2024 JAN 29-31 EIC Asia Workshop

National Cheng Kung University
Department of Physics, Rm 36169(1F)
No.1, University Road, Tainan City, Taiwan

TMD physics

EIC-Asia Workshop,
NCKU Tainan, January 29-31, 2024
Ralf Seidl (RIKEN)

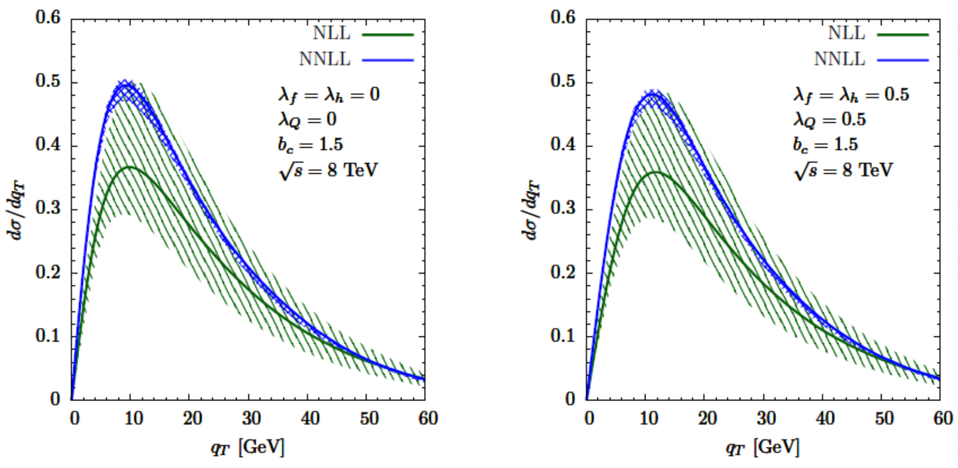
Outline

- TMDs from high to low energies
- TMD factorization, PDFs and FFs
- Important TMD measurements at the EIC
- Input for these measurements:
  - Fragmentation functions
  - SIDIS/pp asymmetries
- Expected impact of EIC measurements

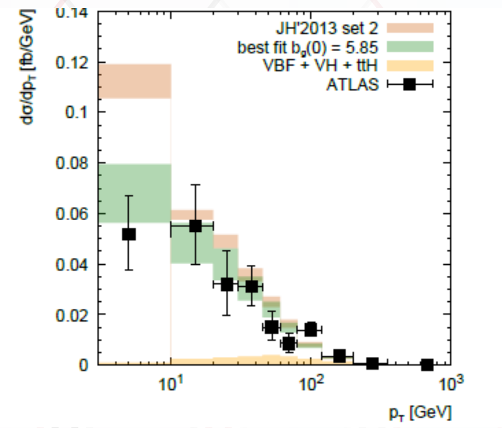
Q: What have the Higgs P_T spectrum and the Sivers function in common?

A: Both contain Transverse momentum dependent (TMD) functions

Higgs P_T cross section: p+p→H+X



[Echevarria et.al. JHEP 07 (2015) 158]

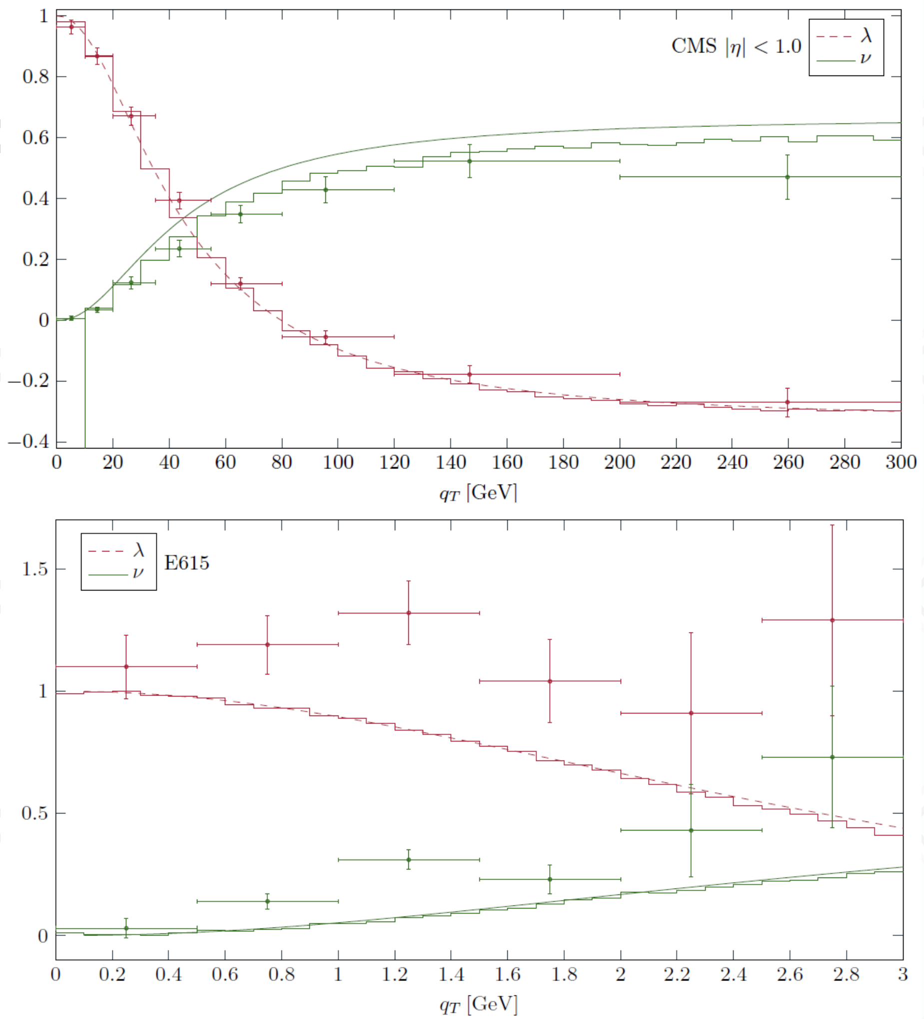


[Lipatov et. al. *PRD* 107 (2023) 1]

- Higher transverse momentum described by higher-order pQCD
- However, low transverse momentum also depends on intrinsic transverse momentum of interacting partons → gluon TMD PDFs
- Relatively large uncertainties due to TMD evolution to Higgs scales

$$\frac{d\sigma^W}{dQ\,dY\,d^2\mathbf{q}_T} = 2H_{\rho\sigma\rho'\sigma'}(Q,\mu)\int d^2\mathbf{b}_T\, e^{i\mathbf{b}_T\cdot\mathbf{q}_T}\,\tilde{f}^{\rho\sigma}_{g/p}(x_a,\mathbf{b}_T,\mu,\zeta_a)\tilde{f}^{\rho'\sigma'}_{g/p}(x_b,\mathbf{b}_T,\mu,\zeta_b)$$

Violation of Lam-Tung Relation in DY (p+p→l^+l^-+X)



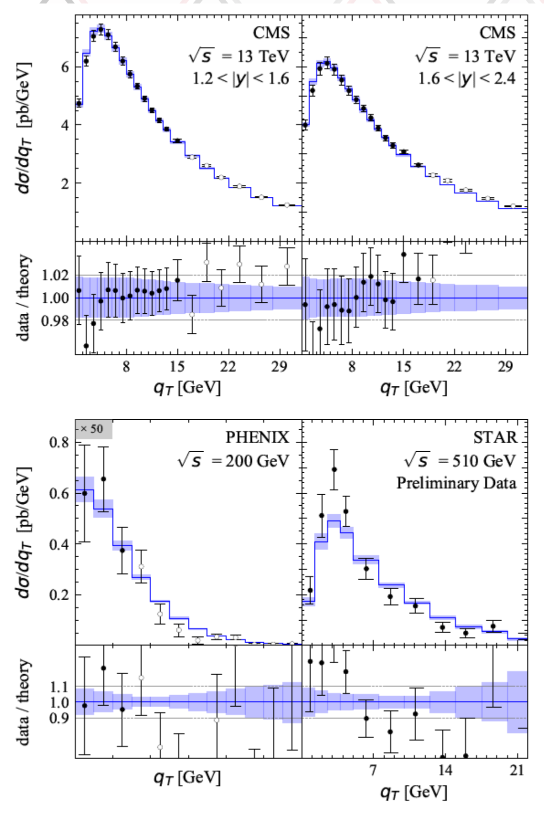
PRD 93 (2016)114013

- DY azimuthal angular cross section:

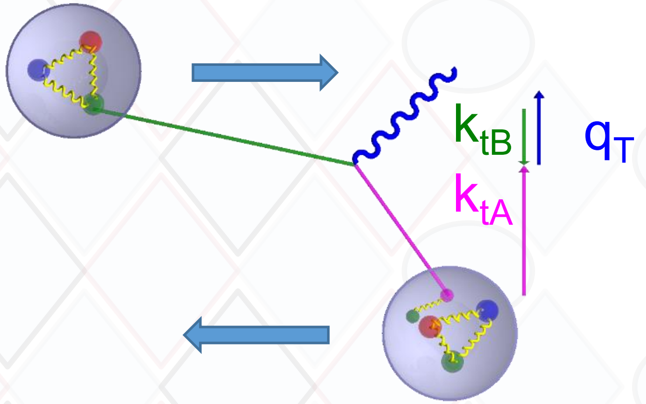
$$\frac{dN}{d\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}\left[1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi\right]$$

- At LO: Lam-Tung relation fulfilled: $1-\lambda-2\nu = 0$
- At NLO modest violations, consistent with high-scale data
- At low scales suggestion of a violation and potential explanation by Boer-Mulders function and higher twist effect (Kahn-like)

TMD factorization in Drell-Yan



Moos et al. 2305.07473



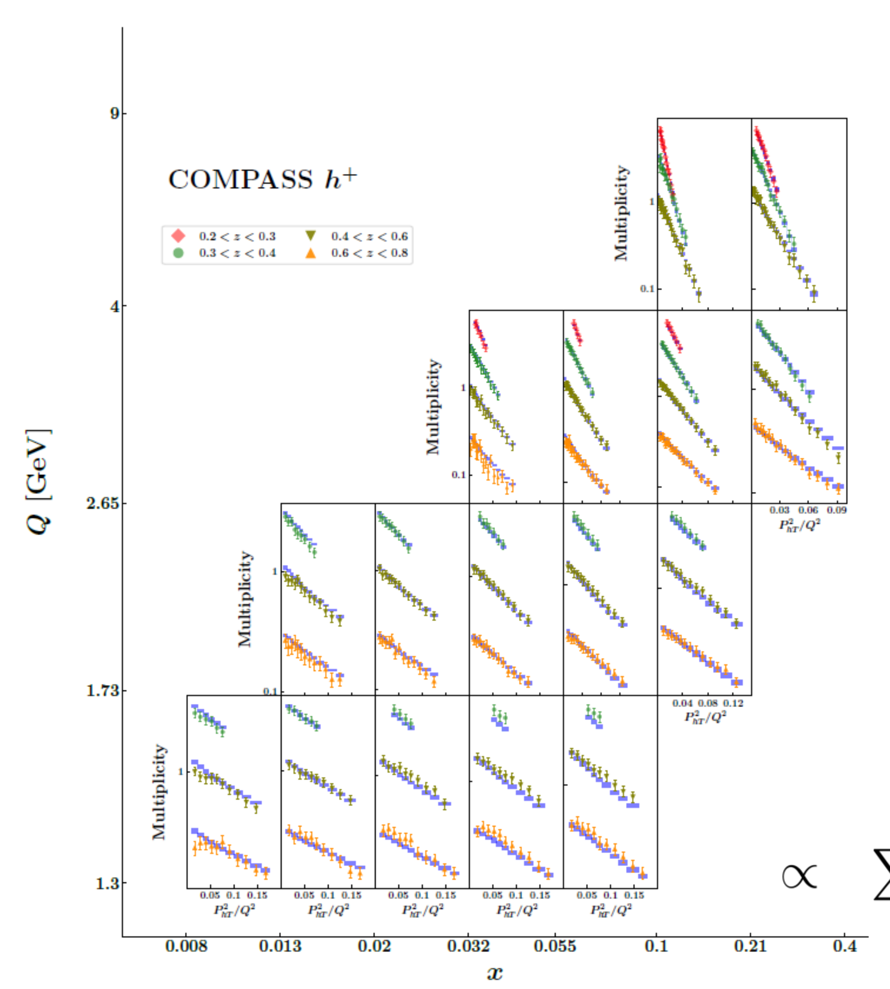
- Cross sections depend not only on the PDFs, but also on their transverse momenta
- Total transverse momentum of virtual photon to be matched with intrinsic momenta

$$F_{UU}(x_A, x_B, \mathbf{q_T}, Q)$$

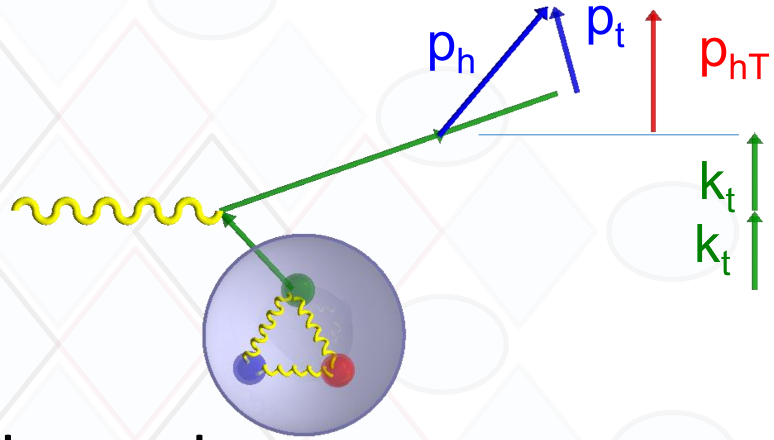
$$\propto \sum_{q,\bar{q}} e_q^2 \int d^2\mathbf{k_{tA}} \int d^2\mathbf{k_{tB}} q_A(x_A, Q^2, k_{tA}) q_B(x_B, Q^2, k_{tB}) \delta^{(2)}(\mathbf{k_{tA}} + \mathbf{k_{tB}} + \mathbf{q_T})$$

$$= \sum_{q,\bar{q}} e_q^2 q_A(x_A, Q^2, k_{tA}) \otimes q_B^h(x_B, Q^2, k_{tB})$$

