Forward Physics with (s)PHENIX

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For the (s)PHENIX Collaboration

Center for Frontiers in Nuclear Science

Forward Physics and Instrumentation from Colliders to Cosmic Rays

17-19 October 20128

Stony Brook

Topics to be discussed

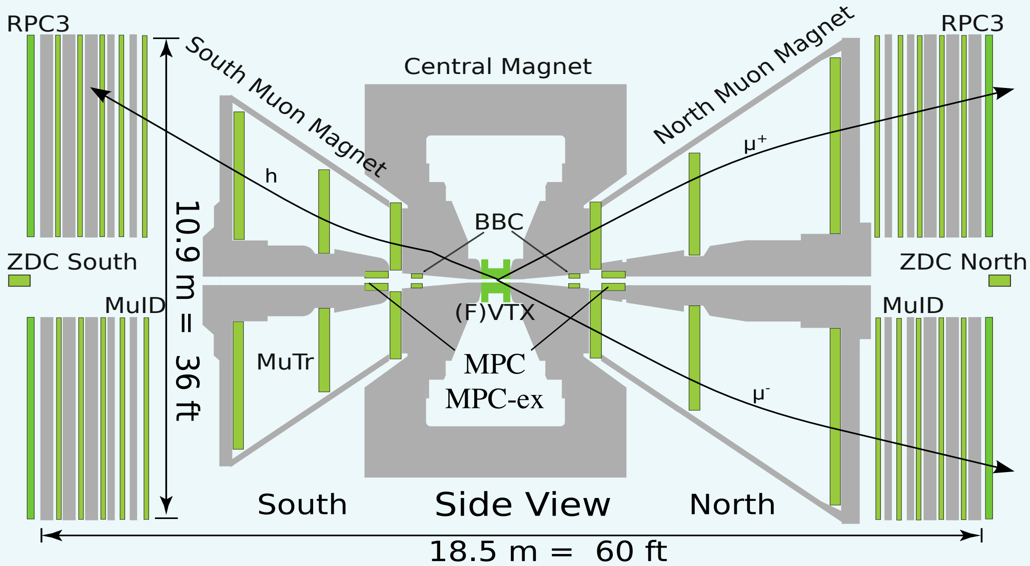
This meeting follows the successful previous "Workshop On Forward Physics And High-energy Scattering At Zero Degrees" held at the Nagoya University in Fall 2015 and 2017. This year, it aims at covering all aspects of forward physics and detector aspects at the LHC, at RHIC, and at the future EIC, benefiting from the experience gained at HERA and the Tevatron, as well as cosmic rays and neutrinos. The spirit of this meeting is to favor fruitful and informal discussions between experimentalists and theorists. Lots of time is devoted to discussion of new results, hot topics, and exciting open problems in forward physics from colliders to cosmic rays.

The topics discussed during the workshop are:

- Low x, Saturation, and Heavy Nuclei
- Photon Exchange, Pomeron, and Hard Diffraction
- Total Cross Section and Soft Diffraction
- Spin, GPDs, and TMDs
- Physics with Heavy Flavors
- Cosmic Rays and Neutrinos
- Future Experiments and Instrumentation

➢ Particle yields
  And nuclear modification
➢ Correlations
➢ Spin Asymmetries

PHENIX-Forward



PHENIX OPERATION ENDED IN 2016

Muon arms:

Vertex + Tracking + hadron absorbers

$1.2<|\eta|<2.2$: **μ, J/ψ, h±**

Muon Piston Calorimeter (MPC) + MPC-ex:

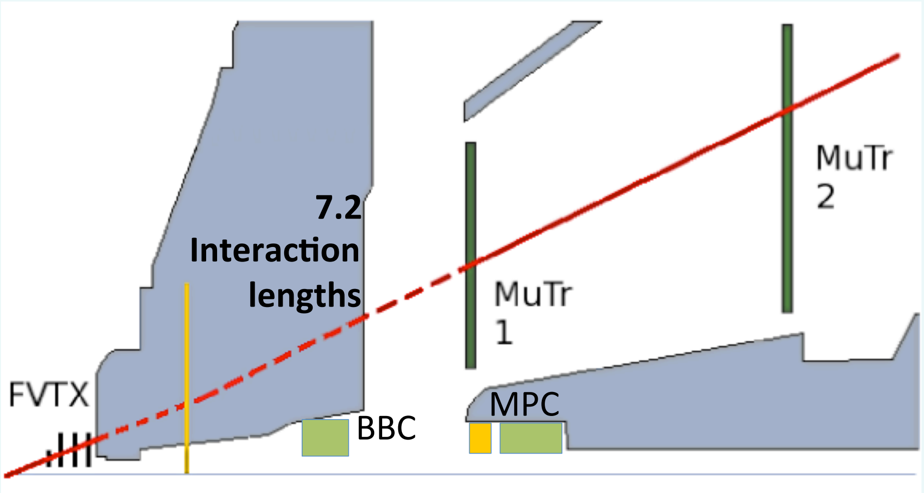
Pre-shower (MPC-ex) + crystal calorimeter

$3.1<|\eta|<3.8$: **π0, η, γ**

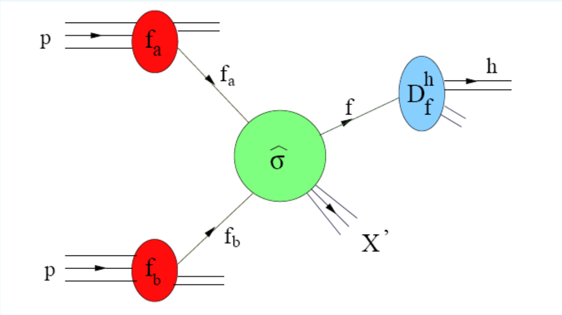
ZDC

Forward hadronic calorimeter

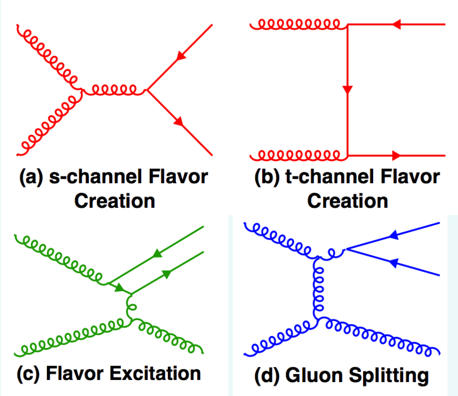
$|\eta|>6.5$: **n**



pQCD, PDF, FF

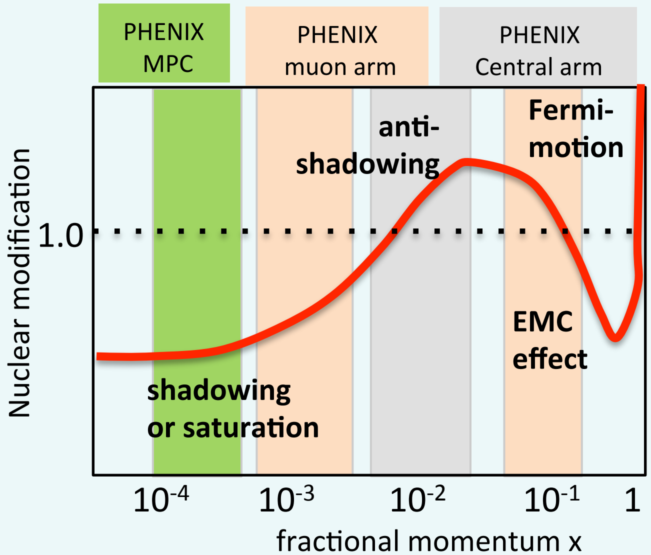


Production Mechanism

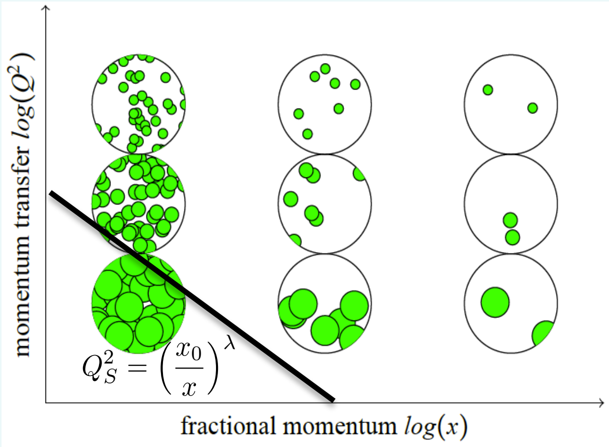


Particle Yields, Correlations

nPDF

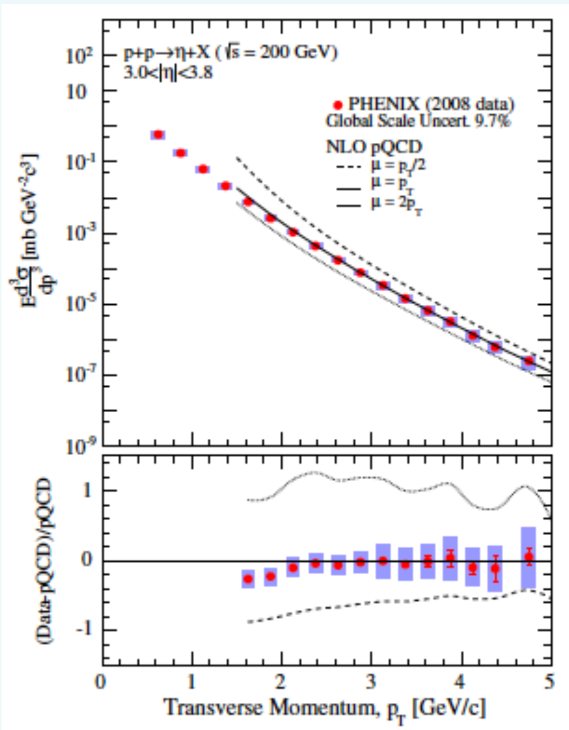


Gluon Saturation



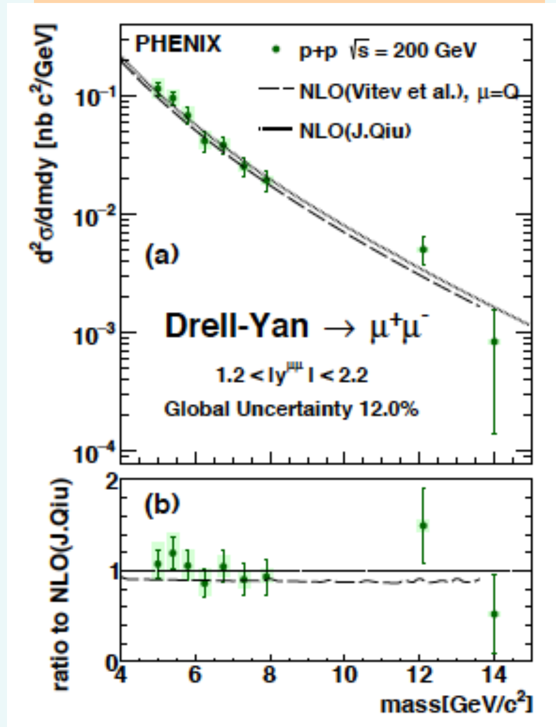
pp → η+X, μ+X, DY

pp → ηX, 3.3<|η|<3.8
PRD90, 072008 (2014)



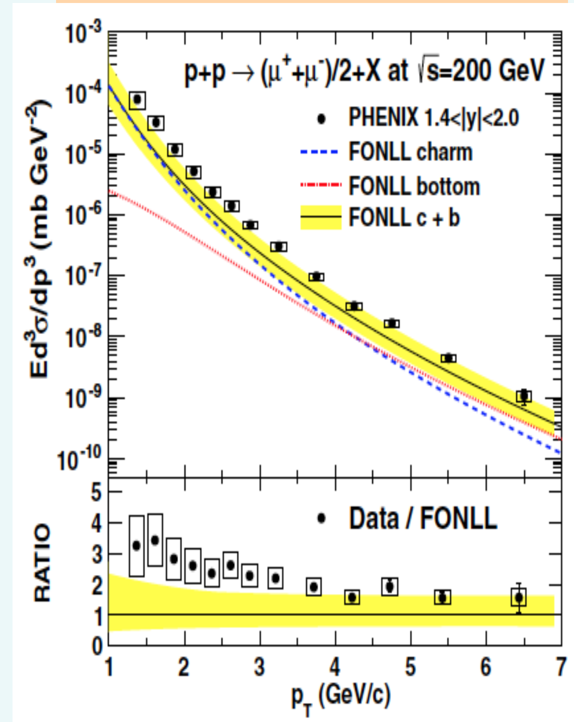
NLO pQCD in excellent agreement with data

