May 25, 2021

Center for Frontiers in Nuclear Science

RHIC Spin Capabilities in connection to the EIC

Renee Fatemi
University of Kentucky

EIC ➠ Nucleon Tomography

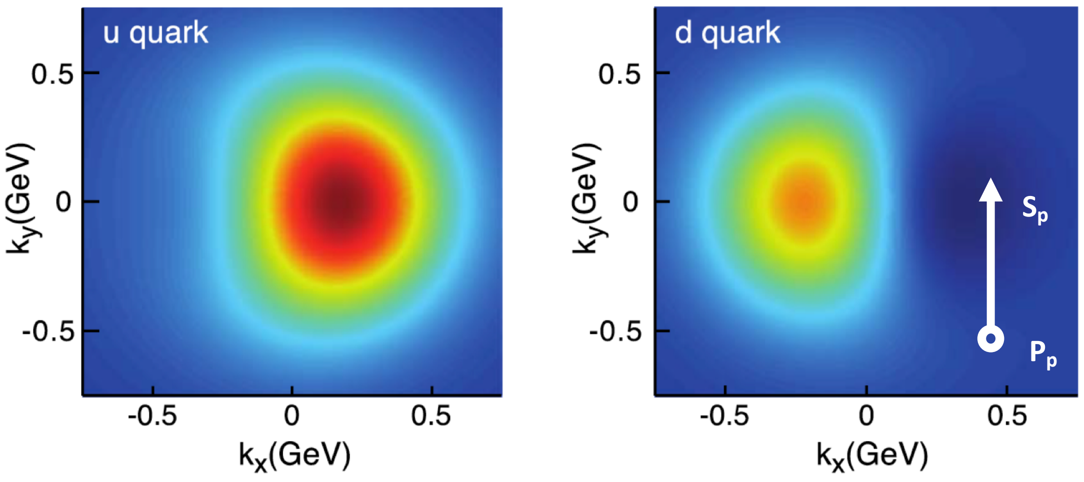
“Imaging by sections or sectioning through the use of any kind of penetrating wave ”

Nucleon Tomography

"Imaging by sections or sectioning through the use of any kind of penetrating wave "

MOMENTUM SPACE

TRANSVERSE MOMENTUM DEPENDENT (**TMD**)
PARTON DISTRIBUTION FUNCTIONS



EIC White Paper arXiv:1212.1701

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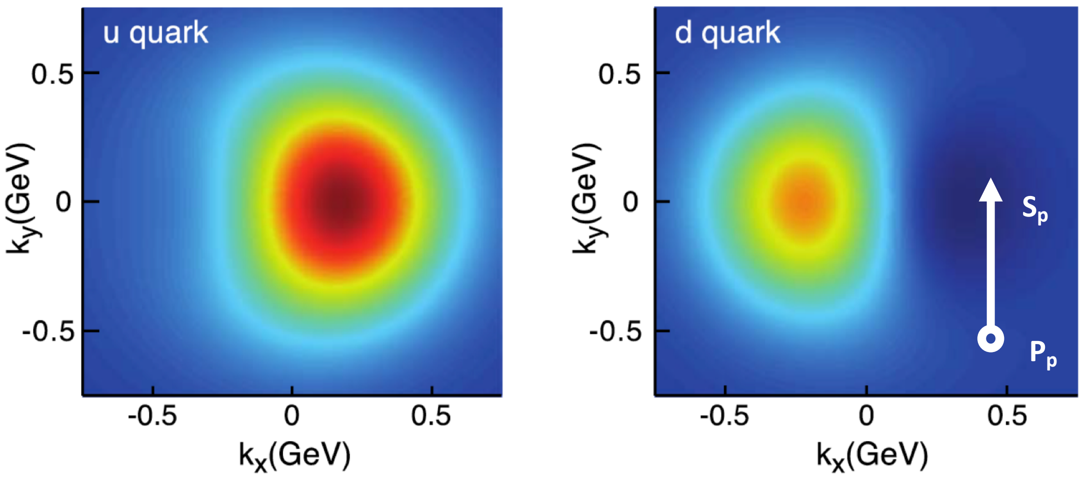
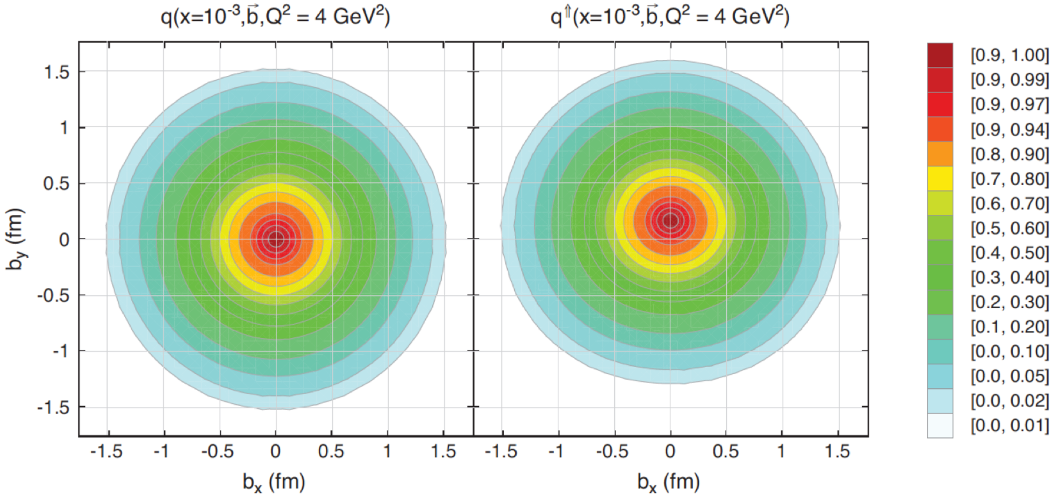


EIC White Paper arXiv:1212.1701

COORDINATE SPACE

GENERALIZED PARTON DISTRIBUTION
FUNCTIONS (**GPD**)



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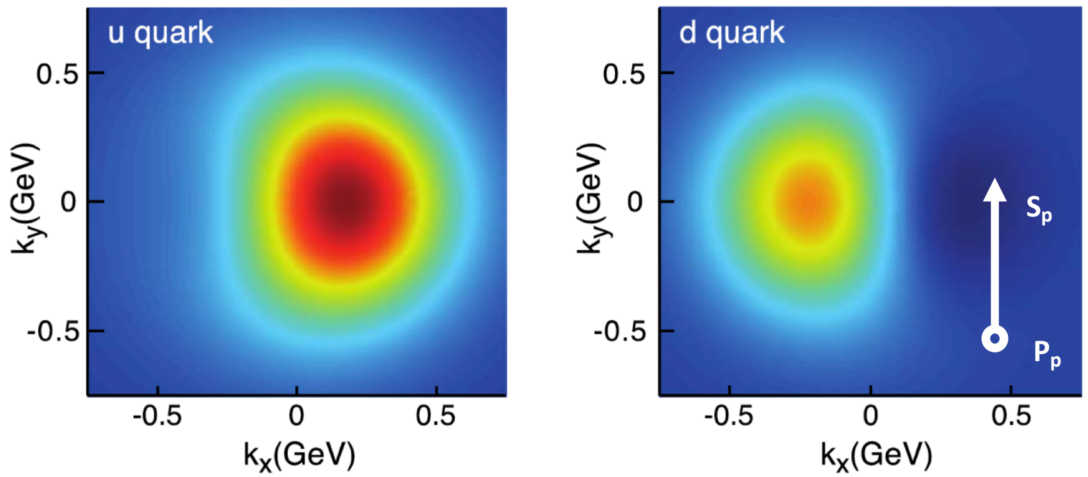

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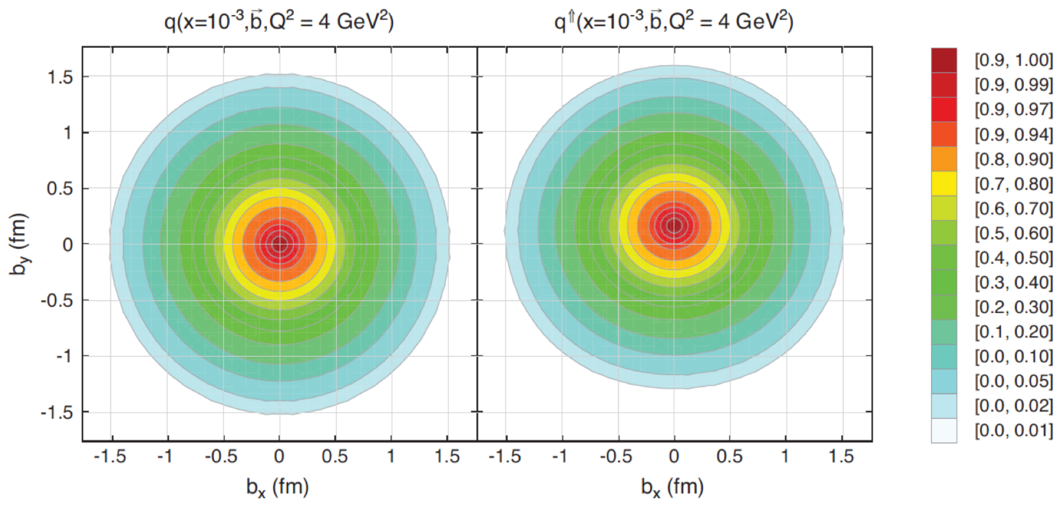
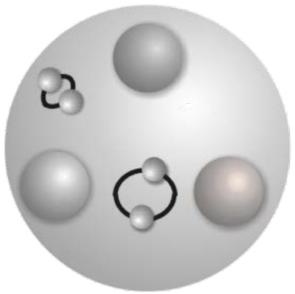


$$\int f(x, k_T, Q^2)\, d^2k_T \quad \Rightarrow \quad \boldsymbol{f(x, Q^2)} \quad \Leftarrow \quad \int f(x, b_T, Q^2)\, d^2b_T$$

Which probe?

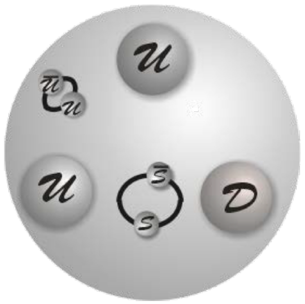
"Imaging by sections or sectioning through the use of any kind of penetrating wave "

ELECTROMAGNETIC
Sensitive to charge^2



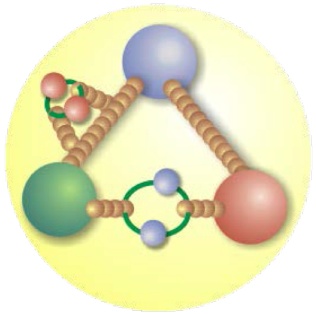
+

WEAK
Sensitive to flavor



+

STRONG
Sensitive to color



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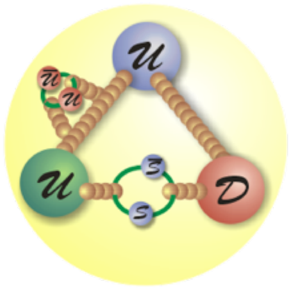
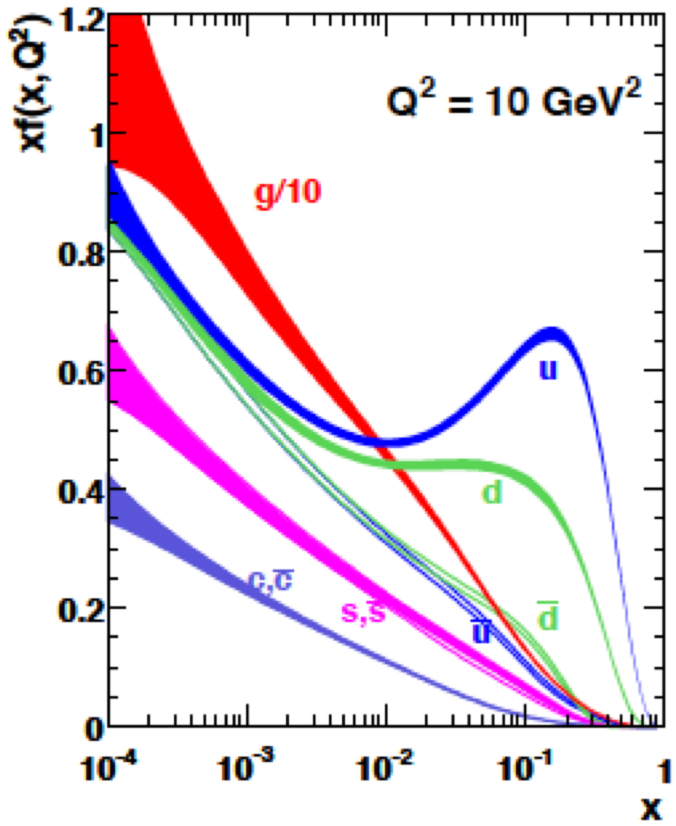
THE BIG PICTURE



Full suite of probes is necessary to rigorously test theoretical frameworks used to extract distributions from experimental results. Precision tests of **Universality, Factorization** and **Evolution** are essential.

Classic Example : $f(x, Q^2)$



A.D. Martin *et al.*, Eur.Phys.J. C63 (2009)

Process	Subprocess	Partons	x range
$\ell^\pm\,\{p,n\} \to \ell^\pm\,X$	$\gamma^* q \to q$	$q, \bar{q}, g$	$x \gtrsim 0.01$
$\ell^\pm\,n/p \to \ell^\pm\,X$	$\gamma^*\,d/u \to d/u$	d/u	$x \gtrsim 0.01$
$pp \to \mu^+\mu^-\,X$	$u\bar{u}, d\bar{d} \to \gamma^*$	$\bar{q}$	$0.015 \lesssim x \lesssim 0.35$
$pn/pp \to \mu^+\mu^-\,X$	$(u\bar{d})/(u\bar{u}) \to \gamma^*$	$\bar{d}/\bar{u}$	$0.015 \lesssim x \lesssim 0.35$
$\nu(\bar{\nu})\,N \to \mu^-(\mu^+)\,X$	$W^* q \to q'$	$q, \bar{q}$	$0.01 \lesssim x \lesssim 0.5$
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$e^+\,p \to \bar{\nu}\,X$	$W^+\,\{d,s\} \to \{u,c\}$	d, s	$x \gtrsim 0.01$
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$p\bar{p} \to (W^\pm \to \ell^\pm\nu)\,X$	$ud \to W, \bar{u}\bar{d} \to W$	$u, d, \bar{u}, \bar{d}$	$x \gtrsim 0.05$
$p\bar{p} \to (Z \to \ell^+\ell^-)\,X$	$uu, dd \to Z$	d	$x \gtrsim 0.05$

Classic Example : $f(x, Q^2)$

FULL SUITE OF PROBES

- **Electromagnetic**
- **Weak**
- **Strong**

Global analysis allows for test of UNIVERSALITY and FACTORIZATION by looking at consistency and tensions between datasets.

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KINEMATIC RANGE

- **FIXED TARGET – e, μ, ν, p, n + N**
- HERA – e+p collider
- TEVATRON – p+pbar collider

Need fixed target and collider to isolate quark and gluon in different kinematic regions.

Fixed target Q^2 is typically lower than and collider Q^2.

