Polarized p+A Physics at Forward Rapidity at STAR

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RBRC workshop @ BNL

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2. STAR Forward Calorimeter
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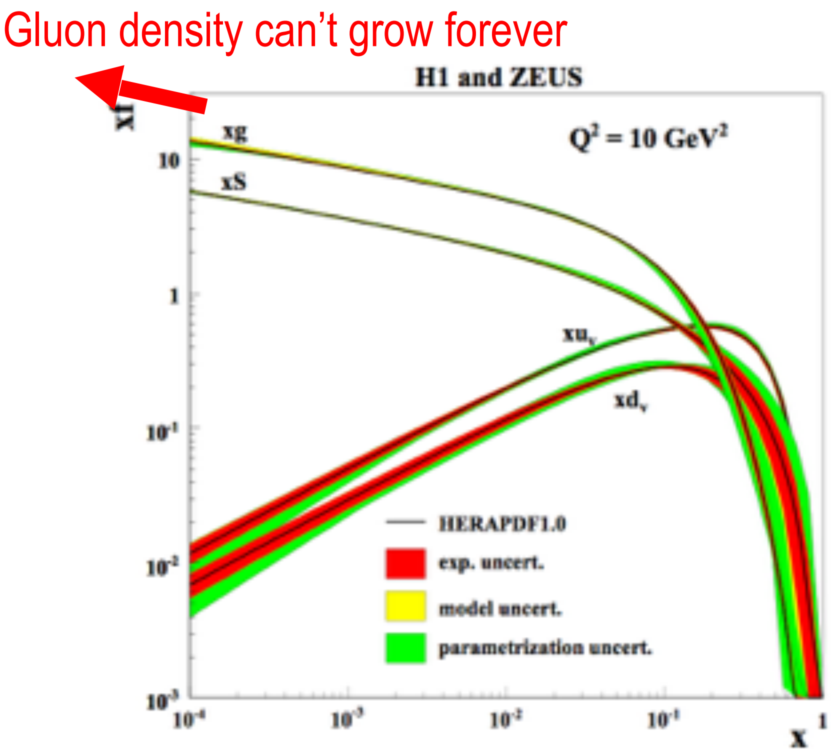
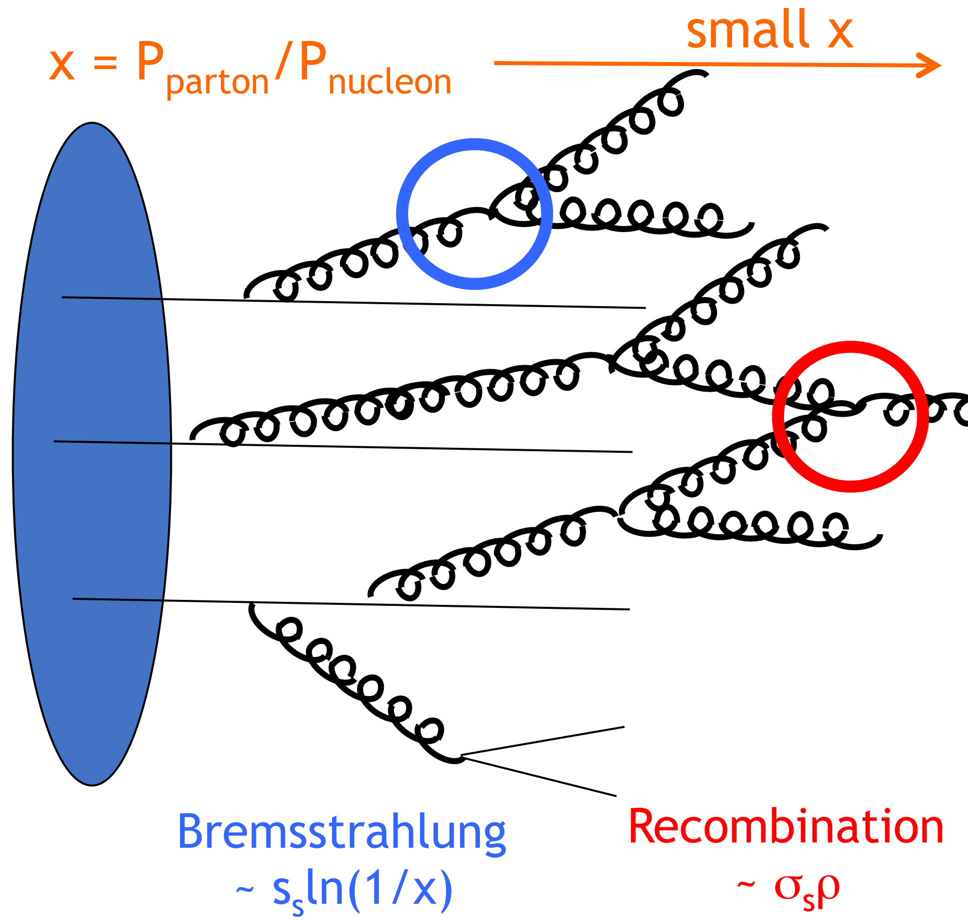
Gluon Density at Low x



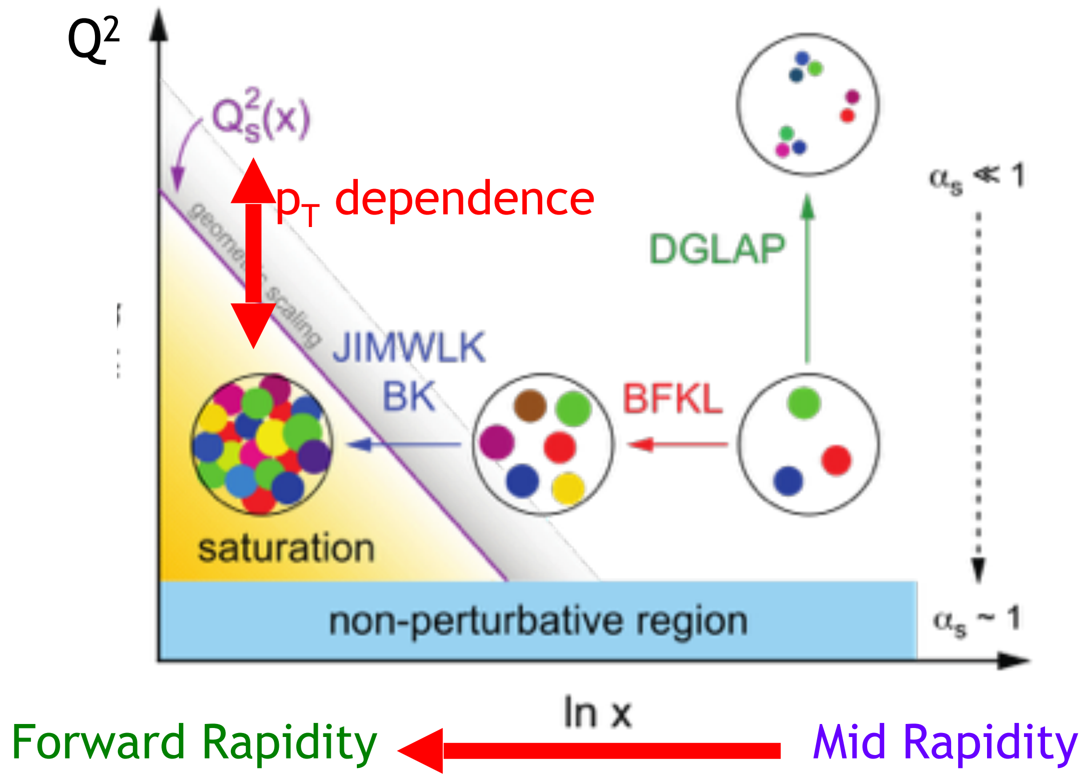
JHEP 1001:109,2010 H1 and Zeus



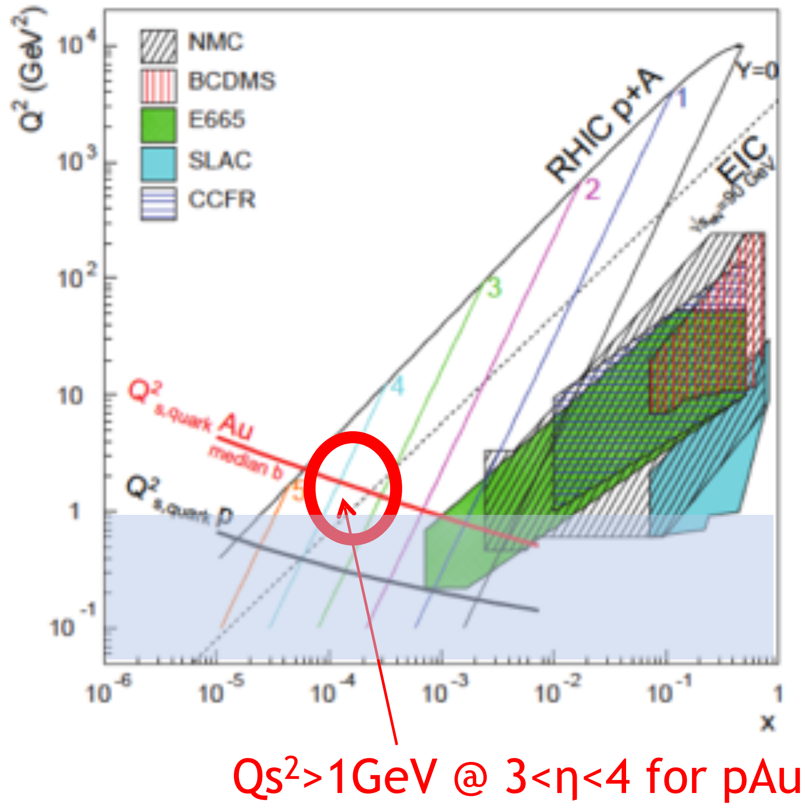
Rapid rise in gluon density described by linear DGLAP & BFKL pQCD evolution

