Understanding the Proton's Spin at STAR: Constraining the Gluon Polarization Distribution with Jet, Dijet, and Neutral Pion Probes

Adam Gibson
Valparaiso University
For the STAR Collaboration

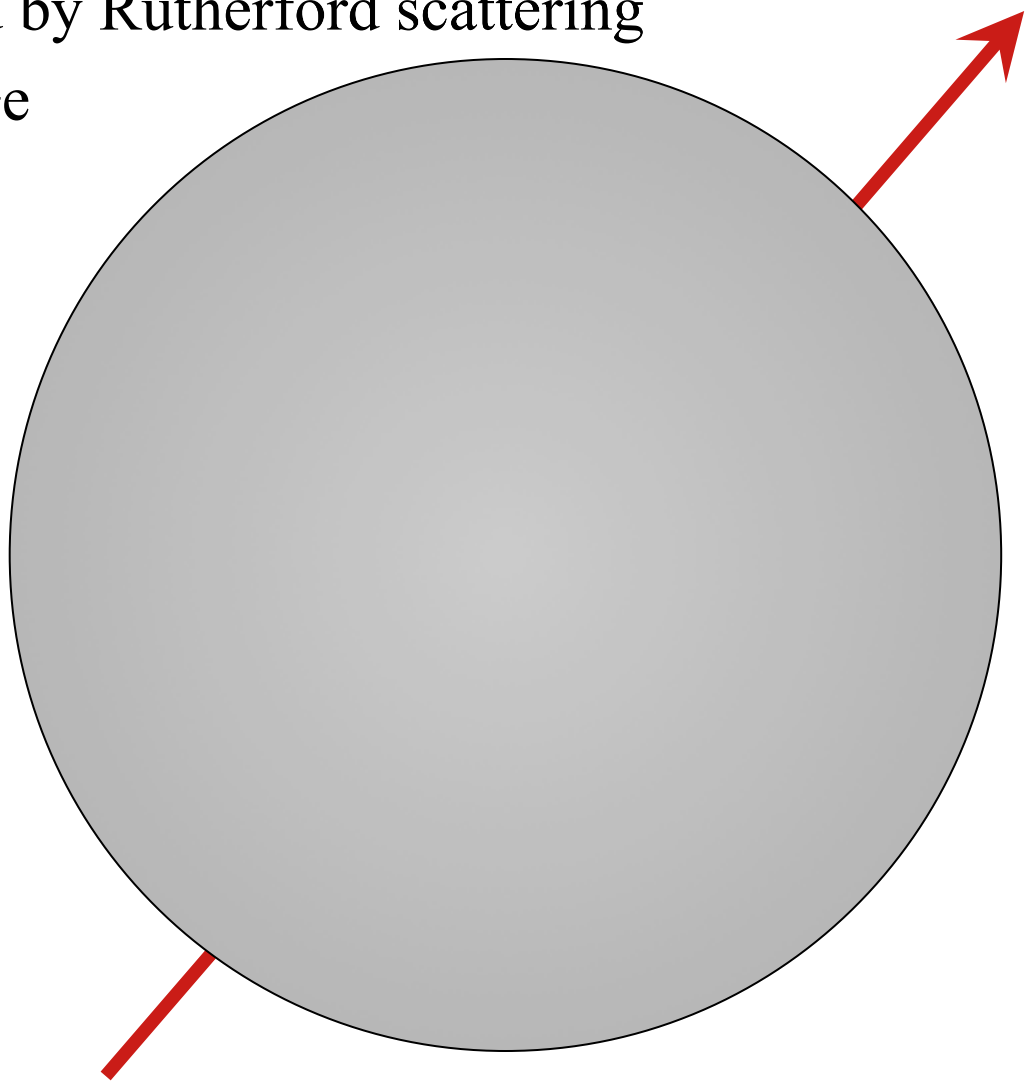
2017 Fall Meeting of the APS Prairie Section

November 11, 2017

U.S. DEPARTMENT OF ENERGY
Office of Science

What do we know about the proton?

- Revealed by Rutherford scattering
- Charge +e

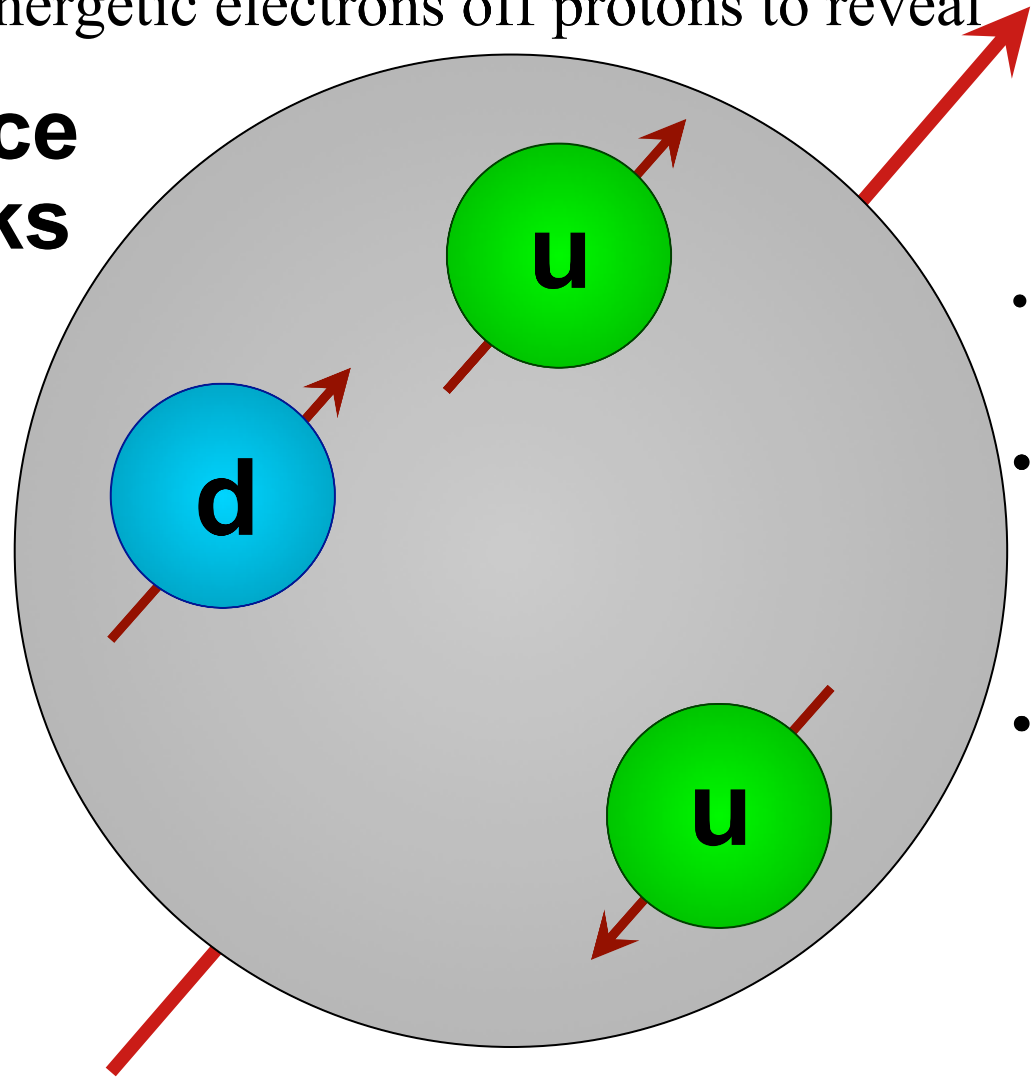


- Spin ½ $\hbar$ (intrinsic angular momentum)

What do we know about proton structure?

- Scatter energetic electrons off protons to reveal

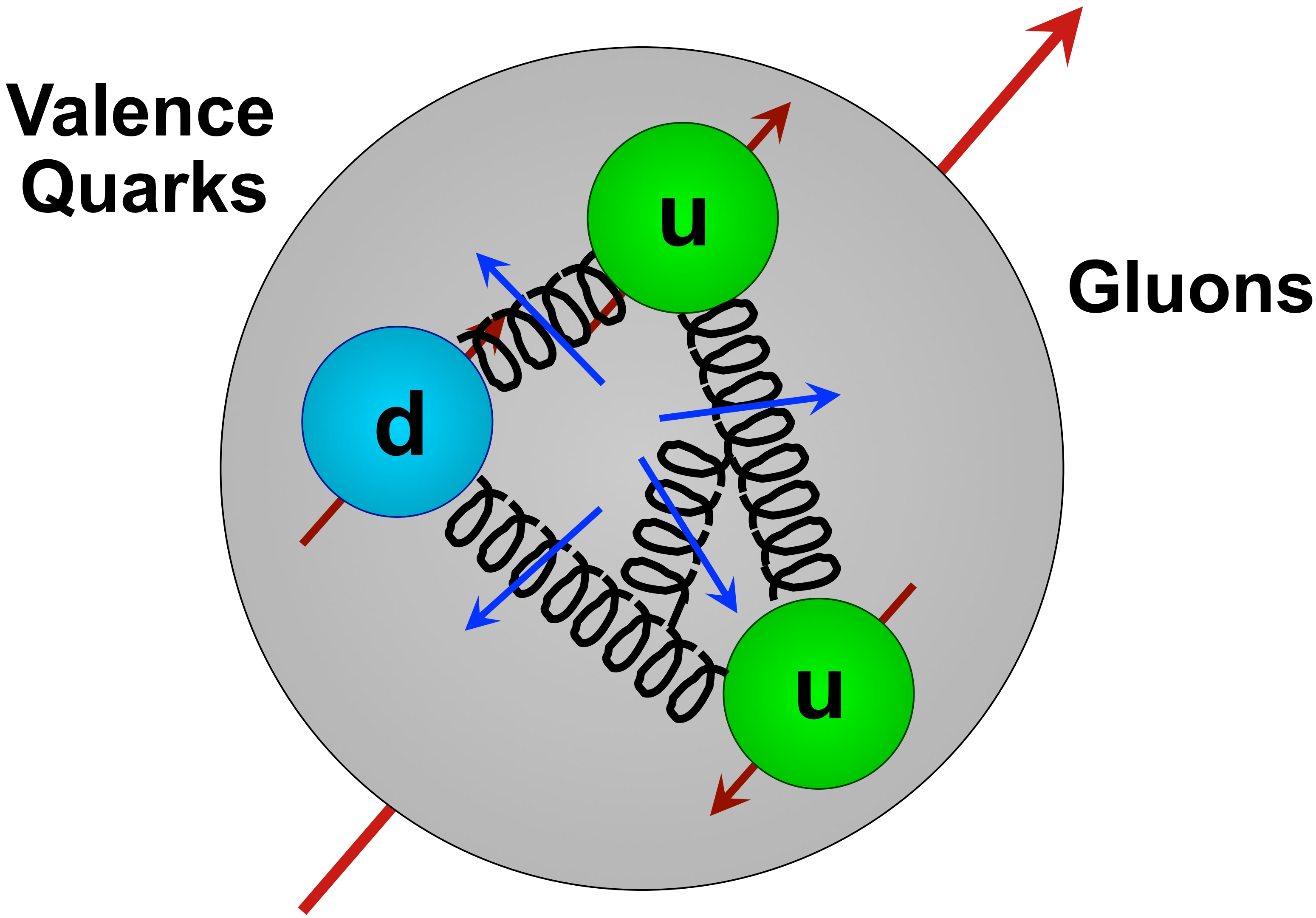
Valence Quarks



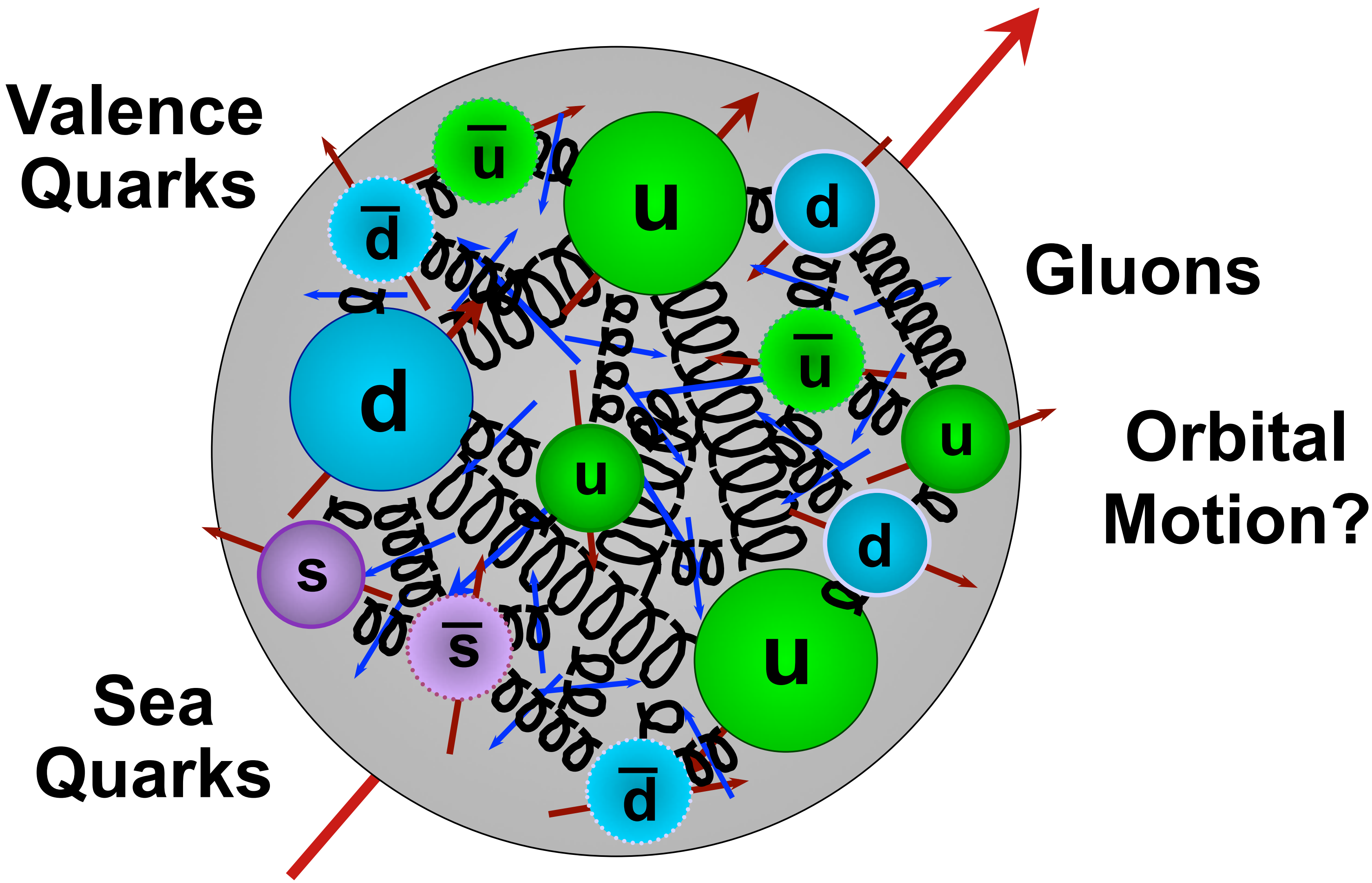
- 2/3e + 2/3e – 1/3e = +e
  Charge works
- (2 + 2 + 5) MeV
  != 938 MeV

  Mass not so well
- How about spin?
  $$\frac{\hbar}{2}+\frac{\hbar}{2}-\frac{\hbar}{2}?=\frac{\hbar}{2}$$

Origin of the proton's spin?

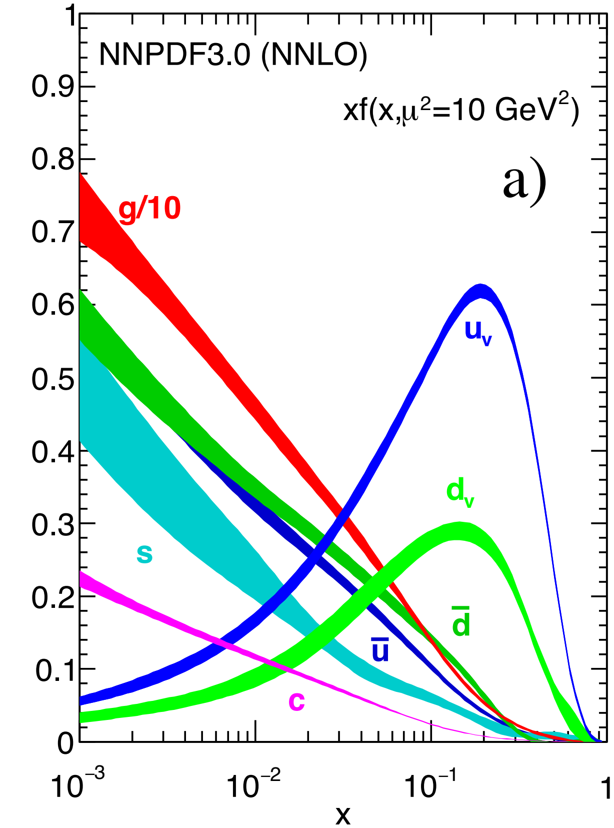


Origin of the proton's spin?



