

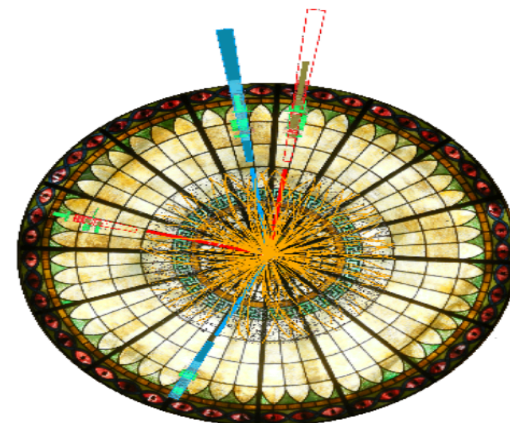
# Jet measurements in polarized p+p collisions at STAR at RHIC

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for STAR Collaboration

**DIS 2015**

XXIII International Workshop on  
Deep-Inelastic Scattering and  
Related Subjects

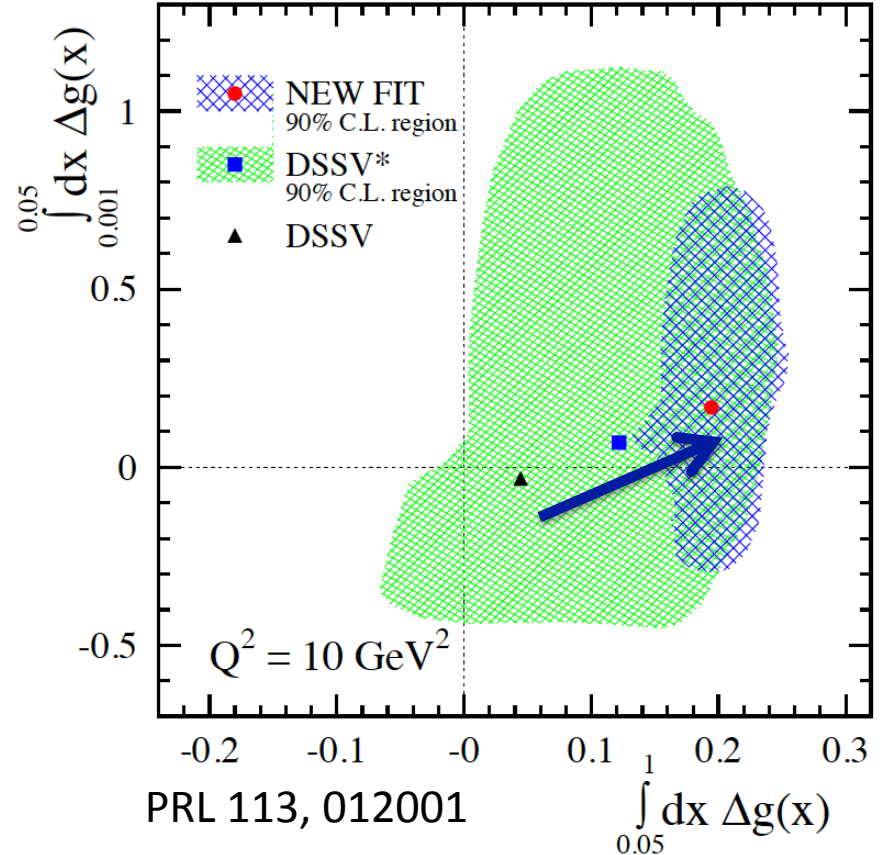
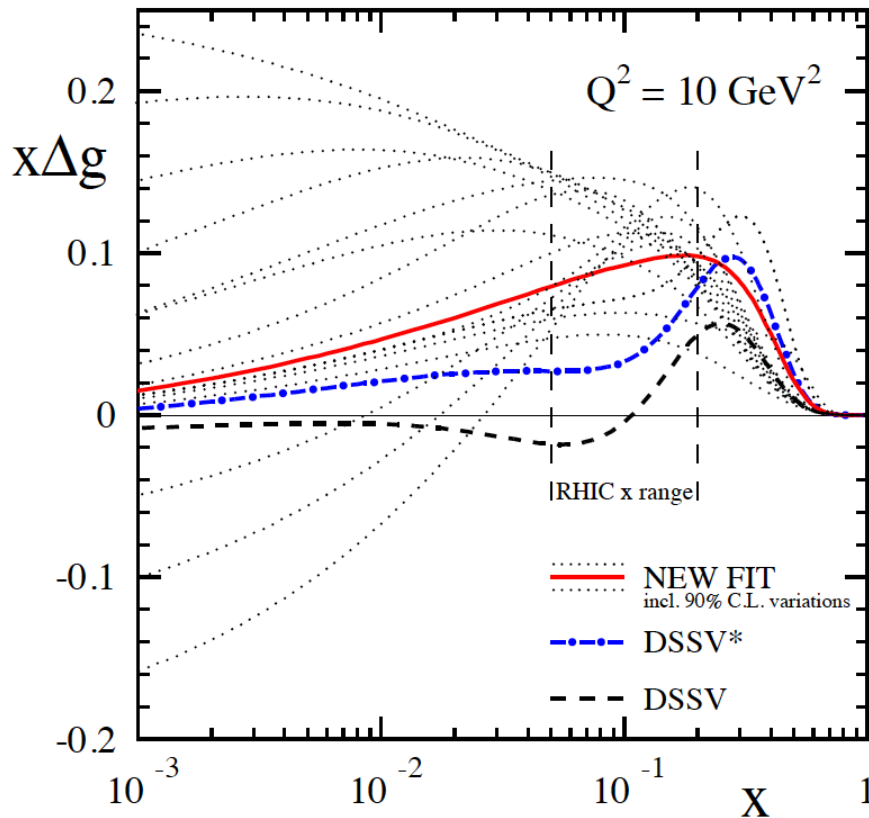
**Dallas, Texas**  
**April 27 – May 1, 2015**



# Outline

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

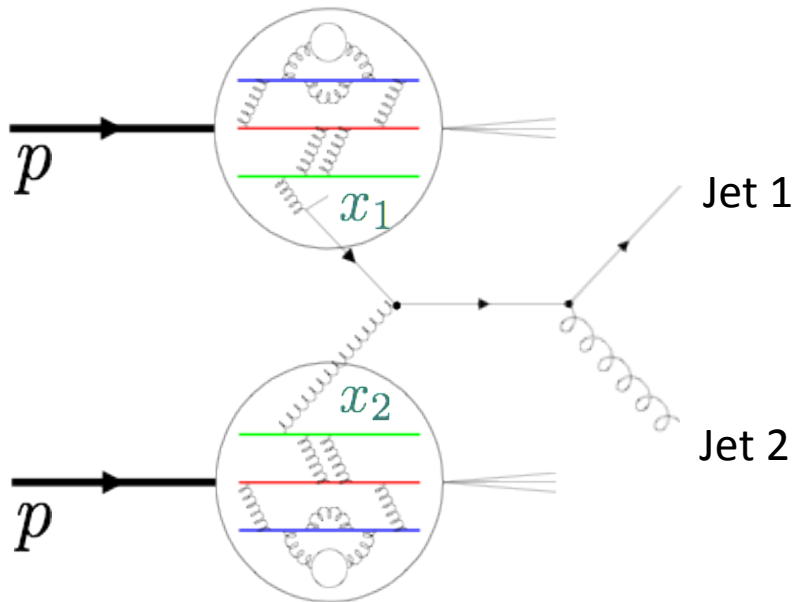
# Current knowledge of polarized gluon PDF



- 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.

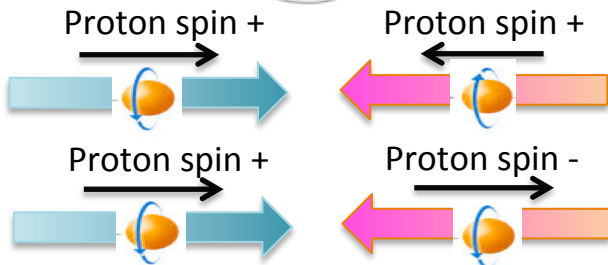
To measure  $\Delta f_{1/2}$ : Quark/gluon helicity

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

known inputs:

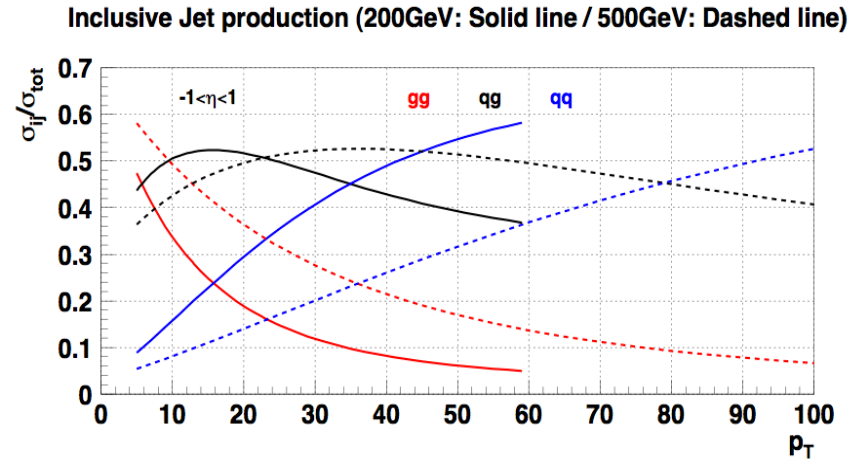
$f_{1/2}$  = unpolarized parton distribution function.

$a_{LL}$ : polarized parton asymmetry

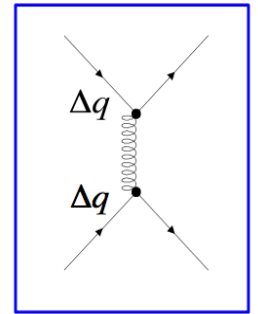
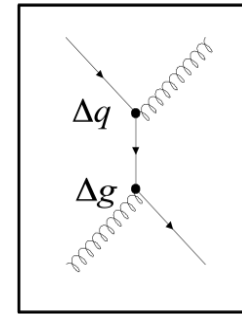
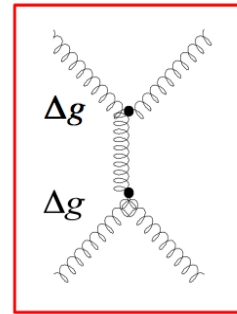


# Inclusive jet $A_{LL}$

- 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).



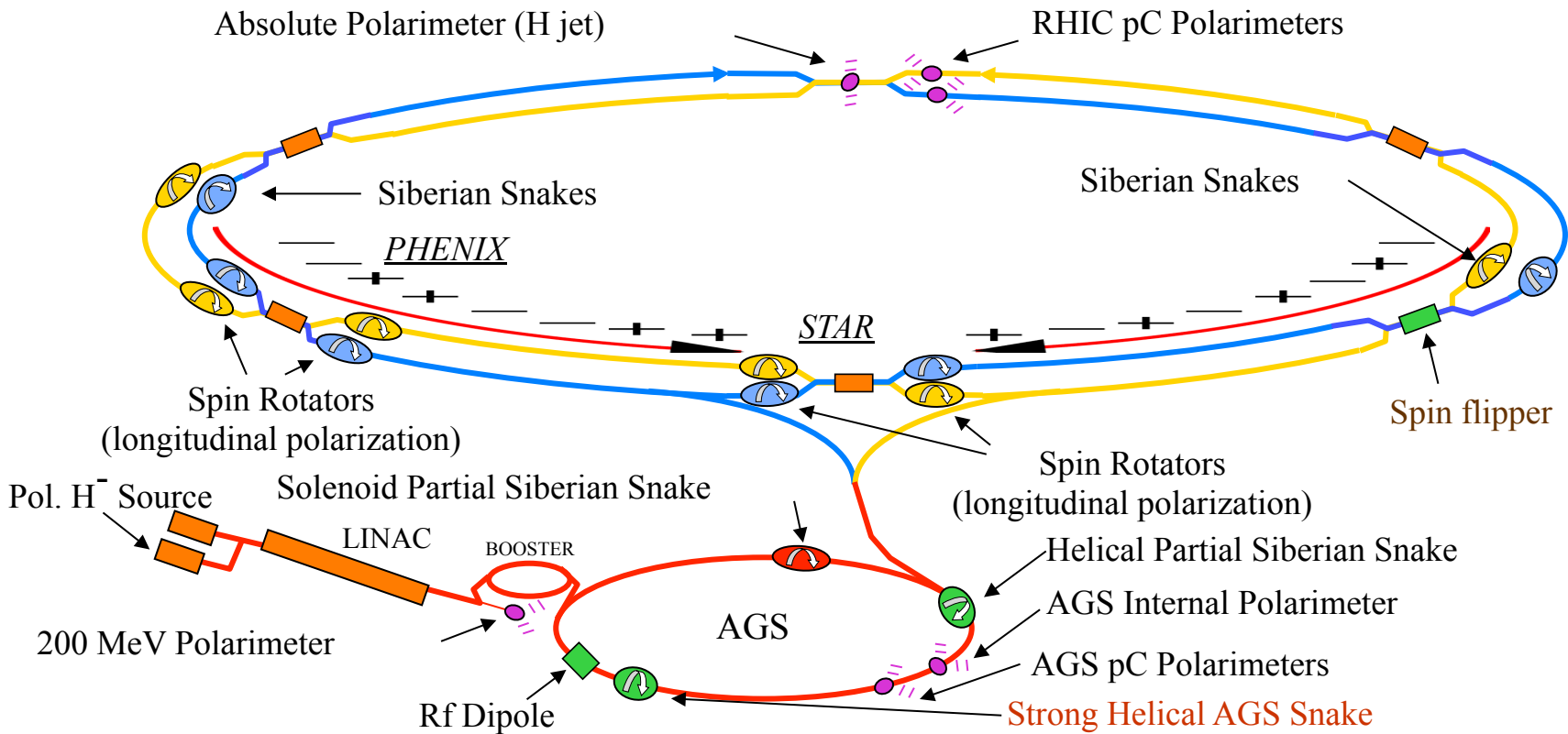
$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \propto \frac{\Delta f_a \Delta f_b}{f_a f_b} \hat{a}_{LL}$$



- 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.

