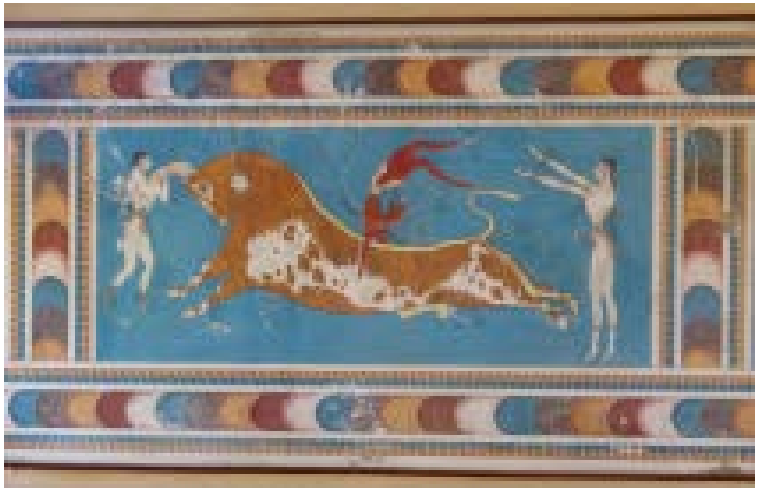


Probing the Origin of the Proton Spin at *STAR*

6th International Conference on New Frontiers in Physics

Carl Gagliardi

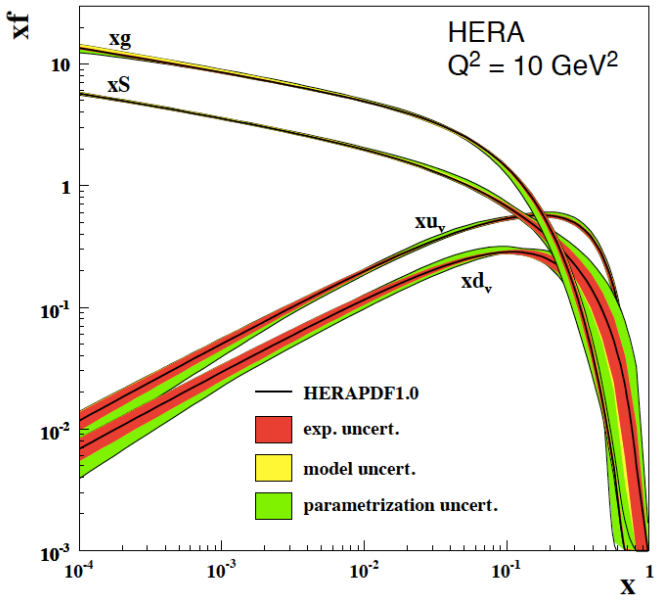
Texas A&M University

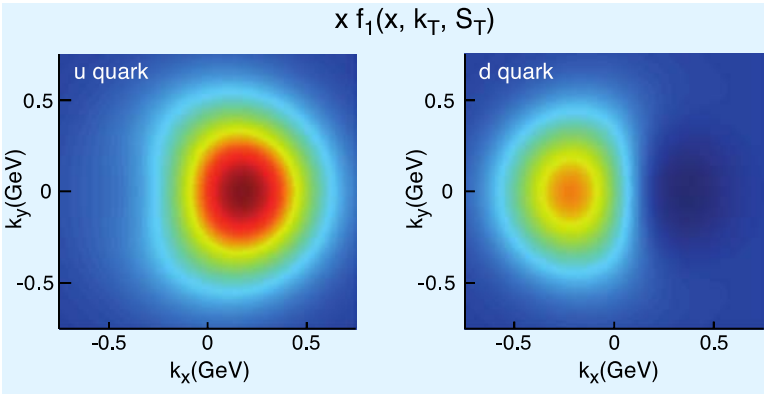
for the *STAR* Collaboration

Outline

- Introduction
- Longitudinal spin structure: gluon and anti-quark polarization
- Transverse spin structure: TMDs and visualizing color interactions

Fundamental questions regarding proton spin



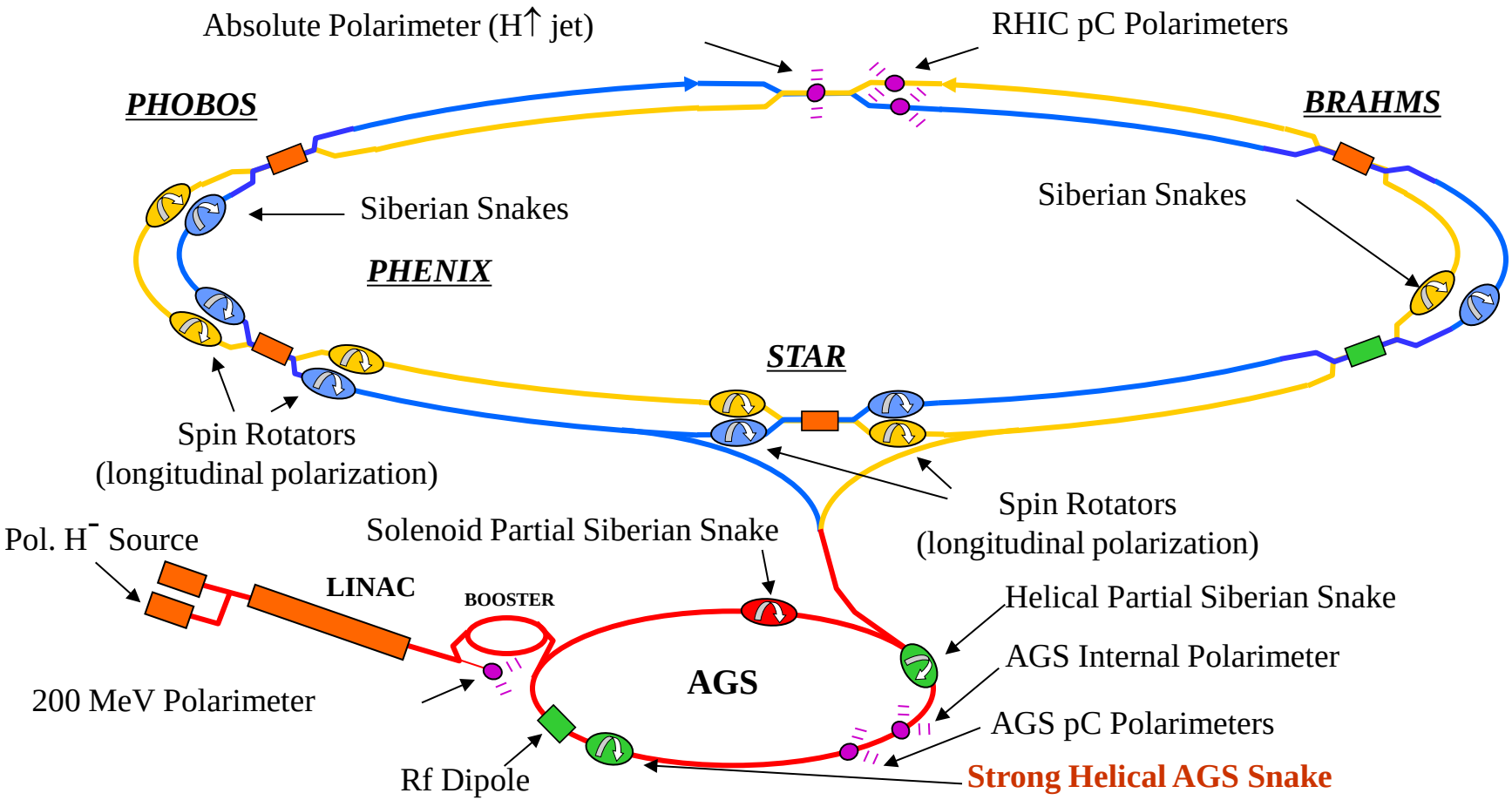


- How do quarks and gluons conspire to provide the proton's spin ½?
  - What is the role of gluons?
    - Reminder – gluons contribute ~50% of the proton's momentum
  - What is the role of sea quarks?
  - How much orbital angular momentum is needed?
- What is the dynamic structure of the proton?
  - How do we go beyond longitudinal parton distribution functions to a 2D+1 picture in coordinate and momentum space?
  - Can we visualize color interactions in QCD?

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

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

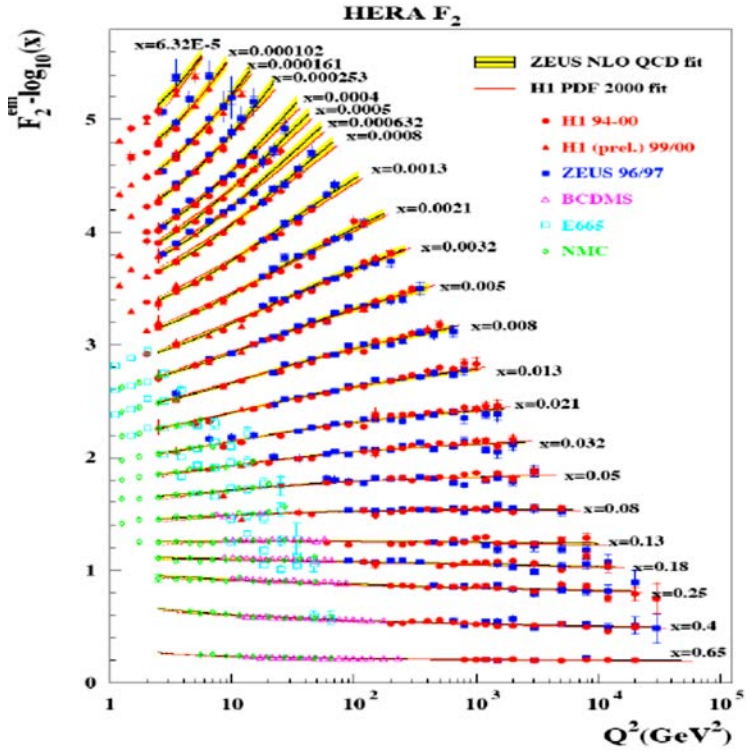


- Spin varies from rf bucket to rf bucket (9.4 MHz)
- Spin pattern changes from fill to fill
- Spin rotators provide choice of spin orientation
- Billions of spin reversals during a fill with little depolarization

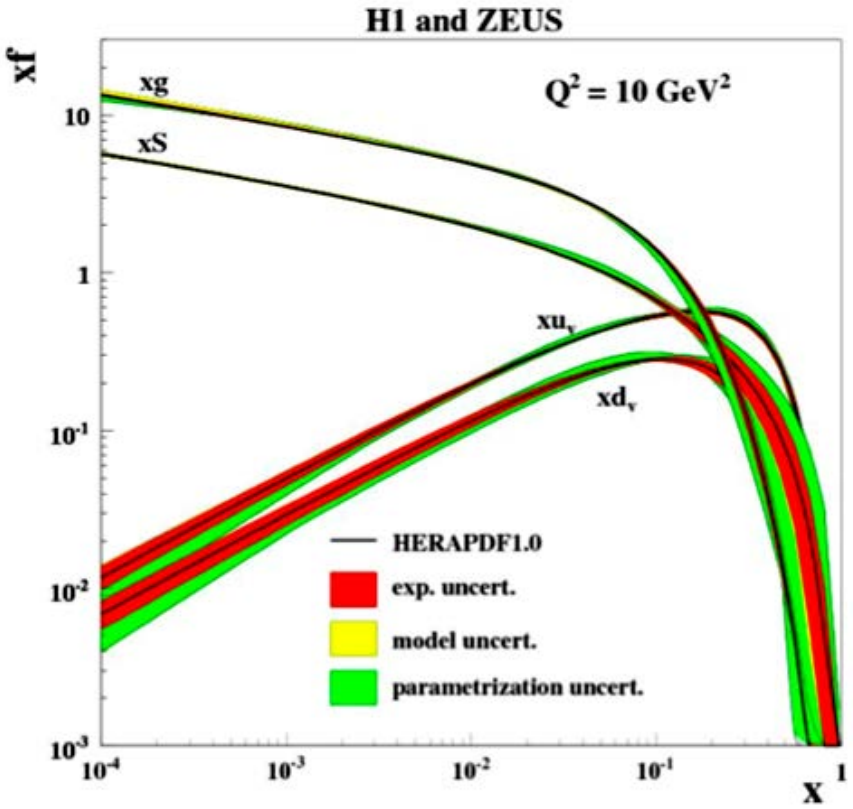
Longitudinal spin structure: Gluon and anti-quark polarization

