Contributions to our Understanding of TMDs from Polarized Proton Collisions at STAR

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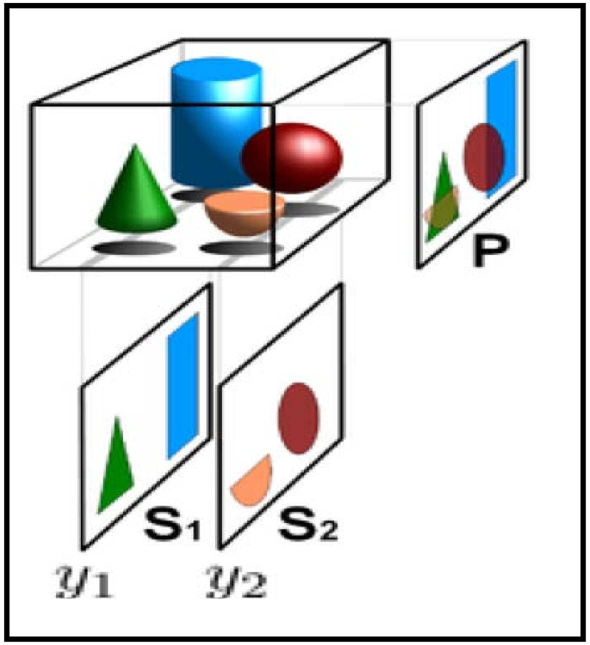
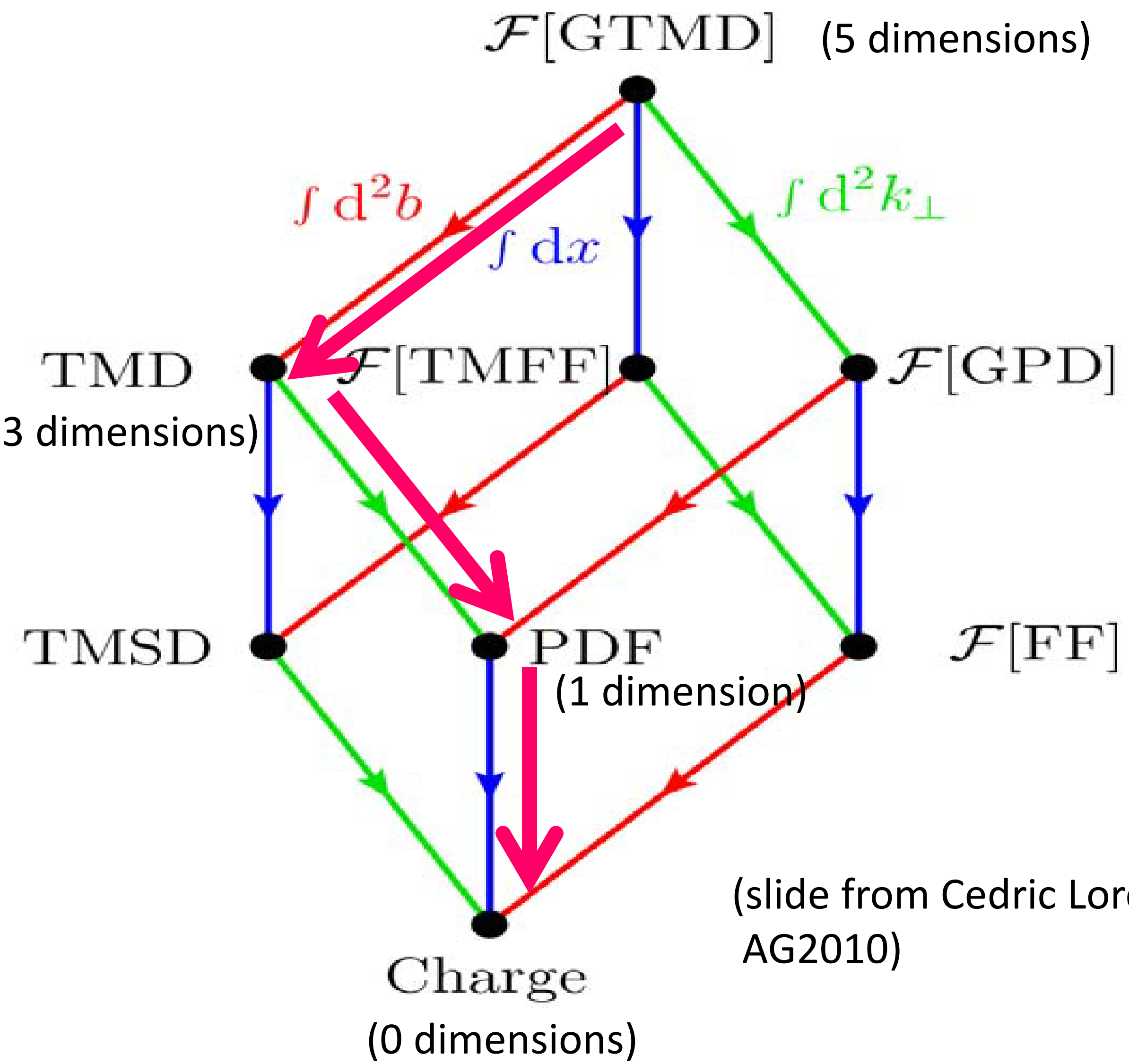
TMDs from Wigner-like Distributions

Momentum ↔ Position

$$\vec{k}_\perp \leftrightarrow \vec{z}_\perp$$

$$\vec{\Delta}_\perp \leftrightarrow \vec{b}$$





(slide from Cedric Lorce, AG2010)

Polarization Effects: TMDs and FFs

nucleon \ quark	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	$h_1, h_{1T}^{\perp}$

Sivers ($f_{1T}^{\perp}$), Transversity (h_1)

hadron \ quark	U	L	T
U	D_1		$H_1^{\perp}$
L		G_{1L}	$H_{1L}^{\perp}$
T	$H_{1T}^{\perp}$	G_{1T}	$H_1, H_{1T}^{\perp}$

Collins ($H_1^{\perp}$)

Possible transverse asymmetries:

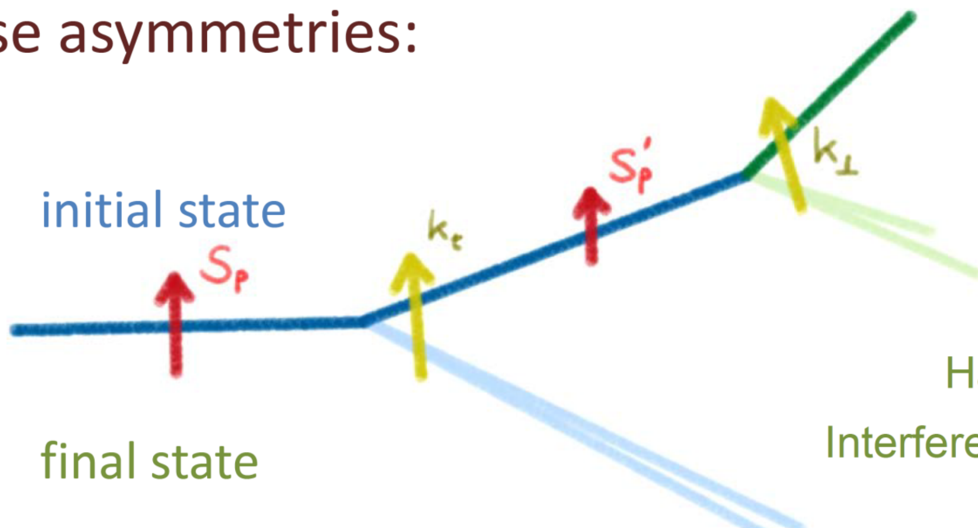
$f_{1T}^{\perp} \otimes f_1 \otimes D_1$
$h_1 \otimes h_1^{\perp} \otimes D_1$
$h_{1T}^{\perp} \otimes h_1^{\perp} \otimes D_1$

} initial state

$h_1 \otimes f_1 \otimes H_1^{\perp}$
$f_{1T}^{\perp} \otimes h_1^{\perp} \otimes H_1^{\perp}$
$h_{1T}^{\perp} \otimes f_1 \otimes H_1^{\perp}$

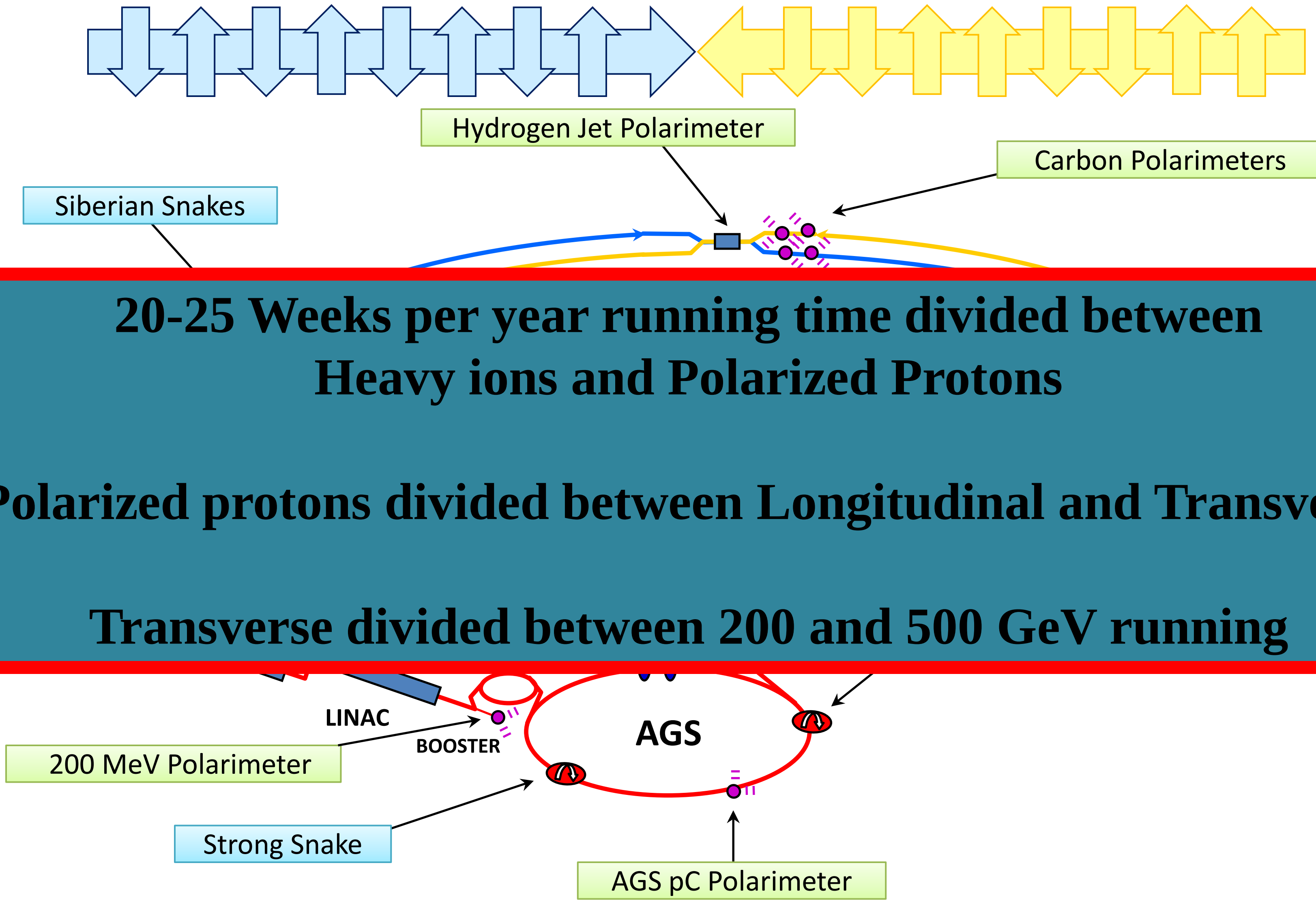
} final state

...



Inclusive hadrons
Direct photons
Jets
Jet structure
Hadron correlations
Interference fragmentation
Drell-Yan
W-bosons

RHIC: Polarized Proton Collider

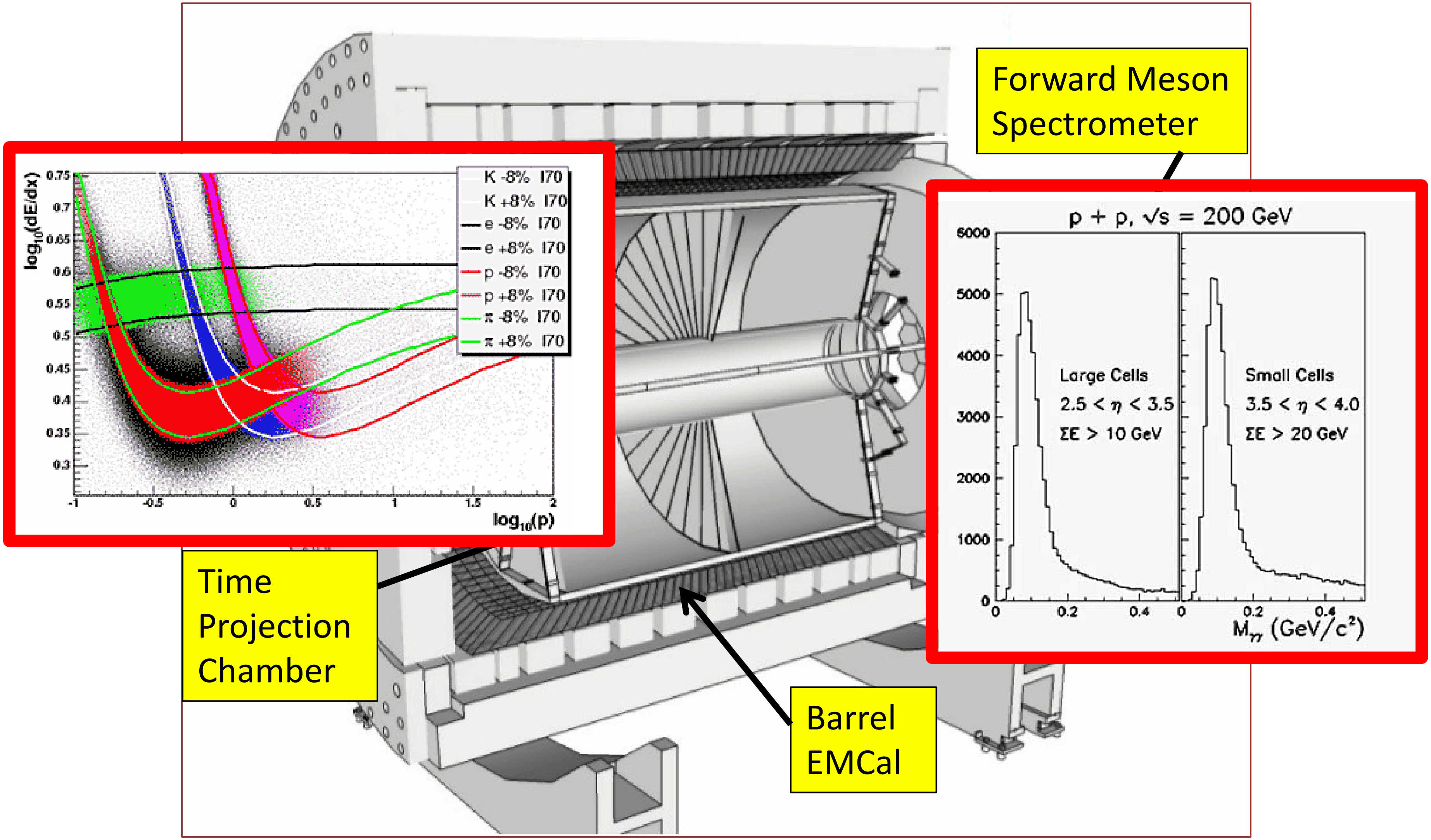


20-25 Weeks per year running time divided between Heavy ions and Polarized Protons