pp: DY→μμ , 1.2<|η|<2.2
arXiv:1805.02448



NLO pQCD in excellent agreement with data

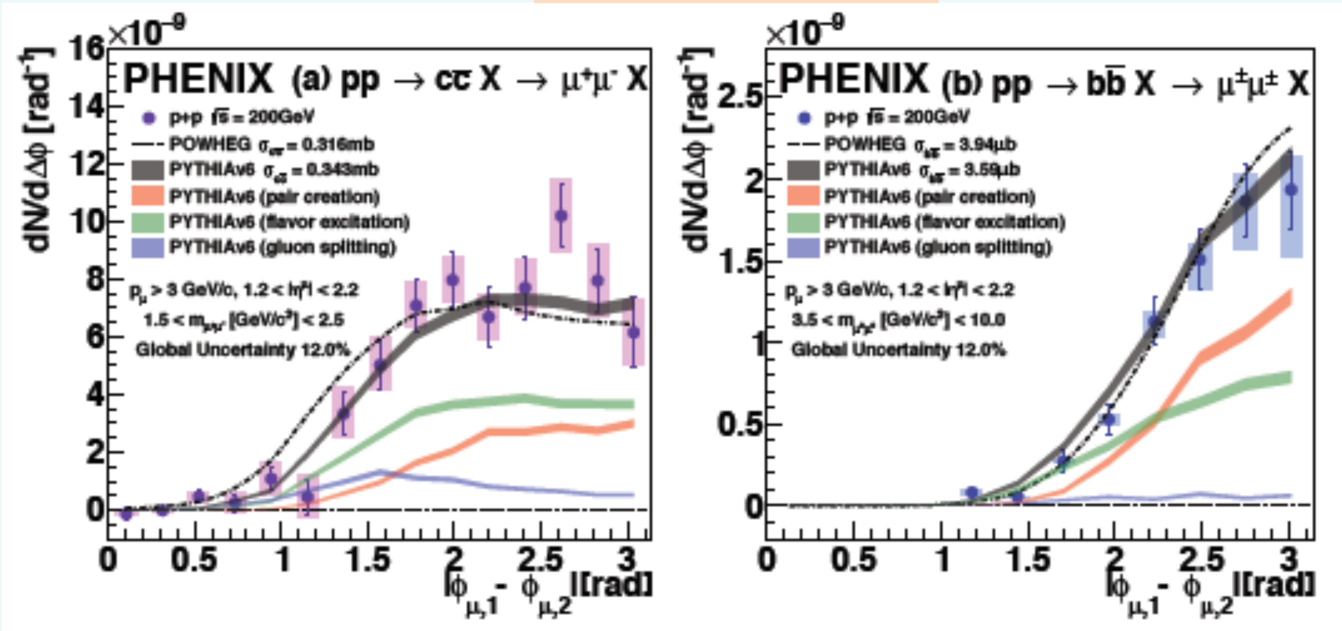
pp → μX, 1.4<|η|<2.0
PRD95, 112001 (2017)



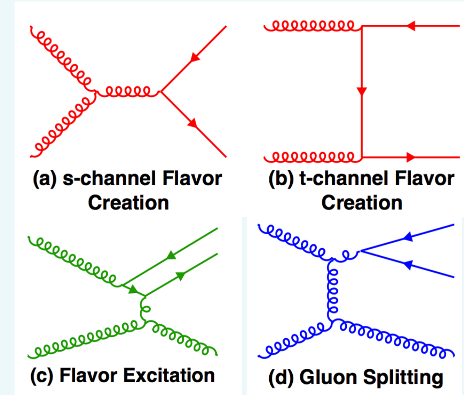
FONLL in reasonable agreement with data at higher pT
Tends to underestimate data at lower pT

$$pp \rightarrow (c\bar{c} \ or \ b\bar{b}) + X$$

arXiv: 1805.02448



Production Mechanism

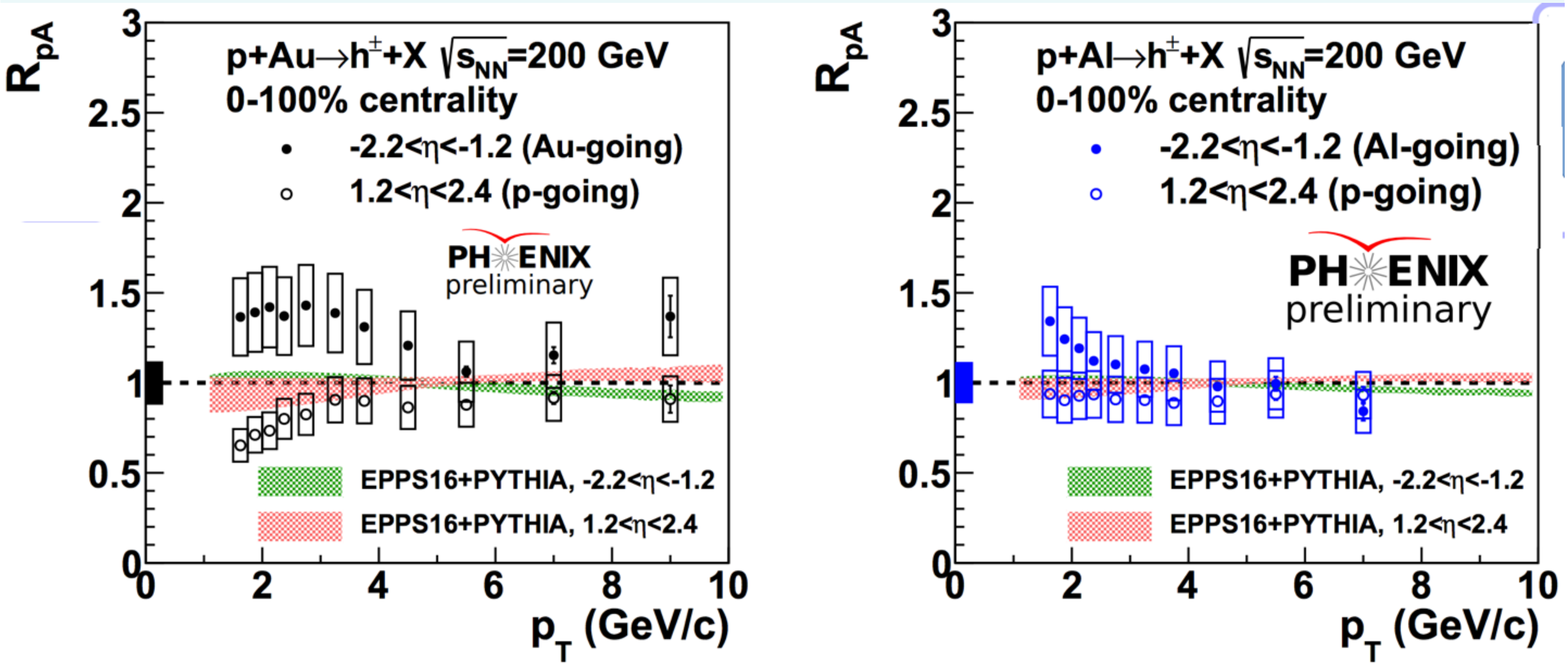


Angular correlations

$c\bar{c}$ produced mainly by NLO flavor excitation

$b\bar{b}$ produced mainly by LO pair creation

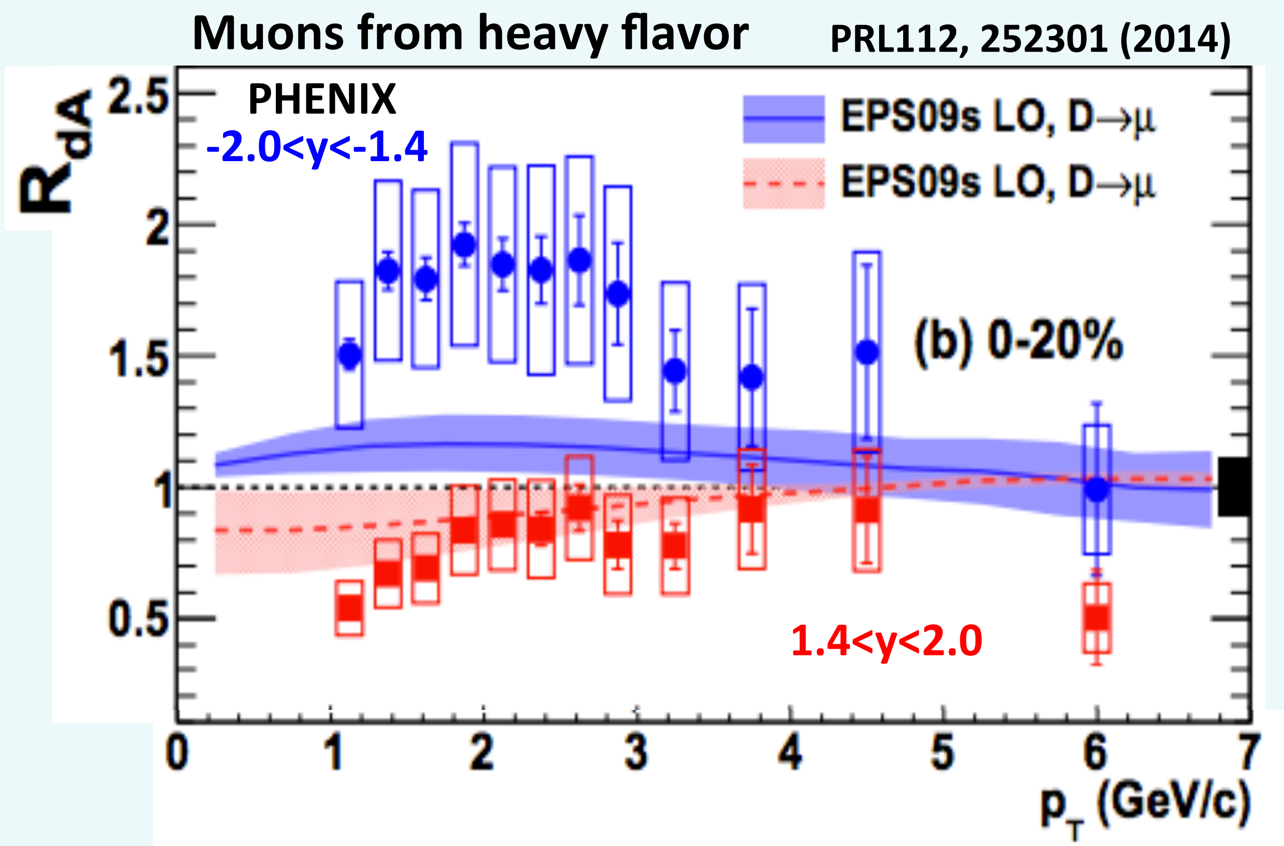
pA → $h^{\pm}$+X



p-going: $R_{CP}<1$
Shadowing? Saturation?
A-going: $R_{CP}>1$
Anti-shadowing?

… Though, not described by current nPDF

pA → $\mu^{\pm}$+X



Similar to $h^{\pm}$:

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

Shadowing? Saturation?

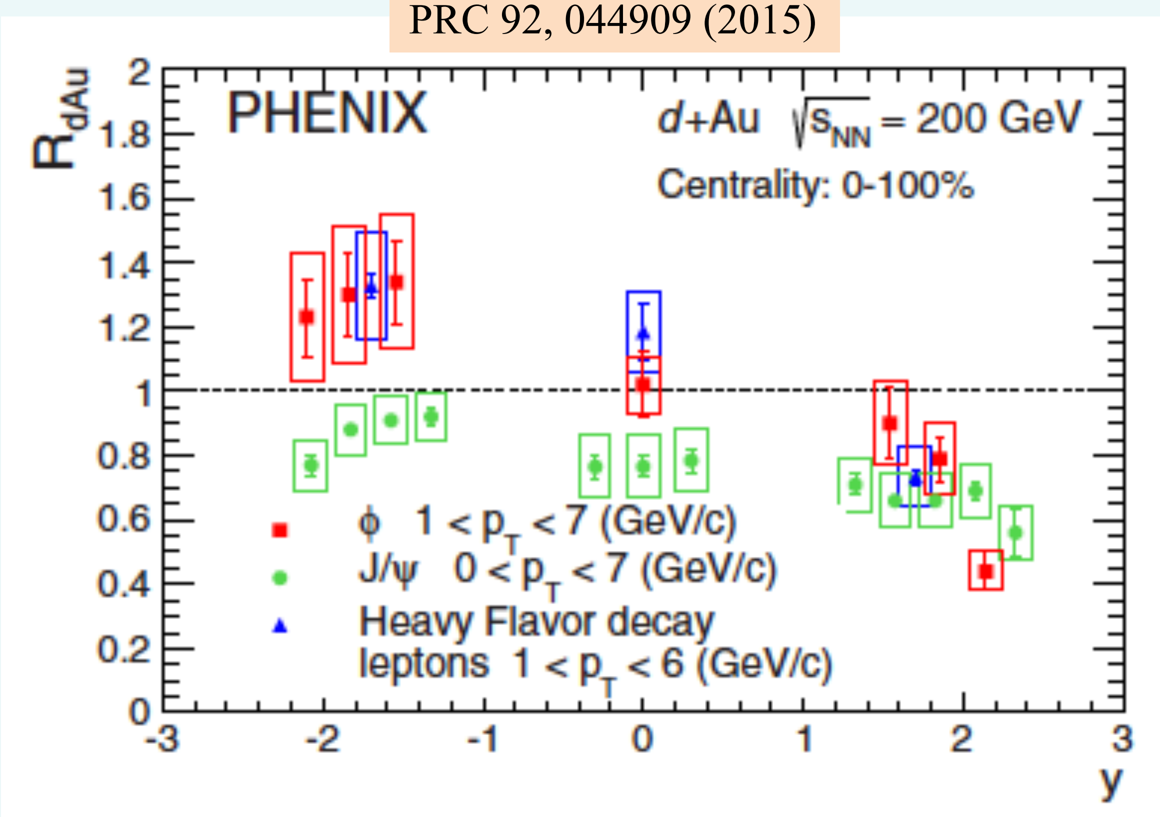
A-going: $R_{CP}>1$

Anti-shadowing?