What do we know about proton structure?

- We'd like to use proton collisions as an additional tool
- Proton colliders control the energy of protons, not of quarks or gluons
- To make predictions about collisions,
  we need to know about q's, g's

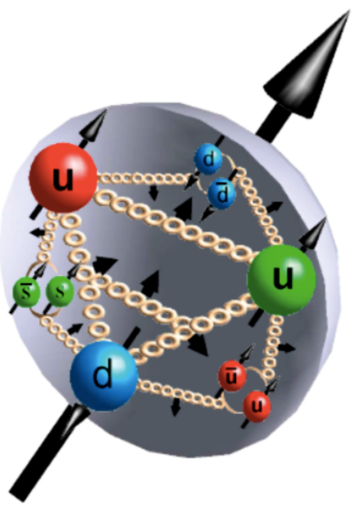


NNPDF, JHEP 1504, 40 (2015)

Particle Data Group, Chin. Phys. C, **40**, 100001 (2016)

- Parton distribution function: PDF
  - A parton is a quark or a gluon
  - With what fraction, x, of the proton's momentum?
- We're interested in the polarized PDF's e.g. $\Delta g(x)$
  - In a polarized proton, as a function of x, to what extent are gluons aligned with the proton's spin, instead of against it?

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: $$\frac{1}{2}\hbar = \frac{1}{2}\sum_q S_q^z + \overbrace{S_g^z + \sum_q L_q^z + L_g^z}$$

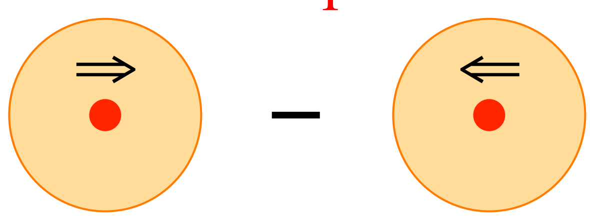
$$S_g^z = \int_0^1 dx \Delta g(x)$$

Gluon's contribution to the proton's spin

Proton momentum ⇒

Proton spin ⇒

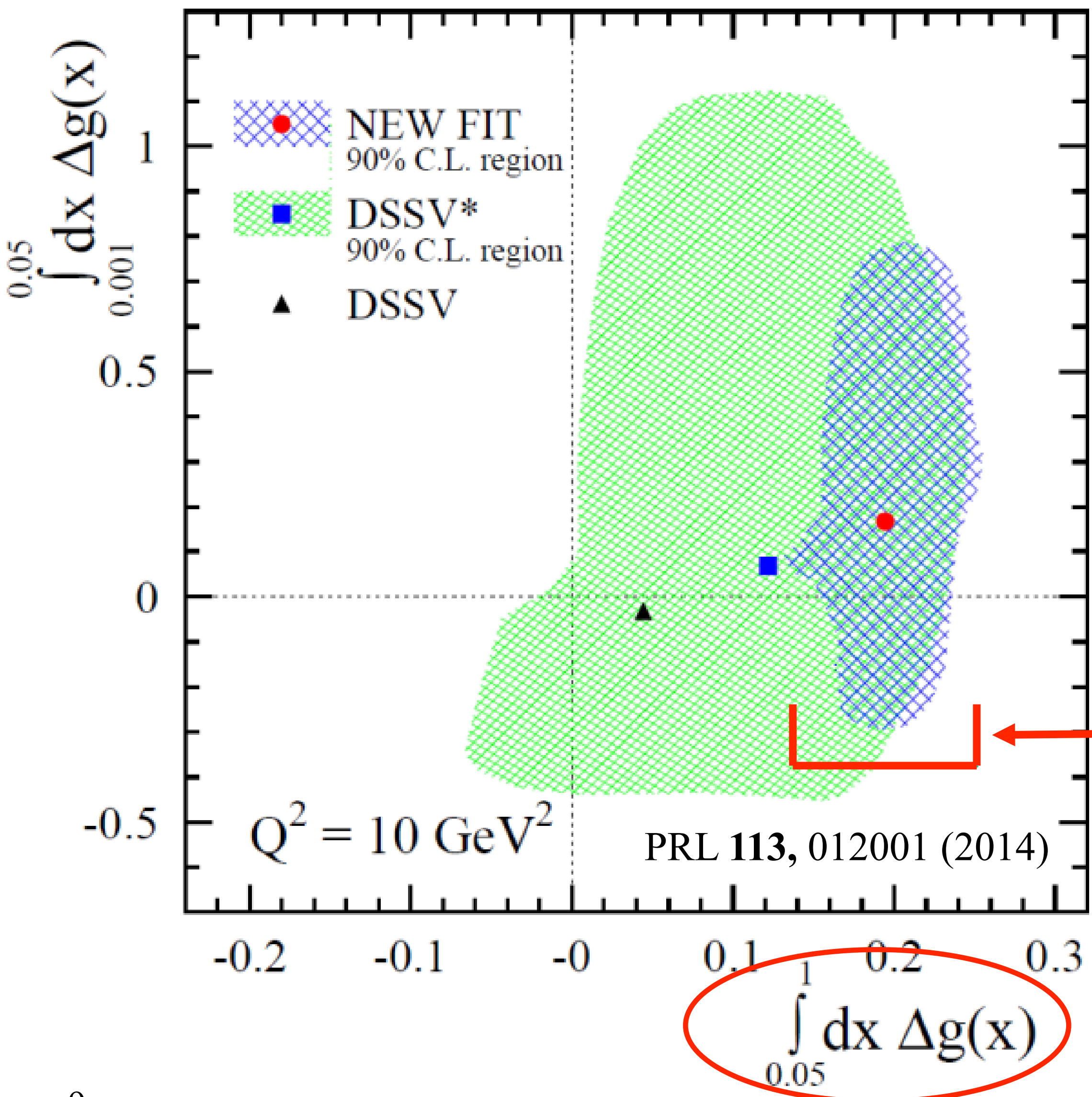
Δq(x)
Δg(x)



Longitudinal Polarization

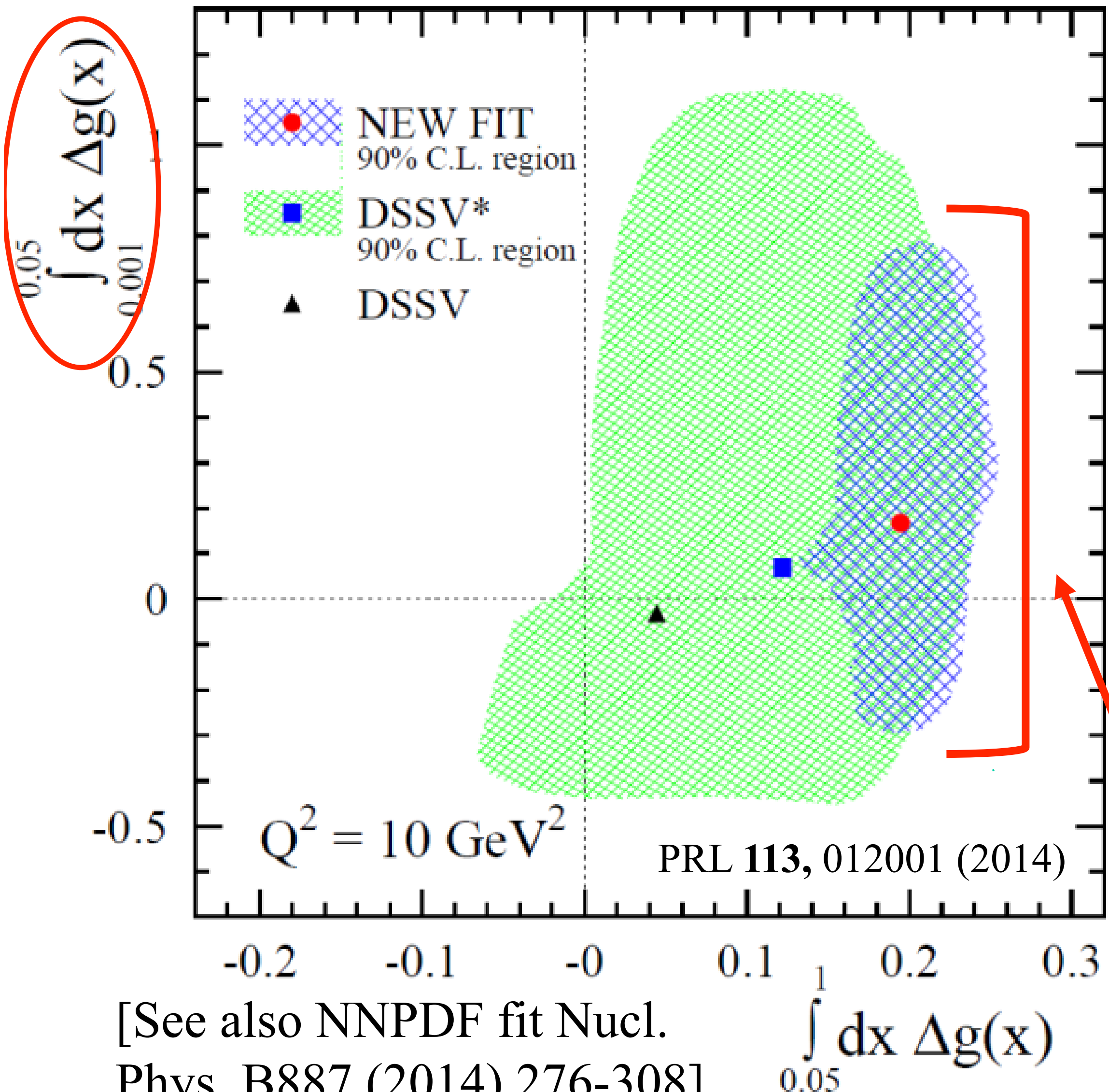
- Current Understanding of $\Delta g(x)$
- STAR Detector
- Jets as a probe of $\Delta g(x)$
- Pushing to Low x with Forward π^0's
  - In the Endcap
  - In the Forward Calorimeter
- Constraining $\Delta g(x)$ with Correlated Probes

New DSSV Fit – S_g Comes into Focus



- With new data from STAR our understanding of the gluon's role in the spin of the proton has improved significantly
- 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
- **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 new data from STAR our understanding of the gluon's role in the spin of the proton has improved significantly
- 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
- Uncertainty on integral over low *x* region is still sizable

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

- Current Understanding of $\Delta g(x)$
- STAR Detector
- Inclusive jets as a probe of $\Delta g(x)$
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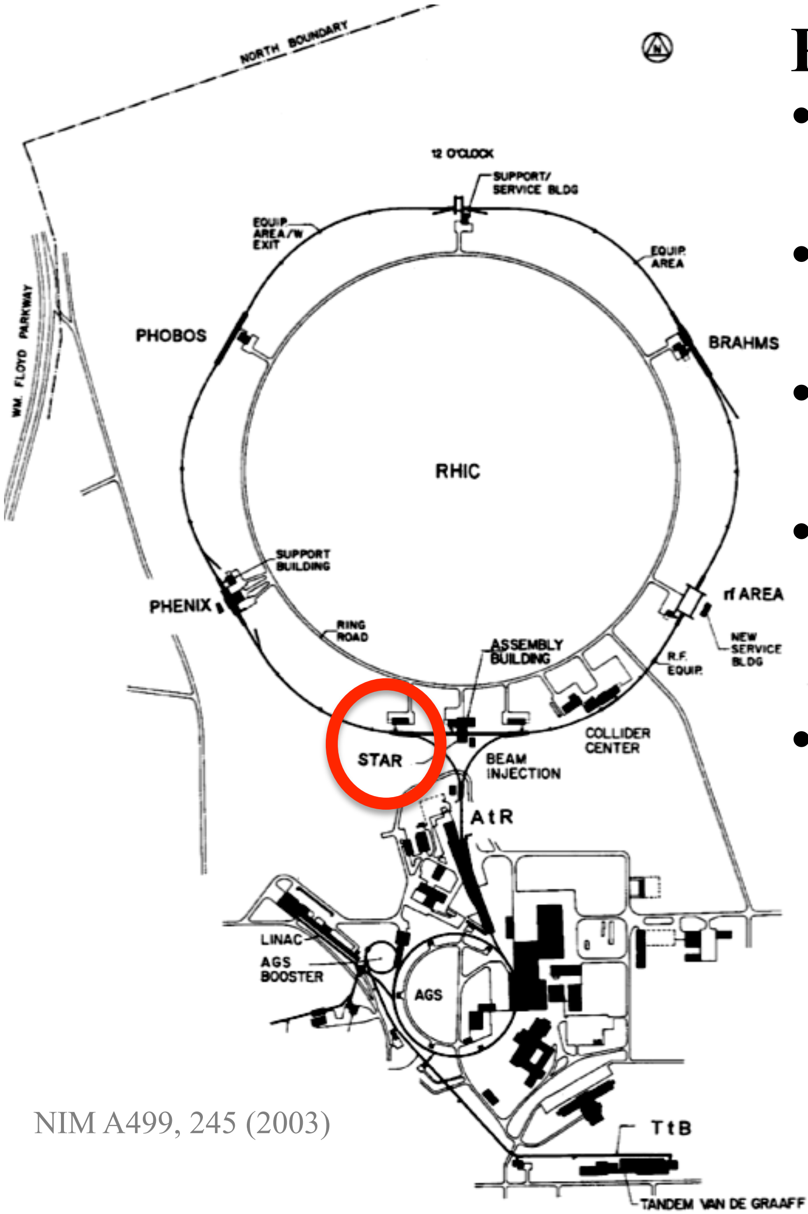
STAR at the Relativistic Heavy Ion Collider (RHIC)

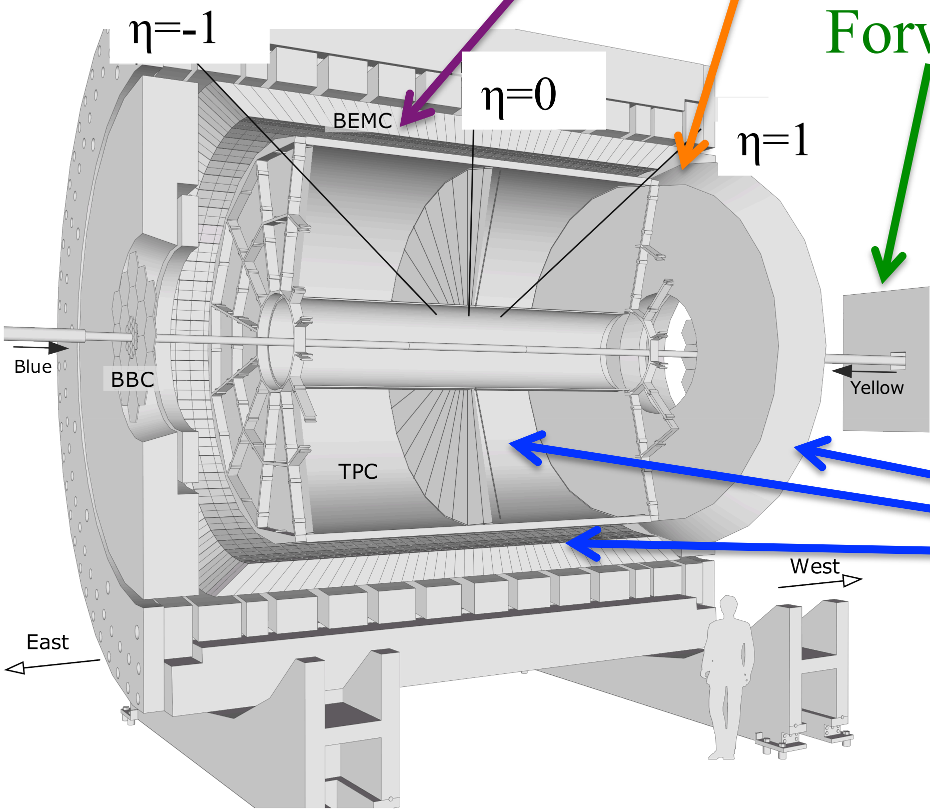


NIM A499, 245 (2003)

