RECENT TRANSVERSE SPIN RESULTS FROM THE STAR EXPERIMENT AT RHIC

Mriganka Mouli Mondal (for the STAR Collaboration)
Texas A&M University

Outline

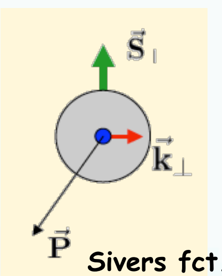
- Introduction
- The polarized RHIC collider and the STAR experiment
- Transverse Single Spin Asymmetries (TSSA) with forward detector, Forward Meson Spectrometer (FMS)
- TSSAs for Jets and di-hadrons
- STAR transverse physics in ongoing transverse run at $\sqrt{s}$ = 200 GeV

TSSA – two theoretical frameworks

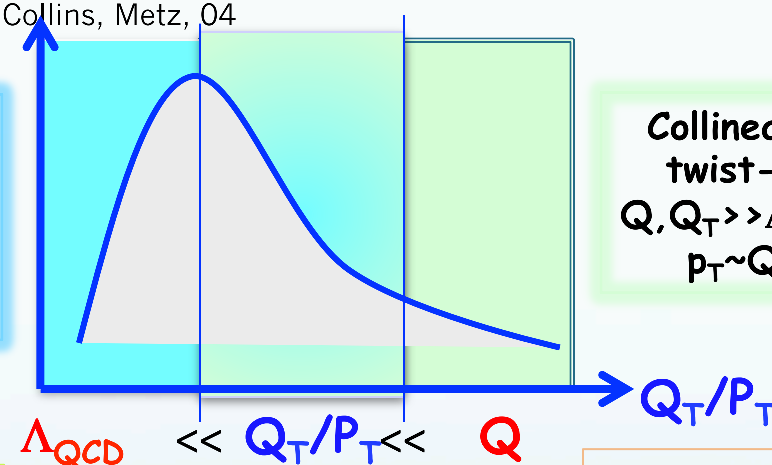
Spin-dependent transverse momentum dependent (TMD) function $S_T.(P \times k_T)$ + **Collins fragmentation functions**	Twist-3 quark-gluon correlations + **Twist three fragmentation functions**

- Sivers function, Sivers90
- Collins function, Collins 93
- Gauge invariant definition of the TMDs: Brodsky, Hwang, Schmidt 02; Collins 02 ; Belitsky, Ji, Yuan 02; Boer, Mulders, Pijlman, 03
- The QCD factorization: Ji, Ma, Yuan, 04; Collins, Metz, 04

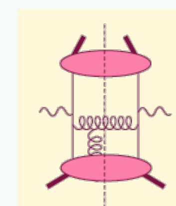
- Efremov-Teryaev, 82, 84
- Qiu-Sterman, 91,98
- Kouvaris,Qiu,Vogelsang,Yuan, 06



Transverse momentum dependent
$Q >> Q_T >= \Lambda_{QCD}$
$Q >> p_T$



Collinear/ twist-3
$Q, Q_T >> \Lambda_{QCD}$
$p_T \sim Q$



Efremov, Teryaev; Qiu, Sterman

Need 2 scales
Q^2 and p_t
Remember pp:
most observables one scale
Some Exceptions:
DY, W/Z-production, jet+hadron

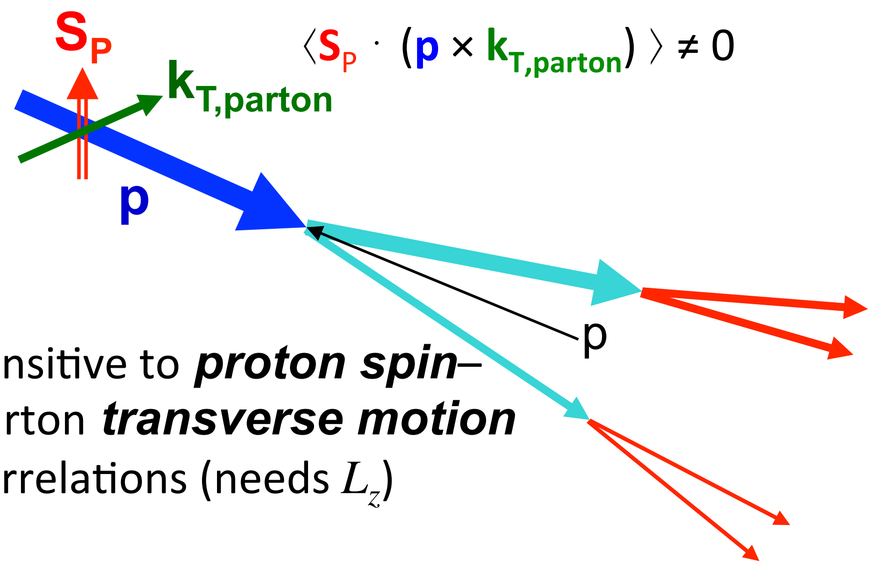
Need only 1 scale
Q^2 or p_t
But
should be of reasonable size
should be **applicable to most pp observables**
$A_N(\pi^0/\gamma/jet)$

Sivers vs. Collins

Sivers mechanism: asymmetry in the forward jet or γ *production*

D. Sivers, PRD 41, 83 (1990); 43, 261 (1991)

$$\langle S_P \cdot (p \times k_{T,parton}) \rangle \neq 0$$



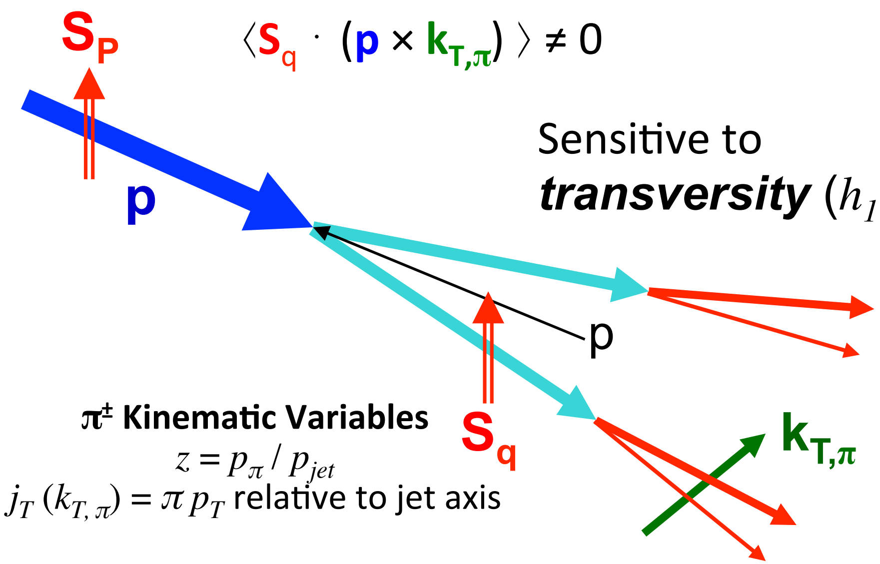
Sensitive to ***proton spin*–** parton ***transverse motion*** correlations (needs L_z)

Collins mechanism: asymmetry in the forward jet *fragmentation*

J. Collins, NP B396, 161 (1993)

$$\langle S_q \cdot (p \times k_{T,\pi}) \rangle \neq 0$$

Sensitive to ***transversity*** (h_1)