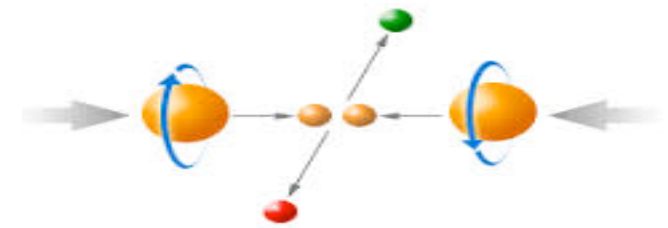
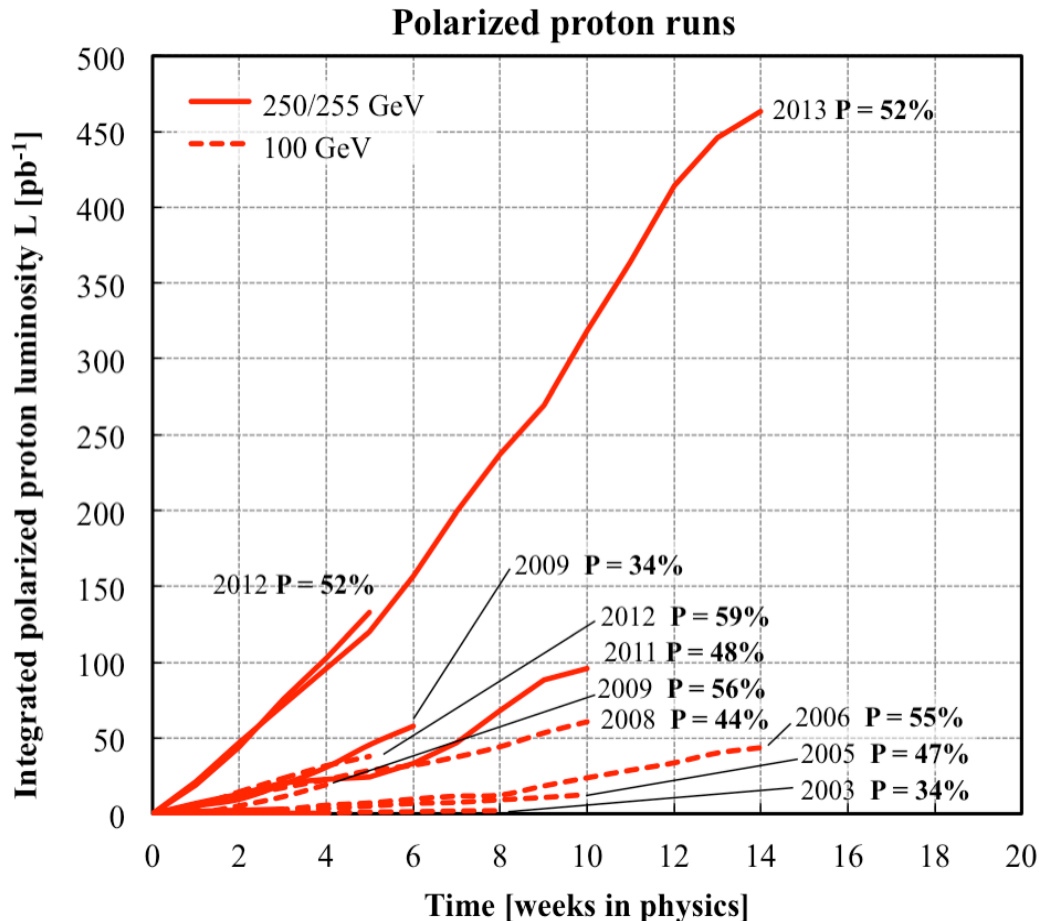
# RHIC: the polarized proton-proton collider

- 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  $\sqrt{s}=200/500$  GeV are sensitive to the gluon polarization.

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

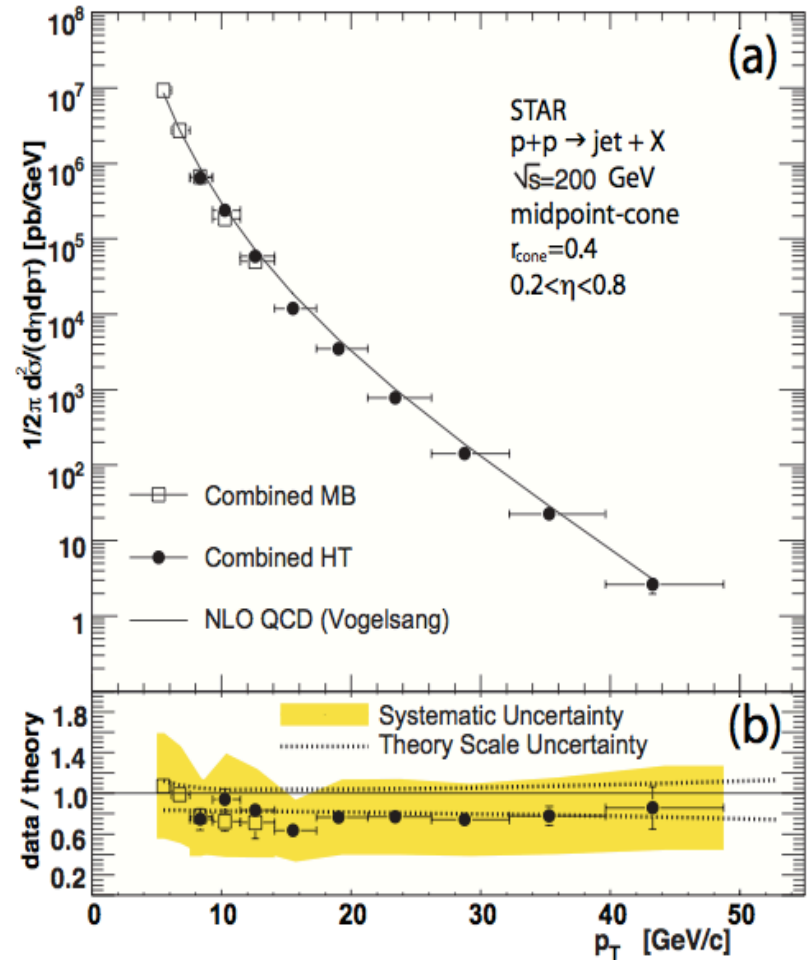




# Motivation for jet cross section

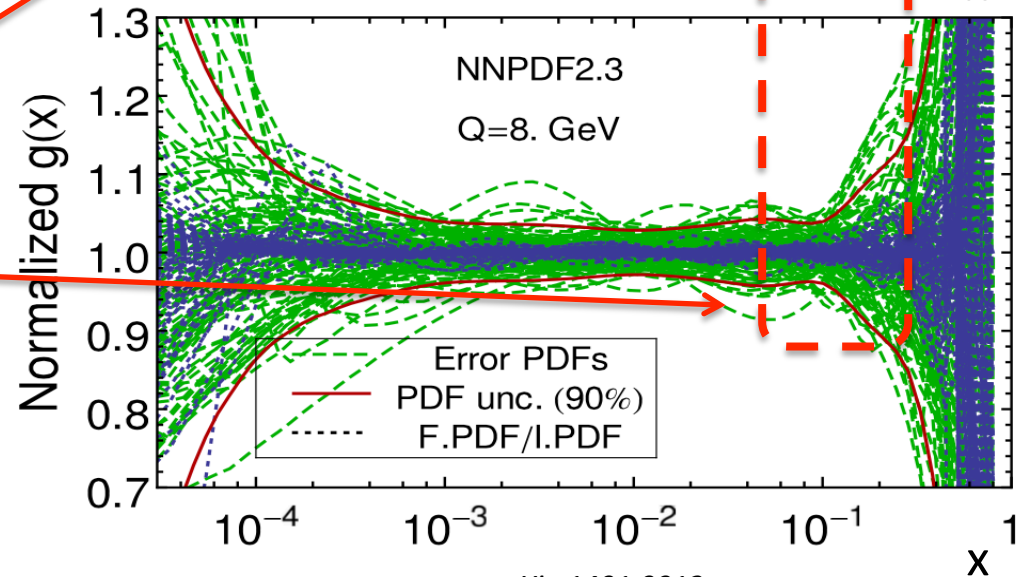
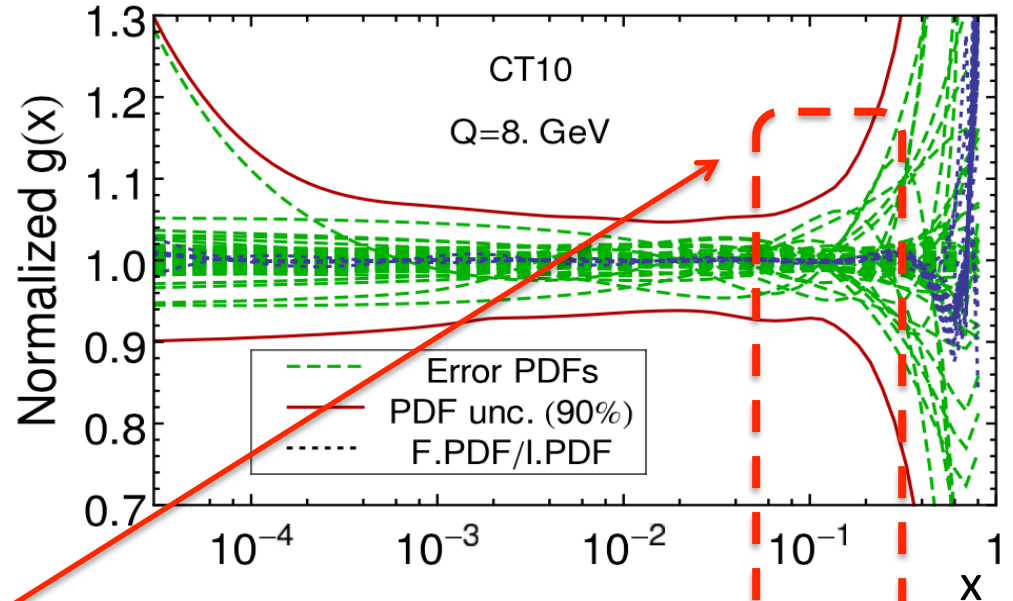
- Previous measurements (shown on the right):
  - Limited acceptance (half detector installed, now we have full detector).
  - Use mid-point cone jet algorithm

Phys.Rev.Lett.97:252001



# 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

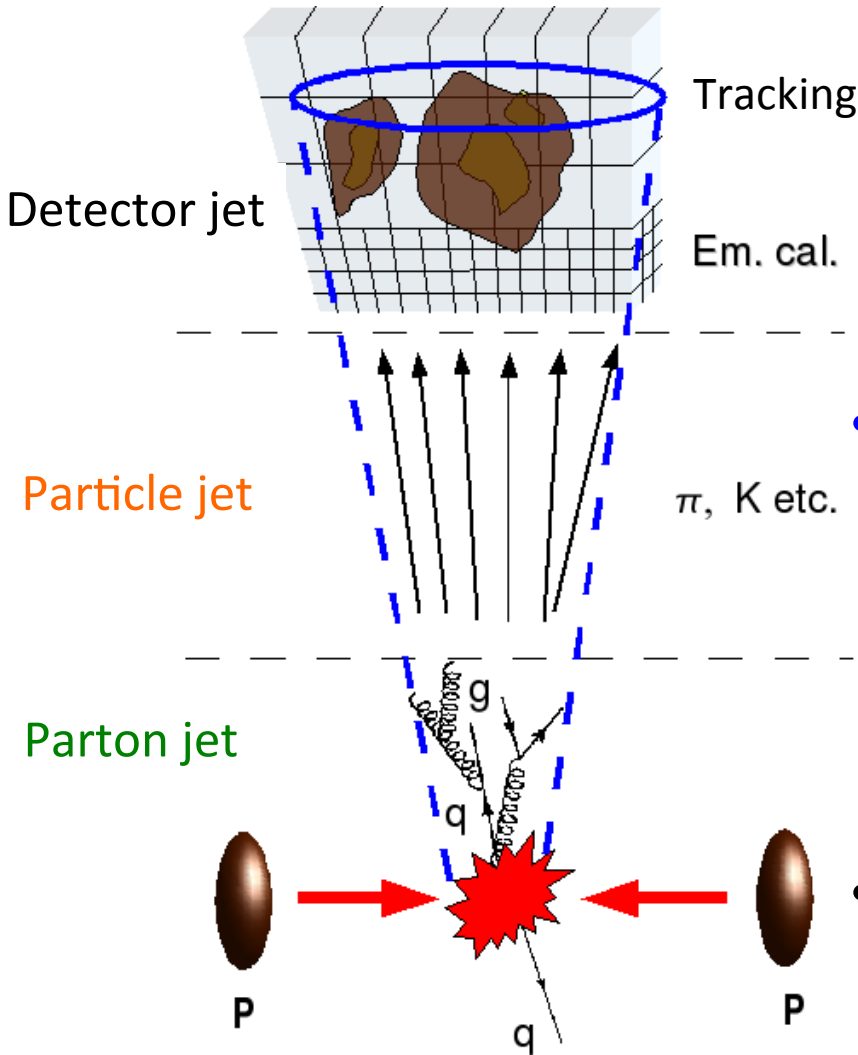
- **Midpoint Cone algorithm**[aXiv:hep-exp/0005012] (used in previous jet study):

- 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]:

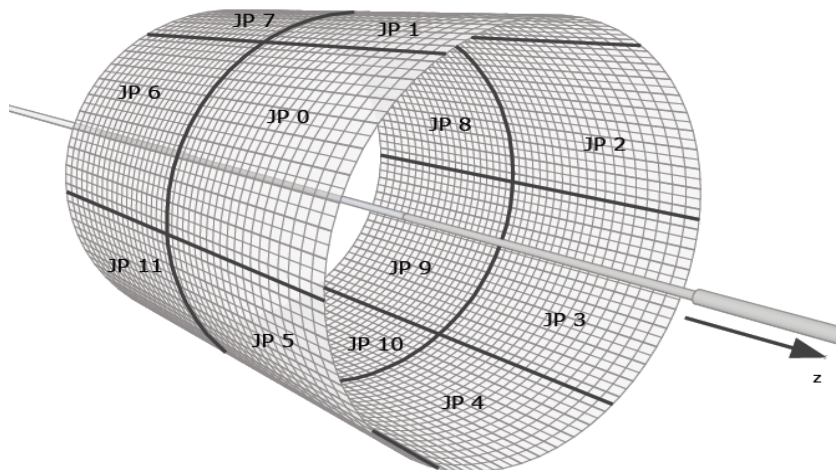
- $d_{ij} = \min\left(\frac{1}{k_{T,i}^2}, \frac{1}{k_{T,j}^2}\right) \frac{\Delta_{ij}^2}{R^2}$      $\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$
- Collect towers+tracks based on particle  $1/k_{T,i}^2$ . Select  $R=0.6$ .
- less UE and pile up.
- Infrared and collinear safe.

