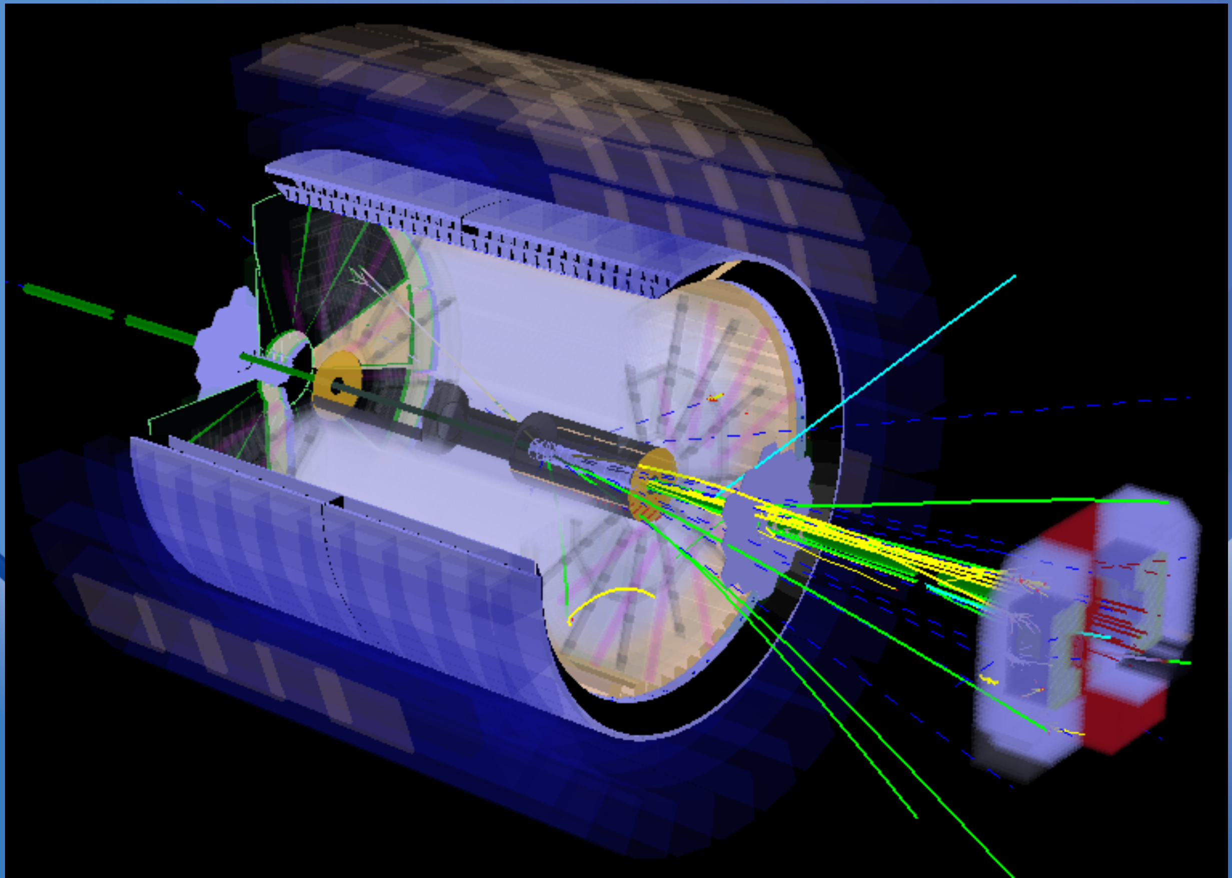
COLD QCD PHYSICS@STAR: A GAZE INTO EIC



E.C. Aschenauer

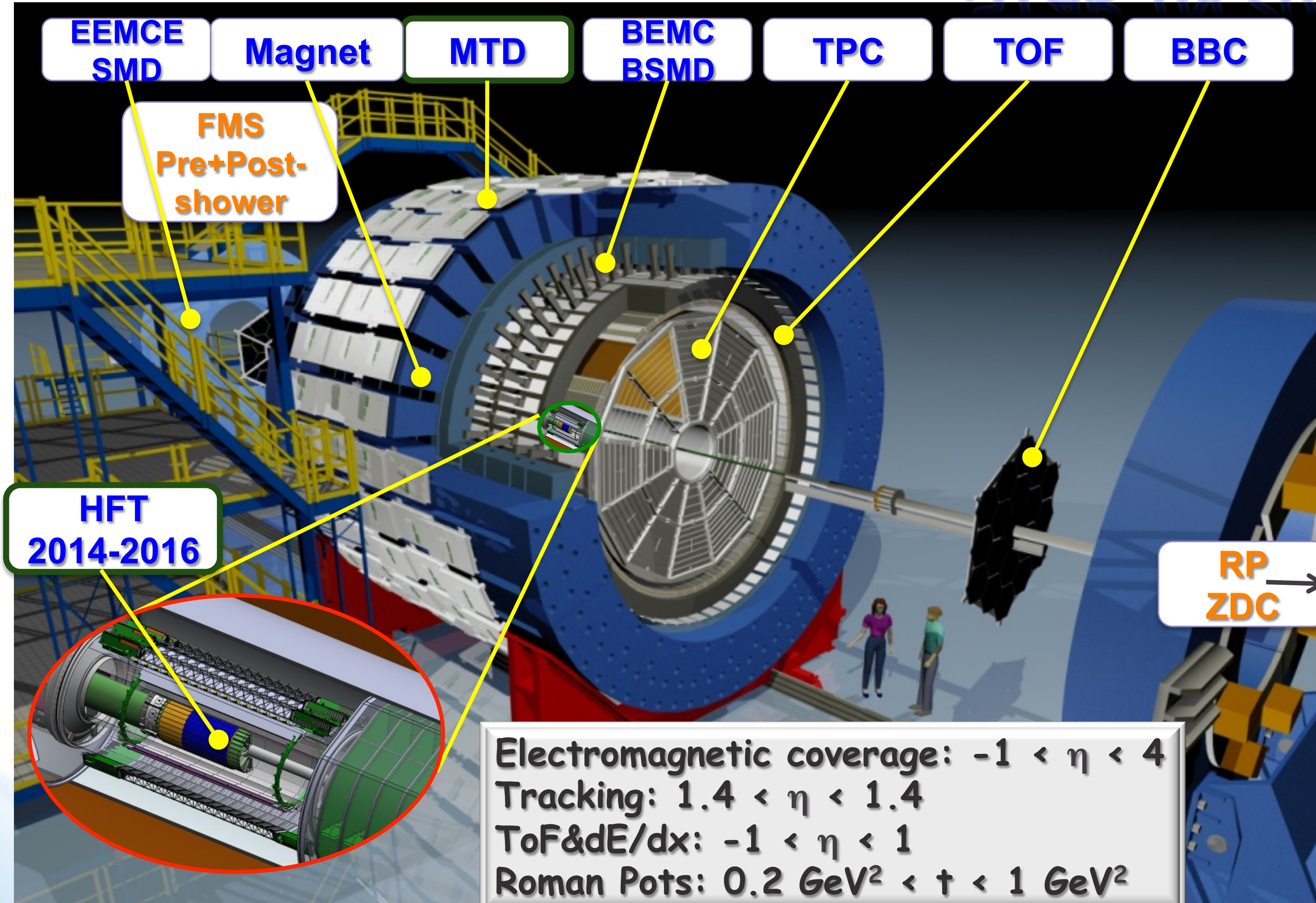
STAR

BROOKHAVEN NATIONAL LABORATORY

a passion for discovery

U.S. DEPARTMENT OF ENERGY | Office of Science

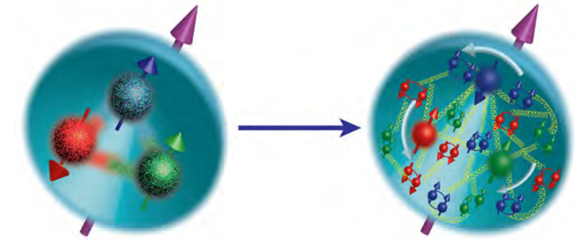
STAR IN 2017

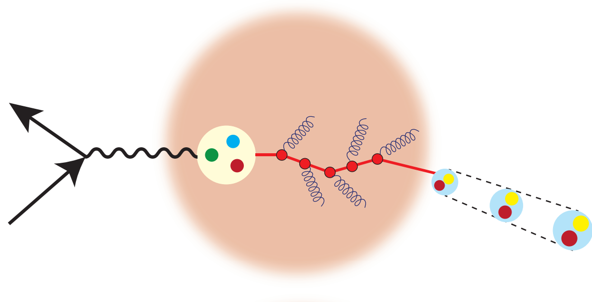


Electromagnetic coverage: $-1 < \eta < 4$
Tracking: $1.4 < \eta < 1.4$
ToF&dE/dx: $-1 < \eta < 1$
Roman Pots: $0.2\ GeV^2 < t < 1\ GeV^2$

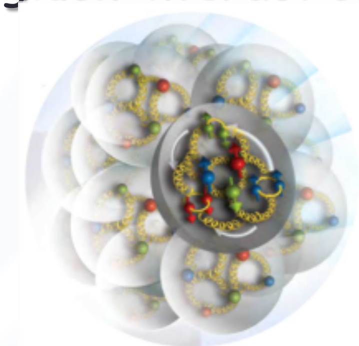
HOT QUESTIONS IN COLD QCD

How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?
How do the nucleon properties emerge from them and their interactions?





How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?
How do the confined hadronic states emerge from these quarks and gluons?
How do the quark-gluon interactions create nuclear binding?

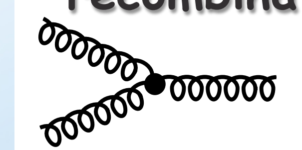


How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?
What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?

gluon emission

?=

gluon recombination



HELICITY STRUCTURE

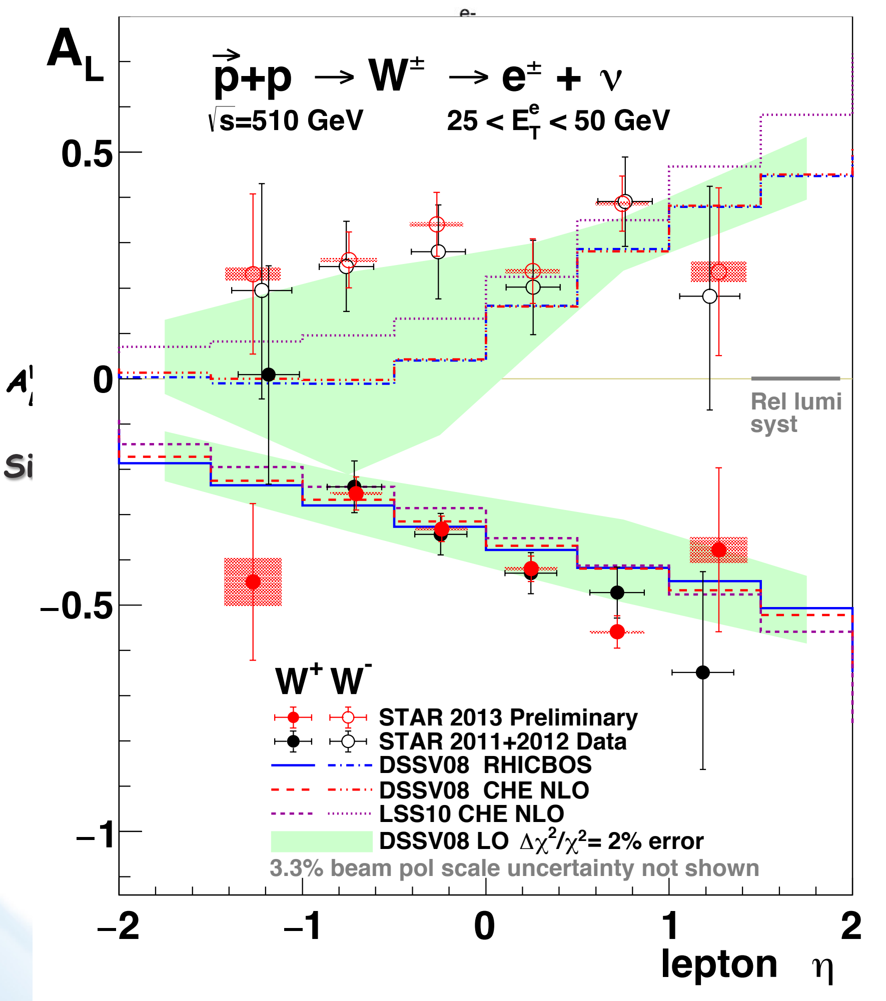
$$\frac{1}{2}\hbar = \left\langle P, \frac{1}{2} | J^z_{QCD} | P, \frac{1}{2} \right\rangle = \overbrace{\sum_q \frac{1}{2} S^z_q}^{\text{quark spin}} + \overbrace{S^z_g}^{\text{gluon spin}} + \sum_q \overbrace{L^z_q + L^z_g}^{\text{angular momentum}}$$

Can quarks and gluons explain all the spin?

→ **what is the role of**

- → **gluons?**
- → **quarks?**
- → **orbital angular momentum**

light Quark Spin



→ stringent test on theory approach for SIDIS

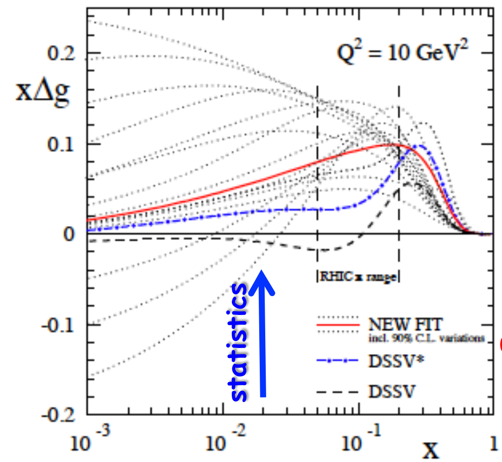
UNIVERSALITY of PDFs

Will provide stringent constraints

→ 2013 uncertainties 40% of 2012

Gluon Spin

Golden Channel: incl. jets & di-jets



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

Data:
STAR 200 GeV
incl. jets &
PHENIX π^0

Need to:
constrain x-shape of PDF
reduce uncertainty at low-x

$$x_1 = \frac{1}{\sqrt{s}}\left(p_{T3}e^{\eta_3} + p_{T4}e^{\eta_4}\right)$$

$$x_2 = \frac{1}{\sqrt{s}}\left(p_{T3}e^{-\eta_3} + p_{T4}e^{-\eta_4}\right)$$

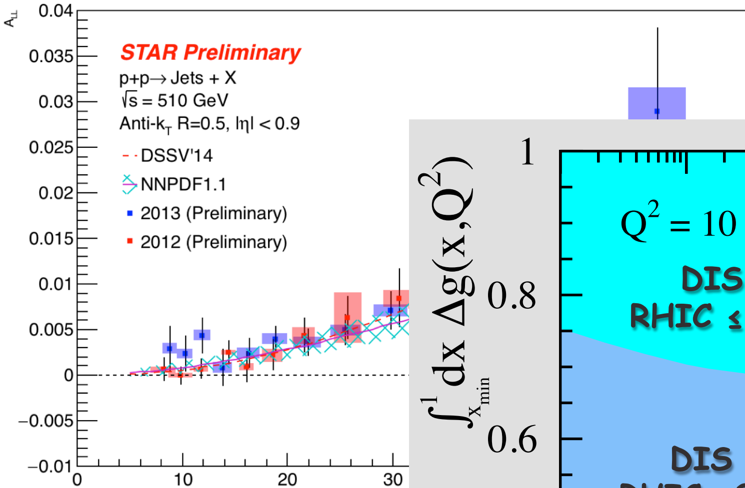
$$M = \sqrt{x_1 x_2 s}$$

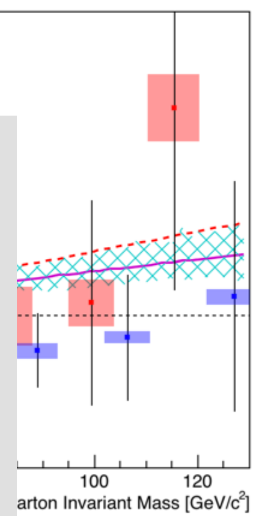
$$\eta_3 + \eta_4 = \ln\frac{x_1}{x_2}$$