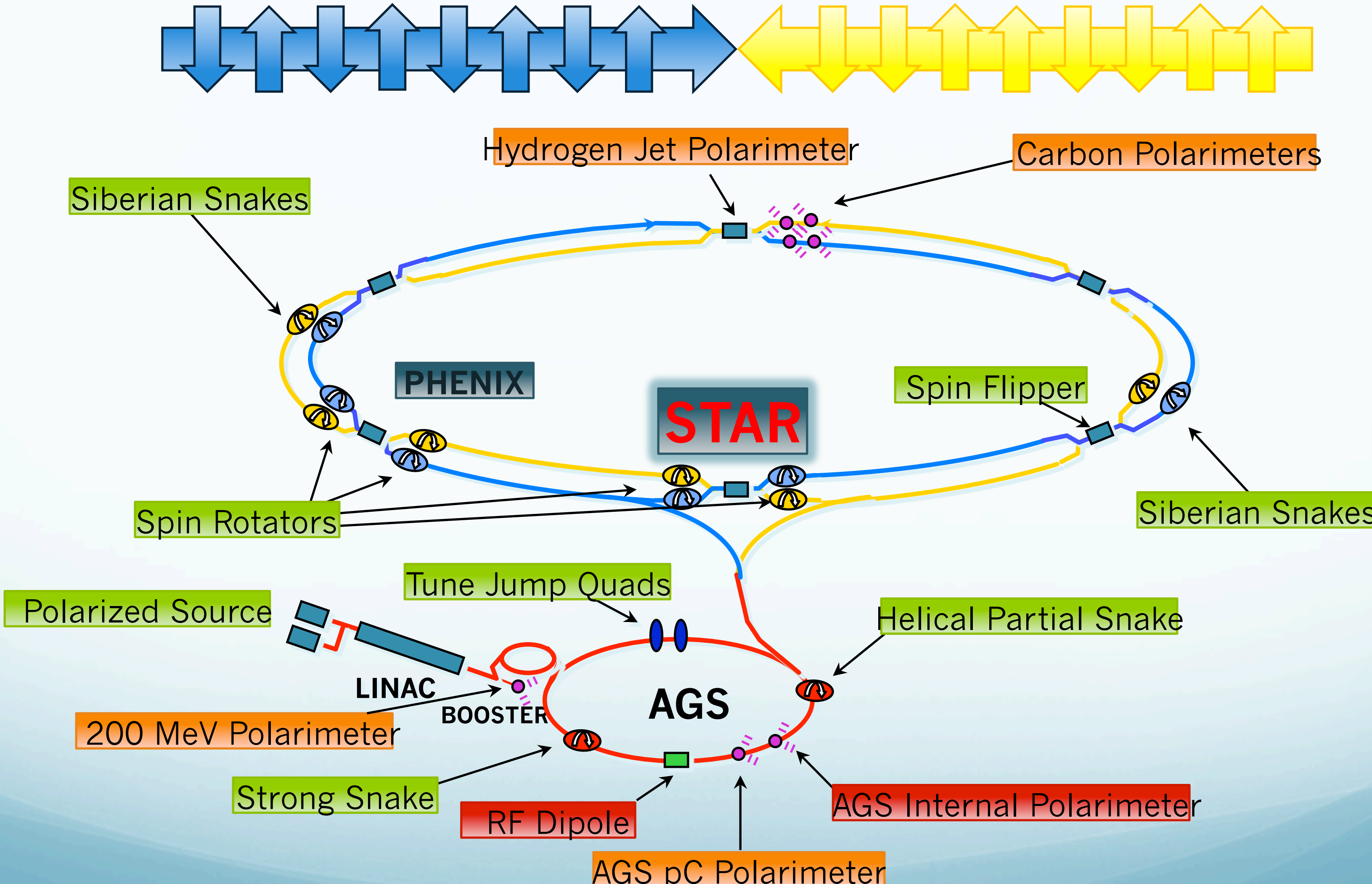


$\pi^{\pm}$ Kinematic Variables

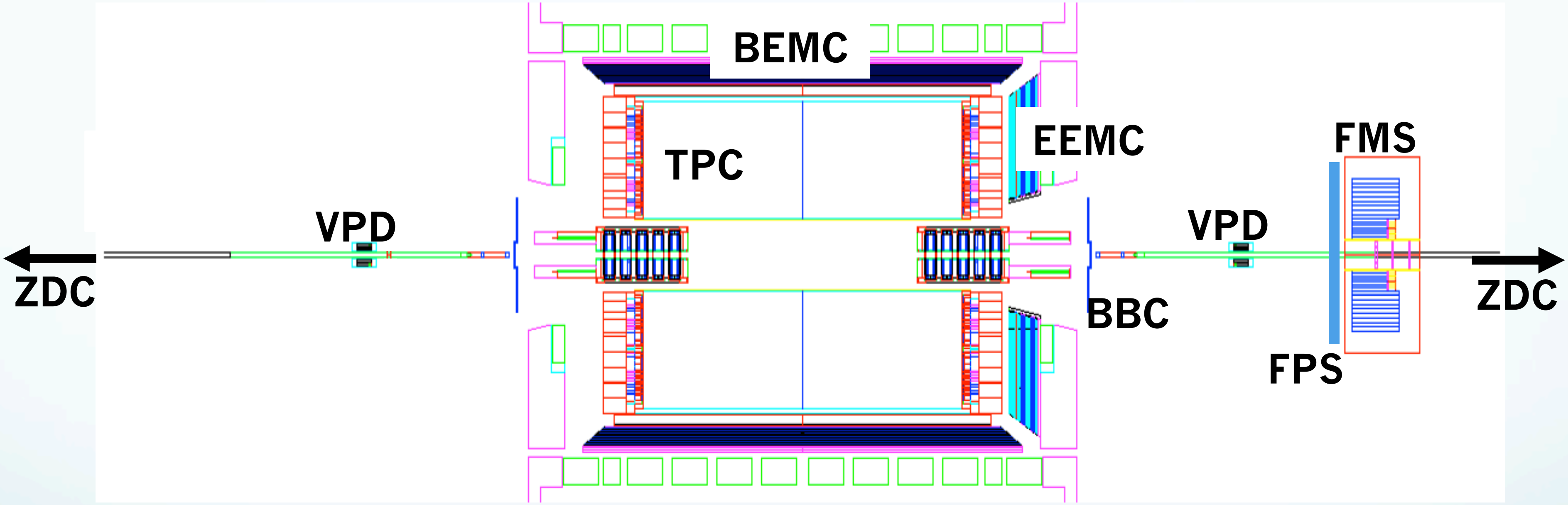
$z = p_\pi / p_{jet}$

$j_T\,(k_{T,\pi}) = \pi\, p_T$ relative to jet axis

RHIC : the world's first and the only polarized proton collider



STAR detector in cross view



STAR at forward rapidity

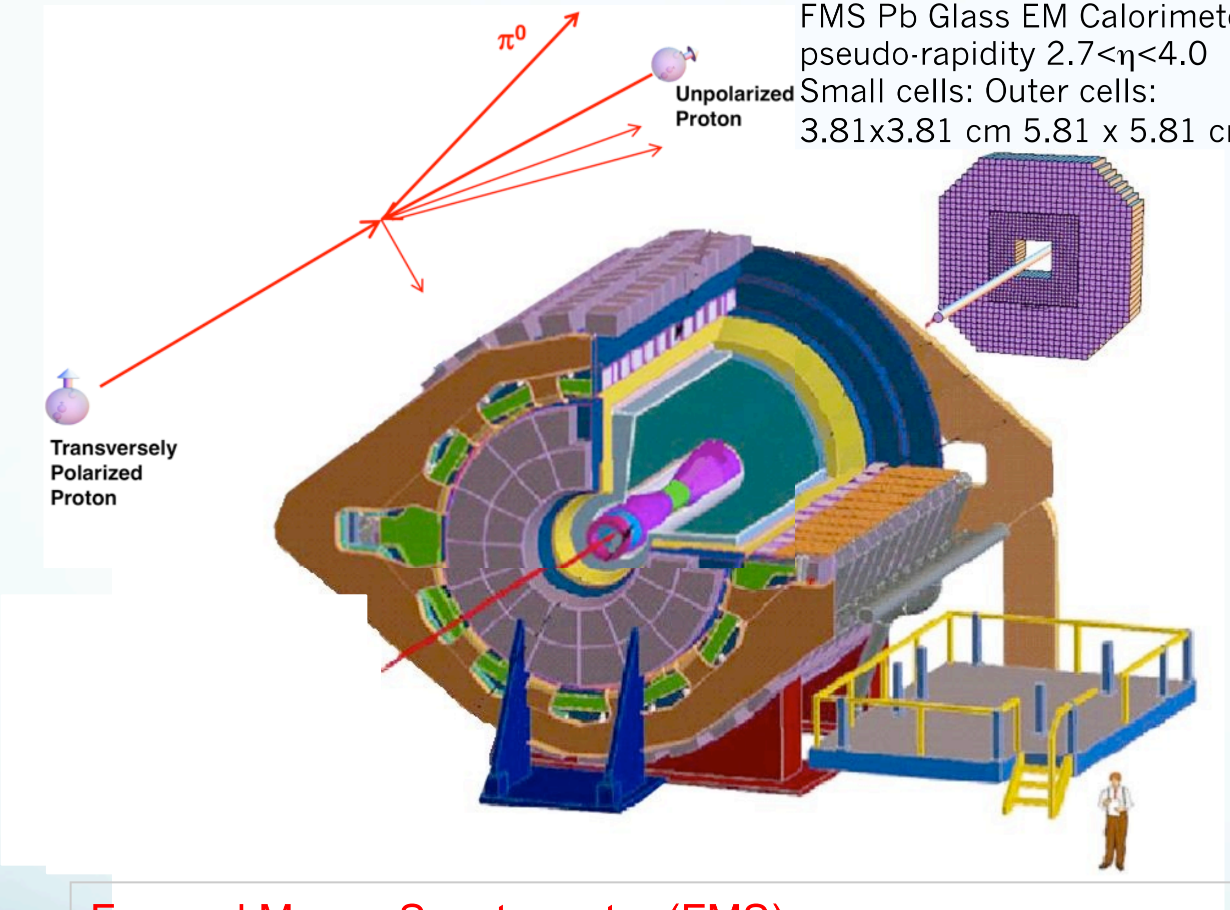
- Forward Meson Spectrometer(FMS), Forward Pre-Shower Detector (FPS, we have for 2015)
- Event topology dependent of TSSA
- Measurements from 2011 transverse data at $\sqrt{s}$ = 500GeV :

---- A_N for electromagnetic jets

---- A_N for inclusive neutral pions

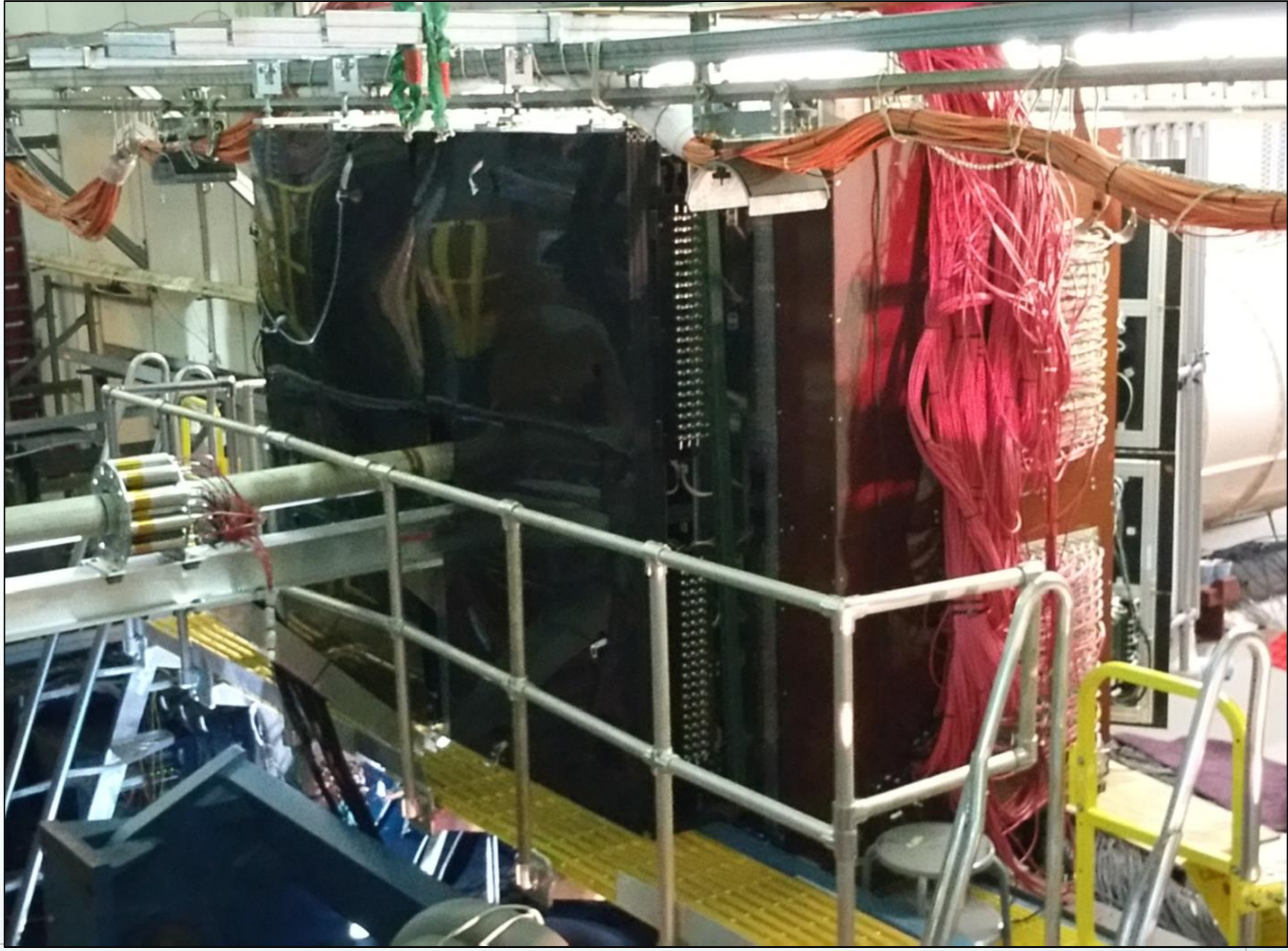
Forward ECAL in STAR

FMS Pb Glass EM Calorimeter
pseudo-rapidity 2.7<η<4.0
Small cells: Outer cells:
3.81x3.81 cm 5.81 x 5.81 cm



Forward Meson Spectrometer (FMS) :
-- Pb glass EM calorimeter covering 2.5< η <4.0
-- Detect π^0,η, direct photons and jet-like events in the kinematic region where transverse spin asymmetries are known to be large.
Forward Preshower Detector in front of FMS in 2015 for direct photon detection

FMS+FPS (2015)



Forward Meson Spectrometer (FMS) :

-- Pb glass EM calorimeter covering 2.5< η <4.0

-- Detect π^0,η, direct photons and jet-like events in the kinematic region where transverse spin asymmetries are known to be large.