TMD factorization in SIDIS (e+p→e'h+X)



MAP: JHEP 10 (2022) 127

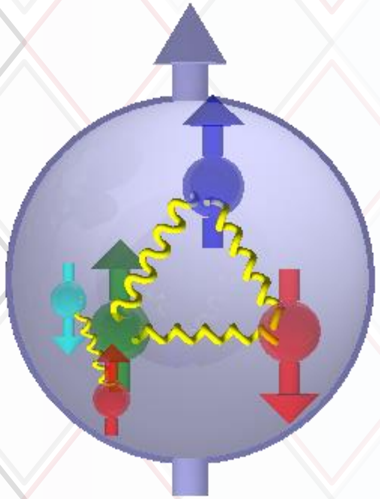


- Cross section depends on intrinsic transverse momenta of PDFs and fragmentation functions
- Convolution over participating transverse momenta

$$F_{UU}(x, z, \mathbf{q_T}, Q)$$

$$\propto \sum_{q,\bar{q}} e_q^2 \int d^2\mathbf{k_t} \int d^2\mathbf{p_t}/z^2 q(x, Q^2, k_t) D_{1,q}^h(z, Q^2, p_t) \delta^{(2)}(\mathbf{k_t} + \mathbf{p_t}/z + \mathbf{q_T})$$

$$= \sum_{q,\bar{q}} e_q^2 q(x, Q^2, k_t) \otimes D_{1,q}^h(z, Q^2, p_t)$$



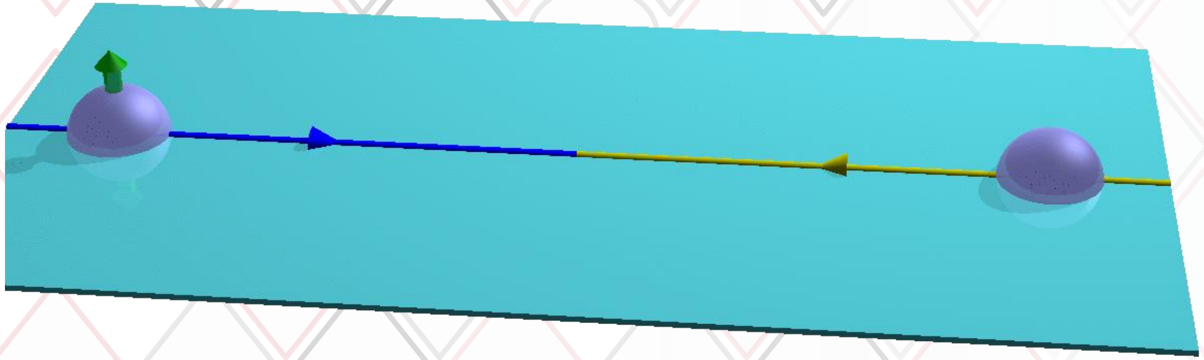
Transverse spin and TMDs

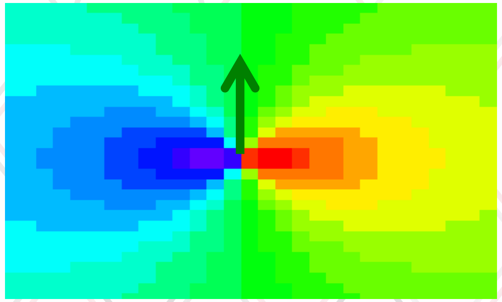
Not only unpolarized TMD PDFs/FFs but also polarized TMDs can contribute, accessible via (transverse) spin and azimuthal asymmetries

Transverse Single spin asymmetries (TSSAs)

- Left-Right asymmetries :

$$A_N = \frac{1}{P}\frac{N^L - N^R}{N^L + N^R}$$





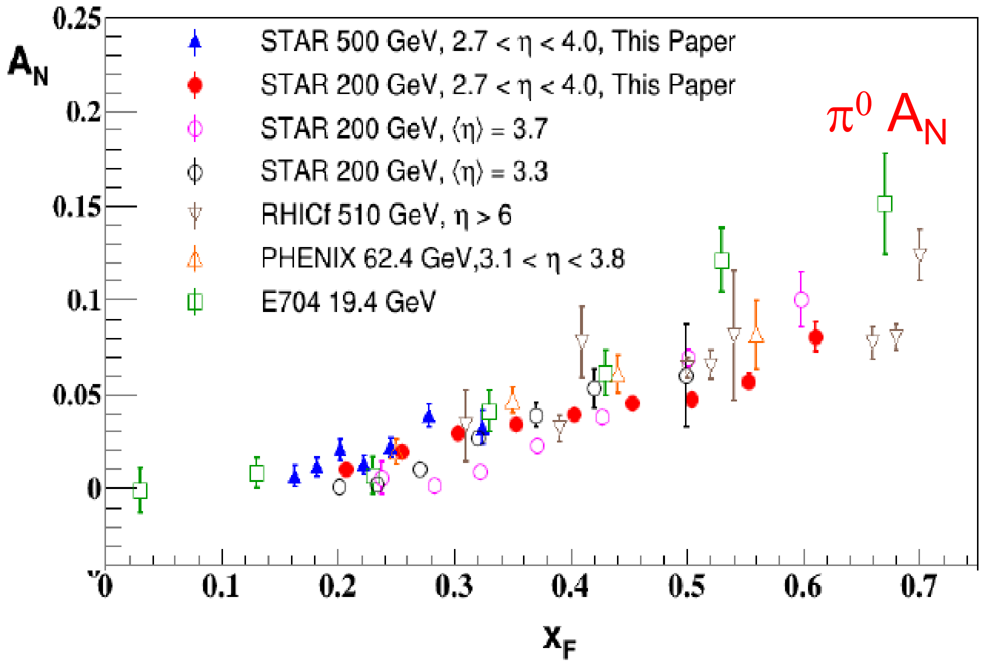
- Relative to the polarized proton spin direction more particles get produced to the left than to the right wrt. spin direction
- The cross section is spin (and azimuthal angle) dependent
- Initially expected to be zero in perturbative QCD (helicity-flip of nearly massless quarks) - G. L. Kane, J. Pumplin, and W. Repko *PRL* **41**, 1689 (1978):

$$A_N \propto \frac{m_q \alpha_S}{P_T} \approx 0.001$$

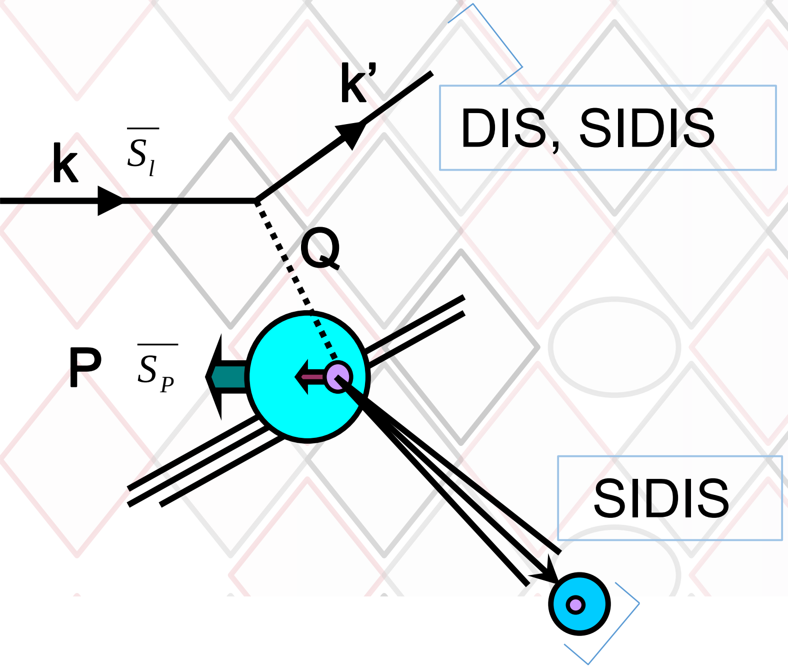
Transverse single spin asymmetries (TSSA)

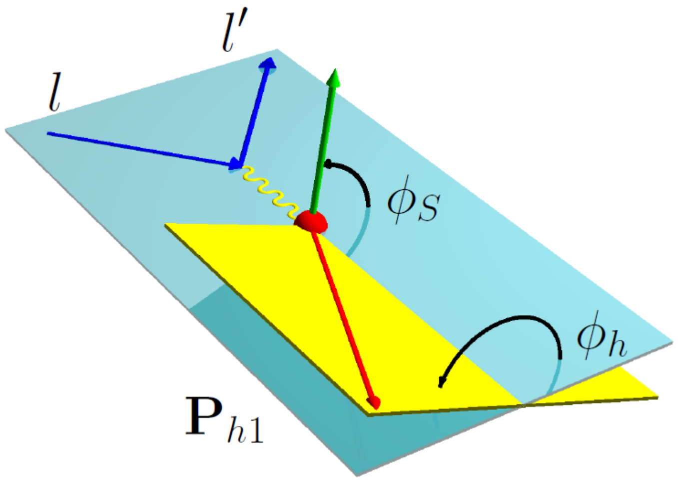
$$A_N = \frac{1}{P}\frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

- Large left-right asymmetries A_N seen in polarized p+p collisions from low energies up to RHIC energies at forward rapidities
- Both initial state and final state effects can contribute in forward pion asymmetries
- Both effects described via higher-twist correlations, but those are related to TMD moments (especially quark, gluon Sivers, Collins FF)



SIDIS Kinematics for TMDs





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

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

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 $u\rightarrow\pi^+$, $d\rightarrow\pi^-$, $s\rightarrow K^-$, etc)
- Transverse momentum and angles rely also on correct boost to hadron rest system

TMD PDFs (at leading order)

TMD: all except f_1,g_1 and h_1 cancel upon integration over k_T
Similar spin-orbit and spin-spin effects between parton and nucleon spins and transverse momentum