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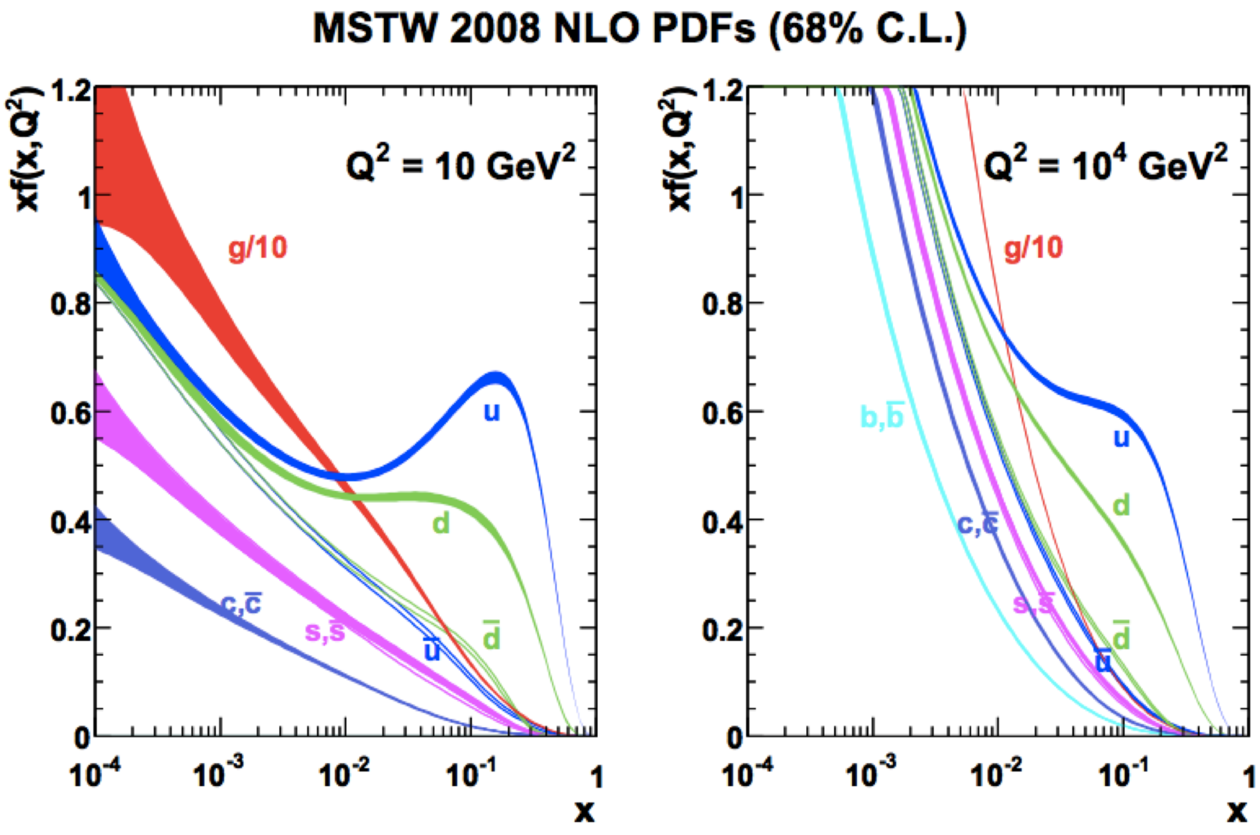
Classic Example : $f(x, Q^2)$

EVOLUTION

- For collinear functions DGLAP gives prescription on how to evolve Q^2 for a fixed x.
- Essential for global analyses – allows for combination of disparate data sets and predictions at different scales
- Unlike collinear evolution, TMD evolution contains non-perturbative pieces. MUST BE MEASURED!

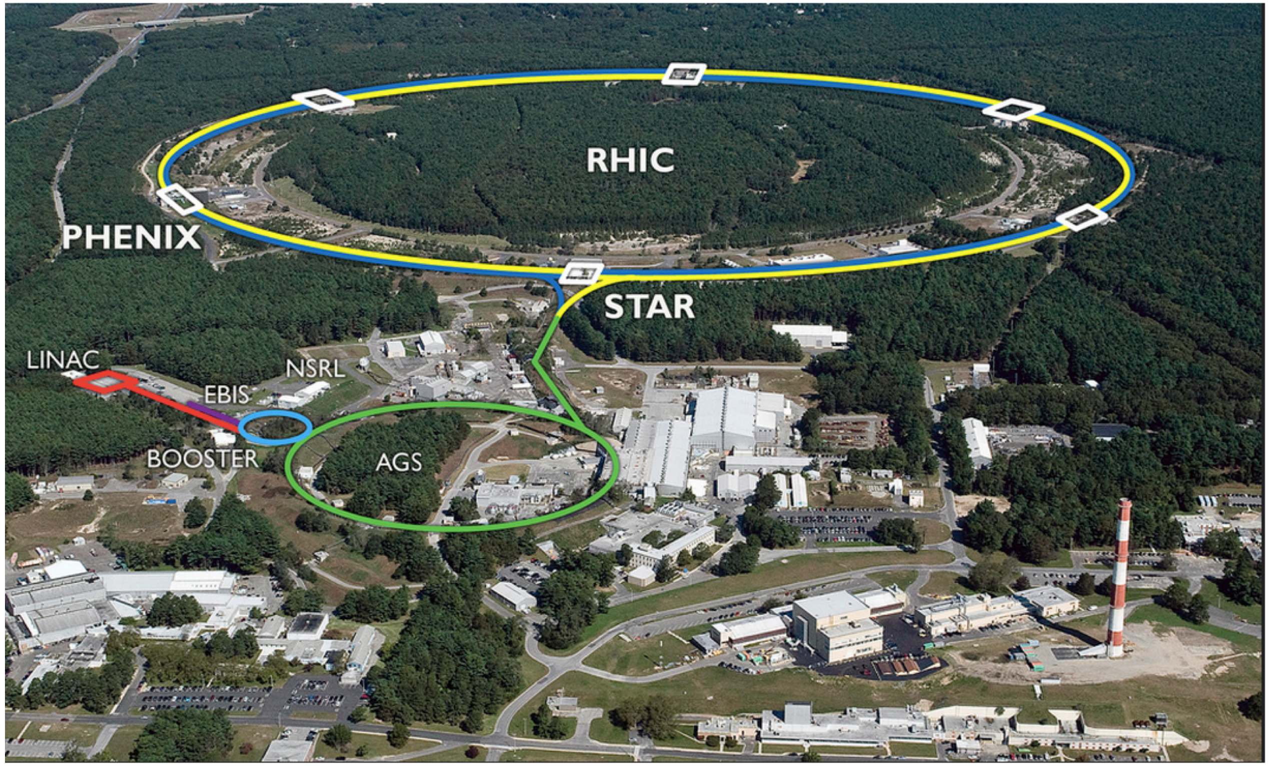


A.D. Martin *et al.,* Eur.Phys.J. C63 (2009)

How can RHIC Contribute in 2022+?

STAR BUR REQUEST

√s species	Polarization	Lumi
510 p+p	transverse	400 pb^{-1}
200 p+p	transverse/radial	235 pb^{-1}
200 p+Au	transverse/radial	1.3 pb^{-1}



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TMD W^+ / W^- / Z^0 and Drell-Yan A_N

TWIST-3 Inclusive Jet and Direct Photon A_N

TMD Dijet Sivers

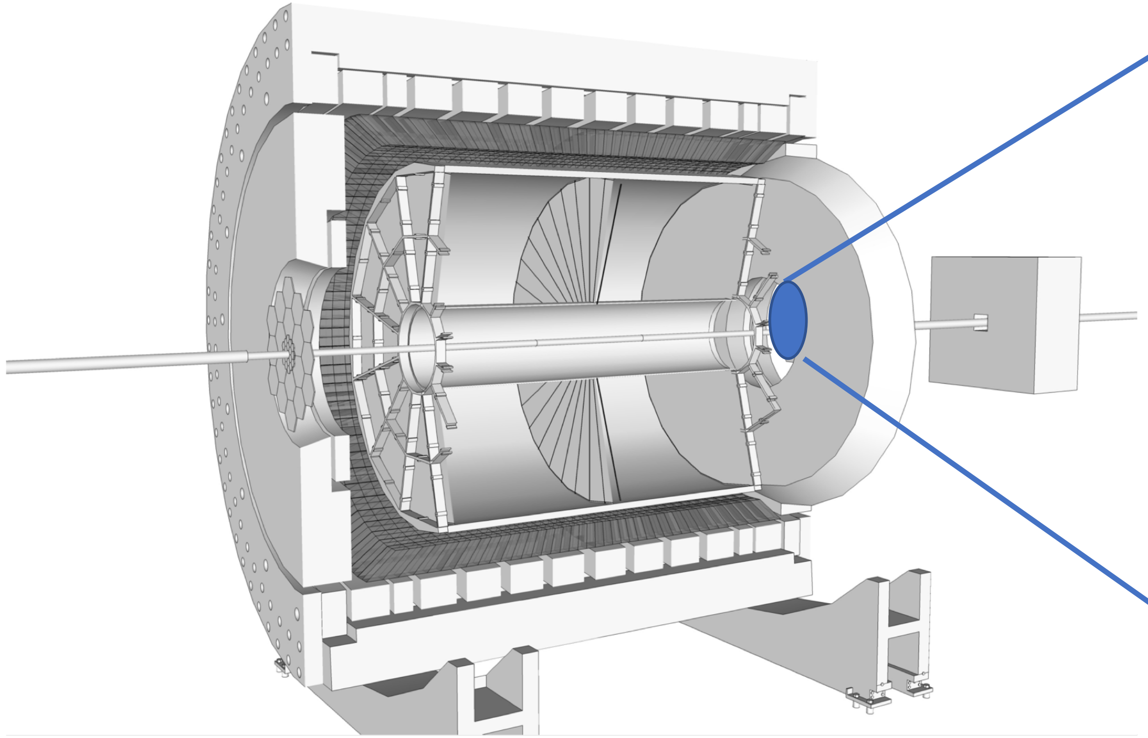
TMD Z Differential cross-section

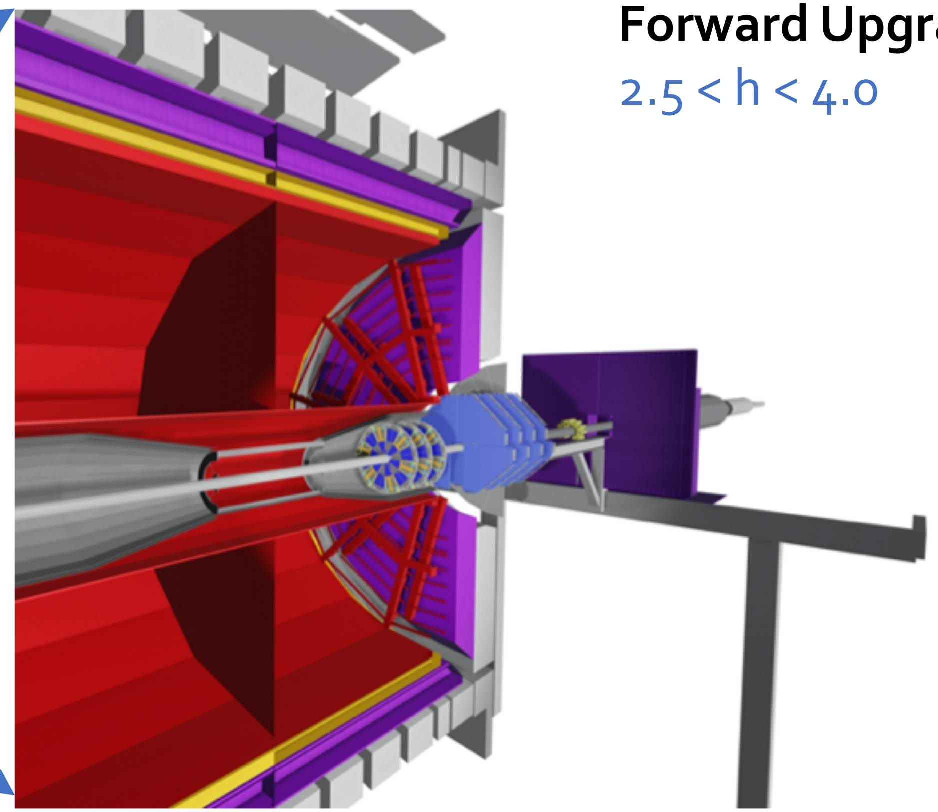
TMD π/K/p in jets A^{UT} and spin integrated FF

GPD E_g from J/ψ in UPC

**Relevant collinear PDF topics I won't have time to cover are IFF, Lambda D_{TT}, Lambda D_{LL}, Inclusive jet cross-section and W+/W- cross-section ratio.*

STAR Detector





Forward Upgrade:

2.5 < h < 4.0

TIME PROJECTION CHAMBER	CHARGED PARTICLE TRACKING
TPC + TOF	CHARGED PARTICLE IDENTIFICATION
EM CALORIMETER **5520 (PbSc) towers**	EM PARTICLE DETECTION HIGH PT TRIGGERING
BEAM BEAM COUNTERS ZERO DEGREE COUNTERS VERTEX POSITION DETECTORS	RELATIVE LUMINOSITY MINIMUM BIAS TRIGGERING

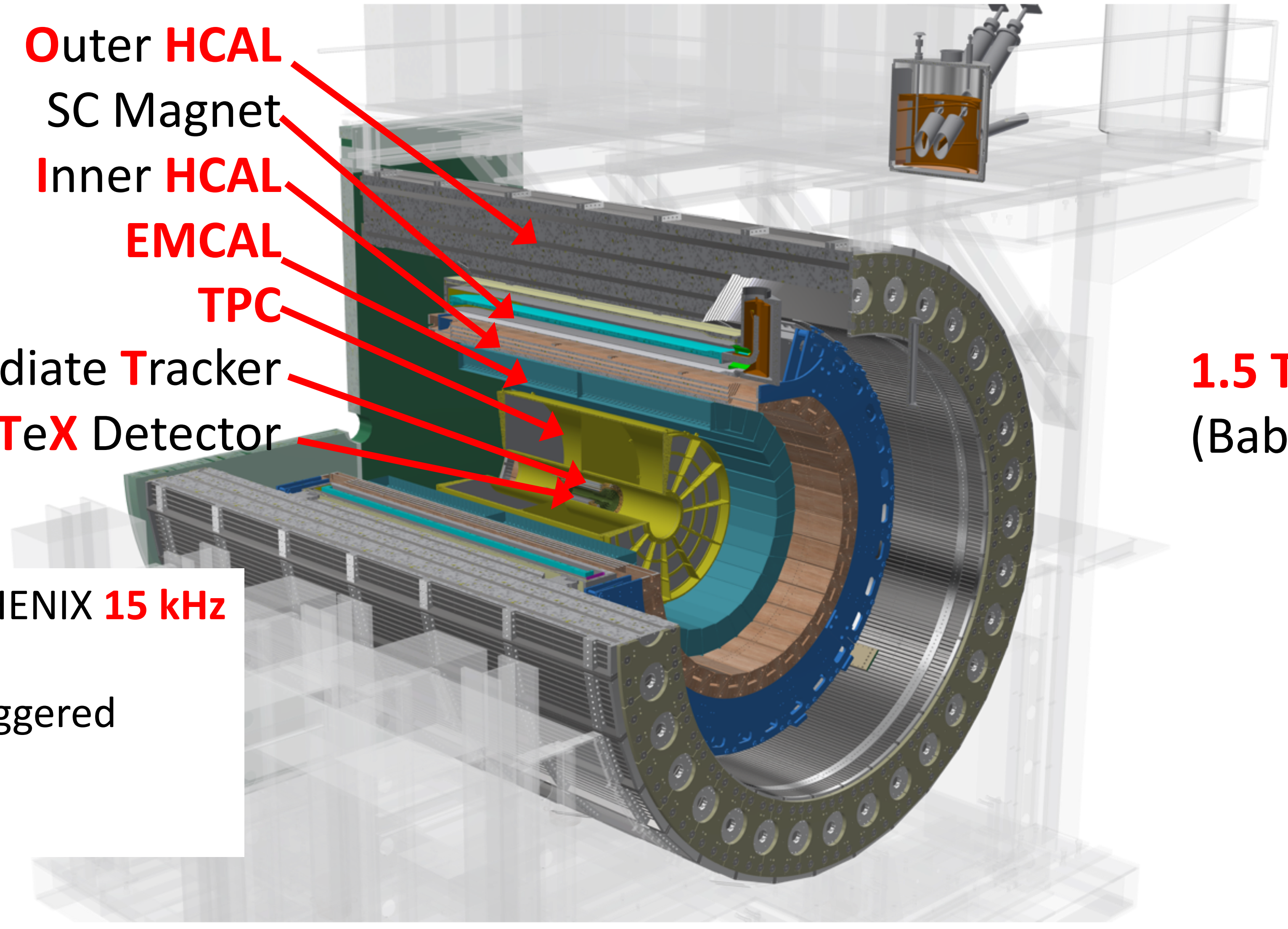
Forward Tracking System (FTS)

