Spin and Forward Physics with *STAR*

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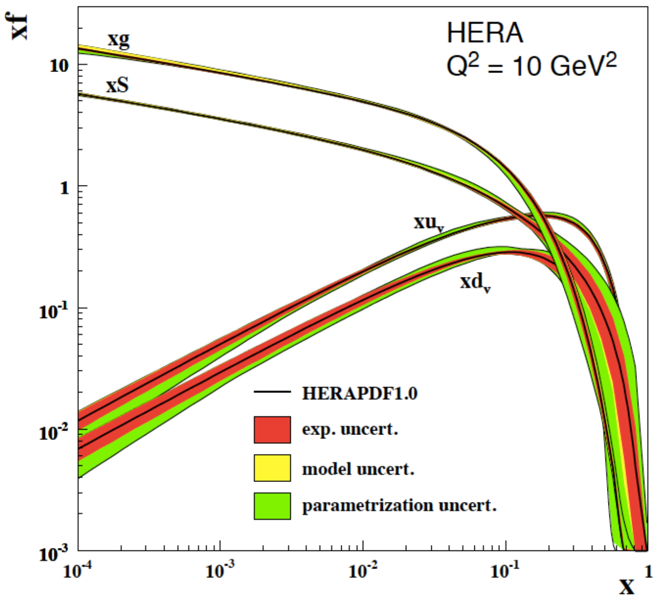
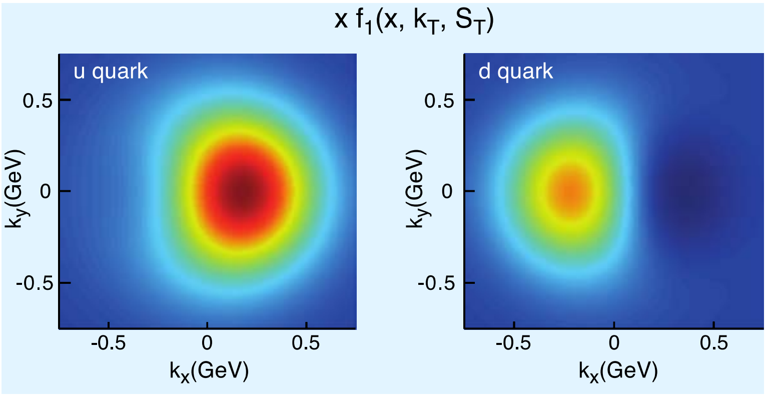
Outline

- Introduction
- Longitudinal spin structure: gluon and anti-quark polarization
- Transverse spin structure: TMDs and visualizing color interactions
- Spin and p+A physics at forward rapidities
- Physics with tagged forward protons

Fundamental questions regarding proton spin



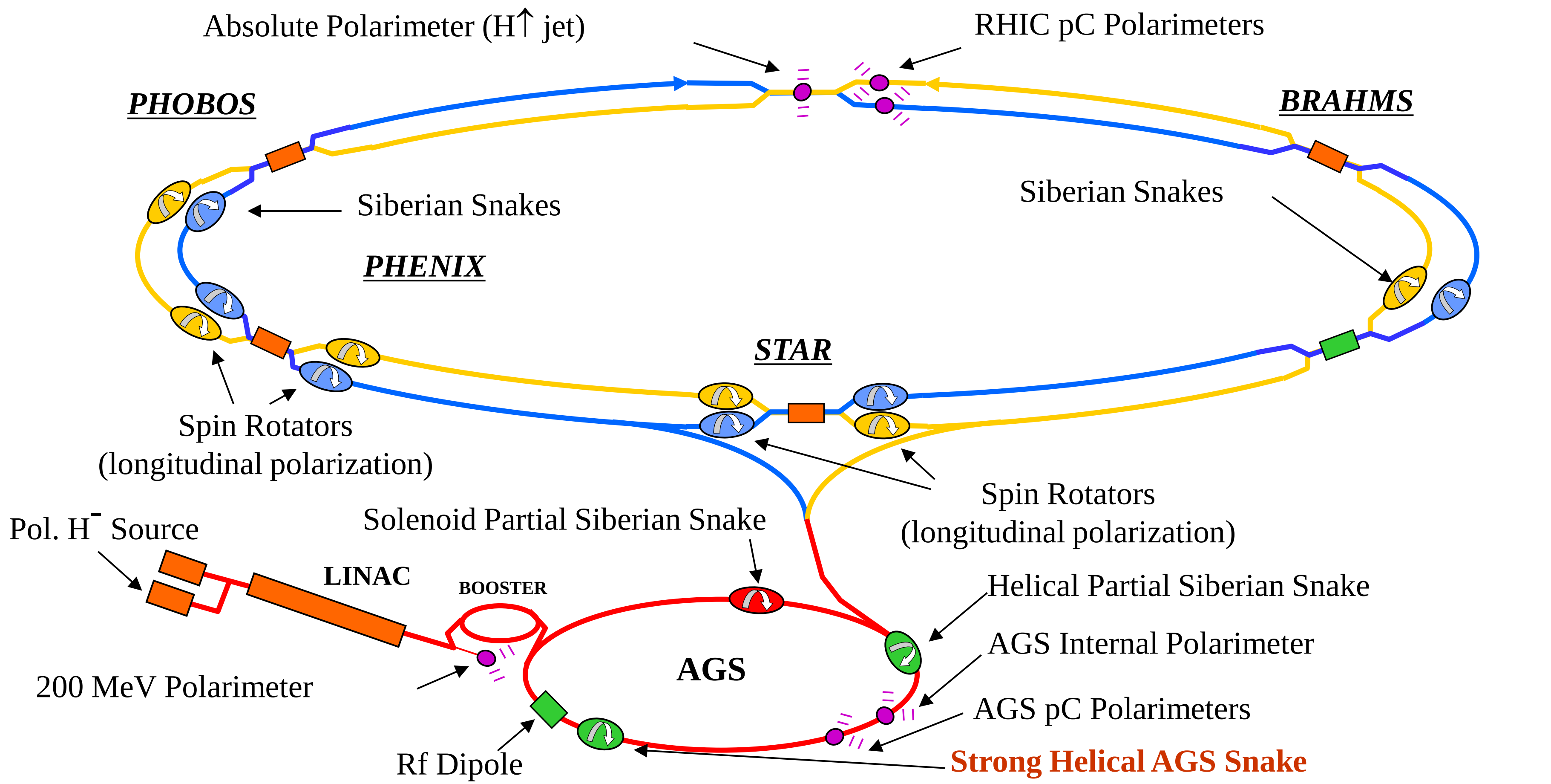


- How do quarks and gluons conspire to provide the proton's spin ½?
  - What is the role of gluons?
    - Reminder – gluons contribute ~50% of the proton's momentum
  - What is the role of sea quarks?
  - How much orbital angular momentum is needed?
- What is the dynamic structure of the proton?
  - 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

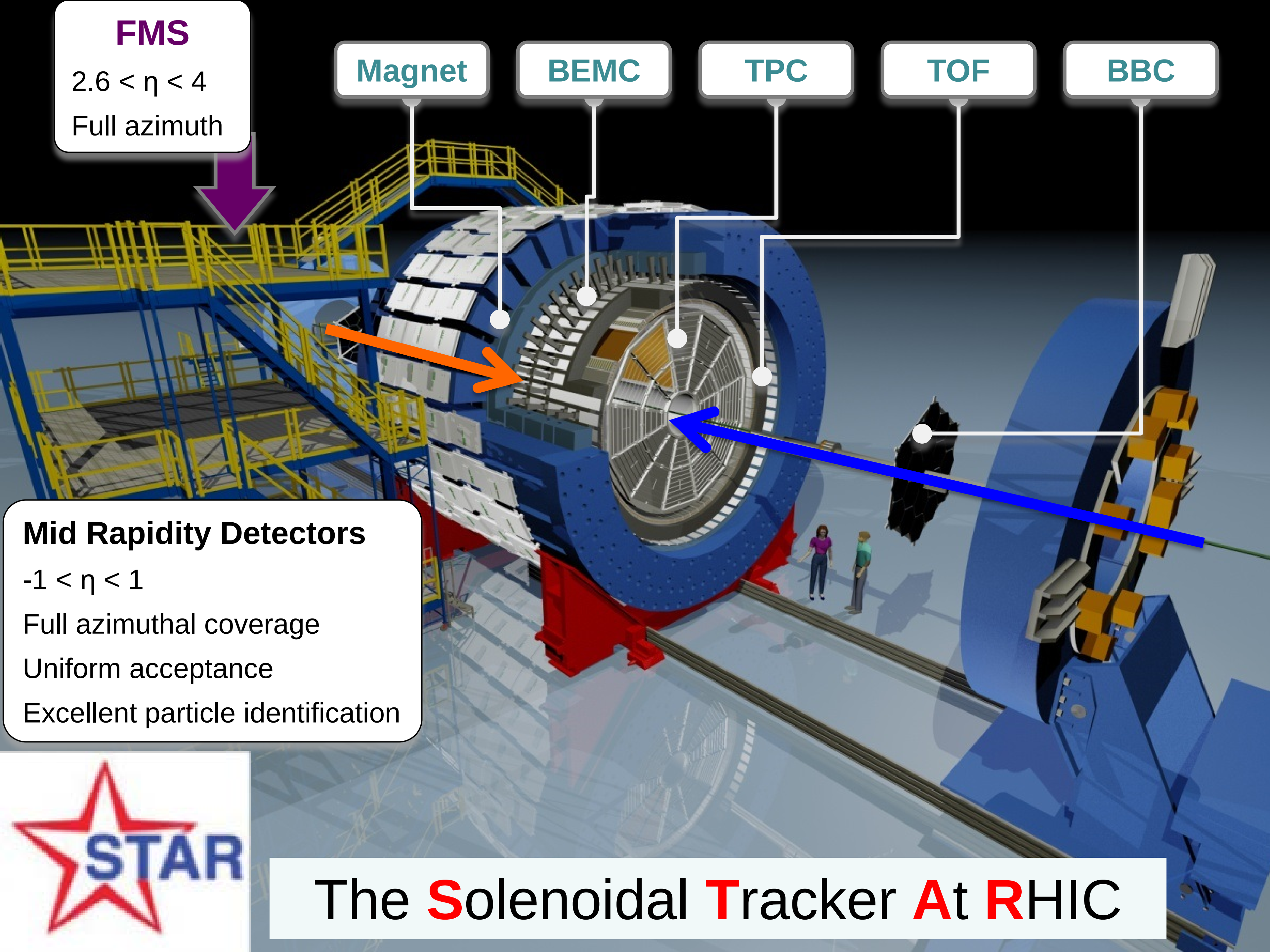
- Search for and study the Quark-Gluon Plasma
- **Explore the partonic structure of the proton**
- **Determine the partonic structure of nuclei**

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

The Solenoidal Tracker At RHIC



Mid Rapidity Detectors

$-1 < \eta < 1$

Full azimuthal coverage

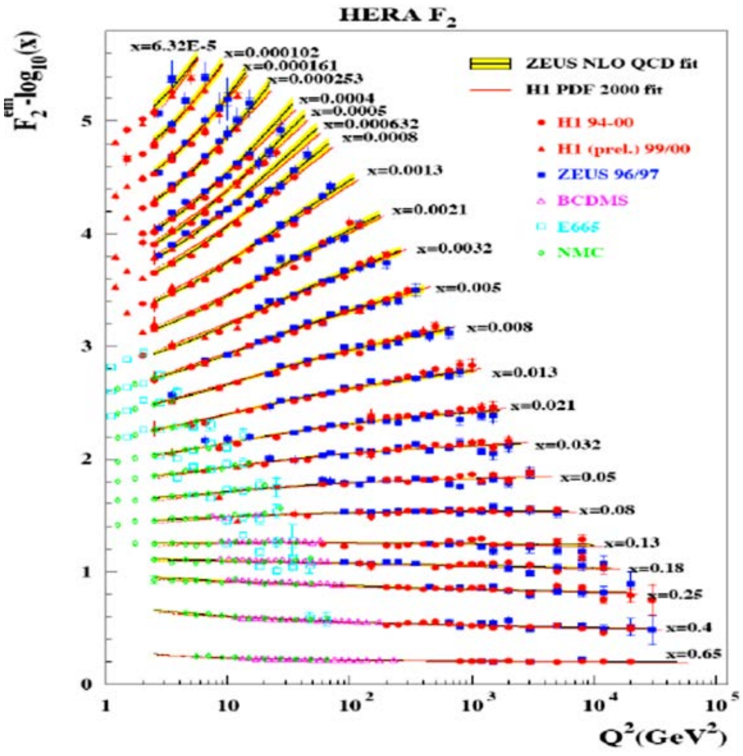
Uniform acceptance

Excellent particle identification

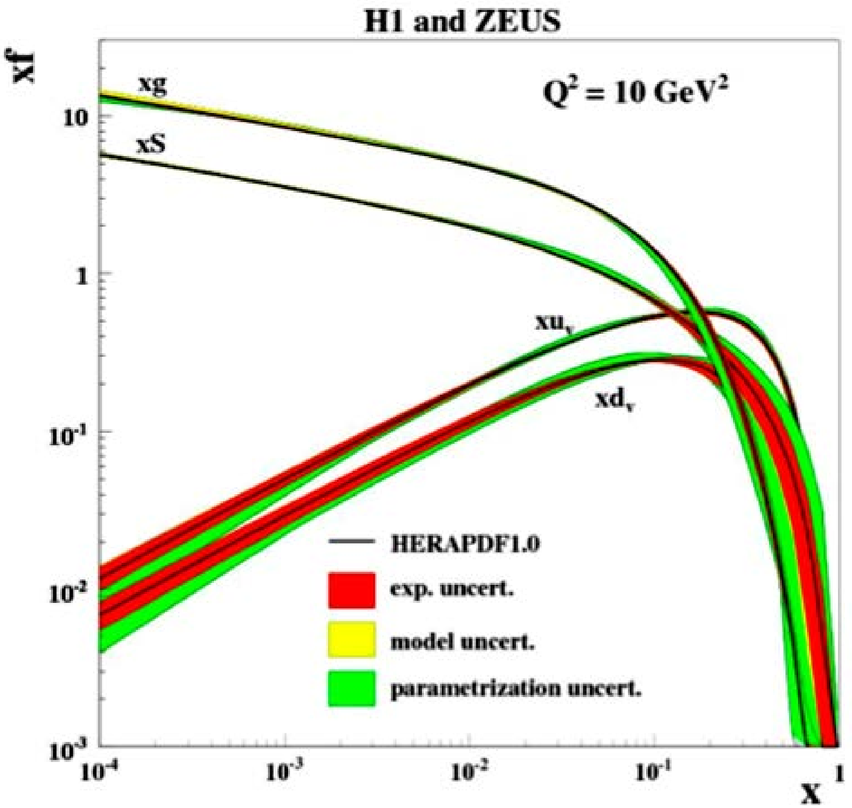
Longitudinal spin structure:
Gluon and anti-quark polarization

Gluon polarization **without** RHIC data

Unpolarized input data



Unpolarized PDFs

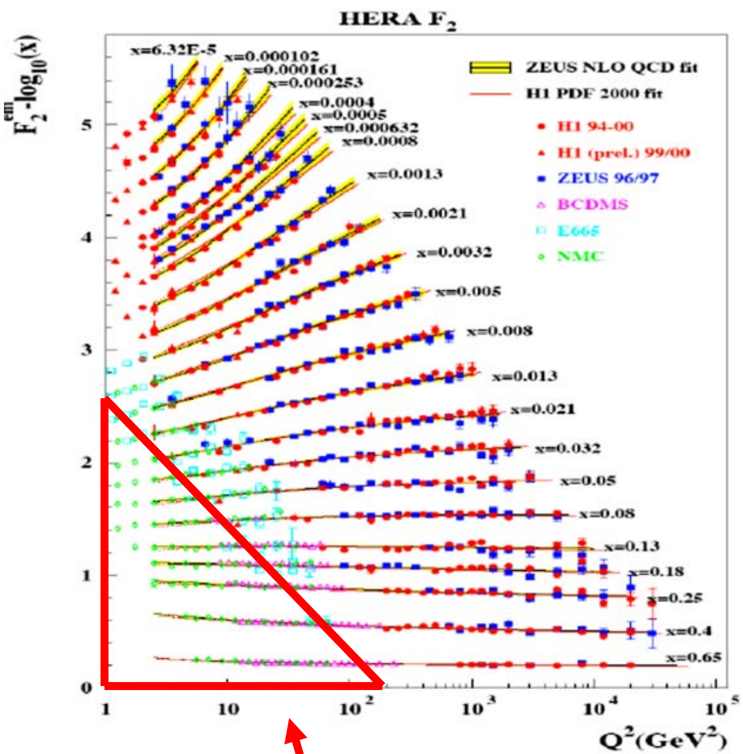


Gluon polarization **without** RHIC data

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

Polarized DIS: ~0.3

Poorly constrained by DIS

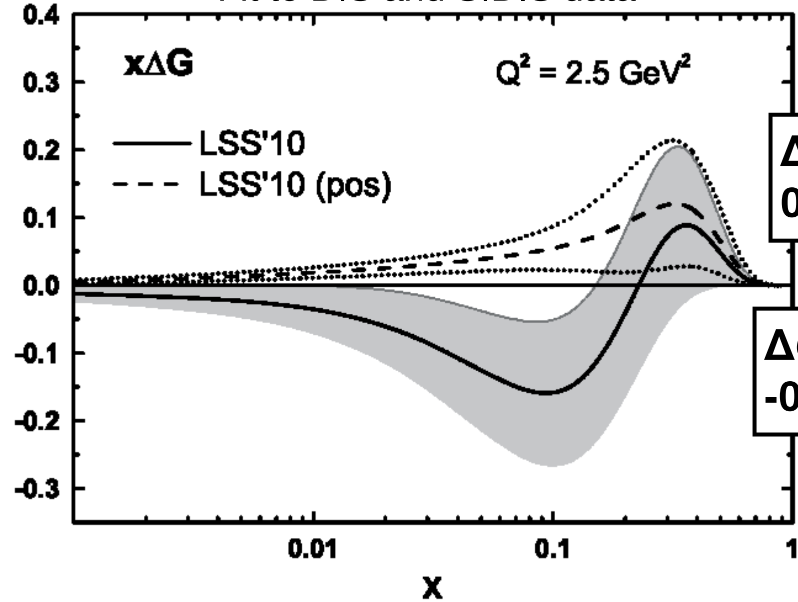


Kinematic region of ***polarized*** measurements

Polarized PDF

Leader et al, PRD 82, 114018 (2010)

Fit to DIS and SIDIS data



ΔG = 0.32±0.19

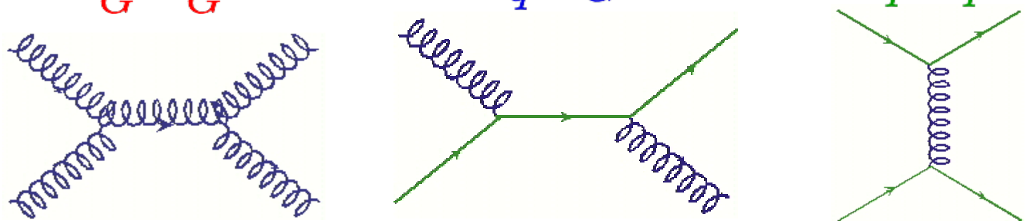
ΔG = -0.34±0.46

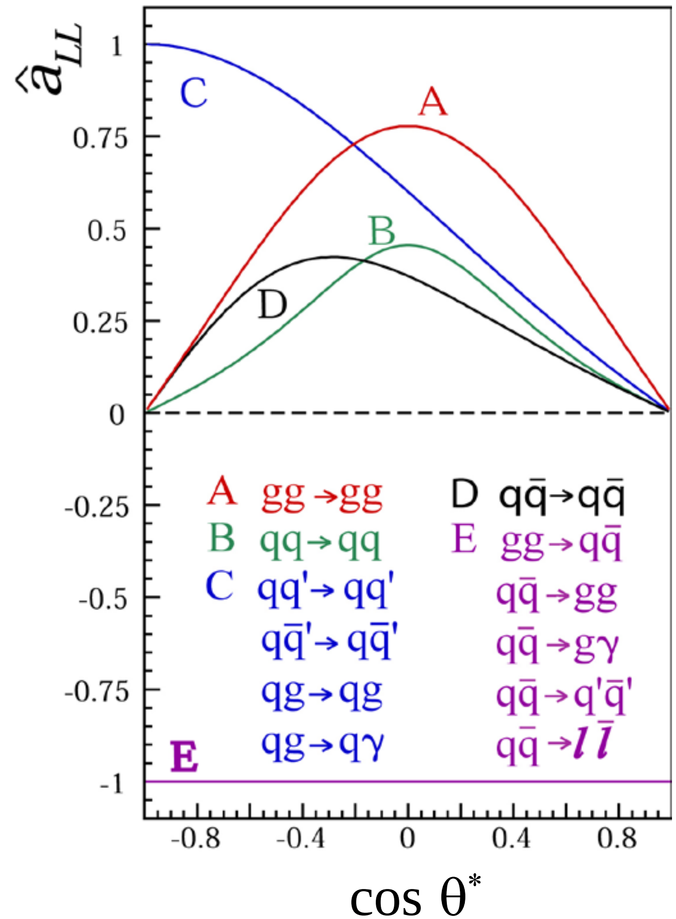
Exploring gluon polarization at RHIC

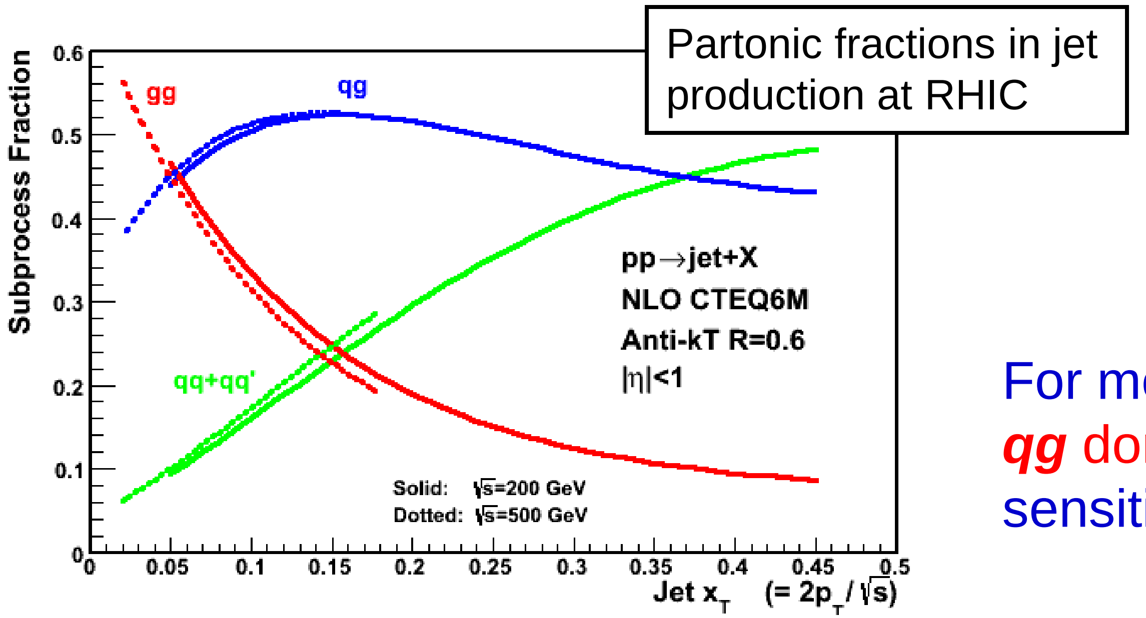
$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \propto \frac{\Delta f_a \Delta f_b}{f_a f_b} \hat{a}_{LL}$$

