DOE NP contract: DE-SC0013405

SEA QUARK AND GLUON HELICITY RESULTS FROM STAR

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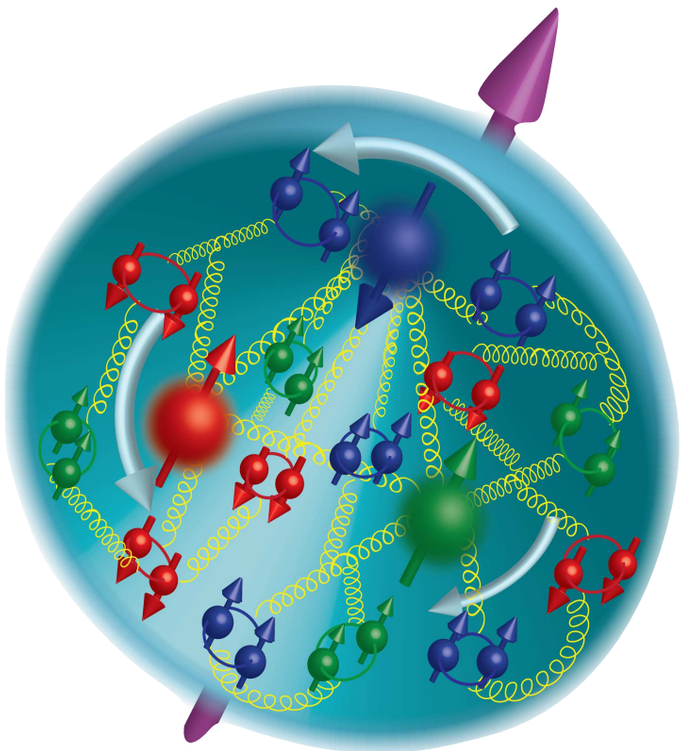
Spin structure of the proton



$$< S_z >= \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$

Polarized DIS : ~25%

DIS : Poorly constrained

Quark/ antiquark Polarization :

$$\Delta\Sigma = \int (\Delta u + \Delta d + \Delta s + \Delta\bar{u} + \Delta\bar{d} + \Delta\bar{s})dx$$

- Integral was well measured in DIS but small (only 25%).
- Large uncertainty for antiquark distribution from SIDIS

Gluon Polarization:

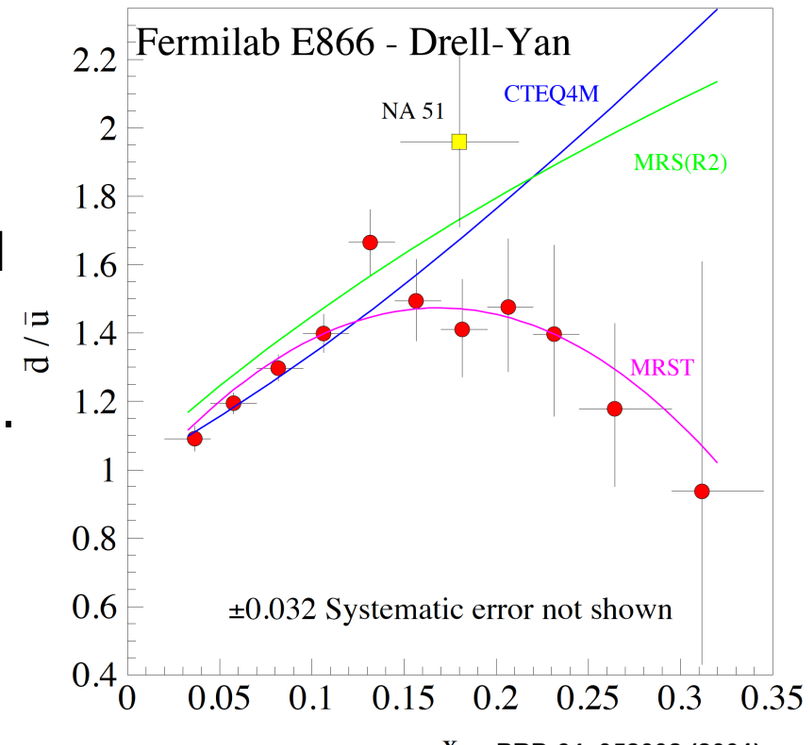
$$\Delta G = \int \Delta g(x)\,dx$$

- Large uncertainty from DIS and SIDIS
- First evidence of non-zero Δg from RHIC 2009 data

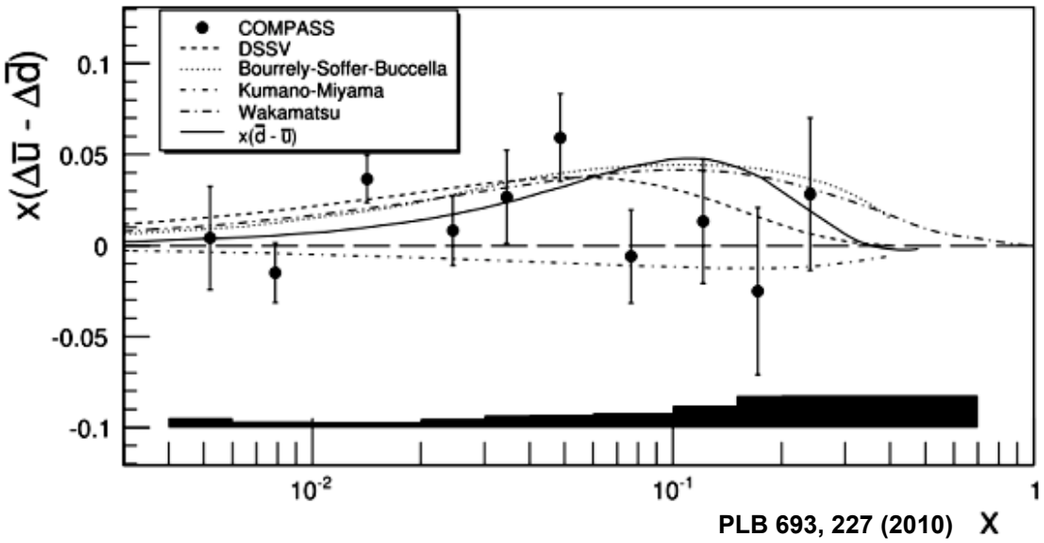
Quark / Antiquark polarization DIS

Unpolarized flavor asymmetry

- Purely perturbative process of gluon splitting into quark and antiquark pair expect to be flavor symmetric.
- E866 results: Significant flavor asymmetric structure in **unpolarized quark / antiquark.**
- Several models **qualitatively explain this feature in the low x region.**
- More data needed to explain the high x region. / FNAL SeaQuest experiment / STAR W measurements.
- Some models have predicted an asymmetry in the respective helicity distributions.



Polarized flavor asymmetry [DIS , SIDIS]



- Uncertainties are large / Tendency for flavor asymmetry.

Quark / Antiquark polarization DIS

Unpolarized flavor asymmetry

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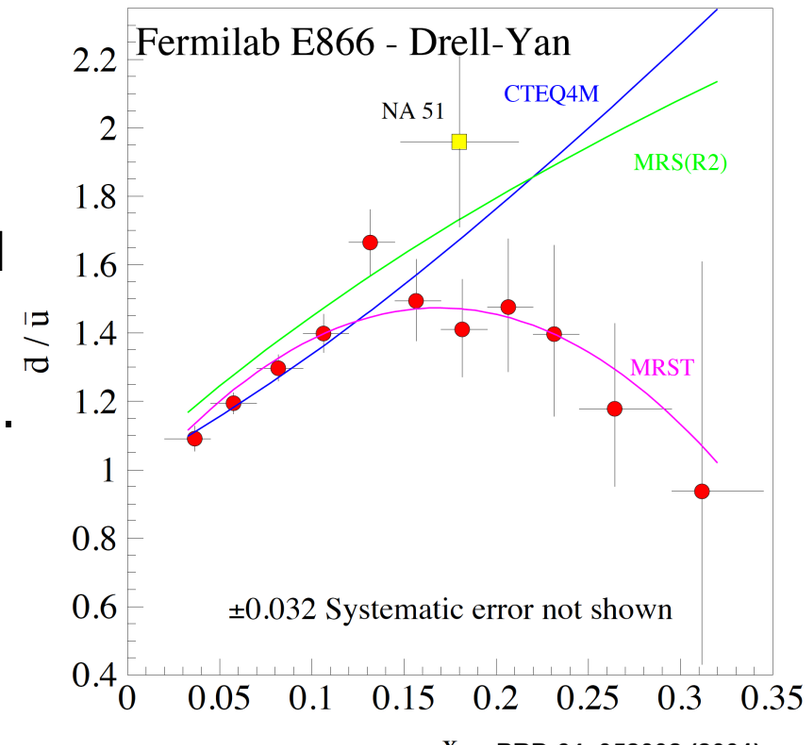
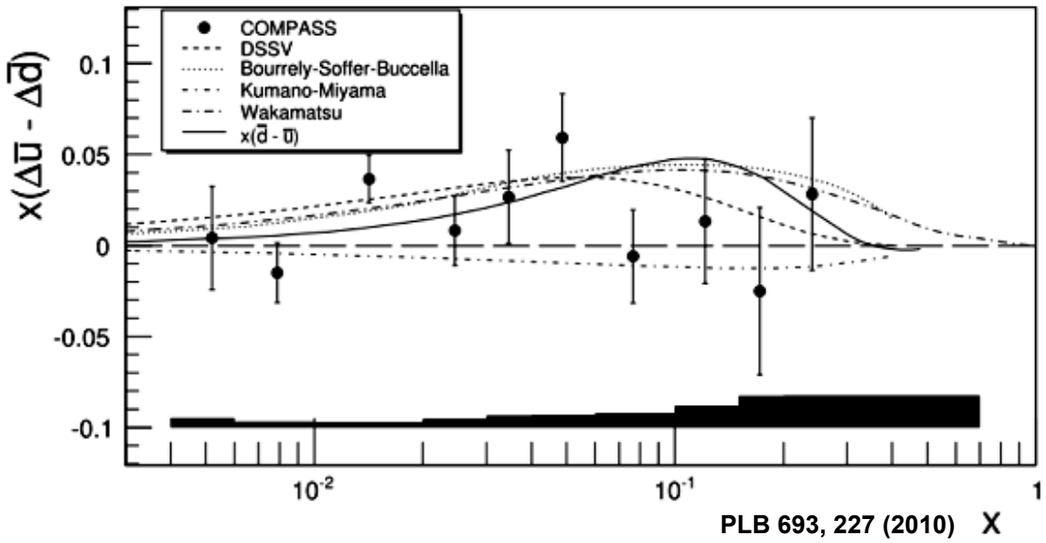
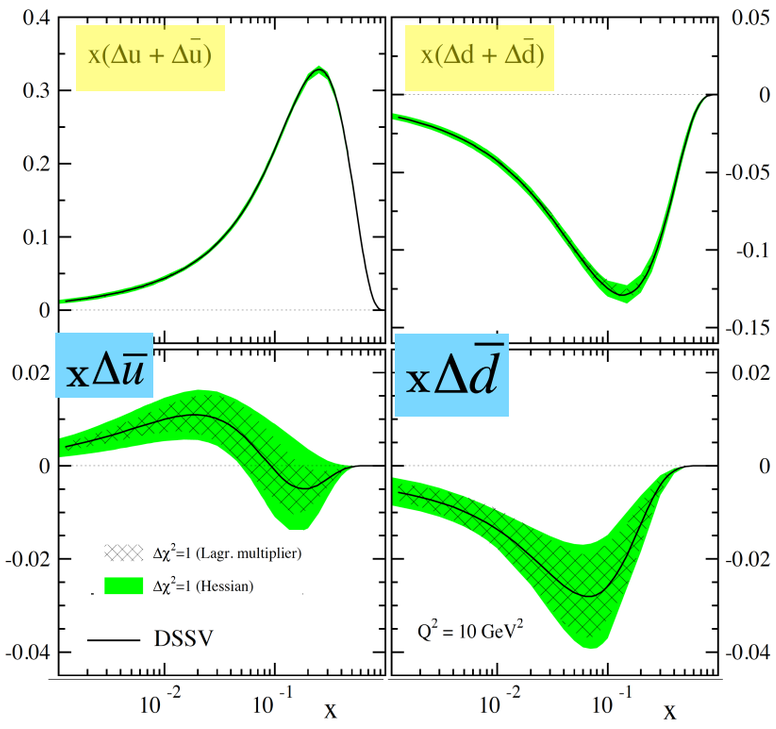


Polarized flavor asymmetry [DIS , SIDIS]



- Uncertainties are large / Tendency for flavor asymmetry.
- W production at RHIC provide direct access to antiquark distributions!

Quark / antiquark polarization measurements from DIS

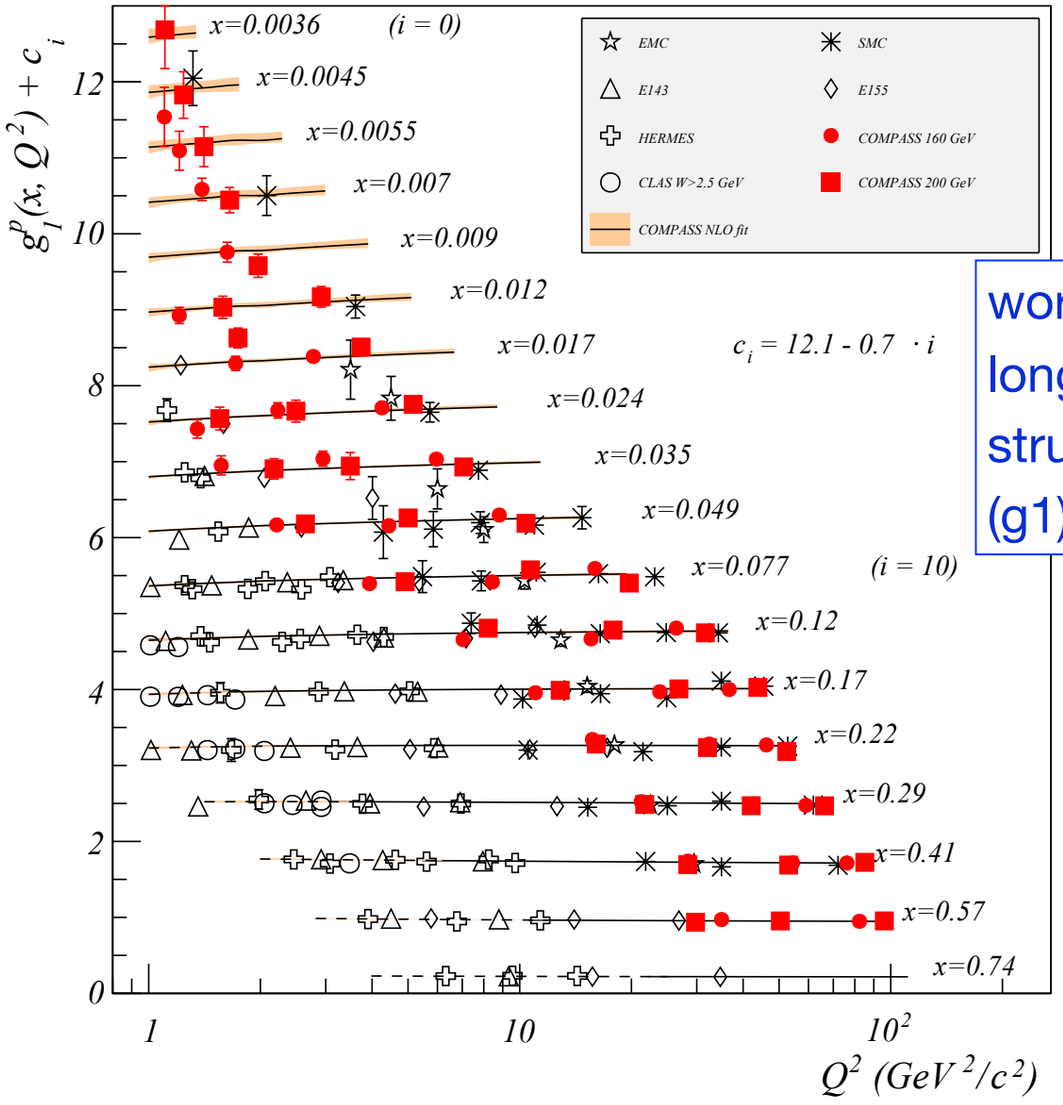


4DSSV global analysis , **PRD 80,034030 (2009)**

- Polarized DIS measure $\Delta u+\Delta\bar{u}$ and $\Delta d+\Delta\bar{d}$
- Polarized SIDIS provide flavor separation.
- Large uncertainty for $\Delta\bar{u}$ *and* $\Delta\bar{d}$
- SIDIS Results depend on FFs.

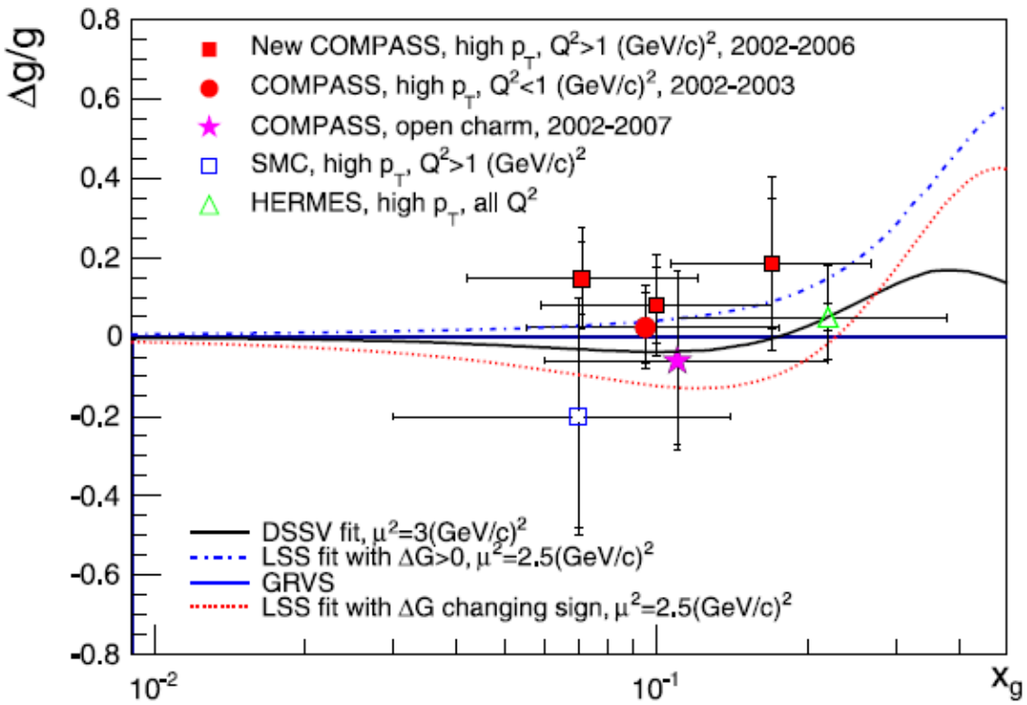
Gluon polarization in DIS

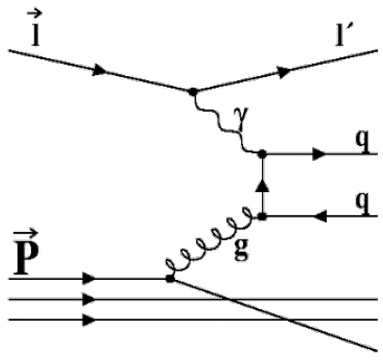
Indirect measurement



world data on longitudinal spin structure function (g1)

