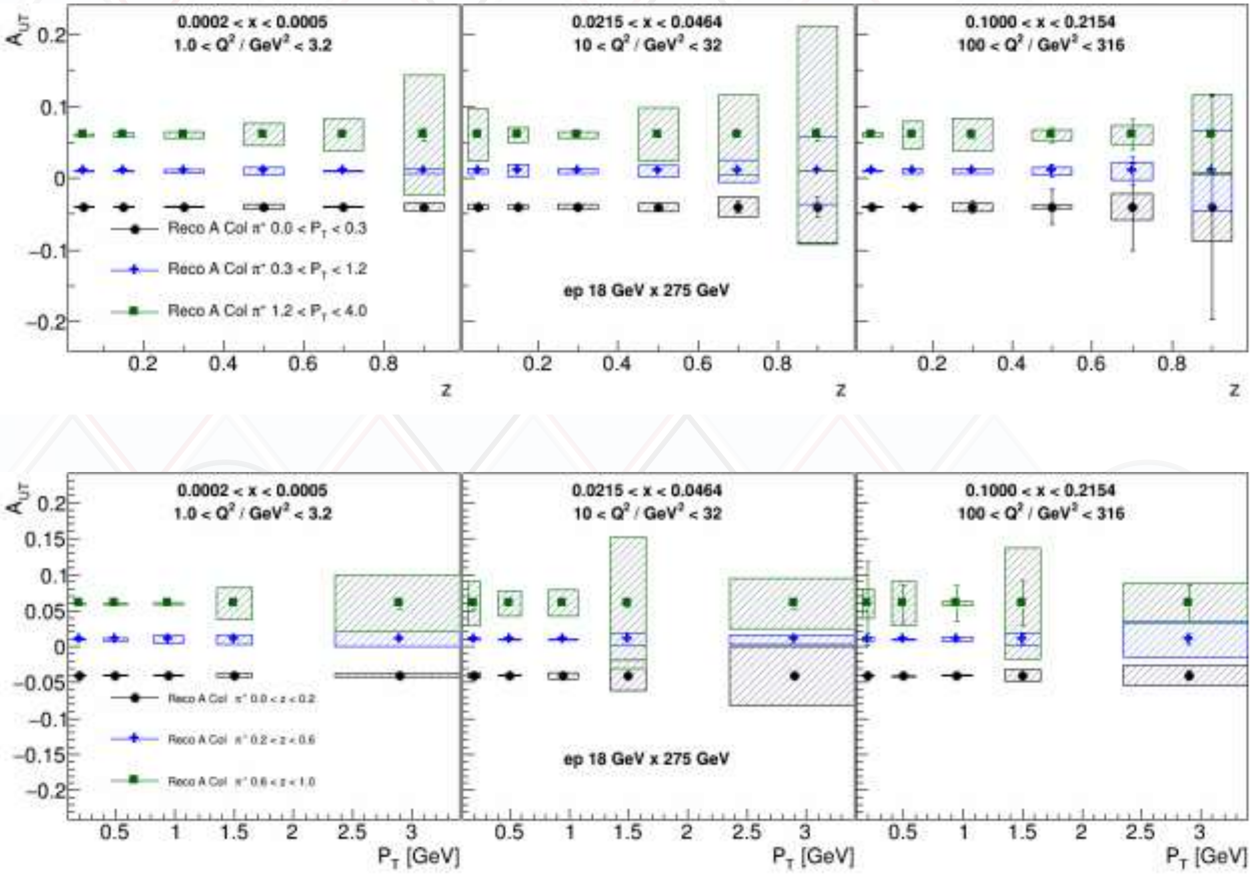
Collins asymmetries at highest energies

- Example of the level of reconstruction and uncertainties give the simulated statistics
- Nonzero asymmetries well reproduced at higher x
- Opposite sign for π^+/π^- seen as expected
- High precision at lower (yet hardly measured) x



