PHENIX pp & pA: Results and Expectations

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For the PHENIX Collaboration

pp&pA: Cold QCD studies in PHENIX

Cold nuclear effects

Necessary for sQGP studies

(n)FF, (n)PDF

Including saturation (CGC)

Factorization, Universality, Evolution

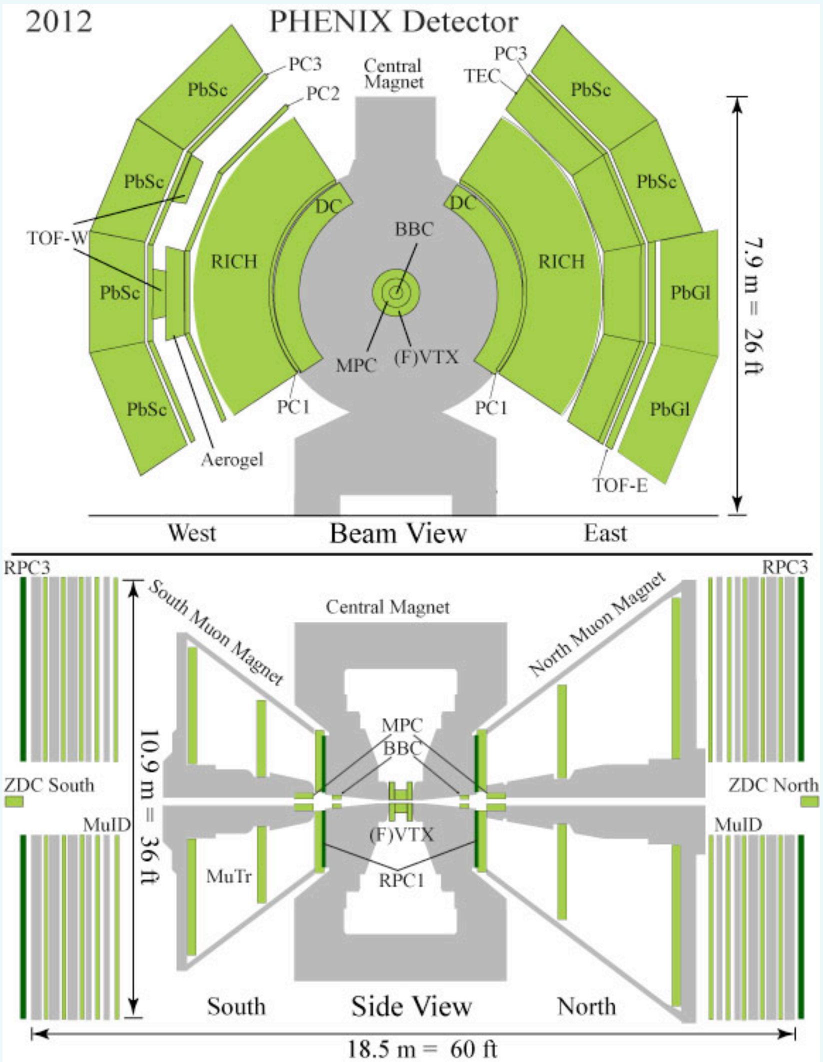
Factorization breaking, modified Universality

- Cross sections
- Spin asymmetries
- Correlations

Data up to 2016 (the last PHENIX data taking Run)

See Nils Feege talk about sPHENIX plans (2020+)

PHENIX Setup



π^0, γ, η

Electromagnetic Calorimeter: **$|\eta|<0.35$**

Muon Piston Calorimeter: **$3.1<|\eta|<3.9$**

$\pi^{\pm}$, e, $J/\psi \rightarrow e^+e^-$, $W \rightarrow e$: **$|\eta|<0.35$**

Drift, Pad Chambers, VTX ($|\eta|<1$)

Ring Imaging Cherenkov Counter, ToF

Electromagnetic Calorimeter

μ, $h^{\pm}$, $J/\psi \rightarrow \mu^+\mu^-$, $W \rightarrow \mu$: **$1.2<|\eta|<2.4$**

Muon Id/Muon Tracker

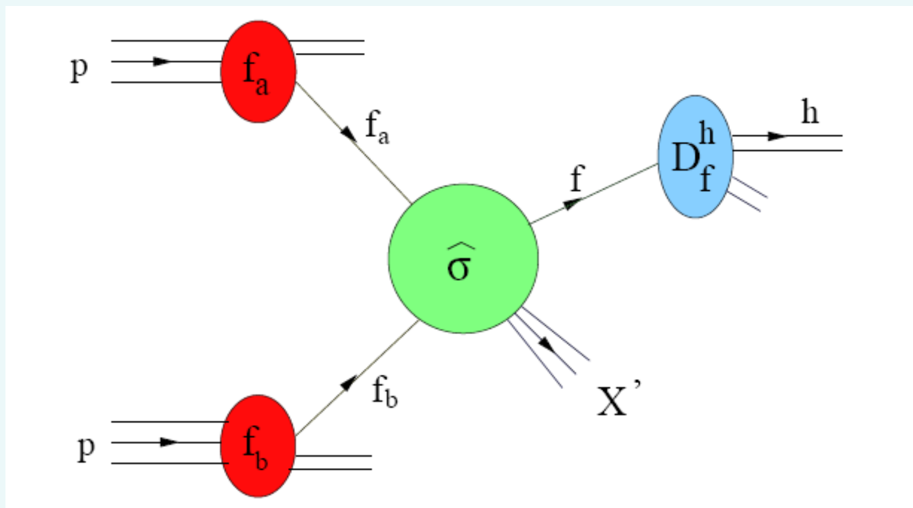
FVTX

Event vertex&time, (rel) luminosity, local polarimetry, etc.

BBC: **$3.0<|\eta|<3.9$**

ZDC: **$|\eta|>6.5$**

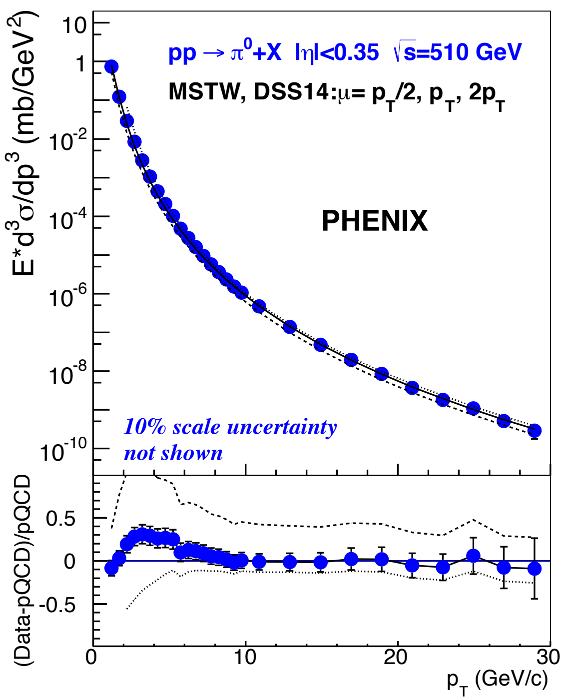
Cross section etc.



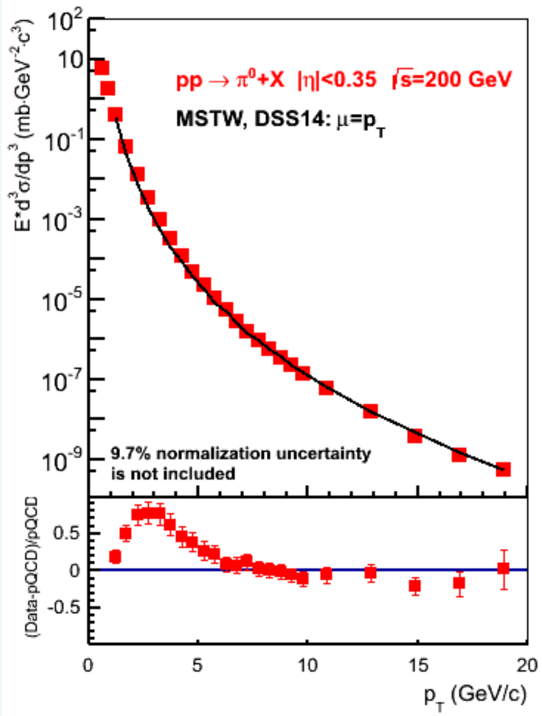
pp: Cross section, √s dependence

Mid-rapidity p+p→π0+X

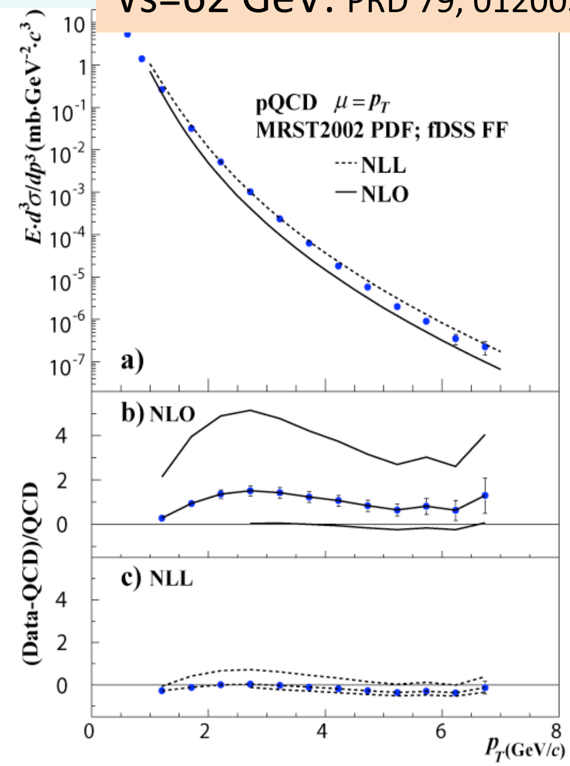
√s=510 GeV: PRD93, 011501 (2016)



√s=200 GeV: PRD 86, 072008



√s=62 GeV: PRD 79, 012003

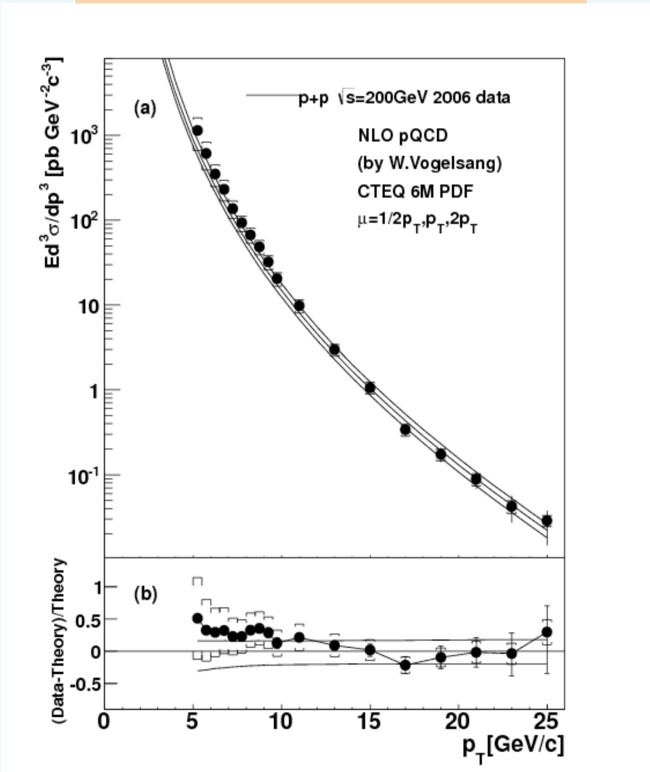


NLO pQCD in excellent agreement with data at pT>5 GeV/c

NLO pQCD not enough, soft gluon resummation needed

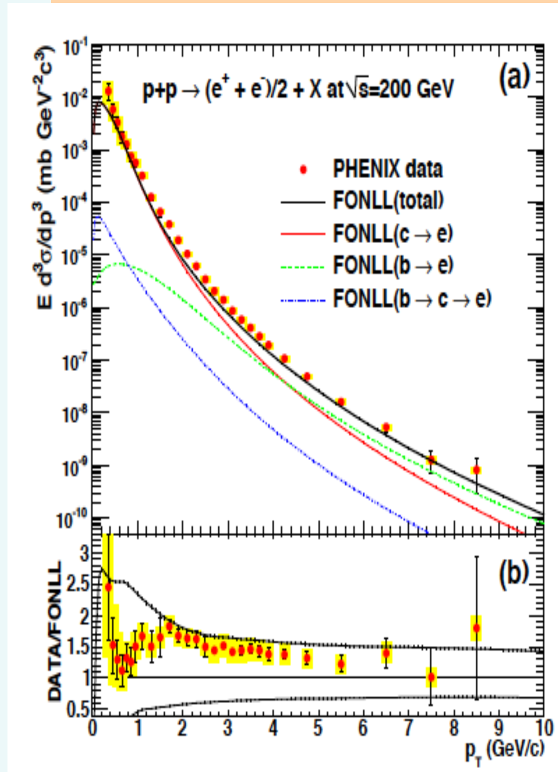
pp: Cross sections

pp → γX
PRD 86, 072008 (2012)