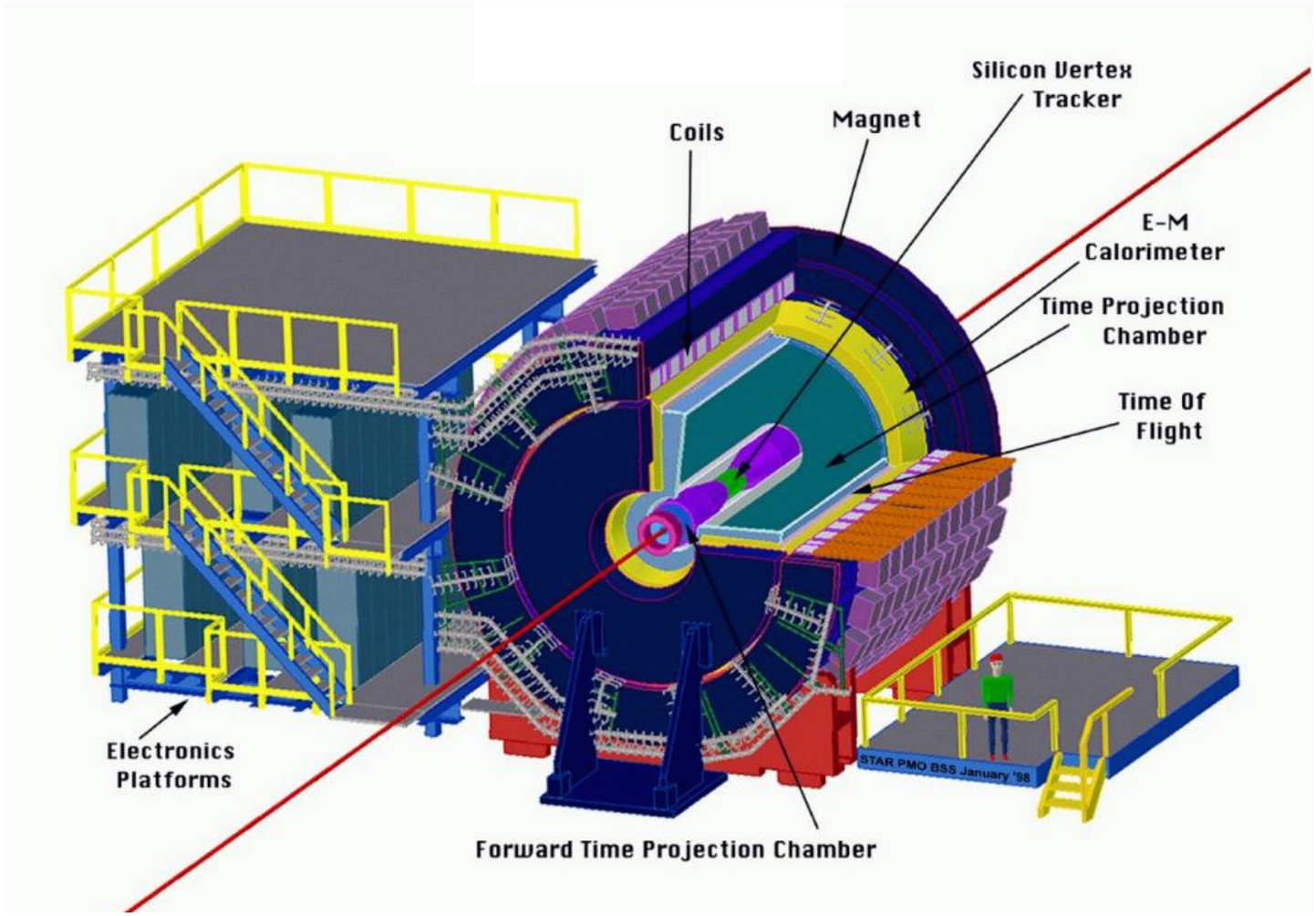
Direct measurement

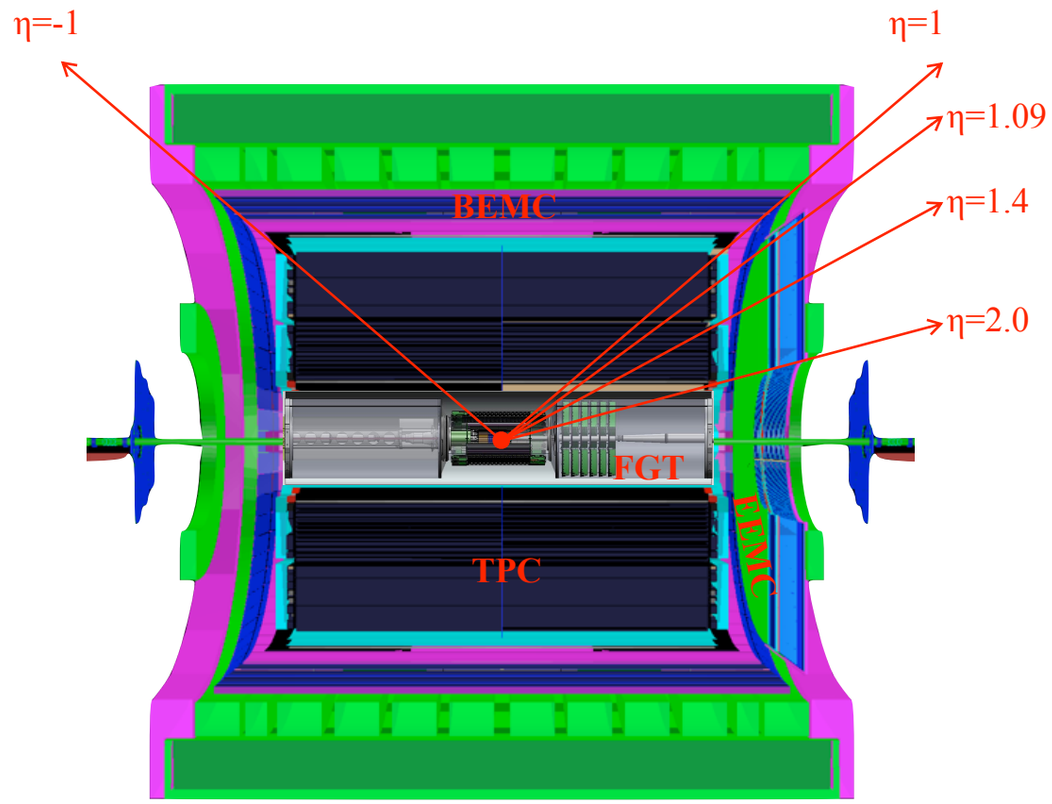




- Polarized DIS data so far **only from fixed-target experiments** / New data from COMPASS / Small lever-arm in Q^2 - Large uncertainties in Δg from scaling violations.
- Direct LO extraction of Δg generally positive and consistent with inclusive DIS measurements and RHIC constraints, but large uncertainties.

STAR Detector



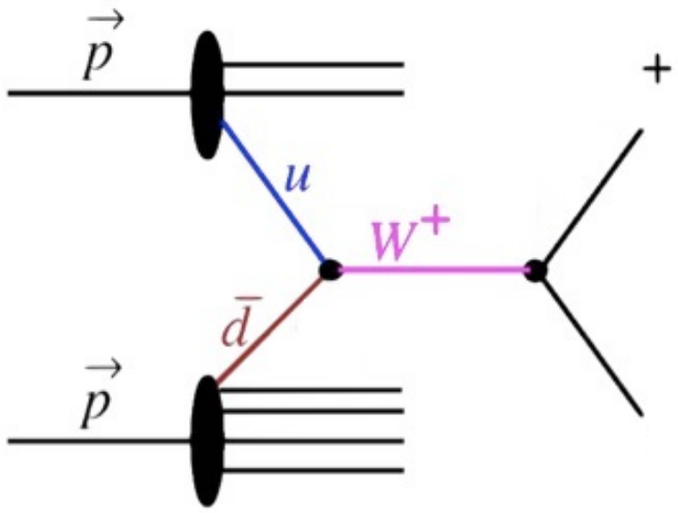


$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

- High precision charged particle tracking and particle ID with the TPC for |η| < 1.4.
- Electromagnetic calorimetry system with 2π coverage [BEMC (|η| < 1.0) , EEMC (1<η<2)].
- Additional detectors (ZDC, BBC, VPD) for relative luminosity measurements and local polarimetry.

Sea Quark Polarization Measurement at STAR

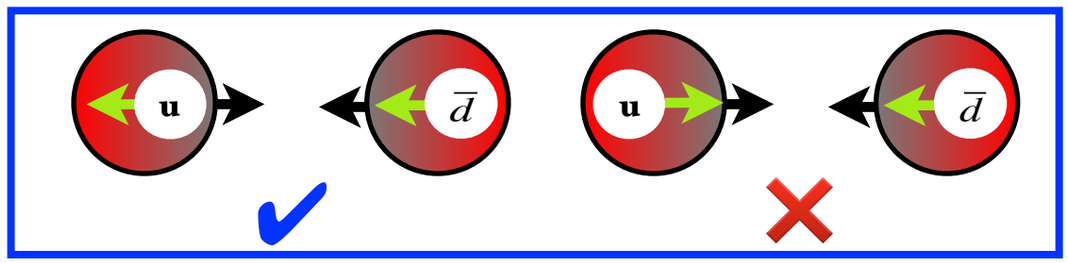
Exploring antiquark polarization at RHIC



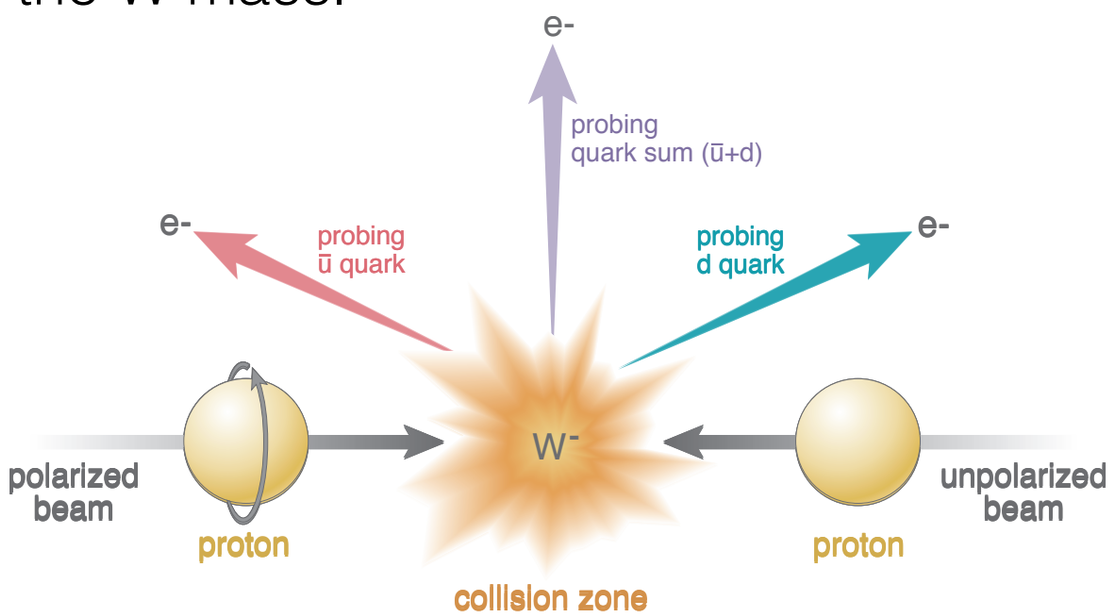
$$u + \bar{d} \rightarrow W^+ \rightarrow e^+ + \nu \qquad \bar{u} + d \rightarrow W^- \rightarrow e^- + \bar{\nu}$$

- Direct Coupling to the Quark and anti Quark of interest.

- Maximum violation of parity leads to perfect spin separation.



- High resolution scale (Q^2) set by the W mass.



- **Easy detection** via the leptonic decay channels.

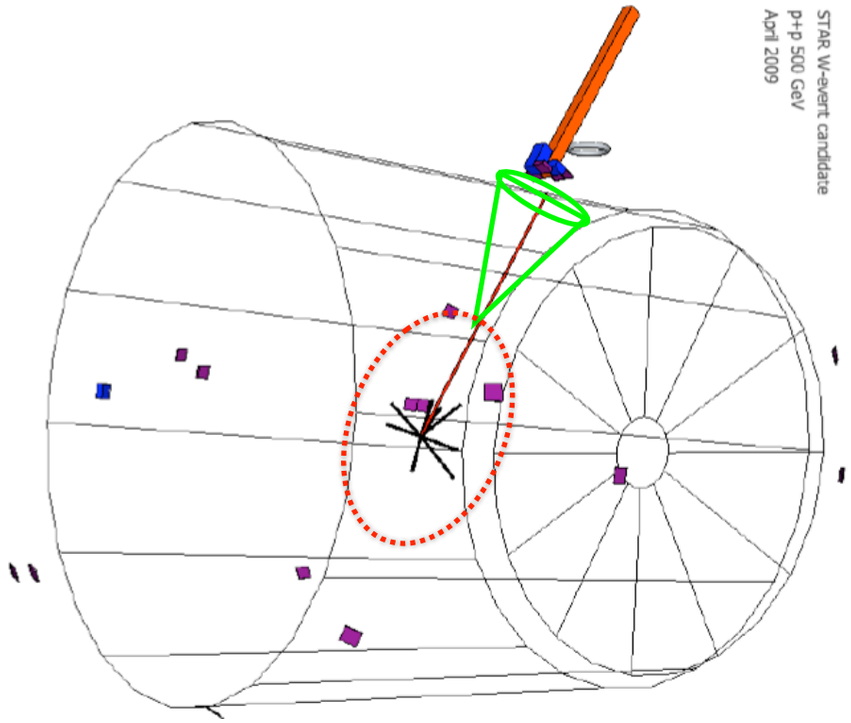
- The parity violating single spin asymmetry, **A_L** for W production provides direct information about antiquark polarization.

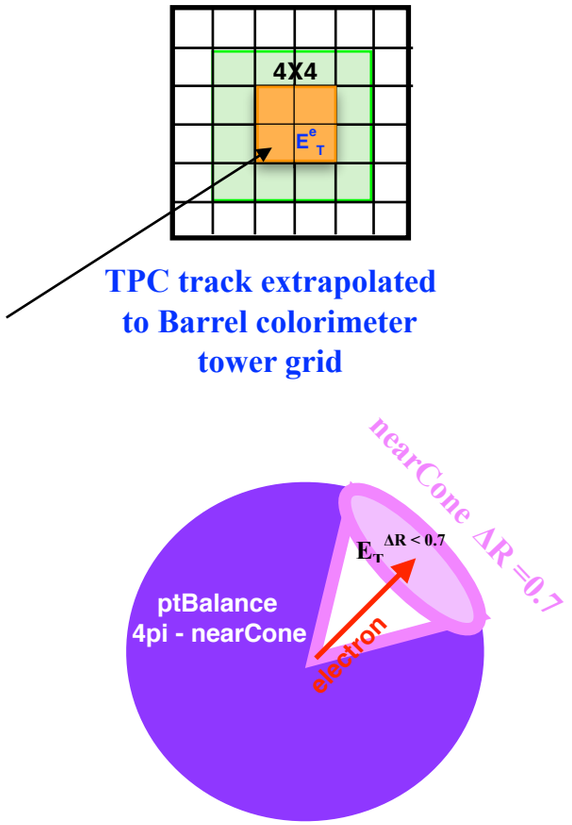
$$A_L^{e^-} \approx \frac{\int_{\otimes(x_1,x_2)} [\Delta\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 - \Delta d(x_1)\bar{u}(x_2)(1+\cos\theta)^2]}{\int_{\otimes(x_1,x_2)} [\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 + d(x_1)\bar{u}(x_2)(1+\cos\theta)^2]}$$

$$A_L^{e^+} \approx \frac{\int_{\otimes(x_1,x_2)} [\Delta\bar{d}(x_1)u(x_2)(1+\cos\theta)^2 - \Delta u(x_1)\bar{d}(x_2)(1-\cos\theta)^2]}{\int_{\otimes(x_1,x_2)} [\bar{d}(x_1)u(x_2)(1+\cos\theta)^2 + u(x_1)\bar{d}(x_2)(1-\cos\theta)^2]}$$

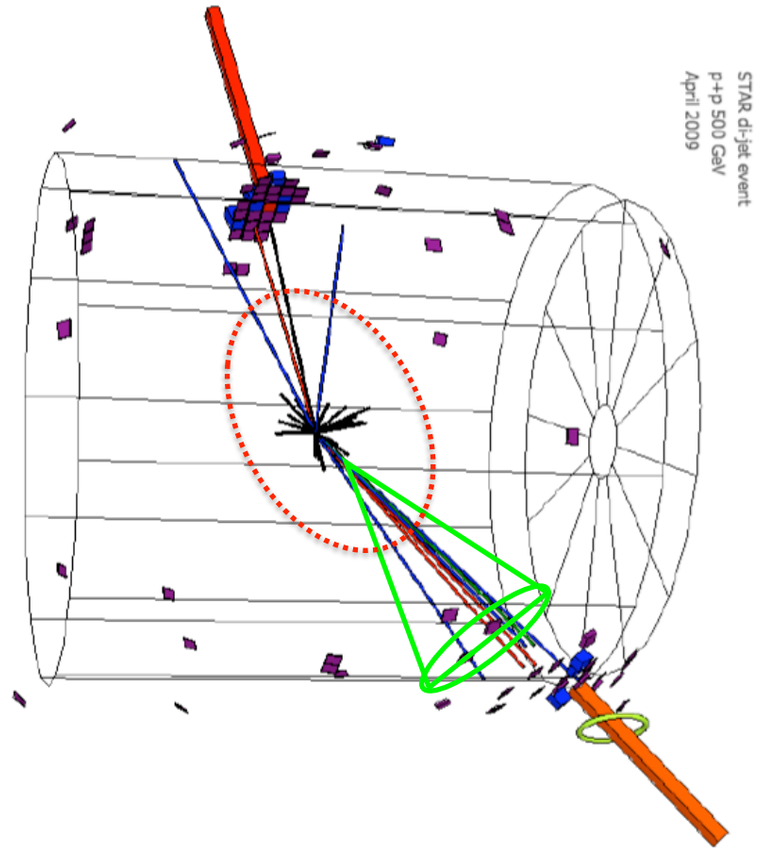
W boson reconstruction at STAR

Calorimeter response from a simulated W event





Calorimeter response from a simulated QCD type di-jet background event



- W candidate events are isolated TPC tracks pointed to isolated calorimeter cluster.
- Due to undetected neutrino large missing energy opposite the electron candidate.
- Large imbalance in the transverse momentum.

- Di-jet BG events are several TPC. tracks pointed to several calorimeter cluster.
- Transverse momentum is balanced by the opposite jet and missing energy is small.

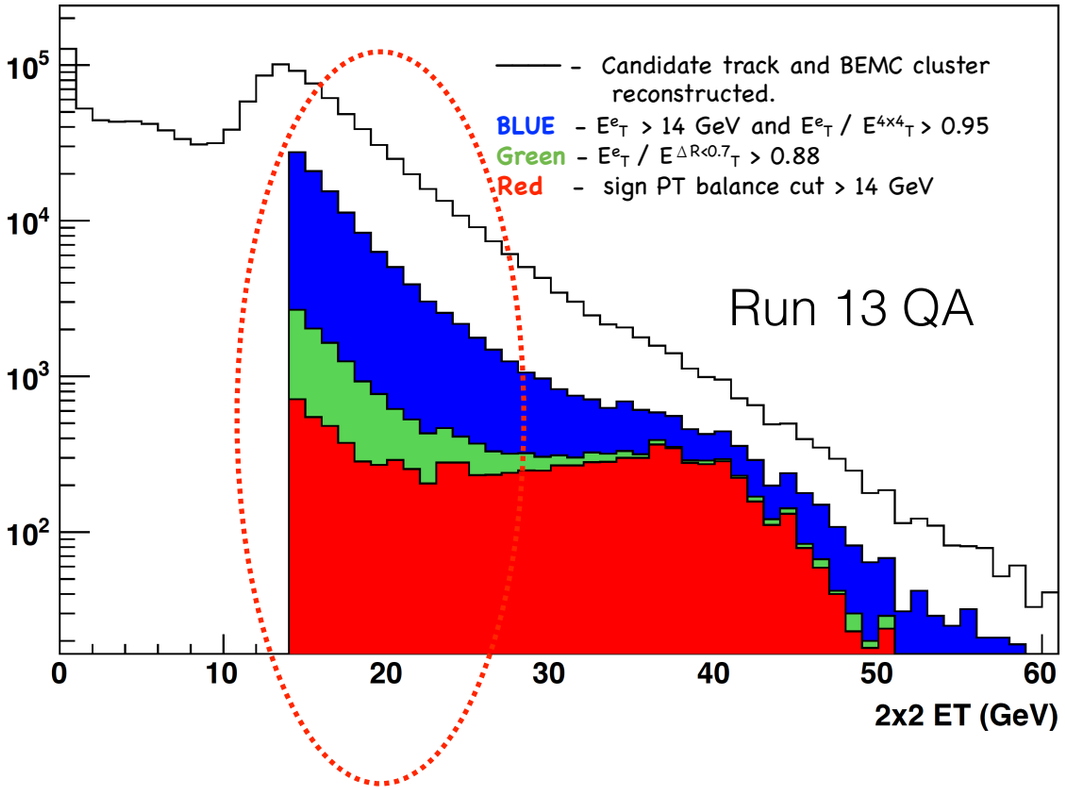
$E^{2x2}_T > 14$ GeV

$E^{2x2}_T / E_T^{4X4} > 95\%$

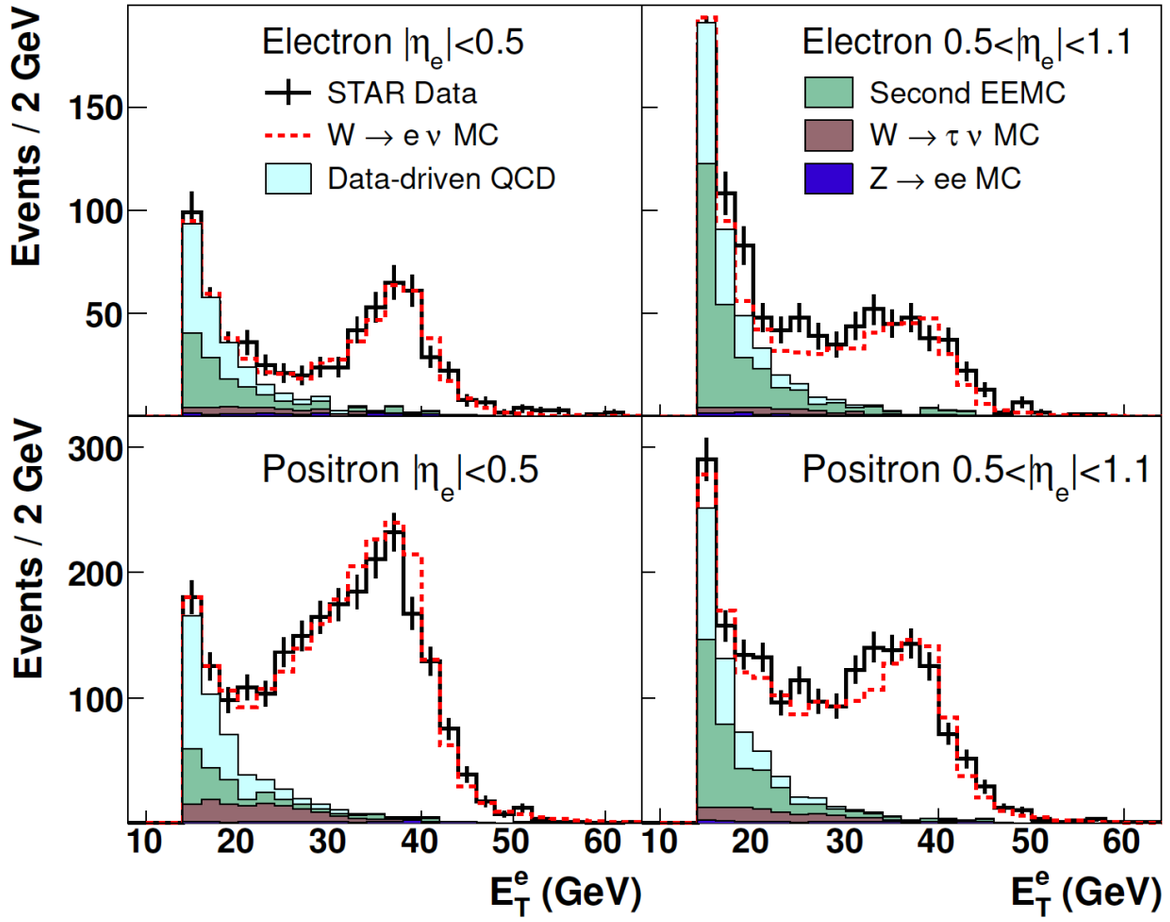
$E^{2x2}_T / E_T^{\Delta R < 0.7} > 88\%$

$$\vec{p}_T^{\,balance} = \vec{p}_T^{\,e} + \sum_{\Delta R > 0.7} \vec{p}_T^{\,jets}$$

