Transverse single spin asymmetries at large Feynman x in the STAR experiment at RHIC

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Outline

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

π^0 A_N Measurements at Forward Rapidity

Inclusive π^0 production

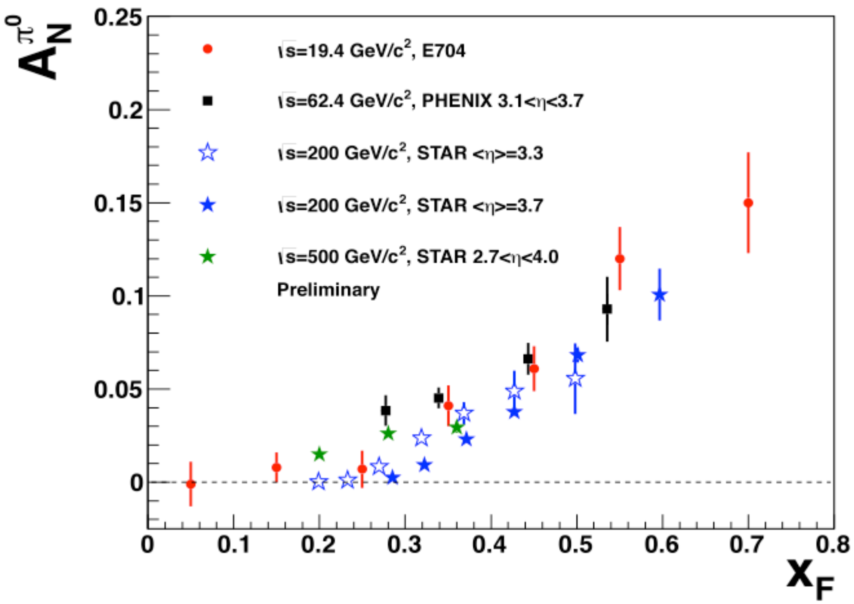
$$p\uparrow + p \rightarrow \pi^0 + X$$

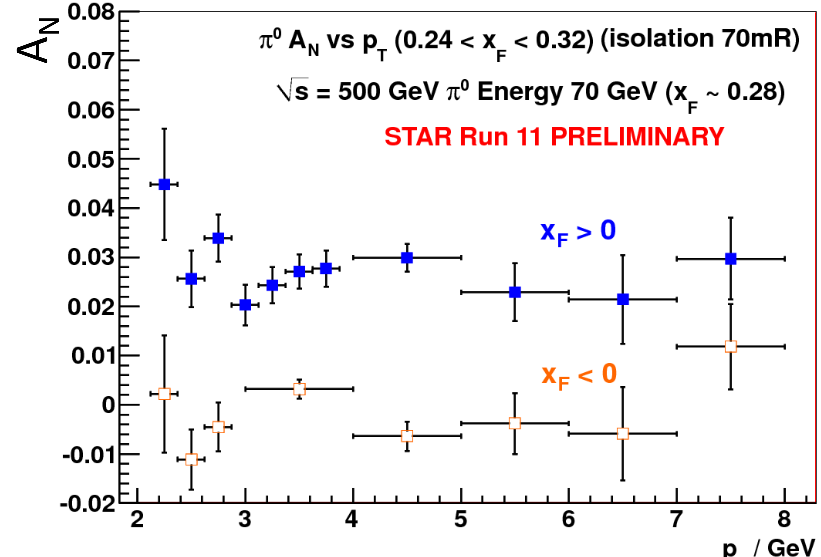
Transverse Single Spin Asymmetry

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

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

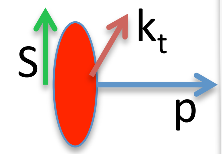
✧ Rising A_N with x_F
✧ A_N nearly independent of $\sqrt{s}$





Sivers and Collins effect

Sivers effect : the correlation between the **transverse momentum (k_t)** of the struck quark and the **spin (S)** and **momentum (p)** of its parent nucleon



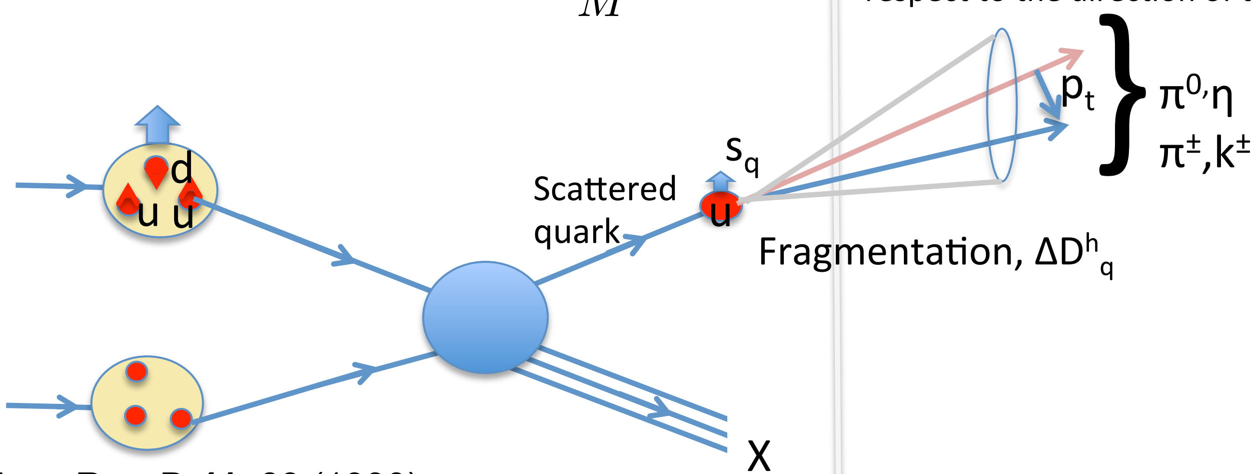
Sivers distribution

$$f_{q/p^{\uparrow}}(x,k_t) = f_1^q(x,k_t^2) - f_{1t}^{\perp q}(x,k_t)\frac{\mathbf{S}\cdot(\mathbf{k_t}\times\hat{\mathbf{p}})}{M}$$

Collins effect :spin-momentum correlation in the hadronization process

$$\mathbf{s_q}\cdot(\mathbf{k_q}\times\mathbf{p_t})$$

s_q = spin of the fragmenting quark
k_q = momentum direction of the quark
p_t = transverse momentum of hadron with respect to the direction of the fragmenting quark



D. Sivers, Phys. Rev. D **41**, 83 (1990)

J. C. Collins, Nucl. Phys. **B396**, 161 (1993)

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

Sensitive to transversity(δq)

Separating Sivers and Collins effects

$$A_N = \underbrace{\propto \bar{f}_{1T}^{\perp q}(x, k_\perp^2)}_{\text{Sivers distribution}} \cdot D_q^h(z) + \propto \underbrace{\delta q(x)}_{\text{Quark transverse spin distribution}} \cdot \underbrace{H_1^\perp(z_2, \bar{k}_\perp^2)}_{\text{Collins FF}}$$

Observed transverse single-spin asymmetries of inclusive hadrons could arise from the **Sivers effect** or **Collins effect**, or from a **linear combination of the two**

