Constraining the Gluon Polarization Distribution with Jet, Dijet, and Neutral Pion Probes at STAR

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For the STAR Collaboration

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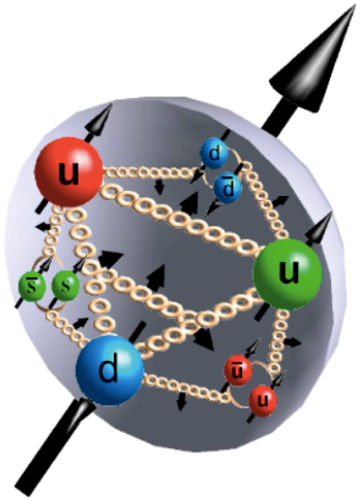
U.S. DEPARTMENT OF ENERGY
Office of Science

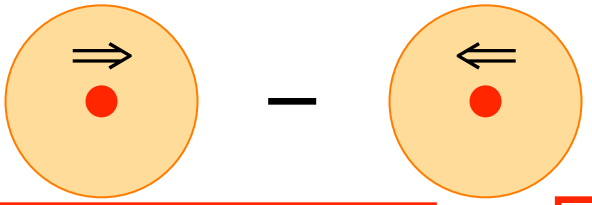
Contributions to the Proton's Spin



Proton momentum ⇒

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

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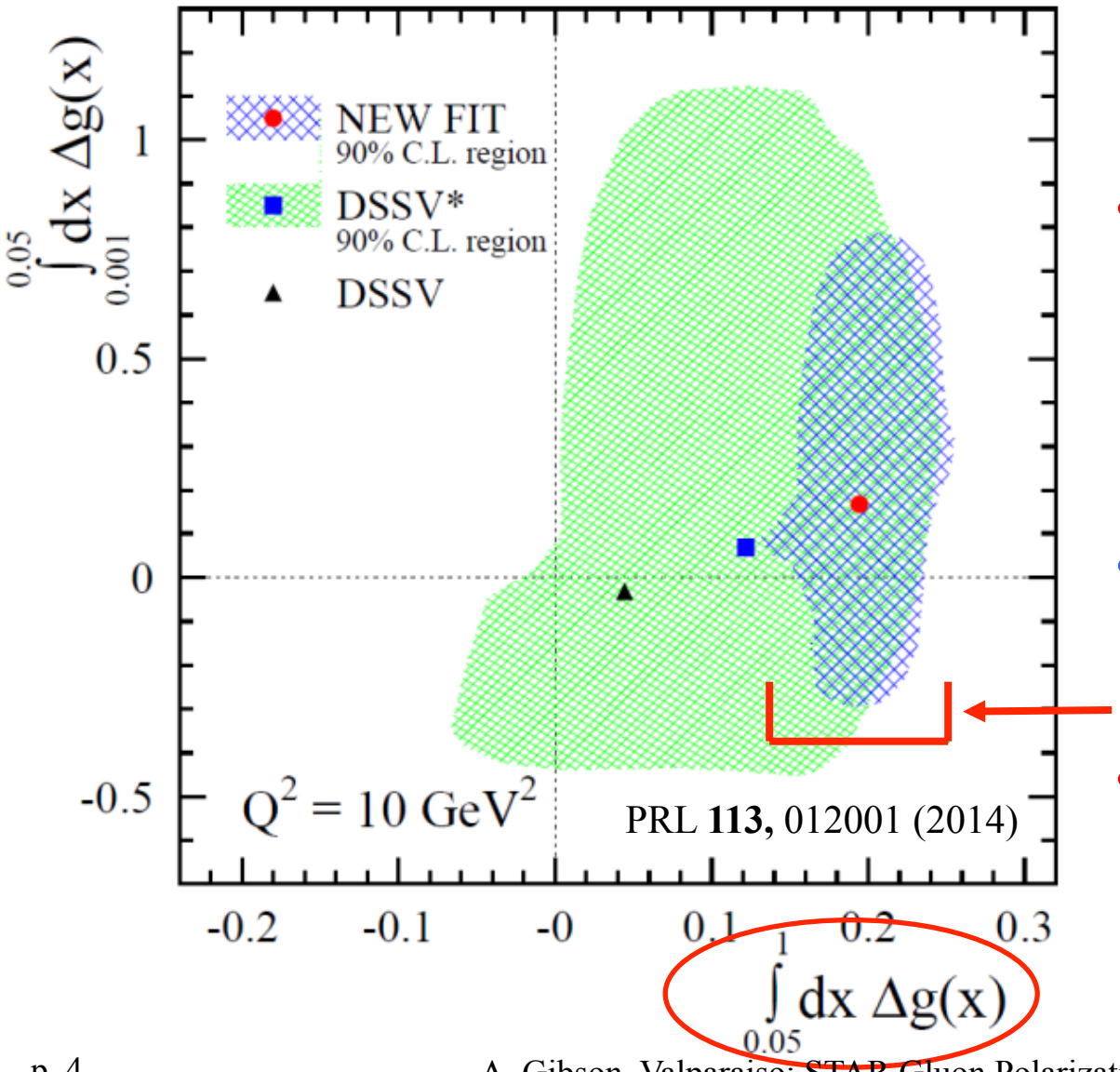
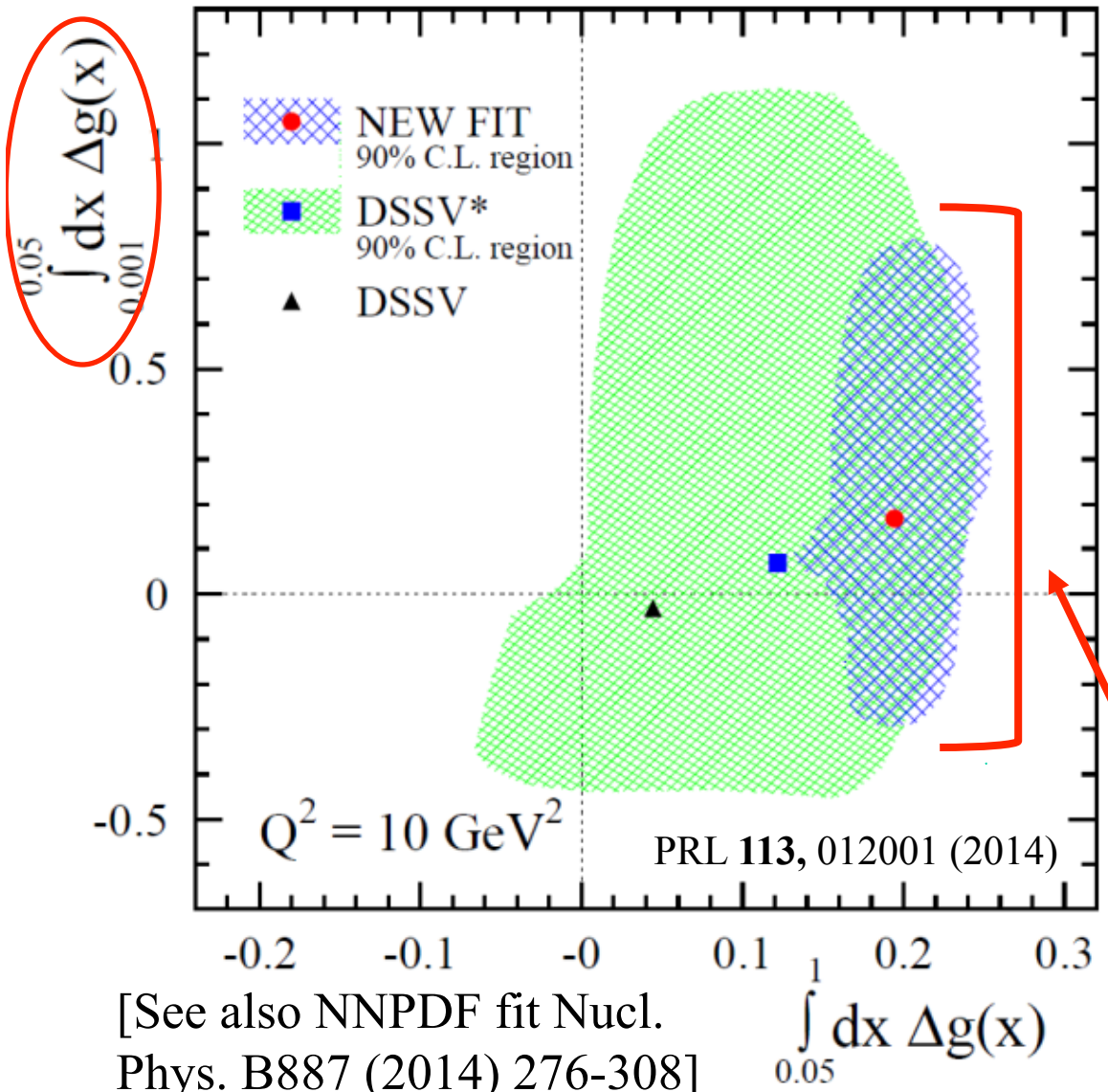
- Current Understanding of $\Delta g(x)$
- STAR Detector
- Inclusive jets as a probe of $\Delta g(x)$
- Pushing to Low x with Forward π^0's
  - In the Endcap
  - In the Forward Calorimeter
- Constraining $\Delta g(x)$ with Correlated Probes
- A Taste of Transversity

New DSSV Fit – ΔG Comes into Focus



- With input from PHENIX π^0's and STAR 2009 jets
- 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 NNPDF fit Nucl. Phys. B887 (2014) 276-308]

- With input from PHENIX π^0's and STAR 2009 jets
- 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

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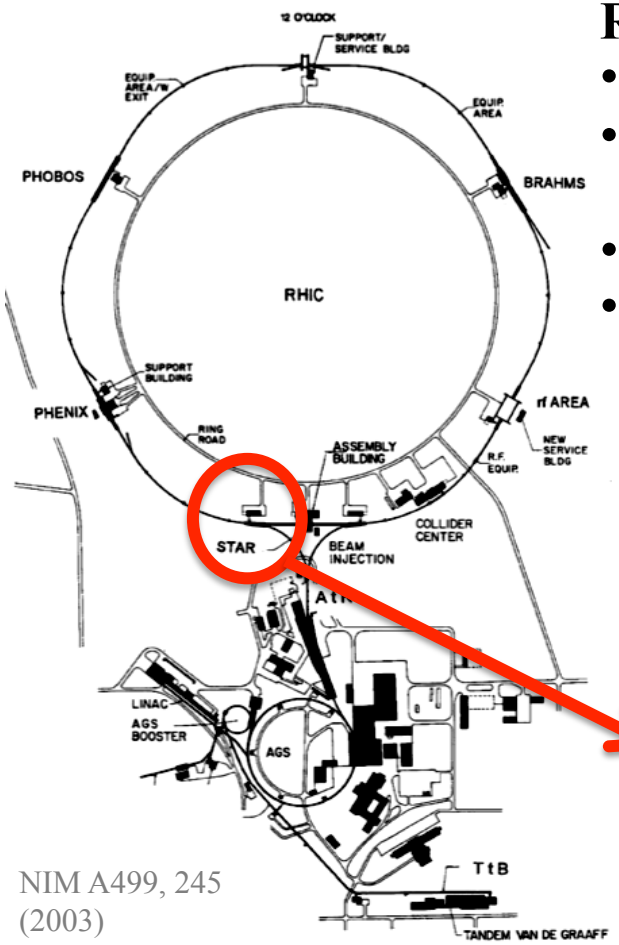
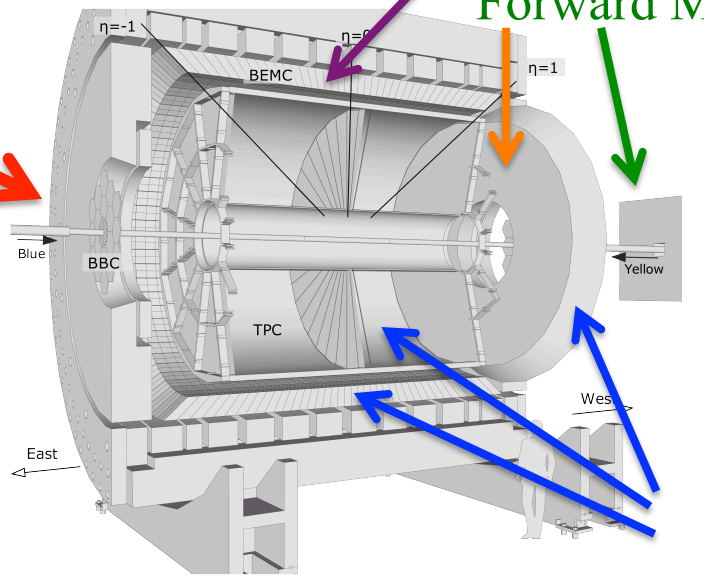
Solenoidal Tracker at RHIC