Not supported by nPDF

pA → ϕ+X, J/ψ+X

PRC 92, 044909 (2015)



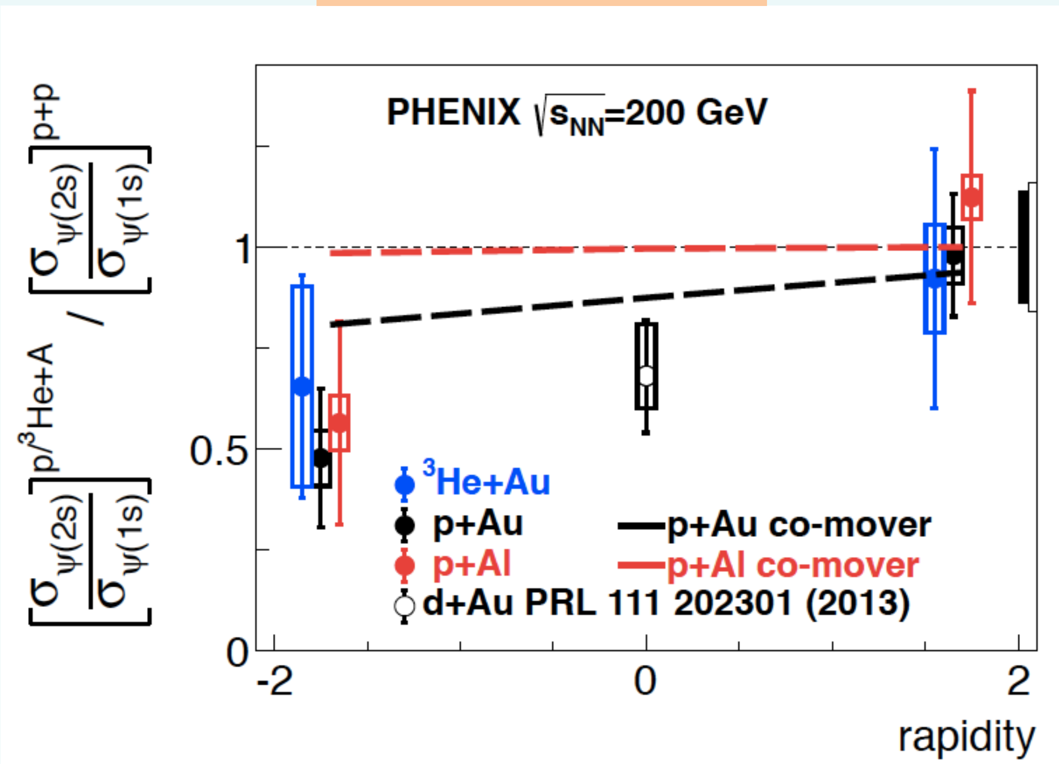
Similar pattern for h±, μ±, ϕ

J/ψ suppressed

Breakup in nuclear matter

p(d,^{3}He)A $\rightarrow$ J/ψ+X vs ψ'+X

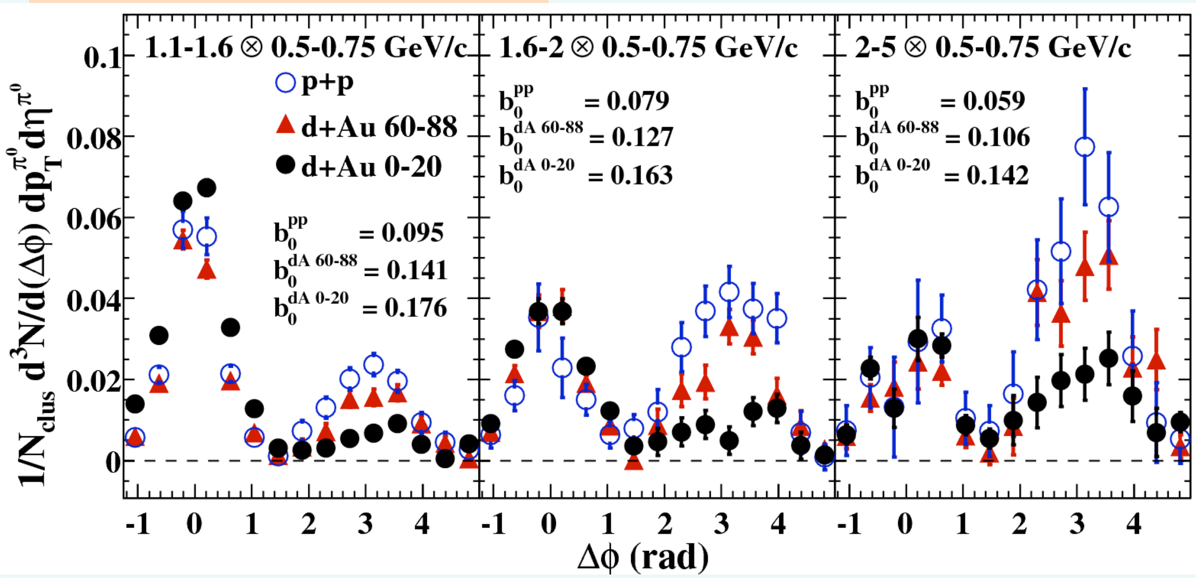
PRC 95, 034904 (2017)



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

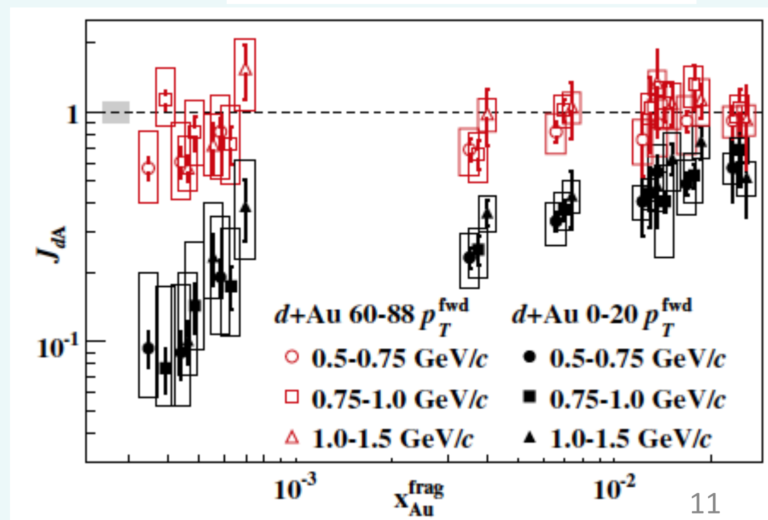
h-h correlation

PRL 107, 172301 (2011)



CGC => suppression of back to back correlation

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



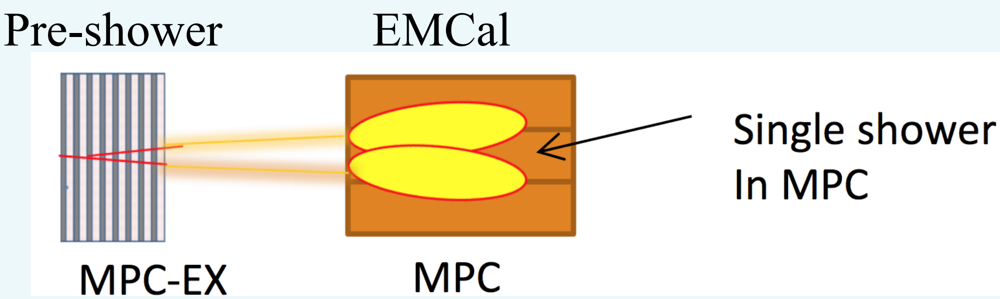
Other mechanisms (including final state effects) may lead to the similar suppression

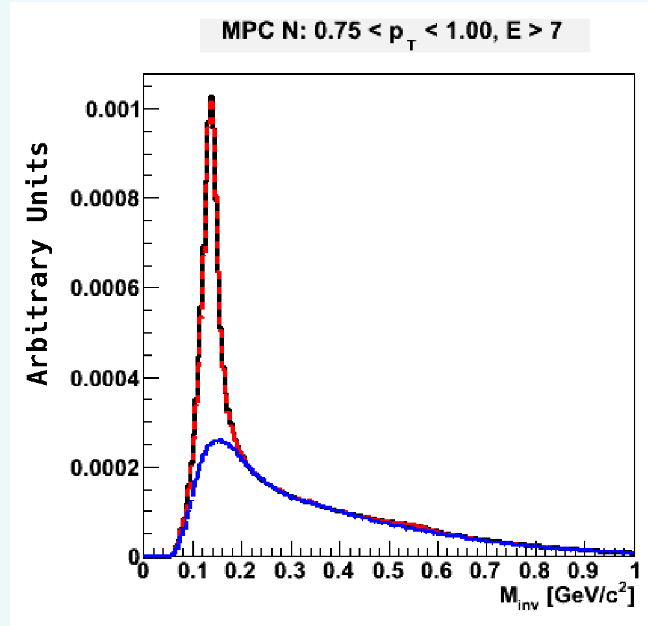
E.g. CNM energy loss

γ-h correlation: final state effect reduced

–> Need a pre-shower in front of forward EMCal

MPC-EX

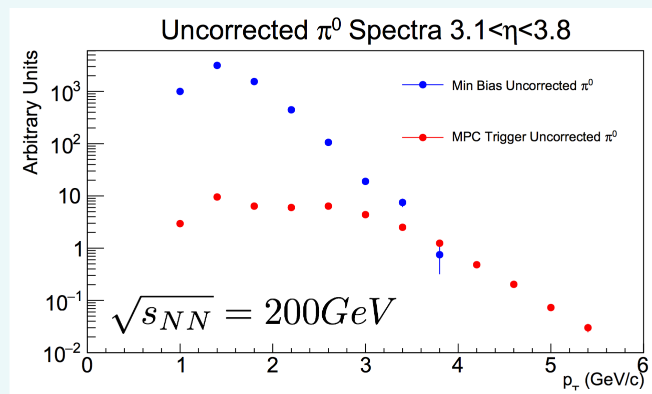




$3.1<|\eta|<3.8$

Pre-shower:

Extends π^0/γ separation from p~20 GeV/c to ~80 GeV/c

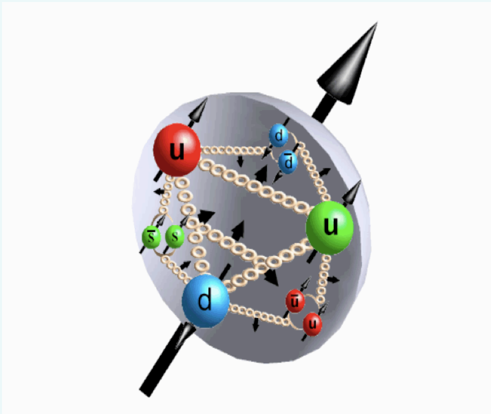


Run16: dAu at 20, 39, 62 and 200 GeV

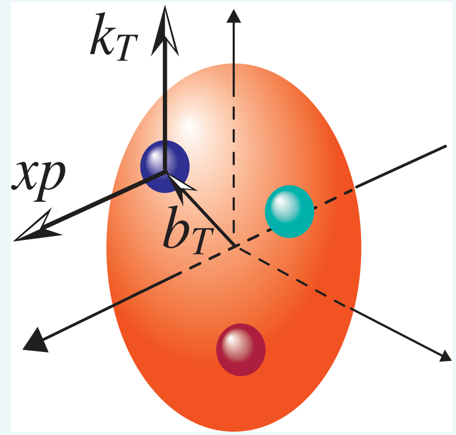
π^0 R_{CP} coming soon

Dir. γ results coming later

Proton Spin Decomposition

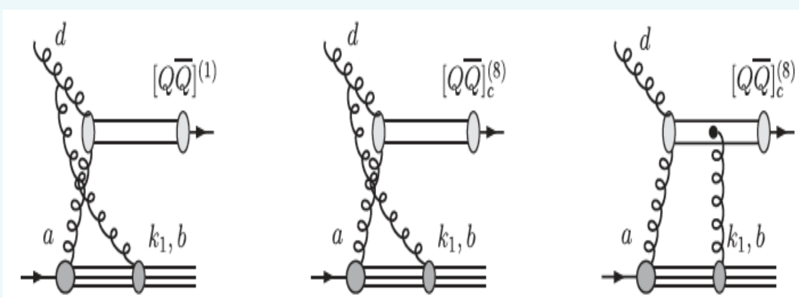


TMD: 3D imaging, parton dynamics

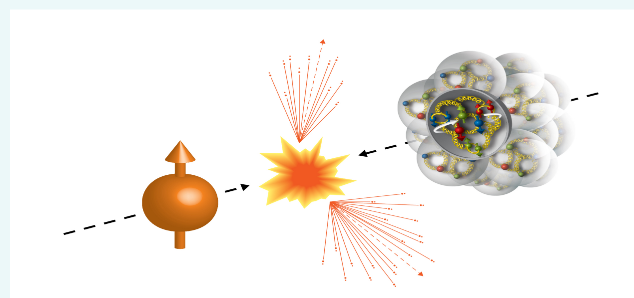


Spin Asymmetries

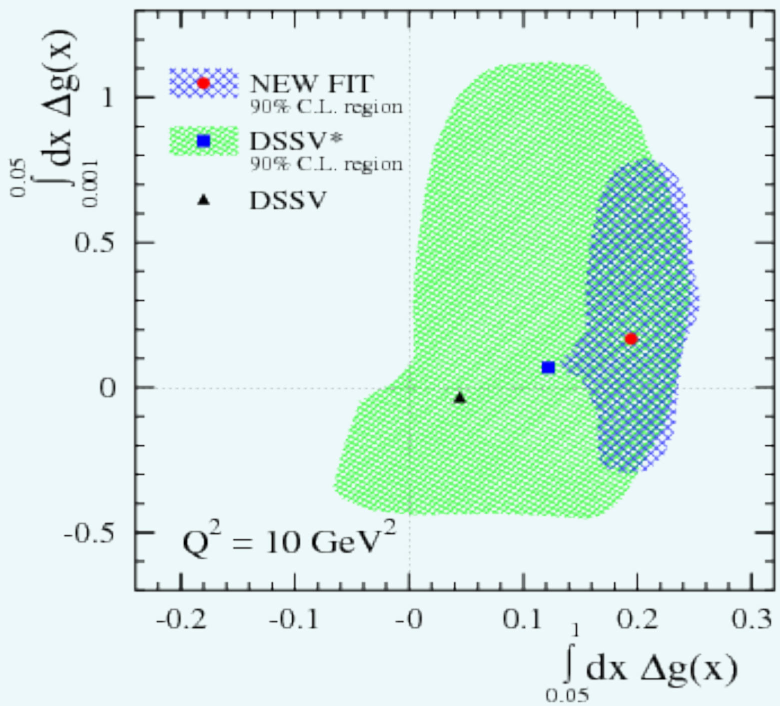
J/ψ production mechanism



Probes CGC



Proton Spin Decomposition: ΔG



pp: PHENIX π0+ STAR jet

DSSV: Phys Rev Lett, 101, 072001 (2008)