But saturation must set in at low-x when gluons start to overlap
and when recombination becomes important

Gluon Saturation

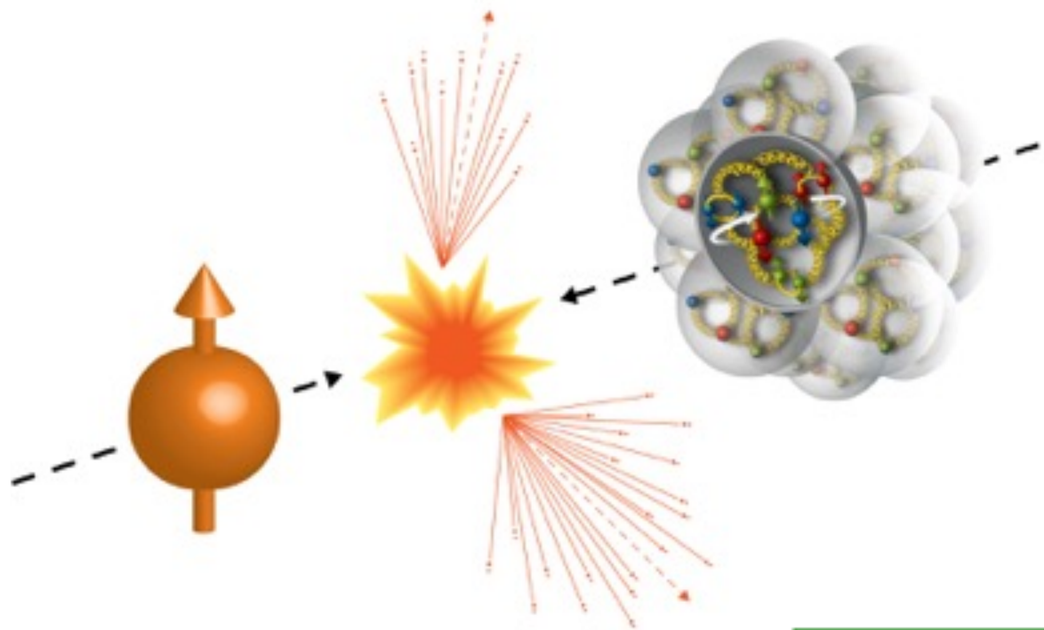


$$x \sim \frac{2p_T}{\sqrt{s}} e^{-y}$$



- 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_s^2 (x)
- RHIC can reach in pA collisions the saturation region at forward rapidity
- p_T scan and rapidity/x scan may allow to cross saturation scale Q_s^2 (x)

Polarized p+A @ RHIC



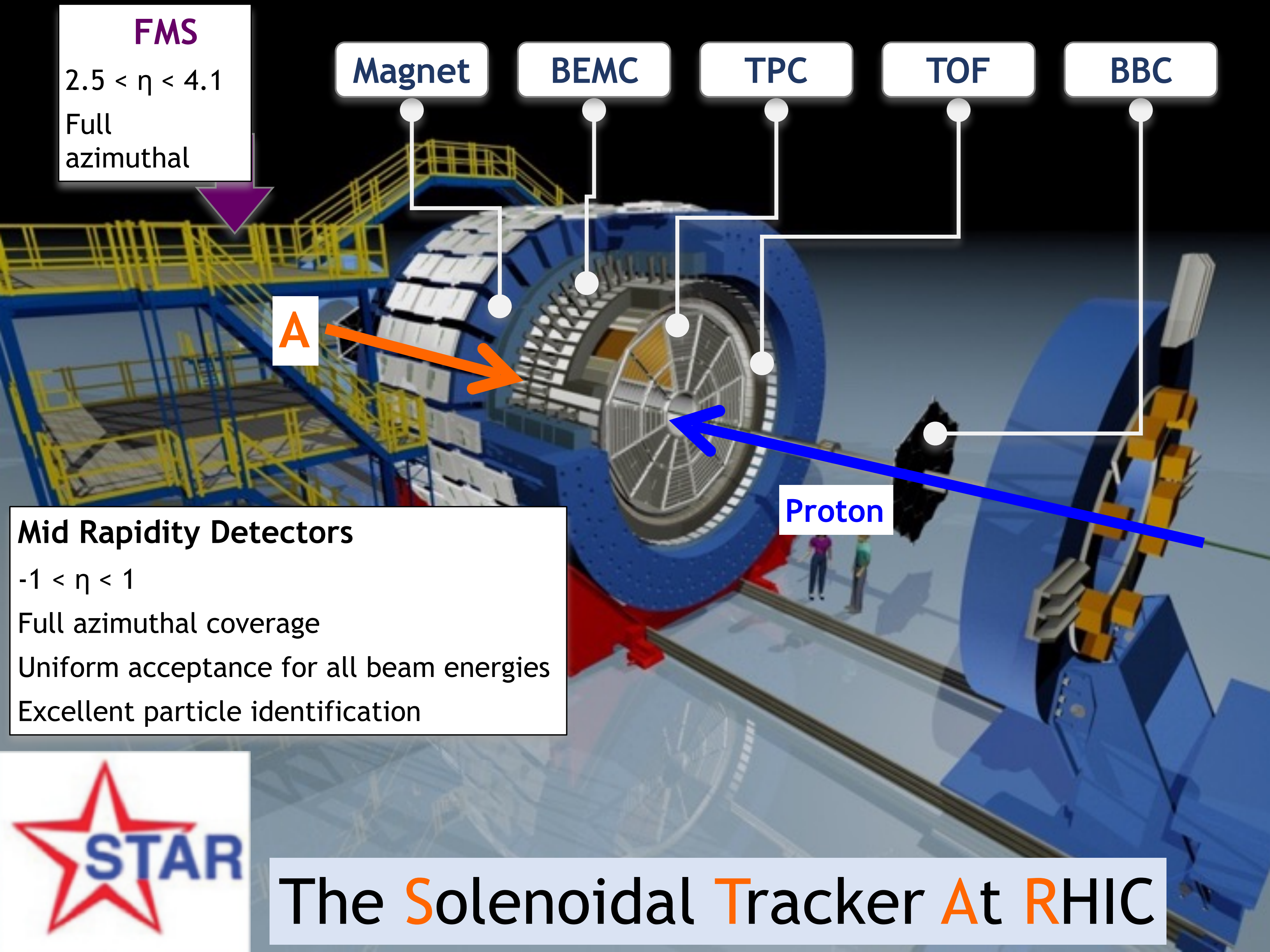
- Polarized protons
- Scanning A → Au, Al, …
- Forward rapidity hadron production
  - can access to low-x gluons
  - with highly polarized & high-x quark probe