- Transversity

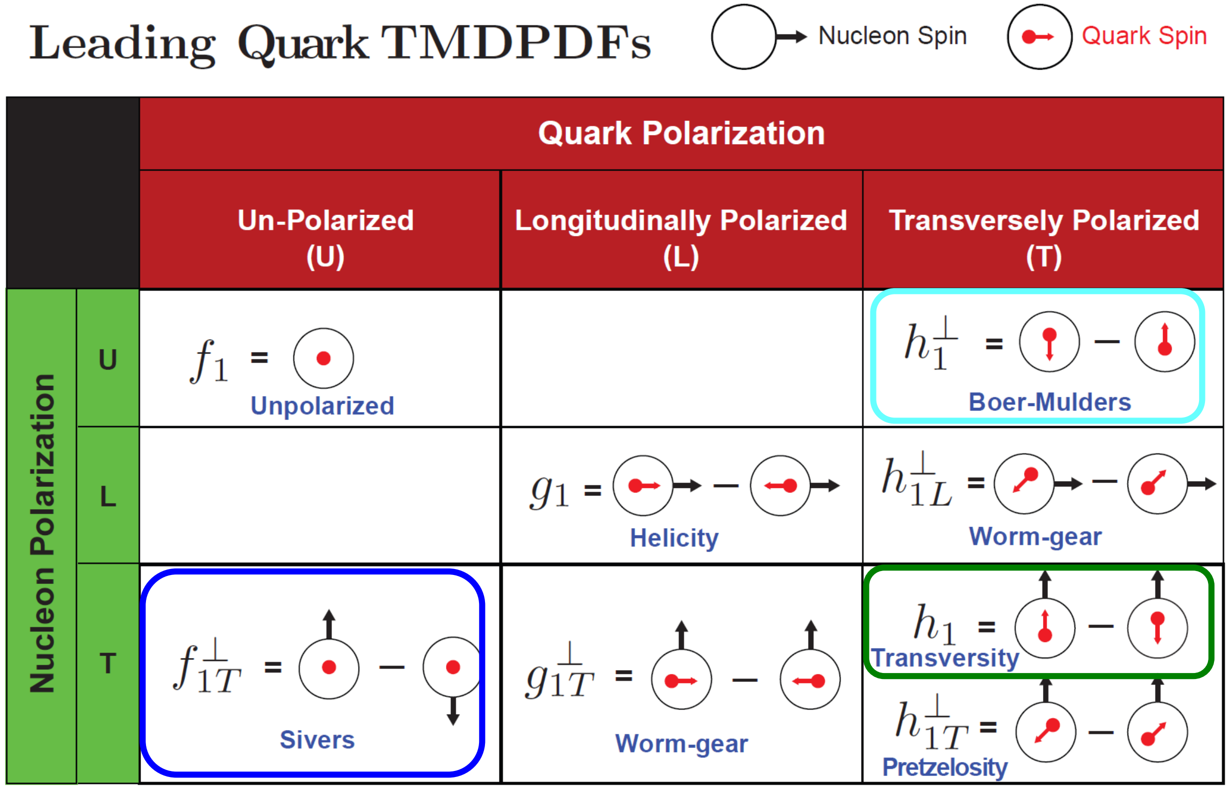
$$h_{1,q}(x)$$

- Sivers Function

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

- Boer Mulders function

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



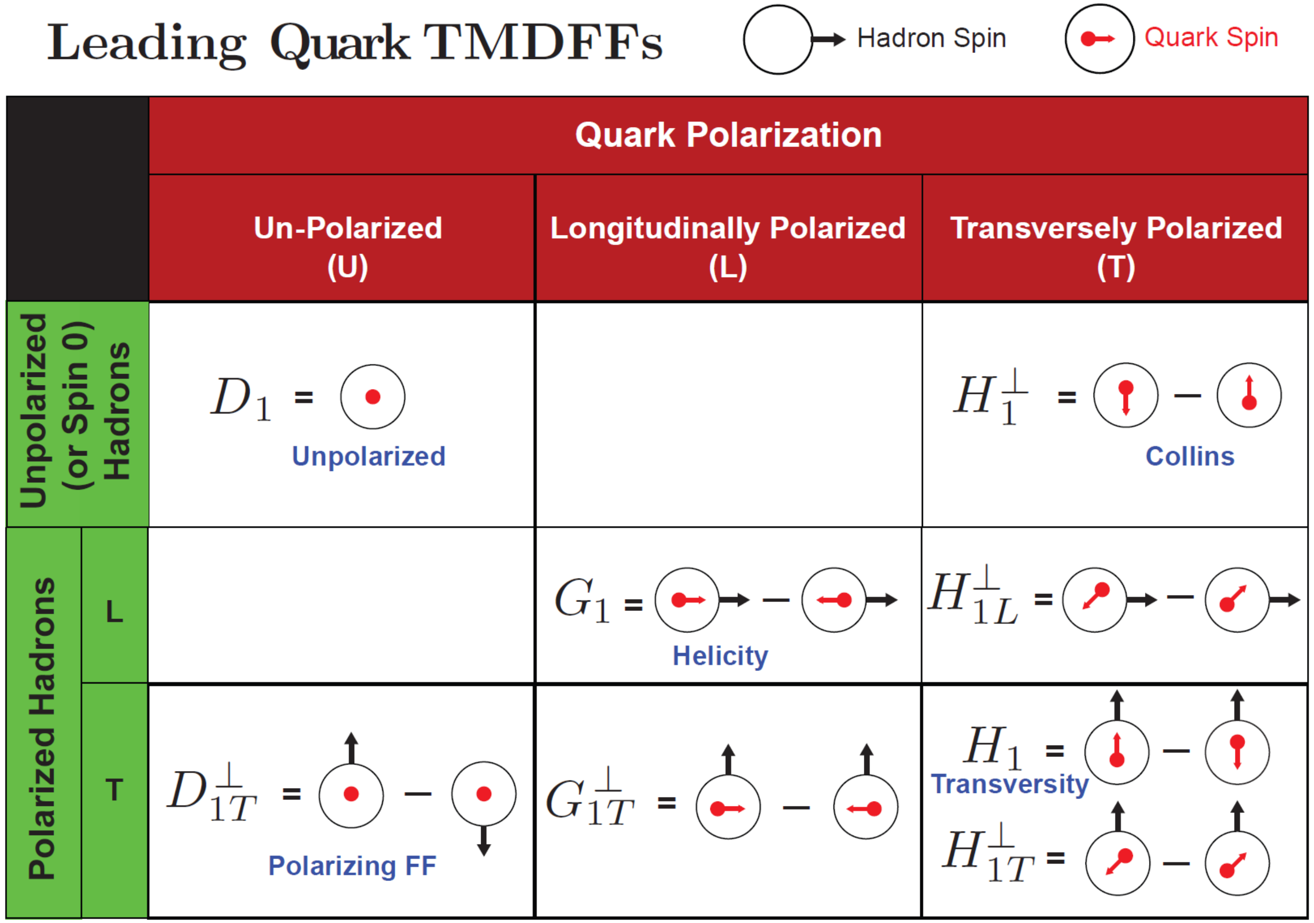
TMD handbook: 2304.03302

Closely related:

- Higher Twist correlations (TMD moments) $T_F(x, x)$

TMD Fragmentation functions

- Similarly 8 TMD FFs at leading twist
- Most typical final states are pions and kaons → only 2 FFs
- If polarized final state (and detection of spin possible) all 8 FFs available, eg Polarizing Λ FF discovered in Belle



[TMD handbook: 2304.03302](https://arxiv.org/abs/2304.03302)

Full SIDIS cross section

- Various terms depend on proton spin, lepton helicity and azimuthal angles of final state hadron and proton spin relative to scattering plane
- Single, double spin and azimuthal asymmetries allow to single out the different TMD contributions

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h}$$

$$+\varepsilon\cos(2\phi_h)F_{UU}^{\cos 2\phi_h}+\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi_h}$$

$$+S_\parallel\Big[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)F_{UL}^{\sin 2\phi_h}\Big]$$

$$+S_\parallel\lambda_e\Big[\sqrt{1-\varepsilon^2}F_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h F_{LL}^{\cos\phi_h}\Big]$$

$$+|S_\perp|\Big[\sin(\phi_h-\phi_S)\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big)$$

$$+\varepsilon\sin(\phi_h+\phi_S)F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\sin(3\phi_h-\phi_S)F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S F_{UT}^{\sin\phi_S}+\sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$

$$+|S_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S F_{LT}^{\cos\phi_S}$$

$$+\sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},$$

JHEP 02 (2007) 093

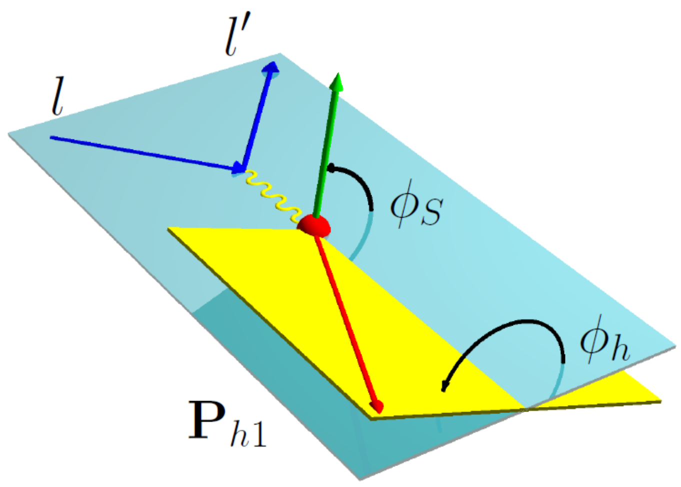
Experimental access to Transversity/tensor charge and Sivers function

- Sivers function obtained from sin (ϕ_h-ϕ_s) modulation

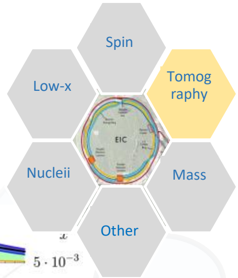
$$A_{UT}^{\sin(\phi_h-\phi_S)}(x,z,P_T) \propto \mathbf{S}_T \frac{\sum_{q,\bar{q}} e_q^2 f_{1T}^{\perp,q}(x,k_t)\otimes D_1(z,p_t)}{\sum_{q,\bar{q}} e_q^2 q(x,k_t)\otimes D_1(z,p_t)}$$

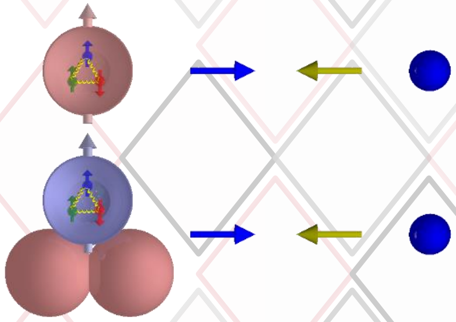
- Collins asymmetry and transverseity obtained from sin(ϕ_h+ϕ_s) modulation

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



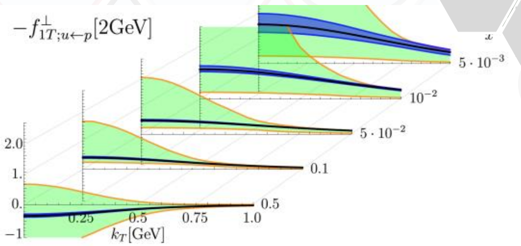
EIC TMD Goals: 3D Transverse spin and momentum structure

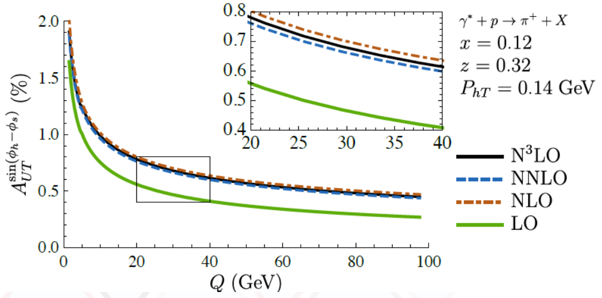


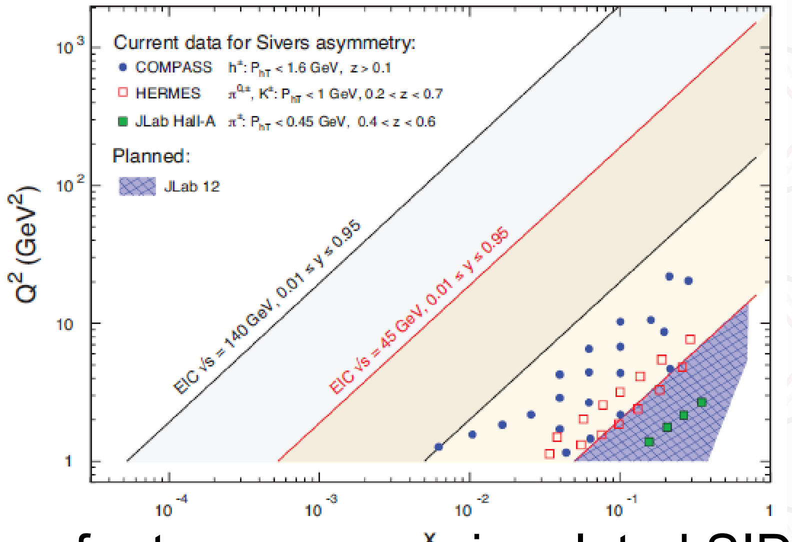


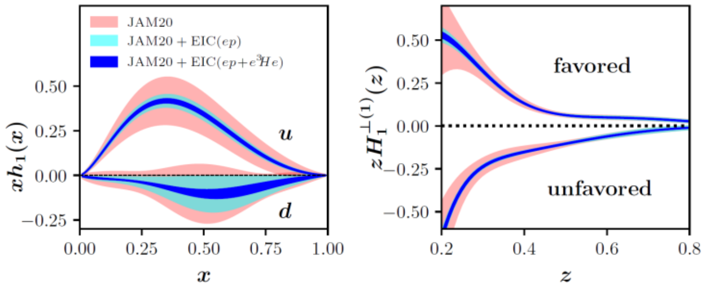
Deliverables	Observables	What we learn	Stage I	Stage II
Sivers & unpolarized TMD quarks and gluon	SIDIS with Transverse polarization; di-hadron (di-jet)	Quantum Interference & Spin-Orbital correlations	3D Imaging of quarks valence+sea	3D Imaging of quarks & gluon; Q^2 (P_{hT}) range QCD dynamics
Chiral-odd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

