Measurement of the Transverse Single-Spin Asymmetries for π^0 and Jet-like Events at Forward Rapidities at STAR in p+p Collisions at $\sqrt{s}$ = 500 GeV

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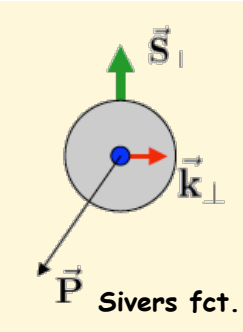
Outline

- ✧ Transverse Single Spin Asymmetries (TSSA)
- ✧ Forward Meson Spectrometer in the STAR experiment
- ✧ EM-Jets in forward and central rapidity
- ✧ A_N measurements from RHIC Run 11 at $\sqrt{s}$ = 500 GeV

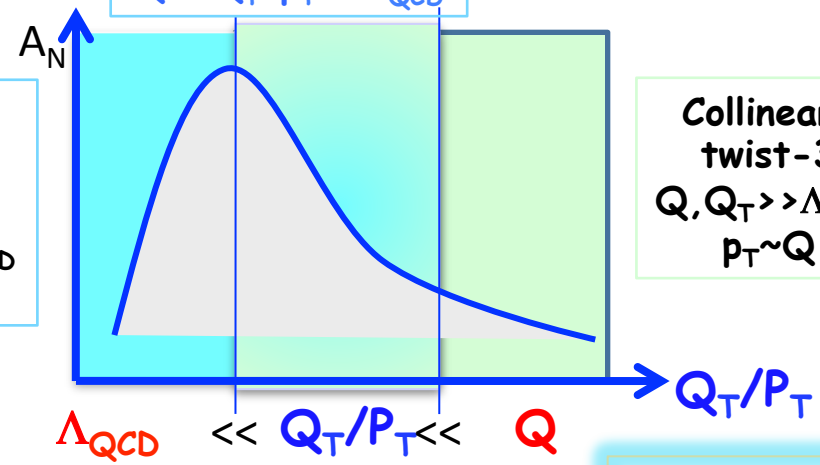
TSSA - 2 theoretical frameworks

Spin-dependent transverse momentum dependent (TMD) function $S_T.(Pxk_T)$
Brodsky, Hwang, Schmidt, 02
Collins, 02, Ji, Belitsky, Yuan, 02



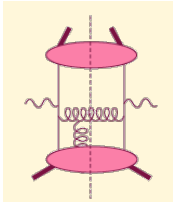
Transverse momentum dependent
$Q >> Q_T >= \Lambda_{QCD}$
$Q >> p_T$

Intermediate Q_T
$Q >> Q_T/p_T >> \Lambda_{QCD}$



Twist-3 quark-gluon correlations
Efremov & Teryaev: 1982 & 1984
Qiu & Sterman: 1991 & 1999

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
Exception:
DY, W/Z-production

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

π^0 A_N Measurements at Forward Rapidity

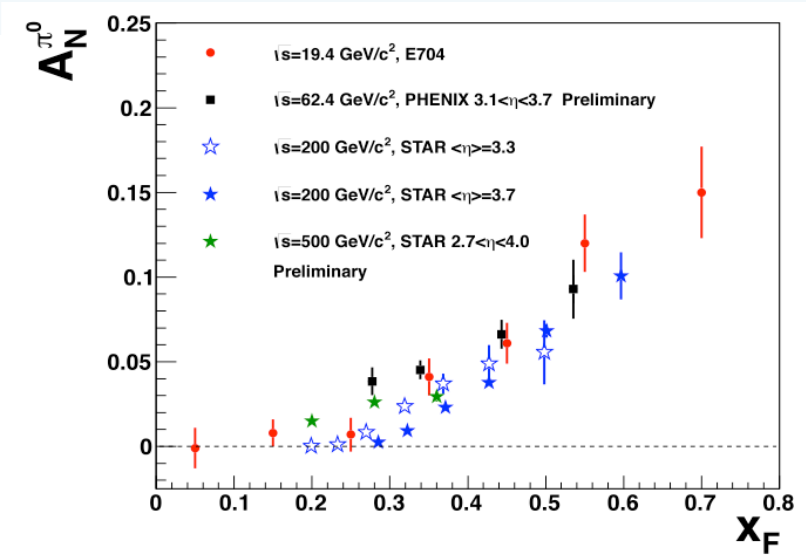
Inclusive π^0 production

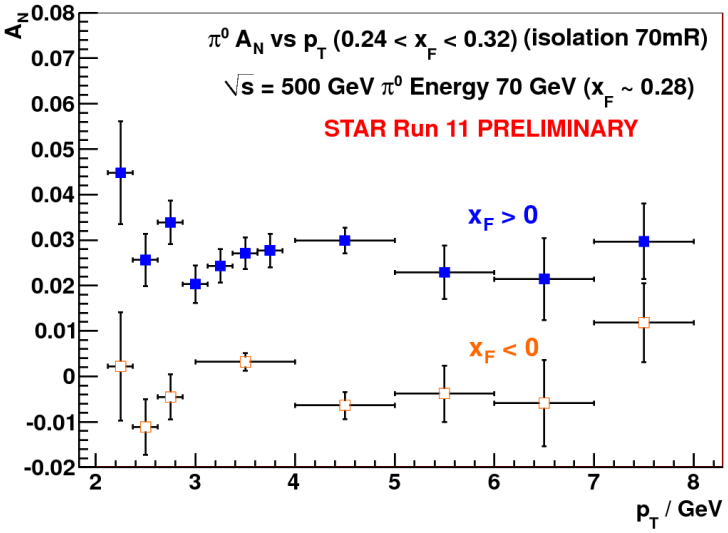
$$p_\uparrow + p \longrightarrow \pi^0 + X$$

Transverse Single Spin Asymmetry

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

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





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

500 GeV Isolated π^0 results

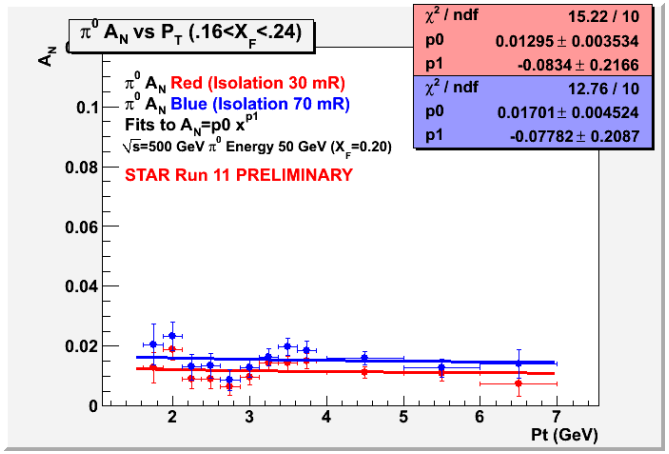
$\sqrt{s}$= 500 GeV (Run 11) Transverse Single Spin π^0 Asymmetry vs P_T for small and large π^0 isolation cones. (Errors shown in these are following plots are statistical)

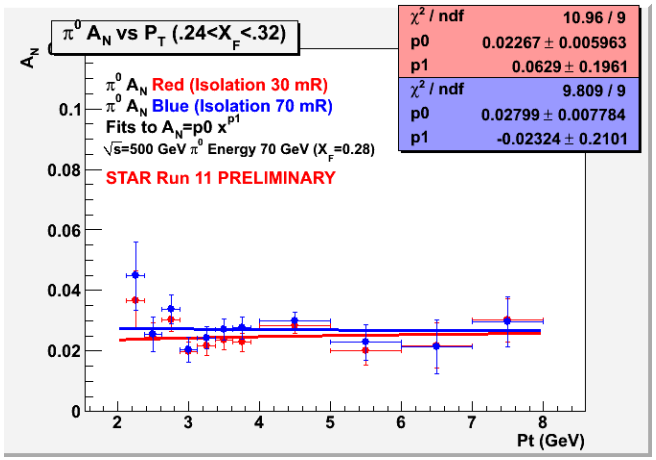
Higher Twist or other pQCD related models suggest **A_N should fall at large P_T with at least 1 power of P_T.**

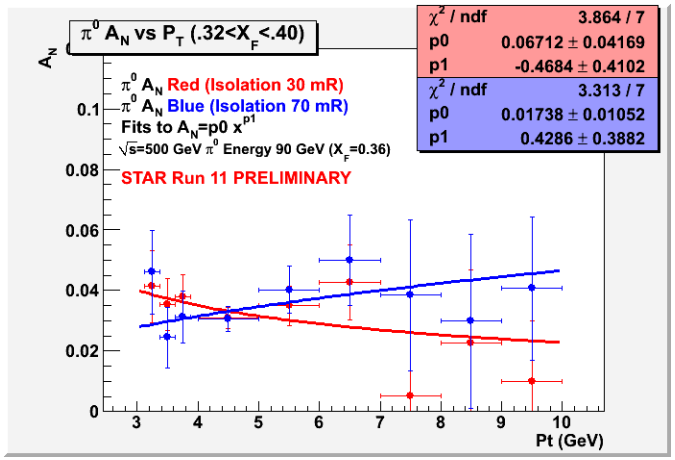
These plots include 2 parameter fits for A_N vs P_T :

$$A_N(P_T) = [p_0] \times (P_T)^{[p_1]}$$

Fits are shown for both the **70 mRad** and **30 mRad** isolation cones.







