Recent Results of the STAR Cold QCD Physics Program

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for the STAR Collaboration

35th Winter Workshop on
Nuclear Dynamics
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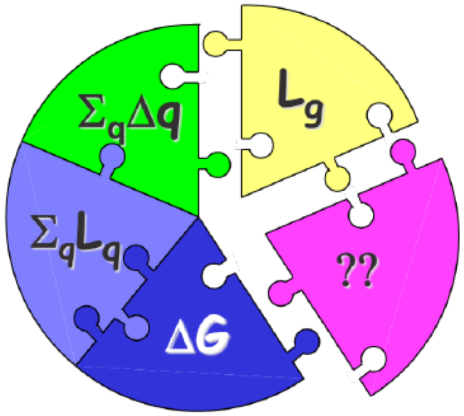
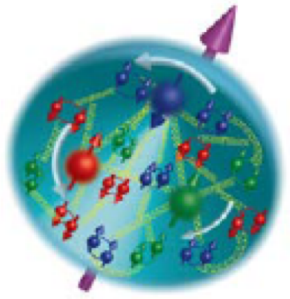
Outline

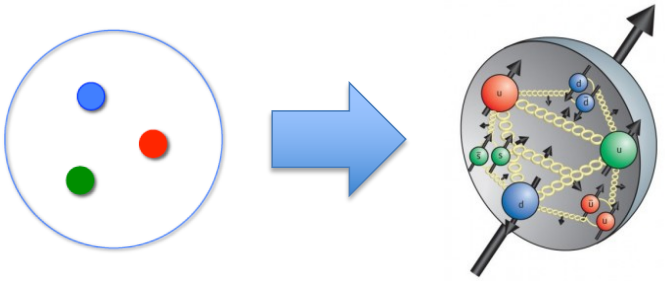


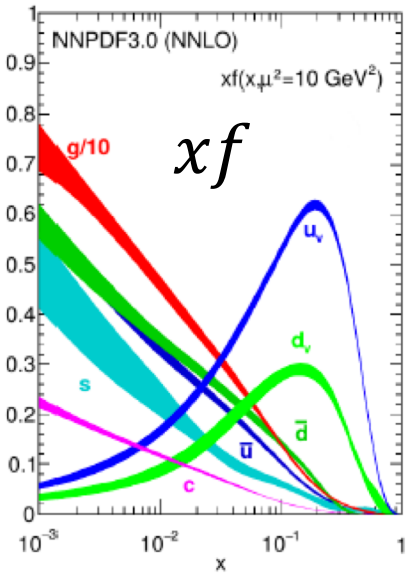
- Proton Structure
- STAR
- Longitudinal Spin Results (quark and **gluon** helicities)
- Transverse Spin Results (Sivers, twist-3, and **transversity**)
- Unpolarized Results
- Summary

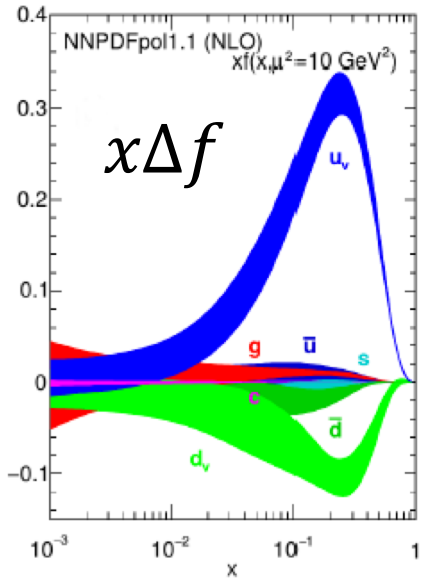


Note: Due to time constraints I will only focus on **p+p collisions**

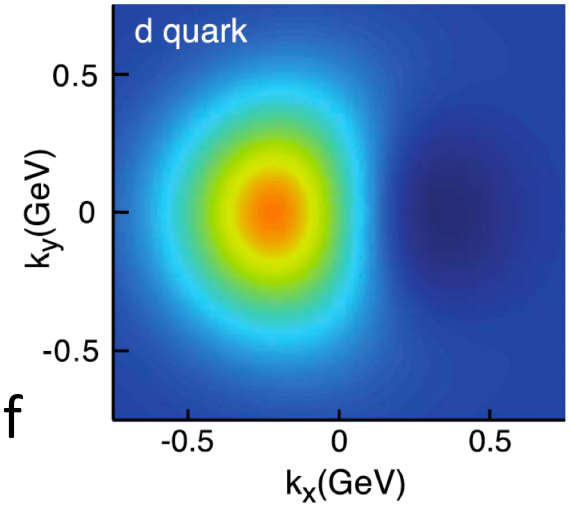
Proton Structure



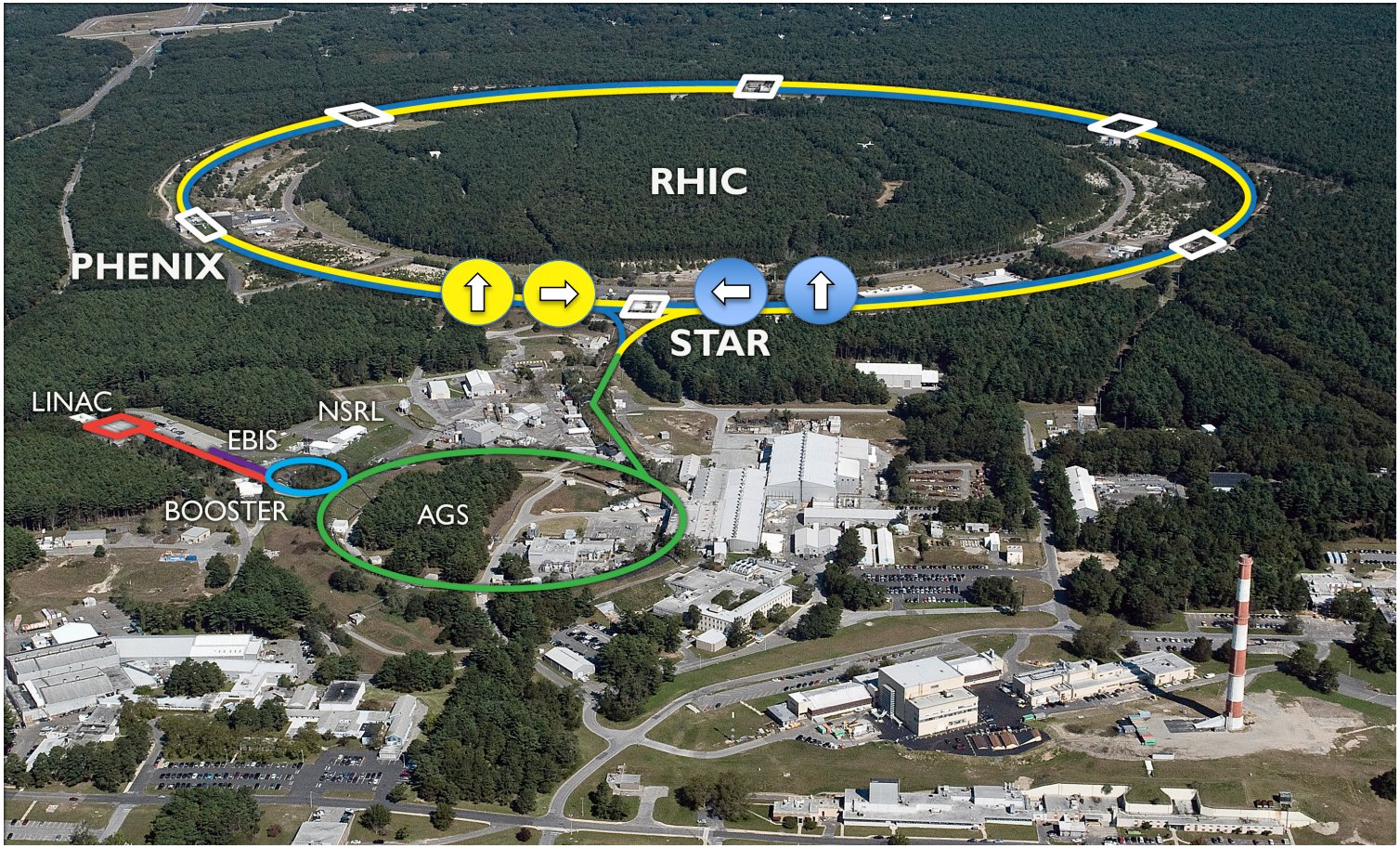




- Unpolarized
  - Parton distributions
  - Fragmentation Functions (FF)
- Longitudinal Spin
  - Parton helicity distributions
  - Polarized FF
- Transverse Spin
  - Transverse momentum distributions (TMDs)
  - Exhibit correlations arising from spin-orbit effects
  - Close connection to twist-3 correlations
  - Polarized FF
- STAR has provided insight into all three areas of proton structure.



Relativistic Heavy Ion Collider (RHIC)



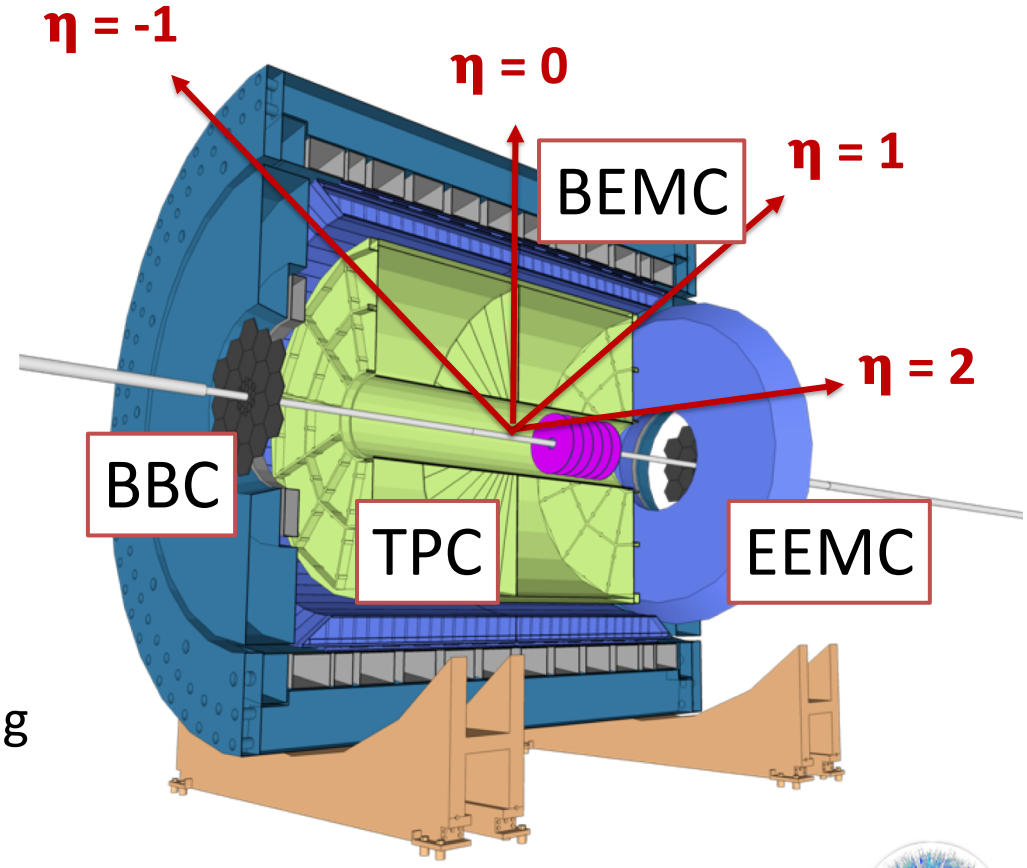
RHIC at
Brookhaven National Laboratory
Long Island, NY

- World's **only** polarized synchrotron collider
- Spin states known for every proton bunch
- Can collide **longitudinally** or **transversely** polarized protons.