Transverse Spin

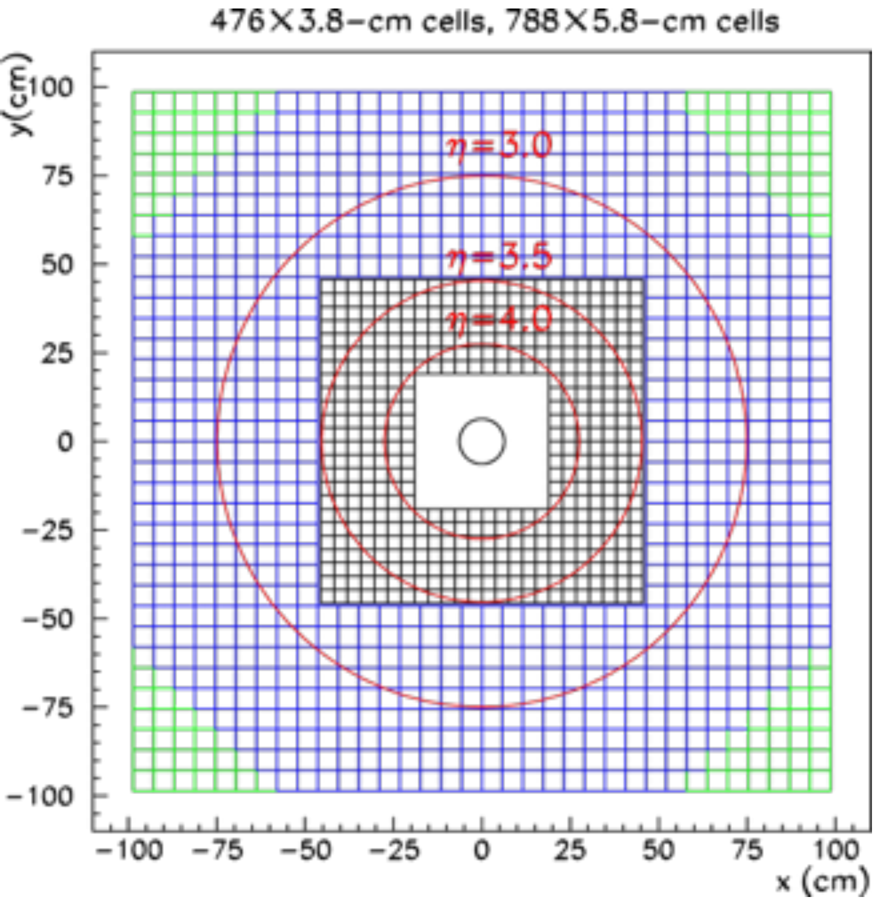
RHIC 2015

- $\vec{p} + p, L_{\text{int}} = 40 + 50\ \text{pb}^{-1}$
- $\vec{p} + Al, L_{\text{int}} = 1.0\ \text{pb}^{-1}$
- $\vec{p} + Au, L_{\text{int}} = 0.45\ \text{pb}^{-1}$

RHIC offers unique opportunities to study low-x gluon and gluon saturation signatures in transverse single spin asymmetries A_N


FMS
2.5 < η < 4.1
Full azimuthal
Magnet
BEMC
TPC
TOF
BBC
A
Proton
Mid Rapidity Detectors
-1 < η < 1
Full azimuthal coverage
Uniform acceptance for all beam energies
Excellent particle identification
STAR
The Solenoidal Tracker At RHIC

STAR Forward Calorimetry: FMS



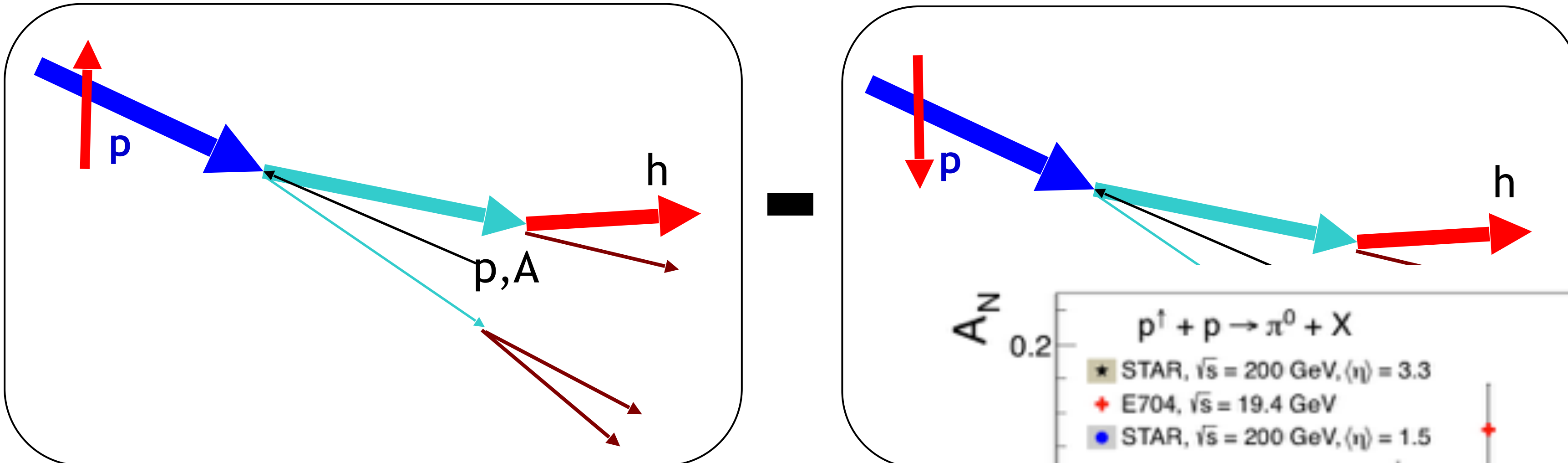
>1400 Pb glass towers with PMT readout

- Neutral pions / eta / EM-jet
- Direct photons with Pre-shower(2015)
- J/ψ and Drell-Yan with Post-shower(2017)

Transverse Single Spin Asymmetry (SSA) A_N at p+p

$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

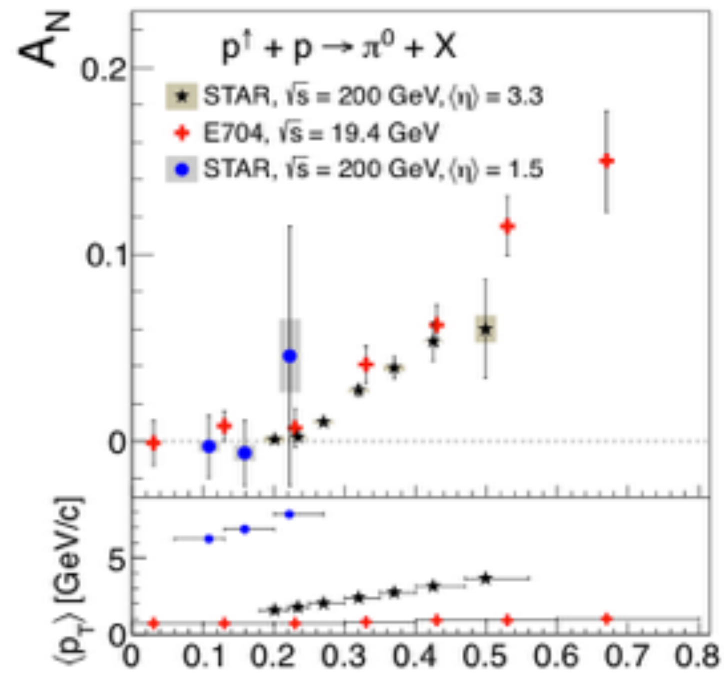
Left-Right Asymmetry
cos(ϕ) modulation



It requires k_T to left or right with respect t
polarization direction generated from

Initial State Effect
Nucleon Spin → Parton k_T → Hadron k_T

Final State Effect
Nucleon spin → Parton Spin → Hadron k_T



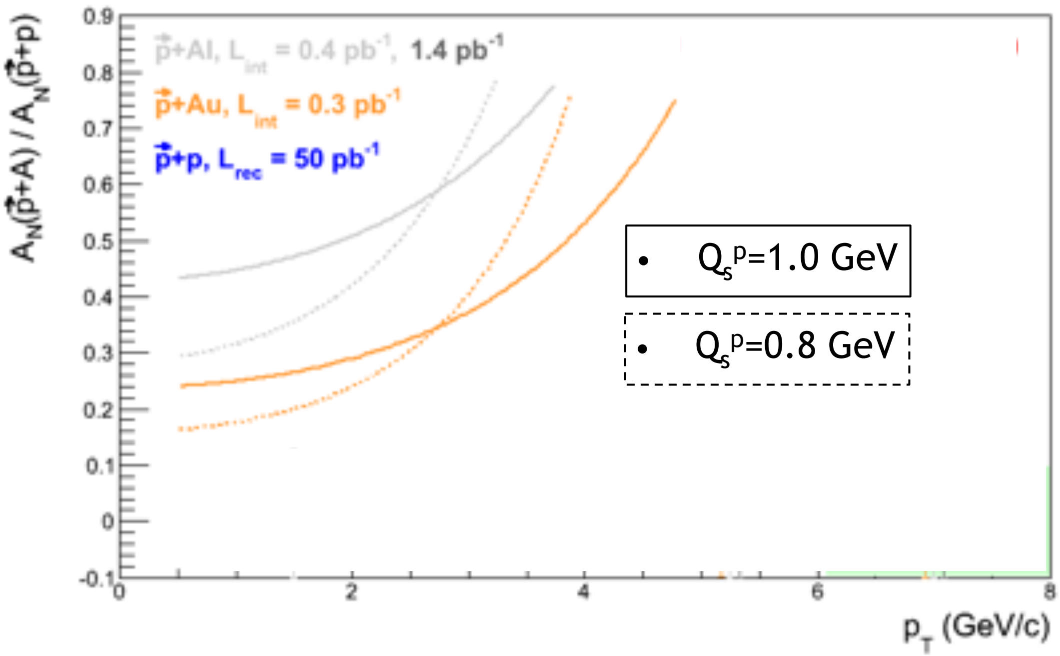
Phys.Rev.Lett.101:222001,2008

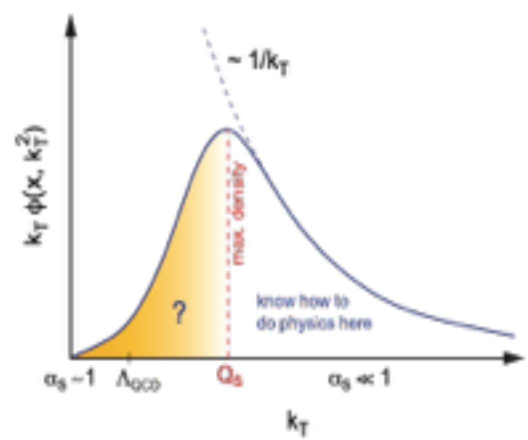
Transverse Single Spin Asymmetry (SSA) A_N at p+A

