Recent transverse spin results from STAR

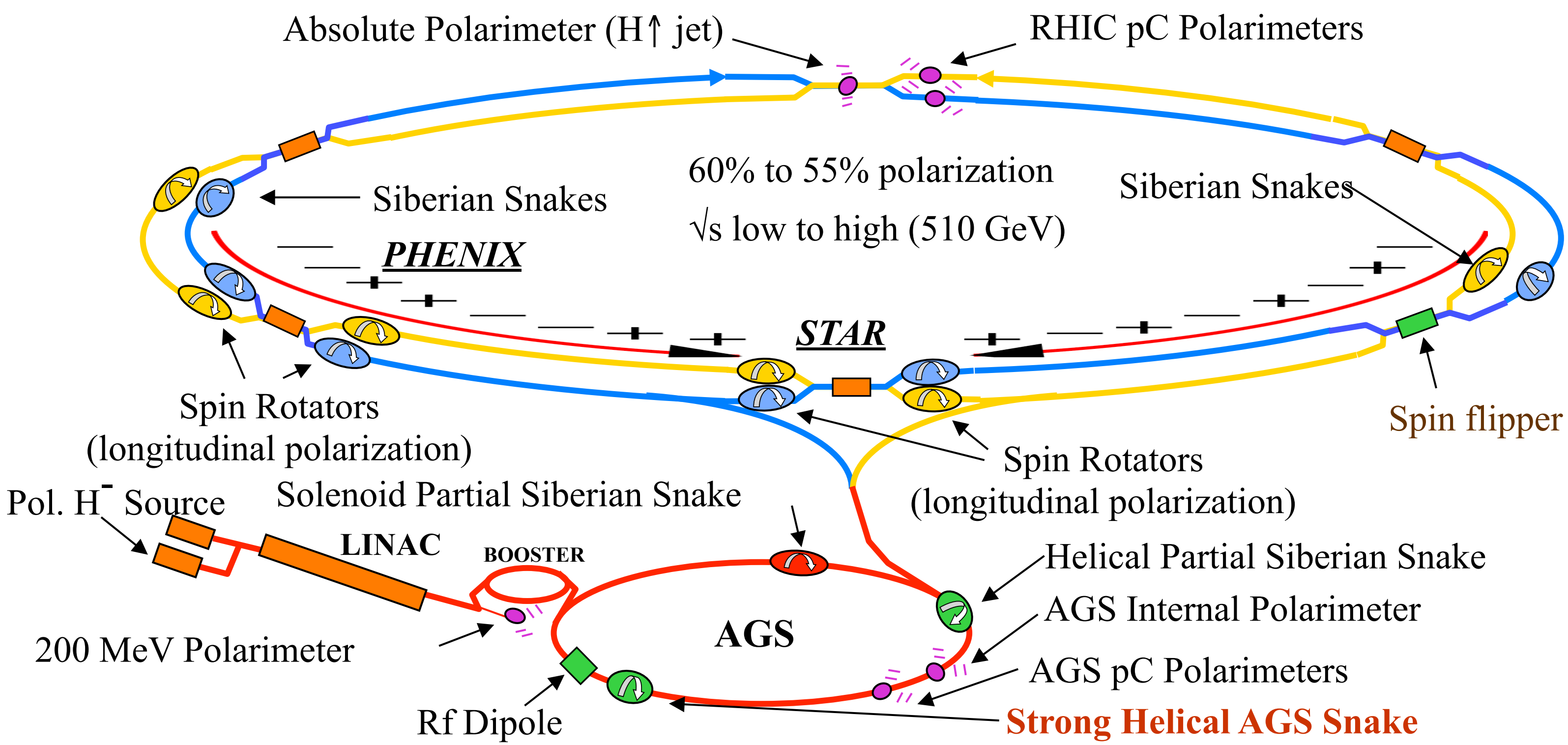
Qinghua Xu, Shandong University

PanSpin2015, Taipei, October 8, 2015

Outline

- Introduction
- Single spin asymmetries in the forward region
- Mid-rapidity hadron-jet correlations (Transversity+Collins)
- Di-hadron spin asymmetries (Transversity+IFF)
- Single spin asymmetries for weak bosons (Sivers)
- Summary & outlook

RHIC- the first polarized pp collider in the world



Data sets for transversely polarized pp

Year	√s (GeV)	Recorded Luminosity for transversely polarized *p+p* STAR	Recorded Luminosity for transversely polarized *p+p* PHENIX	<P> in %
2006	62.4	0.2 pb^{-1}	0.02 pb^{-1}	48
	200	8.5 pb^{-1}	2.7 pb^{-1}	57
2008	200	7.8 pb^{-1}	5.2 pb^{-1}	45
2011	500	25 pb^{-1}	---	53/54
2012	200	22 pb^{-1}	9.7 pb^{-1}	61/58
2015	200	50 pb^{-1}	40 pb^{-1}	60

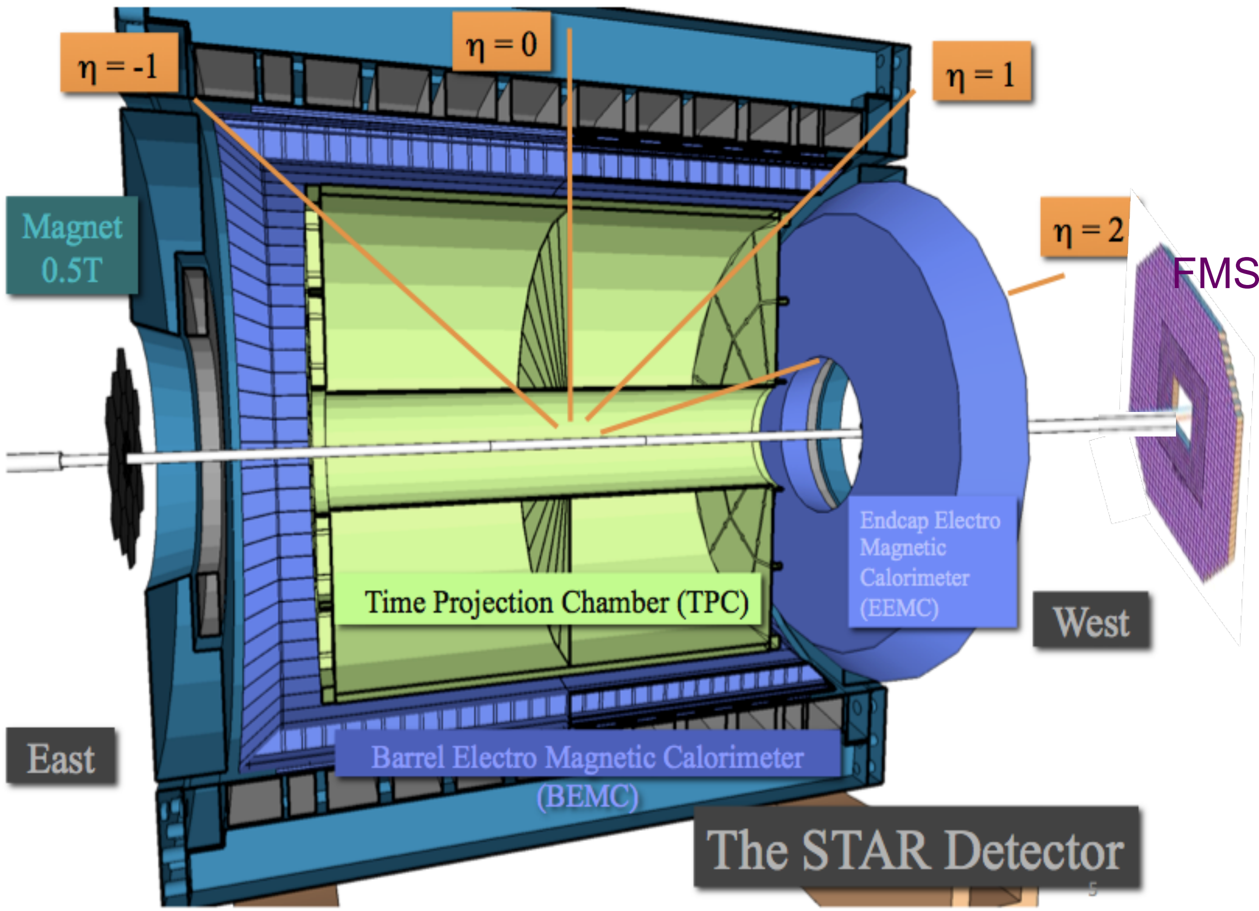
STAR - Solenoid Tracker At RHIC

Magnet
- 0.5 T Solenoid

Triggering & Luminosity Monitor
- Beam-Beam Counters
  - $3.4 < |\eta| < 5.0$
- Zero Degree Calorimeters
- Vertex Position Detector

Central Tracking
- Large-volume TPC
  - $|\eta| < 1.3$

Calorimetry
- Barrel EMC (Pb/Scintilator)
  - $|\eta| < 1.0$
- Endcap EMC (Pb/Scintillator)
  - $1.0 < \eta < 2.0$
- Forward Meson Spectrometer(Pb/Glass)
  - $2.5 < \eta < 4.0$



Tai Sakuma, Thesis, MIT (2010)

Mechanisms for Transverse Single-spin Asymmetries

- Anomalously large A_N observed for nearly 40 years:

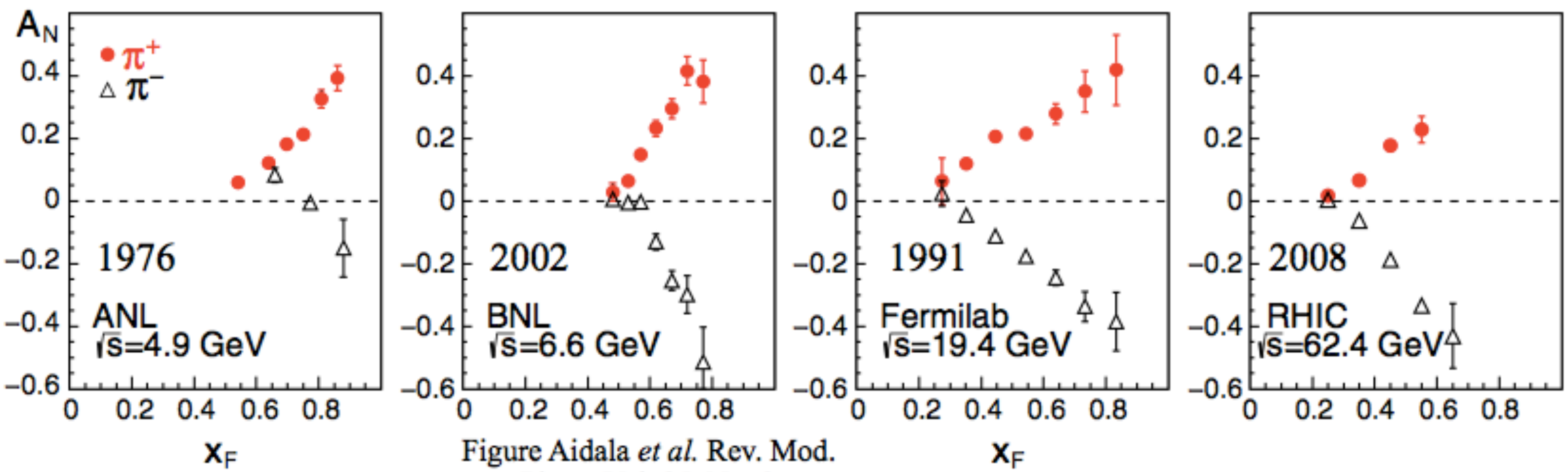


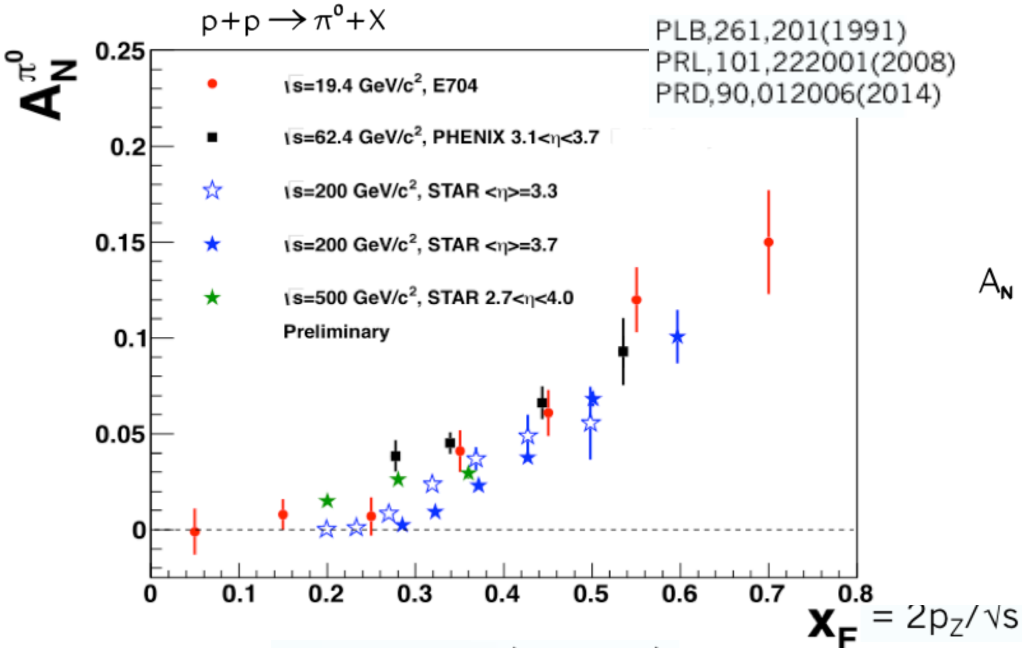
Figure Aidala *et al.* Rev. Mod. Phys., Vol. 85, No. 2

