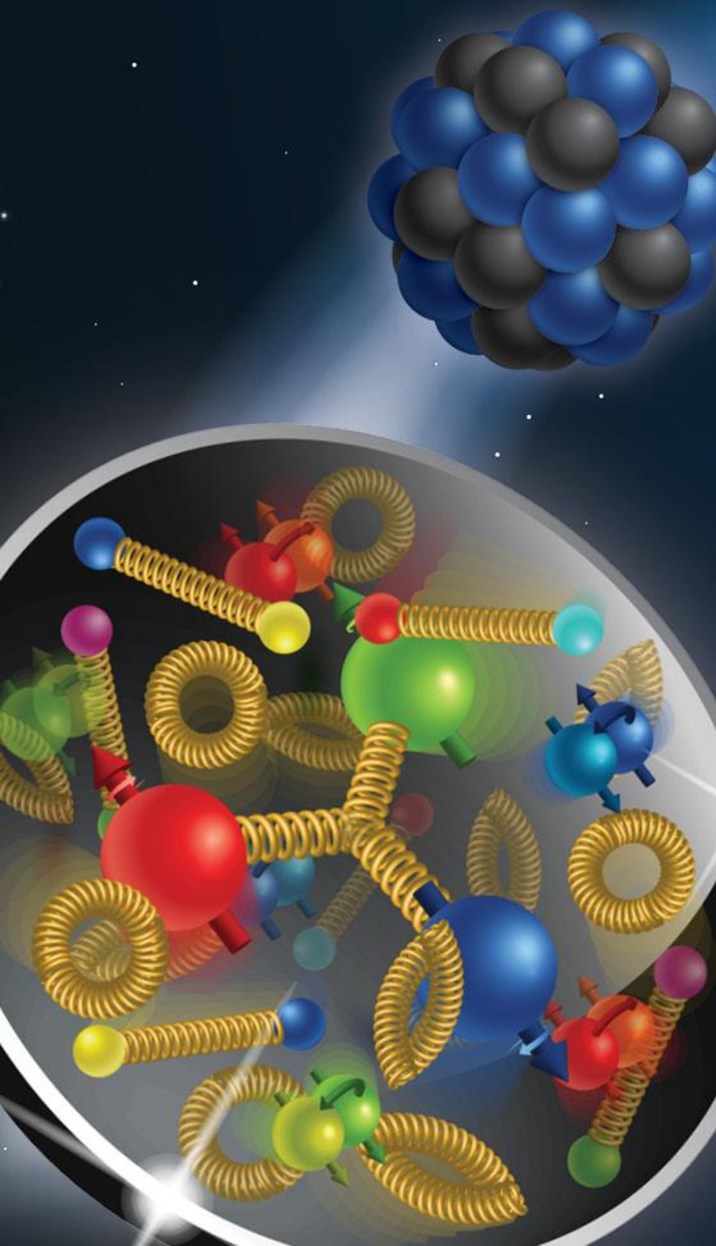
The RHIC Cold QCD Program: A gaze into EIC Physics



E.C. Aschenauer

Due to time not included:

long. and trans. Lambda polarization
Phys.Rev. D98, 091103 (2018)
Phys. Rev. D, 98:112009

any pA results

A_N $h^{+/-}$: arXiv:1903.07422
A_N J/Ψ: Phys.Rev. D98 (2018), 012006
A_N neutron: PRL 120, 022001 (2018)

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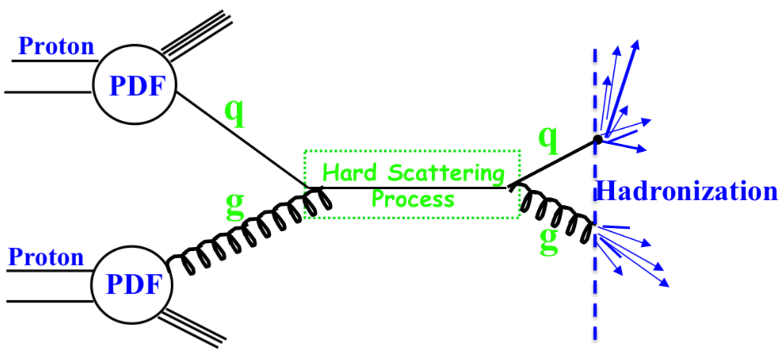
Why p+p and p+A to access Cold QCD

Complementarity

QCD has two concepts which lay its foundation
factorization and universality

To tests these concepts and separate interaction dependent phenomena from intrinsic nuclear properties
different complementary probes are critical
Probes: high precision data from ep, pp, e+e-

Factorization

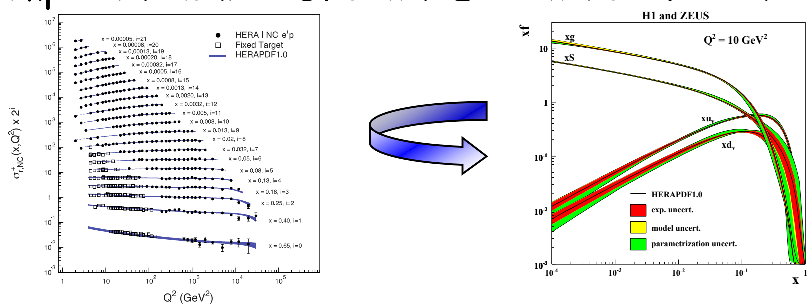


(un)polarized cross section ~
PDF ⊗ hard-scattering ⊗ Hadronization

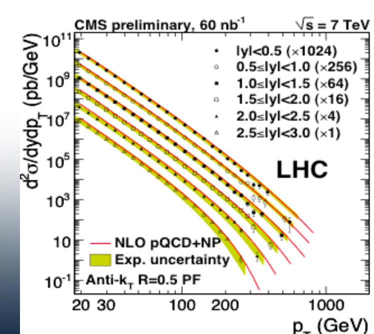
hard-scattering : calculable in QCD
PDFs and Hadronization: need to be determined experimentaly

Universality

Example: Measure PDFs at HERA at $\sqrt{s}$=0.3 TeV:

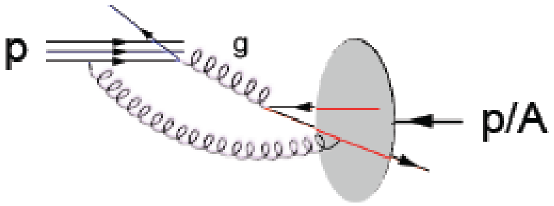


Predict pp and $p\bar{p}$ measurements at $\sqrt{s}$=0.2, 1.96 & 7 TeV



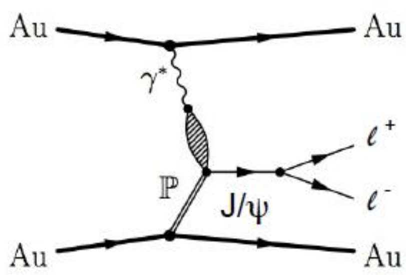
Different Processes

Hadron-Hadron:



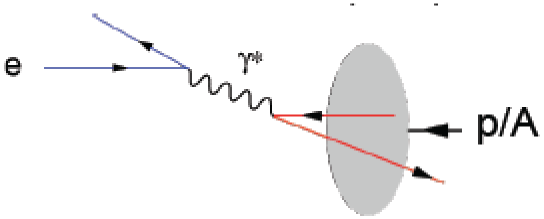
- probe has complex structure
- no simple access to parton kinematics:
  $\eta \rightarrow x$; $p_t^2 \rightarrow Q^2 \rightarrow x\text{-}Q^2$ strongly correlated
- Gluons can be accessed directly → qg & gg
  - gluon fragmentation

Ultra-Peripheral Collisions:



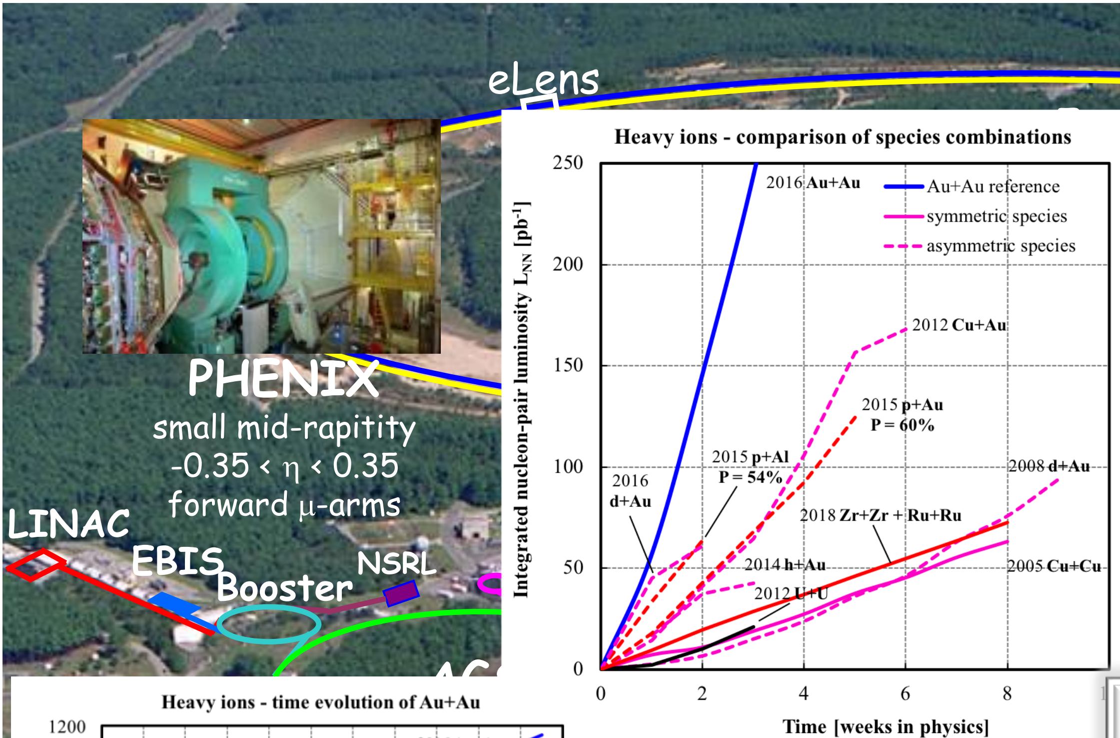
- Photon induced process
- no simple access to parton kinematics:
  $\eta \rightarrow x$; $M^2 \rightarrow Q^2$ can only be varied by VM
- access to initial state

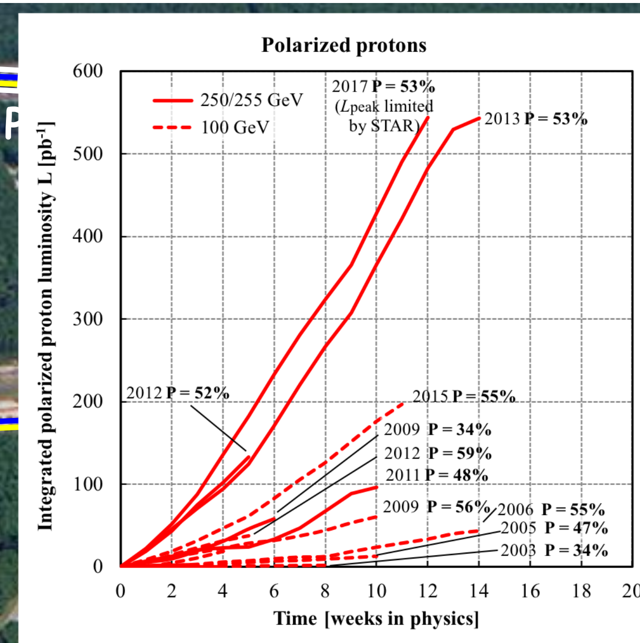
Electron-Hadron:

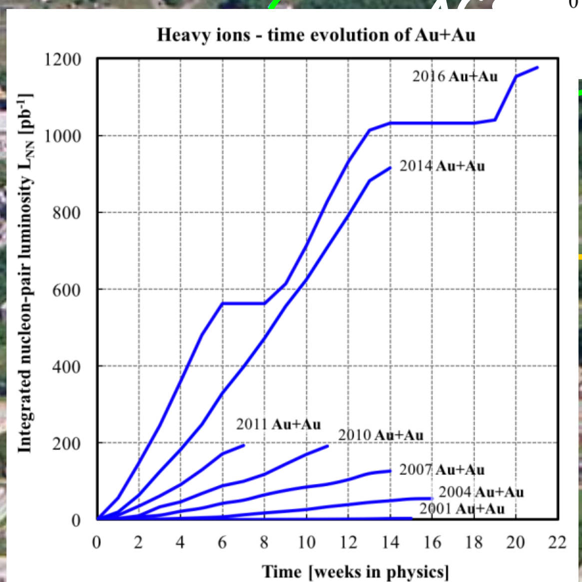


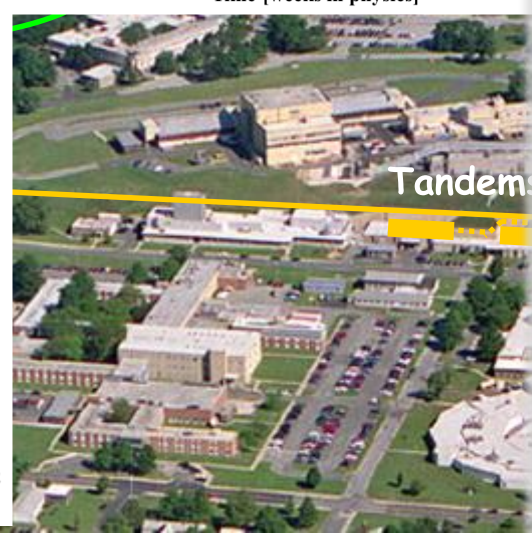
- Point-like probe → resolution
- High precision & access to partonic kinematics through scattered lepton
  → x_B, Q^2
- initial and final state effects can be cleanly disentangled

RHIC@BNL Today







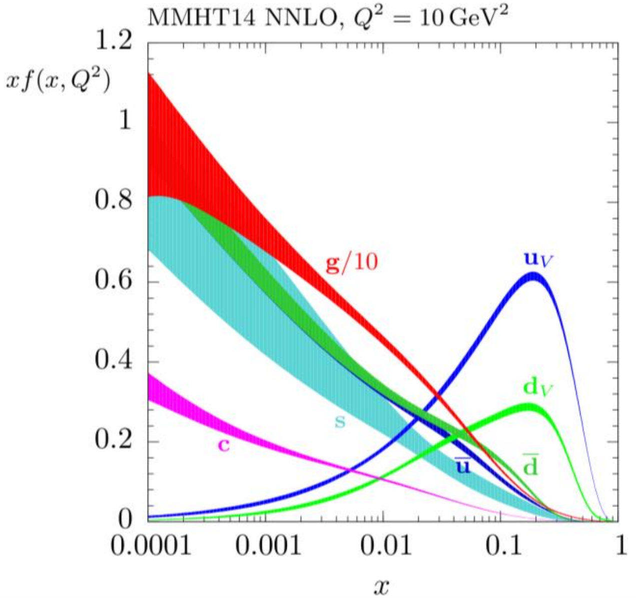


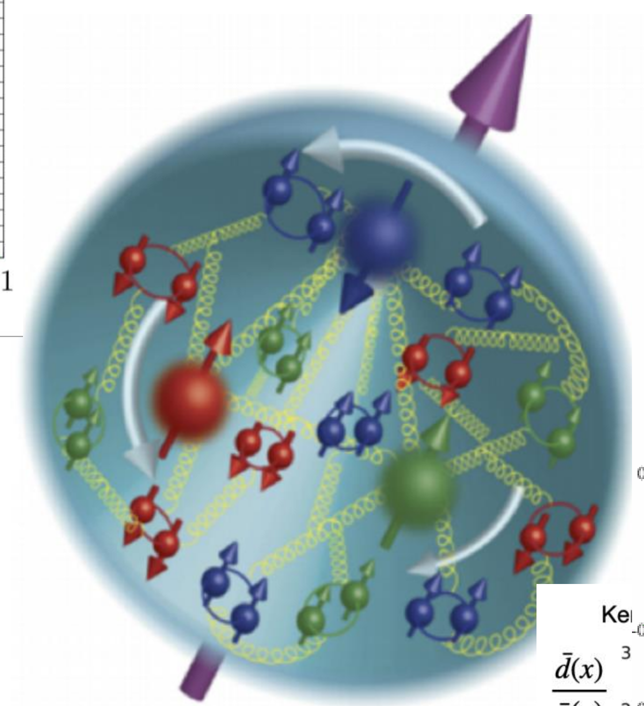
What do we collide ?

p — Polarized protons 24-255 GeV

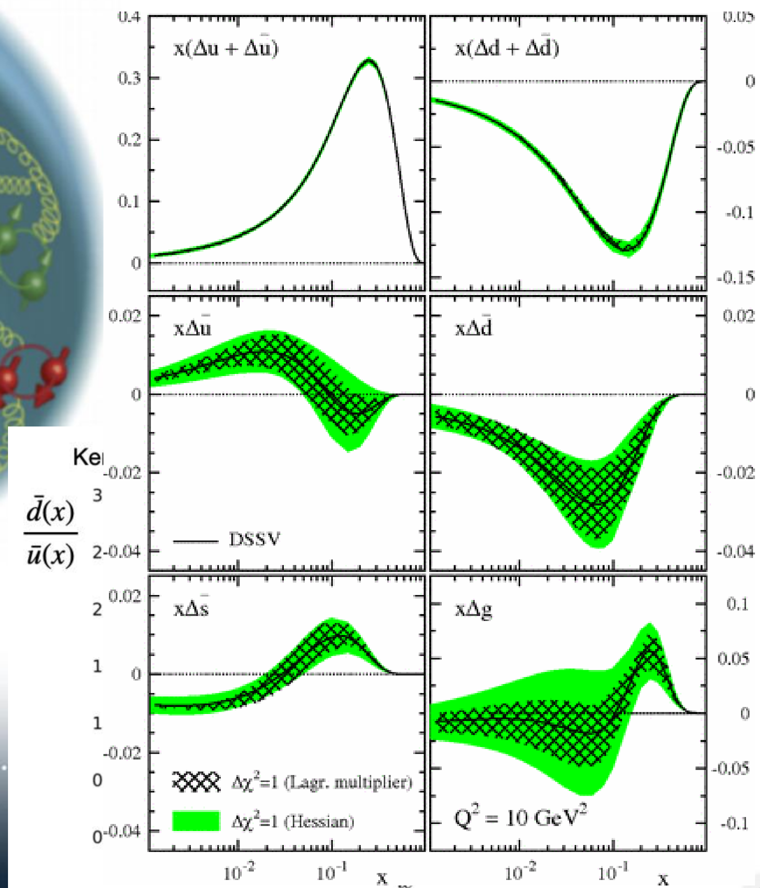
Light ions (d,Si,Cu)
Heavy ions (Au,U)
5-100 GeV/u

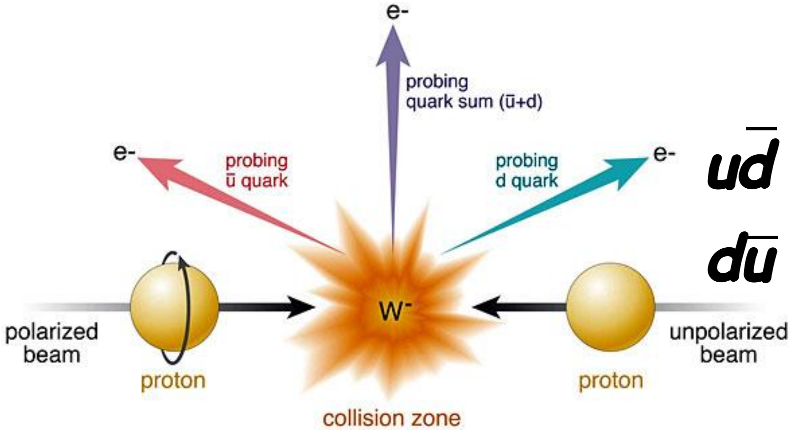
SEA Quarks and Flavor Symmetries





DSSV PRD 80 (2009) 034030





$$u\bar{d} \to W^+$$
$$d\bar{u} \to W^-$$

Ws naturally separate quark flavors
→ rapidity: sea vs. valence quarks

Ws are maximally parity violating
→ Ws couple only to one parton helicity

longitudinal polarized protons:

$$A_L^{W^+} = \frac{\sigma^{\rightarrow} - \sigma^{\leftarrow}}{\sigma^{\rightarrow} + \sigma^{\leftarrow}} \sim \frac{\Delta\bar{d}(x_1)u(x_2) - \Delta u(x_1)\bar{d}(x_2)}{\bar{d}(x_2)u(x_1) + \bar{d}(x_1)u(x_2)}$$

unpolarized protons:

$$A\left(W^+/W^-\right) = \frac{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)}$$

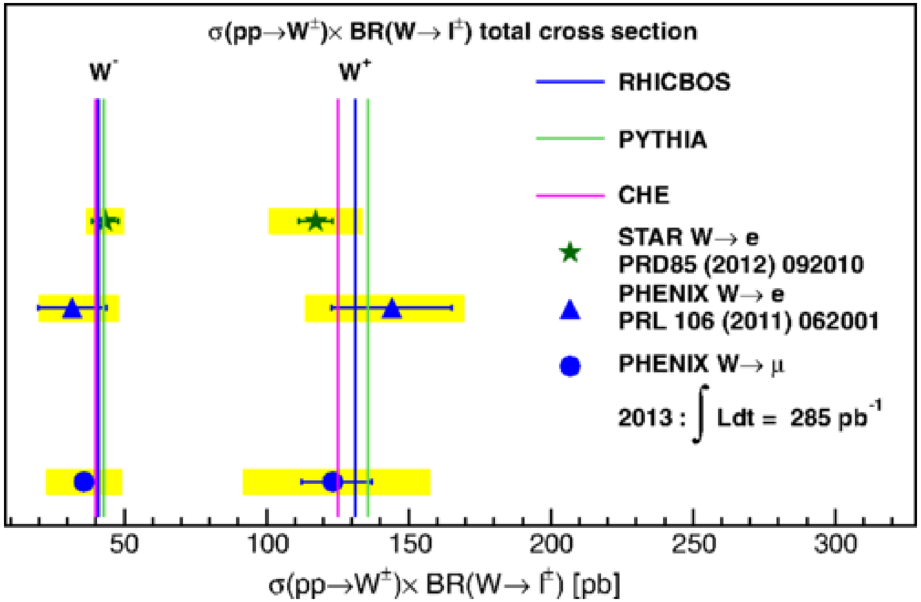
Complementary to SIDIS:
very high Q^2-scale 6400 GeV^2
extremely clean theoretically
No Fragmentation function
→ stringent test on theory approach for SIDIS
UNIVERSALITY of PDFs

$W^{+/-}$ cross section

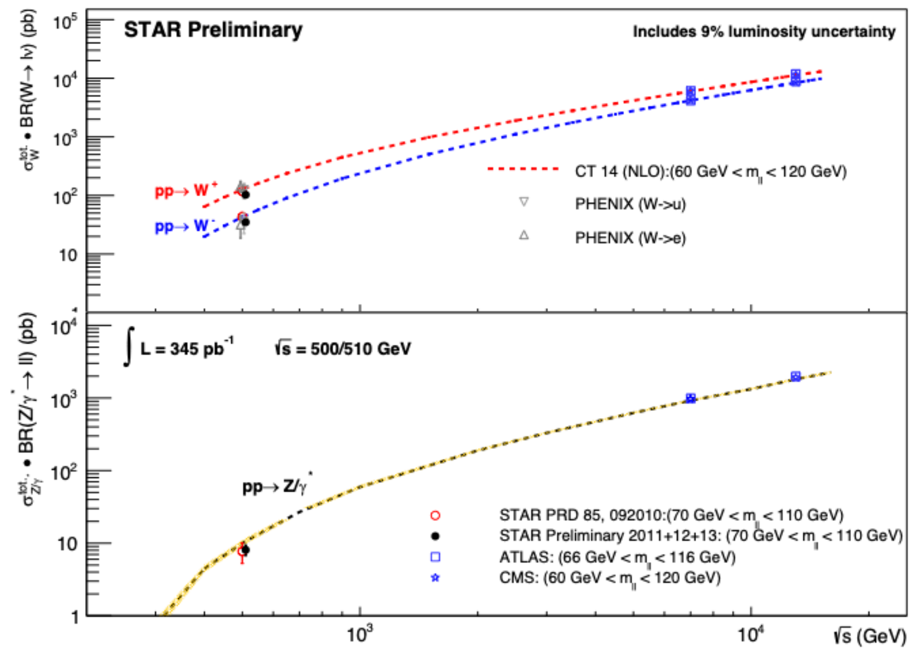
PHENIX

STAR ☆

PHYS. REV. D 98, 032007 (2018)



- Measured at forward and backward rapidity and averaged over arms
- 2013 W→ μ systematic error is dominated by the large uncertainty on the signal-to-background ratios.
- Good agreement with previous measurements and theoretical predictions.

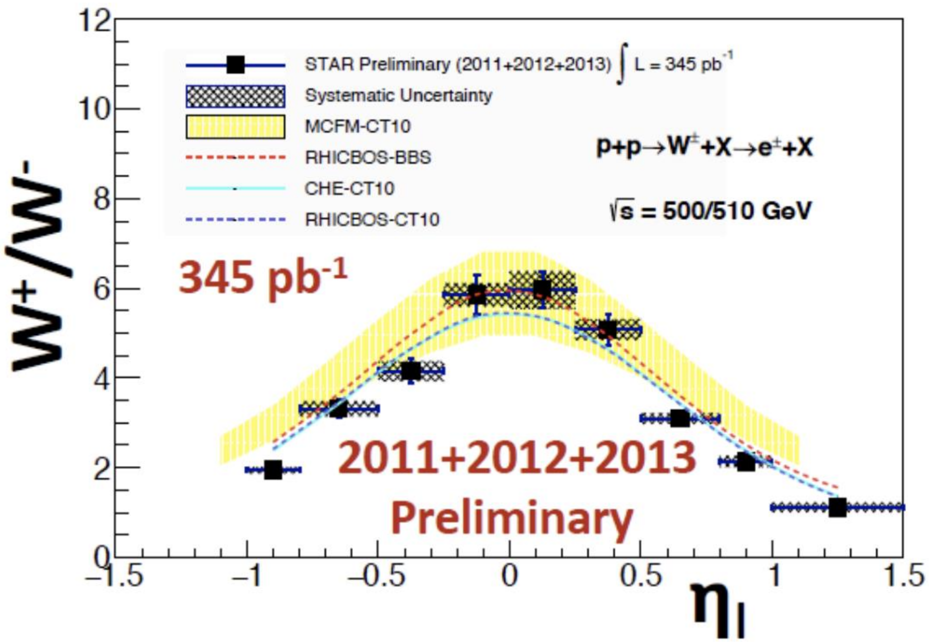


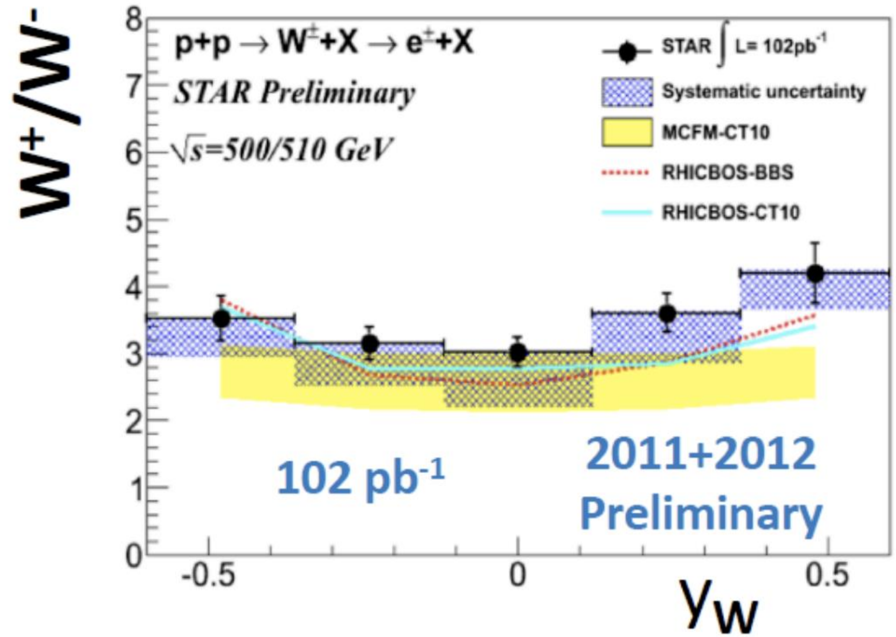
- Good agreement with previous measurements and theoretical predictions.

