Overview of Recent Spin Physics Results from STAR

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For the STAR Collaboration

DSPIN 2015
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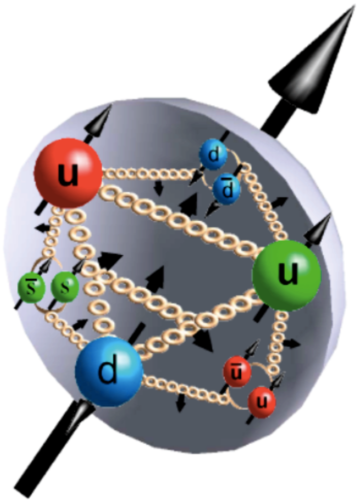
Photo courtesy of Bijan Saha

U.S. DEPARTMENT OF ENERGY
Office of Science

Contributions to the Proton's Spin



Consider proton moving right

Proton spin ⇒

$\Delta q(x)$
$\Delta g(x)$

⇒ – ⇐

Longitudinal Polarization

Polarized DIS: ~0.3
Puzzling for ~25 years

Relatively poorly constrained
But S_g coming into focus!

Proton spin sum rule: $$\frac{1}{2}\hbar = \frac{1}{2}\sum_q S_q^z + S_g^z + \sum_q L_q^z + L_g^z$$

Proton spin ⇑

$\delta q(x)$

⇑ – ⇓

Transverse Polarization

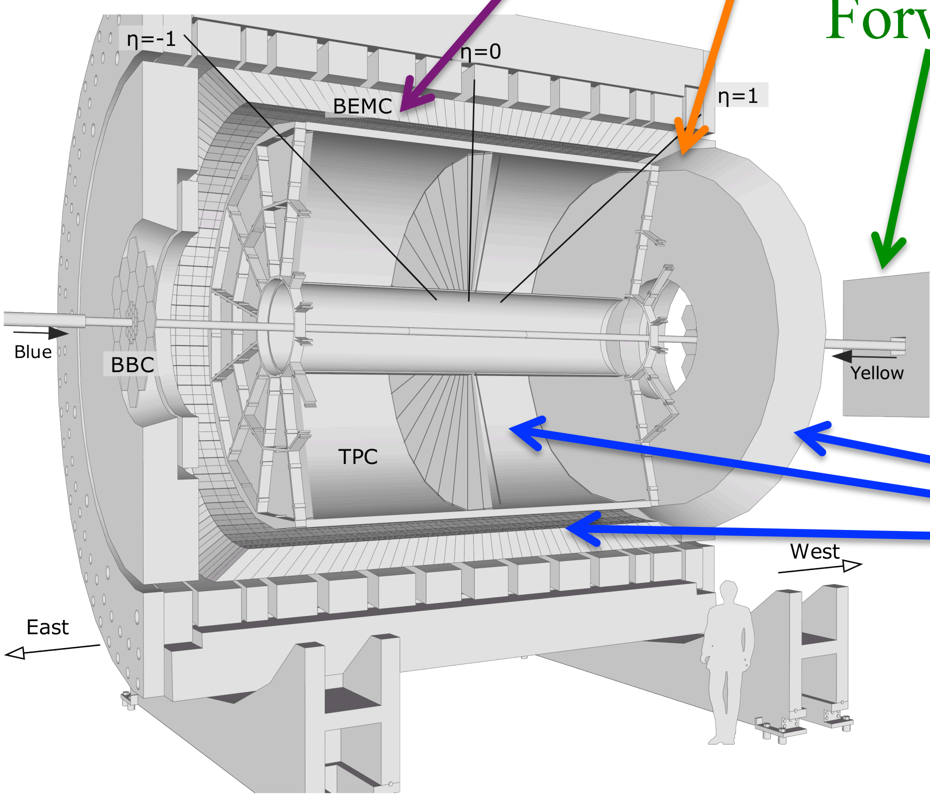
Transversity

Understanding Spin in Proton Collisions at STAR

- Probing Gluon Polarization with Jets and π^0's
- Probing Sea Quark Polarization with W's
- Probing Transverse Structure with Jets and π^0's
  - And with W's, Z's, and other probes
- Looking to the Future

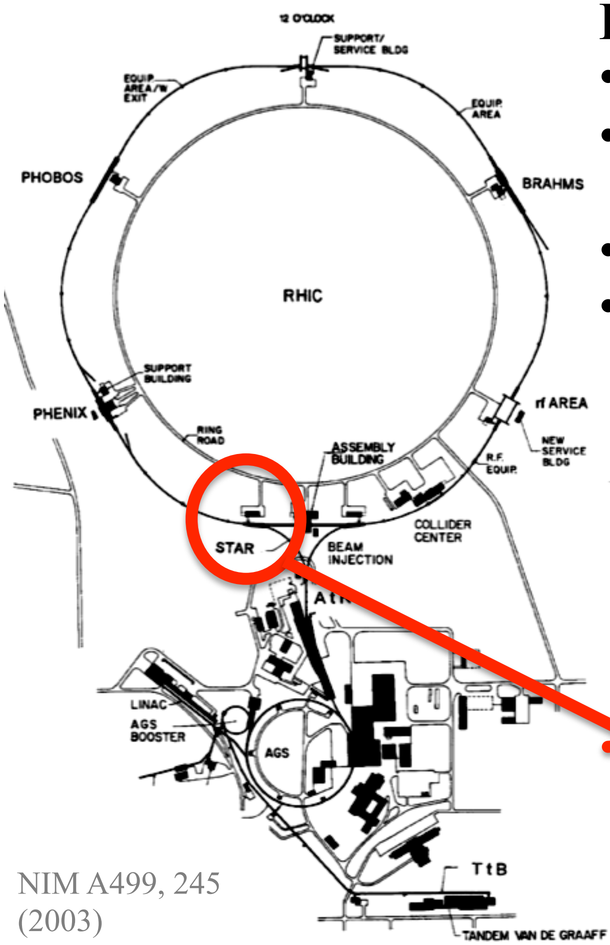
Solenoidal Tracker at RHIC

Inclusive hadron measurements:
Barrel ElectroMagnetic Calorimeter (BEMC),
Endcap ElectroMagnetic Calorimeter (EEMC),
and
Forward Meson Spectrometer (FMS)
FPD (east) not shown



Jet and W/Z measurements:
TPC +
Barrel + Endcap EMC

Solenoidal Tracker at RHIC



NIM A499, 245 (2003)

RHIC as Spin Collider

- "Siberian Snakes" → mitigate depolarization resonances
- Spin rotators provide choice of spin orientation *independent of experiment*
- Spin direction varies bucket-to-bucket (9.4 MHz)
- Spin pattern varies fill-to-fill

Inclusive hadron measurements:
Barrel E/M Calorimeter (BEMC),
Endcap E/M Calorimeter (EEMC),
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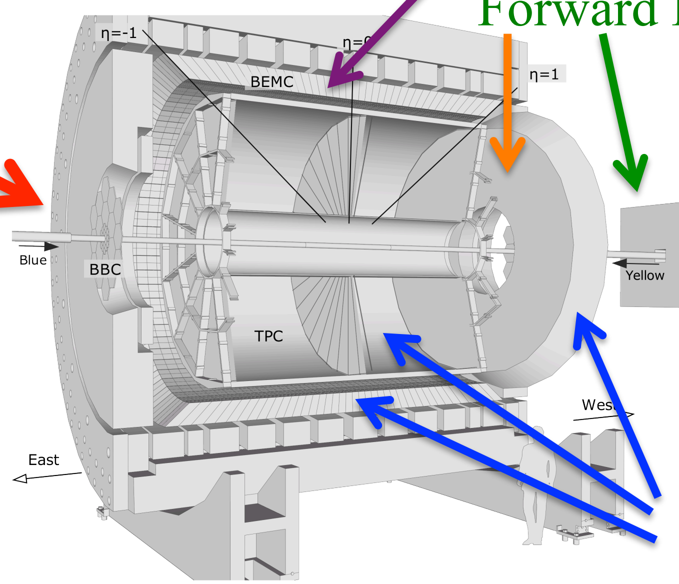
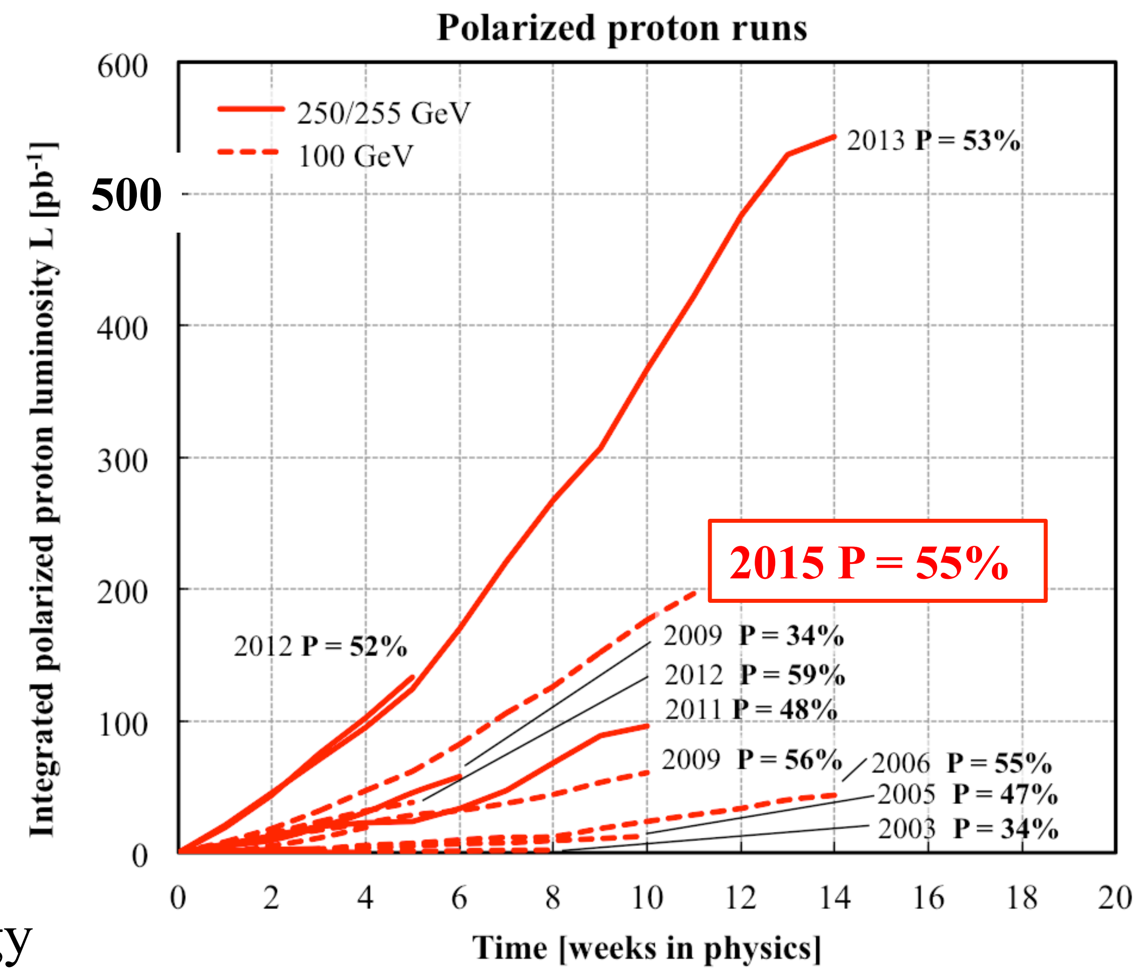
FPD (east) not shown



Jet and W/Z measurements:
TPC + Barrel + Endcap EMC

Datasets from RHIC at STAR

- Many published results from 2006, 2009 datasets
  - And W's more recently
- Preliminary results and work in progress from, especially
  - 2011 500 GeV trans.
  - 2012 200 GeV trans.
  - ***Large*** 510 GeV long. datasets in 2012 and 2013
- 2015 brought increased statistics at 200 GeV, and opened the era of high-energy spin in p+A collisions



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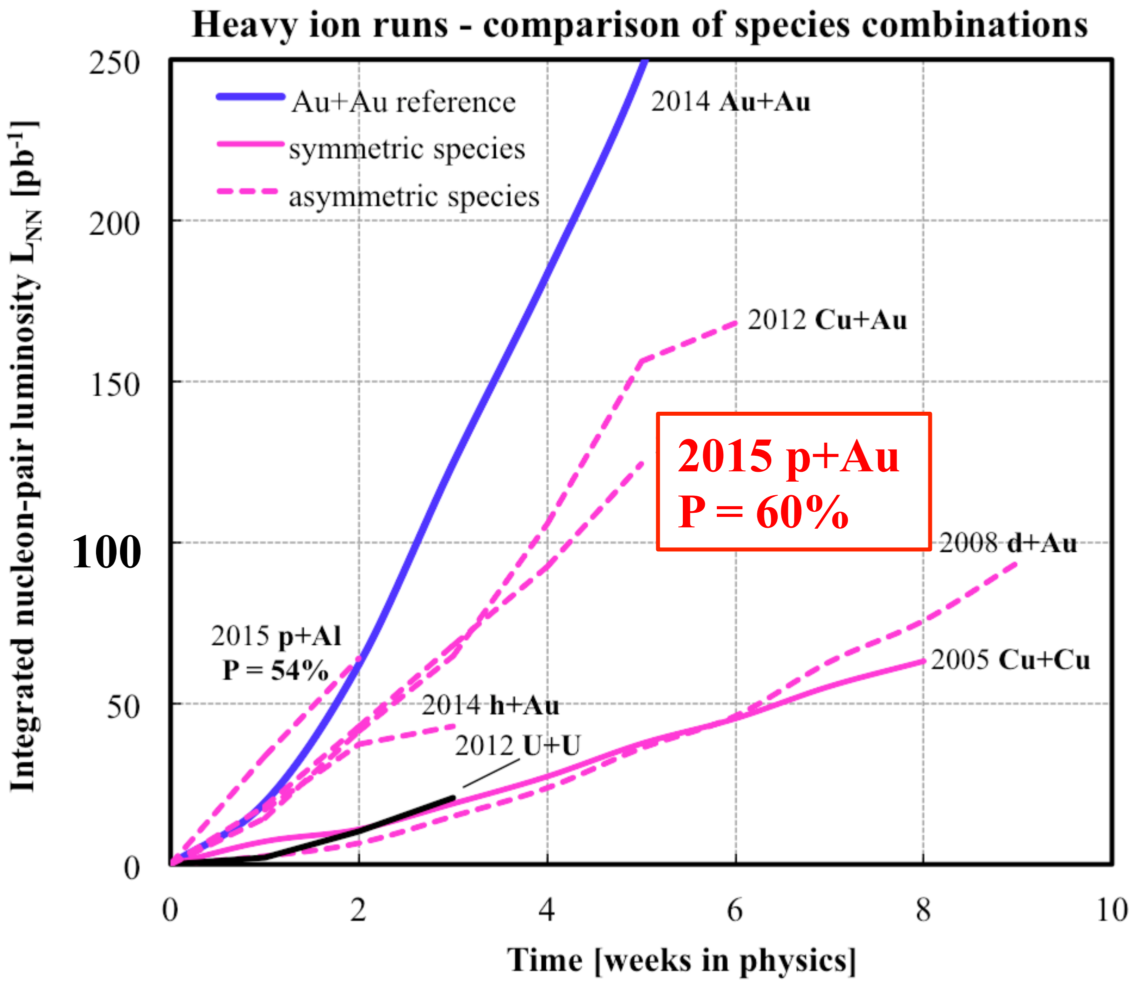

Understanding Spin in Proton Collisions at STAR

- Probing Gluon Polarizations with Jets and π^0's
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  - And with W's, Z's, and other probes
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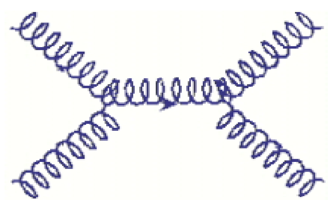
Probing (Gluon) Polarized PDF's With Jets

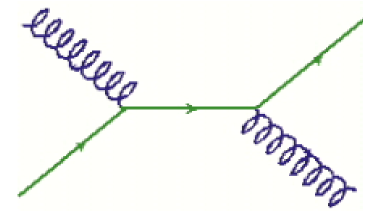
$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \propto \frac{\Delta f_a \Delta f_b}{f_a f_b} \hat{a}_{LL}$$

A_{LL} for, e.g. jets, sensitive to ***polarized PDF's*** (Δf) and ***partonic asymmetry***, $\hat{a}_{LL}$

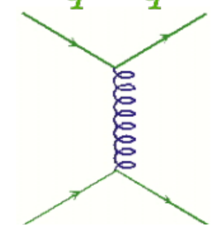
$\frac{\Delta G}{G} \frac{\Delta G}{G}$

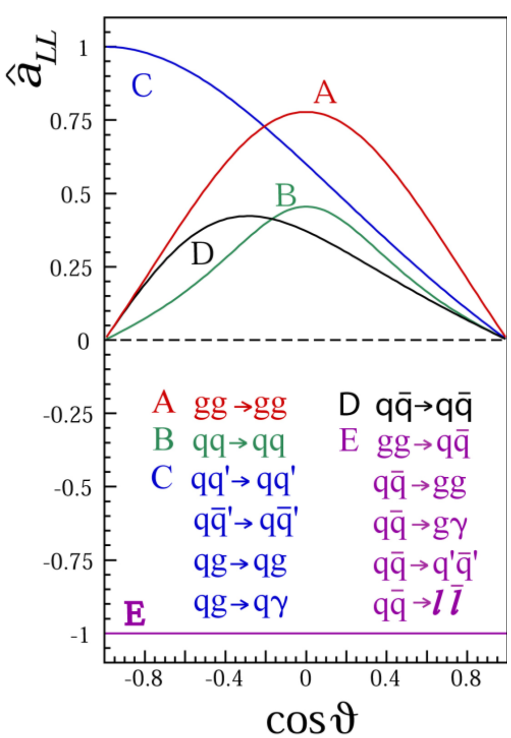


$\frac{\Delta q}{q} \frac{\Delta G}{G}$



$\frac{\Delta q}{q} \frac{\Delta q}{q}$

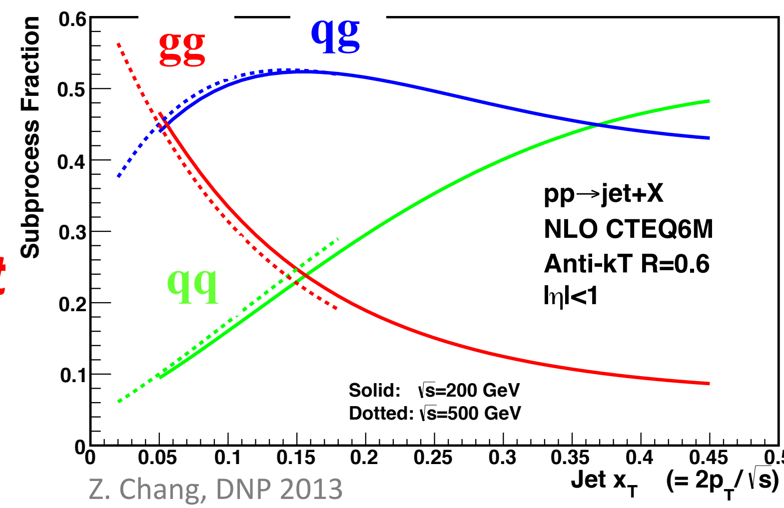




Bunce et al, Annu. Rev. Nucl. Part. Sci. 50, 525 (2000)

Asymmetries at different values of p_T or $\sqrt{s}$

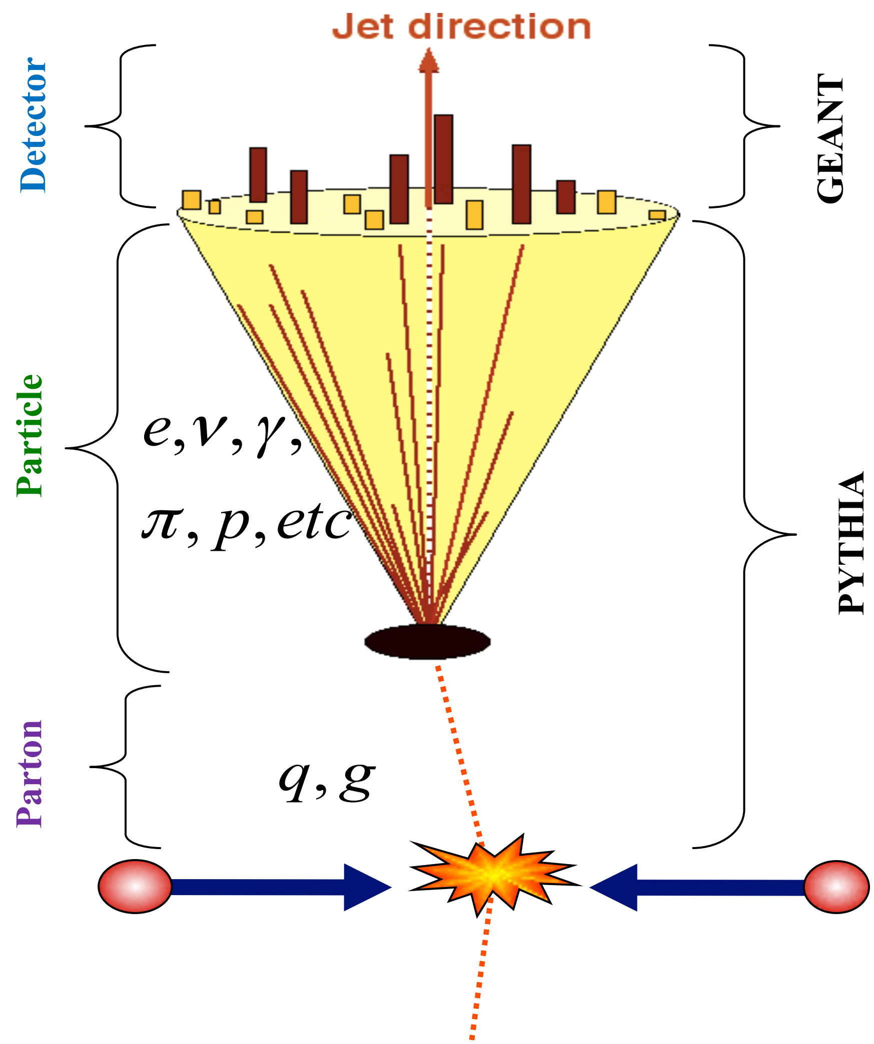
→ ***sample different mix of partonic subprocesses***



Z. Chang, DNP 2013

Jet Reconstruction

Jet Levels MC Jets



STAR Detector has:

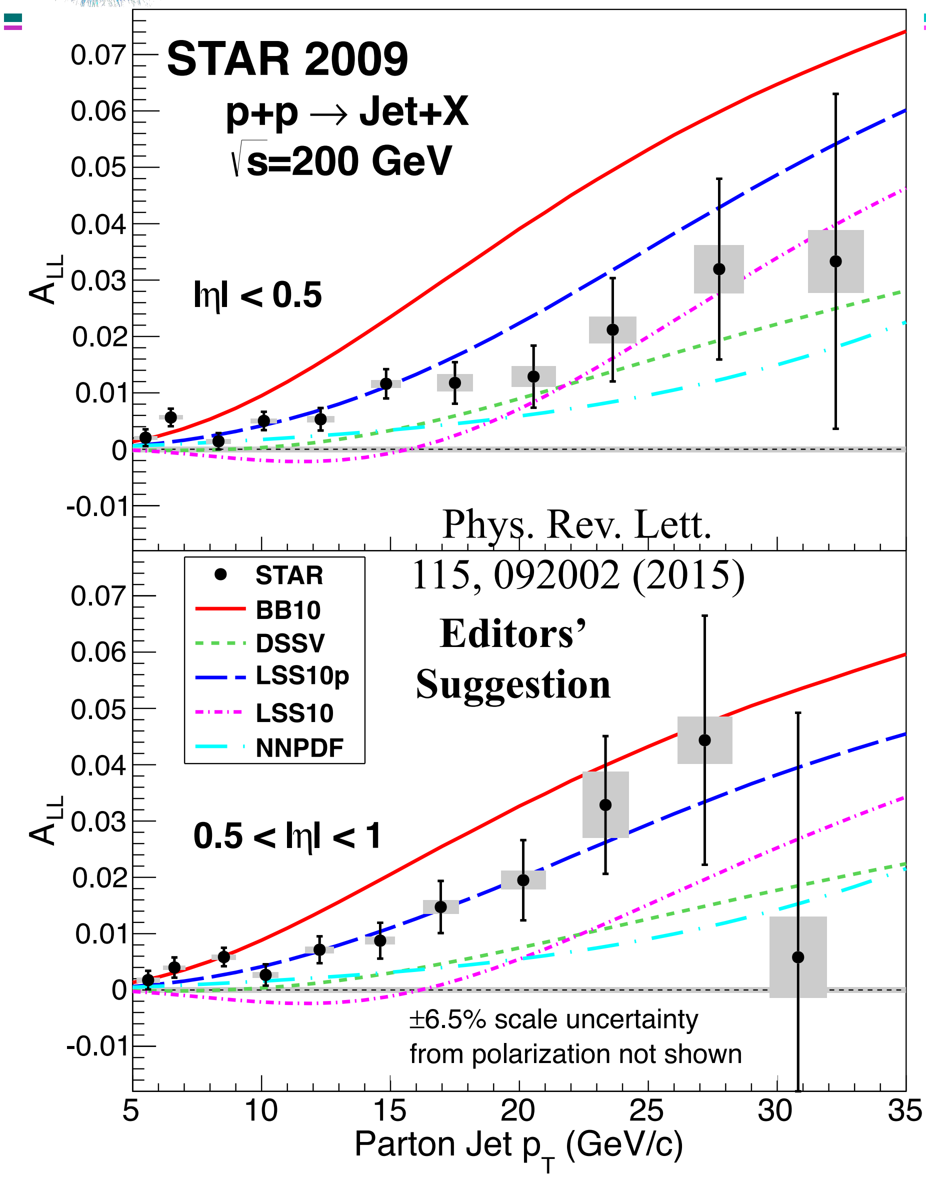
- Full azimuthal coverage
- Charged particle tracking from TPC for $|\eta| < 1.3$
- E/BEMC provide electromagnetic energy reconstruction for $-1 < \eta < 2.0$

STAR well suited for jet measurements

Anti-K_T Jet Algorithm:

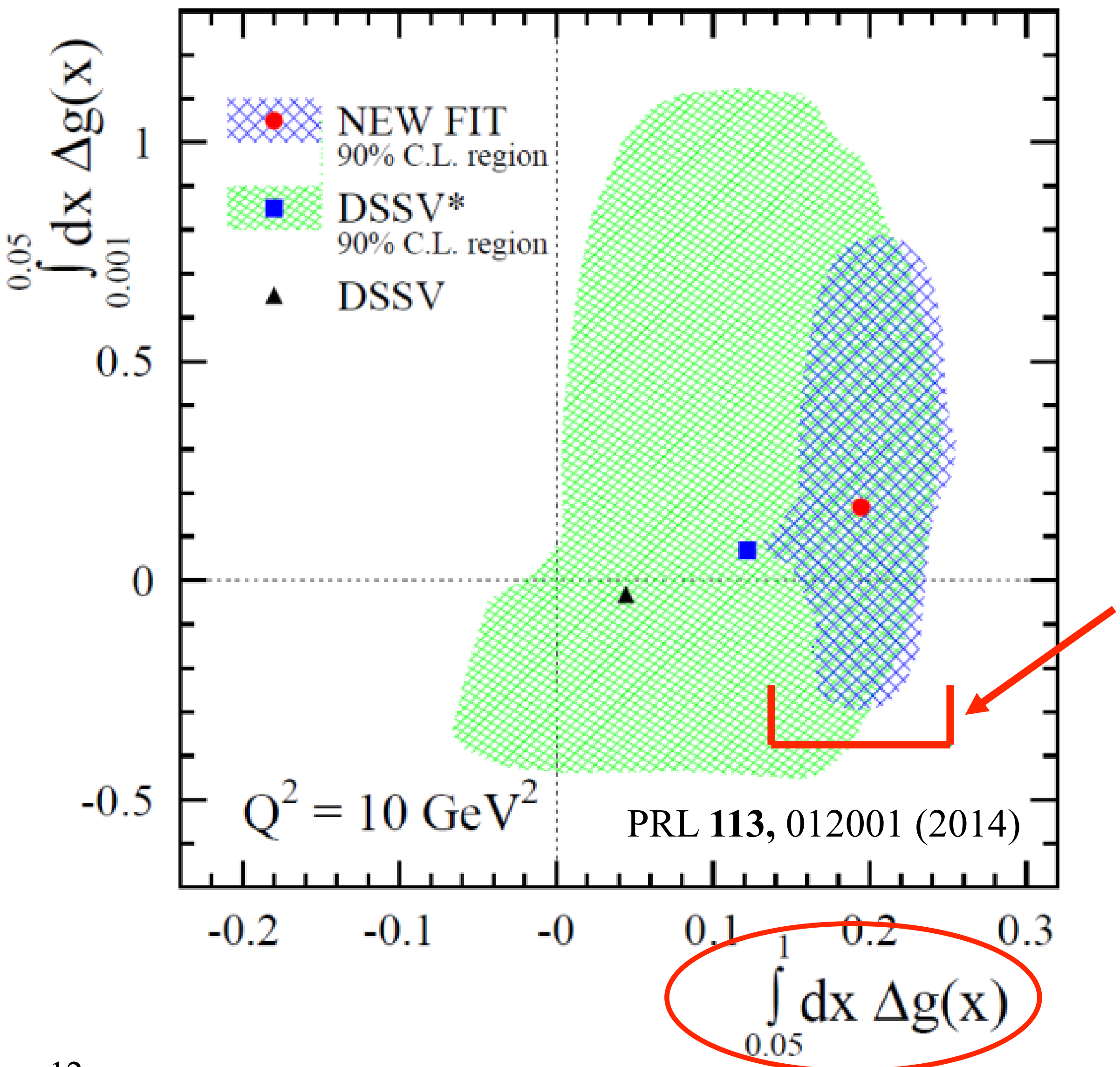
- Radius e.g 0.6 (for 2009 Jet A_{LL})
- Used in both data and simulation

2009 Inclusive Jet A_{LL}



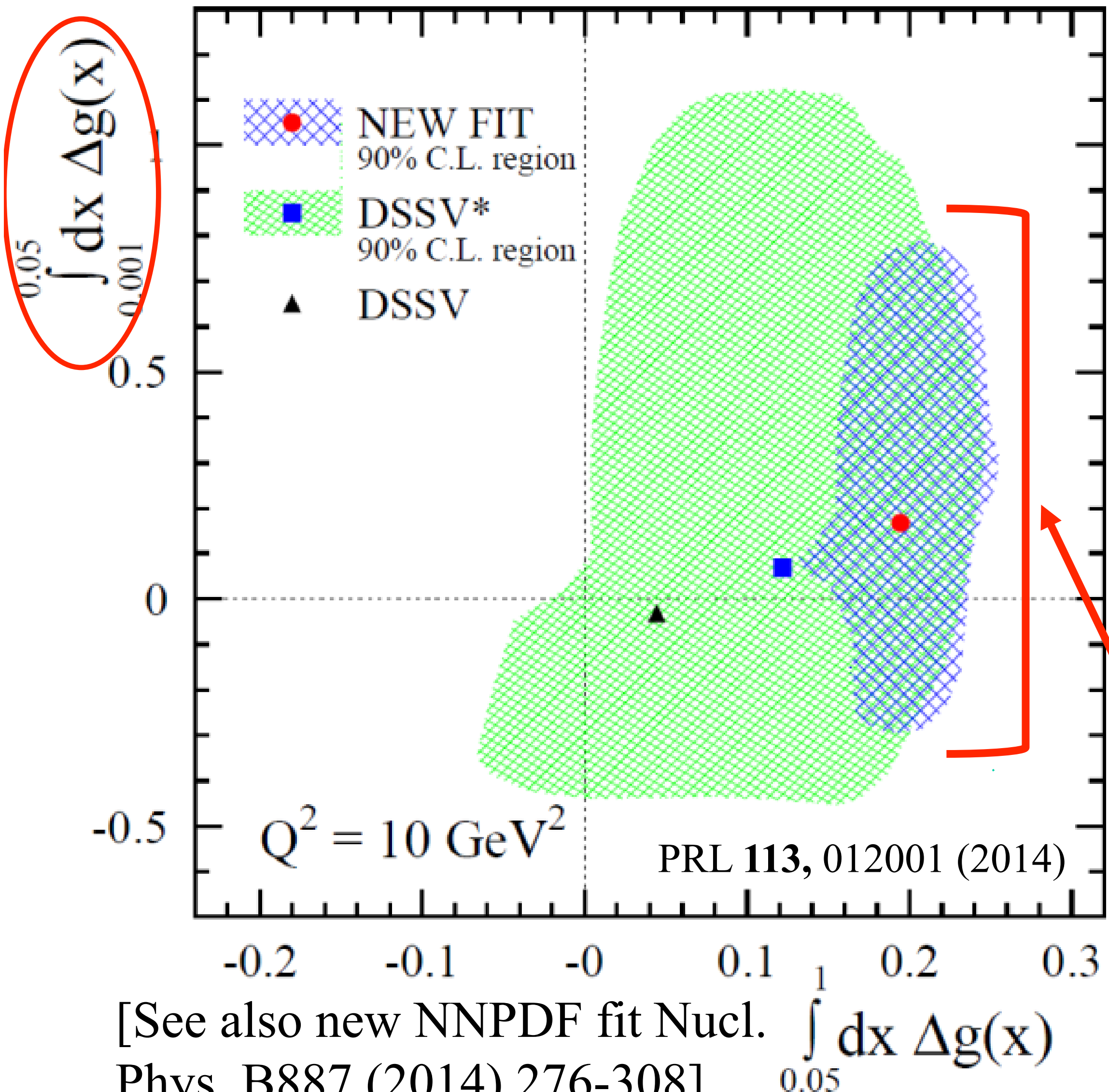
- 2009 results have factor of 3 to 4 better statistical precision than 2006 results
- Result divided into two pseudorapidity ranges which emphasize different partonic kinematics
- Result lies consistently above the 2008 DSSV fit

New DSSV Fit – G Comes into Focus



- Integral of Δg(x) in range $0.05 < x < 1.0$ increases substantially, now significantly above zero.
- Uncertainty shrinks substantially from DSSV* to new DSSV fit
- **First firm evidence of non-zero gluon polarization!**