Forward Preshower Detector in front of FMS in 2015 for direct photon detection

Large TSSA at forward rapidity

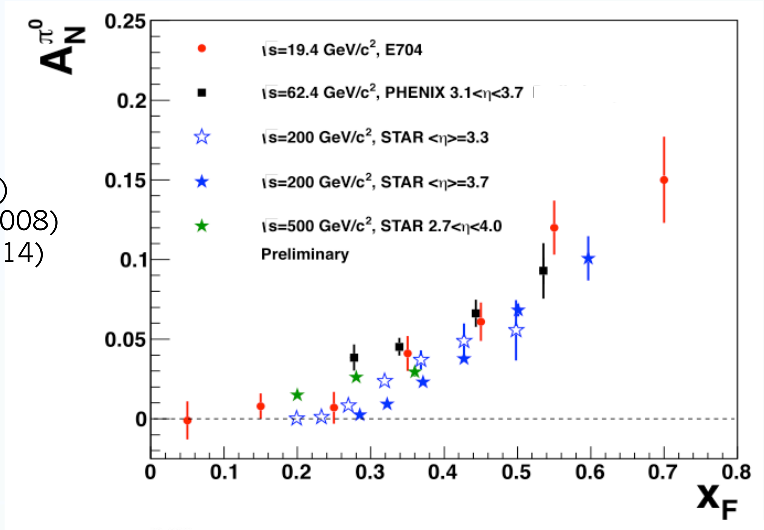
Inclusive π0 production

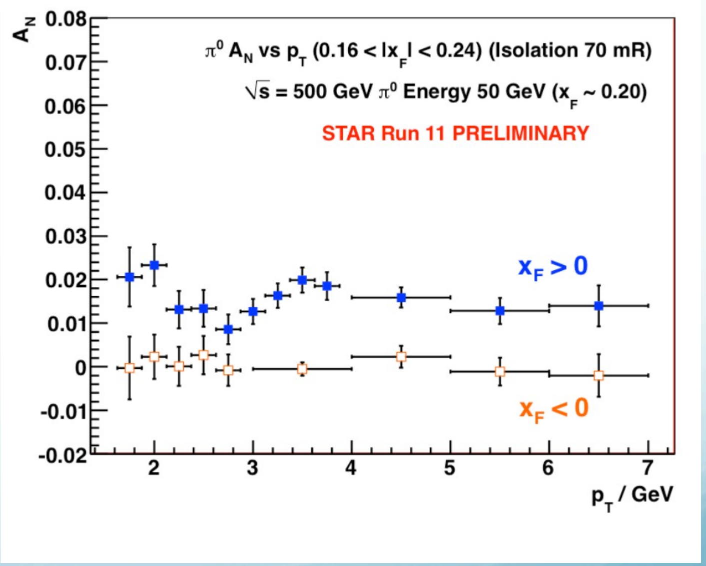
$$p_{\uparrow} + p \rightarrow \pi^0 + X$$

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

$$x_F = 2p_Z/\sqrt{s}$$

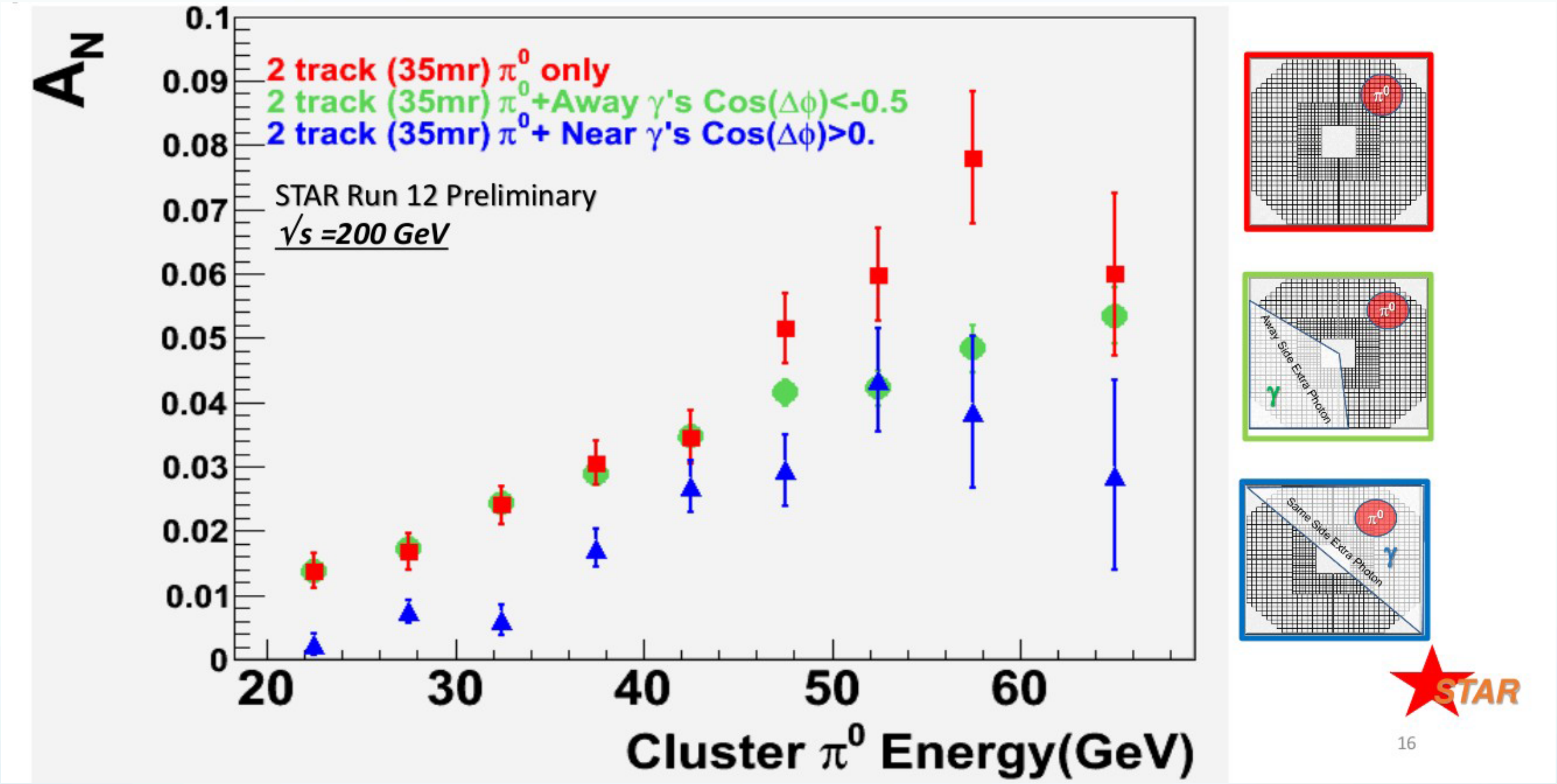
PLB,261,201(1991)
PRL,101,222001(2008)
PRD,90,012006(2014)





- ✧ Rising A_N with X_F
- ✧ A_N nearly independent of √s
- ✧ **No evidence of fall in A_N with increasing P_T**

Event topology dependency A_N



- More isolated pions have greater A_N than those with nearby energy deposits
- Pion A_N is therefore event-topology dependent

EM-Jet characteristics

p+p √s = 500 GeV transverse datasets

Jet algorithm : anti-kt

R-parameter : 0.7

$p_T^{EM\text{-}Jet} > 2.0$ GeV/c

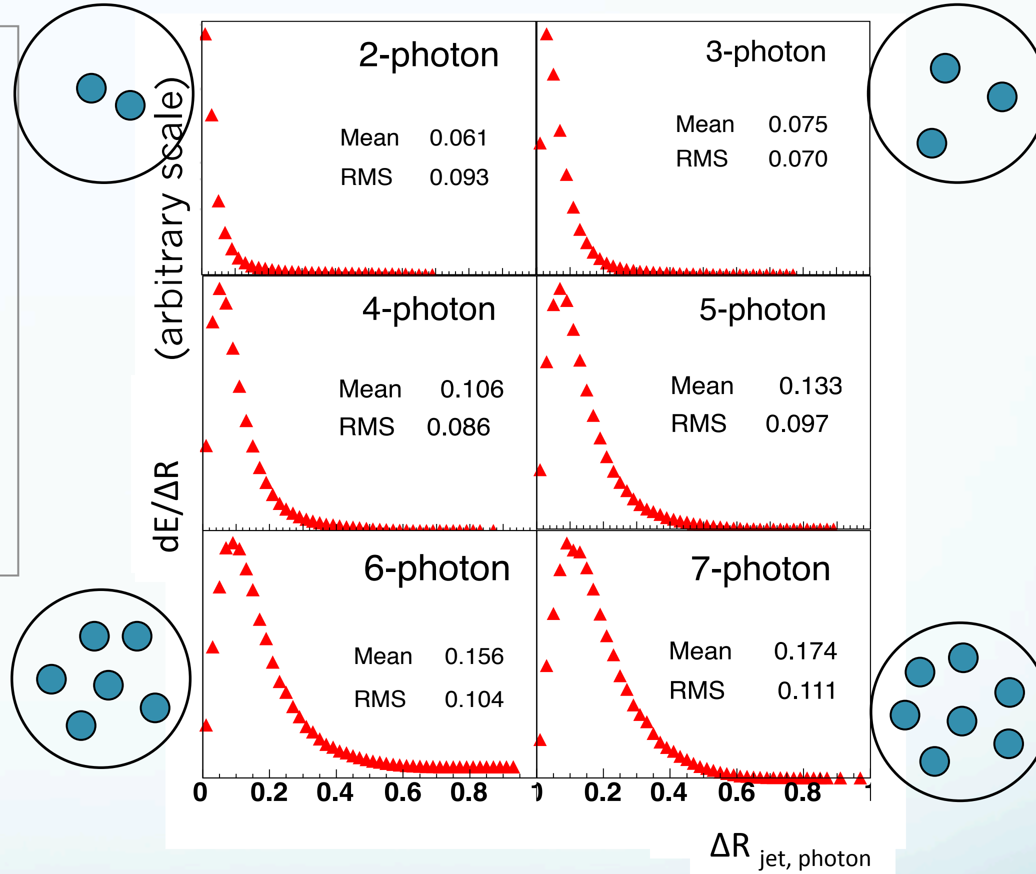
photons with $p_T > 0.001$ GeV/c

Leading EM-Jets :

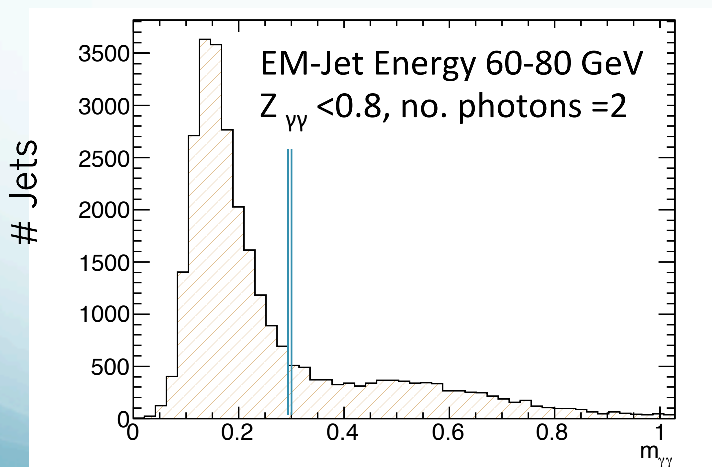
Multi-photon Jets with highest energy

$2.8 < \eta^{EM\text{-}Jet} < 4.0$

40 GeV < $Energy^{EM\text{-}Jet}$ < 100 GeV



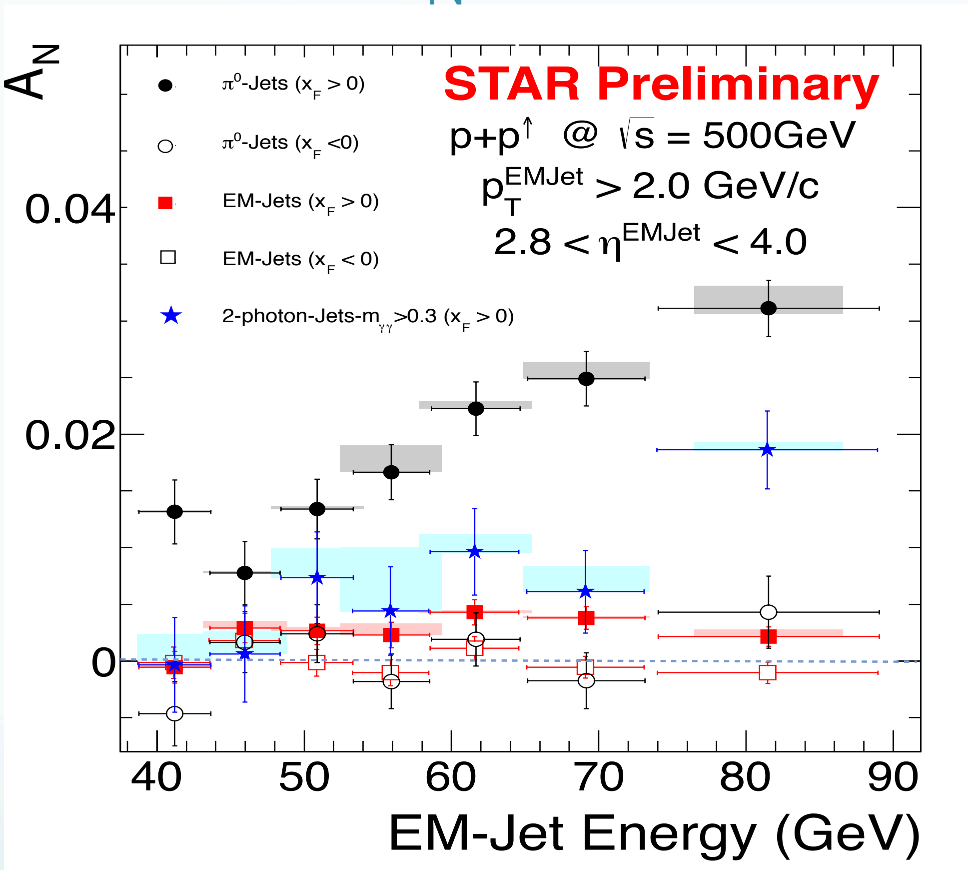
dE/ΔR distribution of EM-Jets



γγ invariant mass 2-photon EM-jets

- ✧ 2-photon jets are mostly π^0
- ✧ Events with more than 2 photons show jet-like energy flow