Solenoid Tracker At RHIC (STAR)

- **Calorimetry** system with 2π coverage: **BEMC** ($|\eta| < 1$) and **EEMC** ($1 < \eta < 2$)
- **TPC**: tracking and particle ID
- **ZDC**: Relative luminosity and local polarimetry
- **BBC**: Relative luminosity and minimum biased trigger.
- **Forward Meson Spectrometer**

  (not shown) extending $2.6 < \eta < 4$



- **Spin structure** is measured via single and double spin asymmetries (spin-dependent cross section differences).

$$A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}\ ,\ A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$$

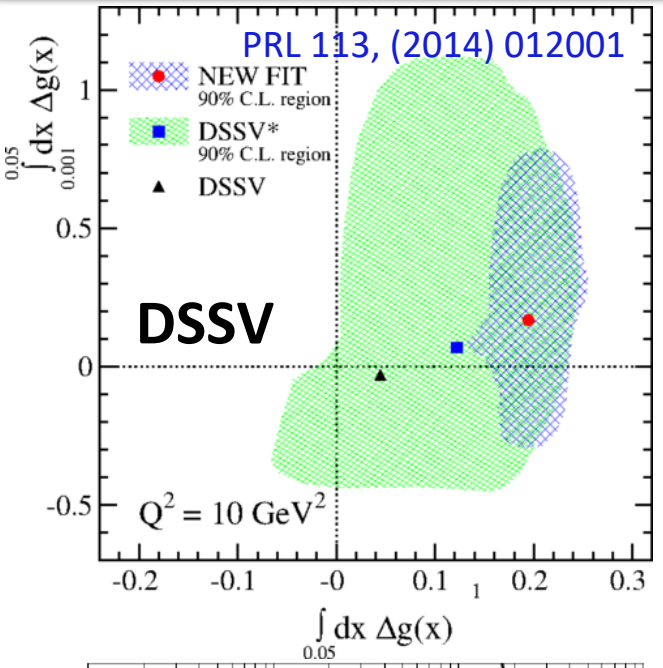
- **Unpolarized structure** is measured using cross sections and cross section ratios.

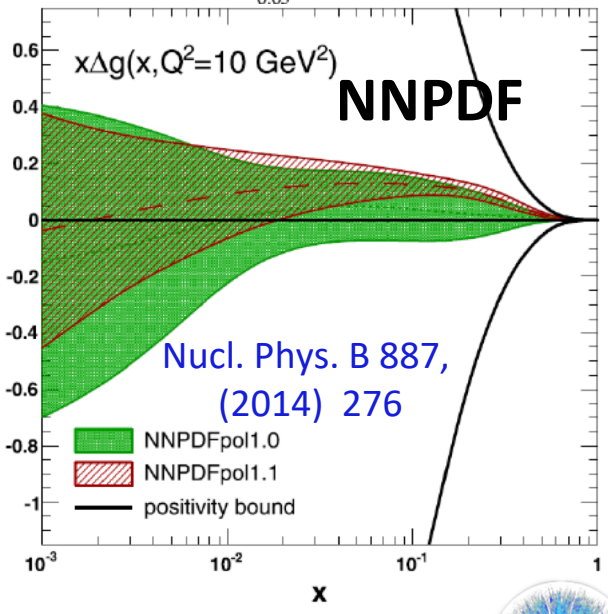
Gluon Polarization (Central Rapidity)

- STAR data has already had a significant impact on understanding the gluon polarization.
- Inclusive Jet A_{LL} at 200 GeV from 2009
  PRL 115, (2015) 092002.

  - Included in DSSV and NNPDF global analyses
  - DSSV $\int_{0.05}^{1} \Delta g(x)\, dx = 0.20^{+0.06}_{-0.07}\ (90\%\ C.L.)$
  - NNPDF $\int_{0.05}^{0.2} \Delta g(x) dx = 0.17 \pm 0.06$

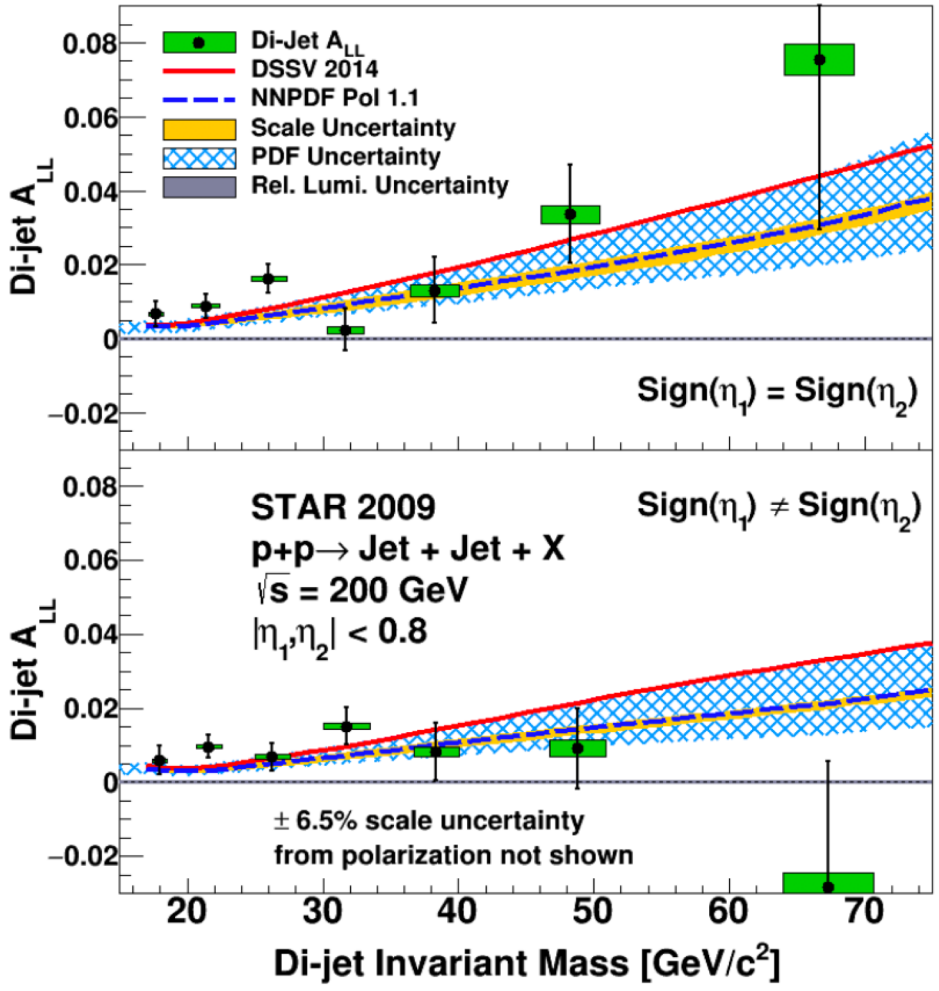
- STAR will further constrain the gluon polarization with additional central rapidity data
  - Di-Jets at **200 GeV** in 2009
  - Jets and di-jets at **200 GeV** in 2015
  - Jets and di-jets at **510 GeV** in 2012 and 2013



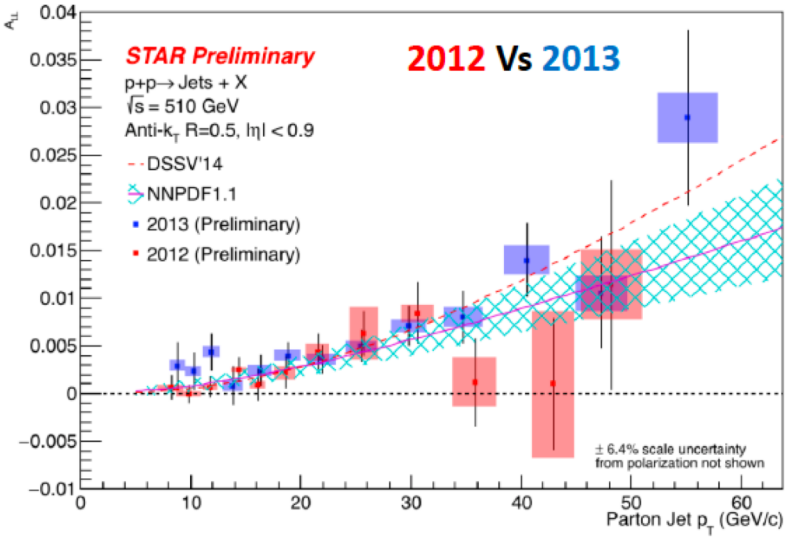


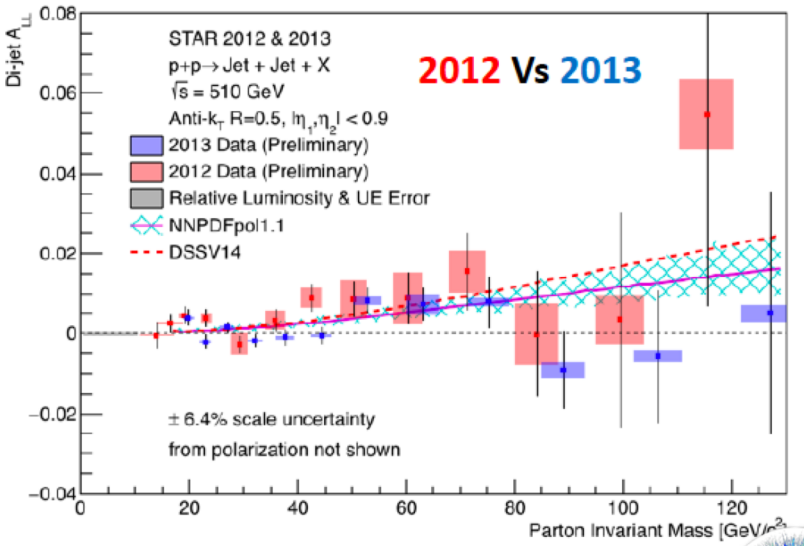
Gluon Polarization (Central Rapidity)