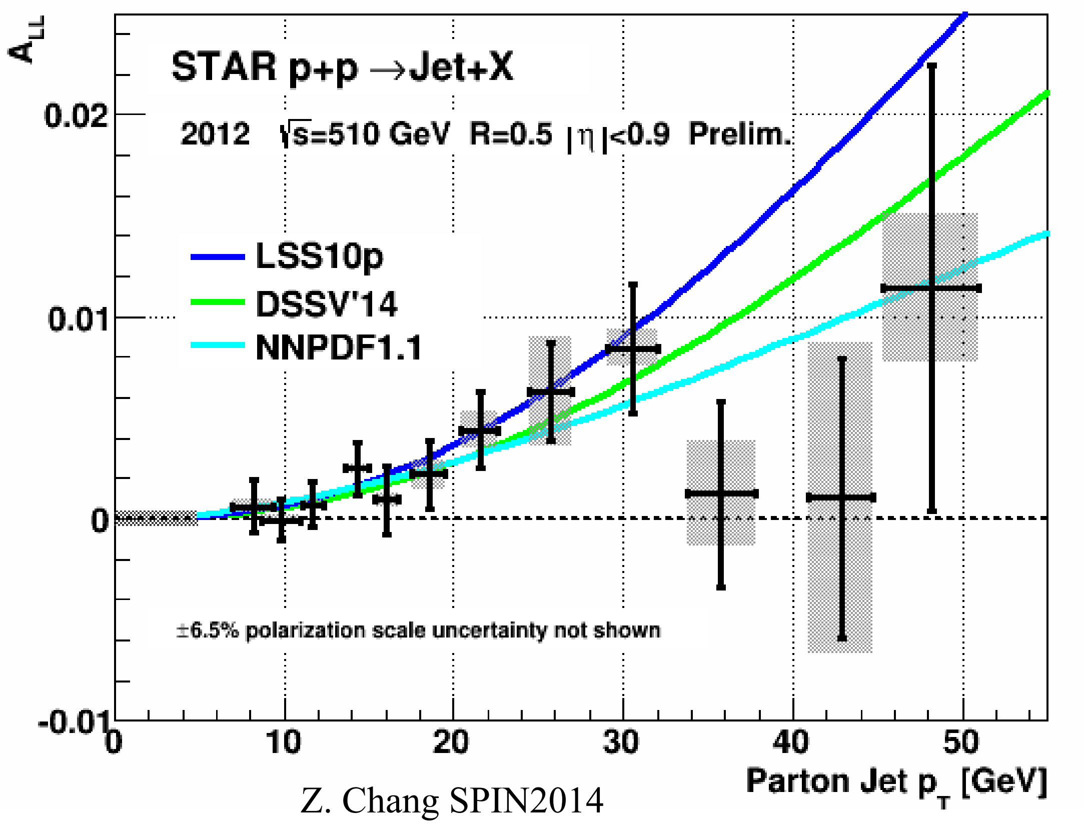
New DSSV Fit – Low x Remains Blurry



[See also new NNPDF fit Nucl. Phys. B887 (2014) 276-308]

- Integral of $\Delta g(x)$ in range $0.05 < x < 1.0$ increases substantially, now significantly above zero.
- Uncertainty shrinks substantially from DSSV* to new DSSV fit
- Uncertainty on integral over low x region is still sizable

2012 Inclusive Jet A_{LL} at 510 GeV



Z. Chang SPIN2014

- Push to lower x_g w/ higher CoM energy
- 50 pb^{-1} at 53% avg. polarization
- Smaller cone, R = 0.5 reduces effect of pileup
- **Agrees well with latest predictions**

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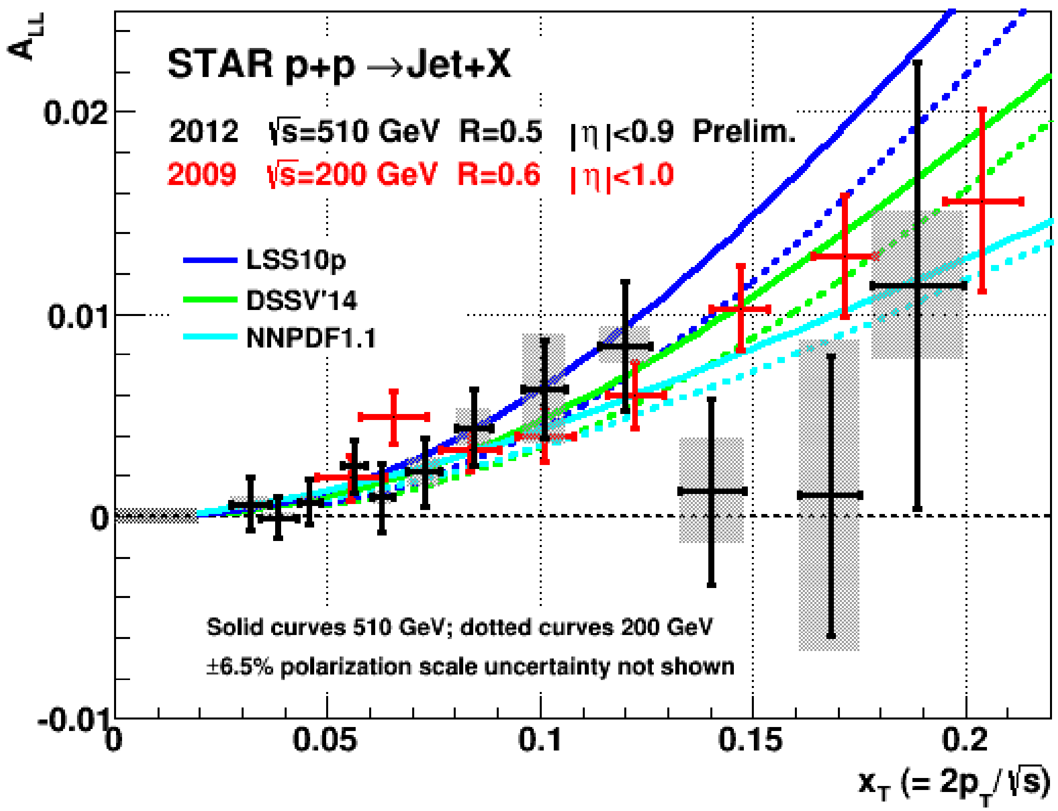


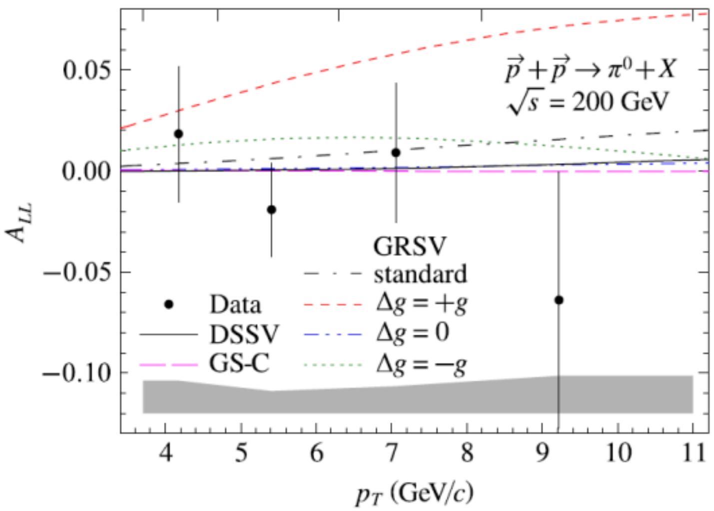
- Push to lower x_G w/ higher CoM energy
- 50 pb^{-1} at 53% avg. polarization
- Smaller cone, R = 0.5 reduces effect of pileup
- **Agrees well with latest predictions**

- Higher CoM pushes to lower x_T
  - Results agree in overlap region

- Higher 200 GeV statistics coming with 2015 dataset

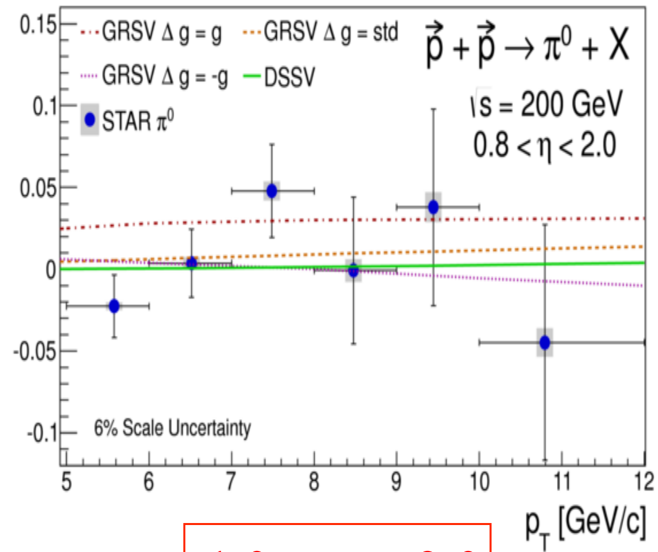
Probing Low x Gluons With π^0 A_{LL}

PRD 80, 111108(R) (2009)



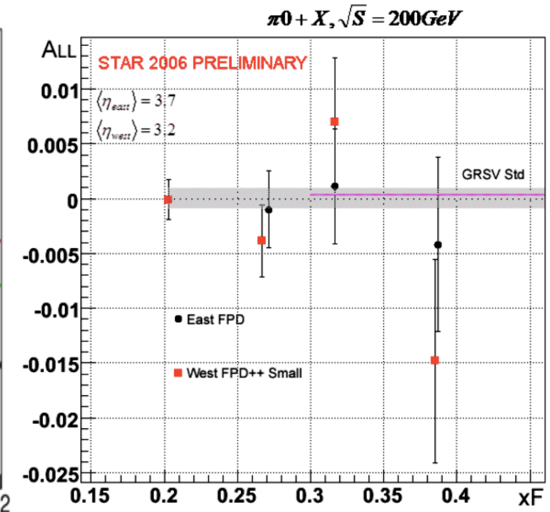
|η| < 0.95

PRD 89, 012001 (2014)



1.0 < η < 2.0

Wissink SPIN2008

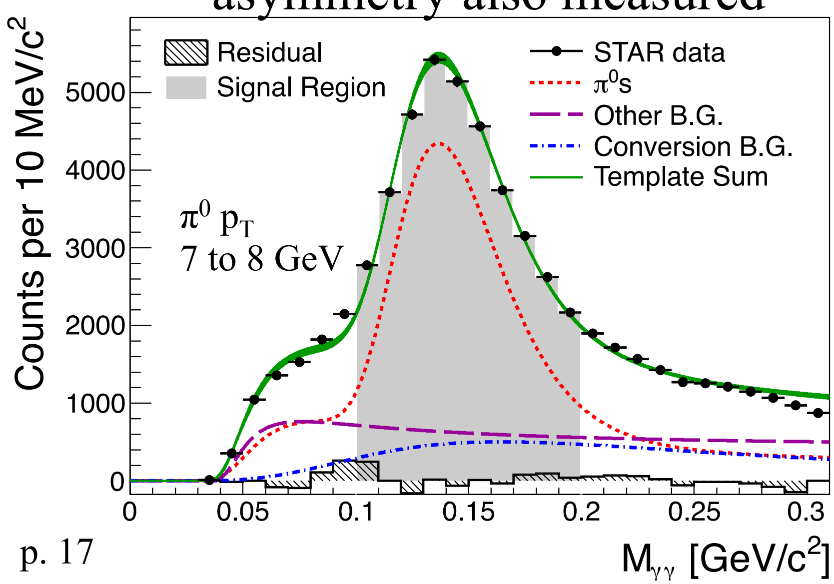


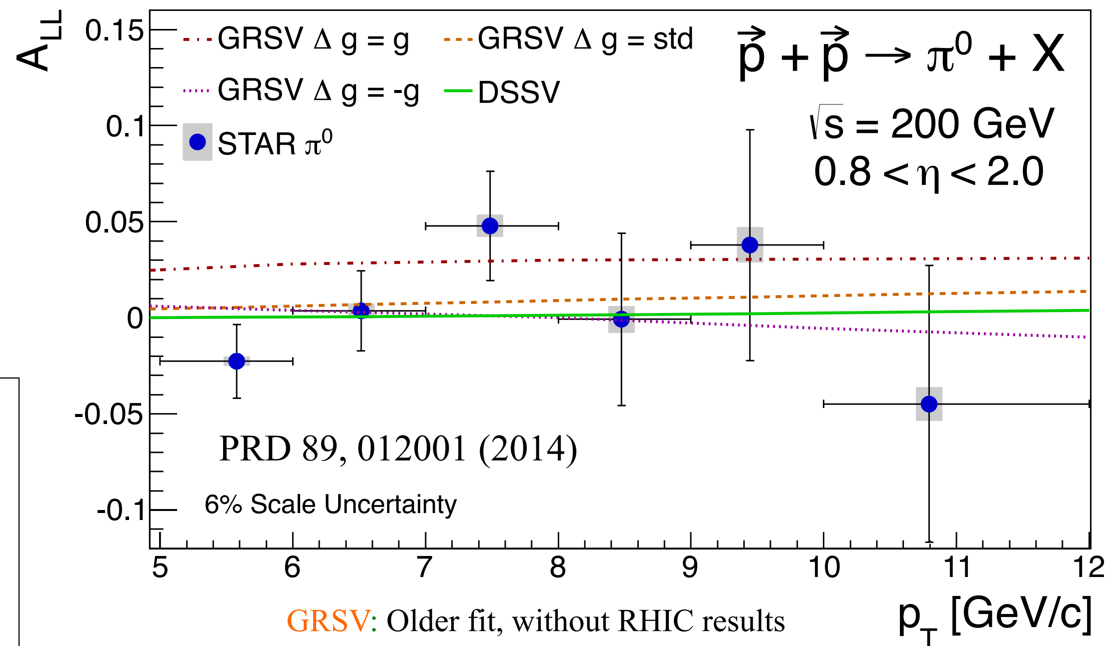
η = 3.2, 3.7

- STAR has measured π^0 A_{LL} in three different pseudorapidity ranges
  - Different kinematics, different fragmentation, different systematics
  - Here with data from 2006
- qg scattering dominates at high η with high x quarks and low x gluons
- **No large asymmetries seen**

A_{LL} in $\pi^0 + X$ at STAR for $0.8 < \eta < 2.0$

- 2006 Dataset in the Endcap Electromagnetic Calorimeter (EEMC)
- Push to reasonably low *x* by going (relatively) forward
- Statistical error (bars) dominate
- Systematic error (boxes)
  - Signal fraction uncertainties from template fits
  - Uncertainty on background asymmetry
- Cross section and transverse asymmetry also measured



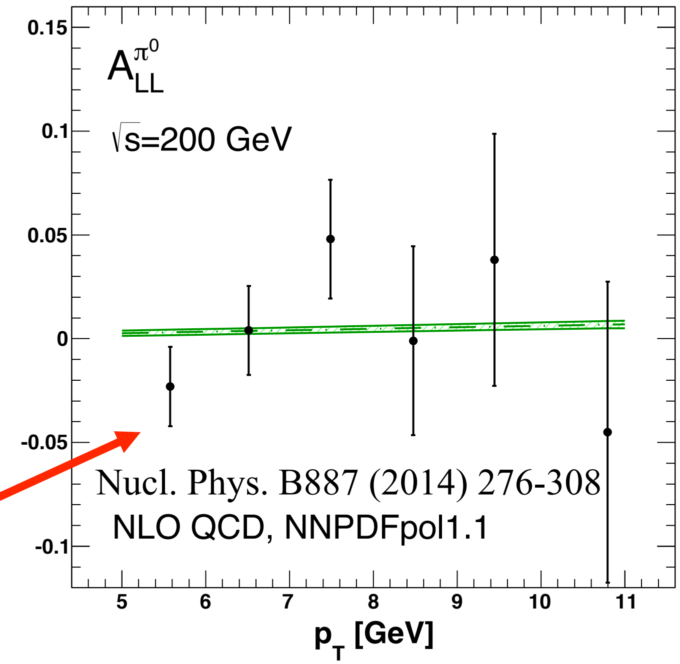


GRSV: Older fit, without RHIC results
PRD 63, 094005 (2001)

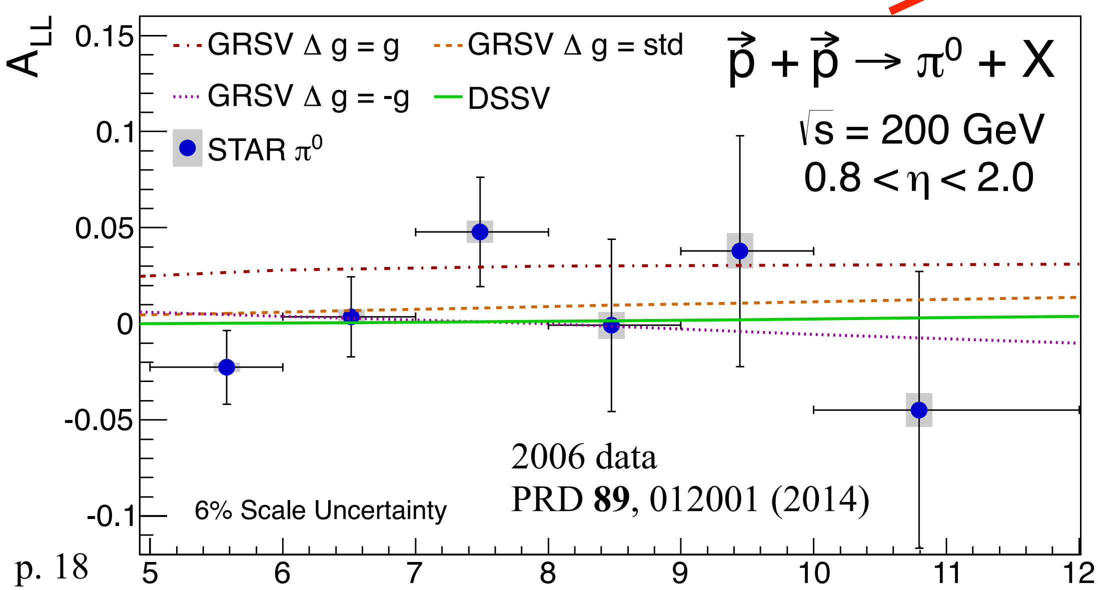
DSSV: First fit to include RHIC results
PRL 101, 072001 (2008)

Updated Prediction for π^0 A_{LL}, $0.8 < \eta < 2.0$

- NNPDFpol1.1 includes jet results from STAR and PHENIX, including the recently submitted 2009 STAR inclusive jets
- Greater precision needed to constrain the fit

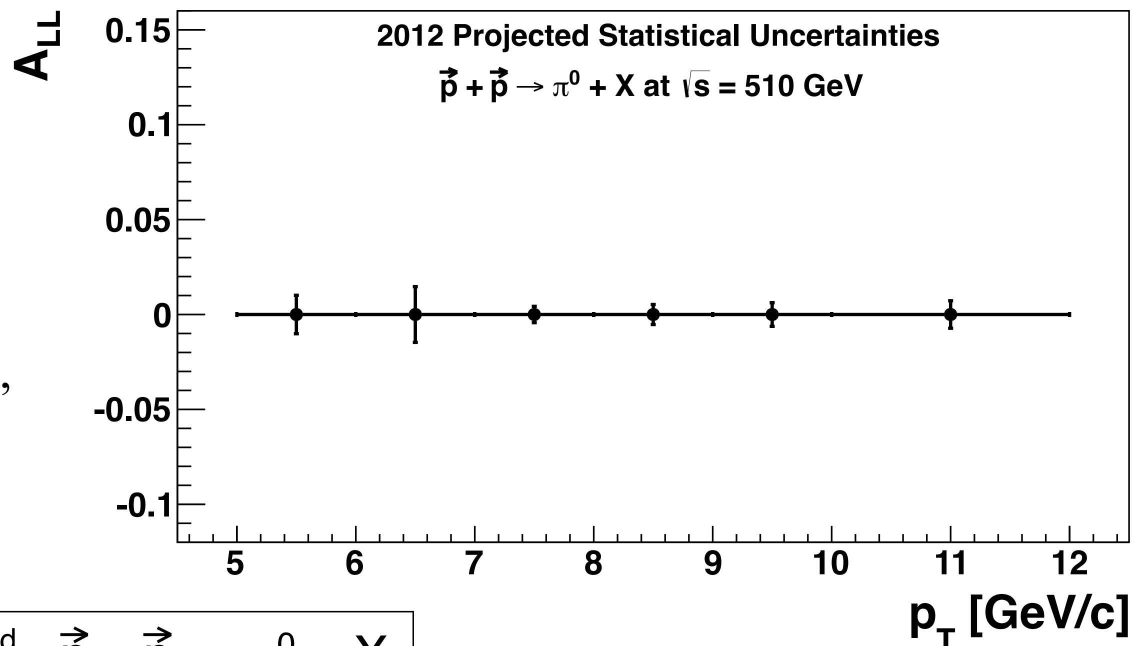


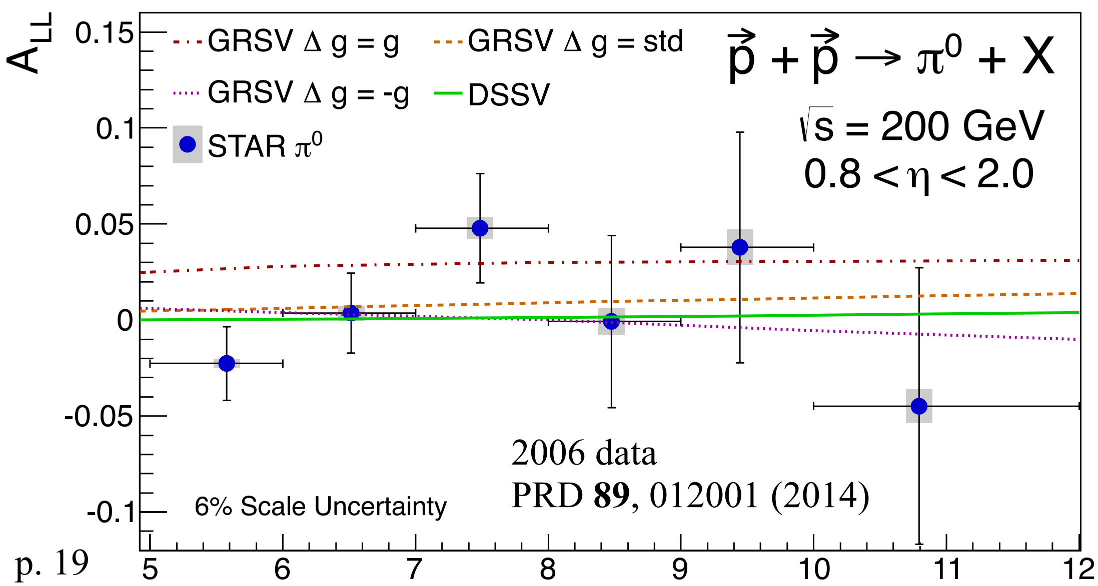
STAR data with NNPDF predictions



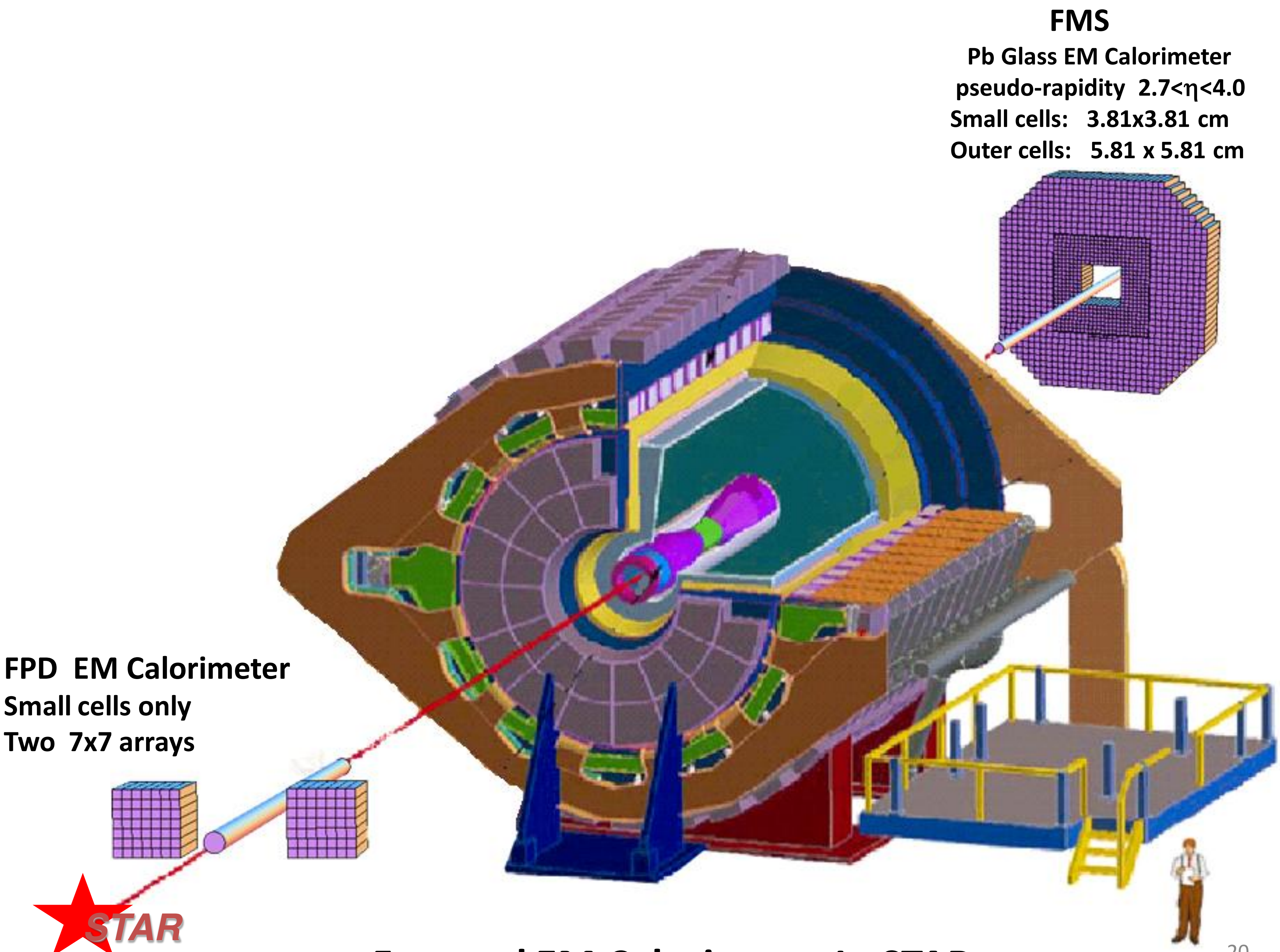
π^0 A_{LL} Prospects in 2012 Dataset

- Work underway at STAR with 2012 dataset (x10 the 2006 luminosity) at intermediate (endcap) pseudorapidity
  – Large improvement in stat. uncertainty projected, as shown





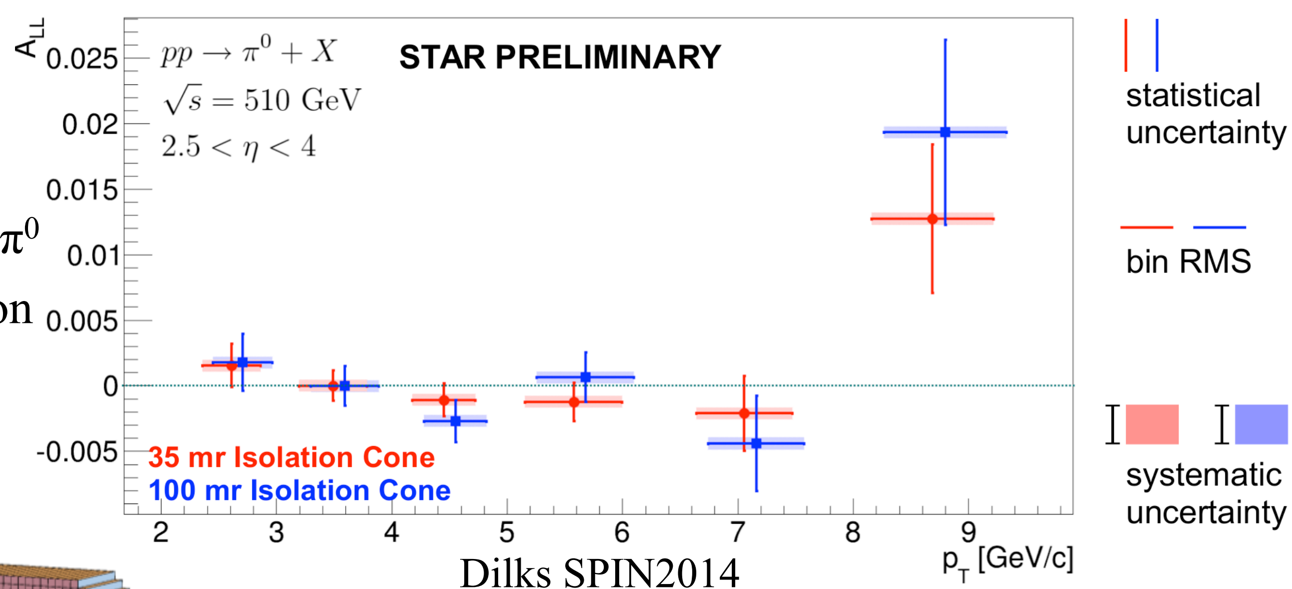
- Higher CoM energy
  - 200 → 510 GeV
  - Pushes to lower *x* gluon



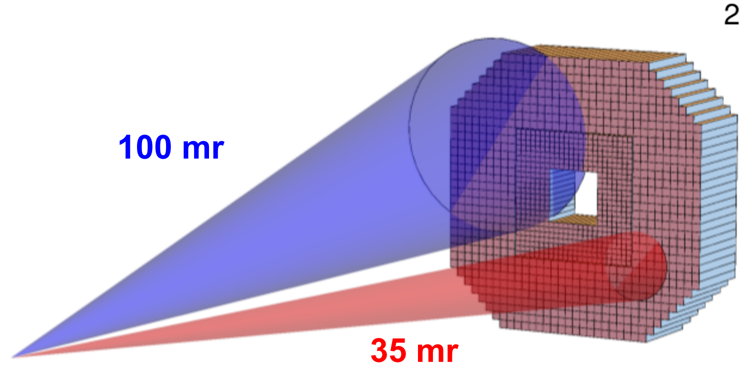
Forward EM Calorimetry In STAR.

π^0 A_{LL} Prospects in Forward Calorimeters

- Pushing even further forward, with the FMS
- Preliminary with large 2012 and 2013 datasets at 510 GeV
  - After prescales, effectively 46 pb^{-1} in 2012, $p_T > 2.5$ GeV
    - And 8 pb^{-1} in 2013, $p_T > 2.0$ GeV
  - An older preliminary result also exists, with the FPD (Wissink SPIN2008)
- Require isolation cone around π^0's
  - Motivated by A_N increase for isolated π^0
  - Now exploring isolation dependence



Dilks SPIN2014



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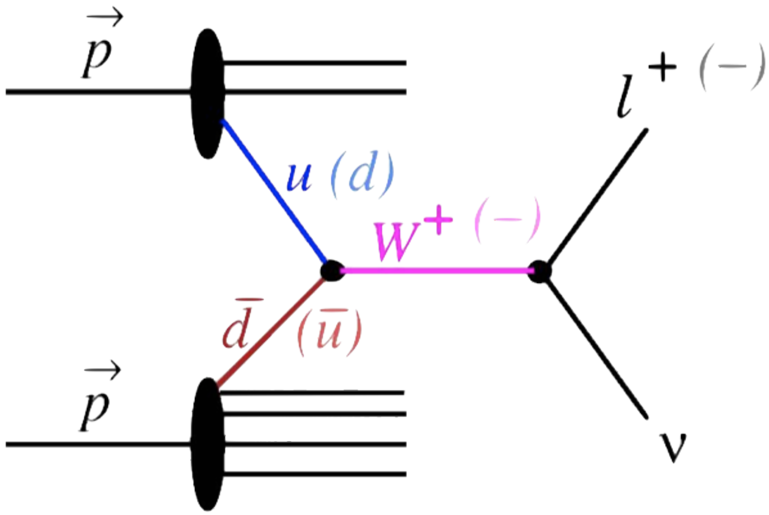
Probing Sea Quark Polarizations With W's



$$u + \bar{d} \to W^+ \to e^+ + \nu$$

$$d + \bar{u} \to W^- \to e^- + \bar{\nu}$$

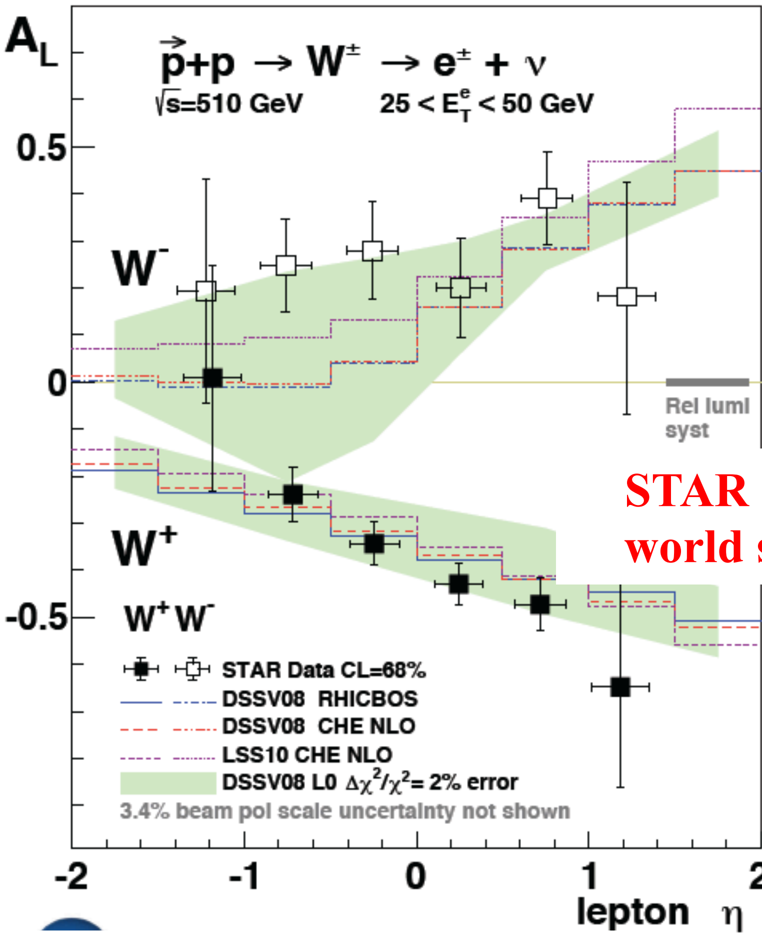
- W's couple directly to the quarks and antiquarks of interest
- Detect W's through e^+/e^- decay channels
- Longitudinally, excellent probes of sea quark polarizations
- Also an important probe of transverse physics

Measure parity-violating single-spin asymmetry:

(Helicity flip in one beam while averaging over the other)

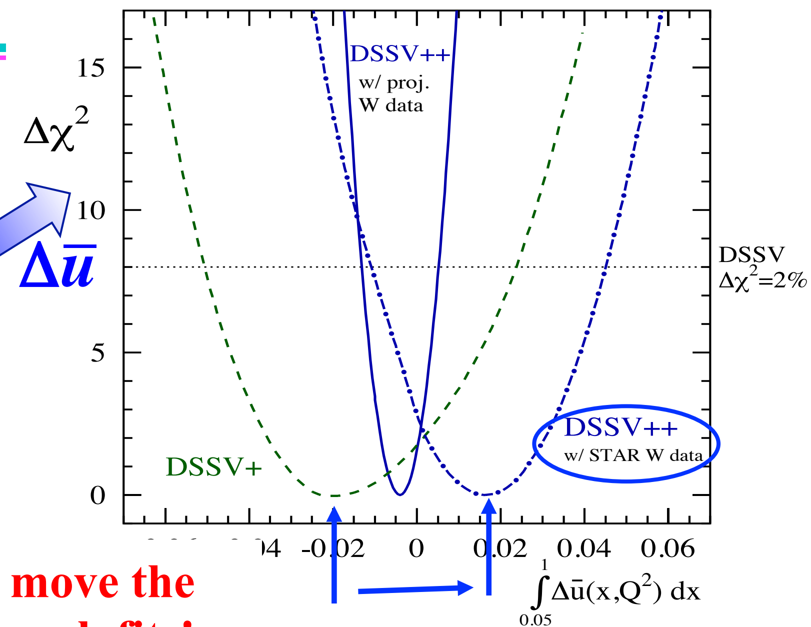
$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

Results from 2012 W's

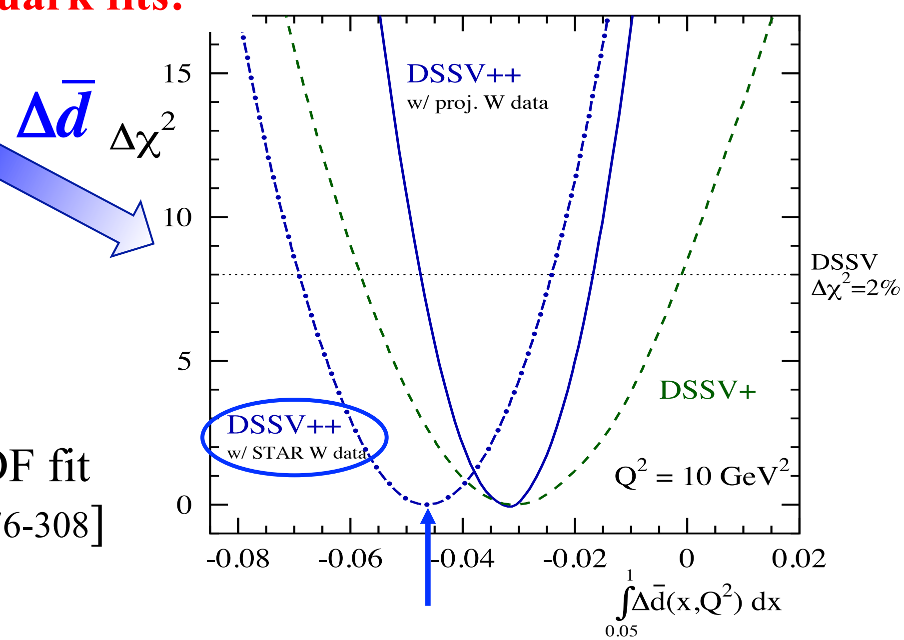


Phys.Rev.Lett. 113 (2014) 072301

arXiv:nucl-ex/1304.0079



STAR data move the world sea quark fits!