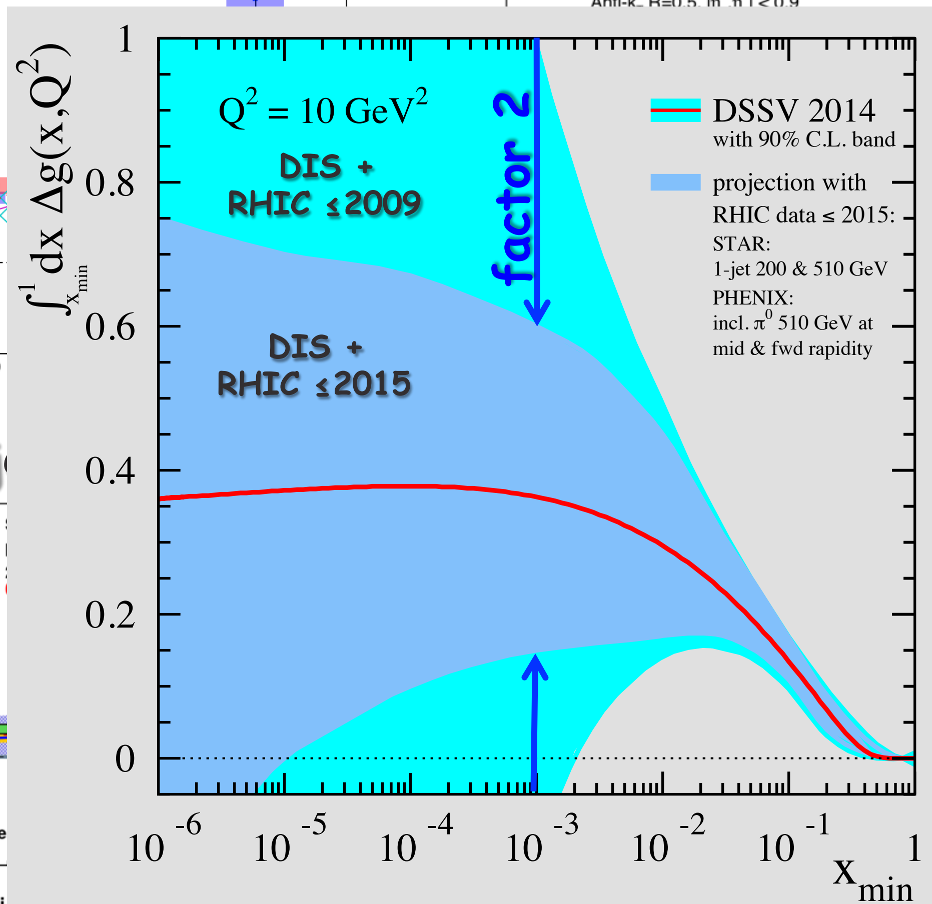
$$\left|\cos\theta^*\right| = \tanh\left|\frac{\eta_3 - \eta_4}{2}\right|$$

HELICITY STRUCTURE: GLUON

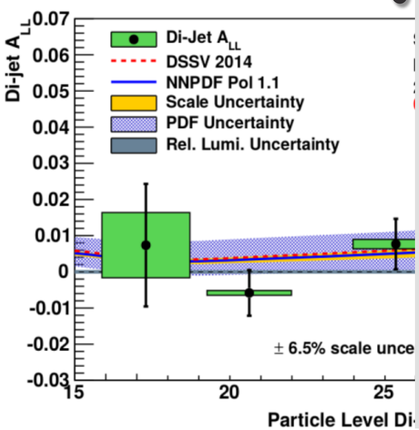
500 GeV incl. and Di-jets:



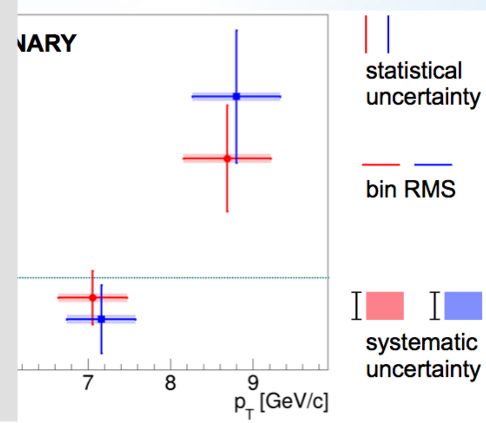


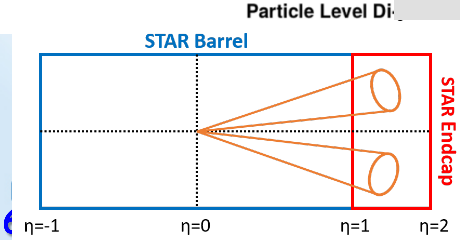


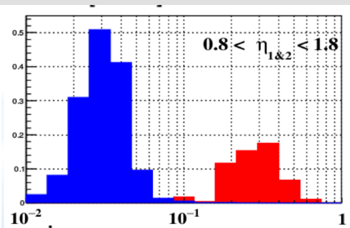
200 GeV Di-j



π⁰ at 2.5 < η < 4:







WHAT CAN POLARIZED pp TELL US

Focus on physics with transversely polarized beams

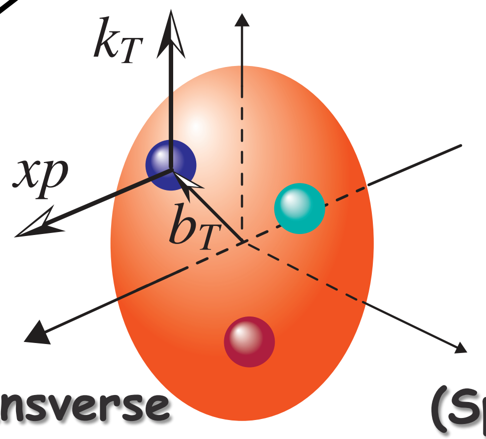
2+1 DIMENSIONAL IMAGING OF QUARKS & GLUONS

Wigner function
$W(x, b_T, k_T)$

QCD genetic map

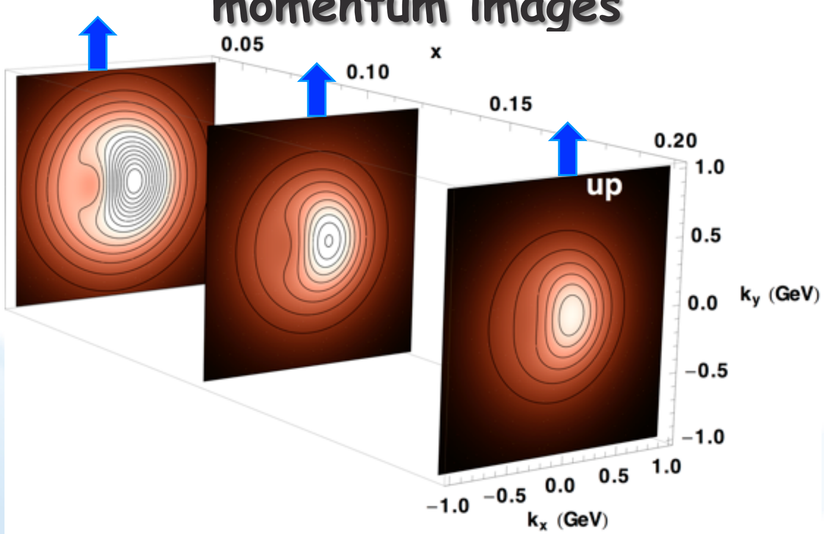
$\int d^2 b_T$ $\qquad$ $\int d^2 k_T$

Momentum space $\qquad$ *Coordinate space*

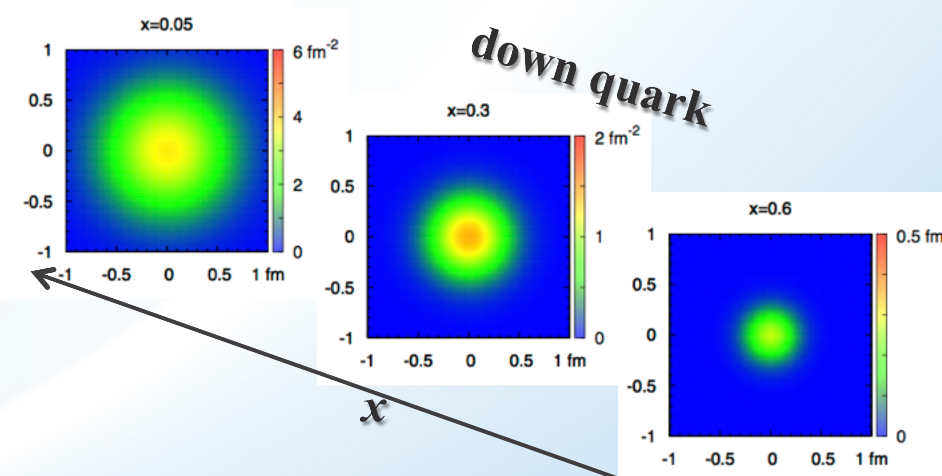


$f(x, k_T)$ **TMDs** $\qquad$ $f(x, b_T)$ **GPDs**

(Spin-dependent) 2+1D transverse momentum images



(Spin-dependent) 2+1D spatial images from exclusive scattering



Recent theoretical work indicates direct access to Gluon Wigner function through diffractive di-jets in UPC (arXiv:1706.01765)

THE STAR OBJECTIVES FOR TMDs

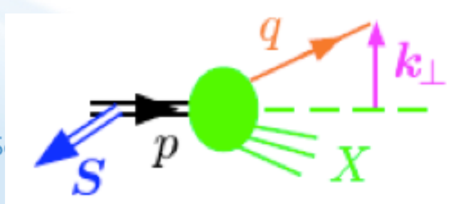
- Constrain TMDs over a wide x and Q^2 range (valence, sea-quarks & gluons)
- data purely sensitive to observables in the TWIST-3 formalism
  - → different $\sqrt{s}$ → evolution
- observables purely sensitive to observables in the TMD formalism
  - → different $\sqrt{s}$ → different p_t at the same x_t → evolution
  - → Test non-universality of TMDs
- observables as transversity can be accessed also in collinear observables
  - → test of TMD factorization

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

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

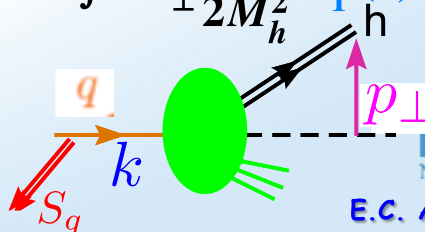


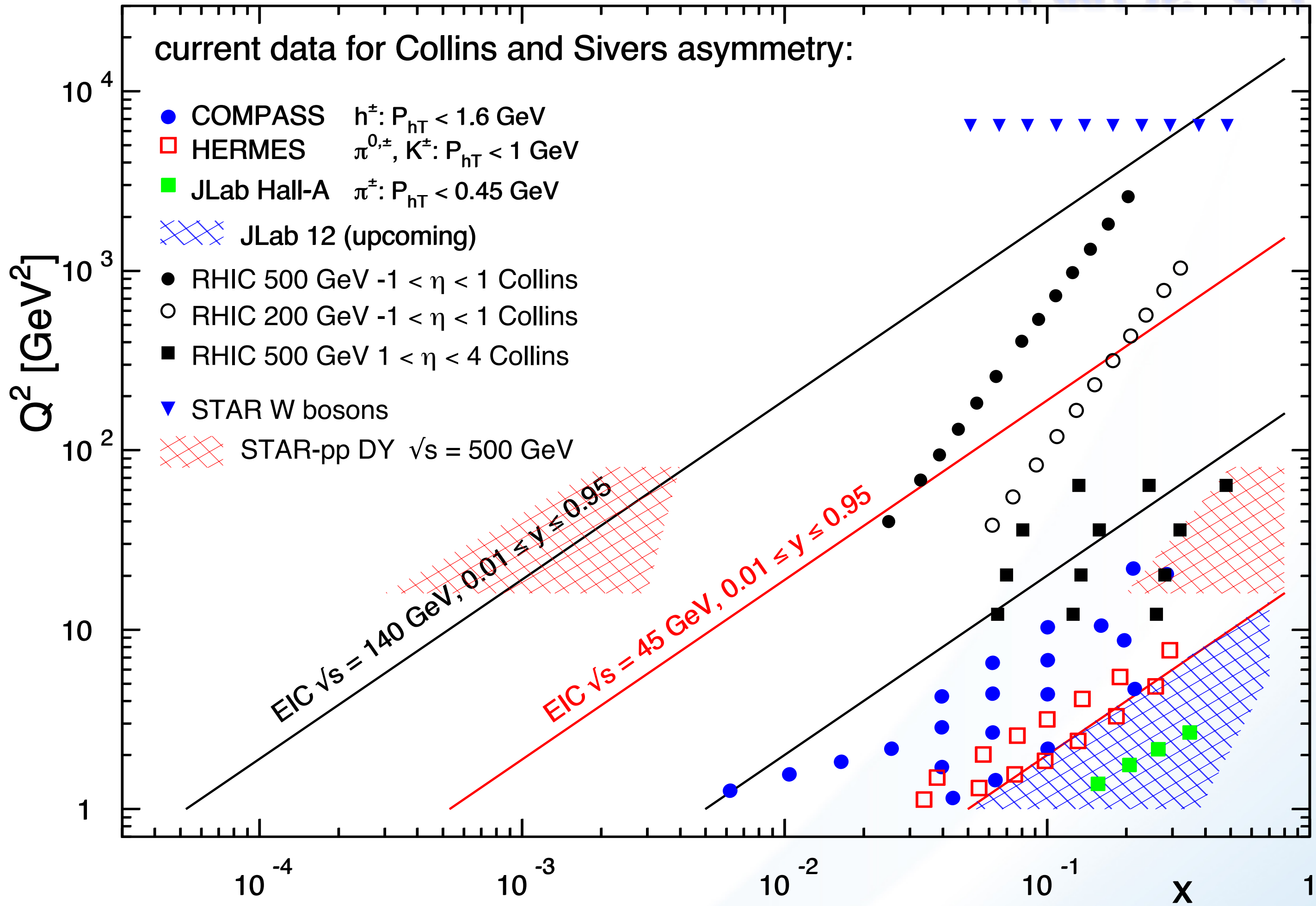
Final State

- 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 π0
  - → Novel Twist-3 FF Mechanisms