Gluon polarization **without** RHIC data

Unpolarized input data

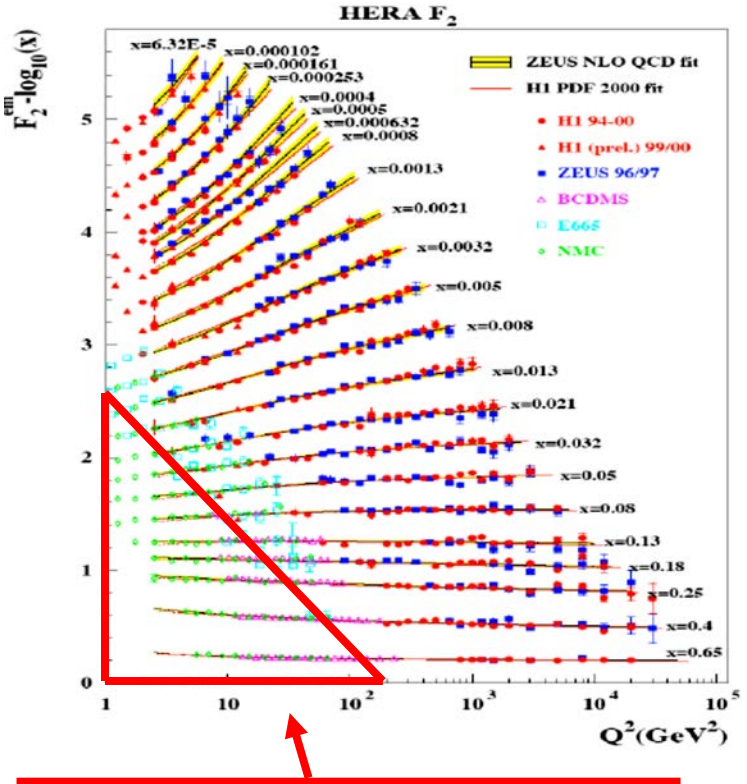


Unpolarized PDFs



Gluon polarization **without** RHIC data

$$S_z = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \langle L_z \rangle$$



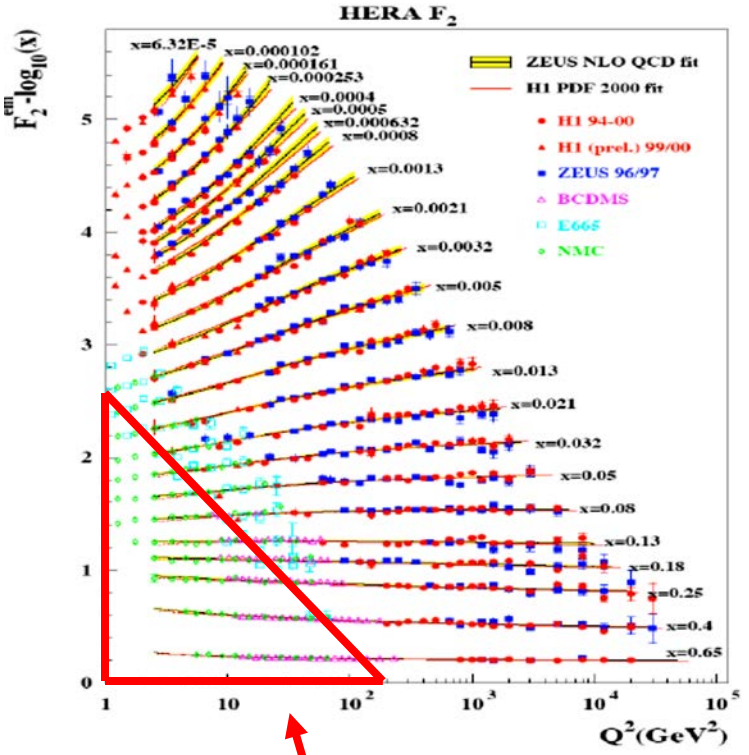
Kinematic region of ***polarized*** measurements

Gluon polarization **without** RHIC data

$$S_z = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \langle L_z \rangle$$

Polarized DIS: ~0.3

Poorly constrained by DIS



Kinematic region of ***polarized*** measurements

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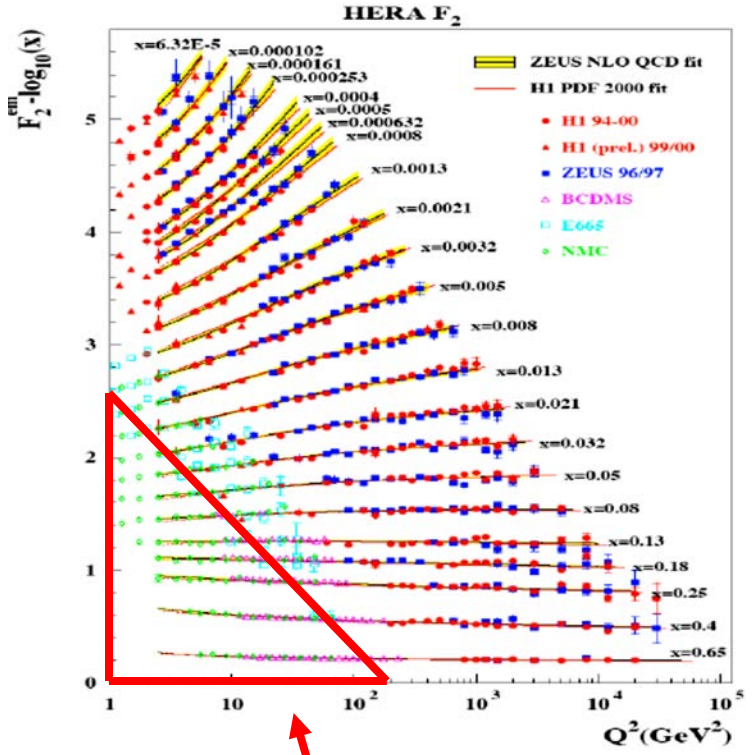
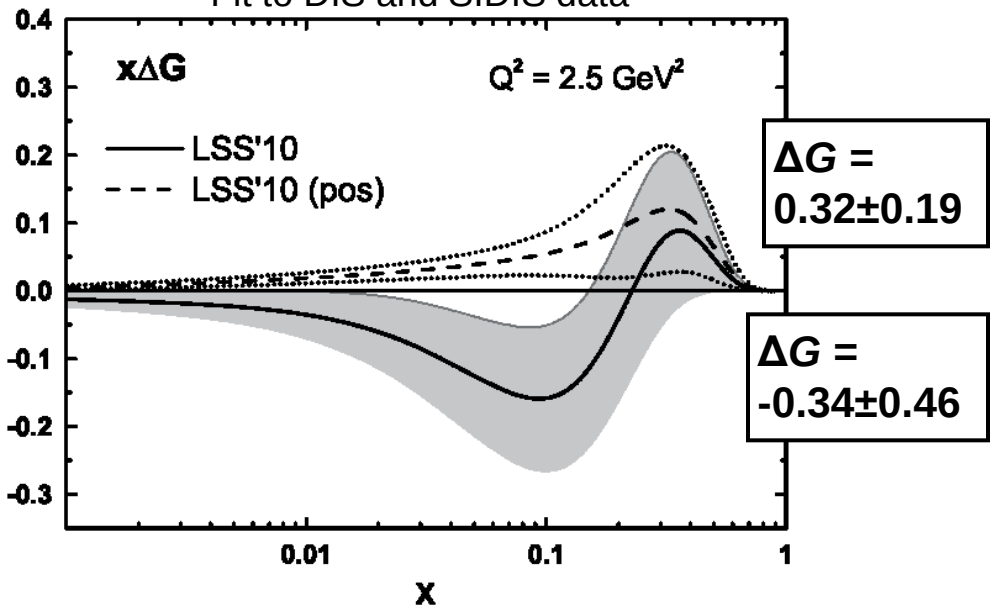


Kinematic region of ***polarized*** measurements

Polarized PDF

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



ΔG = 0.32±0.19

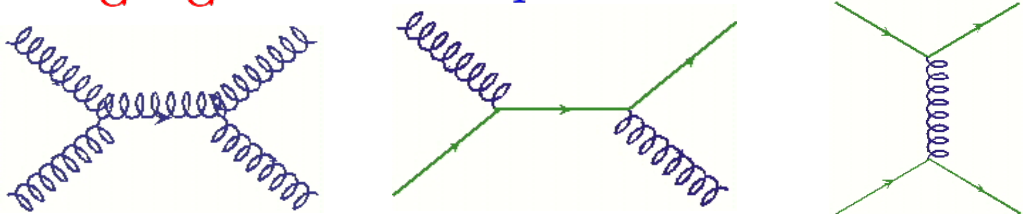
ΔG = -0.34±0.46

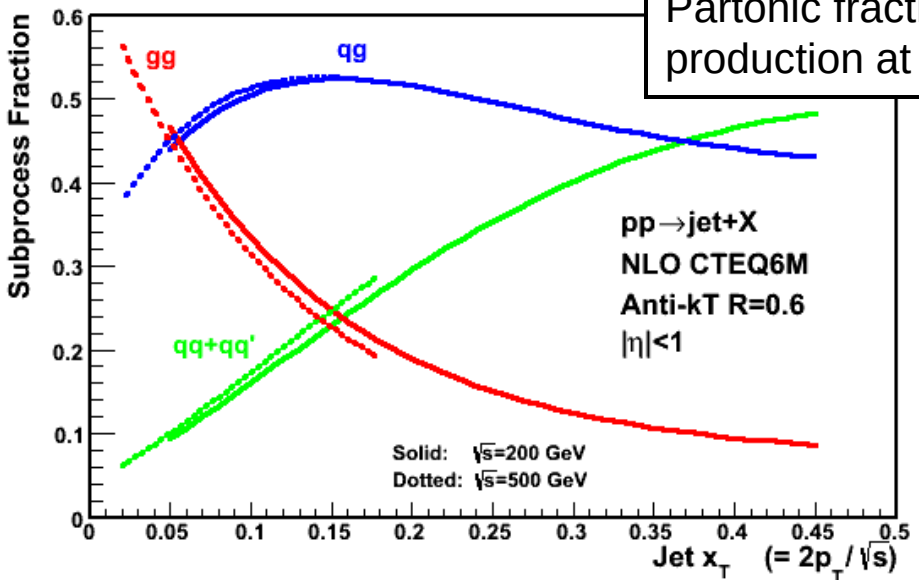
Exploring gluon polarization at RHIC

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

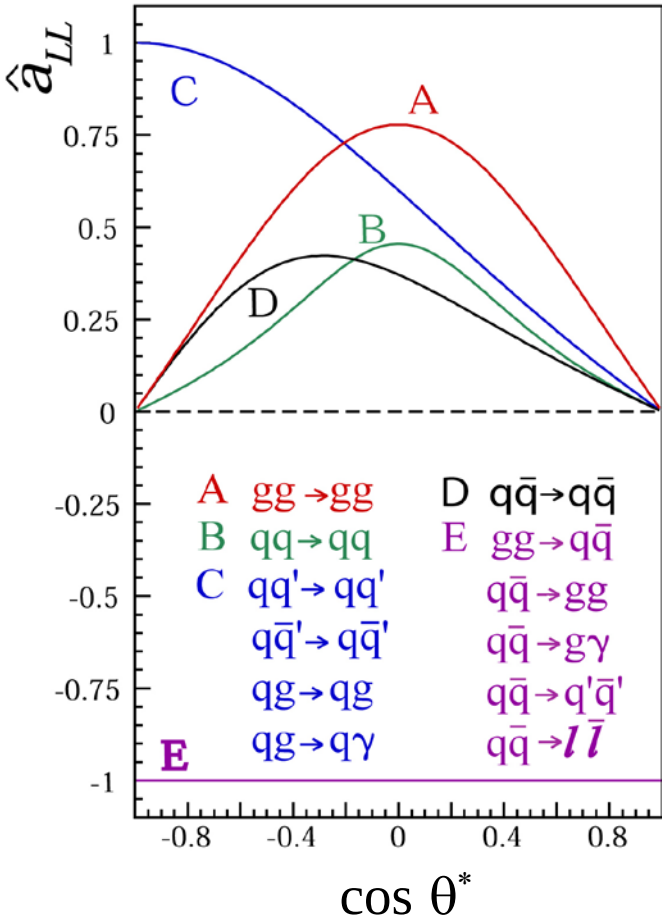
Δf: polarized parton distribution functions

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





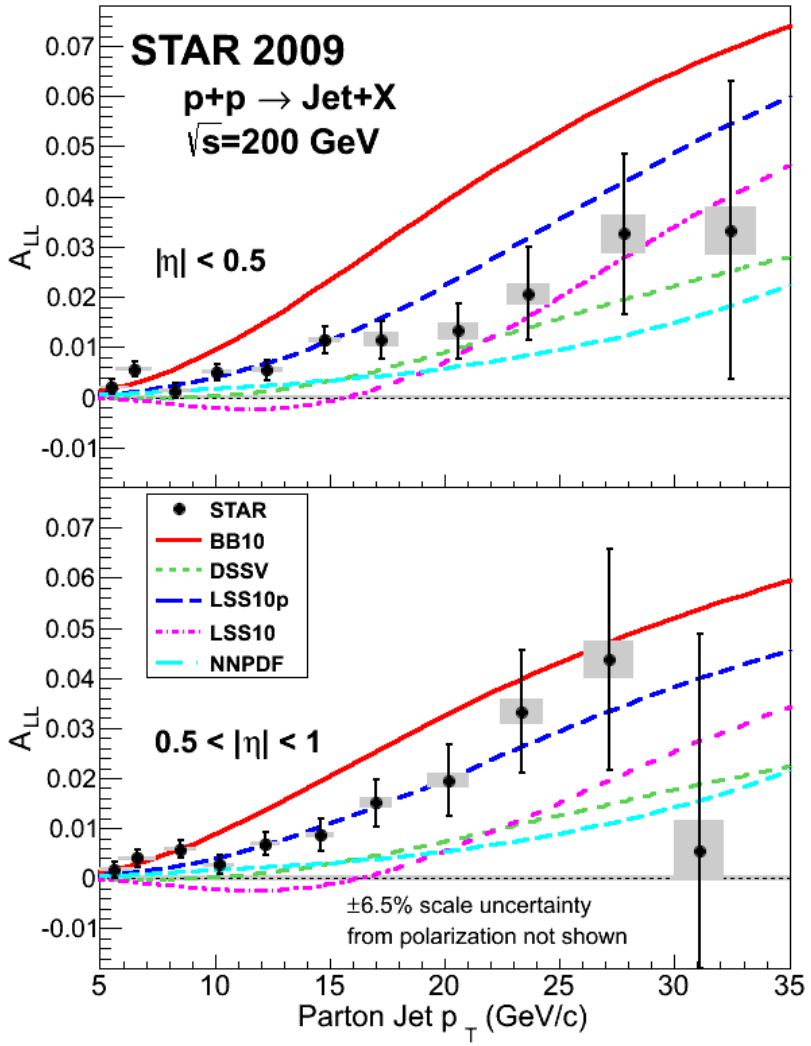
Partonic fractions in jet production at RHIC