A_N vs. EM-Jet Energy



π^0-Jets –
2γ-EM-Jets with
$m_{\gamma\gamma}$ <0.3
$Z_{\gamma\gamma}$ <0.8

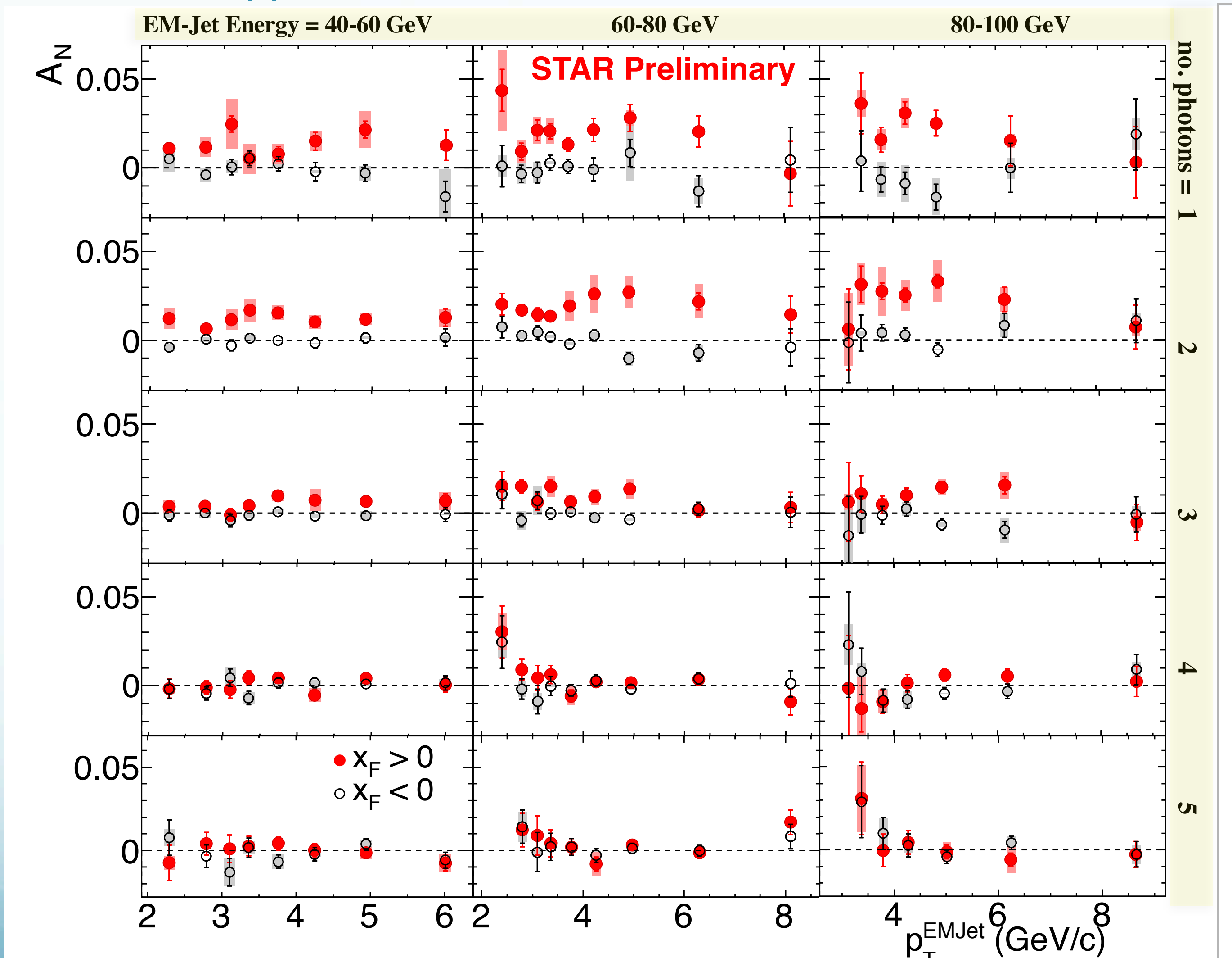
2γ-EM-Jets (η + continuum) –
with $m_{\gamma\gamma}$ > 0.3

EM-Jets –
with no. photons >2

✧ Isolated π^0's have large asymmetries consistent with previous observation (CIPANP-2012 Steven Heppelmann)
https://indico.triumf.ca/contributionDisplay.pycontribId=349&sessionId=44&confId=1383

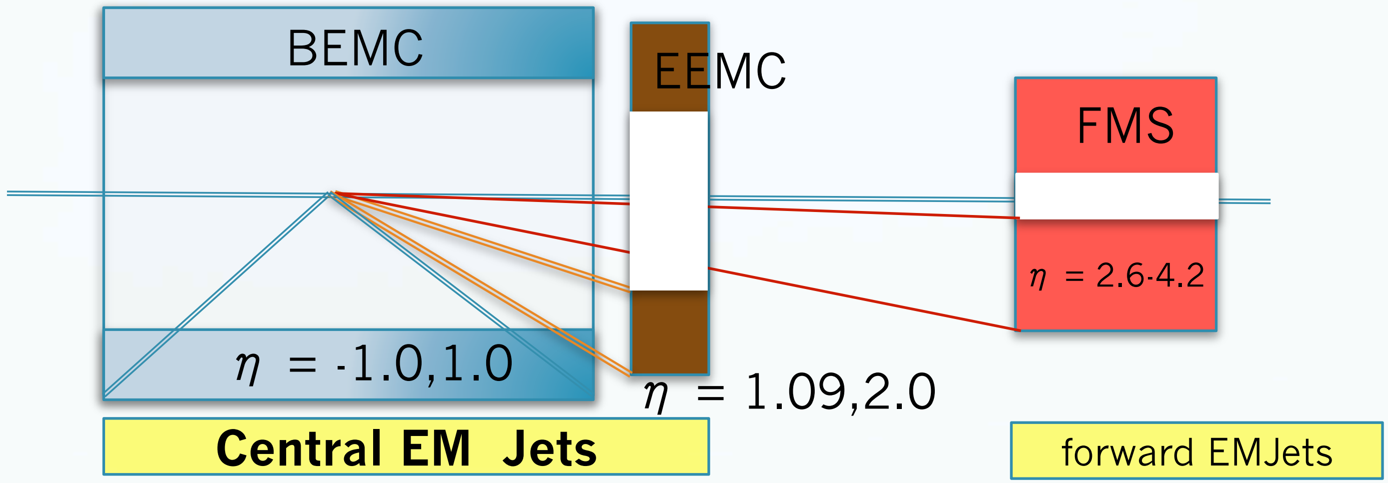
✧ Asymmetries for "jettier" (event complexity) events are much smaller

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")
- ✧ A_N for #photons >5 is similar to that #photons = 5

A_N with mid-rapidity activities



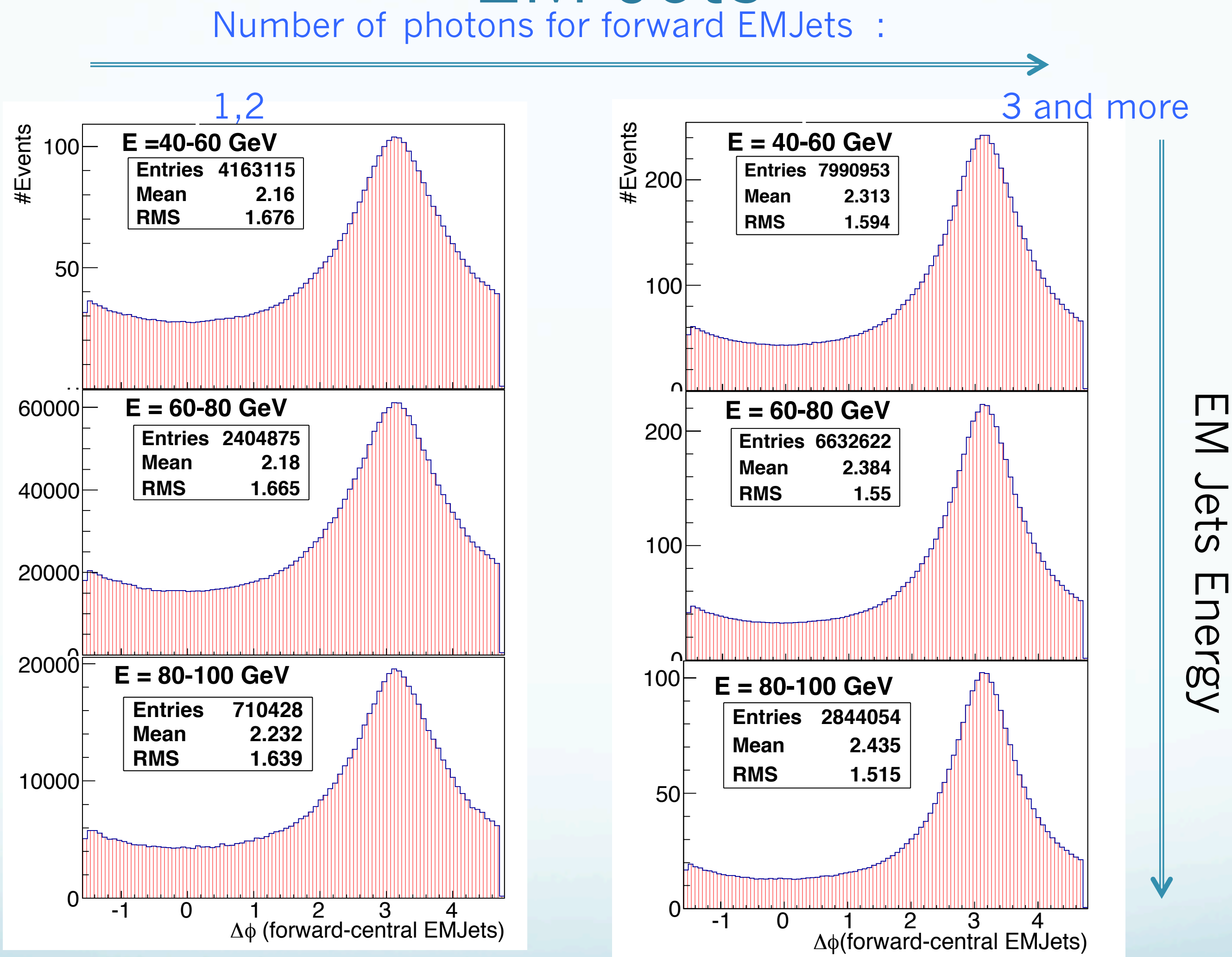
towers (BEMC+EEMC) :

anti-k_T, R = 0.7, $p_T^{EM\text{-}Jet} > 2.0$ GeV/c, $-1.0<\eta^{EM\text{-}Jet}<2.0$