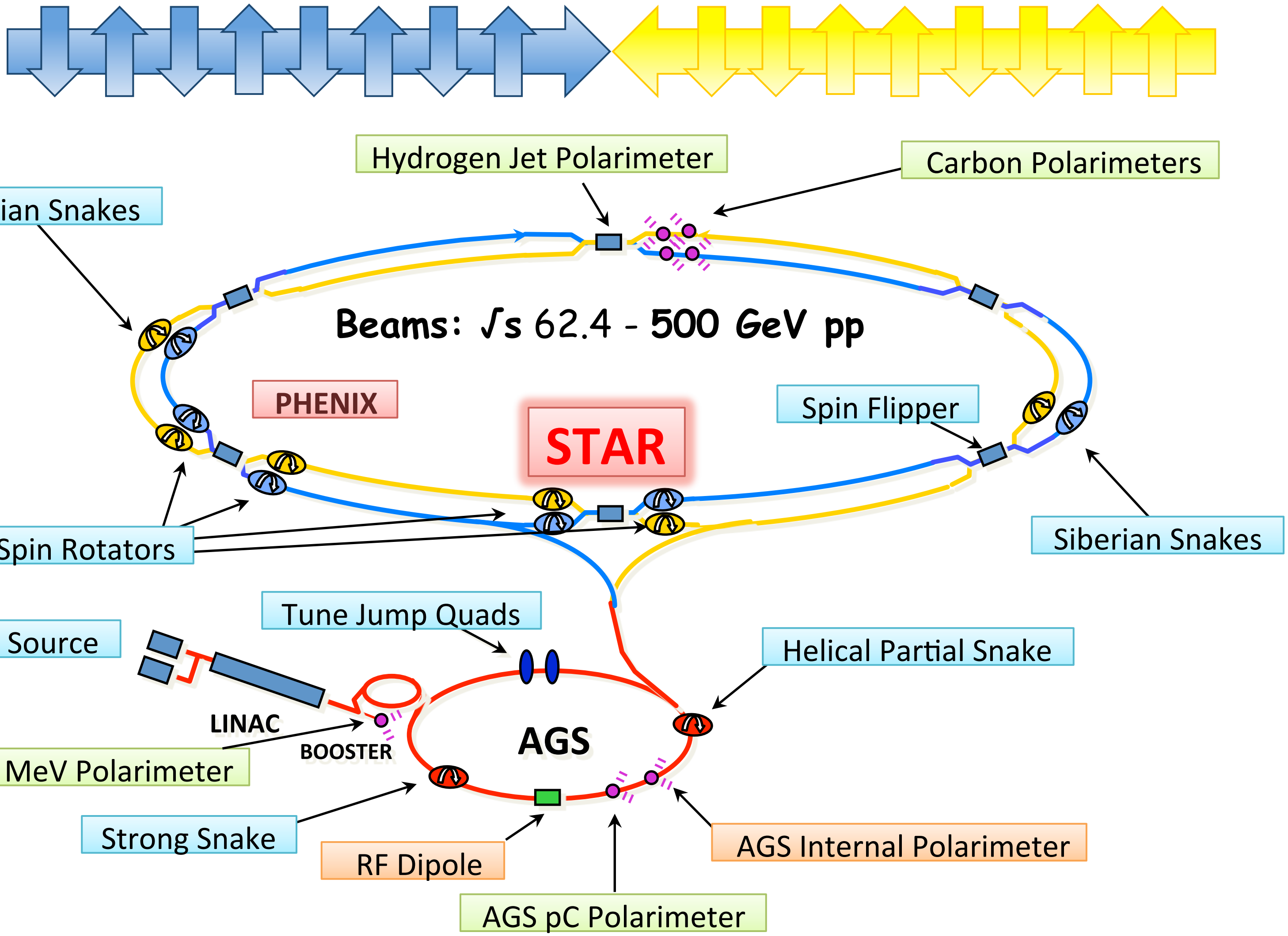
<u>need to move beyond inclusive production</u>

- Sivers effect : **Full Jets**, Direct photons, Drell-Yan
- Collins effect : **azimuthal orientation of particles within a jet**

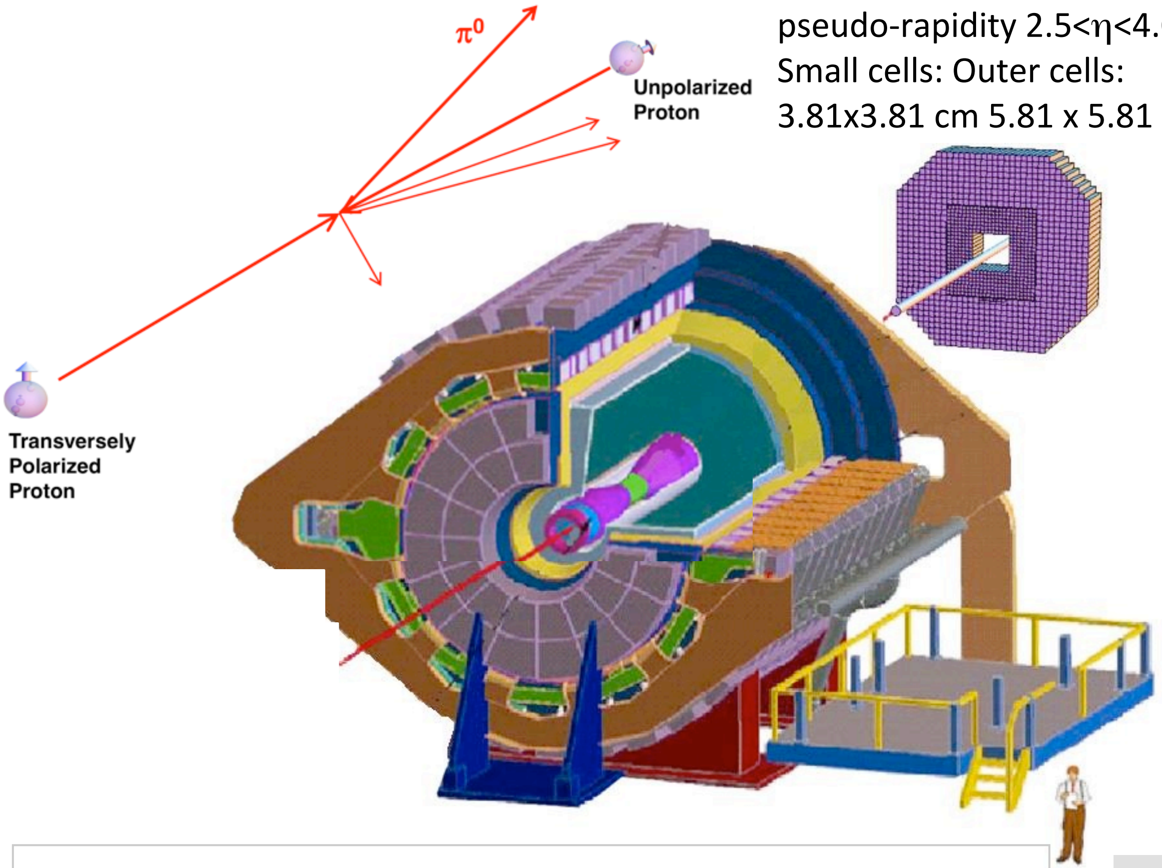
RHIC : the world's first and only polarized proton collider

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

Luminosity =22 pb^{-1}



Forward ECAL in STAR



FMS Pb Glass EM Calorimeter
pseudo-rapidity 2.5<η<4.0
Small cells: Outer cells:
3.81x3.81 cm 5.81 x 5.81 cm

Forward Meson Spectrometer (FMS) - 2011 :
-- 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.

Photons in FMS
Towers→ Clusters→
(shower shape fits)
Photon candidates
(photons)

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

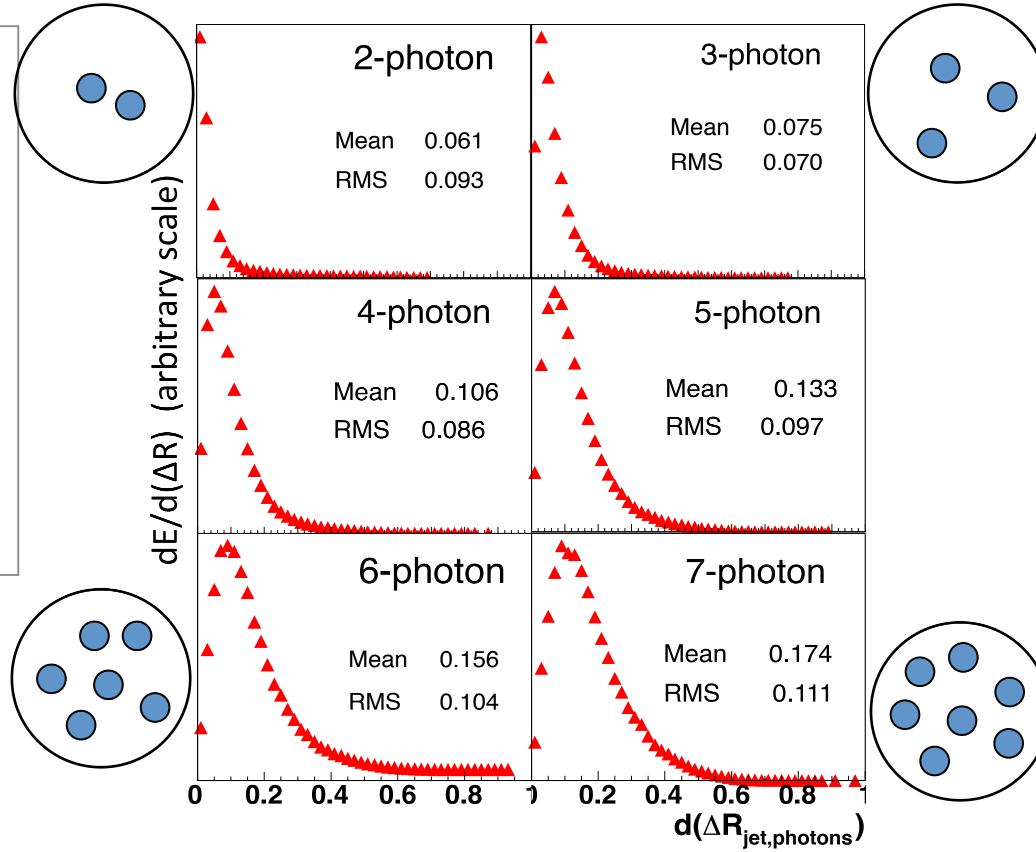
photons with p_T > 0.001 GeV/c

Leading EM-Jets :