PRD 95 (2017) 071103
Di-Jets at 200 GeV



Preliminary
Jets and Di-Jets at 510 GeV

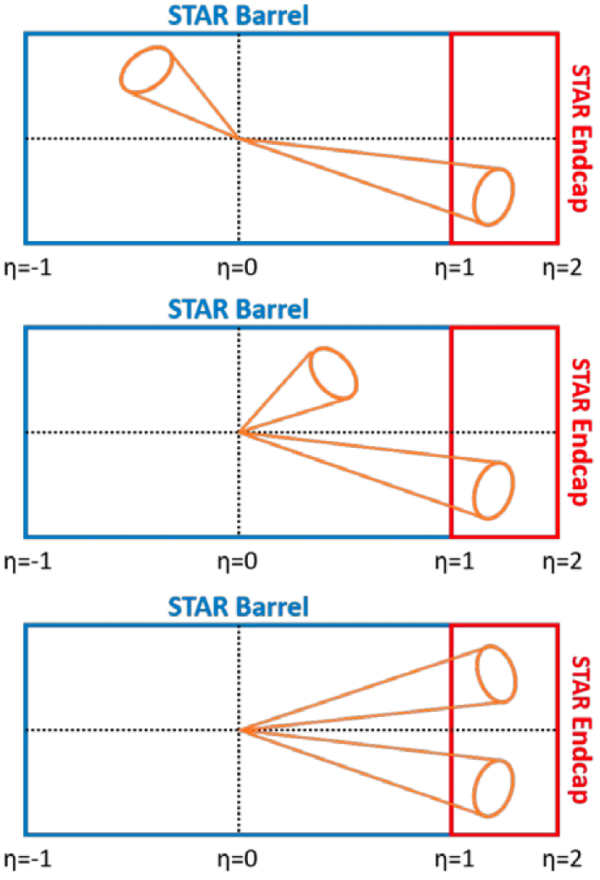


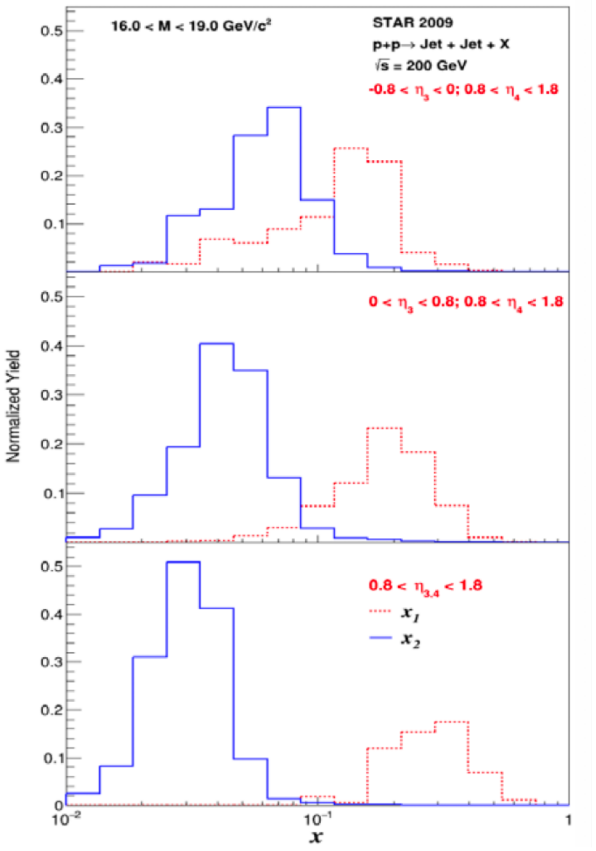


- Higher center of mass energy accesses lower x

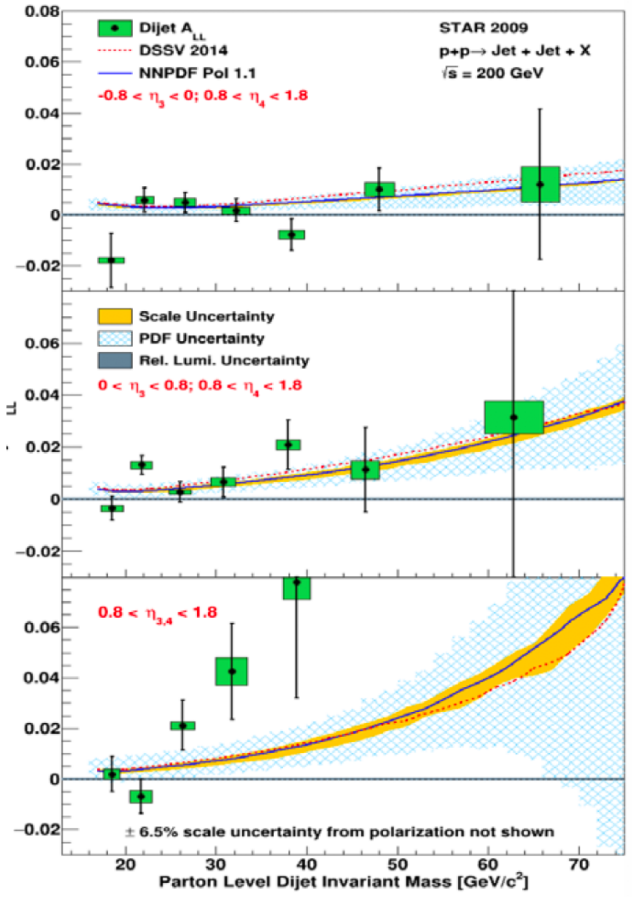
Gluon Polarization (Intermediate Rapidity)

- Requiring more forward jets gives access to even lower x, down to 0.01.





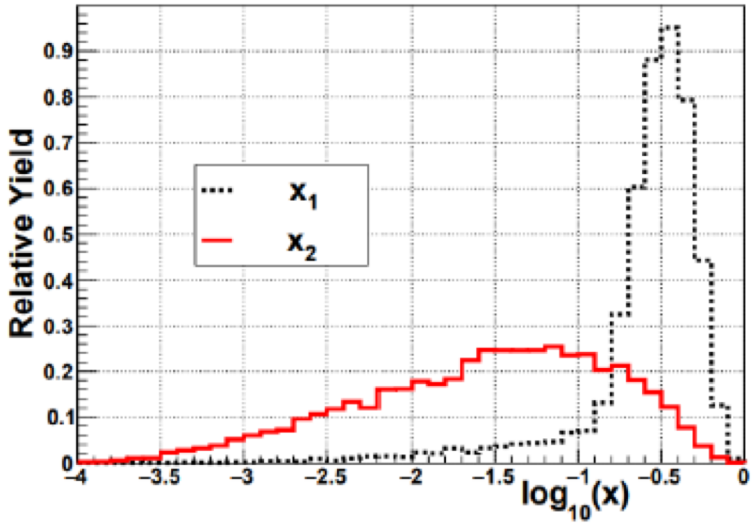
PRD 98 (2018) 032011



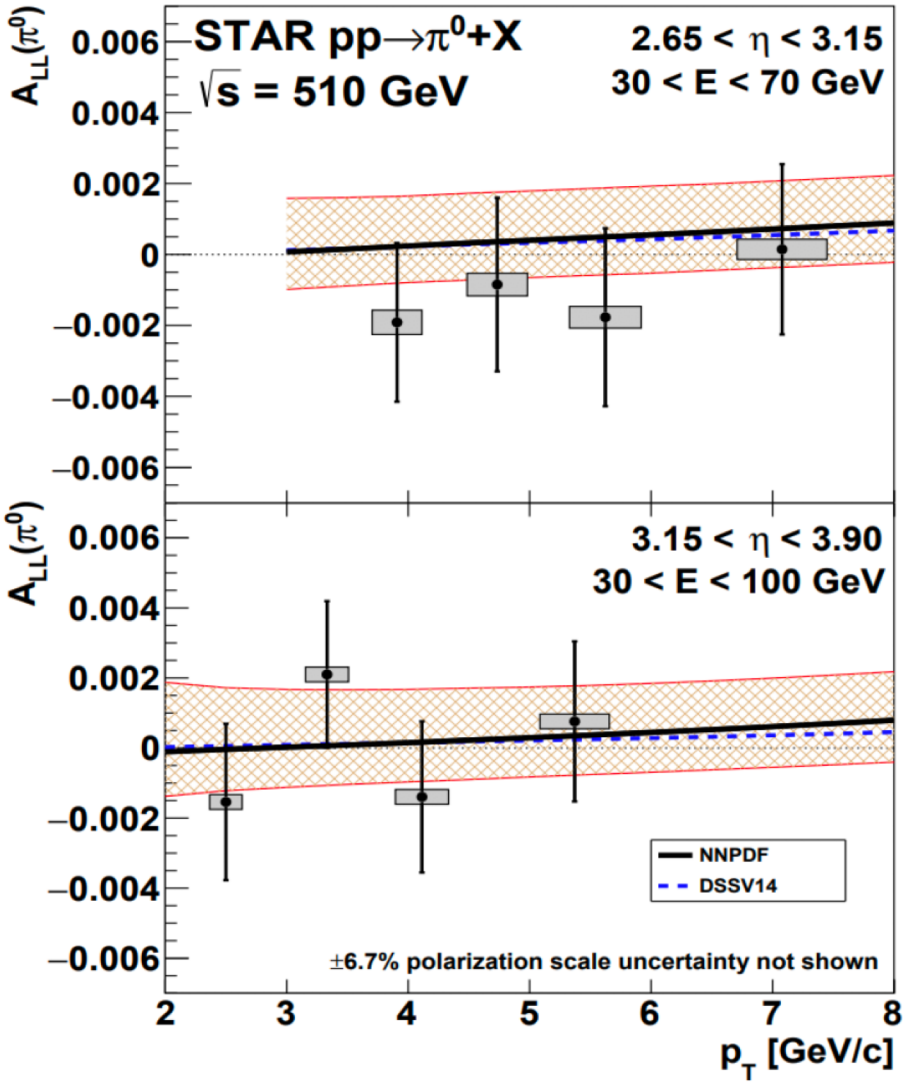
- Recently released and **upcoming** STAR results from **2012** and **2013** at $\sqrt{s} = 510\ GeV$ will further constrain the gluon helicity and begin to determine its shape.