Δf: polarized parton distribution functions

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



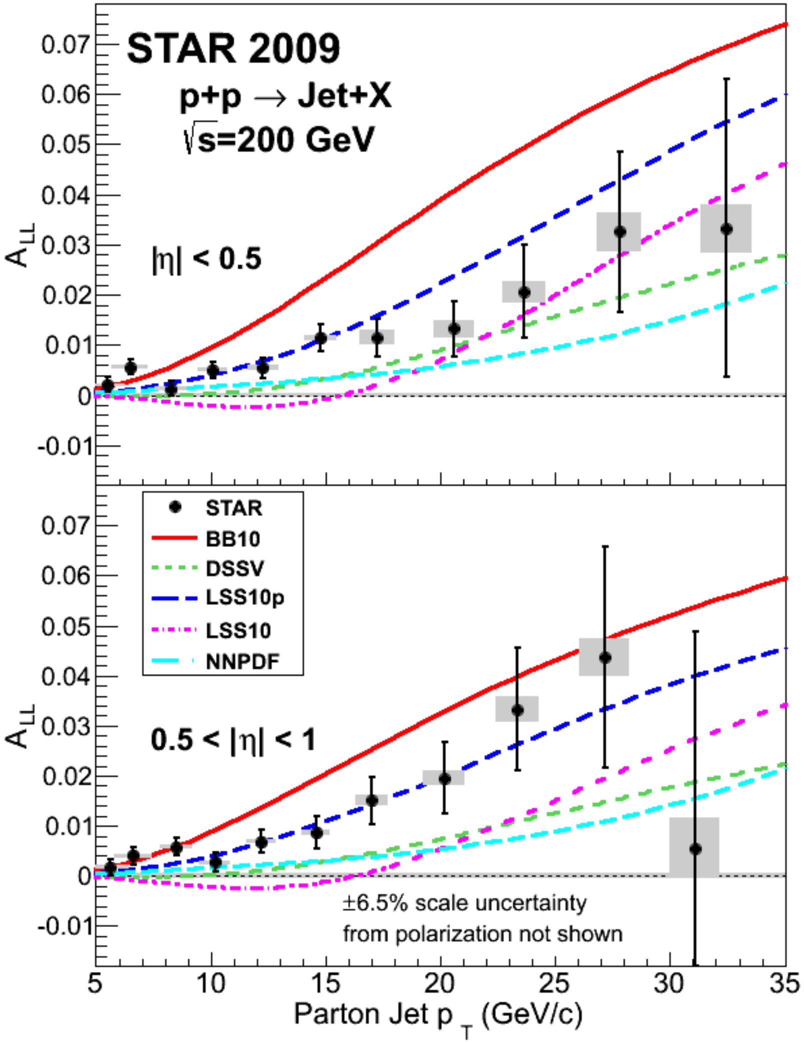




For most RHIC kinematics, ***gg*** and ***qg*** dominate, making ***A_{LL}* for jets** sensitive to **gluon polarization**.

Inclusive jet A_{LL} from the 2009 RHIC run

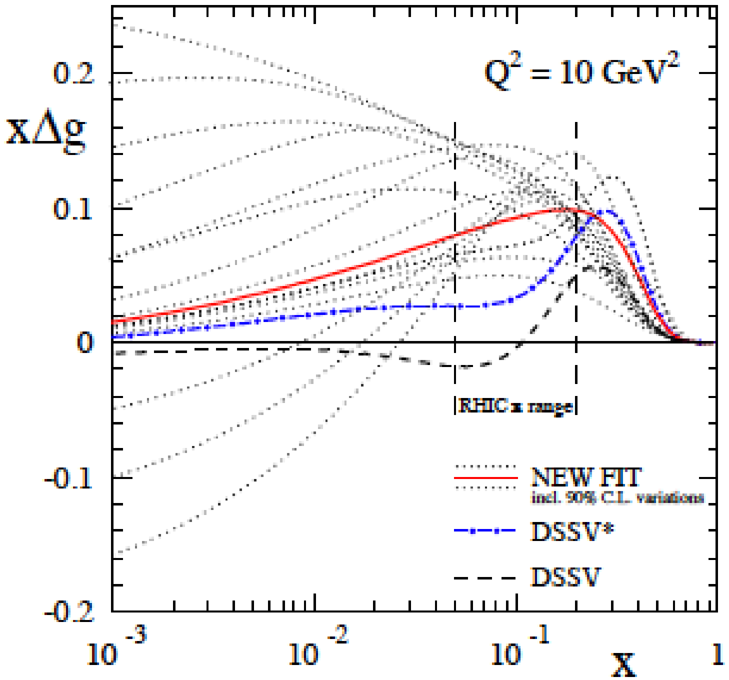
STAR PRL 115, 092002



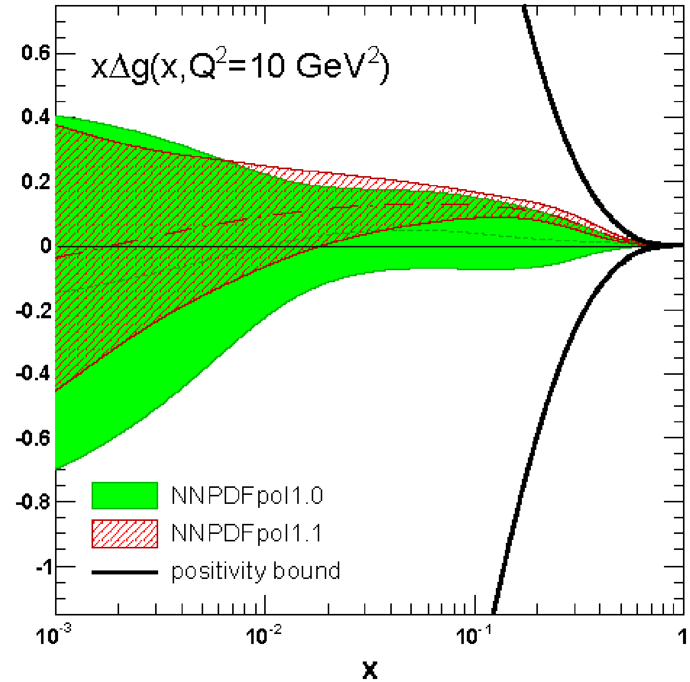
- STAR measured A_{LL} for inclusive jets at 200 GeV during the 2009 RHIC run
- Results draw a narrow road through the previous predictions
- **Far more precise** than previous measurements
- Systematically larger than expected by DSSV'08
- **Positive gluon polarization** in the sampled region $x > 0.05$

Gluon polarization **with** RHIC data

DSSV, PRL 113, 012001



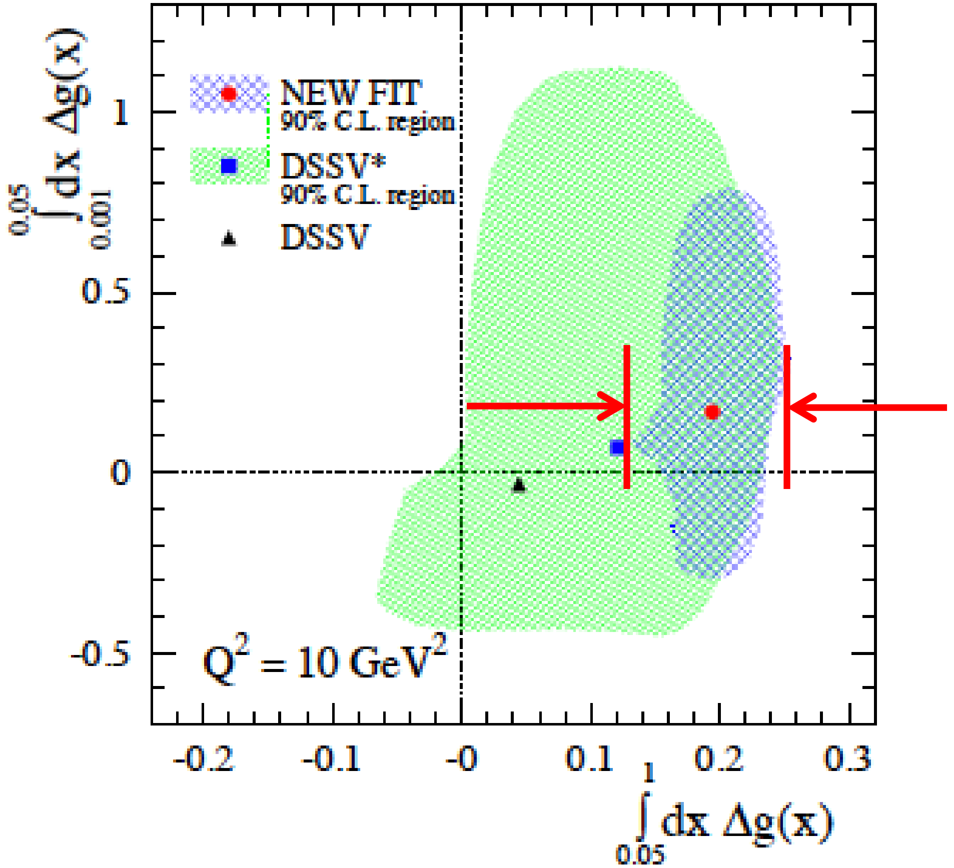
NNPDF, NPB 887, 276



- 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

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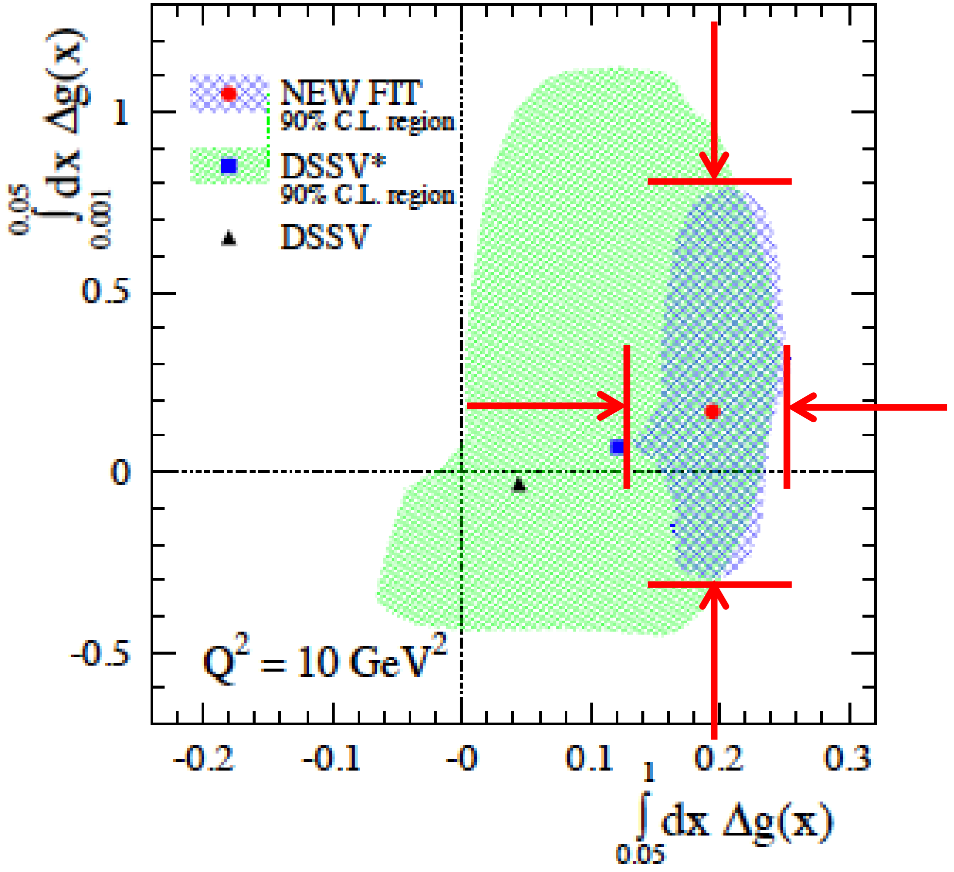
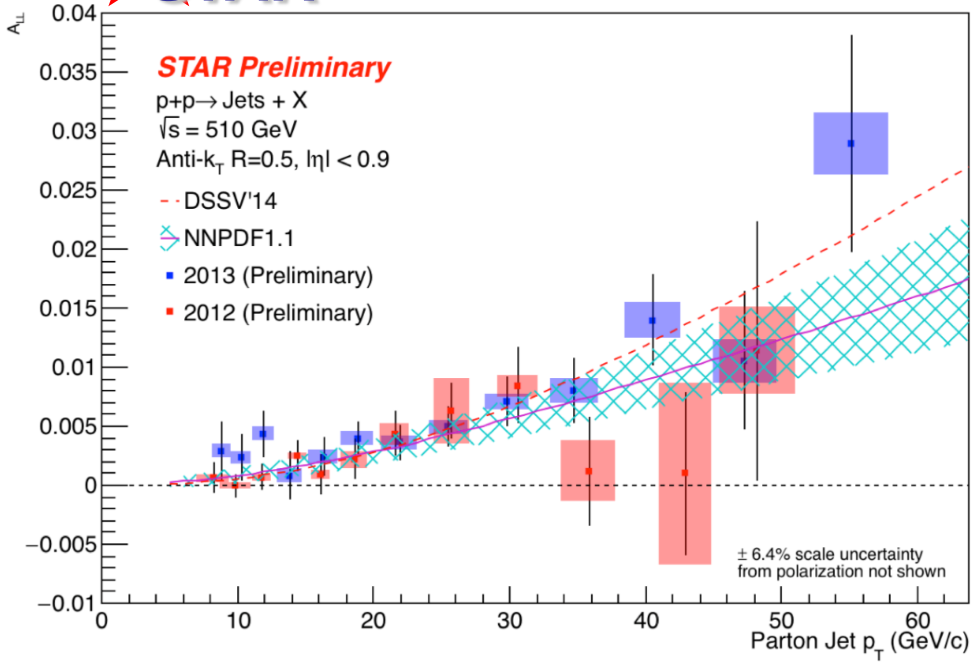
DSSV, PRL 113, 012001



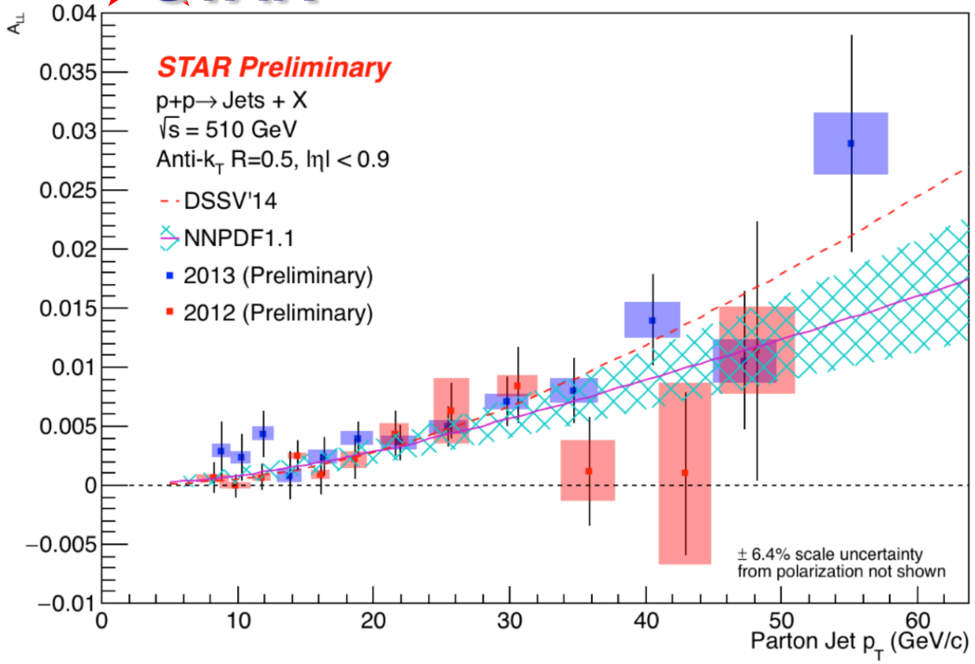
- Need to **increase precision** **in the currently sampled region** to consolidate the observation of non-zero gluon polarization
- Need to **extend sensitivity** **to lower x_g** where current extrapolations have very large uncertainties

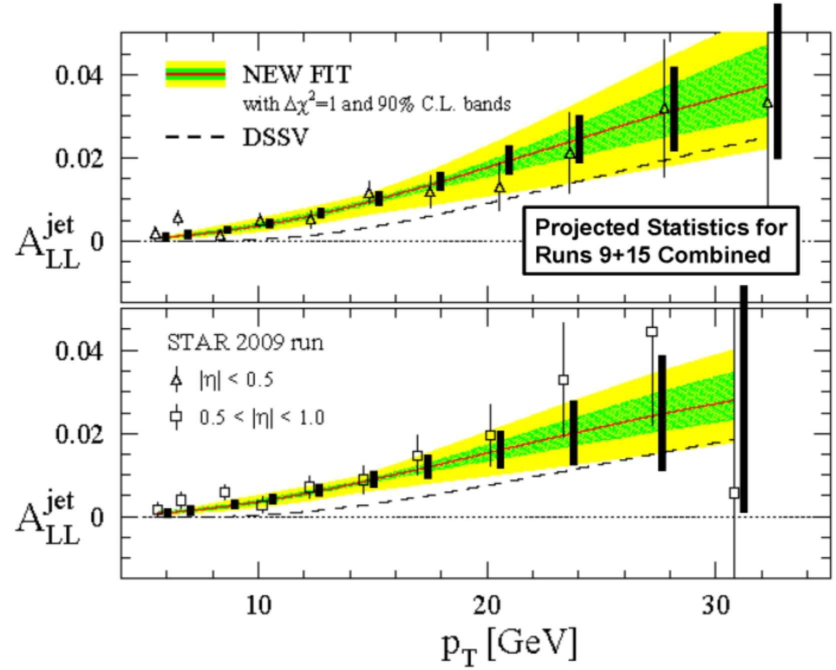
Next steps



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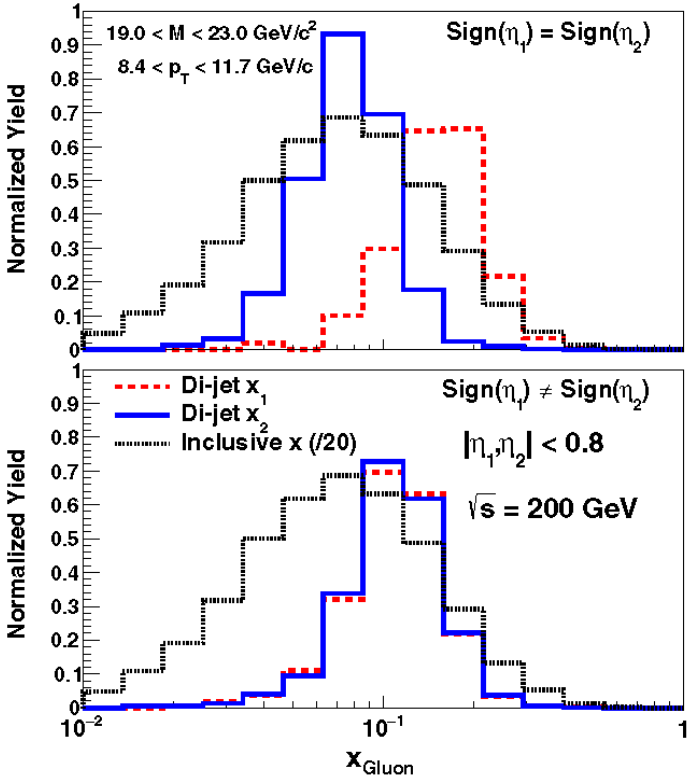
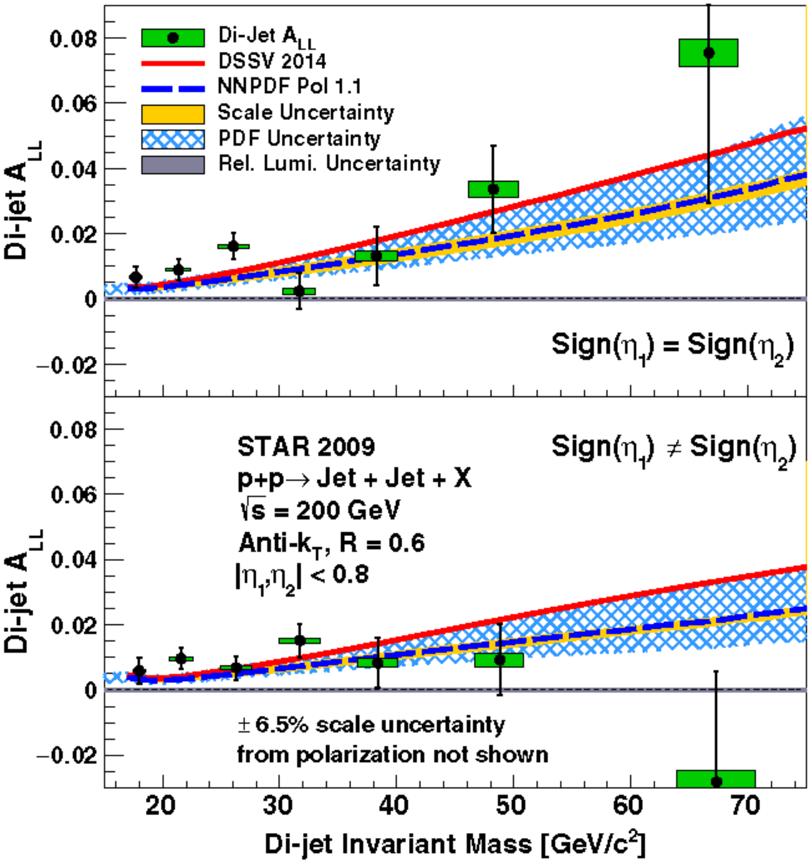
  - Higher center-of-mass energy probes **lower *x* partons**
- **A_{LL} at 510 GeV is well described by global fits** that previously gave a good description of the 2009 measurements at 200 GeV
- STAR took additional 200 GeV pp data during 2015
  - Will reduce uncertainties for A_{LL} at 200 GeV by a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