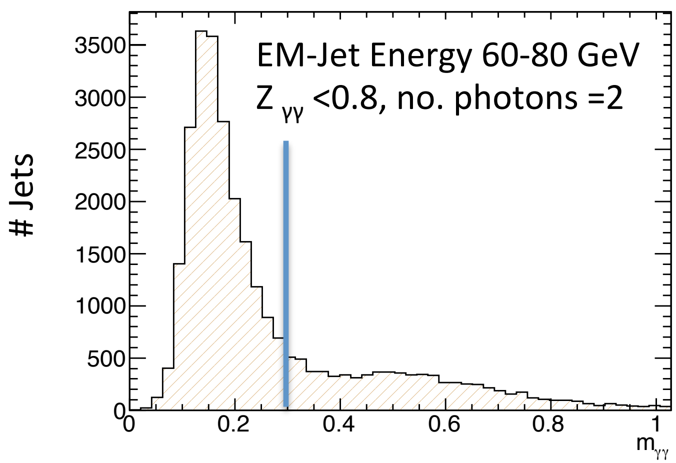
Multi-photon Jets with highest energy

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

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



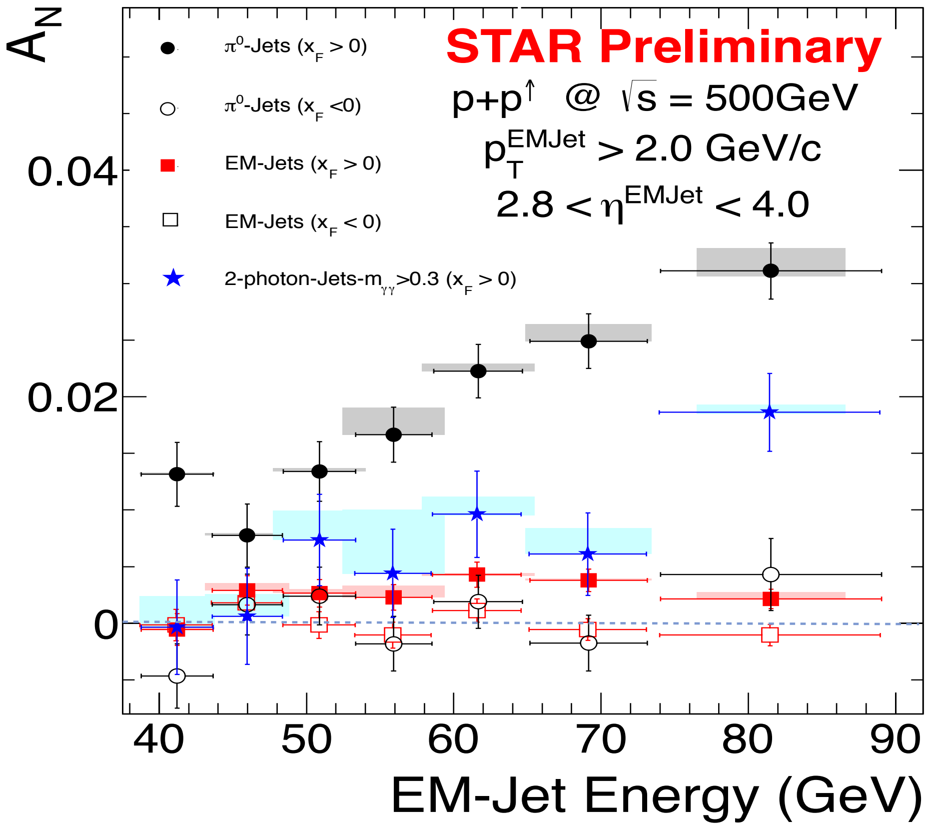
dE/d(ΔR) distribution of EM-Jets



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
$m_{\gamma\gamma} < 0.3$
$Z_{\gamma\gamma} < 0.8$

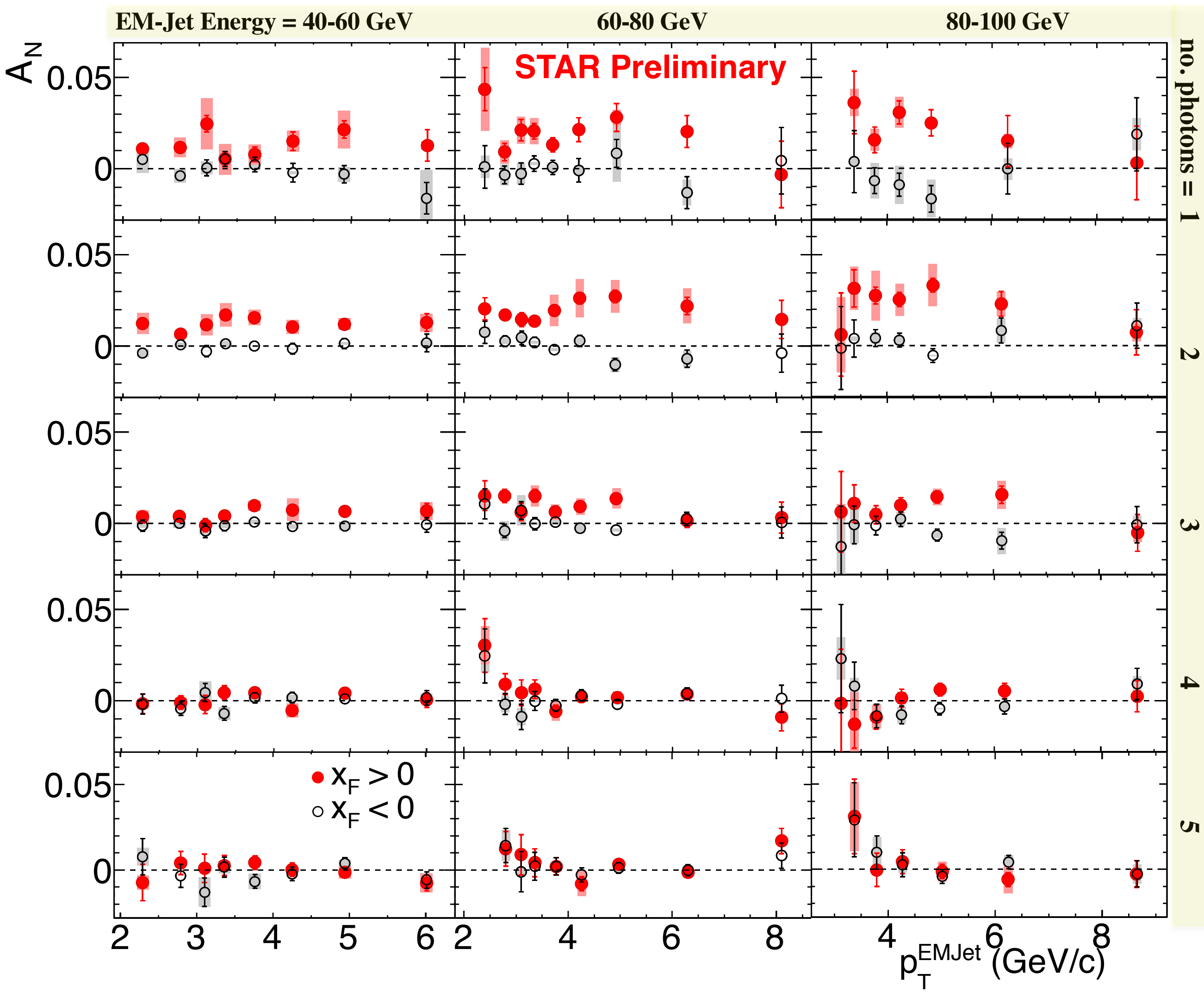
2γ-EM-Jets (η + continuum) –
$m_{\gamma\gamma} > 0.3$