- Silicon microstrip sensors
- Small-Strip Thin Gap Chambers (sTGC)
- Momentum Resolution **< 30%**
- Tracking **Efficiency > 80%** @ 100 tracks / evt

Forward Calorimetry System (FCS)

- Hadronic Calorimeter **~50%/$\sqrt{E}$+10%**
- Electromagnetic Calorimeter **~10%/$\sqrt{E}$ p+p**

sPHENIX → covered by John Lajoie



1.5 Tesla B field
(Babar Magnet)

All can be read out at the sPHENIX **15 kHz trigger rate**

- DAQ hybrid streaming/triggered
- TPC/MVTX streaming
- Calorimeters triggered

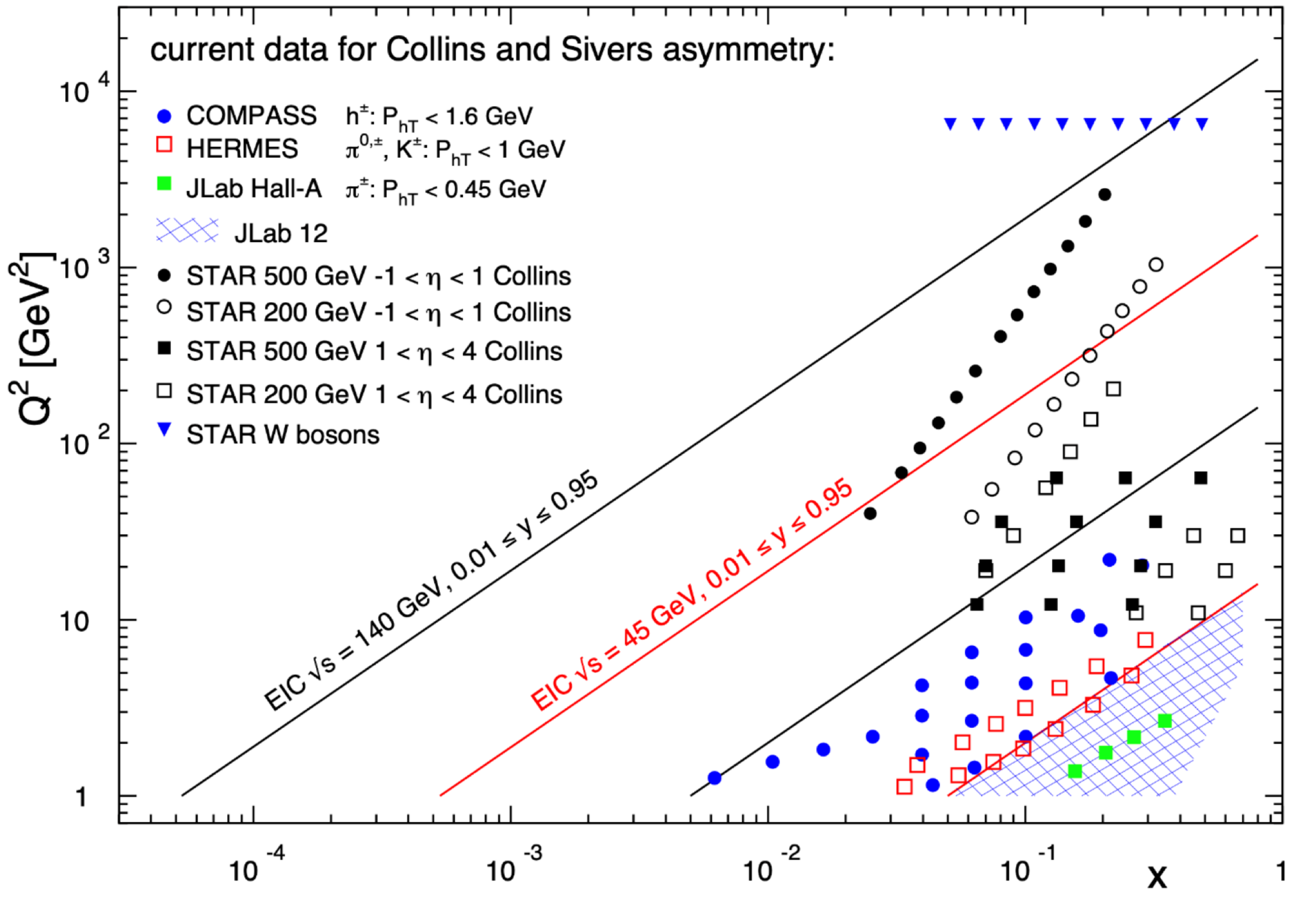
How can RHIC Contribute in 2022+?

1) Covers the same x region as existing fixed target data but at higher Q^2 - no worries about higher twist effects.

2) Higher Q^2 provides important information about TMD evolution.

3) Kinematic overlap with EIC is substantial enough to allow for statistically meaningful test of universality.

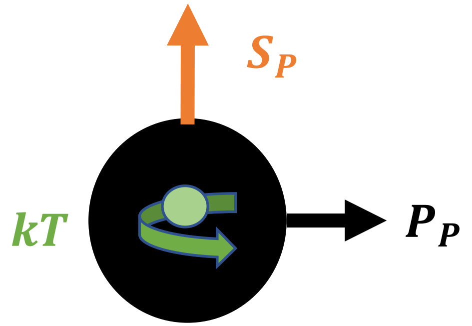
4) Provides direct access to gluon PDFs and FF!



Initial State TMD & Twist-3 Functions

Universality
Factorization
Evolution

TMD : Sivers Function

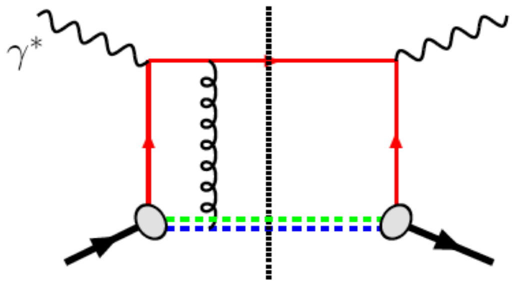


PDF that encapsulates correlations between the proton spin S_P and partonic transverse momentum k_T. Sensitive to partonic orbital angular momentum.

Due to different color interactions Sivers function is predicted to change sign in Drell-Yan compared to SIDIS interactions

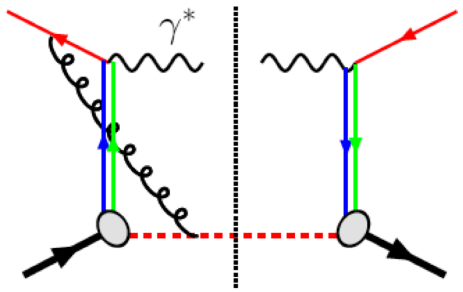
Lepton-proton

Attractive final state interaction



Drell-Yan

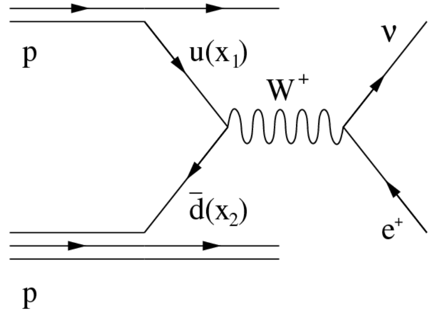
Repulsive initial state interaction



Measurement of the sign change provides a critical test of factorization and ensures we understand how to combine DY and SIDIS results in a global analysis.

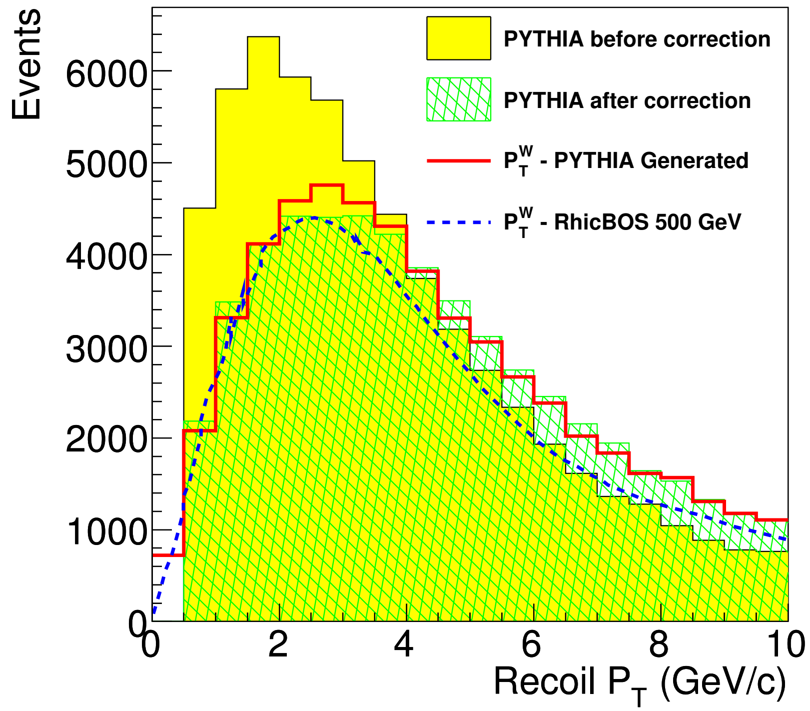
Cleanest way to test for sign change in TMD Sivers is via $W^{+/-}$ & Z^0 A_N and Drell-Yan.

TMD : $W^{+/-}$ & Z^0 A_N



Single Spin Asymmetry of W/Z production in transversely polarized p+p :

- Maximal signal in full reconstruction of W/Z
- Hard scale set by $M_{W/Z}$
- Soft scale set by $P_T^{W/Z}$



- Reconstruction relies on measurement of the hadronic recoil:

$$\vec{P}_T^W = \vec{P}_T^e + \vec{P}_T^\nu = -\vec{P}_T^{recoil}$$

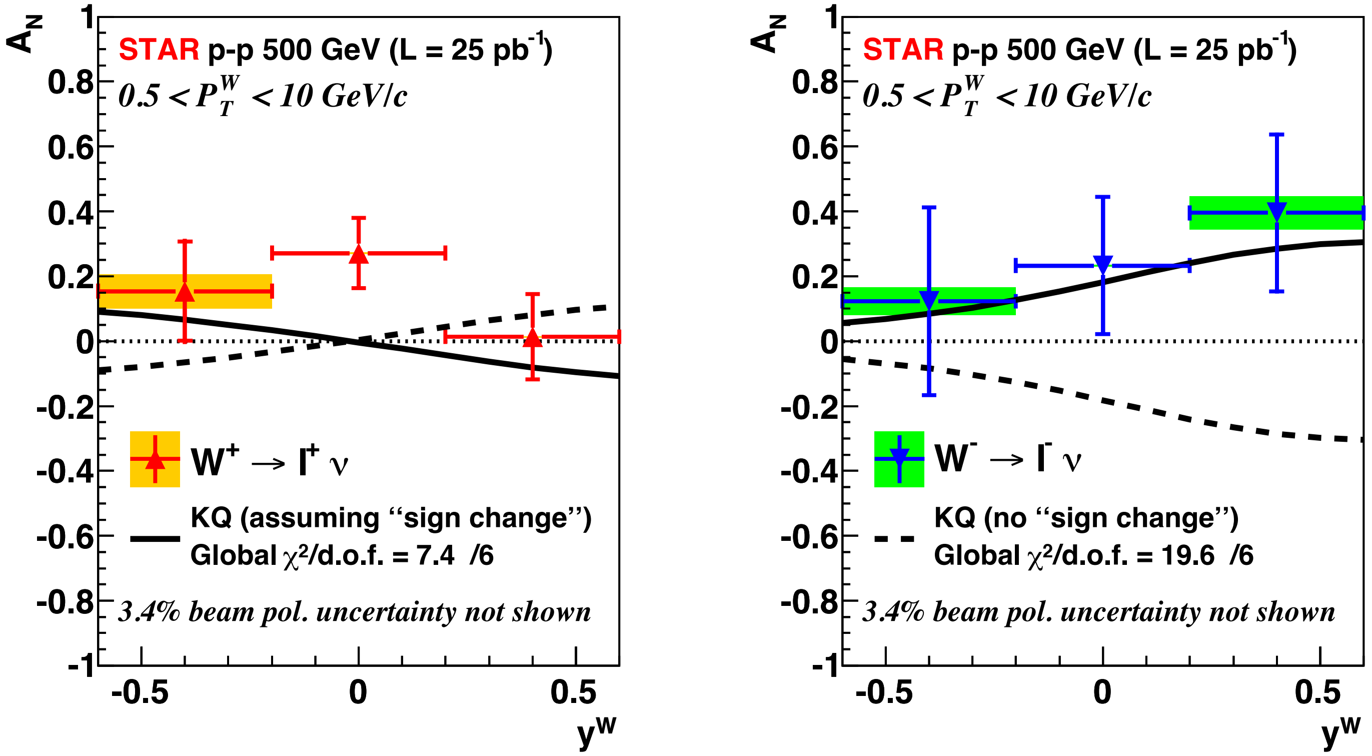
- P_T^{recoil} = sum over towers and tracks excluding $e^{+/-}$
- PYTHIA embedded into data used to correct for efficiency and fiducial losses.
- Method used at LHC and Fermilab and now at STAR!

TMD : $W^{+/-}$ A_N from 25 pb^{-1} in 2011

Theoretical curves include no evolution effects. Z.-B. Kang and J. -W. Qiu, Phys. Rev. Lett. 103, 172001.

Data favor Sivers Function sign change assuming no large evolution effects.

TMD evolution has non-perturbative component that must be measured!

