Postcard credit : CERN

TMDs @ Hadron Colliders

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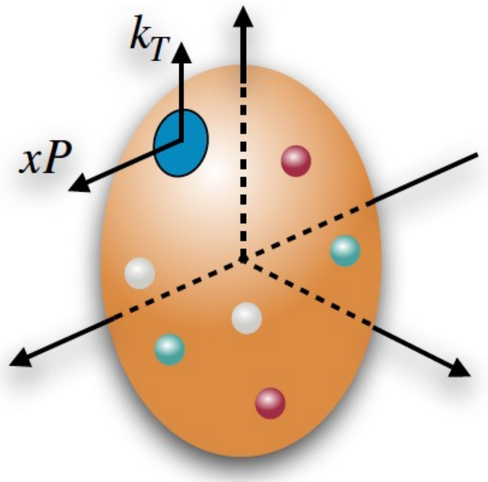
University of Kentucky

June 21, 2023

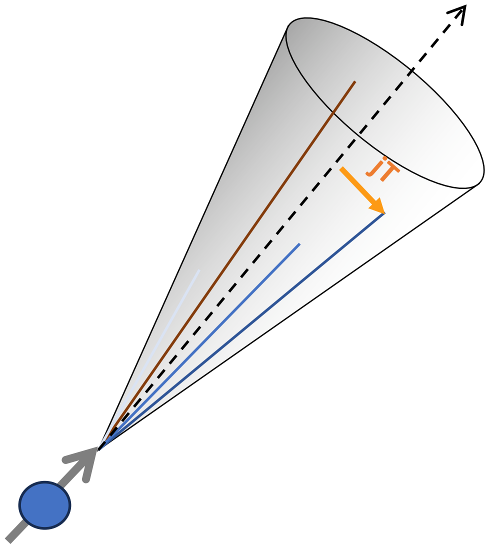
Towards a Synergy between Lattice QCD and Global Analysis, Center for Frontiers of Nuclear Science, Stony Brook University

An experimentalist's introduction to …*Transverse Momentum Distributions*



TMDPDFs : parton distribution functions that characterize the correlations between the partonic spin, partonic momentum (**x, k_T**) and the spin of the parent hadron, at a hard interaction scale **Q.**

TMDFFs : fragmentation functions that characterize the correlations between the spin of a fragmenting parton and the spin and momentum (**z, j_T**) of the emerging hadrons, at a hard interaction scale **Q**.



Exciting opportunities to study proton structure and hadronization in 3D!

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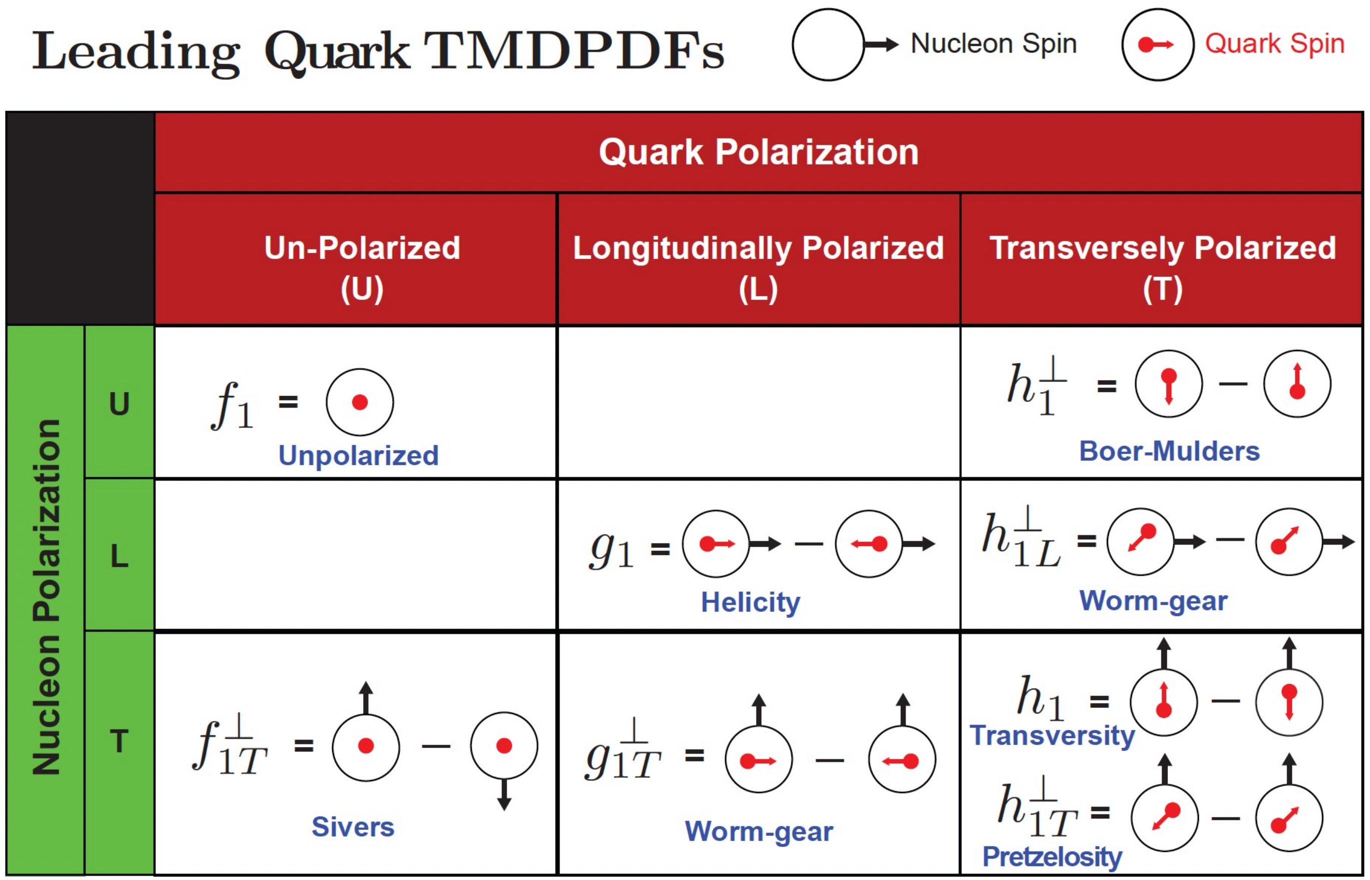

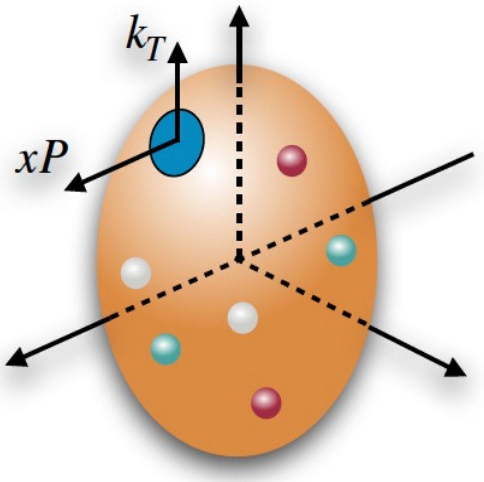

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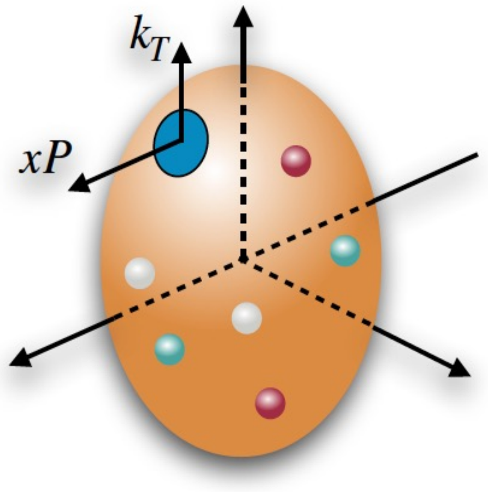
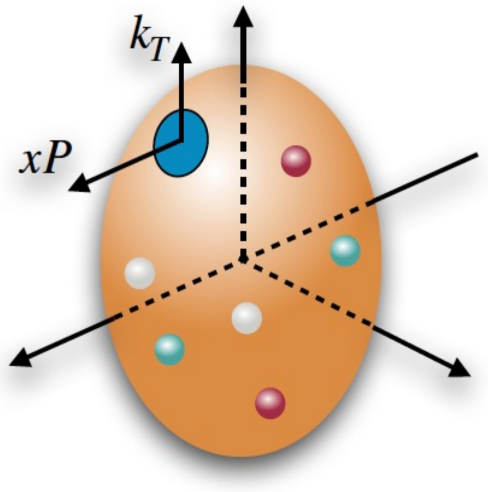


Leading Quark TMDFFs

Hadron Spin — Quark Spin

		Quark Polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Unpolarized (or Spin 0) Hadrons		D_1 = Unpolarized		$H_1^{\perp}$ = − Collins
Polarized Hadrons	L		G_1 = − Helicity	$H_{1L}^{\perp}$ = −
	T	$D_{1T}^{\perp}$ = − Polarizing FF	$G_{1T}^{\perp}$ = −	H_1 = − Transversity $H_{1T}^{\perp}$ = −

An experimentalist's introduction to …*Transverse Momentum Distributions*



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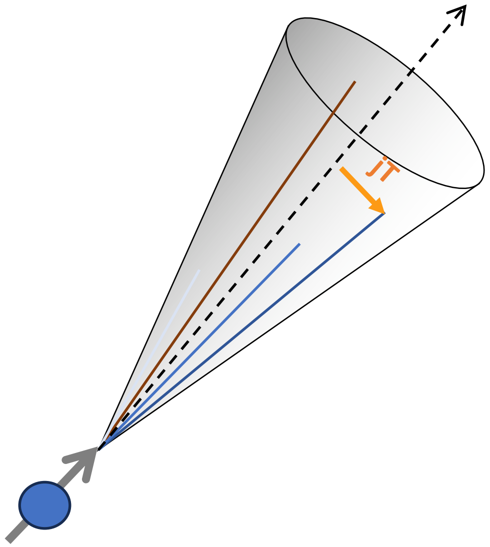


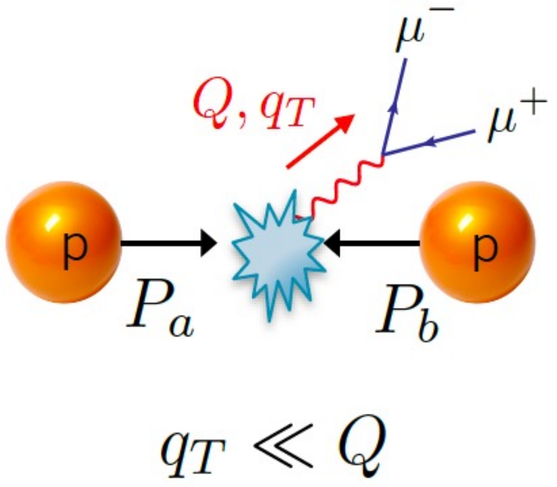
Not possible to directly measure either!

Factorization and pQCD framework

...for example, Drell-Yan

$$\frac{d\sigma_{H_a+H_b\to l\bar{l}+X}}{dQ^2 dY d^2\mathbf{q}_T} = \frac{4\pi\alpha^2}{3N_c Q^2 s}\sum_i e_i^2 \int d^2\mathbf{k}_{aT}\, d^2\mathbf{k}_{bT}\, \delta^{(2)}(\mathbf{q}_T - \mathbf{k}_{aT} - \mathbf{k}_{bT}) \times f_{1(i/H_a)}(x_a, \mathbf{k}_{aT})\, f_{1(\bar{i}/H_b)}(x_b, \mathbf{k}_{bT})$$

$$= \hat{\sigma}_{q\bar{q}\to l\bar{l}} \otimes f_1 \widetilde{\otimes} f_1 .$$



Graphic and equations stolen shamelessly from: https://arxiv.org/pdf/2304.03302.pdf

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$$\times f_{1(i/H_a)}(x_a, \mathbf{k}_{aT})\, f_{1(\bar{i}/H_b)}(x_b, \mathbf{k}_{bT})$$

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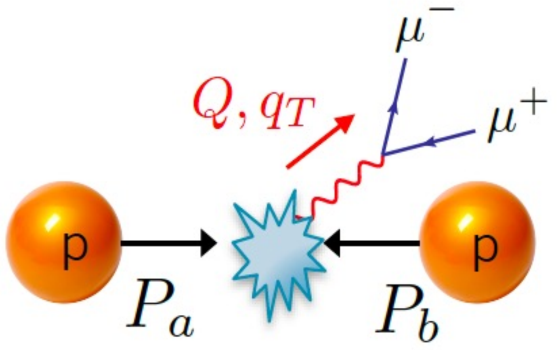
pQCD TMDPDFs



$$q_T \ll Q$$

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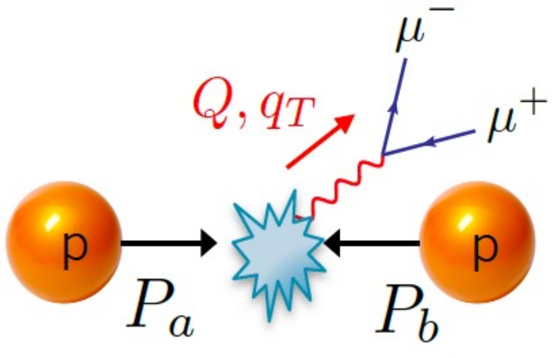
$$

$$
= \hat{\sigma}_{q\bar{q}\to l\bar{l}} \otimes f_1 \tilde{\otimes} f_1 .
$$

observable

pQCD

TMDPDFs



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Factorization and pQCD framework

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observable

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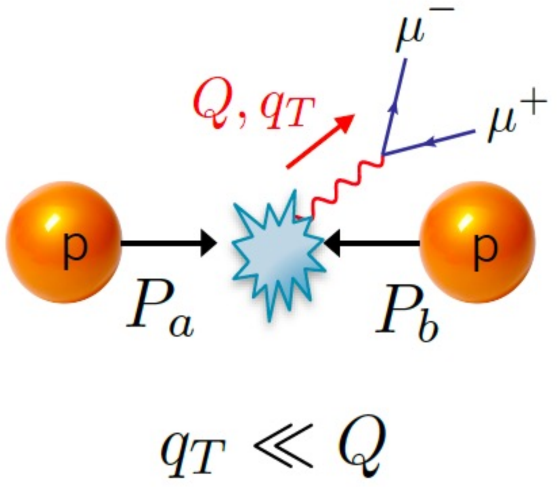
TMDPDFs

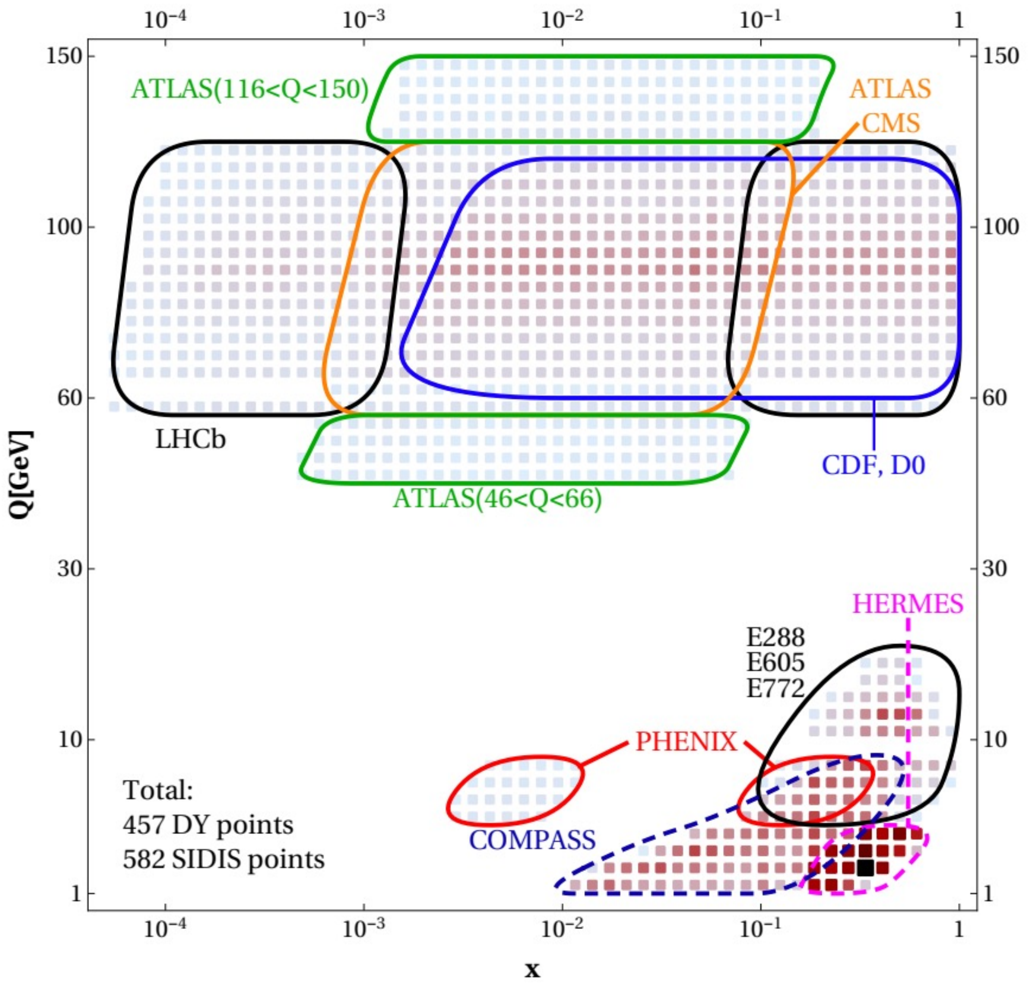


I. Factorization allows for the interpretation of a measured asymmetry or differential cross-section in terms of the TMDs

II. The observable needs to be differential in two scales:
- Hard scale Q >> ƛ$_{QCD}$ to ensure interaction with a single parton.
- Softer scale $q_T < Q$ for sensitivity to transverse momentum.

