Transverse single spin and azimuthal asymmetries in hadronic collisions at STAR

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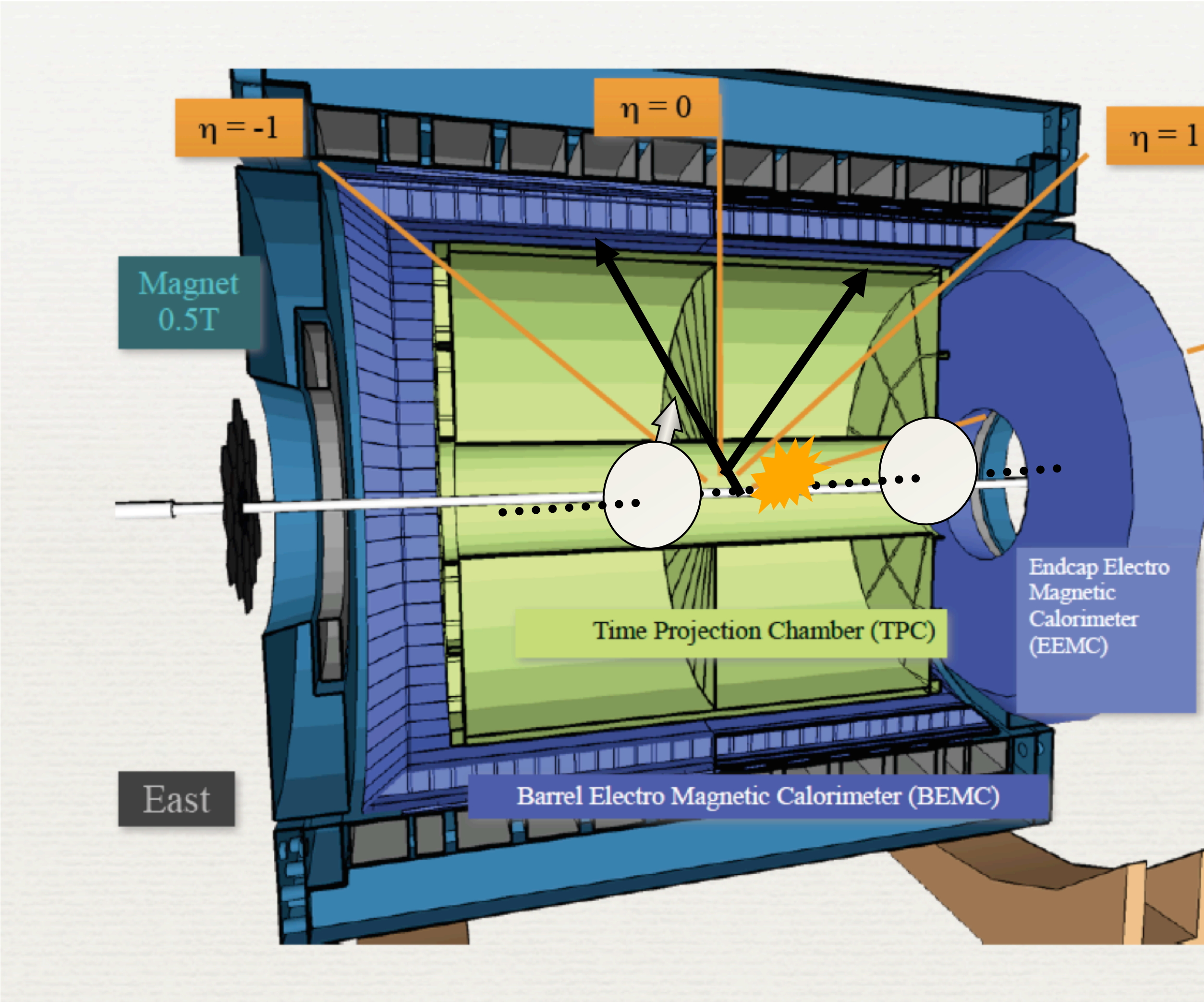
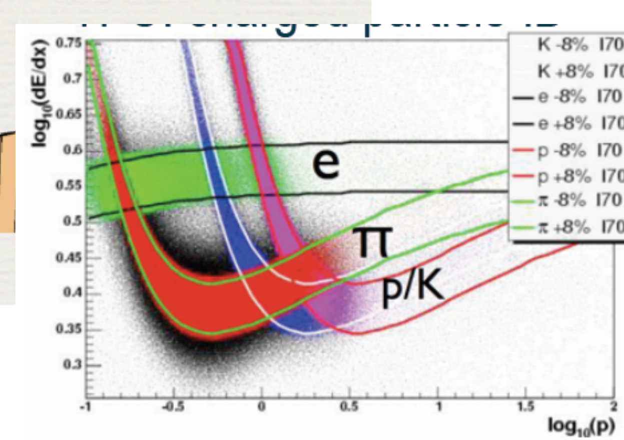
What you should remember from this talk:

- High precision measurement of Collins (etc), IFF:
  - Precision comparable (at least..) to Compass Hermes (final at SPIN)
  - Phase space: high Q, x up to ~0.25 (mid), future: ~0.5 forward
  - Added benefit of p+p: no u quark dominance, high scale,
  - ➢ Measure transversity and gluonic counterparts, learn about color entanglement effects
- EM jet AN topology dependence and correlation measurements
  - ➢ mechanisms behind large forward spin asymmetries
- **Sign change** measurements
- Future **precision** measurement of transverse spin structure in the valence region

STAR

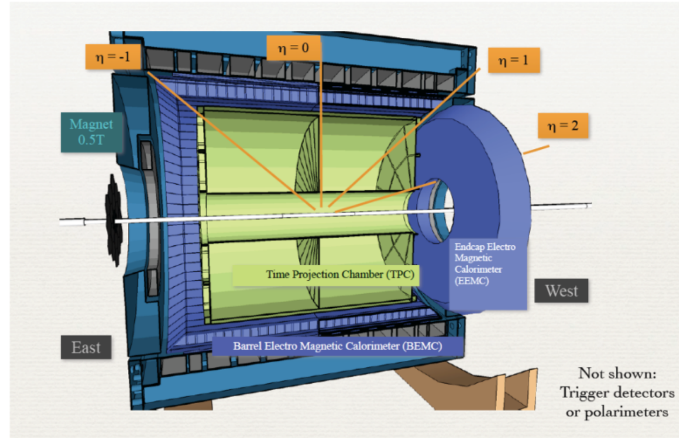




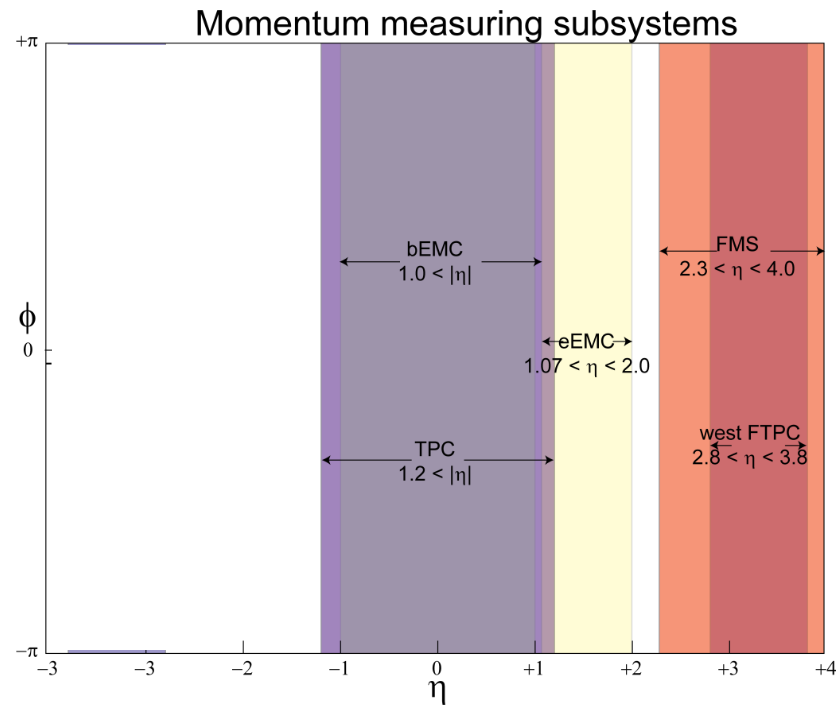
$$\eta = -log(tan\frac{\theta}{2})$$

ϕ : azimuthal angle

- Central Region (-1<η<1)
  - Identified Pions, η
  - Jets
- Endcap (1<η<2)
  - π^0, η, (some) jets
- FMS (2.5<η<4)
  - π^0, η, EM Jets

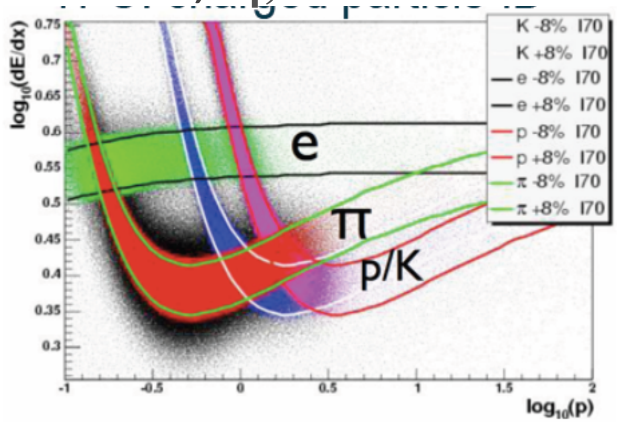


FMS



Full azimuth spanned with nearly contiguous electromagnetic calorimetry from -1<η<4

⇒ approaching full acceptance detector



PID (Barrel) with dE/dx, ToF pi/K separation up to 1.9 GeV

Transversity from di-Hadron SSA in p+p

p+p c.m.s. = lab frame

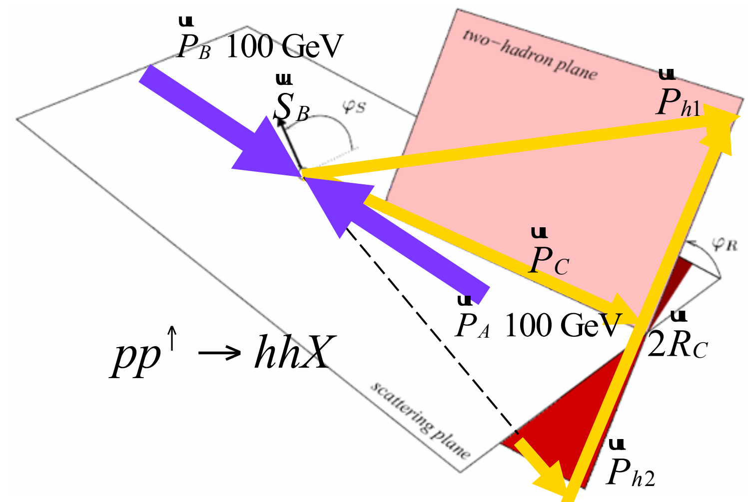
$\vec{P}_A, \vec{P}_B$: momenta of protons

$\vec{P}_{h1}, \vec{P}_{h2}$: momenta of hadrons

$\vec{P}_C = \vec{P}_{h1} + \vec{P}_{h2}$

$\vec{R}_C = (\vec{P}_{h1} - \vec{P}_{h2})/2$

$\vec{S}_B$: proton spin orientation



ϕ_R : from scattering plane to hadron plane

ϕ_S : from polarization vector to scattering plane

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

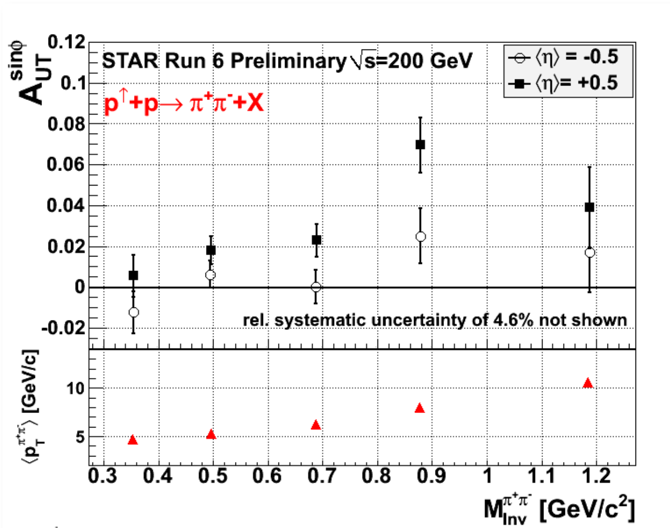
Unpolarized quark distribution
Known from DIS

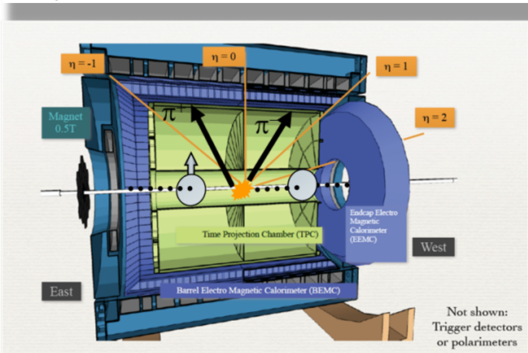
Transversity
to be extracted

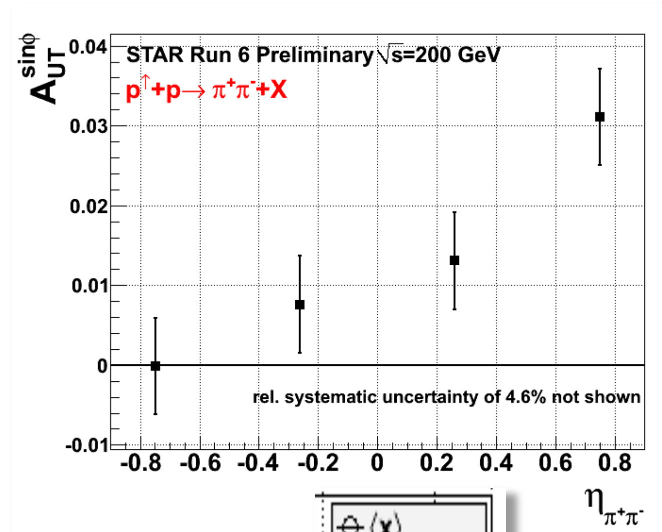
Hard scattering cross section
from pQCD

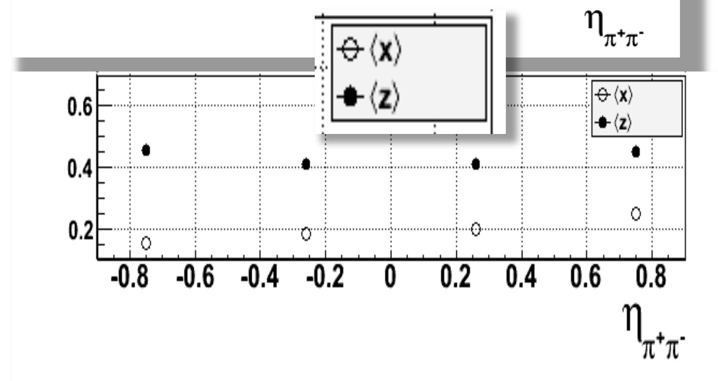
IFF + Di-hadron FF
measured in e+e at Belle-

Di-Hadron Correlations to access transversity





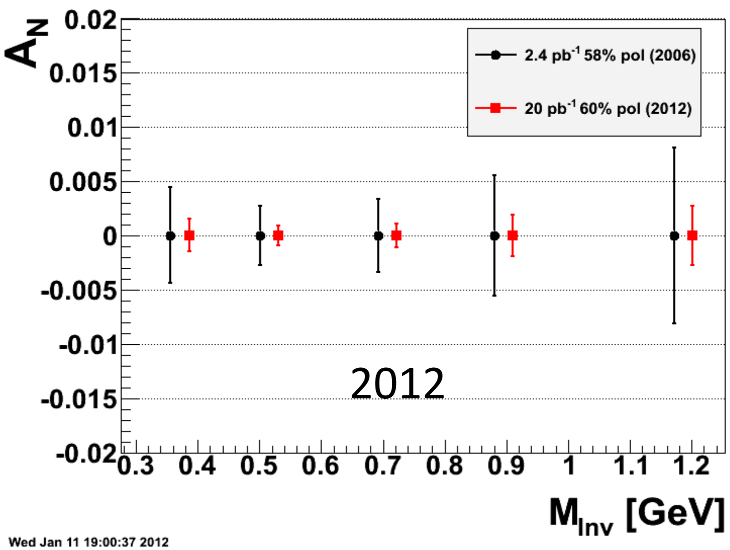


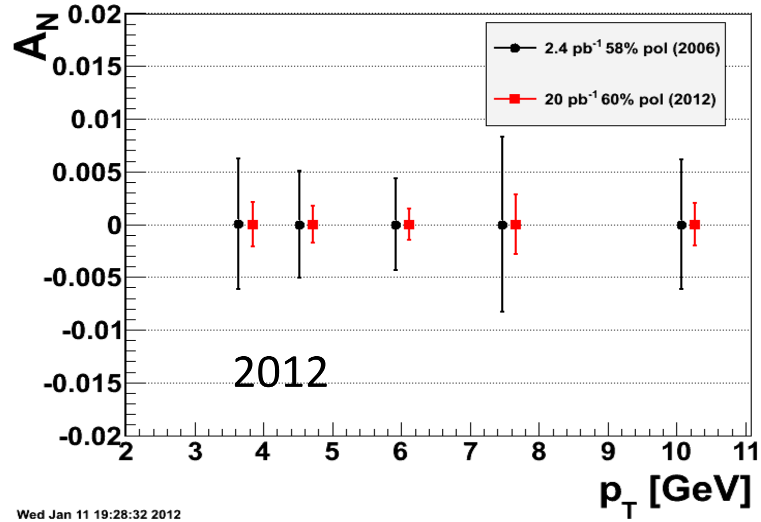


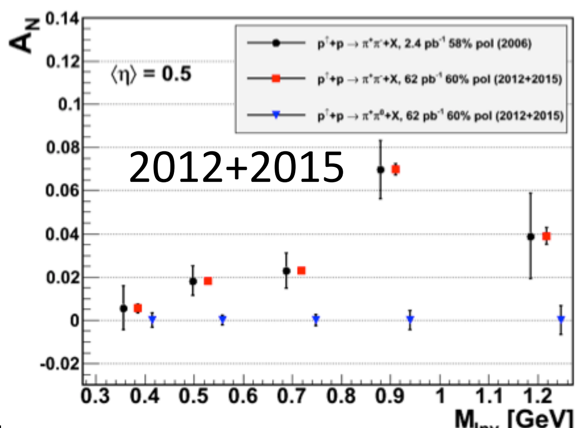
Trigger bias/partonic variables estimated
From Pythia+GEANT simulations