EM-Jets –
photons >2

Isolated π^0 :
I) reconstructed π^0 for 2-photon jet
II) no photon within physical cone (eg. 70mR) of reconstructed π^0

- ✧ 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 jets with photons >2 events are much smaller

A_N for different # photons in EM-Jets



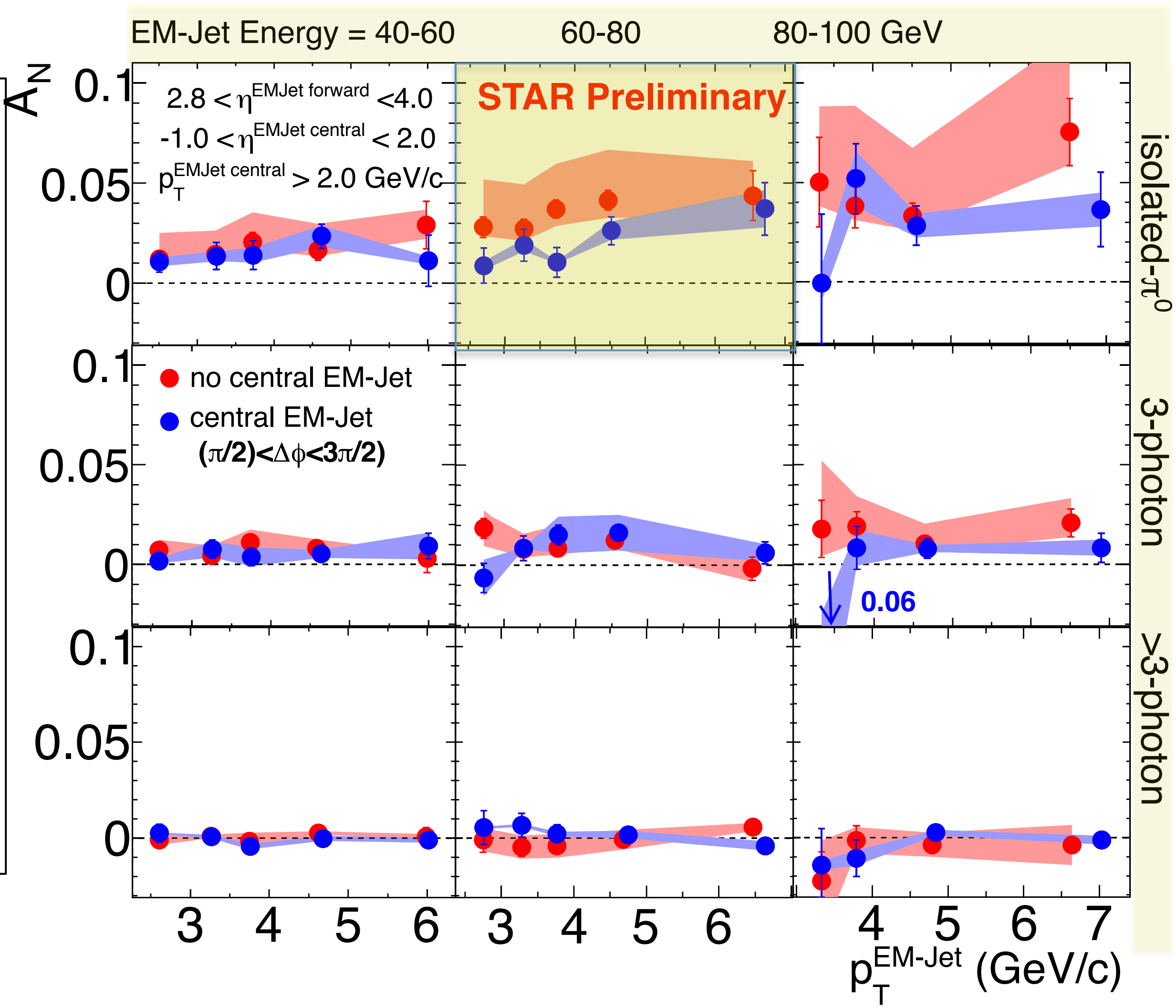
- ✧ 1-photon events, which include a large π^0 contribution in this analysis, are similar to 2-photon events
- ✧ Three-photon jet-like events have a clear non-zero asymmetry, but substantially smaller than that for isolated π^0's
- ✧ A_N decreases as the event complexity increases (more particles in jets)
- ✧ A_N for #photons >5 is similar to that #photons = 5

A_N for correlated central jets and no central jet cases

JETs at central rapidity

- EM Jets are reconstructed in midrapidity BEMC +EEMC, $-1.0<\eta^{EM-Jet}<2.0$
- Back to back $\Delta\phi$ relations used to find if there is any associated jets

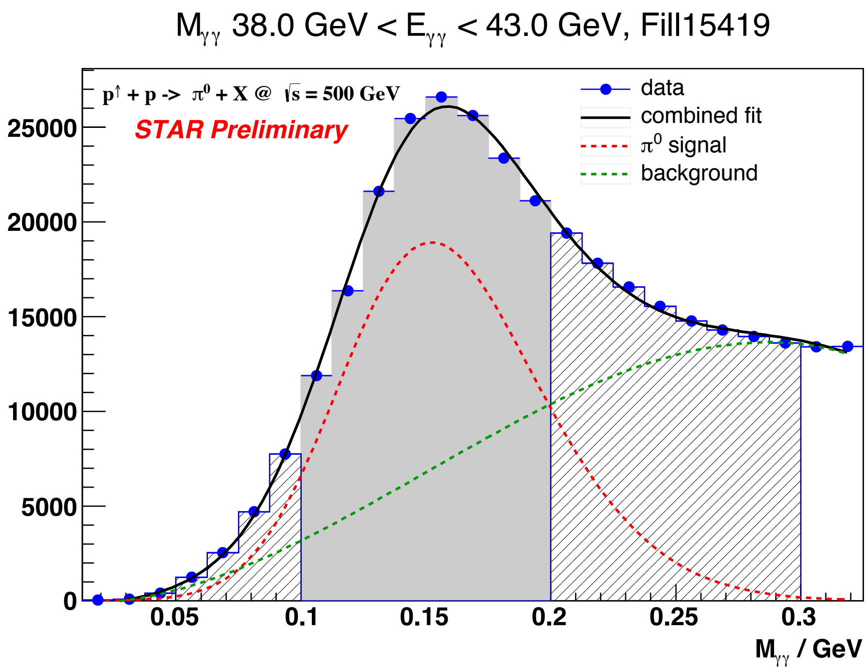
2 →2 parton scattering

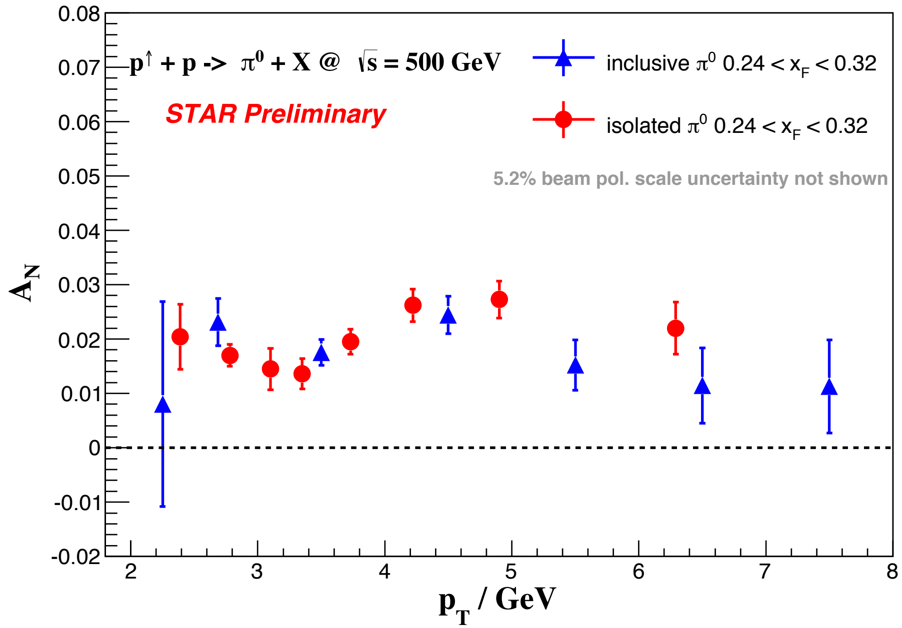


✧ Asymmetries for the forward isolated π^0 are low when there is a correlated away-side jet.