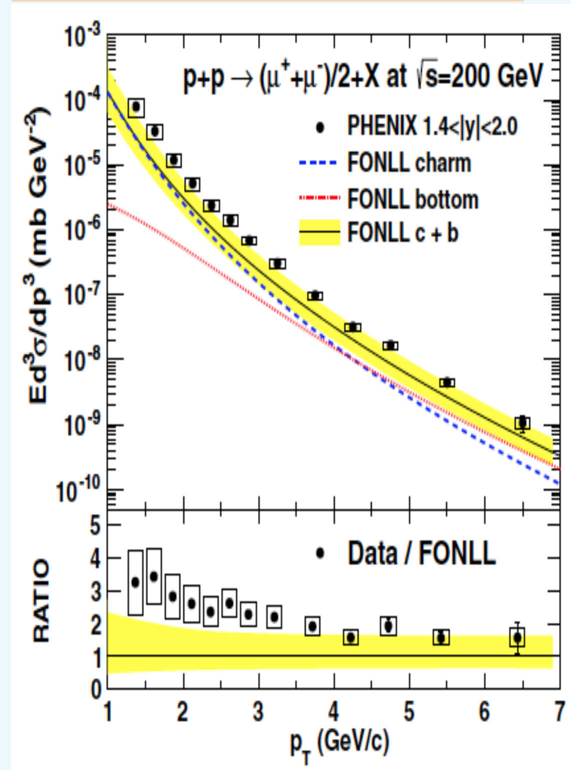
NLO pQCD in excellent agreement with data

pp → eX
PRC 84, 044905 (2011)



FONLL in good agreement with data

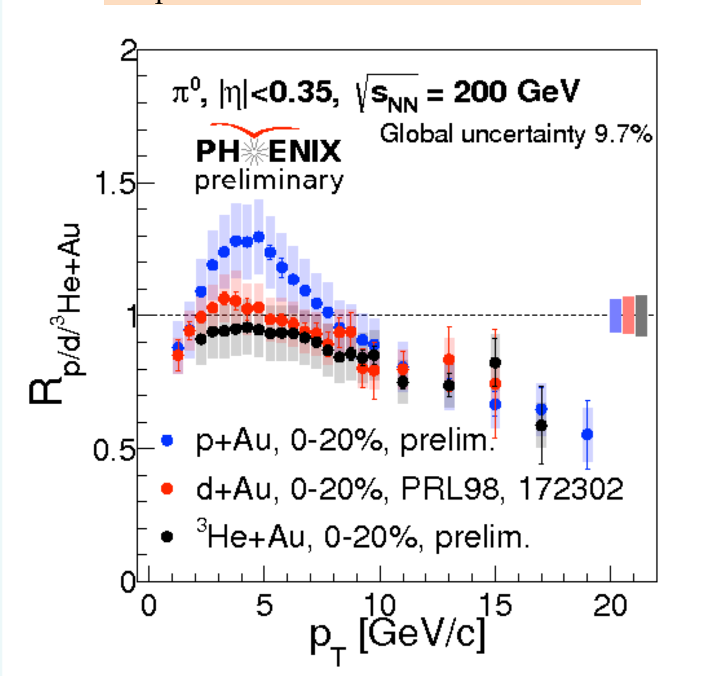
pp → μX
PRD95, 112001 (2017)



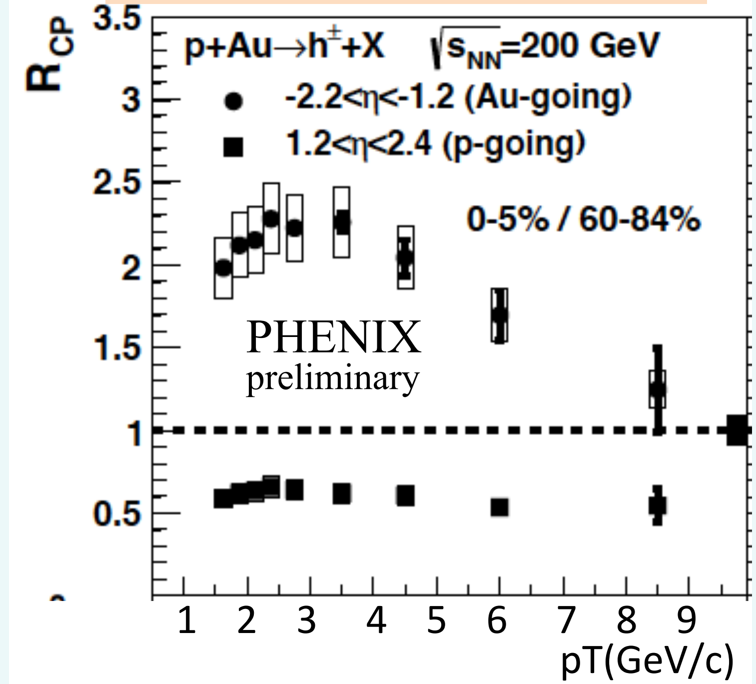
FONLL in reasonable agreement with data

pA: π0, h±

R_{pA}: π^0 in central rapidity



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

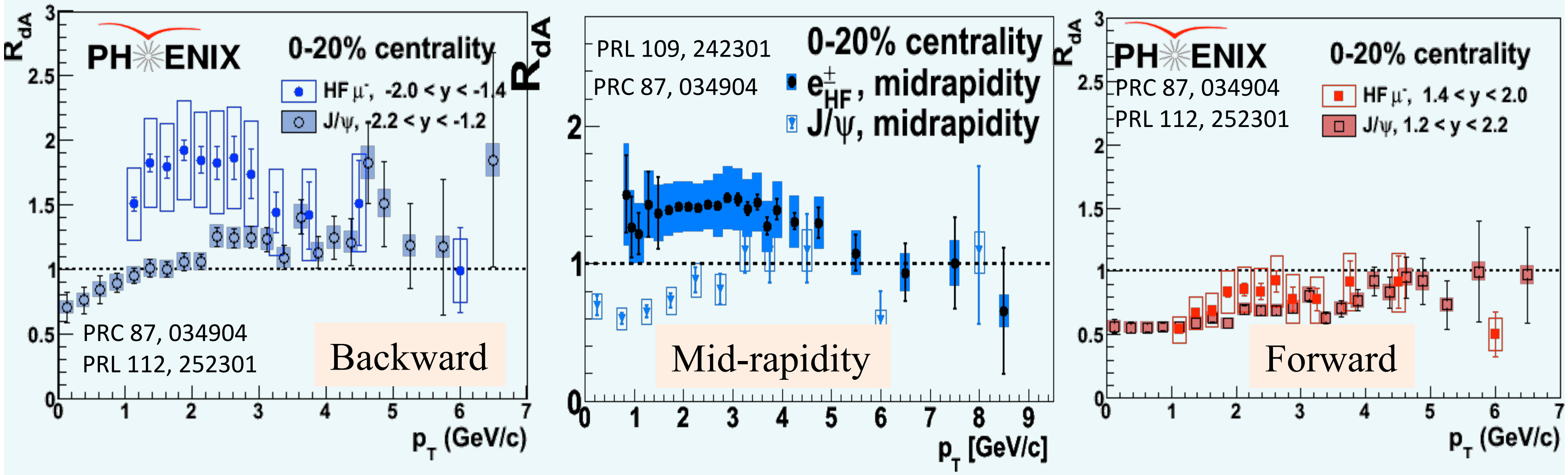
p-going: $R_{CP}<1$

Shadowing? Saturation?

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

Anti-shadowing?

p(d)A: Heavy Flavor



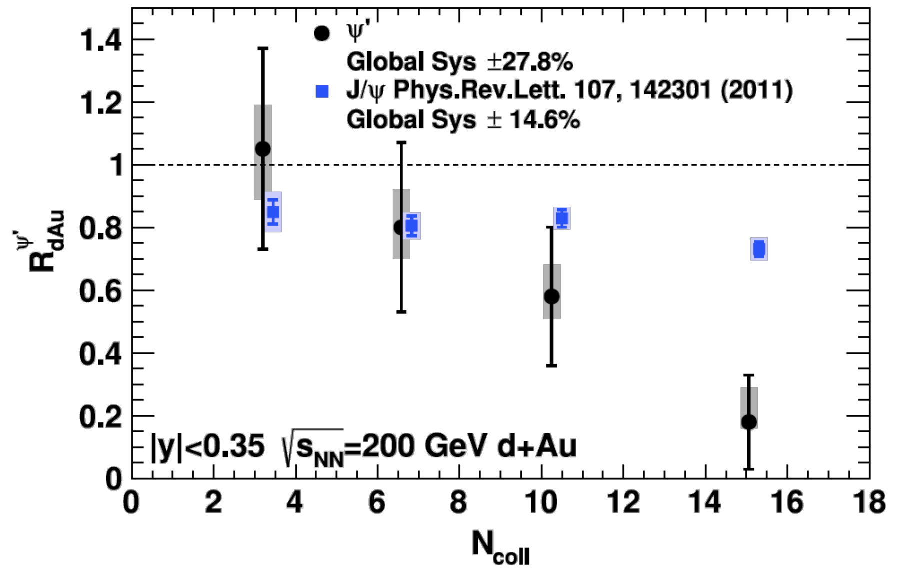
HF is suppressed in d-going direction and enhanced Au-going direction

- Similar to light hadrons
- Parton scattering, shadowing, energy loss, etc.

J/ψ breakup

p(d)A: Charmonia

PRL 111, 202301



Breakup of quarkonia due to interaction with nuclear matter

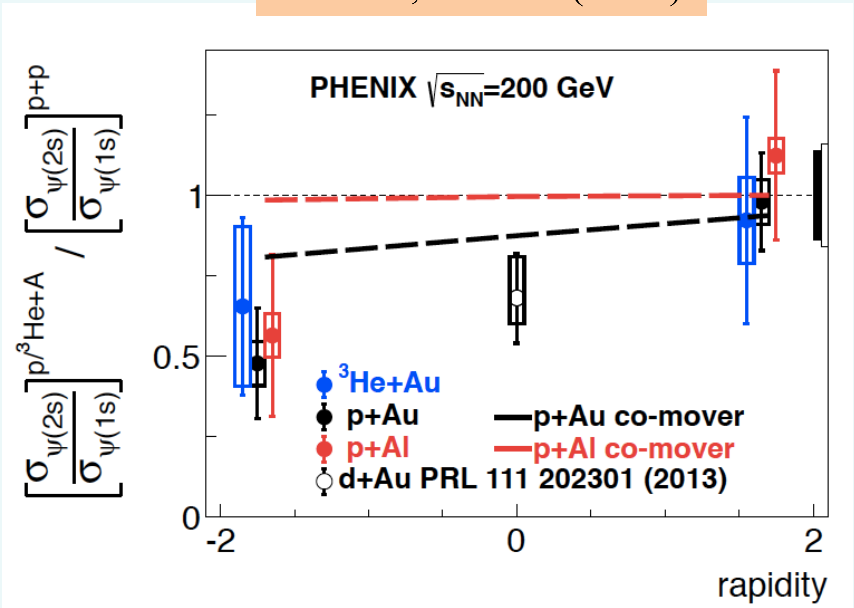
Larger suppression of the weakly bound state ψ'

Larger suppression of ψ' at nucleus going direction

Breakup due to interaction with co-moving particles

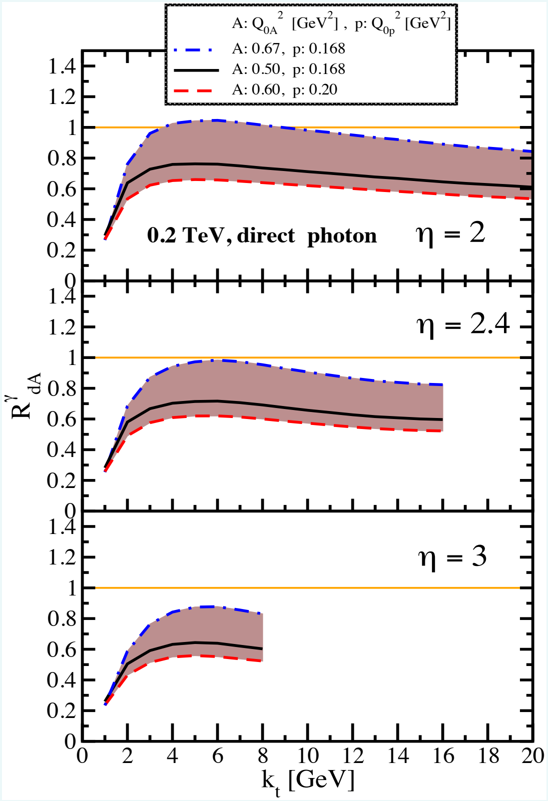
More data coming: Incl. J/ψ, Upsilon, single leptons

