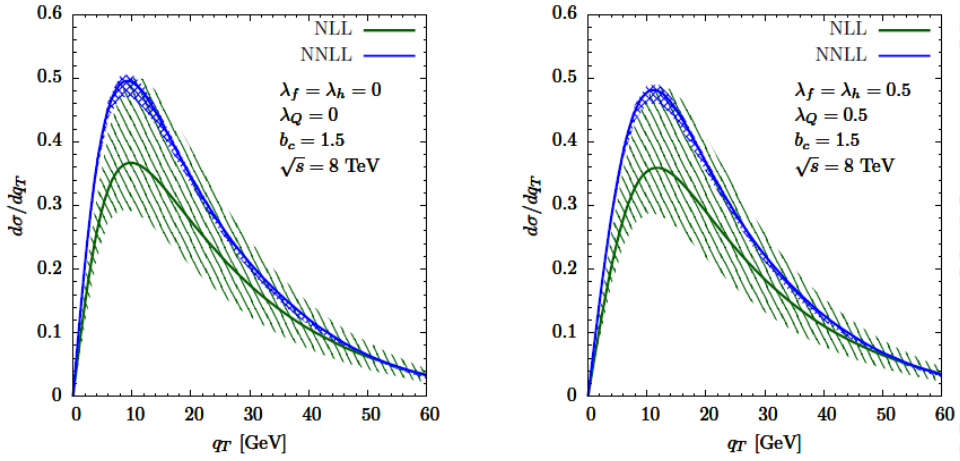
TMD related measurements

From Quarks and Gluons to the Internal Dynamics of Hadrons

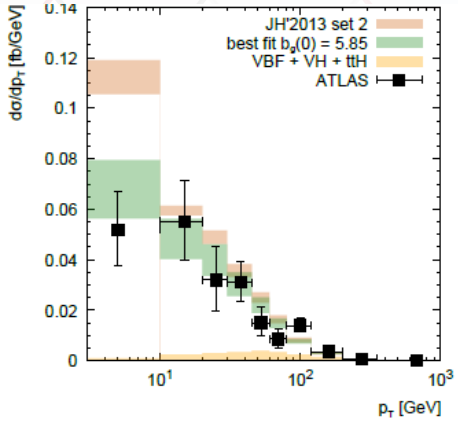
SBU, May 15-17, 2024

Ralf Seidl (RIKEN)

Higgs P_T cross section: p+p→H+X



Echevarria et.al. JHEP 07 (2015) 158

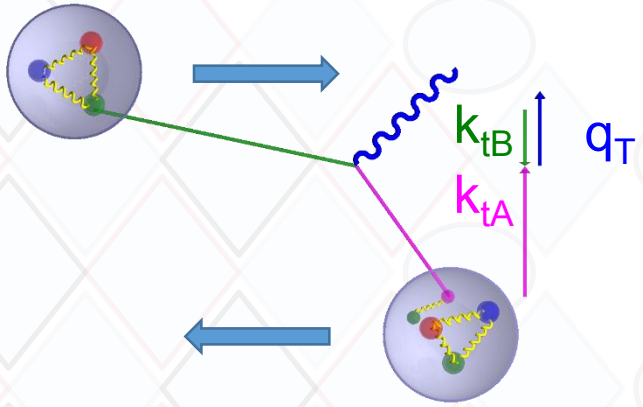


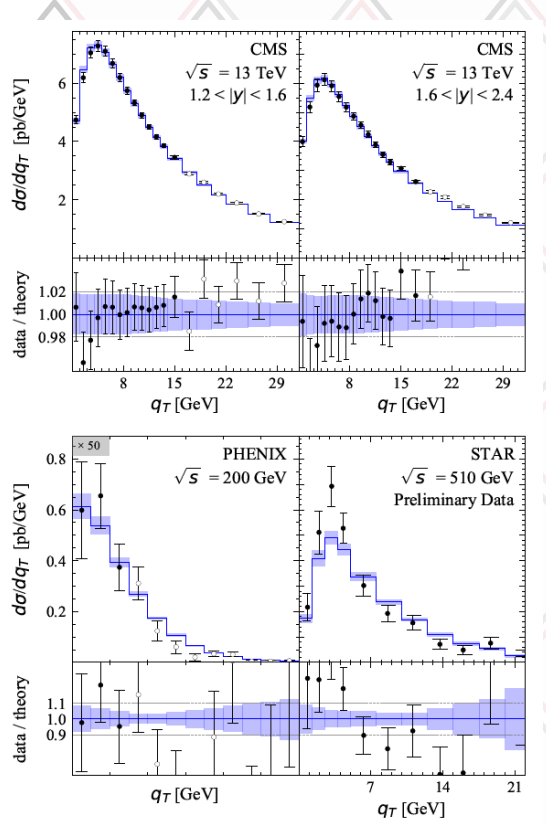
Lipatov et. al. *PRD* 107 (2023) 1

- 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

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

TMD factorization in Drell-Yan





Moos et al. 2305.07473

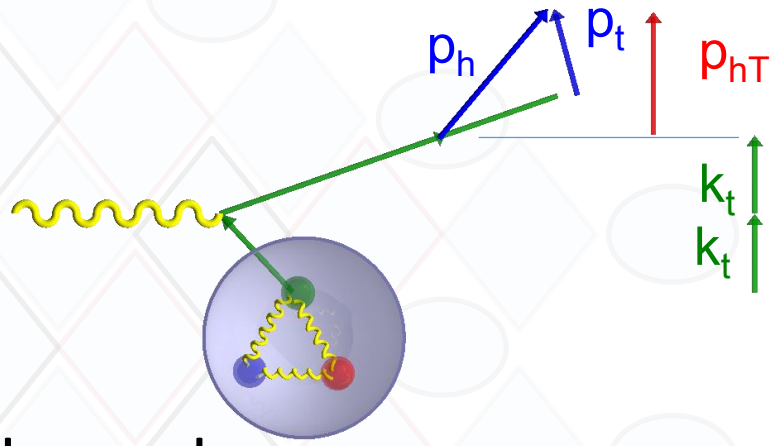
- Cross sections depend not only on the PDFs, but also on their transverse momenta
- Total transverse momentum of virtual photon to be matched with intrinsic momenta