Hybrid Approach Yoshitaka Hattaa,et al, Phys. Rev. D 95, 014008 (2017)

Initial state effect in p + k_T un-integrated gluon distribution in Au + Final State effect

Odderon exchange Yuri V. Kovchegov, Matthew D. Sievert, PhysRevD.86.034028



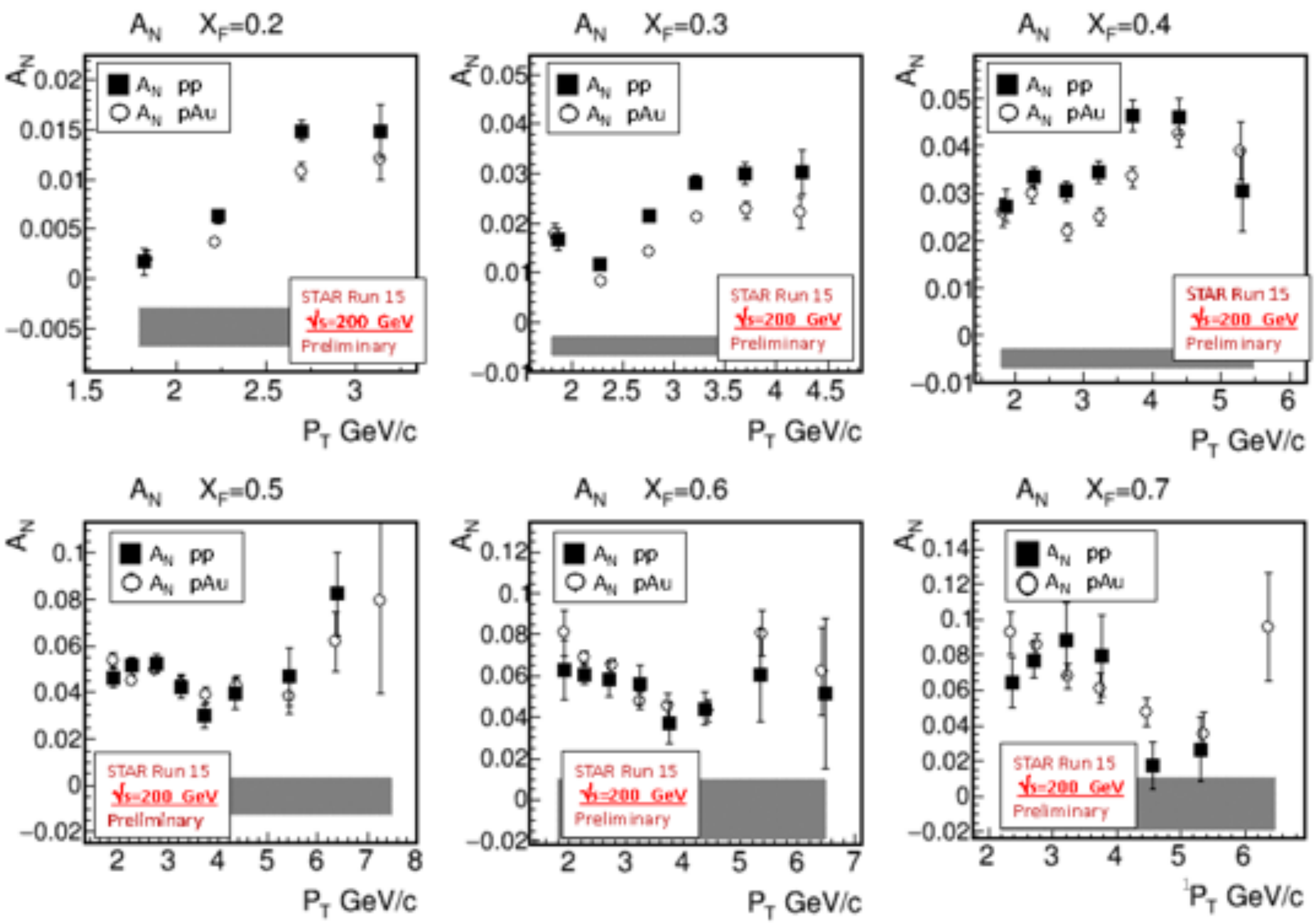


$$Q_s^A = A^{1/3} Q_s^p$$

Both models predict gluon saturation suppresses A_N by ~$A^{1/3}$

Suppression of A_N in $p^{\uparrow}$+A provides sensitivity to Q_s PhysRevD.84.034019, PhysRevD.86.034028

First results from Polarized p+Au

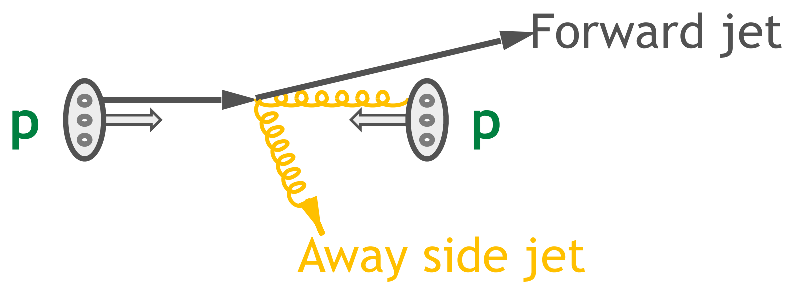


Shaded bands represent systematic uncertainty, dominated by dependence of A_N on observed BBC multiplicity → central vs. peripheral collisions

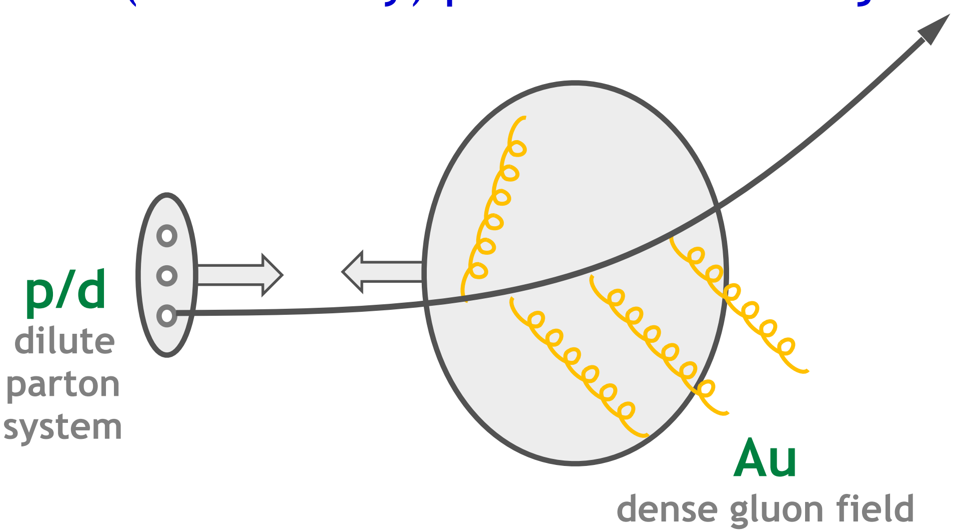
Small to no suppression is observed

Back-to-back Angular Correlations

pQCD 2→2 process = back-to-back di-jet (Works well for p+p)