Further constraining the *x* dependence

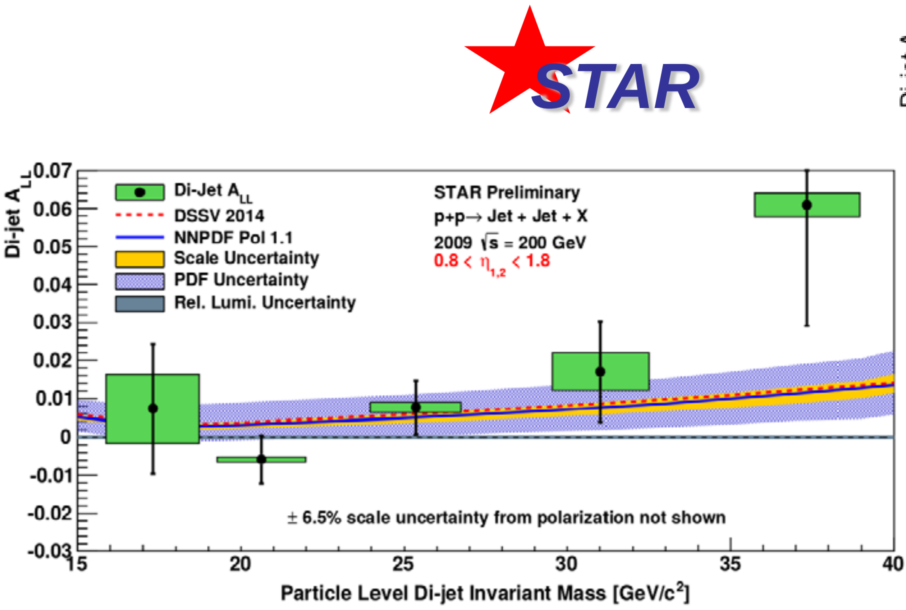
STAR PRD 95,071103(R)

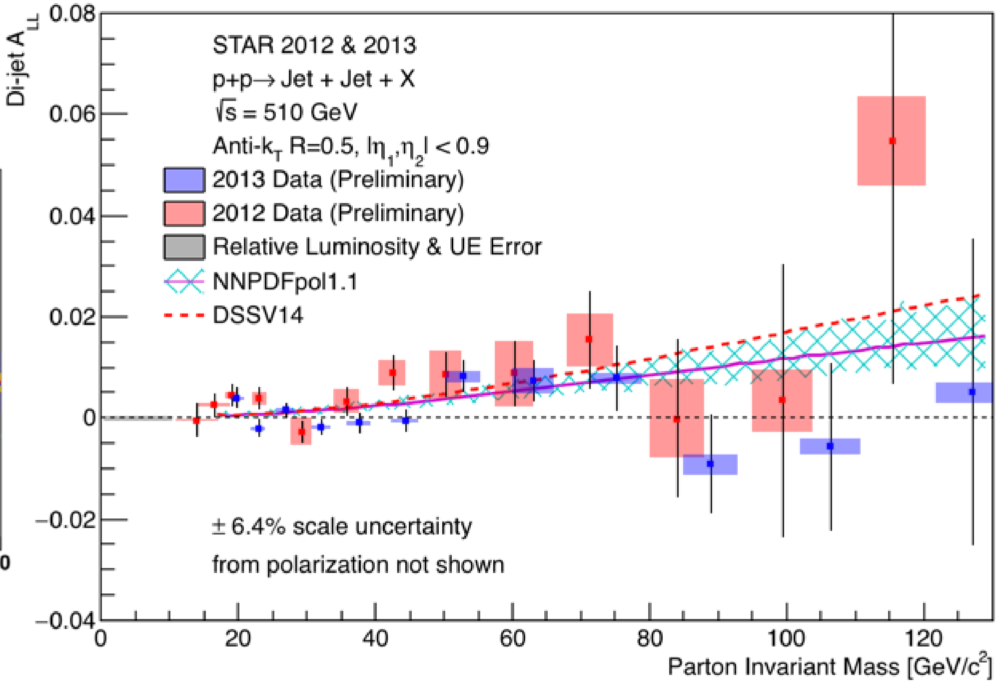




- Di-jet measurements sample a much narrower range of *x* values than inclusive jets
- Use to constrain the shape of $\Delta g(x)$
  - Minimize extrapolation errors outside the sampled region

Di-jets at forward rapidity and higher √s



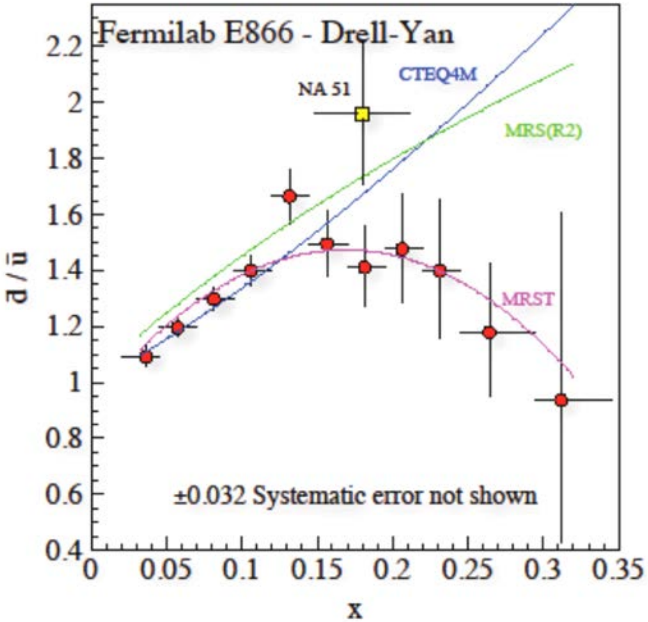


- Di-jet measurements at forward rapidity and higher √s provide more precise mapping of $\Delta g(x)$ at lower x
  - Reaching x of ~0.02 now
  - Will push well below x ~ 0.01 with additional data that has already been recorded
  - Will reach $x \sim 10^{-3}$ in several years with a forward upgrade

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

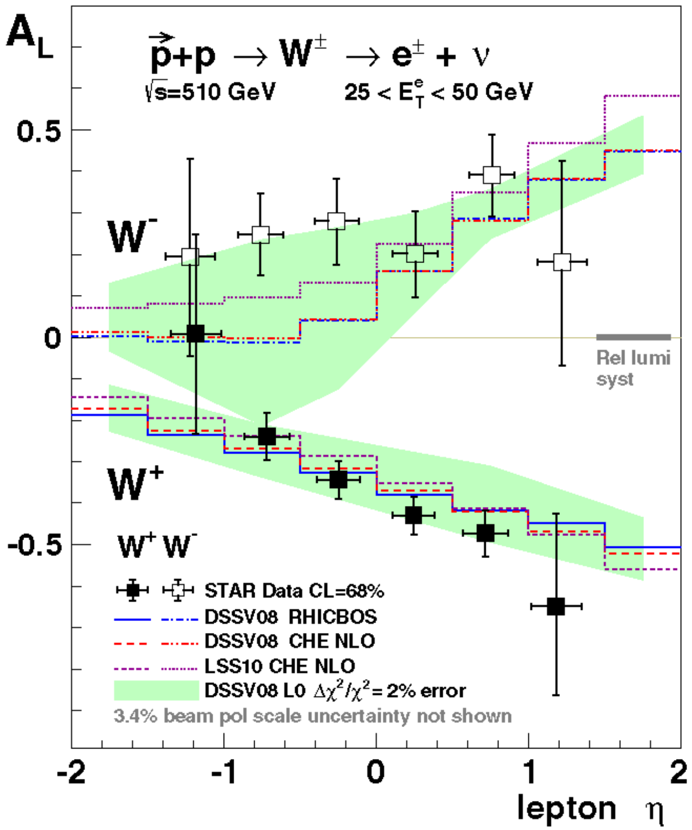


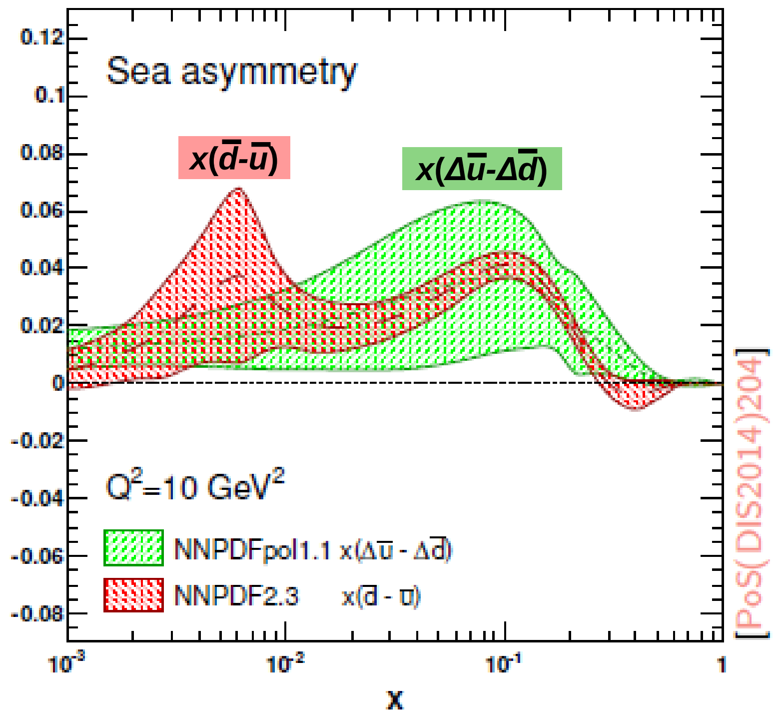
PRD **64**, 052002 (2001)

- 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

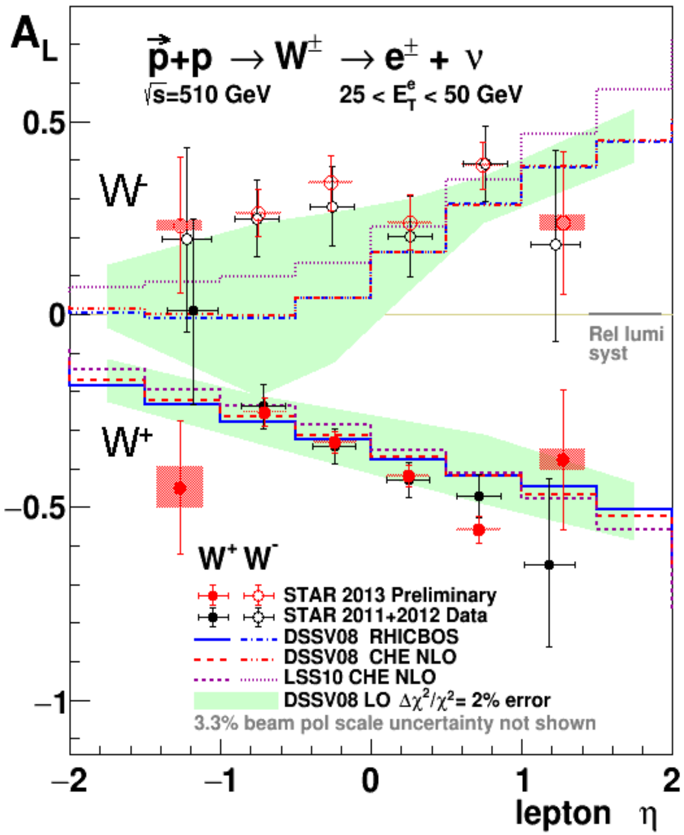
STAR PRL 113, 072301

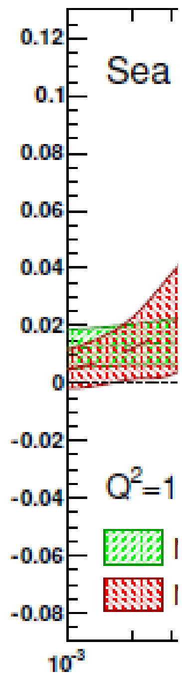


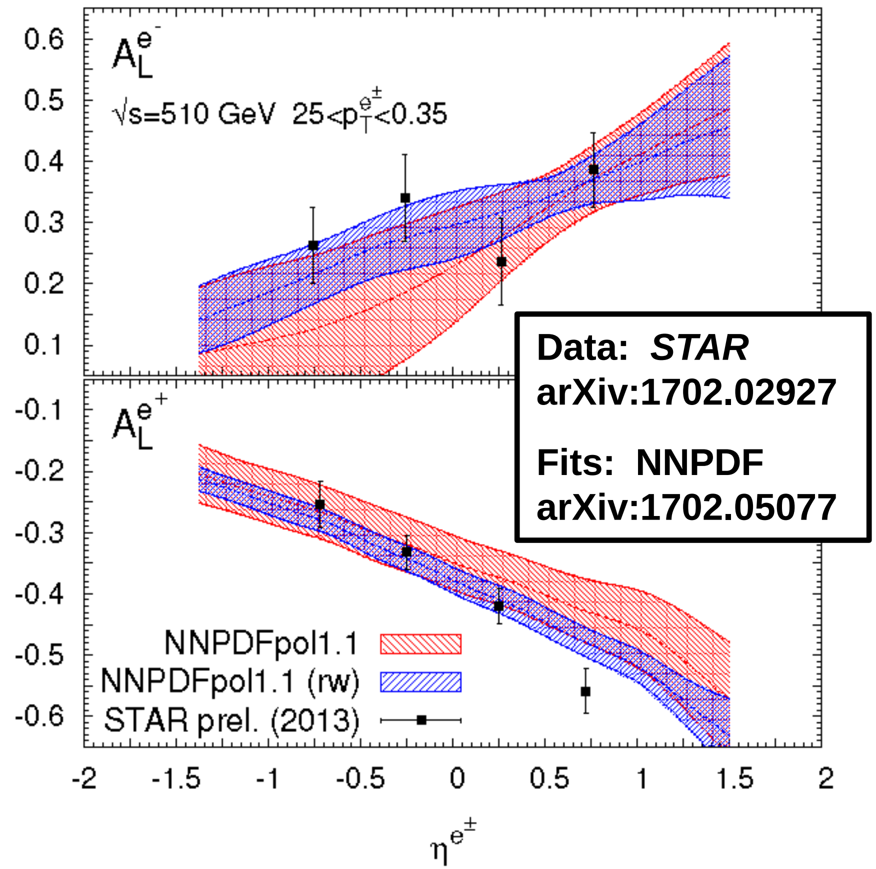


- $W^{+/-}$ asymmetries from 2012 data hint at $\Delta\bar{u} > \Delta\bar{d}$
  - This is opposite from the unpolarized distributions

W A_L and anti-quark polarization



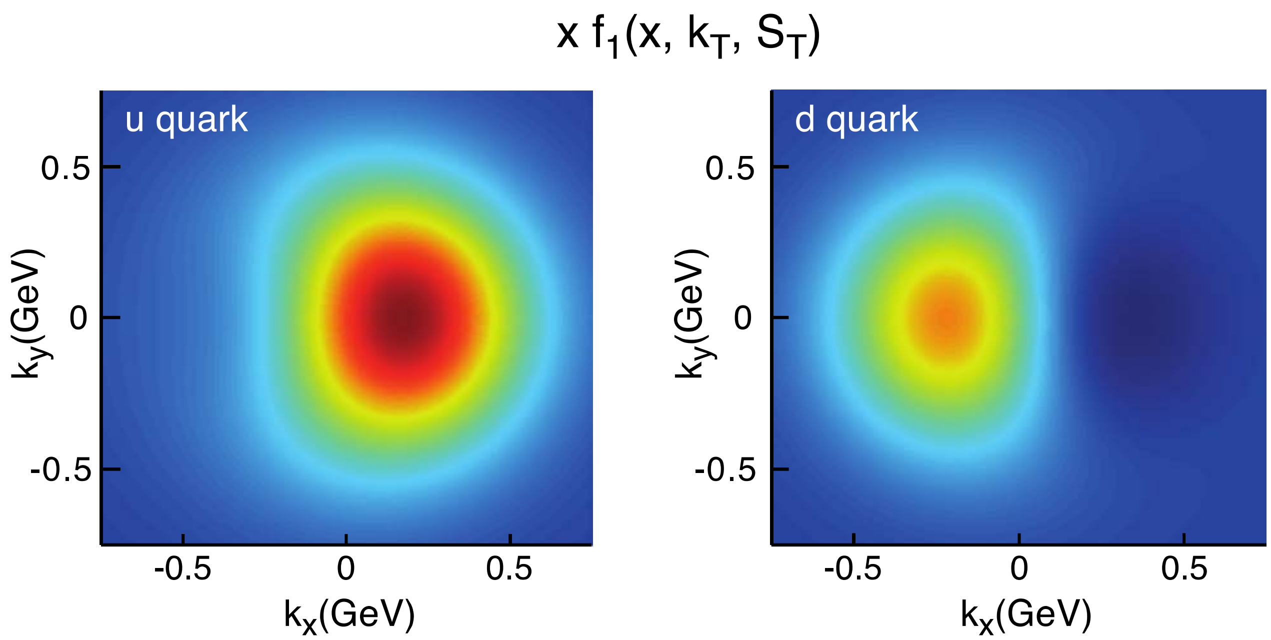




- $W^{+/-}$ asymmetries from 2012 data hint at $\Delta\bar{u} > \Delta\bar{d}$
  - This is opposite from the unpolarized distributions
- Preliminary results from 2013 with much smaller uncertainties **strengthen the hint**

Transverse spin structure: TMDs and visualizing color interactions

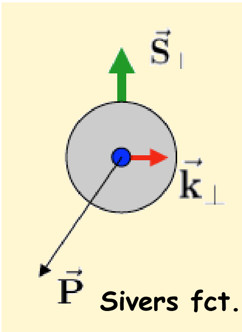
Why TMDs?