Advantages of TMDs @ Hadron Colliders

- ***Gluons!***
  - Access to both quark and gluon TMDs! Strong interactions access gluons directly and are ideally suited for studying observables like *Gluon Fragmentation Functions* and *Gluon Linear Polarization*.
- ***Factorization*** and ***Universality***
  - Separate intrinsic properties of hadrons from interaction dependent dynamics
  - Ideally, we need precision measurements from SIDIS, e+e- and pp to make meaningful comparisons.
  - Push the theoretical envelop
- ***Evolution***
  - non-perturbative factors that must be measured
  - pp colliders access higher Q^2 than fixed target experiments
  - Provides insights into the size of observables we want to measure at an EIC.
- ***Jets!***
  - Clean separation of initial and final state with jet reconstruction



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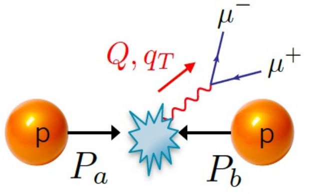
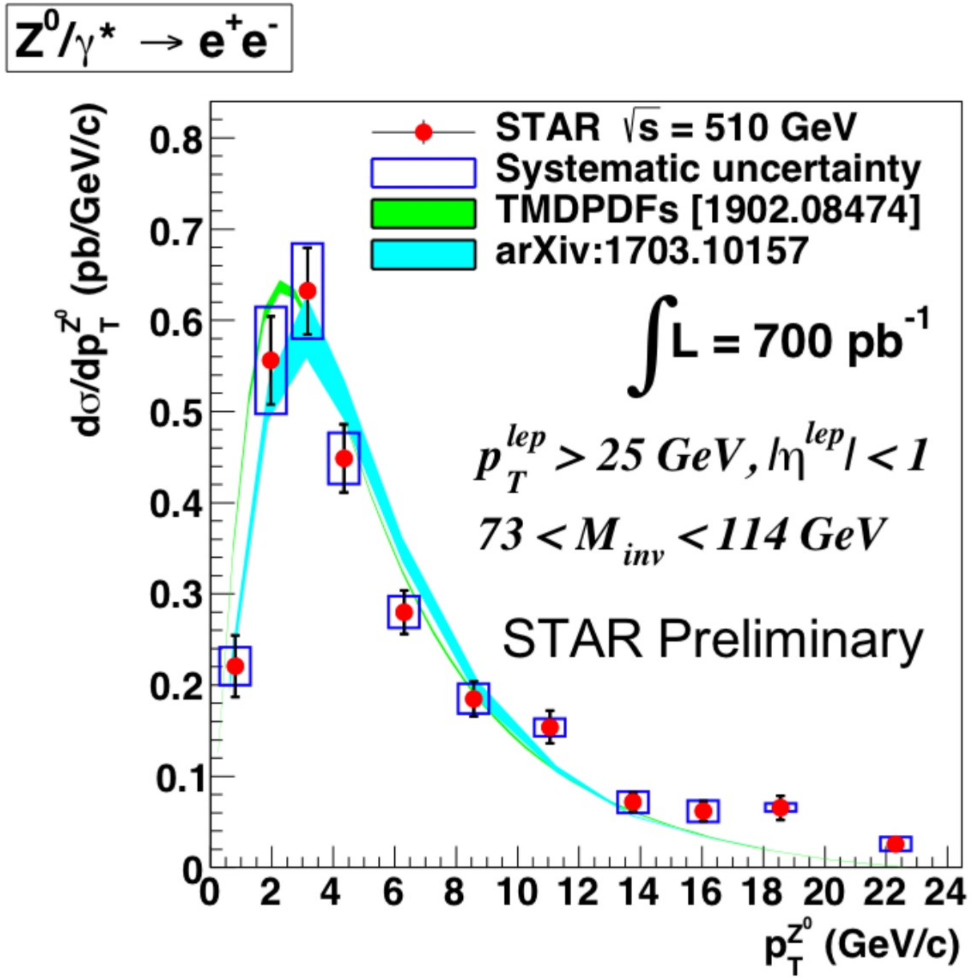
Spin Integrated TMDs

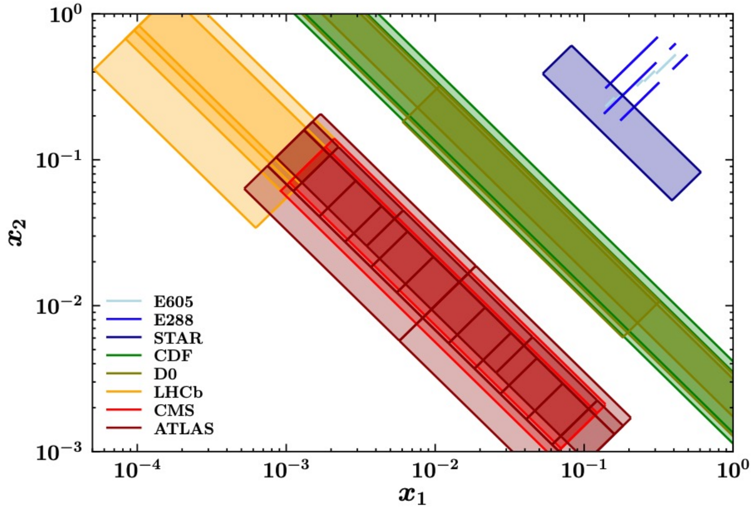
TMDPDF : Drell-Yan differential cross-section



$q_T \ll Q$



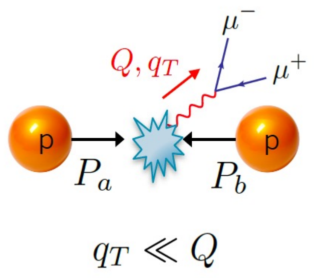
- STAR result provides constraints at high x.
- M_{inv} overlaps with Tevatron data.
- $q_T = k_{TA} + k_{TB} << M_{inv}$

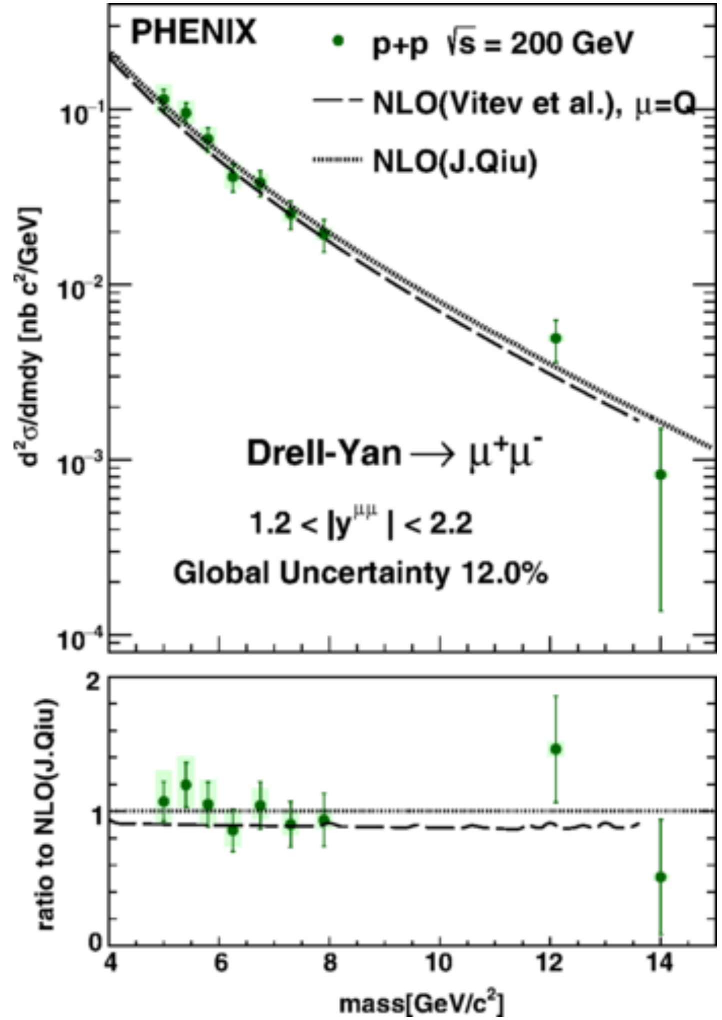


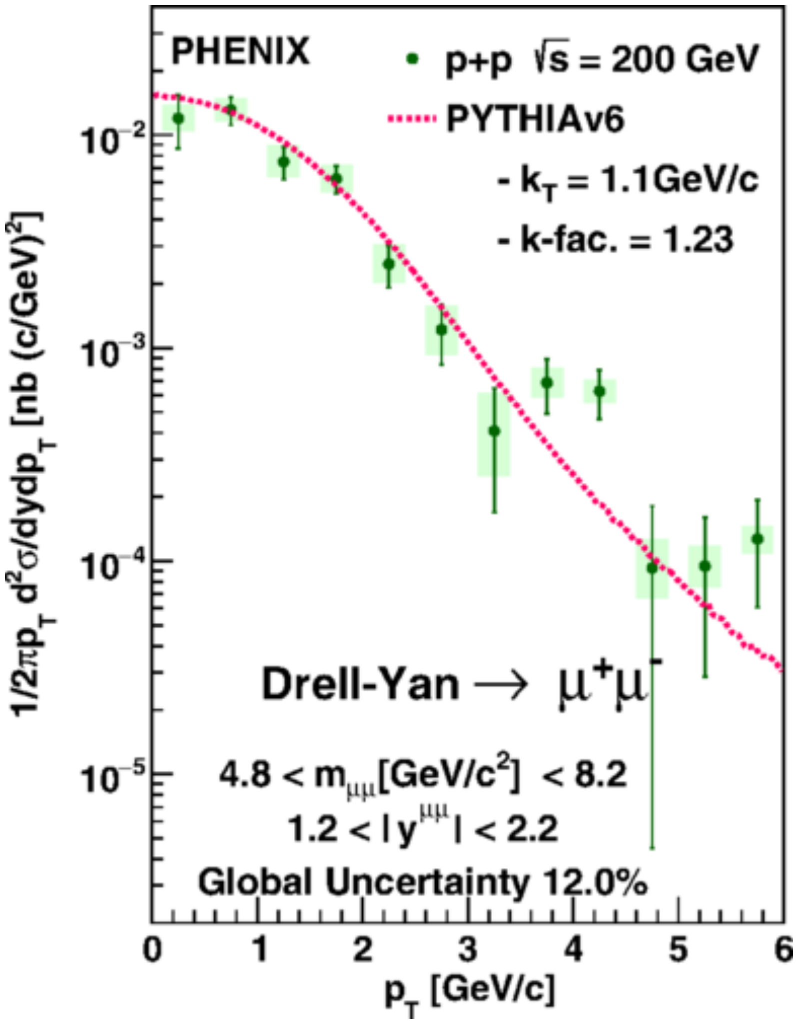
JHEP 07 (2021) 117

- Final publication, with updated N^3LL theory comparisons should be available in next few weeks…
- Expect 50% more data from Run 22

TMDPDF : Drell-Yan differential cross-section

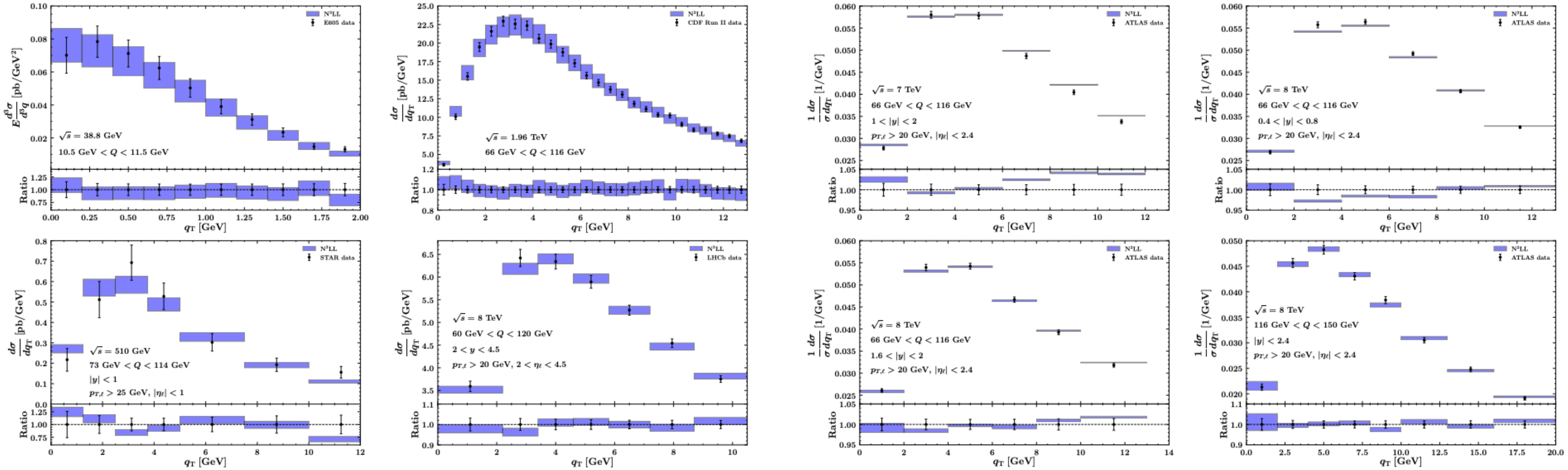






- First Drell-Yan measurement at 200 GeV RHIC energies!
  Phys. Rev. D 99, 072003 (2019)
- Sensitive to x ~ 0.005
- M_{inv} cross-section agrees with with NLO calculations
  Phys. Lett. B 704, 590 (2011)
  Phys. Rev. C 71, 014901 (2005)
- Global analyses need to apply a cut to ensure $q_T/Q < 1$

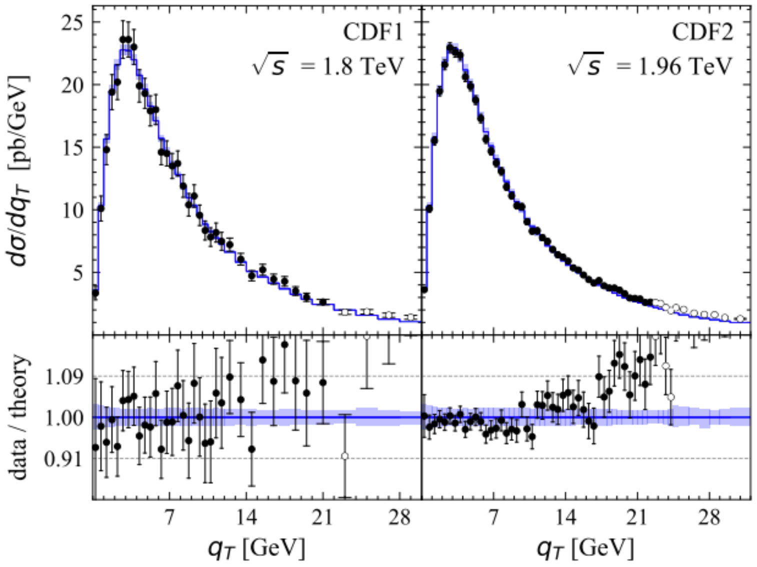
High stats come from LHC and Tevatron data

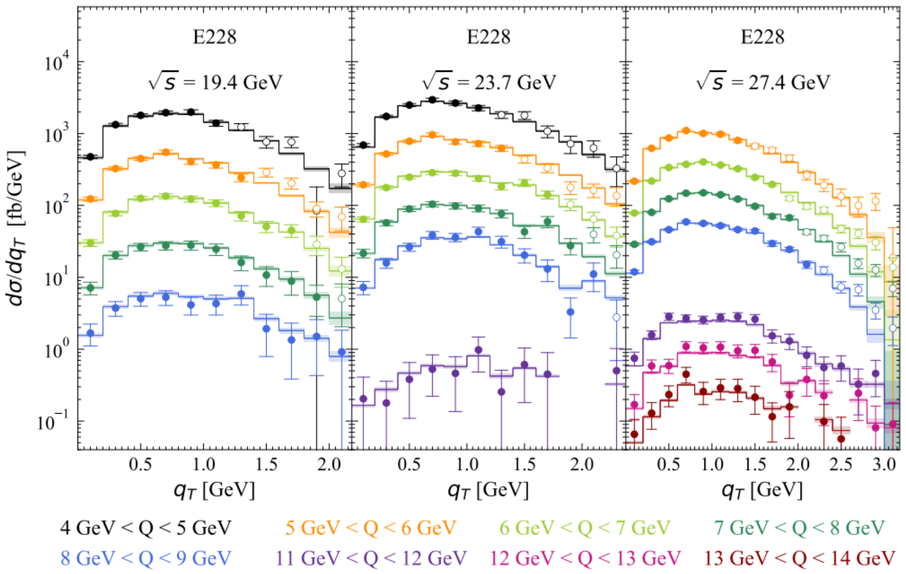


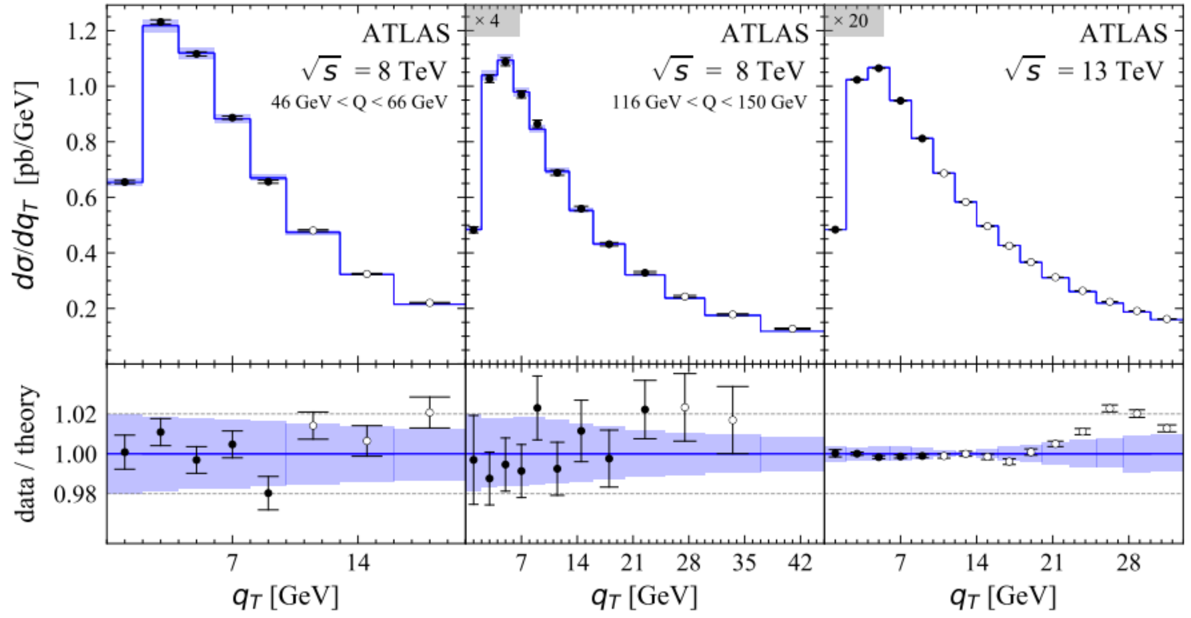
- Representative datasets and comparisons to N^{3}LL fits from *JHEP 07 (2021) 117*.
- Fits reproduce data extremely well over wide kinematic range.
- Allows for extraction of unpolarized TMDs at N^{3}LL precision *JHEP 07 (2021) 117, JHEP 06 (2020) 137.*