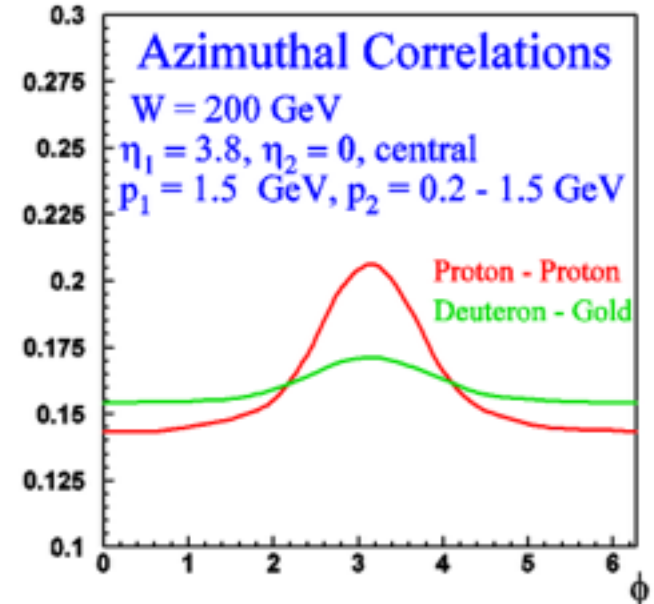


With high gluon density
2→1 (or 2→many) process = Mono-jet



Kharzeev, Levin, McLerran

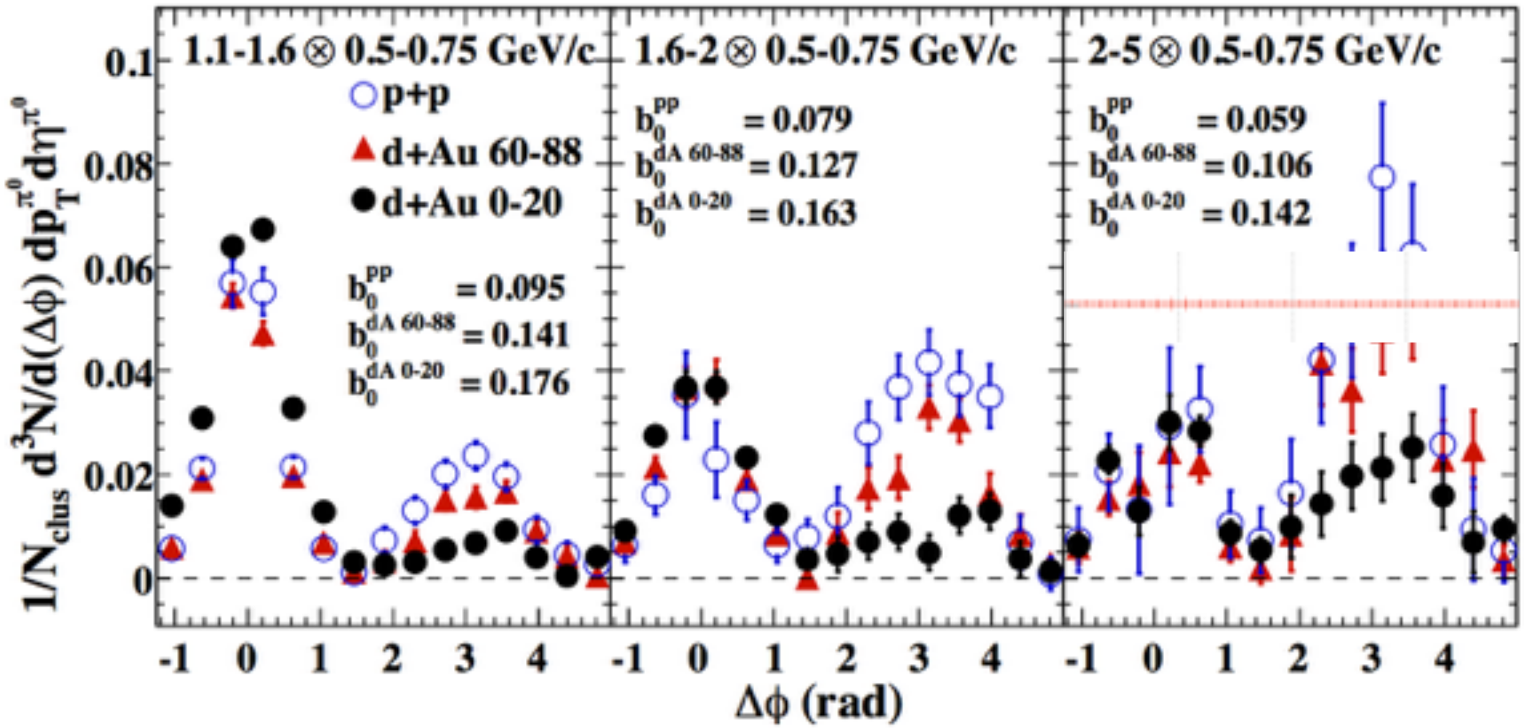
(NPA748, 627)



CGC predicts suppression of back-to-back

Back-to-back Angular Correlations

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



PHENIX

Cluster analysis

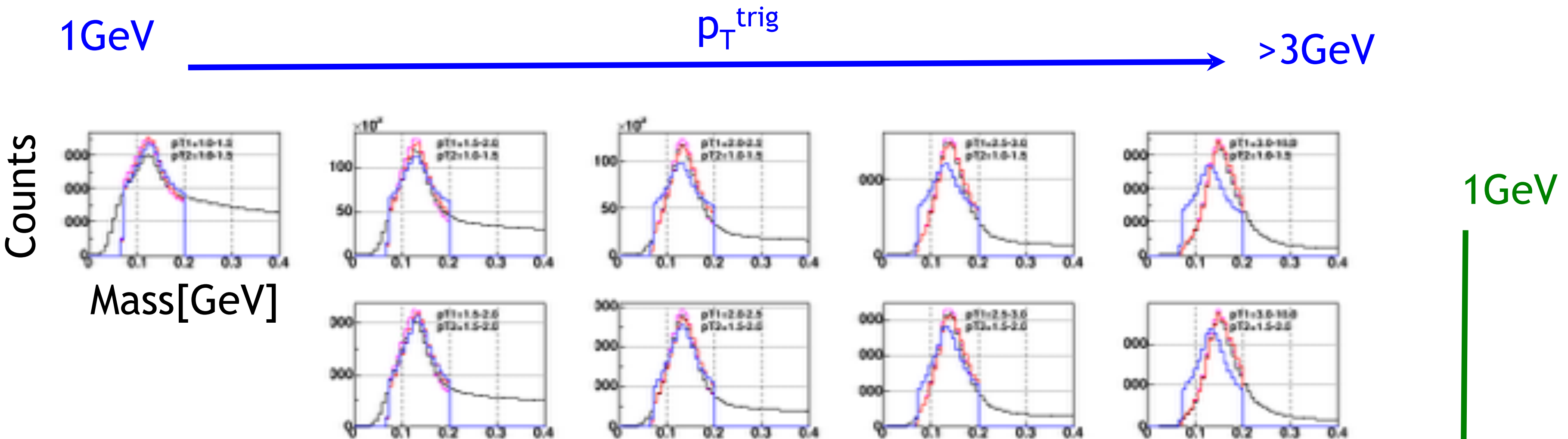
Run15 pA statistic

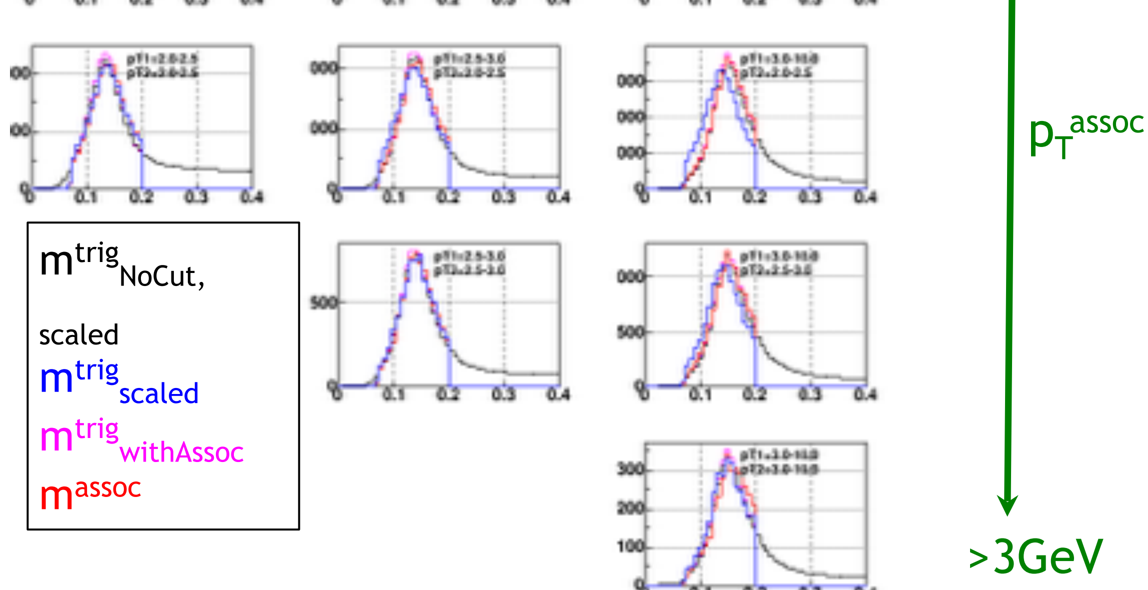
STAR year 2015 data being analyzed for
- π^0-π^0 and EM jet-EM jet correlations
- p+p, p+Al, p+Au (d+Au in 2016)
- p_T^{Trig} dependence from 1GeV ~ 3GeV
- $p_T^{Associated}$ dependence from 1GeV ~ 3GeV
- Centrality / N_{coll} dependence