- ✧ A_N is higher with incerasing isolation radius
- ✧ A_N in increasing with x_F

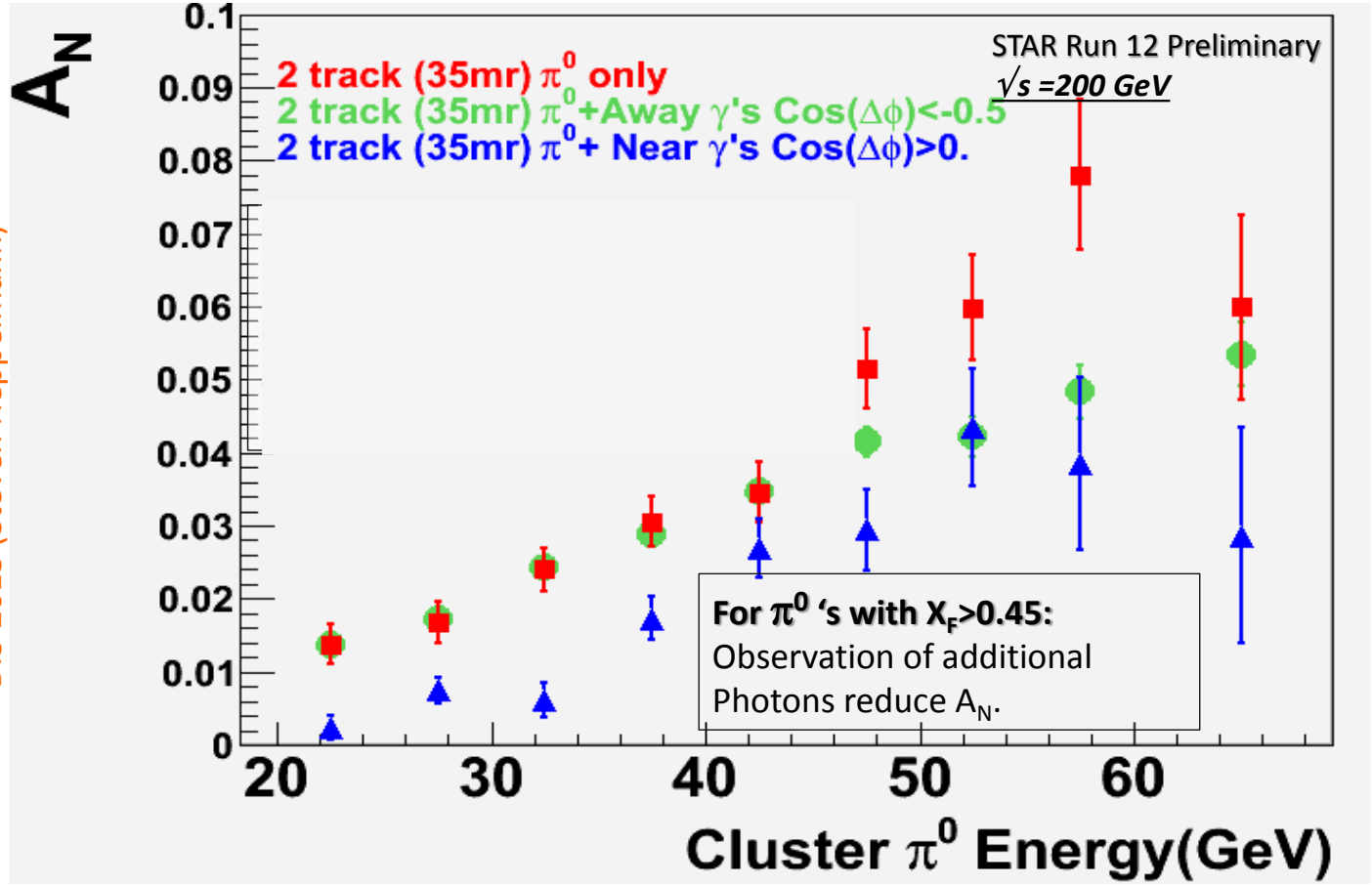
DIS-2013 (Steven Heppelmann)

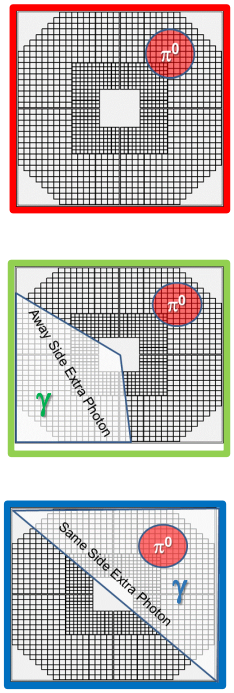
200 GeV Isolated π^0 results

A_N vs. Energy, averaged over pseudo-rapidity.

Compare 3 selection criterion based on photon energy outside the cone (all with 35mR cone and no soft E cut)

DIS-2013 (Steven Heppelmann)





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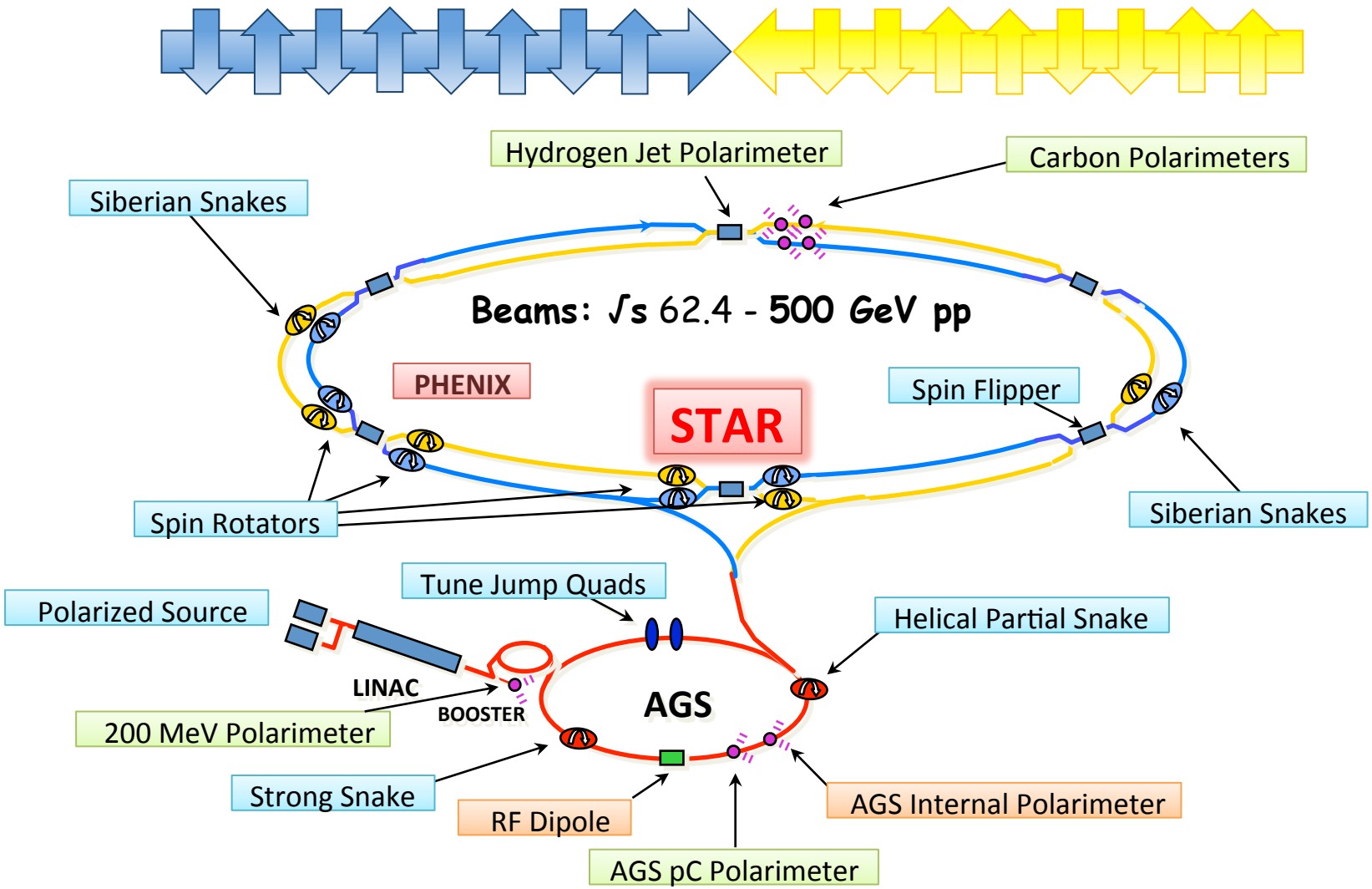
- ✧ Events opposite "side photons" or "no" photons have similar A_N
- ✧ Same side photons lead to much reduced A_N