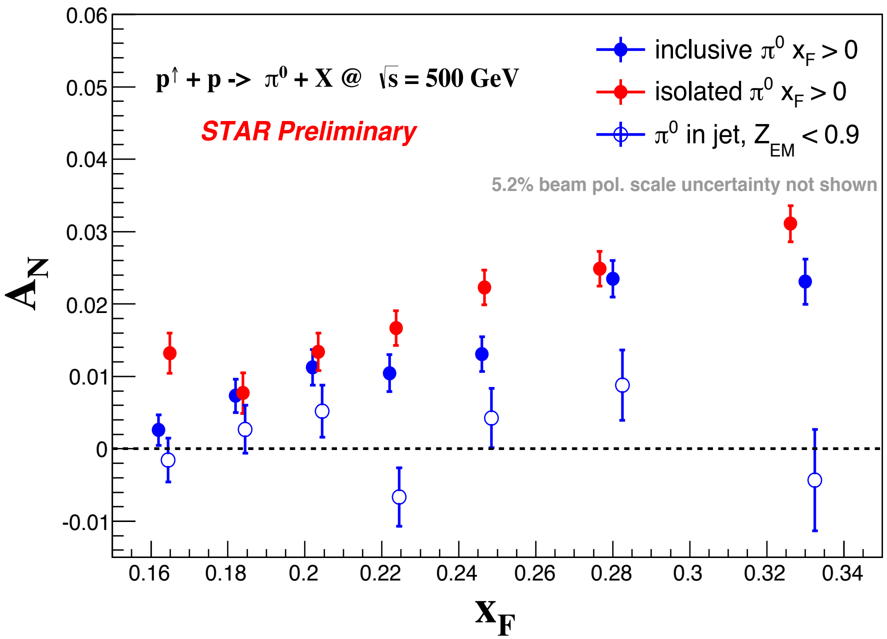
A_N for π^0 and Collins asymmetries of π^0

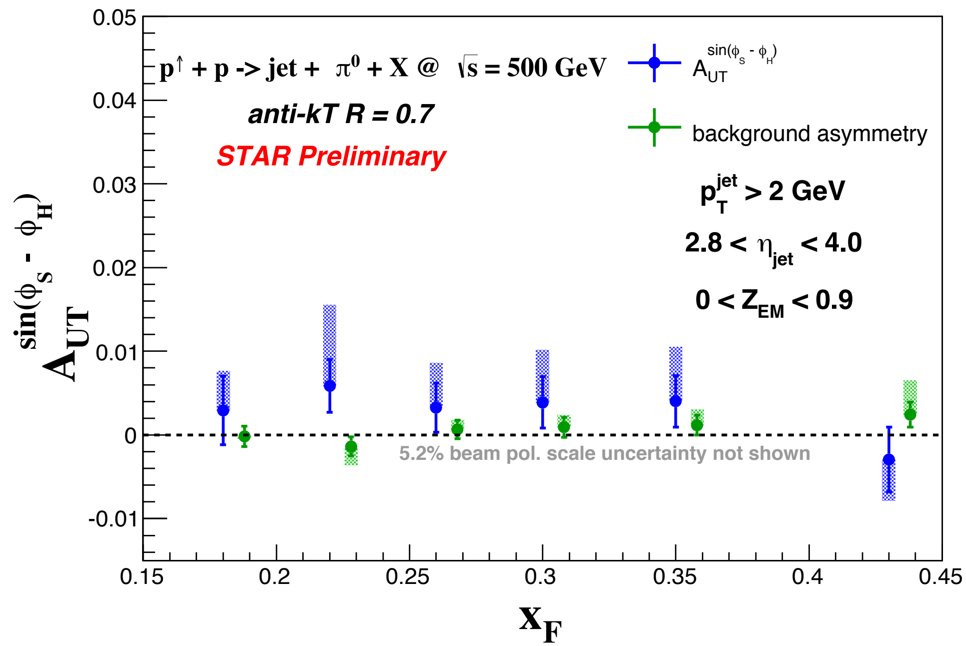
- π^0 is reconstructed from FMS
- Collins asymmetries of π^0 relative to jet axis is being measured





A_N for π^0 and Collins asymmetries of π^0





- Isolated π^0 tend to have significantly larger asymmetries than π^0 associated with jet activities in the vicinity.
- Sivers (EM-Jets) and/or Collins (π^0 relative to jet axis) asymmetries are insufficient to account for the observed inclusive π^0 single spin asymmetries.

Summary and Outlook

- ✧ Jets with isolated π^0 have large asymmetry.
- ✧ A_N decreases as the event complexity increases.
- ✧ Isolated π^0 **asymmetries are smaller when there is a correlated EM-jet** at mid-rapidity.

Large forward π^0 A_N : Comes from 2 → 2 parton scattering with some contribution from diffractive events?

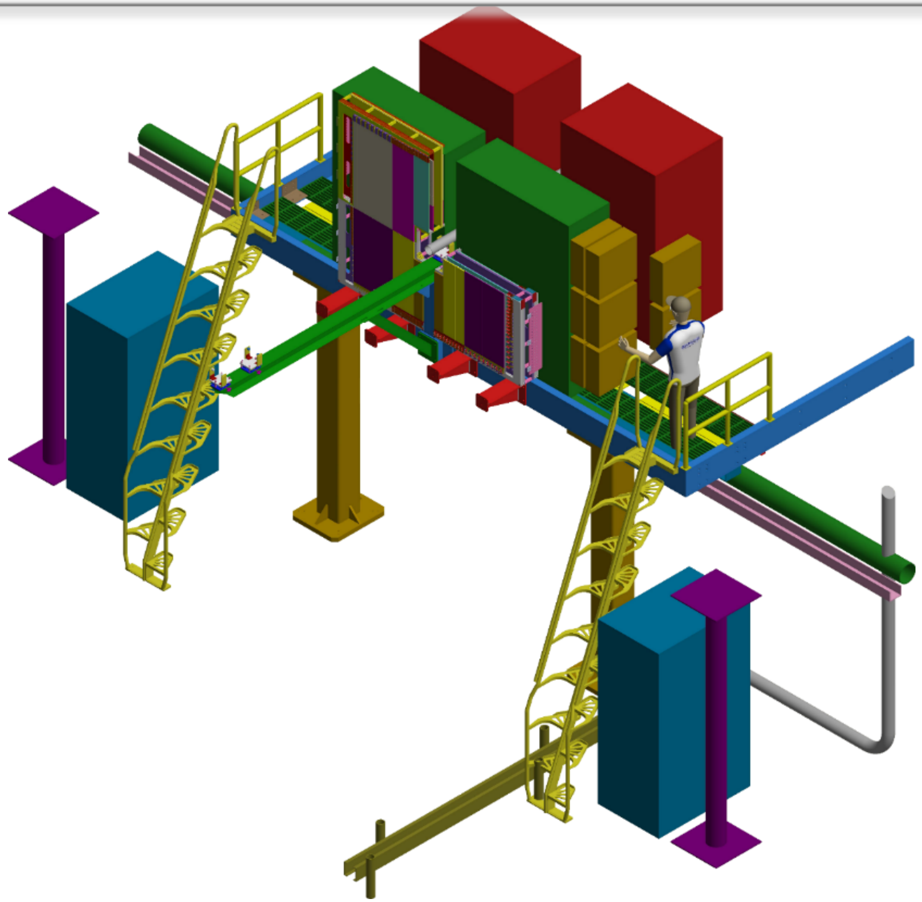
- ✧ Sivers (EM-Jets) and/or Collins (π^0 relative to jet axis) asymmetries are insufficient to account for the observed inclusive π^0 single spin asymmetries.

