Recent Spin Results at STAR: Constraining the Gluon Polarization Distribution with Jet, Dijet, and Neutral Pion Probes

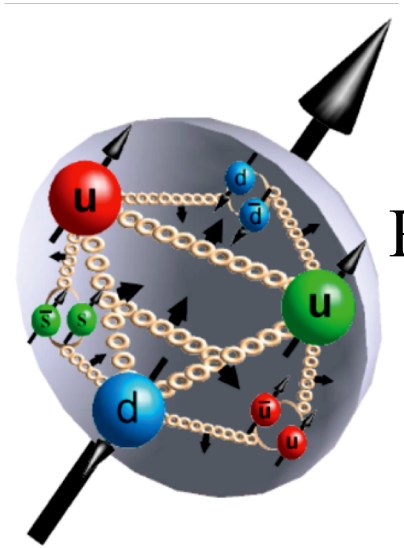
Adam Gibson
Valparaiso University
For the STAR Collaboration

WWND 2020

March 5, 2020

Supported in part by
U.S. DEPARTMENT OF ENERGY
Office of Science

Contributions to the Proton's Spin



Polarized DIS: ~0.3
Puzzling for ~30 years

Relatively poorly constrained but ΔG coming into focus.

Proton spin sum rule: $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$

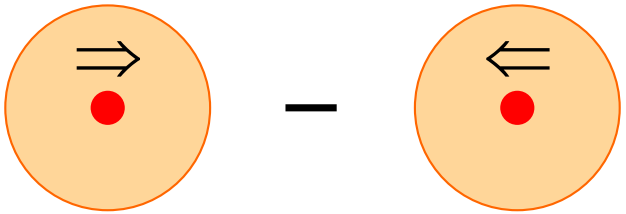
$$\Delta G = \int_0^1 dx \Delta g(x)$$

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 Forward Upgrade

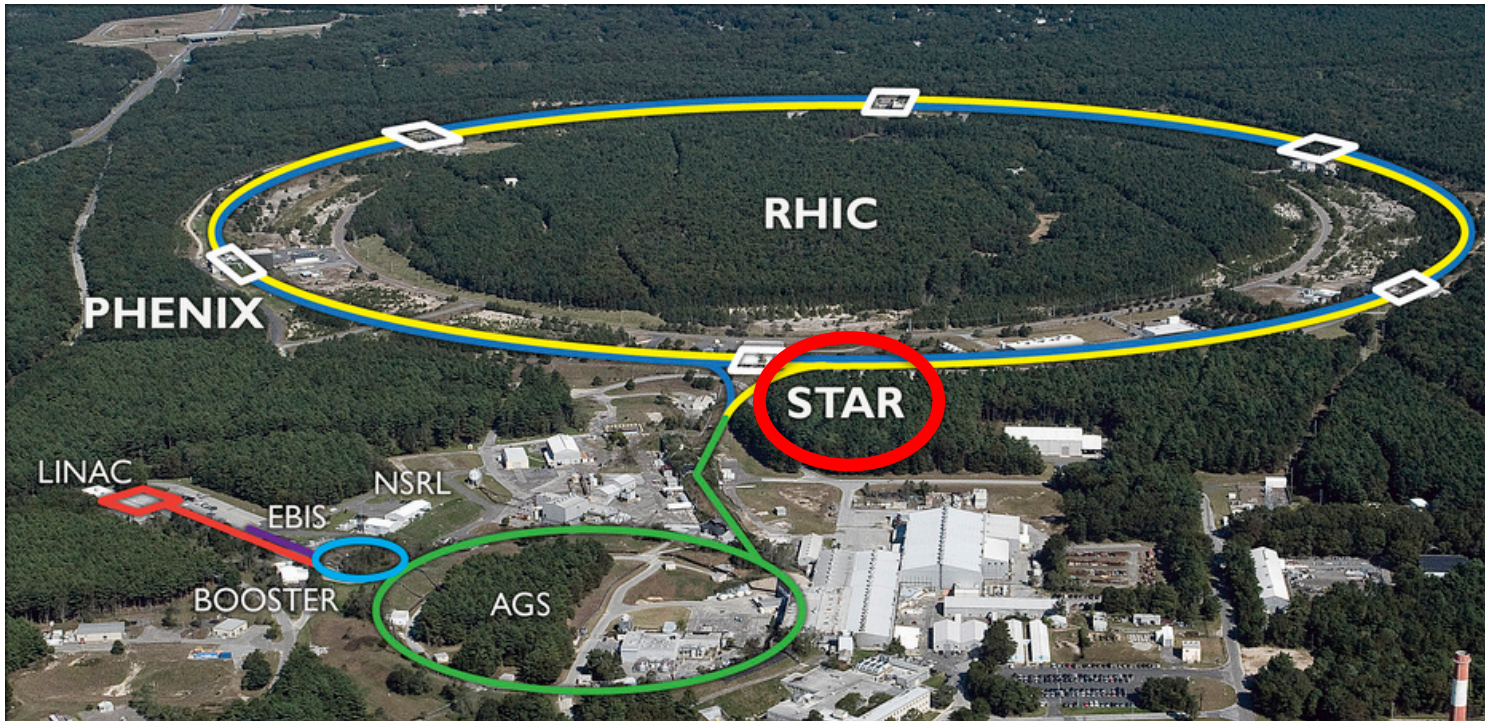
STAR at the Relativistic Heavy Ion Collider (RHIC)

RHIC world's first and only polarized proton collider

- Average polarization 50-60%
  - "Siberian Snakes" preserve polarization
- Luminosity typically ~1×10^{32} 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

NIM A499, 245 (2003)

- 200 and 500/510 GeV collisions (proton-proton center-of-mass energy)



Solenoidal Tracker at RHIC

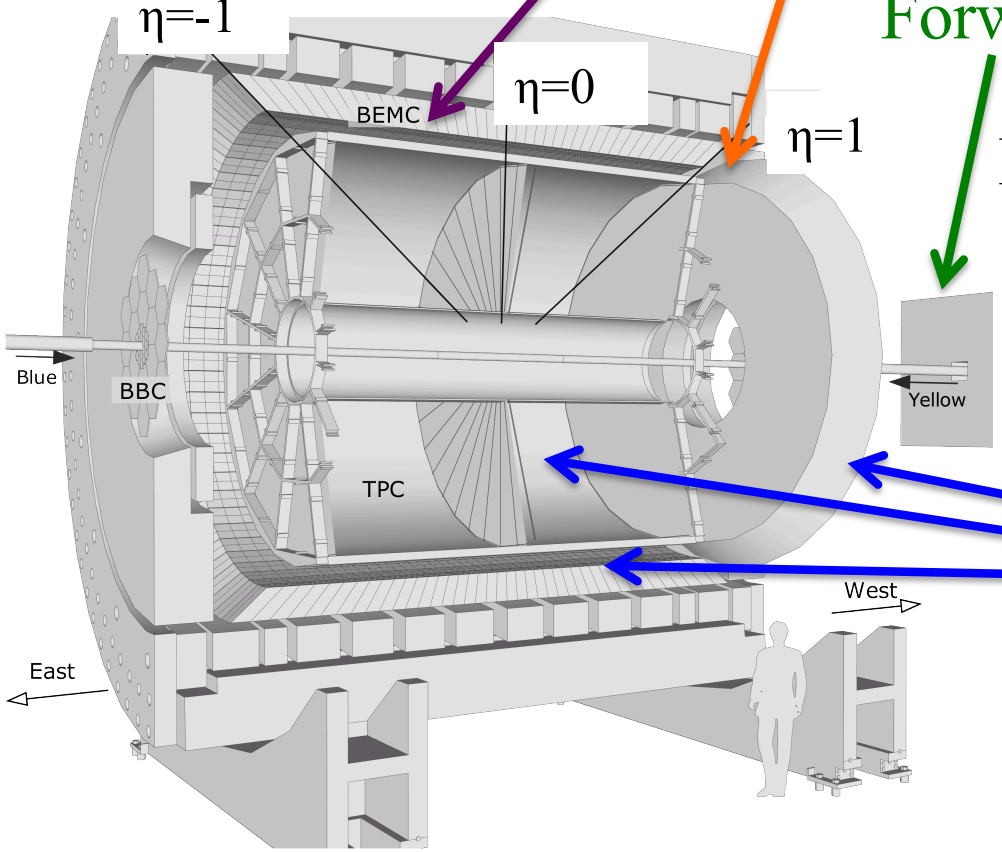
Inclusive hadron (e.g. π^0) measurements:

Barrel ElectroMagnetic Calorimeter (BEMC),

Endcap ElectroMagnetic Calorimeter (EEMC),

and

Forward Meson Spectrometer (FMS)



Relative luminosity measurements:

Beam Beam Counters (BBC) etc.

Jet measurements:

TPC +

Barrel + Endcap EMC

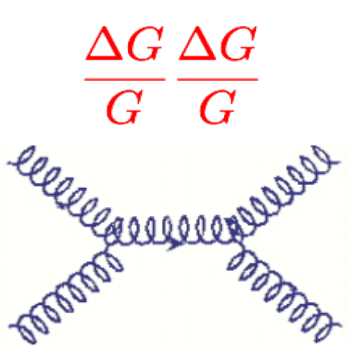
Constraining the Gluon Polarization Distribution with Jet, Dijet, and Neutral Pion Probes at STAR

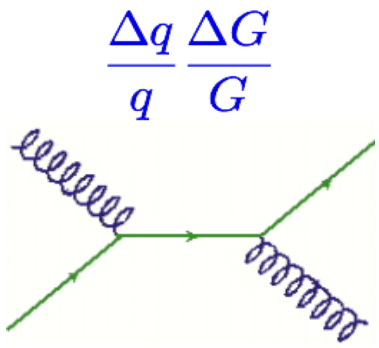
- STAR Detector
- Inclusive jets as a probe of $\Delta g(x)$
- Current Understanding of $\Delta g(x)$
- Pushing to Low x with Forward π^0's
  - In the Endcap Calorimeter
  - In the Forward Calorimeter
- Constraining $\Delta g(x)$ with Correlated Probes: Dijets
- STAR Forward Upgrade

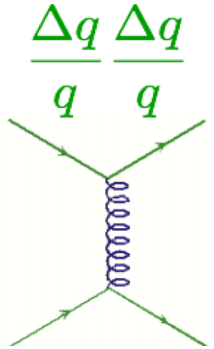
Probing (Gluon) Polarized PDF's With Jets

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

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







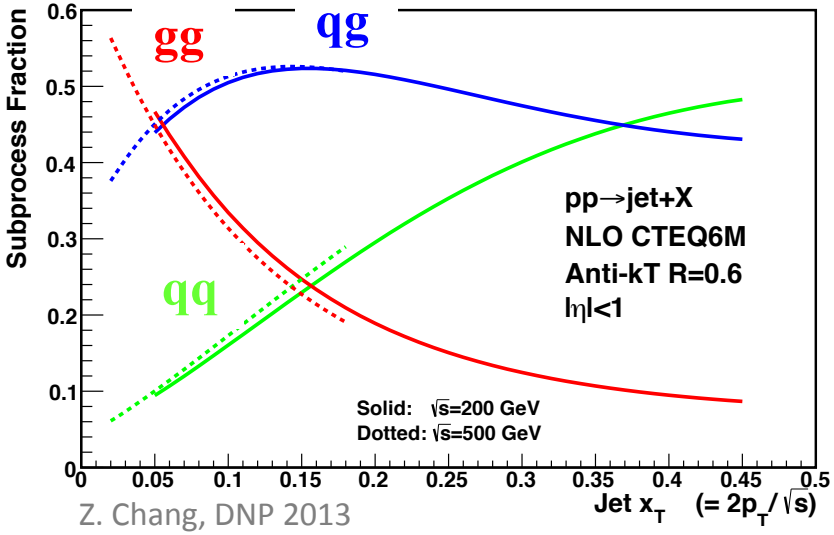
σ^{++}, σ^{+-}

Count jets as a function of proton spin orientation

(+ spin aligned with momentum,
- anti-aligned)

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

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

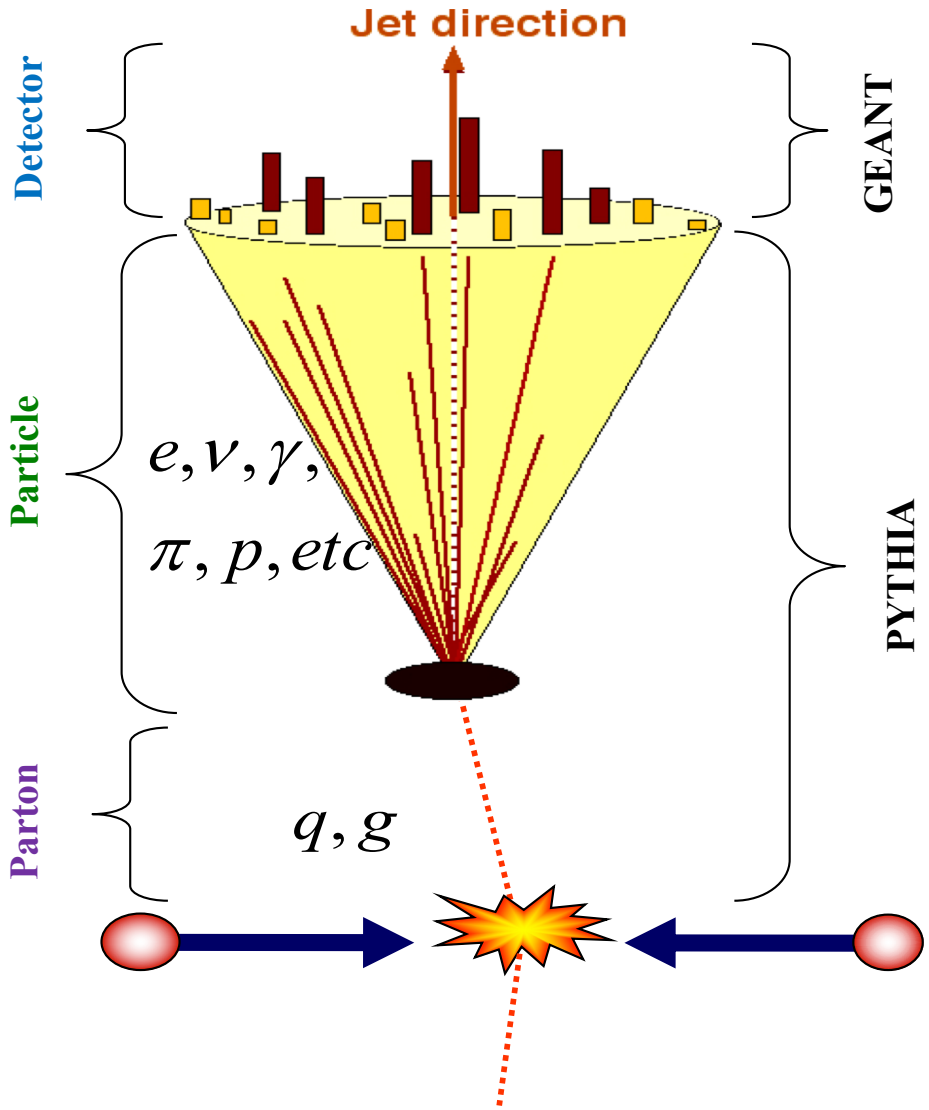


Z. Chang, DNP 2013

Jet Reconstruction

Jet Levels

MC Jets



STAR Detector has:

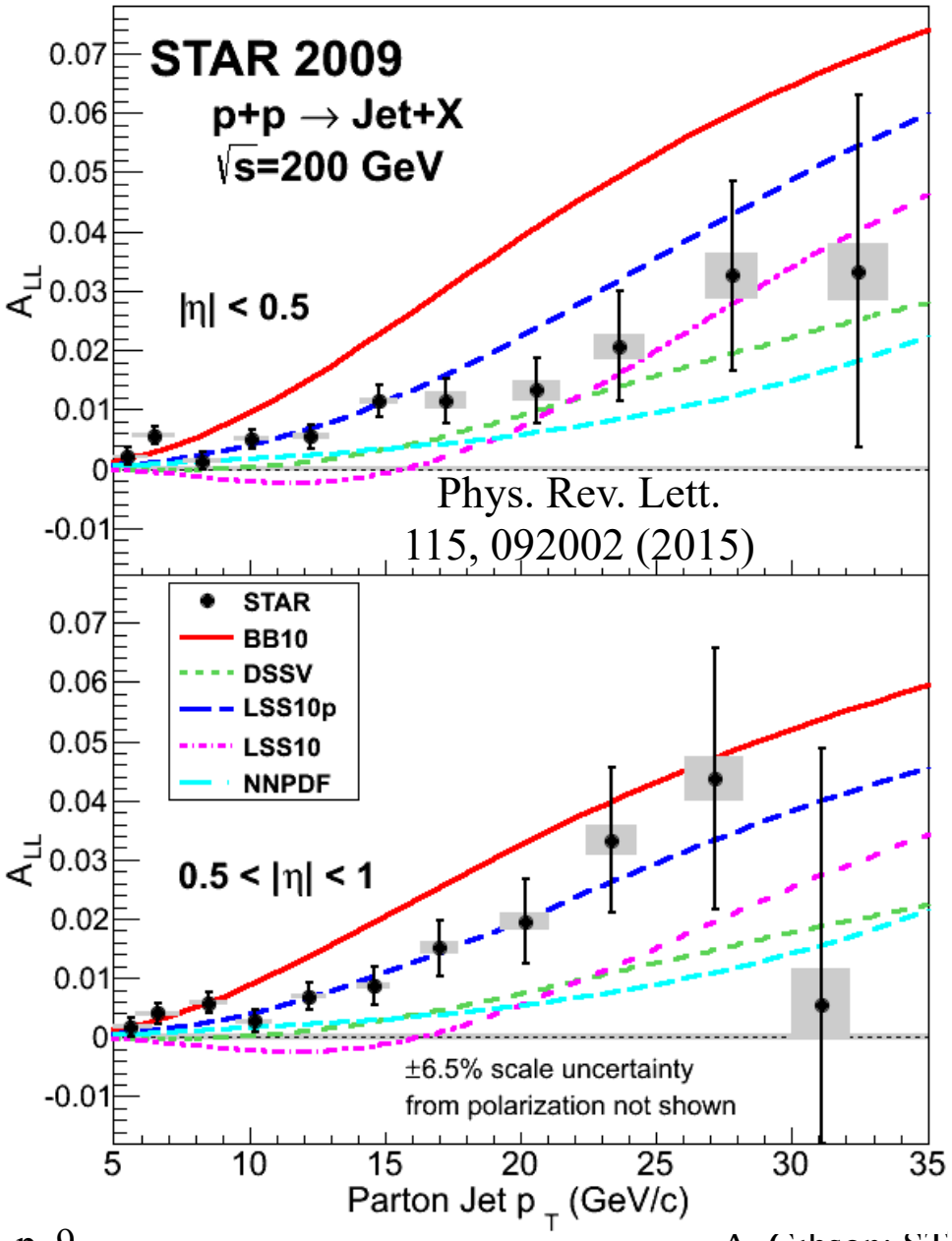
- Full azimuthal coverage
- Charged particle tracking from TPC for $|\eta| < 1.3$
- E/BEMC provide electromagnetic energy reconstruction for $-1 < \eta < 2.0$

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}



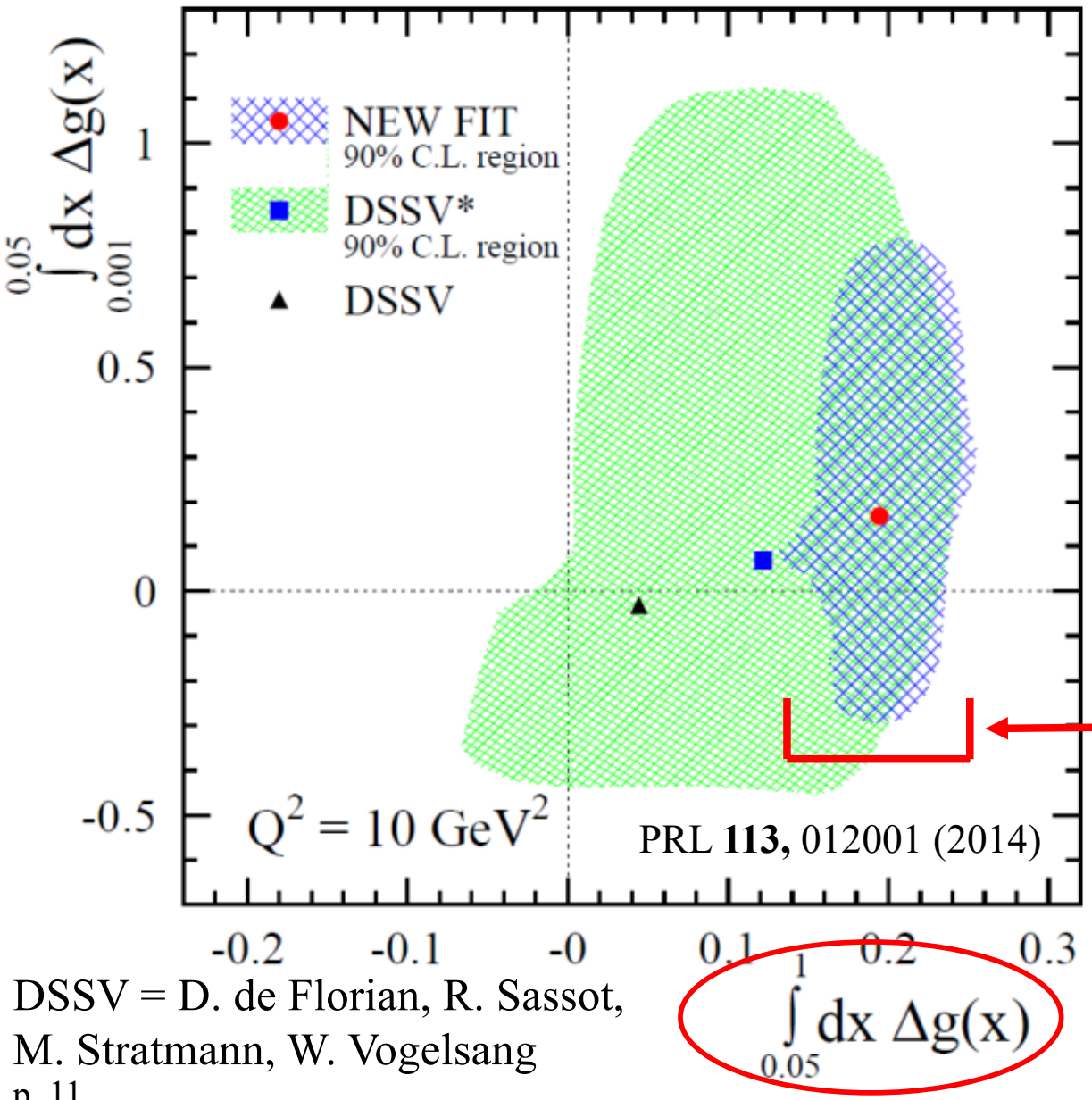
- 2009 results have factor of 3 to 4 better statistical precision than 2006 results that informed the DSSV08 fit
- Results divided into two pseudorapidity ranges which emphasize different partonic kinematics
- **Results lie consistently above the 2008 DSSV fit**

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

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 Forward Upgrade

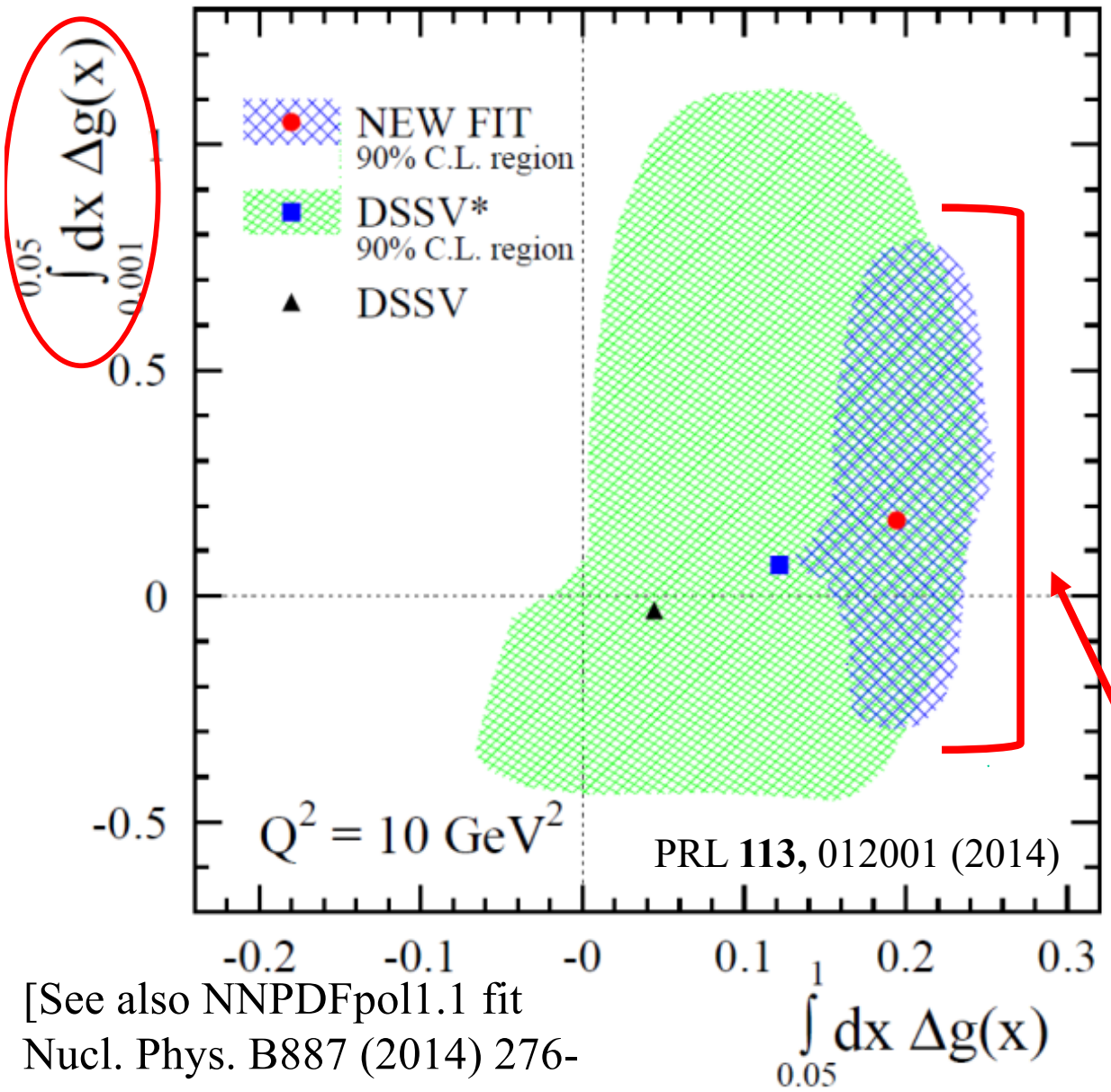
New DSSV14 Fit – ΔG Comes into Focus



- 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 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



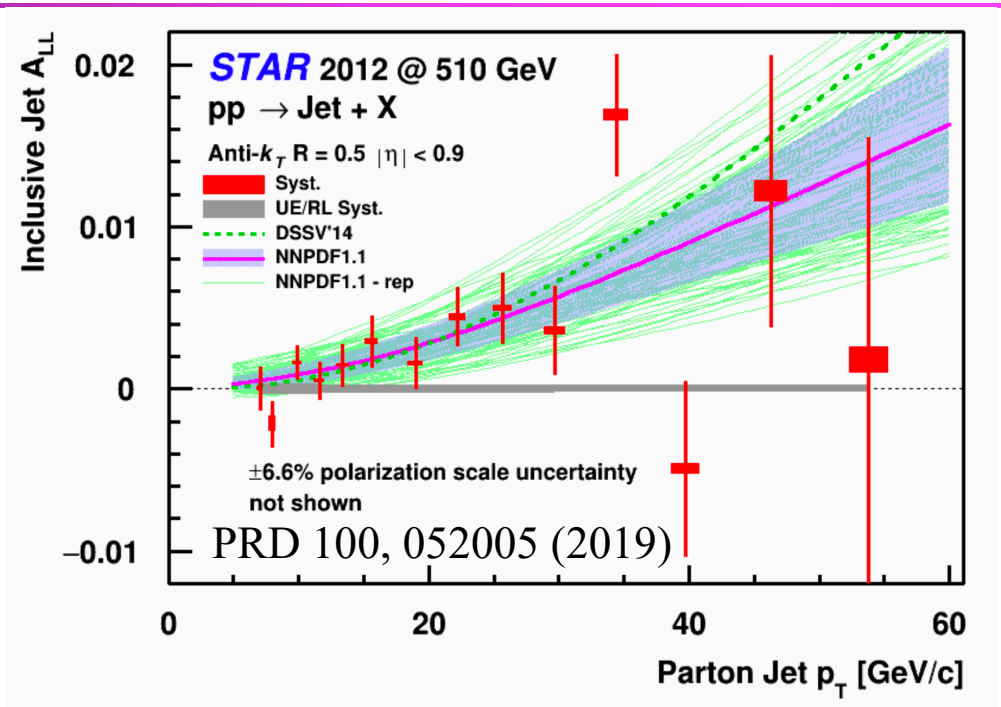
- With input from PHENIX π^0's and STAR 2009 jets
- Integral of $\Delta g(x)$ in range $0.05 < x < 1.0$ increases substantially, now significantly above zero.
- Uncertainty shrinks substantially from DSSV* to new DSSV14 fit
- Uncertainty on integral over low *x* region is still sizable