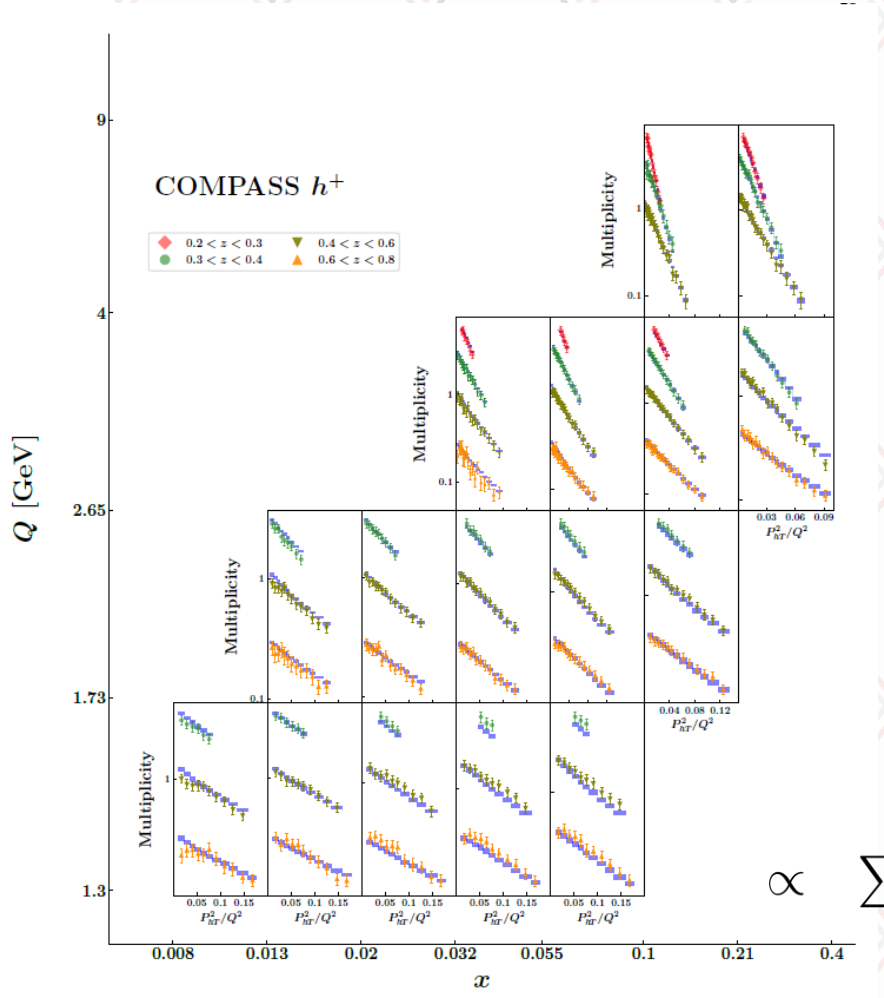
$$F_{UU}(x_A, x_B, \mathbf{q_T}, Q)$$

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

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

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

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

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

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

RIKEN

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

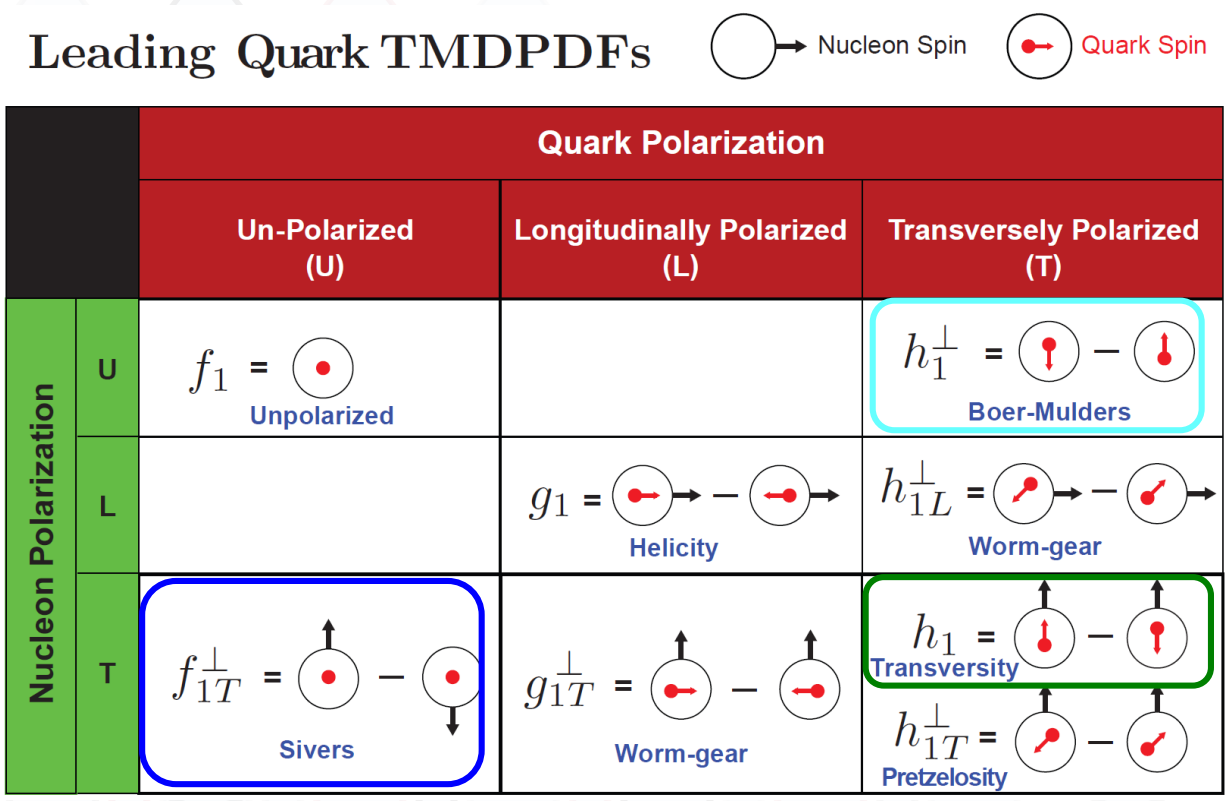
$$h_{1,q}(x)$$

- Sivers Function

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

- Boer Mulders function

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



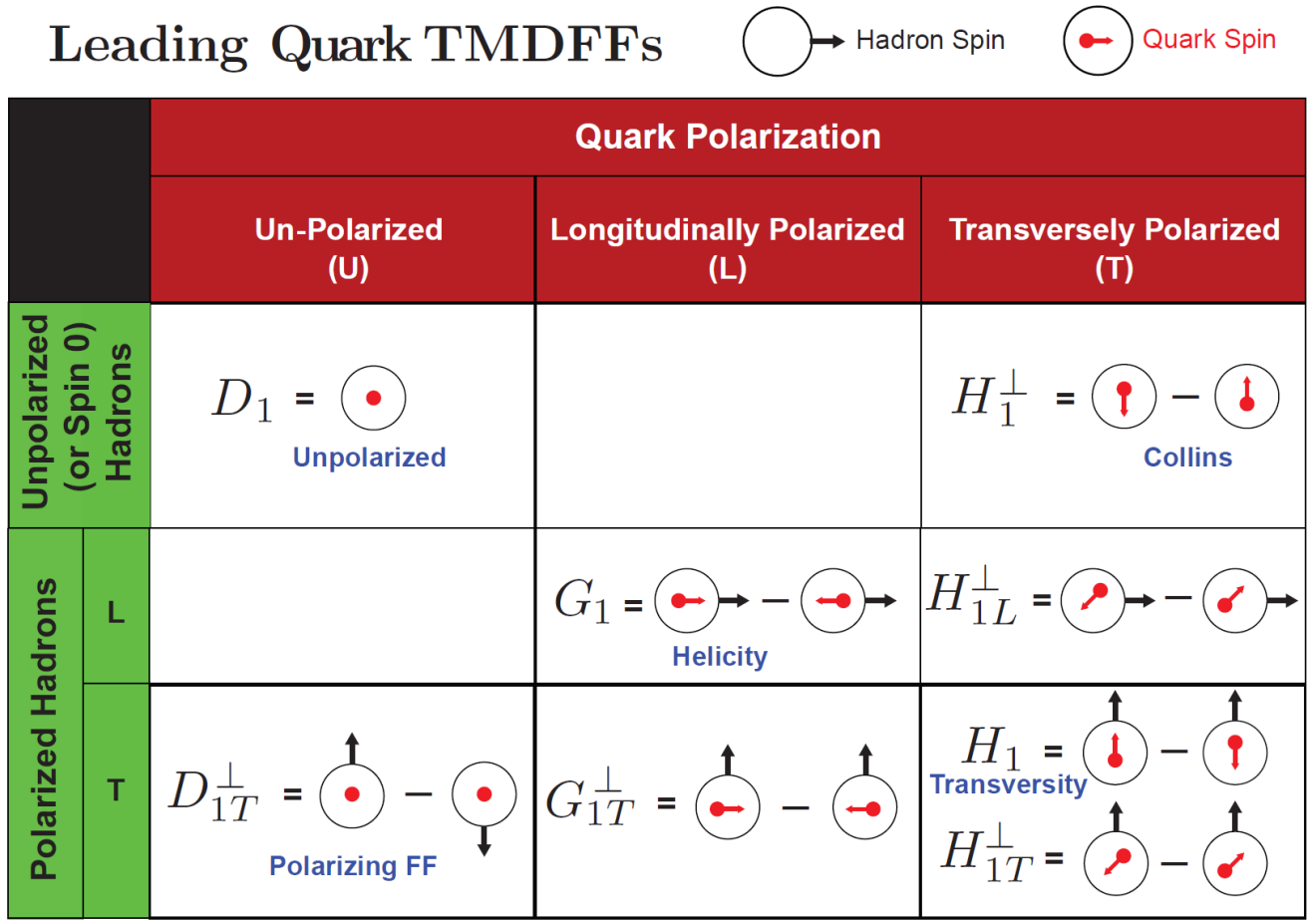
TMD handbook: 2304.03302

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

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

$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \\
&\quad \frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} \\
&\qquad + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + \lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} \\
&\qquad + S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right] \\
&\qquad + S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right] \\
&\qquad + |\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) \\
&\qquad\quad + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&\qquad\quad + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] \\
&\qquad + |\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} \\
&\qquad\quad + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},
\end{aligned}
$$

JHEP 02 (2007) 093

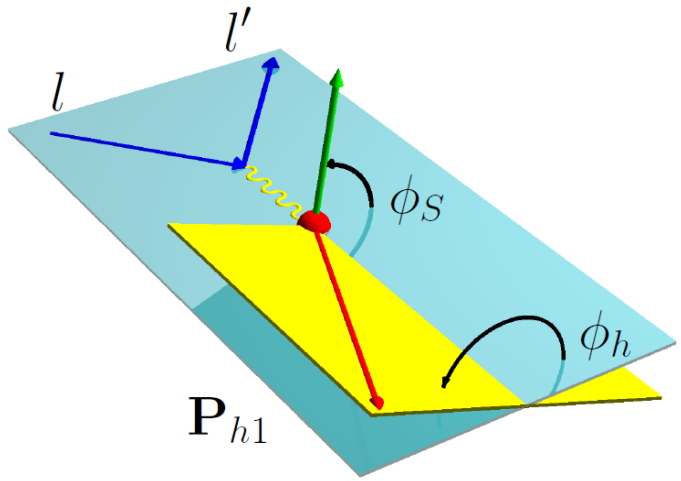
Experimental access to Transversity/tensor charge and Sivers function

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

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

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

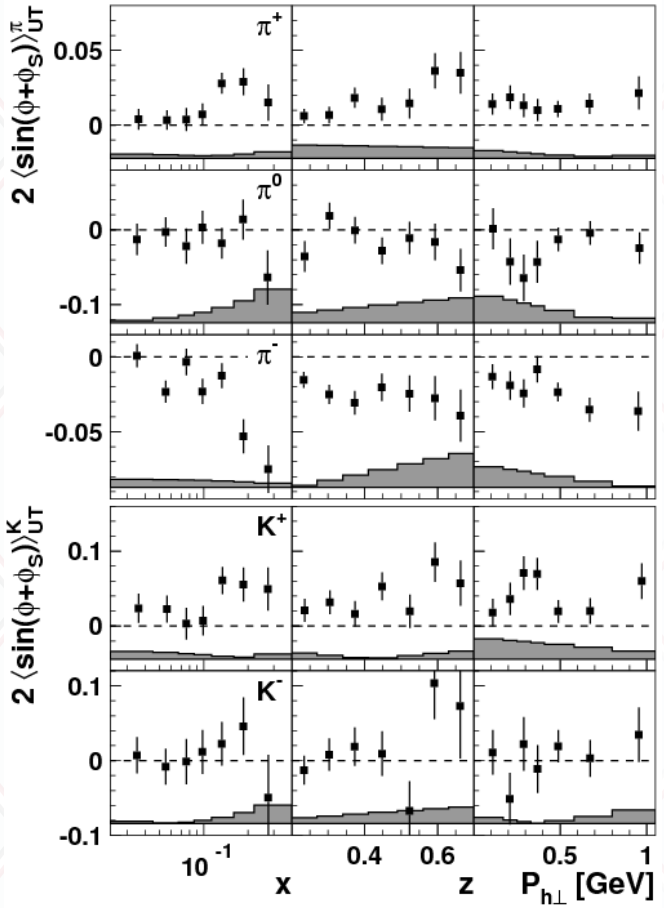
$$A_{UT}^{\sin(\phi_h+\phi_S)}(x,z,P_T) \propto \mathbf{S}_T \frac{\sum_{q,\overline{q}} e_q^2 \delta q(x,k_t)\otimes H_1^{\perp}(z,p_t)}{\sum_{q,\overline{q}} e_q^2 q(x,k_t)\otimes D_1(z,p_t)}$$



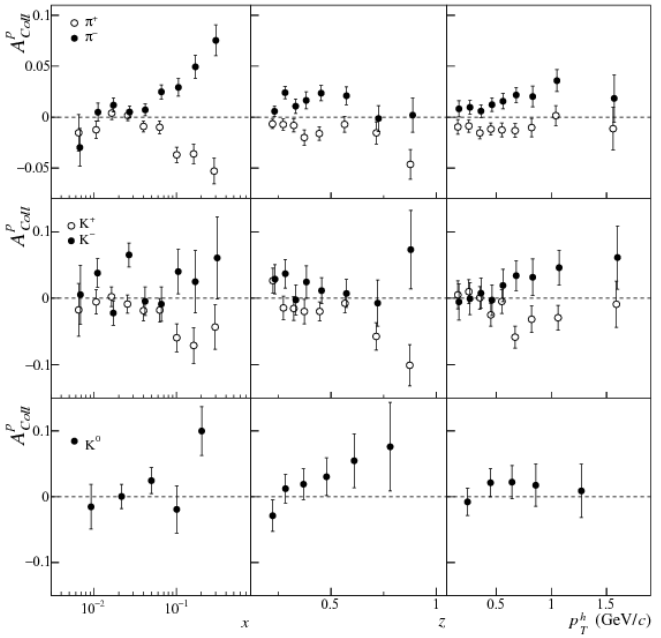
Latest SIDIS Collins data

- 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

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

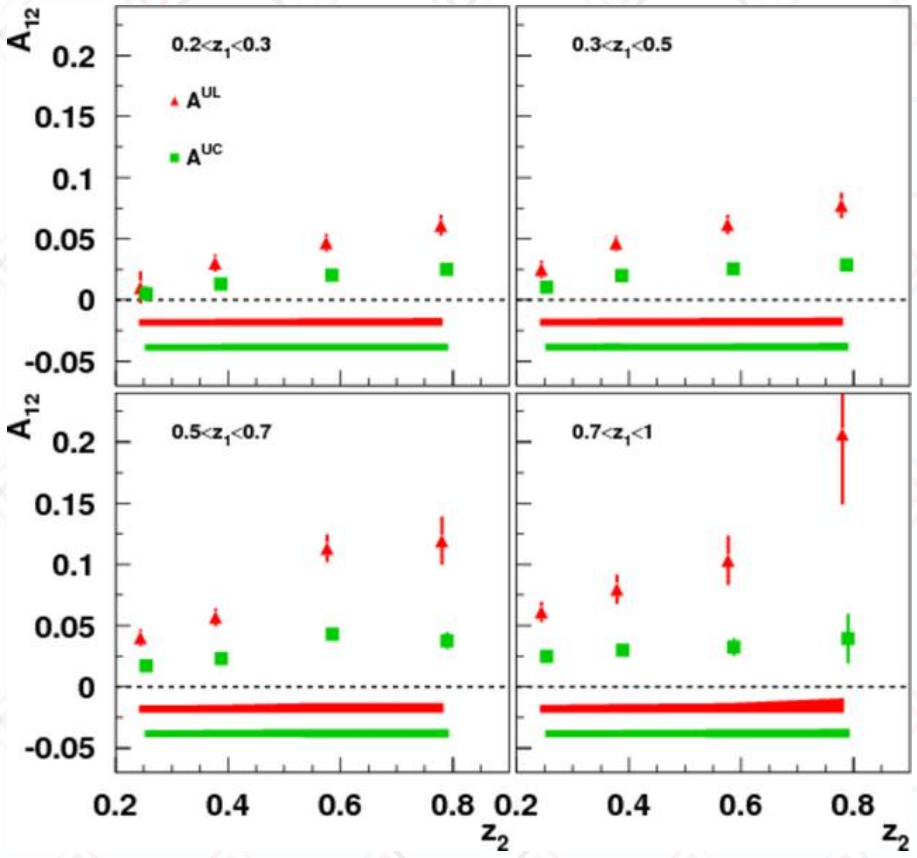


COMPASS: *Phys.Lett.B* 744(2015) 250



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

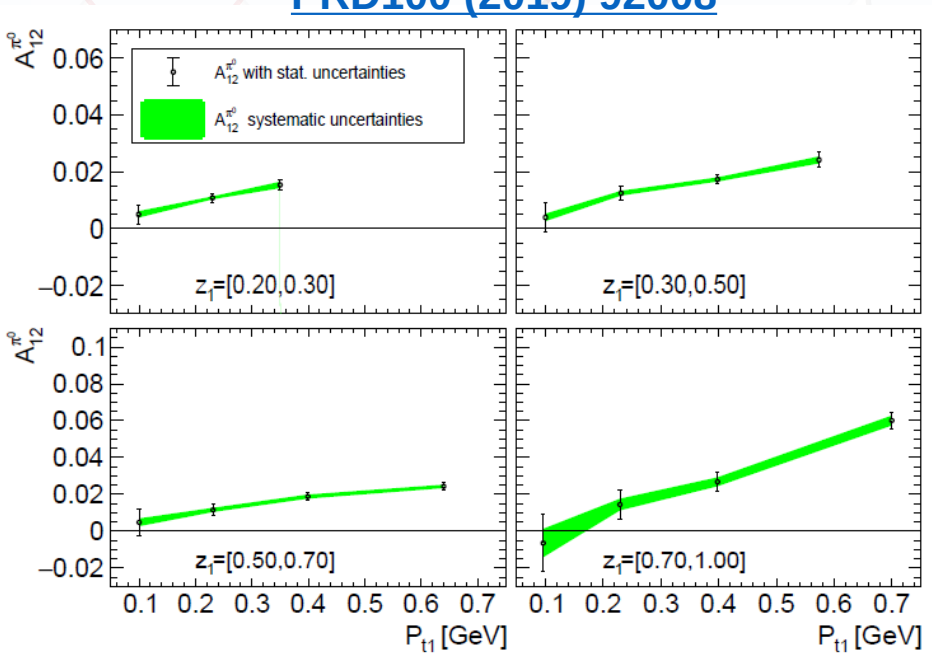


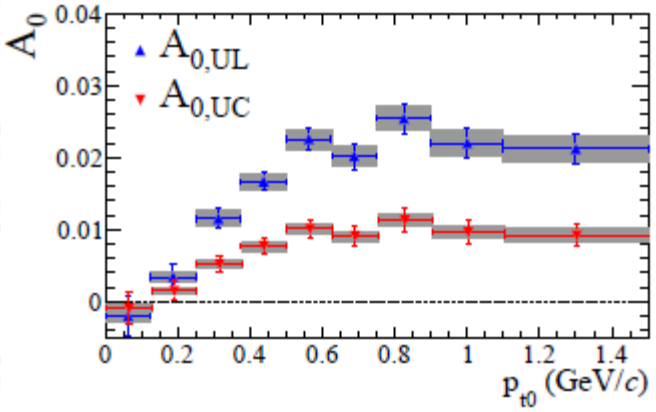
RS et al (Belle), PRL96: 232002
PRD 78:032011, Erratum D86:039905

