Recent Results on Proton Spin Studies from STAR: Constraining the Gluon Polarization Distribution with Jet, Dijet, and Neutral Pion Probes

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Moriond QCD 2018

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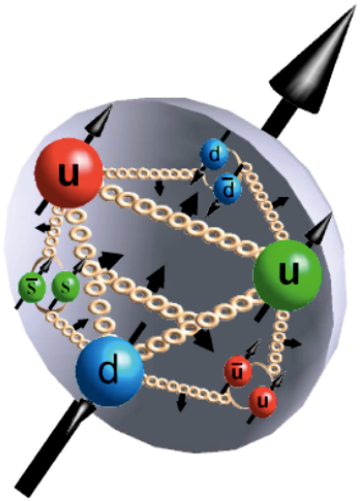
U.S. DEPARTMENT OF ENERGY
Office of Science

Contributions to the Proton's Spin



Polarized e/μ + p: ~0.3
Puzzling for ~30 years

Relatively poorly constrained
But S_g coming into focus!

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

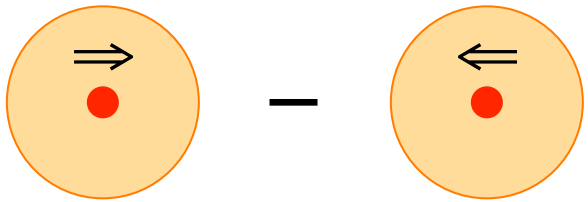
$$S_g^z = \Delta G = \int_0^1 dx \Delta g(x)$$

Gluon's contribution to the proton's spin

Proton momentum ⇒

Proton spin ⇒

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



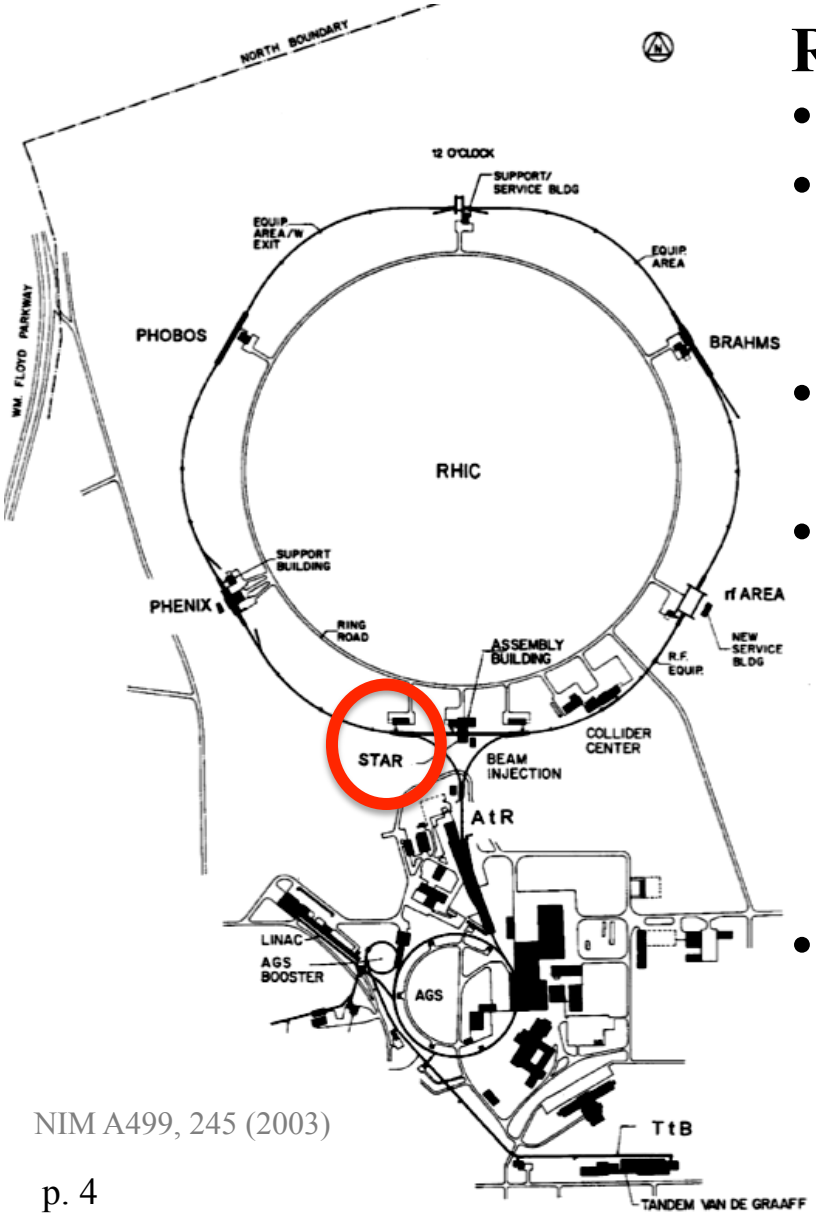
Longitudinal Polarization

See also Y-B Yang et al χQCD Collaboration Phys. Rev. Lett. 118, 102001 (2017) for ΔG on the Lattice

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

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

STAR at the Relativistic Heavy Ion Collider (RHIC)



NIM A499, 245 (2003)

RHIC as a Polarized Proton Collider

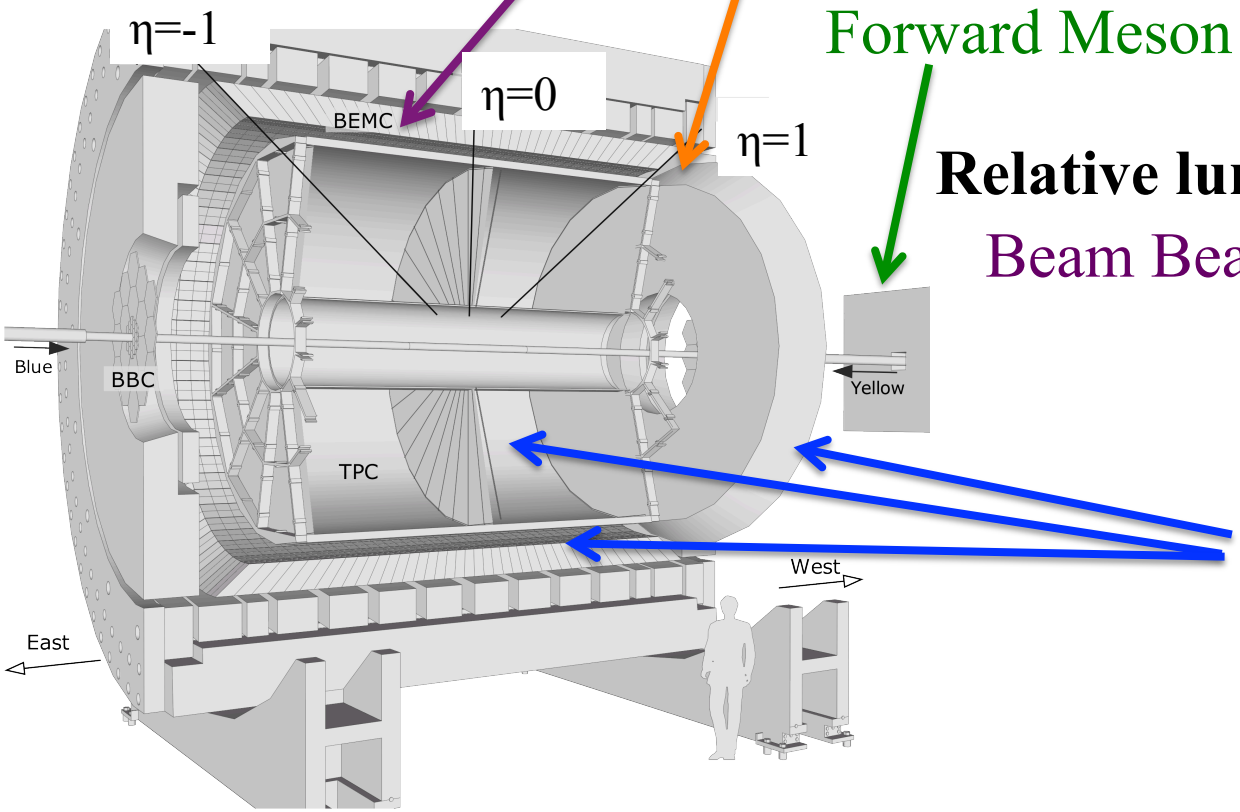
- World's first and only
- Average polarization 50-60%
  - "Siberian Snakes" → mitigate depolarization resonances
- Luminosity typically ~1E32 cm^{-2} s^{-1}
- Spin rotators provide choice of spin orientation *independent of experiment*
  - Spin direction varies bunch-to-bunch (9.4 MHz)
  - Spin pattern varies fill-to-fill
- 200 and 500/510 GeV collisions (proton-proton center-of-mass energy)

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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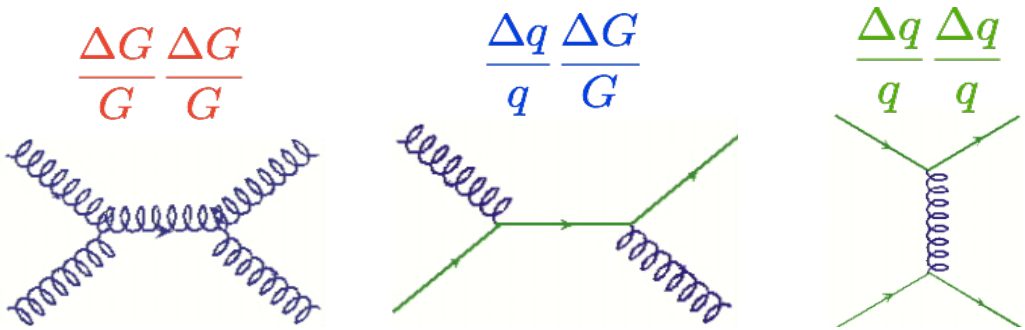
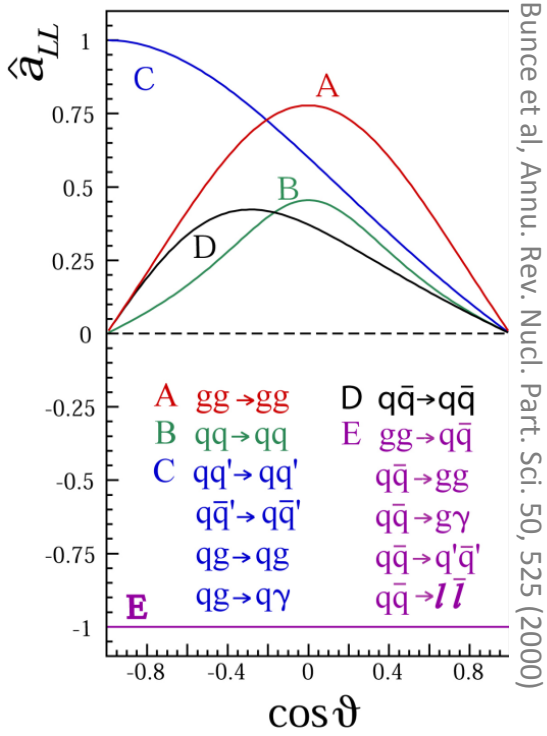
Probing (Gluon) Polarized PDF's With Jets