- $A_{UT} \propto h_1 \cdot H_1^{\sphericalangle}$ →First significant signal of transversity in polarized proton collisions

Projections for di-hadron correlations at STAR from 2012, 2015 Data





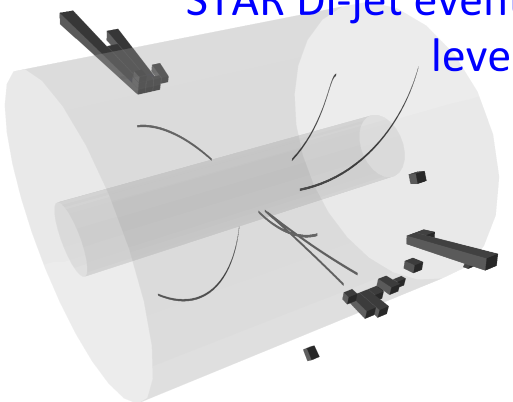


- Reduce Error Bars by factor of 3
- Explore π^0-$\pi^{+/-}$ channels: Access to flavor structure
- 500 GeV from 2011 + 2012 200 GeV to come for SPIN

Jet Reconstruction in STAR

Data jets

STAR Di-jet event at detector-level

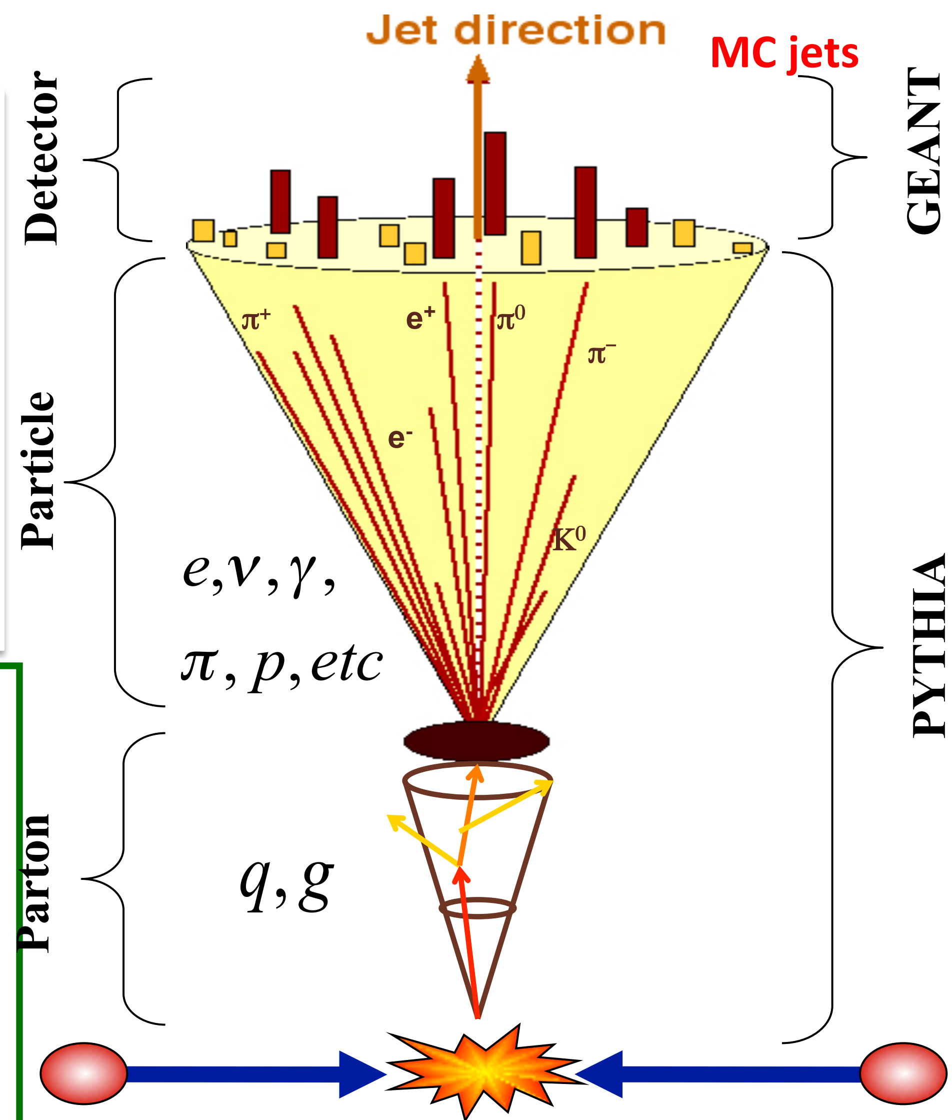


e.g. Anti-k_T algorithm (2011 results)

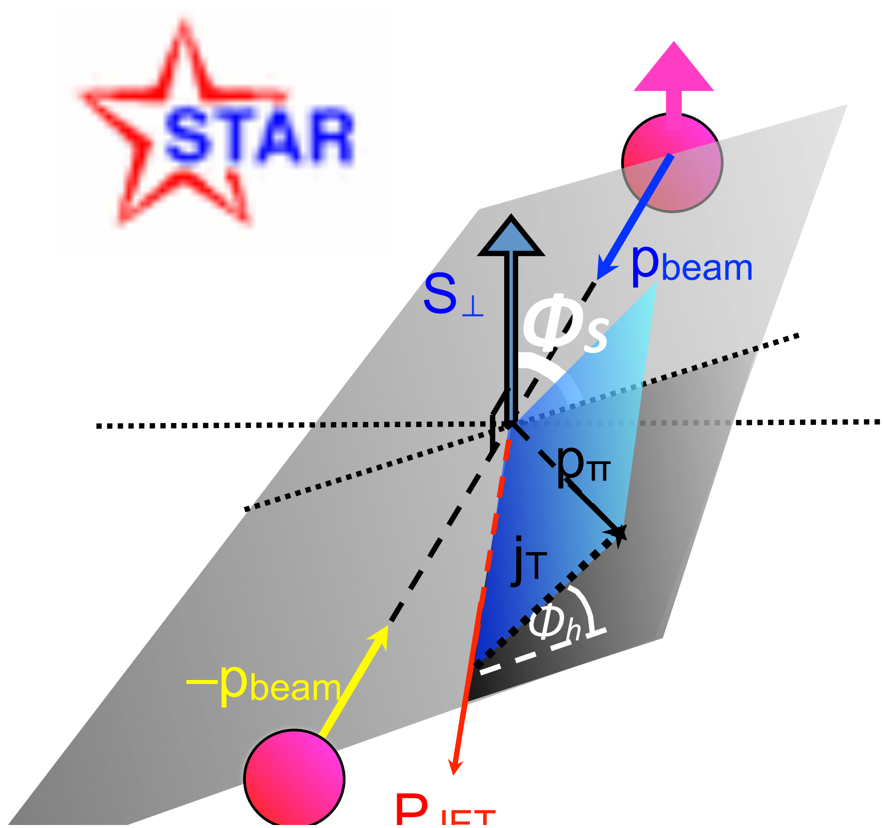
JHEP 0804, 063 (2008)

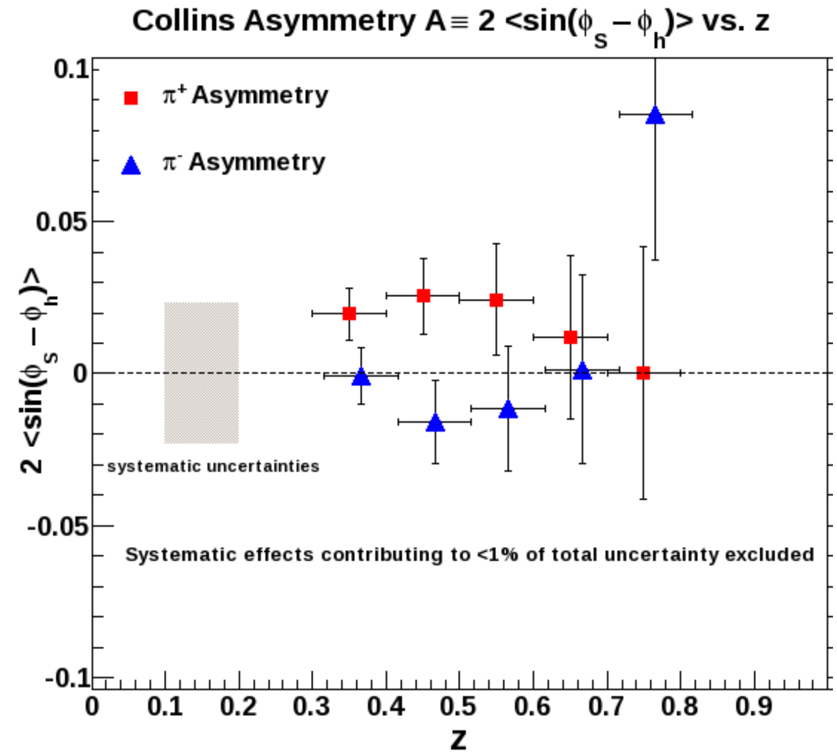
Use **PYTHIA** + **GEANT** to quantify detector response

- Trigger Bias
- Reconstruction smearing/bias (unfolding)
- Reconstruction of partonic variables, parton matching
- Underlying event/pileup effects



Naively: Collins asymmetries, $A^{\sin(\phi S-\phi h)} \propto h_1 \otimes H_1$





$$d\sigma \approx d\sigma^{UU}\left[1 + A_N \sin(\phi_h - \phi_s)\right]$$

Terms in Numerator of TMD SSA for qq scattering	English Names	Modulate
$\Delta^N f_{a/A\uparrow} \bullet f_{b/B} \bullet D_{\pi/q}$	Sivers • PDF • FF	$\sin(\varphi_{S_A})$
$h_1^a \bullet \Delta^N f_{b\uparrow/B} \bullet D_{\pi/q}$	Transversity•Boer-Mulder•FF	$\sin(\varphi_{S_A})$
$h_{1T}^{\perp a} \bullet \Delta^N f_{b\uparrow/B} \bullet D_{\pi/q}$	Pretzelocity•Boer-Mulder•FF	$\sin(\varphi_{S_A})$
$h_1^a \bullet f_{b/B} \bullet \Delta D_{\pi/q\uparrow}$	Transversity•PDF •Collins	$\sin(\varphi_{S_A} - \varphi_\pi)$
$\Delta f_{a/A\uparrow}^N \bullet \Delta^N f_{b\uparrow/B} \bullet \Delta D_{\pi/q\uparrow}$	Sivers•Boer-Mulder•Collins	$\sin(\varphi_{S_A} - \varphi_\pi)$
$h_{1T}^{\perp a} \bullet f_{b/B} \bullet \Delta D_{\pi/q\uparrow}$	Pretzelocity•PDF•Collins	$\sin(\varphi_{S_A} + \varphi_\pi)$
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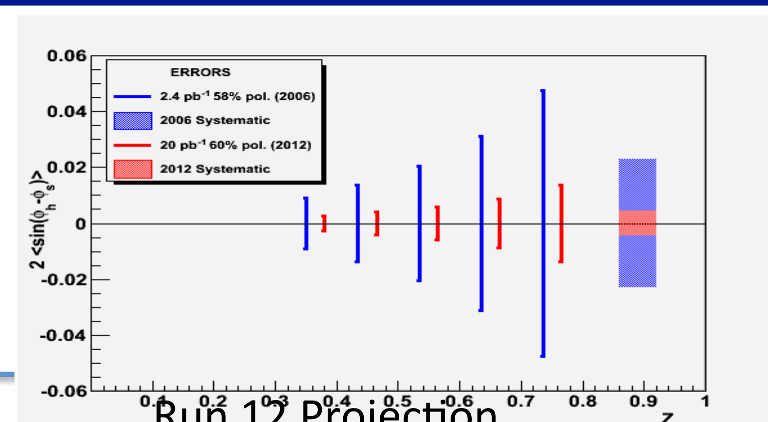
Based on work by F.Yuan (Phys.Rev.Lett.100:032003) and D'Alesio et al. (Phys.Rev. D83, 034021)



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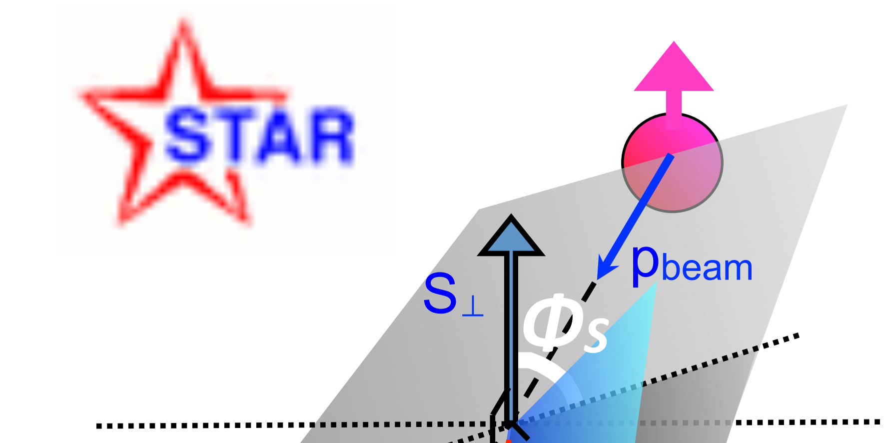

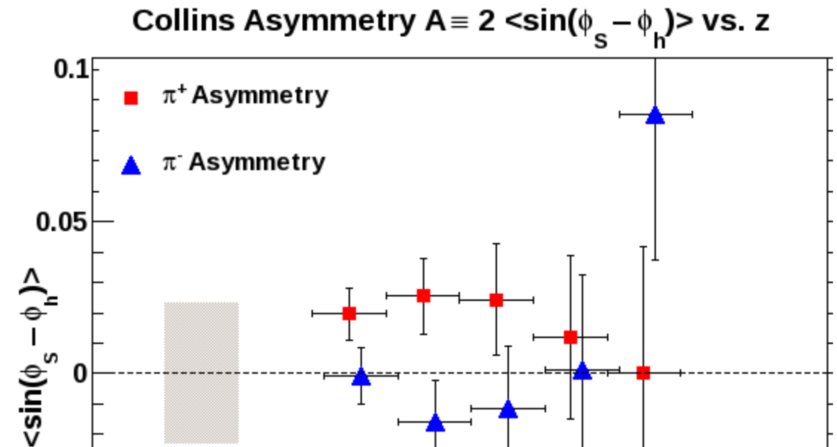

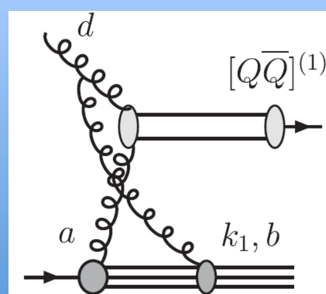

Unknown “Color Entanglement” Effects
(AKA Factorization Breaking)