Data from up to 2006

New DSSV: Phys Rev Lett, 113, 012001 (2014)

Data from up to 2009

$$\int_{0.05}^{1} dx \Delta g(x) = 0.2^{+0.06}_{-0.07} \qquad (90\%\ \mathrm{CL})$$

Significant non-zero Δg(x) in the kin. region probed by RHIC

Similar result from another global fit NNPDF

Still huge uncertainty in unmeasured region (x<0.05)

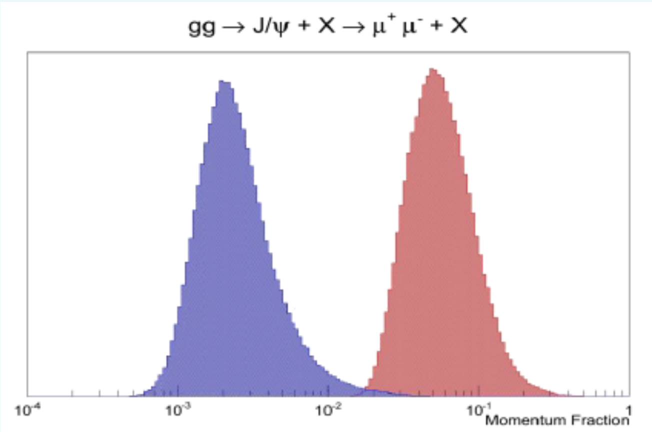
=> Measurements at higher √s and forward rapidity

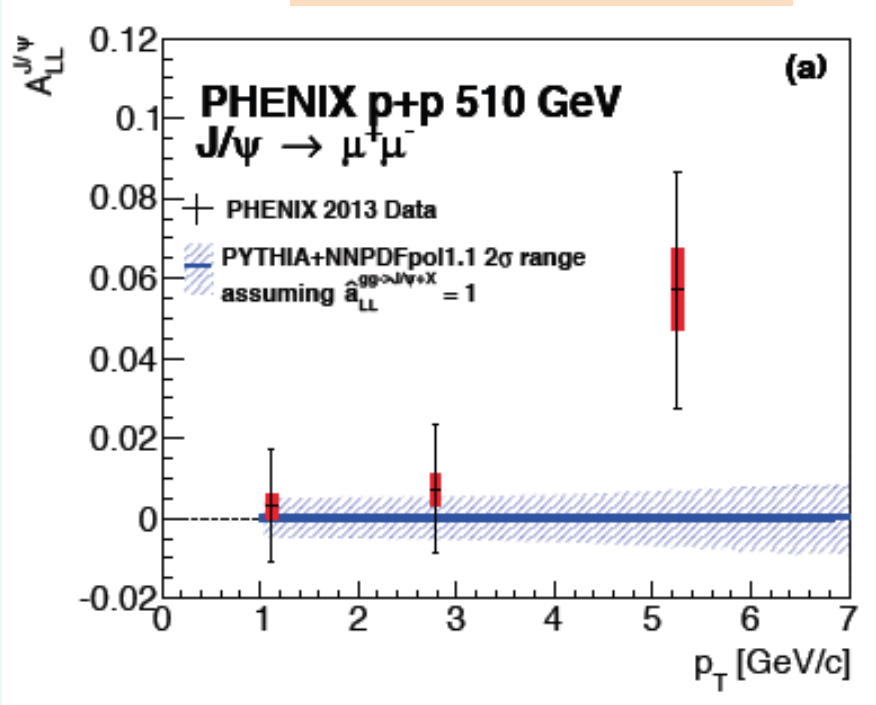
ΔG: Towards lower x

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

pp → *J/ψ* at √s=510 GeV 1.2<|η|<2.4

PRD 94, 112008 (2016)





$$A_{LL} \propto \frac{\Delta g(x_1)}{g(x_1)} \cdot \frac{\Delta g(x_2)}{g(x_2)} \cdot \hat{a}_{LL}^{gg\to J/\psi+X}$$

Get access to x down to 2×10^{-3}

Already constrained by RHIC

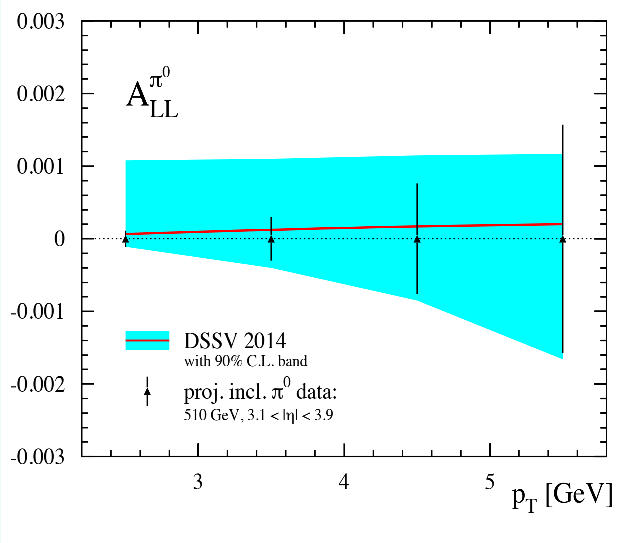
J/ψ production mechanism uncertainty
Not yet in the global fit

ΔG: Towards lower x

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

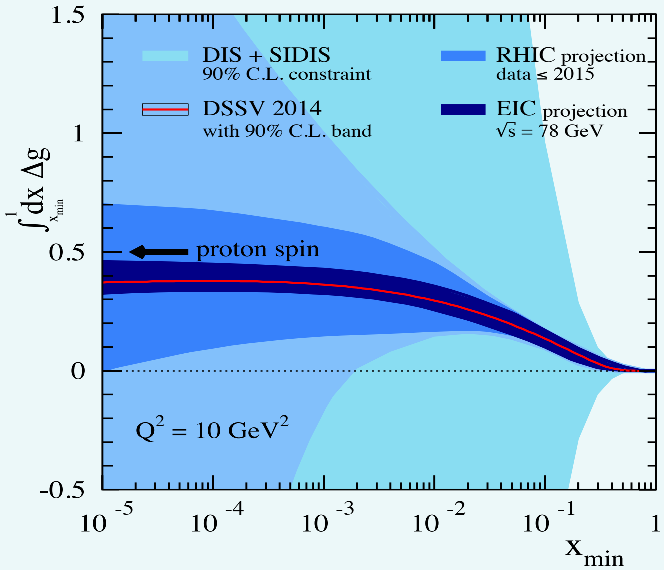
Projection

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

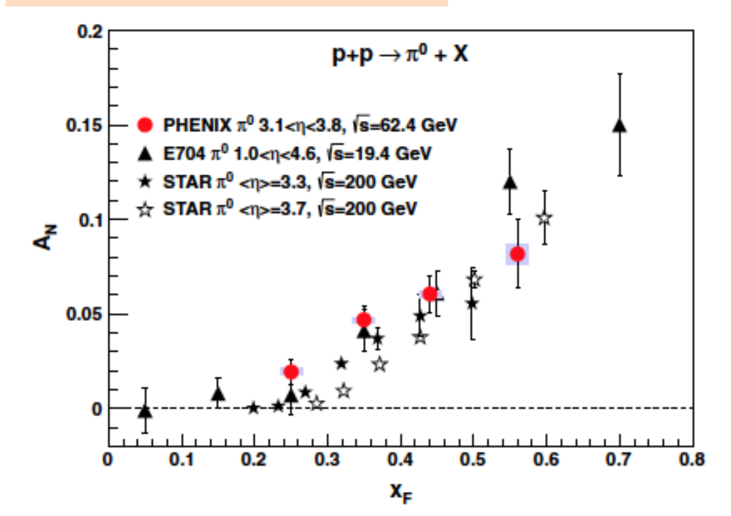
Probes lower x down to ~10^{-3}

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

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

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 $\sqrt{s}$

Perturbative regime!

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

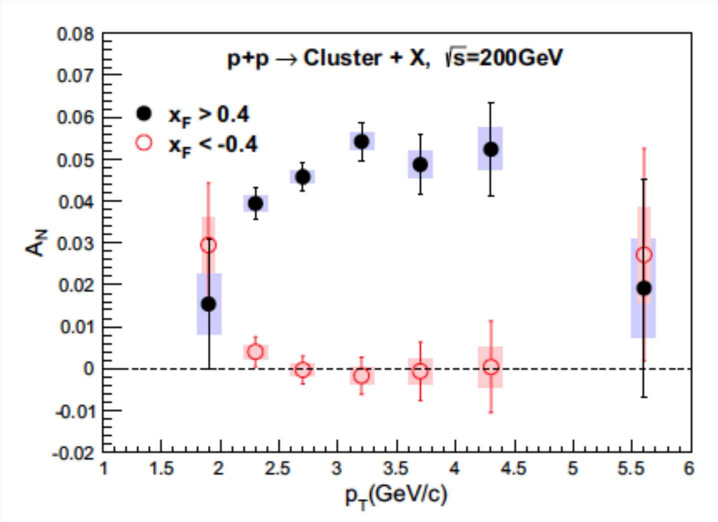
Asymmetries scale with x_F

Collinear (higher twist) pQCD predicts

$A_N \sim 1/p_T$?

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

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



Transverse Spin Physics

Initial State:

Sivers/Twist3 mechanism

- A_N for jets, direct photons
- A_N for heavy flavor ➔ gluon
- A_N for W, Z, DY

Sensitive to correlations
proton spin – parton **transverse motion**

Not universal between SIDIS & pp

- Parton dynamics
- 3D imaging

Final State:

Collins mechanism

- Hadron azimuthal asymmetry in jet
- Hadron pair azimuthal asymmetry
  (Interference fragmentation function)

Sensitive to
transversity x spin-dependent FF

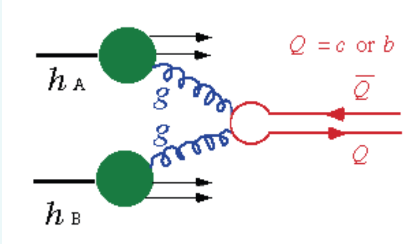
Universal between SIDIS & pp & e+e-

- Quark transversity
- Tensor charge

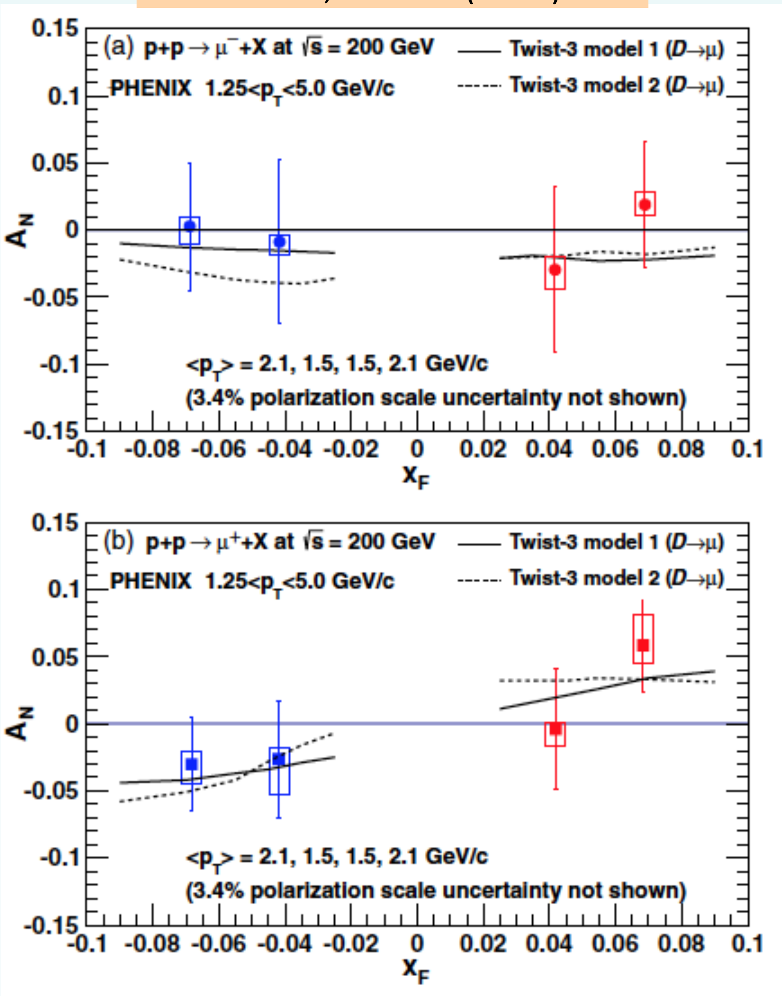
Other mechanisms

- Diffraction

Open Heavy Flavor A_N



pp → μX
PRD95, 112001 (2017)