Polarized protons divided between Longitudinal and Transverse

Transverse divided between 200 and 500 GeV running

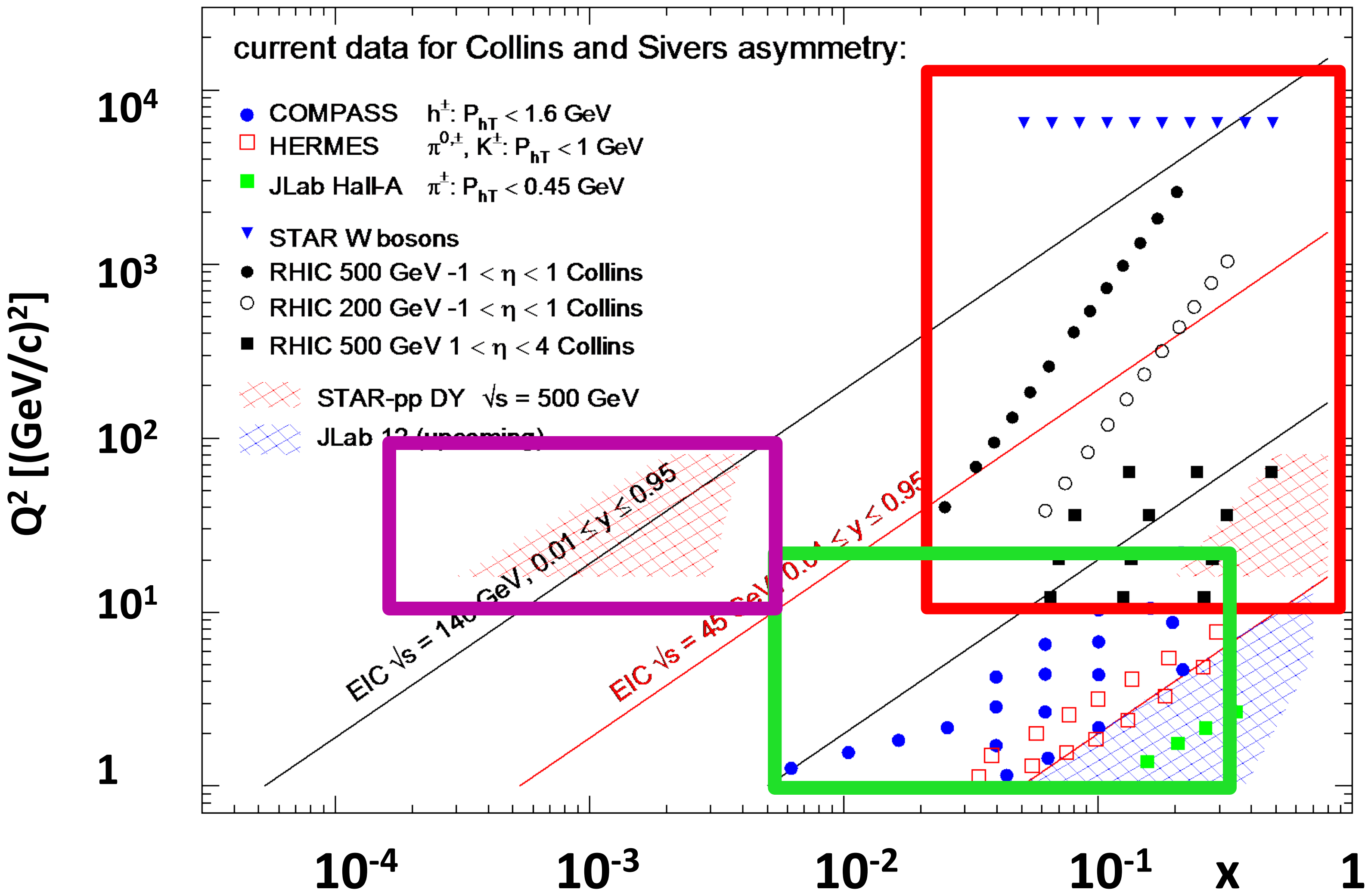
The STAR Detector



EMCal coverage -1<η<4

TPC Tracking/Particle ID coverage |η|<+1.3

RHIC – Contribution to TMD Physics

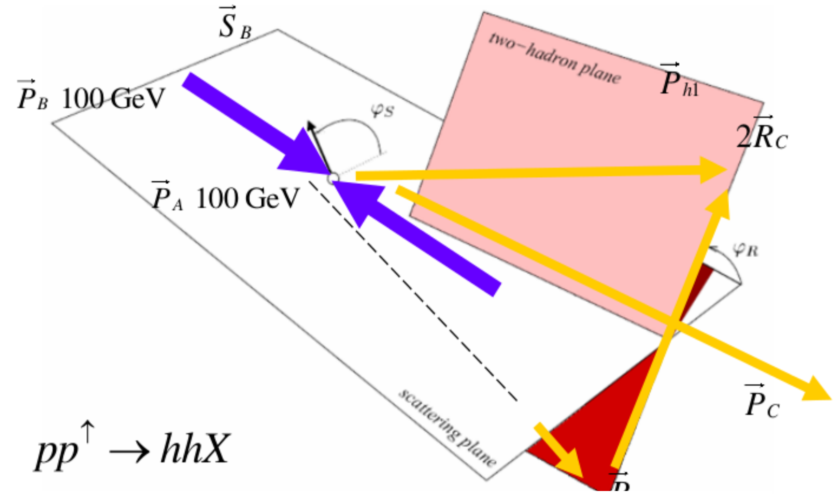


STAR/RHIC and TMDs

- STAR can measure W/Z, jets, identified hadrons within jets, neutral pions in forward direction
- Upgrades will measure DY, direct γ and tagged colliding protons.
- Polarized TMDs: Mechanisms like Collins, Sivers, Twist-3, Transversity can be studied at RHIC
- Q^2 Evolution/k_T summation: Collisions at 200/500 GeV, W/Z mass; Goes beyond DGLAP evolution and gives insight into nature of confinement
- Check universality/factorizability by comparing functions extracted from two different processes, *e.g.*, transversity from IFF or Collins or transversity from pp and SIDIS
- Can check “sign change” of Sivers function
- Polarized pA collisions can use asymmetries as a probe of cold nuclear matter to investigate saturation or nuclear modification effects

Mid-rapidity Di-hadron Production

Extract proton transversity through its coupling with chiral-odd Interference Fragmentation Function



Collinear factorization is preserved
Marco Radici's talk: need unpolarized FF data

$$d\sigma_{UU} = 2\,|\mathbf{P}_{C\perp}| \sum_{a,b,c,d} \int \frac{dx_a dx_b}{4\pi^2 z_c} f_1^a(x_a)\, f_1^b(x_b) \frac{d\hat{\sigma}_{ab\to cd}}{d\hat{t}} D_{1,oo}(\bar{z}_c, M_C^2)$$

Unpolarized quark distribution
Known from DIS

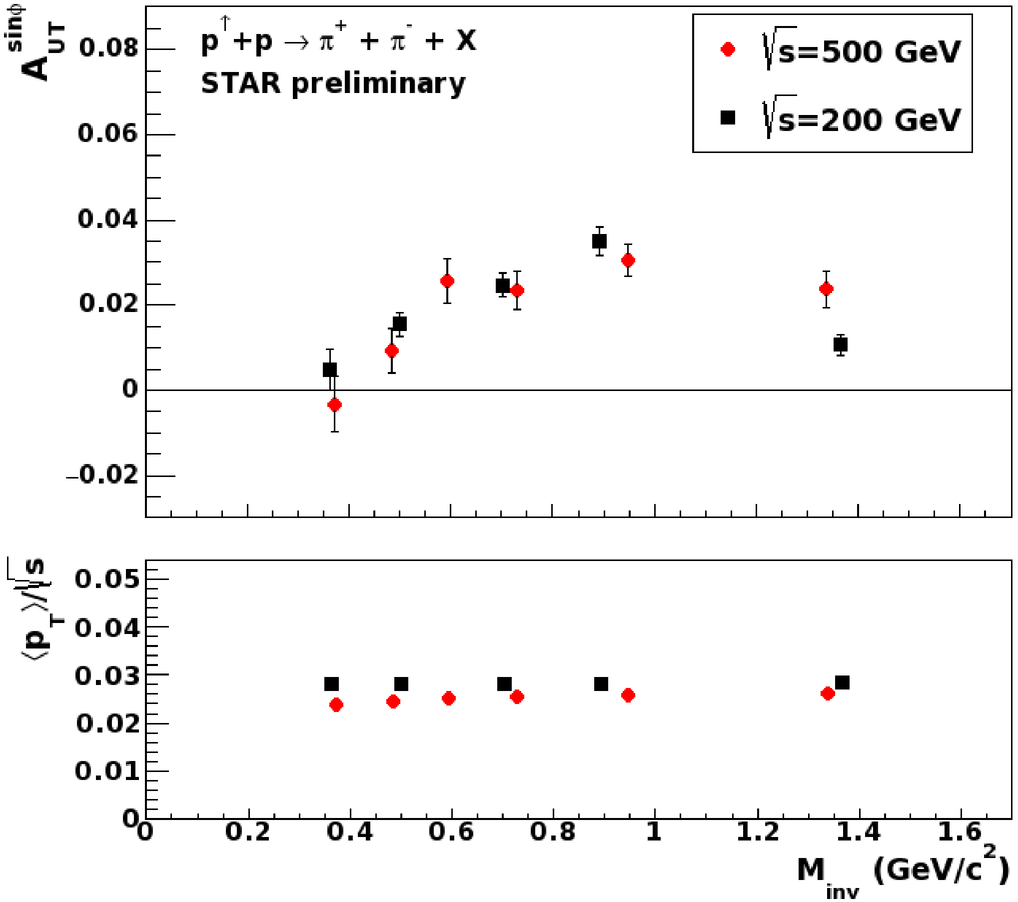
Transversity
to be extracted

Hard scattering cross section
from pQCD

IFF + Di-hadron FF
measured in e+e-

$$d\sigma_{UT} = 2\,|\mathbf{P}_{C\perp}| \sum_{a,b,c,d} \frac{|\mathbf{R}_C|}{M_C} |\mathbf{S}_{BT}| \sin(\phi_{S_B} - \phi_{R_C}) \int \frac{dx_a dx_b}{16\pi z_c} f_1^a(x_a)\, h_1^b(x_b) \frac{d\Delta\hat{\sigma}_{ab^\uparrow\to c^\uparrow d}}{d\hat{t}} H_{1,ot}^{\sphericalangle c}(\bar{z}_c, M_C^2)$$

Transversity Results at $\sqrt{s}$ = 200, 500 GeV



Significant non-zero di-hadron asymmetries which are enhanced around ρ mass

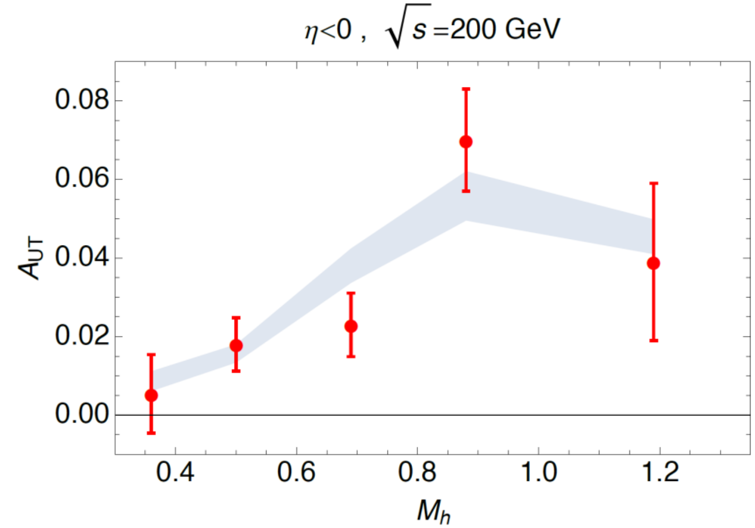
Consistent asymmetries at same $x_T = 2\langle p_T \rangle/\sqrt{s}$

Measured at $\sqrt{s}$ = 200, 500 and as functions of $M_{\pi\pi}$, p_T and η: Gives different mix of x and qq, qg,and gg subprocesses