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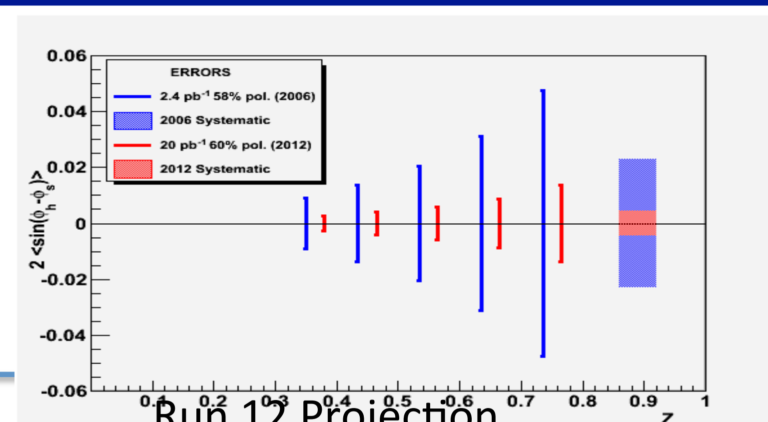
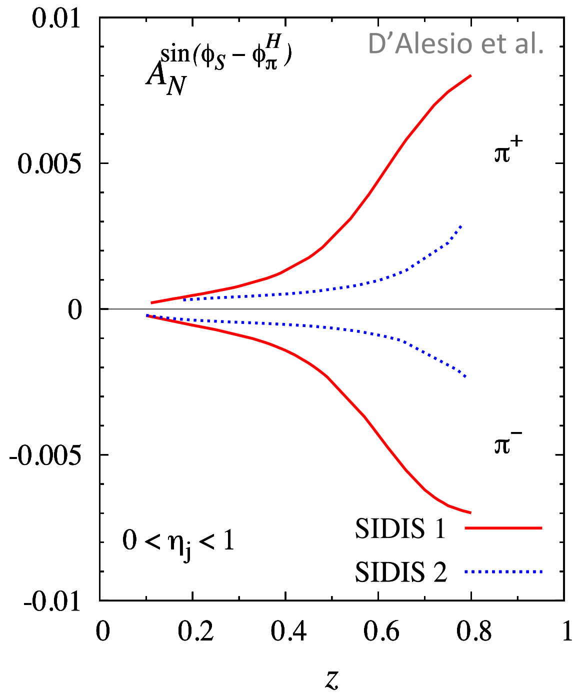
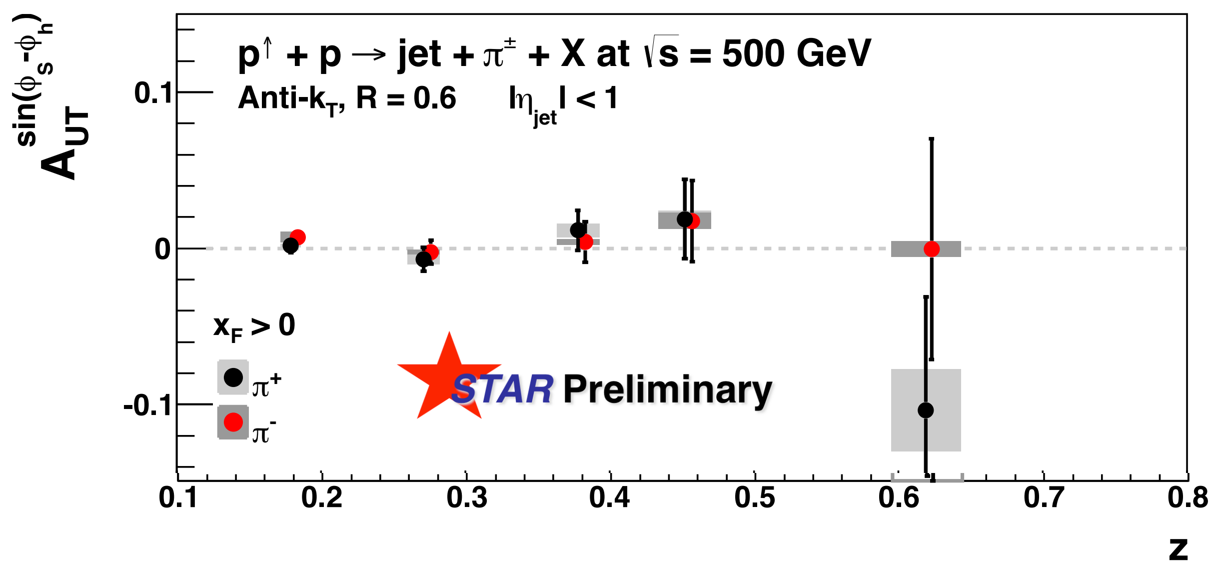


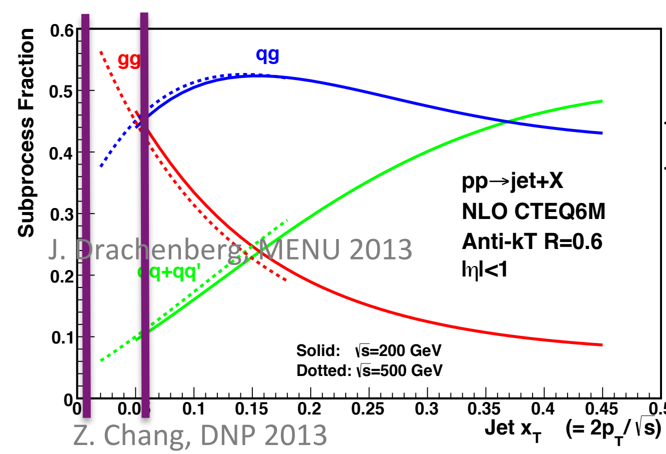
Run 12 Projection

Collins Asymmetry at 500 GeV

Increased gluonic subprocesses at $\sqrt{s}$ = 500 GeV lead to expectation of ***small Collins asymmetry*** until larger z

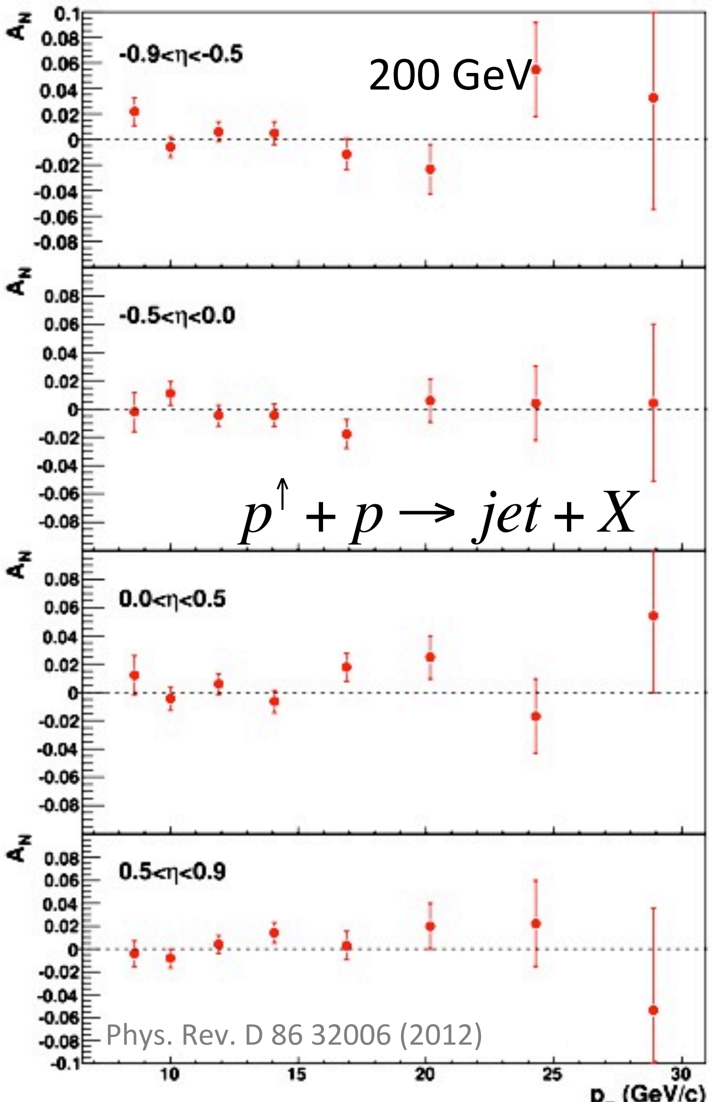


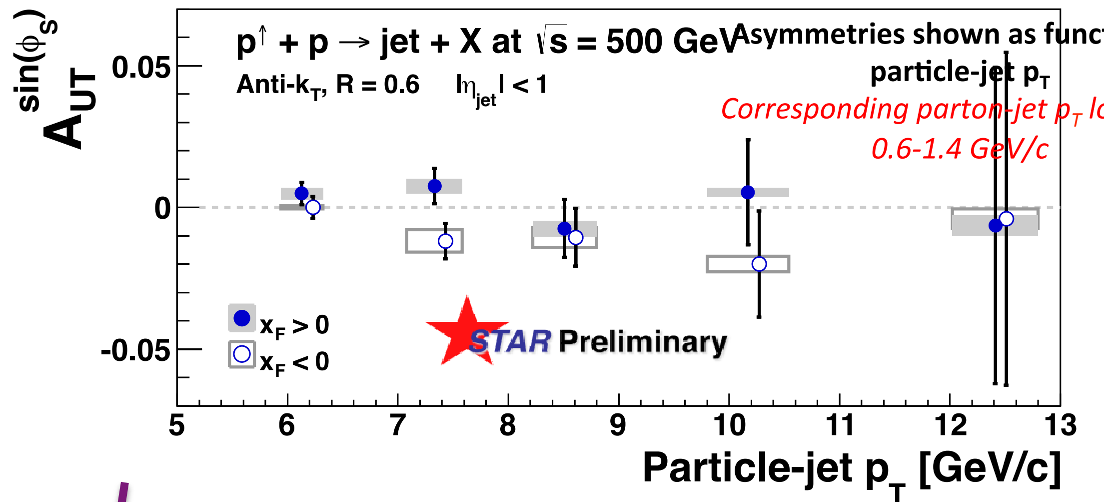


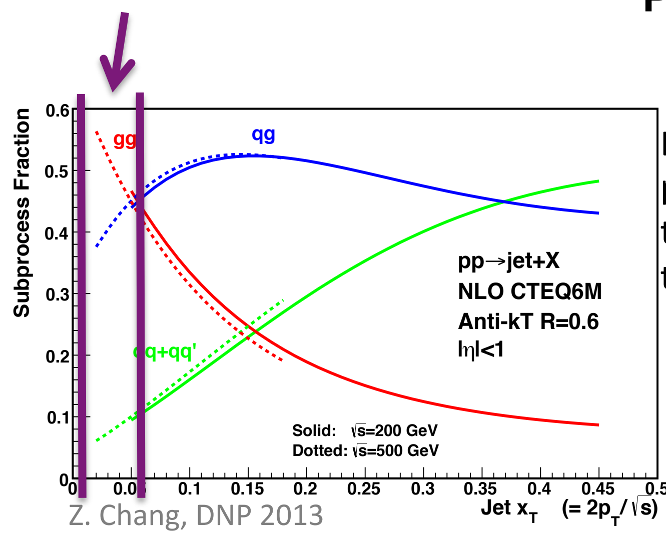


Leading sys.. Error from parton matchin, no sig. trigger bias due to min bias trigger

STAR Jet A_N, $A^{\sin(\phi S)}$ related to $f_1^{\perp}$





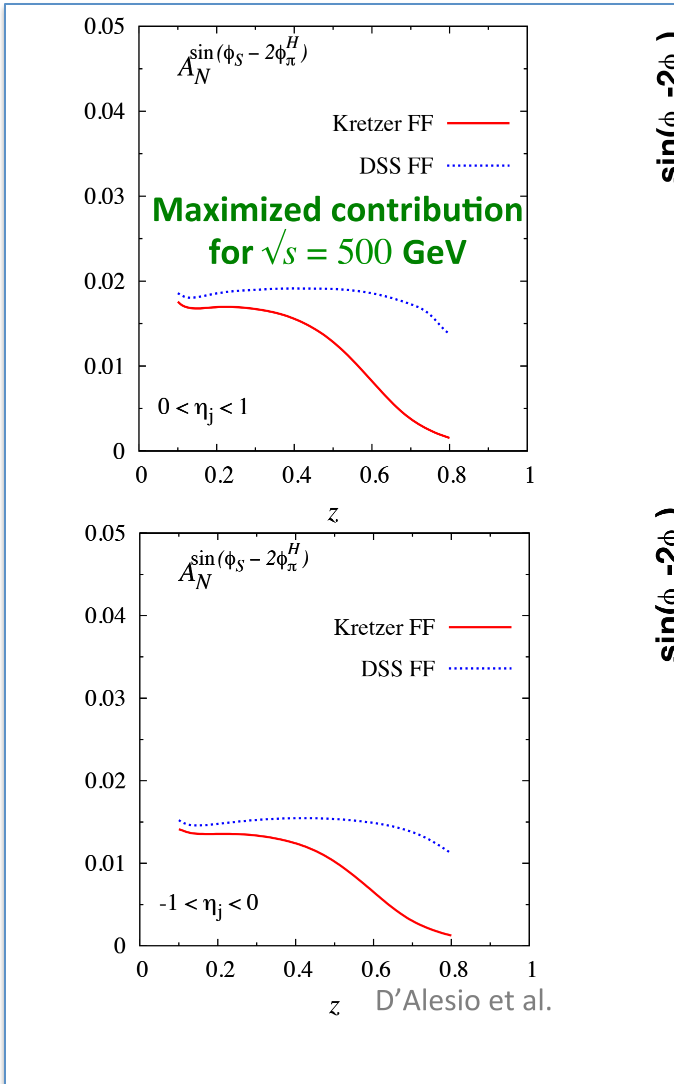


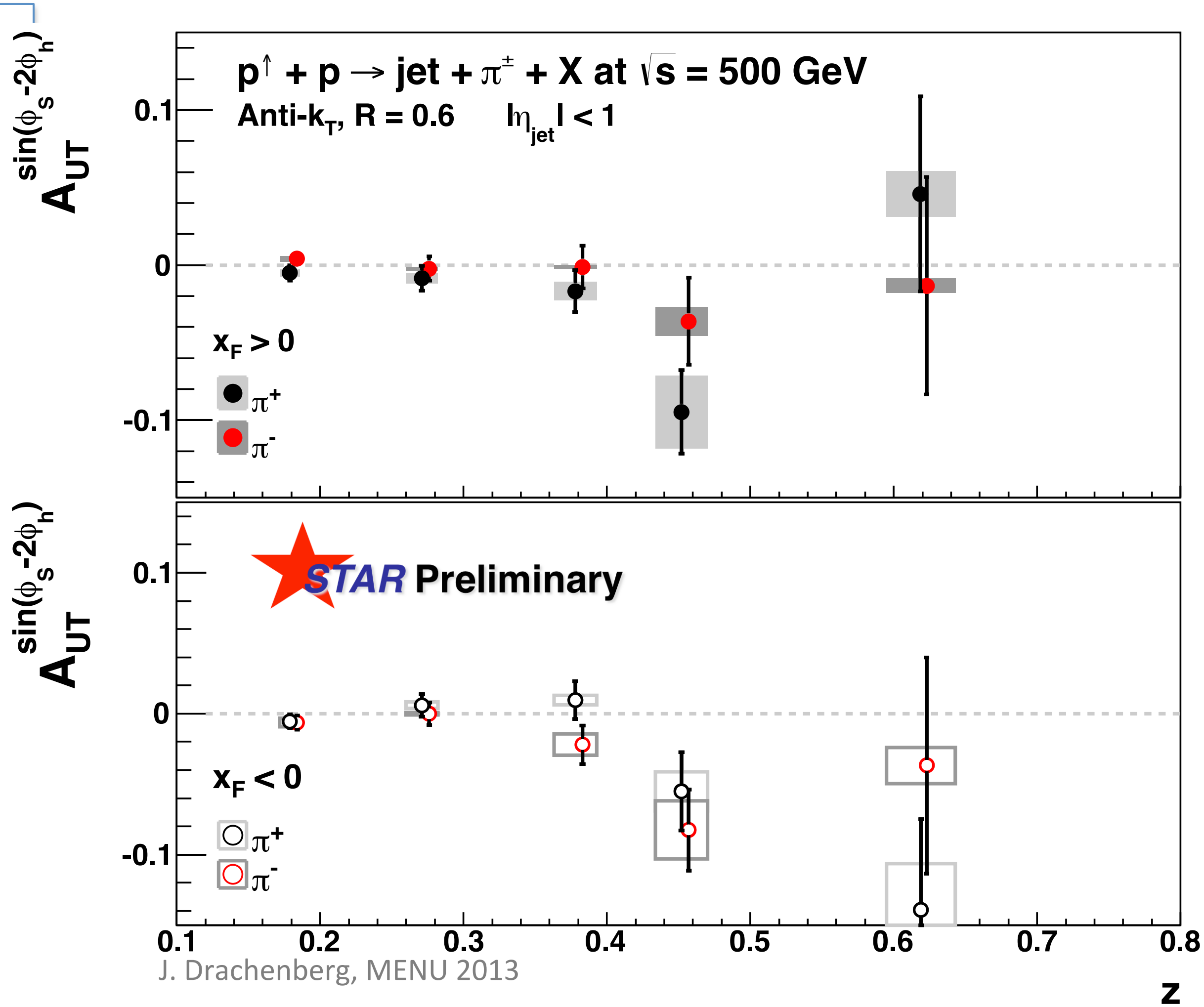
Z. Chang, DNP 2013

Leading sys.. Error from parton matchin, no sig. trigger bias due to min bias trigger

Similarly, di-jet at central psuedorapidity and 200 GeV consistent with zero PRL 99, 142003

