Experimental Results and Future Plans on Spin Physics at STAR

Outline
- RHIC and STAR
- STAR Spin Results
- STAR Forward Upgrade

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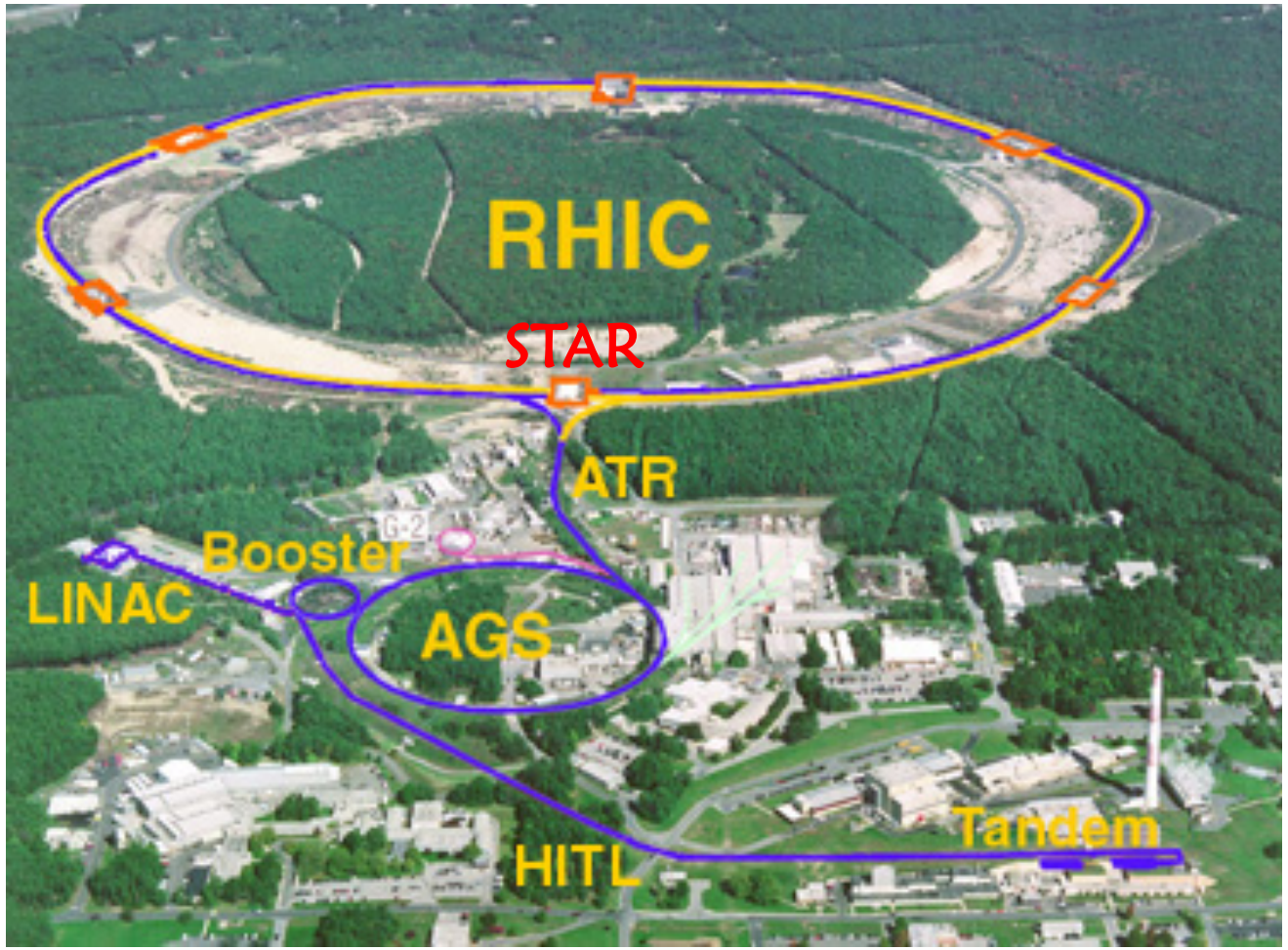
Brookhaven National Laboratory

PacificSpin2019, 2019 Aug 27-30, Miyazaki, Japan

The Relativistic Heavy Ion Collider

BROOKHAVEN NATIONAL LABORATORY



Au+Au
(other light to heavy ions)

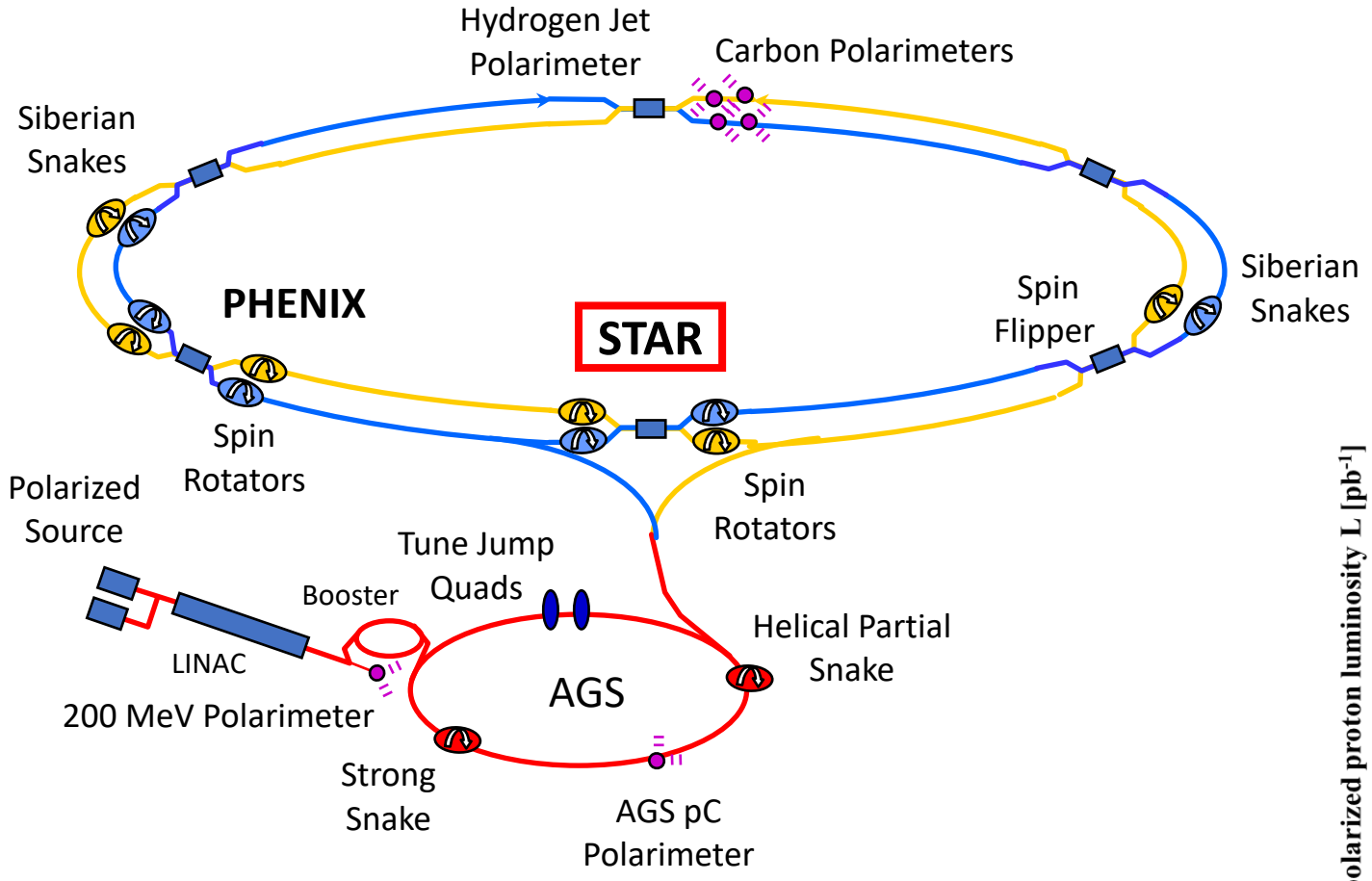
Polarized p+p

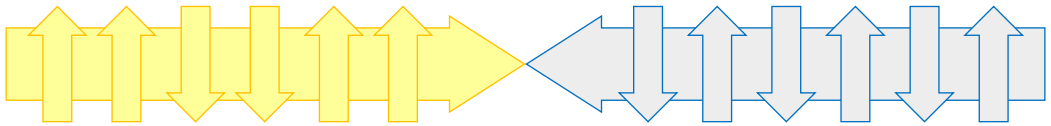
d+Au

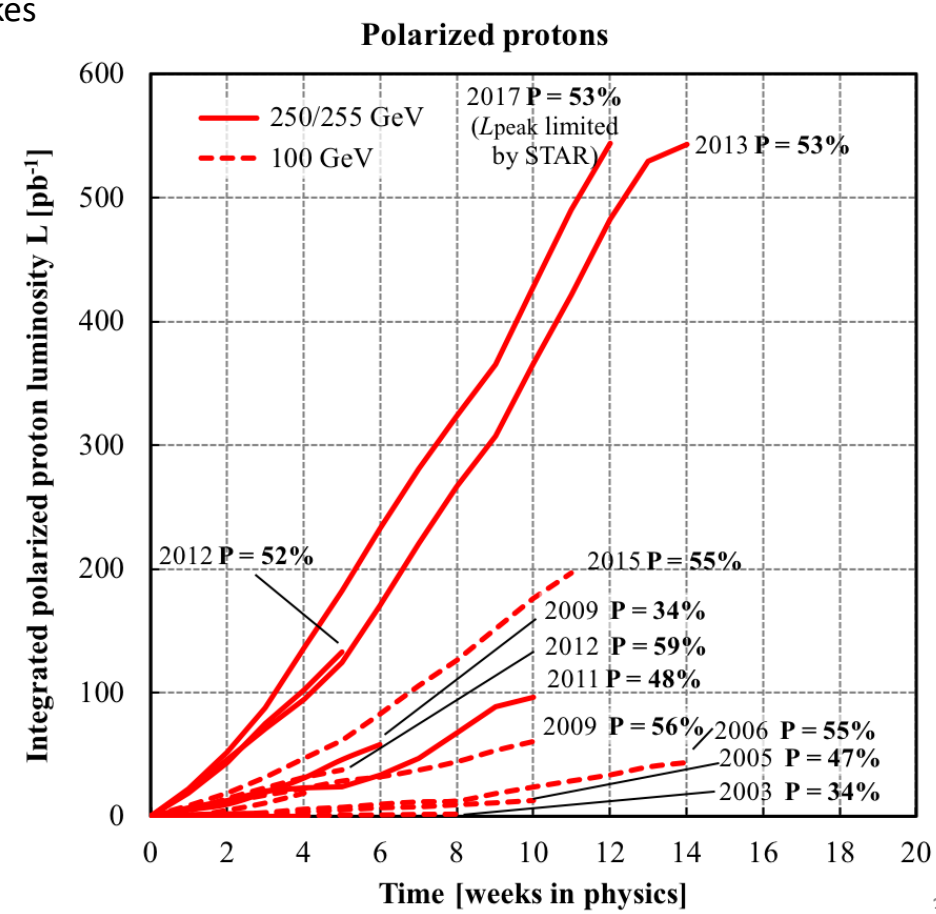
Polarized p + Au/Al

RHIC is a QCD lab

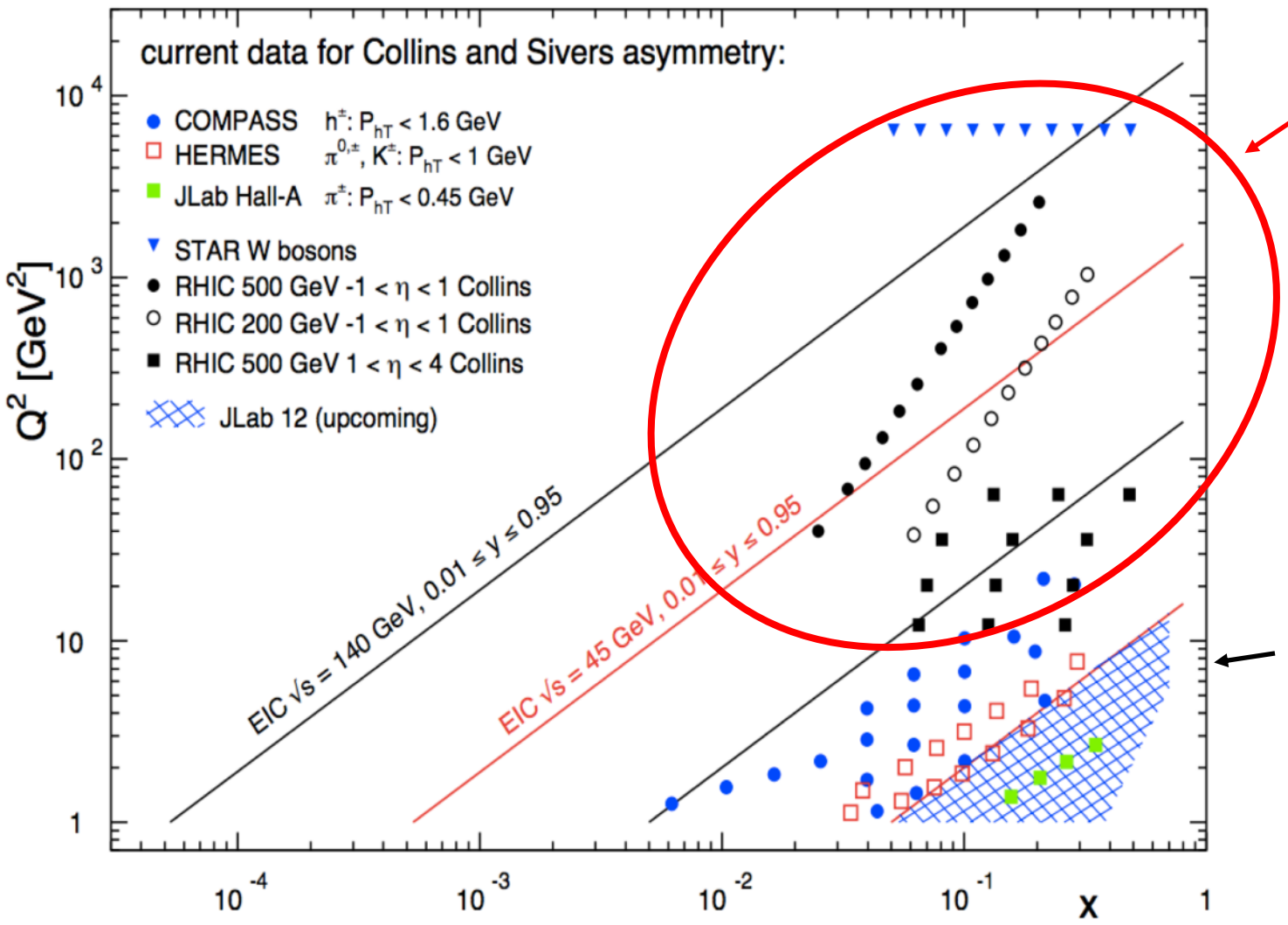
RHIC as a Polarized Proton Collider







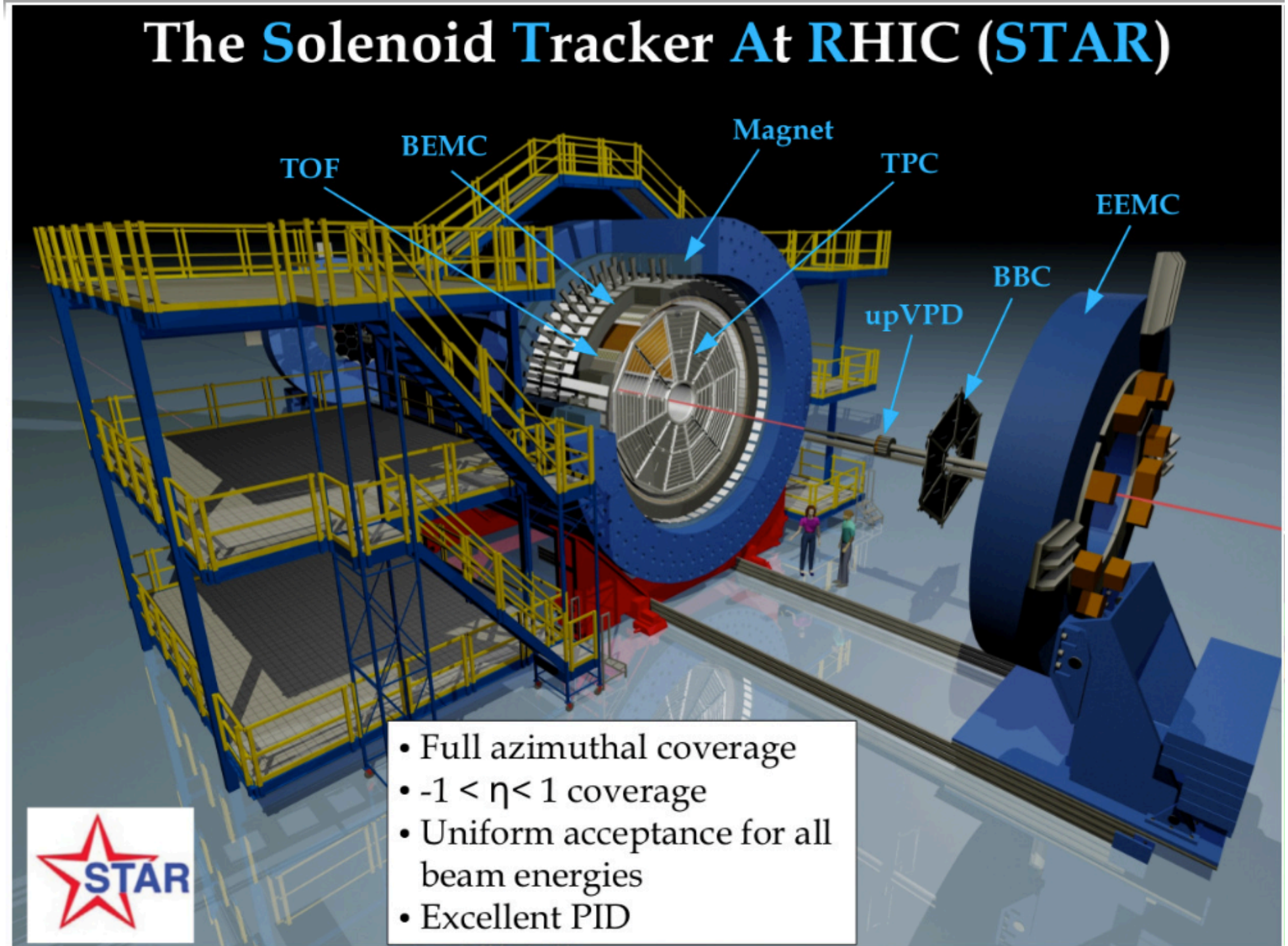
World Polarized Data



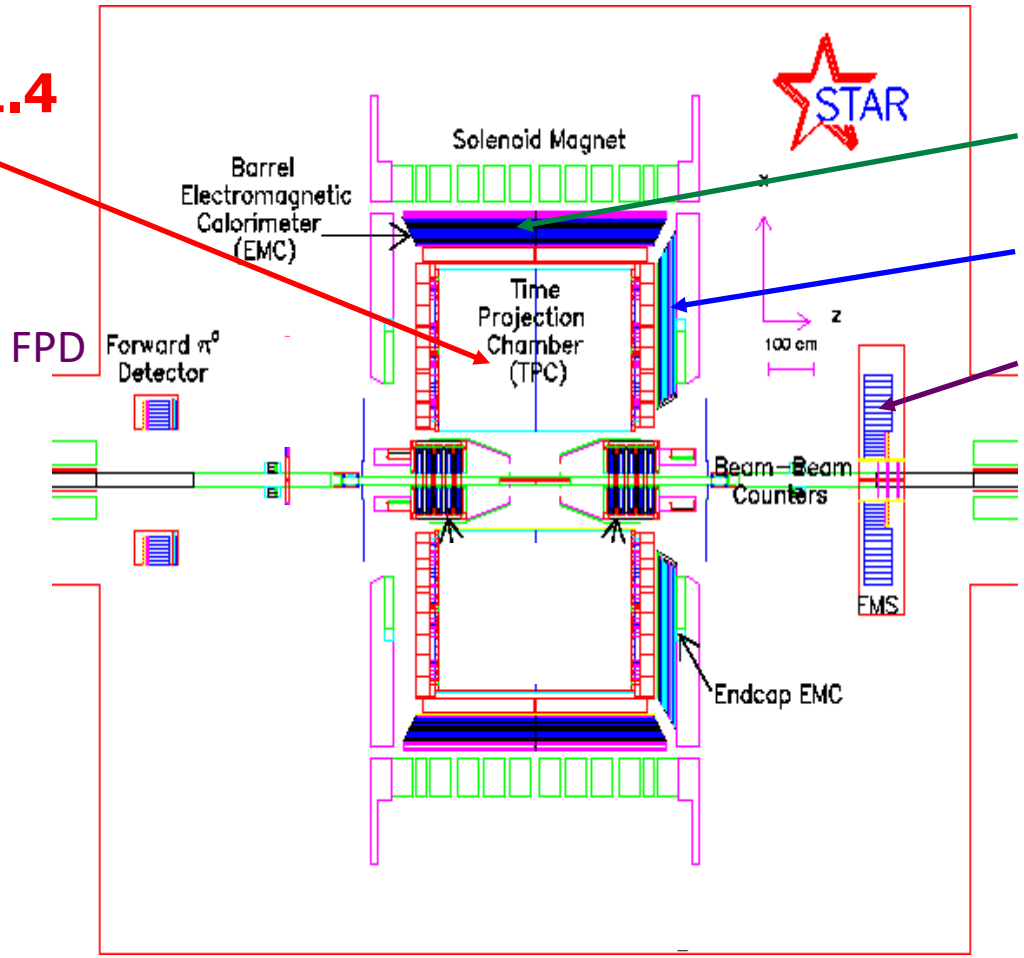
RHIC uses QCD probes
→ Directly access gluon

