ECCE
impact paper preparations

ECCE bi-weekly meeting
April 11, 2022

Ralf Seidl (RIKEN)
Theory/Pheno contributions:
Alexey Vladimirov (Regensburg)

General plan

- Many of the notes that were developed for the ECCE proposal are planned to be published
- Currently all will be part of the same NIM volume, but can be published at different times, following interim publication policy, yesterday also some talk to publish physics related topics in PRC (Richard) or PRD
- All ECCE participants will be authors, choice of order for first authors if developed by a few people, addition of other contributors (theorists) possible

List of planned ECCE papers

ecce-note-comp-2021-01	Computing plan	David Lawrence & Cristiano Fanelli	https://github.com/ecce-notes/ecce-note-comp-2021-01
ecce-note-comp-2021-02	Simulation note	Cameron, Jin, Joe	https://github.com/ecce-notes/ecce-note-comp-2021-02
ecce-note-comp-2021-03	Software tools	Joe, David, Cristiano Fanelli	https://github.com/ecce-notes/ecce-note-comp-2021-03
ecce-paper-phys-2022-01	eA diffractive paper	Peter et al	https://github.com/ecce-papers/ecce-paper-phys-2022-01
ecce-paper-phys-2022-02	diffractive and tagging paper	A. Schmidt, et al	https://github.com/ecce-papers/ecce-paper-phys-2022-02
ecce-paper-comp-2022-01	AI/ML PID	Cristiano &	https://github.com/ecce-papers/ecce-paper-comp-2022-01
ecce-paper-comp-2022-02	AI/ML tracking	Cristiano & Xuan	https://github.com/ecce-papers/ecce-paper-comp-2022-02
ecce-paper-det-2022-01	ECCE detector paper	Ken & Doug	https://github.com/ecce-papers/ecce-paper-det-2022-01
ecce-paper-det-2022-02	ECCE calo paper	Fredi & Nico	https://github.com/ecce-papers/ecce-paper-det-2022-02
ecce-paper-det-2022-03	ECCE tracking paper	Xuan	https://github.com/ecce-papers/ecce-paper-det-2022-03
ecce-paper-phys-2022-03	SIDIS double spin asym.	Charlotte	https://github.com/ecce-papers/ecce-paper-phys-2022-03
ecce-paper-phys-2022-04	HF	Xuan	https://github.com/ecce-papers/ecce-paper-phys-2022-04
ecce-paper-phys-2022-05	Jets	Rosi, Ping, et.al	https://github.com/ecce-papers/ecce-paper-phys-2022-05
ecce-paper-phys-2022-06	SMEFT/EW	Xiaochao	https://github.com/ecce-papers/ecce-paper-phys-2022-06
ecce-paper-phys-2022-07	SIDIS kinematics	Ralf Seidl	https://github.com/ecce-papers/ecce-paper-phys-2022-07
ecce-paper-phys-2022-08	SIDIS spin asymmetries with single hadrons	Ralf Seidl	https://github.com/ecce-papers/ecce-paper-phys-2022-08
ecce-paper-phys-2022-09	SIDIS unpolarized TMD measurements	Ralf Seidl	https://github.com/ecce-papers/ecce-paper-phys-2022-09
ecce-paper-phys-2022-10	Inclusive	Tyler & Claire	https://github.com/ecce-papers/ecce-paper-phys-2022-10
ecce-paper-phys-2022-11	j/psi at threshold	Xinbai & Wangmei	https://github.com/ecce-papers/ecce-paper-phys-2022-11
ecce-paper-det-2022-04	ECCE upgrade paper	Ken & Doug	https://github.com/ecce-papers/ecce-paper-det-2022-04

ECCE unpolarized TMD measurements impact paper preparation

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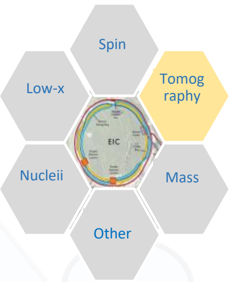
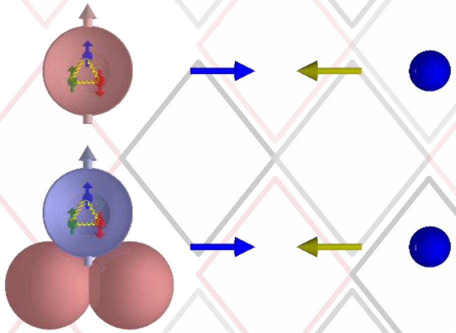
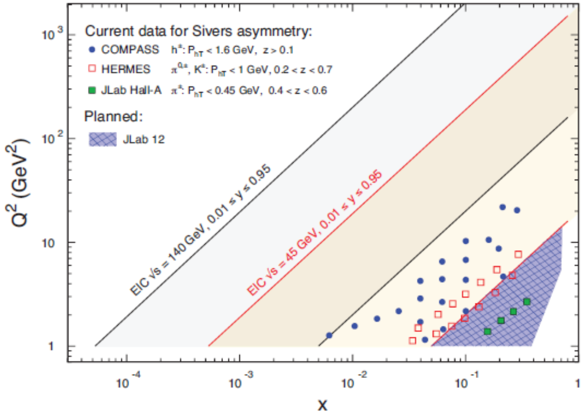


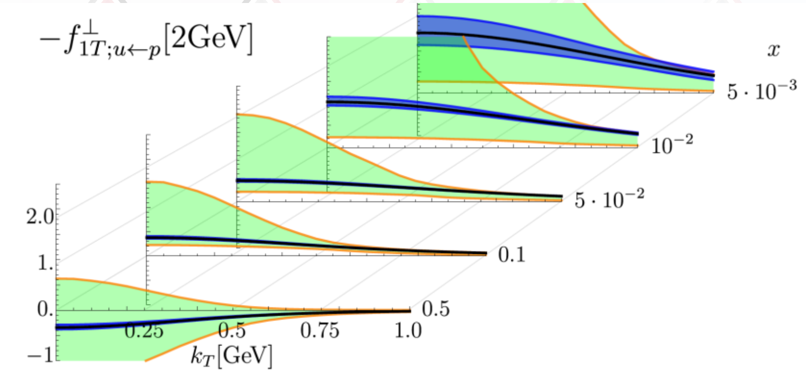
Motivation: 3D Transverse spin and momentum structure

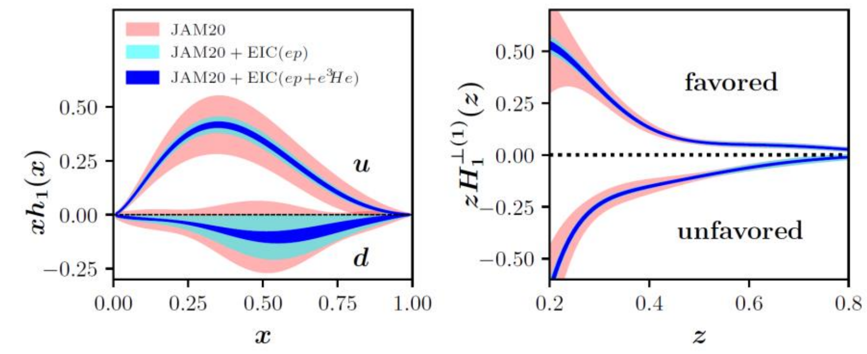


Deliverables	Observables	What we learn	Stage I	Stage II
Sivers & unpolarized TMD quarks and gluon	SIDIS with Transverse polarization; di-hadron (di-jet)	Quantum Interference & Spin-Orbital correlations	3D Imaging of quarks valence+sea	3D Imaging of quarks & gluon; Q^2 (P_{hT}) range QCD dynamics
Chiral-odd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

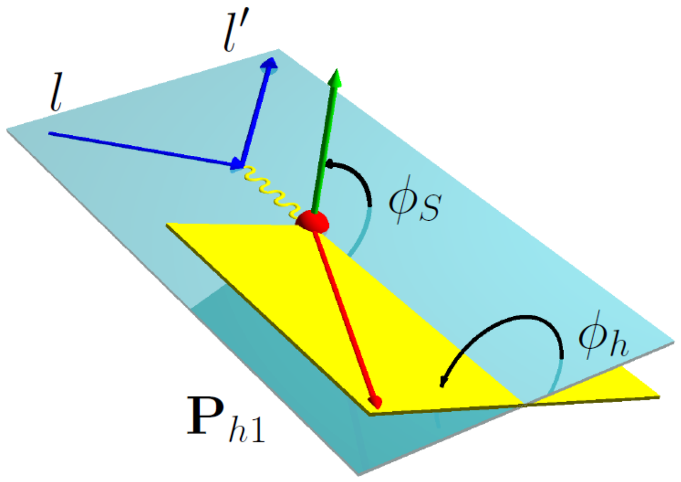




[Gamberg et al *Phys.Lett.B* 816 (2021) 136255]

