Jet measurements in polarized p+p collisions at STAR at RHIC

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for STAR Collaboration

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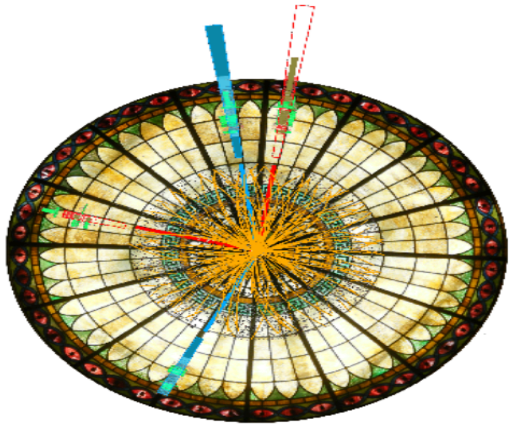
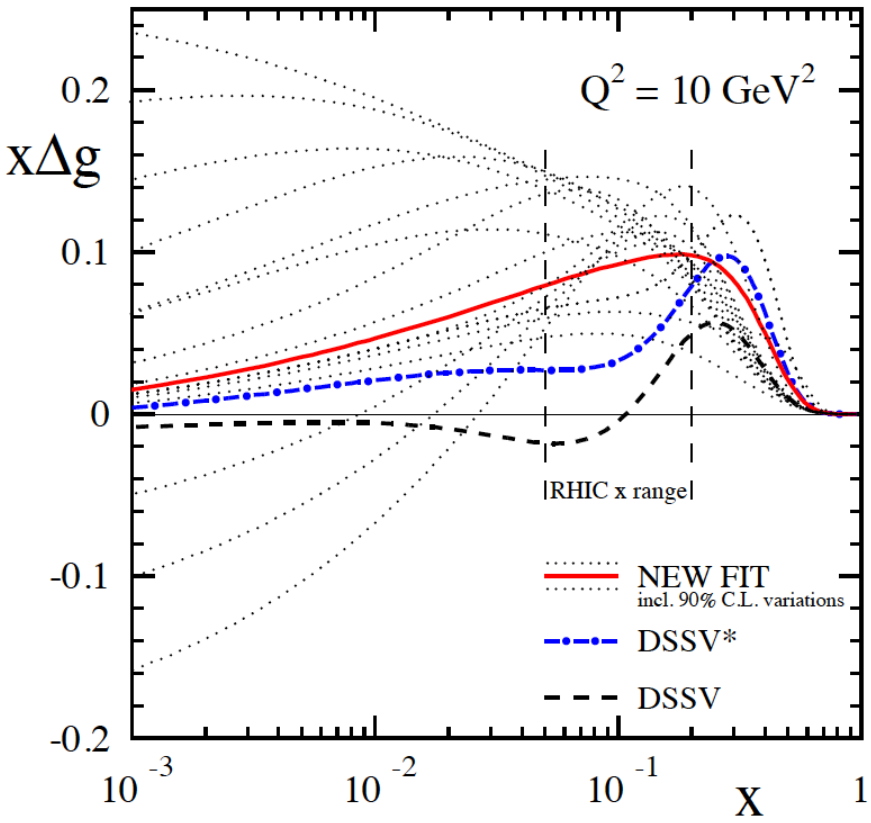
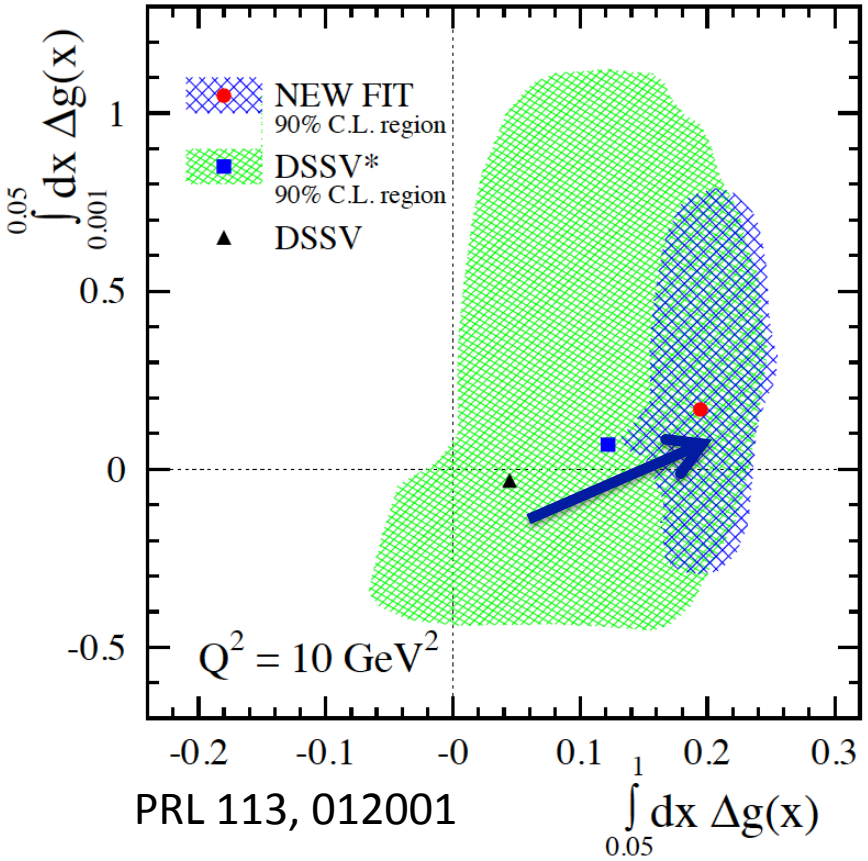


Outline

- Introduction
- Overview of RHIC and STAR
- Selected STAR measurements
  - Inclusive jet cross section measurements.
  - inclusive jet A_{LL} results.
- Summary and Outlook

Current knowledge of polarized gluon PDF

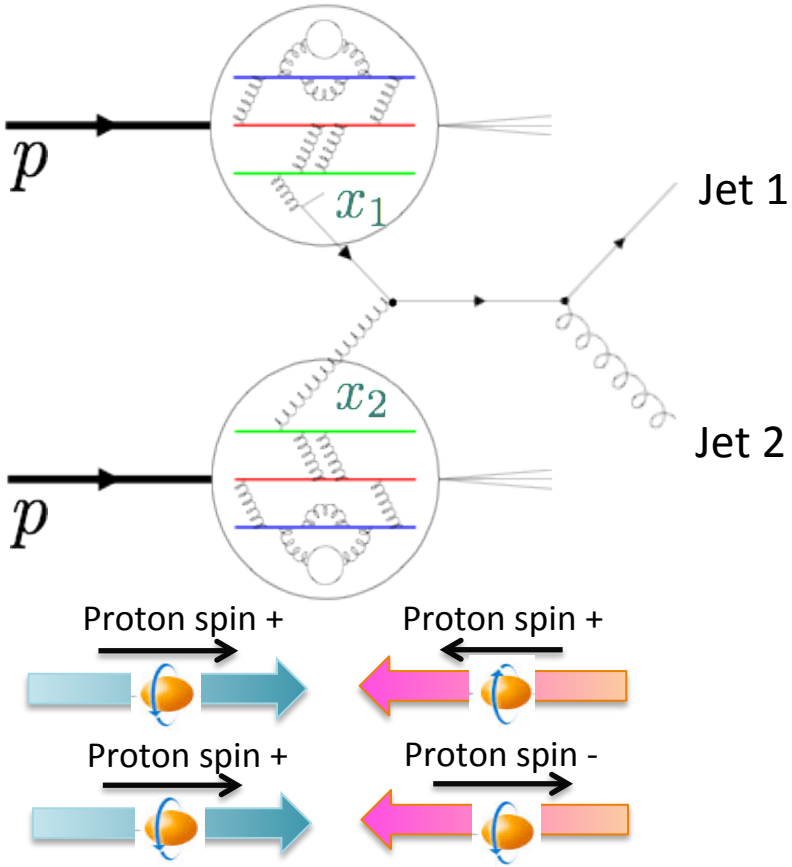




- Gluon pPDF has still large uncertainties in the low x region (x<0.05).
- Data from polarized p+p collisions at RHIC will improve the precision in x region accessible by RHIC data.

How to probe polarized PDFs in p+p collisions?

- Assuming factorization and universal PDFs, asymmetries of final states are proportional to the initial quarks or gluons polarization contributions.



- For example, longitudinal double-spin asymmetry A_{LL} of inclusive jet or di-jets can probe the quark or gluon helicity function.

To measure

$\Delta f_{1/2}$: Quark/gluon helicity

$$A_{LL}(jet) = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} \propto \frac{\Delta f_1 \otimes \Delta f_2 \otimes a_{LL}}{f_1 \otimes f_2}$$

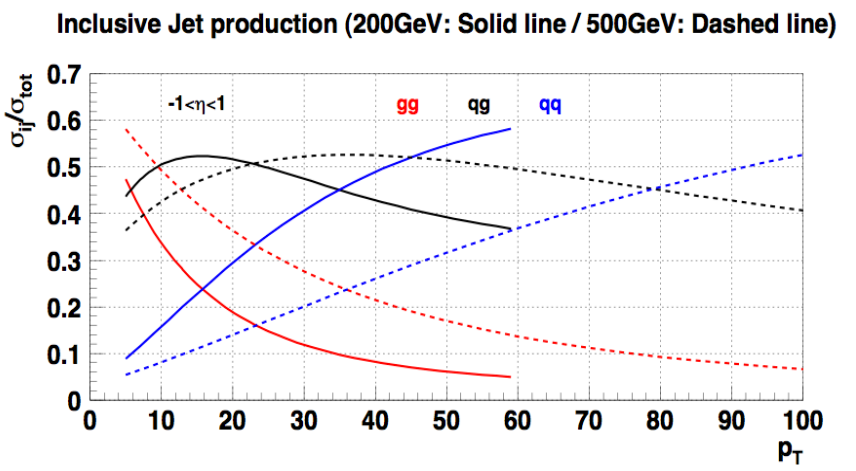
known inputs:

$f_{1/2}$= unpolarized parton distribution function.

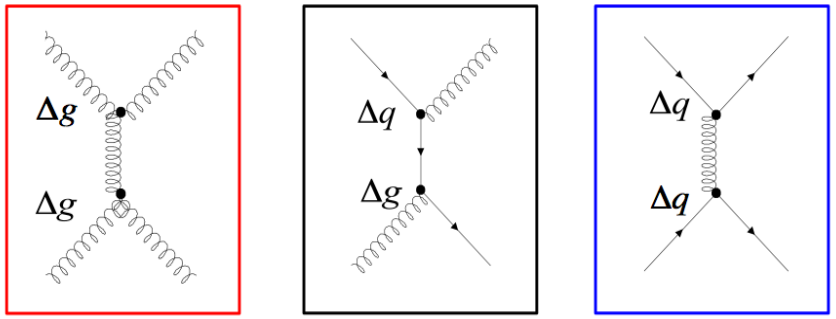
a_{LL}: polarized parton asymmetry

Inclusive jet A_{LL}

- Mid-rapidity inclusive jet production is dominated by g+g and q+g processes in RHIC 500 GeV p+p collisions (q+g process at 200 GeV p+p collisions).



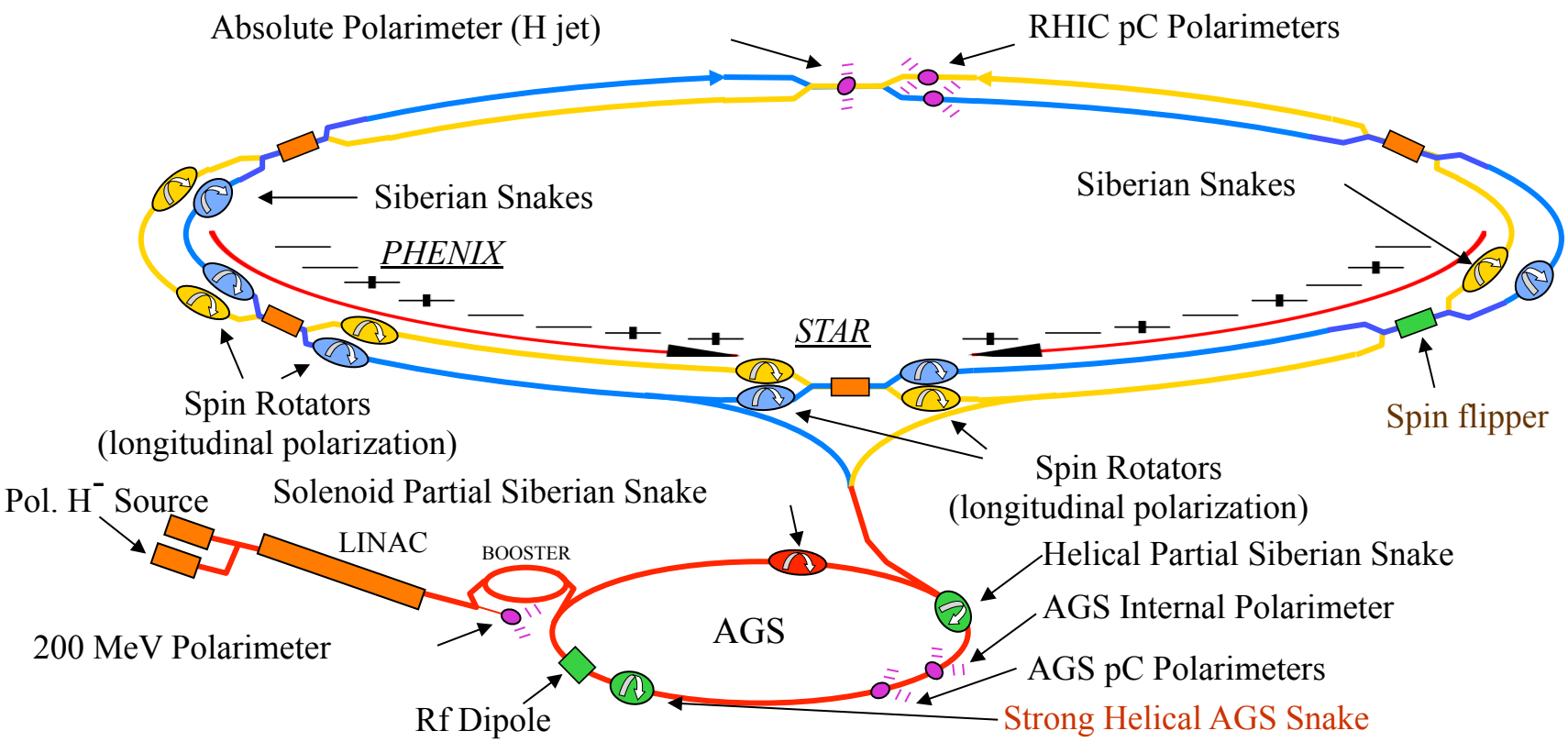
$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \propto \frac{\Delta f_a \Delta f_b}{f_a f_b} \hat{a}_{LL}$$



- Mid-rapidity inclusive jet A_{LL} in 200 GeV p+p collisions is sensitive to the gluon contribution to polarized proton for the 0.05<x<0.2 region.