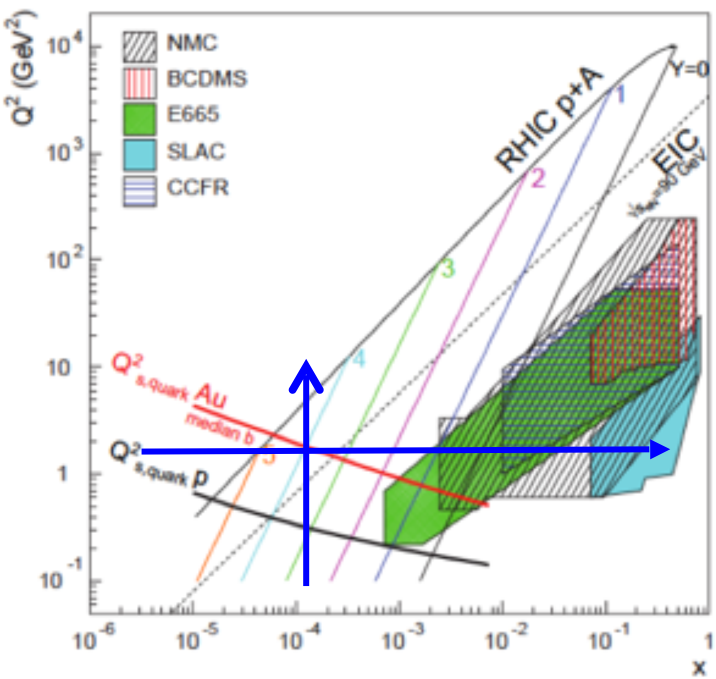
We are still working on
- Gain uniformity and stability
  - (This cancels out in A_N)
- STAR common Centrality / N_{coll}

Scanning in p_T and x

π^0 mass peaks in different p_T bins







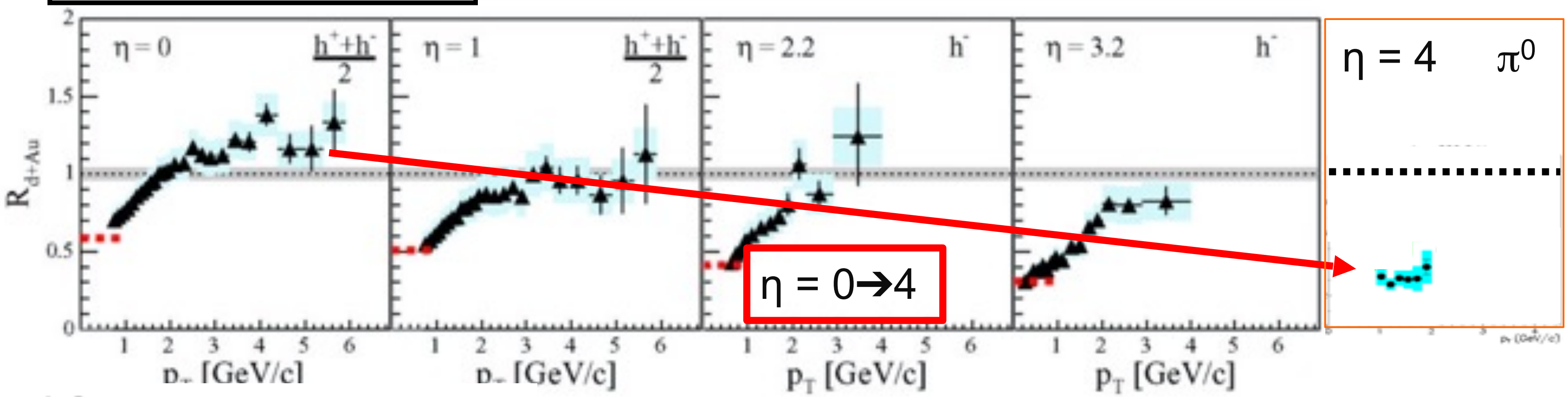
With Year2015 data's statistics,
STAR can study evolution of Q_s^2 (x) with A

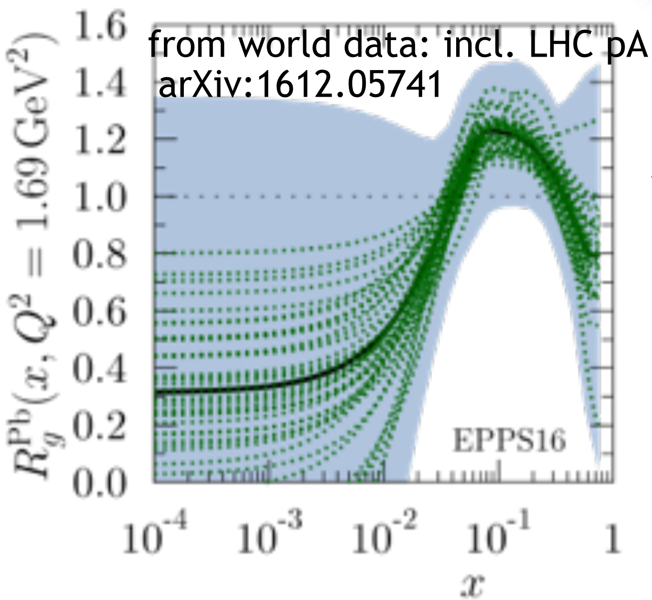
Suppression in Forward Hadron Production

$$R_{dAu} = \frac{1}{2*197}\frac{\sigma_{dAu}}{\sigma_{pp}}$$

BRAHMS PRL 93, 242303

STAR PRL 97, 152302





Observe significant rapidity dependence consistent with expectation from the CGC

World data on nuclear gluon PDF has large uncertain

Work in progress for R_{pA} from Year 2015 data

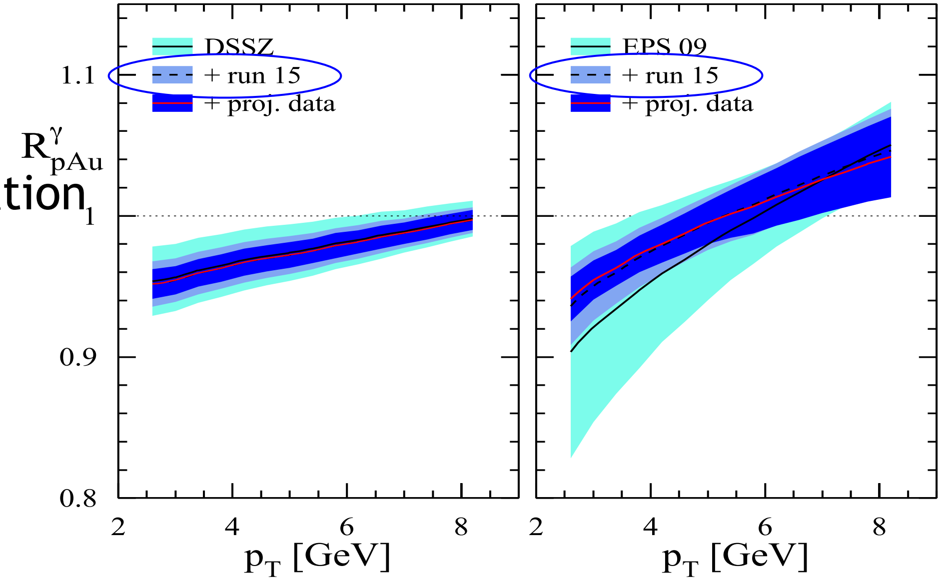
- R_{pAu} and R_{pAl}
- Pi0 and photon final state
- eta 2.7 to 3.9

Leading and Higher Twist Shadowing

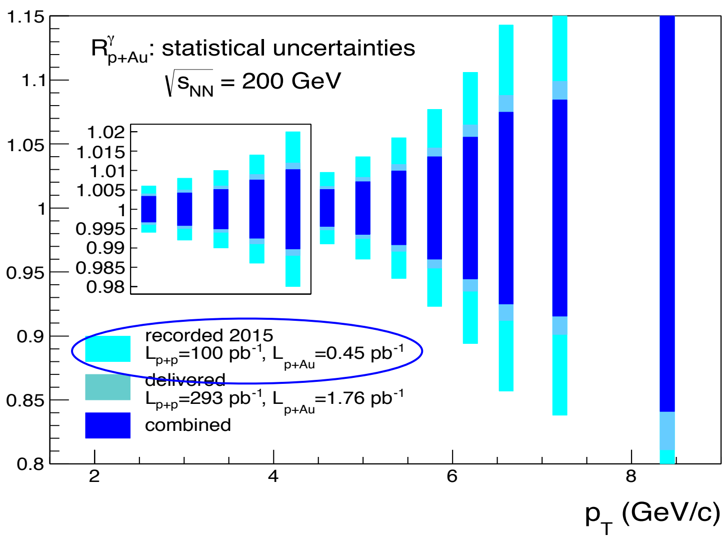
STAR ideal experiment to separate
leading twist → nPDF
from higher twist shadowing → CGC
without the complication of fragmentation