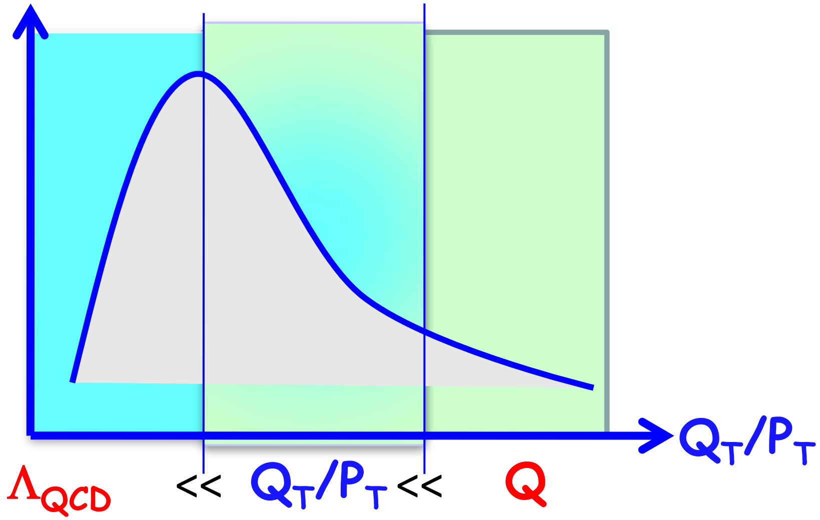


- Image the transverse and longitudinal (2+1d) structure of the nucleon and nuclei
  - **Tomography of the nucleon!**
- Access to transverse momenta at non-perturbative scales
  - Probe at the confinement scale
- Exhibit correlations arising from spin-orbit effects

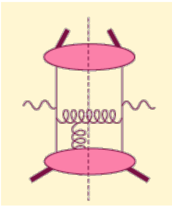
Initial state: TMDs and Twist-3

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

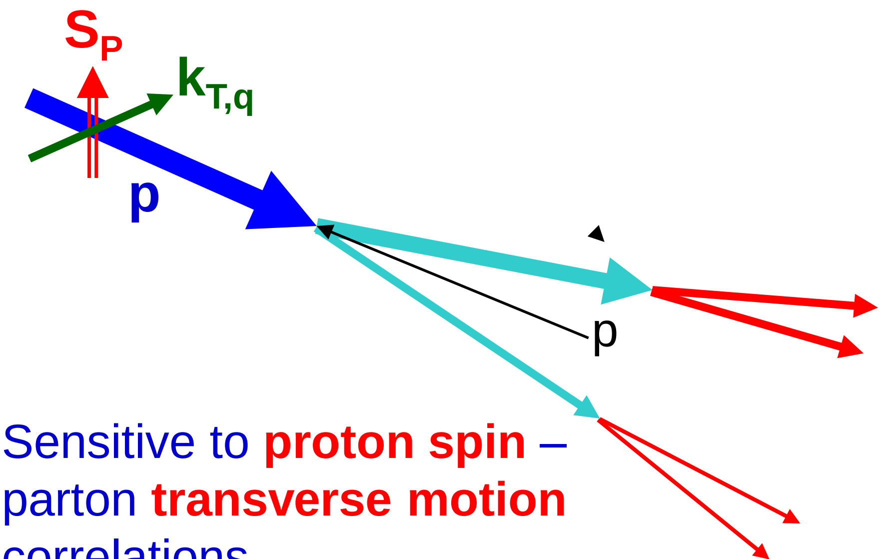
Appropriate for inclusive $A_N(\pi^0, \gamma, \text{jet})$

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

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

Separating initial- from final-state effects

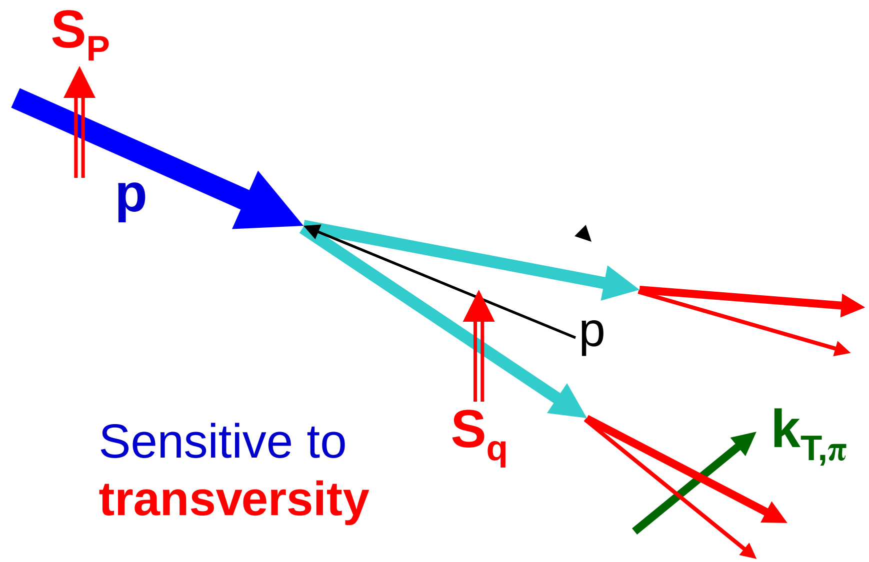
Sivers or twist-3 mechanisms:



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**

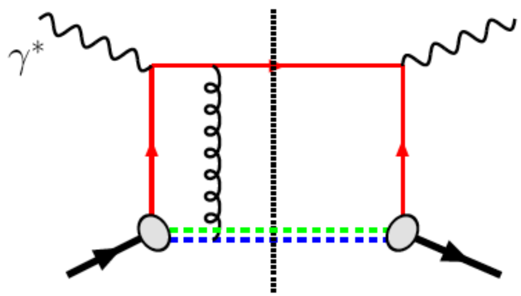
- Signatures:
  - Collins effect
  - Interference fragmentation functions (IFF)
  - A_N for pions → novel FF
- Collins predicted to be universal

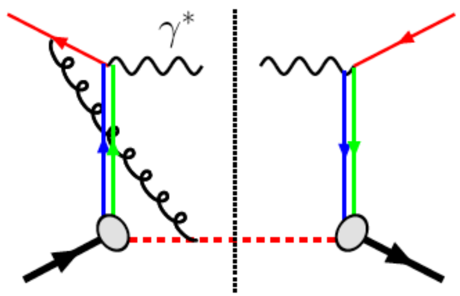
Color interactions in QCD

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**





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

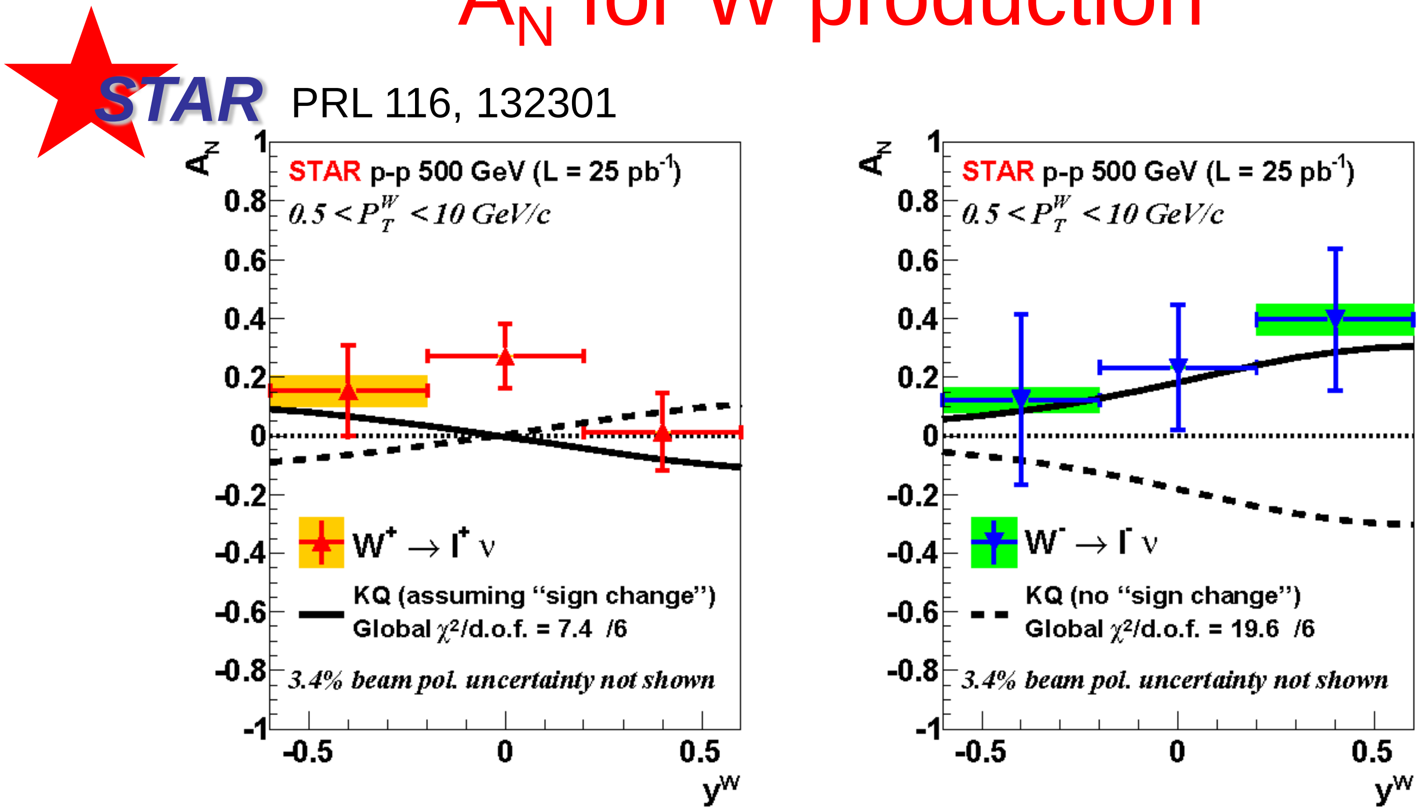
A_N for direct photon has related sign change in Twist-3

Critical test of factorization

Opportunity to visualize the repulsive interaction between like color charges

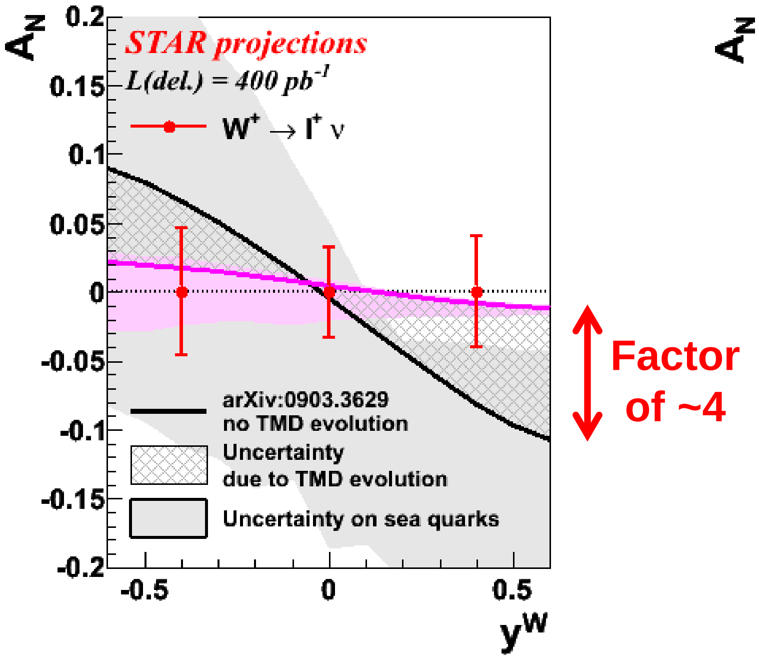
Can explore all of these observables in 510 GeV pp collisions at RHIC

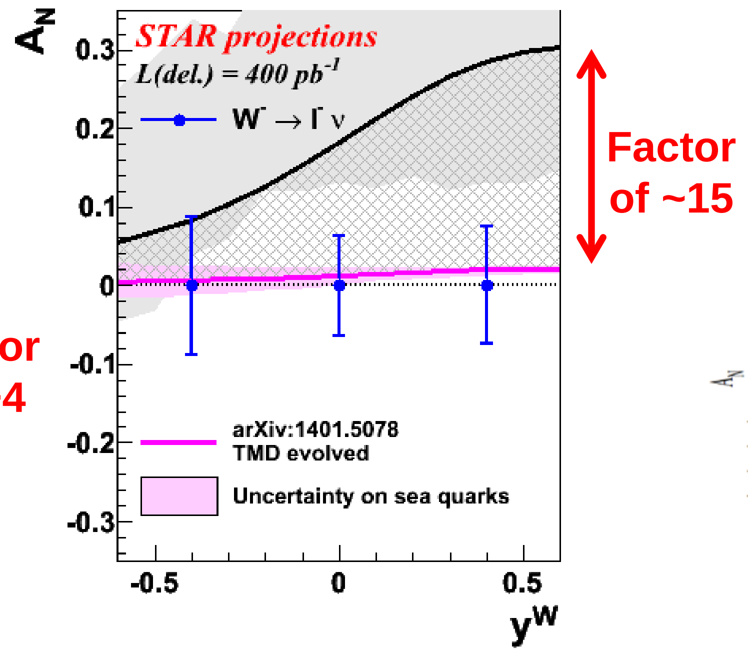
A_N for W production

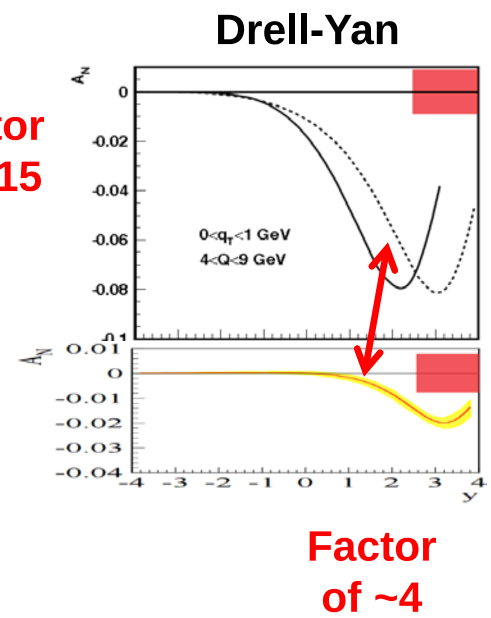


- STAR performed an exploratory measurement of A_N for W production with a small data set recorded in 2011
  - W kinematics fully reconstructed
- Favors **sign change** if evolution effects are modest
  - TMD evolution is non-perturbative at low $k_\perp$ - no absolute theory predictions

Definitive measurement



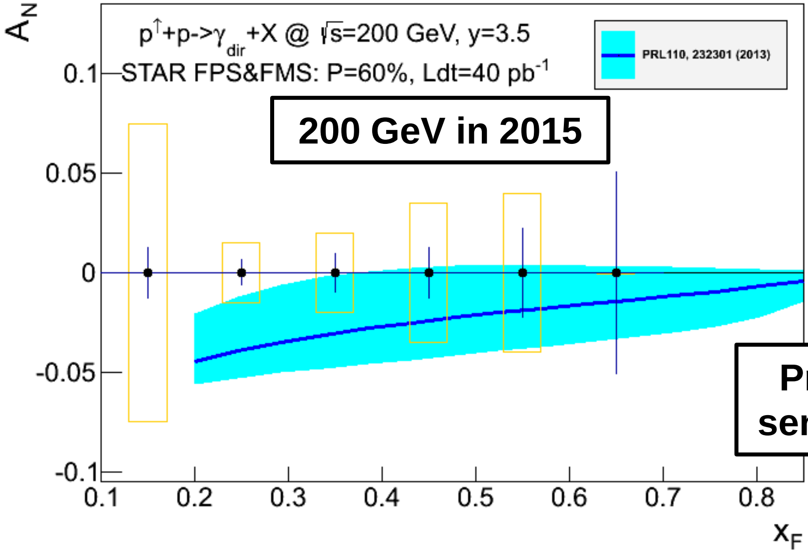


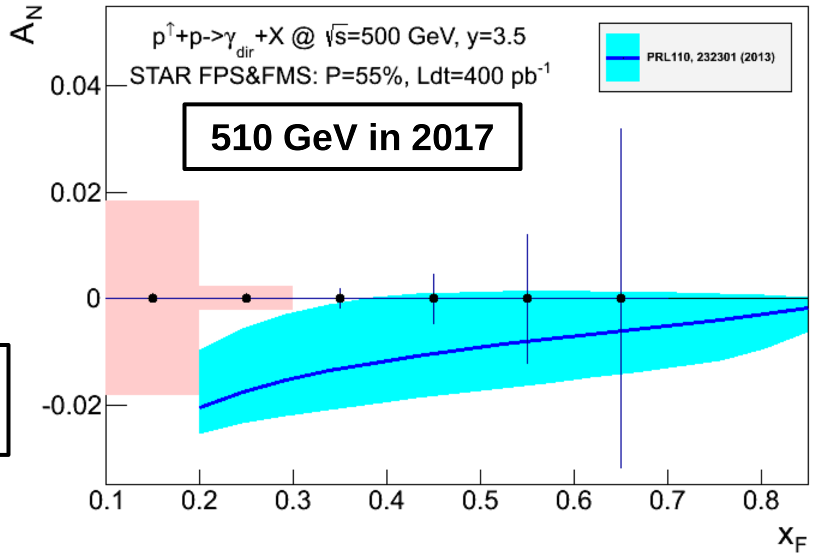


- See the sign change if evolution effects are less than factor of 5
- Probe anti-quark Sivers function for the first time
- Directly measure the evolution effects
  - Need new data to constrain non-perturbative contribution
  - Access similar observables at comparable x but very different Q^2
    -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

Recently completed 2017 RHIC run

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

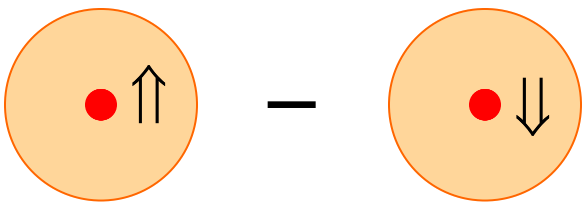
Not a replacement for A_N(W, Z, DY), but an
important complementary piece of the puzzle

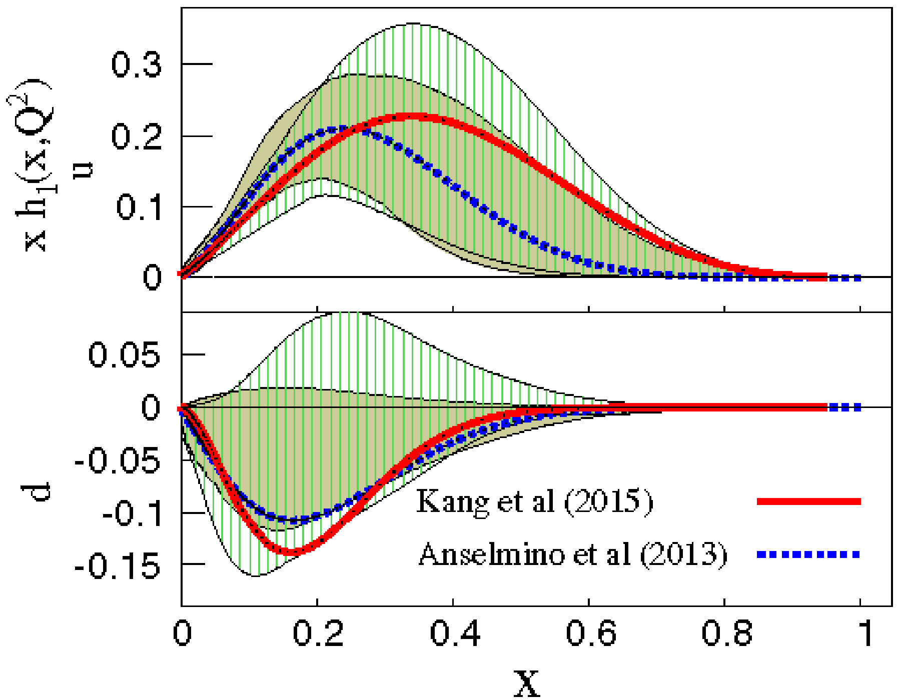
Transversity

Proton momentum →
Proton spin ↑

δq(x)

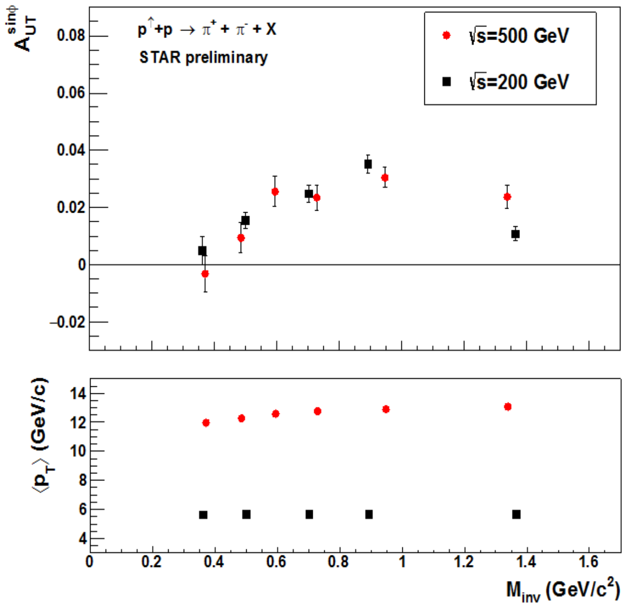
$\Delta_T q(x)$

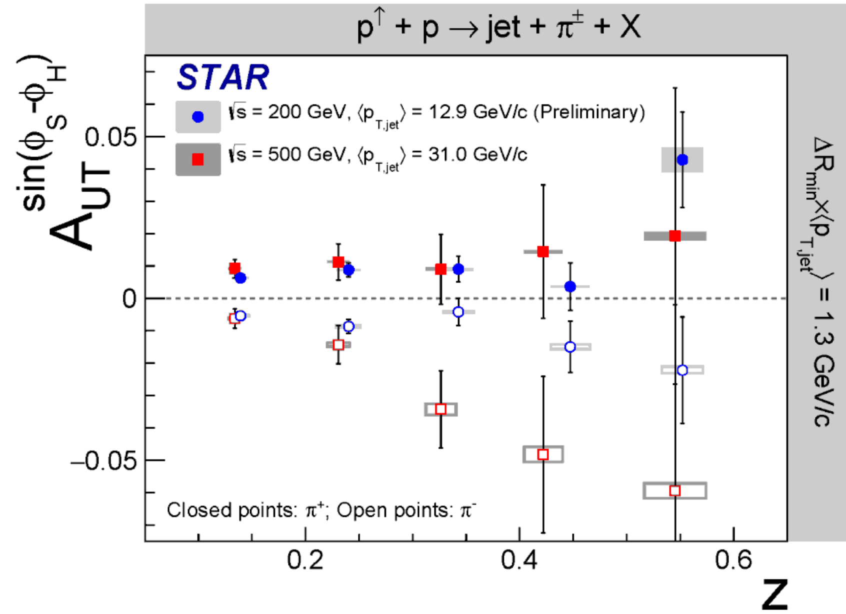




- Quark polarization along spin of a transversely polarized proton
  - Third collinear, leading twist distribution
  - Chiral odd
- Before ***STAR***, only observed in SIDIS combined with e^+e^-
- Much less data than for helicity
- Several recent global analyses including:
  - Collins effect input:
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

