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Probing the Origin of the Proton Spin with Jets at *STAR*

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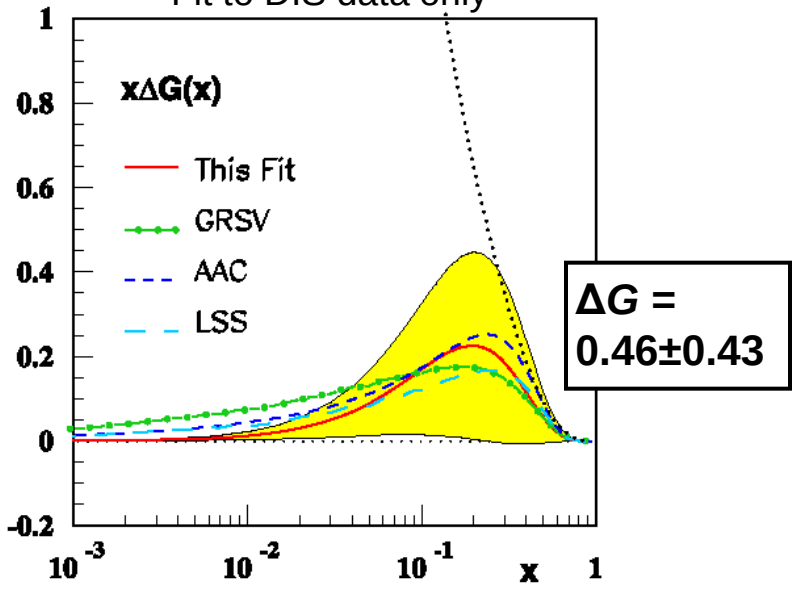
Outline

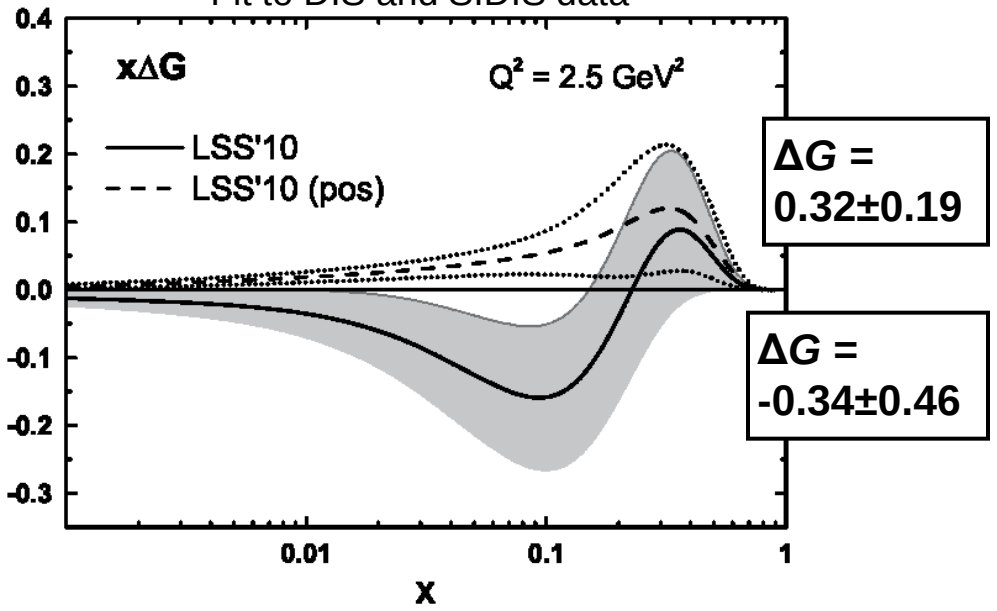
- Introduction
- Gluon polarization with jets and di-jets
- Collins effect and transversity with jets

Gluon polarization **without** RHIC data

Blümlein & Böttcher, NPB 841, 205 (2010)
Fit to DIS data only



Leader et al, PRD 82, 114018 (2010)
Fit to DIS and SIDIS data



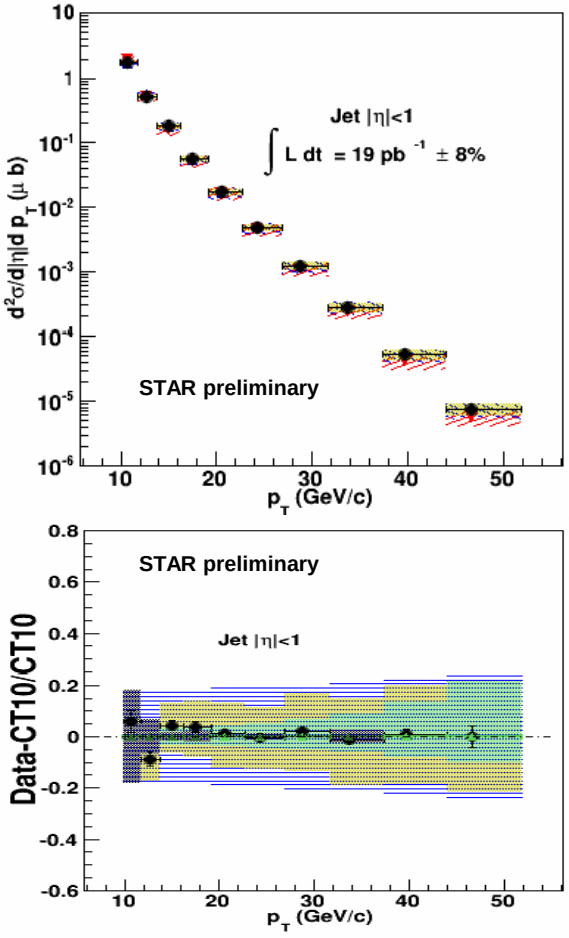
- Two global analyses, both published in 2010
- Very large uncertainties for the gluon polarization
  - Both shape and magnitude

RHIC: the **R**elativistic **H**eavy **I**on **C**ollider

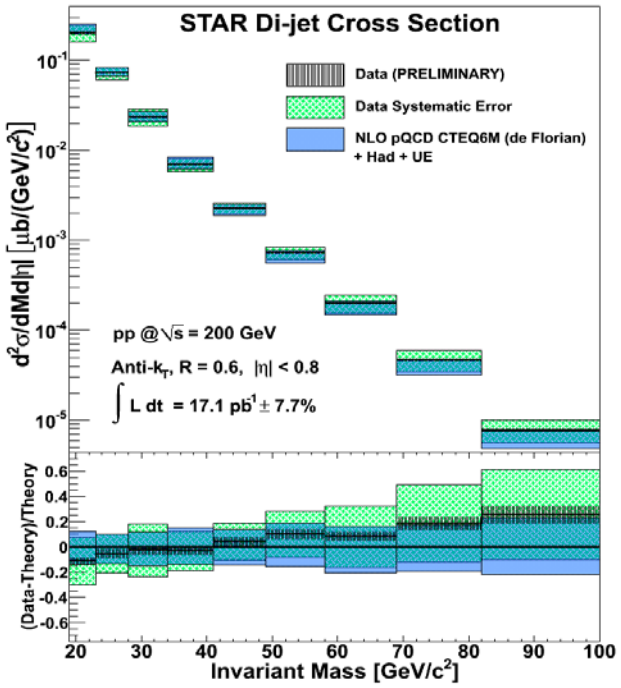
- Search for and study the Quark-Gluon Plasma
- **Explore the partonic structure of the proton**
- Determine the partonic structure of nuclei