- Apply anti- $k_T$  jet algorithm to reconstruct detector, **particle** and **parton** jets in simulation and detector jets in data.

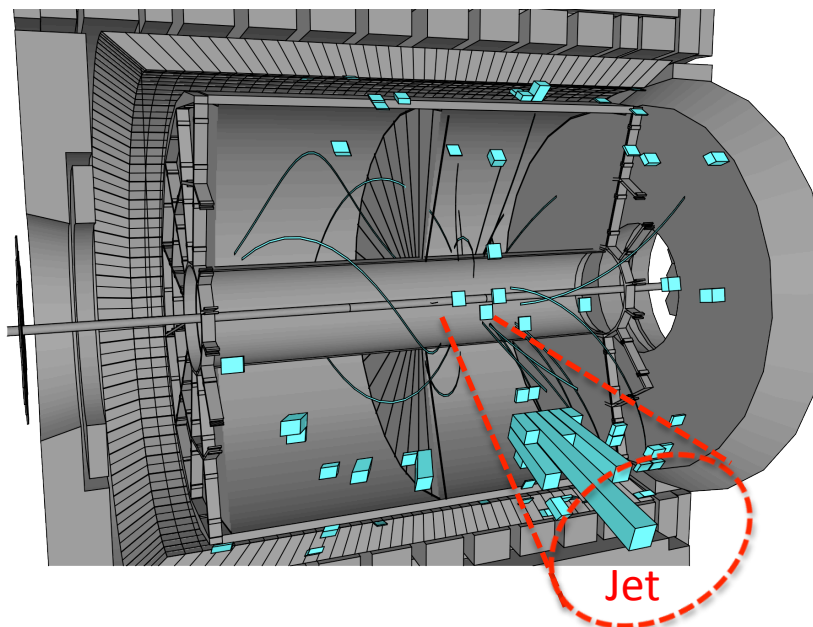


# STAR mid-rapidity jet measurements

BEMC jet patch mapping

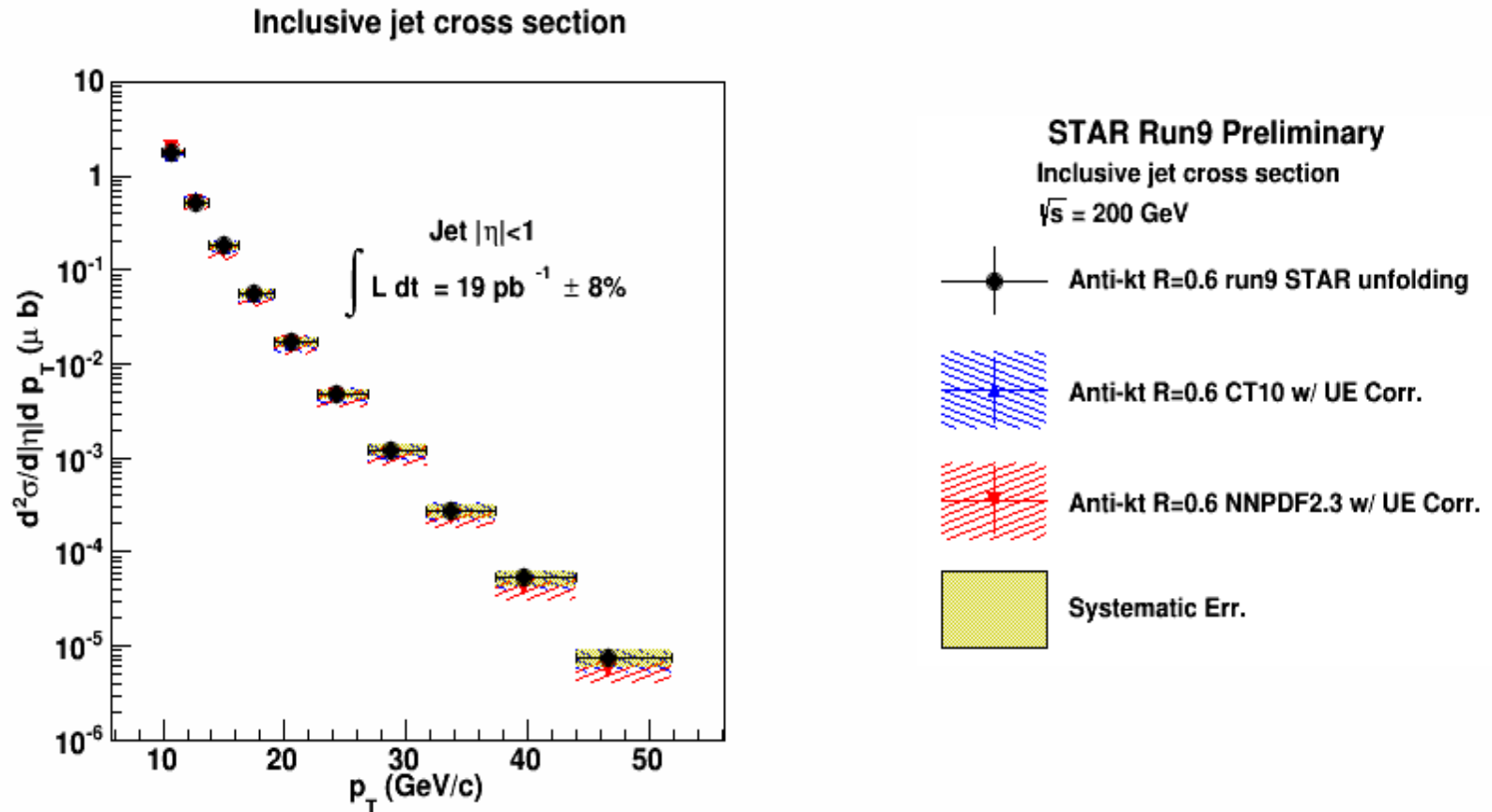


Event display of jet event at STAR



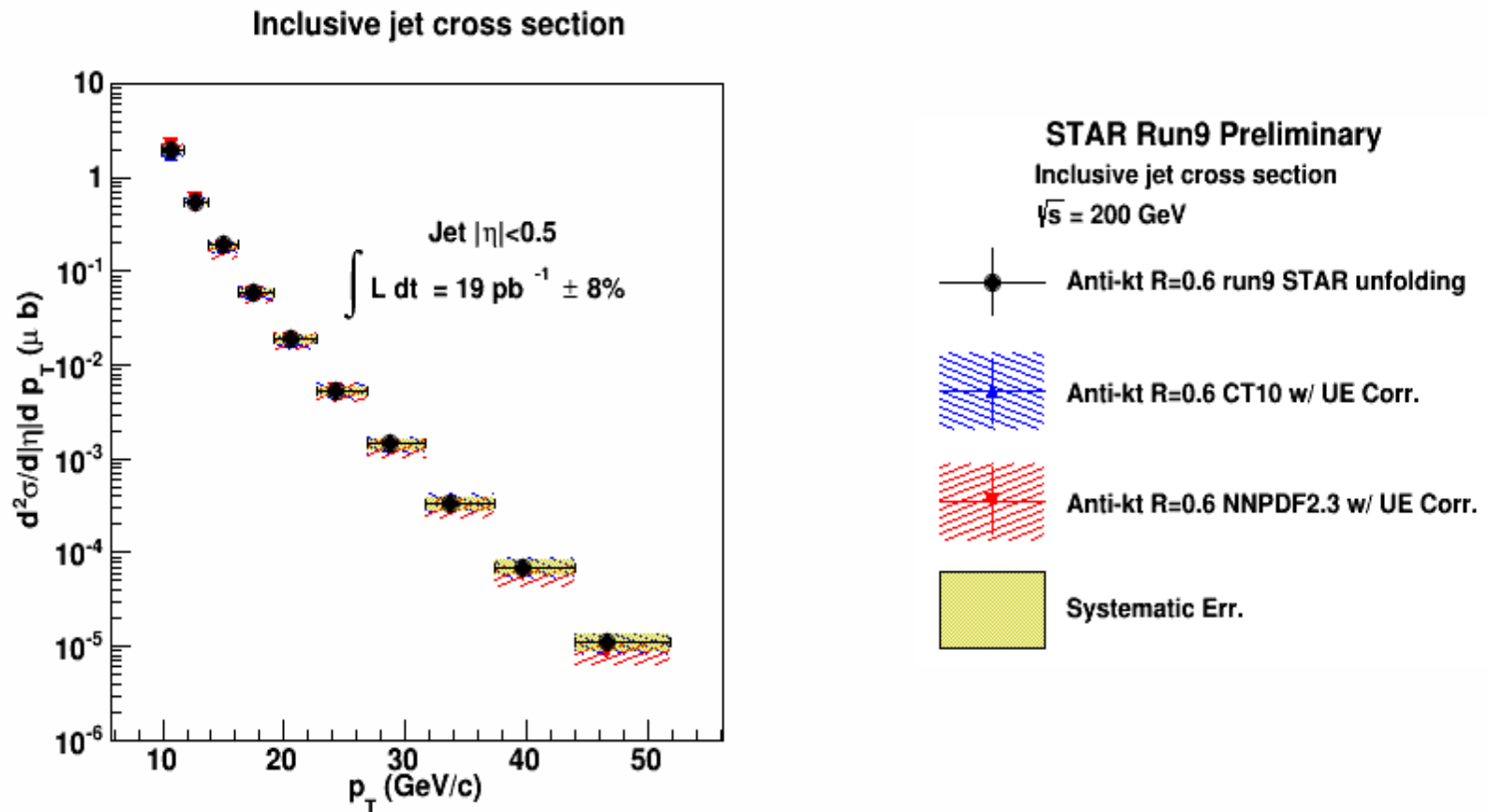
- Triggers for inclusive jet:
  - 30 BEMC, EEMC jet patches are used for jet triggers.
  - L2JetHigh: based on L0 trigger, level 2 algorithm looks for jet in calorimeter only (no tracking info). JP  $E_T > 6.5 \text{ GeV}/c$  + 10% random accept.
- Event cuts
  - z vertex:  $|z_{\text{vert}}| < 90 \text{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

# STAR 2009 inclusive jet cross section in comparison with NLO pQCD calculations ( $|\eta| < 1.0$ )



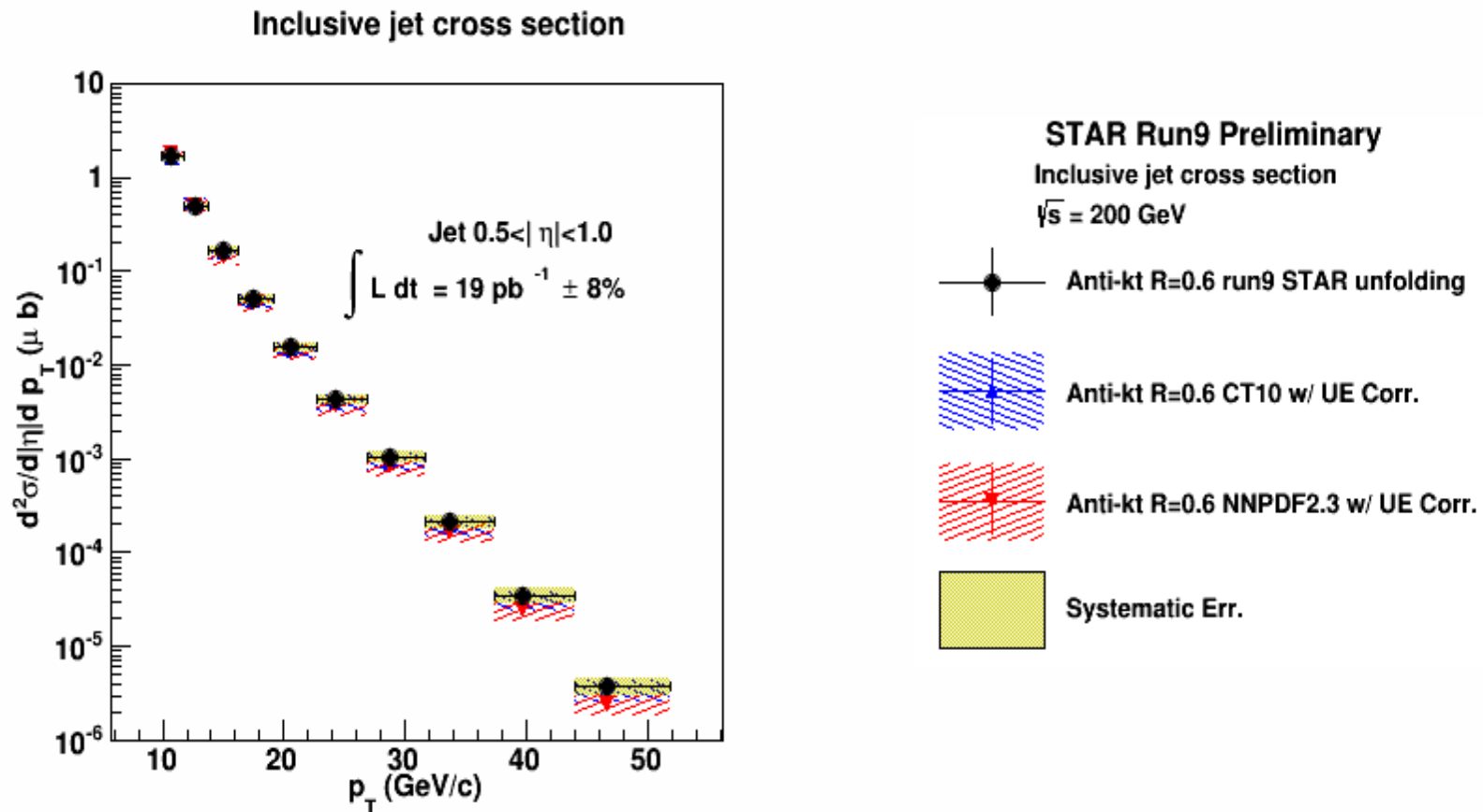
- Unfold detector level jets to particle level jets.
- NLO pQCD calculations with **CT10** and **NNPDF2.3** PDFs with UE contribution corrected to particle level jets. Factorization and renormalization scaling uncertainties are included.

