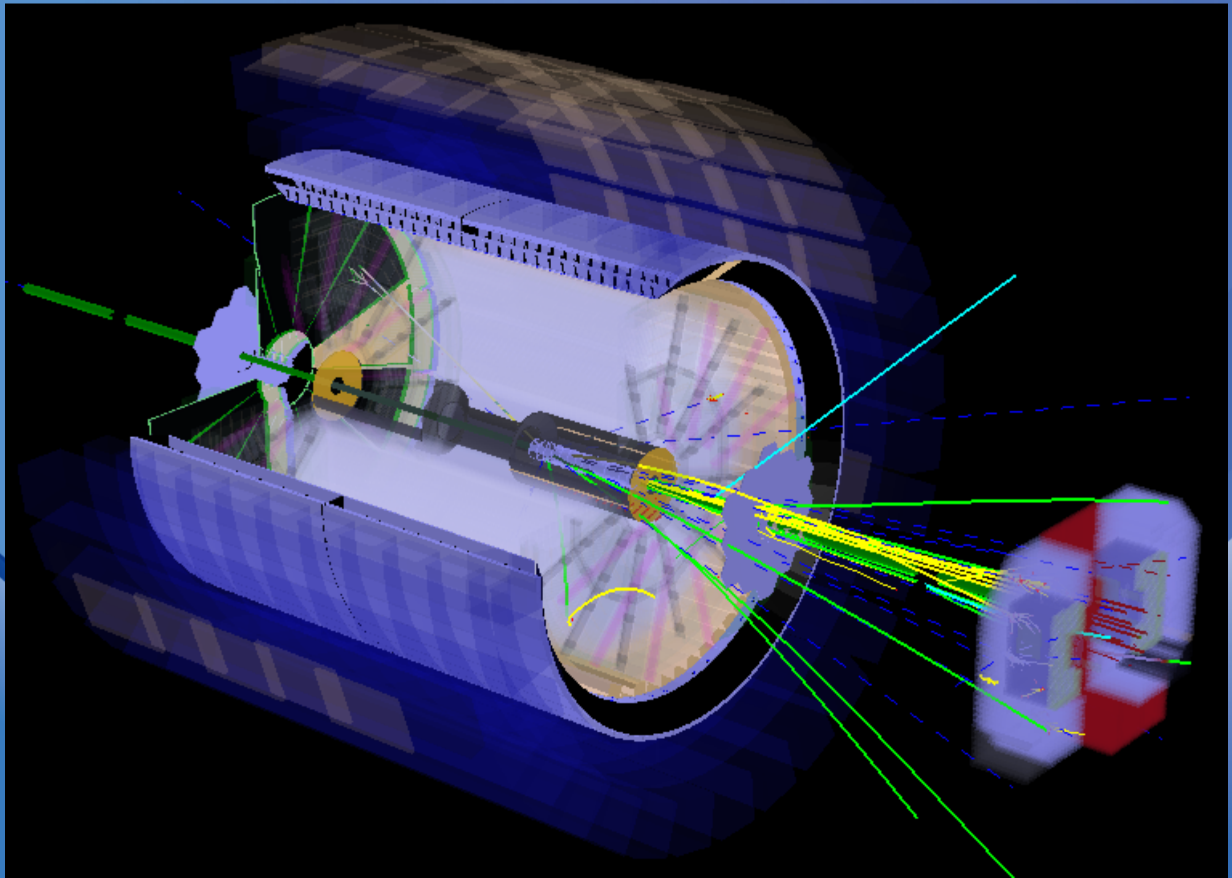
pp, pA & AA PHYSICS WITH THE STAR FORWARD UPGRADE



E.C. Aschenauer

STAR

BROOKHAVEN NATIONAL LABORATORY

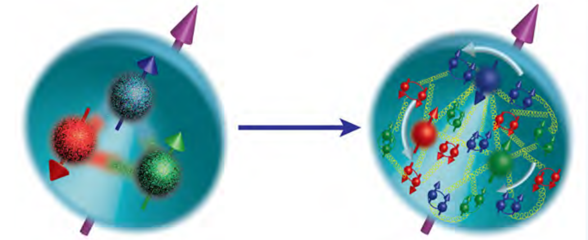
a passion for discovery

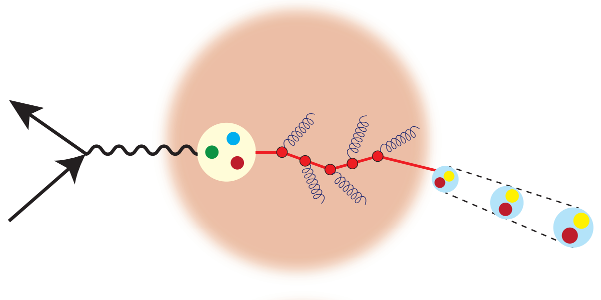
U.S. DEPARTMENT OF ENERGY | Office of Science

THE OBJECTIVES OF THE STAR FORWARD UPGRADE

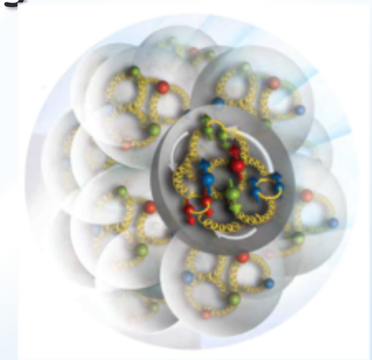
- unique measurements to answer the hot questions in cold QCD

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?



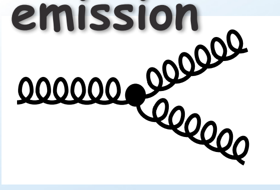


How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?
How do the confined hadronic states emerge from these quarks and gluons?
How do the quark-gluon interactions create nuclear binding?



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



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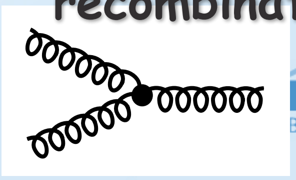
gluon recombination



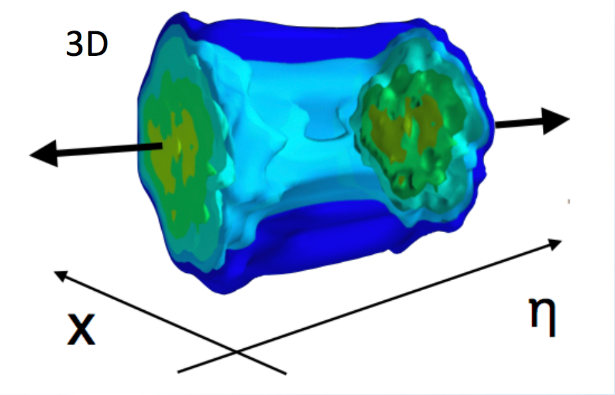
THE OBJECTIVES OF THE STAR FORWARD UPGRADE

- pp and pA:

  unique measurements to answer the hot questions in cold QCD
- AA:

  unique measurements to answer the cold questions in hot QCD

  What is the longitudinal structure of initial condition



- Strengthen and Enhance the EIC physics program
  - lay the groundwork for the EIC, both scientifically and by refining the experimental requirements
  - Test EIC detector technologies under real conditions, i.e SiPMs