"Collins Like": $A^{\sin(\phi S-2\phi h)} \propto h_1^{\perp,g} \otimes H_1$



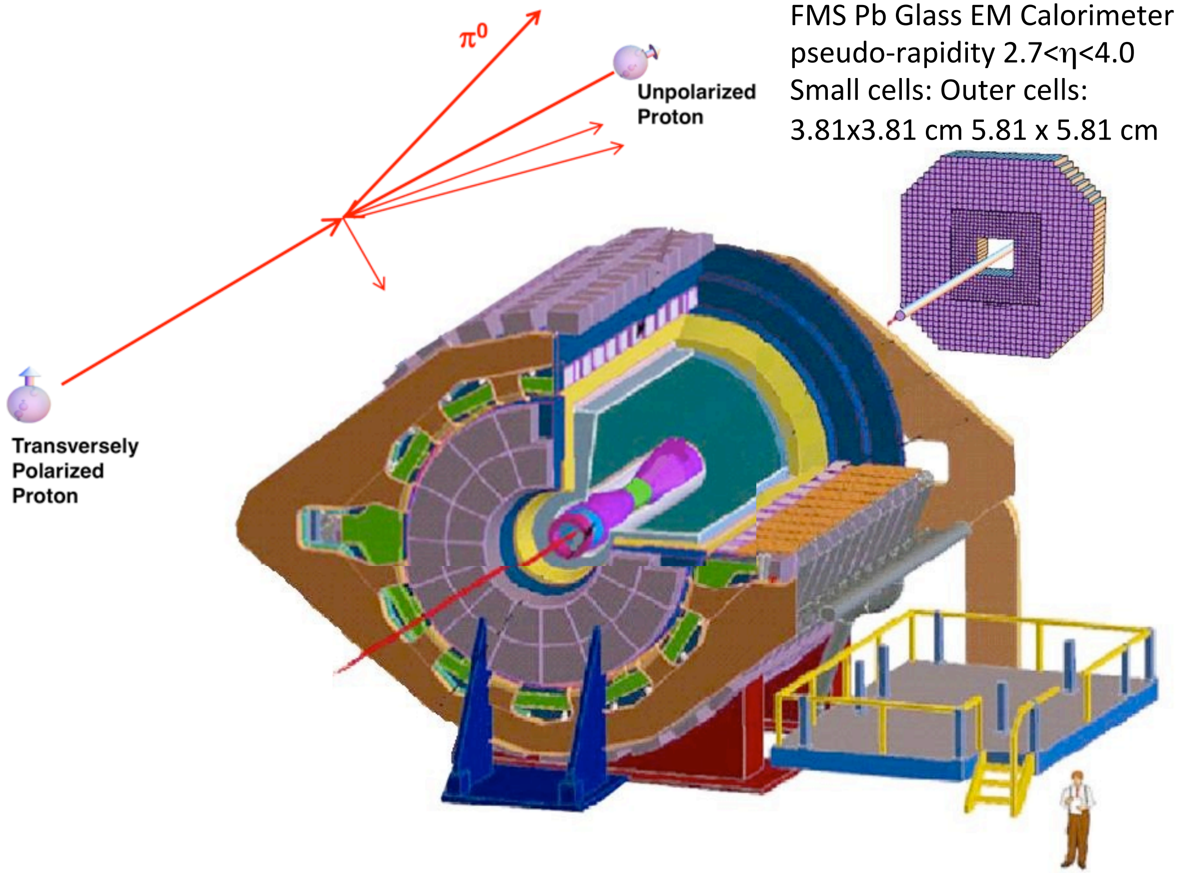


Model predictions shown for "maximized" effect, saturated to positivity bound

Until now, Collins-like asymmetries completely unconstrained

→ ***Sensitive to linearly polarized gluons***

Mechanism behind AN: Forward EM Jet topology and correlations

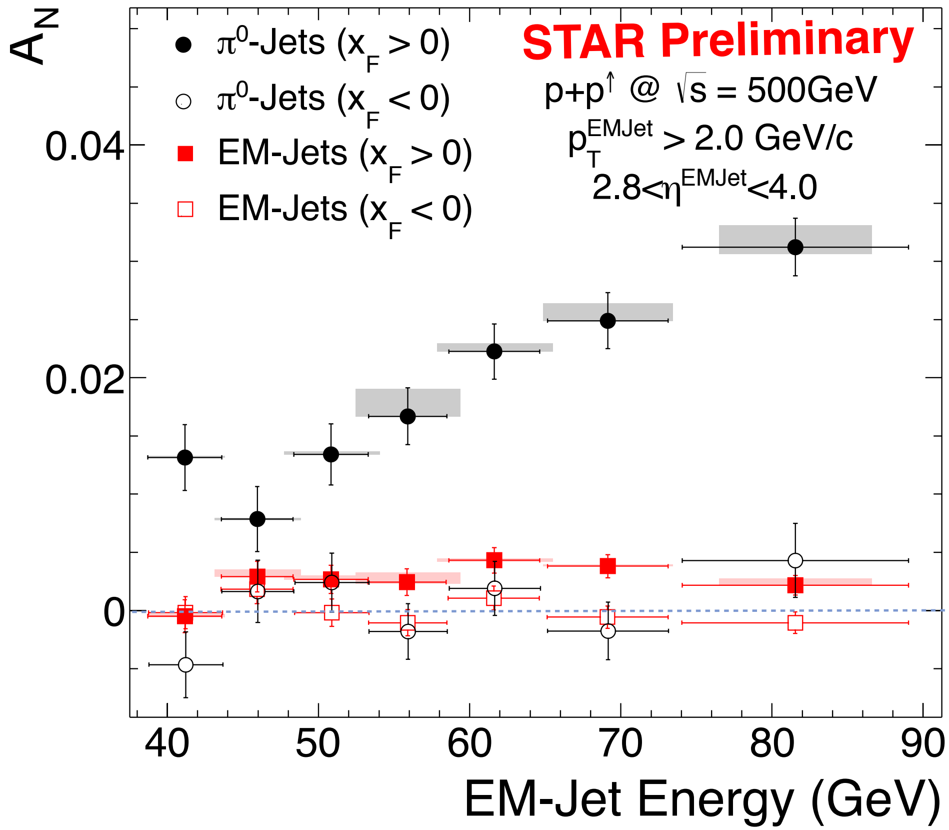


Forward Meson Spectrometer (FMS) :

-- 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.

TSSA for forward EM Jets



π^0-Jets –

2γ-EM-Jets with

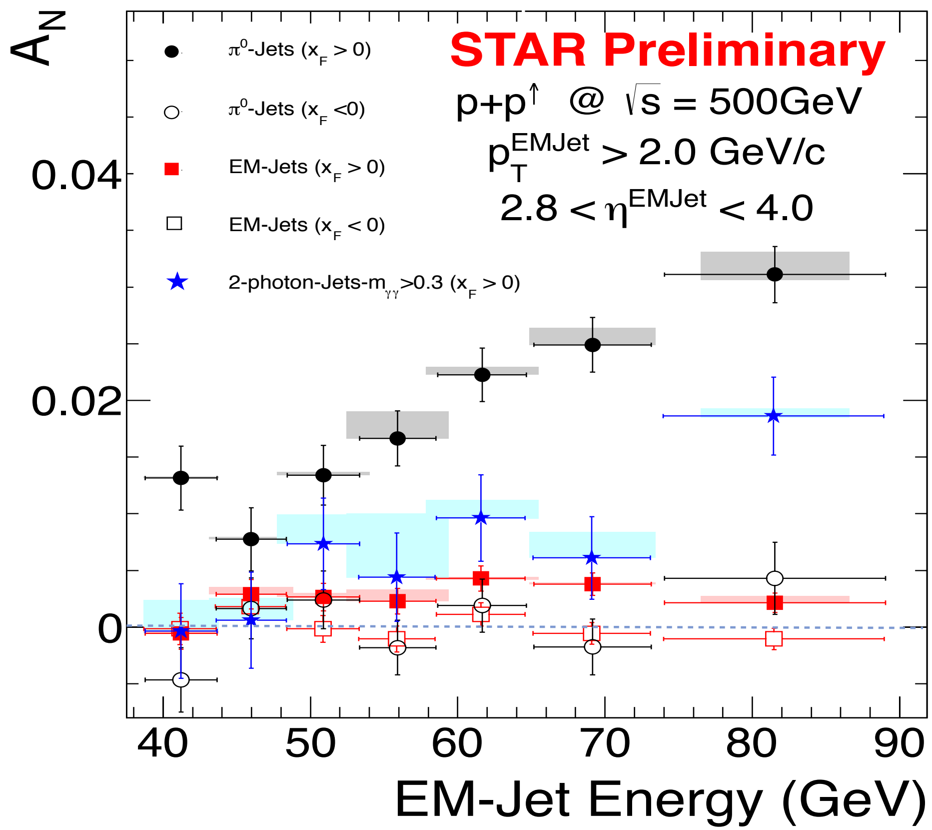
$m_{\gamma\gamma}$ <0.3

$Z_{\gamma\gamma}$ <0.8

EM-Jets –

with no. photons >2

- ✧ Isolated π^0's have large asymmetries consistent with previous observation
- ✧ **Asymmetries for jettier events are much smaller**



π^0-Jets – 2γ-EM-Jets with

$m_{\gamma\gamma}$ <0.3

$Z_{\gamma\gamma}$ <0.8

2γ-EM-Jets (η + continuum) - with

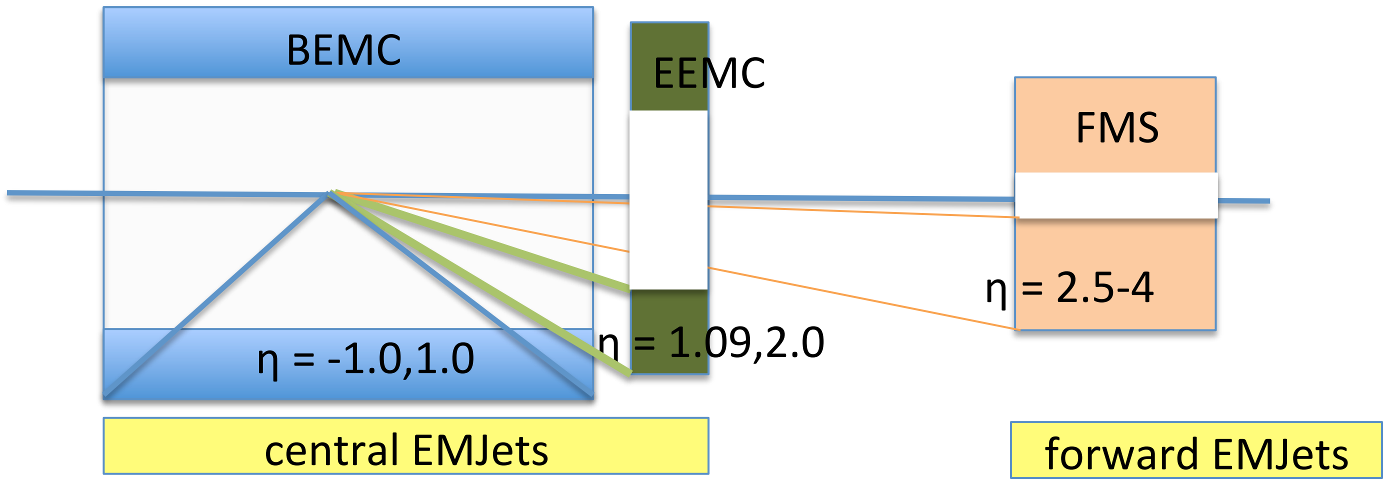
$m_{\gamma\gamma}$ > 0.3

EM-Jets – with

no. photons >2

- ✧ Isolated π^0's have large asymmetries consistent with previous observation
- ✧ **Asymmetries for jettier events are much smaller**

A_N with midrapidity activities



Midrapidity EM Jets

Jet algorithm : anti-k_T, $R = 0.7$

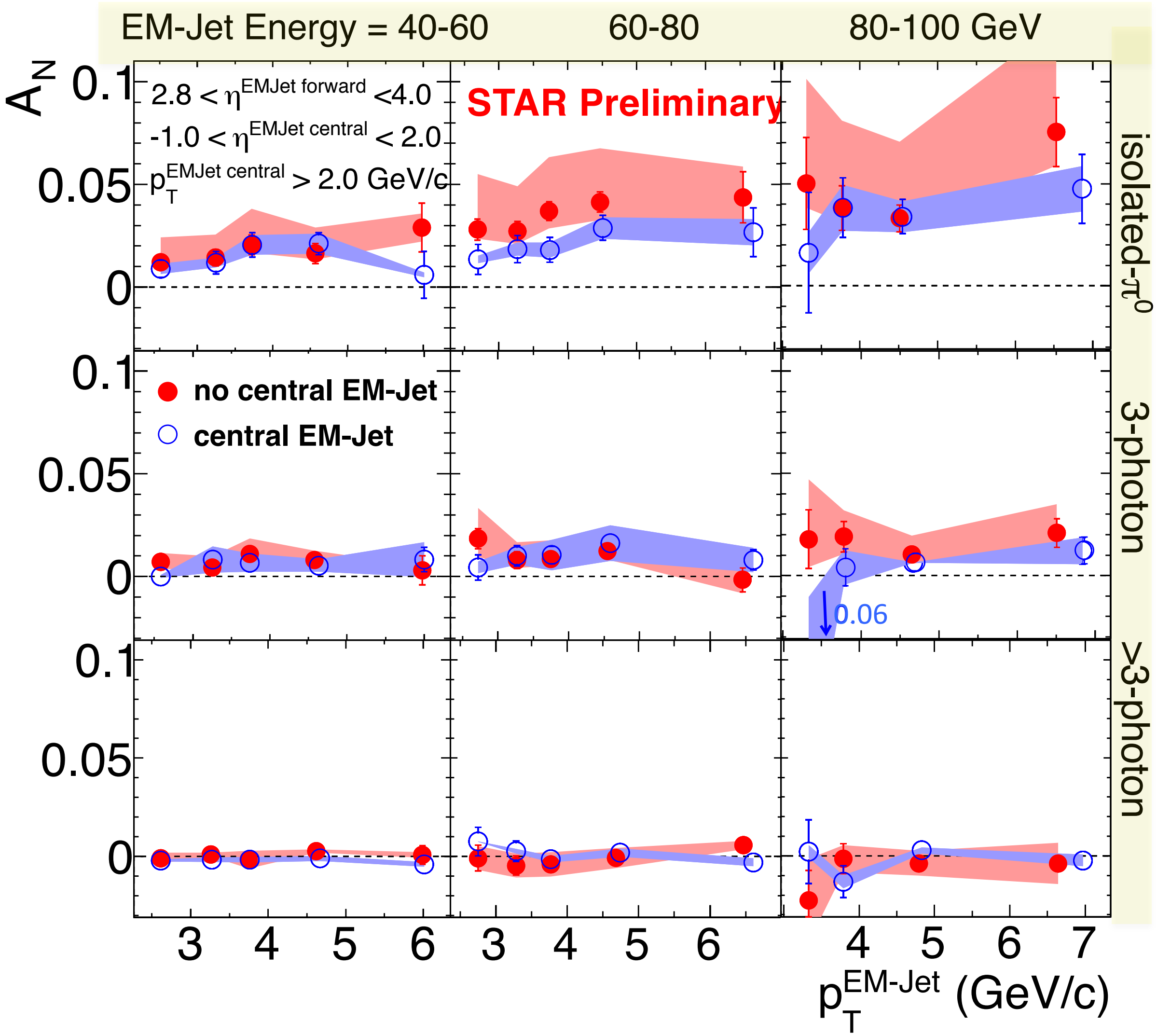
$p_T^{EM\text{-}Jet} > 2.0$ GeV/c, $-1.0<\eta^{EM\text{-}Jet}<2.0$

Inputs for central EMJets : towers from BEMC and EEMC

Leading central EM-Jets : Jet with highest p_T

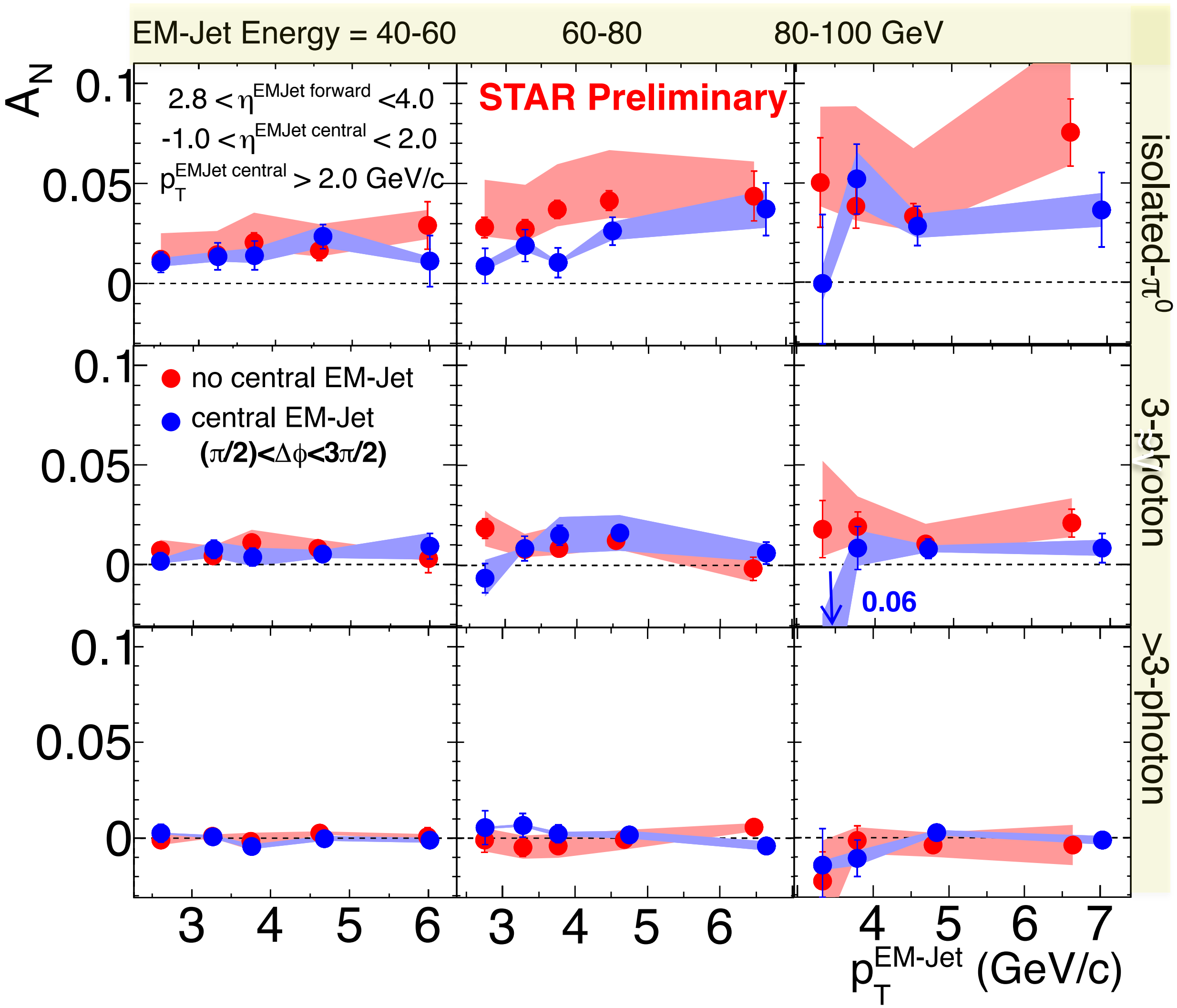
- Case-I : having no central jet
- Case-II : having a central jet

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 **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.

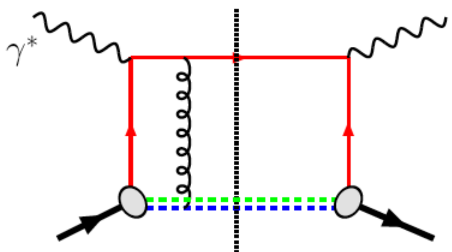
The famous sign change of the Sivers fct.