PRC 95, 034904 (2017)

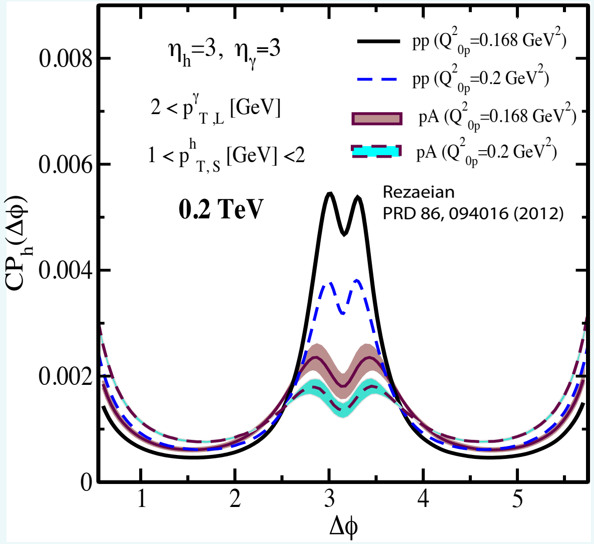


p(d)A: direct photons

CGC prediction for direct photon R_{pA}



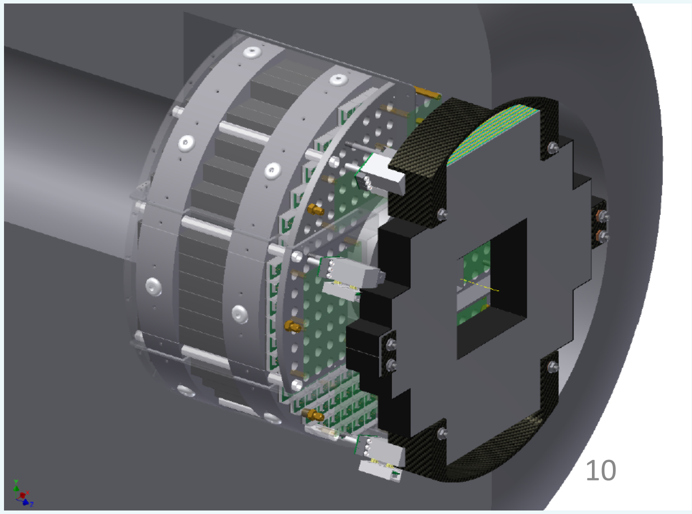
γ-h forward-forward correlations



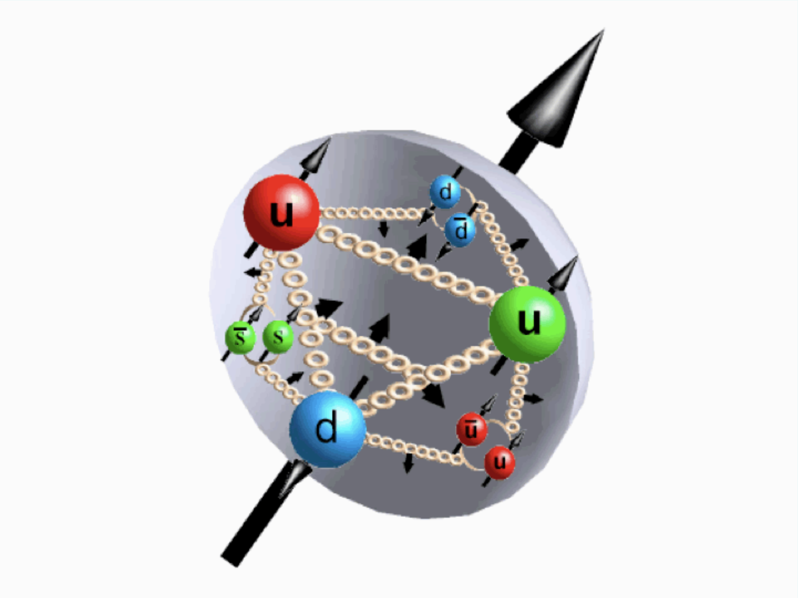
Selects large-x quark in p(d) and low-x gluon in A

MPC-EX: EMCal + Preshower
3.1<|η|<3.8
π^0/γ separation to >80 GeV/c

Analysis of 2016 dAu data is ongoing

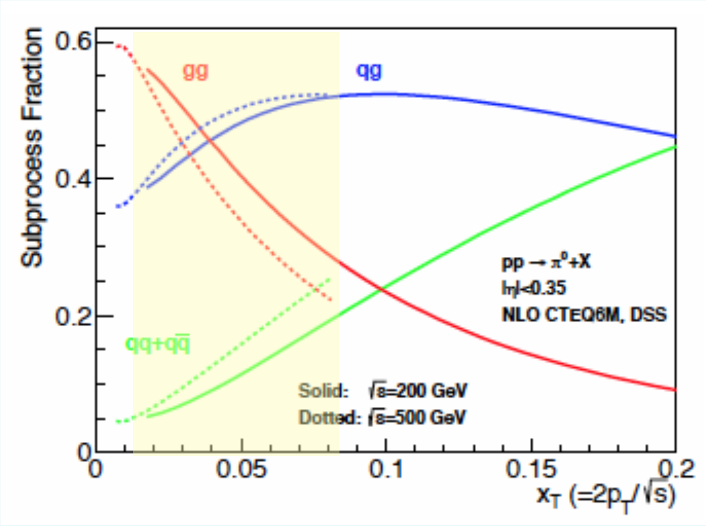


Spin Asymmetries



ΔG: $\pi 0$ A_{LL}

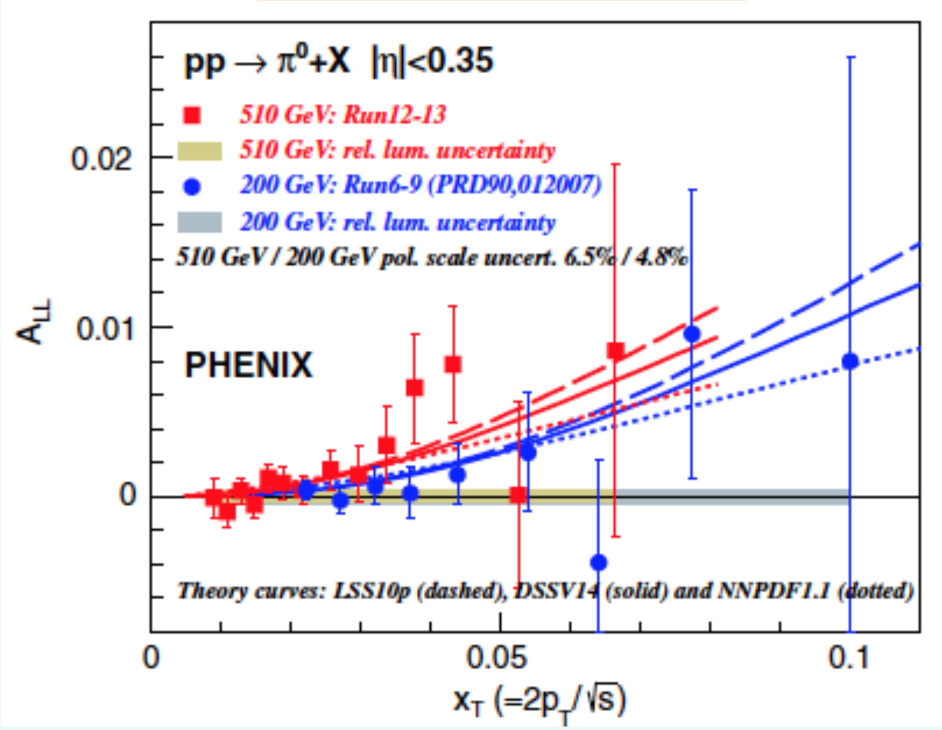
$$\frac{1}{2} = \frac{1}{2}\left(\Delta q + \Delta \bar{q}\right) + \Delta G + L_Z$$



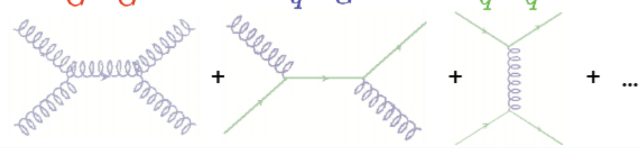
The most abundant probe in PHENIX

(triggering + identification capability)

PRD93, 011501 (2016)



$A_{LL} \sim \frac{\Delta G}{G}\frac{\Delta G}{G} \quad \frac{\Delta q}{q}\frac{\Delta G}{G} \quad \frac{\Delta q}{q}\frac{\Delta q}{q}$



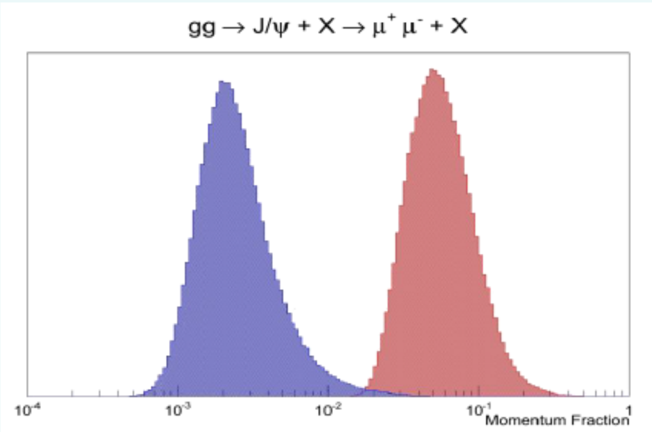
Non-zero A_{LL} associated with non-zero ΔG !

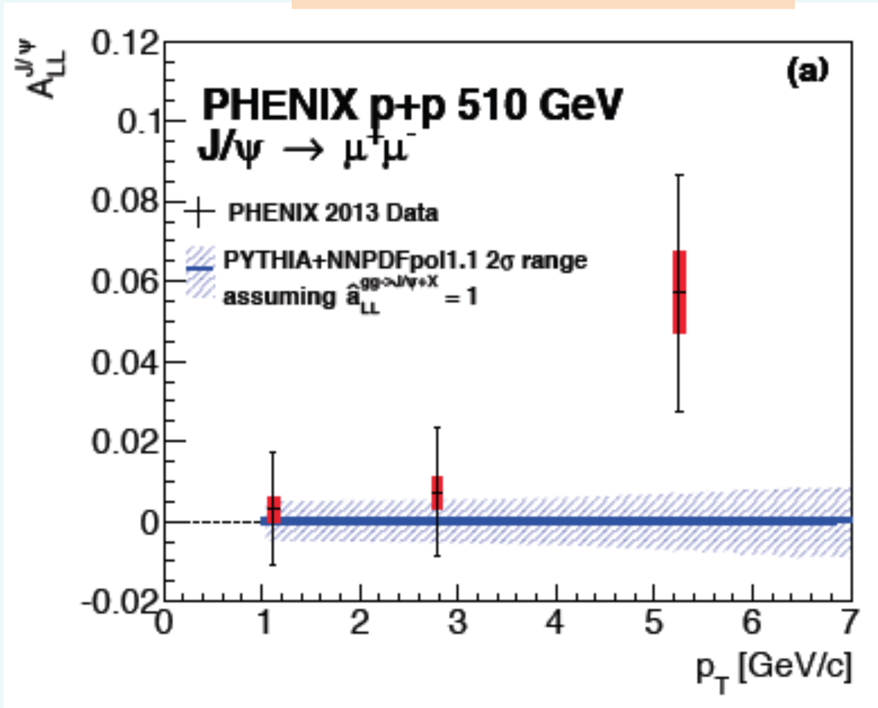
ΔG: Towards lower x

$$\frac{1}{2} = \frac{1}{2}(\Delta q + \Delta \bar{q}) + \Delta G + L_Z$$

pp → *J/ψ* at √s=510 GeV 1.2<|η|<2.4

PRD 94, 112008 (2016)





$$A_{LL} \propto \frac{\Delta g(x_1)}{g(x_1)} \cdot \frac{\Delta g(x_2)}{g(x_2)}$$

Get access to x down to 2×10^{-3}

Already constrained by RHIC

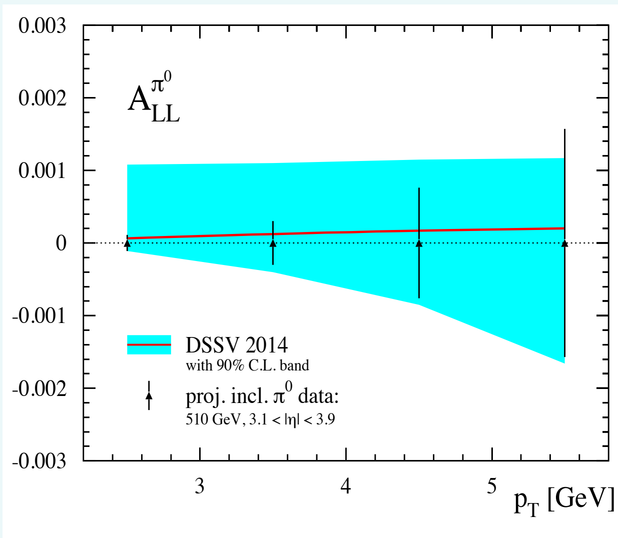
J/ψ production mechanism uncertainty
Not yet in the global fit