First transversity signals in hadronic collisions

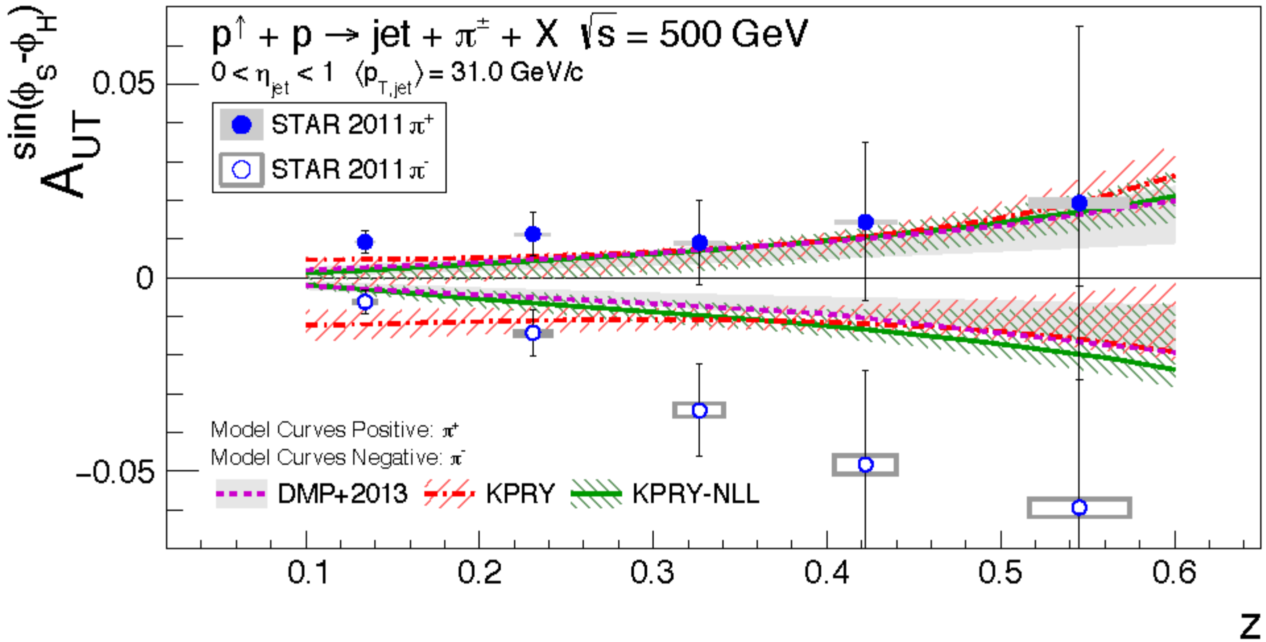




- Significant measurements of transversity convoluted with:
  - Di-hadron interference fragmentation function (IFF)
    - ***STAR*** data now in preliminary global analysis (Radici, DIS 2017)
  - Collins fragmentation function
- Both have similar magnitudes in 200 and 500 GeV pp collisions
- Observations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

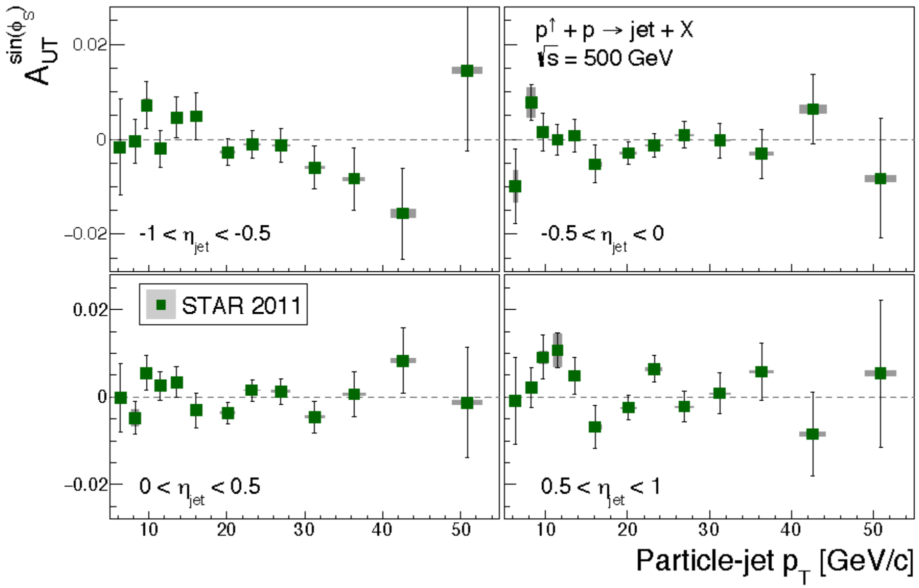


DMP: arXiv:1707.00914
KPRY: arXiv:1707.00913

- 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

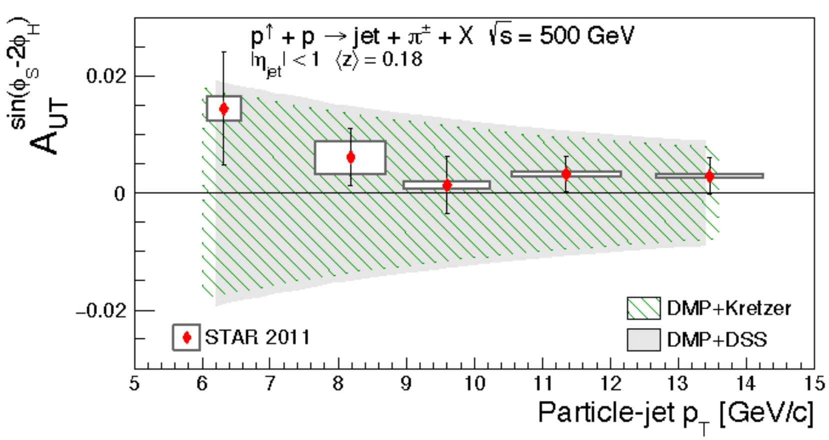
Additional azimuthal modulations

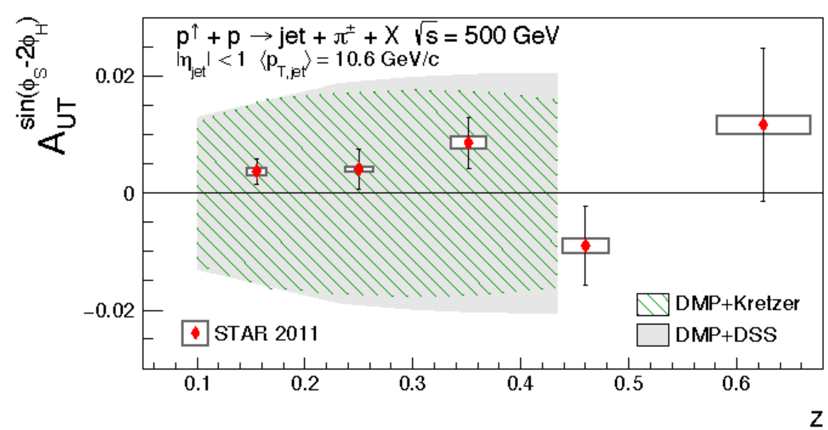
STAR arXiv:1708.07080



- Inclusive jet A_N
  - Sensitive to the gluon Sivers function via the Twist-3 relationship

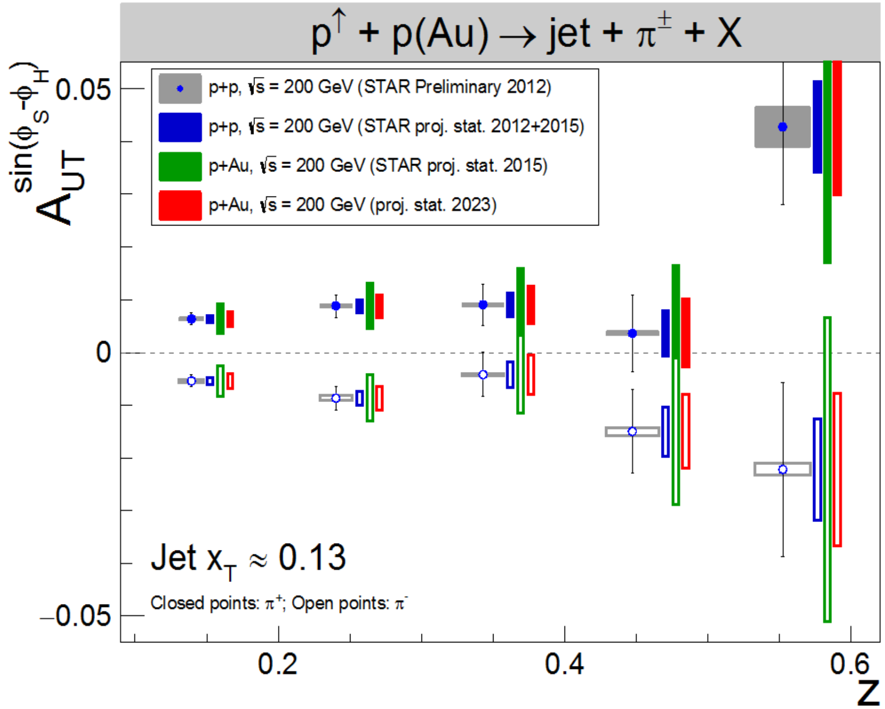
- "Collins-like" effect
  - World's first ever limit on linearly polarized gluons in a polarized proton





Projected uncertainties for upcoming results

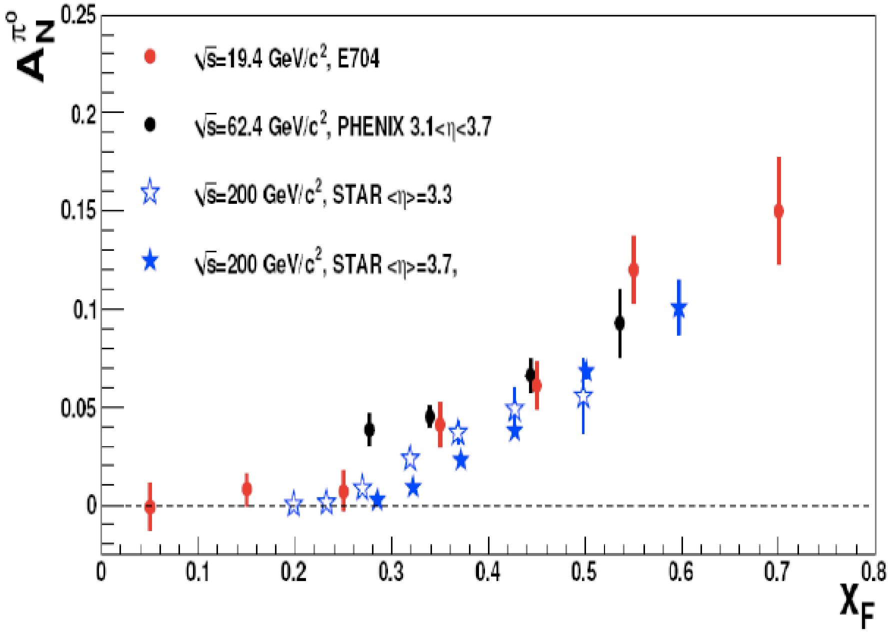
Transversity x Collins



- Final Collins results from 200 GeV collisions will be coming soon
- Recorded > 10 times as much data at 510 GeV in 2017 as in 2011
  - Precision data at fixed *x*, different √s **ideal to constrain TMD evolution**
- Also have data for a first look at the Collins effect in p+Au collisions

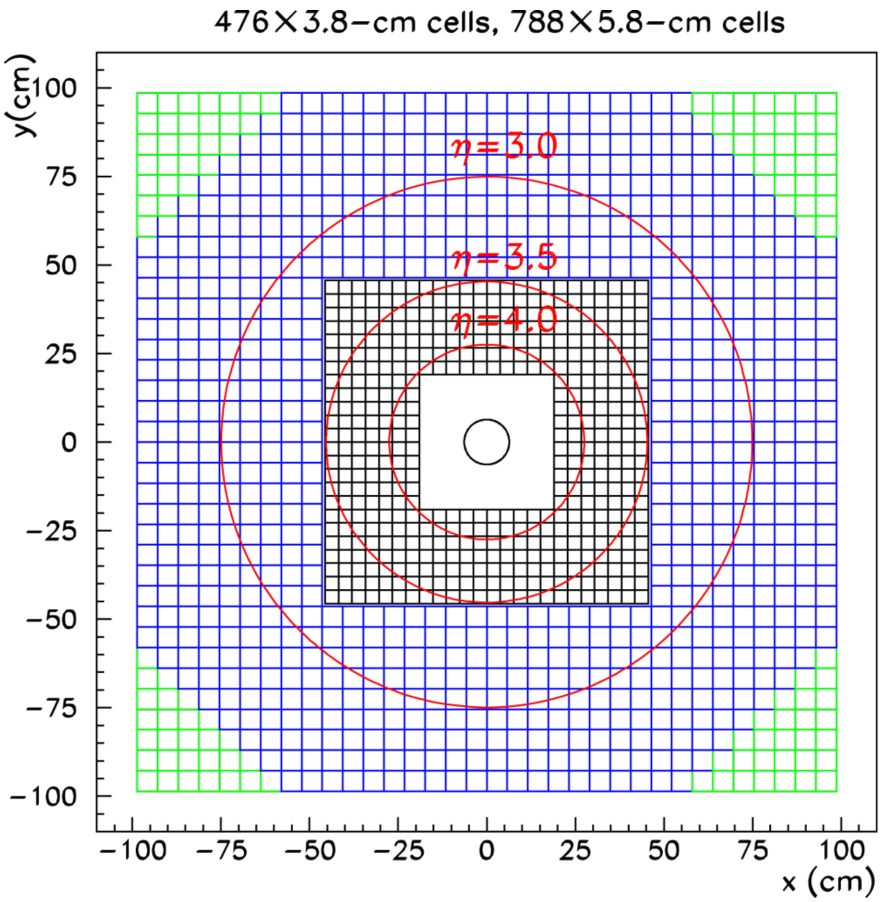
Spin and p+A physics at forward rapidities

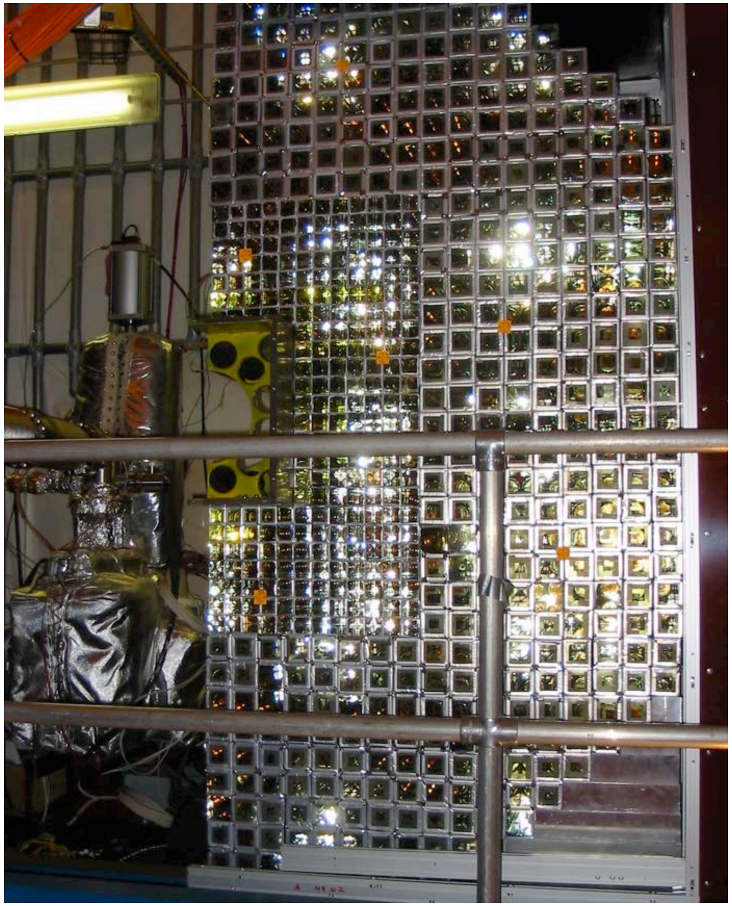
Transverse spin asymmetries in high energy p+p



- Large transverse single-spin asymmetries over a very wide range of $\sqrt{s}$
- Naïve collinear pQCD predicted A_N ~ 0.001
- May arise from
  - Initial-state effects: Sivers effect / twist-3
  - Final-state effects: Transversity + Collins fragmentation function
  - Or a combination of the two

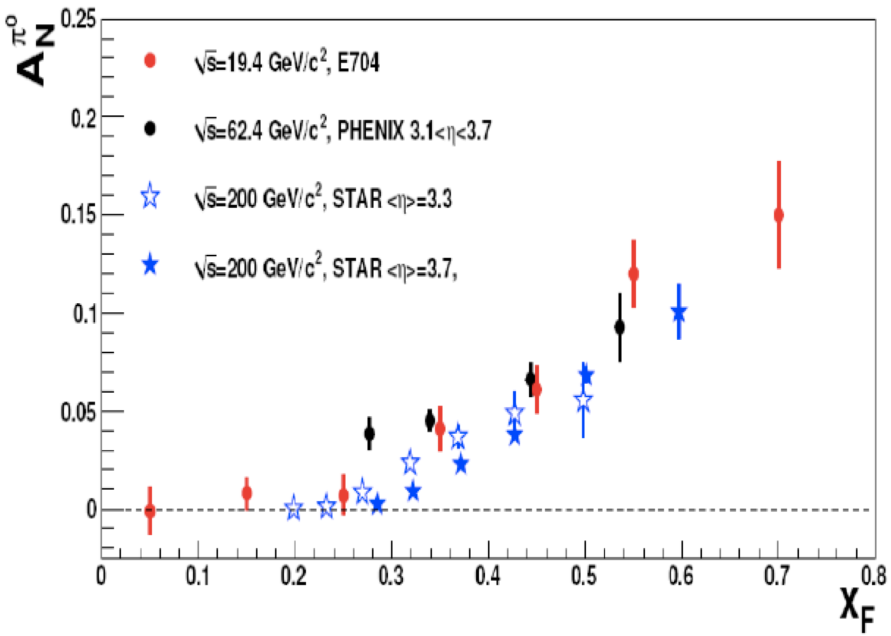
STAR Forward Meson Spectrometer: FMS

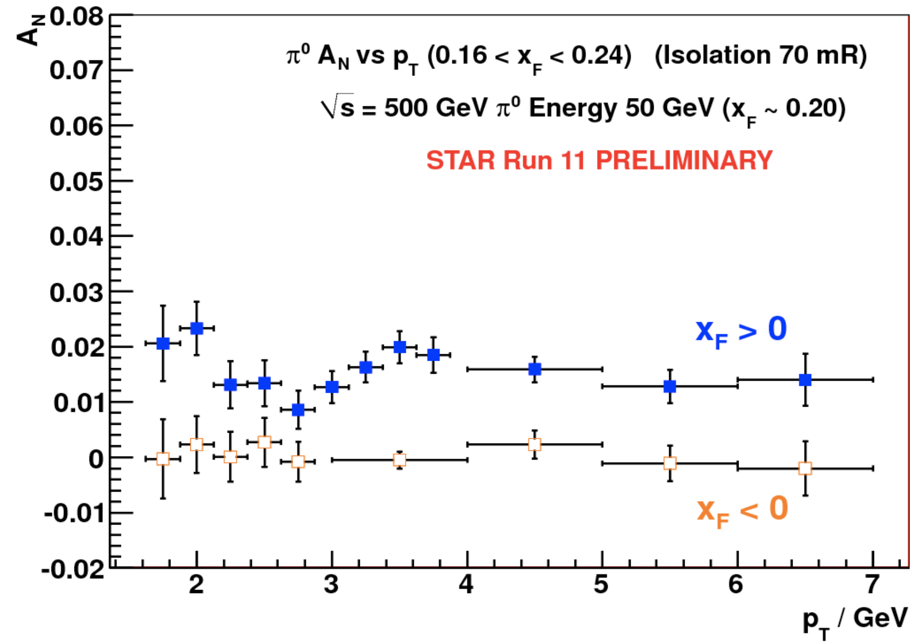




- Pb-glass EM calorimeter covering 2.6 < η < 4 and full azimuth
  - Neutral pions / eta / EM jet-like events
  - Direct photons with addition of Pre-shower before 2015 run
  - Drell-Yan and *J/ψ* with addition of Post-shower before 2017 run

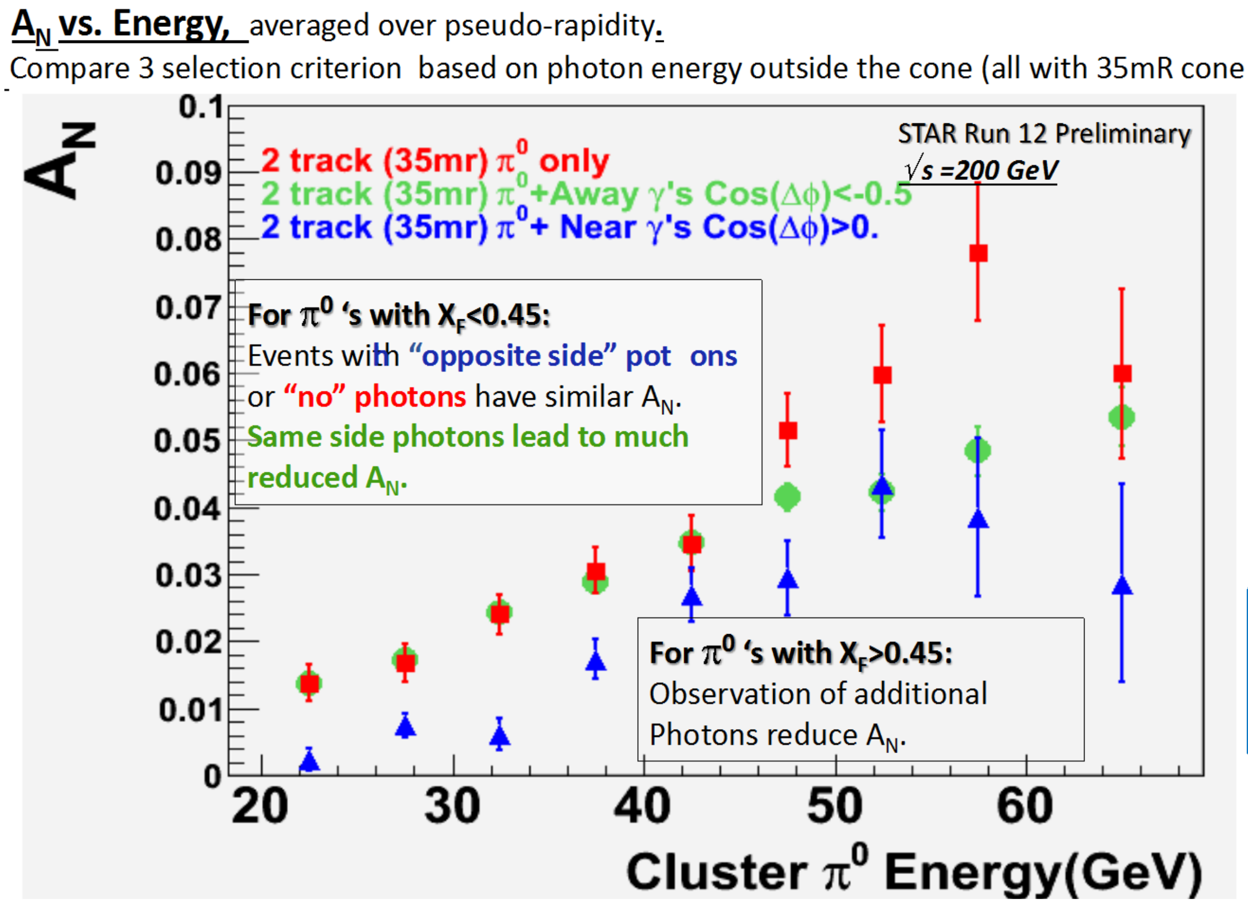
Transverse spin asymmetries in high energy p+p

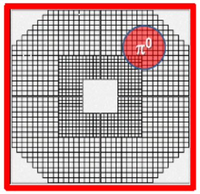


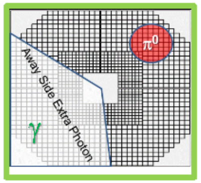


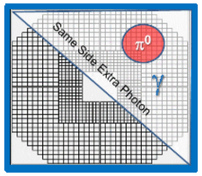
- Large transverse single-spin asymmetries over a very wide range of $\sqrt{s}$
- Naïve collinear pQCD predicts A_N ~ 0.001
- May arise from
  - Initial-state effects: Sivers effect / twist-3
  - Final-state effects: Transversity + Collins fragmentation function
  - Or a combination of the two
- Signal doesn't seem to fall-off at high p_T
  - Maybe something else ?