# STAR 2009 inclusive jet cross section in comparison with NLO pQCD calculations ( $|\eta| < 0.5$ )



- 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.

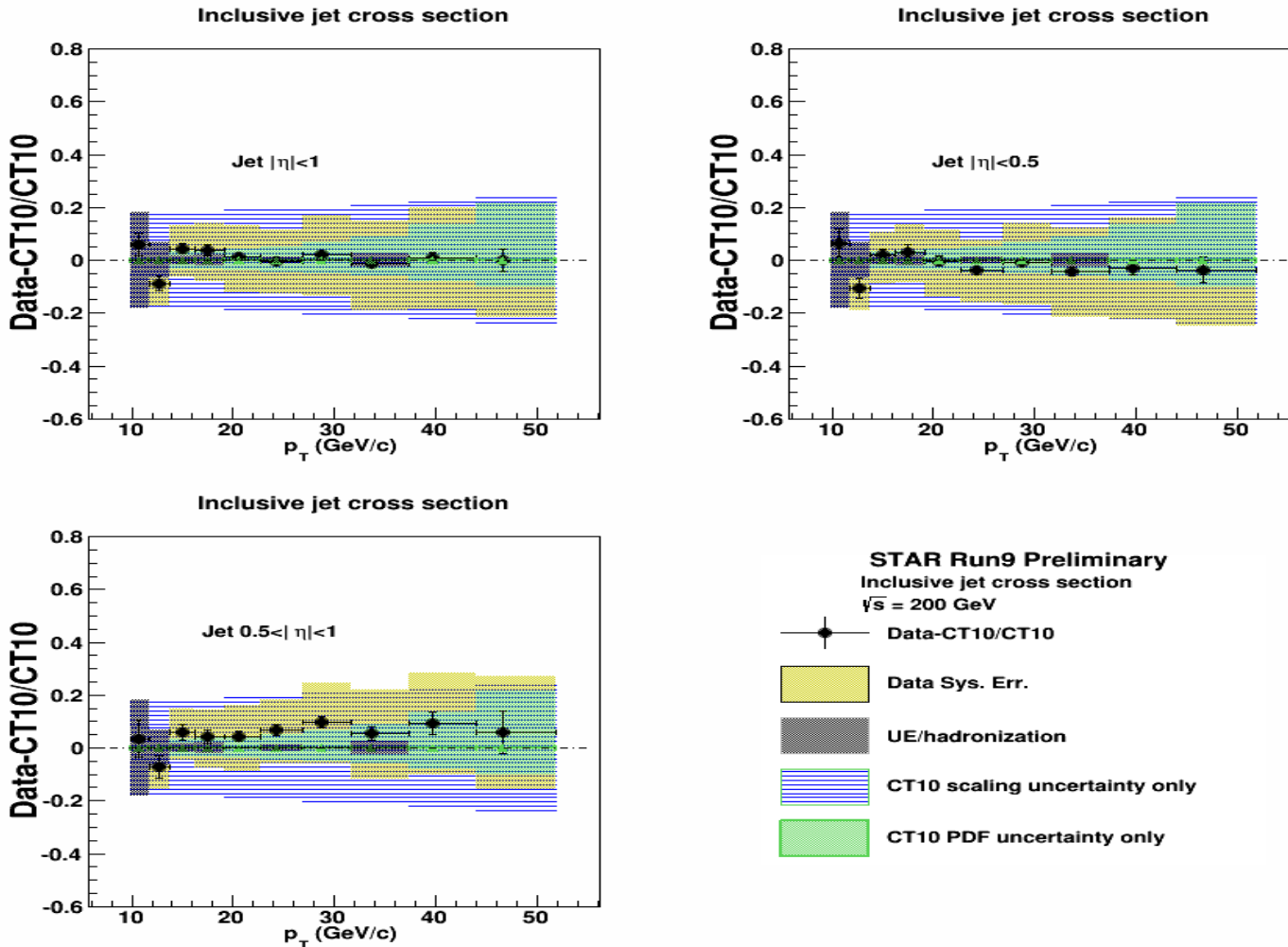
# STAR 2009 inclusive jet cross section in comparison with NLO pQCD calculations ( $0.5 < |\eta| < 1.0$ )



- 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.

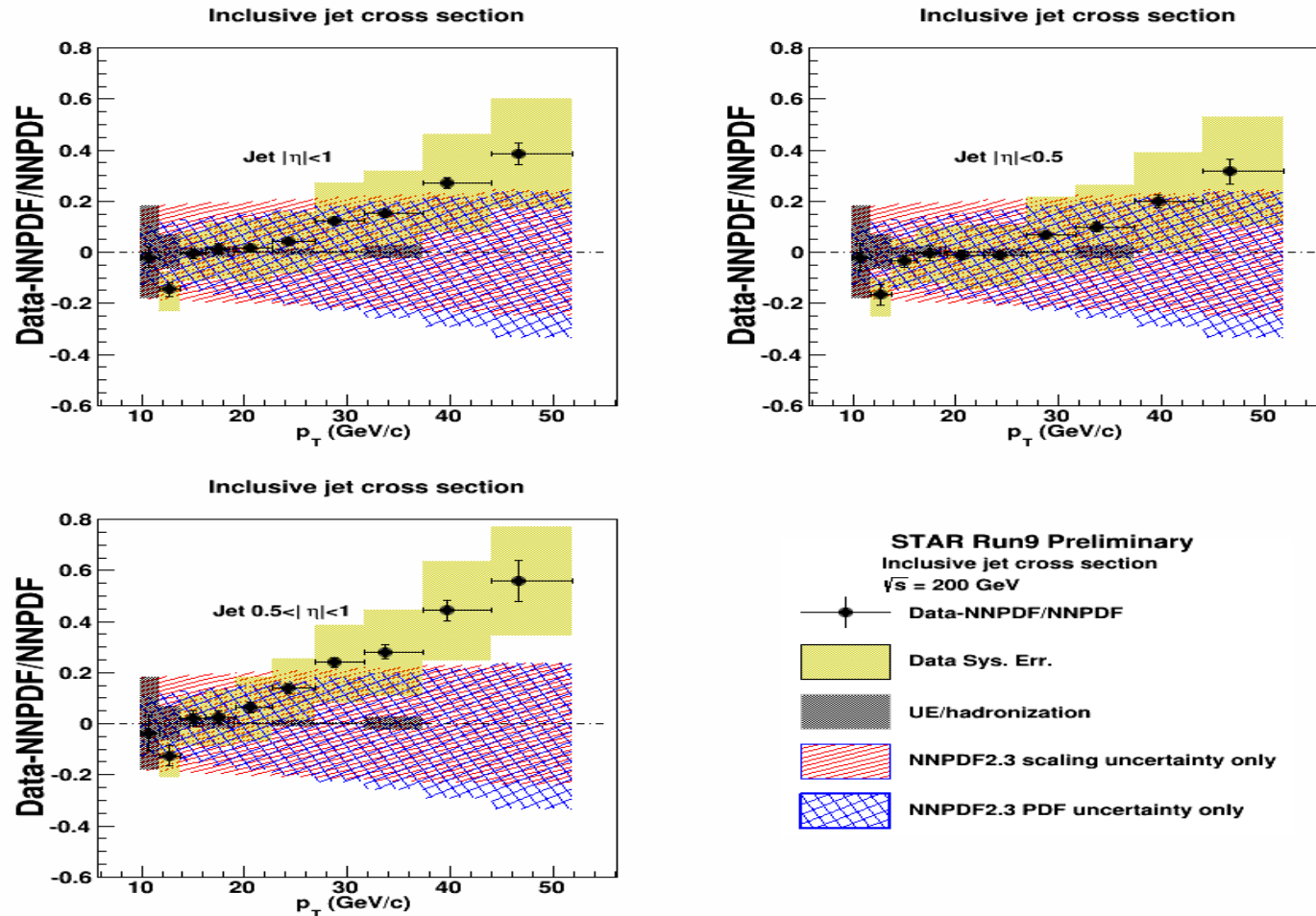


# Data – CT10 / CT10



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

# DATA – NNPDF / NNPDF

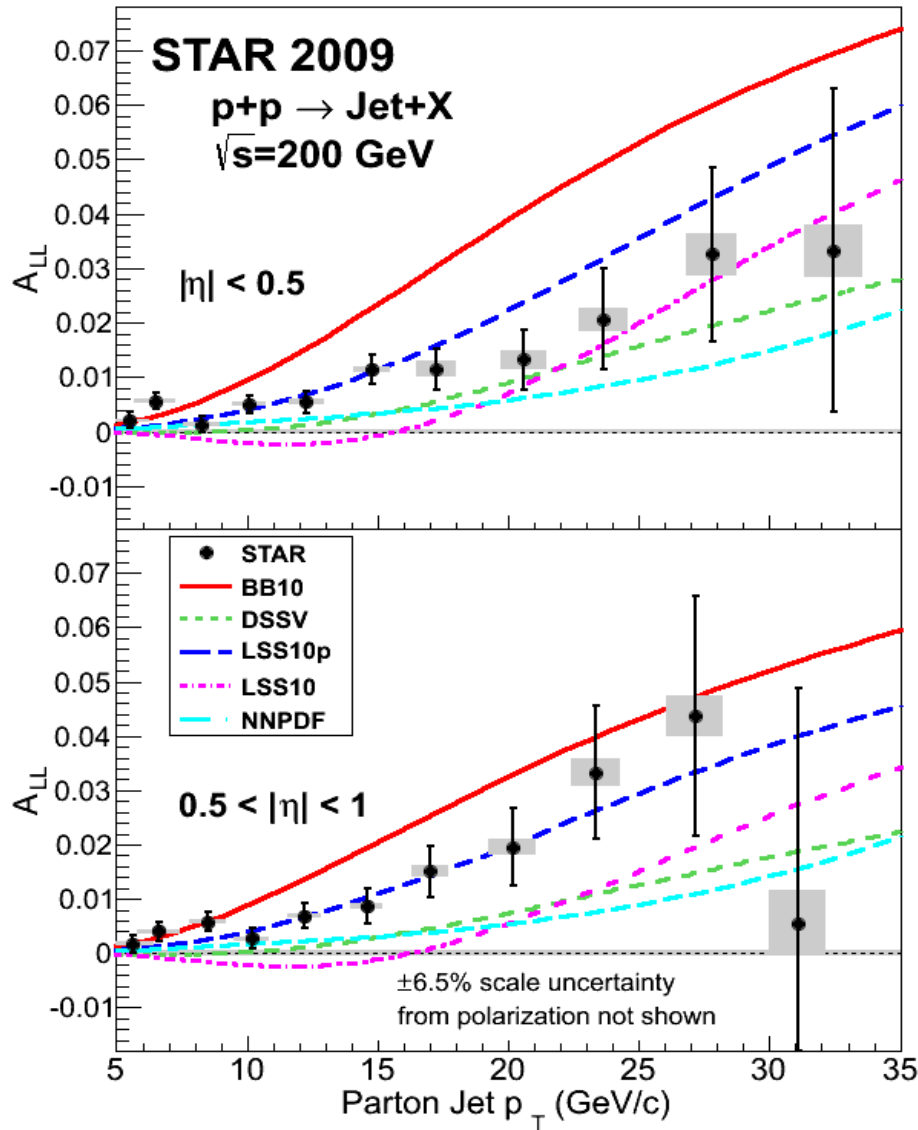


- Agreement between data and NLO pQCD with NNPDF2.3 PDF sets for  $|\eta| < 1.0$  and  $|\eta| < 0.5$  regions. Slightly difference between data and NNPDF calculations for  $0.5 < |\eta| < 1.0$  region.