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

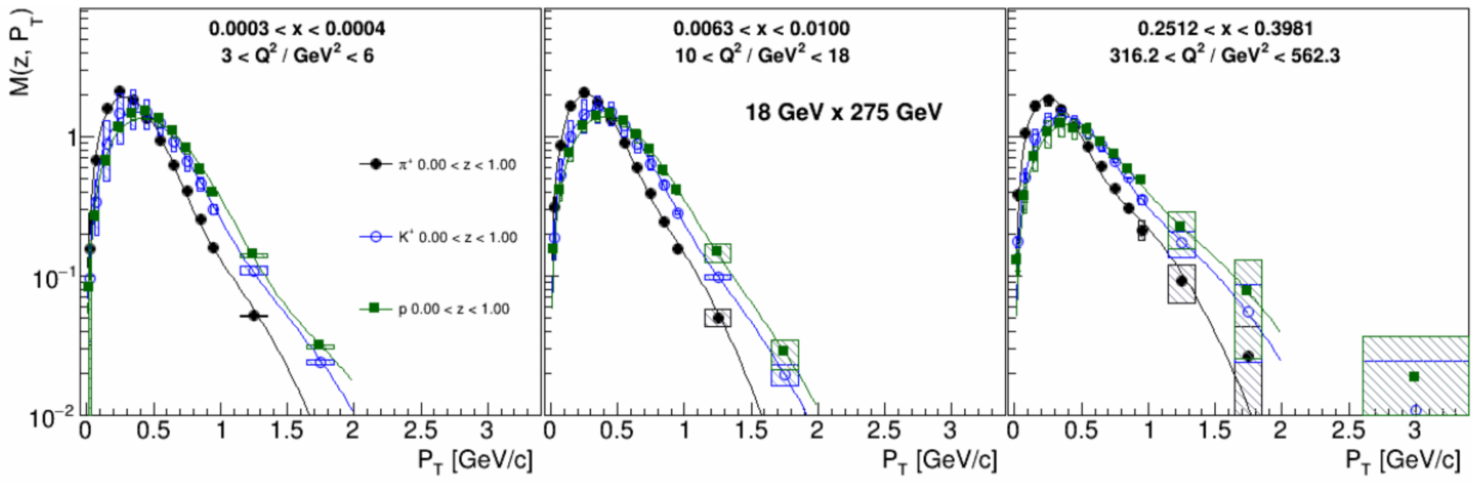
- pythiaeRHIC (Pythia 6) simulations for e+p collisions at 4 energies similar to YR
- Generator output simulated through GEANT4 (prop4)
- Analyzed via slightly modified EventEvaluator TTrees
- Scattered lepton (|η|<3.5) DIS kinematic reconstruction using reco track momenta (assuming perfect eID)
- DIS 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

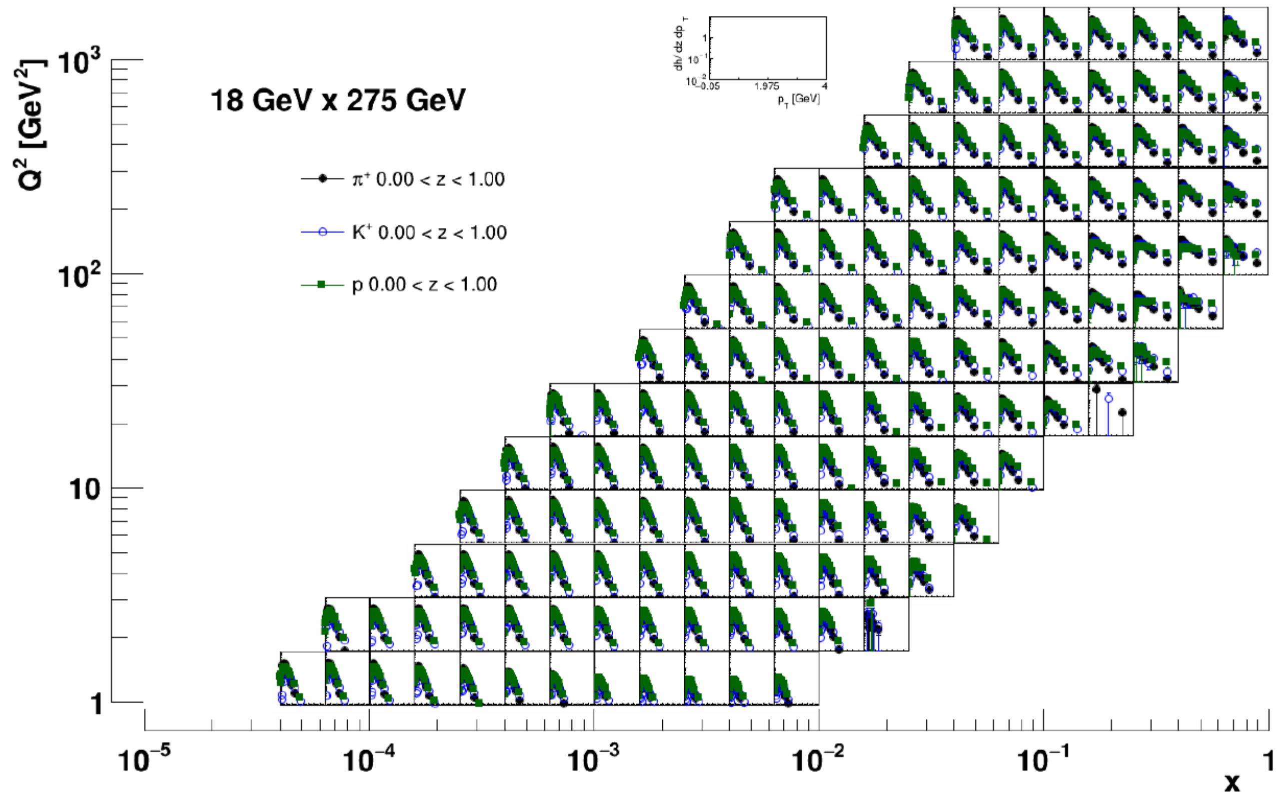
Example figures

- Examples in 3 x and Q^2 bins: Multiplicities for pions, kaons and protons vs P_T (integrated over z)
- Fits of double-Gaussians for low/high P_T behavior also shown



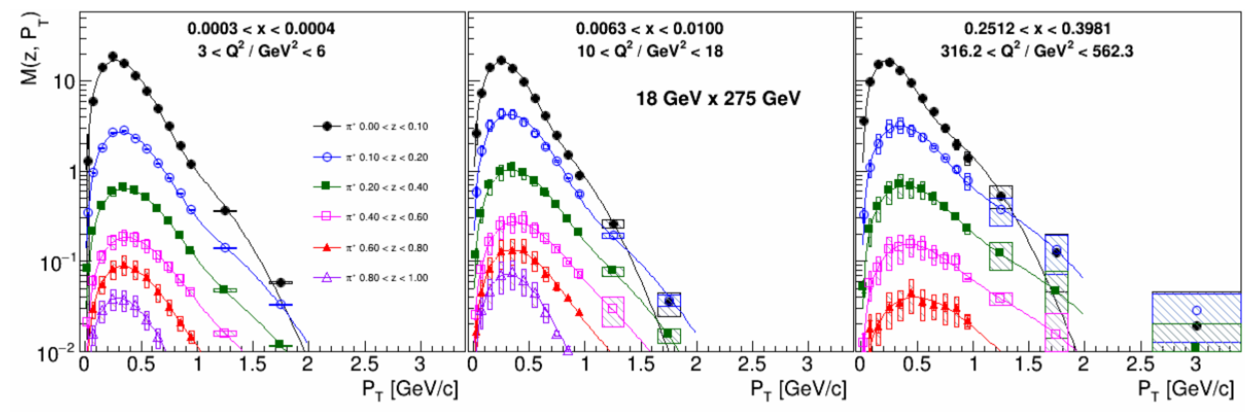
All Multiplicities at highest energies

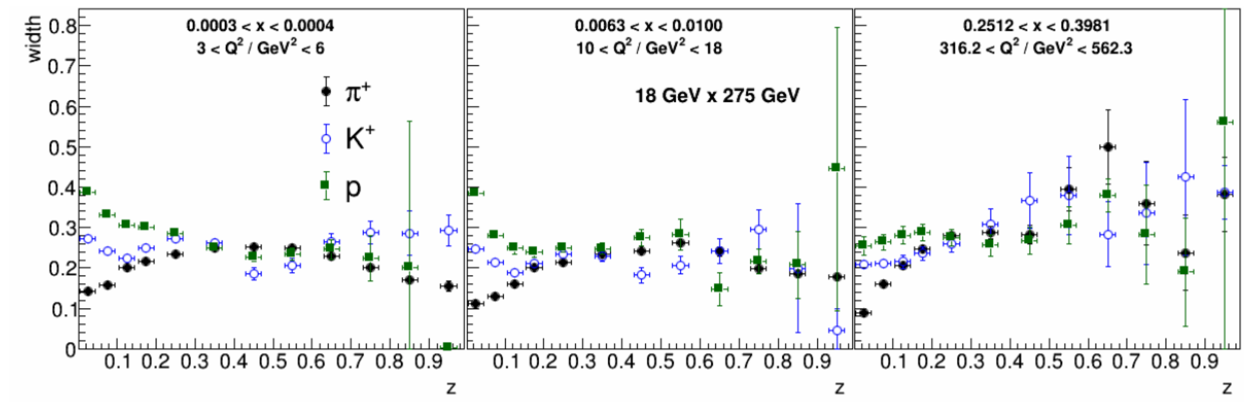
- Pion, kaon and proton multiplicities shown in all x-Q^2 bins as a function of P_T (integrated over z)