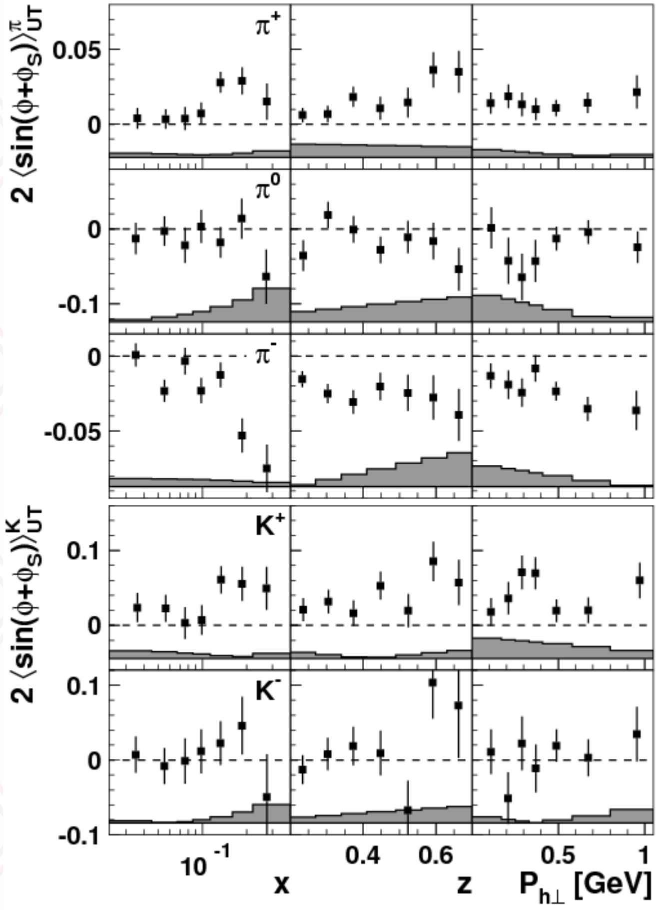
Current status on TMD measurements

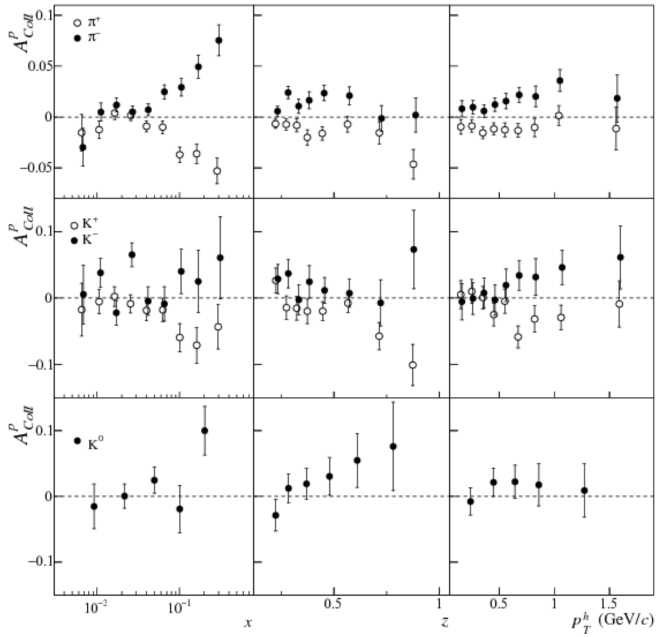
Latest SIDIS Collins data

HERMES: *Phys.Lett.B 693 (2010) 11*

COMPASS: *Phys.Lett.B* 744(2015) 250

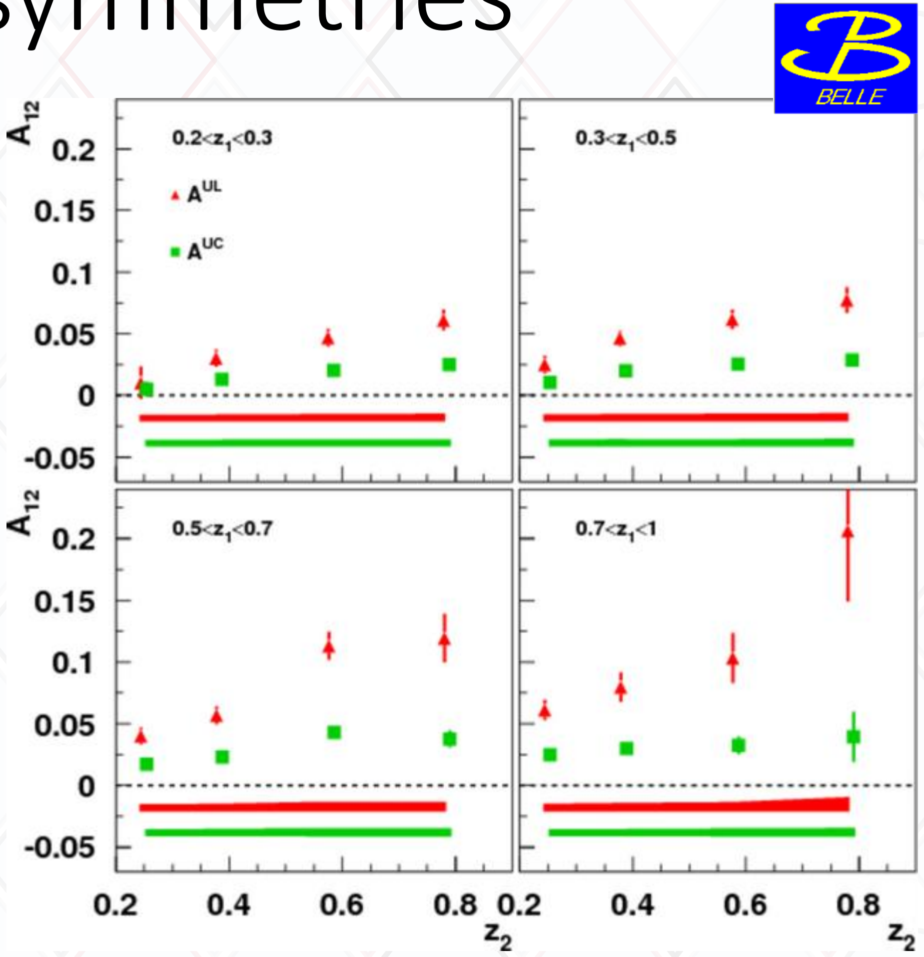
- Final Collins asymmetries of HERMES and COMPASS (<2017) published, including kaons
- More deuteron available by COMPASS (see next slides)
- Transverse target data expected from JLAB in near future





Belle Collins asymmetries

- Red points : $\cos(\phi_1 + \phi_2)$ moment of Unlike sign pion pairs over like sign pion pair ratio : A^{UL}
- Green points : $\cos(\phi_1 + \phi_2)$ moment of Unlike sign pion pairs over any charged pion pair ratio : A^{UC}
- Collins fragmentation is large effect
- Consistent with SIDIS indication of sign change between favored and disfavored Collins FF

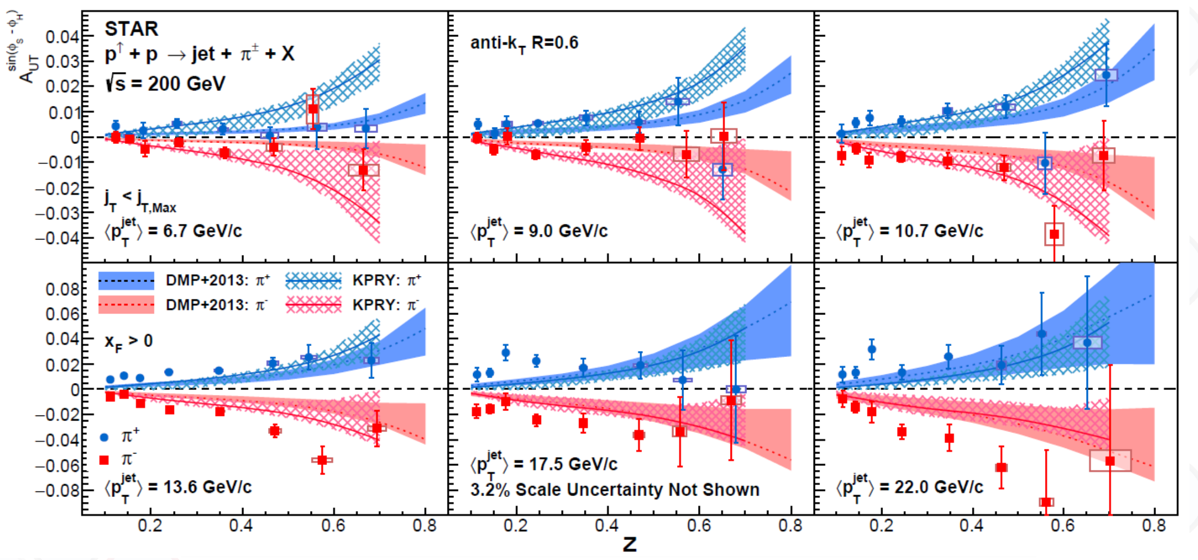


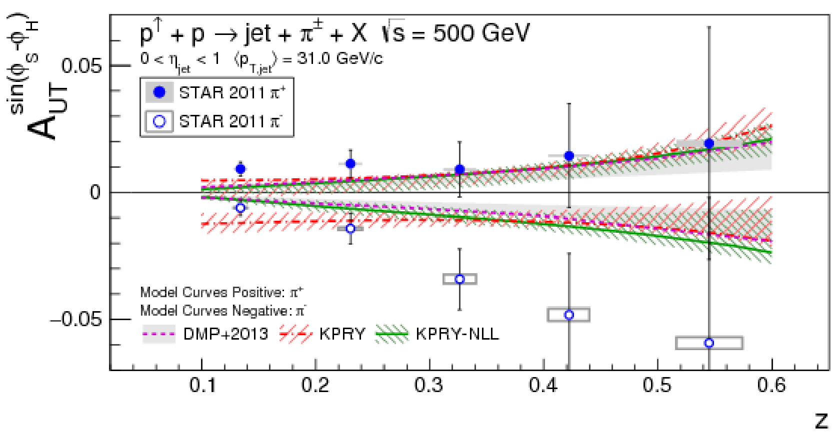
RS et al (Belle), PRL96: 232002
PRD 78:032011, Erratum D86:039905

Transversity in proton collisions

- Nonzero Collins asymmetries (hadron in jets) at central rapidities at 200 and 500 GeV
- Substantial theoretical progress for hadron in jet measurements
  - unpolarized: Kaufmann et al.
  - polarized Kang et al.
- For roughly same x and kt similar size → evolution effects moderate?
- But generally slightly larger than global fits from SIDIS/e+e-
- More to come from sPHENIX in near future

STAR: Phys.Rev.D 106 (2022) 072010, 2022



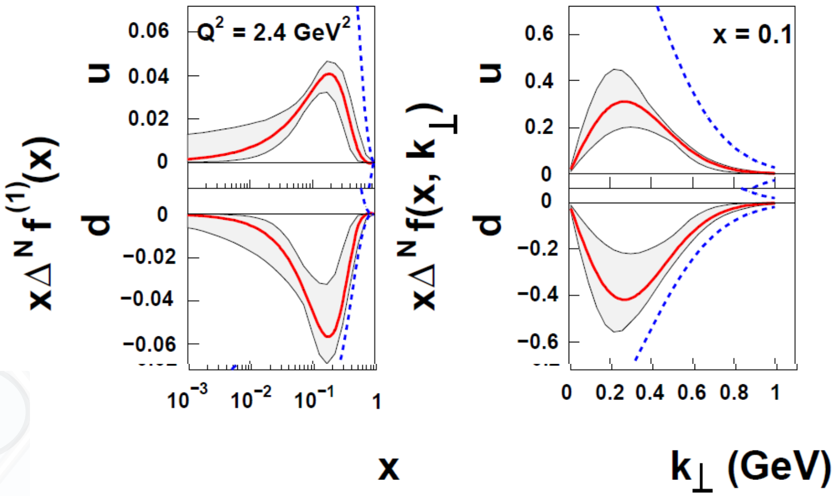


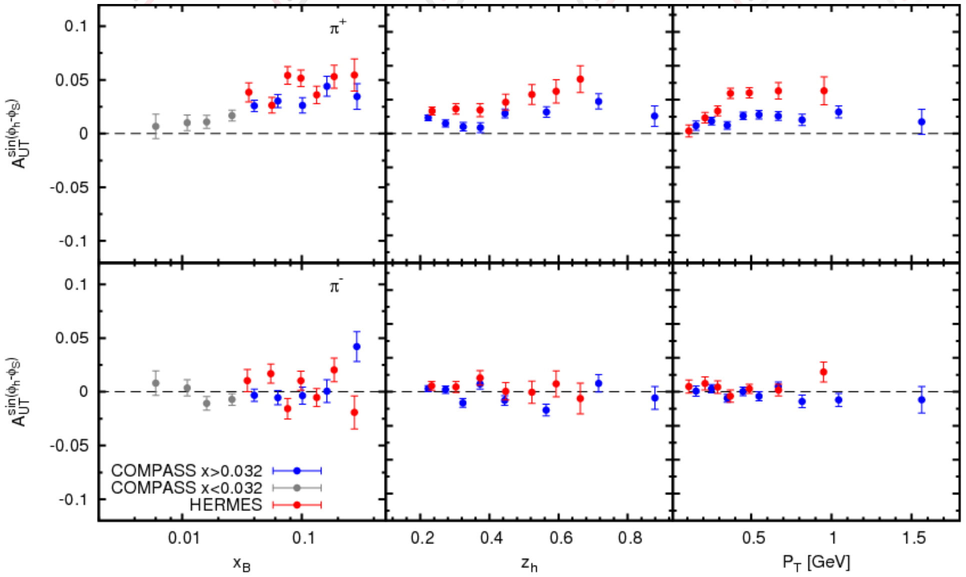
STAR: *Phys.Rev.D 97 (2018) 032004*

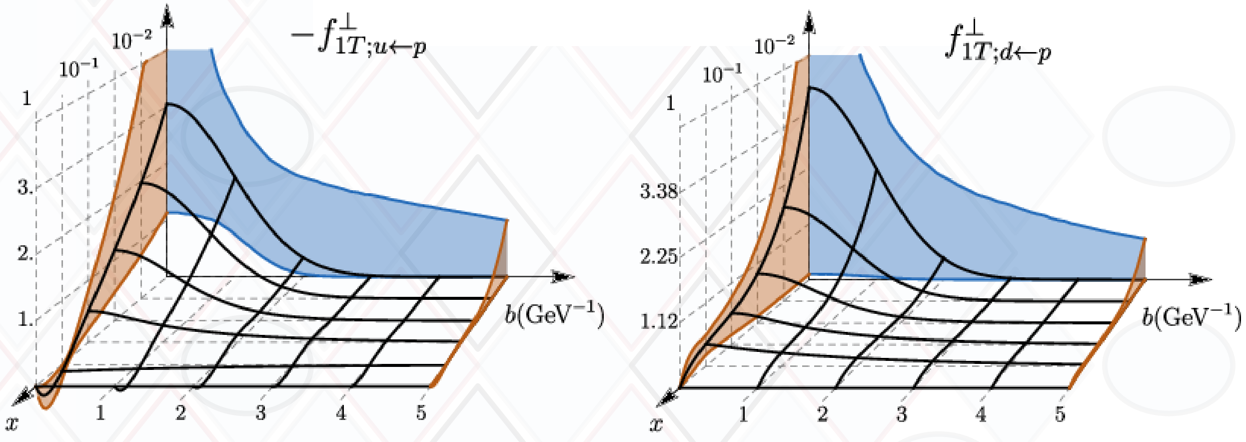
Anselmino et al. *Eur.Phys.J.A* 39 (2009) 89

Sivers Function measurements

- Early fits of SIDIS data show opposite signs, d quarks possibly larger
- Recent updates including evolution higher orders, and STAR W data







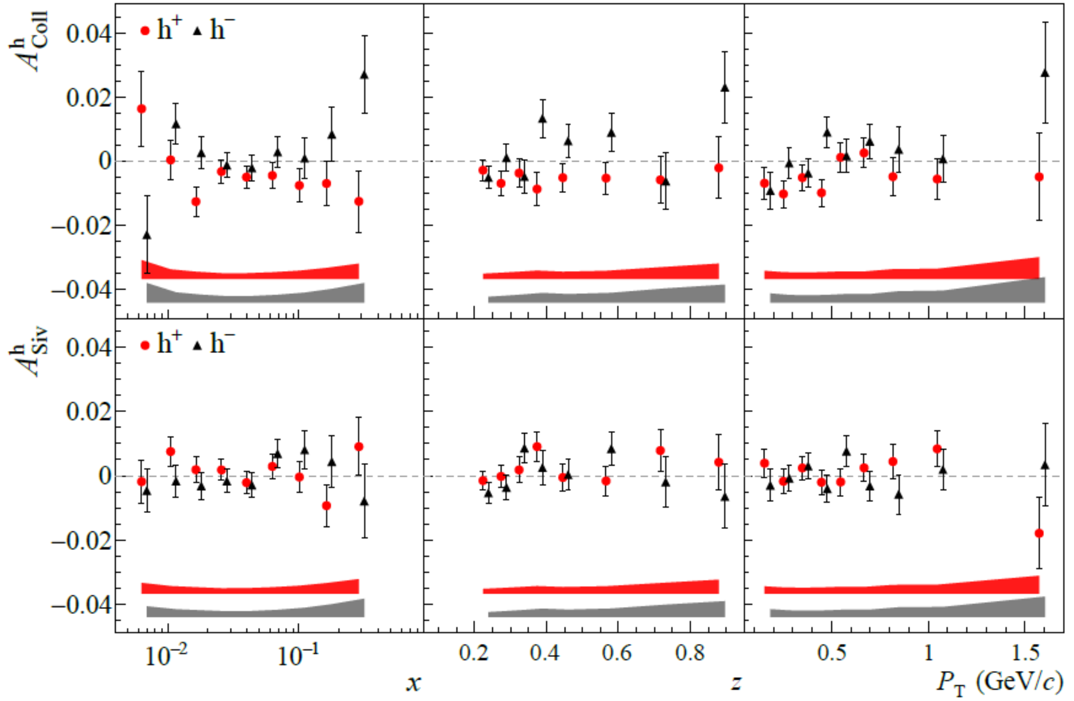
Bury et al. *Phys.Rev.Lett.* 126 (2021) 112002