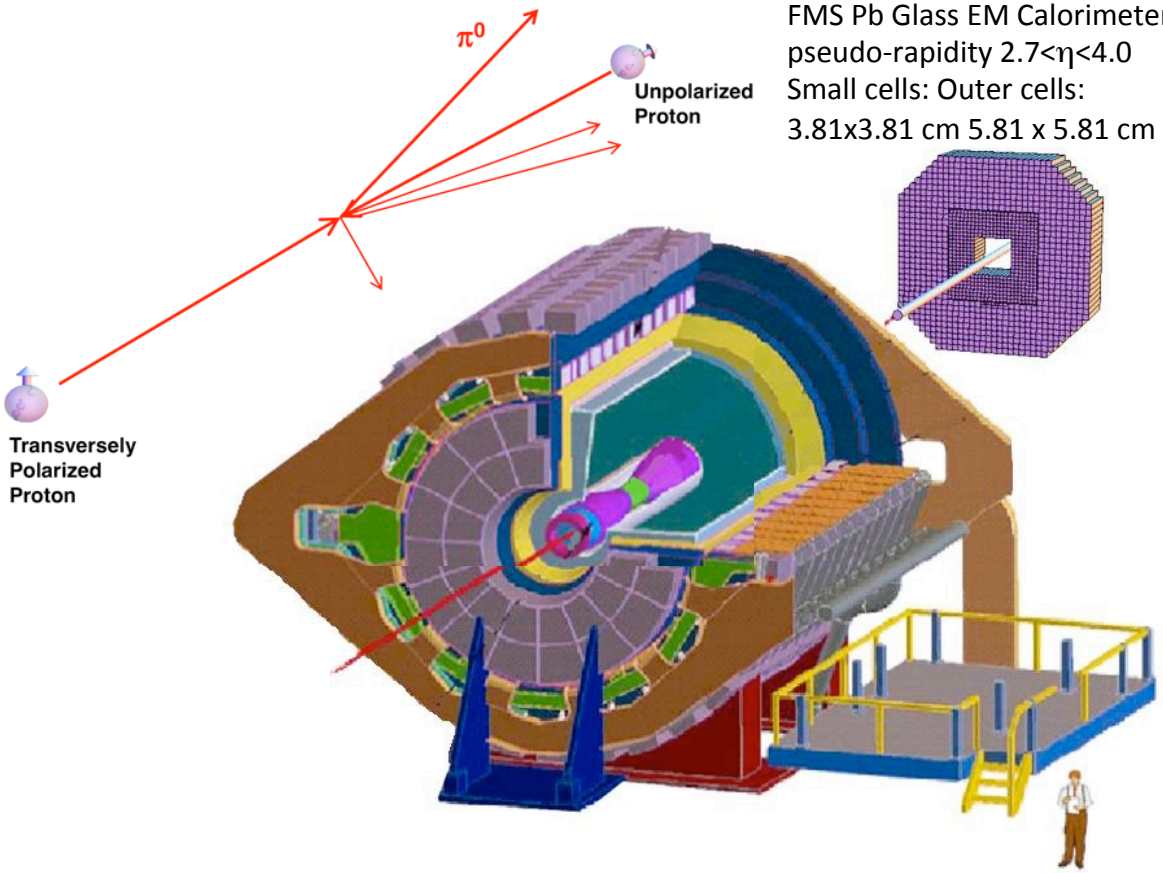
RHIC : the world's first and only polarized proton collider

For 2011 : Average Blue Beam Polarization = 51.6% (Transverse)

Luminosity =22 pb-1



Forward ECAL in STAR



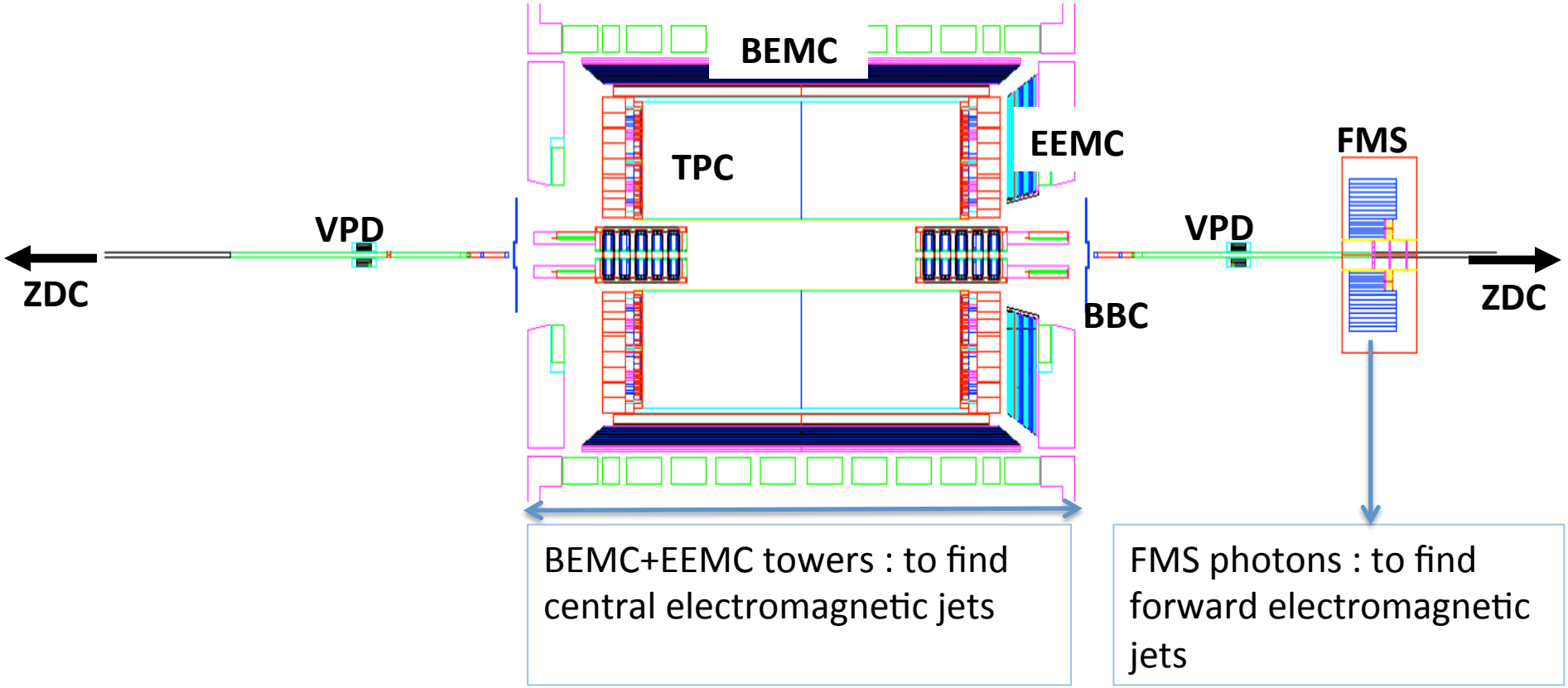
FMS Pb Glass EM Calorimeter
pseudo-rapidity 2.7<η<4.0
Small cells: Outer cells:
3.81x3.81 cm 5.81 x 5.81 cm

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.

STAR detector cross view

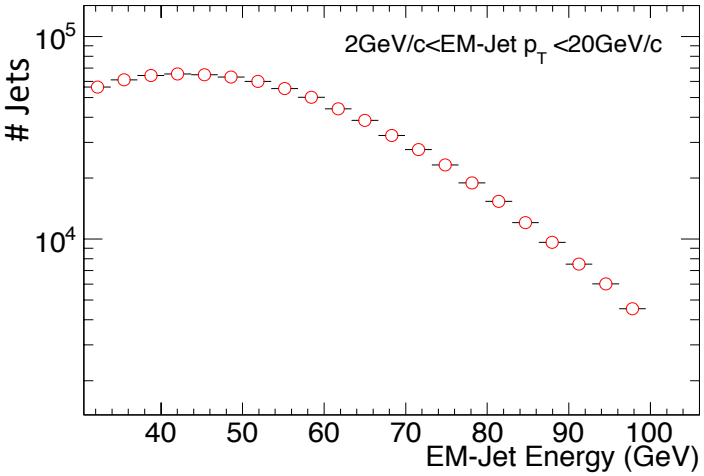


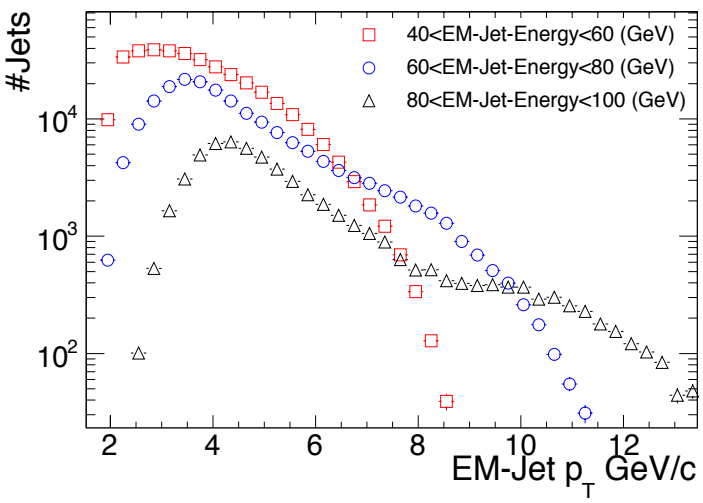
FMS photon reconstruction :

towers → clusters → photon

shower shape fitting

RHIC Run 11 (2011) pp @ √s=500 GeV





Forward Electromagnetic Jets (EM-Jets)

Jet algorithm : anti-k_T

R-parameter : 0.7

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

Leading EM-Jets : defined as EM-Jets with highest energy.