RHIC reaches higher Q^2
→ QCD evolution
(before EIC)
→ W/Z production
flavor separation

Complementary to DIS
→ Factorization
→ Universality


The Solenoid Tracker At RHIC (STAR)
TOF
BEMC
Magnet
TPC
EEMC
BBC
upVPD
• Full azimuthal coverage
• -1 < η< 1 coverage
• Uniform acceptance for all beam energies
• Excellent PID
STAR

STAR Detector



TPC: -1.4 < η < 1.4

BEMC: -1.0 < η < 1.0

EEMC: 1.0 < η < 2.0

FMS: 2.5 < η < 4.2

Zero Degree Calorimeter
+ RHICf
Roman Pot

Mid Rapidity : Charged particles & EM Calorimeter → Jets & W

Forward Rapidity : EM Calorimeters → π^0 & photon & DY

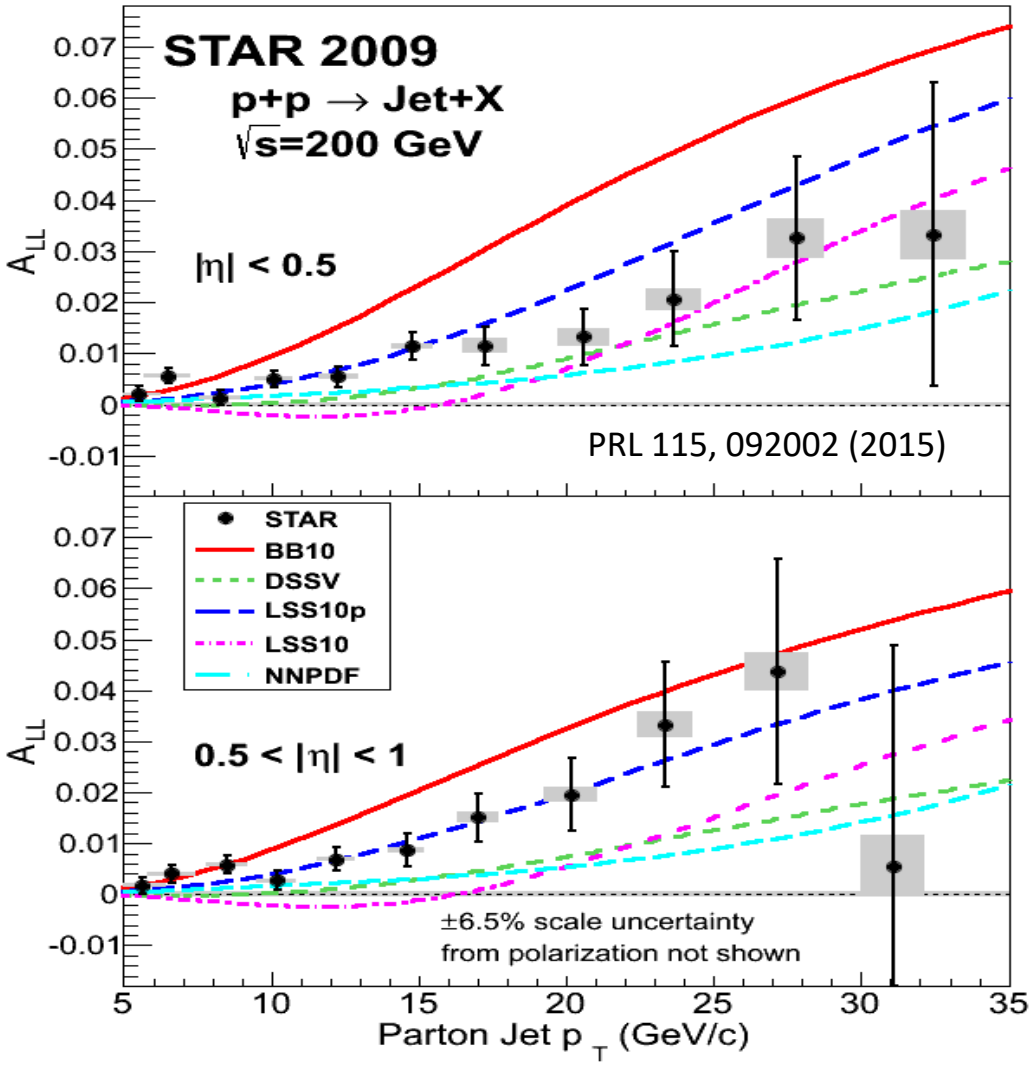
STAR Spin Program

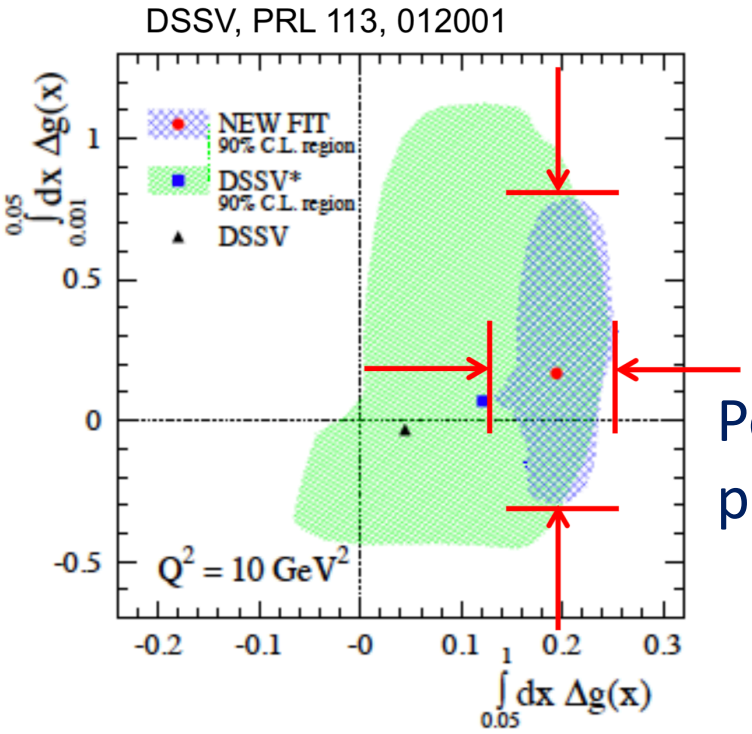
Mid Rapidity TPC BEMC EEMC	Jet Di-Jet	σ High-x gluon density	
		A_{LL} Gluon Spin	← 1
		A_N Collins	← 3
		A_N IFF	←
	W,Z	σ $\bar{d}/\bar{u}$	← 2
		A_L Sea Quark Spin	←
		A_N Sivers	←
Forward Rapidity EEMC FMS	π^0, η, EM-Jet (Photon, DY)	A_{LL} Gluon Spin	3
		A_N Twist-3, Collins, Sivers	←
Zero Degree Roman-Pot RHICf	Proton pi0	Elastic and Diffraction	→ See RHICf talk

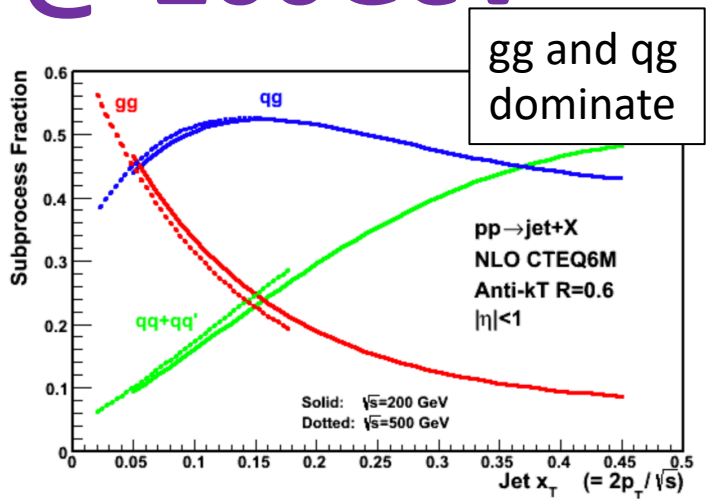
Wide range of physics with longitudinal and transverse polarization (and unpol)

Gluon Spin from A_{LL} : p+p →Jet+X @ 200GeV

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \propto \frac{\Delta f_a \Delta f_b}{f_a f_b} \hat{a}_{LL}$$







Positive Gluon polarization at x>0.05

$$\int_{0.05}^{1} \Delta g(x)dx = 0.23 \pm 0.06 \text{ (NNPDF)}$$

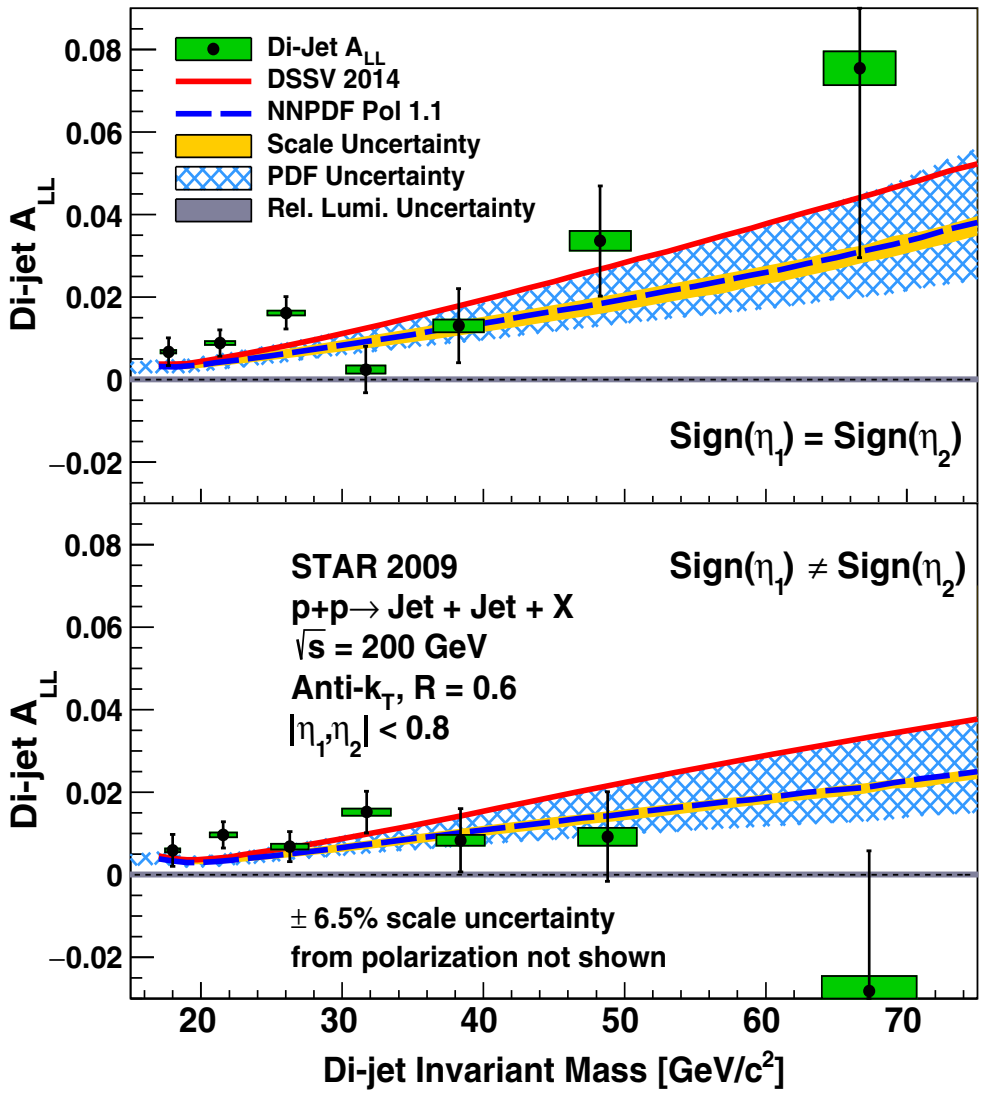
$$\int_{0.05}^{1} \Delta g(x)dx = 0.20^{+0.06}_{-0.07} \text{ (DSSV)}$$

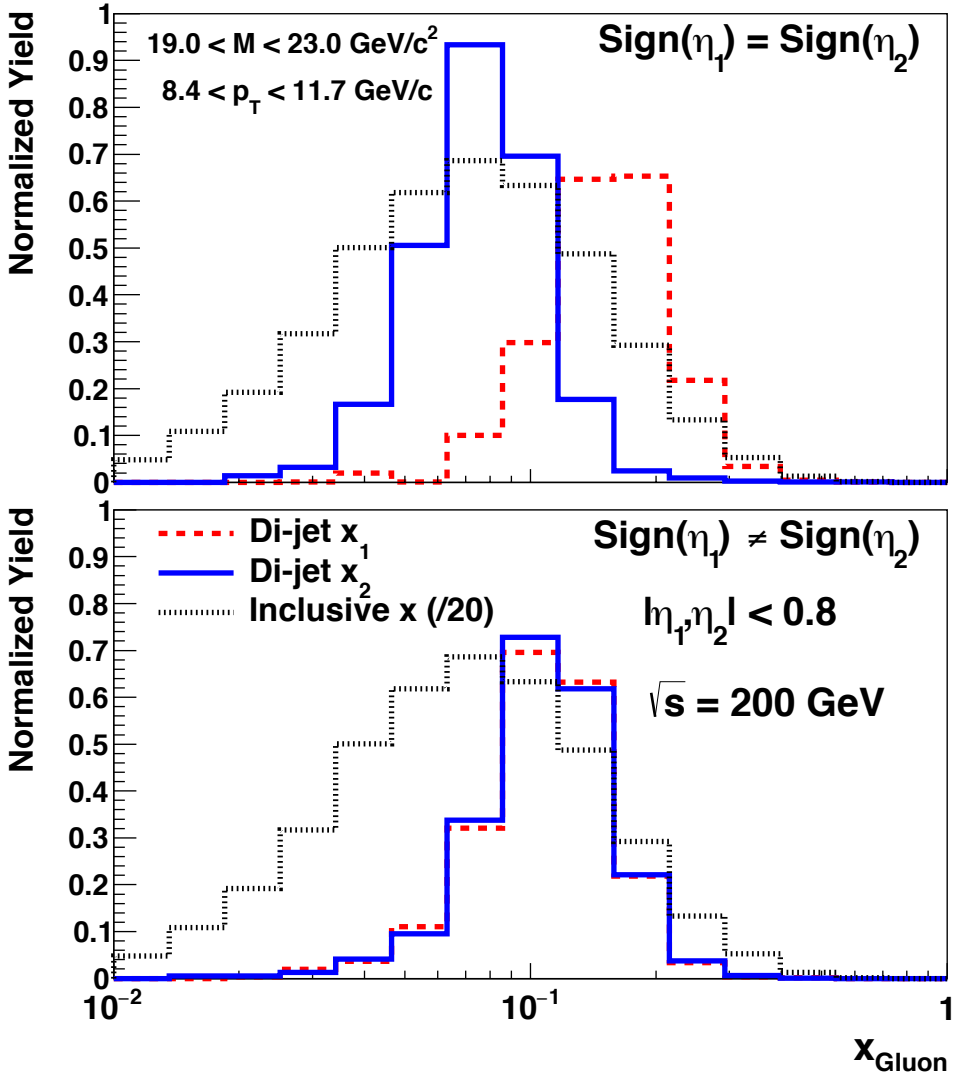
Still large uncertainty at low x

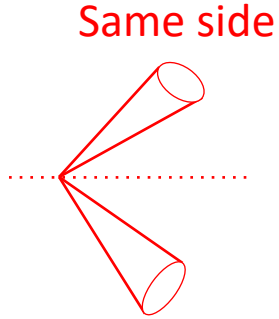
→ Di-Jet, Forward, higher sqrt(s)

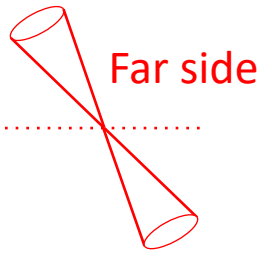
Gluon Spin from A_{LL} : p+p →Jet+Jet+X

Phys.Rev. D95, 071103 (2017)



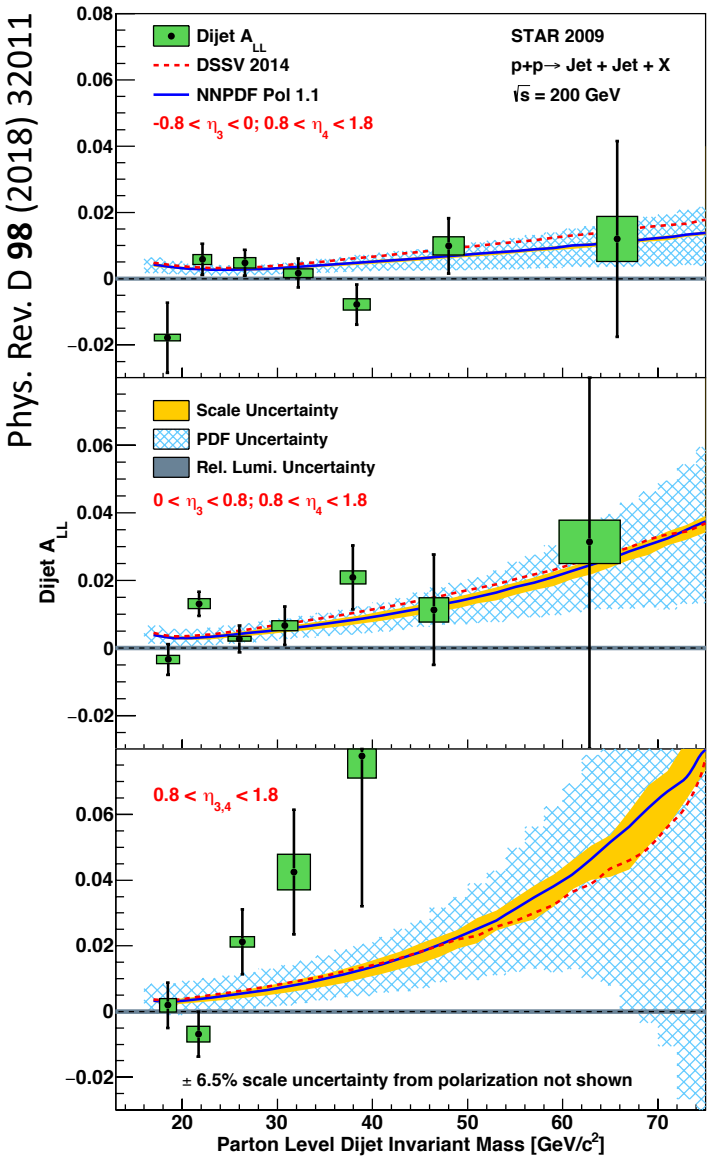


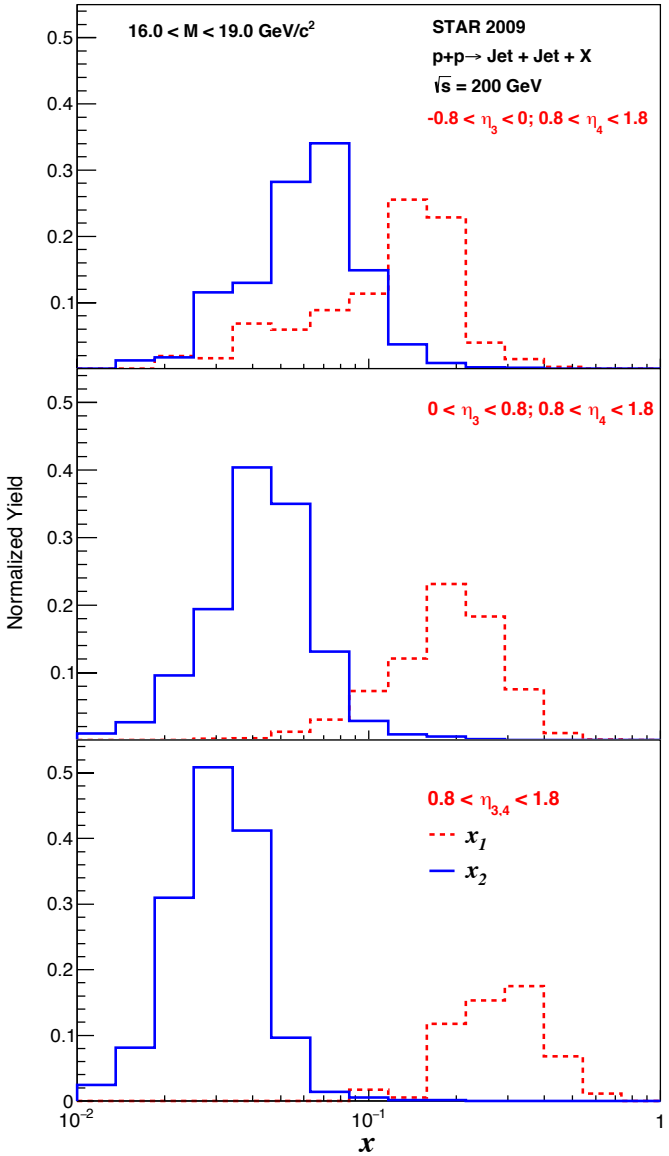


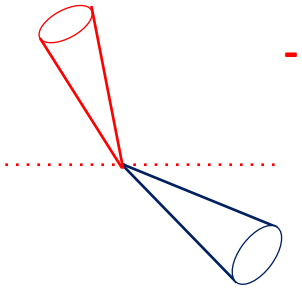


Di-Jet measures narrower range of x → shape of $\Delta G(x)$

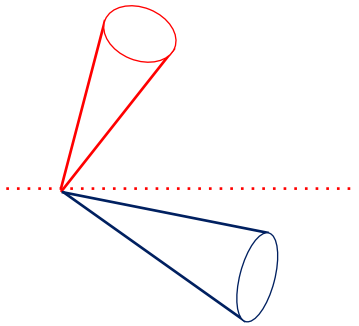
Gluon Spin from A_{LL} : p+p →Jet+Jet+X @ Endcap EMC