2+1 DIMENSIONAL IMAGING OF QUARKS & GLUONS

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

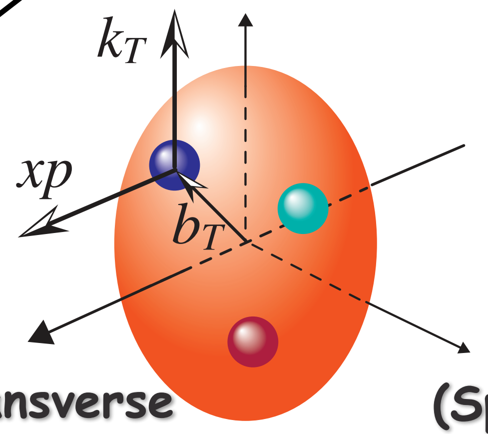
QCD genetic map

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

Momentum space

Coordinate space

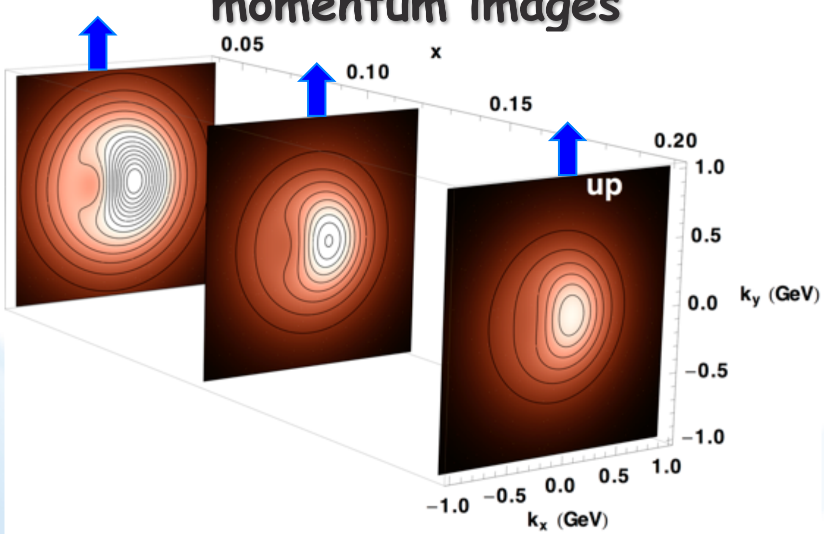
$f(x, k_T)$
TMDs

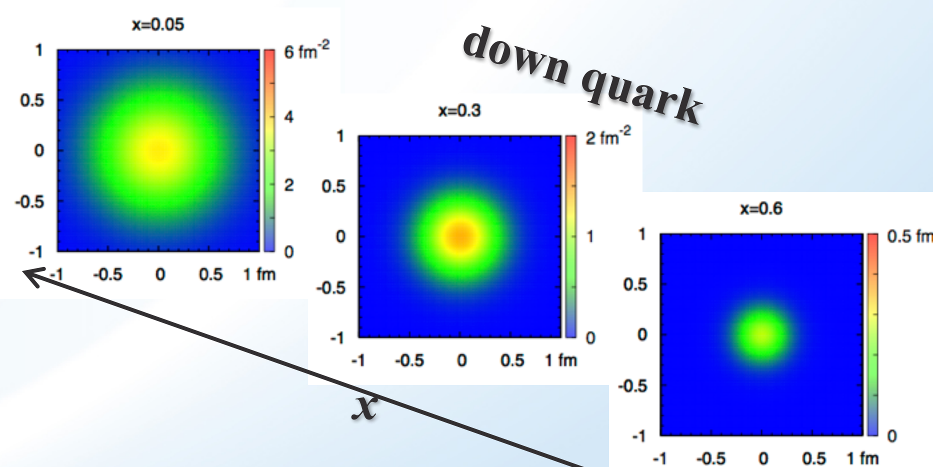


$f(x, b_T)$
GPDs

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

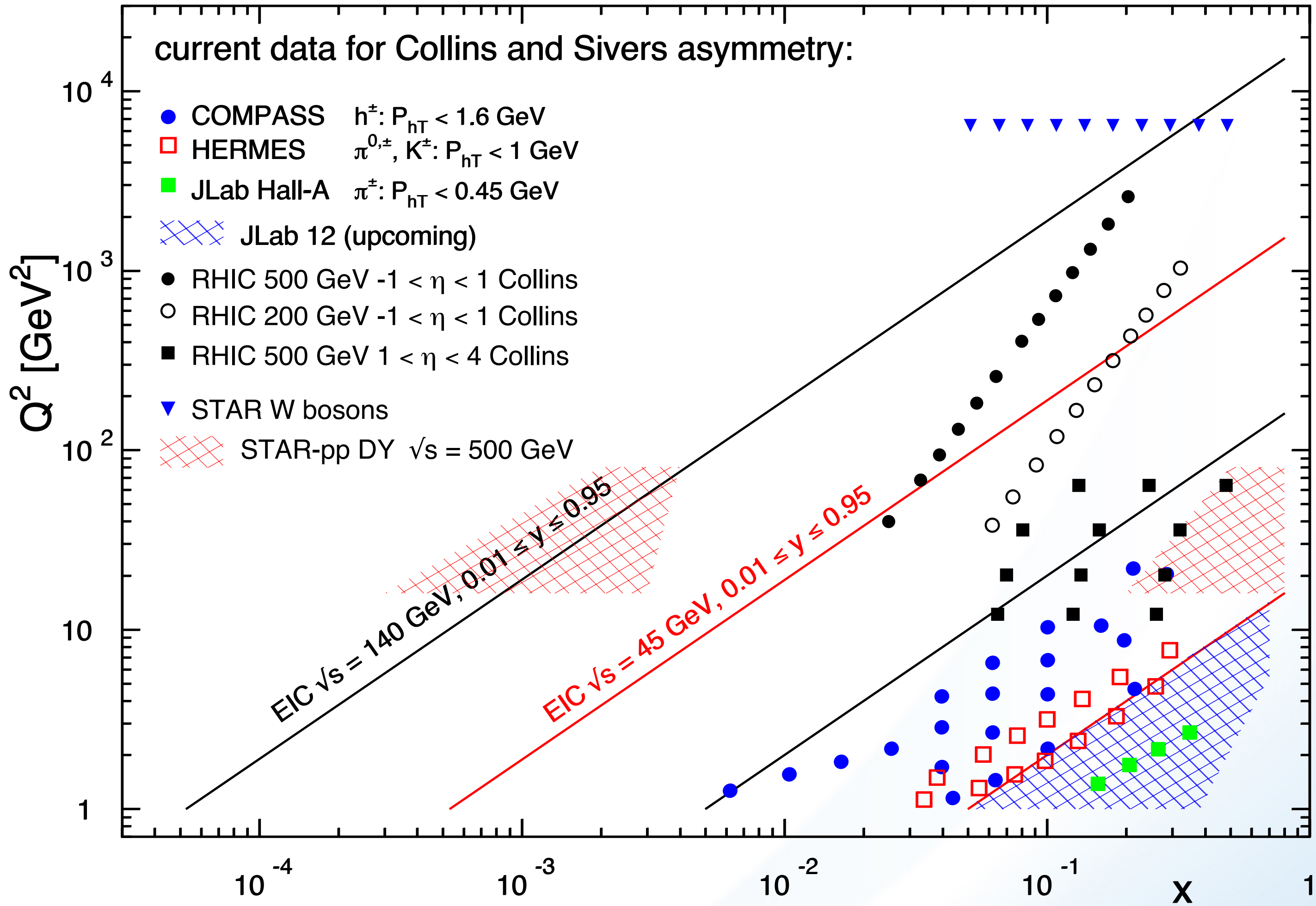
(Spin-dependent) 2+1D spatial images from exclusive scattering





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

TMDs AT STAR



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

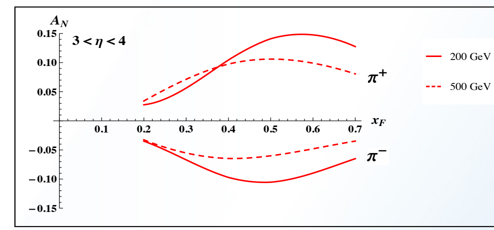
TMDs AT STAR

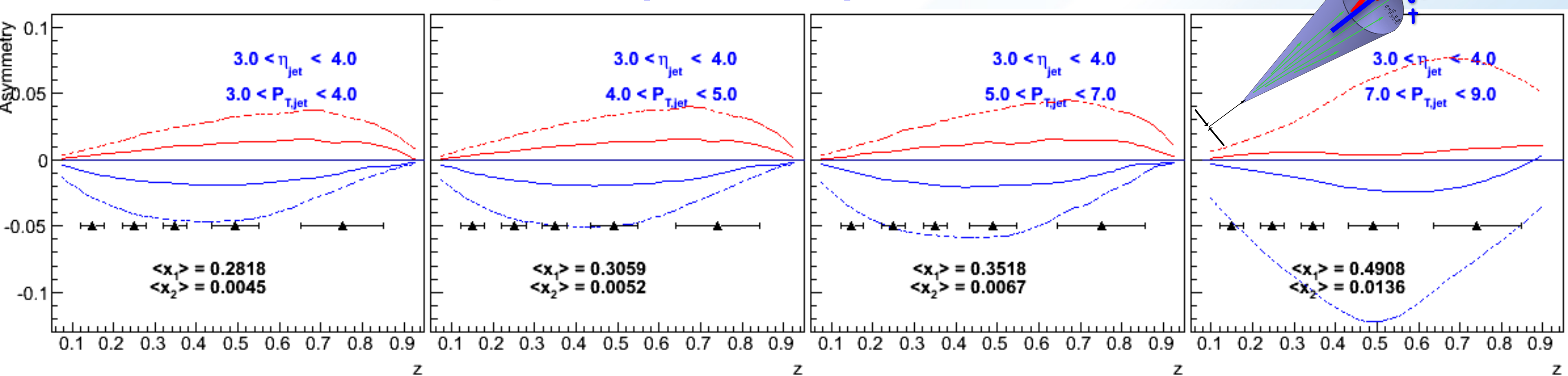
Unique Opportunities:

- 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 a optimal TMD program at EIC

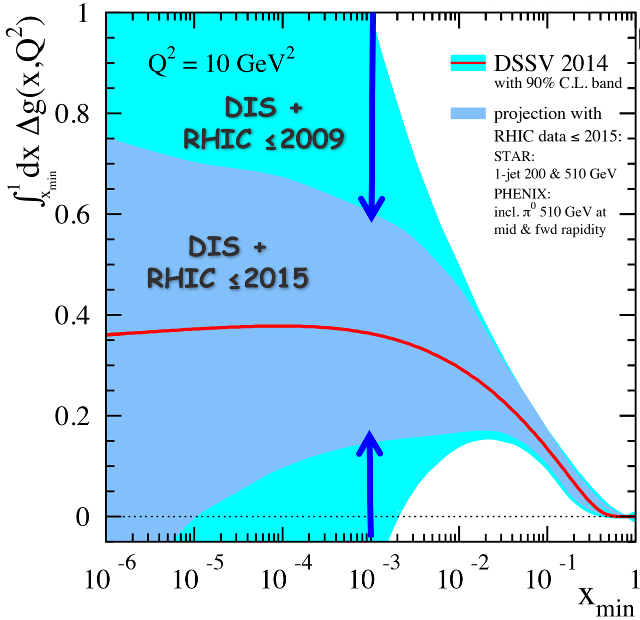
Goals:

- Increase statistics for A_N DY
  → TMD evolution world best constrain ← → $A_N(W^{+/-}\ Z^0)$
  → 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 $\delta q^a = \int_0^1 \left[\delta q^a(x) - \delta \bar{q}^a(x)\right] dx$





HOW POLARIZED ARE THE GLUONS?