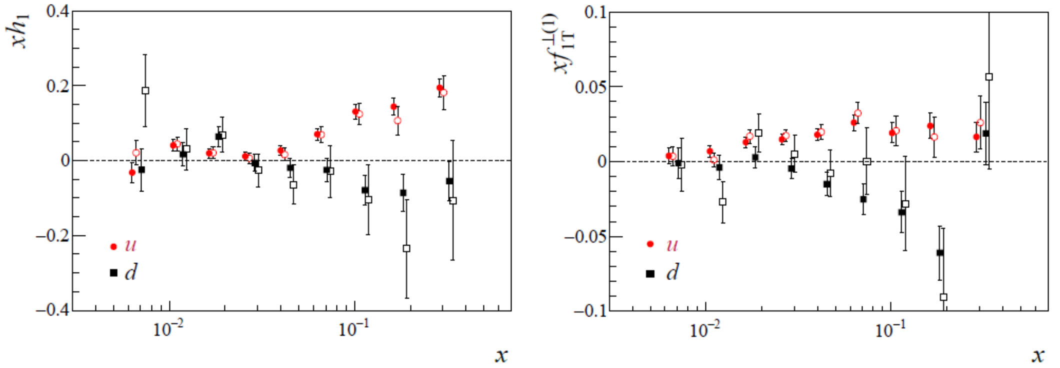
$$f_{1T,q}^{\perp}(x, k_T)$$

New COMPASS deuteron data

COMPASS 2401.00309

- Old COMPASS e+d data consistent with zero due to cancellations (Collins + transversity, Sivers)
- Larger statistics show slightly negative Collins asymmetries for h⁺
- Improved sensitivity to d quarks compared to e+p → d transversity negative

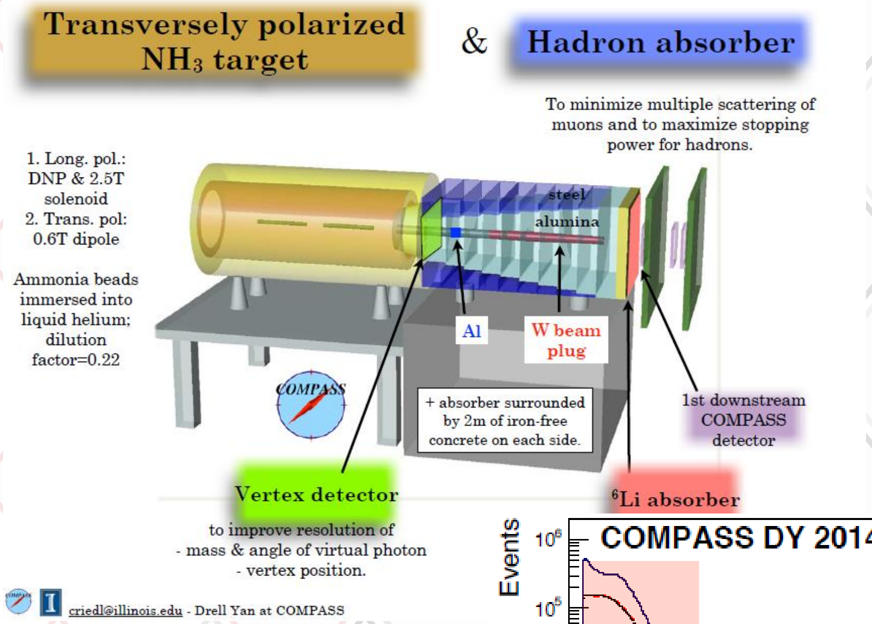


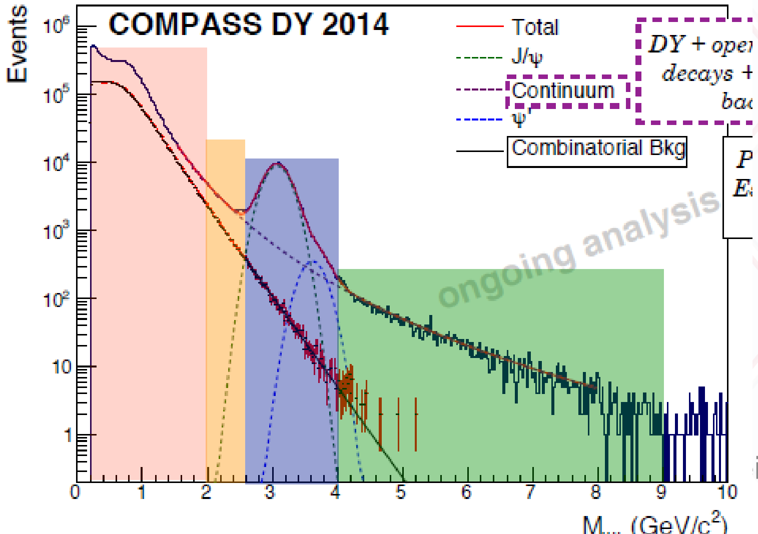


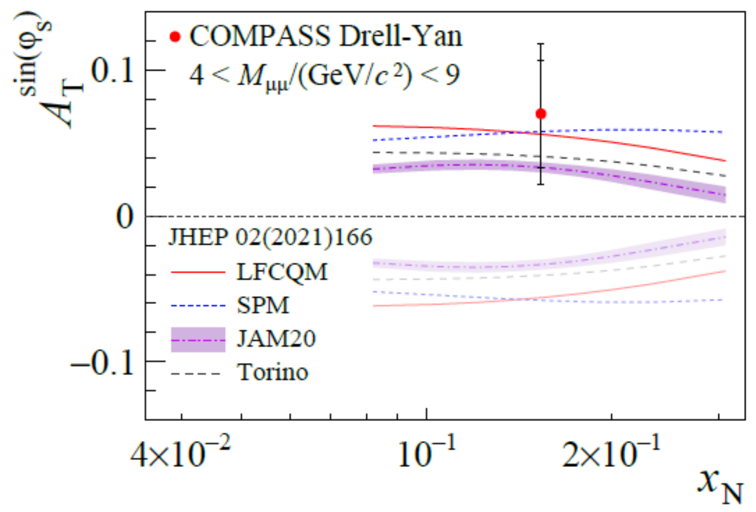
Sivers Sign change

$$f_{1T,q}^{\perp DY}(x,k_T) \stackrel{?}{=} -f_{1T,q}^{\perp DIS}(x,k_T)$$

COMPASS: polarized NH_3 target + 160 GeV π^- beam → Sensitivity to u quark Sivers and sign change



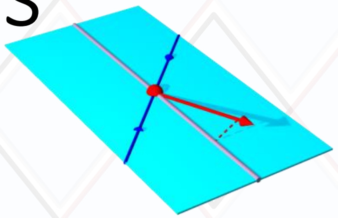


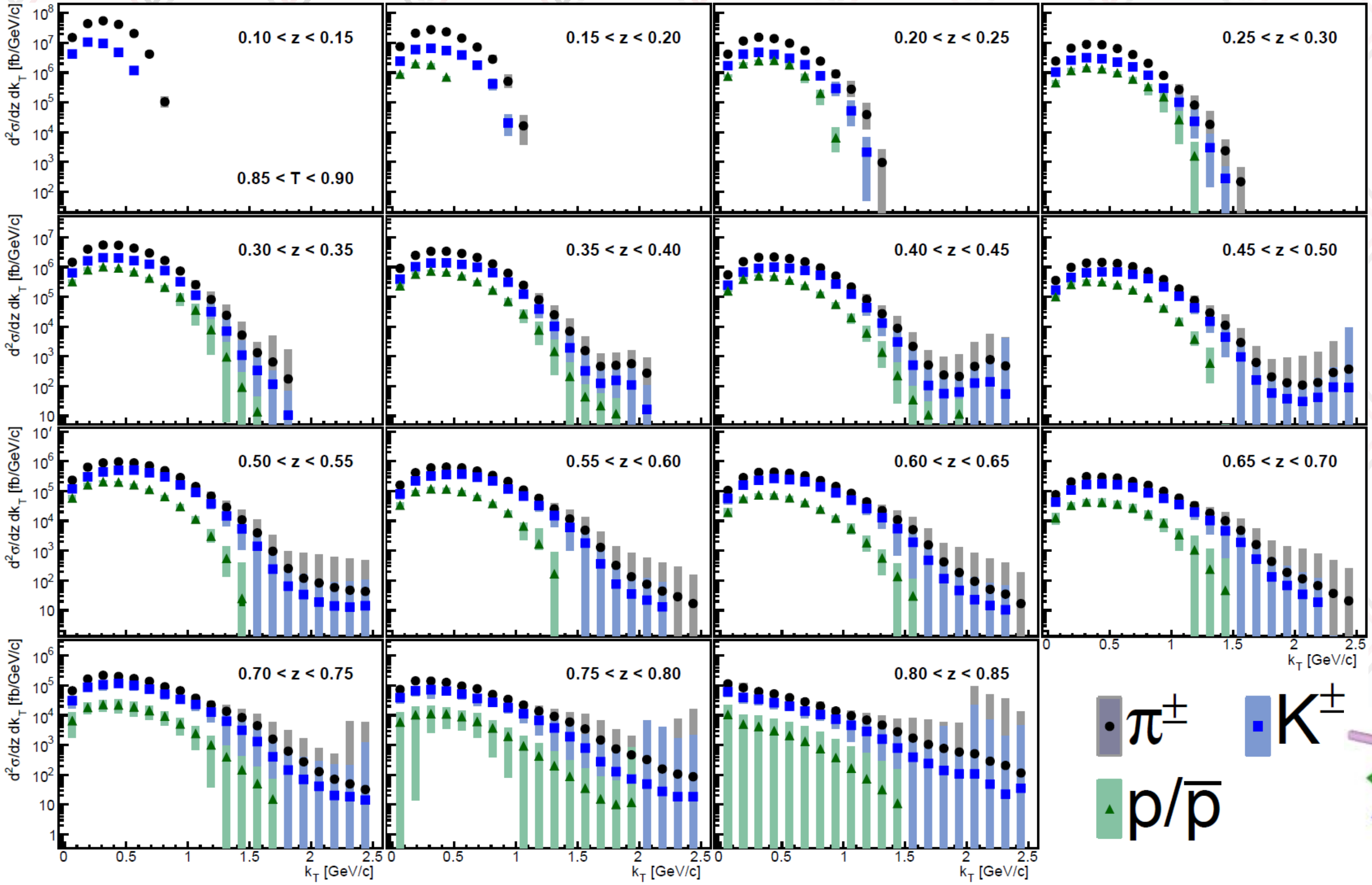


[COMPASS 2312.17379]

- Now a rather clear indication of the sign change!

Transverse momentum dependent cross sections for pions, kaons and protons →TMD FFs



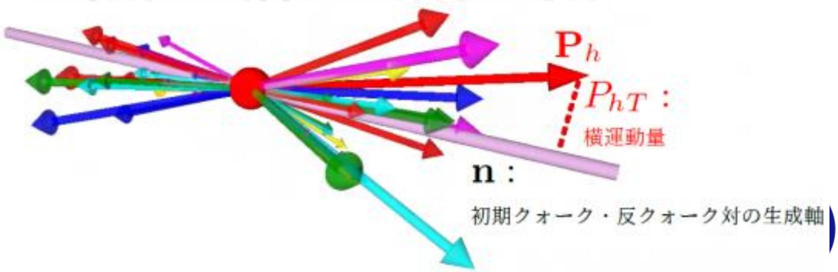


$\frac{d^2\sigma}{dzdP_{hT}}$

P_{hT}

Important baseline for most transverse momentum/spin dependent measurements at RHIC and EIC

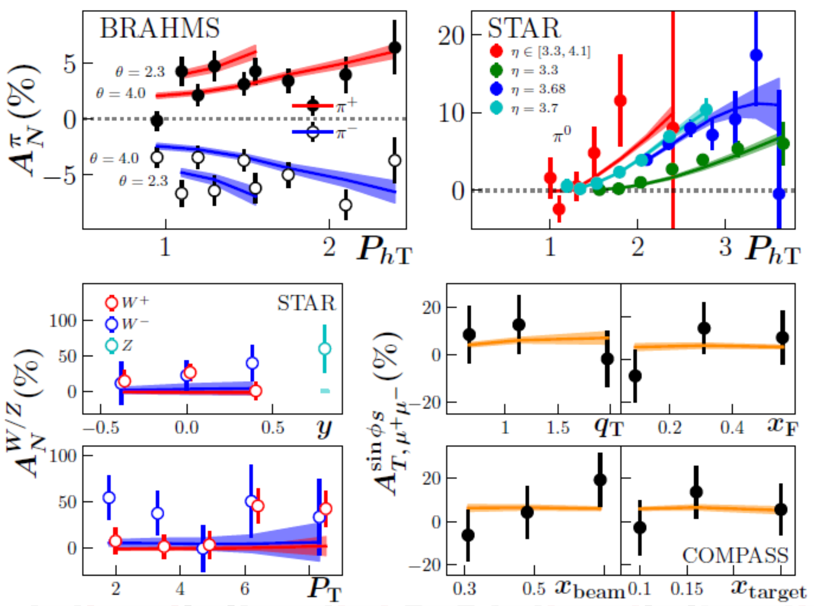
RIKEN Press release: https://www.riken.jp/press/2019/20190615_1/