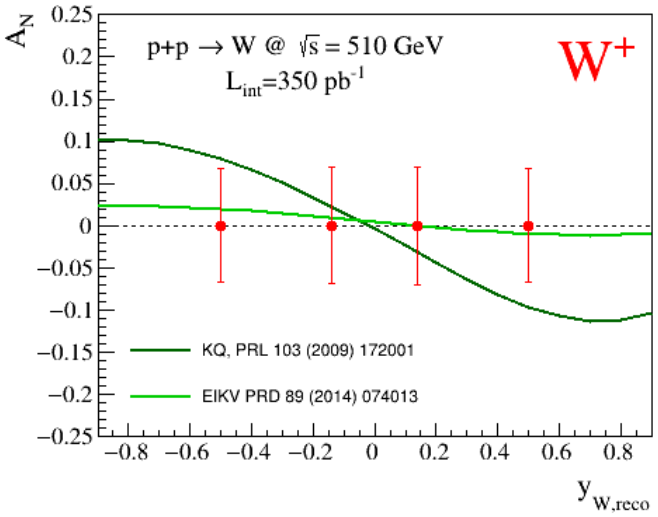


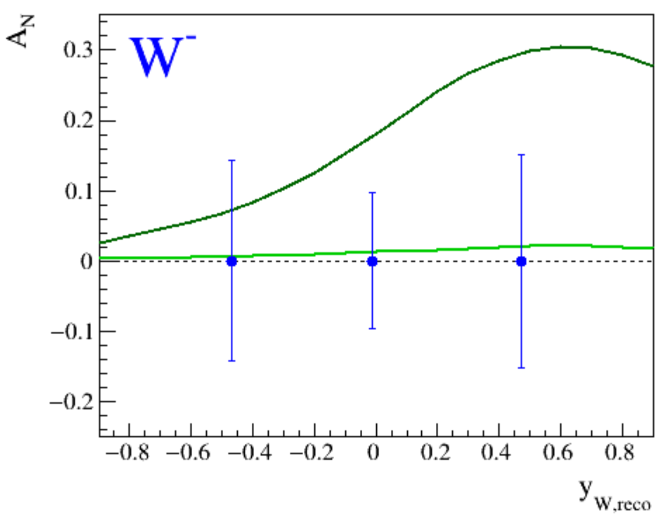
Phys. Rev. Lett. **116** (2016) 132301

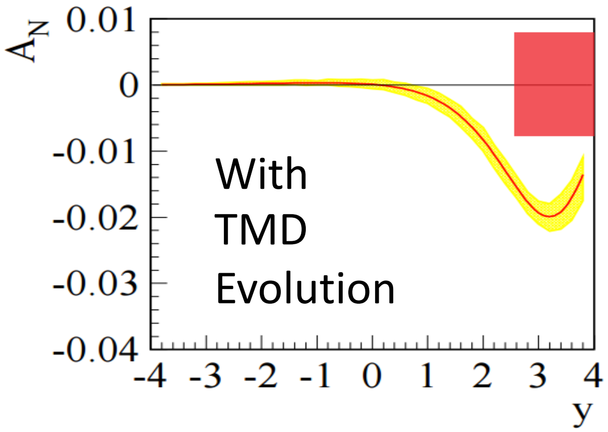
TMD : $W^{+/-}$ A_N from 350 pb^{-1} in 2017 & Beyond

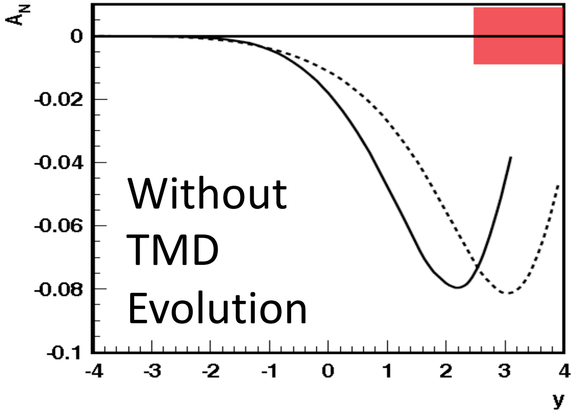
2017 preliminary result will be released for 2021 STAR BUR!

RUN 22 IMPROVEMENTS: iTPC upgrade will expand y_W reconstruction and facilitate a more accurate reconstruction of $\vec{P}_T^{recoil}$









TMD: Drell-Yan A_N in 2017 & Beyond

DY e^+e^- in $2.5 < \eta < 4.0$

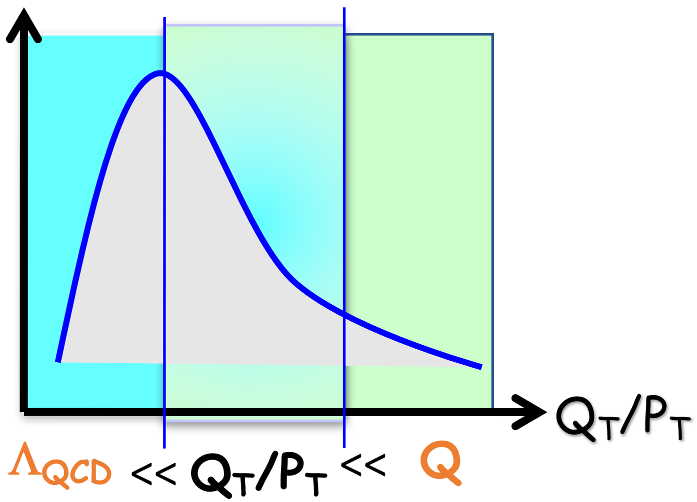
4.0 GeV < M_{e+e-} < 9.0 GeV

The orange square is the statistical uncertainty achievable with 400 pb^{-1} .

TMD

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

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

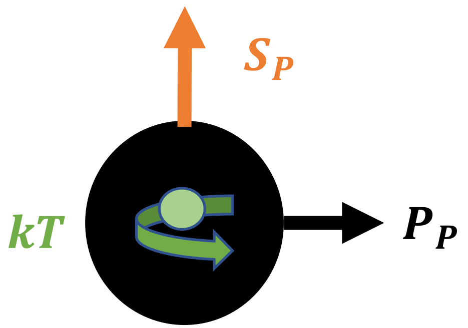


Collinear Twist-3

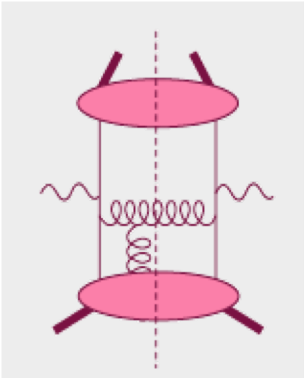
Single hard scale : p_T

Appropriate for inclusive π^0, jet, γ

Sensitive to $\langle k_T \rangle$

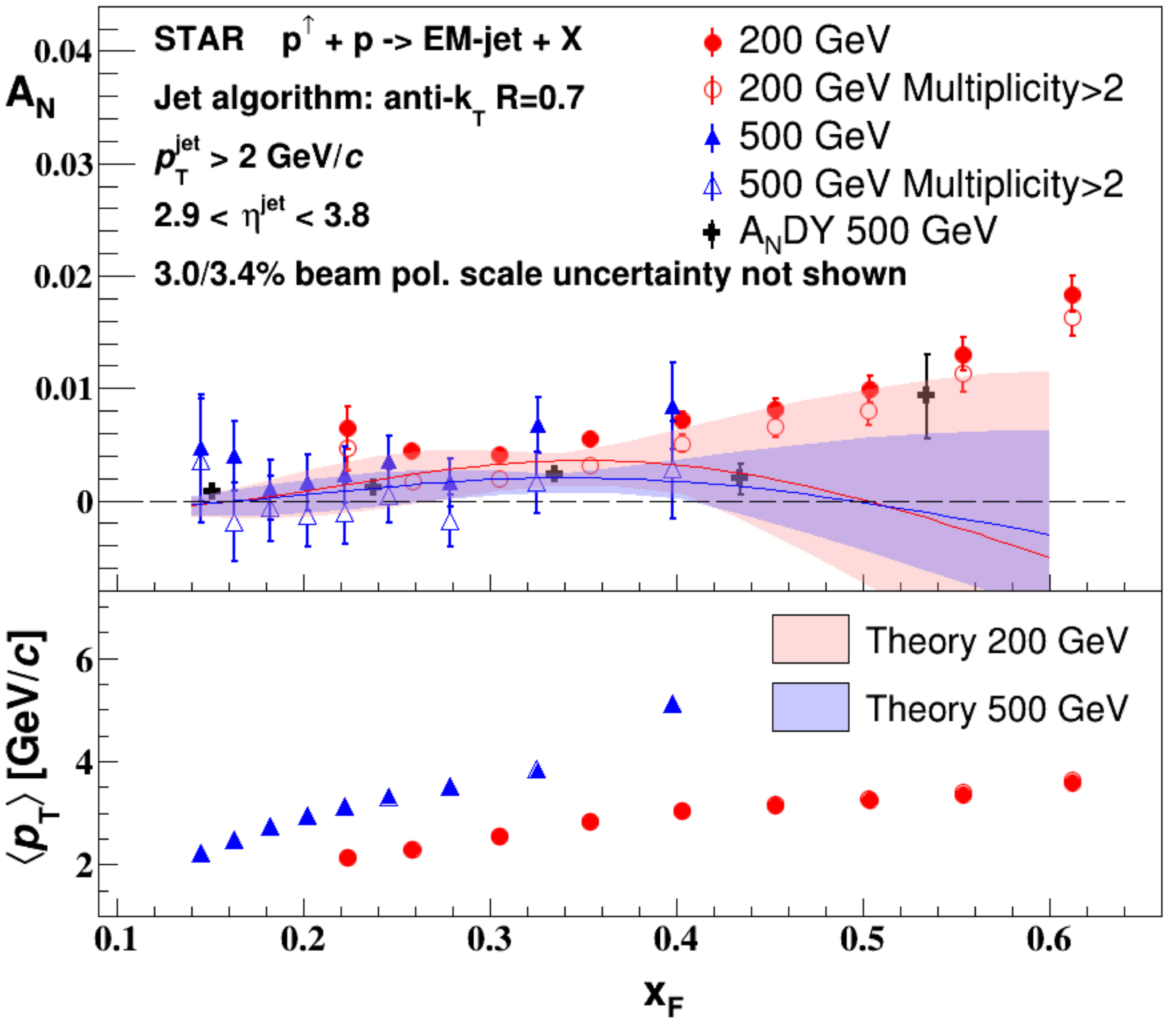


TMDs may be expressed in terms of collinear + twist-3 functions via the Operator product expansion.



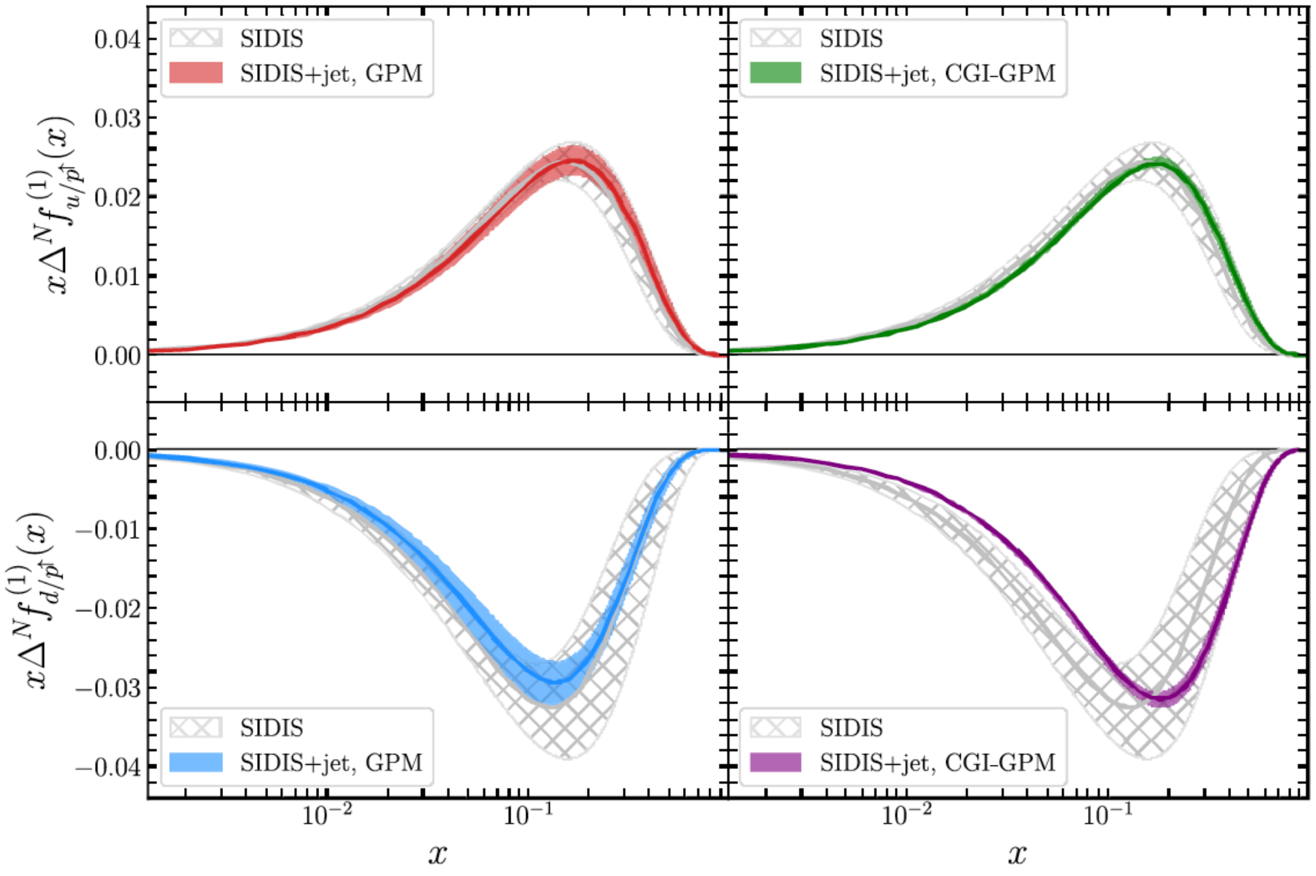
Efremov, Teryaev; Qiu, Sterman

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



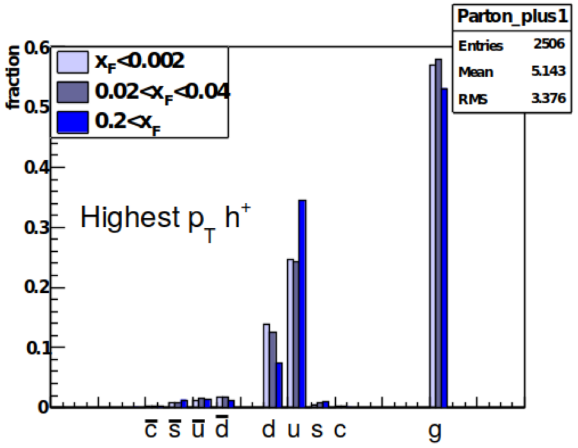
Phys.Lett.B 815 (2021) 136135

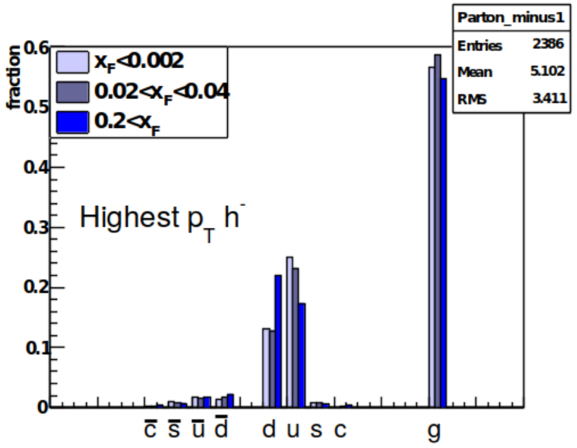
- Impact on Sivers first moment (k_T integrated) is significant – especially for down quark.
- pp data pushes to higher x than existing fixed target SIDIS data
- EIC will measure up to x ~ 0.5 so it is important to have statistically meaningful constraints from pp for tests of universality and evolution.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

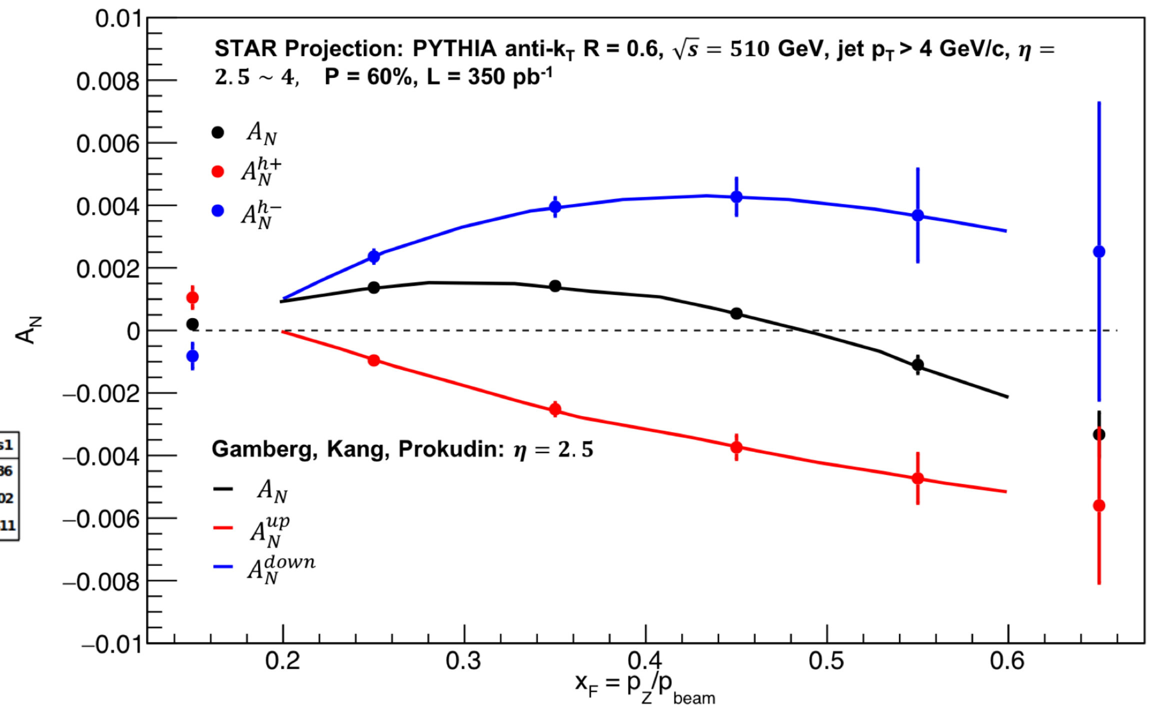
Twist-3: A_{UT} of Forward Jets with high z hadrons

Jet A_{UT} is sensitive to twist-3 "Sivers-like" correlators, which are expected to be opposite sign for u and d quarks.