STAR as a jet and di-jet detector

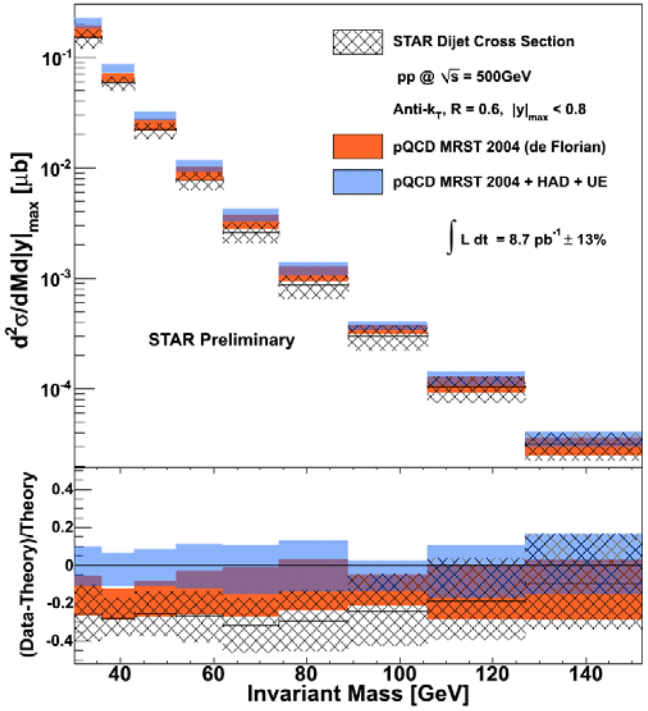
Inclusive jets @ 200 GeV



Di-jets @ 200 GeV



Di-jets @ 500 GeV



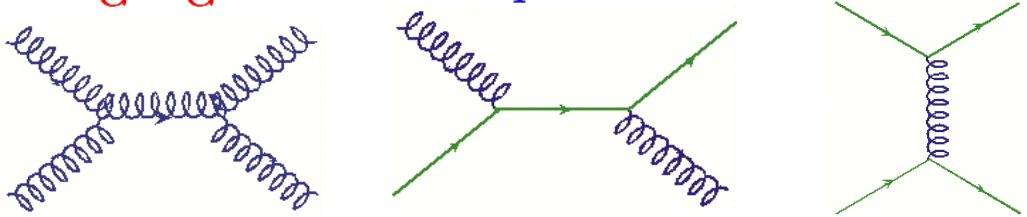
- Large and uniform acceptance makes ***STAR*** an excellent jet detector
- Good agreement with NLO predictions for both inclusive jet and di-jet cross sections

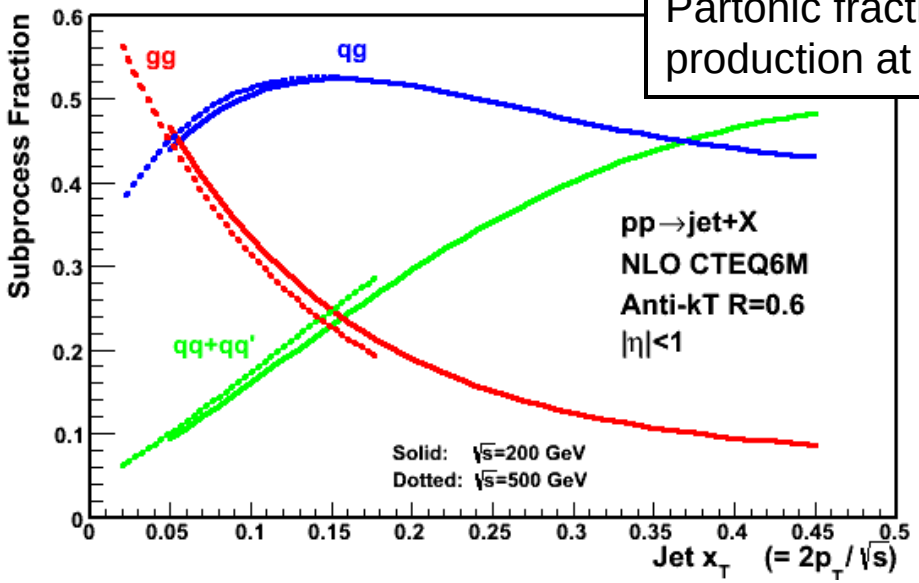
Exploring gluon polarization at RHIC

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

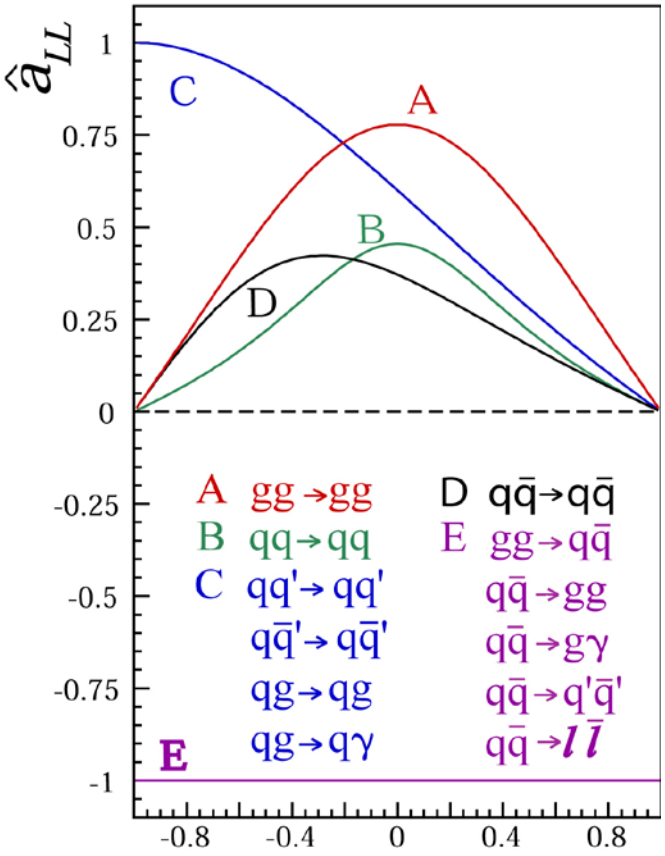
Δf: polarized parton distribution functions

$\frac{\Delta G}{G}\frac{\Delta G}{G}$ $\frac{\Delta q}{q}\frac{\Delta G}{G}$ $\frac{\Delta q}{q}\frac{\Delta q}{q}$





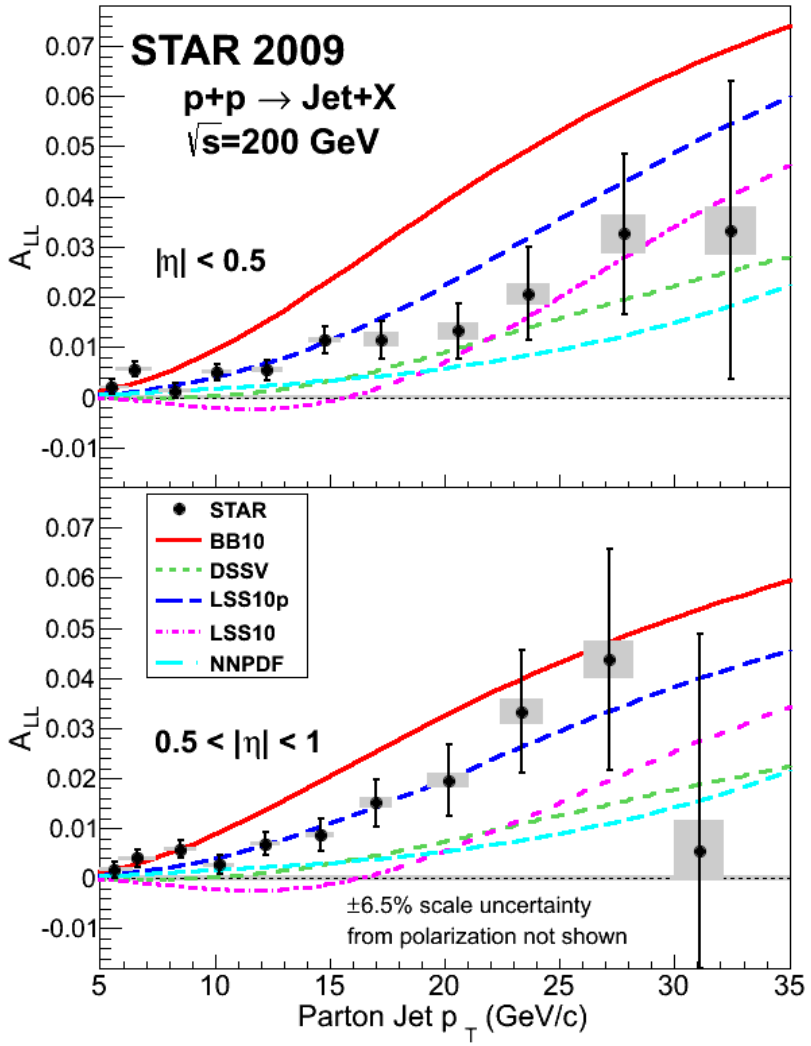
Partonic fractions in jet production at RHIC