z-dependence of multiplicities and widths

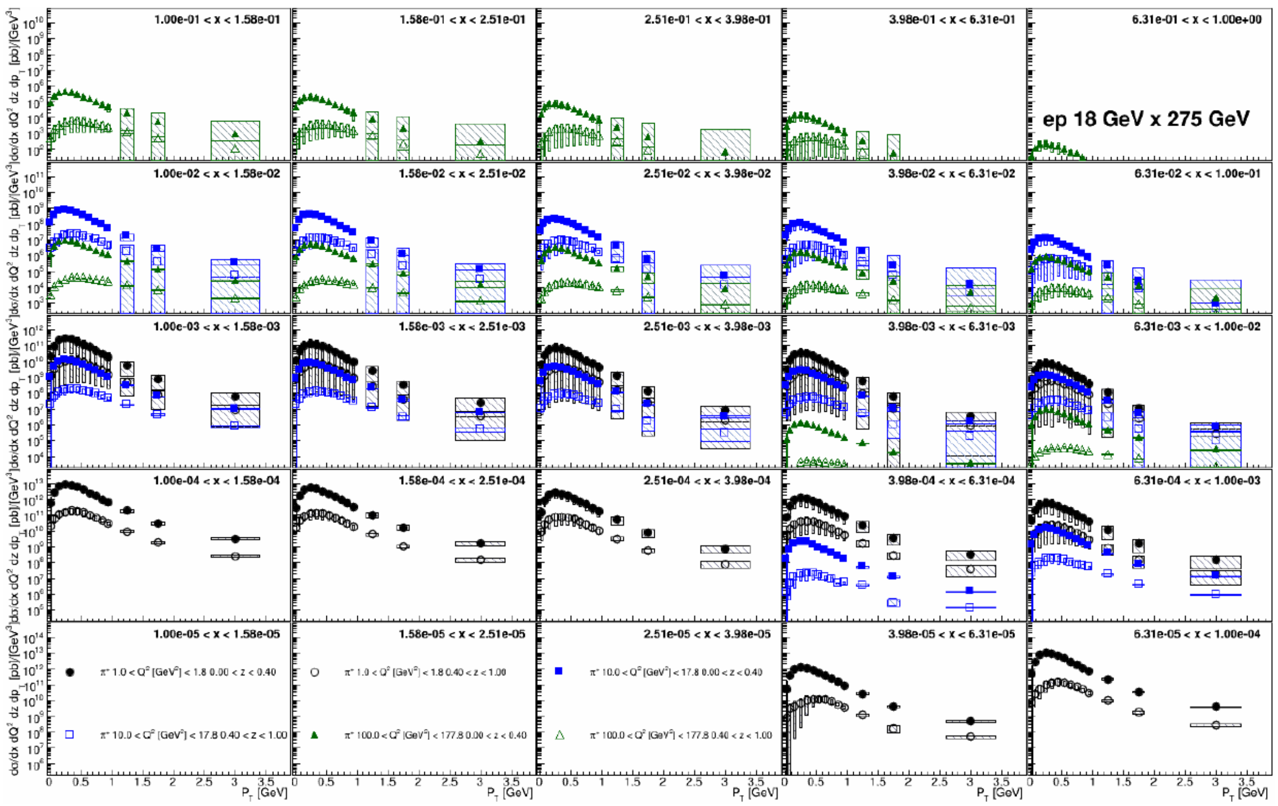
- Top: Explicit z dependence of select pion multiplicities in 3 x-Q^2 bins, including the double-Gaussian fits
- Bottom: behavior of the narrow Gaussian widths vs z for pions, kaons and protons
- Small z discrepancies likely due to target fragmentation





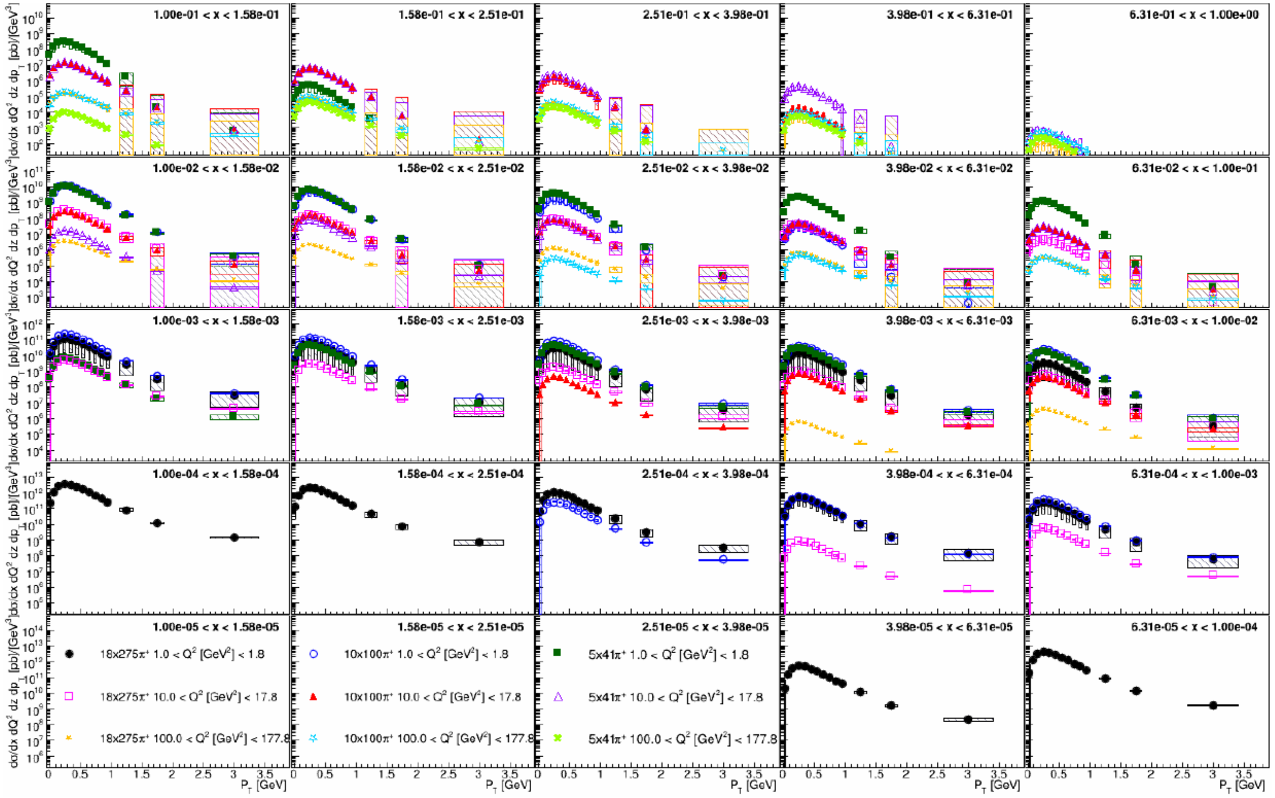
Cross sections

- Example of P_T dependent cross sections for pions, separated into high/low z for several x and Q2 bins



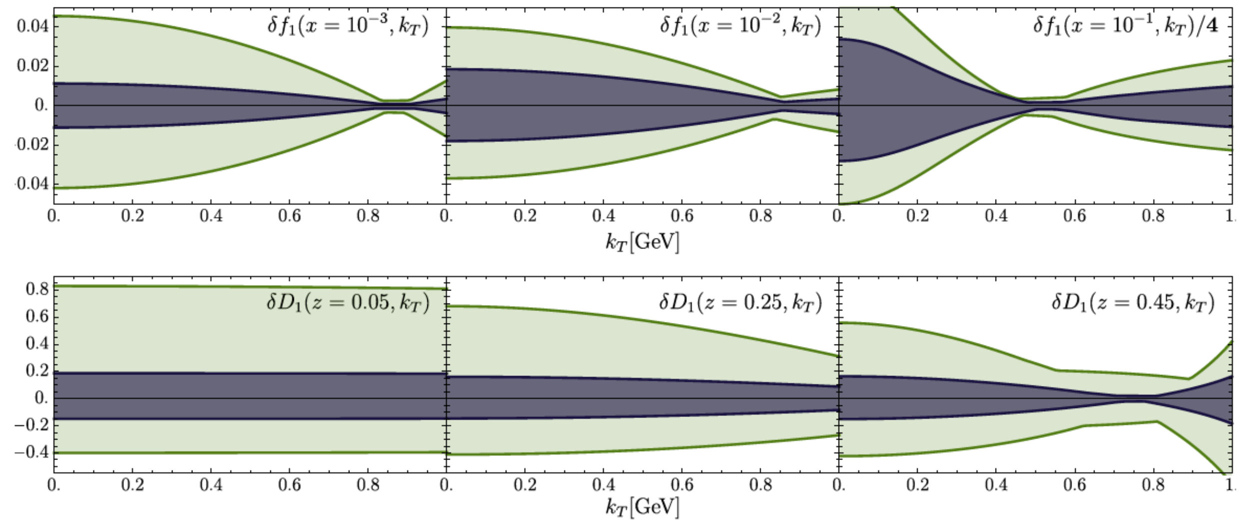
Combination of several collision energies

- 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)



ECCE single transverse spin Asymmetries for single hadrons impact paper preparation

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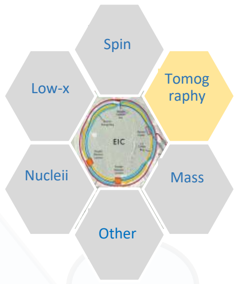
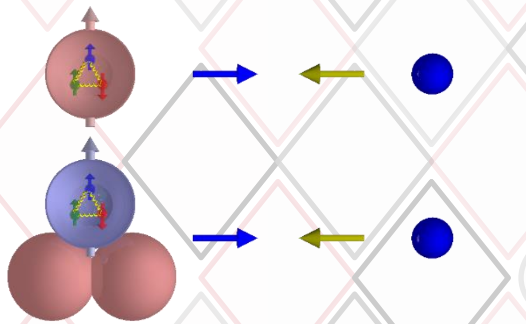
Theory/Pheno contributions:
Alexey Vladimirov (Regensburg)
Alexei Prokudin (PSU)
Daniel Pitonyak (Lebanon College)