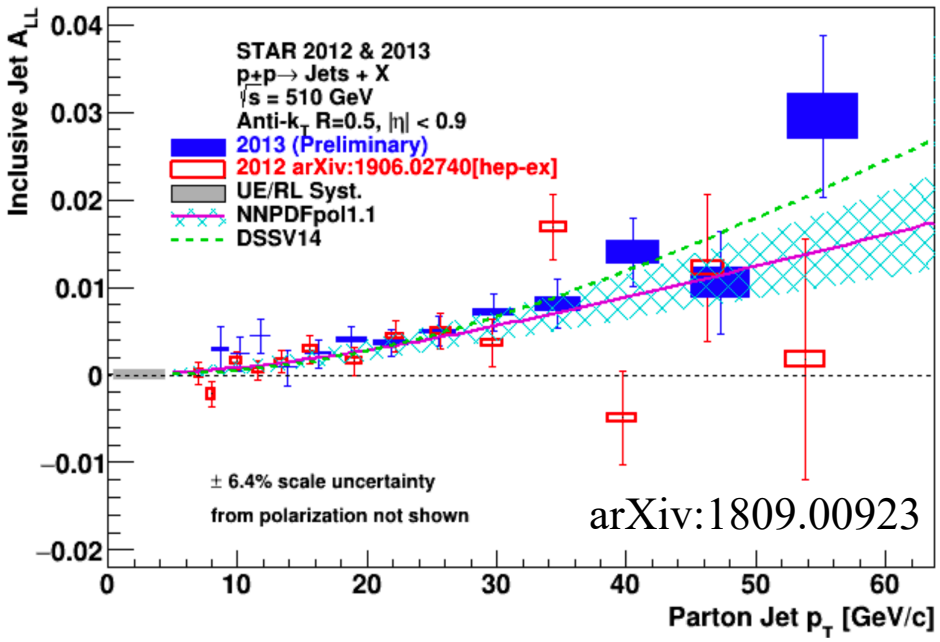
[See also NNPDFpol1.1 fit Nucl. Phys. B887 (2014) 276-308]

Strategy for probing lower *x* gluons

- Larger datasets: reduce our statistical uncertainty
  - 2006 6.8 pb^{-1} longitudinally polarized data collected at STAR, 2009 25 pb^{-1}, 2012 82 pb^{-1}, 2013 300 pb^{-1}, 2015 52 pb^{-1}
- Higher Center-of-Mass Energy
  - For similar p_T reconstructed particles, naturally probe lower *x* partons
  - 2006, 2009, and 2015 200 GeV CoM
  - 2012 and 2013 510 GeV CoM
- Forward detectors
  - Collisions with low *x* gluon, high *x* quark send particles to forward detectors
  - Jets at STAR historically mid-rapidity – lately pushing jets further forward
  - Use π^0s where we have EM calorimetry, but no tracking for jets
- Also, aim to use STAR detector comprehensively
  - Make measurements with all subsystems

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 (~60% shown)
  - Smaller cone, R = 0.5 reduces effect of underlying event and pileup
  - **Fits that incorporated 2009 results continue to describe the data well**

- Also, additional 200 GeV data during 2015 will reduce A_{LL} uncertainties by a factor of ~1.6

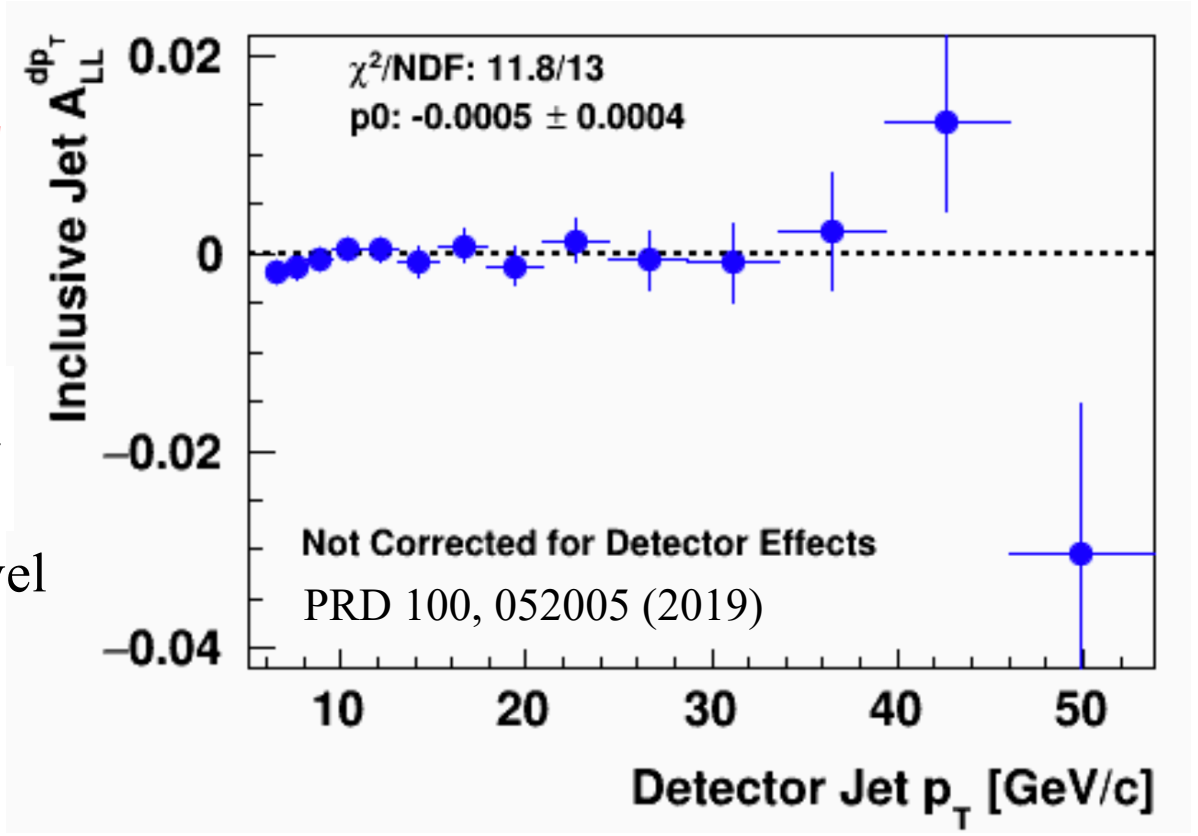
Spin Asymmetries in the Underlying Event?

- 2012 Inclusive Jet Analysis innovations include
  - Extensive Data-MC Comparisons
  - Modified Pythia Perugia 2012 tune to reproduce STAR charged π cross sections
  - Jet-by-jet underlying event subtraction
- Systematic uncertainty considerably reduced from 2009 measurement

- **First ever measurement of A_{LL} for underlying event**
- Define underlying event correction dp_T asymmetry:

$$A_{LL}^{dpT} = \frac{1}{P_A P_B} \frac{< dp_T >^{++} - < dp_T >^{+-}}{< dp_T >^{++} + < dp_T >^{+-}}$$

- Consistent with zero at ~10^{-4} level

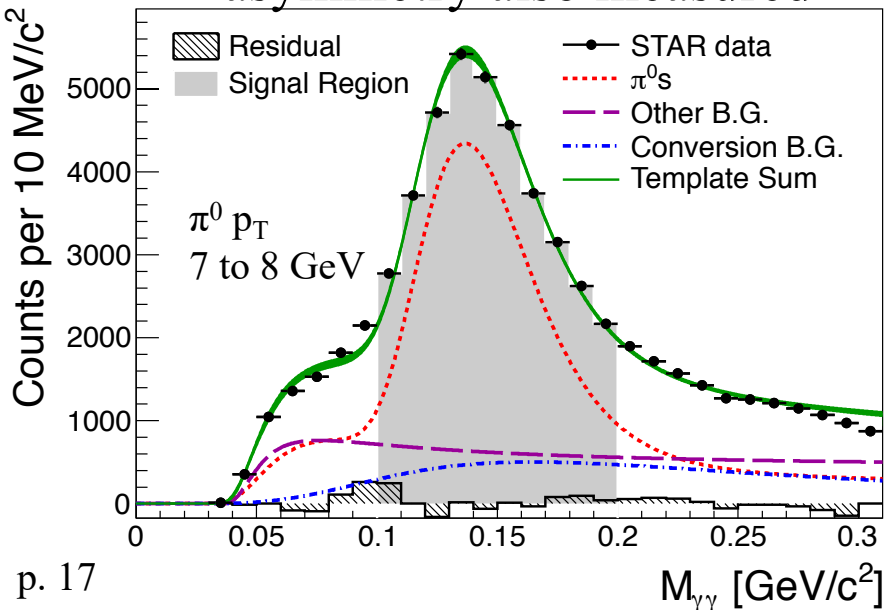


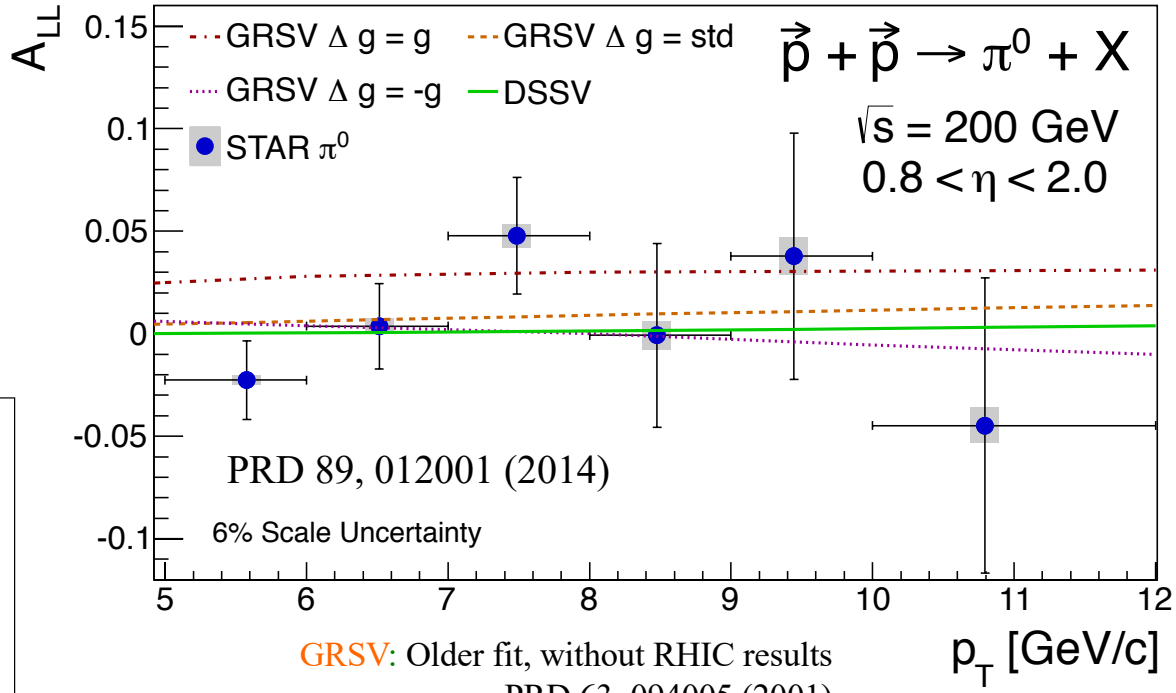
Constraining the Gluon Polarization Distribution with Jet, Dijet, and Neutral Pion Probes at STAR

- 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 Forward Upgrade

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

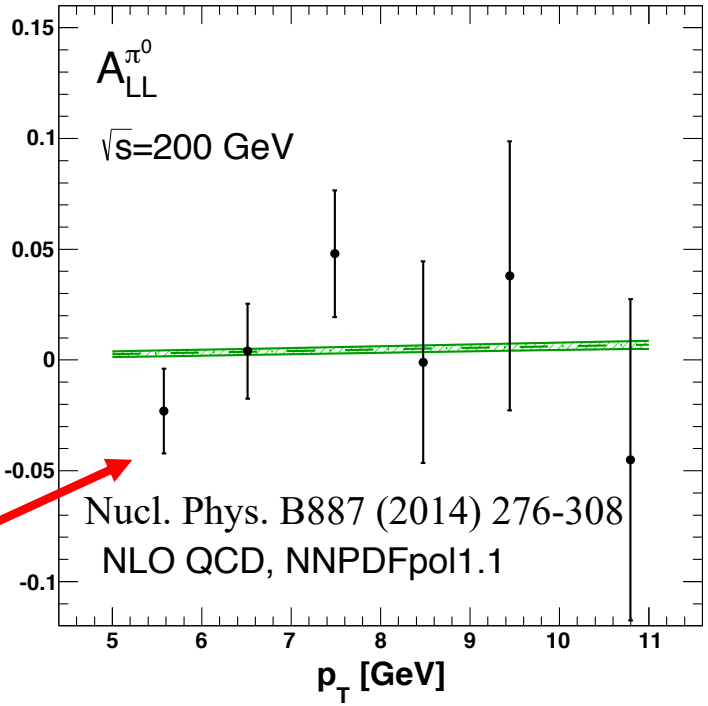




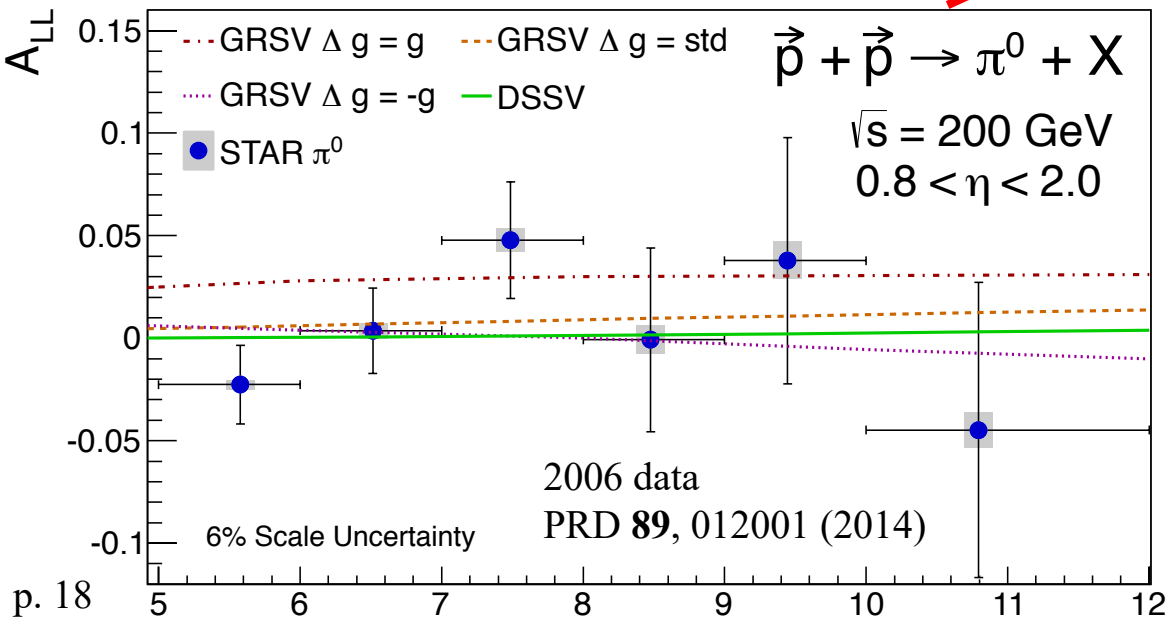
GRSV: Older fit, without RHIC results
PRD 63, 094005 (2001)
DSSV: First fit to include RHIC results
PRL 101, 072001 (2008)