Gluon Polarization (Forward Rapidity)

- STAR Forward Meson Spectrometer provides calorimetry out to a pseudo-rapidity of 2.6 - 4
- A_{LL} of π^0 in FMS at $\sqrt{s} = 510\ GeV$ provides access to gluons down to x ~ 10^{-3}
- Analysis of 200 GeV is underway

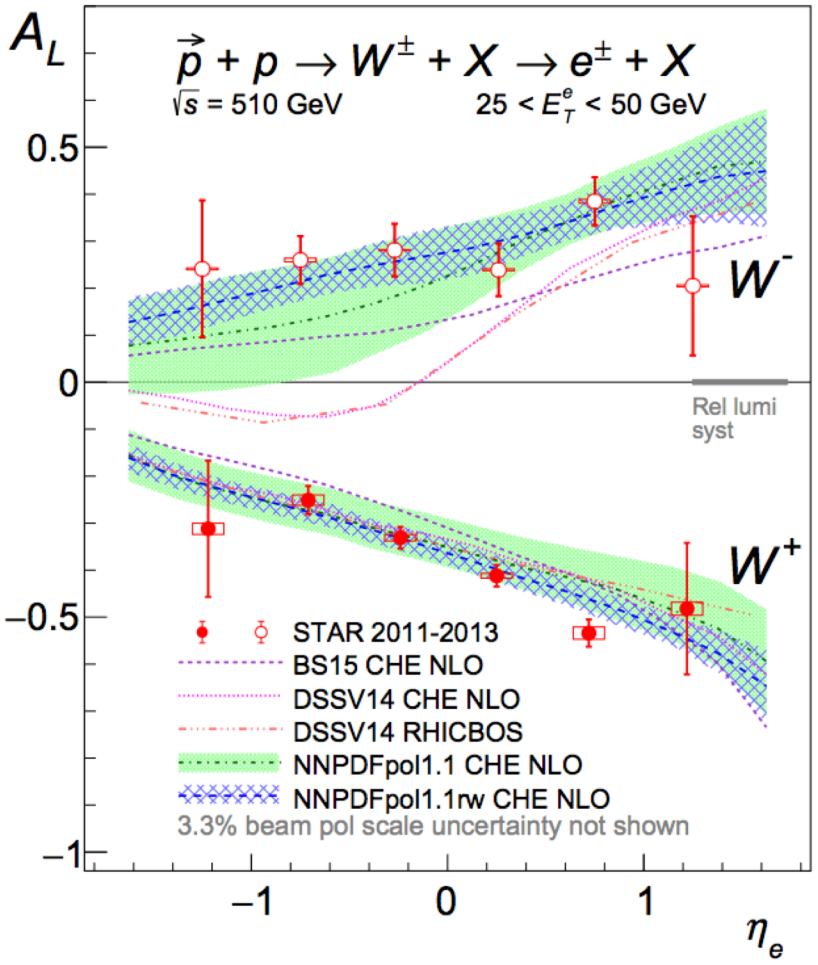


PRD 98, (2018) 032013

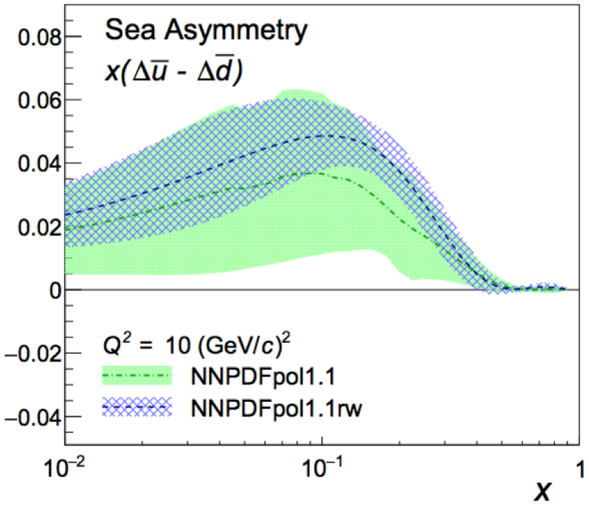


Quark Helicity Distributions

Submitted to PRD Rapid Comm.
arXiv:1812.04817

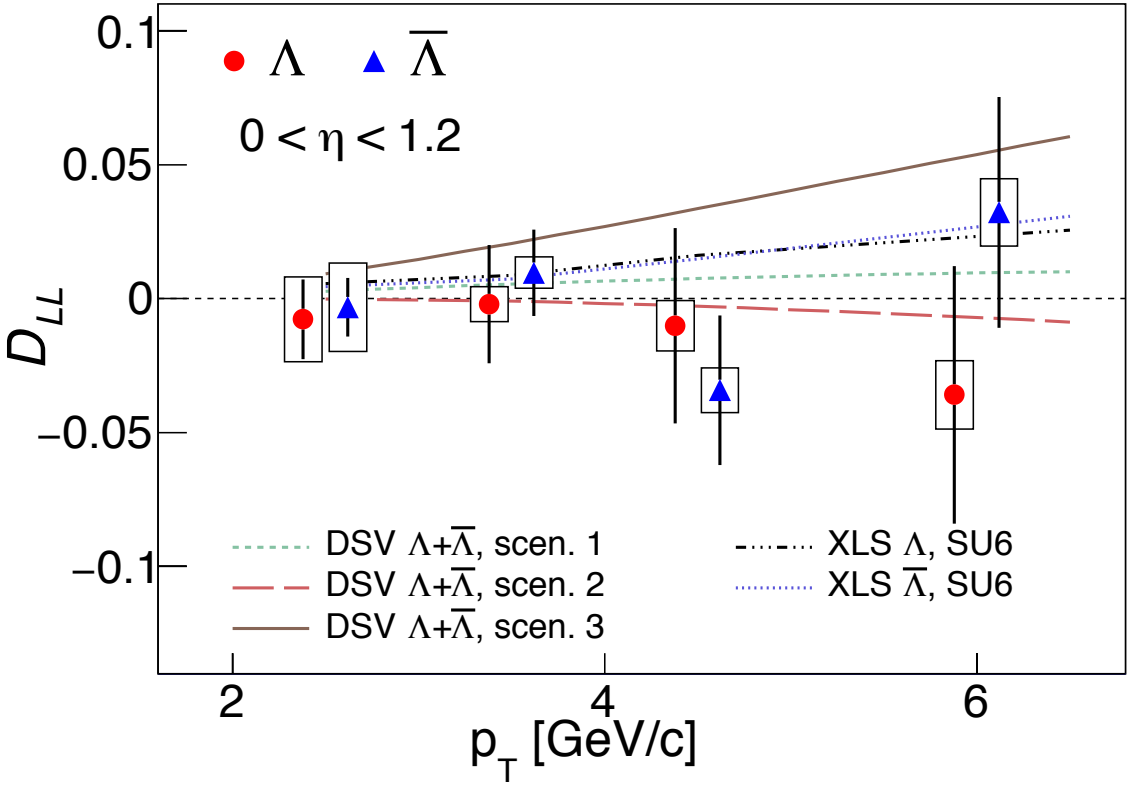


- Sensitive to sea quark helicity distributions.
- STAR (2011+2012+2013) data provides the most precise W A_L measurement
- Provides clear evidence of flavor asymmetry in the polarized sea
  $\Delta\bar{u} > \Delta\bar{d}$
- Will provide significant constraint on sea quark helicity distributions, in particular $\Delta\bar{u}$ and $\Delta\bar{d}$.



Quark Helicity Distributions

- Longitudinal spin transfer D_{LL} is sensitive to helicity distributions and polarized fragmentation function.
- In naïve quark model D_{LL} of $\overline{\Lambda}$ is connected to $\Delta\bar{s}$.
- New results improve on STAR 2009 results.
- D_{LL} of Λ $(\overline{\Lambda})$ consistent with zero.
- More precision is needed to rule out various models.

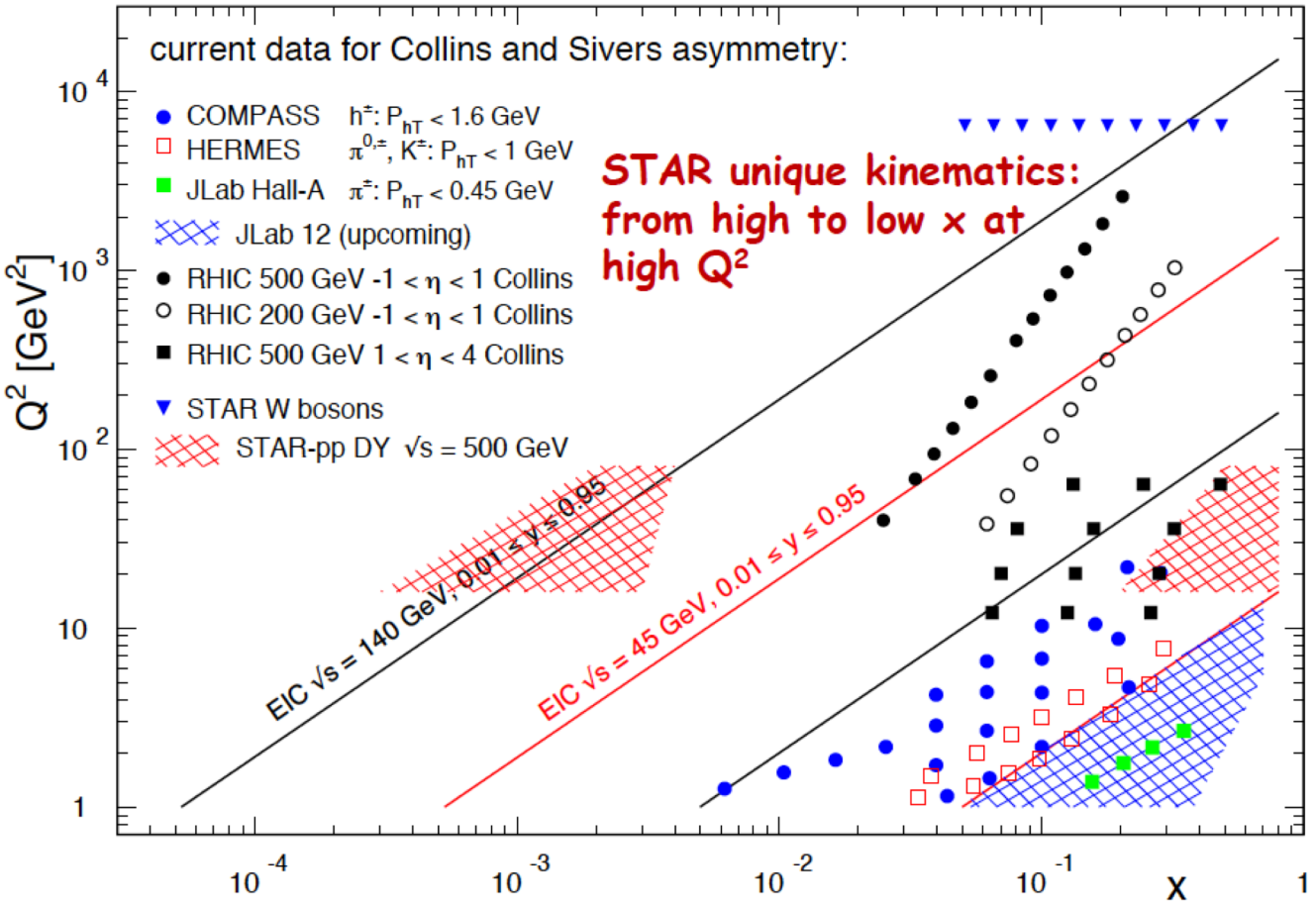


PRD 98, (2018) 112009

Transverse Momentum PDFs (TMDs)

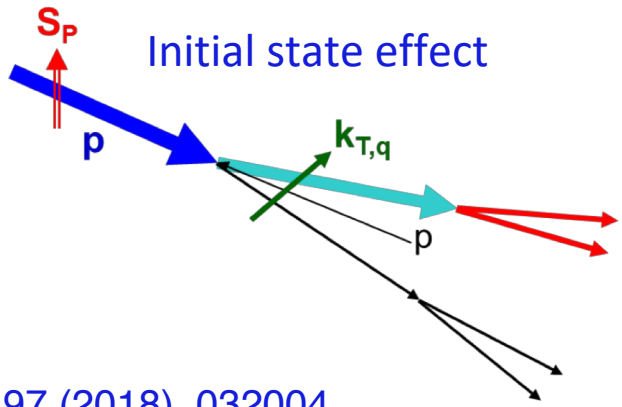
- STAR provides unique kinematic coverage
  - broad range at high Q^2
  - low to high x
  - Provides excellent opportunity to study TMD evolution