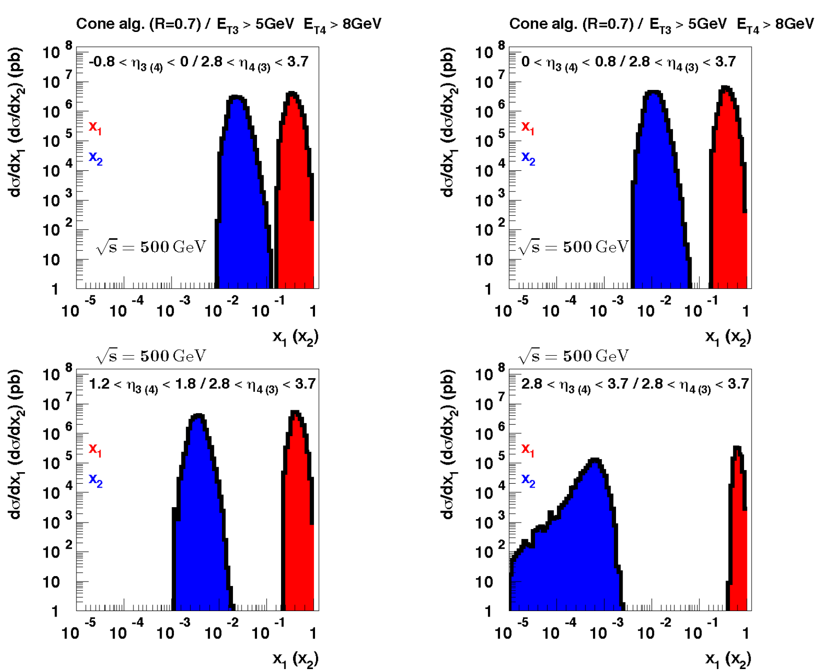


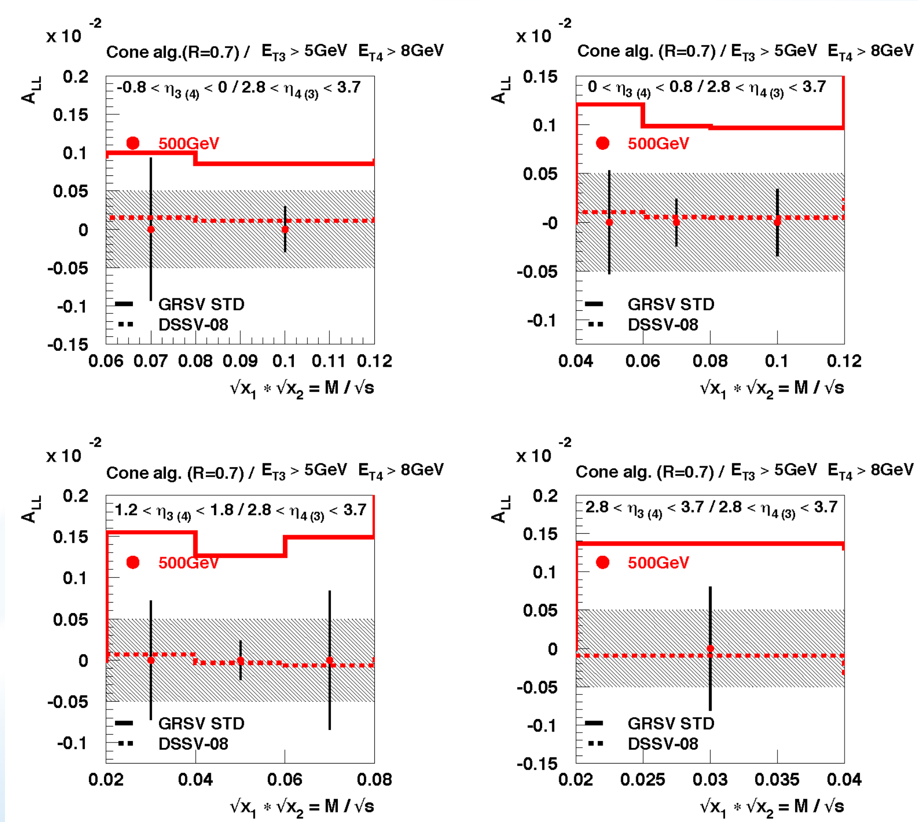
Data till 2009

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

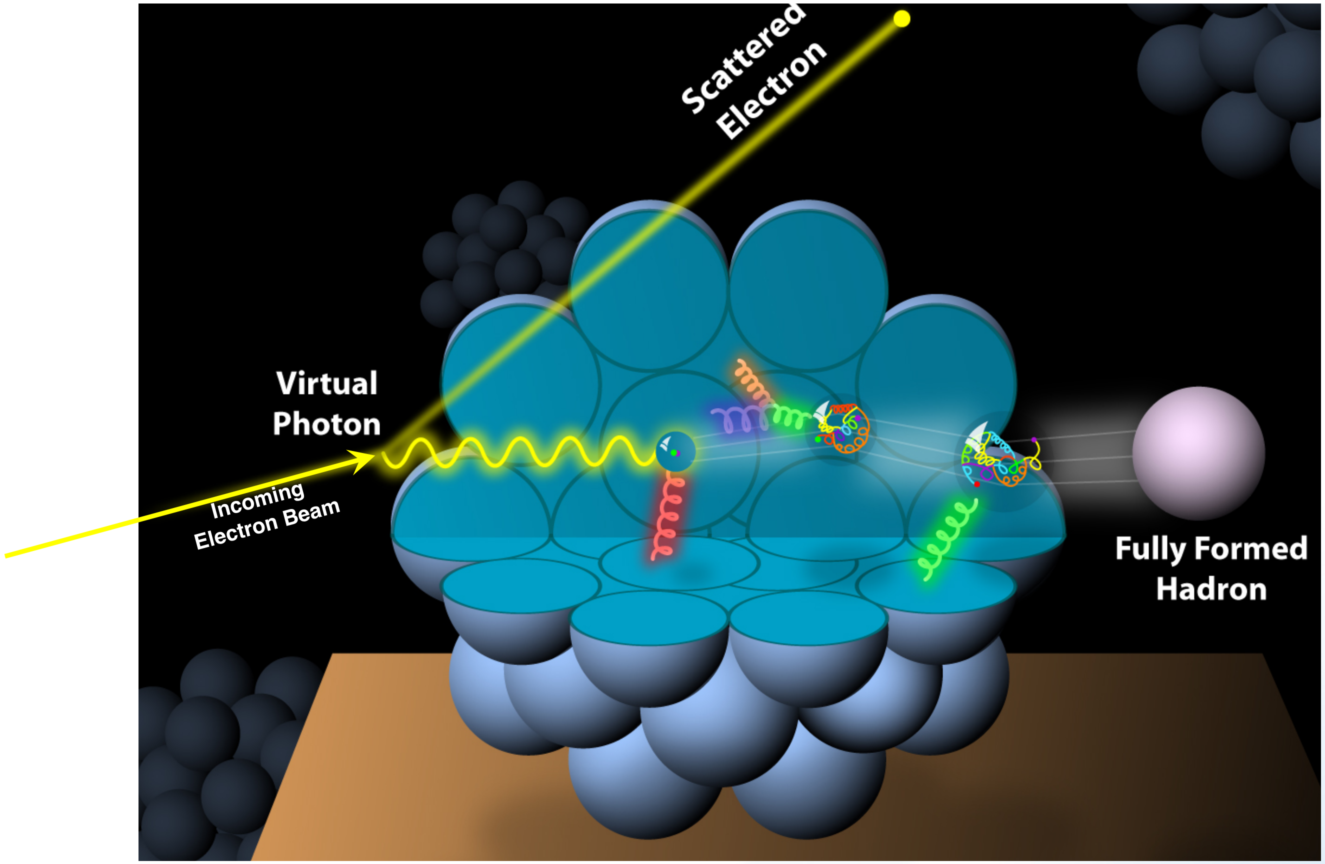
STAR and PHENIX data till 2015 reduce uncertainties at $x \sim 10^{-3}$ by **factor 2**

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





WHAT ABOUT NUCLEI?

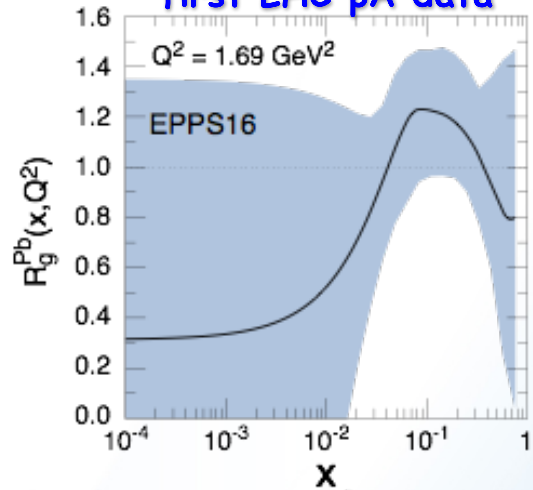


HOW DOES THE INITIAL STATE IN AA LOOK?

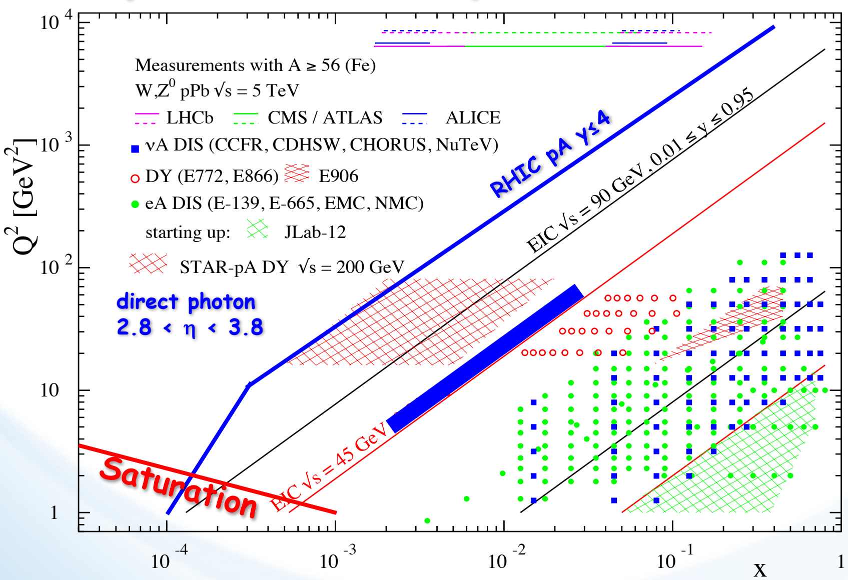
3 conundrums of the initial state:

- 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.

Current knowledge including first LHC pA data



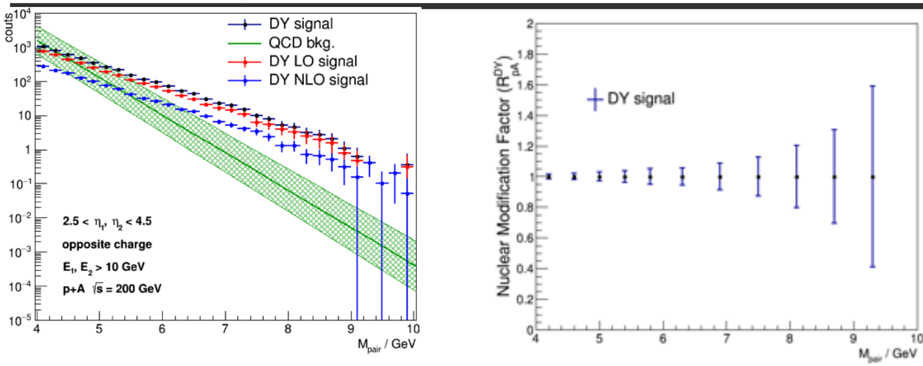
pA@RHIC: unique kinematics



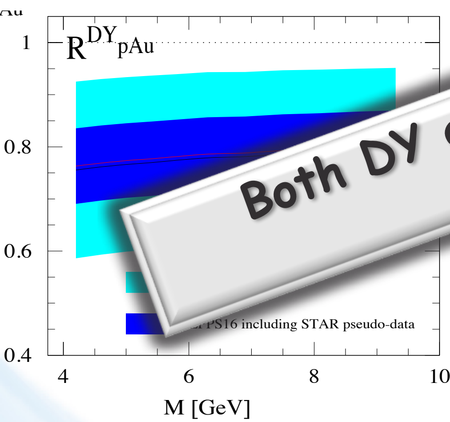
- can measure nPDF in a x-Q^2 region where nuclear effects are large
  - $Q^2 > Q_s^2$ over a wide range in x
- Observables free of final state effects
  - Gluons: R_{pA} for direct photons
  - Sea-quarks: R_{pA} for DY
- Scan A-dependence prediction by saturation models
- can access saturation regime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