- 0.8 < η < 0.0
0.8 < η < 1.8



0.0 < η < 0.8
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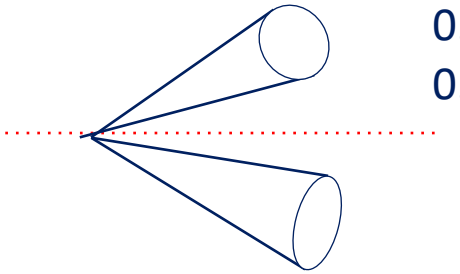
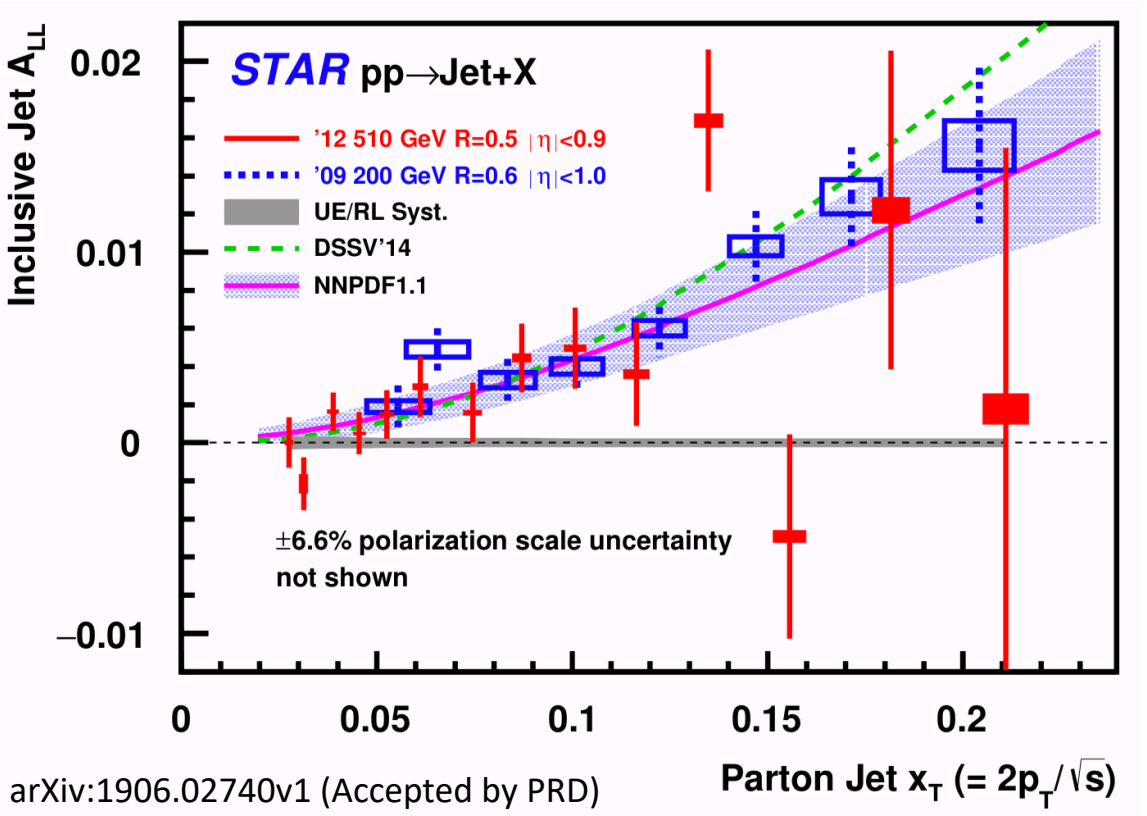


0.8 < η < 1.8
0.8 < η < 1.8

Forward jet at EEMC pushes to lower gluon x, with quark at higher x (with higher polarization)

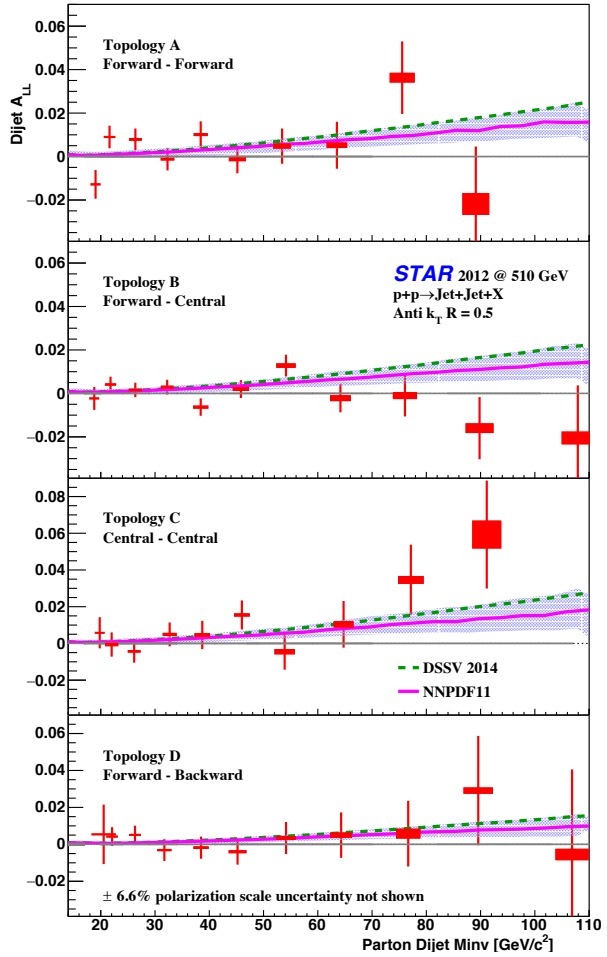
Gluon Spin from A_{LL} : Jet & Di-Jet @ 510GeV

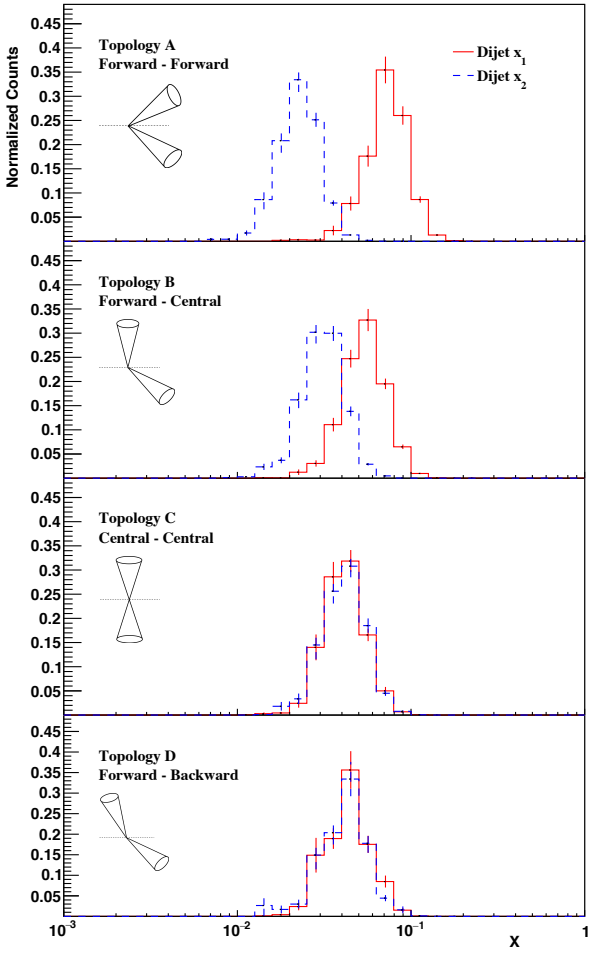
INCLUSIVE JET



arXiv:1906.02740v1 (Accepted by PRD)

DI-JET





510GeV data provide better accuracy at lower x_T (at same p_T)

W/Z measurement at STAR

W's naturally separate quark flavor
→ rapidity: sea vs. valence quarks

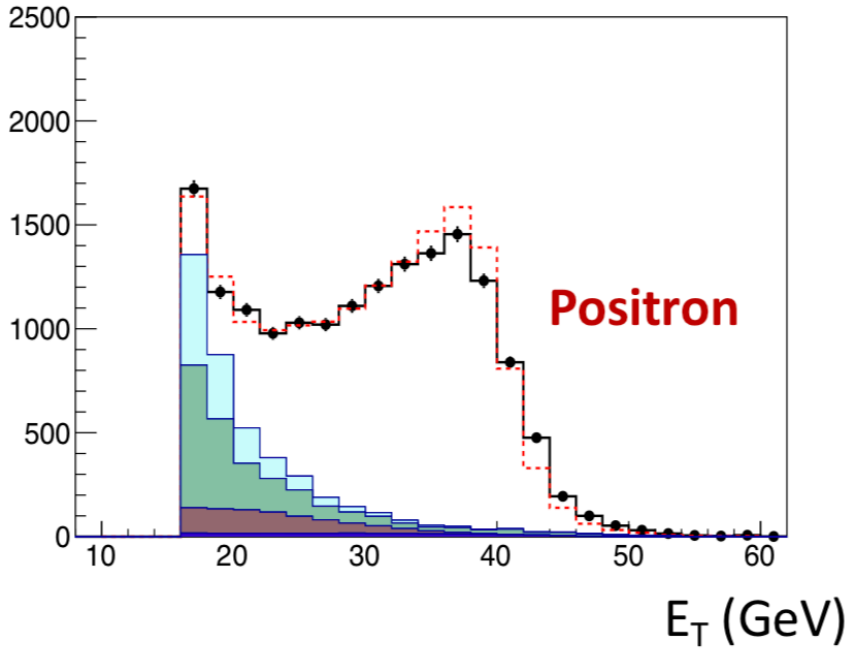
$u\bar{d} \rightarrow W^+$

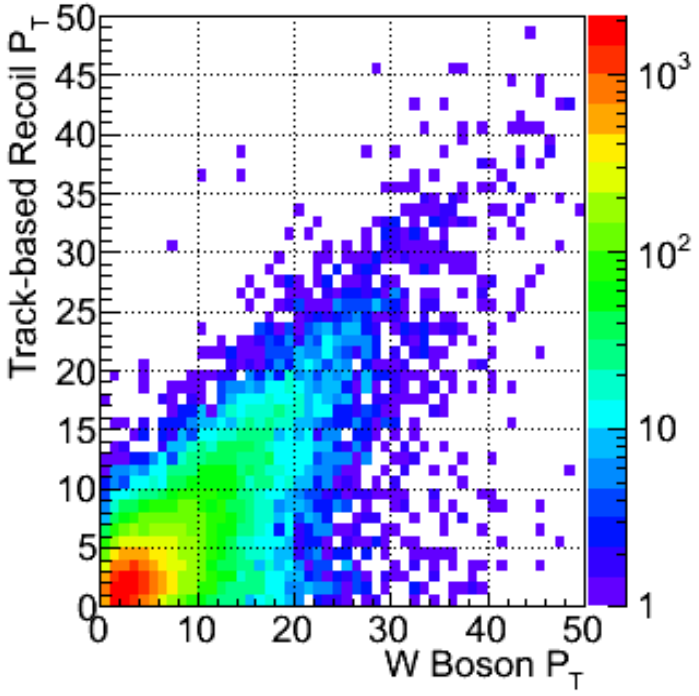
$d\bar{u} \rightarrow W^-$

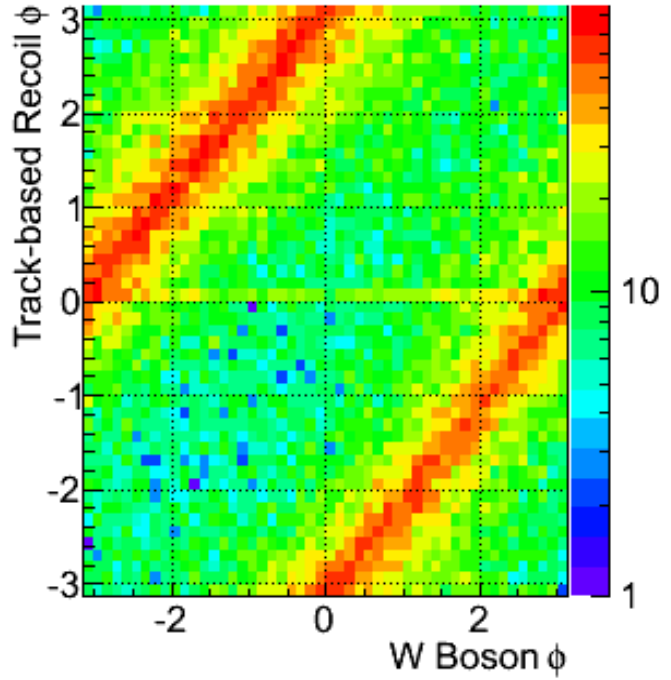
W's are maximally parity violating
→ W's couple only to one parton helicity

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

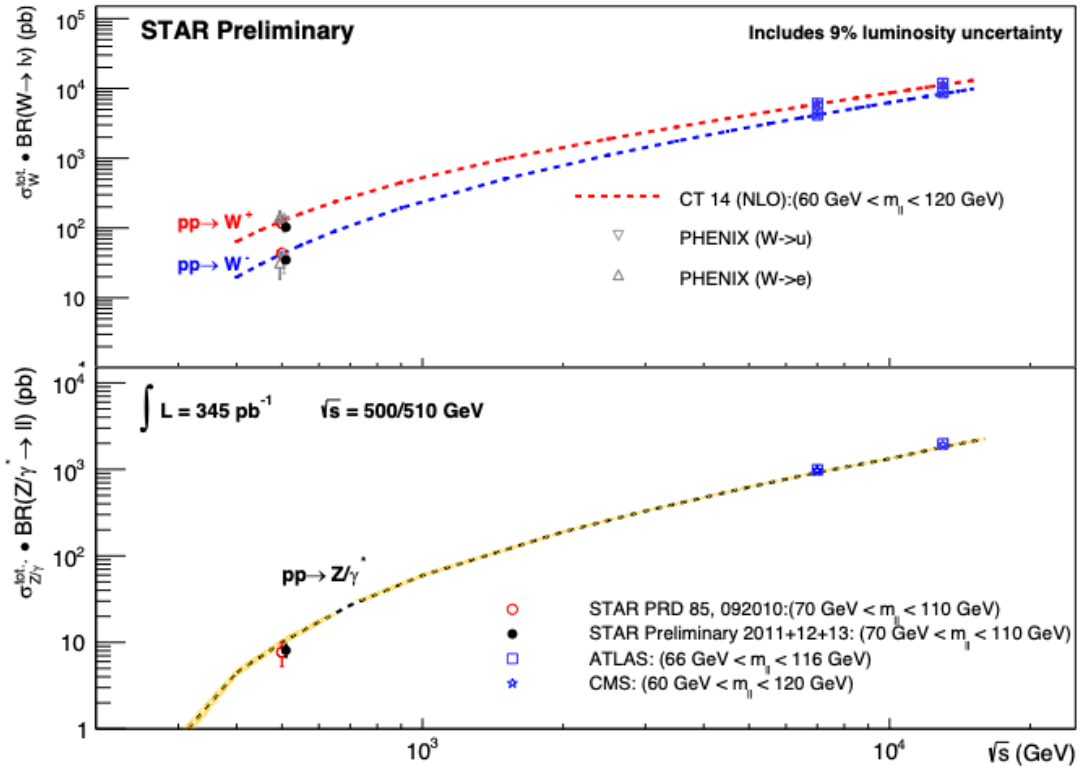
Measuring Recoil to reconstruct W kinematics



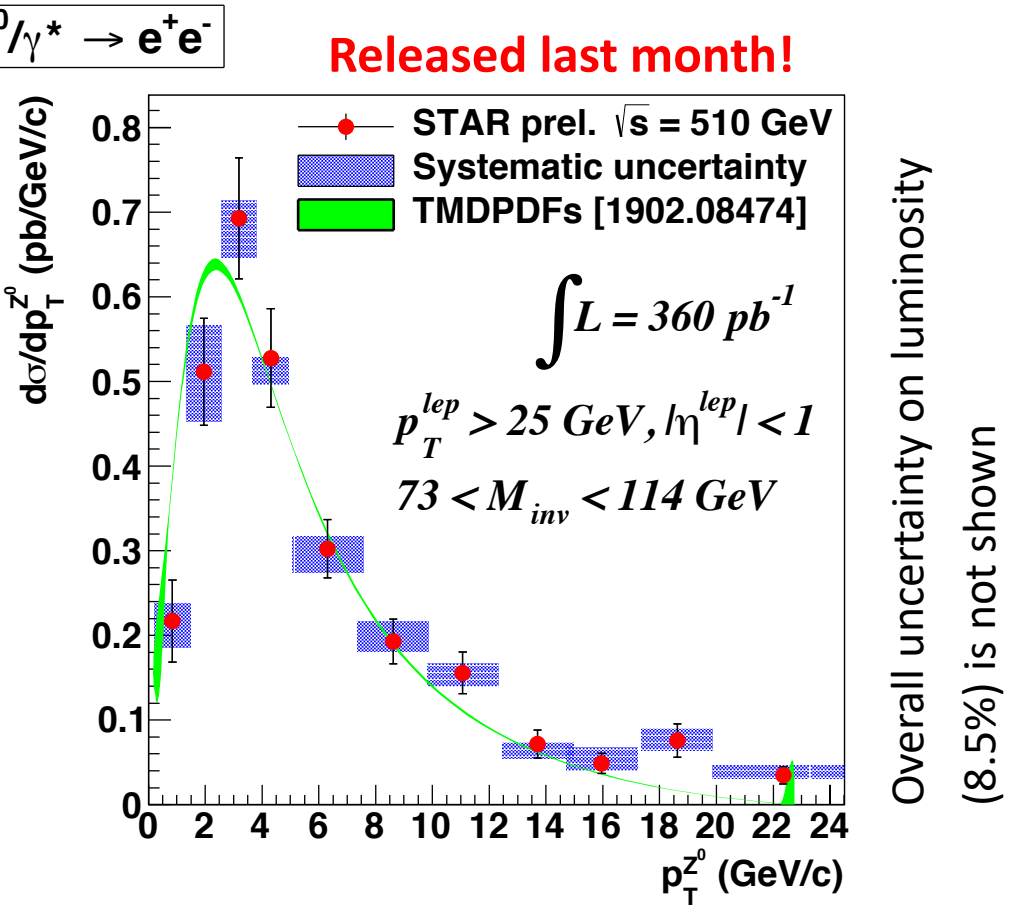




$W^{+/-}$ and Z^0 cross sections



STAR data agree with theoretical prediction which also describe LHC data



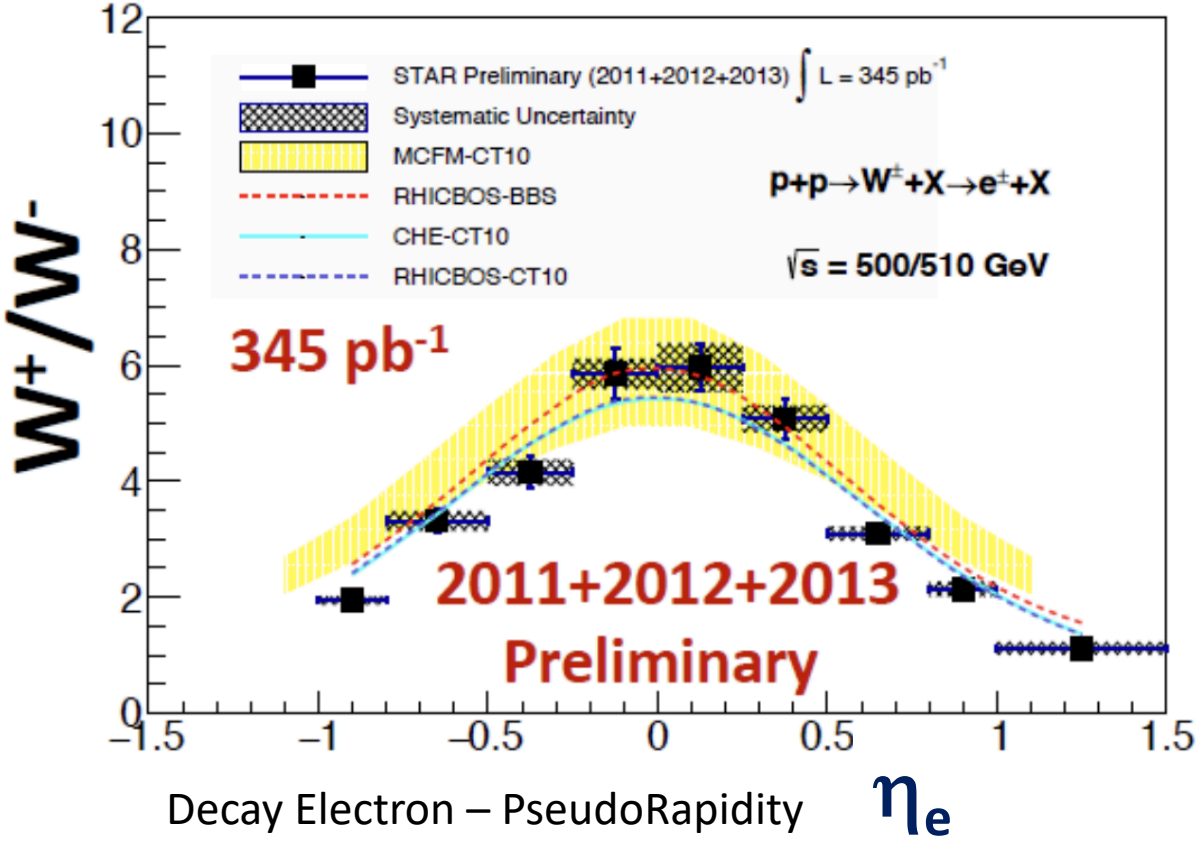
Overall uncertainty on luminosity (8.5%) is not shown