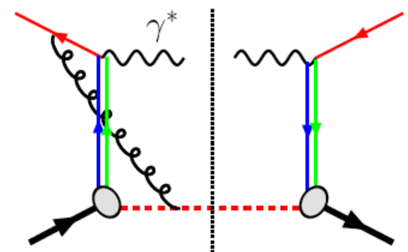
critical test for our understanding of TMD's and TMD factorization

Twist-3 formalism predicts the same

QCD:

DIS: gq-scattering **attractive FSI**	**pp:** qqbar-anhilation **repulsive ISI**





Sivers$_{DIS}$ = - (Sivers$_{DY}$ or **Sivers$_{W}$ or** Sivers$_{Z0}$)

A_N(direct photon) measures the sign change through Twist-3

will also be A_N(DY) and A_N($W^{+/-}$,Z^0) test of TMD evolution

All three observables can be attacked in one 500 GeV Run by STAR

STAR: A_N^W

Analysis Strategy to fully reconstruct Ws:

→ W candidate selection via high p_t lepton

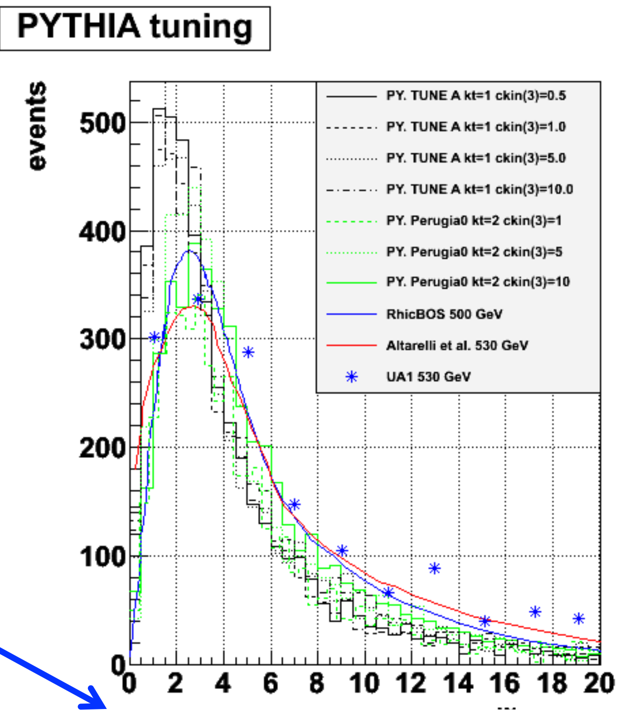
Data set 2011 transverse 500 GeV data set (25 pb^{-1})

✓ In transverse plane: $$\vec{P}_T^W = \vec{P}_T^e + \vec{P}_T^\nu = \vec{P}_T^{recoil}$$

✓ Recoil reconstructed using tracks and towers: $$\sum_{i=tracks+trackless-clusters} \vec{P}_T^i$$

✓ Part of the recoil not within STAR acceptance

→ correction through MC (Pythia)

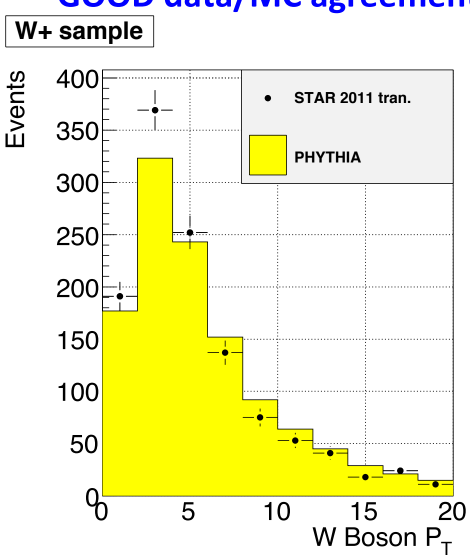


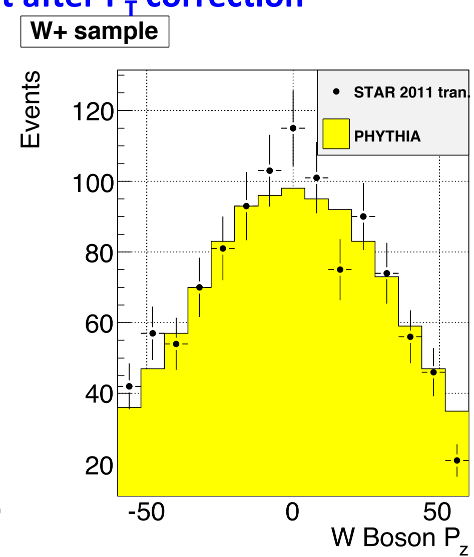
W Rapidity reconstruction:

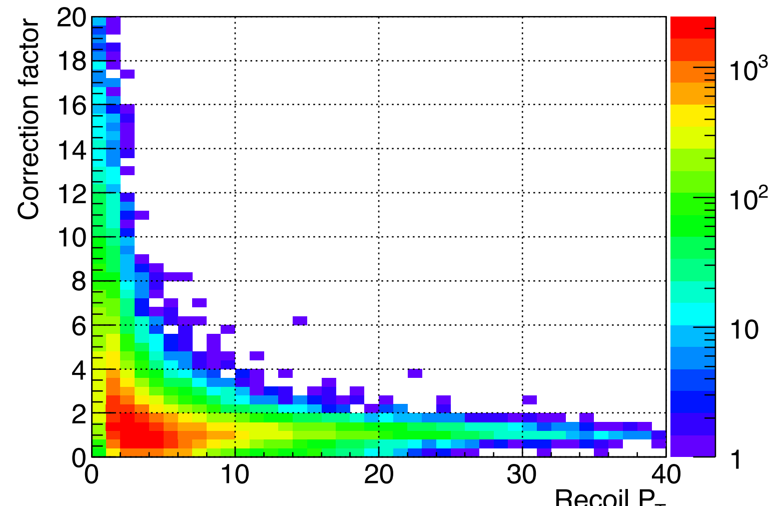
✓ W longitudinal momentum (along z) can be calculated from the invariant mass: $$M_w^2 = (E_e + E_\nu)^2 - (\vec{p}_e + \vec{p}_\nu)^2$$

✓ Neutrino longitudinal momentum component from quadratic equation $$\left|\vec{p}_T^e\right|^2 (p_z^\nu)^2 - 2Ap_z^e p_z^\nu + \left|\vec{p}_T^\nu\right|^2 \left|\vec{p}^e\right|^2 - A^2 = 0 \quad A = \frac{M_W^2}{2} + \vec{p}_T^e \vec{p}_T^\nu$$

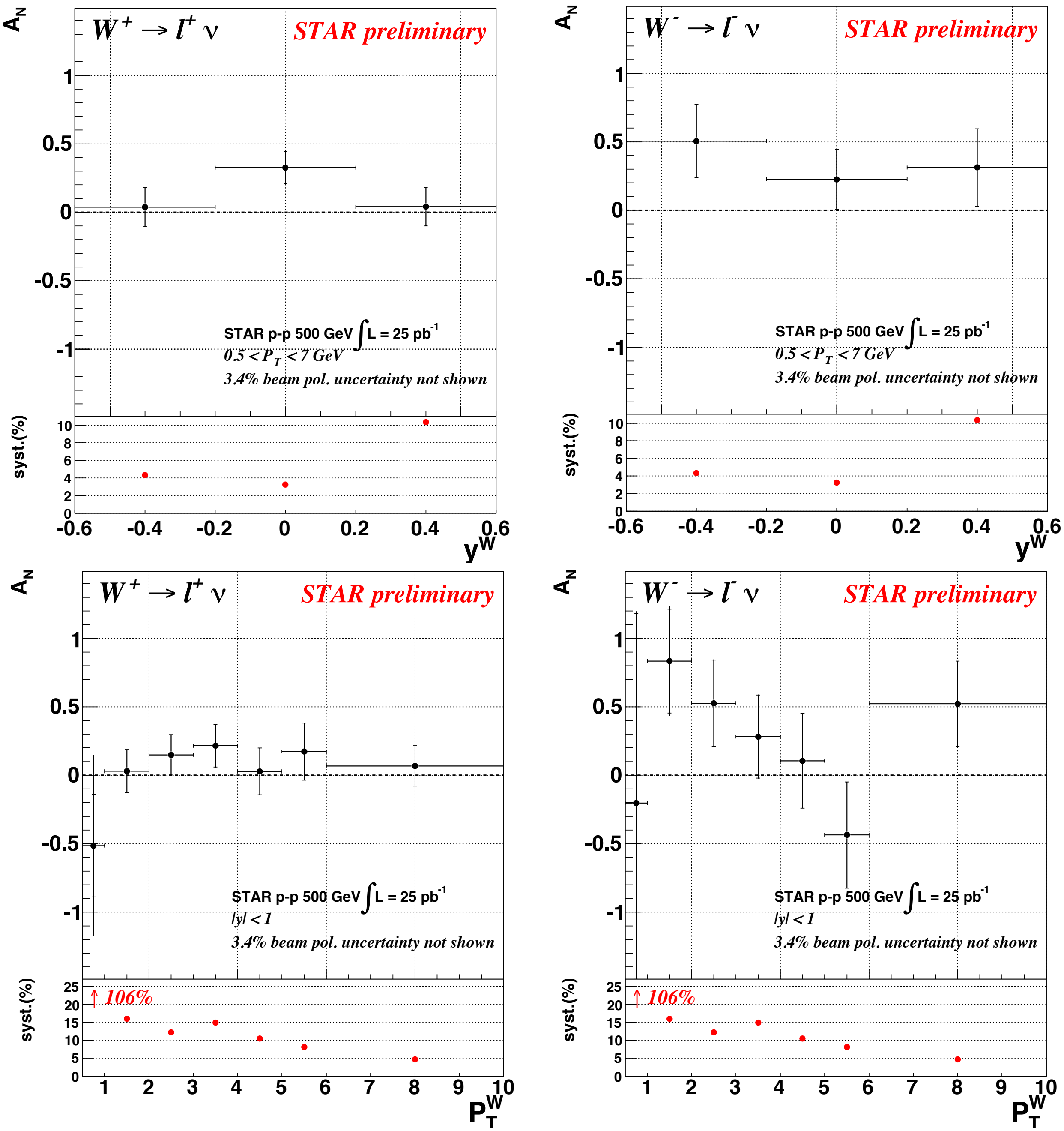
GOOD data/MC agreement after P_T correction

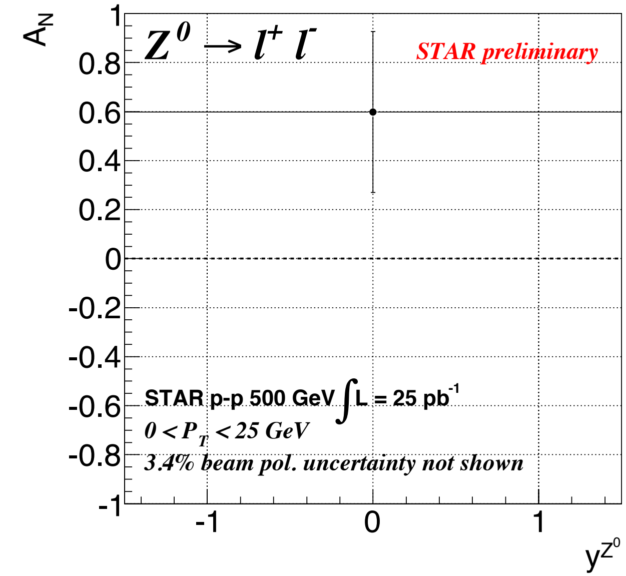






$A_N(W^{+/-},Z^0)$ Results from 2011

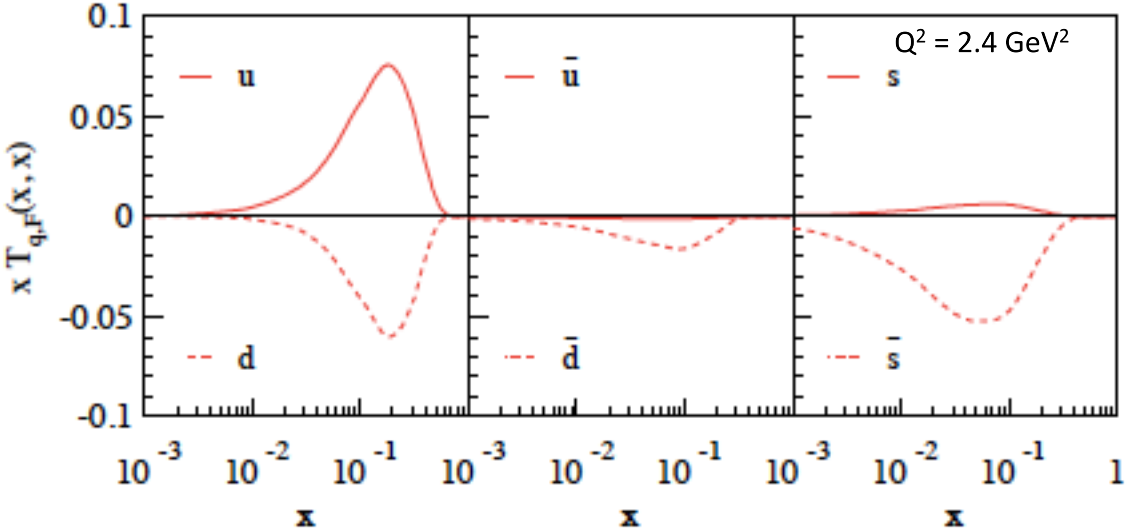




2011:
recorded lumi 25 pb^{-1}

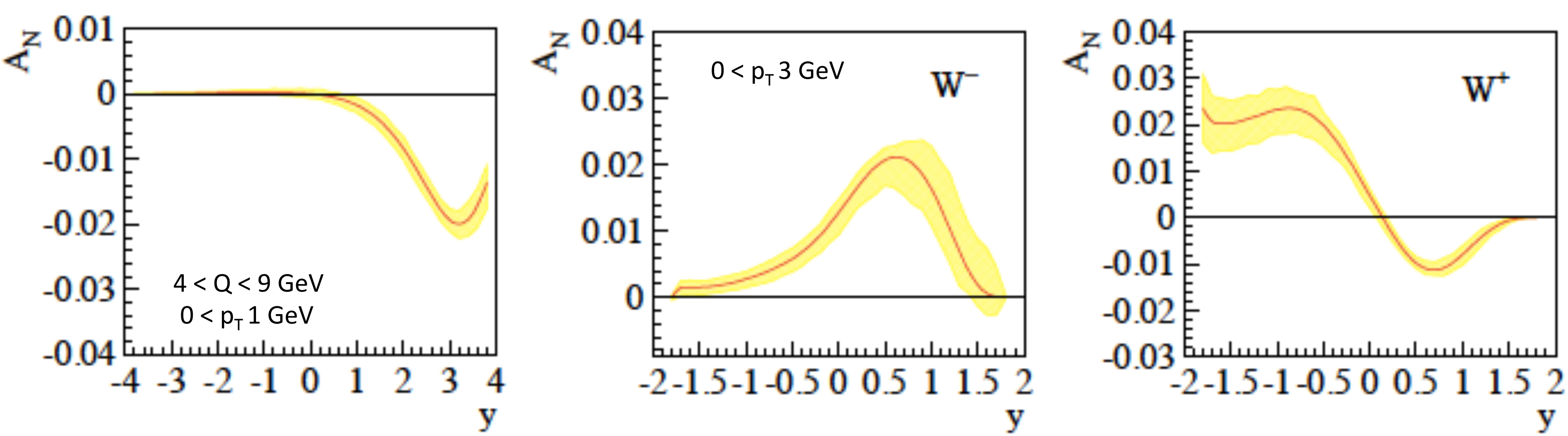
New Theory predictions

Z. Kang et al. arXiv:1401.5078v1



despite fitted,
sea quarks unconstrained

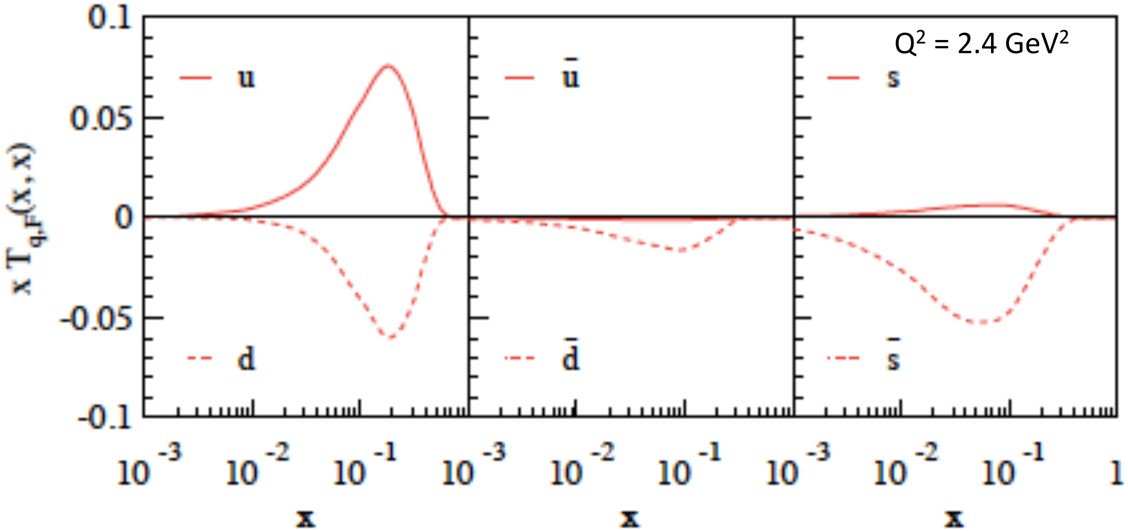
impacts $A_N(W^{\pm}, Z^0)$
new calculations for
$A_N(\gamma)$ coming
and $A_N(W^{\pm}, Z^0)$
maximized sea-quarks