RHIC as a Polarized Proton Collider

- World's first and only
- Average polarization 50-60%
- Luminosity typically ~1E32 cm^{-2} s^{-1}
- Spin rotators provide choice of spin orientation *independent of experiment*
- 200 and 500 GeV collisions (proton-proton center-of-mass energy)

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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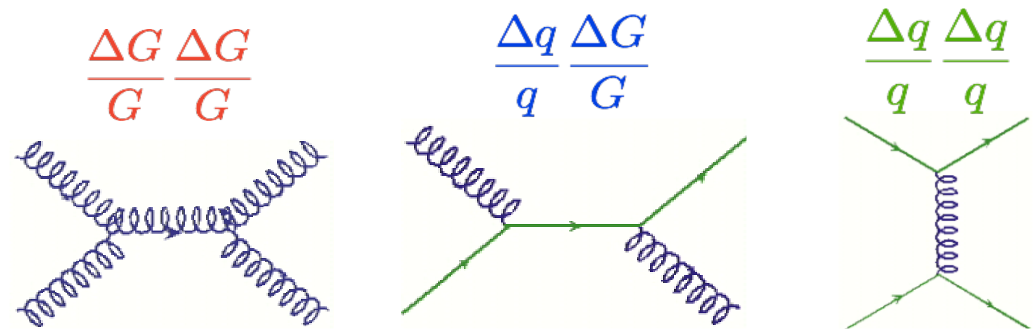
Probing (Gluon) Polarized PDF's With Jets

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

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



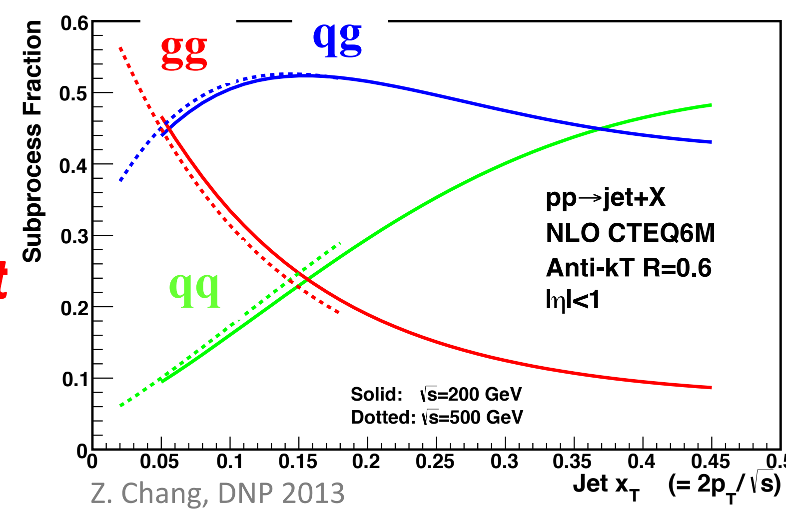
σ^{++}, σ^{+-}

Count jets as a function of proton spin orientation

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

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

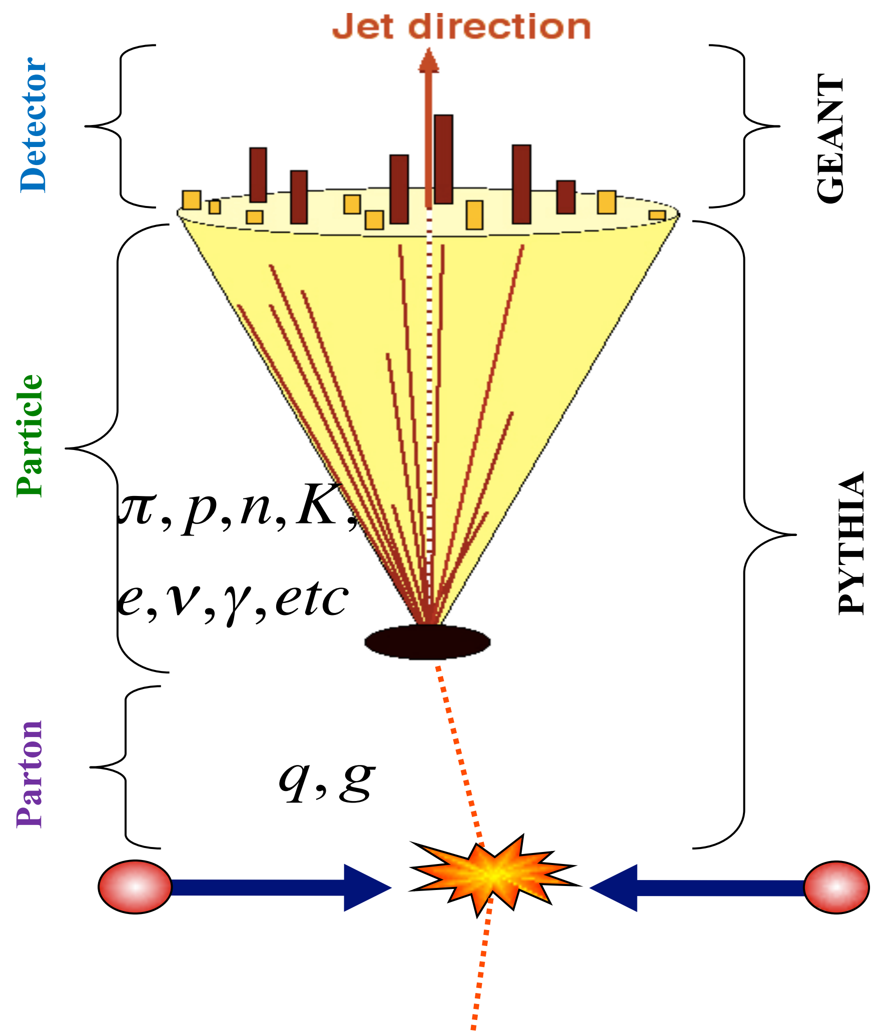
→ ***sample different mix of partonic subprocesses***



Z. Chang, DNP 2013

Jet Reconstruction

Jet Levels MC Jets



STAR Detector has:

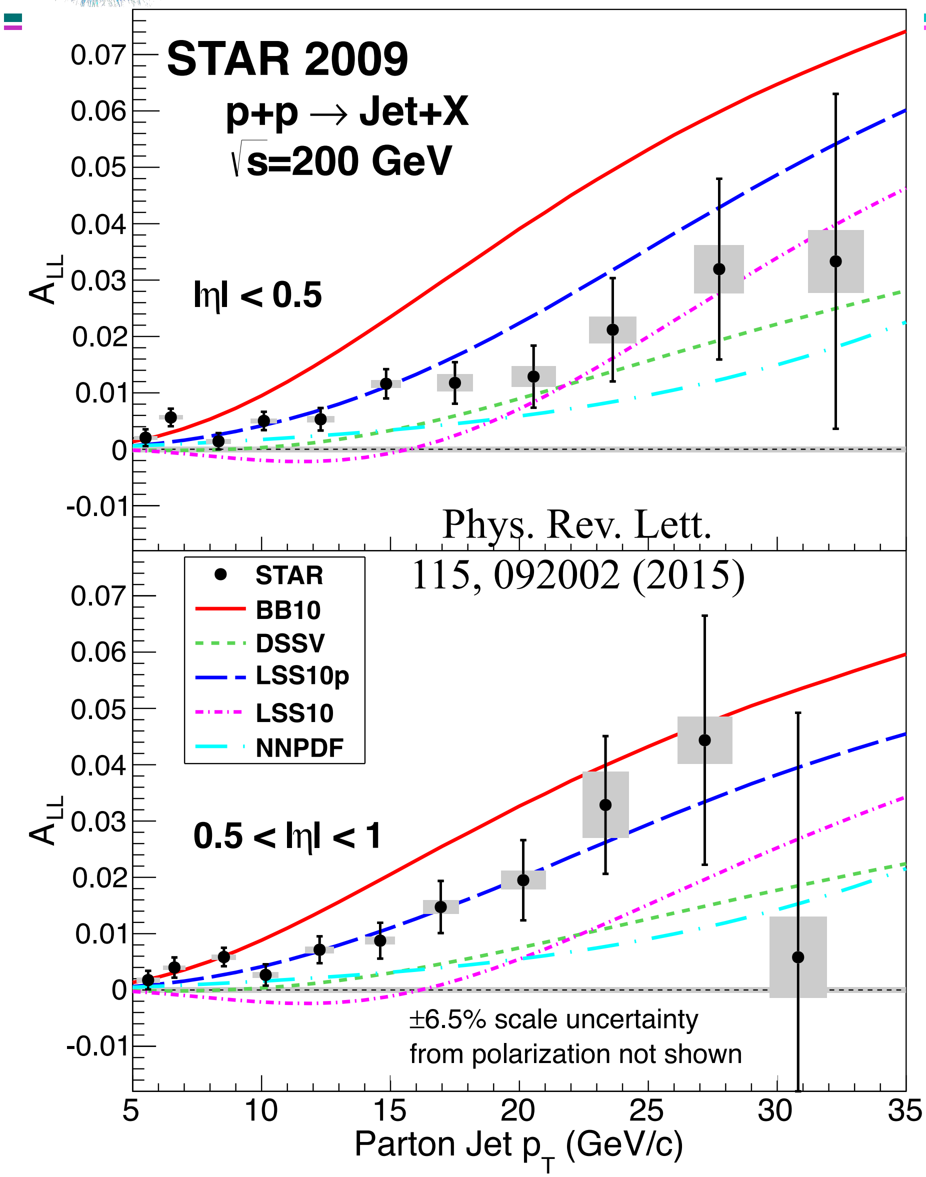
- Full azimuthal coverage
- Charged particle tracking from TPC for $|\eta| < 1.3$
- E/BEMC provide electromagnetic energy reconstruction for $-1 < \eta < 2.0$

STAR well suited for jet measurements

Anti-K_T Jet Algorithm:

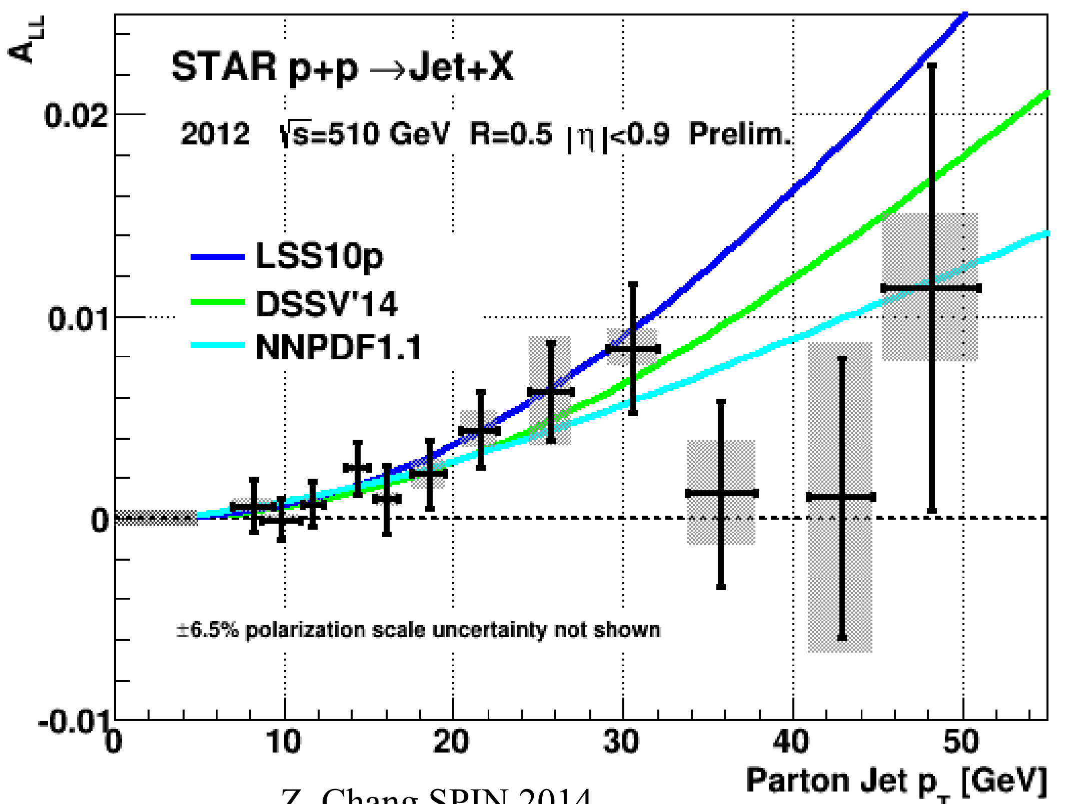
- Radius e.g 0.6 (for 2009 Jet A_{LL})
- Used in both data and simulation

2009 Jet A_{LL}



- 2009 results have factor of 3 to 4 better statistical precision than earlier 2006 results
- Results divided into two η ranges which emphasize different initial-state kinematics
- **Results lie consistently above the 2008 DSSV fit**
- **Played a major role in moving the global Δg fit**

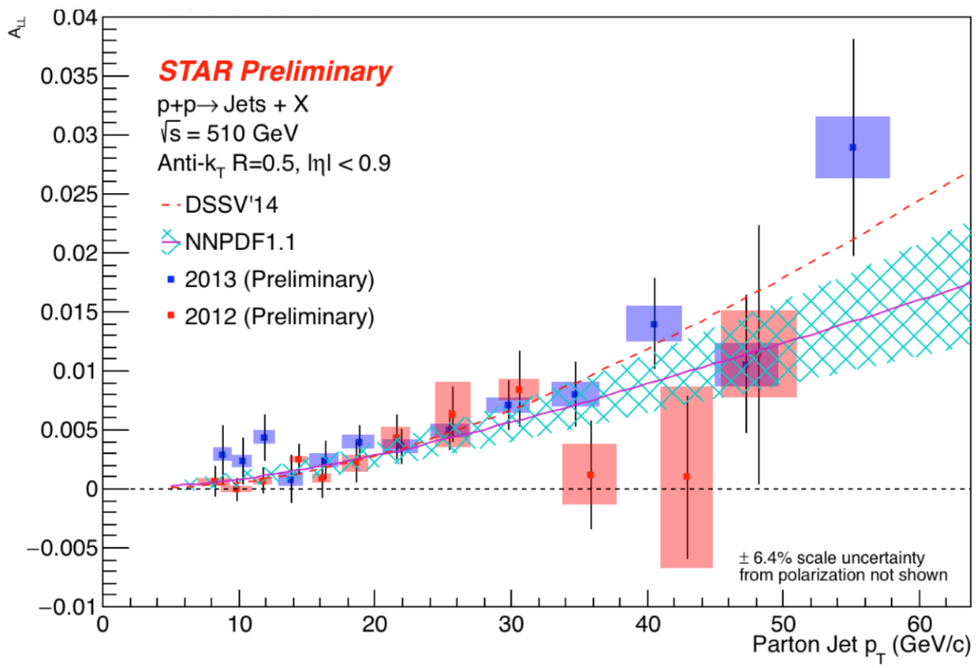
2012 Jet A_{LL} at 510 GeV

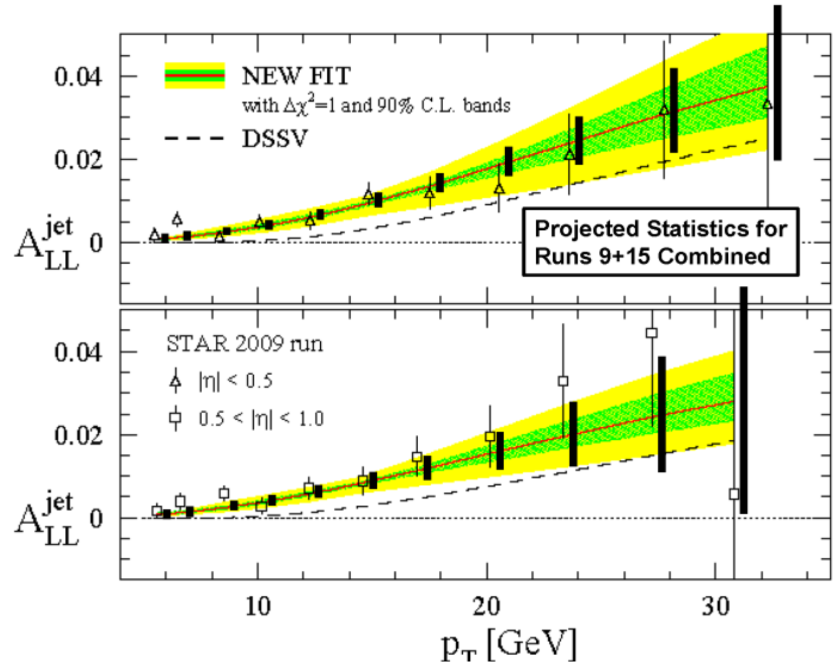


Z. Chang SPIN 2014
arXiv:1512.05400

- Push to lower x_g w/ higher collision energies
  - For similar jet energies, higher proton energies means we sample lower x_g
- **Agrees well with latest predictions based on global polarized PDF (DSSV, NNPDF) analyses**