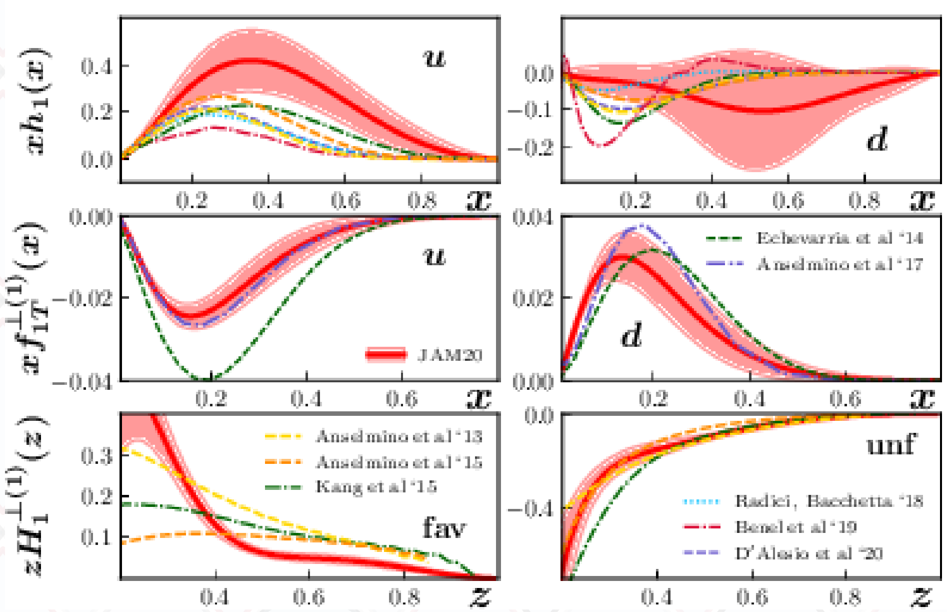
RS. et. al. PRD99 (2019) 112006

Where to go from here? Global fits on transverse quark-gluon structure

Cammarota et al, PRD 102 (2020) 054002



RHIC, SIDIS, DY included



Transversity

Sivers function

Collins FF

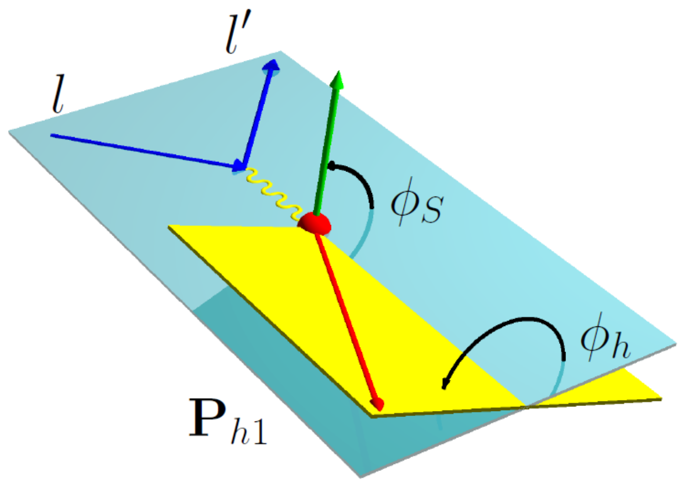
- Recent central rapidity PHENIX results (π,η,Heavy flavor electons, direct photons) not yet included
- Impact on gluon Sivers function (tri-gluon correlator) expected

What to expect before EIC?

- Significantly more SIDIS data from JLAB (Collins, Sivers, Di-hadrons, unpolarized), high-x and low scale
- More updates from RHIC on Collins asymmetries (hadron-in-jet)
- More Fragmentation information from Belle(II) – unpolarized, HF, VMs, etc
- Sea quark Sivers from SpinQuest (polarized fixed-target DY)
- More high-scale unpolarized data from LHC

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

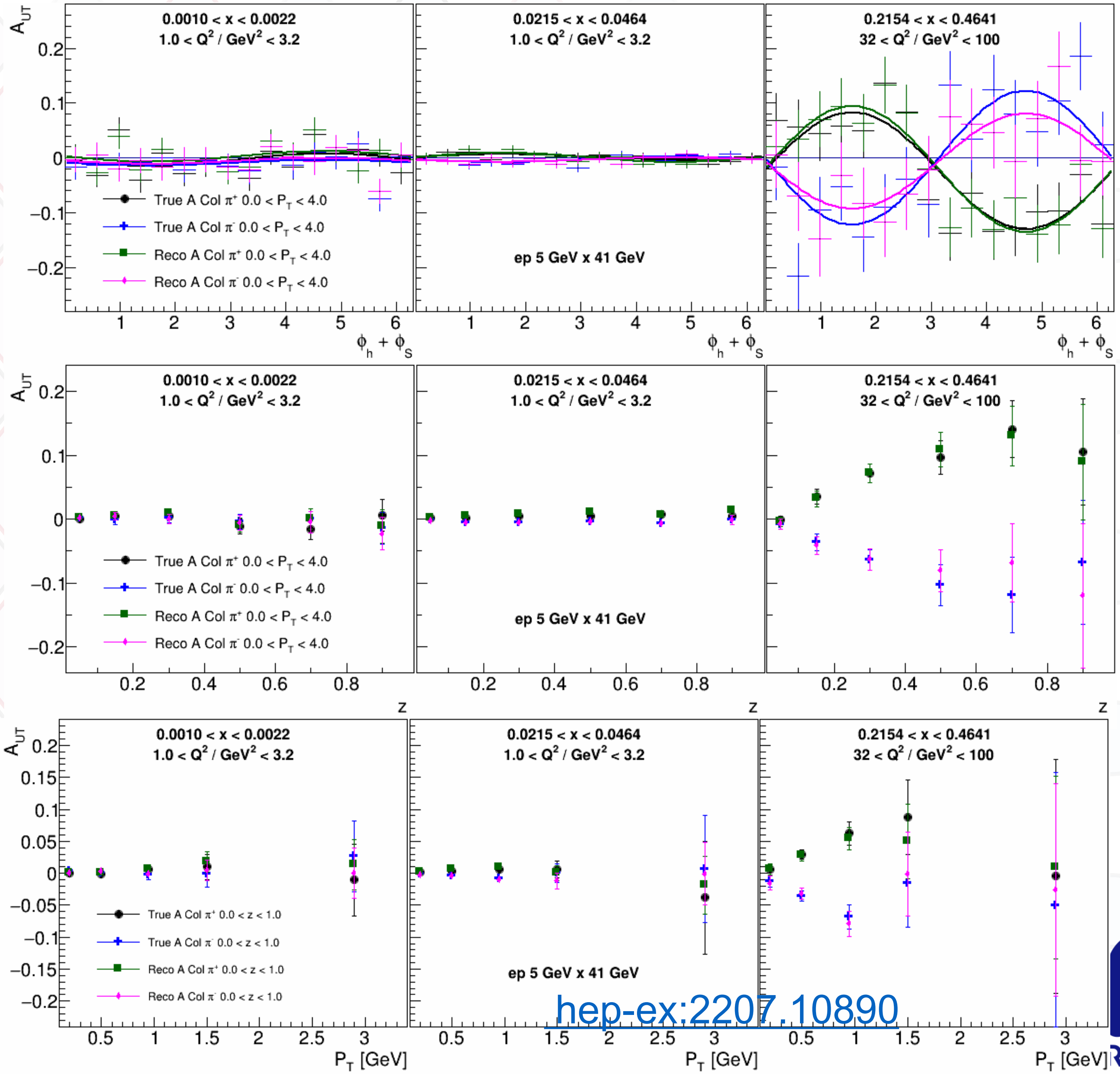


$$A_{UT}^{\sin(\phi_h+\phi_S)}(x,z,P_T) \propto \mathbf{S}_T \frac{\sum_{q,\bar{q}} e_q^2 \delta q(x,k_t) \otimes H_1^{\perp}(z,p_t)}{\sum_{q,\bar{q}} e_q^2 q(x,k_t) \otimes D_1(z,p_t)}$$

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

Example Asymmetries

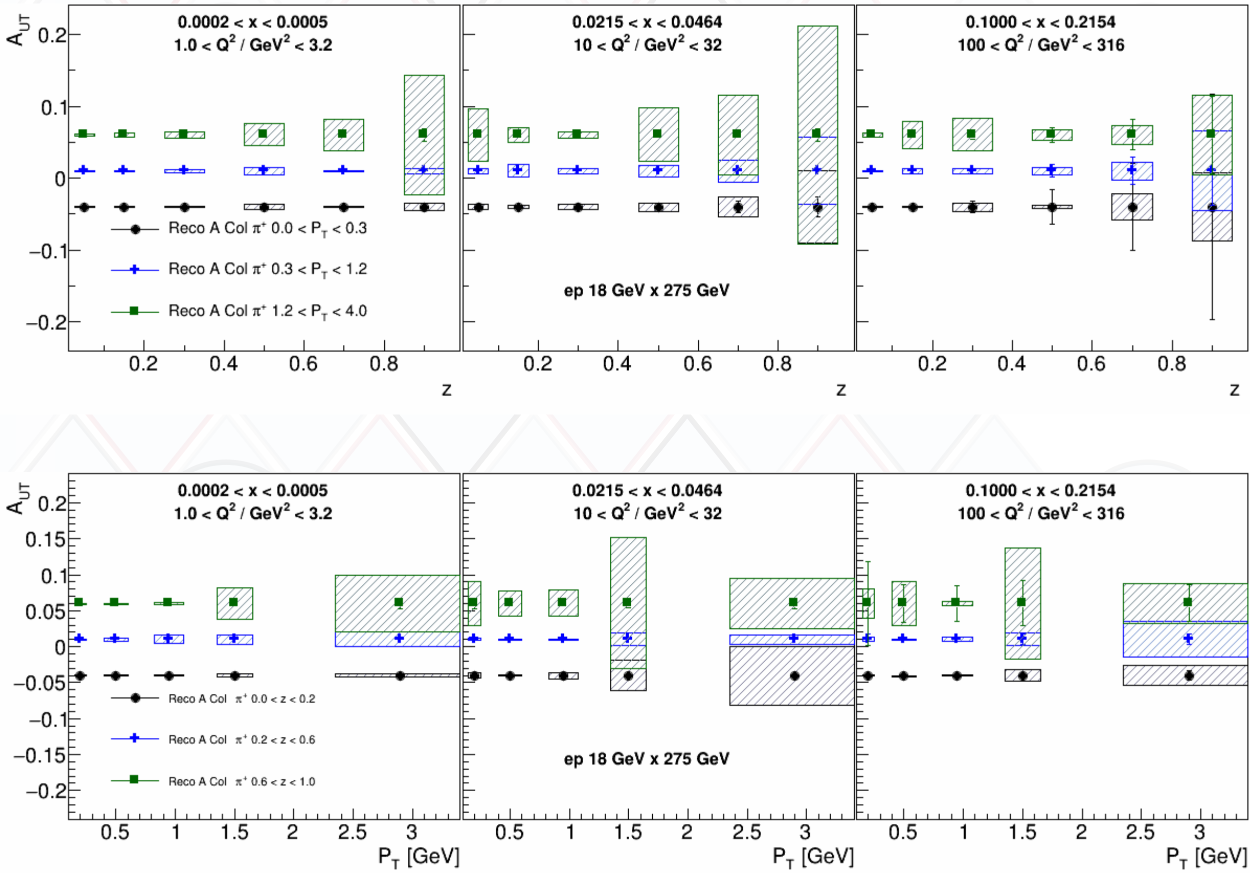
- Examples in 3 x and Q^2 bins: on top for the Collins angular combination for charged pions true and reconstructed in an intermediate z bin
- Lower figures: same, either projected vs z or vs Pt