Z. Kang A_N ($W^{+/-}$,Z^0) accounting for sea quark uncertainties using positivity bound as limit

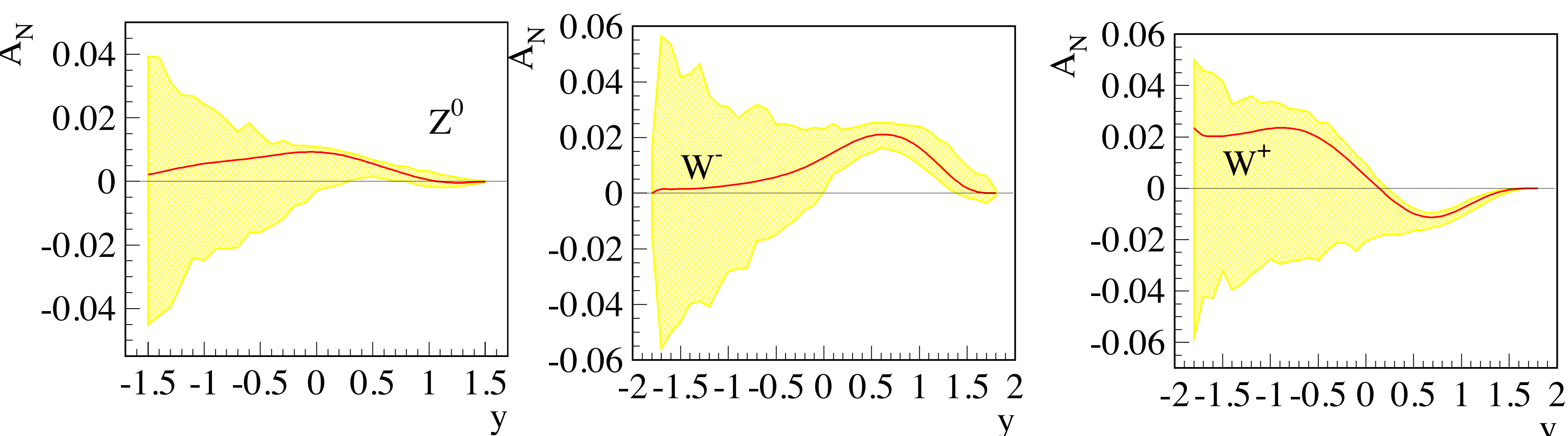
New Theory predictions

Z. Kang et al. arXiv:1401.5078v1



despite fitted,
sea quarks unconstrained

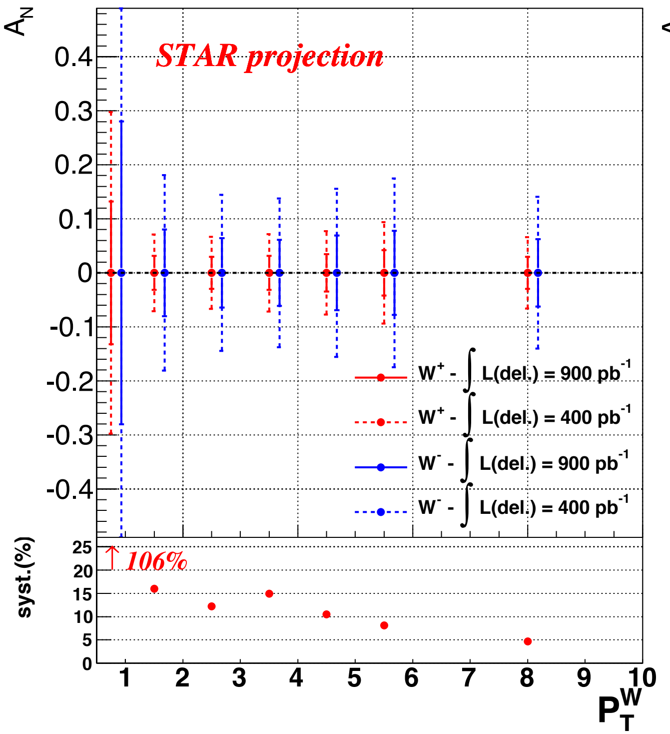
impacts $A_N(W^{\pm}, Z^0)$
new calculations for
$A_N(\gamma)$ coming
and $A_N(W^{\pm}, Z^0)$
maximized sea-quarks

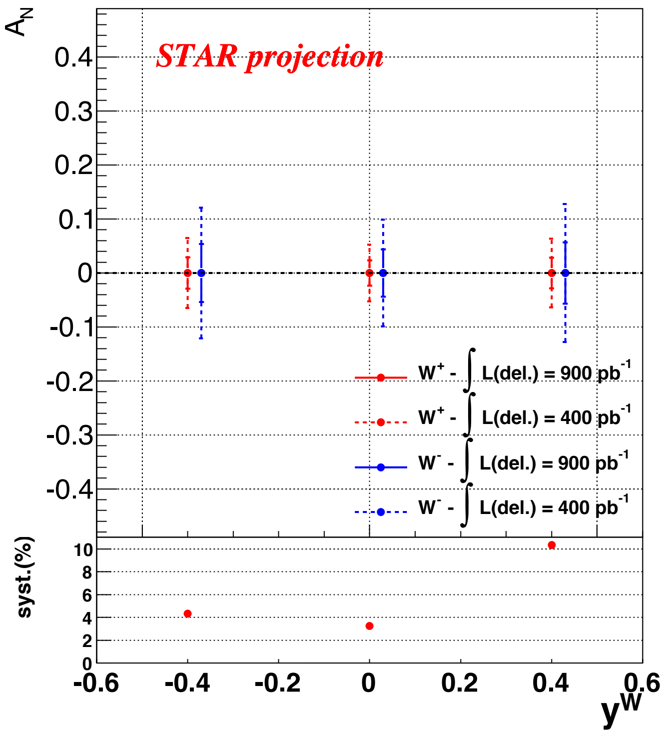


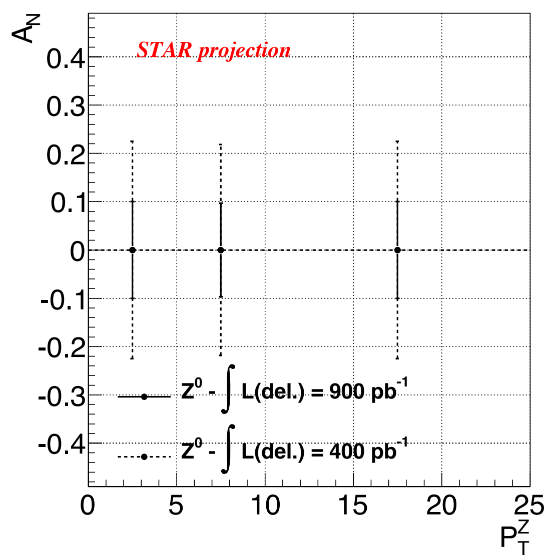
Z. Kang A_N ($W^{+/-}$,Z^0) accounting for sea quark uncertainties
using positivity bound as limit

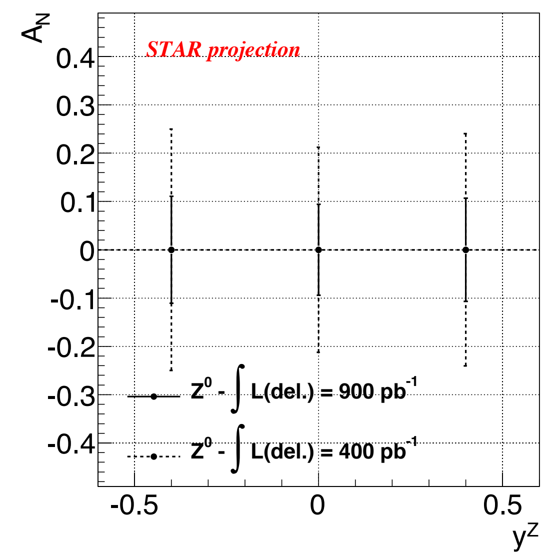
$A_N(W^{+/-},Z^0)$ from Run 2016

2016: possible recorded lumi as big as 900 pb^{-1}





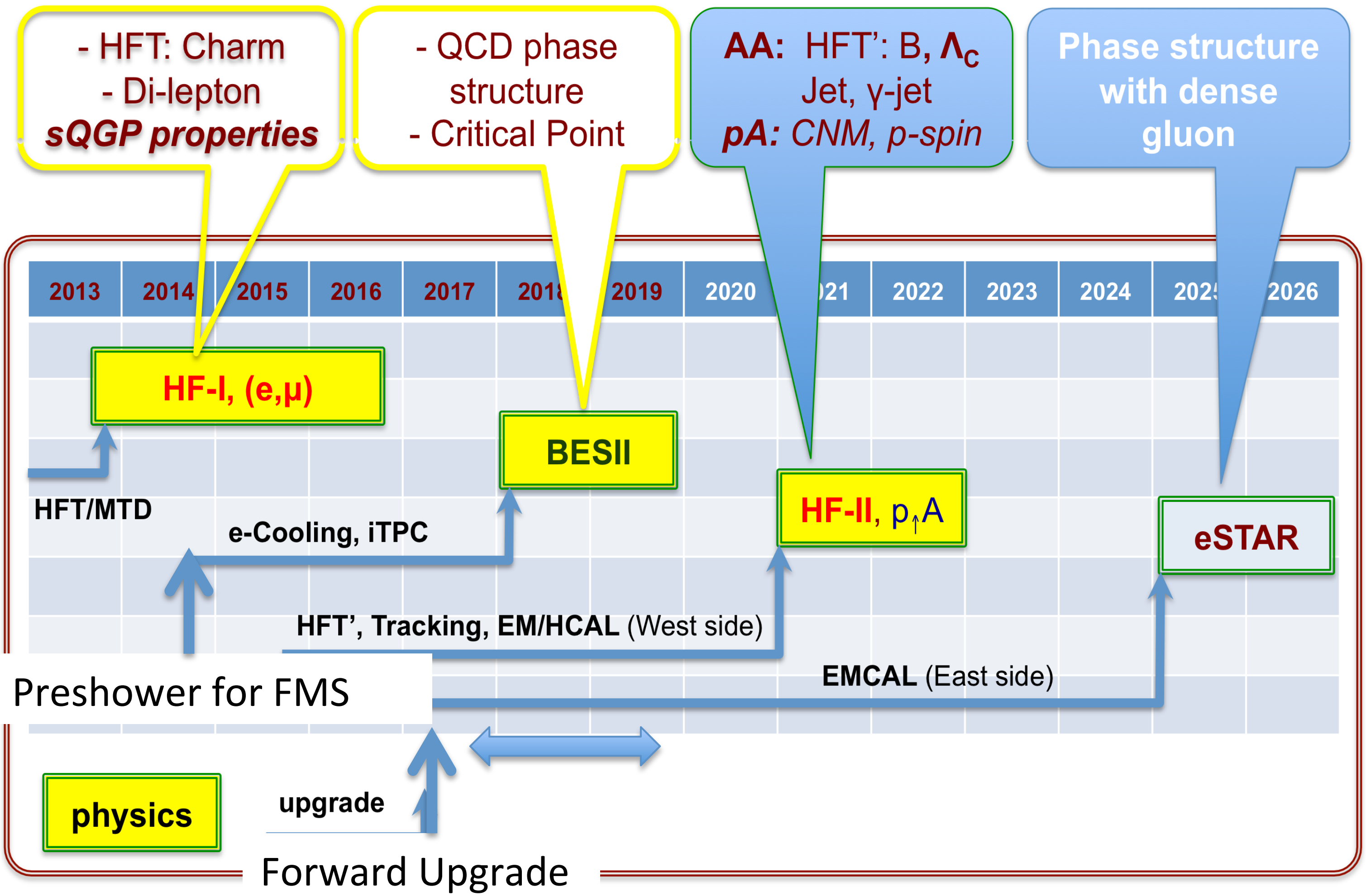




$A_N(W^{+/-},Z^0)$:
will be able to constrain sea quark Sivers
and
make a statement on the sign change

- ❑ $A_N(\gamma)$ up to x_F of 0.6
- ❑ A_N(DY) simulations still ongoing

STAR: Upgrade Plan

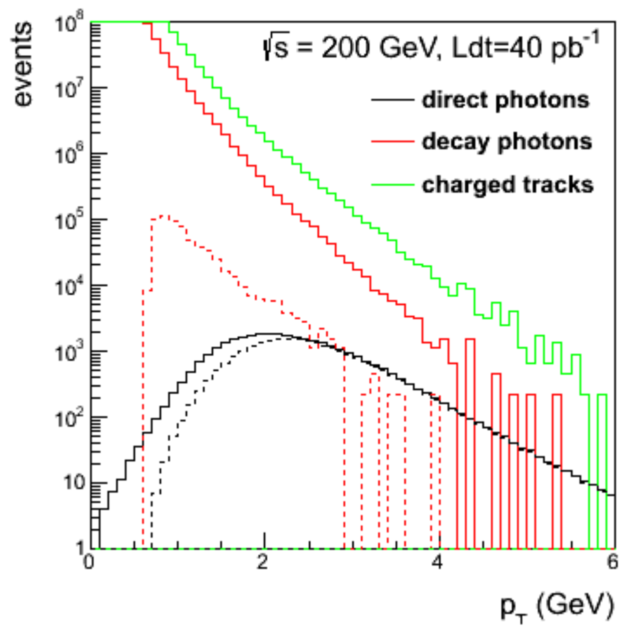


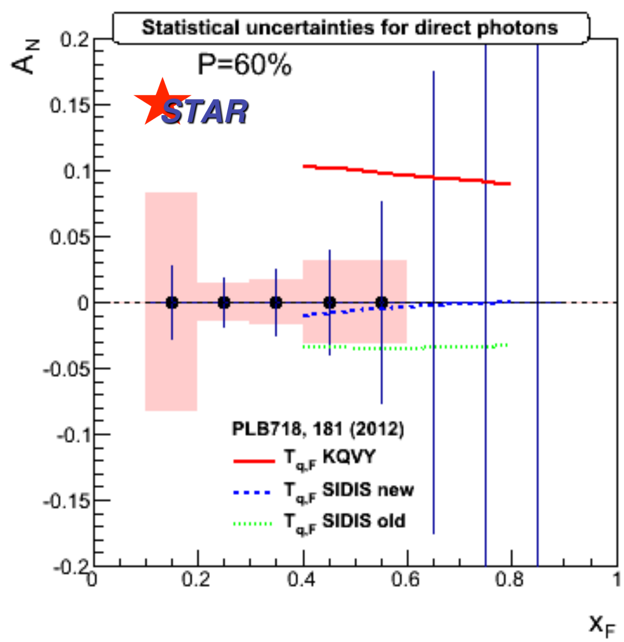
2015-2015:
Direct γ with the FMS Preshower and evaluation of DY

STAR Beam Use Request calls for transverse p+p/A @200GeV (2015) and p+p @510GeV
Direct γ measurement:

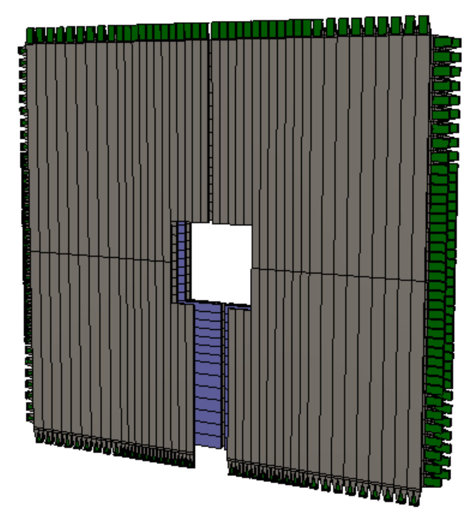
3 layer preshower in front of the FMS,
→ distinguish photons, electrons/positrons
and charged hadrons.