$W^{+/-}$ cross section ratio

Can be used to constrain sea quark PDFs!

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





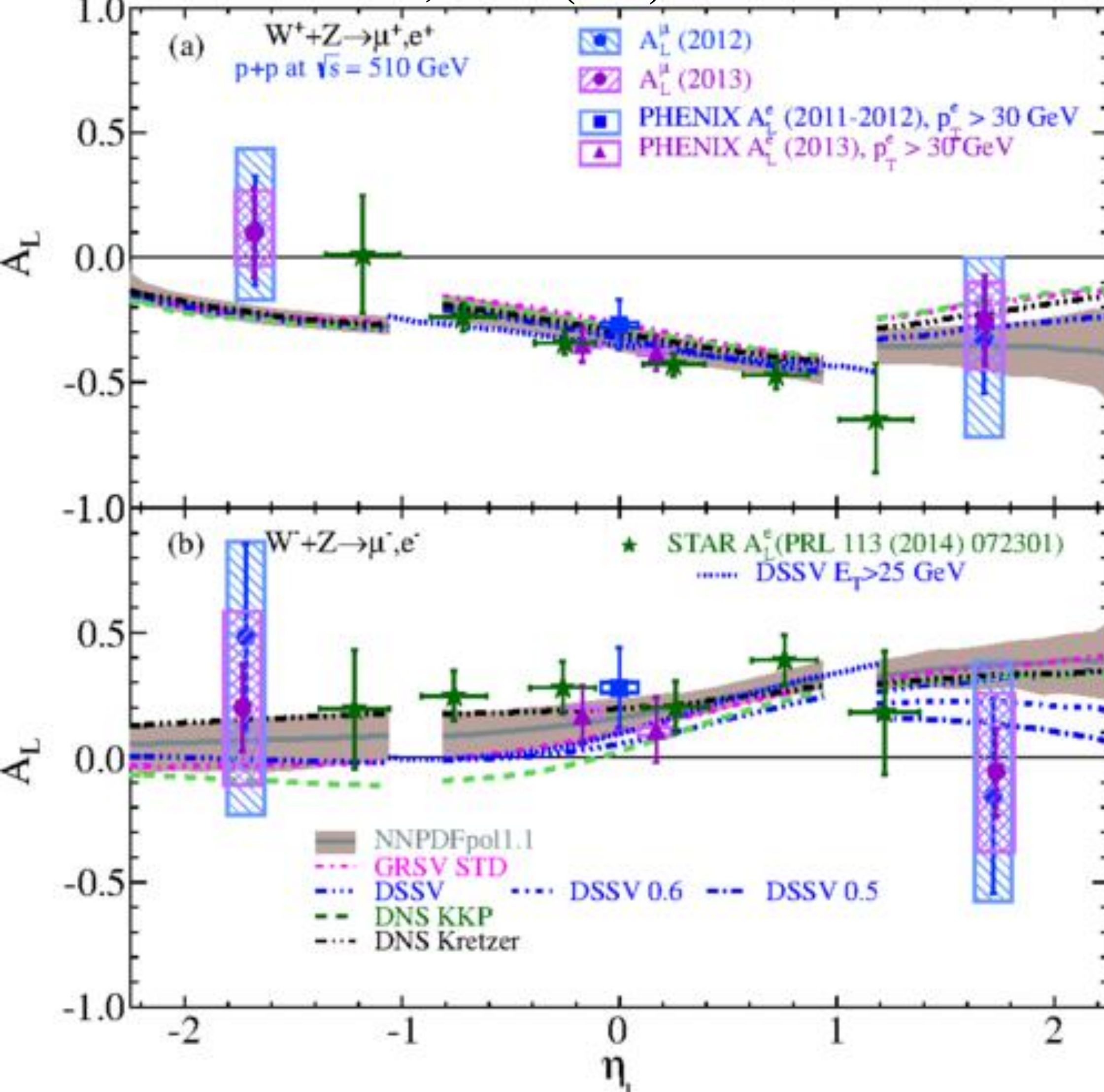
Theoretically extremely clean

Run-17 will double the statistics of run-11, 12 and 13

$W^{+/-}$ – A_L: Helicity PDFs

PHENIX

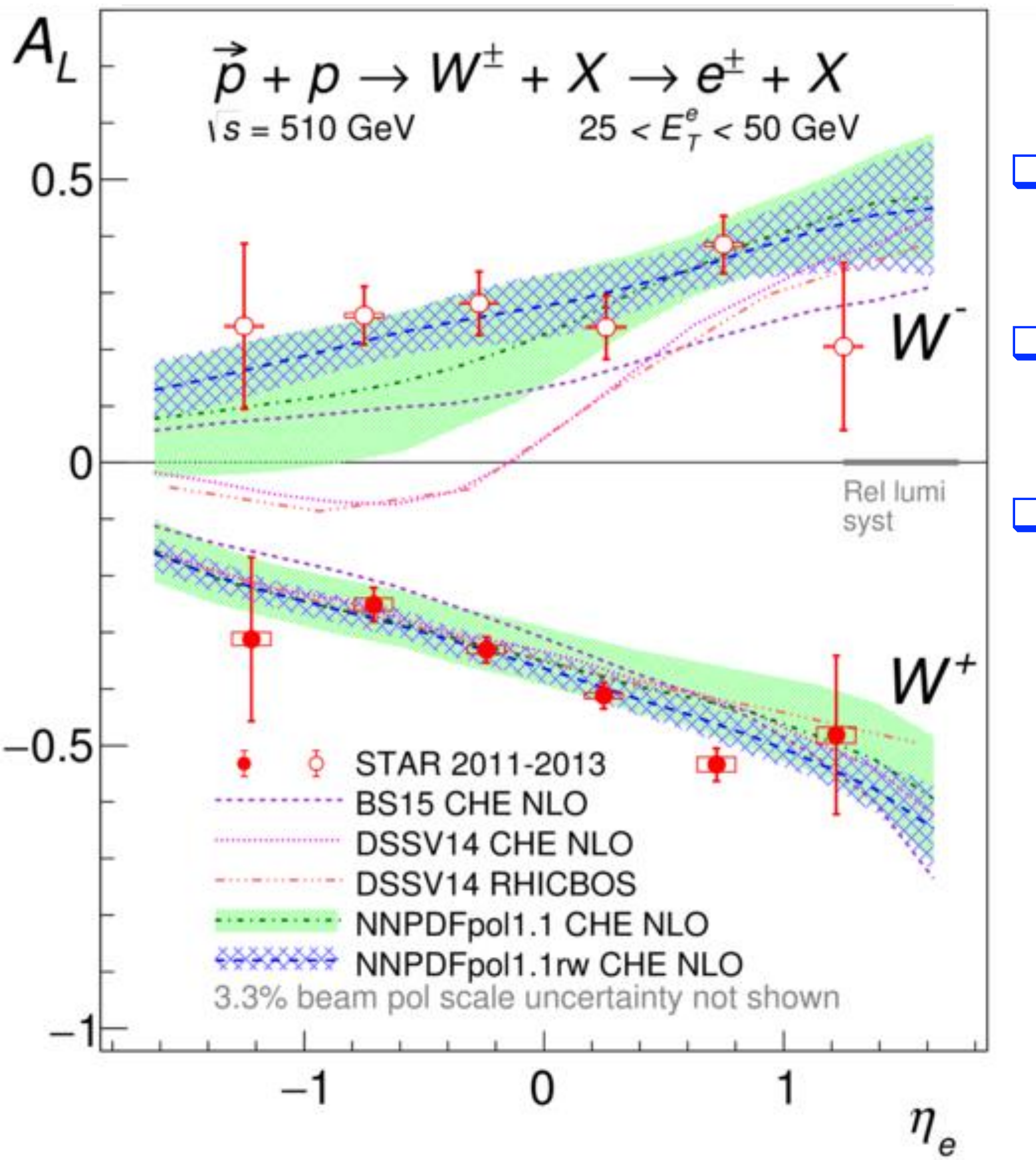
PHYS. REV. D 98, 032007 (2018)



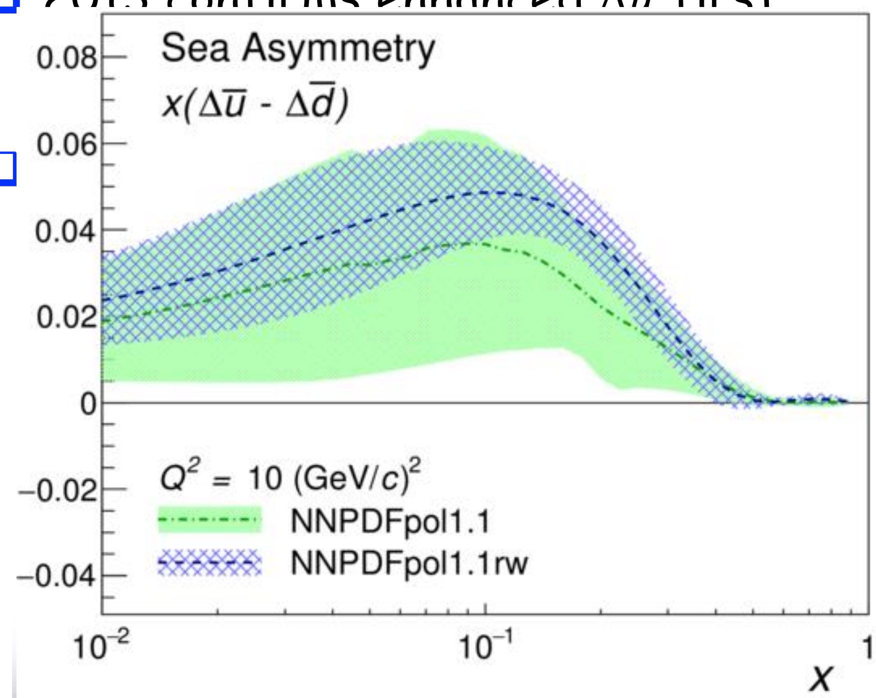
- First muon channel W A_L !
- Theoretical curves use the polarized NLO generator CHE with various global fits implemented.
- Backward μ^- are at upper limit of uncertainty bands indicating $\Delta\bar{u}$ is larger than fits without RHIC data indicate.
- Forward μ^- is below DSSV08 $\rightarrow$ could be explained by sign change in Δd for x > 0.5 ?
- Backward μ^+ show smaller than predicted asymmetries. Possibly due to under-estimated error bars in unpolarized sector.

$$A_L^{W^+} = \frac{\sigma^{\rightarrow} - \sigma^{\leftarrow}}{\sigma^{\rightarrow} + \sigma^{\leftarrow}} \sim \frac{\Delta\bar{d}(x_1)u(x_2) - \Delta u(x_1)\bar{d}(x_2)}{\bar{d}(x_2)u(x_1) + \bar{d}(x_1)u(x_2)}$$

Phys. Rev. D **99**, 051102(R)

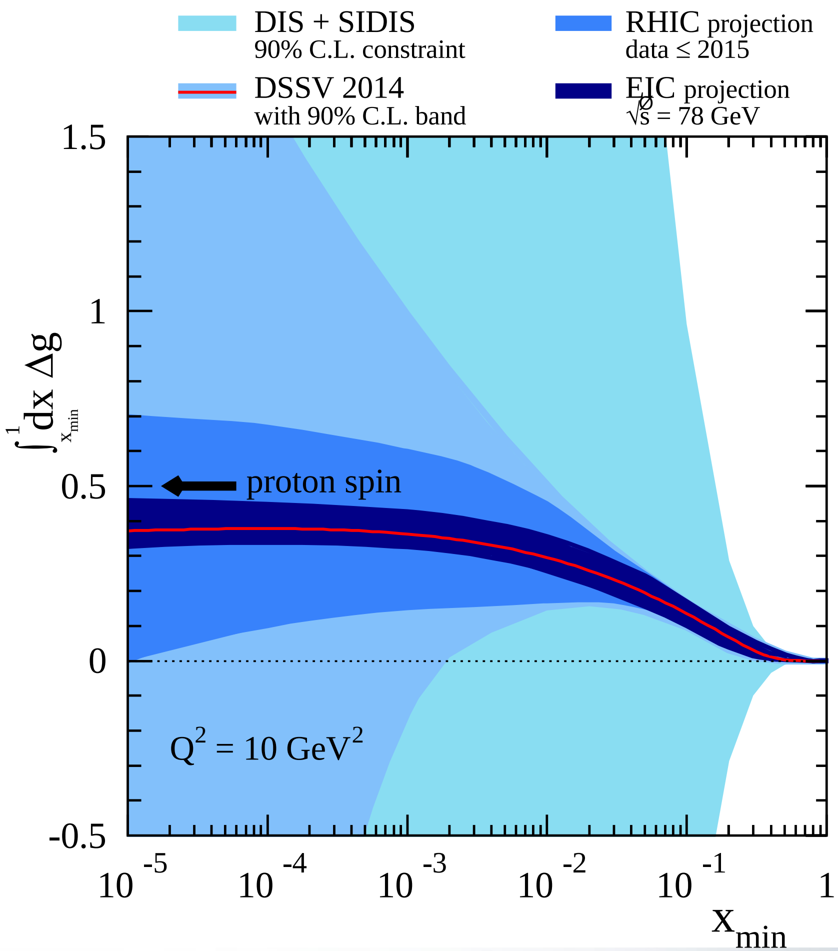


- 2013 results show consistent with previous STAR and PHENIX results
- These data show a significant preference for $\Delta\bar{u} > \Delta\bar{d}$ for $0.05 < x < 0.25$ at $Q^2 = 10$ GeV.
- 2013 confirms enhanced $\Delta\bar{u}$ first



ΔG STATUS Circa ~2015

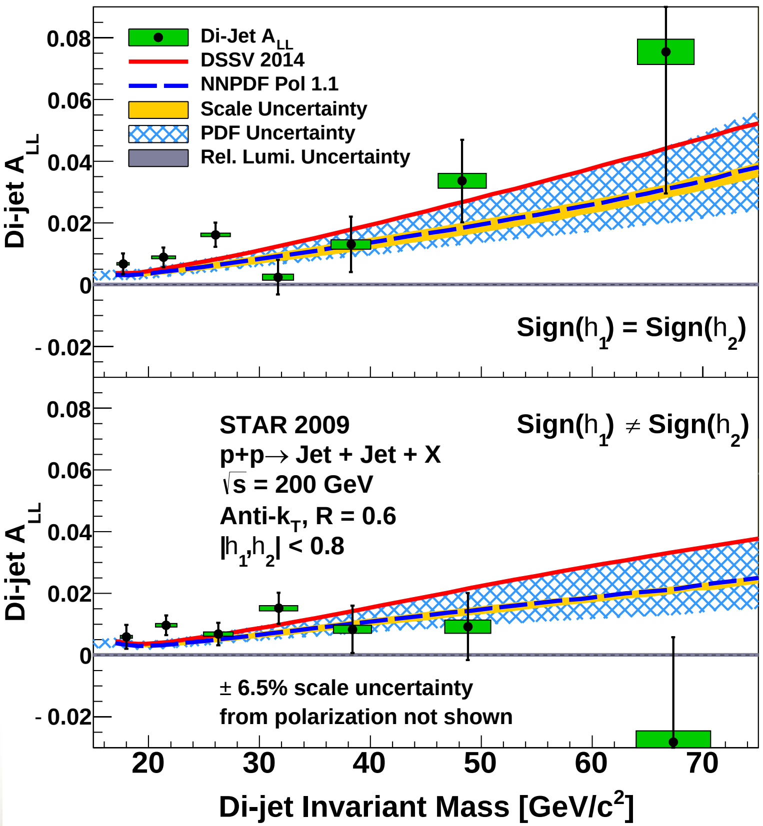
- Based on DSSV14 and includes PHENIX inclusive π^0, π^+, π^- and STAR inclusive jets and forward π^0 at 200 and 62 GeV.
- ΔG saturates at ~10^{-3} and 70% of proton spin
- Uncertainties increase dramatically outside kinematic reach of existing data.
- Two approaches to reduce uncertainties:
  - Measure correlation observables to help map out shape of Δg(x).
  - Measure asymmetries sensitive to lower x

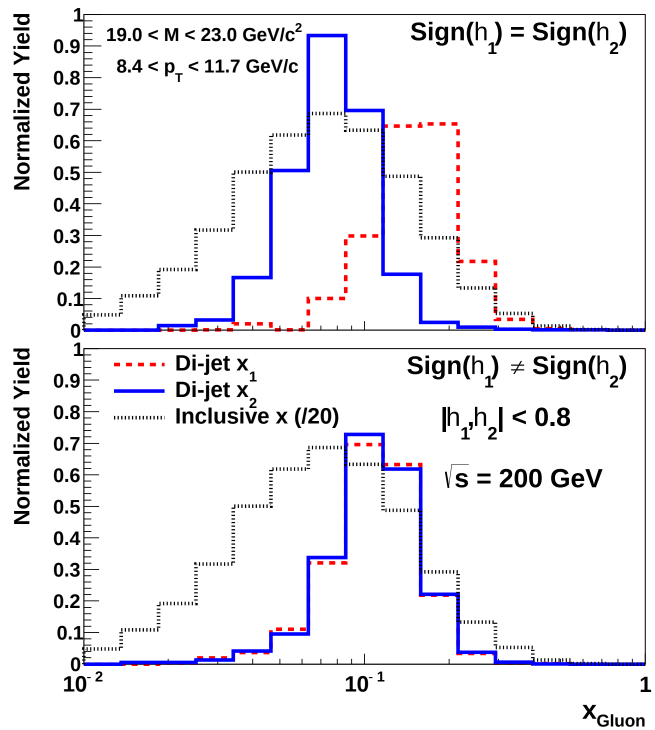


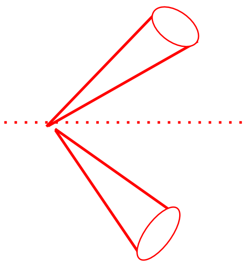
Phys.Rev. *D92*, 094030 (2015)

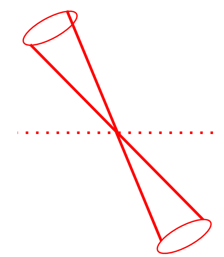
200 GeV Mid-Rapidity Dijets

$$A_{LL} \sim \frac{\sigma^{++;--} - \sigma^{\mp;\pm}}{\sigma^{++;--} + \sigma^{\mp;\pm}}$$



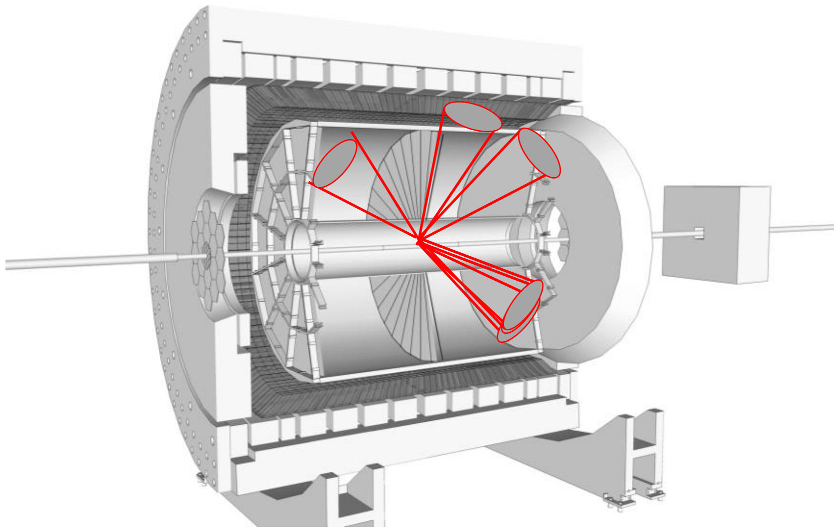


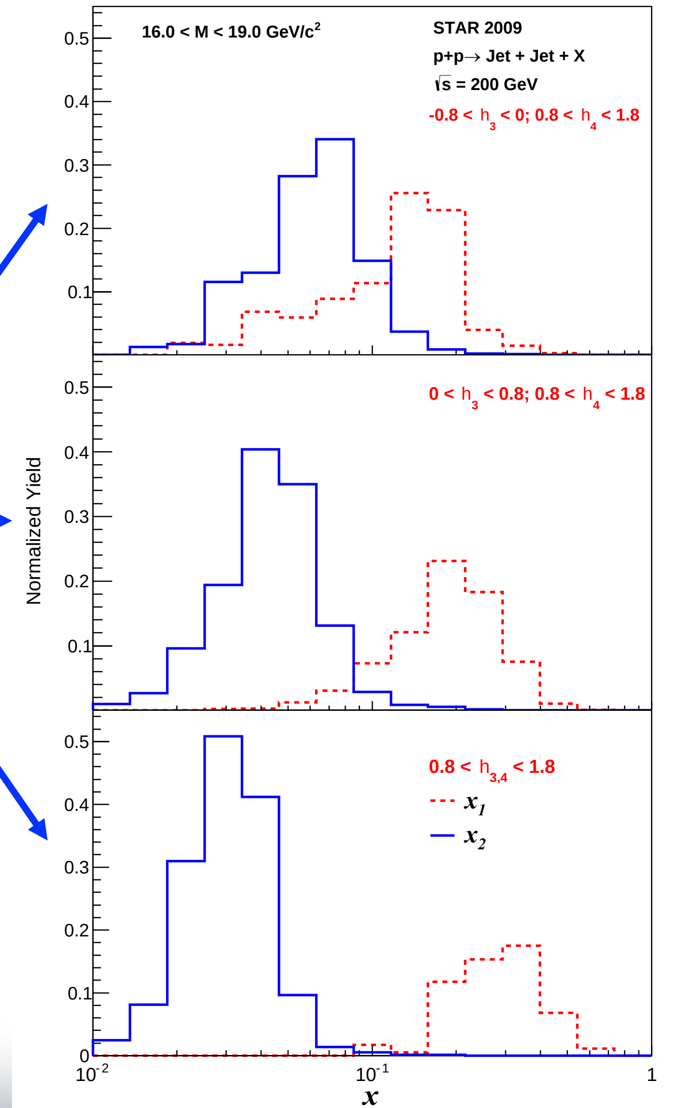




Phys.Rev. D95, 071103 (2017)

200 GeV Forward-Rapidity Dijet

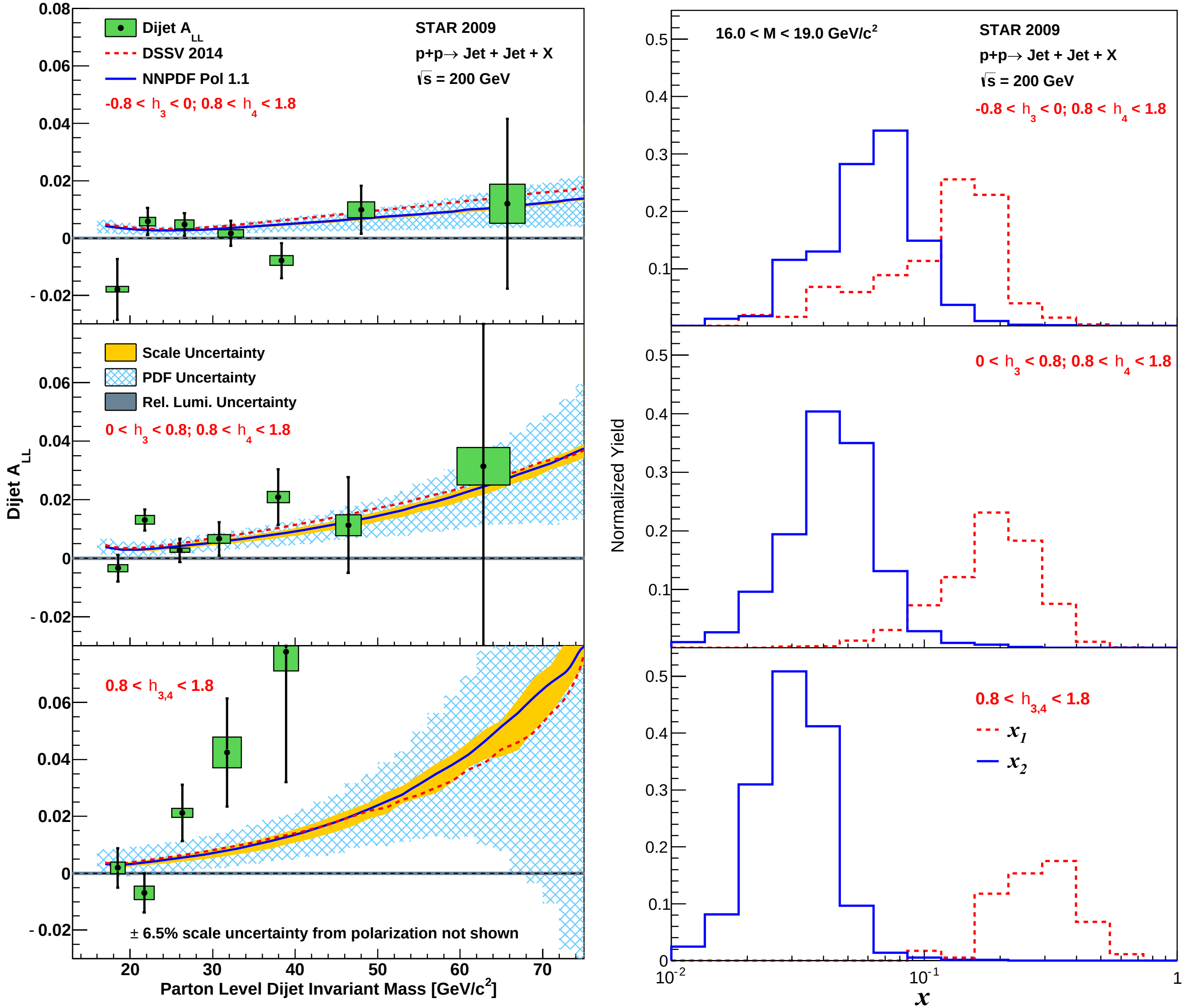




Can push to smaller x by using endcap calorimeter in forward region.