HOW DOES THE INITIAL STATE IN AA LOOK?

pA: DY@2.5 < η < 4.5

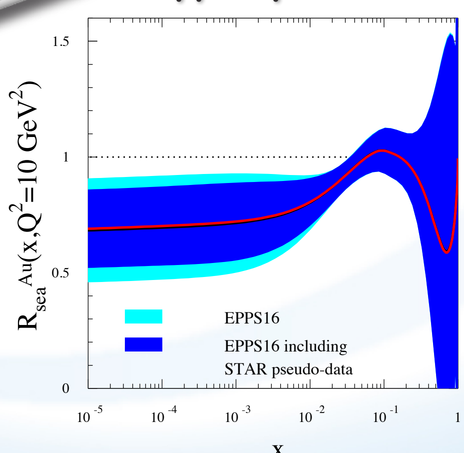


Impact on nPDFs: → sea quarks

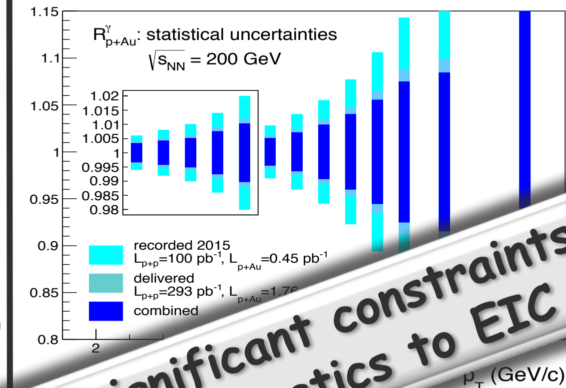


DY:

2023 pp & pA



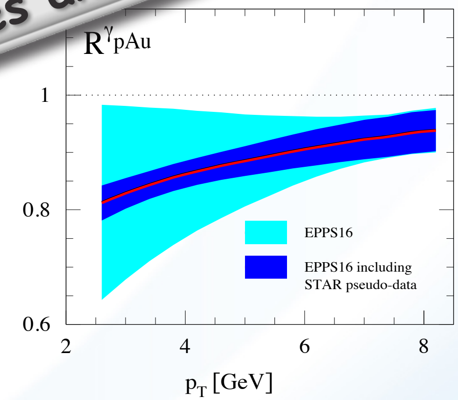
pA: Direct Photon@2.5 < η < 4.5

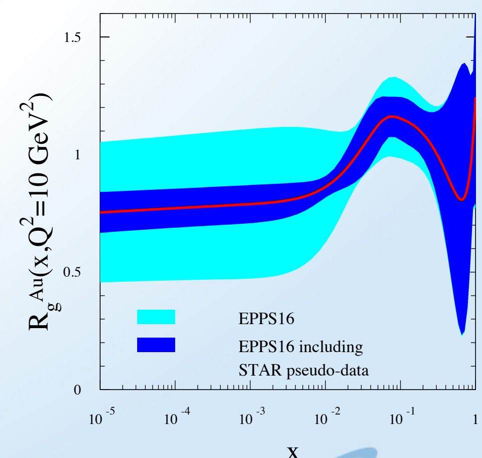


Uncertainties:
2015 + 2023

> 5 GeV²

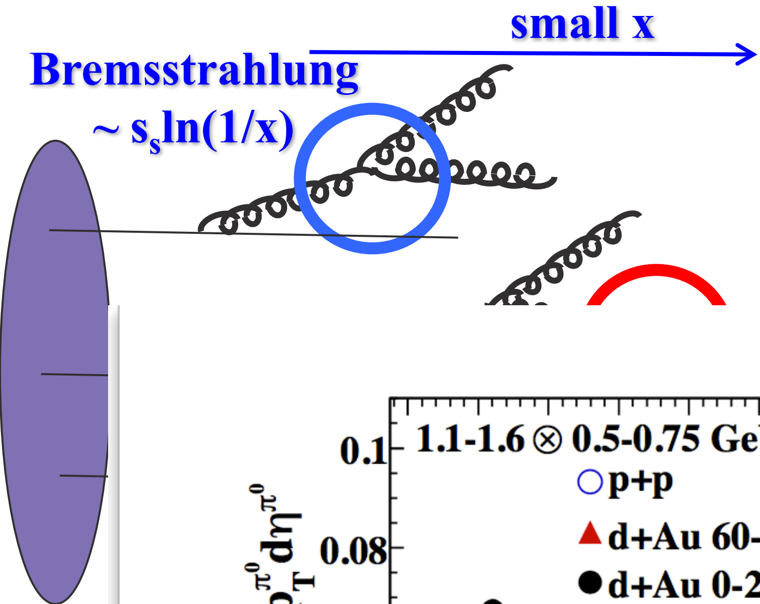
nPDFs: → gluons

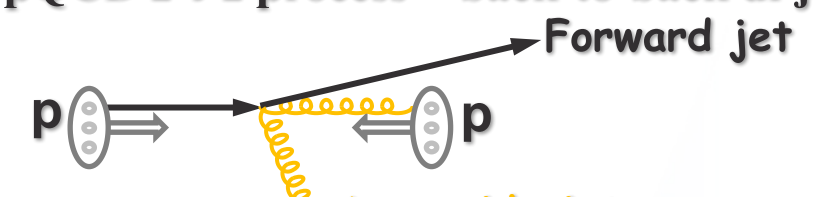


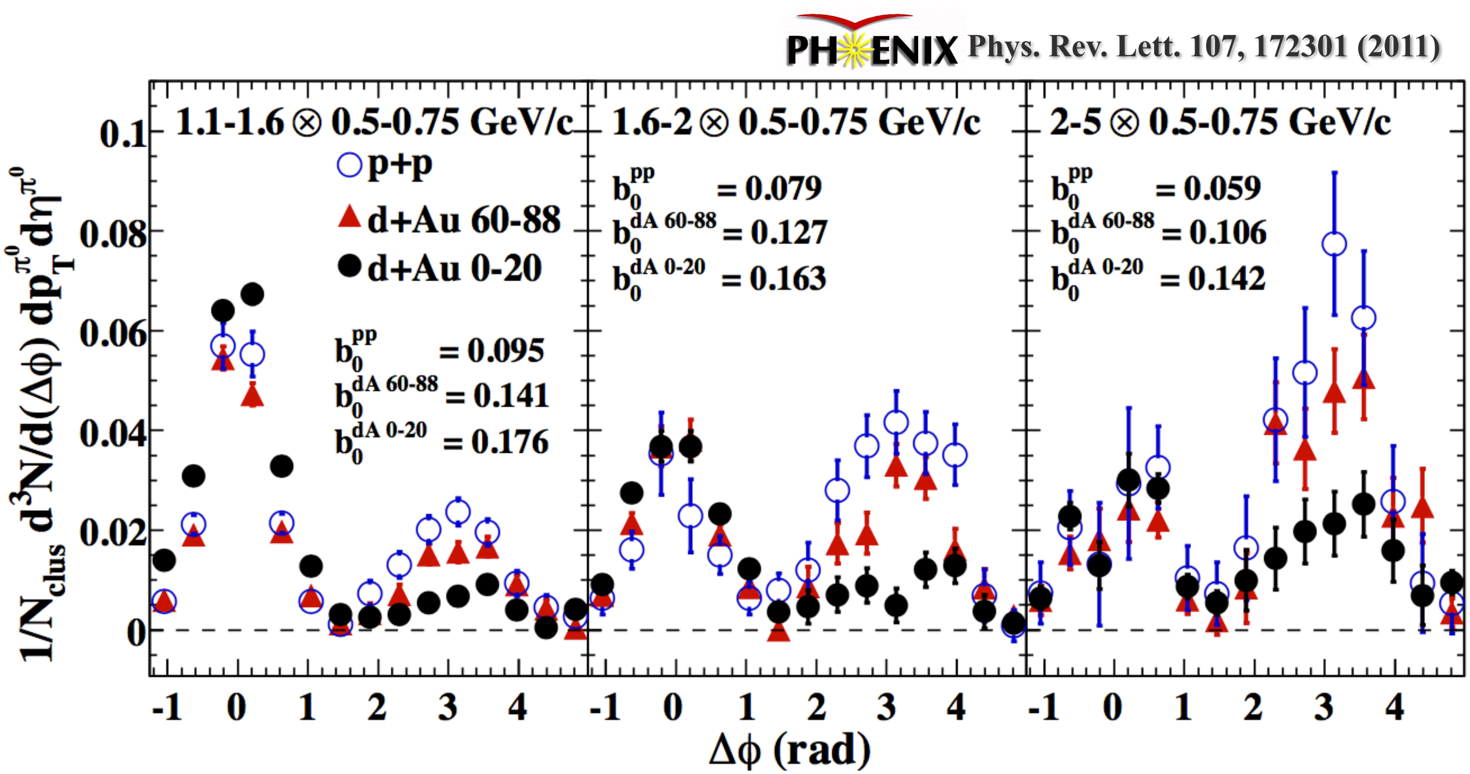


Both DY and direct photon R_{pA} give significant constraints on nPDF alternative observables and kinematics to EIC