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

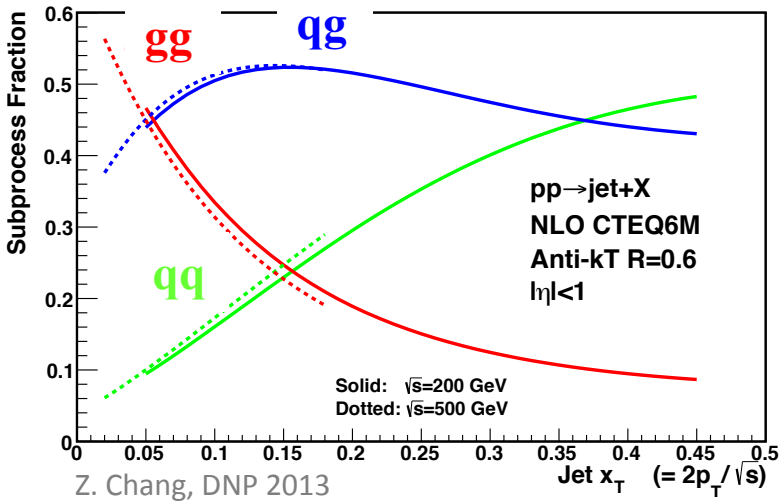
A_{LL} for, e.g. jets, sensitive to ***polarized PDF's*** (Δf) and ***partonic asymmetry***, $\hat{a}_{LL}$





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

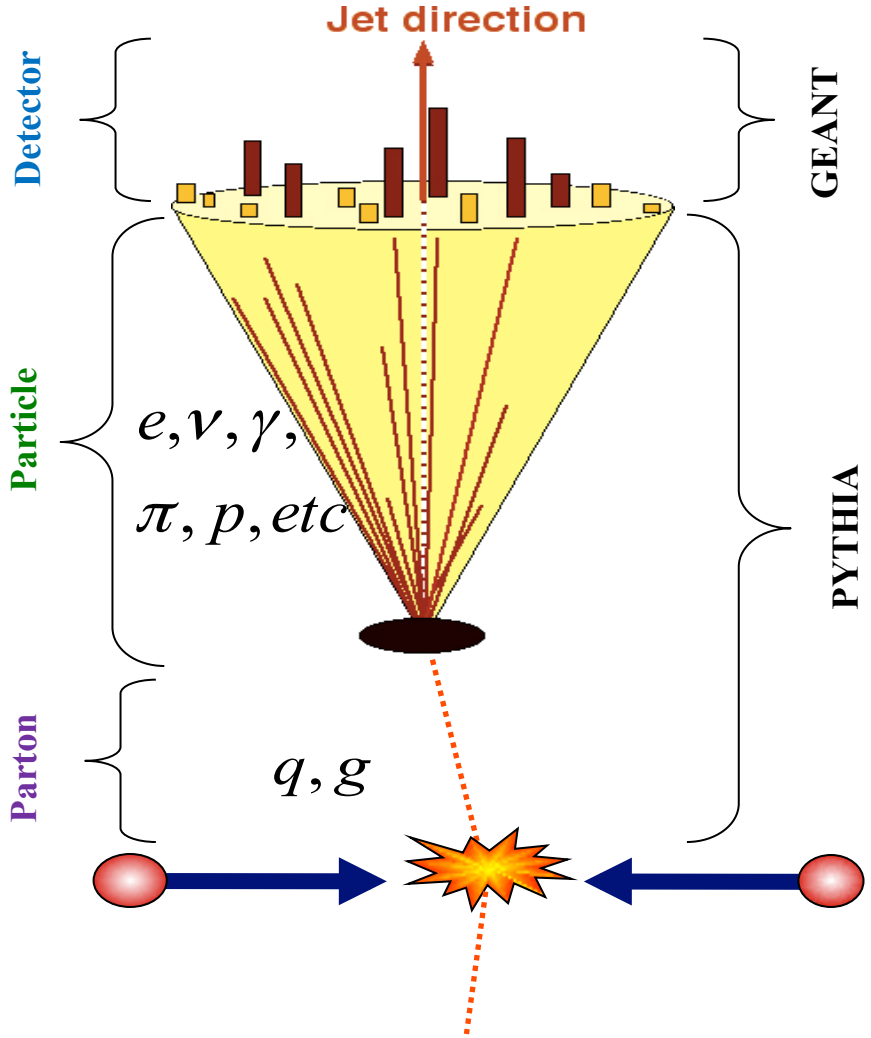
→ ***sample different mix of partonic subprocesses***



Jet Reconstruction

Jet Levels

MC Jets



STAR Detector has:

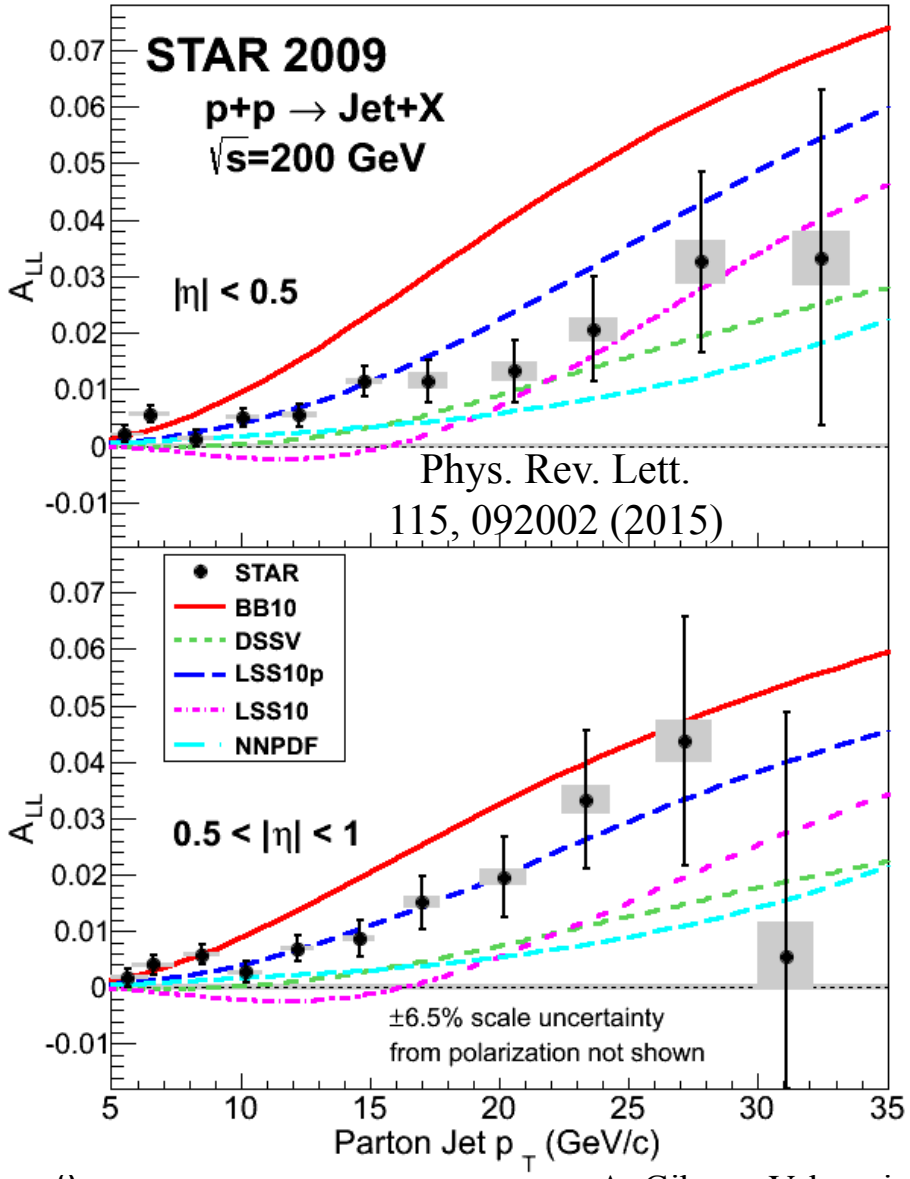
- Full azimuthal coverage
- Charged particle tracking from TPC for $|\eta| < 1.3$
- E/BEMC provide electromagnetic energy reconstruction for $-1 < \eta < 2.0$

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 that informed the DSSV08 fit
- Results divided into two pseudorapidity ranges which emphasize different partonic kinematics
- **Results lie consistently above the 2008 DSSV fit**