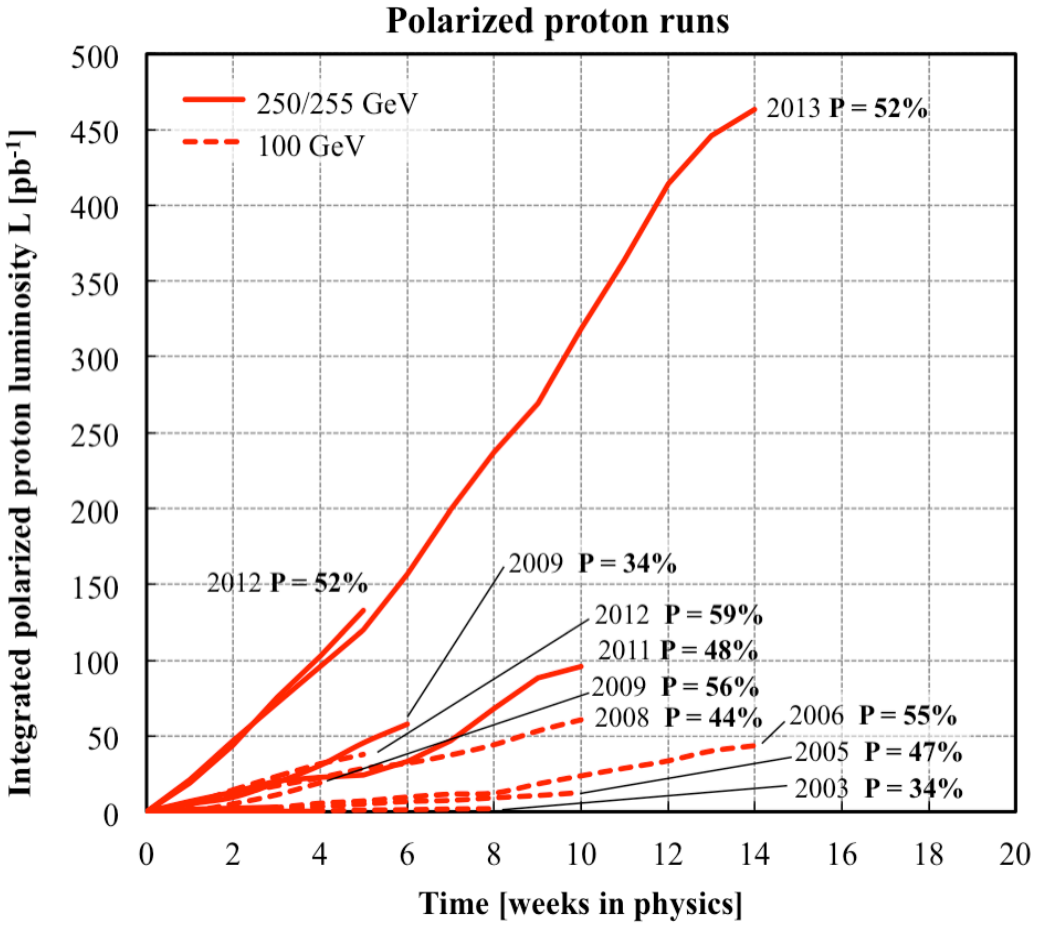
RHIC: the polarized proton-proton collider

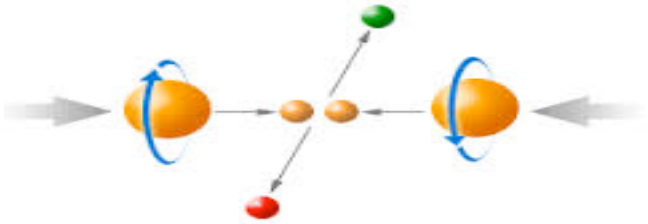
- Schematics of polarized p+p collisions at RHIC



RHIC polarized p+p collision overview

- STAR spin program explores both the longitudinal and transverse polarized proton.



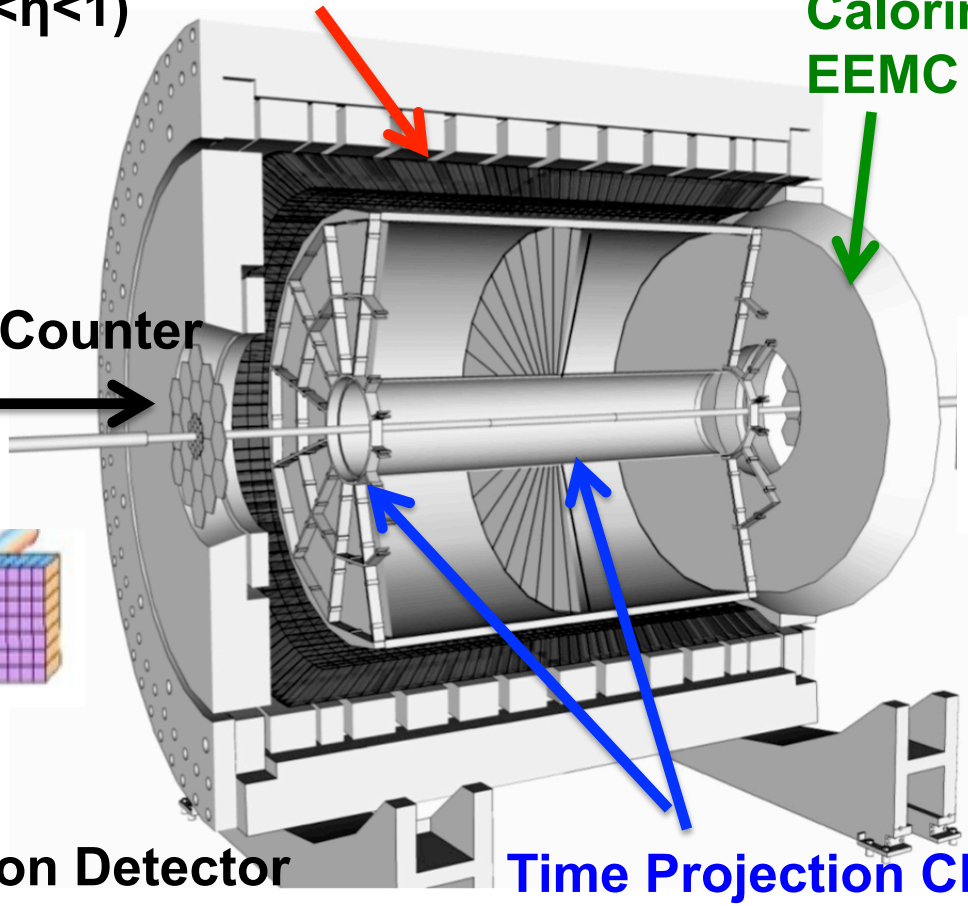


- Jet and di-jet productions in longitudinal polarized p+p collisions at √s=200/500 GeV are sensitive to the gluon polarization.

STAR new inclusive jet cross section with anti-k_T algorithm in 200 GeV p+p collisions

STAR Detector in 2009 data set

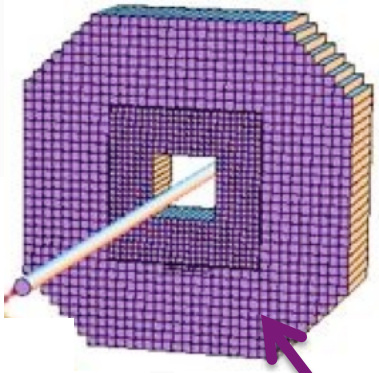
- STAR has nearly full azimuthal coverage in η from -1 to 4.



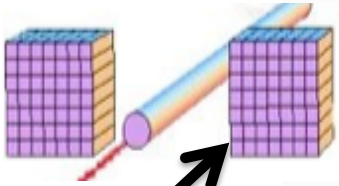
Barrel ElectorMagnetic Calorimeter
BEMC (-1<η<1)

Endcap ElectorMagnetic Calorimeter
EEMC (1<η<2)

Beam Beam Counter (BBC)



West side:
Forward Meson Spectrometer
FMS (2.5<η<4.0)



East side:
Forward Pion Detector
FPD (-4.5<η<-3.6)

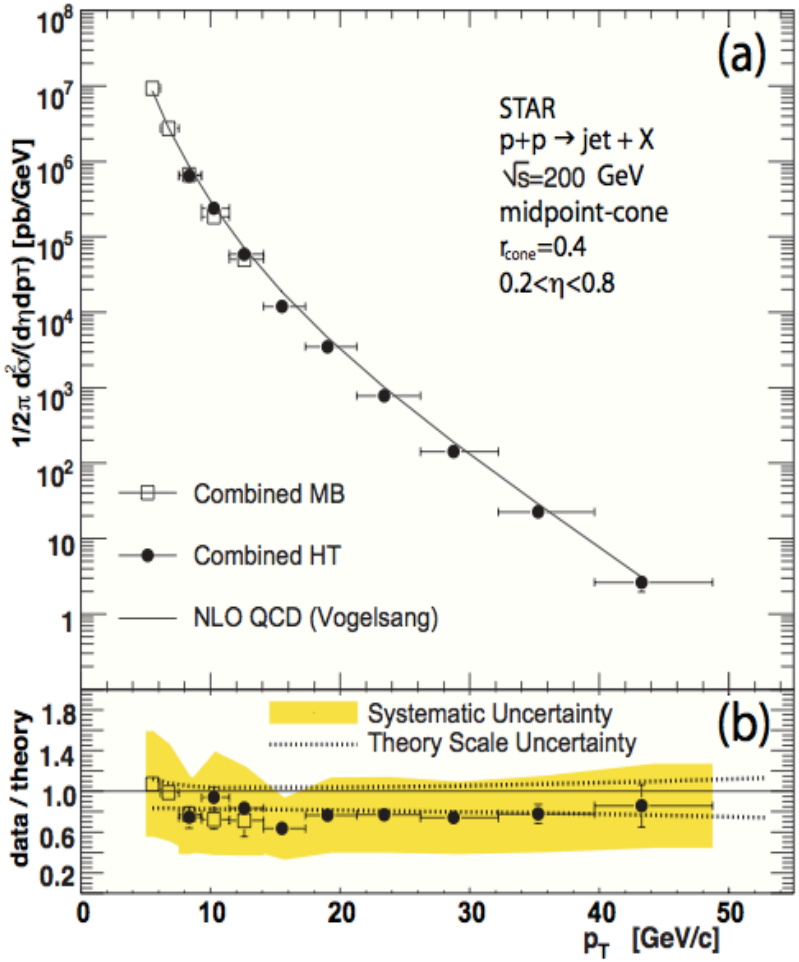
Time Projection Chamber
TPC (|η|<1.3)

$$\eta = -\ln\tan\frac{\theta}{2}$$

Motivation for jet cross section

- Previous measurements (shown on the right):
  - Limited acceptance (half detector installed, now we have full detector).
  - Use mid-point cone jet algorithm

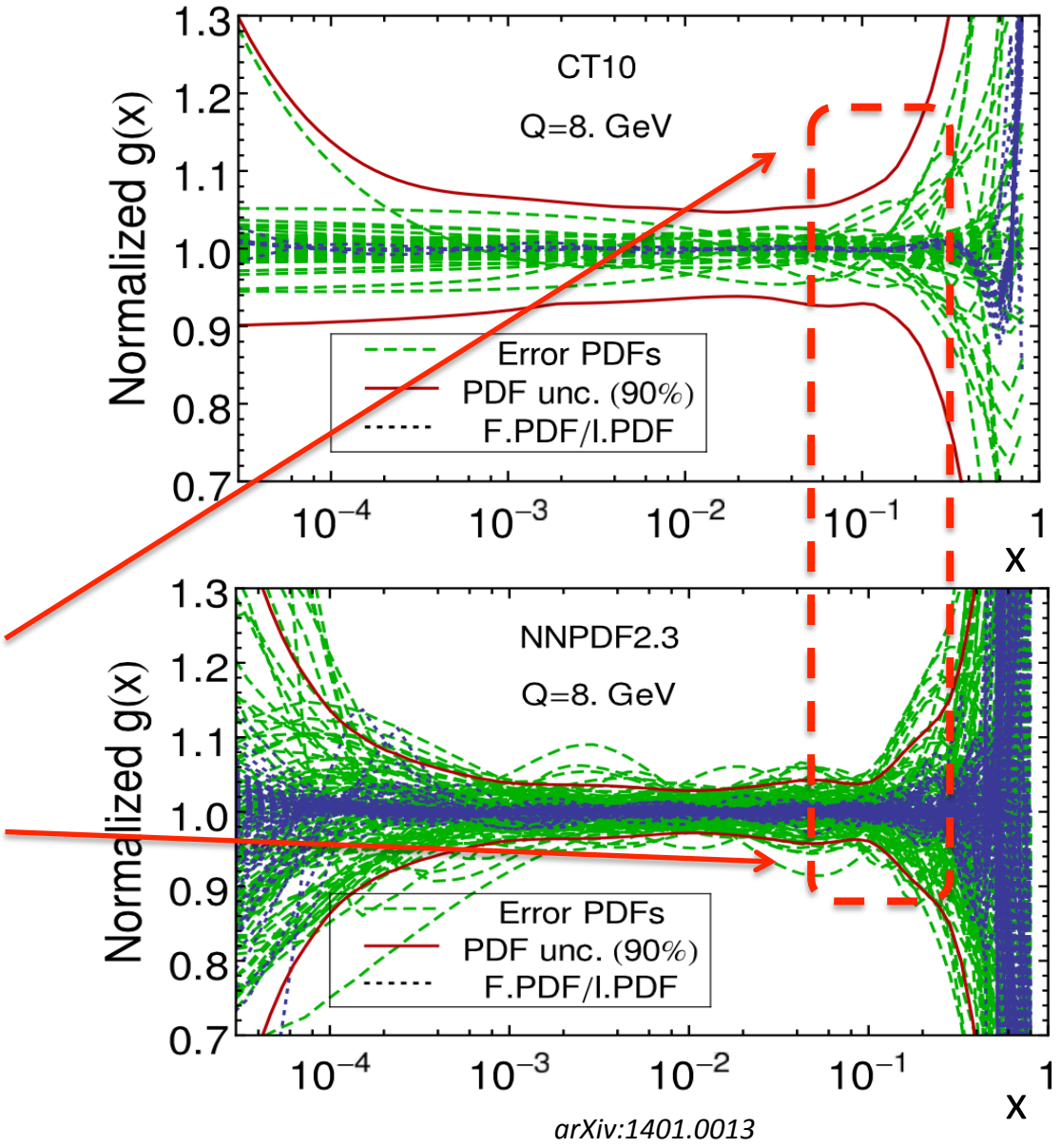
Phys.Rev.Lett.97:252001



arXiv:1401.0013

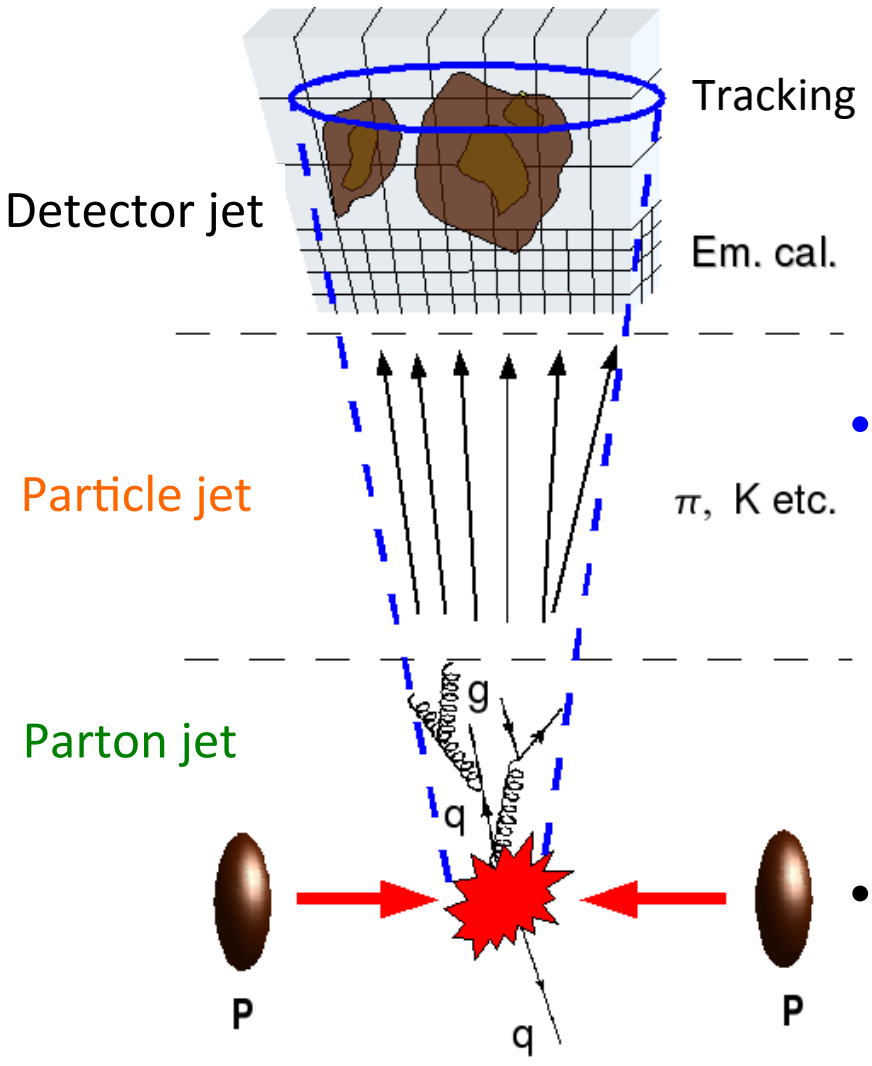
Motivation for jet cross section

- The new inclusive jet cross section with the anti-k_T jet algorithm has improved statistical precision and reduced systematics compared to early measurements.
- Study of proton structure: Constrain unpolarized gluon distribution at high-x