RIKEN

Motivation: 3D Transverse spin and momentum structure





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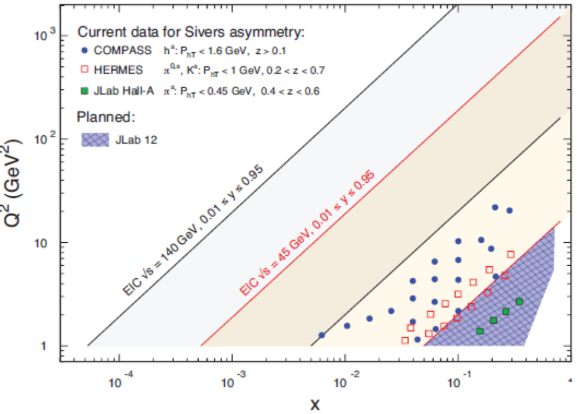

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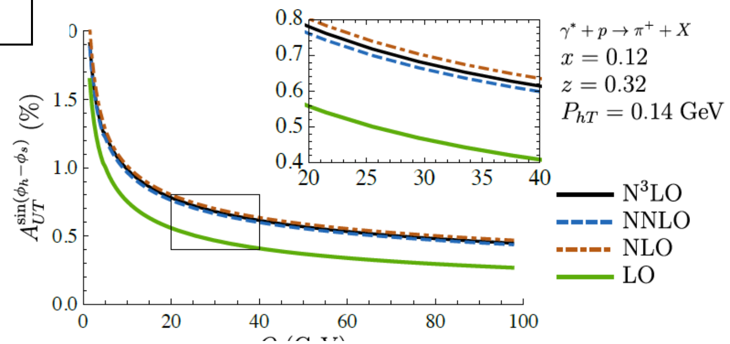
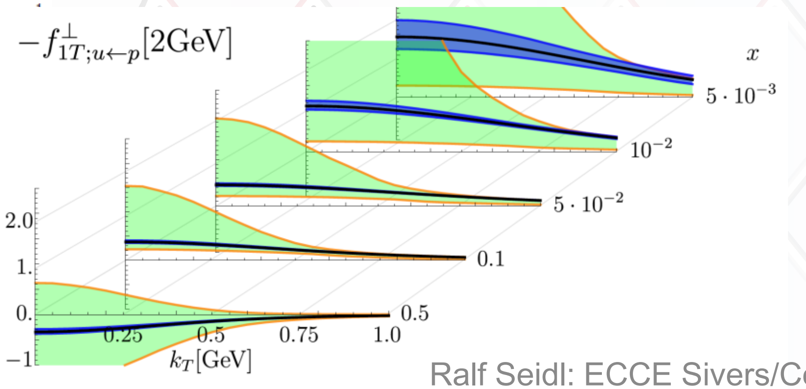
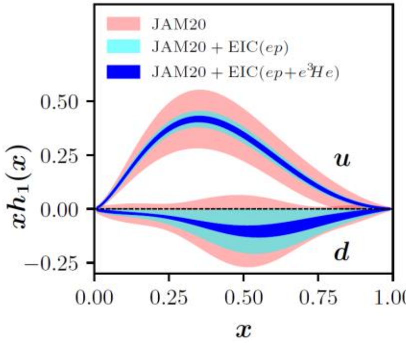
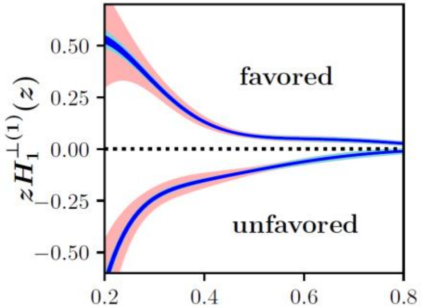


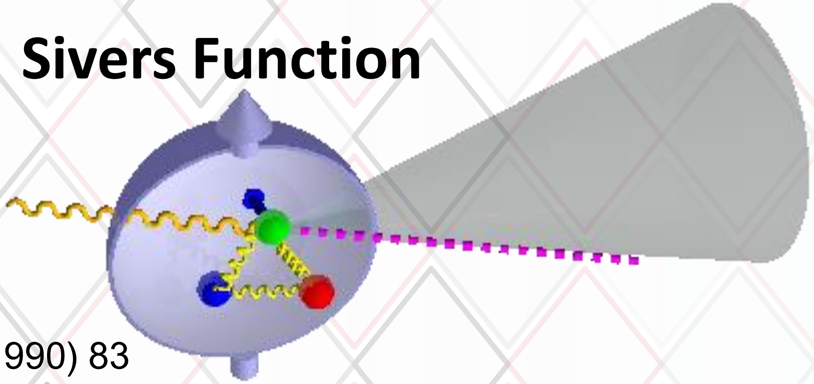






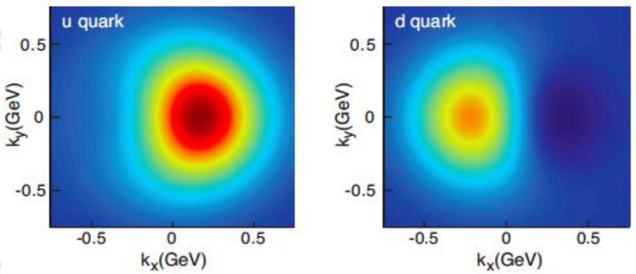
Gamberg et al *Phys.Lett.B* 816 (2021) 136255

Sivers Function



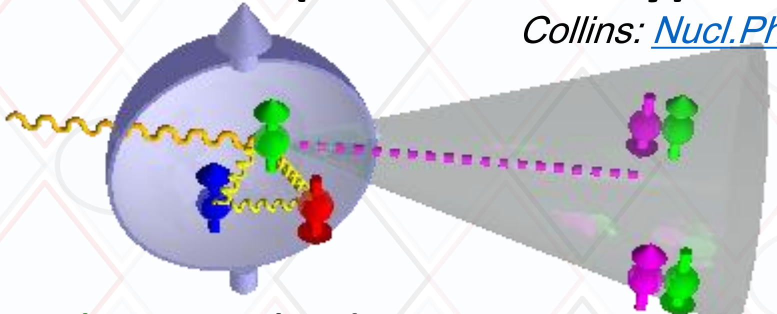
Sivers: *Phys.Rev.D* 41 (1990) 83

- Proton–spin – quark orbit (k_T) correlation (relation to orbital angular momentum)
- Transverse momentum imbalance in nucleon creates asymmetry
- Suggested by Sivers (1990), initially dismissed by Collins, resurrected by Brodsky (2002), Collins →special process dependence (sign change DY↔SIDIS)



Collins Function (x Transversity)

Collins: [*Nucl.Phys.B* 396 (1993) 161]