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)

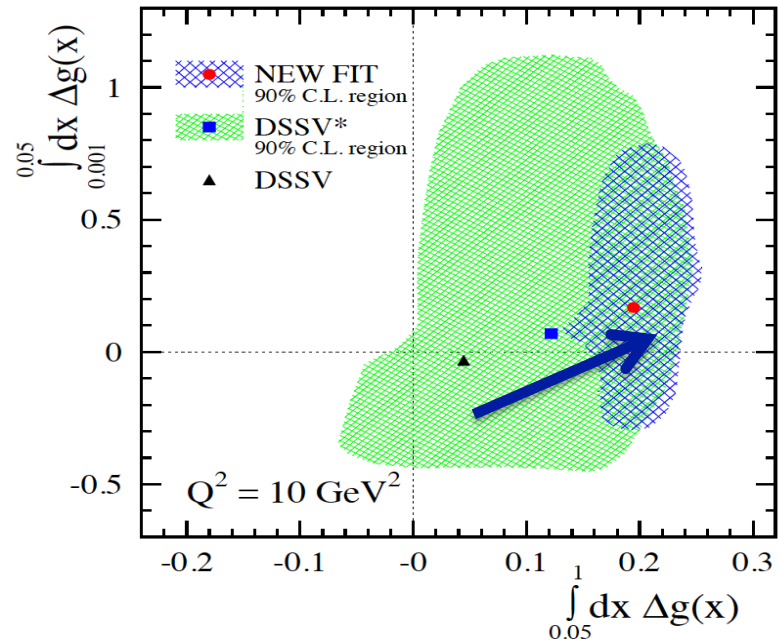
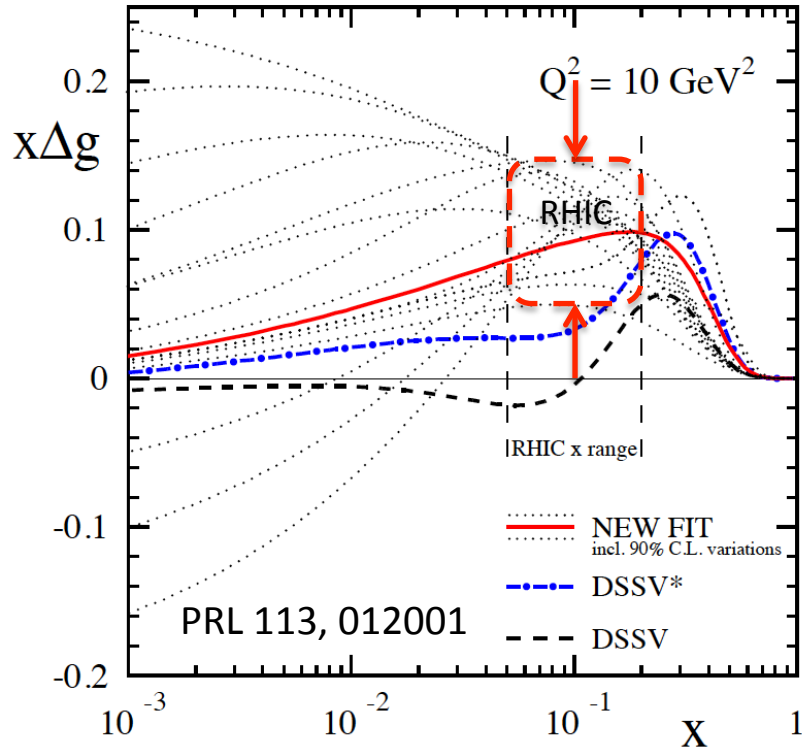
arXiv:1405.5134



- 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  $\Delta G$ ?

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

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

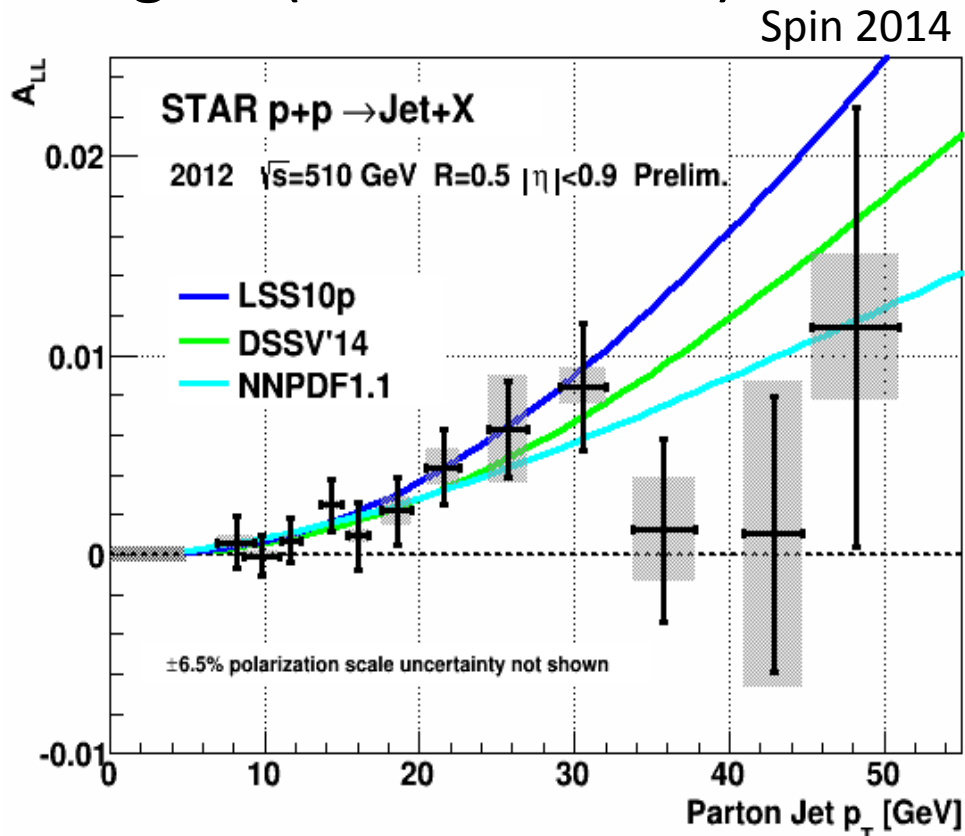


$$\int_{0.05}^1 \Delta g(x, Q^2 = 10 \text{ GeV}^2) dx = 0.2^{+0.06}_{-0.07}$$

- RHIC  $A_{LL}$  results narrow the uncertainties of the fitted  $\Delta g$  and shift the central value of  $\Delta G$ .
- DSSV2014 fit provides first non-zero  $\Delta G$  in the RHIC sensitive region.

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

- Higher  $\sqrt{s}$  (510 GeV) provides sensitivity to lower  $x_g$  region (than 200 GeV).

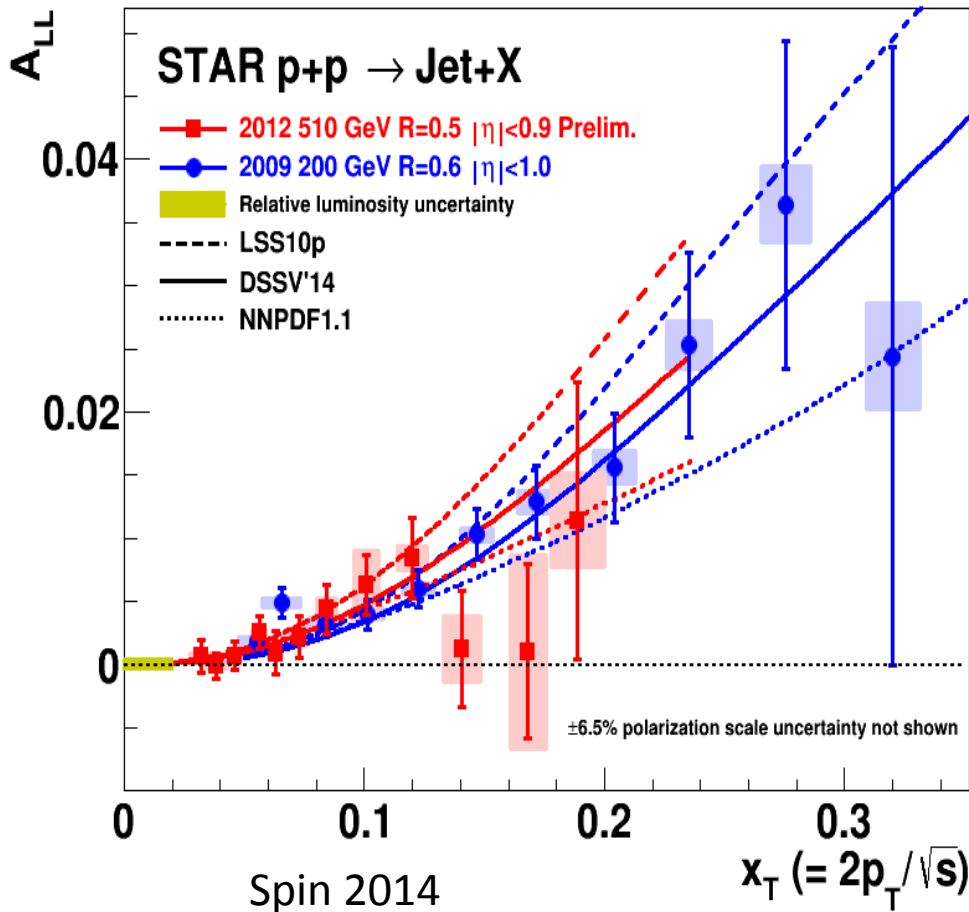


- Same jet reconstruction scheme (anti- $k_T$  jet algorithm).
- Use cone radius  $R=0.5$  to reduce pile up backgrounds and improve matching probability from detector jet to parton jet.
- In comparison with NLO pQCD calculations with polarized PDF sets ( [LSS10p](#), [DSSV14](#) and [NNPDF1.1](#) ).

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

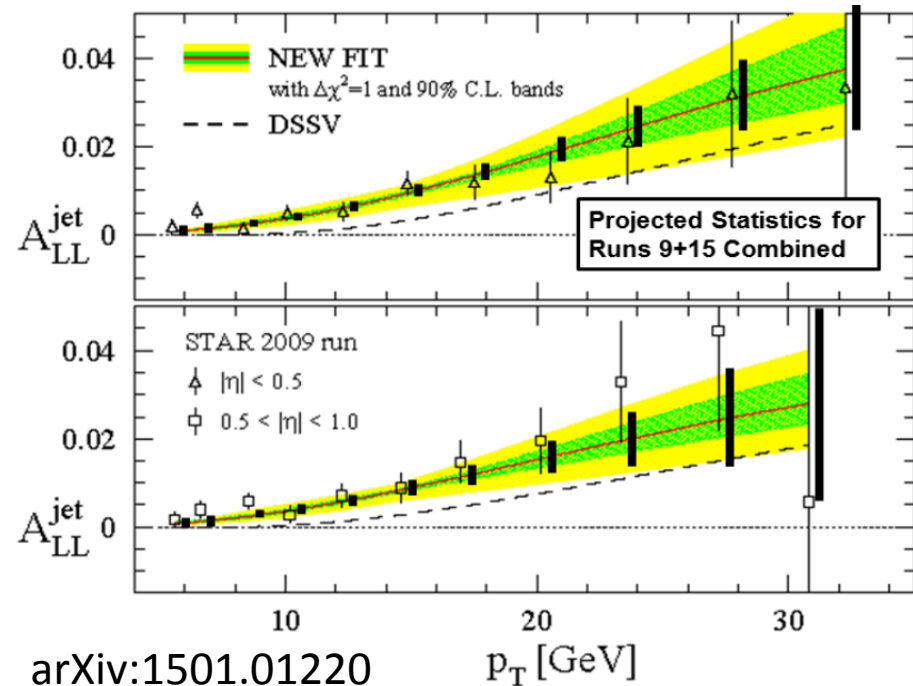
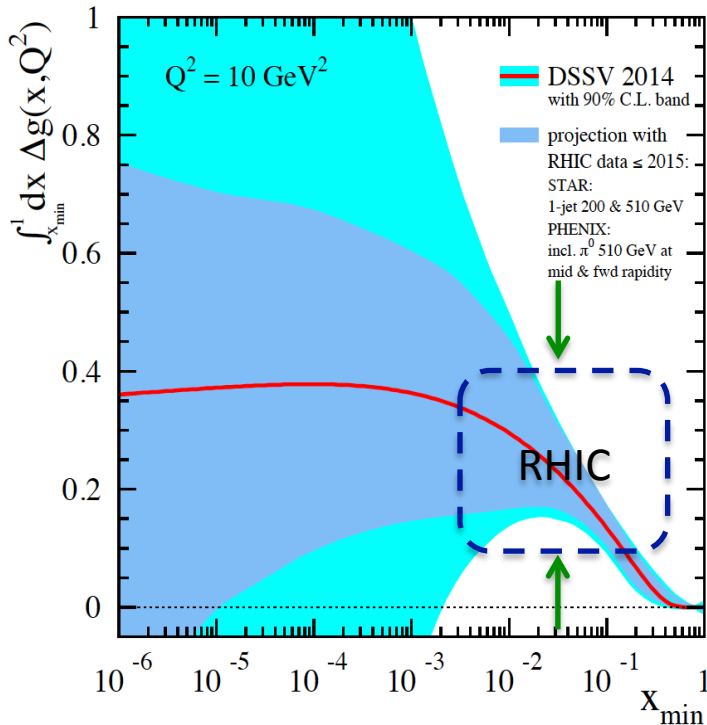
# STAR inclusive jet $A_{LL}$ in 2012 (p+p 510 GeV)

- Higher  $\sqrt{s}$  (510 GeV) provides sensitivity to lower  $x_g$  region (than 200 GeV).



- Higher  $\sqrt{s}$  (510 GeV) inclusive jet  $A_{LL}$  is in good agreement with the lower  $\sqrt{s}$  (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)