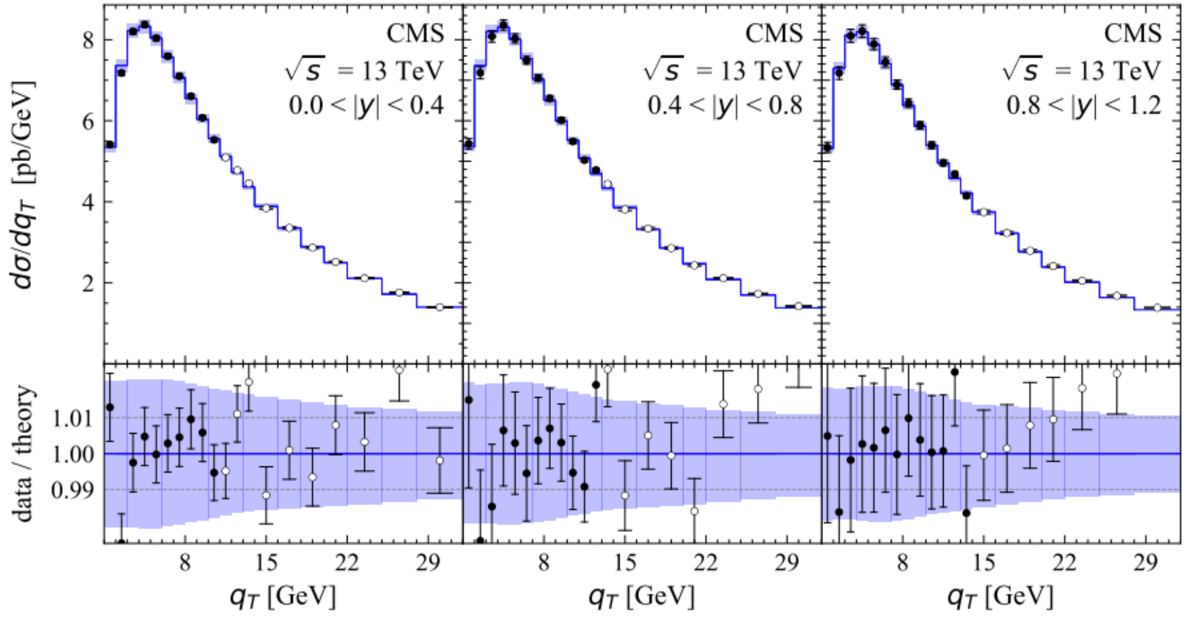
And now also at N^{4}LL!

… arXiv:2305.07473

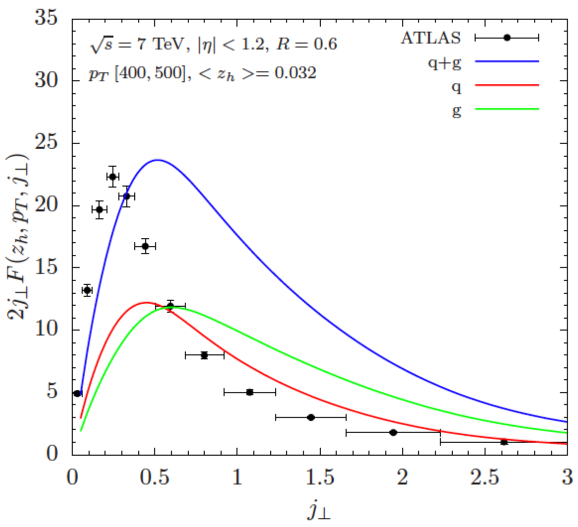


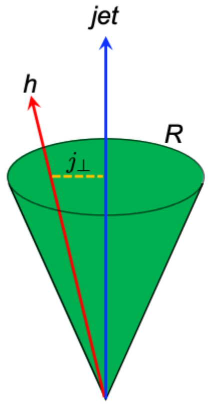






TMDFF : Hadrons-in-jets



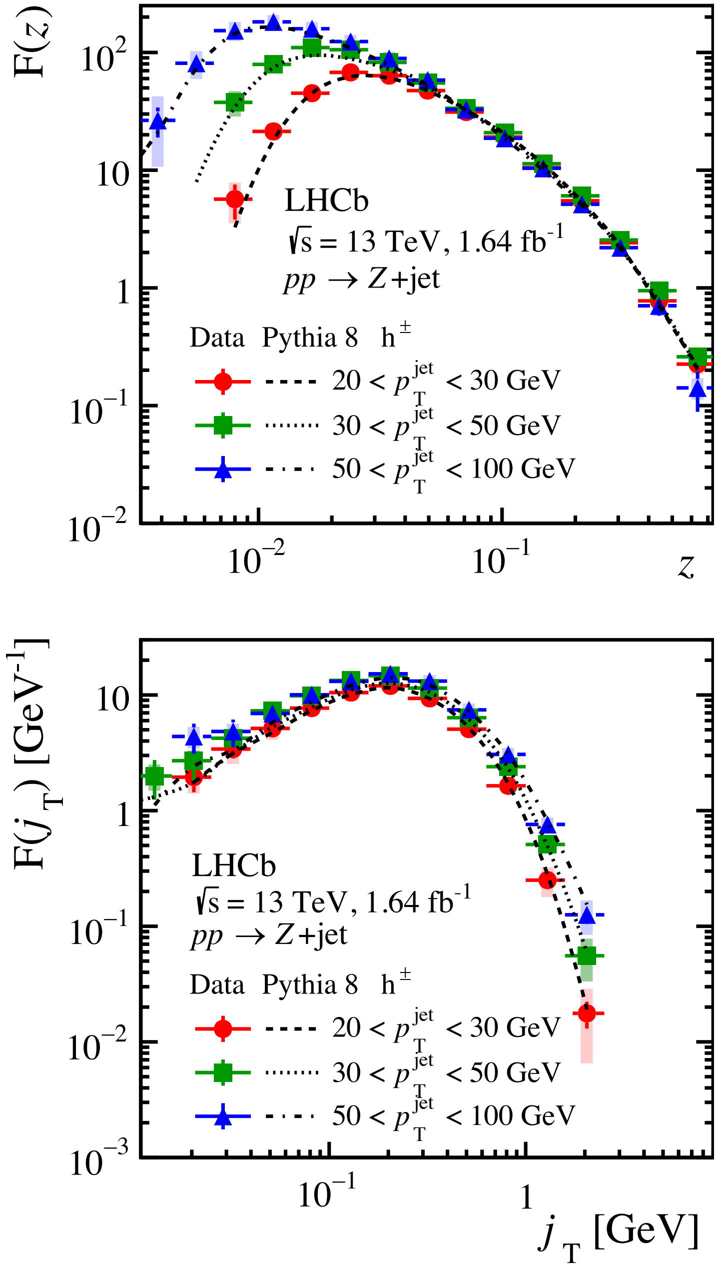


Universal Jet TMD FF

JHEP 11 (2017) 068

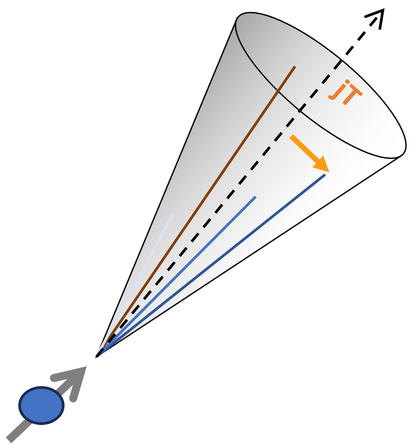
$$F\left(z_h, j_T; p_T, \eta, R\right) = \frac{\dfrac{d\sigma^{pp\to jet+X}}{dp_T^{jet}\, d\eta^{jet}\, d^2 j_T\, dz_h}}{\dfrac{d\sigma^{pp\to jet+X}}{dp_T^{jet}\, d\eta^{jet}}}$$

arXiv : 2208.11691

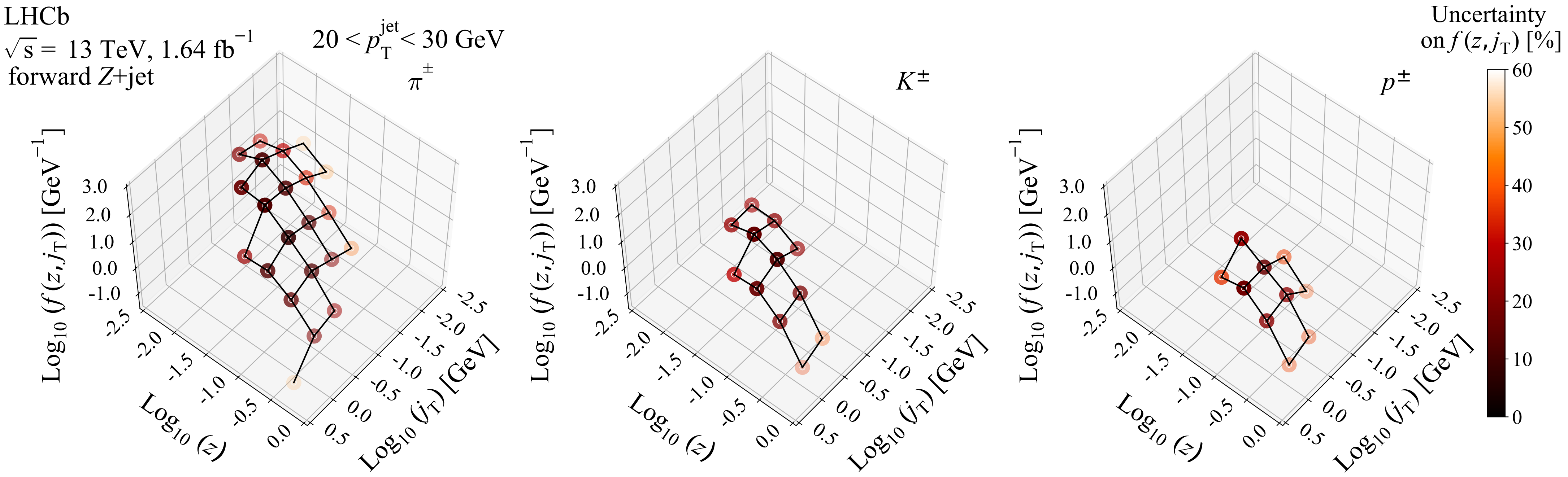


- New results from LHCb in forward region
- Forward jets recoiling off a Z boson selects preferentially quarks
- Provides unique insights into Quark TMD fragmentation.
- Study of charged hadrons as well as fully pi/K/p PID

TMDFF : Hadrons-in-jets *arXiv : 2208.11691*



- First-ever multidimensional measurements of identified charged pions (left), kaons (middle), and protons (right) in jets from LHCb.
- Simultaneous measurement of the longitudinal momentum fraction z and transverse momentum with respect to the jet axis j_T shows correlations between these kinematic variables.



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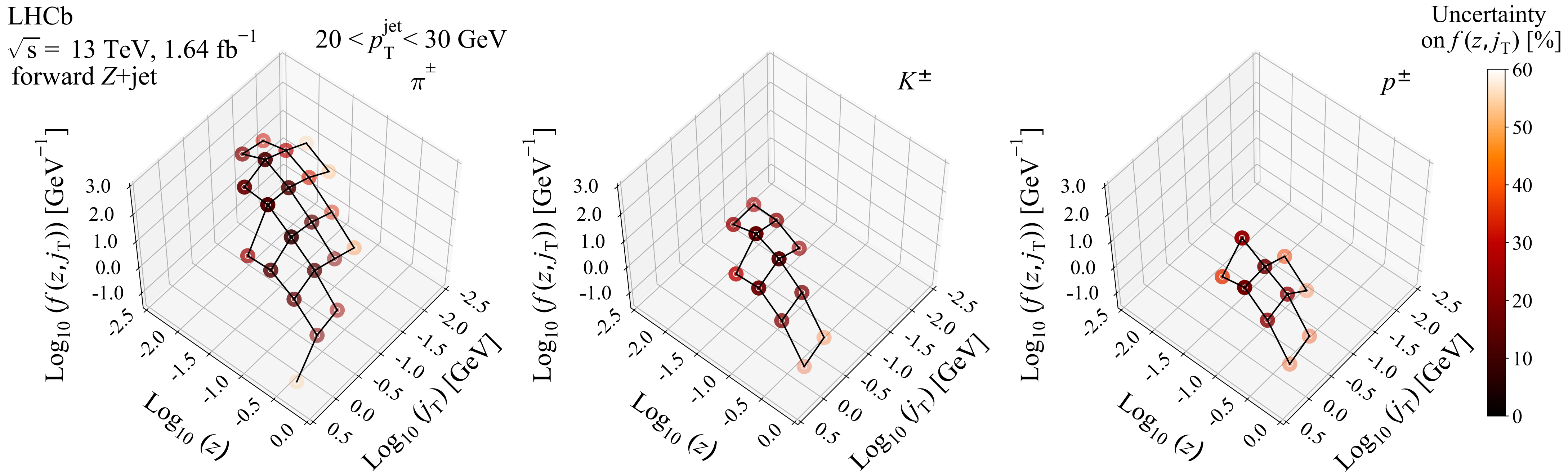
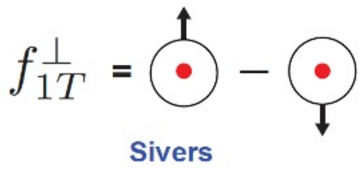
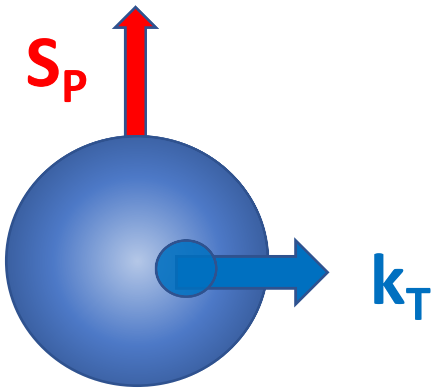
Analysis of jetFF at mid-rapidity in pp and pA @ 200 GeV ongoing at STAR.

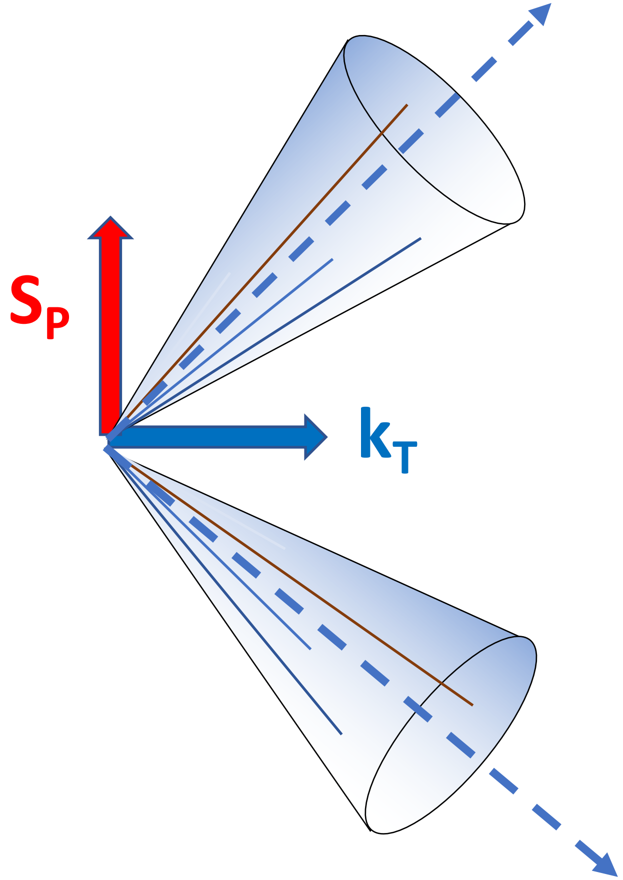


Spin Dependent TMDPDFs



Sivers Effect in DiJET Production





$$\langle \vec{S}_{proton} \cdot (\vec{P}_{proton} \times \vec{k}_T) \rangle$$

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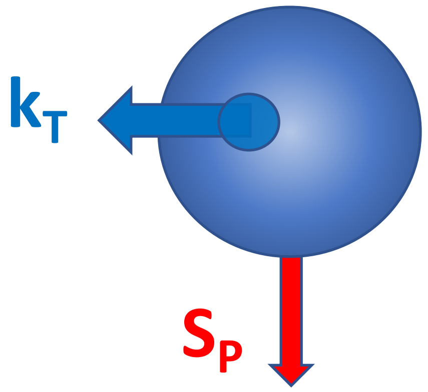
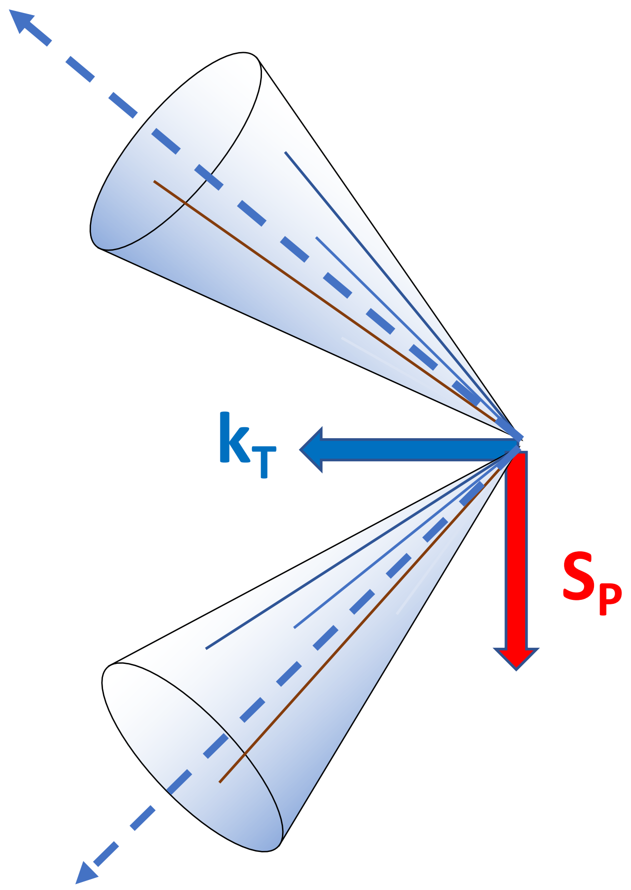