related through

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





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

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

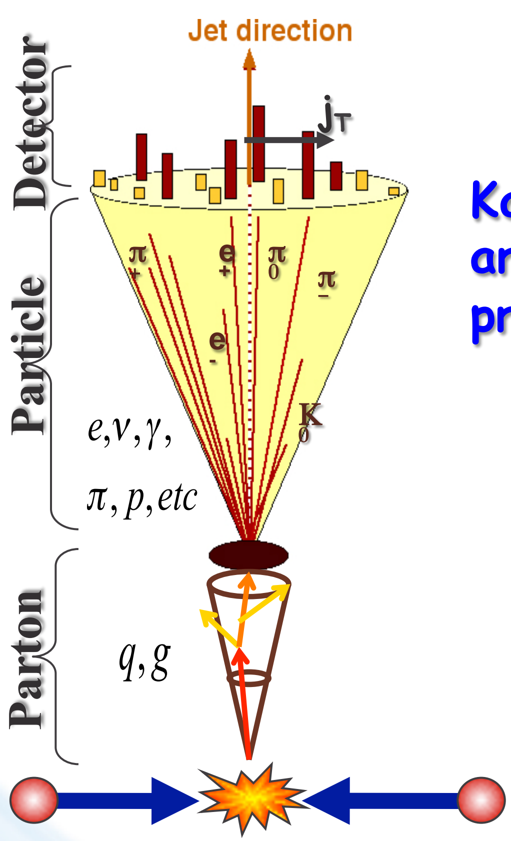
polarised pp at RHIC

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

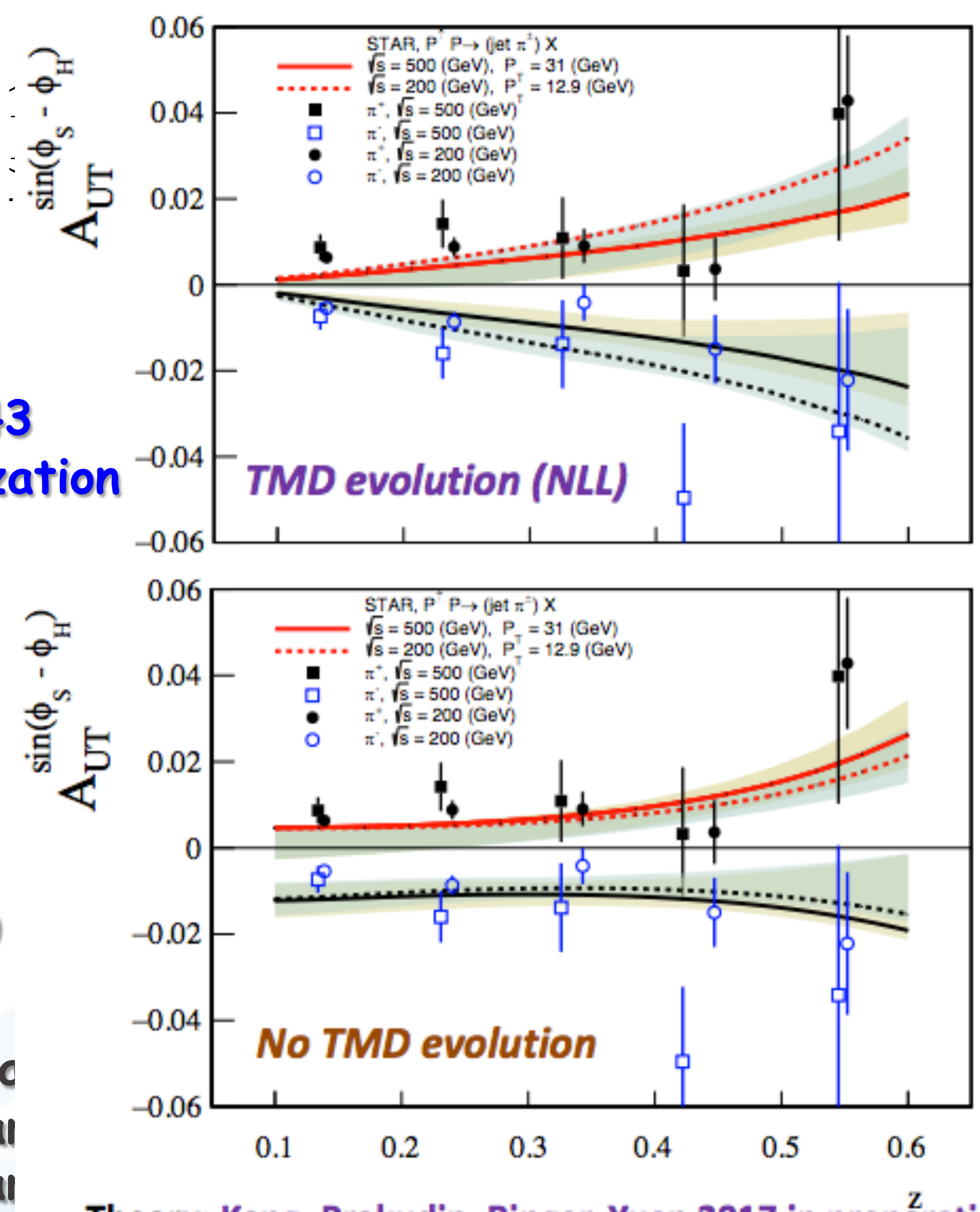
JETS TO ACCESS TRANSVERSITY x COLLINS

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

$$z = \frac{p_t^h}{p_t^{jet}}$$



Kang et al.
arXiv:1705.08443
proof of factorization

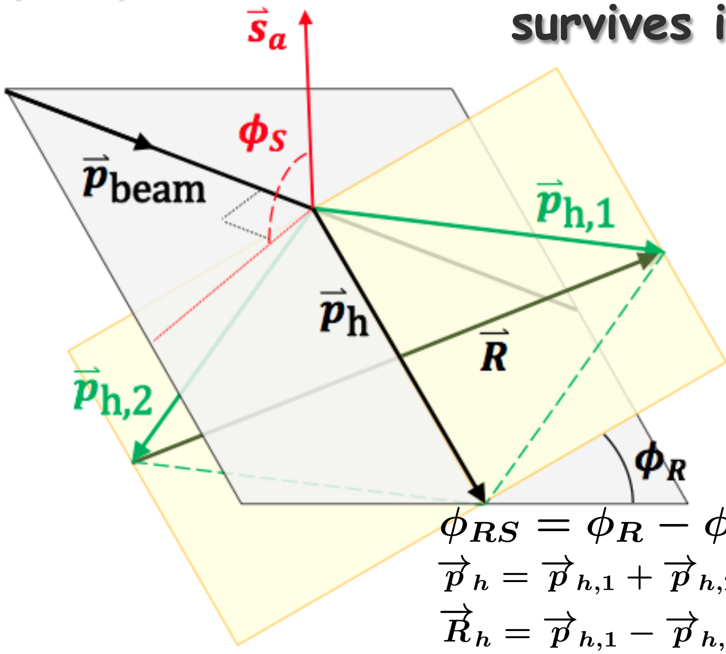


200 vs. 500
- Evolution:
- Test of fa
  - → compar
  - → compar

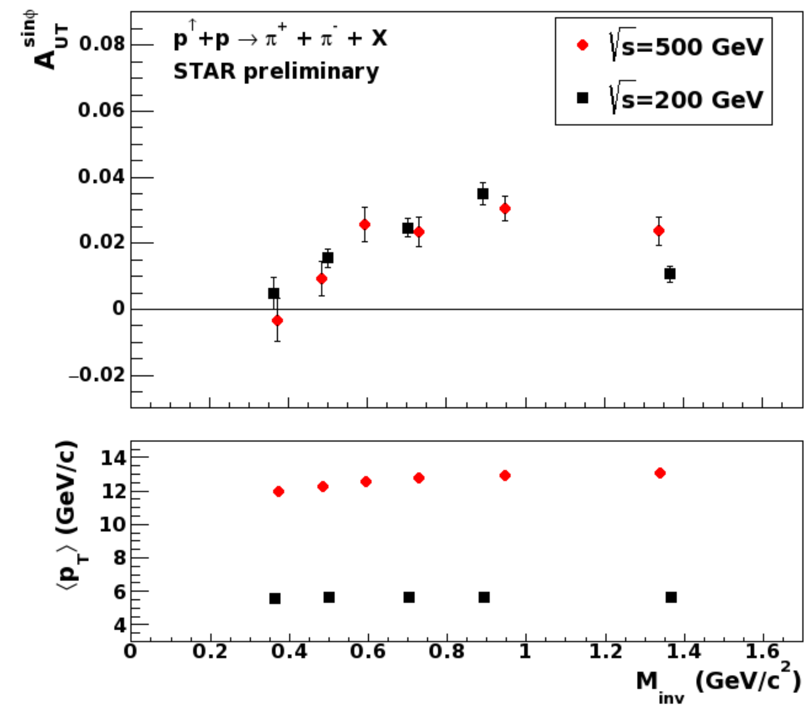
INTERFERENCE FRAGMENTATION FUNCTION (IFF)

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

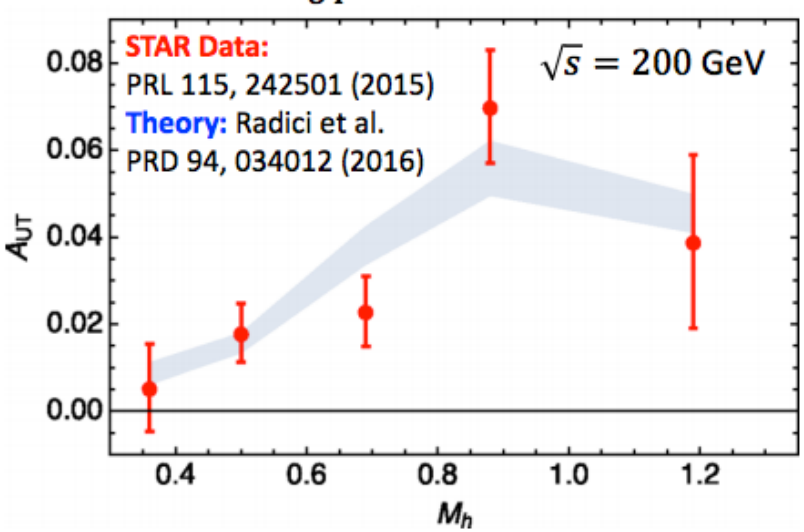
$$A_{UT}\sin(\phi_{RS}) = \frac{1}{Pol}\frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}$$



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



A_{UT} in $\pi^+\pi^-$ IFF



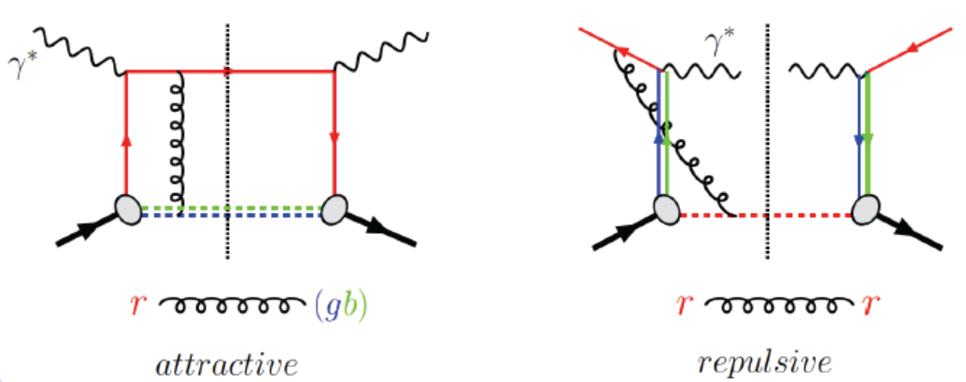
- Significant di-hadron asymmetries both at √s=200GeV and √s=500GeV
- Increasing with p_T
- Access to transversity with a collinear observable

VISUALIZE COLOR INTERACTIONS IN QCD.

Measure non-universality of sivers-function

QCD:

DIS: γq-scattering attractive FSI	pp: qqbar-anhilation repulsive ISI



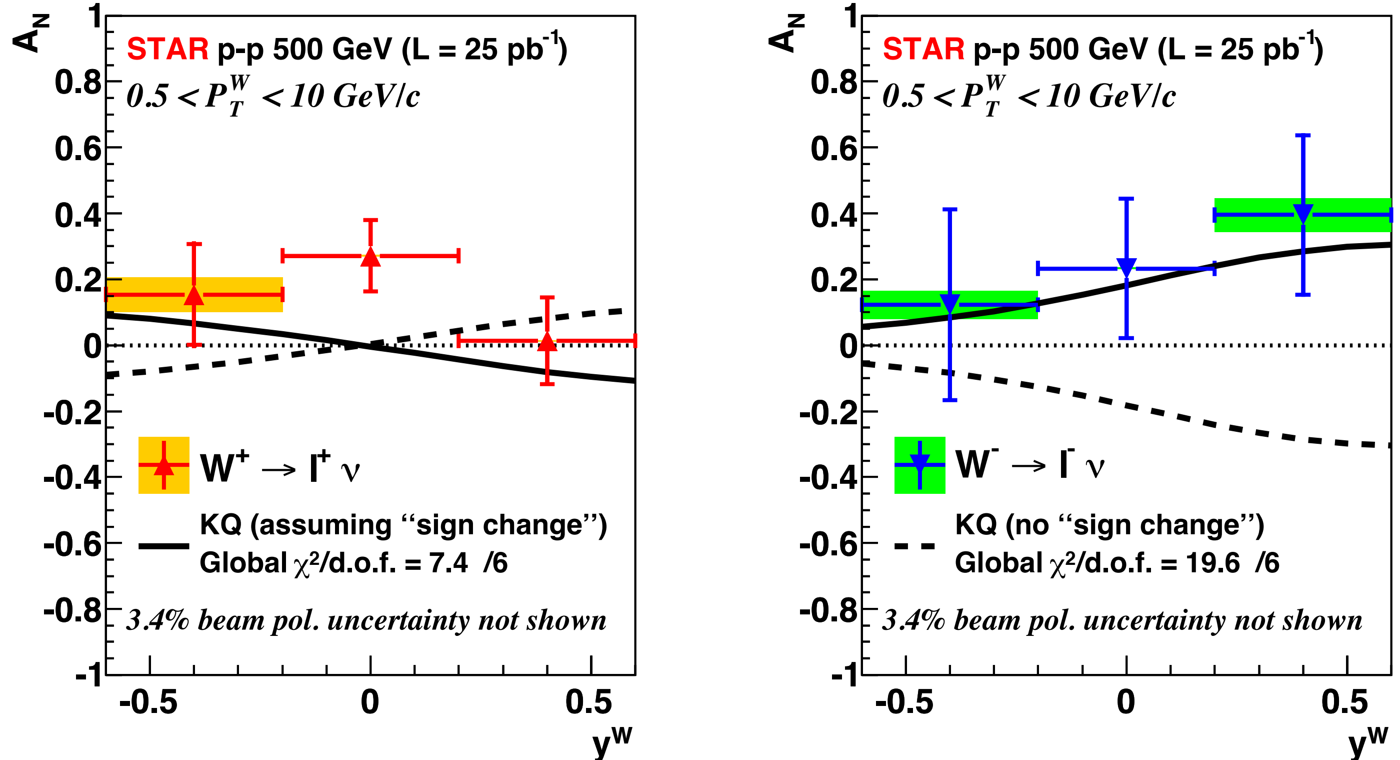
$Sivers_{DIS}$ = **−** ($Sivers_{DY}$ or $Sivers_{W}$ or $Sivers_{Z0}$)

A_N(direct photon) measures the sign change in the Twist-3 formalism

All three observables can be approached
at 500 GeV at STAR
only way to access HP13

FIRST RESULTS: A_N^W

- Results based on 2011 25 pb^{-1} transversely polarized 500 GeV data
  → published in PRL 116 (2016) 132301
- y and p_t for fully reconstructed Ws → recoil combined with MC
  → method used at Fermi-Lab and LHC



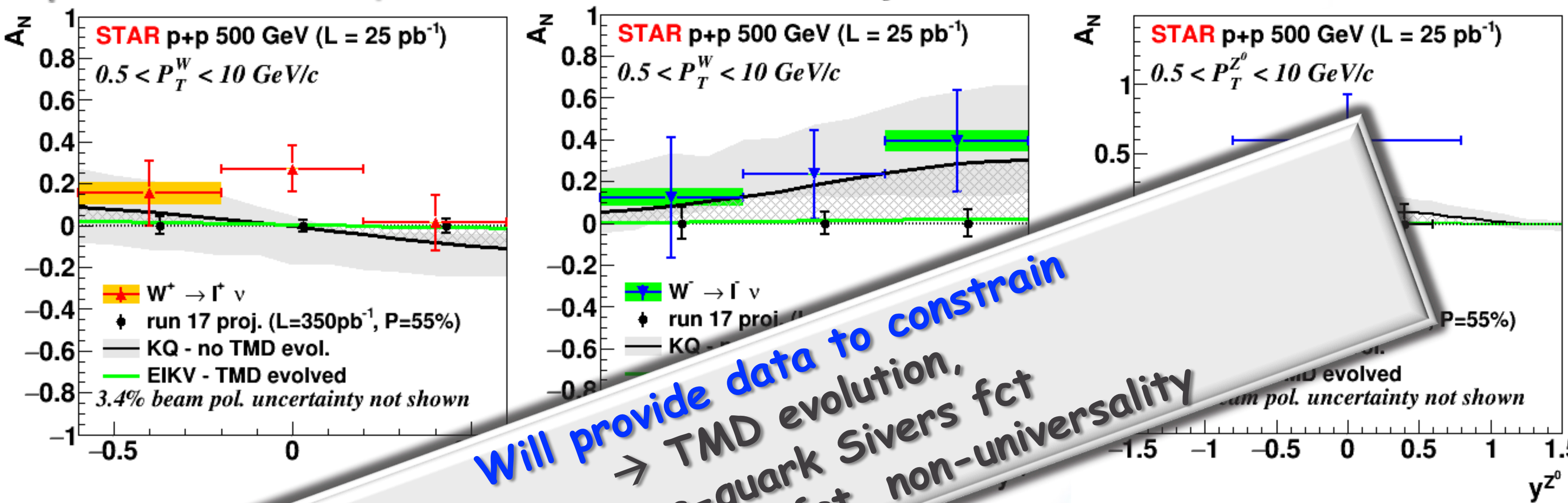
Asymmetry favors Sivers fct. sign change and small TMD evolution for asymmetries

RUN-17: A GOLDMINE FOR TMDs@STAR

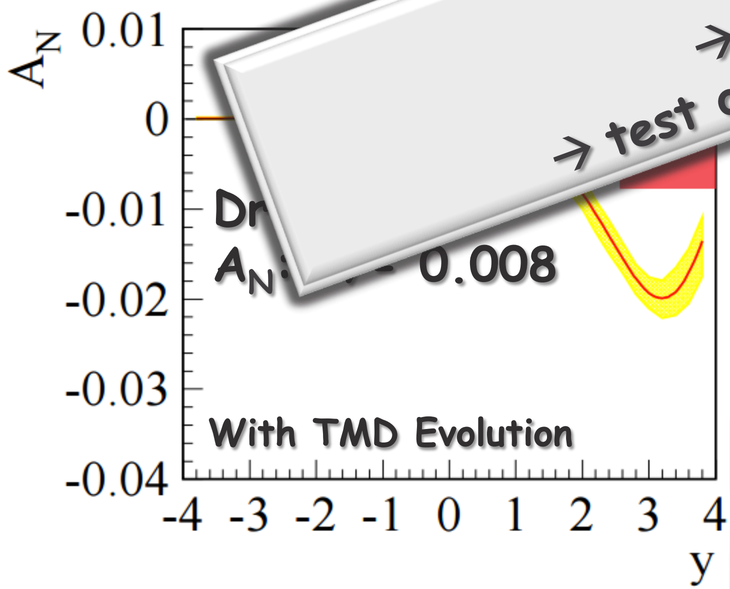
Collected:

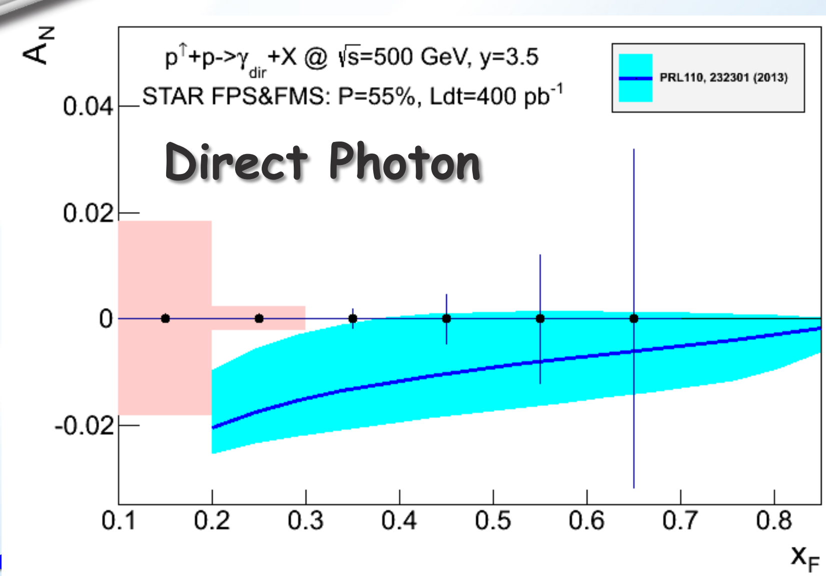
350 pb^{-1} → 14 times Run-11 for $-1 < \eta < 1.8$ → A_N $W^{+/-}$ & Z0, Collins, ……

250 pb^{-1} for $2.8 < \eta < 4$ for DY and direct photon

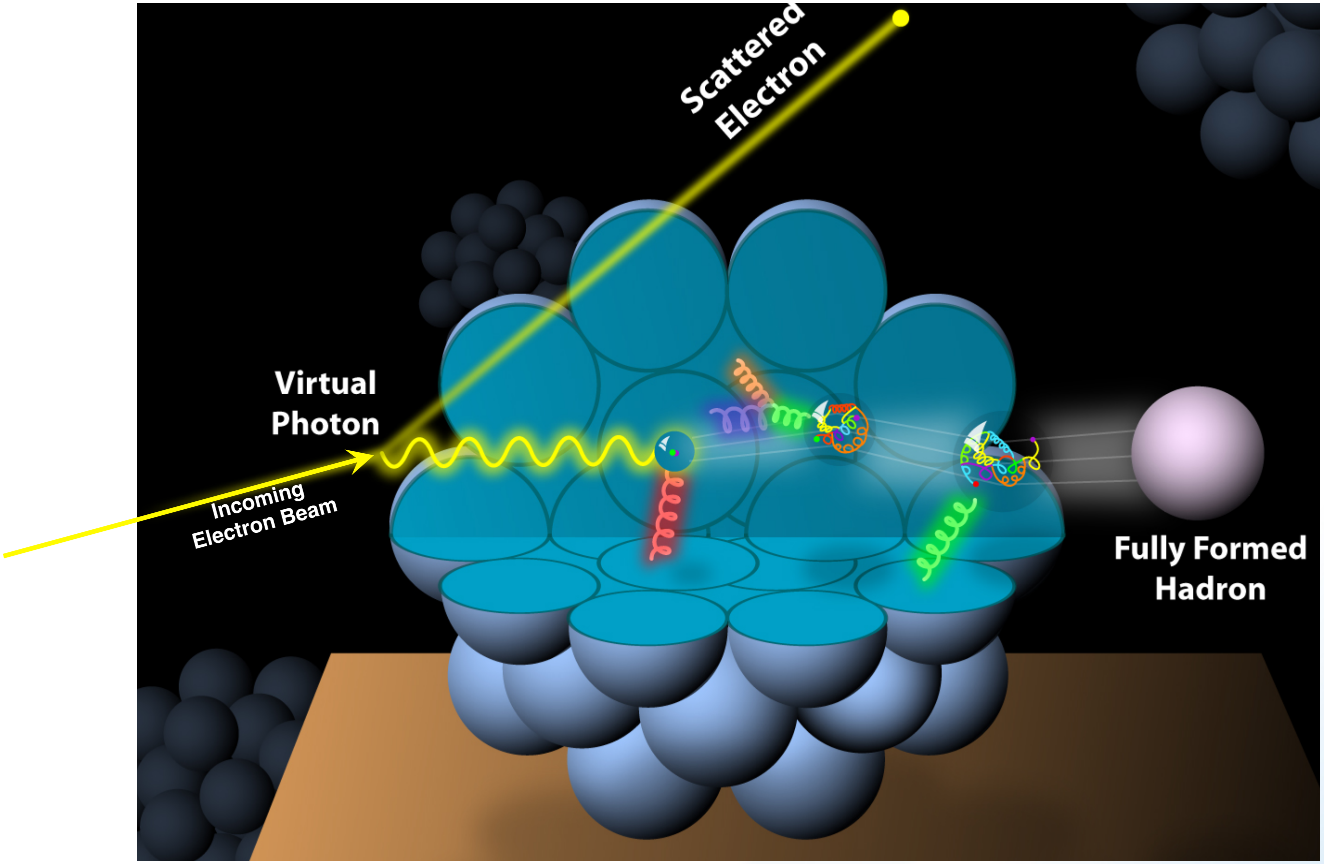


Will provide data to constrain
→ TMD evolution,
→ sea-quark Sivers fct
→ test of Sivers fct. non-universality





WHAT ABOUT NUCLEI?

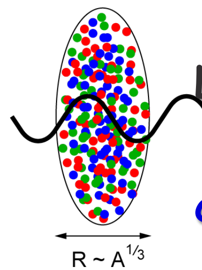


HOW DOES THE INITIAL STATE IN AA LOOK?

3 conundrums of the initial state:

- ❑ 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.

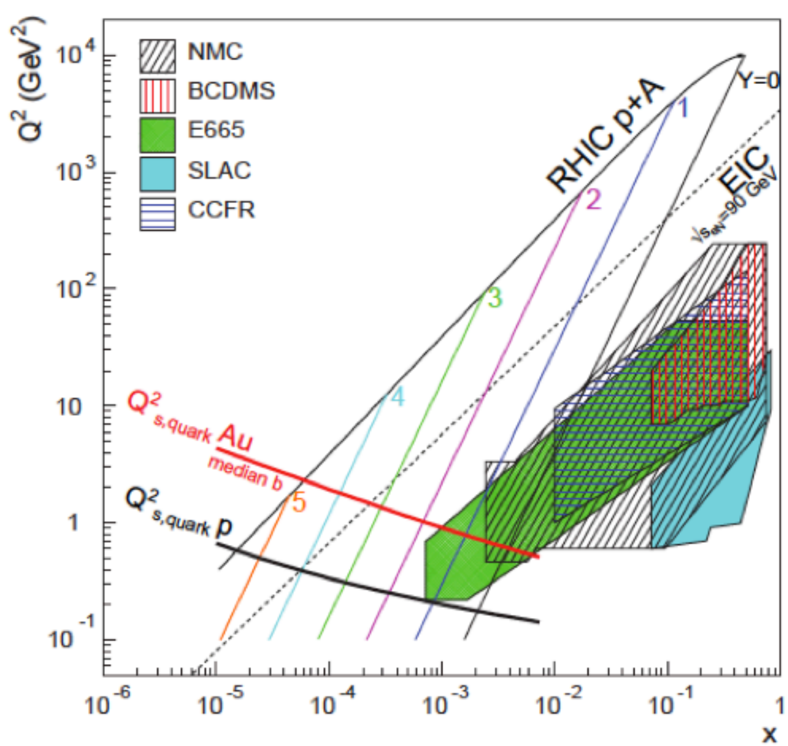
$$(Q_s^A)^2 \sim c Q_o^2 \left(\frac{A}{x}\right)^{1/3}$$



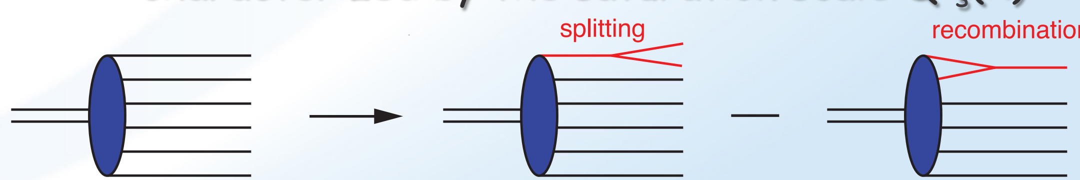
$L \sim (2 m_N x)^{-1} > 2 R_A \sim A^{1/3}$

Probe interacts **coherently** with all nucleons

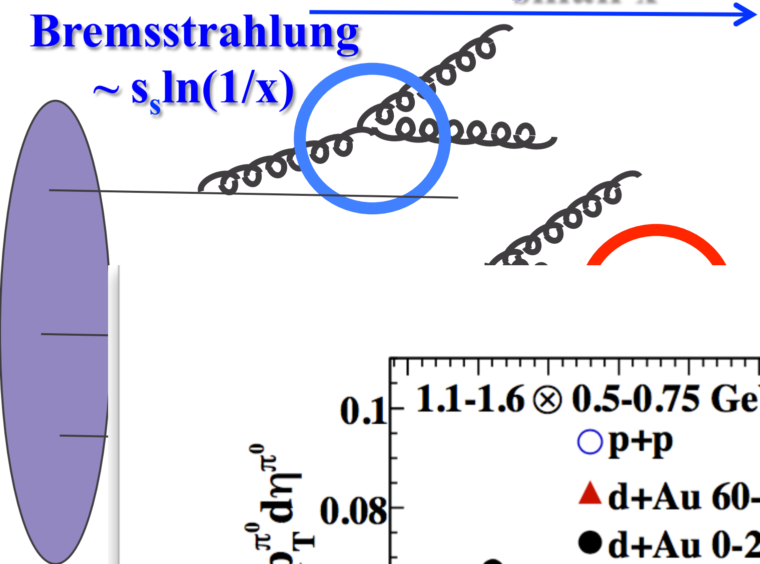
Gold: **197 times smaller effective x !**



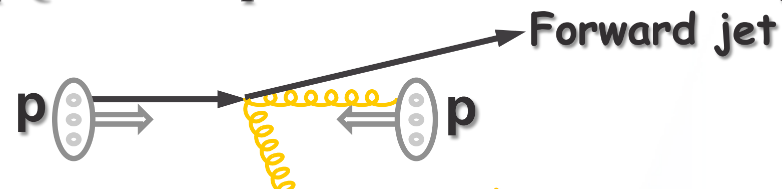
- ❑ Rapid rise in gluons described naturally by linear pQCD evolution equations
- ❑ This rise cannot increase forever - limits on the cross-section
  - → non-linear pQCD evolution equations provide a natural way to tame this growth and lead to a saturation of gluons, characterized by the saturation scale $Q^2_s(x)$