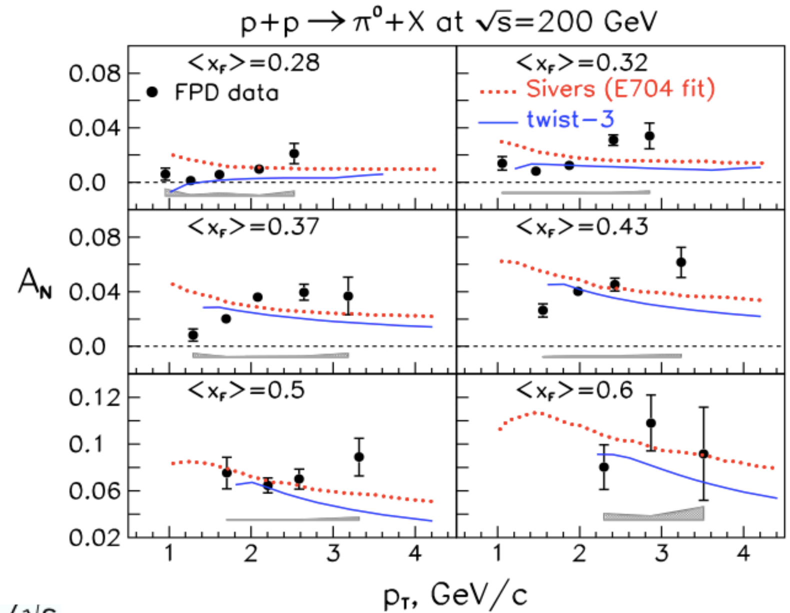
- Sivers effect (*Sivers'90*):
  parton spin and $k_\perp$ correlation in initial state (related to orbital angular momentum)
- Collins effect (*Collins'93*):
  quark spin and k_T correlation in fragmentation process (related to transversity)

Need two scales (Q and p_T), Q>>p_T

- Twist-3 mechanism (*Efremov-Teryaev'82, Qiu-Sterman'91*):
  Collinear/twist-3 quark-gluon correlation + fragmentation functions
  Need one scale (Q or p_T), Q, p_T>>Λ_{QCD}
  Both mechanisms apply when **Q>>p_T>>Λ_{QCD}** Ji-Qiu-Vogelsang-Yuan,2006

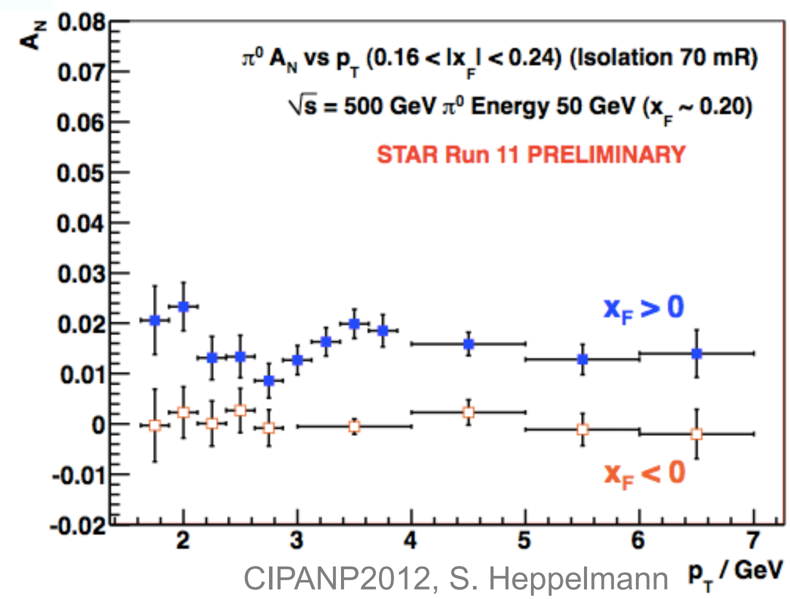
π^0 A_N in the forward region





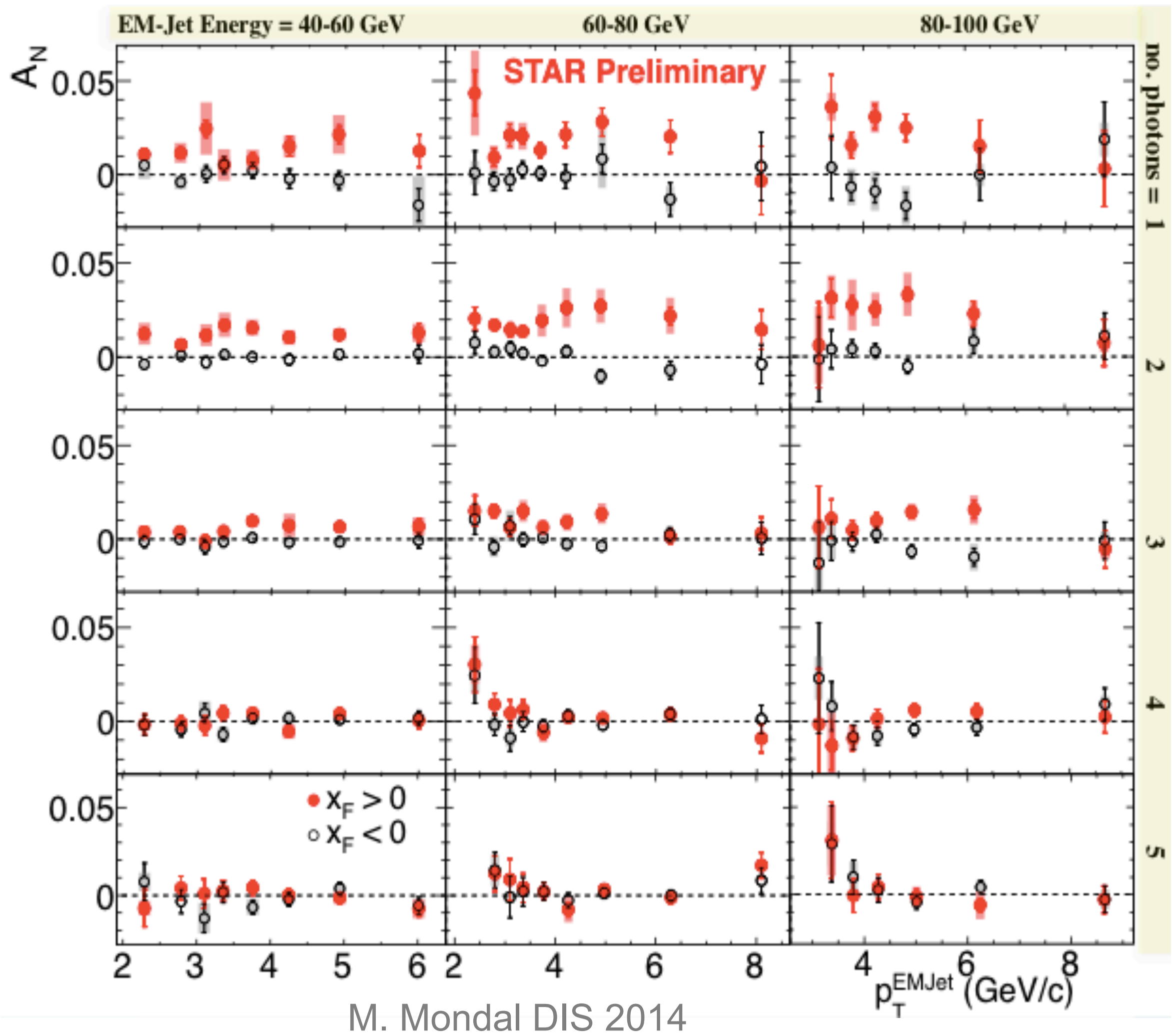
$$A_N \equiv \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

- Rising A_N with X_F
- A_N nearly independent of $\sqrt{s}$
- A_N persist at high p_T, no falling evidence.



Detailed structure for forward π^0 A_N

- A_N for forward EM events: dependence on "jettiness":



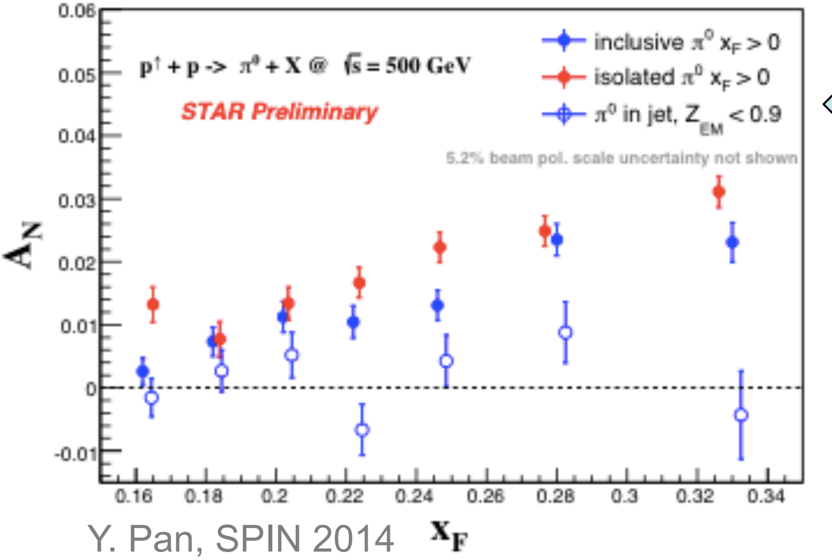
1-photon events, which include a large π0 contribution, are similar to 2-photon events

Three-photon jet-like events have a clear non-zero asymmetry, but substantially smaller than that for isolated π0's

A_N decreases as the event complexity increases(i.e., the "jettiness")

2011 data, 22 pb^{-1} at 500 GeV, anti-k_T jet algorithm on FMS photons, R = 0.7

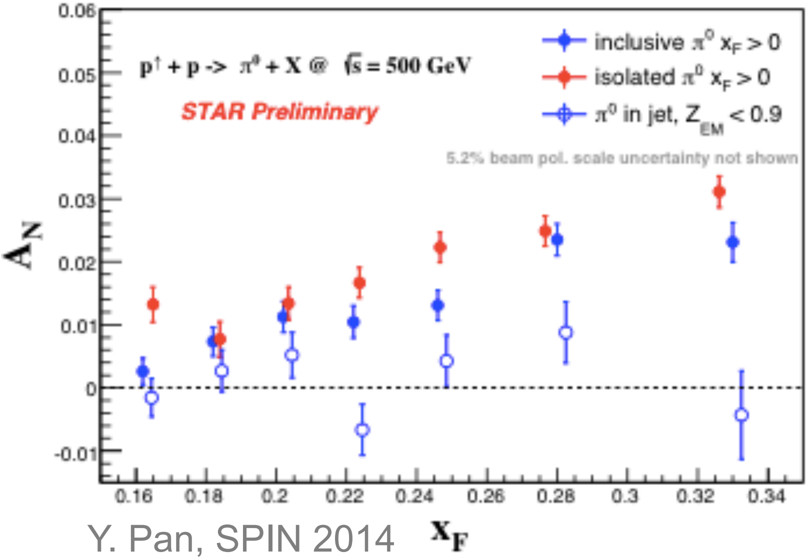
Detailed study for forward π^0 A_N



Y. Pan, SPIN 2014

EM Jets with isolated π^0 have larger asymmetry.