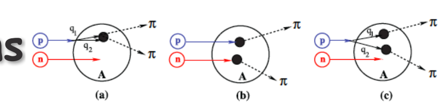
KEY OBSERVABLE FOR SATURATION IN pA





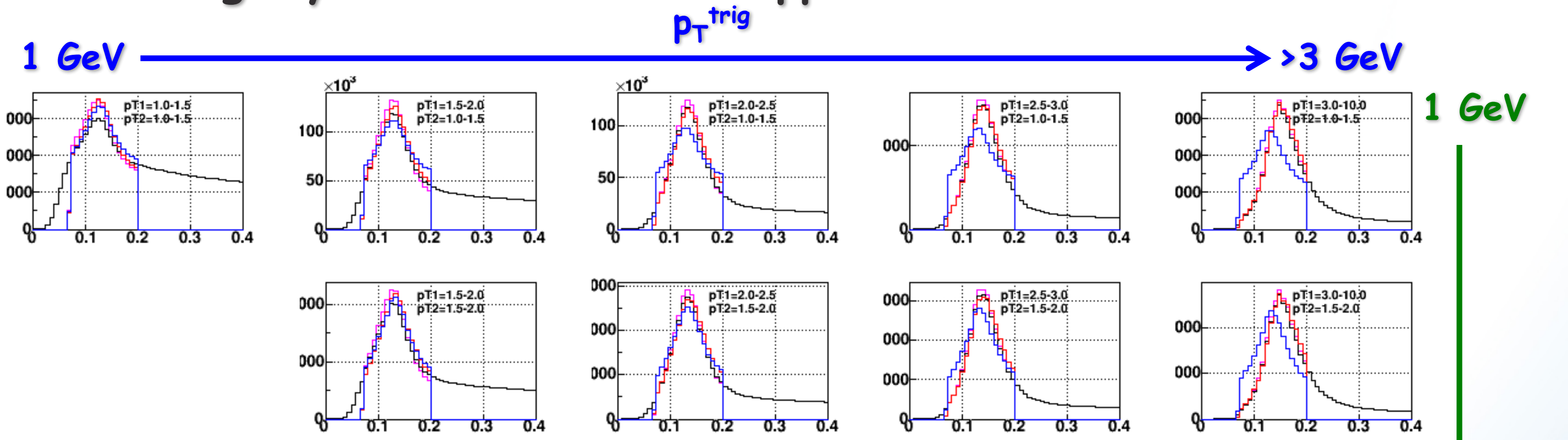


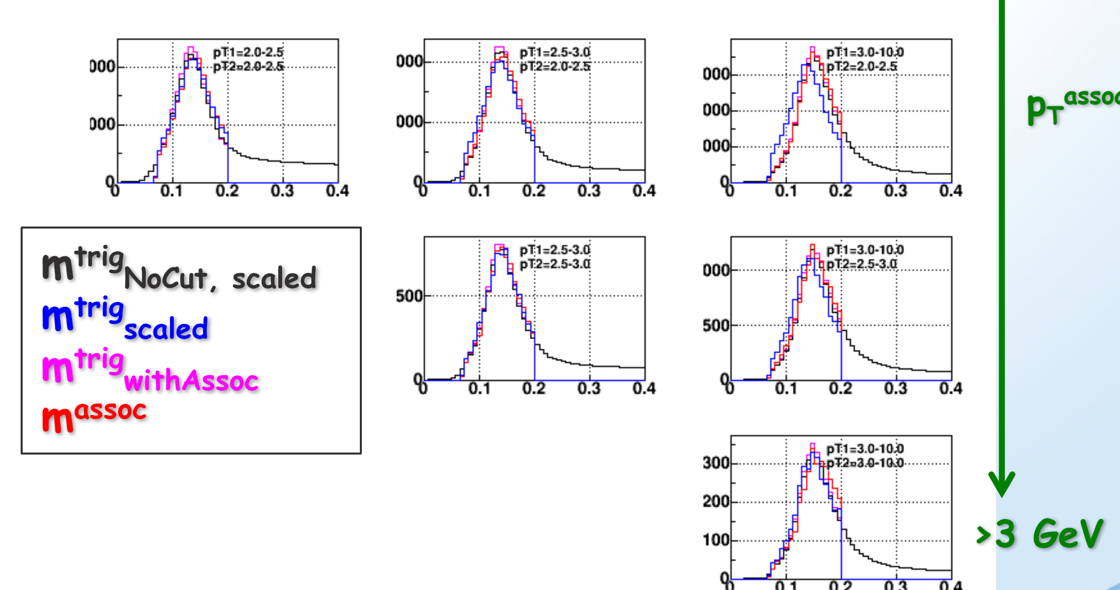
dA: alternative explanation through double interactions

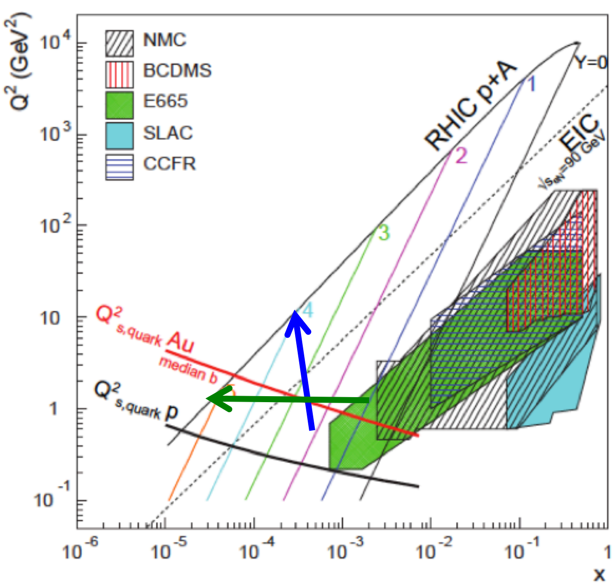


KEY OBSERVABLE FOR SATURATION IN pA

- 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







SATURATION WITH THE FORWARD UPGRADE

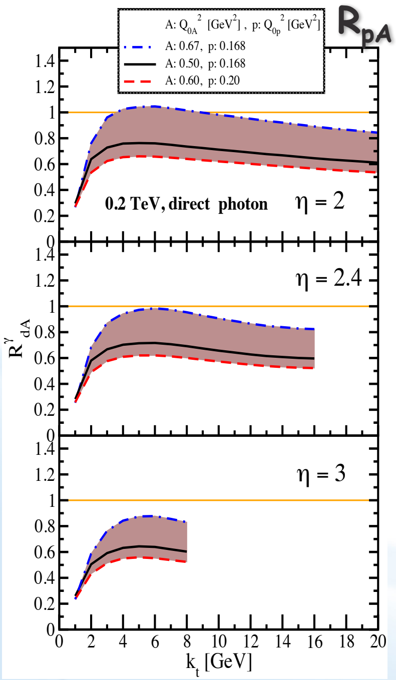
Expand the number of observables:

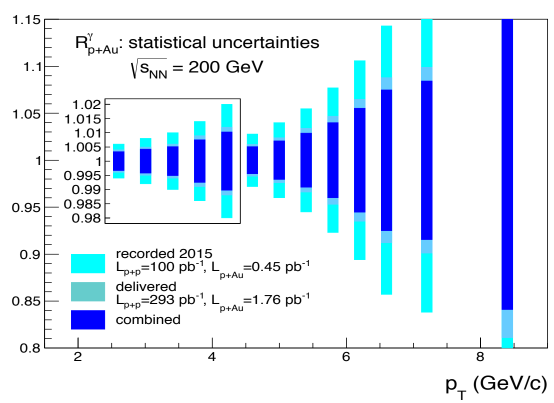
→ rigorous test of theory predictions
→ get a handle on the different gluon distributions
→ provide variety of high precision data to test universality of CGC ←→ EIC
→ study of evolution/universality of Q_s^2 with A and x for different probes

arXiv:1101.0715

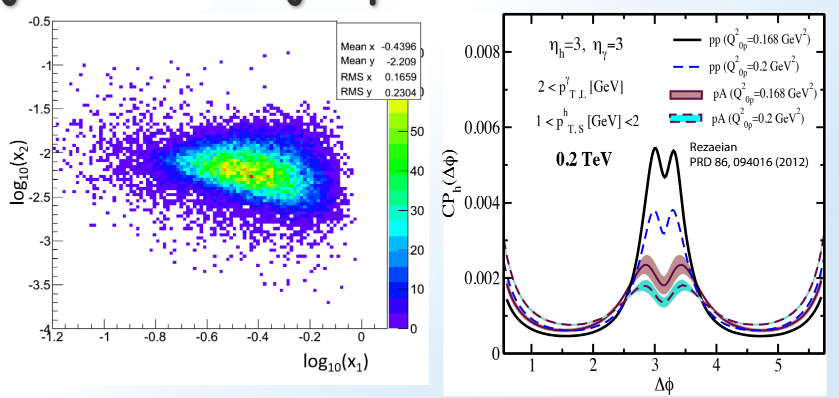
	DIS and DY	SIDIS	hadron in pA	photon-jet in pA	Dijet in DIS	Dijet in pA
$G^{(1)}$ (WW)	×	×	×	×	√	√
$G^{(2)}$ (dipole)	√	√	√	√	×	√

CGC prediction for R_{pA} direct photon:





❑ jet-hadron / jet photon correlations



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

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

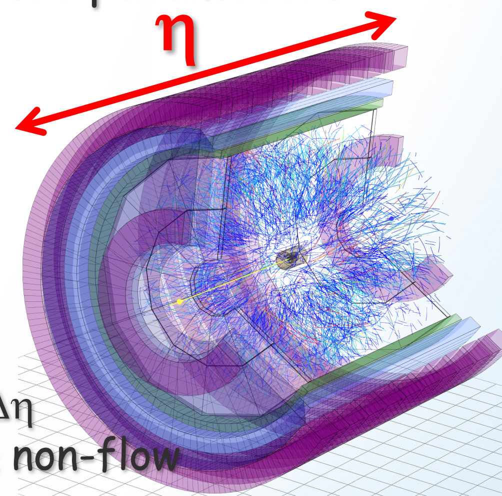
FORWARD PHYSICS IN A+A COLLISIONS

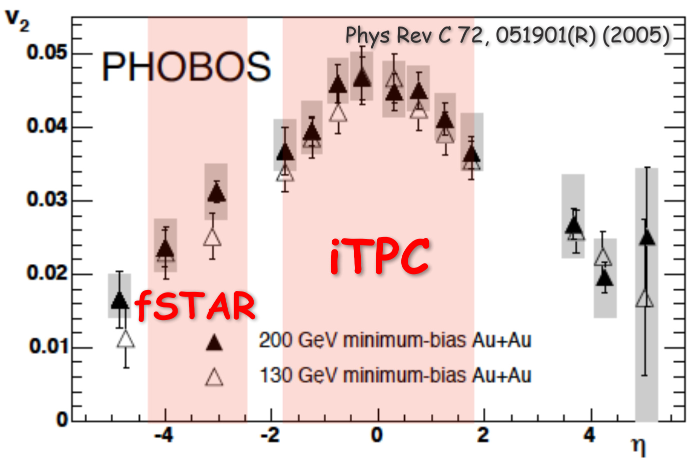
Goal : Measurements of global observables in heavy ion collisions over wide range of rapidity at RHIC

- Constraining longitudinal structure of the initial stages of HICs
- Constraining the temperature dependence profile of transport parameters

Till today:

No RHIC data for higher order flow harmonics (v_3, v_4, v_5) & rapidity density correlations/fluctuations $\left\langle \frac{dN}{dY_1}\frac{dN}{dY_2} \right\rangle$