arXiv:1401.0013

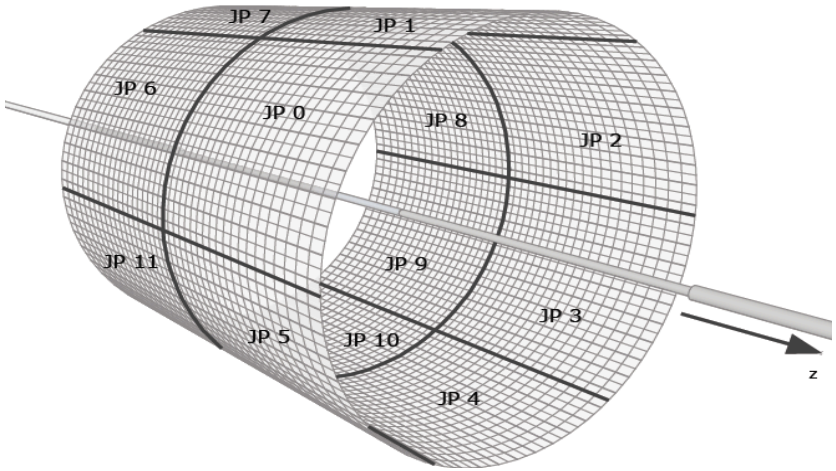
Jet Reconstruction



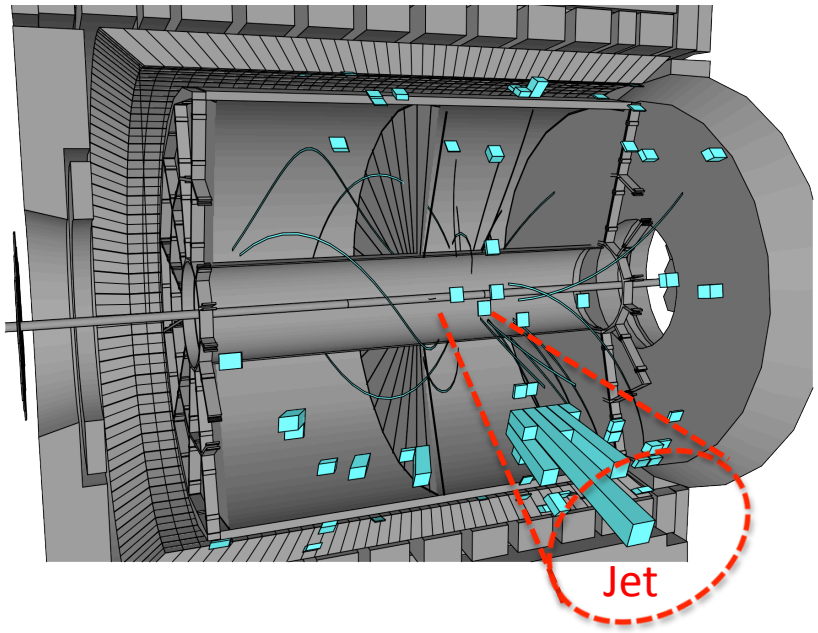
- Midpoint Cone algorithm[aXiv:hep-exp/0005012] (used in previous jet study):
  - Collect towers+tracks within a cone of radius ($R=\sqrt{\Delta\eta^2+\Delta\phi^2}$) 0.7.
  - Split/Merge fraction 0.5.
- Anti-k_T algorithm[JHEP 0804:063,2008]:
  - $d_{ij} = \min(\frac{1}{k_{T,i}^2}, \frac{1}{k_{T,j}^2}) \frac{\Delta_{ij}^2}{R^2}$ $\quad \Delta_{ij}^2 = (y_i - y_j)^2 + (\varphi_i - \varphi_j)^2$
  - Collect towers+tracks based on particle $1/k_{T,i}^2$. Select R=0.6.
  - less UE and pile up.
  - Infrared and collinear safe.
- Apply anti-k_T jet algorithm to reconstruct detector, particle and parton jets in simulation and detector jets in data.

STAR mid-rapidity jet measurements

BEMC jet patch mapping

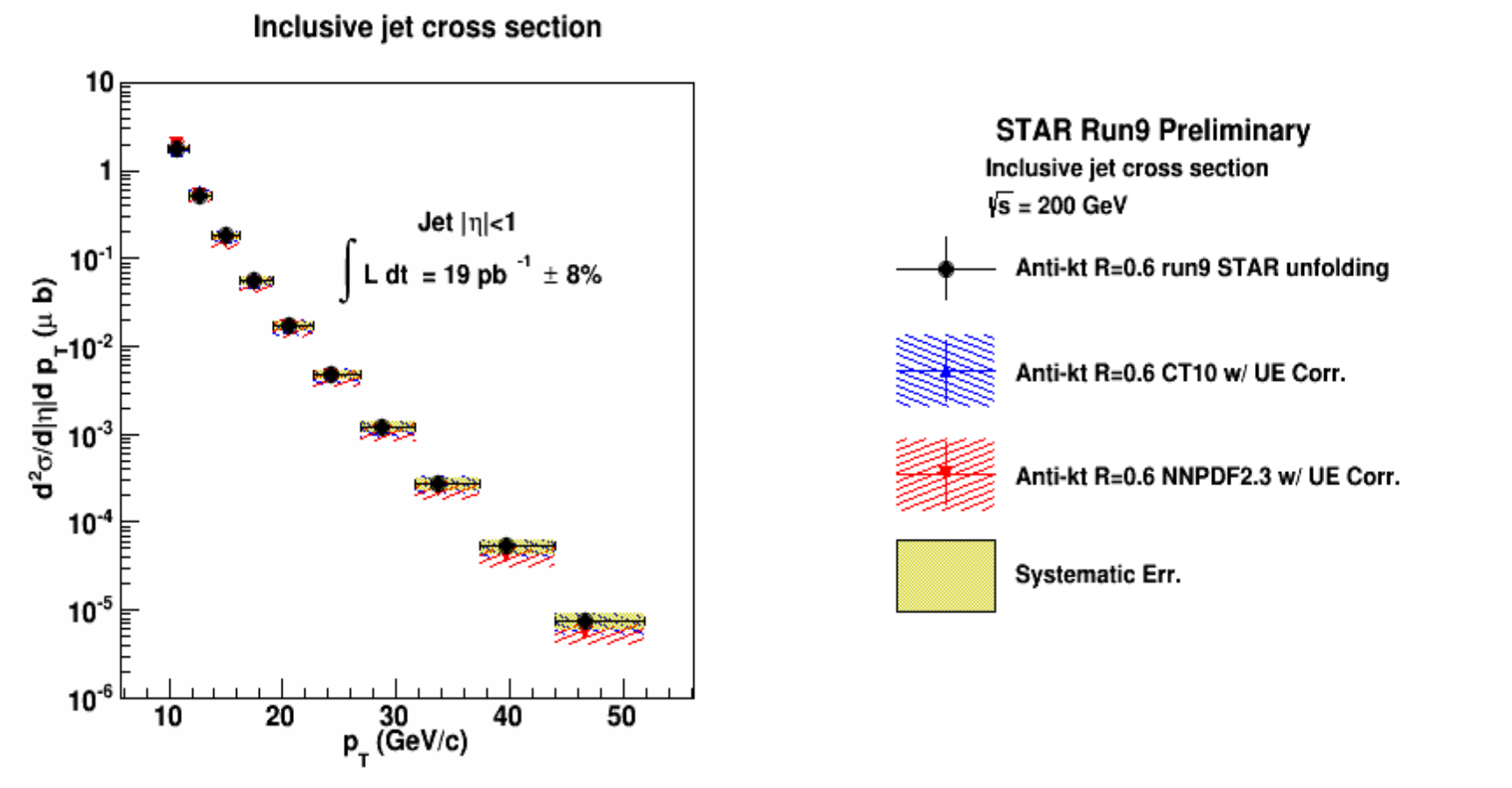


Event display of jet event at STAR



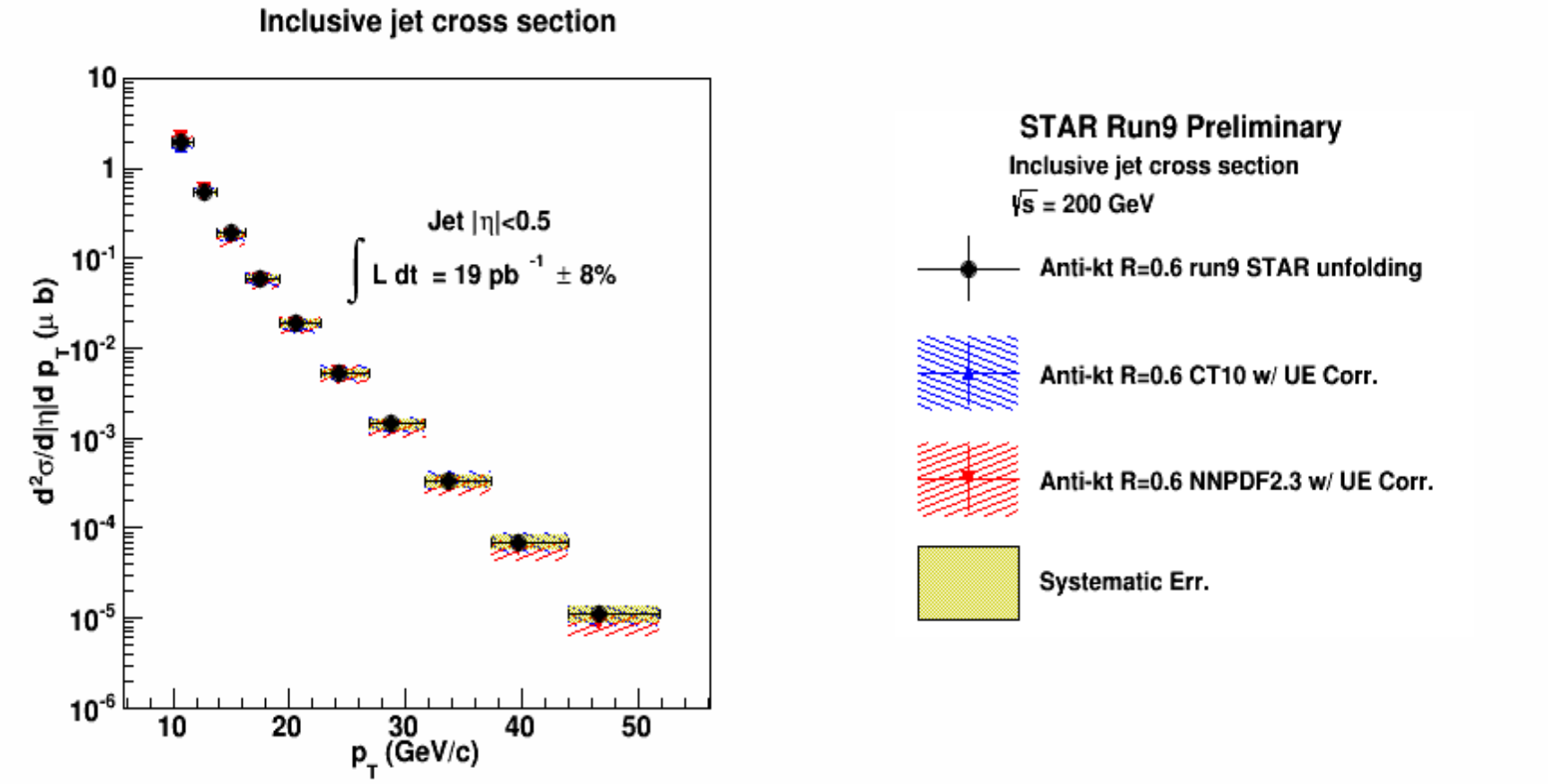
- Triggers for inclusive jet:
  - 30 BEMC, EEMC jet patches are used for jet triggers.
  - L2JetHigh: based on L0 trigger, level 2 algorithm looks for jet in calorimeter only (no tracking info). JP E_T>6.5GeV/c + 10% random accept.
- Event cuts
  - z vertex: $|z_{vert}| < 90cm$.
- Anti-k_T R=0.6 jet algorithm.
- Jet cuts
  - (1) L2JetHigh jet p_T>8.4GeV/c.
  - (2) neutral energy fraction $R_T < 0.94$
  - (3) Σ(tracks p_T) > 0.5GeV/c
  - (4) -0.7 < detector η < 0.9
  - (6) Jet must point toward a triggered Jet Patch or Adjacent Jet Patch.
  - Tracks inside jet should have p_T<30Gev/c.