Mid-rapidity background estimation



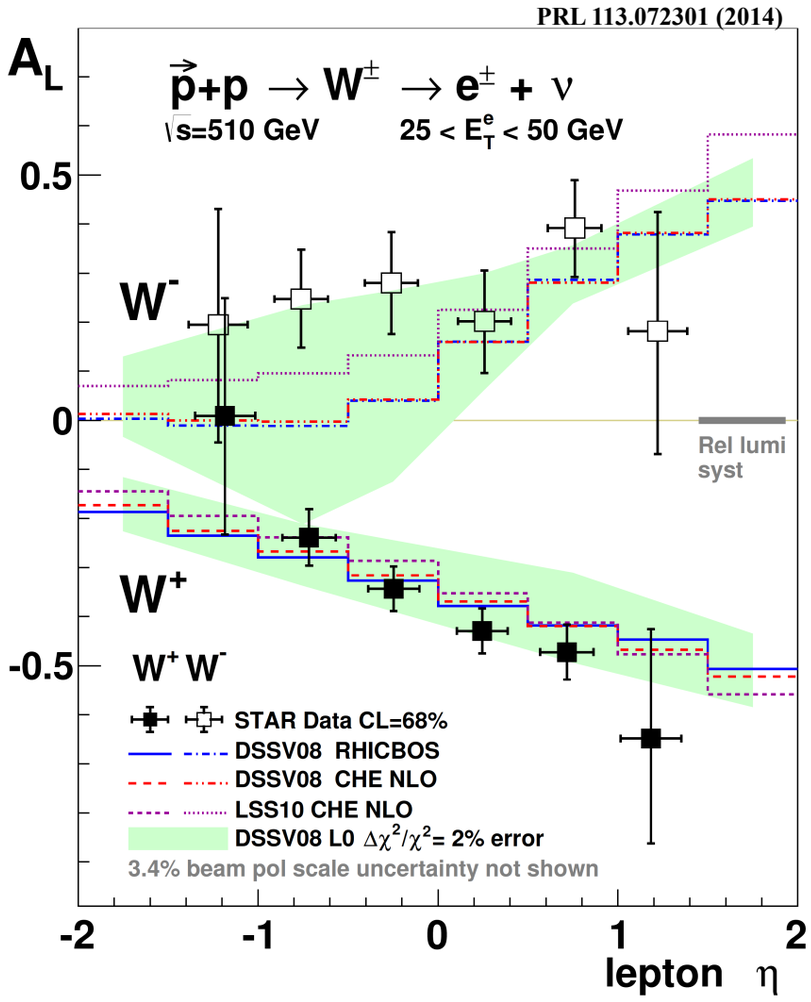
PRL 113.072301 (2014)



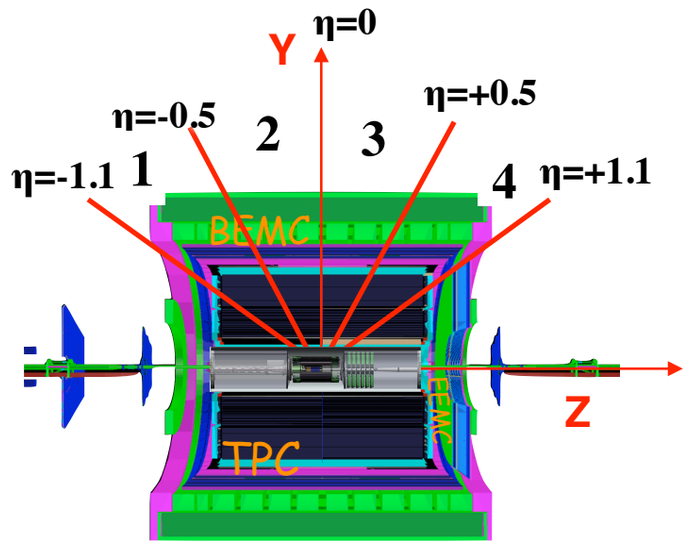
- **QCD background** is estimated using a data-driven procedure and veto ing on EEMC calorimeter
- **Electroweak backgrounds** (W->τ + ν and Z->e^++e^-) estimate using MC simulation

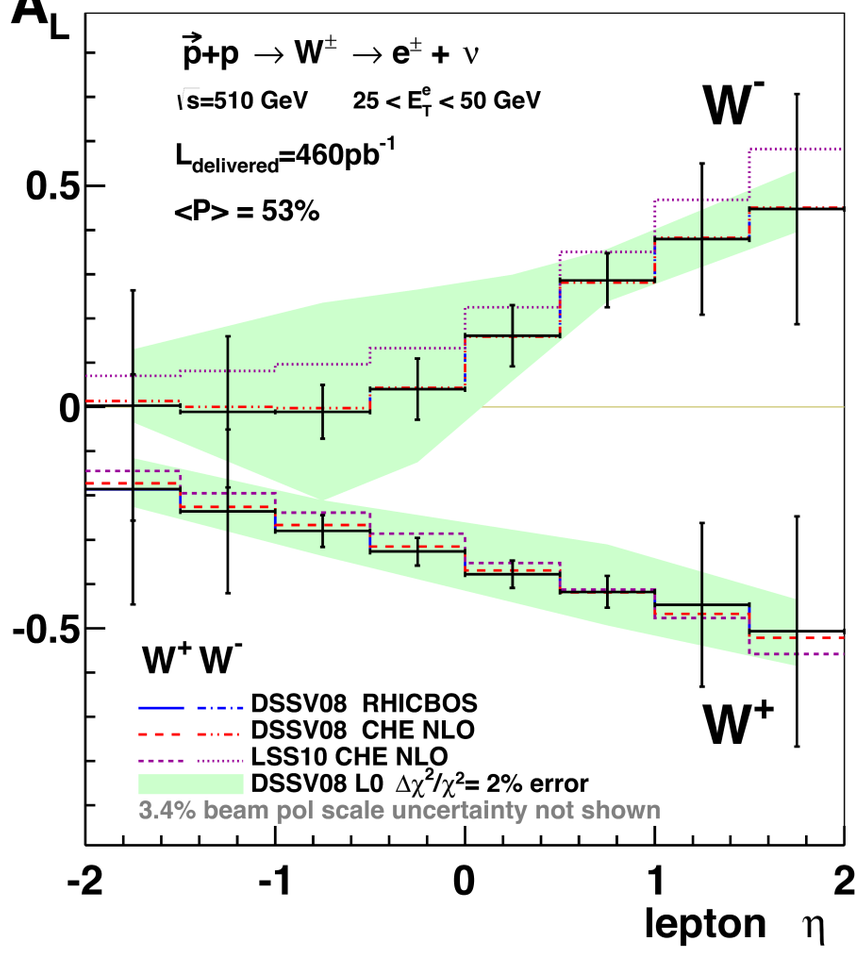
STAR W $A_L(\eta)$

STAR W A_L from 2011 + 2012 data



$$A_L = \frac{1}{P_1}\frac{N_{++} + N_{+-} - N_{--} - N_{-+}}{N_{++} + N_{+-} + N_{--} + N_{-+}}$$



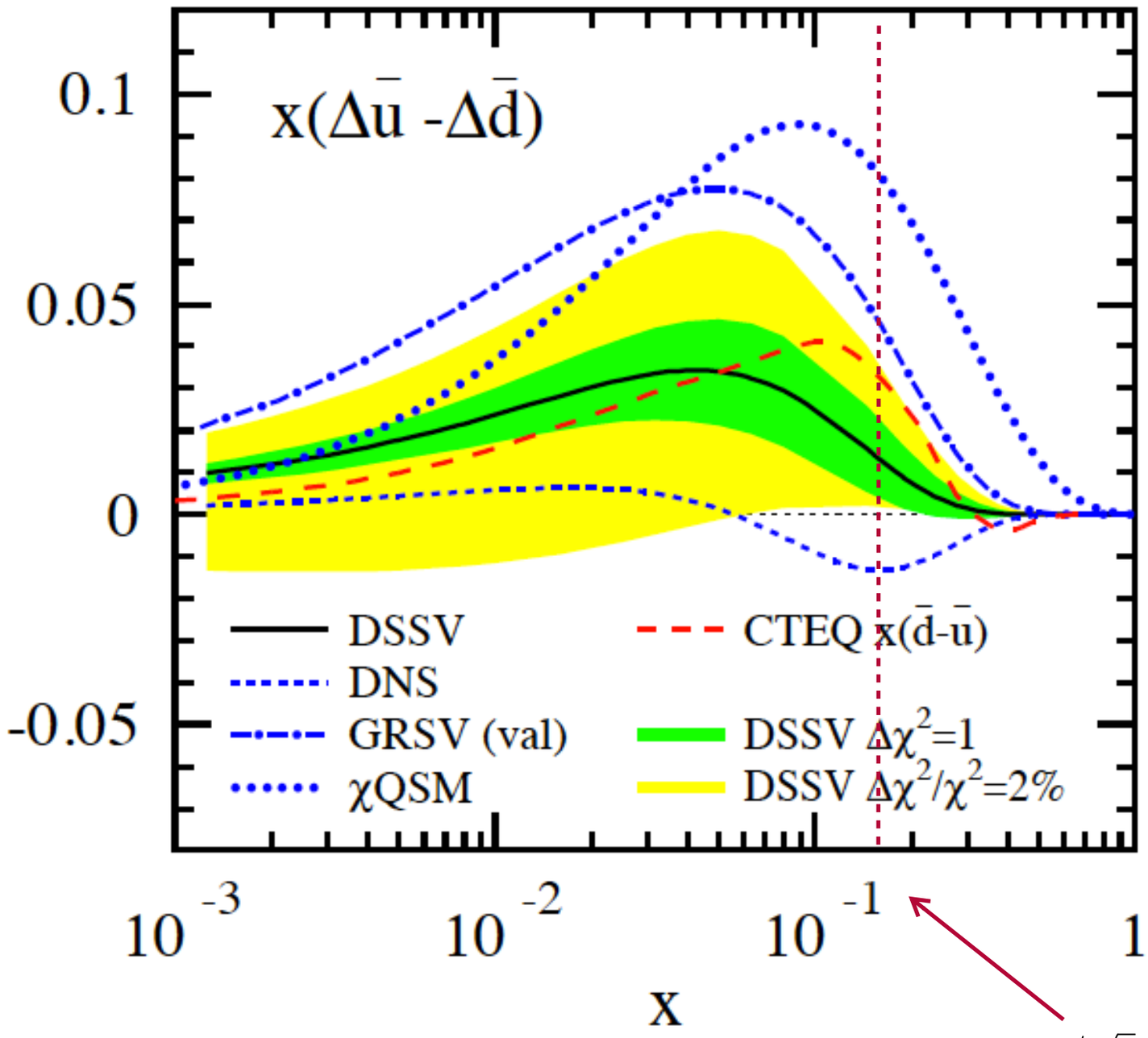


- A_L for W^+ is **consistent with theoretical predictions** constrained by polarized SIDIS data
- A_L for W^- is larger than the prediction for η_e <0 ,which suggest large $\Delta\bar{u}$
- Indication of positive $\Delta\bar{u}$ at 0.05<η<0.2.

- In 2013 STAR recorded **~4 times** as much data than what included in 2012 published results
- Expect significant reduction of the uncertainty
- **Extend kinematic coverage** to forward eta using FGT

STAR W A_L results in global analysis

D. de Florian et al., Phys. Rev. Lett. 101 (2008) 072001



- From recent DSSV++ result incl. STAR A_L data:

$$\int_{0.05}^{1} \Delta\bar{u}(x, Q^2)dx \approx 0.02$$

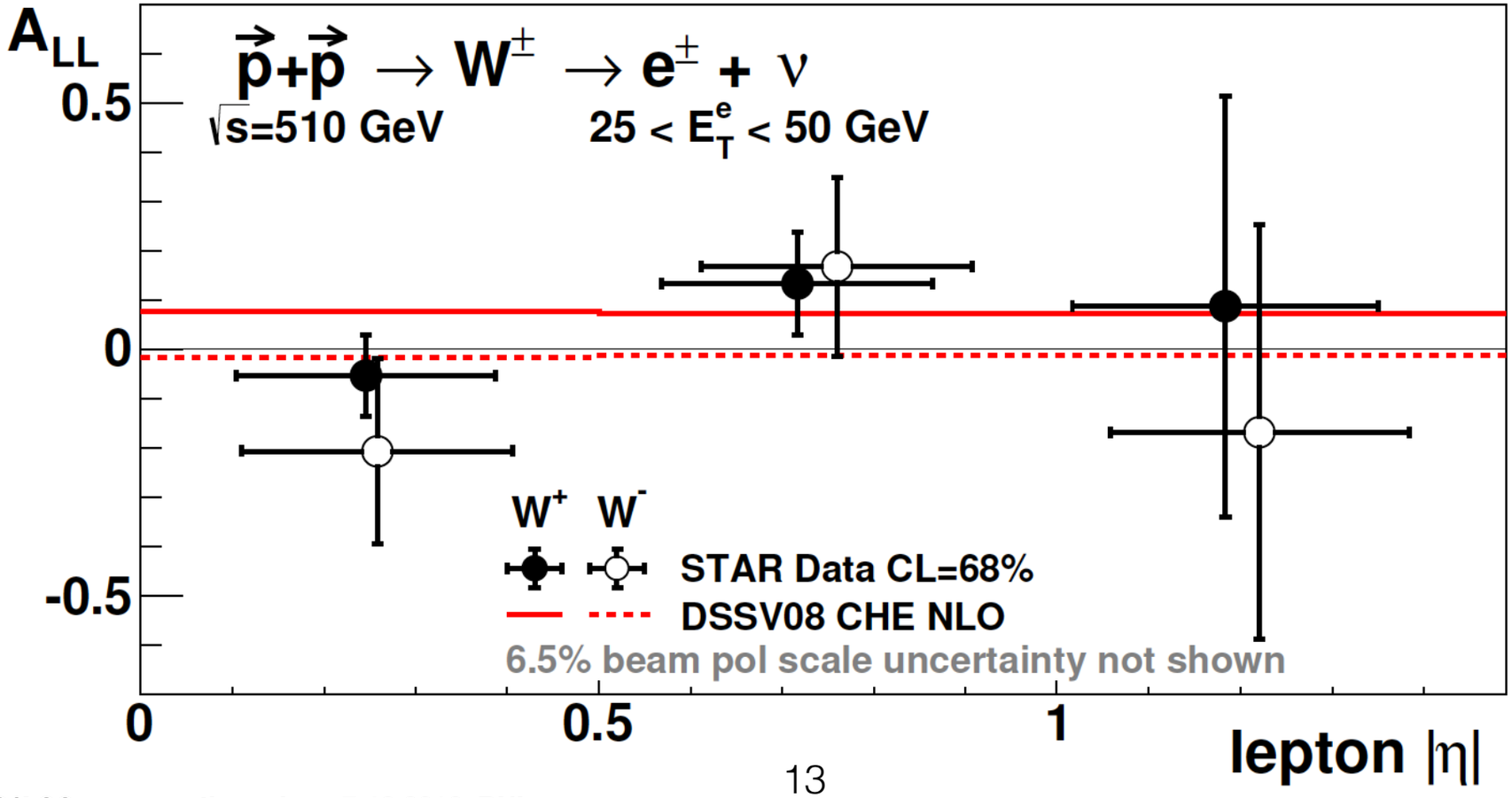
$$\int_{0.05}^{1} \Delta\bar{d}(x, Q^2)dx \approx -0.05$$

STAR W A_{LL} Measurements

- W A_{LL} probe different combinations of quark polarizations
- Asymmetries expected to be smaller, and first measurement consistent with predictions from DIS.

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \qquad A_{LL}^{W+} \sim \frac{\Delta u}{u}\frac{\Delta \bar{d}}{\bar{d}} \qquad A_{LL}^{W-} \sim \frac{\Delta d}{d}\frac{\Delta \bar{u}}{\bar{u}}$$

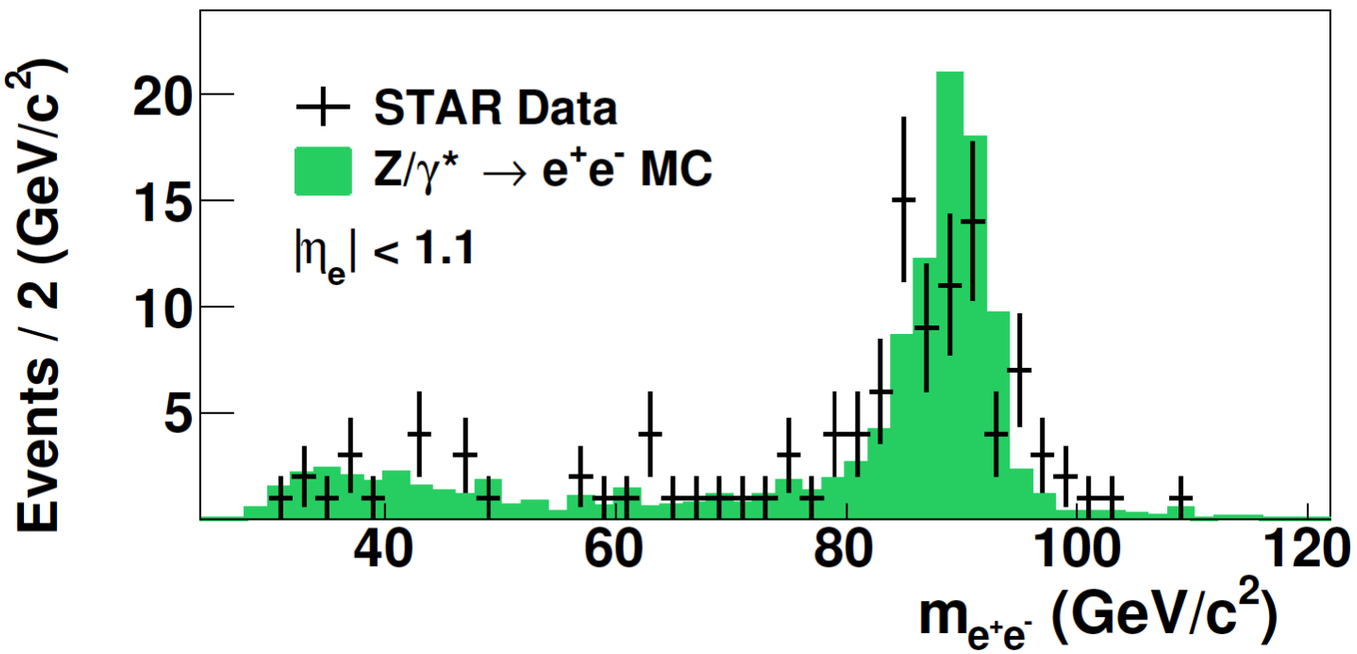
STAR W A_{LL} from 2011 + 2012 data

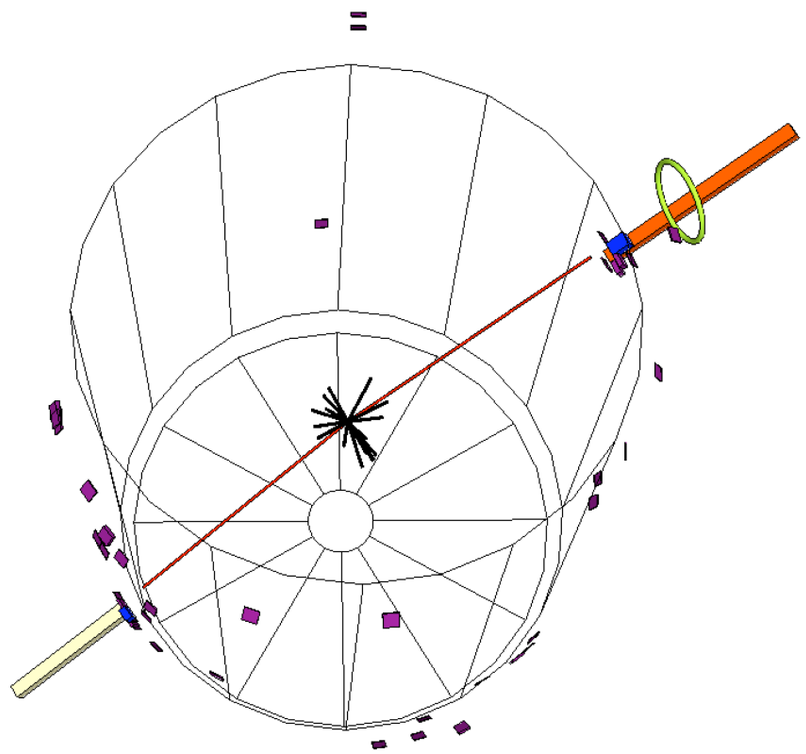


STAR Z A_L

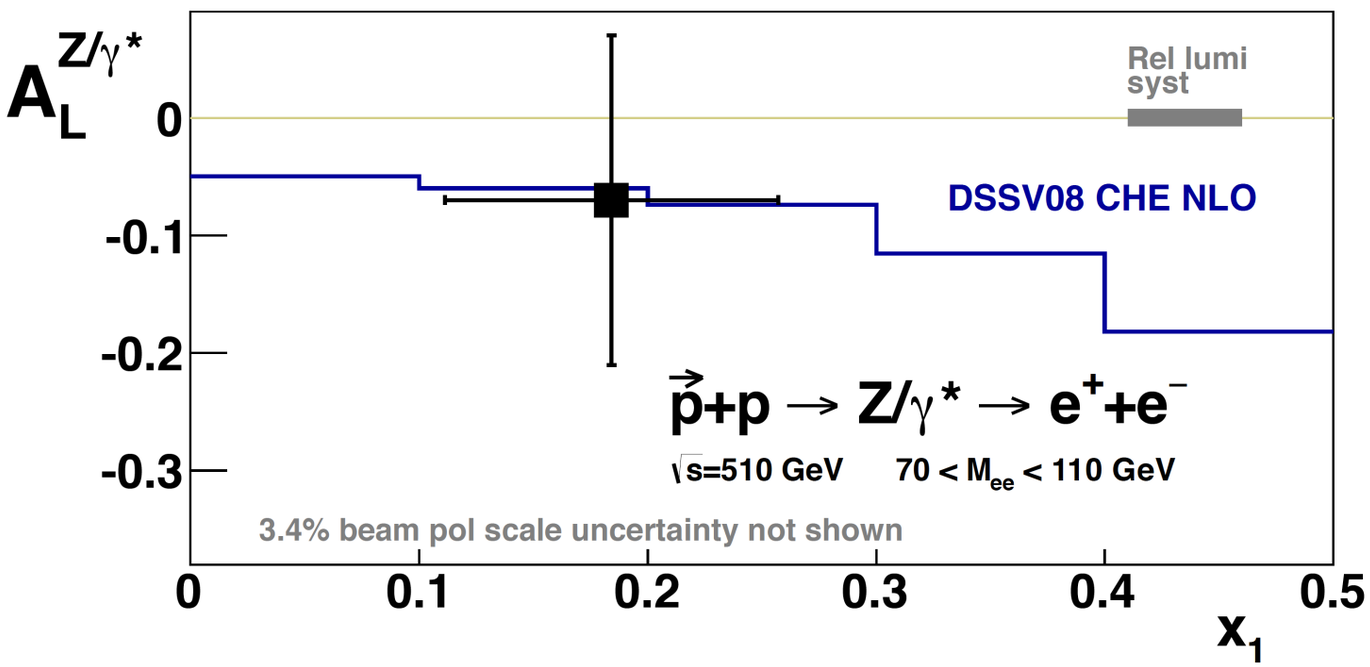
STAR Z->e^++e^- invariant mass distribution from 2011 + 2012 data