Forward π^0 A_N in 200 GeV pp



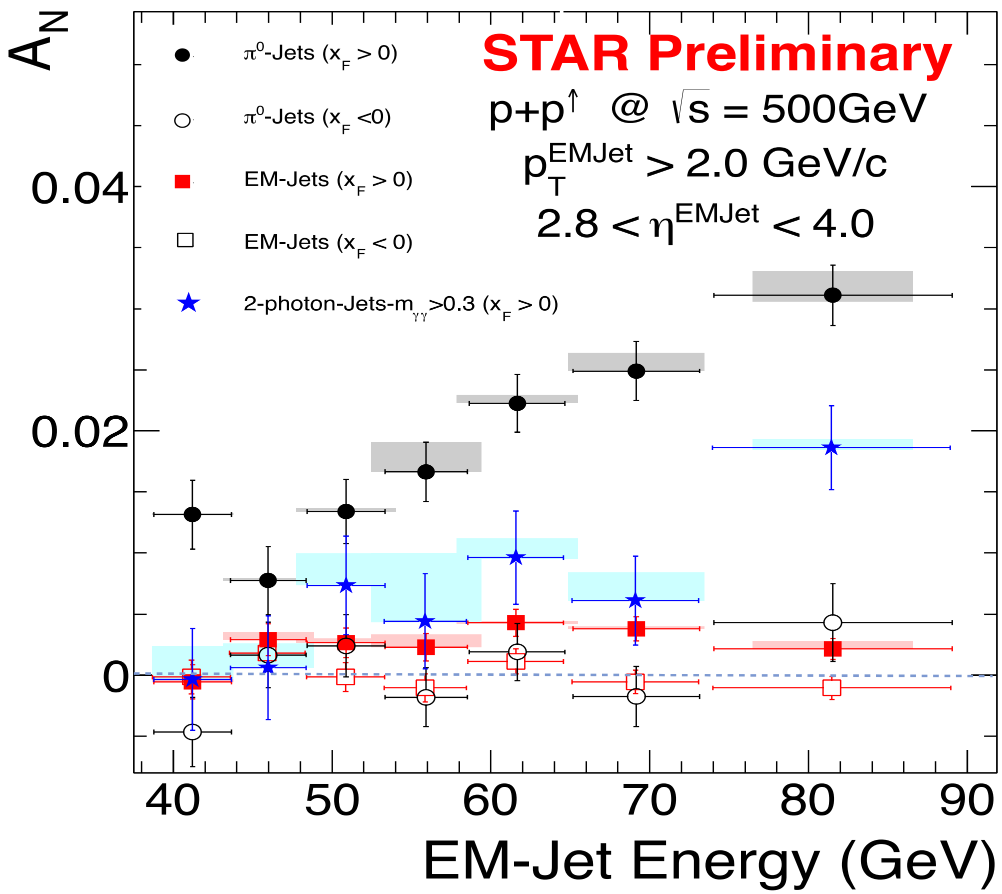






- π^0 with **opposite-side photons** or **no additional photons** have similar asymmetries
- π^0 with **additional same-side photons** lead to much reduced A_N

A_N for EM jet-like events at 500 GeV



Cluster the observed FMS photon candidates using anti-k_T with R=0.7

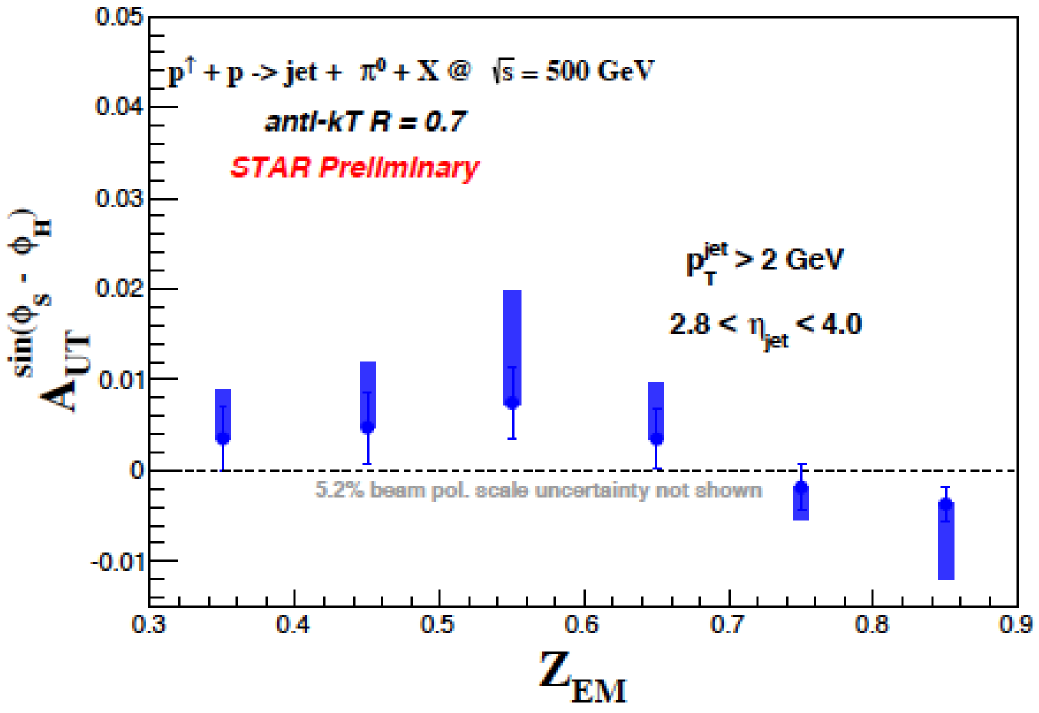
π^0-Jets –
Exactly 2 photon candidates with
$m_{\gamma\gamma} < 0.3$ GeV
$Z_{\gamma\gamma} < 0.8$

2γ-EM-Jets (η + continuum) -
$m_{\gamma\gamma} > 0.3$ GeV

EM-Jets – with
>2 photon candidates

- Isolated π^0 also have large asymmetries in 500 GeV pp
- Asymmetries for jettier events are much smaller

Collins asymmetry for π^0 in EM jet

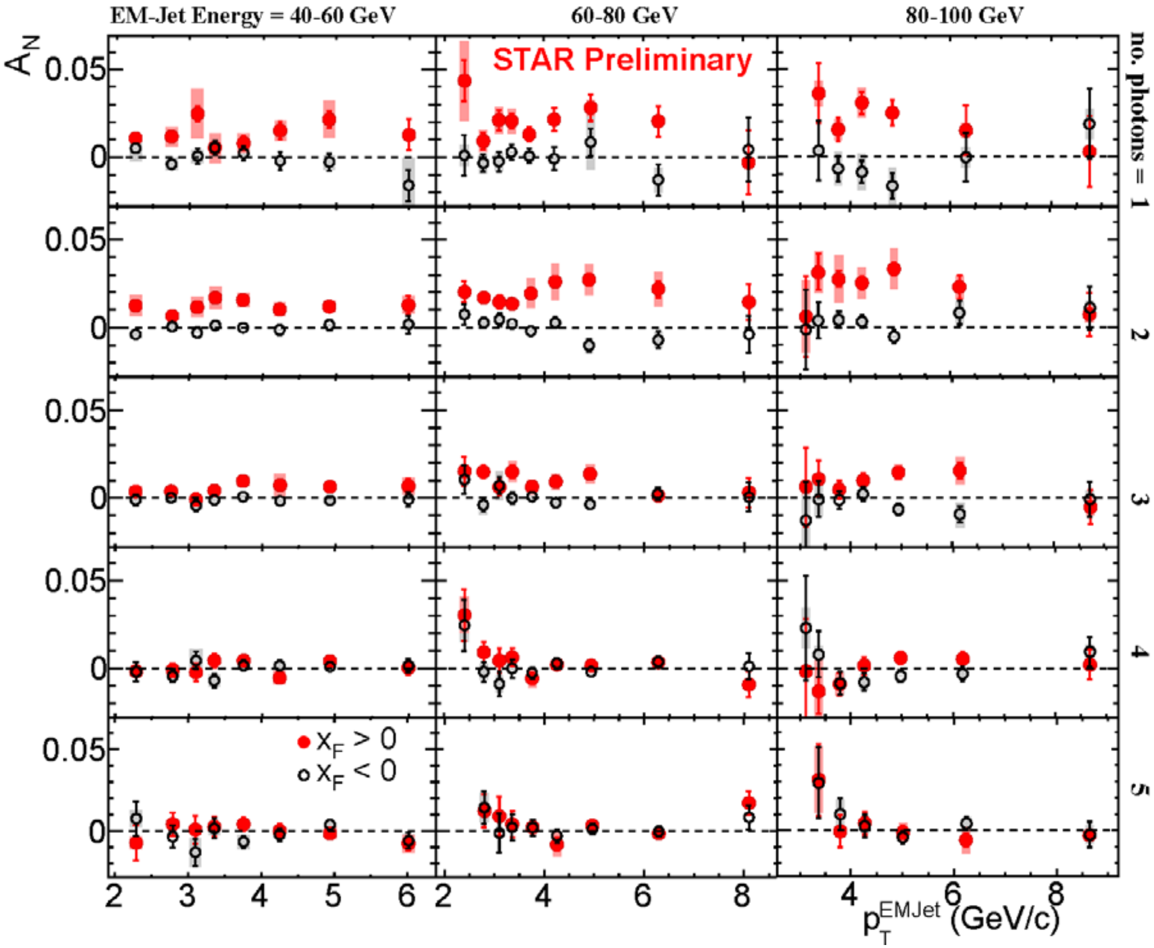


- Collins asymmetry of π^0 in EM jet-like events too small to explain the inclusive π^0 A_N

EM jet-like A_N vs number of photons

Only 1 photon candidate in anti-k_T R=0.7

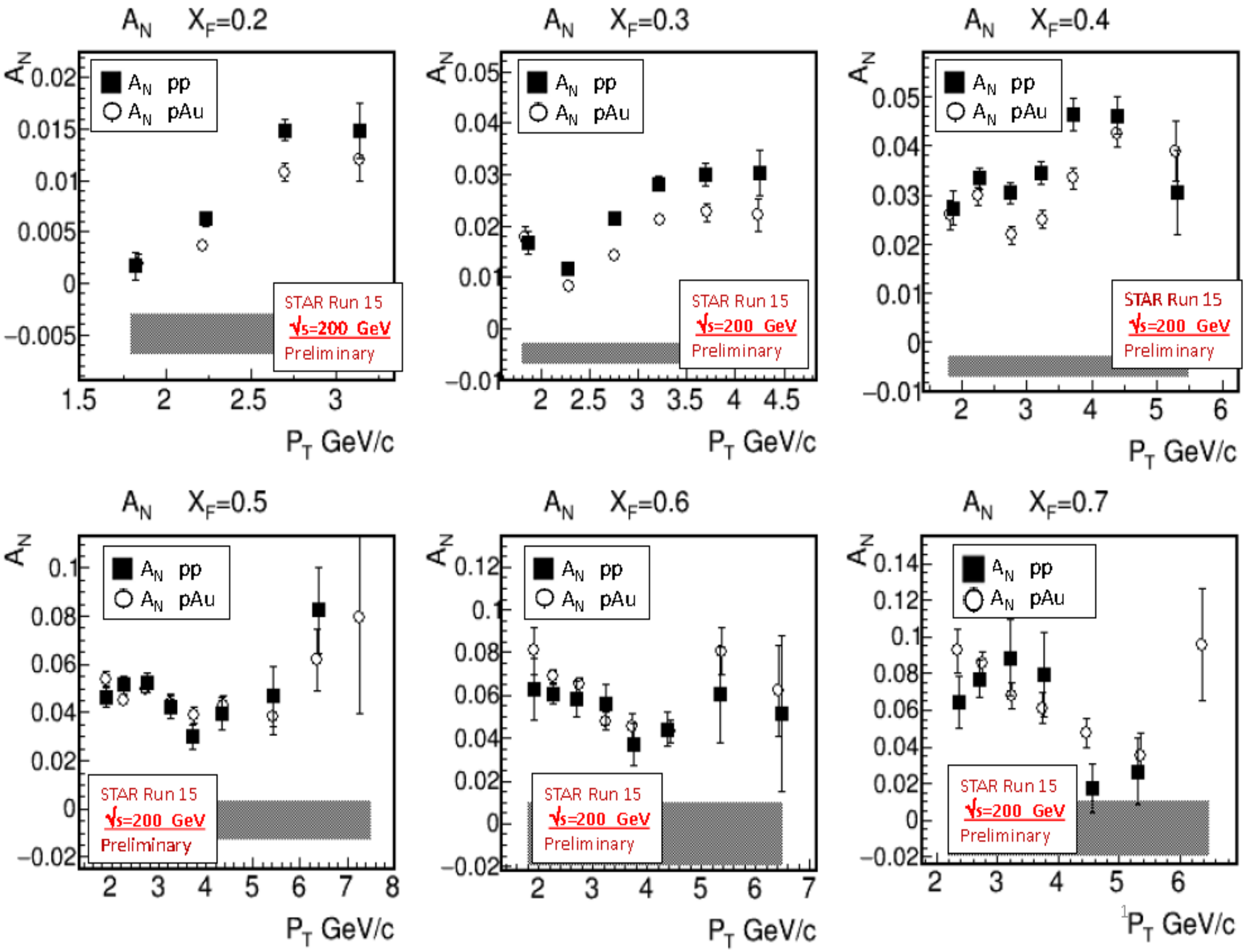
5 photon candidates in anti-k_T R=0.7



Jettier events

- A_N decreases as EM jets become jettier. Also is much smaller when there is a coincident jet at mid-rapidity
  - Raises serious questions how much of the large forward π^0 A_N arises from 2 → 2 parton scattering

First π^0 A_N results from *polarized* p+Au

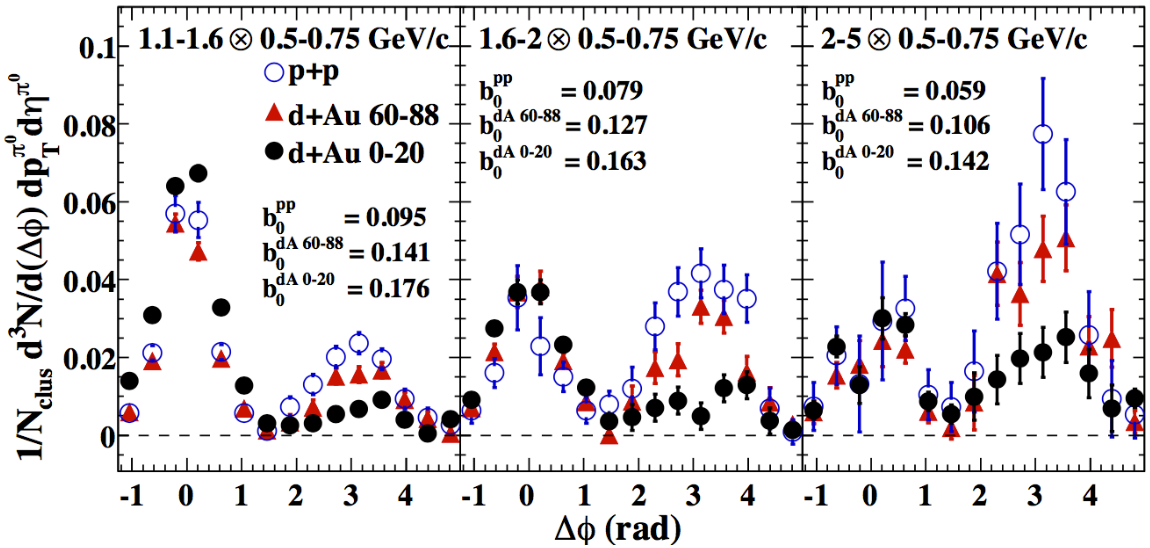


Shaded bands show systematic uncertainty, dominated by dependence of A_N on observed BBC multiplicity → central vs. peripheral collisions

- CGC calculations in some of the possible channels predicted that A_N would be suppressed when scattering off a saturated gluon field
  - Preliminary results from 2015 find little suppression

Back-to-back angular correlations

PHENIX, PRL 107, 172301

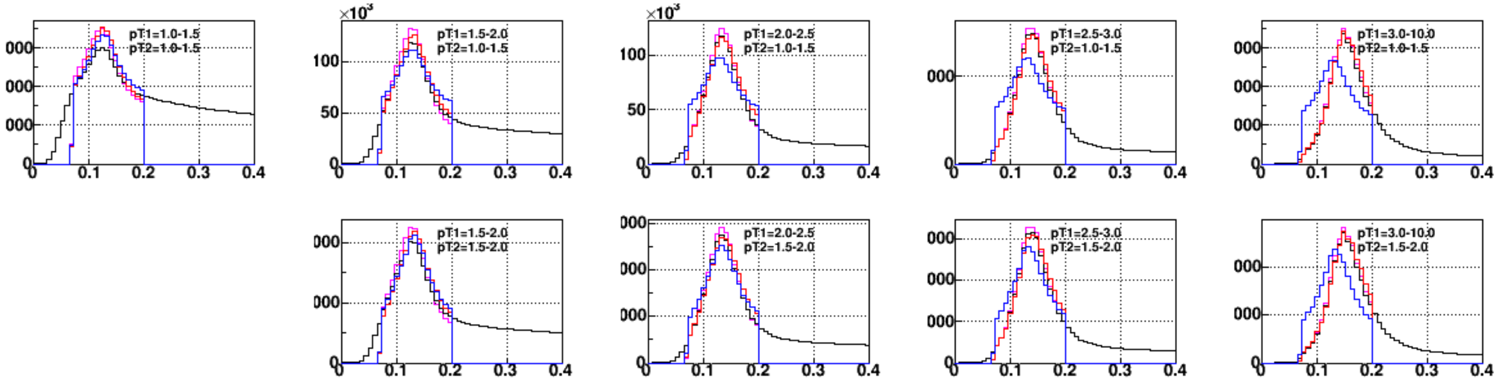


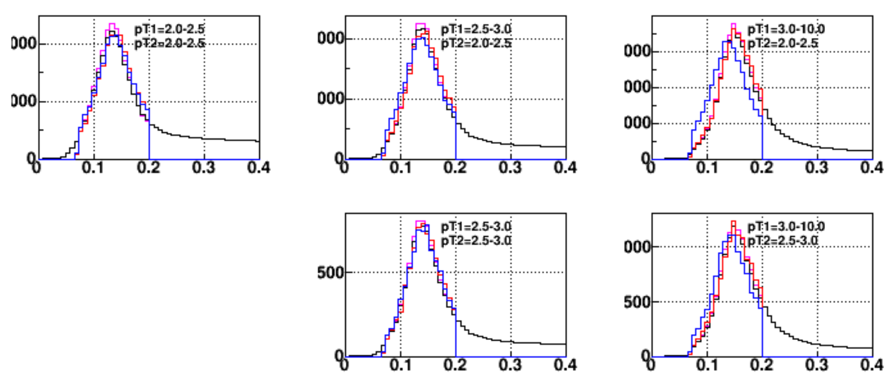
- CGC predicts suppression of back-to-back correlations
- PHENIX found evidence in 200 GeV d+Au collisions