Leading central EM-Jets : Jet with highest p_T

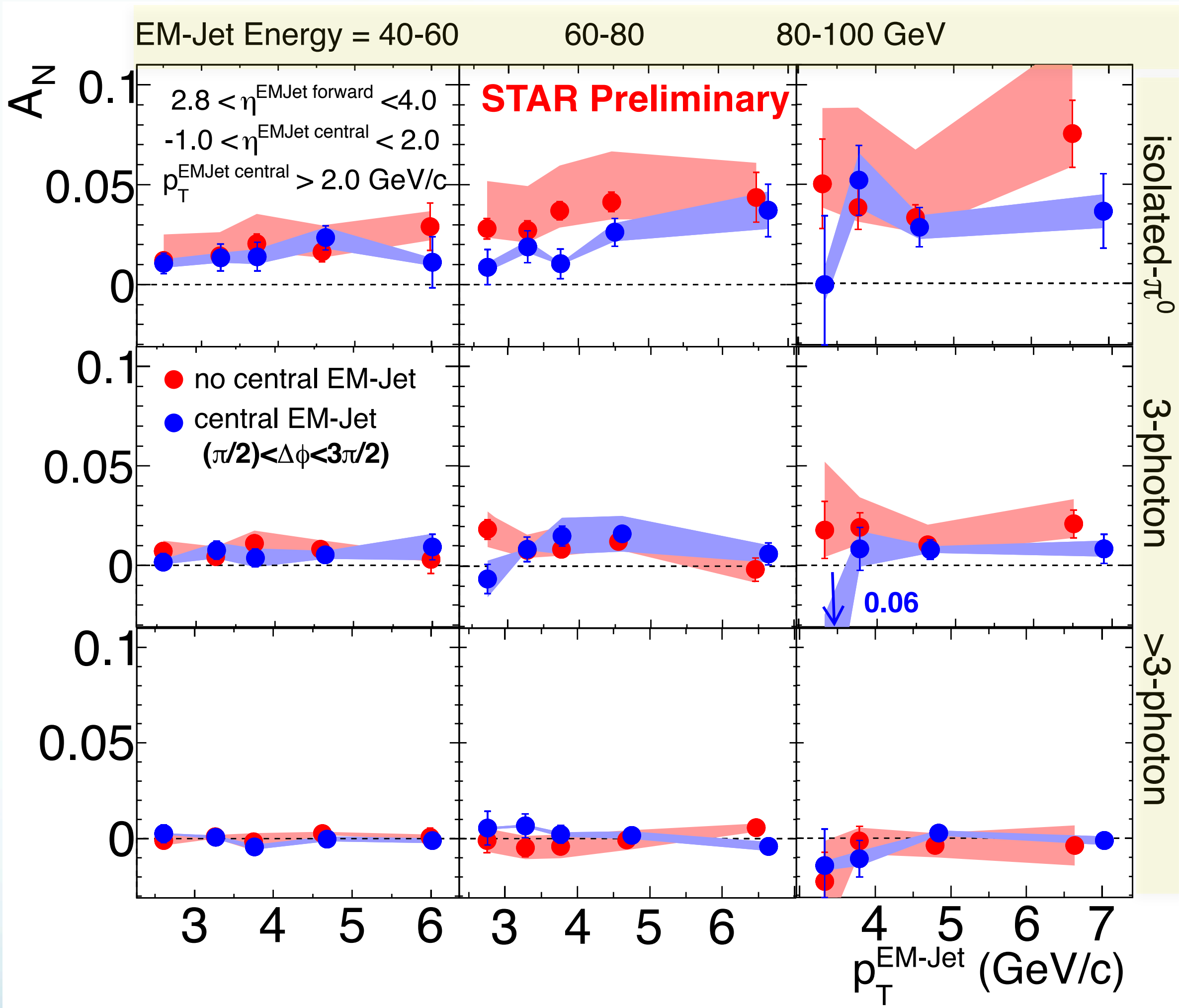
- Case-I : having no central jet
- Case-II : having a central jet

Δ Φ correlations between forward and central EM-Jets



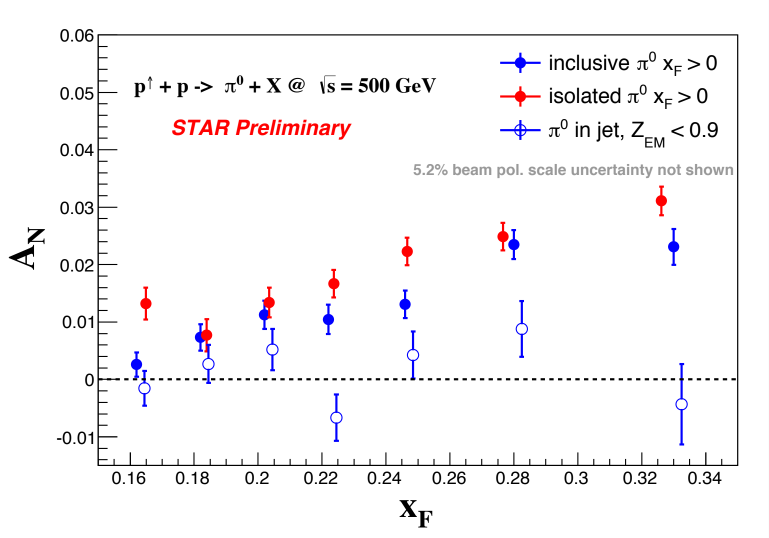
- ✧ Correlation is stronger for more N_photon Jets
- ✧ For higher EMJets energy, correlation grows stronger

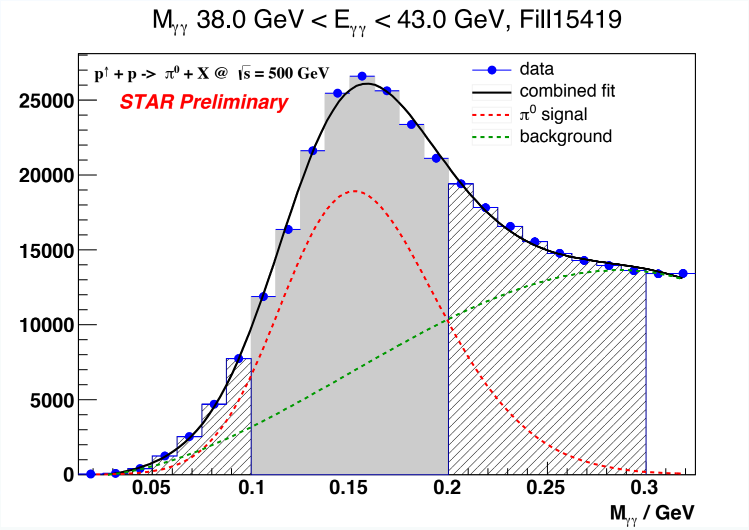
A_N for **correlated central jets** and **no central jet** cases

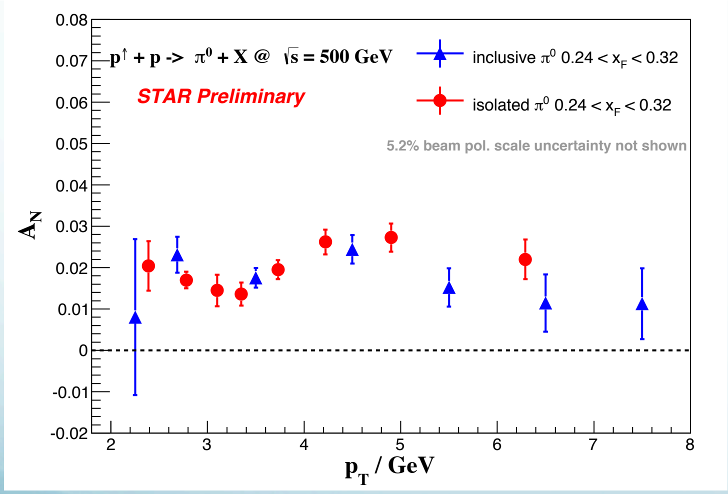


✧ **Asymmetries for the forward isolated π^0 are low when there is a correlated away-side jet.**

Asymmetries for π^0

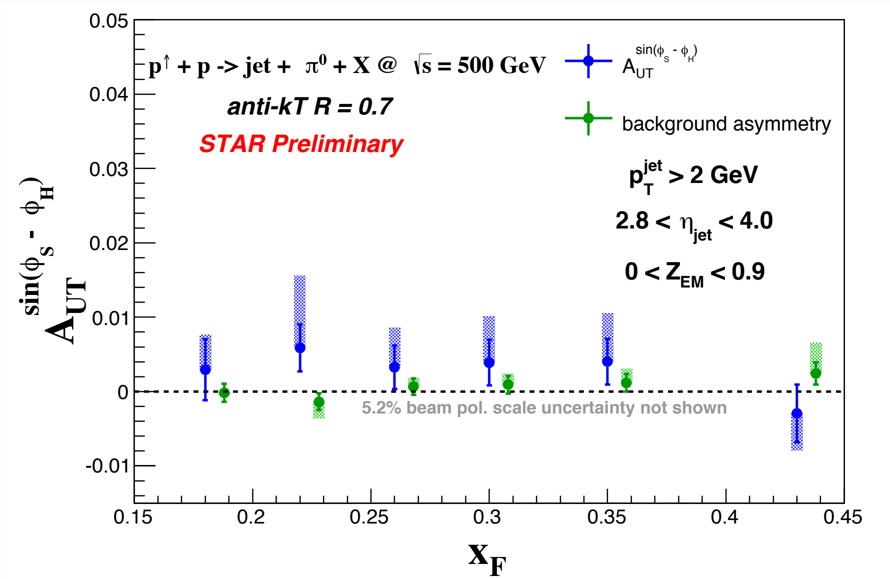


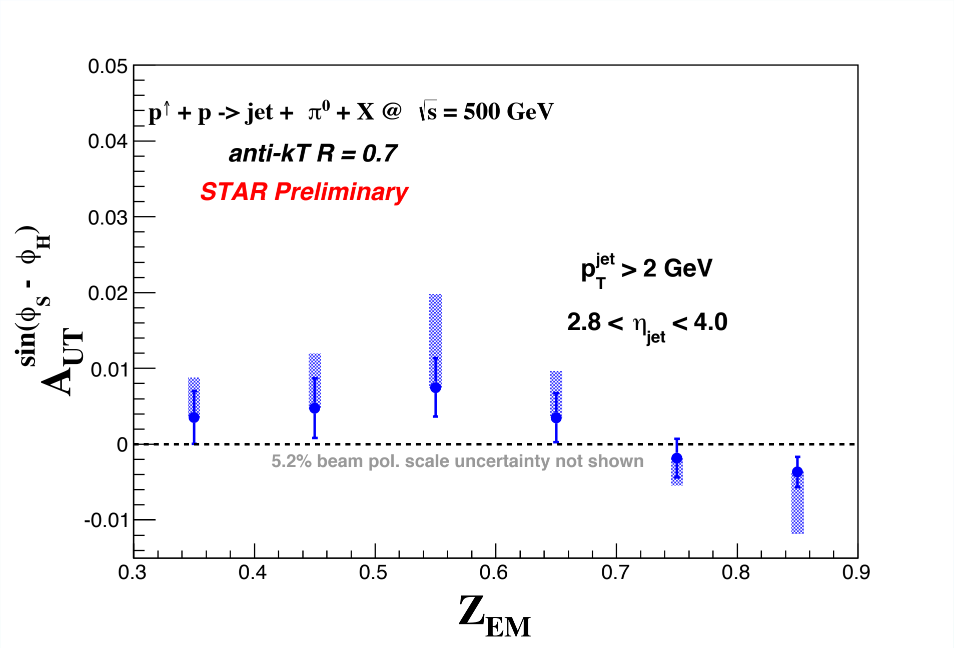




- Isolated π^0 tend to have significantly larger asymmetries than π^0 associated with jet activities in the vicinity.

Collins asymmetries for π^0 relative to jet axis





- **Total of Sivers and Collins asymmetries** of EMjet and π^0 relative to jet axis are found to be insufficient to account for the observed inclusive π^0 single spin asymmetries.