ΔG: Towards lower x

$$\frac{1}{2} = \frac{1}{2}\left(\Delta q + \Delta\bar{q}\right) + \Delta G + L_Z$$

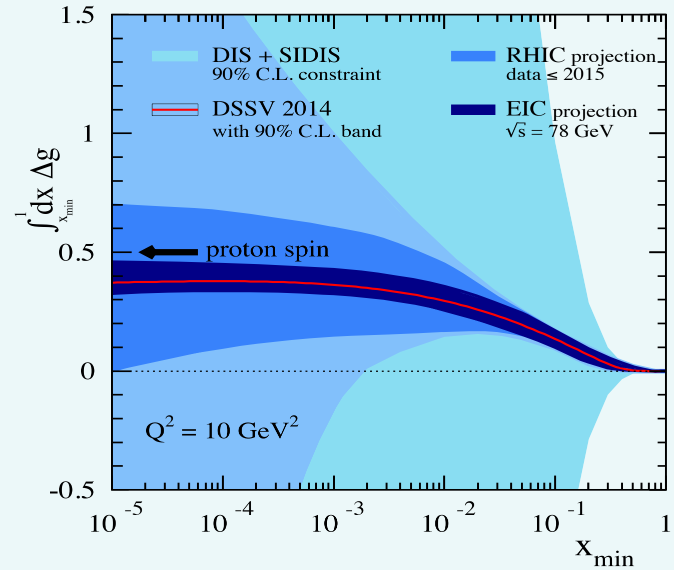
Projection

π0: 3.1<|η|<3.9



From available PHENIX+STAR data from 2011-15

Aschenauer, Stratmann,Sassot
PRD 92, 094030



π0 in forward region at √s=510 GeV:

Based on collected 2013 data

Probes lower x down to ~10^{-3}

Other channels also being measured (but with weaker stat. power)

γ, η, π±, h±, heavy flavor through e and μ, h-h, γ-h

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

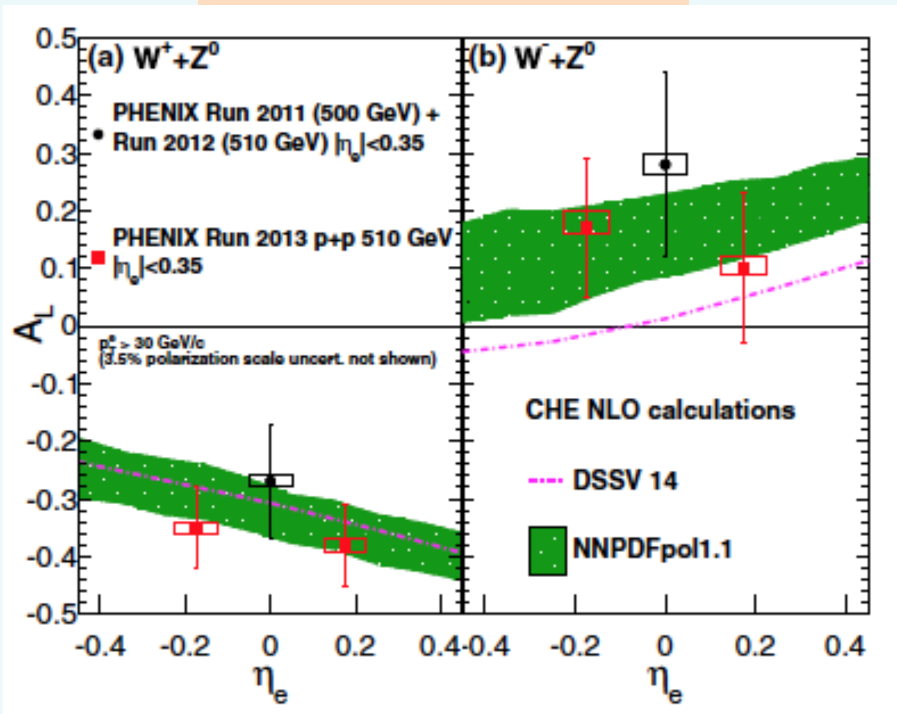
Δq-bar: $W^\pm \to e^\pm$

$$\frac{1}{2} = \frac{1}{2}\left(\Delta q + \Delta \bar{q}\right) + \Delta G + L_Z$$

$|\eta|<0.35$

Constrains flavor separated (anti-)quark polarization at high $Q \sim M_W$ at $x>0.05$, with no fragmentation involved (as in SIDIS)

PRD93, 051103 (2016)



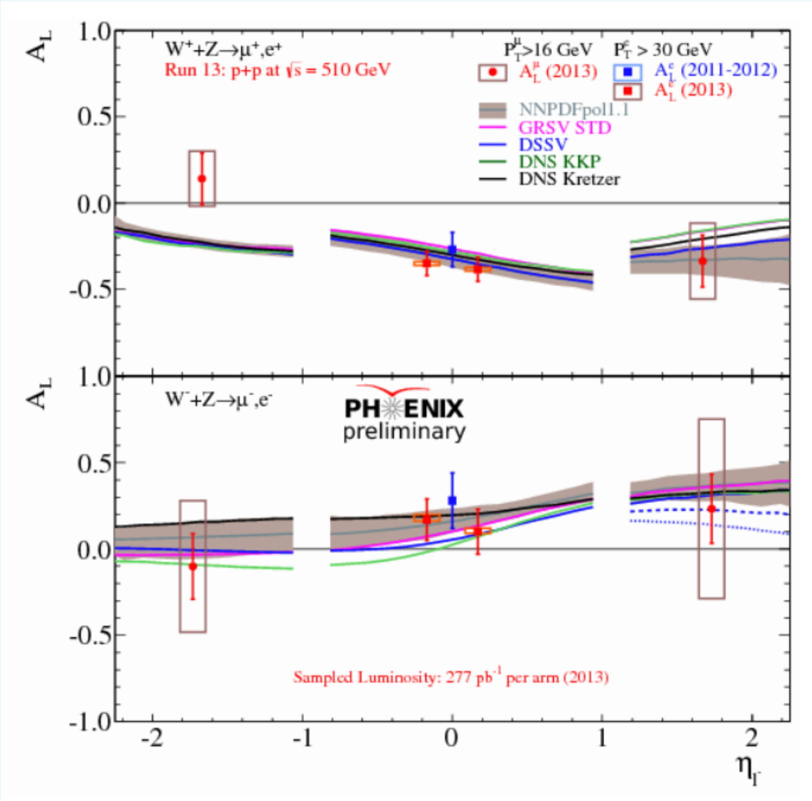
$$d_L \bar{u}_R \rightarrow W^-$$
$$u_L \bar{d}_R \rightarrow W^+$$

Δq-bar: W± → μ±

$$\frac{1}{2} = \frac{1}{2}(\Delta q + \Delta \bar{q}) + \Delta G + L_Z$$

1.2<|η|<2.4

Constrains flavor separated (anti-)quark polarization at high Q~M_W at x>0.05, with no fragmentation involved (as in SIDIS)



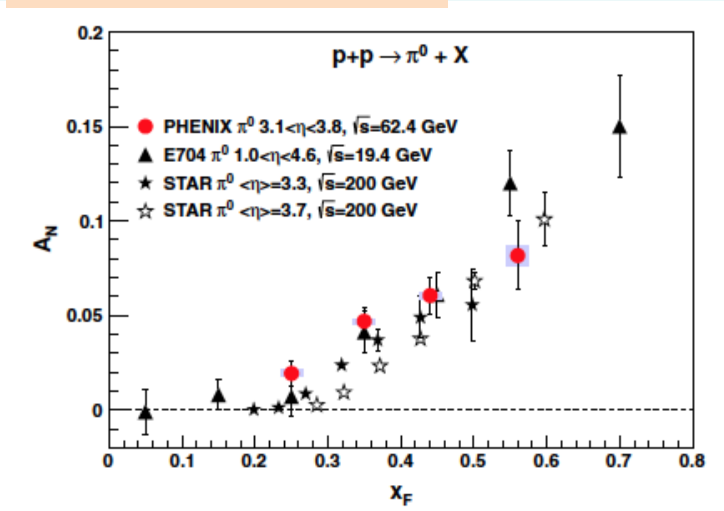
Uncertainties are large due to sizable background (S/B= 0.2−1)

Working to reduce syst. uncertainties

Publication in preparation

Forward-rapidity π0 A_N

PRD90, 012006 (2014)



Naïve collinear pQCD predicts

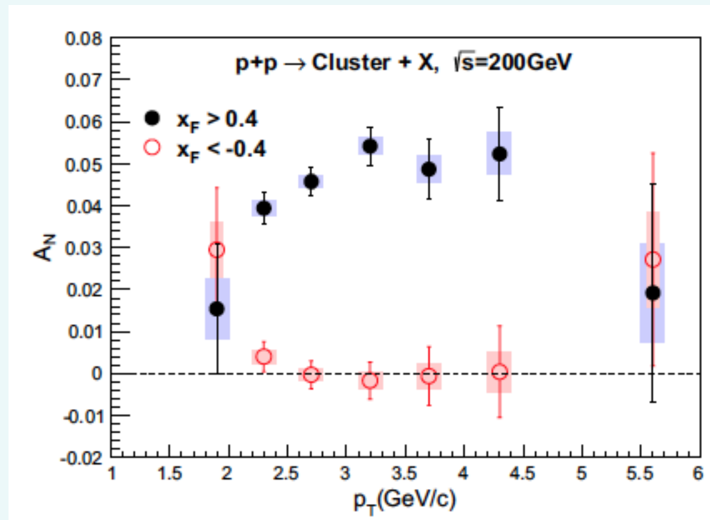
$$A_N \sim \alpha_s m_q / p_T \sim 0$$

Asymmetries survive at highest $\sqrt{s}$

Non-perturbative regime!

Asymmetries of the ~same size at all $\sqrt{s}$

Asymmetries scale with x_F



Collinear (higher twist) pQCD predicts

$$A_N \sim 1/p_T \text{ ?}$$

No fall off is observed out to p_T ~5 GeV/c

STAR showed no fall off up to ~7 GeV/c

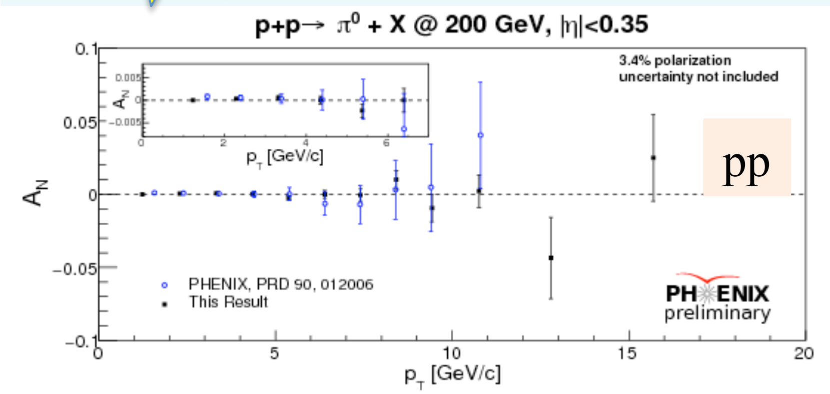
Underlying mechanism?

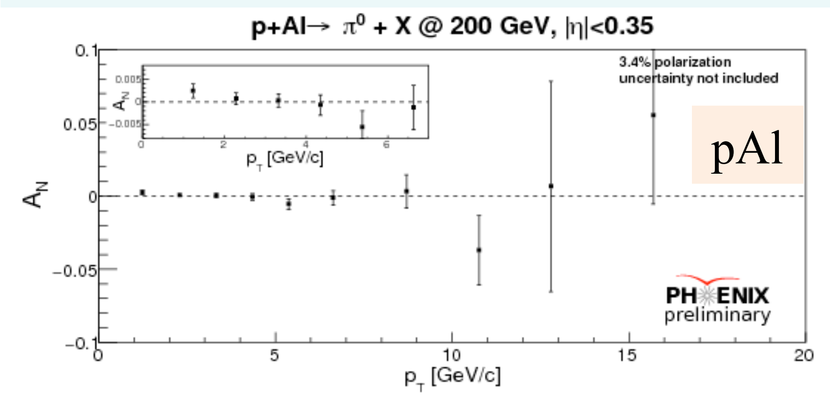
May involve initial state effect (Sivers-like), final state effect (Collins-like) or others

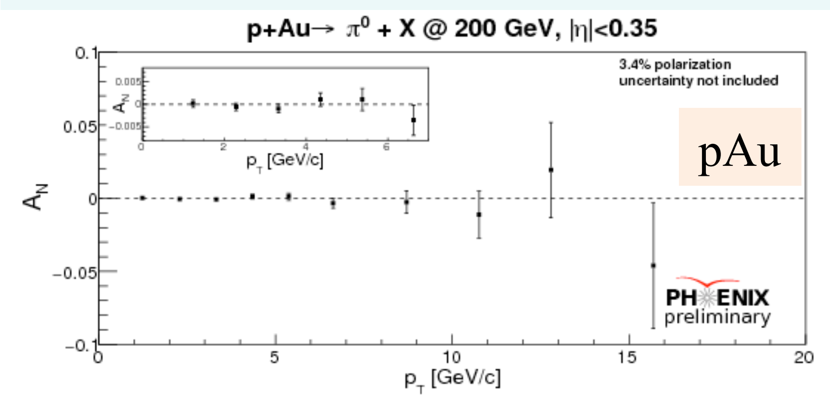
- Imaging in momentum space
- Transversity

pp vs pA!