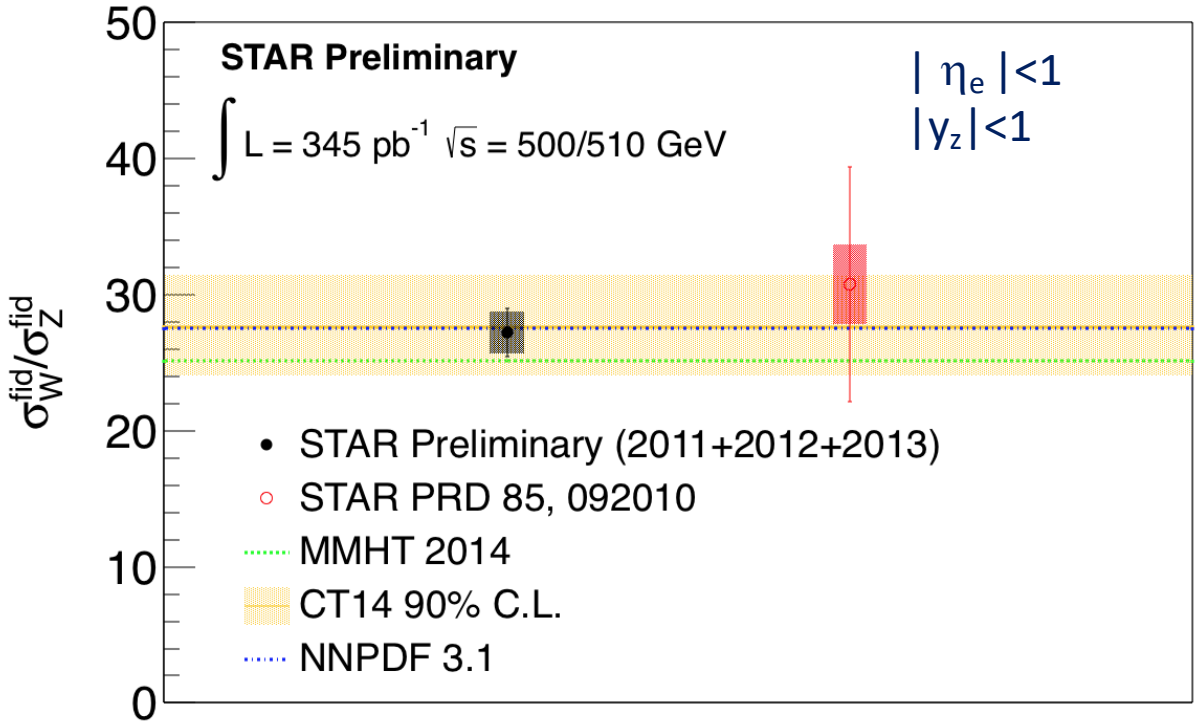
2017 data (~350/pb @ 510GeV) will double the statistics of 2011+12+13 data

$W^{+/-}$ and Z^0 cross section ratios

$$\frac{\sigma_{W^+}}{\sigma_{W^-}} \approx \frac{u(x_1)\,\bar{d}(x_2) + u(x_2)\bar{d}(x_1)}{d(x_1)\bar{u}(x_2) + d(x_2)\bar{u}(x_1)} \rightarrow \bar{d}\,/\,\bar{u}$$

Measurement vs W rapidity is also available using recoil measurement





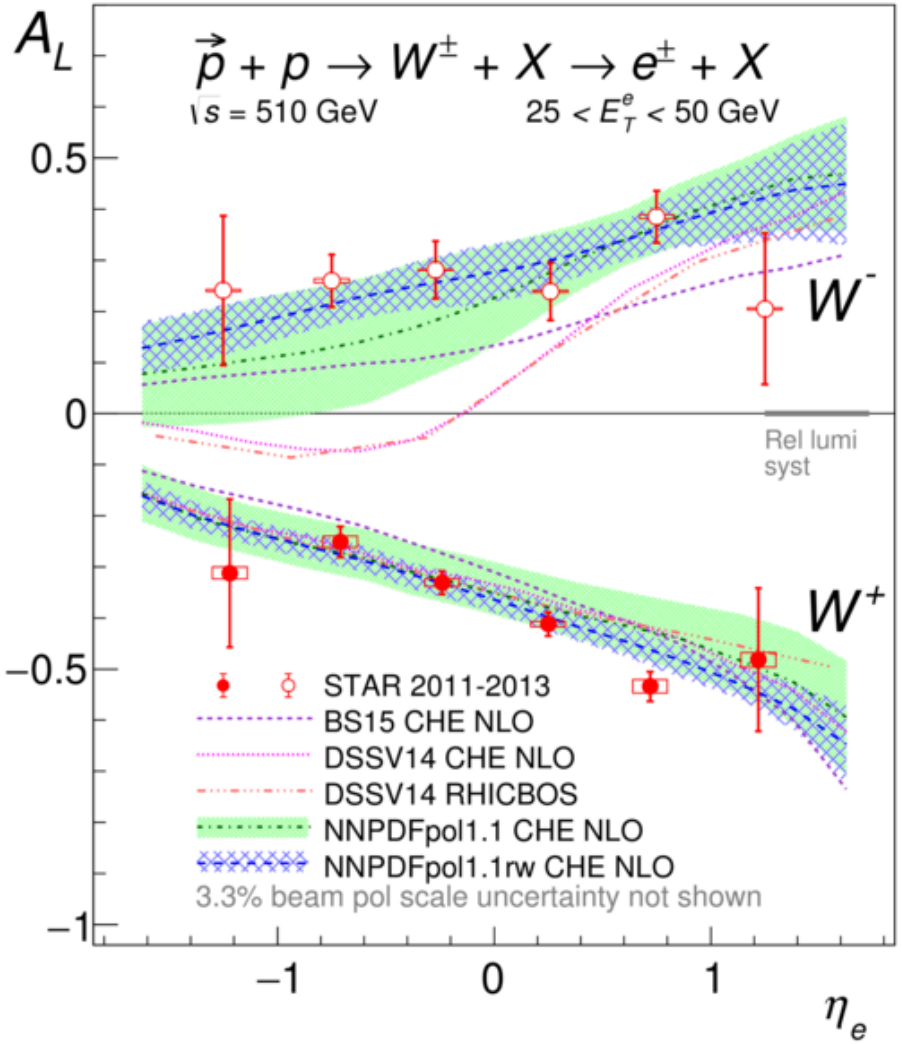
Consistent with DY result (FNAL E866/906) and PDF fit

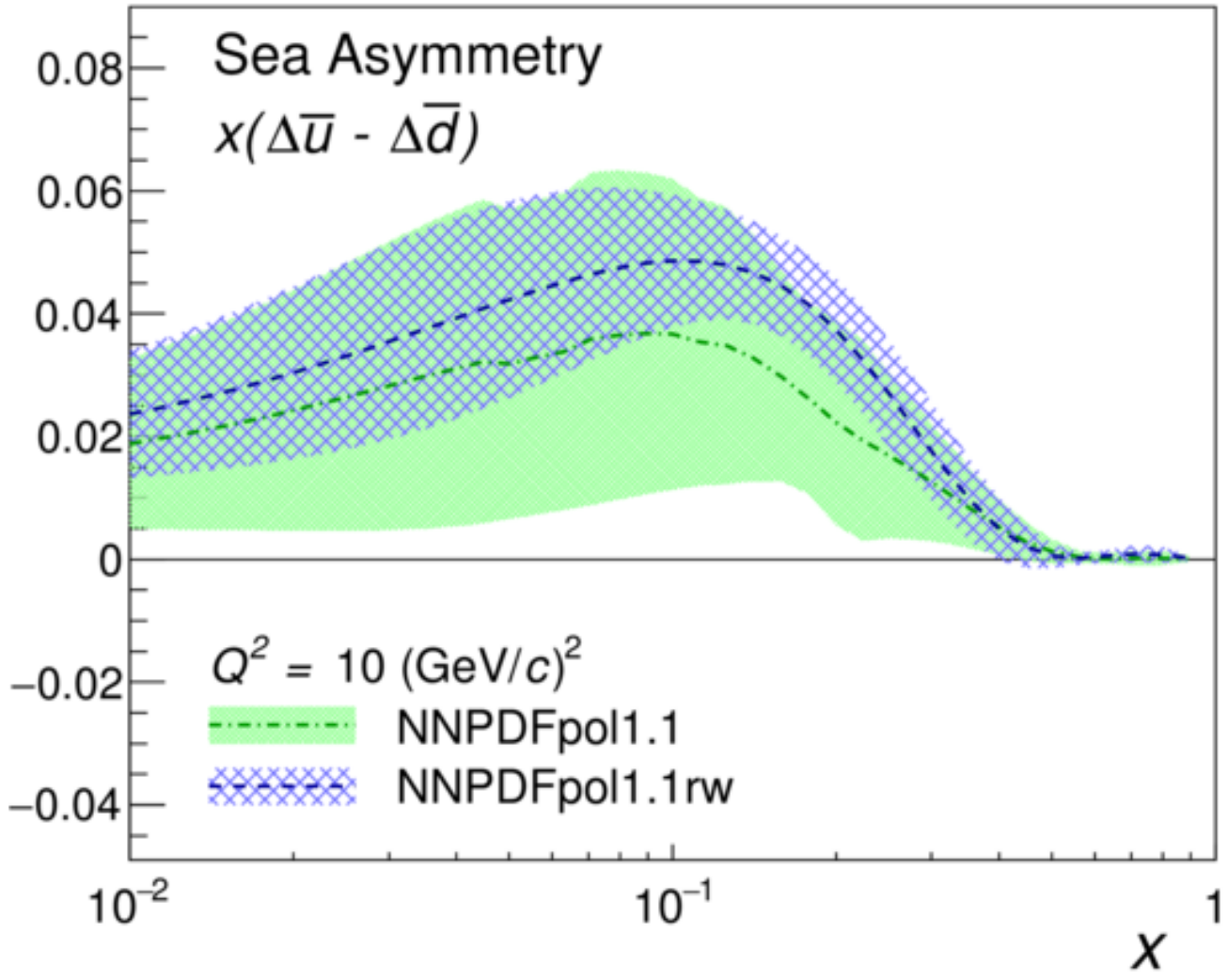
Adding EEMC endcap: extends the x reach to 0.06 < x < 0.4

2017 data (~350/pb) data will double the statistics of 2011+12+13 data

Sea quark spin from A_L : $W^{+/-}$

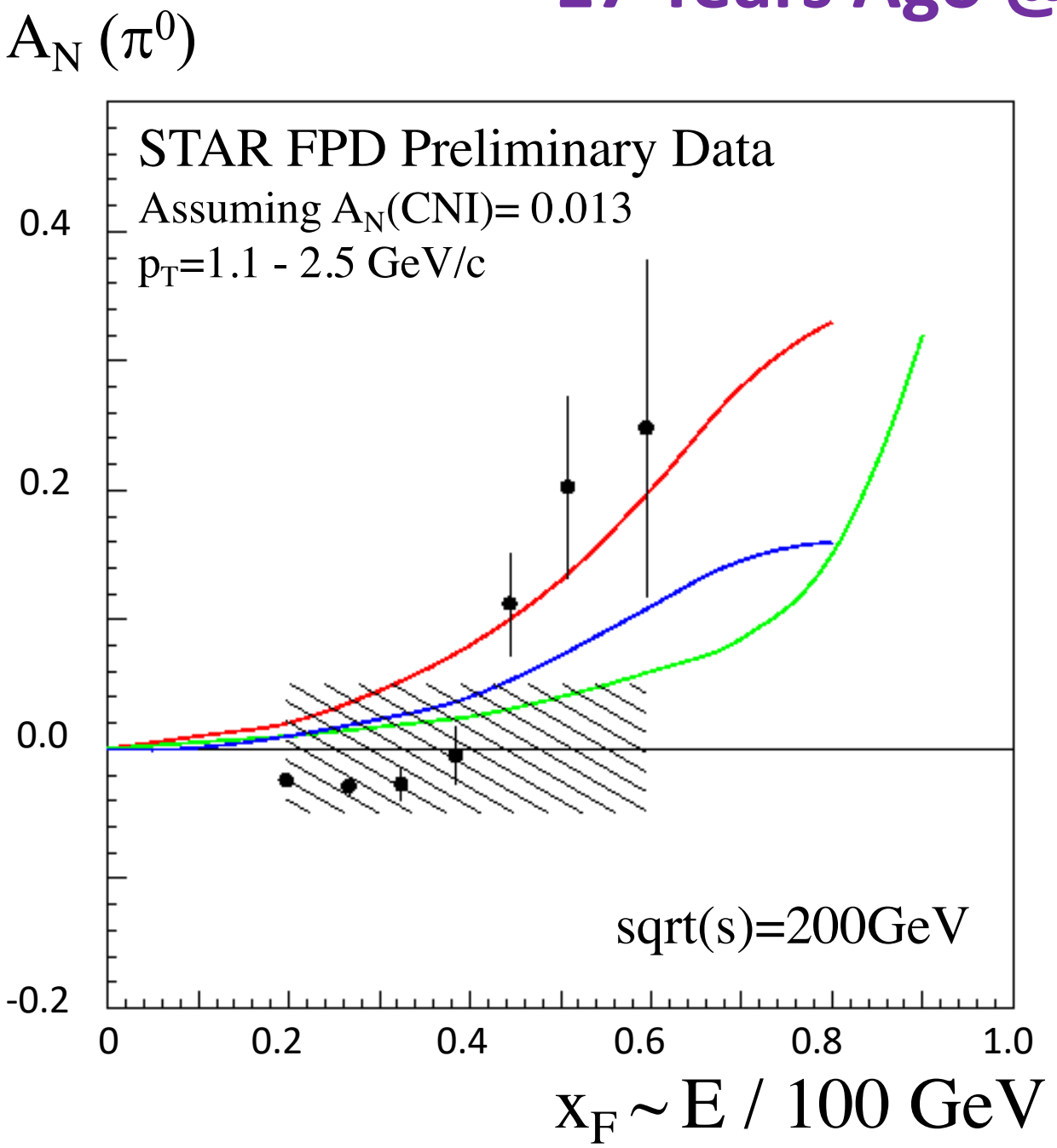
Phys. Rev. D **99**, 051102(R)





Significant preference for $\Delta\bar{u} > \Delta\bar{d}$ at $0.06 < x < 0.25$
while $\bar{u} < \bar{d}$ for unpolarized PDF

17 Years Ago @ SPIN2002



Theory predictions at p_T = 1.5 GeV/c

Collins effect

Anselmino, et al.
PRD 60 (1999) 054027.

Sivers effect

Anselmino, et al.
Phys. Lett. B442 (1998) 470.

Twist 3 effect

Qiu and Sterman,
Phys. Rev. D59 (1998) 014004.

k_T in fragmentation correlated with quark spin

Quark transverse polarization in transversely polarized p

Transversity * Collins Frag. Func.

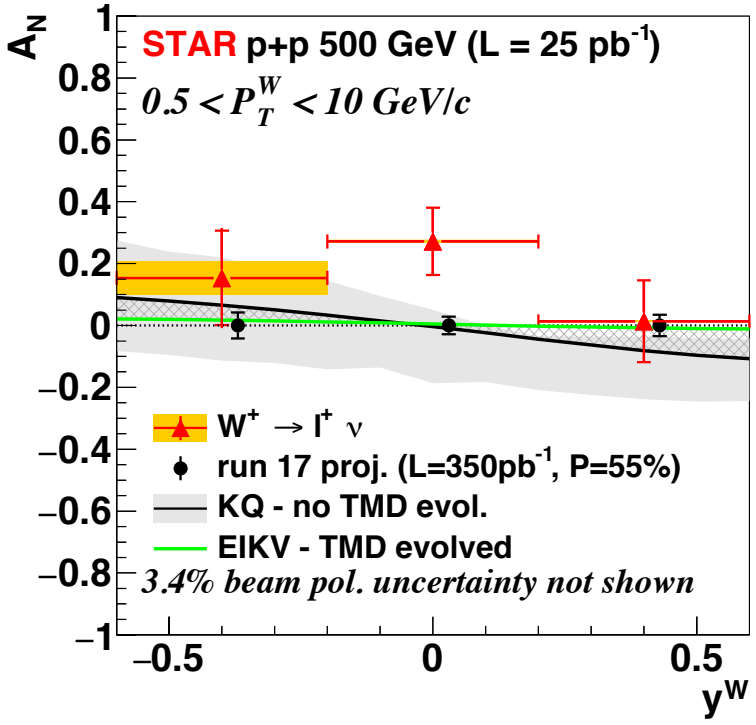
k_T of parton in transversely polarized p