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

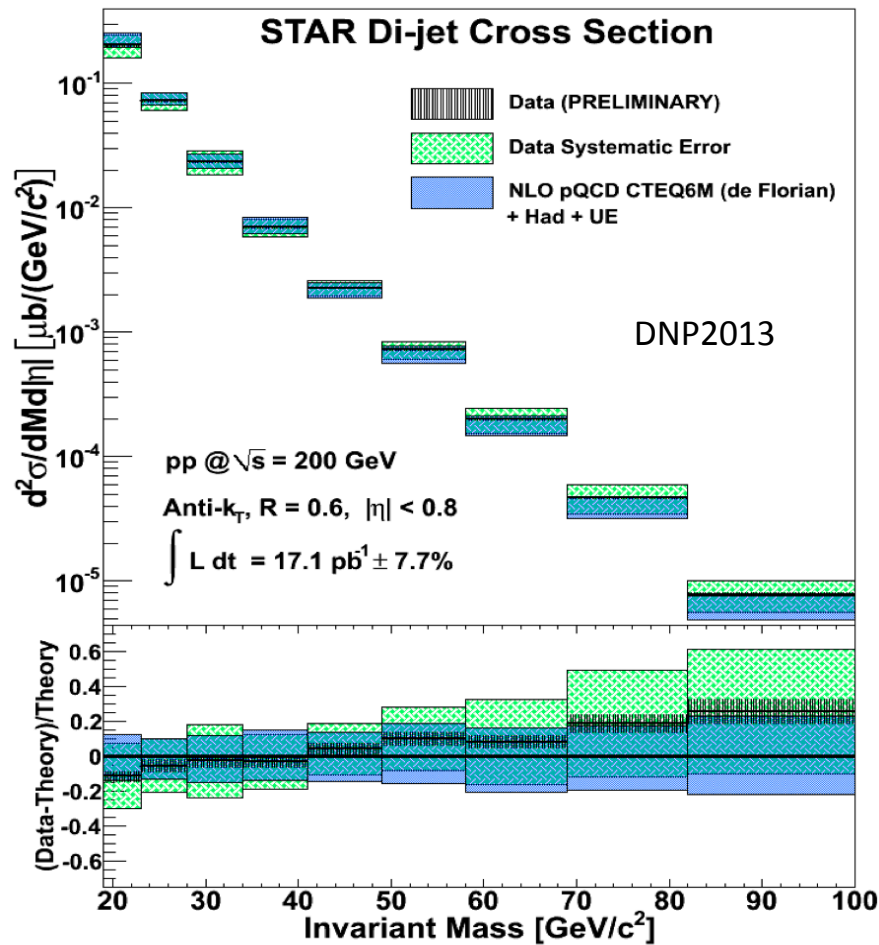


# STAR di-jet measurements

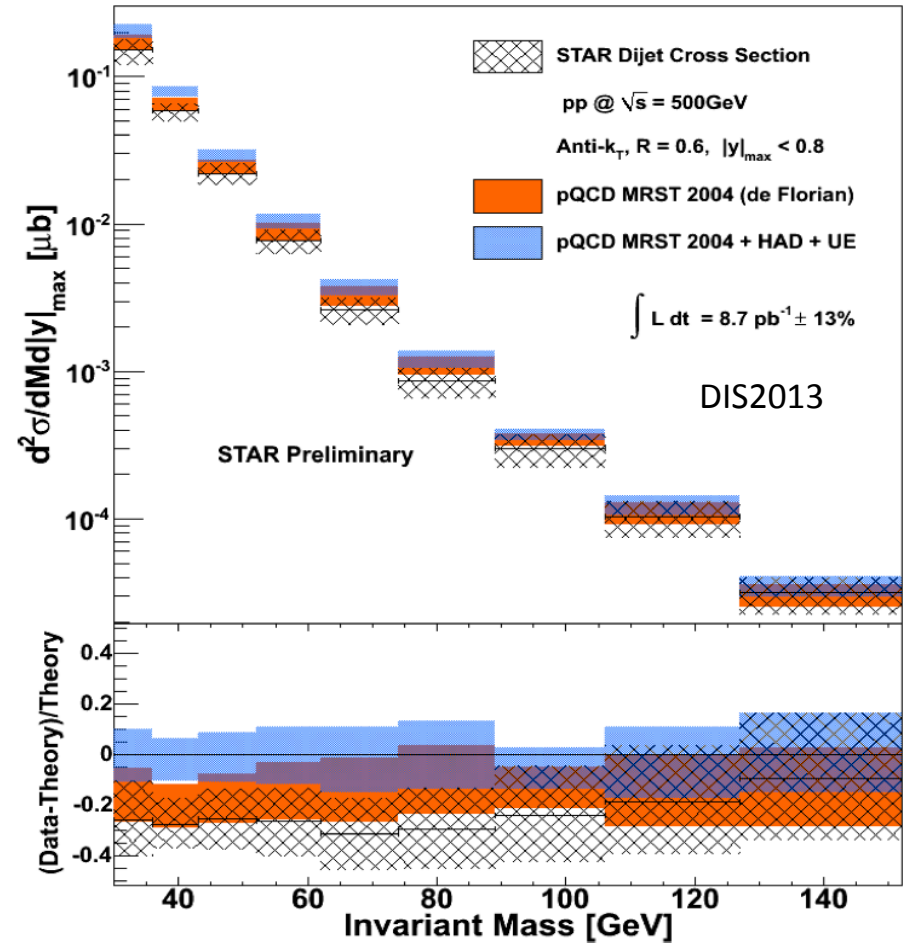
# Di-jet cross section measurements at STAR

- 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  $\eta$  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  $\pi^0 A_{LL}$  gives first evidence of non-zero  $\Delta G$  in the range of  $x_g > 0.05$ .
  - 2012 inclusive jet  $A_{LL}$  measurement opens the path to constrain the shape of  $\Delta g$  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( $\sim 310\text{pb}^{-1}$ ) 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 its components (quarks and gluons).

$$\frac{1}{2} = \frac{1}{2} \Delta \Sigma + L_q + \underbrace{\Delta G + L_g}_{\text{Little known}}$$

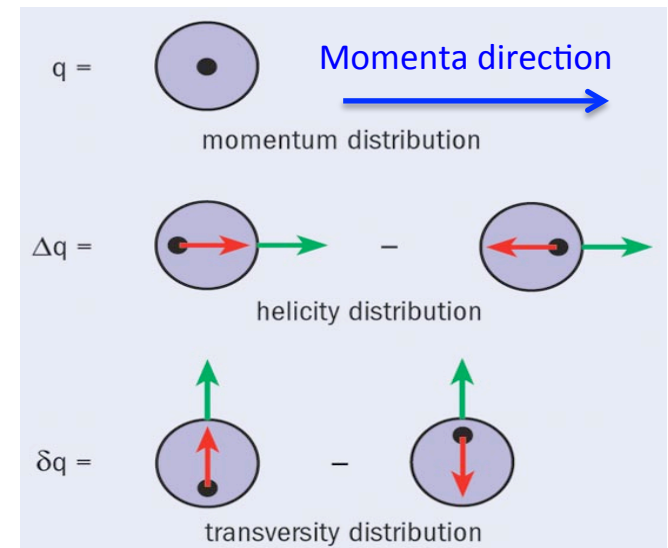
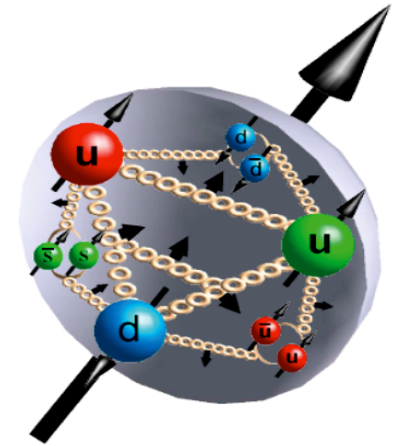
DIS measured ~30%
Little known

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

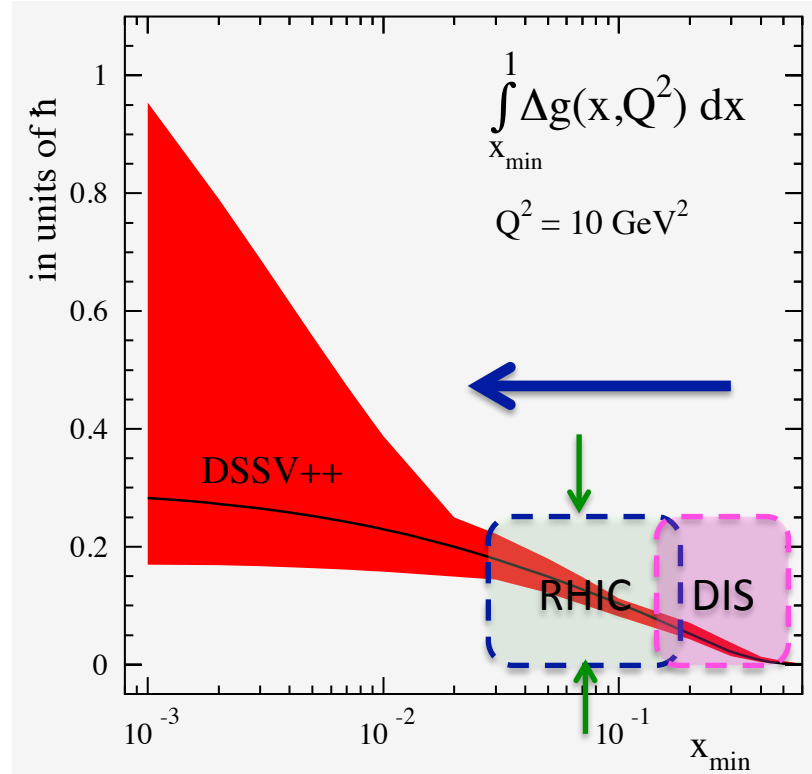
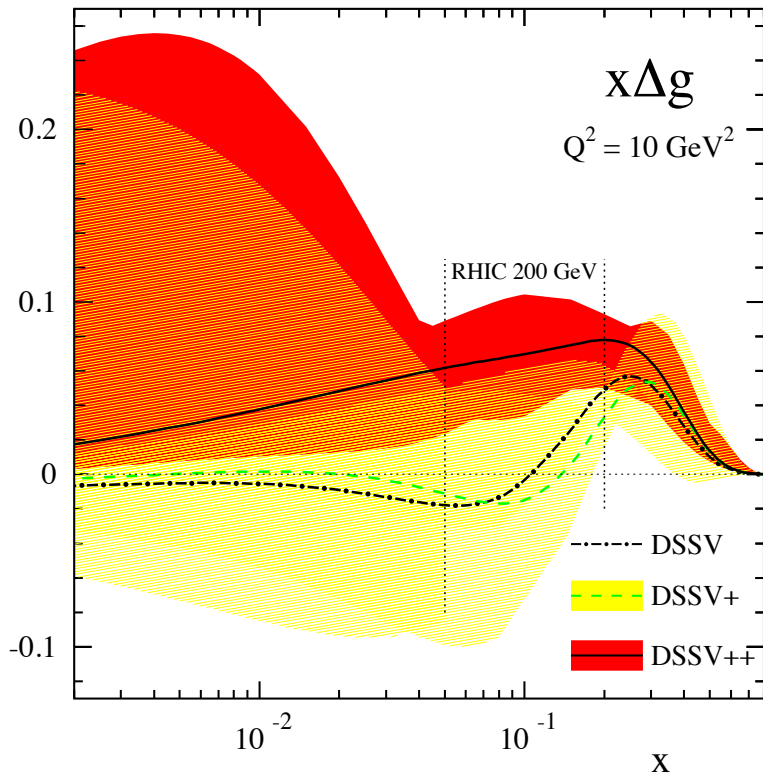
$$\Delta \Sigma = \int (\Delta q(x, Q^2) + \Delta \bar{q}(x, Q^2)) dx$$

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

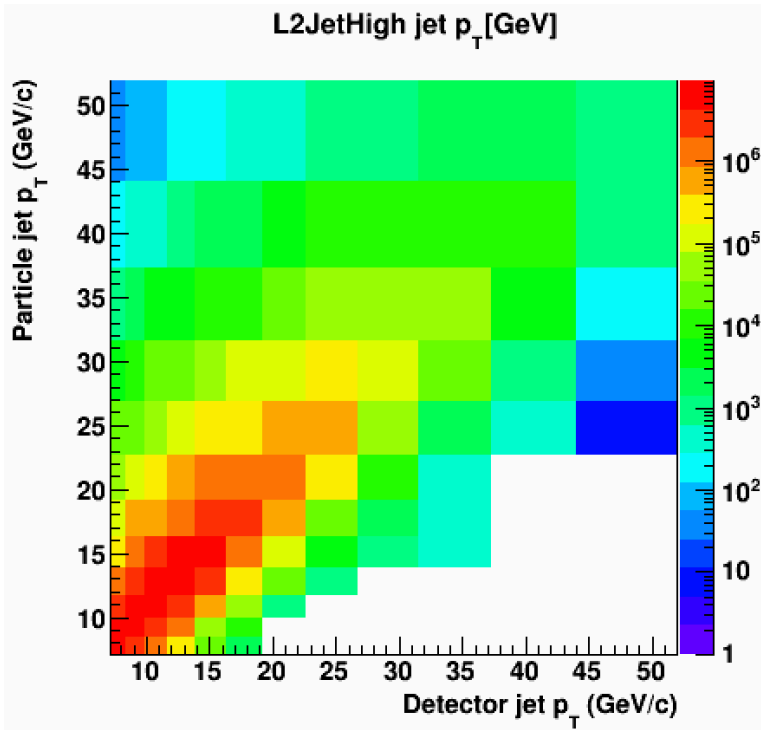


arXiv:1304.0079

- 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

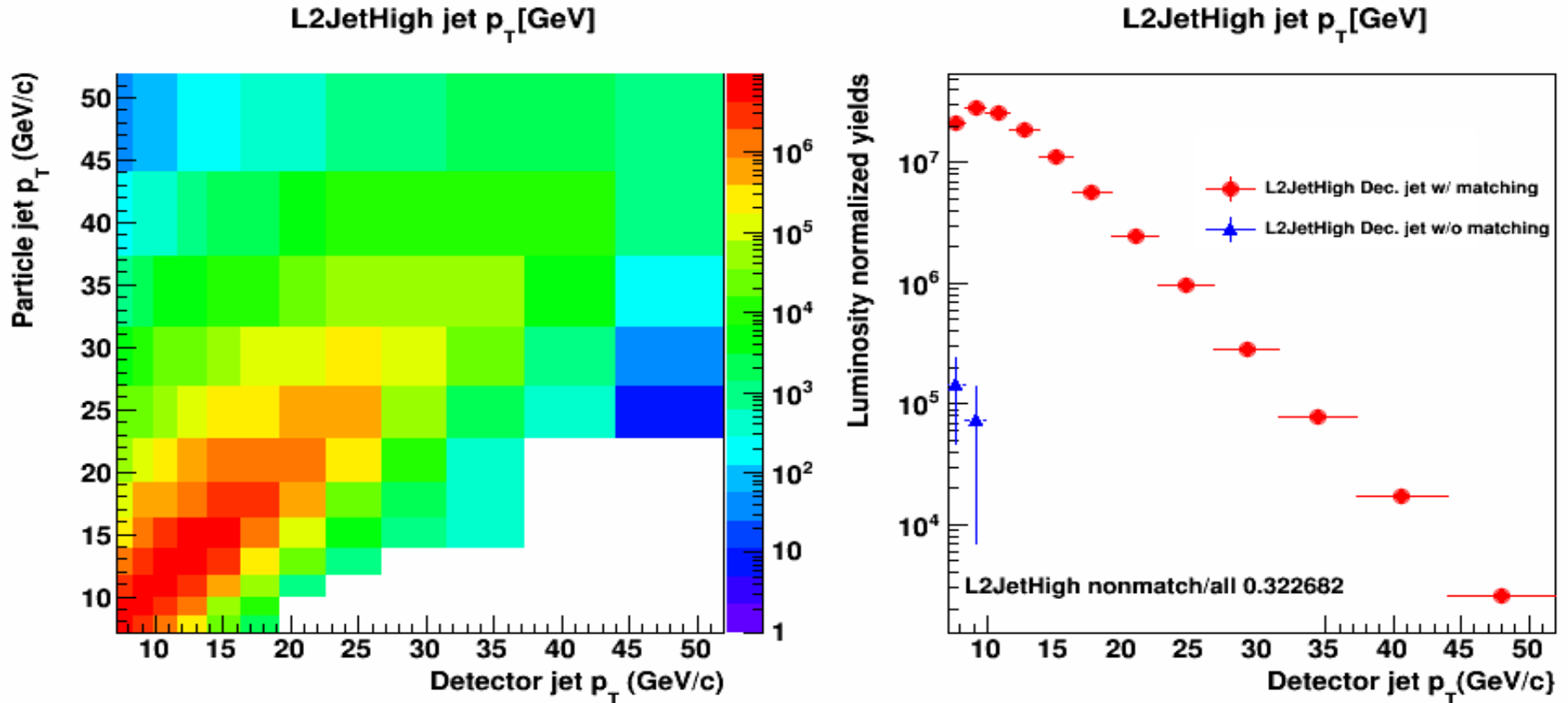
Unfolding Matrix



- 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%.