Dominated by gluon-gluon fusion

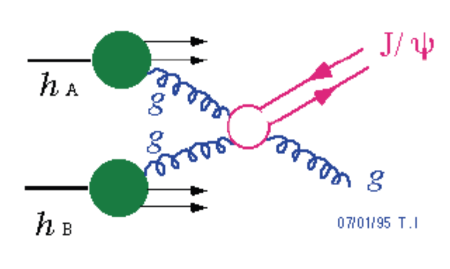
Used to constrain tri-gluon correlation in the Twist-3 collinear framework

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

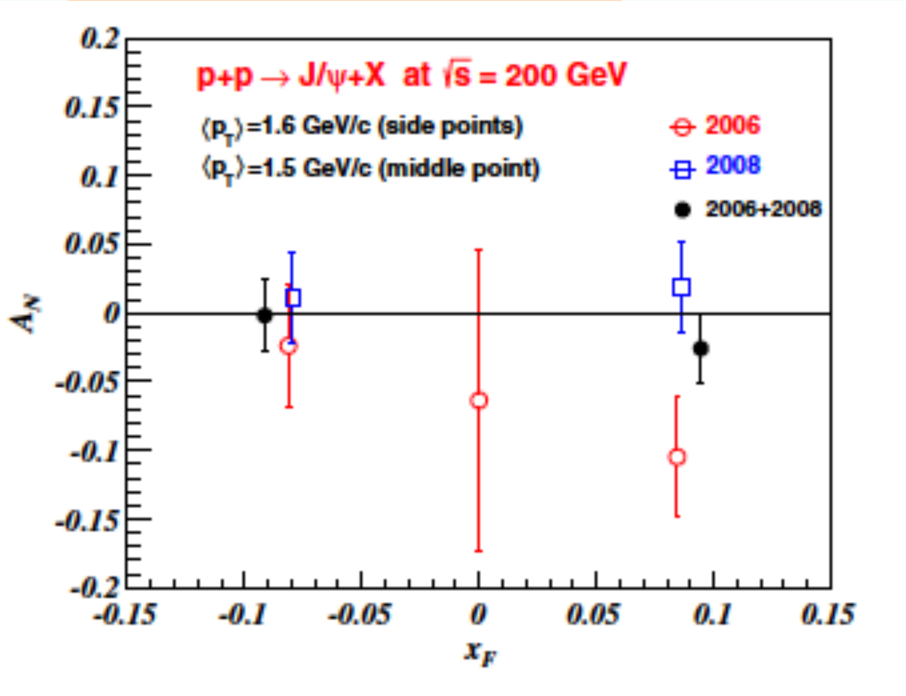
Y.Koike, S.Yoshida, PRD84,014026

Significant reduction in uncertainties expected from 2015 data

J/ψ A_N



PRD86, 099904(E) (2012)



A_N sensitive to J/ψ production mechanism

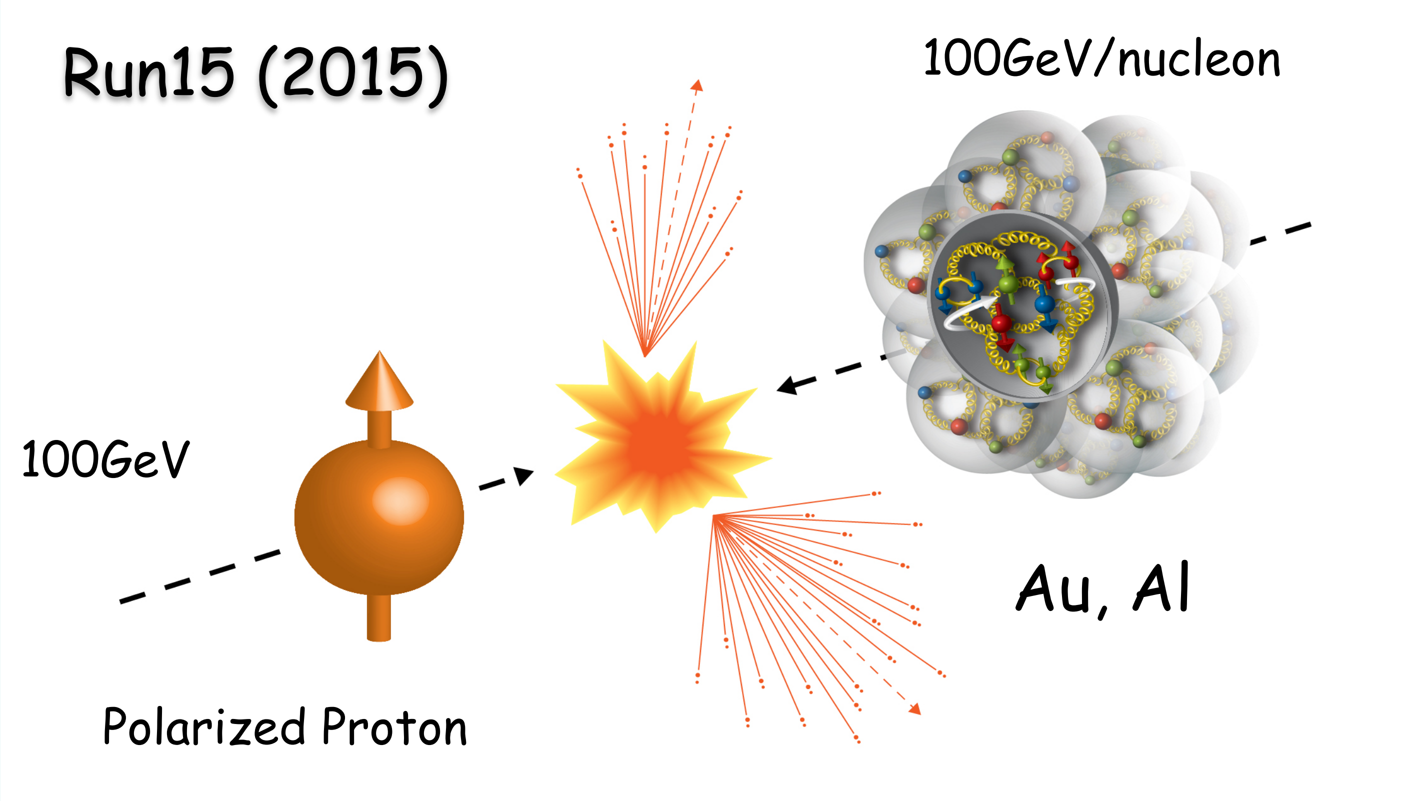
F.Yuan, PRD78, 014024:

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

Consistent with zero

Considerable improvements from 2015 data (see below)

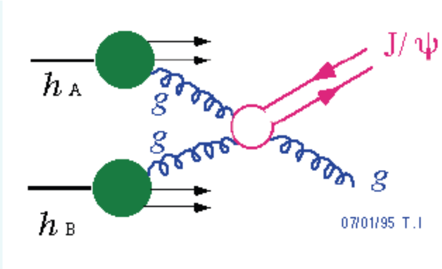
First $p^{\uparrow} + A$ data !!!



- Pin down the origin of A_N
- Study gluon saturation effect with a polarized probe!

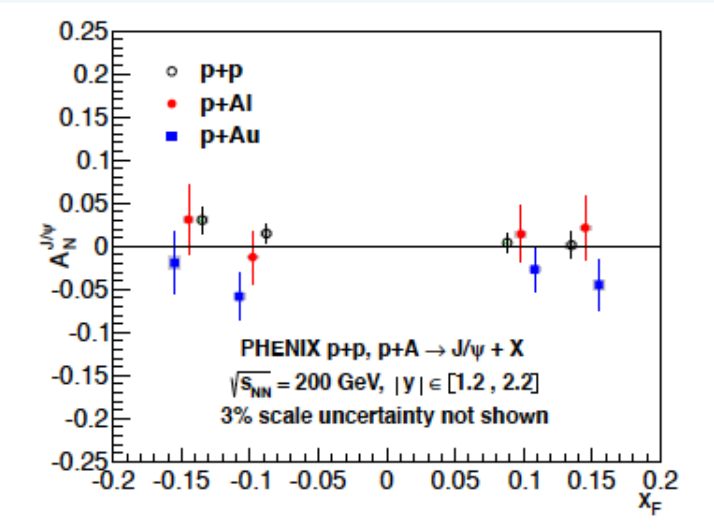
Kang&Yan PRD84 034019, Kovchegov&Sivert PRD86 034028, Hatta et al PRD95 014008

pA: J/ψ A_N



1.2<|η|<2.4

PRD 98, 012006 (2018)



J/ψ production sensitive to gluon distribution

A_N sensitive to J/ψ production mechanism

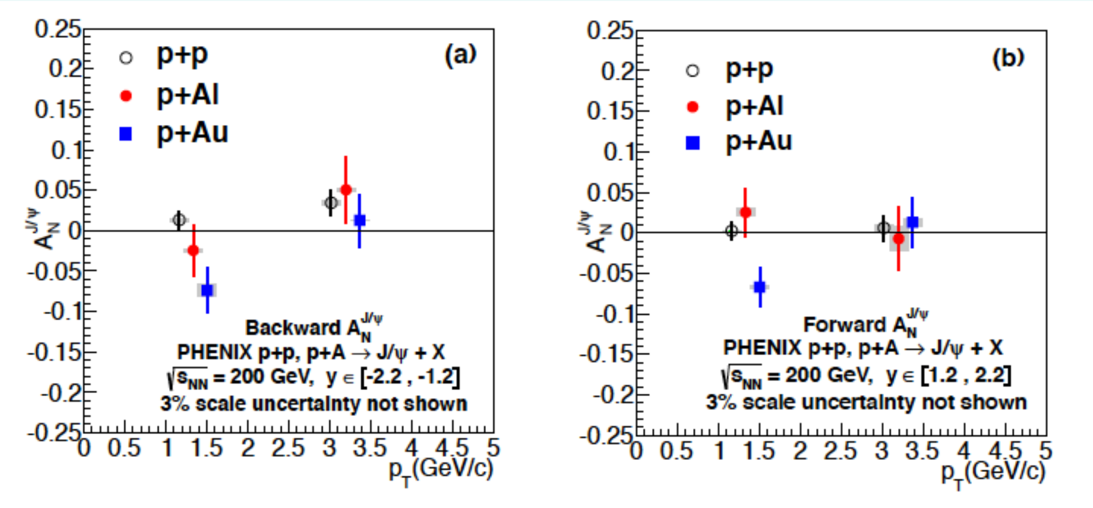
F.Yuan, PRD78, 014024:

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

In p+p and p+Al: $A_N \sim 0$

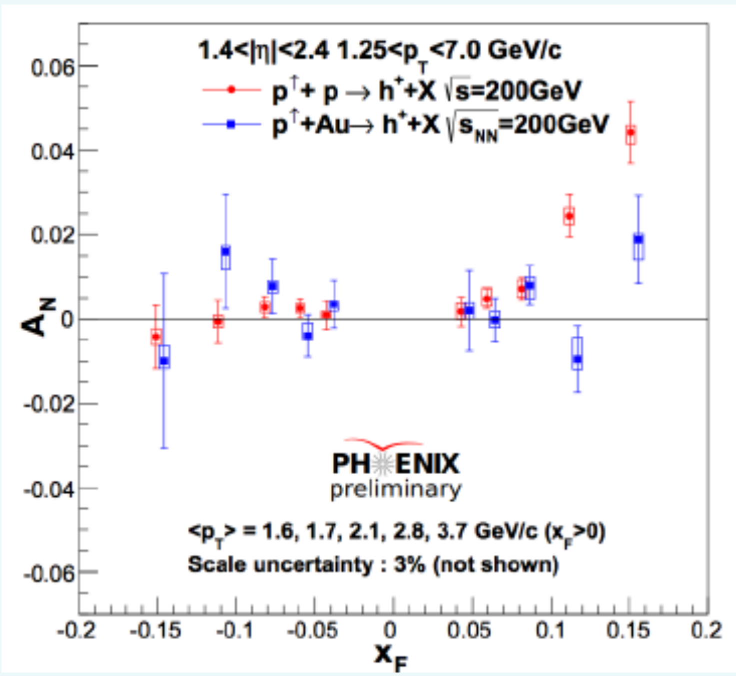
In p+Au: trends to $A_N < 0$

??