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

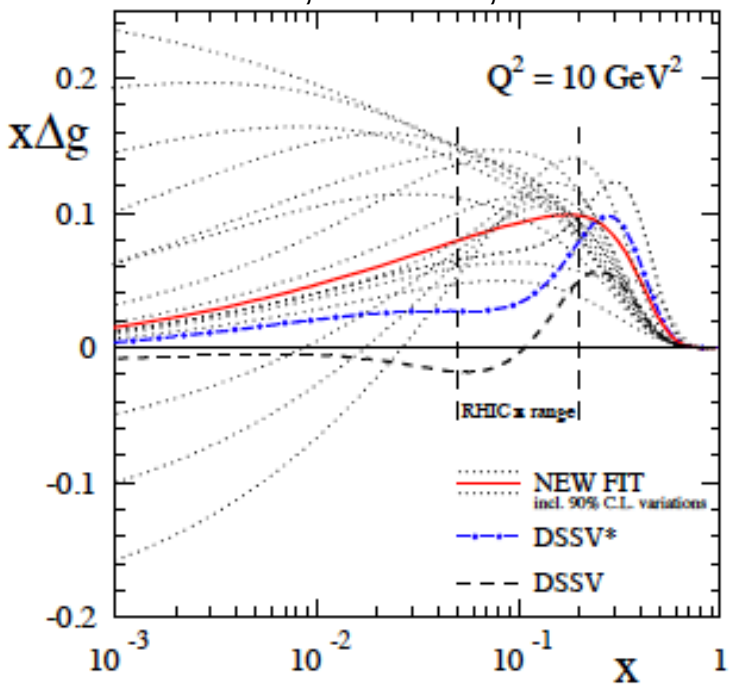
STAR PRL 115, 092002



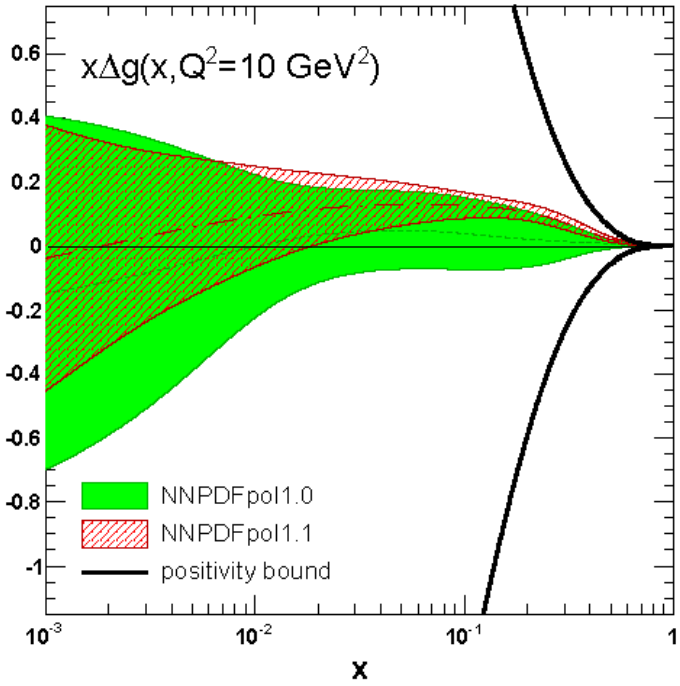
- STAR measured A_{LL} for inclusive jets at 200 GeV during the 2009 RHIC run
- Results draw a narrow road through the previous predictions
- **Far more precise** than previous measurements
- Systematically larger than expected by DSSV'08
- **Positive gluon polarization** in the sampled region $x > 0.05$

Gluon polarization **with** RHIC data

DSSV, PRL 113, 012001



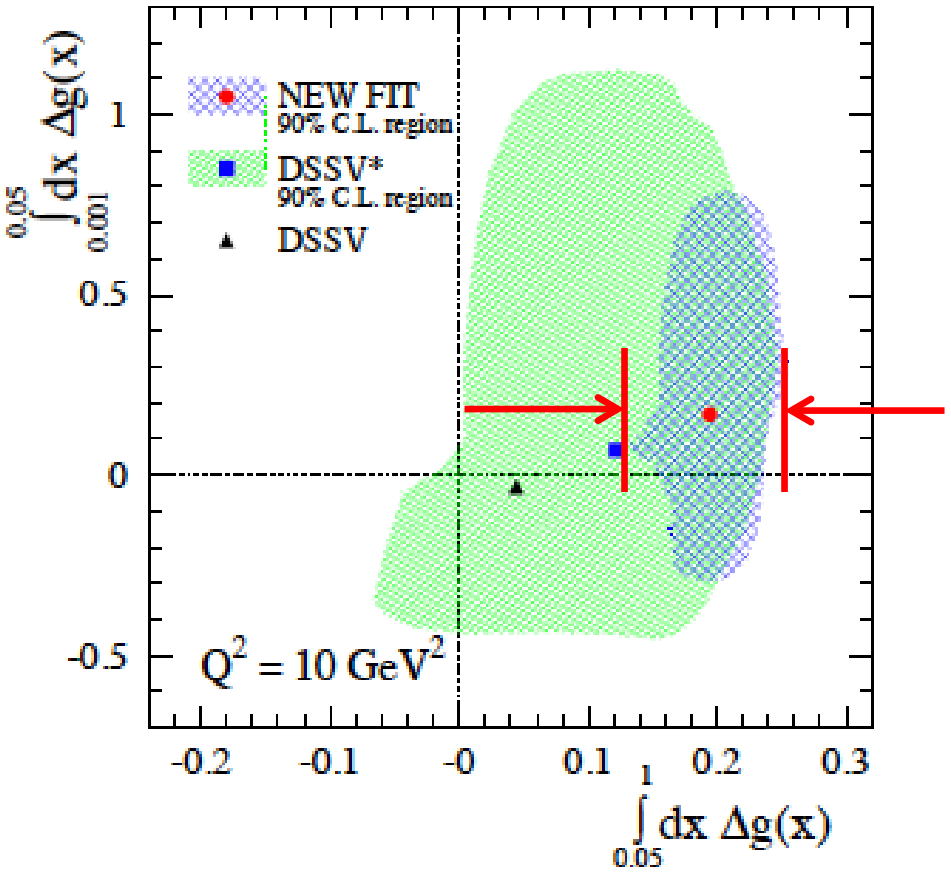
NNPDF, NPB 887, 276



- 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?

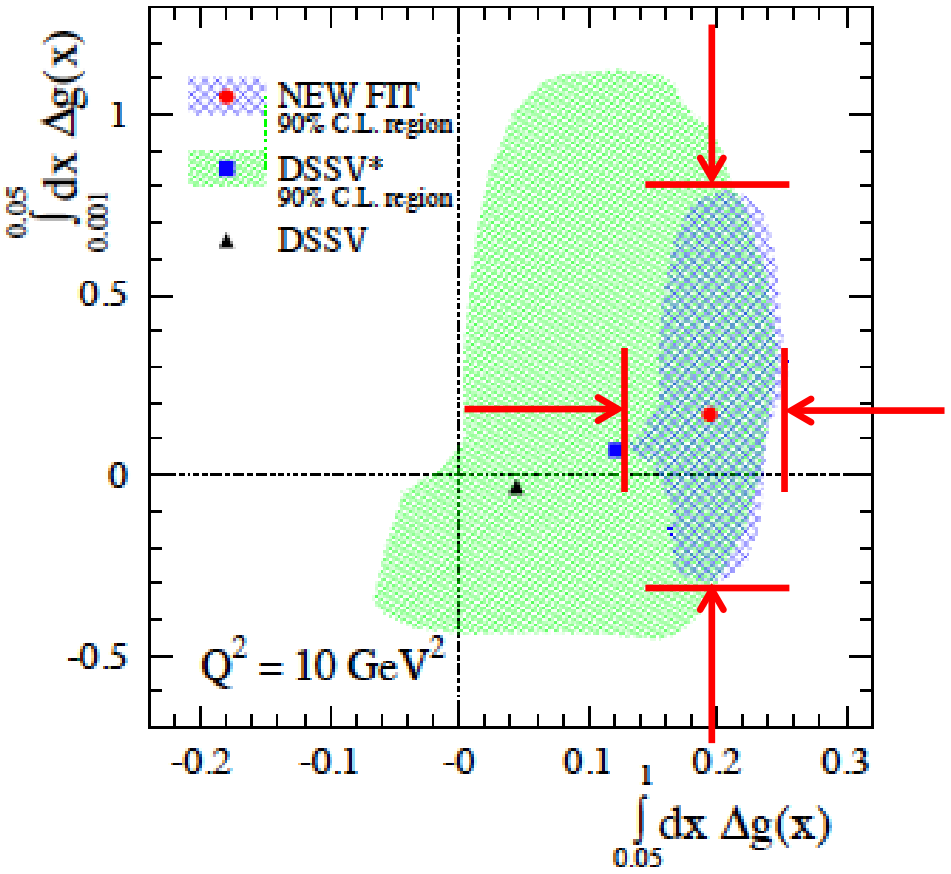
DSSV, PRL 113, 012001



- Need to **increase precision in the currently sampled region** to consolidate the observation of non-zero gluon polarization

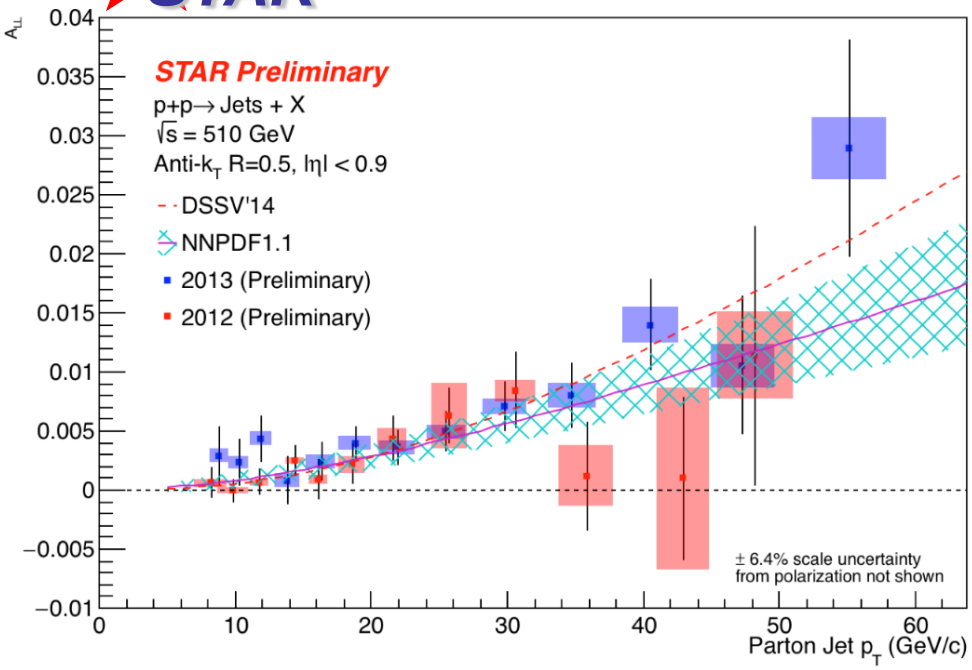
What's next?