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



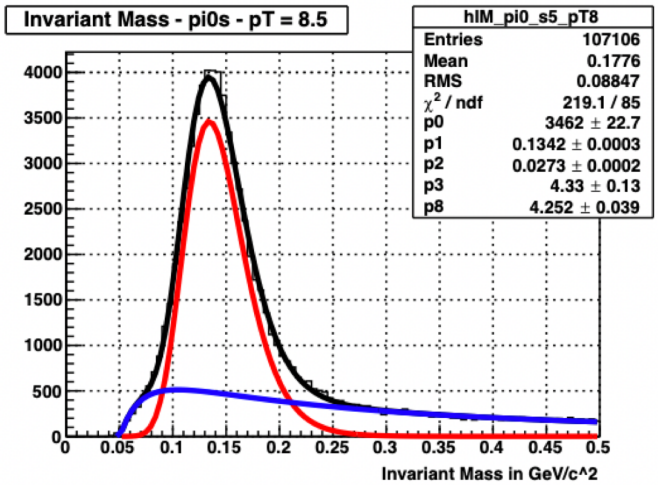
STAR data with NNPDF predictions



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

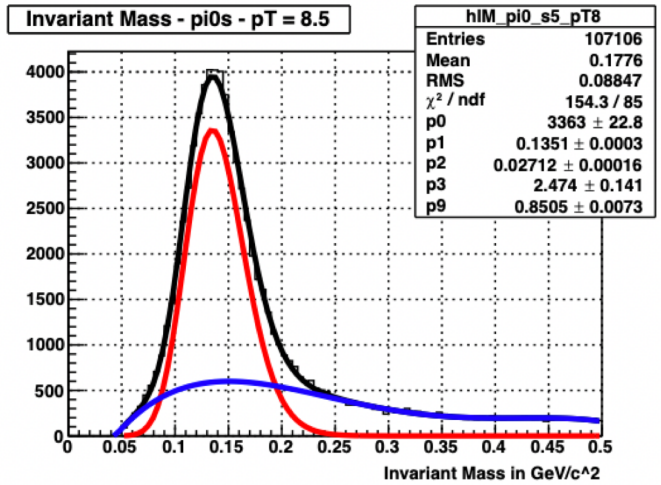
A_{LL} in Endcap π^0s with Larger Dataset

- 2012 dataset being analyzed now
  - x10 the 2006 statistics; ~80 pb^{-1}, ~50% polarization
  - 510 GeV CoM energy w/ similar trigger and reconstruction thresholds allows access to **lower *x* gluons**
- Pursuing a data-driven background model; skewed Gaussian for signal
  - Several background models considered; comparable quality
  - Chebyshev polynomial current default



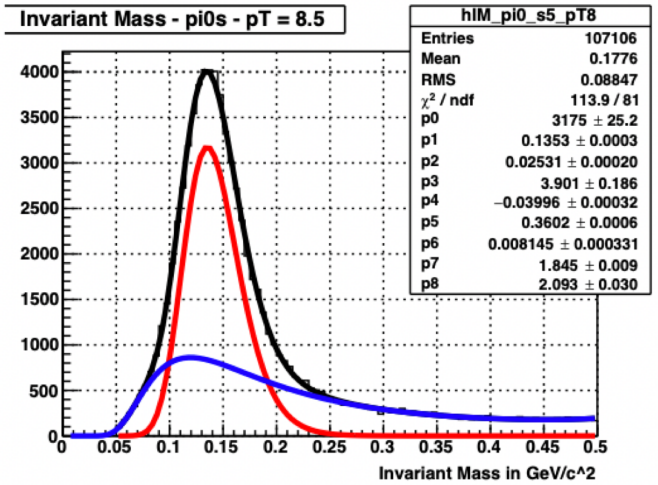
Polynomial in 1/x

$$B = c_1 + \frac{c_2}{x} + \frac{c_3}{x^2} + \frac{c_4}{x^3}$$



Chebyshev polynomials

$B=c_0+c_1(x)+c_2(2x^2-1)+c_3(4x^3-3x)+c_4(8x^4-8x^2+1)$

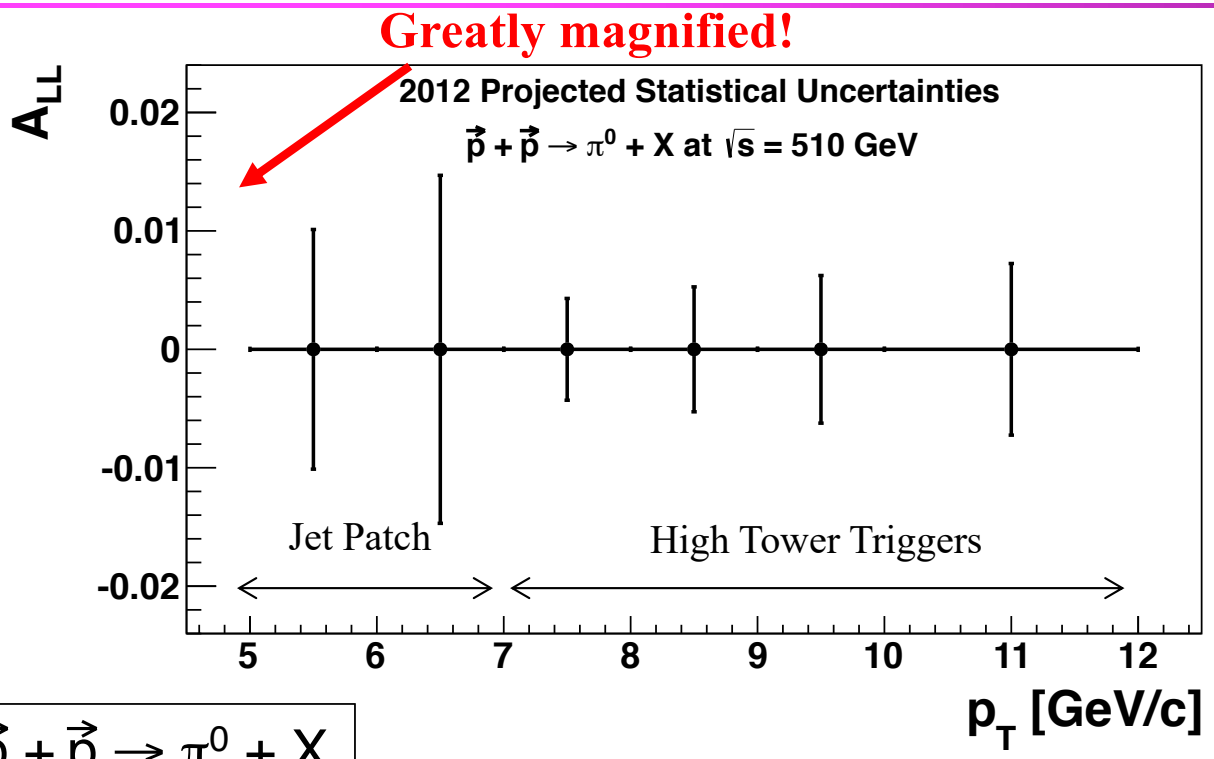


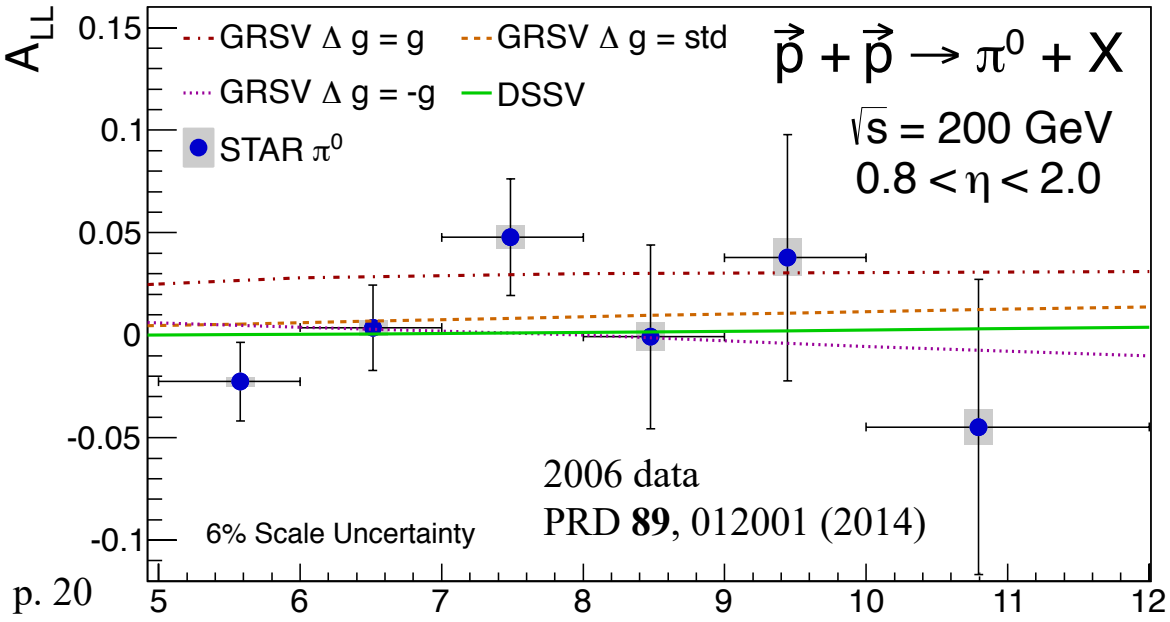
Planck function

$$B = \frac{1}{(x - c_1)^5 \left(exp\left(\frac{c_2}{x - c_3}\right) - c_4\right)}$$

π^0 A_{LL} Prospects in 2012 Dataset

- Not ready to show 2012 A_{LL} yet, but can show projections
  - HT trigger above 7 GeV
  - JetPatch trigger 5-7 GeV
- Our 2012 analysis focuses on High Tower (HT) triggers, for now





- Large improvement in stat. uncertainty projected, as shown
- And ~4 times the statistics available in 2013!