PRL 113.072301 (2014)





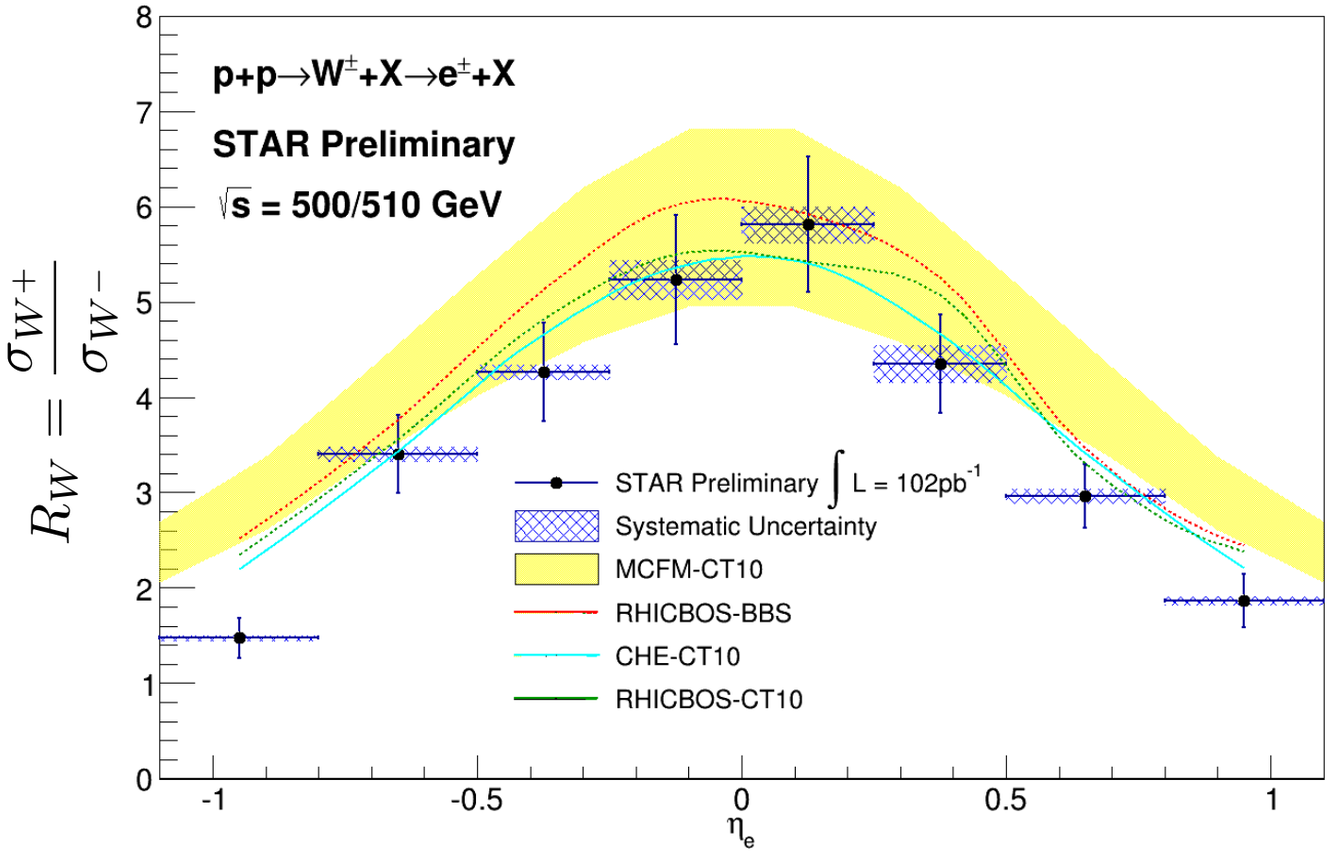
STAR Z A_L from 2011 + 2012 data

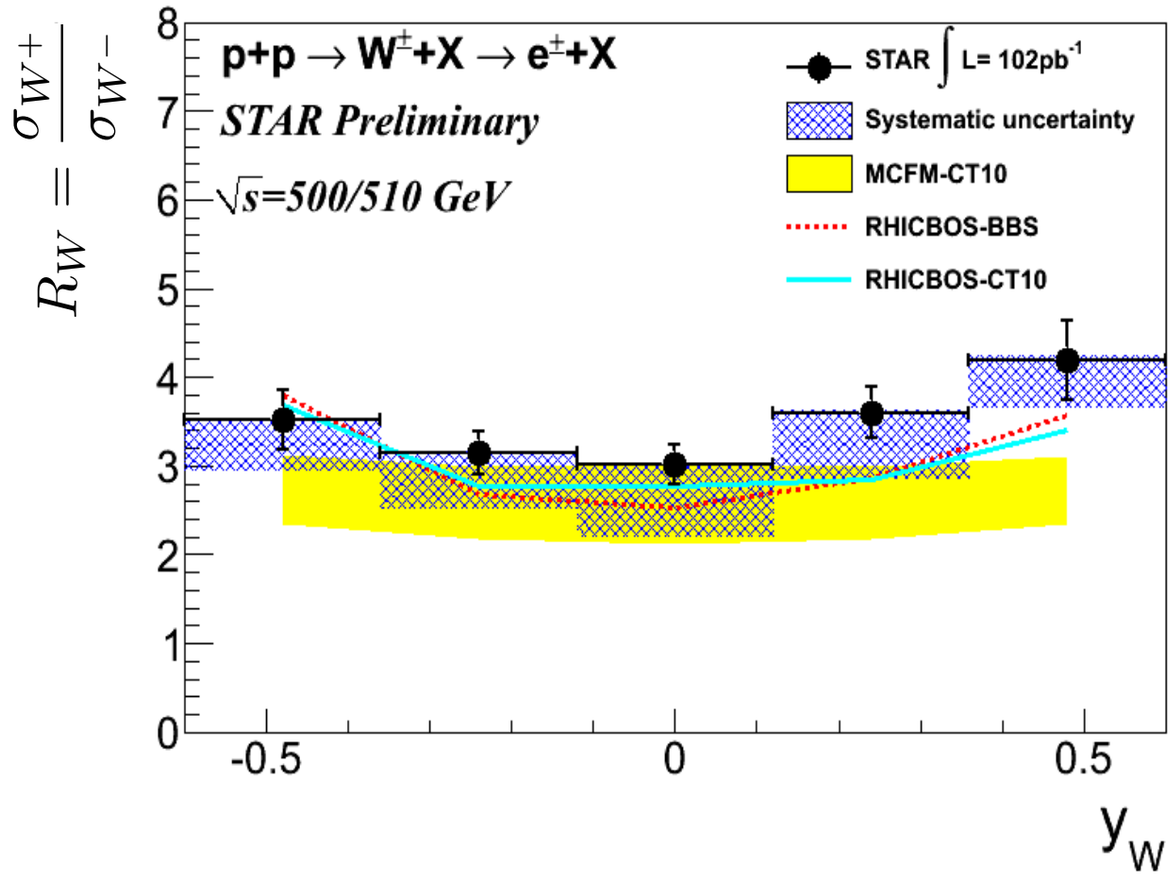


- Measurements of Z production at RHIC are limited by small production cross section.
- But Z allows initial state kinematics to be determined event by event at LO due to fully reconstructed e^+/e^- final states.

STAR W Cross Section Ratio Measurements

- STAR: W cross-section ratio measurements





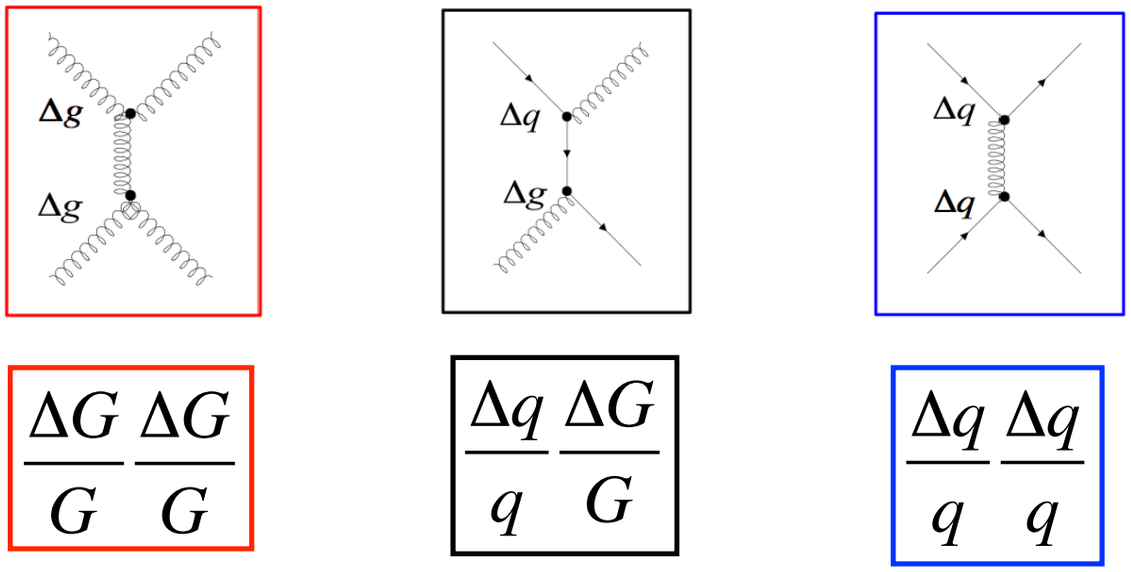
- Run 11 + Run 12 preliminary result: ~100pb^{-1}
- Run 13 data sample with ~300pb^{-1} will provide important improvement on precision
- Planned Run 17 data sample of ~400pb^{-1}
- W boson kinematics can be determined by reconstructing the W kinematics via its recoil. Combination of data/MC simulations allows W boson rapidity reconstruction
- Critical for transverse single-spin asymmetry result of W production probing Sivers sign change

Gluon Polarization Measurement at STAR

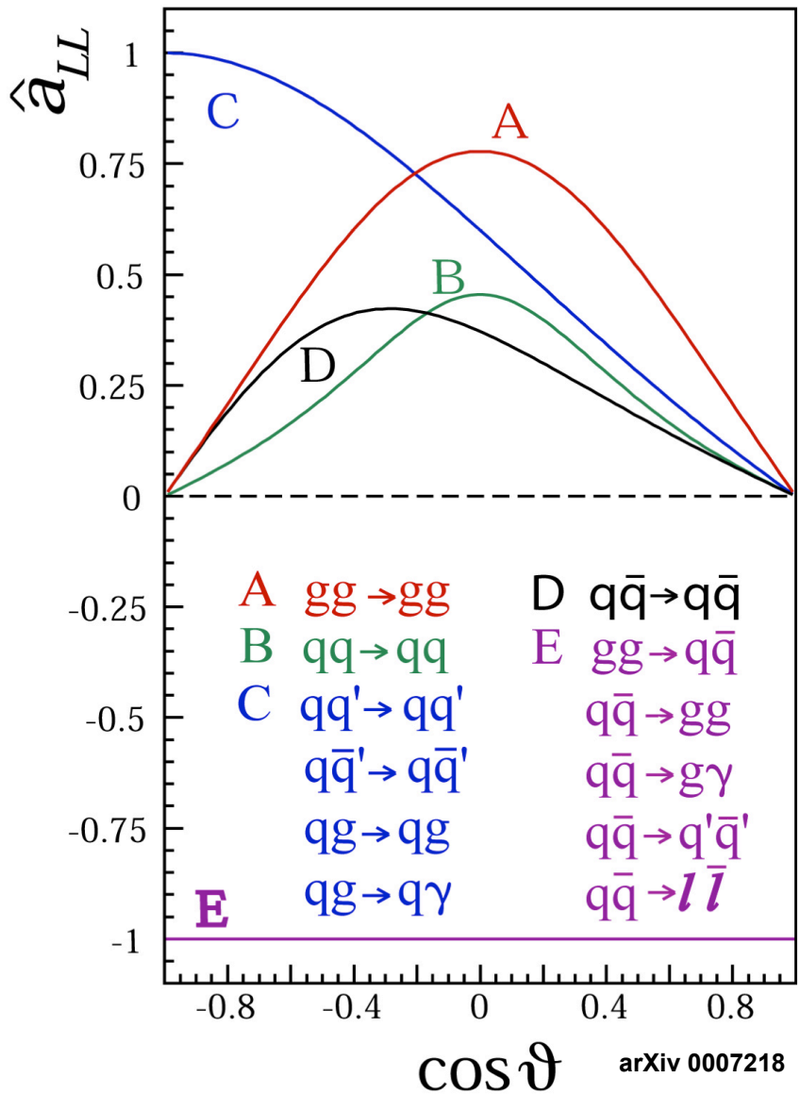
Exploring gluon polarization at RHIC

Parity conserved longitudinal double spin asymmetry

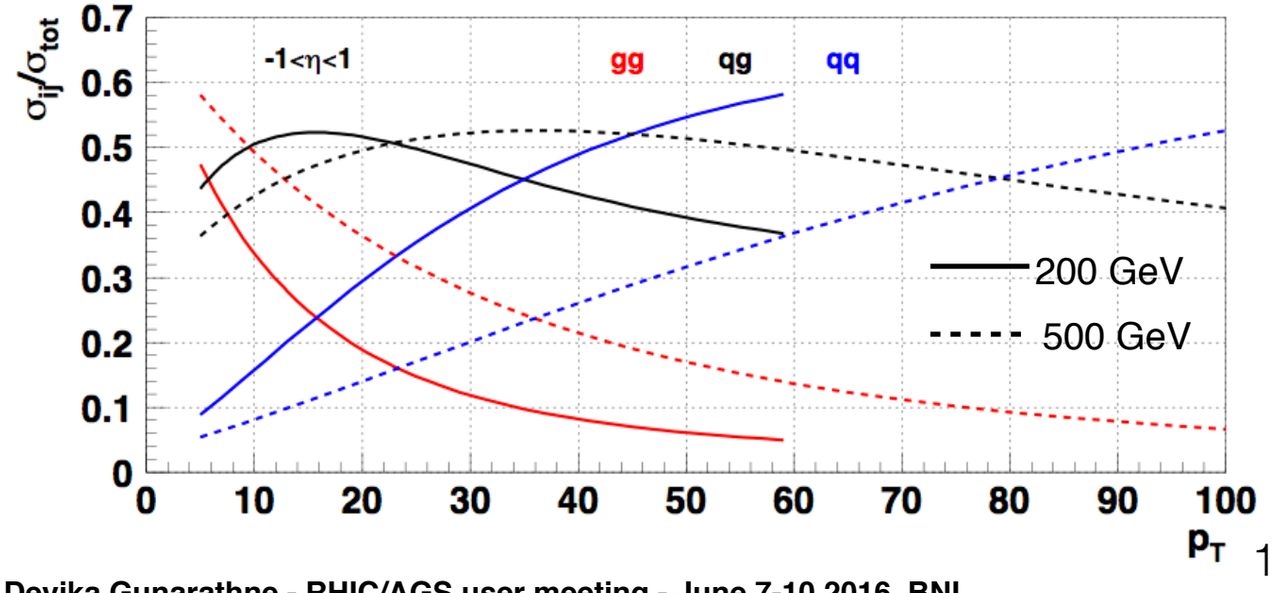
$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \propto \frac{\Delta f_a \Delta f_b}{f_a f_b} \hat{a}_{LL}$$



LO analyzing powers for various RHIC p+p inclusive reaction



Partonic fractions in jet production at RHIC

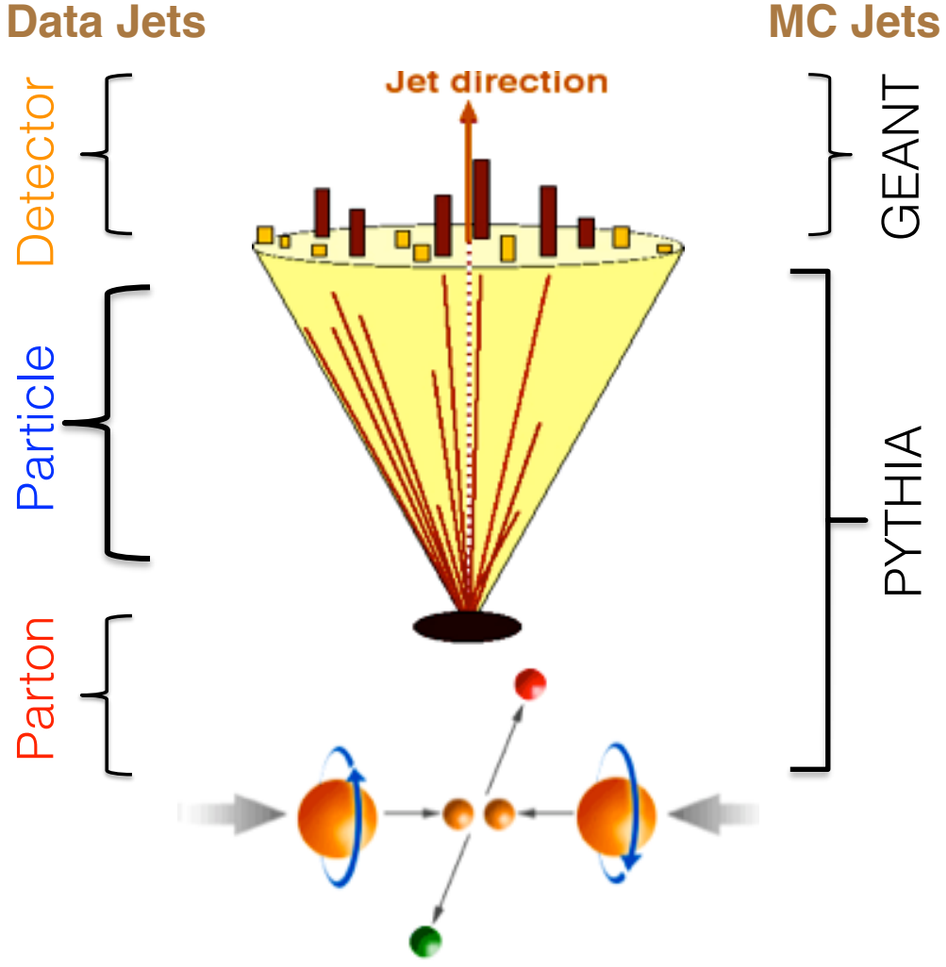


- For most of the RHIC kinematic (mid-rapidity) **qg** and **gg** (**qg**) dominate in 500 (200) GeV p+p collisions , making A_{LL} for inclusive probes (jets, π^0, etc) sensitive to gluon polarization.

How STAR experiment accesses gluon polarization ?