- ❑ 2015 : installation **of FMS-Preshower and Roman pots** - p+p 200 GeV longitudinal & transverse p↑+Au/Al 200 GeV transverse, **Spin effects in diffraction**
- ❑ 2017 : installation of **FMS-Postshower** - p+p 510 GeV transverse A_N for Dell Yan, direct photons

Forward Upgrade (≧2021) Overview

Requirements:

- **wide acceptance mid-rapidity detector with good PID (p,K,p)**
- **forward rapidities ($1.0 < \eta < 4.5$) Ecal + HCal + charge identification**



Forward rapidities

- $2.5 < \eta < 4.5$

Preshower detector

EM calorimeter

- PHENIX PbSc

Hadronic calorimeter

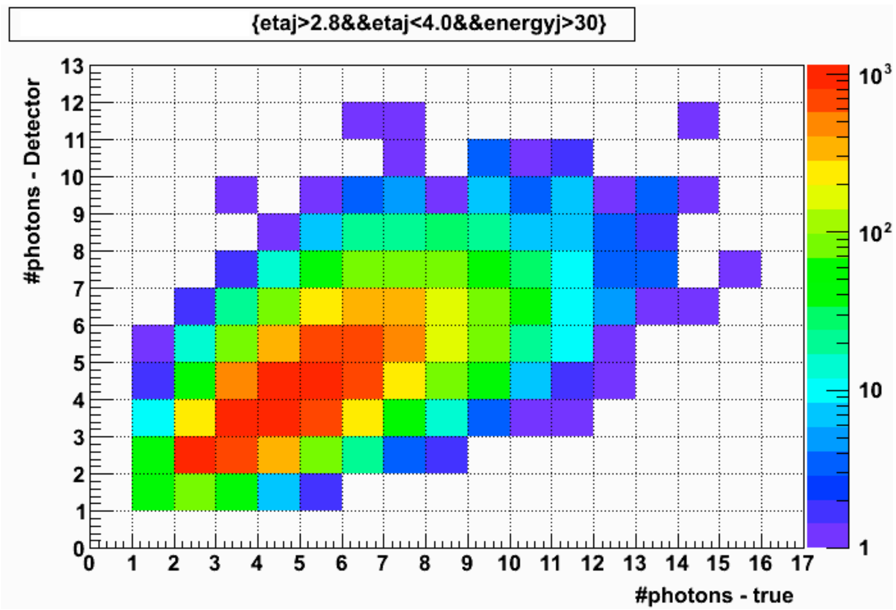
- $L = 4\lambda_I$

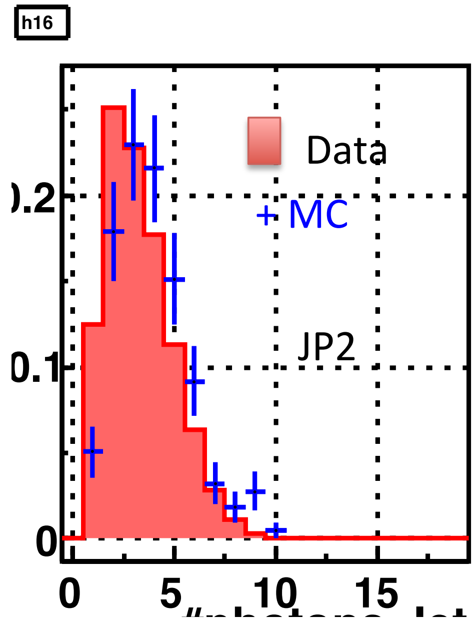
4-6 additional layers of Silicon Microstrip and/or small-strip Thin Gap Chamber

backup

Data point corrections and better understanding Detector with GEANT simulations

- Understanding FMS data with full PYTHIA simulations with standard STAR framework.
- Construct the matrix - #true photon vs. #photons detected : This would be used for correcting $A_{N,EM\text{-}Jets}$ of a certain n-photon-class from the effect of probability misidentifying to the other n-photon-clases





#photons in Jets

#photons in Jets in MC and data was not matching :

1. Attenuation was not there in GEANT energy deposition mode. GEANT is used with an attenuation factor.

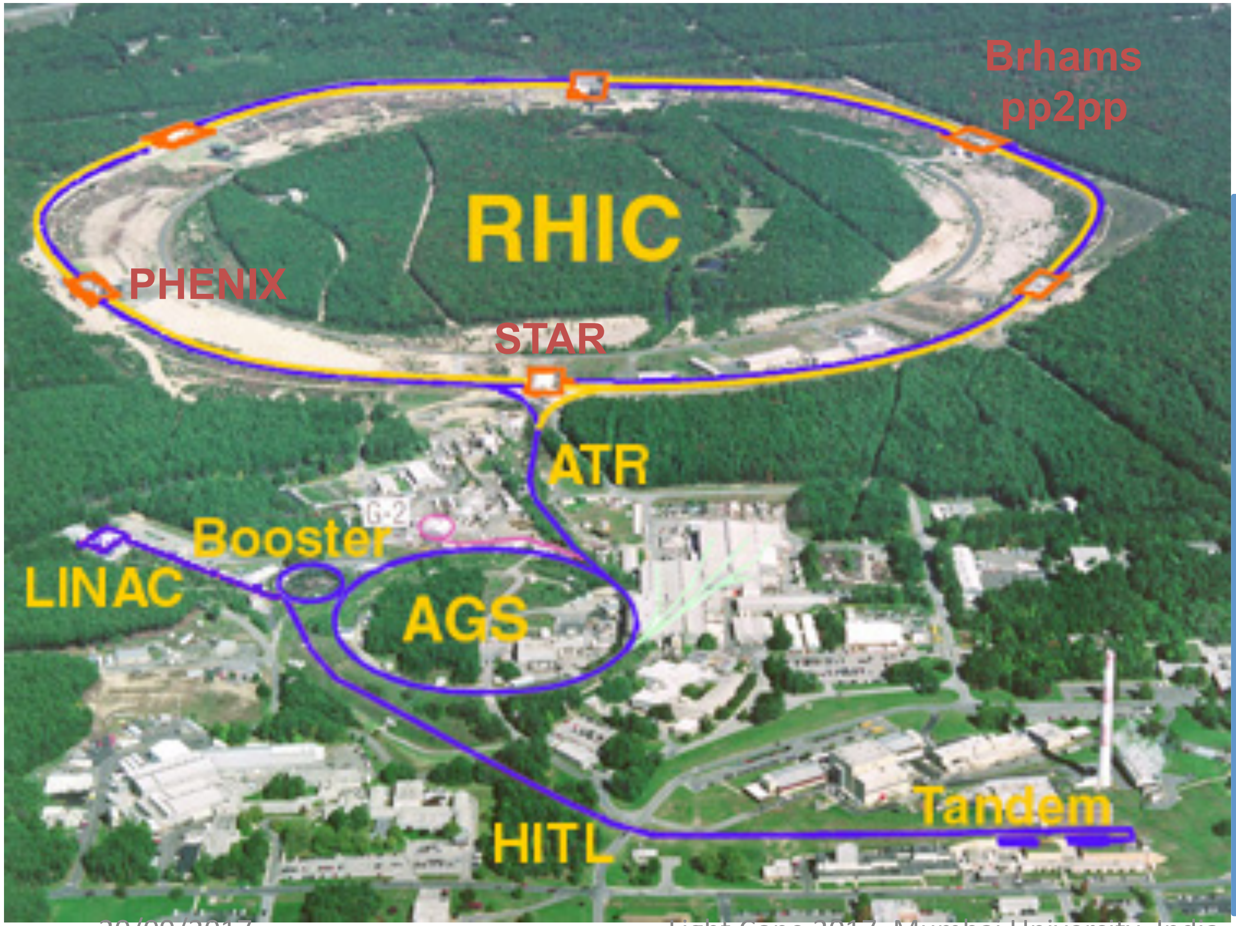
2. PYTHIA tune dependencies are checked : Hard diffraction not in current scope of PYTHIA6