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

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

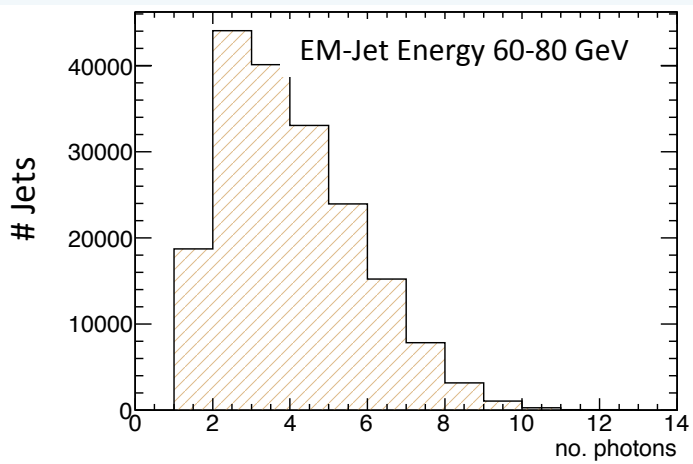
($0.16 < x_F < 0.4$)

Structure in EM-Jet p_T :

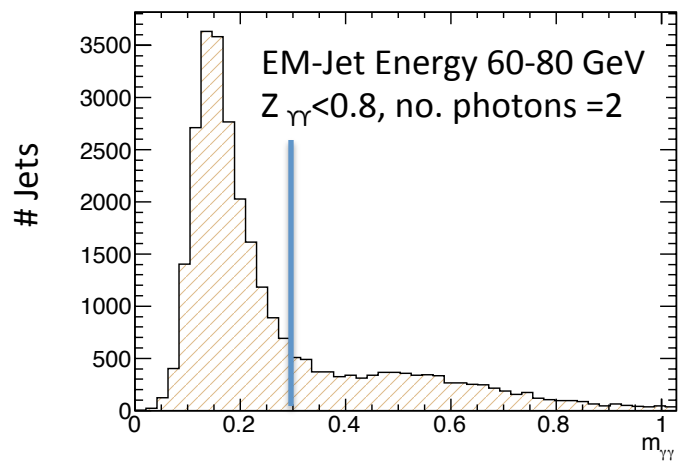
-- Acceptance non uniformity in small and large tower boundary inside FMS

-- Different trigger threshold influence different p_T region

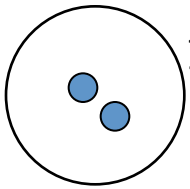
Forward EM-Jet characteristics

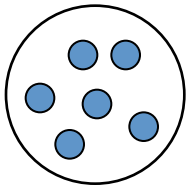


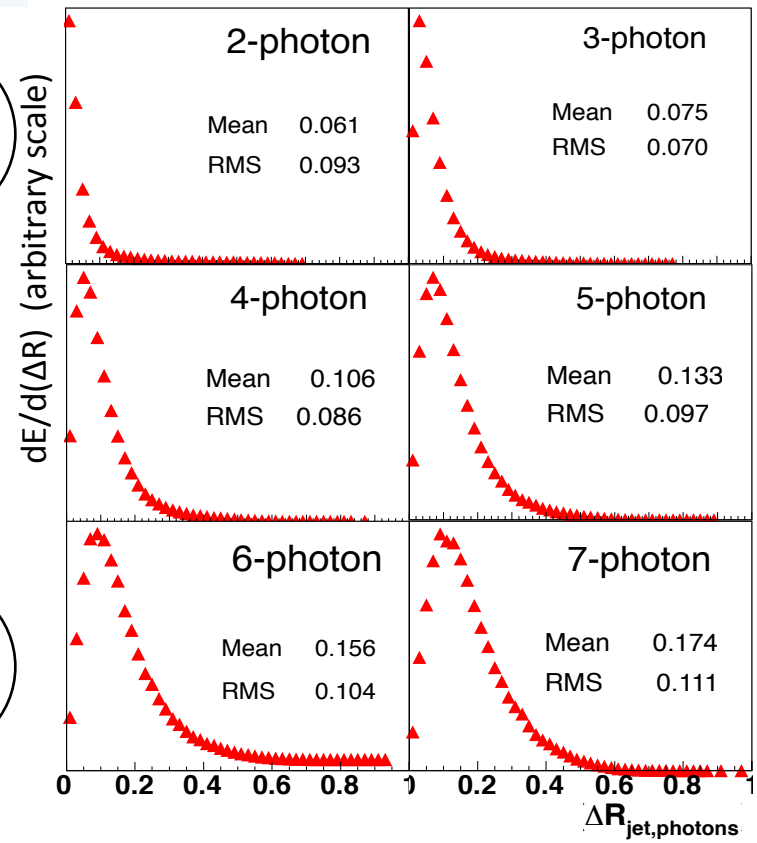
No. of photons in leading EM-Jets

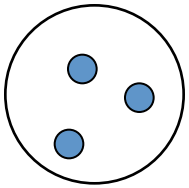


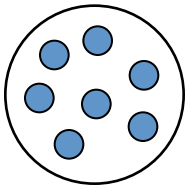
γγ invariant mass 2-photon EM-jets











dE/d(ΔR) distribution of EM-Jets

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

A_N from fits

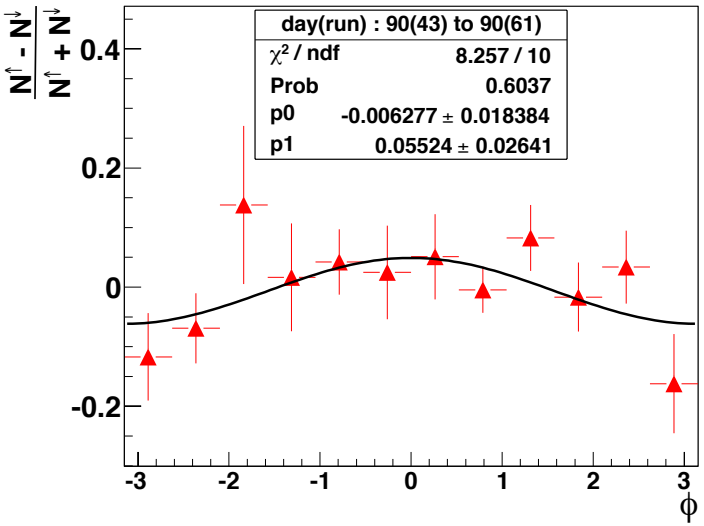
✧ **A_N is calculated from p0 + P×A_N cos(φ) fits over each fill on**

$$\frac{N\uparrow(\phi)-N\downarrow(\phi)}{N\uparrow(\phi)+N\downarrow(\phi)} = p0 + P\times A_N \cos(\phi)$$

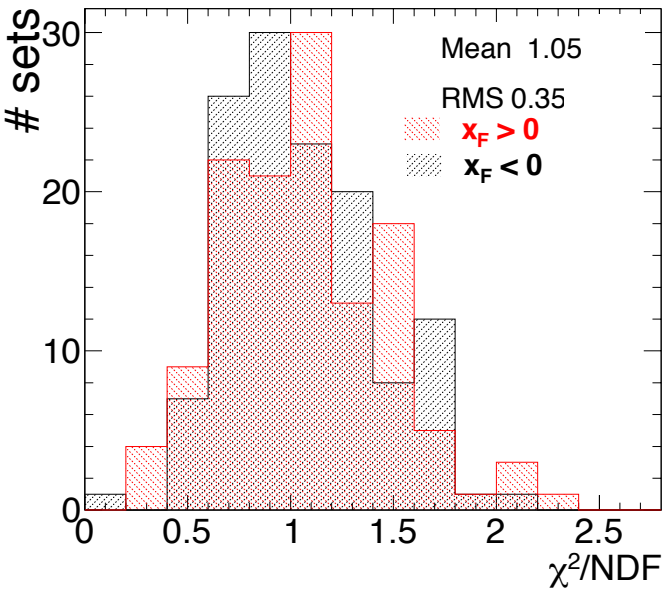
p0 = relative luminosity
A_N = asymmetry
P = polarization

--- A_N's are corrected for polarization values from RHIC-fills
--- A_N and χ^2/NDF are calculated over entire fills

EM-Jet Energy = 55-57.5 GeV

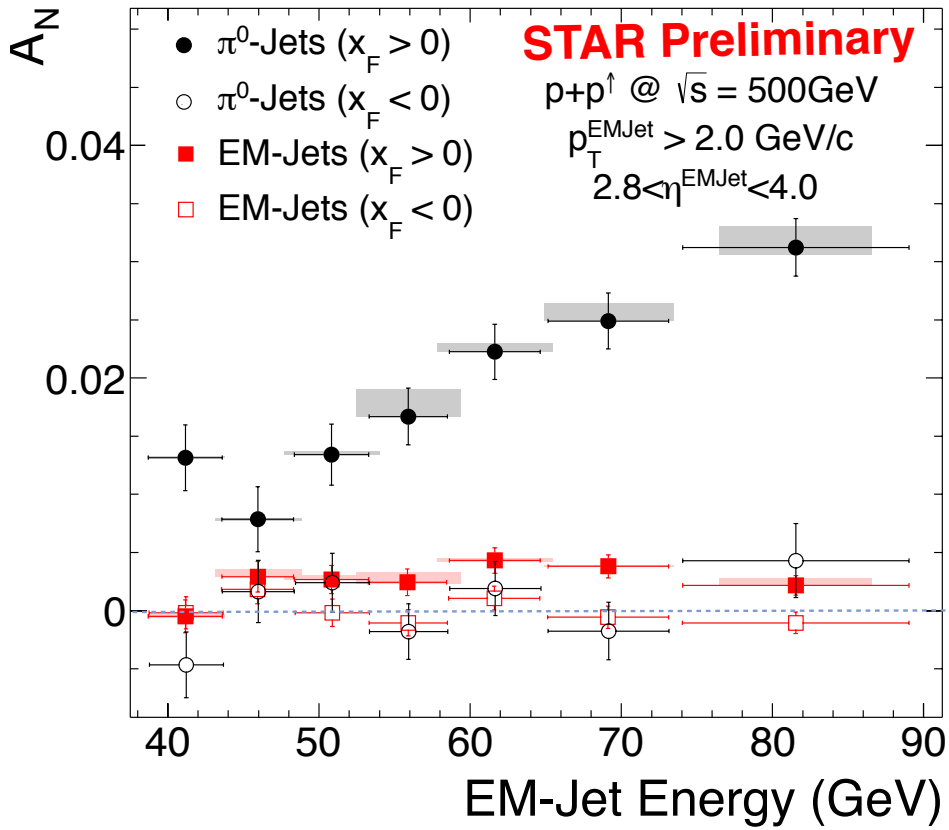


For 2-photon isolated π^0



For each slice of data averaged over ~18 fills. Fits are well in control.