hep-ex:2207.10890

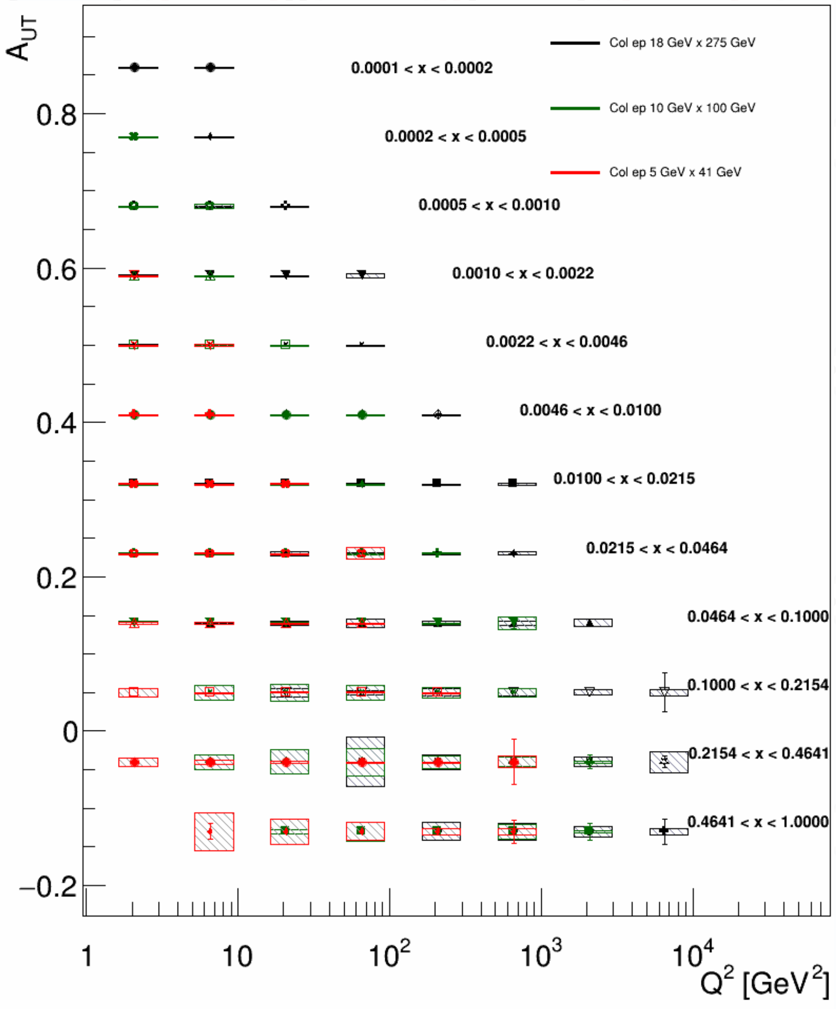
Projections to 10fb^{-1}

- 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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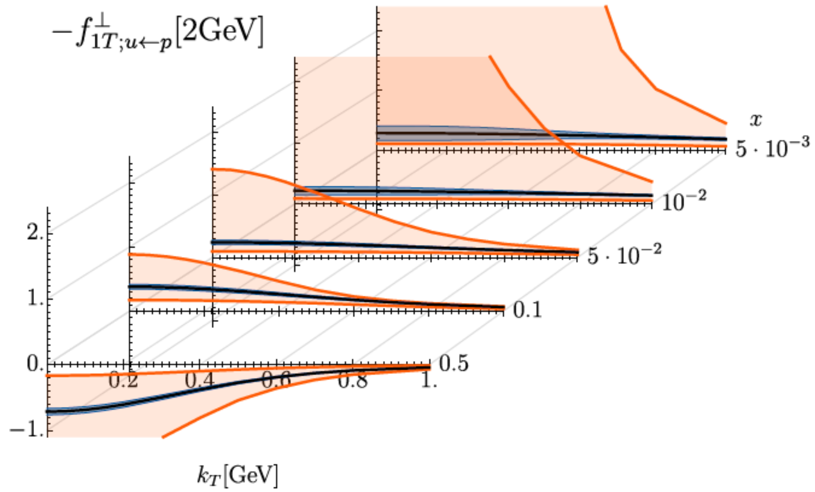
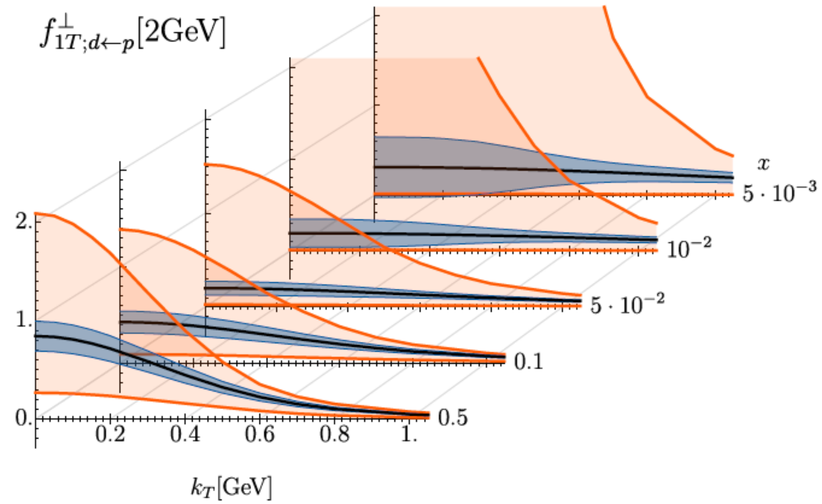
Impact for Sivers functions

- 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 ePIC





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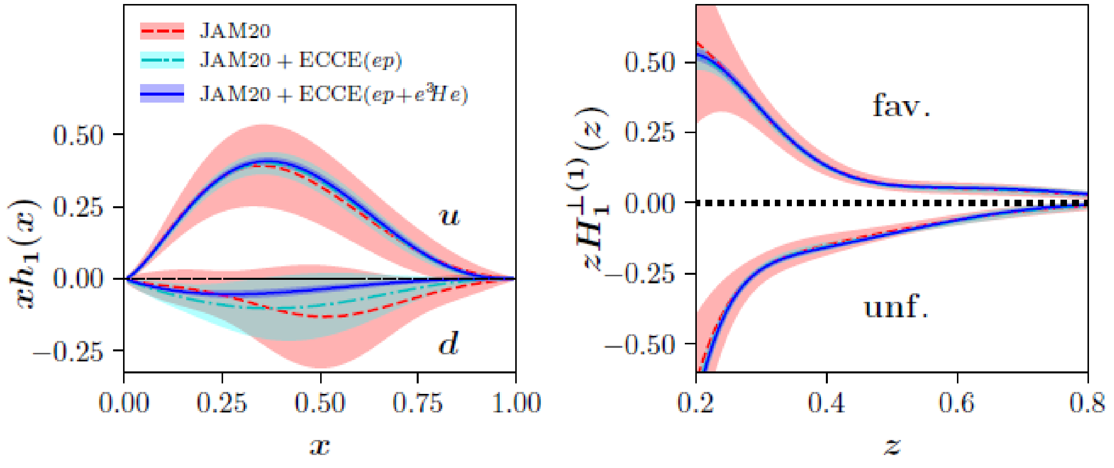
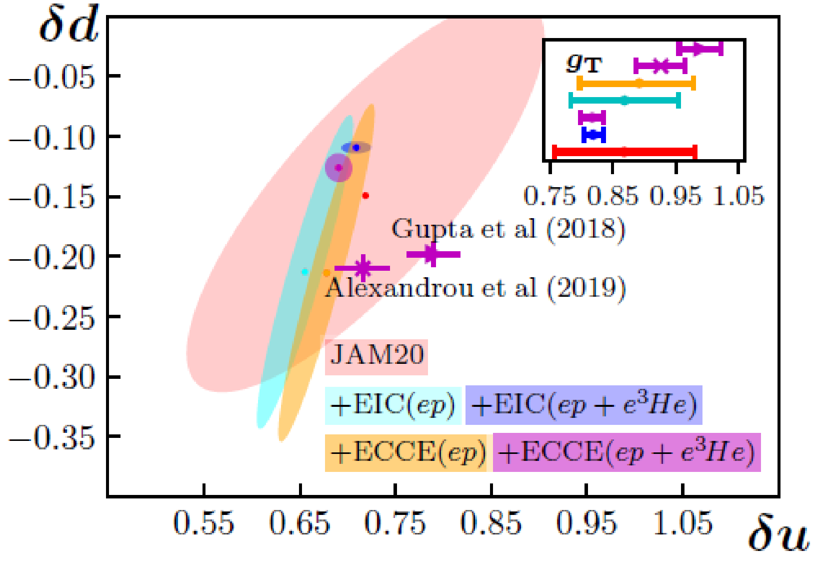
Tensor charge impact

- 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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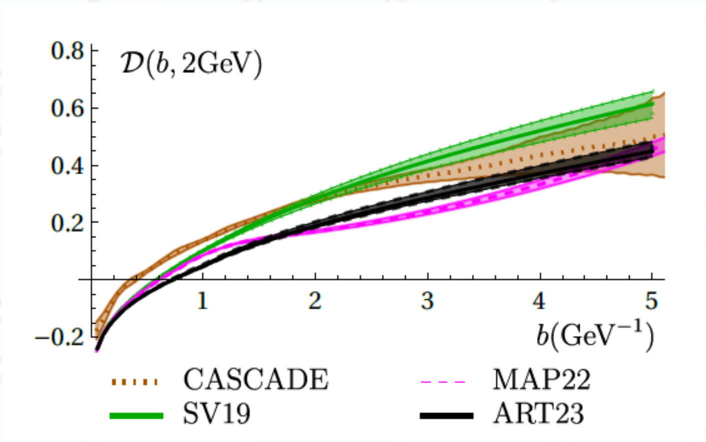
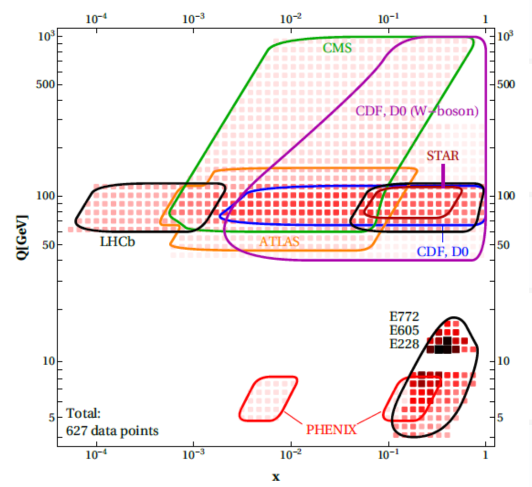
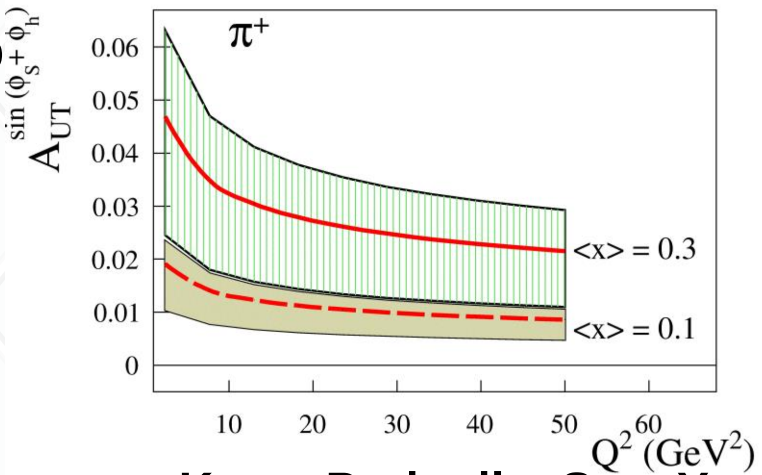
About TMD evolution

Moos et al.
https://arxiv.org/abs/2305.07473

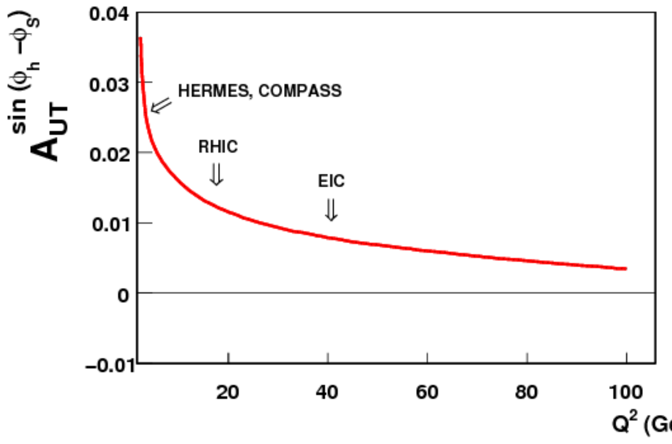
- Large theoretical effort to understand TMD evolution (see for example Evolution and REF workshop series)
- Large overlap with low-x community
- Despite predominantly using CSS formalism large differences due to treatment of non-perturbative terms in evolution → relevant for many spin related TMDs
- Data needed to pin down TMD evolution





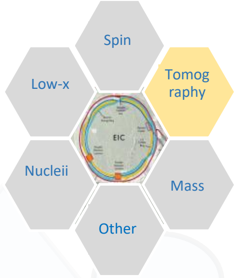


Kang, Prokudin, Sun, Yuan
PRD 93 (2016) 014009



Aybat, Prokudin, Rogers
PRL 108 (2012) 242003

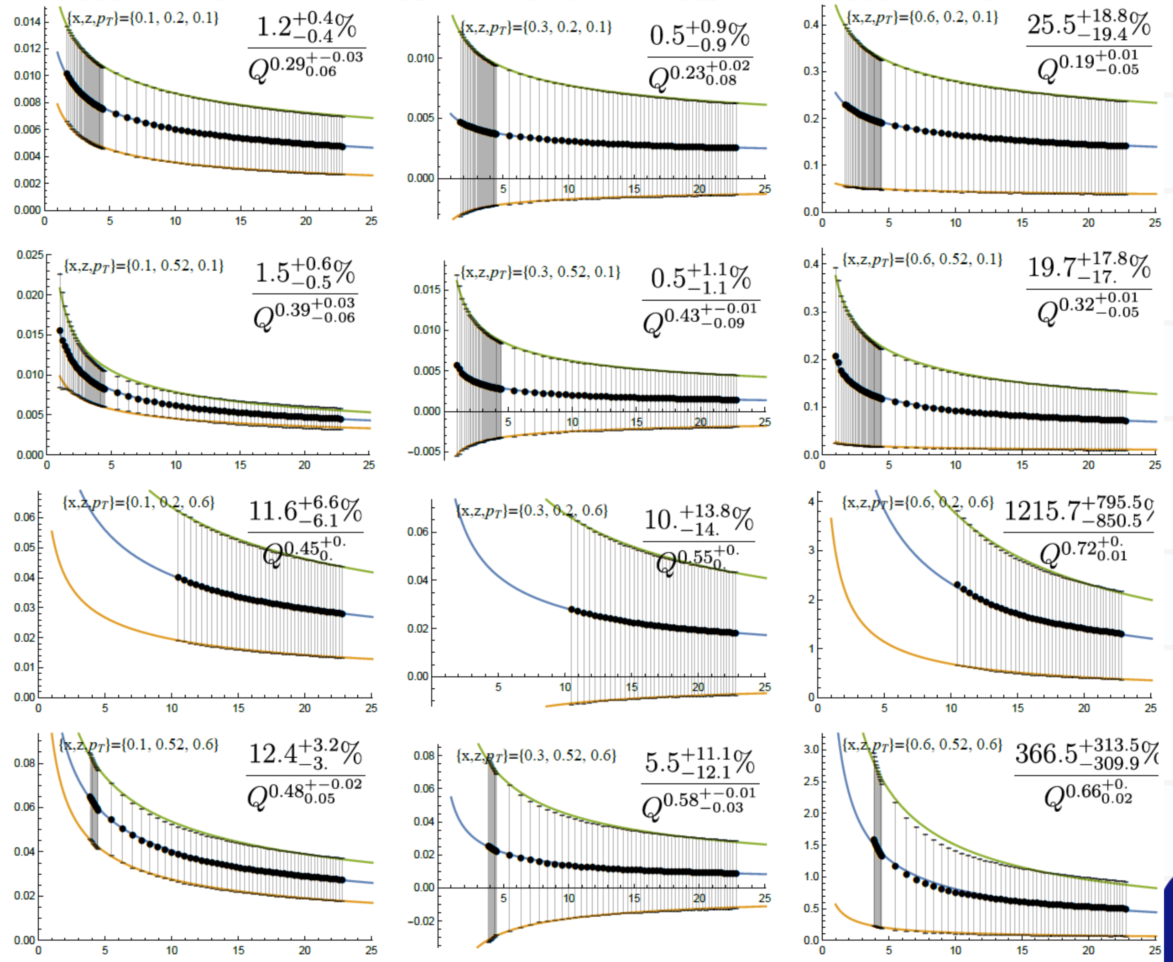
TMD evolution



- Very important aspect is the study of TMD evolution
- Part of the evolution kernel is non-perturbative, but current lever arm not sufficient
- Sivers asymmetries are expected to decrease at higher scales, but only logarithmically (ie they do NOT “disappear”)
- At higher x Asymmetries of several % expected