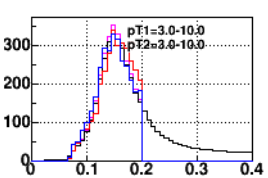
- STAR 2015 data are being analyzed for $\pi^0\pi^0$ and EM jet – EM jet azimuthal correlations in **pp**, **p+Al**, **p+Au** (and **d+Au** in 2016)
  - Still working on FMS gain uniformity and stability
    - Both cancel out in A_N

Scanning the FMS $\pi^0\pi^0$ correlation in p_T and x

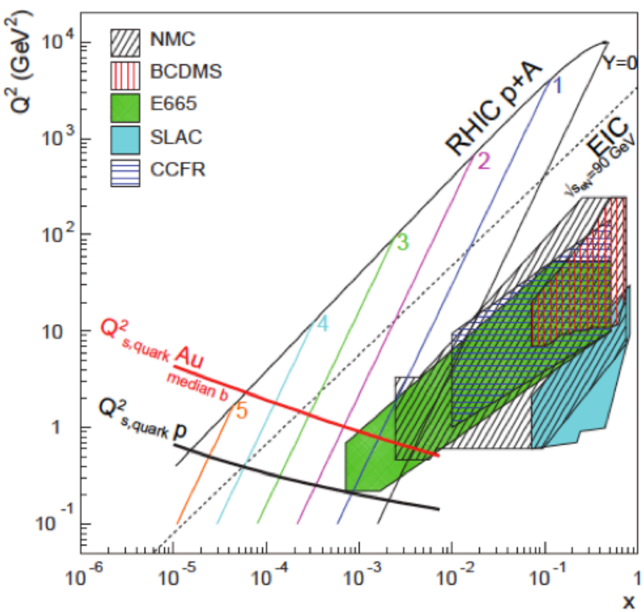
1 GeV → p_T^{trig} → >3 GeV







1 GeV ↓ p_T^{assoc} ↓ >3 GeV

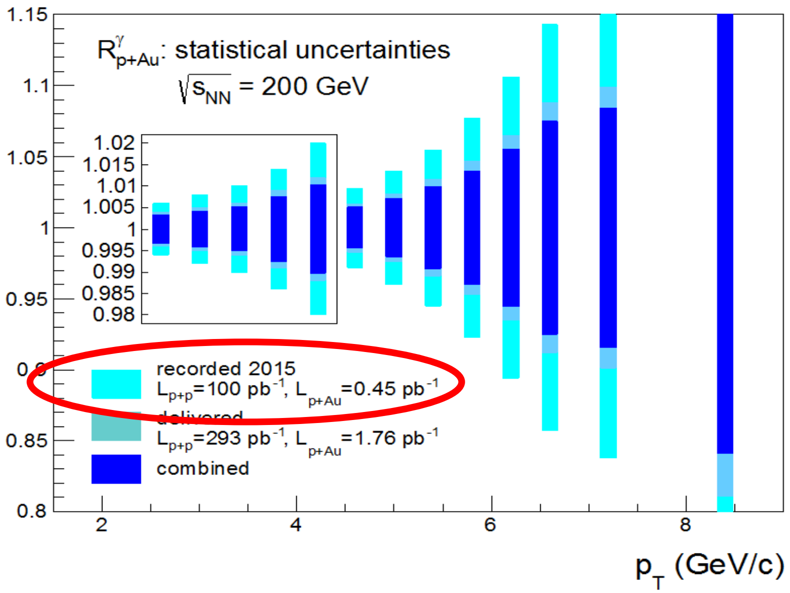


Blue: Trigger π^0 mass
Red: Assoc π^0 mass

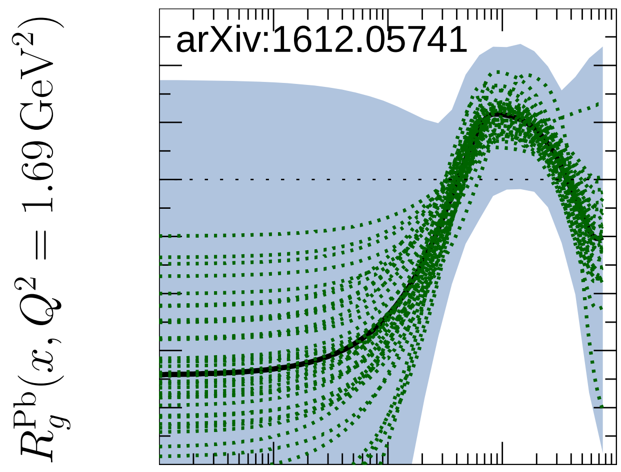
- With 2015 statistics, STAR can study the evolution of $Q_s^2(x)$ with A

Direct photon R_{pAu}

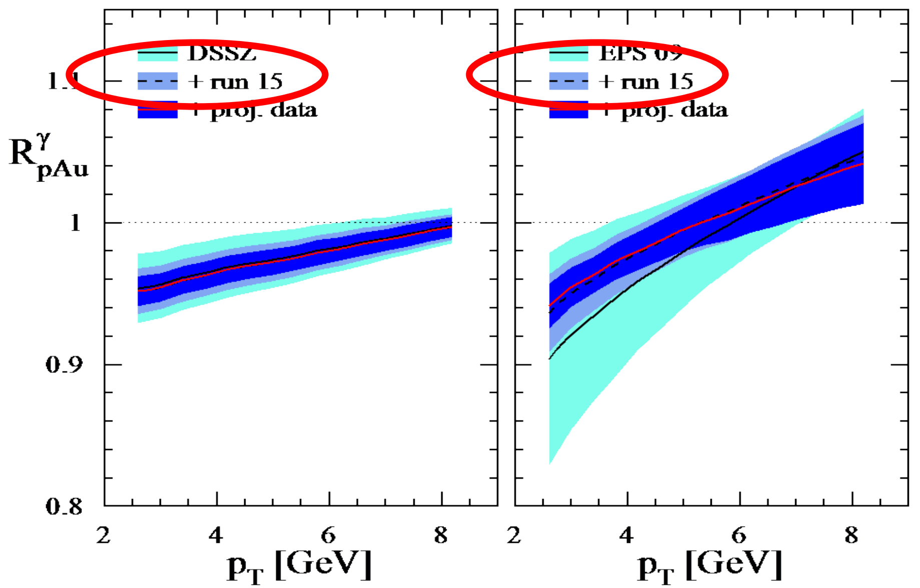
Data from p+Au run in 2015 (and 2023)



from world data: incl. LHC pA



Projected impact on gluon nPDFs

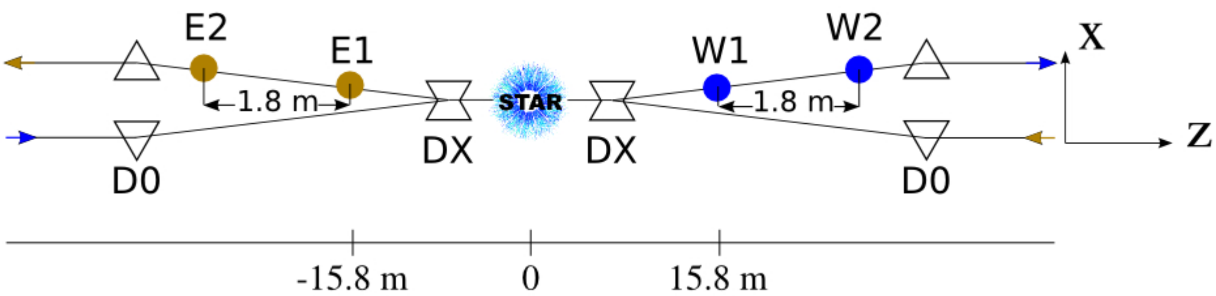


- Direct photon will provide:
  - Substantial improvement in our understanding of nuclear PDFs in the near term
  - Alternative observable and kinematics to EIC in the long term
- 2015 data analysis well underway

Physics with forward tagged protons

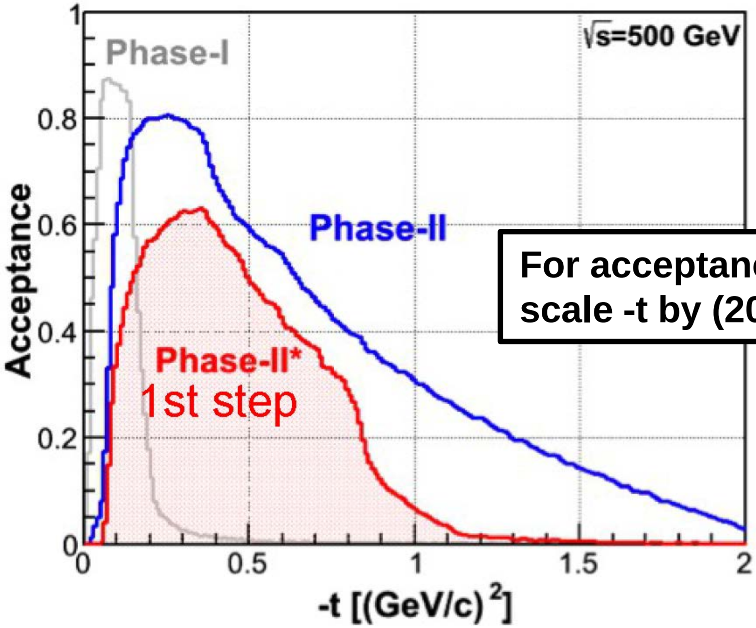
Roman pots in STAR

Current configuration



- Roman pots from pp2pp were installed 55 m each side of the STAR interaction region prior to the 2009 RHIC run
  - Had dedicated 4-day running time with special beam optics
- Roman pots were moved much closer to interaction point prior to the 2015 RHIC run (Phase II*)
  - Now can operate with normal RHIC beam optics
  - Integrated a large fraction of the total delivered luminosity during the 2015 ($\sqrt{s}$ = 200 GeV) and 2017 ($\sqrt{s}$ = 510 GeV) RHIC runs

Roman pots in STAR



For acceptance at 200 GeV, scale -t by $(200/500)^2$

- Roman pots from pp2pp were installed 55 m each side of the STAR interaction region prior to the 2009 RHIC run
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  - Now can operate with normal RHIC beam optics
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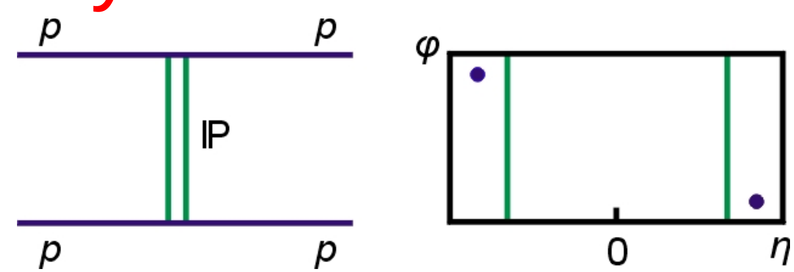
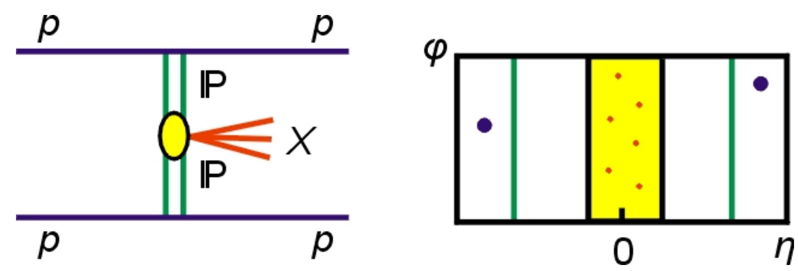
Ongoing analyses

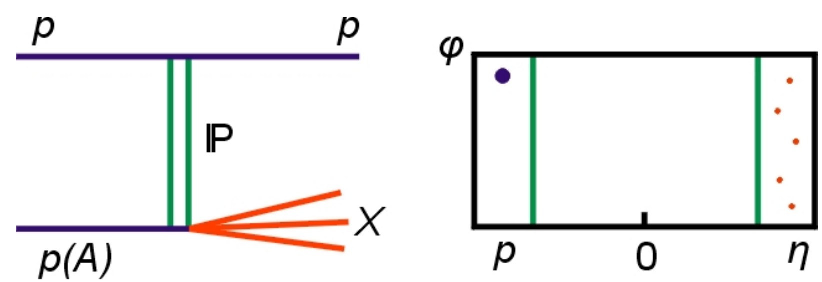
- Elastic scattering



- Central Exclusive Production (CEP)
  - **p + p → p + X + p**
  - **Diffractive X = particles, glueballs**

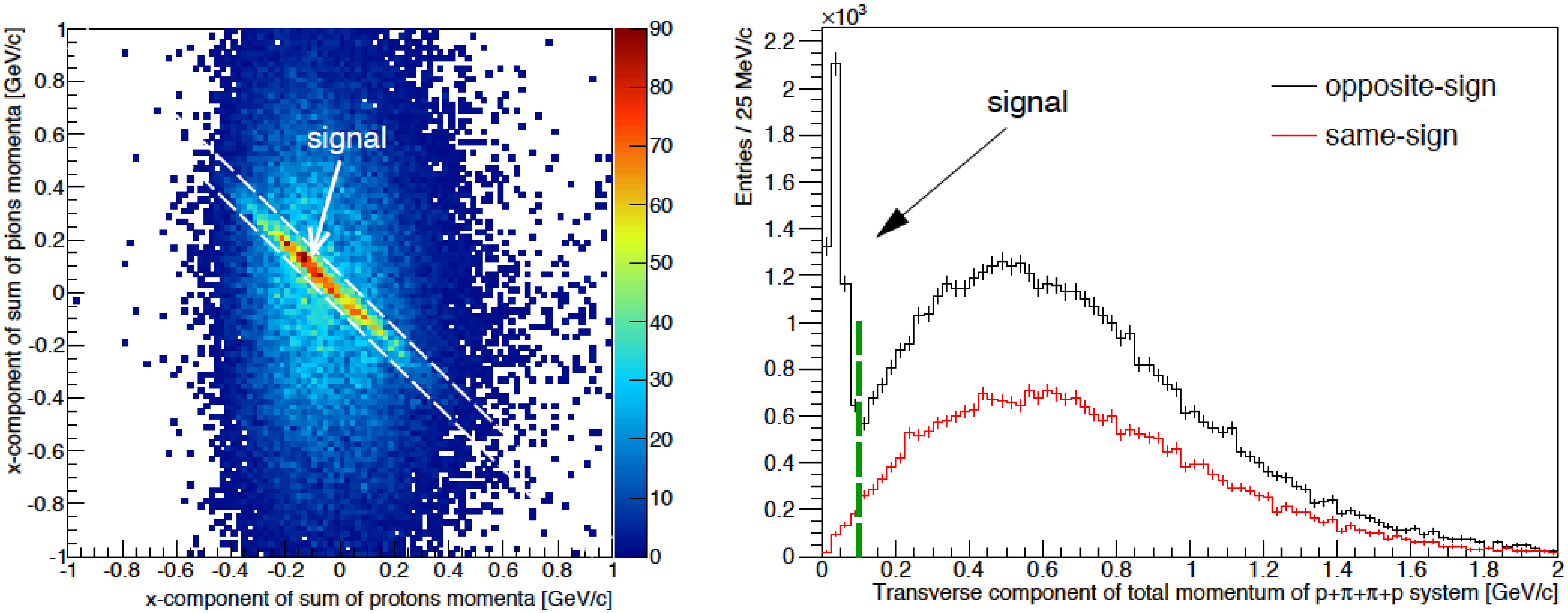


- Single Diffraction Dissociation



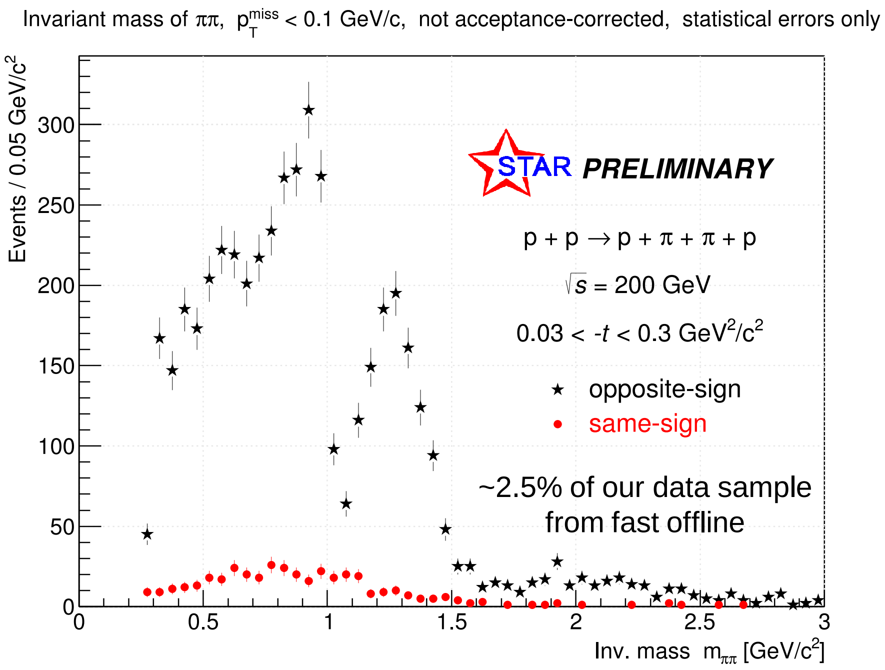
- Took high-quality data on all three processes during the 2015 (200 GeV) run, and even more during the 2017 (510 GeV) run
  - Here only show preliminary 2015 results on CEP at 200 GeV
- Also looking at correlation of forward π^0 A_N with Roman pot activity
  - Could a large fraction of the π^0 A_N be diffractive?

Identifying CEP: the $\pi^+\pi^-$ case



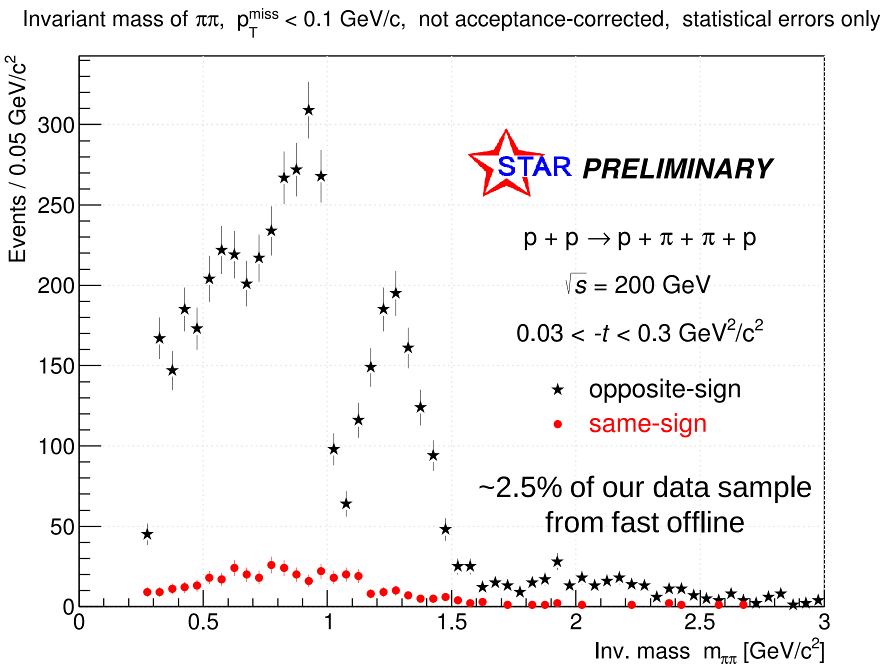
- Identification and momentum reconstruction of all final state particles provides the ability to ensure exclusivity of the system via momentum balance check
- **Very small background !**

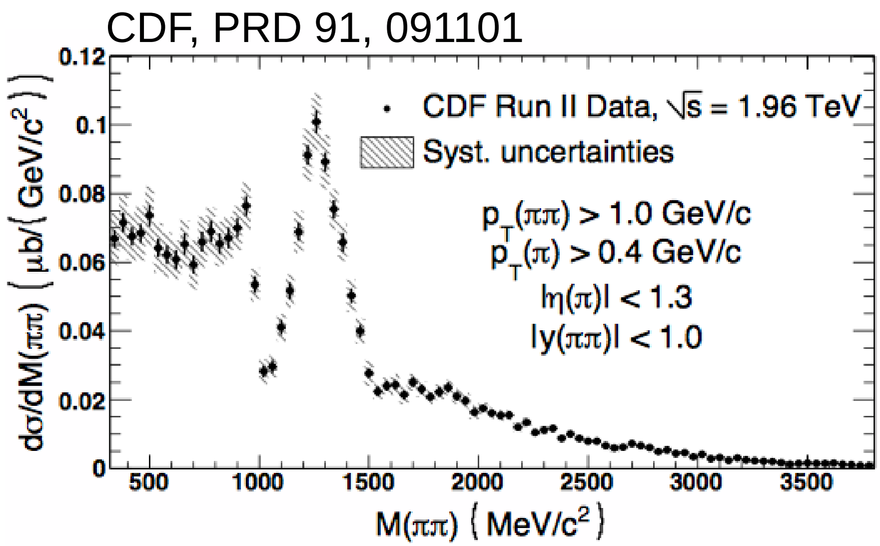
$\pi^+\pi^-$ invariant mass distribution at 200 GeV



- Broad structure extending from $\pi^+\pi^-$ threshold to ~1 GeV
- Sharp drop at about 1 GeV
- Resonance-like structure between 1-1.5 GeV
  - Expect ~70K events with $M(\pi^+\pi^-) > 1$ GeV from full 2015 data set