DSSV = D. de Florian, R. Sassot, M. Stratmann, W. Vogelsang

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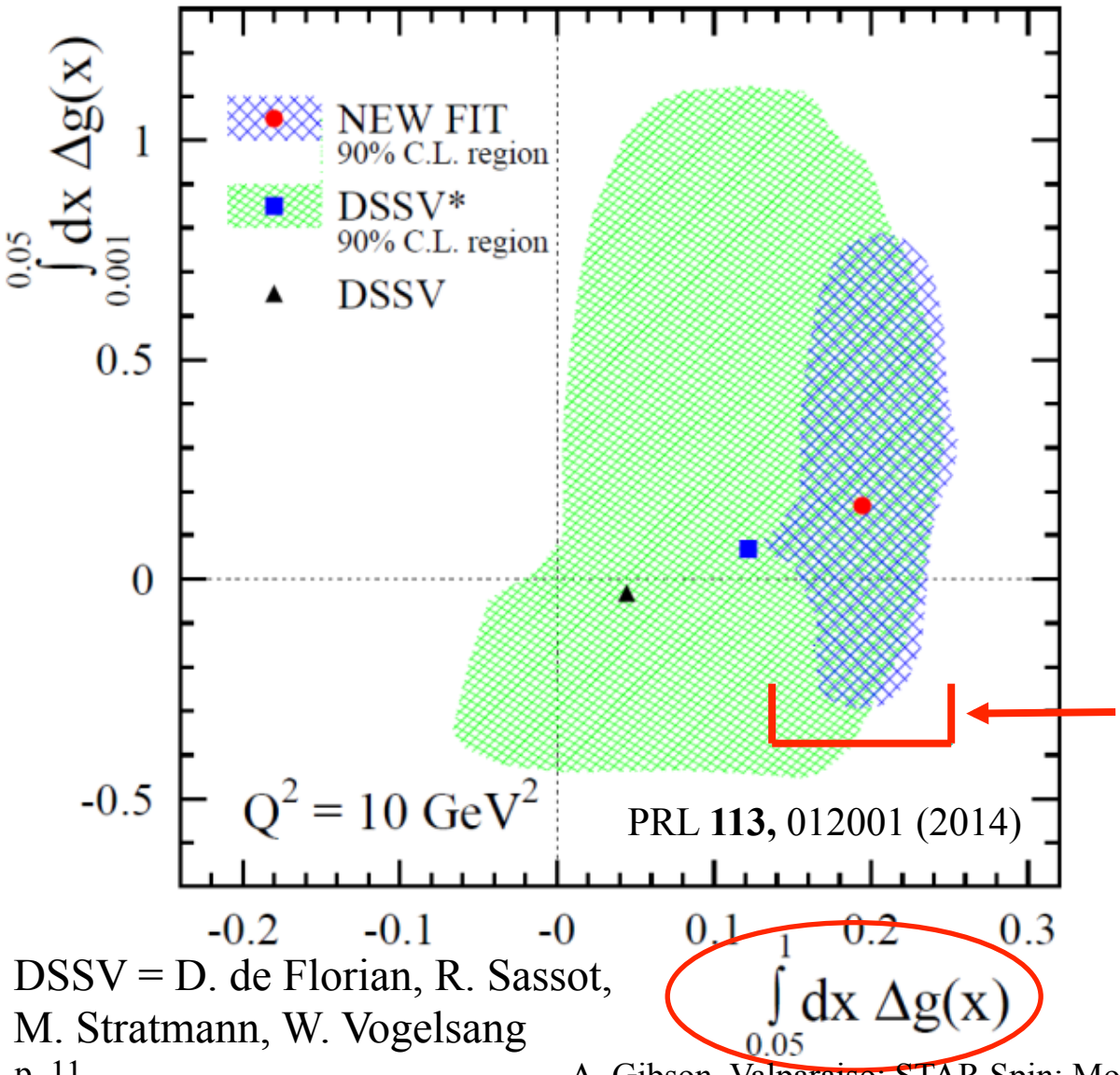
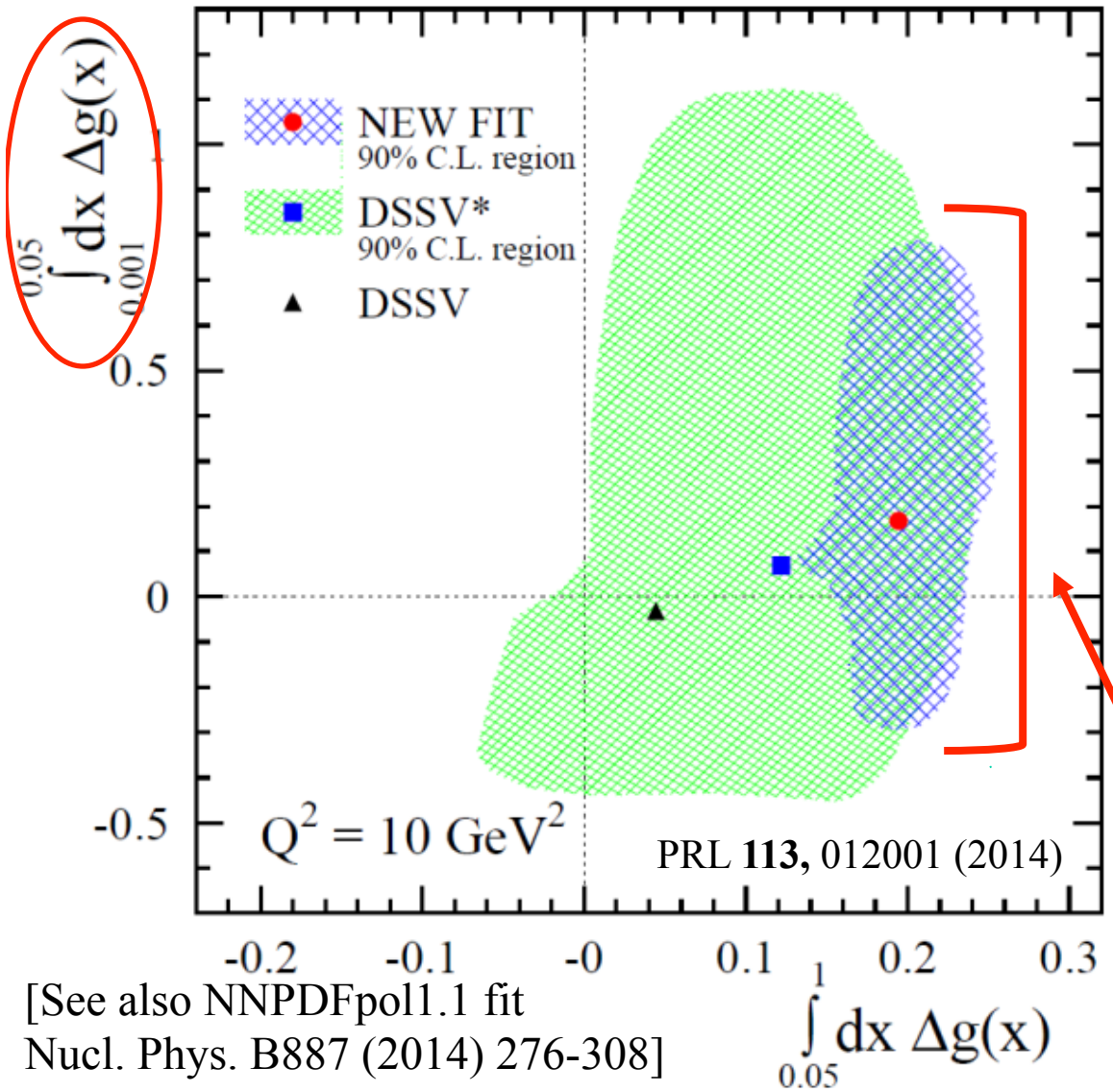
New DSSV14 Fit – ΔG Comes into Focus



- 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 DSSV14 fit
- **First firm evidence of non-zero gluon polarization!**

DSSV = D. de Florian, R. Sassot, M. Stratmann, W. Vogelsang

New DSSV14 Fit – Low *x* Remains Blurry



[See also NNPDFpol1.1 fit
Nucl. Phys. B887 (2014) 276-308]

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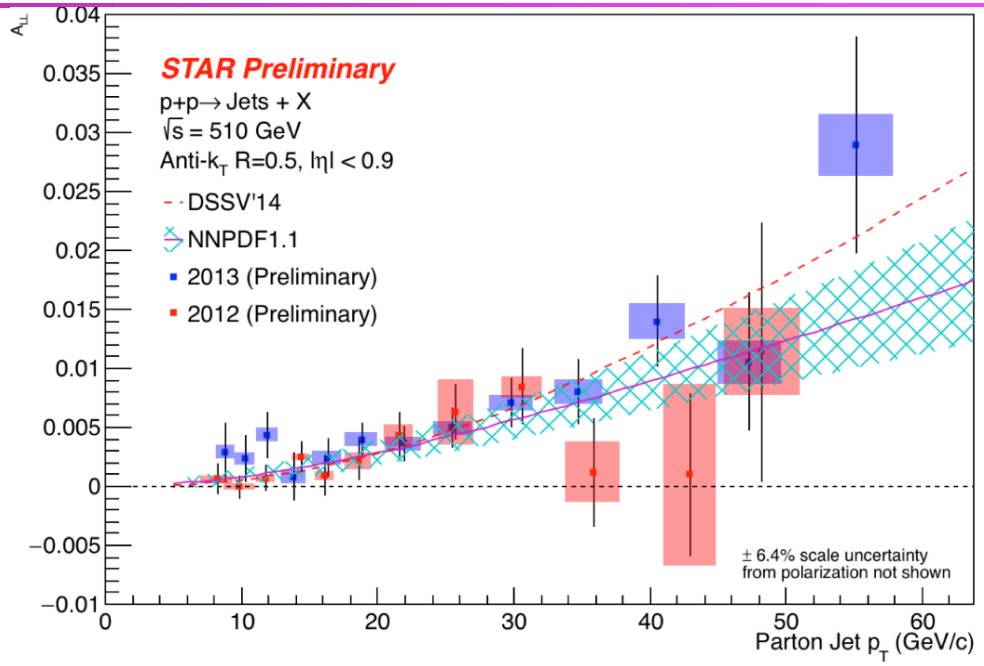
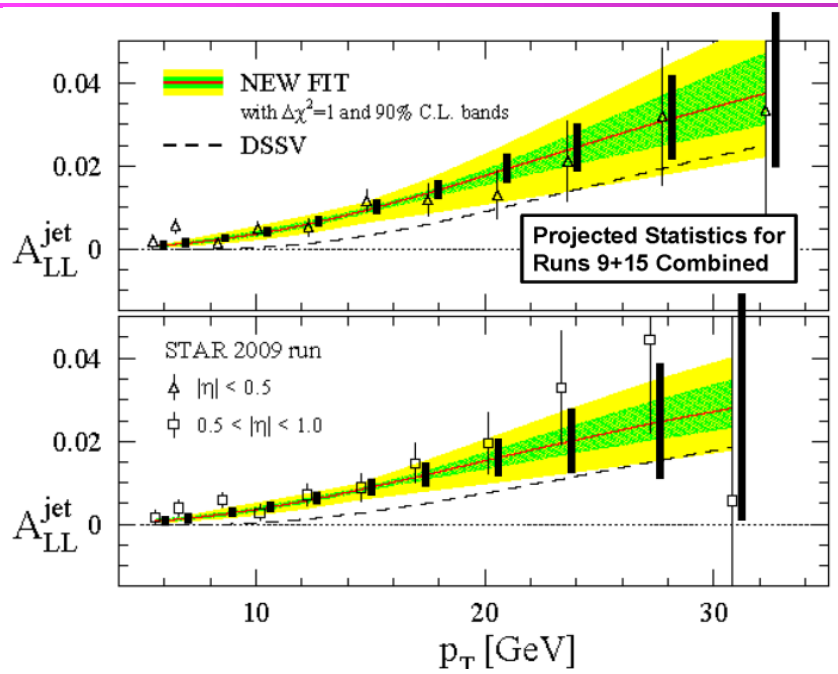
- Uncertainty on integral over low *x* region is still sizable