200 GeV Forward-Rapidity Dijet A_{LL}

- First forward jet analysis
- Utilized machine learning techniques to deal with dropping TPC efficiency
- Incorporated underlying event subtraction
- Asymmetries sample both low x gluons and high x quarks!
- Phys. Rev. D **98** (2018) 32011



A theoretical interlude

arXiv 1902.10548

Monte Carlo sampling variant of the DSSV14 set of helicity parton densities

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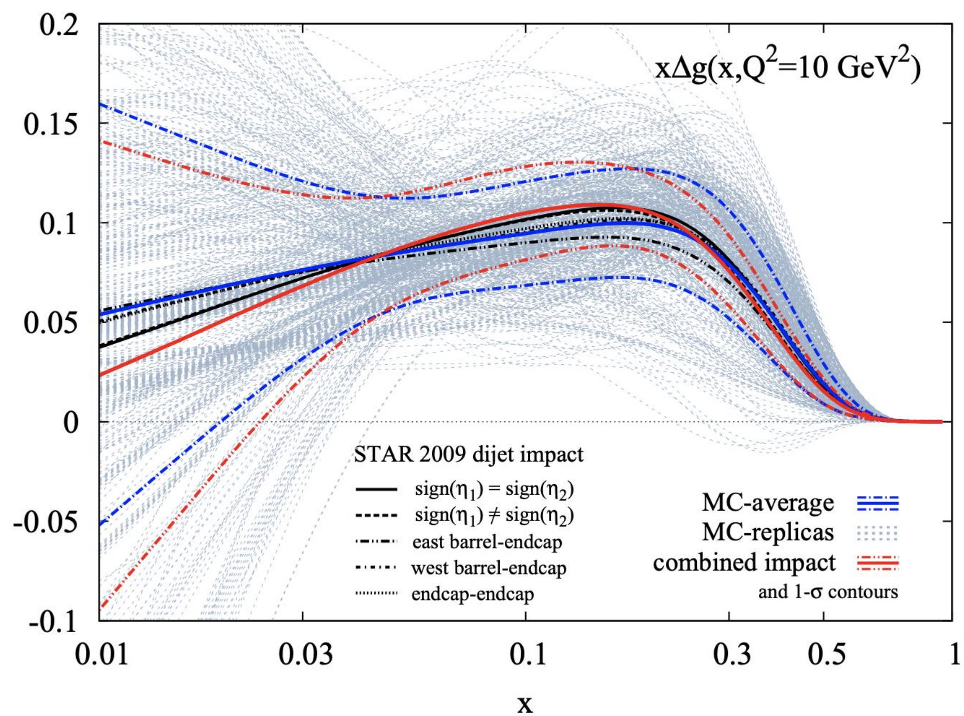
Marco Stratmann§ and Werner Vogelsang¶
Institute for Theoretical Physics, University of Tübingen, Auf der Morgenstelle 14, 72076 Tübingen, Germany

- New paper implements reweighting with STAR 200 GeV mid+forward rapidity dijets .
- Moderate increase of gluon polarization in the range 0.05 < x < 0.2 - change is within uncertainty of the DSSV14 replicas.
- Sizable reduction of width of 1-sigma uncertainty band, especially for x > 0.2.

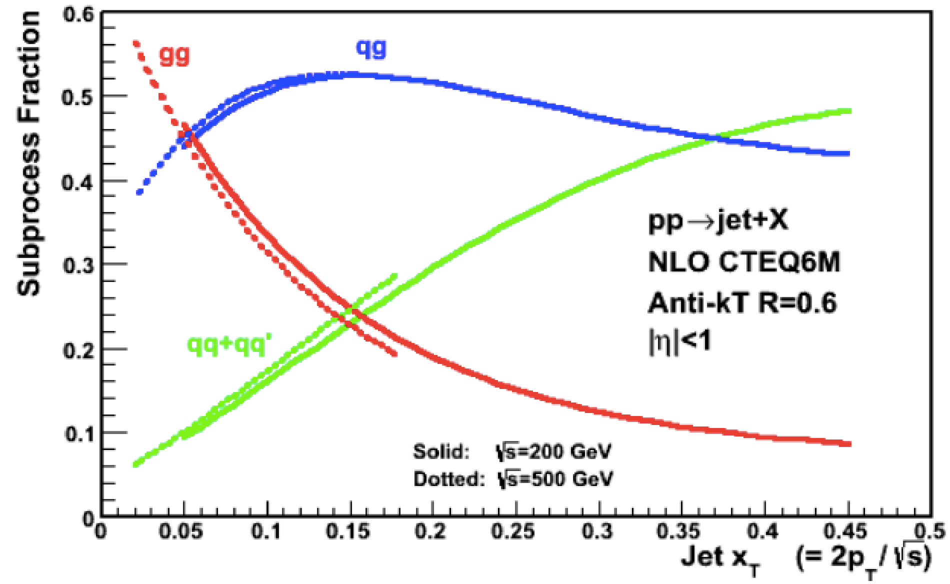


500 GeV Mid-rapidity Inclusive and Dijet A_{LL}

- Measurements at higher $\sqrt{s}$ access lower partonic x

$$x \approx x_T e^{\pm\eta} = \frac{2p_T}{\sqrt{s}} e^{\pm\eta}$$

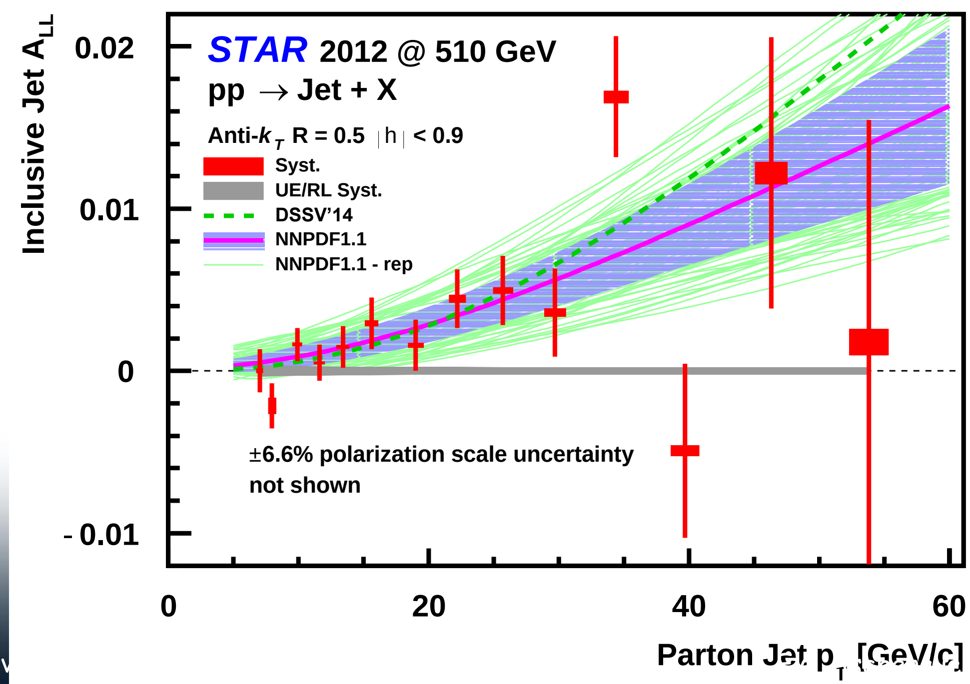
- Optimize R_{jet} = 0.5 to accommodate increased UE and pileup at higher center of mass energies



- Excellent agreement with theoretical expectations

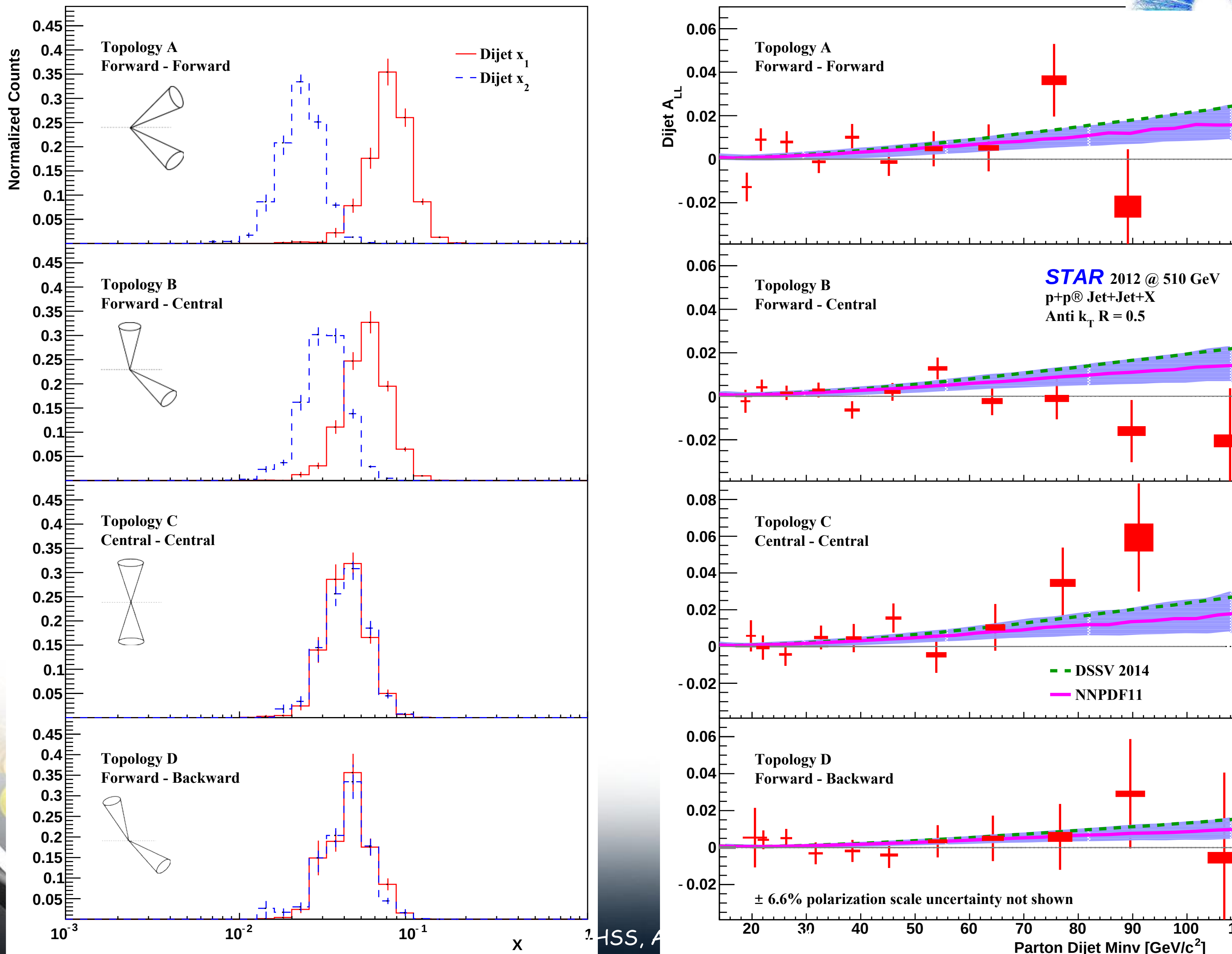
- Data-driven event-by-event UE subtraction developed for this result.

[arXiv: 1906.02740](https://arxiv.org/abs/1906.02740)



RUN-12 510 GEV MID-RAPIDITY DI-JET A_{LL}

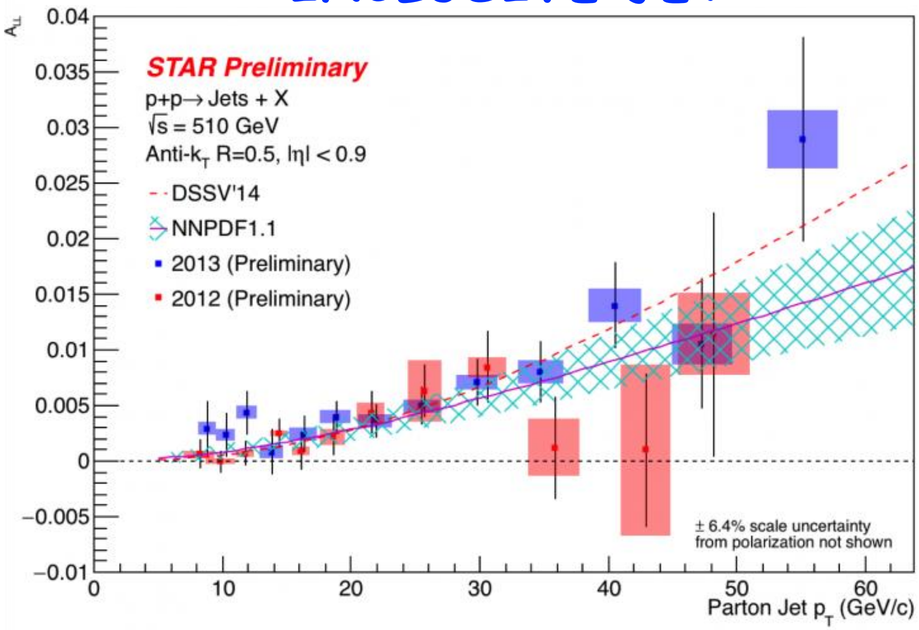
arXiv: 1906.02740



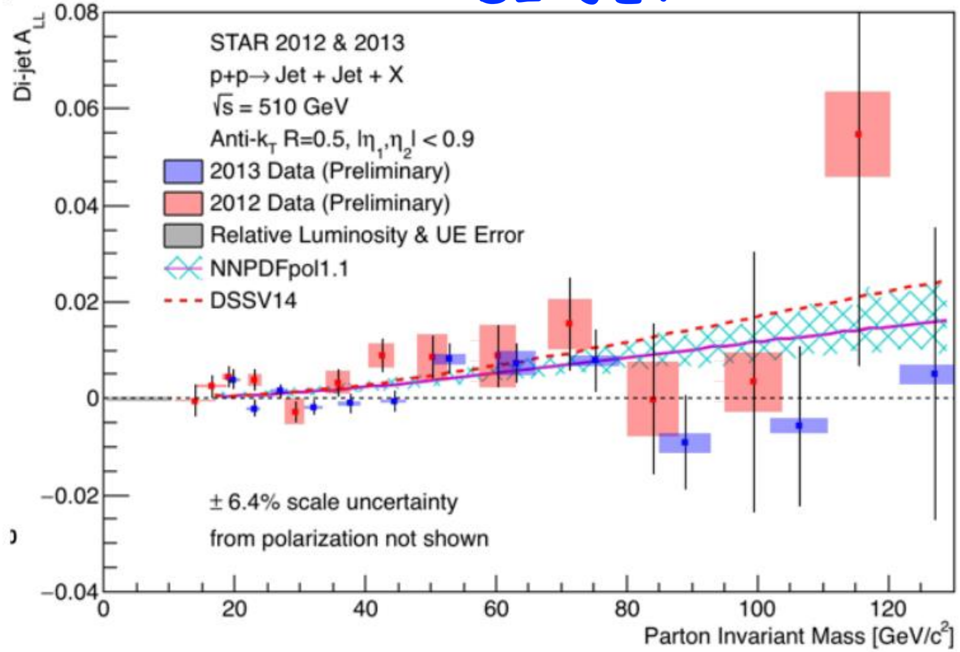
E.C. Aschenauer

Run 13 510 GeV Mid-rapidity Inclusive and DIJET A_{LL}

INCLUSIVE JET

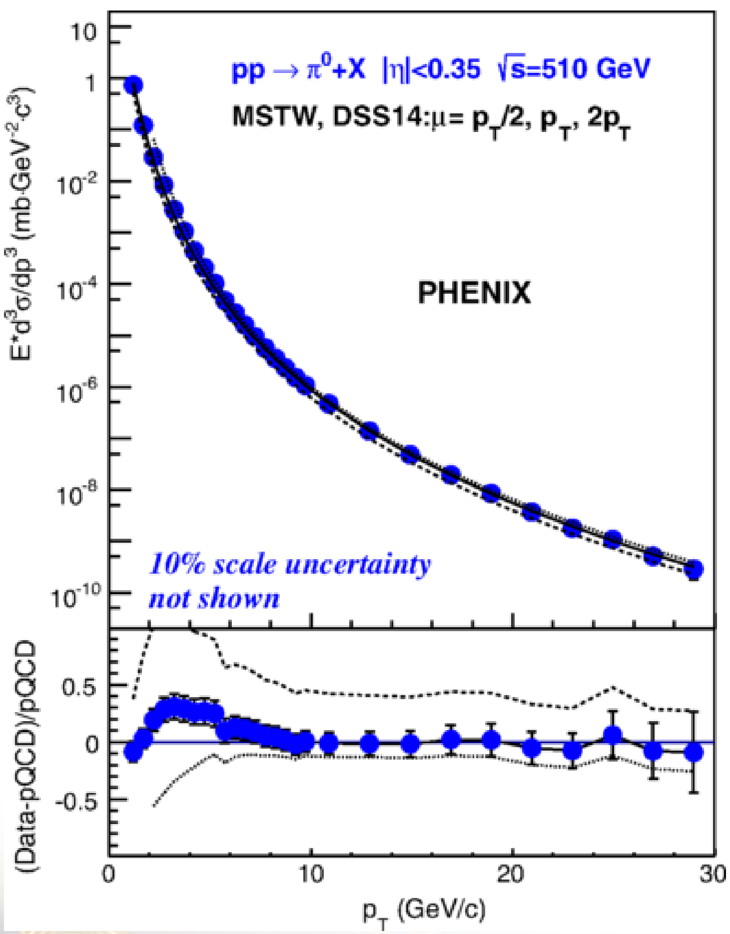


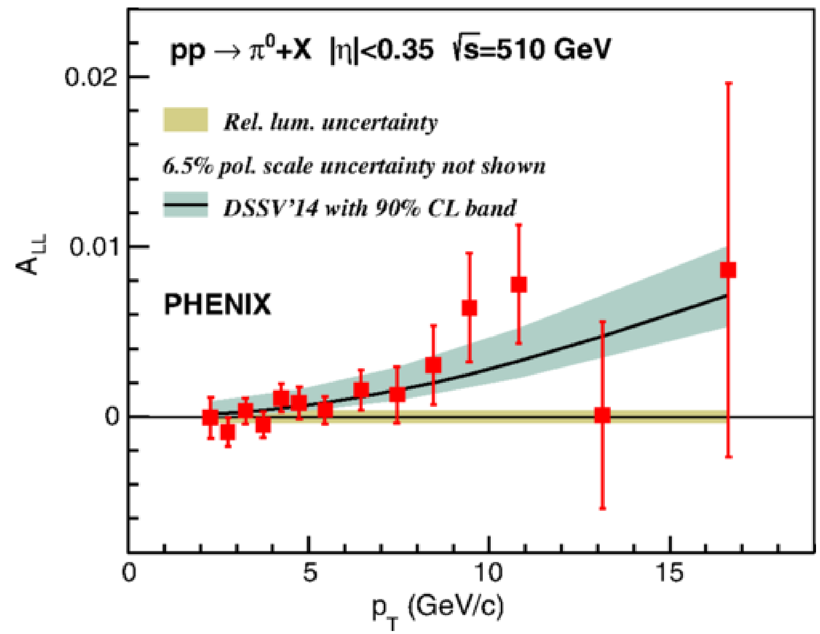
DI-JET

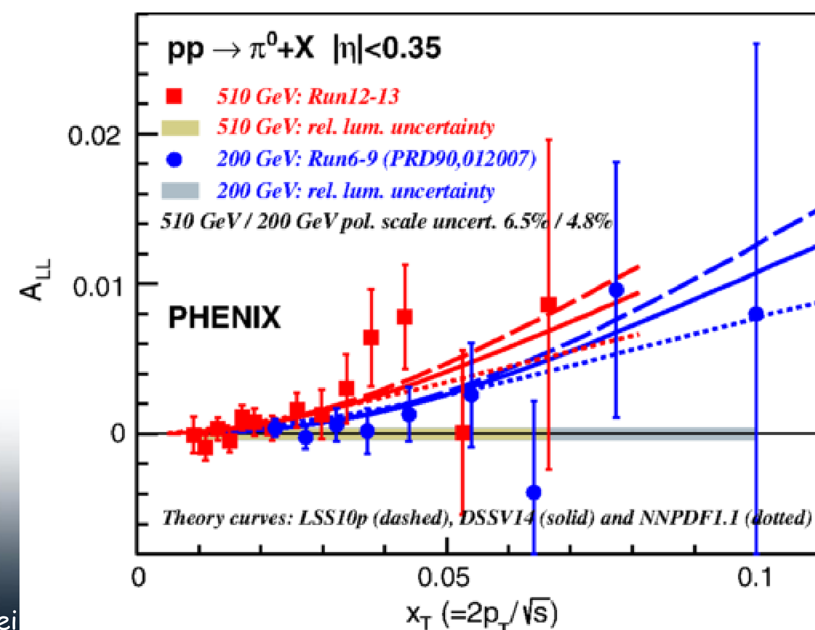


510 GeV Inclusive midrapidity π^0

Phys. Rev. D **93**, 011501(R)



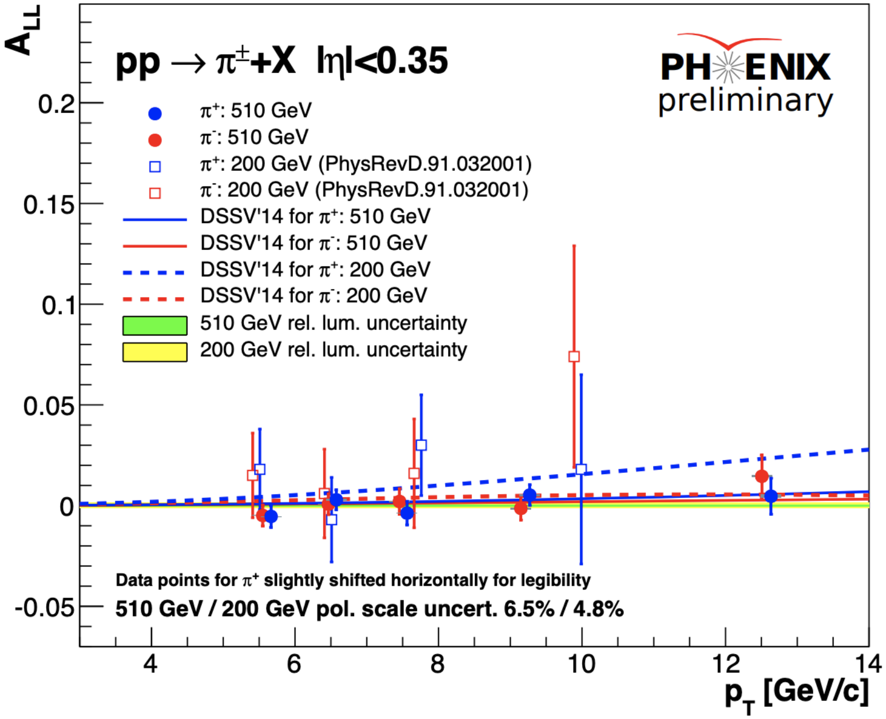




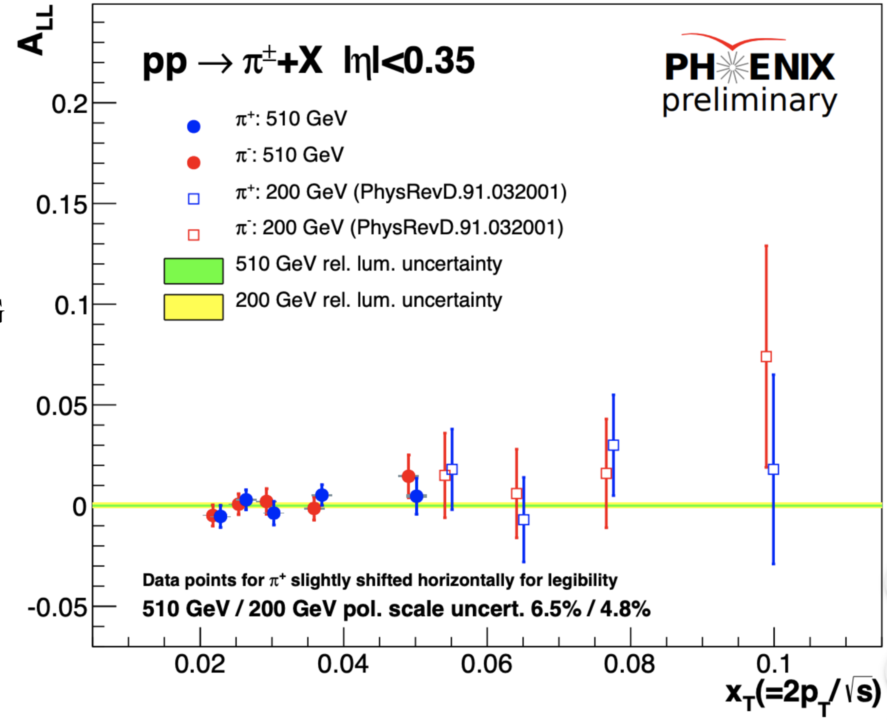
Excellent agreement between data and theory!

510 GeV Inclusive Midrapidity $\pi^{+/-}$

Sensitive to the sign of ΔG - $A_{LL}^{+} > A_{LL}^{-}$



ΔG



What can transverse polarized pp tell us

Objectives:

- Establish transverse momentum dependent PDFs survive at low x and/or high Q^2
  → critical input to make a TMD program at EIC successful
  → high precision data to test factorization and universality of TMDs
  pp ← → DIS@EIC

Advantages to access TMDs in p+p

Gluons:

One of the driving motivations behind an EIC is the study of gluons. Strong interactions access gluons directly (qg & gg) and are well suited for studying TMD observables like Gluon Fragmentation Functions and Gluon Linear Polarization.

DIS: F_L, tag PGF (di-jets, heavy flavor)

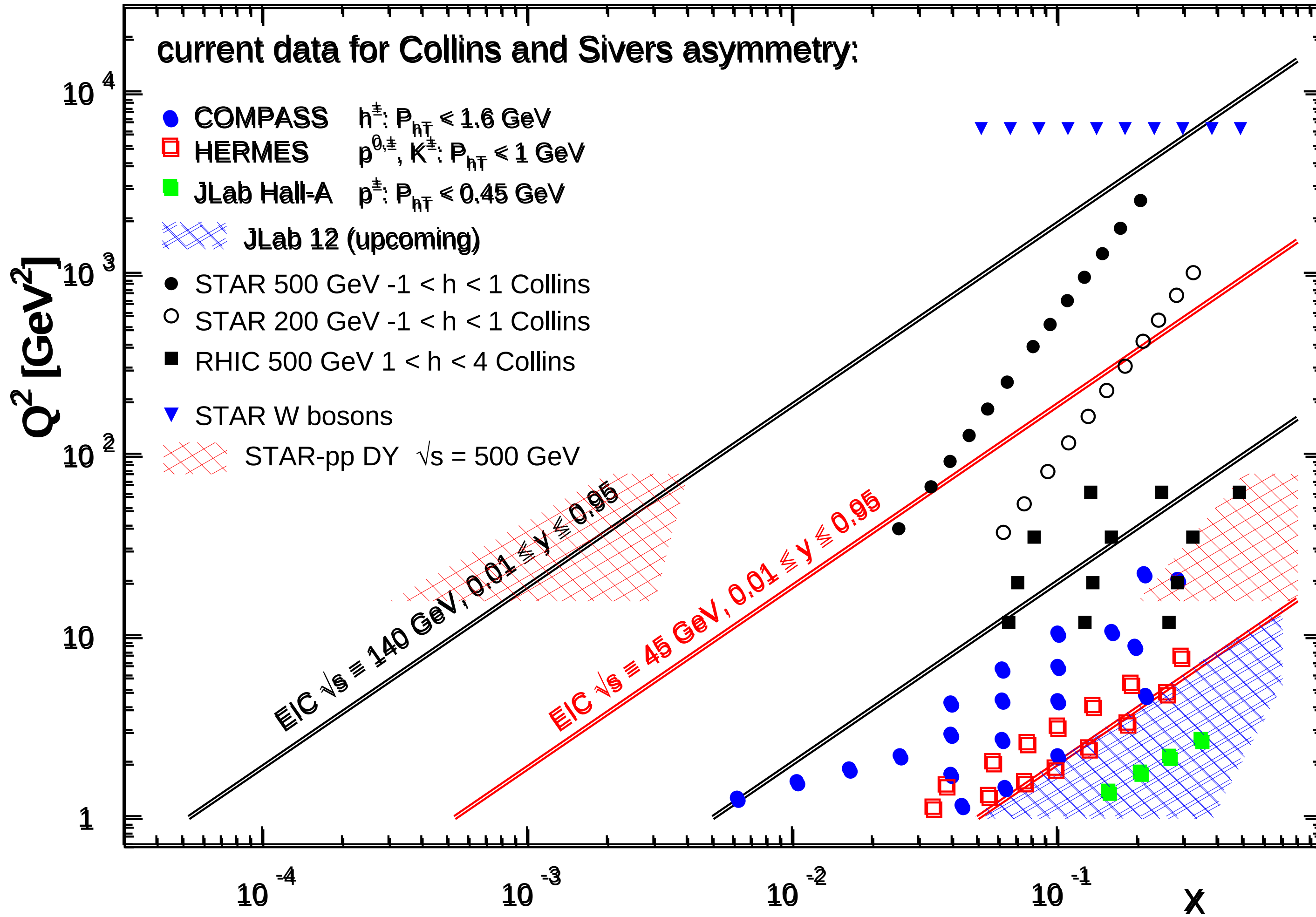
Evolution:

TMD evolution is area of active theoretical research!