Detailed study for forward π^0 A_N



Y. Pan, SPIN 2014

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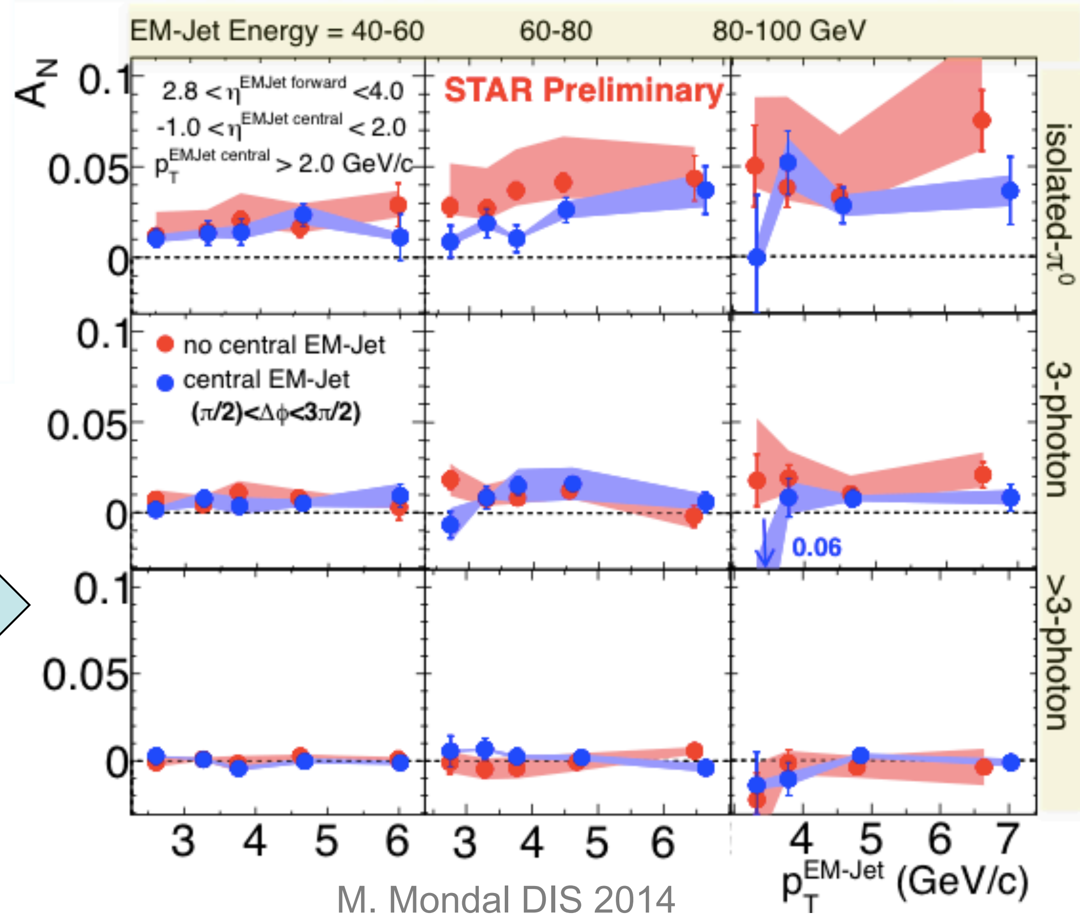


A_N for **correlated central jets** and **no central jet** cases.

A_N of isolated π^0 are lower when there is a correlated away -side jet

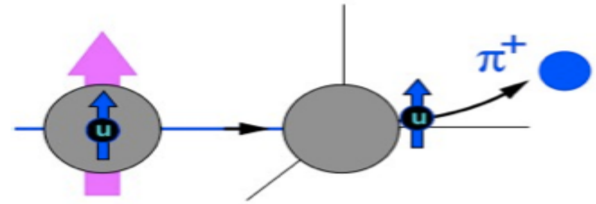
M. Mondal DIS 2014

How much of the large forward π^0 A_N comes from partonic scattering?

->diffractive effect? New Roman pots at STAR

Mid-rapidity hadron-jet correlations (Collins)

- Study proton transversity through its coupling to Collins function:



$$A_{UT} \propto \mathbf{h_1(x)} \otimes \mathbf{H_1^{\perp}(z, j_T)}$$

- Collins asymmetries:

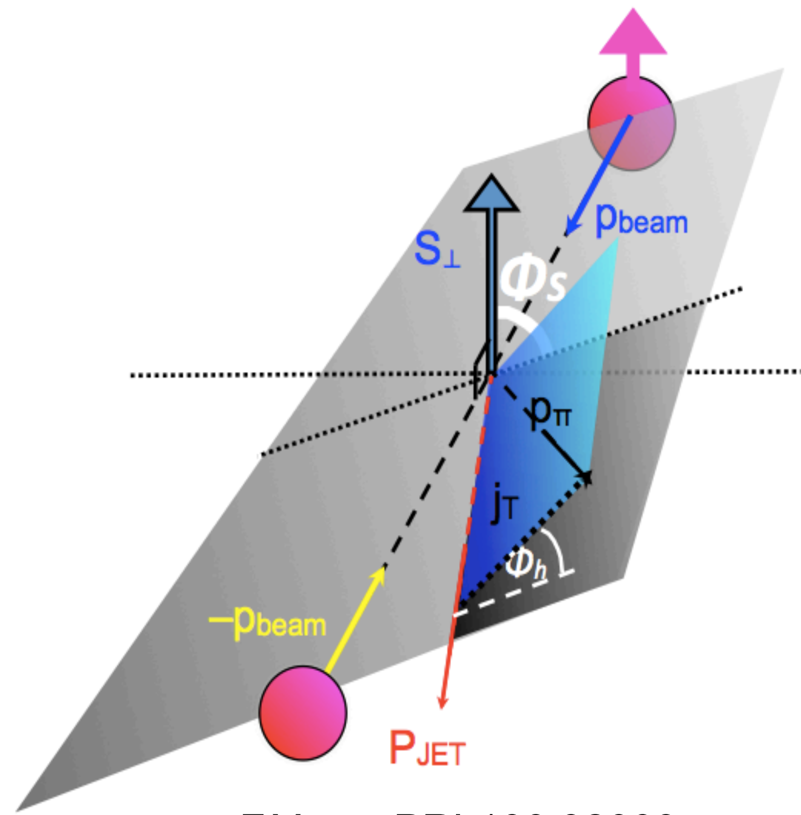
Collins angle: $\Phi_c=\Phi_s-\Phi_h$

Collins modulation: $\sin(\Phi_s-\Phi_h)$

j_T: transverse momentum in jet

Φ_s: azimuthal angle of beam spin

Φ_h: azimuthal angle of hadron

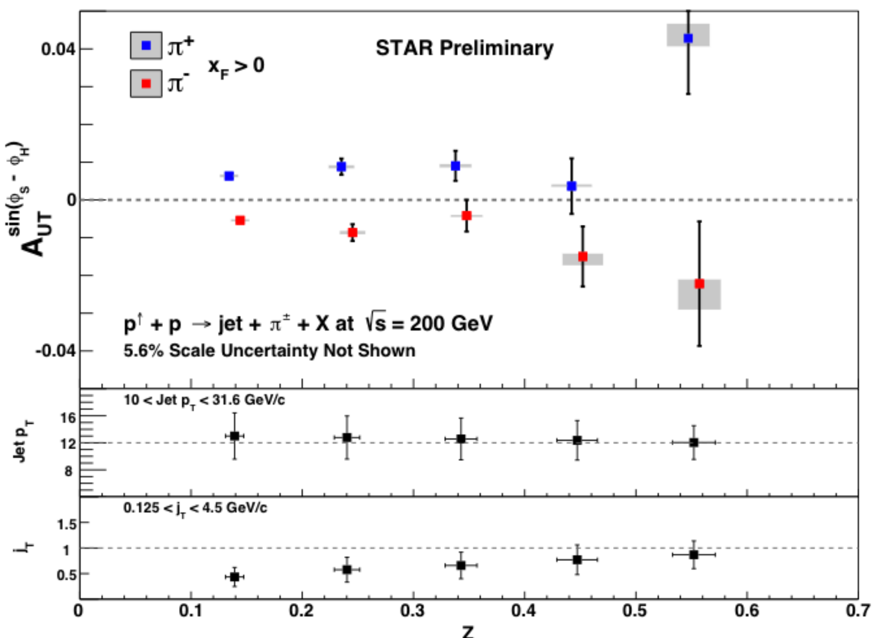


-F.Yuan, PRL100,32003

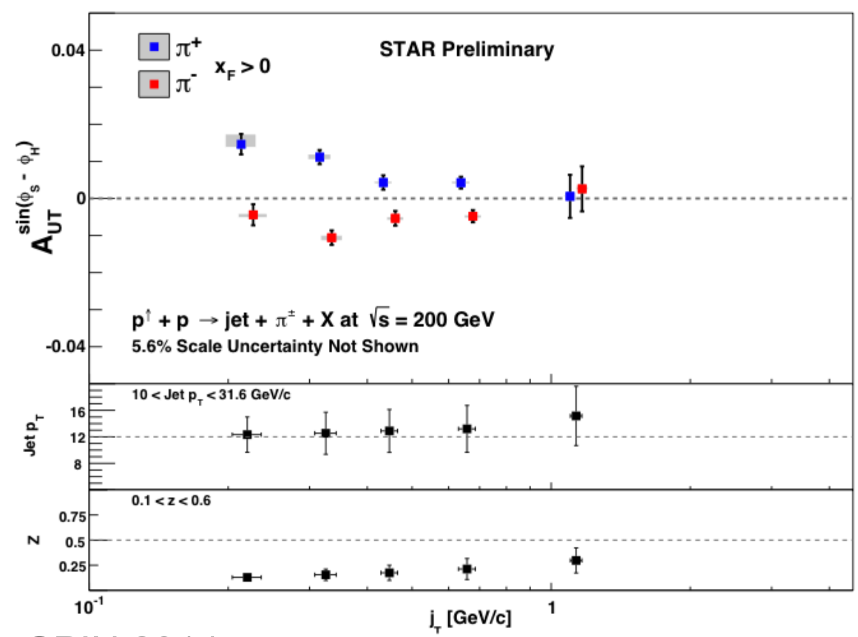
Mid-rapidity hadron-jet correlations (Collins)