For most RHIC kinematics, ***gg*** and ***qg*** dominate, making A_{LL} **for jets sensitive to gluon polarization.**

Inclusive jet A_{LL} from the 2009 RHIC run

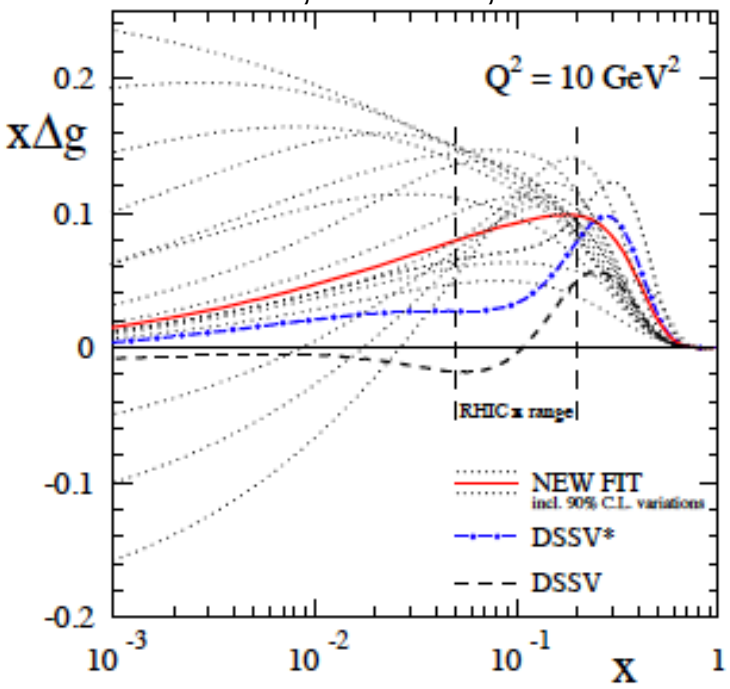
STAR PRL 115, 092002



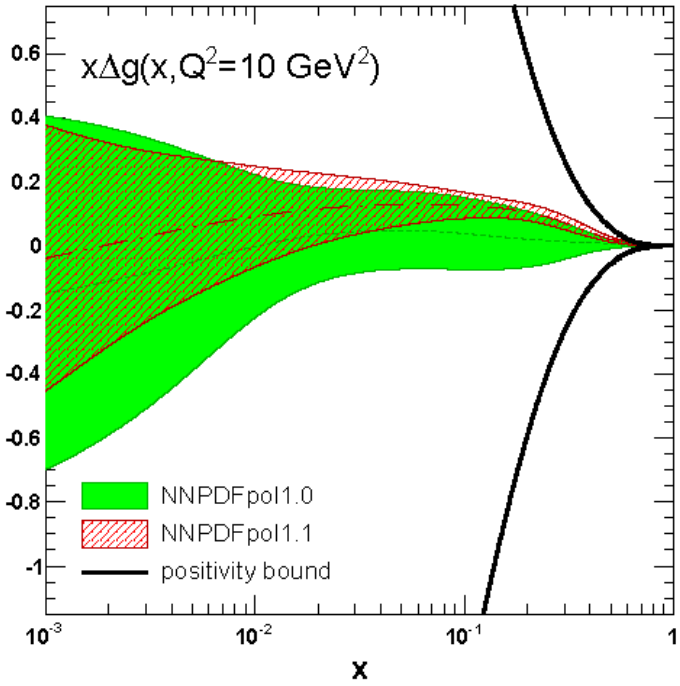
- STAR measured A_{LL} for inclusive jets at 200 GeV during the 2009 RHIC run
- Results draw a narrow road through the previous predictions
- **Far more precise** than previous measurements
- Systematically larger than expected by DSSV'08
- **Positive gluon polarization** in the sampled region $x > 0.05$

Gluon polarization **with** RHIC data

DSSV, PRL 113, 012001



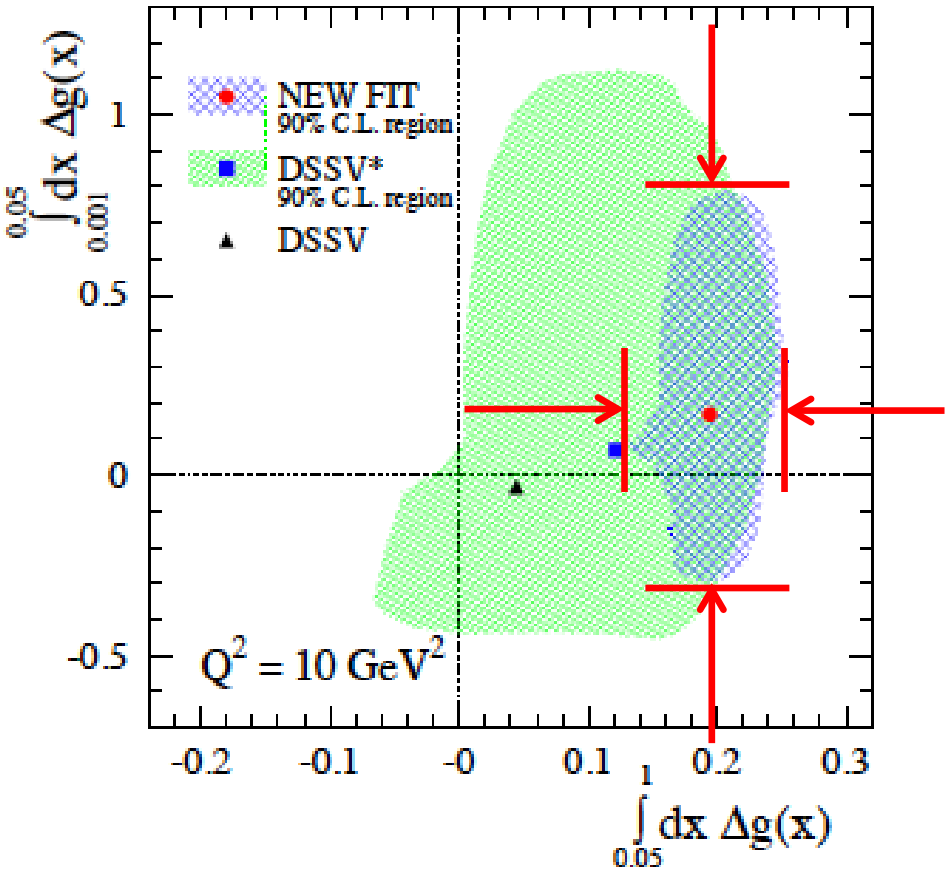
NNPDF, NPB 887, 276



- Both DSSV and NNPDF have released new polarized PDF fits
- Both find the **2009 RHIC results provide significantly tighter constraints on gluon polarization** than previous measurements
- Both find **evidence for positive gluon polarization** in the region $x > 0.05$
  - **DSSV: $0.19^{+0.06}_{-0.05}$ at 90% c.l. for $0.05 < x$**
  - **NNPDF: 0.23 ± 0.07 for $0.05 < x < 0.5$**