DSSV, PRL 113, 012001



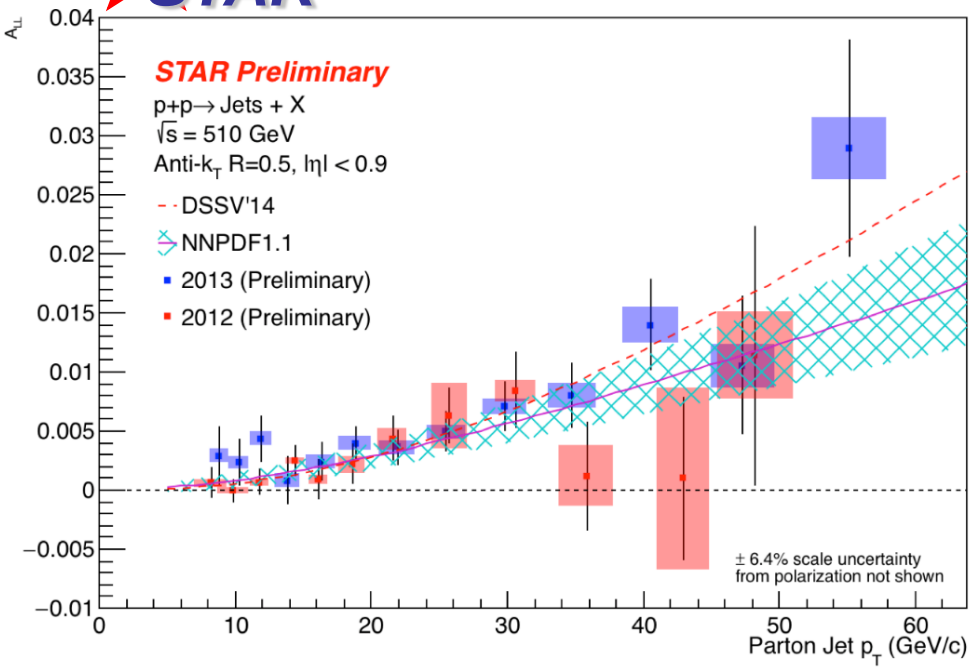
- Need to **increase precision in the currently sampled region** to consolidate the observation of non-zero gluon polarization
- Need to **extend sensitivity to lower x_g** where current extrapolations have very large uncertainties

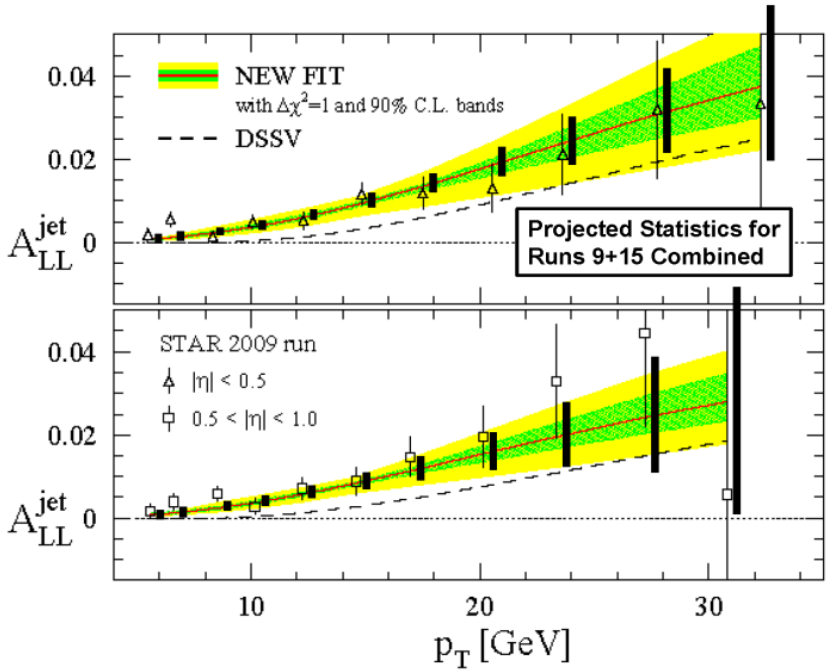
Next steps



- 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

Next steps





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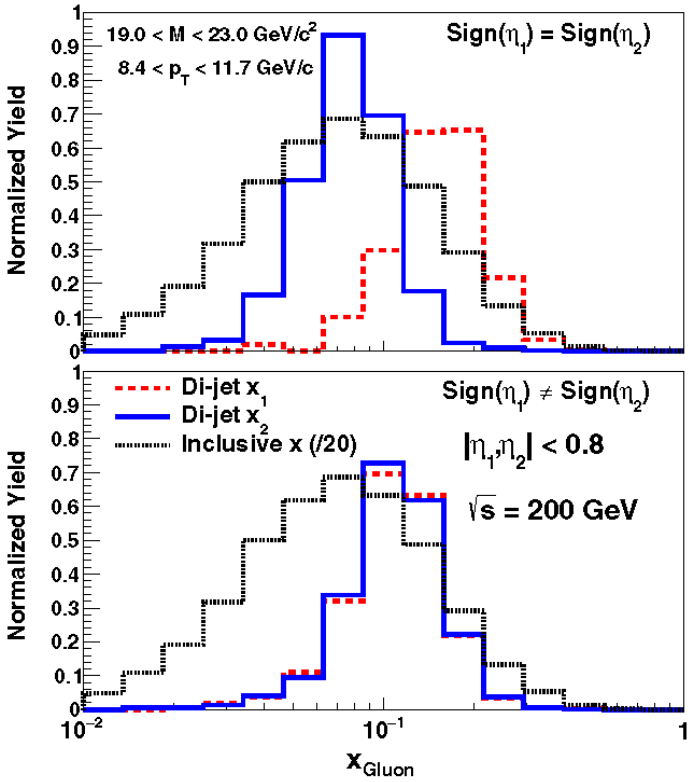
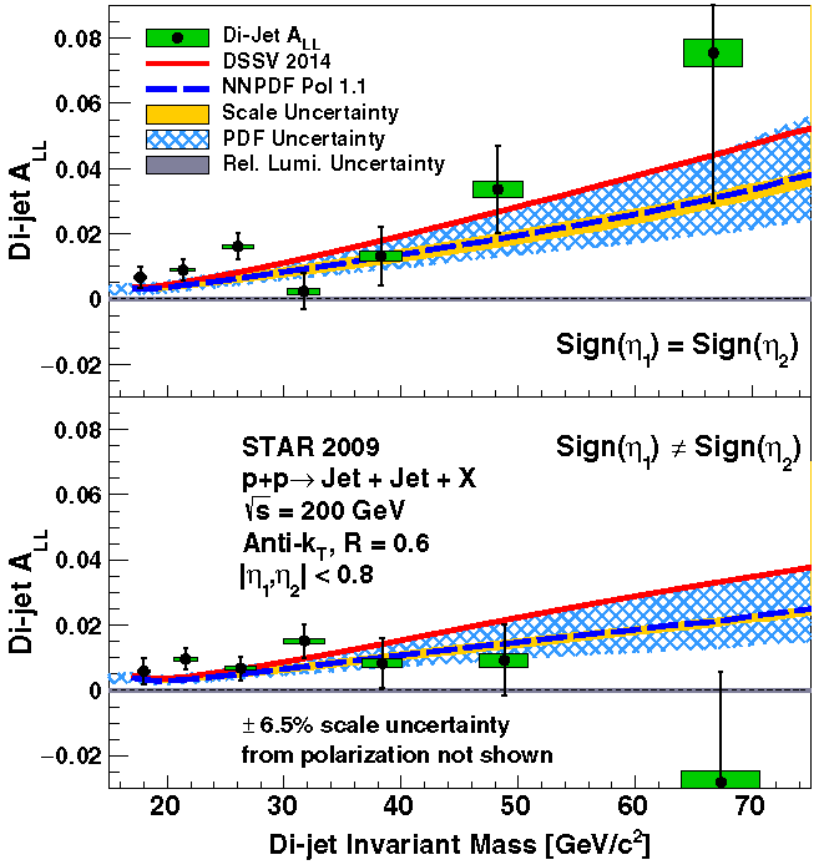
  - Higher center-of-mass energy probes **lower *x* partons**
- **A_{LL} at 510 GeV is well described by global fits** that previously gave a good description of the 2009 measurements at 200 GeV
- STAR took additional 200 GeV pp data during 2015
  - Will reduce uncertainties for A_{LL} at 200 GeV by a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

Further constraining the *x* dependence

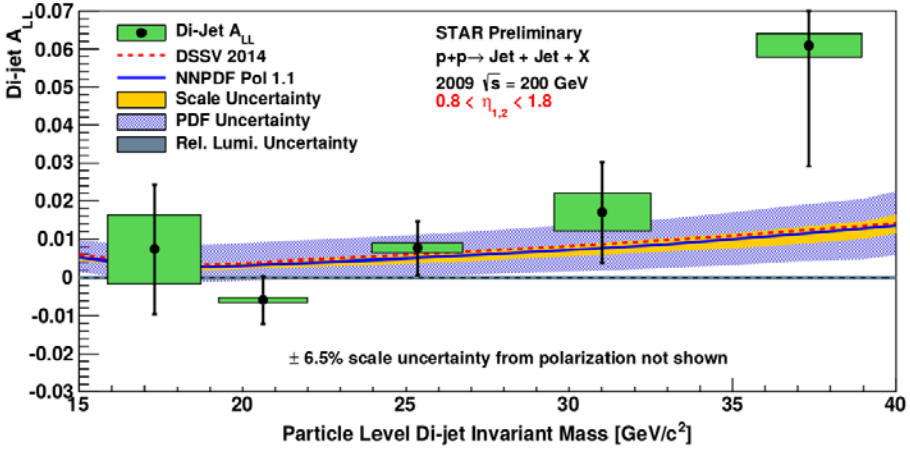
STAR PRD 95,071103(R)

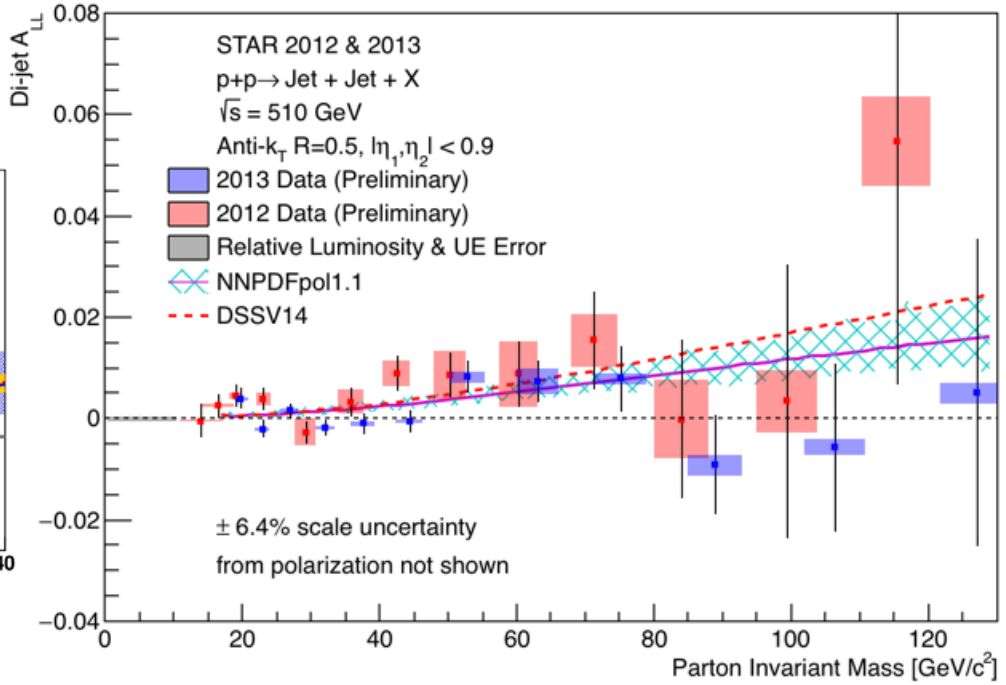




- Di-jet measurements sample a much narrower range of *x* values than inclusive jets
- Use to constrain the shape of $\Delta g(x)$
  - Minimize extrapolation errors outside the sampled region

Di-jets at forward rapidity and higher $\sqrt{s}$



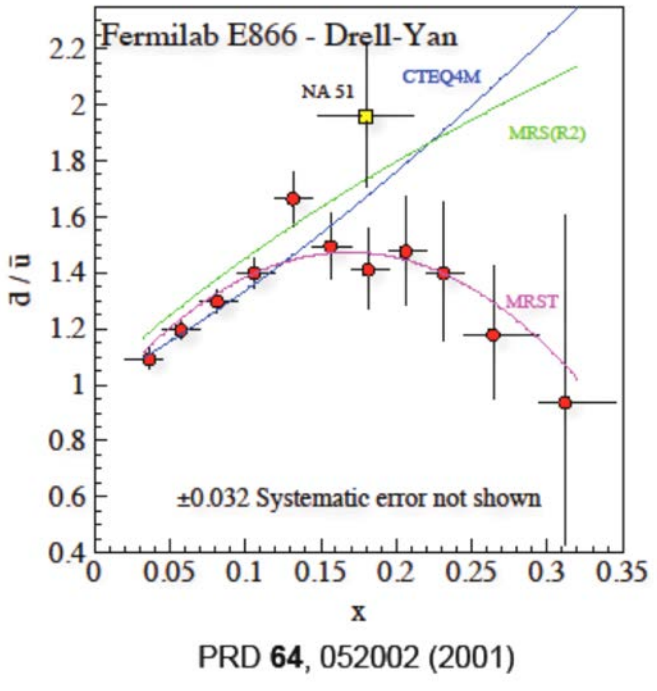


- Di-jet measurements at forward rapidity and higher $\sqrt{s}$ provide more precise mapping of $\Delta g(x)$ at lower x
  - Reaching x of ~0.02 now
  - Will push well below x ~ 0.01 with additional data that has already been recorded
  - Will reach $x \sim 10^{-3}$ in several years with a forward upgrade

Why is ΔΣ so small?

$$\Delta\Sigma = \int_0^1 (\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s})\, dx$$

- Polarized inclusive DIS data measure $\Delta u+\Delta\bar{u}$ and $\Delta d+\Delta\bar{d}$
- Polarized semi-inclusive DIS data provide flavor separation, but uncertainties remain large