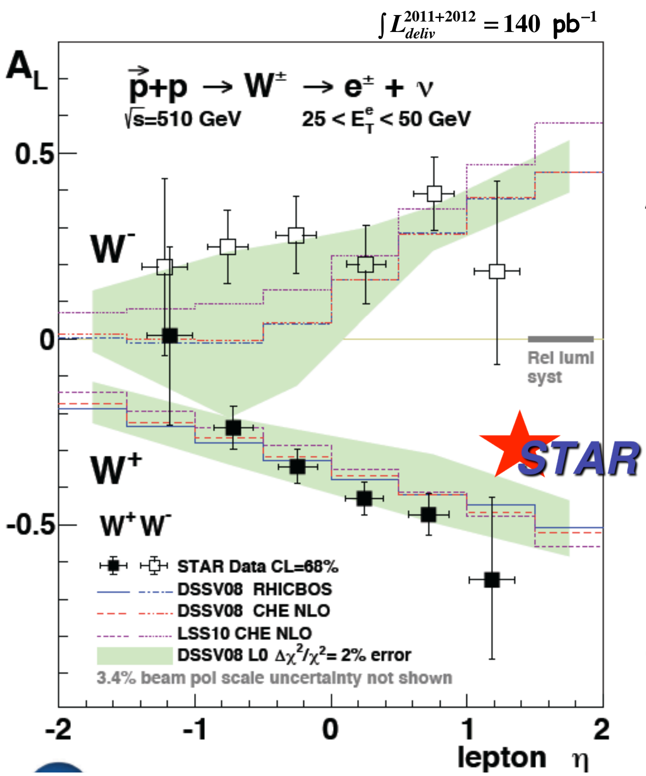


[See also new NNPDF fit Nucl. Phys. B887 (2014) 276-308]

DSSV+: DSSV+COMPASS
DSSV++: DSSV+ & STAR-W 2012
DSSV++: DSSV+ & RHIC-W proj. (2009-2013)

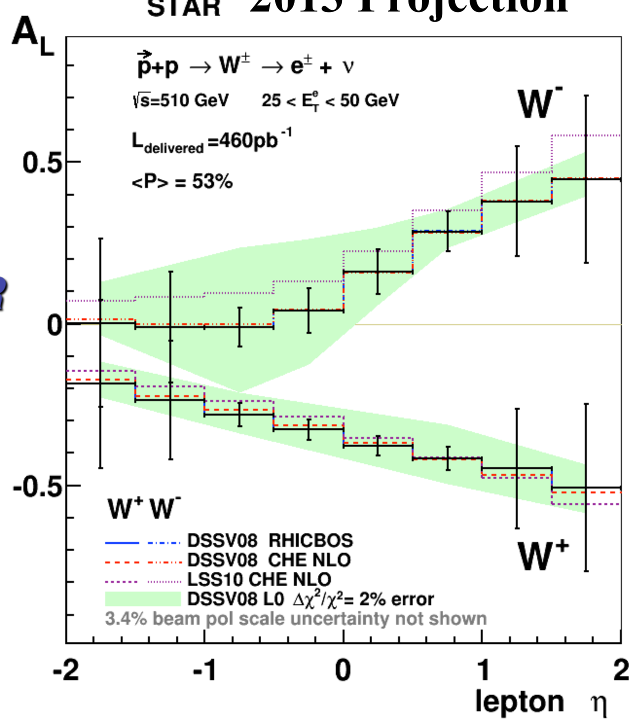
W Projections

2011-2012 Results

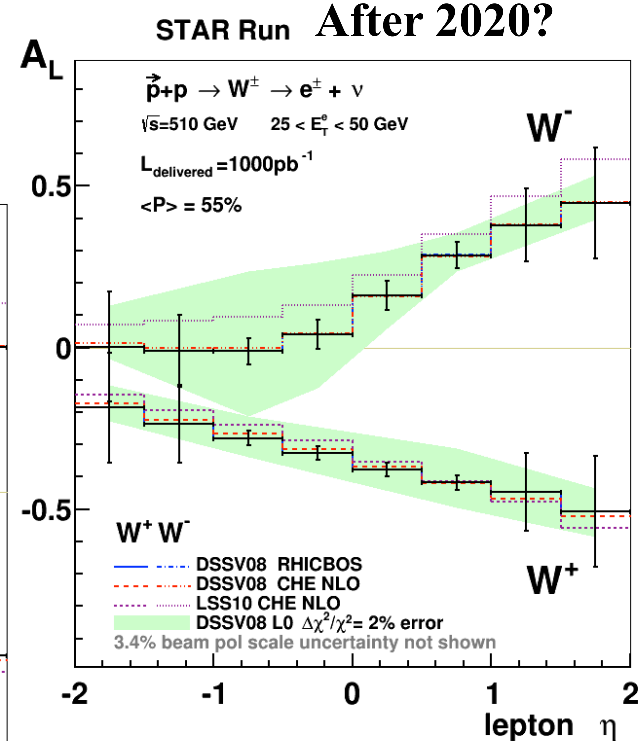


Phys.Rev.Lett. 113 (2014) 072301

2013 Projection



1 fb^{-1} Projection After 2020?



Includes **F**orward **G**EM **T**racker at STAR, fully installed in 2013

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Puzzle of Large Transverse Spin Asymmetries, A_N

- Anomalously large A_N observed for nearly 40 years
  - In naïve, co-linear, leading-order/leading-twist QCD expect very small A_N, especially at high energy

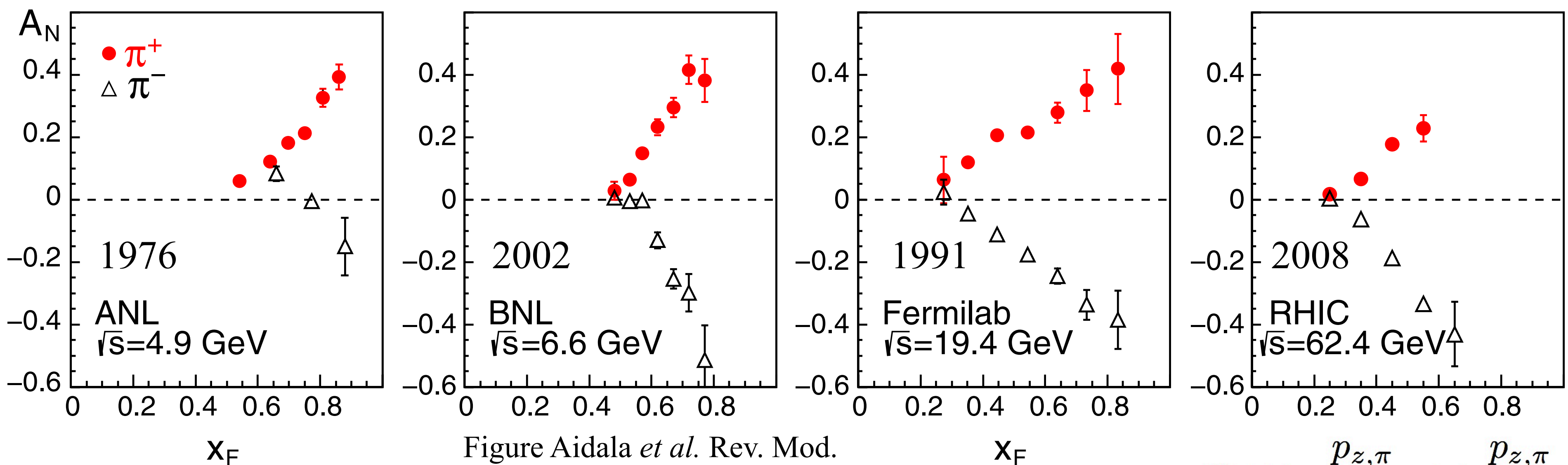
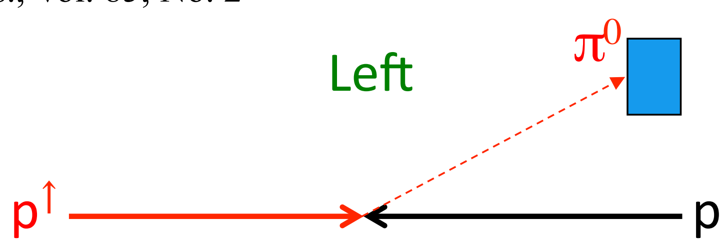


Figure Aidala *et al.* Rev. Mod. Phys., Vol. 85, No. 2

$$x_F = \frac{p_{z,\pi}}{p_{z,\max}} = \frac{p_{z,\pi}}{\sqrt{s}/2}$$

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

$d\sigma^{\uparrow(\downarrow)}$ – cross section for leftward scattering when beam polarization is spin-up(down)

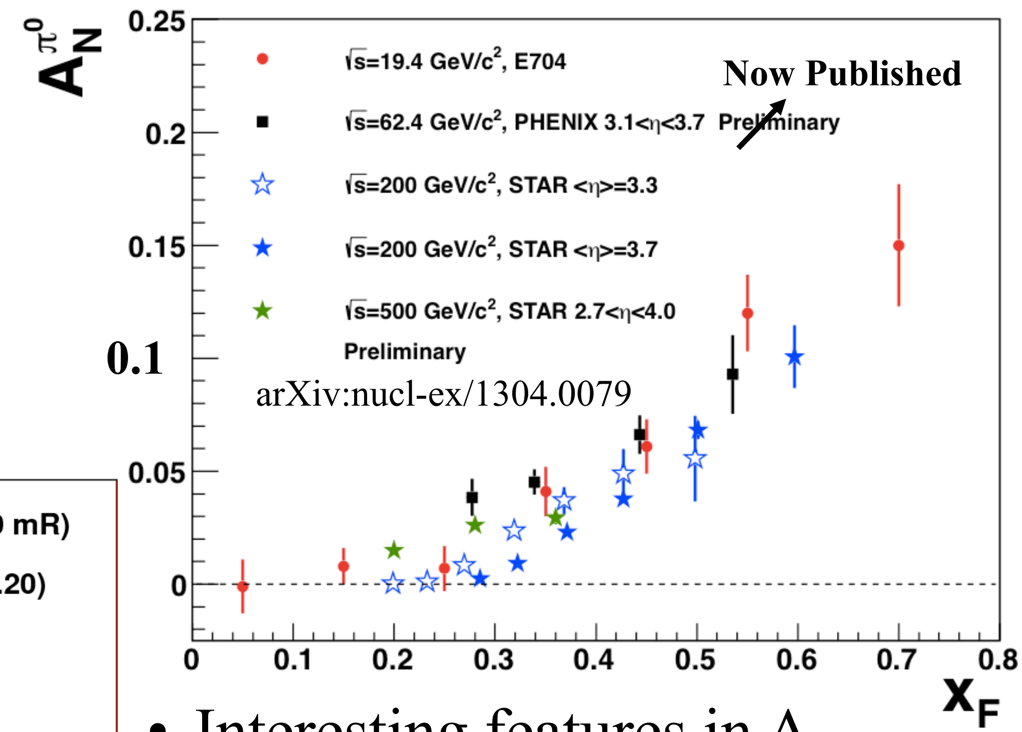


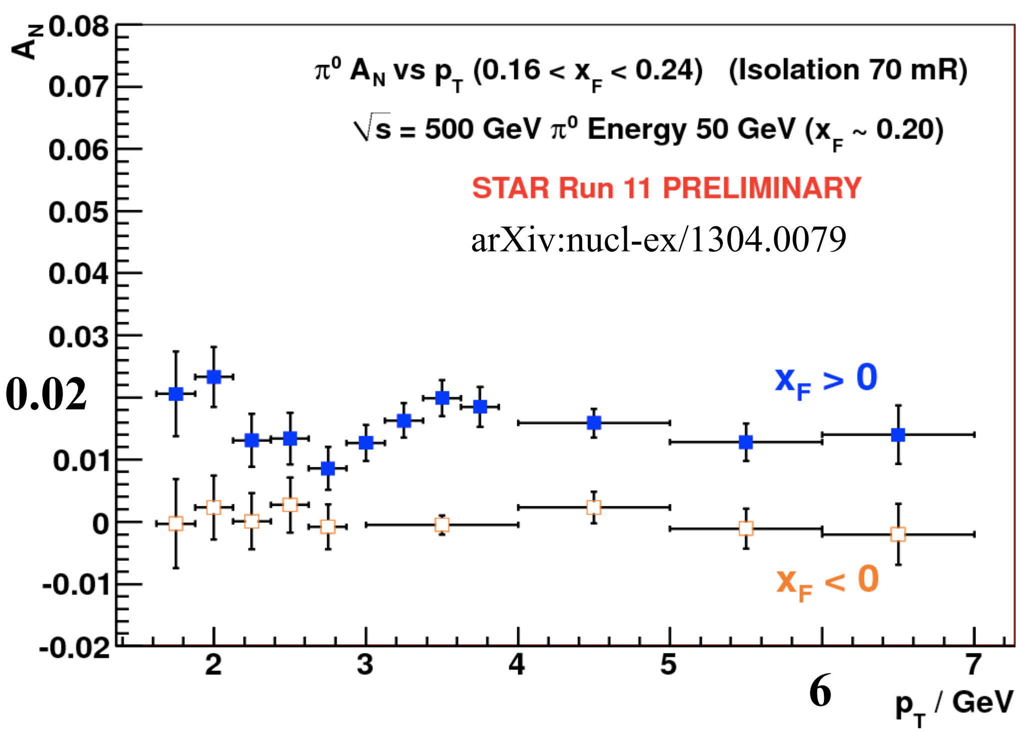
Positive A_N – more π^0 to ***left*** of (up) polarized beam

For a 2π detector, A_N manifests as an azimuthal (ϕ) asymmetry

Puzzle of Large Transverse Spin Asymmetries, A_N

- Persists at STAR/RHIC
  - At forward pseudorapidity
  - At high x_F

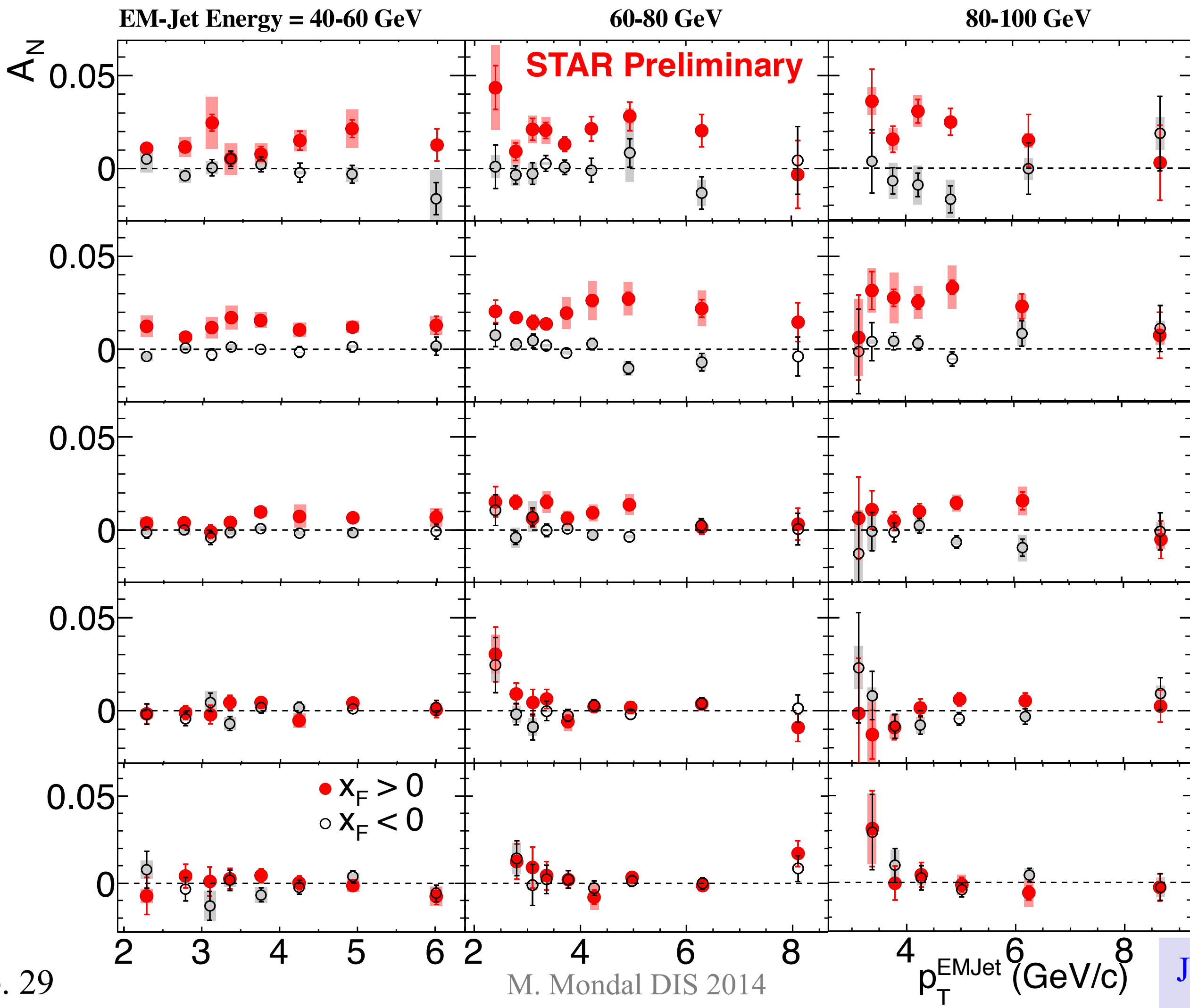




- Interesting features in A_N
  - Persists to surprisingly large p_T
  - Larger in η's than π^0's?
  - In relatively isolated π^0's, not in jets
  - Smaller when there's central activity
  - Diffractive physics?
    - **New Roman Pots in 2015**

A_N for Forward EM Events: Dependence on Jettiness

- 2011 Dataset in FMS, 22 pb^{-1} with 52% pol., 500 GeV
  Anti-k_T jet algorithm on FMS photons, R = 0.7



✧ 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"

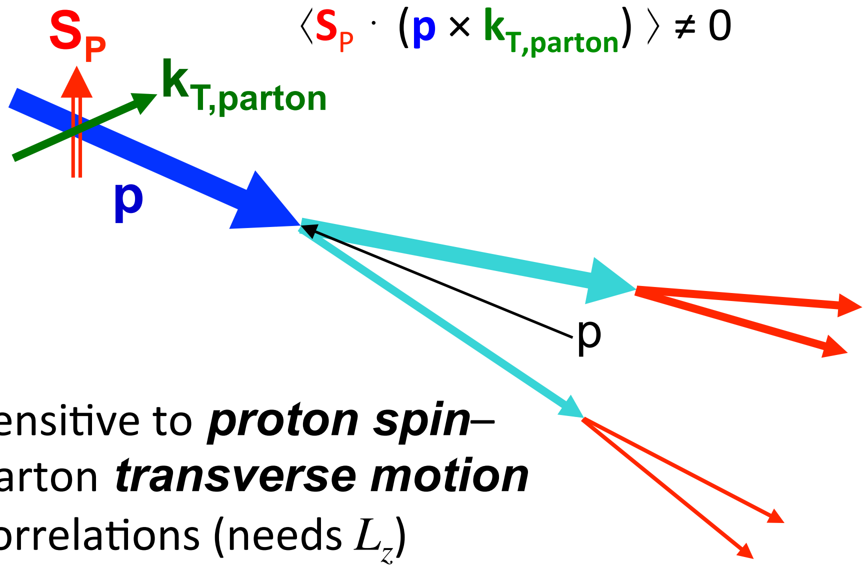
✧ A_N for #photons >5 is similar to that for #photons = 5

Jettier events

Mechanisms for Transverse Single-spin Asymmetries

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

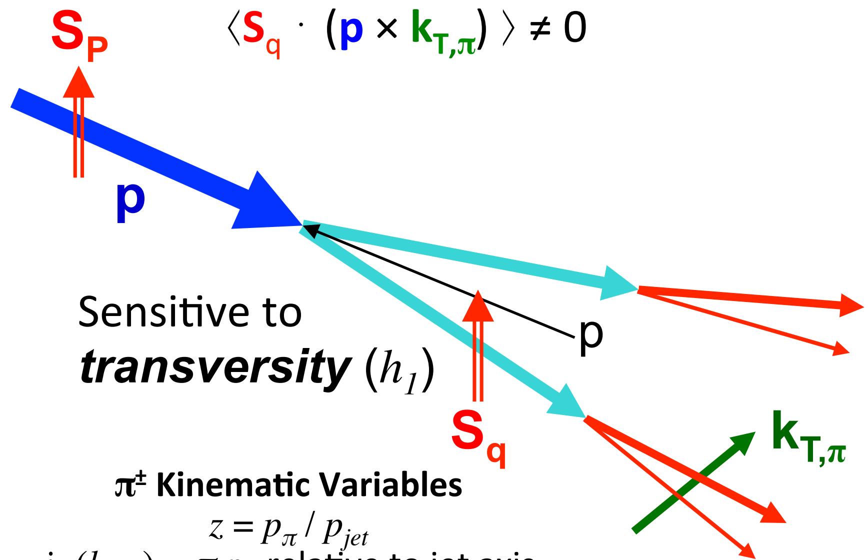
D. Sivers, PRD 41, 83 (1990); 43, 261 (1991)



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

Collins mechanism: asymmetry in the forward jet *fragmentation*

J. Collins, NP B396, 161 (1993)

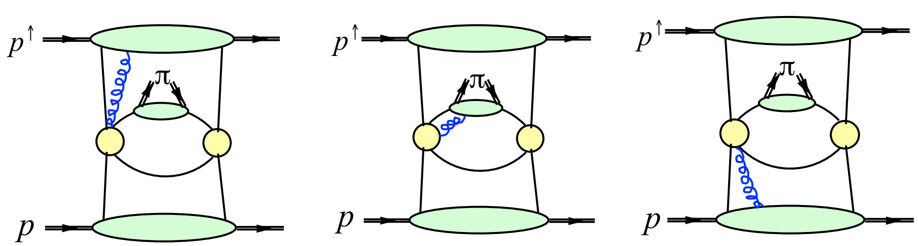


Sensitive to ***transversity*** (h_1)

π± Kinematic Variables

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

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



Y. Koike, RSC Discussion (2004)

Twist-3 mechanism: Asymmetry from multi-parton correlation functions

e.g. Qiu and Sterman, PRL 67, 2264 (1991); PRD 59, 014004 (1998)
e.g. Efremov, Teryaev

Correlators closely related to k_T moments of TMD's

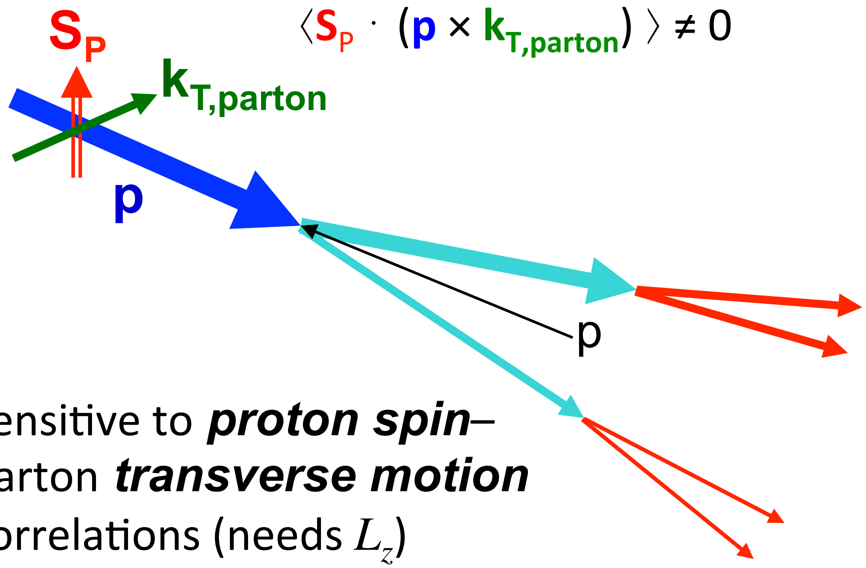
Boer, Mulders, Pijlman, NPB 667, 201 (2003)

Mechanisms for Transverse Single-spin Asymmetries

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

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

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

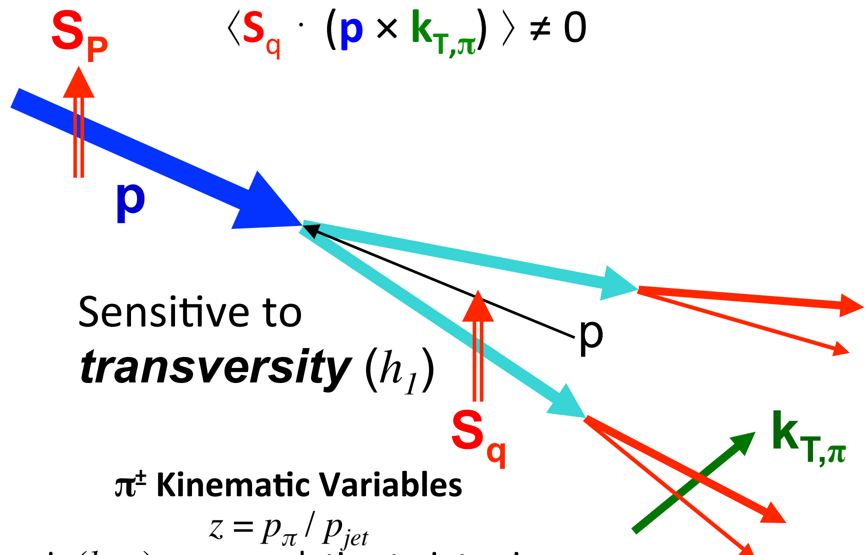


Sensitive to ***proton spin*–** parton ***transverse motion*** correlations (needs L_z)

Collins mechanism: asymmetry in the forward jet *fragmentation*

J. Collins, NP B396, 161 (1993)

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



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

$\pi^{\pm}$ Kinematic Variables

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

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

Inclusive hadron asymmetries:

Unable to islolate contributions

Sivers, Collins, twist-3 $\sim \sin(\phi_S)$

ϕ_S—*angle between spin and event plane*

Mechanisms for Transverse Single-spin Asymmetries

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

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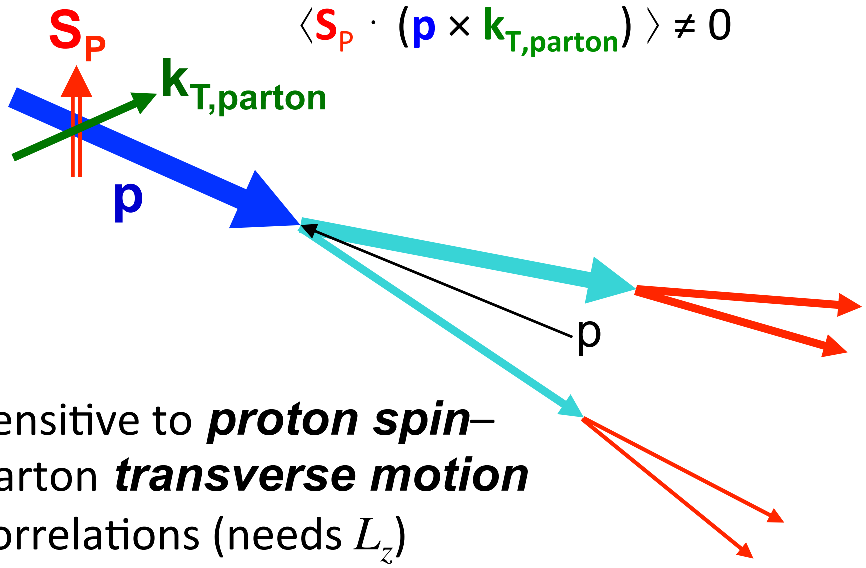

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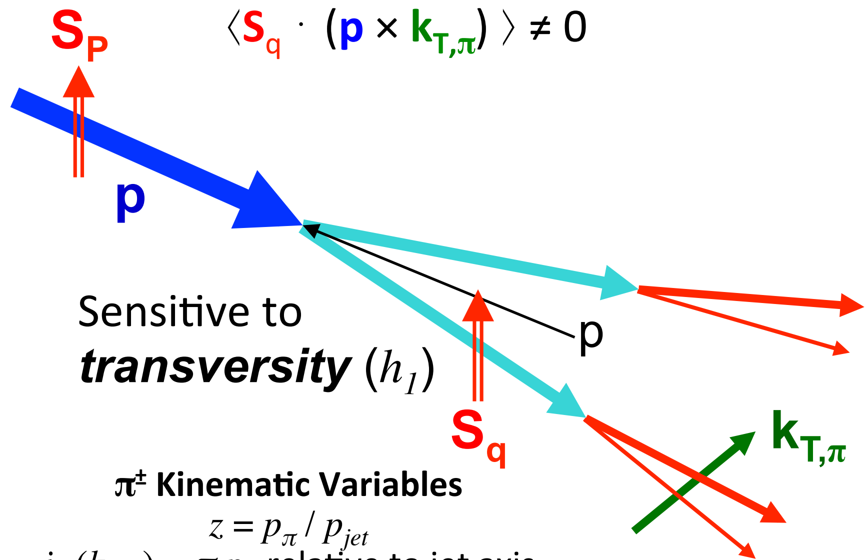

Sensitive to ***transversity*** (h_1)

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

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

Separate Sivers and Collins:

Go beyond inclusive production - *e.g. Jets, correlations, direct photons*

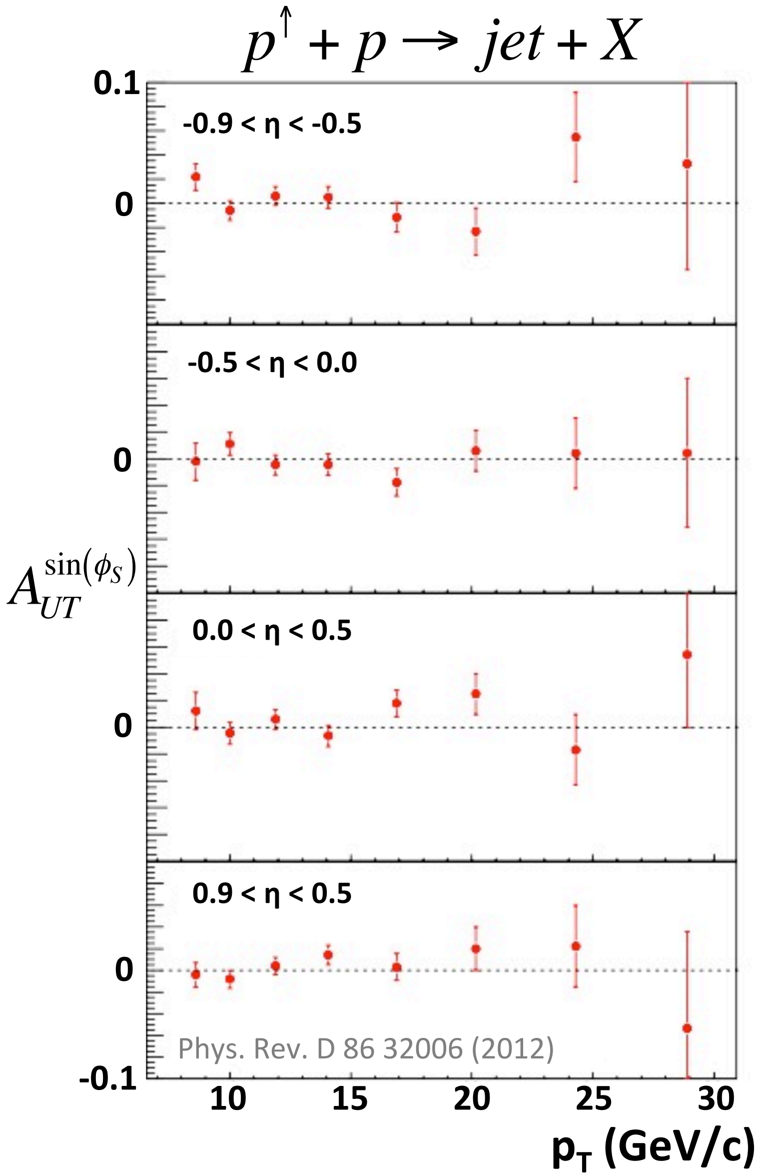
Sivers ~ $\sin(\phi_S)$

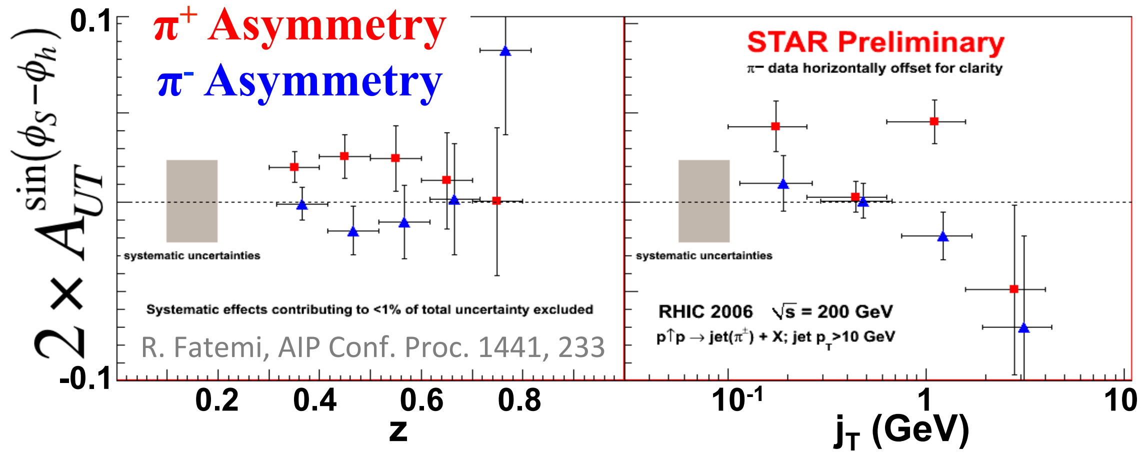
ϕ_S—*angle between spin and event plane*