A_N vs. EM-Jet Energy



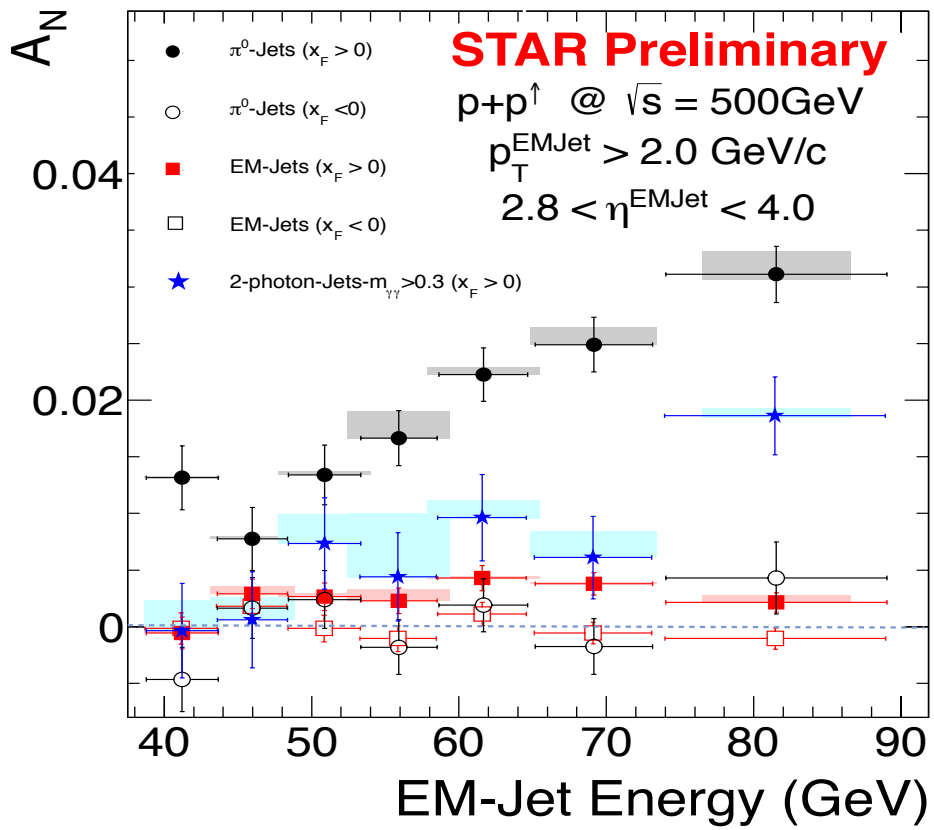
π^0-Jets –
2γ-EM-Jets with
$m_{\gamma\gamma} < 0.3$
$Z_{\gamma\gamma} < 0.8$

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 events are much smaller**

A_N vs. EM-Jet Energy



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

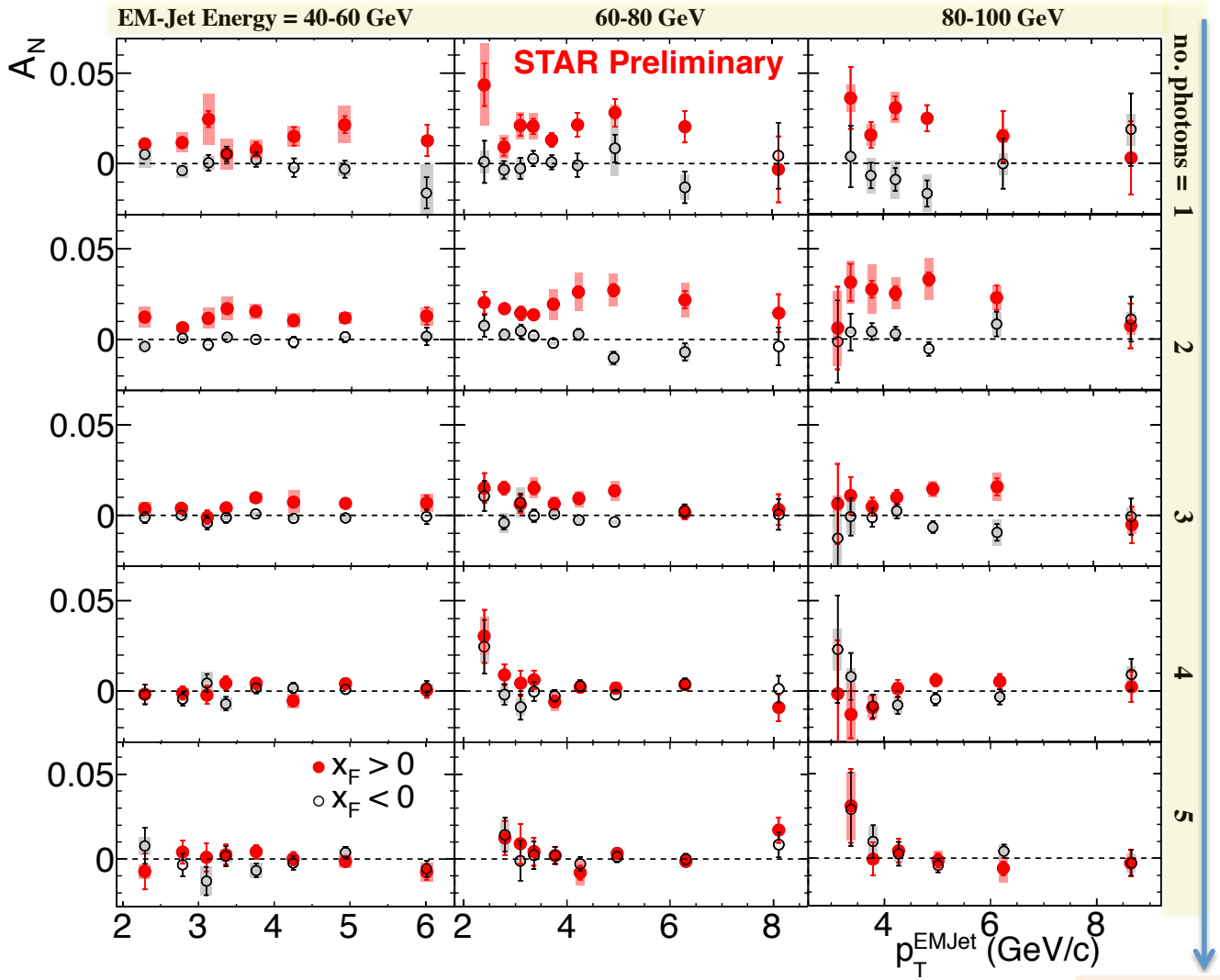
2γ-EM-Jets (η + continuum) - with
$m_{\gamma\gamma}$ > 0.3

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 events are much smaller**

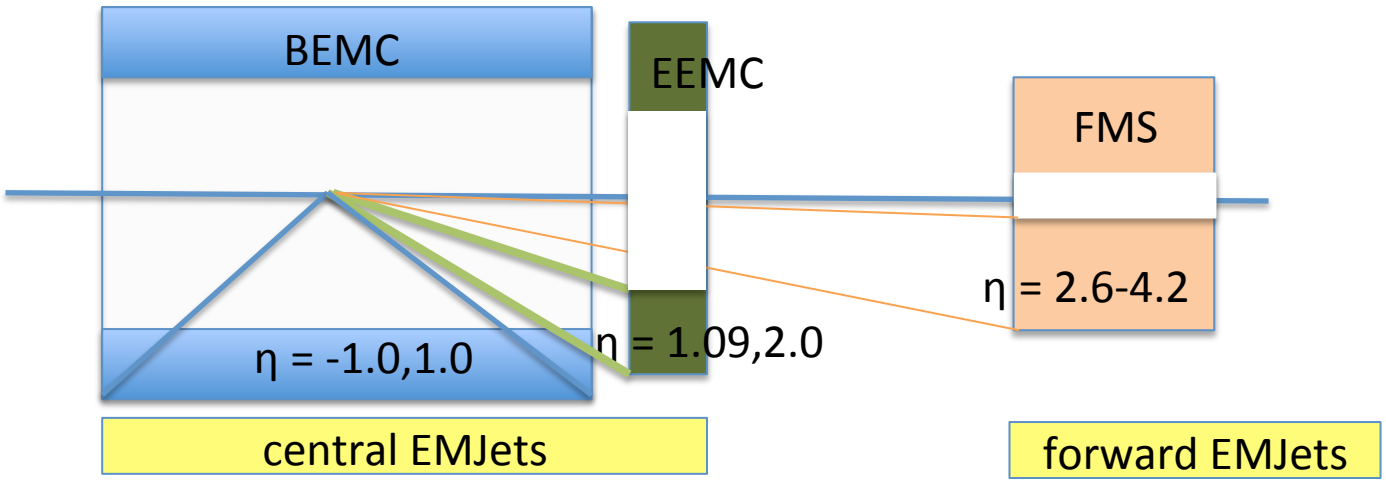
A_N for different # photons in EM-Jets



Jettier events

- 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 for #photons = 5

A_N with midrapidity activities



Midrapidity EM Jets

Jet algorithm : anti-k_T, R = 0.7

$p_T^{EM\text{-}Jet} > 2.0$ GeV/c, $-1.0<\eta^{EM\text{-}Jet}<2.0$

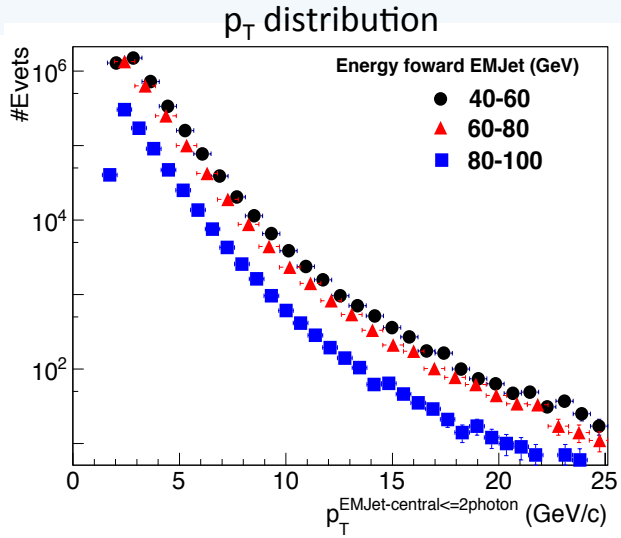
Inputs for central EMJets : towers from BEMC and EEMC