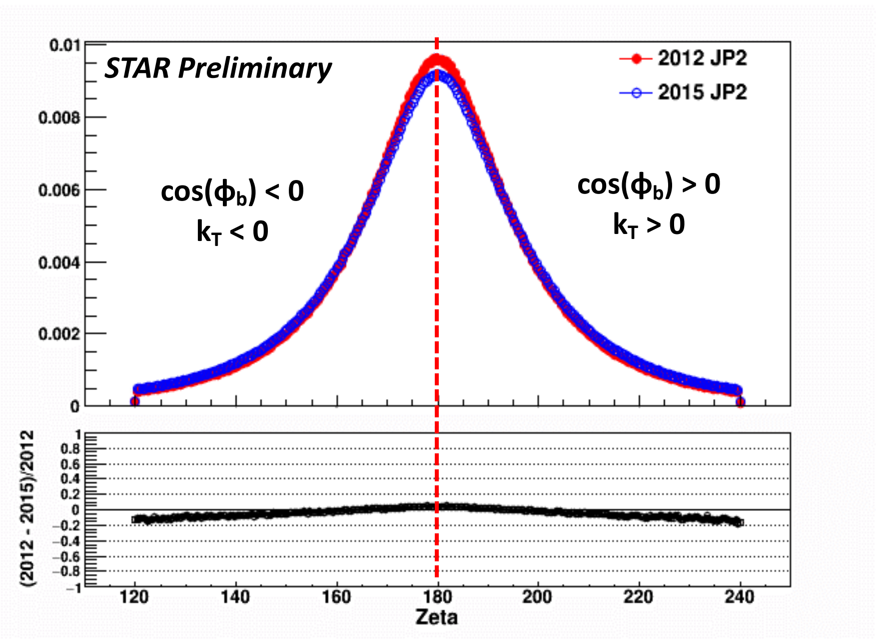


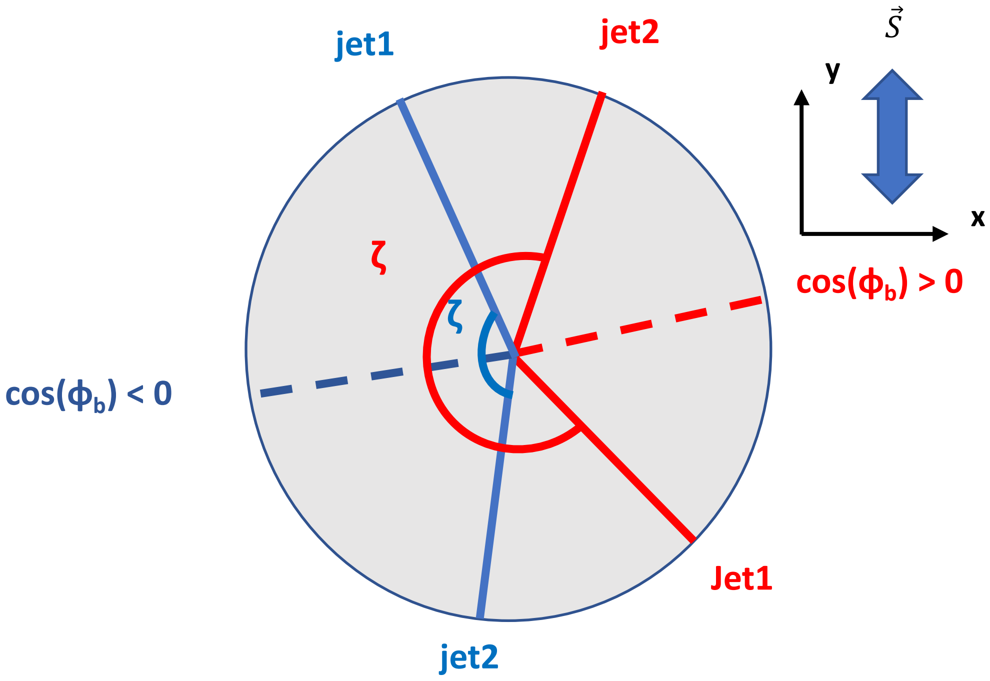
$$\langle \vec{S}_{proton} \cdot (\vec{P}_{proton} \times \vec{k}_T) \rangle$$

Observable in DiJET Production

- ϕ_b is di-jet bisector angle (the ray points to the tilt direction of the two jets)
- ζ is the opening angle of dijet in the transverse plane
  - $\zeta > \pi$ when $\cos(\phi_b) > 0$
  - $\zeta < \pi$ when $\cos(\phi_b) < 0$

Distribution of ζ [deg] in 2012 and 2015 data taken by JetPatch2 Trigger*





Observable in DiJET Production

$$A = \frac{\langle \xi + \rangle - \langle \xi - \rangle}{P}$$

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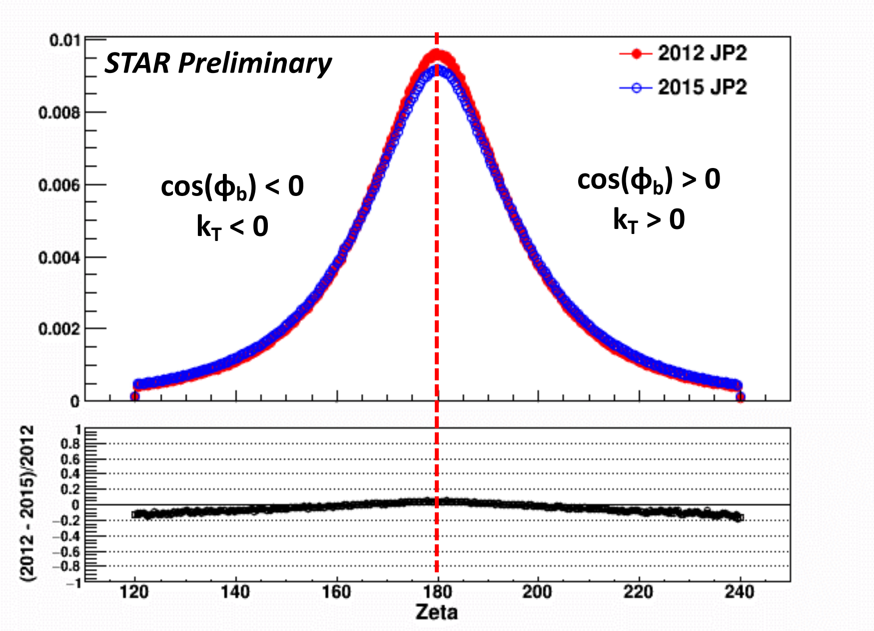
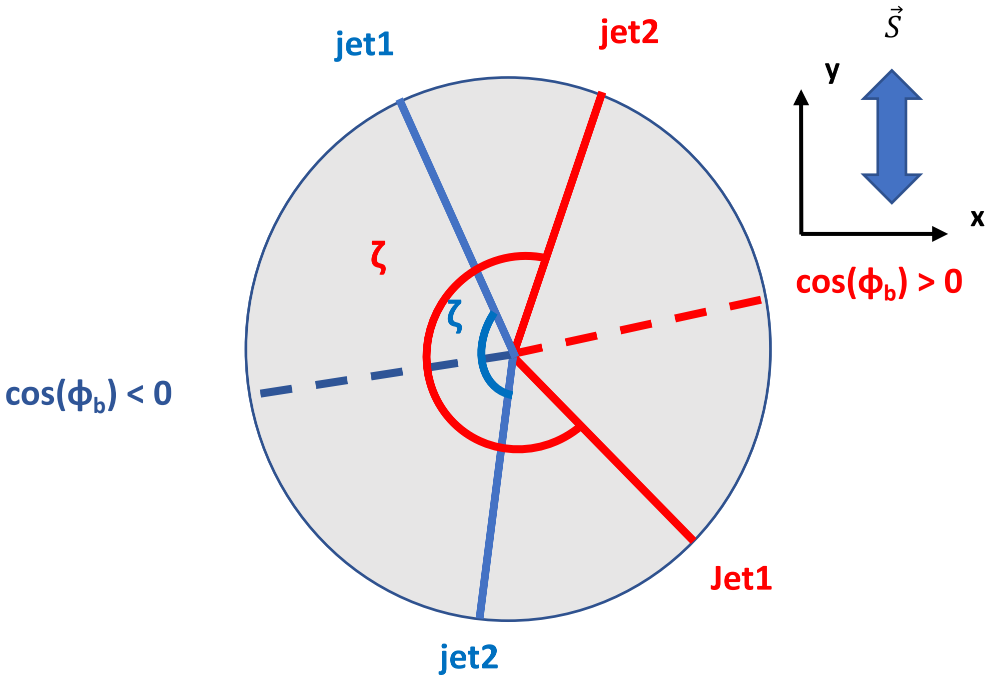


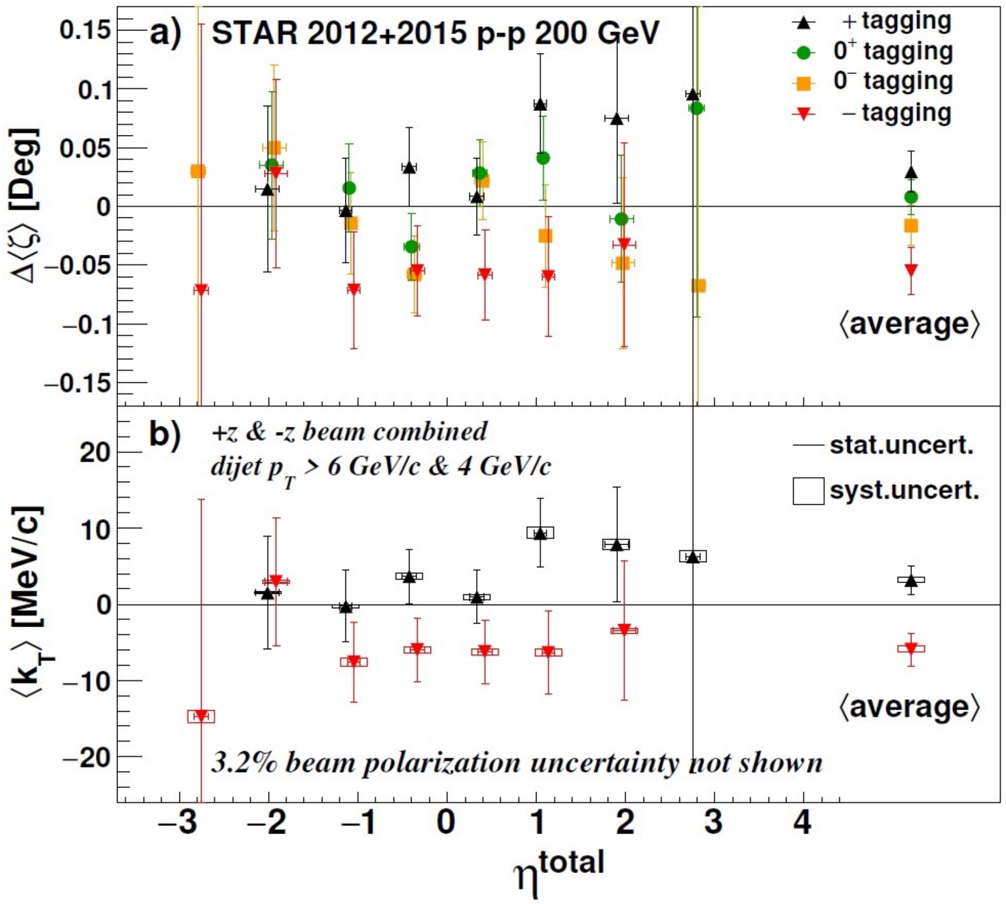


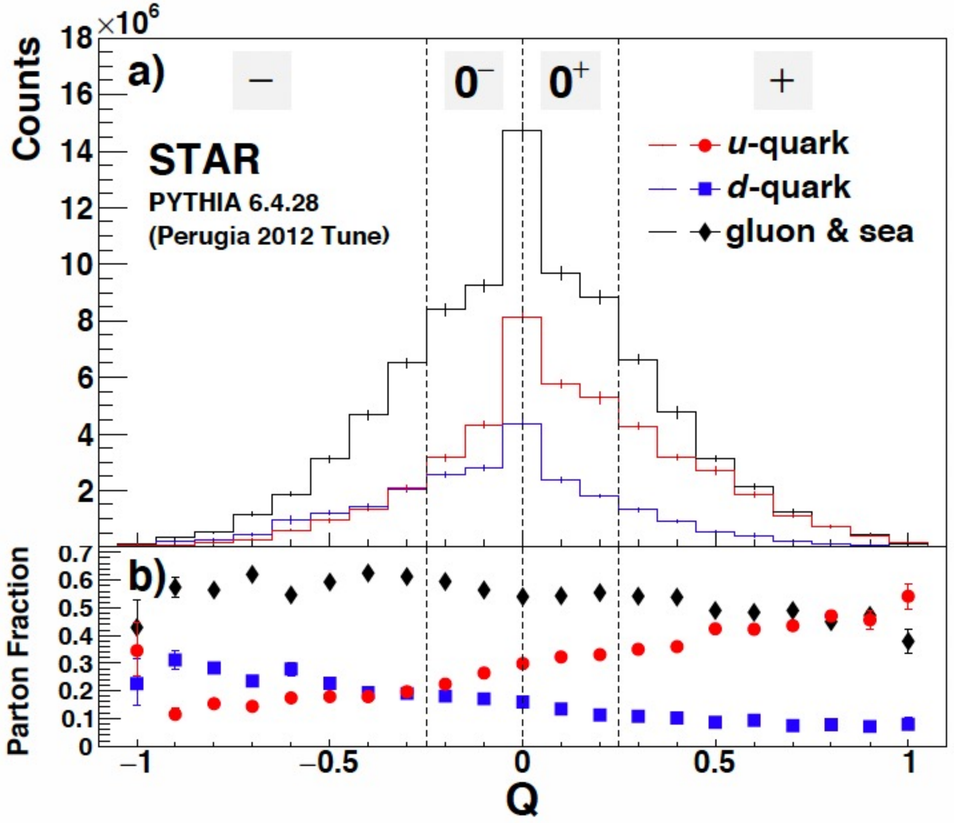
Jet Flavor Tagging

arXiv:2305.10359

Tag associated jets to enhance the purities of ***u*-quarks and *d*-quarks** separately.

$$Q = \sum_{\substack{\text{all the tracks} \\ \text{with } pT>0.8GeV}} \frac{track\ pT}{jet\ pT} \cdot track\ charge$$





Jet Flavor "TaGGING"

[arXiv:2305.10359](https://arxiv.org/abs/2305.10359)