Collins ~ $\sin(\phi_S - \phi_h)$

ϕ_h—*angle of hadron around jet axis*

Sivers and Collins Analyses for Jets at 200 GeV, early (2006) data set





STAR measured transverse single-spin asymmetries for inclusive jet production at central pseudorapidity and $\sqrt{s}$ = 200 GeV (2006)

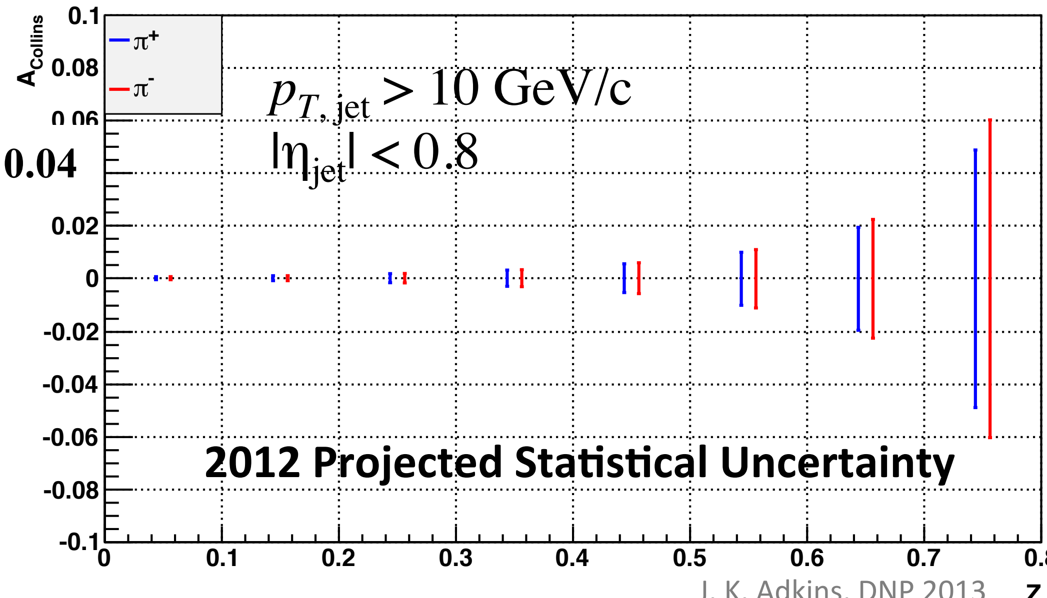
$A_{UT}^{\sin(\phi_S)}$: consistent with zero

$A_{UT}^{\sin(\phi_S - \phi_h)}$: hints of non-zero asymmetry with charge-sign dependence

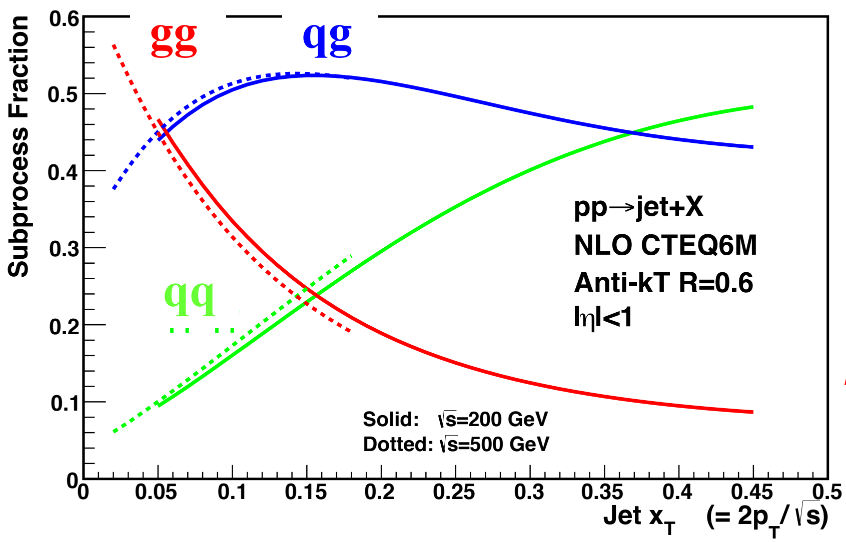
Prospects for Sivers and Collins Jet Analyses

One year ago

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

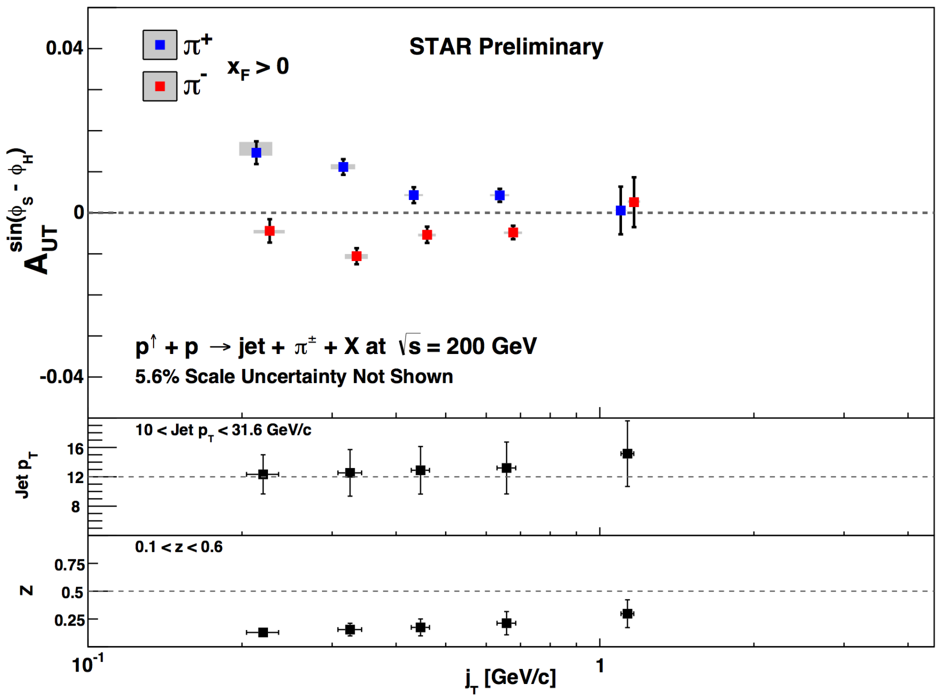


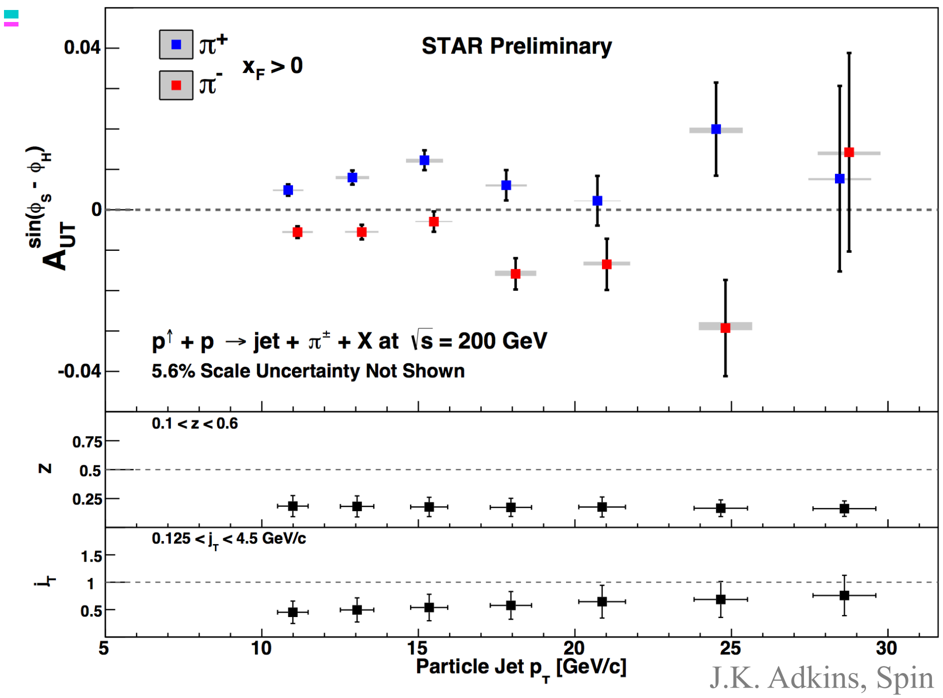
J. K. Adkins, DNP 2013



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

New Collins Results at $\sqrt{s}$ = 200 GeV



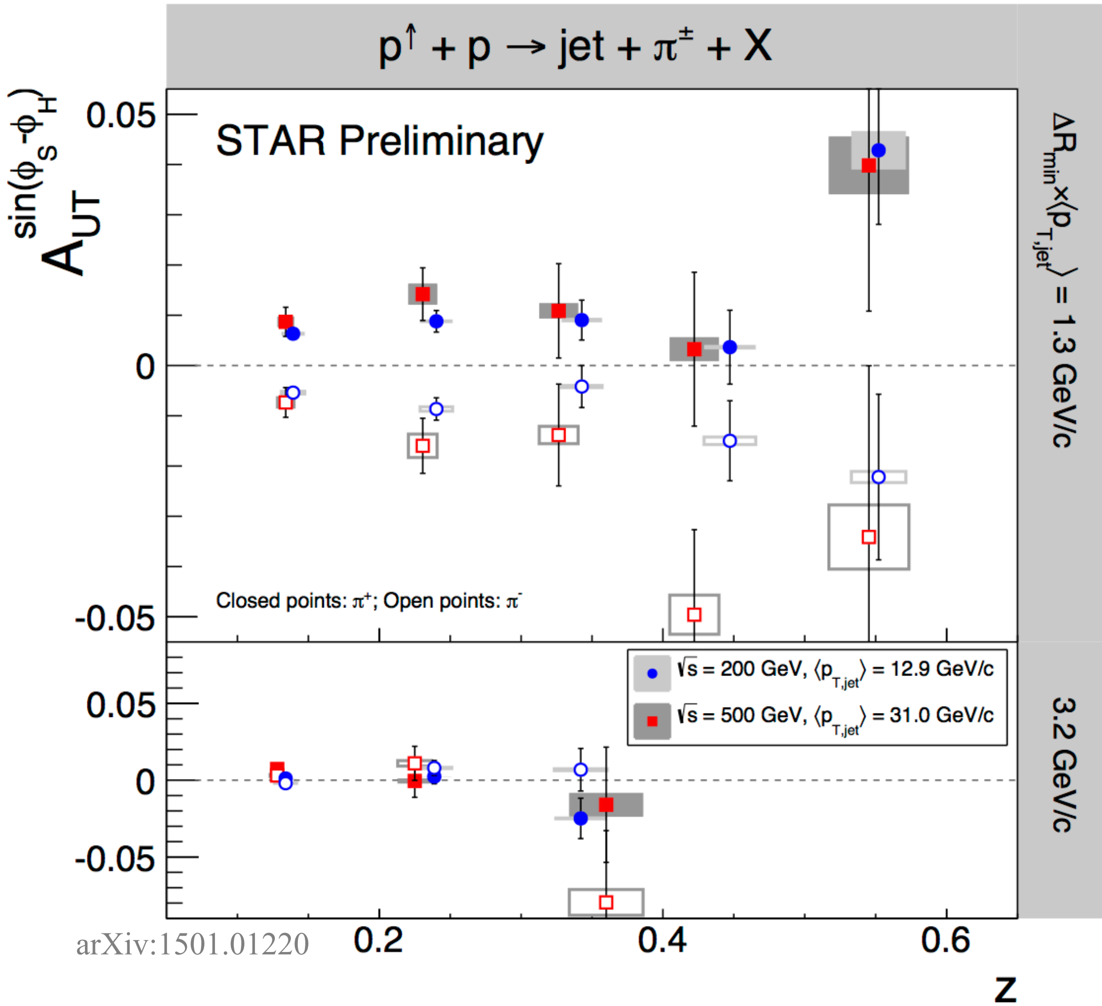


J.K. Adkins, Spin 2014

STRONG dependence upon j_T

First observation of Collins asymmetry in *p+p*!

Collins Results at $\sqrt{s}$ = 500 GeV



arXiv:1501.01220

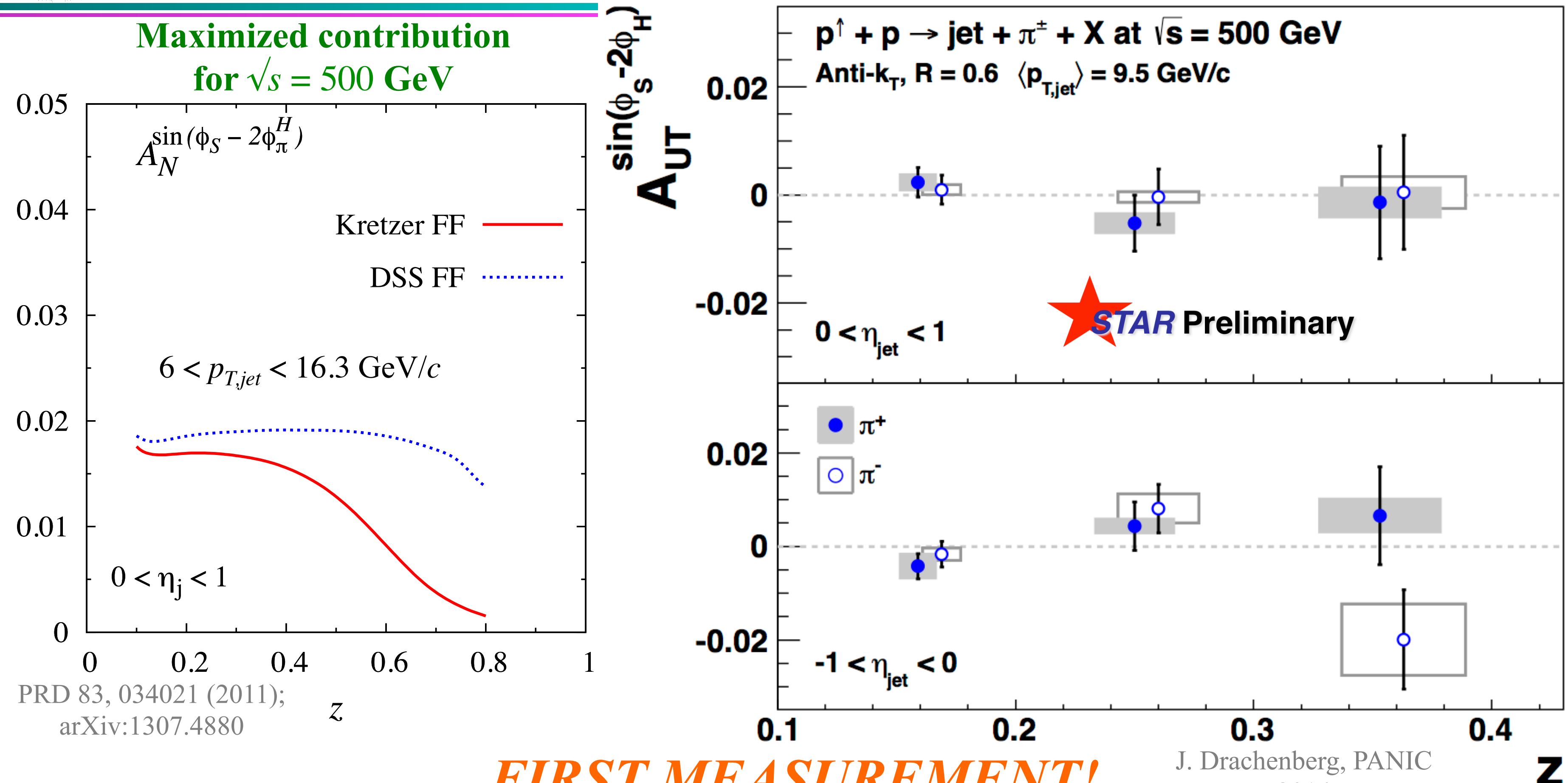
Non-zero Collins asymmetries observed at $\sqrt{s}$ = 500 GeV!

- Consistent with $\sqrt{s}$ = 200 GeV results for consistent cuts and x_T
- Suggests slow TMD evolution from 200 to 500 GeV?

Related first measurement (consistent with zero) of Collins-like asymmetries, sensitive to gluon linear polarization (J. Drachenberg, PANIC 2014)

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

Maximized contribution for $\sqrt{s}$ = 500 GeV



PRD 83, 034021 (2011); arXiv:1307.4880

J. Drachenberg, PANIC 2014

FIRST MEASUREMENT!

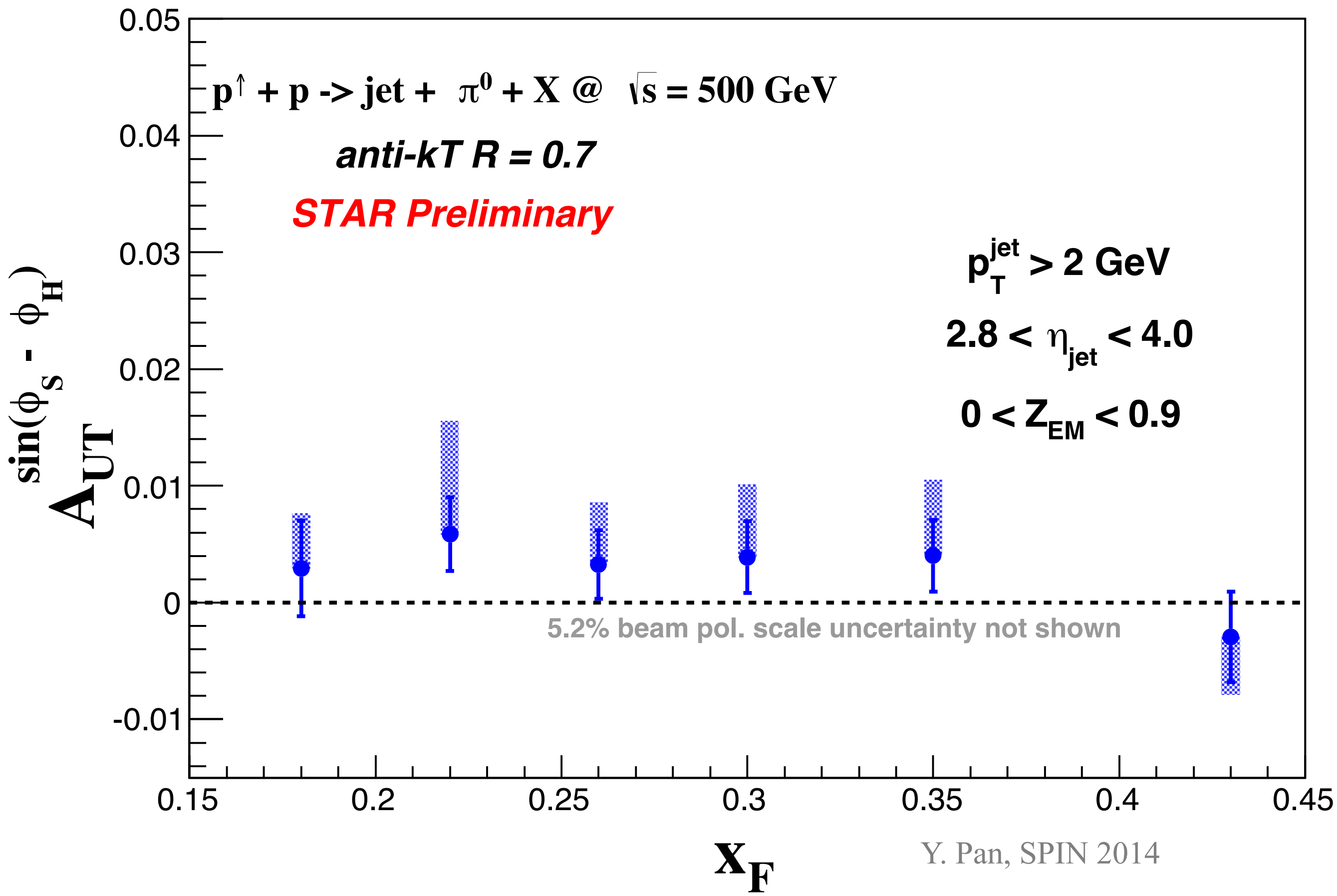
Present data sit well below maximized contribution of ~2% at low z

Present data should provide first constraints on Collins-like effect

(sensitive to linearly polarized gluons)

Collins Asymmetries for π^0 in Forward EM Jets

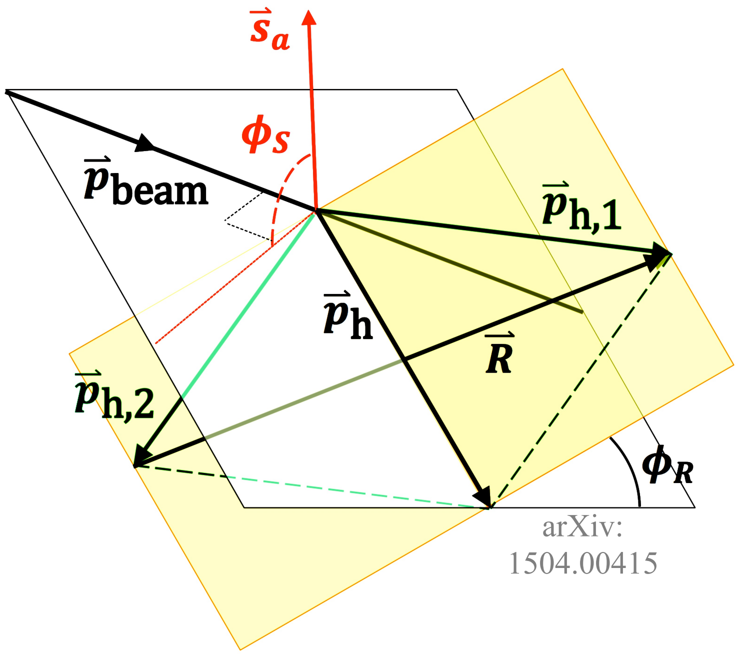
- 2011 Dataset in FMS 22 pb^{-1} with 52% pol.
- Anti-k_T jet algorithm on FMS photons, R = 0.7
- Calculate Collins asymmetries for π^0 within EM jets



- **Hints of possible non-zero Collins asymmetries!**

Transverse Asymmetries from Di-hadrons

Another path to transversity: Di-hadron Asymmetries



arXiv: 1504.00415

$$A_{UT}^{\sin(\phi_{RS})} \propto h_1 \otimes H_1^{\angle}$$

Survives in collinear framework

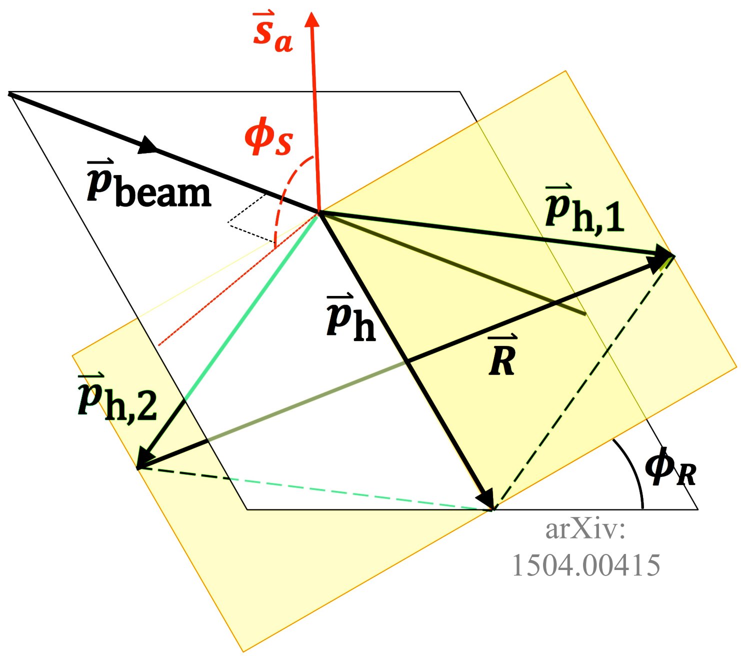
$$\phi_{RS} = \phi_R - \phi_S$$

Angle between polarization vector and di-hadron plane

—"Interference Fragmentation Function"

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

Another path to transversity: Di-hadron Asymmetries



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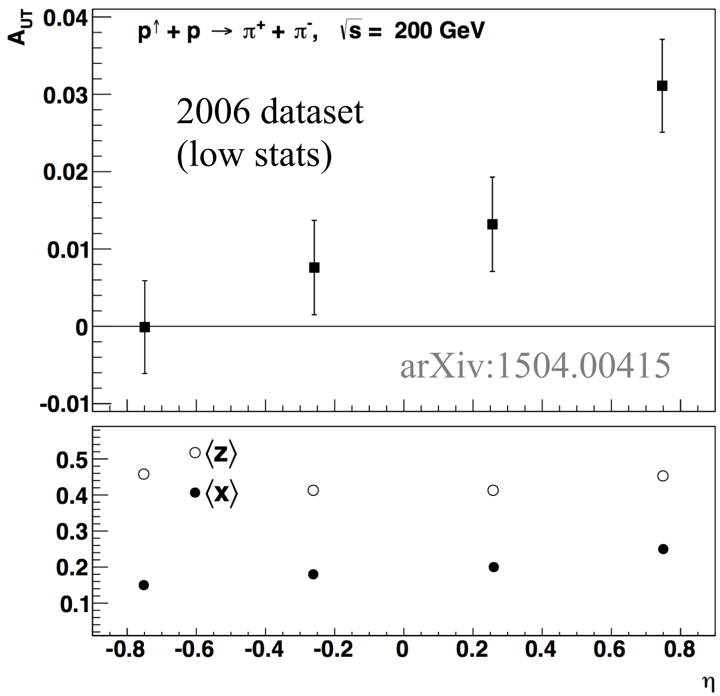
—"Interference Fragmentation Function"

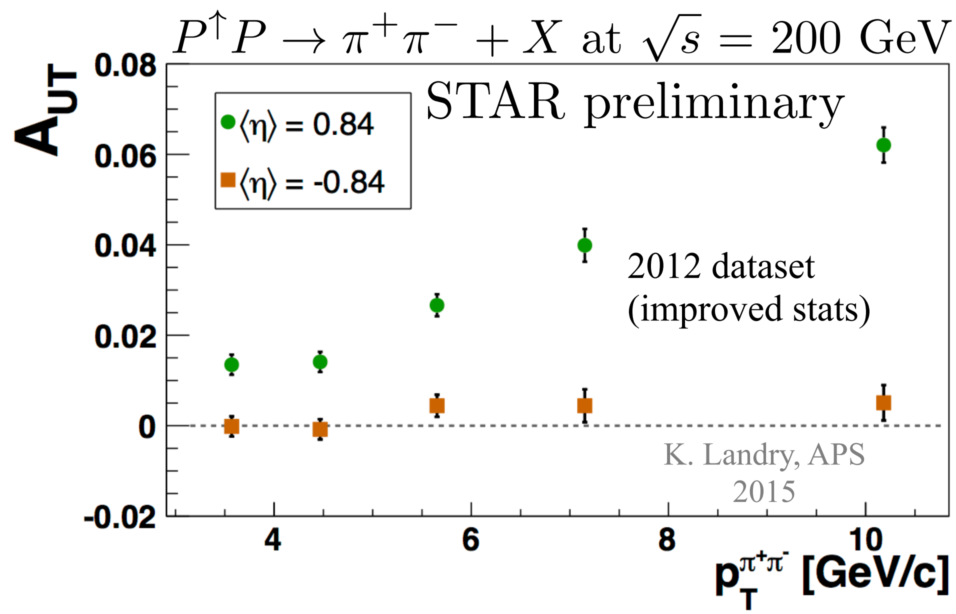
e.g. Bacchetta and Radici, PRD 70, 094032 (2004)

Studying both jet+hadron and di-hadron asymmetries over range of collision energy:

- ***Extend kinematic reach*** beyond existing measurements
- ***Probe evolution*** of transversity and TMDs
- ***Probe open theoretical questions***, e.g. TMD factorization-breaking and universality

Transverse Asymmetries from Di-hadrons





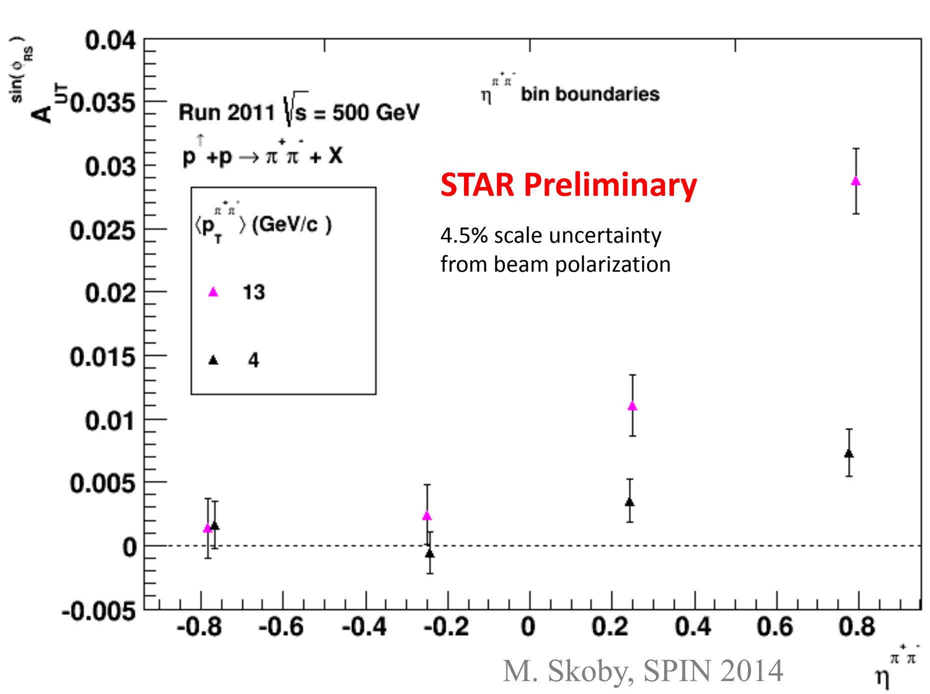
Significantly non-zero di-hadron asymmetries for charged pions at central pseudorapidity

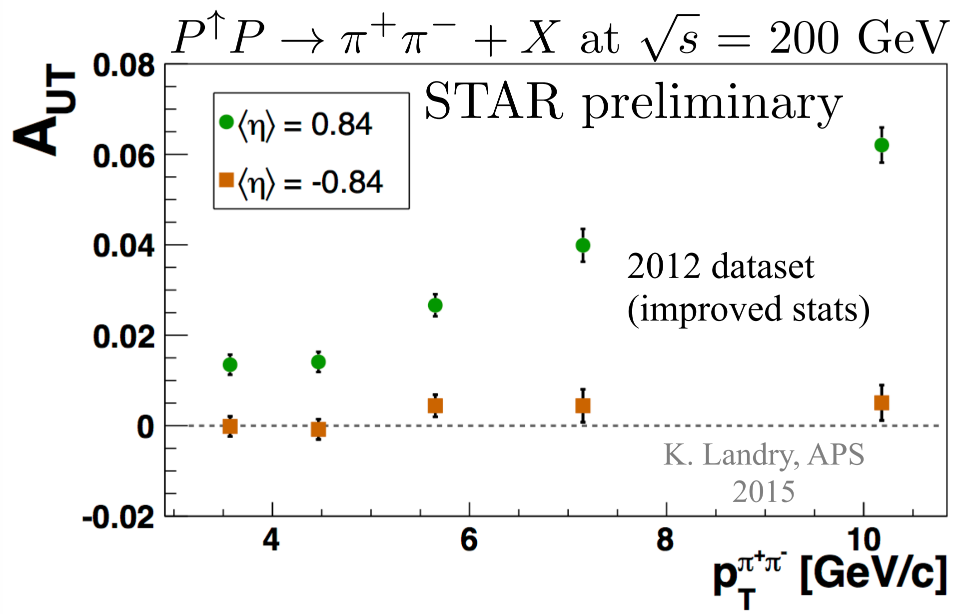
Significant, high-precision di-hadron asymmetries

Non-zero Collins + Di-hadron Asymmetries

→ ***Access to transversity in p+p!***

Transverse Asymmetries from Di-hadrons





Significantly non-zero di-hadron asymmetries for charged pions at central pseudorapidity

Significant, high-precision di-hadron asymmetries

Significant non-zero IFF observed also at 500 GeV, increasing with pion pT (more bins available), with intriguing mass dependence

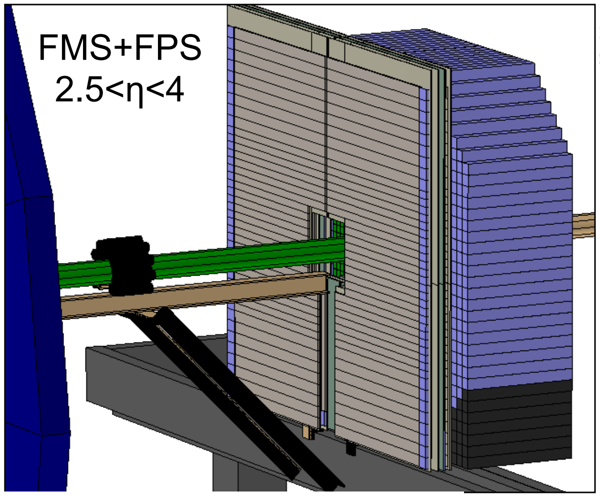
Understanding Spin in Proton Collisions at STAR

- Probing Gluon Polarizations with Jets and π^0's
- Probing Sea Quark Polarization with W's
- Probing Transverse Structure with Jets and π^0's
  - And with W's, Z's, and other probes
- Looking to the Future

Sivers Function and Sign Change Prospects at STAR with W, Z, Drell-Yan

- A_N in Drell-Yan, W/Z production at RHIC provide excellent complement to SIDIS
  - Attractive from a theoretical perspective (no frag. func. needed as for π^0's, etc.)
  - Sivers function "famously" changes sign when comparing with transverse asymmetries from SIDIS
    - Collins, J. C., 2002, Phys. Lett. B 536, 43
  - Direct photon sign change as well
  - Probe wide range of Q^2
  - Test the universality and factorization of TMD's, constrain their evolution – important tests of QCD
  - **Major targets for 2015-2017**

STAR FMS-PreShower:

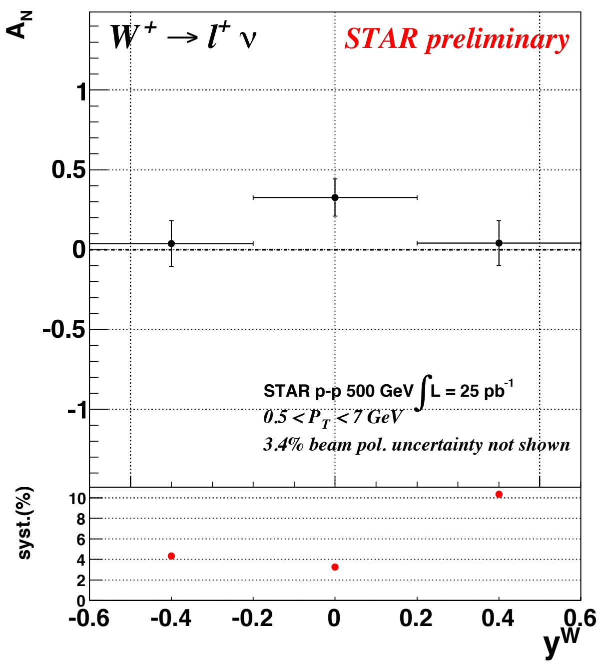


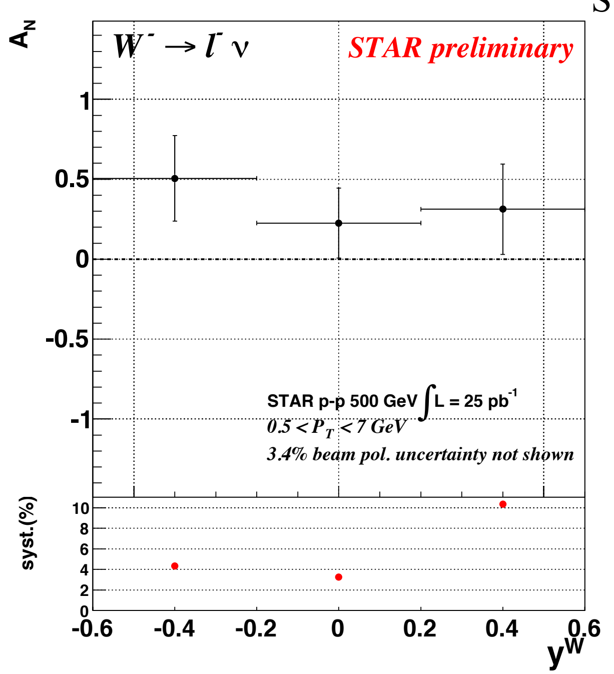
- FMS (forward EM calorimetry) Preshower Upgrade in 2015
  - Allows separation among photons, π^0's, charged hadrons, and electrons
  - Supports direct photon and DY measurements