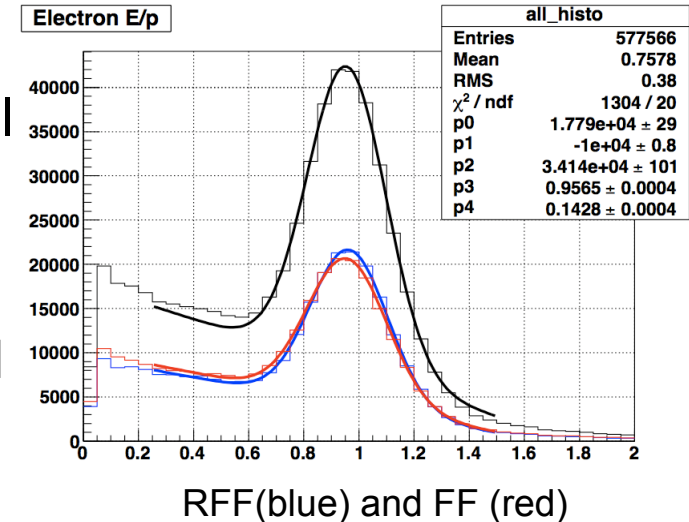


# BTOW "Tower ADC" (electron) calibrations

## Run 9 (200 GeV):

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

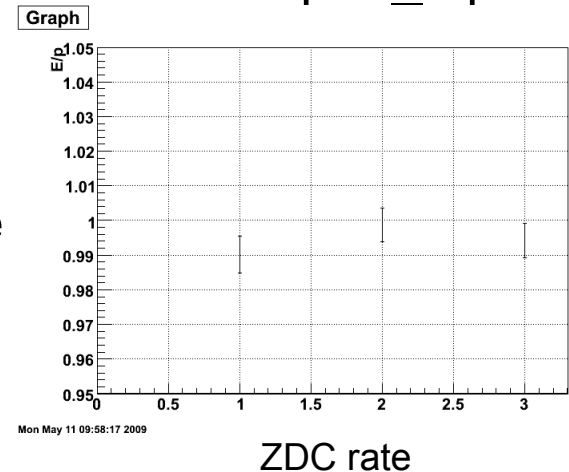
- "on-axis" statistics augmented by **MC** correction of tracked events in fiducial vol
- calibrations obtained for both  $e^+$  and  $e^-$  and their sum for FF and RFF settings
- a composite  $\sim 1.9\%$  systematic is quoted (other systematic effects not considered)



## Run 6 (200GeV):

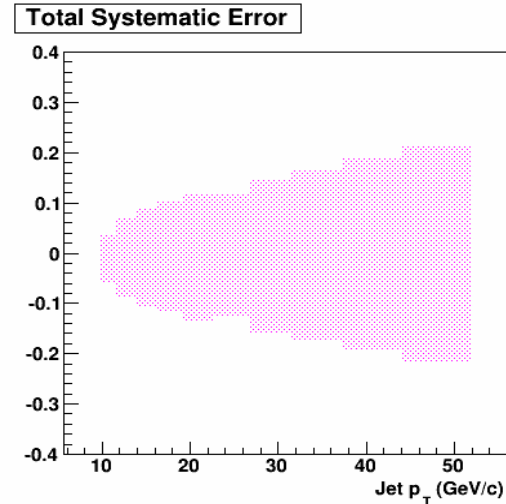
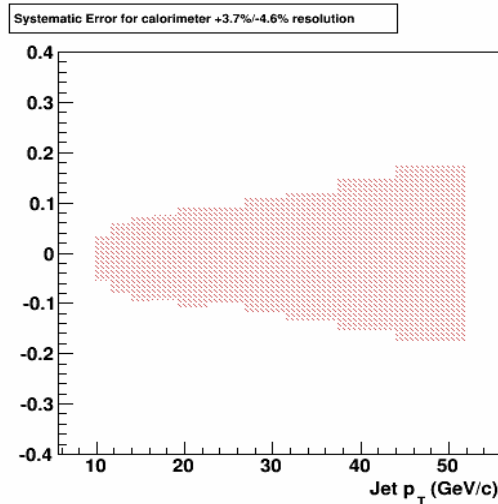
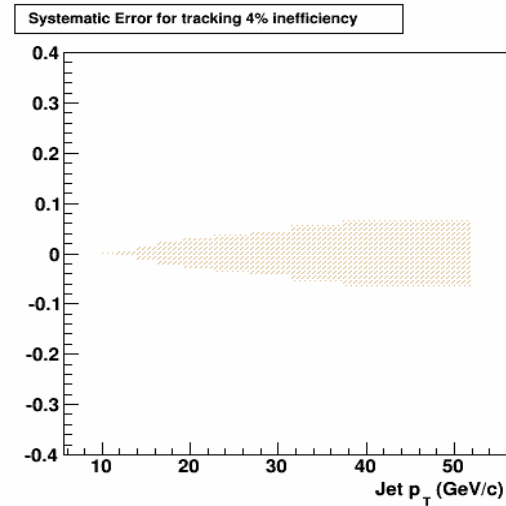
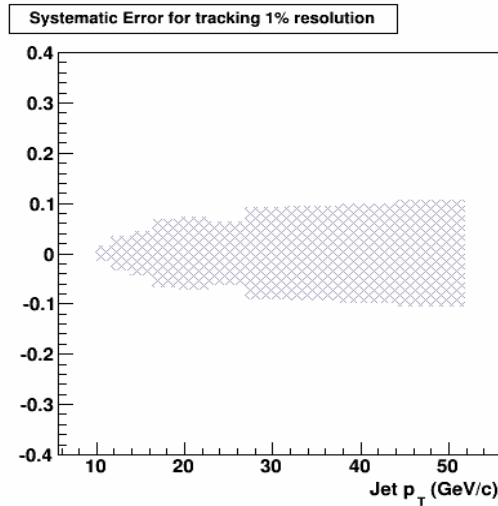
[http://drupal.star.bnl.gov/STAR/system/files/2006-CalibrationReport\\_3.pdf](http://drupal.star.bnl.gov/STAR/system/files/2006-CalibrationReport_3.pdf)

- 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  $\sim 1.6\%$  systematic is quoted

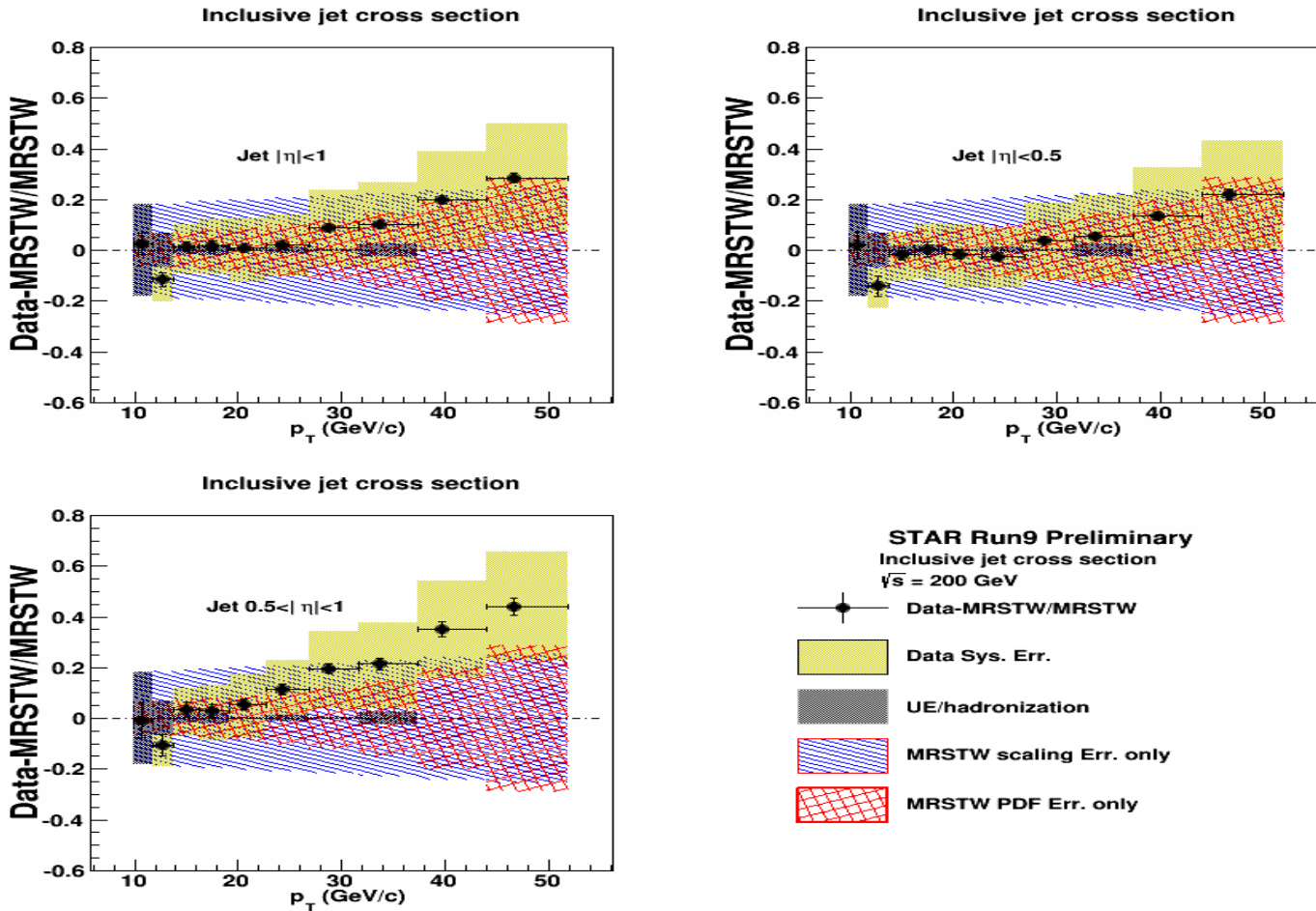


# Total systematic error

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



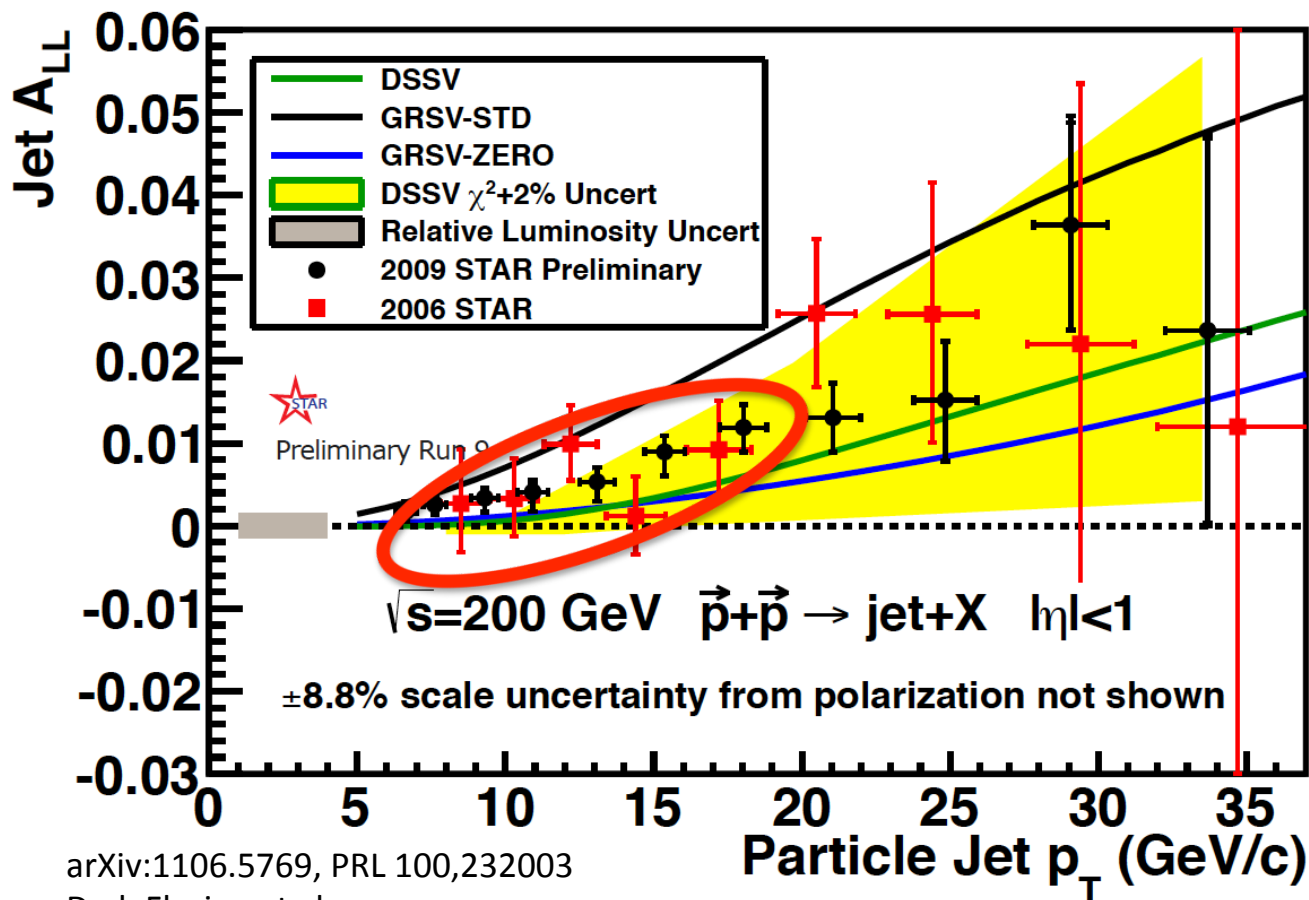
# DATA – MRSTW / MRSTW



- Agreement between data and NLO pQCD with MRSTW2008 PDF sets for  $|\eta| < 1.0$  and  $|\eta| < 0.5$  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  $p_T < 15 \text{ GeV}/c$  region.