Tag jets with h+/h- z > 0.5 and enhance u/d



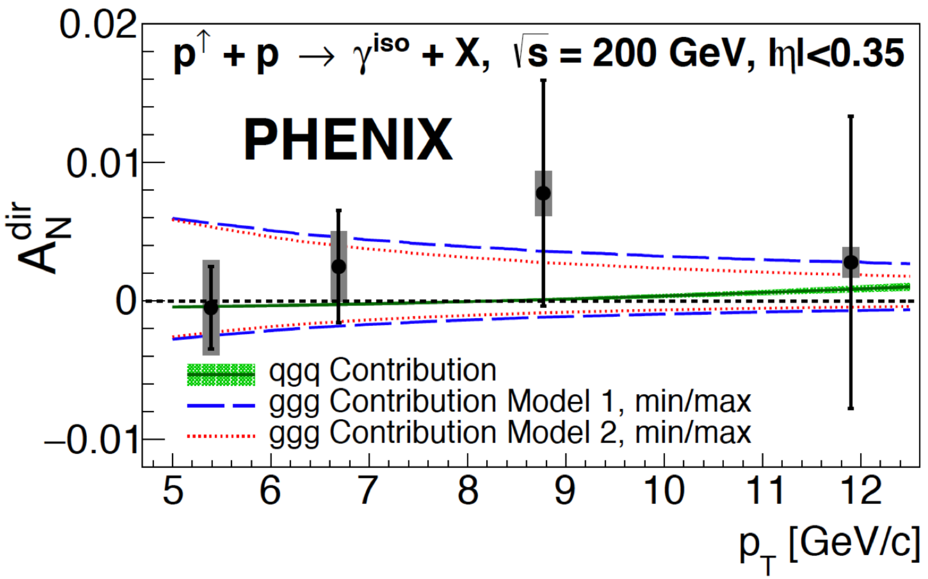




Tests connection between twist-3 and TMDs via ETQS relationship.

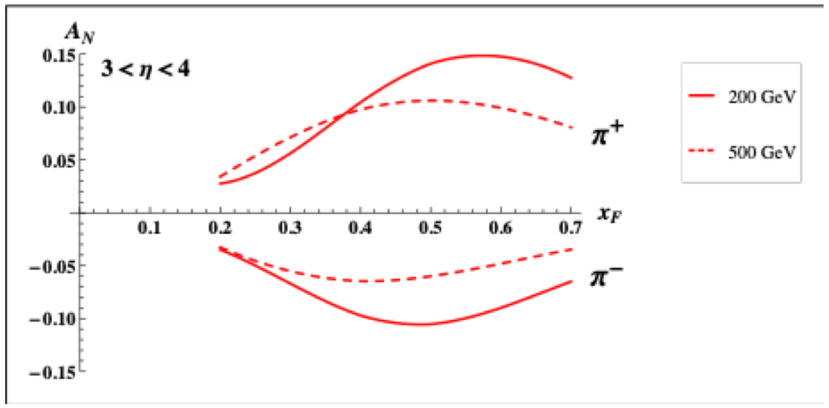
2022+ Full jet reconstruction in forward region. No PID in forward region, but charged sign separation for h+/h- should allow for reconstruction of significant asymmetries.

TWIST-3: Direct photon A_N



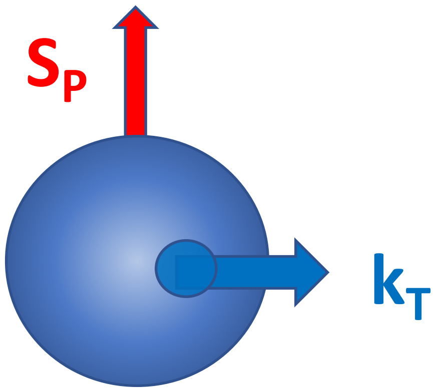
- Dominated by q-g Compton scattering
- Model 1 & 2 by Koike and Yoshida, Phys.Rev.D 85, 034030 (2012) and Pitonyak (qgq). All re-evaluated for mid-rapidity.
- Provide constraints on ggg twist-3 "Sivers" functions at low p_T

2022+ : STAR Forward Upgrade will push A_N measurement of inclusive photons, neutral and charged pions into forward η. Provide worlds best data on evolution of twist-3 ETQS functions and determine role of twist-3 FF in large forward asymmetries.

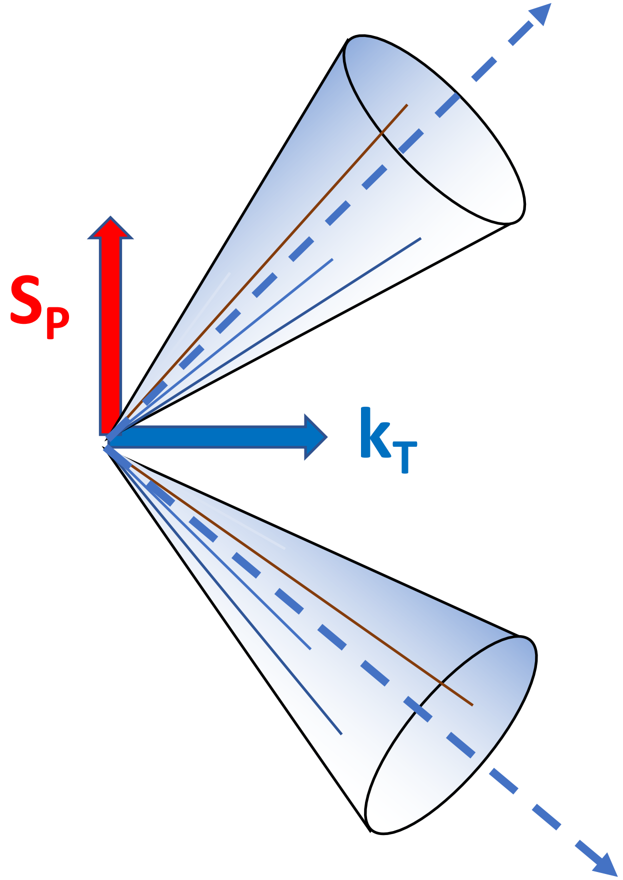


Phys. Rev. D, 89:111501 (2014)

TMD: Sivers Effect in Dijet Production



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



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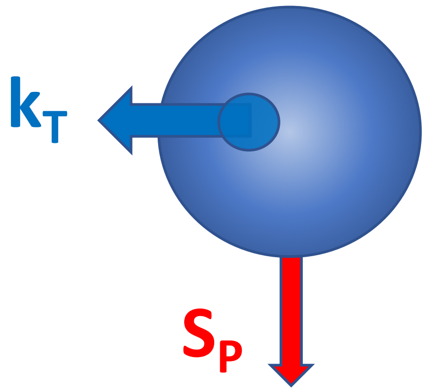
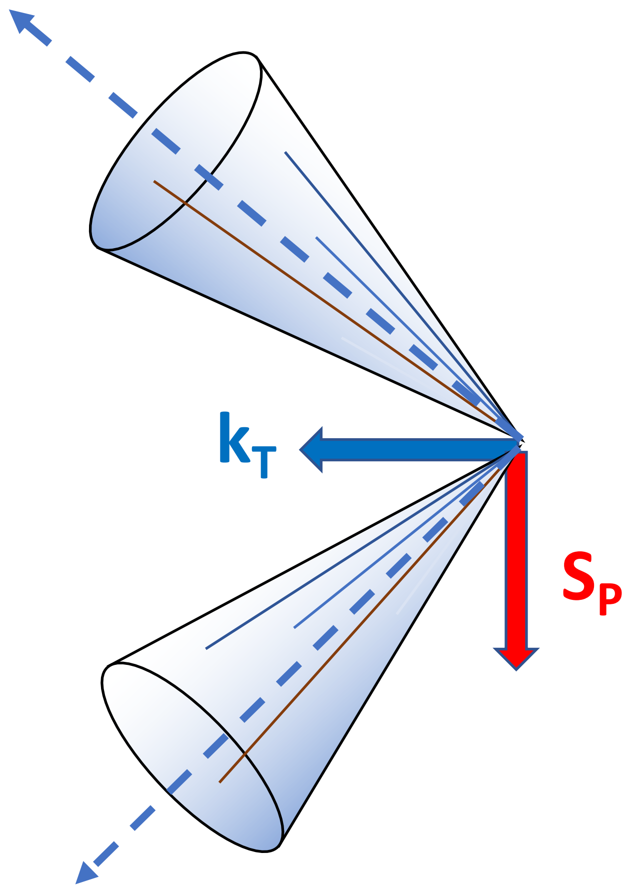


$$\langle \vec{S}_{proton} \cdot (\vec{P}_{proton} \times \vec{k}_T) \rangle$$



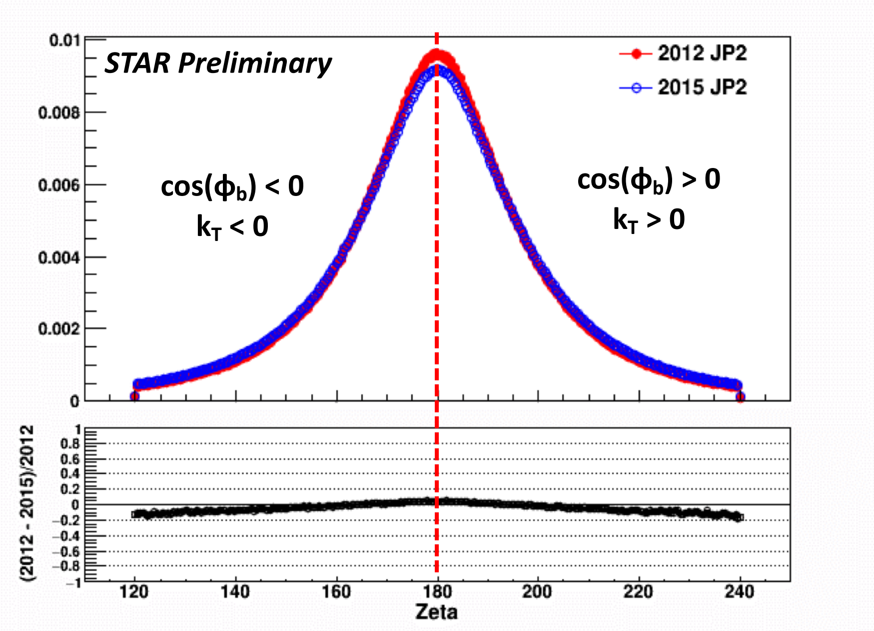
Observable in Dijet Production

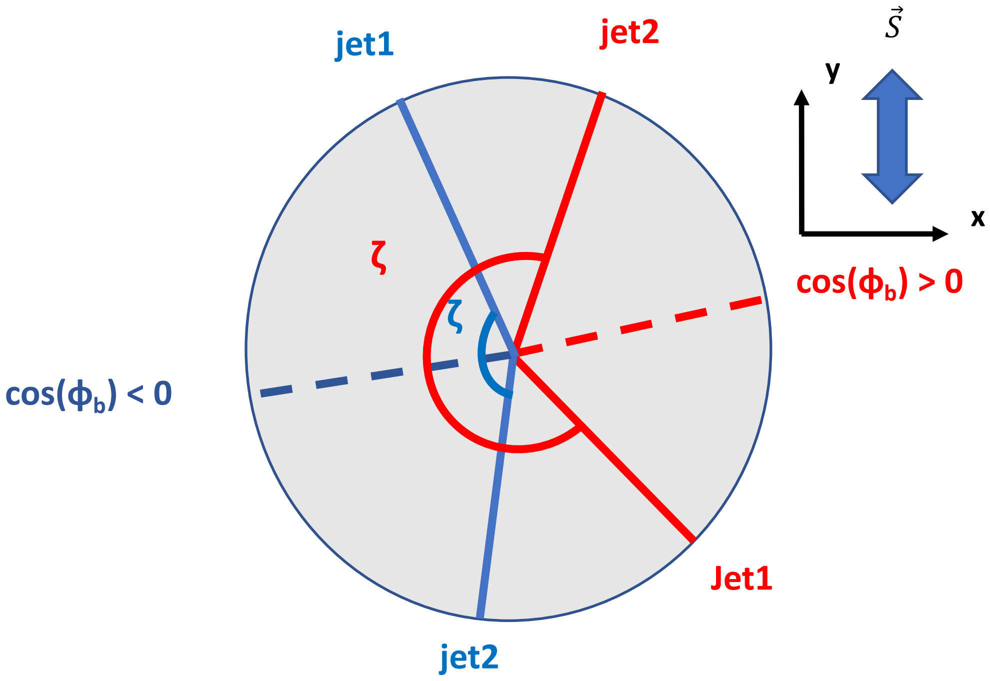
- ϕ_b is di-jet bisector angle
- ζ is the opening angle of dijet in the transverse plane

  $\zeta > \pi$ when $\cos(\phi_b) > 0$ $\zeta < \pi$ when $\cos(\phi_b) < 0$

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

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



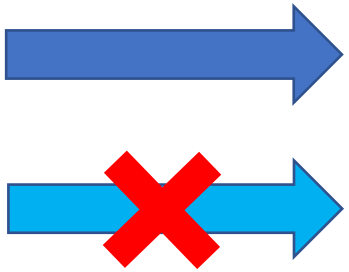


Jet Flavor "Tagging"

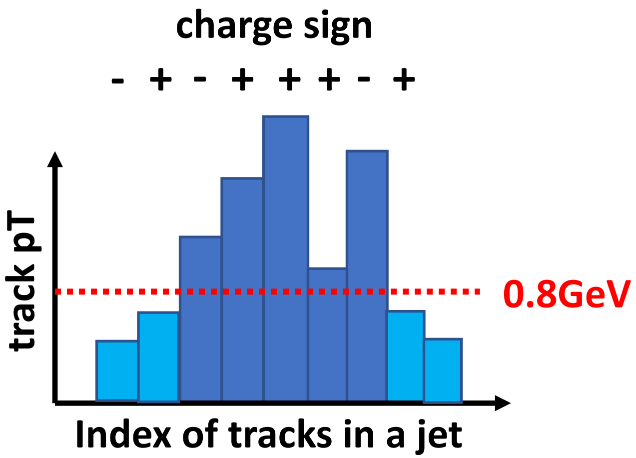
Tag associated jets to enhance the purities of ***u*-quarks and *d*-quarks** separately.