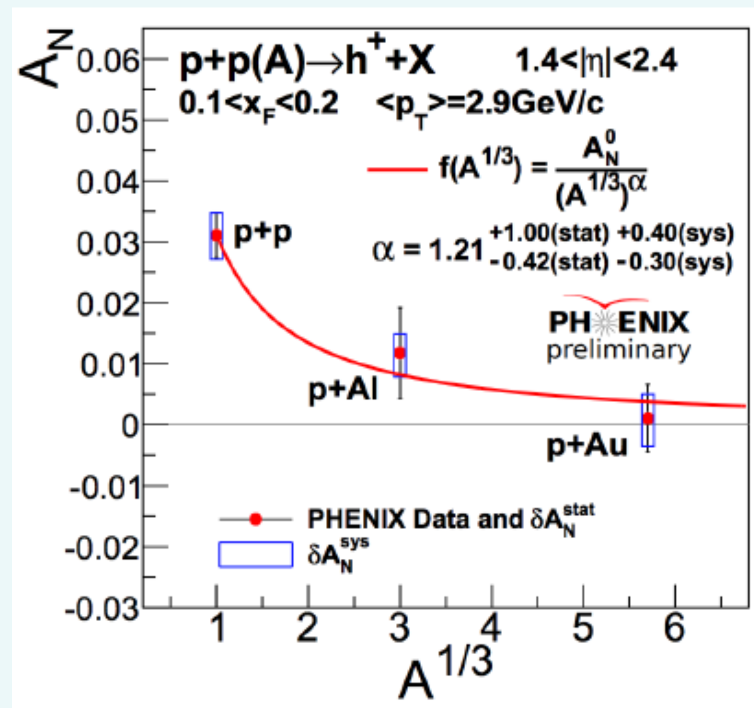
pA: h^+ A_N

$1.2<|\eta|<2.4$



A_N >0 in p+p forward

A_N ~ 0 (suppressed!) in p+Au



Theory expects $A_N \sim 1/A^{1/3}$ due to gluon saturation

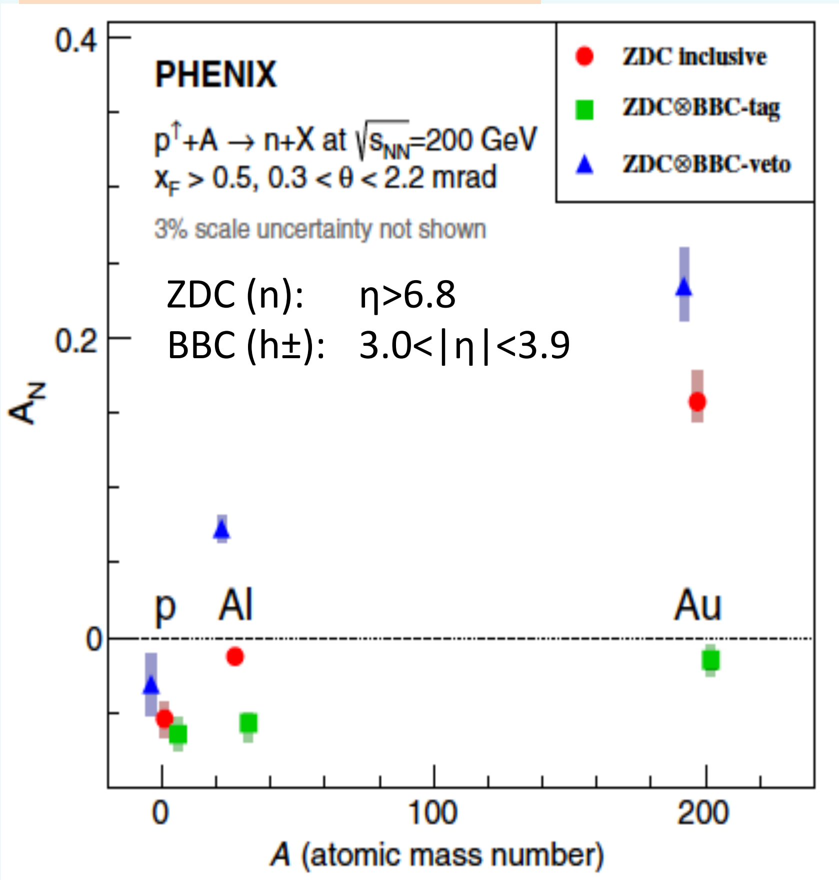
Z.Kang and F.Yuan, PRD 84, 034019 (2011)

Supported by our data!

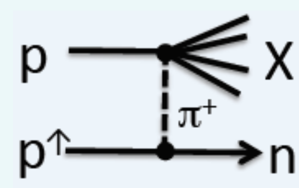
pA: n A_N

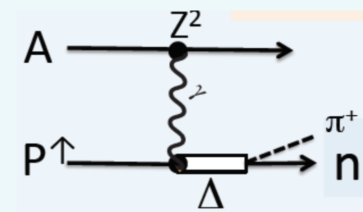
n at $|\eta|>6.8$

PRL 120, 022001 (2018)



- Strong dependence on A and particle production in other rapidity regions
- Likely multiple mechanisms contribute





One pion exchange:
B.Kopeliovich et al
PRD 84, 114012

Electromagnetic interaction:
G.Mitsuka, PRC95 044908

- Correlation with particle production in other rapidities, and different A and √s will help to isolate different channels

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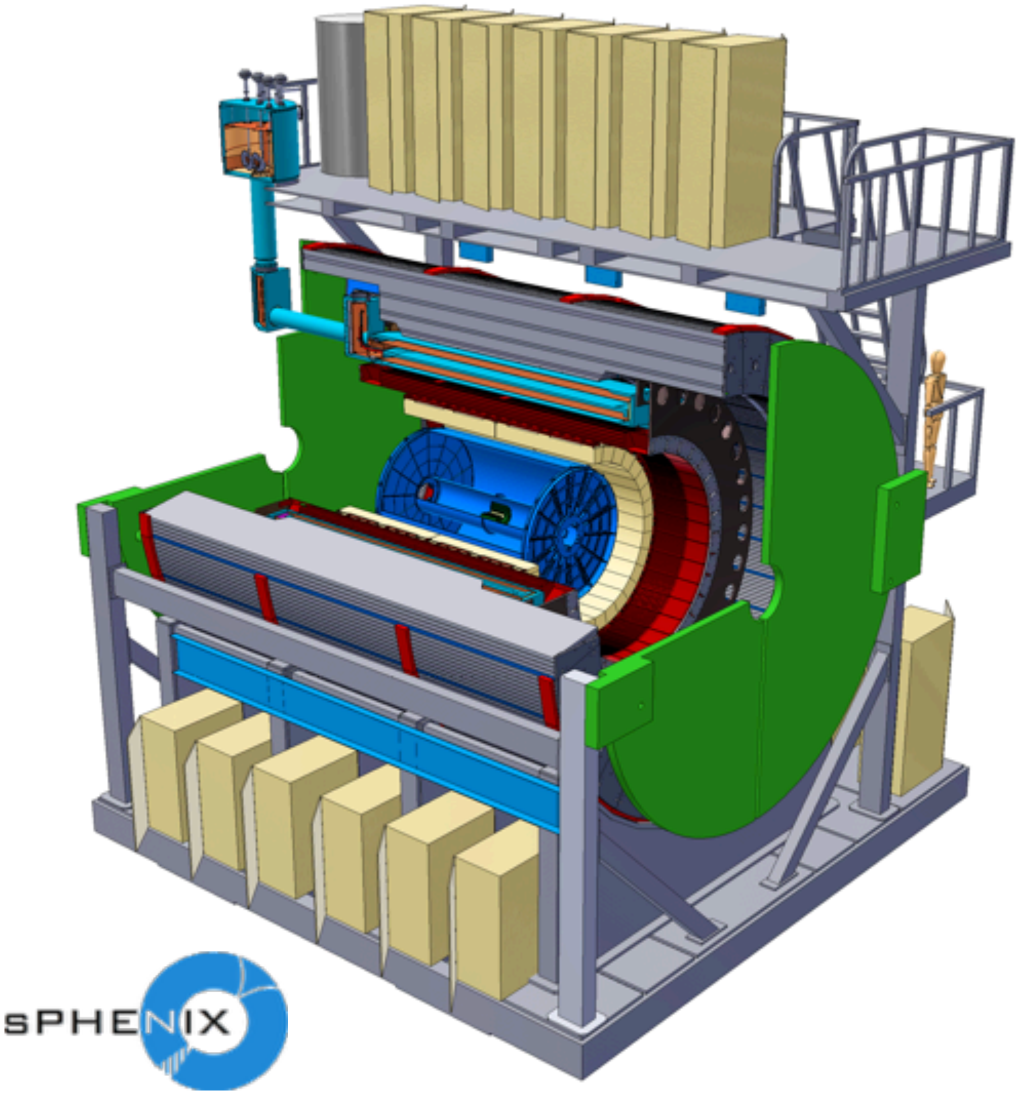

New detector for the RHIC facility at BNL (USA)

- New Collaboration formed
- >70 institutions and counting

For studies of the strongly interacting Quark-Gluon Plasma using jet, photon and heavy-flavor observables

- With strong capabilities for Spin Physics measurements

Time line:

- CD0 Review - Sep 2016
- CD1/3a Review - May 2018
- Installation complete - 2022
- Running – 2023

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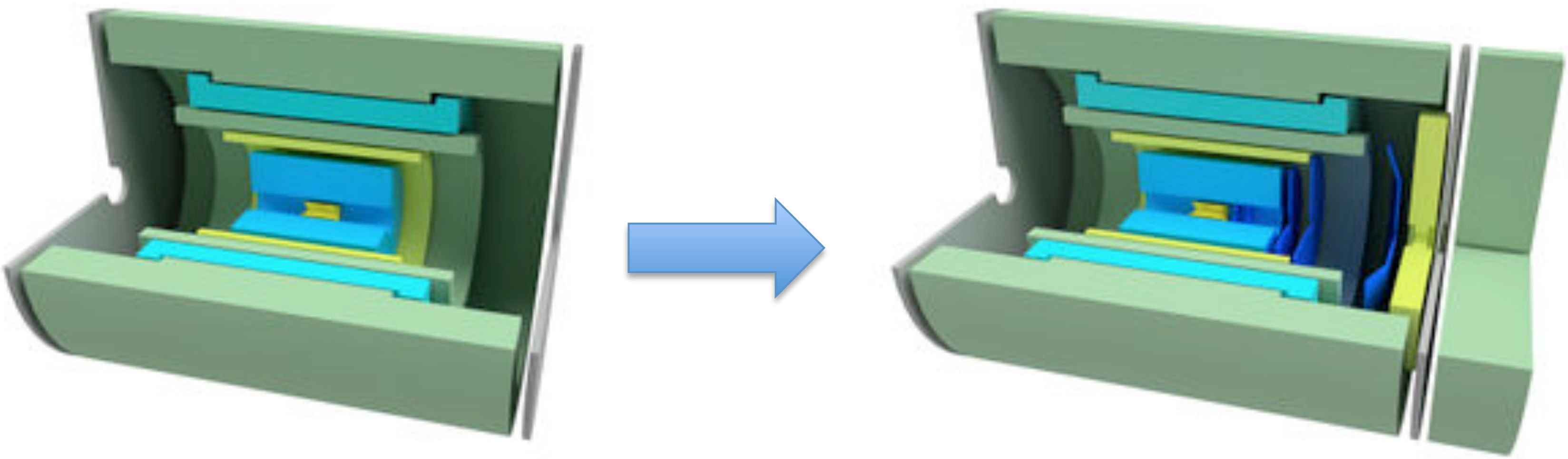
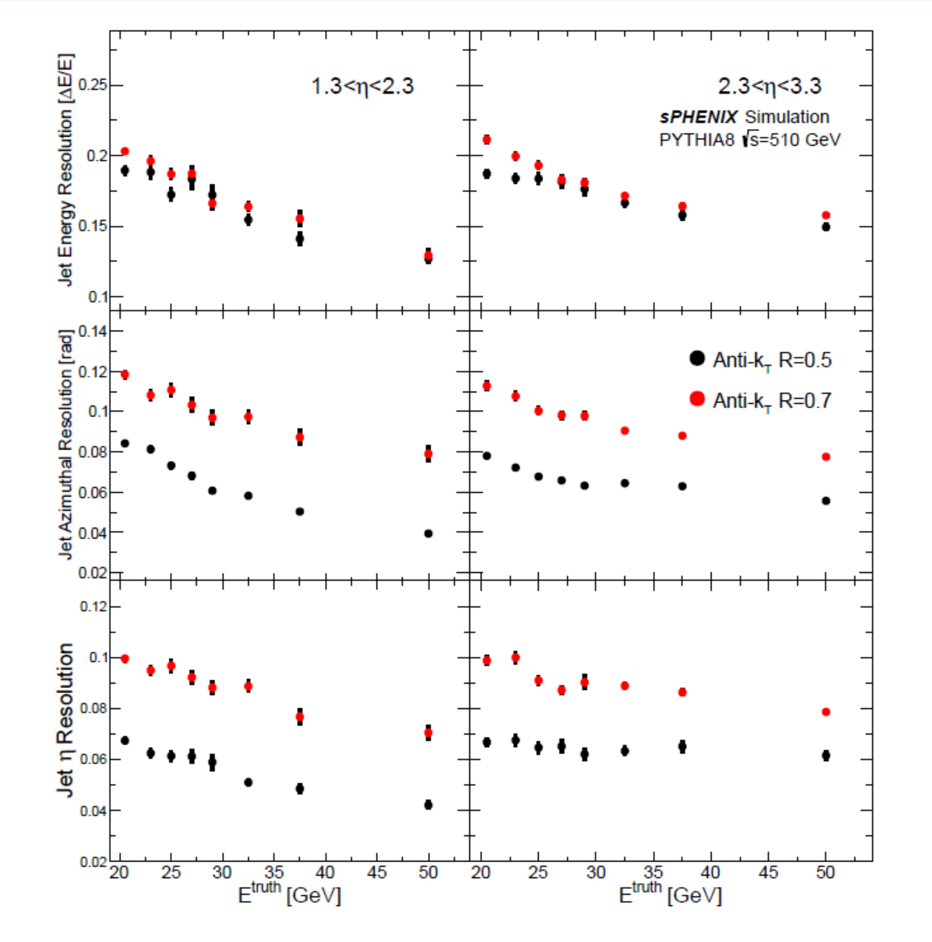