- Proton colliders routinely access higher Q^2 and p_T than fixed target experiments (as well as some running scenarios for an EIC).

→ Provides insights into the size of observables we want to measure at an EIC.

TMDs at RHIC



Till today TMDs came only from fixed target data → high x @ low Q^2

need to establish concept at high Q^2 and wide range in x

polarised pp at RHIC

RHIC unique kinematics: from low to high x at high Q^2

only way to access gluon TMDs before an EIC

The objectives for TMDs

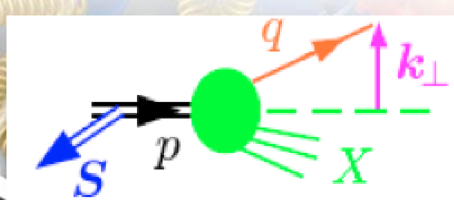
- Constrain TMDs over a wide x and Q^2 range (valence, sea-quarks & gluons)
  - → need 2 scale processes (DY, W, Z^0, Di-jet, $h^\pm$ in jet)
  - → different √s → different p_t at the same x_t → evolution
  - → Test non-universality of TMDs ← → SIDIS
- observables as transversity can be accessed also in collinear observables (IFF)
  - → test of TMD factorization & universality
- observables purely sensitive (1-scale (π^0/γ/jet)) to the TWIST-3 formalism
  - → different √s → evolution

Initial State

- A_N for $W^{+/-}$, Z^0, DY
  - → Sivers
- A_N for jets
  - → g-Sivers in Twist-3
- direct photons
  - → q-Sivers in Twist-3

related through

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

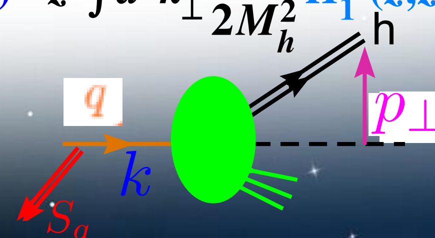


Final State

- A_{UT} $\pi^{+/-}\pi^0$ **azimuthal distribution in jets**
  - → Transversity x Collins
- A_{UT} in dihadron production
  - → Transversity x Interference FF
- A_N for π+/- and π^0
  - → Novel Twist-3 FF Mechanisms

related through

$$\hat{H}(z) = z^2 \int d^2\vec{k}_\perp \frac{\vec{k}_\perp^2}{2M_h^2} H_1^\perp(z,z^2,\vec{k}_\perp^2)$$



A GoldeN Observable: "Hadrons in Jet"

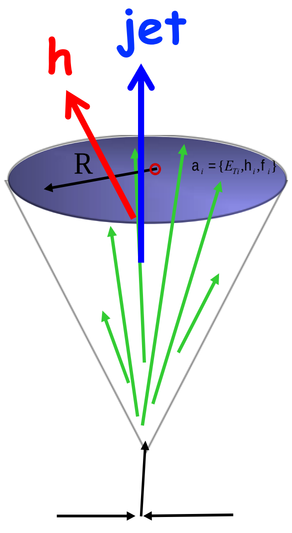
Observable: Hadron distribution inside jet

- Study a hadron distribution inside a fully reconstructed jet

$$F(z,p_t)=\frac{d\sigma^h}{dydp_t dz}/\frac{d\sigma}{dydp_t} \qquad f(z,p_t,j_t)=\frac{d\sigma^h}{dydp_t dz dj_t}/\frac{d\sigma}{dydp_t} \qquad z=\frac{p_t^h}{p_t^{jet}}$$

W. Vogelsang et al. arXiv:1506.01415

j_T: hadron transverse momentum with respect to the jet direction

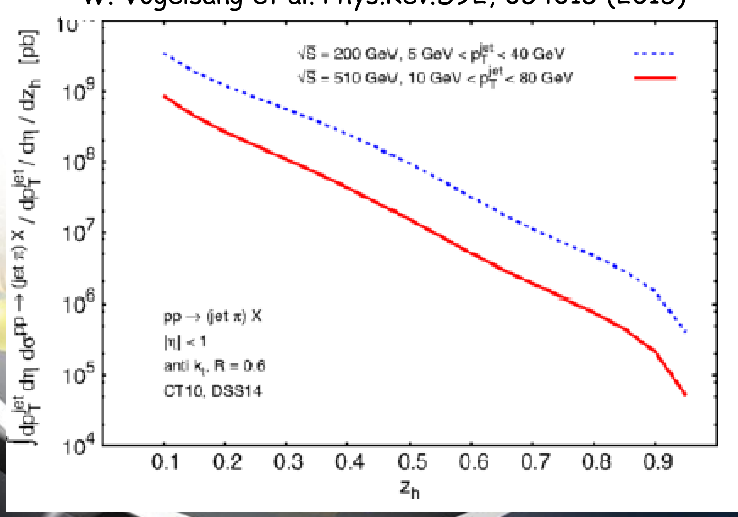


- The 1st observable is collinear, while the 2nd observable is a TMD

Cross section for hadrons in jet

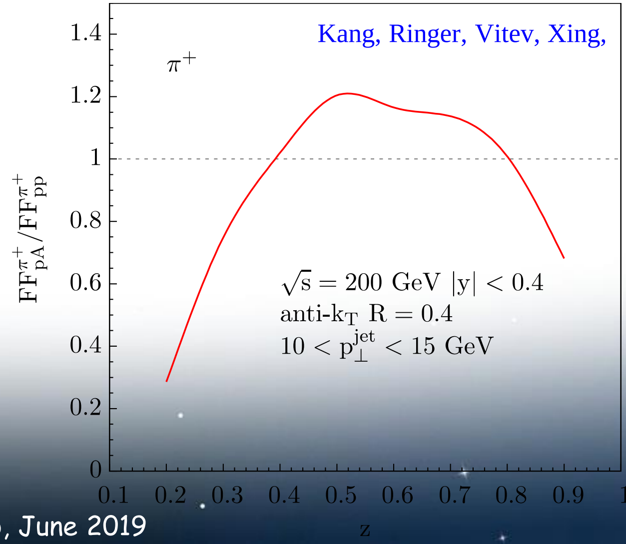
- High sensitivity to Gluon FF
- Unique to pp

W. Vogelsang et al. Phys.Rev.D92, 054015 (2015)



Nuclear dependence of FFs

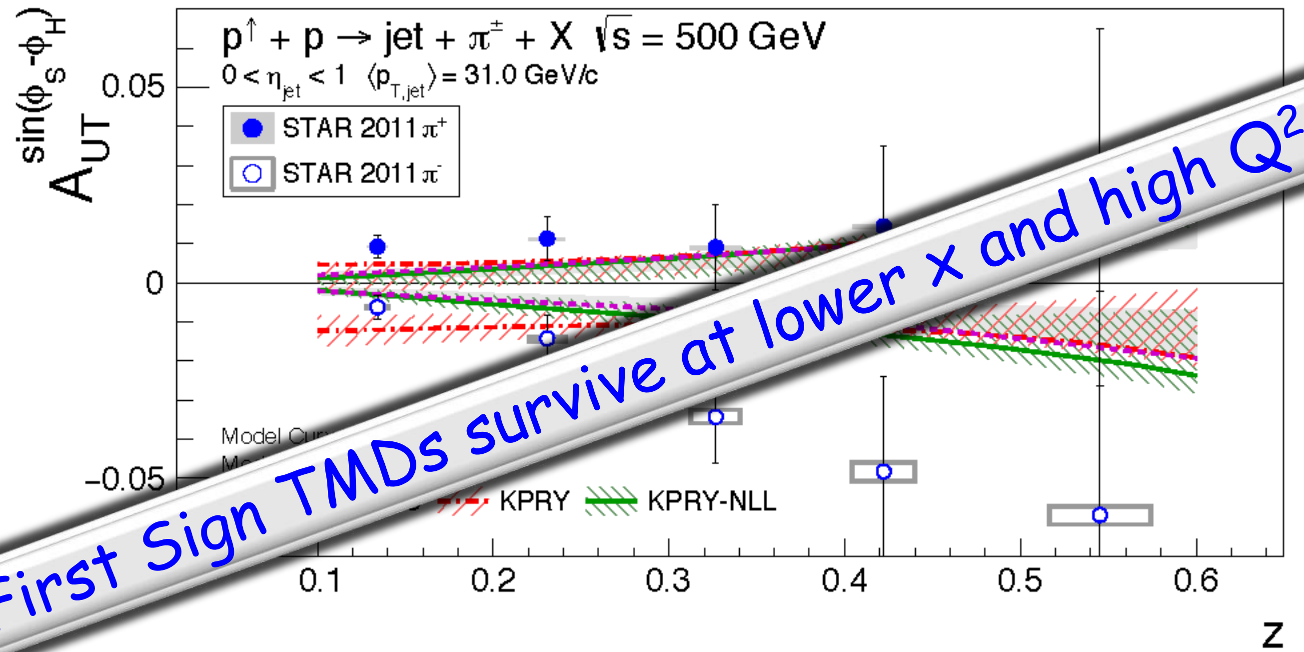
- Seems to follow the feature of p+Pb at LHC
- Will see how energy loss picture will compare



Jets to access Transversity x Collins

$$A_{UT}^{\rho^{\pm}} \approx \frac{h_1^{q_1}(x_1,k_T) f_{q_2}(x_2,k_T)\hat{s}_{UT}(\hat{s},\hat{t},\hat{u}) DD_{q_1}^{\rho^{\pm}}(z,j_T)}{f_{q_1}(x_1,k_T) f_{q_2}(x_2,k_T)\hat{s}_{UU} D_{q_1}^{\rho^{\pm}}(z,j_T)}$$

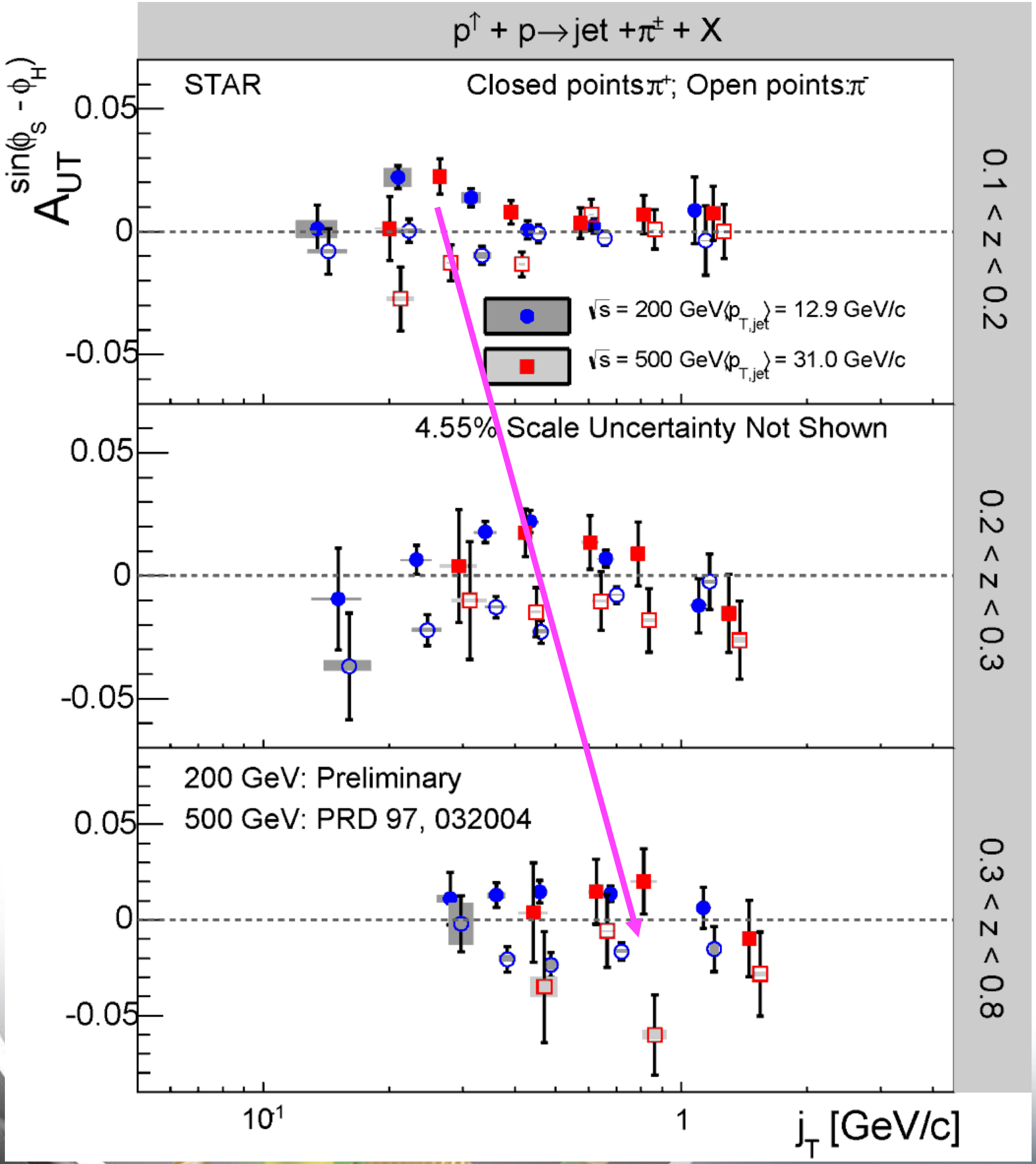
STAR arXiv:1708.07080
DMP: PLB 773, 300 (2017)
KPRY: PLB 774, 635 (2017)



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**
  - Kang et al, JHEP 11, 068 (2017)
- TMD evolution effects appear to be small

Collins effect vs j_T in separate z-bins

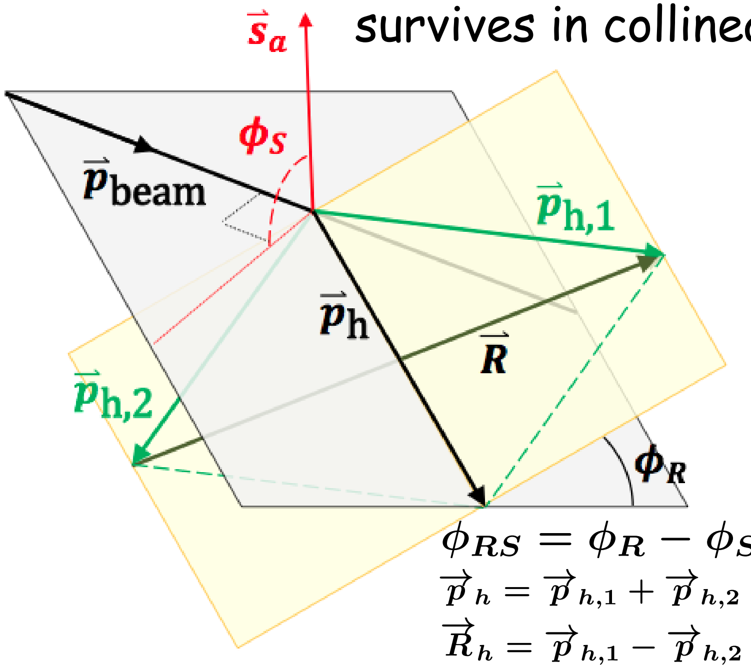


- 500 GeV pp results hinted the A_{UT} peak shifts to higher j_T as z increases
  - 2017 data factor 14 more statistics
- New preliminary **200 GeV pp results provide confirming evidence**

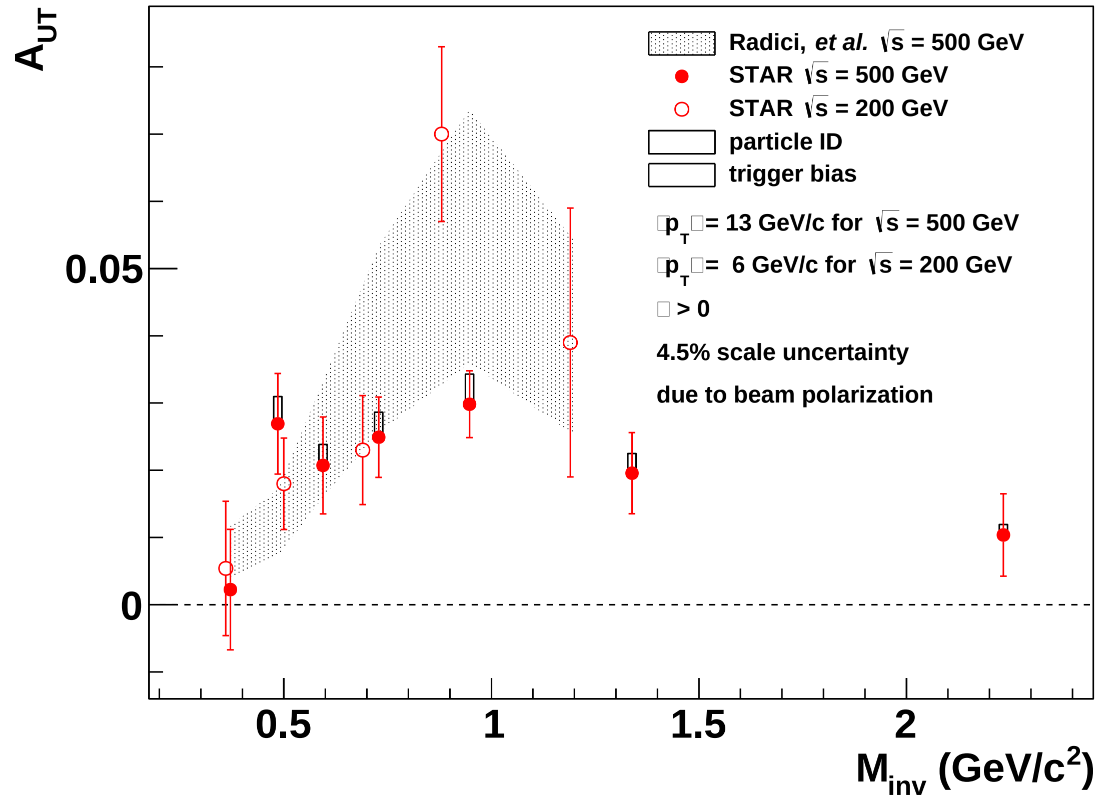
Interference Fragmentation Function (IFF)

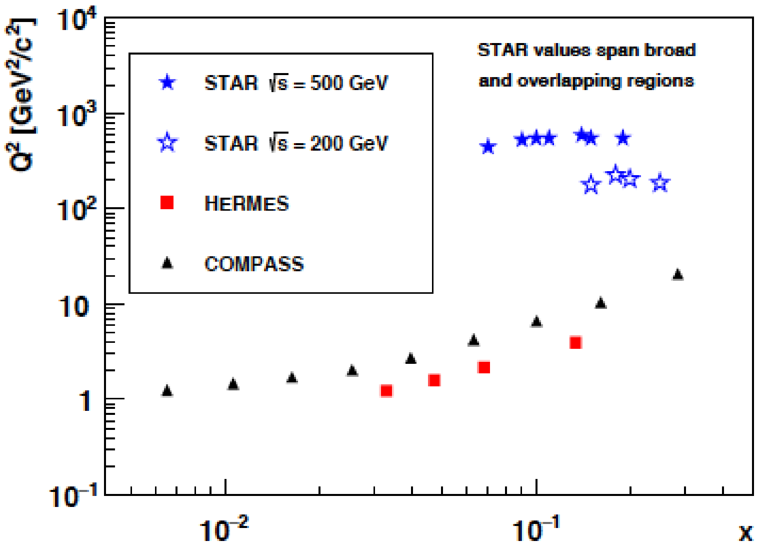
$p^{\uparrow}+p \rightarrow \pi^+\pi^-+X \rightarrow$ transversity x IFF survives in collinear framework

$$A_{UT}\sin(\phi_{RS}) = \frac{1}{Pol}\frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$



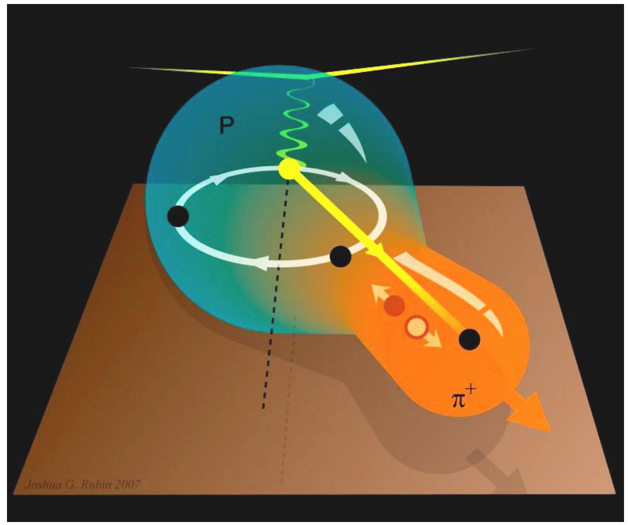
$$\phi_{RS} = \phi_R - \phi_S$$
$$\vec{p}_h = \vec{p}_{h,1} + \vec{p}_{h,2}$$
$$\vec{R}_h = \vec{p}_{h,1} - \vec{p}_{h,2}$$





- Significant di-hadron asymmetries both at √s=200GeV and √s=500GeV (arXiv:1710.10215)
- Increasing with p_T
- Access to transversity with a collinear observable
- more data at 200 GeV from 2012 and 2015 (factor 15) and 500 GeV 2017 (factor 14)

What Do We Know about Gluon TMDs

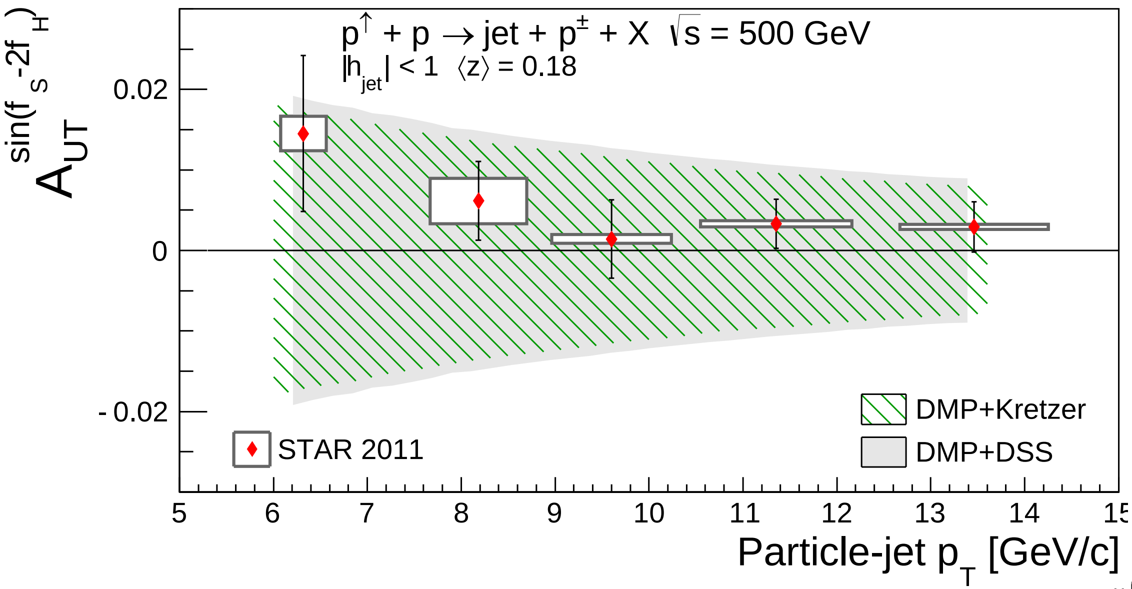


un-integrated gluon density $g(x,Q^2,k_T)$ important for physics at small x

- → CGC
- → applications at LHC, i.e. Higgs production

N \ g	U	L	linear
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	h_1^g, $h_{1T}^{\perp g}$

Collins like Effect

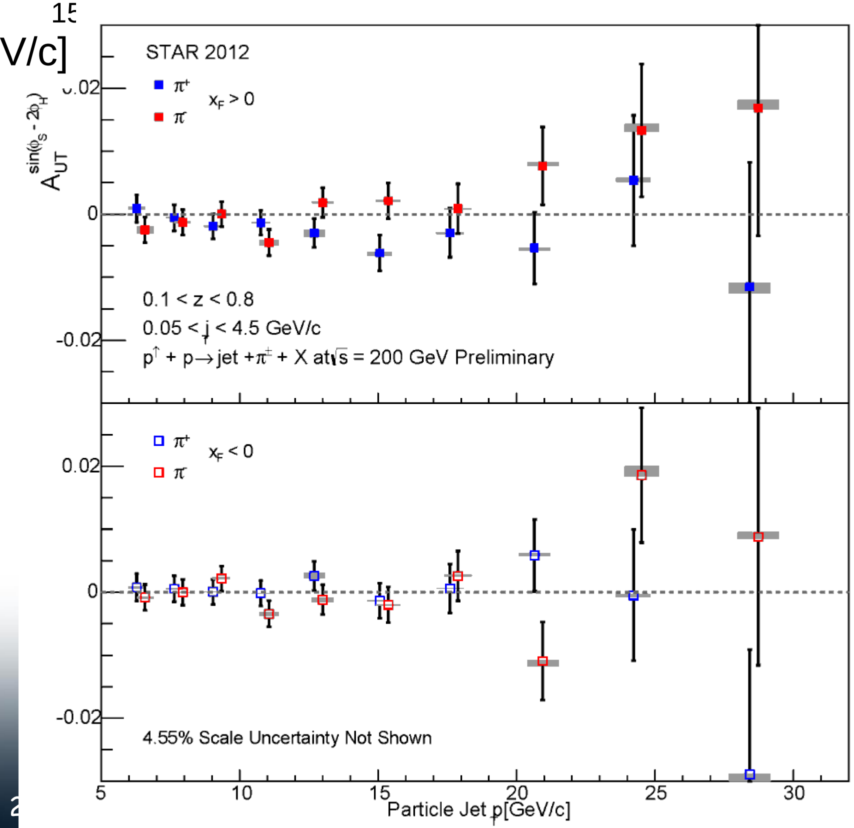


Until now, Collins-like asymmetries completely unconstrained

World's first ever limit

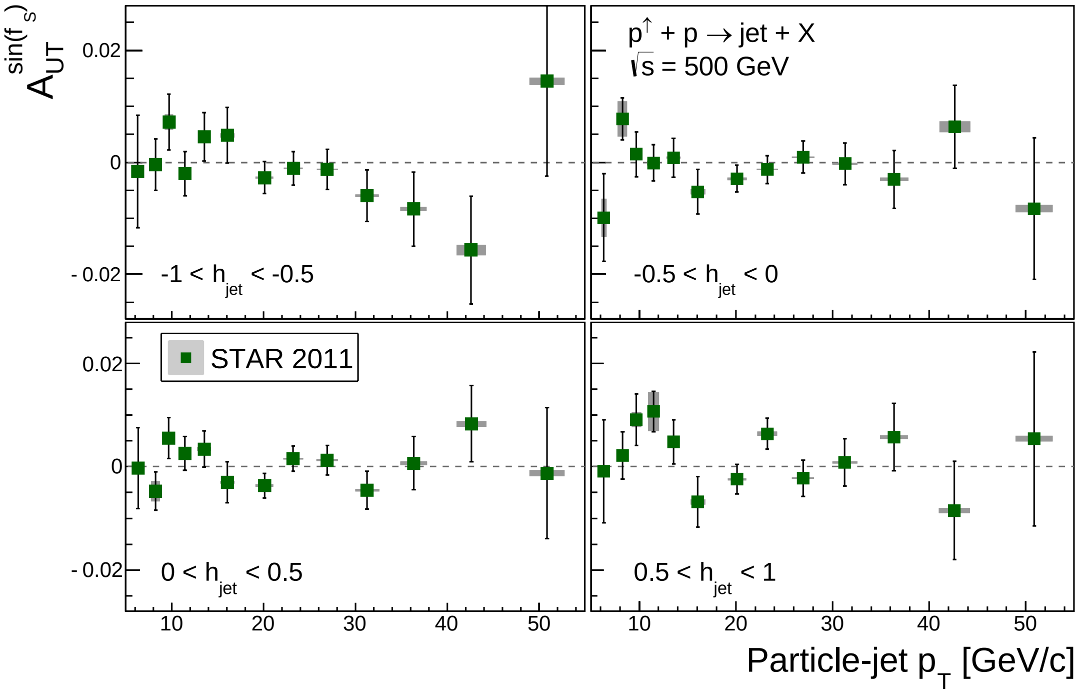
on linearly polarized gluons in a polarized proton