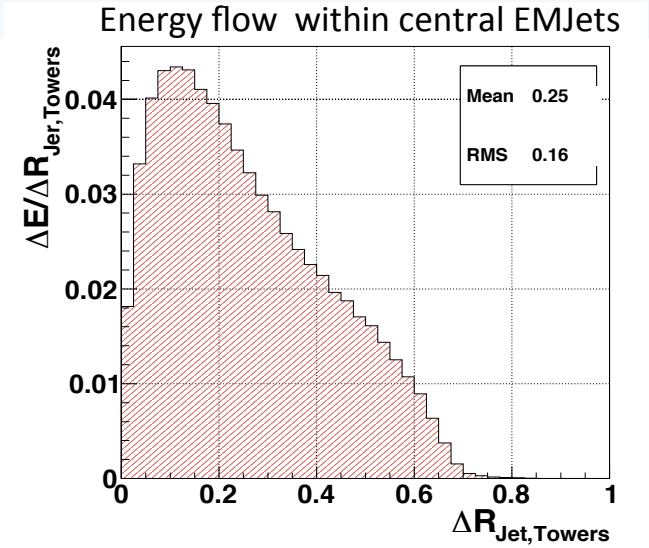
Leading central EM-Jets : Jet with highest p_T

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

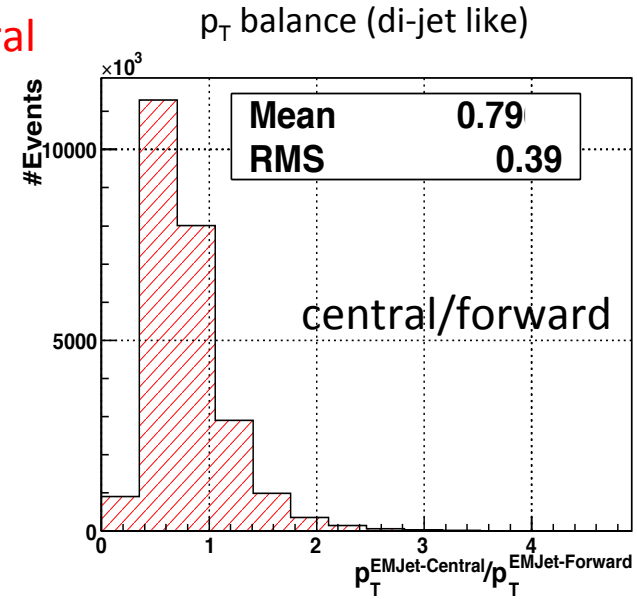
Characteristics of Coincident Central EM-Jets (case-II)