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),
Forward Meson Spectrometer (FMS)

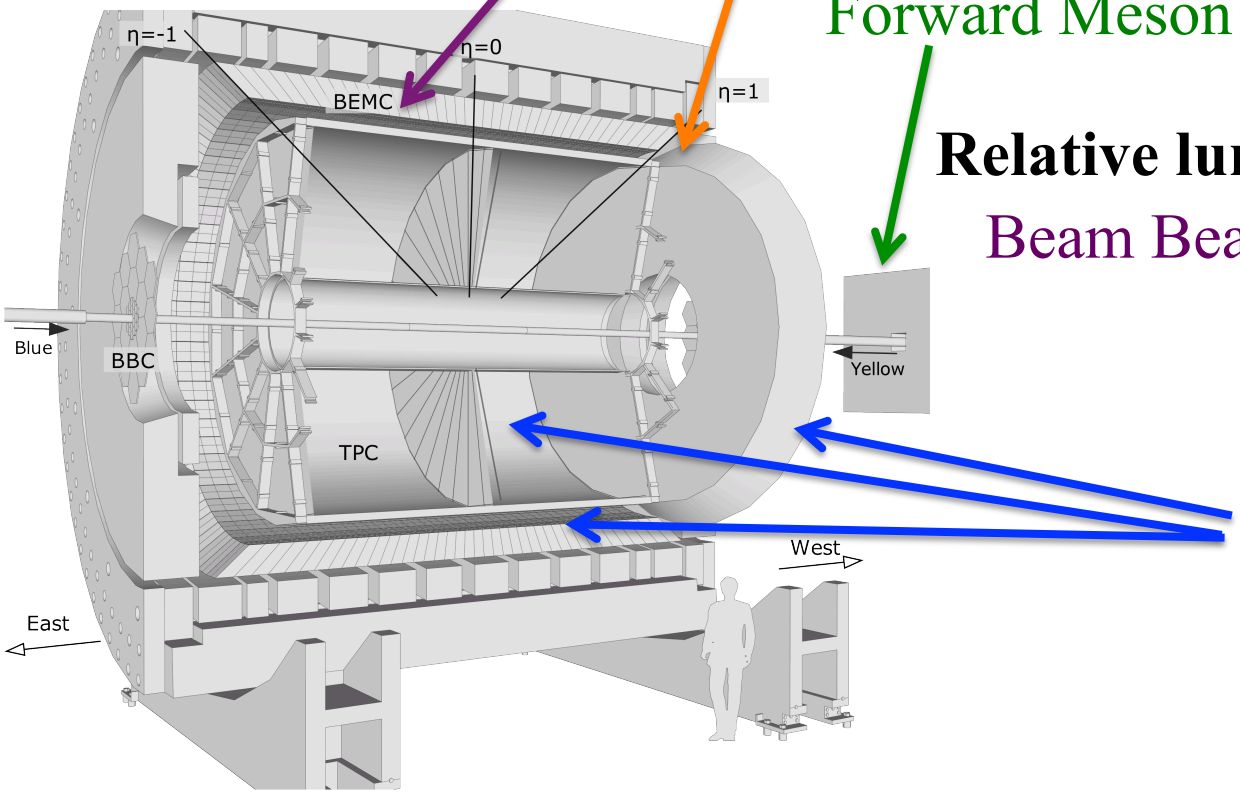
Jet and W/Z measurements:
TPC + Barrel + Endcap EMC

Solenoidal Tracker at RHIC

Inclusive hadron (e.g. π^0) measurements:
Barrel ElectroMagnetic Calorimeter (BEMC),
Endcap ElectroMagnetic Calorimeter (EEMC),
and
Forward Meson Spectrometer (FMS)

Relative luminosity measurements:
Beam Beam Counters (BBC) etc.

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



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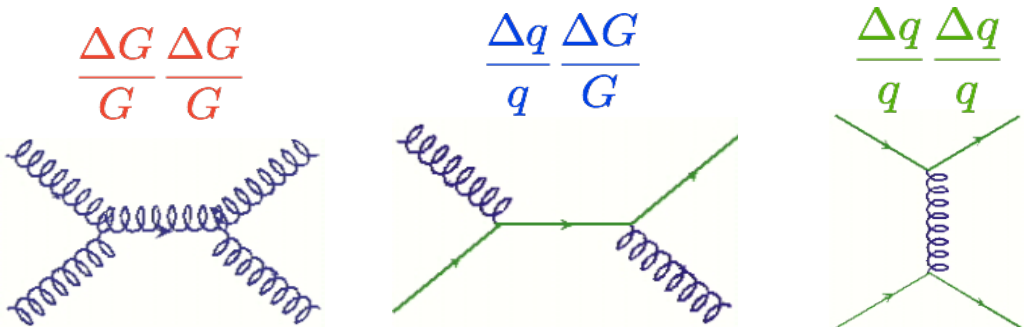
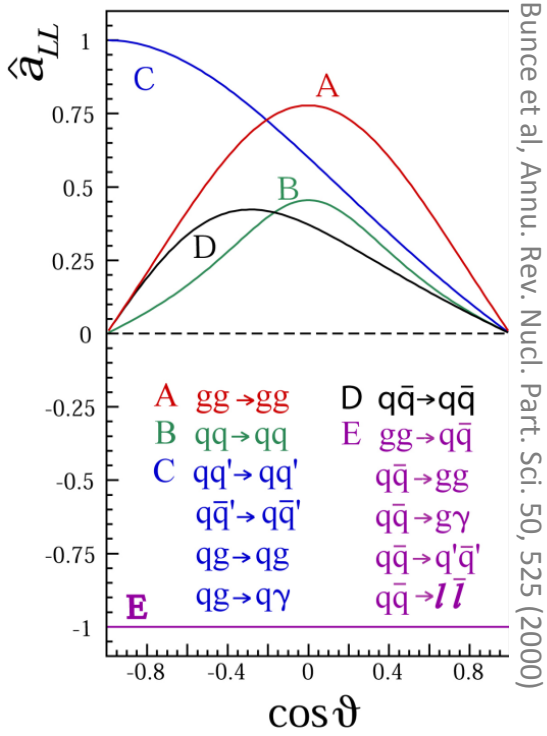
Probing (Gluon) Polarized PDF's With Jets

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

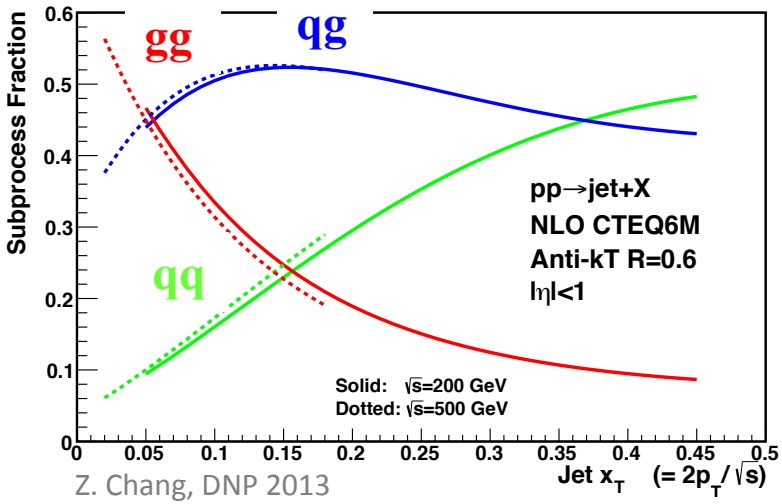
A_{LL} for, e.g. jets, sensitive to ***polarized PDF's*** (Δf) and ***partonic asymmetry***, $\hat{a}_{LL}$





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

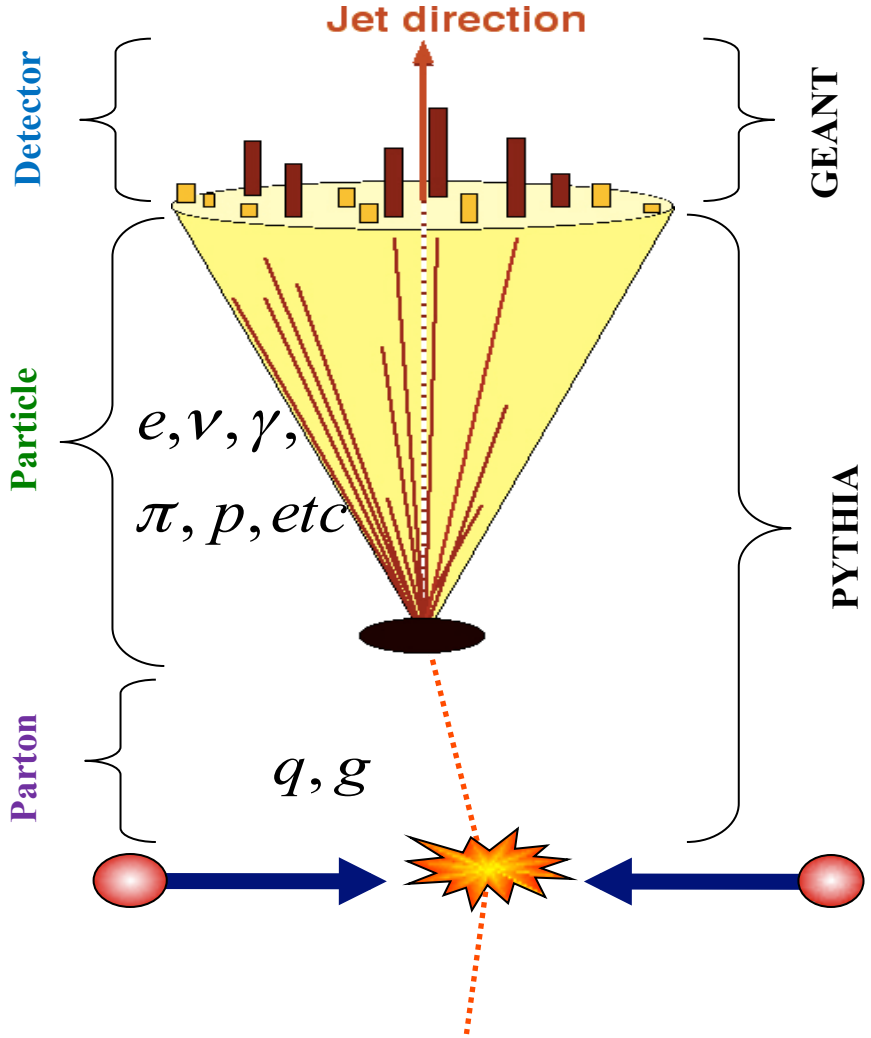
→ ***sample different mix of partonic subprocesses***



Jet Reconstruction

Jet Levels

MC Jets



STAR Detector has:

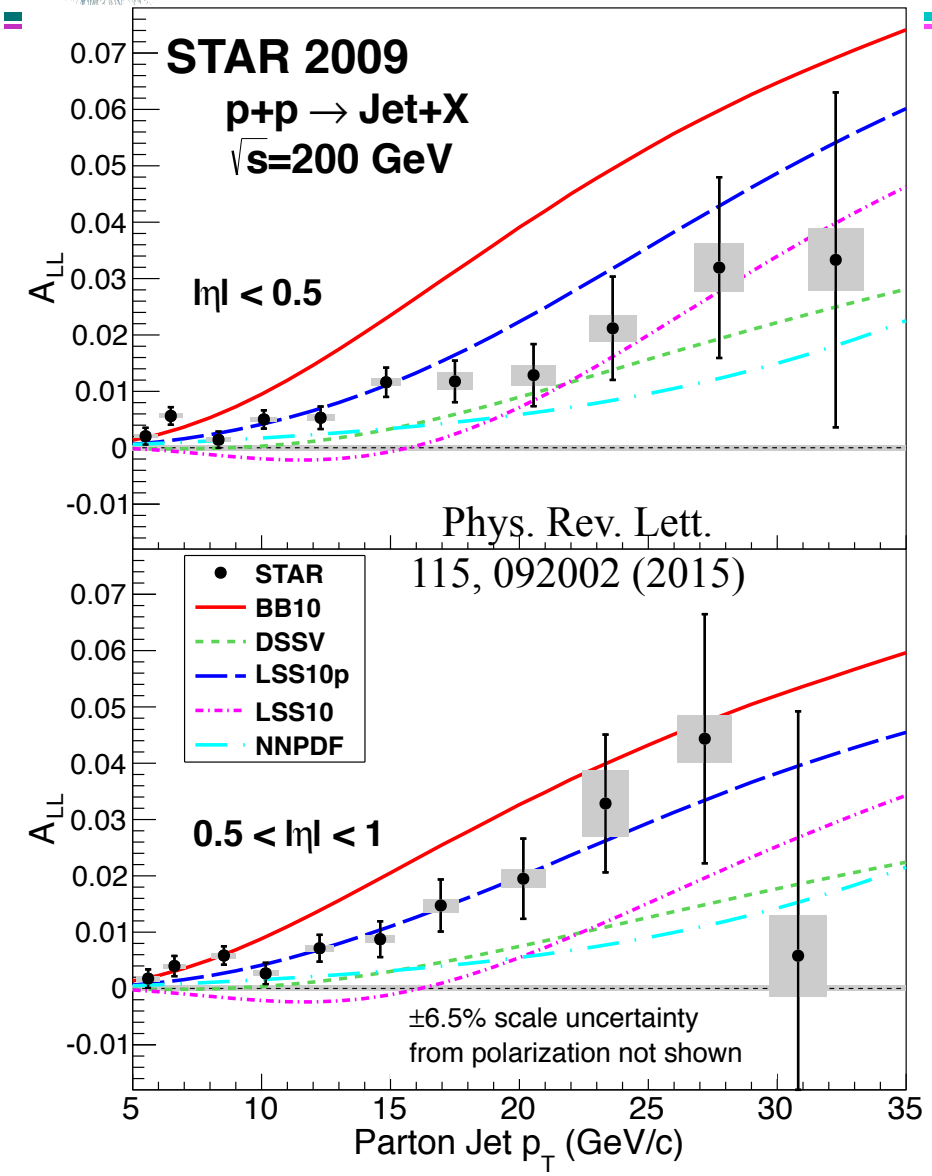
- Full azimuthal coverage
- Charged particle tracking from TPC for $|\eta| < 1.3$
- E/BEMC provide electromagnetic energy reconstruction for $-1 < \eta < 2.0$

STAR well suited for jet measurements

Anti-K_T Jet Algorithm:

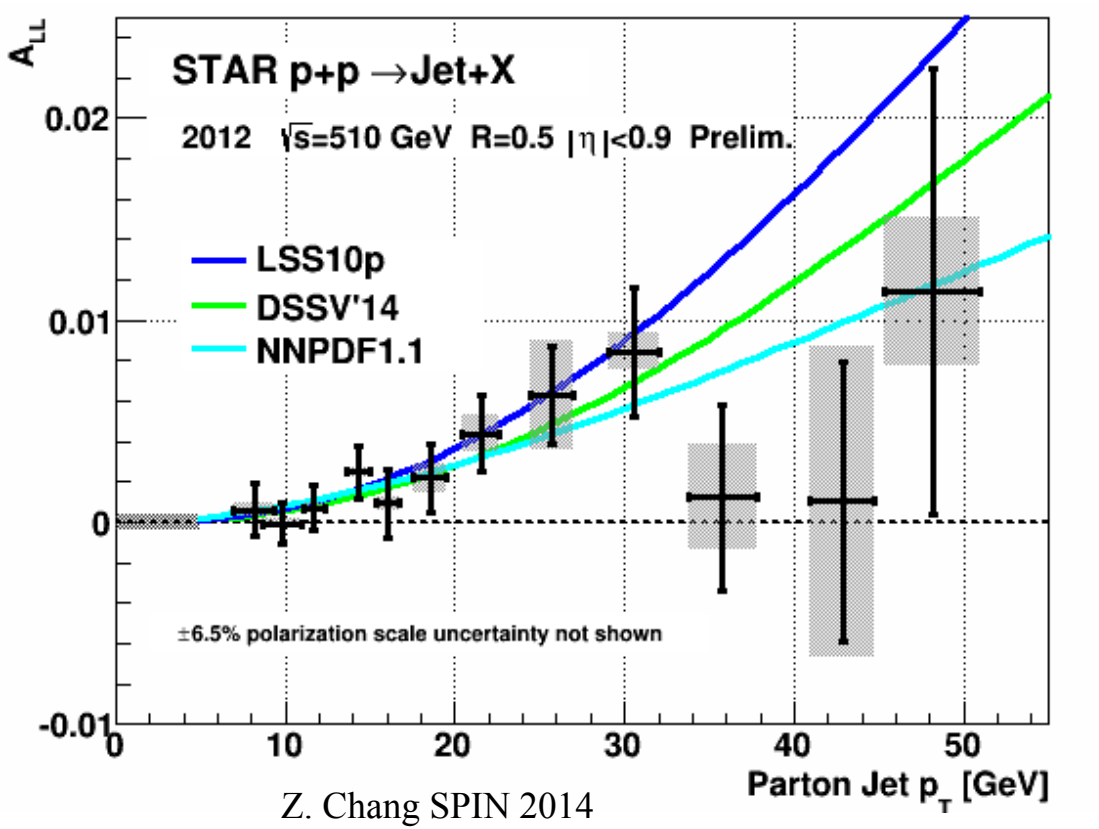
- Radius (e.g 0.6 for 2009 Jet A_{LL})
- Used in both data and simulation

2009 Inclusive Jet A_{LL}



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

2012 Inclusive Jet A_{LL} at 510 GeV



Z. Chang SPIN 2014
arXiv:1512.05400

- 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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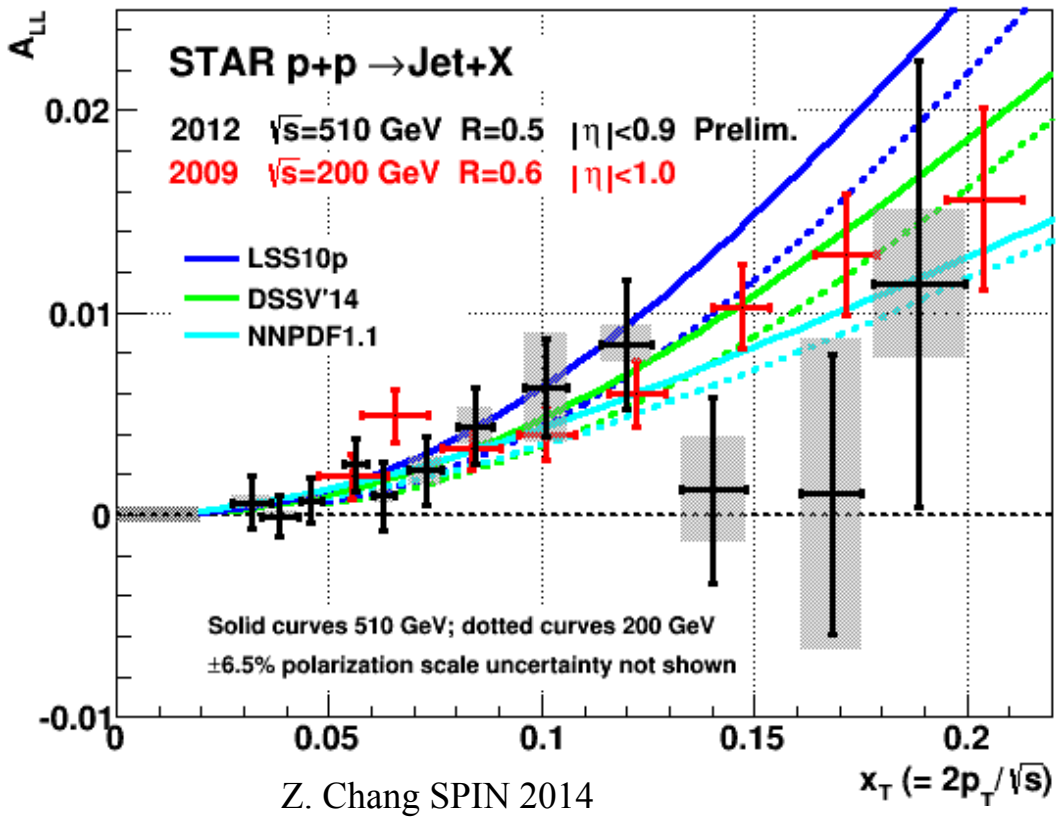

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- Push to lower x_g w/ higher CoM energy
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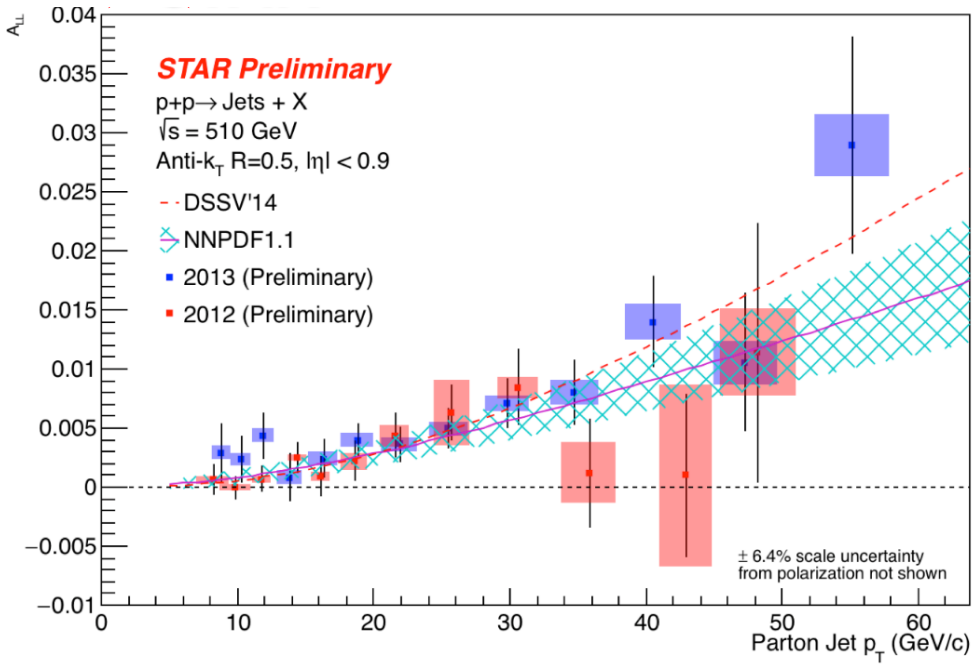
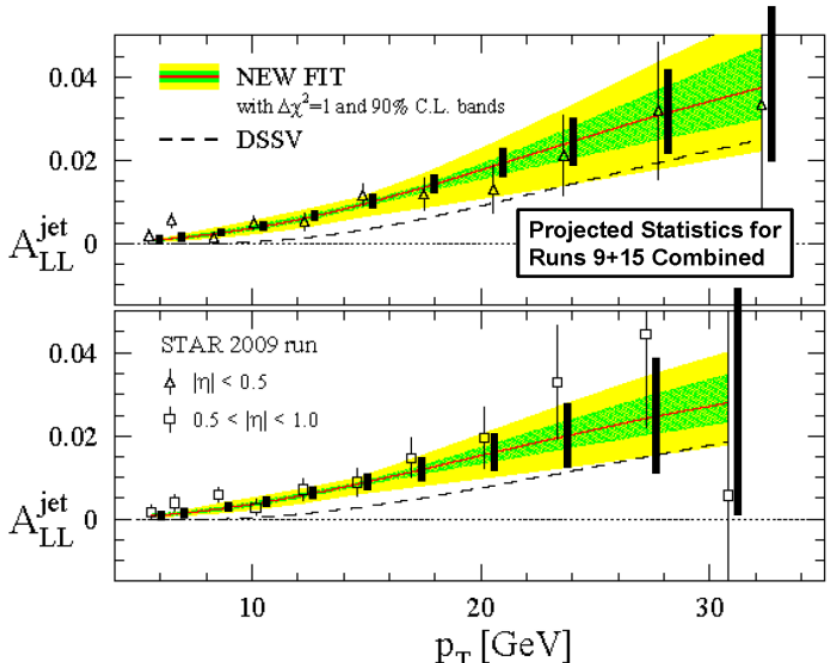
- Higher CoM pushes to lower x_T
  - Results agree in overlap region