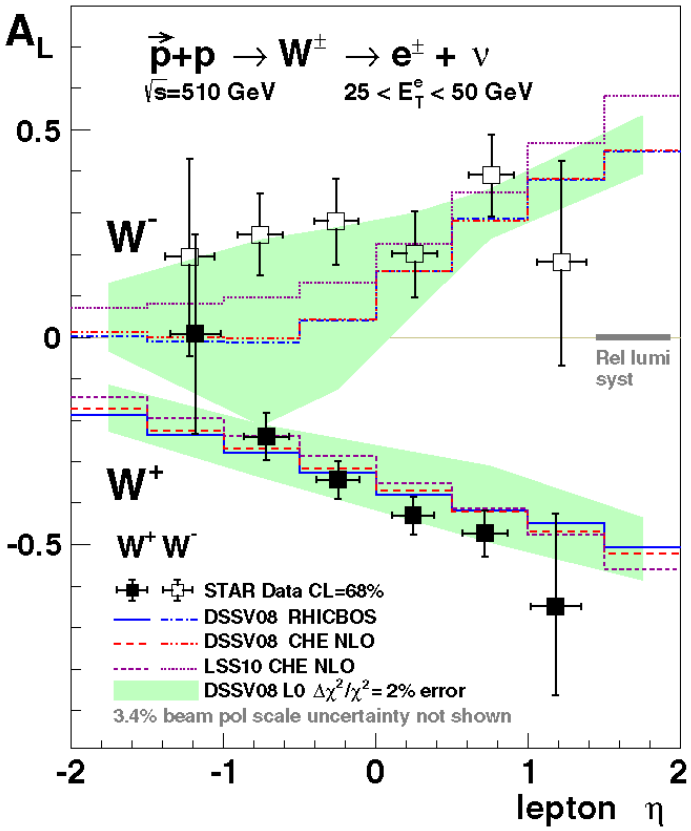


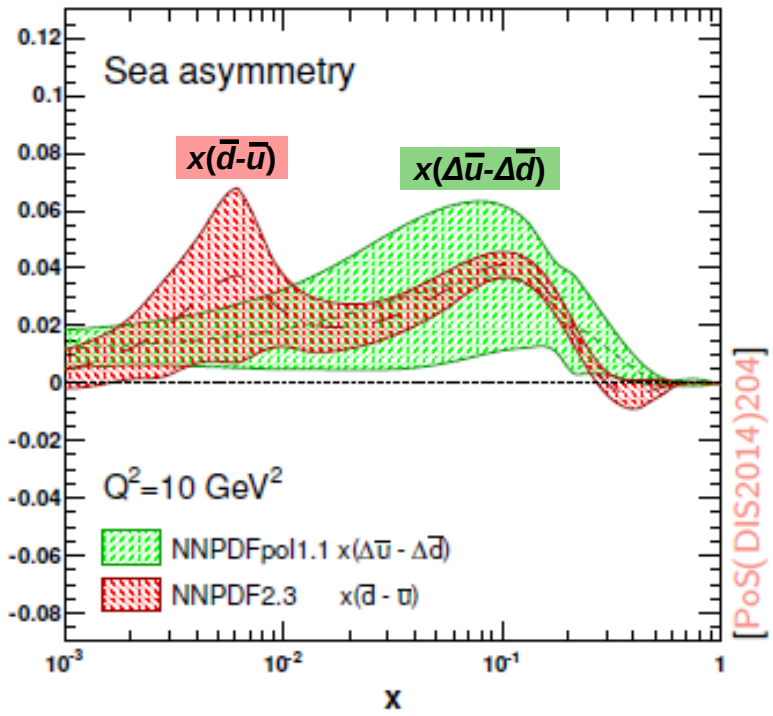
PRD **64**, 052002 (2001)

- FNAL E866 found surprising structure in the unpolarized anti-quark distributions
- **Might the polarized anti-quark distributions also contain surprises?**
- **Can separate polarized quark and anti-quark flavors with W production**
  - Only left-handed quarks and right-handed anti-quarks participate
  - Complementary to semi-inclusive DIS
  - No fragmentation function uncertainties
  - Extremely clean theoretically

W A_L and anti-quark polarization

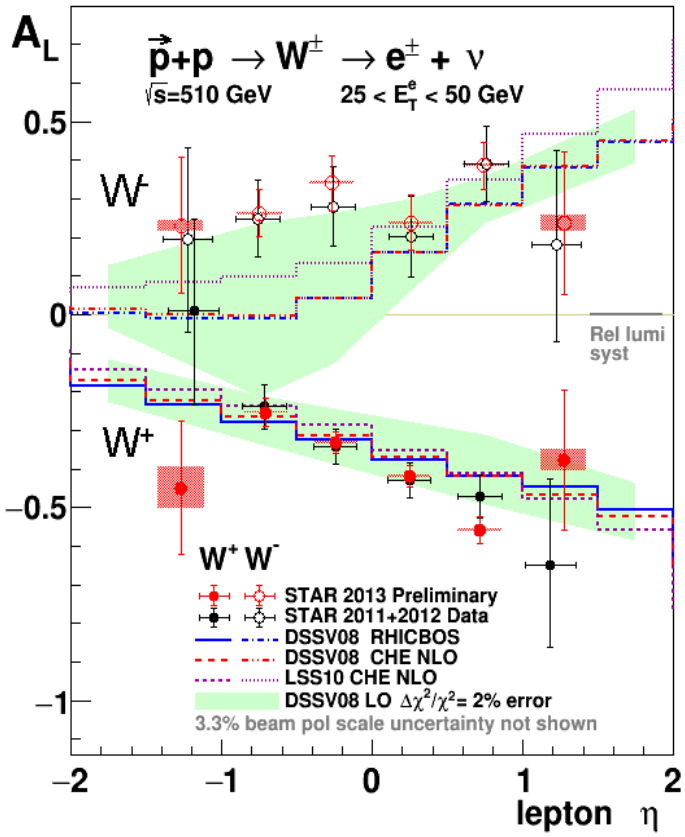
STAR PRL 113, 072301

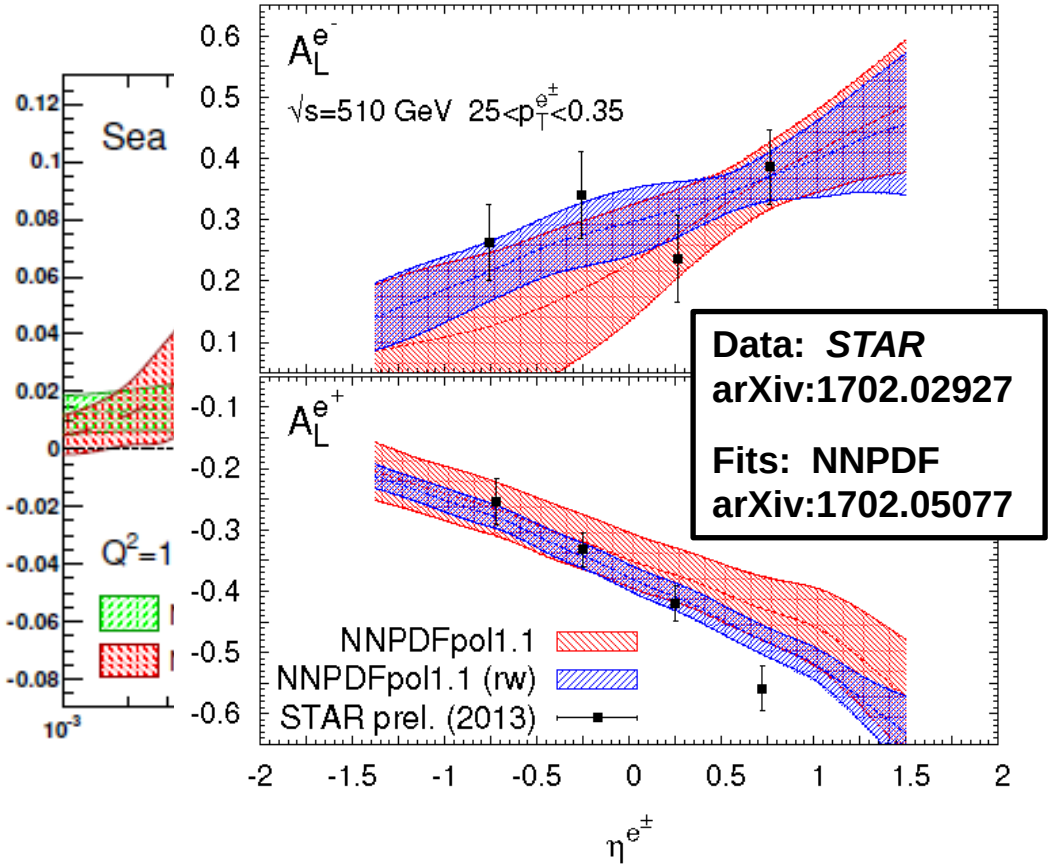




- $W^{+/-}$ asymmetries from 2012 data hint at $\Delta\bar{u} > \Delta\bar{d}$
  - This is opposite from the unpolarized distributions

W A_L and anti-quark polarization



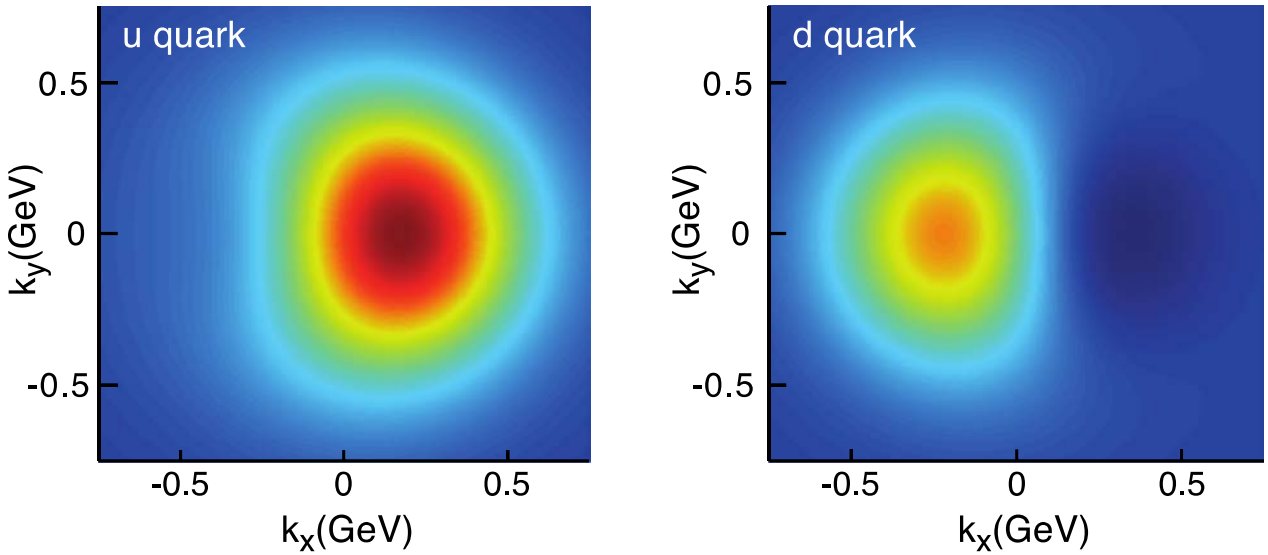


- $W^{+/-}$ asymmetries from 2012 data hint at $\Delta\bar{u} > \Delta\bar{d}$
  - This is opposite from the unpolarized distributions
- Preliminary results from 2013 with much smaller uncertainties **strengthen the hint**

Transverse spin structure:
TMDs and visualizing color interactions

Why TMDs?

$x\, f_1(x, k_T, S_T)$



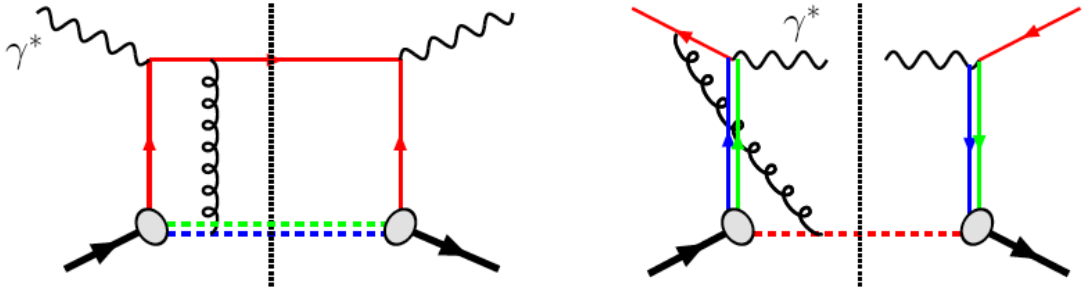
- Image the transverse and longitudinal (2+1d) structure of the nucleon and nuclei
  - **Tomography of the nucleon!**
- Access to transverse momenta at non-perturbative scales
  - Probe at the confinement scale
- Exhibit correlations arising from spin-orbit effects

Color interactions in QCD

Controlled non-universality of the Sivers function

QCD:

DIS	Drell-Yan, W or Z
Final-state interaction	Initial-state interaction
Opposite colors attract	Like colors repel



$$\text{Sivers}_{DIS} = -\,\text{Sivers}_{\text{Drell-Yan}} \text{ or } \text{Sivers}_{W} \text{ or } \text{Sivers}_{Z}$$