Higher Statistics for Inclusive Jet A_{LL}





- **Push to lower x_g w/ higher CoM energy**
- **RHIC had very successful, high luminosity runs in 2012 *and* 2013**
  - 50 pb^{-1} at 53% avg. polarization in 2012, and ~200 pb^{-1} in 2013
  - Smaller cone, R = 0.5 reduces effect of pileup
  - **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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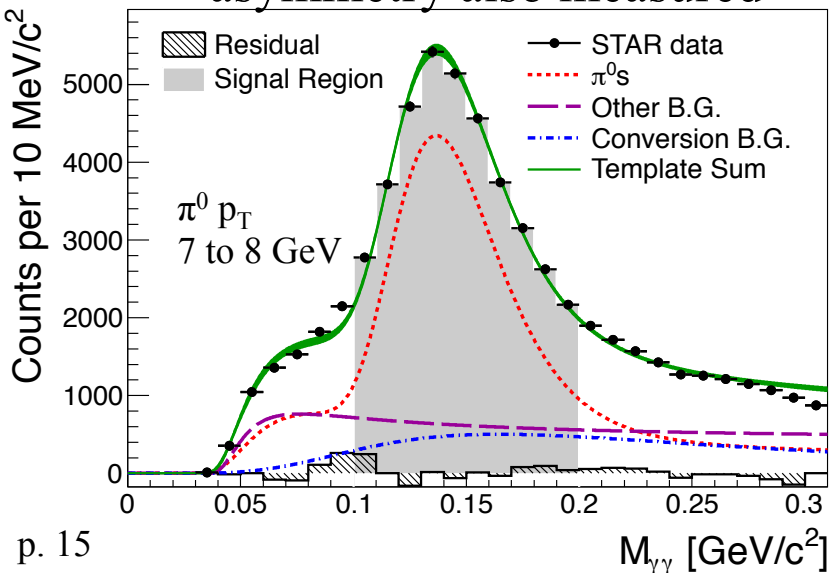
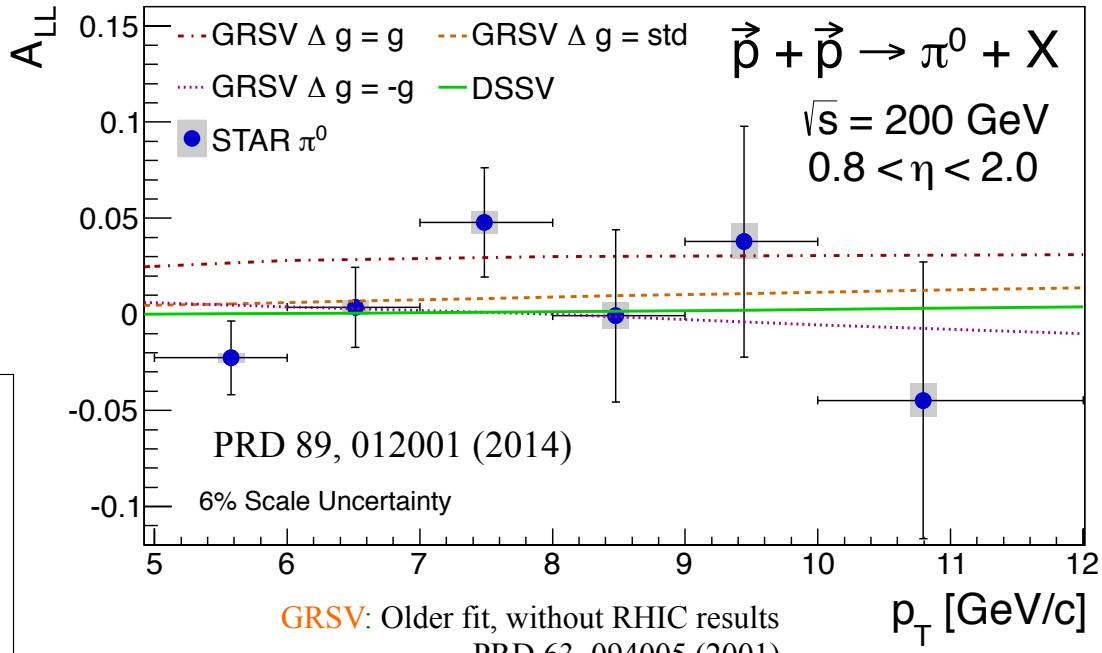
A_{LL} in π^0 + X at STAR for $0.8 < \eta < 2.0$

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



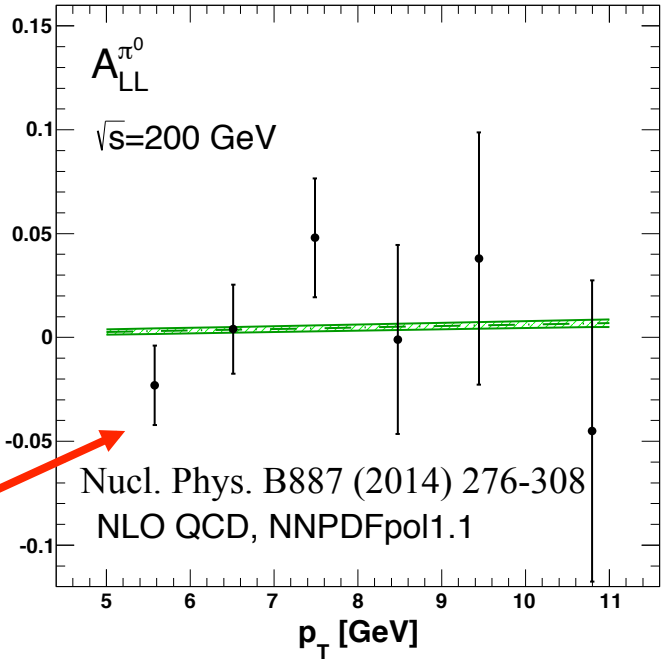


GRSV: Older fit, without RHIC results
PRD 63, 094005 (2001)

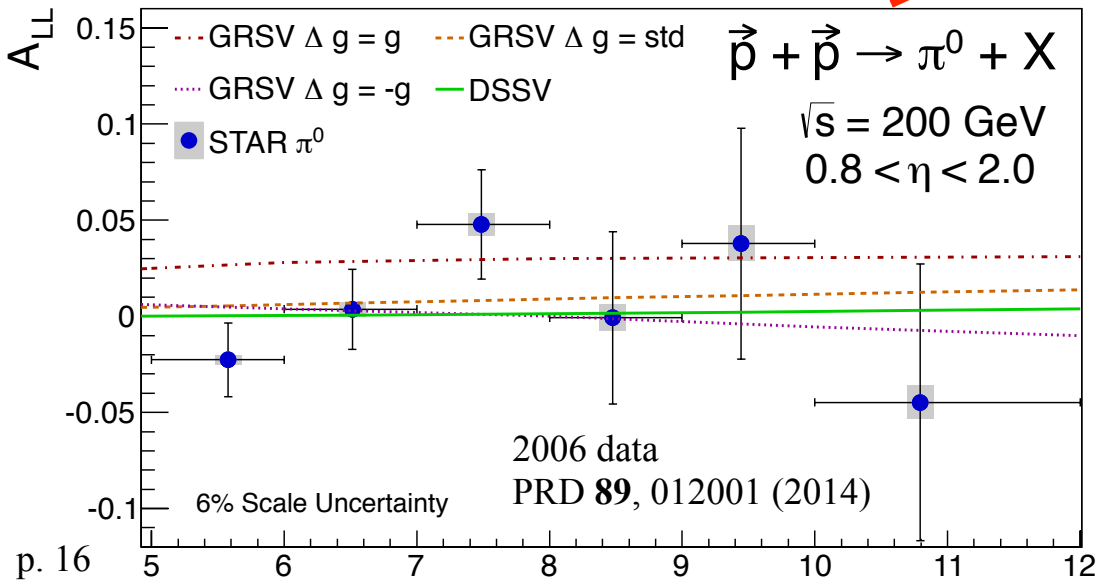
DSSV: First fit to include RHIC results
PRL 101, 072001 (2008)

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



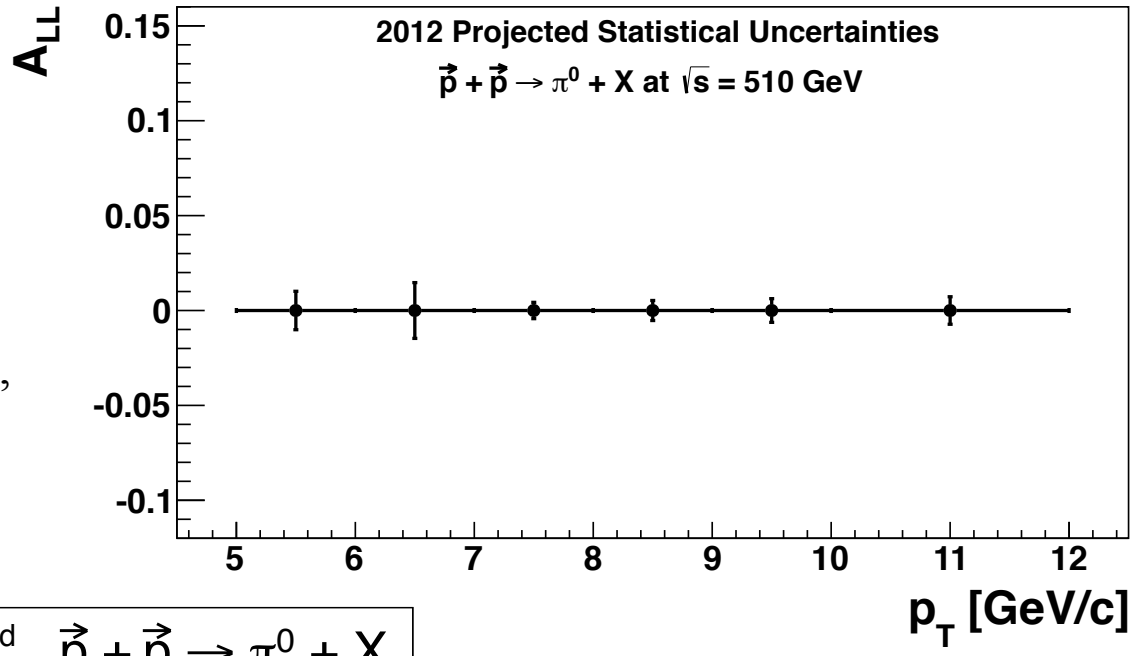
STAR data with NNPDF predictions

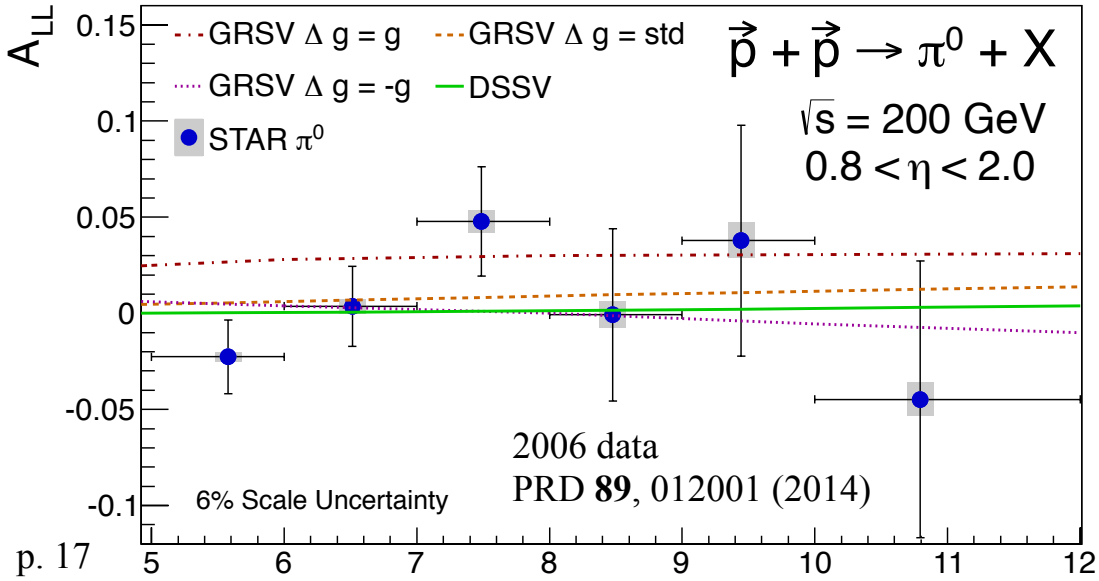


NNPDFpol1.1 from E. Nocera, R. Ball, S. Forte, G. Ridolfi, J. Rojo Nucl. Phys. B887 (2014) 276-308