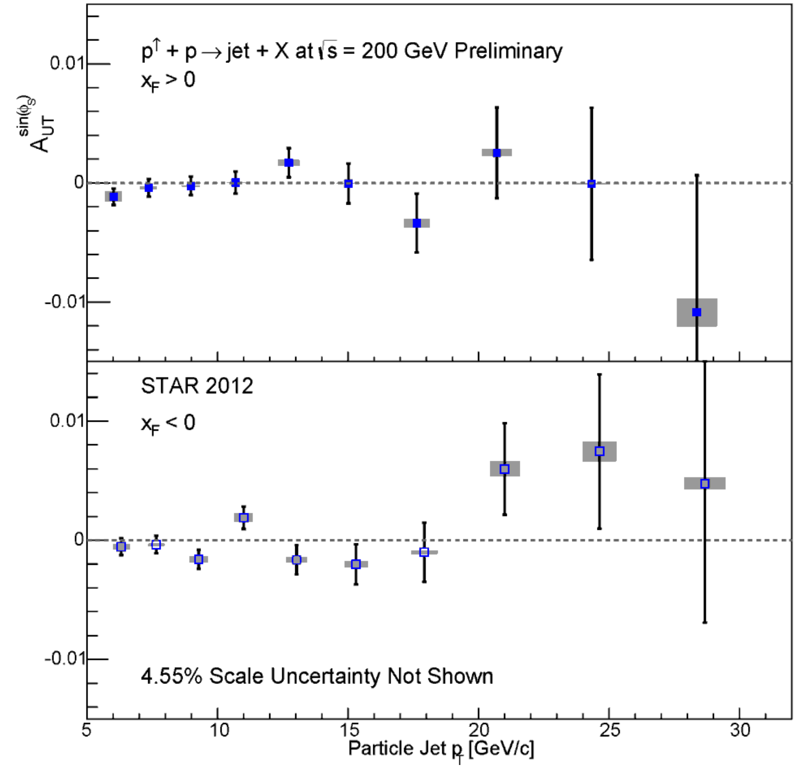
Shaded bands represent maximal predictions from D'Alesio, Murgia, and Pisano, arXiv:1707.00914 utilizing Kretzer and DSS FF

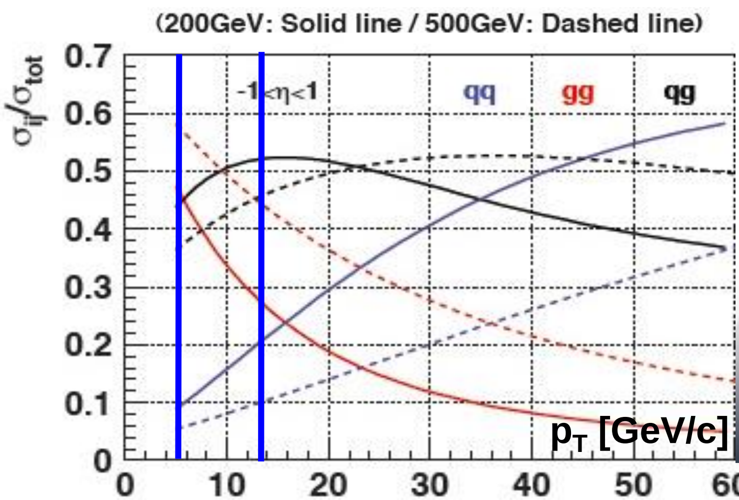


New preliminary results from 200 GeV pp collisions will provide much stronger limits

"Twist-3 Sivers" through Inclusive Jets







No sign of sizable azimuthal asymmetry in jet production at $\sqrt{s}$ = 500 GeV & 200 GeV

Consistent with expectation from inclusive jets, di-jets, and neutral pions at $\sqrt{s}$ = 200 GeV

What Will Come

to

STAR Physics program after BES-II

Mid-rapidity $-1.5<\eta<1.5$ | Forward-rapidity $2.8<\eta<4.2$

A+A

Beam:
Full Energy AuAu

Physics Topics:
a deep look into the properties of the QGP:
γ & e+e- pairs
- chiral symmetry restoration
- temperature and lifetime of hot, dense medium

Hypertriton Lifetime Measurement

Precision measurements of direct photon yields and v_n

p+p & p+A

Beam:
500 GeV: p+p
200 GeV: p+p and p+A

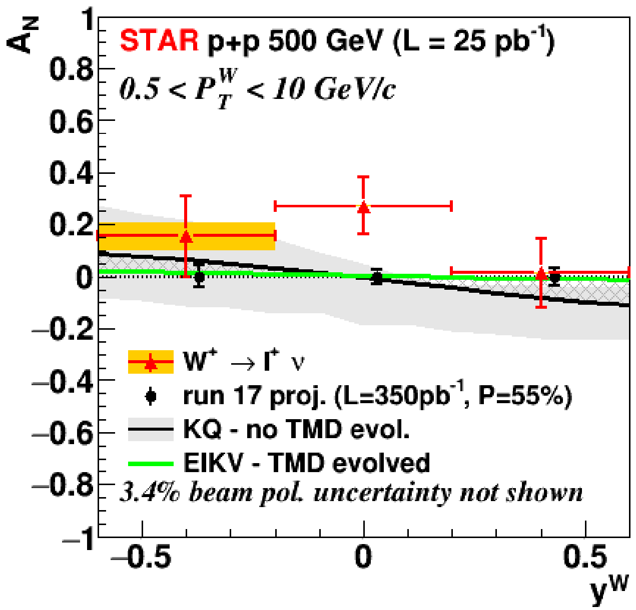
Physics Topics:
- Improve statistical precision
- TMD measurements, i.e. Collins, Sivers, …
- Access s & Δs through Kaons in jets
- Measurement of GPD E_g through UPC J/Ψ
- First access to Wigner functions through di-jets in UPC
- Gluon and quark vacuum fragmentation
- Gluon and quark fragmentation in nuclear medium
- Nuclear dependence of Collins FF

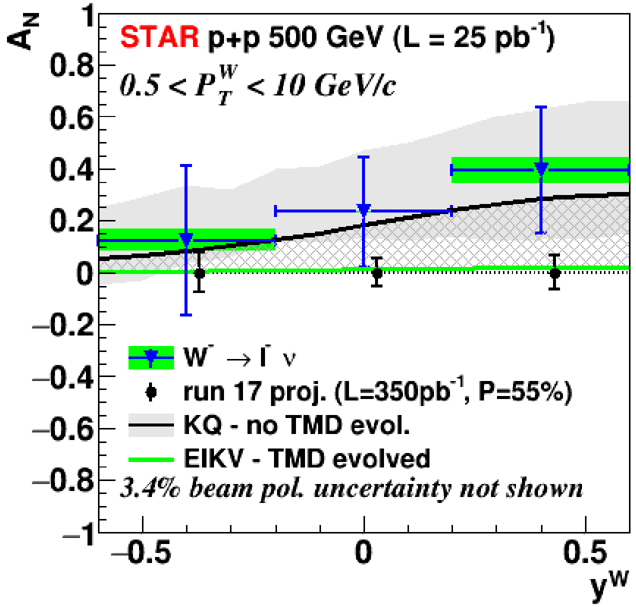
2021: provides a nice opportunity to run 500 GeV polarized pp
All other data taking in parallel to sPHENIX data taking campaign

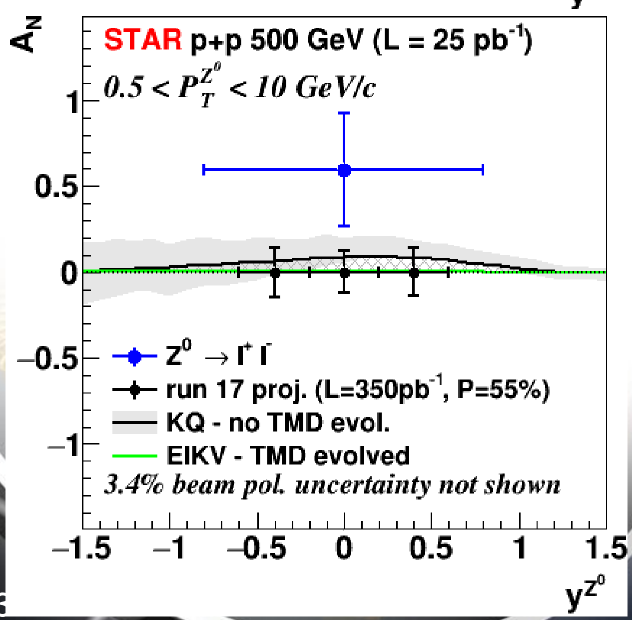
RUN-17: A goldmine for TMDs@STAR

Collected:

350 pb^{-1} → 14 times Run-11 for $-1 < \eta < 1.8$ → A_N $W^{+/-}$ & Z^0, Collins, ……







→ Z^0 very clean channel no corrections

Will provide data to constrain

→ TMD evolution,

→ sea-quark Sivers fct

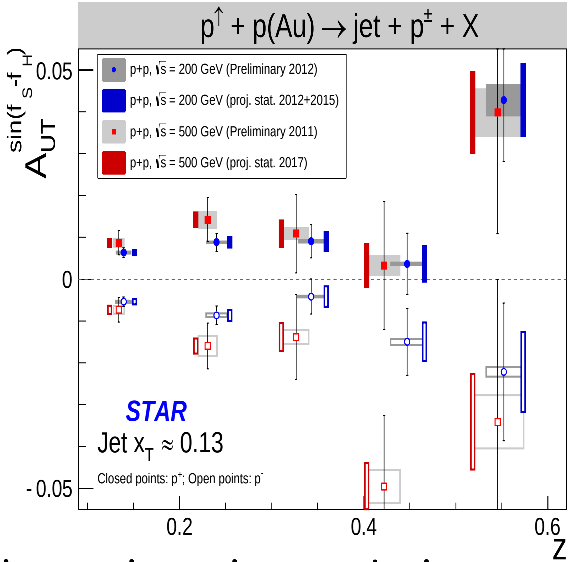
→ through rapidity distribution → neg. η

→ till now no constrain from SIDIS

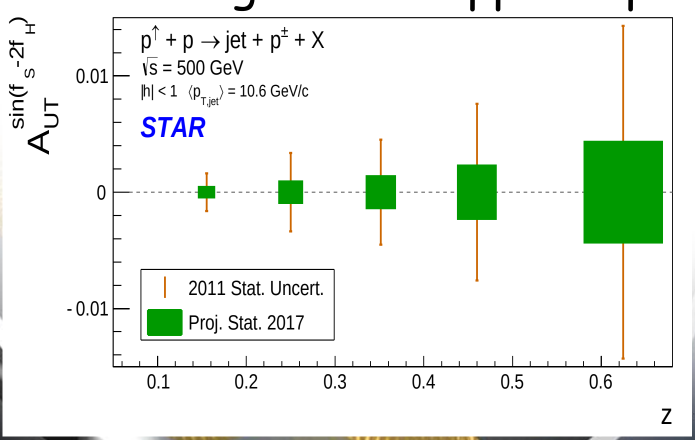
→ resolve Sivers fct. non-universality

At 500 GeV in 2017:

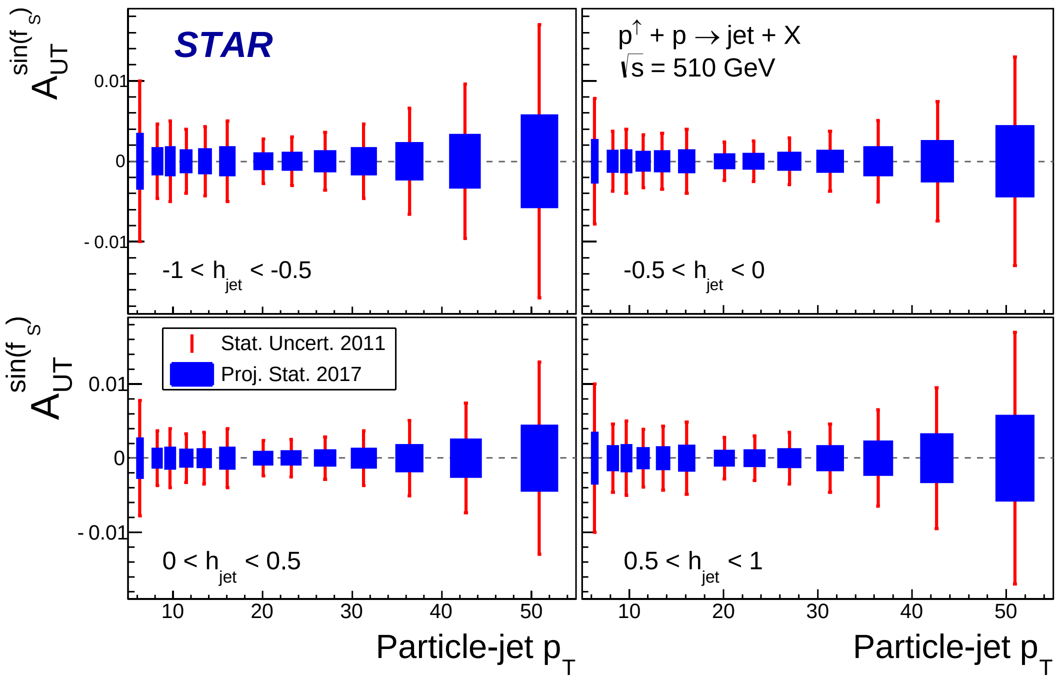
Transversity x Collins



linearly polarised gluons
→ could be an explanation for the ridge seen in pp and pA



Sivers function through TWIST-3:



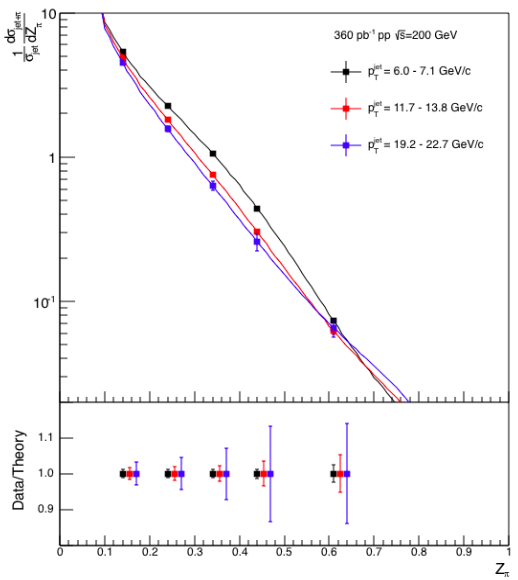
To have high precision data at different √s
→ constrain TMD evolution
→ fixed x and Q^2 → p_T different

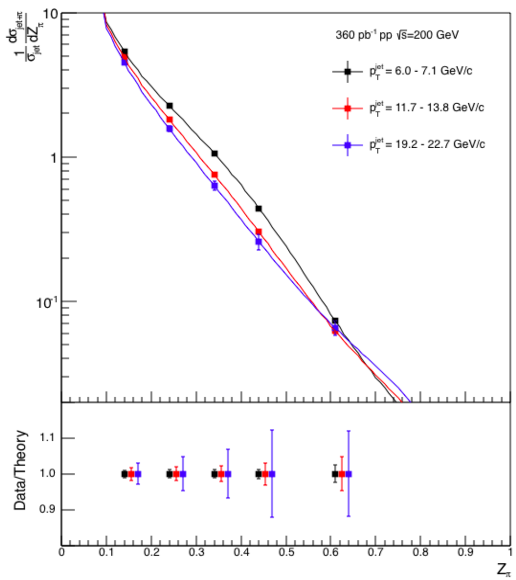
Fragmentation Functions in pp and pA

Observable: hadron in jet

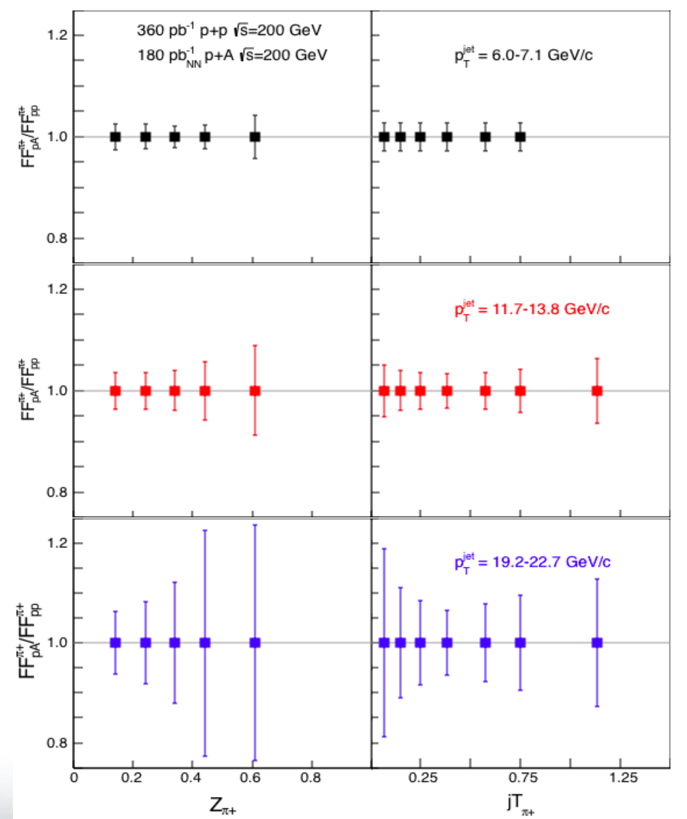
→ pp best way to measure gluon PDFs → direct access through qg and gg scattering

p+p: $\pi+$ $\pi-$

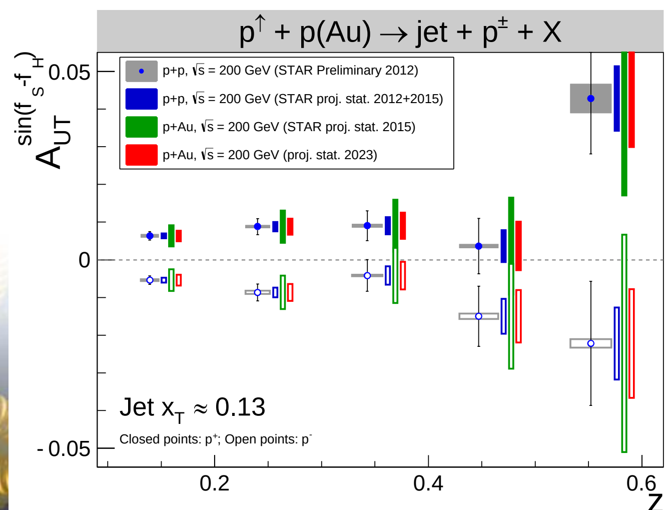




fragmentation functions in p+A/p+p at $|\eta| < 0.4$



only at RHIC: measure nuclear effects for polarized FF → nCollins



E.C. Aschenauer

STAR Physics program after BES-II

Mid-rapidity $-1.5<\eta<1.5$ | **Forward-rapidity $2.8<\eta<4.2$**

A+A (Mid-rapidity)

Beam:
Full Energy AuAu

Physics Topics:
a deep look into the properties of the QGP:
γ & e+e- pairs
- chiral symmetry restoration
- temperature and lifetime of hot, dense medium

Hypertriton Lifetime Measurement

Precision measurements of direct photon yields and v_n

p+p & p+A (Mid-rapidity)

Beam:
500 GeV: p+p
200 GeV: p+p and p+A

Physics Topics:
- Improve statistical precision
  - ➢ TMD measurements, i.e. Collins, Sivers, …
  - ➢ Access s & Δs through Kaons in jets
- Measurement of GPD E_g through UPC J/Ψ
- First access to Wigner functions through di-jets in UPC
- Gluon and quark vacuum fragmentation
- Gluon and quark fragmentation in nuclear medium
- Nuclear dependence of Collins FF

A+A (Forward-rapidity)

Beam:
Full Energy AuAu

Physics Topics:
- Temperature dependence of viscosity through flow harmonics up to η~4
- Longitudinal decorrelation up to η~4
- Global Lambda Polarization
  → strong rapidity dependence

p+p & p+A (Forward-rapidity)

Beam:
500 GeV: p+p
200 GeV: p+p and p+A

Physics Topics:
- TMD measurements at high x
  transversity → tensor charge
- Improve statistical precision for Sivers through DY
- $\Delta g(x,Q2)$ at low x through Di-jets
- Gluon PDFs for nuclei
  - ➢ R_{pA} for direct photons & DY
- Test of Saturation predictions through di-hadrons, γ-Jets

2021: provides a nice opportunity to run 500 GeV polarized pp
All other data taking in parallel to sPHENIX data taking campaign

Objective:

unique program addressing several fundamental questions in QCD

→ essential to
- the mission of the RHIC physics program in cold and hot QCD
- fully realize the scientific promise of the EIC

ts

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loca

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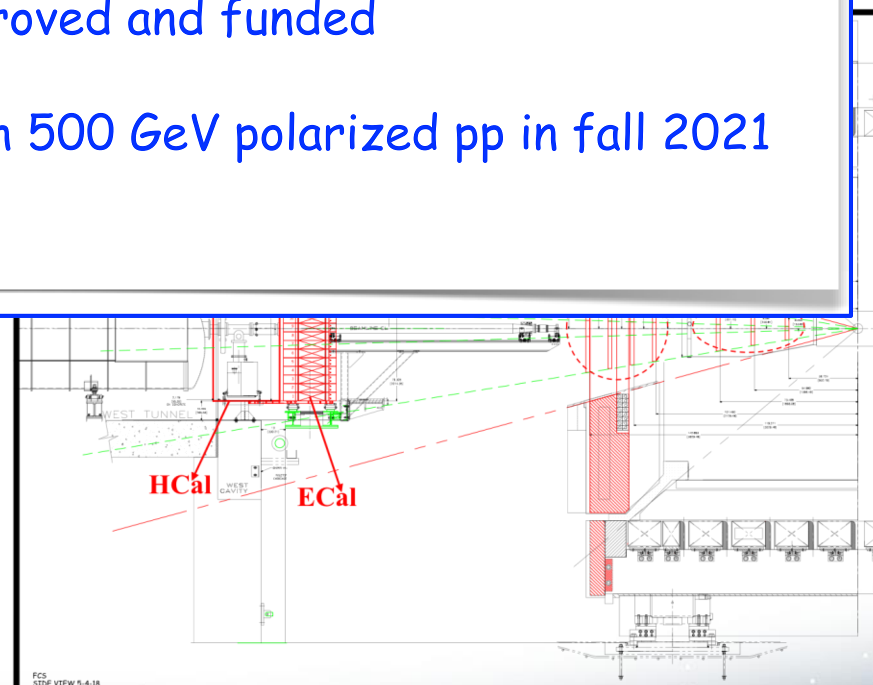
Ele

with SiPM readout & new ADC + Trigger modules

Project is fully approved and funded

on schedule for first data taking with 500 GeV polarized pp in fall 2021



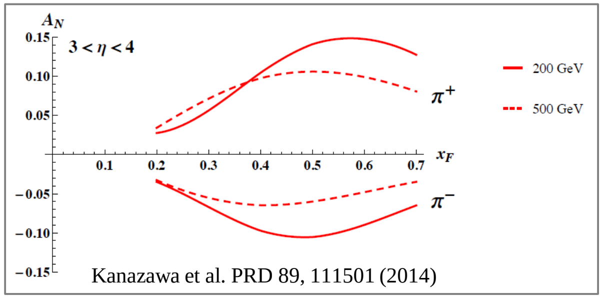
with Tracking
Silicon detectors and
small-strip Thin Gap Chambers (sTGC)

Operation:

pp, pA and AA data taking in FY2021/22 and parallel with sPHENIX data taking period

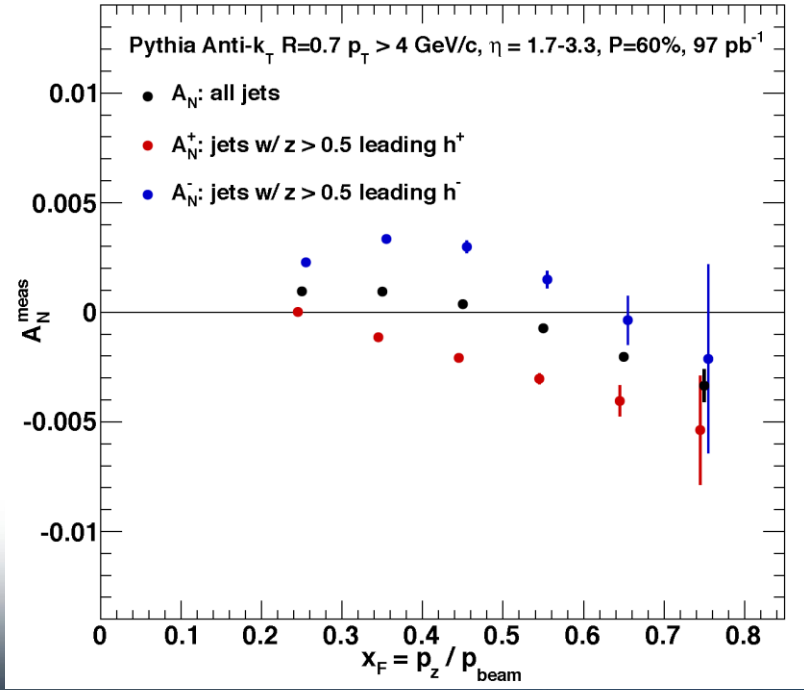
Goals for TMDs:

- Increase statistics for A_N DY
  - → TMD evolution world best constraint ← → $A_N(W^{+/-}\ Z^0)$
  - → Sivers sign change
- Unravel the mystery what is the underlying process of A_N
  - → measure A_N for $h^{+/-}$ and π^0
  - → clear prediction of importance of special Collins like FF
- flavor tagging of the Twist-3 equivalent of the Sivers fct.
  - → Observable $h^{+/-}$ with z > 0.5 in jet



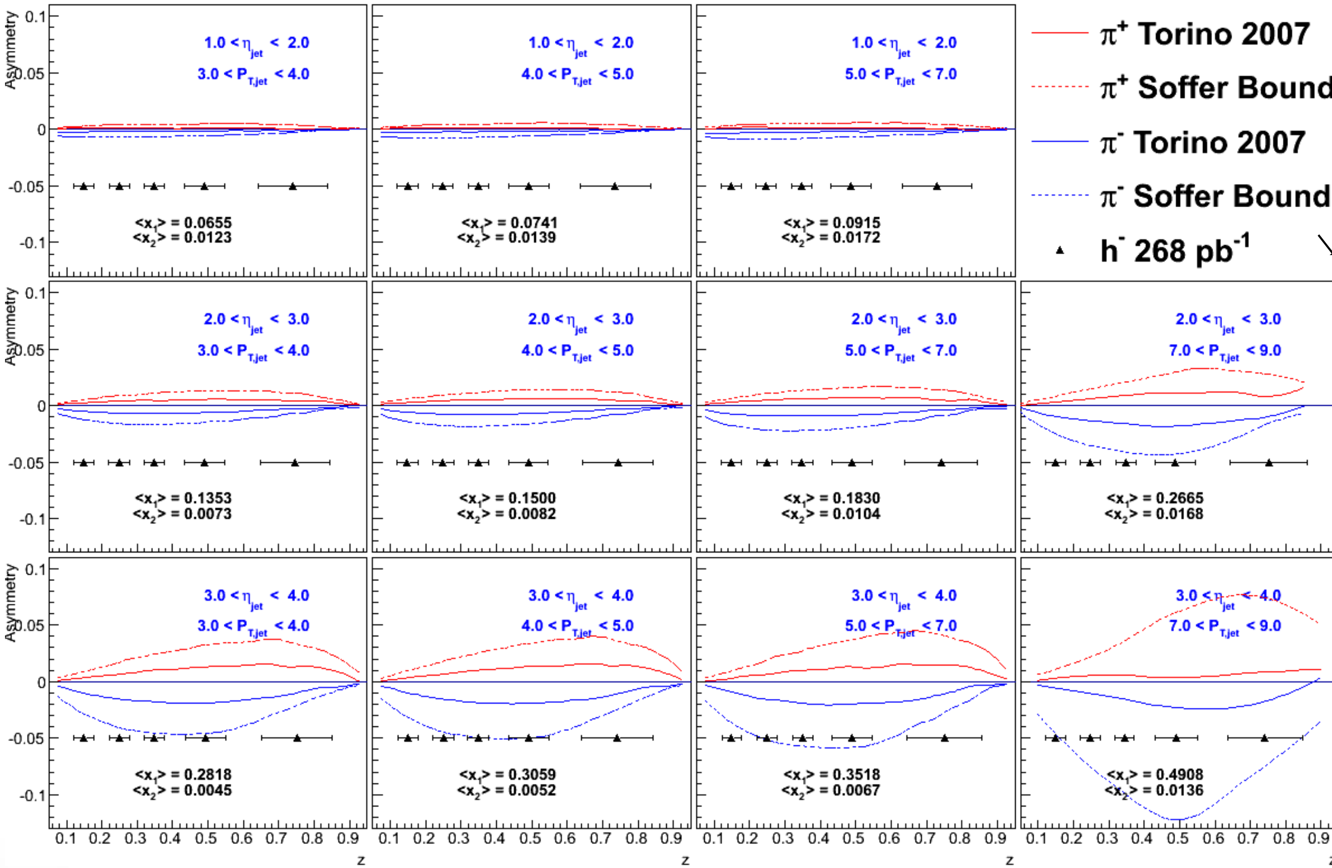
A_N for jets with tagged h^+, h^-

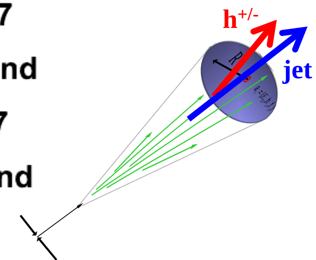
→ stringent test for opposite sign but equal magnitude of u and d quark Sivers fct.