STAR 2009 inclusive jet cross section in comparison with NLO pQCD calculations (|η|<1.0)



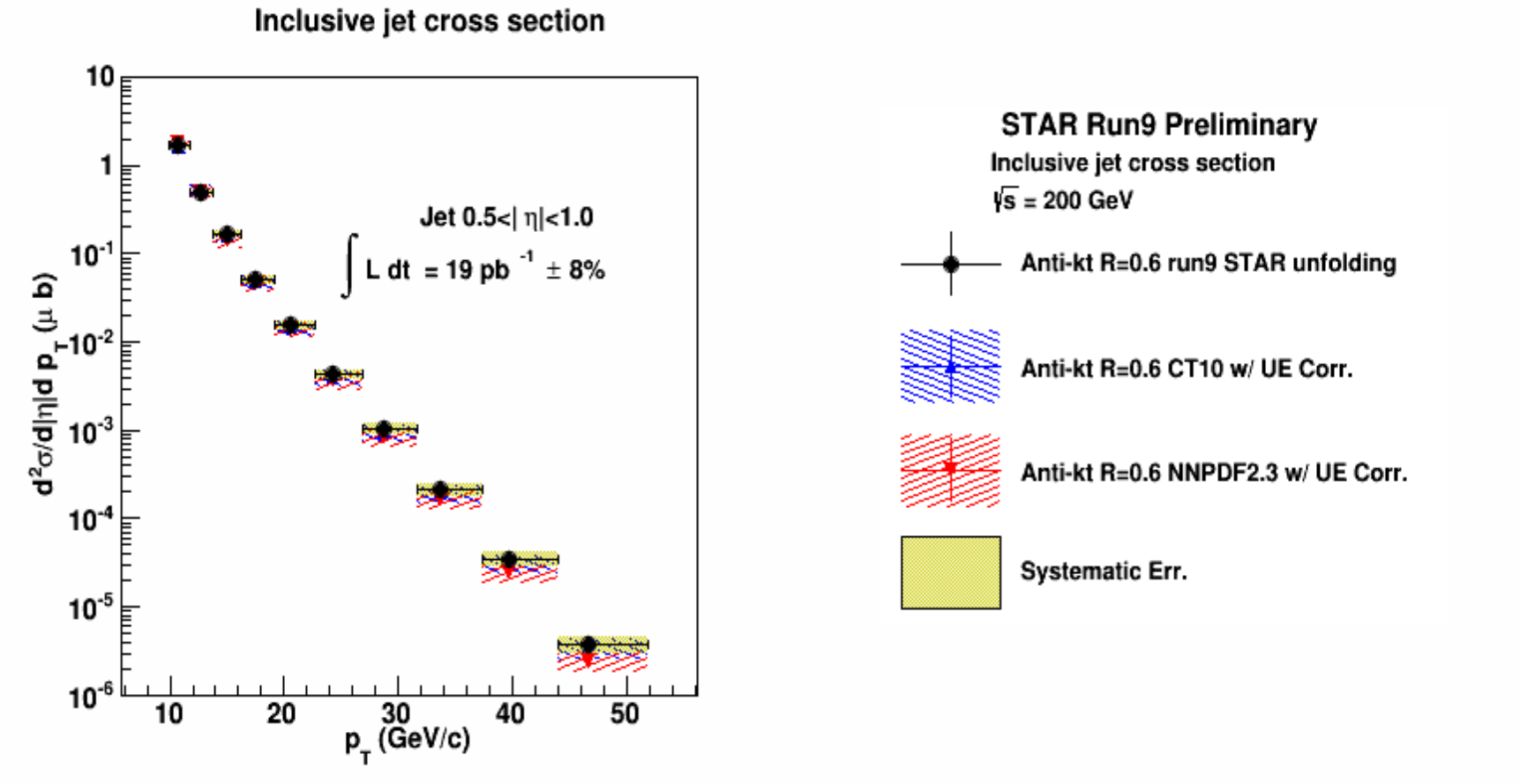
- Unfold detector level jets to particle level jets.
- NLO pQCD calculations with CT10 and NNPDF2.3 PDFs with UE contribution corrected to particle level jets. Factorization and renormalization scaling uncertainties are included.

STAR 2009 inclusive jet cross section in comparison with NLO pQCD calculations (|η|<0.5)



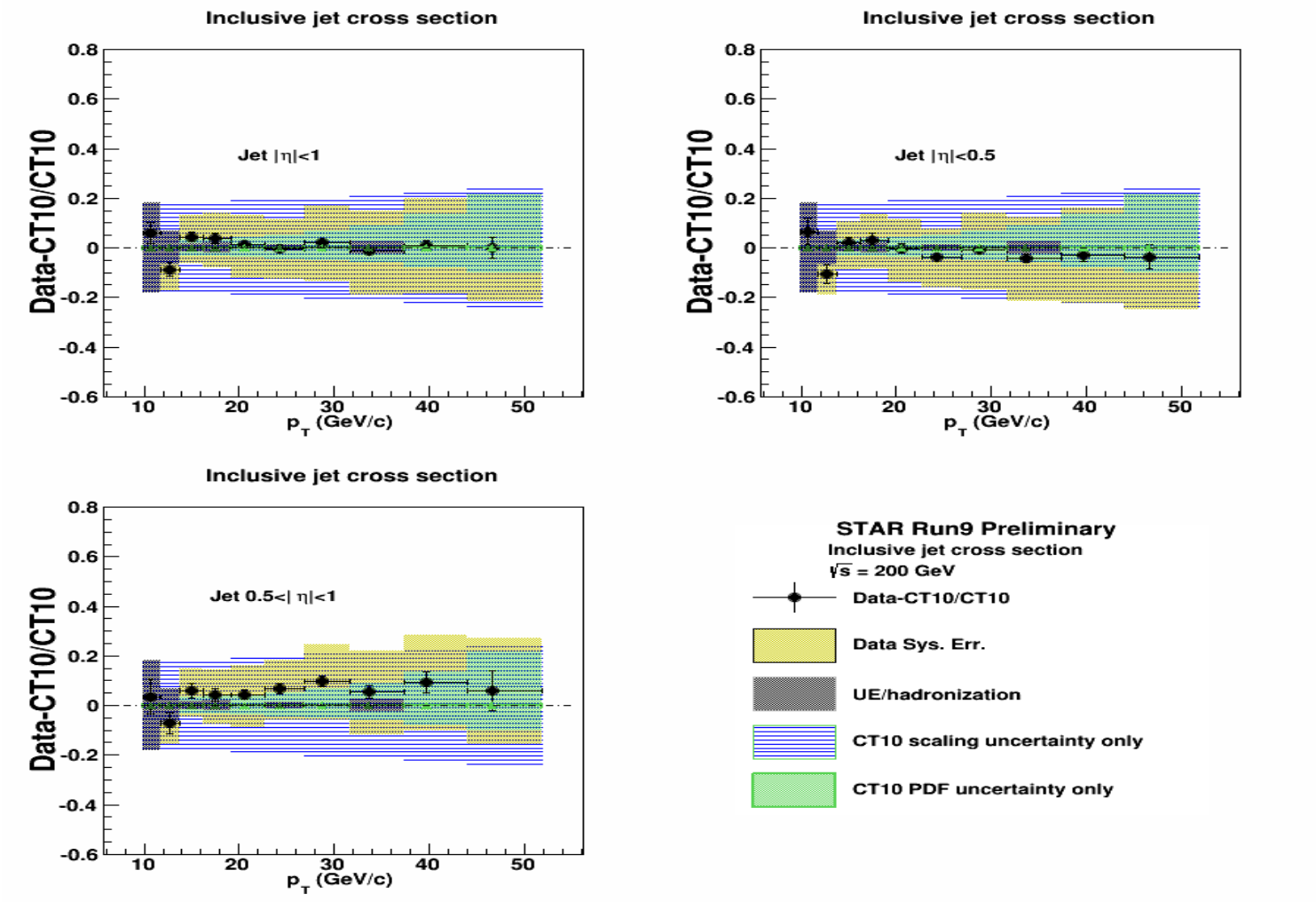
- Unfold detector level jets to particle level jets.
- NLO pQCD calculations with CT10 and NNPDF2.3 PDFs with UE contribution corrected to particle level jets. Factorization and renormalization scaling uncertainties are included.

STAR 2009 inclusive jet cross section in comparison with NLO pQCD calculations (0.5<|η|<1.0)



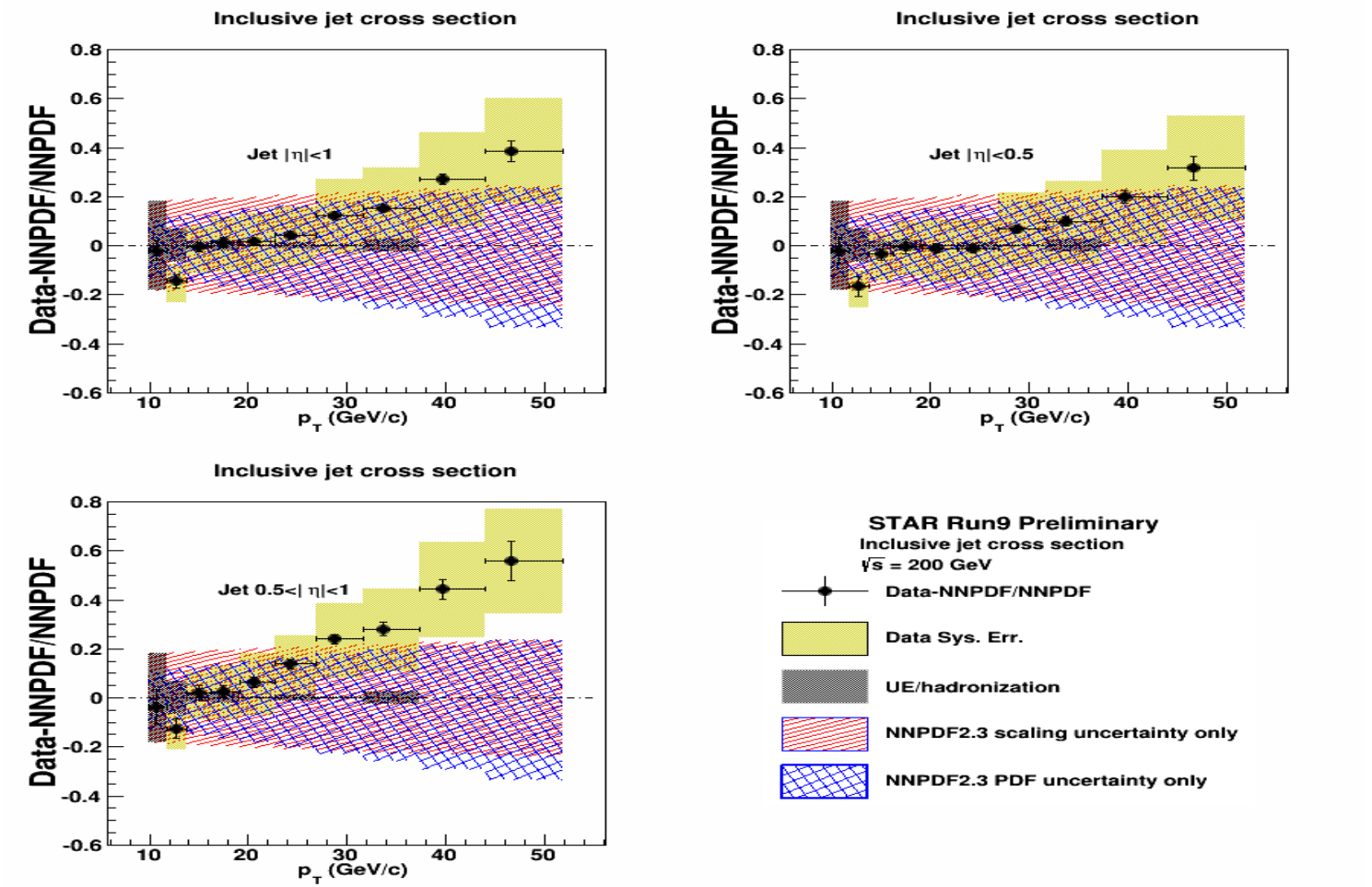
- Unfold detector level jets to particle level jets.
- NLO pQCD calculations with CT10 and NNPDF2.3 PDFs with UE contribution corrected to particle level jets. Factorization and renormalization scaling uncertainties are included.

Data – CT10 / CT10



- Dominant systematic error comes from calibration and inefficiency.
- Good agreement between data and NLO pQCD with CT10 PDF sets.

DATA – NNPDF / NNPDF

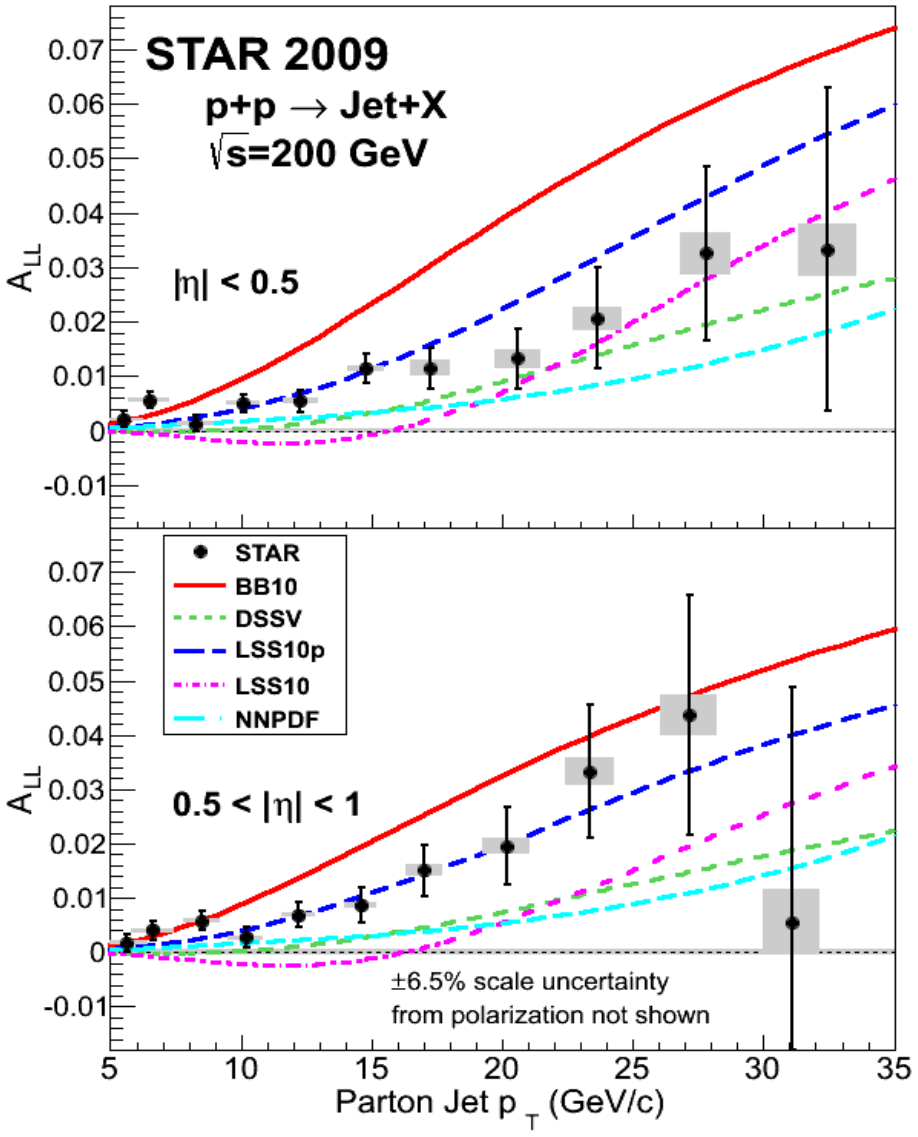


- Agreement between data and NLO pQCD with NNPDF2.3 PDF sets for |η|<1.0 and |η|<0.5 regions. Slightly difference between data and NNPDF calculations for 0.5<|η|<1.0 region.