Findings from forward rapidity

- Jets with isolated π^0 have large asymmetry.
- A_N decreases as the event complexity increases(i.e., the "jettiness")
- Isolated π^0 asymmetries are smaller when there is a correlated EM-jet at mid-rapidity.
- Both of these dependences raise serious question about how much of the large forward π^0 A_N comes from 2 → 2 parton scattering (diffractive events?).
- Total of **Sivers and Collins asymmetries** of **EMjet and π^0 relative to jet axis** are found to be insufficient to account for the observed inclusive π^0 single spin asymmetries.

STAR at central rapidity

- **Asymmetric distributions of di-hadrons (**π^+ and π^- **)**

coupling **transversity** to the so-called “interference fragmentation function” (IFF) in the framework of collinear factorization

- **Collins Asymmetry from Jets**

coupling **transversity** to the transverse-momentum-dependent (TMD) Collins FF

2011

- 25 pb^{-1} at $\sqrt{s} = 500$ GeV
- Average polarization = 53%

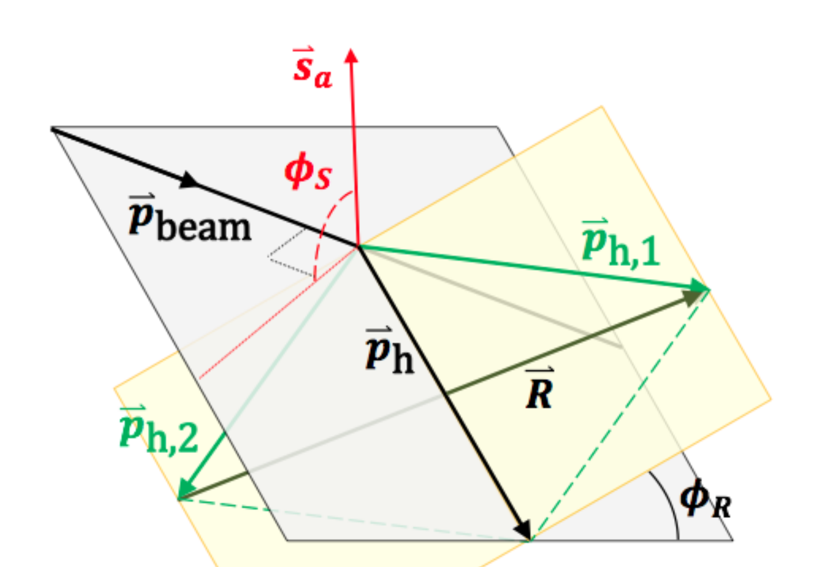
2012

- 22 pb^{-1} at $\sqrt{s} = 200$ GeV
- Avg polarization = 63%

Interference Fragmentation Function (IFF)

$$P^{\uparrow} + P \rightarrow \pi^{+}\pi^{-} + X$$

$$d\sigma_{UT} \propto P_T^{\pi^+\pi^-} \boxed{\sin(\phi_{RS})} \int dx_a dx_b f_1(x_a) \boxed{h_1(x_b)} \frac{d\Delta\hat{\sigma}}{d\hat{t}} \boxed{H_1^{\sphericalangle}(z, M_{inv}^{\pi^+\pi^-\,2})}$$



—"Interference Fragmentation Function"

e.g. Bacchetta and Radici, PRD 70, 094032 (2004)

$$\phi_{RS} = \phi_R - \phi_S$$

$$\vec{p}_h = \vec{p}_{h,1} + \vec{p}_{h,2}$$

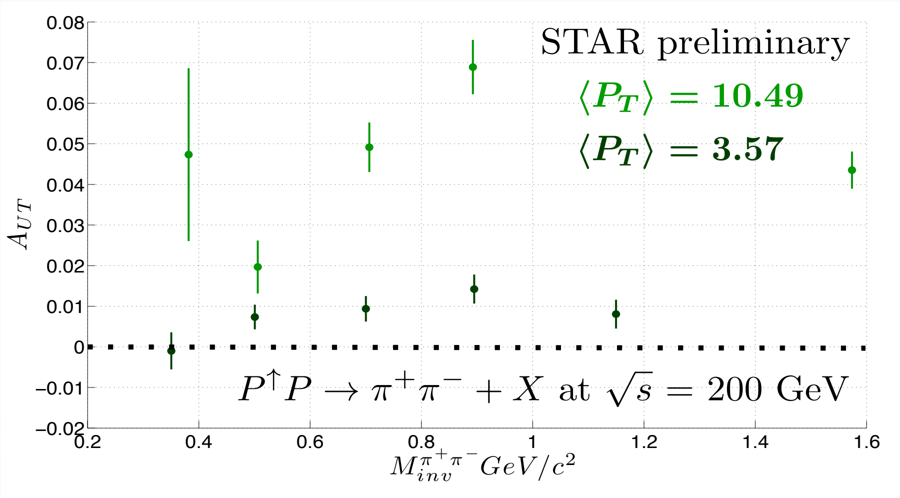
$$\vec{R}_h = \vec{p}_{h,1} - \vec{p}_{h,2}$$

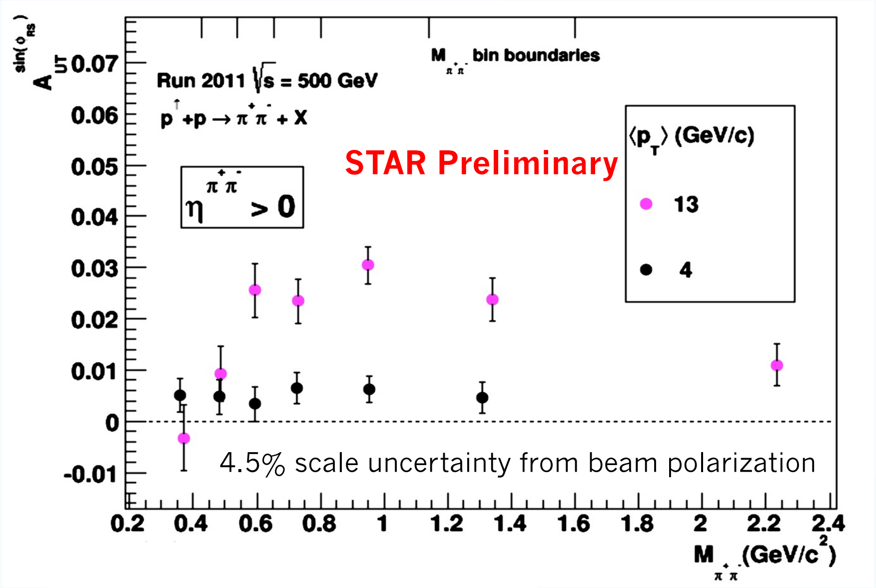
$$\boxed{A_{UT}\sin(\phi_{RS}) = \frac{1}{Pol}\frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}}$$

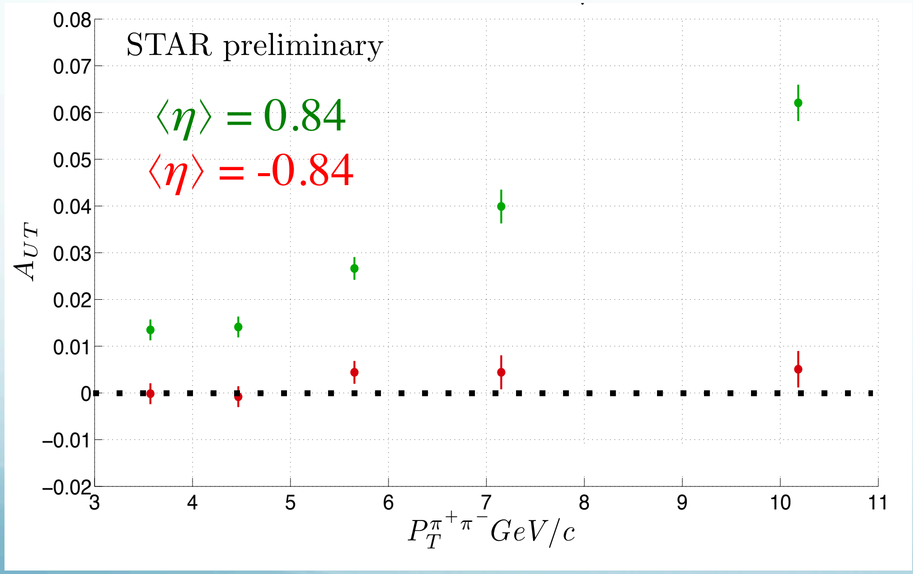
$$\propto h_1 \otimes H_1^{\angle}$$

Survives in collinear framework

Asymmetry with m_{inv} and p_T for π^+ and π^- pairs

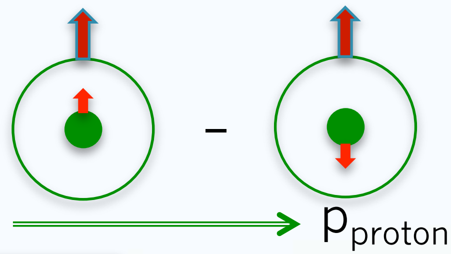


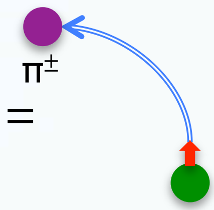




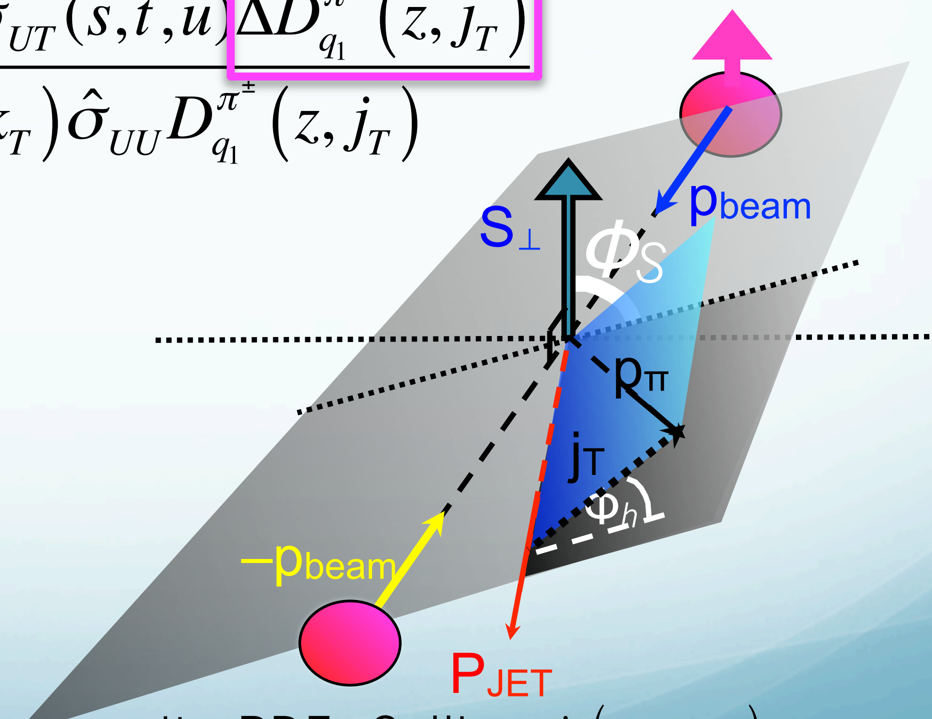
- Significant di-hadron asymmetries both at √s=200GeV and √s=500GeV
- Increasing with p_T
- Enhancement to asymmetry is seen around ρ mass

Jets to access Transversity

Transversity =


Collins FF =


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



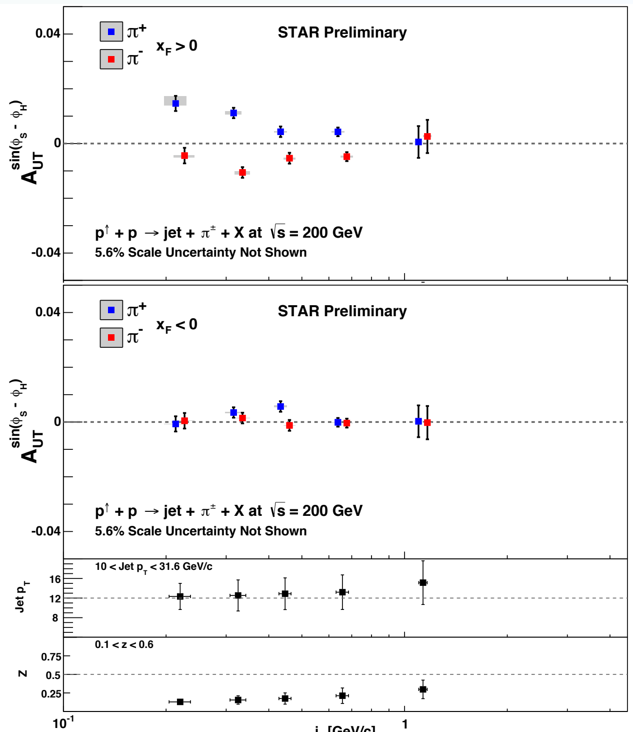
Key search in region x (0.1 < x < 0.35)

- dependence of the Collins FF on pion transverse momentum (j_T)
- Collins asymmetry universal?
- do these asymmetries evolve with √s?