Higher Statistics for Jet A_{LL}





- RHIC had very successful, high luminosity runs at 510 GeV 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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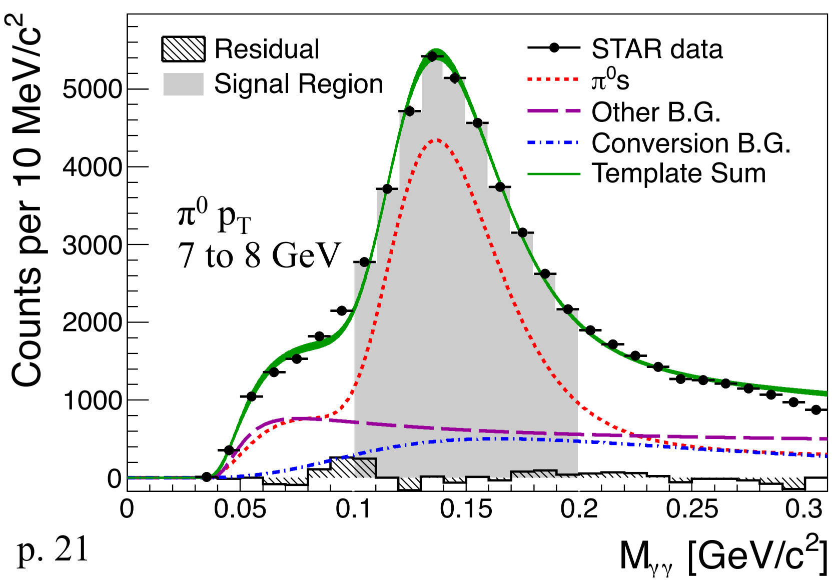
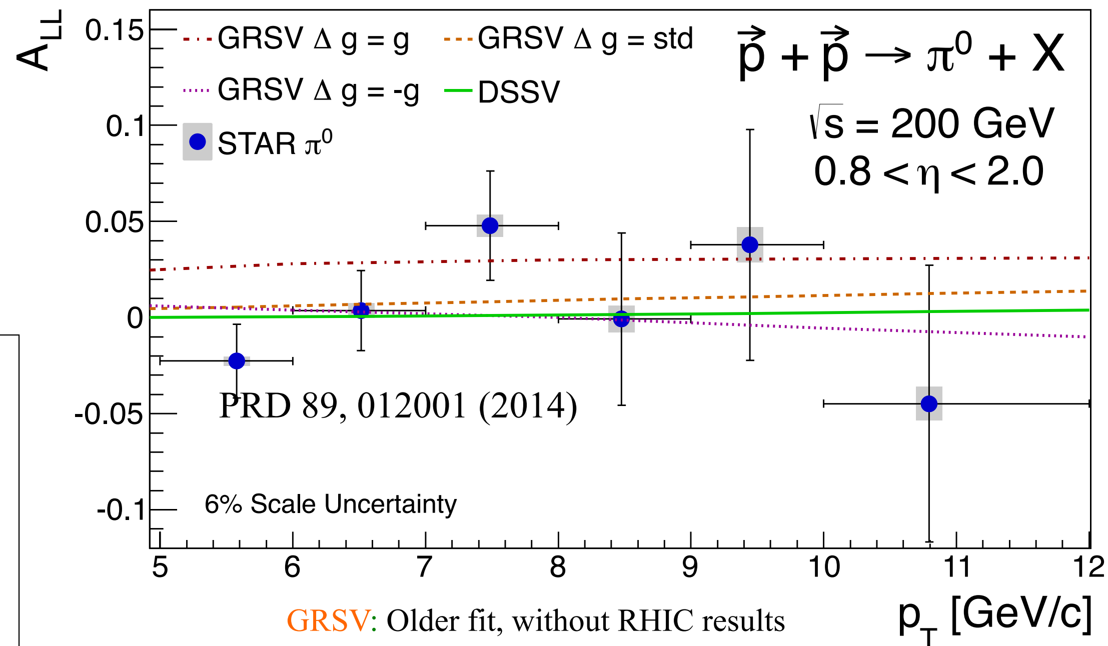
A_{LL} in π^0 at STAR for $0.8 < \eta < 2.0$

- 2006 Dataset in the Endcap Electromagnetic Calorimeter (EEMC)
- Push to reasonably low *x* by going (relatively) forward
  - In forward detectors collisions between one high *x* and one low *x* particle are common
- Statistical error (bars) dominate relative to systematic error (boxes)

Poster 23 has more details about the π^0 analysis



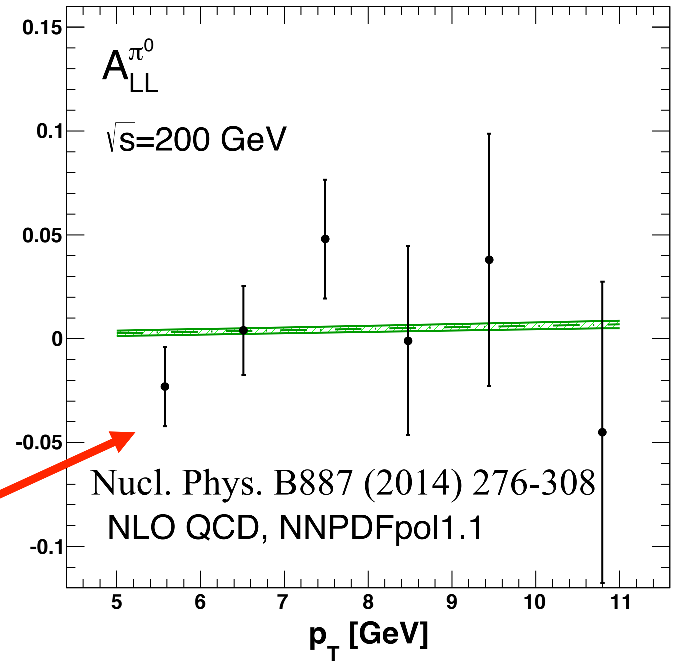


GRSV: Older fit, without RHIC results
PRD 63, 094005 (2001)
DSSV: First fit to include RHIC results
PRL 101, 072001 (2008)

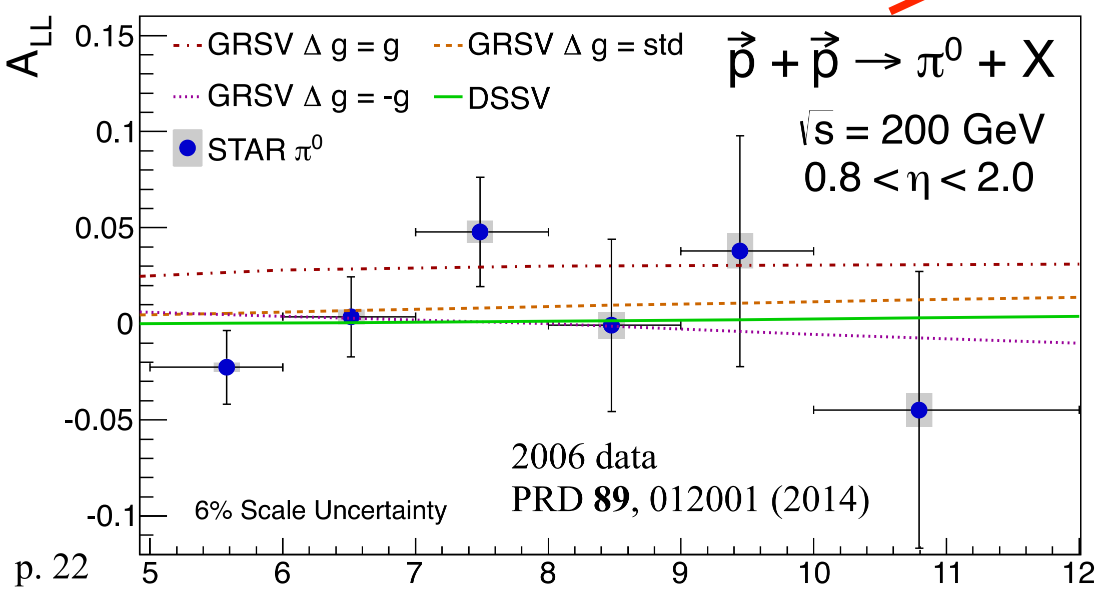
Updated Prediction for π^0 A_{LL} , $0.8 < \eta < 2.0$