BROOKHAVEN NATIONAL LABORATORY

The Relativistic Heavy Ion Collider

Au+Au + Cu+Au

Polarized p+p, d+Au
Polarized p + Au
RHIC is a QCD lab



RHIC Physics Focus

1) Heavy-ion Program
   - -- Study medium properties, EoS
   - --pQCD in hot and dense medium
2) RHIC beam energy scan
   - --search of critical point
   - -- chiral symmetry restoration

1) Longitudinal and transverse spin programs
   - --Study proton intrinsic properties
2) **Forward program**
   - **-- spin structure of proton**
   - --*Study of low x properties and* ***search for CGC***

Tagged forward physics
--Study elastic and inelastic processes
--Investigate gluonic exchanges and search for gluonic matter

TSSA – two theoretical framework

Spin-dependent transverse momentum dependent (TMD) function $S_T.(Pxk_T$

Brodsky, Hwang, Schmidt, 02

Collins, 02, Ji, Belitsky, Yuan, 02

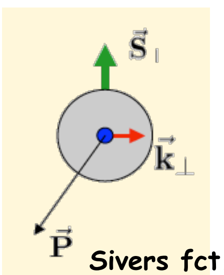
+ Collins fragmentation functions

Twist-3 quark-gluon correlations

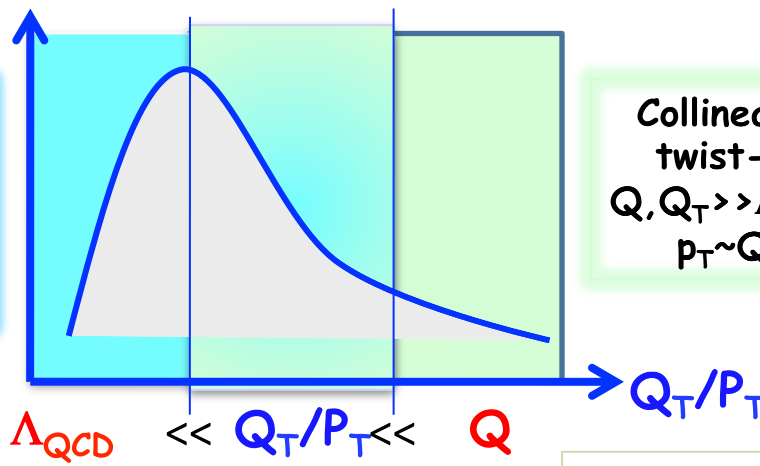
Efremov & Teryaev: 1982 & 1984

Qiu & Sterman: 1991 & 1999

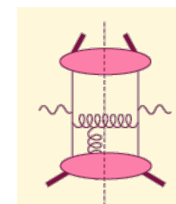
+ Twist three fragmentation functions



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
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**
$A_N(\pi^0/\gamma/jet)$

A_N from fits

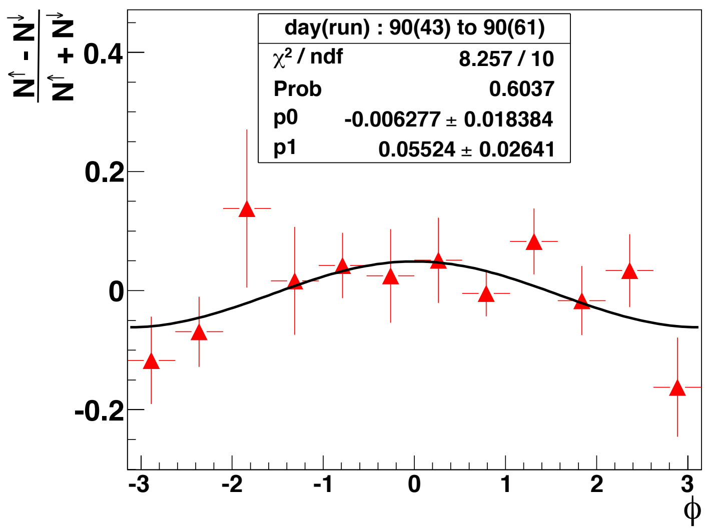
✧ **A_N is calculated from p0 + P×A_N cos(φ) fits over each fill on**

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

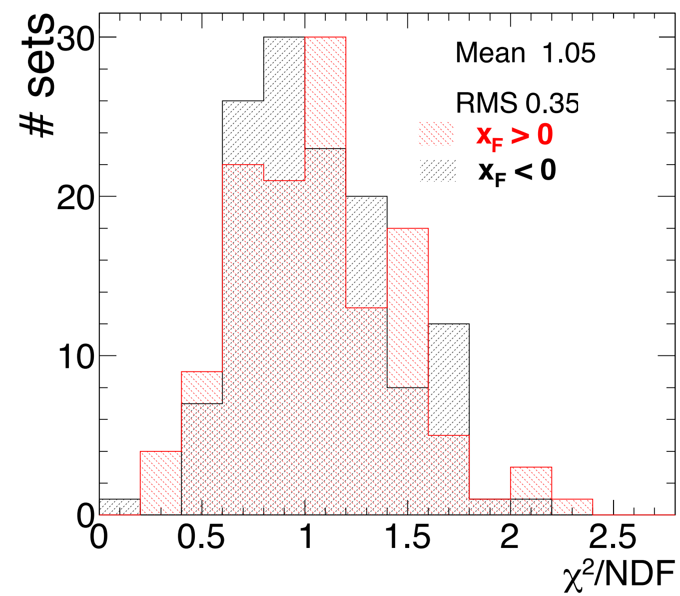
p0 = relative luminosity
A_N = asymmetry
P = polarization