- TMD can be further studied by including other experimental data



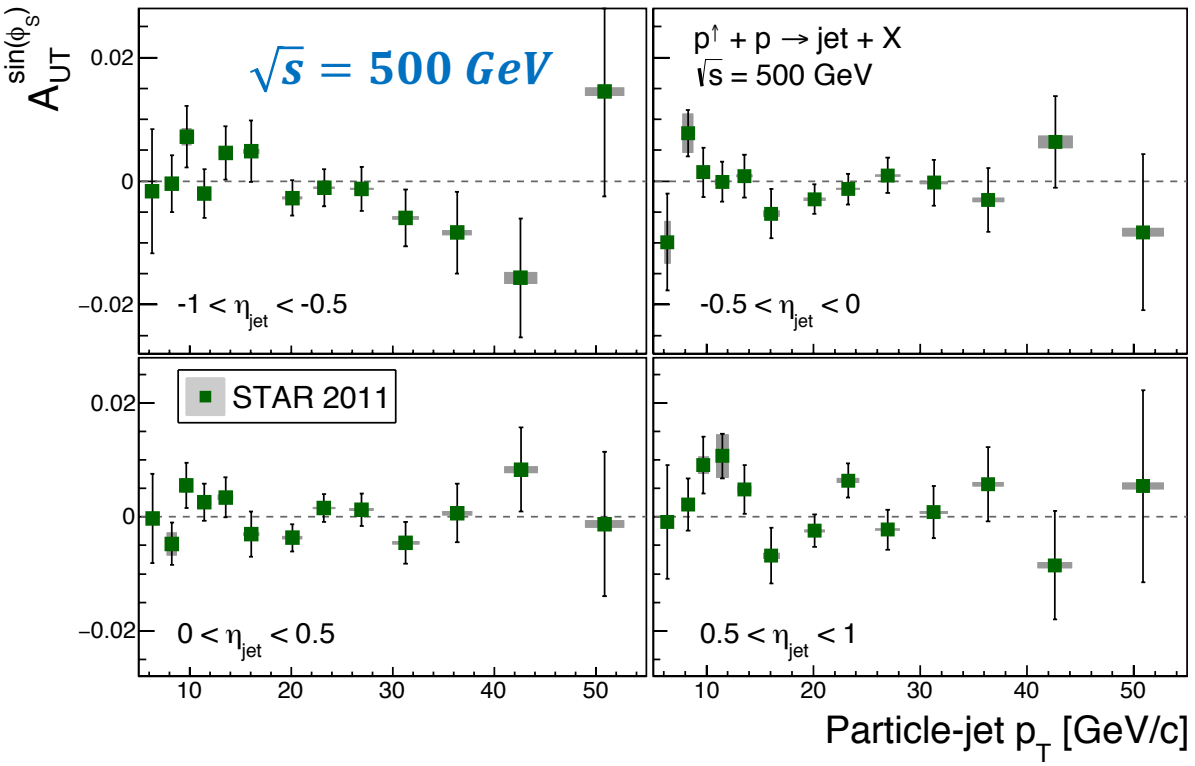
Sivers Function: Inclusive Jet A_N

- Sivers mechanism correlates proton spin to quark k_T, and is an initial state effect.
- Sivers function can be related to twist-3 correlation functions and couples to parton orbital angular momentum.



- Inclusive jet A_N measurements are sensitive to the gluon Sivers function.
- Asymmetries should help constrain twist-3 PDFs for gluonic interactions, which are connected to the gluon Sivers function

PRD 97 (2018), 032004



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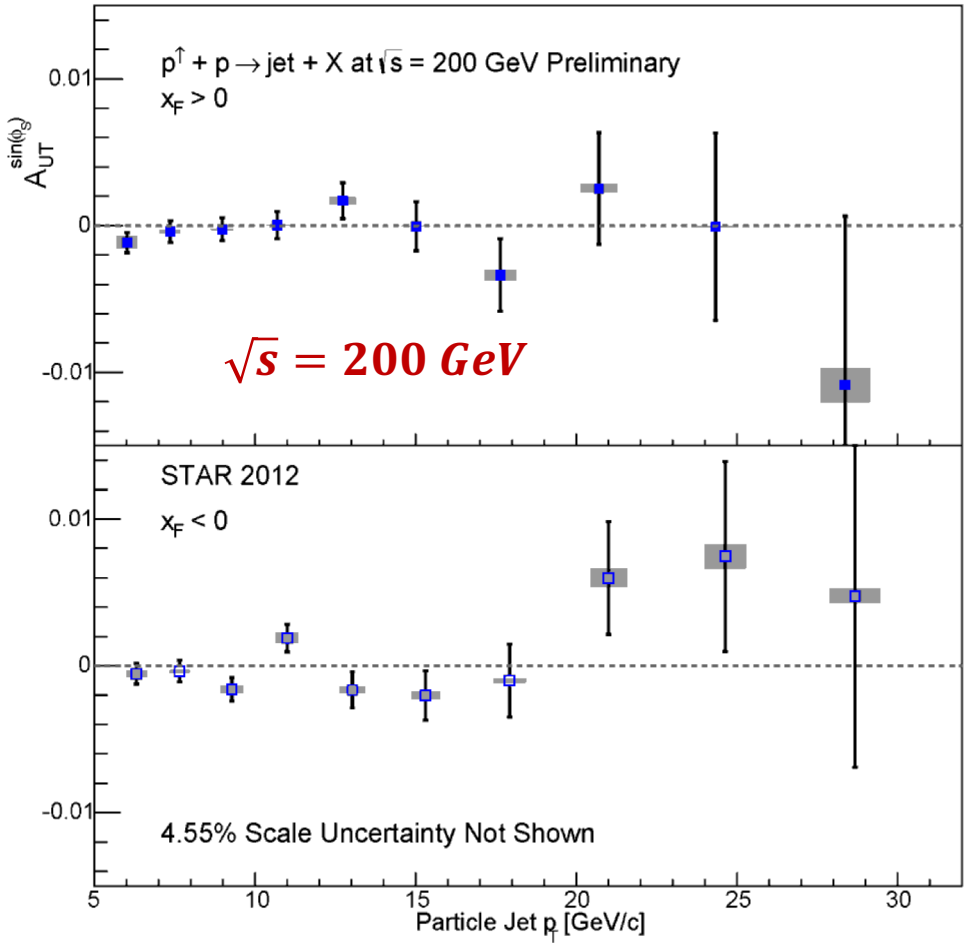
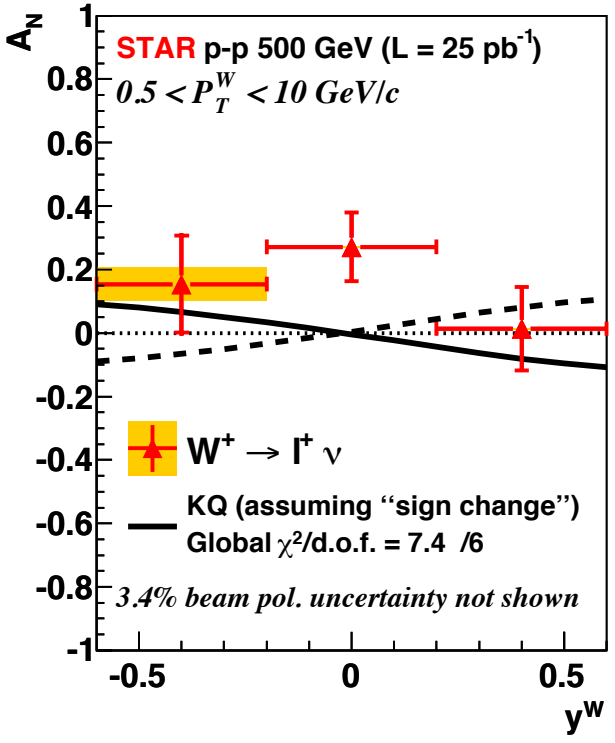
- Inclusive jet A_N measurements are sensitive to the gluon Sivers function.
- Asymmetries should help constrain twist-3 PDFs for gluonic interactions, which are connected to the gluon Sivers function
- New preliminary results at 200 GeV
  - Provide better precision than 500 GeV data

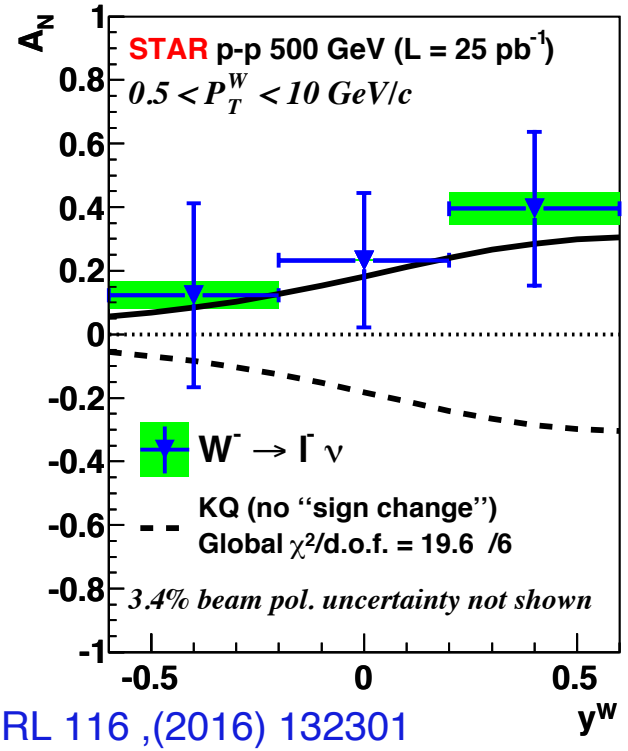
Preliminary



Sivers Function: W A_N

- W A_N is sensitive to the anti-quark Sivers functions.
- When compared to SIDIS results can provide a test of the sign change predicted from QCD factorization: $Sivers_{SDIS} = -Sivers_{DY,W/Z}$
- **Run 2011 :** Exploratory $A_N(W), 25\ pb^{-1}$
  - W kinematics fully reconstructed
  - Favors **sign change**, assuming evolution effects are small