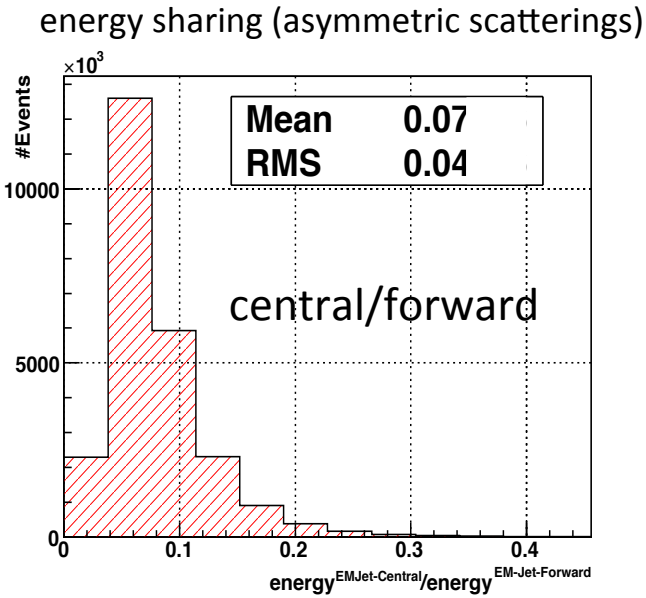
For Central EMJets





Forward-central correlations

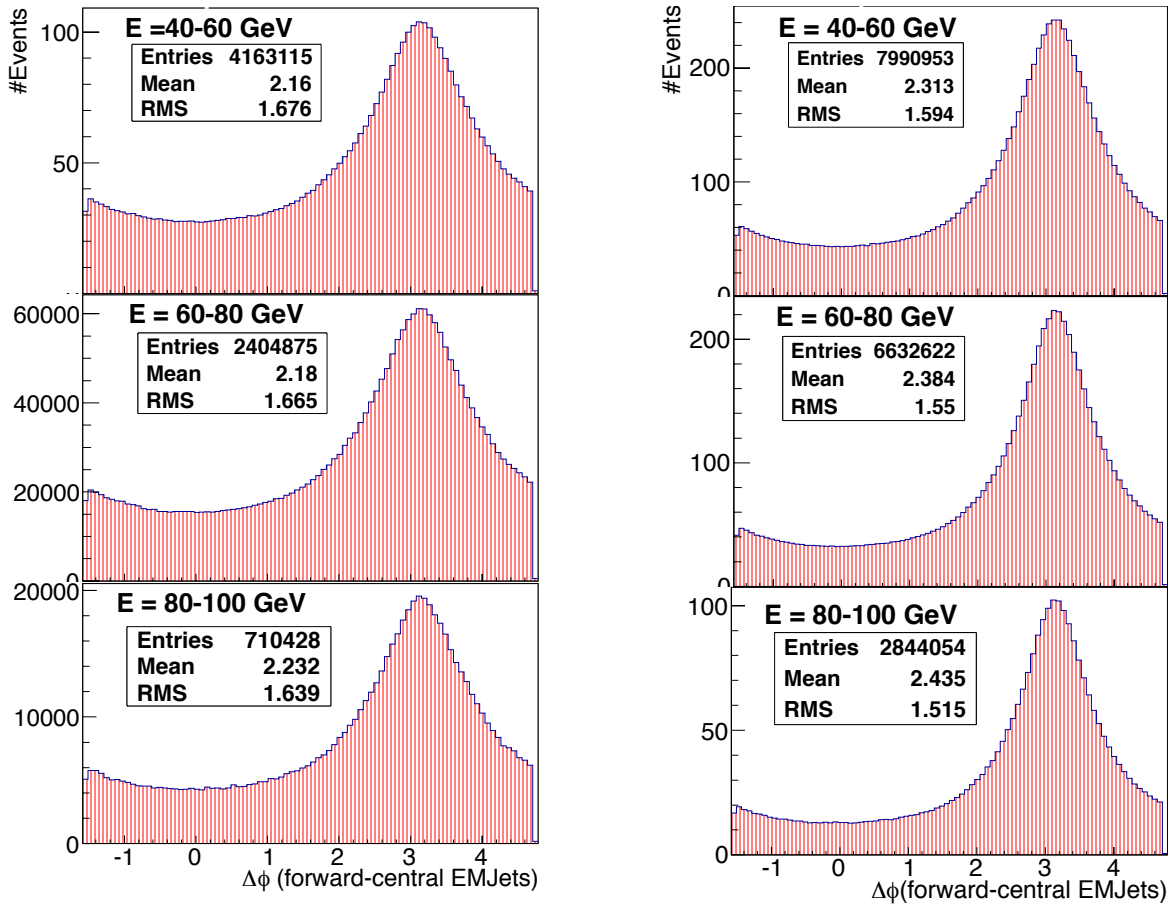




Δϕ correlation between forward and central EMJets

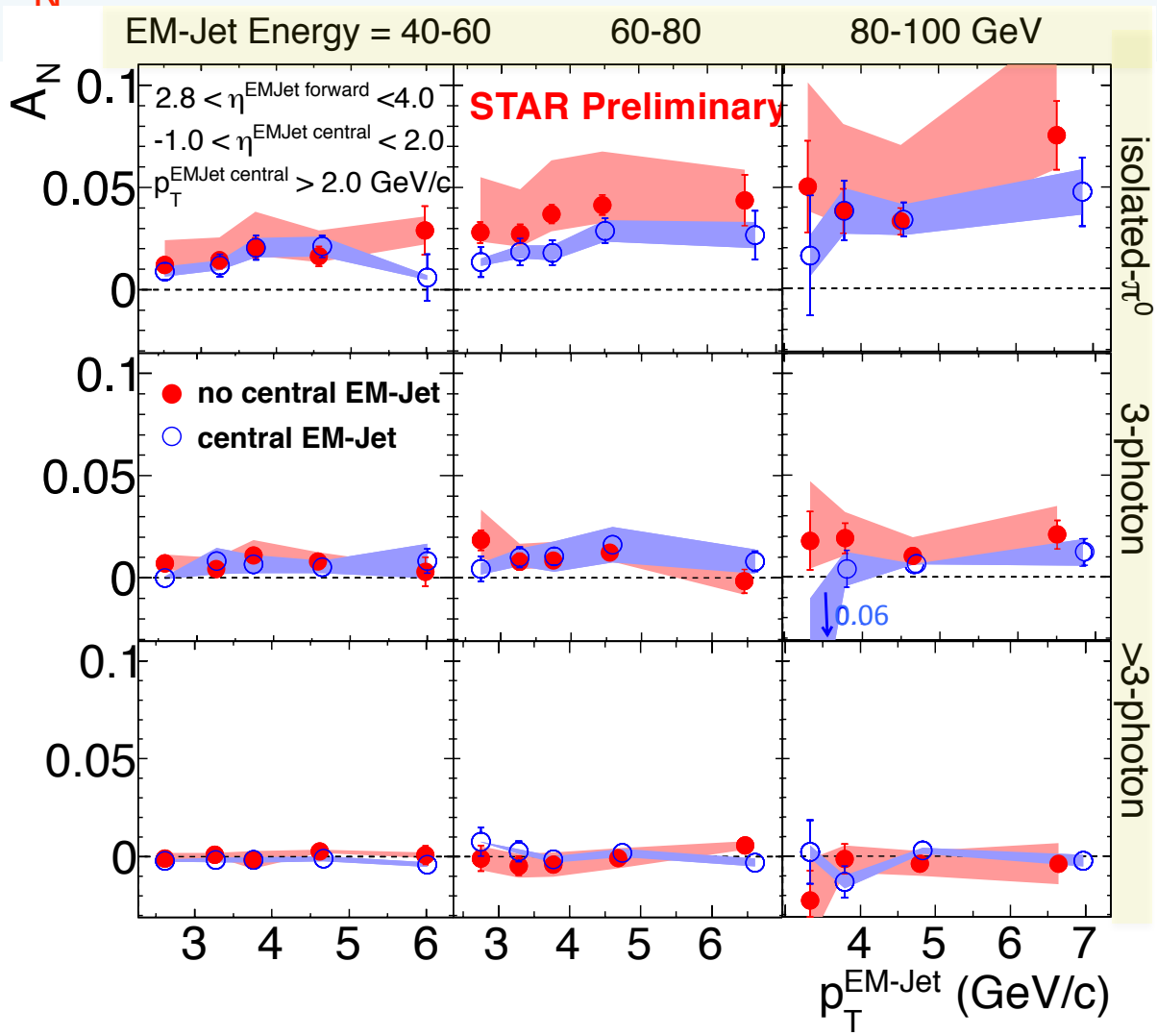
Number of photons for forward EMJets :

1,2 | 3 and more



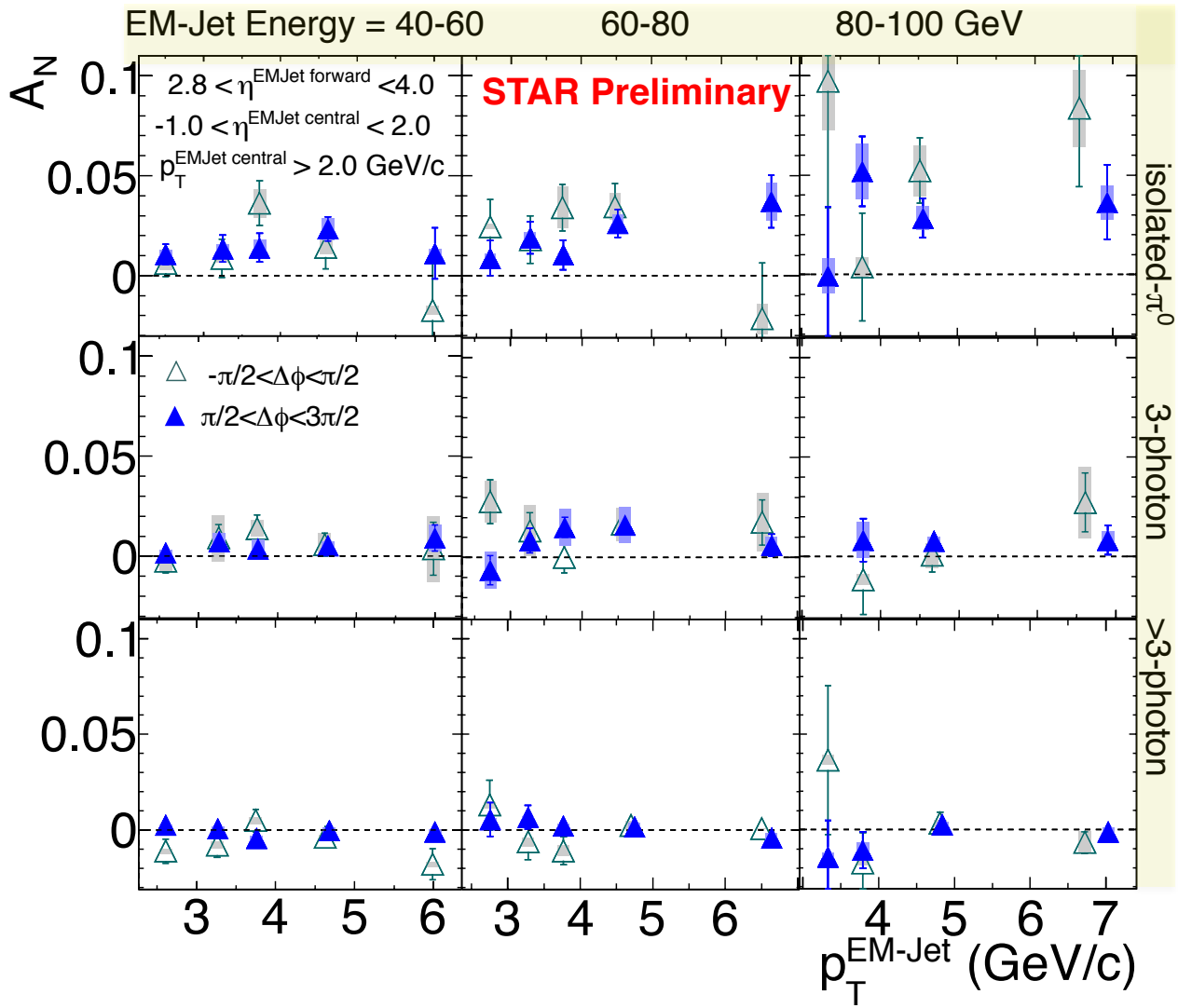
- ✧ Correlation is stronger for more N_photon Jets
- ✧ For higher EMJets energy, correlation grows stronger

A_N for **with** and **without** a central EM-Jet

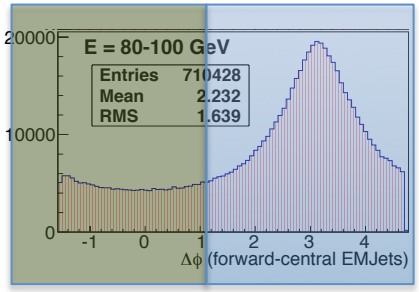


✧ An EM-jet in the central rapidity region reduces the asymmetries for the forward isolated π^0