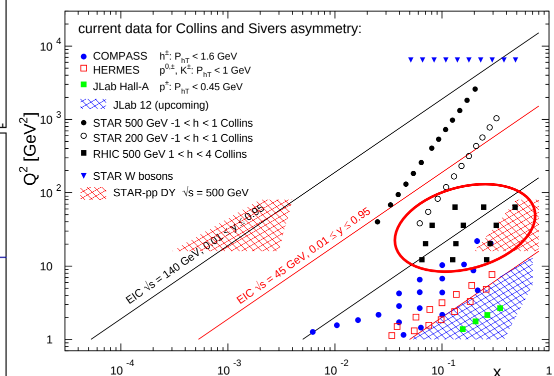


Forward rapidity pp Physics

Transversity x Collins FF through hadron in jet





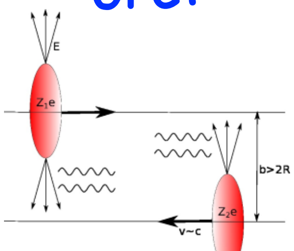


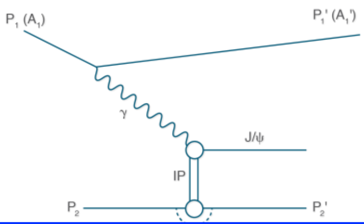
500 GeV: access high x (0.05 – 0.5) at high Q² (10 – 100 GeV²)

very strong constrain for tensor charge $\delta q^a = \int_0^1 \left[\delta q^a(x) - \delta \bar{q}^a(x)\right] dx$

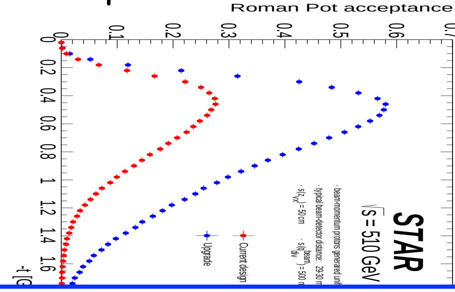
UPC: Access to GPD E_g

UPC:





p' detected in RPs

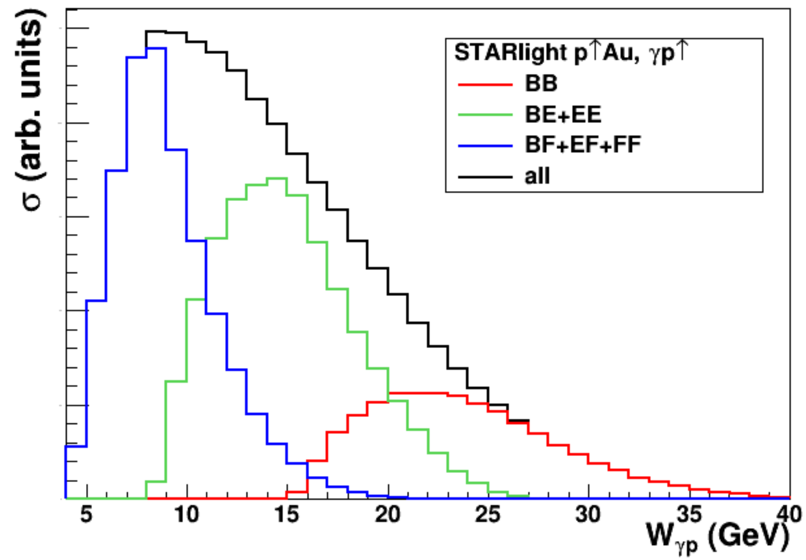


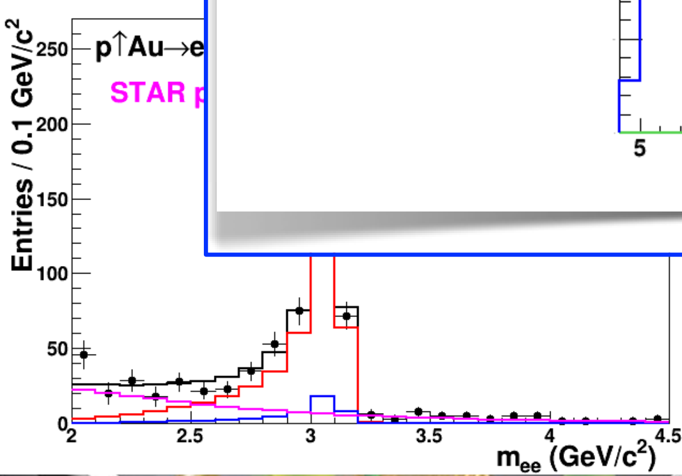
world wide
→ J/Ψ pr

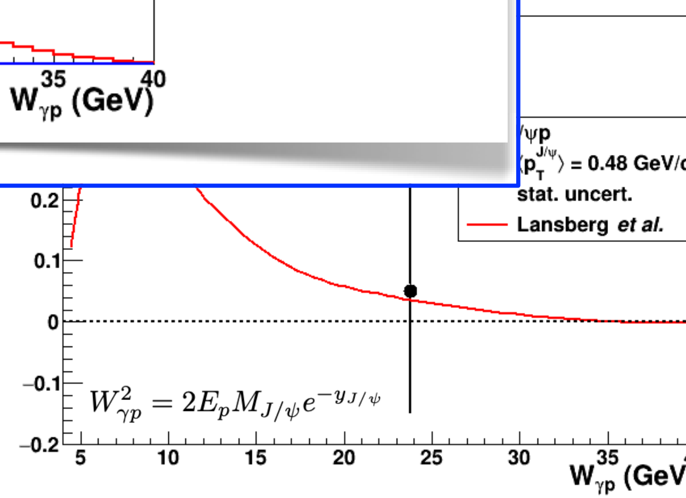
$A_{UT}(t,t) \sim$

2015 p

Forward rapidity gives access to the large asymmetry region



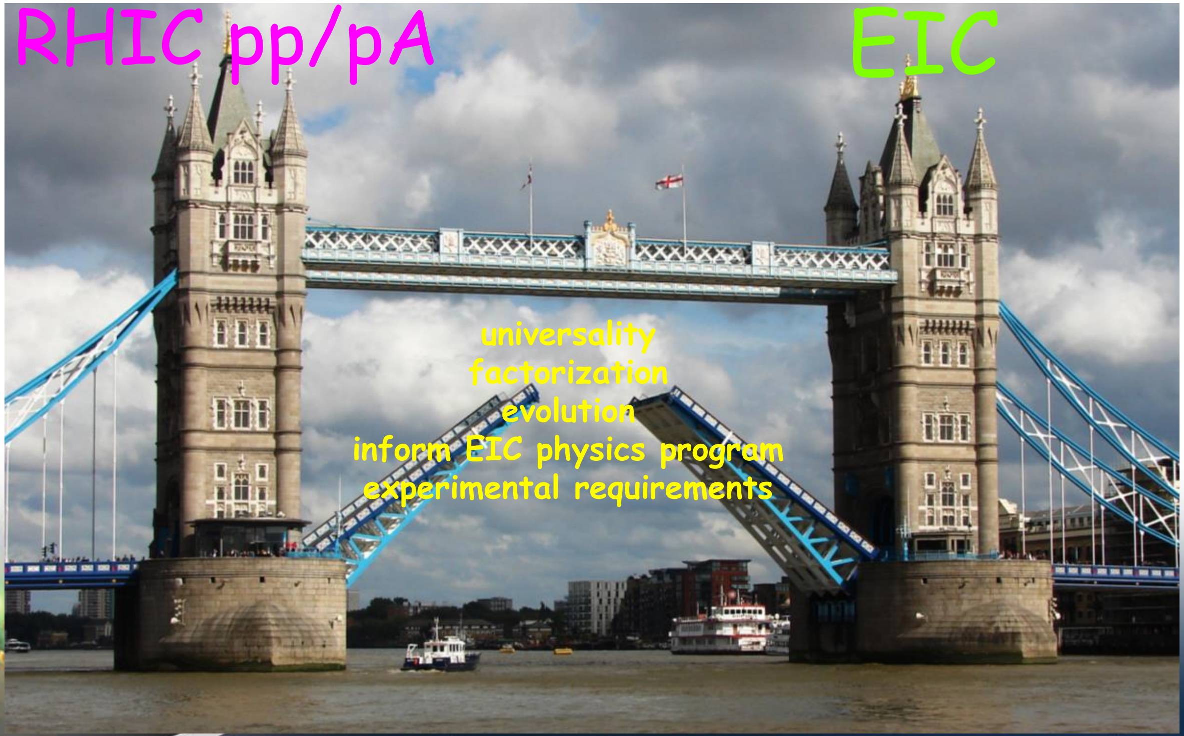




Summary

Unique RHIC forward and midrapidity pp/pA program addressing several fundamental questions in QCD

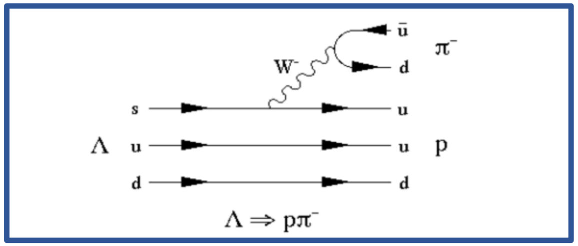
- essential to the mission of the RHIC physics program
- pp/pA program essential to fully realize the scientific promise of the EIC
  - inform the physics program
  - quantify experimental requirements
- Recent RHIC pp/pA result triggered a lot of new theory work
  - dedicated workshops on the RHIC pp/pA program
- Forward upgrade also important to RHIC A+A program

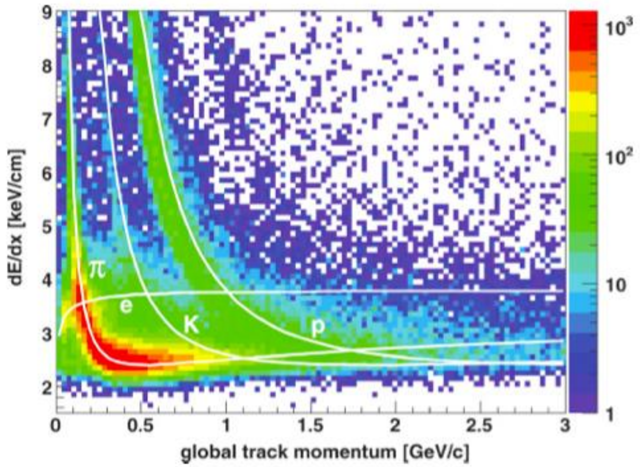


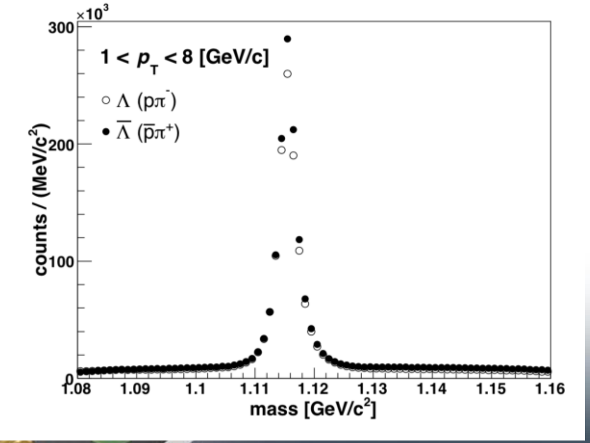
BACK UP

LAMBDA Transvese Spin TRANSFER D_{TT}

$$D_{TT} = \frac{d\sigma^{p\uparrow p\to\Lambda\uparrow X} - d\sigma^{p\uparrow p\to\Lambda\downarrow X}}{d\sigma^{p\uparrow p\to\Lambda\uparrow X} + d\sigma^{p\uparrow p\to\Lambda\downarrow X}} = \frac{d\Delta_T\sigma}{d\sigma}$$





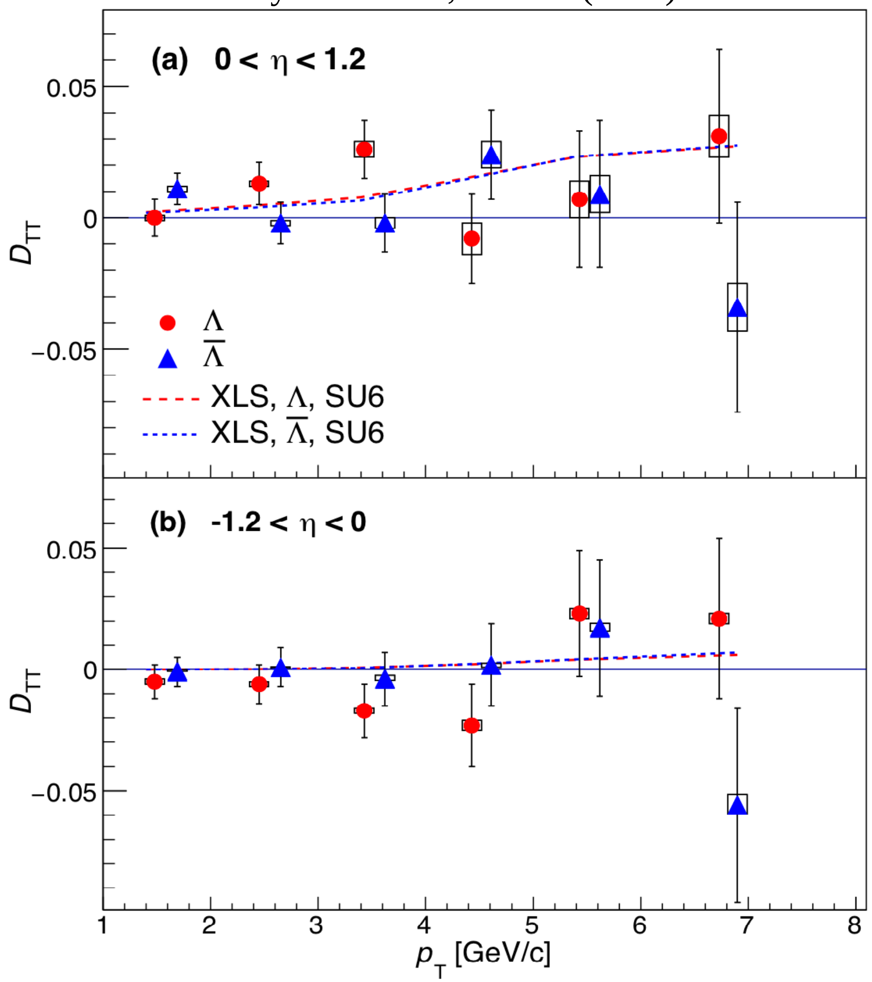


If the Λ spin direction is highly correlated with the strange constituent quark spin orientation, $|\Lambda\rangle = (ud)_{00}s^{\uparrow}$, then D_{TT} is sensitive to both the strange transversity PDF and the transversely polarized Λ FF.

Lambda D_{TT}

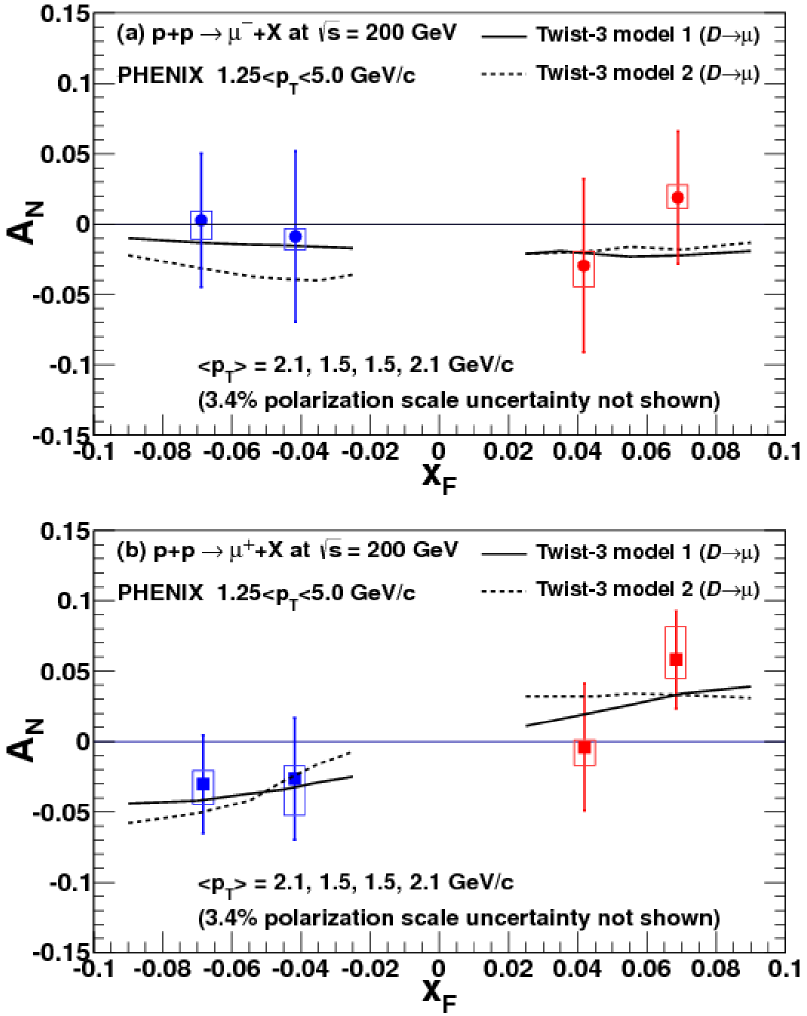
- First extraction of D_{TT} from 18 pb^{-1} in $\sqrt{s}$ = 200 GeV p+p collisions.
- Lambda asymmetries are consistent with model predictions by Xu, Liang and Sichtermann, PRD 73 (2006) 077503

Phys.Rev. D98, 091103 (2018)

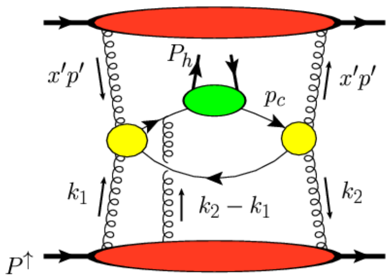


Sensitivity to Gluon "TMDs"

Phys.Rev. D95 (2017) 112001

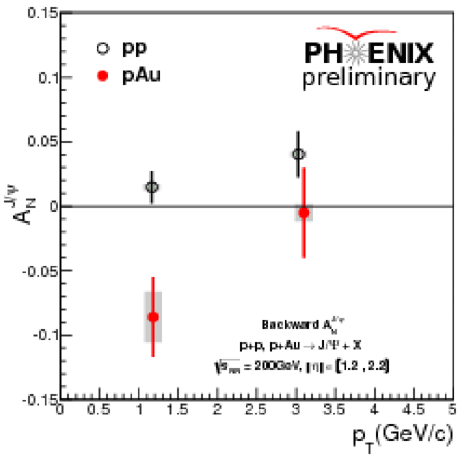


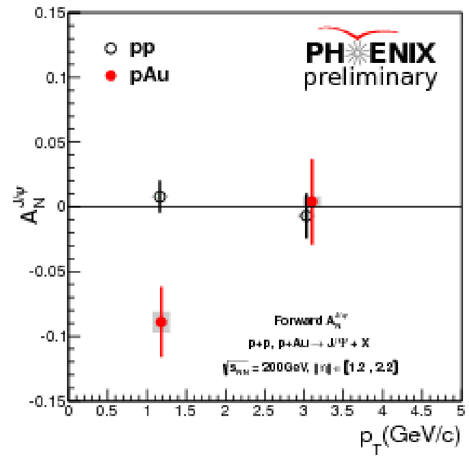
Model calculations from: Koike et.al.
Phys.Rev. D84 (2011) 014026

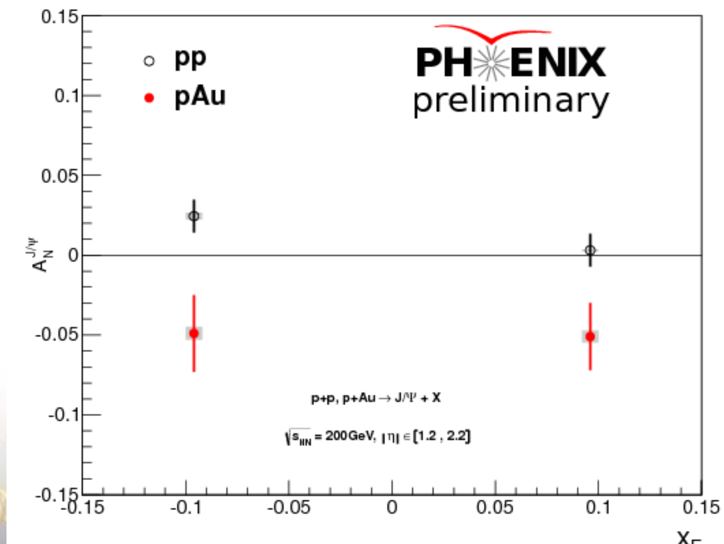


- Heavy flavor asymmetries most sensitive to Twist-3 counterpart of Gluon Sivers and tri-gluon correlator,
- no final state effects expected due to heavy quark mass
- Both contributions poorly known

Sensitivity to Gluon "TMDs"

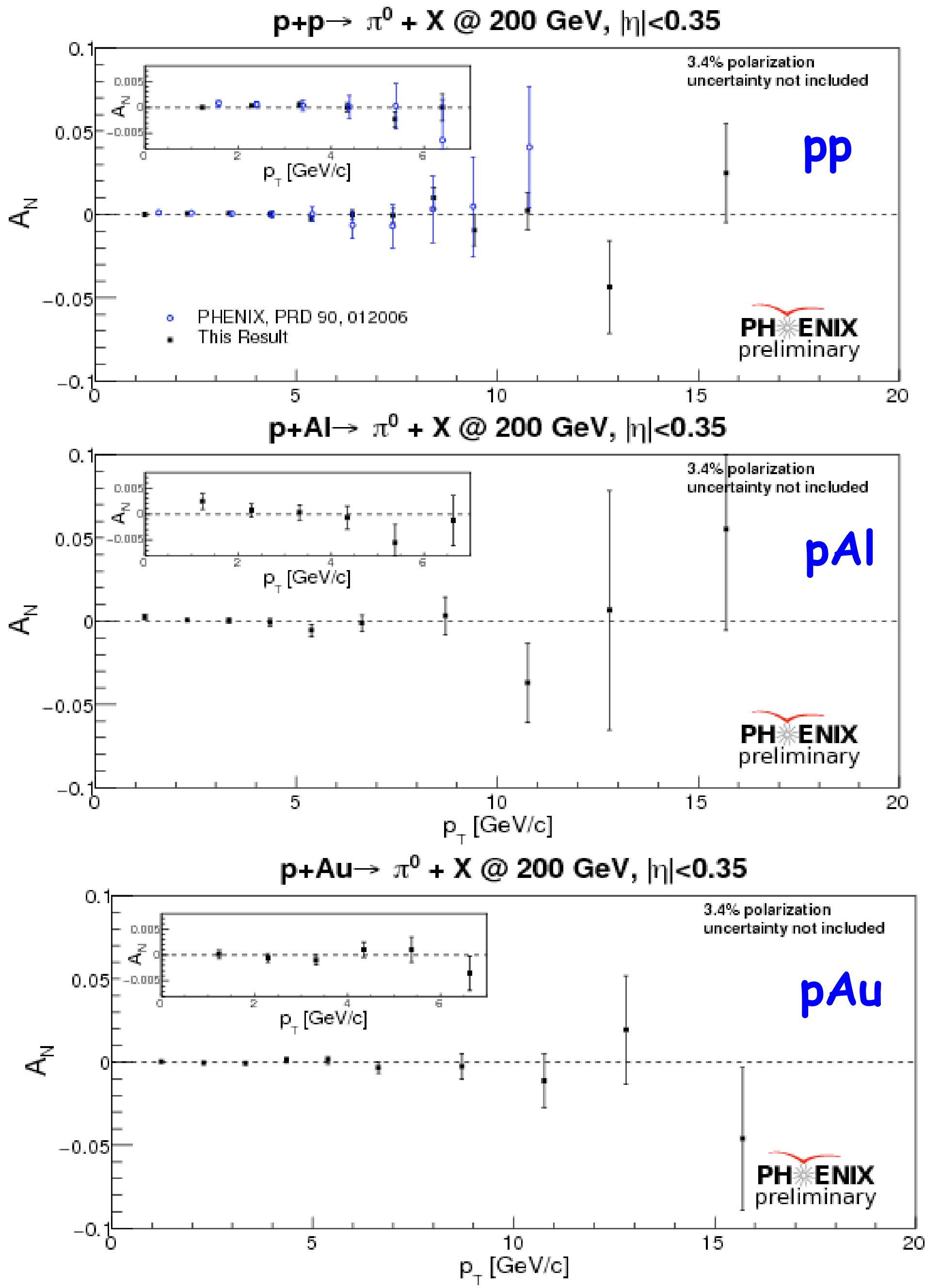






- Surprising nonzero J/Psi A_Ns seen in pAu collisions while pp Asymmetries are mostly consistent with zero
- Nonzero effect only visible at the lowest available P_t
- Diffractive effects as cause not very likely due to coincidence with hard collision trigger
- pAl data is being analyzed