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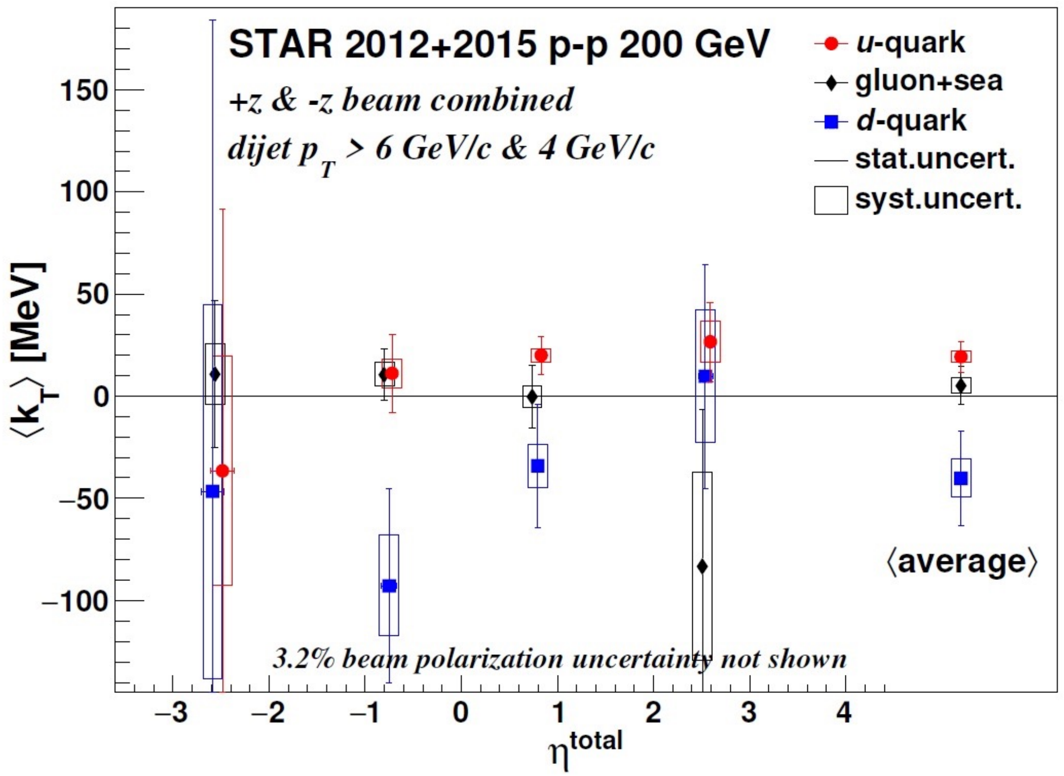
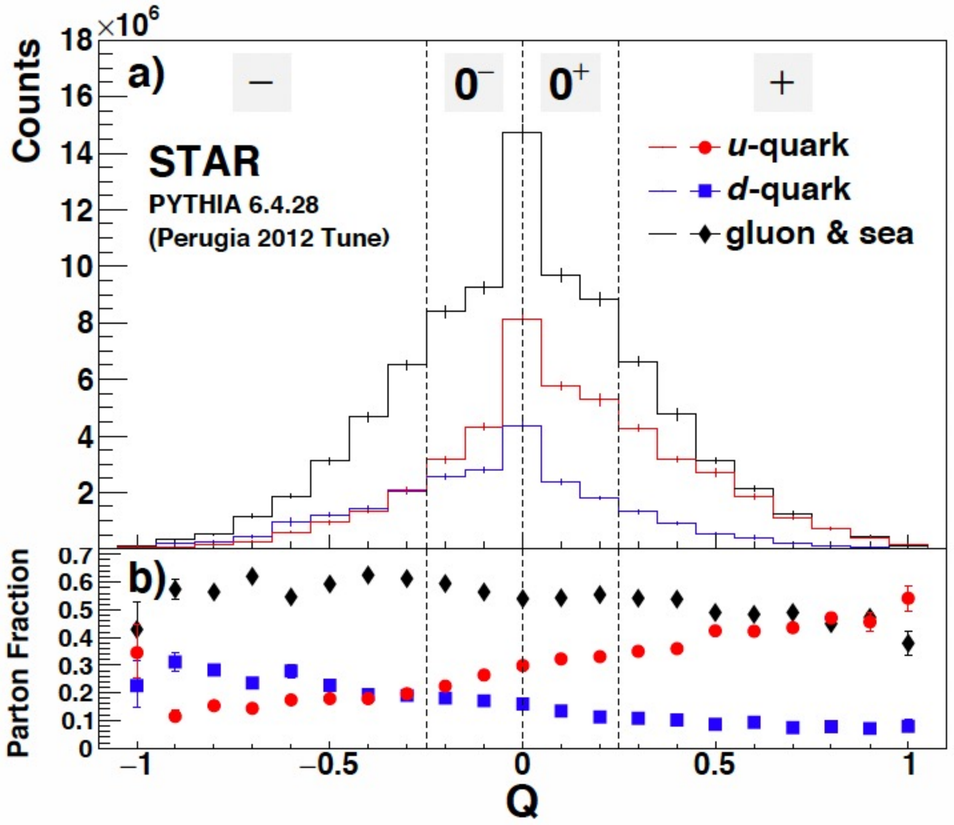
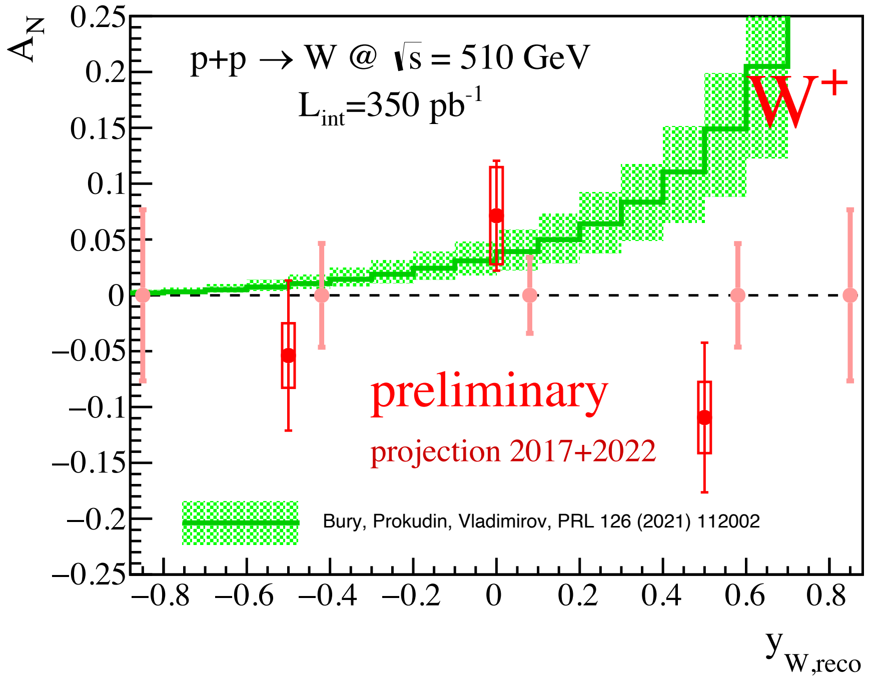
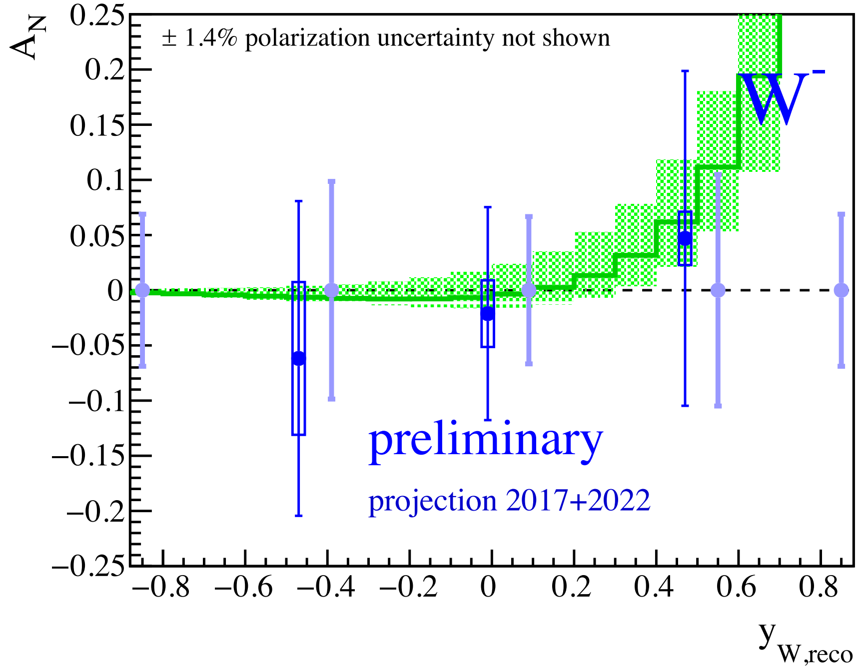




TMDPDFs : $W^{+/-}$ Production

- Reconstruction of W boson via e+v channel isolates sensitivity to the initial state.
- $W^{+/-}$ A_N constrains the quark and anti-quark Sivers functions
- Provides input on question of Sivers sign change in DY vs SIDIS interactions
- First results were from limited 2011 sample. Run 17 had x14 more data than 2011, resulting in more precise, but also smaller asymmetries.
- Data compared to calculations with N^3LL accuracy and TMD evolution.
- Analysis of the last RHIC dataset at 500 GeV (Run 22) is critical to provide a conclusive answer about the Sivers sign change.
- Tracking upgrades to STAR in 2022 will allow for expanded rapidity.

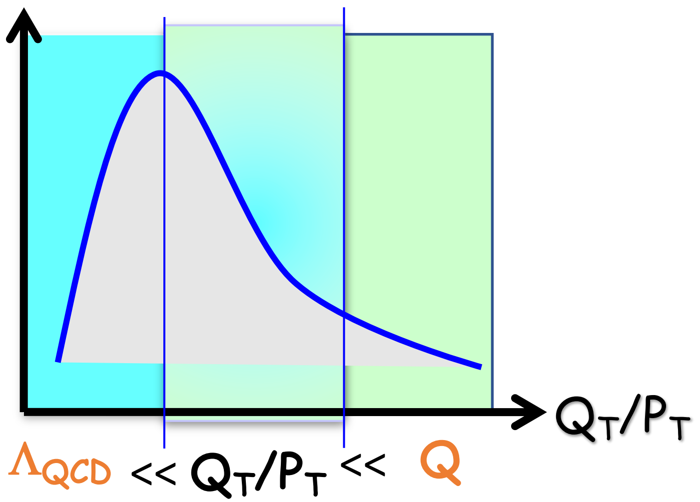




TMD

Requires two scales:
Hard scale Q^2
Soft scale : p_T

Appropriate for SIDIS, DY, $W^{+/-}$ & Z, hadrons in jets

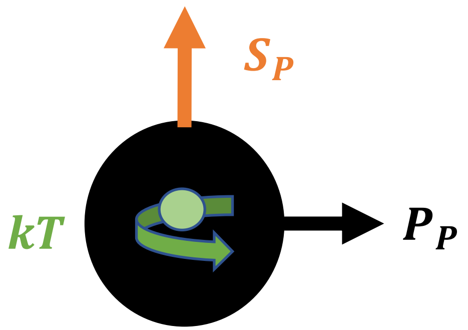


Collinear Twist-3

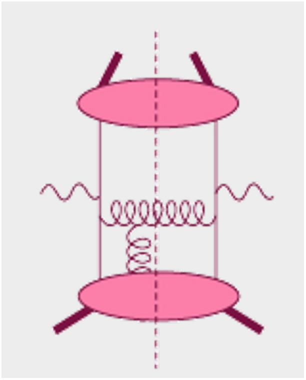
Single hard scale : p_T

Appropriate for inclusive π^0, jet, γ

Sensitive to $<k_T>$

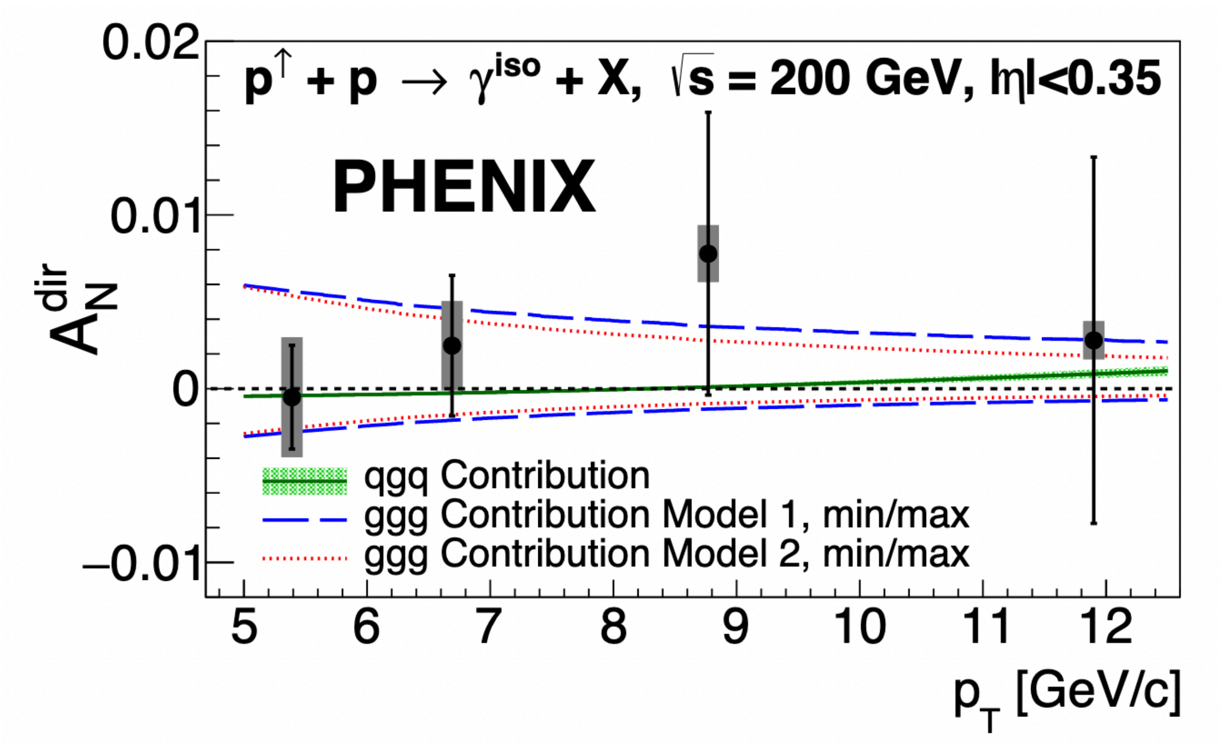


TMDs may be expressed in terms of collinear + twist-3 functions via the Operator product expansion.



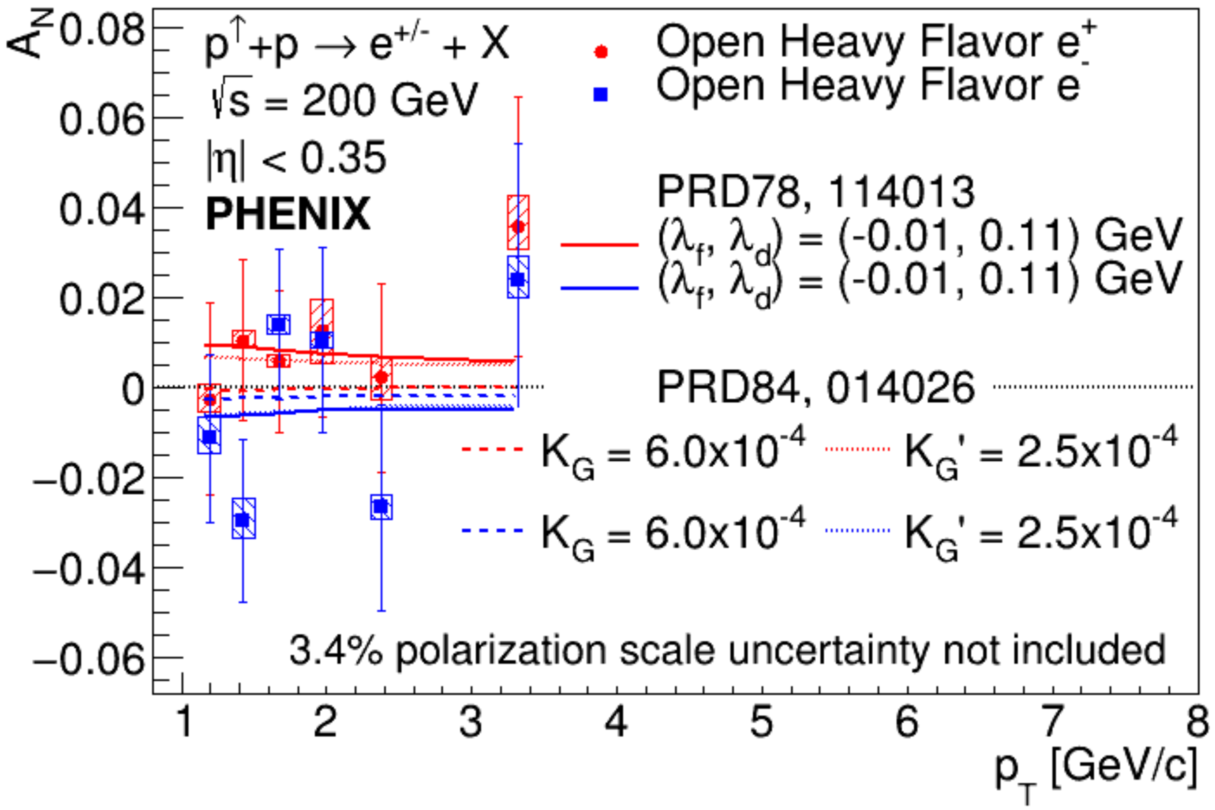
Efremov, Teryaev; Qiu, Sterman

Twist 3 : Direct Photon A_N



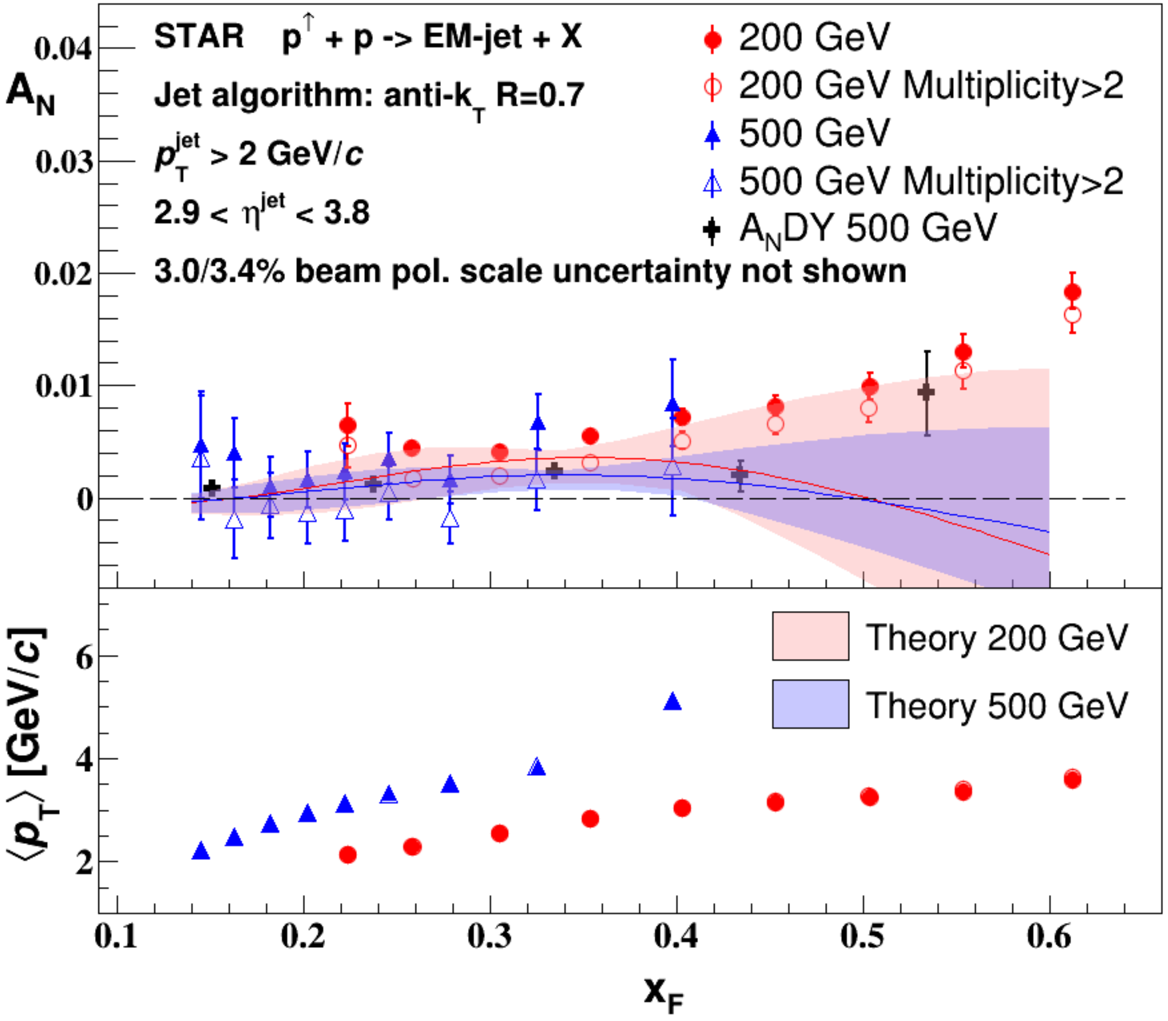
- First direct photon measurement!
  Phys. Rev. Lett. 127, 162001 (2021)
- Dominated by quark-gluon Compton scattering process.
- Very clean probe of gluon dynamics in the initial state.
- Consistent with zero to 1%.
- Constrains twist-3 collinear correlation functions.
  Phys. Rev. D 91, 014013 (2015)
  Phys. Rev. D 85, 034030 (2012)
- Factor of 2 smaller error bars expected with final dataset.