Higher Statistics for Inclusive Jet A_{LL}





- RHIC had very successful, high luminosity runs in 2012 *and* 2013
  - Fits that incorporated 2009 results continue to describe the data well
- Additional 200 GeV data during 2015
  - Will reduce A_{LL} uncertainties by a factor of ~1.6

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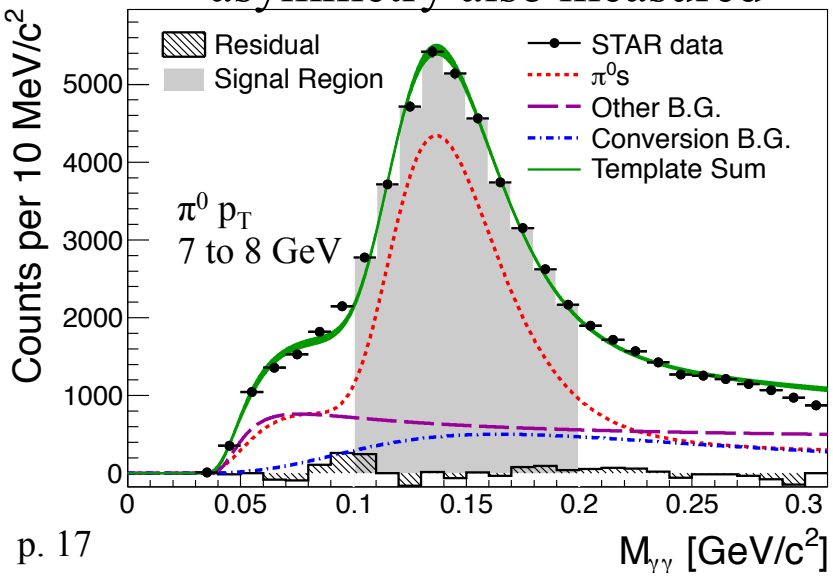
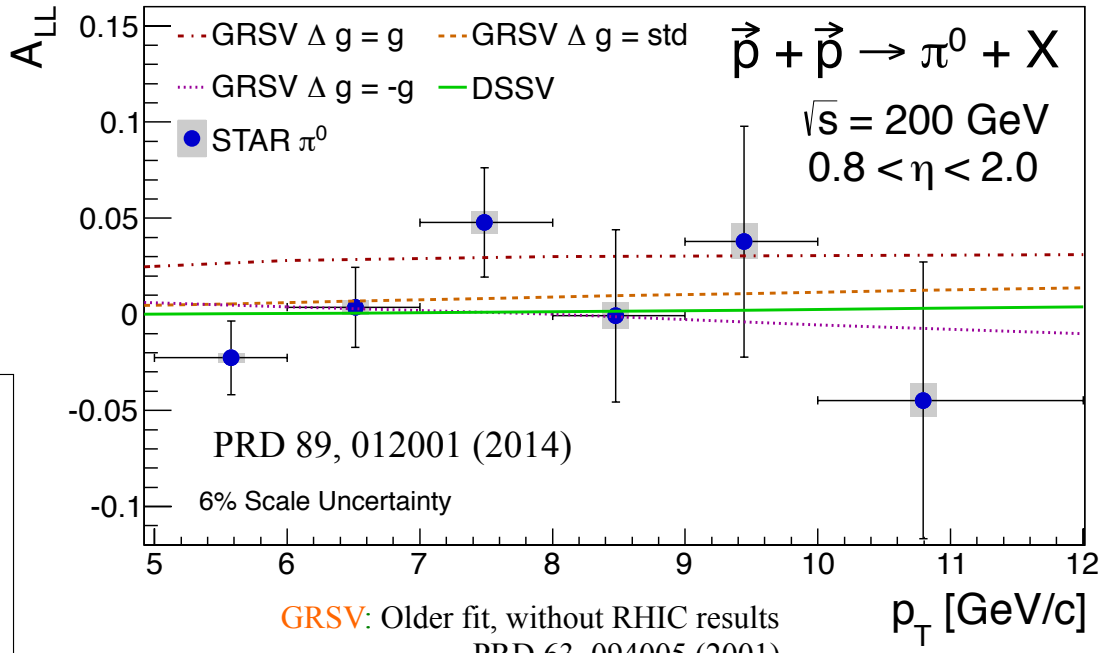
A_{LL} in π^0 + X at STAR for $0.8 < \eta < 2.0$

- 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



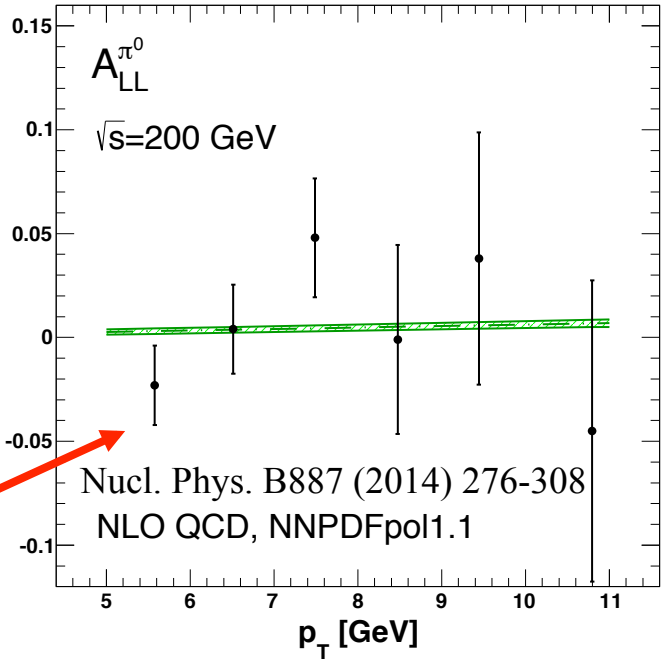


GRSV: Older fit, without RHIC results
PRD 63, 094005 (2001)

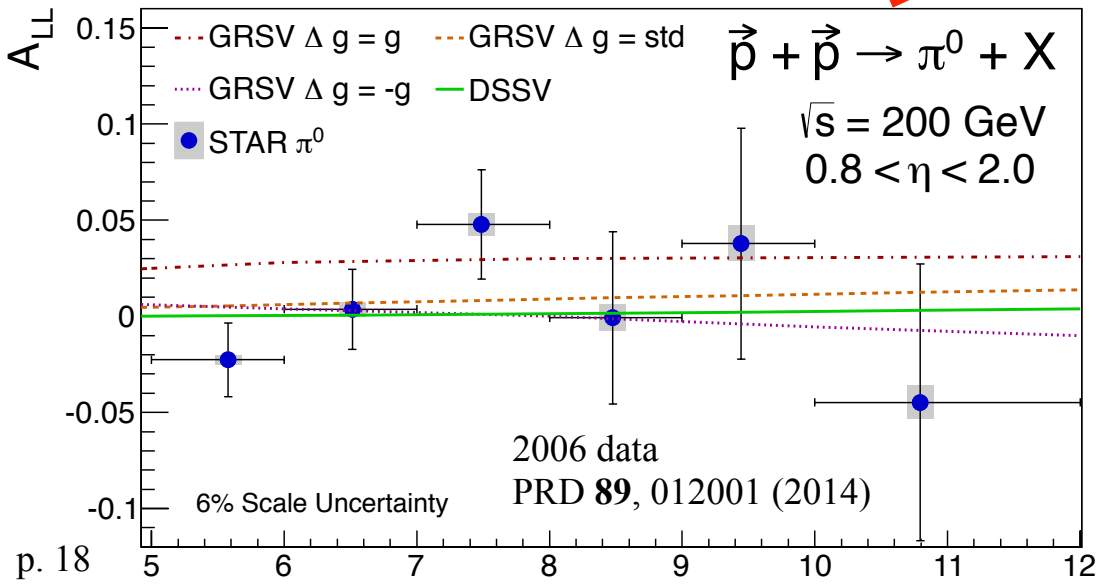
DSSV: First fit to include RHIC results
PRL 101, 072001 (2008)