→J/Ψ
→for p+p @510GeV in run16 currently evaluating the most cost
Effective approach in forward calorimeter and possible tracking option
to do DY measurement

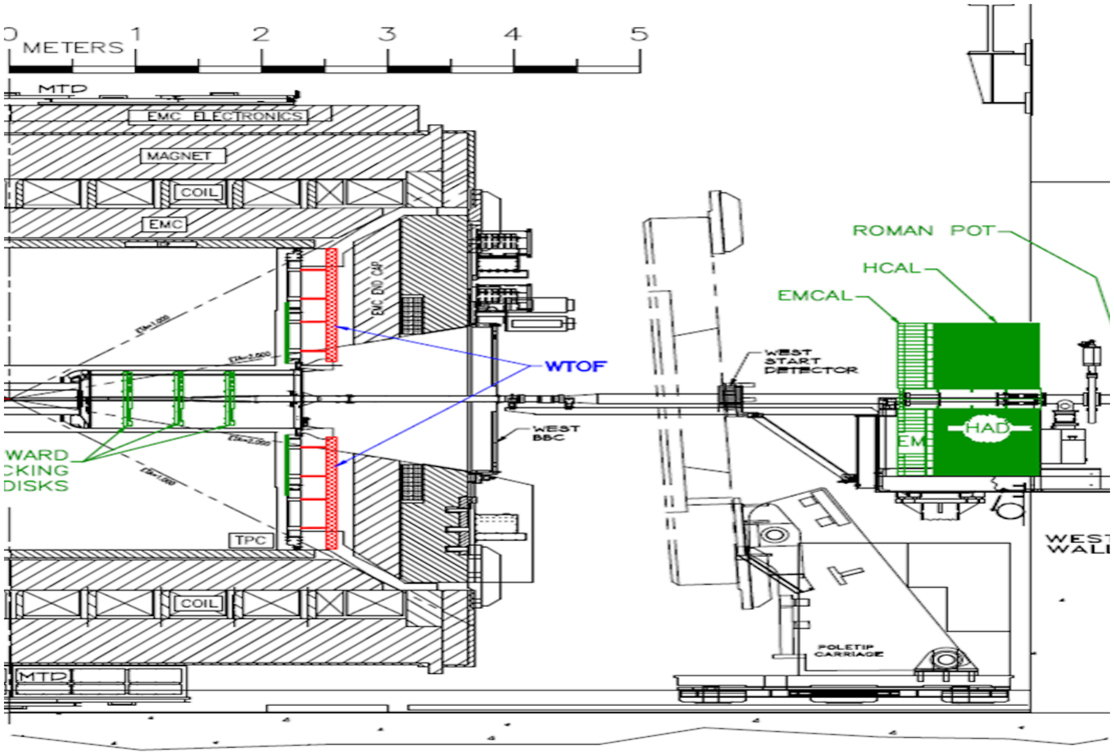


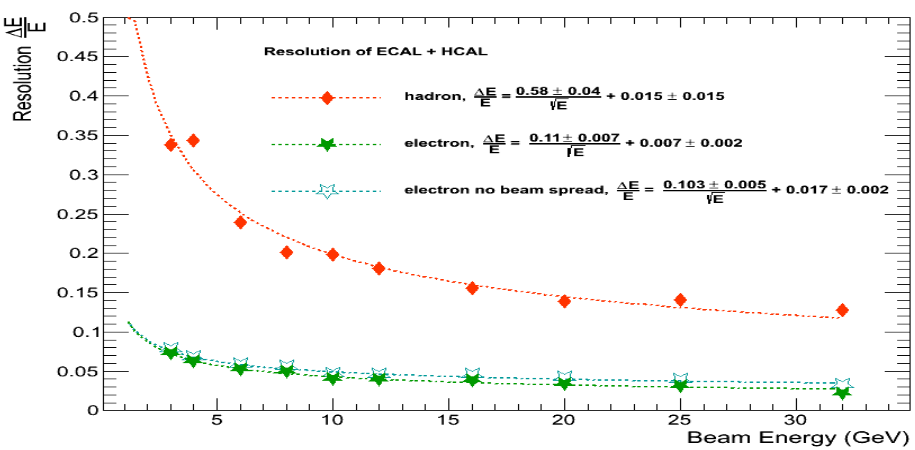


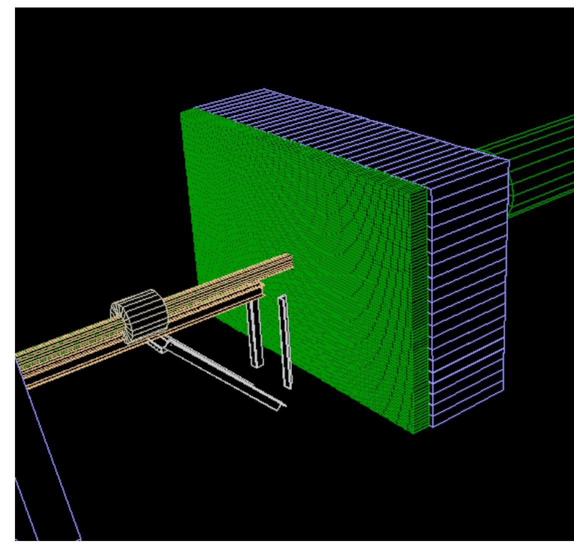
STAR FMS-PreShower:



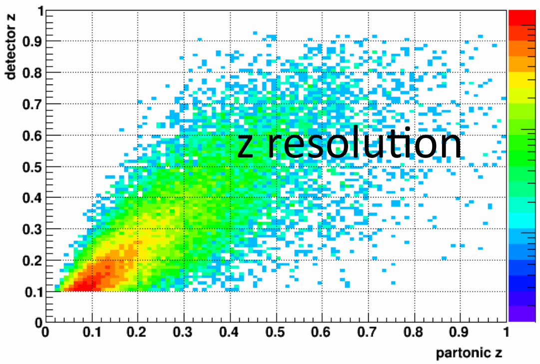
Forward ECAL/HCAL (FCS) ~2020



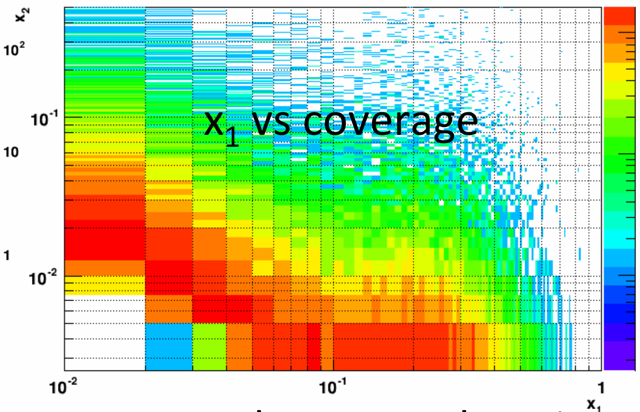




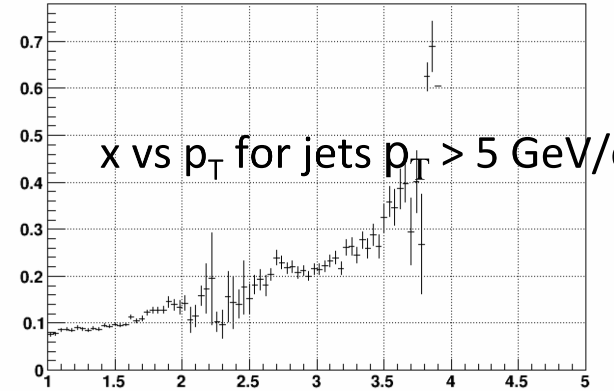
Kinematics covered by Forward Upgrade in p+p (from simulation)



Good z resolution

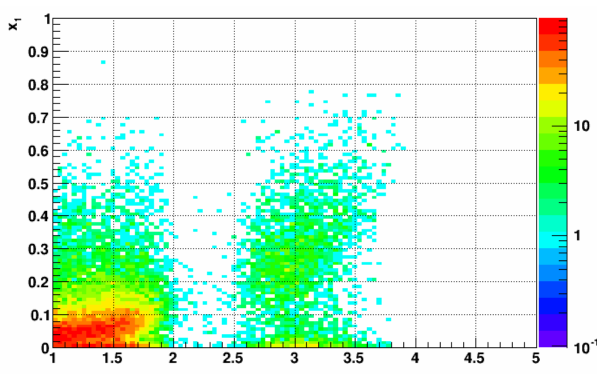


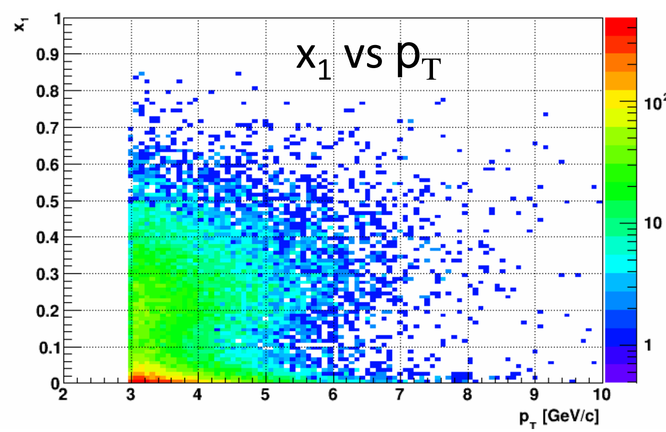
Valence quark region



Select x with p_T/η

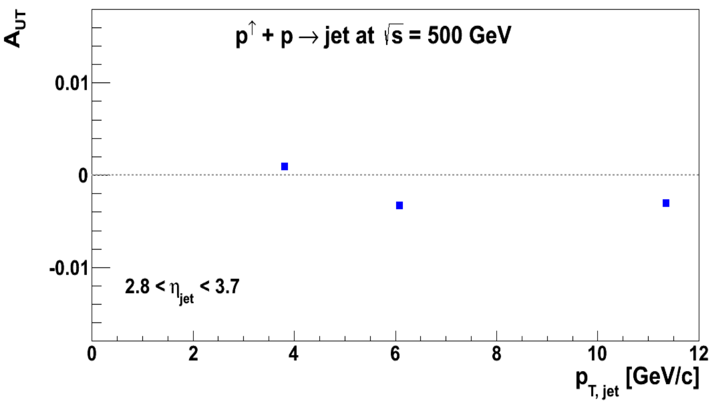
x_1 vs η

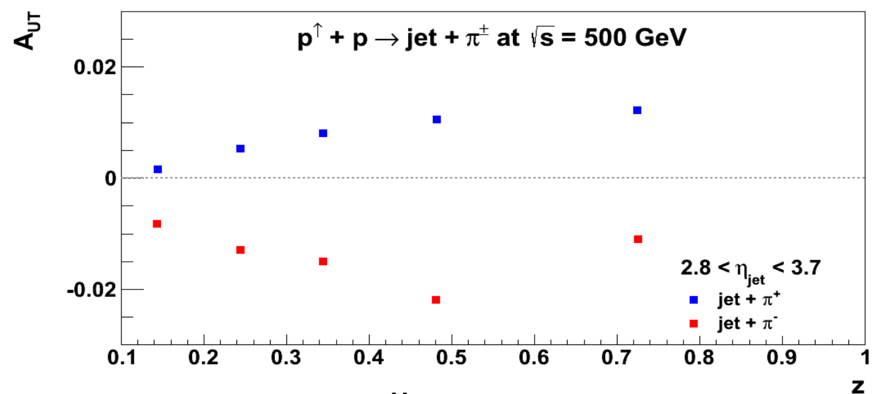




Significant Forward TSSAs Expected

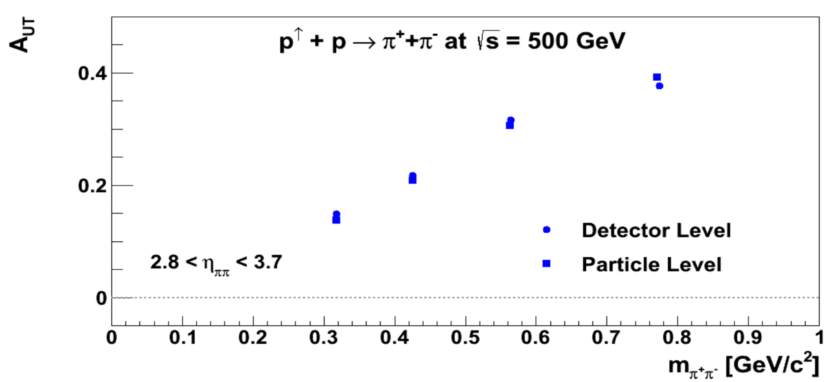
- Torino Parametrization for Sivers/Collins





Collins Asymmetries

Forward Jet
(sensitive to Sivers effect)



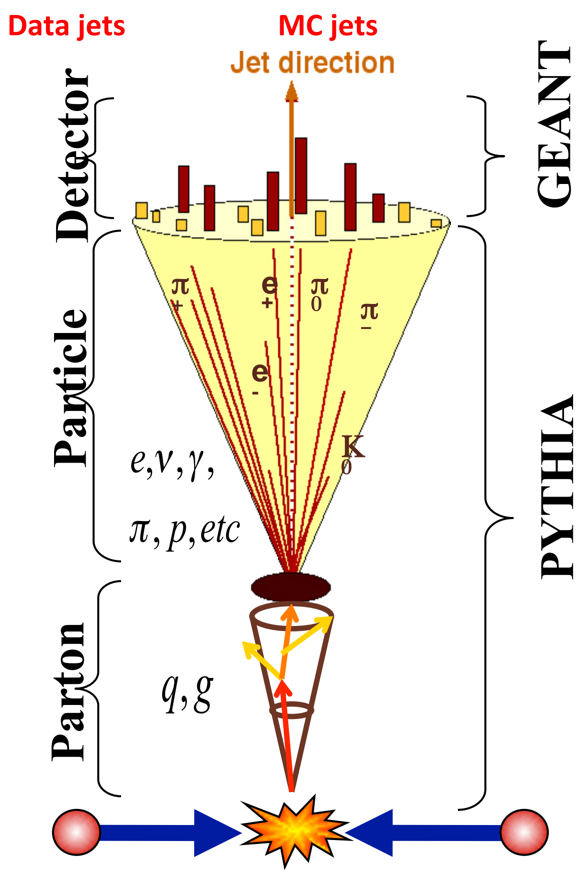
IFF Detector smearing effect

Conclusion

- After exciting longitudinal results, STAR is fulfilling transverse spin promise of RHIC!
- High precision correlation measurements to extract transversity
- Added p+p capabilities:
  - Probing color entanglement effects
  - Origin of largest transverse spin effect seen to date
- Need more theory effort, e.g. IFF predictions, dihadron x-section
- 2015+: Direct photons, pA
- ~2020: Forward jet physics and DY with upgrade
- Look out for new STAR results at SPIN!

Transverse PHYSICS through jets

STAR: Jets reconstructed with Anti-k_t algorithm

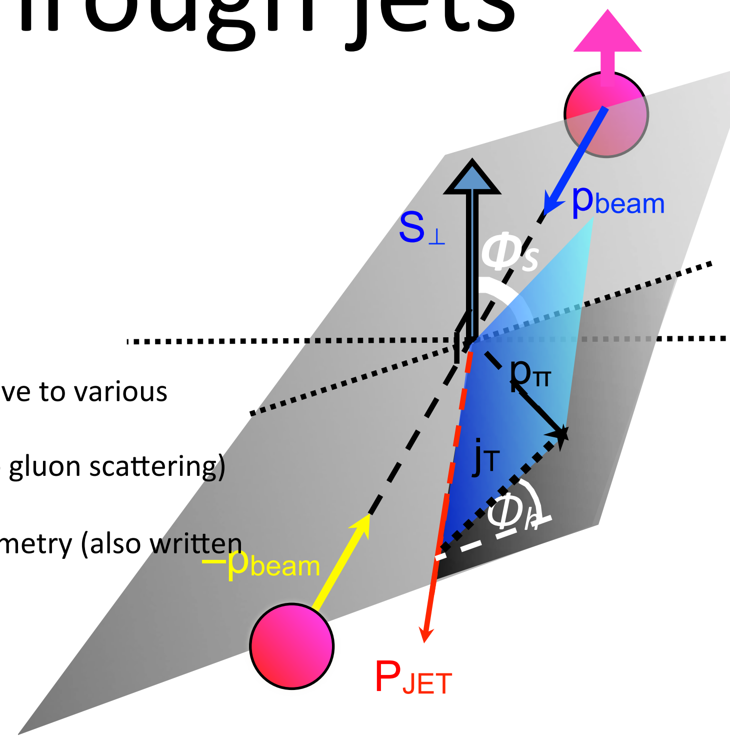


Use PYTHIA + GEANT to quantify detector response

- Trigger Bias (bias for specific processes)
- Reconstruction smearing/bias (unfolding)
- Reconstruction of partonic variables, parton matching
- Underlying event/pileup effects

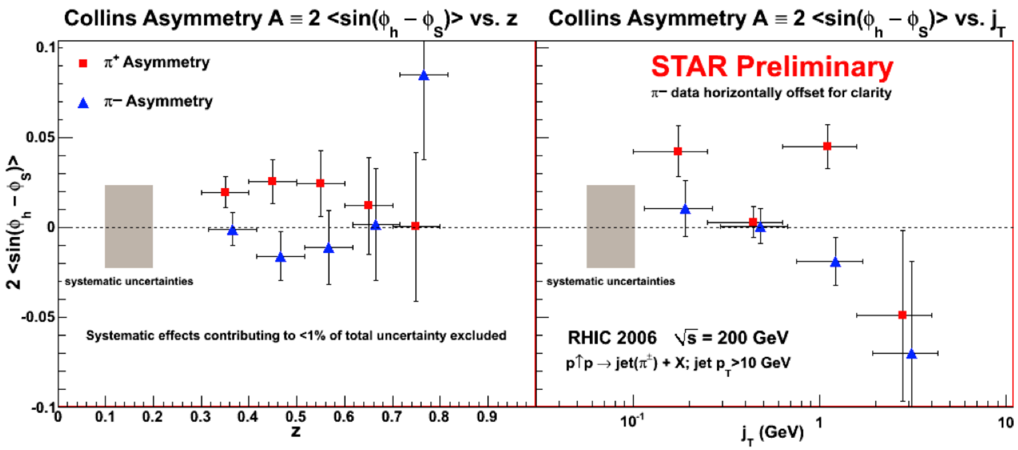
Asymmetry moments sensitive to various contributions
(analogous moments sensitive to gluon scattering)

A_{UT} – Transverse single-spin asymmetry (also written A_N)