Transverse momentum

- Add transverse momentum to Collins asymmetries' z dependence
- Currently only 1 or 2-dimensional extractions available (q_t, z_1x z_2, p_{t1}x p_{t2},z_1xp_{t1})
- Increasing asymmetries with both z and pt, but pt reach limited
- Multidimensional extractions needed

PRD100 (2019) 92008



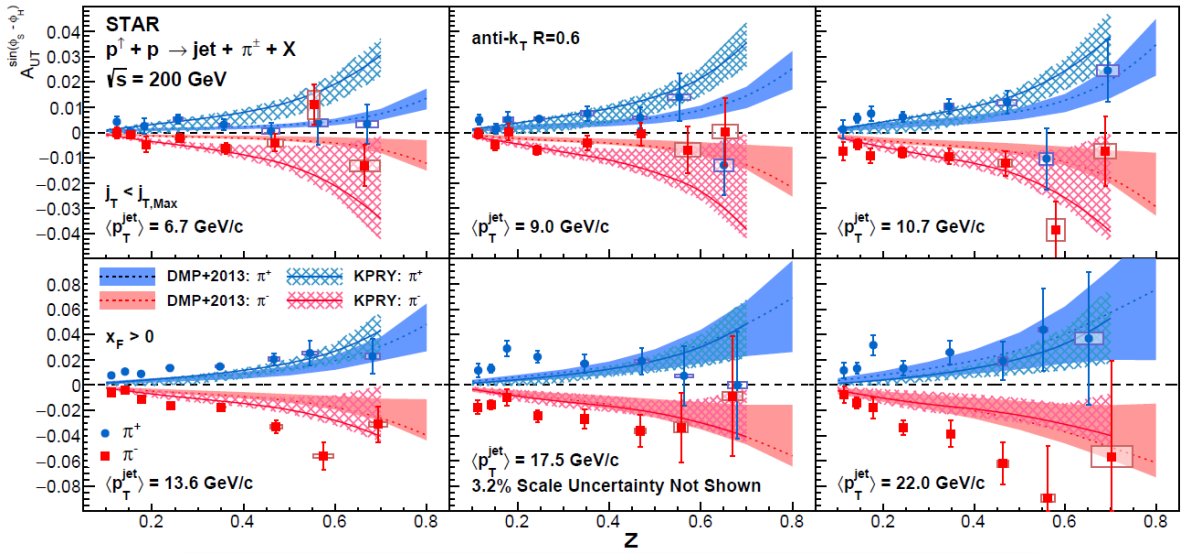


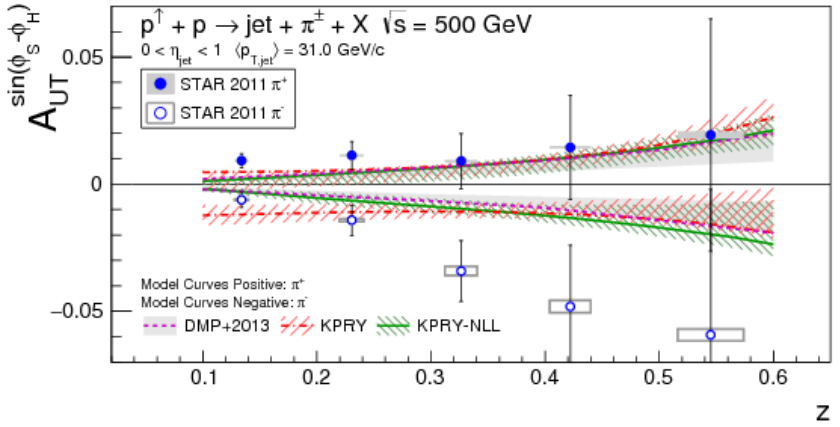
PRD 90 (2014) 052003 (Babar)