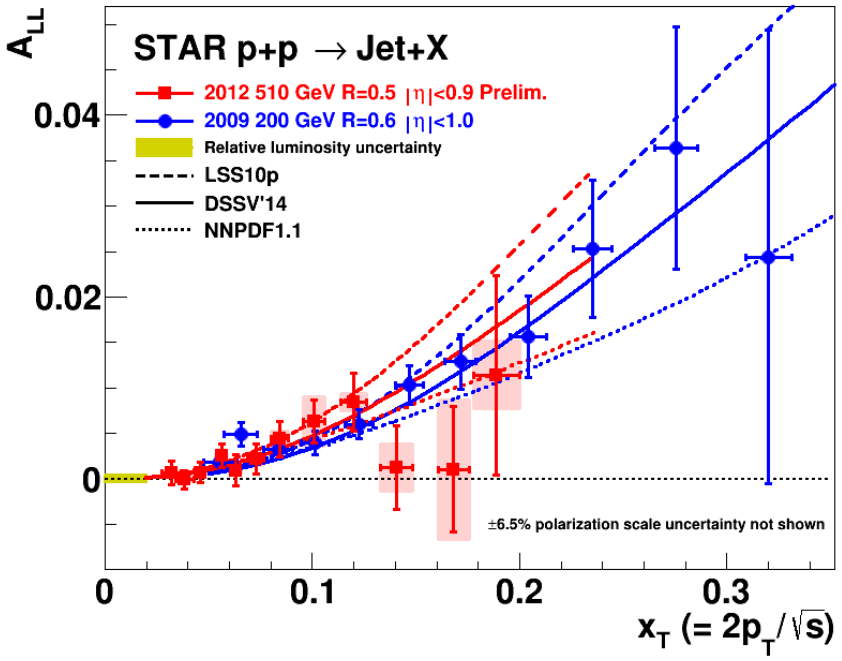
What's next?

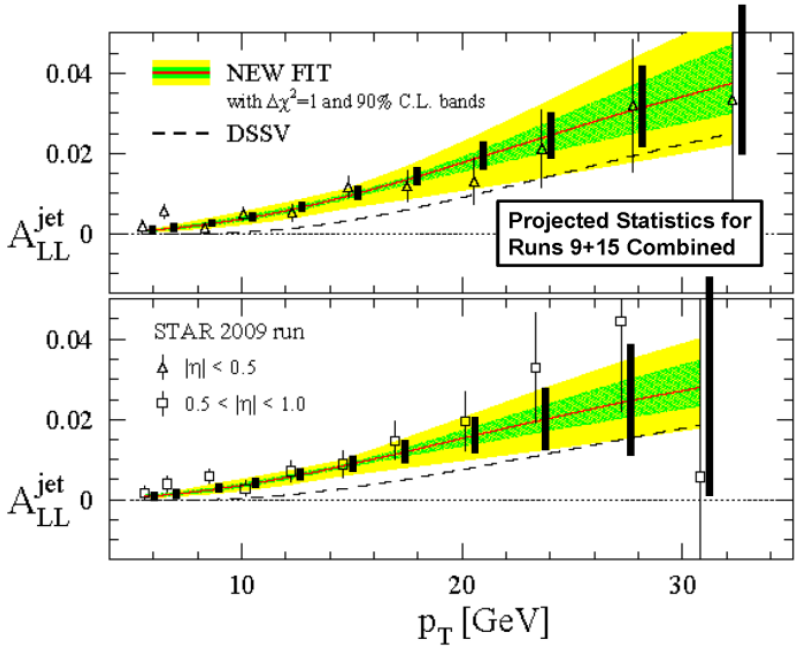
DSSV, PRL 113, 012001



- Need to **increase precision in the currently sampled region** to consolidate the observation of non-zero gluon polarization
- Need to **extend sensitivity to lower x_g** where current extrapolations have very large uncertainties

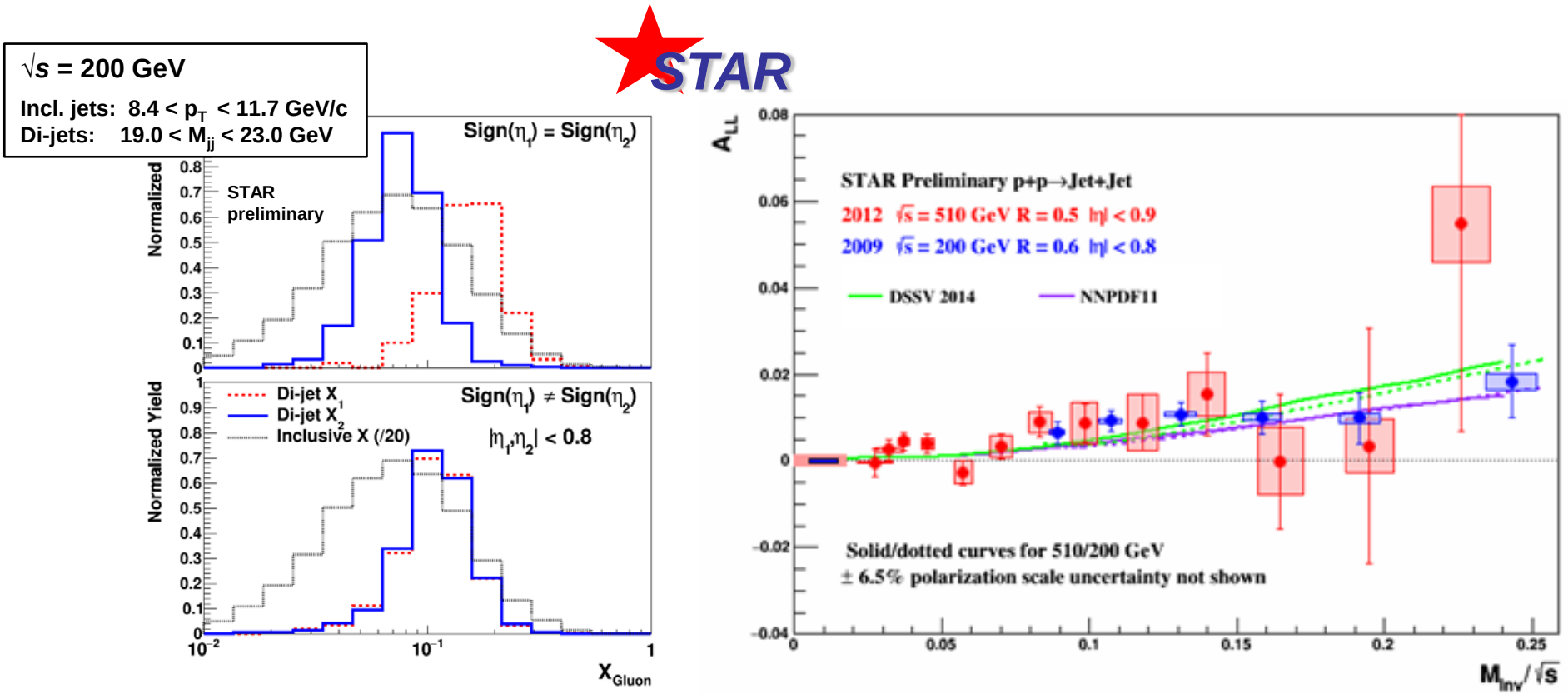
Next steps





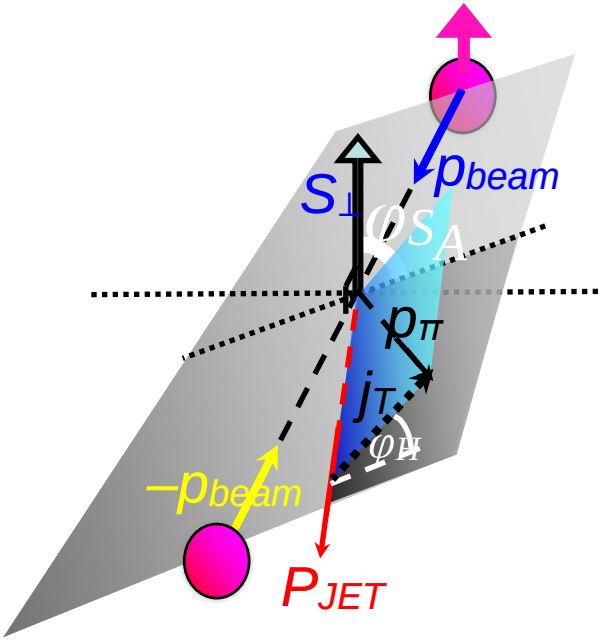
- RHIC had very successful runs with 510 GeV pp collisions during 2012 and 2013
  - Higher center-of-mass energy probes **lower *x* partons**
- **A_{LL} at 510 GeV is well described by global fits** that previously gave a good description of the 2009 measurements at 200 GeV
- STAR took additional 200 GeV pp data during 2015
  - Will reduce uncertainties for A_{LL} at 200 GeV by a factor of ~1.6