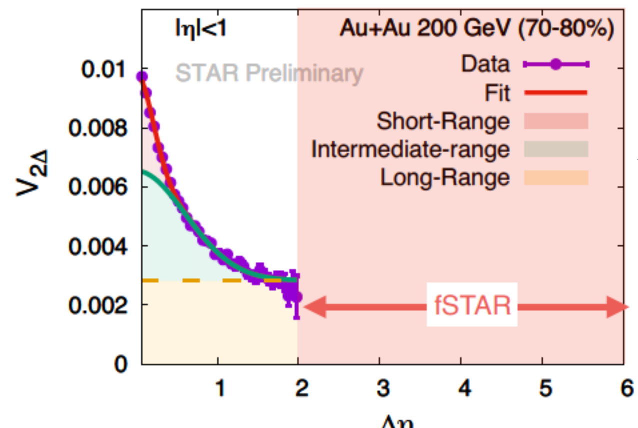




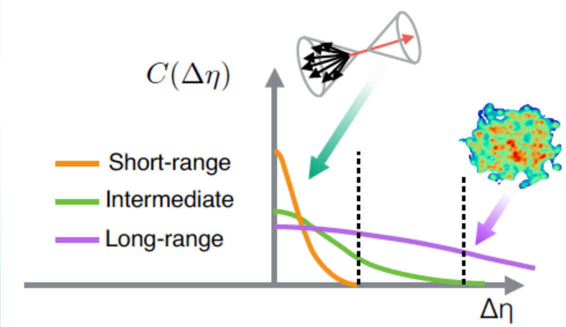
Why do we need wider window in rapidity?

- Flow like correlations are early time long-range → large $\Delta\eta$
- Background comes from Jets & non-flow → small $\Delta\eta$

Precise extraction of flow (azimuthal correlations) requires measurements over wide window of rapidity



$$V_{2\Delta} = \left\langle \cos\left(2\left(\phi_1(\eta_1) - \phi_2(\eta_2)\right)\right)\right\rangle$$

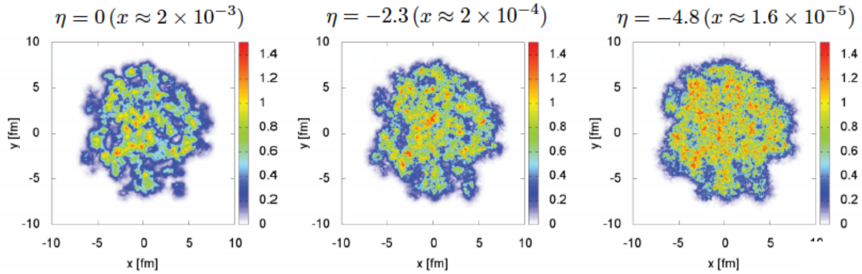


FORWARD PHYSICS IN A+A COLLISIONS

Long-range two particle correlations are of great interest → ridge in small systems

Rapidity ←→ x

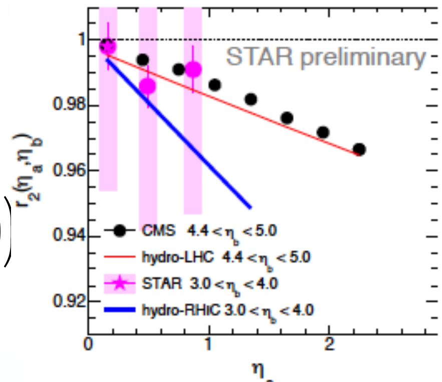
Schenke, Schlichting 1605.07158



Rapidity evolutions → predictions of non-linear regime of High energy QCD effective theory (CGC)
→ LHC data provide constrains for BK, JIMWLK, RHIC data will provide test

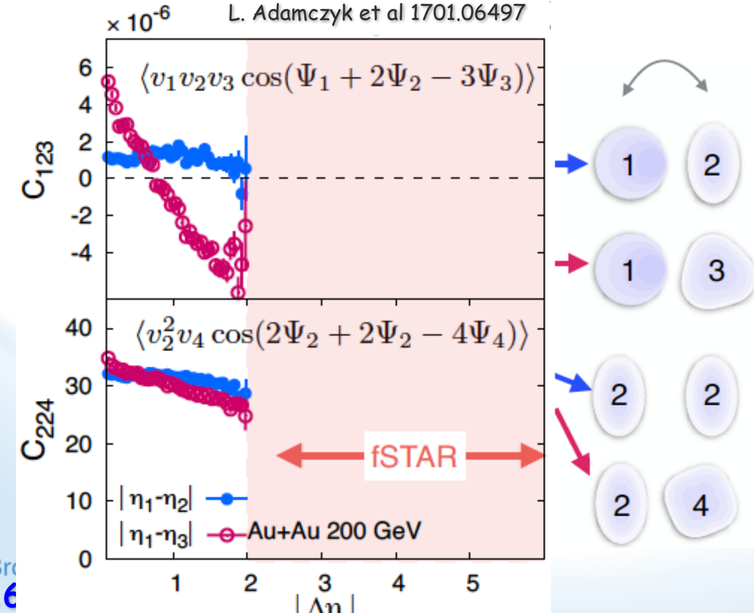
Observables: $r_n(\eta^a,\eta^b) \equiv \frac{V_{n\Delta}(-\eta^a,\eta^b)}{V_{n\Delta}(\eta^a,\eta^b)}$

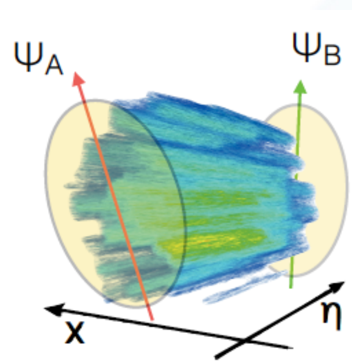
$$V_{n\Delta} = \left\langle \cos\left(n\left(\phi_1(\eta_1) - \phi_2(\eta_2)\right)\right)\right\rangle$$



Stronger De-correlation predicted at RHIC than LHC

L. Adamczyk et al 1701.06497





Measurement from STAR with existing detectors :
- Hint of longitudinal de-correlations
- Wider Δη can probe this in more details

SUMMARY OF FORWARD AA MEASUREMENTS

Physics Measurements		Longitudinal de-correlation $C_n(\Delta\eta)$ $r_n(\eta_a,\eta_b)$	$\eta/s(T)$, $\zeta/s(T)$	Mixed flow Harmonics $C_{m,n,m+n}$	Ridge	Event Shape and Jet-studies
Detectors	**Acceptance**					
Forward Calorimeter **(FCS)**	$-2.5 > \eta > -4.2$ E_T (photons, hadrons)	One of these detectors necessary		One of these detectors necessary	Good to have	One of these detectors needed
Forward Tracking System **(FTS)**	$-2.5 > \eta > -4.2$ (charged particles)		Important		Important	

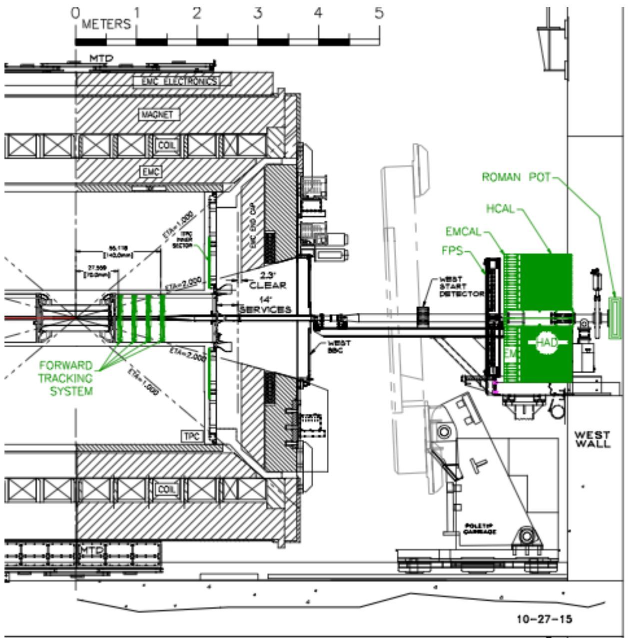
forward STAR upgrade unique opportunity to:

study the structure of the initial state that leads to breaking of boost invariance in heavy ion collisions and to explore of the transport properties of the hot and dense matter formed in heavy ion collisions near the region of perfect fluidity.

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

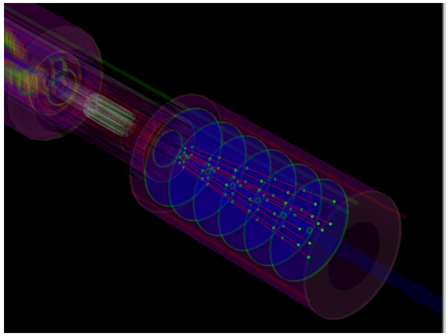
Cost:

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

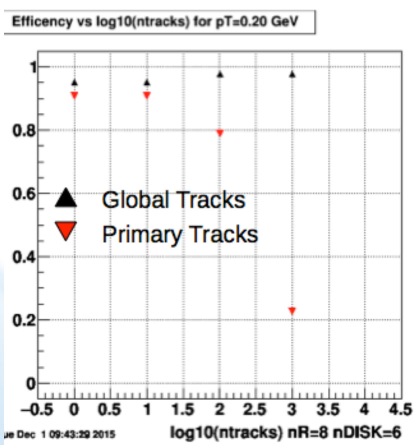
Silicon mini-Strip Detectors only

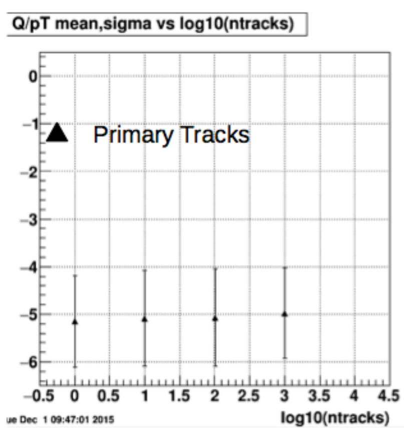


6 disks
12 wedges, each with 128 strips in φ at fixed radius and 8 strips in the radial direction at a fixed φ
60 – 180 cm from IP