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

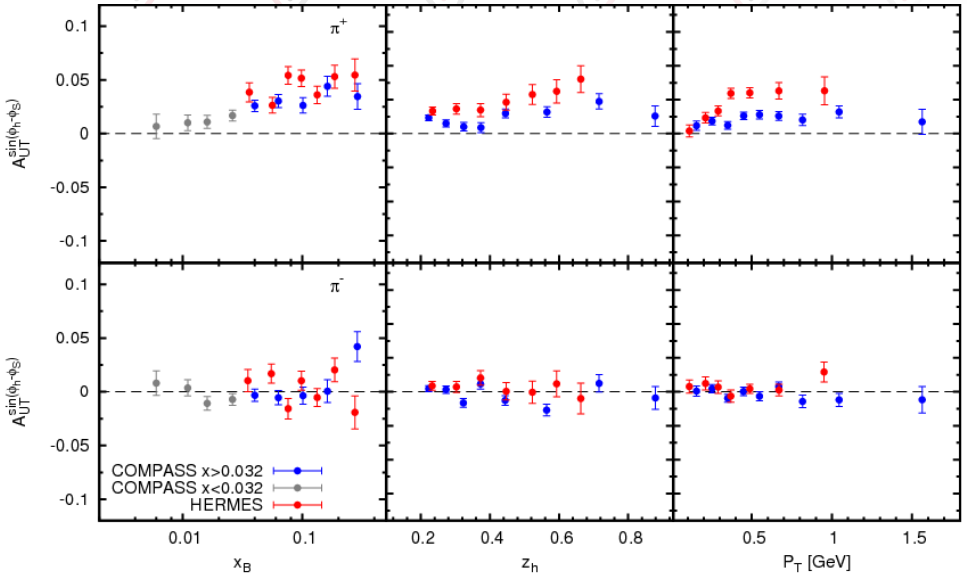




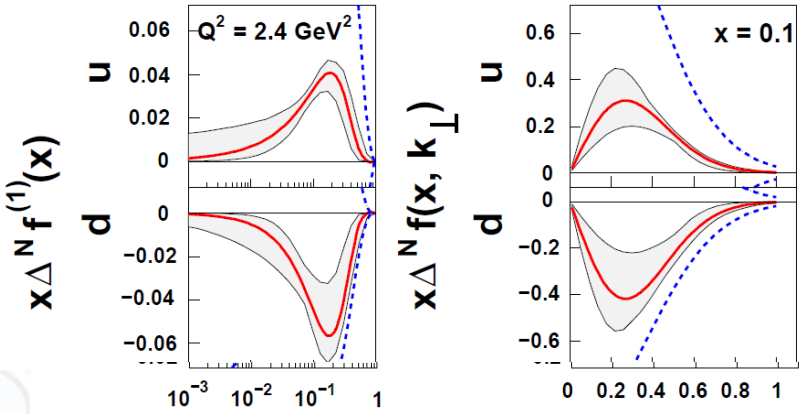
STAR: Phys.Rev.D 97 (2018) 032004

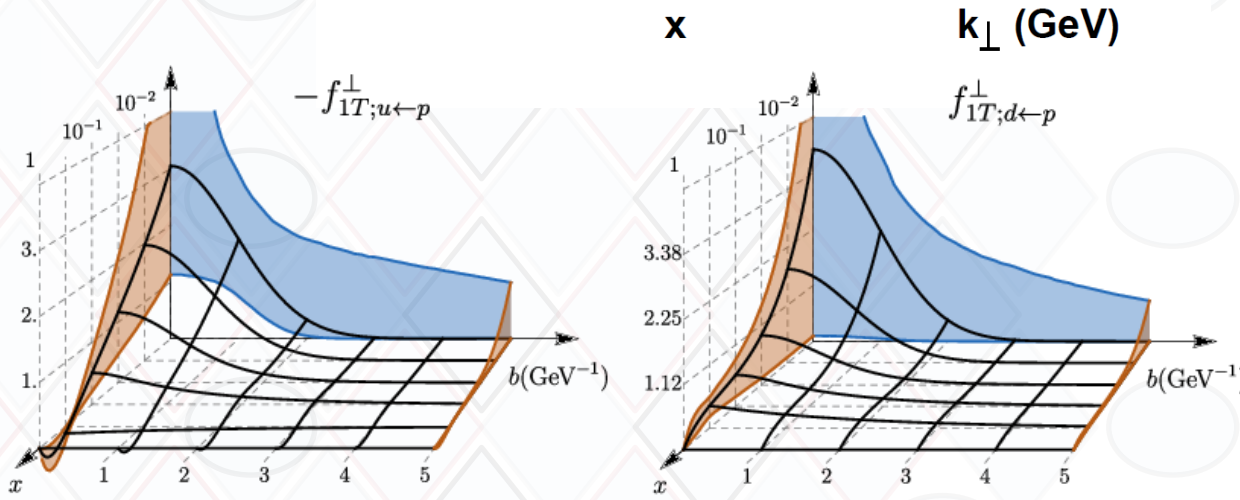
Sivers Function measurements

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



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





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

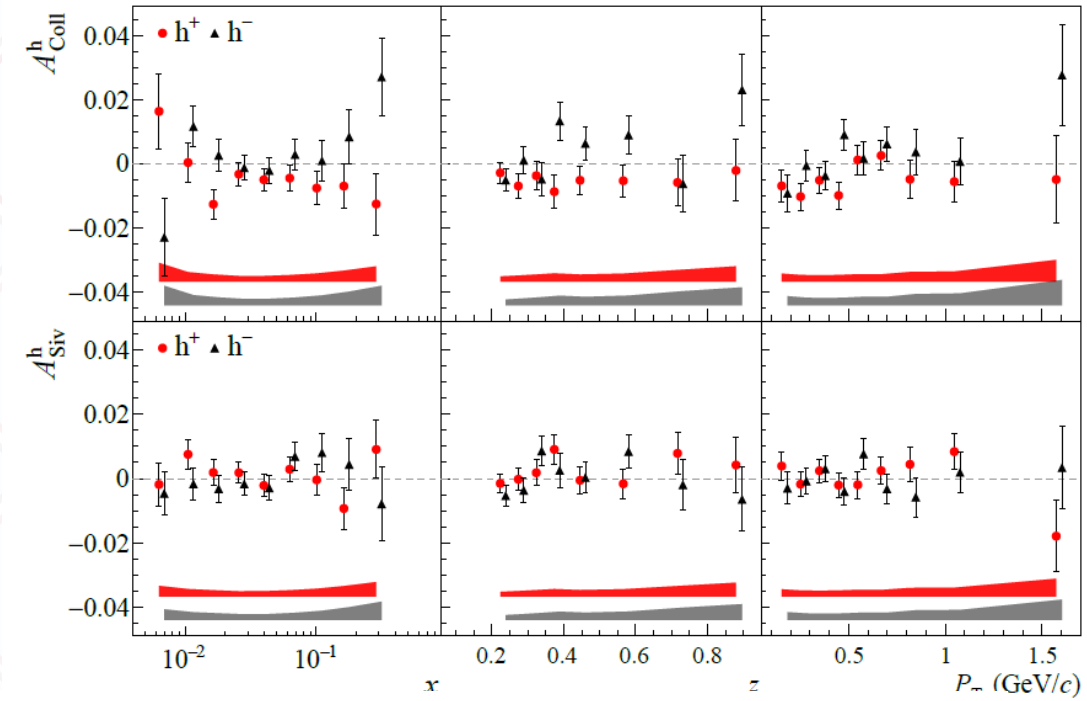
$f_{1T,q}^{\perp}(x, k_T)$

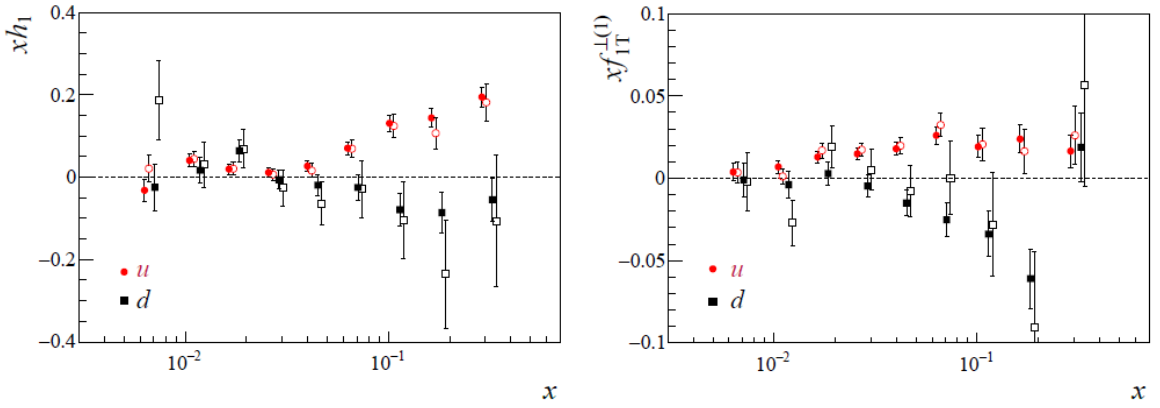
RIKEN

New COMPASS deuteron data

COMPASS 2401.00309

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

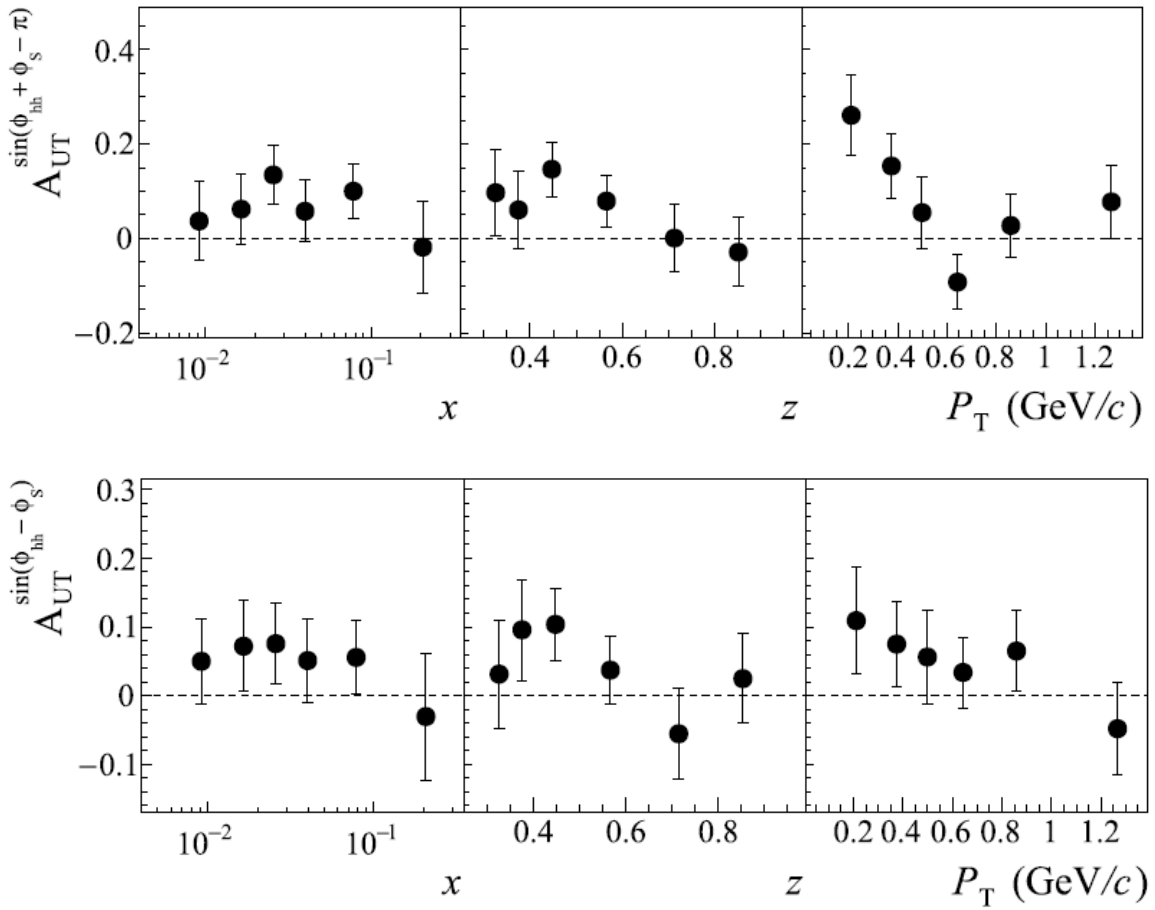




VM Collins asymmetries

- Interesting to look also to VM production for TMD measurements
- Especially in Collins case expect opposite sign to same charge PS meson in Artru model
- Sivers asymmetries should be similar to PS mesons
- ρ asymmetries consistent with expectations

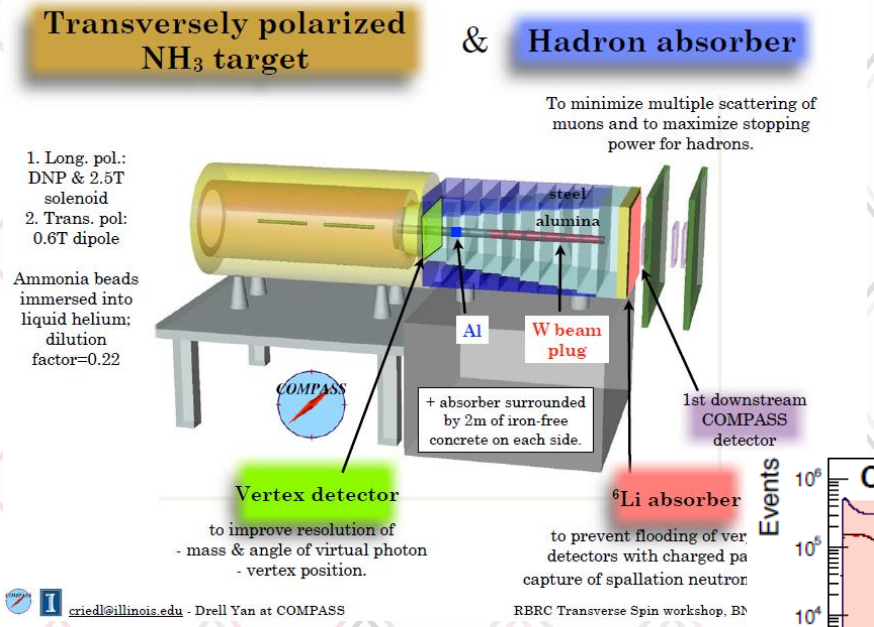
PLB 843 (2023) 137950

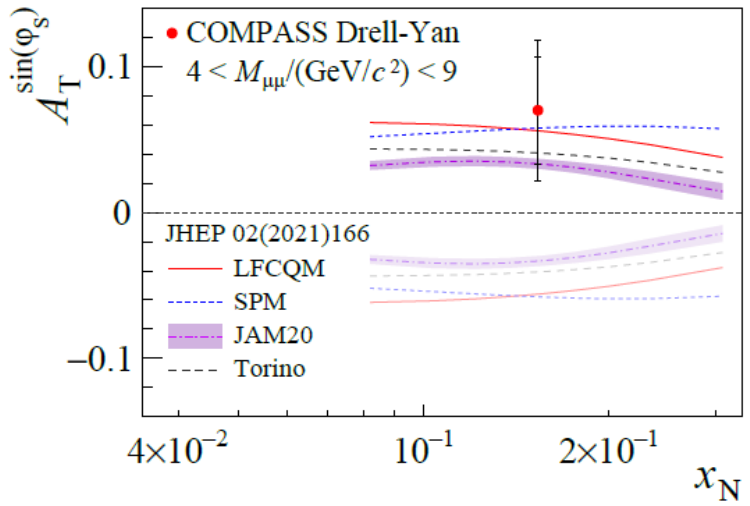


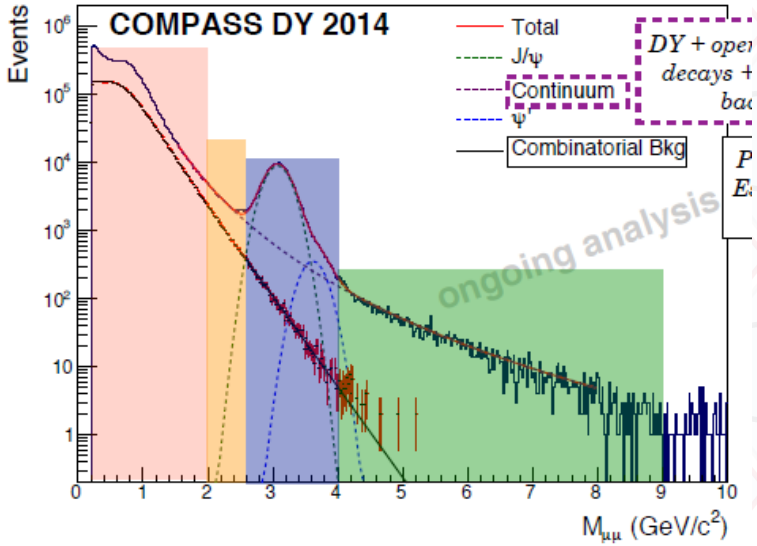
Sivers Sign change

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

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



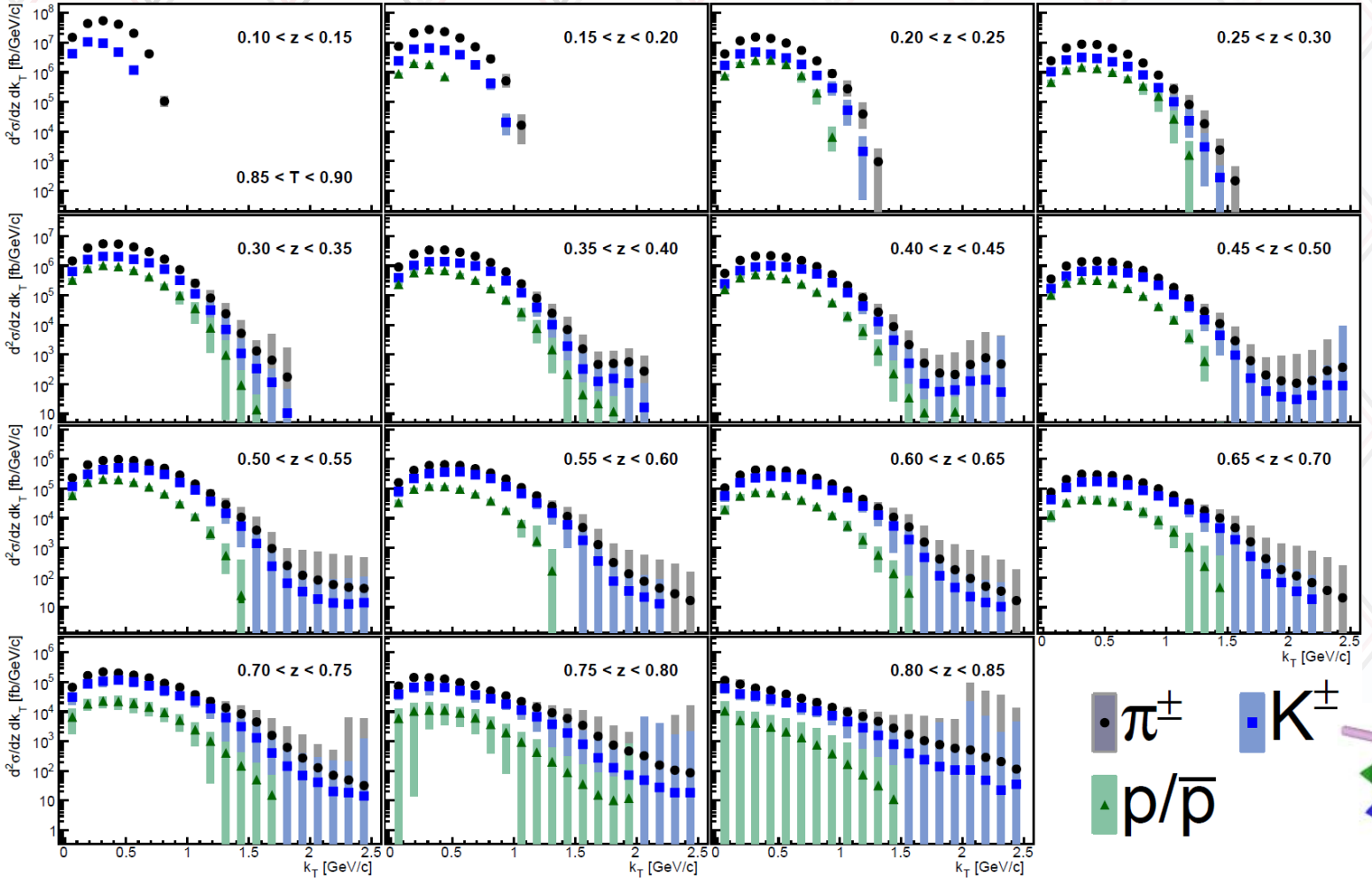




COMPASS 2312.17379

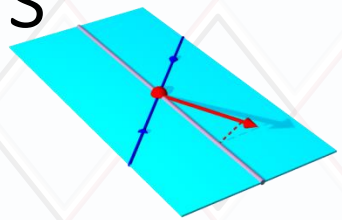
- Now a rather clear indication of the sign change!