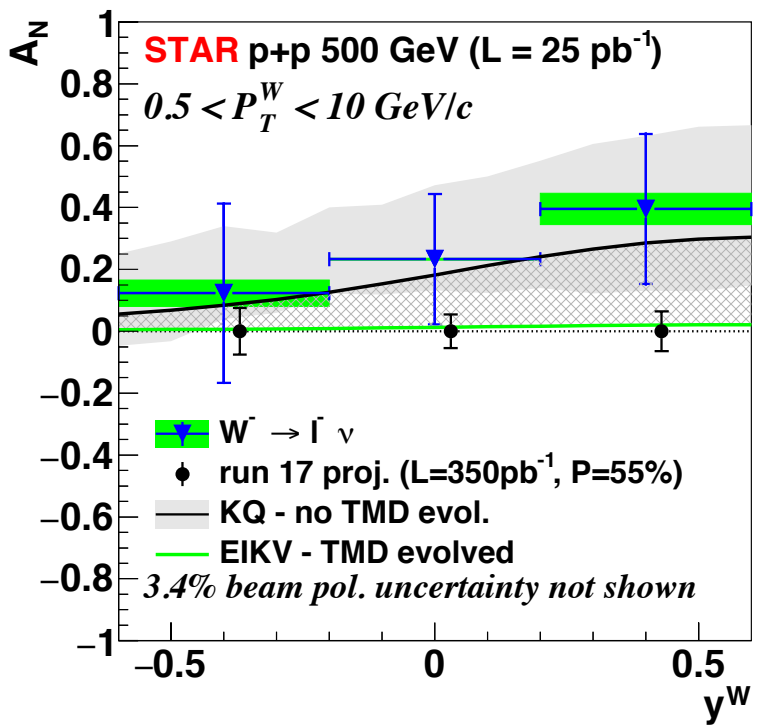
Sign change between DIS vs DY

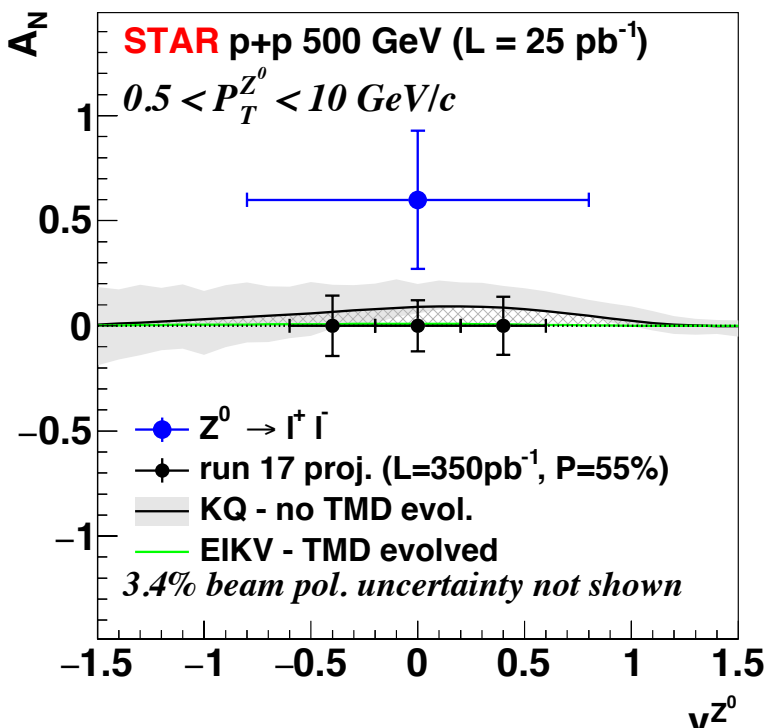
Sivers Effect from W/Z

Phys. Rev. Lett. 116, 132301 (2016)
Theory : Phys. Rev. Lett. 103, 172001

Reconstruct W kinematics using recoil







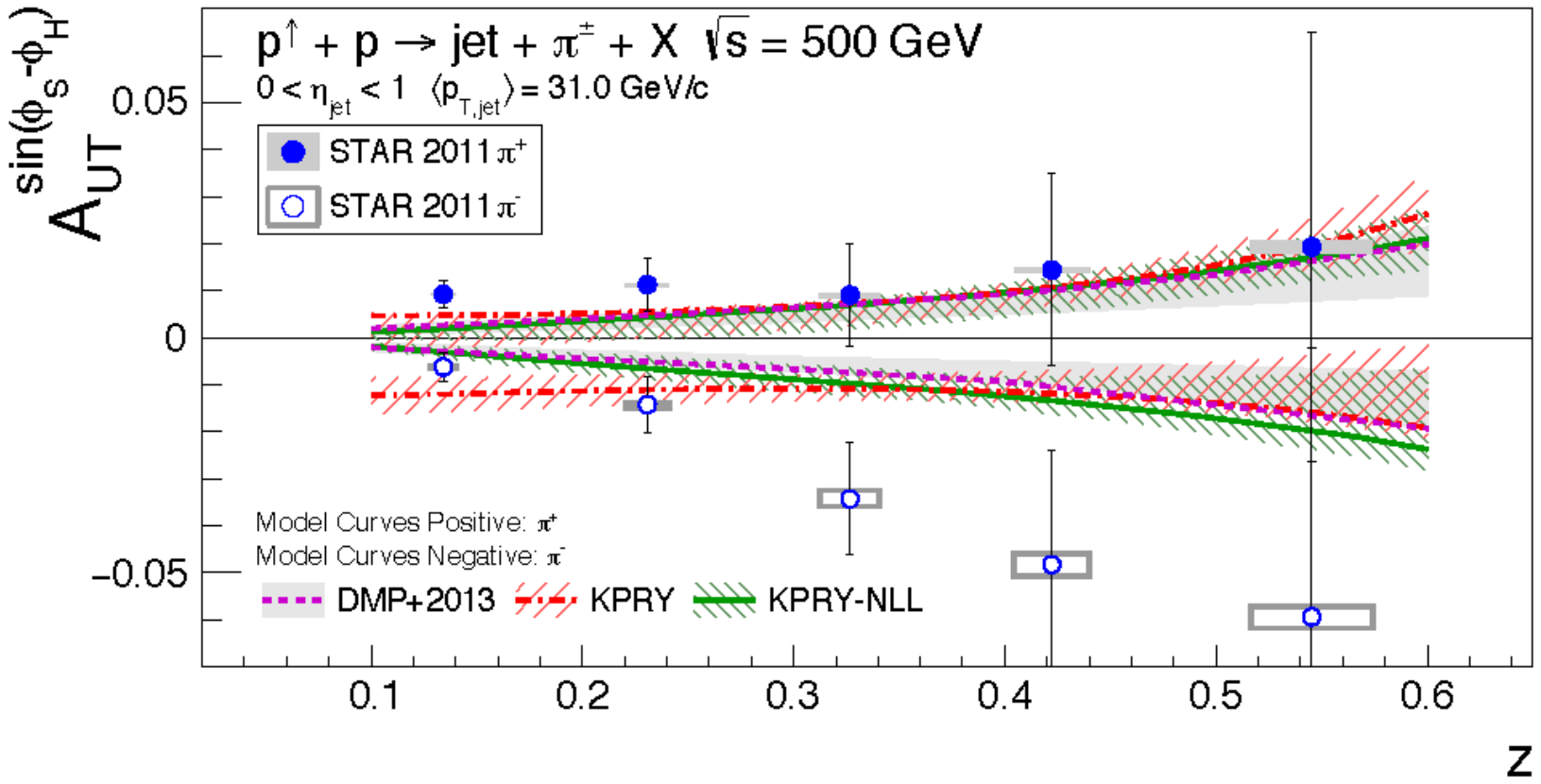
Results show the first hint for Sivers sign-change and small TMD evolution effects in asymmetries

STAR collected x14 more statistics (350/pb) transverse p+p in 2017 statistical error projection shown as black points above

Transversity x Collins from A_{UT} : Jet+π

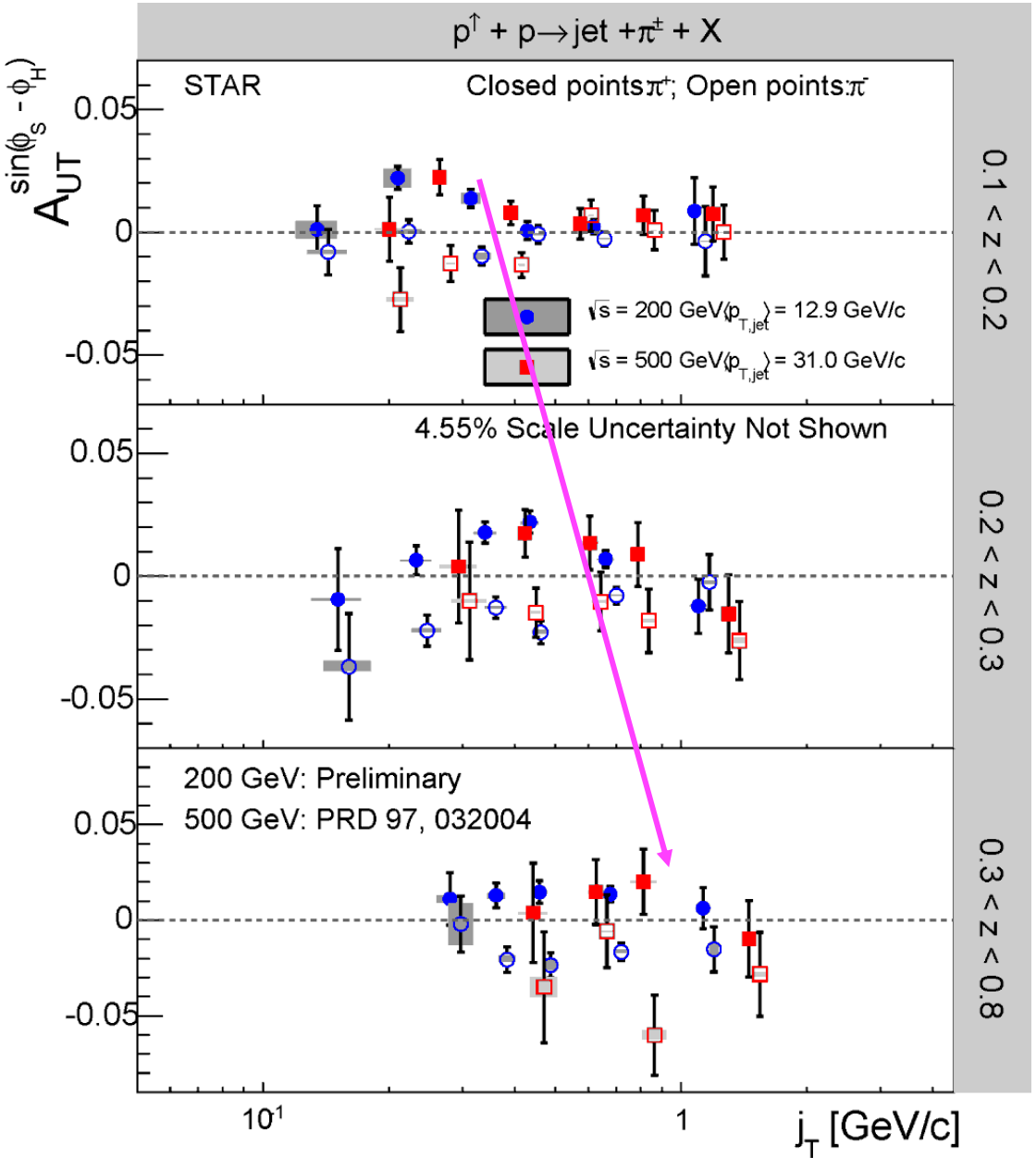
$$A_{UT}^{\pi^{\pm}} \approx \frac{h_1^{q_1}(x_1,k_T) f_{q_2}(x_2,k_T) \hat{\sigma}_{UT}(\hat{s},\hat{t},\hat{u}) \Delta D_{q_1}^{\pi^{\pm}}(z,j_T)}{f_{q_1}(x_1,k_T) f_{q_2}(x_2,k_T) \hat{\sigma}_{UU} D_{q_1}^{\pi^{\pm}}(z,j_T)}$$

STAR Phys. Rev. D 97, 032004 (2018)
DMP: PLB 773, 300 (2017)
KPRY: PLB 774, 635 (2017)



First Collins x Transversity measurements in pp collisions at high Q^2
Consistent with fit to SIDIS + e+e-
A test of Universality. TMD evolution small?
2017 (510GeV) data factor x14 more statistics

Collins effect vs j_T in z-bins



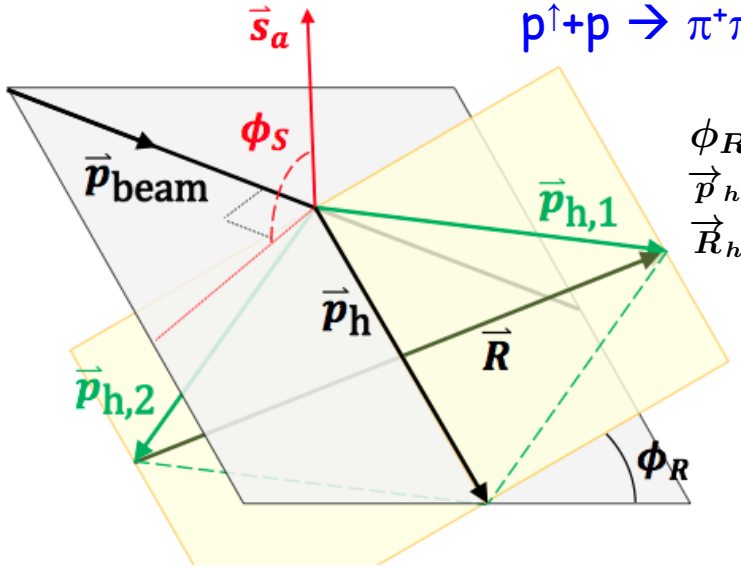
500 GeV pp results hinted the A_{UT} peak shifts to higher j_T as z increases

New preliminary 200 GeV pp results provide confirming evidence

2017 (510GeV) data factor x14 more statistics

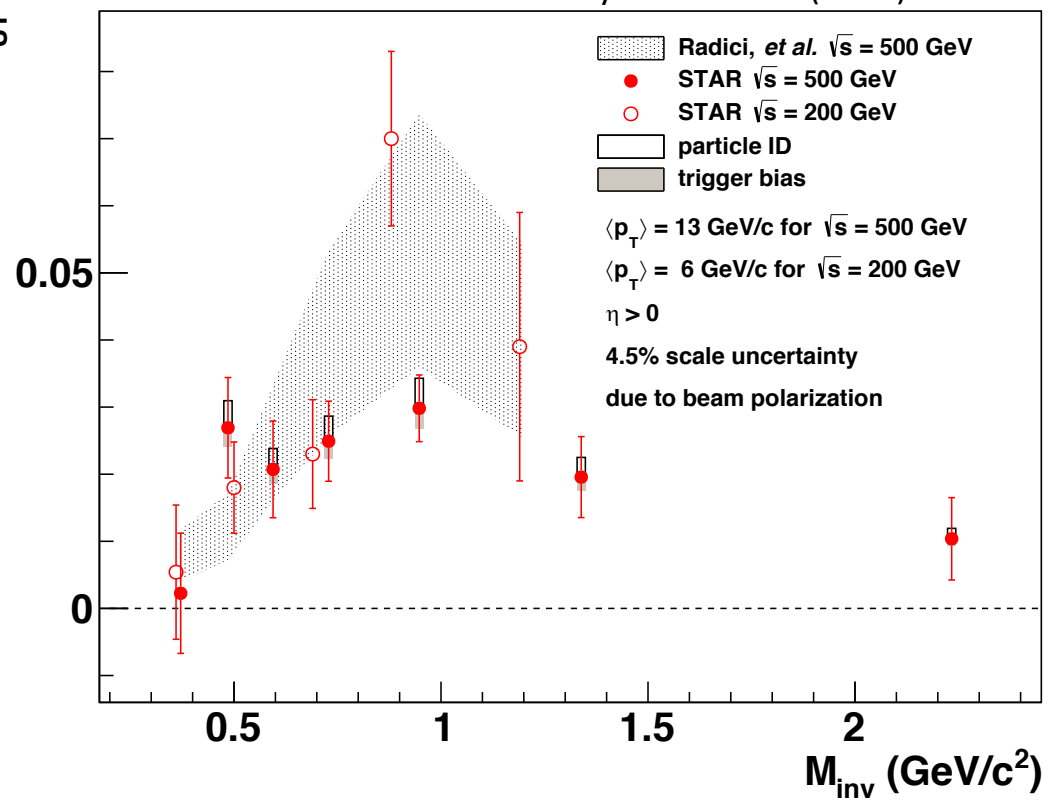
Interference Fragmentation Function (IFF)

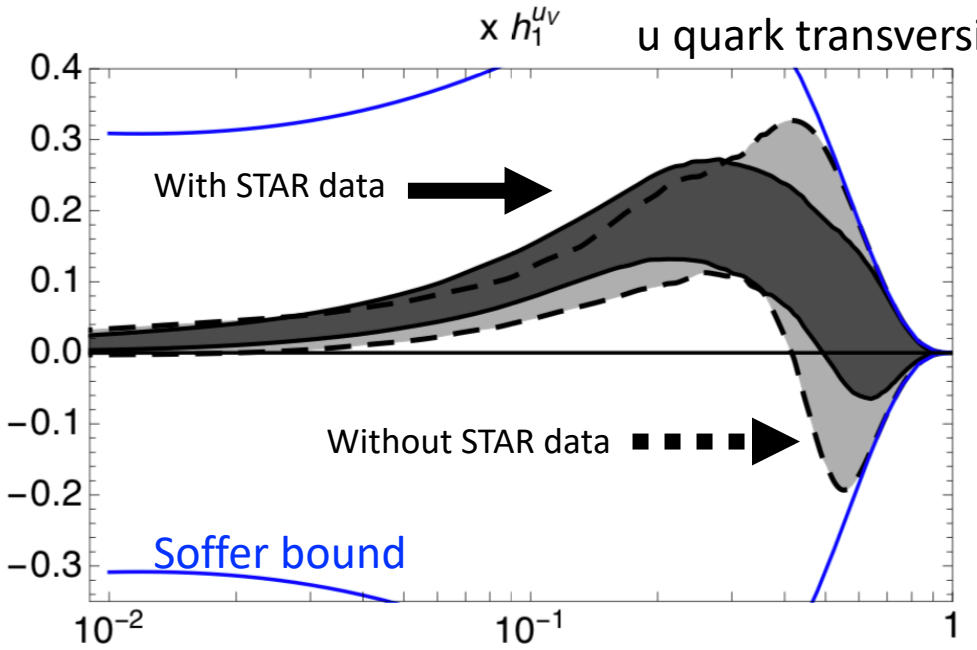
$p^{\uparrow}+p \rightarrow \pi^{+}\pi^{-}+X \rightarrow$ transversity x IFF in collinear framework



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

Phys. Lett. B780 (2018) 332-339





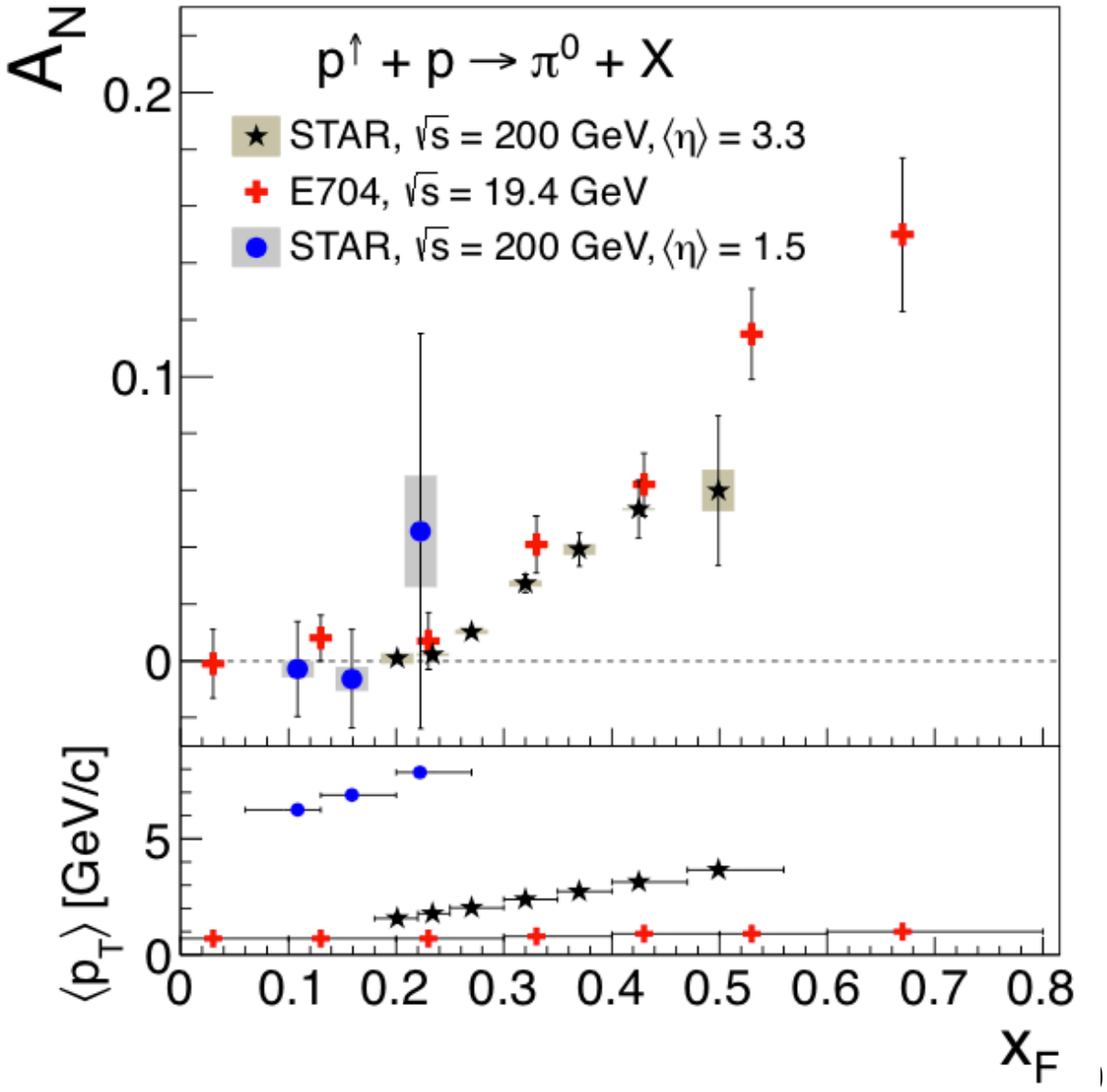
PRL 120, 192001 (2018)

Significant di-hadron asymmetries both at √s=200GeV and √s=500GeV
Increasing with p_T, peaks at M~1GeV

More data :
- at 200 GeV from 2012 and 2015 (x 15)
- at 500 GeV 2017 (x 14)

Substantial reduction in the uncertainties at the valence x region in global fit to SIDIS/e^+e^- + STAR

Forward A_N : π^0



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Collins & IFF * Transversity
at SIDIS, B-factories & RHIC

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Sivers effect at
at SIDIS & RHIC

Twist 3 effect
Qiu and Sterman,
Phys. Rev. D59 (1998) 014004.