Sensitivity to Gluon "TMDs"

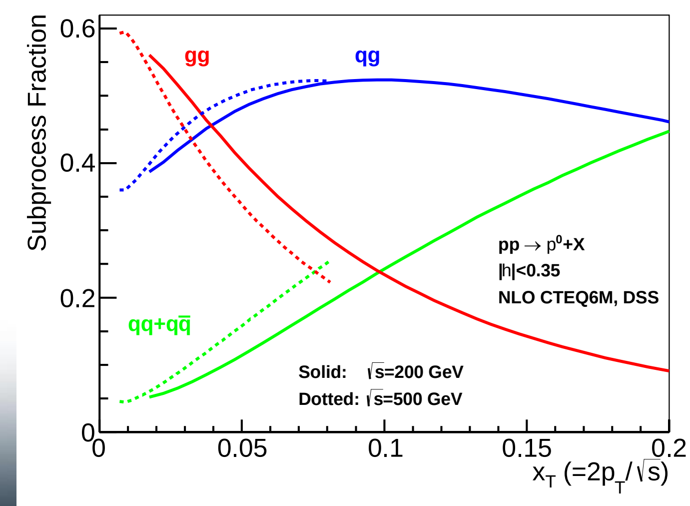


pp:

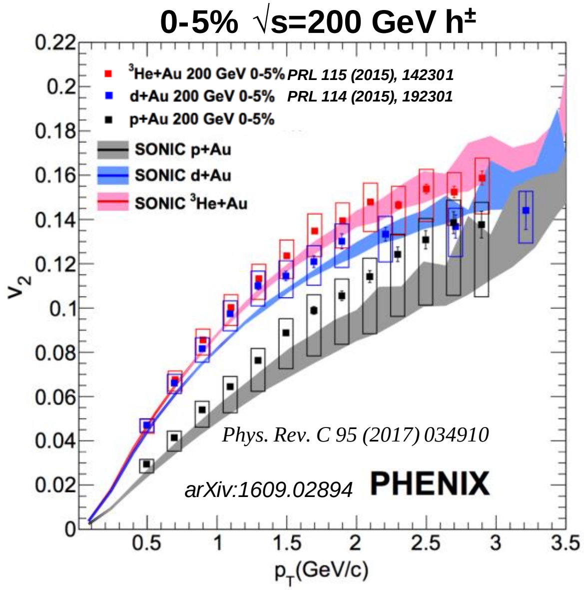
- Improved results from 2015!
- Consistent with 0
  to 3~10^{-4} precision level at low p_T
- constrain of gluon Sivers effect
  Anselmino et al, PRD 74 (2006), 094011
  D'Alesio et al, JHEP 1509 (2015), 119

pA:

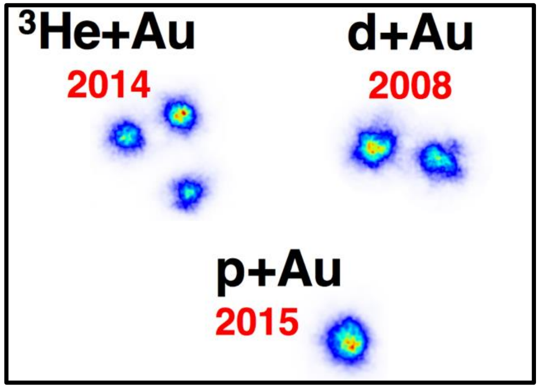
high precision test of nuclear effects



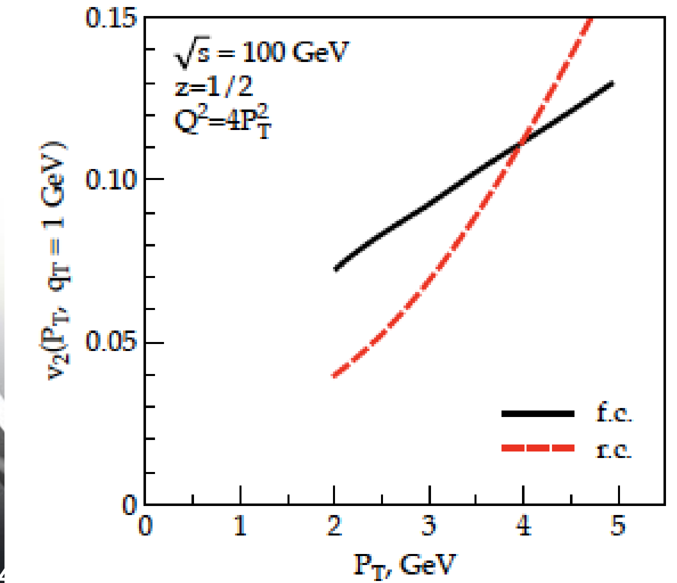
TMDs and "QGP" in small systems



Collective flow signatures seen even in the smallest systems and at the lowest RHIC energies



TMD formalism in DIS predicts a distribution for linearly polarized gluons in an unpolarized target. This is reflected in cos(2φ) asymmetries in dijet production



Study azimuthal anisotropy as a function of the rapidity dis-balance of the jets

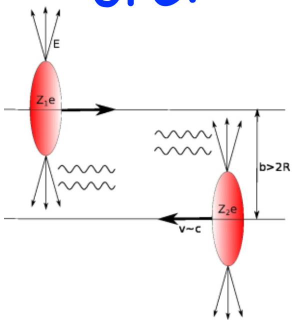
→ Process sensitive to unpolarized and linearly polarized gluon distribution

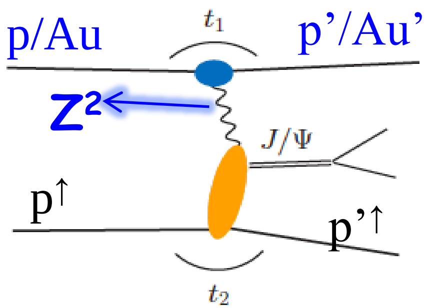
$$xG^{ij}_{ww} = \frac{1}{2}\delta^{ij} xG^{(1)} - \frac{1}{2}\left(\delta^{ij} - \frac{2k^i k^j}{k^2}\right) xh_{\perp}^{(1)}$$

Phys.Rev. D94 (2016) no.1, 014030
Phys.Rev.Lett. 115 (2015) no.25,252301
Phys.Rev. D91 (2015) no.7, 074006
Phys.Lett. B743 (2015) 134-137

STAR: UPC with polarized p↑

UPC:



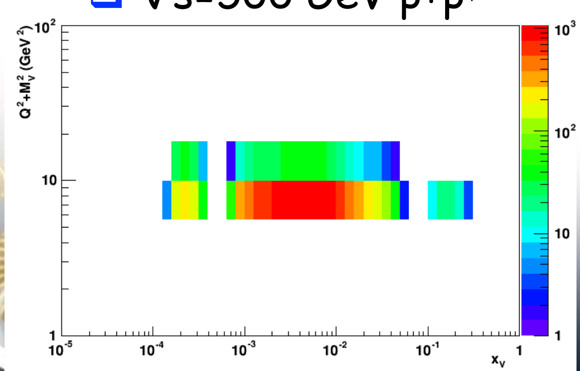


world wide only access to GPD E for gluons before EIC
→ J/Ψ production in p↑Au /p↑p UPC

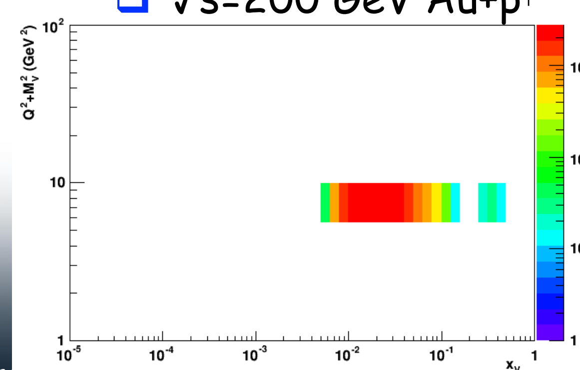
- WW photon from one beam particle
- Target particle polarized proton p↑:
  - ds/df ∝ (1 + A_{UT}·cosϕ) , ϕ = J/Ψ azimuthal angle w.r.t. p↑
  - measure J/Ψ transverse asymmetry A_{UT}
    (Unpolarized beam g, Transverse polarized target p↑)
- A_{UT} calculable with GPDs:

$$A_{UT}(\tau, t) \sim \frac{\sqrt{t_0 - t}}{m_p} \frac{\mathrm{Im}(E^* H)}{|H|} \qquad \tau = \frac{M^2_{J/\Psi}}{s}$$

- √s=500 GeV p+p↑



- √s=200 GeV Au+p↑



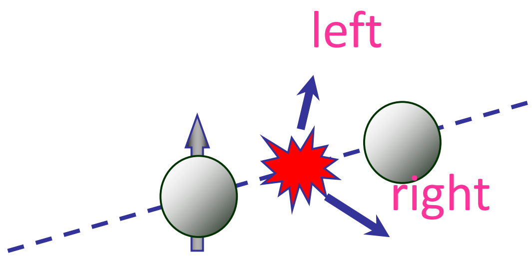
STAR: UPC with polarized p↑

What is measured:

Single-spin transverse asym.

$$A_N \equiv \frac{1}{P_1} \frac{N_\uparrow/\mathcal{L}_\uparrow - N_\downarrow/\mathcal{L}_\downarrow}{N_\uparrow/\mathcal{L}_\uparrow + N_\downarrow/\mathcal{L}_\downarrow}$$

where ↑ (↓) are defined with respect to reaction plane



Stat. Unc. $\sim 1/(P_1 \sqrt{N})$

Statistics:

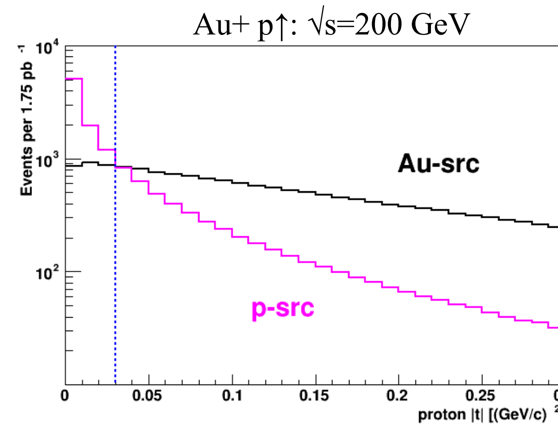
2017 p↑+p 400 pb^{-1}

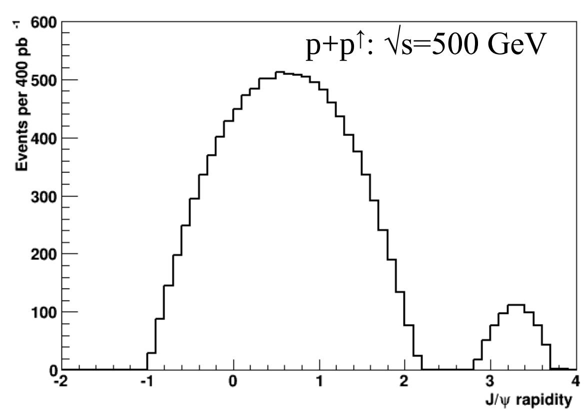
→ 1k J/Ψs

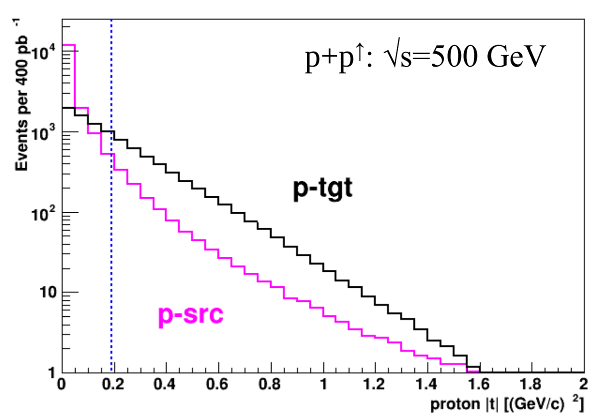
→ δA_{UT}: +/-0.2 in 3 t-bins

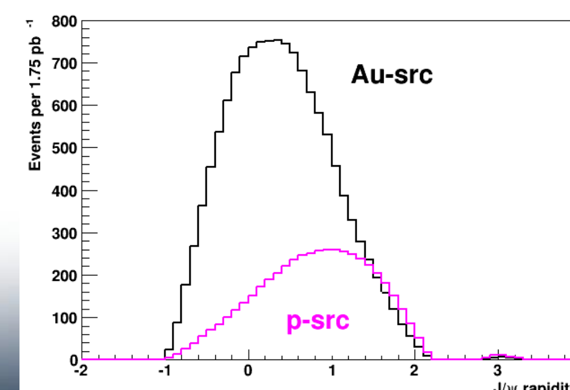
2015 pA: ~300 J/Ψ

- Trigger on:
  - 2 EM showers STAR calorimeters (J/Ψ→e+e-)
  - Hit in either Roman Pot
  - no BBC activity (ensure diffractive)
- RP measures
  - 500 GeV:0.19<|t|<1.9 $(GeV/c)^2$
  - 200 GeV: 0.03 <|t|<0.3 $(GeV/c)^2$
  - source of photon (lower |t|)
  - target of photon (higher |t|)
- J/Ψ →e+e- in STAR EMC:



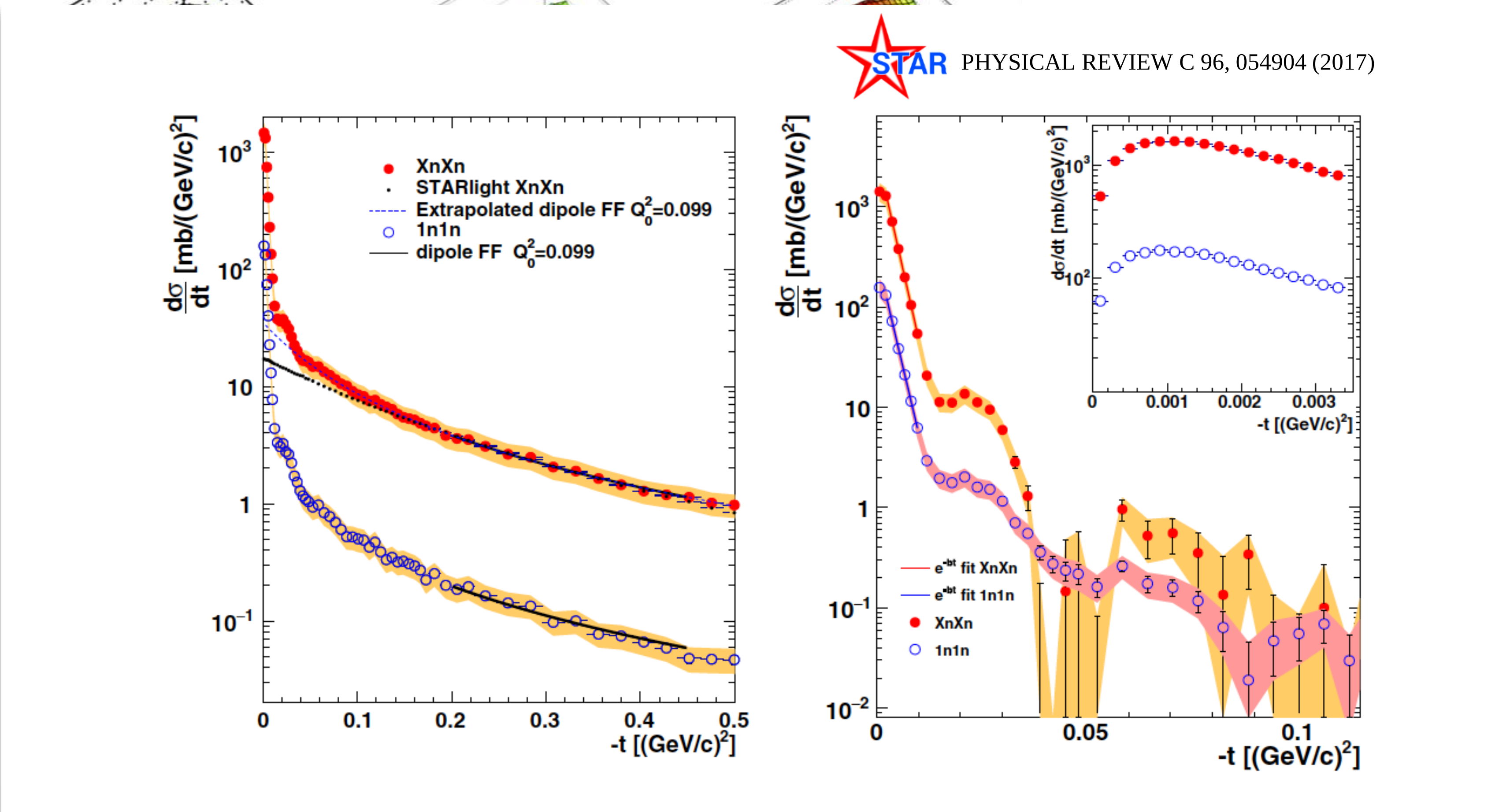


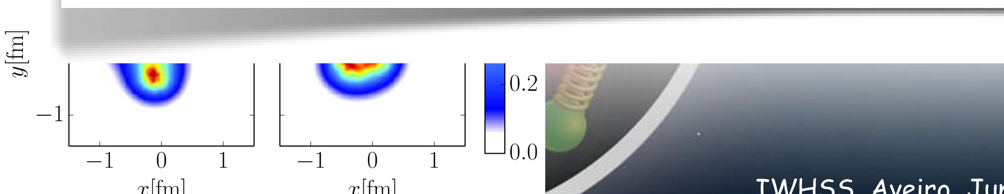


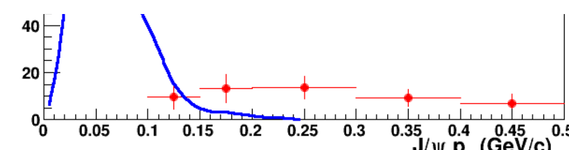


Proton structure important for QGP in small systems

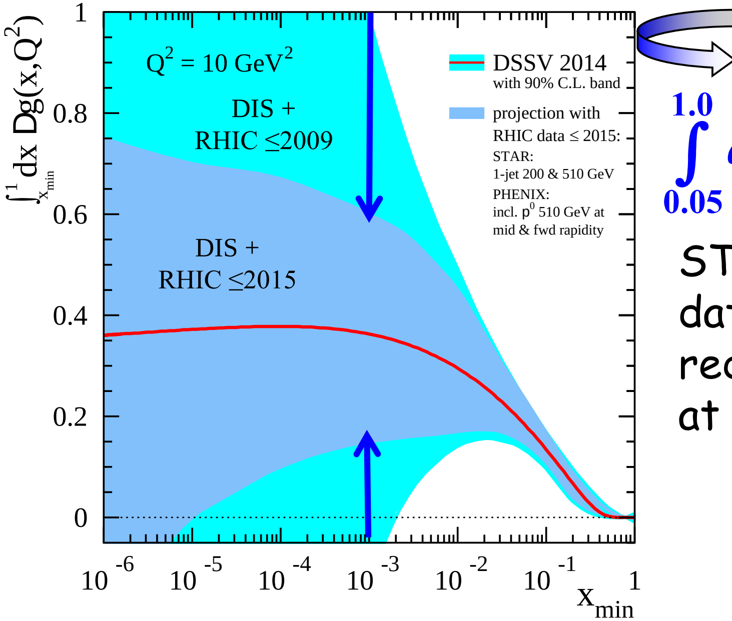
Collective phenomena seen in pA collisions, i.e. ATLAS 1409.792







How polarized are the Gluons?

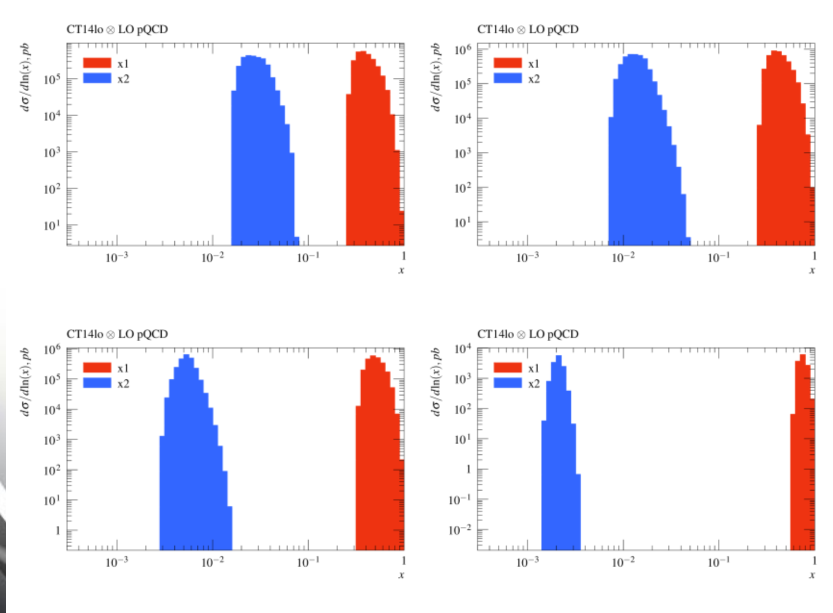


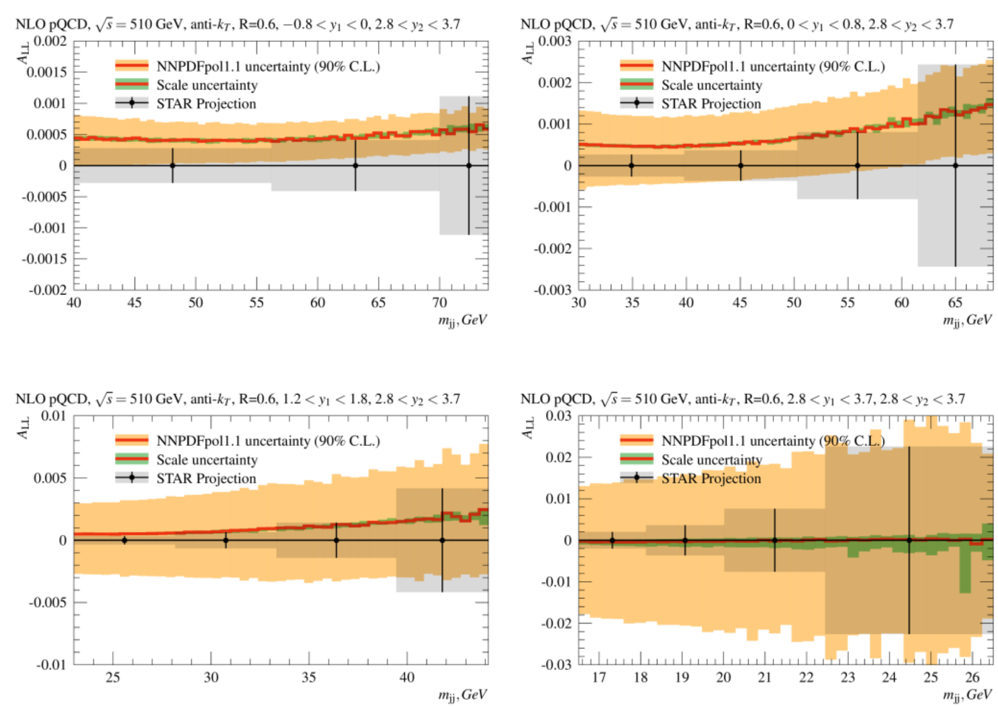
Data till 2009

$$\int_{0.05}^{1.0} dx\Delta g \sim 0.2 \pm^{0.06}_{0.07} @\ 10\ GeV^2$$

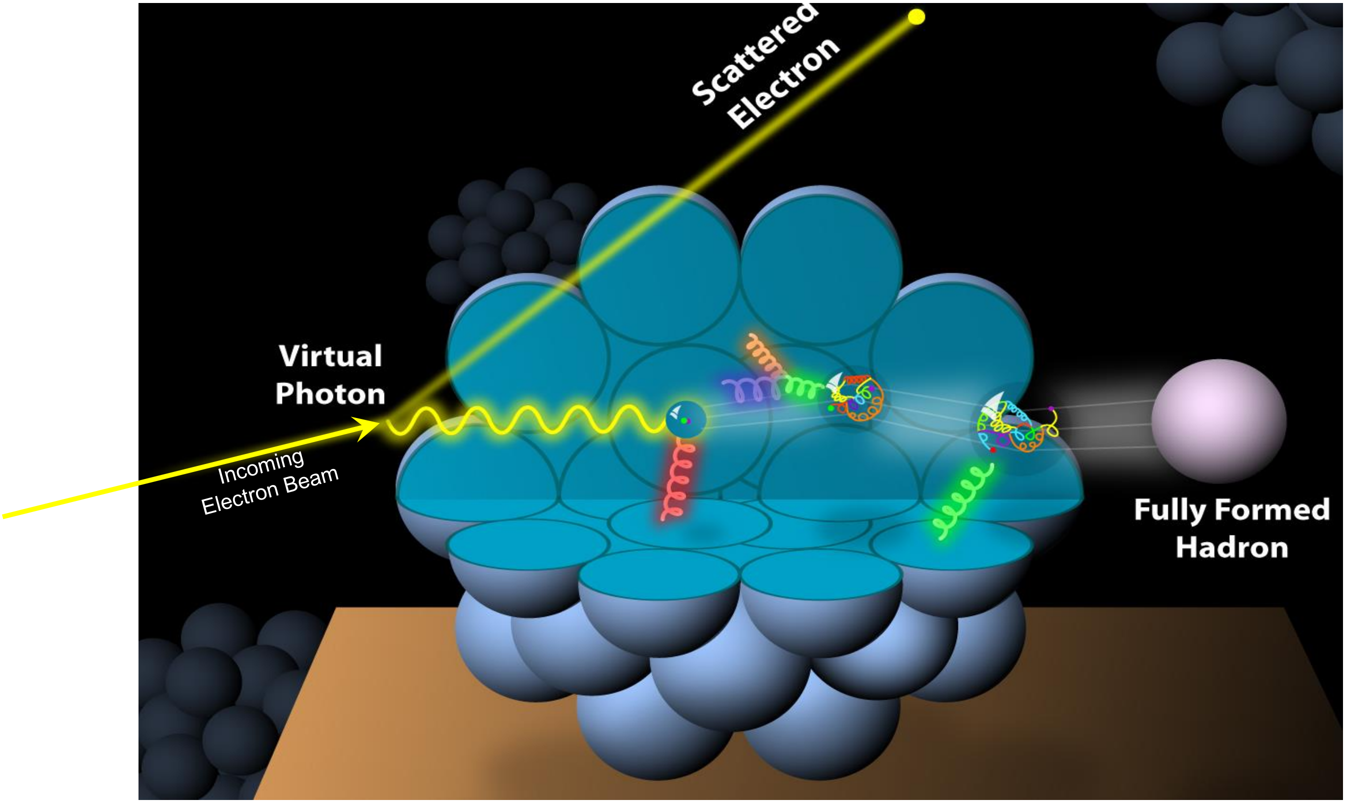
STAR and PHENIX data till 2015 reduce uncertainties at x ~ 10^{-3} by factor 2

only way to constrain low x further
→ go forward
Di-Jets@2.5 < η < 4.0





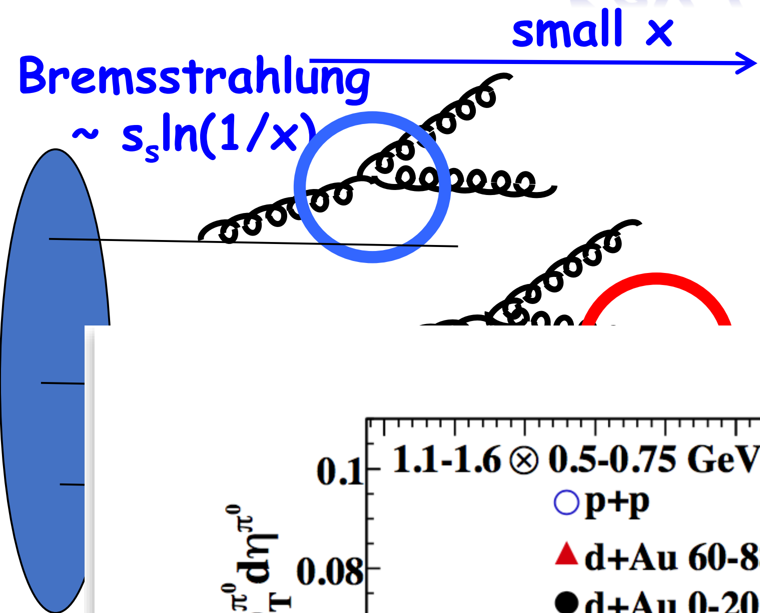
What about Nuclei?