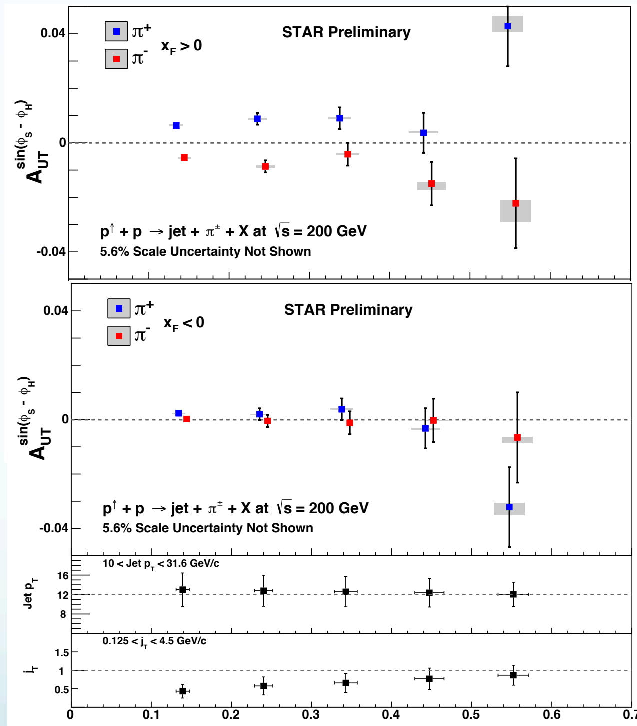
Transversity•PDF •Collins $\sin\left(\varphi_{S_A} - \varphi_\pi\right)$

20 pb^{-1} transversely polarized p+p collisions at $\sqrt{s}$ **= 200 GeV**
Average event weighted polarization: 63%
Anti-k_T (R = 0.6) jet reconstruction
$|\eta_{jet}| < 1$
Jet p_T > 10 GeV/c (x_T > 0.1) reduces gluon contamination
$\Delta R_{min} > 0.1$

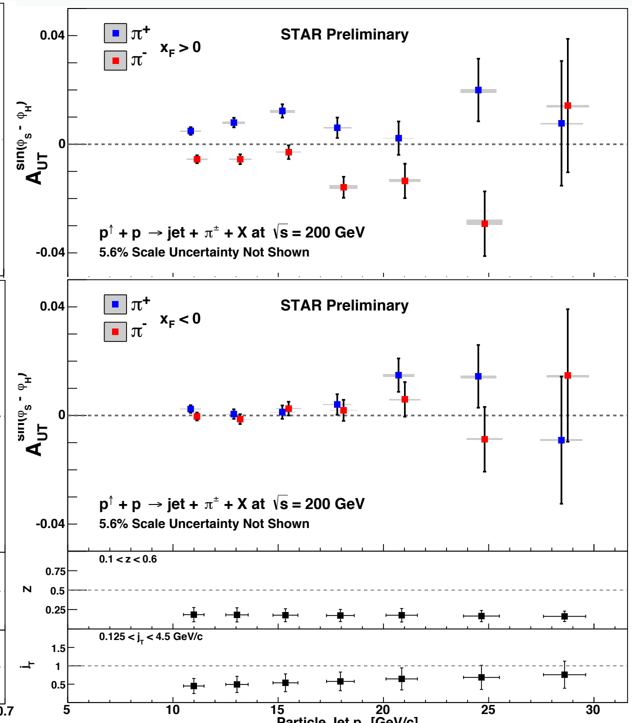
A_{UT} vs. j_T



A_{UT} vs. z

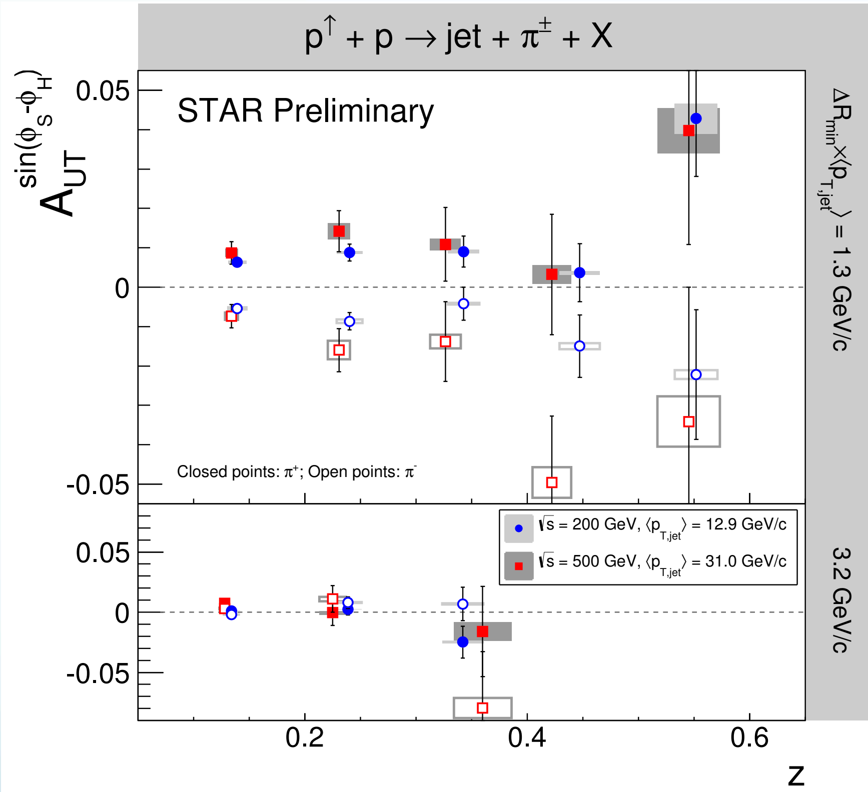


A_{UT} vs. p_T



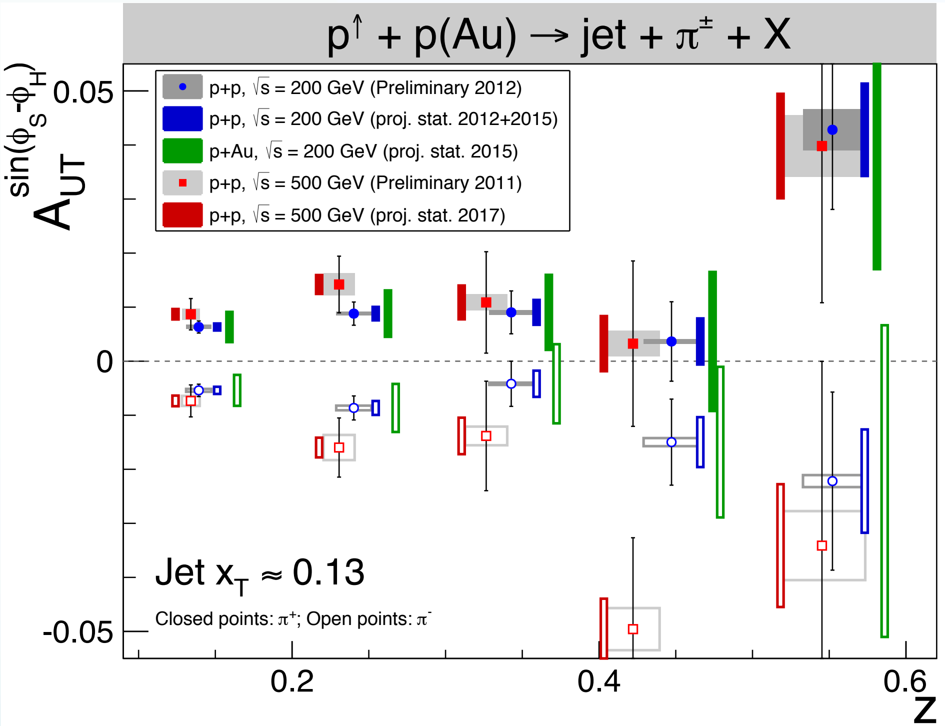
The first statistically significant non-zero Collins asymmetries in pp collisions

200 vs. 500 GeV Comparison



- These measurements coupled with the interference fragmentation function (IFF) measurements at both 200 and 500 GeV will provide insight into the Q^2 evolution and universality of TMD functions.
- These results could lend sensitivity to the size of potential factorization-breaking in Collins in p+p.

Projections till year 2017

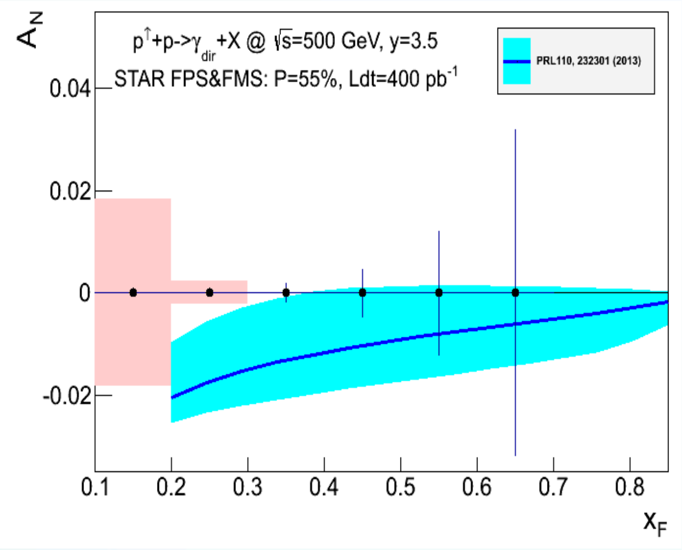


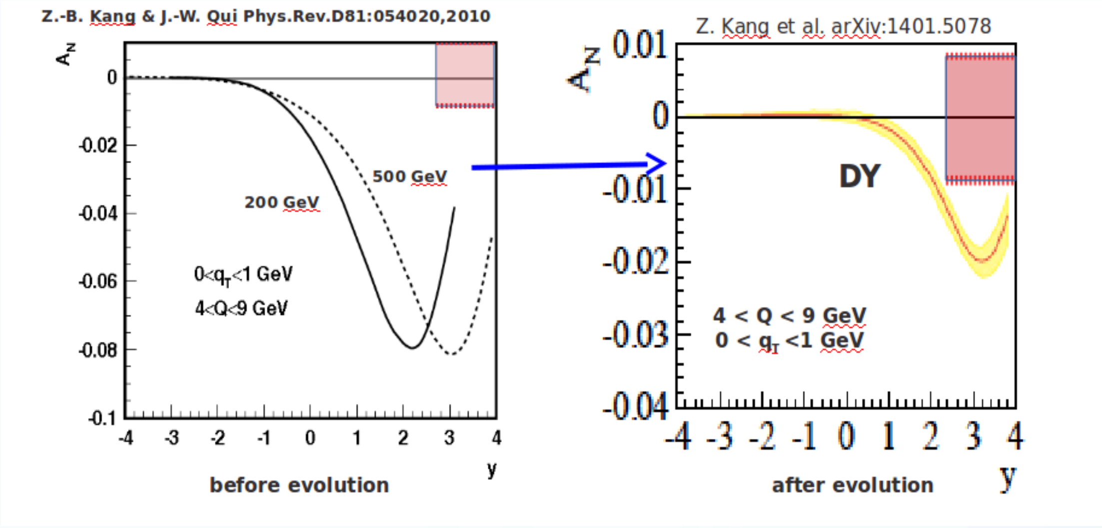
- These measurements coupled with the interference fragmentation function (IFF) measurements at both 200 and 500 GeV will provide insight into the Q^2 evolution and universality of TMD functions.
- These results could lend sensitivity to the size of potential factorization-breaking in Collins in p+p.