TMD and Twist3
relation

$$-\int d^2k_\perp \frac{|k_\perp^2|}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{SIDIS} = T_{q,F}(x,x)$$

Twist3 Fragmentation effect

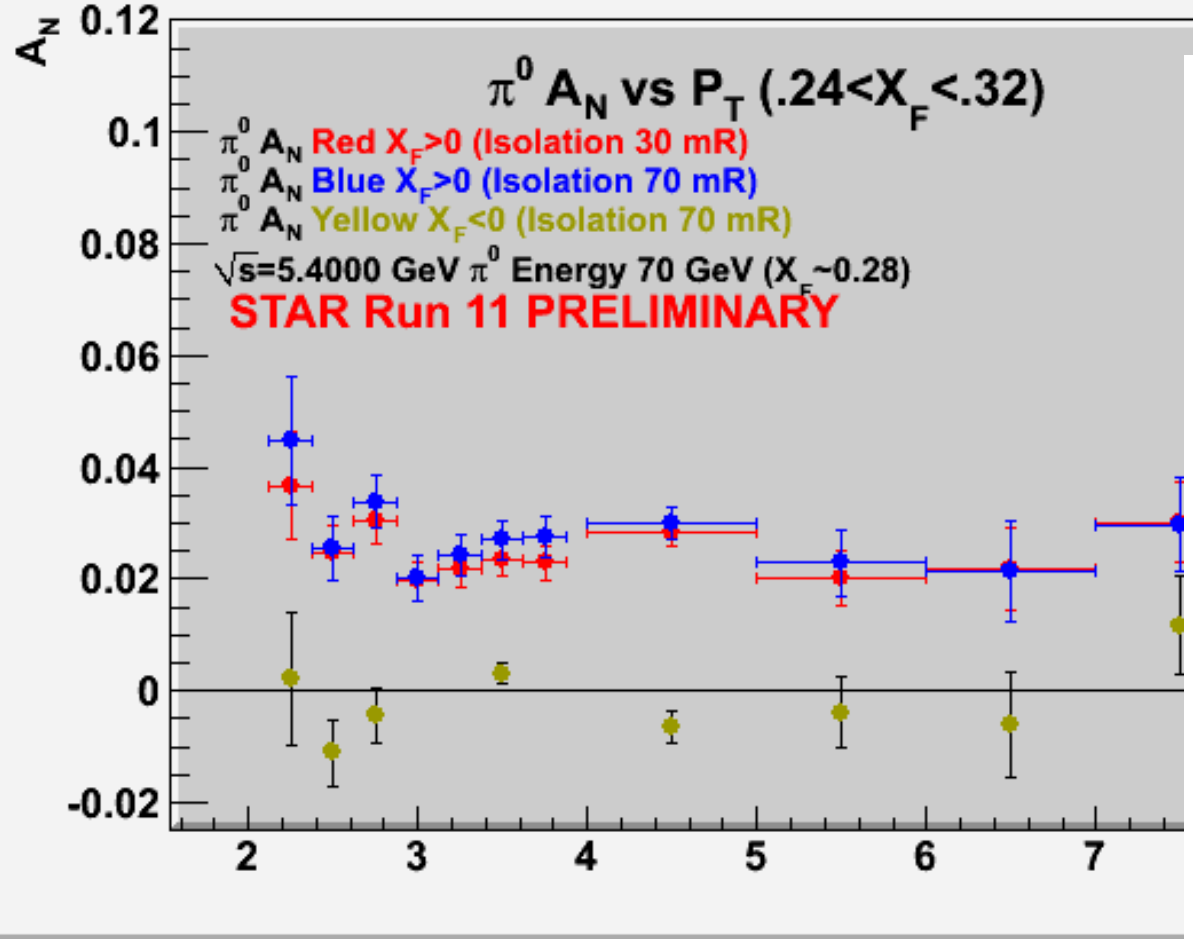
Koike Nucl.Phys. A721 (2003) 364-367

Kanazawa,Koike,Metz,Pitonyak PhysRevD.89.111501

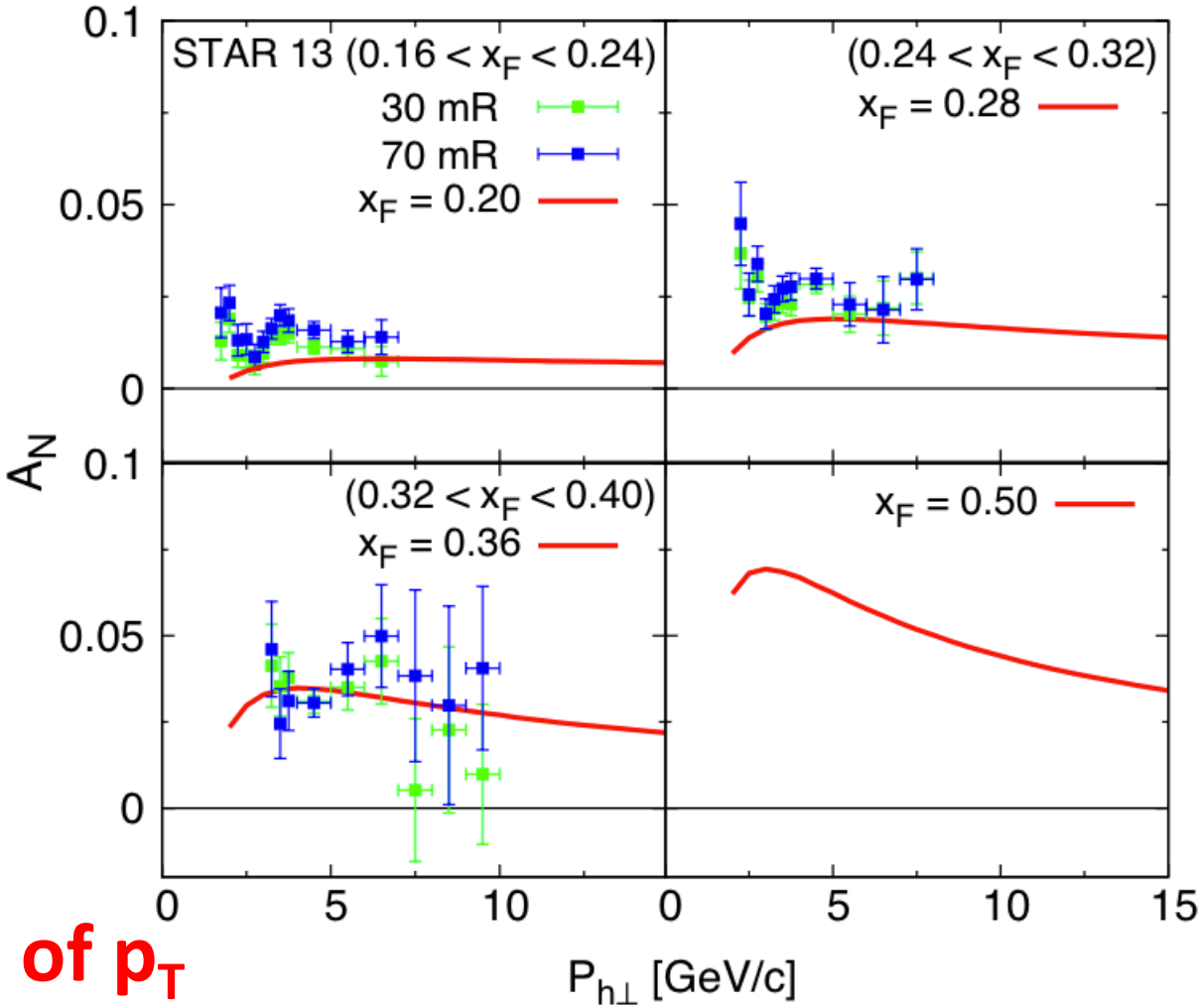
3 parton correlator

p_T dependence of forward A_N : π^0

Expected from pQCD $A_N = \frac{\Delta\sigma}{2\sigma} \propto \frac{1}{P_T}$

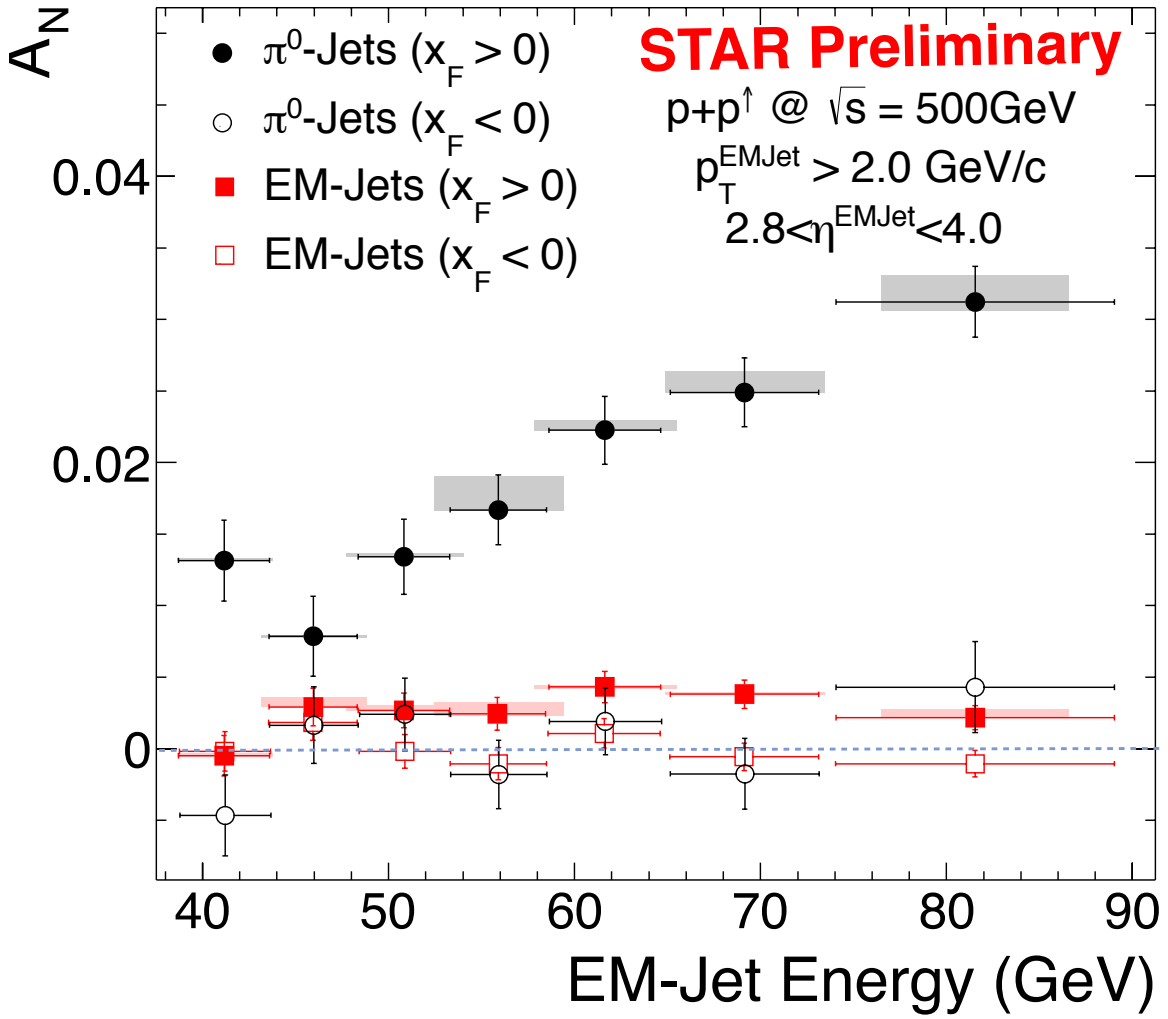


PhysRevD.89.111501



Asymmetries looks flat as function of p_T

Forward A_N : EM-jet vs isolated π^0



Isolated π^0

2γ-EM-Jets with

$m_{\gamma\gamma}$ <0.3 GeV/c^2

$Z_{\gamma\gamma}$ <0.8

EM-Jets

with no. photons >2

A_N for jettier events are much smaller than isolated π^0

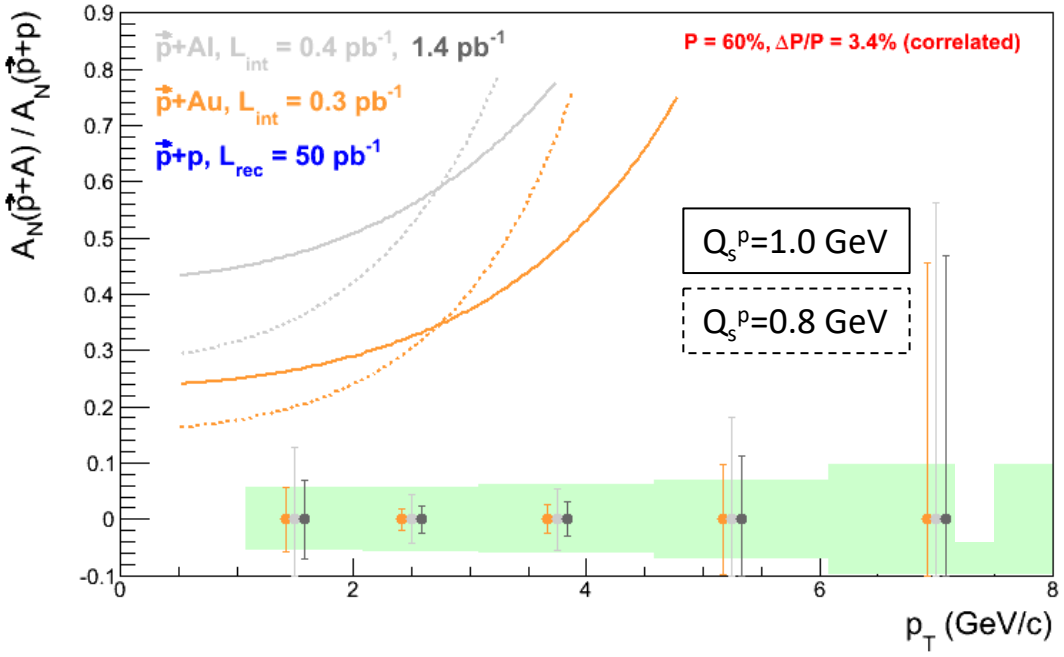
Forward A_N : p+p vs p+Au

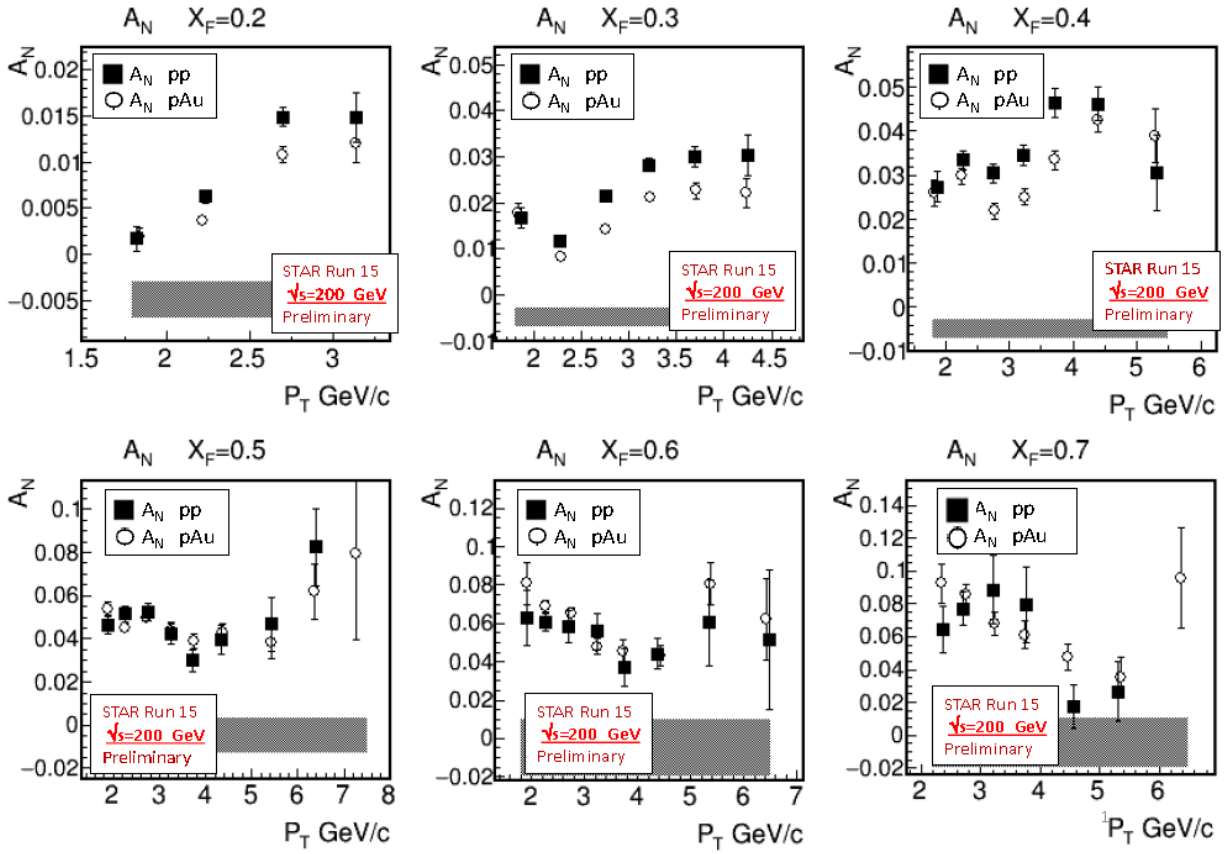
Hybrid Approach Yoshitaka Hatta,et al, Phys. Rev. D 95, 014008 (2017)

Initial state effect in p + k_T un-integrated gluon distribution in Au + Final State effect