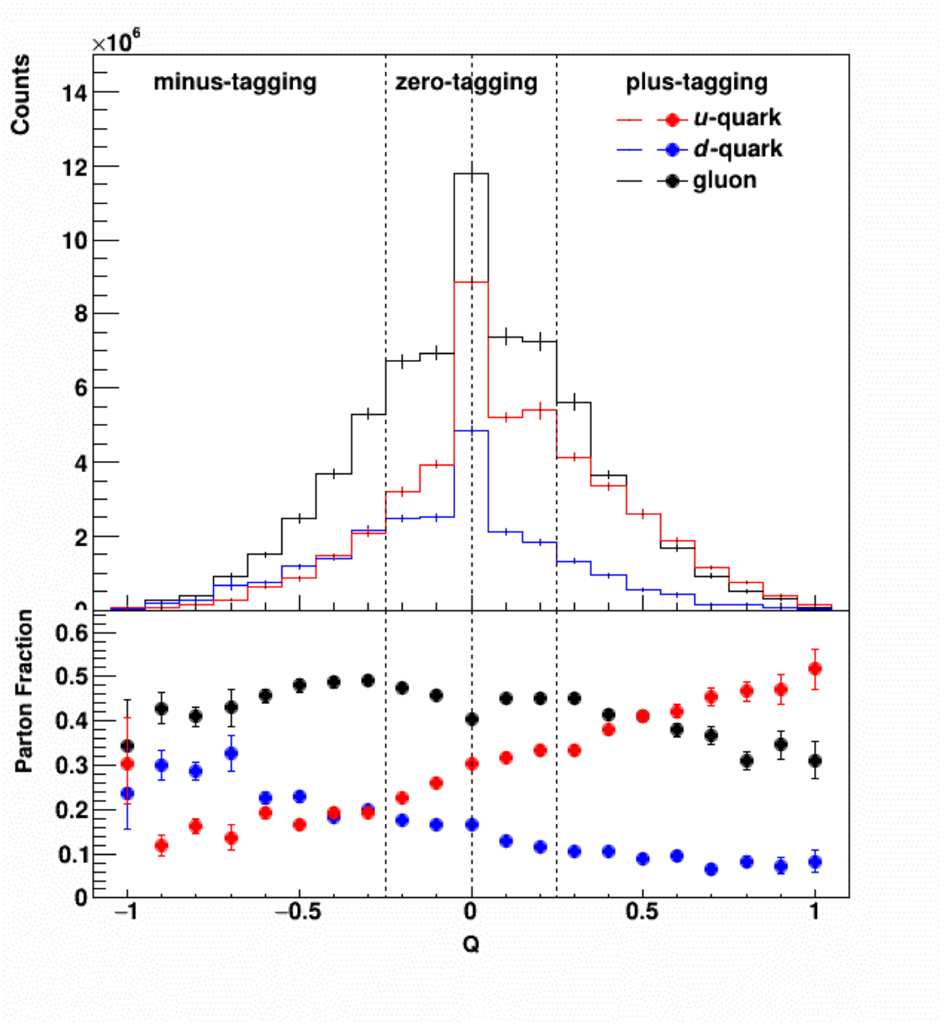
$$Q = \sum_{\substack{all\ the\ tracks \\ with\ pT>0.8GeV}} \frac{track\ |p|}{jet\ \ |p|} \cdot track\ charge$$

Mostly from parton fragmentations



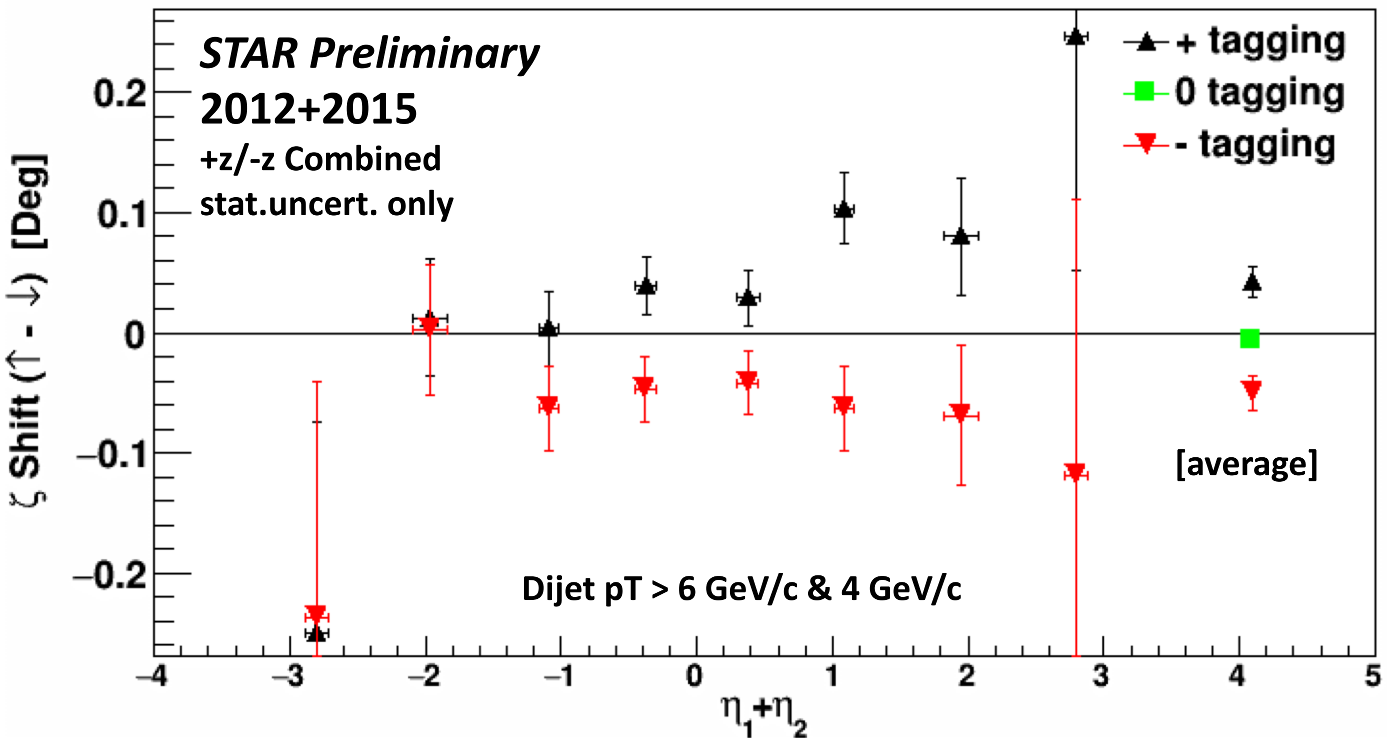
Contaminated by tracks from underlying events





2012+2015 Data — Dijet Sivers Asymmetry

- Clear separation between + and - tagging.
- Asymmetry systematically shifts from + to – as ***u*** and *d* quark fractions shift.
- zero-tagging is consistent with zero.
- Simple kinematic scaling allows for interpretation in terms of partonic k_T.



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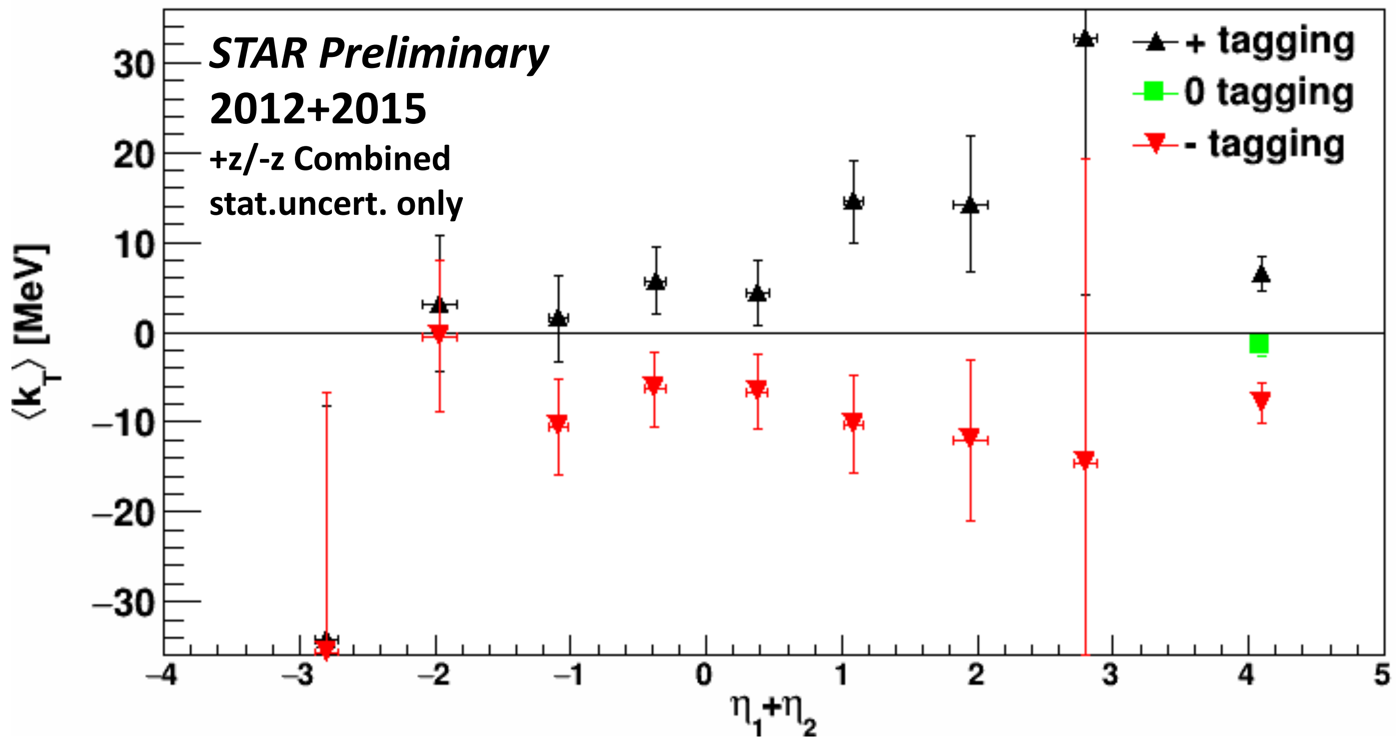
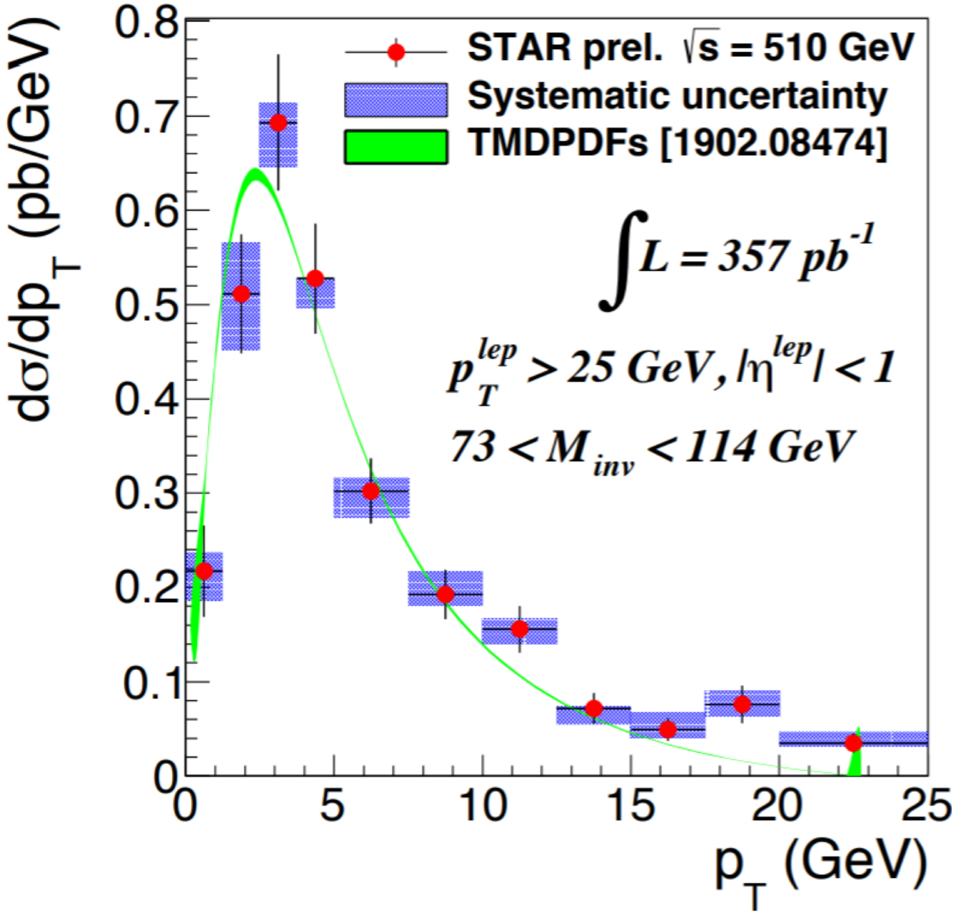


Run 2022+ - Extended tracking and calorimeter coverage from iTPC and Forward Upgrade will allow coverage from -1 < η < 4 (with a gap for 1.5-2.5). Will problem low x gluon and high x quark Sivers Functions.

TMD : Z differential cross-section



Use clean Z signal to extract unpolarized TMD PDFs.
Note : unpolarized TMDs really important for extracting spin dependent TMDs!

STAR result provides constraints at high x.

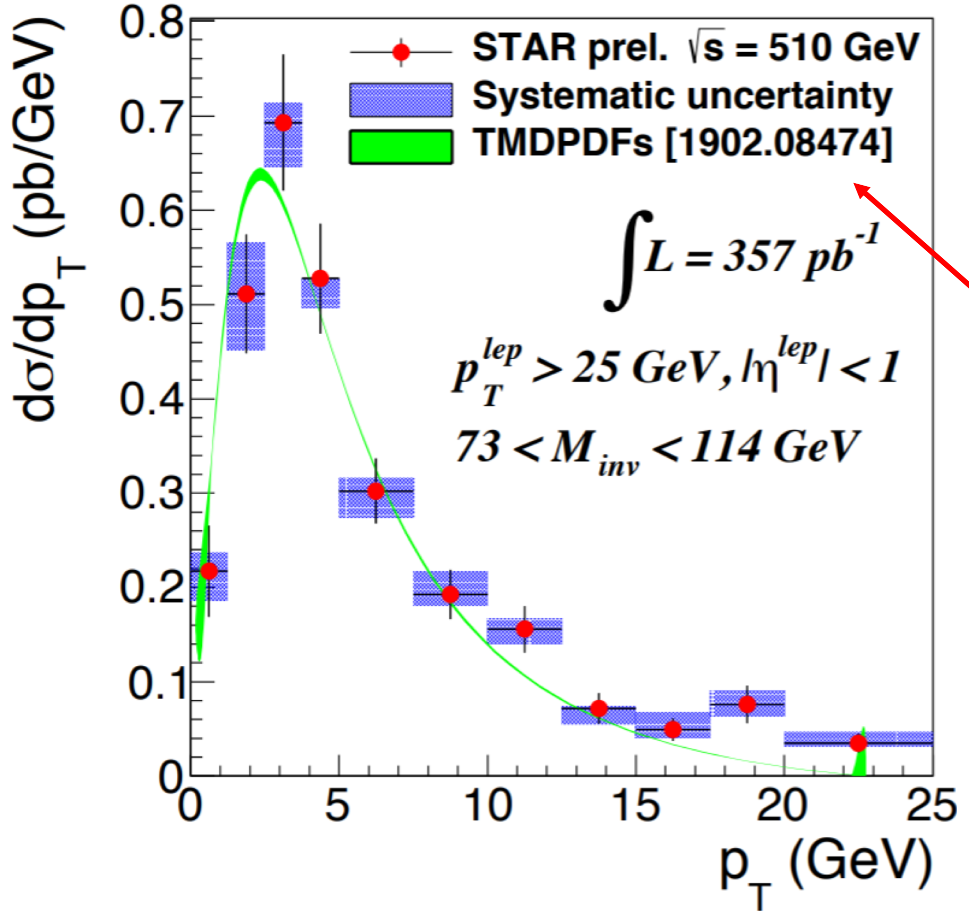
Bertone, Scimemi & Vladimirov theoretical curve is global analysis of world DY and Z differential cross-sections

Systematic errors at low p_T are driven by gain uncertainties.