2015 Rich Transverse physics data with STAR forward upgrades

STAR future measurements

Observable without fragmentation func. : Drell-Yan, $W^{\pm}$ /Z, jets, direct photons

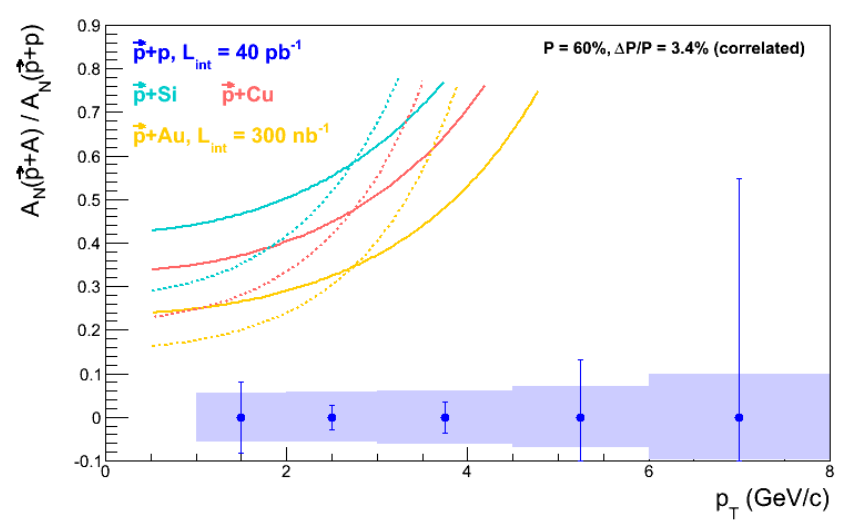




measurements γ_{direct} measurements as a test of twist-3 framework

$Sivers_{DIS}$ = - Sivers (DY or W or Z)

STSAs in nuclear medium



understand the underlying sub-process leading the big forward SSA in transverse polarized p+p

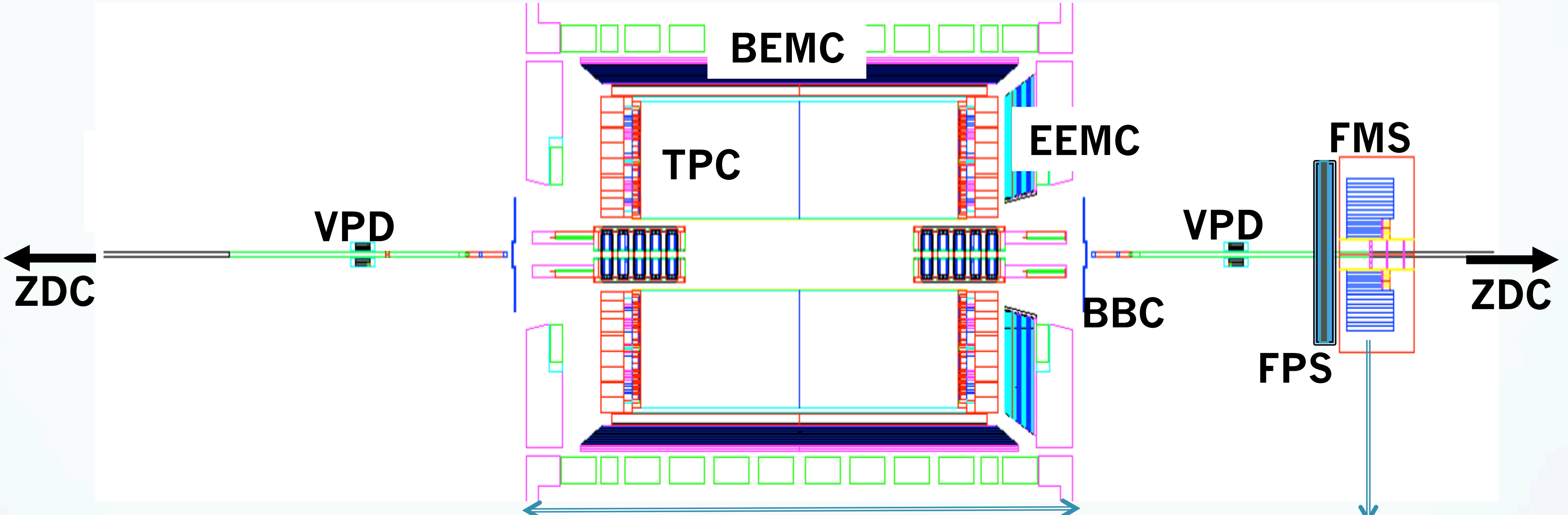
STAR forward goals **for data taking on 2015**

- **Direct Photon** x-section & A_N at pT>2.0GeV (**FMS + Pre-shower**)
- **Pi0 A_N - Jetty vs Isolated** :
  pp vs pA(p+Au, p+Al), diffractive vs non-diffractive (**Roman Pots**)
- Study di-electron channel (J/psi) towards DY

Summary

- STAR measurements play an important role in understanding nucleon spin structure.
- **TSSA for $\pi^{0's}$ and EMJets at forward rapidity** for $\sqrt{s}$ =500GeV shed light to the origin of large transverse asymmetry
- **IFF measurements** show high asymmetry for π^+ and π^- pairs and an **enhancement at ρ mass region**.
- **First Measurement of Transversity in p+p** : *consistent with x_T scaling from 200 to 500 GeV.*
- Data for 2015 moving toward **A_N measurement of direct photons and DY at forward rapidity**.
- **Collisions p↑+p↑ and p↑+Au and p↑+Al would provide new insight** in understanding the underlying sub-process leading the big forward SSA in transverse polarized p+p.

STAR detector in cross view



BEMC+EEMC towers : to find central electromagnetic jets

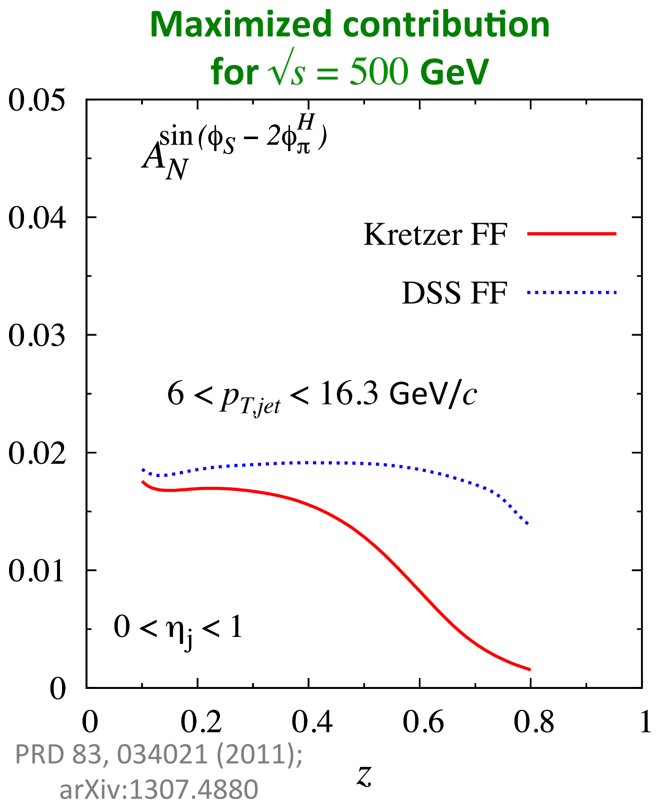
FMS photons : to find forward electromagnetic jets

FMS photon reconstruction :

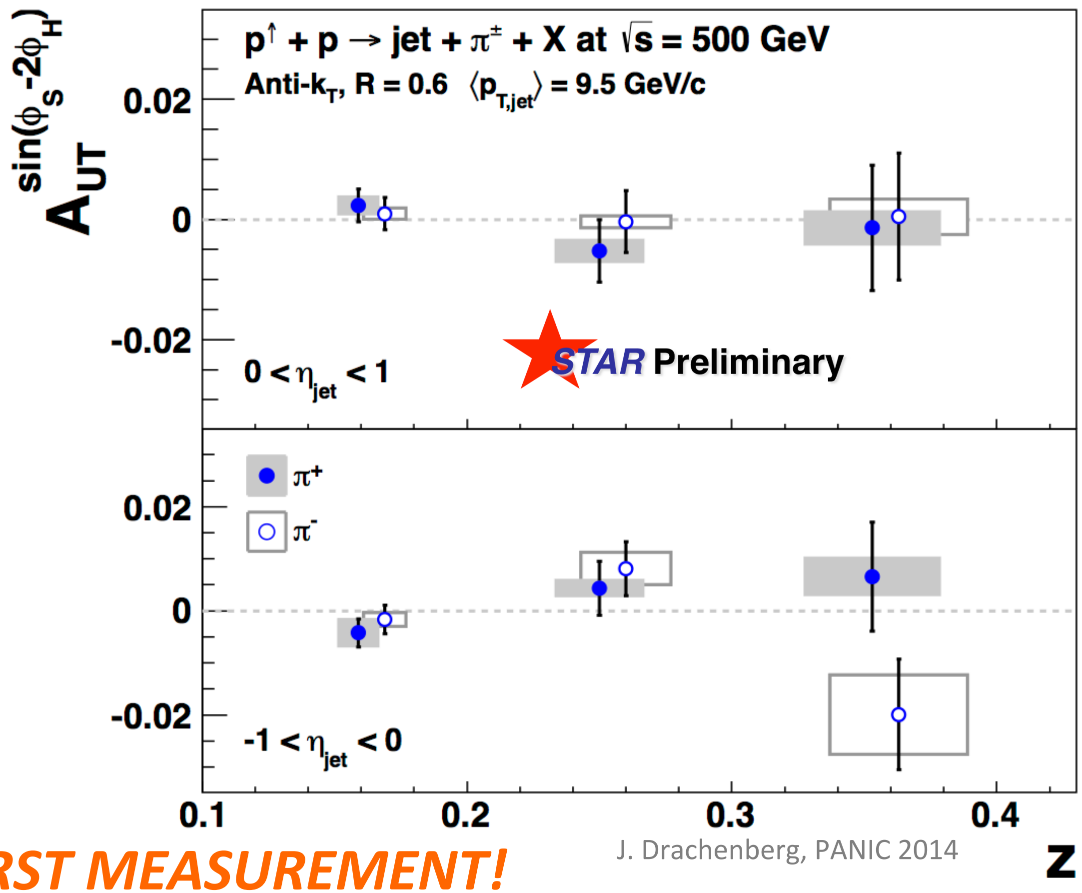
towers → clusters → photon

shower shape fitting

Collins-like Asymmetries at $\sqrt{s}$ = 500GeV



PRD 83, 034021 (2011);
arXiv:1307.4880



J. Drachenberg, PANIC 2014

FIRST MEASUREMENT!

Present data sit well below maximized contribution of ~2% at low z

Present data should provide first constraints on Collins-like effect

(sensitive to linearly polarized gluons)