- Non-zero Collins asymmetries observed from run2012 200 GeV

A_{UT} vs. z for $x_F > 0$



A_{UT} vs. j_T for $x_F > 0$

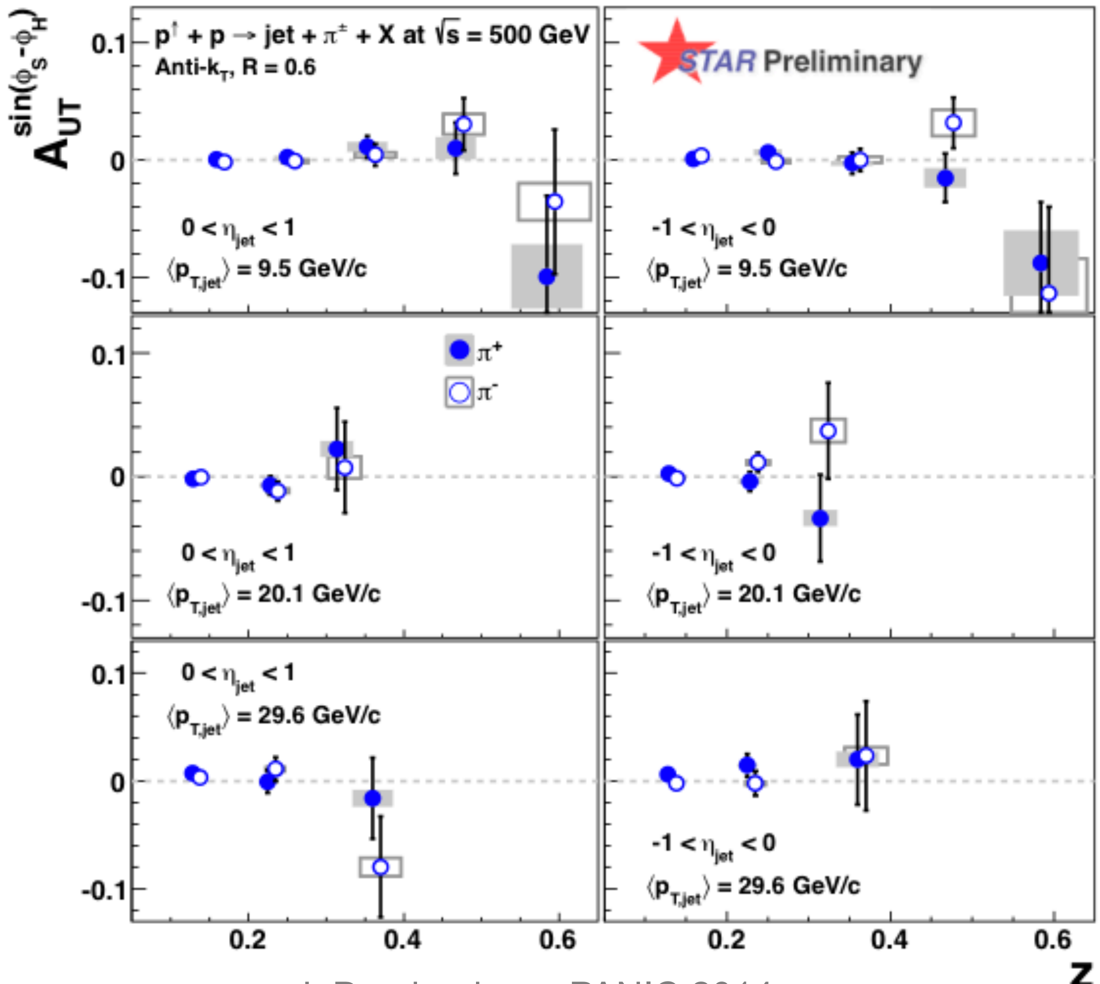


J.K. Adkins, SPIN 2014

2012 data, 20 pb^{-1} at 200 GeV, Pb=61%, anti-k_T jet algorithm, R = 0.7

Collins asymmetries at 500 GeV

Zero asymmetry at 500 GeV? High Q^2 ?

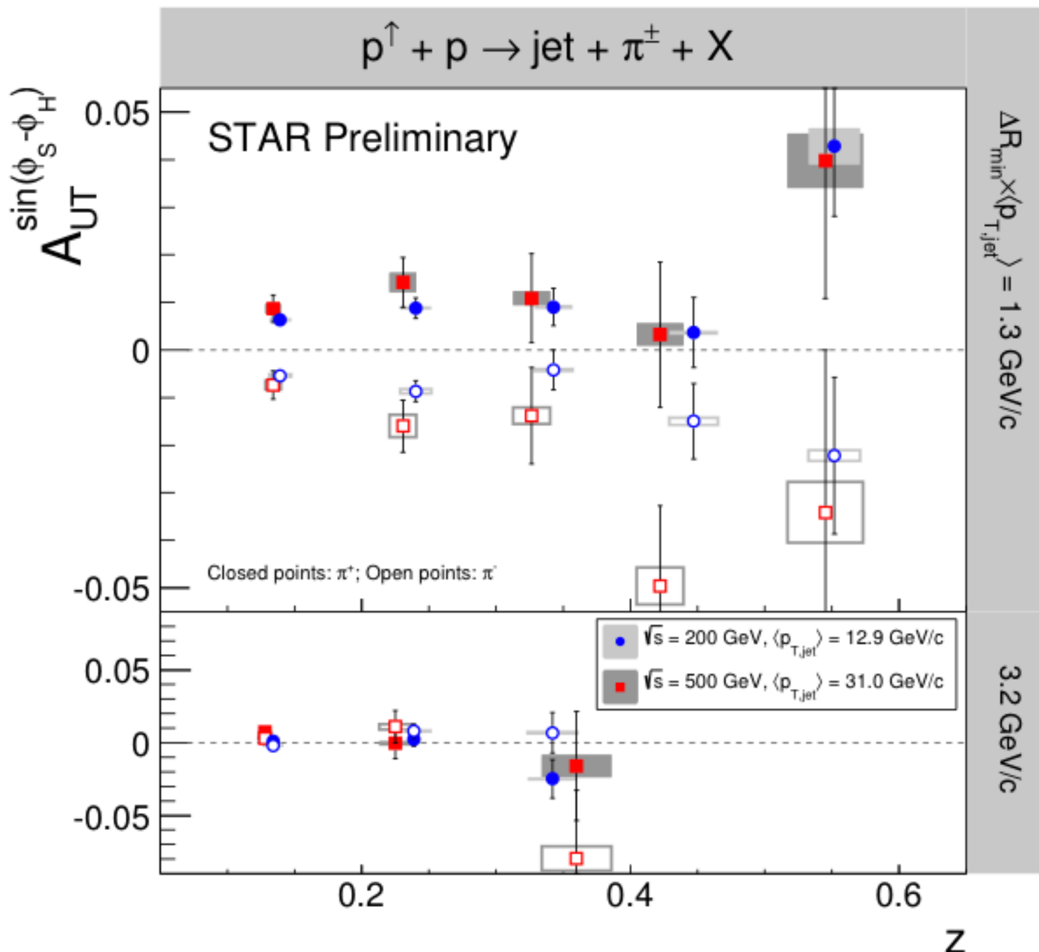


J. Drachenberg, PANIC 2014

2011 data, 25 pb^{-1} at 500 GeV, anti-k_T jet algorithm, R = 0.7

Collins asymmetries at 500 GeV

- Comparison of Collins asymmetries at 200 & 500 GeV:



arXiv:1501.01220

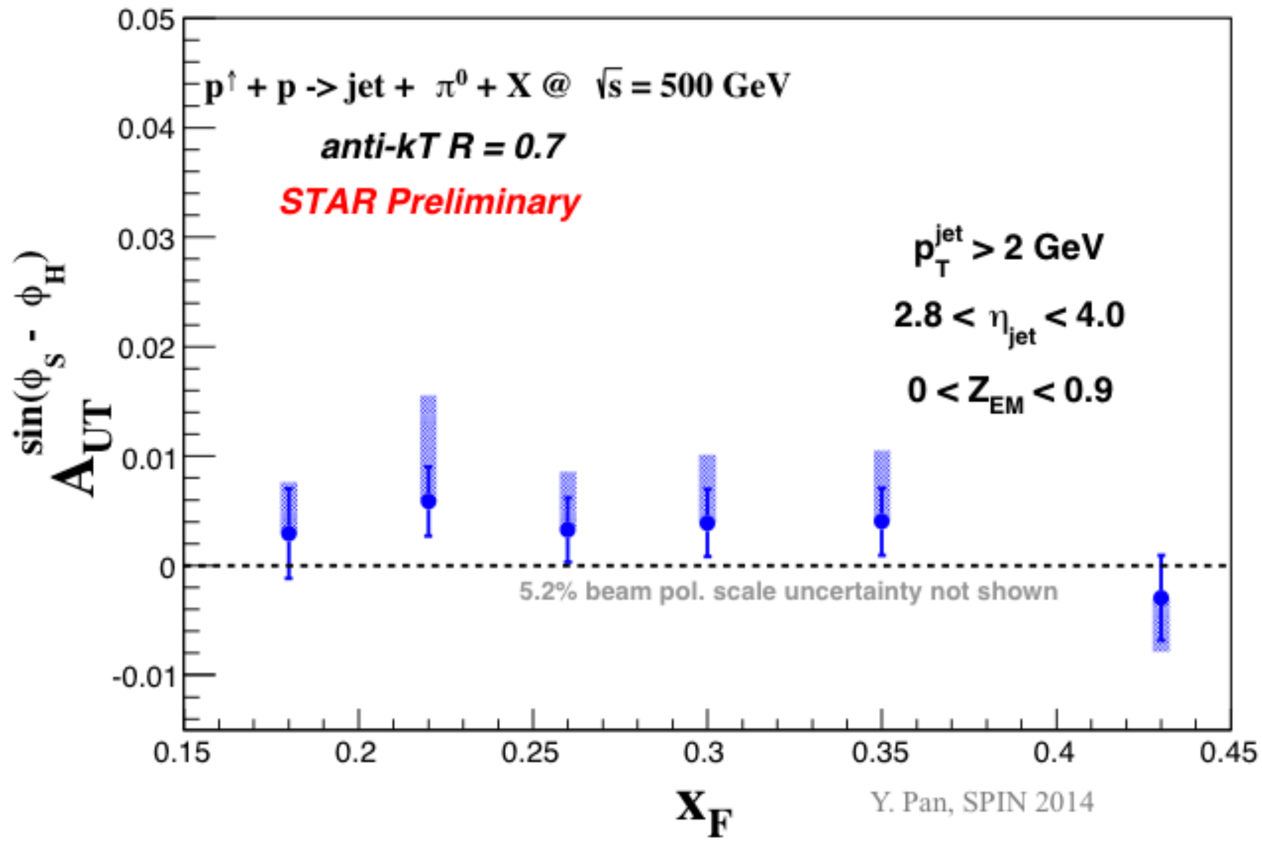
- Kinematics are dictated by the ΔR_{min} cut:

$$\langle j_T \rangle_{\min} \approx z \times \Delta R_{\min} \times \langle p_T \rangle$$

- Collins asymmetry depends on j_T and z correlation.
- Consistent results at both 200 and 500 GeV with same j_T !
- The higher j_T asymmetries (bottom) both go away.
- Higher Q^2 and same x?

Collins assymmetry for π^0 in forward EM Jets

- Collins asymmetries for π^0 with EM jets in 500 GeV pp:



  - Hints of possible non-zero Collins asymmetries!

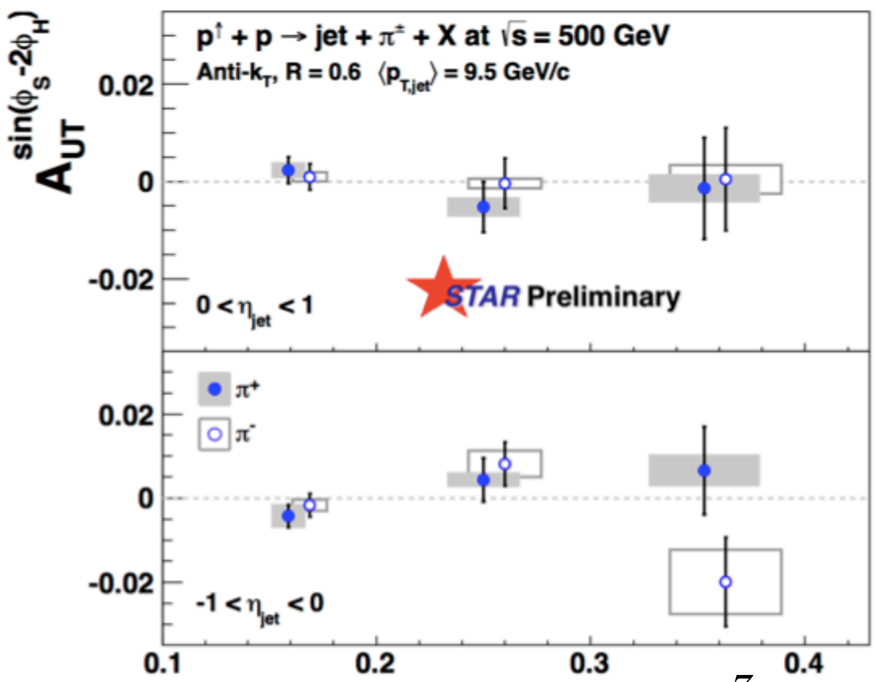
Collins-like Asymmetries at 500 GeV

- Collins-like asymmetry $A_{UT}^{\sin(\phi_s-2\phi_H)}$, provide sensitivity to gluon linear polarization.