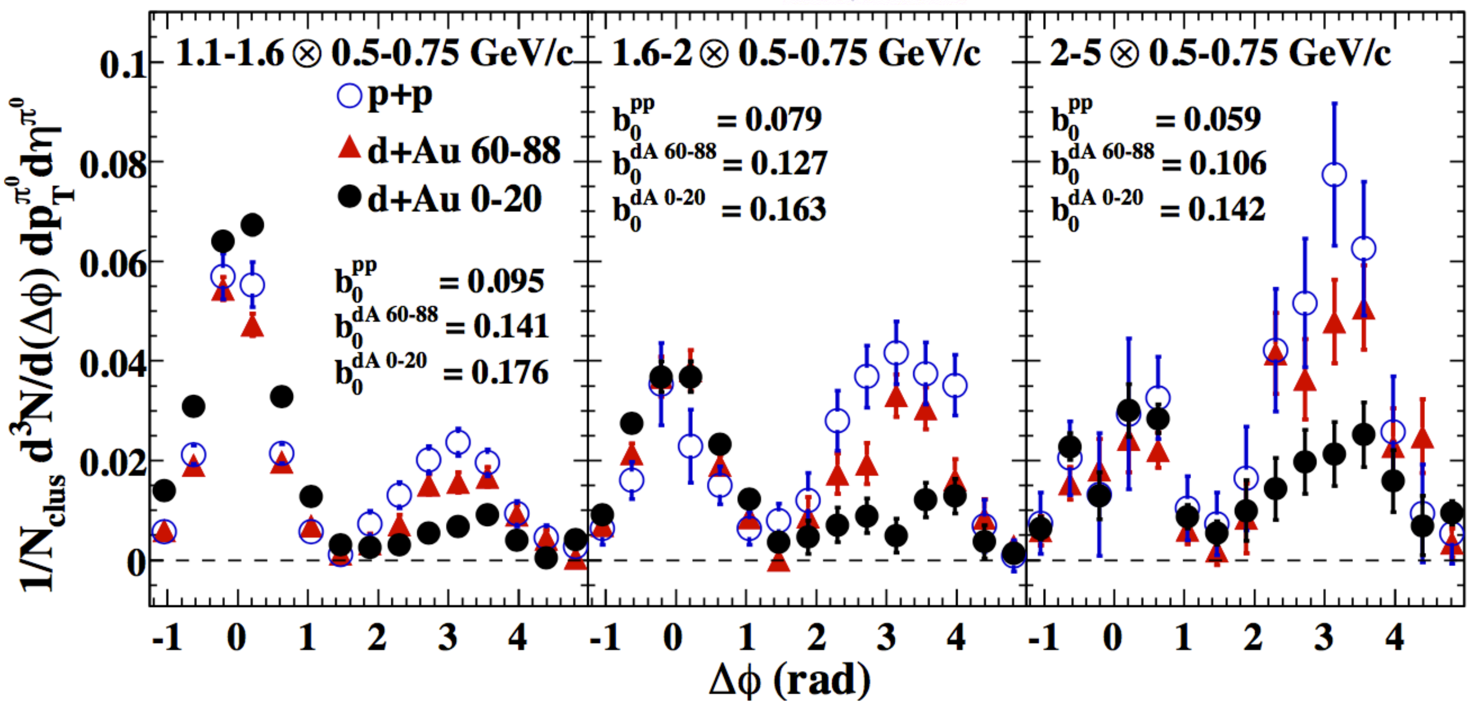


KEY OBSERVABLE FOR SATURATION IN pA

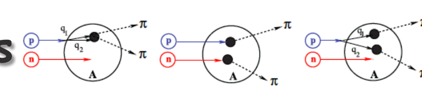


pQCD 2→2 process = back-to-back di-jet



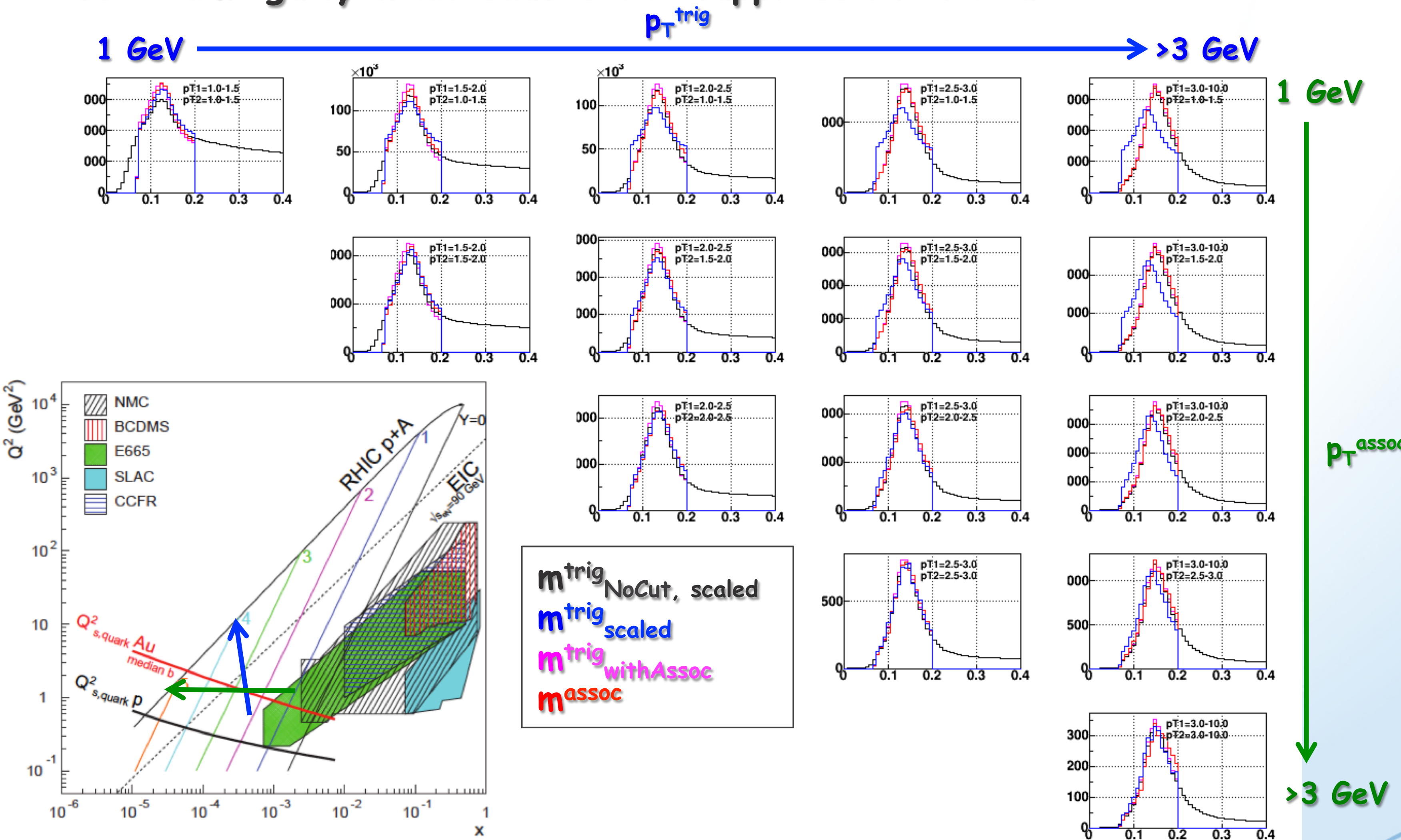


dA: alternative explanation through double interactions



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



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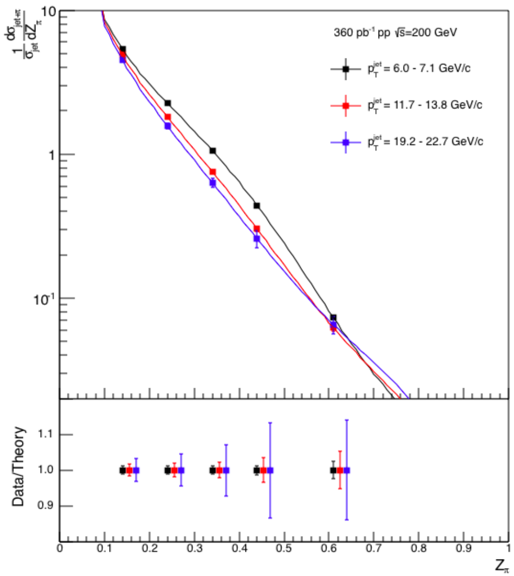
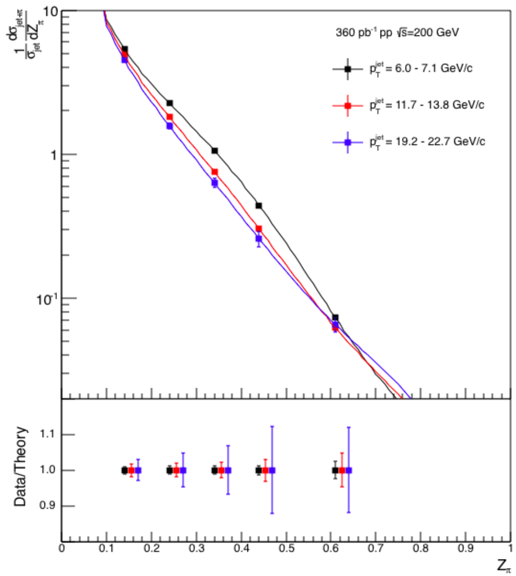
FRAGMENTATION FUNCTIONS IN pp AND pA

Observable: hadron in jet

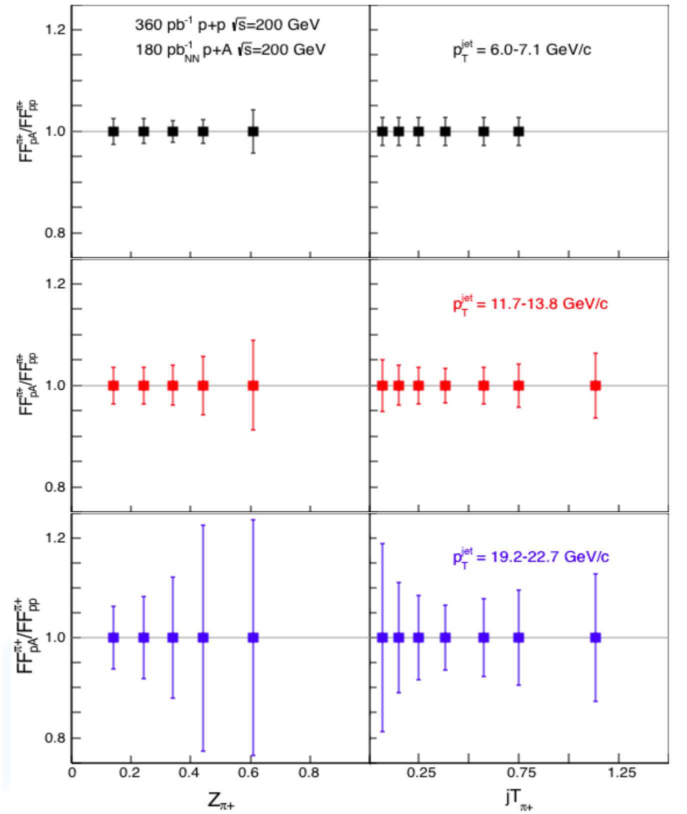
p+p:

$\pi+$ $\pi-$

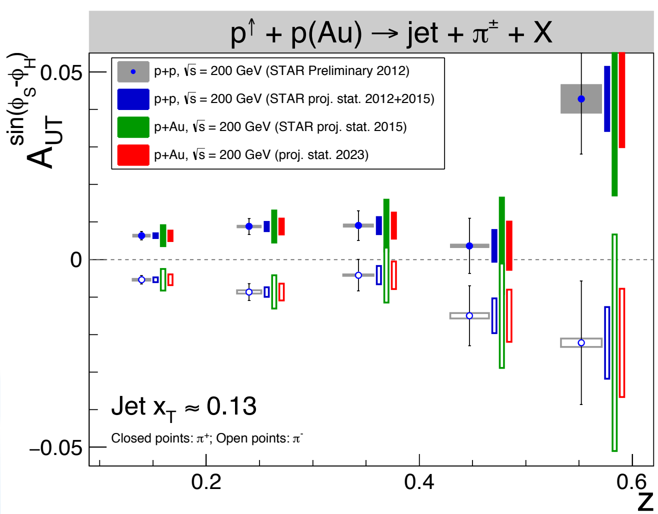




fragmentation functions in p+A/p+p at $|\eta| < 0.4$



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



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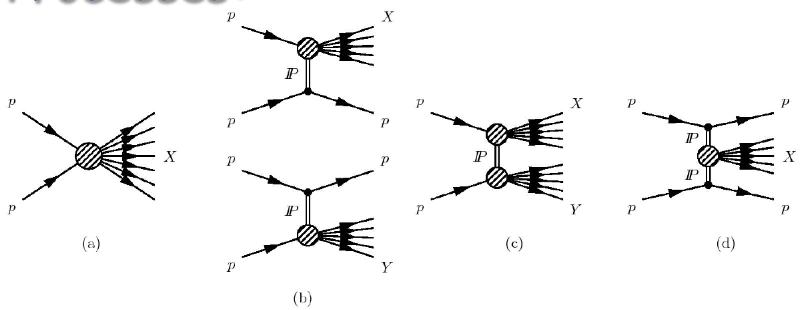
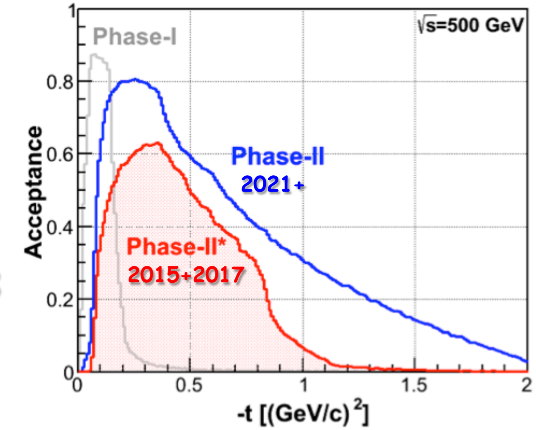
DIFFRACTION: A NEGLECTED CHILD AT RHIC

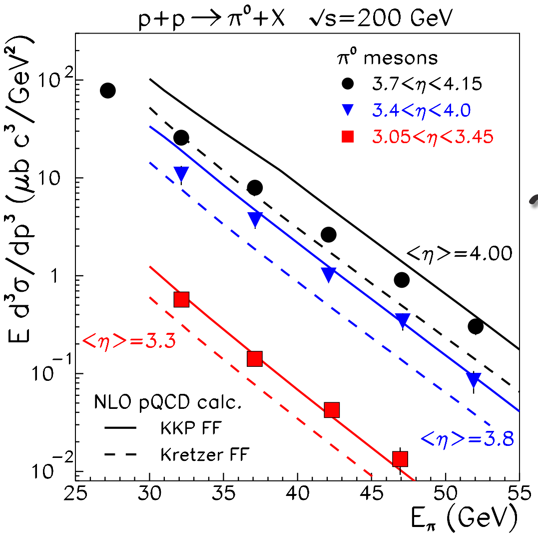
Processes:



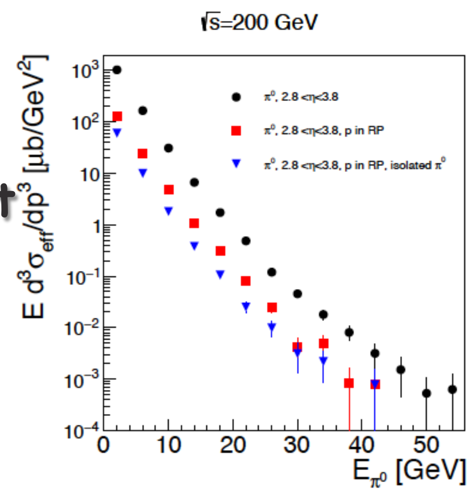
STAR RP the optimal tool to tag diffractive processes

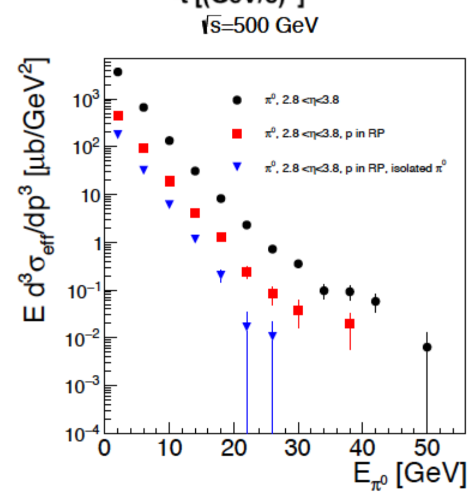


inclusive cross section



Pythia-8
~20% at least diffractive

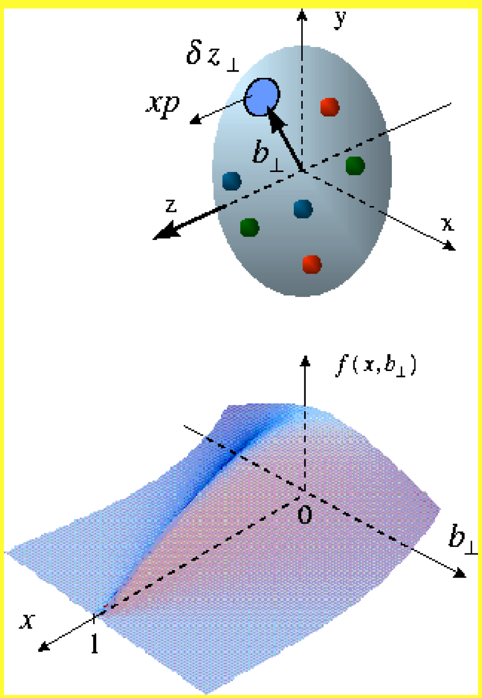




Many more interesting physics opportunities with diffraction
→ SSA for UPC J/Ψ production → GPDs
→ Di-jets in UPC → gluon Wigner function (arXiv:1706.01765)
→ R_{pA} for diffractive events → saturation

THE MISSING PIECE: ORBITAL ANGULAR MOMENTUM

GPDs: PDFs that correlated parton momentum and their distributions in transverse space



exclusive reactions the vehicle to access L_q & L_g
golden channel: J/Ψ

new theoretical concept: Generalized Parton Distributions

Spin-Sum-Rule in PRF:

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

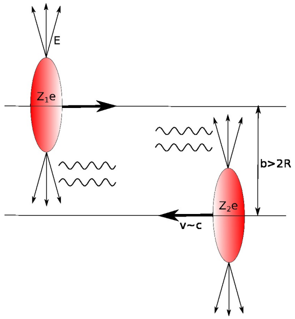
$$J_{q,g}^z = \frac{1}{2}\left(\int_{-1}^{1} x\,dx\left(H^{q,g} + E^{q,g}\right)\right)_{t\to 0}$$

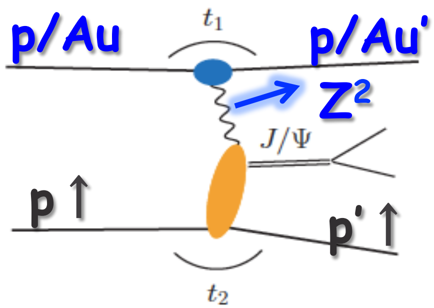
responsible for orbital angular momentum

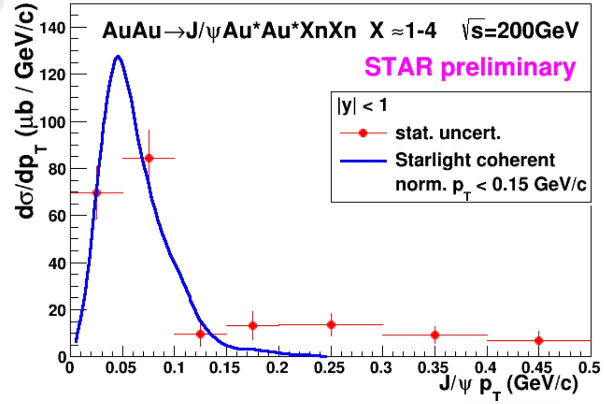
J/Ψ production in p↑Au UPC
→ world wide only access to GPD E for gluons

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

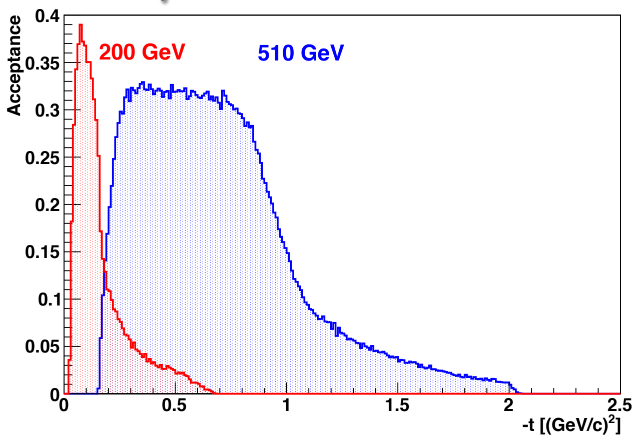
RUN-15&17: J/Ψ IN pp/pA UPC



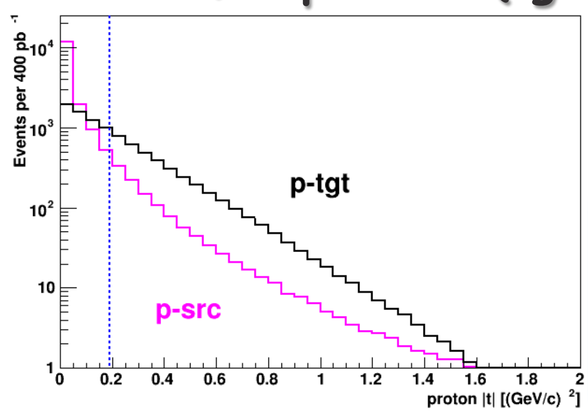




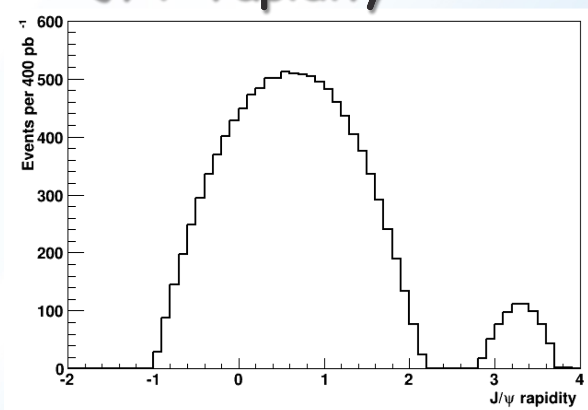
RP acceptance for scattered proton:

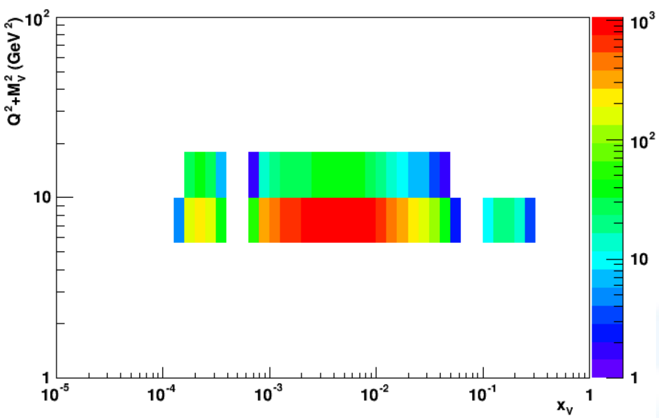


t-dist for protons (tgt & γ-src):



J/Ψ-rapidity





Required:

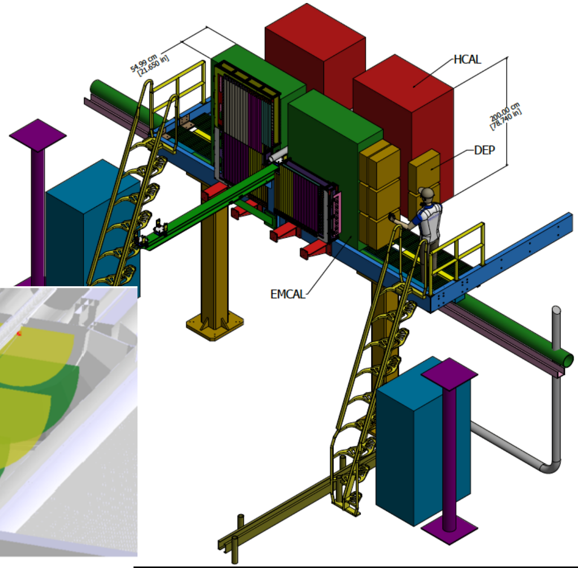
2017 p↑+p 400 nb-1

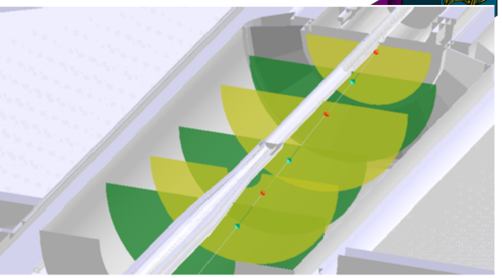
→ 1k J/Ψs

→ δA_{UT}: +/-0.2 in 3 t-bins

Run-15: ~300 J/Ψ

STAR IN 2021



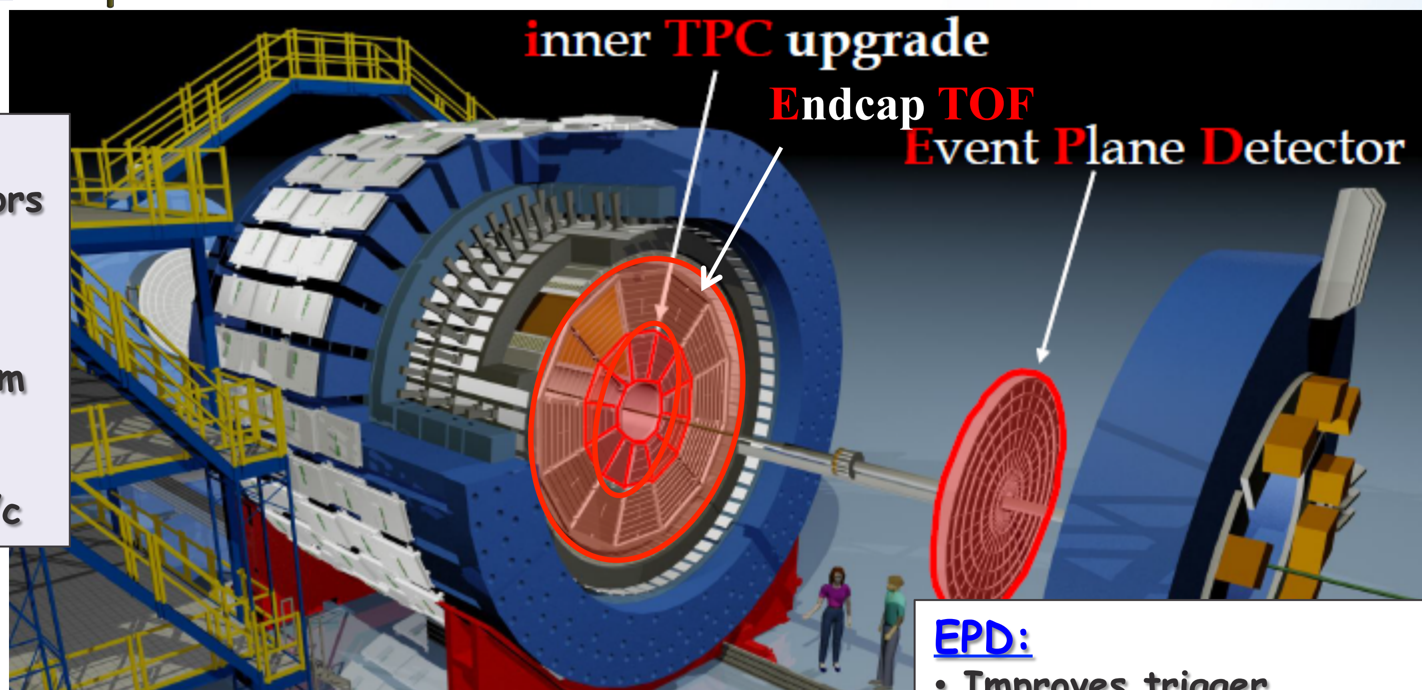


STAR forward upgrade 2.5 < η < 4.5

Ecal: reuse PHENIX Ecal

Hcal: design ala
STAR fHCal and EIC fHCal

Tracking:
4-6 Si strip-disks

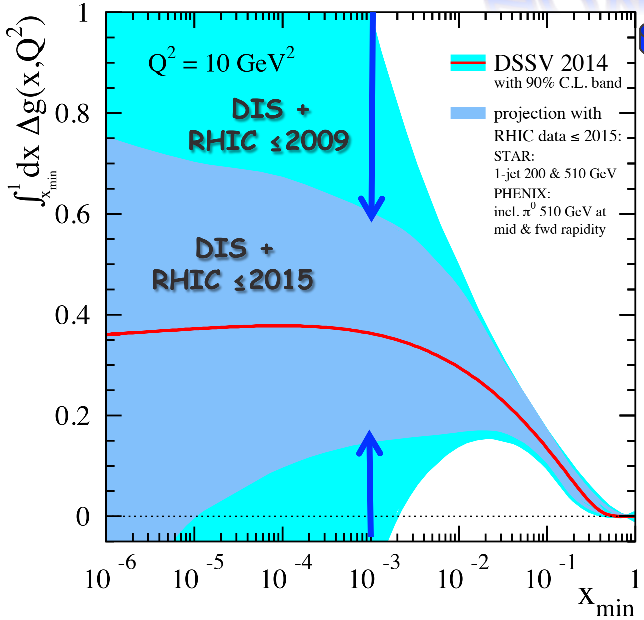


iTPC:
- Rebuilds the inner sectors of the TPC
- Continuous Coverage
- Improves dE/dx
- Extends η coverage from 1.0 to 1.5
- Lowers p_T cut-in from 125 MeV/c to 60 MeV/c

EndCap TOF:
PID at η = 0.9 to 1.5

EPD:
- Improves trigger
- Reduces background
- Allows a better and independent reaction plane

HOW POLARIZED ARE THE GLUONS?

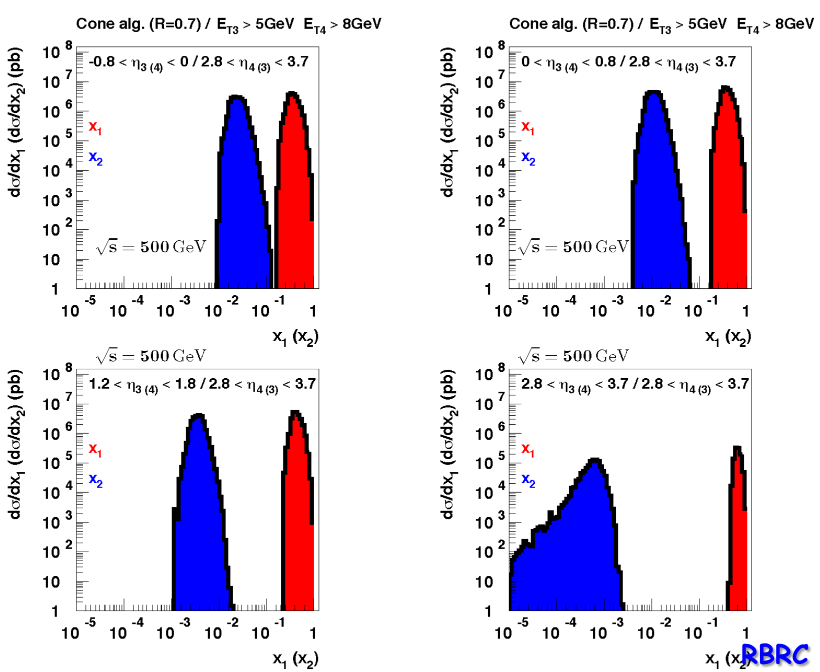


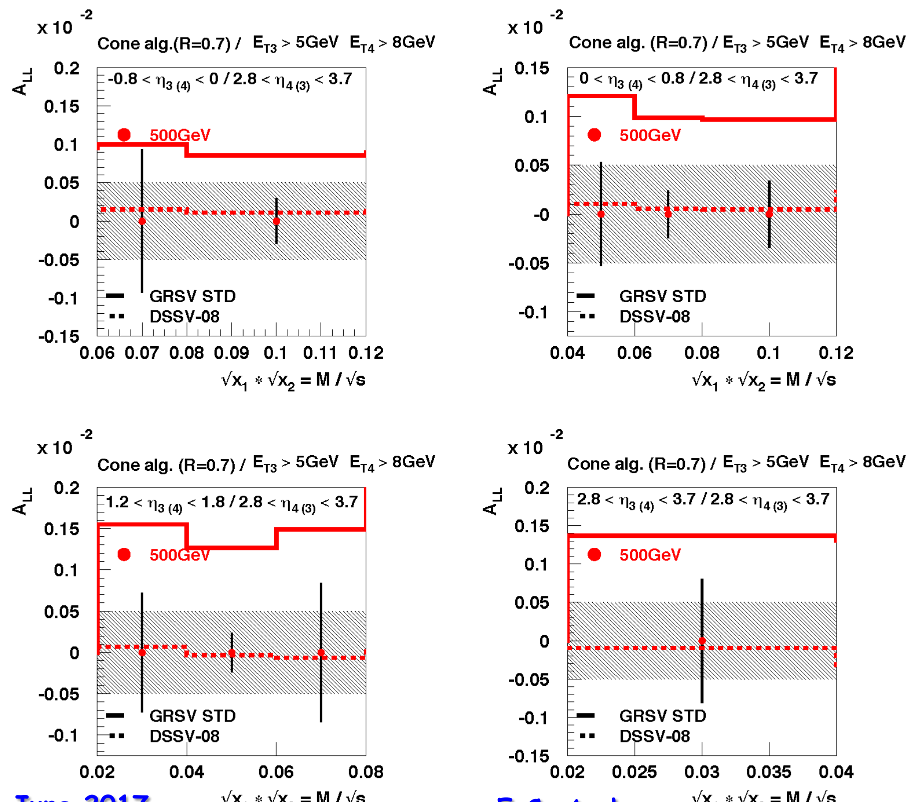
Data till 2009

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

STAR and PHENIX data till 2015 reduce uncertainties at $x \sim 10^{-3}$ by **factor 2**

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





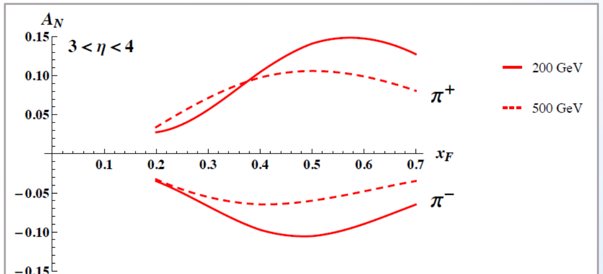
TMDs AT STAR

Unique Opportunities:

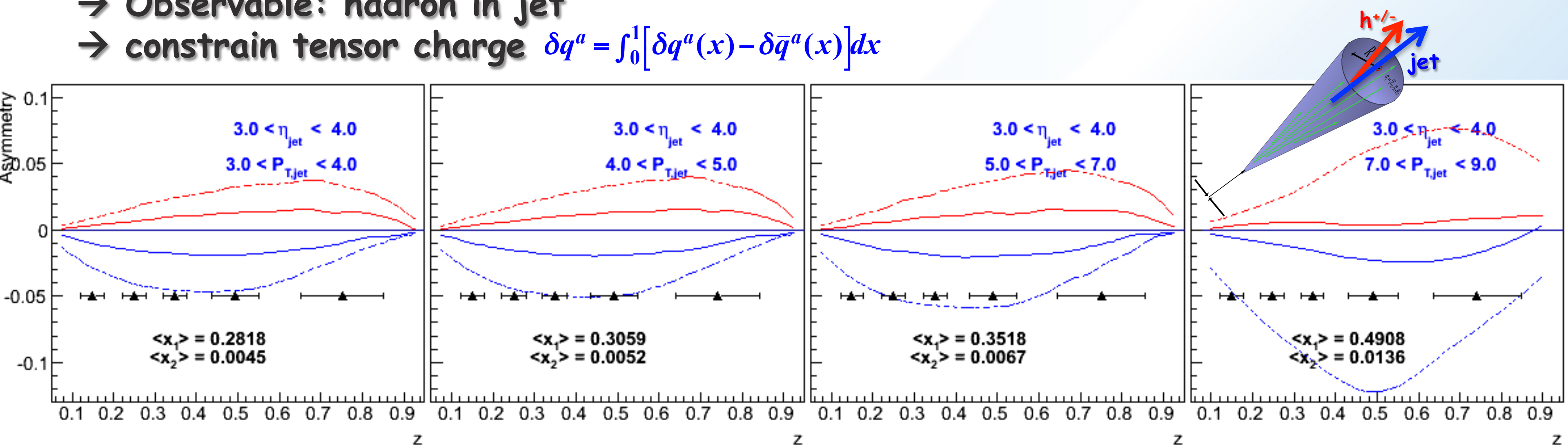
- constrains TMD evolution
- are TMDs relevant in the gluon and sea-quark dominated regime?
- high precision data sets to test QCD concepts of factorization and universality
  → answers critical to have an optimal TMD program at EIC

Goals:

- 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 $\pi^{+/-}$
  → 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
- measure transversity at high x
  → Observable: hadron in jet
  → constrain tensor charge $\delta q^a = \int_0^1 \left[\delta q^a(x) - \delta \bar{q}^a(x)\right] dx$



Kanazawa et al. PRD 89, 111501 (2014)

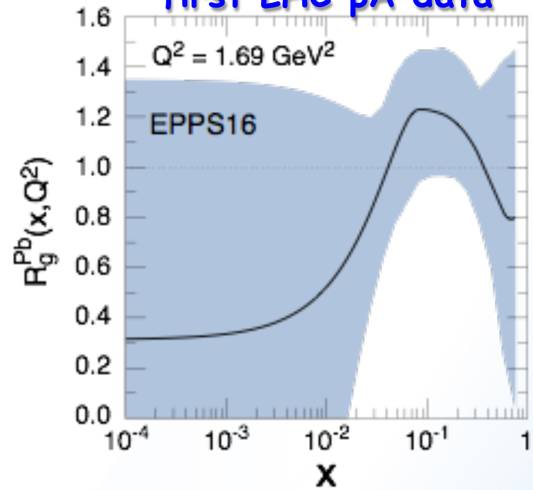


HOW DOES THE INITIAL STATE IN AA LOOK?