Twist-3 : Open Heavy Flavor A_N



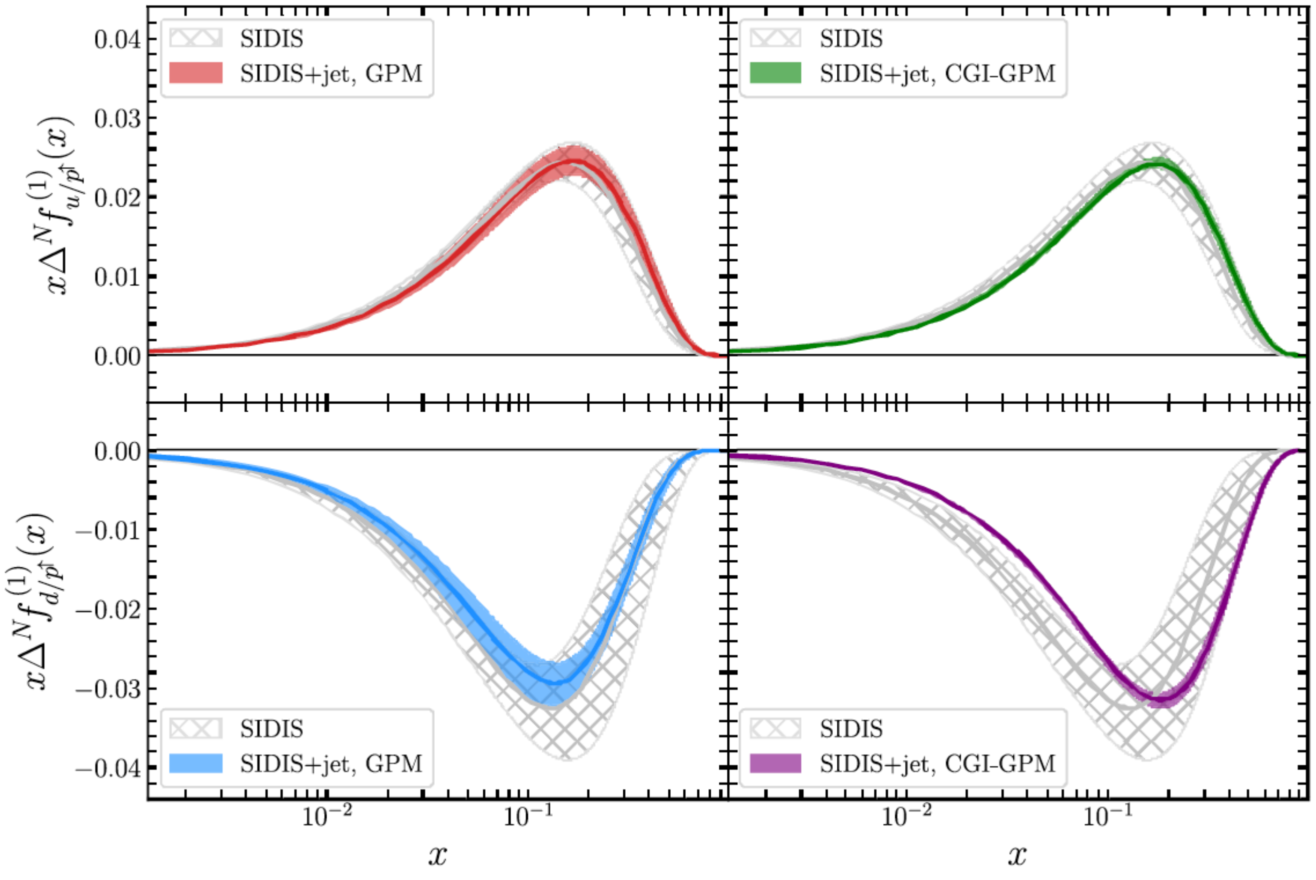
- Dominated by gg fusion at RHIC energies
  arXiv: 2204.12899
- Primarily sensitive to the initial state
- First analysis to quantify the gluon-correlators that can ultimately be used to constrain gluon orbital angular momentum.
- In 2024 sPHENIX should be able to repeat and improve on this measurement.

TWIST-3: Far-Forward Jet TSSA



- 2011 500 GeV and 2015 200 GeV data
- No charged tracks – EM jets only.
- TSSA reduced with photon multiplicity > 2 requirement is placed.
- AnDY results shows TSSA of fully reconstructed jet and is consistent with EM jet with 3+ photon requirement.
- Theory curves : *L. Gamberg, Z. Kang, A. Prokudin, Phys.Rev.Lett. 110 23, 232301 (2013)*

TWIST-3: Far-Forward Jet TSSA

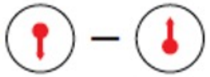


Phys.Lett.B 815 (2021) 136135

- Impact on Sivers first moment (k_T integrated) is significant – especially for down quark.
- pp data pushes to higher x than existing fixed target SIDIS data
- EIC will measure up to x ~ 0.5 so it is important to have statistically meaningful constraints from pp for tests of universality and evolution.
- 2022+ - Full jet (HCAL+ECAL) reconstruction in forward upgrade will provide additional data.

Spin dependent TMDFFs

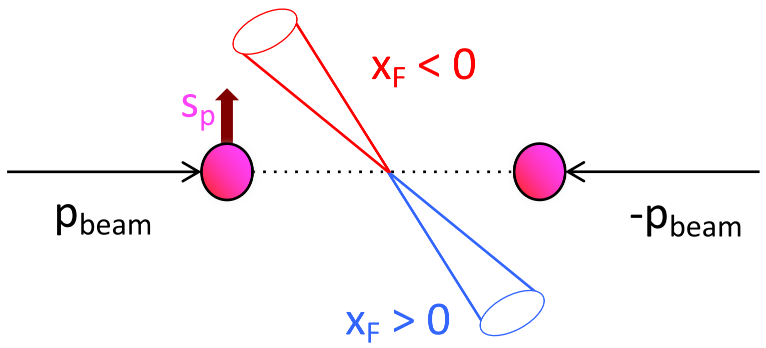
$H_1^{\perp}$ =



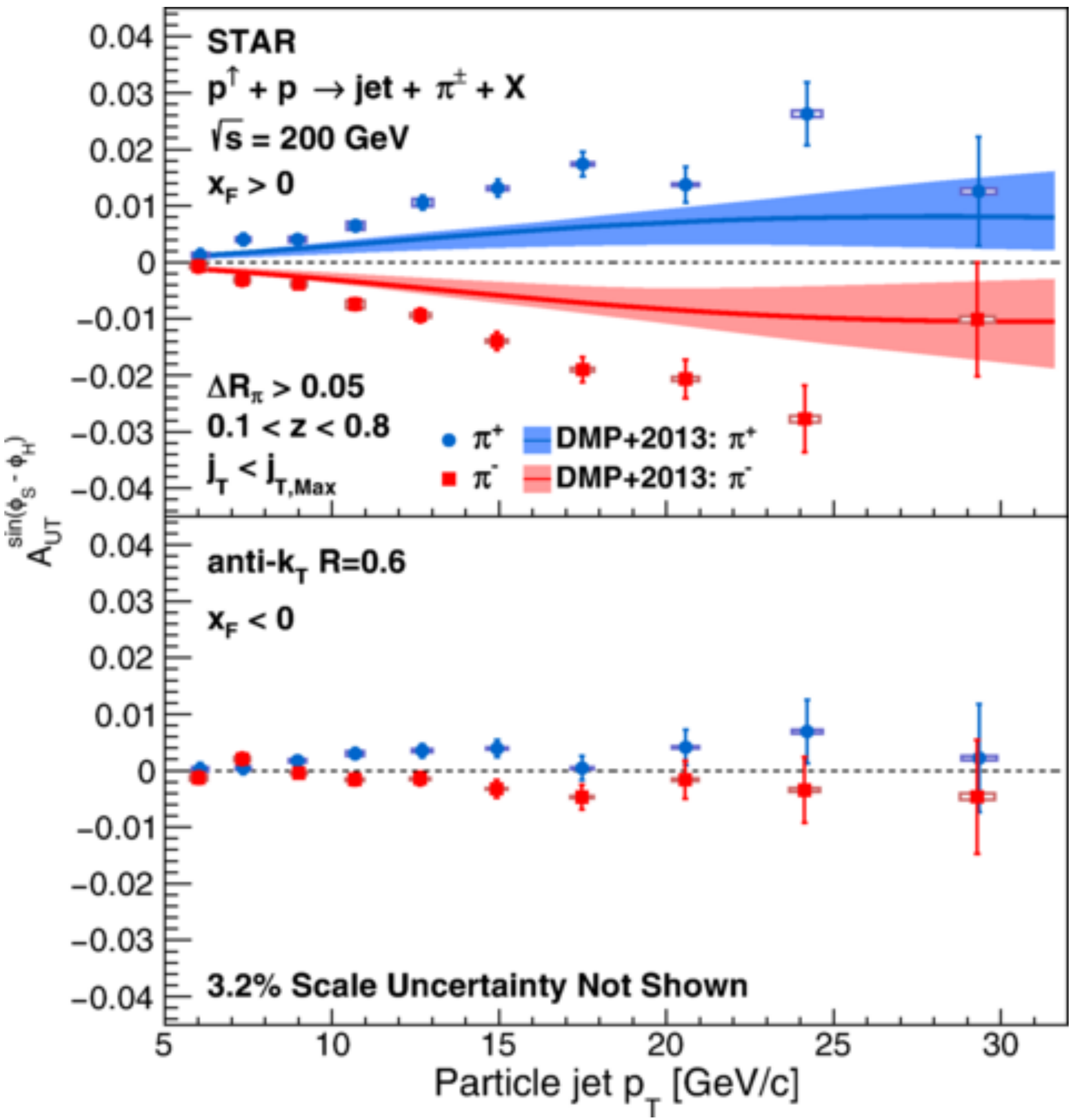
Collins

TMDFF : Hadrons-in-jets

- $A_{UT}^{\sin(\phi_S-\phi_H)}$ is sensitive to correlations between the spin of the parent quark and the azimuthal distribution of the hadrons inside the jet – Collins TMDs.
- Large spin asymmetries for charged pions in jets - sign flips with charge
- Clear dependence on jet p_T
- Signal reduced for backward $x_F < 0$ jets