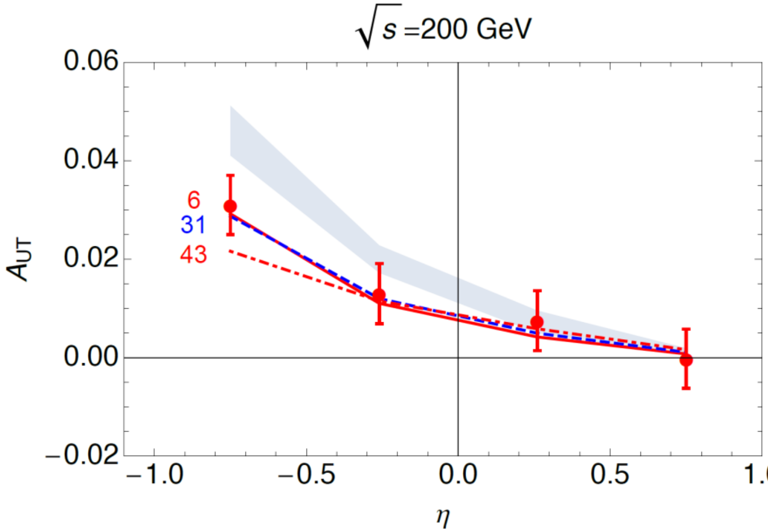
Compare Transversity from RHIC/SIDIS

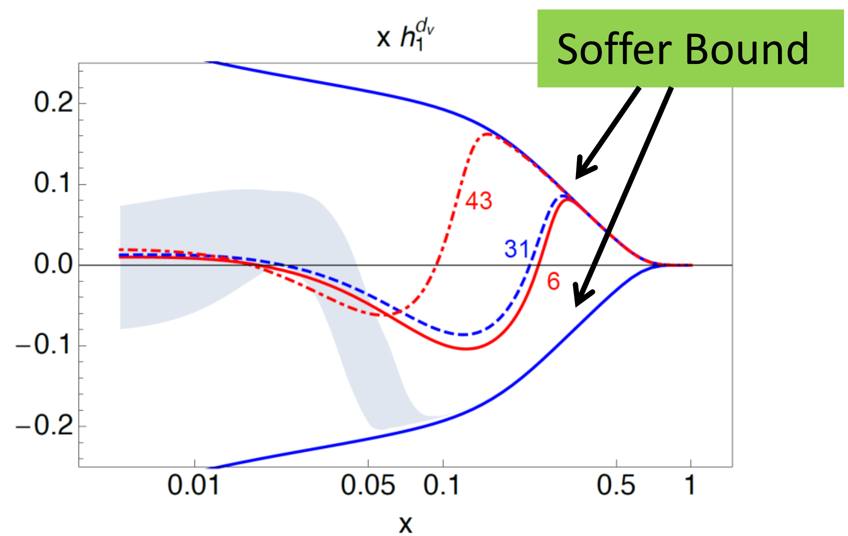
Compare 2006 STAR data with transversity replicas extracted from HERMES/COMPASS SIDIS data and BELLE IFF Fragmentation Functions.

Consistent in $M_{\pi\pi}$, discrepancy in η



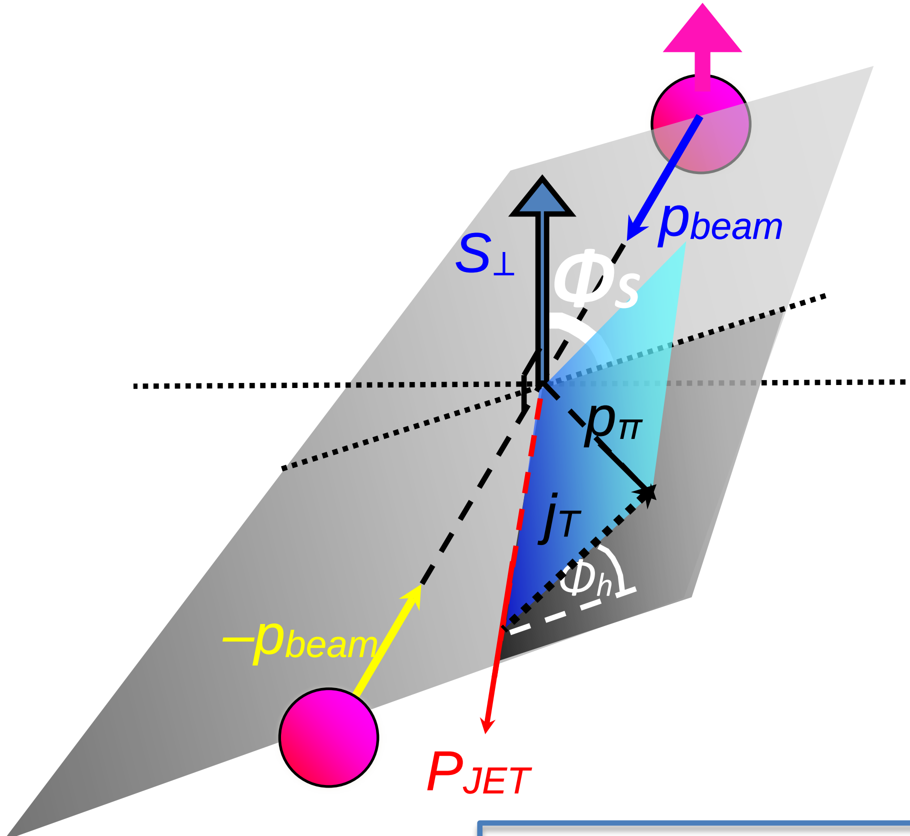
PAVIA Group: Radici et al, arXiv: 1604.06585v1





SSA in pp sensitive to Collins/Transversity:

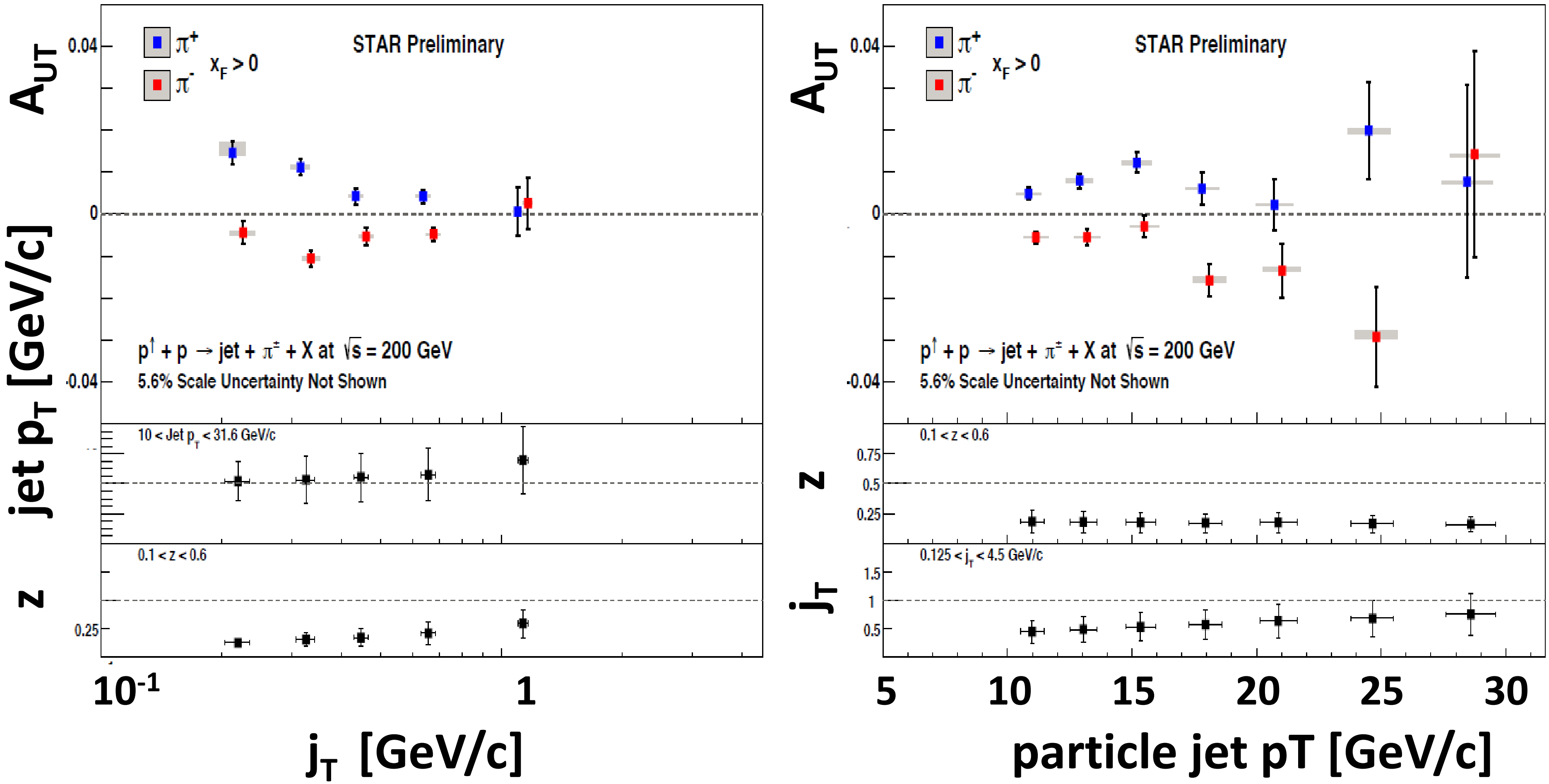
Azimuthal distributions of pions in Jets



- φ_S is defined as the angle between proton spin and reaction plane
- j_T defines particle transverse momentum in jet
- φ_H defines angle between jet particle transverse momentum and reaction plane
- $\varphi_C = \varphi_S - \varphi_H$ (Collins Angle)

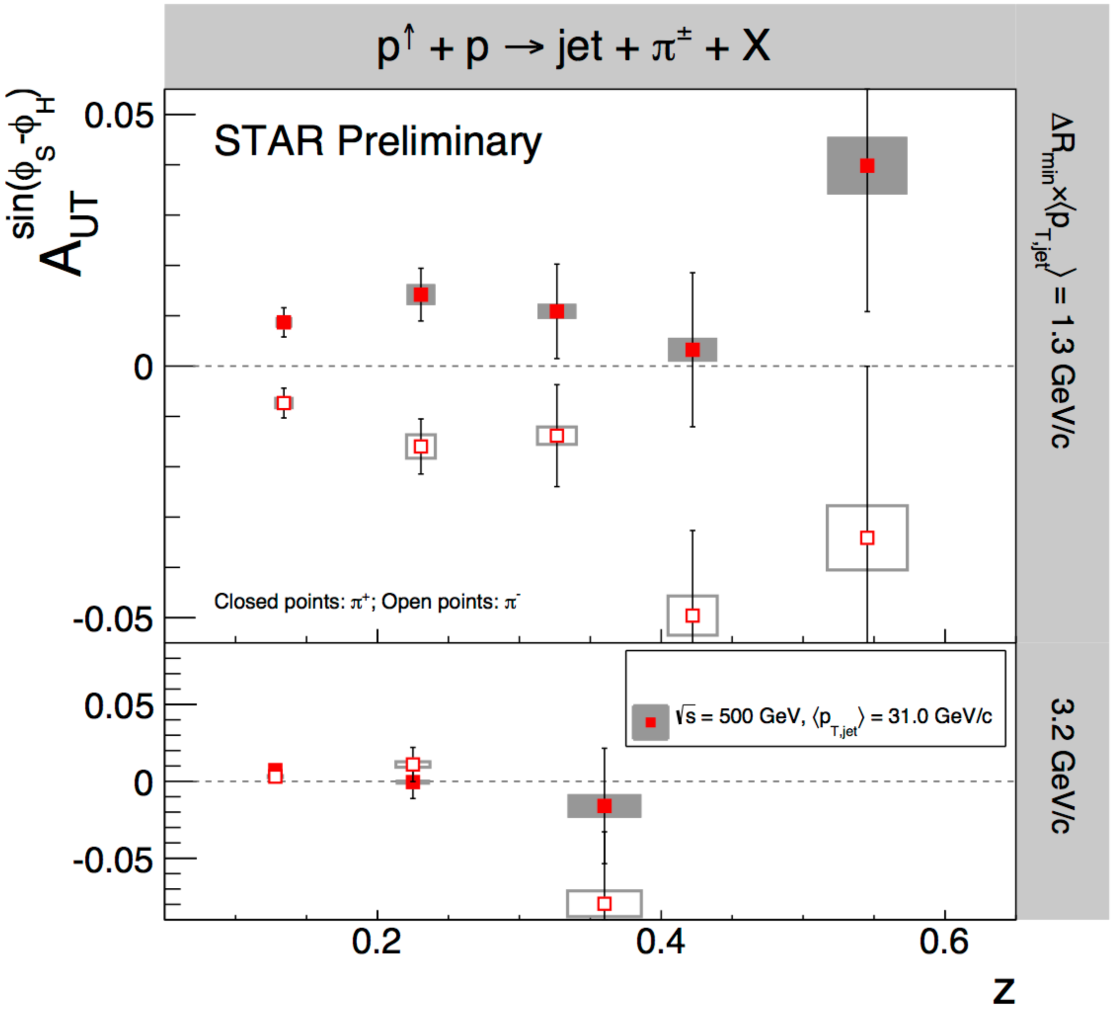
$$\frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow}(\varphi_C) = A_{UT}^{\sin\varphi_C}\sin(\varphi_C) \propto \Delta_T q \otimes H_1^\perp$$