STAR inclusive jet A_{LL} measurements to access the $\Delta g(x,Q^2)$ (gluon polarization)

STAR inclusive jet A_{LL} in 2009 (p+p 200 GeV)

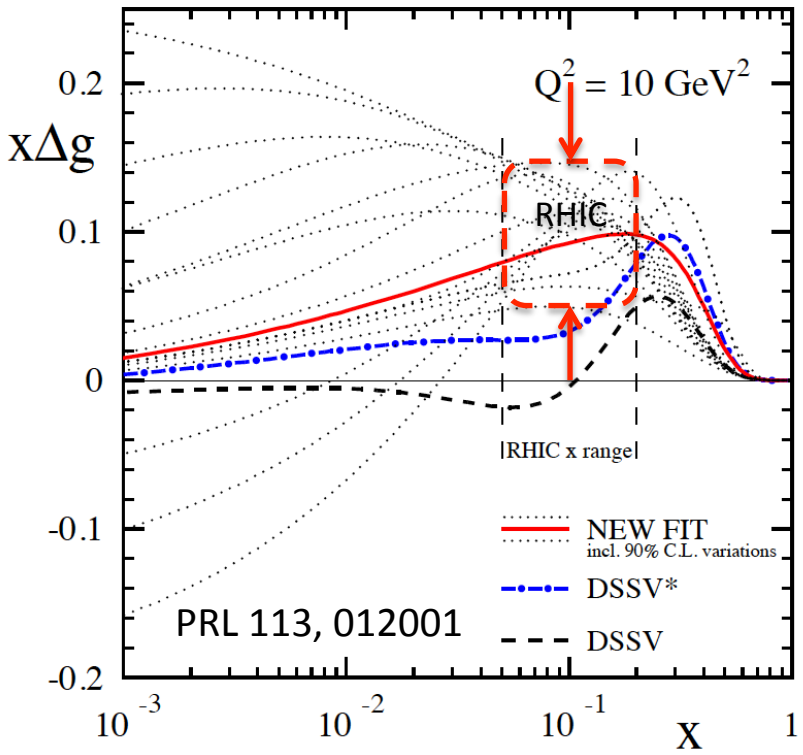
arXiv:1405.5134

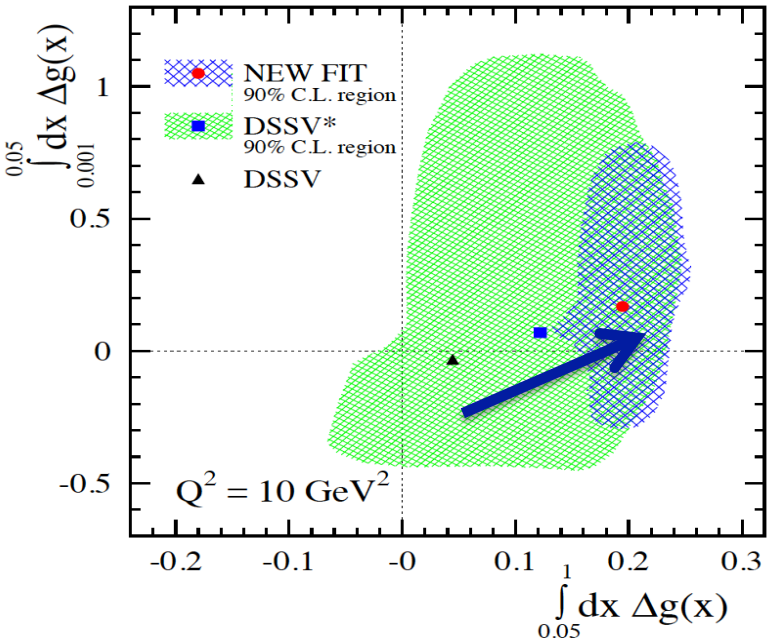


- The 2009 STAR inclusive jet A_{LL} (anti-k_T cone radius R=0.6) samples around 4 times of statistics than previous 2006 result.
- The inclusive jet A_{LL} falls between the predictions from different polarized PDF sets (BB10, DSSV, LSS10p, LSS10 and NNPDF).
- What's the impacts from this result on ΔG?

STAR inclusive jet A_{LL} in 2009 (p+p 200 GeV)

- STAR inclusive jet and PHENIX π^0 A_{LL} indicates non-zero gluon polarization in 0.05<x<1.



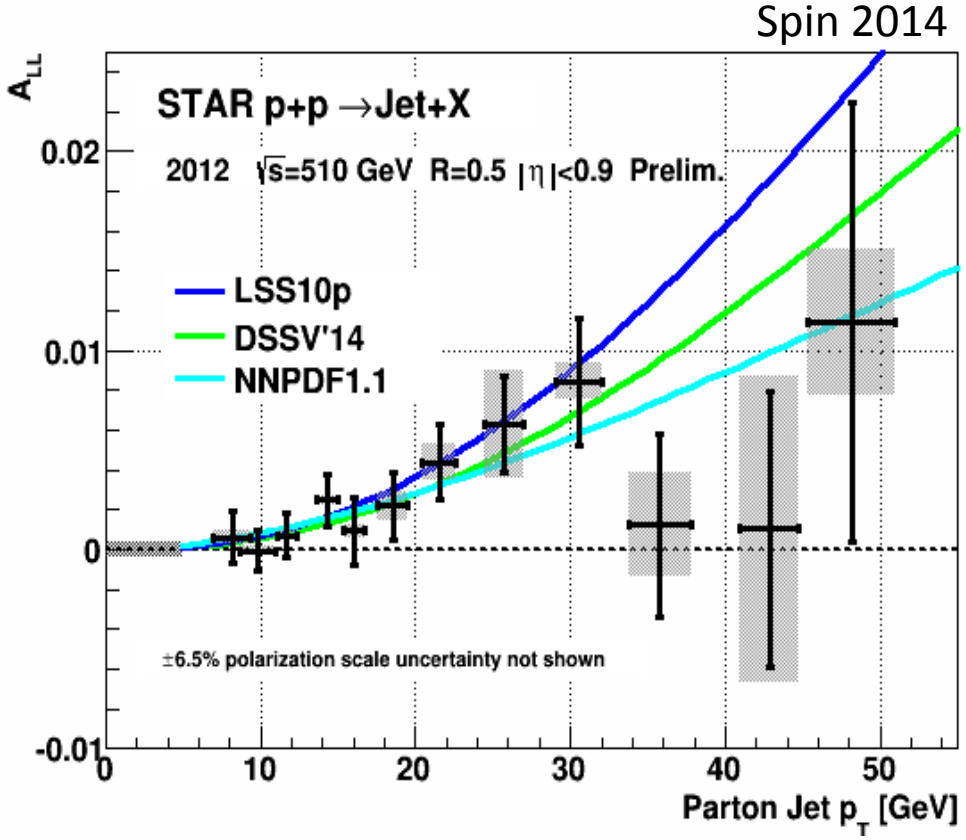


$$\int_{0.05}^{1} \Delta g(x, Q^2 = 10 GeV^2)\, dx = 0.2^{+0.06}_{-0.07}$$

- RHIC A_{LL} results narrow the uncertainties of the fitted Δg and shift the central value of ΔG.
- DSSV2014 fit provides first non-zero ΔG in the RHIC sensitive region.

STAR inclusive jet A_{LL} in 2012 (p+p 510 GeV)

- Higher √s (510 GeV) provides sensitivity to lower x_g region (than 200 GeV).

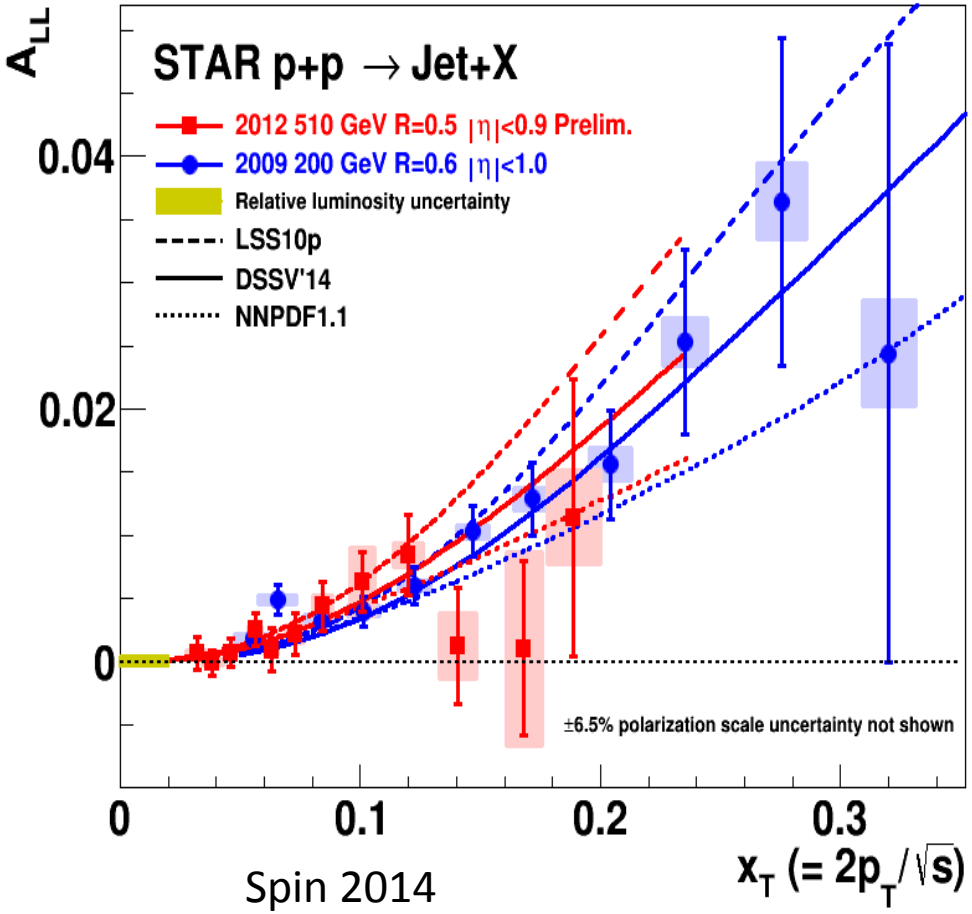


- Same jet reconstruction scheme (anti-k_T jet algorithm).
- Use cone radius R=0.5 to reduce pile up backgrounds and improve matching probability from detector jet to parton jet.
- In comparison with NLO pQCD calculations with polarized PDF sets (LSS10p, DSSV14 and NNPDF1.1).

- Data are in agreement with the latest polarized PDF sets predictions.

STAR inclusive jet A_{LL} in 2012 (p+p 510 GeV)

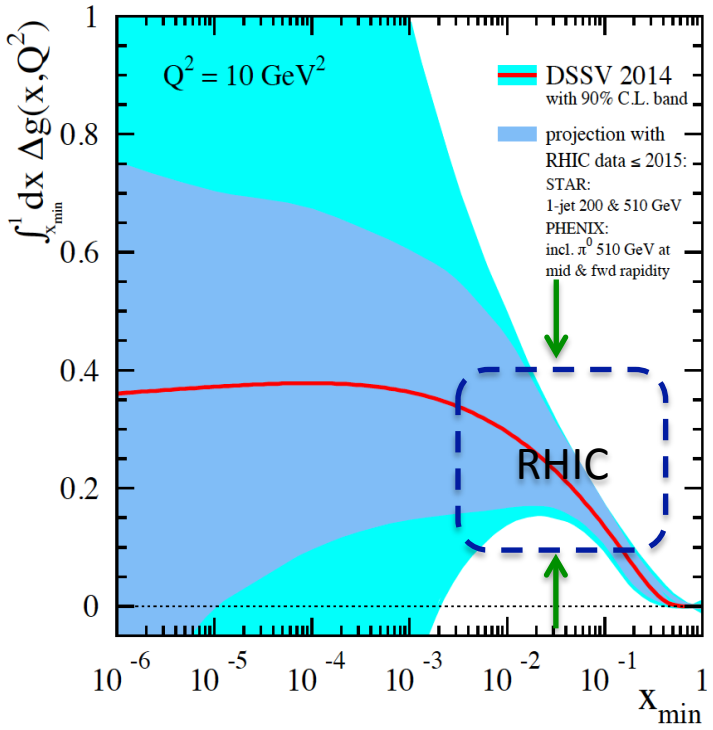
- Higher √s (510 GeV) provides sensitivity to lower x_g region (than 200 GeV).

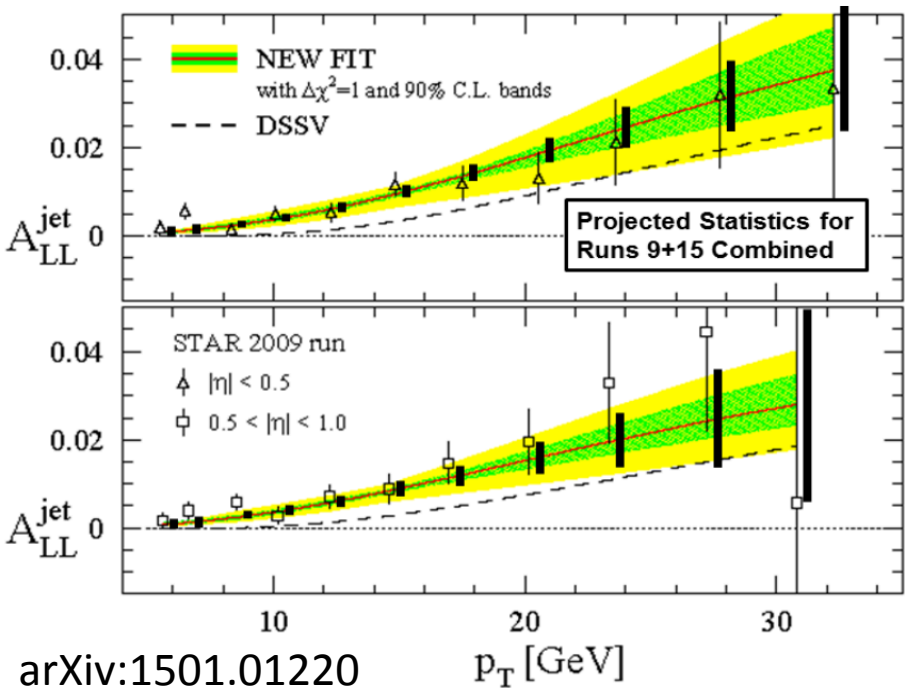


Spin 2014

- Higher √s (510 GeV) inclusive jet A_{LL} is in good agreement with the lower √s (200 GeV) result in the overlapping region.
- 2013 500 GeV data will further constrain the polarized gluon distribution function in lower x region.

Projections for inclusive jet A_{LL} (p+p 200/500GeV)





arXiv:1501.01220

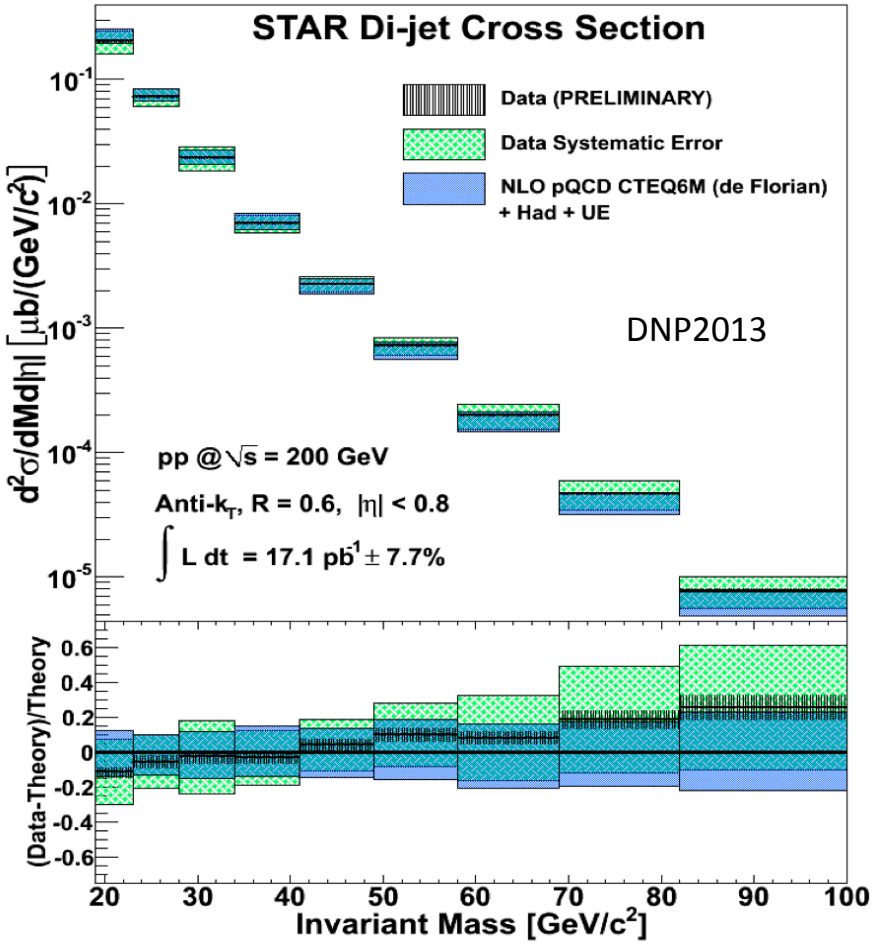
- In 2013, RHIC has large longitudinal √s = 500GeV p+p data sample which allows us to continue access lower x region with higher √s.
- For 2015 200GeV p+p run, expect to reduce the stat. errors by a factor of ~~2~~ (1.6). Data at forward rapidity to access low x.