- STAR provides access to gluon polarization in three modes via double spin asymmetry A_{LL} measurements in longitudinally polarized p+p 200 and p+p 510 GeV collisions
  - **Inclusive Jet**
  - **Di-jet**
  - **Inclusive π^0**

Jet reconstruction at STAR

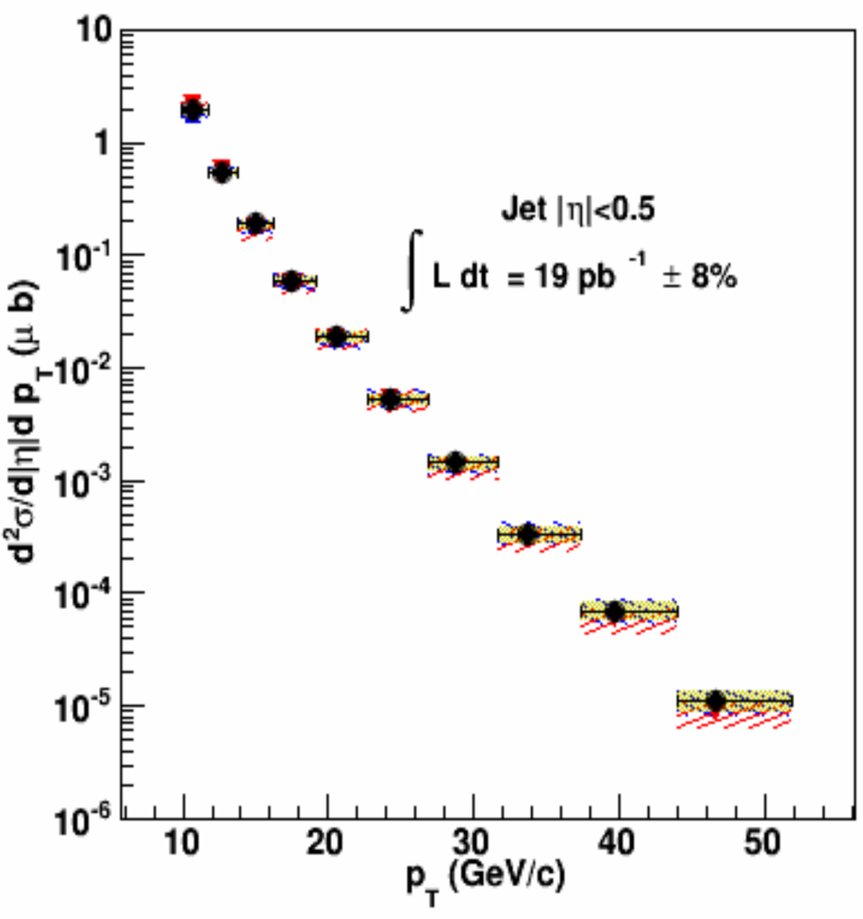


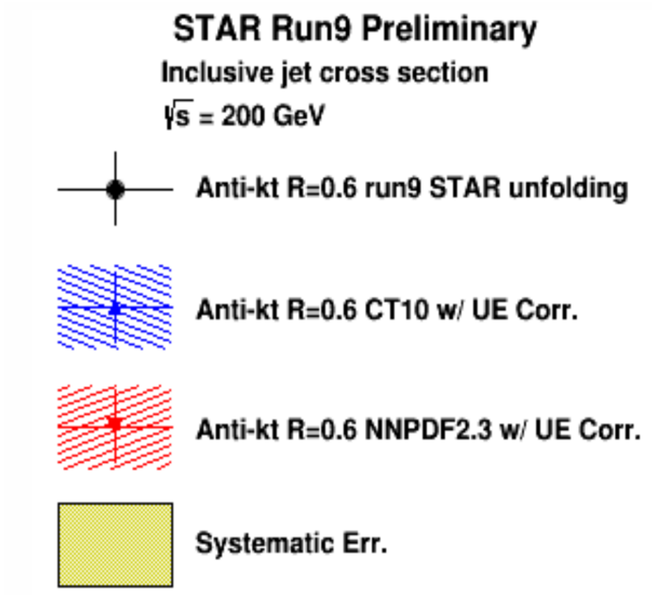
Progression of the collisions in parton, particle and detector levels.

- For STAR 2006 data Midpoint cone algorithm (cone radius - 0.7)
- For STAR 2009 data and beyond Anti-k_T algorithm (Cacciari, Salam and Soyez, JHEP 0804, 063: Cone radius - 0.6 (0.5) for 200 (510) GeV)

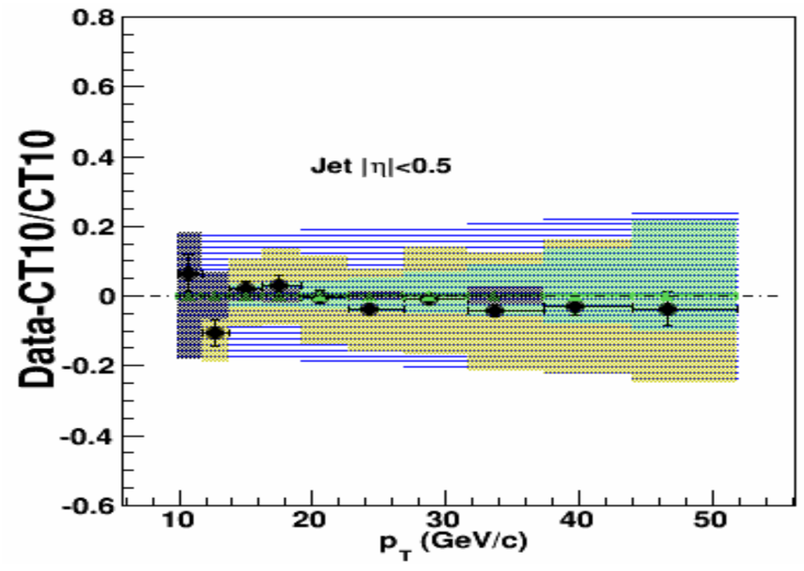
2009 Inclusive jet measurement at STAR

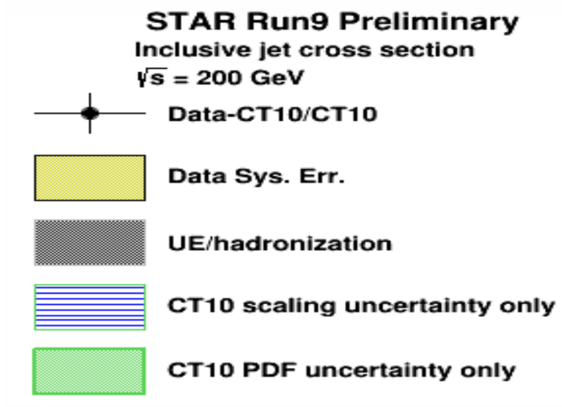
Inclusive jet cross section





Quantitative comparison between data and theory

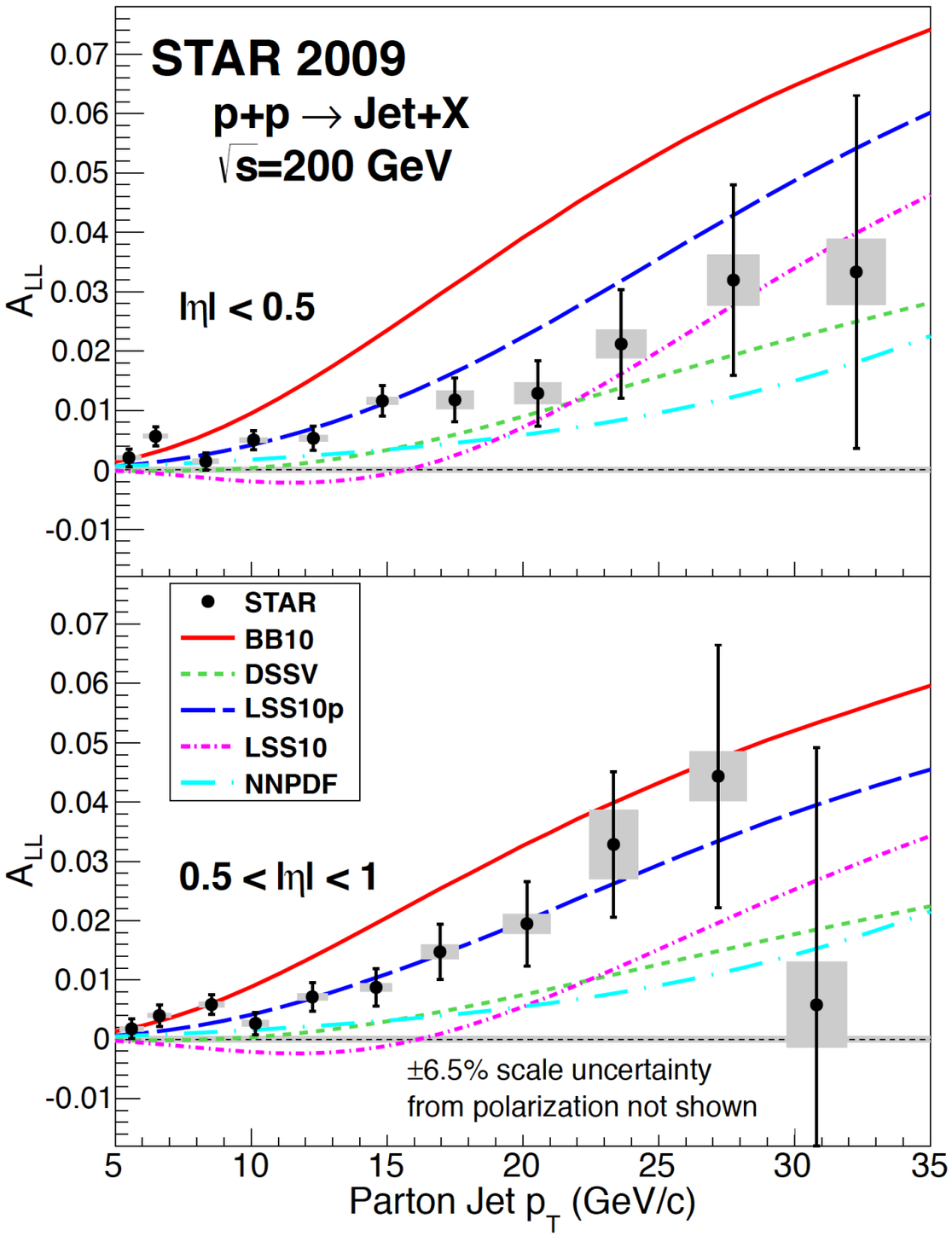




- Unfolded inclusive jet cross-section using anti-k_T algorithm (R=0.6) (Smaller dependence on underlying event (UE) and Pile-up)
- Corrected to particle level for three different pseudo-rapidity regions of $|\eta|<1$, $|\eta|<0.5$ and $0.5<|\eta|<1.0$
- Hadronization and UE corrections evaluated using PYTHIA applied to pure NLO calculations for data comparison
- Comparison to NLO calculations for CT10, NNPDF3.0 and MRST-W2008 with a preference for CT10

2009 Inclusive jet measurements at STAR

Inclusive jet A_{LL} at p+p 200 GeV

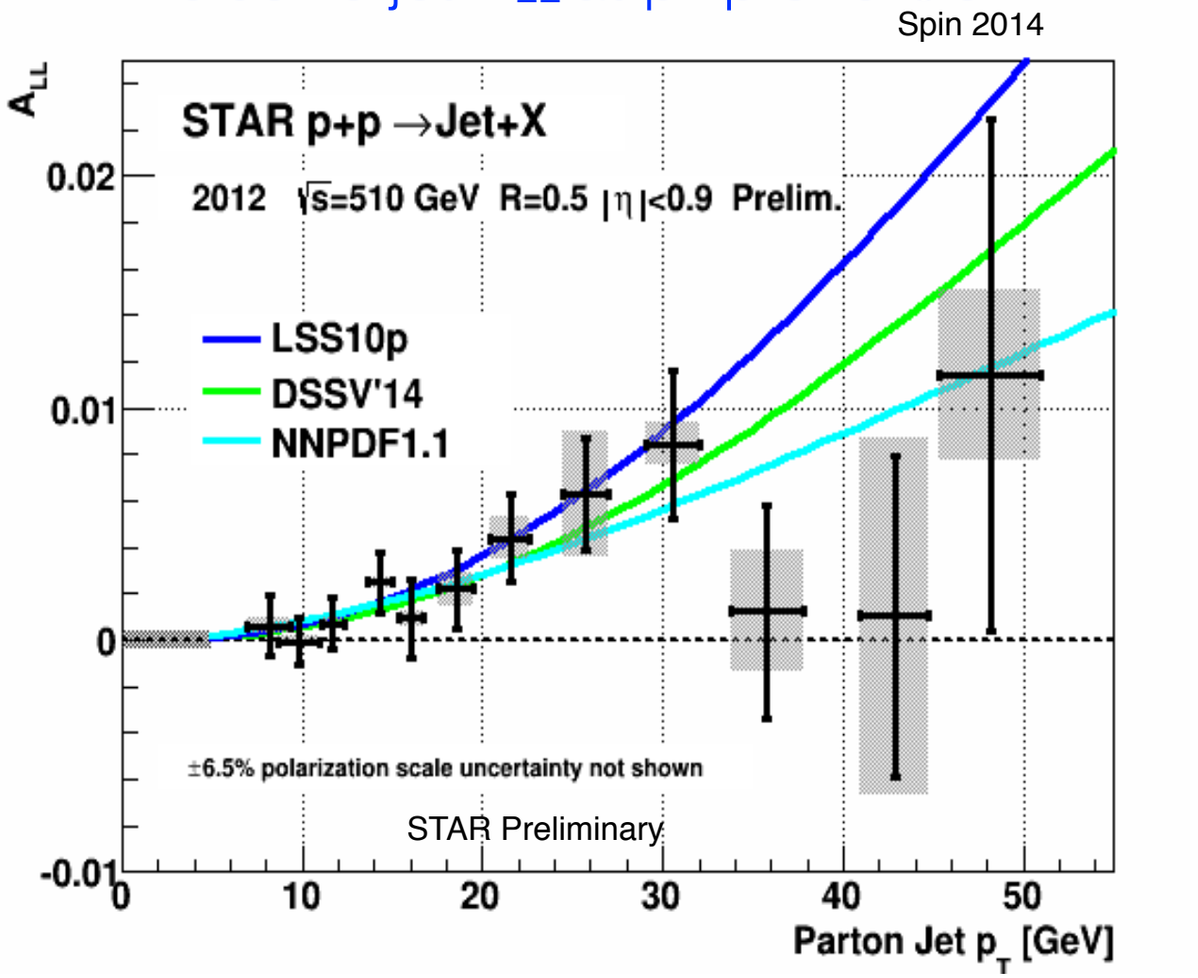


L. Adamczyk et al. (STAR Collaboration), Phys. Rev. Lett. 115, (2015) 092002.

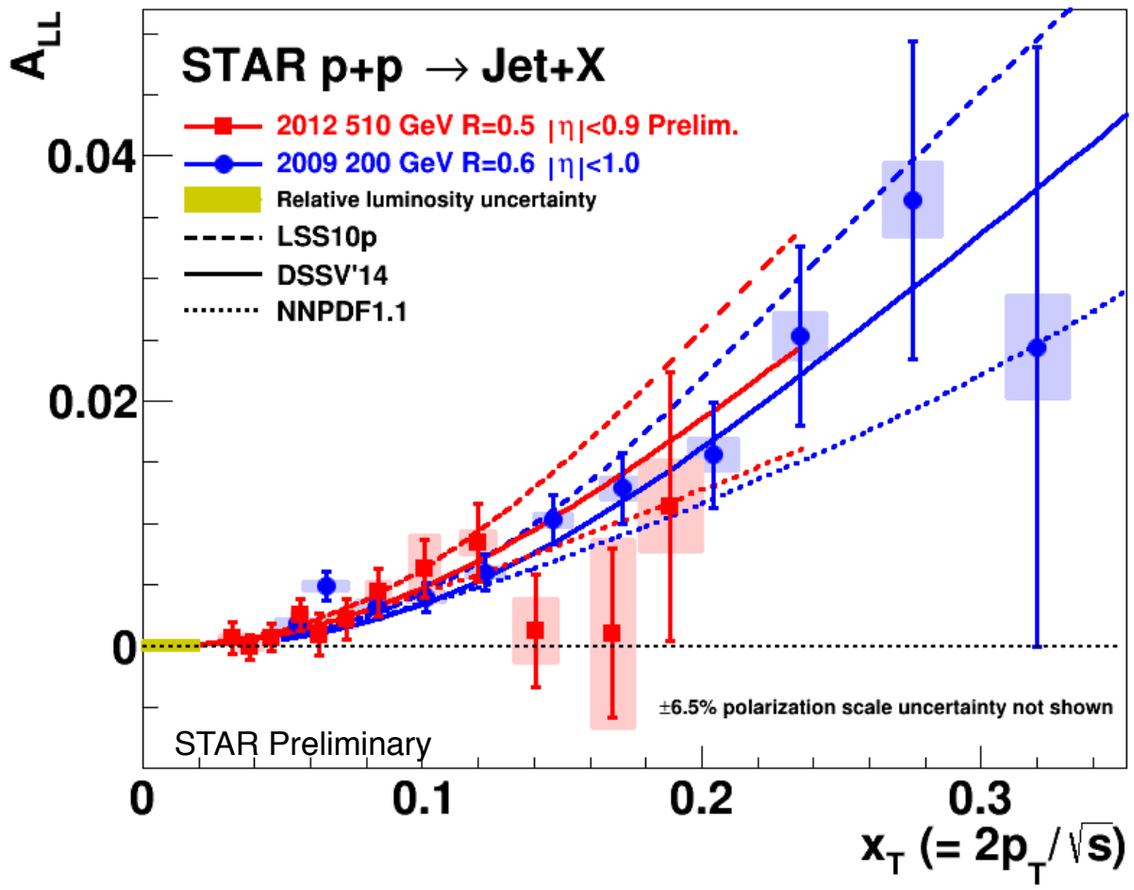
- Run 9 A_{LL} measurement between BB10 and DSSV / Clearly above zero at low p_T
- Larger asymmetry at low p_T suggests larger gluon polarization compared to DSSV
- With global analysis, A_{LL} jet result provides evidence for positive gluon polarization for $x > 0.05$

2012 Inclusive jet measurement at STAR

Inclusive jet A_{LL} at p+p 510 GeV



In comparison to 2009 200 GeV A_{LL}

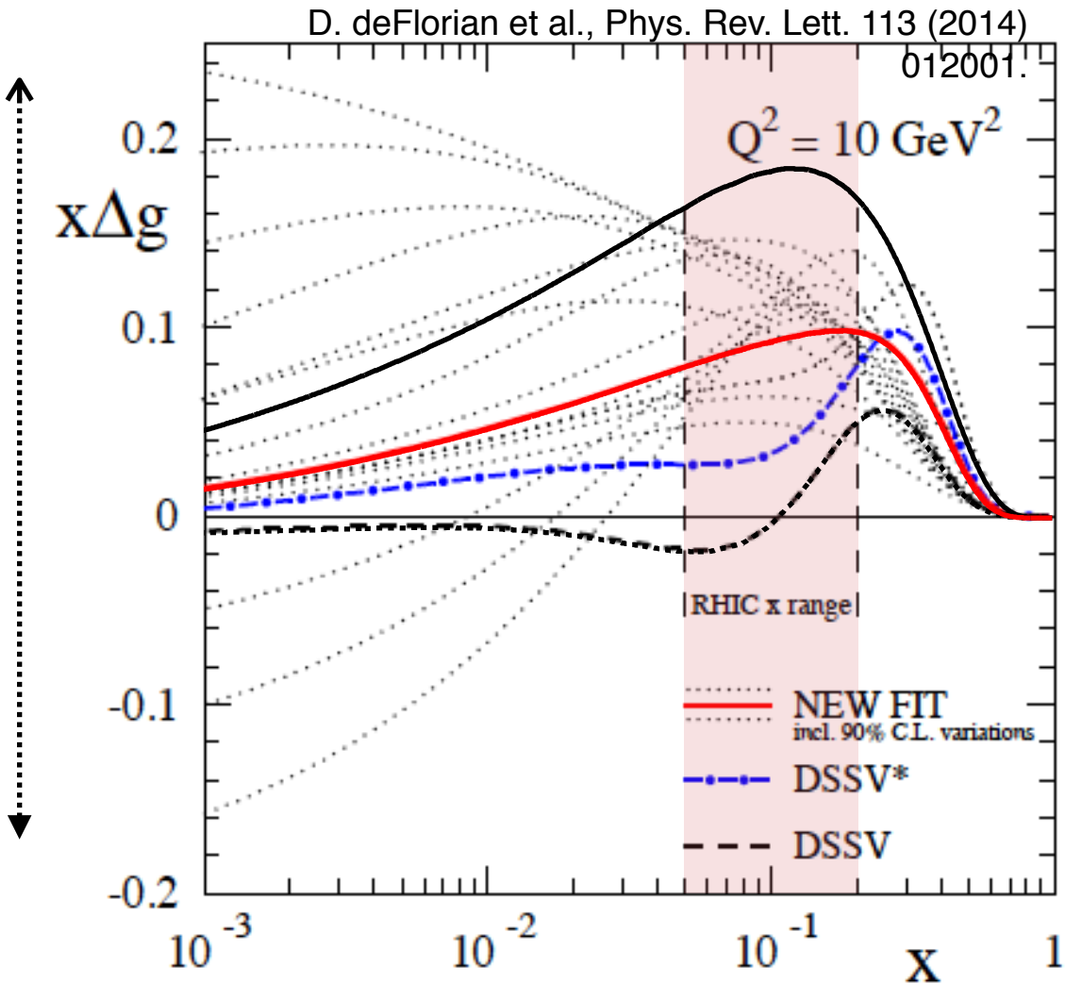


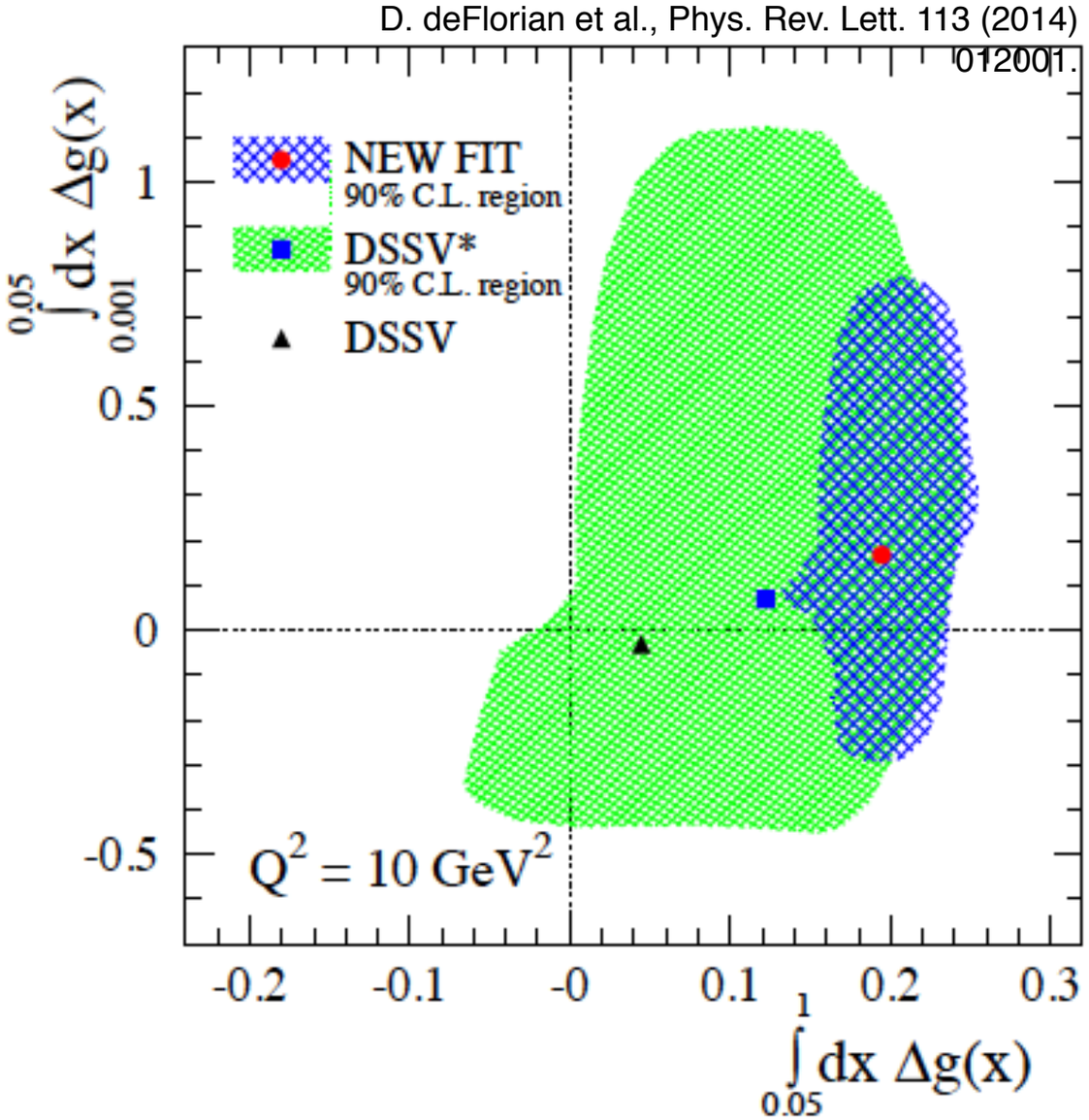
- Run 12 p+p 500 GeV A_{LL} measurement of inclusive jets (anti-k_T algorithm) probes smaller x values
- Run 12 A_{LL} measurement in **good agreement with most recent DSSV14 fit including Run 9 A_{LL} results**
- 2012 p+p 510 GeV A_{LL} is in **good agreement with 2009 p+p 200** GeV A_{LL} in the overlapping region

Global analysis including RHIC data

- Impact on Δg from RHIC data

Wide spread at low x (x<0.05) of alternative fits consistent within 90% of C.L.