Further constraining the *x* dependence



- Di-jet measurements sample a much narrower range of *x* values than inclusive jets
- Use to constrain the shape of $\Delta g(x)$
  - Minimize extrapolation errors outside the sampled region

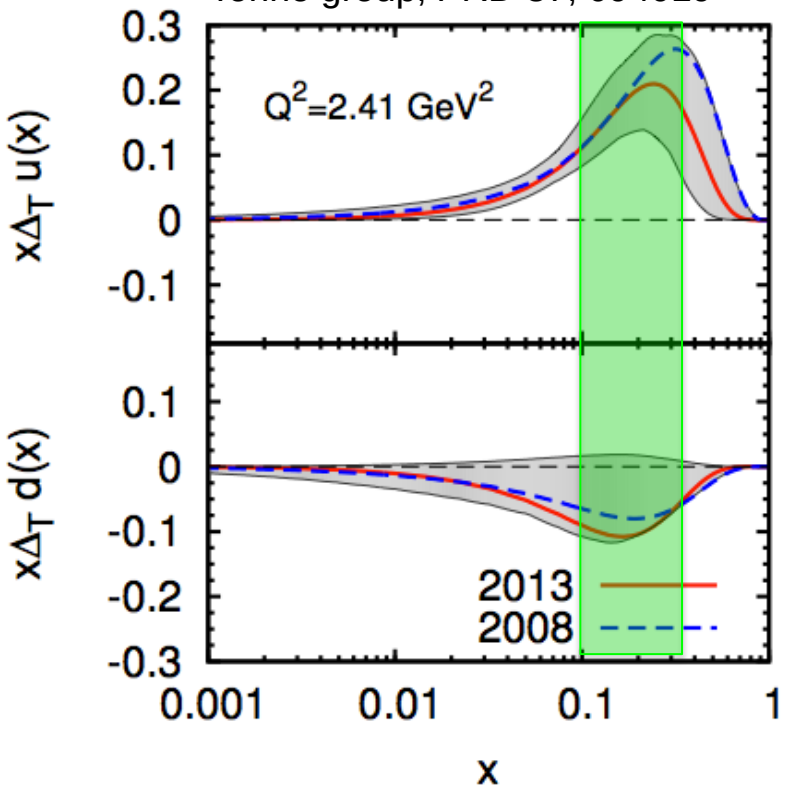
Collins effect in jets at ***STAR***

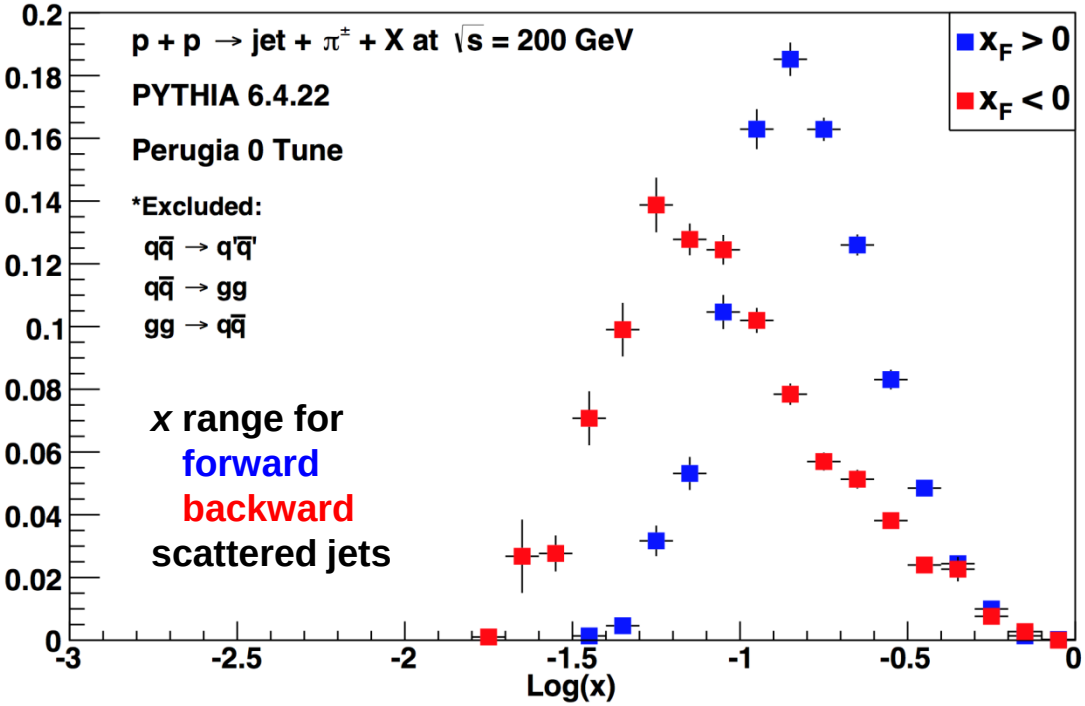


- With transversely polarized proton beams, pion production demonstrates an azimuthal modulation about the jet thrust axis
  - Arises through a convolution of **quark transversity with the Collins fragmentation function**
  - Appears as a **$\sin(\varphi_S-\varphi_H)$ modulation**
- Test the predicted universality of the Collins fragmentation function
- Extend Q^2 reach by two orders of magnitude compared to SIDIS
  - Probe TMD evolution