Collins/Transversity Results at $\sqrt{s}$ = 200 GeV



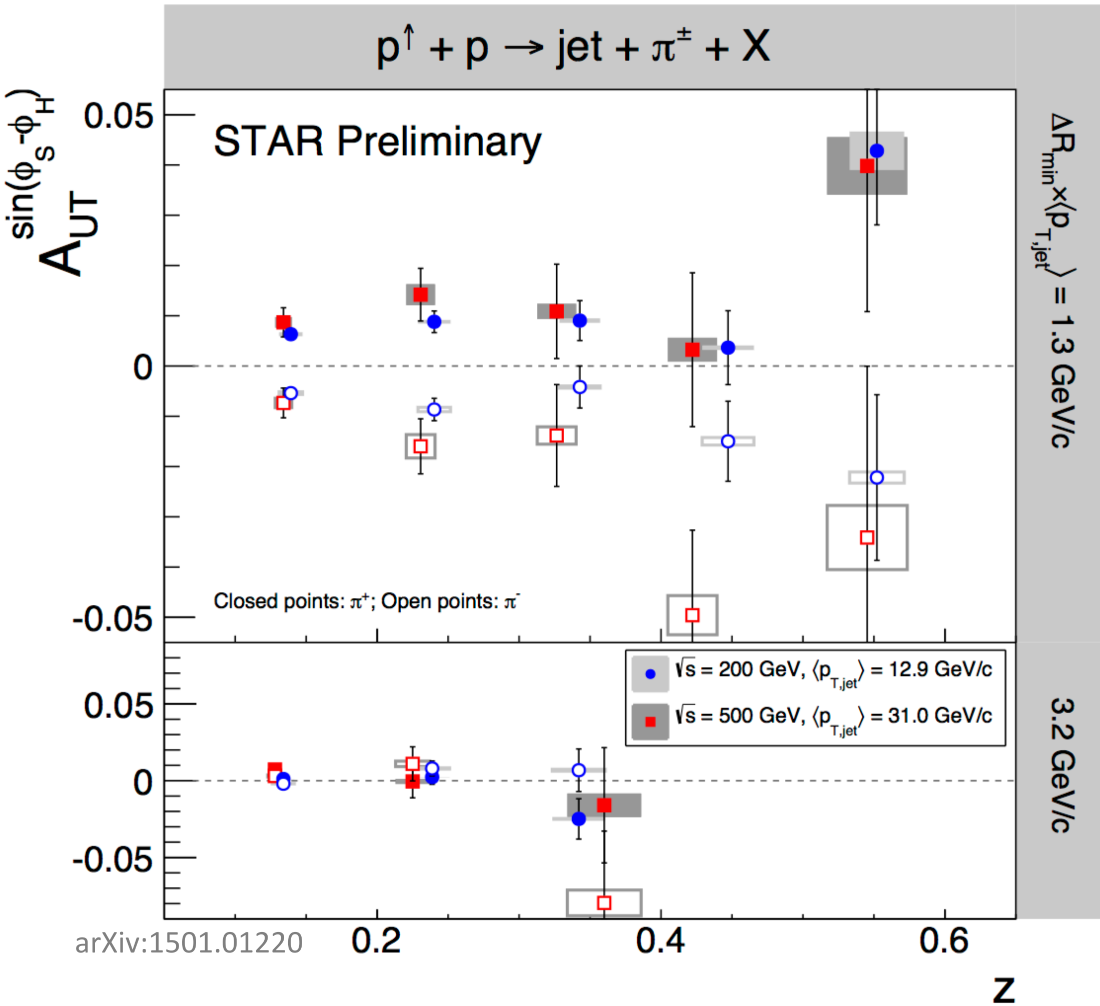
Collins A_{UT} as functions of Jet p_T, and j_T,

Collins/Transversity Results at $\sqrt{s}$ = 500 GeV



Non-zero Collins asymmetries observed at $\sqrt{s}$ = 500 GeV

Collins/Transversity Results at $\sqrt{s}$ = 500 GeV



arXiv:1501.01220

Non-zero Collins asymmetries observed at $\sqrt{s}$ = 500 GeV

Consistent with $\sqrt{s}$ = 200 GeV results for consistent cuts and x_T

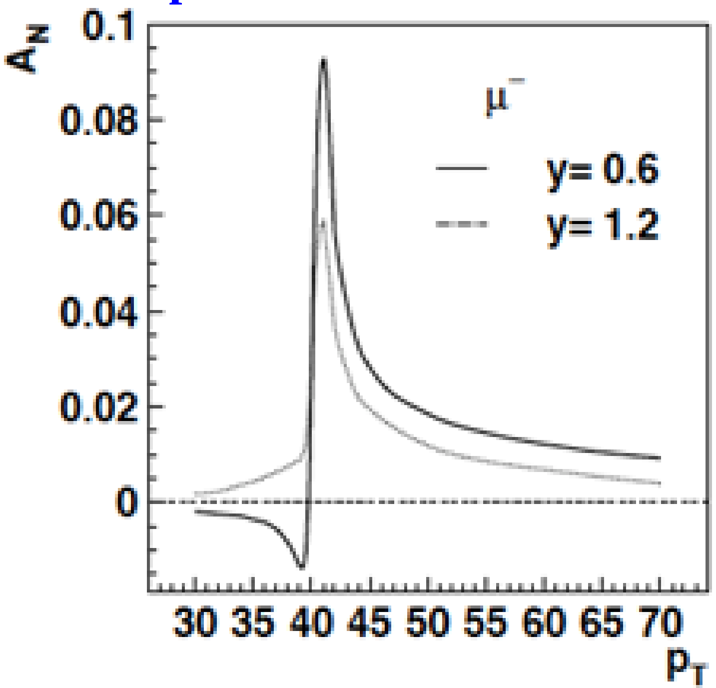
Suggestive of slow TMD evolution/validity of factorization?

Transversity/Collins from pp

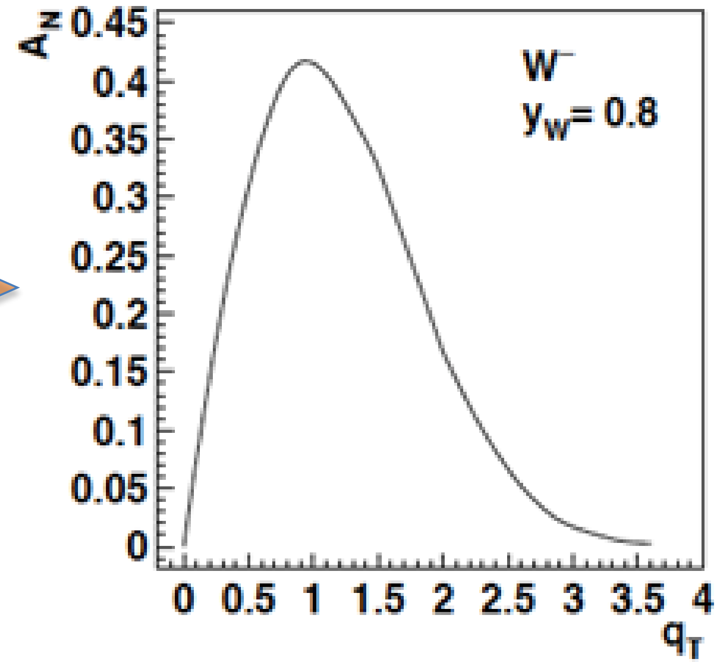
- Transversity accessed thru IFF and Collins Asymmetries
- New STAR IFF measurements at 200 and 500 GeV are higher precision, functions of $M_{\pi\pi}$, p_T, η
- Consistency at 200/500 indicates slow Q^2 evolution
- Will shed light on transversity for $x>0.1$
- New STAR Collins/Transversity measurements at 200 and 500 GeV give consistent, non-zero Collins functions
- Checks consistency of Transversity, Q^2 evolution and validity of factorization.
- New data analysis underway for Collins in pAu

Sivers Sign Change: A_N for Weak Bosons

Lepton's transverse momentum



Boson's transverse momentum



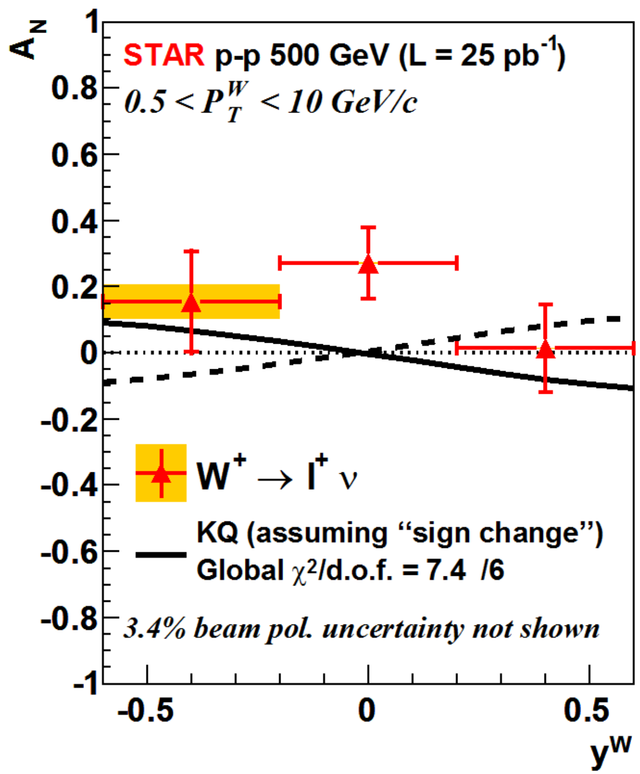
Asymmetry from lepton-decay is small →

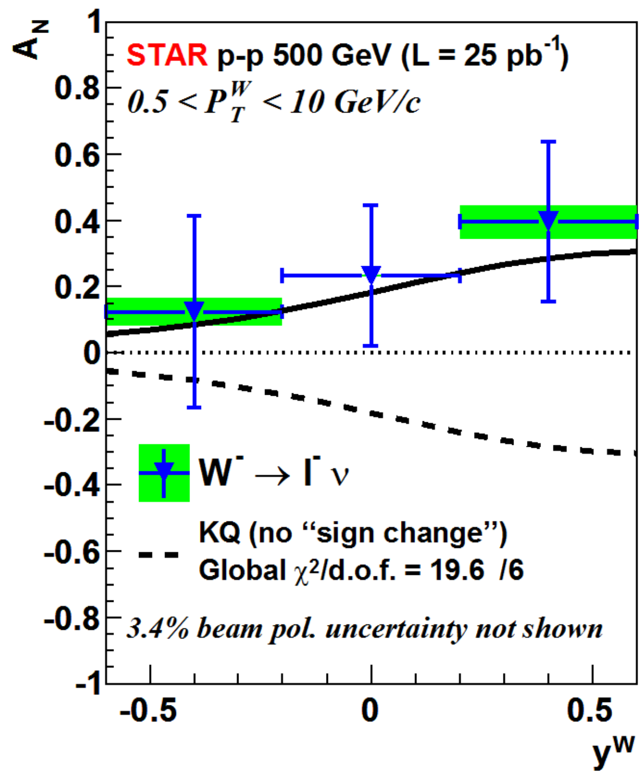
Need <u>full kinematic reconstruction of W/Z</u>

- **> Z^0 easy to reconstruct (but small cross-section)**
- **> W kinematics can be reconstructed from the hadronic recoil (first time at STAR)**

Sivers' Sign Change (No TMD Evolution)

[Phys. Rev. Lett. 116, 132301 (2016)]





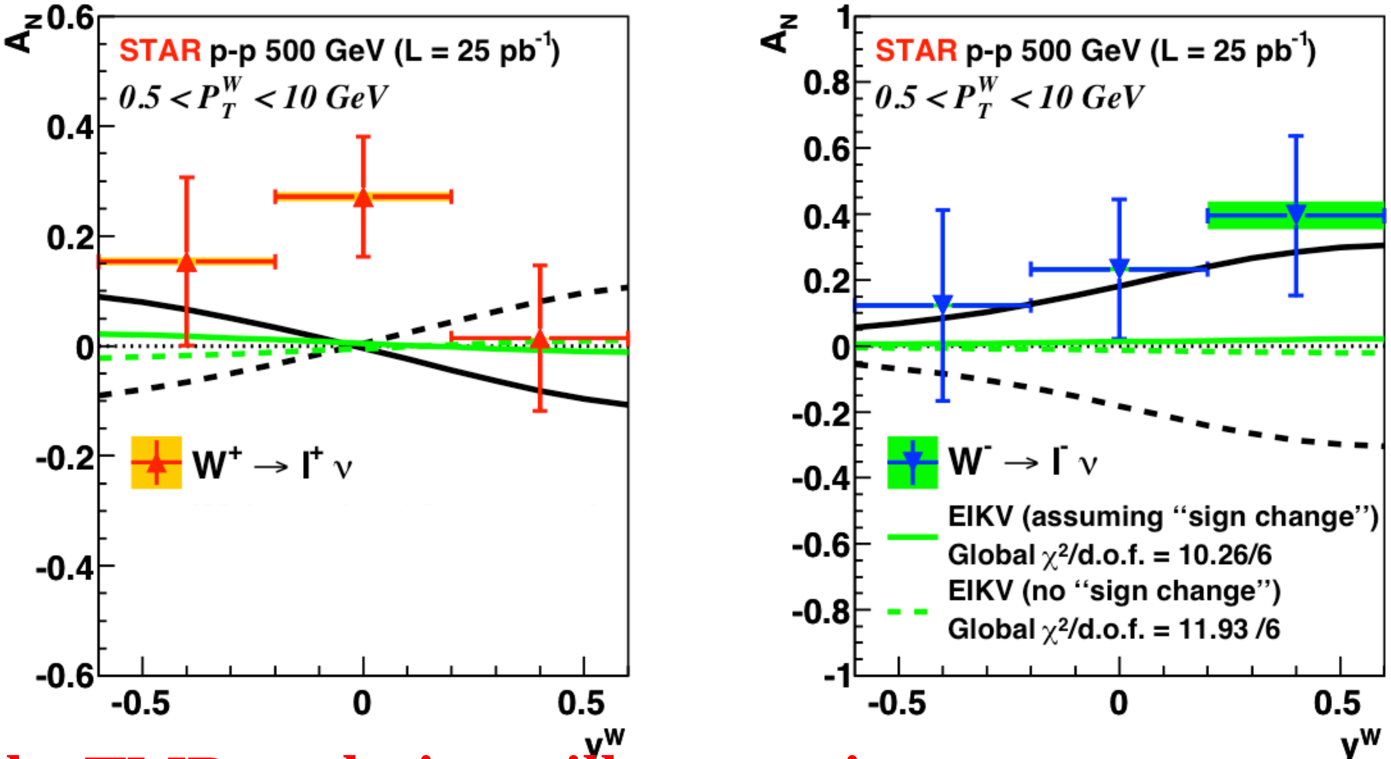
Kang and Qiu, Phys. Rev. Lett., 103 ,172001 (2009)

A global fit to the (unevolved) KQ prediction was performed:

- **solid line:** assumption of a sign change in the Sivers function → χ^2**/d.o.f. = 7.4/6**
- **dashed line:** assumption of no sign change in the Sivers function → χ^2**/d.o.f. = 19.6/6**