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

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

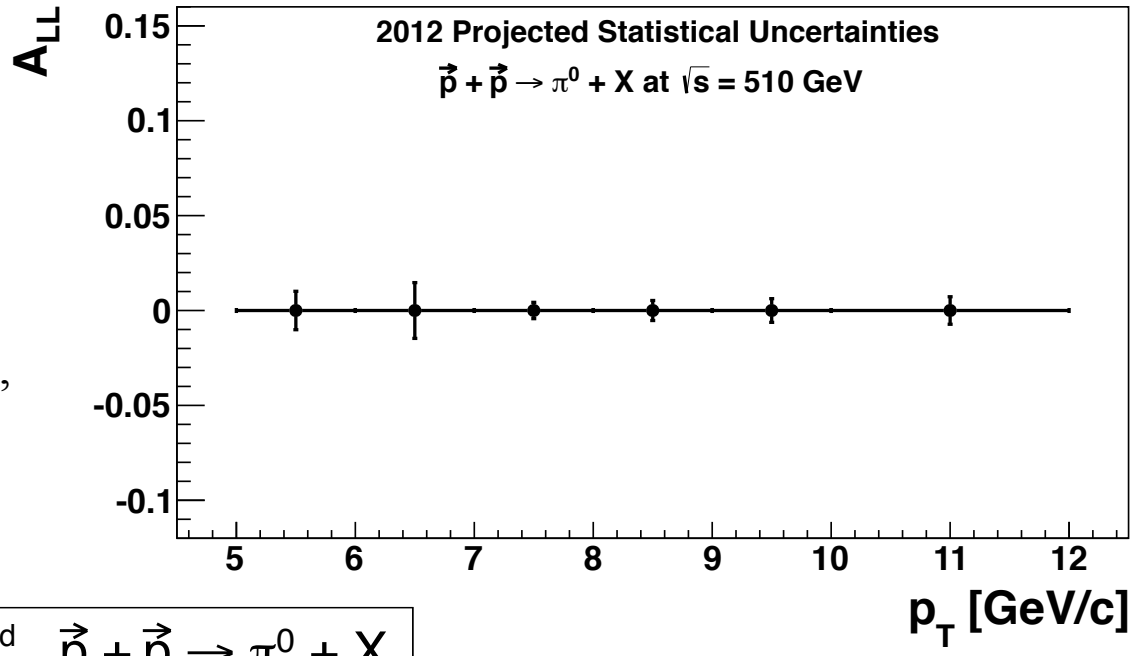


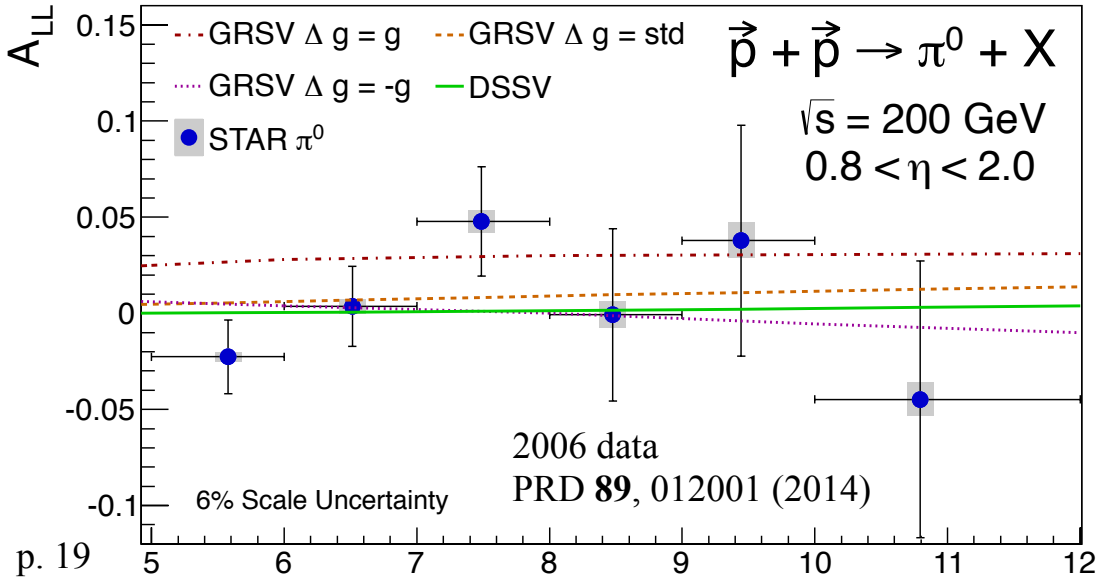
STAR data with NNPDF predictions



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

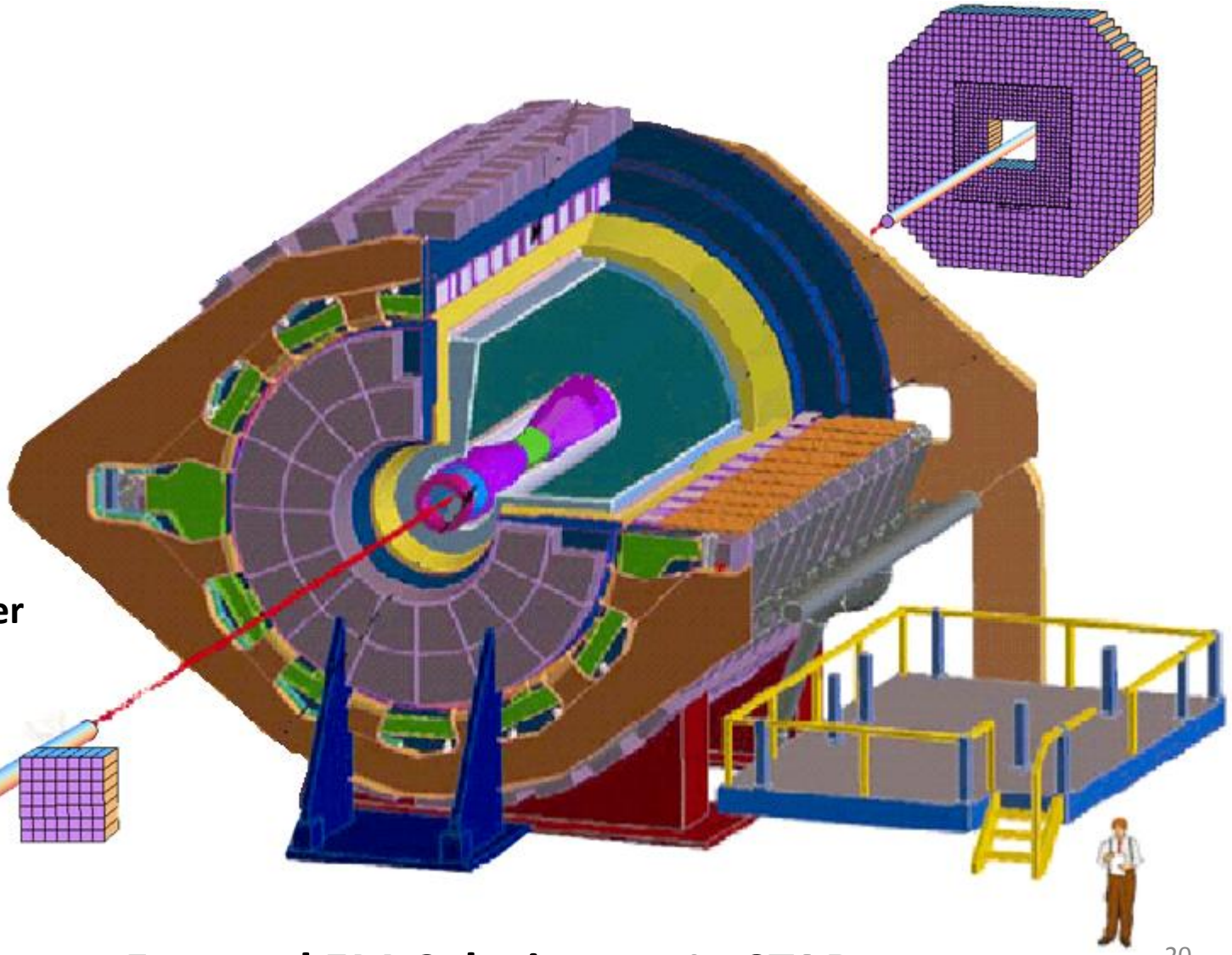
FMS

Pb Glass EM Calorimeter

pseudo-rapidity $2.7<\eta<4.0$

Small cells: 3.81x3.81 cm

Outer cells: 5.81 x 5.81 cm



FPD EM Calorimeter

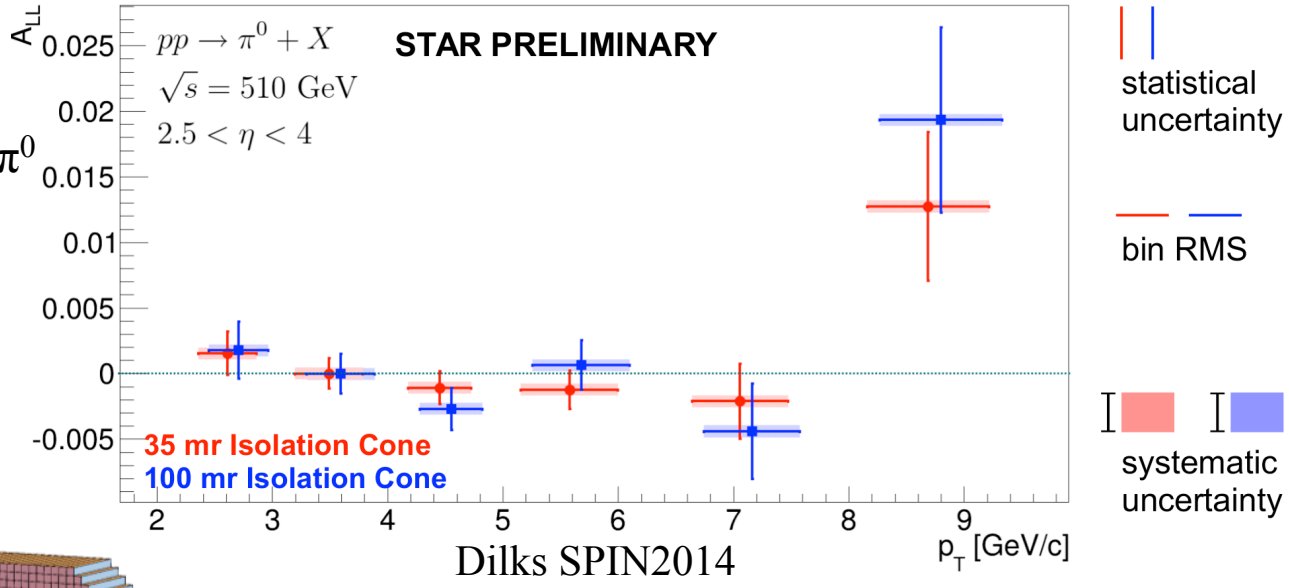
Small cells only

Two 7x7 arrays

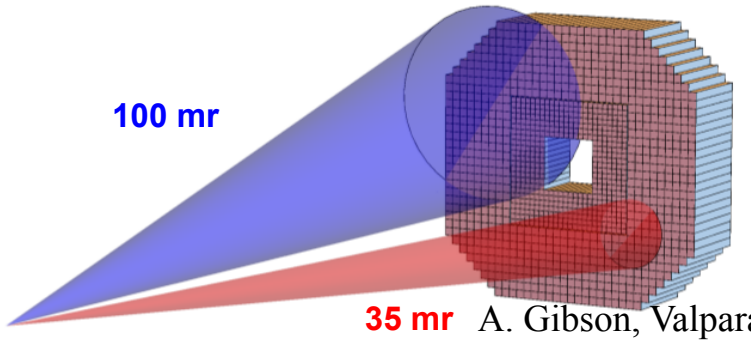
Forward EM Calorimetry In STAR.

π^0 A_{LL} Prospects in Forward Calorimeters

- Pushing even further forward, with the FMS
- Preliminary results 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
- Here requiring an isolation cone around π^0
  - Was motivated by A_N increase for isolated π^0
  - Inclusive analysis coming soon



Dilks SPIN2014



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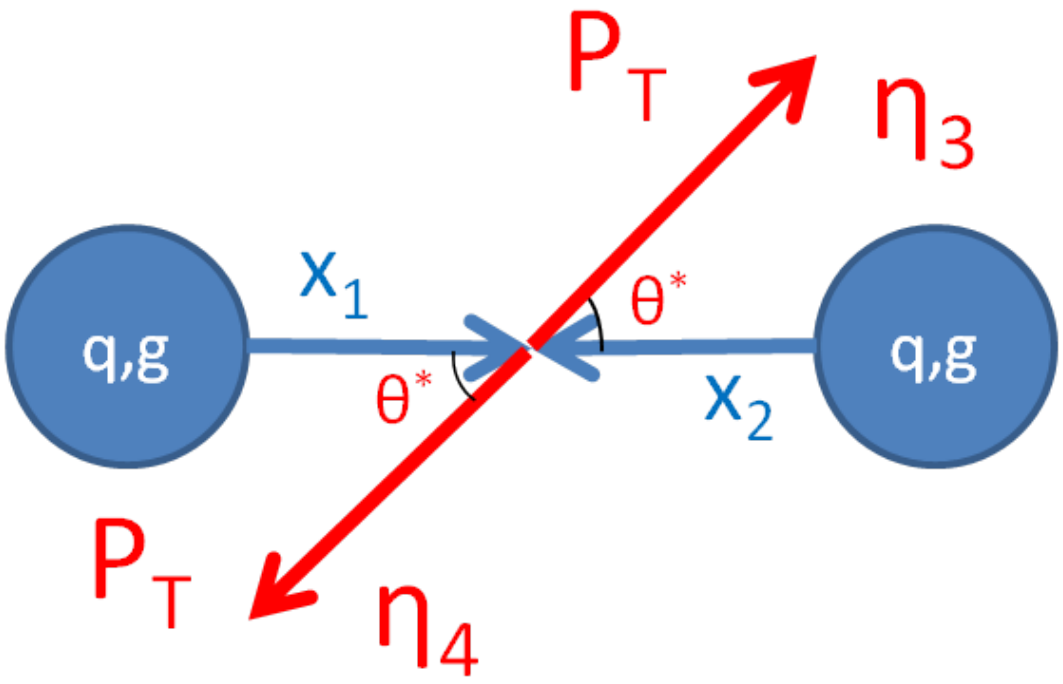
Dijet Measurements