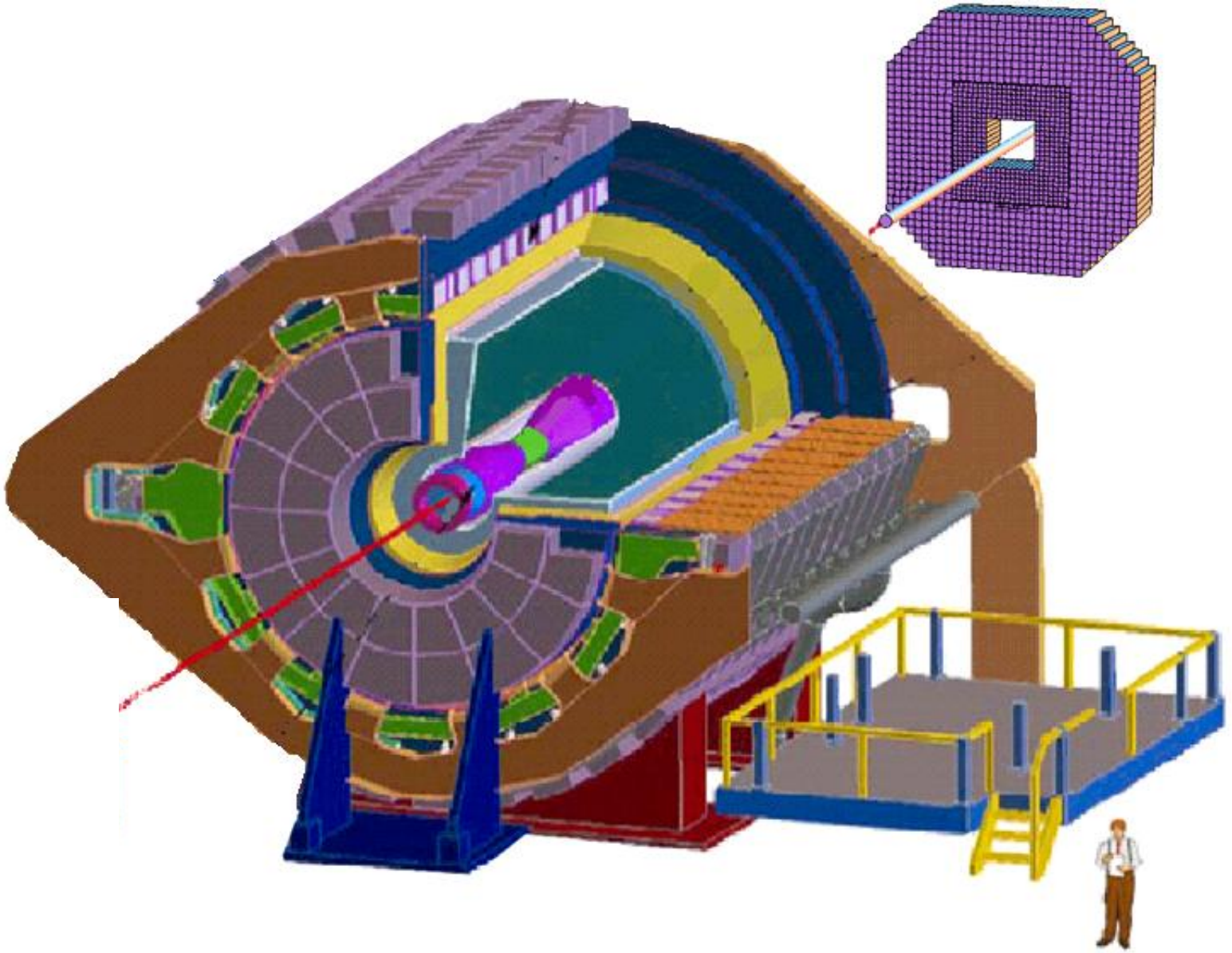
FMS

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

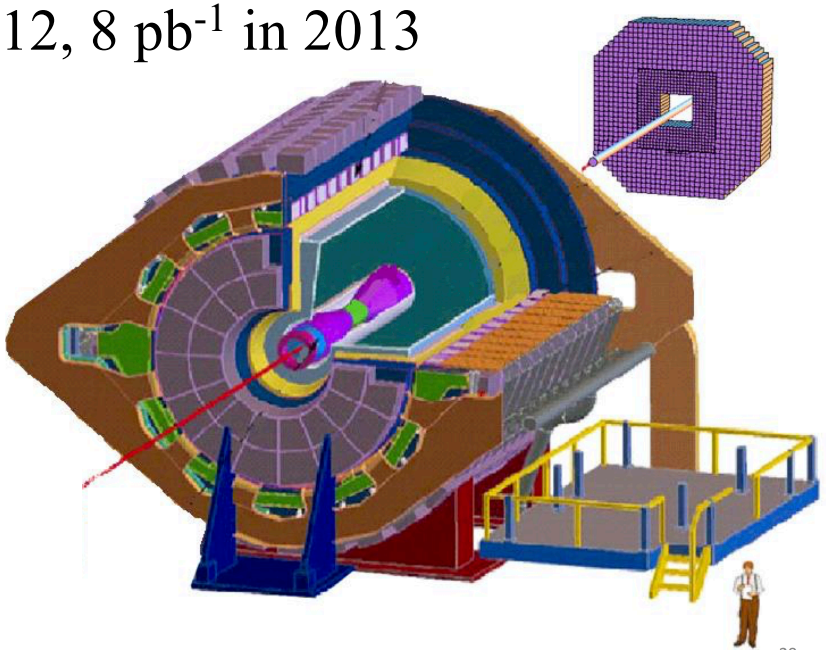


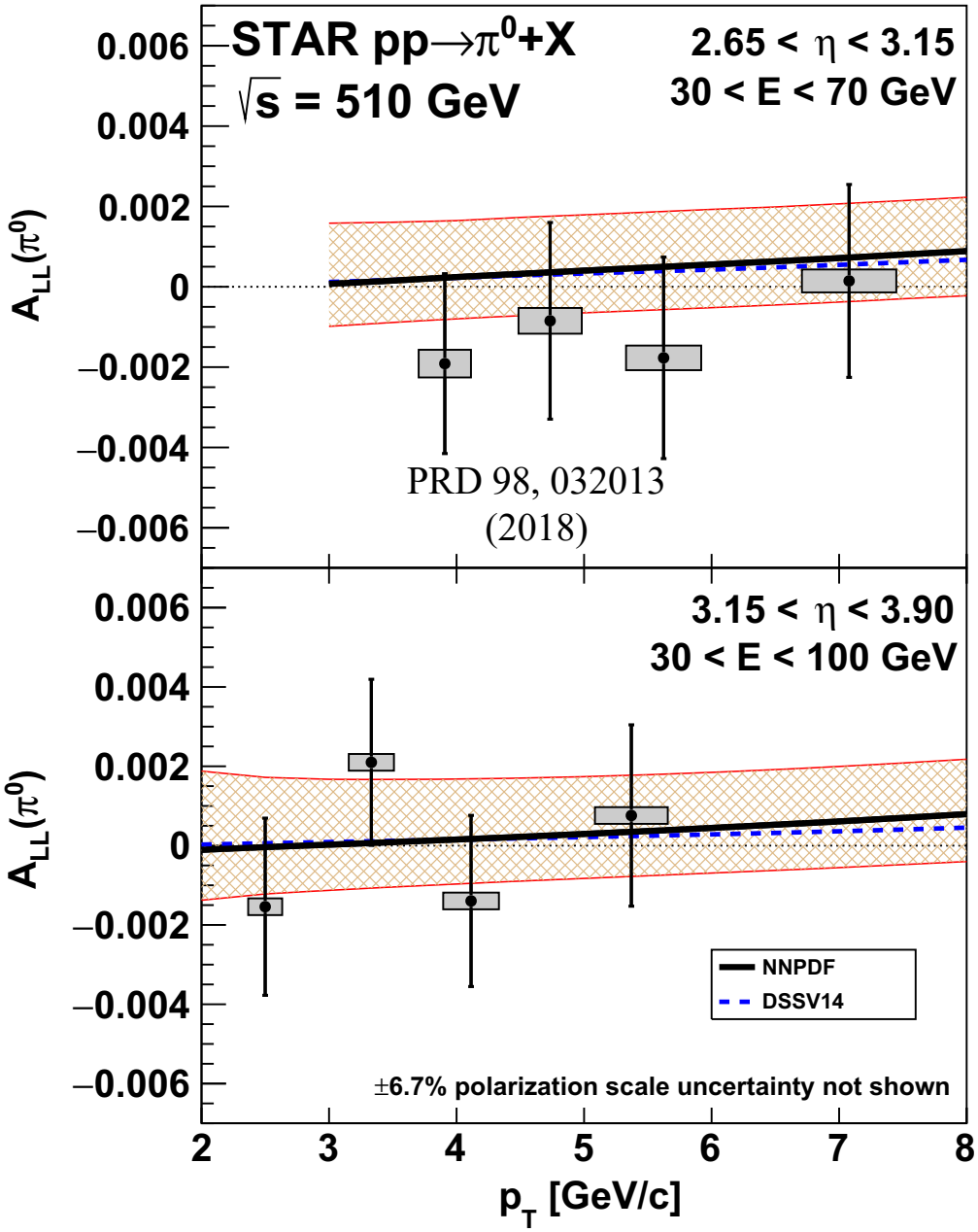
Forward EM Calorimetry In STAR.

π^0 A_{LL} in Forward Calorimeters: FMS

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

- qg scattering dominates at high η with high *x* quarks and low *x* gluons
- Highest η calorimeter at STAR recently is lead-glass Forward Meson Spectrometer (FMS)
- After prescales, effectively 46 pb^{-1} in 2012, 8 pb^{-1} in 2013

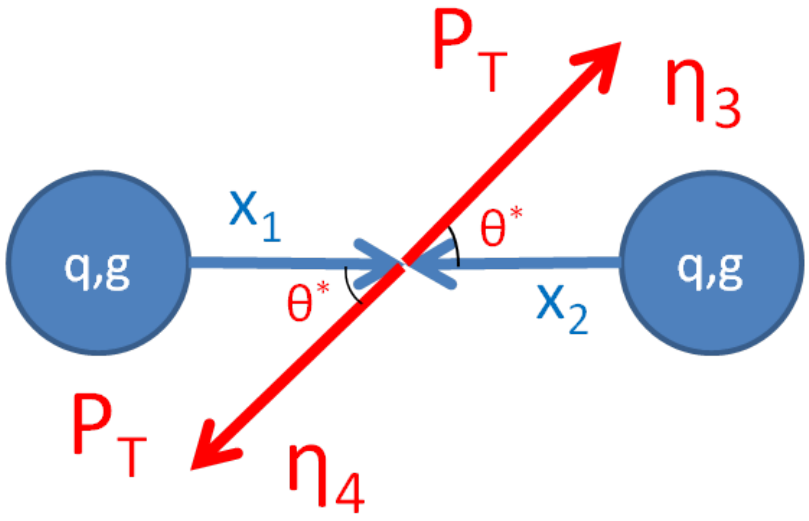




Constraining the Gluon Polarization Distribution with Jet, Dijet, and Neutral Pion Probes at STAR

- 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 Forward Upgrade

Dijet Measurements



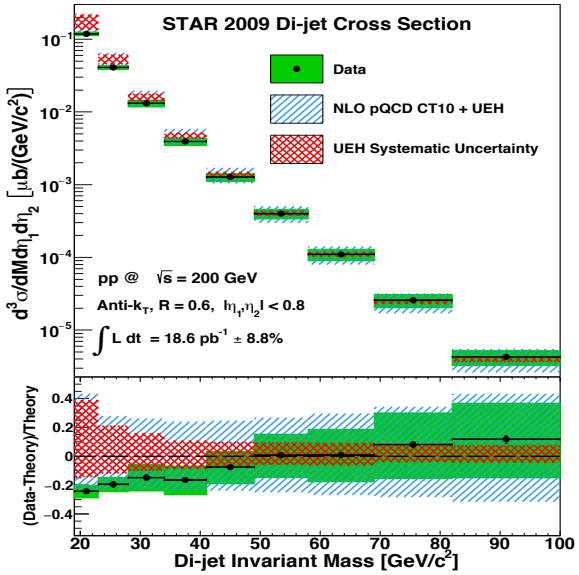
$$x_1 = \frac{1}{\sqrt{s}}\left(p_{T3}e^{\eta_3} + p_{T4}e^{\eta_4}\right)$$

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

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

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

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

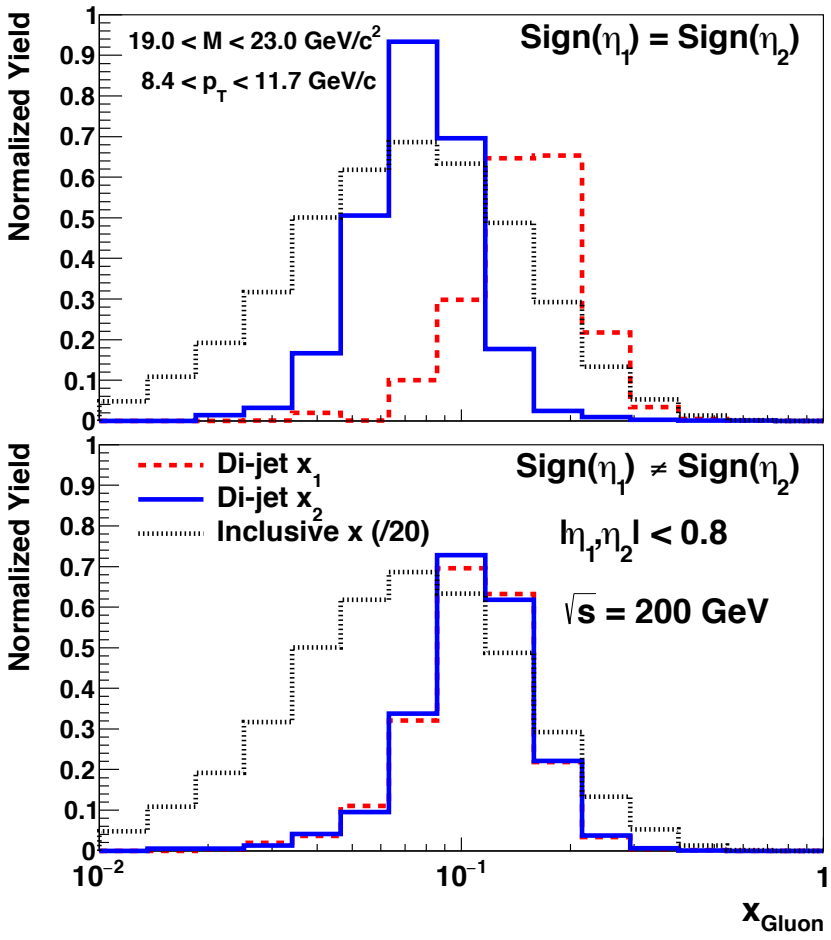


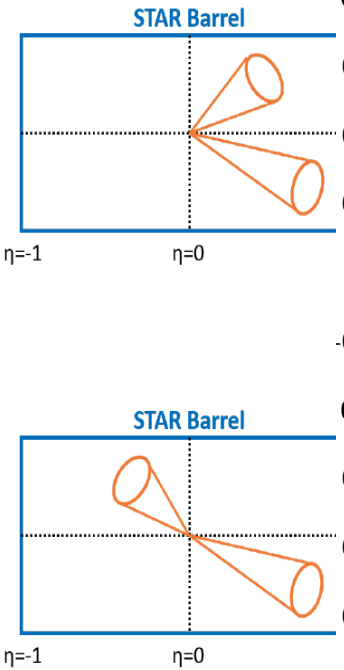
Phys. Rev. D 95, 071103(R) (2017)

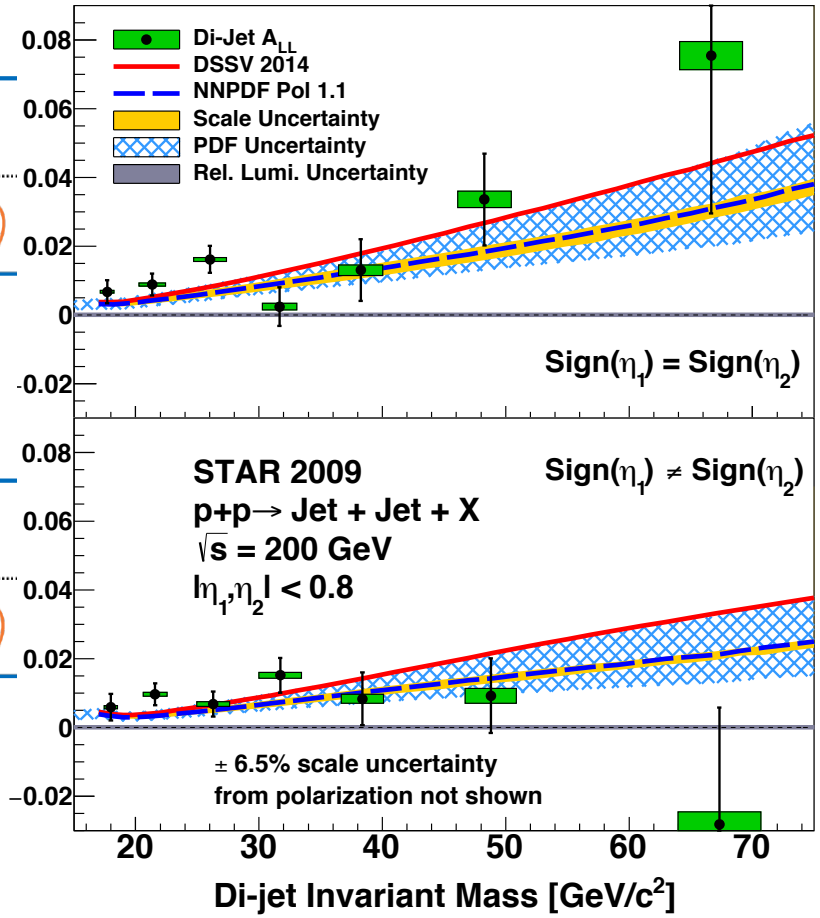
- Inclusive measurements have been the workhorse of STAR Δg program to date
  - Broad *x* range sampled in each p_T bin
- Dijet or other correlation measurements which reconstruct the full final state are sensitive to initial kinematics at leading order
  - Prospect of mapping out the shape of Δg(*x*)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