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



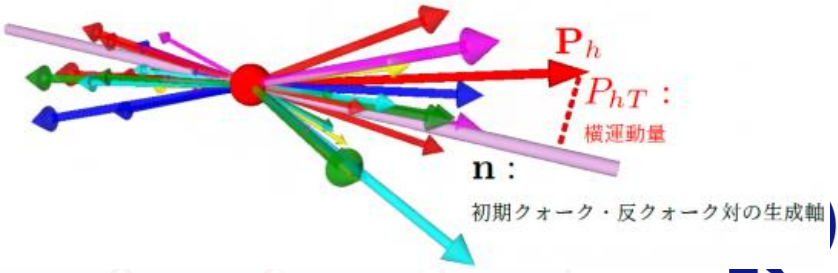
$\frac{d^2\sigma}{dzdP_{hT}}$

P_{hT}



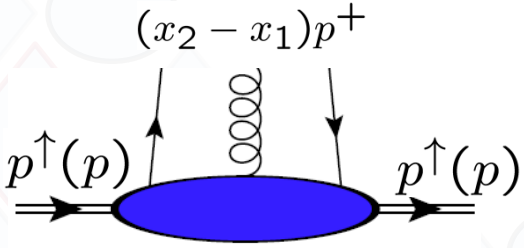
Important baseline for most transverse momentum/spin dependent measurements at RHIC and EIC

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



RS. et. al. PRD99 (2019) 112006

TSSAs at RHIC→Quark-gluon dynamics!

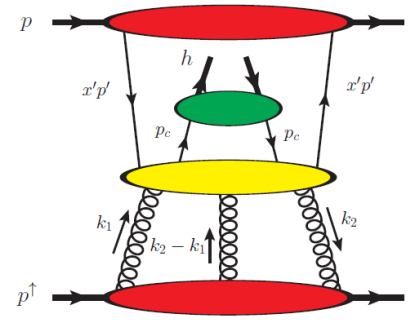


q-g correlation (↔ quark Sivers)

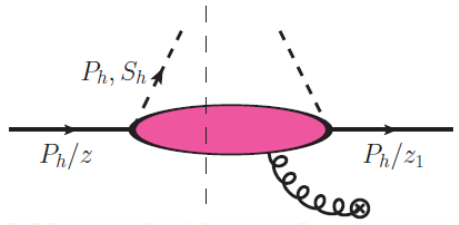
- Sivers and Collins effects rely on an explicitly transverse momentum dependent (TMD) framework where two scales are observed: high scale (typically Q^2) and intermediate scale (transverse momentum $P_T << Q^2$)
- In inclusive pp measurements usually only one, hard scale accessible (transverse momentum P_T)

→requires higher Twist, collinear framework, contributions are multi-parton correlators (both in initial state and final state)

- Both frameworks found to be related via moments over intrinsic transverse momenta



g-g correlation (trigluon ↔ gluon Sivers)



q-g FF correlation (↔ Collins)

Single spin asymmetry contributions in p+p

pol proton PDF* unpol proton PDF* FS particle FF*

$$A_N \approx \sum_{a,b,c} \phi^{(3)}_{a/A}(x_1, x_2, s) \otimes \phi_{b/B}(x') \otimes D_{c\to C}(z)$$

$$+ \sum_{a,b,c} \delta q_{a/A}(x, s) \otimes \phi^{(3)}_{b/B}(x'_1, x'_2) \otimes D_{c\to C}(z)$$

$$+ \sum_{a,b,c} \delta q_{a/A}(x, s) \otimes \phi_{b/B}(x') \otimes D^{(3)}_{c\to C}(z_1, z_2)$$

a,b/c initial/final parton flavors
A,B/C initial/final hadron/particle types

Efremov, Teryaev Phys.Lett.B 348 (1995) 577
Qiu, Sterman Phys.Rev.D 59 (1999) 014004
Kanazawa, Koike Phys.Lett.B 478 (2000) 121-126
Metz, Pitonyak Phys.Lett.B 723 (2013) 365-370

- Generally three pieces to p+p single transverse spin asymmetries:
  - Twist three correlation functions (quarks or gluons) in polarized proton ↔ Sivers function
  - Twist three correlation function in unpolarized proton (with transversity) ↔ Boer Mulders function
  - Twist three correlation in fragmentation ↔ Collins function

➔Different final states single out different contributions (via hard processes)

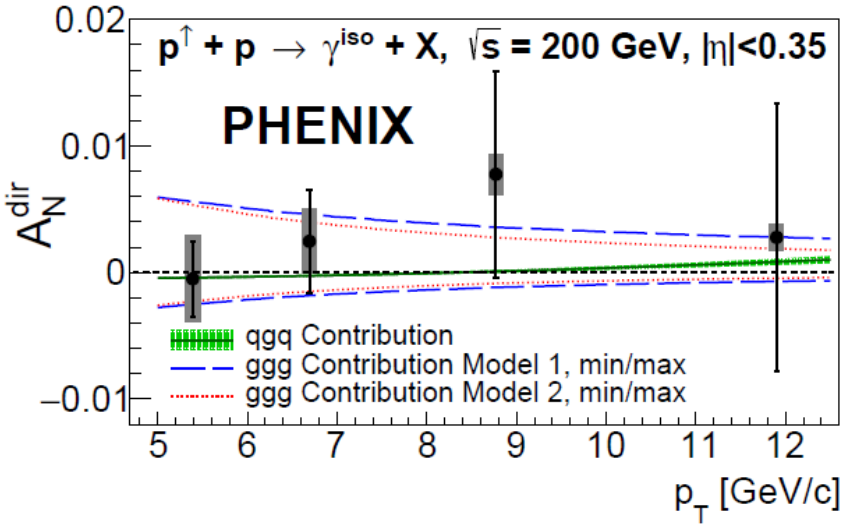
First direct photon A_Ns

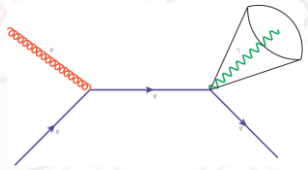
- First direct photon A_N extracted at RHIC
- Mostly sensitive to initial state effects (no fragmentation) → quark-gluon and gluon-gluon correlation functions
- Power to constrain gluon-gluon correlation function well, since quark impact expected to be small

RIKEN Press release: https://www.riken.jp/press/2021/20211015_1/index.html

BNL Press release: https://www.bnl.gov/newsroom/news.php?a=119077

PRL 127 (2021) 162001

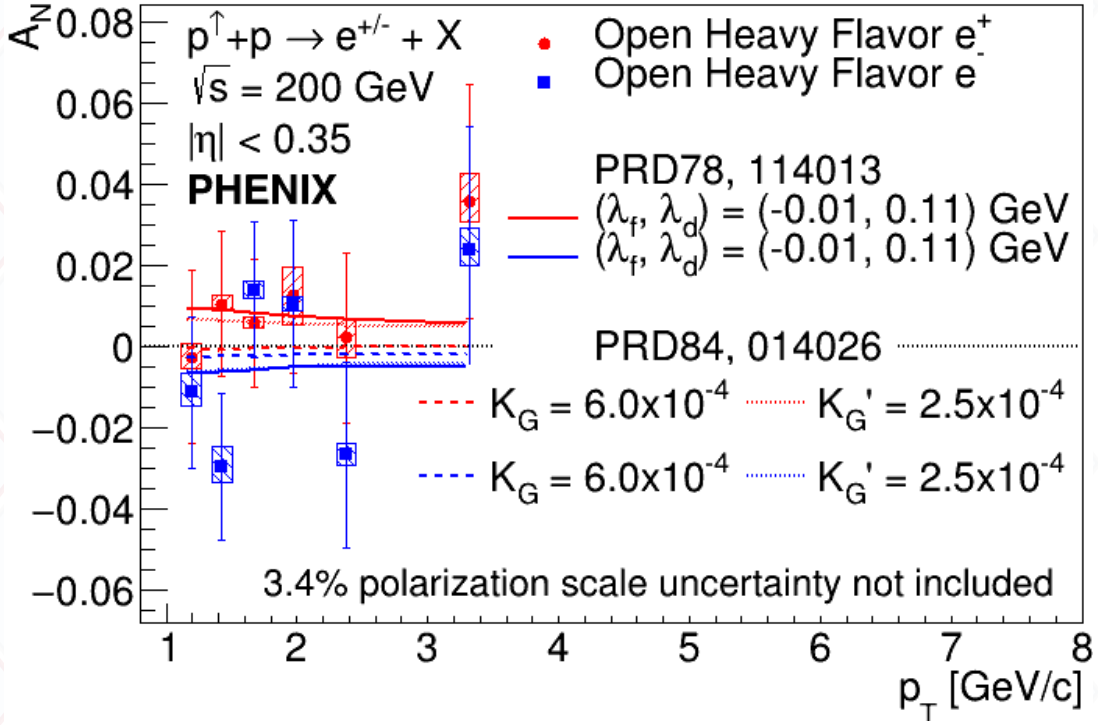


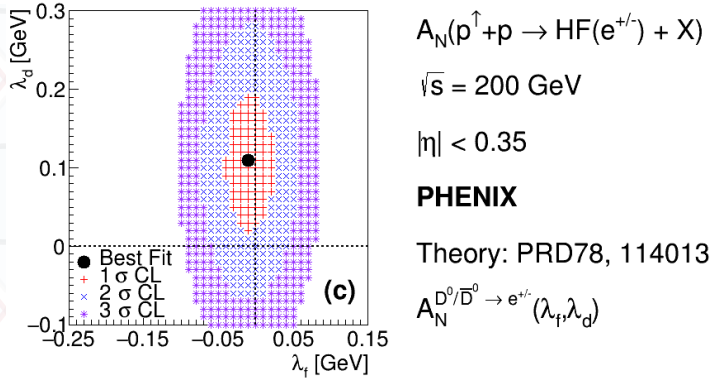


Heavy Flavor electron A_Ns

PRD 107 (2023) 052012.