Phys.Rev.D 106, 072010

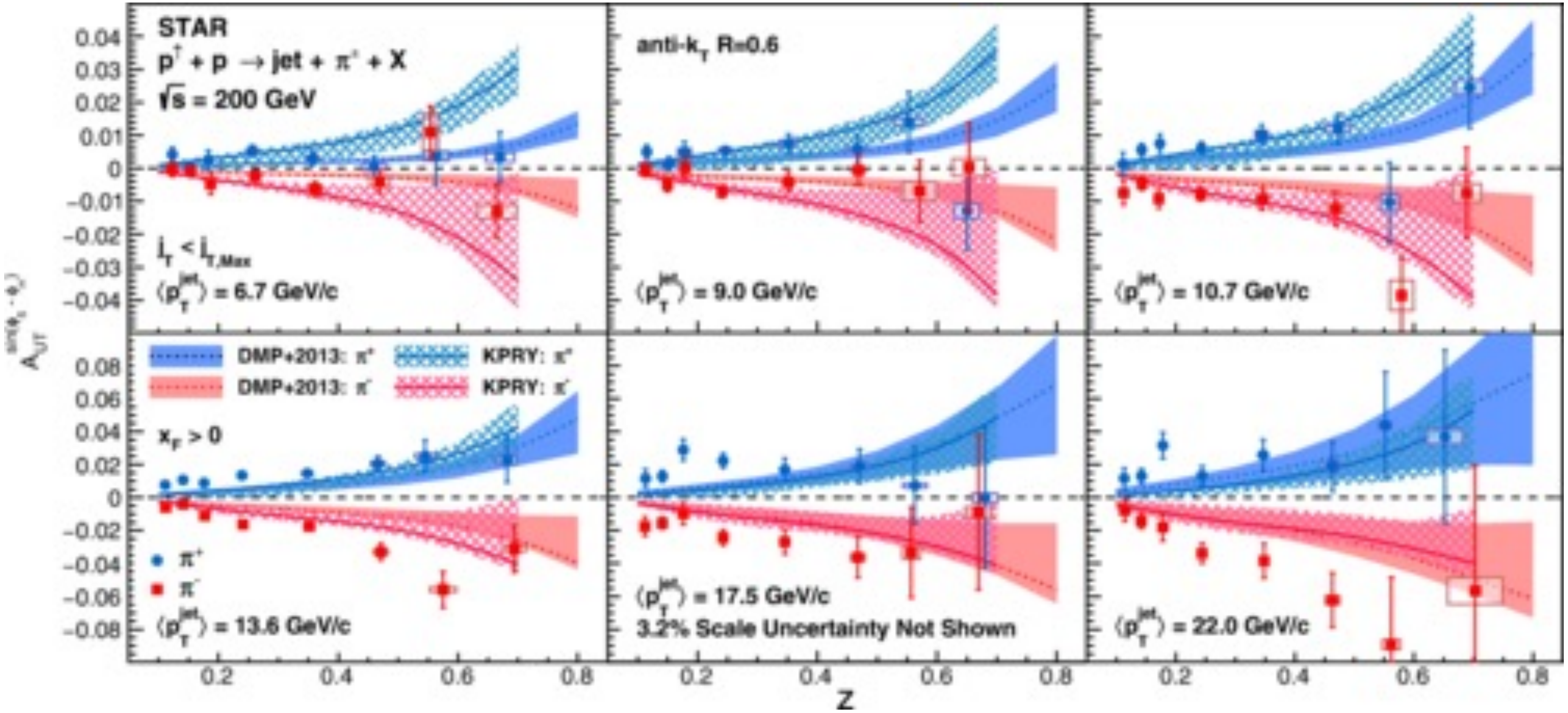


$A_{UT}^{\sin(\phi_S-\phi_H)}$ vs Z in bins of p_T @ 200 GeV

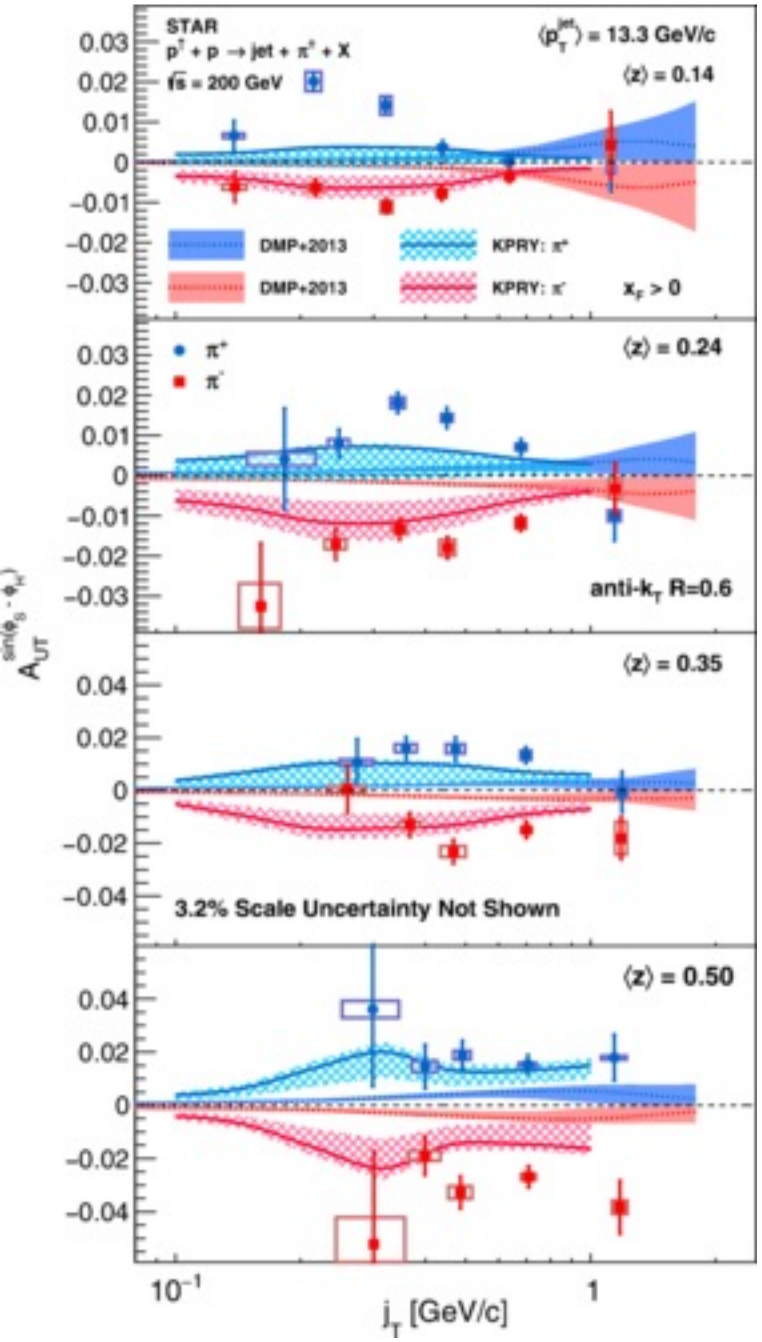
STAR data compared to calculations by

1. D'Alesio, Murgia & Pisano, Phys. Lett. **B773**, 300 (2017)

2. Kang, Prokudin, Ringer, & Yuan, Phys.Lett. **B774** 635-642 (2017) without and with evolution.



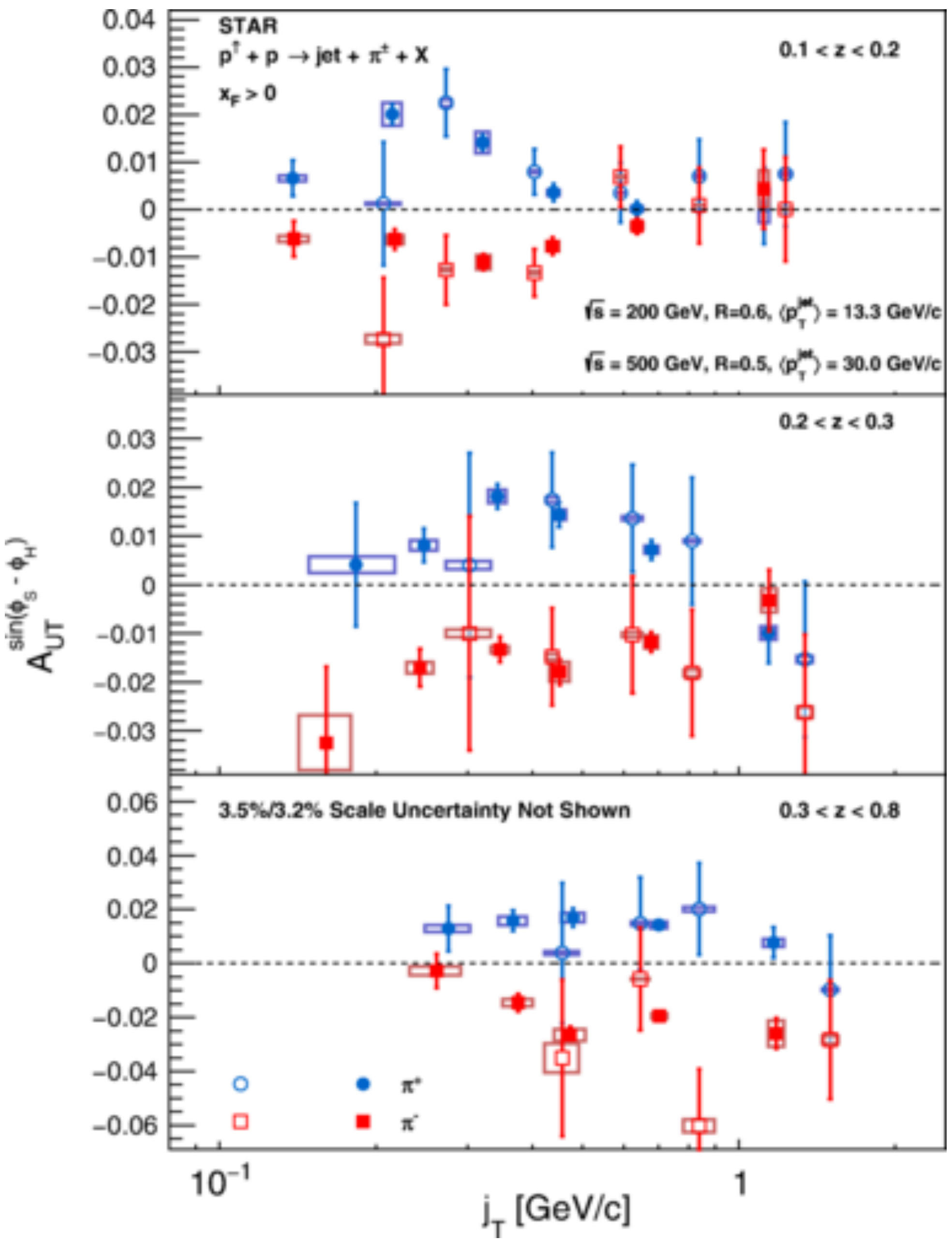
Phys.Rev.D 106, 072010



$A_{UT}^{\sin(\phi_S-\phi_H)}$ vs j_T in bins of z

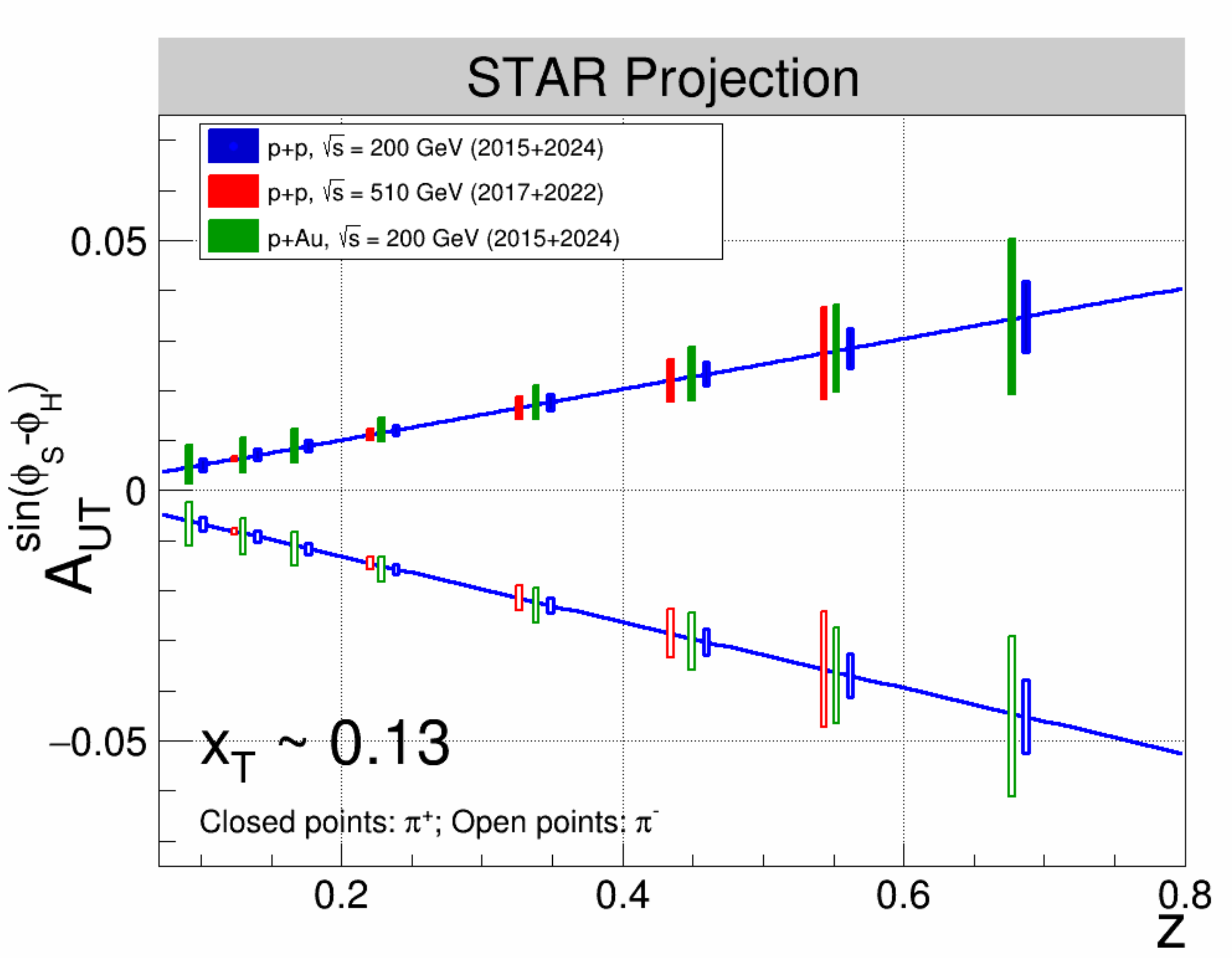
- Shape of j_T changes with z
- Peak of distribution moves higher as z increases.
- In contrast to SIDIS measurements hadron j_T is independent of initial state transverse momentum.
- 200 and 500 GeV tell the same story.
- Additional 500 GeV data is being analyzed.

Phys.Rev.D 106, 072010

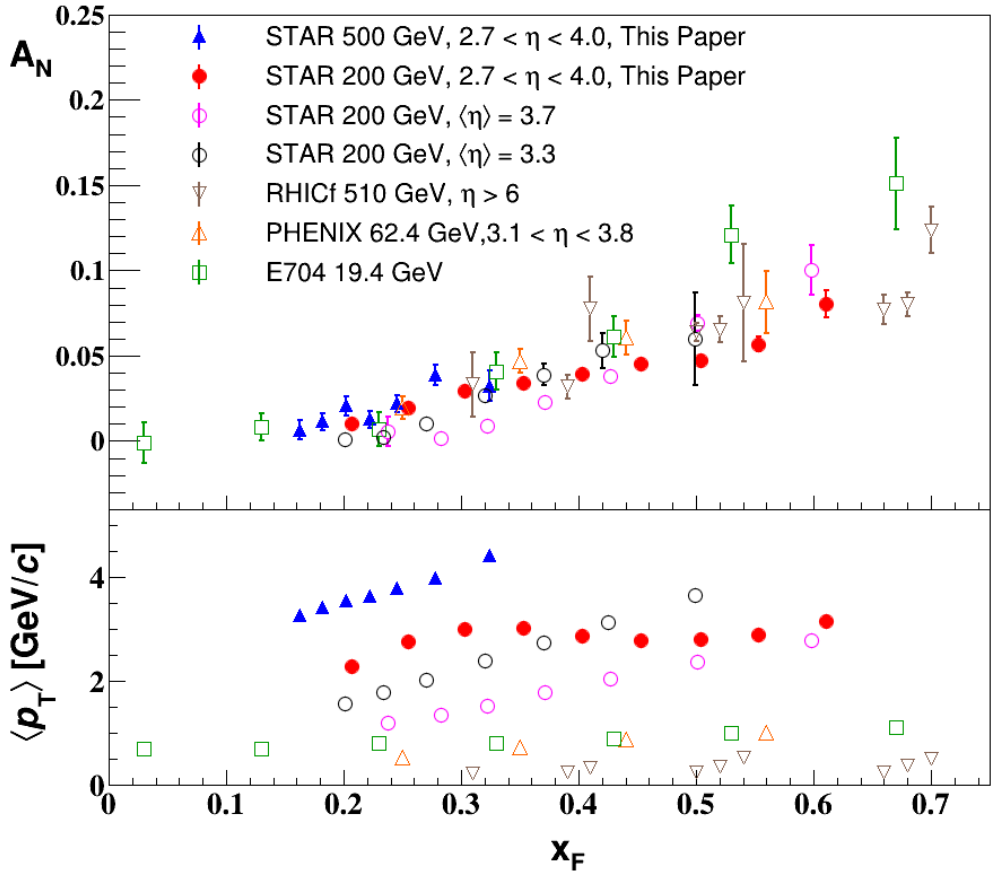


TMDFF : Nuclear effects

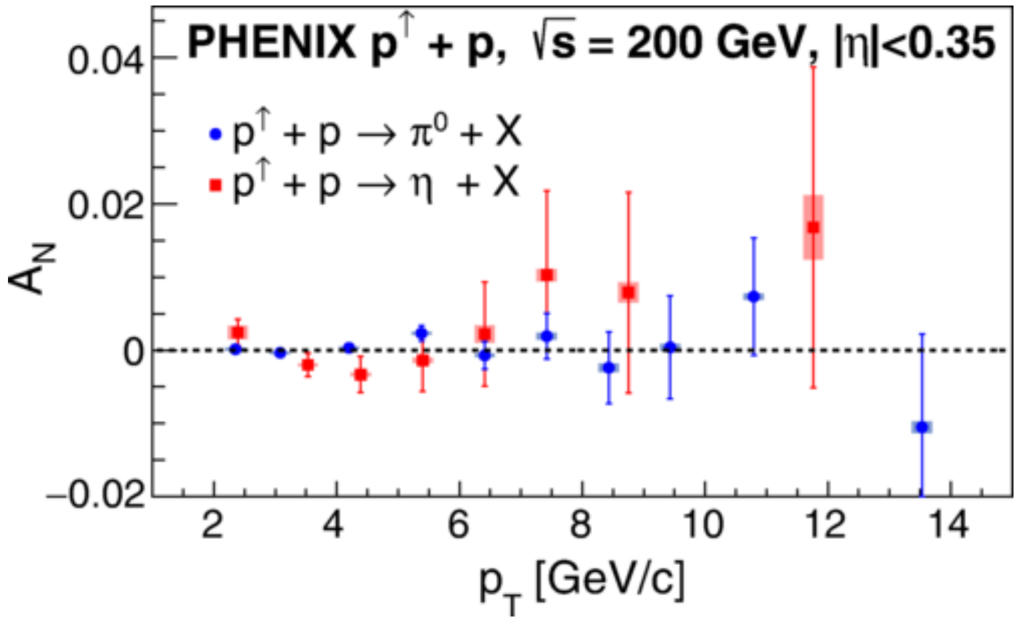
- Interesting to extend Hadron-in-jet Collins analysis to p+A
- Projections are guided by 200 GeV pp analysis
- Exploratory dataset taken in 2015 and analysis is ongoing.
- Effects are likely to be small so additional data to be taken in 2024 will be critical.



Twist 3: Inclusive pion & eta A_N

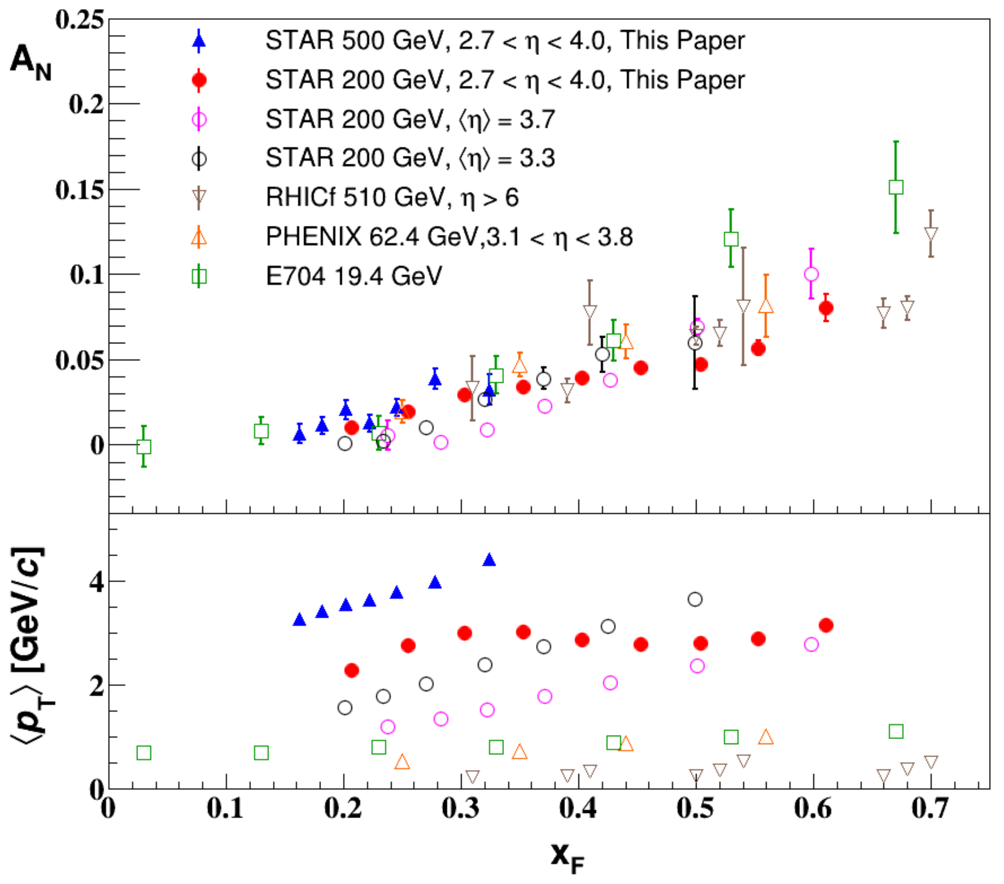


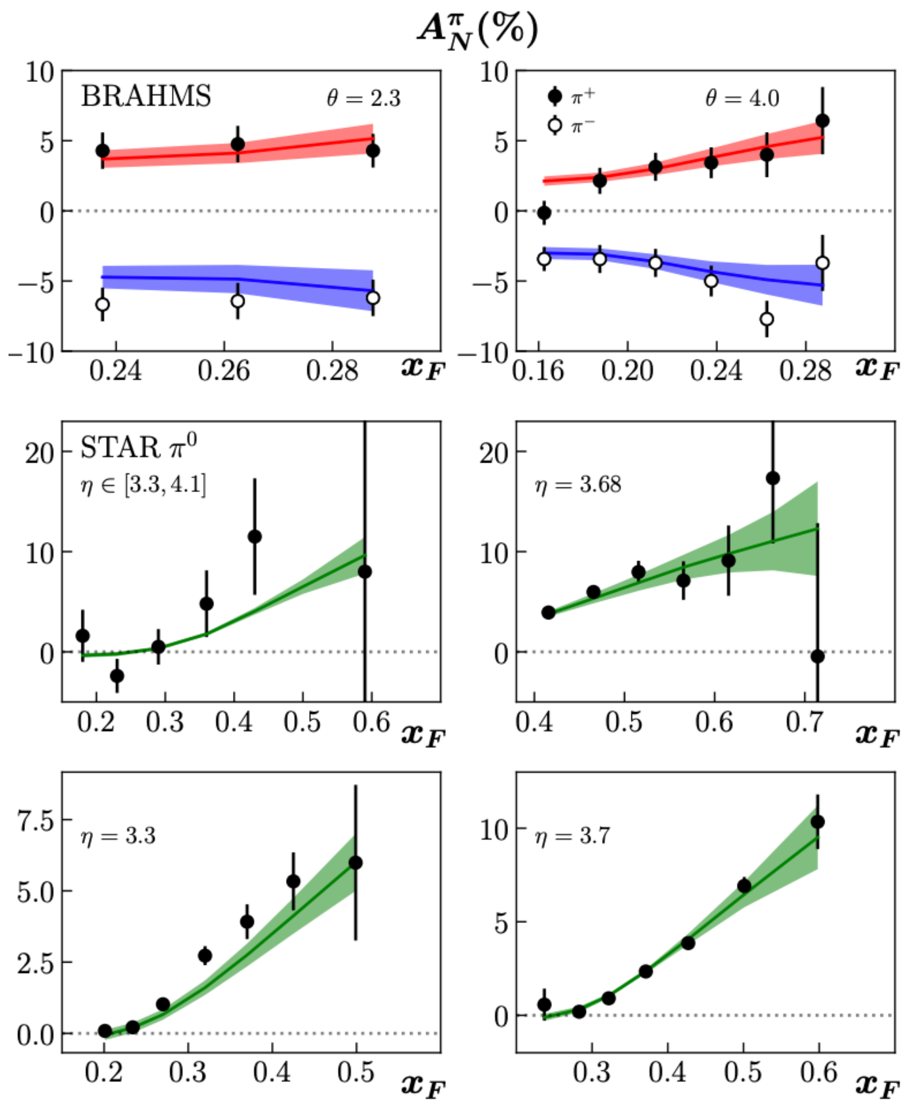
Phys. Rev. D 103, 052009



Twist 3: Inclusive pion & eta A_N

PRD 103, 092009 (2021)