- NNPDFpol1.1 includes jet results from STAR, including the 2009 jets

- Greater precision needed to test the fit

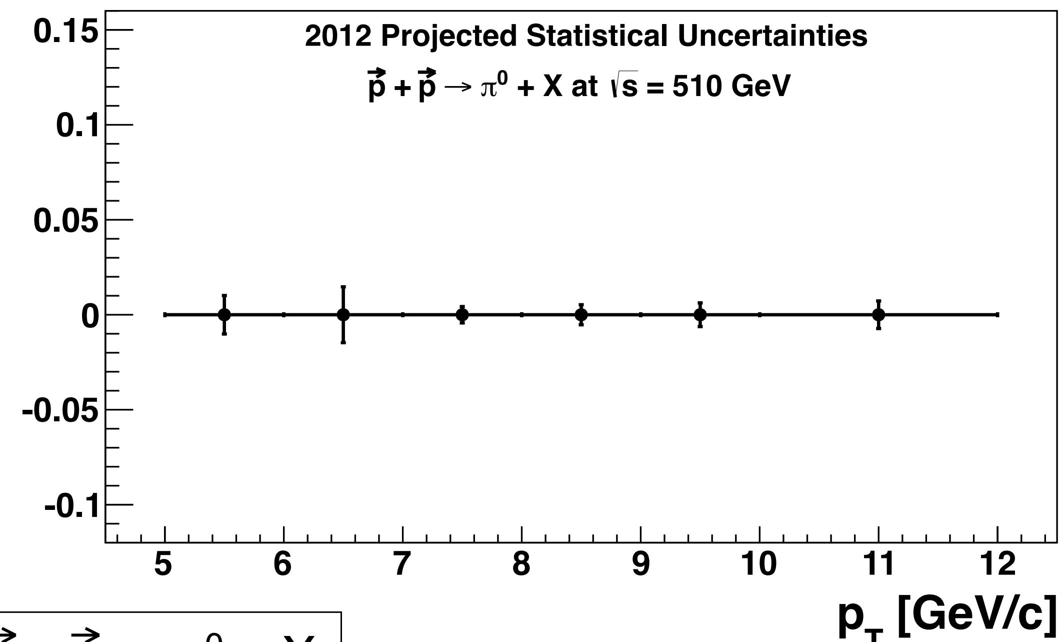


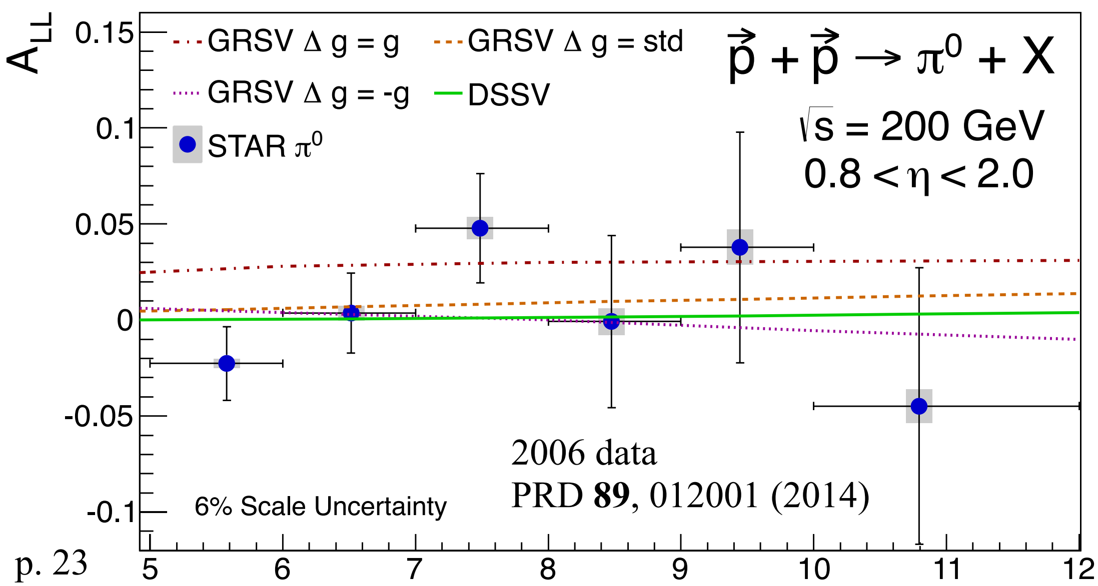
STAR data with NNPDF predictions



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

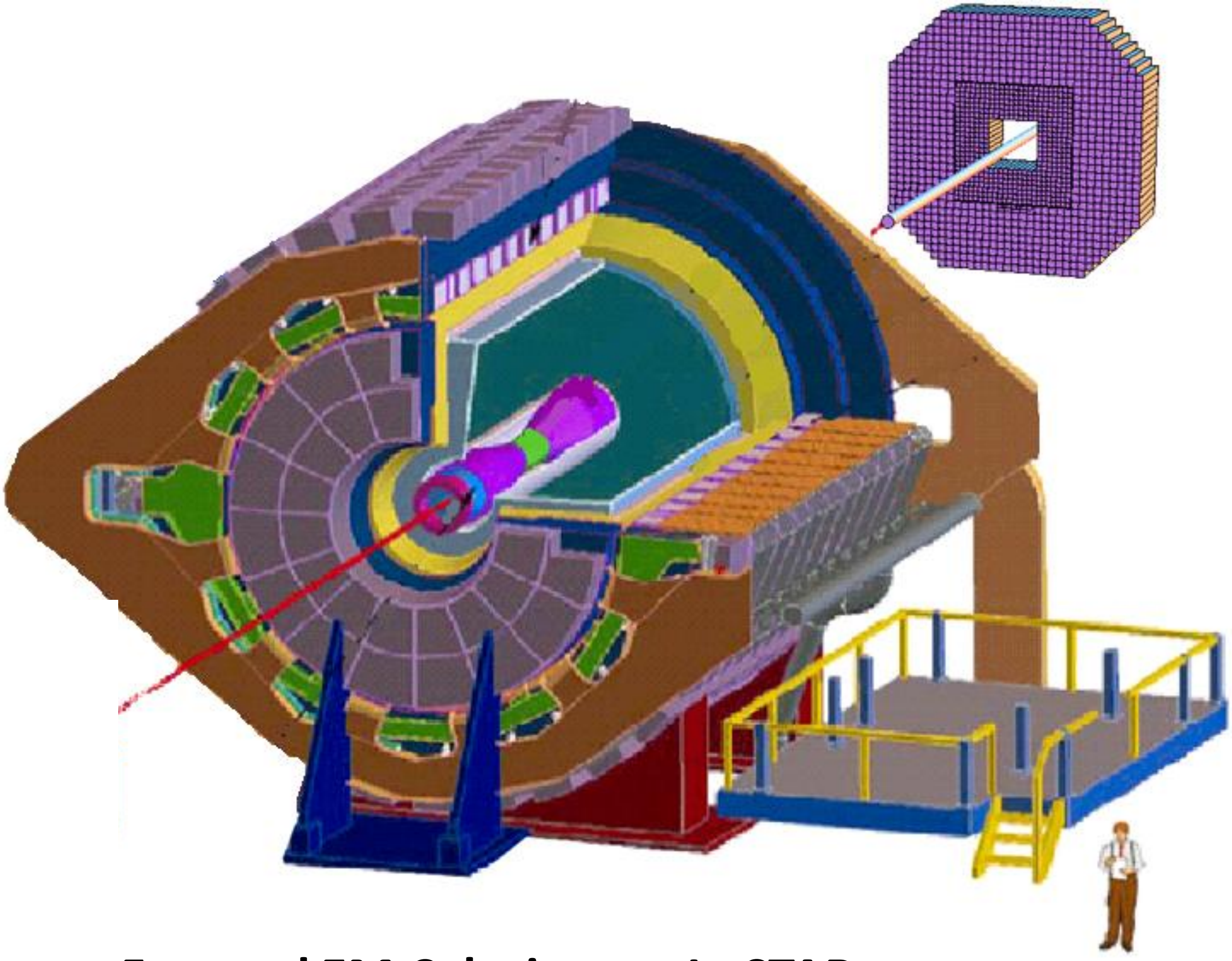




- Higher CoM energy
  - 200 → 510 GeV
  - Pushes to lower *x* gluon

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

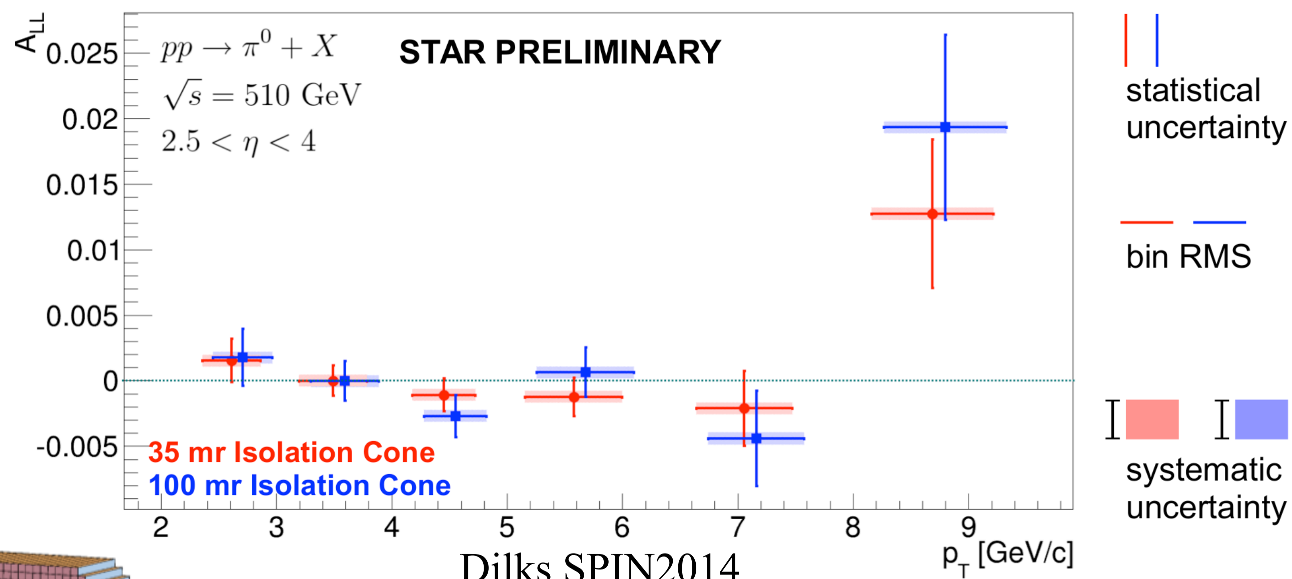


Forward EM Calorimetry In STAR.

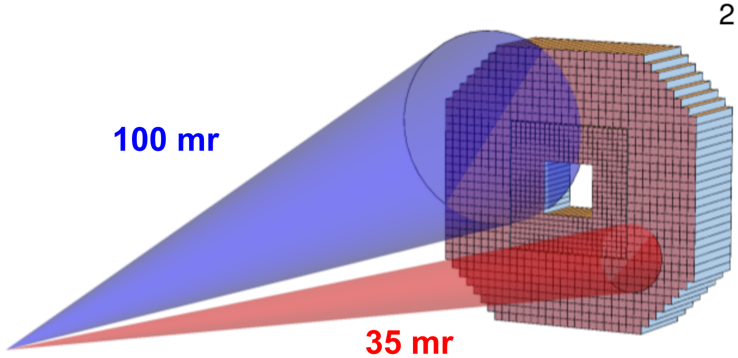
π^0 A_{LL} Prospects in Forward Calorimeters

- Pushing even further forward, with the FMS Forward Calorimeter
- Preliminary results with large 2012 and 2013 datasets at 510 GeV

- Here requiring an isolation cone around π^0
  - Inclusive analysis coming soon



Dilks SPIN2014



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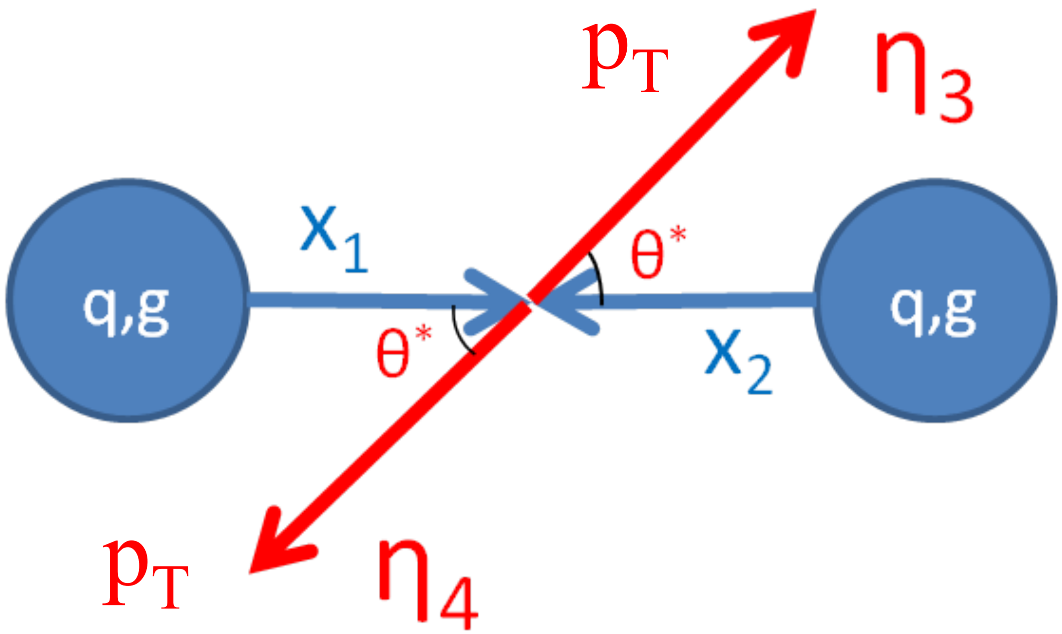
Dijet Measurements



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

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

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

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

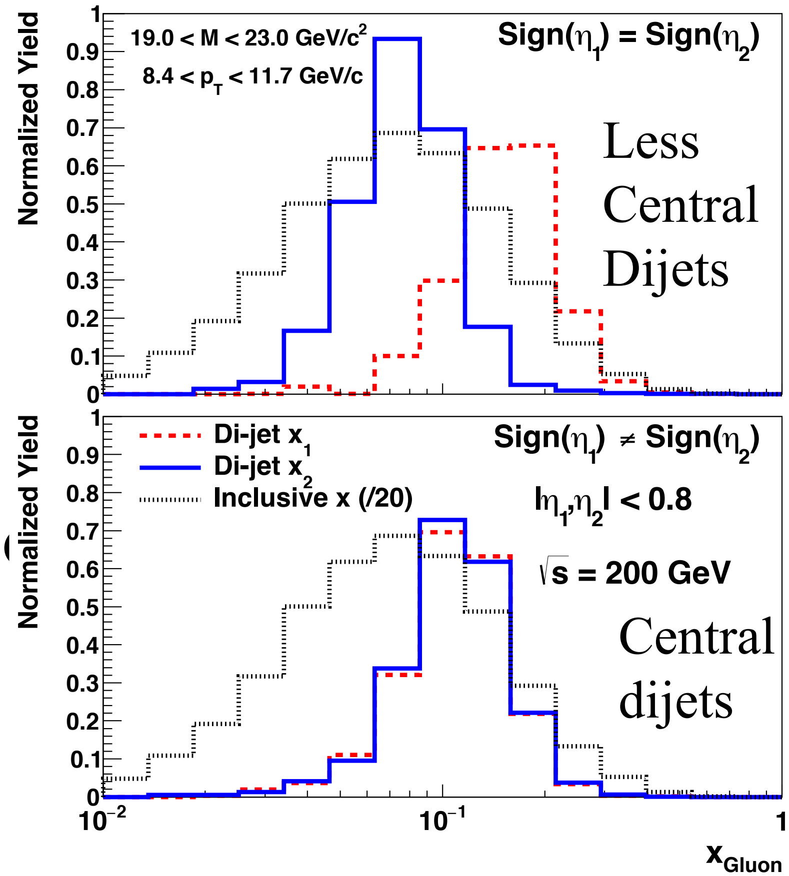
$$|\cos\theta^*| = \tanh\left|\frac{\eta_3 - \eta_4}{2}\right|$$

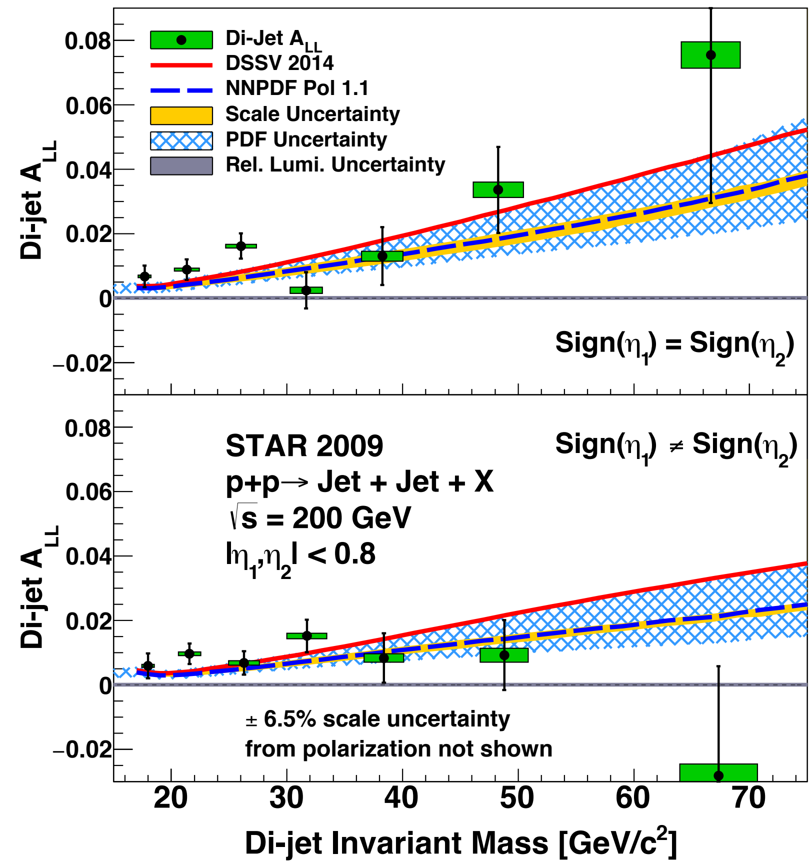
- Inclusive jet measurements have been the workhorse of STAR Δg program to date

  But sample a broad x range in each p_T bin
- Dijet or other correlation measurements which reconstruct the full final state are sensitive to initial kinematics
- Prospect of mapping out the shape of $\Delta g(x)$

2009 Dijet Asymmetries and *x* Reach

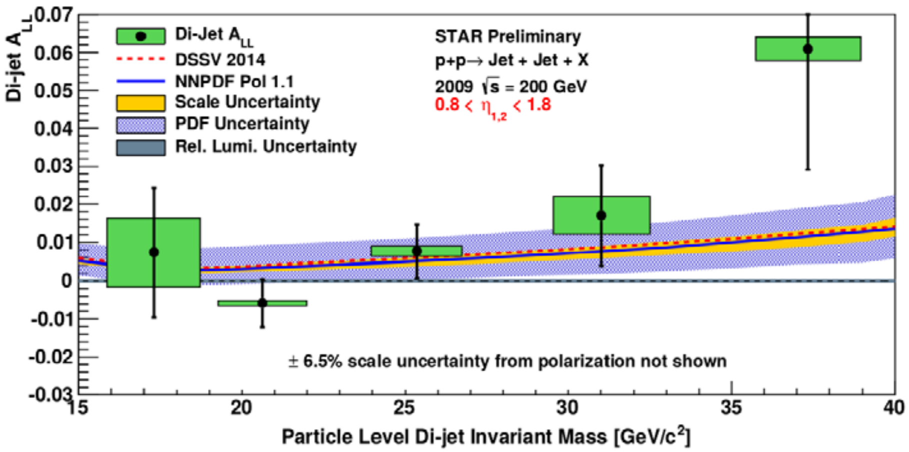
Phys. Rev. D 95, 071103(R) (2017)

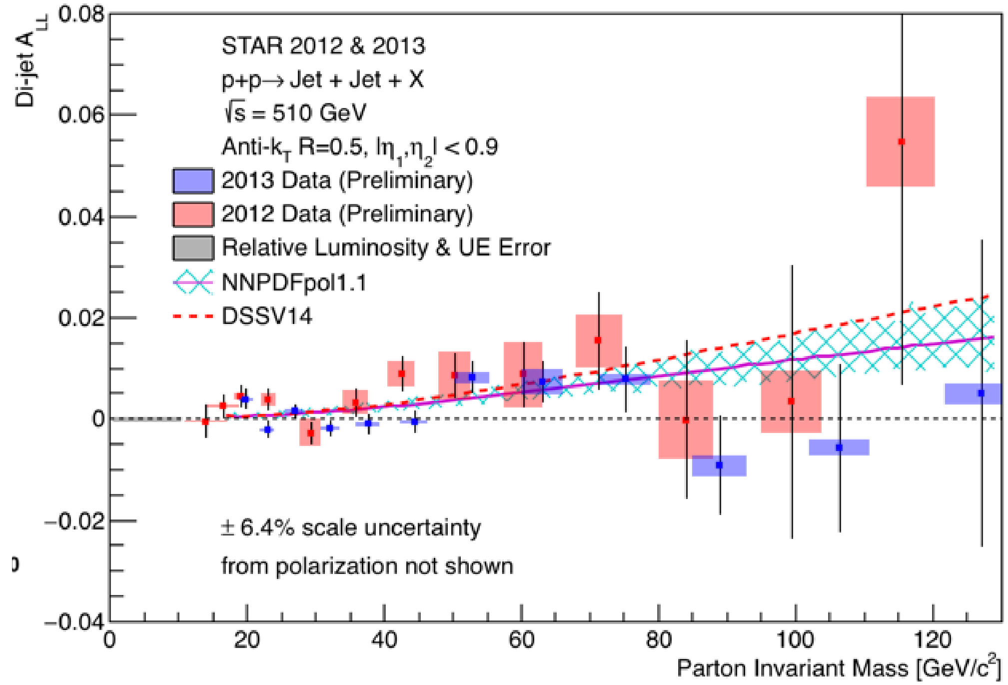




- Dijets probe a much narrower range of x_g than inclusive jets
- Asymmetries consistent with predictions, ~subset of the dataset used to extract polarized PDF's; some evidence dijets prefer a larger Δg?

Dijets at Forward Rapidities and 510 GeV

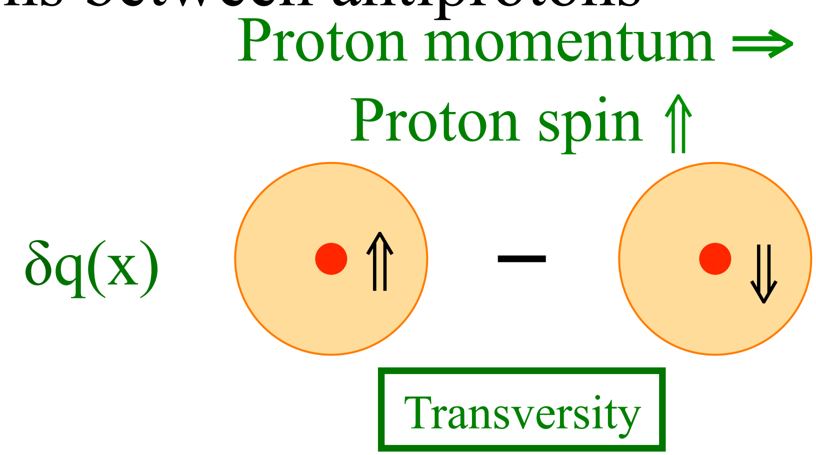




- Probe lower x_g with dijets by moving to forward rapidities and higher collision energy
  - Reaching x ~ 0.02 now
  - Can push below x = 0.01 with additional data already recorded
  - And to x ~ 10^{-3} in a few years with a forward upgrade

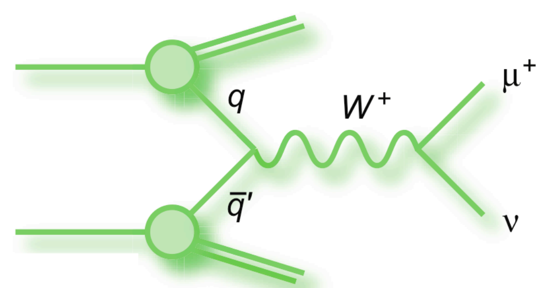
Many Additional Topics at STAR

- Quark Gluon Plasma
- Properties of Antimatter
  - Discovery of anti-^{4}He, interactions between antiprotons
- Transverse Spin Physics



- W's to probe anti-quark polarization distributions

Next two speakers will tell us about some other parts of STAR's diverse physics program



Understanding the Proton's Spin at STAR: Constraining the Gluon Polarization Distribution with Jet, Dijet, and Neutral Pion Probes

- Jets at STAR
  - After 25 years, **evidence of non-zero gluon polarization** in the proton
  - Large datasets reduce uncertainties, higher energy collisions allow us to probe lower *x*
- π^0's with forward detectors (EEMC, FMS) probe lower *x*
- Map $\Delta g(x)$ as a function of *x* with correlated probes like dijets

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

S_g coming into focus!