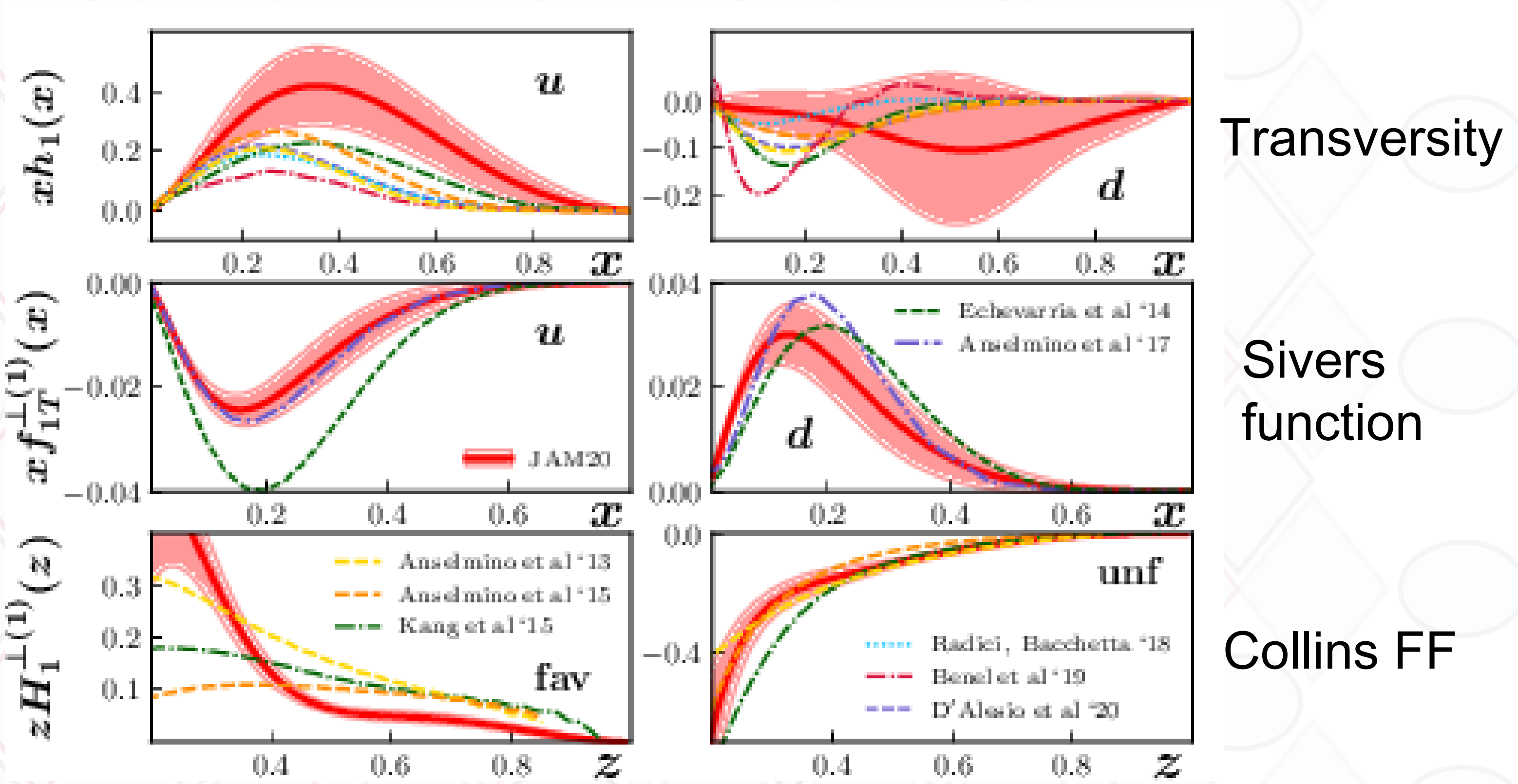


- Quark spin – hadron transverse momentum correlation (in fragmentation)
- Preferred direction of hadron creates asymmetry
- Analyzer for quark transversity (transverse quark spin) → access to tensor charge (Lattice, BSM?)
- A polarized (ie signed) fragmentation function

Both effects measured separately for quarks in SIDIS, FFs in e^+e^-

Current knowledge on these functions

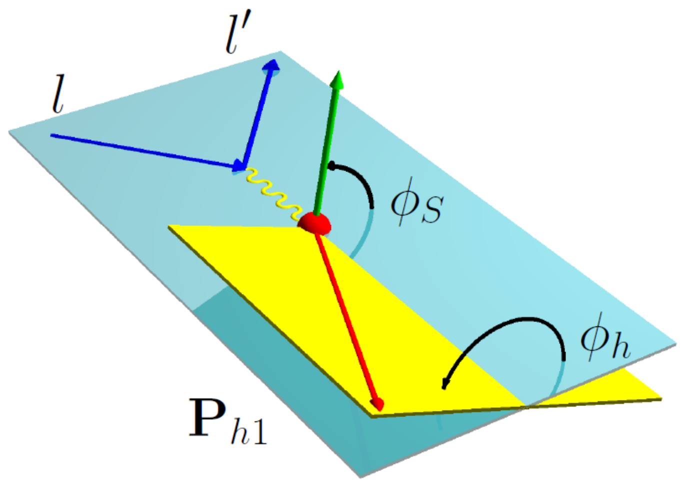
- Only valence quark Sivers and Transversity functions known at this time with substantial uncertainties
- Experimentally covered range 0.01 < x < 0.3
- So far no sensitivity to sea quarks and gluons* and lower x



[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)



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

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

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 ($|\eta|<3.5$) 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 ($|\eta|<3.5$), 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
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Kinematic variable	Bin boundaries
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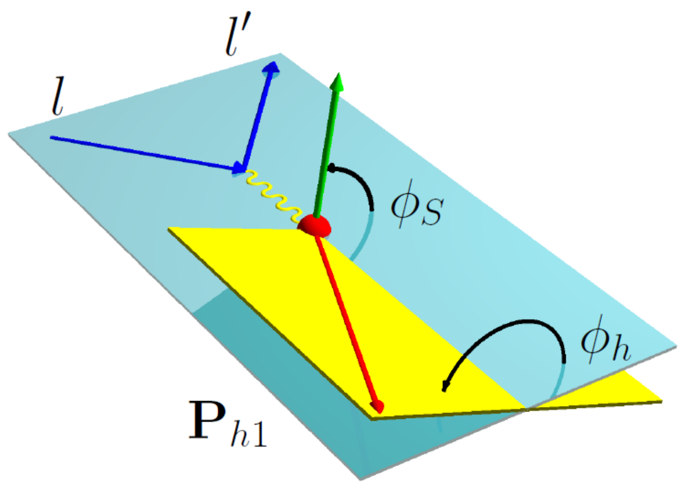
Q^2	$1.0x10^{0}$, $3.162x10^{0}$, $1.0x10^{1}$, $3.162x10^{1}$, $1.0x10^{2}$, $3.162x10^{2}$, $1.0x10^{3}$, $3.162x10^{3}$, $1.0x10^{4}$
z	0, 0.05, 0.1, 0.15, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0
P_T	0, 0.05, 0.1, 0.2, 0.3, 0.5, 0.7, 0.9, 1.2, 1.5, 1.8, 2.4 ,4.0

Sivers/Collins measurements in SIDIS

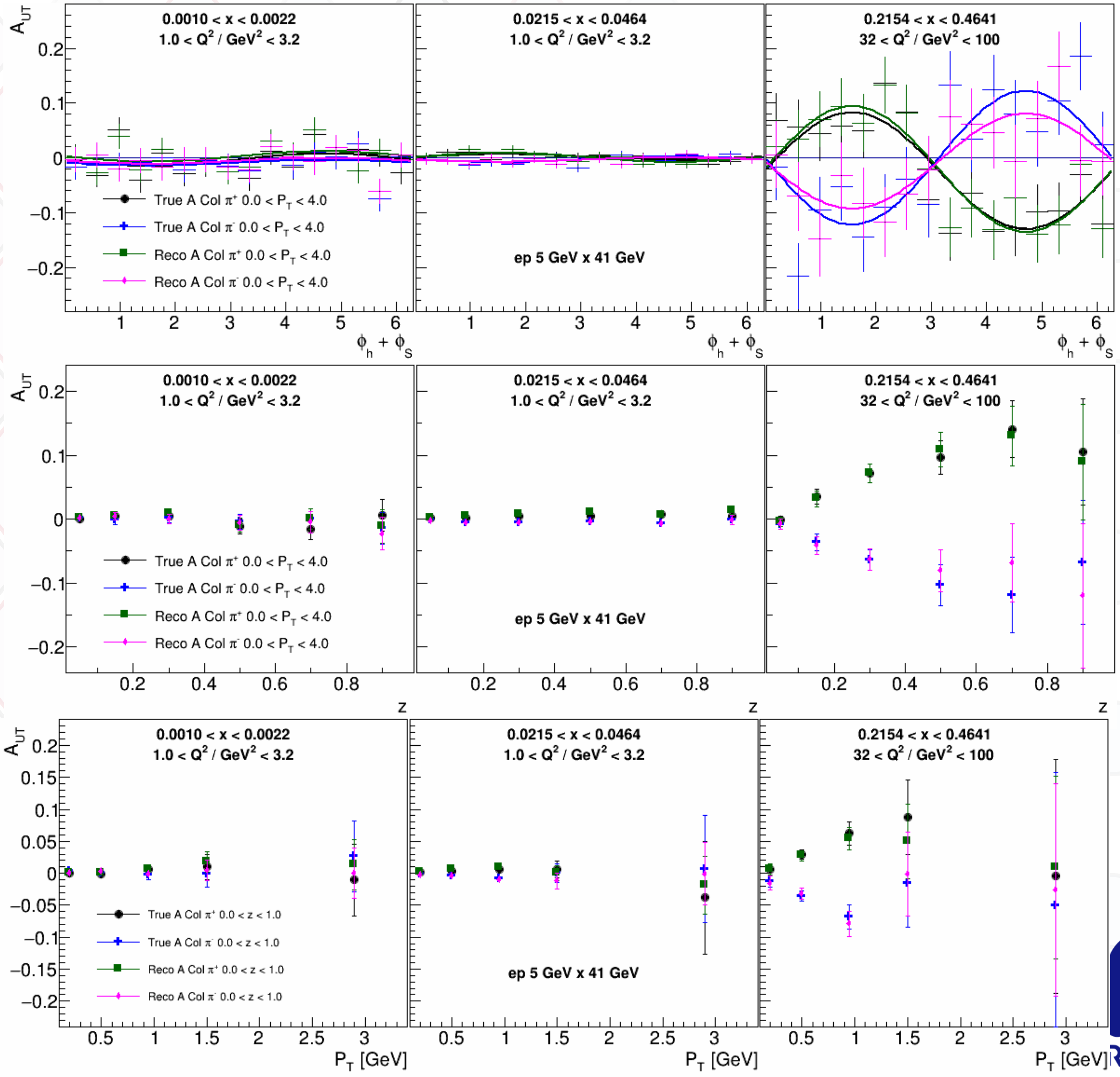
- Reweight events according to true parton flavor q, hadron h, x, z, Q^2, P_{hT}, azimuthal angles and random spin orientation
- $ep^{\uparrow} \rightarrow e'hX$
- A_{UT} asymmetries (Unpolarized lepton beam, Transversely polarized target)
- Different azimuthal modulations related to Sivers effect ($\sin(\phi-\phi_s)$)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