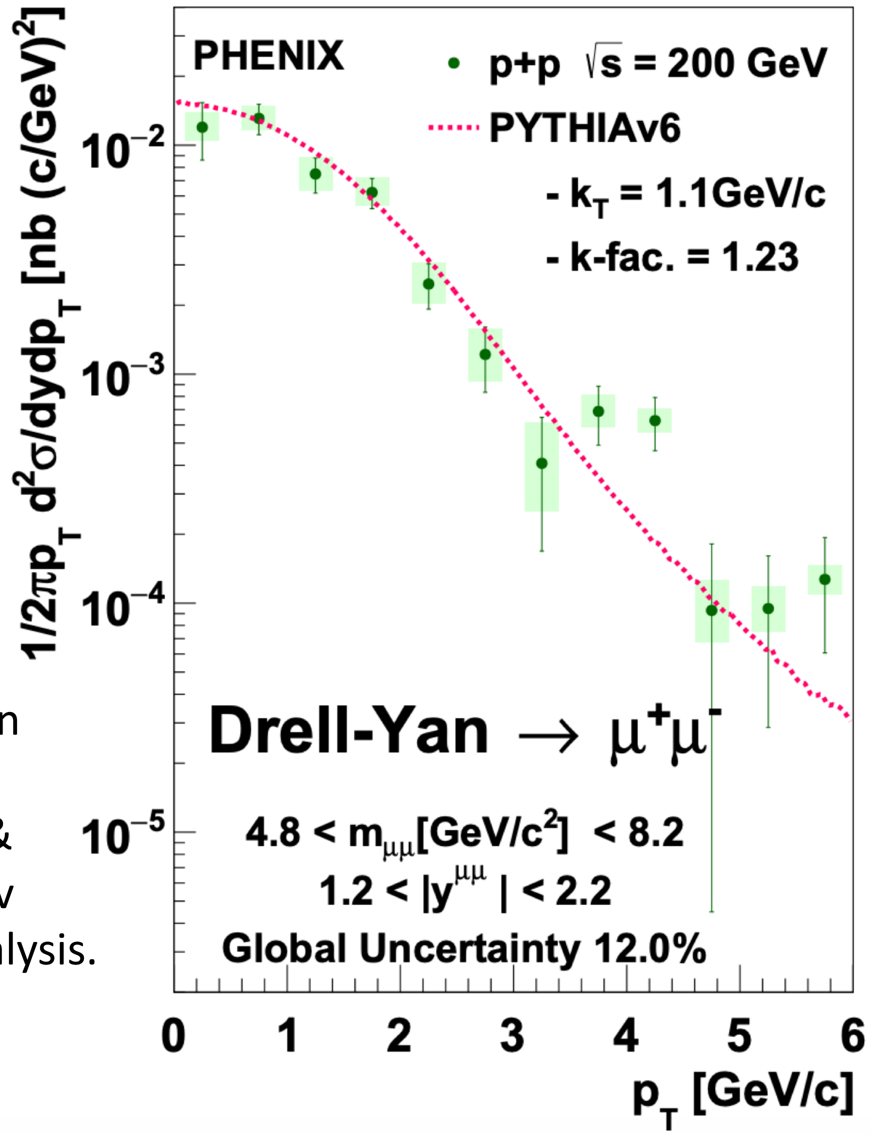
Run 17 update released for STAR 2021 BUR!

Run 17 + Run 22 would triple total statistics

TMD : Drell-Yan differential cross-section



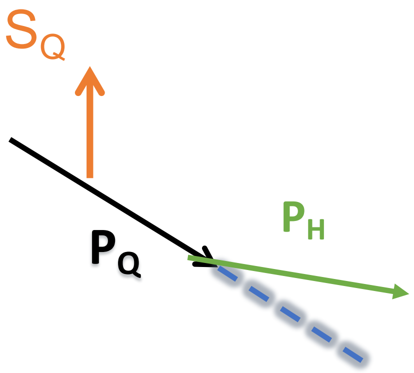
Included in Bertone, Scimemi & Vladimirov global analysis.



Final State TMD Function

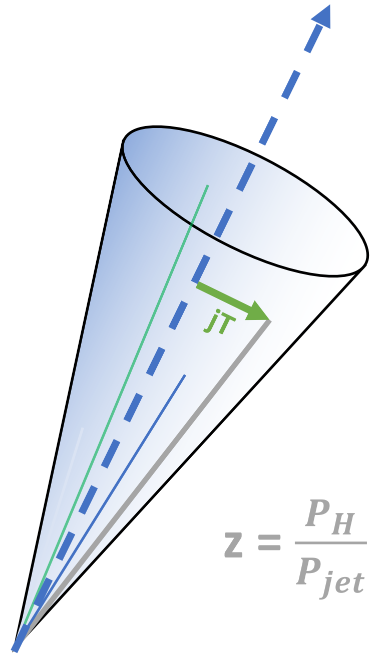
Universality
Factorization
Evolution

TMD : Fragmentation Function



FF that encapsulates correlations between the quark spin S_Q and the transverse momentum j_T of the daughter hadron.

Use reconstruction of hadrons in jets to access Collins FF
- -Fraction of the jet momentum (z) carried by the hadron
- -The component of the hadron momentum that is transverse to the jet axis (j_T)



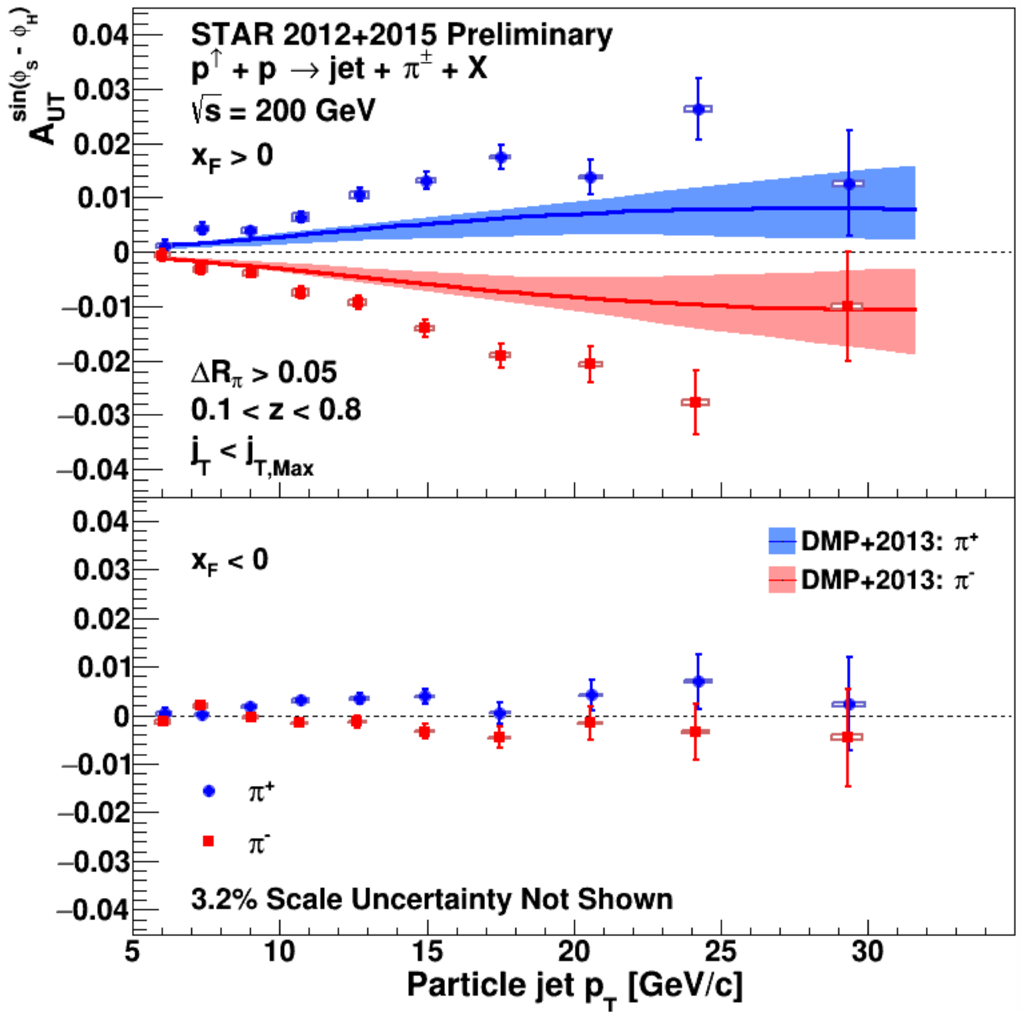
Use single spin asymmetries A_{UT} in **transversely polarized** proton collisions to gain sensitivity to both gluon and quark TMDs.

$$A_{UT}^{\sin\phi}\sin(\phi) = \frac{\sigma^{\uparrow}(\phi)-\sigma^{\downarrow}(\phi)}{\sigma^{\uparrow}(\phi)+\sigma^{\downarrow}(\phi)} \propto \frac{\sum_{AB}\Delta_T q_A f_B \times \Delta\sigma_{AB\to jet+\pi}\times \mathbf{H}_1^{\perp}}{\sum_{AB} q_A f_B \times \sigma_{AB\to jet+\pi}\times D}$$

$z = \frac{P_H}{P_{jet}}$

$\phi = \phi_s - \phi_H$ moment is sensitive to **Collinear** Transversity PDF $\Delta_T q_A(x_A, Q)$ **+ TMD** Collins FF $H_1^{\perp}(Z, J_T, Q)$. Provides a cleaner kinematic separation of transverse TMD physics than in SIDIS which convolutes the Transversity TMD PDF with Collins TMD FF.

TMD : Collins $\pi^{+/-}$ FF @ 200 GeV

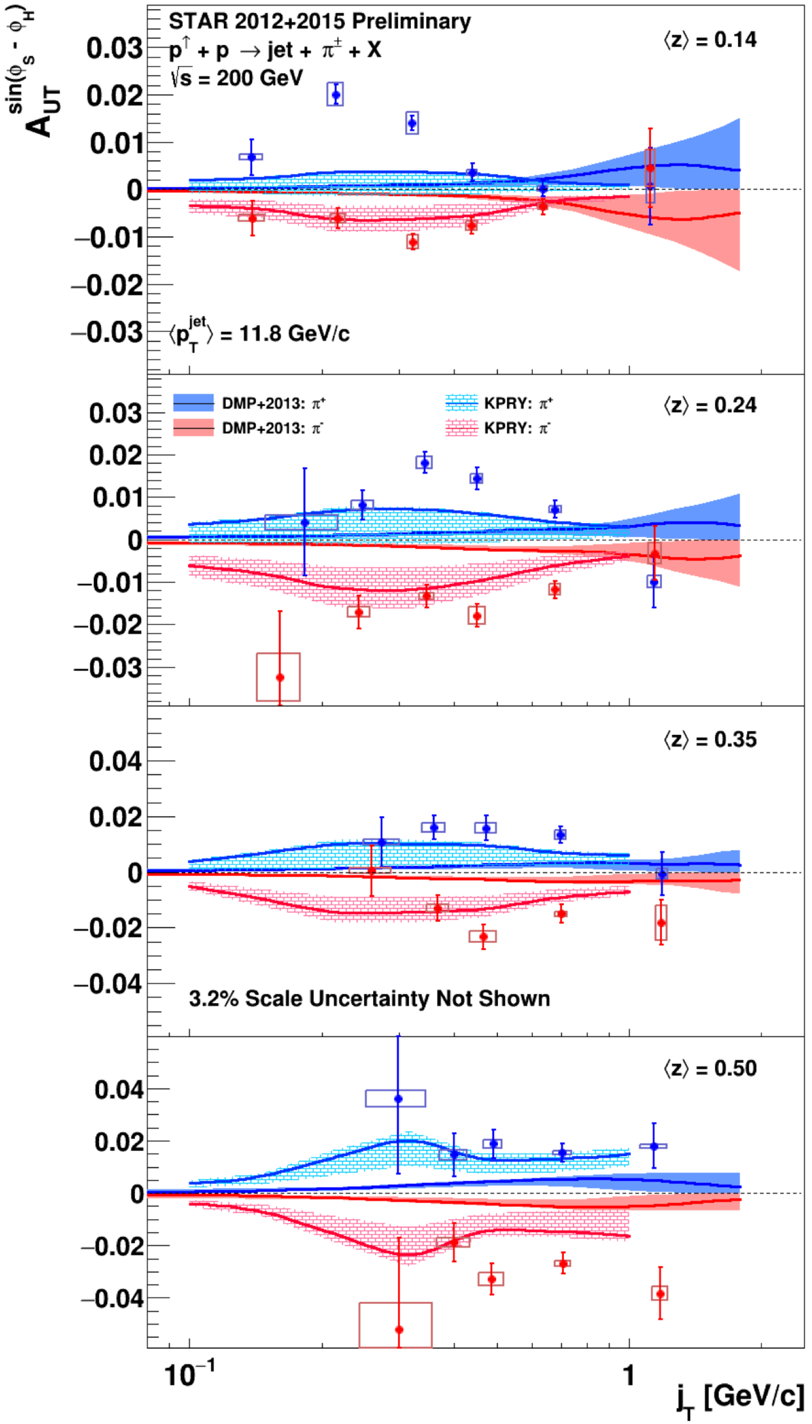


Plotting differentially in <z> and <j_T> provides input on flavor separated shape of Collins TMDFF.

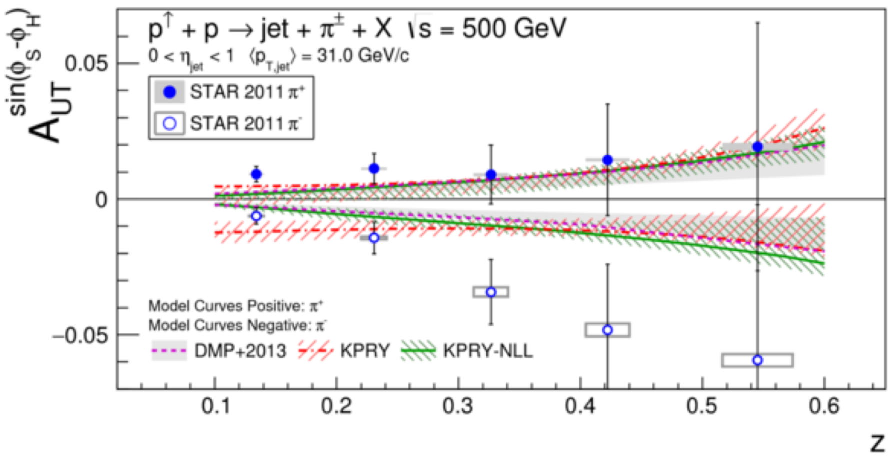
Theory:

1) DMP, Phys. Lett. **B773**, 300 (2017)
2)KPRY Phys.Lett. **B774** 635-642 (2017)

p/K A_{UT} in backup!