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

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

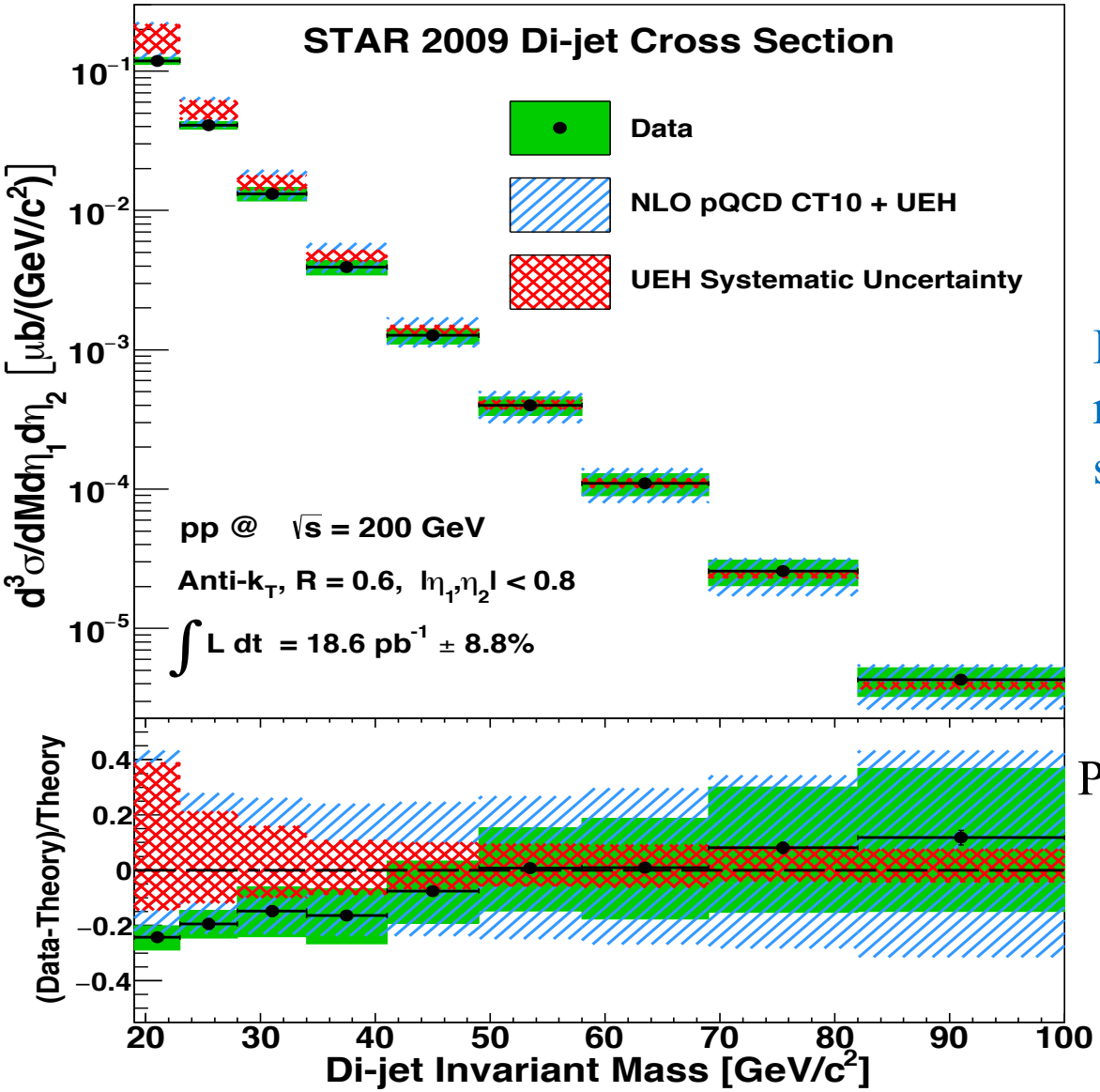
$$M = \sqrt{x_1 x_2 s}$$

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

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

- 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

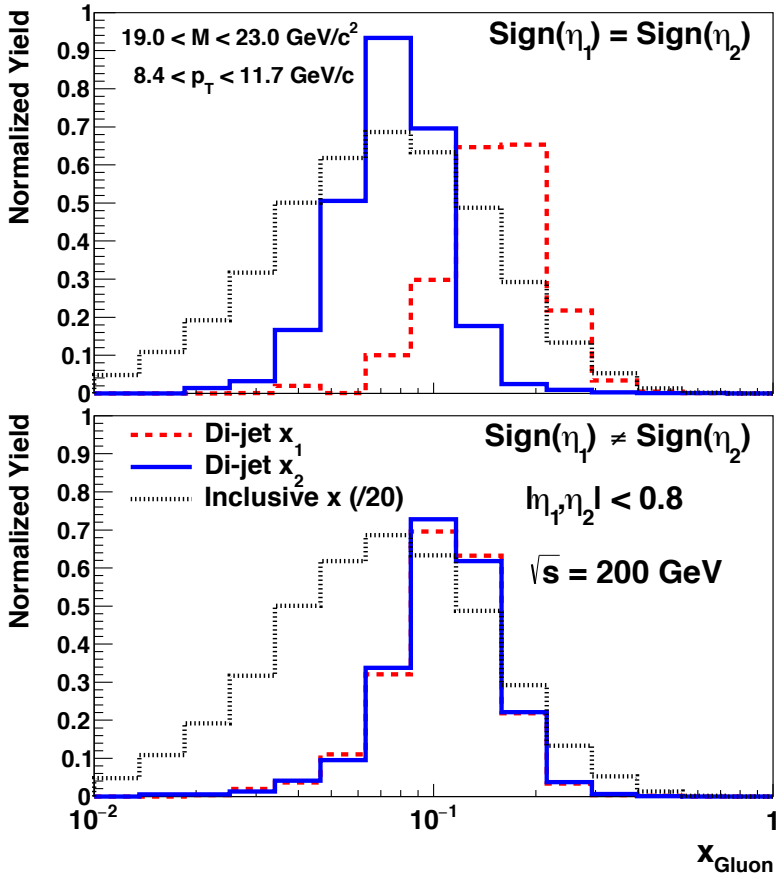
Green box is symmetric about data point and is the quadrature sum of all systematic errors

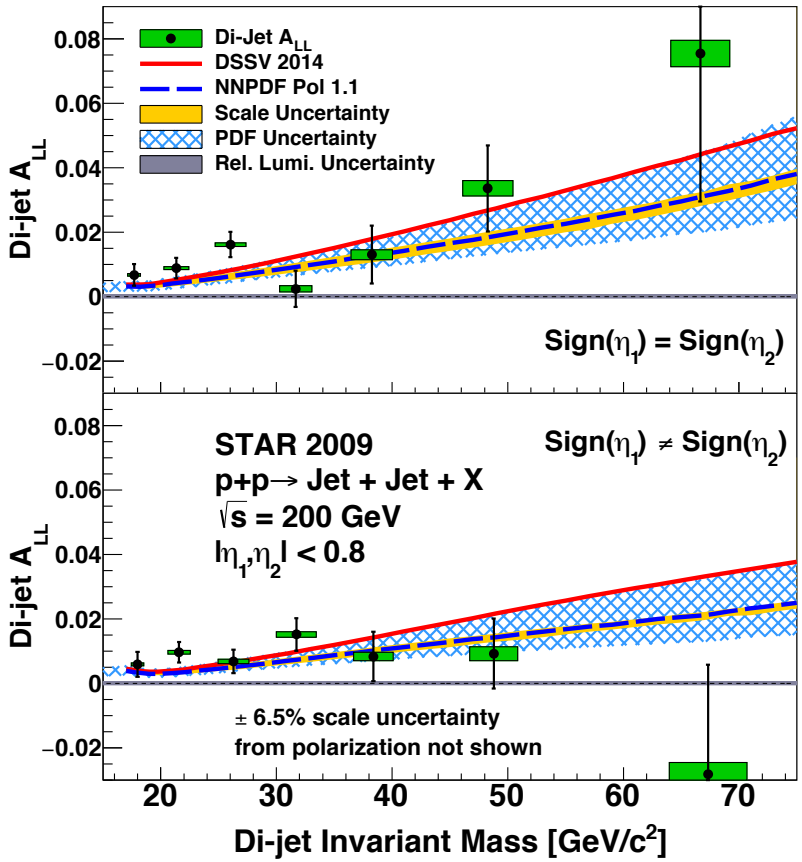
Blue box is theory error: renormalization and factorization scales x0.5, x2

Phys. Rev. D 95, 071103(R) (2017)

2009 Dijet Asymmetries and *x* Reach

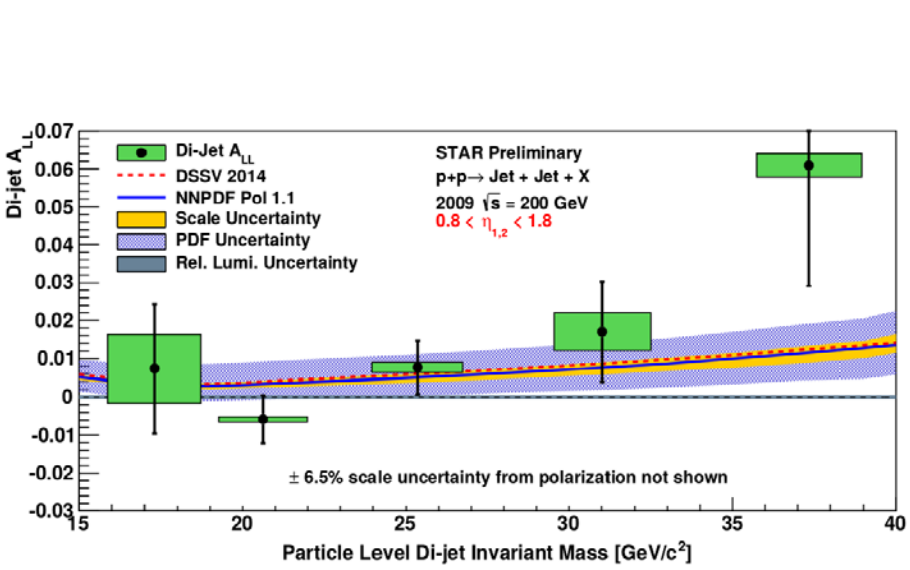
Phys. Rev. D 95, 071103(R) (2017)

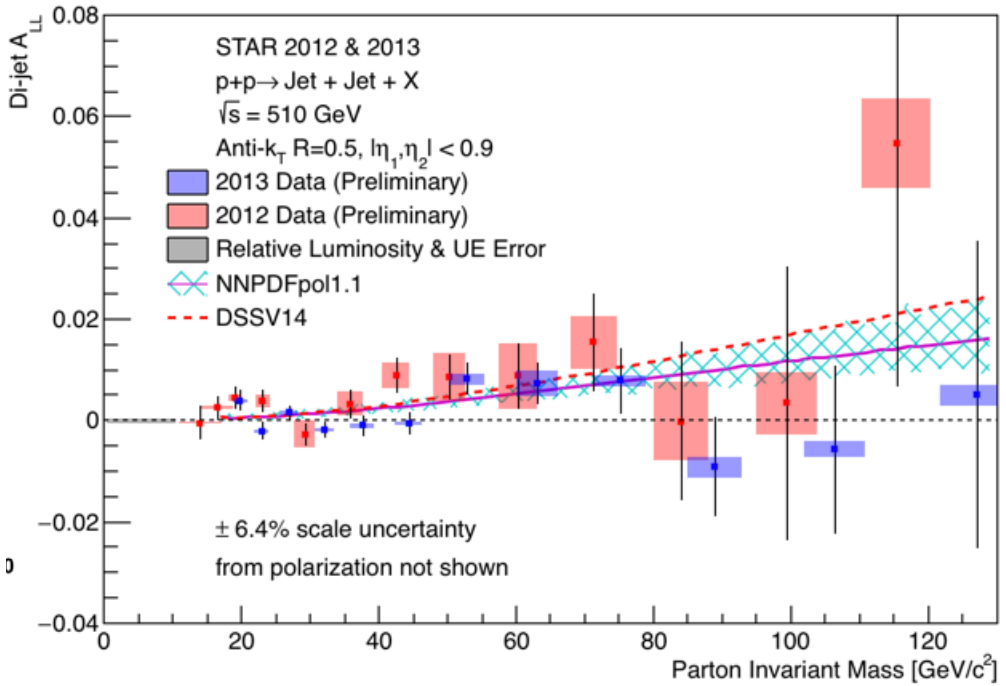




- Dijets probe a much narrower range of x_g than inclusive jets
- Asymmetries consistent with predictions, ~subset of the dataset used to extract polarized PDF's; some evidence dijets prefer a larger Δg?