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

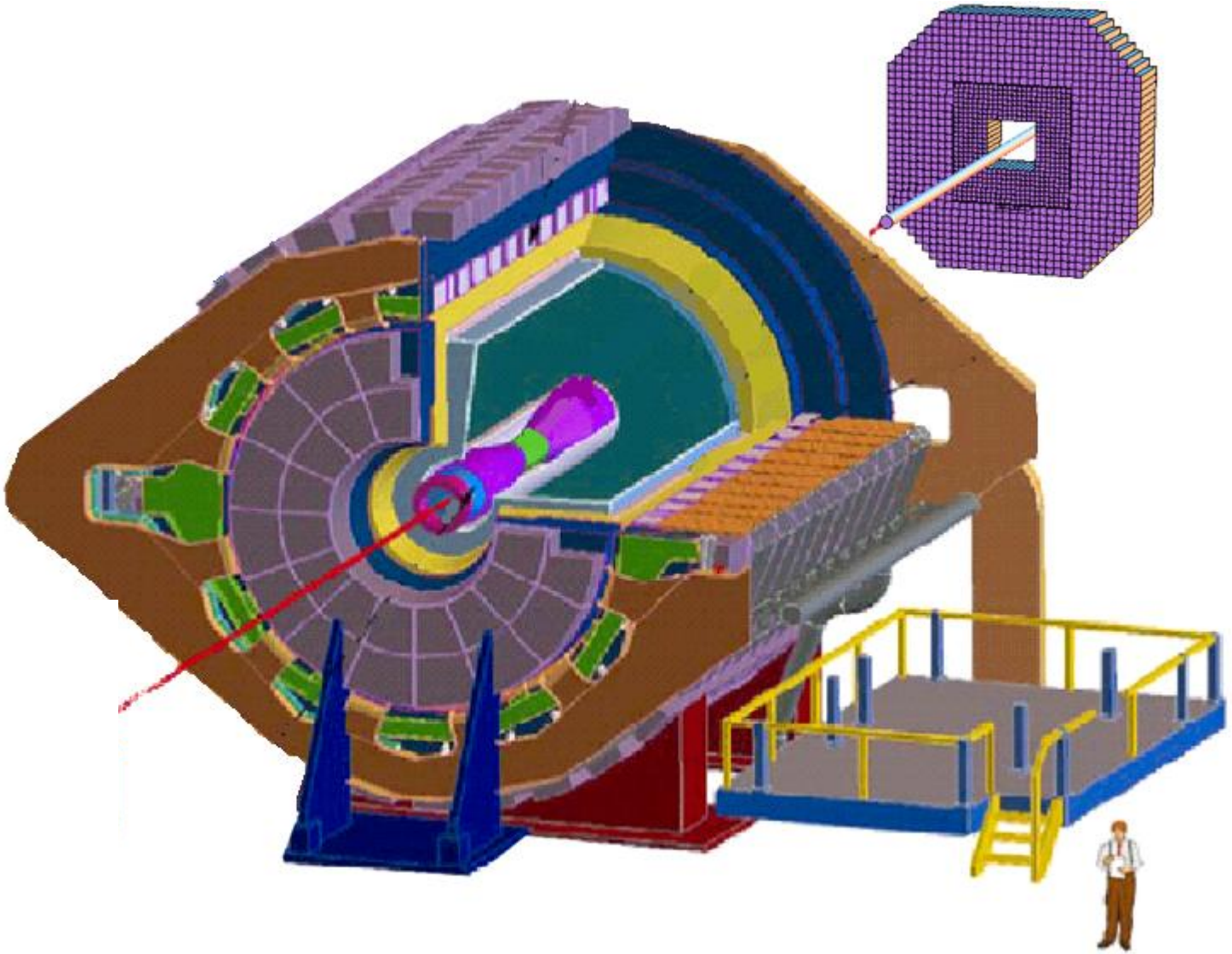
FMS

Pb Glass EM Calorimeter

pseudo-rapidity $2.7<\eta<4.0$

Small cells: 3.81x3.81 cm

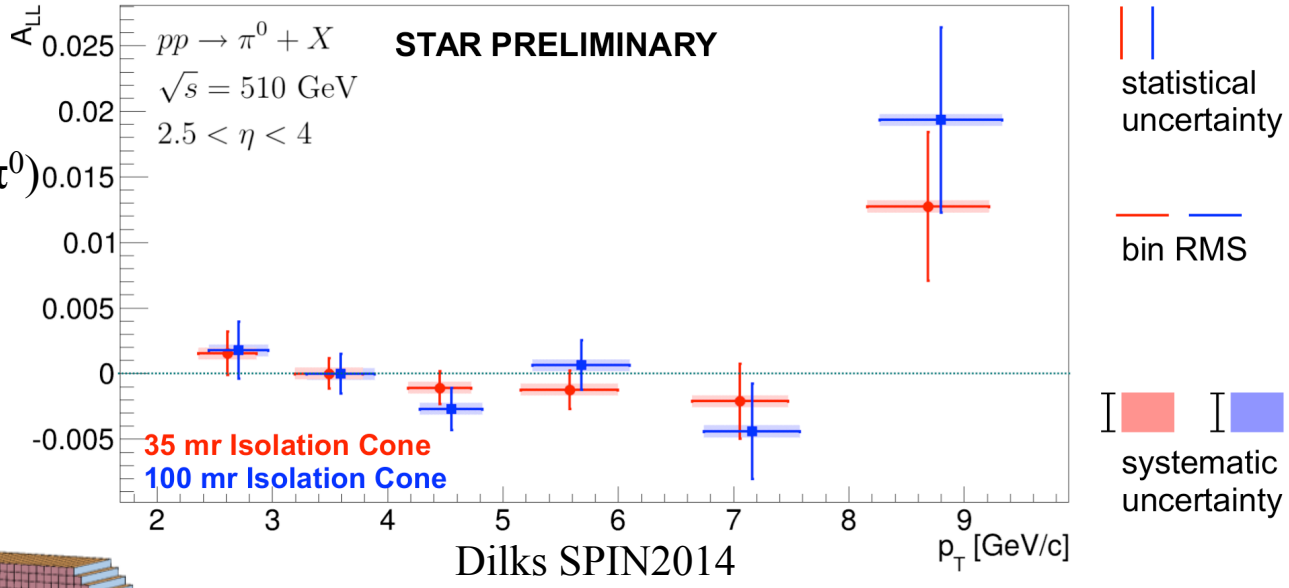
Outer cells: 5.81 x 5.81 cm



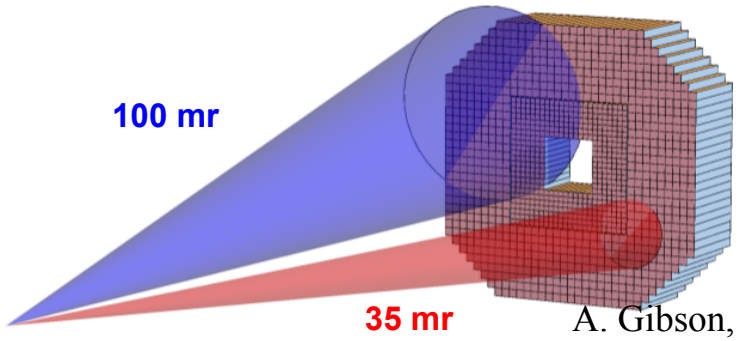
Forward EM Calorimetry In STAR.

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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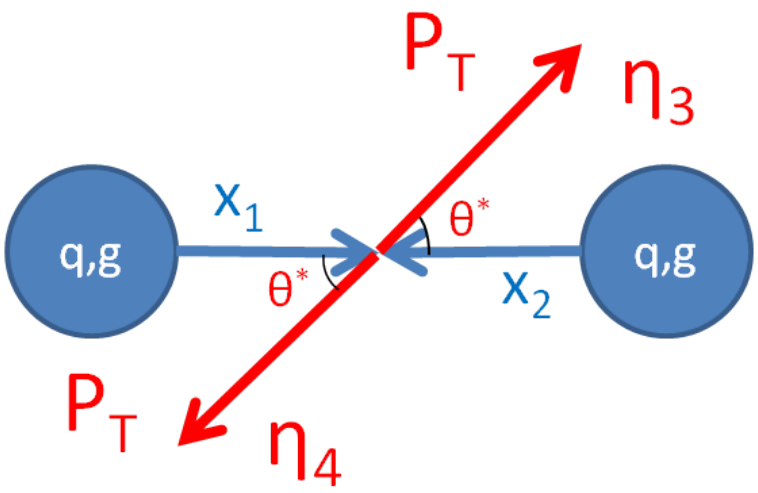
Dijet Measurements



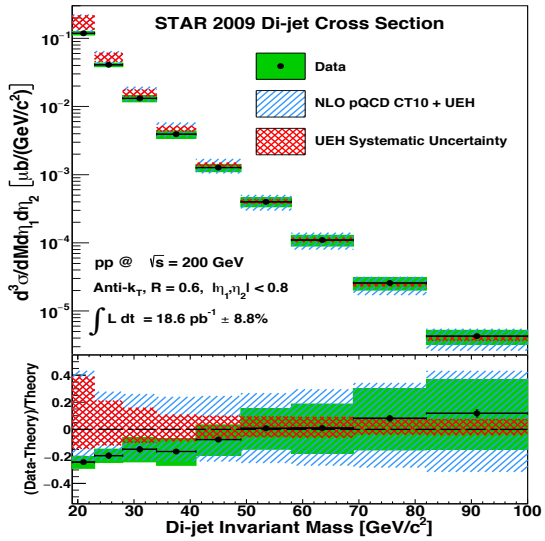
$$x_1 = \frac{1}{\sqrt{s}}\left(p_{T3}e^{\eta_3} + p_{T4}e^{\eta_4}\right)$$