Transversity reach of ***STAR***

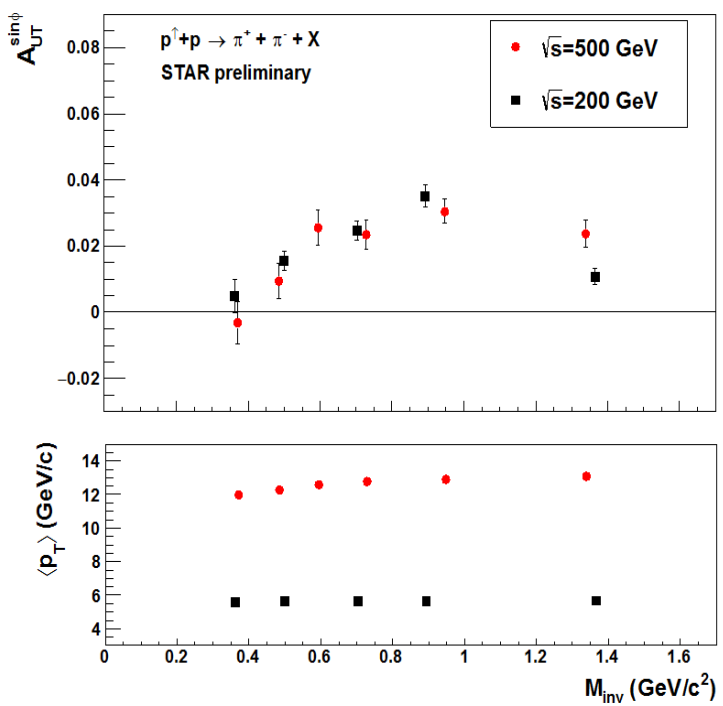
Torino group, PRD 87, 094019

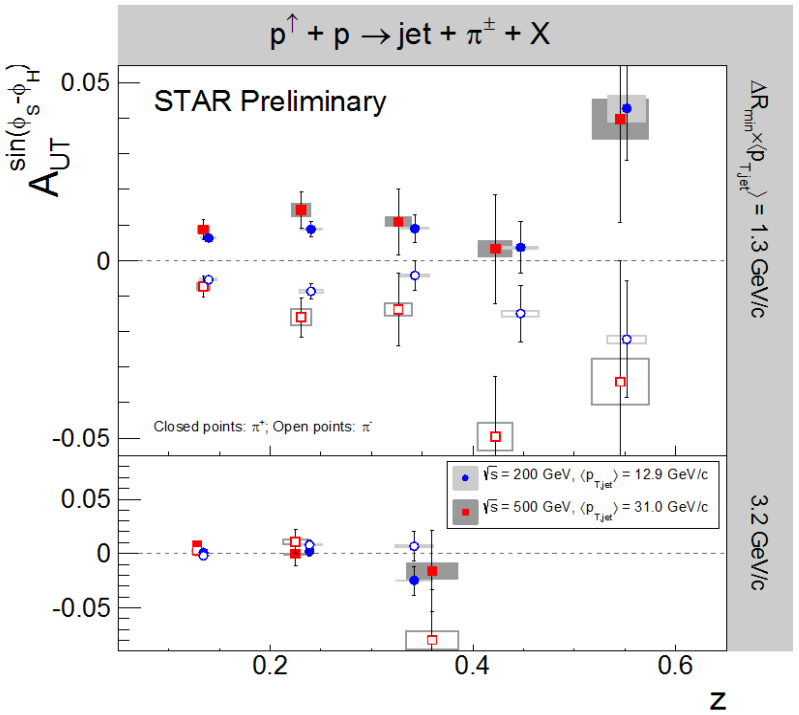




- Green band indicates the region that ***STAR*** has probed to date
  - Will expand in the future
- Study a region where current transversity uncertainties are large
- Strong interactions don't experience *u*-quark dominance
  - Greater sensitivity to *d*-quark effects

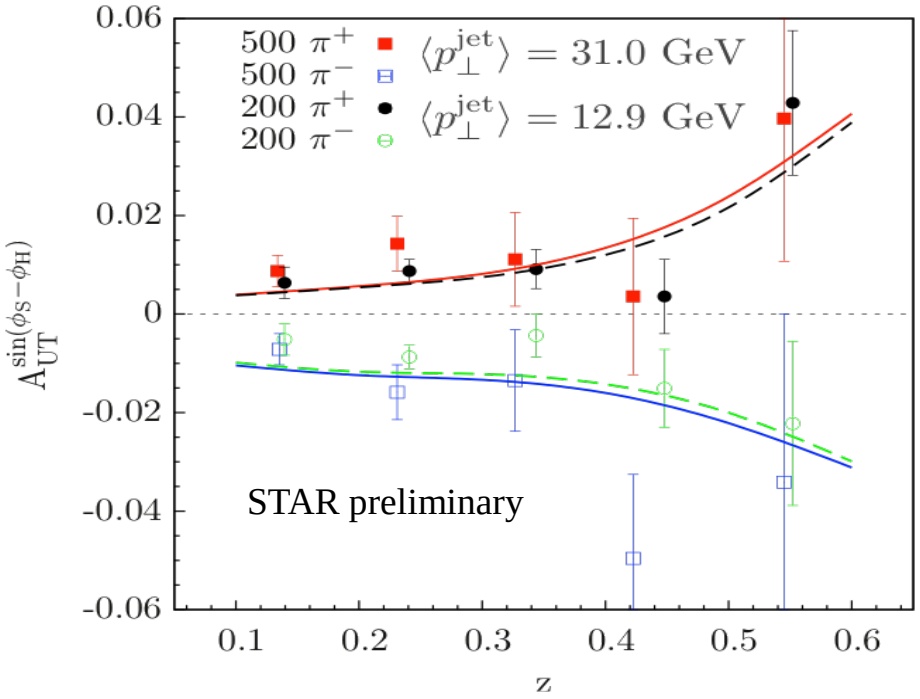
First transversity signals in hadronic collisions





- Significant measurements of transversity convoluted with:
  - Di-hadron interference fragmentation function (IFF)
  - Collins fragmentation function
- Both have similar magnitudes in 200 and 500 GeV pp collisions
- Observations of transversity at very high scales
  - Q^2 up to >900 GeV^2 for Collins at 500 GeV
- Complementary results that obey different evolution equations

Final state: $\pi^{+/-}$ azimuthal distribution in jets

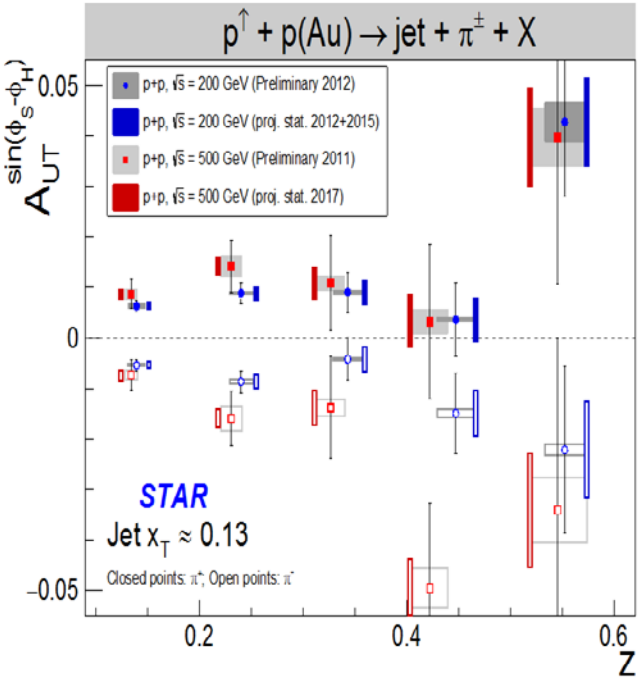


Calculations from Kang et al, in preparation

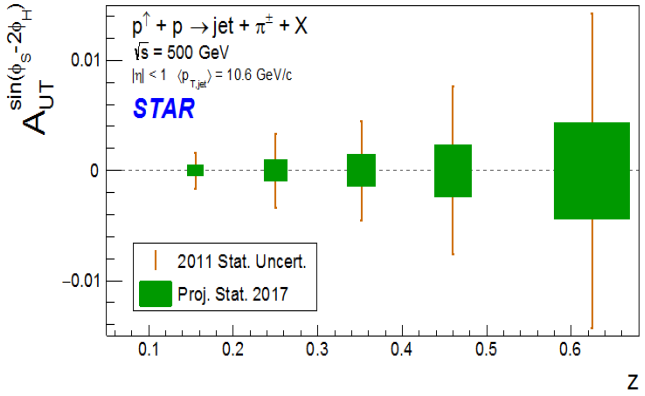
- First Collins effect measurements in pp collisions are well described by calculations that convolute the transversity distribution from SIDIS with the Collins FF from e^+e^- collisions
  - Tests the predicted **universality of the Collins FF**
  - No TMD evolution in this calculation
    - Maybe small?
    - Maybe cancels between numerator and denominator for asymmetries?

Many azimuthal modulations possible

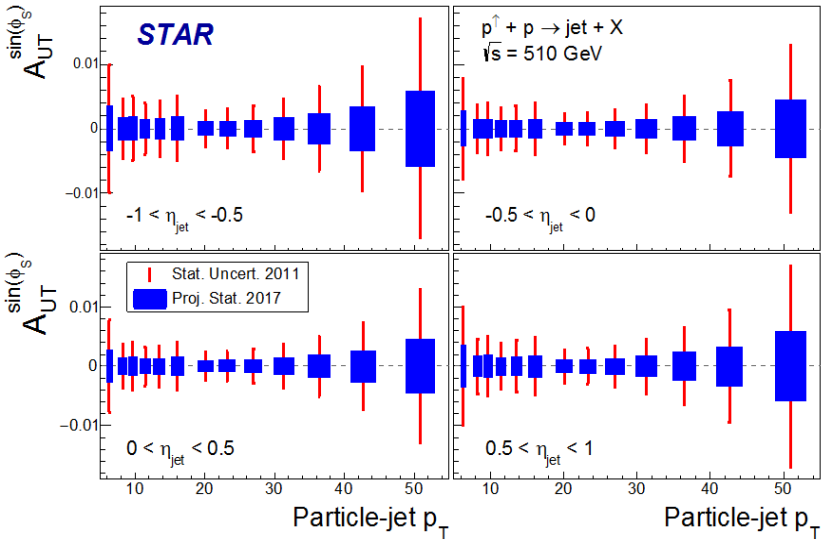
Transversity x Collins



Linearly polarized gluons:
Possible explanation for the ridge in pp/pA?