Solenoid 1.4T
EMCal & HCal
Tracking

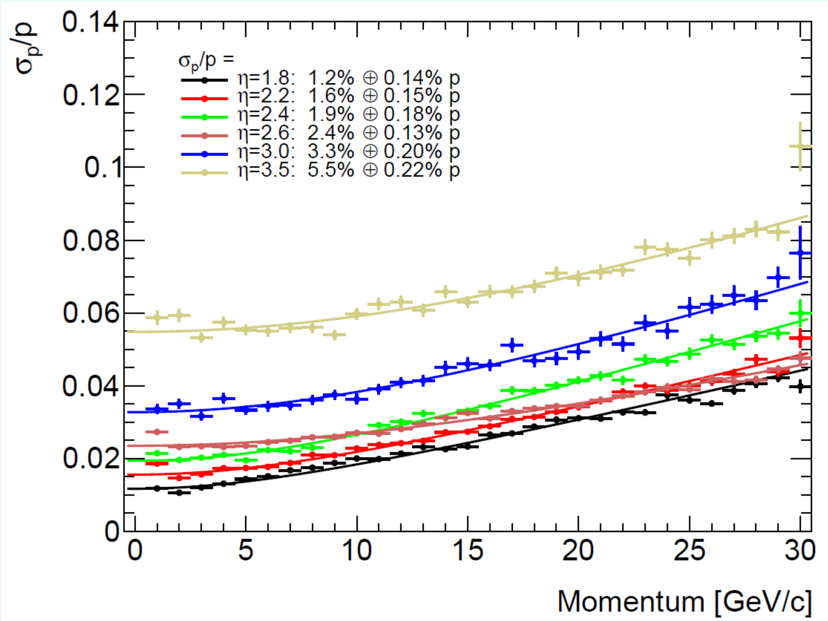
+ Forward EMCal & Hcal
+ Forward tracking

Forward Jet and h±

Good jet resolution for E, η, φ

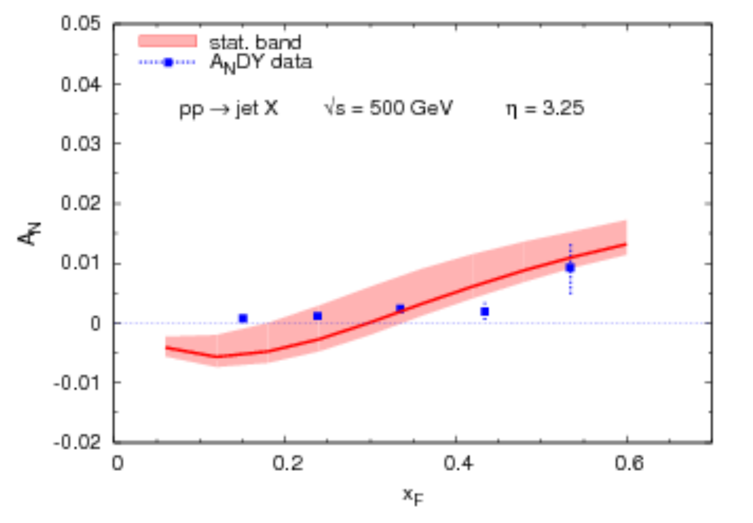


Excellent charged track momentum resolution even in forward region



Jet A_N

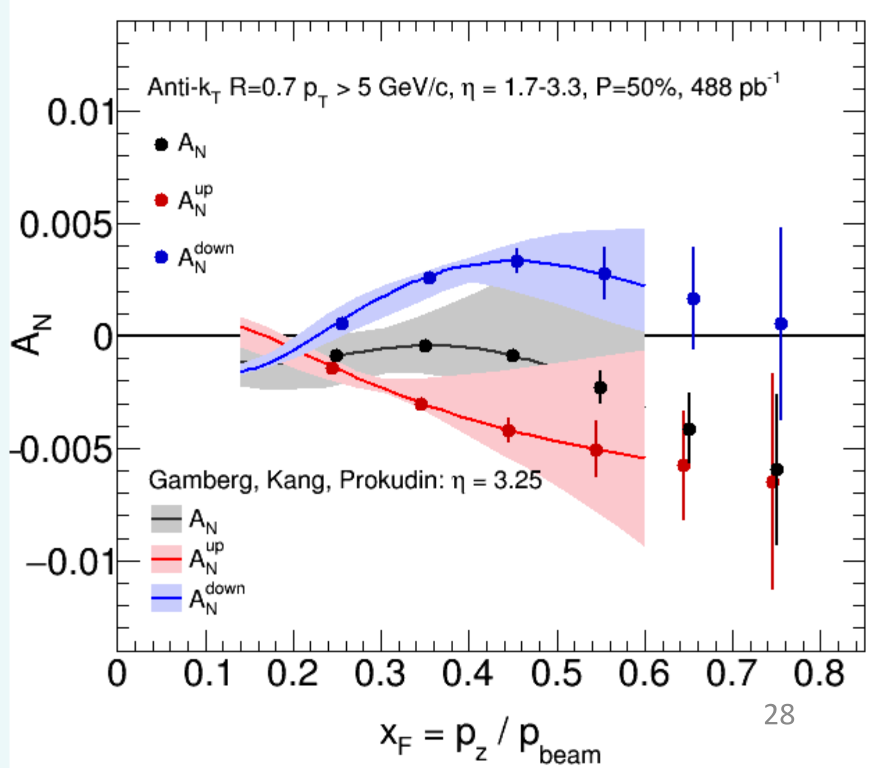
A_NDY: PLB 750, 660



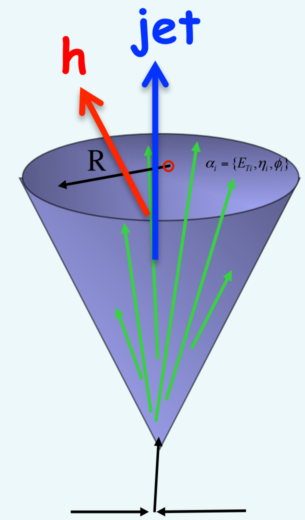
Sensitive to Sivers fnct.

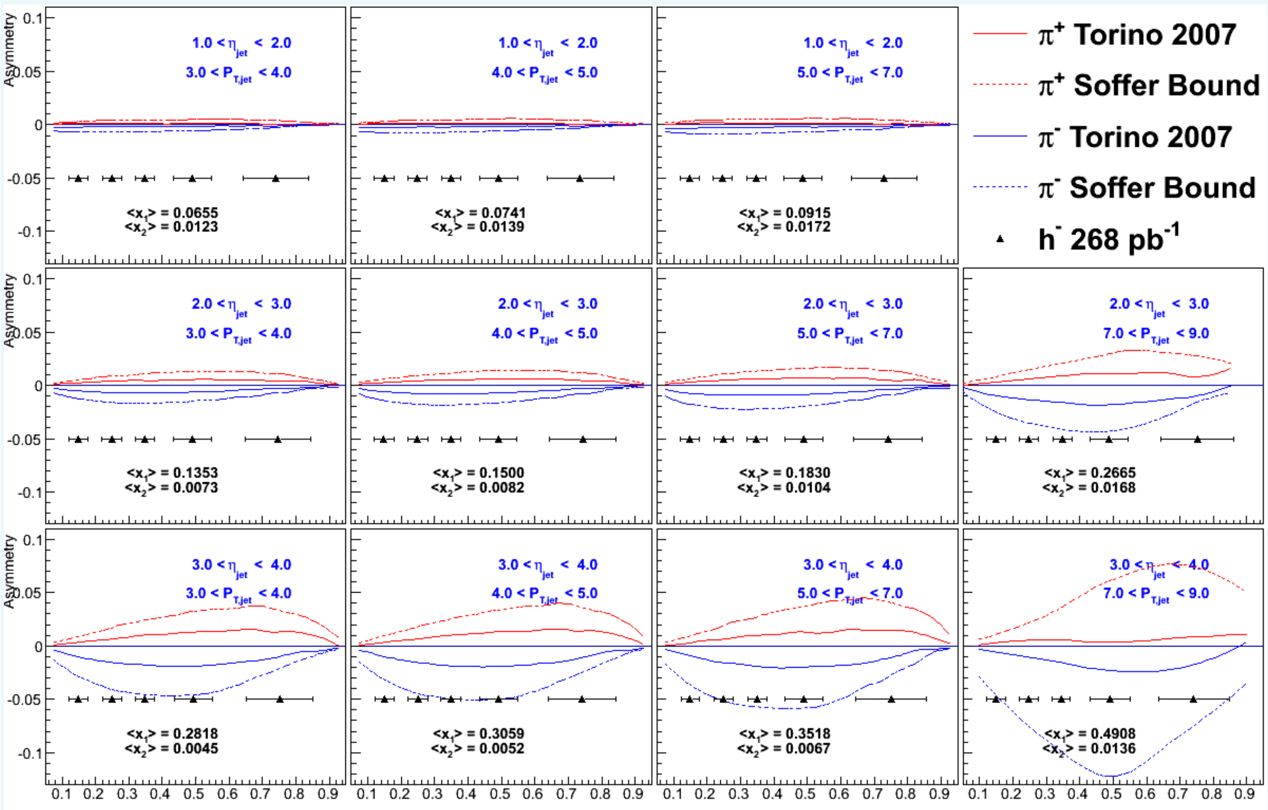
Jet A_N~0 => cancellation from u&d?

Tagging jets with the charge of leading hadron changes jet composition
=> ability to separate effects from u and d



Hadron in Jet: Collins Asymmetry





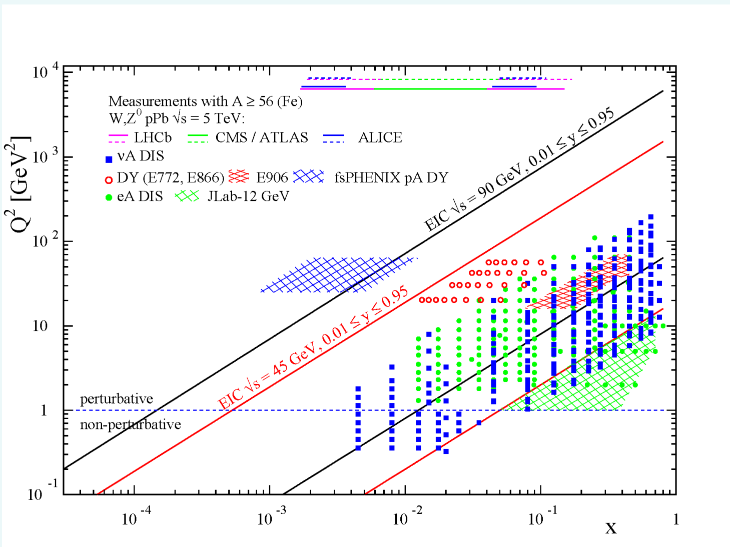
Gives access to transversity
Expands x-range to higher values => necessary for tensor charge

$$\delta q^a = \int_0^1 \left(\delta q^a(x) - \delta \bar{q}^a(x)\right) dx$$

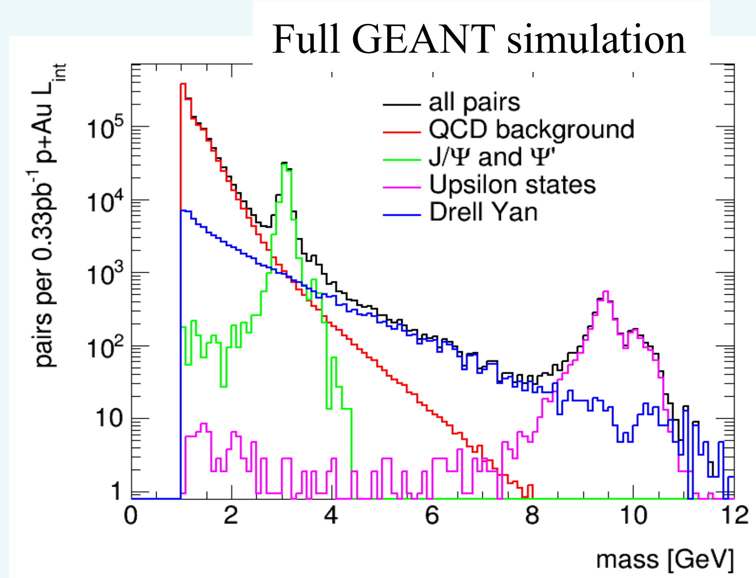
Calculable on lattice

DY for nPDF

Current nPDF are mainly constrained by DIS data (affected also by final state effect)
DY: no final state effect, kinematics reconstruction at LO, directly tag antiquarks