Mid-rapidity π0 A_N







Improved pp results from 2015!

Consistent with 0

To 3×10^{-4} precision level at low p_T

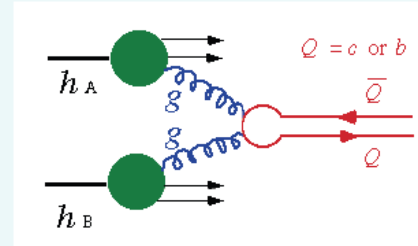
Sensitive to gluons

Used to constrain gluon Sivers effect:

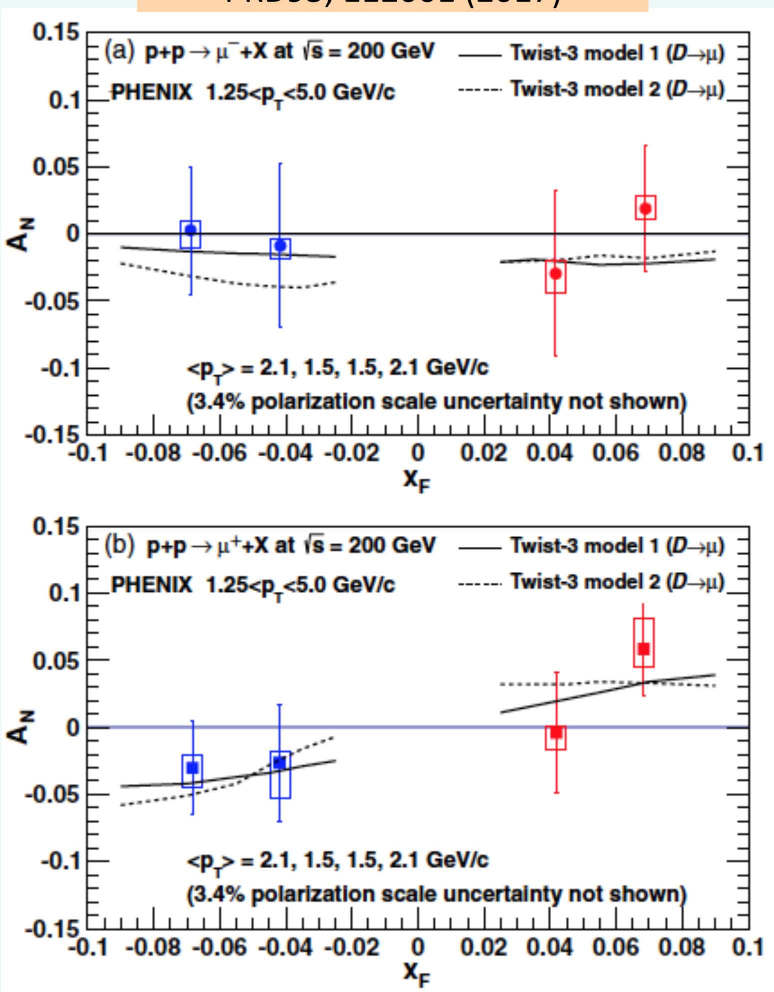
Anselmino et al, PRD 74 (2006), 094011

D'Alesio et al, JHEP 1509 (2015), 119

Open Heavy Flavor A_N



pp → μX
PRD95, 112001 (2017)



Dominated by gluon-gluon fusion

Used to constrain tri-gluon correlation in the Twist-3 collinear framework

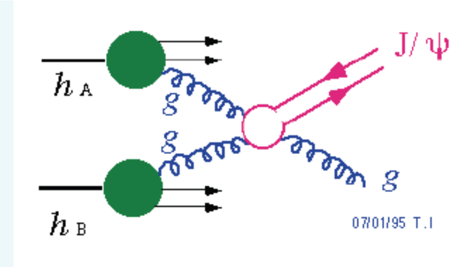
Z.Kang, J.Qiu, W.Vogelsang, F.Yuan, PRD78,114013

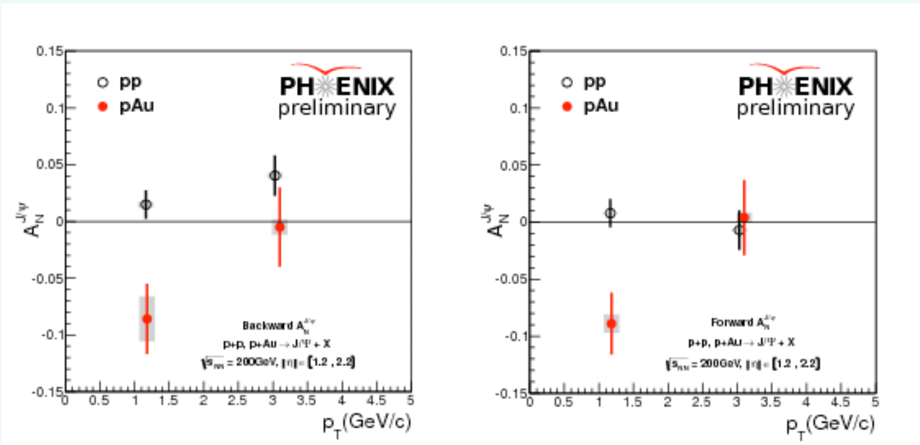
Y.Koike, S.Yoshida, PRD84,014026

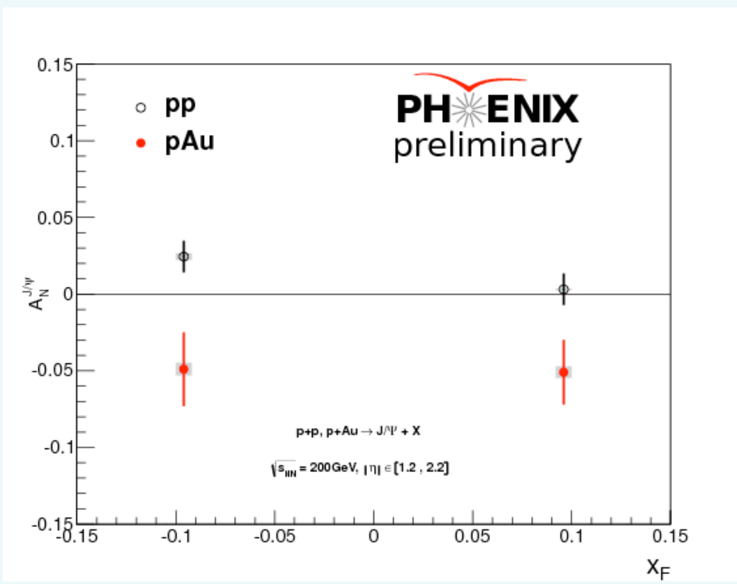
Significant reduction in uncertainties expected from 2015 data

pp vs pA!

J/ψ A_N







Improved pp results from 2015!

First ever pA→J/ψ A_N data!

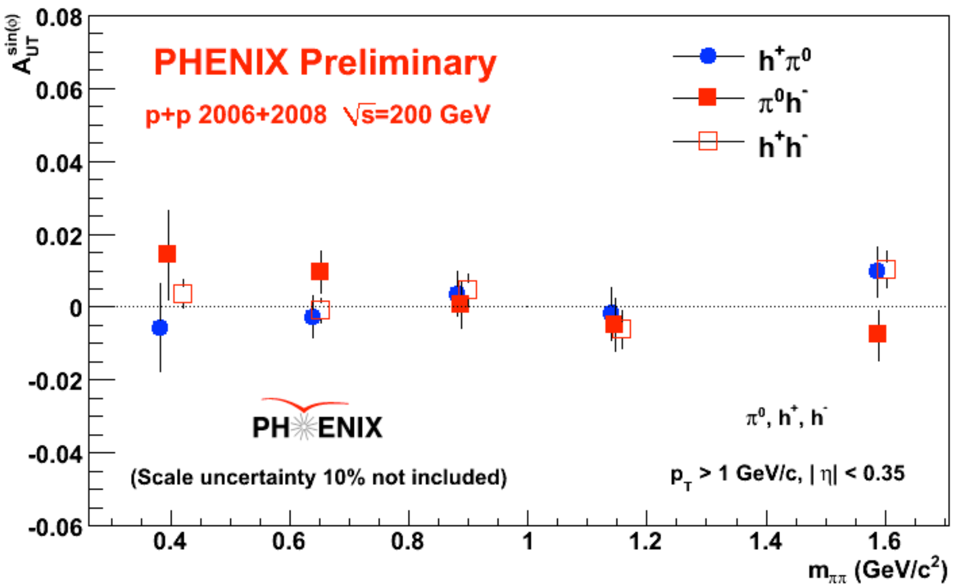
A_N sensitive to J/ψ production mechanism

F.Yuan, PRD78, 014024:

For non-zero gluon Sivers, A_N vanishes in color octet model, but survives in color singlet model

Access to transversity: IFF

In collinear (Twist-3) framework

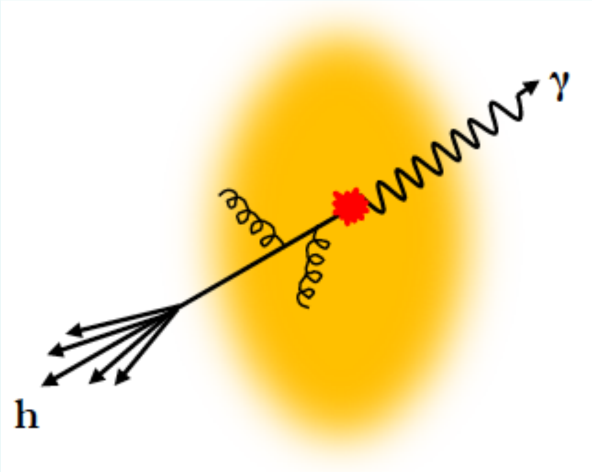


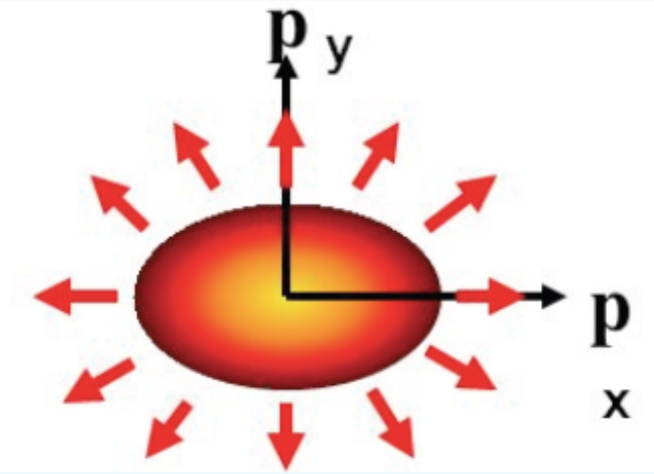
Much more data available from 2012 and 2015:

$|\eta|<0.35$: h^+h^-, $h^+\pi^0$, $h^+\pi^0$, $\pi^+\pi^-$, $\pi^+\pi^0$, $\pi^+\pi^0$