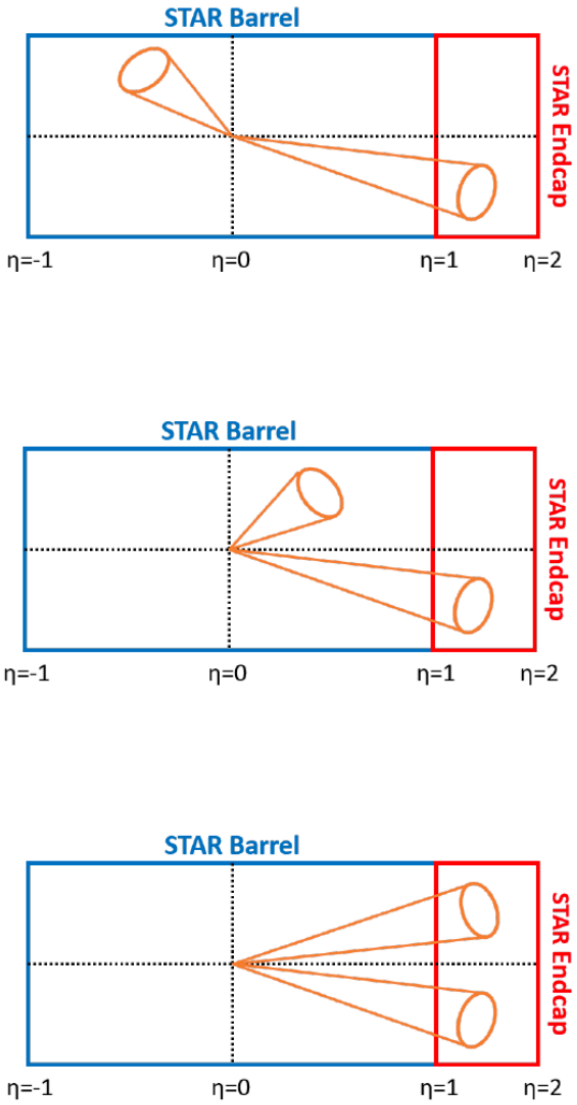


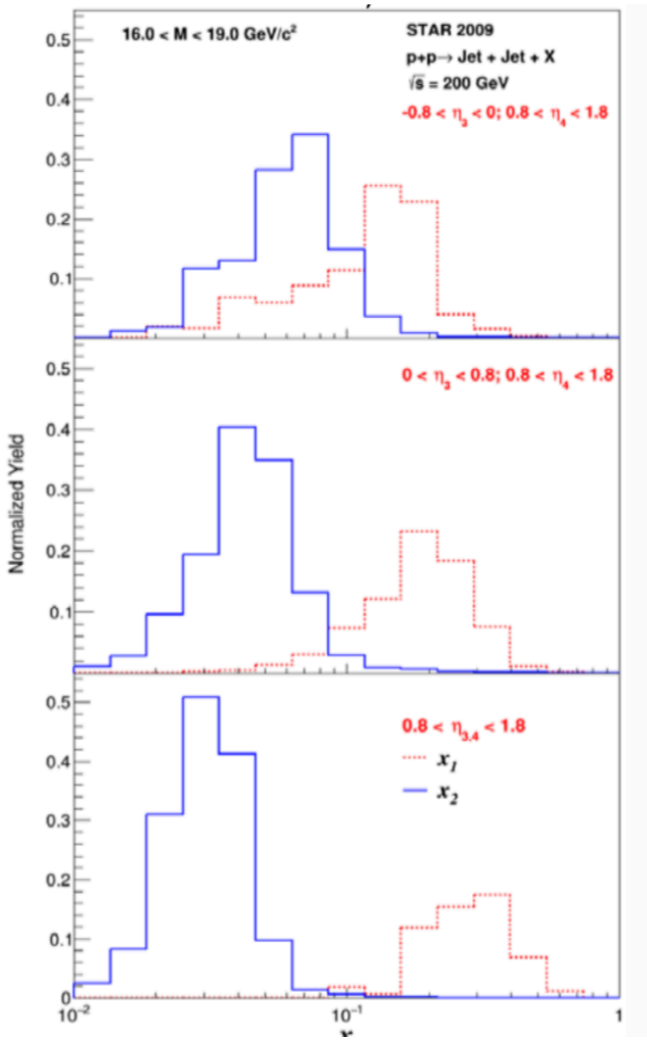
- Dijets probe a much narrower range of x_g than inclusive jets
- Asymmetries consistent with predictions from global fits, albeit this is a ~subset of the dataset used to extract polarized PDF's

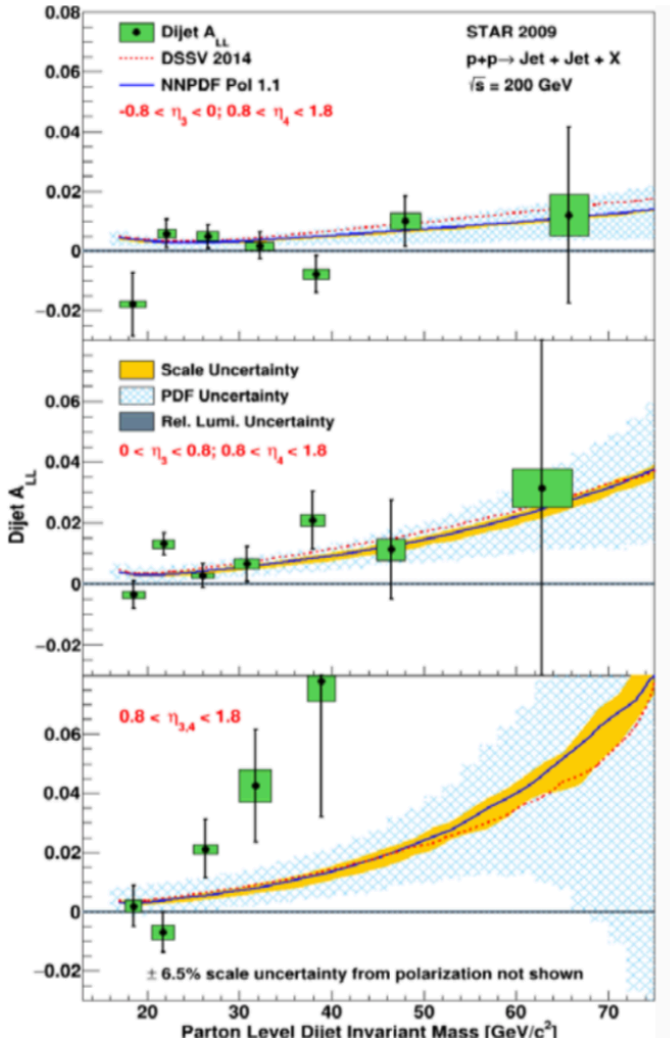
2009 Dijets into the Endcap

- As with π^0's, pushing to forward rapidity (here to $\eta < 1.8$) probes lower x

Phys. Rev. D 98, 032011 (2018)







Dijet Impact On Latest Global Fit

- STAR 2009 Inclusive Jets already included in DSSV-**14**
- A new global fit, with a MC reweighting technique, also incorporates all STAR 2009 dijet results; thus, only 200 GeV data included thus far
- Uncertainty remains large at low x

Before reweighting:

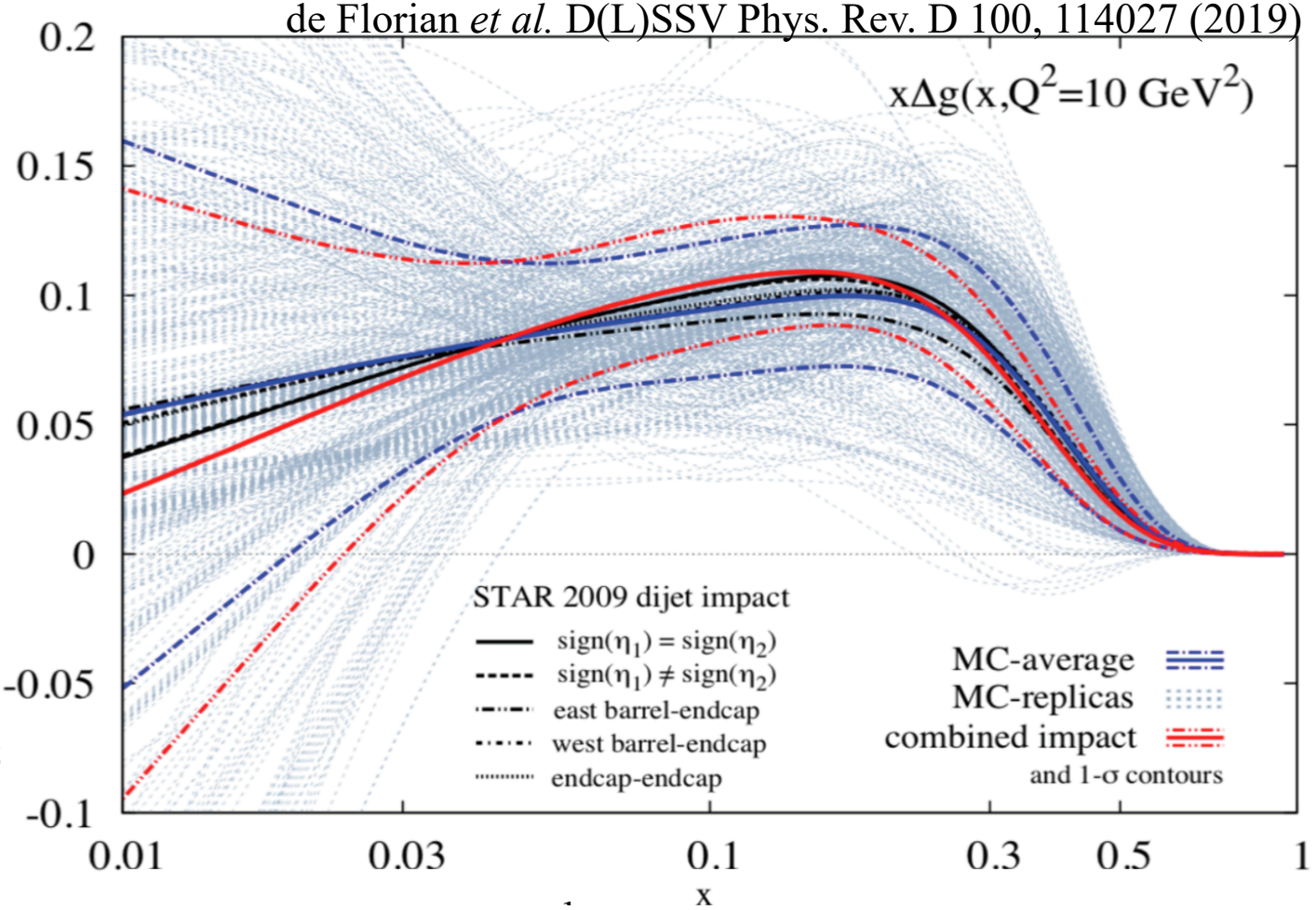
$\int_{0.1}^{1} \Delta g(x)dx = 0.133 \pm 0.035$

After reweighting:

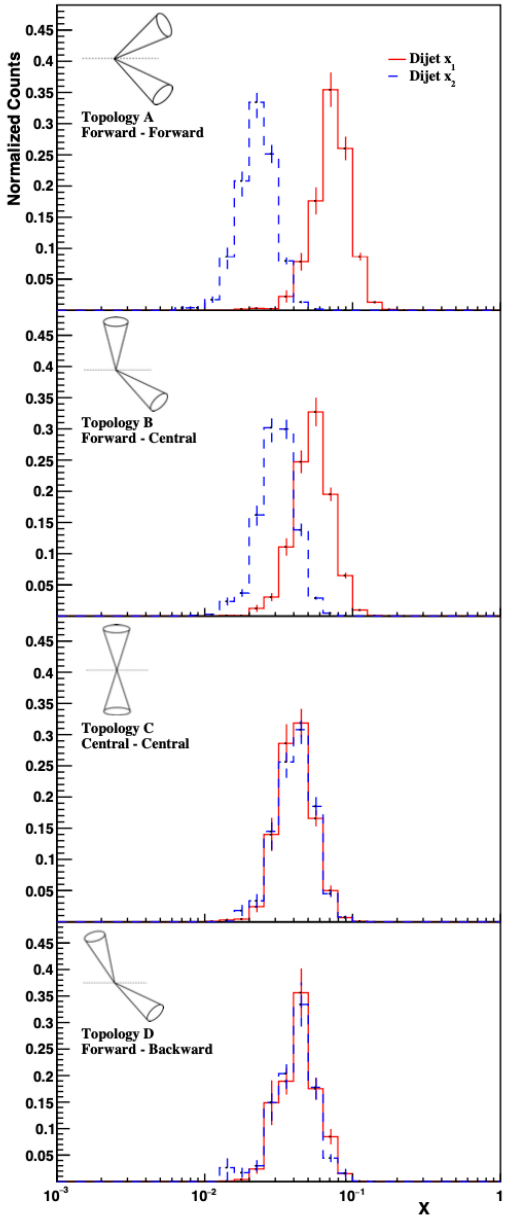
$\int_{0.1}^{1} \Delta g(x)dx = 0.126 \pm 0.023$

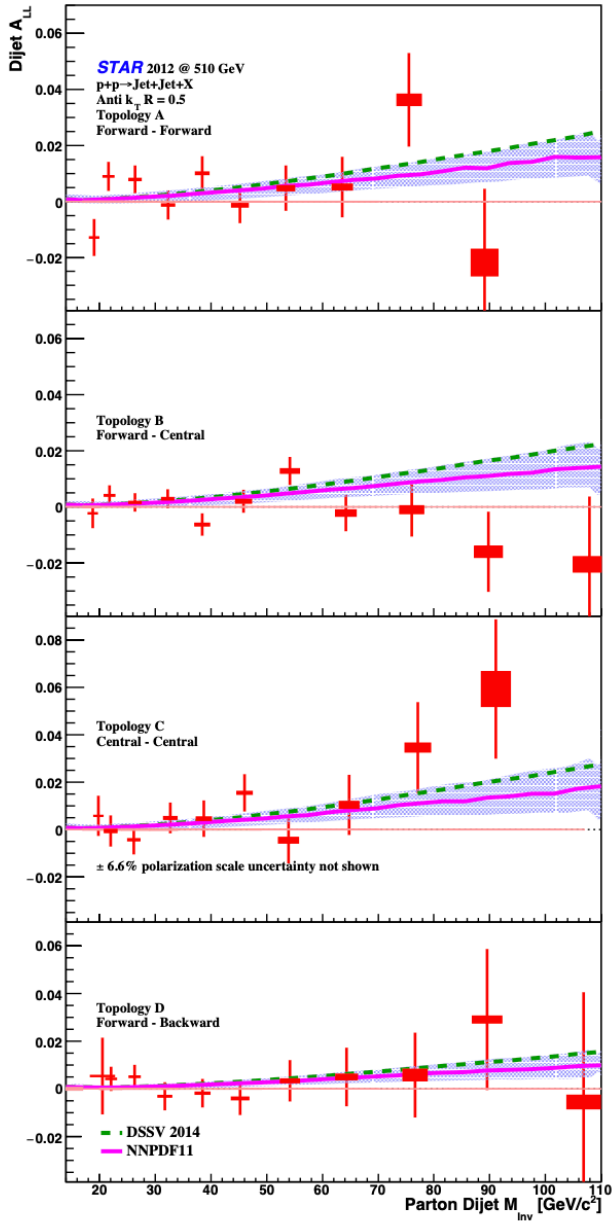
$\int_{0.01}^{1} \Delta g(x)dx = 0.296 \pm 0.108$

de Florian *et al.* D(L)SSV Phys. Rev. D 100, 114027 (2019)



Dijets at $\sqrt{s}$= 510 GeV





- Dijets at $\sqrt{s}$= 510 GeV from 2012 recently published PRD 100, 052005 (2019)
- Four η topologies narrow the sampled *x* ranges