Poorly constrained

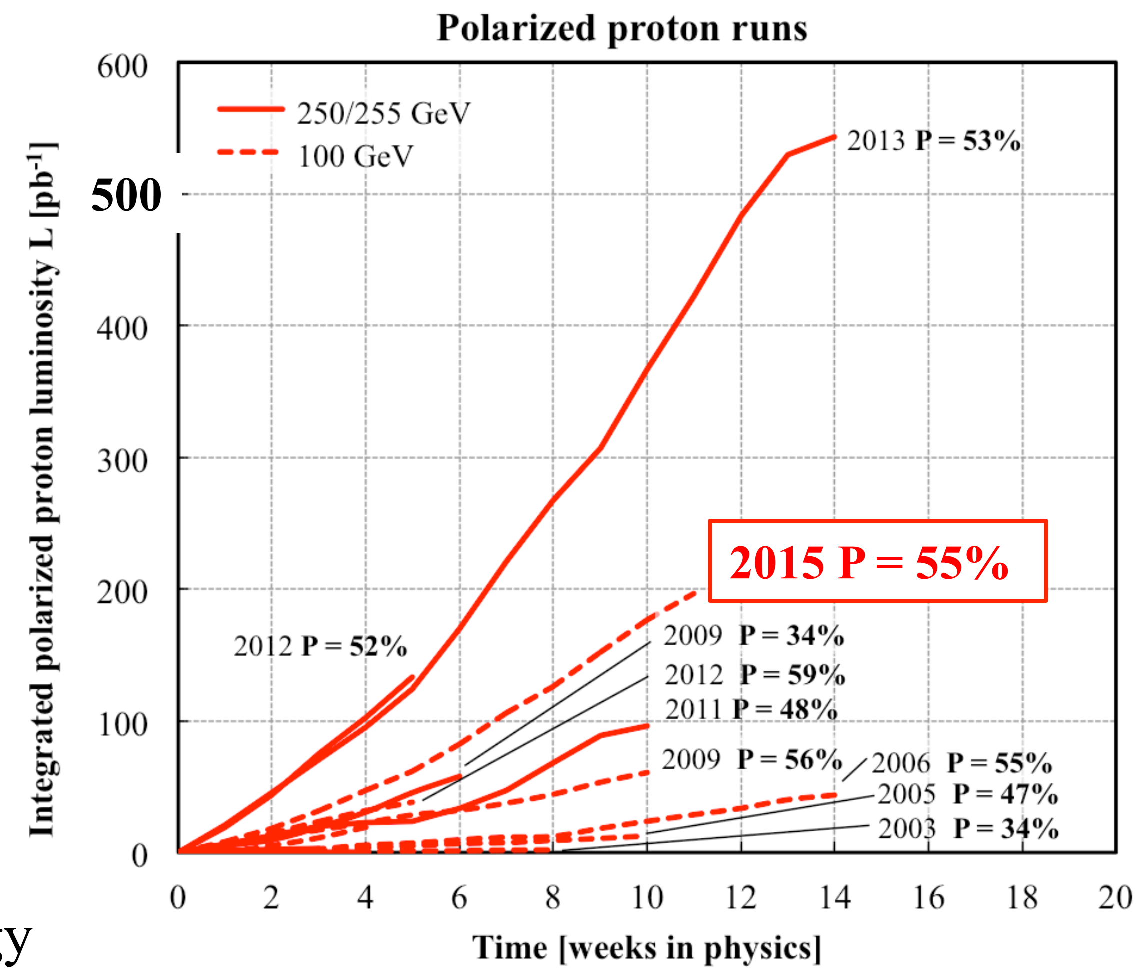
Proton spin sum rule: $$\frac{1}{2}\hbar = \frac{1}{2}\sum_q S_q^z + S_g^z + \overbrace{\sum_q L_q^z + L_g^z}$$

- 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



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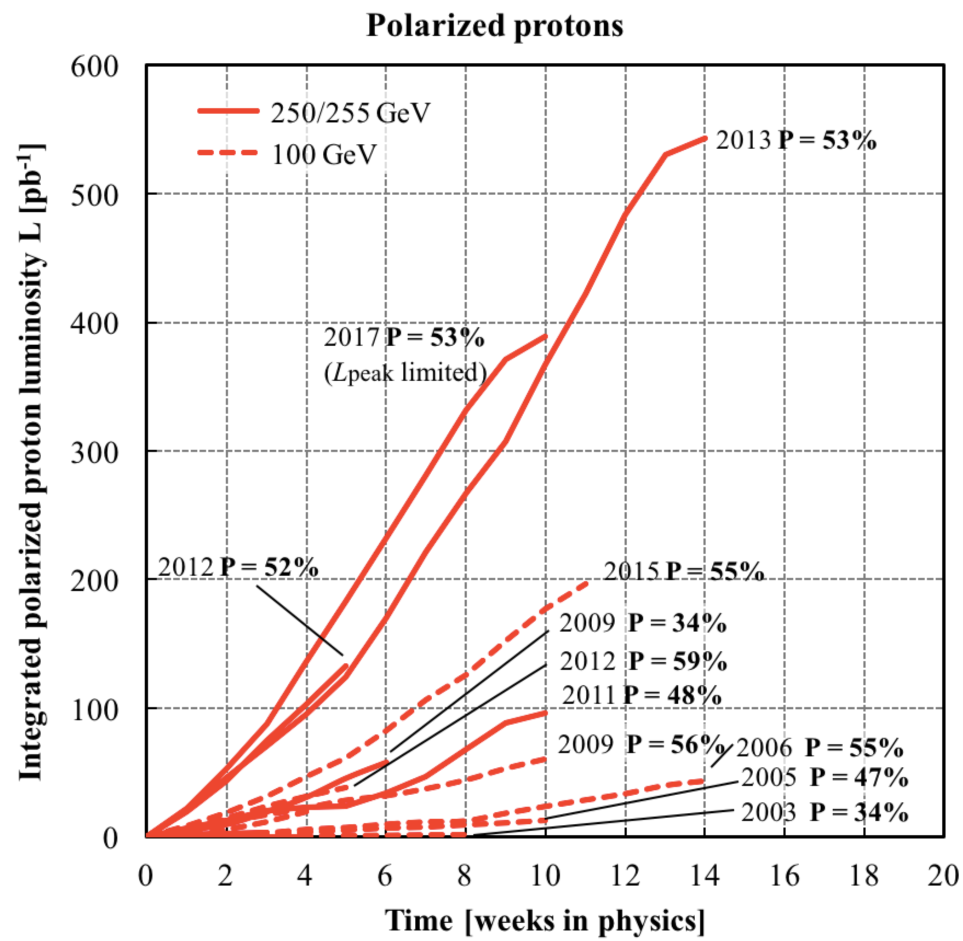
Polarized protons
250/255 GeV
100 GeV
2013 P = 53%
2017 P = 53%
(Lpeak limited)
2012 P = 52%
2015 P = 55%
2009 P = 34%
2012 P = 59%
2011 P = 48%
2009 P = 56%
2006 P = 55%
2005 P = 47%
2003 P = 34%
Integrated polarized proton luminosity L [pb-1]
Time [weeks in physics]
0
100
200
300
400
500
600
0
2
4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

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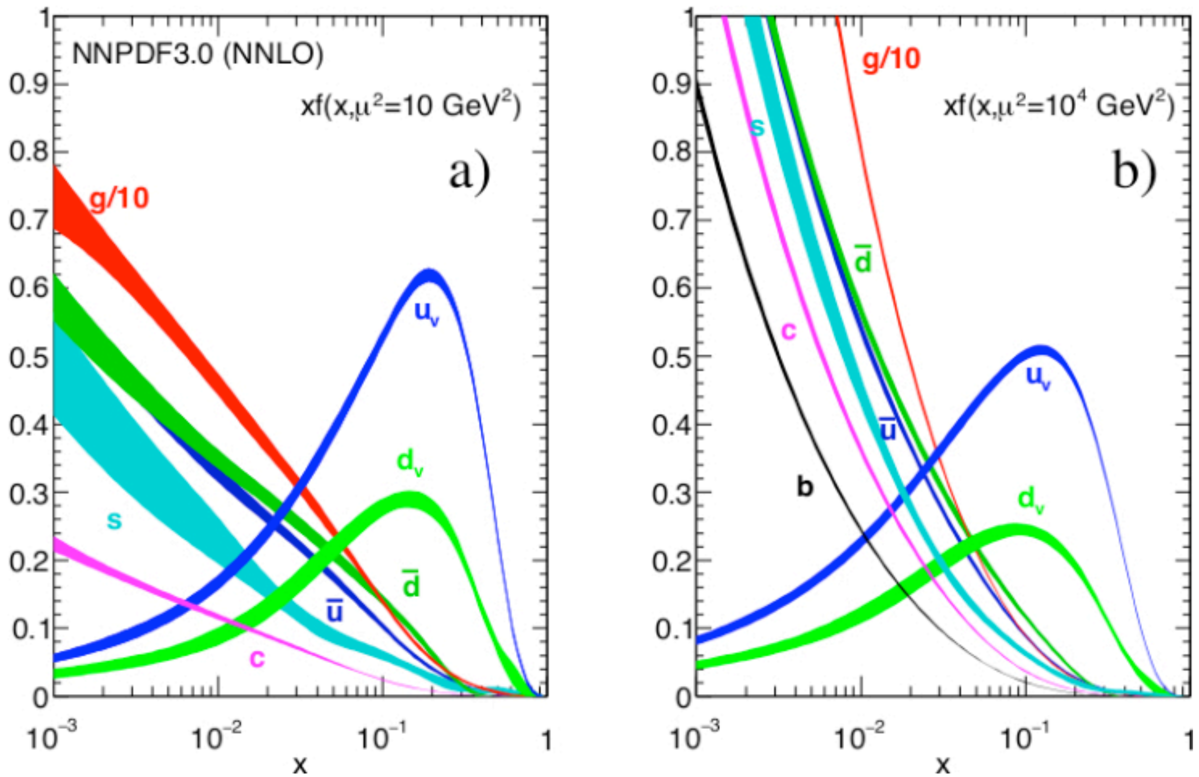
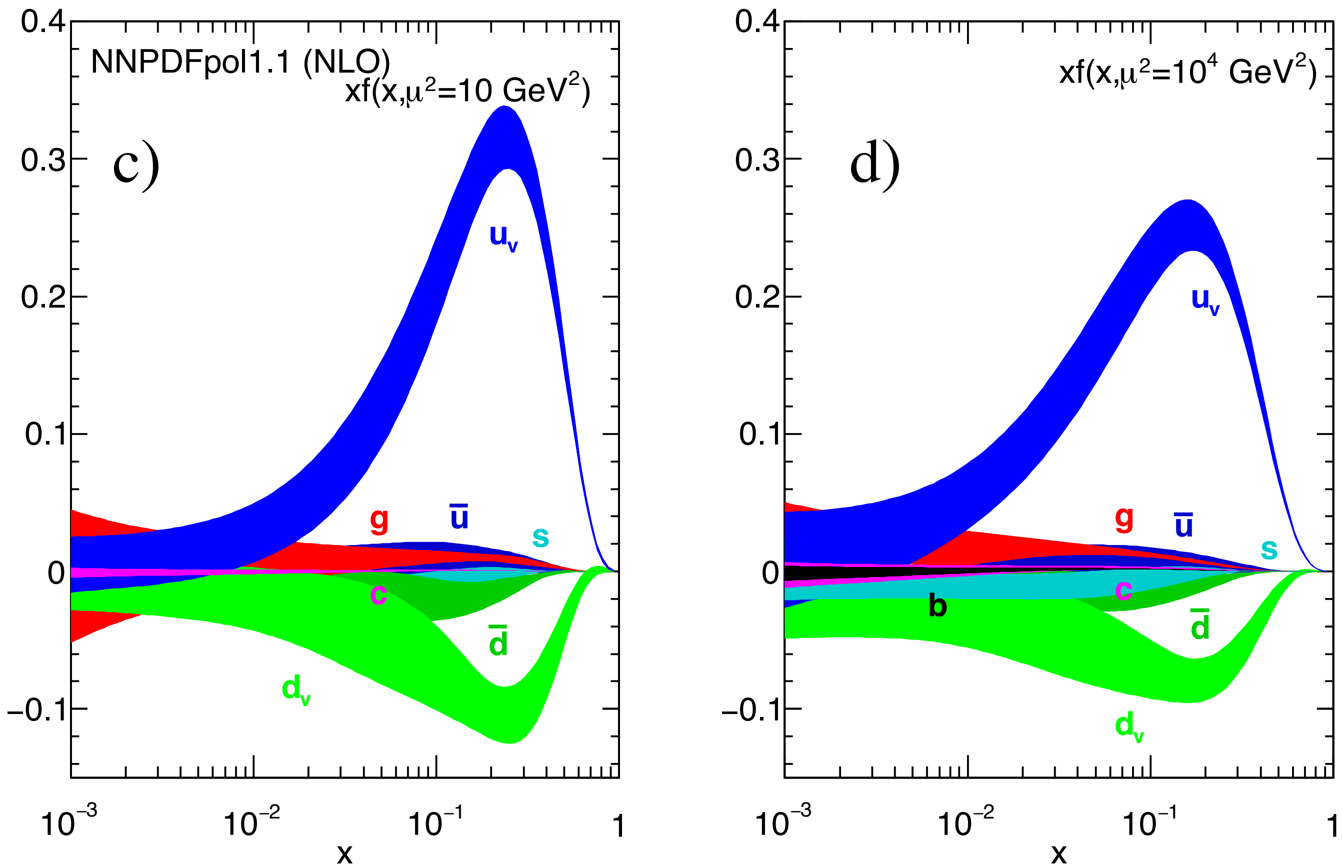


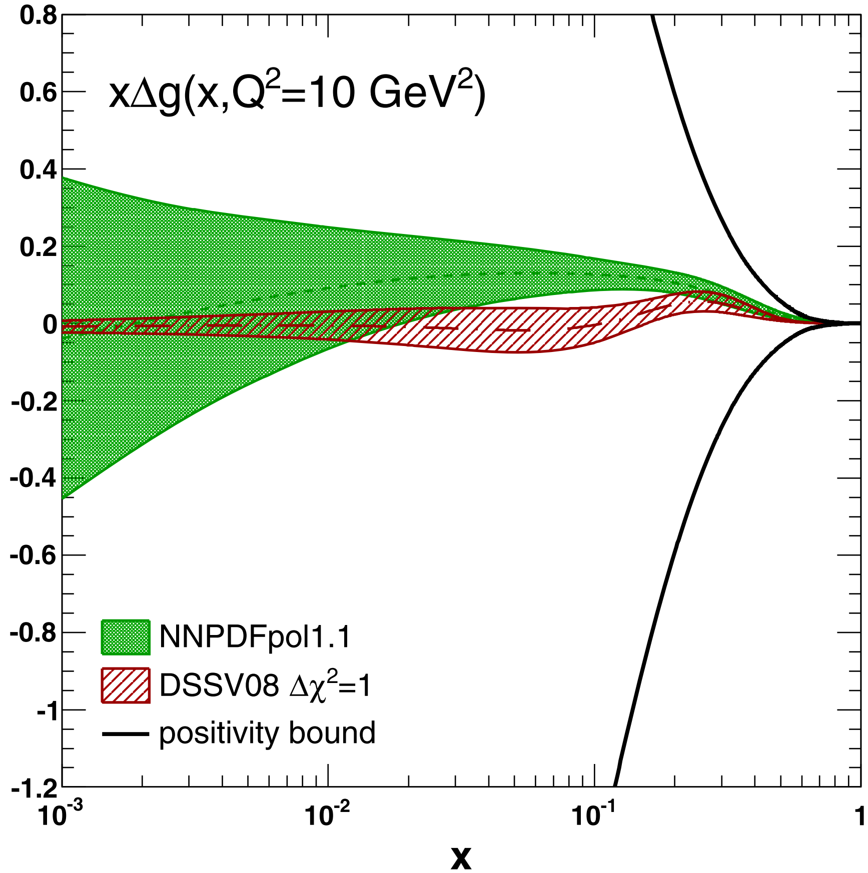
NNPDF3.0 (NNLO)
xf(x,μ²=10 GeV²)
a)
g/10
u_v
d_v
s
$\bar{d}$
$\bar{u}$
c
xf(x,μ²=10⁴ GeV²)
b)
b
x

•



NNPDFpol1.1 (NLO)
xf(x,μ²=10 GeV²)
c)
u_v
g
ū
s
c
d̄
d_v
0.4
0.3
0.2
0.1
0
−0.1
10⁻³
10⁻²
10⁻¹
1
x
xf(x,μ²=10⁴ GeV²)
d)
u_v
g
ū
s
b
c
d̄
d_v
x

•



Nuclear Physics B 887 (2014) 276–308

Fig. 13. The NNPDFpol1.1 parton set compared to DSSV08 [6] at $Q^2 = 10\ \mathrm{GeV}^2$.