- DSSV: Original global analysis incl. first RHIC results (Run 5/6)
- DSSV*: New COMPASS inclusive and semi-inclusive results in addition to Run 5/6 RHIC updates
- DSSV - NEW FIT: Strong impact on Δg(x) with RHIC run 9 results: $0.20^{+0.06}_{-0.07}$ 90% C.L. for $0.05 < x$
- Similar conclusion by independent global analysis of NNPDF: $0.23^{+0.07}_{-0.07}$ for $0.05 < x < 0.5$

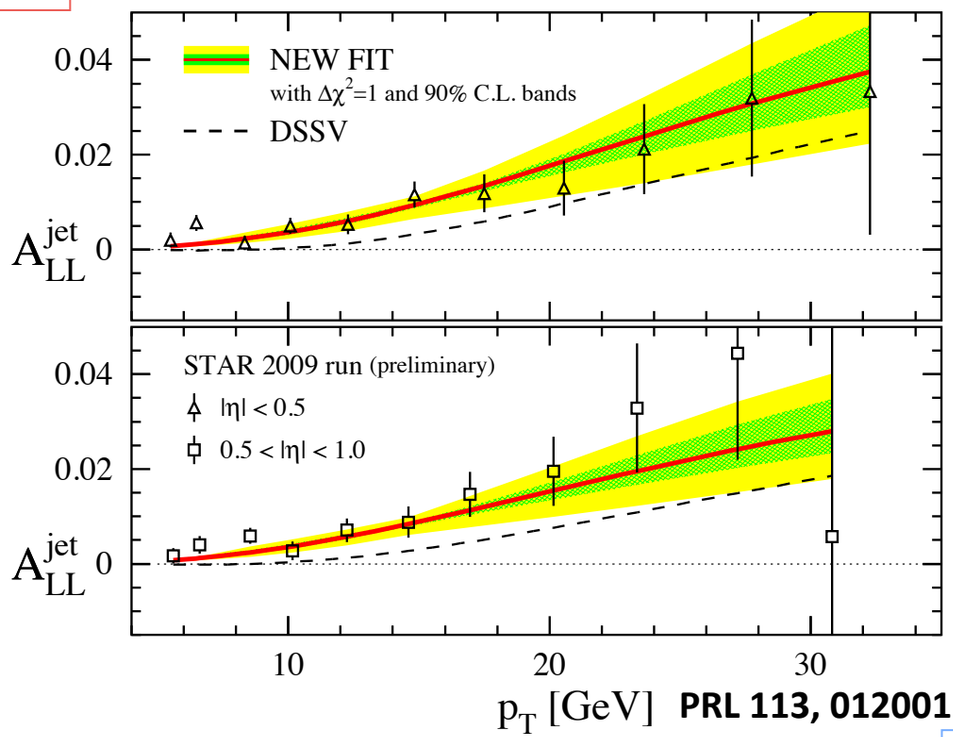
"…better small-x probes are badly needed."

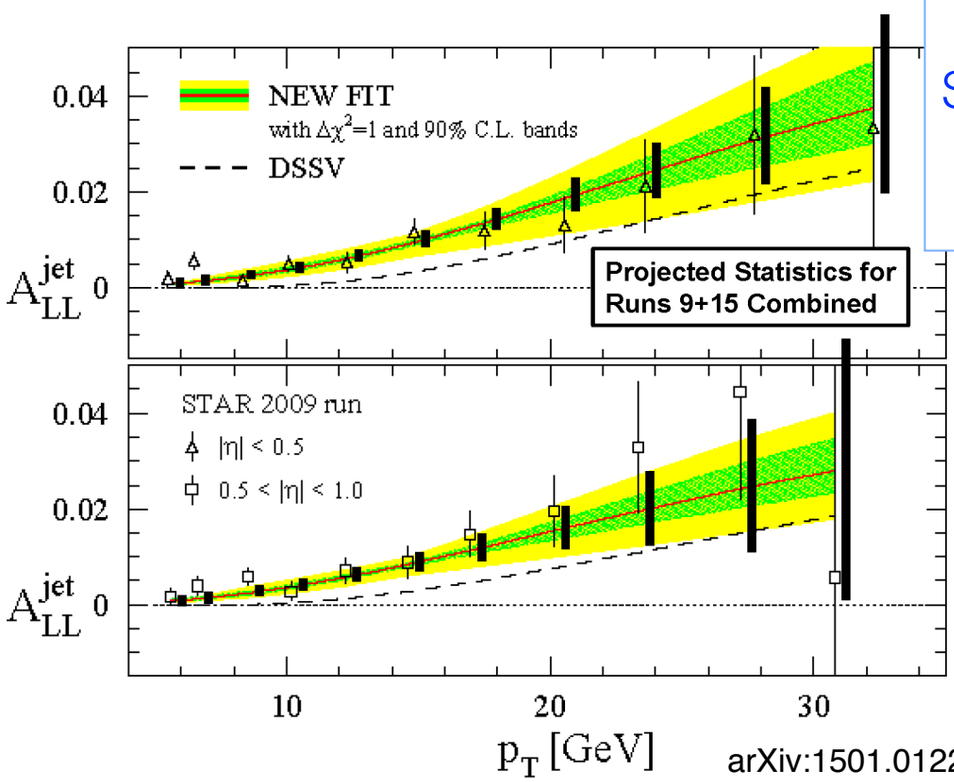
E. R. Nocera et al., Nucl. Phys. B887 (2014) 276.

Global analysis with polarized jets and Projections

DSSV

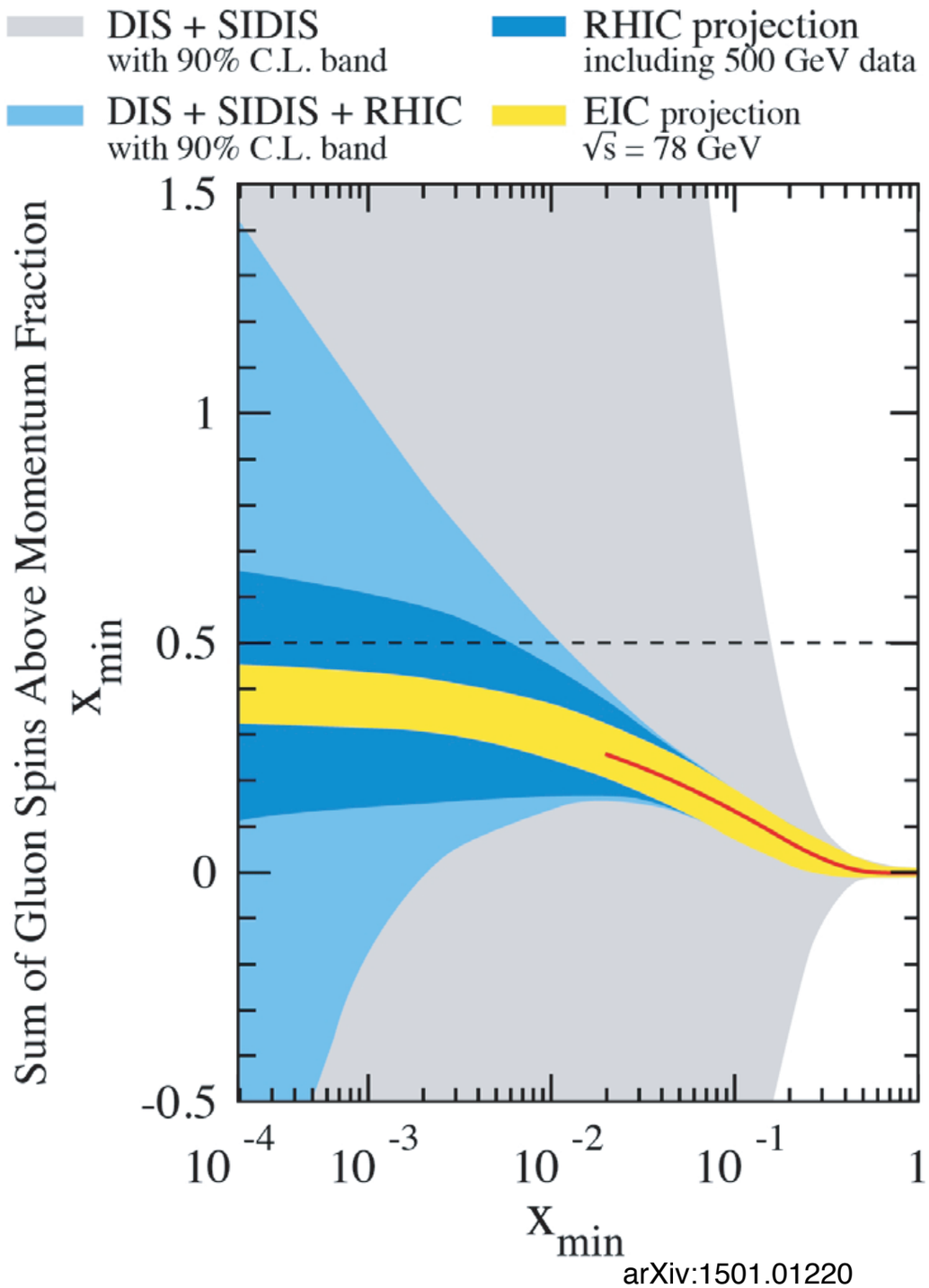
New global analysis (include STAR 2009 data)





Projections for STAR 2009 and 2015 data combined

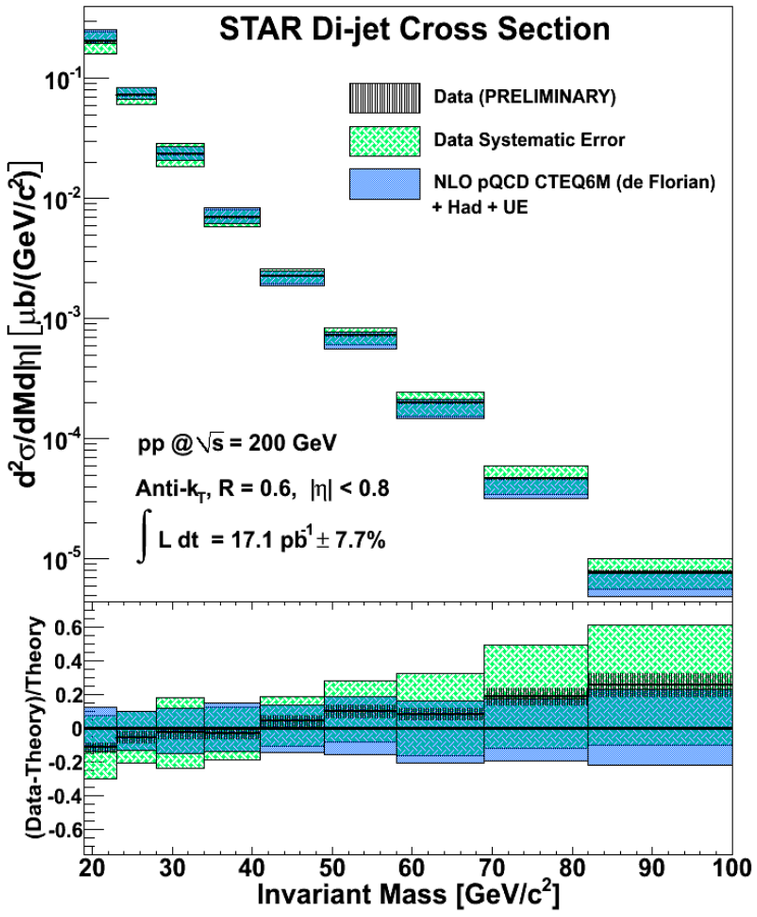
RHIC Projections

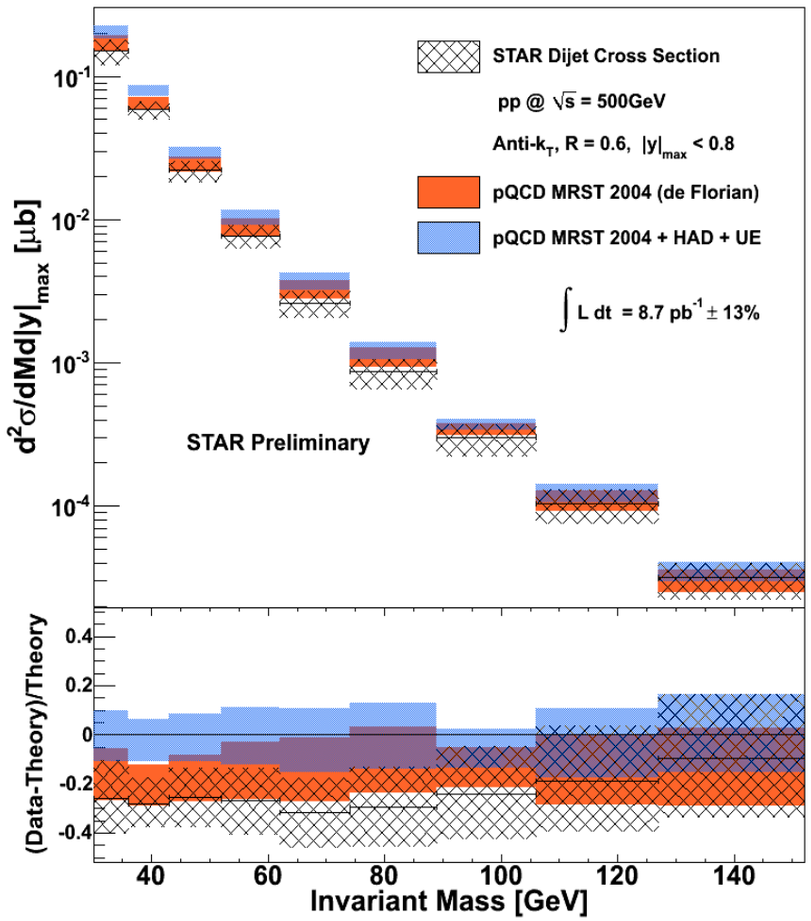


STAR di-jet measurement

- Di-jet permit event by event calculations of x_1 and x_2 at leading order .
- Di-jet cross section is well-described by NLO pQCD with corrections for hadronizations and underlying event.

STAR 2009 di-jet cross section results





$$x_1 = \frac{1}{\sqrt{s}}\left(p_{T,3}e^{\eta_3} + p_{T,4}e^{\eta_4}\right)$$

$$x_2 = \frac{1}{\sqrt{s}}\left(p_{T,3}e^{-\eta_3} + p_{T,4}e^{-\eta_4}\right)$$

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

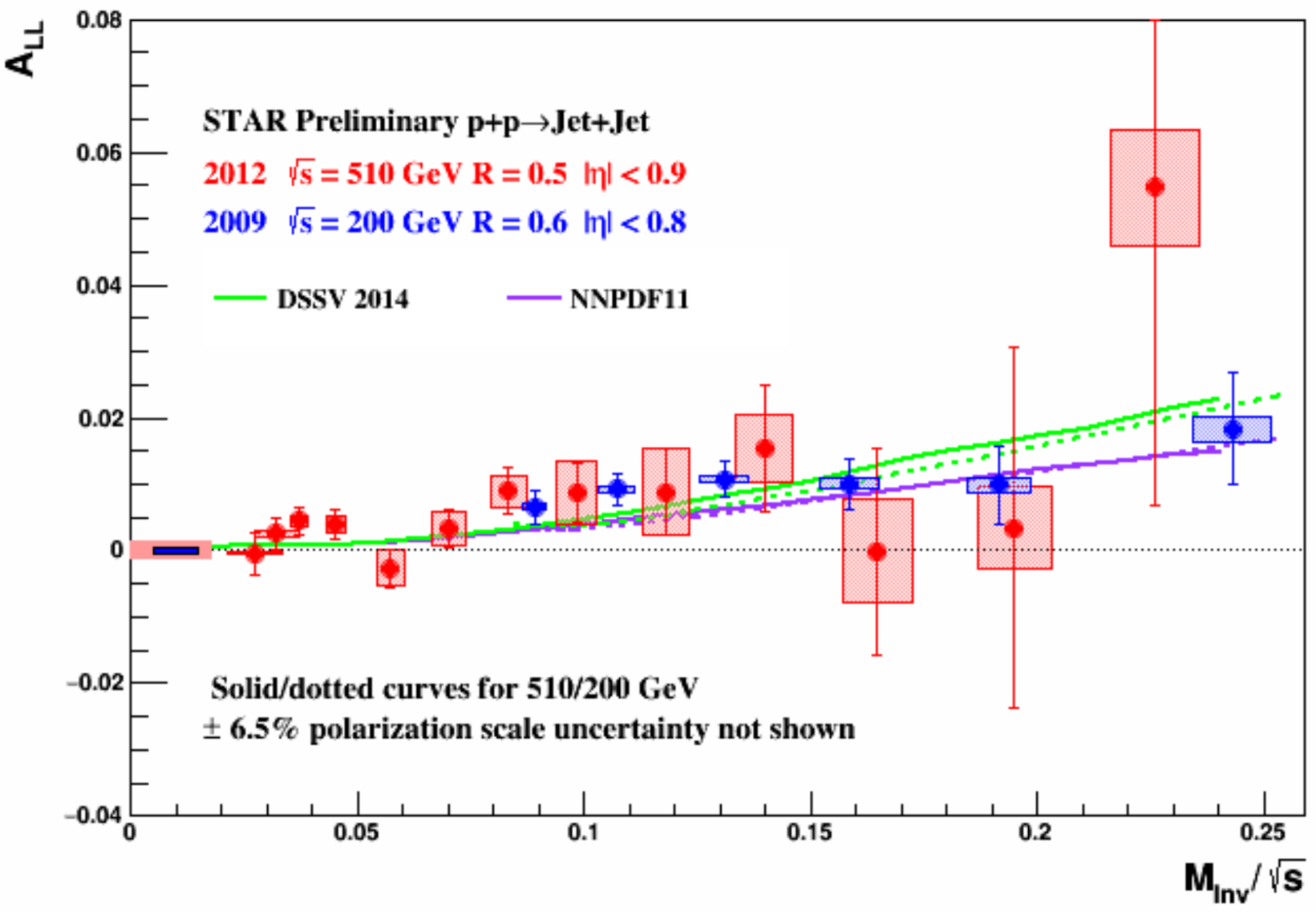
$$y = \frac{1}{2}\ln\frac{x_1}{x_2} = \frac{\eta_3 + \eta_4}{2}$$

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

- Di-jet cross section results are well described by the NLO pQCD calculations.