If there are no evolution effects (or cancellation of evolution in the ratio) our data favor the hypothesis of Sivers sign change

Sivers' Sign Change (Strong TMD Evolution)



Echevarria, A. Idilbi, Z.-B. Kang, I. Vitev, PRD 89 074013(2014)

Size of the TMD evolution still uncertain

-> terms calculable from QCD + non-perturbative terms (need data)

A global fit to the EIKV prediction (largest predicted evolution effect):

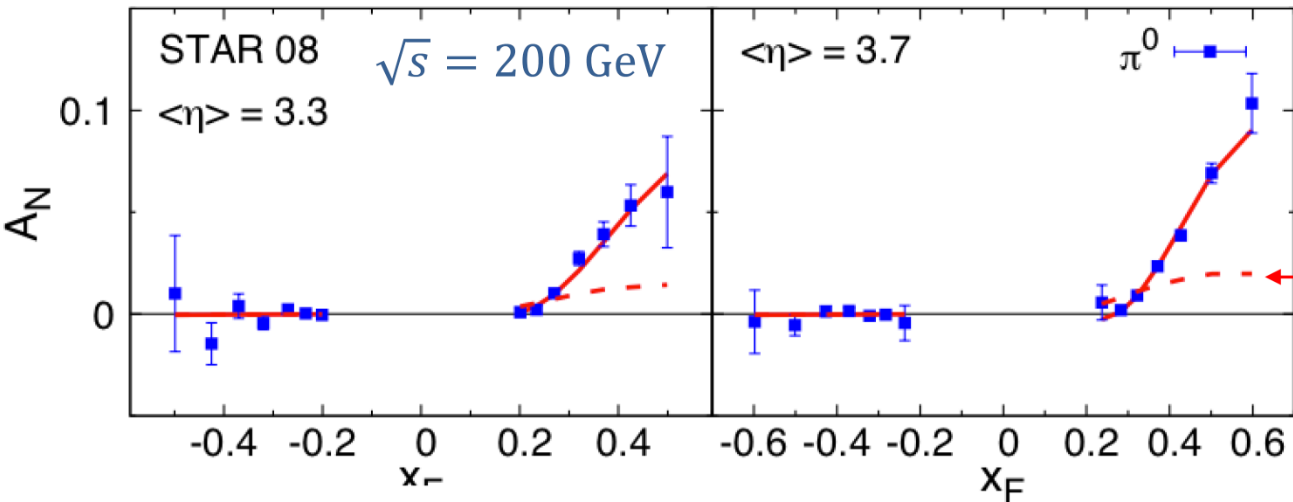
- **solid line:** assumption of a sign change in the Sivers function → χ^2**/d.o.f. = 10.26/6**
- **dashed line:** assumption of no sign change in the Sivers function → χ^2**/d.o.f. = 11.93/6**

Our uncertainties are still too high to compare with predictions

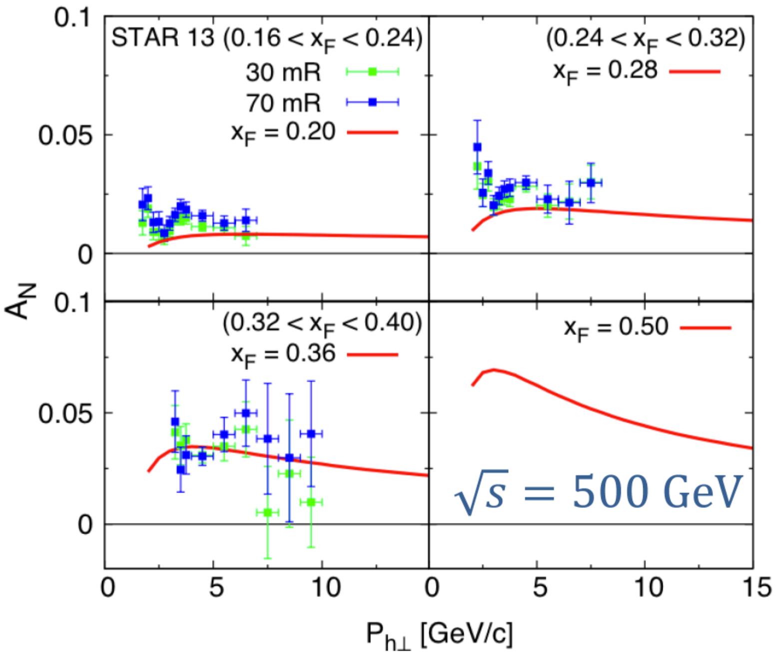
W/Z Transverse Asymmetries

- Reconstruction of W vastly improves ability to address Sivers "sign change"
- Data currently favors sign change
- Data agreement with sign change implies either slow Q^2 evolution or cancellation of Q^2 in polarized/unpolarized ratio
- Factor of 10 more data planned for 2017 along with upgrades to do DY/γ in forward direction

Forward Pion Asymmetries and Twist-3



$\widehat{H}_{FU}^{\Im}$ switched off



Kanazawa et al, PRD 89 111501 (2014)

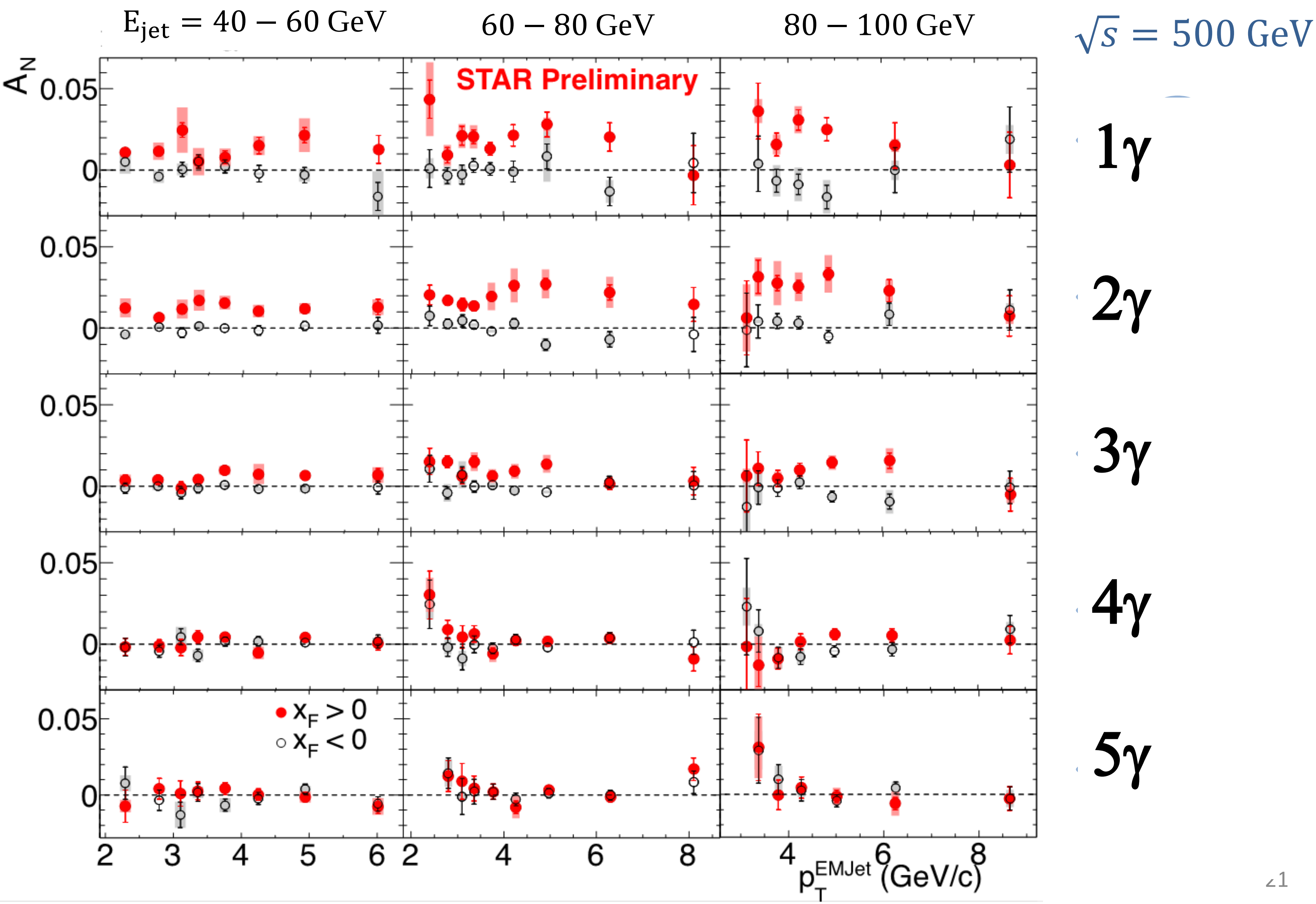
Collinear twist-3 factorization

$$\widehat{H}^{h/q}(z) = z^2 \int d^2\vec{k}_\perp \frac{\vec{k}_\perp^2}{2M_h^2} H_1^{\perp h/q}\left(z, z^2\vec{k}_\perp^2\right)$$

and additional input from SIDIS and $e^+e^- \to h_1 h_2 X$

$\widehat{H}_{FU}^{\Im}$ directly related to average k_T in fragmenting parton

Event Topology: Forward TSSAs



Event Topology

- Twist-3 + TMDs currently favored for generating large asymmetries in forward direction. No simple interpretation but largest piece directly related to average k_T in fragmenting parton.
- Forward Asymmetries large for single pions
- Disappears rapidly with increasing amount of energy in event (including energy at mid-rapidity as well)
- Casts doubt on 2->2 parton interpretation of origin of asymmetries
- Roman Pot data taken in 2015/2017 will address diffractive nature of events with high asymmetry by tagging intact protons from collisions

Polarized $\vec{p} + A$ collisions

Original predictions:

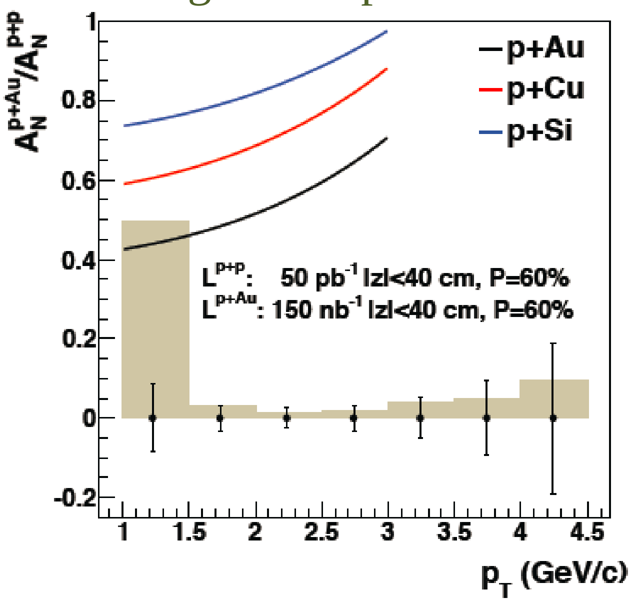
Kang and Yuan, Phys. Rev. D84, 034019 (2011)

Transverse asymmetries are sensitive to gluon saturation:

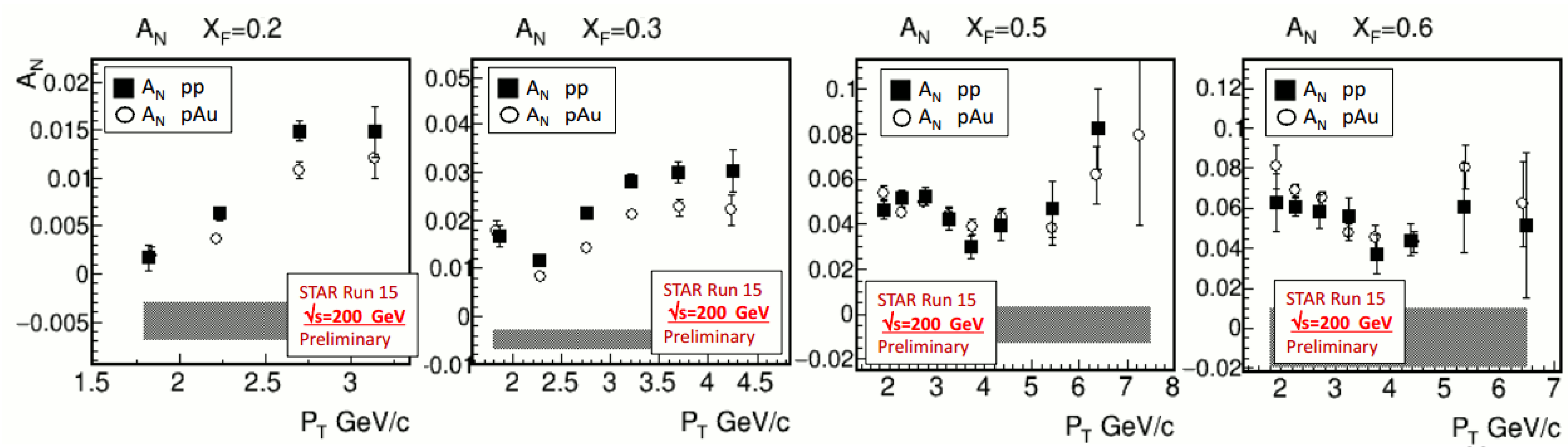
$$Q_S^A = A^{1/3} \cdot Q_S^p$$

$$Q_S^p = 1\text{ GeV}$$

original π^0 predictions:



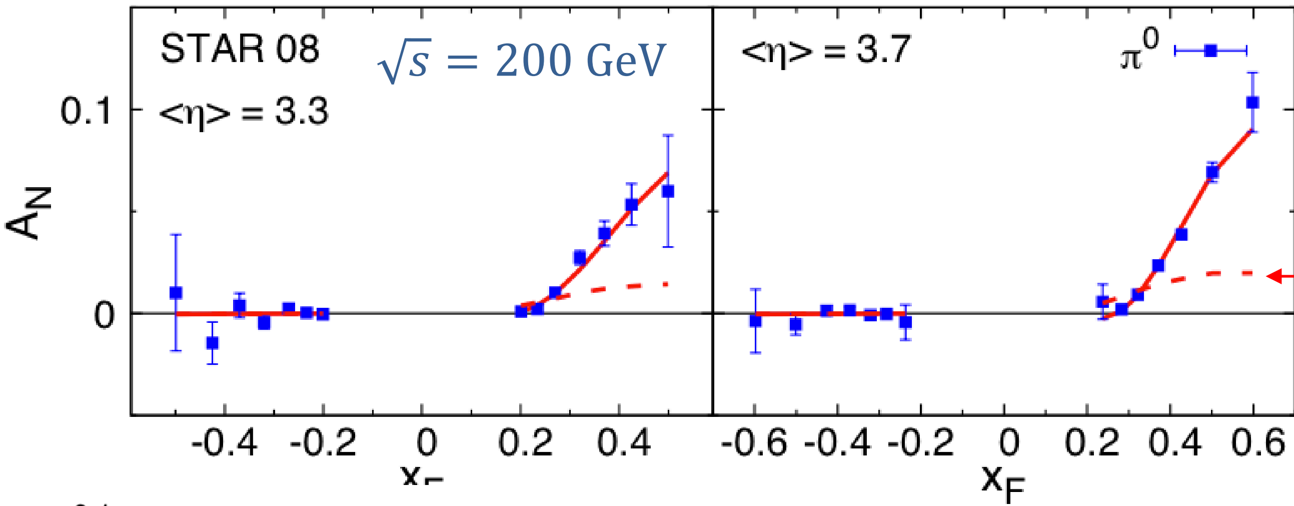
However! Hatta et al., arXiv1606.08640v1 finds that nuclear effects cancel in forward direction and predict A_N^{pA} / A_N^{pp} ~ 1



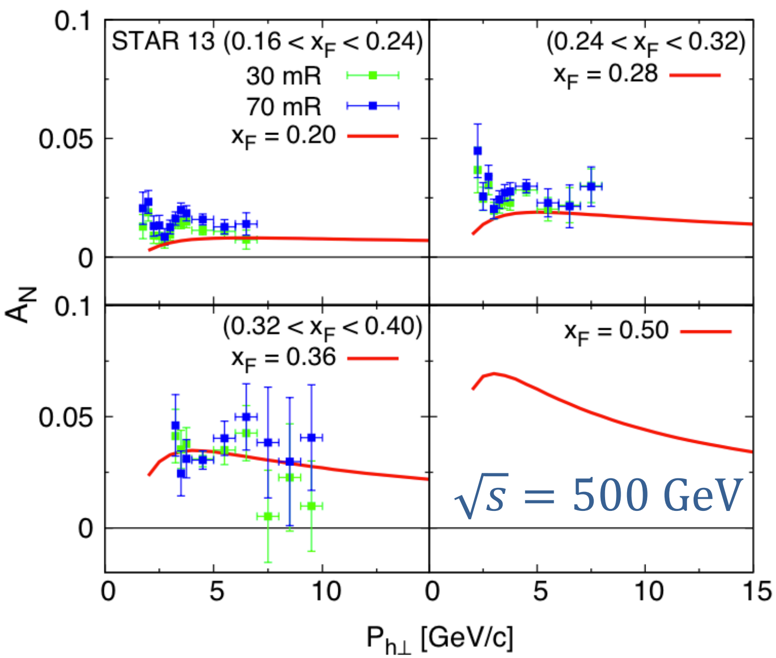
Conclusions: TMDs and STAR

- RHIC/STAR data can address Transversity, Sivers, Collins and Twist-3.
- Examine Sivers sign change in W/Z & DY
- Measurements of Transversity in di-hadron IFF
- Measurements of Collins and Transversity in Jets.
- Twist-3 in Forward pion SSAs
- Early understanding of Q^2 /k_T evolution
- Can use asymmetries in pA/pp to explore nuclear modification/saturation: Forward A_N and Collins
- Solid basis for detailed exploration by EIC

Forward Pion Asymmetries and Twist-3



$\widehat{H}_{FU}^{\Im}$ switched off



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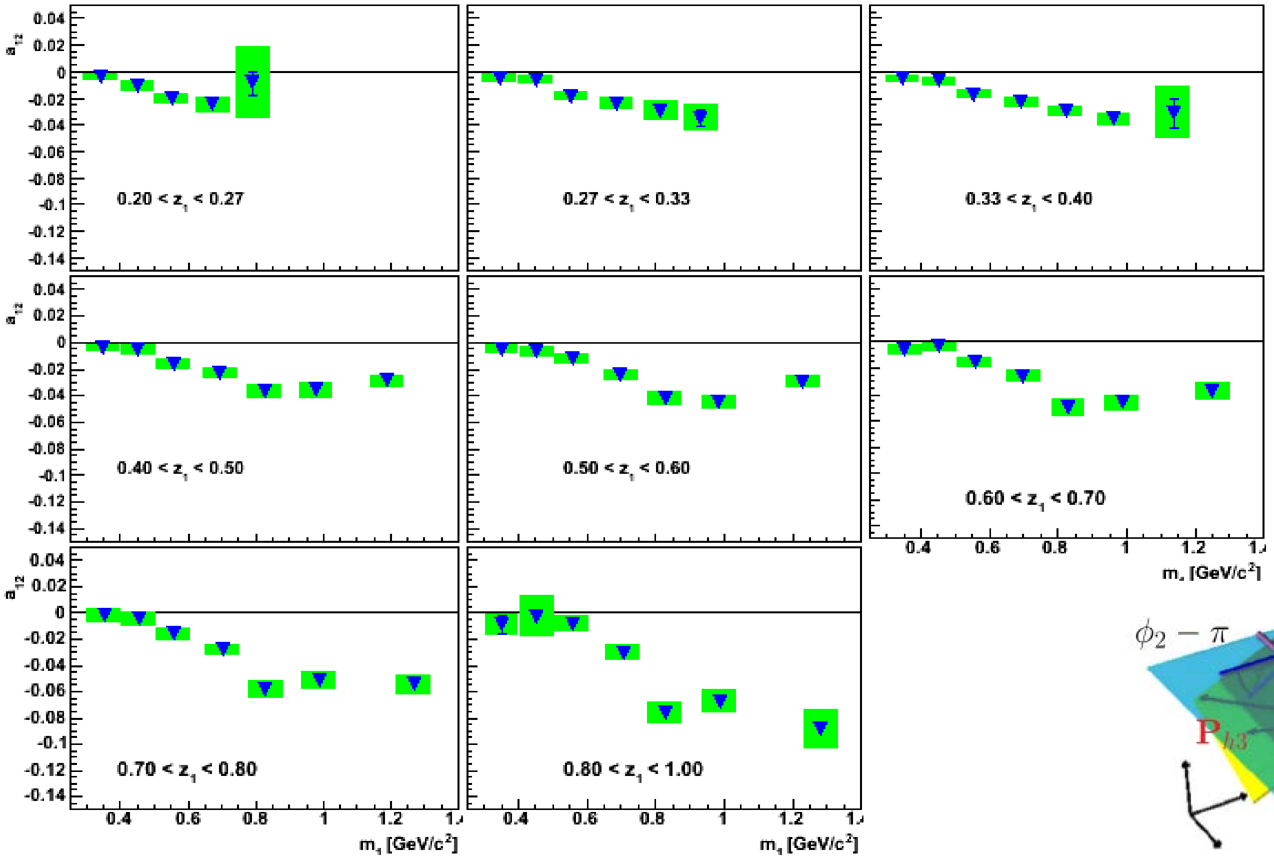
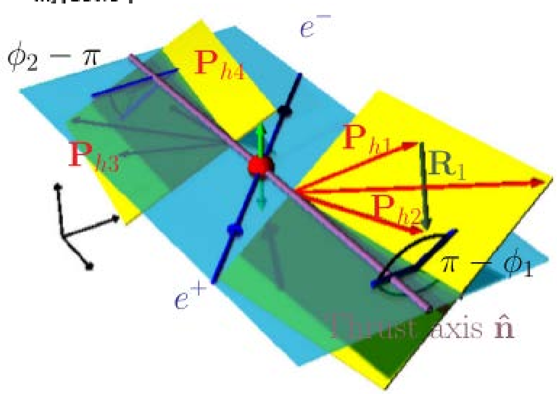
and additional input from SIDIS and $e^+e^- \to h_1 h_2 X$

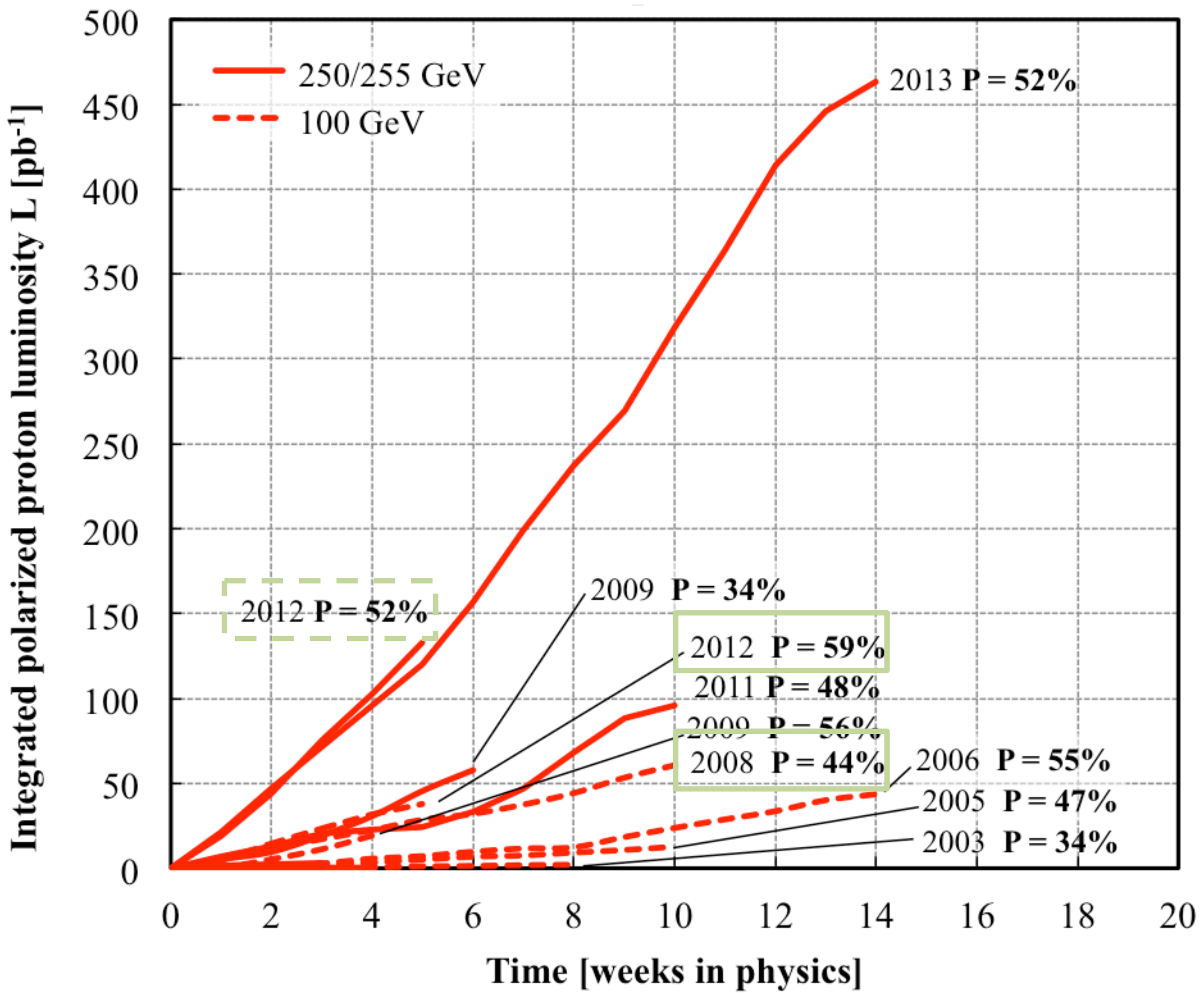
$\widehat{H}_{FU}^{\Im}$ directly related to average k_T in fragmenting parton

Mid-rapidity di-hadron production

Interference Fragmentation Function measured in e^+e^- annihilation at the Belle facility at KEK, Japan





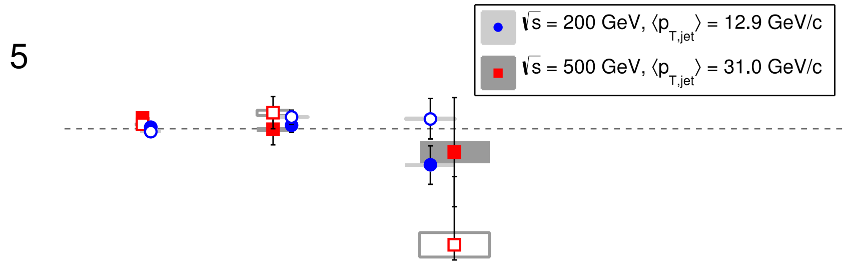


Goal for 2015: PHENIX 40 pb^{-1}, STAR 50 pb^{-1}

Final state mechanism: Transversity x Collins

$$A_{UT}^{\pi^\pm} \approx \frac{h_1^{q_1}(x_1,k_T) f_{q_2}(x_2,k_T)\hat{\sigma}_{UT}(\hat{s},\hat{t},\hat{u})\Delta D_{q_1}^{\pi^\pm}(z,j_T)}{f_{q_1}(x_1,k_T) f_{q_2}(x_2,k_T)\hat{\sigma}_{UU} D_{q_1}^{\pi^\pm}(z,j_T)} \qquad z = \frac{p_t^h}{p_t^{jet}}$$

$$p^\uparrow + p \rightarrow jet + \pi^\pm + X$$



200 vs. 500 GeV Comparison:

- These measurements coupled with the interference fragmentation function (IFF) measurements at both 200 and 500 GeV are **sensitive to the evolution and universality of TMD functions.**
- These results could be sensible to the size of potential factorization-breaking in Collins in p+p.
- dependence of the Collins FF on pion transverse momentum (j_T)