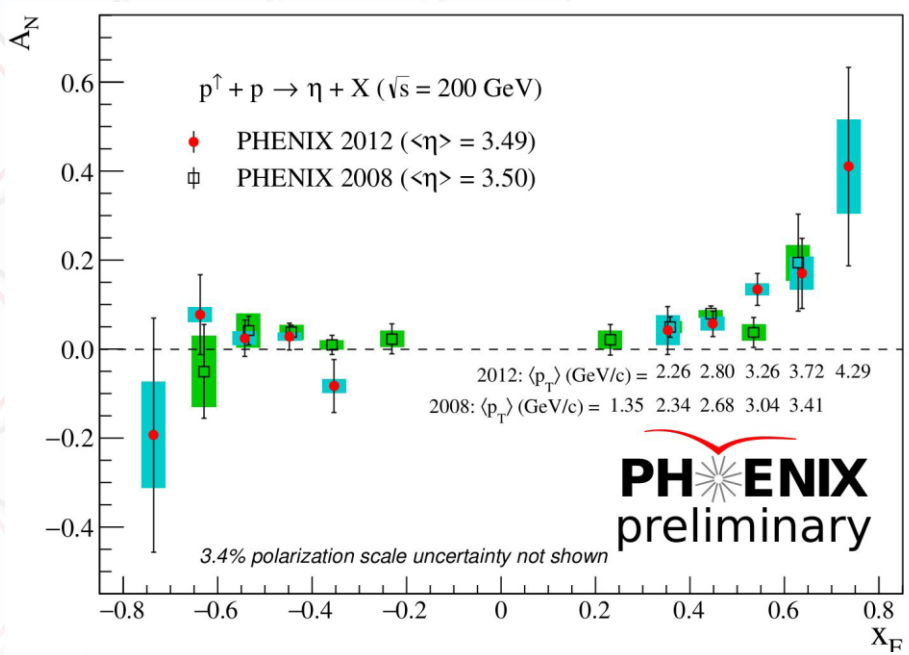
- Almost only gluon related, no final state effects → tri-gluon correlation
- Potential to constrain parameter ranges in D meson A_N theory calculations: PRD78, 114013 (Z.B. Kang, J.W. Qiu, W. Vogelsang, F. Yuan)
- Comparison or charges provides further sensitivity

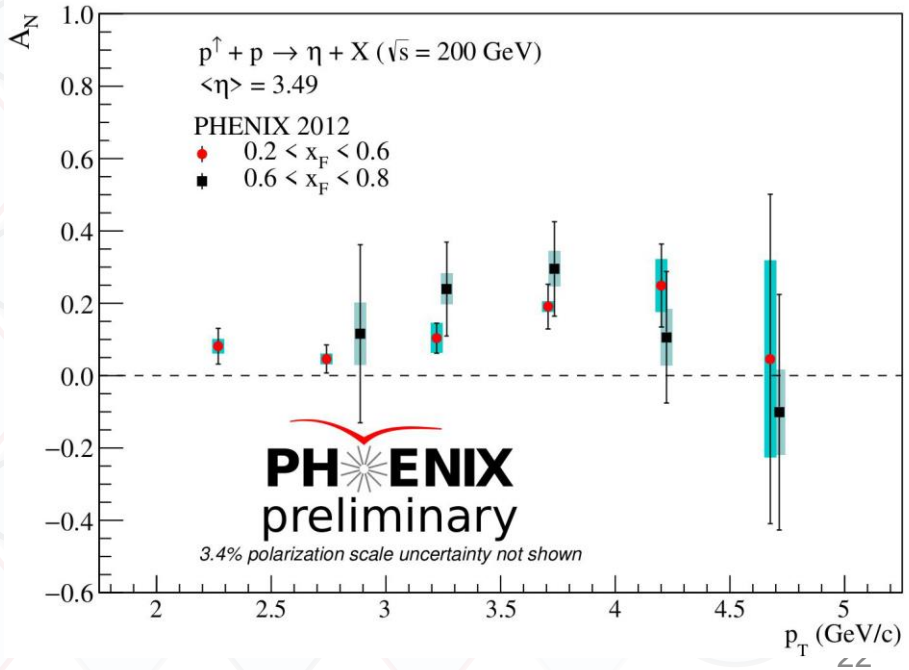




Forward eta A_Ns

- Update of forward η A_N measurements with better statistics
- Asymmetries sizeable, maybe a hint of turnaround expected at higher p_T due to HT nature of asymmetries

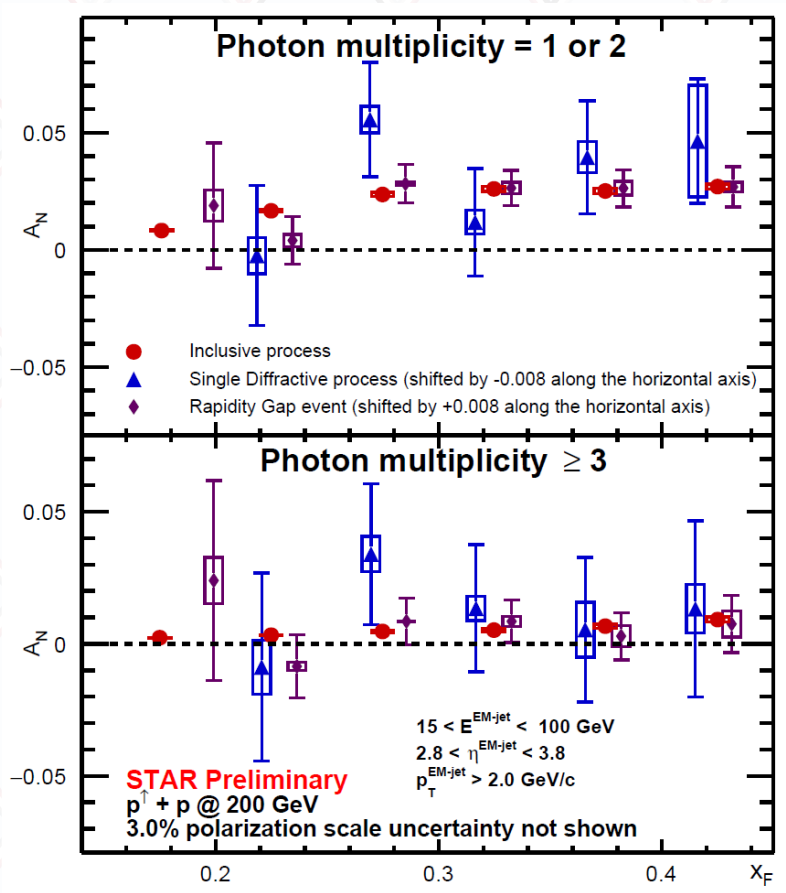




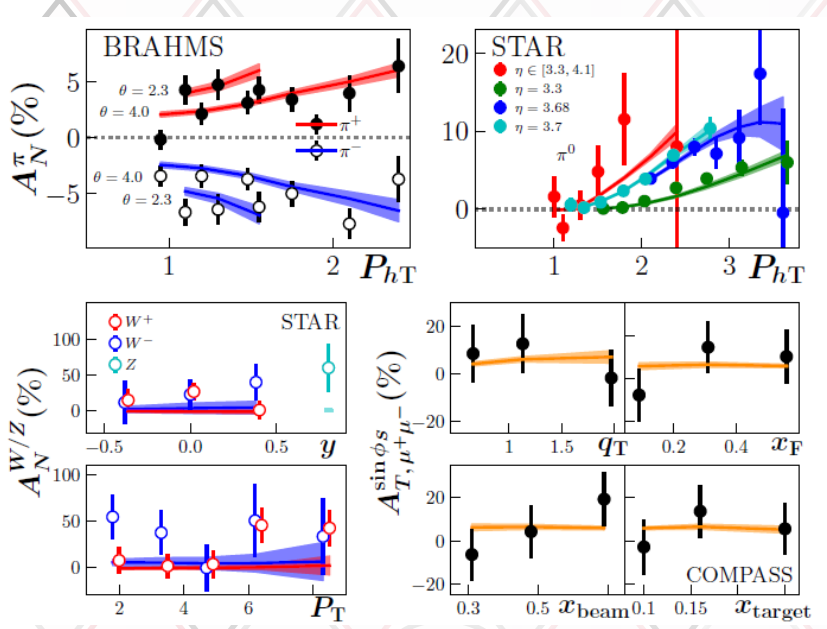
Diffractive contributions?

- Both single diffractive and rapidity gap events show asymmetry comparable to inclusive asymmetry
- To compensate for small contribution of diffractive events to inclusive events asymmetry had to be much larger
- Conclusion: Diffractive events are not main cause for nonzero ANs

STAR forward EM-"jet" ANs

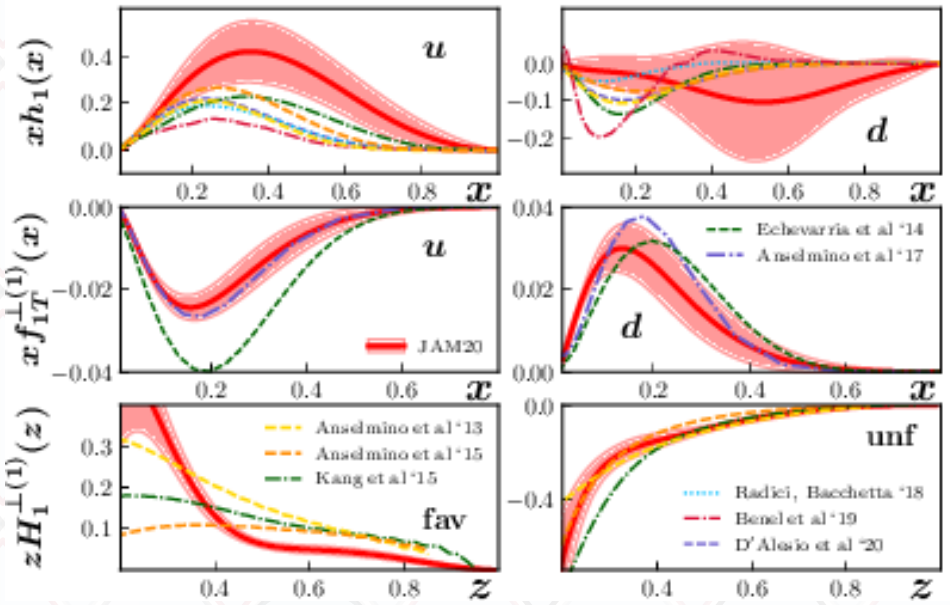


Where to go from here? Global fits on transverse quark-gluon structure



RHIC, SIDIS, DY included

Cammarota et al, PRD 102 (2020) 054002



Transversity

Sivers function

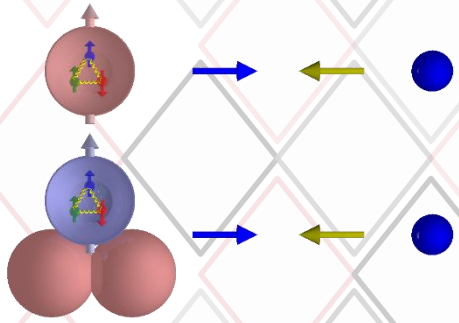
Collins FF

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

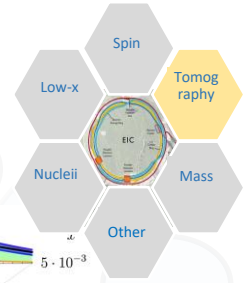
What to expect before EIC?

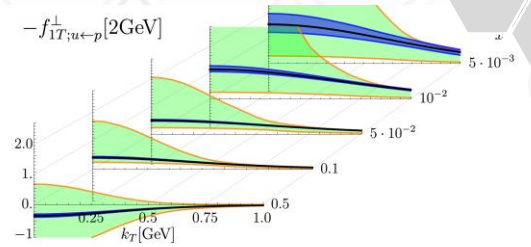
- Significantly more SIDIS data from JLAB (Collins, Sivers, Di-hadrons, unpolarized), high-x and low scale
- More updates from RHIC on Collins asymmetries (hadron-in-jet)
- More Fragmentation information from Belle(II) – unpolarized, HF, VMs, etc
- Sea quark Sivers from SpinQuest (polarized fixed-target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

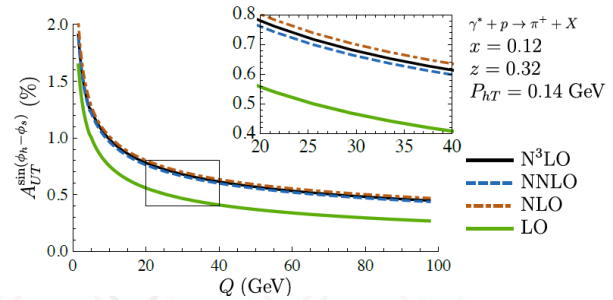
EIC TMD Goals: 3D Transverse spin and momentum structure