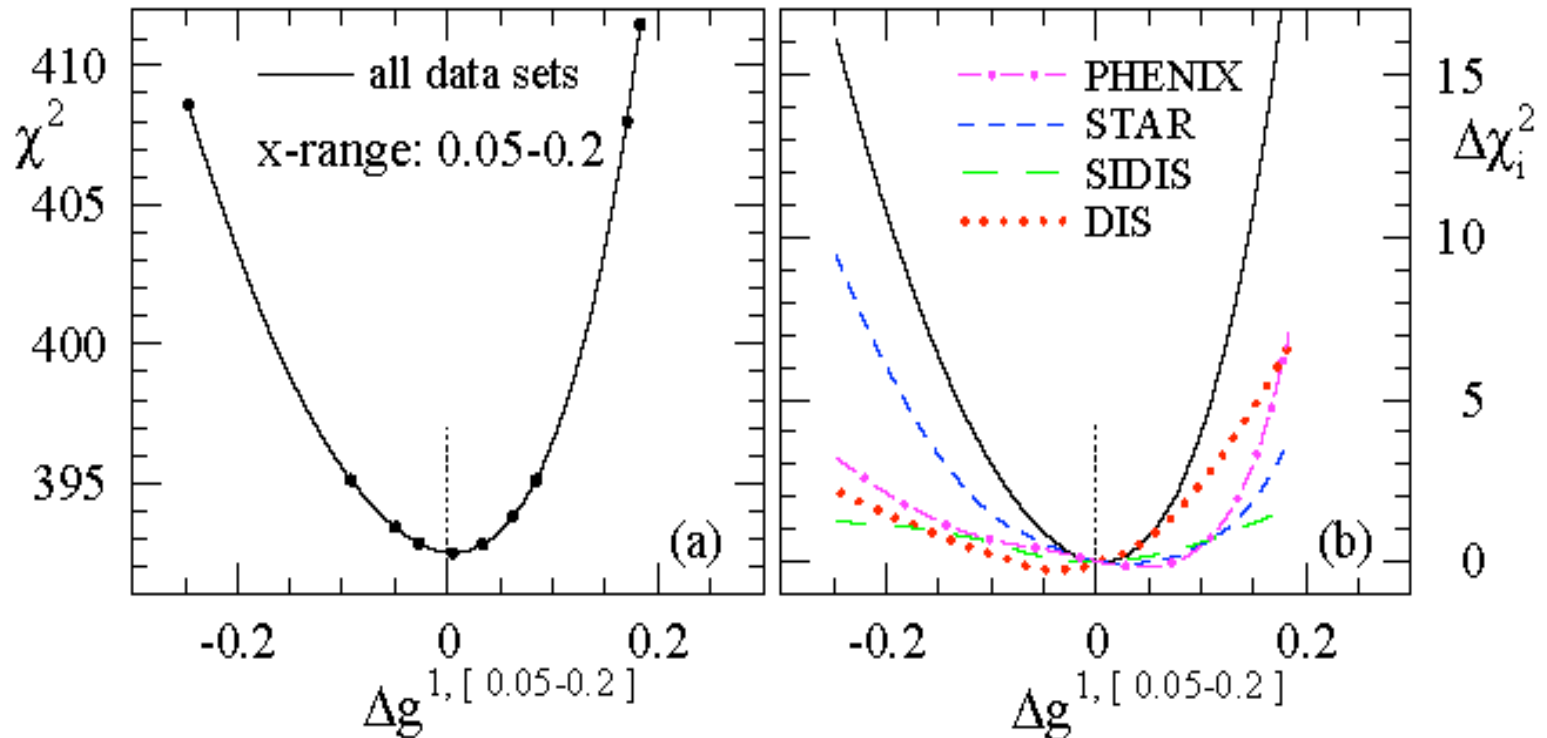
arXiv:1106.5769, PRL 100,232003

D. deFlorian et al.,

Prog. Nucl. Part. Phys. 67, 251 (2012)

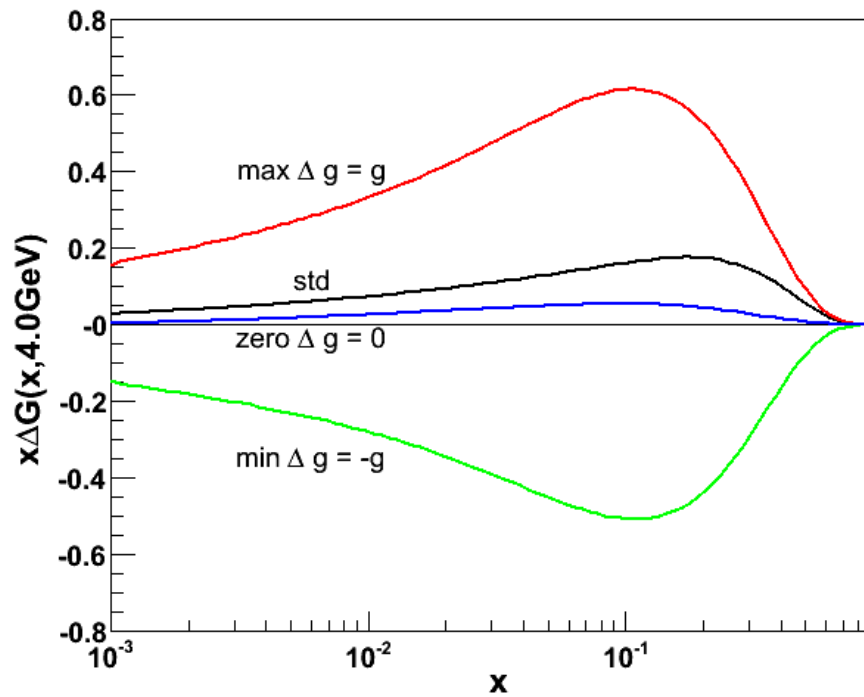
# STAR inclusive jet $A_{LL}$ in 2009 (p+p 200GeV)

- DSSV2008 fit.



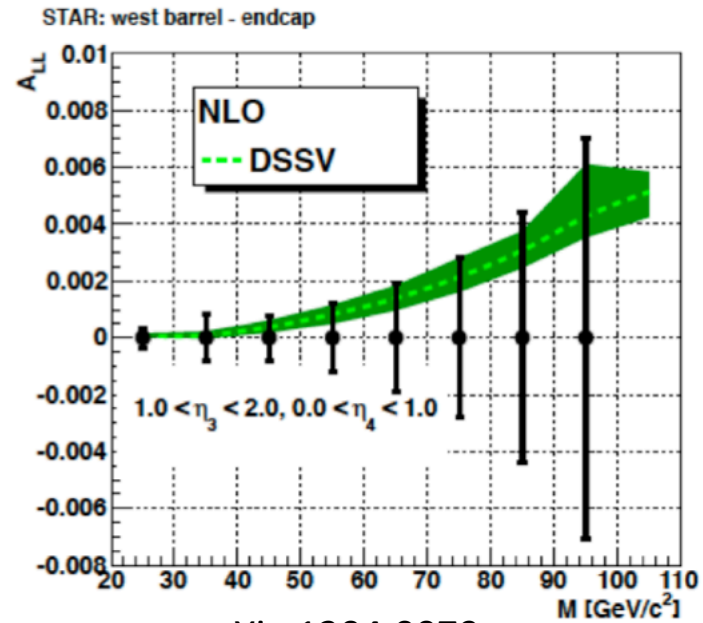
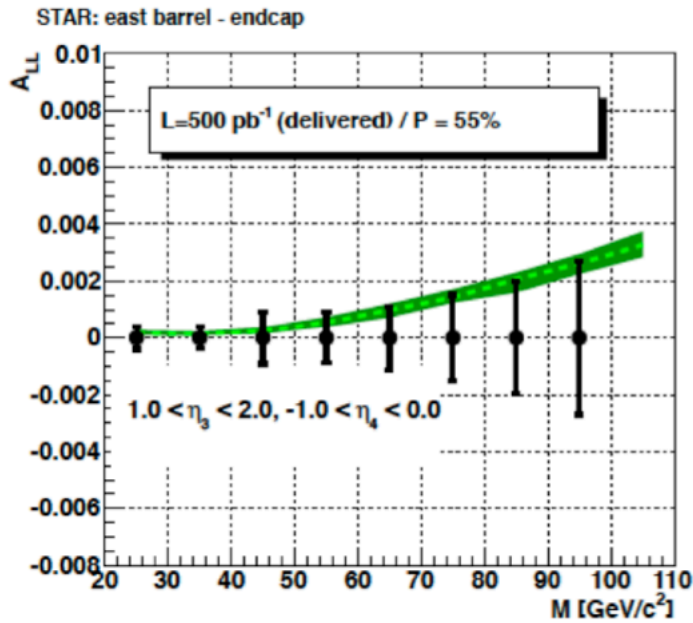
# Global fit

- GRSV

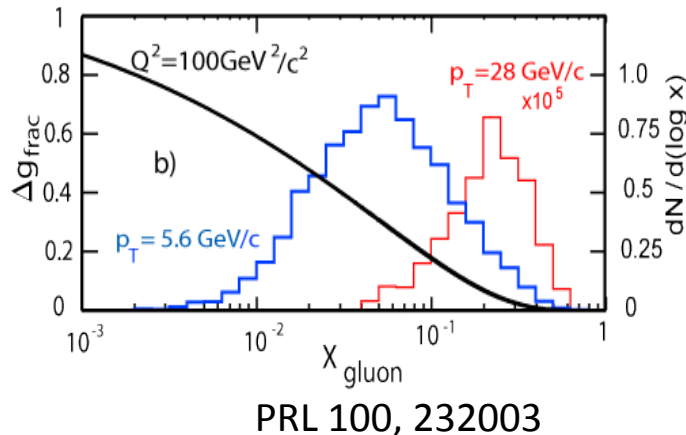


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# Projections for di-jet $A_{LL}$ (p+p 500GeV)



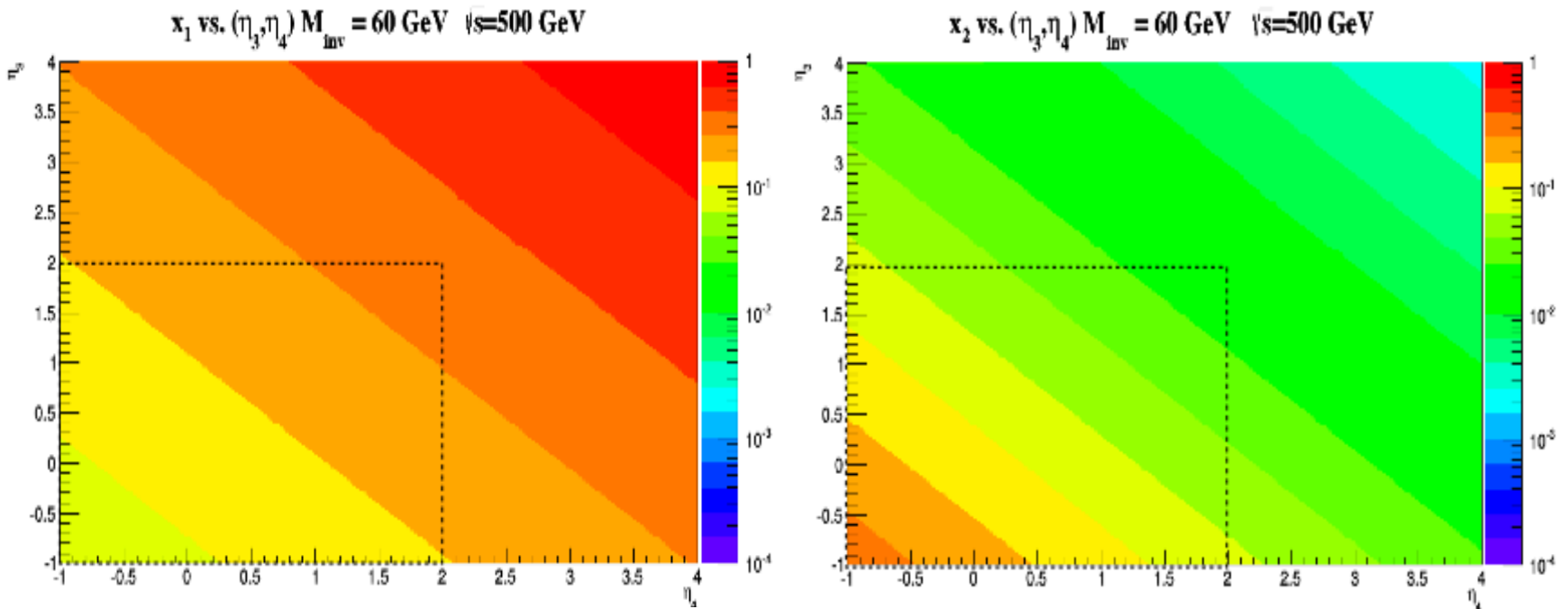
arXiv:1304.0079



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

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

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



$$x_{1(2)} = \frac{1}{\sqrt{s}} \left( p_{T3} e^{\eta_3(-\eta_3)} + p_{T4} e^{\eta_4(-\eta_4)} \right)$$