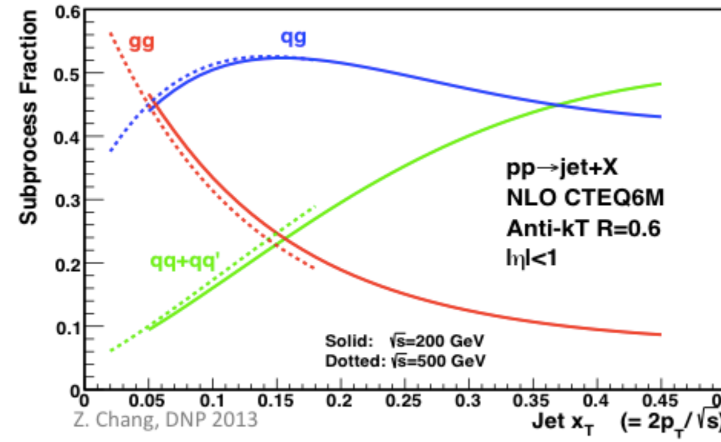
Gluon helicity density matrix

$$\rho = \frac{1}{2}\begin{pmatrix} 1+P_{circ} & -P_{lin}e^{-2i\phi} \\ -P_{lin}e^{2i\phi} & 1-P_{circ} \end{pmatrix}$$

- First measurement on $A_{UT}^{\sin(\phi_s-2\phi_H)}$

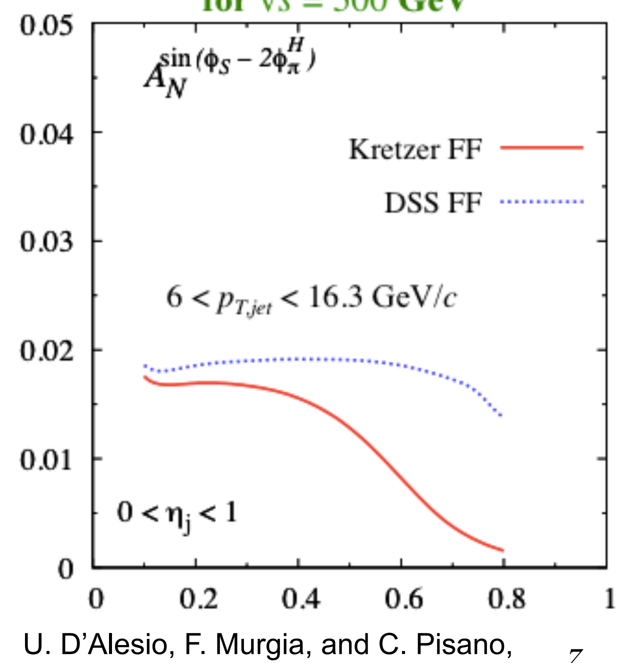


J. Drachenberg, PANIC 2014



Z. Chang, DNP 2013

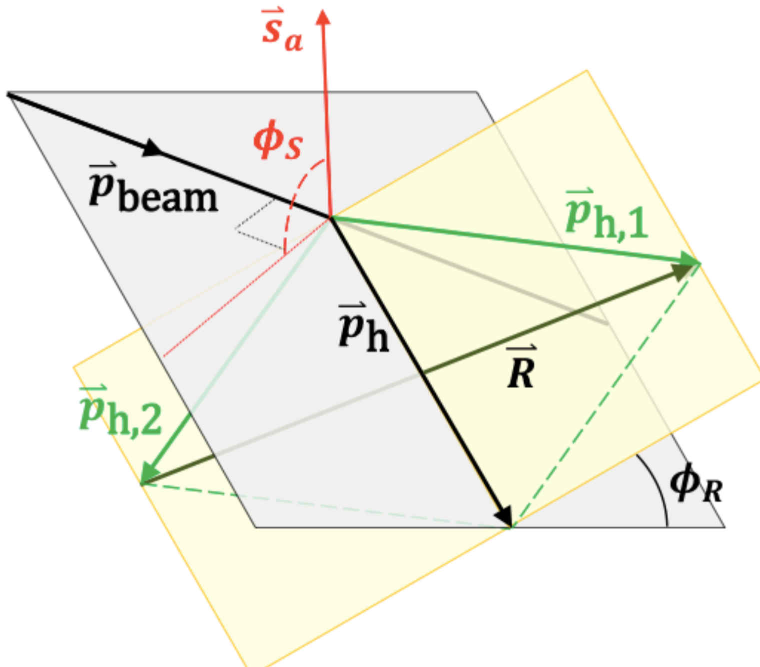
Maximized contribution for $\sqrt{s}$ = 500 GeV



U. D'Alesio, F. Murgia, and C. Pisano, PRD 83, 34021 (2011); 1307.4880

Di-hadron spin asymmetries at STAR

- Di-hadron correlation provides access to IFF& transversity:



$$A_{UT}\sin(\phi_{RS}) = \frac{1}{Pol}\frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

$$A_{UT}^{\sin(\phi_{RS})} \propto h_1 \otimes H_1^{\angle}$$

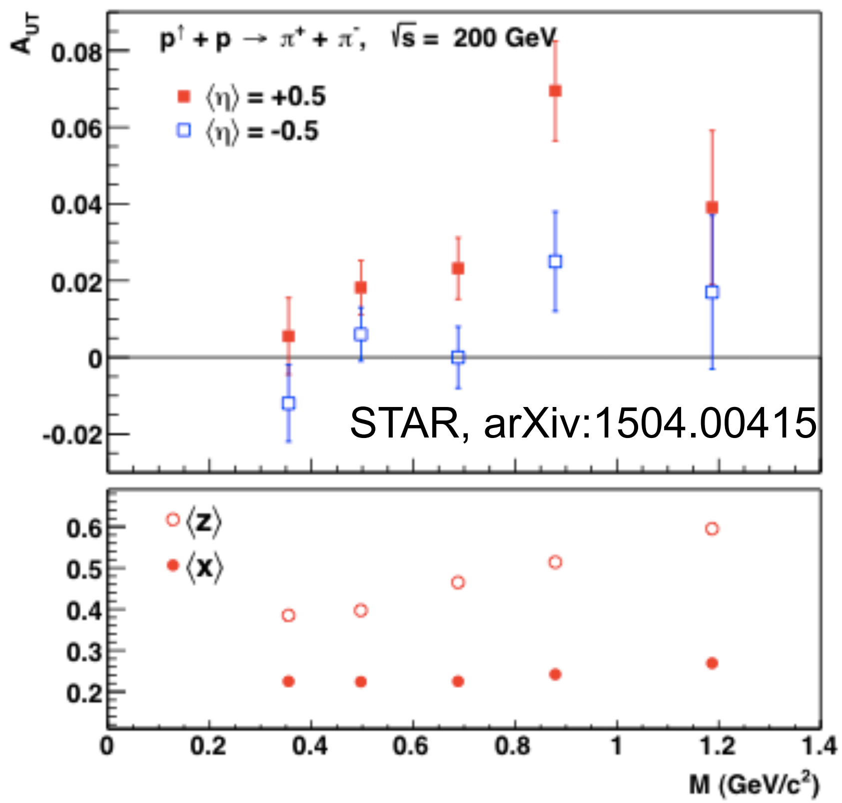
$$\phi_{RS} = \phi_R - \phi_S$$
$$\vec{p}_h = \vec{p}_{h,1} + \vec{p}_{h,2}$$
$$\vec{R}_h = \vec{p}_{h,1} - \vec{p}_{h,2}$$

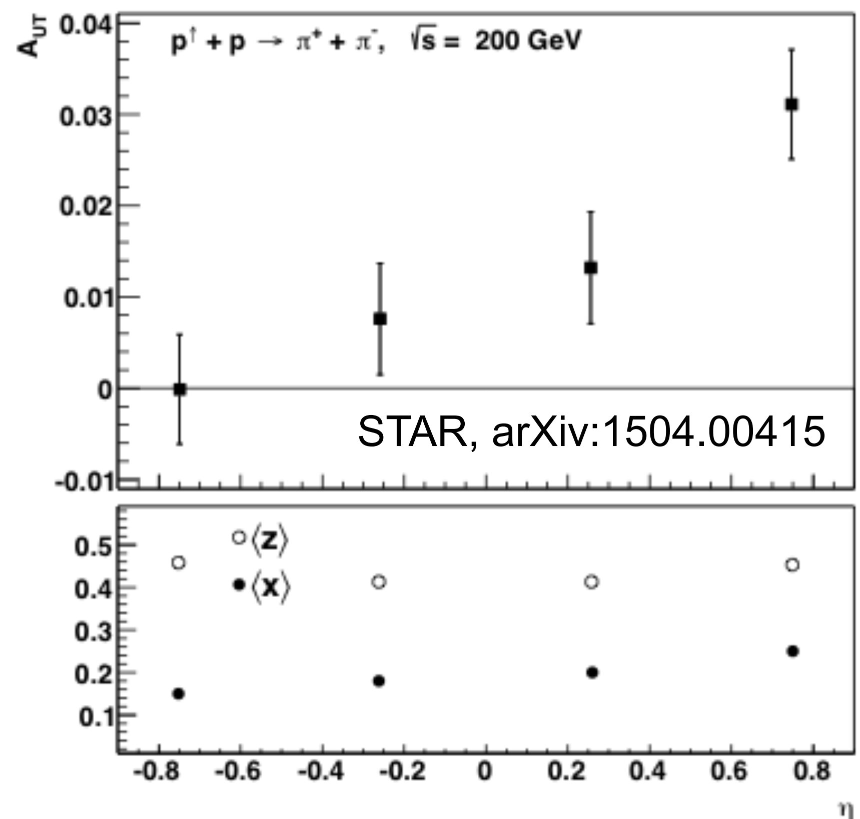
—"Interference Fragmention Function"

Bacchetta, Radici, Phys.Rev. D70 (2004)

Di-hadron spin asymmetries at STAR

- Significantly non-zero di-hadron asymmetries from run6 data:

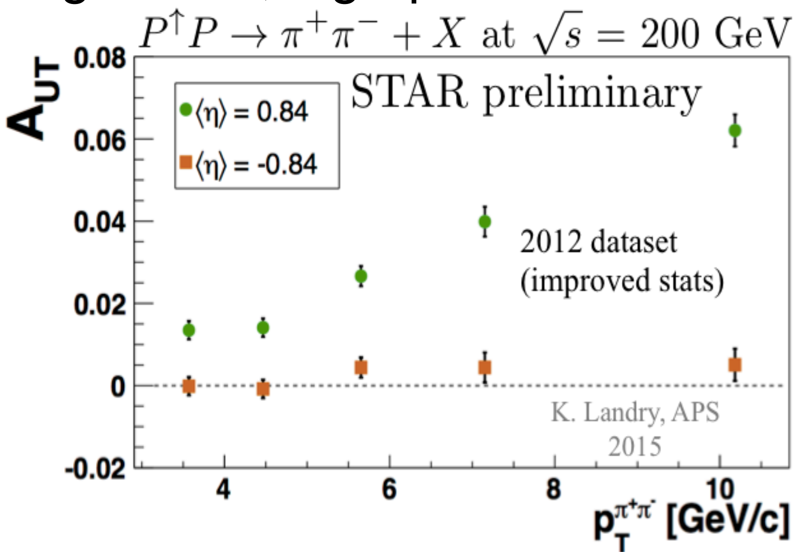


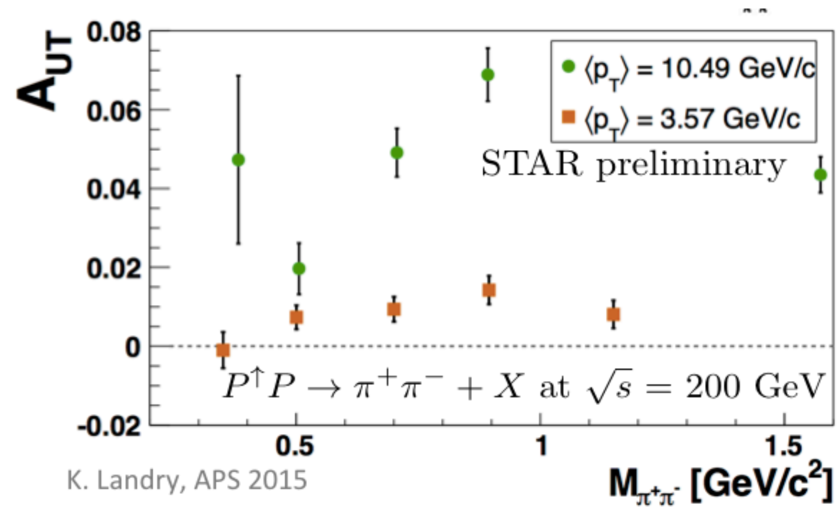


Sign of non-zero signal for di-hadron transverse single spin asymmetries-> constraints on transversity!