Dijets at Forward Rapidities and sqrt(s) = 510 GeV



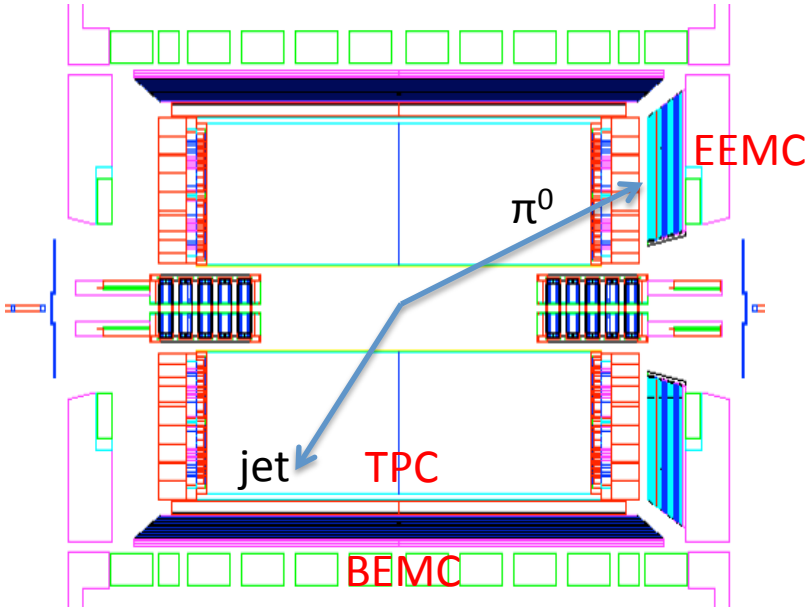


- Probe lower x_g with dijets by moving to forward rapidities and higher CoM energy
  - Reaching x ~ 0.02 now
  - Can push below x = 0.01 with additional data already recorded
  - And to x ~ 10^{-3} in a few years with a forward upgrade

π^0 - Jet A_{LL} measurements at STAR

Yaping Wang
Friday September 1, 16:55

Channel: Using a jet in the mid-rapidity region correlated with an opposite-side neutral pion in the forward rapidity region $1.08 < \eta < 2.0$ in the STAR EEMC provides a new tool to access the $\Delta G(x)$ distribution at Bjorken-x down to 0.01.



$$x_1 = \frac{p_T^{jet}}{\sqrt{s}}(e^{\eta_{jet}} + e^{\eta_{\pi^0}}),$$

$$x_2 = \frac{p_T^{jet}}{\sqrt{s}}(e^{-\eta_{jet}} + e^{-\eta_{\pi^0}}),$$

$$\sqrt{\hat{s}} = \sqrt{x_1 x_2 s}.$$

- Compared to inclusive jet measurements, this π^0 – jet channel also allows to constrain the initial parton kinematics, such as x_1, x_2 and $\sqrt{\hat{s}}$.
- Theoretical description of hadron-jet A_{LL} by next-to-leading order (NLO) model calculation: Daniel de Florian, PRD **79** (2009) 114014.

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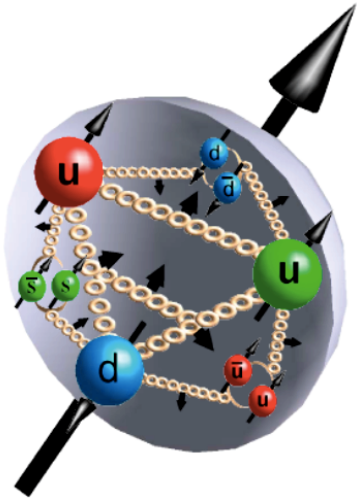
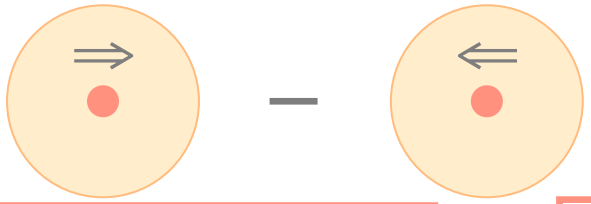
Contributions to the Proton's Spin: A Taste of Transverse Spin Physics



Proton momentum ⇒

Proton spin ⇒

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



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Puzzling for ~25 years

Relatively poorly constrained
But S_g coming into focus!

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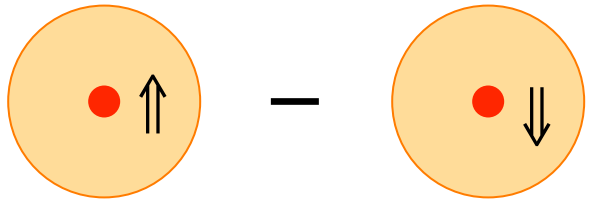
Proton spin ⇑

$\delta q(x)$

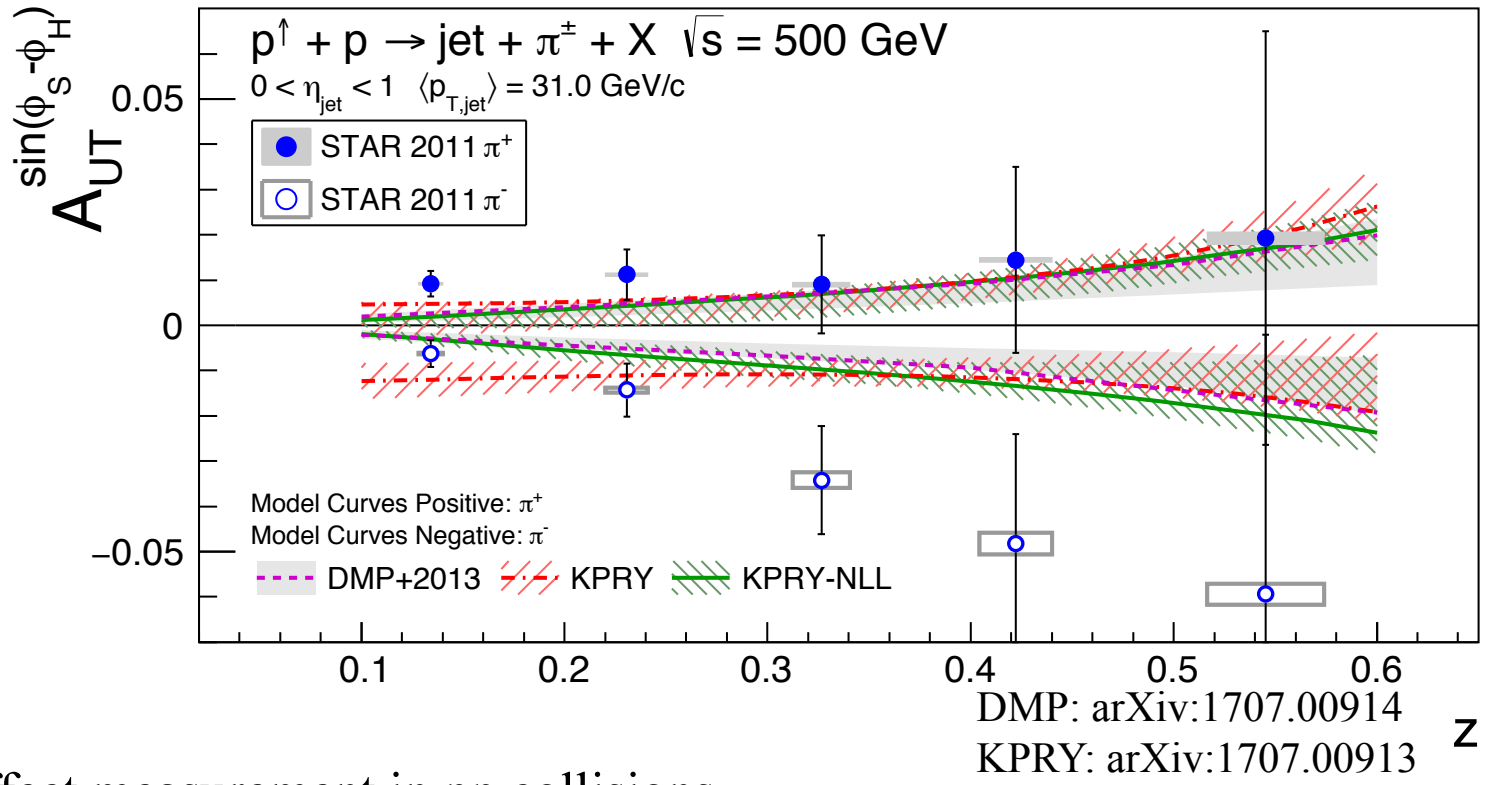


Transverse Polarization

Transversity

Pion Azimuthal Distributions in Jets: Evidence for Transversity at a Hadron Collider

- Just submitted to Phys Rev D (arXiv:1708.07080)
- Probes transversity coupled to Collins fragmentation function (or Twist 3 analog)
- Transversity at very high scales (Q^2 up to 900 GeV^2)



DMP: arXiv:1707.00914
KPRY: arXiv:1707.00913

- First Collins effect measurement in pp collisions
  - Transversity at STAR also seen in dihadron asymmetries, which survive in collinear QCD
- Compared with two calculations of SIDIS transversity + e^+e^- Collins
  - Tests universality of Collins function
  - Data show slight preference for model w/ no TMD evolution (KPRY vs. KPRY-NLL)

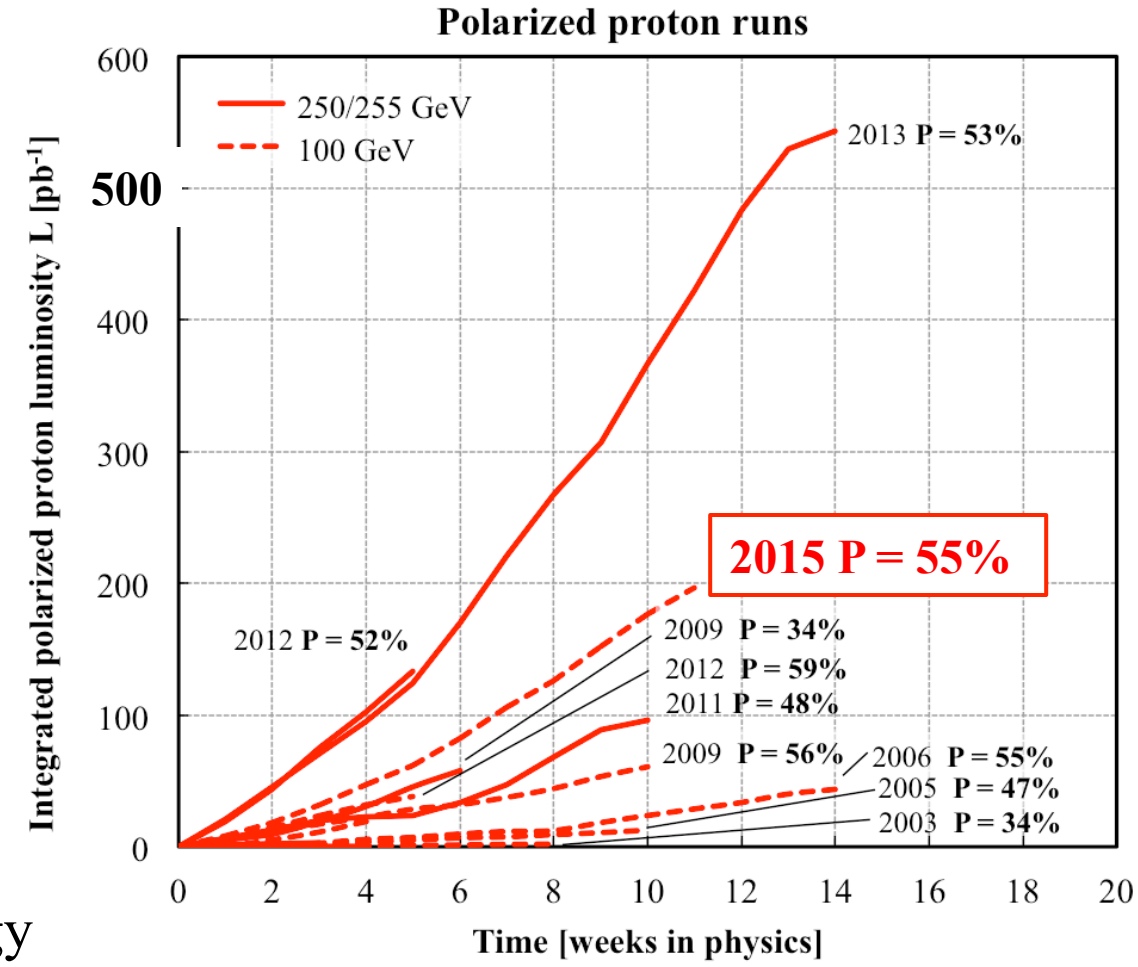
Constraining the Gluon Polarization Distribution with Jet, Dijet, and Neutral Pion Probes at STAR