What we see

Non-zero Collins asymmetry

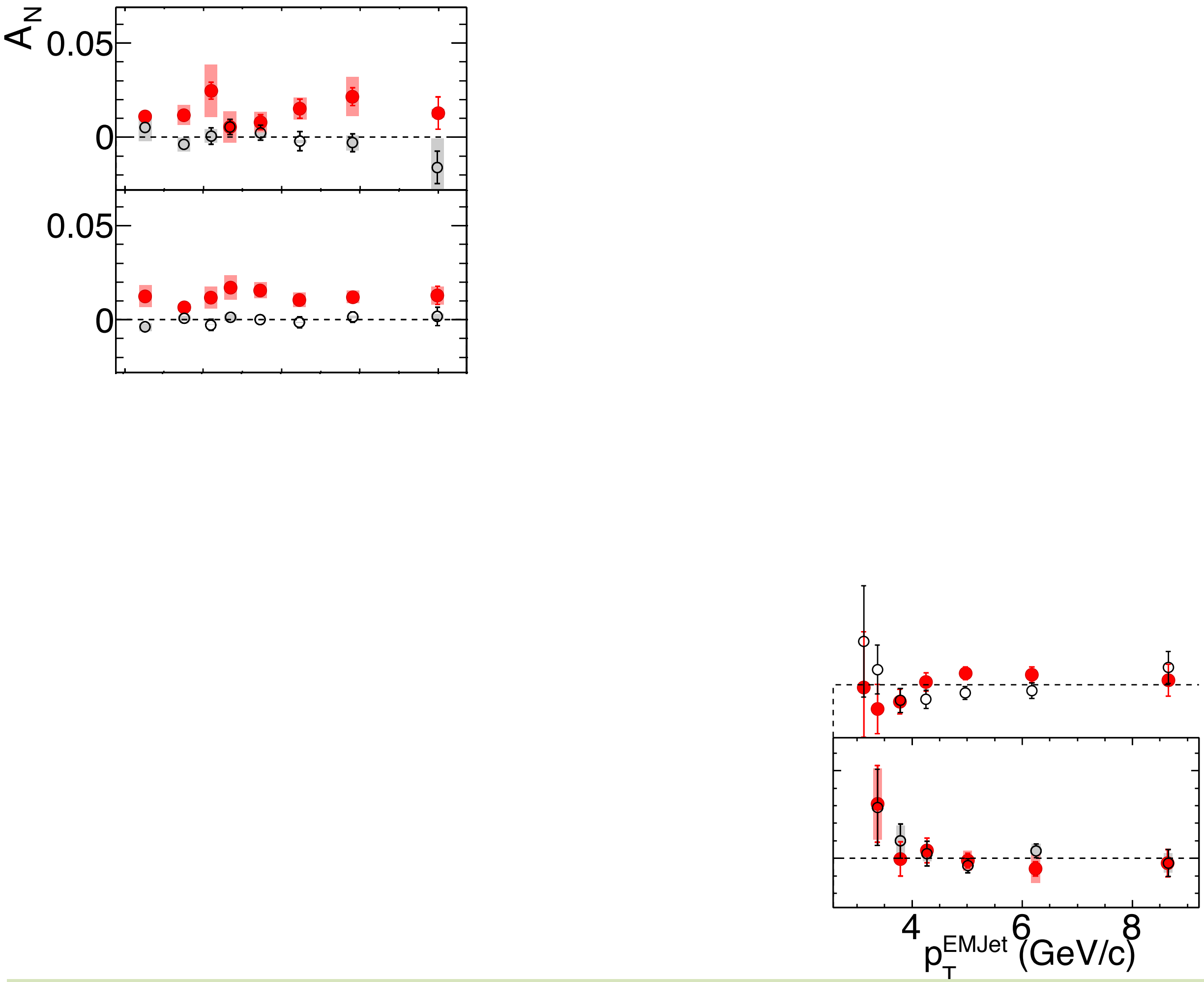
-> Access to transversity!

Similar size asymm. in 200 and 500 GeV

-> Small TMD evolution?

-> Cancellation in num/denom may also be the key

Diffraction Effects as Source of Forward TSSA?



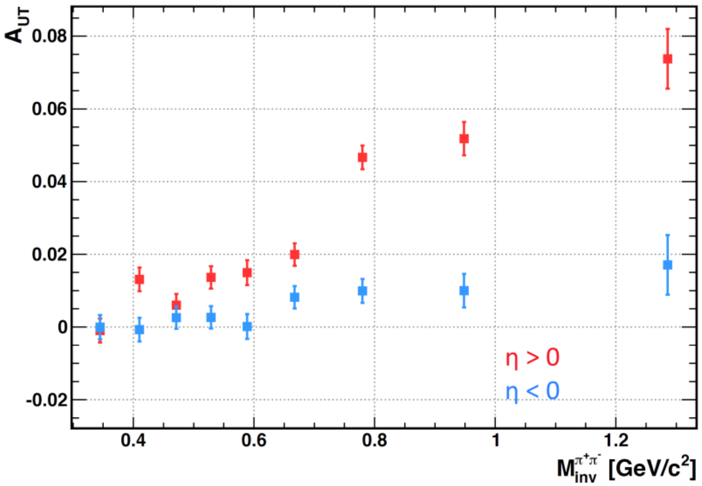
Jettier events

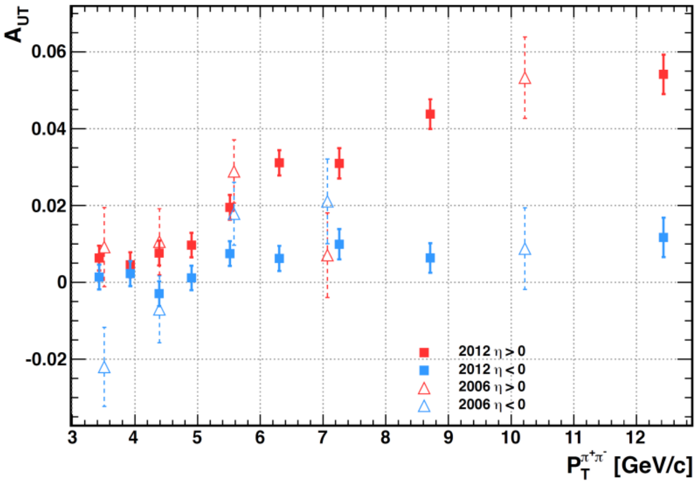
A_N for different # photons in EM-Jets

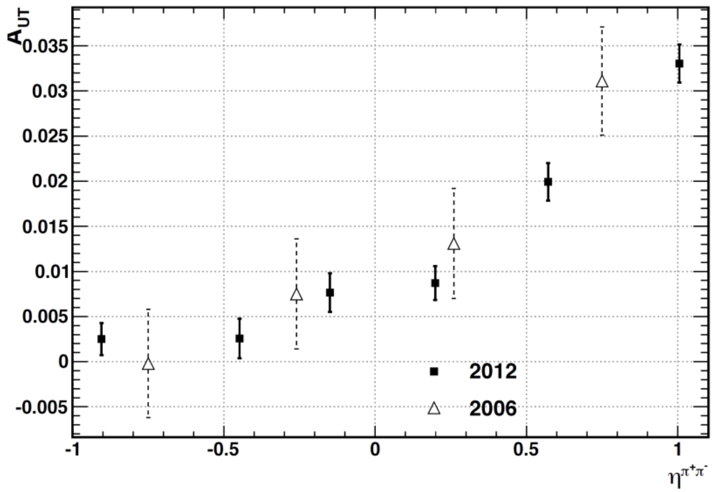
- 1-photon events, which include a large π^0 contribution in this analysis, are similar to 2-photon events
- Three-photon jet-like events have a clear non-zero asymmetry, but substantially smaller than that for isolated π^0's
- A_N decreases as the event complexity increases (i.e.,the "jettiness")
- Several other Asym. for jettier events are also very small. Collins contribution is ~1% over the entire x_F range

- Sivers-type asymmetry in the jets is too small to explain π^0 asymmetry
- A_N for π^0 may be dominated by hard diffraction: $p^{\uparrow}+p \rightarrow \pi^0 + p' + X$
- Run 15 – STAR has collected data using RPs to measure forward scattered protons

IFF 200 GeV 1D Binning







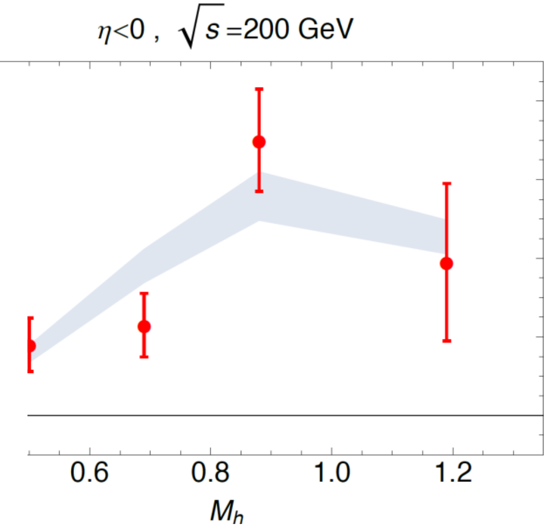
STAR/RHIC and TMDs

- Measure Transversity, Collins and Sivers
- Complements SIDIS and e+e-
- Addresses consistency of measurements
- Adresses fundamental QCD questions
  - Applicability of pQCD
  - Factorization
  - Q^2 and k_T, j_T evolution
  - Validity of resummation
- New phenomenon in Forward Direction
- Saturation/Nuclear Modification effects in pA/pp

Compare Transversity from RHIC/SIDIS

PAVIA Group: Radici et al, arXiv: 1604.06585v1

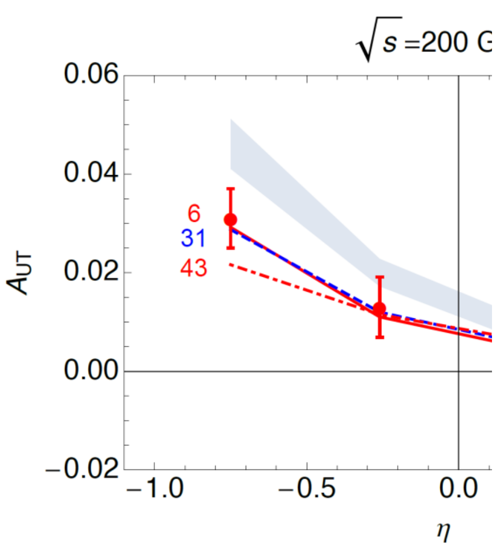
Compare STAR data with transv
replicas extracted from HERMES
SIDIS data and BELLE IFF Fragme
Functions

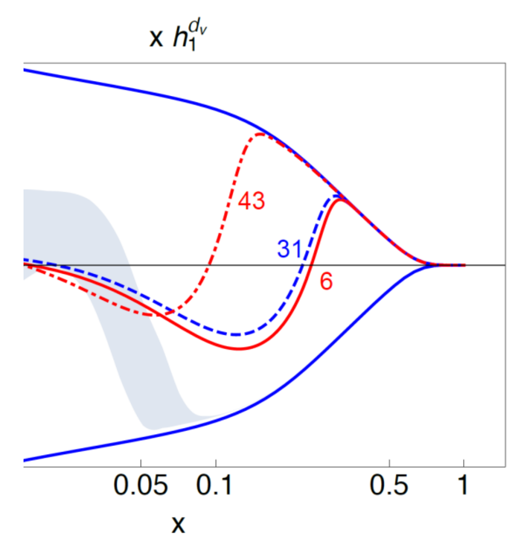


transversely polarized proton and deuteron targets. The dark solid lines with no labels represent the upper and lower limits of the Soffer bound. The plot corresponds to the darker band with solid borders in the right panel of Fig. 8 in Ref. [18]. The replicas in the band tend to saturate the lower limit of the Soffer bound because they are driven by the COMPASS deuteron data, in particular by the 7th and 8th bins in Ref. [18]. The light (red) solid line with label "6" reproduces the transversity from the corresponding replica. Similarly, the dashed (blue) line refers to replica "31", while the dot-dashed (red) line to replica "43".

Their trajectories do not follow the trend of the 68% band at large x. Rather, they deviate towards the upper Soffer bound and they saturate it. Hence, at large $x \gtrsim 0.1$ there seems to be a tension between the COMPASS deuteron data and the STAR data for forward asymmetries. However, this tension concerns at most two bins in x of the SIDIS analysis. It is reasonable to expect that when more data for semi-inclusive $(\pi^+\pi^-)$ production will become available (particularly from the analysis of runs 2011 and 2012 for proton-proton collisions at c.m. energies of $\sqrt{500}$ and $\sqrt{200}$ GeV, respectively, by the STAR collaboration) and a global fit of SIDIS, e^+e^-, and proton-proton collisions will become feasible, the above two bins in x from the SIDIS deuteron data will become statistically less relevant and the above tension will most likely disappear.