A_N for the central jet : **near** and **away** in φ to the forward jet



Near and **away** side

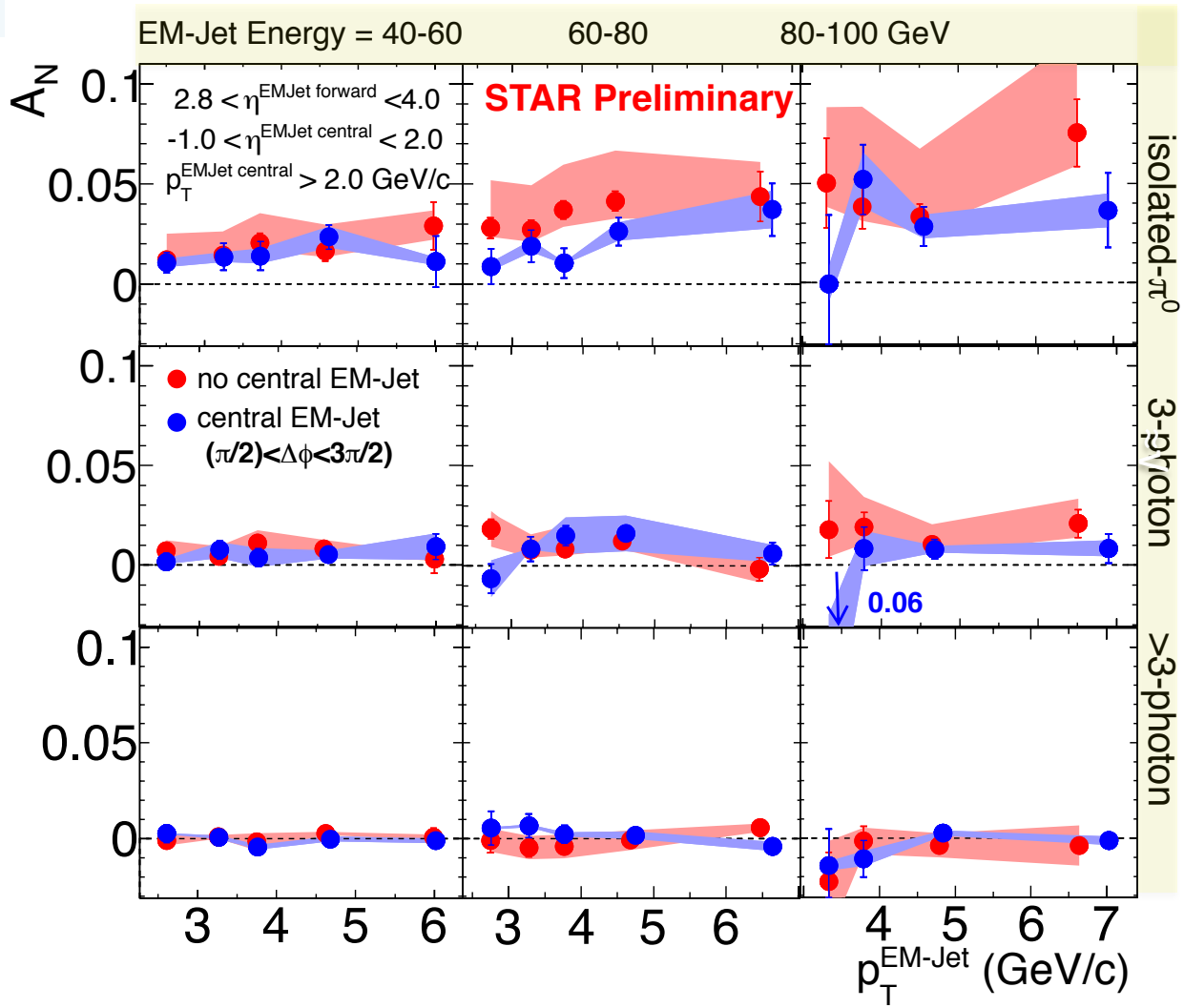


Uncorrelated central EM-Jet

Correlated central EM-Jet

✧ Uncorrelated central EM-Jet is separated out

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.

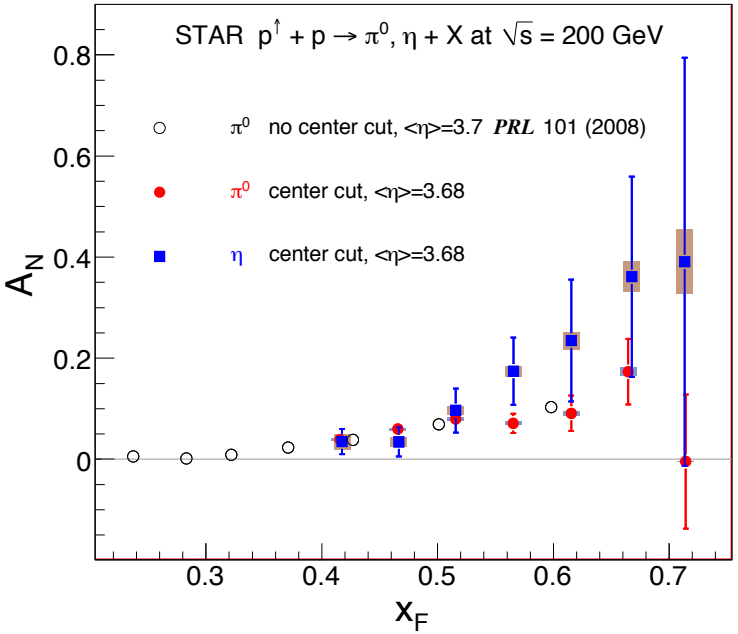
Conclusion

- EM-jets are reconstructed from photons detected in the FMS at STAR.
- Jets with **isolated π^0 have large asymmetry**.
- 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")
- Isolated π^0 **asymmetries are smaller when there is a correlated EM-jet** at mid-rapidity.

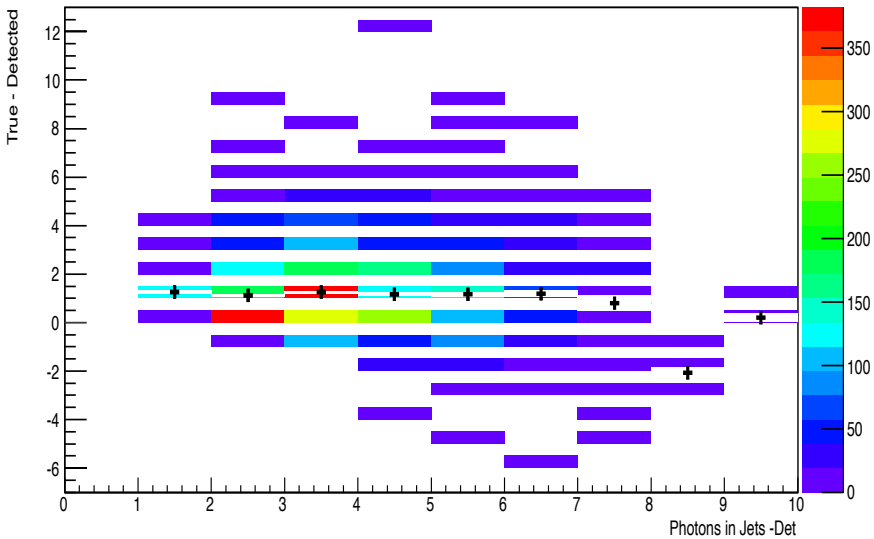
- **Both of these dependences raise serious question how much of the large forward π^0 A_N comes from 2 → 2 parton scattering.**

Backup ..

Transverse Single-Spin Asymmetry and Cross-Section for π^0 and η Mesons at Large Feynman-x in $p^\uparrow + p$ Collisions at $\sqrt{s} = 200$ GeV

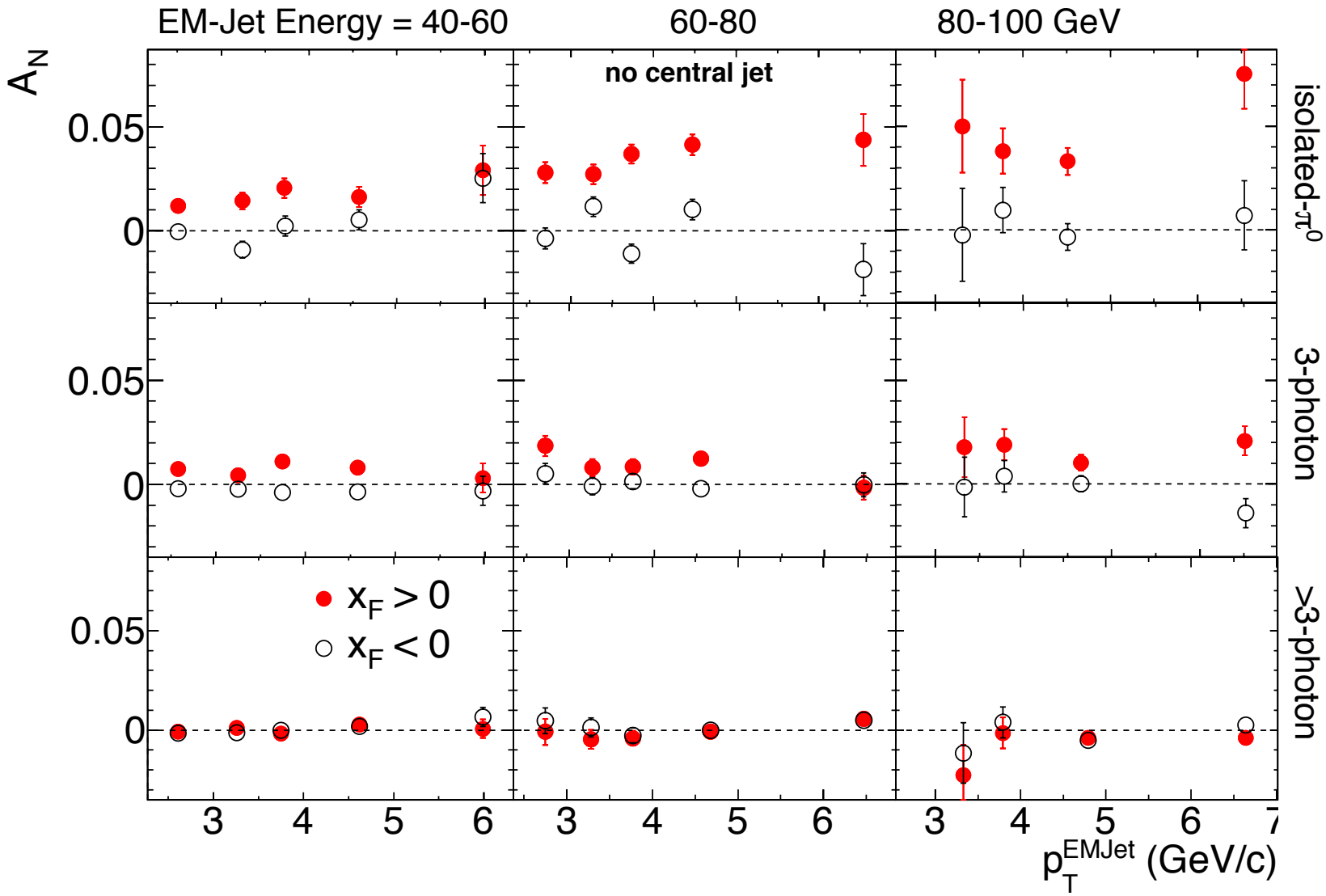


PRD 86 051101(R) (2012)



Systematics arising from intermixing of event classes

No EM-jet within -1<η<2 (p_T>2.0GeV/c)



With a EM-jet with -1<η<2 (p_T>2.0GeV/c)