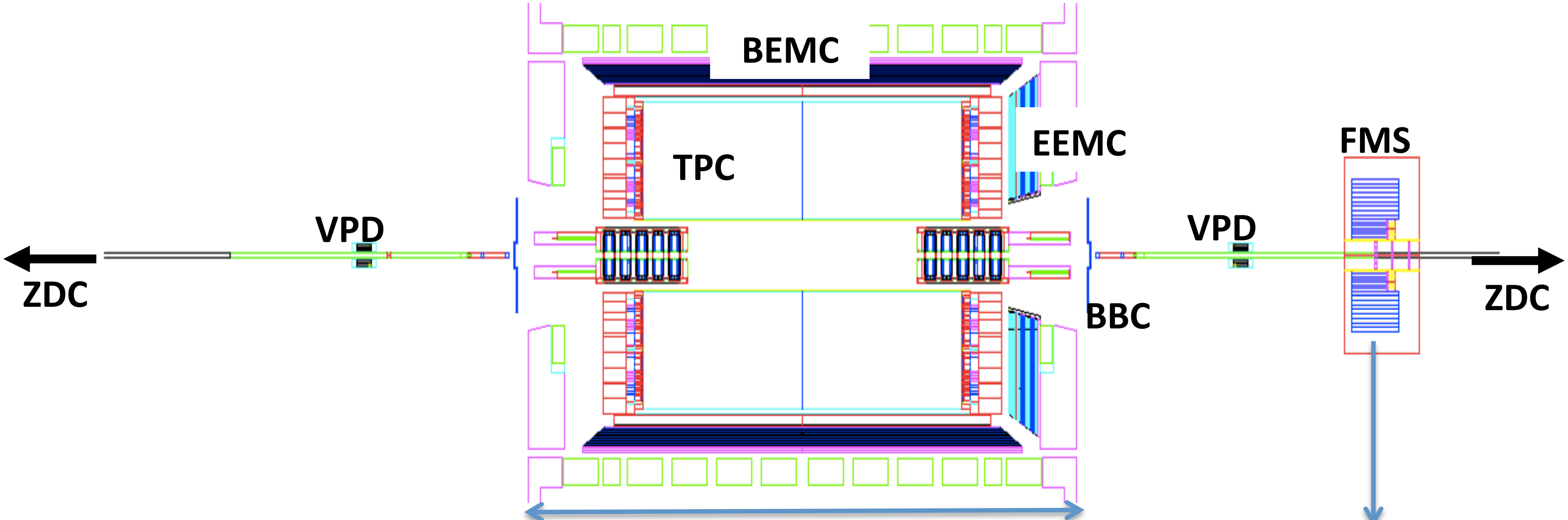


F. Yuan, PRL 100, 032003 (2008)
D'Alesio et al., PRD 83, 034021 (2011)

Terms in Numerator of TMD SSA for qq scattering	English Names	Modulate
$\Delta^N f_{a/A\uparrow} \bullet f_{b/B} \bullet D_{\pi/q}$	Sivers • PDF • FF	$\sin(\varphi_{S_A})$
$h_1^a \bullet \Delta^N f_{b\uparrow/B} \bullet D_{\pi/q}$	Transversity • Boer-Mulders • FF	$\sin(\varphi_{S_A})$
$h_{1T}^{\perp a} \bullet \Delta^N f_{b\uparrow/B} \bullet D_{\pi/q}$	Pretzelocity • Boer-Mulders • FF	$\sin(\varphi_{S_A})$
$h_1^a \bullet f_{b/B} \bullet \Delta D_{\pi/q\uparrow}$	Transversity•PDF •Collins	$\sin(\varphi_{S_A} - \varphi_\pi)$
$\Delta f_{a/A\uparrow}^N \bullet \Delta^N f_{b\uparrow/B} \bullet \Delta D_{\pi/q\uparrow}$	Sivers • Boer-Mulders • Collins	$\sin(\varphi_{S_A} - \varphi_\pi)$
$h_{1T}^{\perp a} \bullet f_{b/B} \bullet \Delta D_{\pi/q\uparrow}$	Pretzelocity•PDF•Collins	$\sin(\varphi_{S_A} + \varphi_\pi)$
$\Delta f_{a/A\uparrow}^N \bullet \Delta^N f_{b\uparrow/B} \bullet \Delta D_{\pi/q\uparrow}$	Sivers•Boer-Mulders•Collins	$\sin(\varphi_{S_A} + \varphi_\pi)$



Collins Asymmetry A ≡ 2 <sin(φh − φS)> vs. z
Collins Asymmetry A ≡ 2 <sin(φh − φS)> vs. jT
π+ Asymmetry
π− Asymmetry
STAR Preliminary
π− data horizontally offset for clarity
systematic uncertainties
systematic uncertainties
Systematic effects contributing to <1% of total uncertainty excluded
RHIC 2006 √s = 200 GeV
p↑p → jet(π±) + X; jet pT>10 GeV
2 <sin(φh − φS)>
z
jT (GeV)



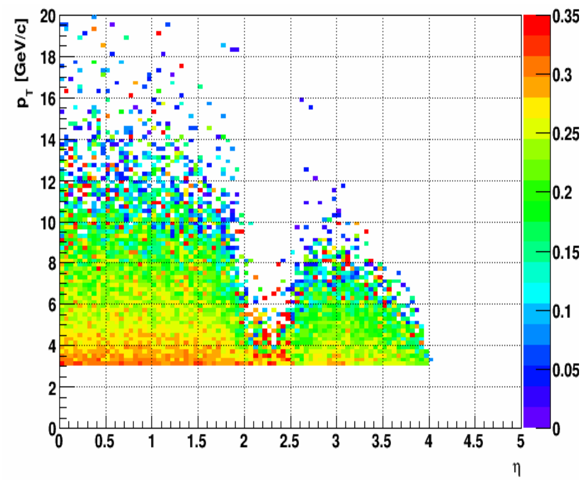
BEMC+EEMC towers : to find central electromagnetic jets

FMS photons : to find forward electromagnetic jets

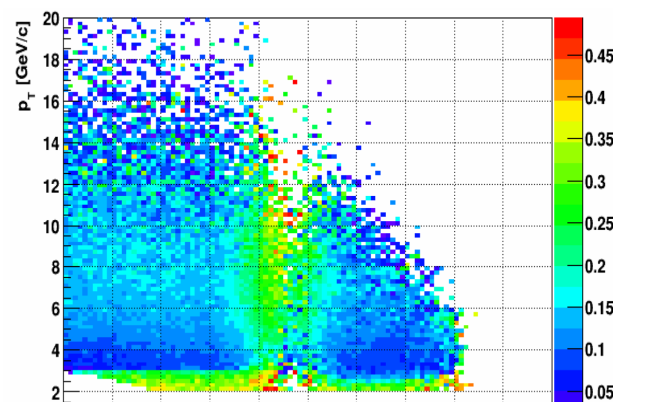
FMS photon reconstruction :

towers → clusters → photon

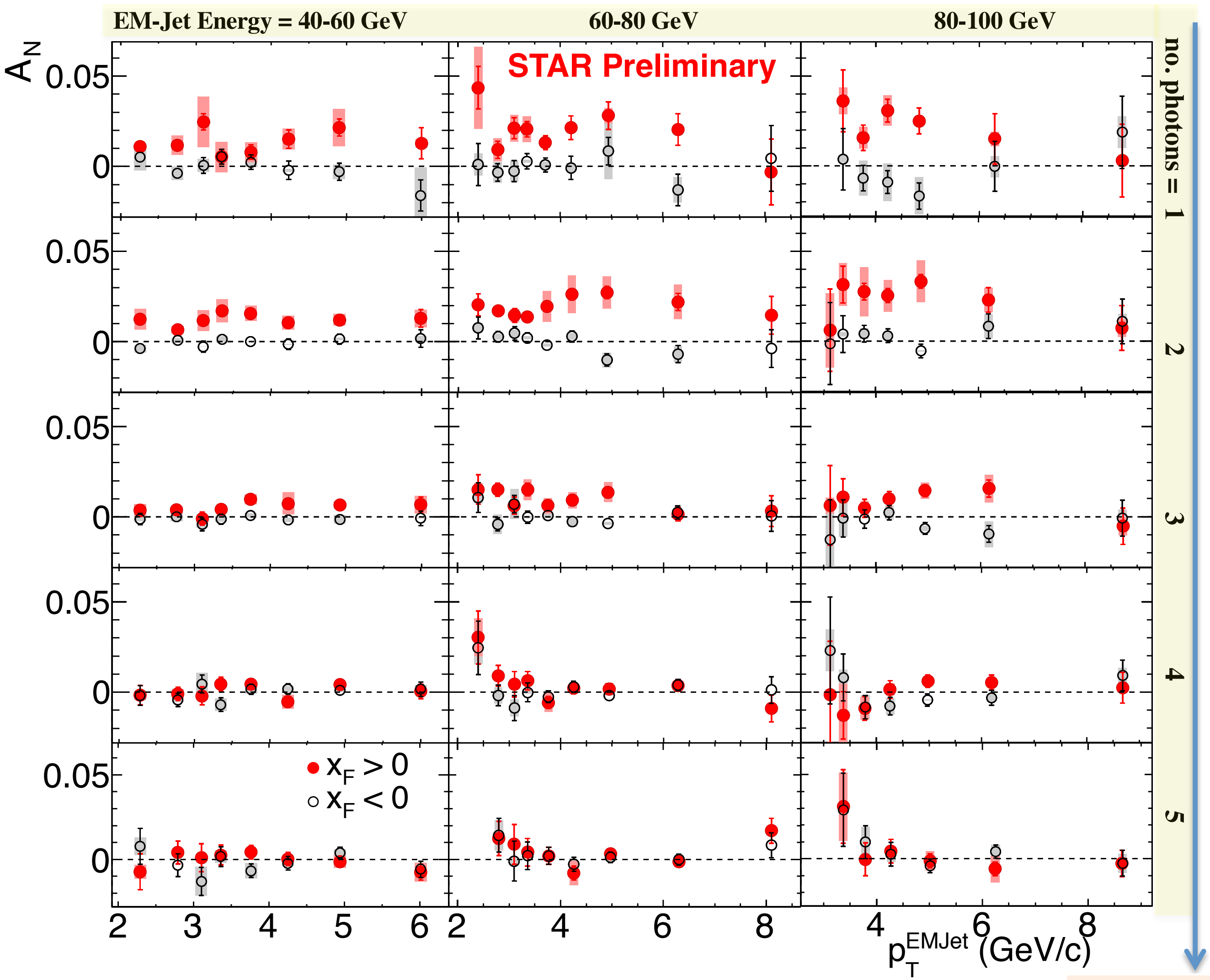
shower shape fitting



p_T [GeV/c]
0
2
4
6
8
10
12
14
16
18
20
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
η
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35



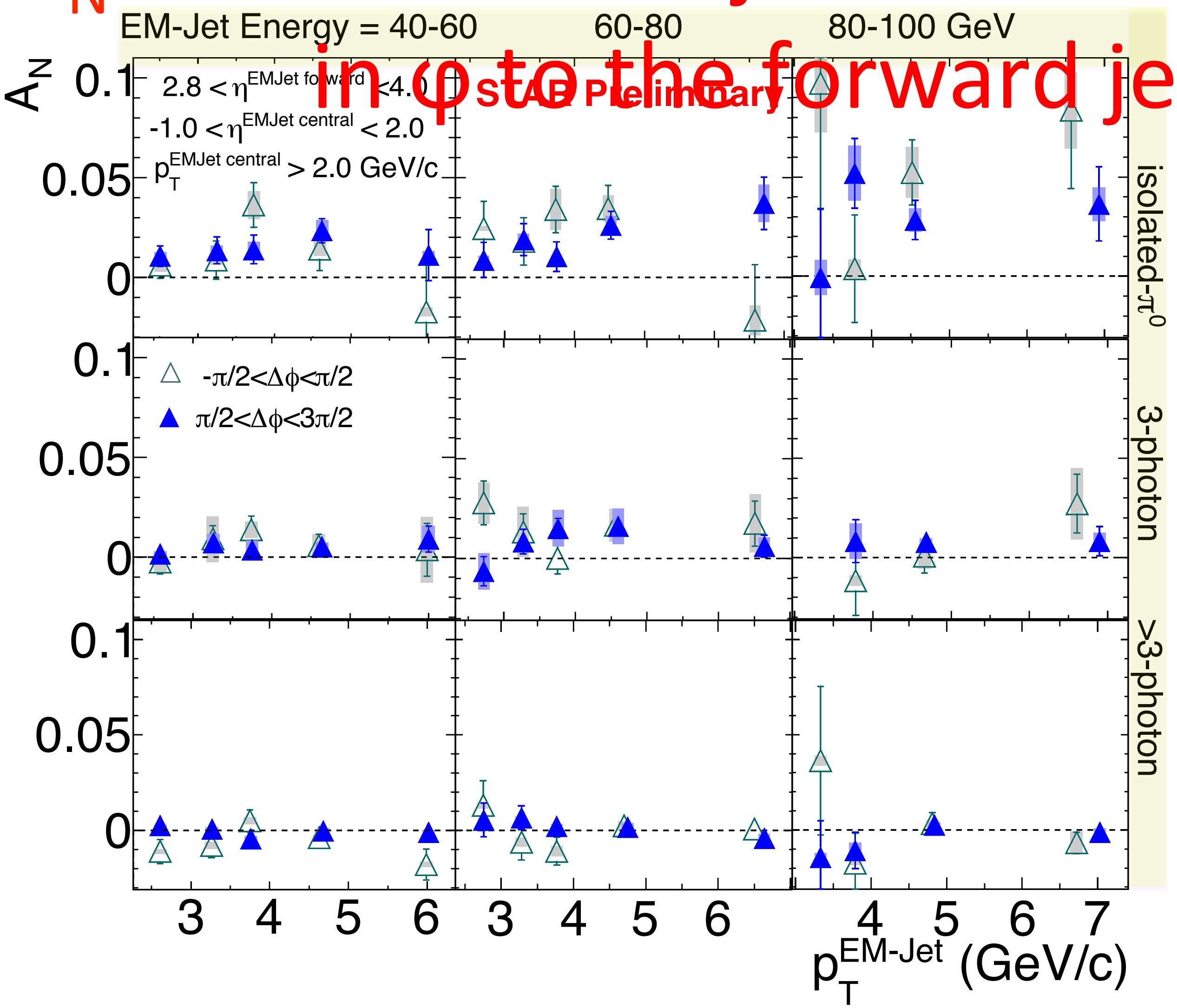
p_T [GeV/c]
2
4
6
8
10
12
14
16
18
20
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45



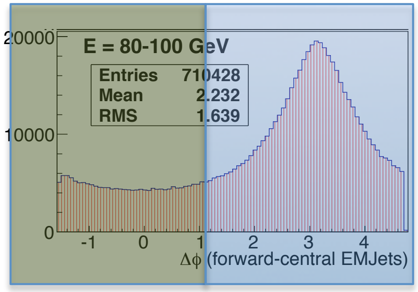
- ✧ 1-photon events, which include a large π^0 contribution in this analysis, are similar to 2-photon events
- ✧ Three-photon jet-like events have a clear non-zero asymmetry, but substantially smaller than that for isolated π^0's
- ✧ A_N decreases as the event complexity increases (i.e., the "jettiness")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

Jettier events

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



Near and away side



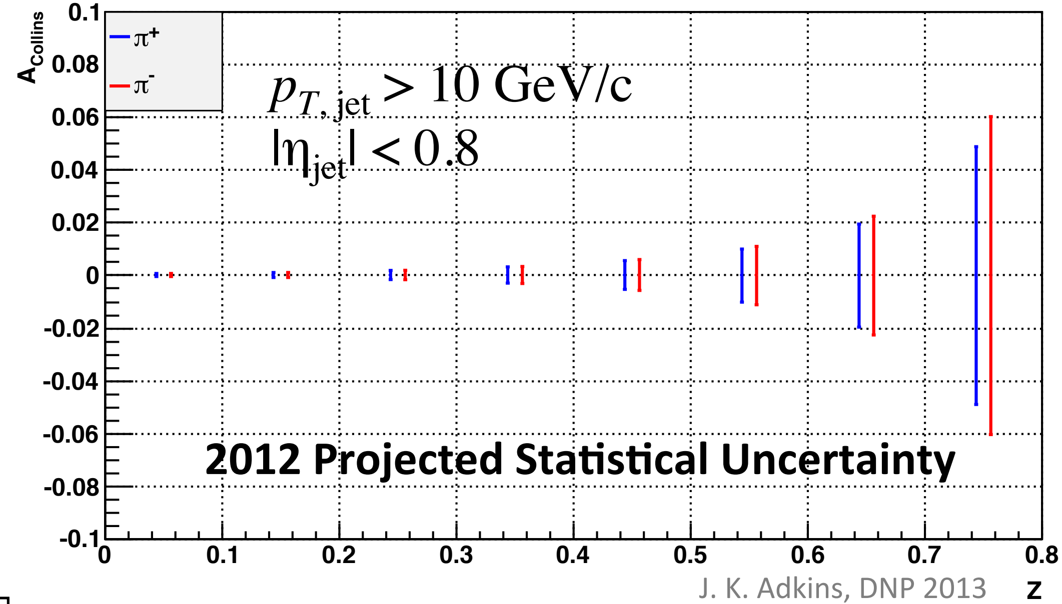
Uncorrelated central EM-Jet

Correlated central EM-Jet

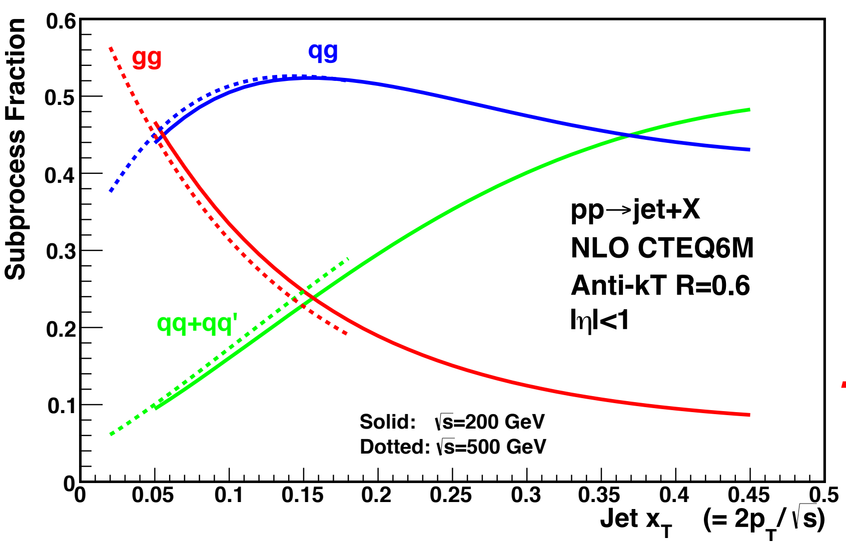
✧ Uncorrelated central EM-Jet is separated out

STAR Transverse Asymmetries from Jet Production

2012 STAR data provide opportunity for ***higher precision*** *and* ***greatly reduced systematic uncertainties*** *at* $\sqrt{s} = 200$ *GeV* ***analysis well underway***



J. K. Adkins, DNP 2013



2011 STAR data provide opportunity for first measurements of **central pseudorapidity inclusive jet asymmetries at $\sqrt{s} = 500$ GeV**

→ ***Increased sensitivity to gluonic subprocesses***