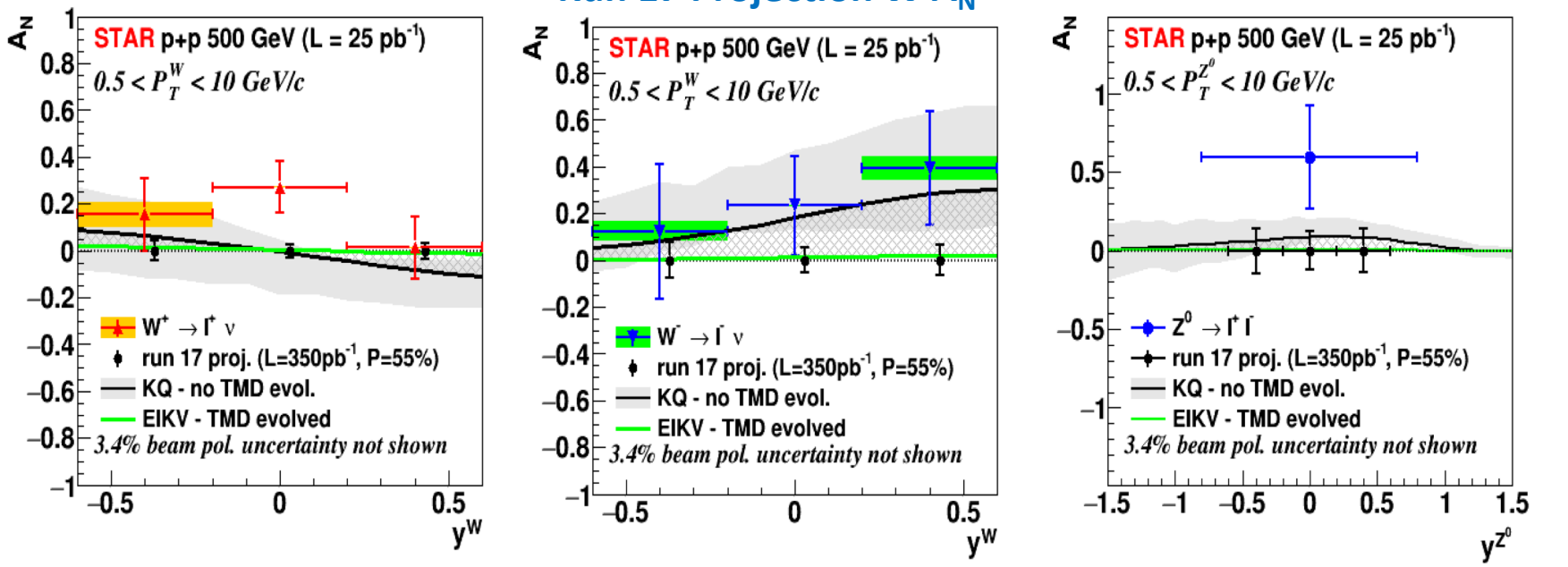




PRL 116 ,(2016) 132301

Sivers Function: W A_N

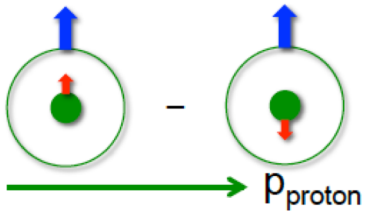
Run 17 Projection W A_N



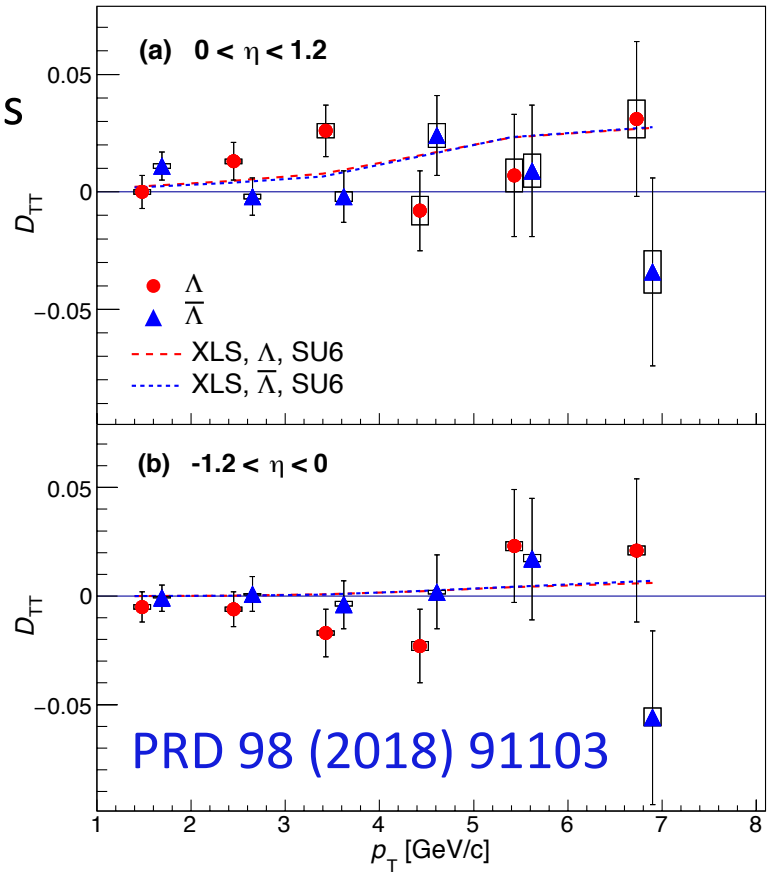
- **Run 2017 :** Definitive $A_N(W,Z), A_N(DY), A_N(\gamma)$ $\mathbf{350\ pb^{-1}}$
  - See sign change if evolution effects are less than a factor of 5
  - Probe **anti-quark Sivers function** for the first time.
  - Directly measure evolution effects using W/Z and Drell-Yan
    - Both have similar x, but different Q^2
    - W/Z central and Drell-Yan forward rapidity
  - Currently under analysis

Transversity: Spin Transfer

Transversity:

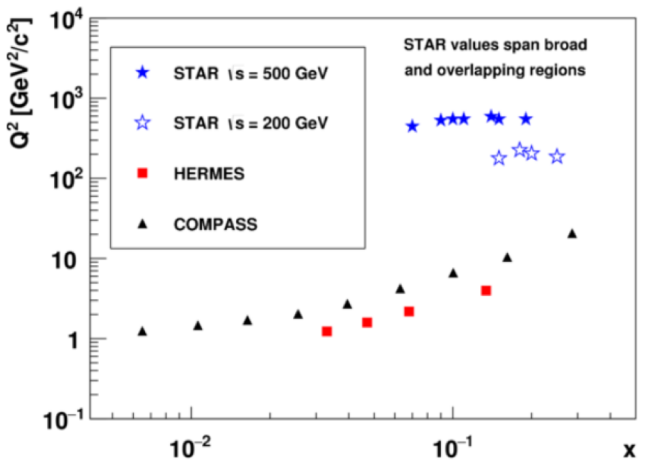


- Measurements of **transversity** convoluted with
  - Spin transfer
  - Di-hadron interference fragmentation functions (IFF)
  - Collins fragmentation function
- Transverse spin transfer of hyperons provide access to transversity and transversely polarized fragmentation function.
- First transverse spin transfer measurement in p+p collisions at RHIC.
- D_{TT} of Λ ($\overline{\Lambda}$) are consistent with model prediction.
- Asymmetries are small and consistent with zero

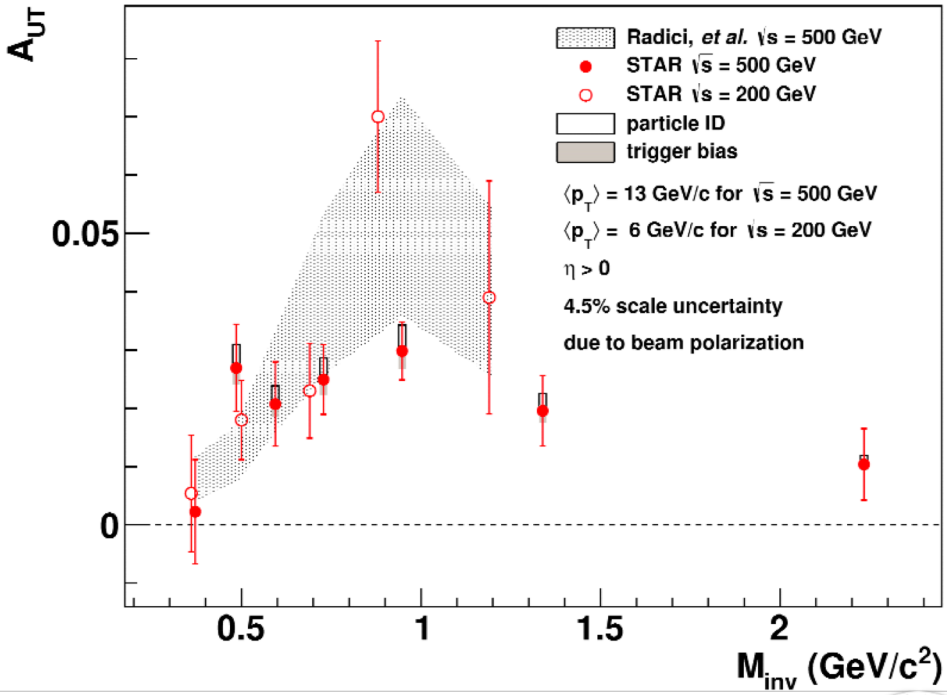


Transversity: IFF

- IFF Asymmetry correlates quark polarization to azimuthal distribution of final state hadron pairs
- STAR measurements provide first observations at large Q^2
- Significant IFF asymmetries at both $\sqrt{s} = 200\ and\ 500\ GeV$
  - Provides basis to investigate Q^2 evolution of transversity.
- STAR measurements are well described by recent IFF calculations (from e^+e^- and SIDIS fits) hints at universality.