FMS + FPS: R_{pA} for direct photons

Impact on nPDFs: → mainly on gluon



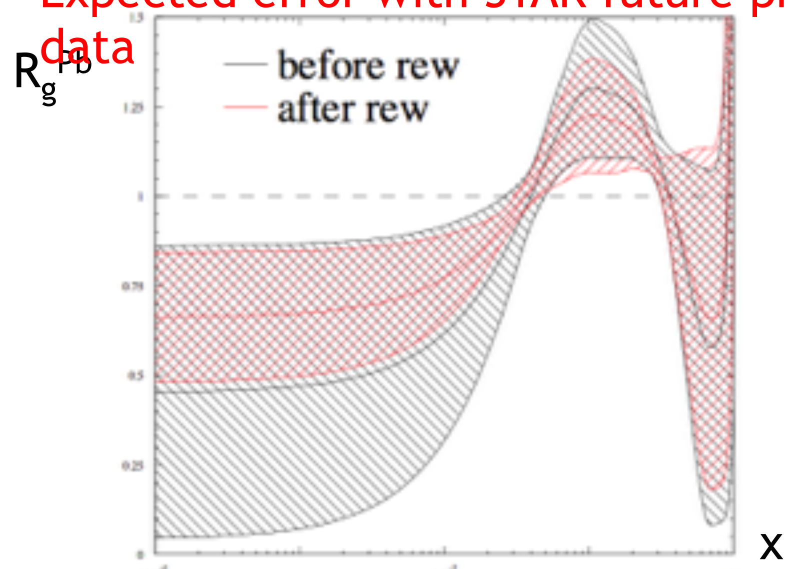
Direct photon @ 2.8 < η < 4.0



The STAR forward upgrade will allow R_{pA} for DY to constrain sea quarks

EPS09 (1.3GeV)

Expected error with STAR future photon data



RHIC Cold QCD Plan and STAR forward upgrade

2015 2017 ≧2021 ≧ 2025

➢ wide accepta ,p)

➢ forward rapi ntification

longitudinal &
transverse
❑ p↑+Au/Al 200 GeV
transverse

Goal:
❑ $\Delta g(x,Q^2)$
❑ transverse spin structure of the p
❑ Search for exotics

❑ Spin effects in diffraction
❑ J/Ψ in UPC →GPD E_g

❑ nPDF: $g(x,Q^2)$
❑ Saturation

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❑
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à
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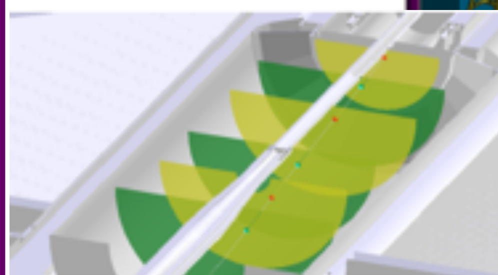
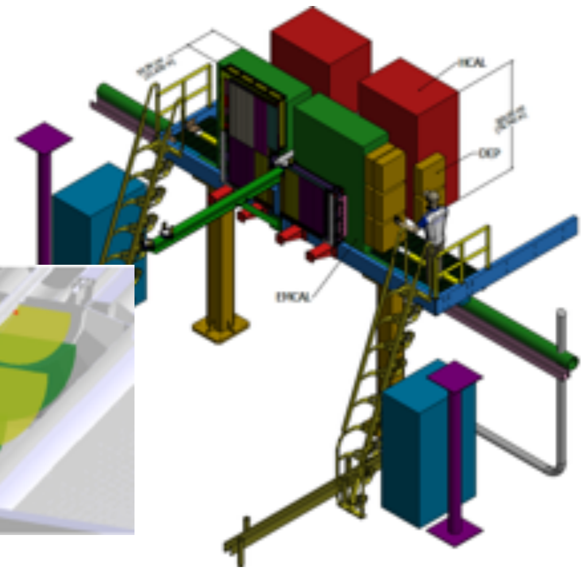
❑
❑
❑





Add to existing STAR at rapidity
$2.5 < \eta < 4.5$

Ecal:
reuse PHENIX Ecal

Hcal:
STAR fHCal and EIC fHCal

Tracking:
4-6 Si strip-disks

602.03922 [nucl-ex]

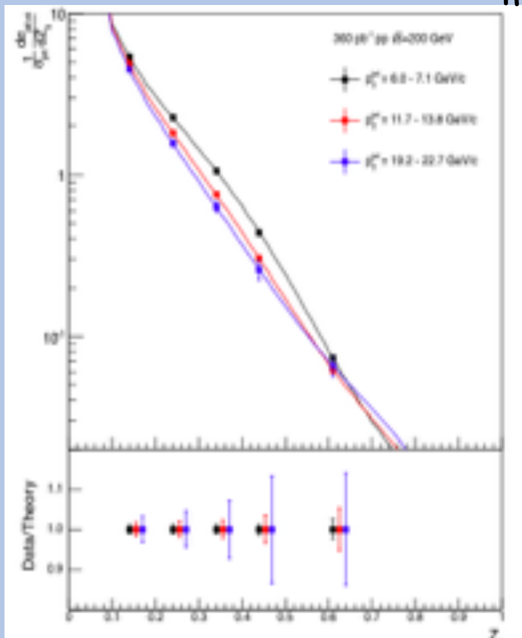
Run2023+ Physics Opportunities

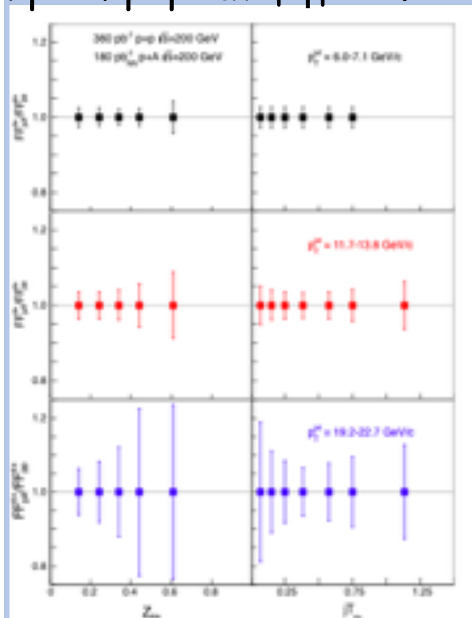
	Year	$\sqrt{s}$ (GeV)	Delivered Luminosity	Scientific Goals	Observable	Required Upgrade
Scheduled RHIC running	2017	$p^{\uparrow}p$ @ 510	400 pb^{-1} 12 weeks	Sensitive to Sivers effect non-universality through TMDs and Twist-3 $T_{q,F}(x,x)$ Sensitive to sea quark Sivers or ETQS function Evolution in TMD and Twist-3 formalism	A_N for γ, $W^{\pm}$, Z^0, DY	A_N^{DY}: Postshower to FMS@STAR
				Transversity, Collins FF, linear pol Gluons, Gluon Sivers in Twist-3	$A_{UT}^{\sin(\phi_s-2\phi_h)}$ $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, $A_{UT}^{\sin(\phi_s)}$ for jets	None
				First look on GPD E_g	A_{UT} for J/Ψ in UPC	None
	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	Yes Forward instrum.
				properties and nature of the diffractive exchange in p+p collisions	A_N for diffractive events	None
	2023	$p^{\uparrow}Au$ @ 200	1.8 pb^{-1} 8 weeks	What is the nature of the initial state and hadronization in nuclear collisions	R_{pAu} direct photons and DY	R_{pAu}(DY): Yes Forward instrum.
				Nuclear dependence of TMDs and nFF	$A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, nuclear FF	None
				Clear signatures for Saturation	Dihadrons, γ-jet, h-jet, diffraction	Yes Forward instrum.
	2023	$p^{\uparrow}Al$ @ 200	12.6 pb^{-1} 8 weeks	A-dependence of nPDF,	R_{pAl}: direct photons and DY	R_{pAl}(DY): Yes Forward instrum.
				A-dependence of TMDs and nFF	$A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, nuclear FF	None
				A-dependence for Saturation	Dihadrons, γ-jet, h-jet, diffraction	Yes Forward instrum.
Potential future running	202X	$p^{\uparrow}p$ @ 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 $\eta > 1$ and mid-rapidity	Yes Forward instrum.
				quantitative comparisons of the validity and the limits of factorization and universality in lepton-proton and proton-proton collisions		None
	202X	$\vec{p}\vec{p}$ @ 510	1.1 fb^{-1} 10 weeks	$\Delta g(x)$ at small x	A_{LL} for jets, di-jets, h/γ-jets at $\eta > 1$	Yes Forward instrum.