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

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

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

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

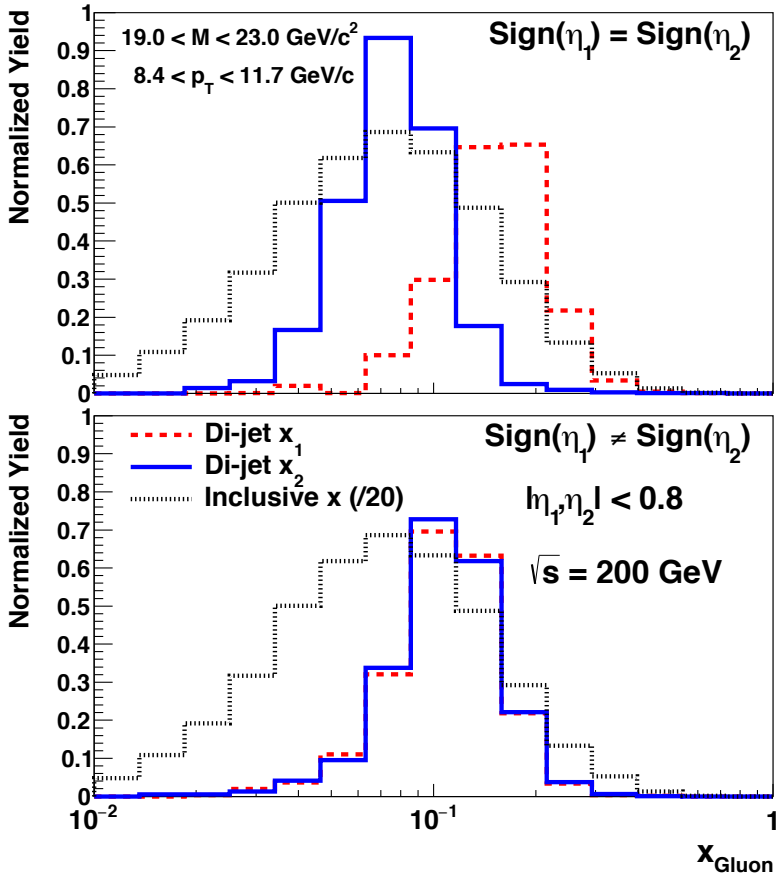


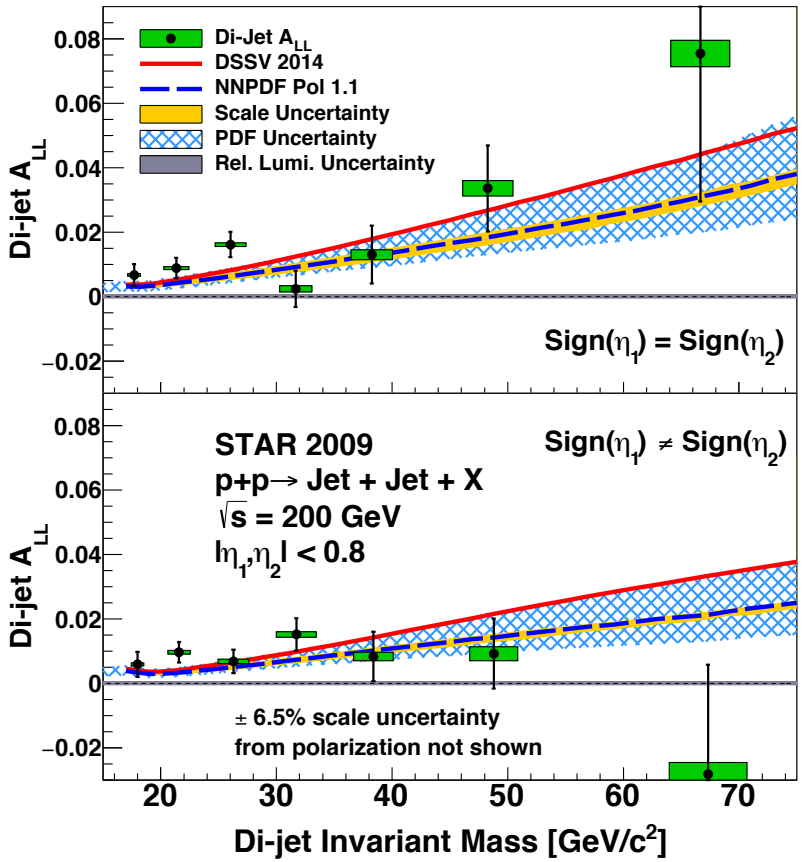
Phys. Rev. D 95, 071103(R) (2017)

- 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*)
- Aside: STAR has a complementary program of unpolarized QCD e.g. the dijet cross-section along with the A_{LL} spin asymmetry

2009 Dijet Asymmetries and *x* Reach

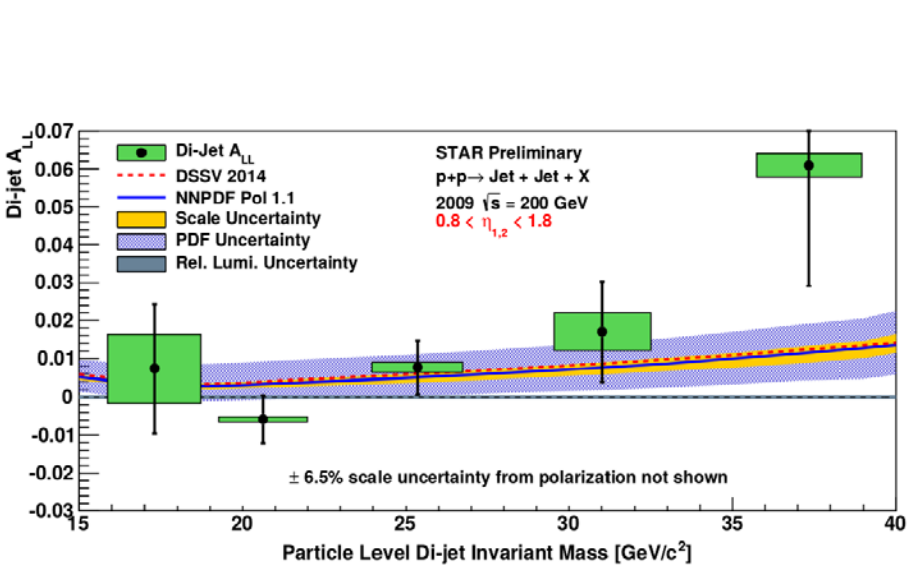
Phys. Rev. D 95, 071103(R) (2017)

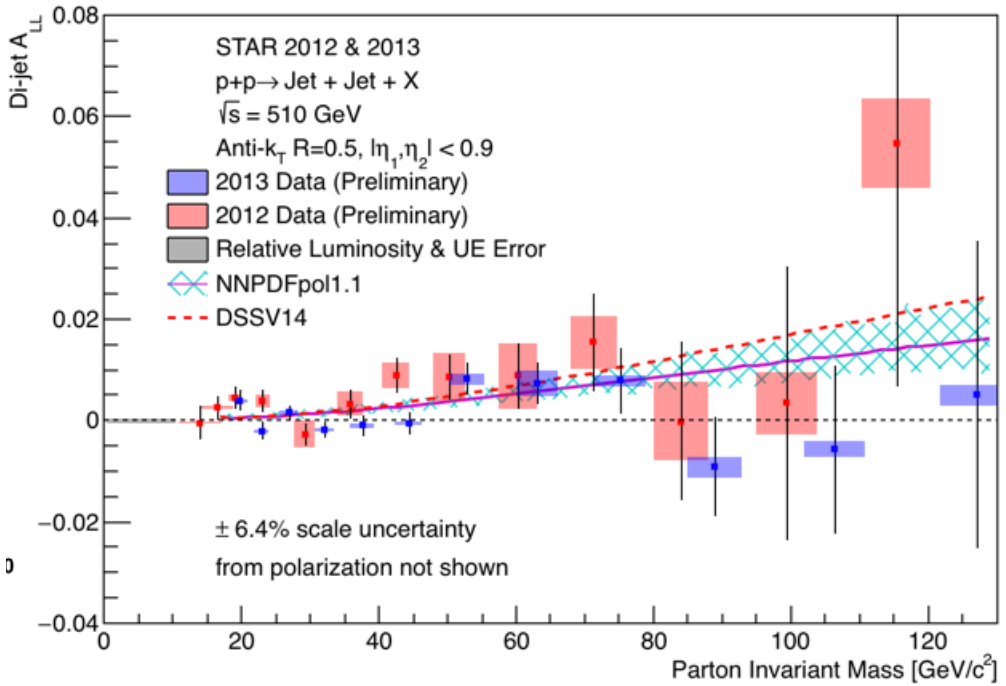




- Dijets probe a much narrower range of x_g than inclusive jets
- Asymmetries consistent with predictions from global fits, albeit this is a ~subset of the dataset used to extract polarized PDF's; some evidence dijets prefer a larger Δg?

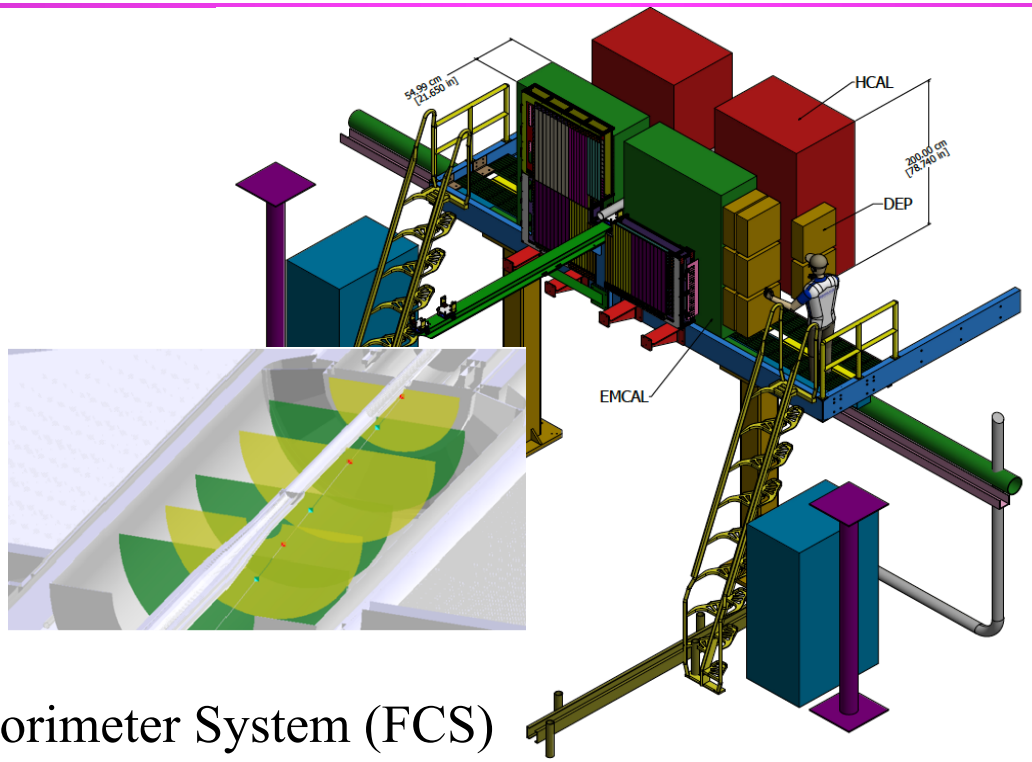
Dijets at Forward Rapidities and sqrt(s) = 510 GeV