STAR di-jet measurement

STAR di-jet A_{LL} as a function of invariant mass over square root of C.M energy

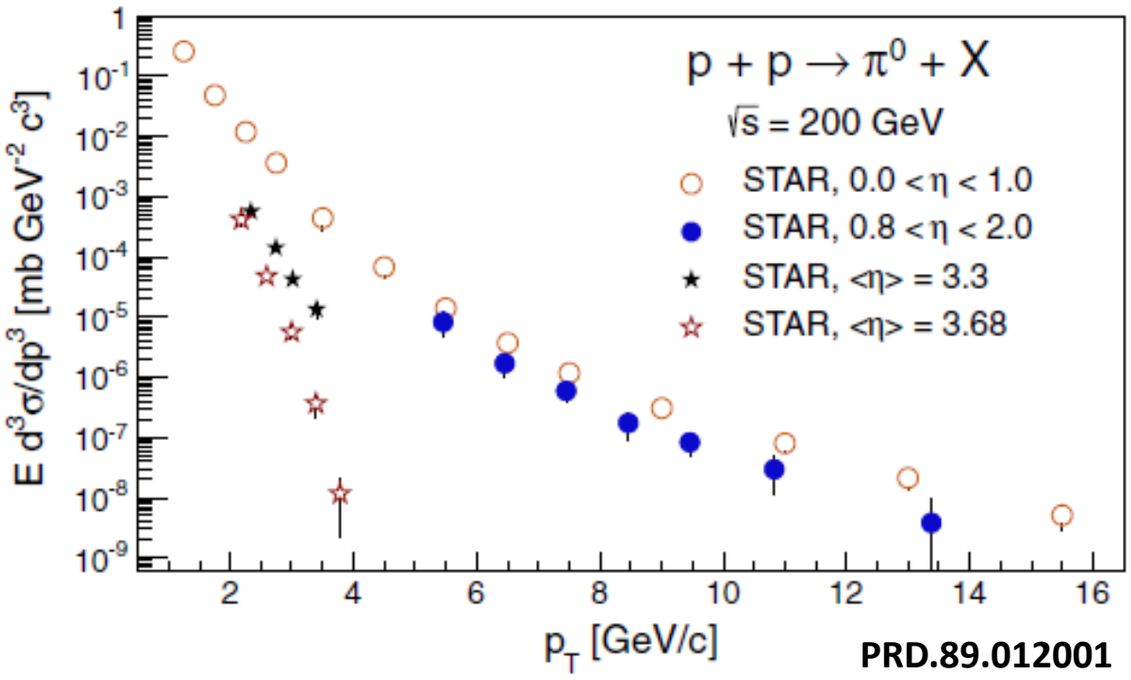


arXiv 1602:03922

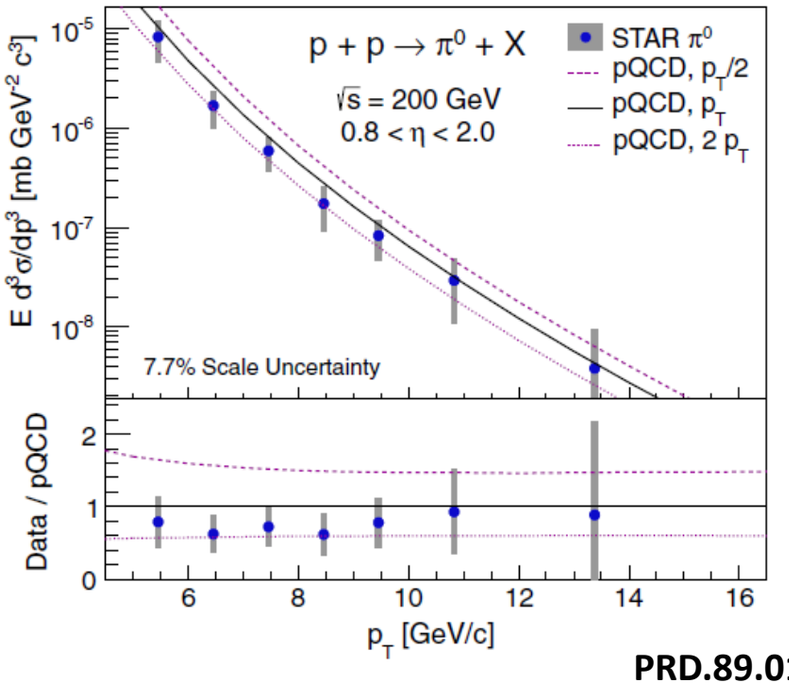
- Data are compared to model predictions based on DSSV14 NNPDFpol1.1.
- The uncertainties are expected to be reduced by a factor of ~ 1.7 with data in STAR 2013 (510 GeV) and 2015 (200 GeV).

STAR inclusive π^0 measurements

STAR Inclusive π^0 cross section



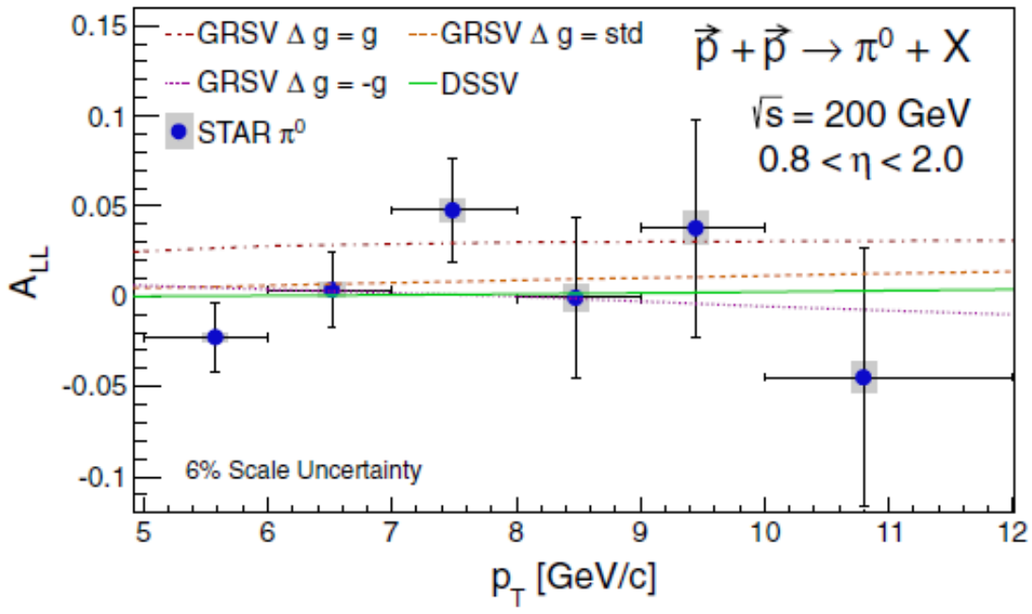
PRD.89.012001



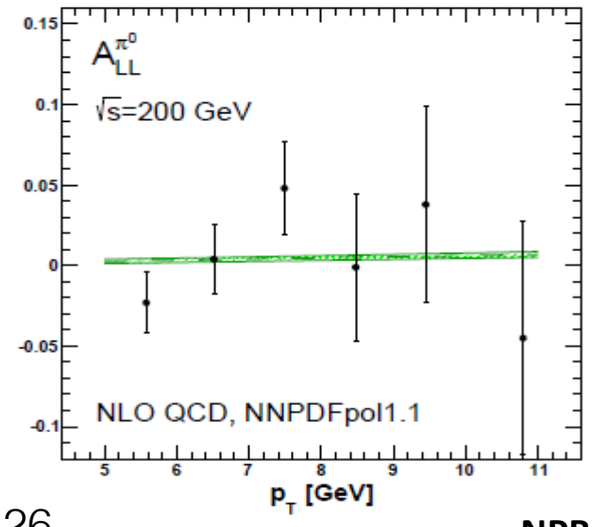
PRD.89.012001

- STAR studied π^0 production at $0.8<\eta<2$ by measuring two photon decay.
- Energy measurement using Endcap calorimeter

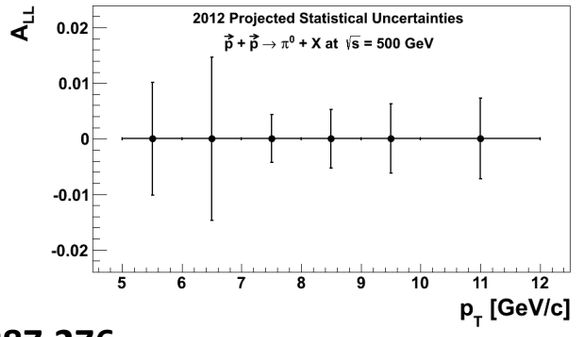
STAR Inclusive π^0 Double spin asymmetry



NNPDFpol1.1 prediction with STAR 200 GeV data (0.8 < η < 2.0)

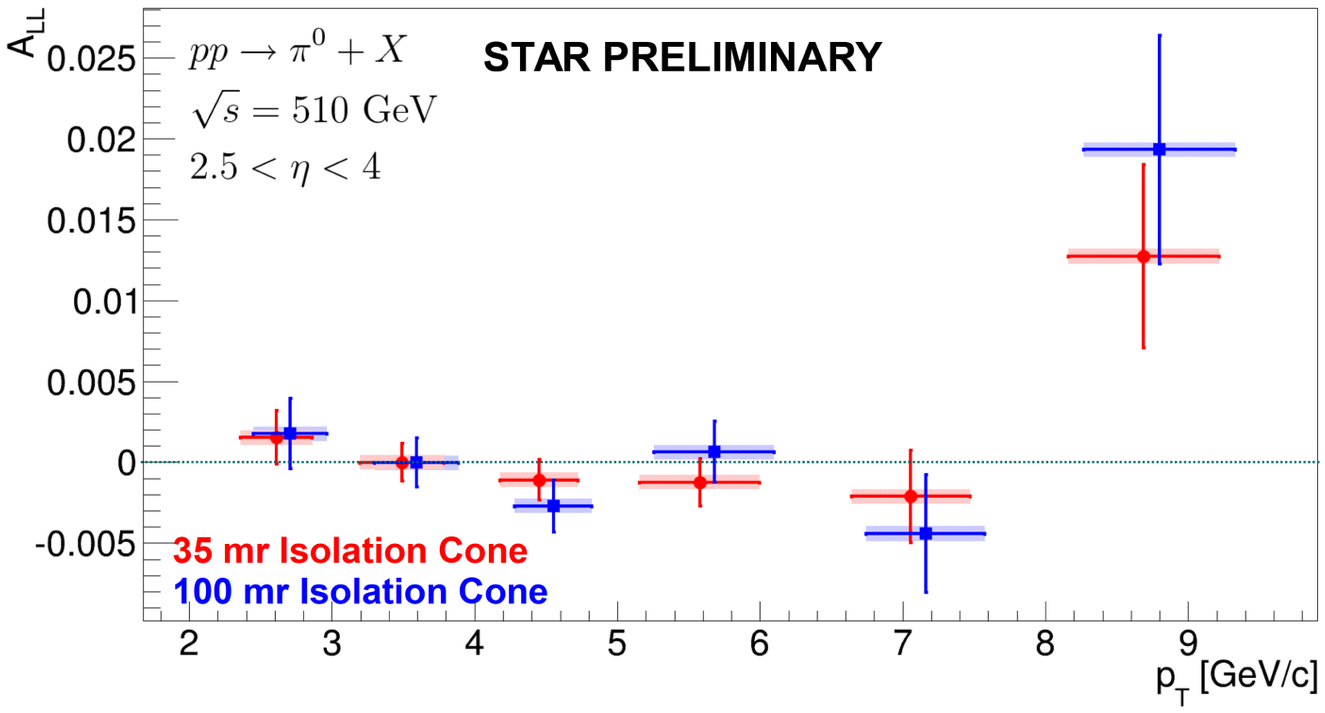


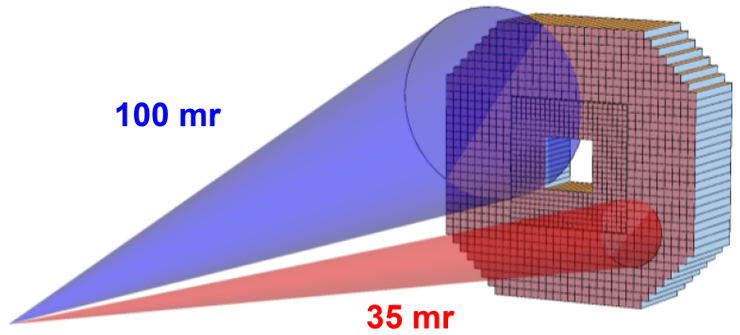
- Need more precise results to constrain NLO
- STAR 2012 510 GeV data are being analyzed and expect reduce the uncertainty.



NPB 887.276

STAR π0 measurements using Forward meson Tracker (FMS)



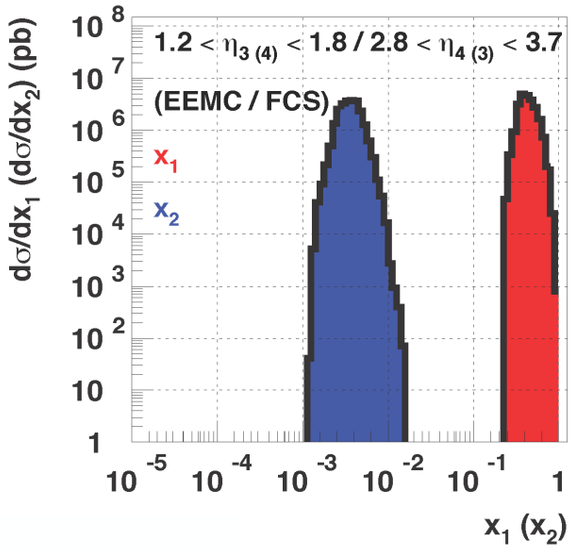


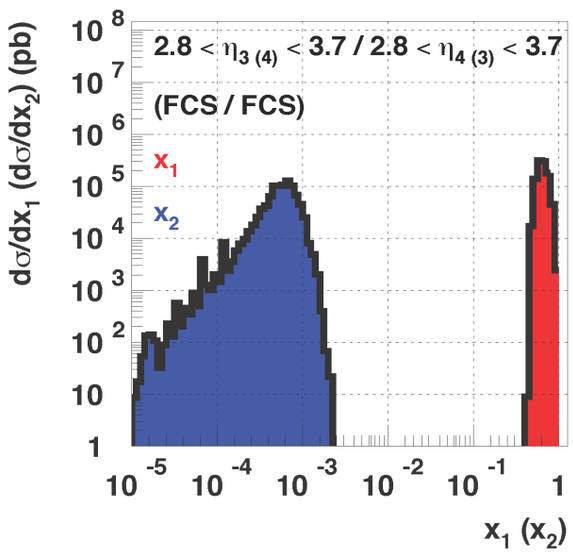
- π0 measured in FMS at 2.5 < η < 4.0 by using 2012 and 2013 510 GeV data
- Isolated π0 measured by 2-γ isolation cone with cone radius 35 mr and 100 mr
- A_{LL} does not depend on isolation cone cut
- Isolated π0 A_{LL} is consistent with 0

Future STAR di-jet measurements

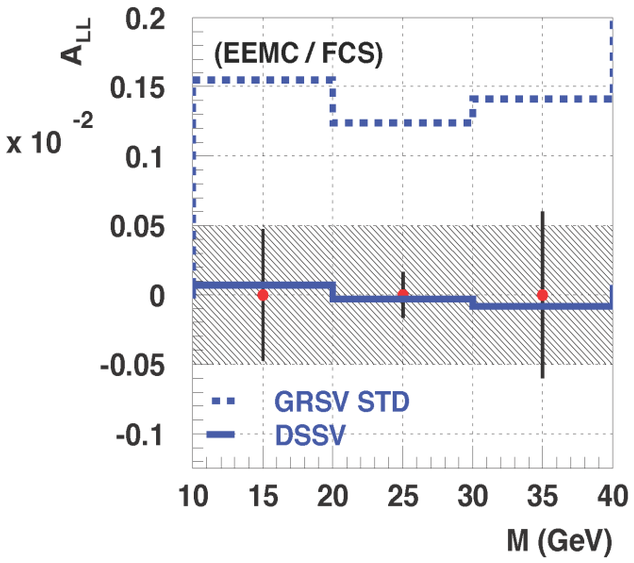
- STAR plans to install Forward Calorimeter System (FCS) in ~ 2020.
- This will enable di-jet measurements with one or both jets at forward region ($2.8 < \eta < 3.7$)
- FCS will be able to provide data to constrain Δg at $x \sim 5\times10^{-3}$ and $x =< 10^{-3}$ with FCS-EEMC jets and FCS-FCS jets respectively

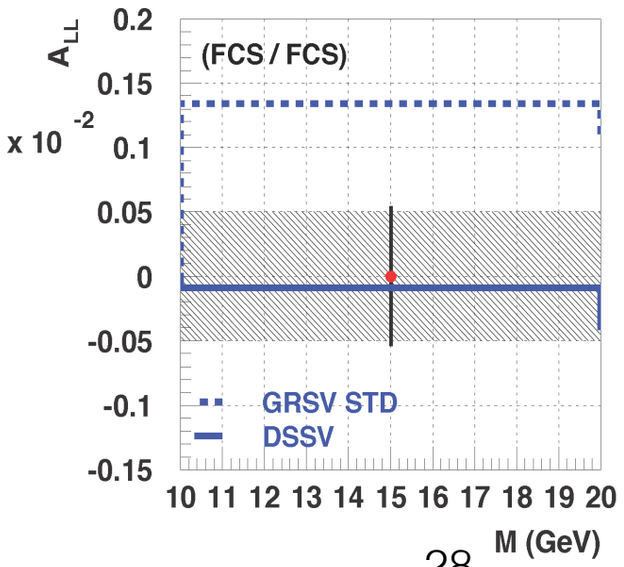
Projection for di-jet A_{LL} using STAR future FCS





- √s = 500 GeV
- Cone Algorithm , R=0.7
- Assumed integrated luminosity - 1000 pb^{-1}
- Assumed polarization 60%





- Forward di-jets will further constrain Δg at low xg region.

Summary

- W boson program
  - Mid-rapidity: New W^- results suggest large anti-u quark polarization along with broken QCD sea
  - Strong physics case of unpolarized $\bar{d}$ / $\bar{u}$ probe using W production
  - Backward/Forward rapidity: STAR FGT (Forward GEM Tracker) / Ongoing analysis

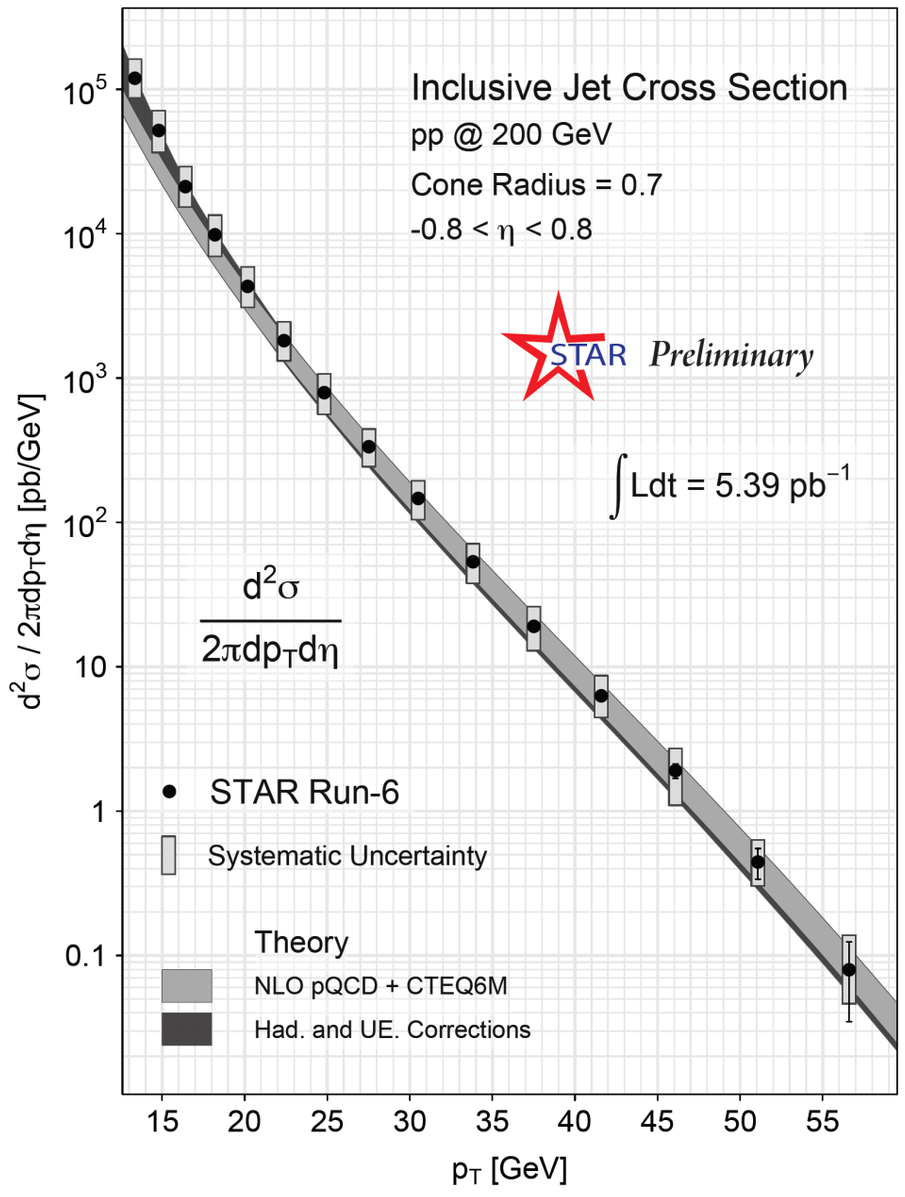
- Gluon polarization program
  - Several final states (Hadron / Jet) have been measured all pointing to the same conclusion that the gluon polarization is small consistent with COMPASS findings
  - Precise Run 9 A_{LL} measurement: Non-zero ΔG of similar magnitude as quark polarization!
  - First Di-Jet measurement opens the path to constrain the shape of Δg
  - New inclusive jet cross-section: Important constraints for unpolarized gluon at high x

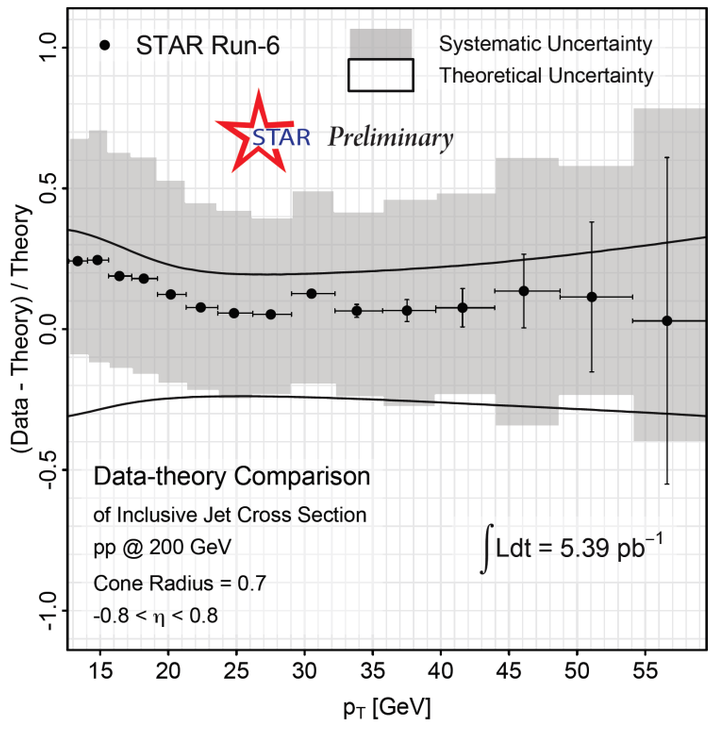
- Run 13 / 15 and future
  - Run 13: Long. 510GeV Run 13 (~300pb^{-1} rec.): W (Anti-quarks) and Jet production (Gluons)
  - Run 15: 200GeV (Run 15) with long. pol. p-p running