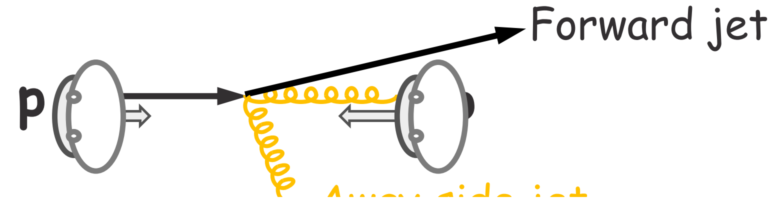
Answer 3 conundrums of the initial state of Nuclei:

- What are the nPDFs at low-x?
- How saturated is the initial state of the nucleus?
- What is the spatial transverse distributions of nucleons and gluons?
  → How much does the spatial distribution fluctuate? Lumpiness, hot-spots etc.

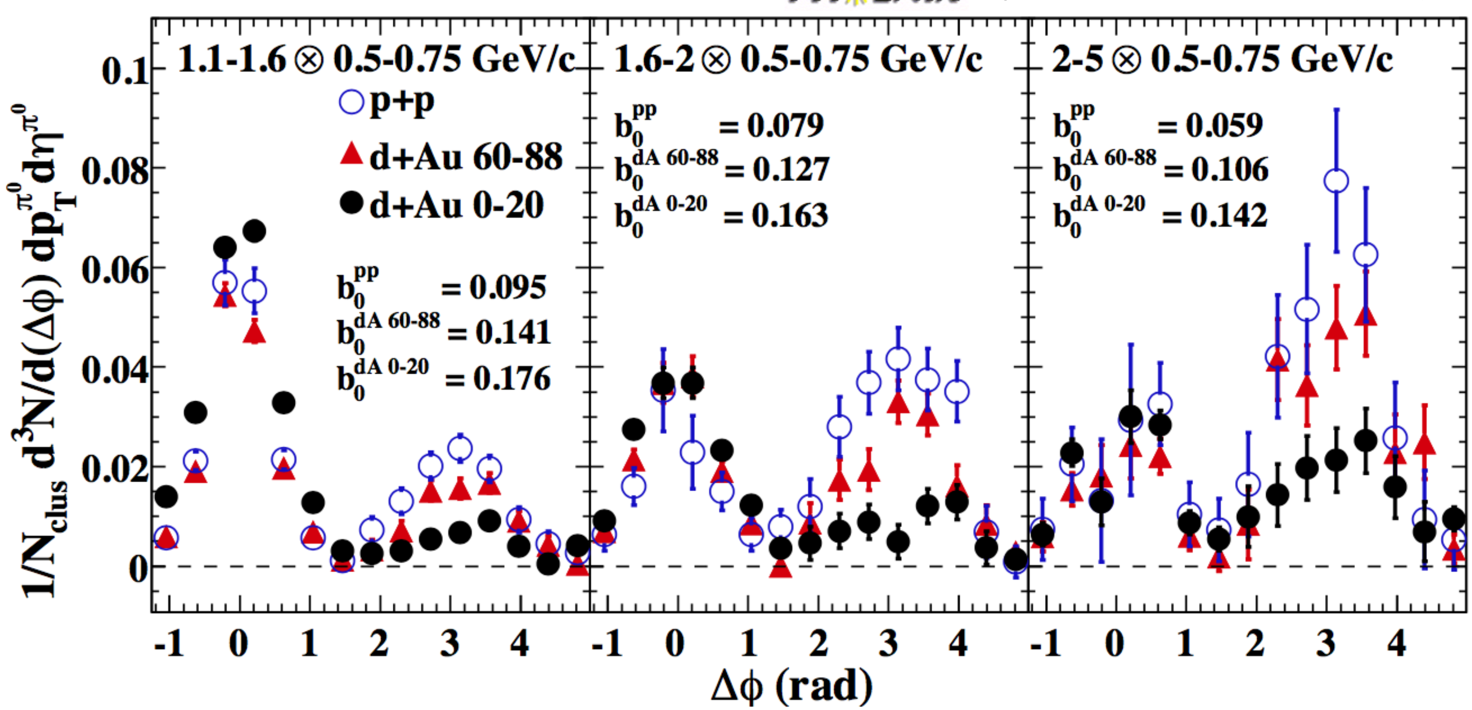
Key Observable for Saturation in pA



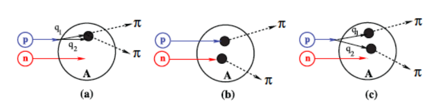
pQCD 2→2 process = back-to-back di-jet



PHENIX Phys. Rev. Lett. 107, 172301 (2011)

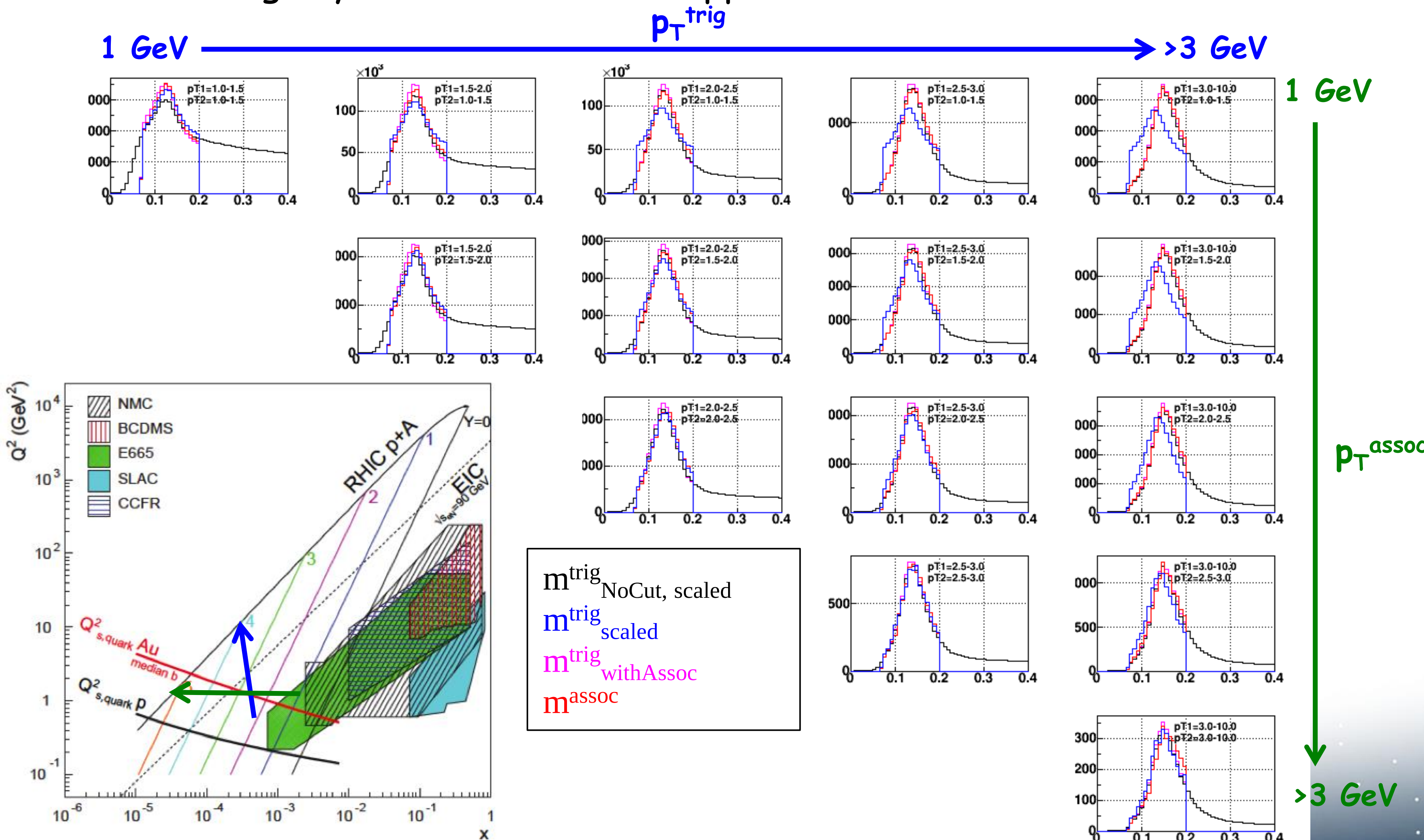


dA: alternative explanation through double interactions



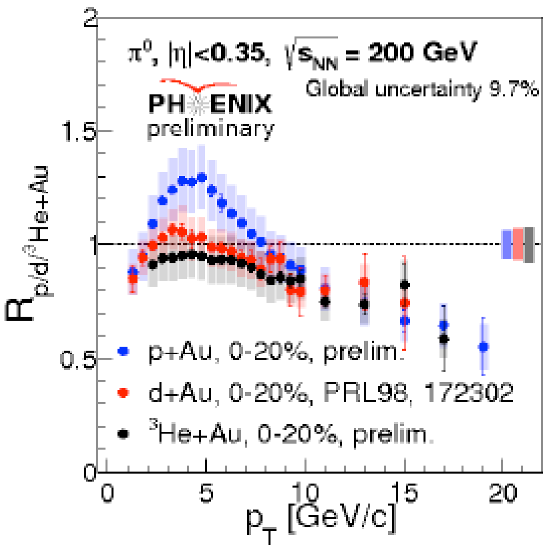
Key Observable for Saturation in pA

2015 Di-hadron correlations: scanning in x → study the evolution of Q_s^2 in x
Scan A-dependence: pAu and pAl → study the evolution of $Q_s^2(x)$ with A
Resolve ambiguity what causes the suppression in dAu



Nuclear effects in initial and Finals STATE

R_{pA}: π^0 in central rapidity



High p_T: R<1

Moderate p_T: $R_{pAu}>R_{dAu}>R_{3HeAu}$

Proton size fluctuations, energy loss in CNM, mult. scattering, shadowing etc.

No models can yet reproduce a peak at ~5 GeV/c

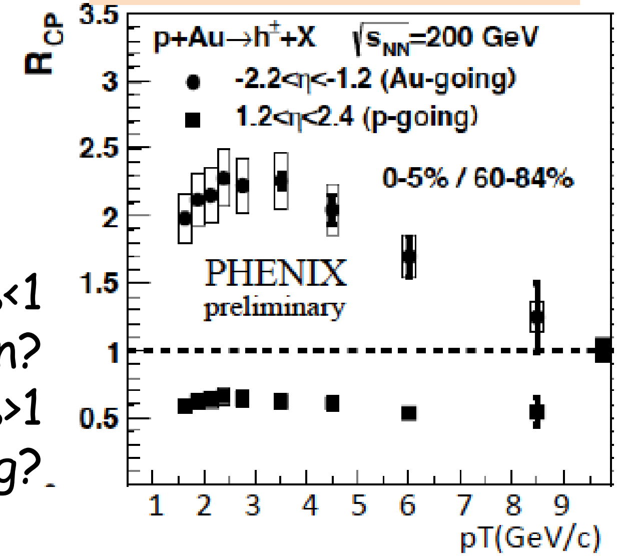
R_{CP}: $h^{\pm}$ in forw/back rapidity

p-going: $R_{CP}<1$

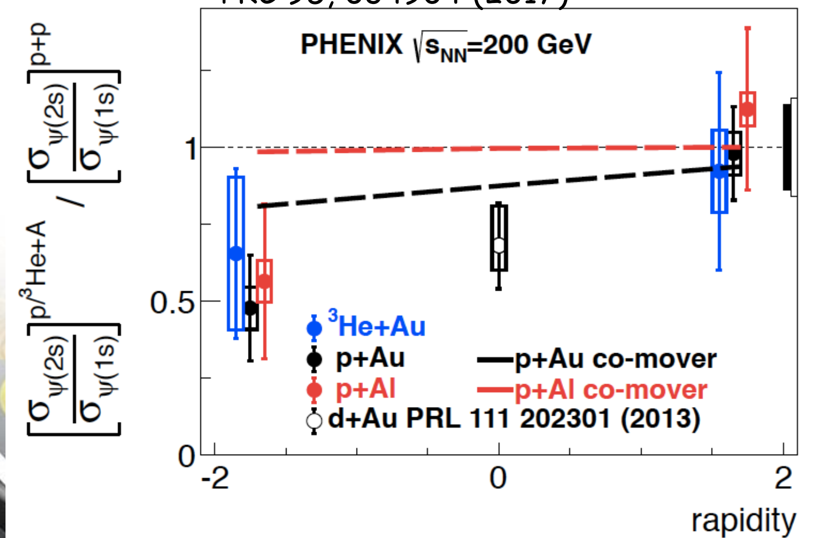
Shadowing? Saturation?

Au-going: $R_{CP}>1$

Anti-shadowing?



PRC 95, 034904 (2017)



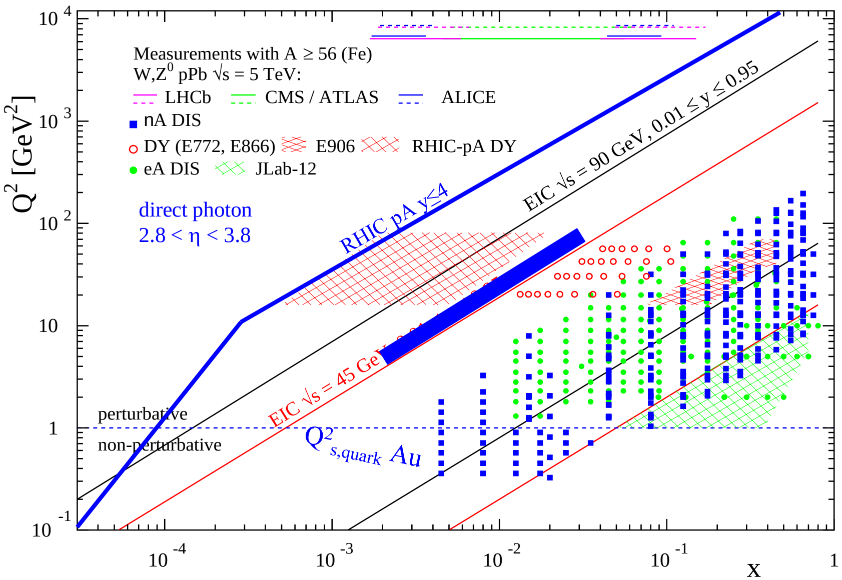
Larger suppression of ψ′ at nucleus going direction

Breakup due to interaction with co-moving particles

More data coming: Incl. J/ψ, Upsilon, single leptons

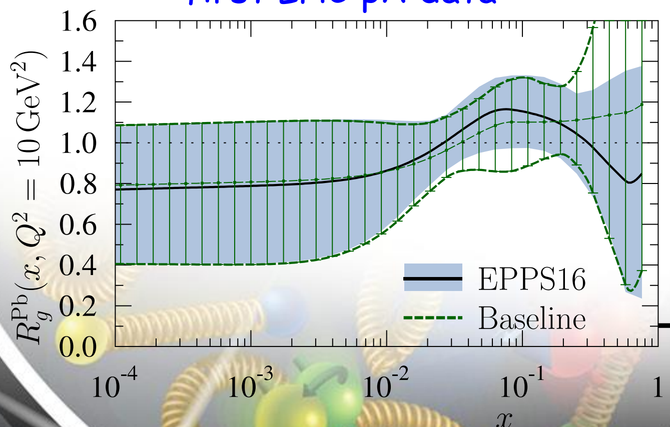
How Does The initial state IN AA Look?

pA@RHIC: unique kinematics

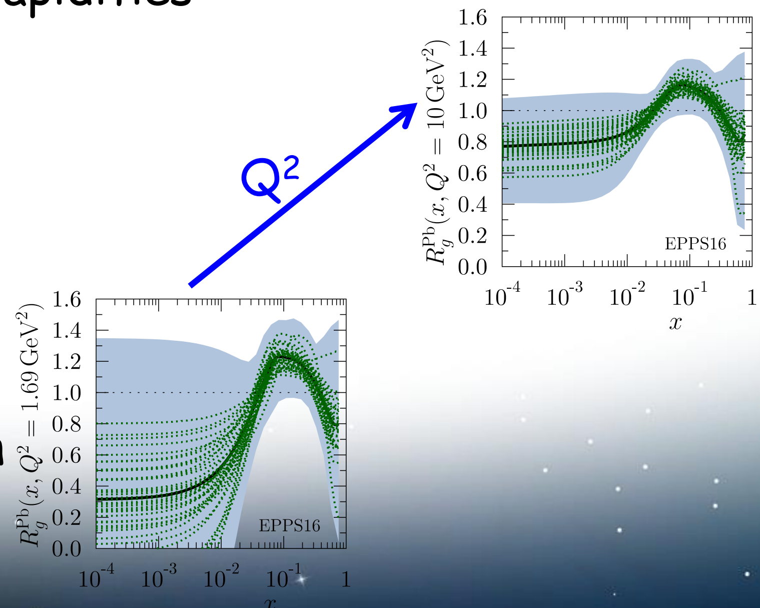


- can measure nPDF in a x-Q^2 region where nuclear effects are large
  - $Q^2 > Q_s^2$ over a wide range in x
- Observables free of final state effects
  - Gluons: R_{pA} for direct photons
  - Sea-quarks: R_{pA} for DY
- Scan A-dependence prediction by saturation models
- can access saturation regime at forward rapidities

R_g^{Pb} Current knowledge including first LHC pA data

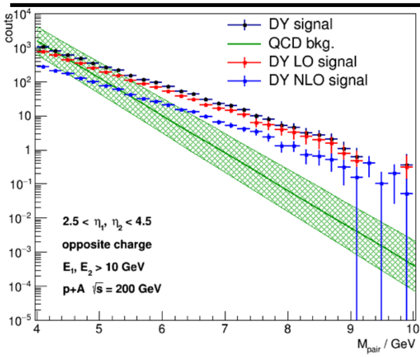


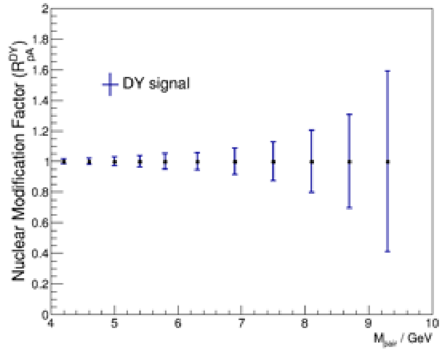
LHC pA data impact small because nuclear effect get smaller with Q^2 increasing
→ very high precision data



How Does The initial state IN AA Look?

pA: DY@2.5 < η < 4.5

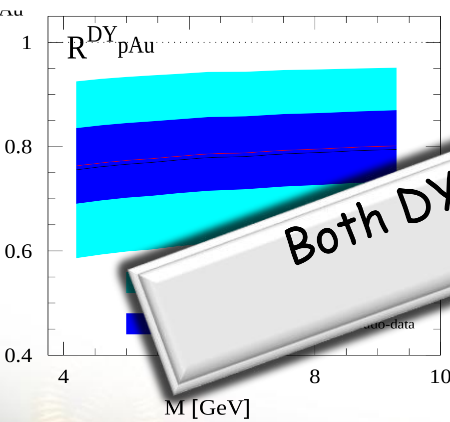


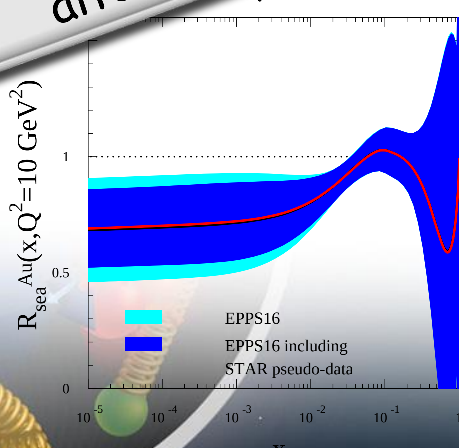


Impact on nPDFs: → sea quarks

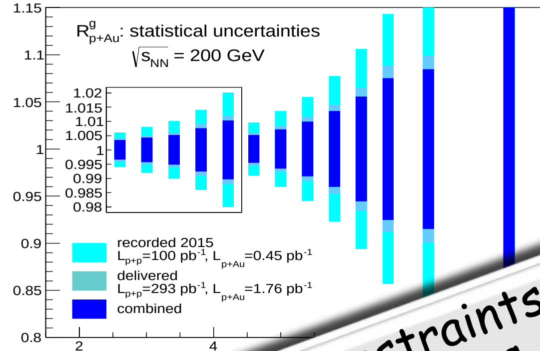
DY:
Q^2: ~M^2

pA





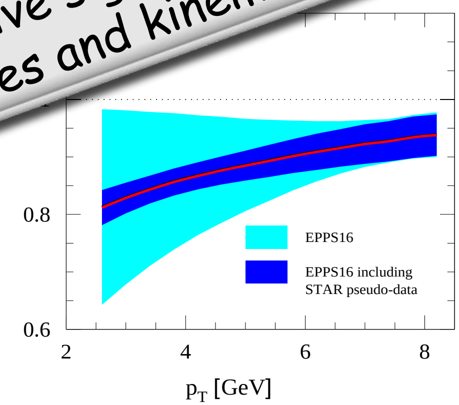
pA: Direct Photon@2.5 < η < 4.5

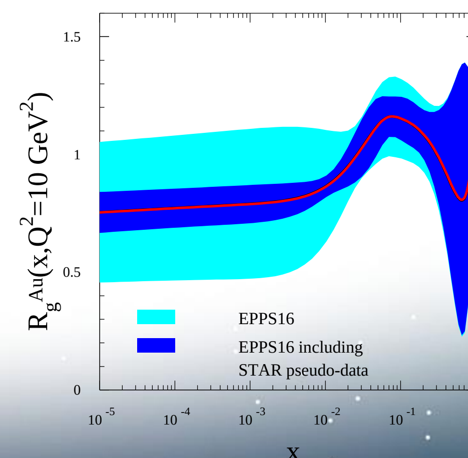


Uncertainties:
2015 + 2023 pp&pA

direct

→ gluons





Both DY and direct photon R_{pA} give significant constraints on nPDF alternative observables and kinematics to EIC

Saturation with the forward upgrade

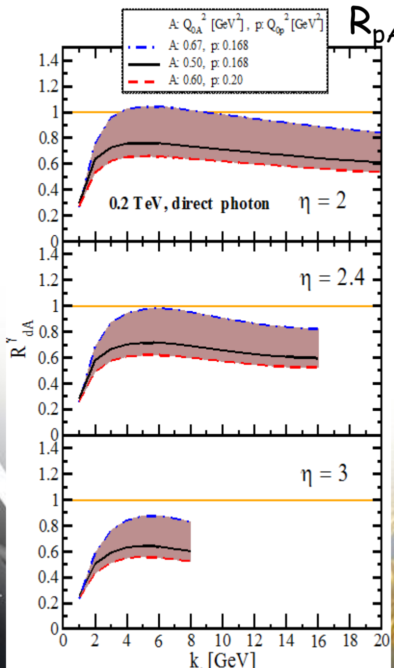
Expand the number of observables:

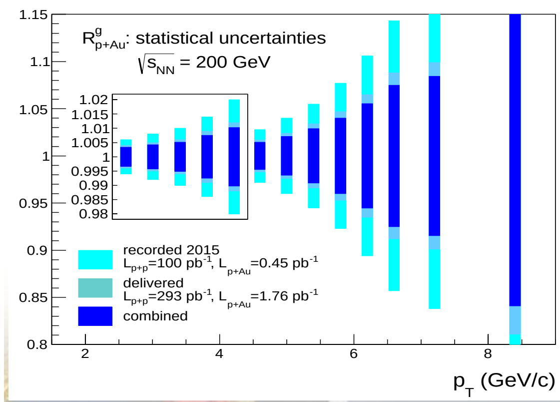
→ rigorous test of theory predictions
→ get a handle on the different gluon distributions
→ provide variety of high precision data to test universality of CGC ←→ EIC
→ study of evolution/universality of Q_s^2 with A and x for different probes

arXiv:1101.0715

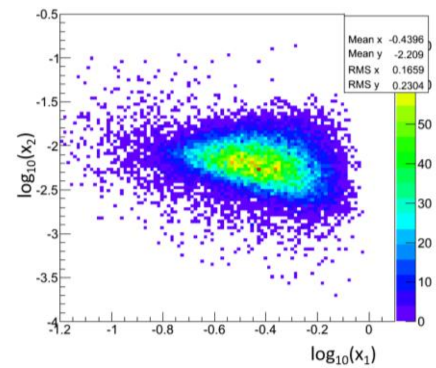
	DIS and DY	SIDIS	hadron in pA	photon-jet in pA	Dijet in DIS	Dijet in pA
$G^{(1)}$ (WW)	×	×	×	×	√	√
$G^{(2)}$ (dipole)	√	√	√	√	×	√

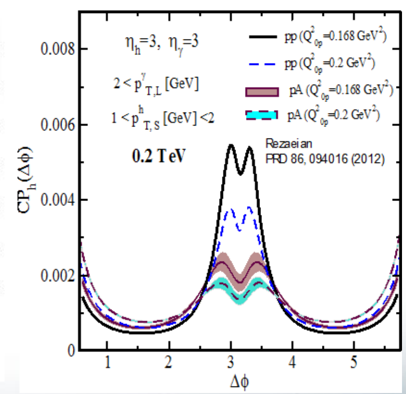
CGC prediction for R_{pA} direct photon:





❑ jet-hadron / jet photon correlations





→ 1M events with forward upgrade in 2023 pAu and pAl