STAR di-jet measurements

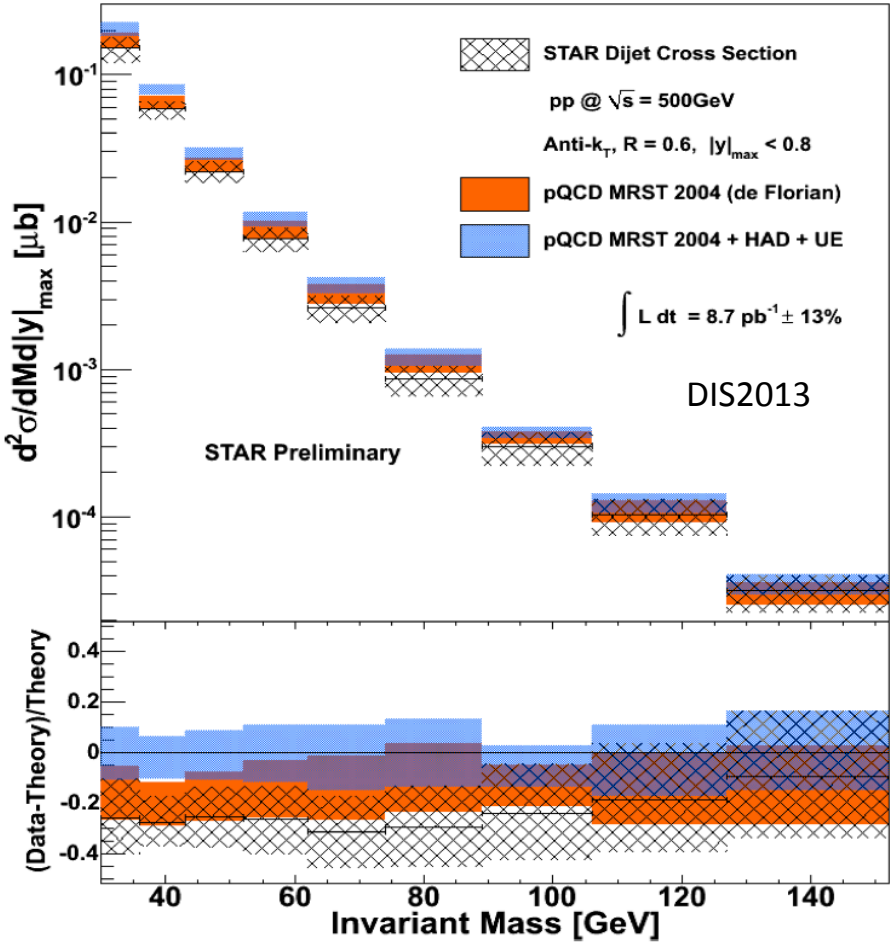
Di-jet cross section measurements at STAR

- Di-jet cross section results in p+p collisions are consistent with NLO pQCD calculations after Had+UE corrections.

Di-jet in p+p 200GeV



Di-jet in p+p 500GeV



Summary and Outlook

- Inclusive jet cross-section:
  - Measured cross section for all η regions are consistent within uncertainties with NLO pQCD calculations with a preference for CT10.
- Gluon polarization program:
  - 2009 inclusive jet A_{LL} measurement together with PHENIX π^0 A_{LL} gives first evidence of non-zero ΔG in the range of $x_g > 0.05$.
  - 2012 inclusive jet A_{LL} measurement opens the path to constrain the shape of Δg in lower x_g region.
  - Di-Jet measurements provide direct sensitivity to partonic kinematics / New measurements at 500GeV in preparation.
- 2013 run and future
  - Long. 500 GeV run in 2013(~310pb^{-1}) and 200 GeV run in 2015 allows us to achieve higher precision measurements.
  - Longer term upgrades are planned to prepare for the transition from RHIC to an EIC.

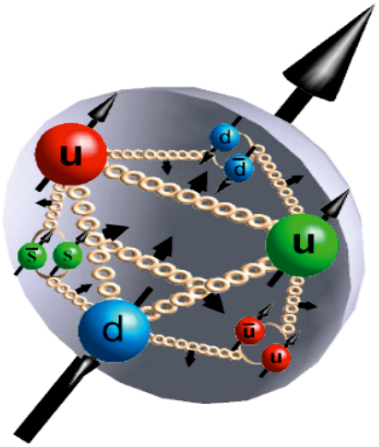
Backup

Spin structure of the proton

- Proton spin is carried by it components (quarks and gluons).

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

DIS measured ~30% Little known

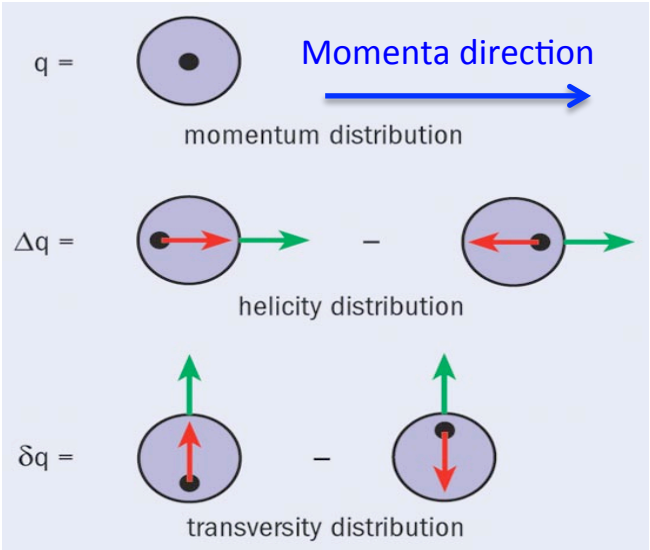


$$\Delta G = \int \Delta g(x,Q^2)\,dx$$

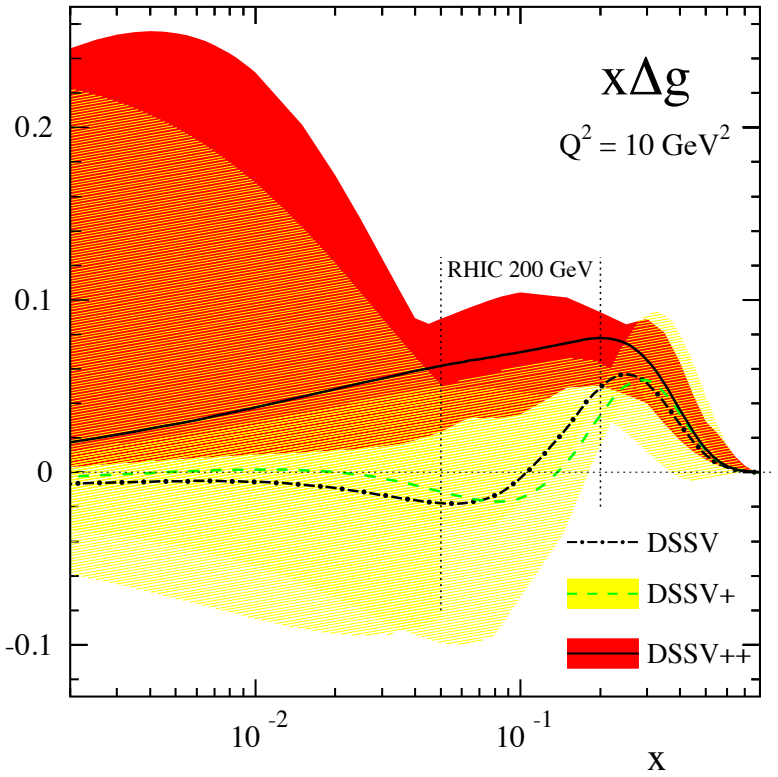
$$\Delta\Sigma = \int (\Delta q(x,Q^2) + \Delta\overline{q}(x,Q^2)\,dx$$

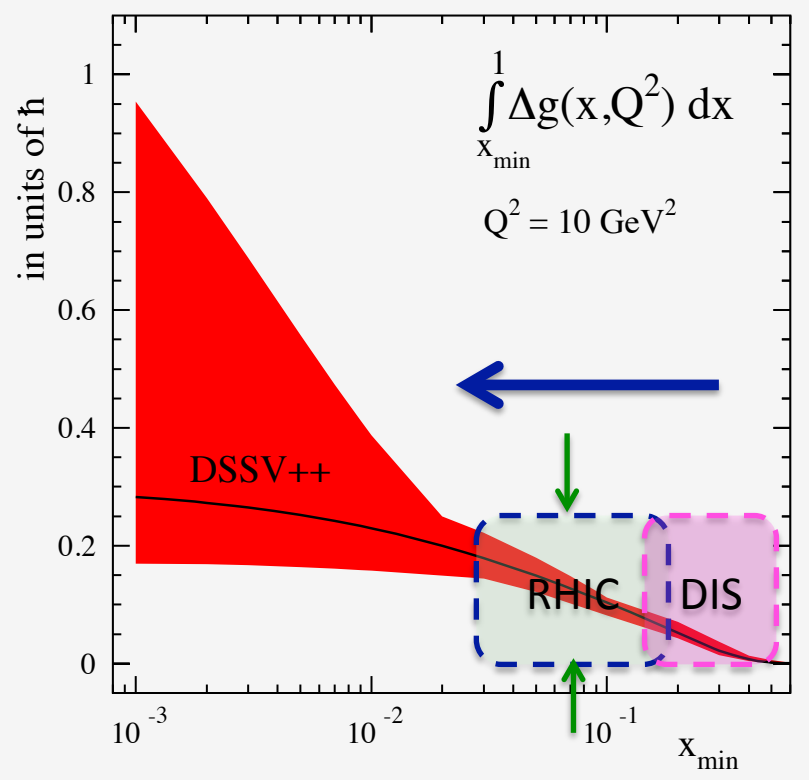
Where q = u, d, s (heavy quarks excluded)

- Polarized parton distribution function (pPDF): $\Delta q(x,Q^2)/\Delta g(x,Q^2)$ is the probability to find a quark/gluon with its spin aligned minus its spin anti-aligned to the spin of the proton.



Current knowledge of pPDF



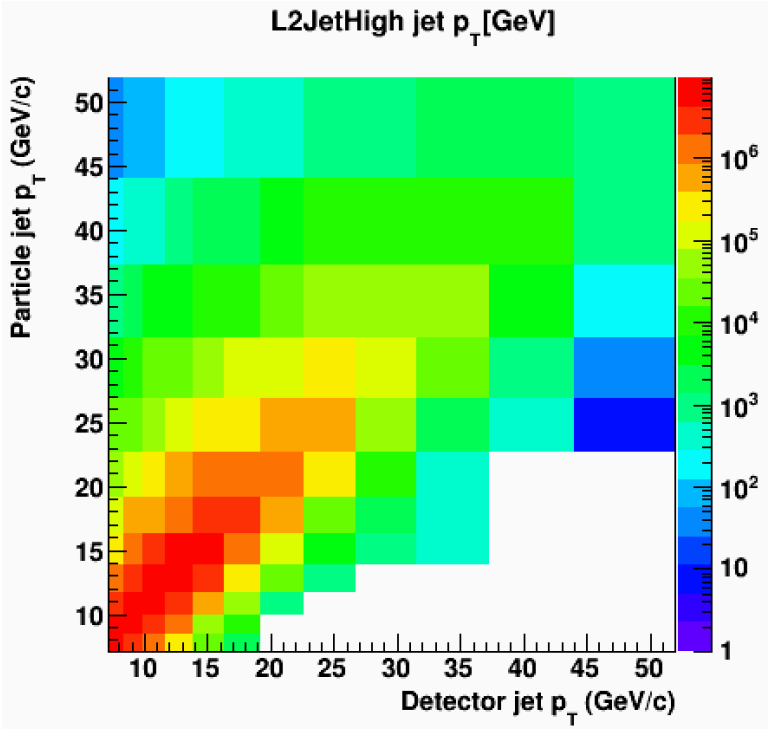


arXiv:1304.0079

- Gluon pPDF has large uncertainties, especially in low x region.
- Data from polarized p+p collisions at RHIC will improve the precision and measured different x region from the DIS experiments.