- 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

Planned Forward Upgrade for the 2020's



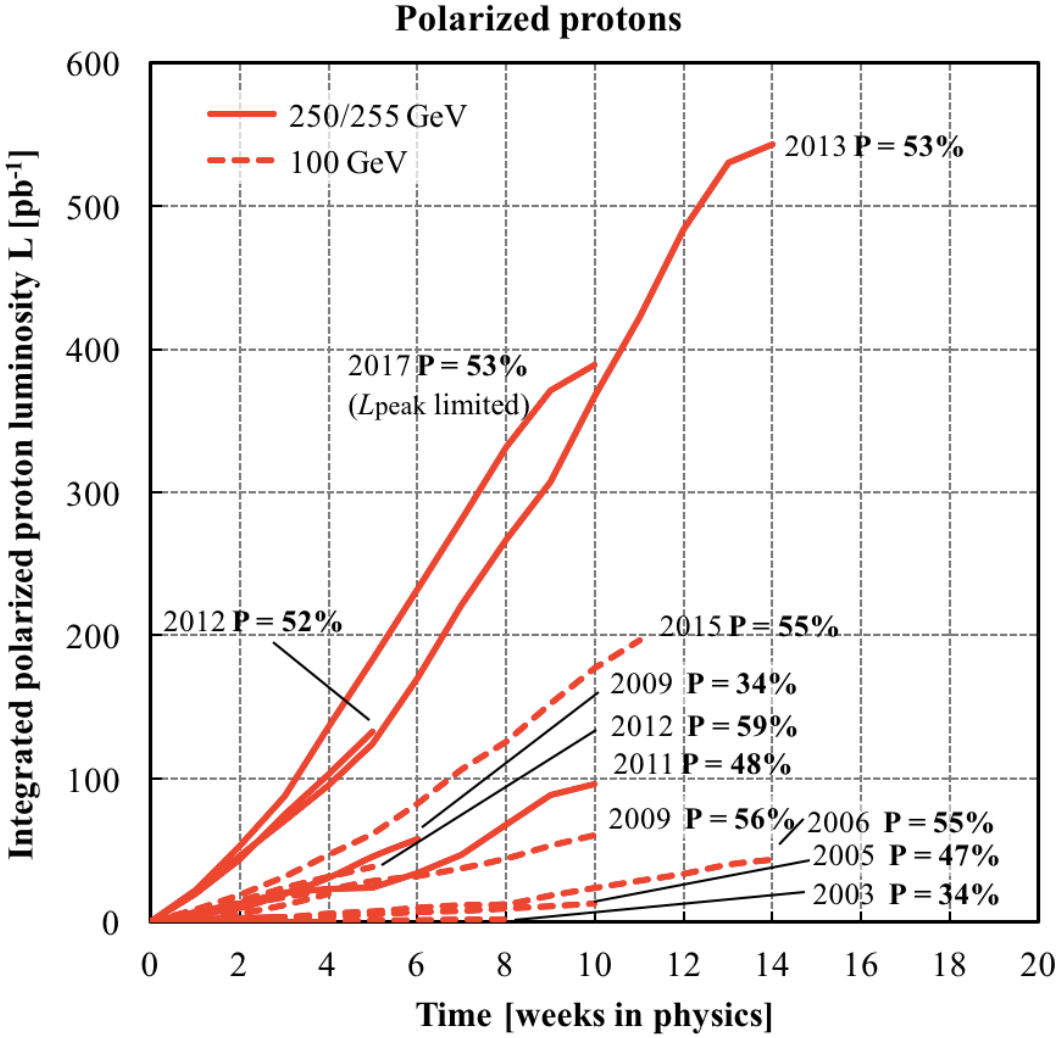
- Forward Calorimeter System (FCS)
  - Refurbish a portion of the PHENIX ECal, new Fe-scintillator HCal
  - Forward di-jets will extend gluon polarization to $x <\sim 10^{-3}$
- Forward Tracking System: Silicon discs and sTGC wheels (following ATLAS design)
- An extensive suite of measurements in transverse spin and p+A collisions
- First physics planned for 2021

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

- Inclusive Jets
  - After 30 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 Endcap Calorimeter
  - $2.5 < \eta < 4.0$ in the FMS Forward Calorimeter
- Map $\Delta g(x)$ as a function of x with correlated probes
  - Dijets and also e.g. correlated jet - forward π^0
- W boson A_L for flavor-separated polarized pdf's
- Rich **transverse spin program** as well
  - Evidence, at a hadron collider, for transversity in the proton
- **Large datasets being analyzed, upgrades planned; stay tuned!**
  - New global fits expected around the time of DIS 2018, next month

Backup

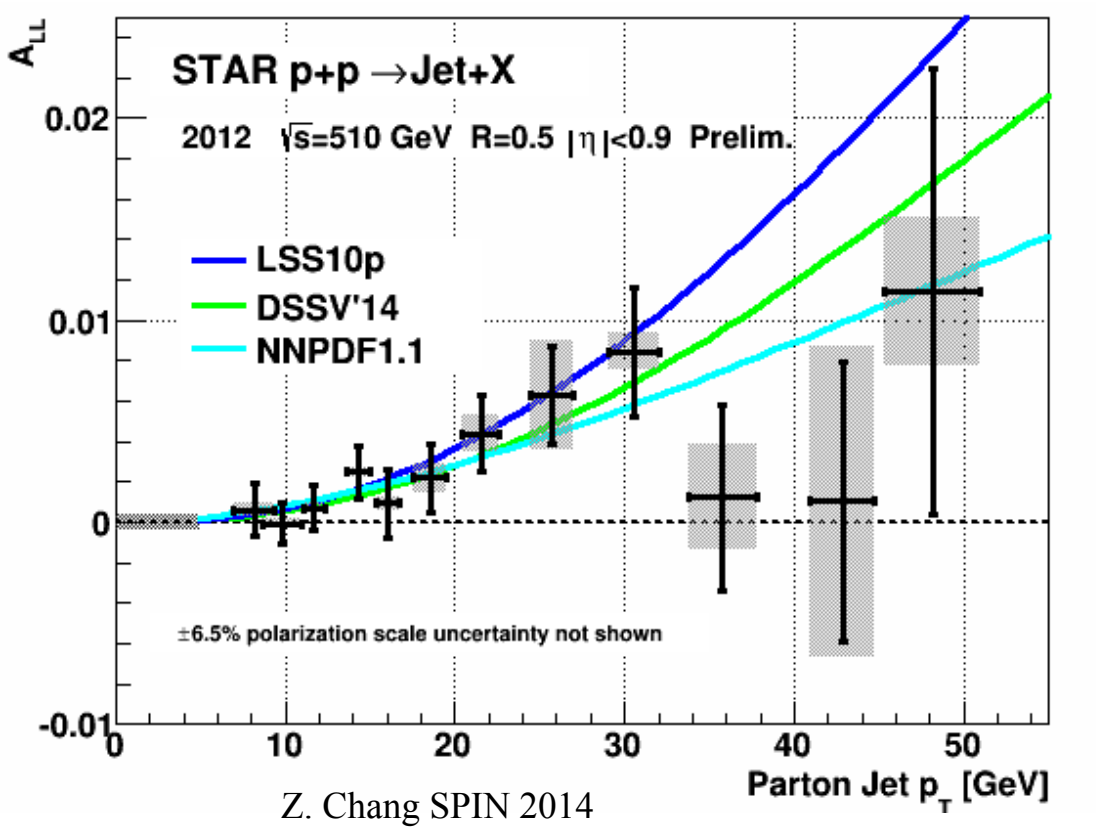
RHIC Luminosity



Year	$\sqrt{s}$ (GeV)	Recorded Luminosity for longitudinally / transverse polarized p+p STAR	Recorded Luminosity for longitudinally / transverse polarized p+p PHENIX	<P> in %
2006	62.4	-- pb^{-1} / 0.2 pb^{-1}	0.08 pb^{-1} / 0.02 pb^{-1}	48
	200	6.8 pb^{-1} / 8.5 pb^{-1}	7.5 pb^{-1} / 2.7 pb^{-1}	57
2008	200	-- pb^{-1} / 7.8 pb^{-1}	-- pb^{-1} / 5.2 pb^{-1}	45
2009	200	25 pb^{-1} / -- pb^{-1}	16 pb^{-1} / -- pb^{-1}	55
	500	10 pb^{-1} / -- pb^{-1}	14 pb^{-1} / -- pb^{-1}	39
2011	500	12 pb^{-1} / 25 pb^{-1}	18 pb^{-1} / -- pb^{-1}	48
2012	200	-- pb^{-1} / 22 pb^{-1}	-- pb^{-1} / 9.7 pb^{-1}	61/56
	510	82 pb^{-1} / -- pb^{-1}	32 pb^{-1} / -- pb^{-1}	50/53
2013	510	300 pb^{-1} / -- pb^{-1}	155 pb^{-1}/ -- pb^{-1}	51/52
2015	200	52 pb^{-1} / 52 pb^{-1}	-- pb^{-1}/ 60 pb^{-1}	53/57

Table 1-3: Recorded luminosities for collisions of longitudinally and transverse polarized proton beams at the indicated center-of-mass energies for past RHIC runs since 2006. The PHENIX numbers are for |vtx| < 30cm. The average beam polarization as measured by the Hydrogen-jet polarimeter, if two polarization numbers are given if the average polarization for the two beams was different

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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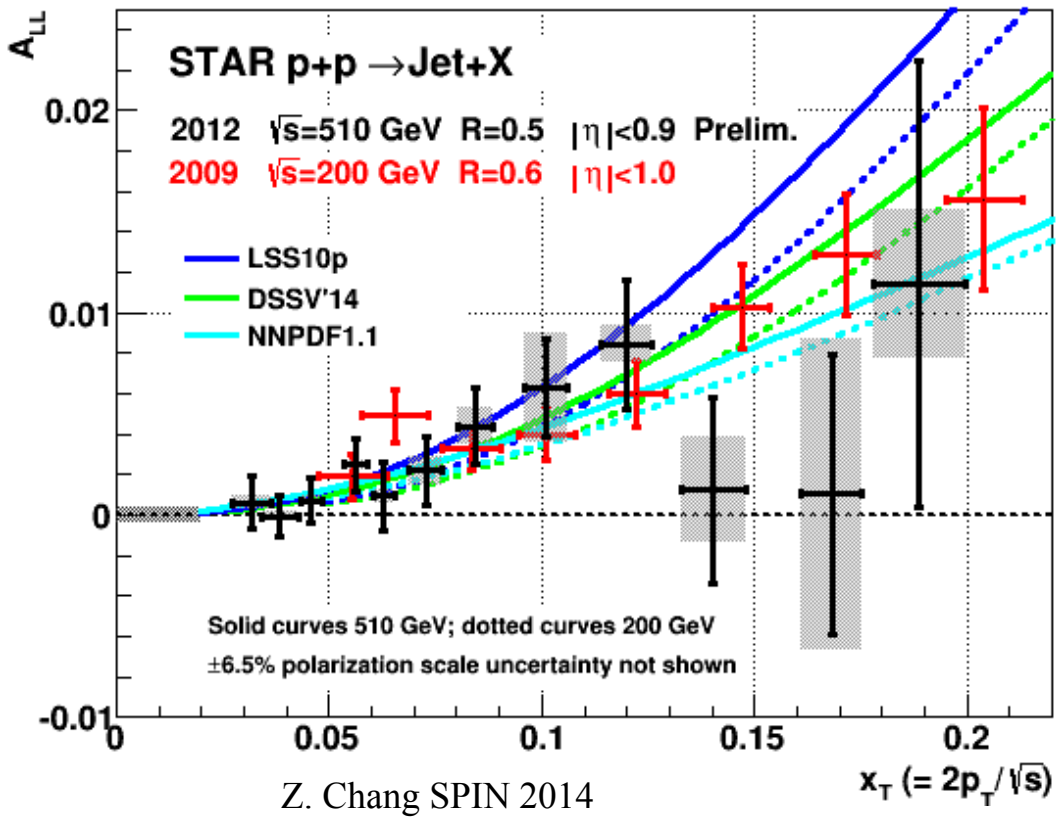