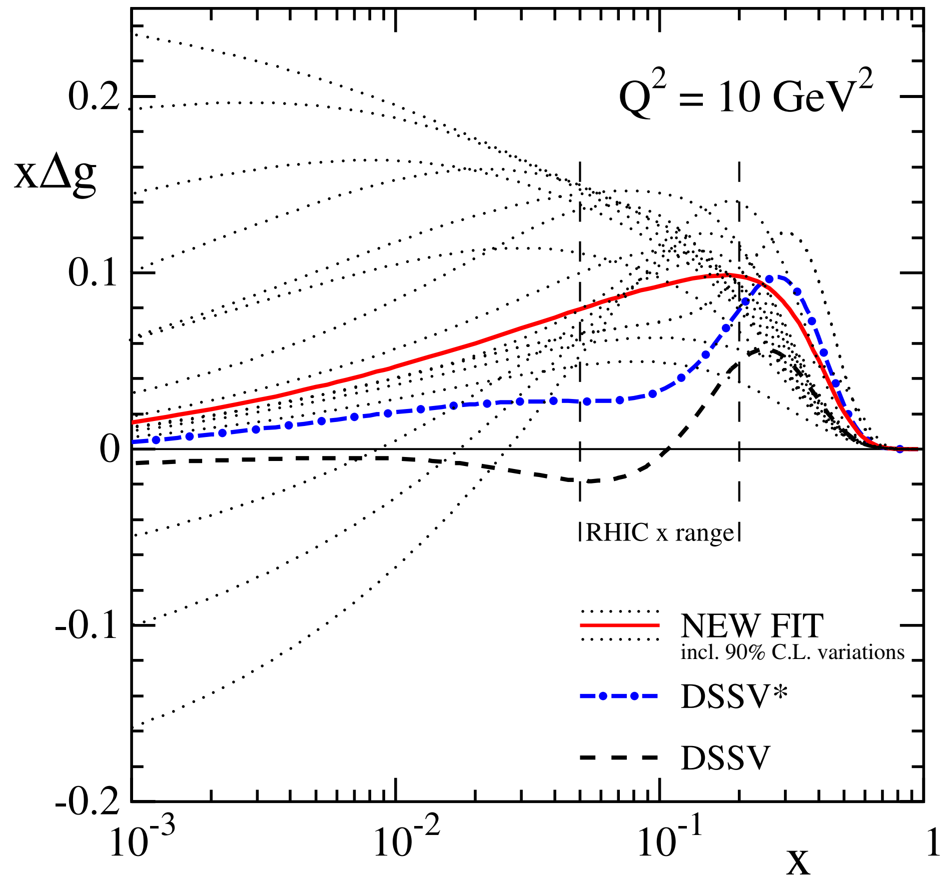
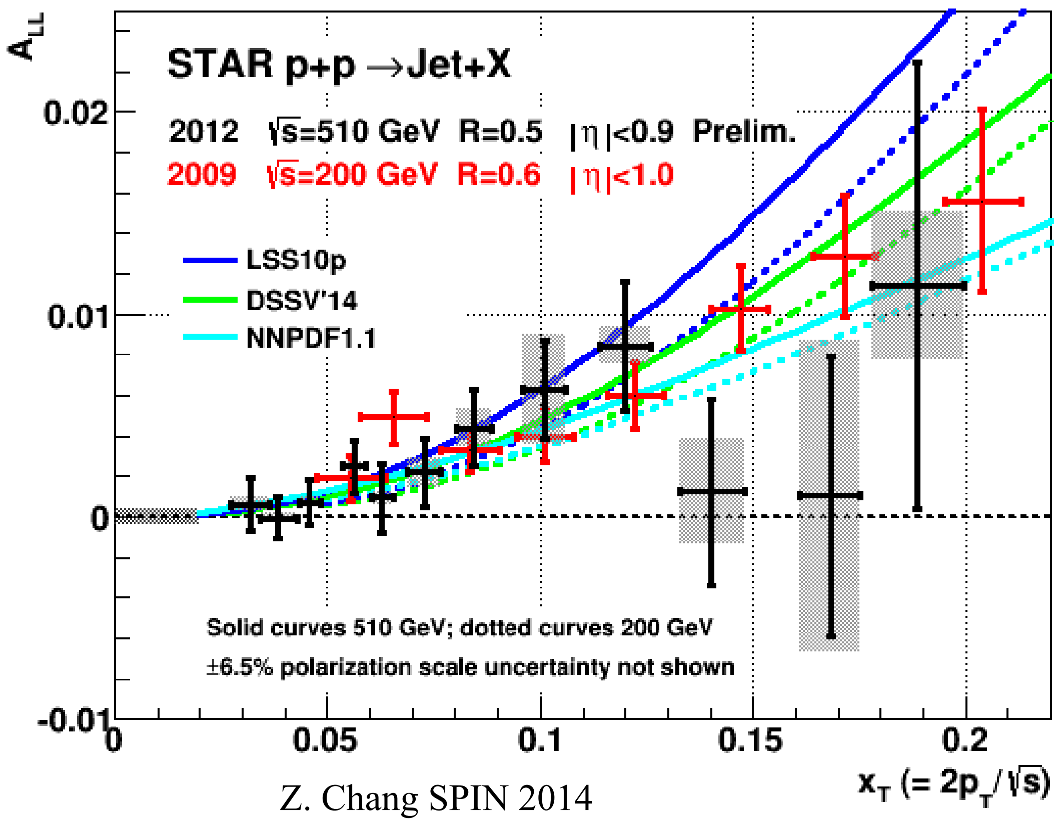


FIG. 1 (color online). Gluon helicity distribution at $Q^2 = 10\ \mathrm{GeV}^2$ for the new fit, the original DSSV analysis of [3], and for an updated analysis without using the new 2009 RHIC data sets (DSSV*, see text). The dotted lines present the gluon densities for alternative fits that are within the 90% C.L. limit. The x range primarily probed by the RHIC data is indicated by the two vertical dashed lines.

PRL 113, 012001 (2014)

2012 Inclusive Jet A_{LL} at 510 GeV



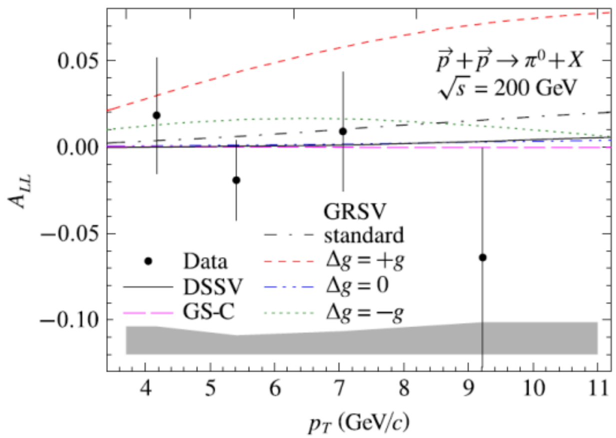
Z. Chang SPIN 2014
arXiv:1512.05400

- 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**

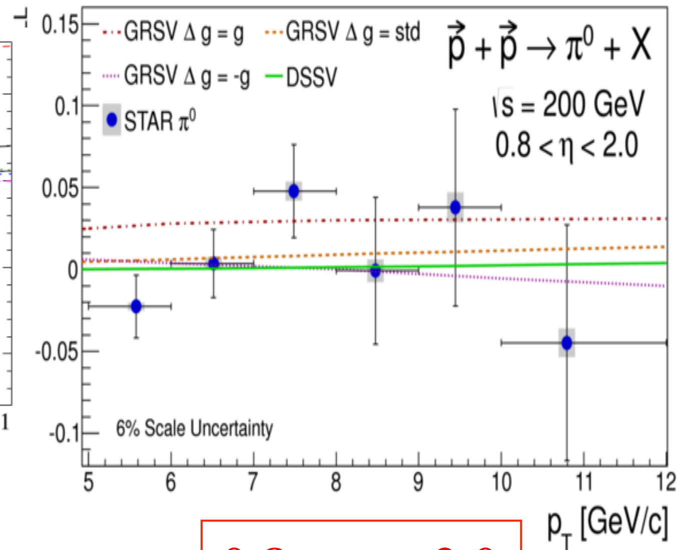
- Higher CoM pushes to lower x_T
  - Results agree in overlap region

Probing Low x Gluons With π^0 A_{LL}

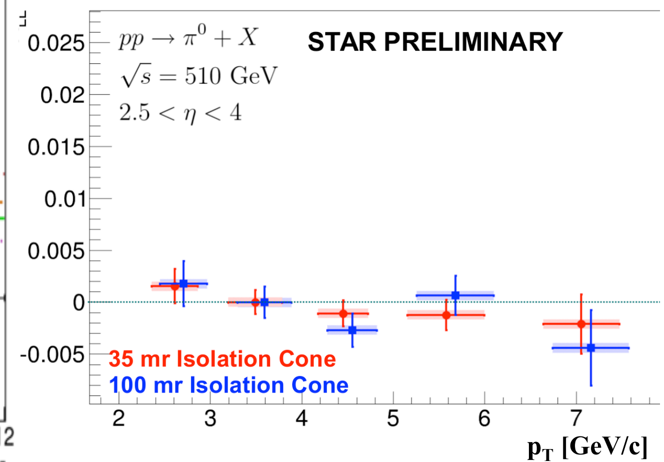
PRD 80, 111108(R) (2009)



PRD 89, 012001 (2014)



Dilks SPIN2014



|η| < 0.95

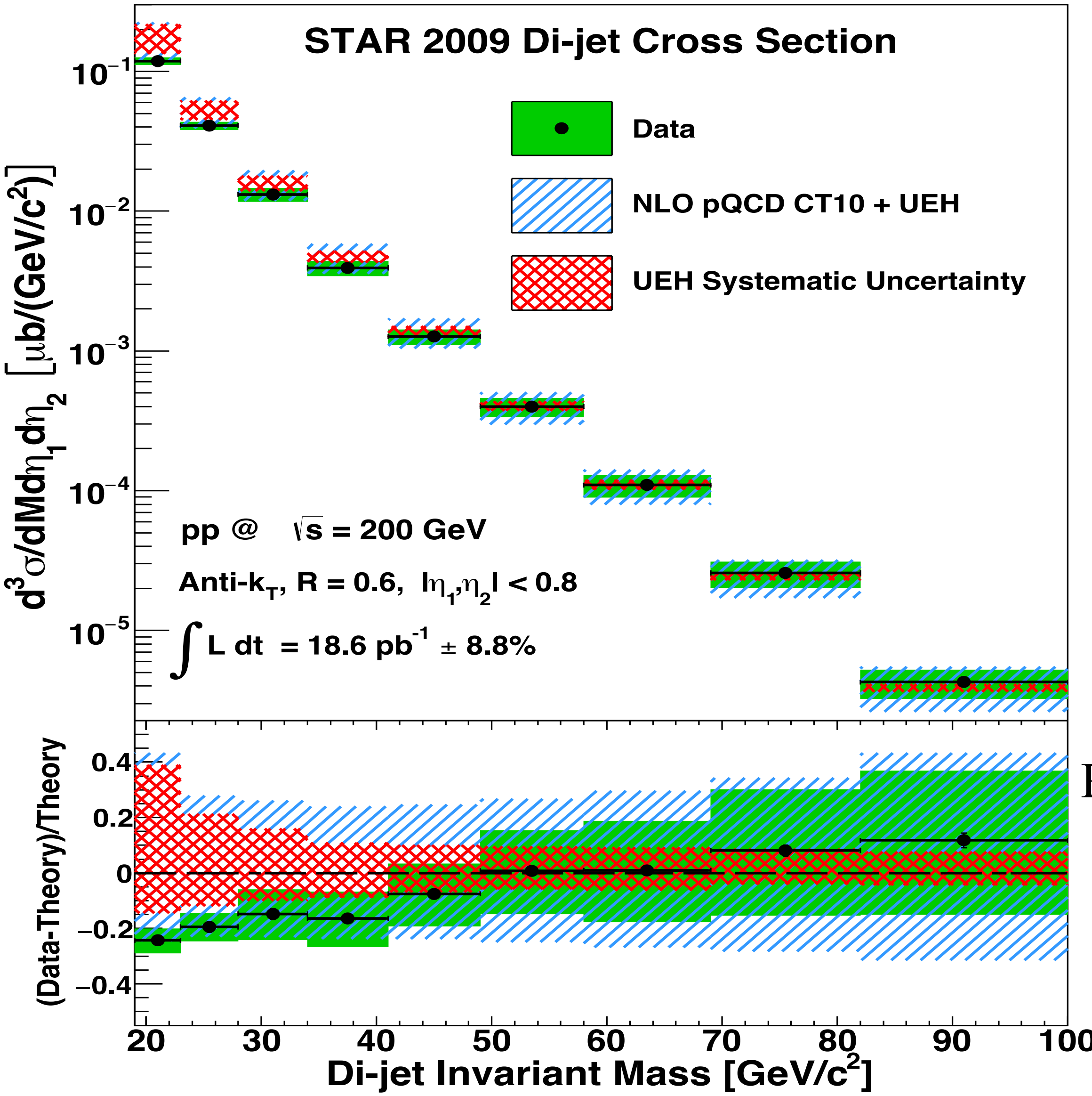
0.8 < η < 2.0

2.5 < η < 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**

2009 Dijet Cross Section Results



Vertical black hashing stat. error

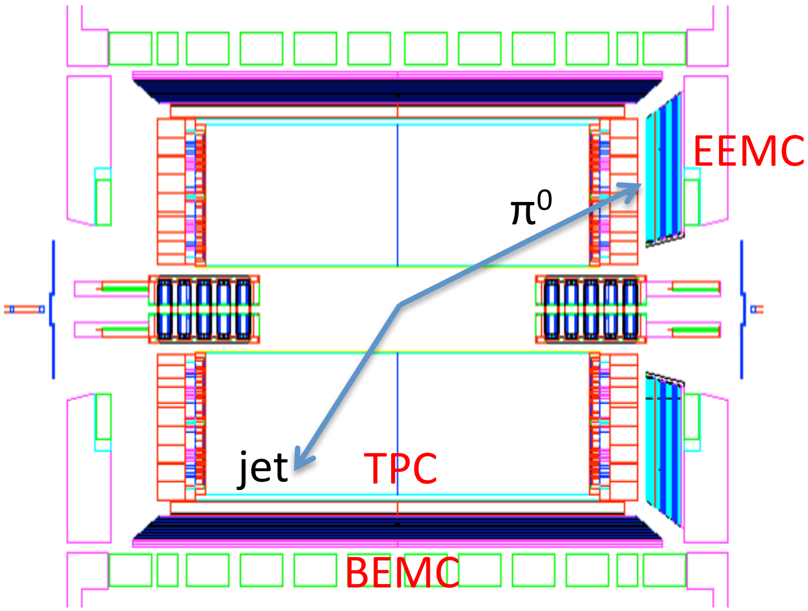
Green box is symmetric about data point and is the quadrature sum of all systematic errors

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

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

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.



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

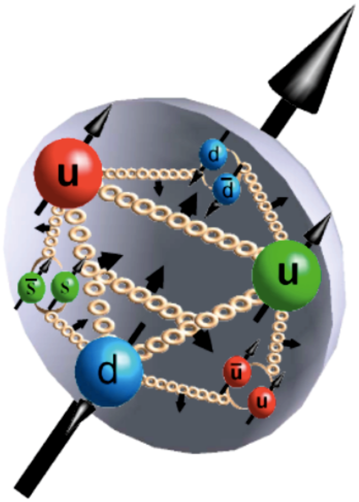
$$x_2 = \frac{p_T^{jet}}{\sqrt{s}}\left(e^{-\eta_{jet}} + e^{-\eta_{\pi^0}}\right),$$

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

- 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.