$\pi^+\pi^-$ invariant mass distribution at 200 GeV





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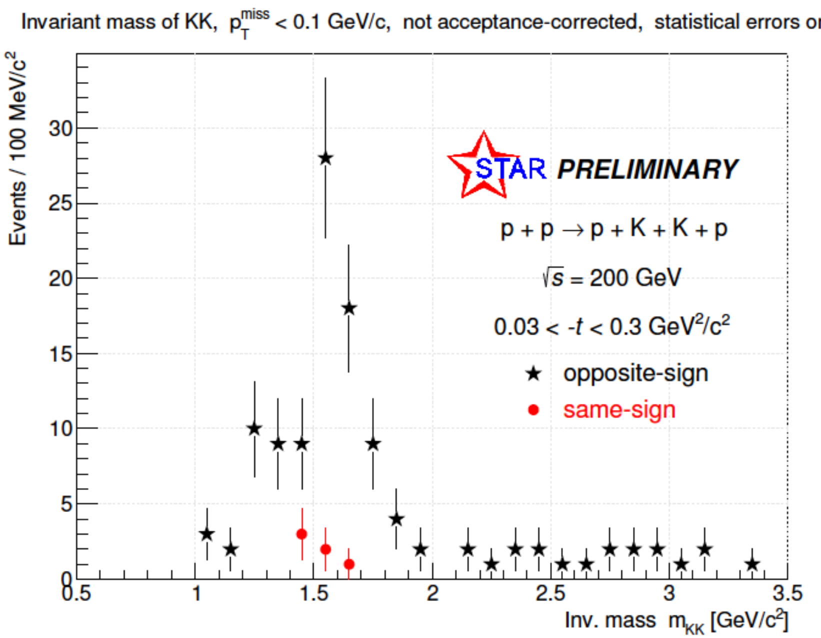
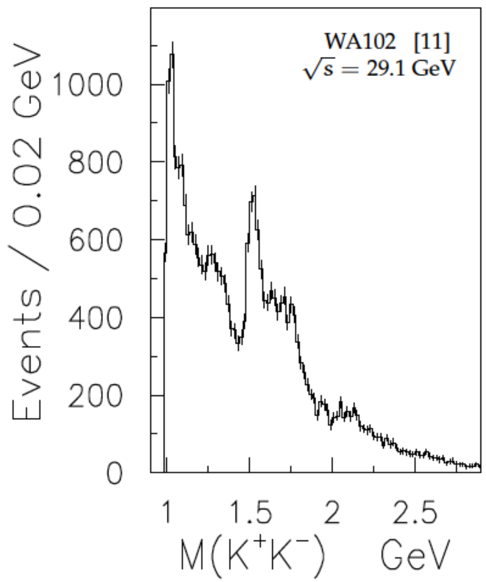
- Sharp drop at about 1 GeV
- Resonance-like structure between 1-1.5 GeV
  - Expect ~70K events with $M(\pi^+\pi^-) > 1$ GeV from full 2015 data set
- Essential features are similar to measurements in *pp* at 63 GeV (AFS at ISR) and *p*$\bar{p}$ 1.96 TeV (CDF)

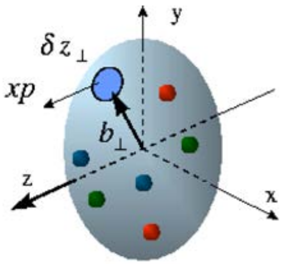
K^+K^- invariant mass distribution at 200 GeV

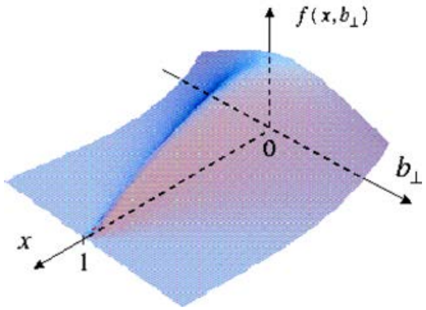


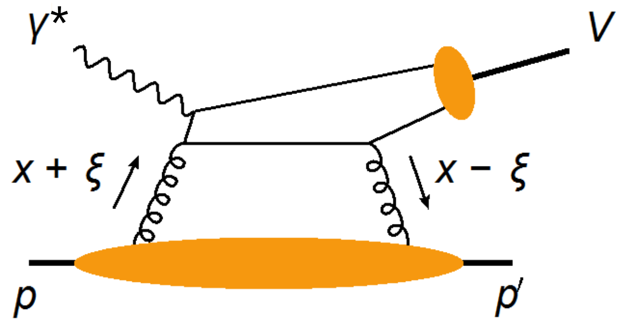


- Prominent peak around 1.5-1.6 GeV
- Some enhancement in the f2(1270)/f0(1370) region
- In spectrum measured by WA102 (fixed target), there is a significant contribution from f0(980) not seen by STAR
  - *K* acceptance is very small at such low p_T
- Expect ~10^4 exclusive K^+K^- events in the full 2015 data set
  - Will permit cross section and partial wave analyses

What about orbital angular momentum?







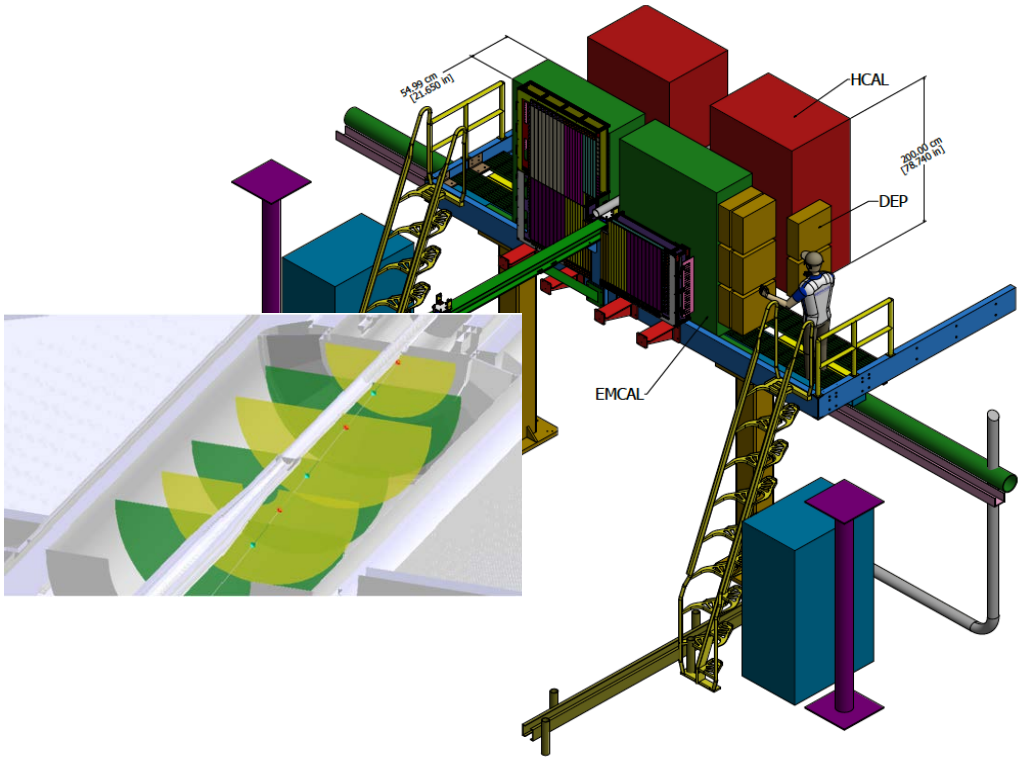
quark contribution

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

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

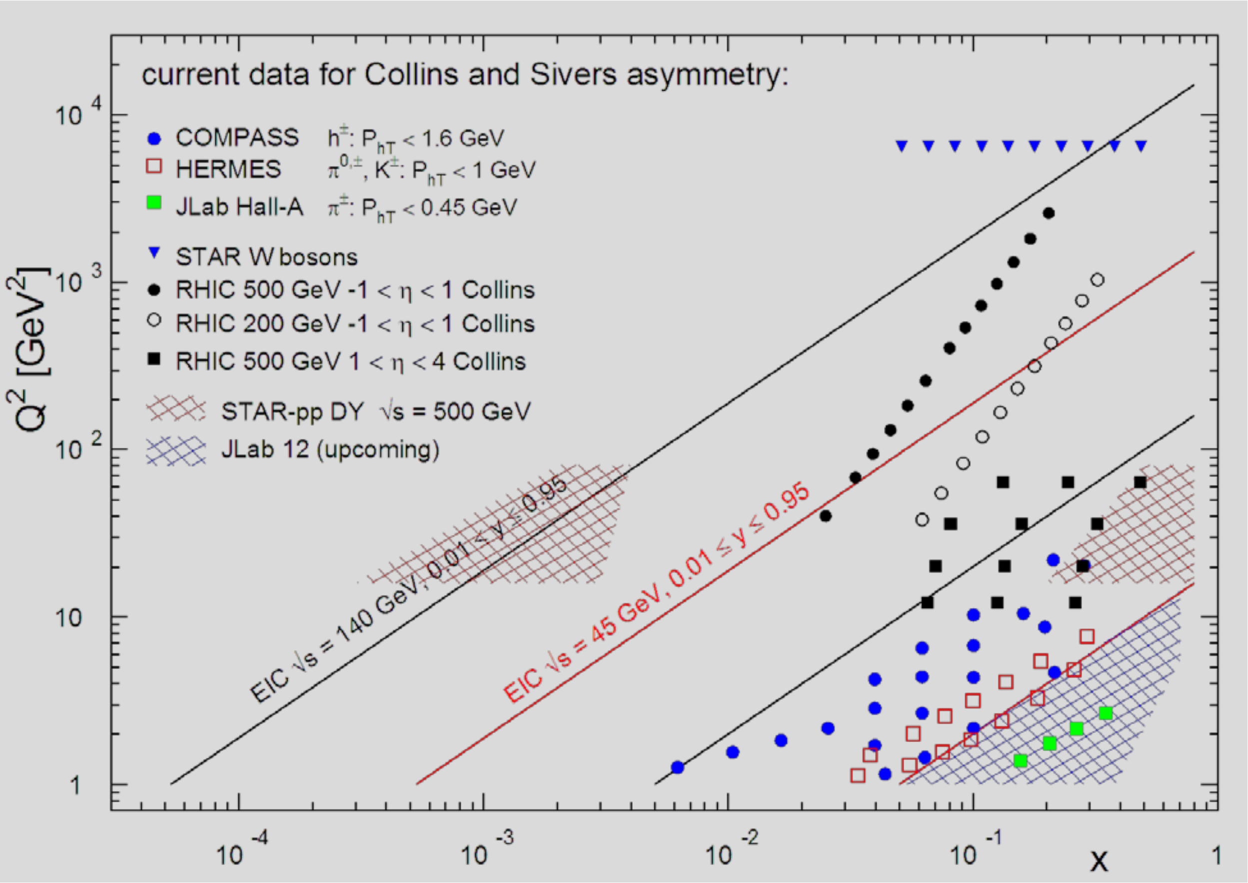
- Generalized parton distributions (GPDs), measured via exclusive reactions, provide **access to L_q and L_g**
- Exclusive *J/ψ* production in ultra-peripheral collisions with transversely polarized p+p and p+Au provides access to the GPD E_g
  - The GPD *E* is responsible for orbital angular momentum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

Planned forward upgrade for the 2020's



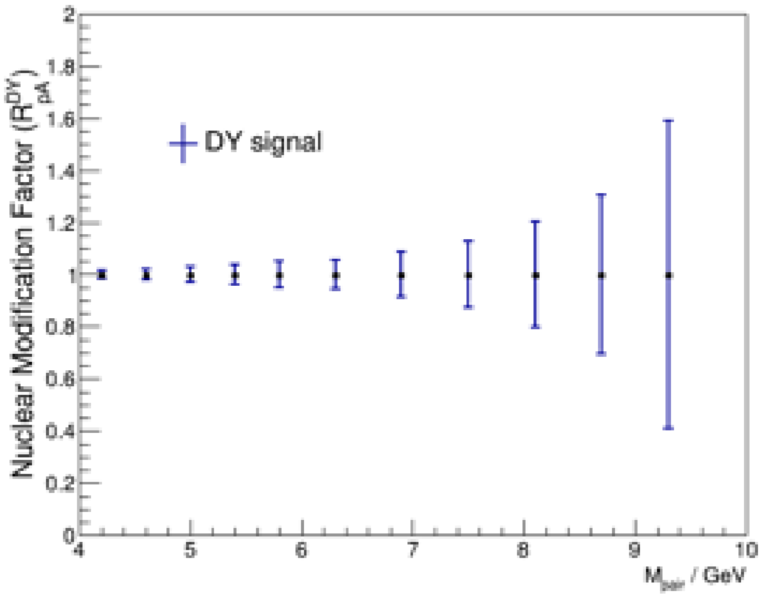
- Forward di-jets will extend gluon polarization to x <~ 10^{-3}
- Transverse spin phenomena:
  - Precision TMDs through jets at forward rapidity
  - Precision A_N(Drell-Yan) to complete the Sivers measurements
- Also an extensive suite of measurements in p+A collisions

Sivers and Collins coverage at RHIC

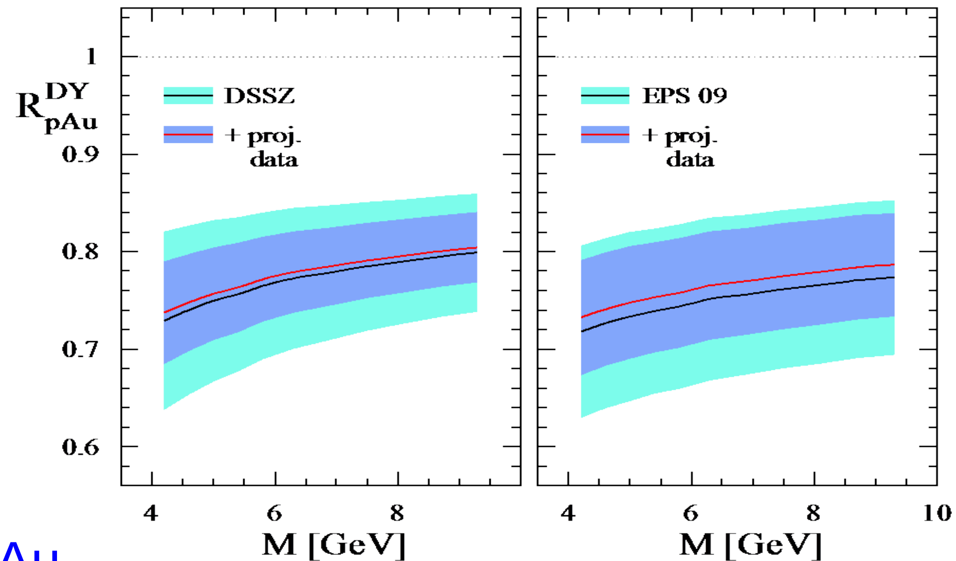


- Kinematics of RHIC
  - Dramatic extension in (x, Q^2) reach before EIC
  - *W* production probes the highest Q^2 over a wide x range
  - **Precision tests of universality** when EIC data become available

Drell-Yan R_{pA} at 200 GeV

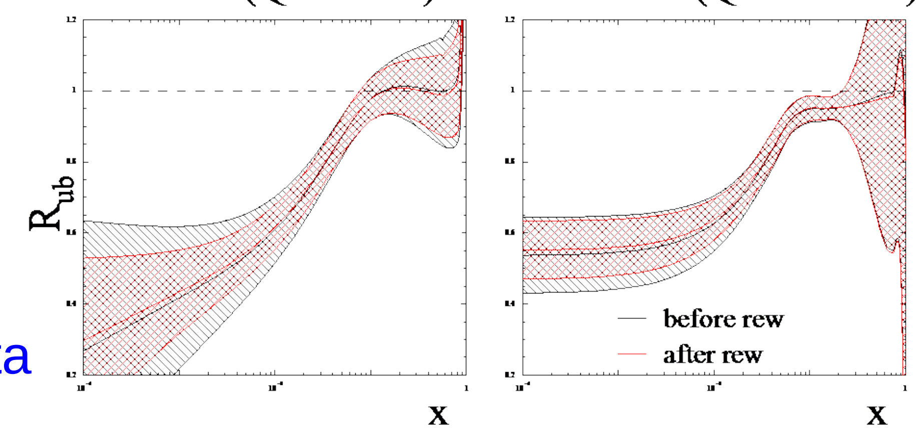


Projected impact on sea quark nPDFs



DSSZ (Q=1 GeV)

EPS09 (Q=1.3 GeV)



- Similar statistics in 200 GeV pp, p+Au, p+Al
- Significant improvement in our knowledge of sea quark densities in heavy nuclei
- Significant extension of the Q^2 lever arm at low x relative to future EIC data

Conclusions

- The ***STAR*** Spin and Forward Physics programs have made a number of striking observations

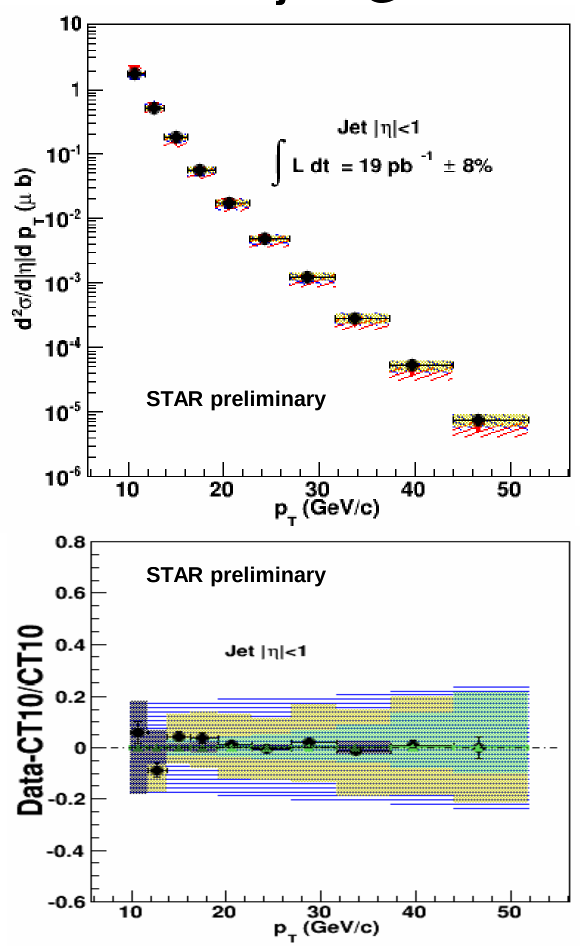
- ***STAR*** has a huge body of additional spin and forward physics data under analysis

- The ***STAR*** Forward Upgrade will provide a bright future for ***STAR*** in the coming decade

- ***STAR*** is a key component of the RHIC Cold QCD program: an essential bridge between the physics of RHIC and the physics of the future Electron Ion Collider

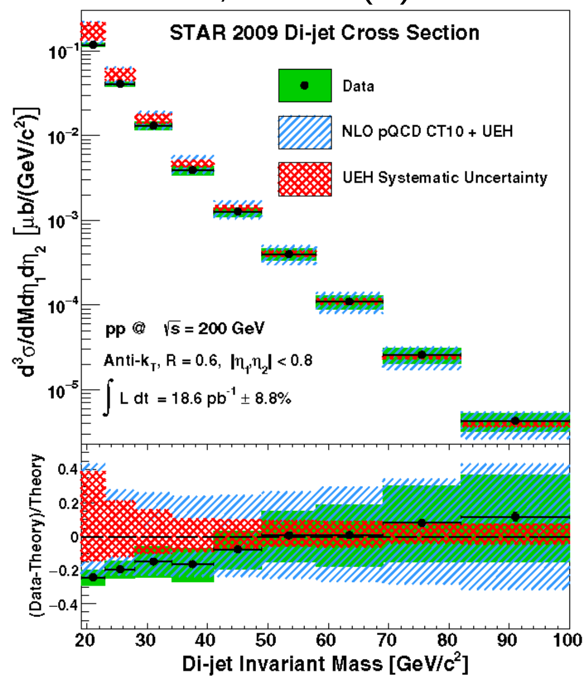
STAR as a jet and di-jet detector

Inclusive jets @ 200 GeV

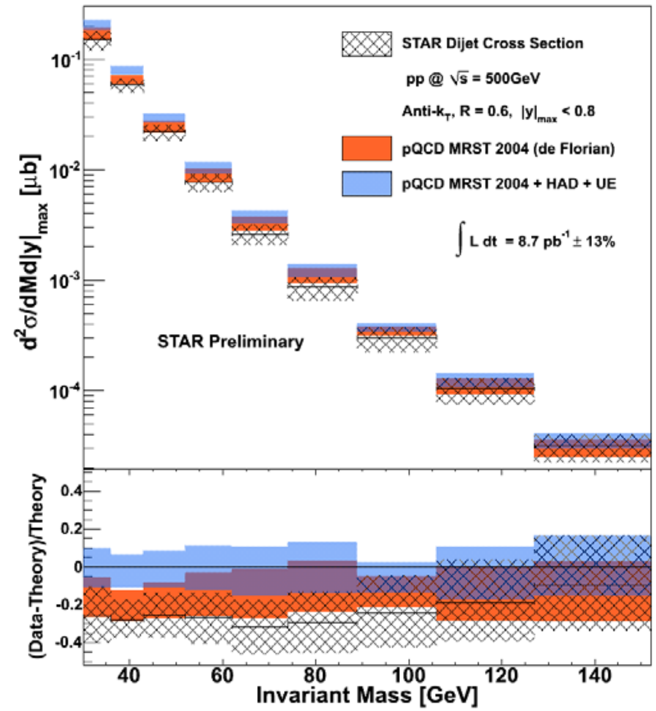


Di-jets @ 200 GeV

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