$1.2<|\eta|<2.4$: h^+h^-

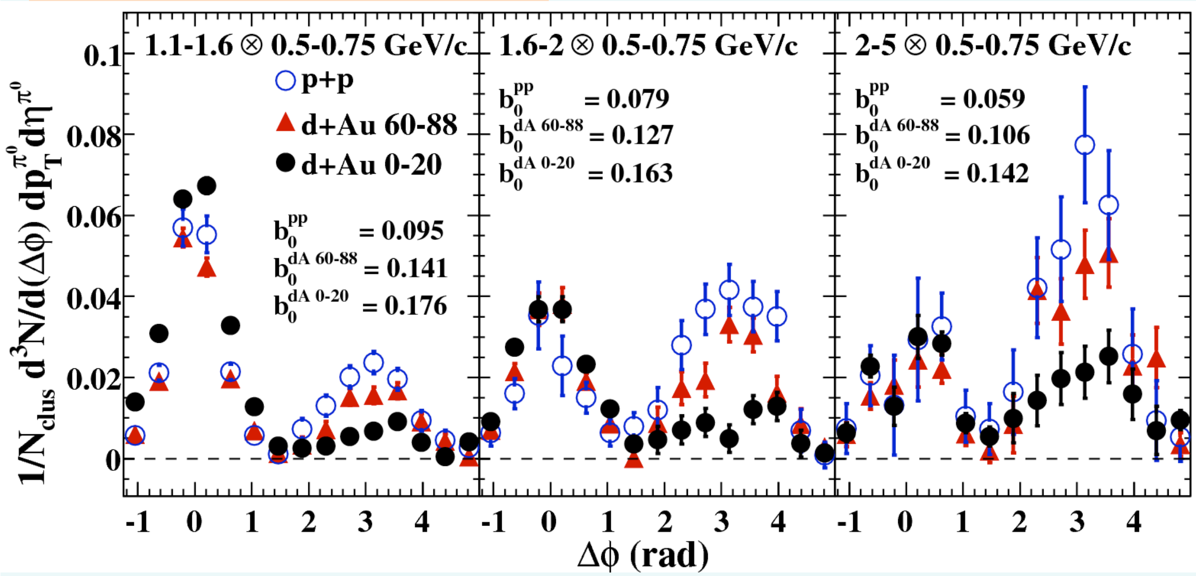
Correlations, Collectivity





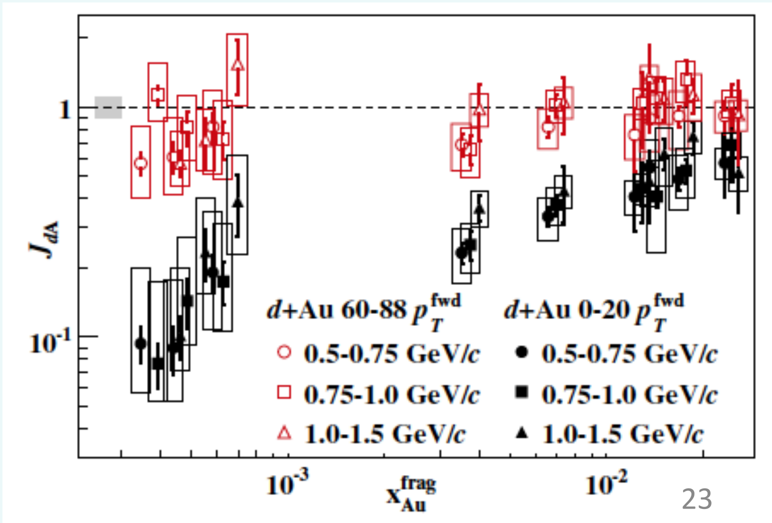
h-h correlation

PRL 107, 172301 (2011)



CGC => suppression of back to back correlation

$$J_{dA} = \frac{1}{\langle N_{coll} \rangle} \frac{\sigma_{dA}^{pair} / \sigma_{dA}}{\sigma_{pp}^{pair} / \sigma_{pp}}$$



Other mechanisms (including final state effects) may lead to the similar suppression

E.g. CNM energy loss

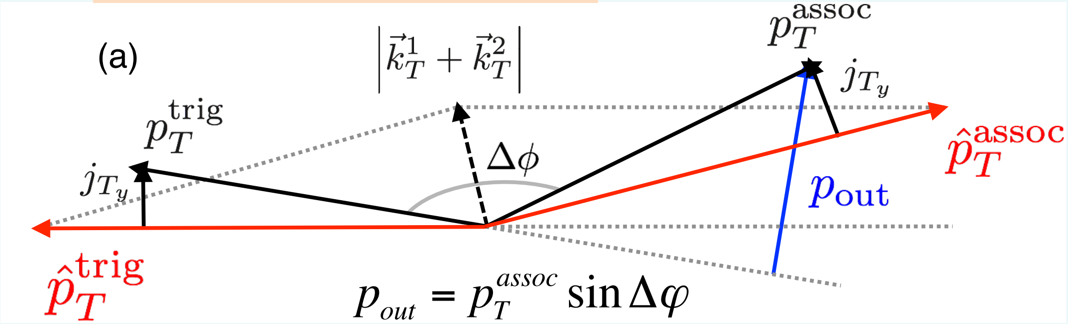
γ-h correlation: final state effect reduced

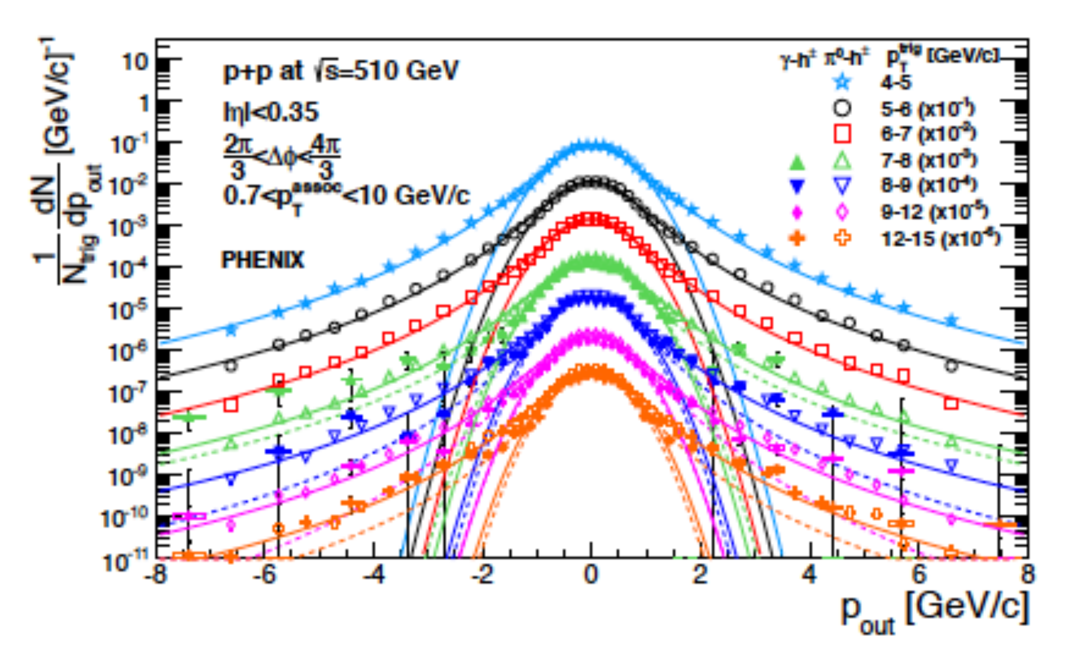
MPC-EX allows for π^0/γ separation to >80 GeV/c

Run16 dA analysis ongoing

π^0-$h^\pm$ and γ-$h^\pm$ correlation

PRD 95, 072002 (2017)





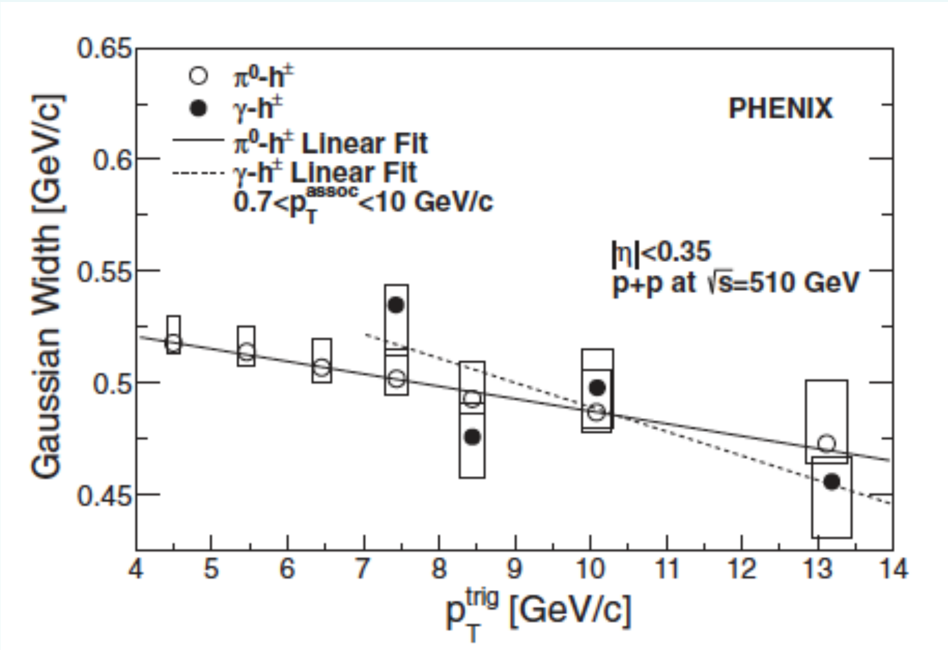
Gives access to non-perturbative transverse momentum effects:

p_{out} includes k_T and j_T

Measure p_{out} from azimuthal correlation, as a function of p_T^{trig}

From TMD factorization, expect increasing transverse momentum (p_{out}) with increasing hard scale (p_T^{trig})

π^0-$h^\pm$ and γ-$h^\pm$ correlation

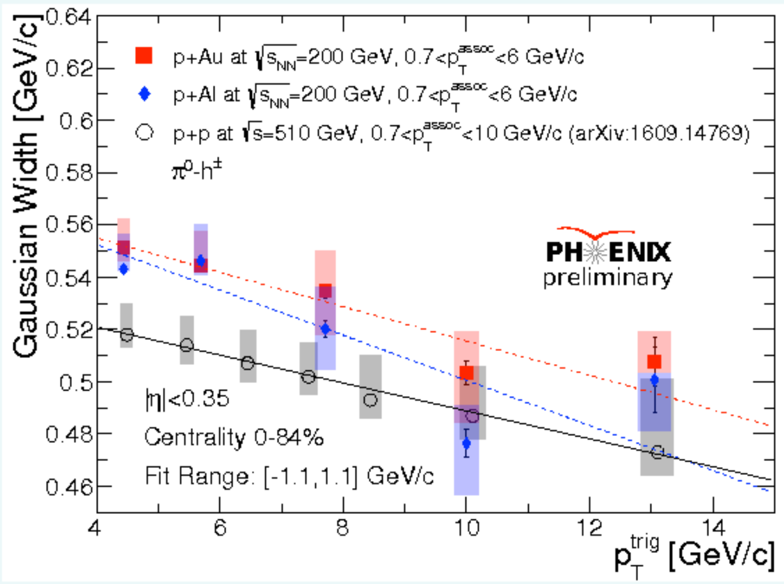


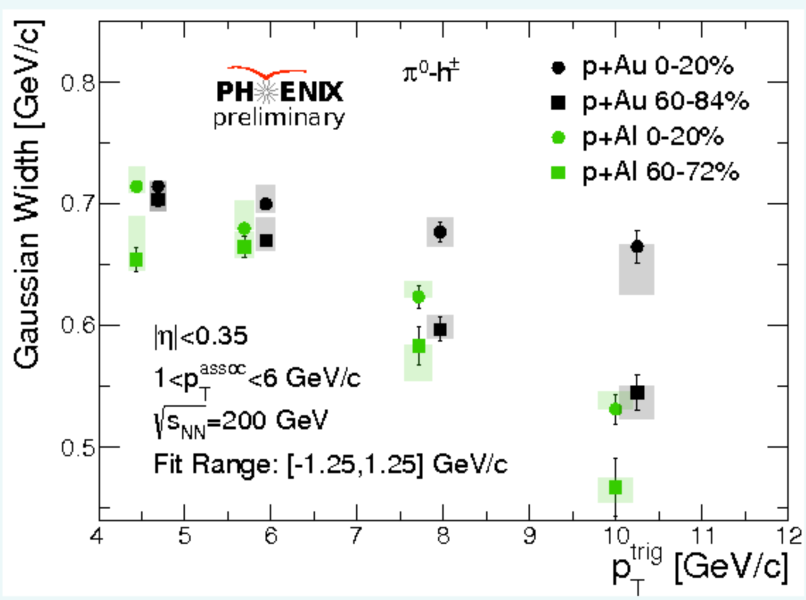
Decreasing width!

Factorization breaking?

pp vs pA!