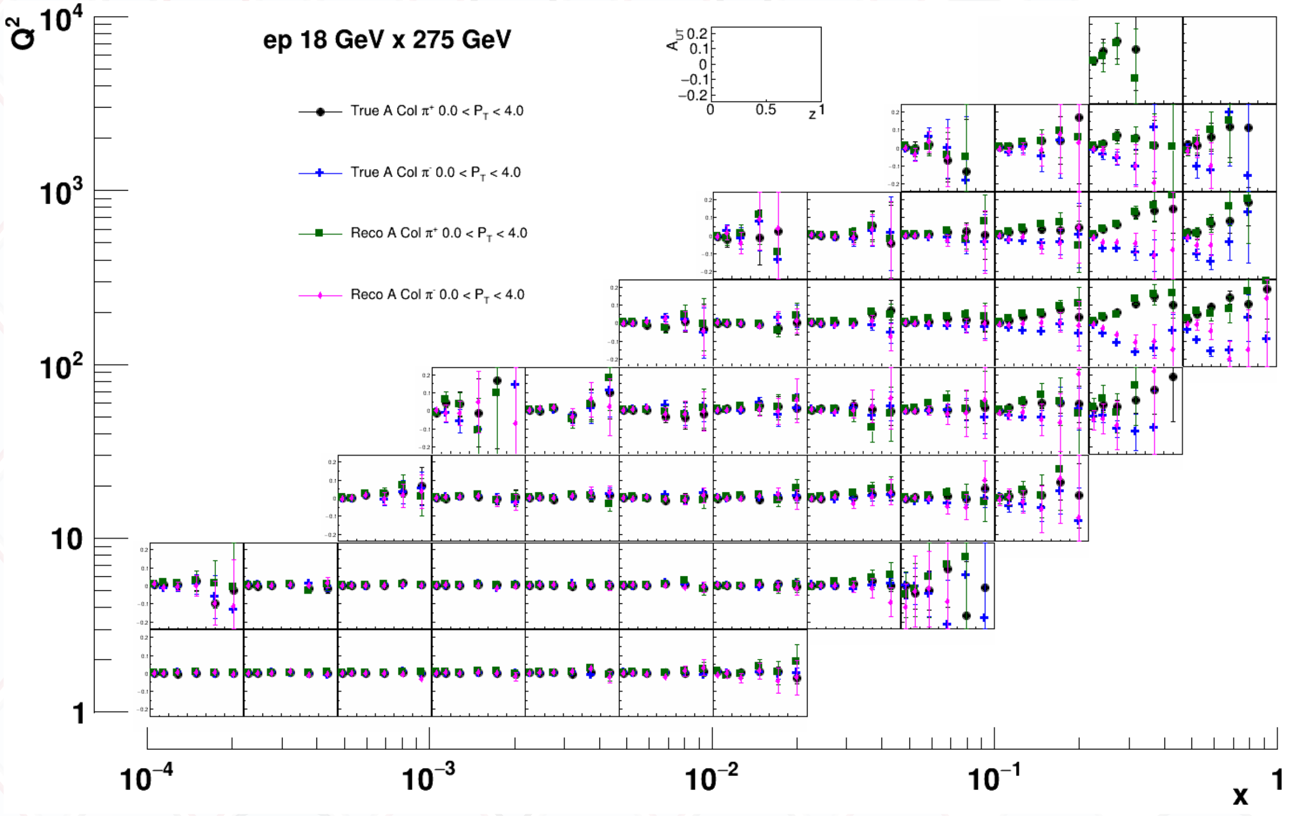
Example figures

- 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



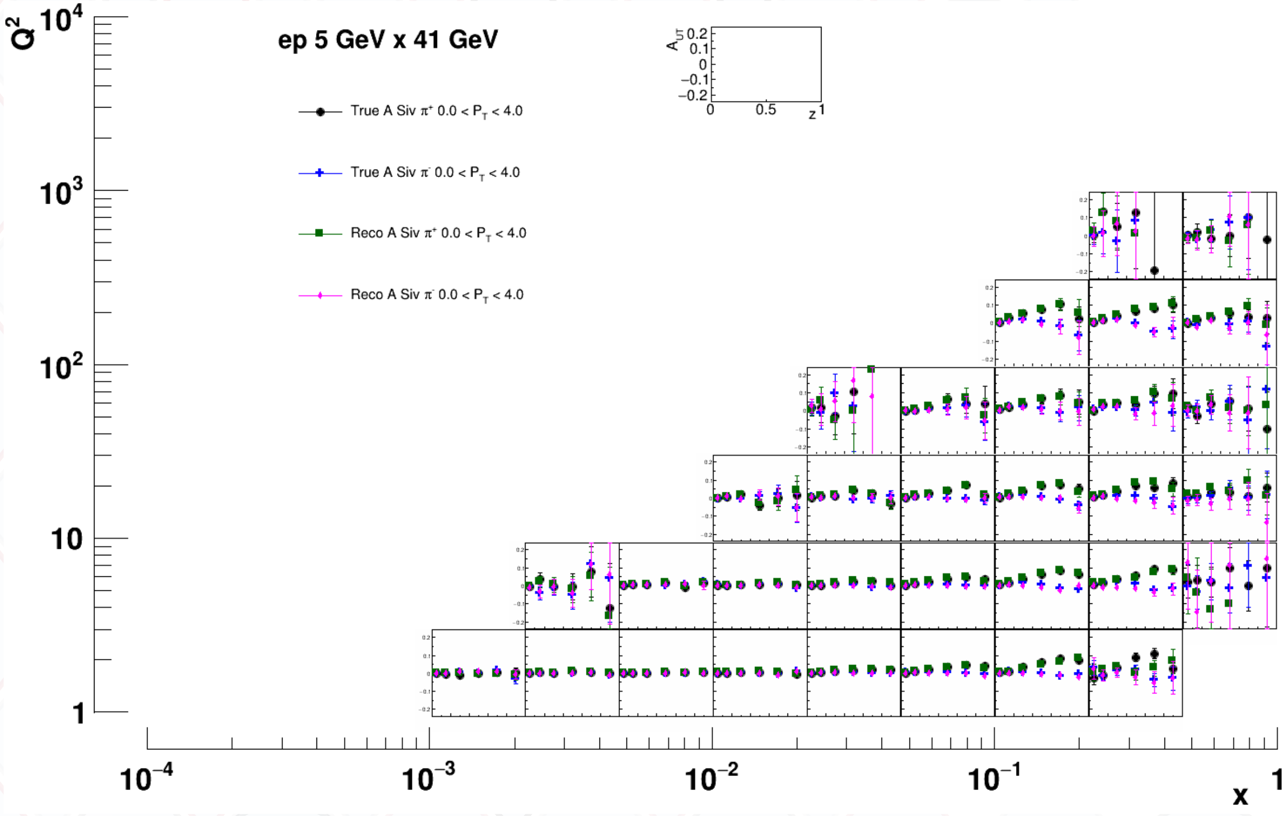
Collins asymmetries at highest energies

- 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



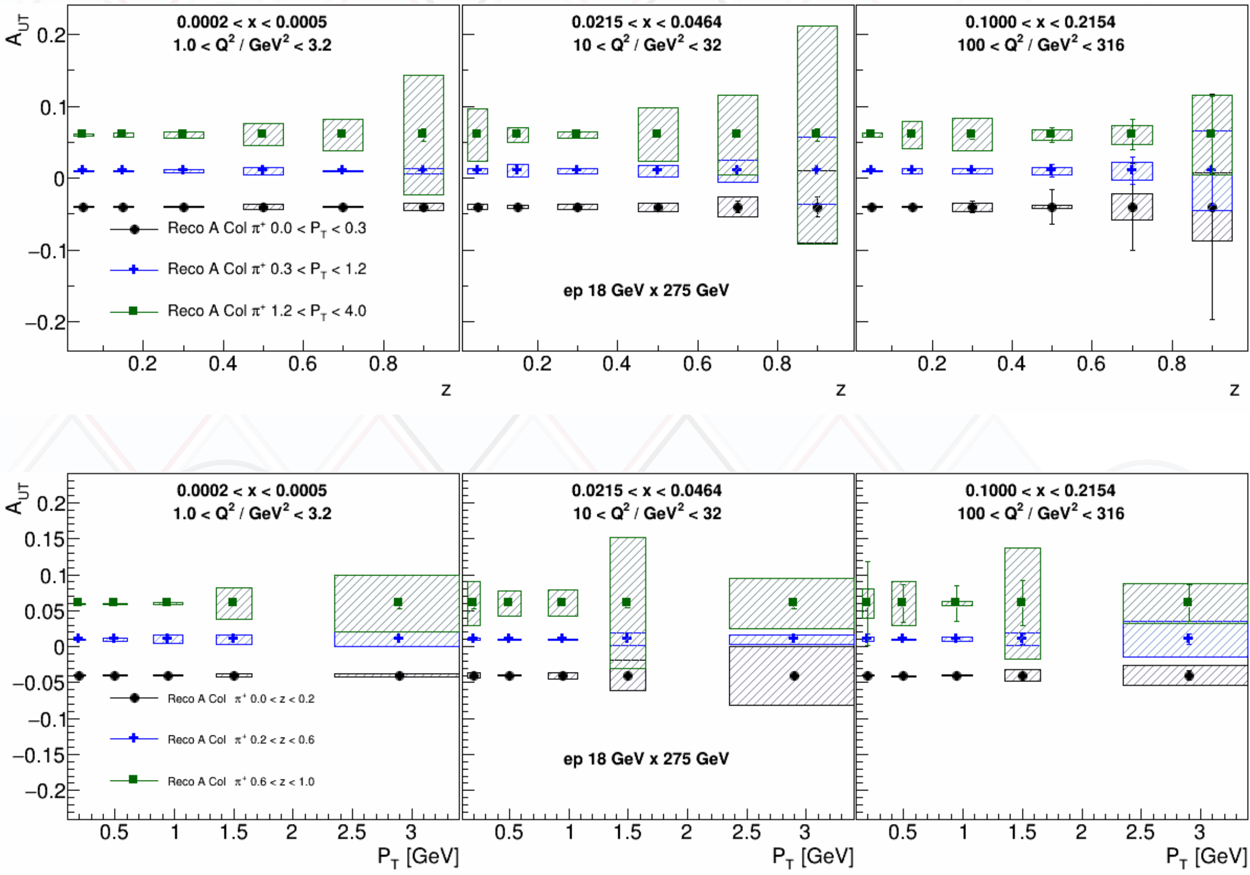
Sivers asymmetries at lowest energies

- Similar figure for the Sivers asymmetries
- Positive asymmetries seen for π^+ at higher x
- π^- asymmetries compatible with zero due to up/down/favored/disfavored cancellation
- High precision already with simulated statistics