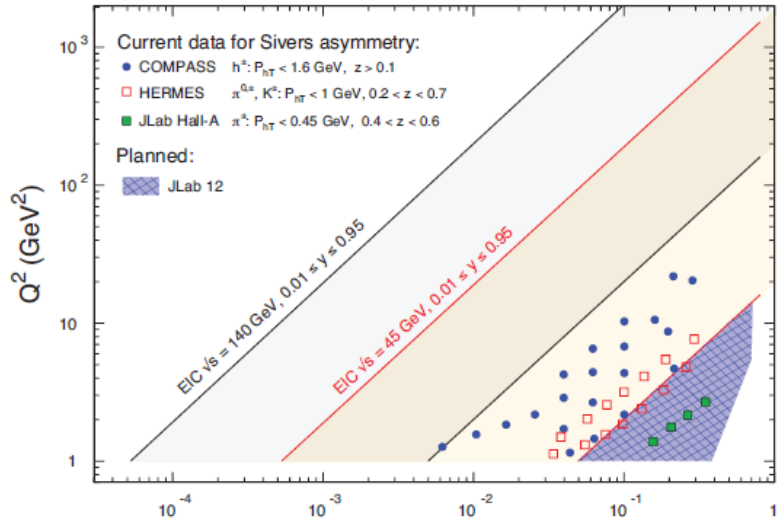
Deliverables	Observables	What we learn	Stage I	Stage II
Sivers & unpolarized TMD quarks and gluon	SIDIS with Transverse polarization; di-hadron (di-jet)	Quantum Interference & Spin-Orbital correlations	3D Imaging of quarks valence+sea	3D Imaging of quarks & gluon; Q^2 (P_{hT}) range QCD dynamics
Chiral-odd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

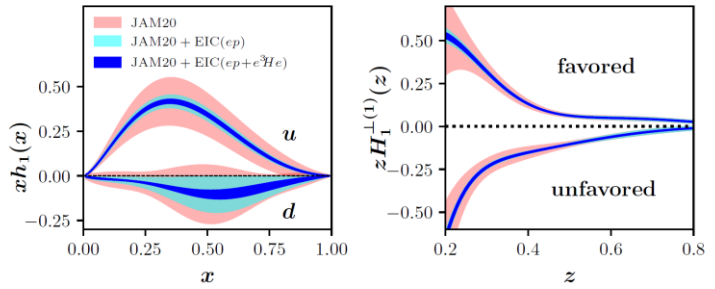






Tables from original EIC white paper

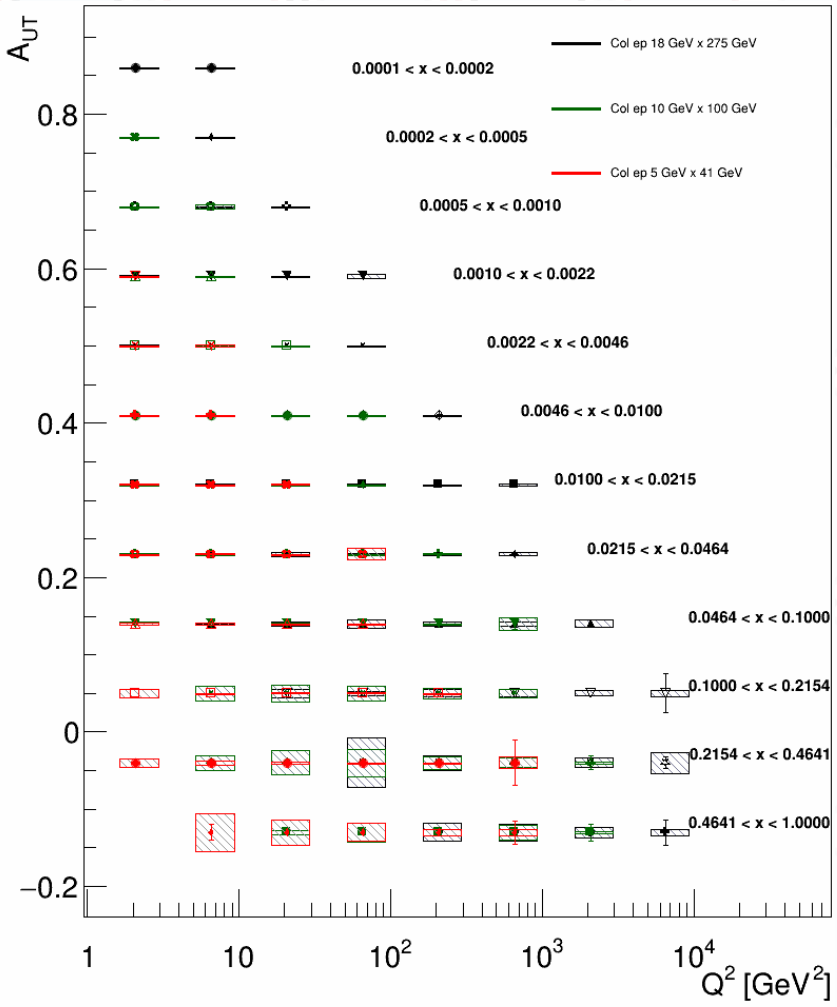




Current coverage for transverse spin related SIDIS measurements

Scale dependence (and interplay of collision energies)

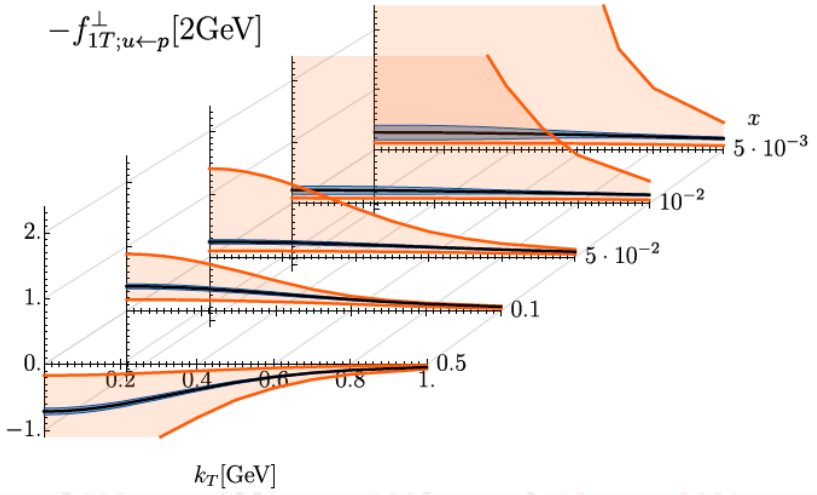
- An example of the expected uncertainties in x and Q^2 to study the scale dependence of the Sivers/Collins asymmetries (as TMD evolution is not very well known/contains other nonperturbative pieces)
- Overlap of the different energies shows how they increase the lever arm
- Note: in future evolution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

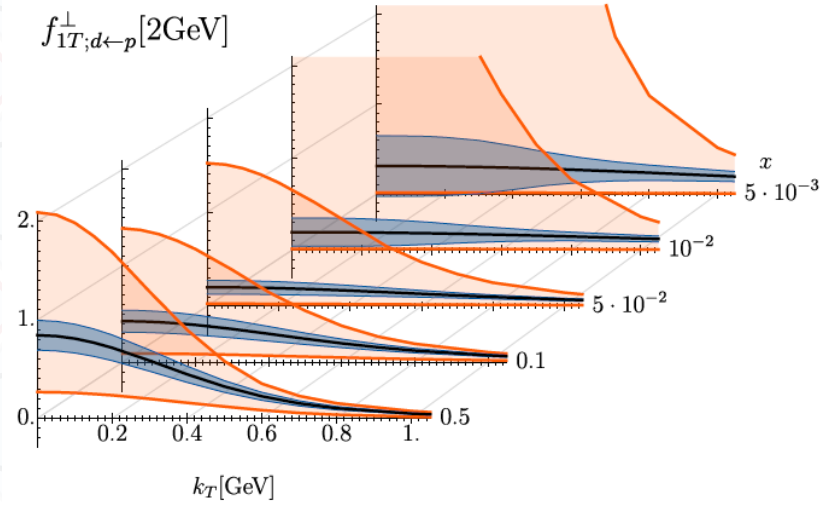


NIM.A 1049 (2023) 168017

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





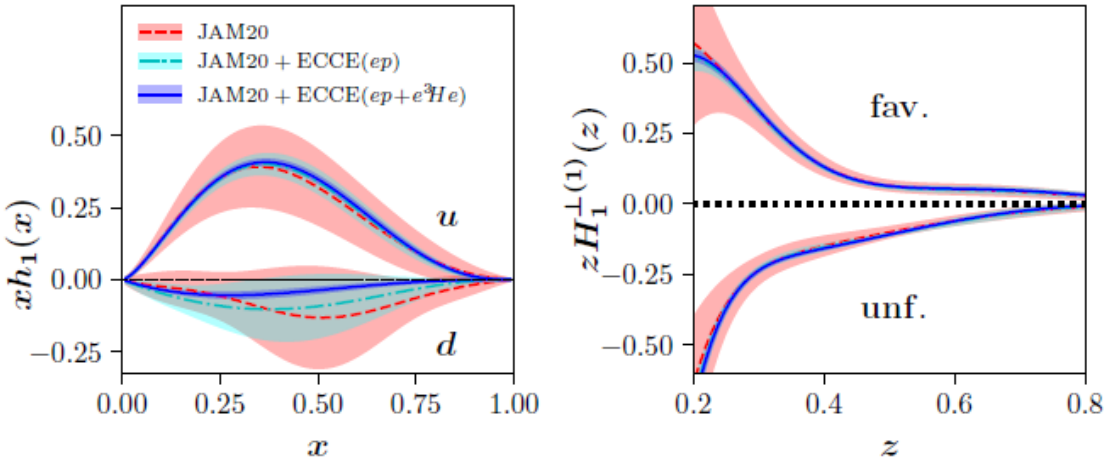
NIM.A 1049 (2023) 168017

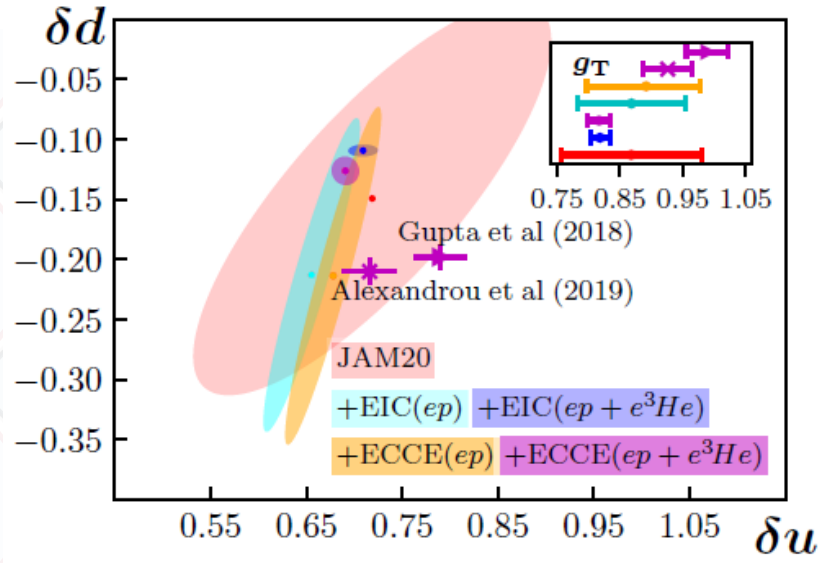
Tensor charge impact

- 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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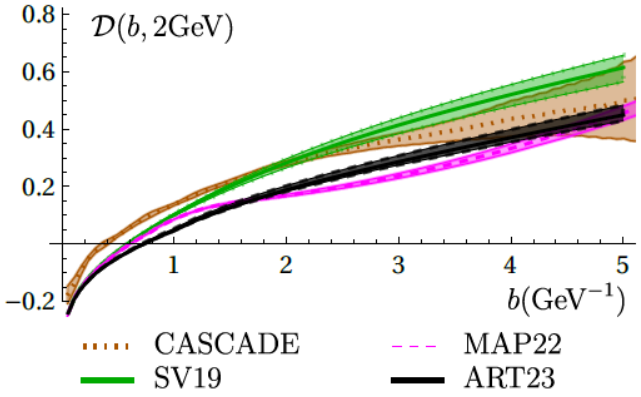
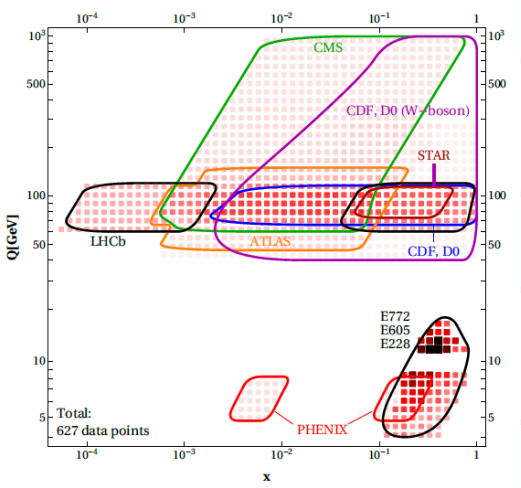
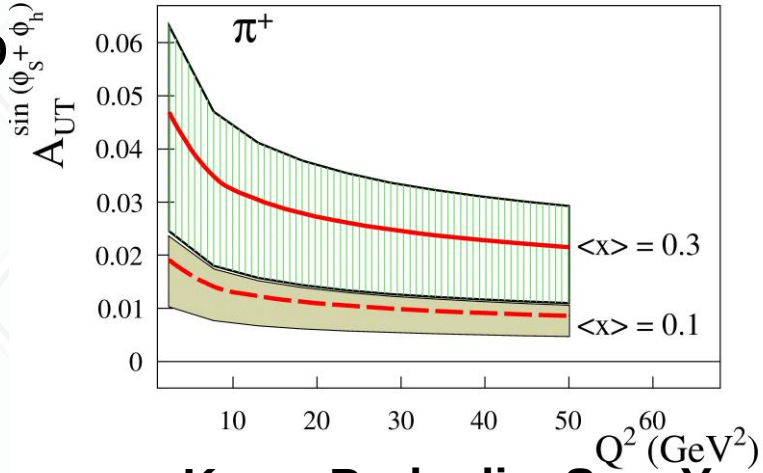
About TMD evolution