Backup

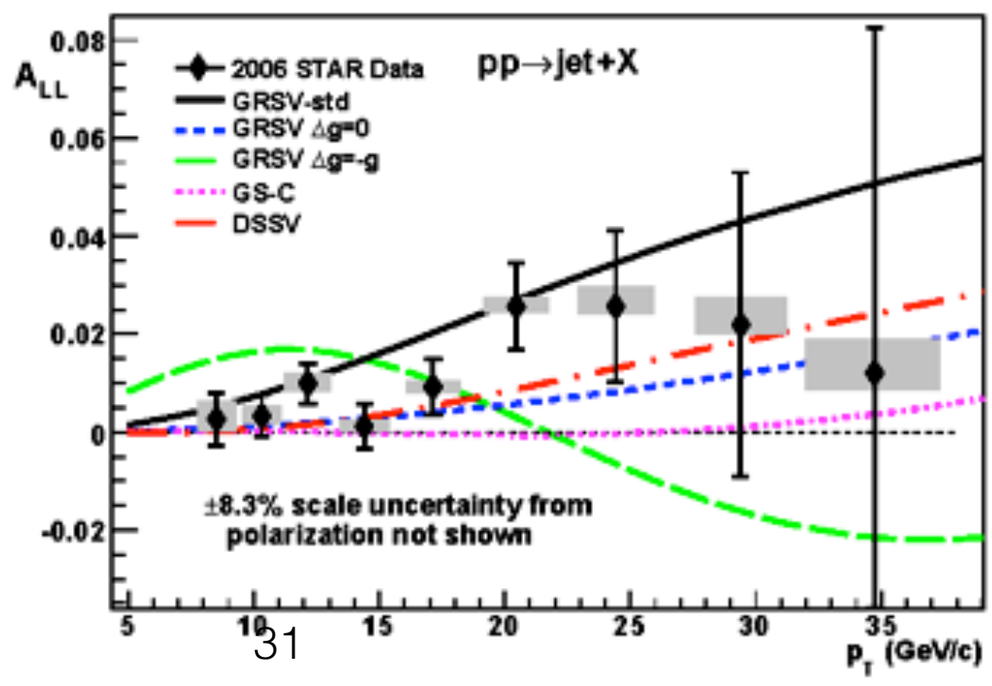
Inclusive jet measurement : 2006

Inclusive jet cross section

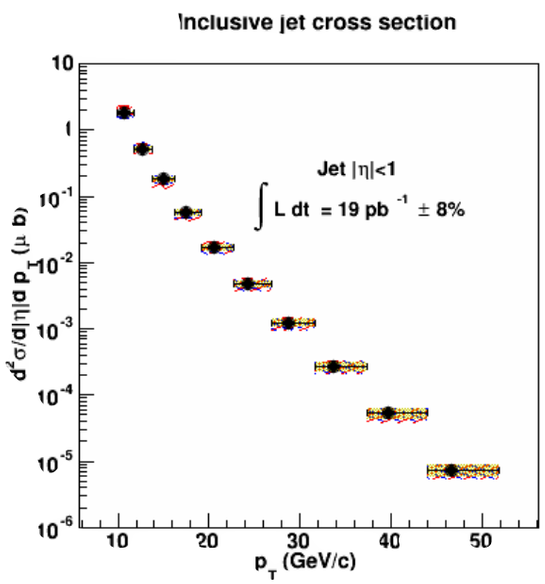


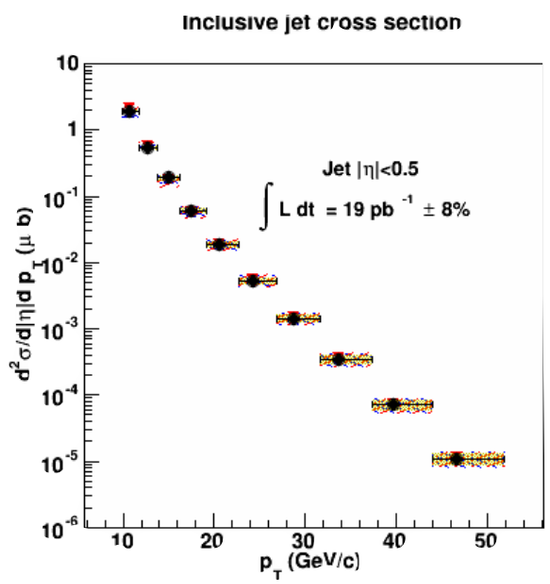


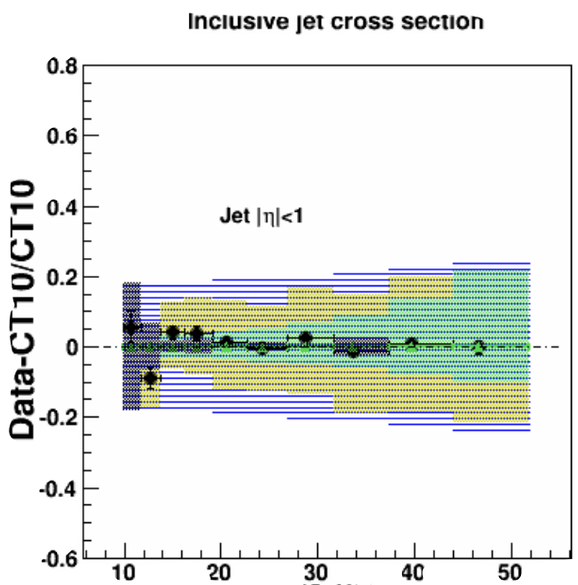
Inclusive jet A_{LL}

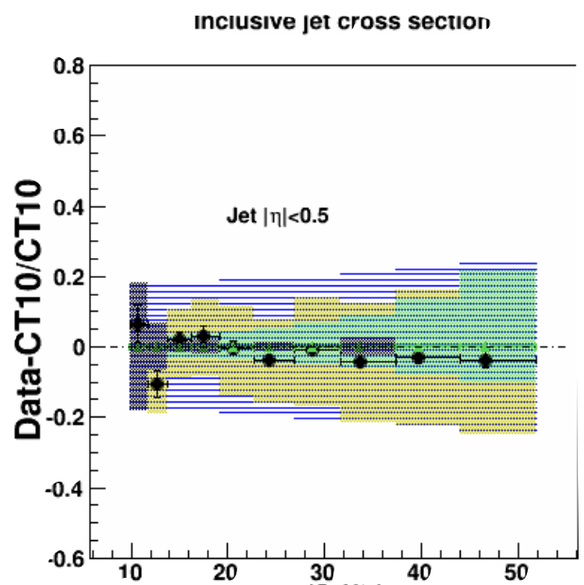


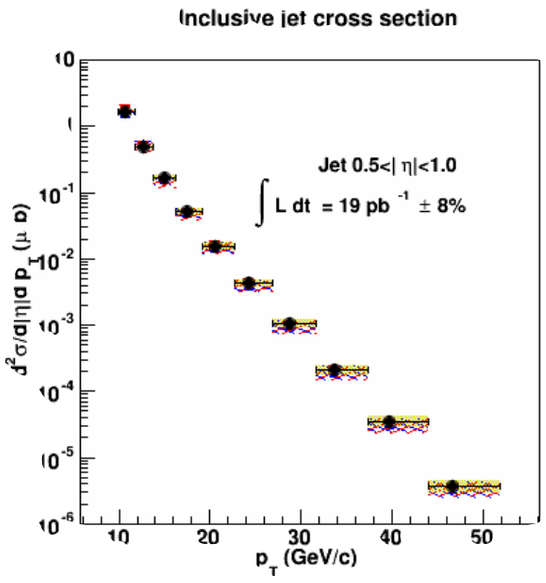
Inclusive jet cross section run 9

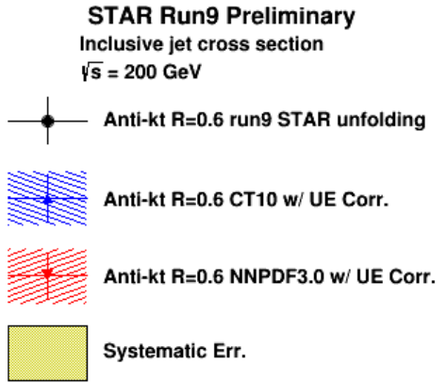


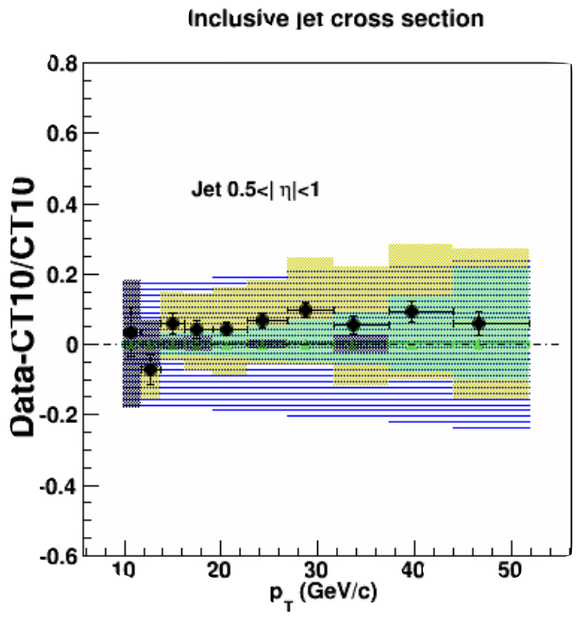


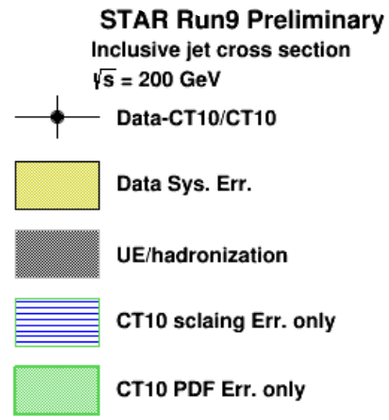






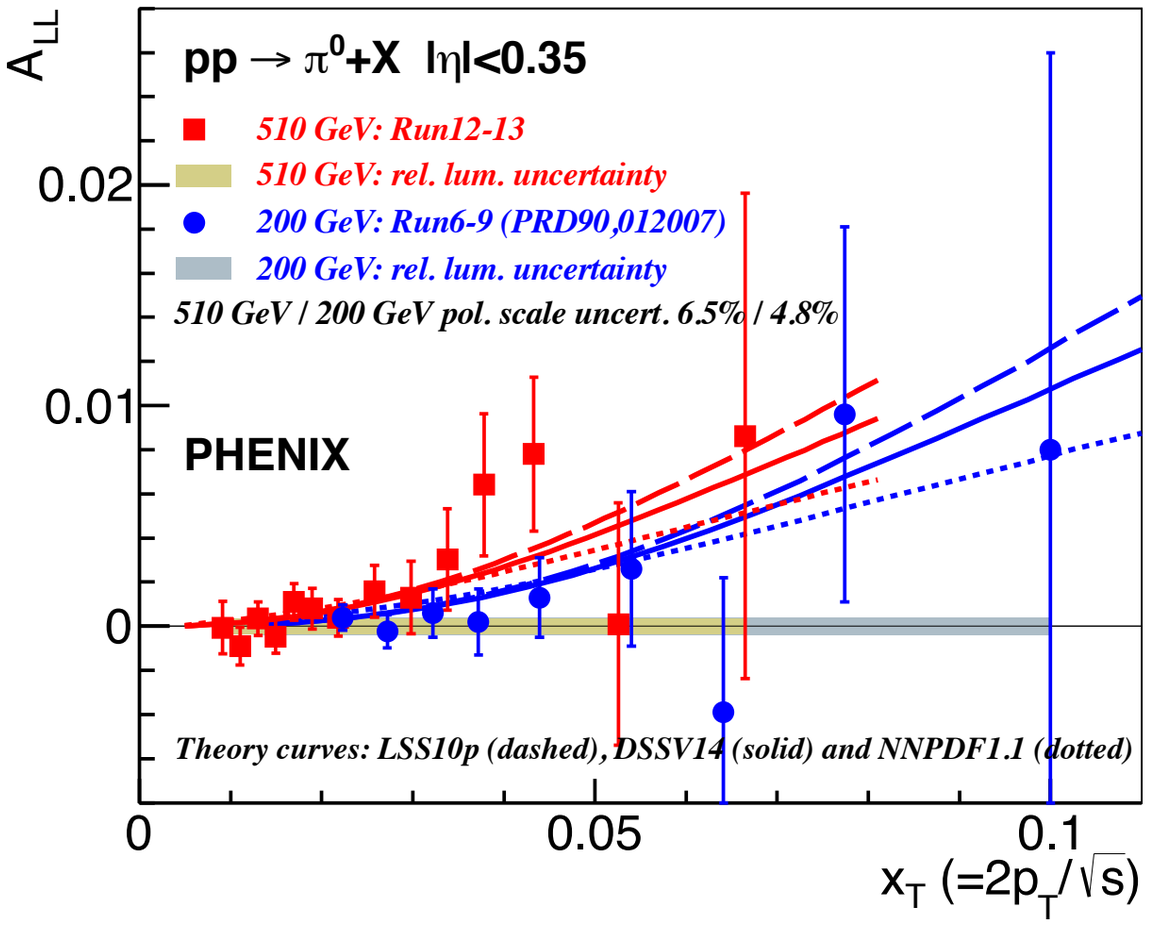


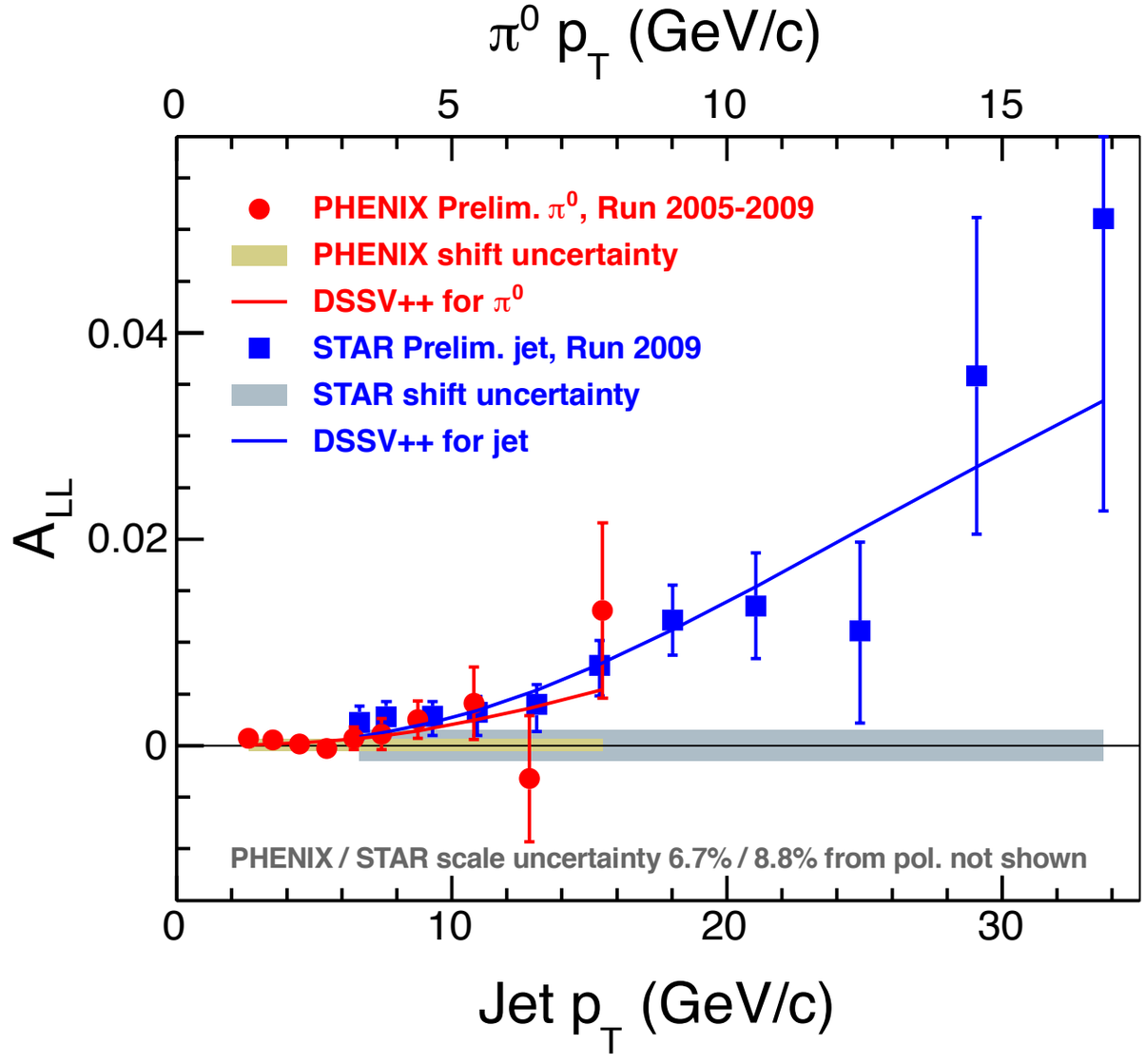




Momentum $q_i(x)$ and helicity distributions

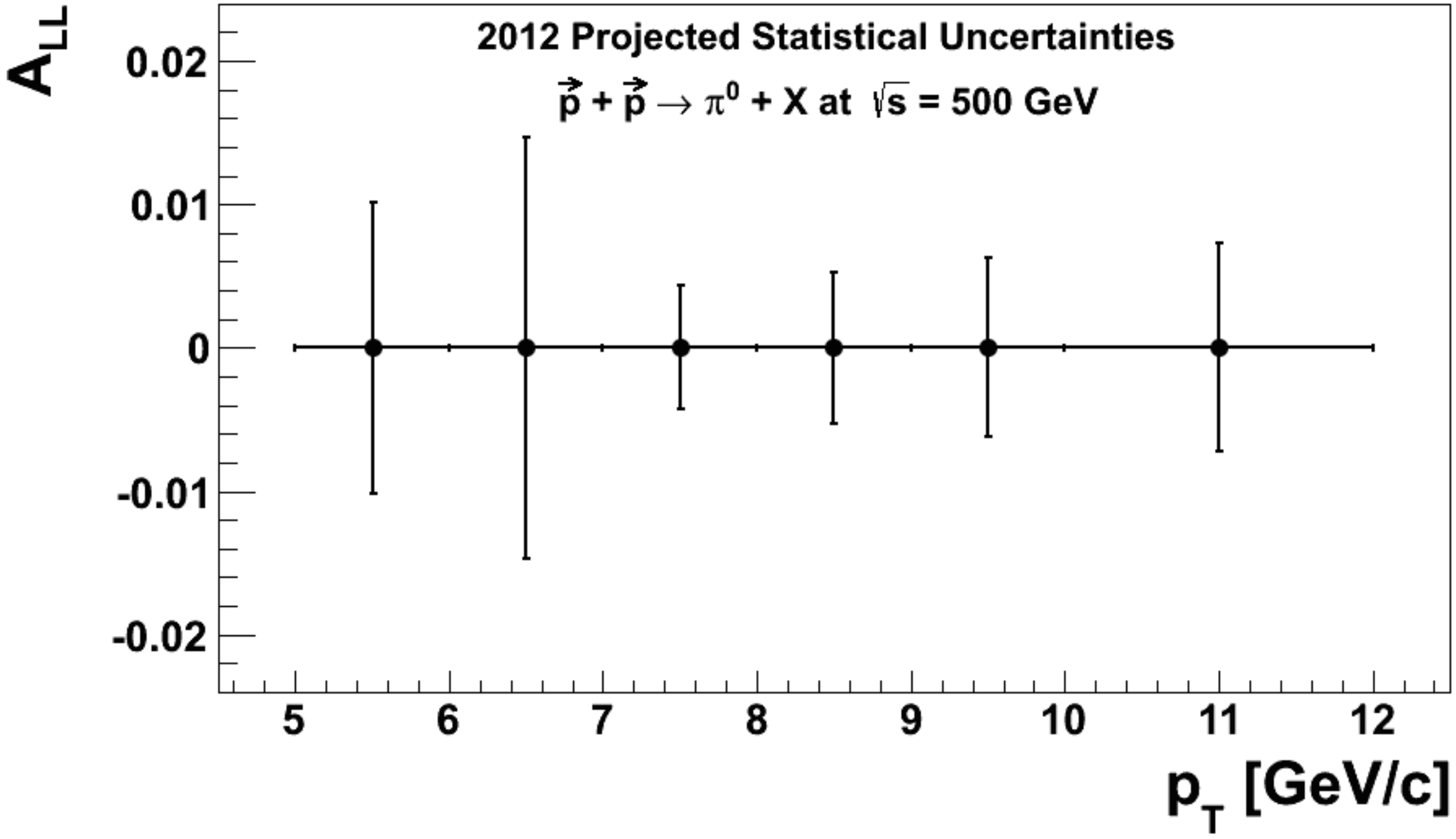
- PHENIX: Mid-rapidity neutral pion A_{LL} measurement A_{LL} measurement





A. Adare et al. (PHENIX Collaboration), arXiv:1510/02317.

- Data are well described by NLO pQCD calculations
- New PHENIX Run 13 results at 510GeV
- Consistency between PHENIX and STAR results!


2012 Projected Statistical Uncertainties
$\vec{p} + \vec{p} \rightarrow \pi^0 + X$ at $\sqrt{s}$ = 500 GeV
A_{LL}
0.02
0.01
0
-0.01
-0.02
5
6
7
8
9
10
11
12
p_T [GeV/c]