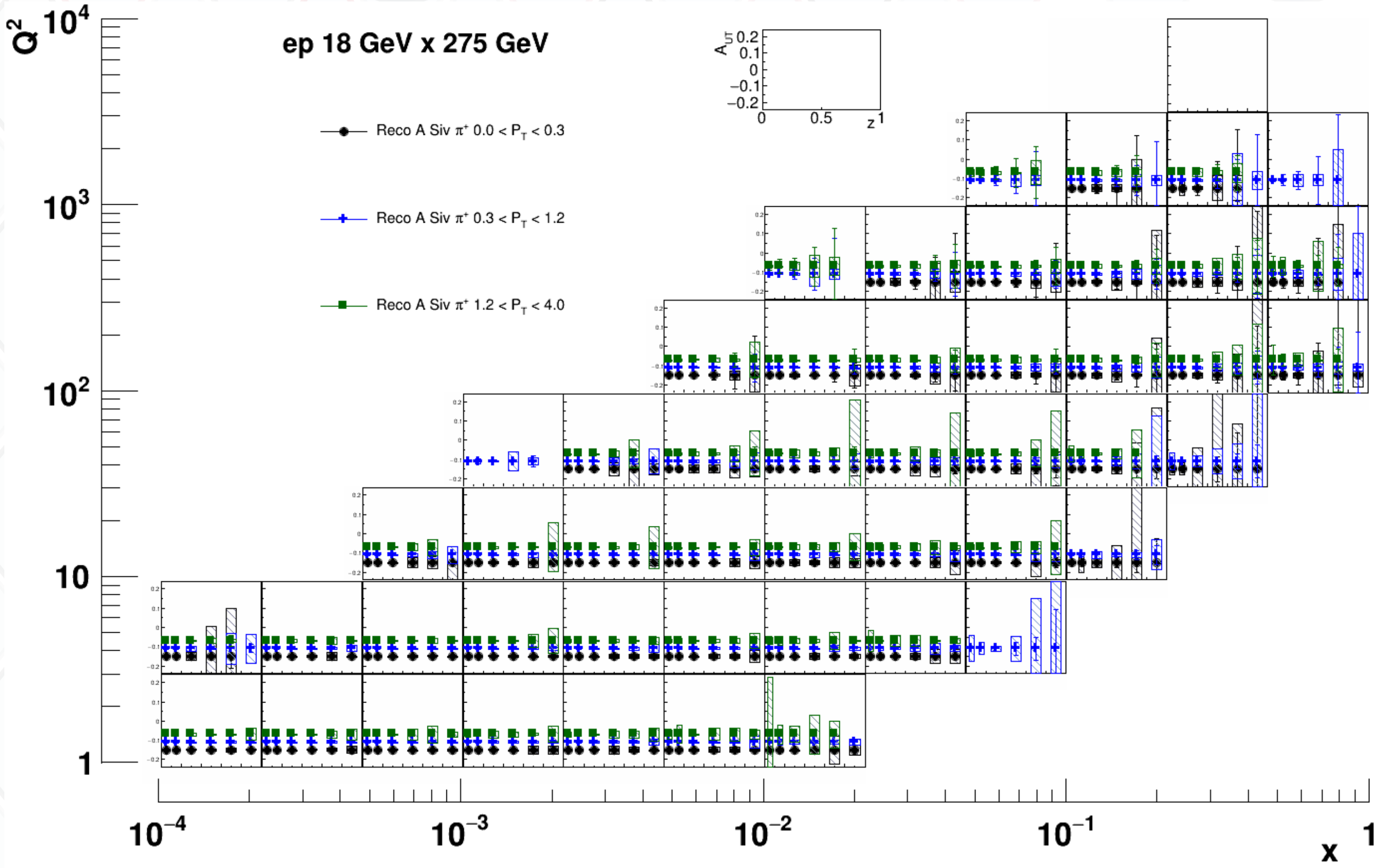
Projections to 10fb^{-1}

- 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



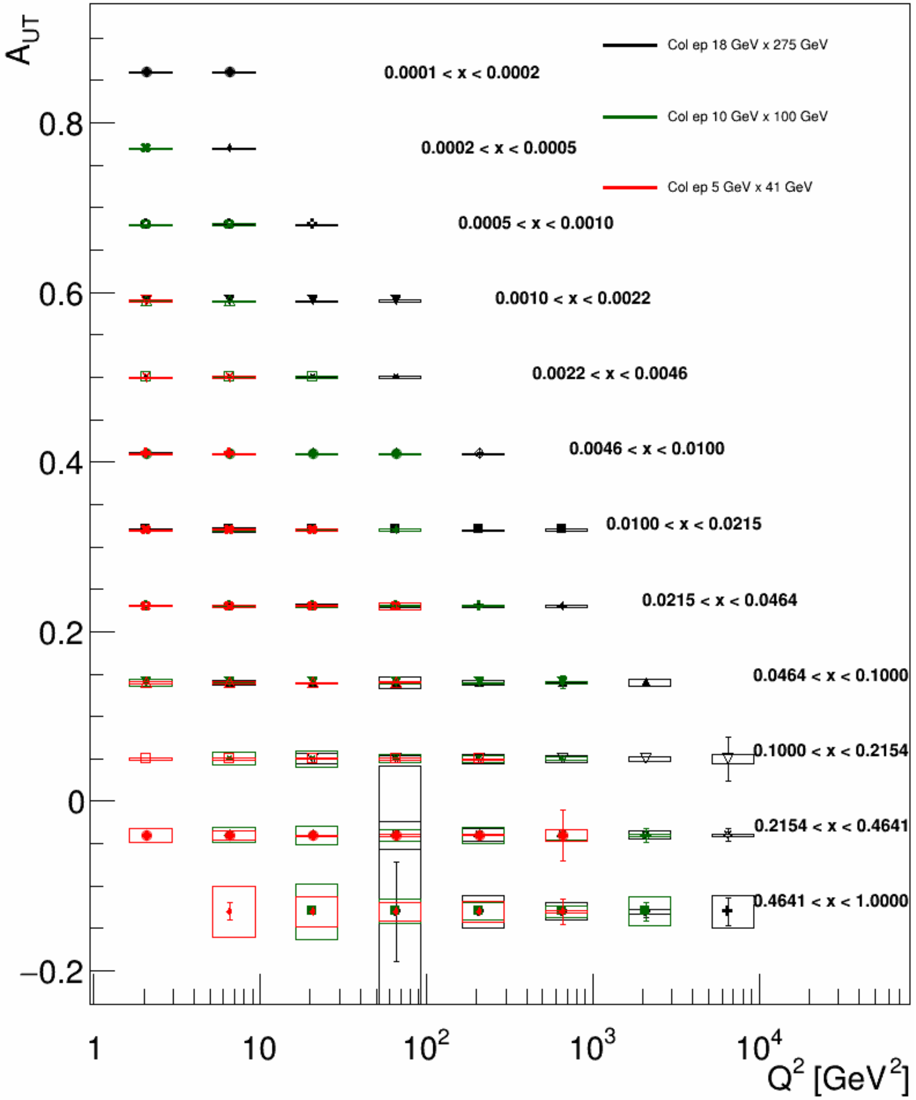
Full projections

- Projected uncertainties in all (accessible) x-Q2 bins as a function of z (or Pt) integrated over Pt (or z)
- Currently shown in paper draft: highest and lowest collision energies and both Sivers and Collins asymmetries



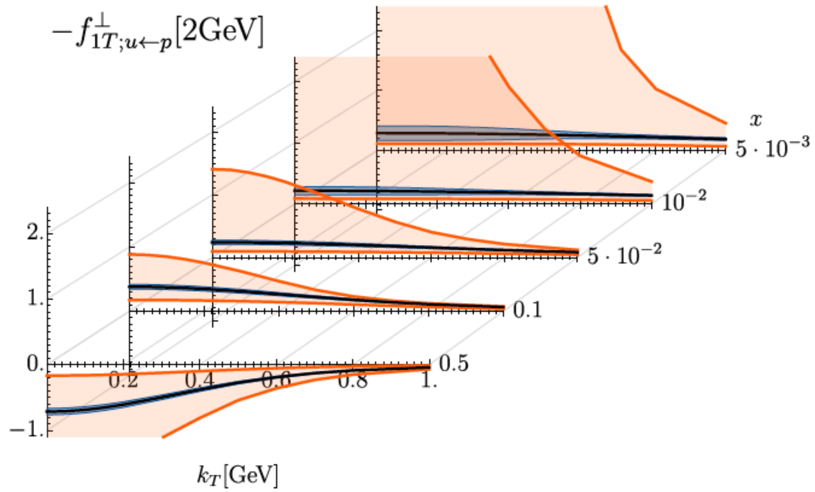
Scale dependence (and interplay of collision energies)