A_N for direct photon has related sign change in Twist-3

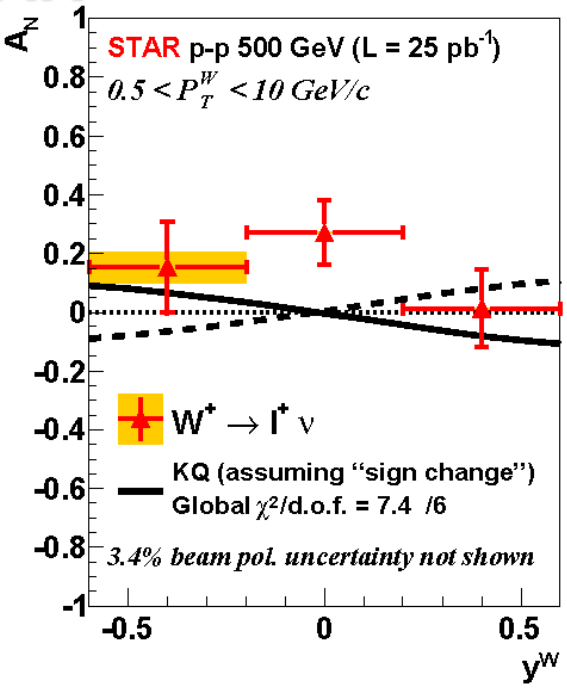
Critical test of factorization

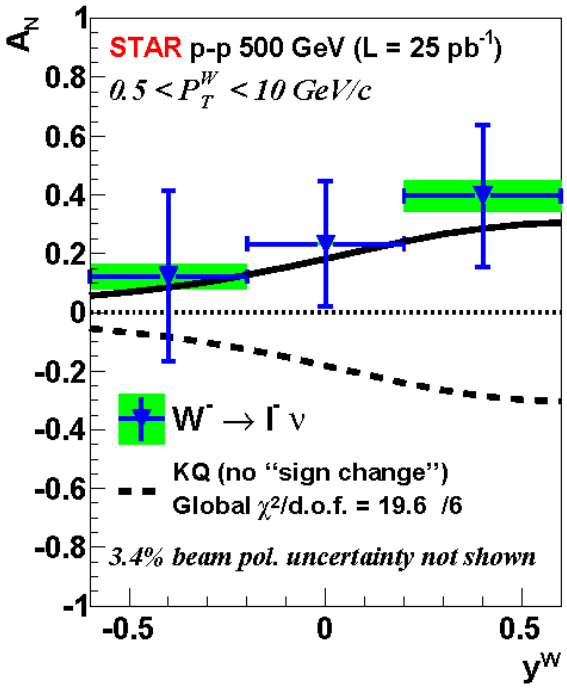
Opportunity to visualize the repulsive interaction between like color charges

Can explore all of these observables in 510 GeV pp collisions at RHIC

A_N for W production

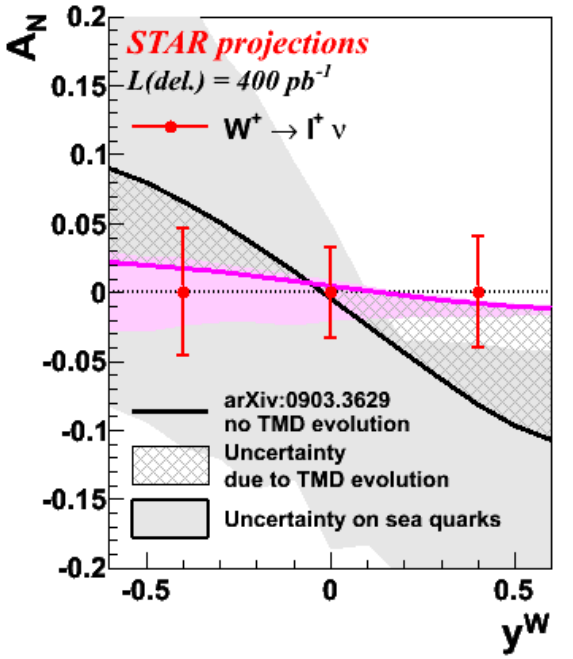
STAR PRL 116, 132301



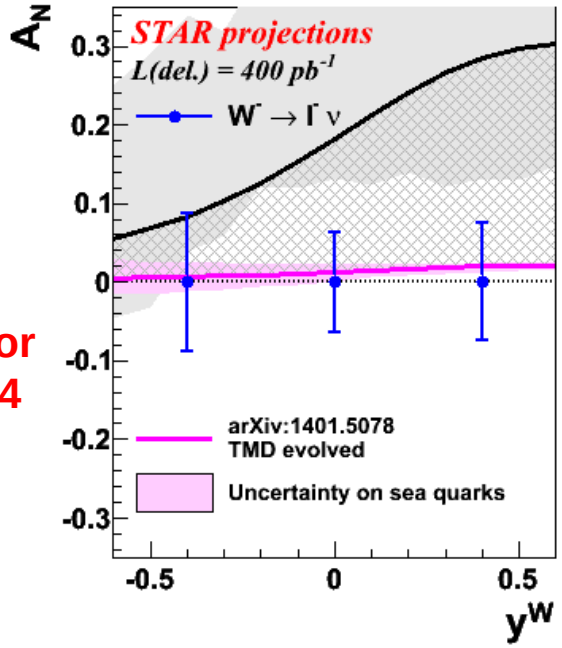


- STAR performed an exploratory measurement of A_N for W production with a small data set recorded in 2011
  - W kinematics fully reconstructed
- Favors **sign change** if evolution effects are modest
  - TMD evolution is non-perturbative at low $k_\perp$ - no absolute theory predictions

Definitive measurement

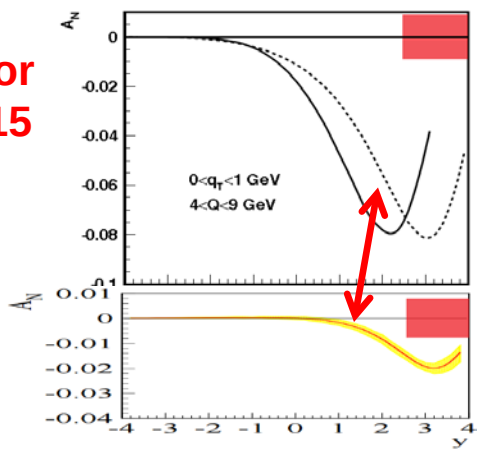


Factor of ~4



Factor of ~15

Drell-Yan

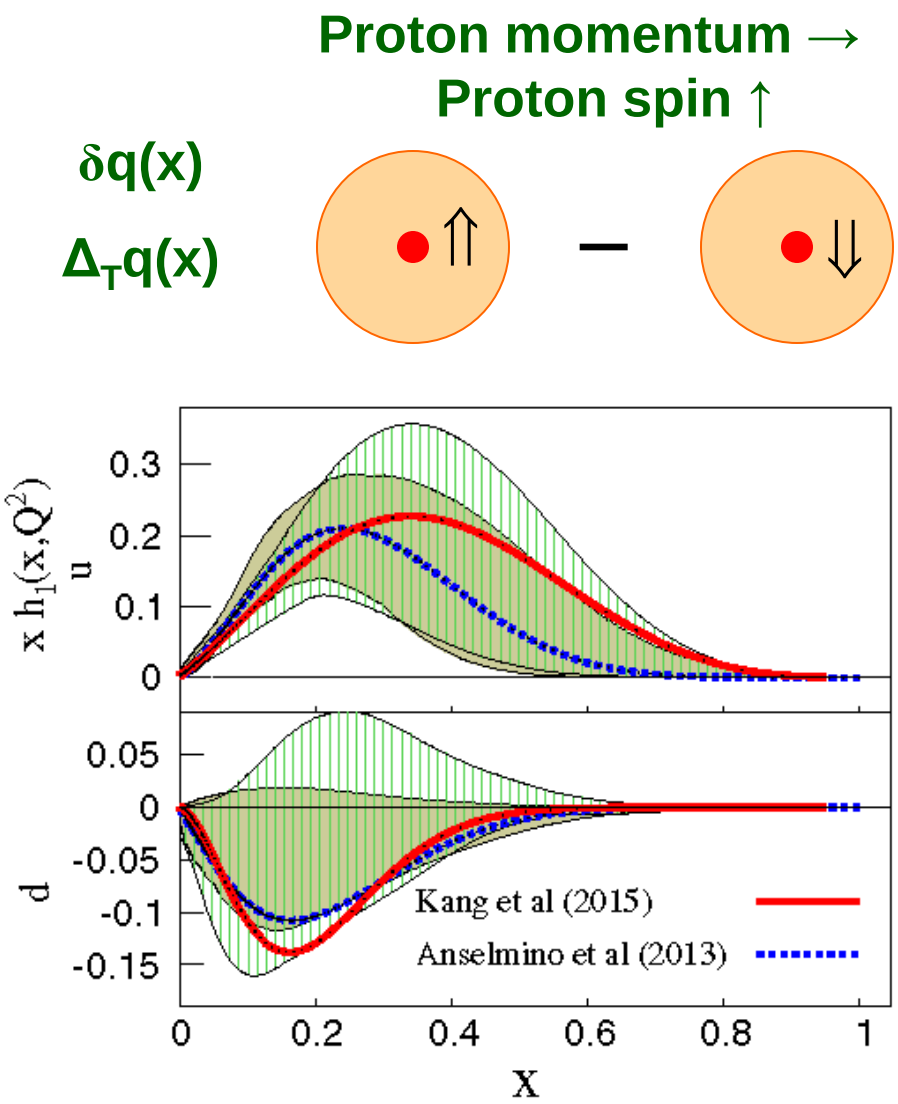


Factor of ~4

- See the sign change if evolution effects are less than factor of 5
- Probe anti-quark Sivers function for the first time
- Directly measure the evolution effects
  - Need new data to constrain non-perturbative contribution
  - Access similar observables at comparable *x* but very different Q^2
    - W and Z A_N at 510 GeV
    - Drell-Yan at 510 GeV

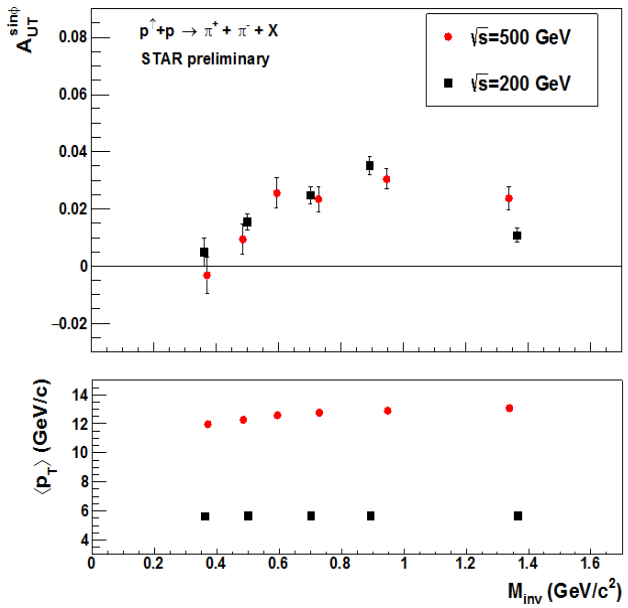
} **Recently completed 2017 RHIC run**

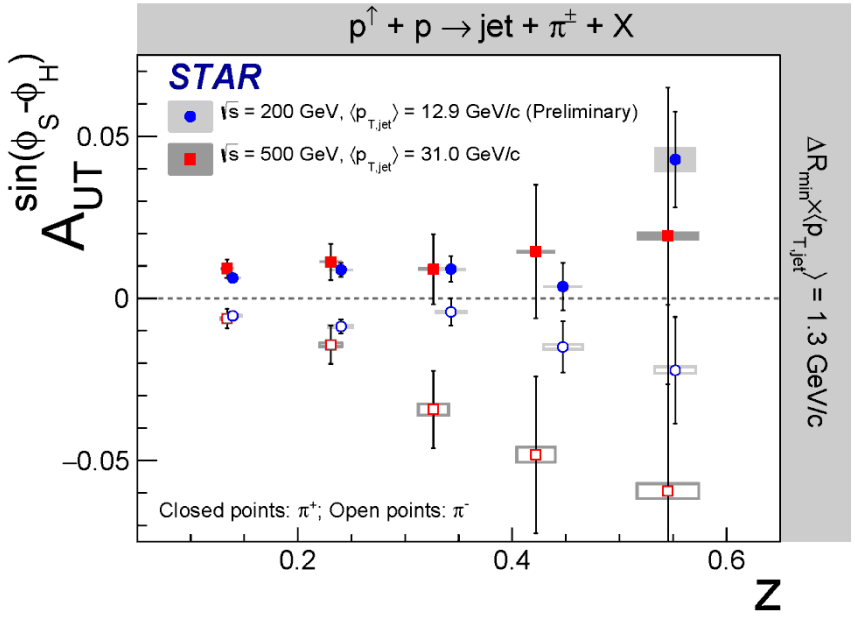
Transversity



- Quark polarization along spin of a transversely polarized proton
  - Third collinear, leading twist distribution
  - Chiral odd
- Before ***STAR***, only observed in SIDIS combined with e^+e^-
- Much less data than for helicity
- Several recent global analyses including:
  - Collins effect input:
    - PRD 93, 014009
    - PRD 92, 114023
  - IFF input:
    - PRD 94, 034012
  - All show large uncertainties