Gluon Sivers function via Twist-3 relationship

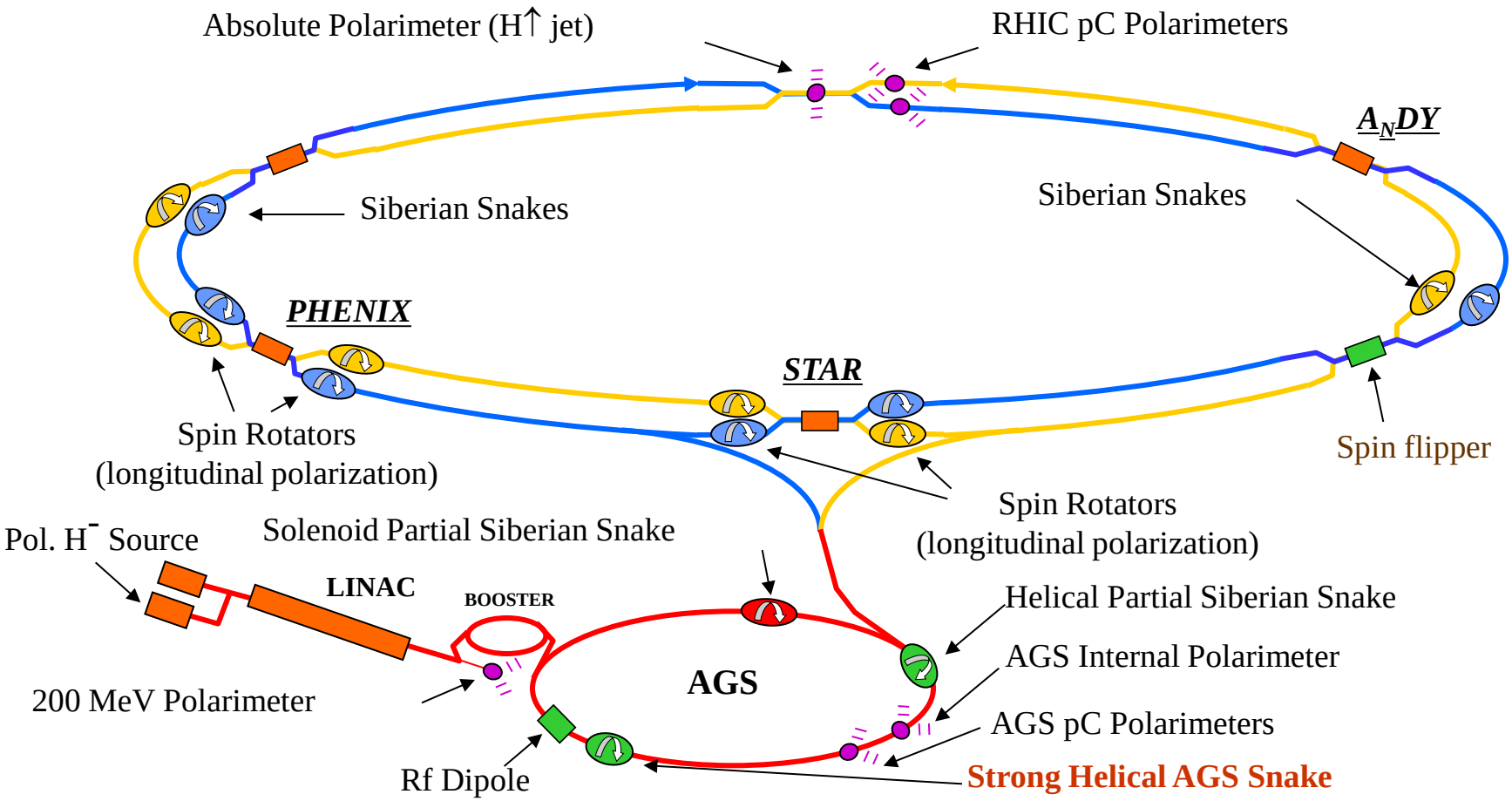


- Precision data at fixed *x*, different √*s* **ideal to constrain TMD evolution**
- Upcoming 2017 data, when combined with existing 2011, ‘12, and ‘15 data, will provide stringent tests

Conclusions

- We still have a great deal to learn about the structure of the proton
- ***STAR* is making significant contributions** to several poorly constrained pieces of the puzzle
  - **Gluon polarization**
    - May contribute as much or more to the proton spin as the quarks and anti-quarks
  - **Transversity and TMDs**
    - Clear evidence of transversity has been seen in pp collisions
    - Test universality and TMD evolution
    - Measure transversity where current uncertainties are large
- More data have been **recorded and are being analyzed** at this moment, and still more are expected soon. **Stay tuned!**

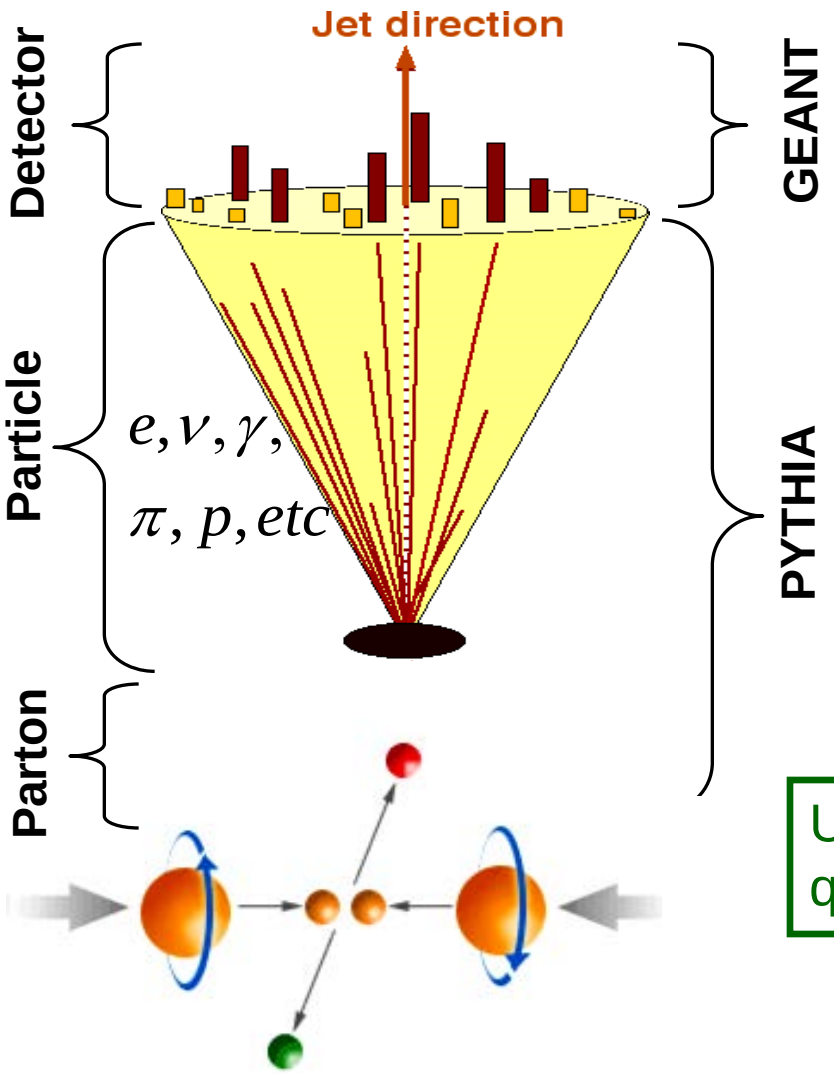
RHIC: the world's first (and only!) polarized hadron collider