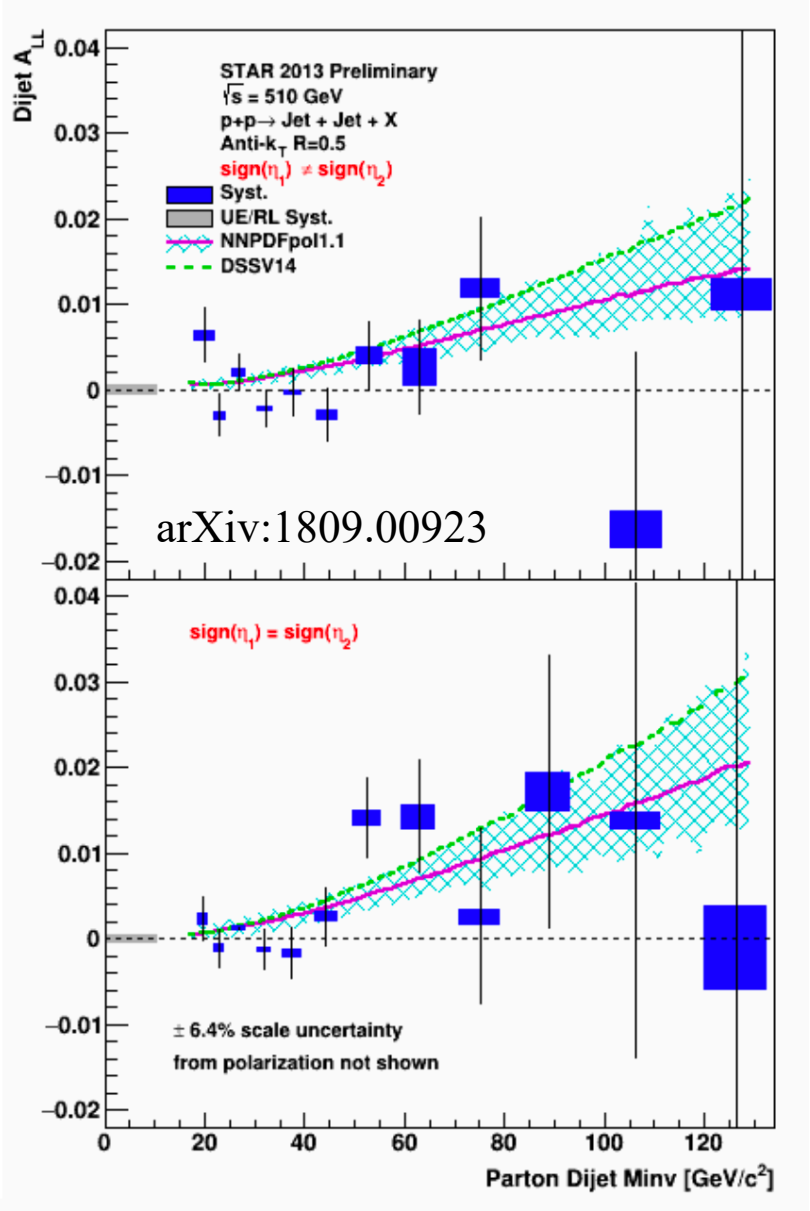
A/Forward-Forward:
$0.3 < |\eta_{3,4}| < 0.9$
$\eta_3 \cdot \eta_4 > 0$
B/Forward-Central:
$|\eta_{3,4}| < 0.3$
$0.3 < |\eta_{4,3}| < 0.9$
C/Central-Central:
$|\eta_{3,4}| < 0.3$
D/Forward-Backward:
$0.3 < |\eta_{3,4}| < 0.9$
$\eta_3 \cdot \eta_4 < 0$

More Dijets at $\sqrt{s}$ = 510 GeV

- Study of large 2013 dataset well advanced
  - ~60% incorporated so far
- Here A_{LL} shown for two topologies
- Final systematic studies are underway

- Studies of endcap dijets ($\eta > 0.9$) at $\sqrt{s}$ = 510 GeV are also underway

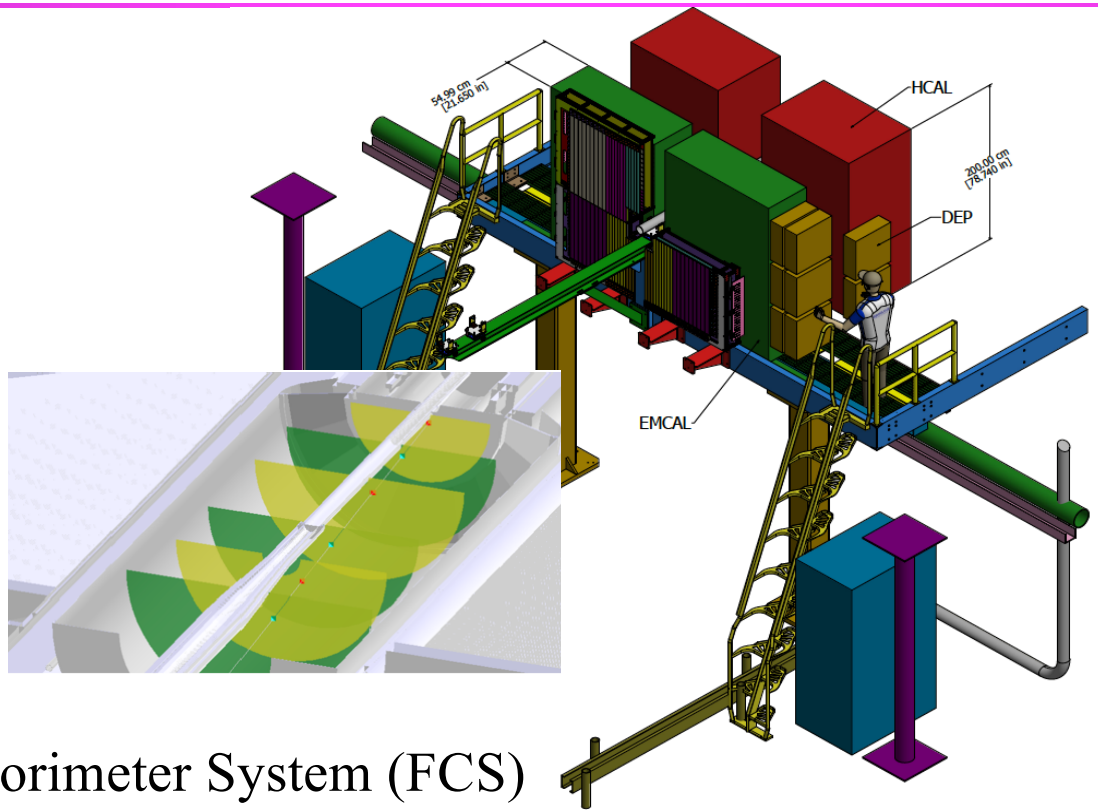
- Probe lower x_g with dijets by moving to forward rapidities and higher CoM energy
  - Reaching $x \sim 0.015$ now
  - Can push below $x = 0.01$ with additional data already recorded
  - And to $x \sim 10^{-3}$ in a few years with a forward upgrade



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 Forward Upgrade

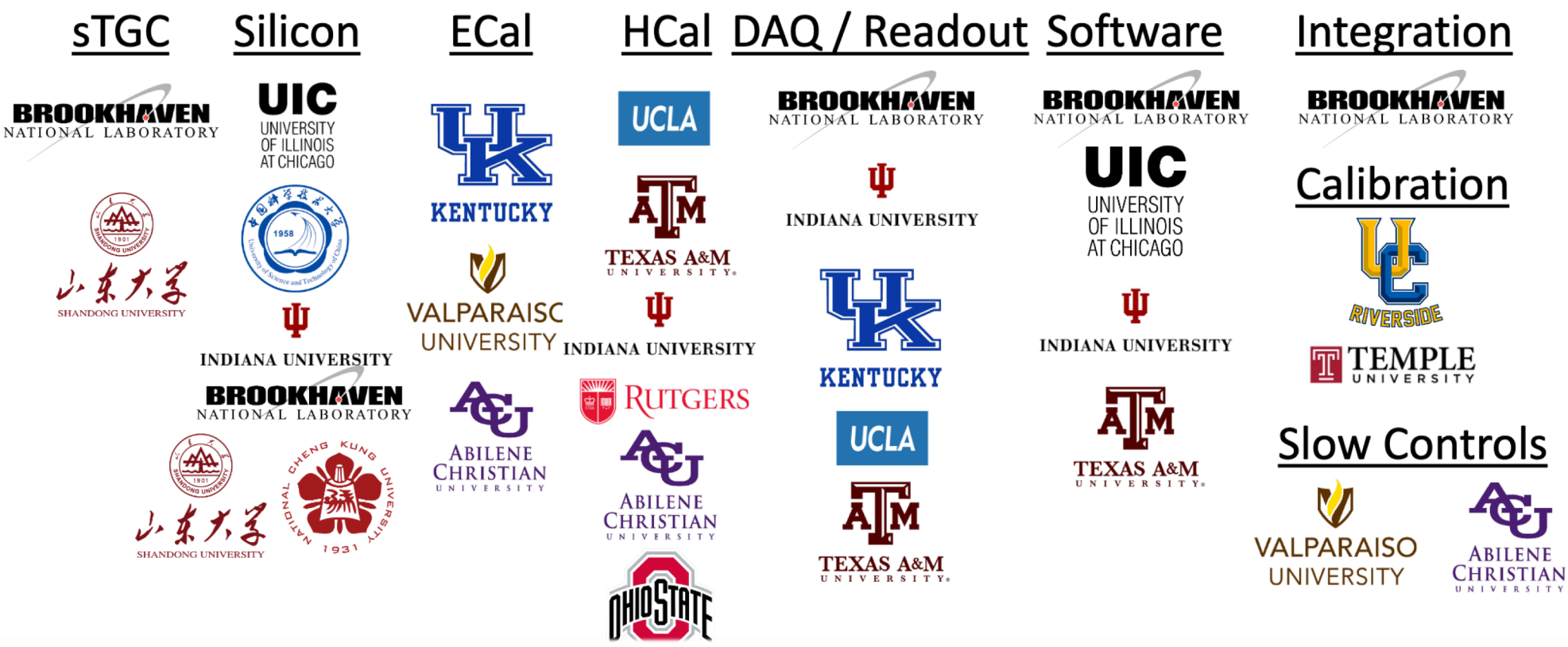
STAR Forward Upgrade for the 2020's



- Forward Calorimeter System (FCS)
  - Refurbish a portion of the PHENIX ECal, new Fe-scintillator HCal
  - Forward di-jets will extend gluon polarization to x <~ 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

Institutional Support for STAR Forward Upgrade

- Broad Range of Institutional Interest and Support

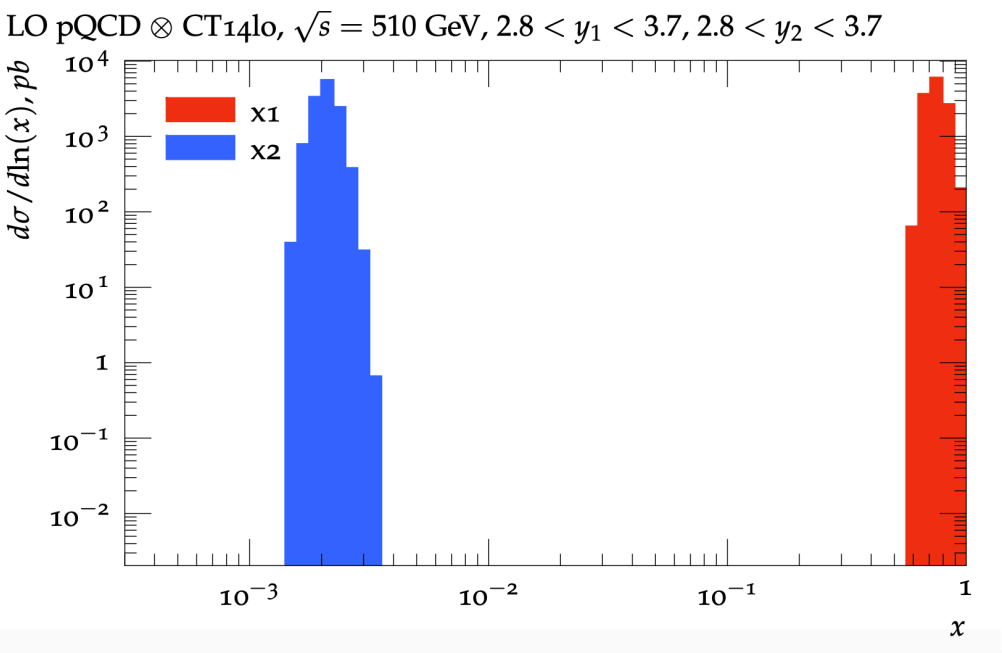


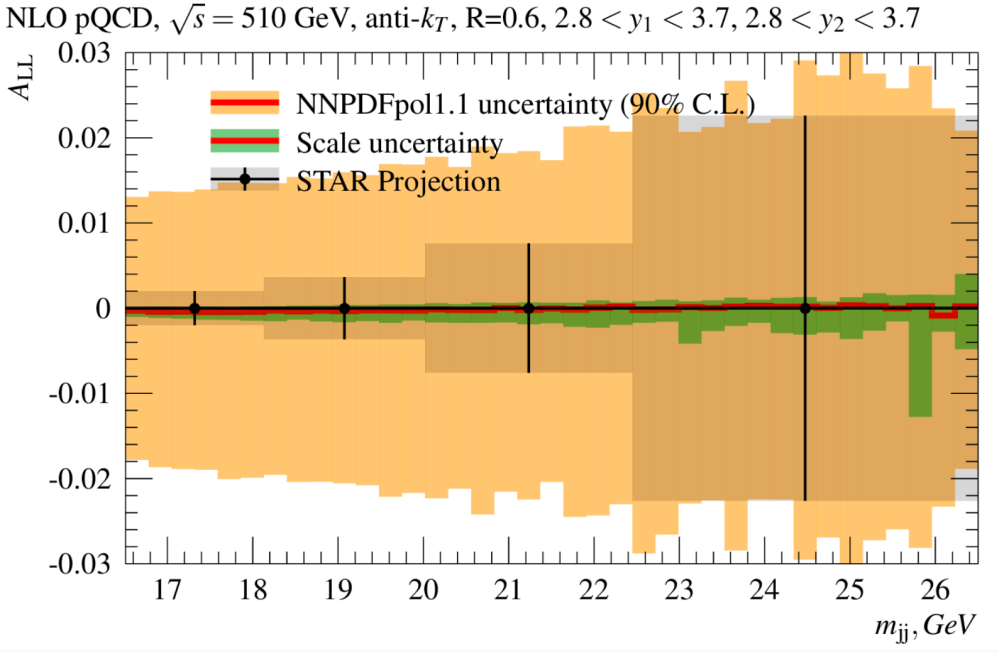
- Fully approved and funded, on track for first 500 GeV polarized pp data taking in Fall 2021