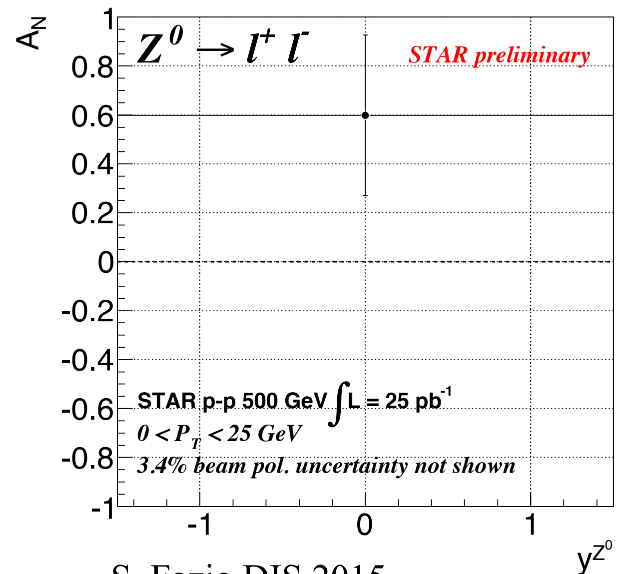
$A_N(W^{+/-}, Z^0)$ Results from 2011

- Preliminary results with 25 pb^{-1} of data
- Projections for 2017 show $A_N(W^{+/-},Z^0)$ will constrain sea quark Sivers distribution ***and*** make a statement on the Sivers sign change

S. Fazio and D. Smirnov PoS(DIS2014)237





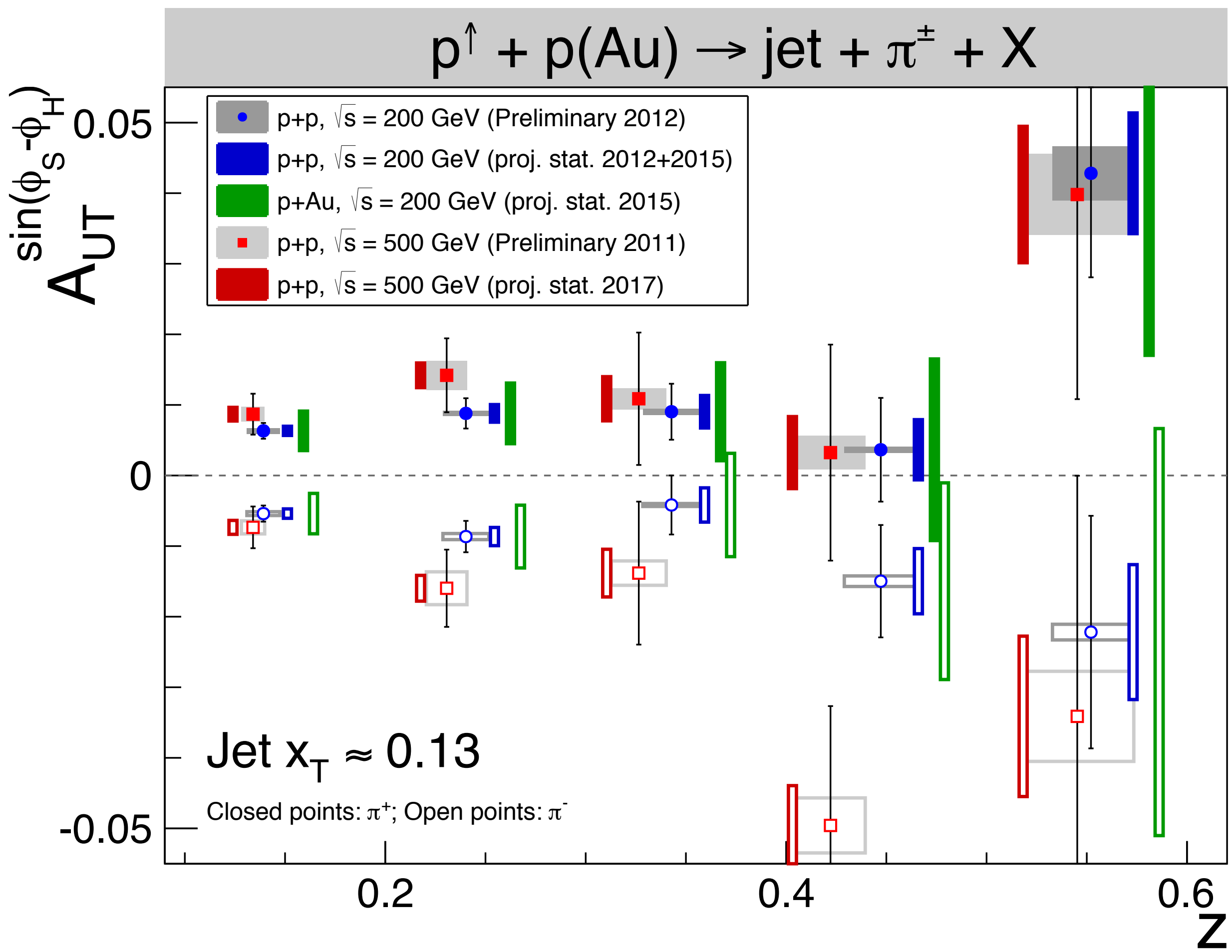


S. Fazio DIS 2015

- An excellent complement to SIDIS
  - No fragmentation (and so no fragmentation function uncertainty)
  - High Q^2
  - Sign flip

Near Future: Collins Projections

- Transversely polarized p Au collisions recorded for the first time in 2015
  - Should allow for first glimpse of Collins asymmetries in p+A?
  - Saturation effects?
- Long transverse run planned for 2017 at 500 GeV



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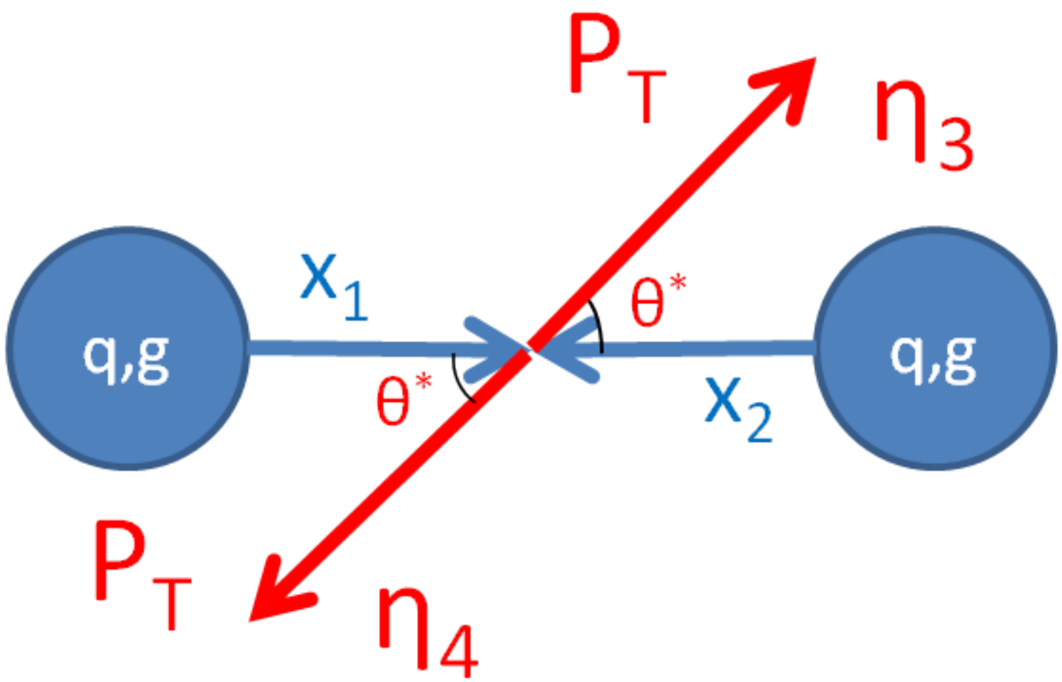
- Probing Gluon Polarizations with Jets and π^0's
- Probing Sea Quark Polarization with W's
- Probing Transverse Structure with Jets and π^0's
  - And with W's, Z's, and other probes
- Looking to the Future
  - Dijet measurements as one example

Dijet Measurements



$$x_1 = \frac{1}{\sqrt{s}}\left(p_{T3}e^{\eta_3} + p_{T4}e^{\eta_4}\right)$$

$$x_2 = \frac{1}{\sqrt{s}}\left(p_{T3}e^{-\eta_3} + p_{T4}e^{-\eta_4}\right)$$

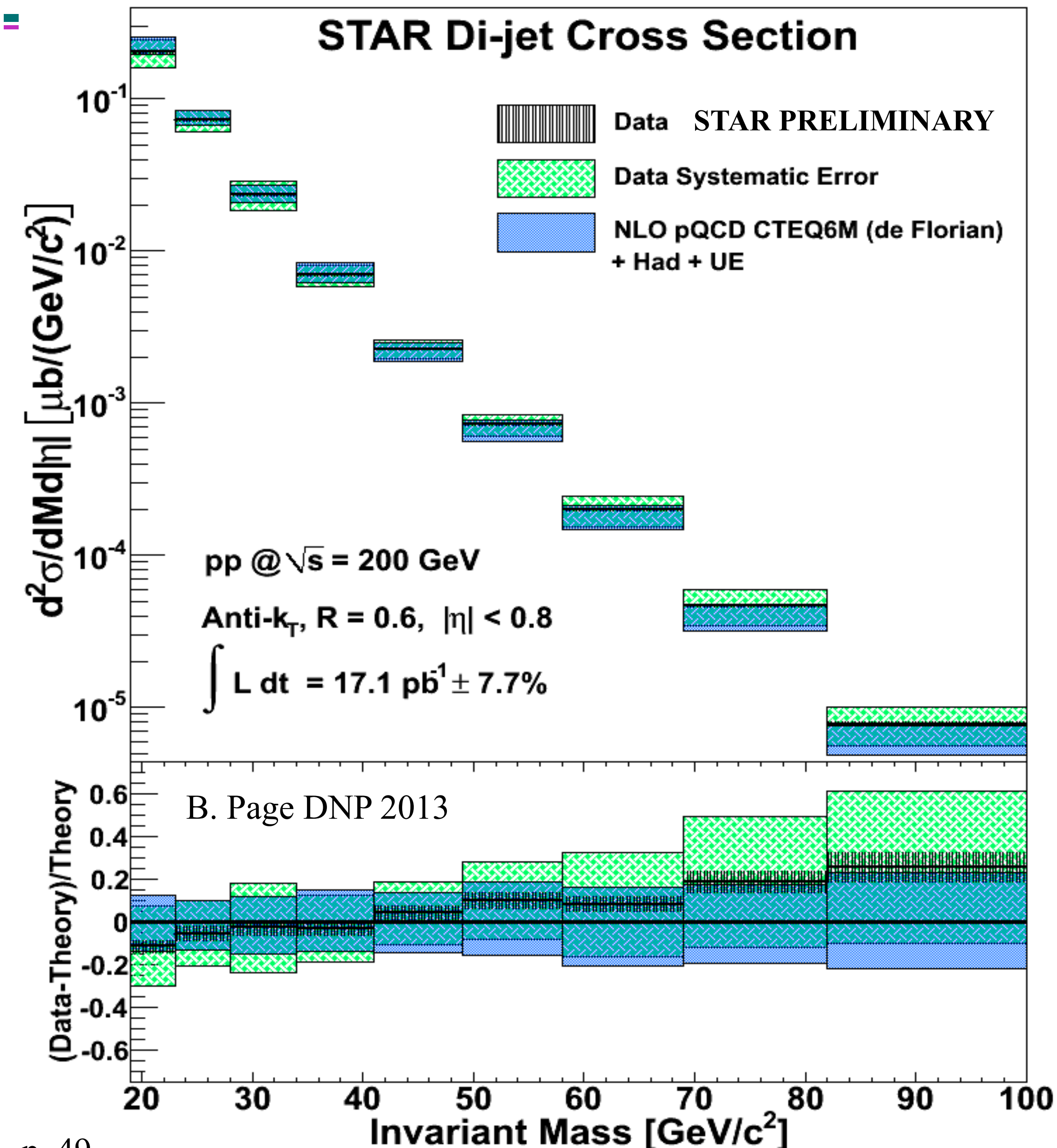
$$M = \sqrt{x_1 x_2 s}$$

$$\eta_3 + \eta_4 = \ln\frac{x_1}{x_2}$$

$$\left|\cos\theta^*\right| = \tanh\left|\frac{\eta_3 - \eta_4}{2}\right|$$

- Inclusive measurements have been the workhorse of STAR ΔG program to date
- Broad *x* range sampled in each p_T bin
- Dijet or other correlation measurements which reconstruct the full final state are sensitive to initial kinematics at leading order
    - Prospect of mapping out the shape of Δg(*x*)

2009 Dijet Cross Section Results



Vertical black hashing stat. error

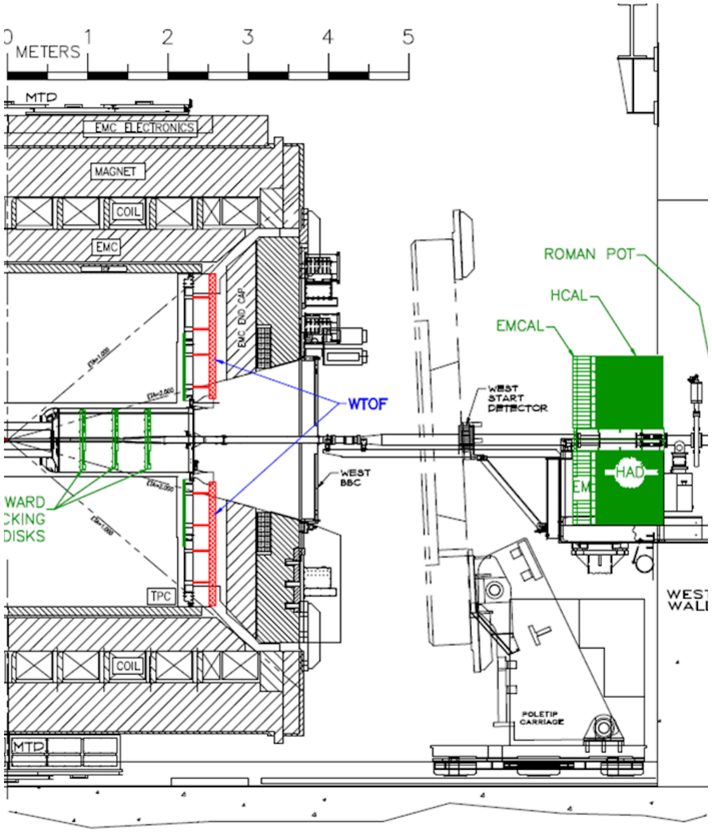
Green box is symmetric about data point and is the quadrature sum of all systematic errors

Blue box is theory error: renormalization and factorization scales x0.5, x2

Also a 2009 result at 500 GeV
G. Webb PoS(DIS2013) 215

And a 2006 result from 200 GeV
T. Sakuma, M. Walker, Journal of Physics: Conference Series 295, 012068 (2011).

Probing *very* low *x* gluons with Forward Calorimeter Upgrade: 2020



ECal:

Tungsten-Powder-Scintillating-fiber

2.3 cm Moliere Radius, Tower-size: $2.5 \times 2.5 \times 17$ cm^3

23 X_o

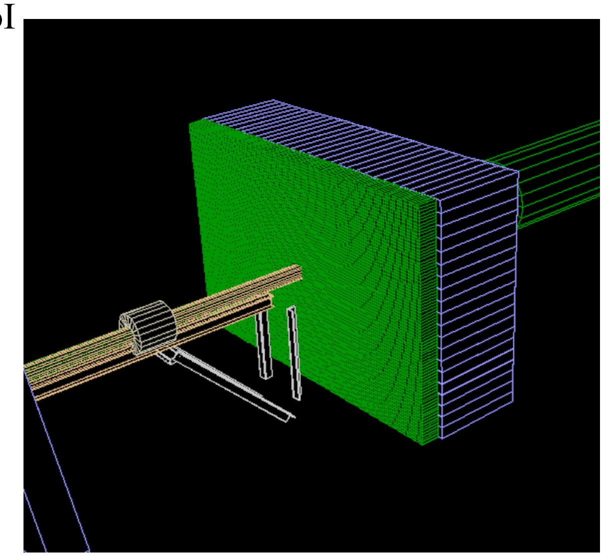
HCal:

Lead and Scintillator tiles, Tower size of $10 \times 10 \times 81$ cm^3

4 interaction length

https://drupal.star.bnl.gov/STAR/starnotes/public/sn0605

STAR polarized p+p and p+A LoI



Dijet Projections with the Forward Calorimeter Upgrade

$\sqrt{s} = 500\ GeV$

$-1 < \eta < 2$

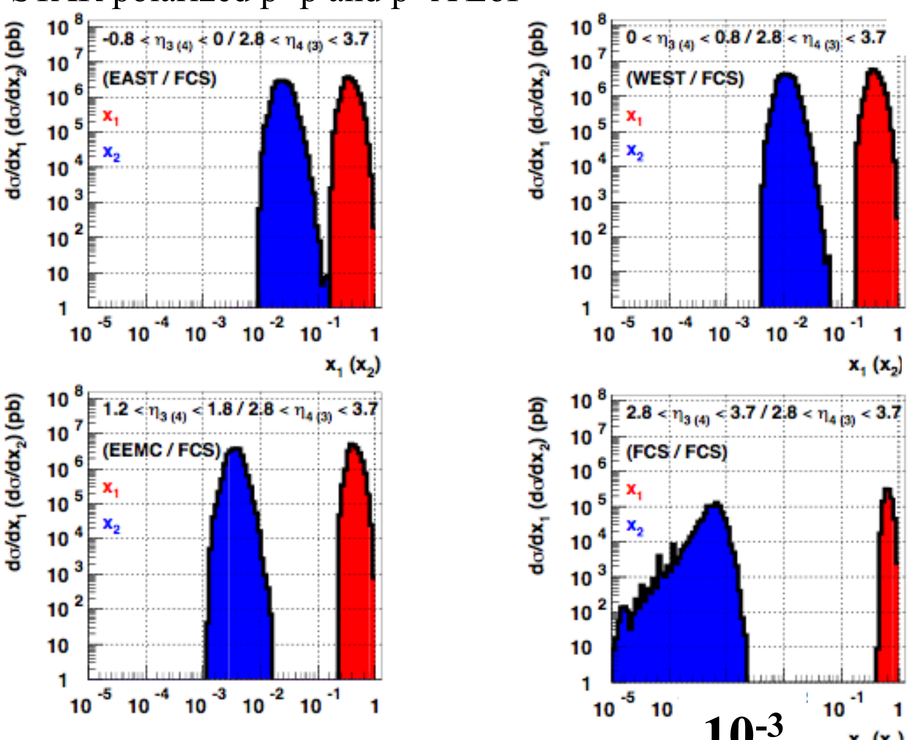
$2.8 < \eta < 3.7$

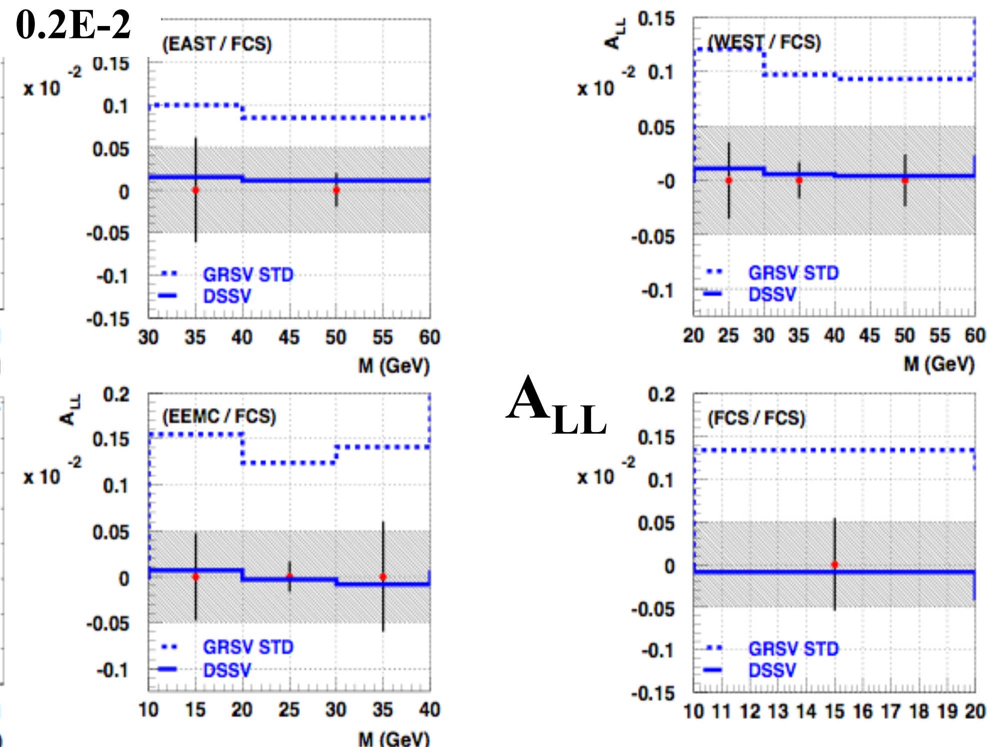
$R_{cone} = 0.7$
$E_{T1} > 8$ GeV
$E_{T2} > 5$ GeV

$L = 1 fb^{-1}$
P=60%

https://drupal.star.bnl.gov/STAR/starnotes/public/sn0605
STAR polarized p+p and p+A LoI

B. Surrow PoS(DIS2014) 241





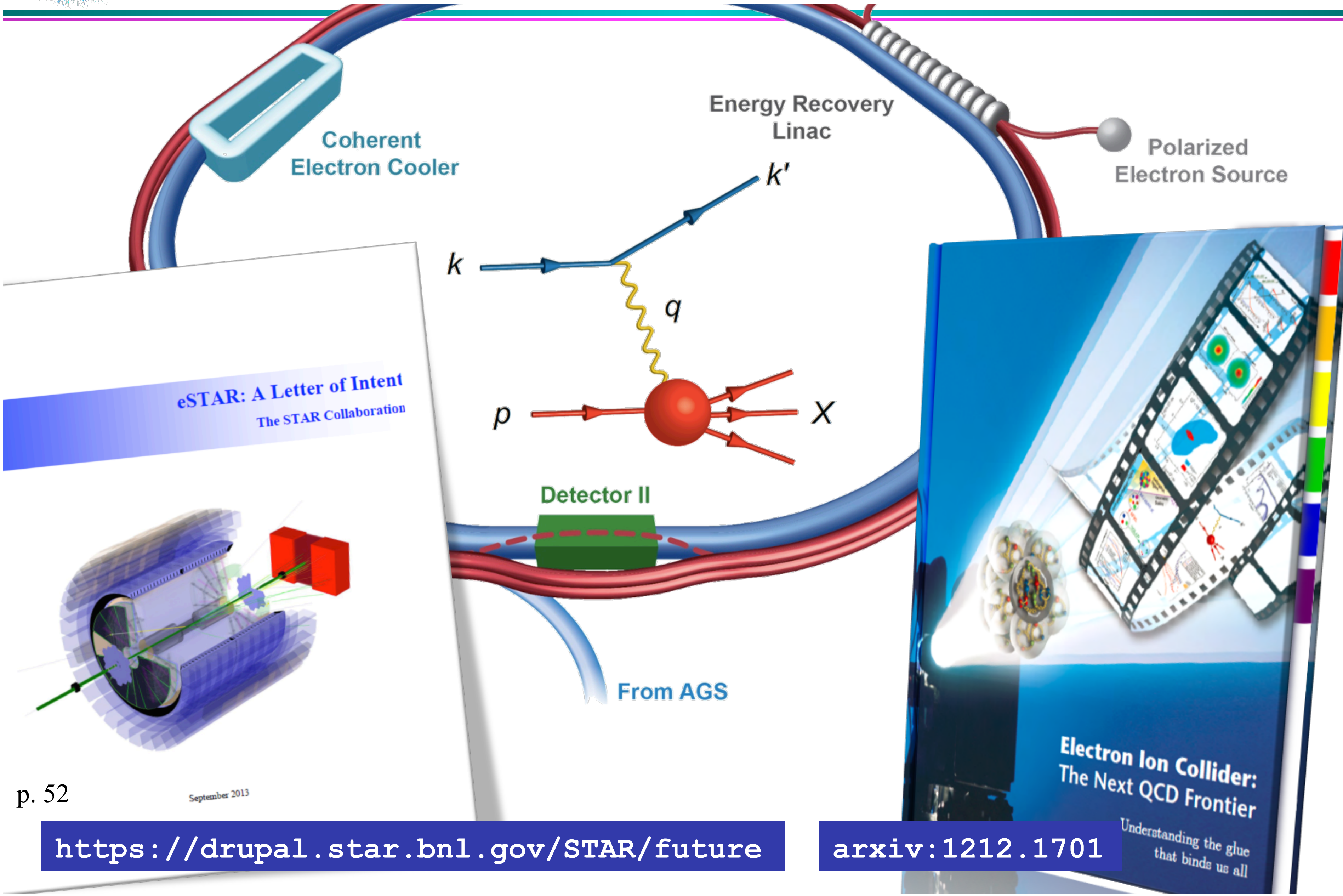
$x_1\ (x_2)$

M (GeV)

Probe gluons to $x \sim 10^{-3}$

An attractive probe at rather low x before the EIC era

eRHIC and eSTAR (>2025) will offer unprecedented reach in Q^2 and x



https://drupal.star.bnl.gov/STAR/future

arxiv:1212.1701

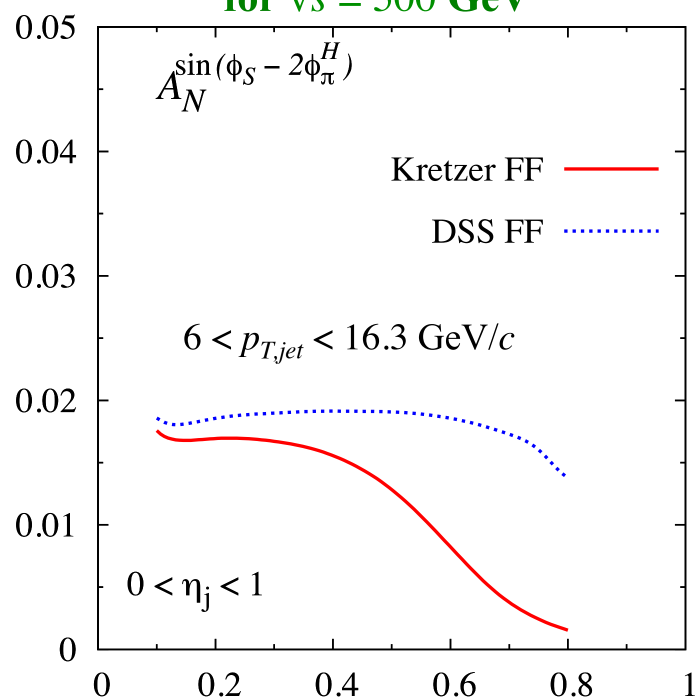
Spin Physics at STAR

- Inclusive Jets
  - After 25 years, **evidence of non-zero gluon polarization** in the proton
- Pushing to **lower *x* gluons**
  - With forward detectors, sqrt(s) = 510 GeV, large datasets, detector upgrades
- **W's and Z's** improving our understanding of **sea quark polarizations**
- Exploration of transverse asymmetries, A_N, continues
  - TMD (e.g Sivers, Collins) and Twist-3 phenomenology
  - **First observations of transversity in polarized p + p!**
  - **Tests of universality, factorization, and evolution of TMD's**
  - **Polarized p+A has begun**
- **Large datasets on hand, analyses underway**
  - 2011, 2012, 2013, 2015
- **Detector upgrades continue**
  - FGT forward tracking 2013, forward calorimetry: FPS+FMS and RP 2015, FCS 2020
- **Continuing data taking planned**
  - 2016, 2017, and beyond
- **Stay tuned!**

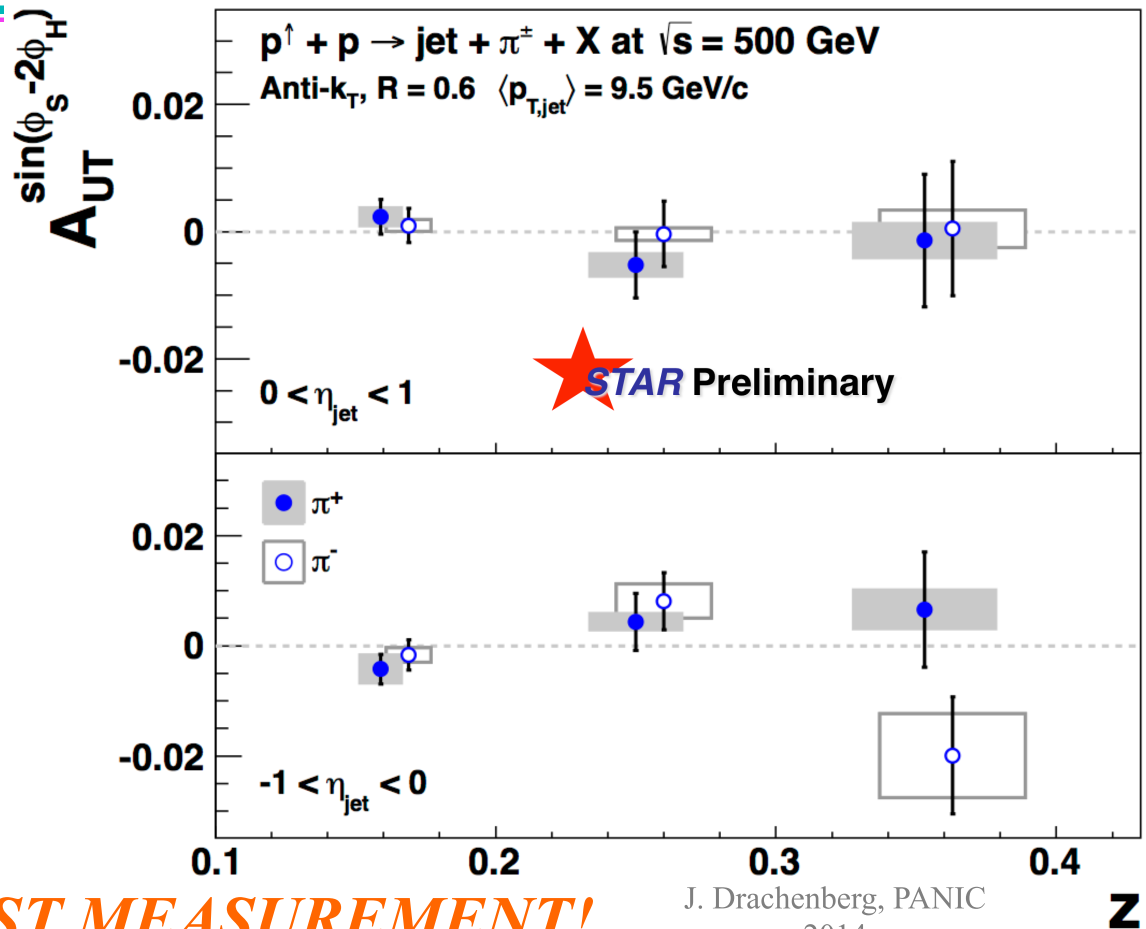
Backup

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

Maximized contribution for $\sqrt{s}$ = 500 GeV



PRD 83, 034021 (2011); arXiv:1307.4880



J. Drachenberg, PANIC 2014

FIRST MEASUREMENT!