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

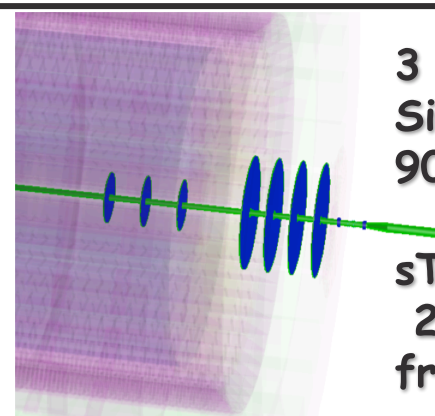
6 disk 8 R 128*12 PHI





Cost: 4.1 M$

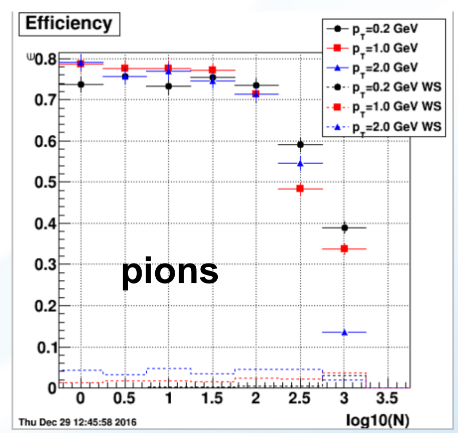
Si + Small-strip Thin Gap Chambers

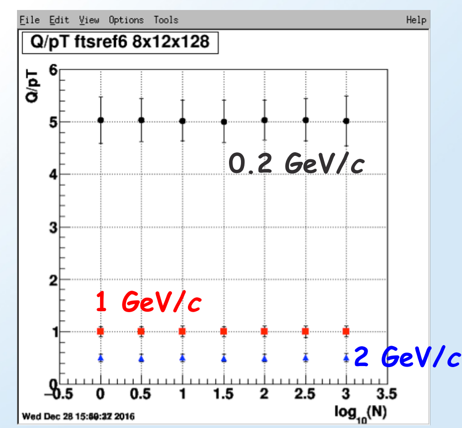


3 Si disks + 4 sTGC
Si- disks:
90, 140, 187 cm from IP

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





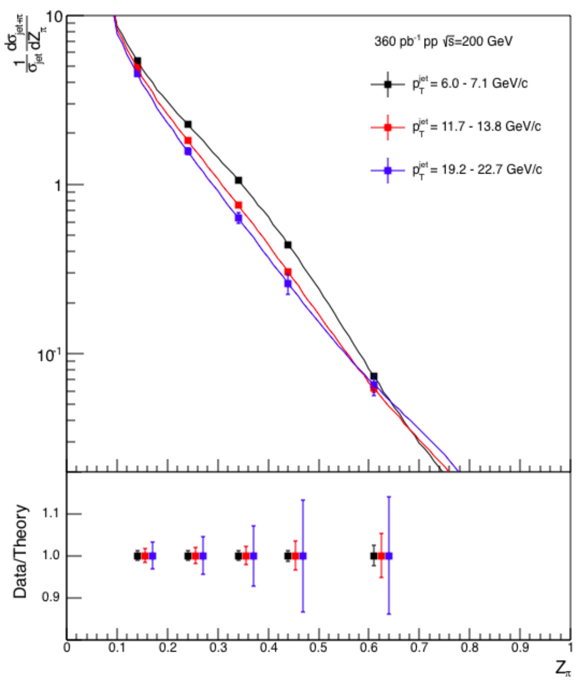
Cost: 3.3 M$

pp, pA, AA PHYSICS AT MIDRAPIDITY

- Rich unique program building on the strength of STAR detector
- measurements complement the forward physics program
  - extending kinematics
  - addressing complement physics topics
  - diffractive & UPC program with Roman Pots, i.e. Wigner functions

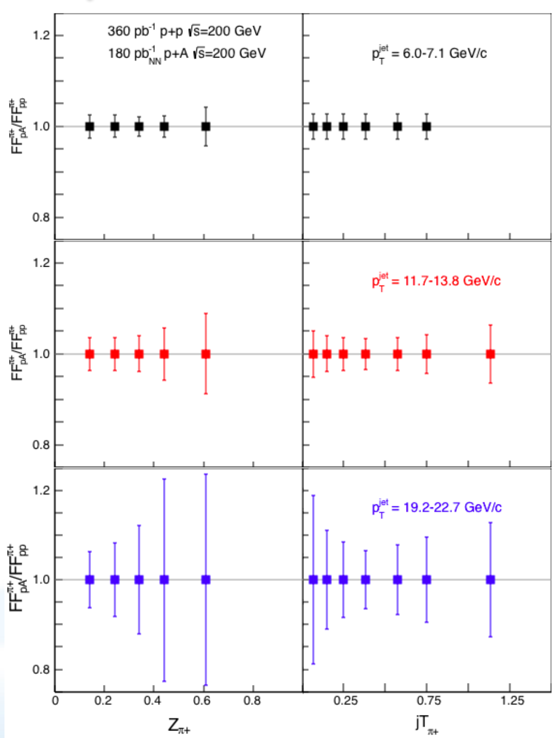
pp:

Fragmentation functions
High precision TMD measurements
→ Universality test → EIC



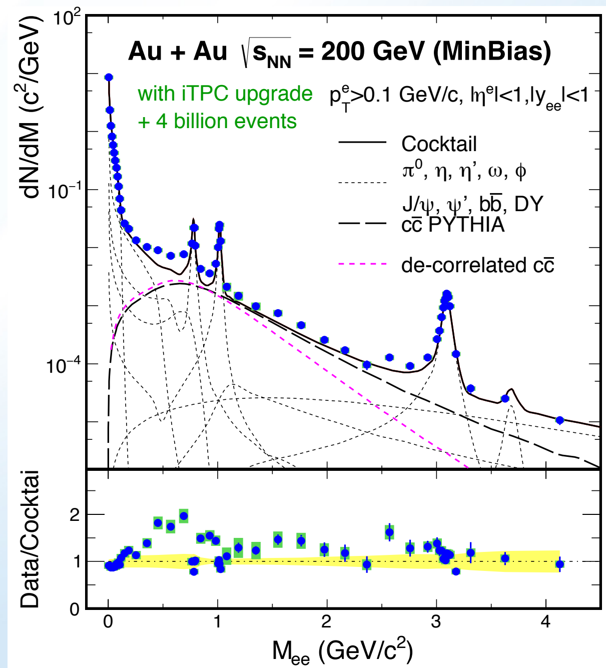
pA:

nuclear Fragmentation functions
complement to nPDFs
only at RHIC p↑A:
→ spin effects in nFF → Collins FF



AA:

a deep look into the properties of the QGP: γ & e+e- pairs
→ chiral symmetry restoration
→ thermal radiation of QGP



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

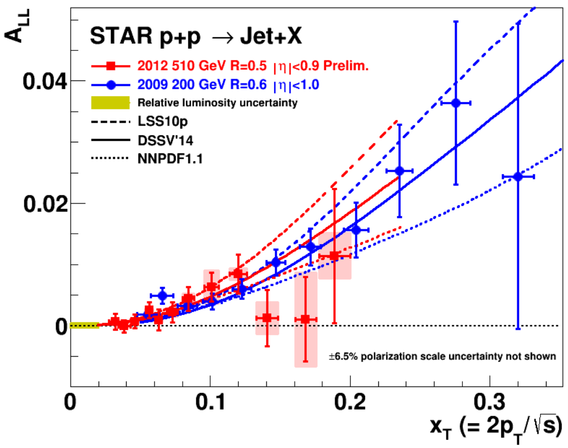
- essential to complete the mission of the RHIC physics program
- Cost effective upgrade: Total 5.5 M$ including contingency and manpower
- pp/pA program essential to fully realize the scientific promise of the EIC
  - inform the physics program
  - quantify experimental requirements

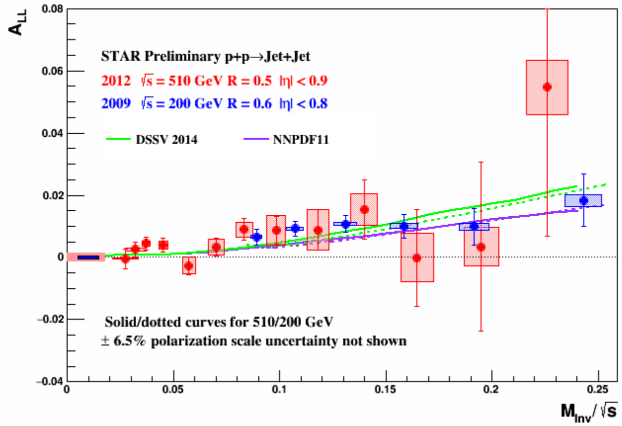

BACK UP

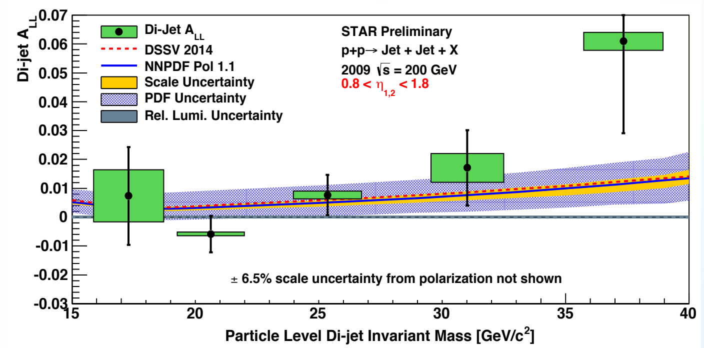
HOW POLARIZED ARE THE GLUONS?