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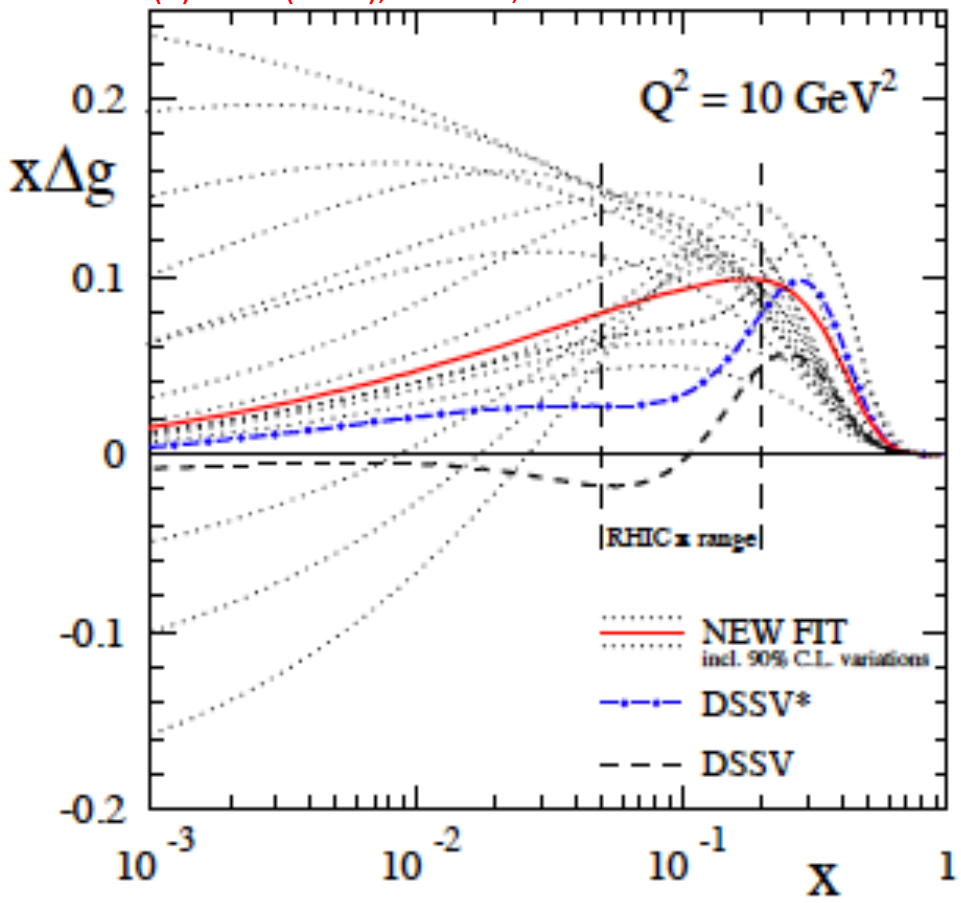
- **Agrees well with latest predictions**

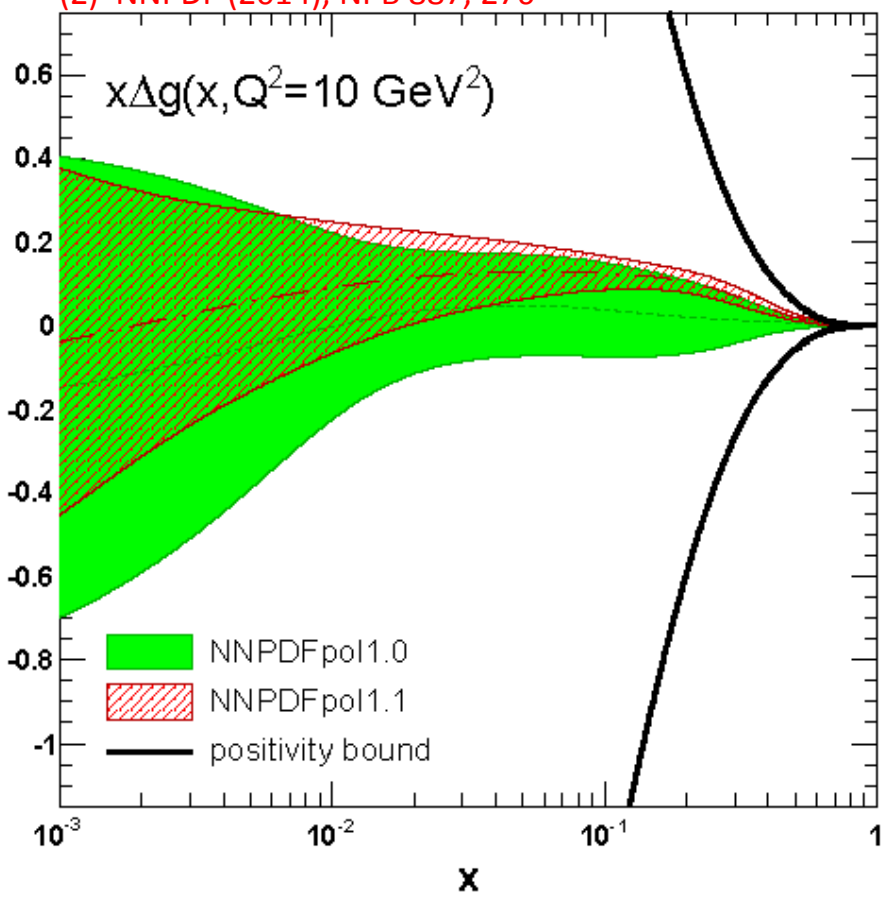
- Higher CoM pushes to lower x_T
  - Results agree in overlap region

Current polarized gluon pdf fits

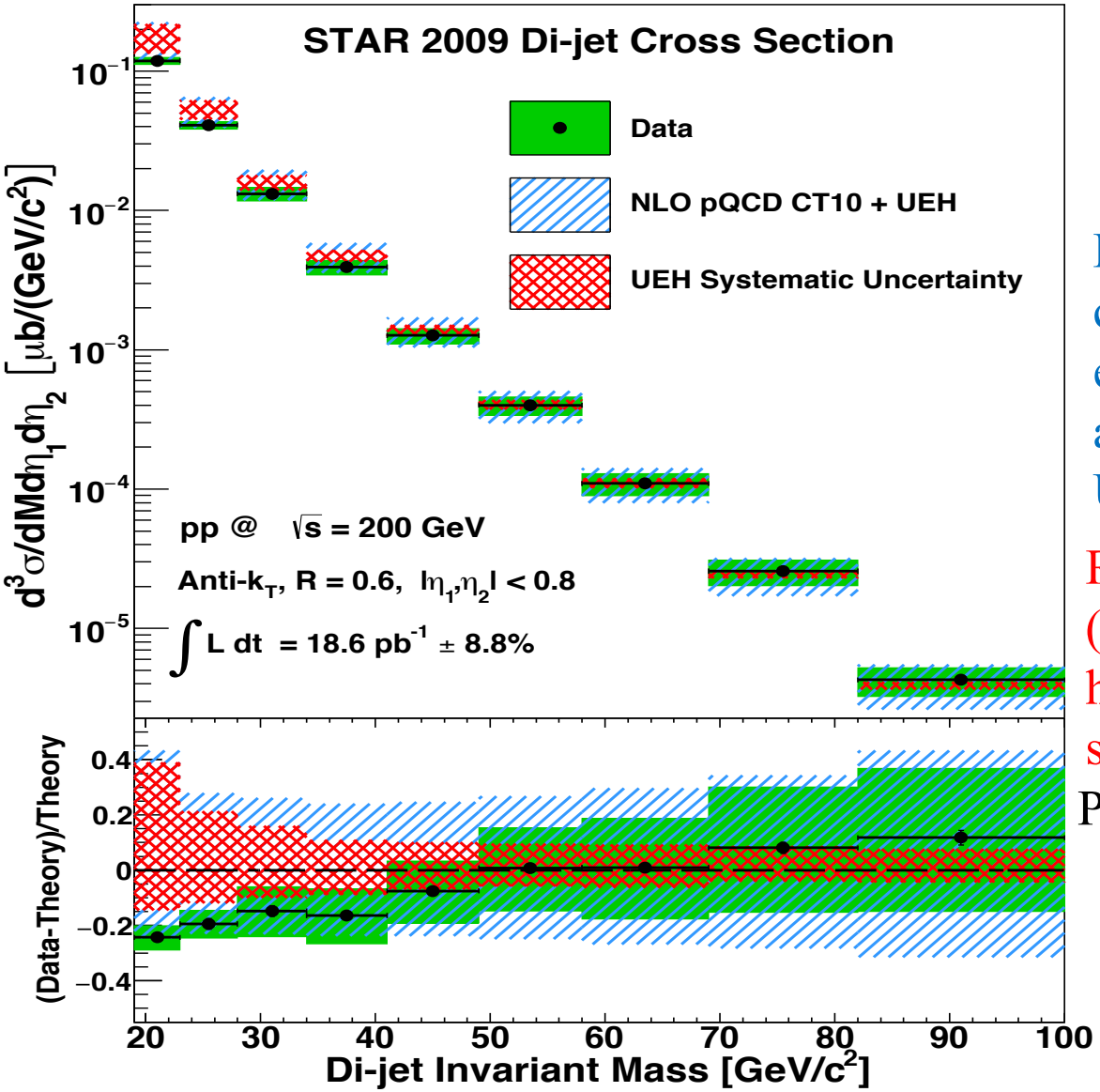
(1) DSSV (2014), PRL 113, 012001



(2) NNPDF (2014), NPB 887, 276



2009 Dijet Cross Section Results



Green box includes quadrature sum of systematic errors on the data

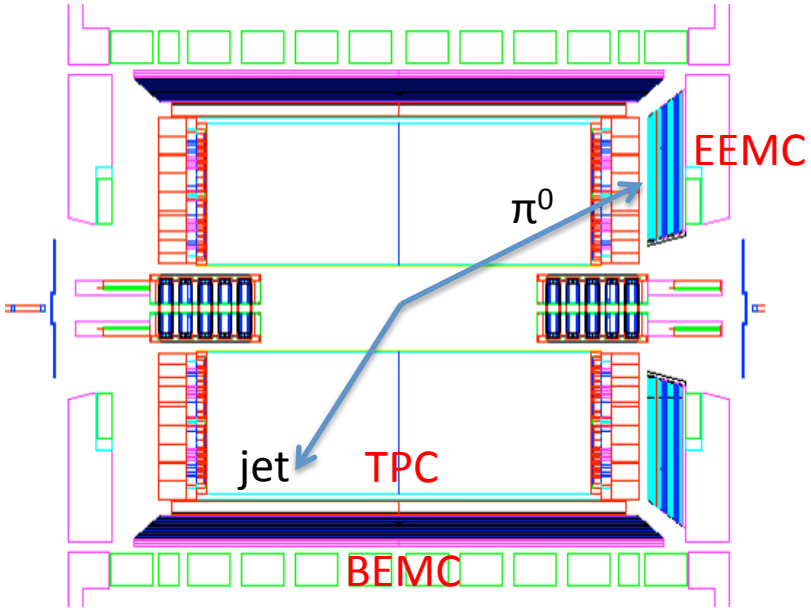
Blue box is theory + UEH correction and width is theory error (pdf uncert, renormalization and factorization scales x0.5, x2, UEH uncert)

Red box is syst errors on the UEH (underlying event and hadronization effects) correction, shown separately

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

π^0 - Jet A_{LL} measurements at STAR

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.


STAR

La Bataille de Reines; Col du Petit St. Bernard; August 2010