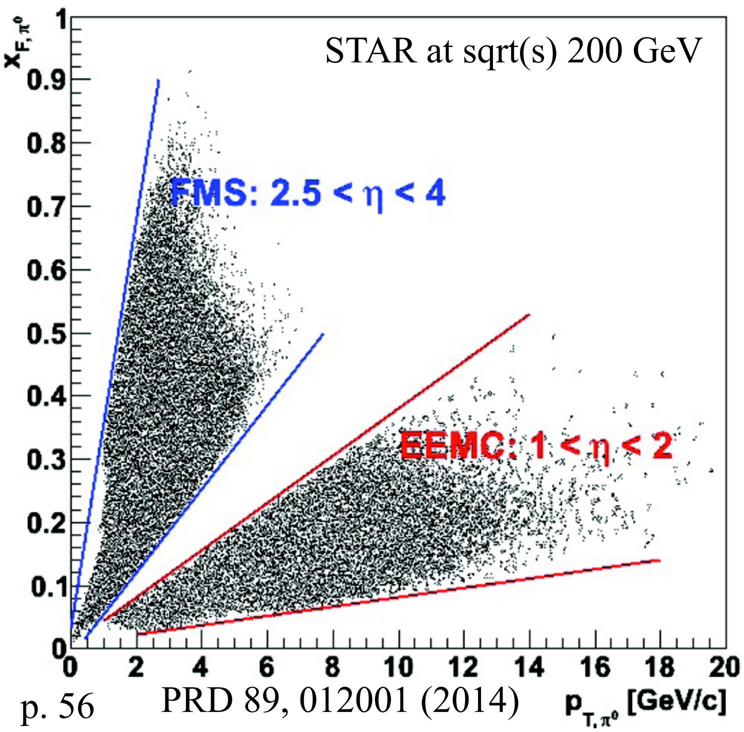
Present data sit well below maximized contribution of ~2% at low z

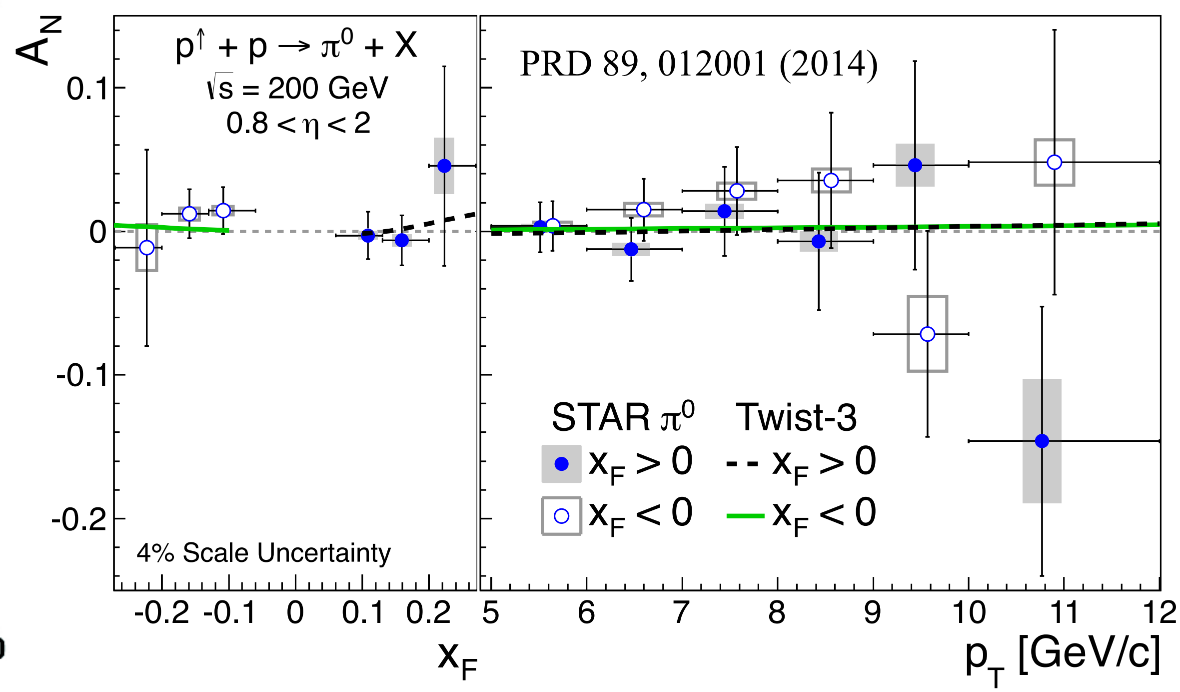
Present data should provide first constraints on Collins-like effect

(sensitive to linearly polarized gluons)

A_N in $\pi^0 + X$ at STAR for $0.8 < \eta < 2.0$

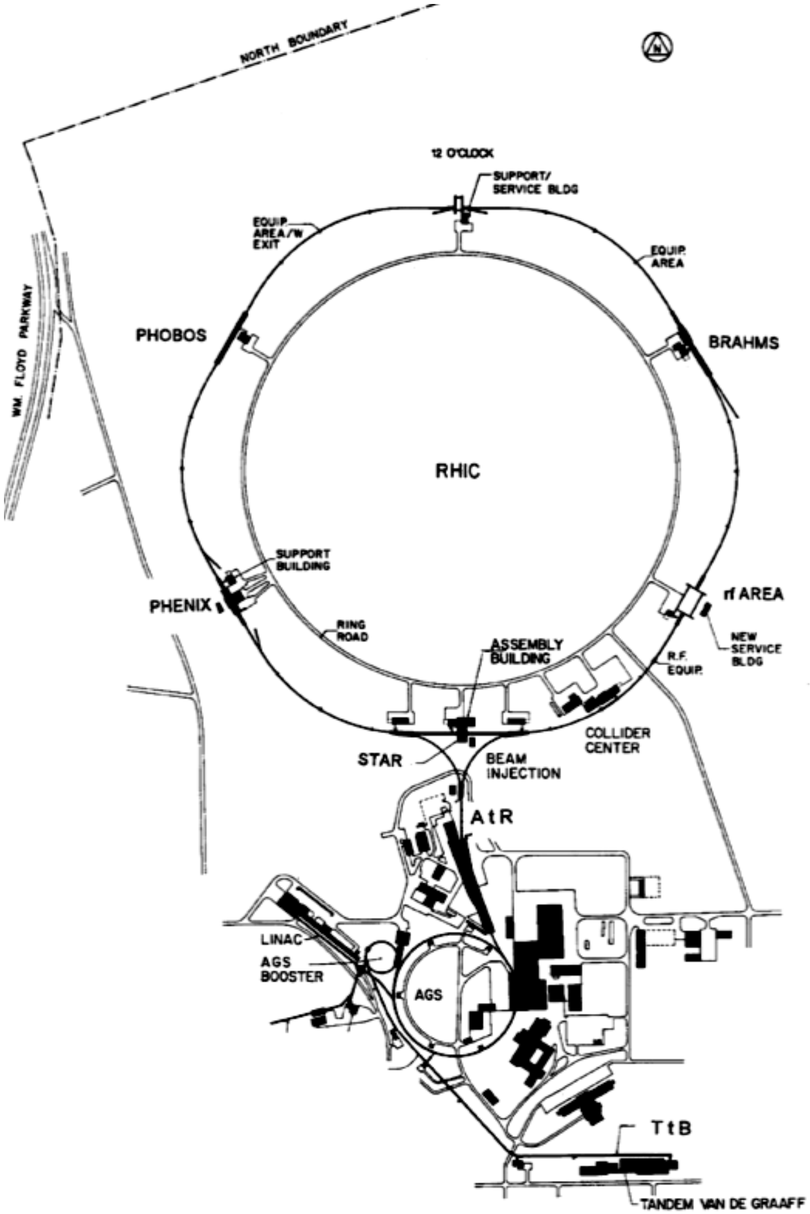
- Transverse asymmetries for the EEMC mid-rapidity 2006 dataset
- Plotted in bins of π^0 p_T (integrated over $0.06 < x_F < 0.27$), and in bins of x_F
- Statistical error (bars) dominates over systematic error (boxes)
- Twist-3 prediction
  - K. Kanazawa and Y. Koike,
  - Phys. Rev. D 83, 114024 (2011)





 PRD 89, 012001 (2014)

Relativistic Heavy Ion Collider as a Spin Collider



Concert of Facilities

- OPPIS → LINAC → AGS → RHIC

Polarized-proton Collider

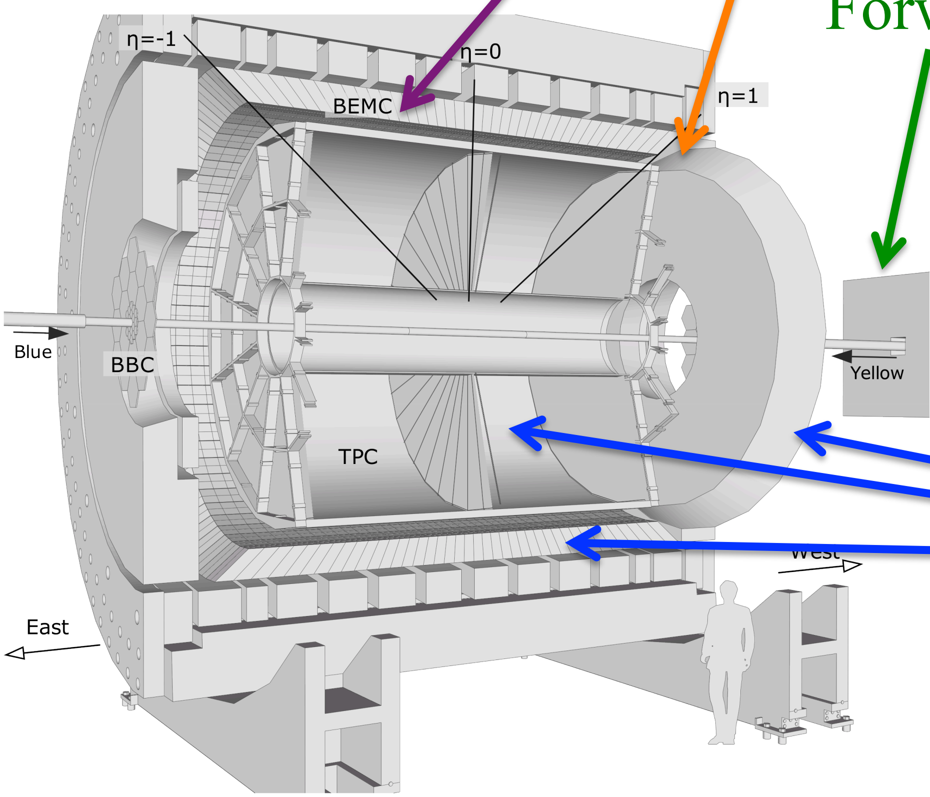
- Mitigate effects of depolarization resonances with "Siberian Snakes"
- Polarization measured with CNI polarimeter
- Spin rotators provide choice of spin orientation *independent of experiment*

RHIC Beam Characteristics

- Clockwise beam: "**blue**"; counter-clockwise beam: "**yellow**"
- Spin direction varies bucket-to-bucket (9.4 MHz)
- Spin pattern varies fill-to-fill

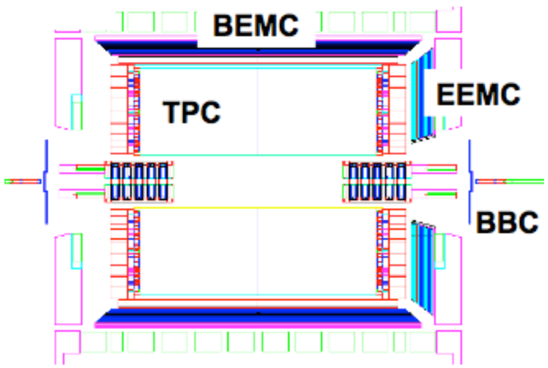
Solenoidal Tracker at RHIC

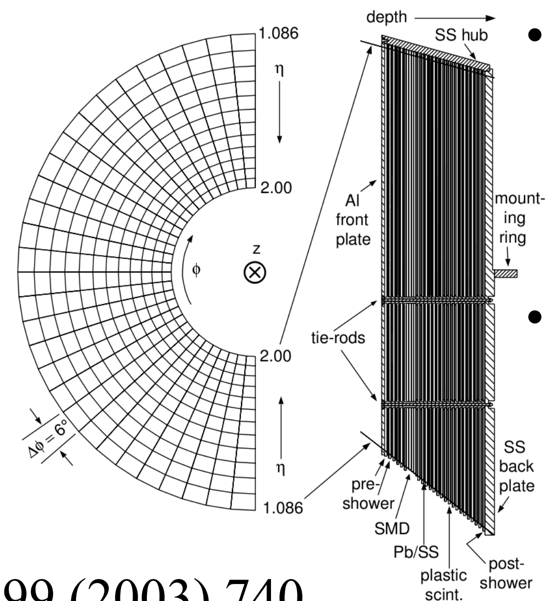
Inclusive hadron measurements:
Barrel ElectroMagnetic Calorimeter (BEMC),
Endcap ElectroMagnetic Calorimeter (EEMC),
and
Forward Meson Spectrometer (FMS)
FPD (east) not shown



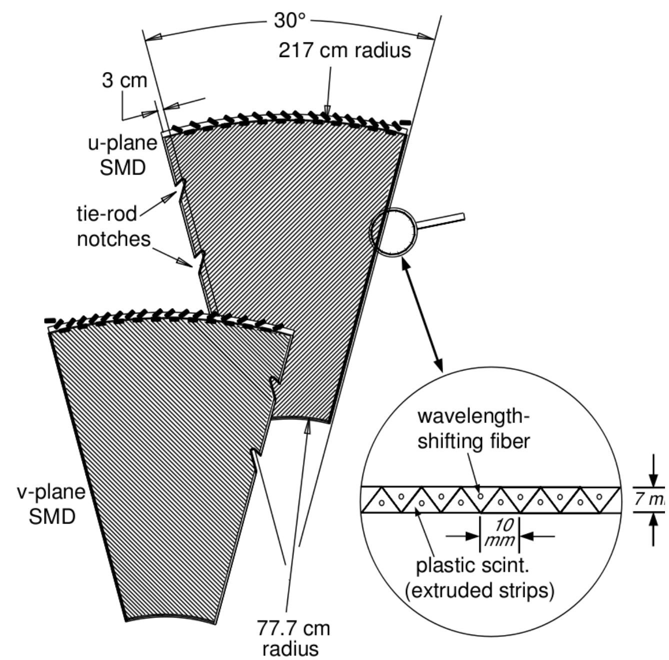
Jet and W/Z measurements:
TPC + Barrel + Endcap EMC

STAR's Endcap Electromagnetic Calorimeter





- Scintillating strip SMD
  - ϕ segmented into 12 sectors
  - Two active planes
  - 288 strips per plane
- Resolution of a few mm



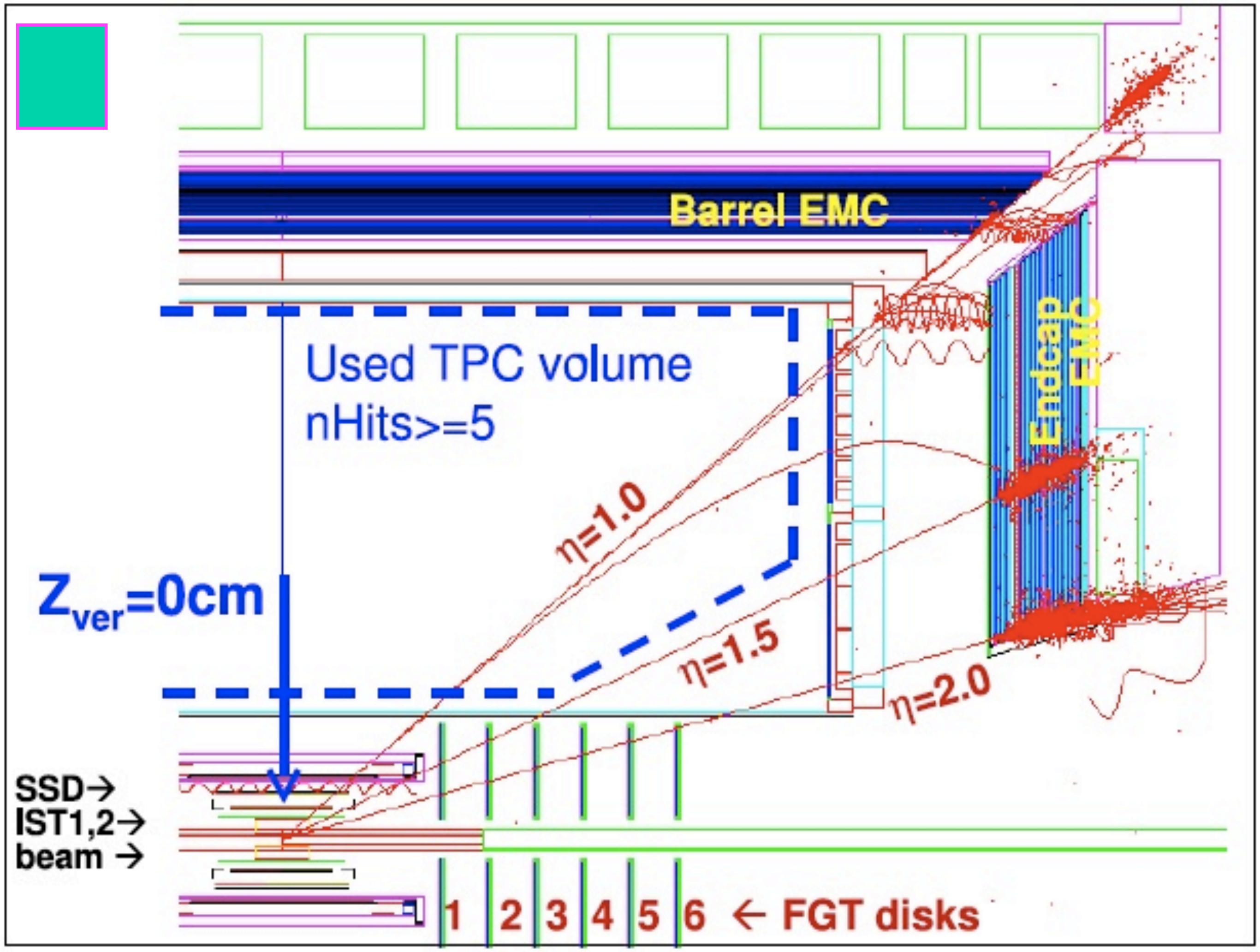
- Nucl. Instrum. Meth. **A** 499 (2003) 740.
- Lead/scintillator sampling EM calorimeter
  - Covers 1.09 < η < 2.00 over full 2π azimuth
  - 720 optically isolated projective towers (~22 X_0)
  - 2 pre-shower, 1 post-shower layers, and an additional shower maximum detector (SMD)
- Photon trigger places thresholds on maximum tower energy and the 3x3 patch of surrounding towers

STAR FGT Detector

Improve charged particle tracking at very forward angles

Obtain better measurement of W decay particles

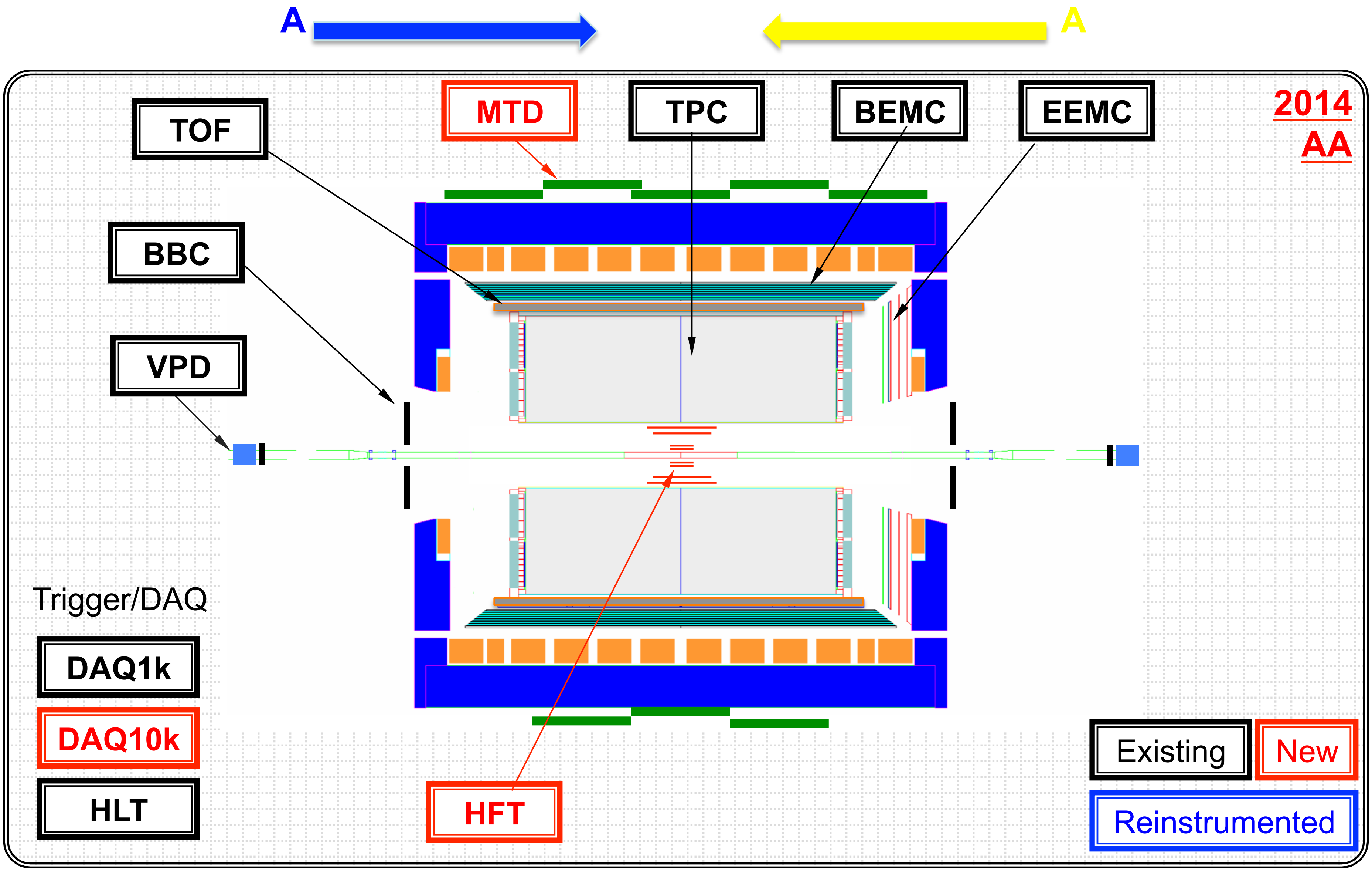
Install 6 planes of GEM detectors



FGT = Forward GEM Tracker

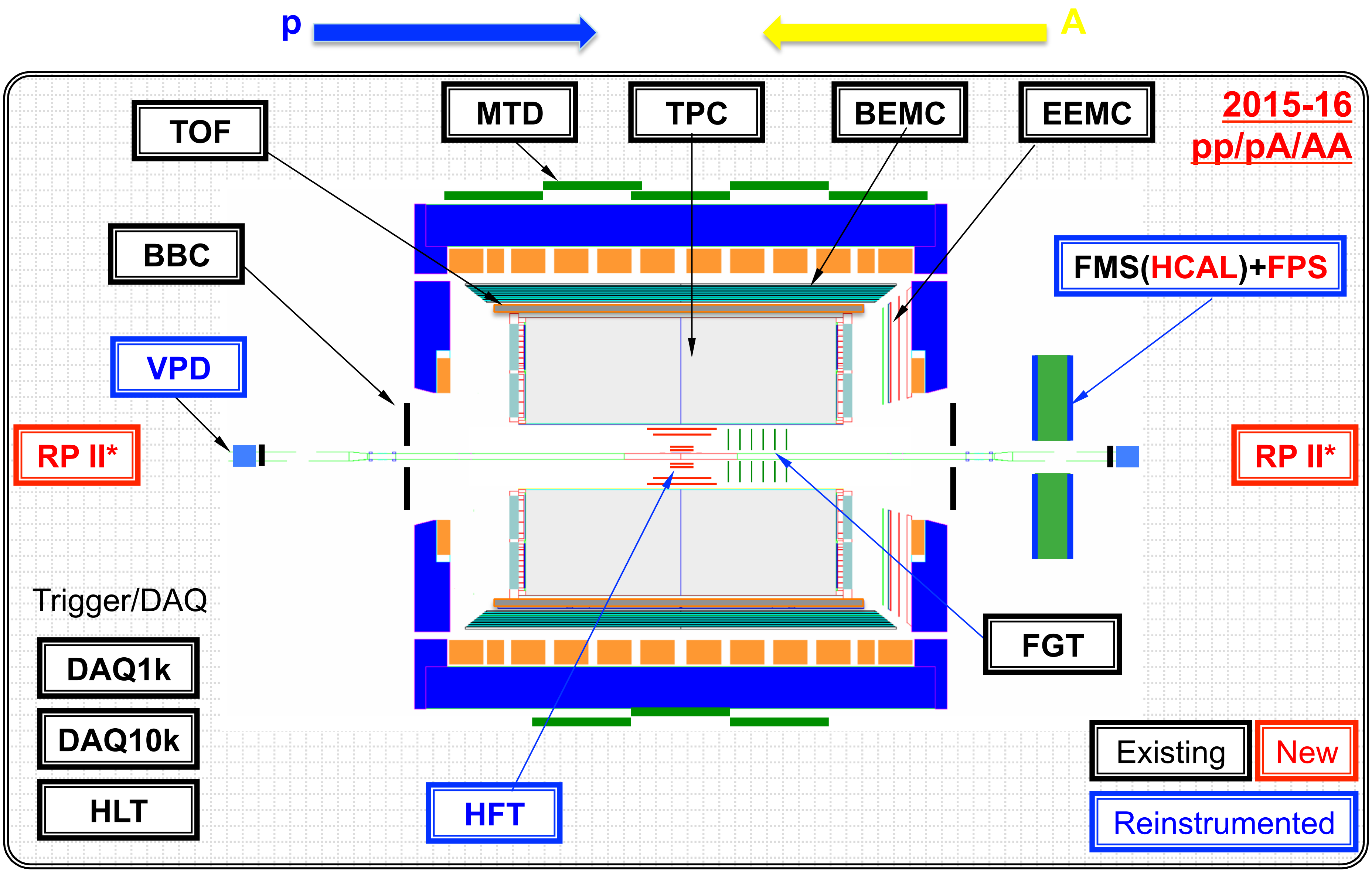
GEM = gaseous electron multiplier

STAR Detector in 2014



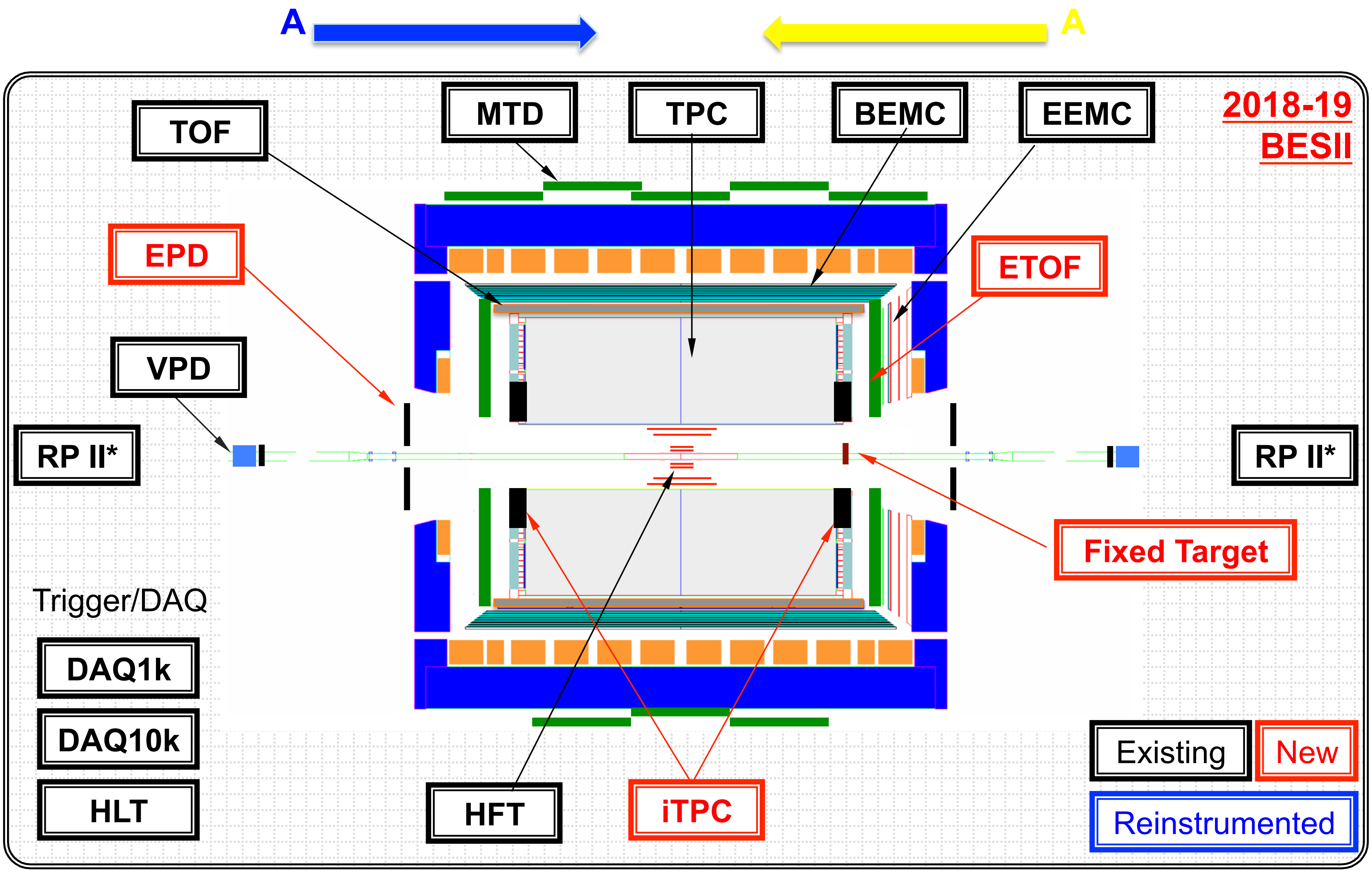
HFT: Heavy Flavor Tracker, **MTD**: Muon Telescope Detector

STAR Detector in 2015-2016



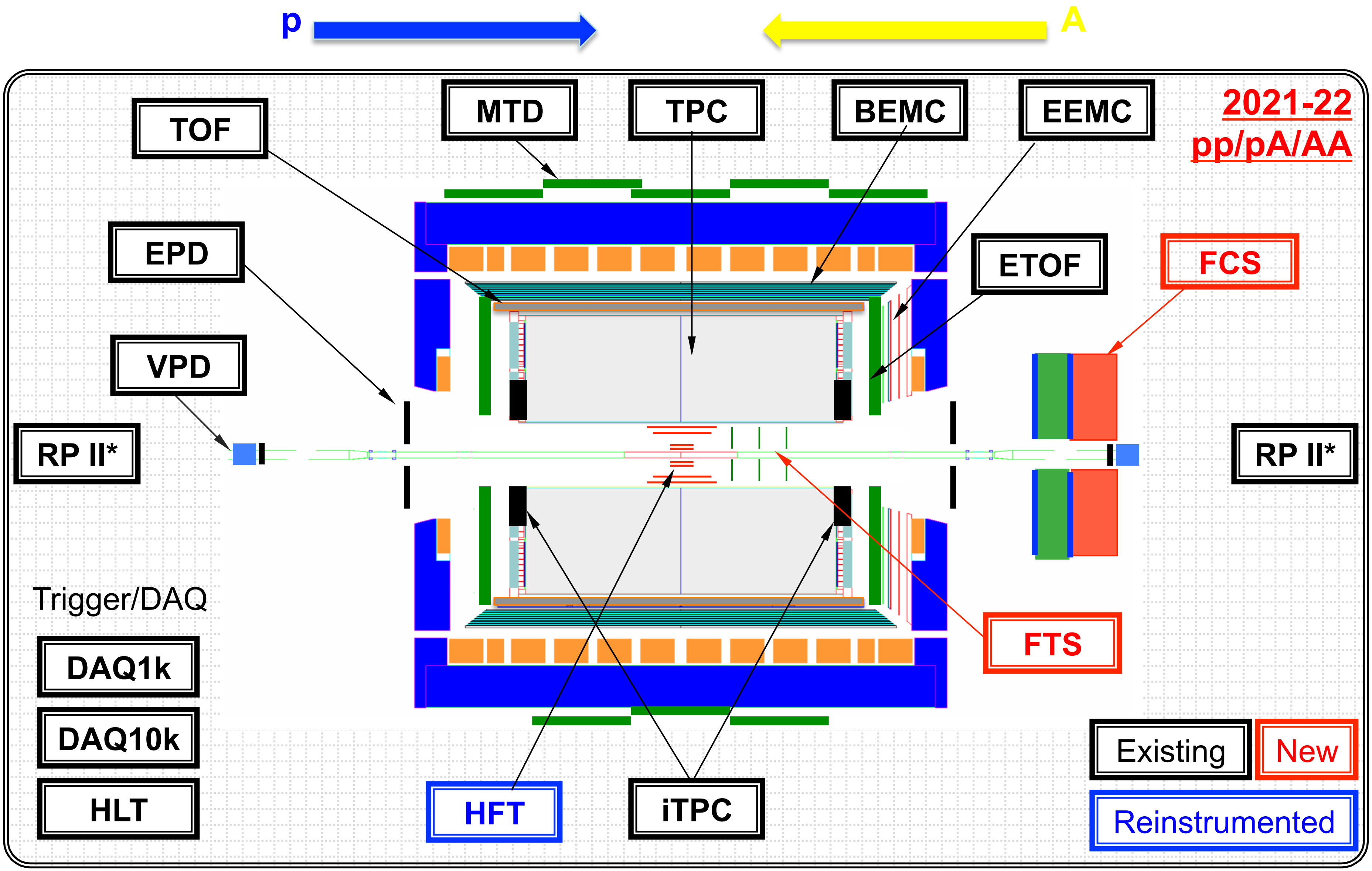
FMS: Forward Meson Spectrometer, **FPS**: Forward Preshower, **RP II***: Roman Pot Phase II*

STAR Detector in 2018-2019



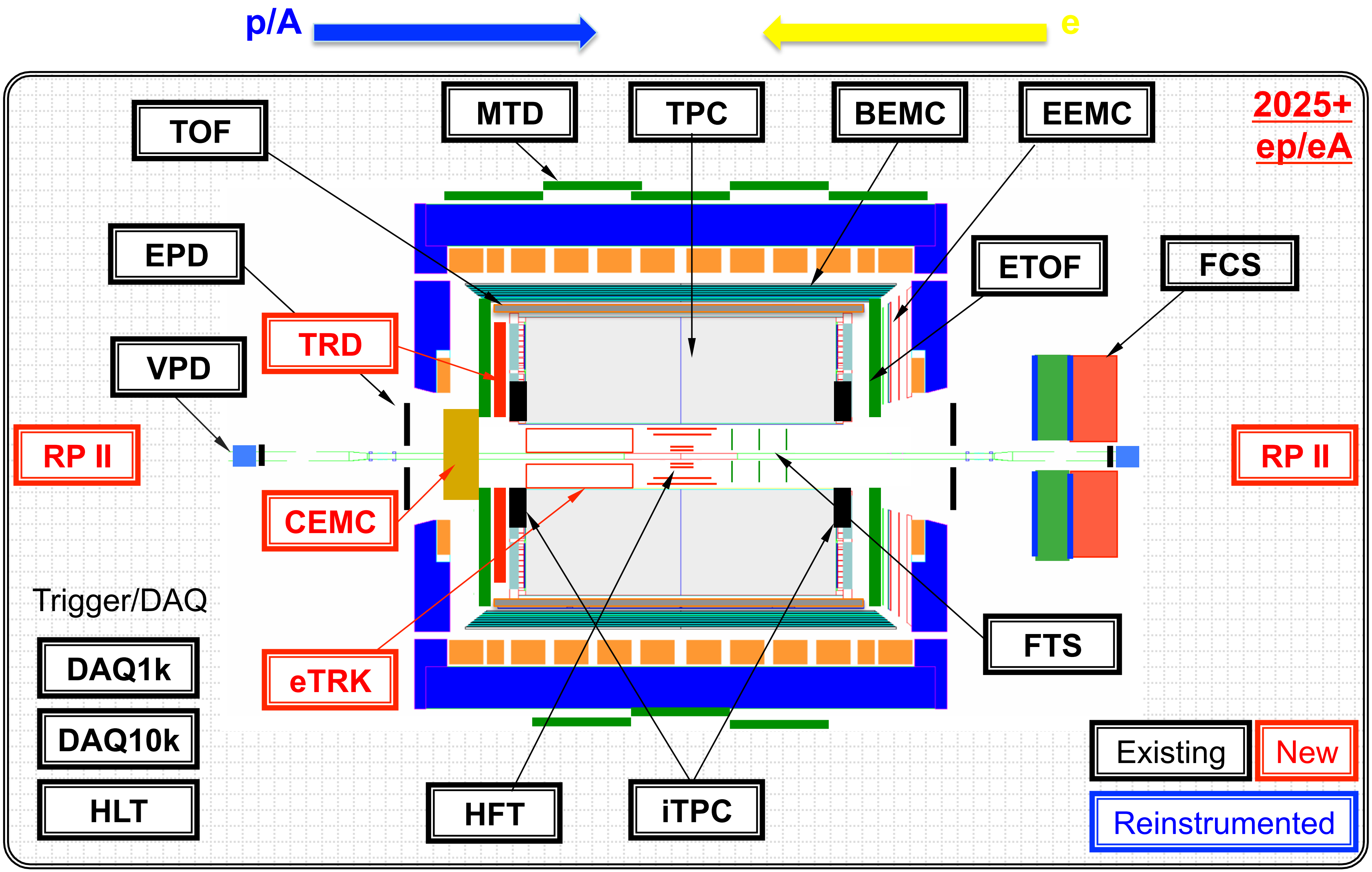
iTPC: inner TPC, **EPD**: Event Plane and Centrality Detector, **ETOF**: End-cap TOF, **Fixed Target**