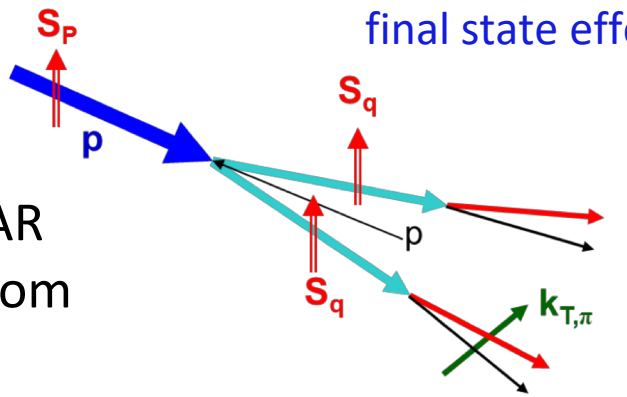


PLB 780 (2018) 332

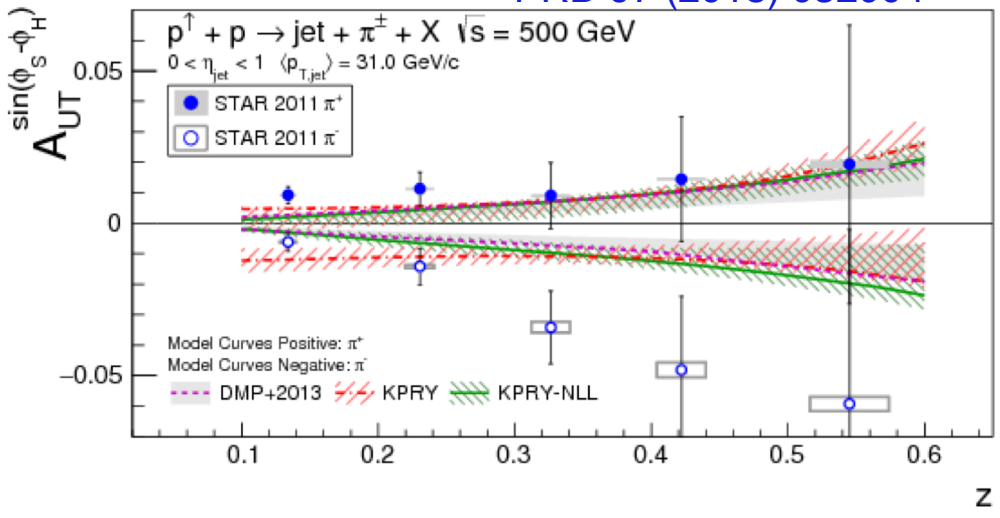


Transversity: Collins

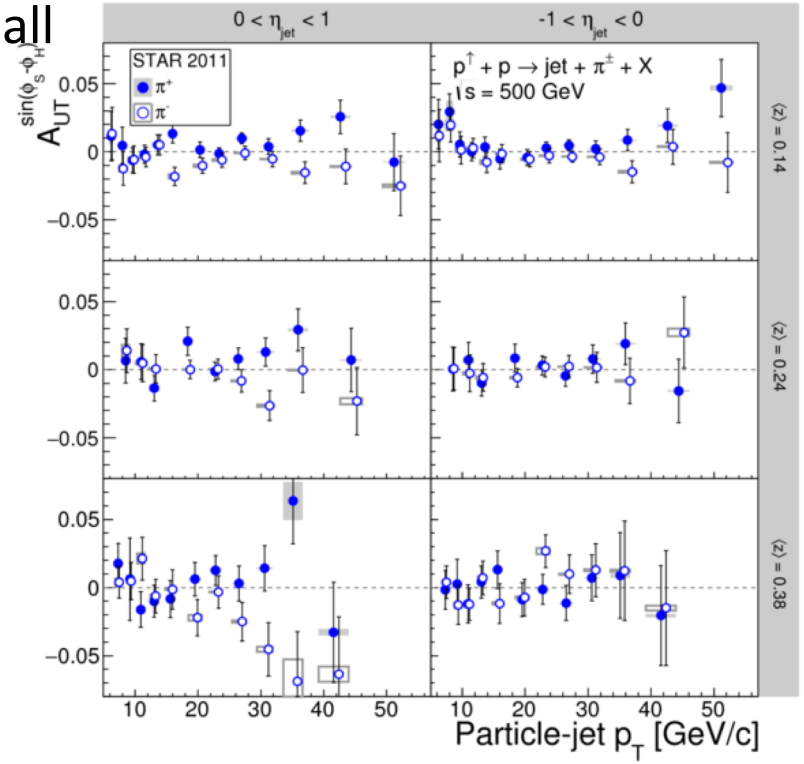
- Collins asymmetry sensitive to **quark transversity**
  - best sensitivity at higher p_T
- First observation in polarized proton collisions by STAR
- Data agrees well with theory predictions extracted from SIDIS and e^+e^-
  - Suggests universality of Collins function and small factorization breaking.



final state effect



PRD 97 (2018) 032004



PRD 97 (2018) 032004

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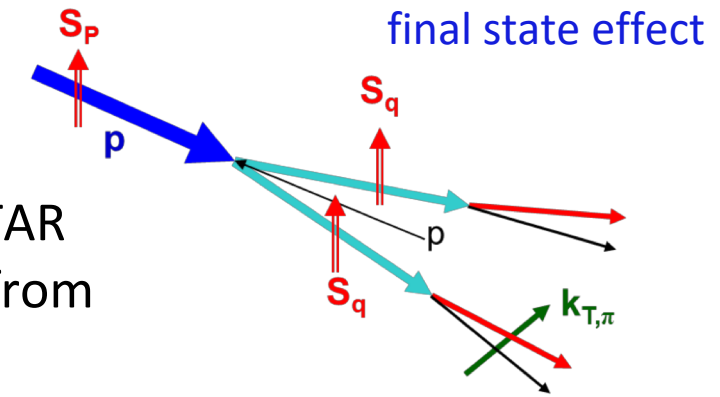
- First observation in polarized proton collisions by STAR
- Data agrees well with theory predictions extracted from SIDIS and e^+e^-
  - Suggests universality of Collins function and small factorization breaking.
- Q^2 evolution can be looked at when 200 GeV data is included



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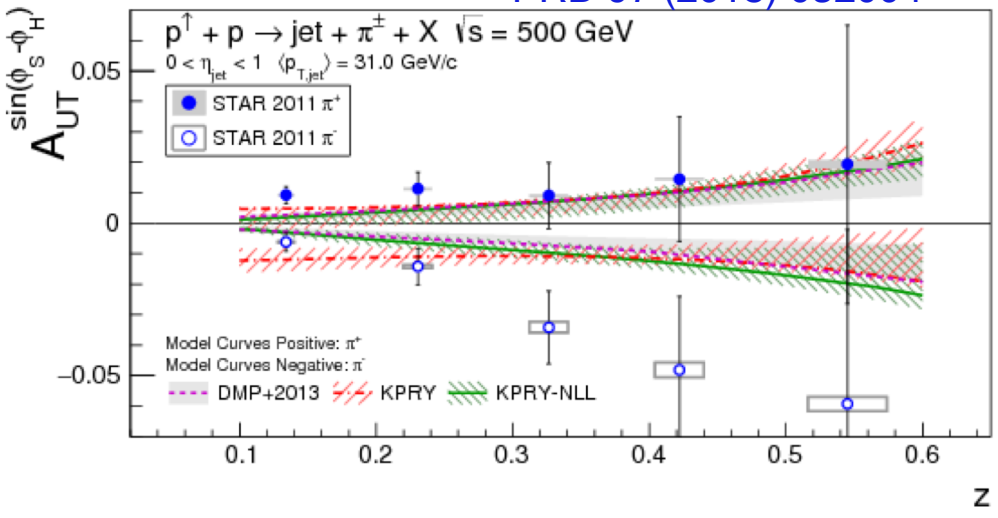
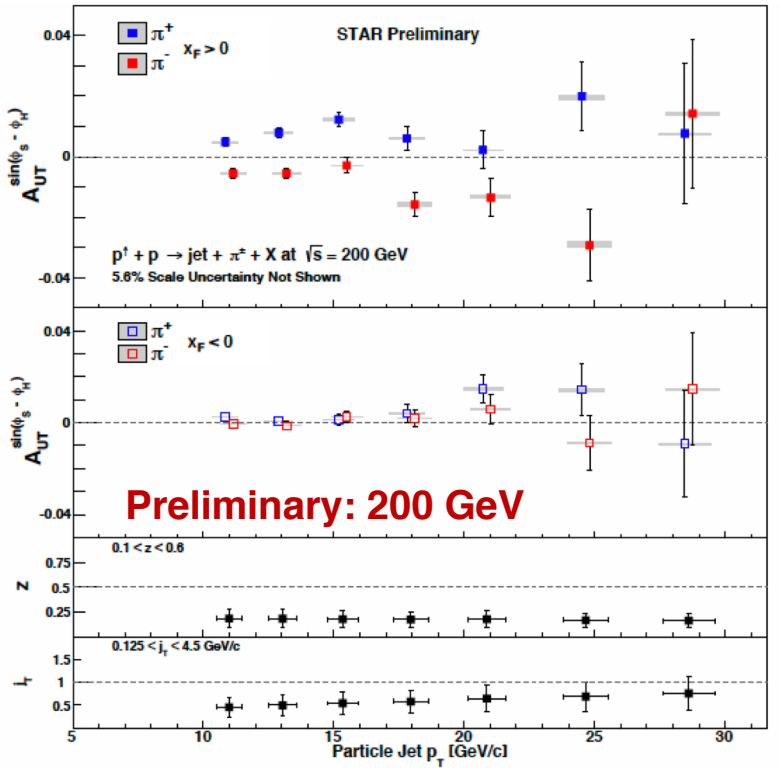
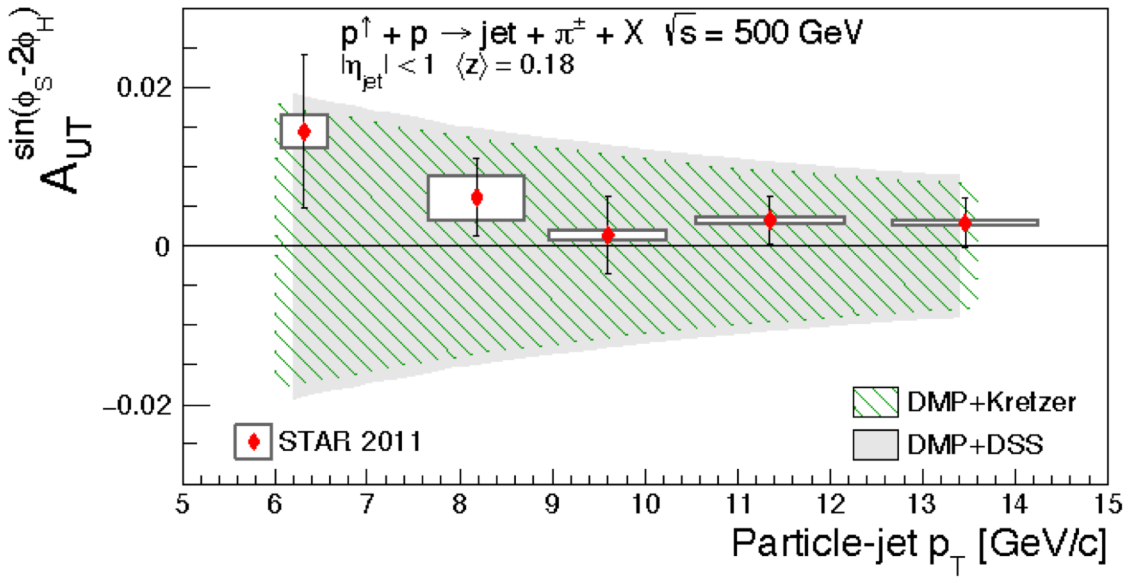




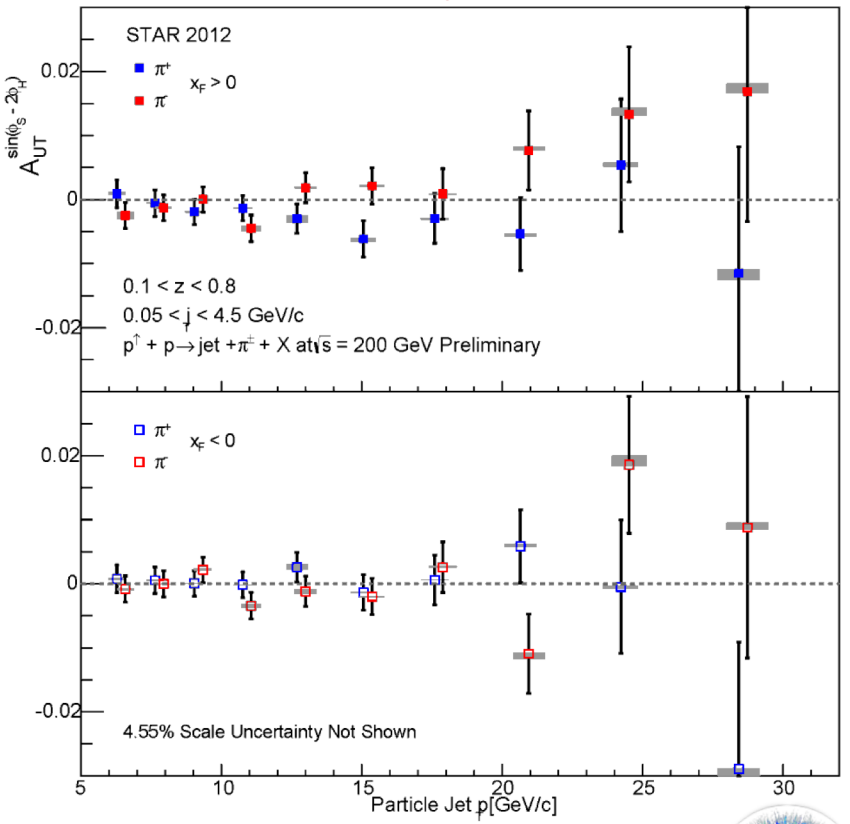
Constraining Gluon Linear Polarization

- First ever measured **Collins-like asymmetry**
  - Gluon analog to Collins FF
  - Sensitive to **gluon linear polarization**
  - Best sensitivity at low p_T
  - Provide first ever input on linearly polarized gluons in a polarized proton to constrain models.
- Preliminary results from 200 GeV will provide stronger constraints.