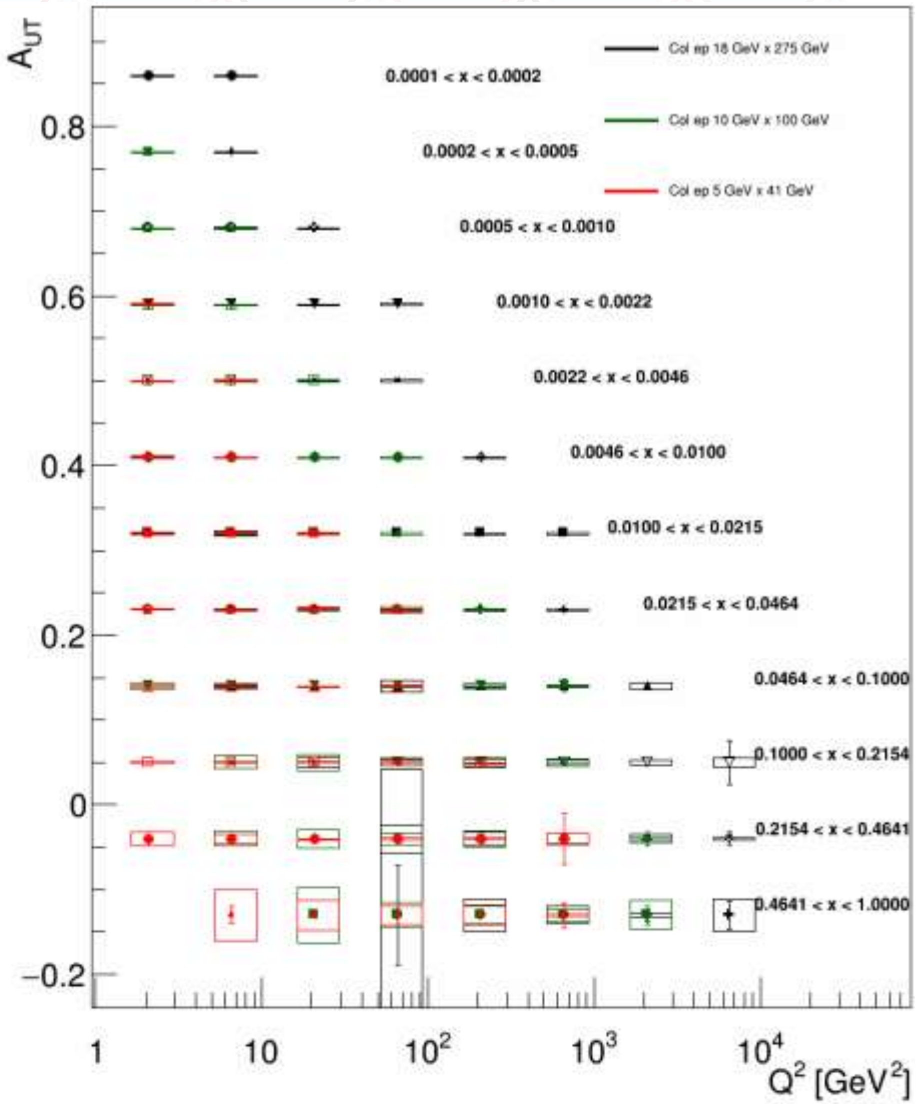
Projections to 10fb^{-1}

- 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



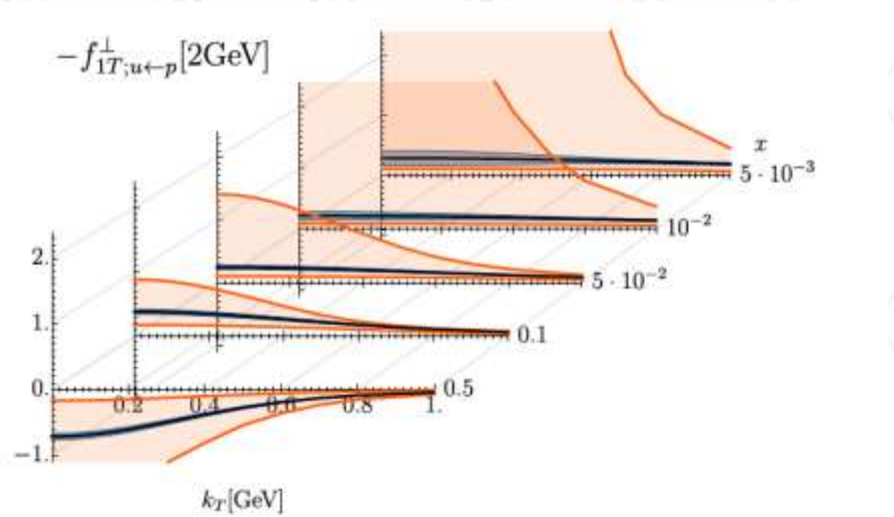
Scale dependence (and interplay of collision energies)