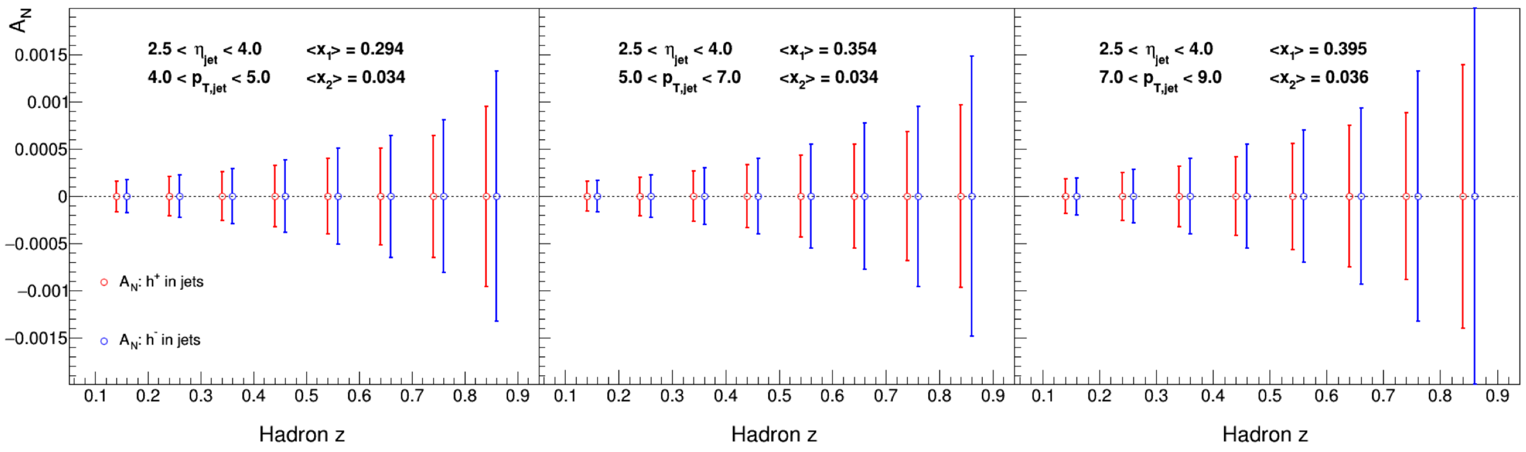


TMD : Collins $\pi^{+/-}$ FF @ 500 GeV



Data and theory agree - **TMD Evolution effects appear to be small.** At the current level of precision the data supports theoretical work by by Kang, Liu, Ringer and Xing JHEP 1711 (2017) 068 , ie **universality holds for Collins TMDs in p+p collisions.** Need more 510 GeV mid-rapidity data!

2022+: STAR Forward Upgrade provides provides full jet reconstruction as well as $h^{+/-}$ ID. Expect dilution of ~26% from p+K in h^+, while h^- will have a purity of 78%.



TMD : Fragmentation Functions

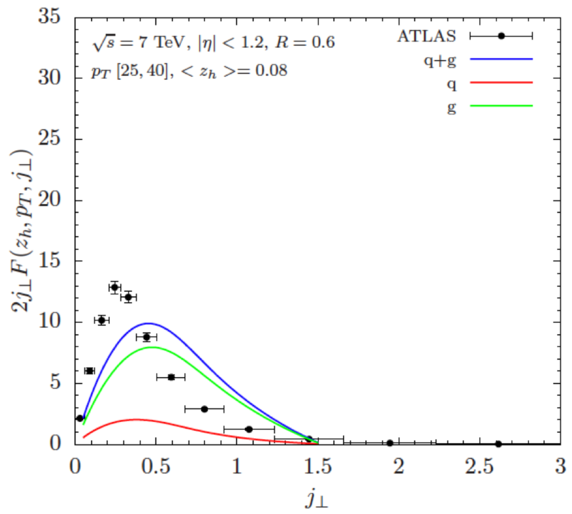
Work by Kang, Liu, Ringer and Xing defined a universal TMD FF:

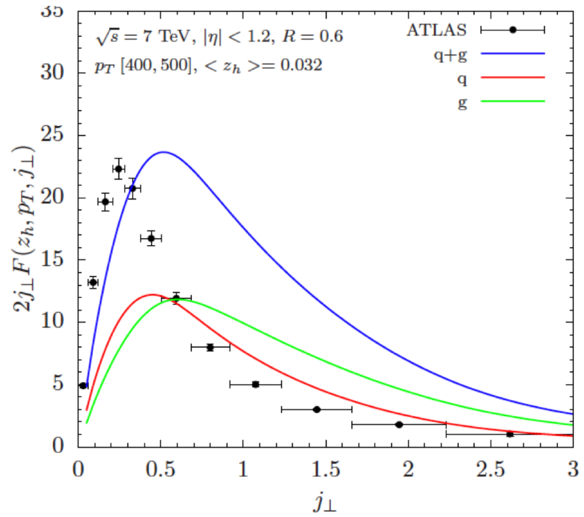
$$F\left(z_h, j_T; p_T, \eta, R\right) = \frac{\dfrac{d\sigma^{pp\to jet+X}}{dp_T^{jet}\, d\eta^{jet}\, d^2 j_T\, dz_h}}{\dfrac{d\sigma^{pp\to jet+X}}{dp_T^{jet}\, d\eta^{jet}}}$$

It is especially sensitive to the **GLUON** TMD FF, which is at this time virtually unconstrained.

Unlike in SIDIS, the TMDFF's accessed in pp do not depend on the TMDPDFs!

2022+ Measurement at mid and forward rapidity.

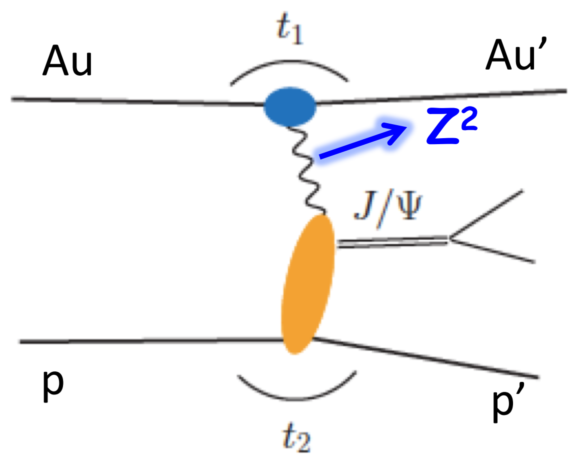




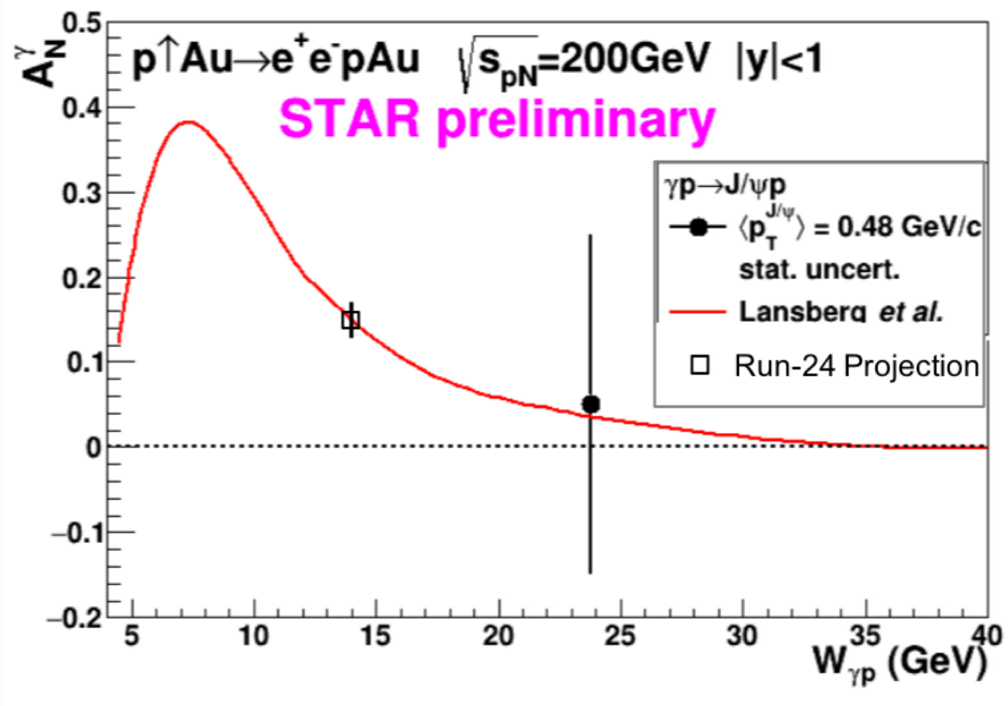
JHEP 11 (2017) 068

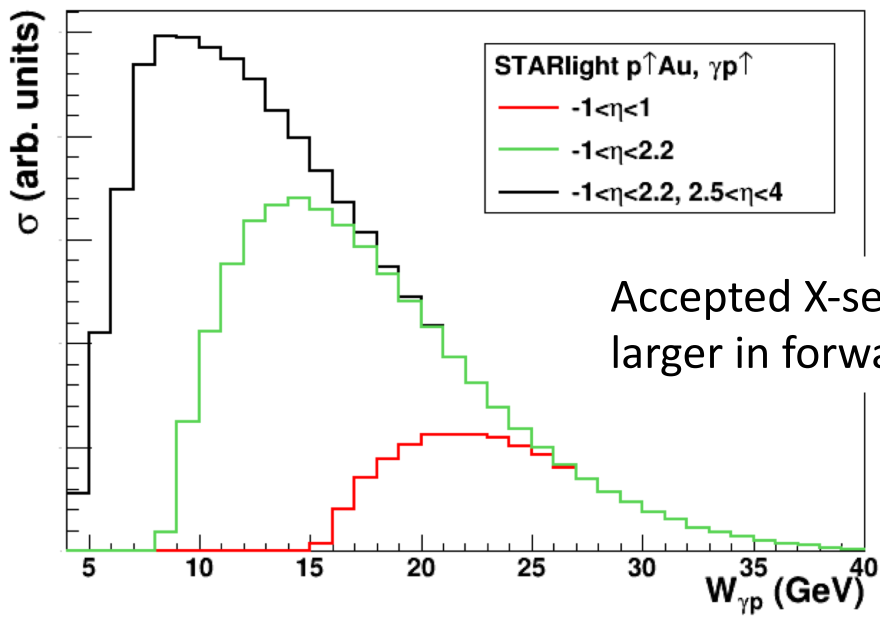
First look at GPD E_g

GPD : E_g from J/ψ in UPC



- RHIC can access the GPD E function for gluons via measurements of **A_{UT}** of **J/ψ** in ultra-peripheral collisions
- GPD E_g is sensitive to spin-orbit correlations and provides input on **angular momentum** component of the spin puzzle.





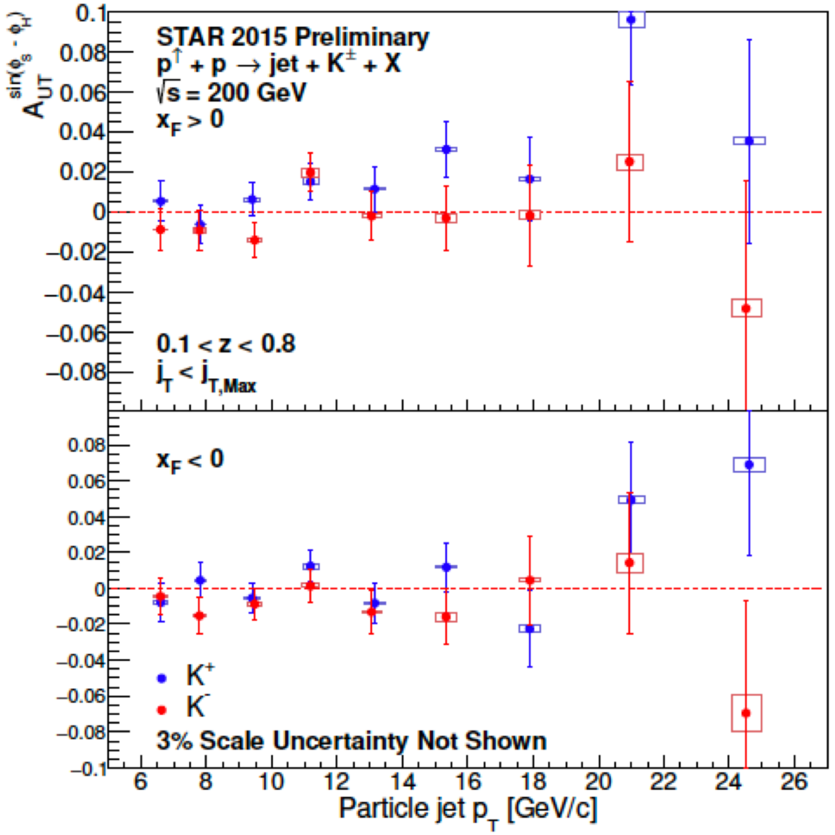
Accepted X-section larger in forward region

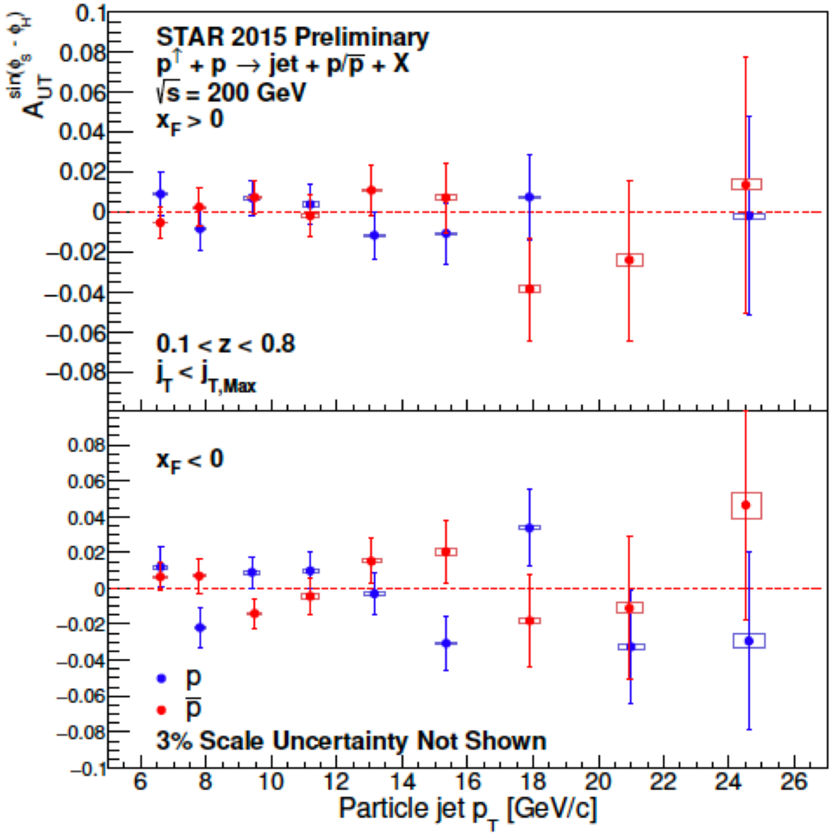
Take Away

- A robust and complete picture of the nucleon requires scattering data from electromagnetic, weak and strong probes.
- Tests of factorization and universality require significant kinematic overlap for data with different probes.
- STAR iTPC and Forward upgrade will provide full jet reconstruction spanning from $-1 < \eta < 4$ (with a gap for 1.5-2.5).
- RHIC Runs 22-24 provide last opportunity to make important measurements
  1. "Sivers" sign-change, in both TMD and twist-3 framework.
  2. Use jet reconstruction in the forward upgrade to probe high x distributions for Sivers and transversity.
  3. Push to higher precision on mid-rapidity TMDFF via hadrons-in-jets -> both for Collins and unpolarized FF.
  4. Definitively determine role of twist-3 FF in large forward TSSA.

Back-up

TMD: Collins p/K @ 200 GeV





Gluon Linear Polarization

- $\sin(\Phi_S - 2\Phi_H)$ modulation in jet A_{UT} is sensitive to gluon linear polarization signal.
- First measurement - completely unconstrained! Possible cause of the ridge in pp/pA? *Phys.Rev. D94 no.1, 014030, arXiv:1708.08625*
- Shaded bands represent maximal predictions from *U. D'Alesio, F. Murgia, and C. Pisano, arXiv:1707.00914* utilizing Kretzer and DSS fragmentation functions.

arXiv:1708.07080