Forward Dijets with STAR Upgrade

- EM calorimeter: 18 X_0 PbSc, resolution $\sim 10\%/\sqrt{E}$
- Hadronic calorimeter: 4.5 λ FeSc, resolution $\sim 60\%/\sqrt{E}$
- Dijet A_{LL} with one or both jets in the forward ($2.8 < \eta < 3.7$) region
  - Probe $x_g \sim 10^{-3}$
- An attractive low x probe before the EIC era

RHIC Cold QCD Plan
arXiv:1602.03922



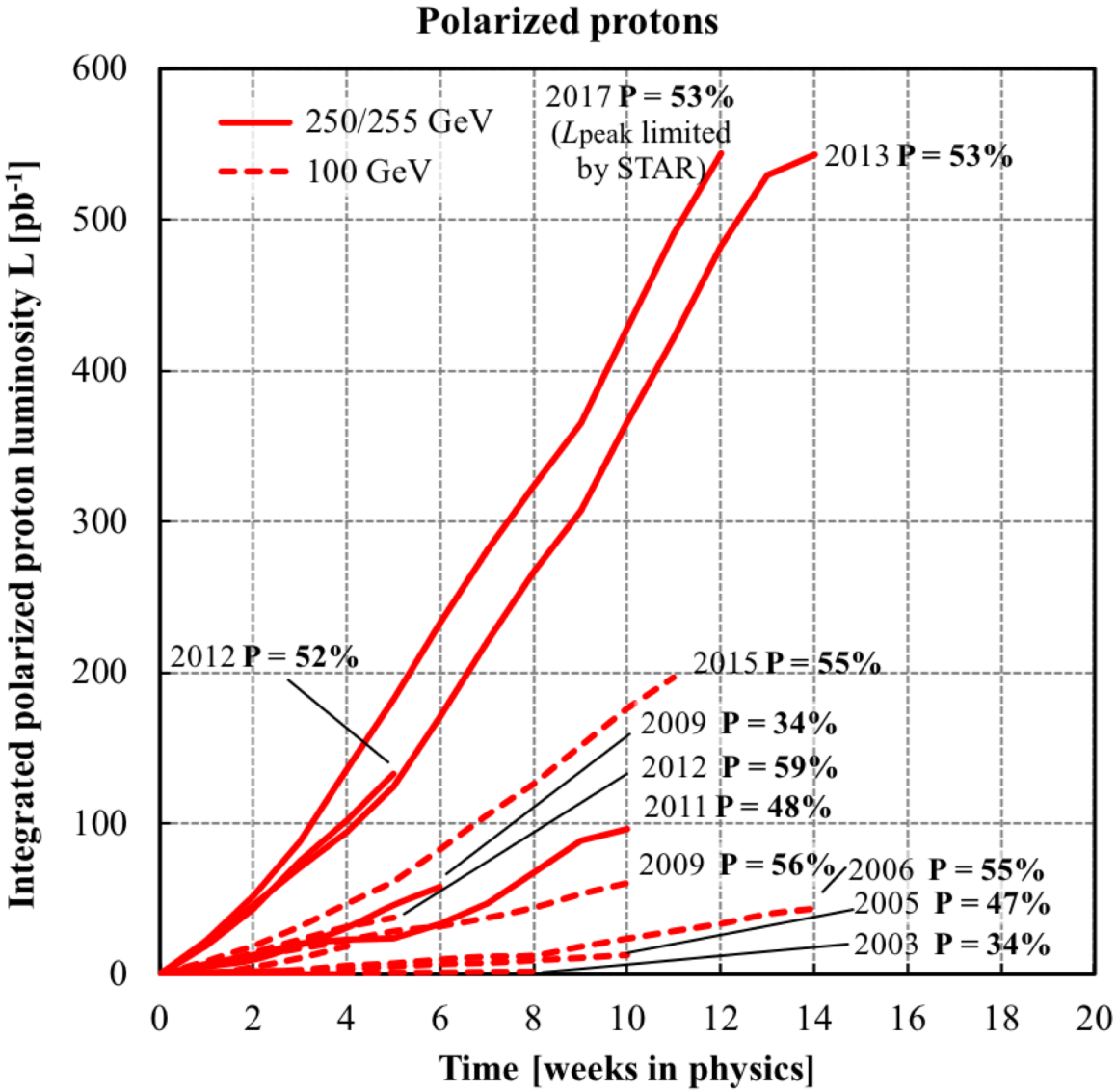


Constraining the Gluon Polarization Distribution with Jet, Dijet, and Neutral Pion Probes at STAR

- After 30 years, **significant gluon polarization** in the proton
  - Inclusive jets at STAR have played a major role
  - **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 dijets
- STAR Forward Upgrade under way
  - Polarized pp run in 2021/22… activity planned through 2024 and EIC
  - Forward dijets will probe $\Delta g(x)$ to $x \sim 10^{-3}$
- **Large datasets being analyzed, upgrades underway, new data taking planned; stay tuned!**

Backup

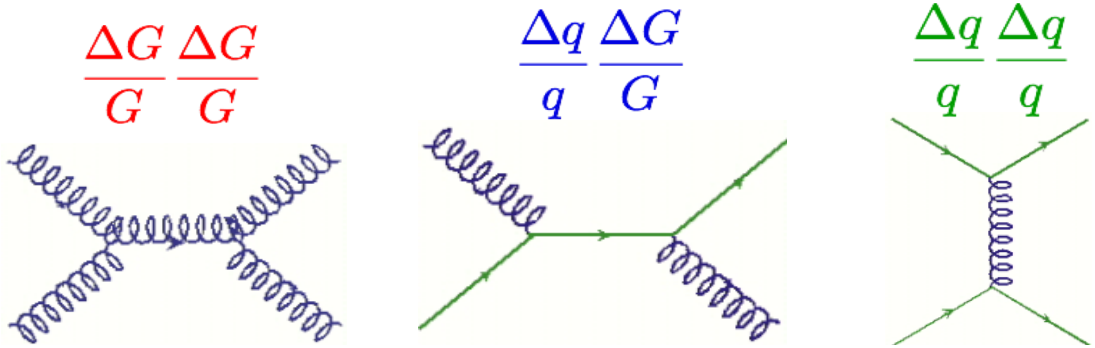
RHIC Luminosity

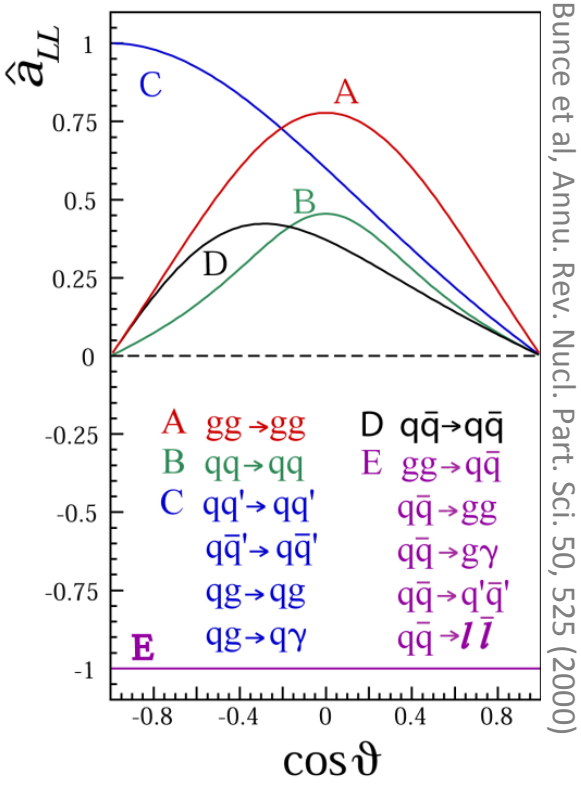


Probing (Gluon) Polarized PDF's With Jets

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

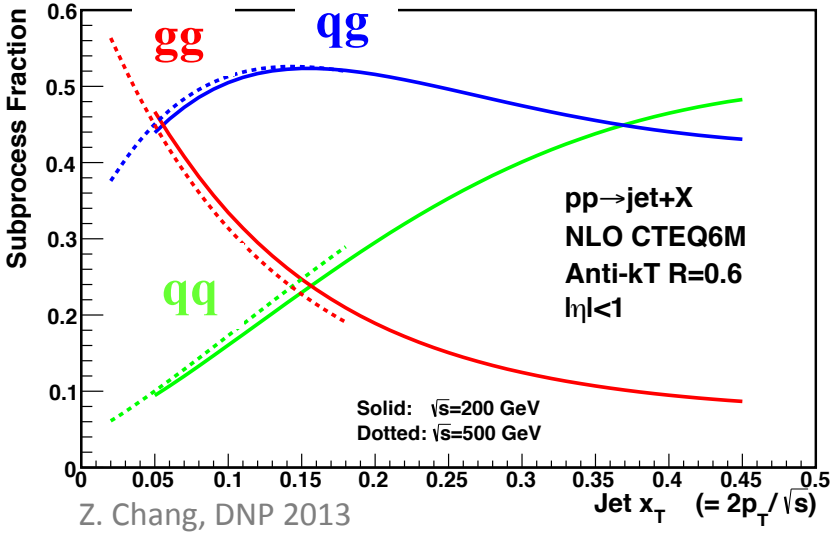
A_{LL} for, e.g. jets, sensitive to ***polarized PDF's*** (Δf) and ***partonic asymmetry***, $\hat{a}_{LL}$



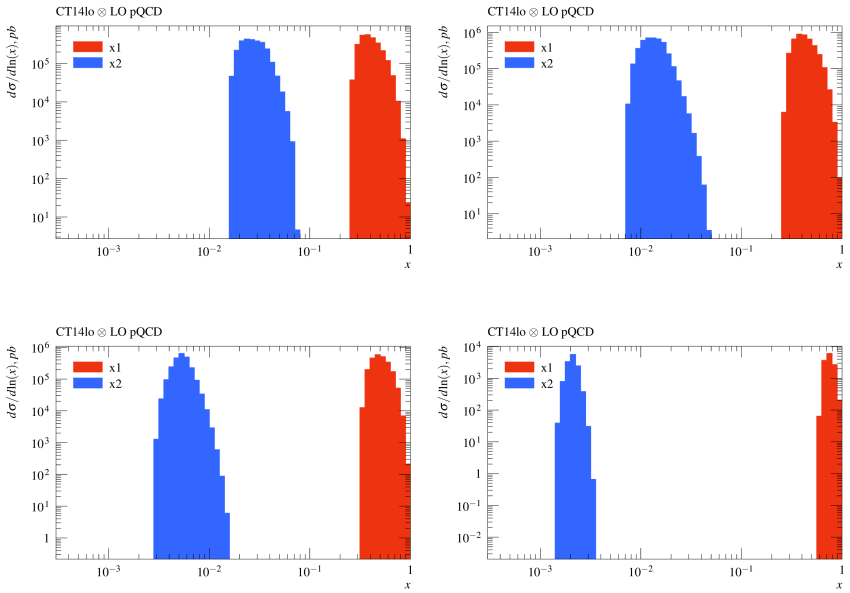


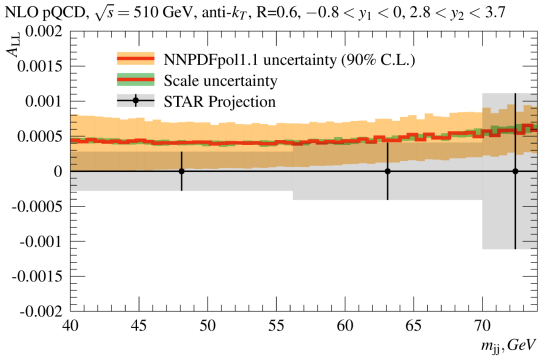
Asymmetries at different values of p_T or $\sqrt{s}$

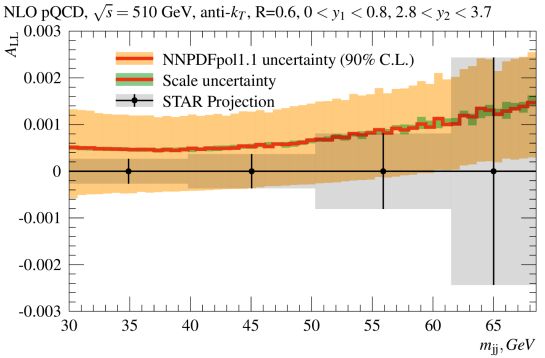
→ ***sample different mix of partonic subprocesses***

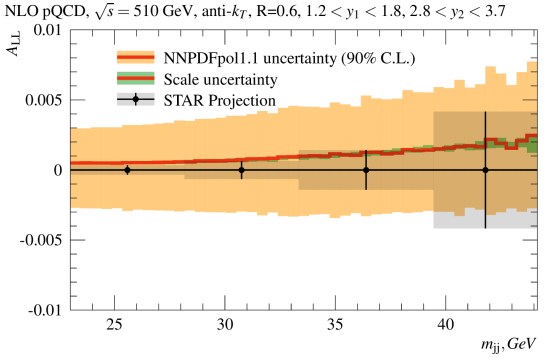


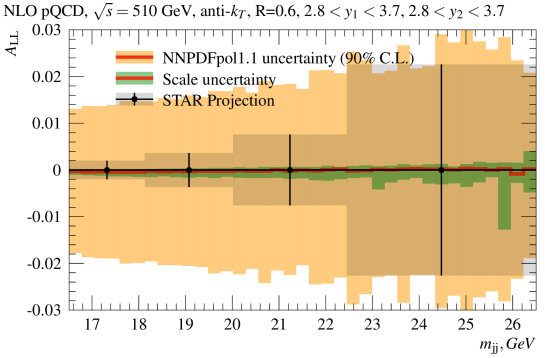
FCS dijets


CT14lo ⊗ LO pQCD
x1
x2
CT14lo ⊗ LO pQCD
x1
x2
CT14lo ⊗ LO pQCD
x1
x2
CT14lo ⊗ LO pQCD
x1
x2


NLO pQCD, $\sqrt{s} = 510$ GeV, anti-k_T, R=0.6, $-0.8 < y_1 < 0$, $2.8 < y_2 < 3.7$
A_{LL}
NNPDFpol1.1 uncertainty (90% C.L.)
Scale uncertainty
STAR Projection
m_{jj}, GeV


NLO pQCD, $\sqrt{s} = 510$ GeV, anti-k_T, R=0.6, $0 < y_1 < 0.8$, $2.8 < y_2 < 3.7$
A_{LL}
NNPDFpol1.1 uncertainty (90% C.L.)
Scale uncertainty
STAR Projection
m_{jj}, GeV


NLO pQCD, $\sqrt{s} = 510$ GeV, anti-k_T, R=0.6, $1.2 < y_1 < 1.8$, $2.8 < y_2 < 3.7$
A_{LL}
NNPDFpol1.1 uncertainty (90% C.L.)
Scale uncertainty
STAR Projection
m_{jj}, GeV


NLO pQCD, $\sqrt{s} = 510$ GeV, anti-k_T, R=0.6, $2.8 < y_1 < 3.7$, $2.8 < y_2 < 3.7$
A_{LL}
NNPDFpol1.1 uncertainty (90% C.L.)
Scale uncertainty
STAR Projection
m_{jj}, GeV