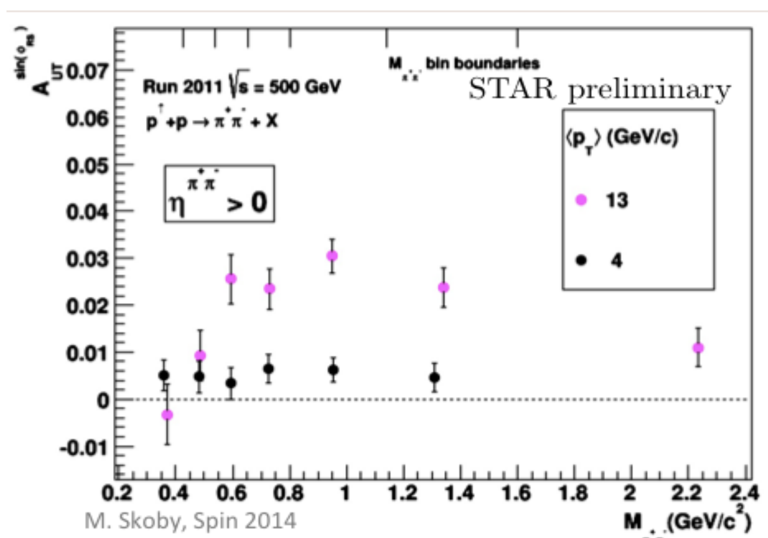
Di-hadron spin asymmetries at STAR

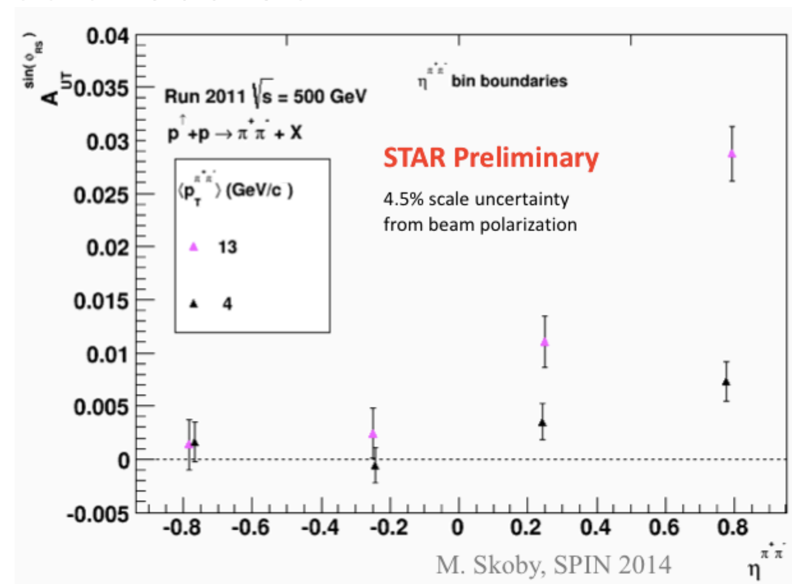
- Significant, high-precision di-hadron asymmetries with 2012 data:





- Significant non-zero IFF observed also at 500 GeV:

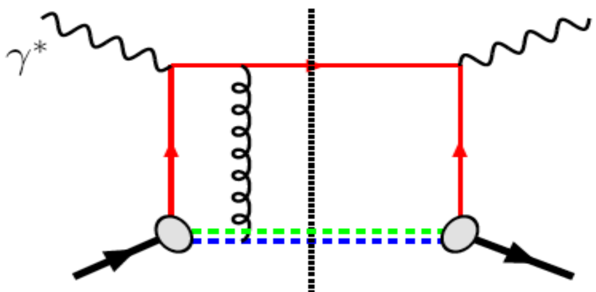




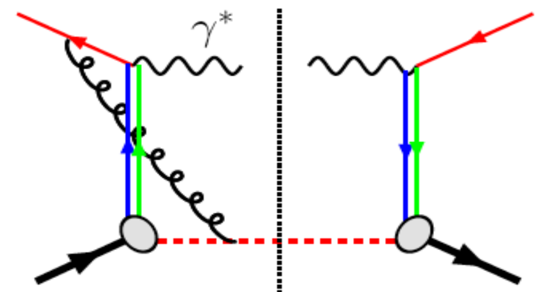
Single spin asymmetry of weak boson

- Sivers sign change in DIS and DY/W/Z process:

DIS: γq scattering
attractive FSI



pp: $q/\bar{q}$ annihilation
repulsive ISI



$$\text{Sivers}_{\text{DIS}} = - \text{Sivers (DY or W or Z)}$$

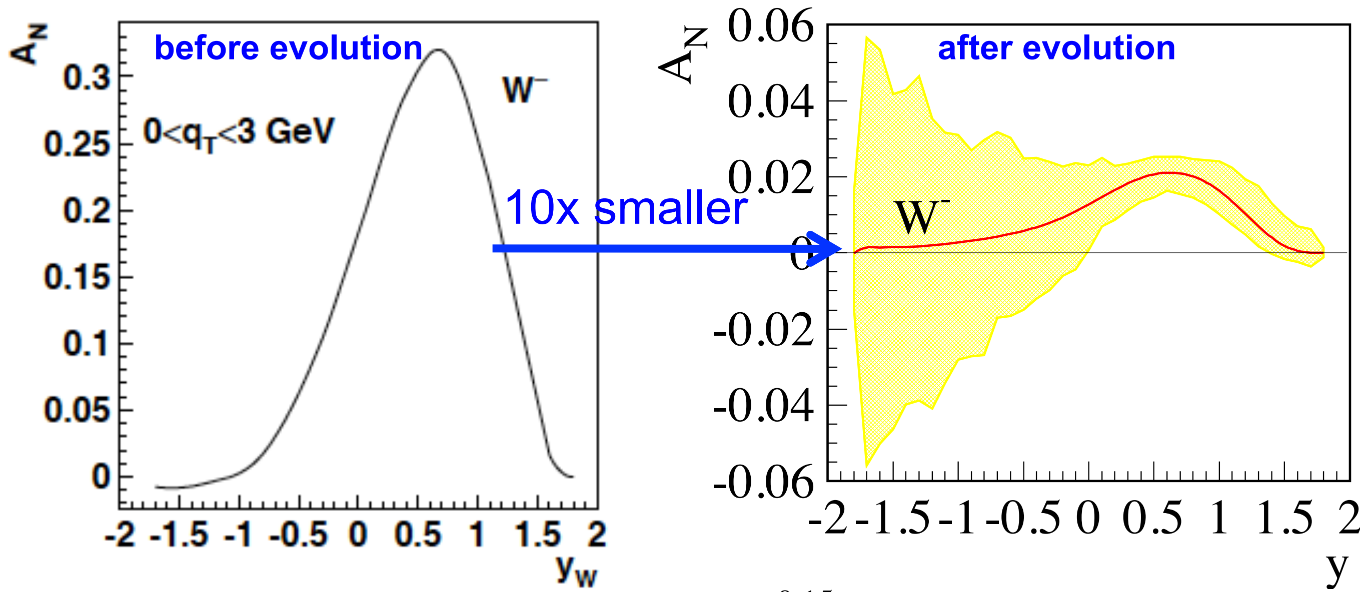
-Critical test for our understanding of TMD's and TMD factorization

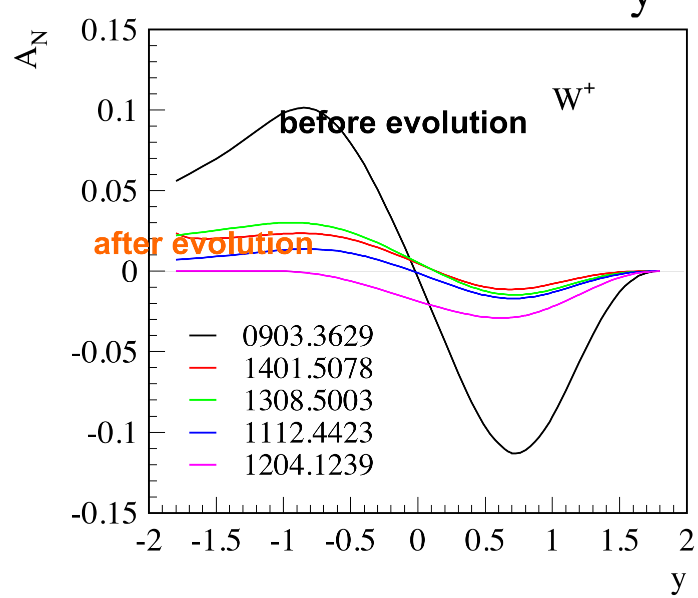
- **Advantages of weak boson production**
  - Low background
  - High Q^2-scale (~ W/Z boson mass)

STAR goal: ***measure sign change and pin down TMD -evolution*** *by measuring A_N for all the processes:* γ, $W^{\pm}$, Z^0, DY

The effects from TMD evolution

Z.-B. Kang & J.-W. Qiu, PRL103, 172001(2009) M. Echevarria et al, PRD89, arXiv:1401.5078

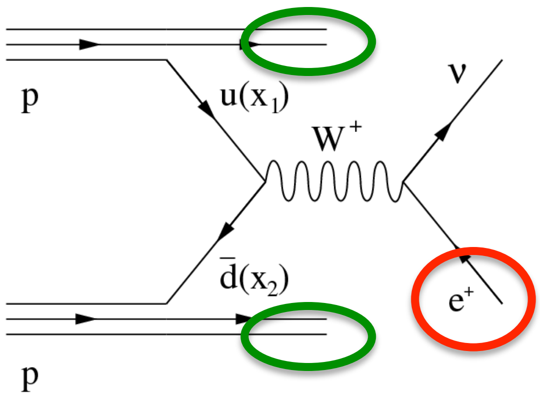




Very strong TMD evolution effects size of the asymmetry, still under discussion in theory community.

Strong dependence on y_W,
-> need fully reconstruction
of W kinematics!

Strategy to reconstruct W kinematics at STAR



W boson momentum reconstruction technique in h-h collision, has been well tested at Fermi Lab and LHC

CDF: PRD 70, 032004 (2004);

ATLAS: JHEP 1012 (2010) 060

- **Select events with the W-signature (Step 1)**
  - Isolated high P_T electron
- **Neutrino transverse momentum is reconstructed from missing P_T (Step 2)**

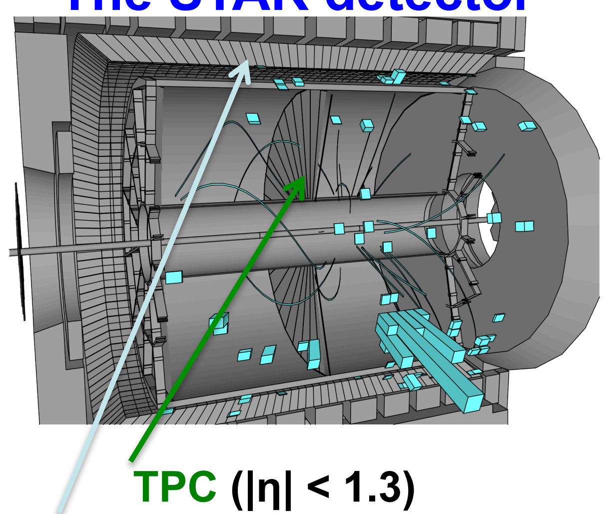
$$\vec{P}_T^W = \vec{P}_T^e + \vec{P}_T^\nu = -\vec{P}_T^{recoil}$$

Recoil reconstructed using tracks and towers, MC correction applied to incorporate those outside of STAR acceptance.