--- 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

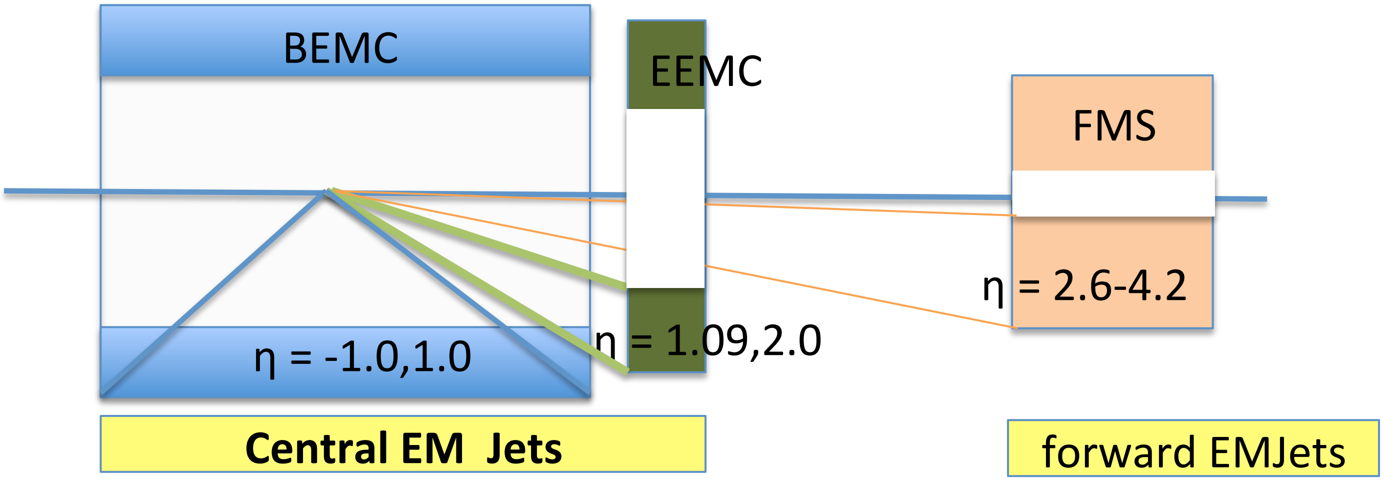


For 2-photon isolated π^0



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

A_N with mid-rapidity activities



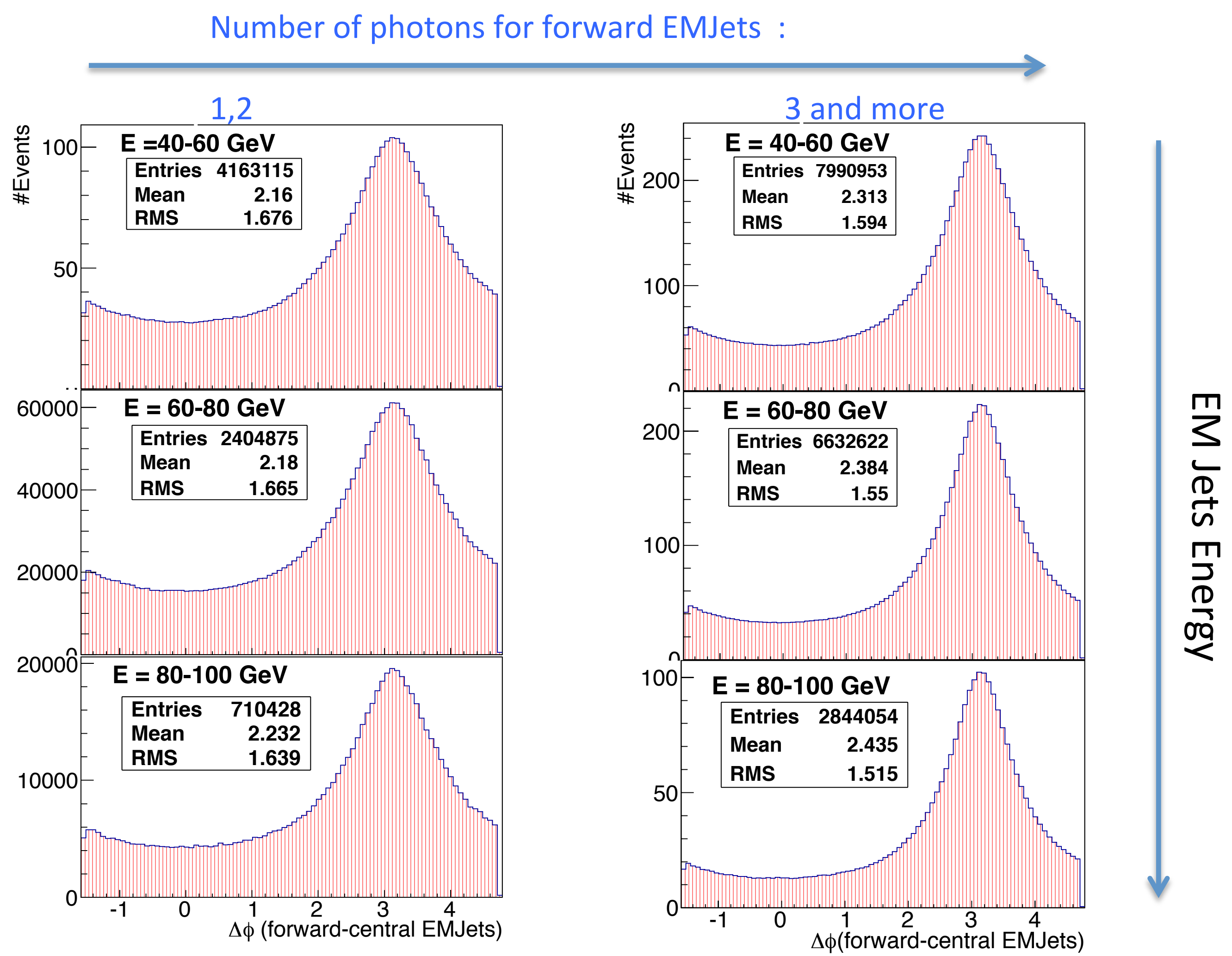
towers (BEMC+EEMC) :

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

ΔΦ correlations between forward and central EM-Jets



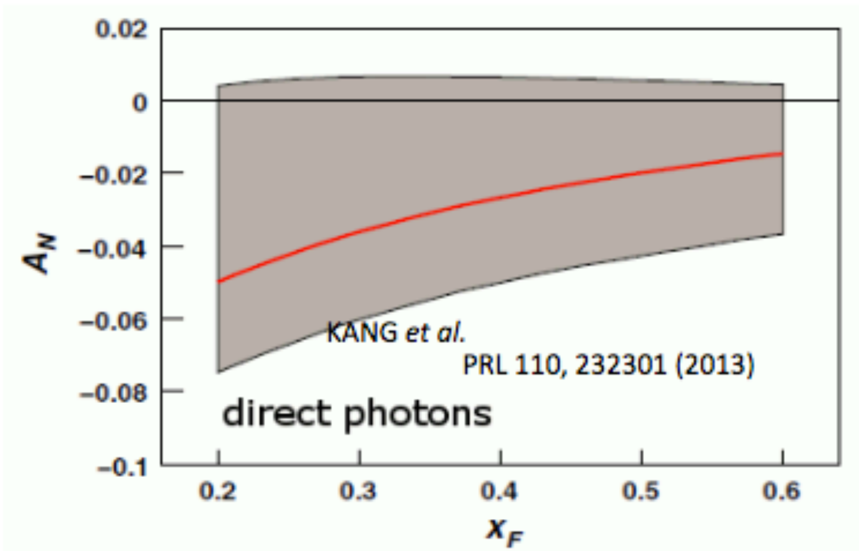
- ✧ Correlation is stronger for more N_photon Jets
- ✧ For higher EMJets energy, correlation grows stronger

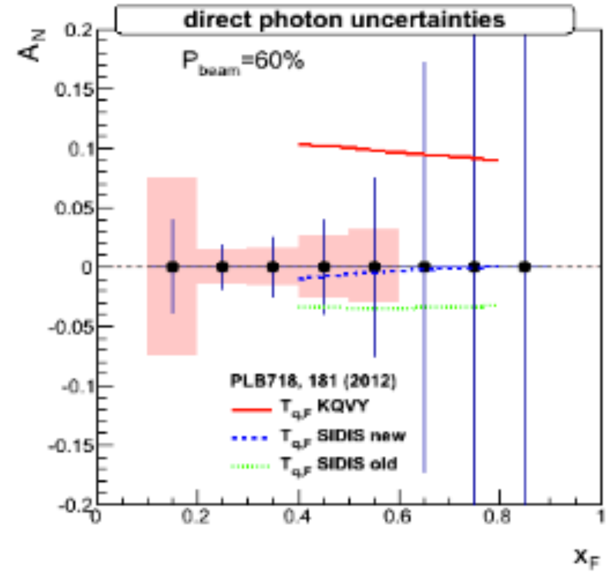
RHIC Cold QCD Schedule

Year	$\sqrt{s}$ (GeV)	Delivered Luminosity	Scientific Goals	Observable	Required Upgrade
2017	$p^{\uparrow}p$ @ 510	400 pb^{-1} 12 weeks	Sensitive to Sivers effect non-universality through TMDs and Twist-3 $T_{q,F}(x,x)$ Sensitive to sea quark Sivers or ETQS function Evolution in TMD and Twist-3 formalism Transversity, Collins FF, linearly pol. Gluons, Gluon Sivers in Twist-3 First look at GPD E_g	A_N for γ, $W^{\pm}$, Z^0, DY $A_{UT}^{\sin(\phi_s-2\phi_h)}$ $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, $A_{UT}^{\sin(\phi_s)}$ for jets A_{UT} for J/Ψ in UPC	A_N^{DY}: Postshower to FMS@STAR **None** **None**
2023	$p^{\uparrow}p$ @ 200	300 pb^{-1} 8 weeks	subprocess driving the large A_N at high x_F and η evolution of ETQS fct. properties and nature of the diffractive exchange in p+p collisions.	A_N for charged hadrons and flavor enhanced jets A_N for γ A_N for diffractive events	Yes Forward instrum. **None** **None**
2023	$p^{\uparrow}Au$ @ 200	1.8 pb^{-1} 8 weeks	What is the nature of the initial state and hadronization in nuclear collisions Nuclear dependence of TMDs and nFF Clear signatures for Saturation	R_{pAu} direct photons and DY $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, nuclear FF Dihadrons, γ-jet, h-jet, diffraction	R_{pAu}(DY):Yes Forward instrum. **None** Yes Forward instrum.
2023	$p^{\uparrow}Al$ @ 200	12.6 pb^{-1} 8 weeks	A-dependence of nPDF, A-dependence of TMDs and nFF A-dependence for Saturation	R_{pAl}: direct photons and DY $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, nuclear FF Dihadrons, γ-jet, h-jet, diffraction	R_{pAl}(DY): Yes Forward instrum. **None** Yes Forward instrum.

STAR future measurements

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





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

STAR :
pp 200GeV, L = 40/pb, P=60%

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