π^0-$h^\pm$ correlation





Stronger p_T^{trig} dependence in pA

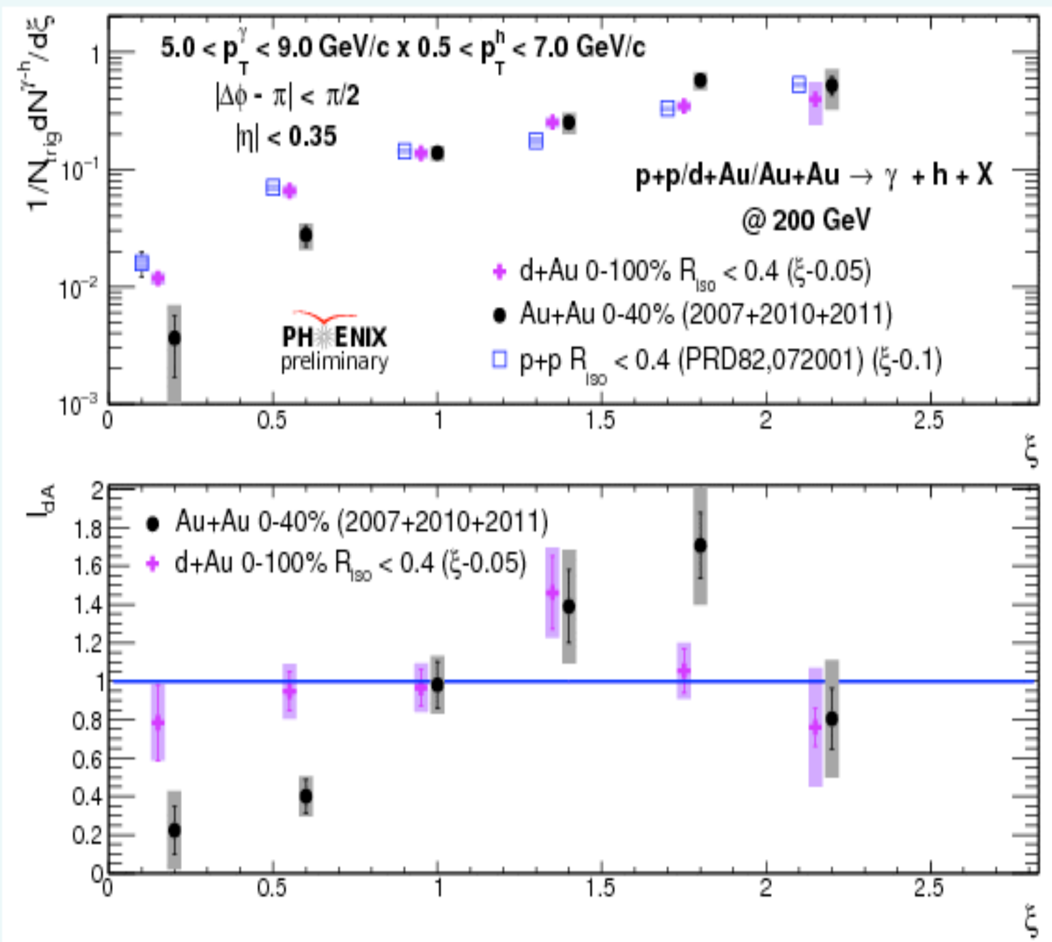
- Stronger gluonic field?
- Multiple scattering?

Clear centrality dependence, particularly in heavy nucleus (Au)

- kT broadening?
- Multiple scattering?
- Flow?

pp vs pA!

γ-h± correlation => FF



Access FF with integrated away side yield

$$p_T^{\gamma} \approx p_T^{Jet} \qquad z_T = \frac{p_T^h}{p_T^{\gamma}}$$

$$\varsigma = \ln\left(\frac{1}{z_T}\right) \qquad D(\varsigma) = \frac{1}{N_{evt}} \frac{dN(\varsigma)}{d\varsigma}$$

FF modification:

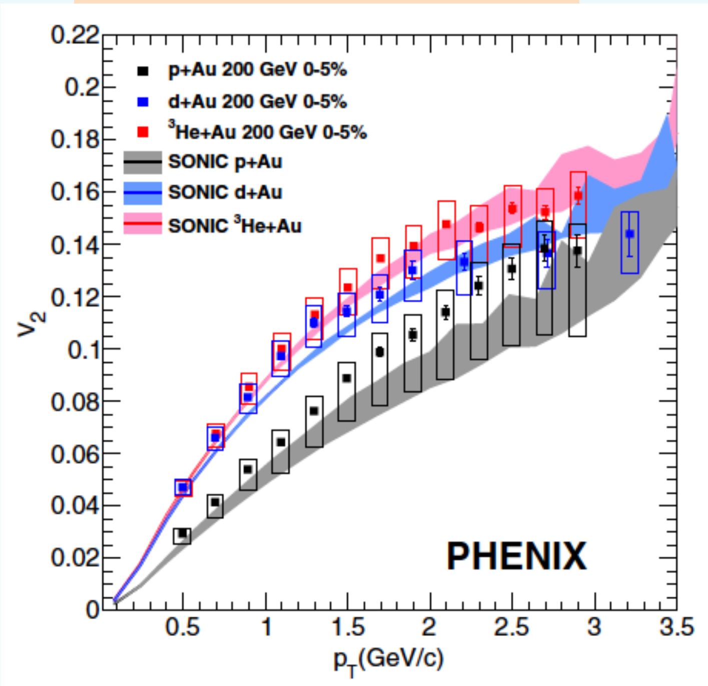
$$I_{dA} = \frac{Y_{dA}}{Y_{pp}} \approx \frac{D_{dA}(\varsigma)}{D_{pp}(\varsigma)}$$

No FF modification in dAu (within uncertainty)

Significant FF modification in AuAu

Collectivity (Flow)

PRD 95, 034910 (2017)



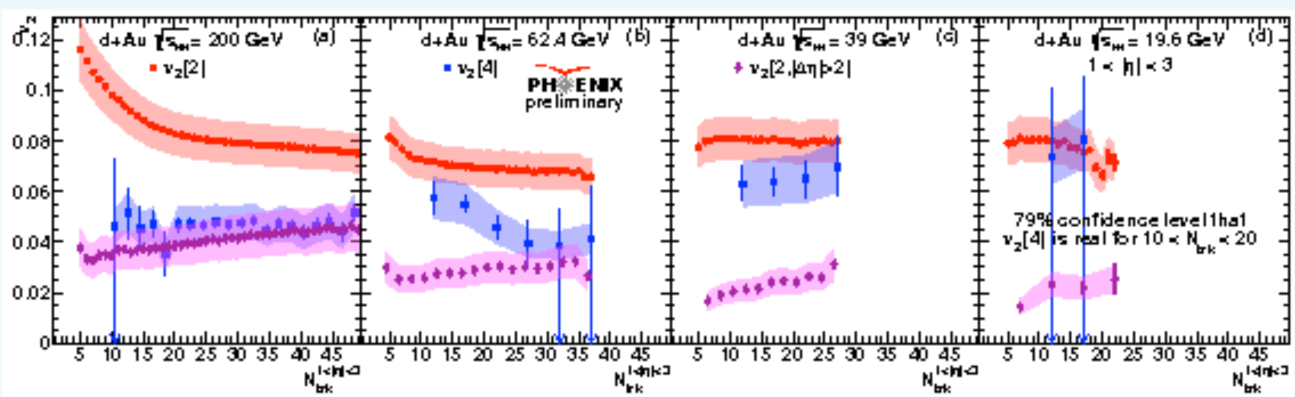
May be contributed by multiple particle correlation in CGC

Geometry and energy scan from PHENIX:

v_n in p/d/^{3}He + Au and p+Al at $\sqrt{s}$=200 GeV

v_n in d+Au $\sqrt{s}$=200, 62.4, 39, 19.6 GeV

PID-ed v_n



Summary

- ✓ A lot of PHENIX results contributing to all aspects of Cold QCD studies
- ✓ A lot more results to come

  Collected data on disk/tape are being actively analyzed

  New young researchers joining the collaboration

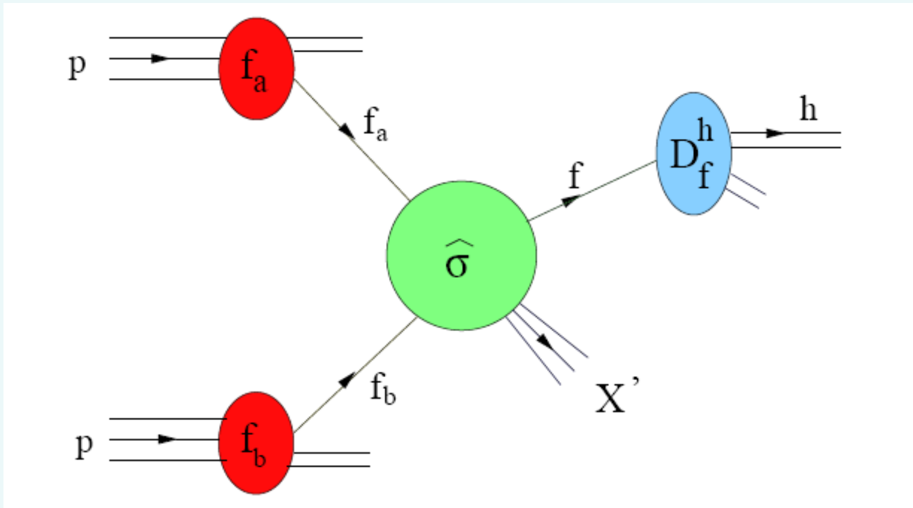
- ✓ Stay tuned for new PHENIX results!

PHENIX → sPHENIX transition for 2020+ physics: see Nils's talk next

√s [GeV]	p+p	p+Al	p+Au	d+Au	³He+Au	Cu+Cu	Cu+Au	Au+Au	U+U
510	✓								
200	✓	✓	✓	✓	✓	✓	✓	✓	✓
130								✓	
62.4	✓			✓		✓		✓	
39				✓				✓	
27								✓	
20				✓		✓		✓	
14.5								✓	
7.7								✓	

Backup

Factorization – a Cornerstone of QCD



Predictive power (for hard probes):

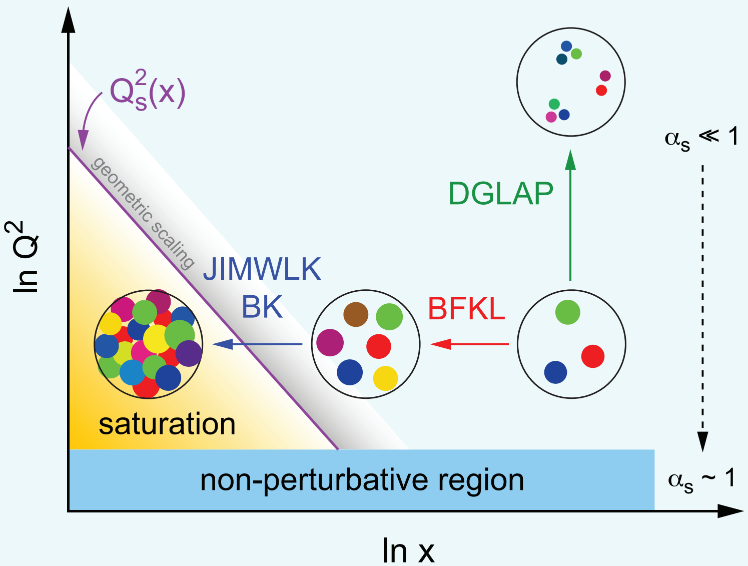
$$\sigma(pp \to hX) \sim f_a(x_1) \otimes f_b(x_2) \otimes \hat{\sigma}^{f_a f_b \to f}(\hat{s}) \otimes D_f^h(z)$$

Parton Distribution Func.
from experiment
Universal

Partonic x-section
from pQCD
Process dependent

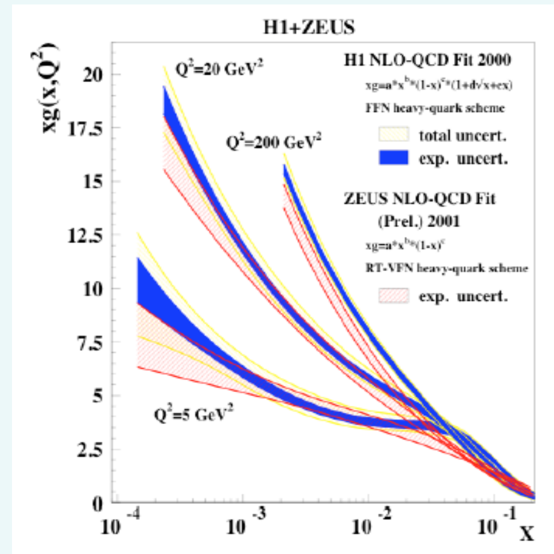
Fragmentation Func.
from experiment
Universal

Evolution in QCD



DGLAP

f(x) -> f(x,Q)



Evolution is different (more complicated) for:

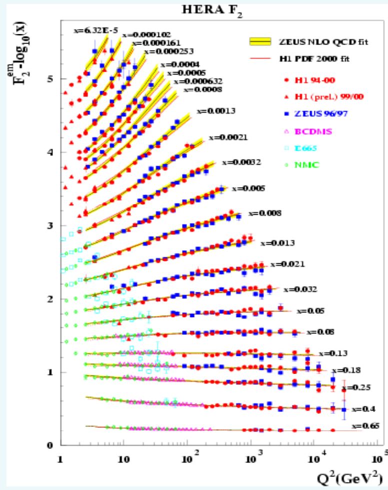
TMD: f(x) -> f(x,k_T)