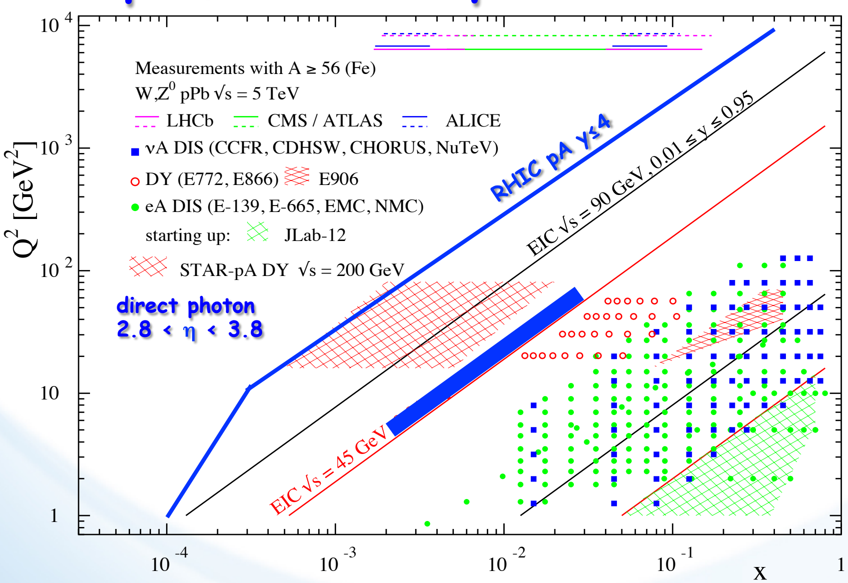
3 conundrums of the initial state:

- ❑ 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.

Current knowledge including first LHC pA data



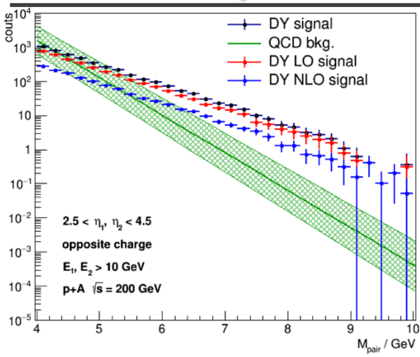
pA@RHIC: unique kinematics

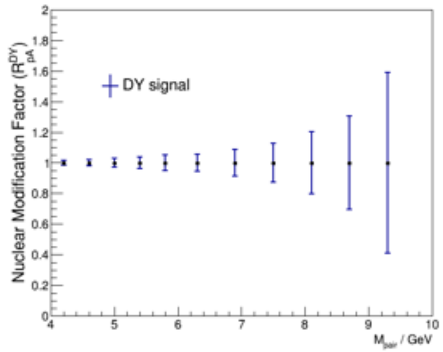


- ❑ can measure nPDF in a x-Q^2 region where nuclear effects are large
  - ➢ $Q^2 > Q_s^2$ over a wide range in x
- ❑ Observables free of final state effects
  - ➢ Gluons: R_{pA} for direct photons
  - ➢ Sea-quarks: R_{pA} for DY
- ❑ Scan A-dependence prediction by saturation models
- ❑ can access saturation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

HOW DOES THE INITIAL STATE IN AA LOOK?

pA: DY@2.5 < η < 4.5





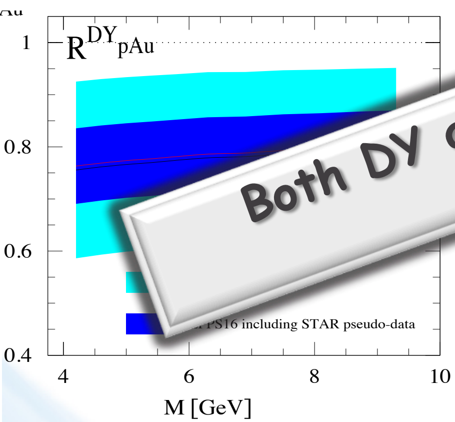
Impact on nPDFs: → sea quarks

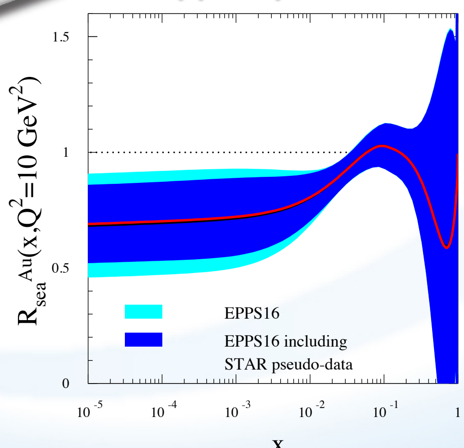
DY:

Q²

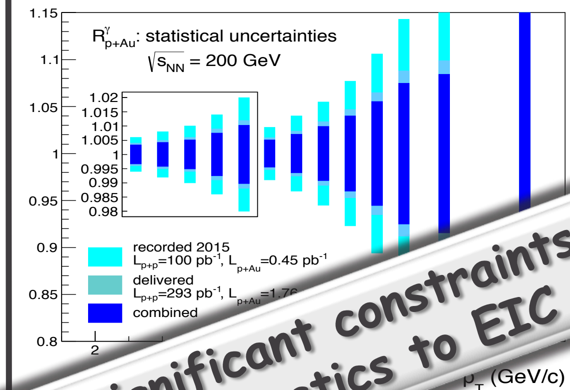
…ainties:

2023 pp & pA





pA: Direct Photon@2.5 < η < 4.5

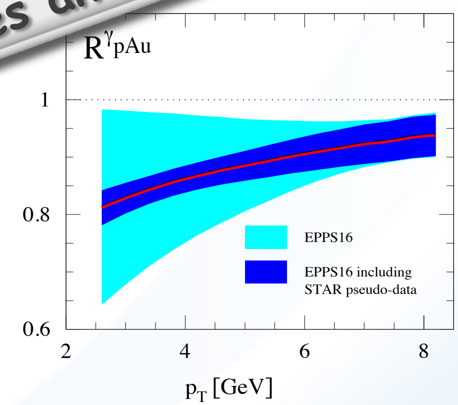


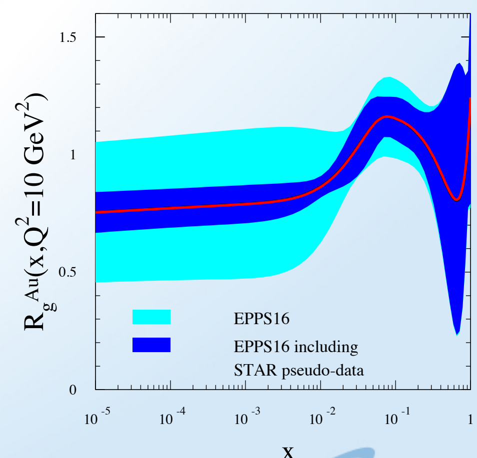
Uncertainties:

2015 + 2023 pp&pA

… 5 GeV²

… nPDFs: → gluons





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

SATURATION WITH THE FORWARD UPGRADE

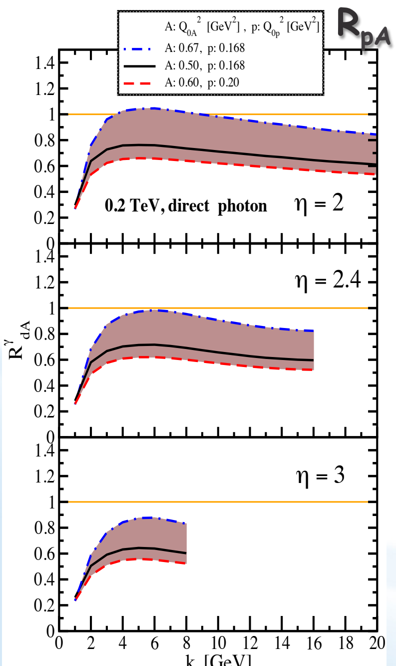
Expand the number of observables:

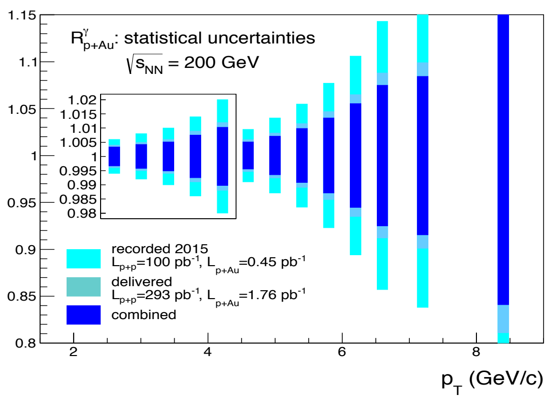
→ rigorous test of theory predictions
→ get a handle on the different gluon distributions
→ provide variety of high precision data to test universality of CGC ←→ EIC
→ study of evolution/universality of Q_s^2 with A and x for different probes

arXiv:1101.0715

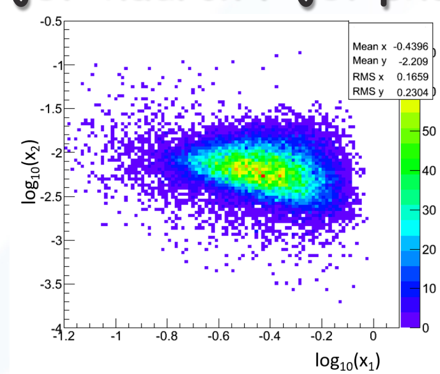
	DIS and DY	SIDIS	hadron in pA	photon-jet in pA	Dijet in DIS	Dijet in pA
$G^{(1)}$ (WW)	×	×	×	×	√	√
$G^{(2)}$ (dipole)	√	√	√	√	×	√

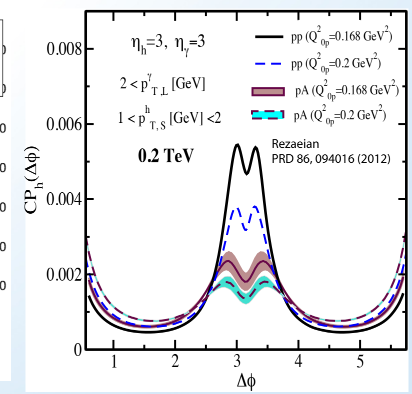
CGC prediction for R_{pA} direct photon:





❑ jet-hadron / jet photon correlations





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

STAR forward and midrapidity pp/pA unique program addressing several fundamental questions in QCD

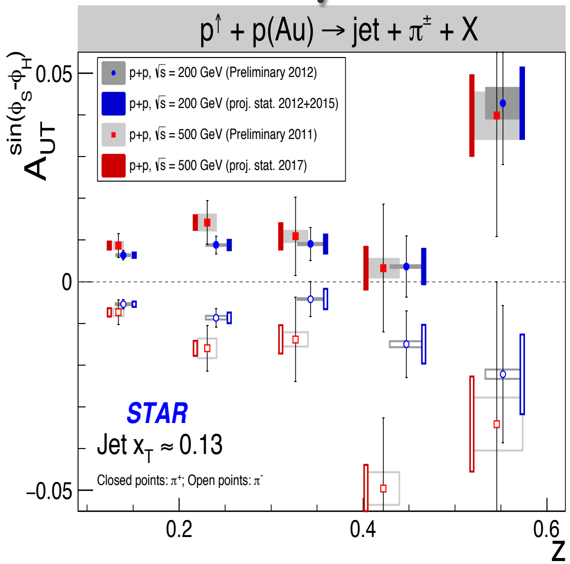
- essential to complete the mission of the RHIC physics program
- Cost effective forward upgrade: Total 5.5 M$ including contingency and manpower
- pp/pA program essential to fully realize the scientific promise of the EIC
  - inform the physics program
  - quantify experimental requirements


BACK UP

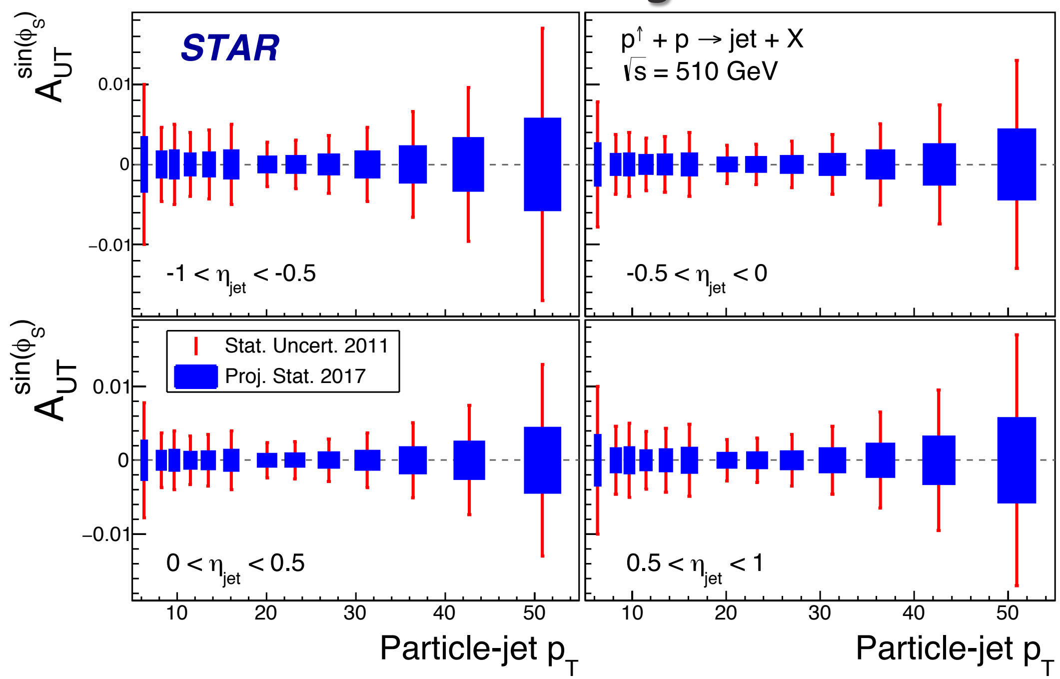
MID-RAPIDITY OBSERVABLES

At 500 GeV in 2017:

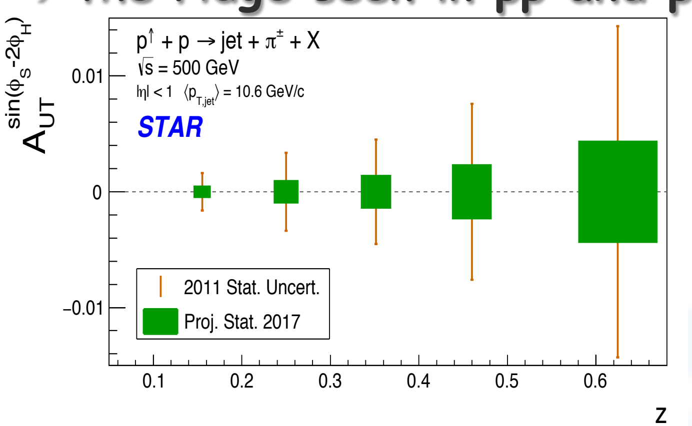
Transversity x Collins



Sivers function through TWIST-3:



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



To have high precision data at different √s

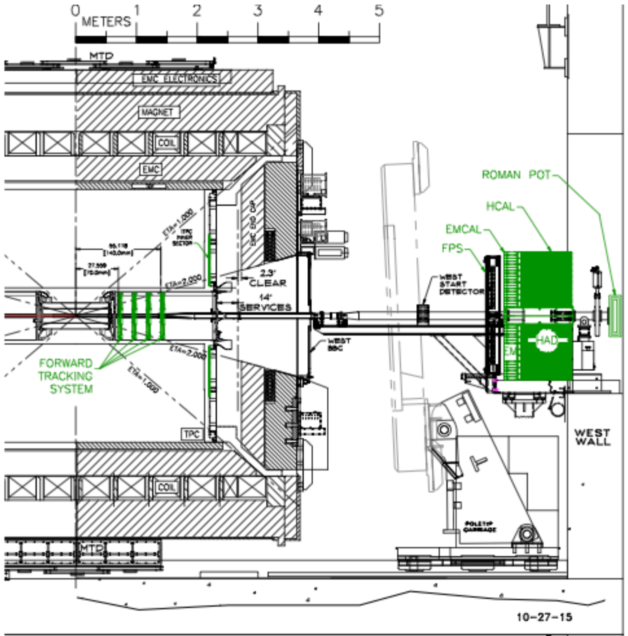
→ constrain TMD evolution

→ fixed x and Q^2 → p_T different

THE STAR FORWARD UPGRADE

Requirements from Physics:

Detector	pp and pA	AA
ECal	~10%/√E	~20%/√E
HCal	~60%/√E	---
Tracking	charge separation photon suppression	$0.2<p_T<2$ GeV/c with 20-30% $1/p_T$



Calorimeter System:

Intensive R&D work on both ECal and Hcal as part of STAR and EIC Detector R&D

→ several beam test and STAR in situ tests

→ system optimized for cost and performance

ECal:

- ❑ reuse PHENIX PbSC calorimeter
  with new readout on front instead of W/ScFi SPACAL
  significant cost reduction ☺
  uncompensated calorimeter system ☹

HCal:

- ❑ sandwich iron-scintillator plate sampling Calo

Same readout for both calorimeters → cost

Cost:

ECal: 0.57 M$

Hcal: 1.53 M$

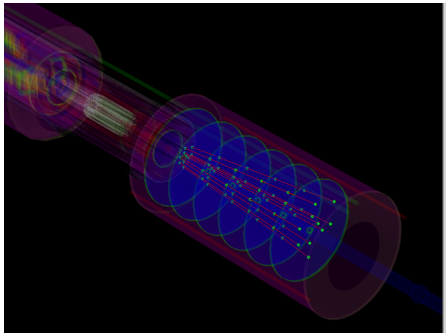
Preshower: 0.06 M$

Total: 2.2 M$

based on extensive experience from prototypes

contingency and manpower included

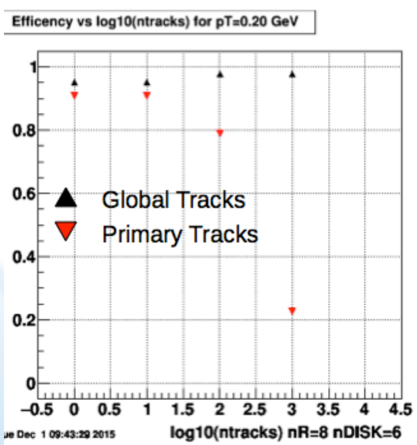
Silicon mini-Strip Detectors only

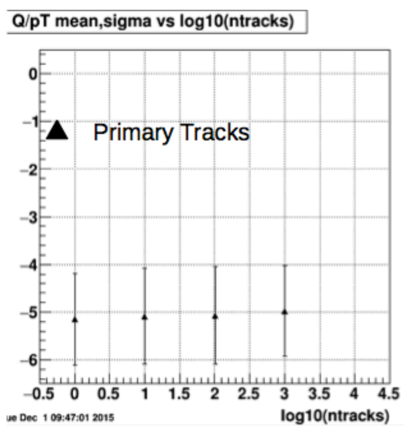


6 disks
12 wedges, each with 128 strips in φ at fixed radius and 8 strips in the radial direction at a fixed φ
60 – 180 cm from IP

Momentum resolution: 20-30%
for $0.2 < p_T < 2$ GeV/c
track finding efficiency: 95%@100 tr/ev

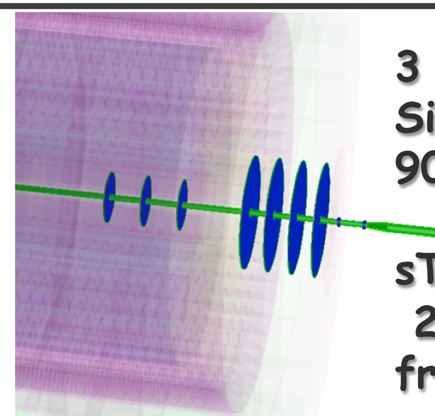
6 disk 8 R 128*12 PHI





Cost: 4.1 M$

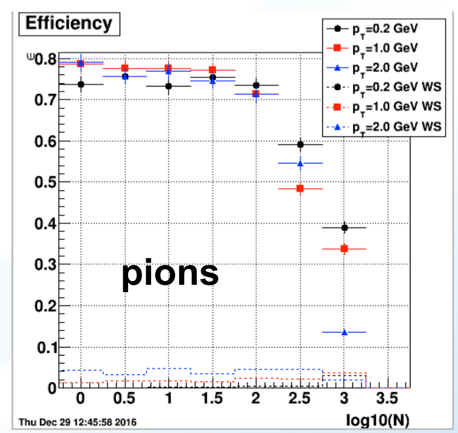
Si + Small-strip Thin Gap Chambers

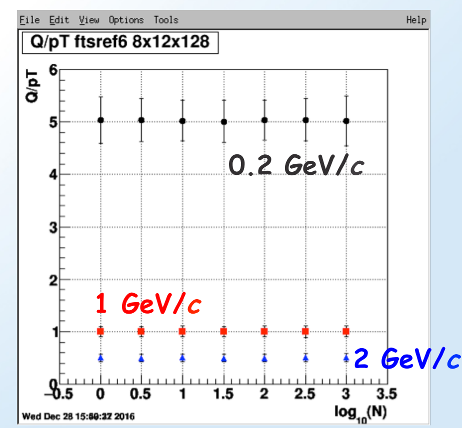


3 Si disks + 4 sTGC
Si- disks:
90, 140, 187 cm from IP

sTGC:
270, 300, 330, 360 cm from IP (outside Magnet)

Momentum resolution: 20-30%
for $0.2 < p_T < 2$ GeV/c
track finding efficiency: 80%@100 tr/ev





Cost: 3.3 M$

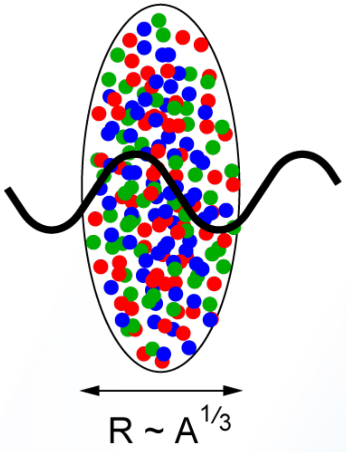
SUMMARY OF FORWARD pp & pA MEASUREMENTS

	Year	$\sqrt{s}$ (GeV)	Delivered Luminosity	Scientific Goals	Observable	Required Upgrade
Scheduled RHIC running	2023	$p^{\uparrow}p$ @ 200	300 pb^{-1} 8 weeks	Subprocess driving the large A_N at high x_F and η	A_N for charged hadrons and flavor enhanced jets	Forward instrum. ECal+HCal+Tracking
	2023	$p^{\uparrow}$Au @ 200	1.8 pb^{-1} 8 weeks	What is the nature of the initial state and hadronization in nuclear collisions Clear signatures for Saturation	R_{pAu} direct photons and DY Dihadrons, γ-jet, h-jet, diffraction	Forward instrum. ECal+Hcal+Tracking
	2023	$p^{\uparrow}$Al @ 200	12.6 pb^{-1} 8 weeks	A-dependence of nPDF, A-dependence for Saturation	R_{pAl}: direct photons and DY Dihadrons, γ-jet, h-jet, diffraction	Forward instrum. ECal+HCal+Tracking
Potential future running	2021	$p^{\uparrow}p$ @ 510	1.1 fb^{-1} 10 weeks	TMDs at low and high x	A_{UT} for Collins observables, i.e. hadron in jet modulations at $\eta > 1$	Forward instrum. ECal+HCal+Tracking
	2021	$\vec{p}\vec{p}$@ 510	1.1 fb^{-1} 10 weeks	$\Delta g(x)$ at small x	A_{LL} for jets, di-jets, h/γ-jets at $\eta > 1$	Forward instrum. ECal+HCal

STUDYING NON-LINEAR EFFECTS

Scattering of electrons off nuclei:

- Probes interact over distances $L \sim (2m_N x)^{-1}$
- For $L > 2\,R_A \sim A^{1/3}$ probe cannot distinguish between nucleons in front or back of nucleon
- Probe interacts *coherently* with all nucleons



$$Q_s^2 \sim \frac{\alpha_s\, xG(x,Q_s^2)}{\pi R_A^2} \qquad \text{HERA}: \; xG \sim \frac{1}{x^{0.3}} \qquad \text{A dependence}: \; xG_A \sim A$$

Nuclear "Oomph" Factor
Pocket Formula:

$$\boxed{(Q_s^A)^2 \approx c Q_0^2 \left(\frac{A}{x}\right)^{1/3}}$$

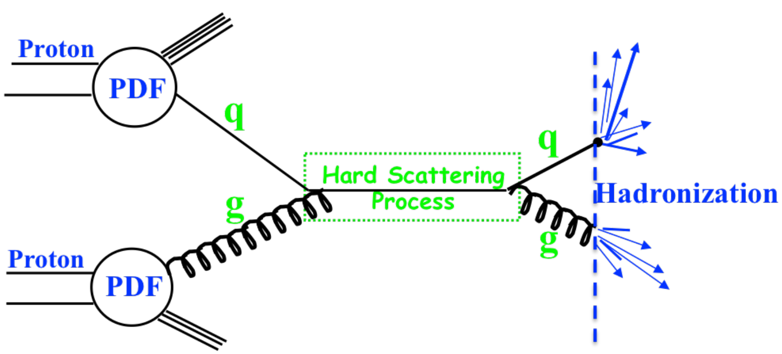
Enhancement of Q_S with A $\Rightarrow$ non-linear QCD regime reached at significantly lower energy in A than in proton

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

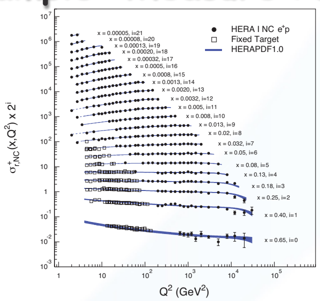


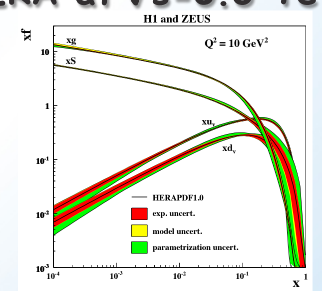
(un)polarized cross section ~
PDF ⊗ hard-scattering ⊗ Hadronization

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

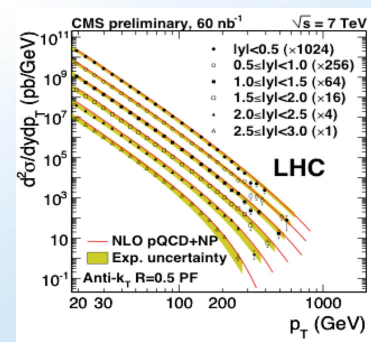
Universality

Example: Measure PDFs at HERA at √s=0.3 TeV:

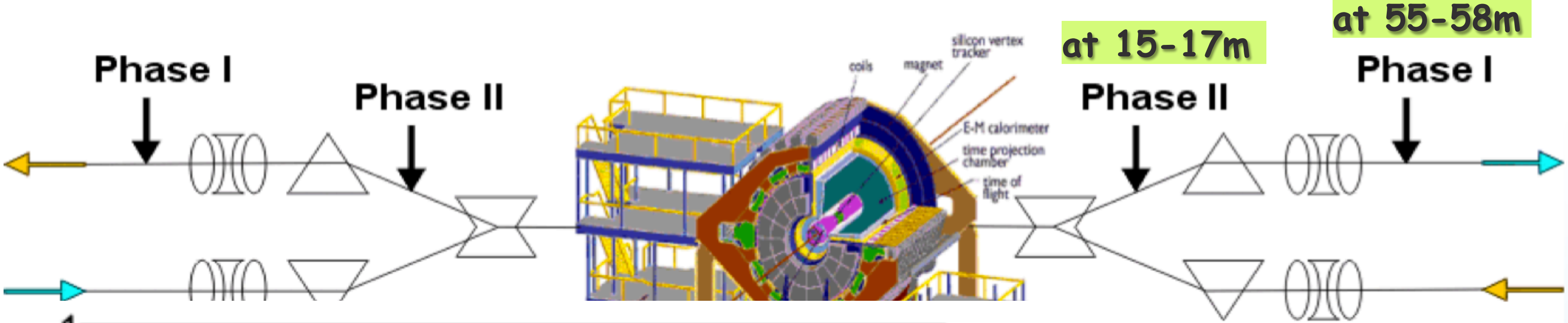


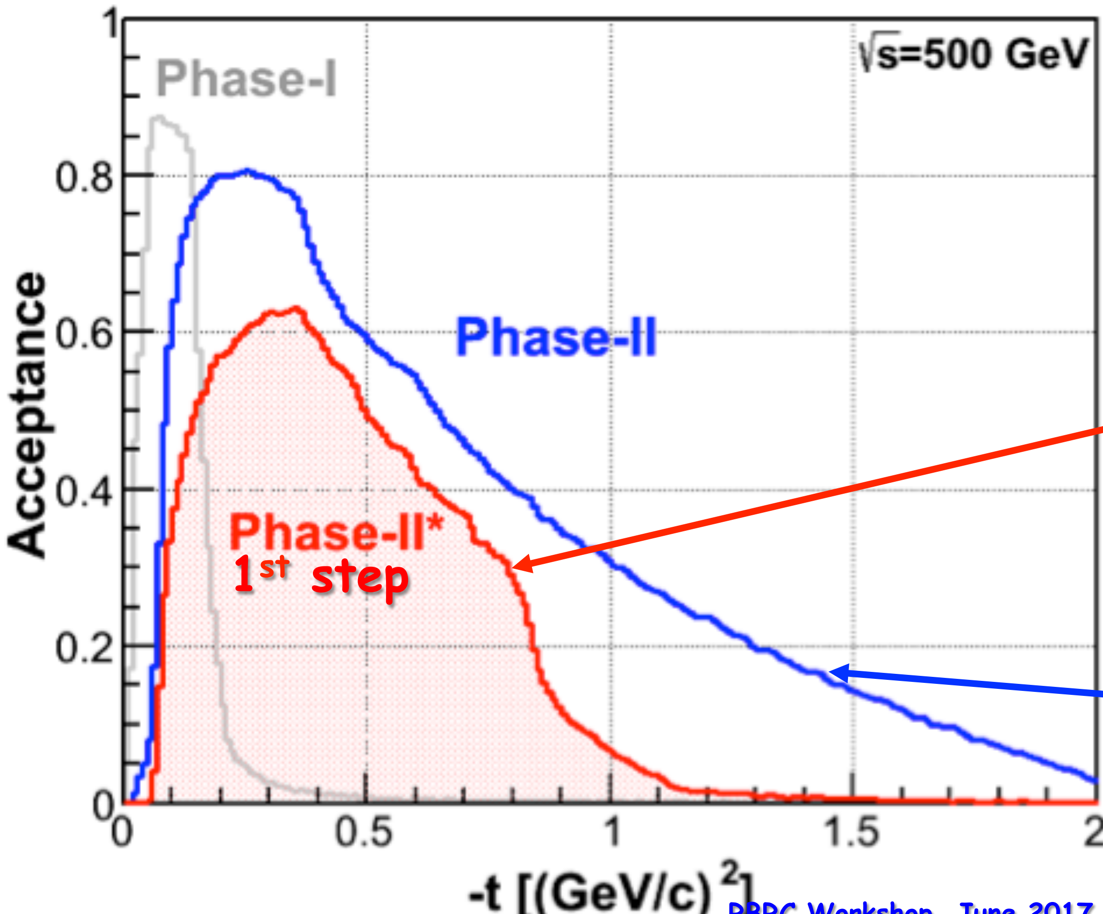


Predict pp and $\mathbf{p\bar{p}}$ measurements at √s=0.2, 1.96 & 7 TeV



FORWARD PROTON TAGGING UPGRADE

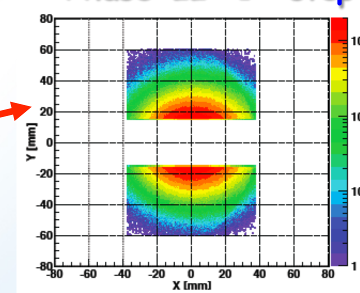




run pp2pp@STAR with

ny more

Phase-II: 1st step



n x-direction

onstraints

full Phase-II