- **Neutrino's longitudinal momentum is reconstructed from the decay kinematics (Step 3)**

$$M_W^2 = \left(E_e + E_\nu\right)^2 - \left(\vec{p}_e + \vec{p}_\nu\right)^2$$

The STAR detector



TPC (**|η| < 1.3**)
Barrel EMCAL (**|η| < 1**)

First W, Z A_N results at 500 GeV from STAR

Data: STAR 2011 transverse run @ 500 GeV, integrated luminosity ~25 pb^{-1}

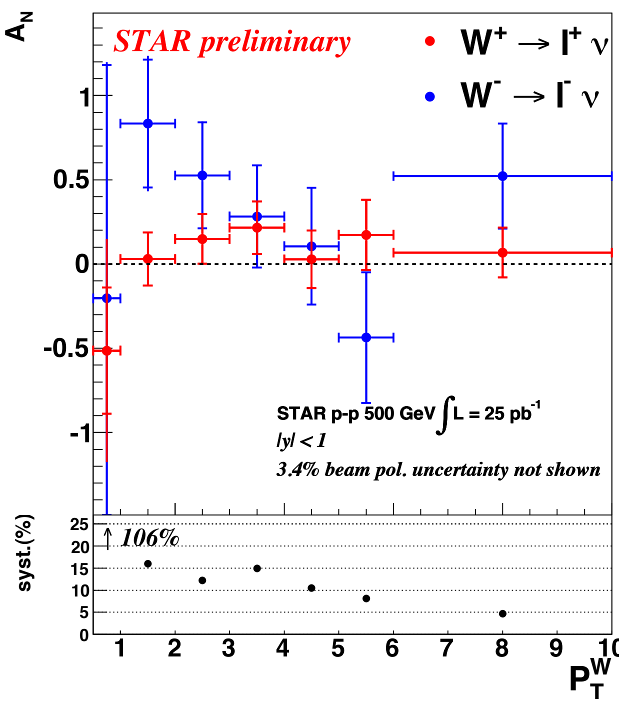
Average beam polarization → P = 53%

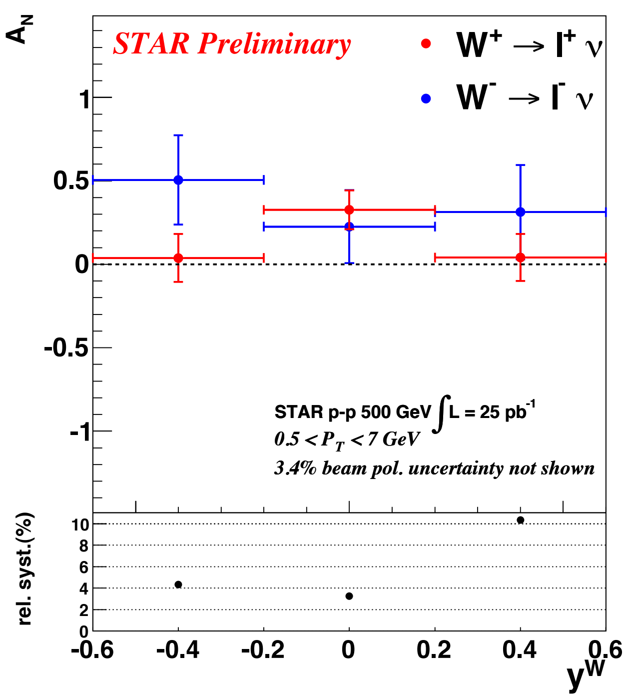
Systematics estimated based Monte Carlo package

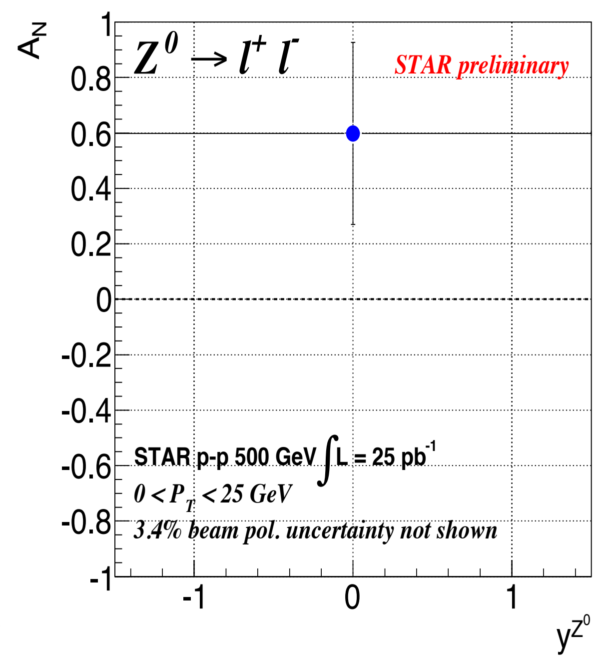
"Left-right" cross ratio formula for A_N:

$$A_N \approx \frac{1}{P}\frac{\sqrt{N_R^{\uparrow}N_L^{\downarrow}}-\sqrt{N_L^{\uparrow}N_R^{\downarrow}}}{\sqrt{N_R^{\uparrow}N_L^{\downarrow}}+\sqrt{N_L^{\uparrow}N_R^{\downarrow}}}$$

- A_N for $W^{\pm}$ and Z :



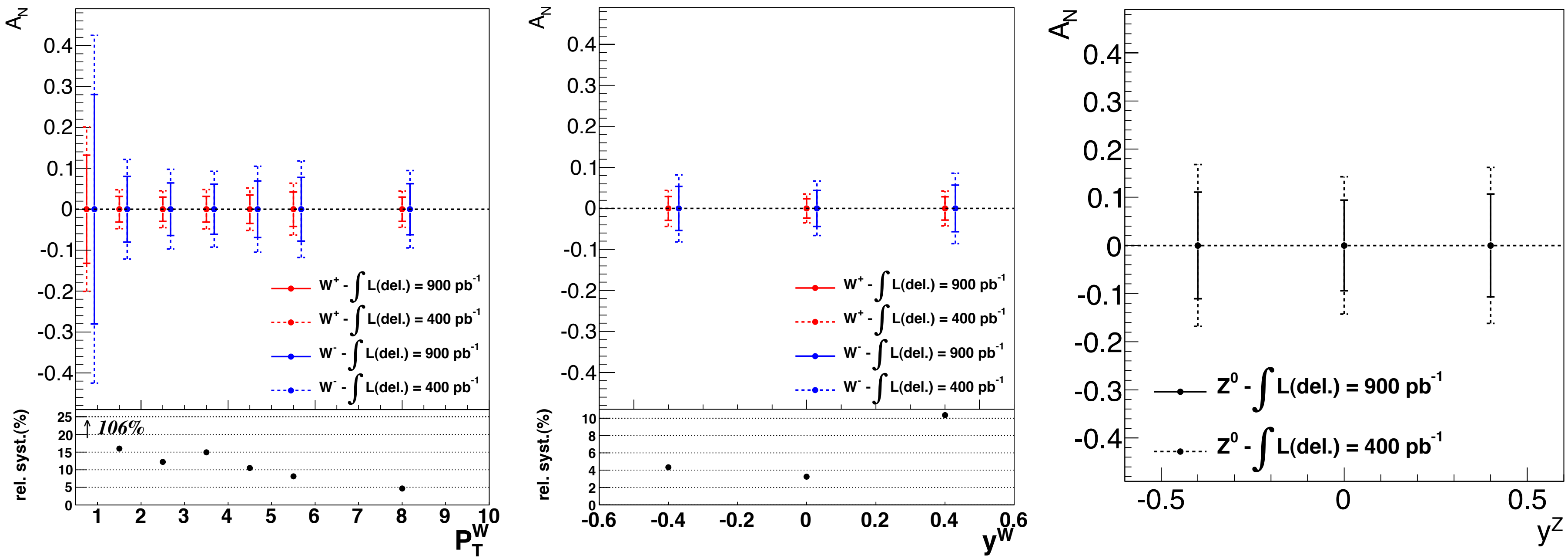




S. Fazio and D. Smirnov, DIS2014

Future measurements of W/Z A_N at STAR

- STAR plans to collect ~400 pb^{-1} transverse pp in 2017:



S. Fazio - DIS 2015

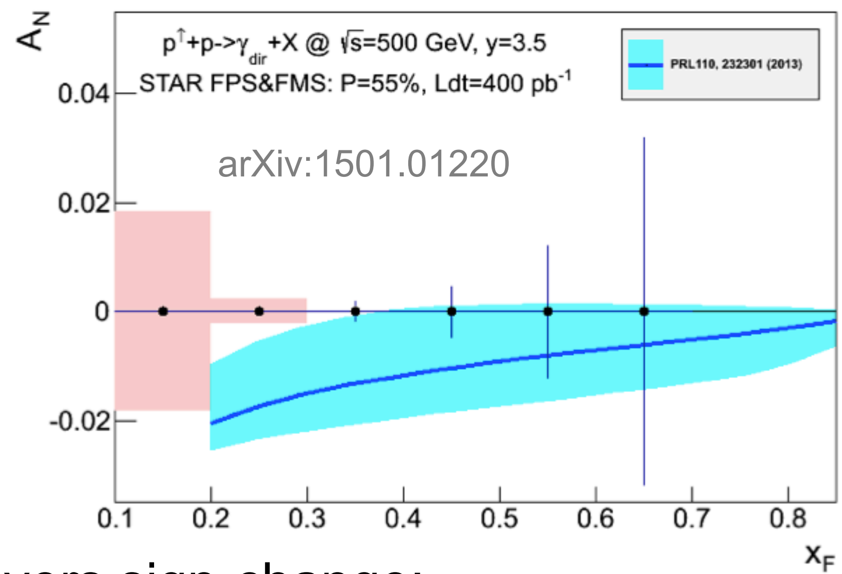
Goal:

✓ Constrain TMD evolution sea-quark Sivers function

✓ Test sign-change if TMD-evolution suppression factor ~5 or less

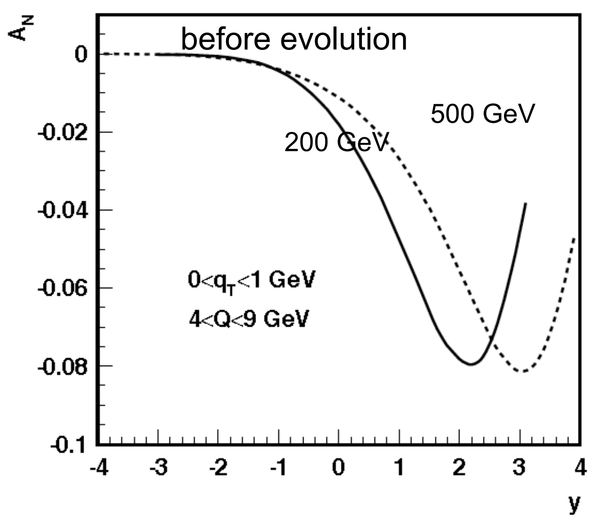
Future measurements of photon at STAR

- Projection for direct γ asymmetry with 400 pb^{-1} pp data at STAR:

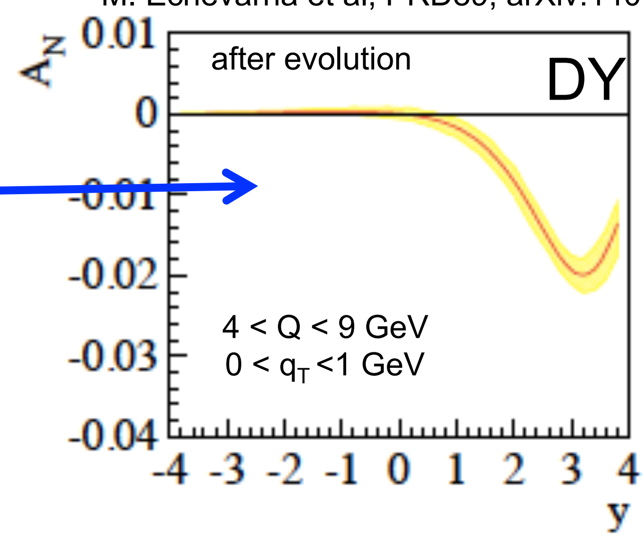


- Observables with DY for Sivers sign-change:

Z.-B. Kang & J.-W. Qiu PRD81,054020(2010)

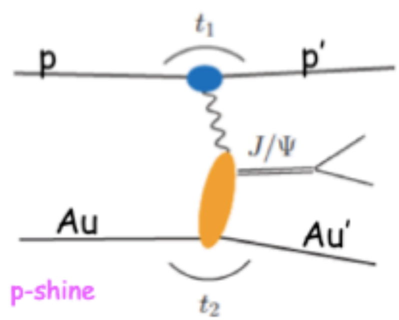


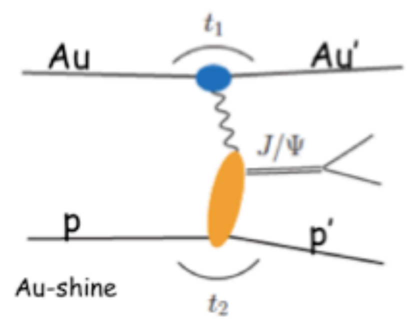
M. Echevarria et al, PRD89, arXiv:1401.5078