STAR 2009 inclusive jet cross section analysis

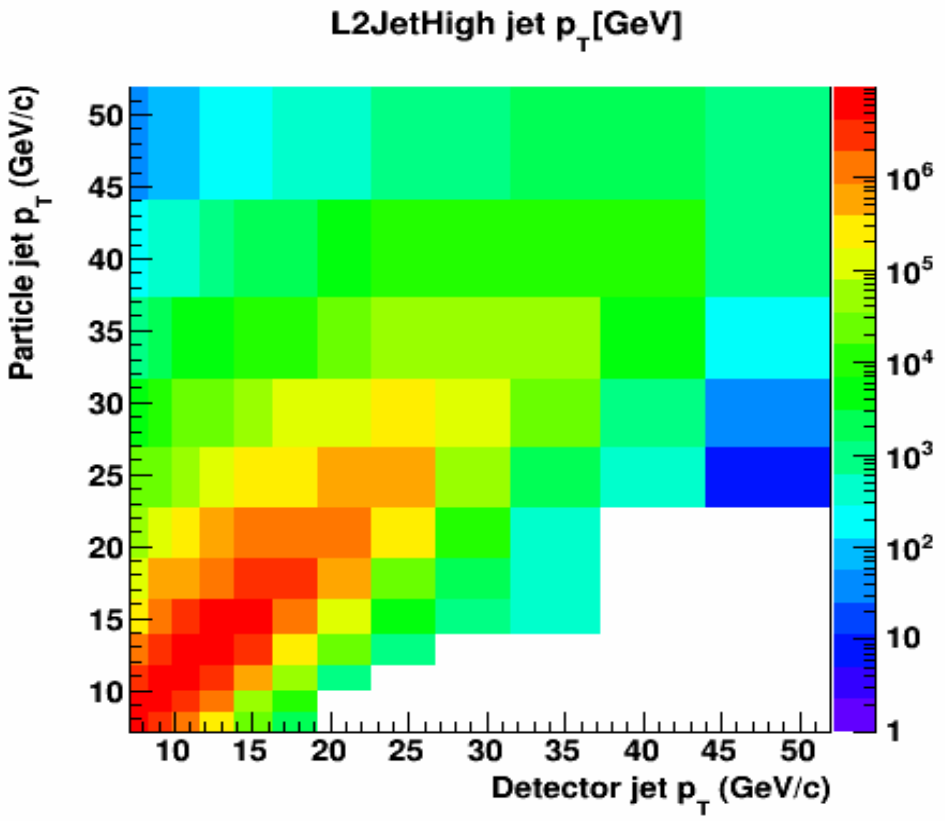
Unfolding Matrix

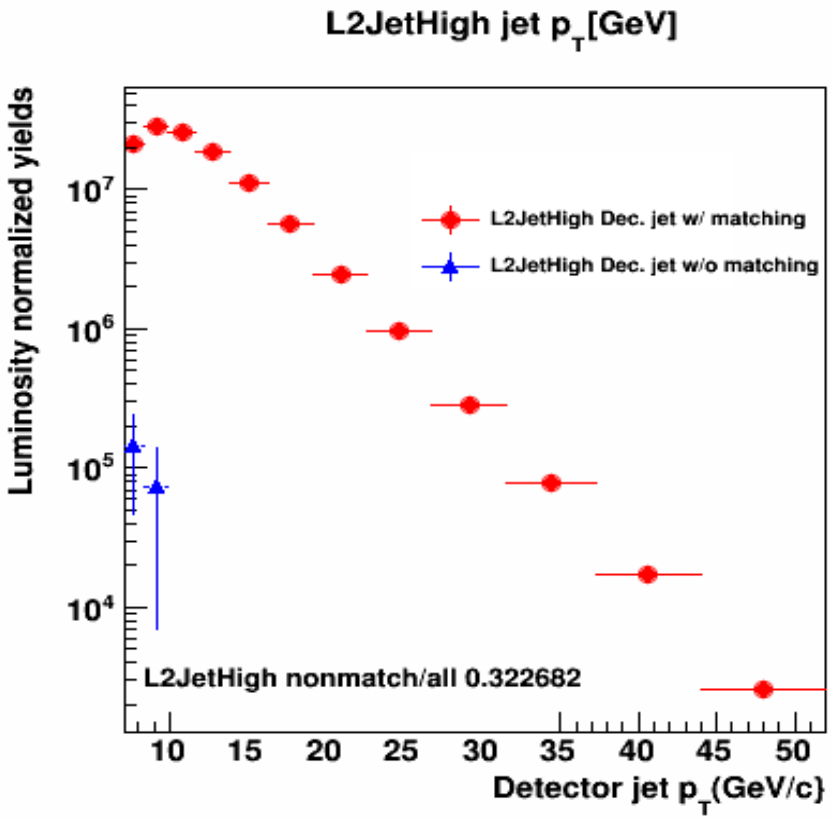


- Reconstructed detector level jets in data.
- Determine the unfolding matrix according matched detector level jet versus particle level jet (shown on the left).
- Use RooUnfold 345 to unfold detector level jets in data to particle level jets.
- Evaluate the UE/ Hadronization contribution from PYTHIA (with CTEQ5).

Probability of matching to particle jet

- After applying the matching cut of $R_{min}<0.6$.





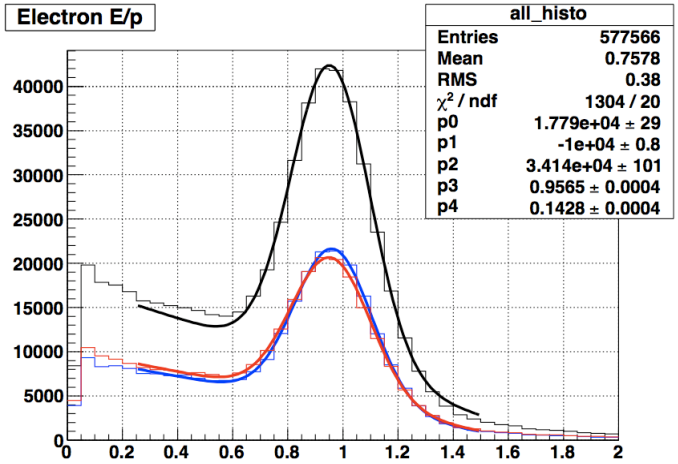
- Left: matching parton jet p_T versus detector jet p_T. Right: L2JetHigh detector jet p_T with/without matching.
- Matching probability is around 99.7%.

BTOW "Tower ADC" (electron) calibrations

Run 9 (200 GeV):

http://drupal.star.bnl.gov/STAR/system/files/2009-Calibration-Report.pdf

- "on-axis" statistics augmented by **MC** correction of tracked events in fiducial vol
- calibrations obtained for both e^+ and e^- and their sum for FF and RFF settings
- a composite ~ 1.9% systematic is quoted (other systematic effects not considered)

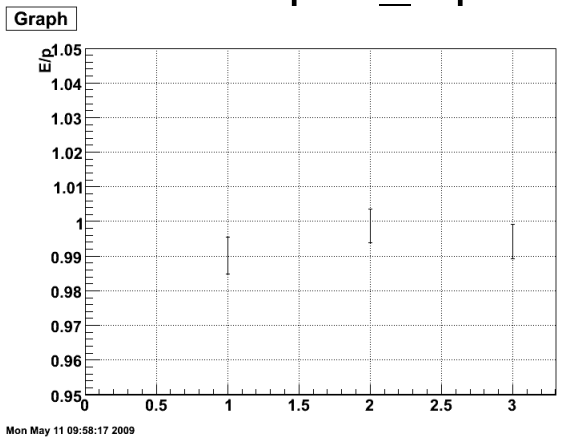


RFF(blue) and FF (red)

Run 6 (200GeV):

http://drupal.star.bnl.gov/STAR/system/files/2006-CalibrationReport_3.pdf

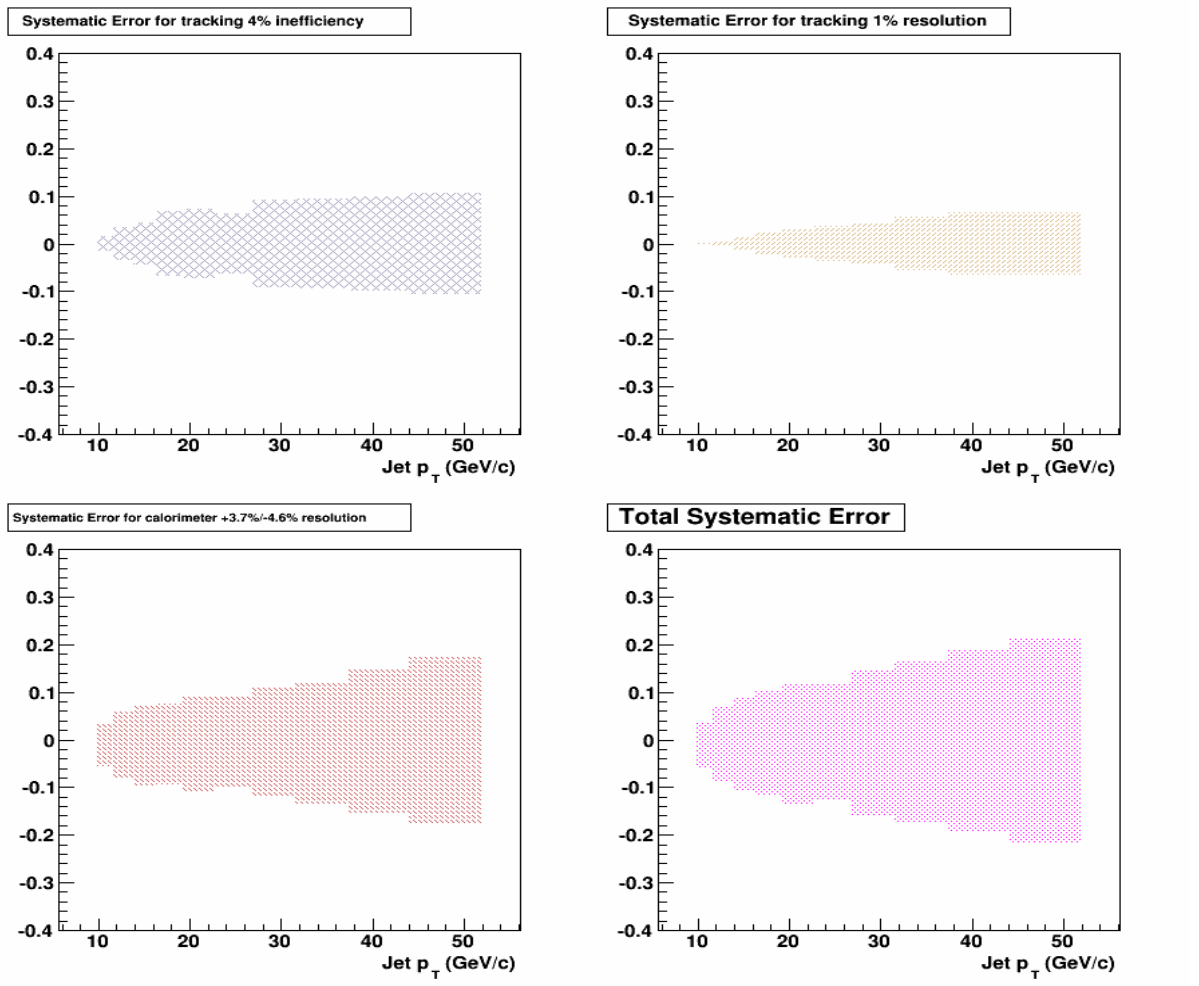
- tight cut on center of tower electrons
- investigation of several systematic types
- marginal statistics to properly quantify some effects ("null" picked over "ruled out" level)?
- a composite ~ 1.6% systematic is quoted



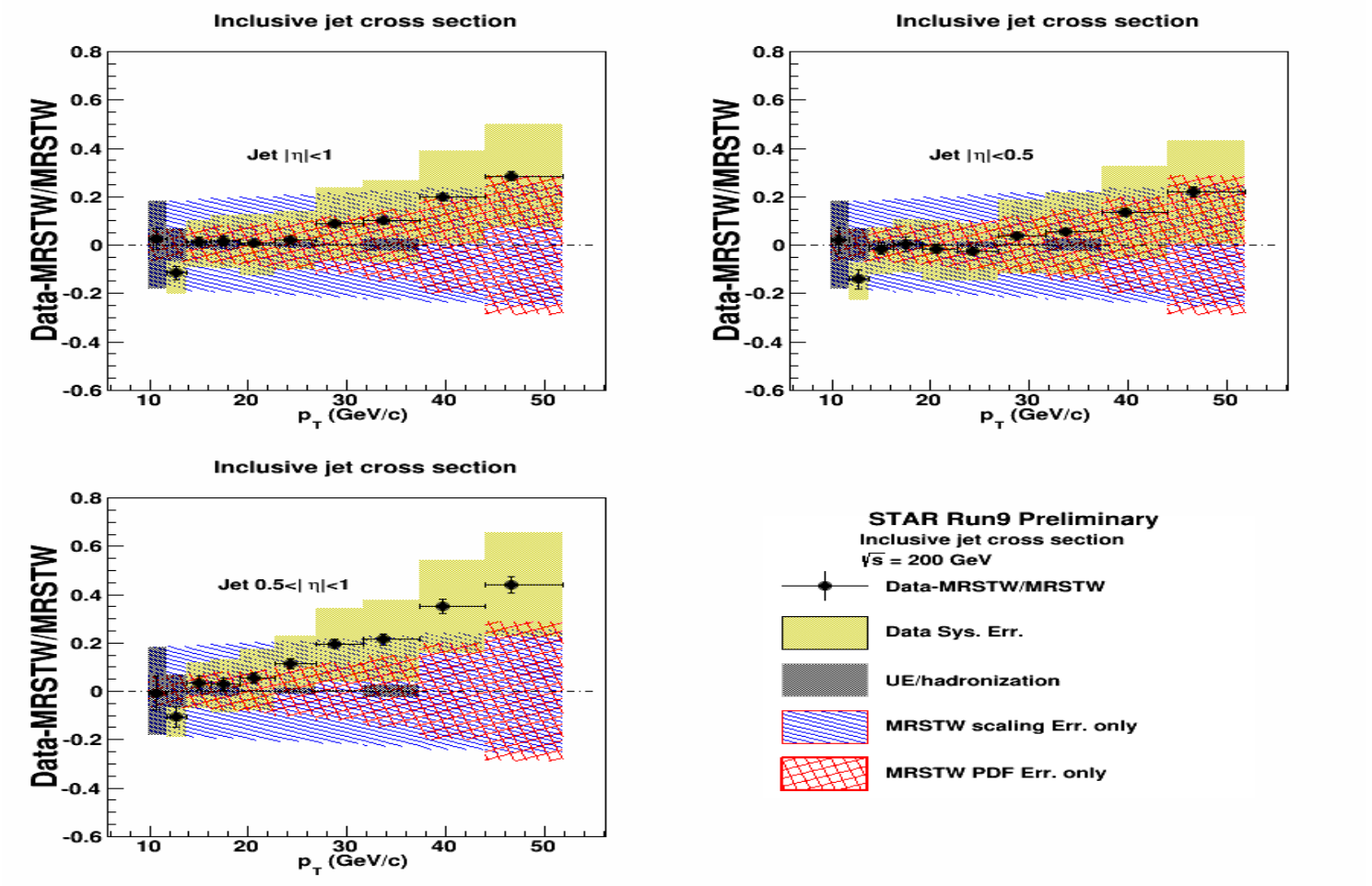
ZDC rate

Total systematic error

- Total sys. error = quadrature sum of individual sys. errors



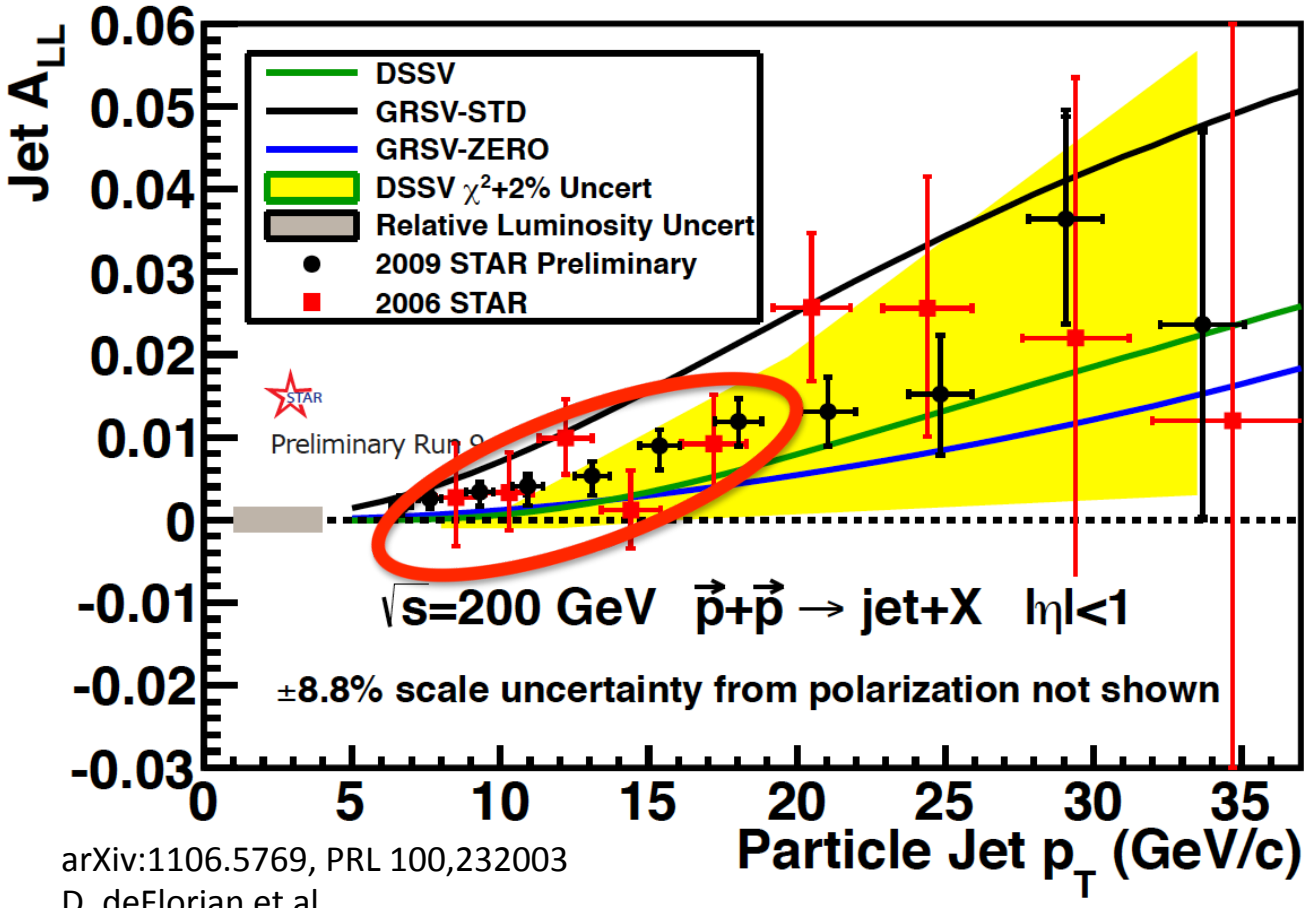
DATA – MRSTW / MRSTW



- Agreement between data and NLO pQCD with MRSTW2008 PDF sets for |η|<1.0 and |η|<0.5 regions.
- Deviations in the high p_T region are within uncertainties.