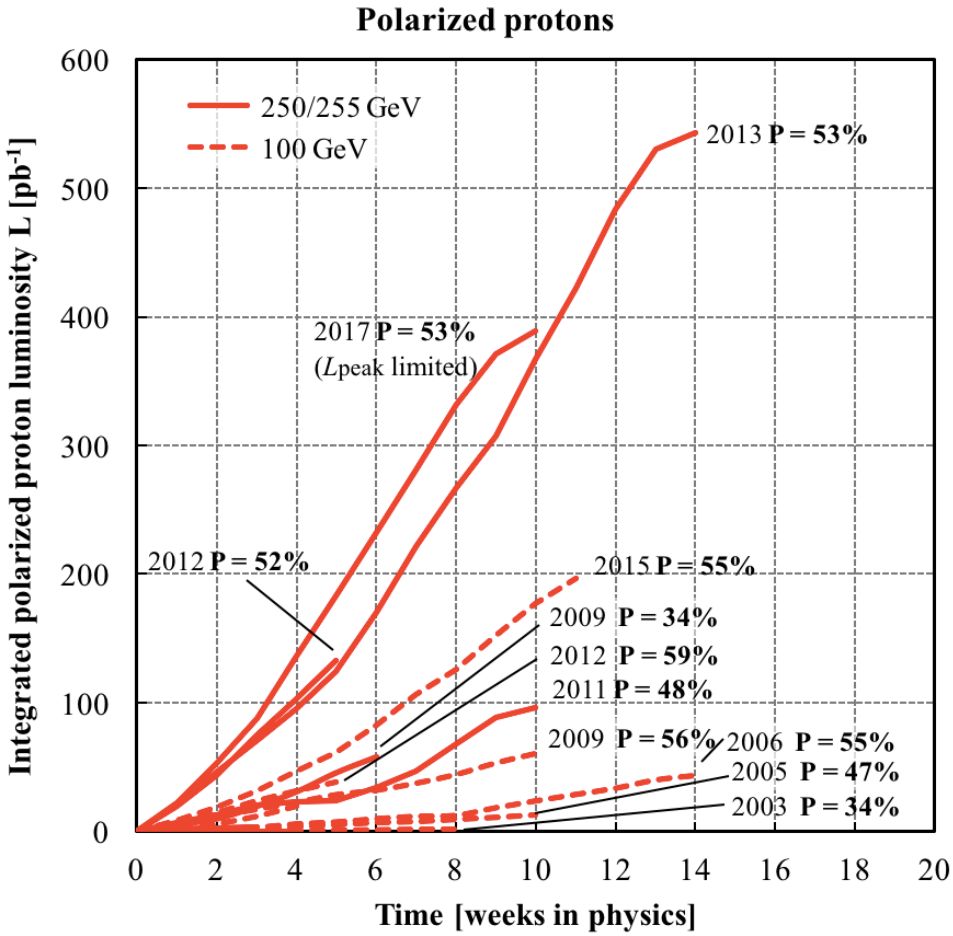
- Inclusive Jets
  - After 25 years, **evidence of non-zero gluon polarization** in the proton
  - Large datasets reduce uncertainties, higher sqrt(s) pushes to lower *x*
- π^0's with forward detectors probe lower *x* as well
  - $0.8 < \eta < 2.0$ in the EEMC
  - $2.5 < \eta < 4.0$ in the FMS
- Map $\Delta g(x)$ as a function of *x* with correlated probes
  - Dijets
  - A_{LL} w/ correlated jet - forward π^0
  - Yaping Wang Friday September 1, 16:55
- A rich transverse spin program as well
  - Evidence, at a hadron collider, for transversity in the proton
- Large datasets being analyzed, upgrades planned; stay tuned!

Backup

Datasets from RHIC at STAR

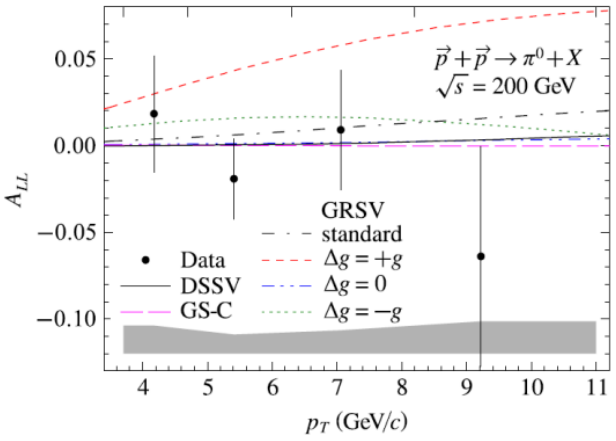
- Many published results from 2006, 2009 datasets
  - And W's more recently
- Preliminary results and work in progress from, especially
  - 2011 500 GeV trans.
  - 2012 200 GeV trans.
  - ***Large*** 510 GeV long. datasets in 2012 and 2013
- 2015 brought increased statistics at 200 GeV, and opened the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




Polarized protons
Integrated polarized proton luminosity L [pb^{-1}]
Time [weeks in physics]
250/255 GeV
100 GeV
2013 P = 53%
2017 P = 53%
(Lpeak limited)
2012 P = 52%
2015 P = 55%
2009 P = 34%
2012 P = 59%
2011 P = 48%
2009 P = 56%
2006 P = 55%
2005 P = 47%
2003 P = 34%
0
100
200
300
400
500
600
0
2
4
6
8
10
12
14
16
18
20

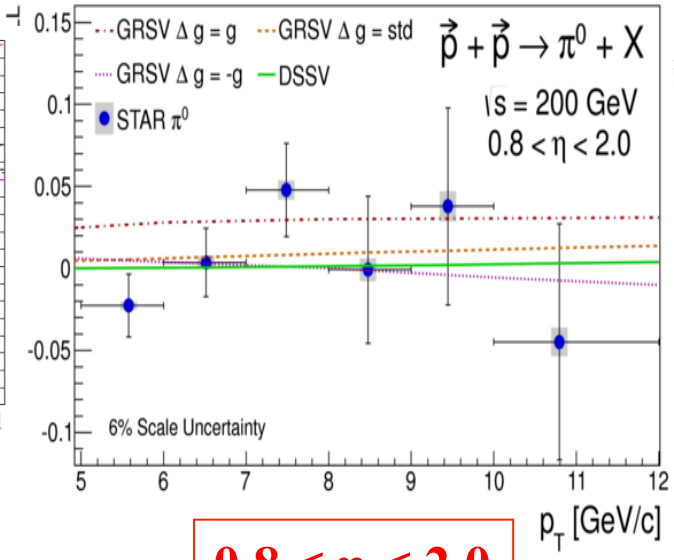
Probing Low *x* Gluons With π^0 A_{LL}

PRD 80, 111108(R) (2009)



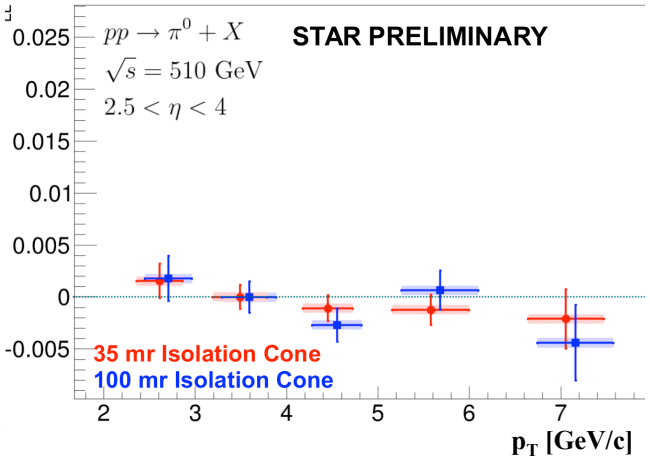
$|\eta| < 0.95$

PRD 89, 012001 (2014)



$0.8 < \eta < 2.0$

Dilks SPIN2014

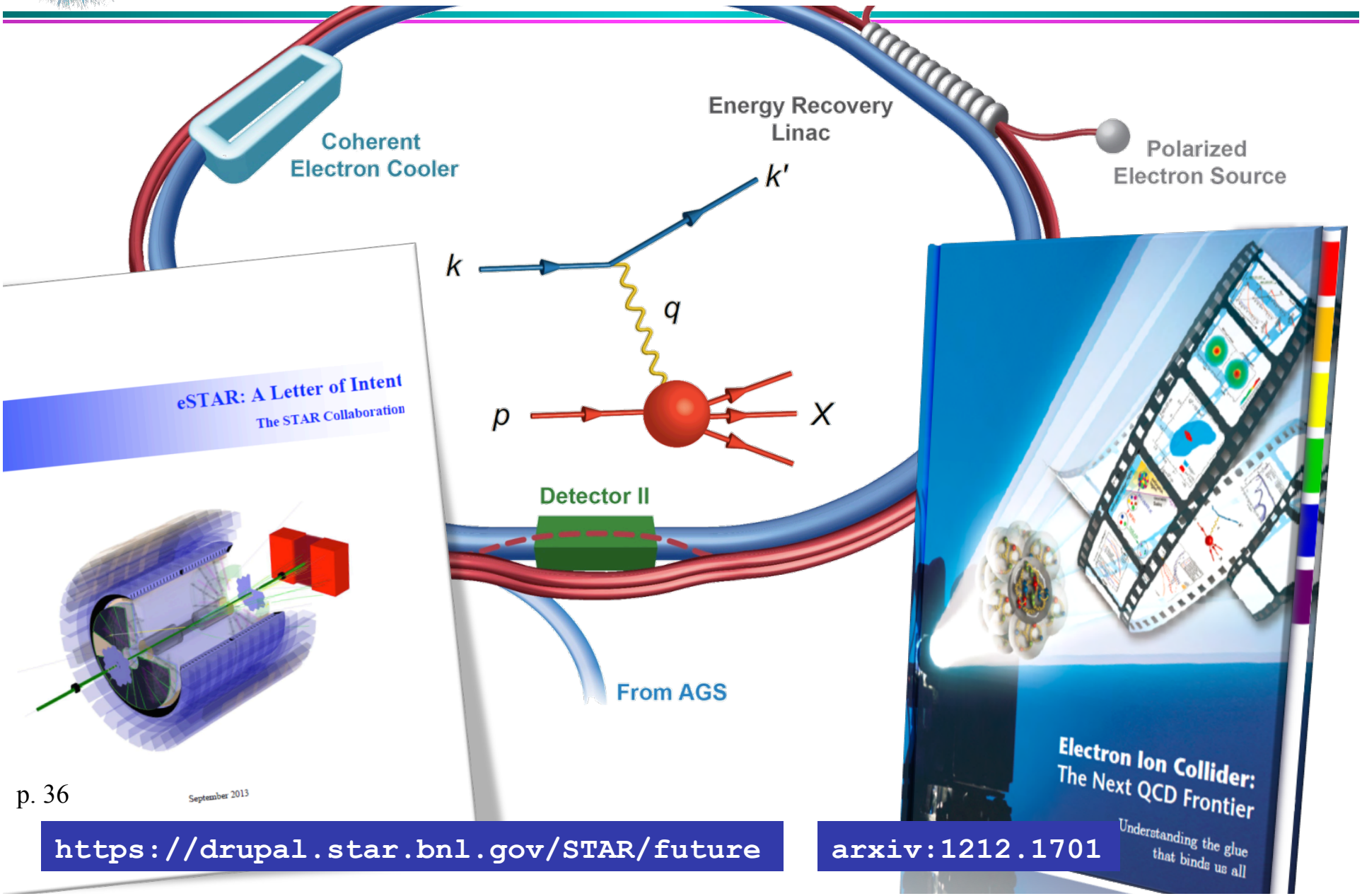


$2.5 < \eta < 4.0$

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

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

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



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

arxiv:1212.1701