Accessing the gluon GPD in pAu

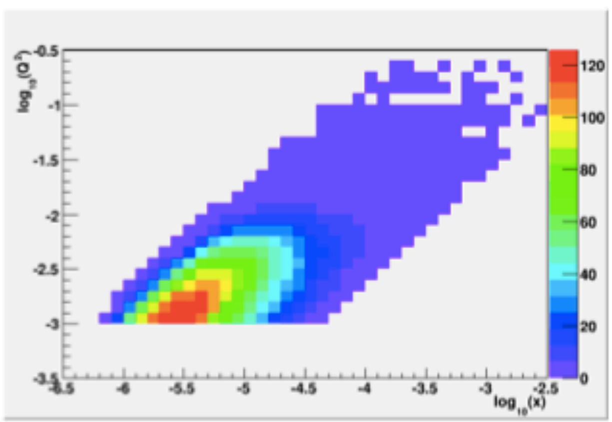
- Unique opportunity to measure A_N for exclusive J/ψ in ultra peripheral p↑Au collisions:

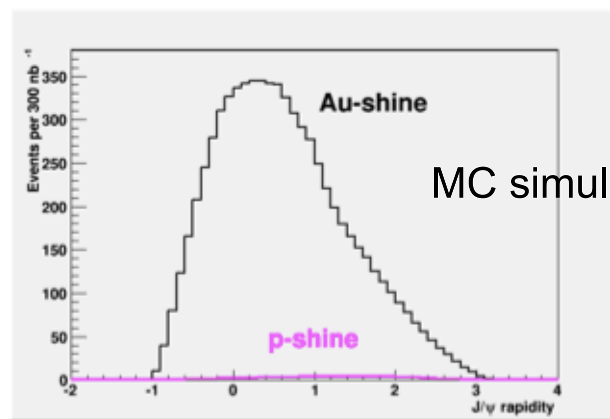




arXiv:1501.01220
S. Klein, J.Nystrand, hep-ph/0310223

-possible process





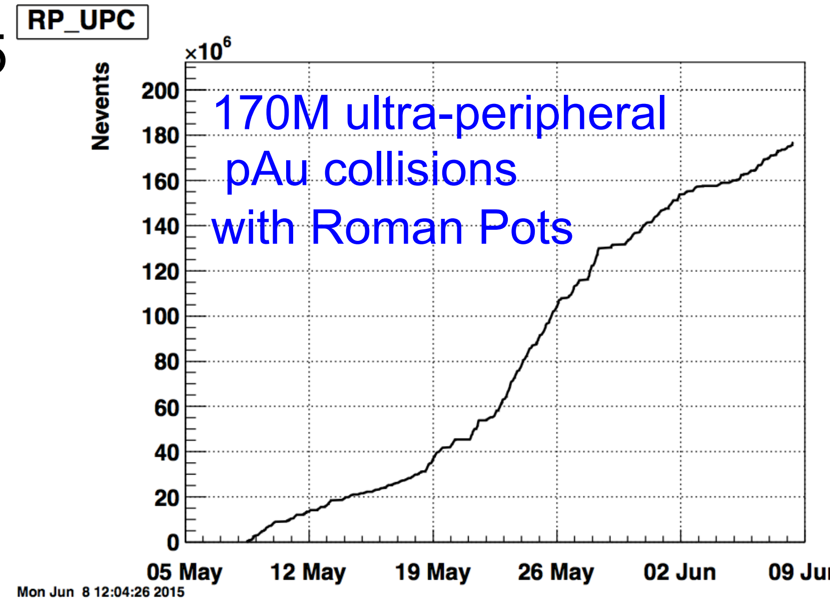
MC simulation

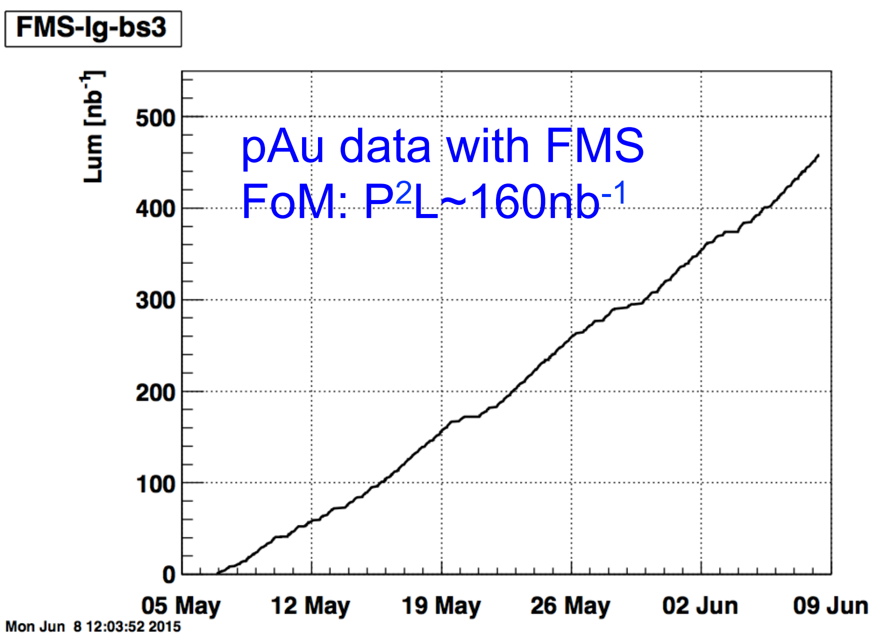
Detect the scattered proton in “Roman Pots” and veto the break-up of Au

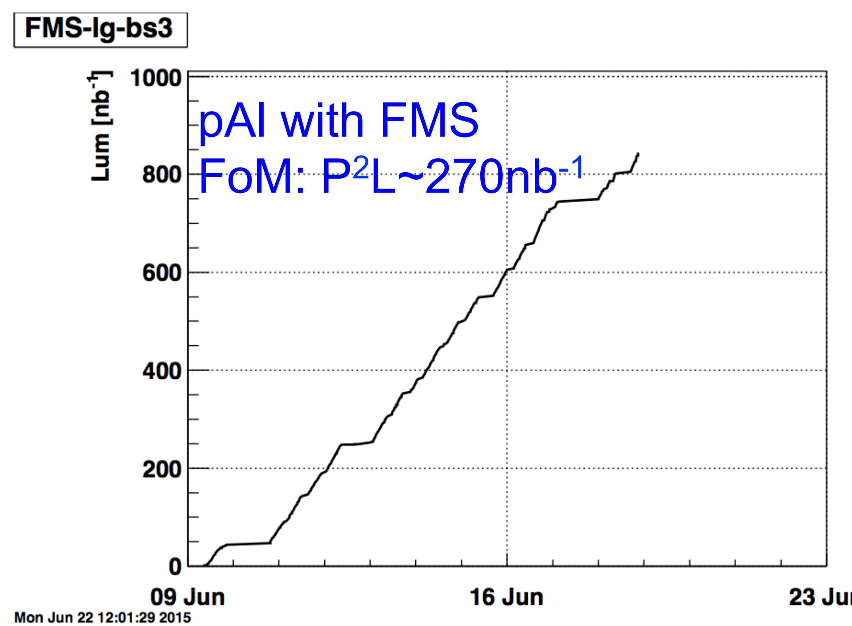
A nonzero asymmetry would be the first signature of a nonzero GPD *E* for gluons.

Transverse pA run in 2015

- Successful pA run at STAR in 2015
- Why pA?
  - ✓ Saturation effects-CGC
  - ✓ Nuclear effect of A_N
  - ✓ Distinguish different mechanisms for A_N
  - ✓ Exclusive J/Ψ for GPD
  - ...



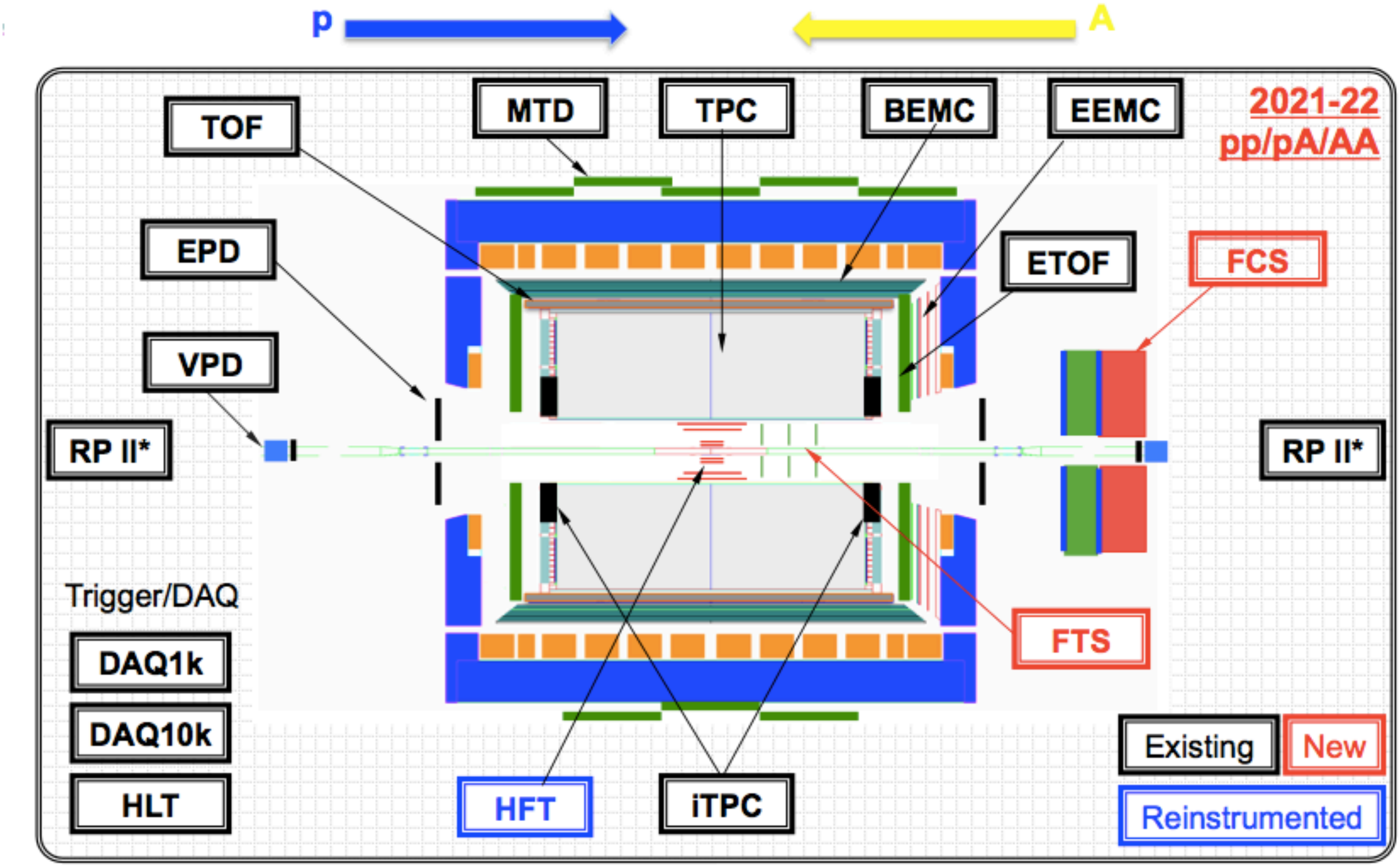




Summary & Outlook

- Exploration of transverse spin asymmetries at STAR:
  - ✓ Single spin asymmetries in the forward region observed, π^0 asymmetry with different event topology studied.
  - ✓ Observation of non-zero Collins asymmetries at 200GeV & 500GeV.
  - ✓ Non-zero di-hadron spin asymmetries (IFF) observed.
  - ✓ First measurements of weak boson $A_{N,}$ gain insights into TMD evolution and sea quark Sivers function.
- Transversely polarized pA data taken for the first time in 2015
  - A_N asymmetries in p+A
  - Exclusive J/φ in ultra peripheral pAu-> gluon GPD
- Long transverse run planned for 2017 at 500 GeV
  - A_N for W,Z, gamma-> TMD evolution, Sivers sign change.
- Future measurements for DY, forward di-jet in 2020+ with dedicated detector upgrades.

STAR Detector in 2021-2022



FCS/FTS: Forward Calrimeter/Tracking System, **RP II**: Full Roman Pot Phase II

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