STAR inclusive jet A_{LL} in 2009 (p+p 200GeV)

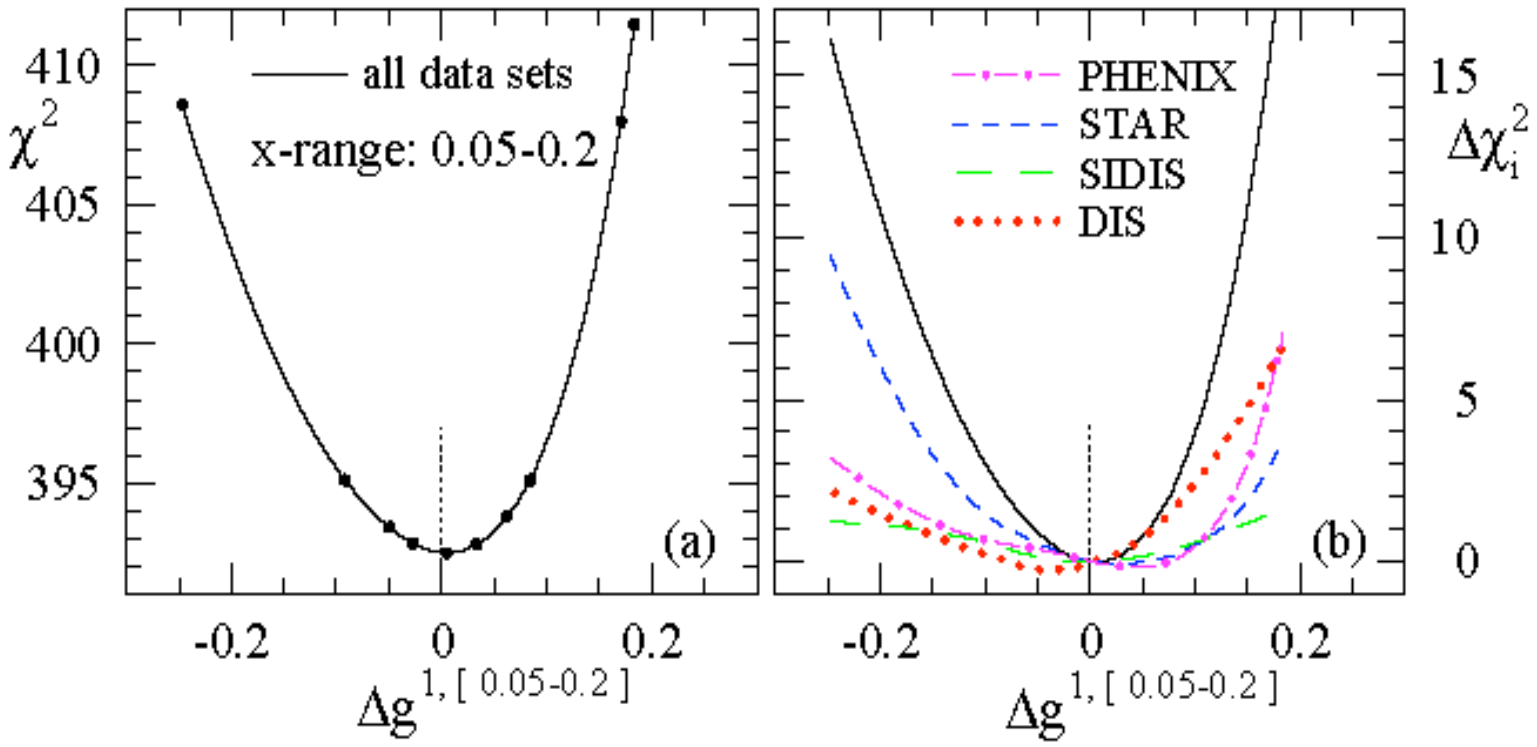
- STAR inclusive jet A_{LL} falls between DSSV and GRSV-STD, but larger than GRSV-ZERO for p_T<15GeV/c region.



arXiv:1106.5769, PRL 100,232003
D. deFlorian et al.,
Prog. Nucl. Part. Phys. 67, 251 (2012)

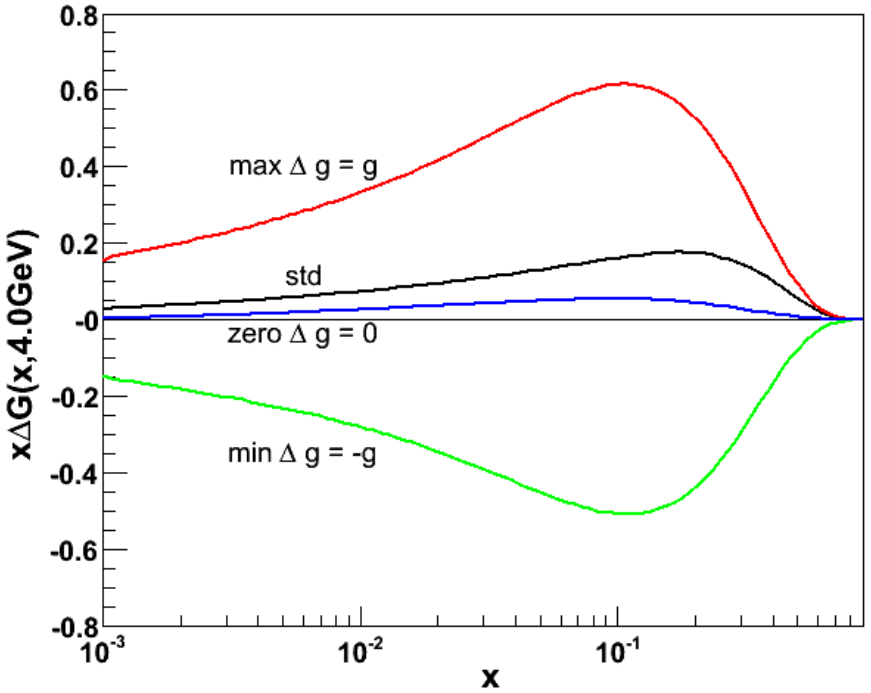
STAR inclusive jet A_{LL} in 2009 (p+p 200GeV)

- DSSV2008 fit.



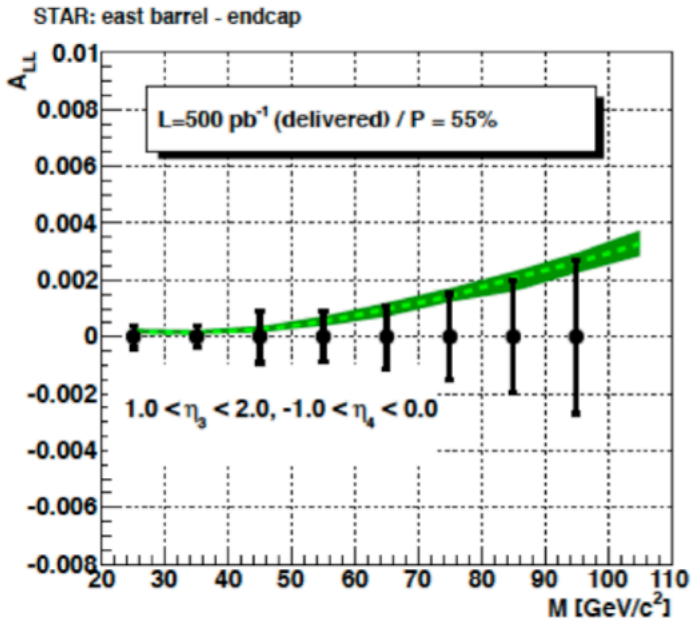
Global fit

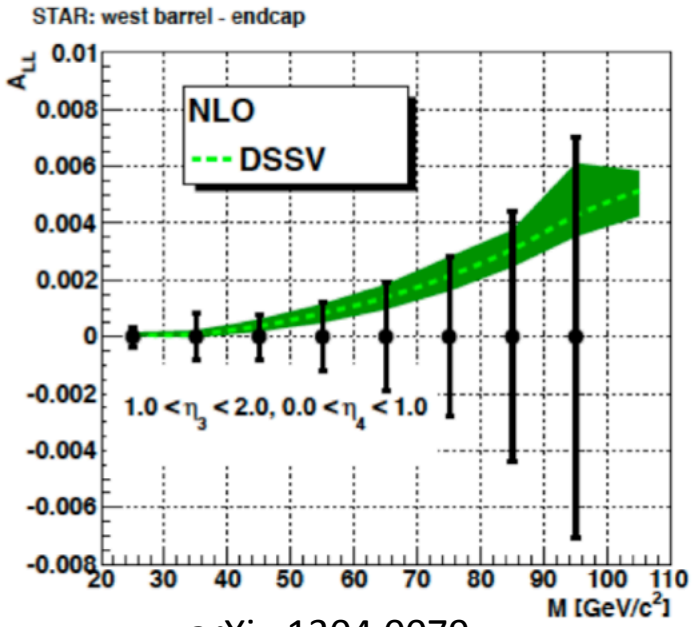
- GRSV



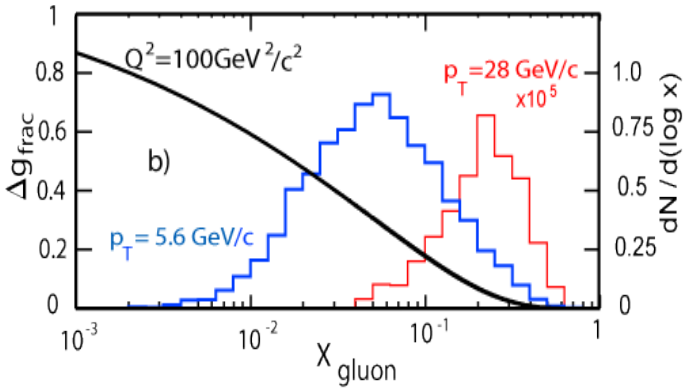
PRD 63 (2001) 094005

Projections for di-jet A_{LL} (p+p 500GeV)





arXiv:1304.0079

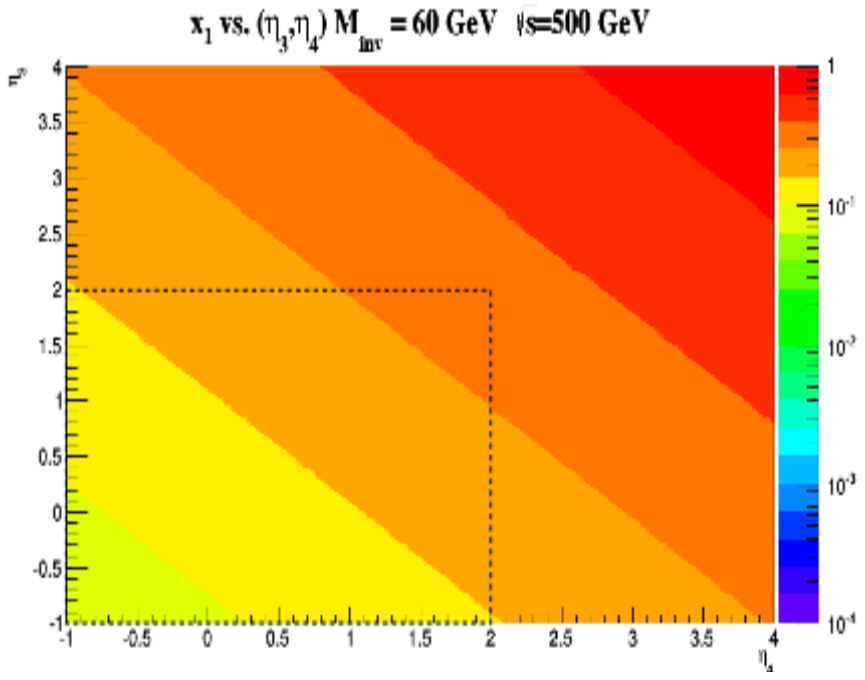


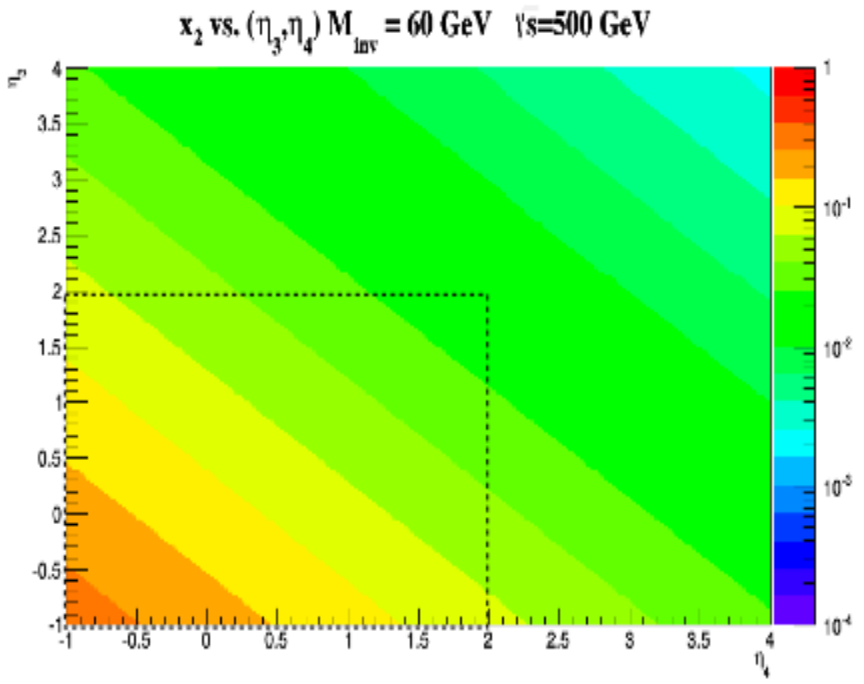
PRL 100, 232003

- At fixed Q^2, di-jet production constrains the probed gluon x region.
- Correlations in different η regions access different x region, higher η lower x.

Di-jet kinematics in 500GeV p+p collisions (simulation)

$$M = \sqrt{s}\sqrt{x_1 x_2} \qquad \eta_3 + \eta_4 = \ln \frac{x_1}{x_2}$$





$$x_{1\,(2)} = \frac{1}{\sqrt{s}}\left(p_{T_3} e^{\eta_3(-\eta_3)} + p_{T_4} e^{\eta_4(-\eta_4)}\right)$$