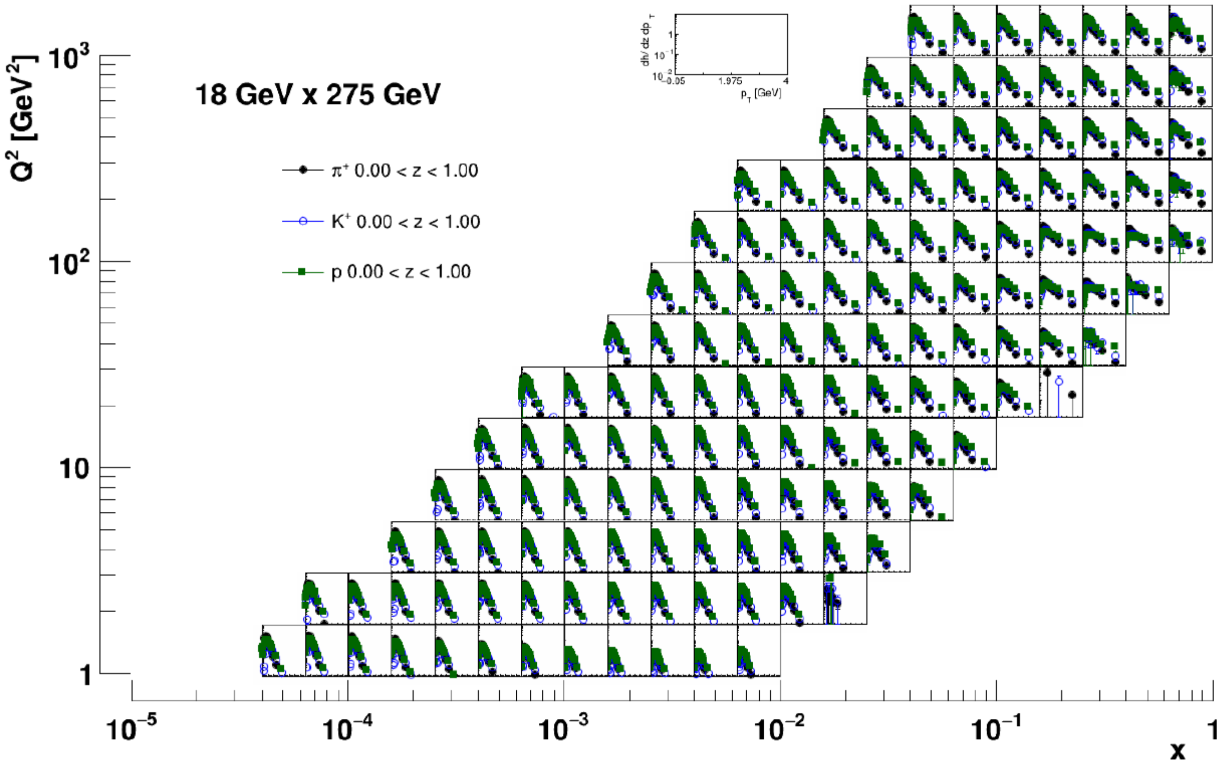
➔Well accessible with EIC over wide range in x and Q^2

Vladimirov et al.



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 ($|\eta|<3.5$) 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)
- 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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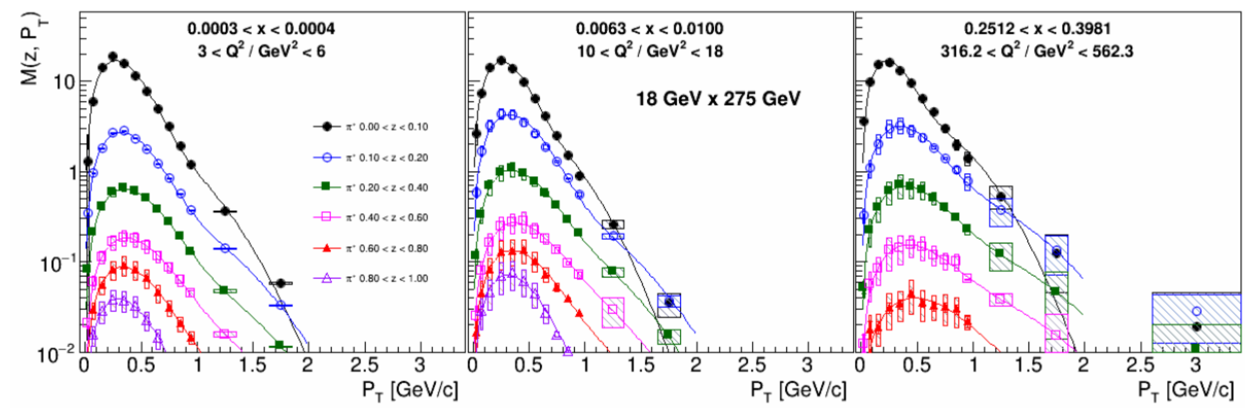
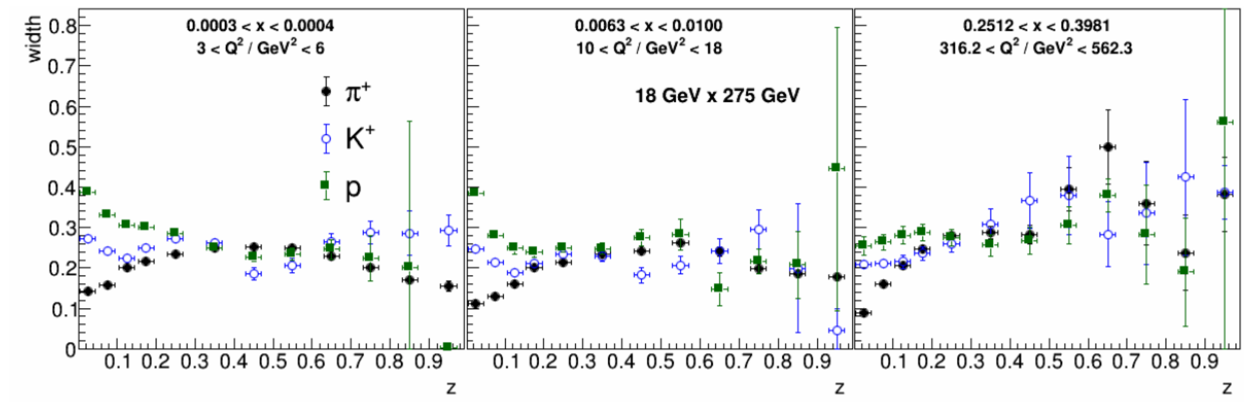
z-dependence of multiplicities and widths

- 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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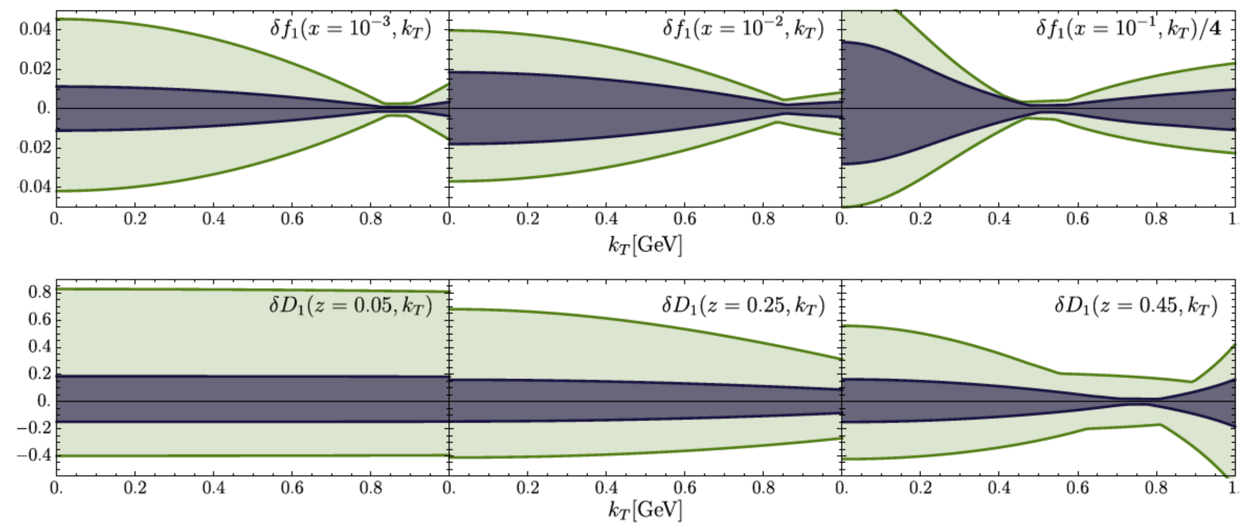
Impact for unpolarized TMD functions

- 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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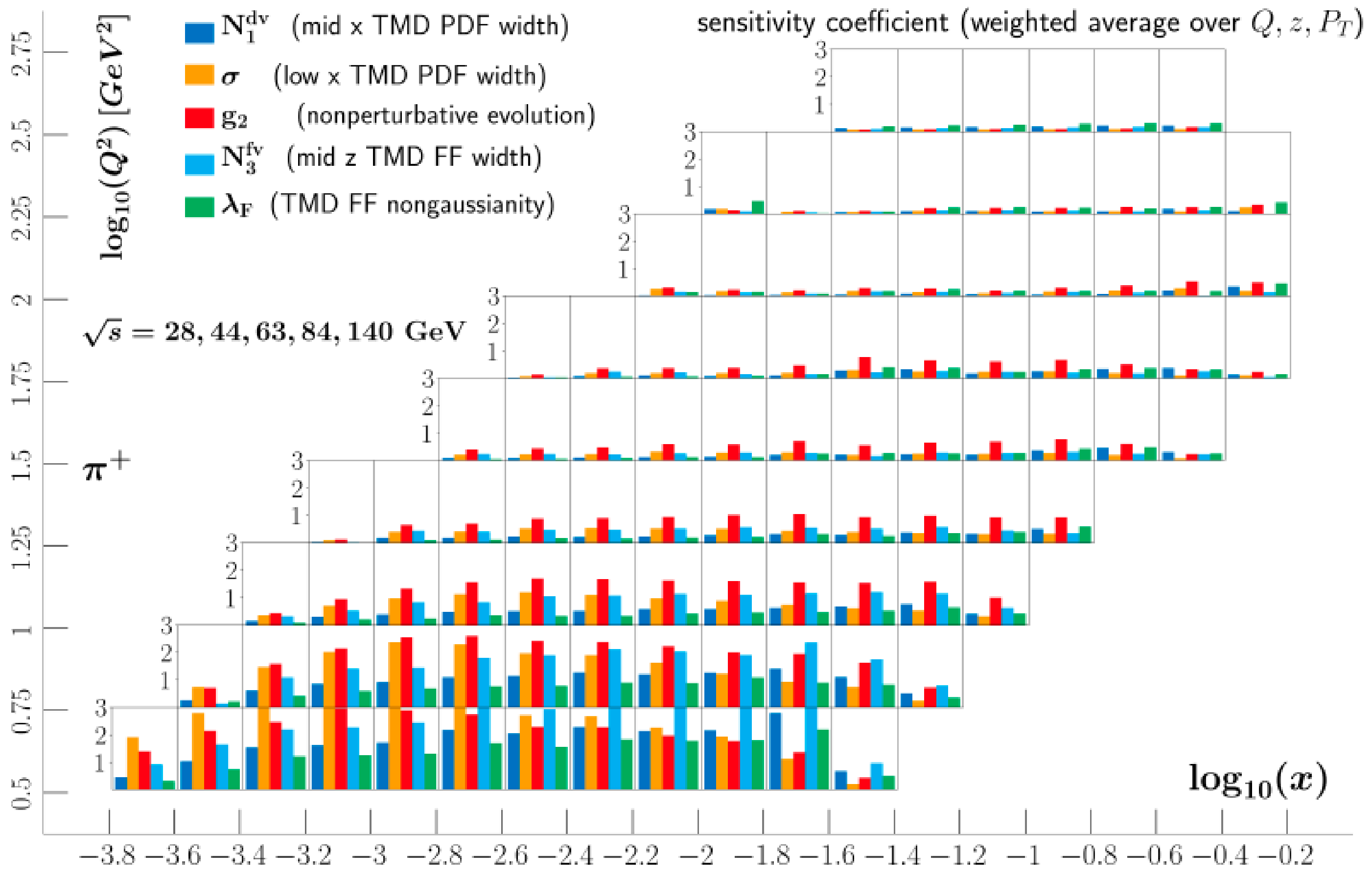
Simple impact on TMD evolution and unpol TMDs

- Impact on unpolarized TMDs at lower x, nonperturbative part of evolution and fragmentation functions expected from unpolarized TMD measurements



YR

Summary

- TMDs play a role from relatively low energies up to Higgs energies
- They particularly allow to access the full spin structure
- Some knowledge on unpol. TMDs, Sivers function and Transversity but many uncertainties still
- EIC data will improve on these TMDs in great detail
- Particular interest on TMD evolution which is still poorly understood
- Previous YR/ECCE/ATHENA impact studies are being revisited with more realistic ePIC simulations