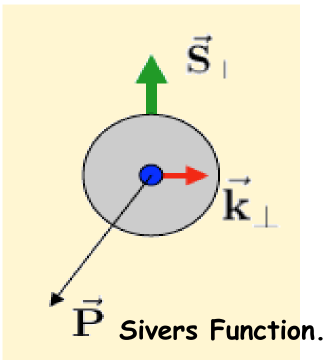
In summary, for the first time we have exposed the predicted connection between the experimental evidence of transverse-spin azimuthal asymmetries in the distribu-

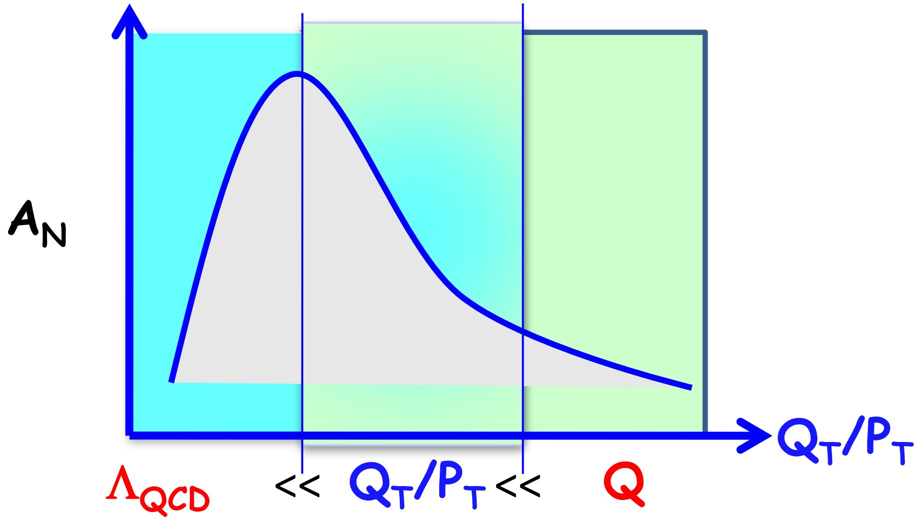




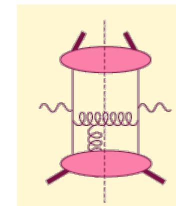
Initial state: TMDs and Twist-3

TMD





Twist-3



Efremov, Teryaev;
Qiu, Sterman
or
Twist-3 FF

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

SIDIS, Drell-Yan, W/Z, …

Access the full transverse momentum dynamics k_T

Single hard scale: p_T

Appropriate for inclusive $A_N(\pi^0, \gamma, \text{jet})$

Access the average transverse momentum $\langle k_T \rangle$

$$-\int d^2k_\perp \frac{{k_\perp}^2}{M} f_{1T}{}^{\perp q}(x, {k_\perp}^2)|_{SIDIS} = T_{q,F}(x,x)$$

Process Dependence of Sivers Function: Sign Change

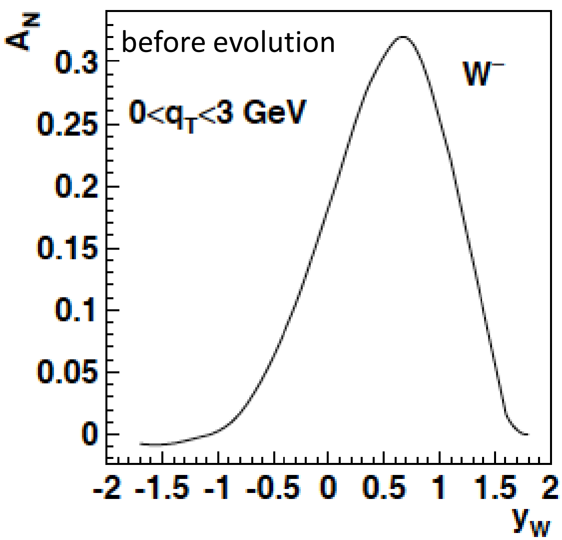
In semi-inclusive deep inelastic scattering (SIDIS), the Sivers function is associated with a final-state effect through gluon exchange between the struck parton and the target nucleon remnants [4]. In p+p collisions, on the other hand, the Sivers asymmetry originates from the initial state of the interaction for the DY process and W±/Z0 boson production.

$$f_{q/h^\uparrow}^{\mathrm{SIDIS}}(x, k_T, Q^2) = -f_{q/h^\uparrow}^{p+p\to \mathrm{DY}/W^\pm/Z^0}(x, k_T, Q^2)$$

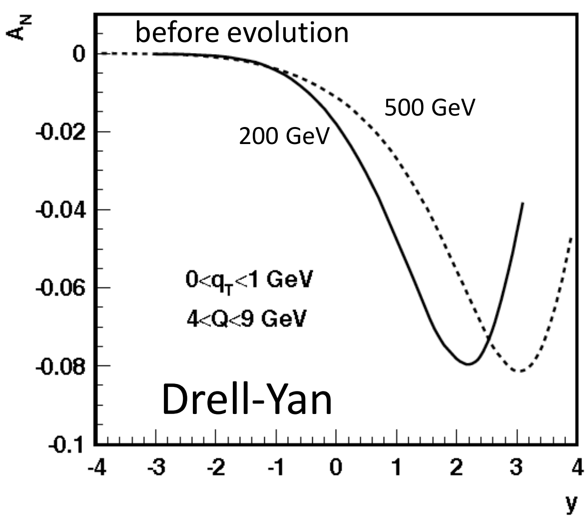
DY and $W^\pm$, Z^0 production in $p+p$ collisions provide the two scales required to apply the TMD framework to transverse single-spin asymmetries. A hard scale is given by the photon virtuality (Q^2) or by the mass of the produced boson ($M^2 \sim Q^2$), while a soft scale of the order of the intrinsic k_T is given by the transverse momentum.

TMD Evolution & Sea-quarks Sivers

Z.-B. Kang & J.-W. Qui arXiv:0903.3629

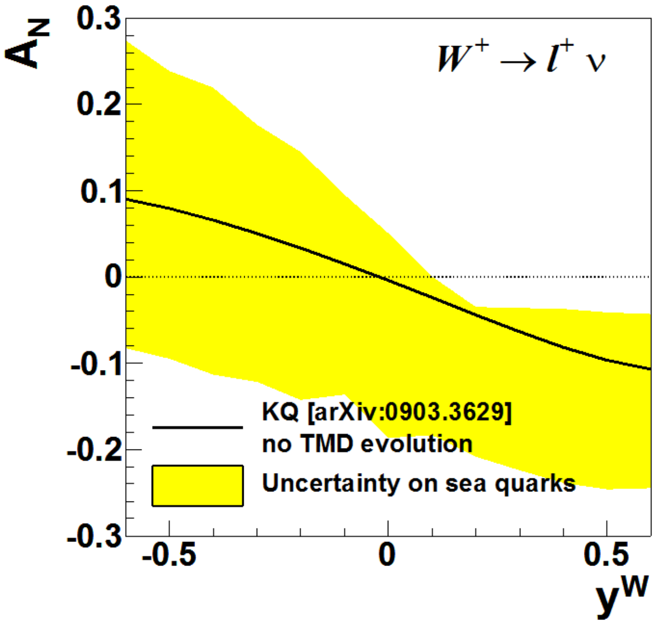


Z.-B. Kang & J.-W. Qui Phys.Rev.D81:054020,2010



- **Size of the TMD evolution effect still under discussion in theory community**

For details see
J. Collins, T. Rogers, Phys.Rev. D91 (2015) 7, 074020

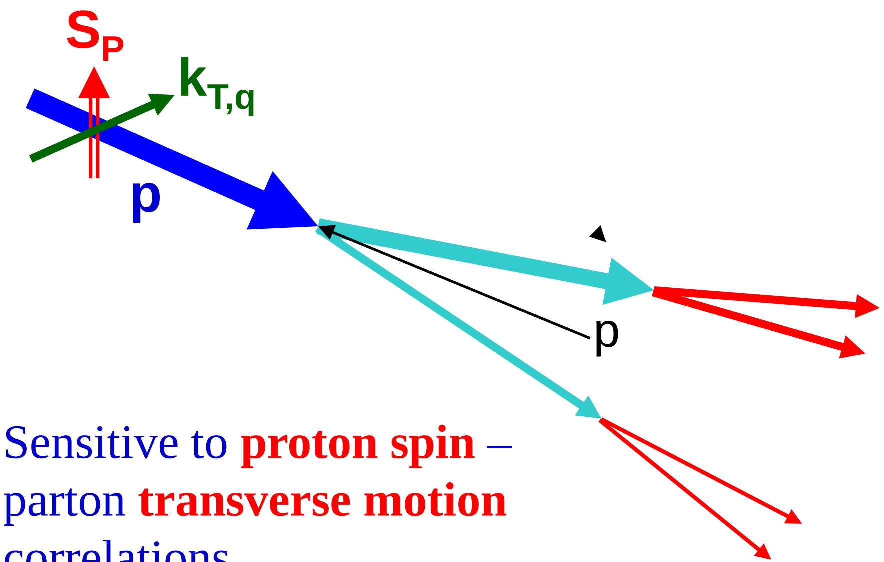


- **What is the sea-quark Sivers function?**
  - → ***Sea quarks are mostly unconstrained from existing SIDIS data...*** ***but*** **they can give a relevant contribution!**
  - → W's ideal → rapidity dependence of A_N separates quarks from antiquarks

$W^{\pm}$ data can constrain the sea-quark Sivers function

Separating Initial- from Final-state Effects

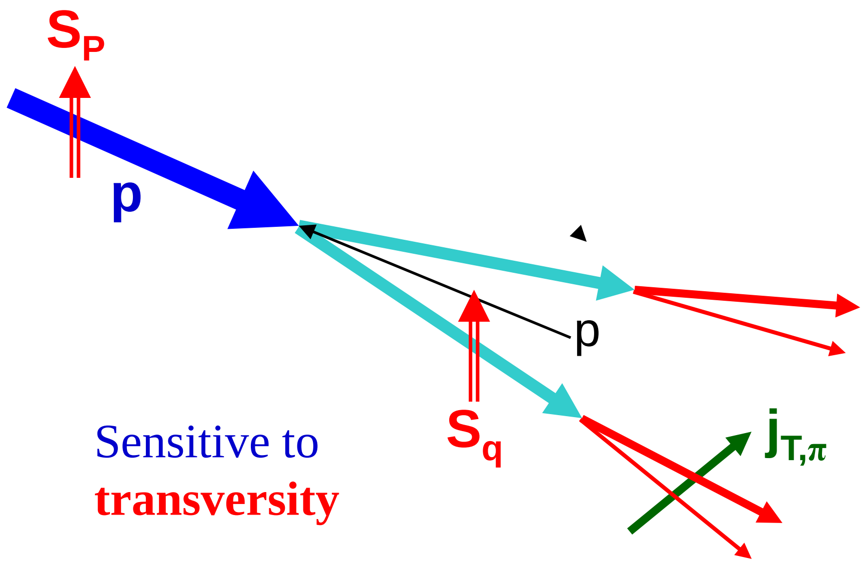
Sivers or Twist-3 Mechanisms:



Sensitive to **proton spin** – parton **transverse motion** correlations

- Signatures:
  - A_N for jets or direct photons
  - A_N for $W^{+/-}$, Z^0, Drell-Yan
  - A_N for heavy flavor (gluon)
  - x, k_T dependences in nucleon
- Sivers NOT universal
  - Sign change from SIDIS to W, Z, and Drell-Yan

Collins or Twist-3/Novel FF Mechanisms:



Sensitive to **transversity**

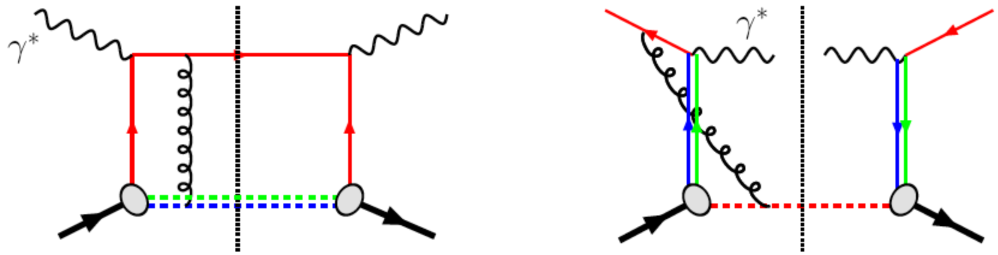
- Signatures:
  - Collins effect
  - Interference fragmentation functions (IFF)
  - A_N for pions → novel FF
  - z, j_T dependence within jet
- Collins predicted to be universal

Color interactions in QCD

Controlled non-universality of the Sivers function

QCD:

DIS	**Drell-Yan, W or Z**
Final-state interaction	**Initial-state interaction**



$\text{Sivers}_{\text{DIS}} = -\text{Sivers}_{\text{Drell-Yan}}$ or Sivers_{W} or Sivers_{Z}

A_N for direct photon has related sign change in Twist-3

Critical test of factorization

Opportunity to visualize the repulsive interaction between like color charges

Can explore all of these observables in 500 GeV pp collisions at RHIC

Polarization Effects: TMDs and FFs

nucleon \ quark	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$ (Sivers)	g_{1T}	h_1 (Transversity), $h_{1T}^{\perp}$

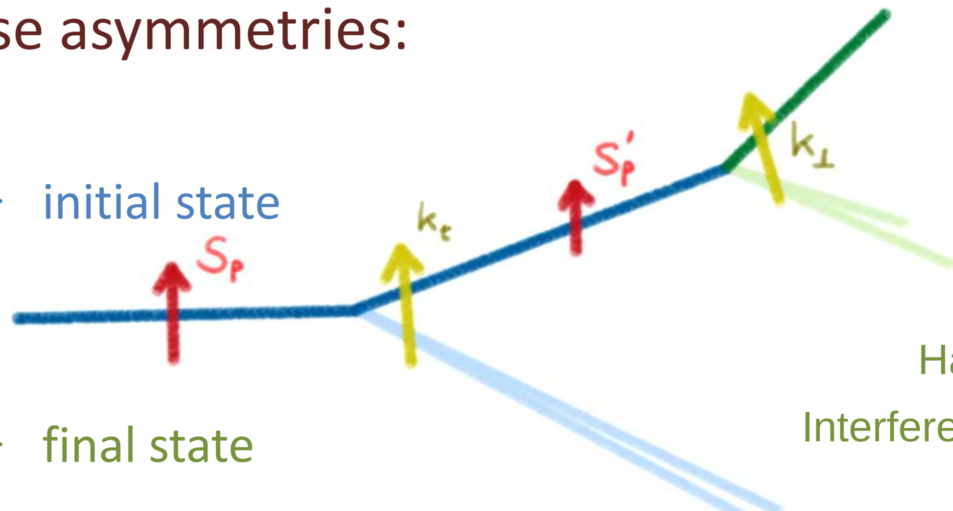
hadron \ quark	U	L	T
U	D_1		$H_1^{\perp}$ (Collins)
L		G_{1L}	$H_{1L}^{\perp}$
T	$H_{1T}^{\perp}$	G_{1T}	$H_1, H_{1T}^{\perp}$

Possible transverse asymmetries:

$f_{1T}^{\perp} \otimes f_1 \otimes D_1$
$h_1 \otimes h_1^{\perp} \otimes D_1$
$h_{1T}^{\perp} \otimes h_1^{\perp} \otimes D_1$
} initial state

$h_1 \otimes f_1 \otimes H_1^{\perp}$
$f_{1T}^{\perp} \otimes h_1^{\perp} \otimes H_1^{\perp}$
$h_{1T}^{\perp} \otimes f_1 \otimes H_1^{\perp}$
} final state

...



Inclusive hadrons
Direct photons
Jets
Jet structure
Hadron correlations
Interference fragmentation
Drell-Yan
W-bosons