- Spin varies from rf bucket to rf bucket (9.4 MHz)
- Spin pattern changes from fill to fill
- Spin rotators provide choice of spin orientation
- Billions of spin reversals during a fill with little depolarization

Jet reconstruction in ***STAR***

Data jets **MC jets**



For 2009 data and beyond

Anti-k_T algorithm

Cacciari, Salam, and Soyez, JHEP 0804, 063

- R = 0.6 for 200 GeV
- R = 0.5 for 500/510 GeV

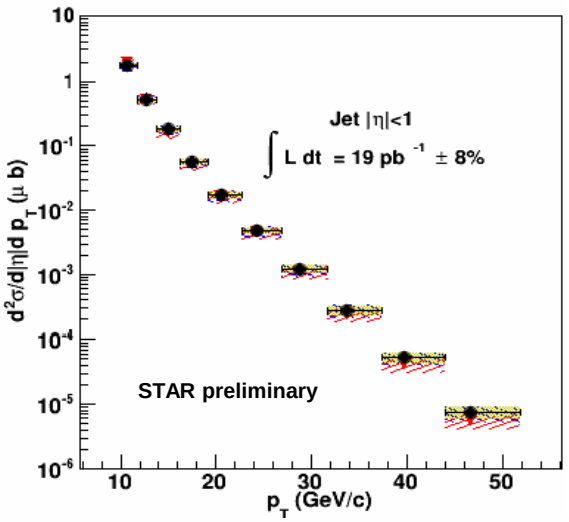
Use **PYTHIA** + **GEANT** to quantify detector response

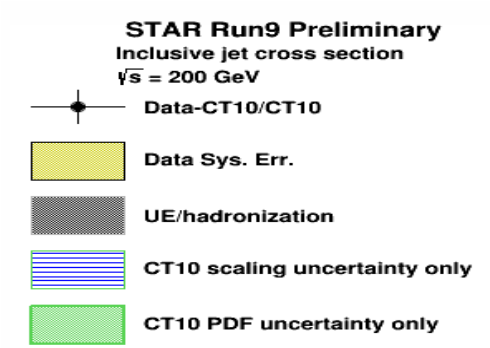
Sjostrand, Mrenna, and Skands, JHEP 05, 026

P. Z. Skands, arXiv:1005.3457v5

STAR as a jet detector

Inclusive jets @ 200 GeV

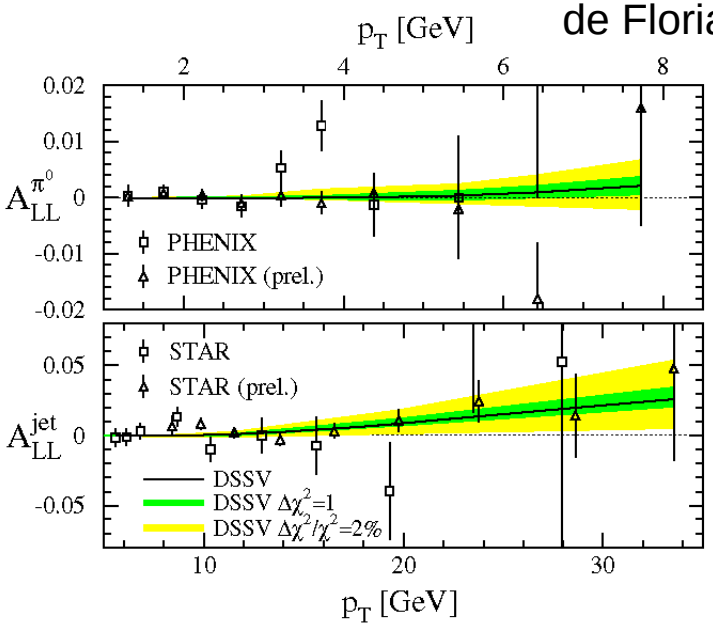


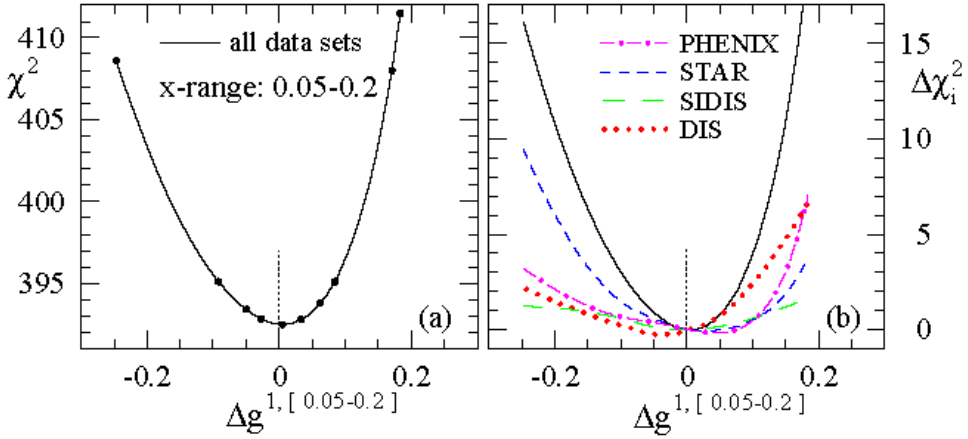


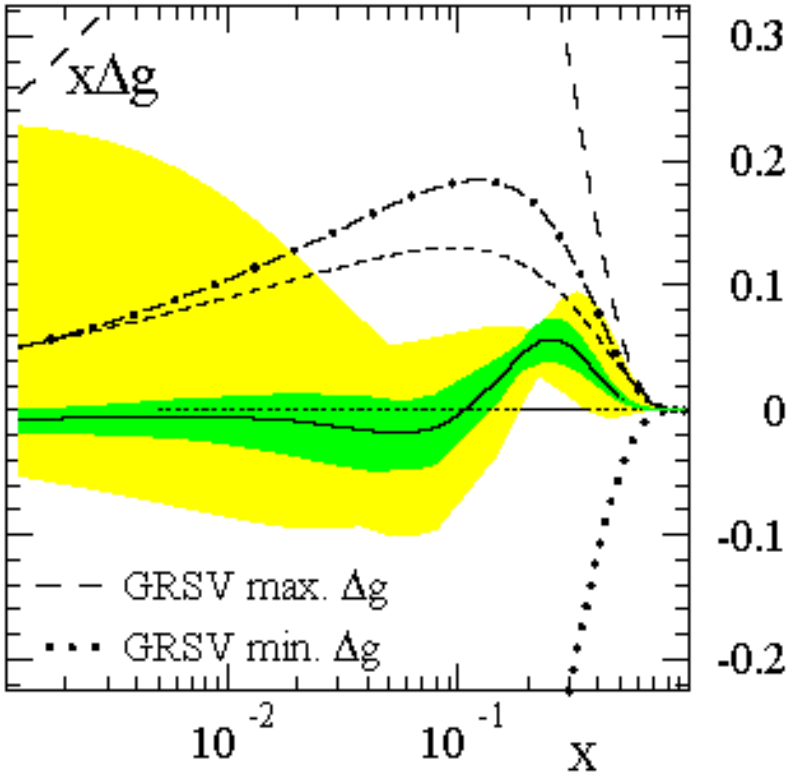
- Large and uniform acceptance makes ***STAR*** an excellent jet detector
- Good agreement with NLO predictions for inclusive jet cross section in 200 GeV pp collisions

First global analysis with RHIC pp data

de Florian et al., PRL 101, 072001







- DSSV'08 was the first global analysis to include inclusive DIS, semi-inclusive DIS (SIDIS), and RHIC pp data on an equal footing