First transversity signals in hadronic collisions

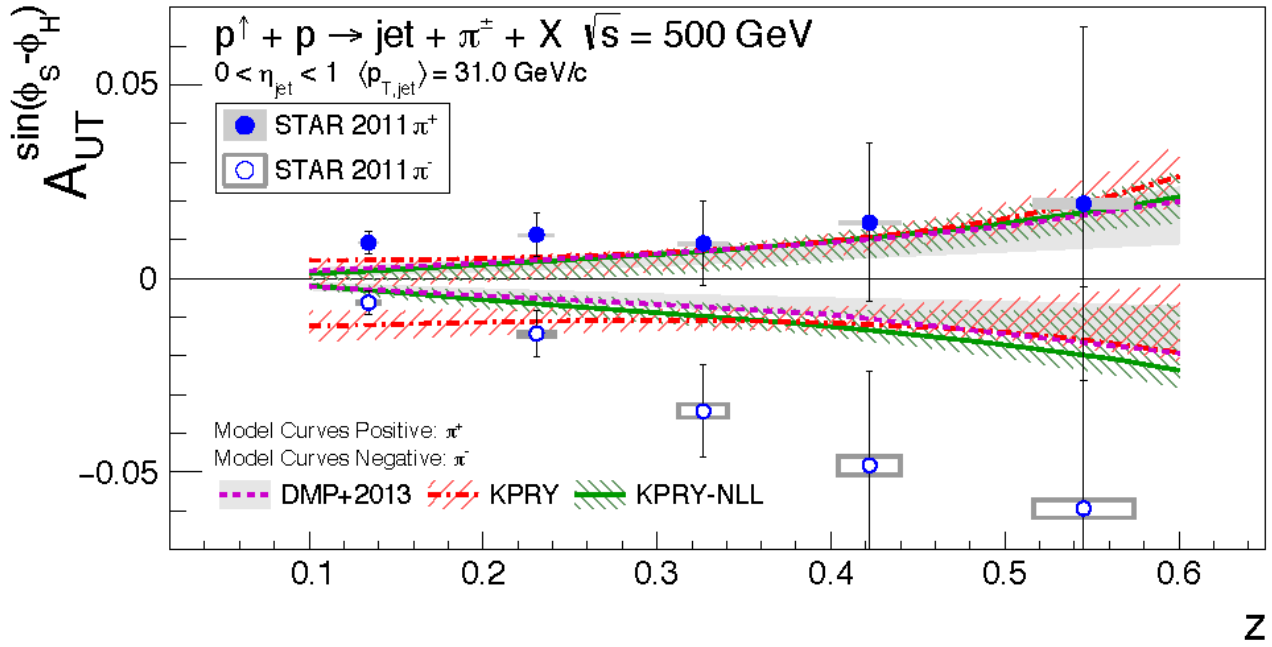




- Significant measurements of transversity convoluted with:
  - Di-hadron interference fragmentation function (IFF)
    - ***STAR*** data now in preliminary global analysis (Radici, DIS 2017)
  - Collins fragmentation function
- Both have similar magnitudes in 200 and 500 GeV pp collisions
- Observations 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

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

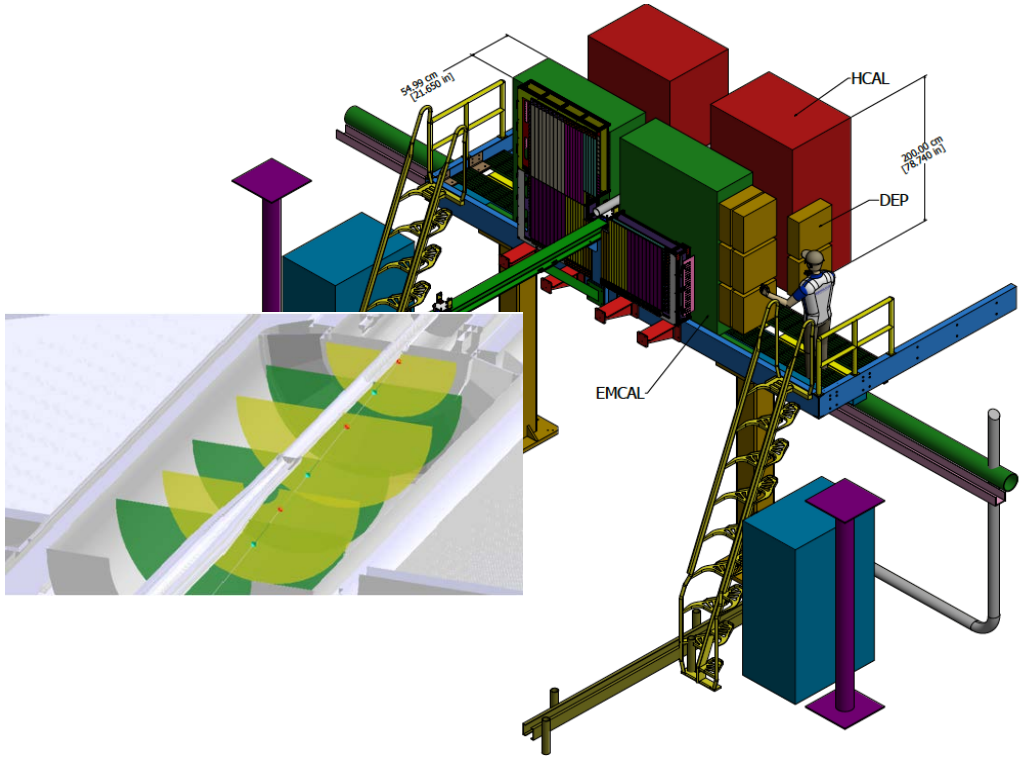
STAR arXiv:1708.07080



DMP: arXiv:1707.00914
KPRY: arXiv:1707.00913

- First Collins effect measurements in pp collisions are reasonably described by two recent calculations that convolute the transversity distribution from SIDIS with the Collins FF from e^+e^- collisions
  - Tests the predicted **universality of the Collins FF**
  - TMD evolution effects appear to be small

Planned forward upgrade for the 2020's



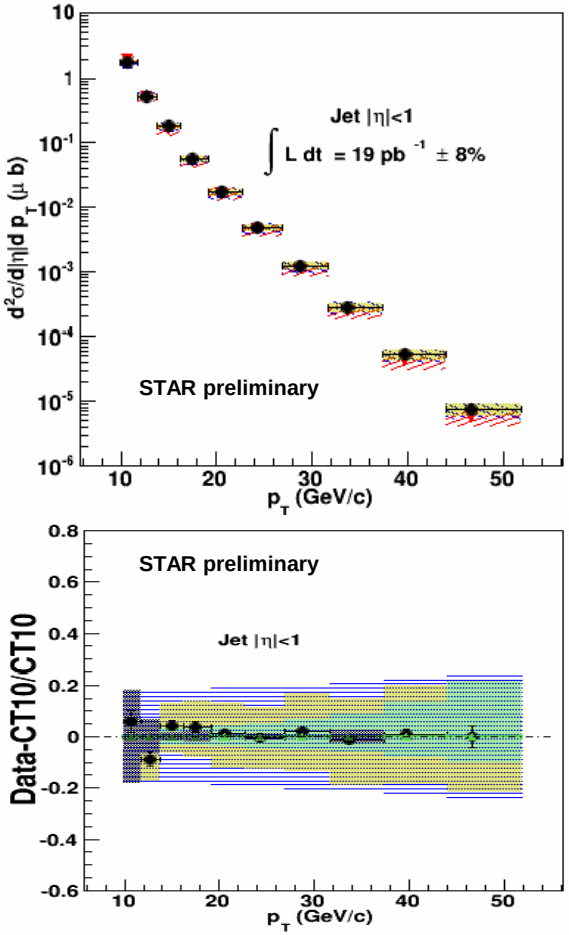
- Forward di-jets will extend gluon polarization to x <~ 10^{-3}
- Transverse spin phenomena:
  - Precision TMDs through jets at forward rapidity
  - Precision A_N(Drell-Yan) to complete the Sivers measurements
- Also an extensive suite of measurements in p+A collisions

Conclusions

- **The *STAR* Spin program has already:**
  - Found evidence for positive gluon polarization in the region $x > 0.05$
  - Found indications of an asymmetry in the polarized anti-quark sea
  - Made the first observation of transversity in pp collisions
- **During the next several years, *STAR* will**:
  - Measure gluon polarization down to $x \sim 10^{-3}$
  - Place strong constraints on anti-quark polarizations
  - Provide a first look at gluon orbital angular momentum
  - Observe color interactions in QCD
  - Test TMD evolution with a very broad Q^2 lever arm
  - …
- **RHIC Spin program is an essential bridge between the physics of RHIC and the physics of the future Electron Ion Collider**

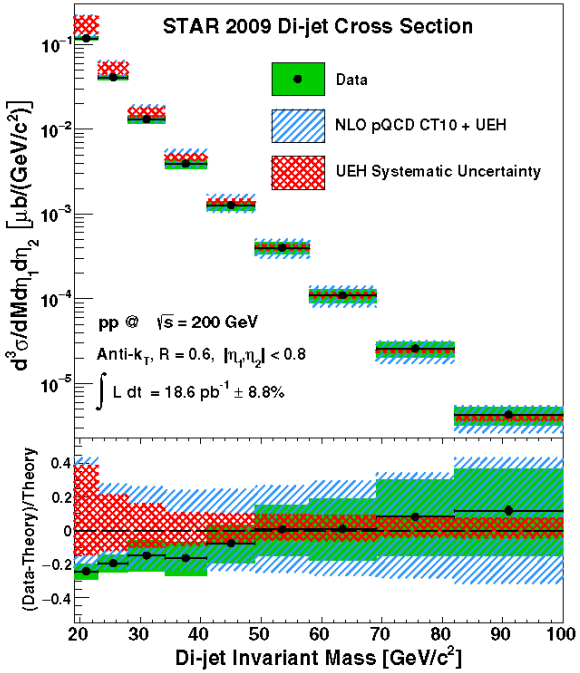
STAR as a jet and di-jet detector

Inclusive jets @ 200 GeV

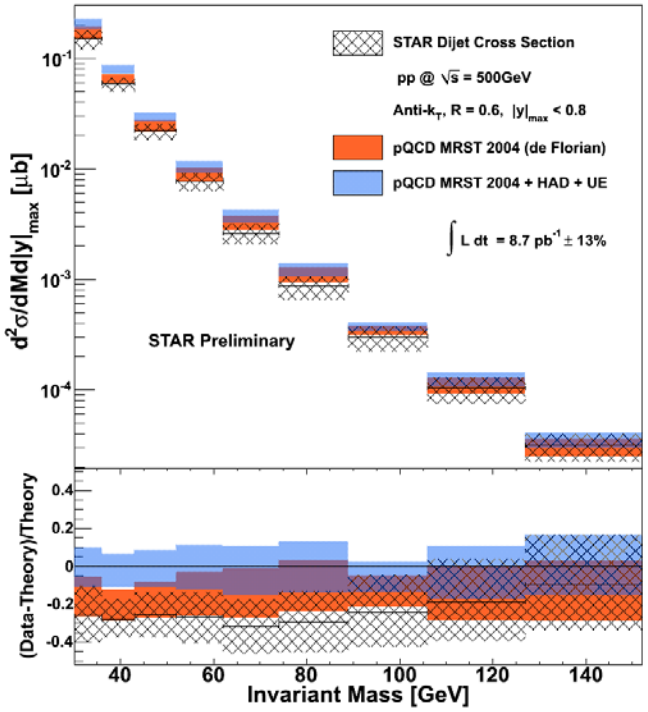


Di-jets @ 200 GeV

PRD 95, 071103(R)



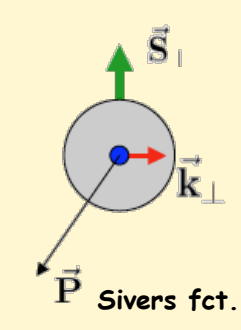
Di-jets @ 500 GeV

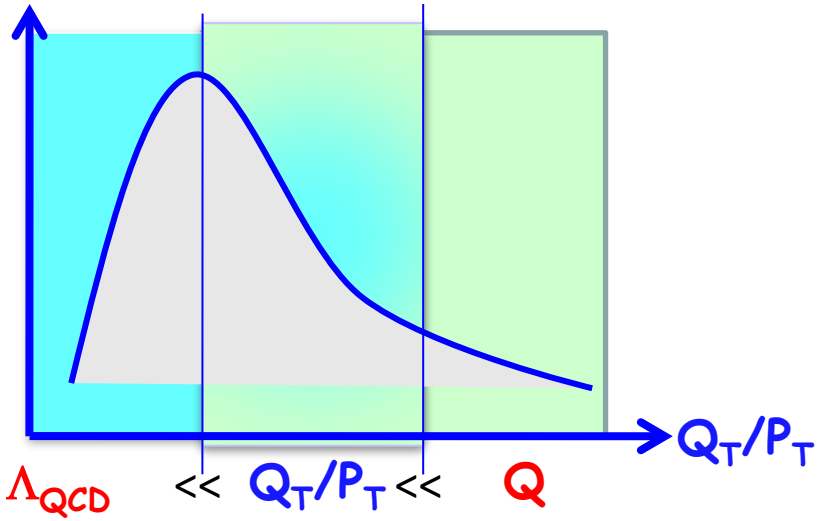


- Large and uniform acceptance makes ***STAR*** an excellent jet detector
- Good agreement with NLO predictions for both inclusive jet and di-jet cross sections