PRD 97 (2018) 032004: 500 GeV



Preliminary: 200 GeV



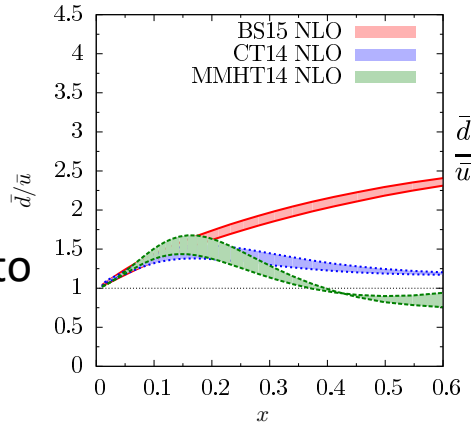
Unpolarized Sea Quarks

- The sea quark distributions need to be better understood, in particular $\bar{d}/\bar{u}$.
- It is evident from global PDF extraction and experiment that more data is needed.
- W cross section ratio at LO is sensitive to $\bar{d}/\bar{u}$:

$$\frac{\sigma_{W^+}}{\sigma_{W^-}} \approx \frac{u(x_1)\,\bar{d}(x_2)+u(x_2)\bar{d}(x_1)}{d(x_1)\bar{u}(x_2)+d(x_2)\bar{u}(x_1)}$$

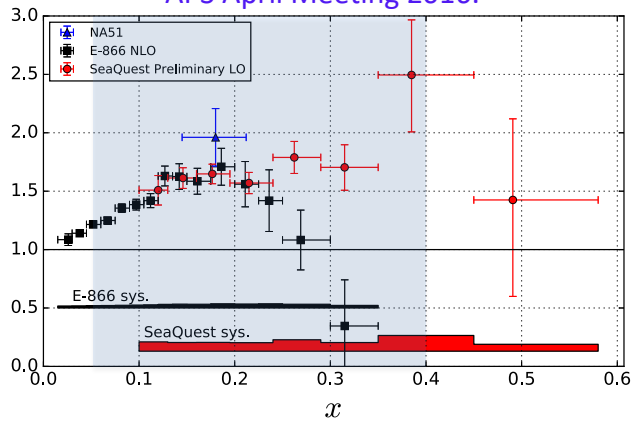
- STAR can provide data in the kinematic range of $0.06 \leq x \leq 0.4$ corresponding to $-2 \leq \eta_e \leq 2$
- Provide constraints on $\bar{d}/\bar{u}$
- 2017 W data will double preliminary statistics.
- STAR differential W/Z cross sections can also be used to help constrain TMDs in global fits (under analysis).

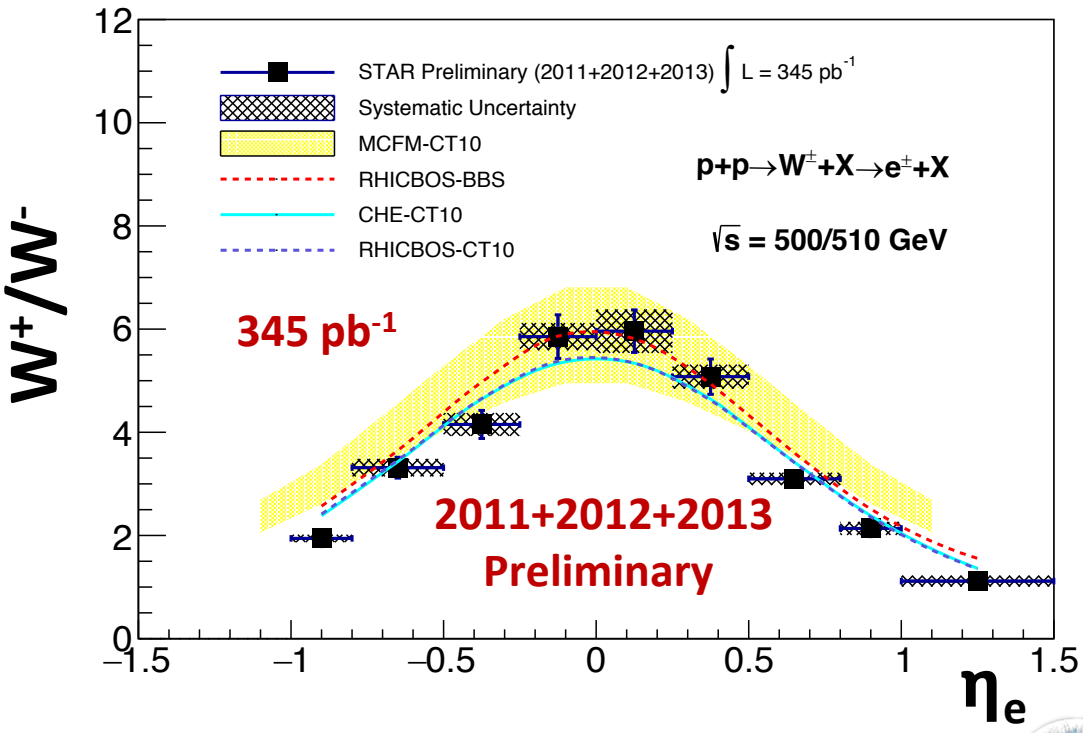
[C. Bourrely and J. Soffer]



$\frac{\bar{d}(x)}{\bar{u}(x)}$

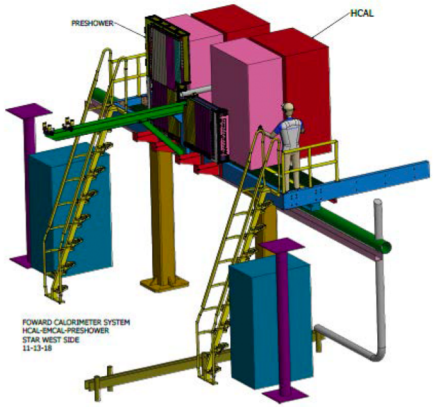
B. Kerns et al. (SeaQuest Collaboration), APS April Meeting 2016.

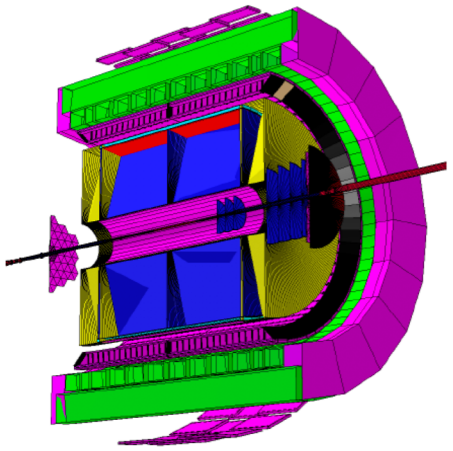


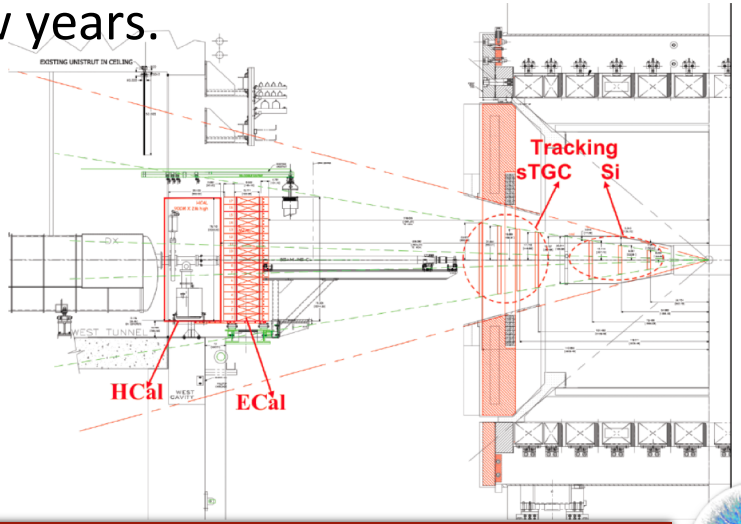


STAR Beyond 2020

- STAR has an opportunity to extend its cold QCD program **beyond 2020** and continue to answer some **fundamental questions** in QCD via a **forward upgrade**.
  - Full details presented in RHIC cold QCD plan: **arXiv:1602.03922**
- This instrumentation upgrade includes **forward calorimeter** and **tracking detectors** that will allow STAR to reach study in more details the forward rapidity range ($2.5 < \eta < 4$).
  - Ability to probe **higher-x valence region** and **lower x** where **gluons and sea quarks are prominent.**
- Serve as a bridge to EIC physics and an in-situ testing ground for EIC R&D technology.
- **Strongly** endorsed by BNL PAC over the last few years.







Summary

- STAR has played and will continue to play a **critical** and **complementary** role in resolving the structure of the proton.
- **Longitudinally** polarized p+p collisions have provided insight into
  - **Sea quark** distributions via W/Z production.
  - **Polarized gluon** distribution through jet,di-jet, and π A_{LL}
- **Transversely** polarized p+p collisions have accessed the transverse spin structure of the proton such as
  - the **Silvers** function through W/Z production.
  - **twist-3** quark/gluon correlators via inclusive Jet asymmetries.
  - **Transverity** sensitive quantities have been probed through the Collins asymmetry and IFF.
- **Unpolarized** p+p collisions have provided and will provide constraints for global analyses
  - Sea quark distributions
  - TMDs
- **STAR forward upgrade** will allow measurements in the rapidity range of $2.5 \leq \eta \leq 4.0$ and continue to investigate the structure of the proton.