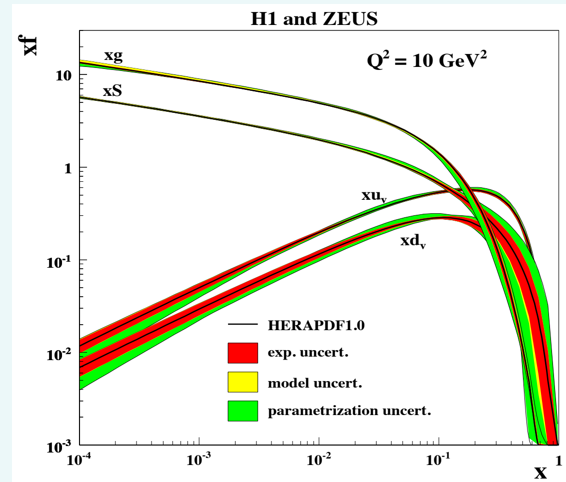
Twist-3: f(x) -> T(x,x)

➔ Important for Spin effects studies

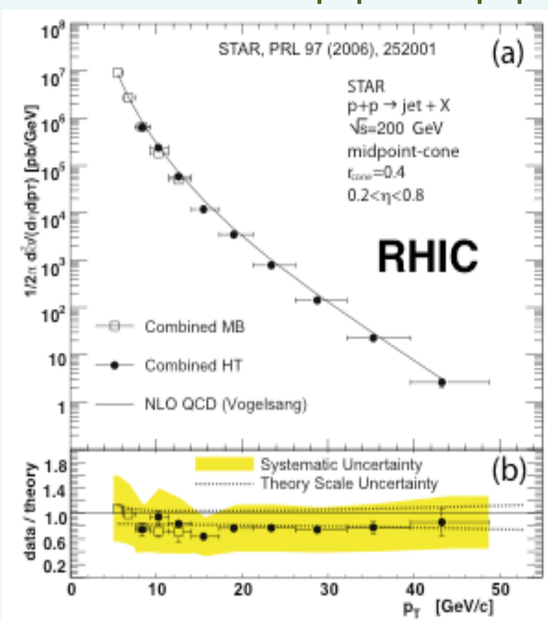
PDF (and FF) Universality

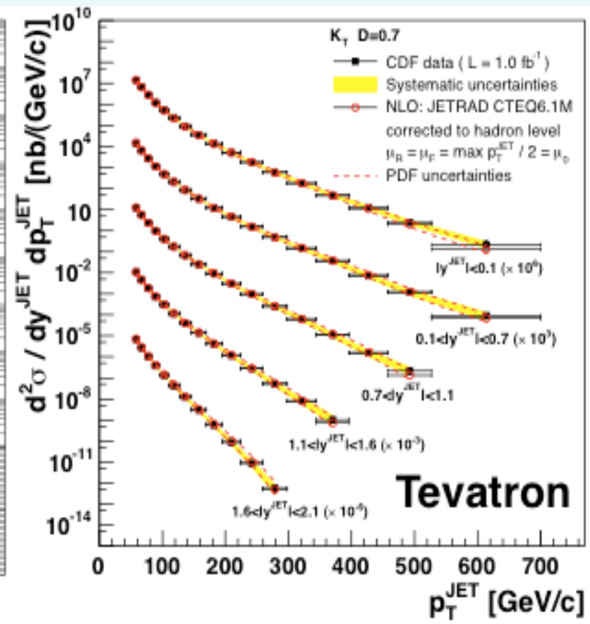
Measure PDFs in ep at 0.3 TeV (HERA):

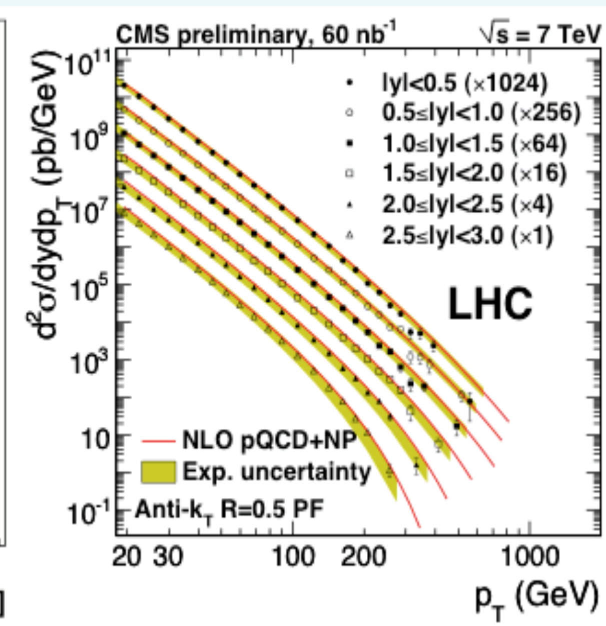


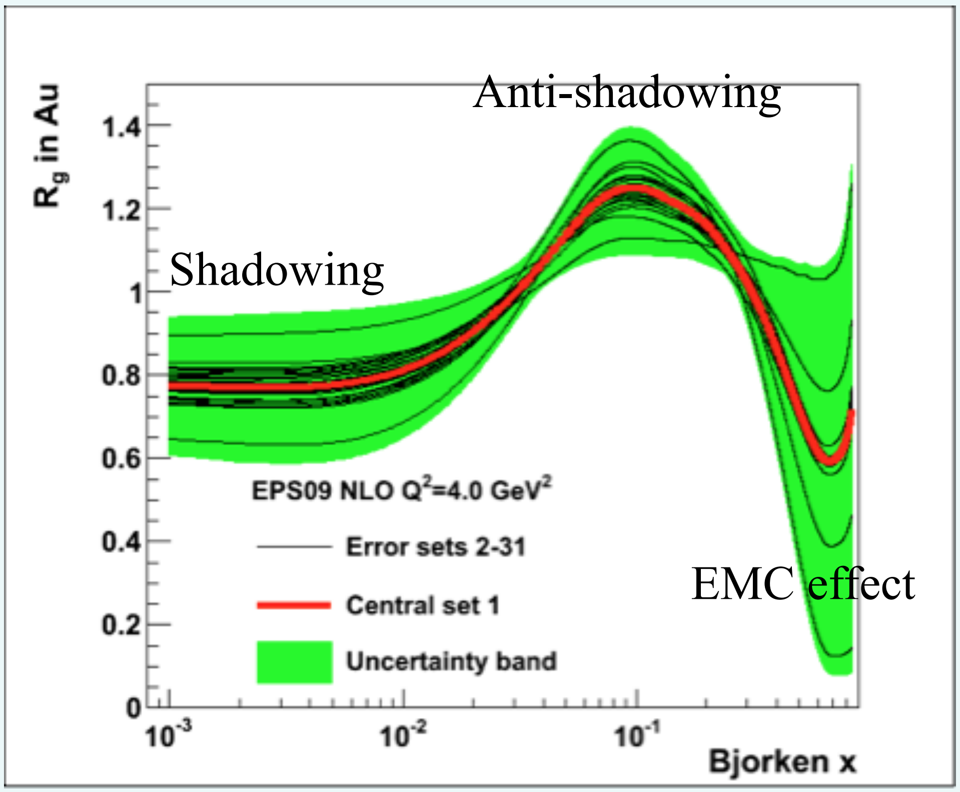


Predict p-p and p-pbar at 0.2, 1.96, and 7 TeV







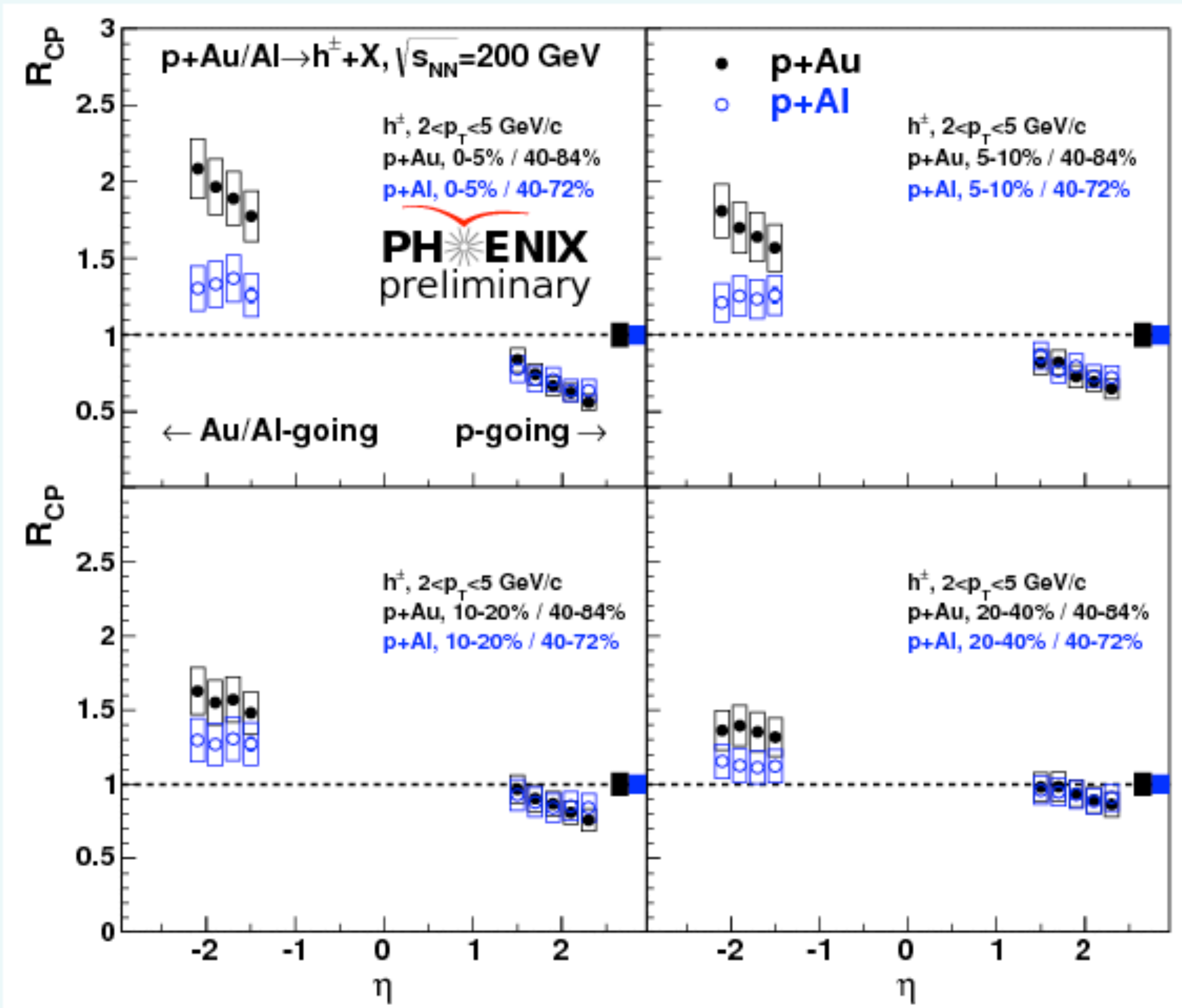


PDF in nuclei are modified compared to nucleon

Also:
Scattering with nuclear matter
(initial and/or final effect)
kT broadening
Energy loss

R_{pA}: forward-backward

Nucleus size and rapidity dependence

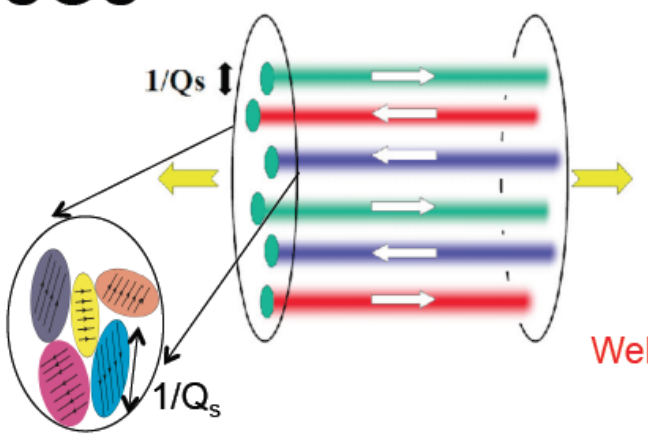


From J.Jia

Examples of initial vs final state scenarios

3

CGC



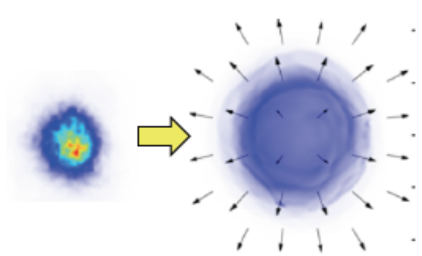
Domain of color fields of size $1/Q_s$, each produce multi-particles correlated across full η.

Uncorr. between domains, strong fluct. in Q_s

More domains, smaller v_n, more Q_s fluct, stronger v_n

Well motivated model framework, need systematic treatment

Hydro



Hot spots (domains) in transverse plane e.g IP-plasma, boost-invariant geometry shape

Expansion and interaction of hot spots generate collectivity

v_n depends on distribution of hot spots (ε_n) and transport properties.

Ongoing debate whether hydro is applicable in small systems