- 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

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



Proton momentum $\Rightarrow$

Proton spin $\Rightarrow$

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

$\Rightarrow$ – $\Leftarrow$

Longitudinal Polarization

Polarized DIS: ~0.3
Puzzling for ~25 years

Relatively poorly constrained
But S_g coming into focus!

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

Proton spin $\Uparrow$

$\delta q(x)$

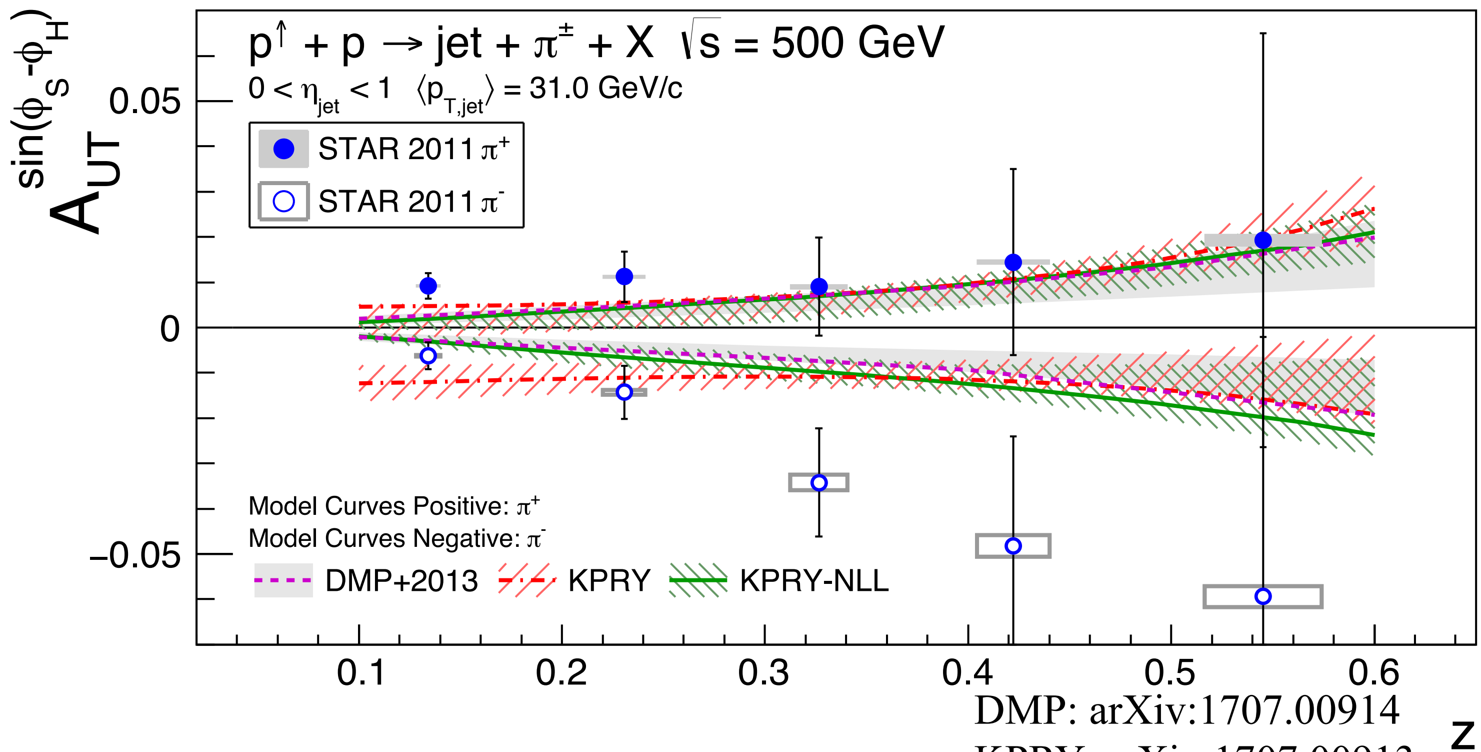
$\Uparrow$ – $\Downarrow$

Transverse Polarization

Transversity

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

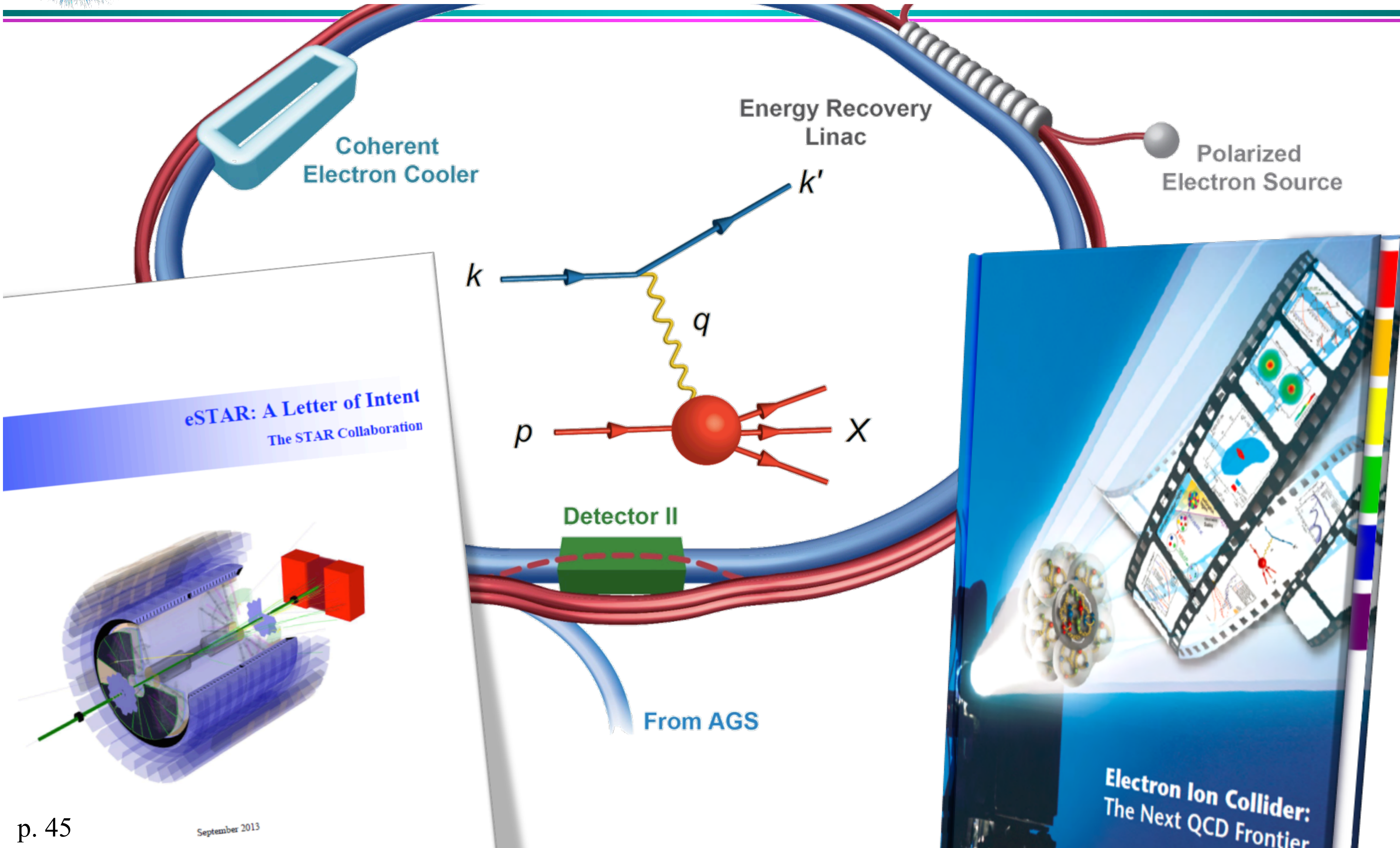
- Recently submitted to Phys Rev D (arXiv:1708.07080)
- Probes transversity coupled to Collins fragmentation function (or Twist 3 analog)
- Transversity at very high scales (Q^2 up to 900 GeV^2)



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)

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

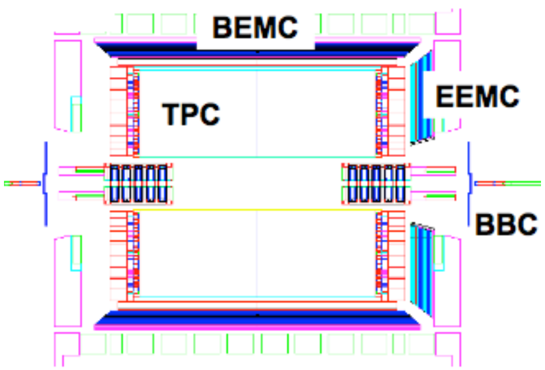


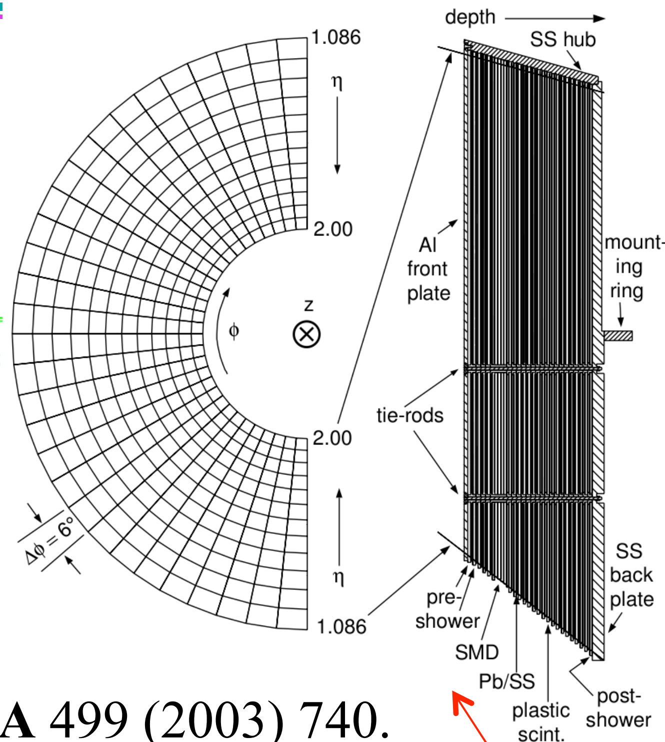
p. 45

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

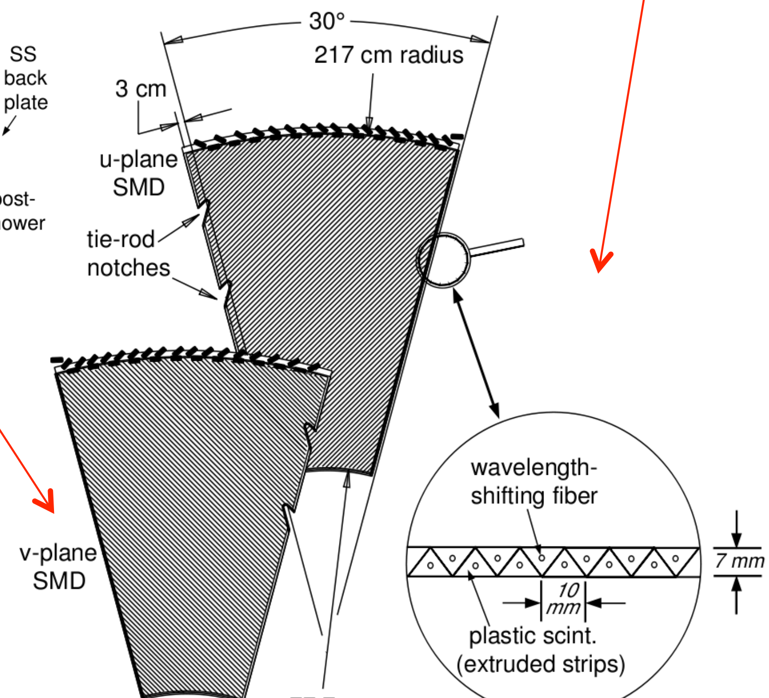
arxiv:1212.1701

STAR's Endcap Electromagnetic Calorimeter





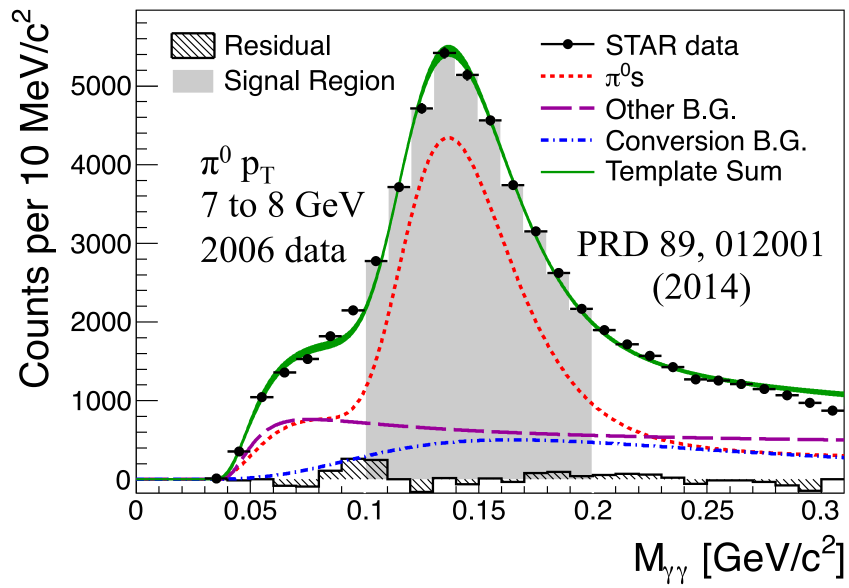
- Scintillating strip SMD
  - ϕ segmented into 12 sectors
  - Two active planes
  - 288 strips per plane
- Resolution of a few mm

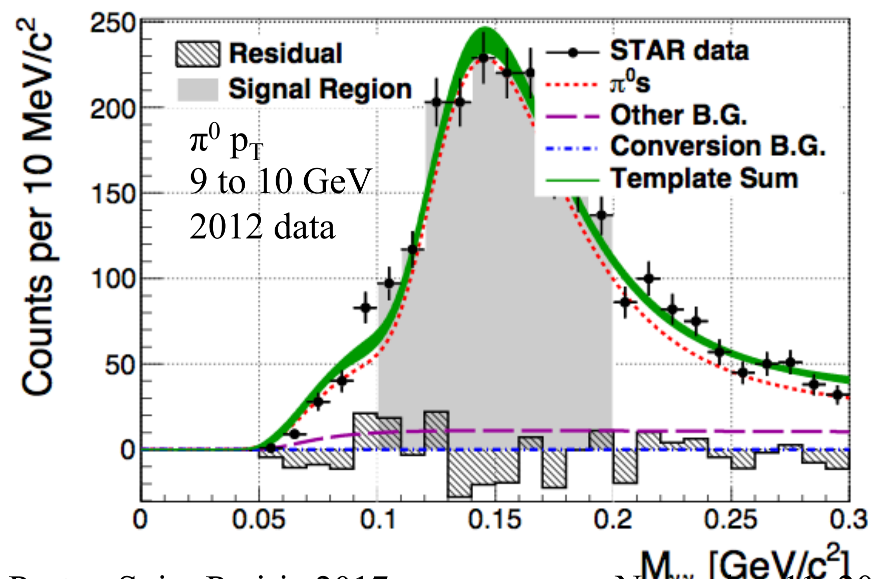


- Nucl. Instrum. Meth. **A** 499 (2003) 740.
- Lead/scintillator sampling EM calorimeter
  - Covers $1.09 < \eta < 2.00$ over full 2π azimuth
  - 720 optically isolated projective towers (~22 X_0)
  - 2 pre-shower, 1 post-shower layers, and an additional shower maximum detector (SMD)
- High Tower, Jet Patch, and Photon (high tower + 3x3 tower patch triggers)

π^0 Signal and Background Computation

- Inclusive π^0 mass distribution fit to 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
- 2012 dataset being analyzed now
  - x10 statistics; ~80 pb^{-1}, ~50% polarization
  - 510 GeV CoM energy w/ similar trigger, reconstruction thresholds allows access to **lower *x* gluons**
  - ~1% of data is shown here, on HT trigger
  - For now with 2006 MC templates





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