Odderon exchange

Yuri V. Kovchegov, Matthew D. Sievert, PhysRevD.86.034028





Both models predicted gluon saturation suppresses A_N by ~$A^{1/3}$

Suppression of A_N in $p^{\uparrow}$+A provides sensitivity to Q_s

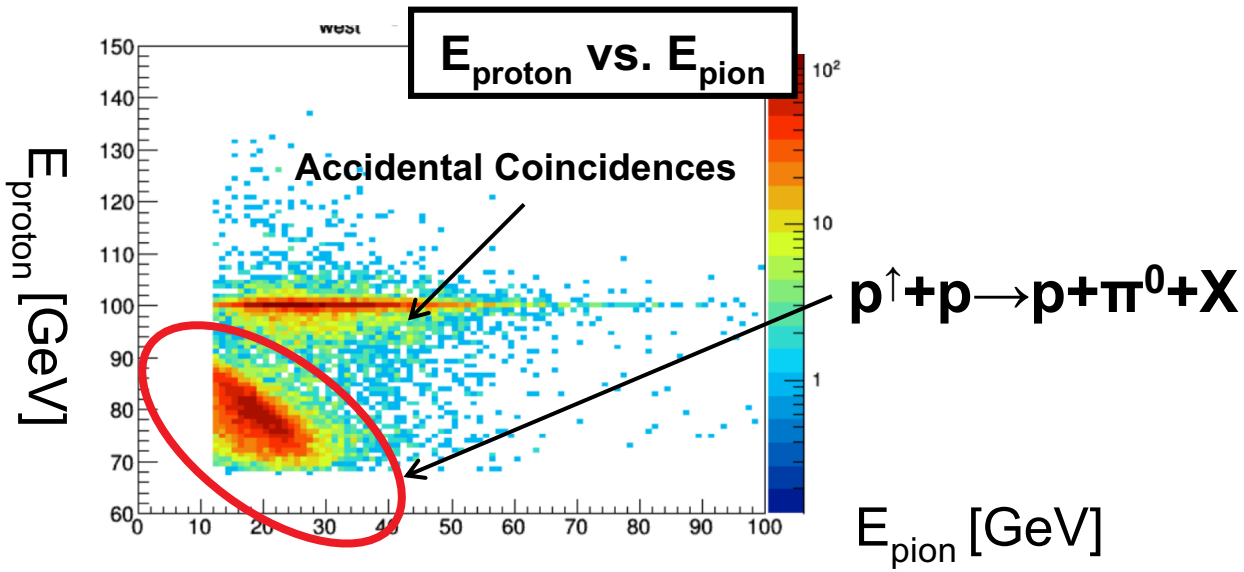
PhysRevD.84.034019, PhysRevD.86.034028

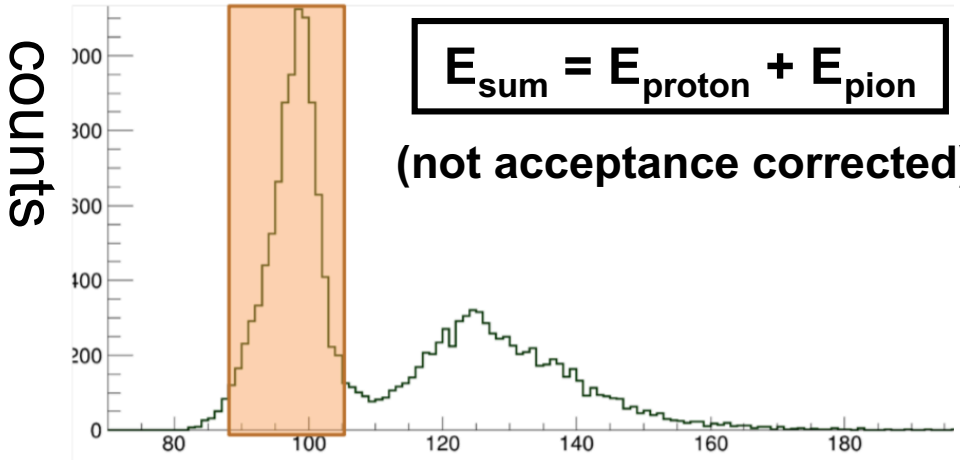
Small to no suppression is observed

Something new (and old?) : $p^{\uparrow}+p \rightarrow p+\pi^0+X$

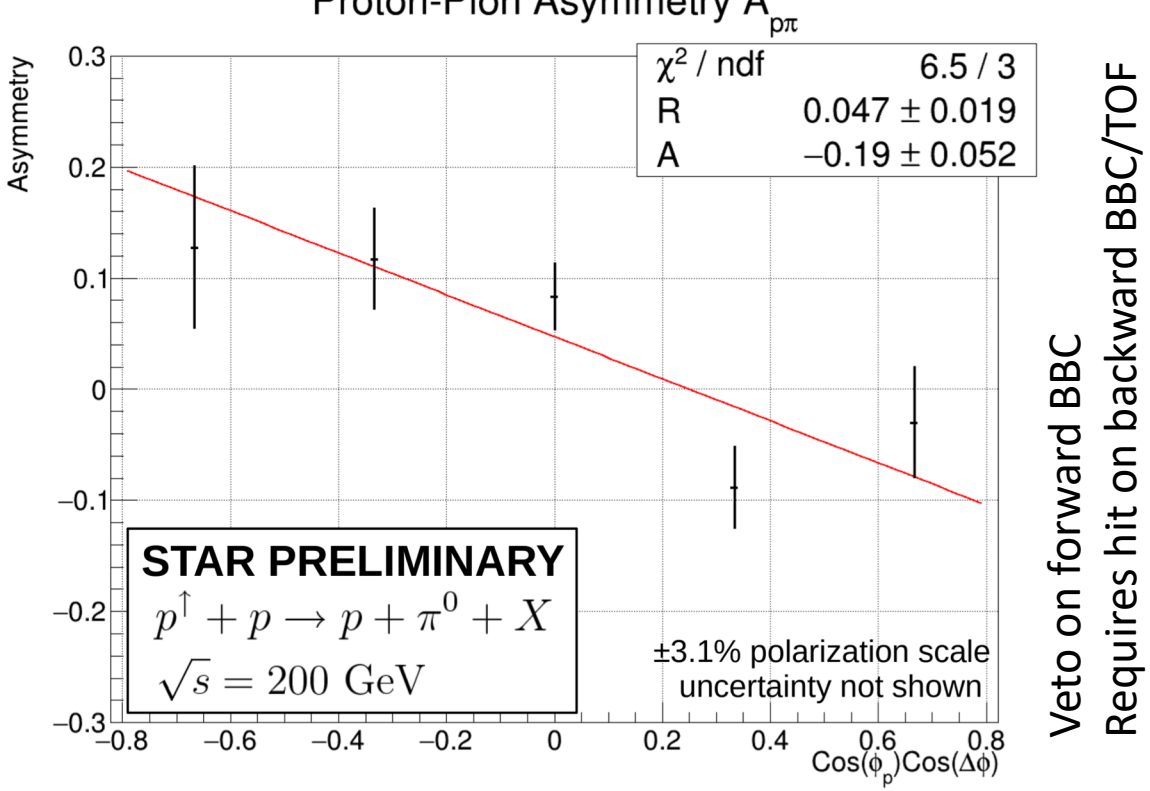
Forward Roman Pot (same side as FMS)

FMS @ forward





p_T^{pion} ~ 1~4 GeV/c
p_T^{proton} ~ 0.1~0.45 GeV/c



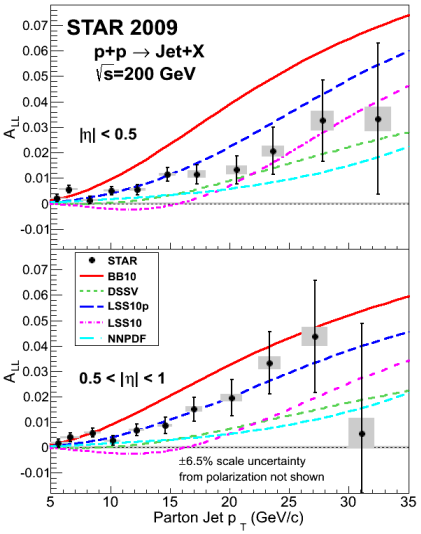
Veto on forward BBC
Requires hit on backward BBC/TOF

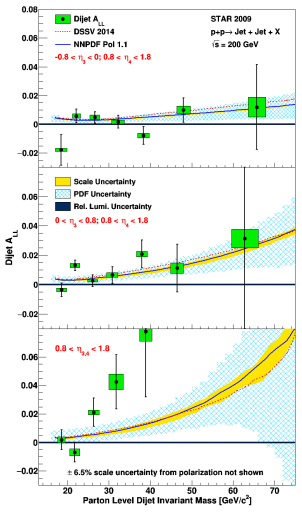
$\mathrm{Cos}(\Phi_P)\mathrm{Cos}(\Phi_\pi - \Phi_P)$

Significant pion asymmetry in the scattering plane of the proton

STAR Spin Summary

Jet and Dijet: Positive gluon polarization

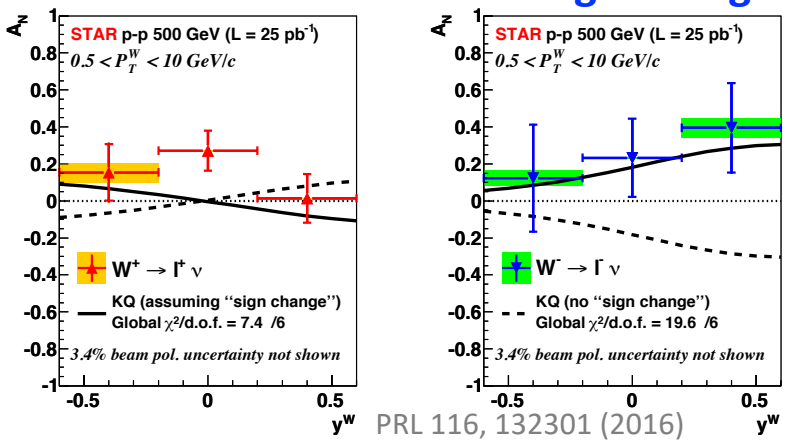




PRL 115, 092002 (2015)

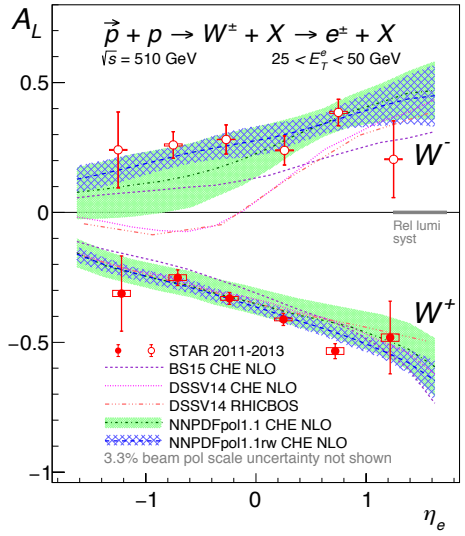
PRD 98, 32011 (2018)

W : The first hint of Sivers sign change



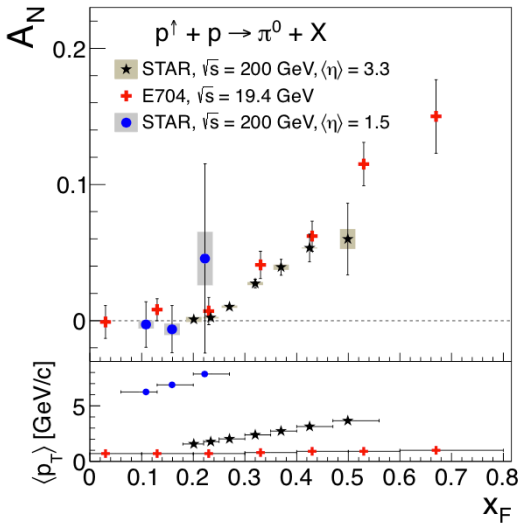
PRL 116, 132301 (2016)

W : Positive flavor asymmetry in the polarized sea

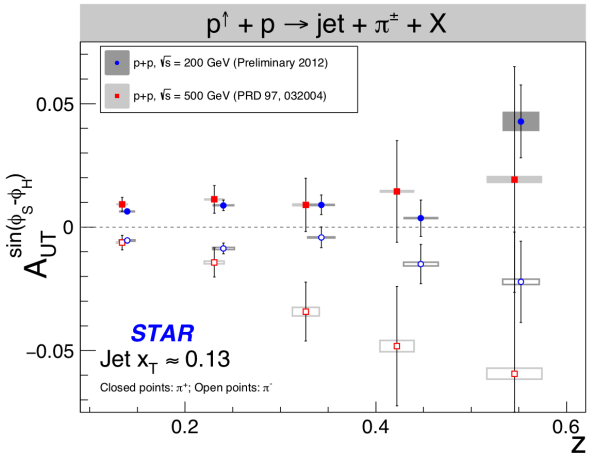


PRD 99, 51102 (2019)

π⁰ A_N : p_T dep, Jet/Isolated, pA

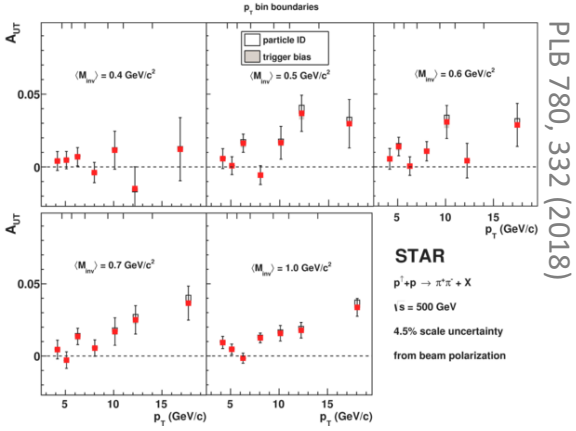


Jet+π$^{+/-}$: First Collins effect in $p + p$



PRD 97, 032004 (2018)

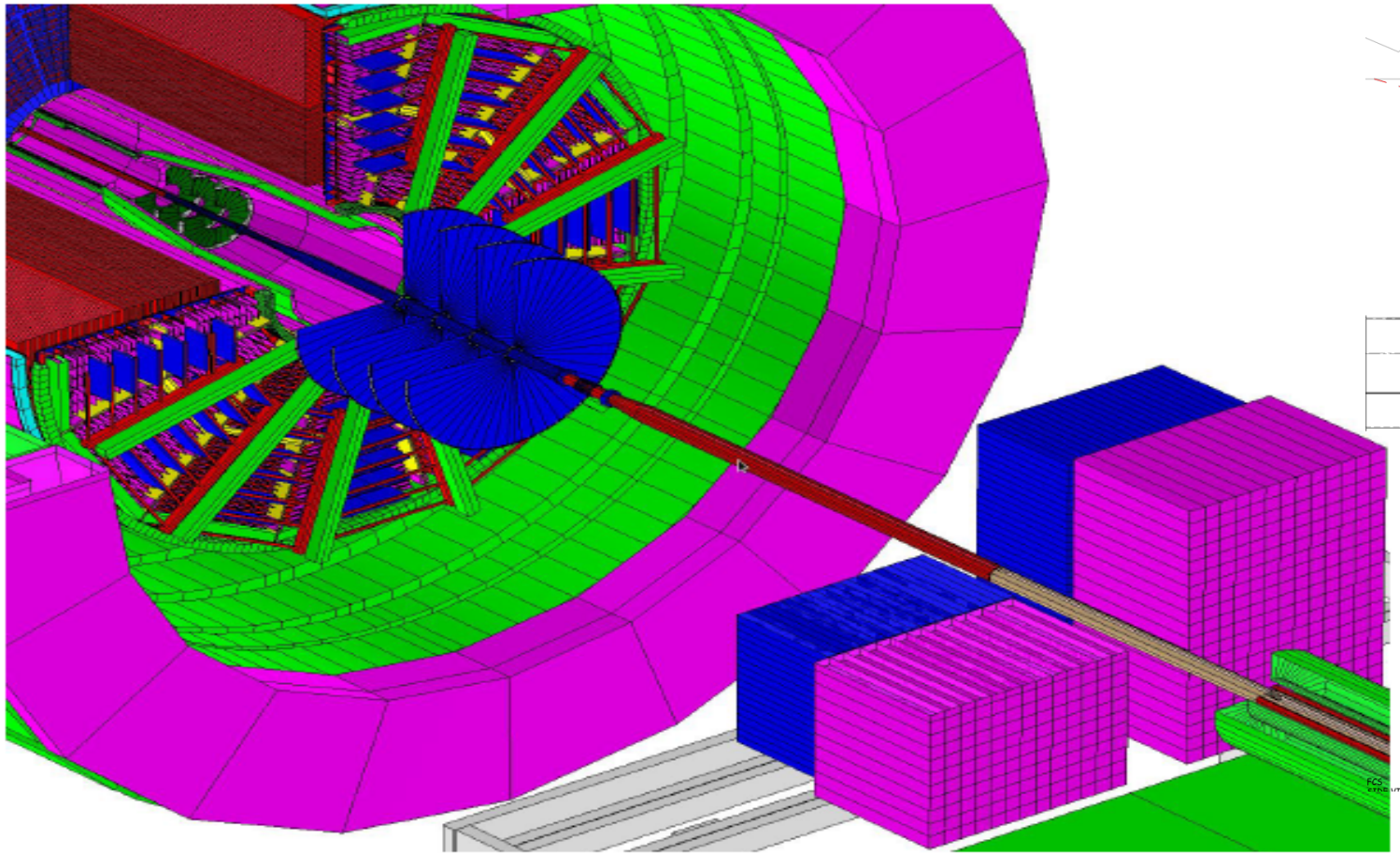
π+π : Transversity * IFF

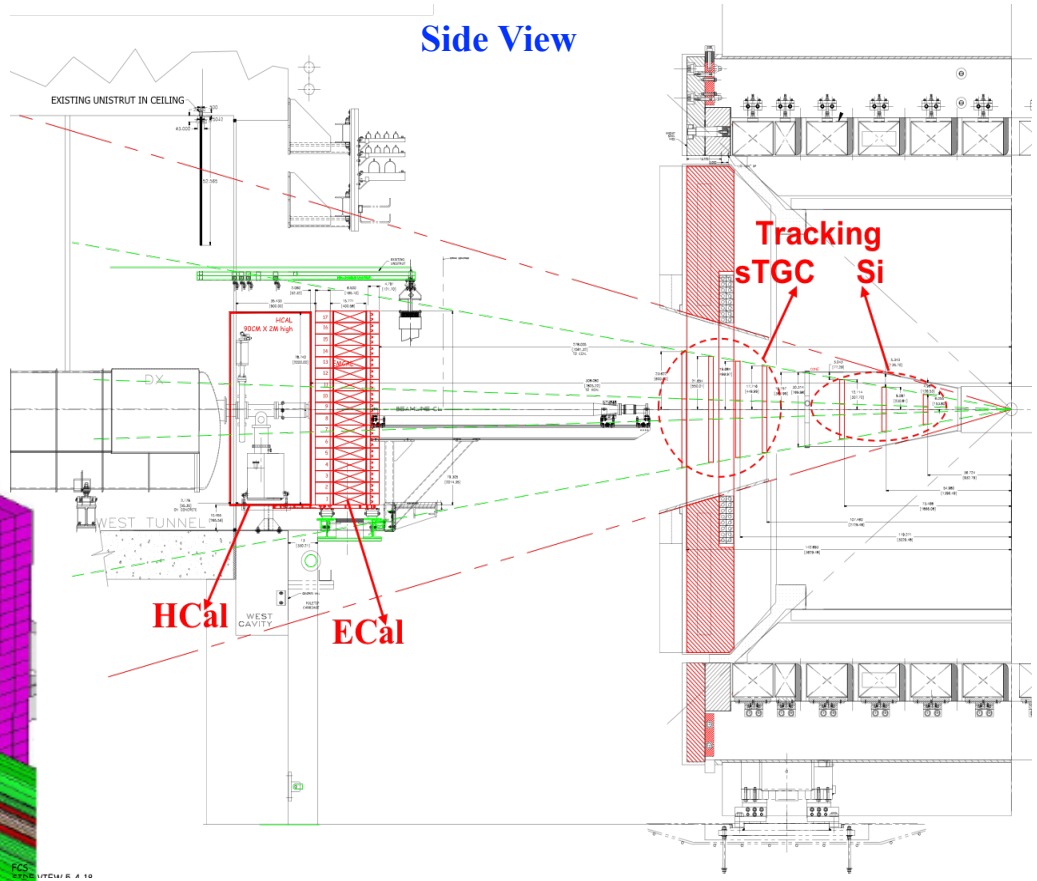


PLB 780, 332 (2018)

A_N Direct Photon and DY from 2015/17 data being analyzed

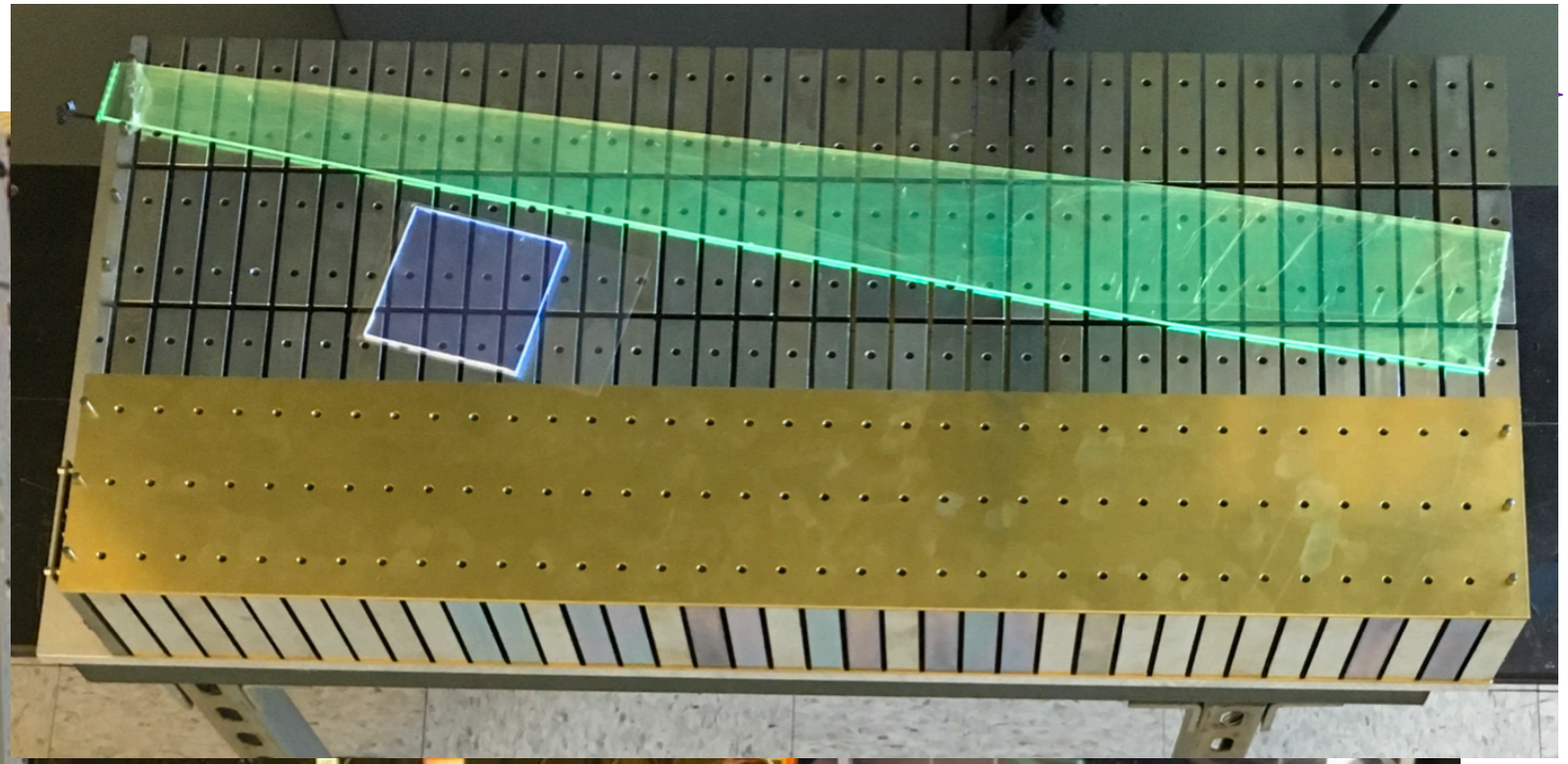
STAR Forward Upgrade

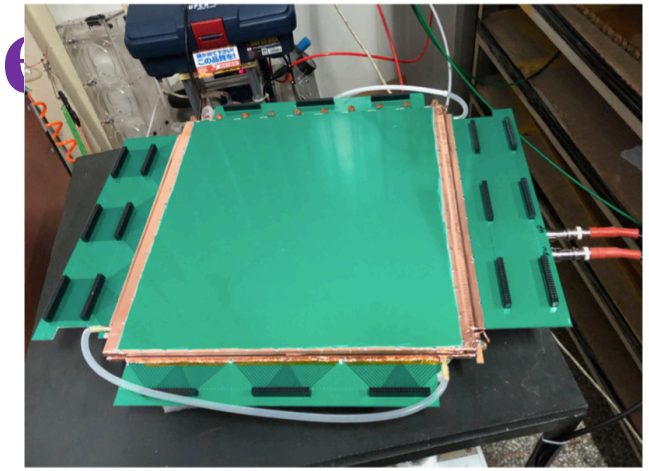




HCAL Prototype @ STAR

STGC Prototype @ STAR





Replace FMS with
a compact Ecal and
add Hcal + Tracking

A PHENIX Ecal super sector being modified @ STAR

Small scale system test @ run19

Project is fully approved
and funded

On schedule for first data
taking with 500 GeV polarized pp
in fall 2021

STAR Physics program 2021~ (after BES2)