STAR Detector in 2021-2022



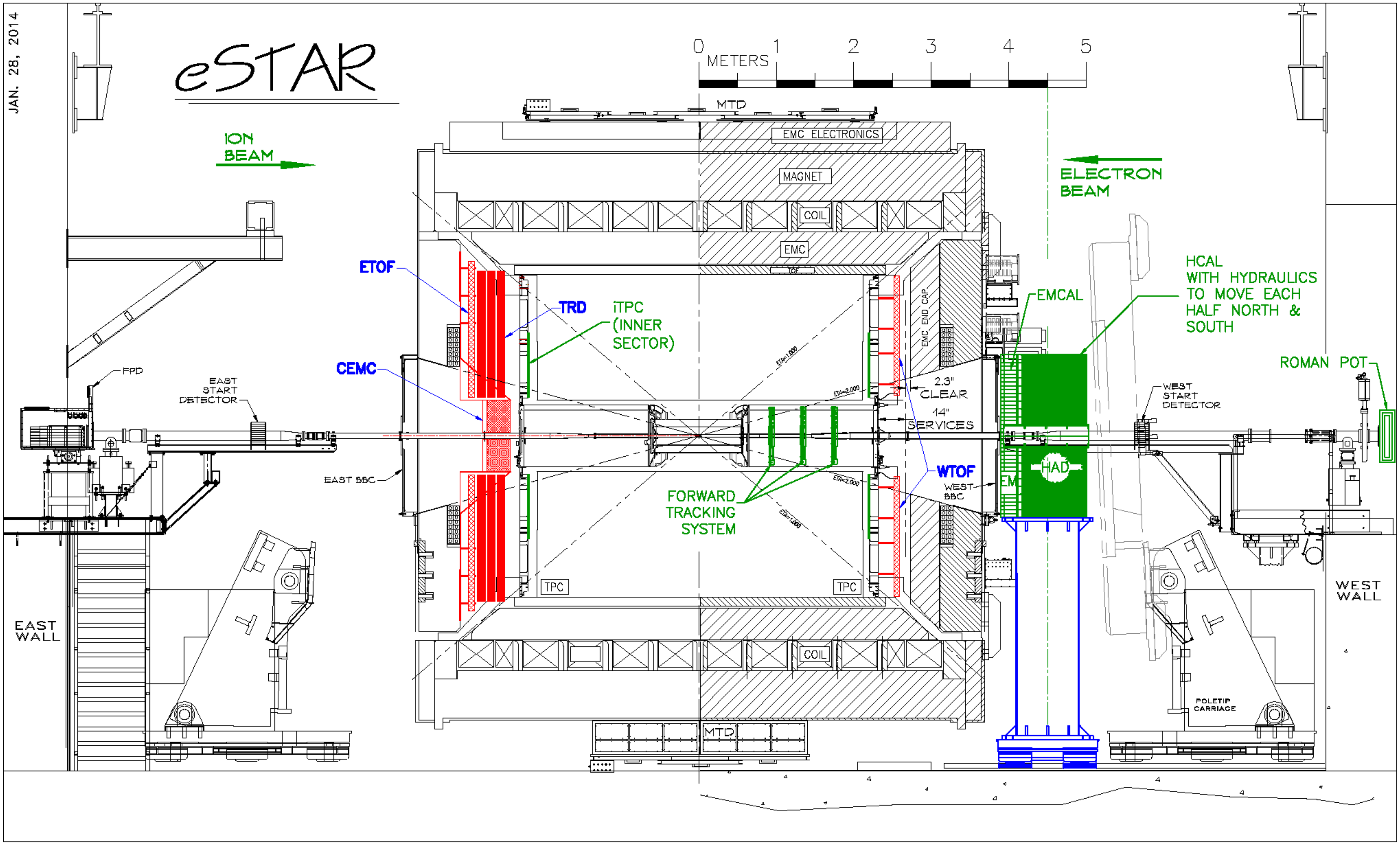
FCS/FTS: Forward Calrimeter/Tracking System, **RP II**: Full Roman Pot Phase II

STAR Detector in 2025+



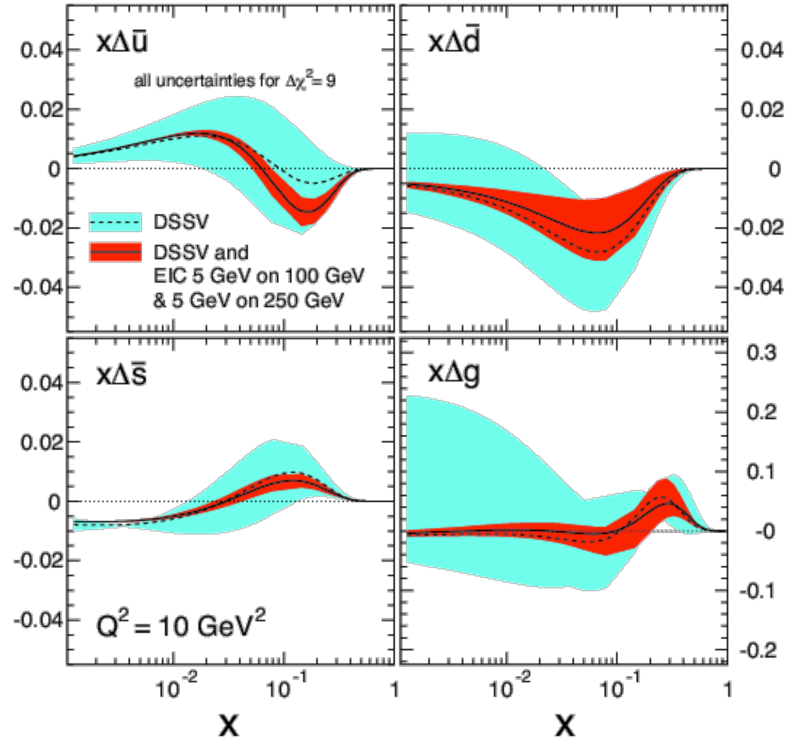
CEMC: Central EM Calorimeter, **eTRK:** electron Tracker, **TRD:** Transition Radiation Detector

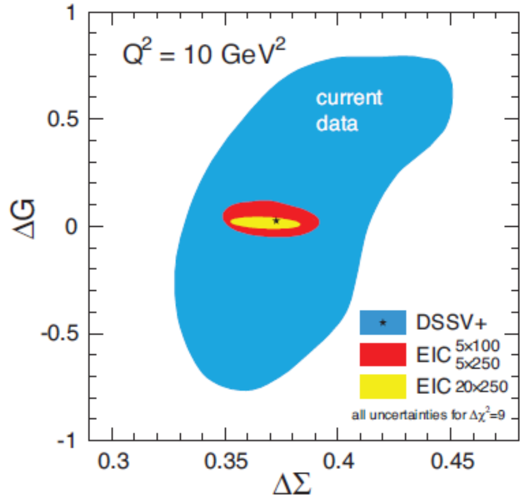
eSTAR Detector in 2025+



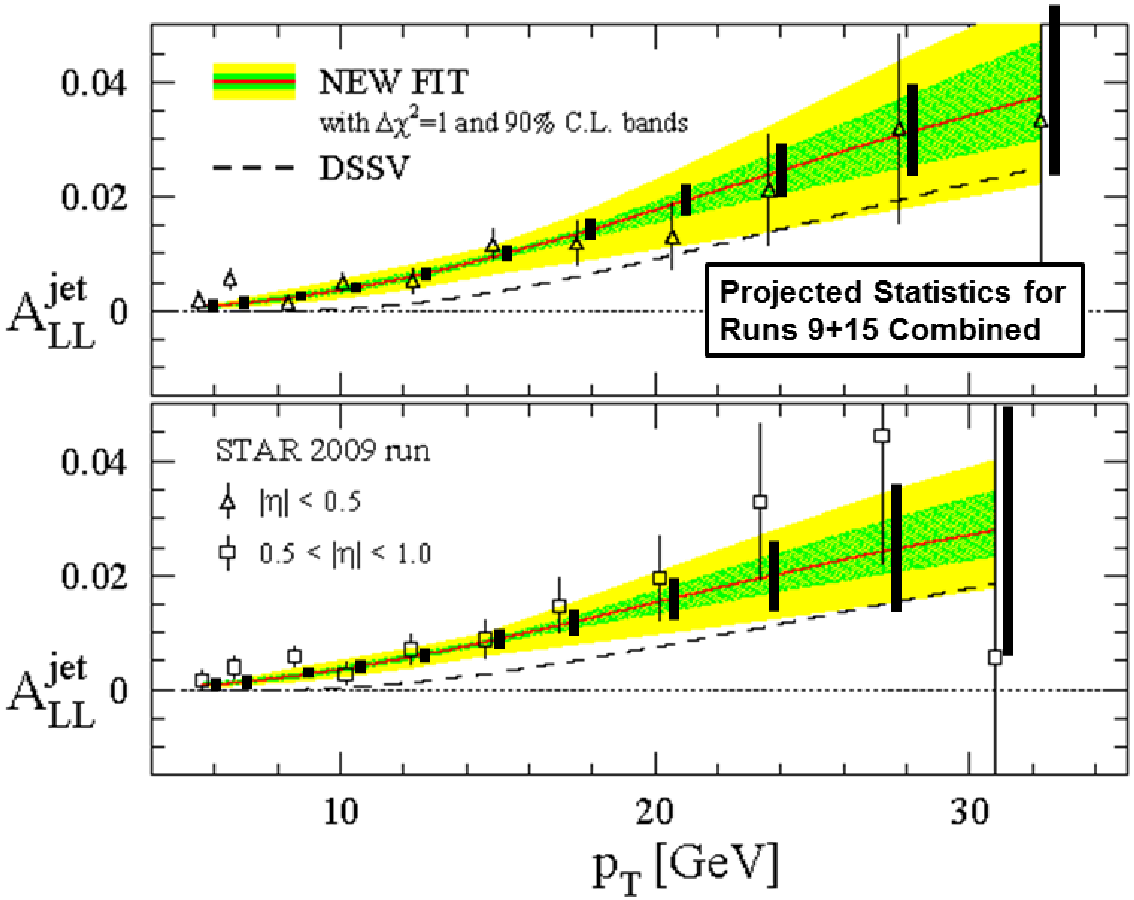
The very successful STAR detector will **evolve into an EIC detector**

Proton Helicity Structure



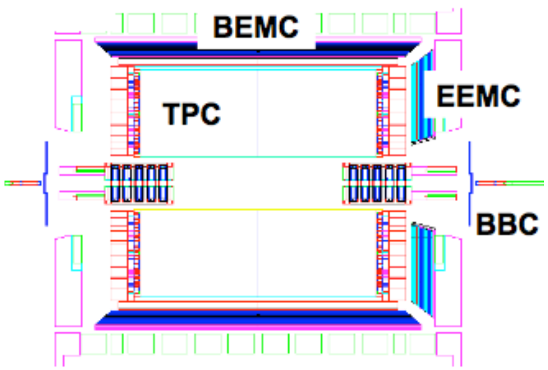


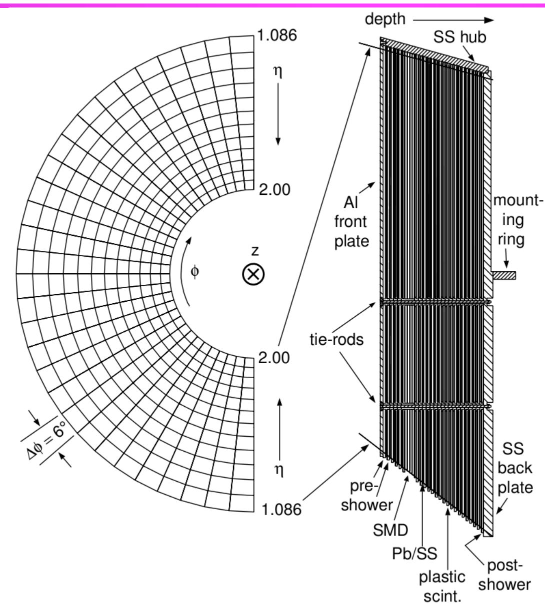
Increased Precision at 200 GeV Coming Soon



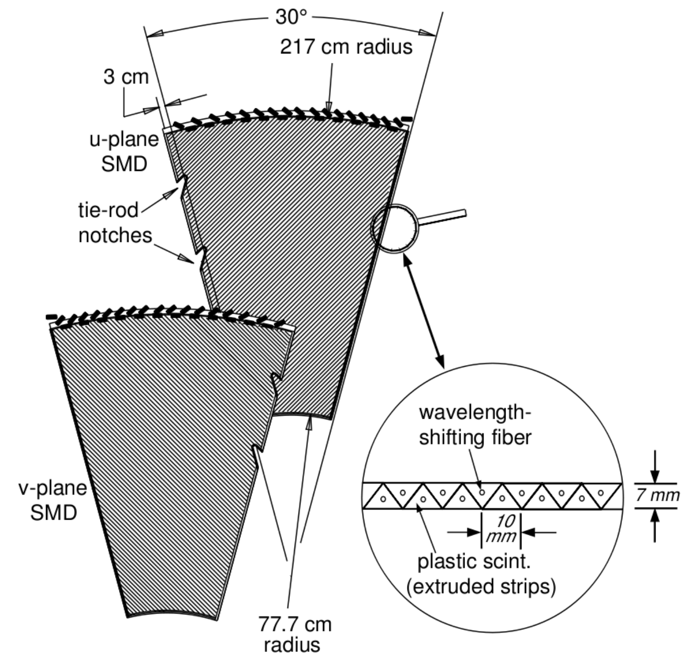
- **STAR also anticipates significant future reductions in the uncertainties for 200 GeV collisions relative to the 2009 results**
    - Hope to record **triple** the existing 200 GeV data during **the 2015 RHIC run**

STAR's Endcap Electromagnetic Calorimeter





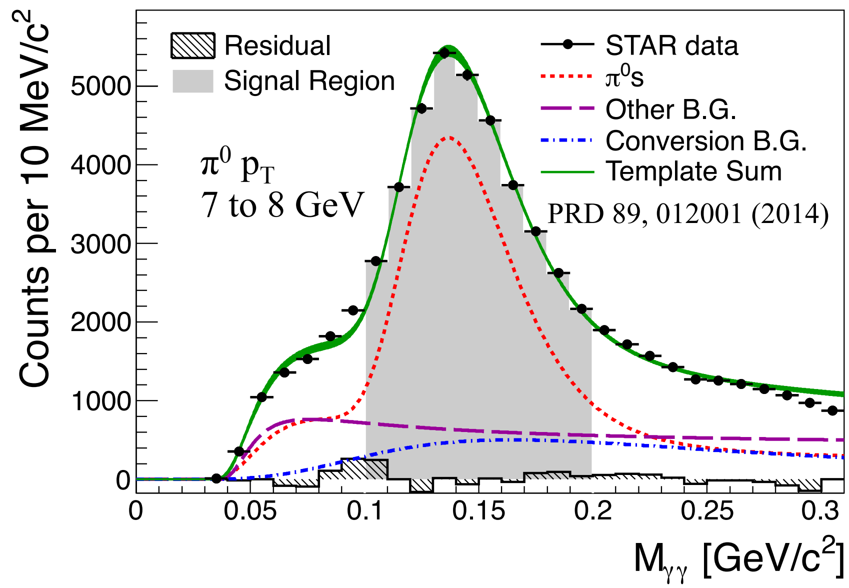
- Scintillating strip SMD
  - ϕ segmented into 12 sectors
  - Two active planes
  - 288 strips per plane
- Resolution of a few mm



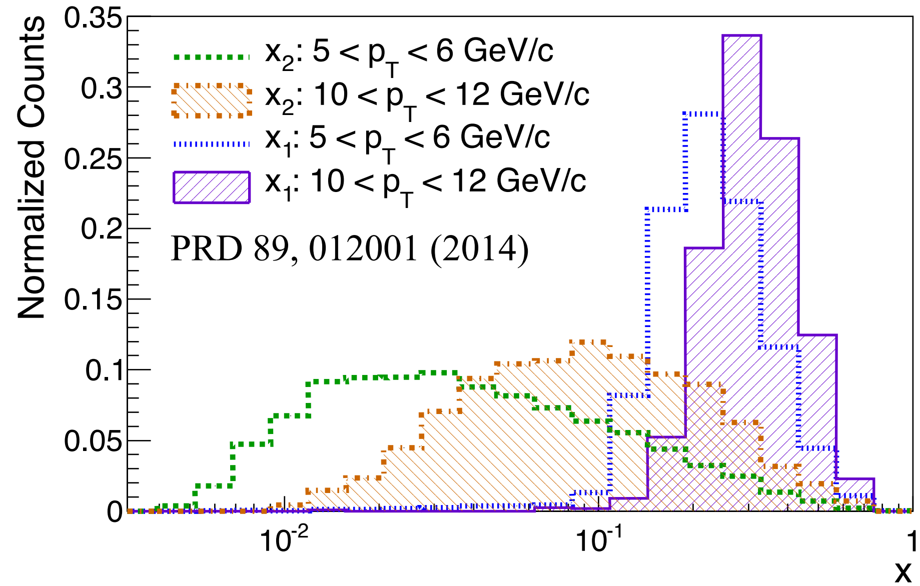
- Nucl. Instrum. Meth. **A** 499 (2003) 740.
- Lead/scintillator sampling EM calorimeter
  - Covers $1.09 < \eta < 2.00$ over full 2π azimuth
  - 720 optically isolated projective towers (~22 X_0)
  - 2 pre-shower, 1 post-shower layers, and an additional shower maximum detector (SMD)
- Photon trigger places thresholds on maximum tower energy and the 3x3 patch of surrounding towers

π^0 Background and Cross-Section Computation $0.8 < \eta < 2.0$ with 2006 Dataset

- Inclusive π^0 mass distribution fit to MC templates, in bins of π^0 p_T
  - Signal
  - Conversion BG (π^0 candidate is from gamma → e+ e-)
  - All other BG (extra or missing photons, π^0 candidate is gamma and e-, etc.)
  - Shapes from MC, relative fraction (and thus signal fraction) extracted from fit to data

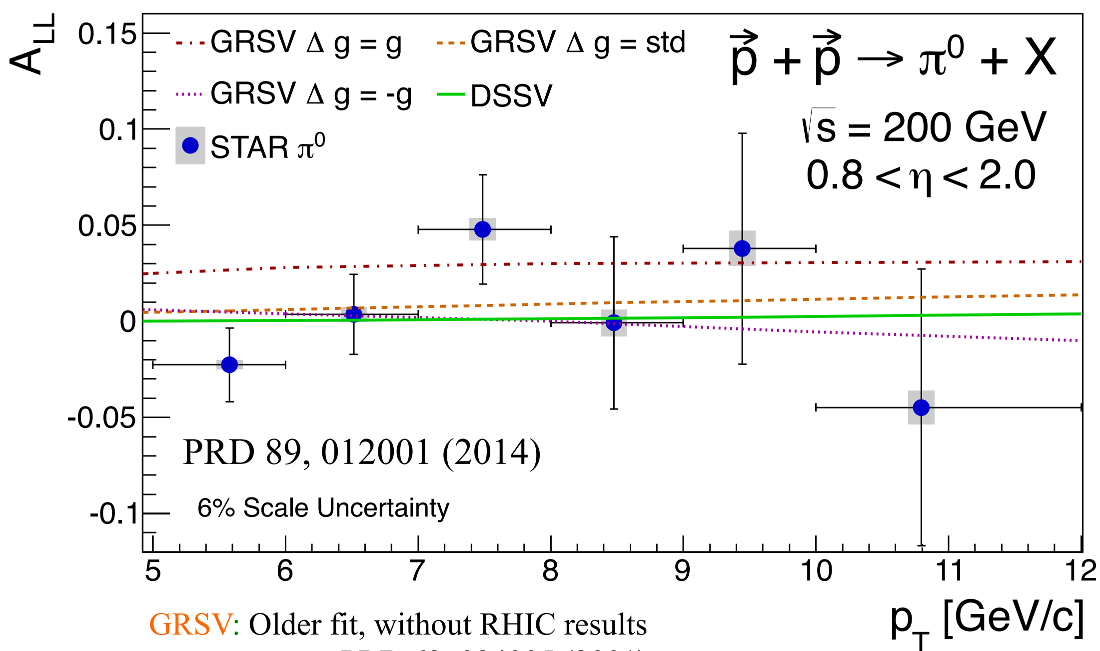


STAR π^0's at low and high p_T,
for sqrt(s) 200 GeV
(PYTHIA, unpolarized CTEQ 5L)



A_{LL} in $\pi^0 + X$ at STAR for $0.8 < \eta < 2.0$

- Statistical error (bars) dominate
- Systematic error (boxes)
  - Signal fraction uncertainties from template fits
  - Uncertainty on background asymmetry
- Integrated across p_T probably constrains GRSV Δg-max?
- PRD 89, 012001 (2014)
- Cross section and transverse asymmetry also measured

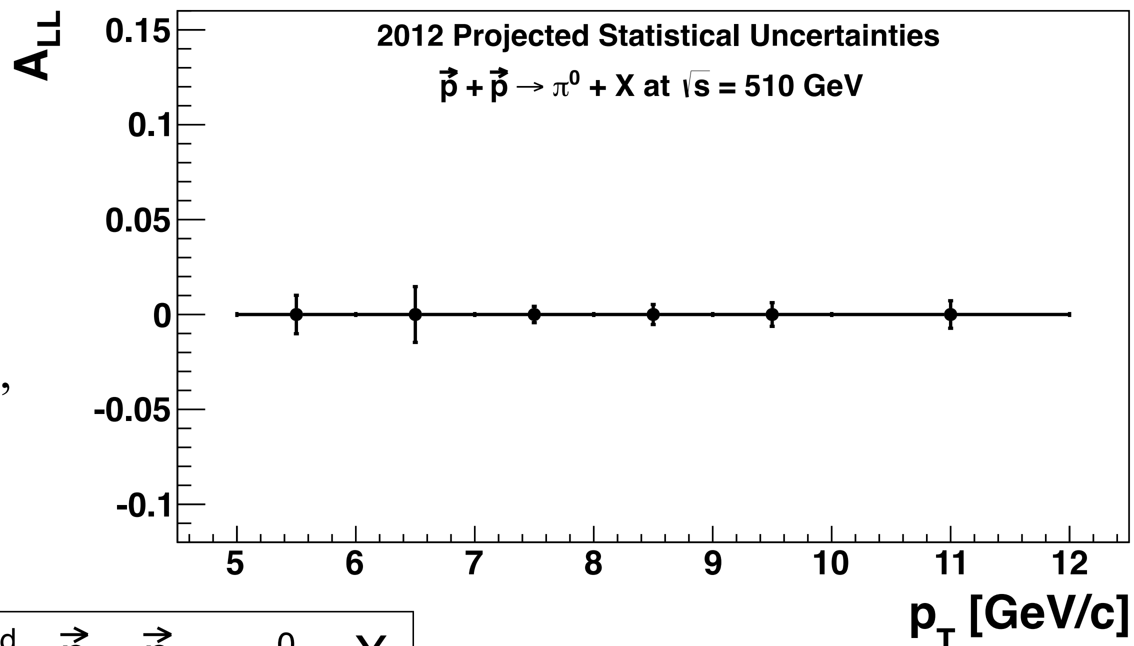


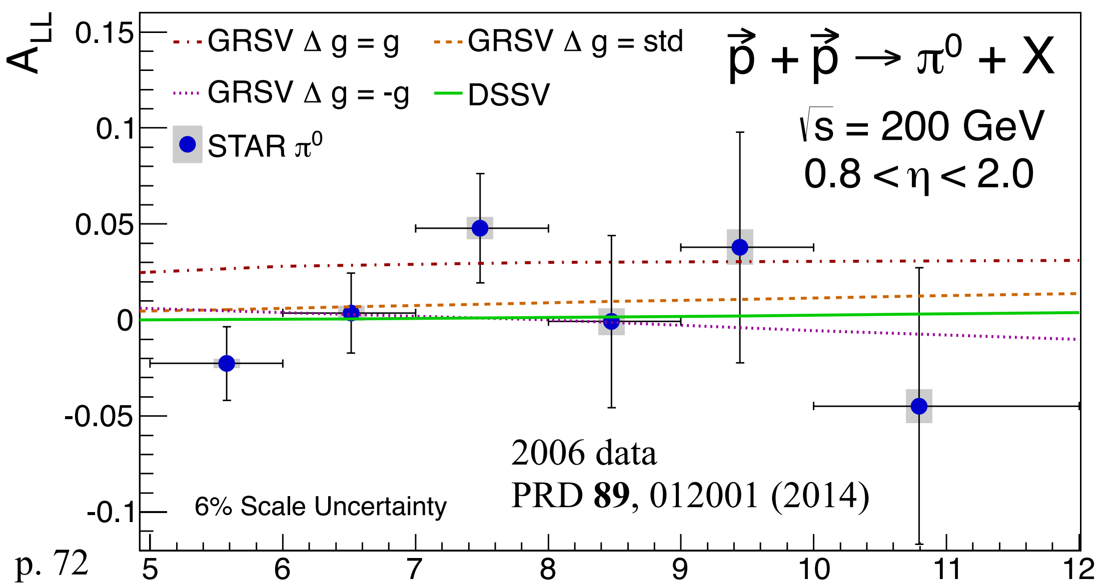
GRSV: Older fit, without RHIC results PRD 63, 094005 (2001)

DSSV: First fit to include RHIC results PRL 101, 072001 (2008)

π^0 A_{LL} Prospects in 2012 Dataset

- Work underway at STAR with 2012 dataset (x10 the 2006 luminosity) at intermediate (endcap) pseudorapidity
  - Large improvement in stat. uncertainty projected, as shown





- Higher CoM energy
  - 200 → 510 GeV
  - Pushes to lower *x* gluon

π^0 A_{LL} Prospects in 2012 Dataset

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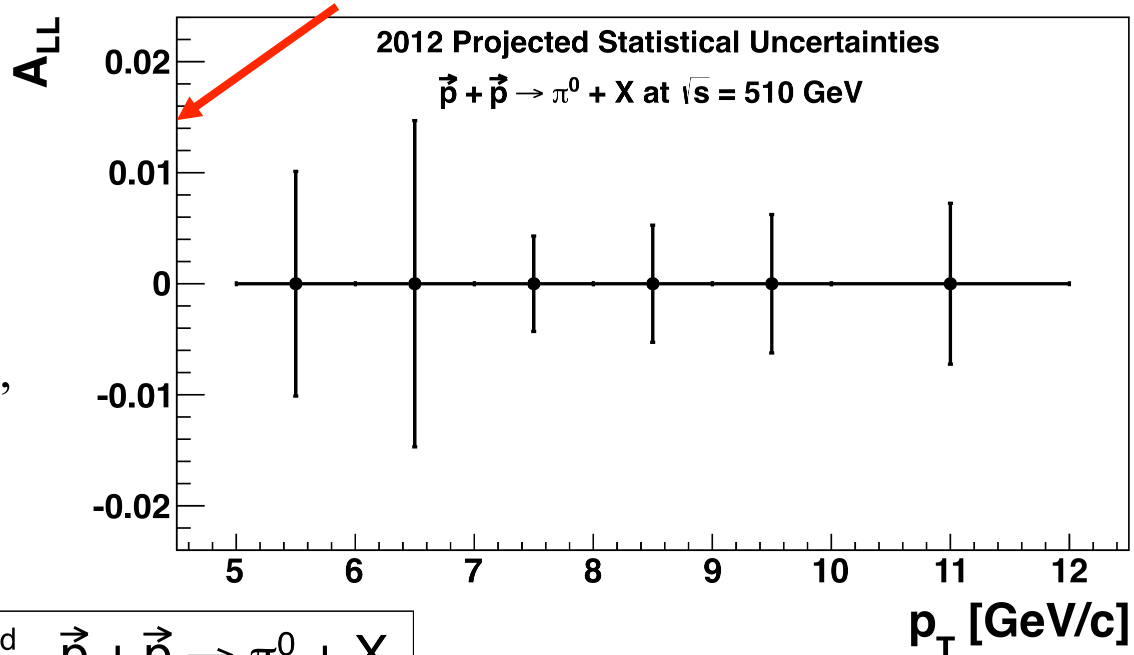
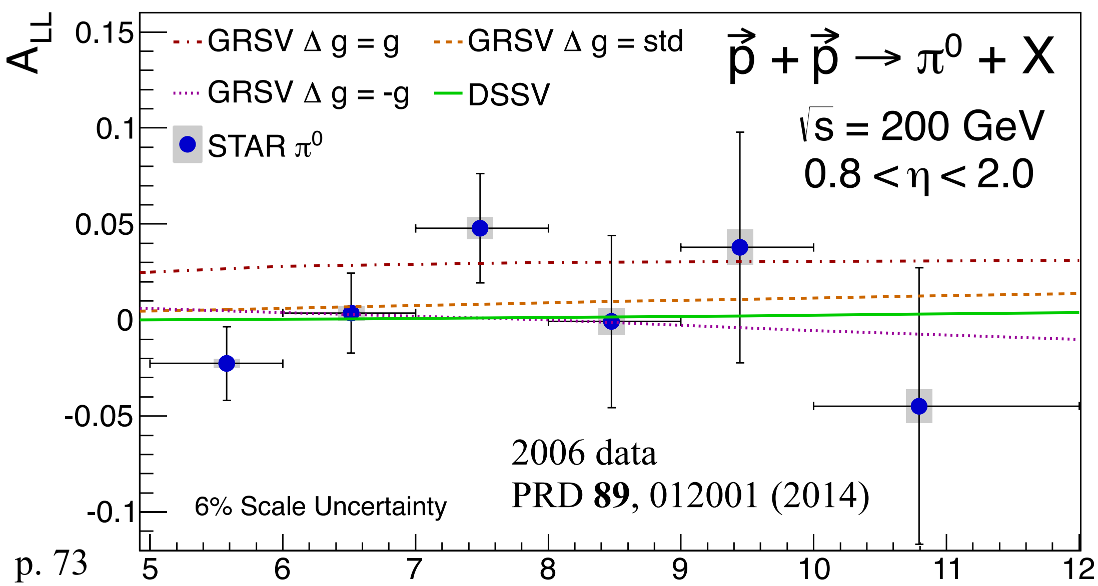
Greatly magnified!





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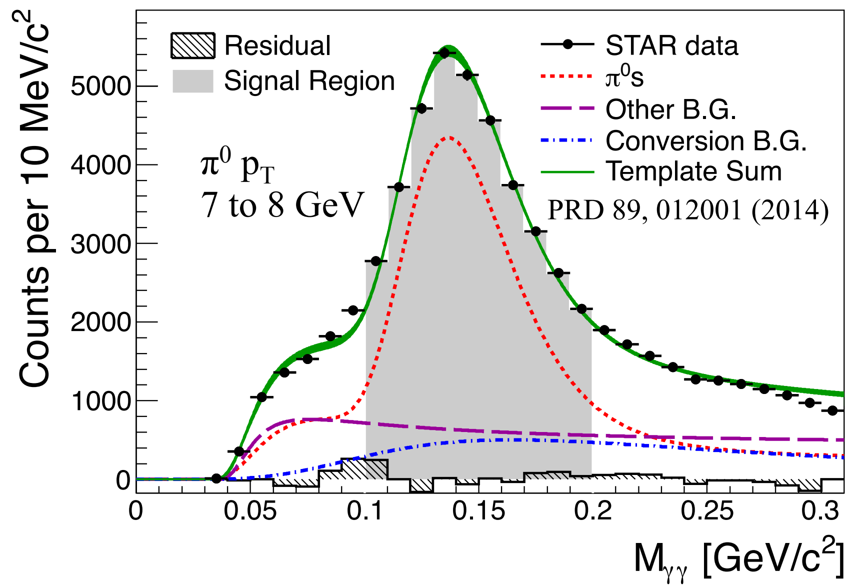
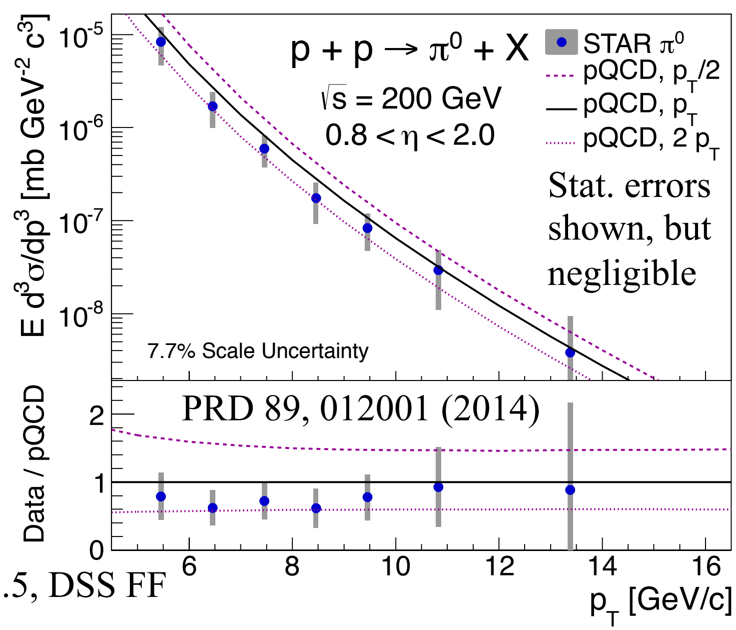
- Inclusive π^0 mass distribution fit to MC templates, in bins of π^0 p_T
  - Signal
  - Conversion BG (π^0 candidate is from gamma → e+ e-)
  - All other BG (extra or missing photons, π^0 candidate is gamma and e-, etc.)
  - Shapes from MC, relative fraction (and thus signal fraction) extracted from fit to data
- Lowest analyzed bin is 5-6 GeV π^0 p_T
  - Data-MC agreement unsatisfactory below this
  - Large amount of passive material, not well modeled
- Unfolded cross section calculated with a "smearing matrix"
  - Dominant systematic is EEMC energy scale
  - Consistent with NLO pQCD (thanks M. Stratmann)
    - B. Jaeger et al., Phys. Rev. D 67, 054005 (2003) CTEQ 6.5, DSS FF