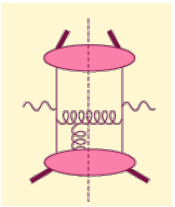
Initial state: TMDs and Twist-3

TMD





Twist-3



Efremov, Teryaev;
Qiu, Sterman
or
Twist-3 FF

Requires 2 scales:
- **Hard scale Q^2**
- **Soft scale p_T**

SIDIS, Drell-Yan, W/Z, …

Access the full transverse momentum dynamics k_T

Single hard scale: p_T

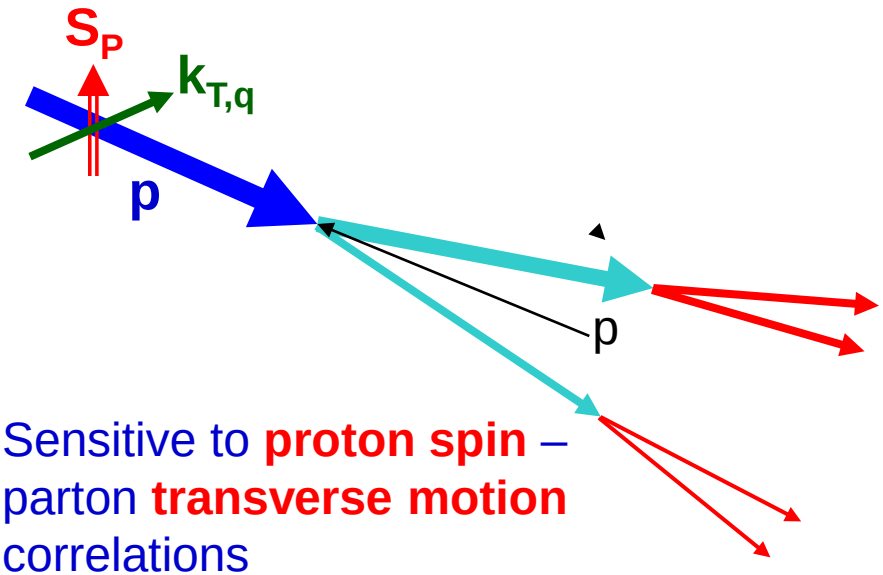
Appropriate for inclusive $A_N(\pi^0, \gamma, \text{jet})$

Access the average transverse momentum $\langle k_T \rangle$

$$-\int d^2k_\perp \frac{{k_\perp}^2}{M} f_{1T}^{\perp q}\left(x, {k_\perp}^2\right)\Big|_{SIDIS} = T_{q,F}(x,x)$$

Separating initial- from final-state effects

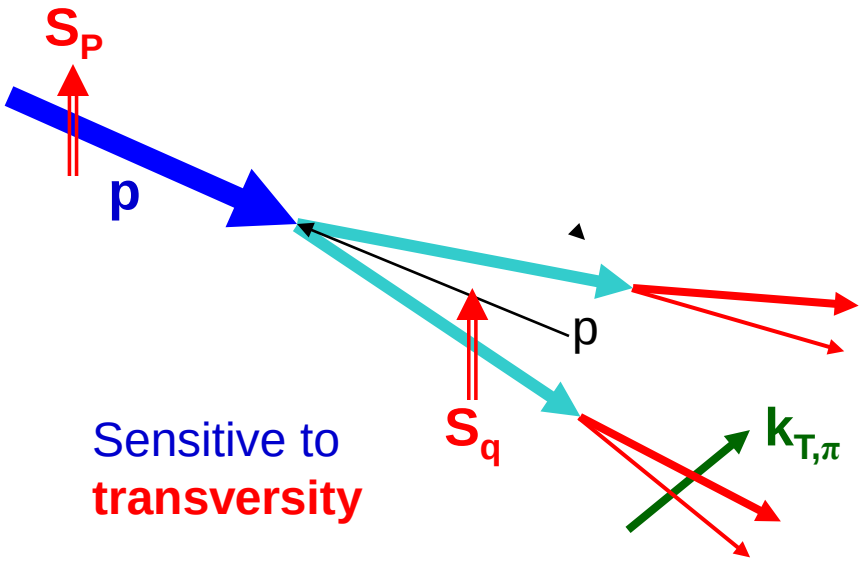
Sivers or twist-3 mechanisms:



Sensitive to **proton spin** – parton **transverse motion** correlations

- Signatures:
  - A_N for jets or direct photons
  - A_N for $W^{+/-}$, Z^0, Drell-Yan
  - A_N for heavy flavor (gluon)
- Sivers NOT universal
  - Sign change from SIDIS to W, Z, and Drell-Yan

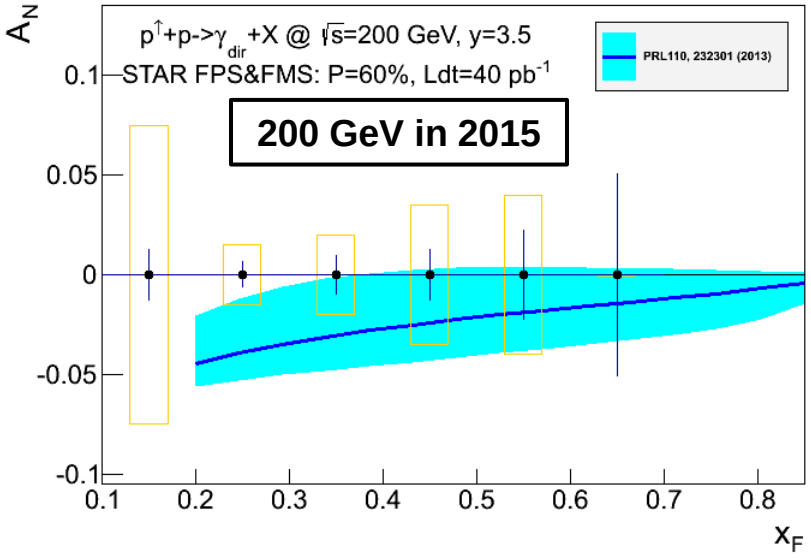
Collins or novel FF mechanisms:

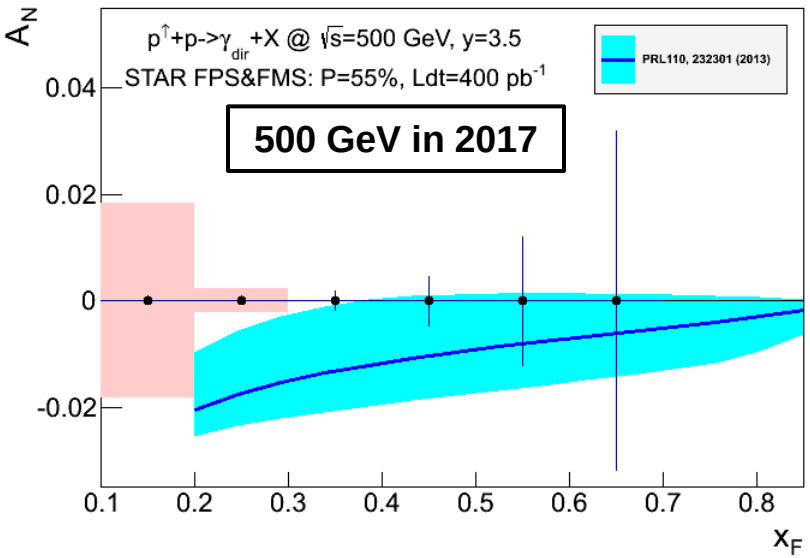


Sensitive to **transversity**

- Signatures:
  - Collins effect
  - Interference fragmentation functions (IFF)
  - A_N for pions → novel FF
- Collins predicted to be universal

A_N for direct photon



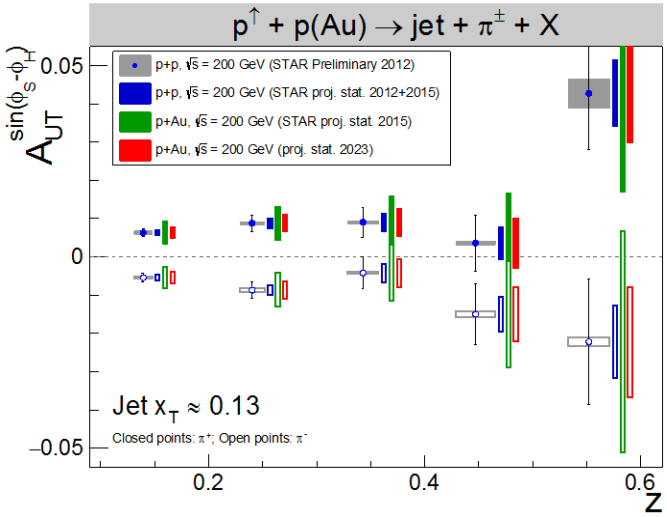


- Sensitive to the sign change in the Twist-3 formalism
- Collinear objects, but more complicated evolution than DGLAP
  - Not sensitive to TMD evolution
- Provides an indirect constraint on the Sivers function via their integral relationship

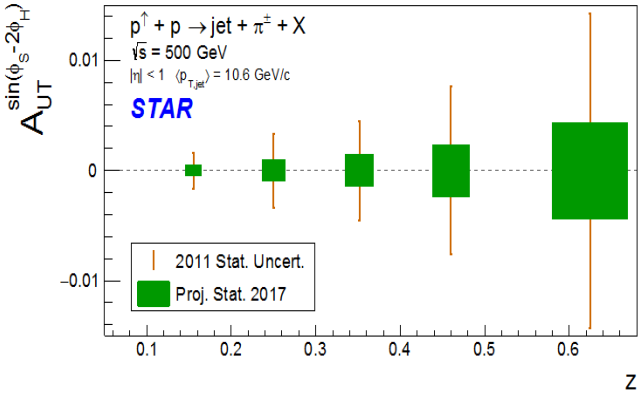
Not a replacement for A_N(W, Z, DY), but an
important complementary piece of the puzzle

Many azimuthal modulations possible

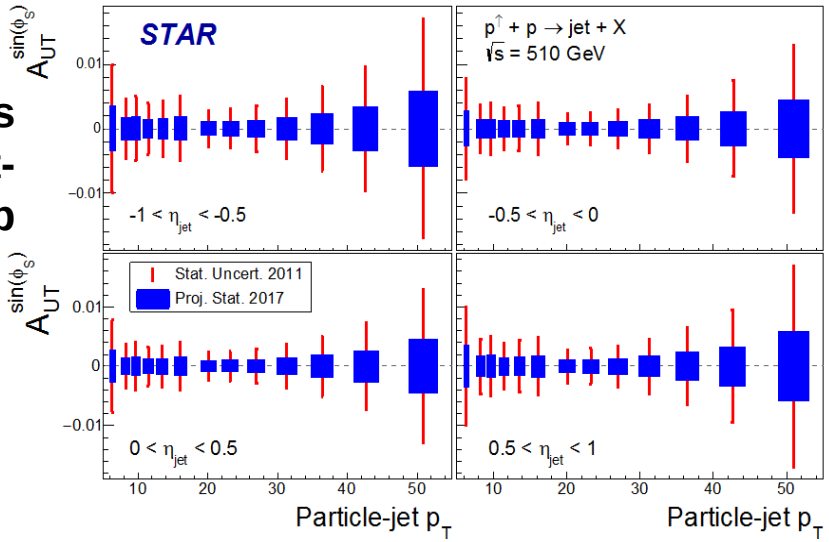
Transversity x Collins



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

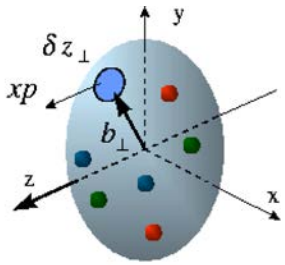


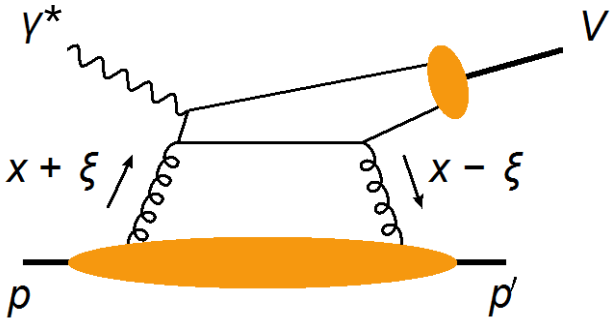
Gluon Sivers function via Twist-3 relationship

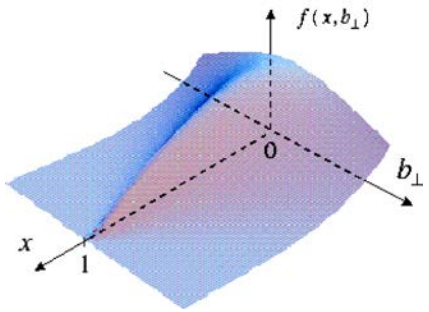


- Precision data at fixed *x*, different √*s* **ideal to constrain TMD evolution**

What about orbital angular momentum?







quark contribution

$$\frac{1}{2} = J_q^z + J_g^z = \frac{1}{2}\Delta\Sigma + \sum_q \mathcal{L}_q^z + J_g^z$$

$$J_{q,g}^z = \frac{1}{2}\left(\int_{-1}^{1} x\,dx\left(H^{q,g} + E^{q,q}\right)\right)_{t\to 0}$$

- Generalized parton distributions (GPDs), measured via exclusive reactions, provide **access to L_q and L_g**
- Exclusive J/ψ production in ultra-peripheral collisions with transversely polarized p+p and p+Au provides access to the GPD E_g
  - The GPD E is responsible for orbital angular momentum
  - **Only access world-wide to E_g before EIC**
- First measurements started in 2015 enabled by the Roman Pot phase II* upgrade to STAR