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

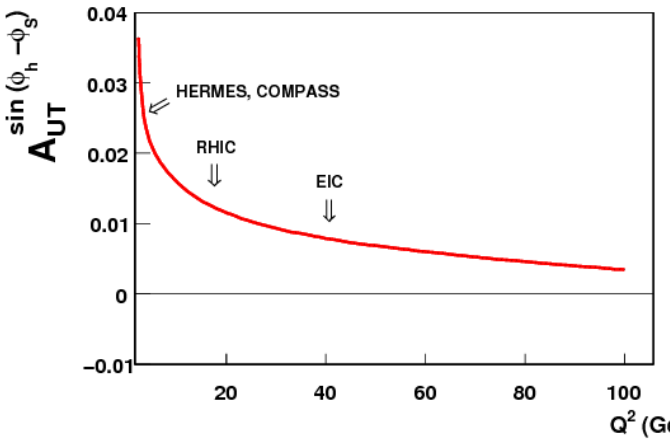
- Large theoretical effort to understand TMD evolution (see for example Evolution and REF workshop series)
- Large overlap with low-x community
- Despite predominantly using CSS formalism large differences due to treatment of non-perturbative terms in evolution → relevant for many spin related TMDs
-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







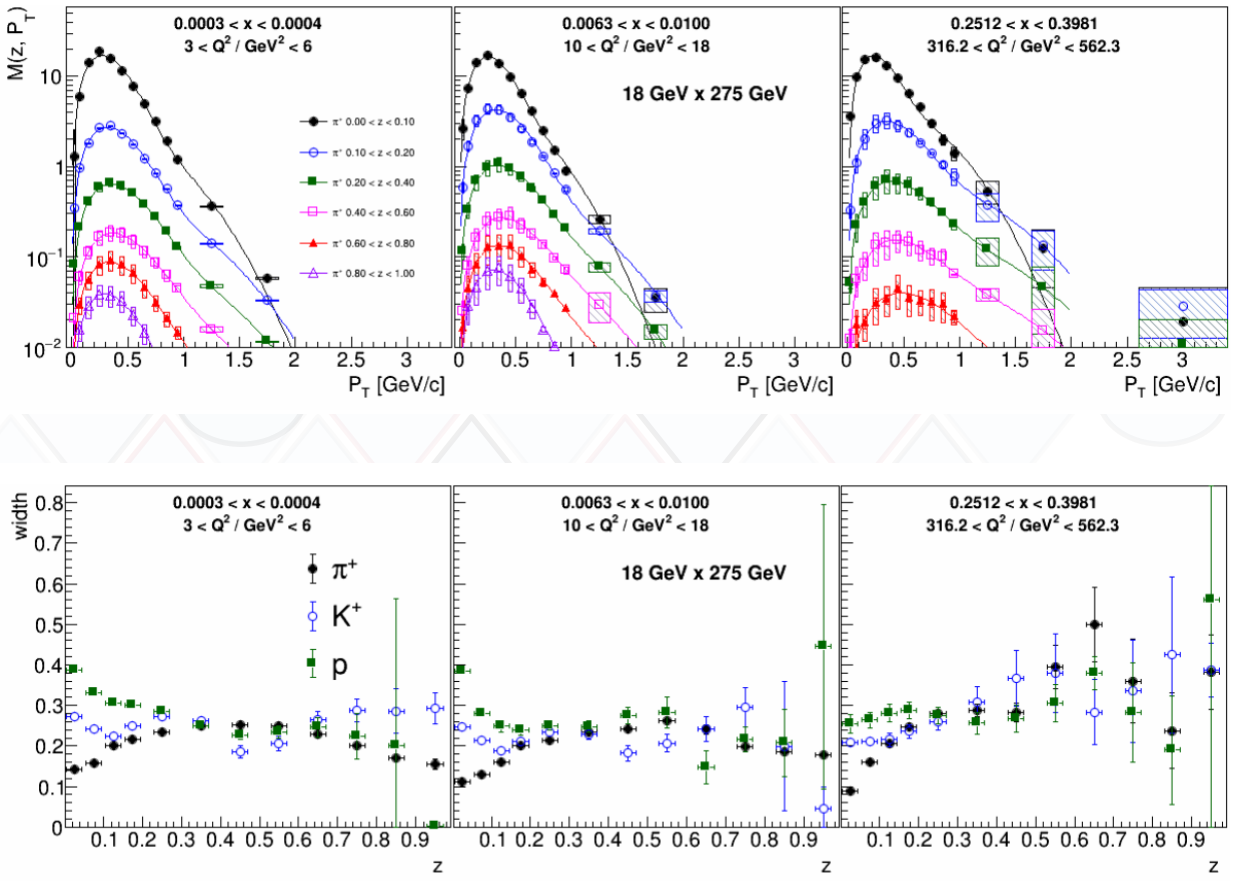
Kang, Prokudin, Sun, Yuan
PRD 93 (2016) 014009



Aybat, Prokudin, Rogers
PRL 108 (2012) 242003

z-dependence of multiplicities and widths

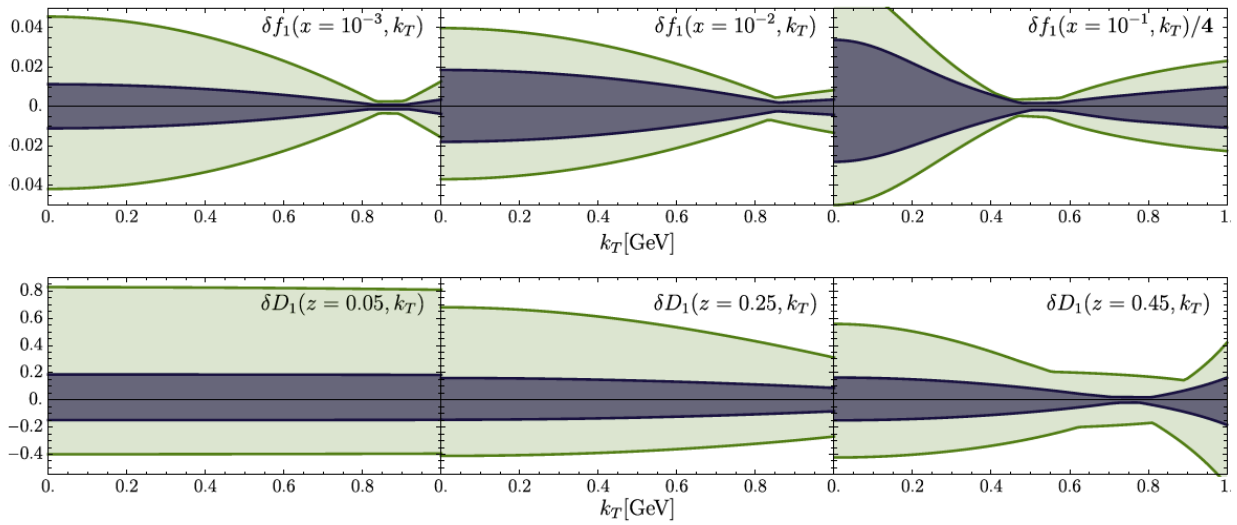
- Top: Explicit z dependence of select pion multiplicities in 3 x-Q^2 bins, including the double-Gaussian fits
- Bottom: behavior of the narrow Gaussian widths vs z for pions, kaons and protons
- Small z discrepancies likely due to target fragmentation



NIMA 1055 (2023) 168458

Impact for unpolarized TMD functions

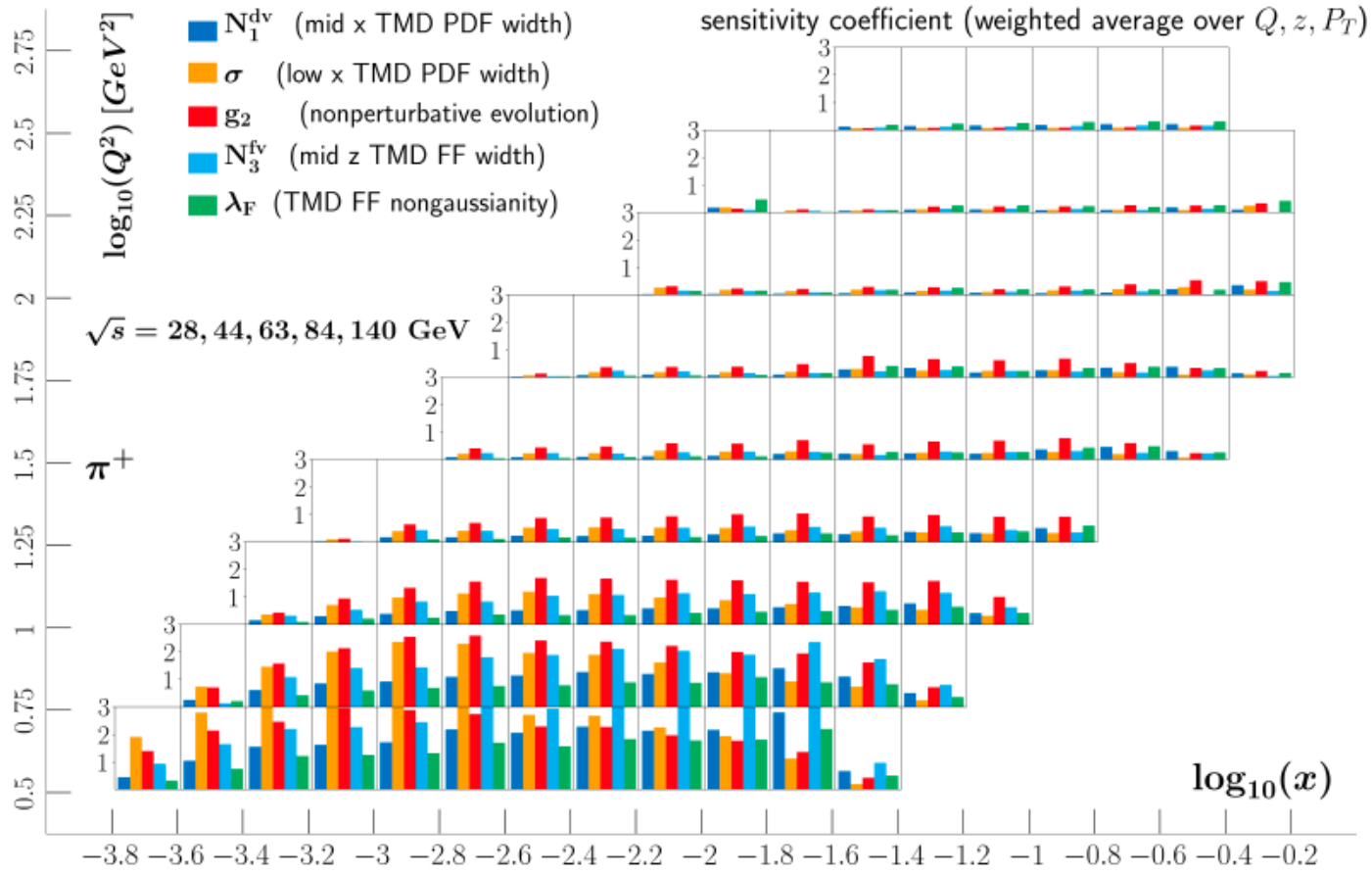
- Similar to YR impact studies following the latest SV global fit (https://arxiv.org/abs/1912.06532) for the unpolarized TMDs based on the existing SIDIS +DY data
- Consistent with Yellow Report expected impact



NIMA 1055 (2023) 168458

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