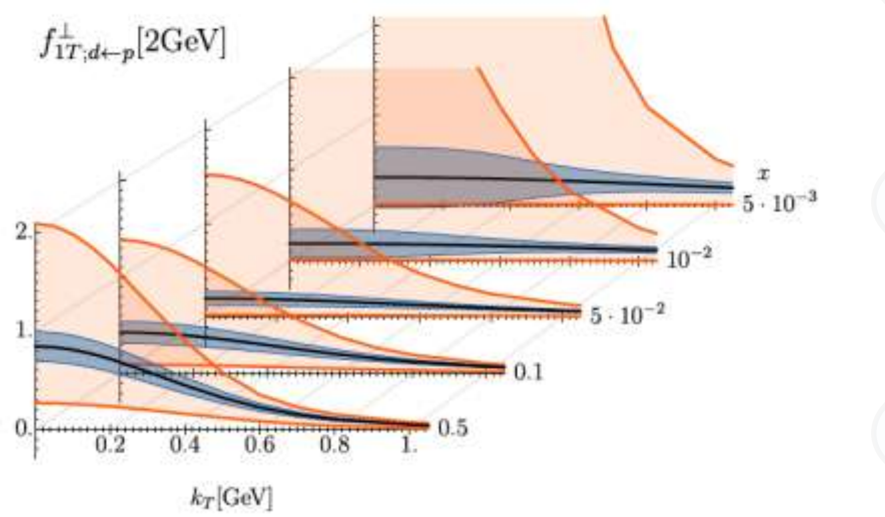
- An example of the expected uncertainties in x and Q^2 to study the scale dependence of the Sivers/Collins asymmetries (as TMD evolution is not very well known/contains other nonperturbative pieces)
- Overlap of the different energies shows how they increase the lever arm
- Note: in future evolution analysis likeely more Q^2 bins and maybe not as fine x binning



Impact for Sivers functions

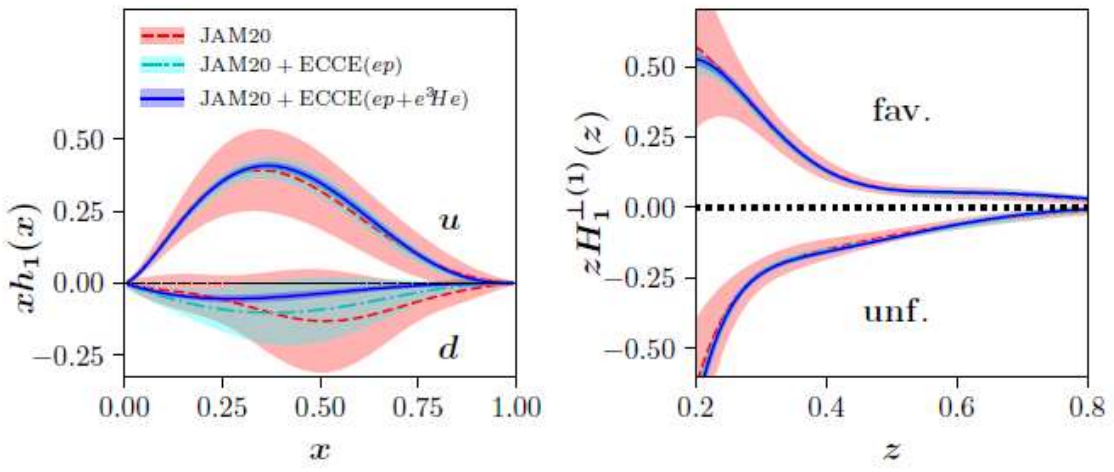
- Similar to YR impact studies following the latest BPV global fit (arXiv:2103.03270) for the Sivers function based on the existing SIDIS +DY data
- Uncertainties are shown for current level of knowledge on up/down Sivers functions at various x vs kt and expected impact from ECCE