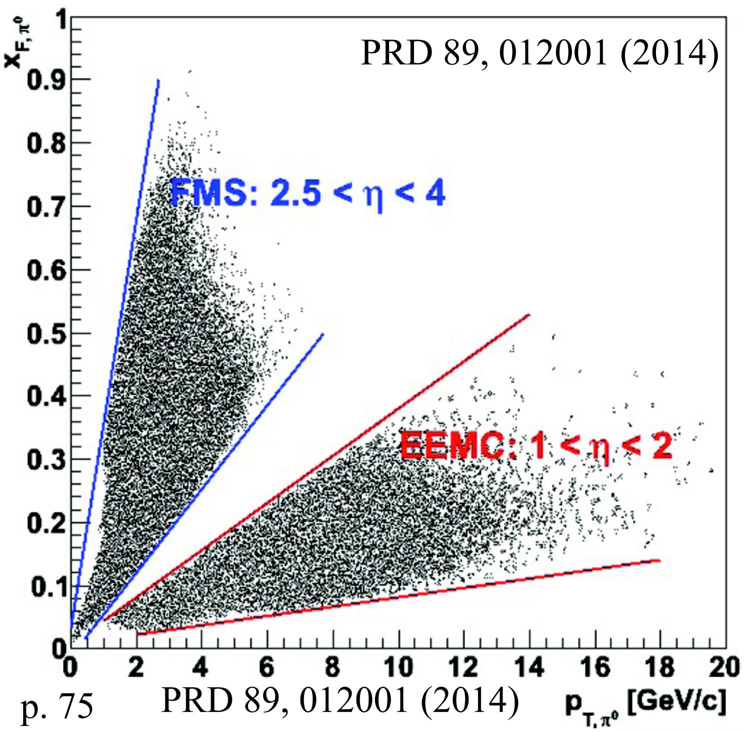




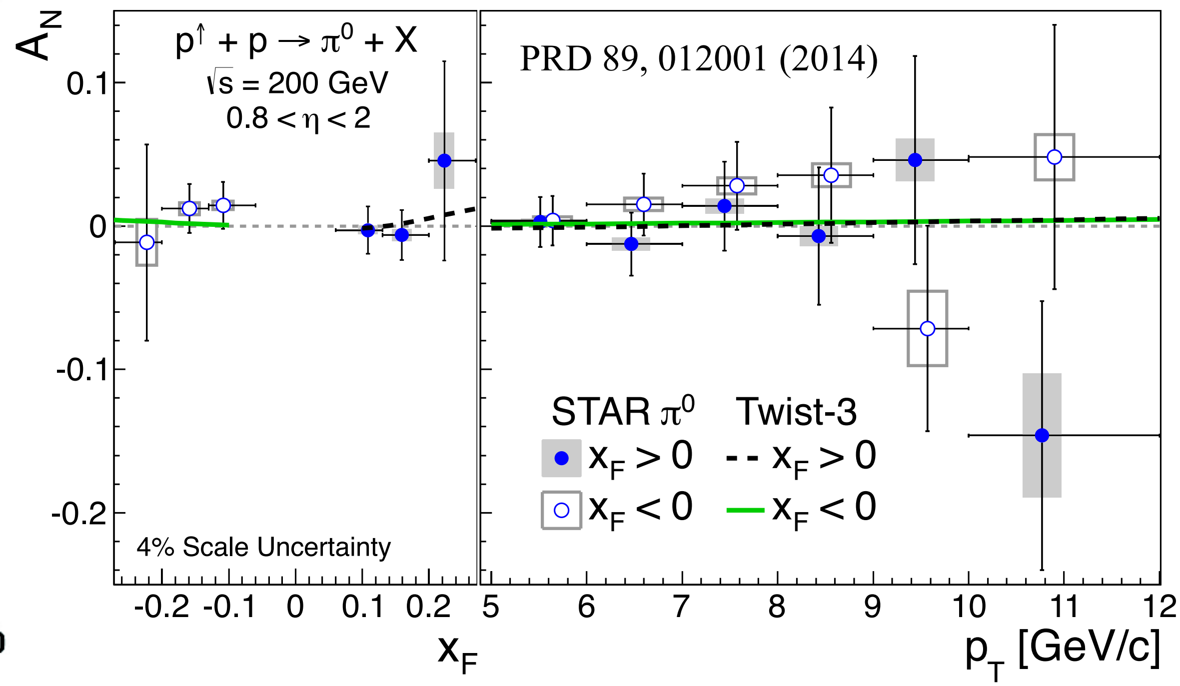
A_N in $\pi^0 + X$ at STAR for $0.8 < \eta < 2.0$

- Transverse asymmetries as well!
- Plotted in bins of π^0 p_T (integrated over $0.06 < x_F < 0.27$), and in bins of x_F
- Statistical error (bars) dominates over systematic error (boxes)
- Twist-3 prediction
  - K. Kanazawa and Y. Koike,
  - Phys. Rev. D 83, 114024 (2011)

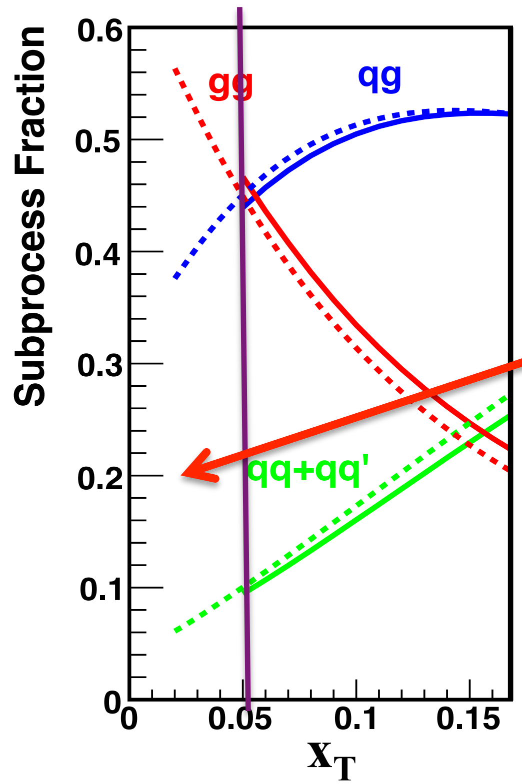
STAR at sqrt(s) 200 GeV

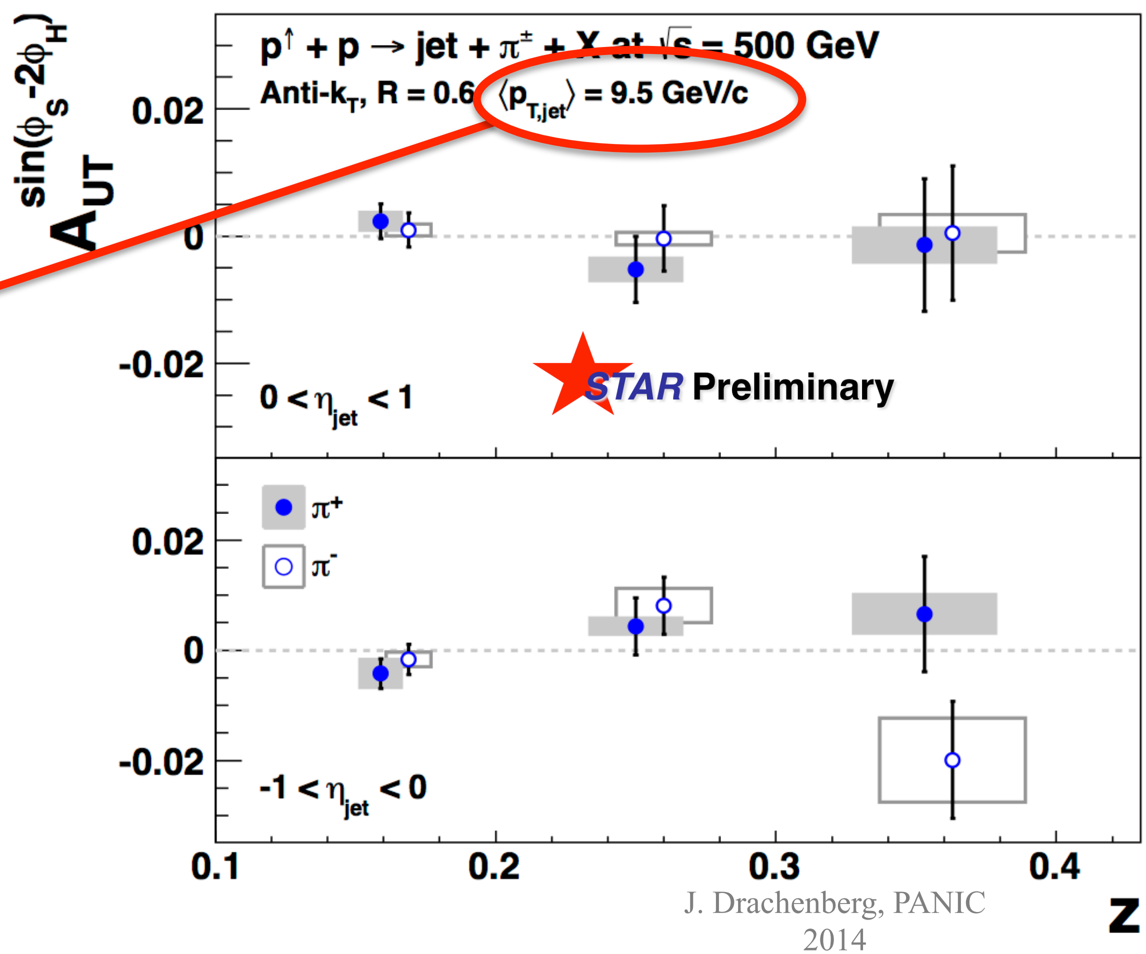


p. 75 PRD 89, 012001 (2014)



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





Gluon helicity density matrix

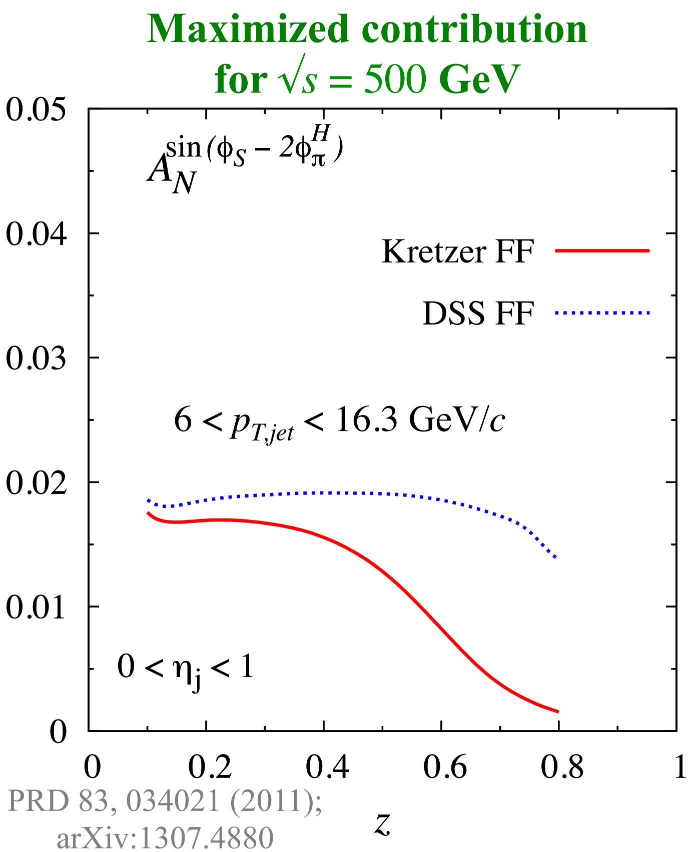
$$\rho = \frac{1}{2}\begin{pmatrix} 1+P_{circ} & -P_{lin}e^{-2i\phi} \\ -P_{lin}e^{2i\phi} & 1-P_{circ} \end{pmatrix}$$

Off-diagonal terms related to linear polarization in (xy) plane at angle φ to x-axis

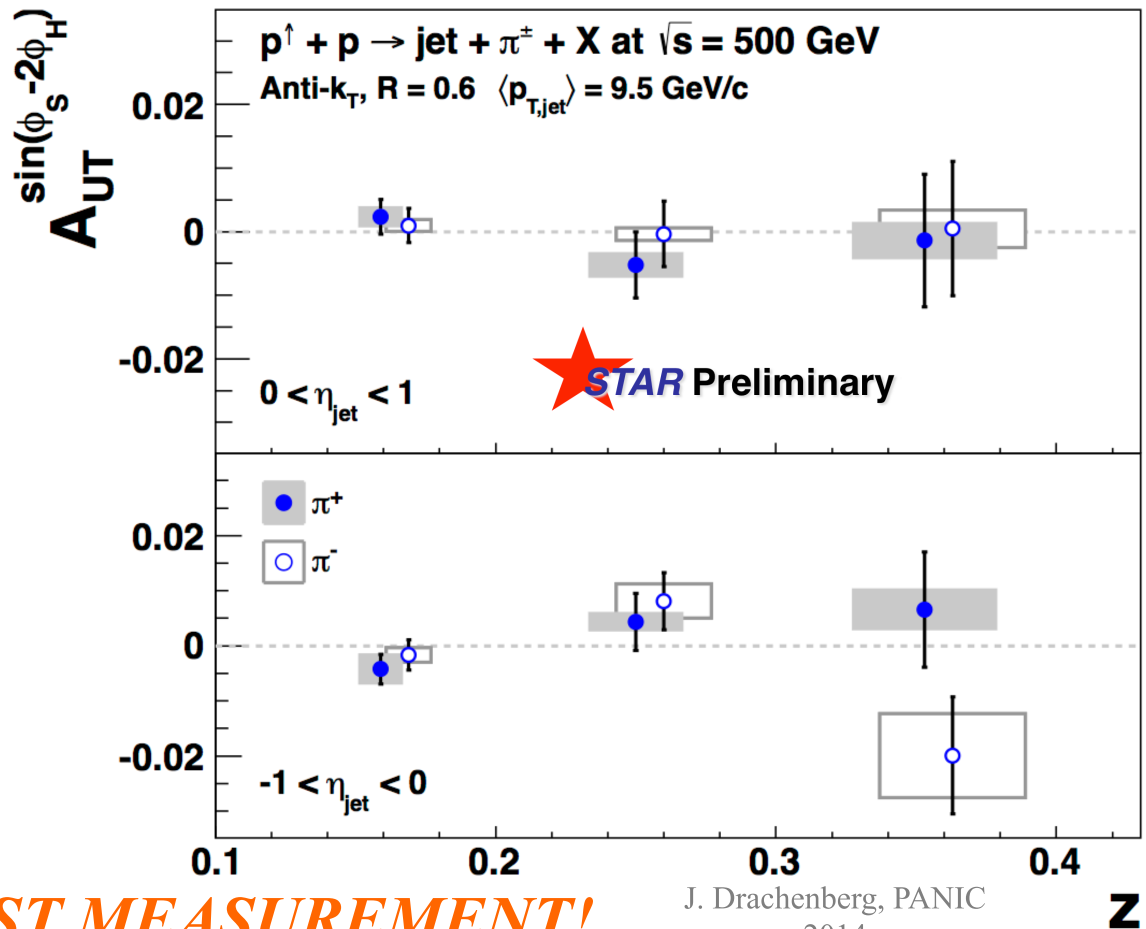
Phys Rev. D 73, 014020 (2006)

500 GeV provides opportunity to probe effects (e.g. gluon linear polarization) with ***enhanced sensitivity to gluonic subprocesses***

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



PRD 83, 034021 (2011); arXiv:1307.4880



J. Drachenberg, PANIC 2014

FIRST MEASUREMENT!

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

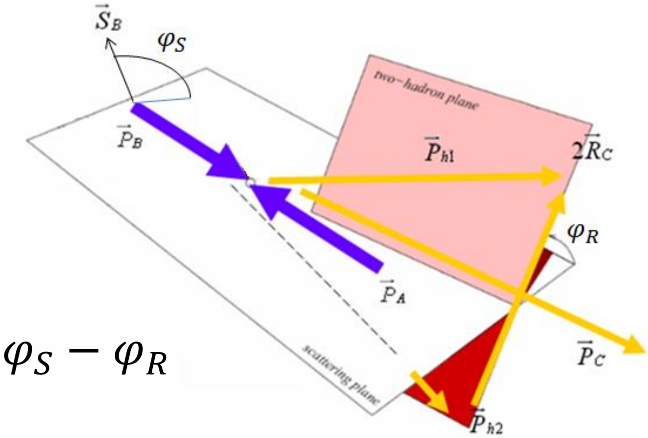
Present data should provide first constraints on Collins-like effect

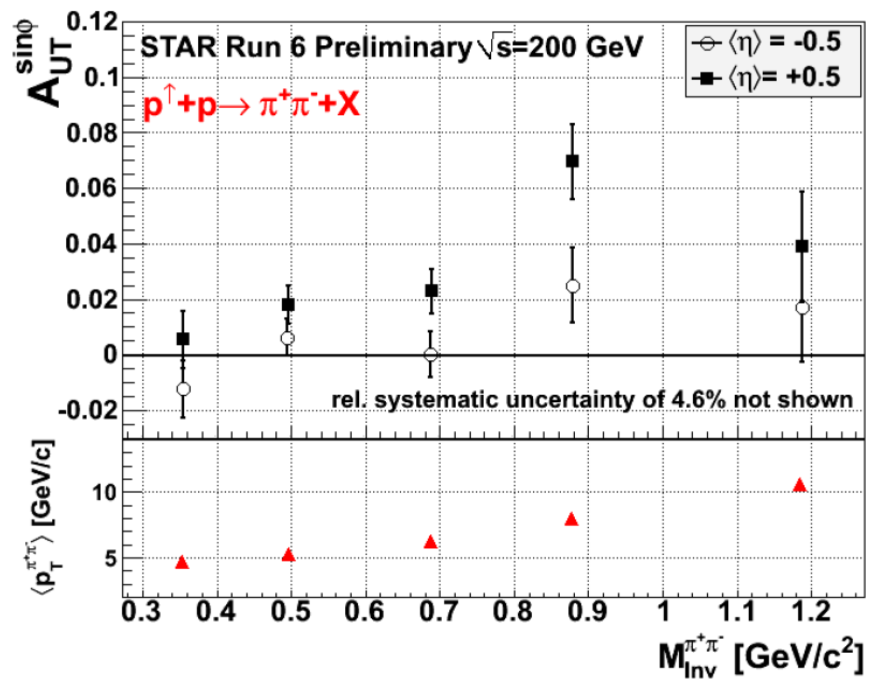
(sensitive to linearly polarized gluons)

Asymmetry Observable

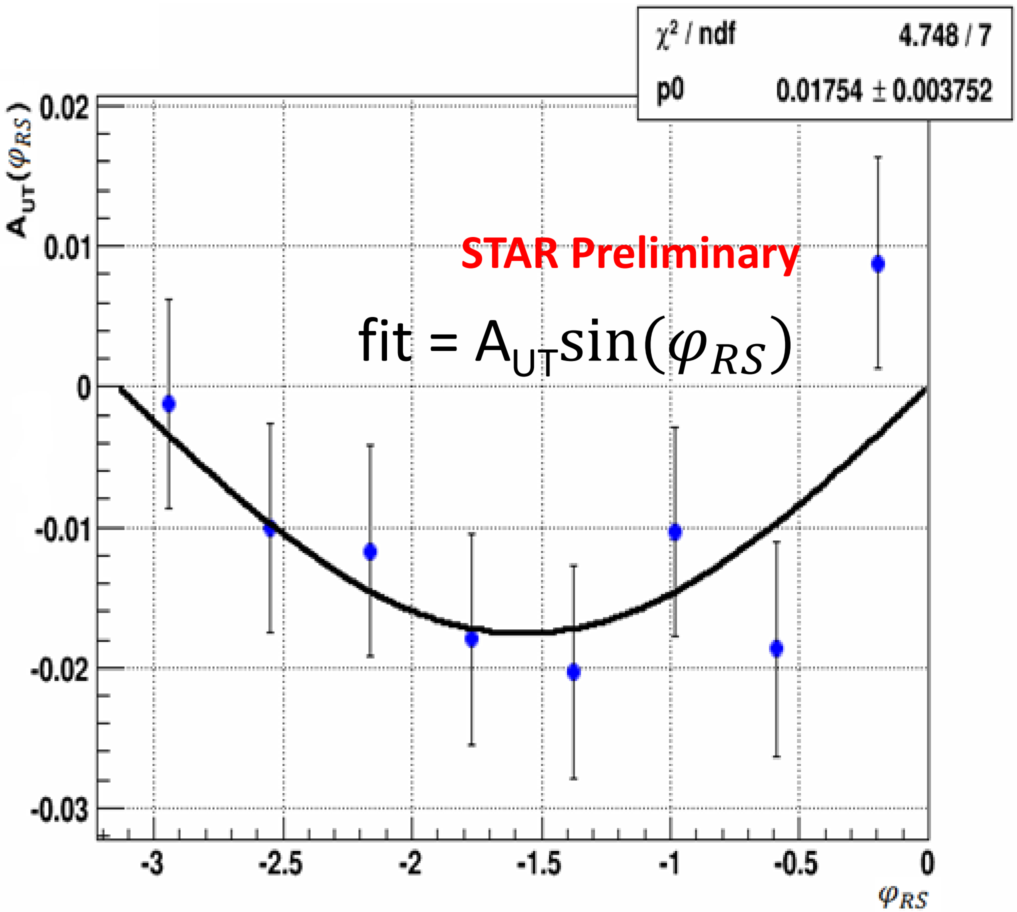
- Calculated for $\boldsymbol{P_B}$ as incident beam, $\boldsymbol{P_A}$ as target
- Incident beam is polarized and target unpolarized by summing over bunches
- Pion separation = $\sqrt{(\Delta\eta^2 + \Delta\phi^2)} < 0.7$
- $A_{UT} \propto h_1 \cdot H_1^{\sphericalangle}$
  - Transversity (h_1)
  - Interference Fragmentation Function ($H_1^{\sphericalangle}$)
- A_{UT} is expected to depend on the invariant mass (M_{Inv}) and p_T of the pion pair

$\varphi_{RS} = \varphi_S - \varphi_R$





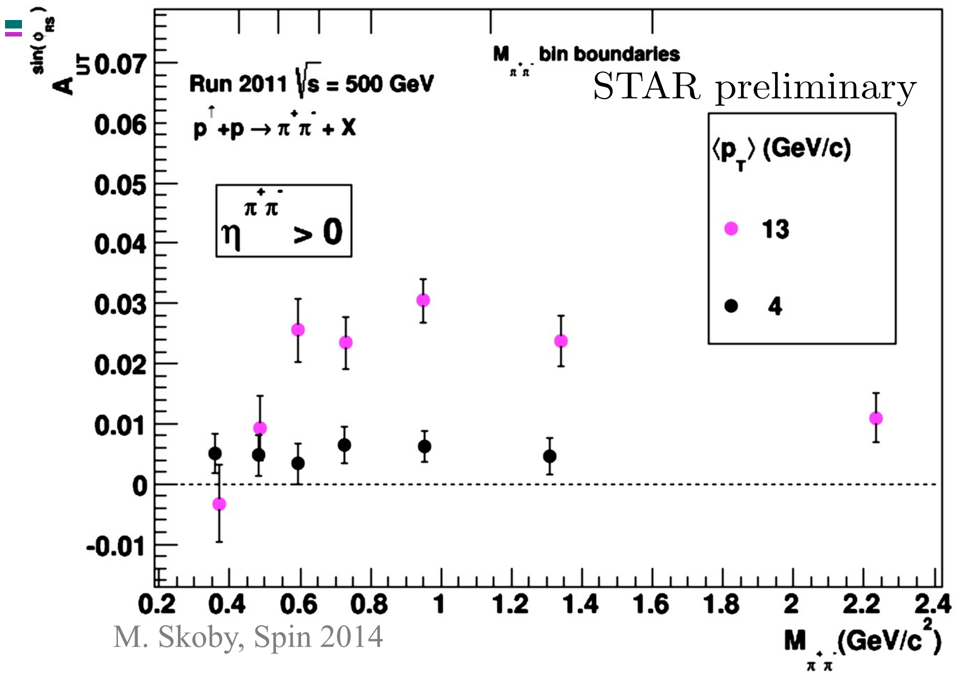
Extract A_{UT}



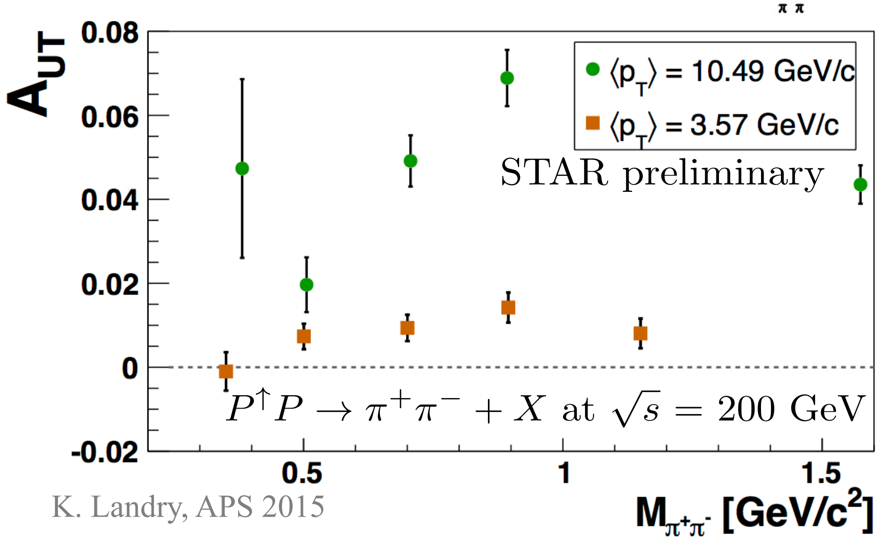
- Particle p_T > 1.5 GeV/c
- Pair p_T > 3.75 GeV/c
- For a given M_{Inv}, p_T bin the asymmetry is calculated for 8 ϕ_{RS} bins
- The asymmetry is the amplitude extracted from a single-parameter fit
- Example shown here is one M_{Inv}, p_T bin

$$A_{UT}(\varphi_{RS}) = \frac{1}{P}\frac{\sqrt{N\uparrow(\varphi_{RS})N\downarrow(\varphi_{RS}+\pi)} - \sqrt{N\downarrow(\varphi_{RS})N\uparrow(\varphi_{RS}+\pi)}}{\sqrt{N\uparrow(\varphi_{RS})N\downarrow(\varphi_{RS}+\pi)} + \sqrt{N\downarrow(\varphi_{RS})N\uparrow(\varphi_{RS}+\pi)}}$$

STAR IFF Results at $\sqrt{s}$ = 500 GeV



M. Skoby, Spin 2014



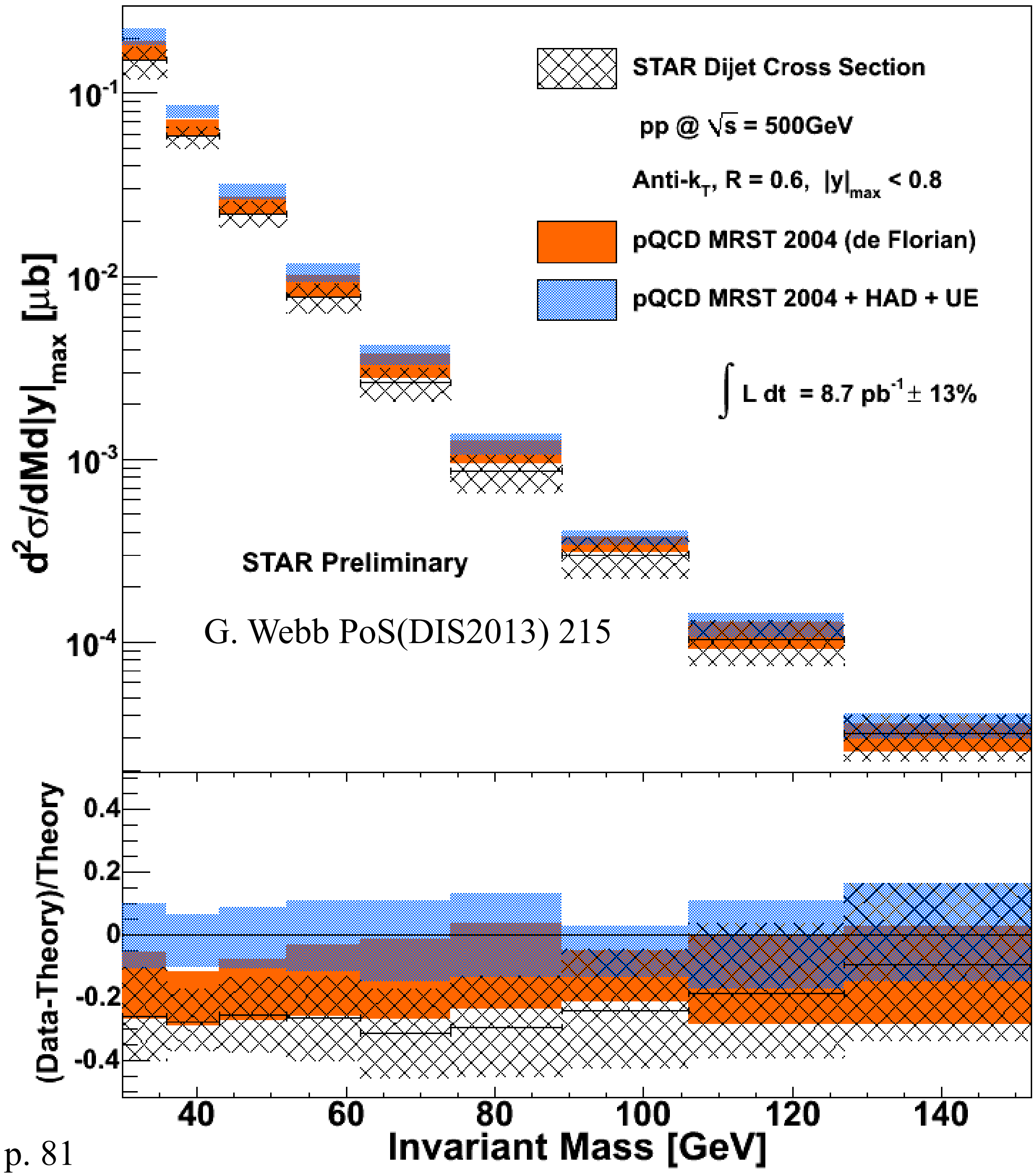
K. Landry, APS 2015

Significant non-zero di-hadron asymmetries at $\sqrt{s}$ = 500 GeV!

- Increasing with pion p_T
- Enhanced around ρ mass

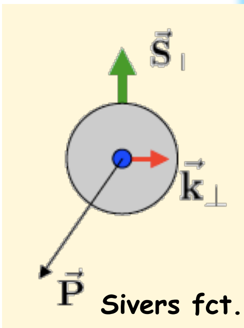
Similar behavior observed in $\sqrt{s}$ = 200 GeV

2009 Dijet Cross Section at 500 GeV



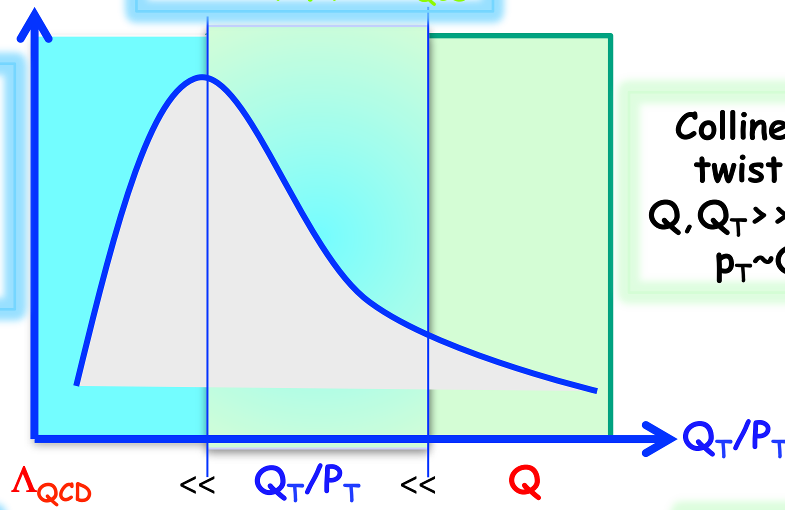
- Also a preliminary 2006 dijet cross section at 200 GeV
  - T. Sakuma, M. Walker, Journal of Physics: Conference Series 295, 012068 (2011).

Theory: TMDs vs. Twist-3

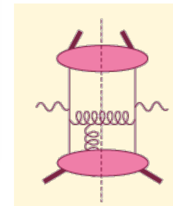


Transverse momentum dependent
$Q >> Q_T >= \Lambda_{QCD}$
$Q >> p_T$

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



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
$A_N(\pi^0/\gamma/\text{jet})$

A_N: How to get to THE underlying Physics

Goal: measure less inclusive

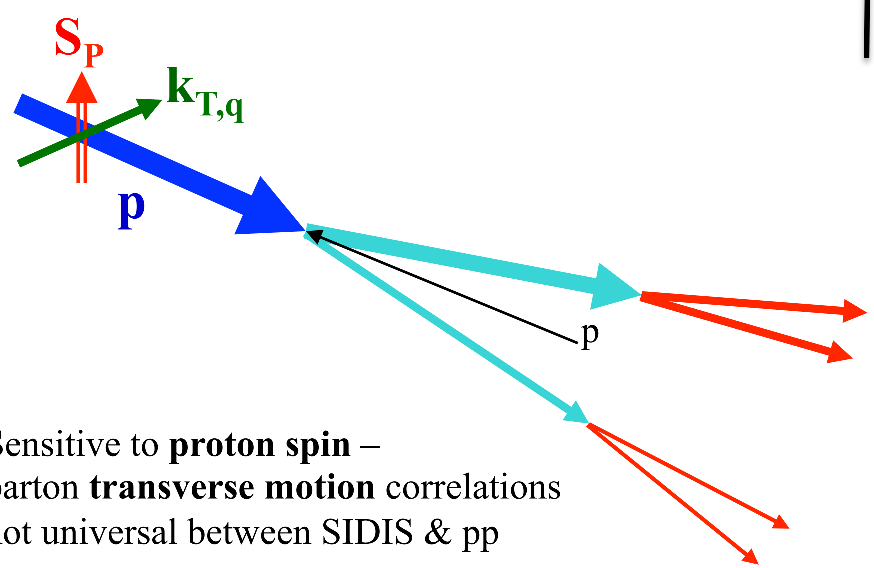
SIVERS/Twist-3 | Collins Mechanism

Rapidity dependence of

- ❑ A_N for π^0 and eta with increased p_t coverage

SIVERS/Twist-3

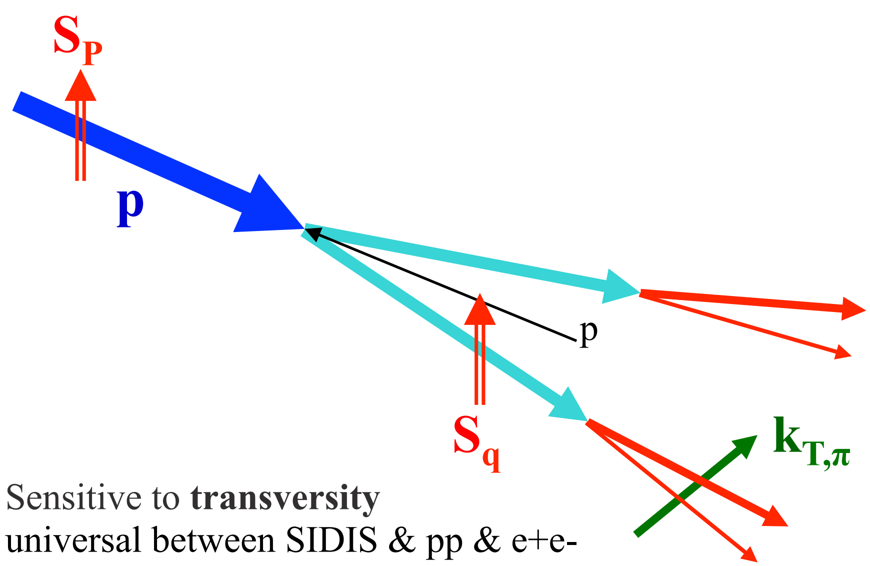
- ❑ A_N for jets, direct photons
- ❑ A_N for heavy flavour → gluon
- ❑ A_N for $W^{+/-}$, Z^0



Sensitive to **proton spin** –
parton **transverse motion** correlations
not universal between SIDIS & pp

Collins Mechanism

- ❑ asymmetry in jet fragmentation
  - ❑ $\pi^{+/-}\pi^0$ azimuthal distribution in jets
  - ❑ Interference fragmentation function



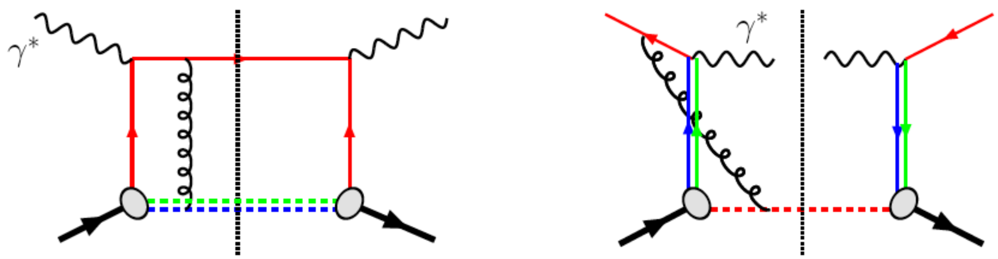
Sensitive to **transversity**
universal between SIDIS & pp & e+e-

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:	pp:
γq-scattering	qqbar-anhilation
attractive FSI	**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