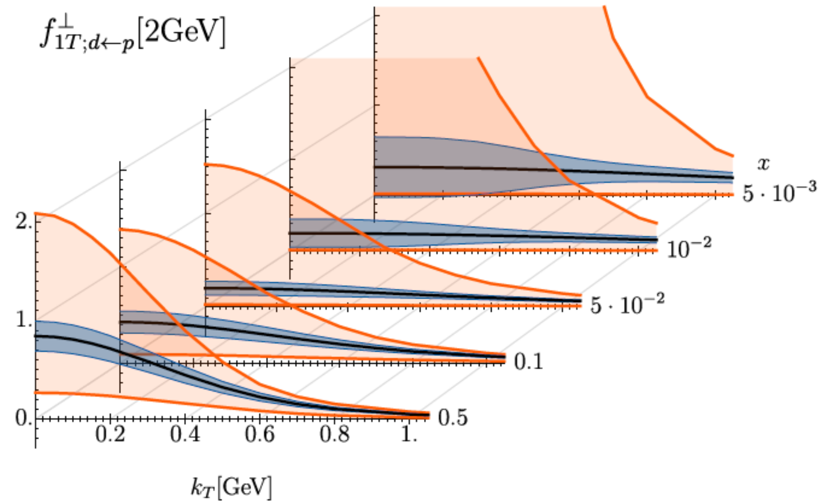
- An example of the expected uncertainties in x and Q^2 to study the scale dependence of the Sivers/Collins asymmetries (as TMD evolution is not very well known/contains other nonperturbative pieces)
- Overlap of the different energies shows how they increase the lever arm
- Note: in future evolution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



Impact for Sivers functions

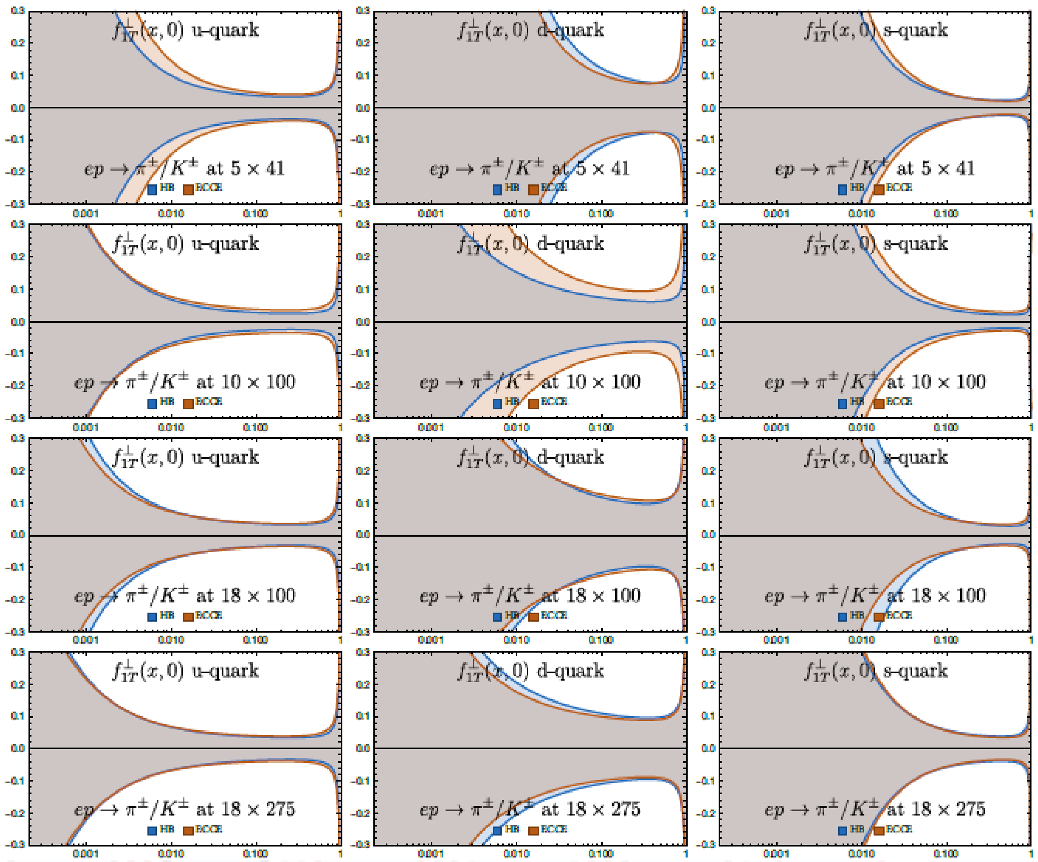
- Similar to YR impact studies following the latest BPV global fit (arXiv:2103.03270) for the Sivers function based on the existing SIDIS +DY data
- Uncertainties are shown for current level of knowledge on up/down Sivers functions at various x vs kt and expected impact from ECCE





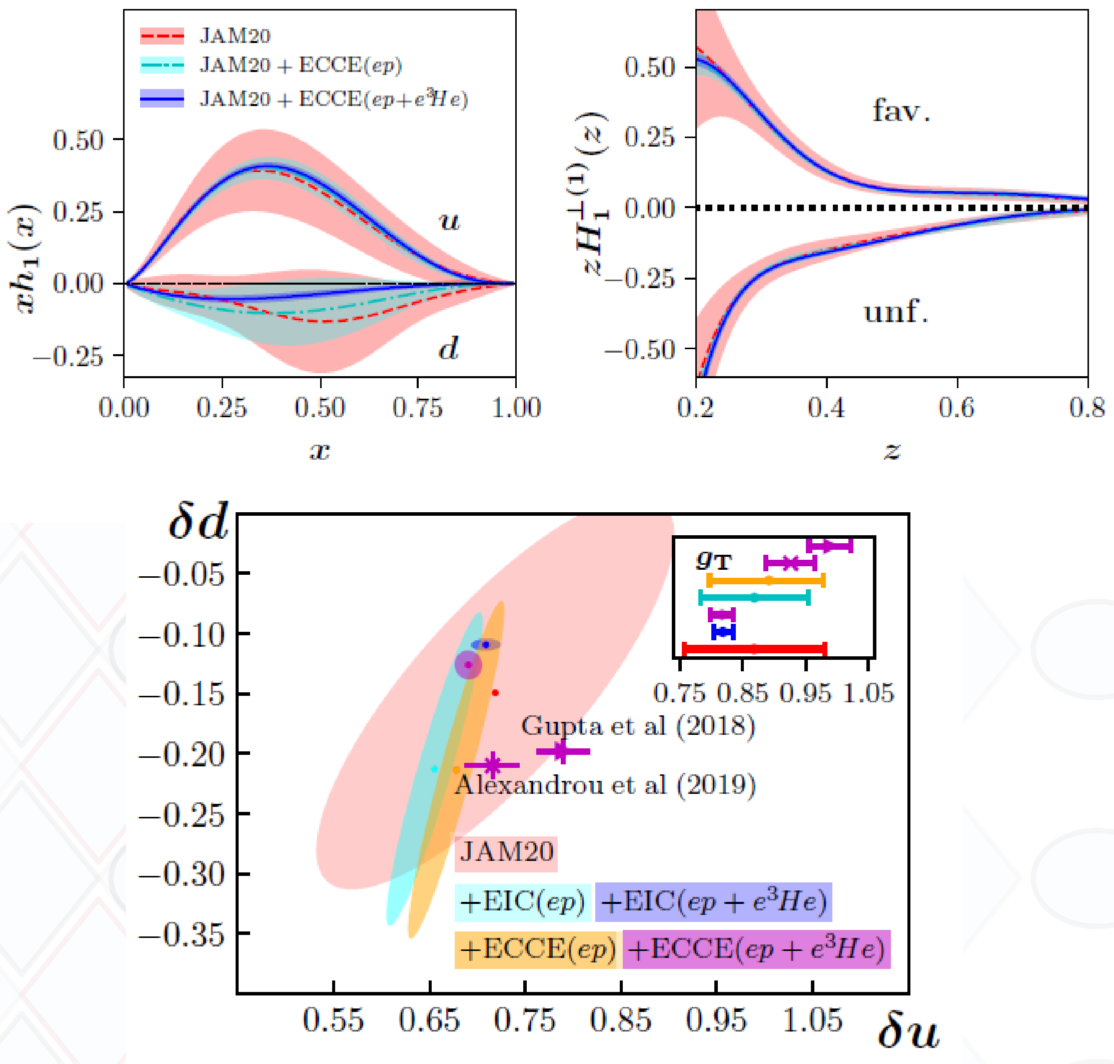
ECCE Impact compared to YR handbook detector (pseudo-data parametrized via eic-smear)

- The relative size of the up, down and s quark Sivers function uncertainties compared to the expected uncertainties from the YR studies
- Some minor differences but essentially similar level as YR HB detector (parametrized via eic-smear)



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

- Unpolarized TMD SIDIS paper essentially ready
- Sivers/Collins SIDIS paper essentially ready

- Some reduction in introduction (removal of motivational figure 1 from note)

- Follow up on these studies as ECCE detector evolves and consider studying the proper unfolding of kinematic smearing as well as particle identification
- Consider more explicit TMD evolution studies
- Authorlist provided with paper template still leaves many institution names empty -- theory contributors added by hand
- Similar studies still needed for gluon Sivers channel