Mid-rapidity -1.5<η<1.5 | **Forward-rapidity 2.8<η<4.2**

A+A (Mid-rapidity)

Beam:
Full Energy AuAu

Physics Topics:
a deep look into the properties of the QGP: γ & e+e- pairs

- chiral symmetry restoration
- temperature and lifetime of hot, dense medium

Hypertriton Lifetime Measurement

Precision measurements of direct photon yields and v_n

p+p & p+A (Mid-rapidity)

Beam:
500 GeV: p+p
200 GeV: p+p and p+A

Physics Topics:

- Improve statistical precision
  - ➢ TMD measurements, i.e. Collins, Sivers, …
  - ➢ Access s & Δs through Kaons in jets
- Measurement of GPD E_g through UPC J/Ψ
- First access to Wigner functions through di-jets in UPC
- Gluon and quark vacuum fragmentation
- Gluon and quark fragmentation in nuclear medium
- Nuclear dependence of Collins FF

A+A (Forward-rapidity)

Beam:
Full Energy AuAu

Physics Topics:

- Temperature dependence of viscosity through flow harmonics up to η~4
- Longitudinal decorrelation up to η~4
- Global Lambda Polarization
  → strong rapidity dependence

p+p & p+A (Forward-rapidity)

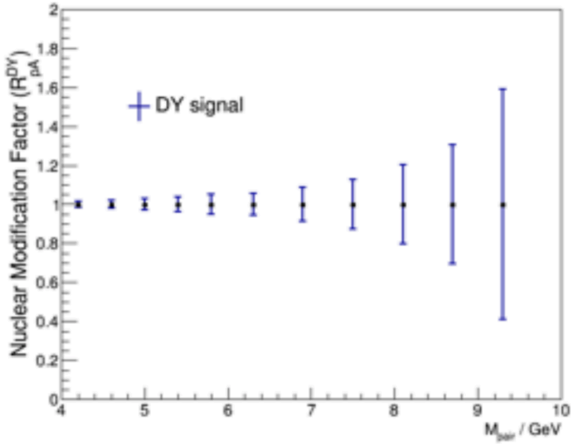
Beam:
500 GeV: p+p
200 GeV: p+p and p+A

Physics Topics:

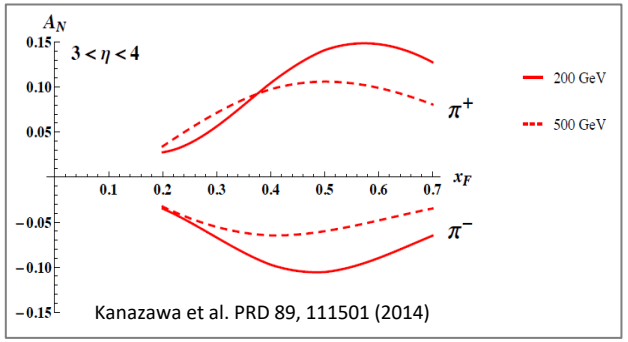
- TMD measurements at high x
  transversity → tensor charge
- Improve statistical precision for Sivers through DY
- Δg(x,Q2) at low x through Di-jets
- Gluon PDFs for nuclei
  - ➢ R_{pA} for direct photons & DY
- Test of Saturation predictions through di-hadrons, γ-Jets

Physics with STAR forward upgrade

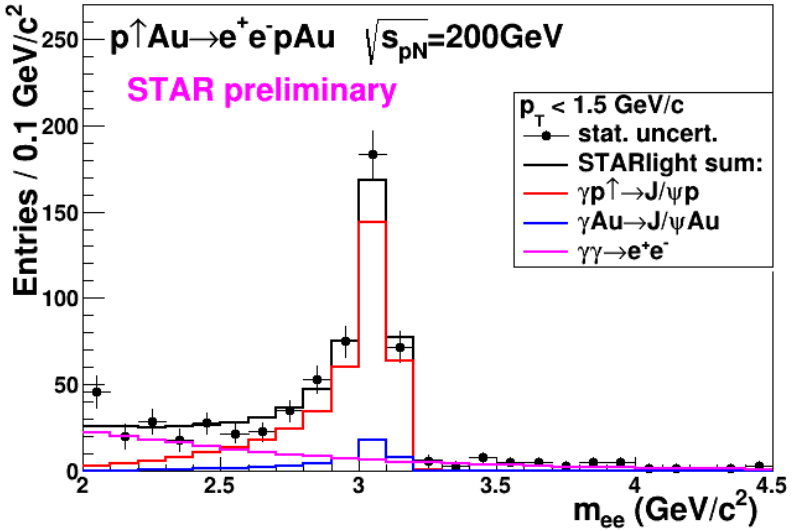
DY: Sivers sign change/TMD evolution



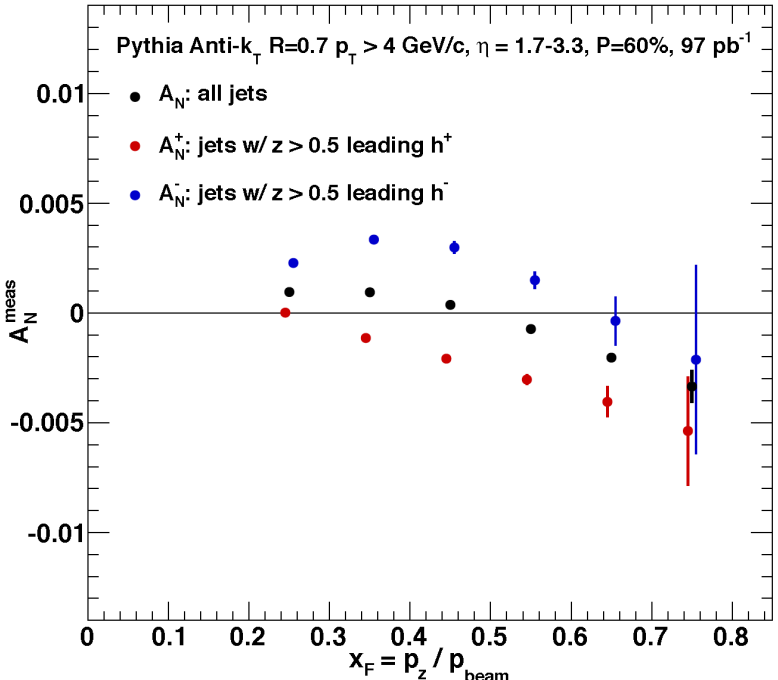
A_N : forward $h^{+/-}$



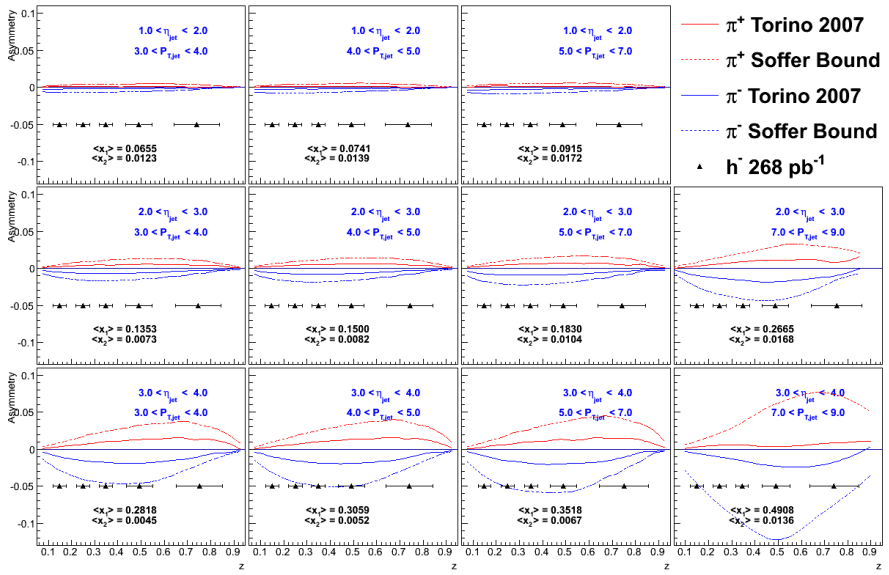
UPC J/psi for GPD E_g



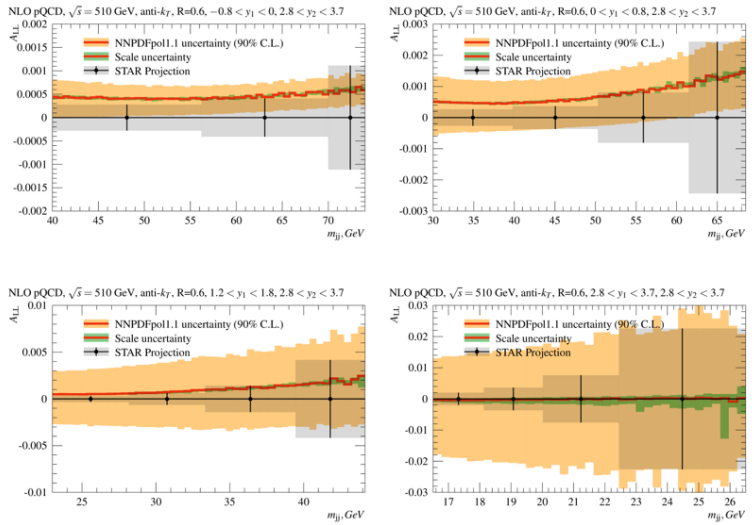
A_N: charge tagged Jet



Transversity * Collins/IFF at forward



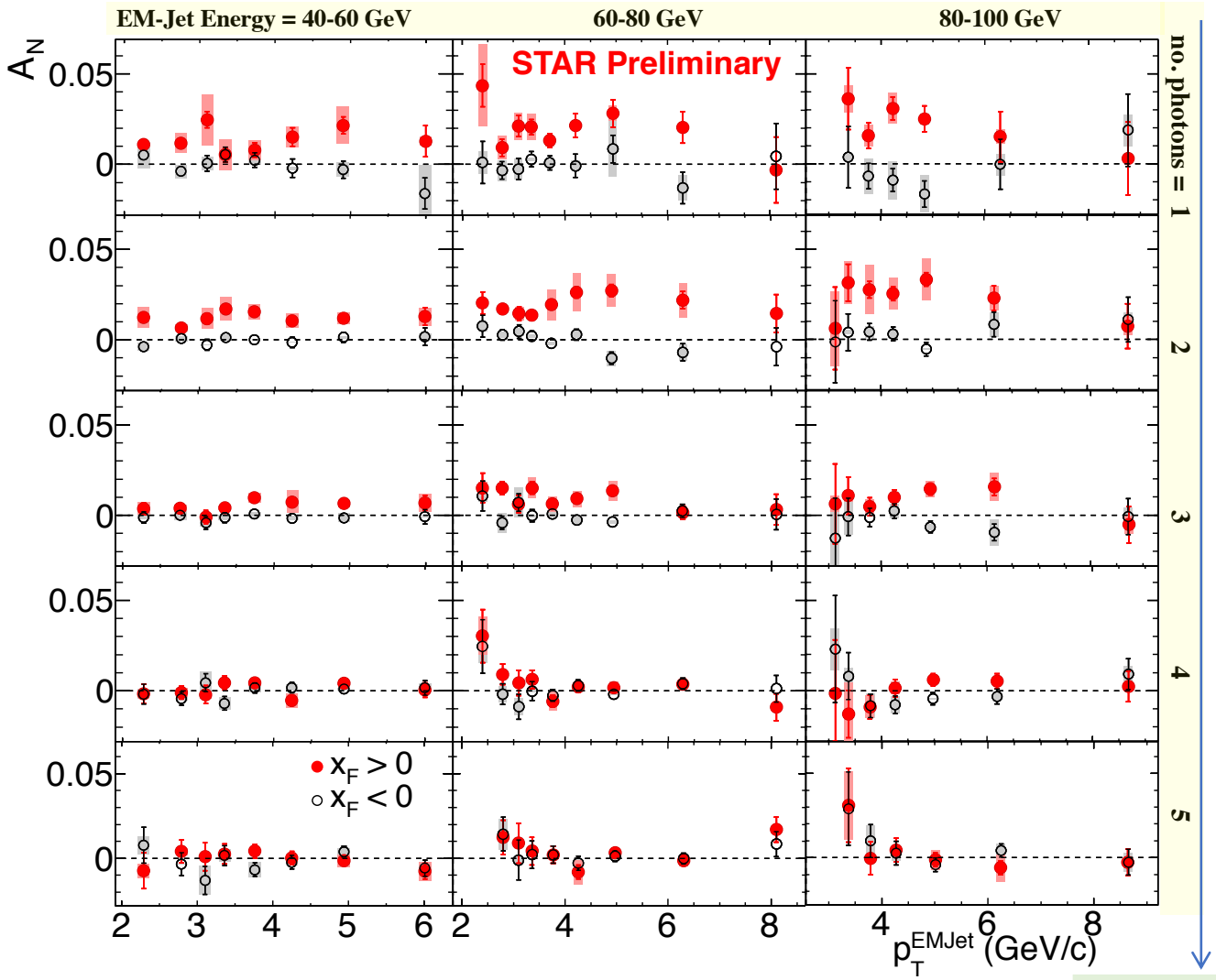
Forward Jet A_{LL} : ΔG at small x



And more physics on both cold and hot QCD with pp, pAu,AuAu

Backup

A_N for different # photons in EM-Jets

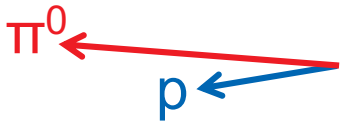


- 1-photon events, which include a large π^0 contribution in this analysis, are similar to 2-photon events
- Three-photon jet-like events have a clear non-zero asymmetry, but substantially smaller than that for isolated π^0's
- A_N decreases as the event complexity increases (i.e., the "jettiness"
-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

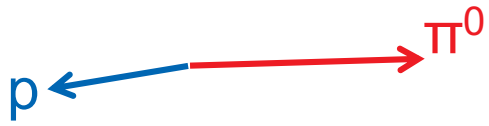
Jettier events

Asymmetries for jettier events are much smaller

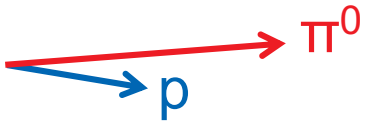
$Cos(\Phi_p)Cos(\Delta\Phi)$ Asymmetry Interpretation



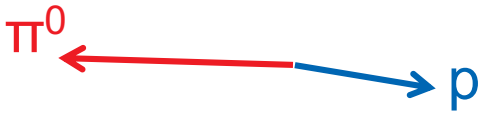
Negative Asymmetry



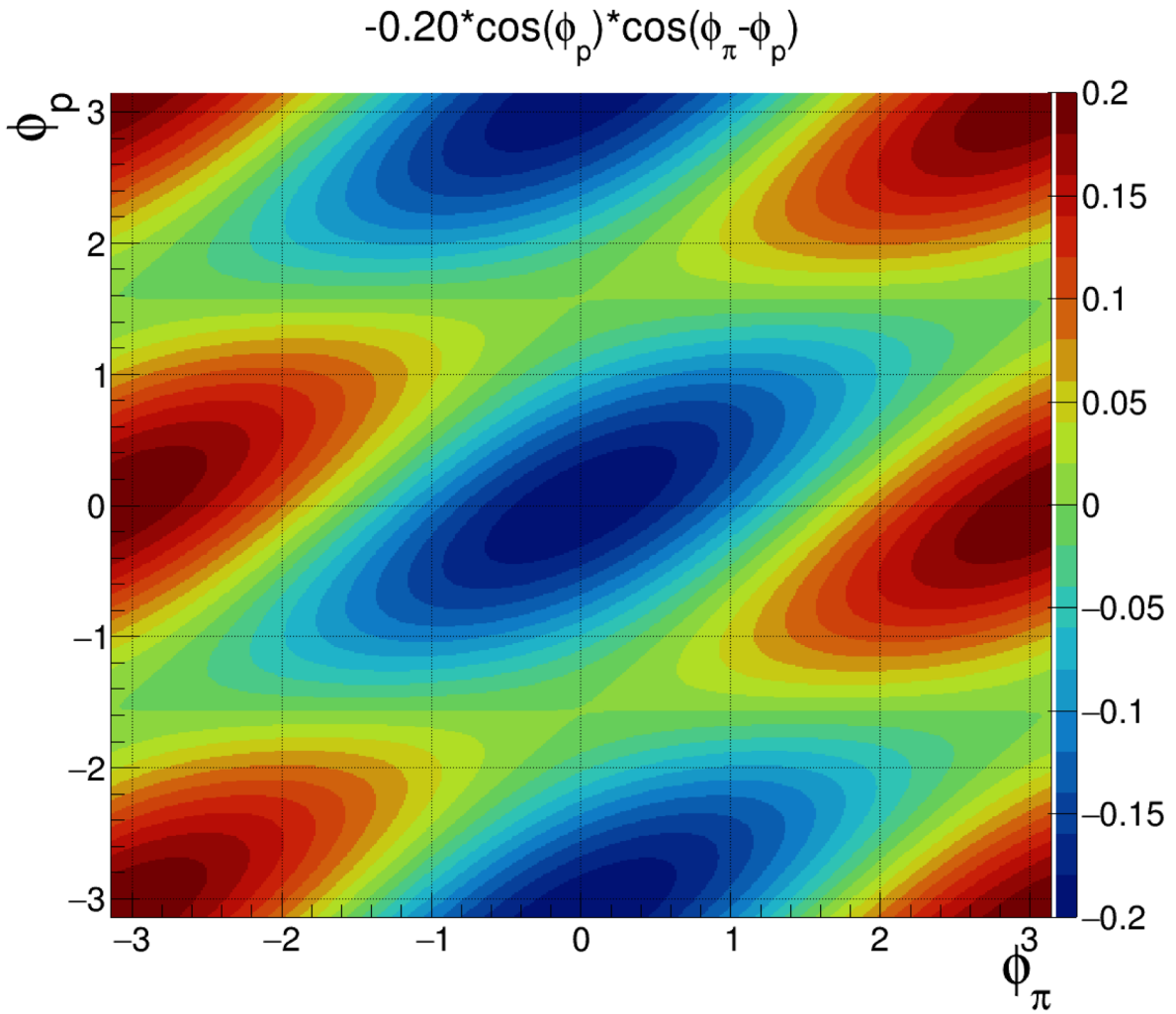
Positive Asymmetry



Positive Asymmetry



Negative Asymmetry



$L_p = p_{beam} \times P_p$

$L_\pi = p_{beam} \times P_\pi$

Parity even and rotation invariant

$\sigma = (L_p \cdot L_\pi)(L_p \cdot S) \sim \cos(\Phi_p)\cos(\Phi_\pi - \Phi_p)$

This is a pion asymmetry, in the scattering plane of the proton