Opportunities

p+p FF π+

fragmentation functions in p+A/p+p at |η| < 0.4



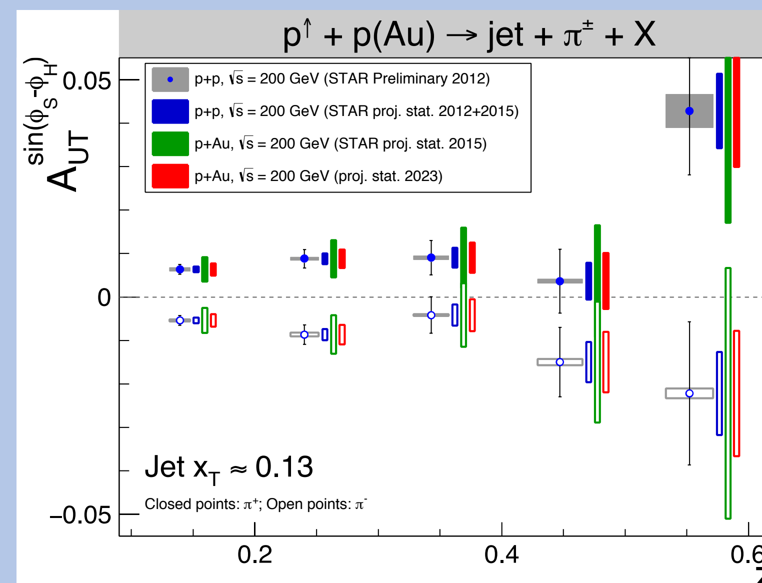


Critical to have π,K,p PID

	Observable	Required Upgrade
hrough TMDs function alism	A_N for γ, $W^{\pm}$, Z^0, DY	A_N^{DY}: Postshower to FMS@STAR
Gluons,	$A_{UT}^{\sin(\phi_s-2\phi_h)}$ $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, $A_{UT}^{\sin(\phi_s)}$ for jets	None
	A_{UT} for J/Ψ in UPC	None
x_F and η	A_N for charged hadrons and flavor	Yes Forward instrum

	2023	$p^{\uparrow}$Al @ 200	12.6 pb^{-1} 8 weeks	A-dependence of nPDF, A-dependence of TMDs and A-dependence for Saturati
Potential future running	202X	$p^{\uparrow}p$ @ 510	1.1 fb^{-1} 10 weeks	TMDs at low and high x quantitative comparisons of the validity factorization and universality in lepton-p proton collisions
	202X	$\vec{p}\vec{p}$ @ 510	1.1 fb^{-1} 10 weeks	$\Delta g(x)$ at small x

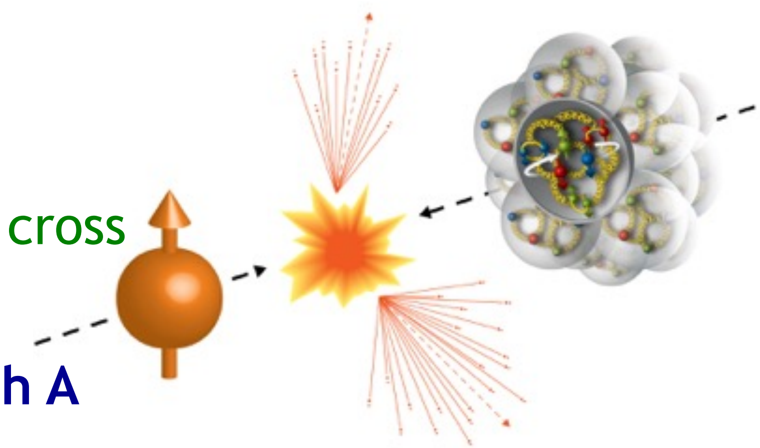
First measurement of nuclear spin effects polarized FF → nCollins



only at RHIC!

Summary and Outlook

- STAR @ RHIC can reach the saturation region at forward rapidity in p+A
- Polarized protons
- Scanning A ➔ Au, Al, …
- p_T scan and rapidity/x scan may allow to cross saturation scale Q_s^2 (x)



STAR can study evolution of $Q^2_s(x)$ with A

- First results on Transverse Single Spin Asymmetry A_N
  - Small to no suppression in p+Au
- Results coming soon for
  - Di-hadron angular correlation
  - R_{pA} for π^0 and photons

RHIC 2015

- $\vec{p} + p, L_{\text{int}} = 40 + 50\ \text{pb}^{-1}$
- $\vec{p} + Al, L_{\text{int}} = 1.0\ \text{pb}^{-1}$
- $\vec{p} + Au, L_{\text{int}} = 0.45\ \text{pb}^{-1}$

- Future forward upgrade at STAR is proposed, including saturation/pA physics at forward and mid-rapidity

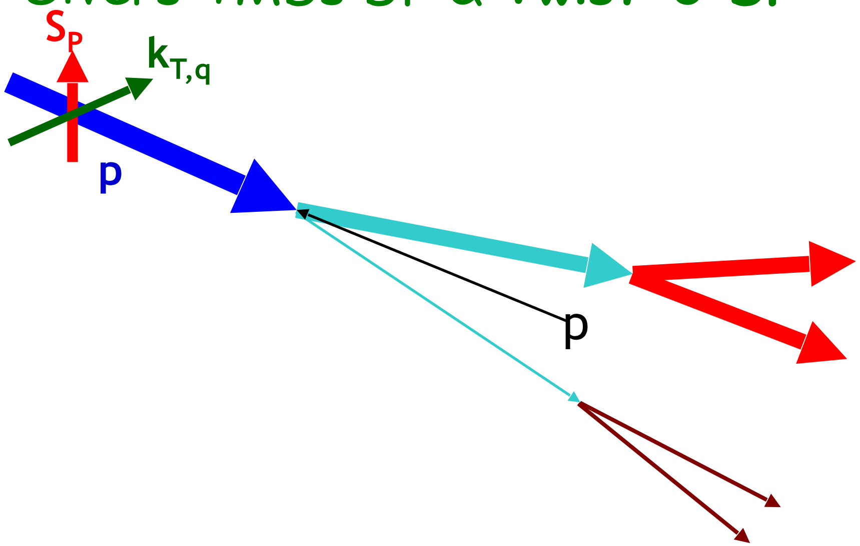
STAR at RHIC offers unique opportunities to study low-x gluon

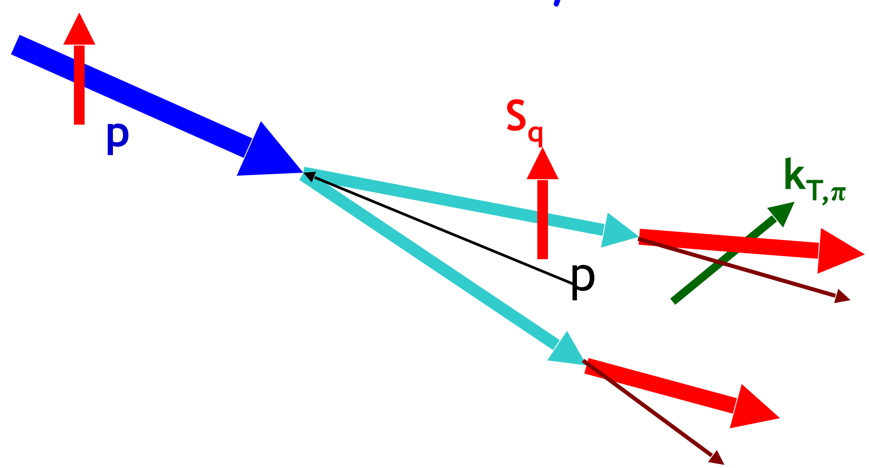
Backup

Transverse Single Spin Asymmetry (SSA) : A_N

Transverse Momentum Dependent (TMD) or Twist-3 DF or FF required

Initial State	**Final State**
Sivers TMDs DF & **Twist-3 DF**	**Collins TMD FF & Twist-3 FF** * Transversity





Sensitive to correlations between **proton spin** & parton **transverse motion**

Not universal (sign change) between SIDIS & pp

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

Sensitive to quark transverse spin and **spin-dependent** fragmentation function

Universal between SIDIS & pp & e+e-

Or something else…

Transverse Single Spin Asymmetry (SSA) : A_N

p+p

Initial State	Final State
Nucleon Spin ➔ Parton k_T	Nucleon spin ➔ Parton Spin ➔ Hadron k_T
Sivers TMD PDF	Transversity * Collins TMD Frag.Func.
$$-\int d^2k_\perp \frac{\lvert k_\perp^2 \rvert}{M} f_{1T}^{\perp q}(x,k_\perp^2)\vert_{SIDIS} = T_{q,F}(x,x)$$	Only one part
Twist-3 PDF	Twist-3 Frag.Func = “Collins” + 3 Parton Corr.

p+A

Dominant in p+p, and NOT suppressed at p+A

Yoshitaka Hattaa,et al, Phys. Rev. D 95, 014008 (2017)
Leonard Gamberg, Zhong-Bo Kang, Daniel Pitonyak, Alexei Prokudin arXiv:1701.09170v1

Hybrid Approach (Yoshitaka Hattaa,et al, arXiv:1611.04746v1)
Twist-3 + k_T un-integrated gluon distribution

Odderon exchange (Yuri V. Kovchegov, Matthew D. Sievert, arXiv:1201.5890v5)

Both predict A_N suppression for p+A