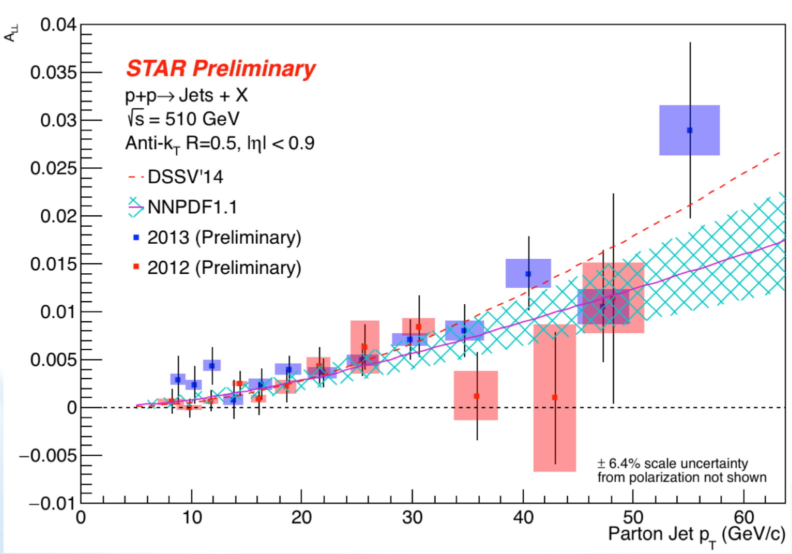
To Date:

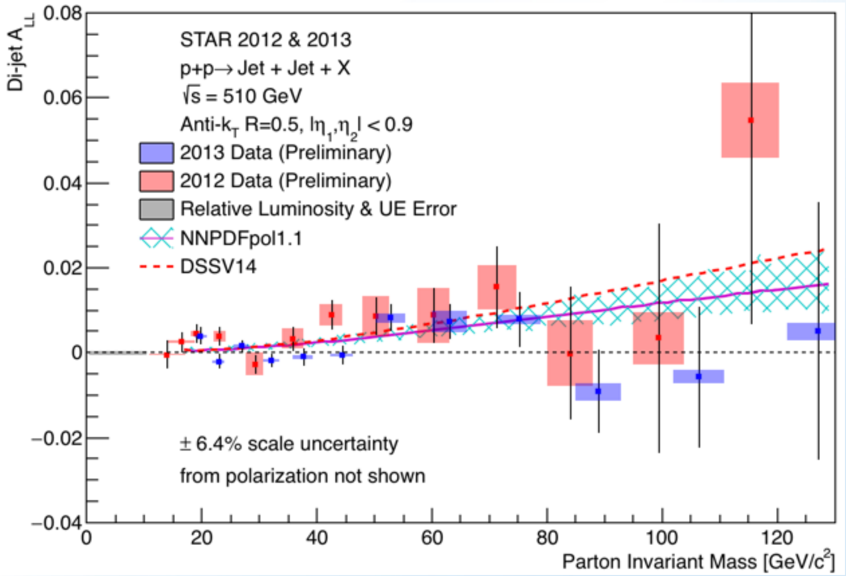
Jets and Di-Jets at -1 < η < 1.8:











BROOKHAVEN NATIONAL LABORATORY

GOLDEN OBSERVABLES

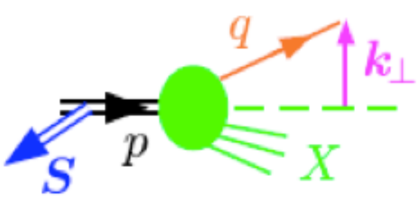
Initial State

SIVERS/Twist-3

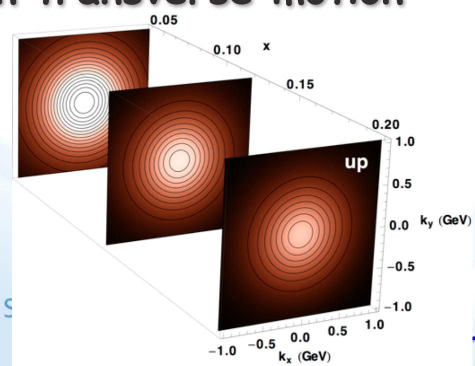
- A_N for heavy flavour → gluon
- A_N for $W^{+/-}$, Z^0, DY
- A_N for jets, direct photons

related through

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



Probes correlations of proton spin to parton transverse motion



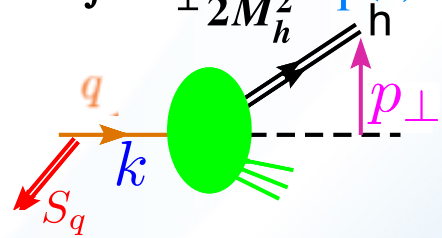
Final State

Collins Mechanism

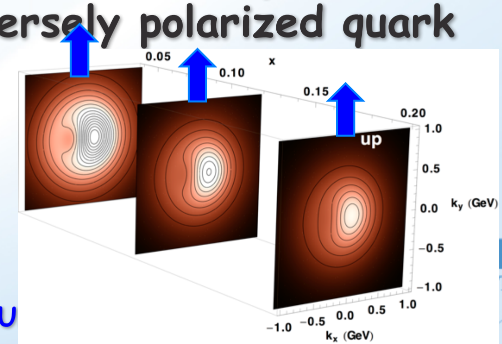
- asymmetry in jet fragmentation
  - $\pi^{+/-}$-π^0 azimuthal distribution in jets
  - Interference fragmentation function
- A_N for pions
  → **Novel Twist-3 FF Mechanisms**

related through

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

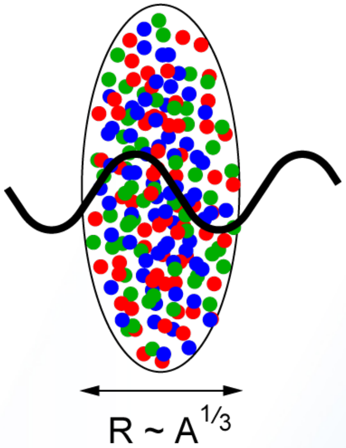


Probes transversity x spin-dependent FF
Collins function: unpolarized hadron from a transversely polarized quark



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:

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

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

Complementarity

QCD has two concepts which lay its foundation

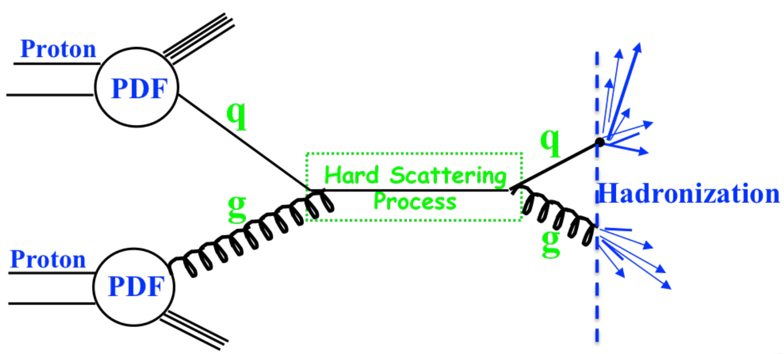
factorization and universality

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 ~

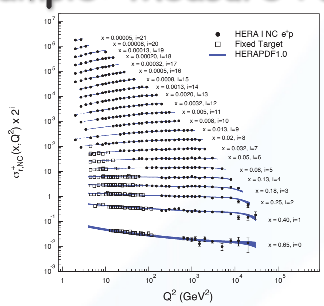
PDF ⊗ hard-scattering ⊗ Hadronization

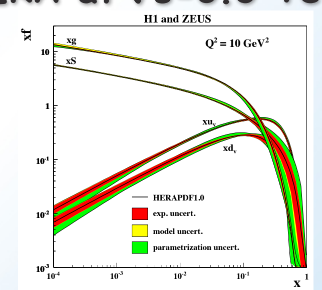
hard-scattering : calculable in QCD

PDFs and Hadronization: need to be determined experimentaly

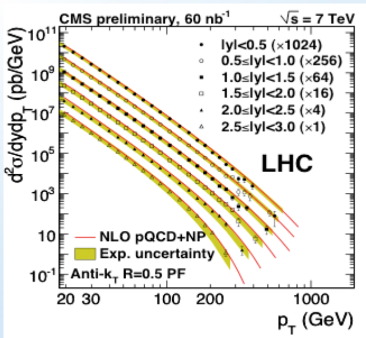
Universality

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

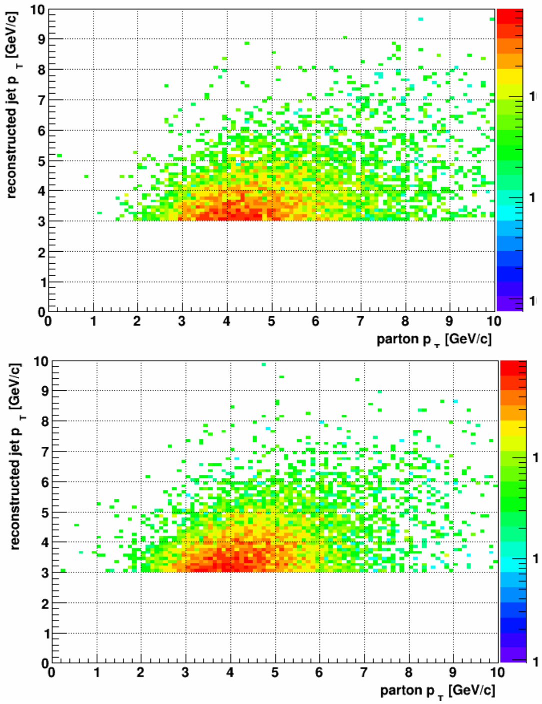


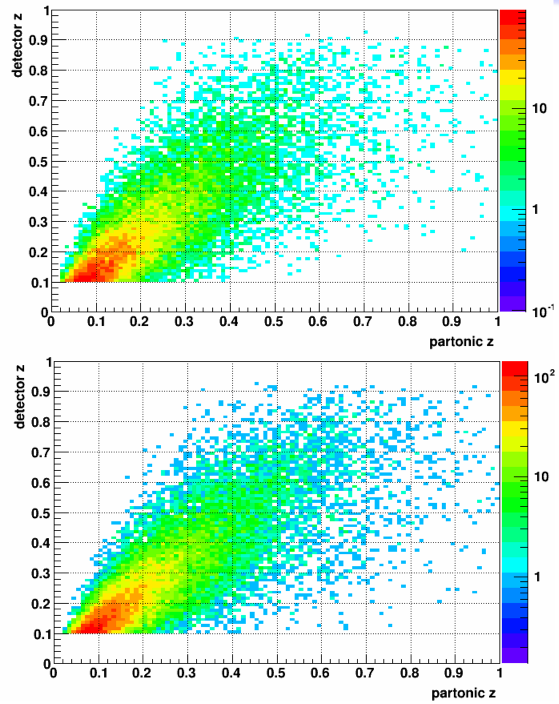


Predict pp and $\mathbf{p\bar{p}}$ measurements at √s=0.2, 1.96 & 7 TeV



STAR FORWARD UPGRADE PERFORMANCE





Transverse momentum smearing for reconstructed jets compared to that of the associated parton. The upper figure shows the smearing for jets with 2<h<3 and the lower for those with 3<η<4.

Smearing of *z*, the fractional momentum of the outgoing parton/jet carried by the outgoing hadron. The upper figure shows the smearing for jets with 2<h<3 and the lower figure for jets with 3<h<4.