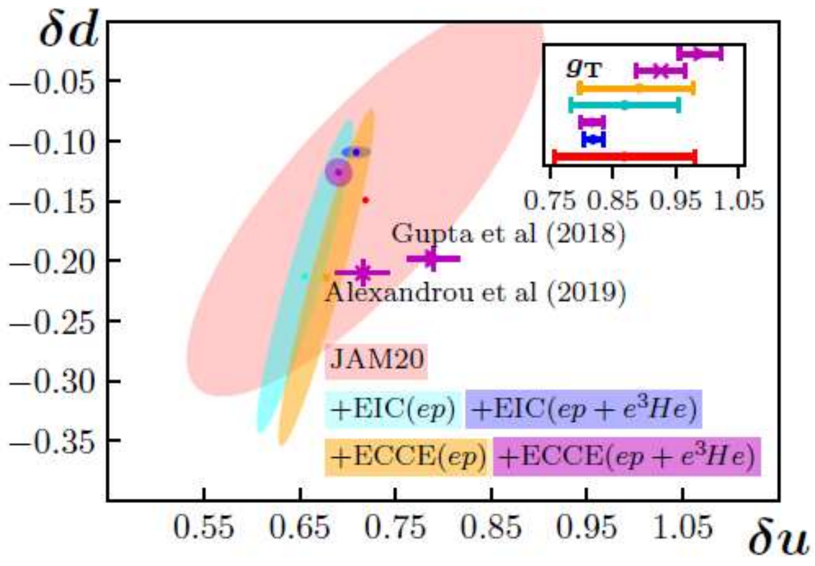




Tensor charge impact

- 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)





Summary

- Full GEANT simulations to study the reconstruction of DIS and SIDIS variables using various reconstruction methods (lepton, DA, JB)

➔Follow up with further studies as detector evolves:
  - Add EMCAL info where better for electron DIS reconstruction
  - Add Sigma method, study hadronic methods' tracking vs cluster performance more (currently only clusters if trackless – neutrals)
  - Optimize interplay between best methods

- Unpolarized and Sivers/Collins TMD SIDIS studies performed using full GEANT simulations, impact plots prepared

➔Follow up on these studies as project detector evolves:
  - Improved DIS kinematics reconstruction/different methods
  - consider studying the proper unfolding of kinematic smearing as well as particle identification
  - Radiative effects
  - Consider more explicit TMD evolution studies

DIS Kinematic reconstruction using hadronic Final State:

- JB method: use only hadronic final state

$$y_{JB} = \frac{E_p \sum_h E_h - p_{z,p} \sum_h p_{z,h} - m_p^2}{E_p E_e - p_{z,p} p_{z,e}}$$

$$Q^2_{JB} = \frac{\sum_h p^2_{x,h} + \sum_h p^2_{y,h}}{1-y}$$

$$x_{JB} = \frac{Q^2}{ys}$$

- Double Angle method: use both

$$y_{DA} = \frac{\tan\theta_h/2}{\tan\theta_e/2 + \tan\theta_h/2}$$

$$Q^2_{DA} = \frac{4E_2^2}{\tan\theta_e/2\,(\tan\theta_e/2 + \tan\theta_h/2)}$$

$$x_{DA} = \frac{Q^2}{ys}$$

$$\tan\theta_h/2 = \frac{\sum_h E_h - \sum_h p_{z,h}}{\sqrt{\sum_h p^2_{x,h} + \sum_h p^2_{y,h}}}$$