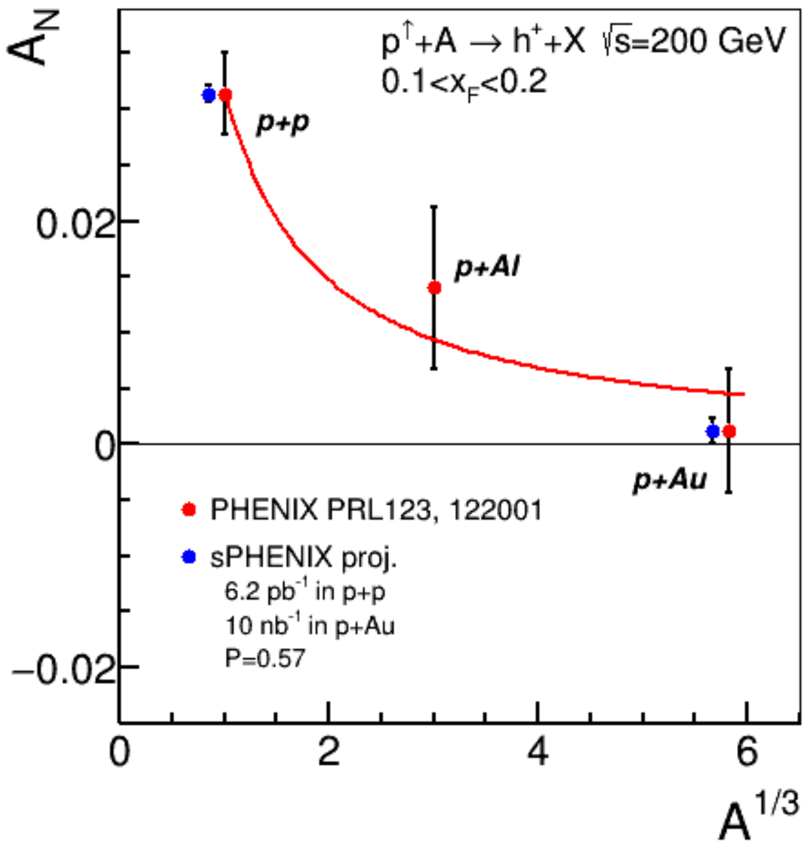


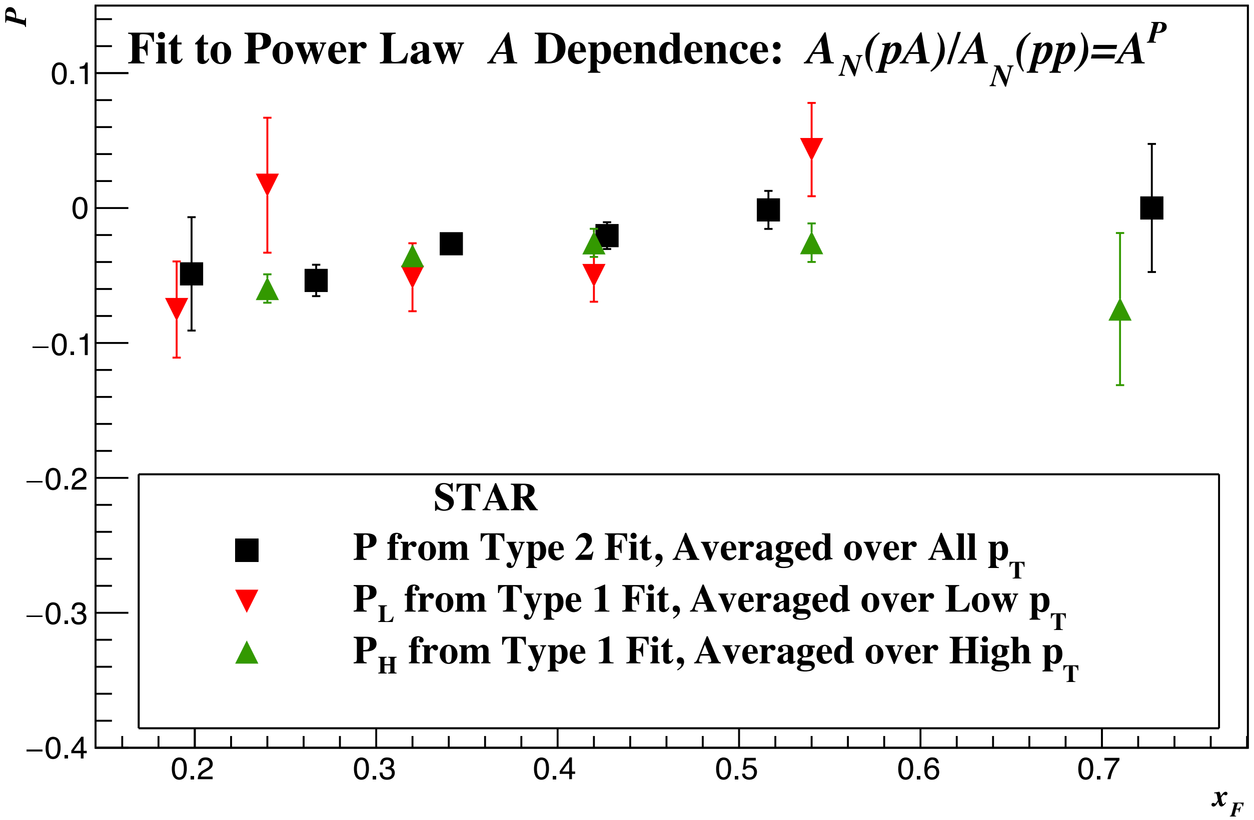


Phys. Rev. D 106 (2022) 3

Nuclear Dependence of TSSAs

PRD 103, 072005 (2021)





Conclusions

- There is a lot of data from hadron colliders that significantly impact TMD and related twist-3 functions.

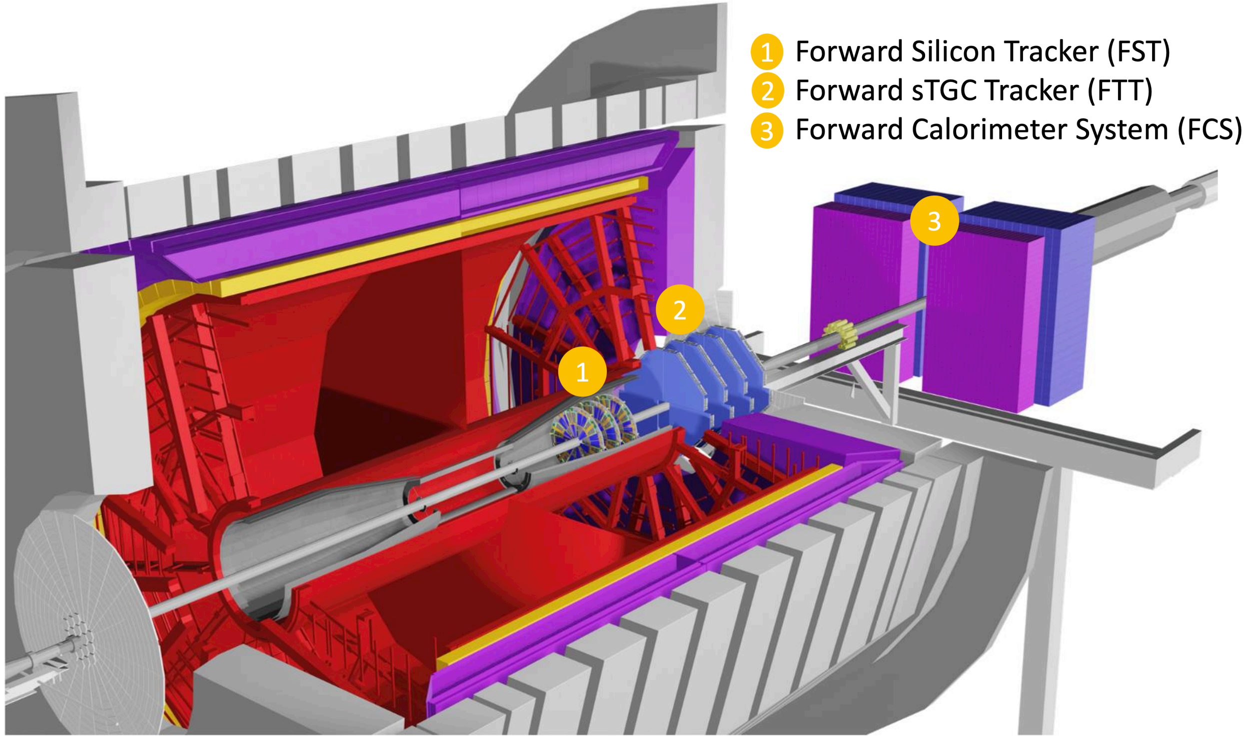
- There is even more theoretical work devoted to developing the frameworks needed to interpret this data!

- Hadron colliders provide some unique inputs for the study of TMDs
  - Direct access to gluons
  - Wide kinematic reach in x and Q^2 – important for studying evolution effects
  - Comparisons with TMDs from e+p and e+e- provide mportant tests of factorization and universality

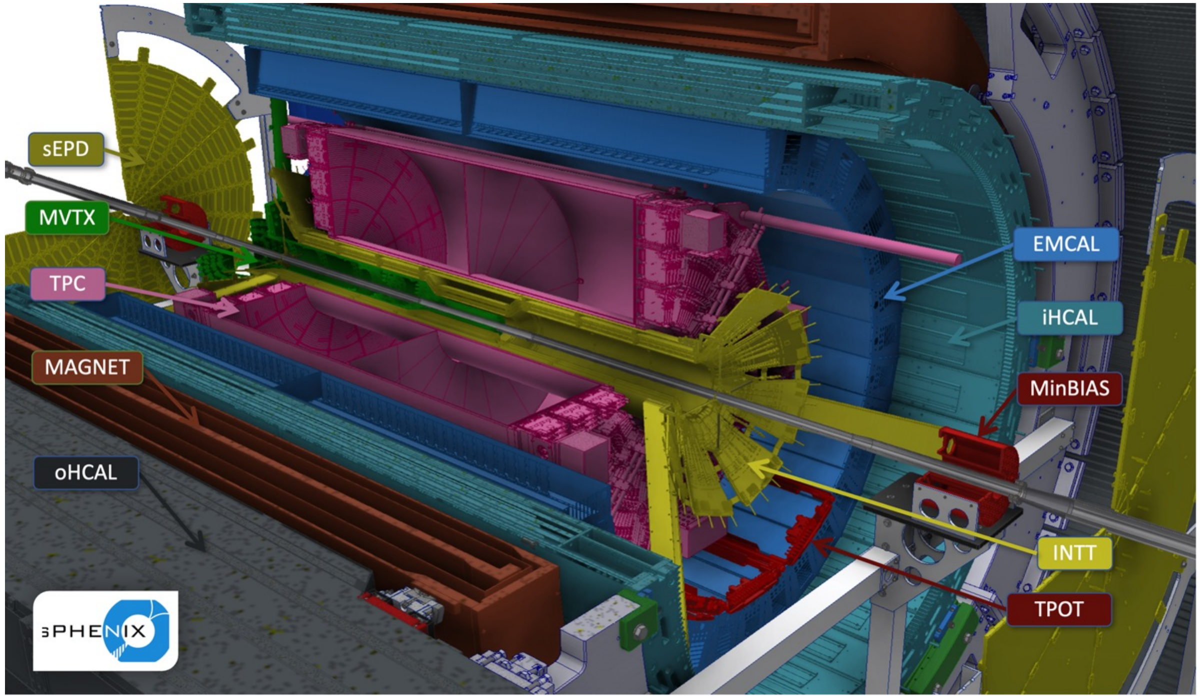
- As RHIC prepares to turn off we need to collect and analyze as much TMD related pp, pA data as possible. Where possible we need to expand the current TMD programs at the LHC.

Backup

RHIC Upgrades & New Detectors

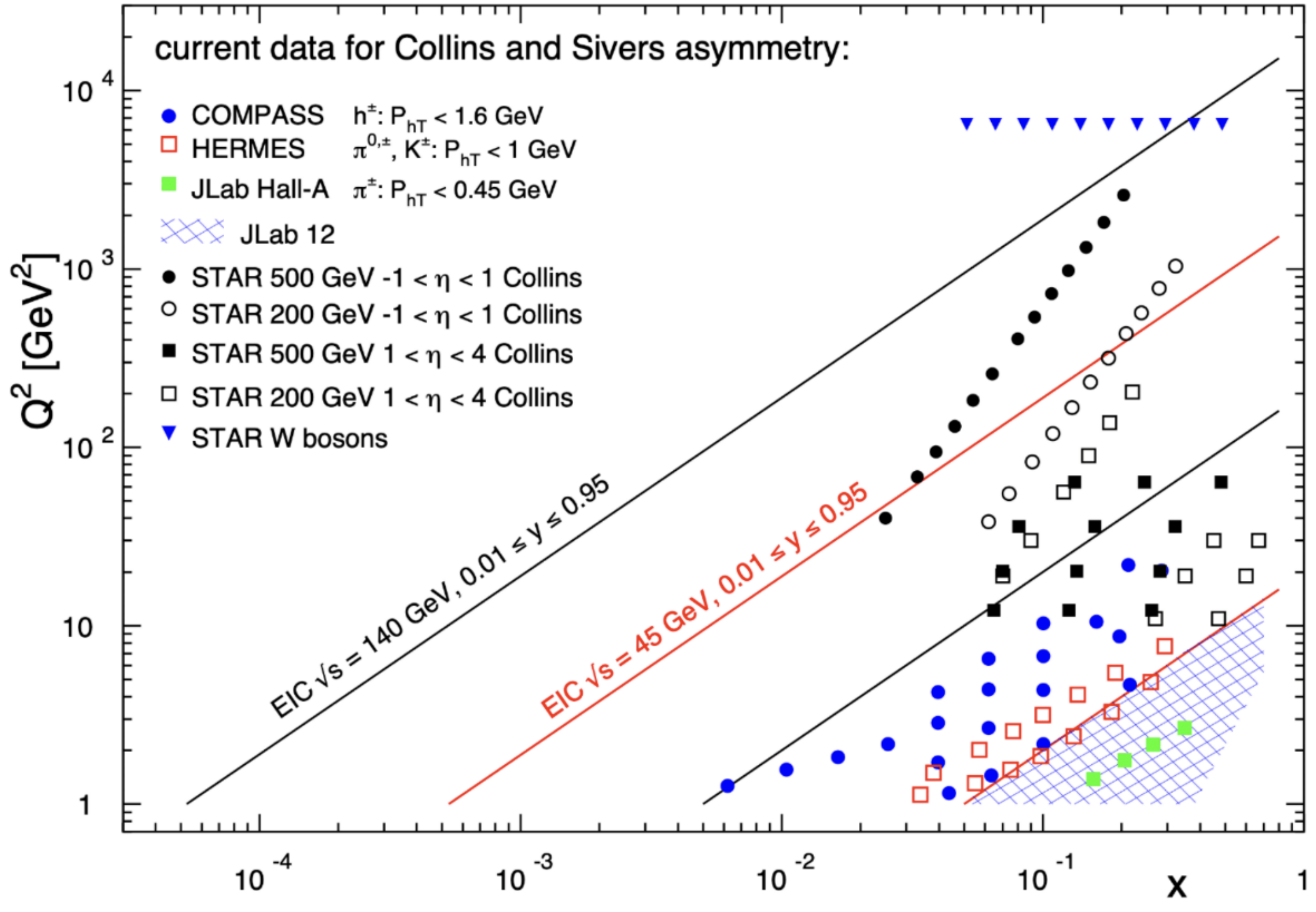


STAR Forward Upgrade



sPHENIX

Collins and Sivers Kinematic Coverage



Collins in Forward E+M jet