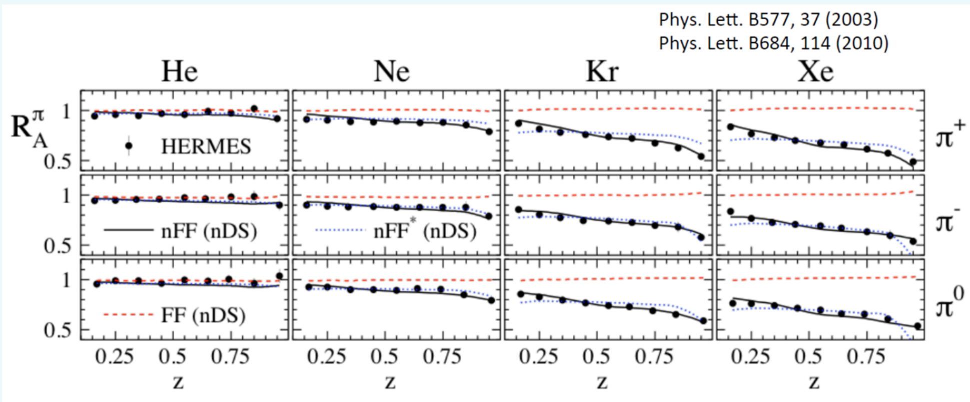
Unique kinematics coverage
compared to fixed target and LHC



Can do measurements at 5<m<8 GeV/c^2

A comprehensive set of measurements will be crucial for nPDF: DY, γ+jet, jet+jet, HF

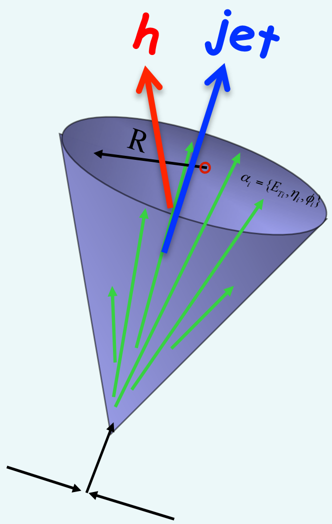
Fragmentation in a Nuclear Environment



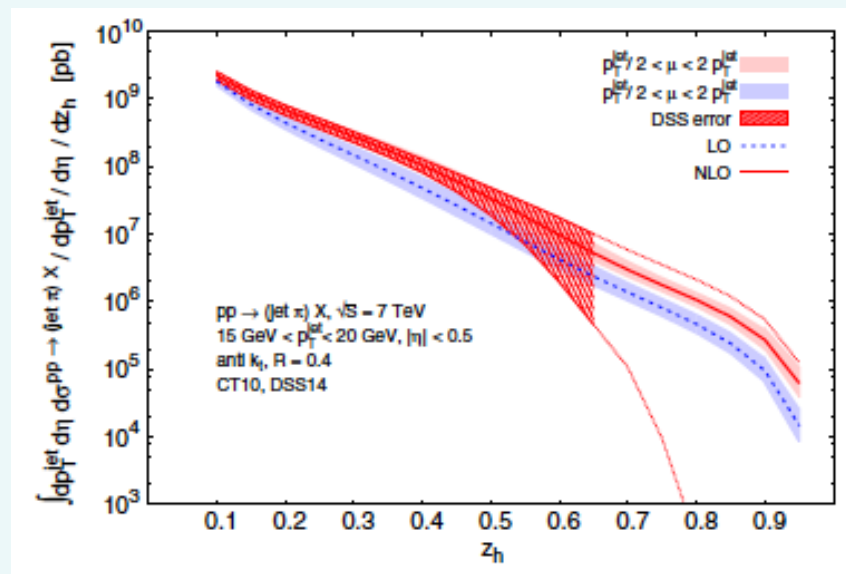
Hadron production in e+A suppressed compared to e+p
=> fragmentation modification

Access fragmentation function (FF) through p+p(A) –> (jet h)+X

Direct access to gluon FF



Kaufmann, Mukherjee, Vogelsang: PRD 92, 054015



Summary

- ✓ A lot of PHENIX results contributing to all aspects of Forward Physics
- ✓ A lot more results to come

  Collected data on disk/tape are being actively analyzed

  New young researchers joining the collaboration

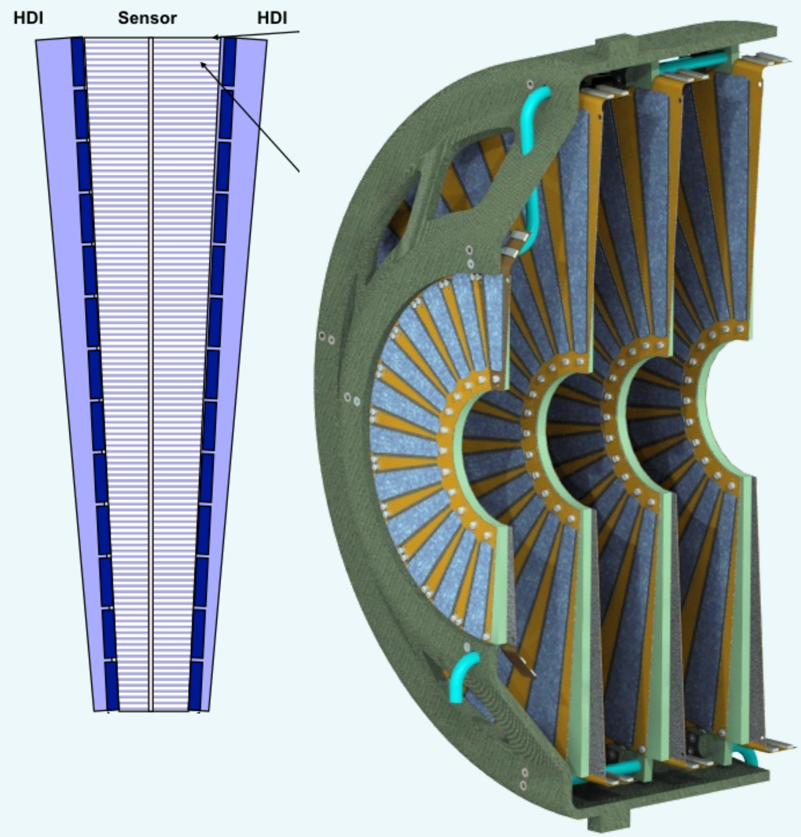
- ✓ Stay tuned for new PHENIX results!

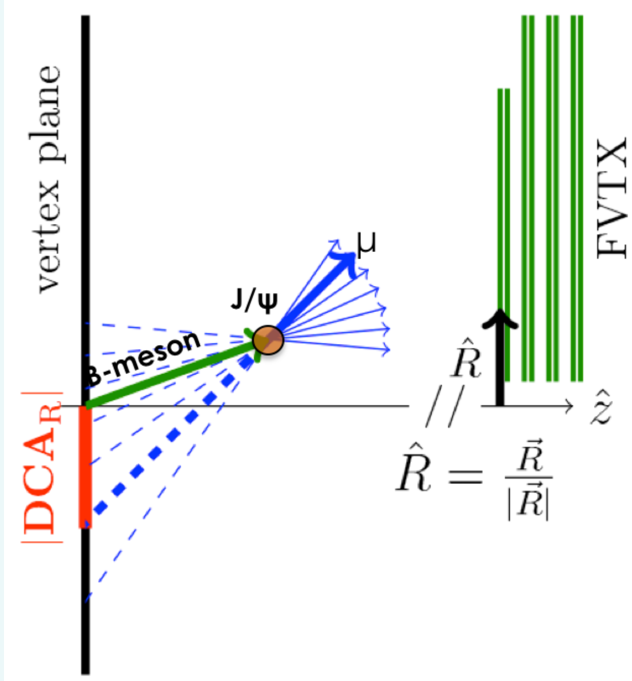
PHENIX → sPHENIX transition for 2020+ physics

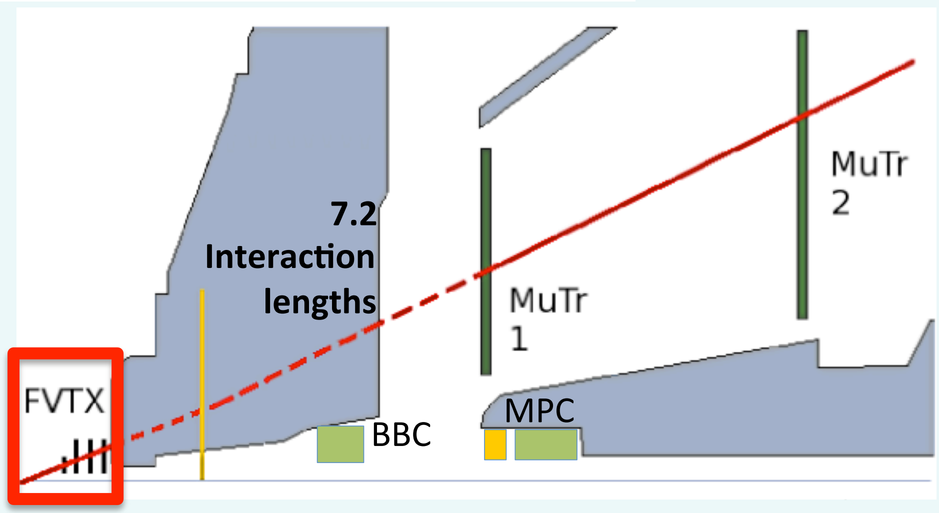
√s [GeV]	p+p	p+Al	p+Au	d+Au	³He+Au	Cu+Cu	Cu+Au	Au+Au	U+U
510	✓								
200	✓	✓	✓	✓	✓	✓	✓	✓	✓
130								✓	
62.4	✓			✓		✓		✓	
39				✓				✓	
27								✓	
20				✓		✓		✓	
14.5								✓	
7.7								✓	

Backup

Forward Vertex Detector (FVTX)







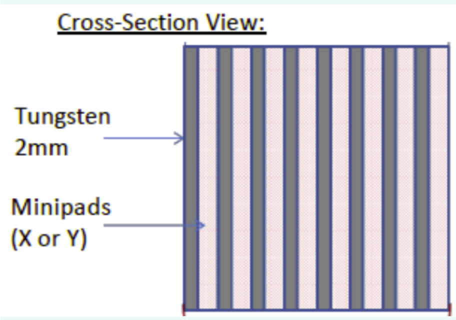
75 µm radial segmentation

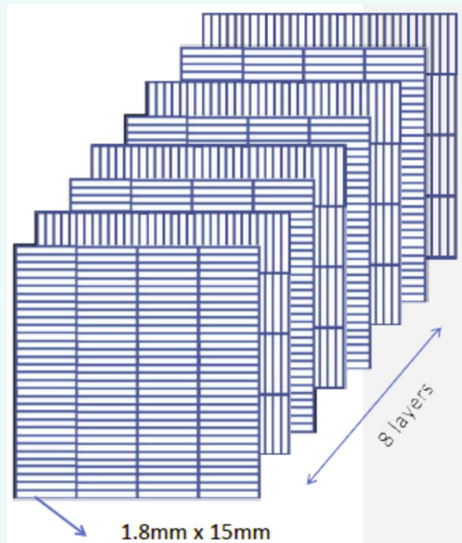
$\Delta\phi$=7.5° / strip

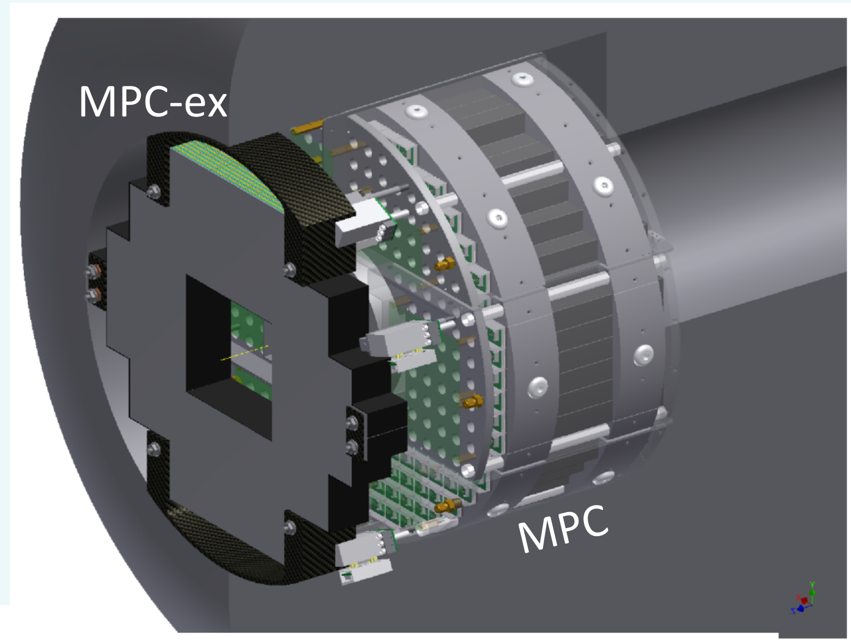
Measures radial distance of the closest approach (DCA_R) to the vertex.

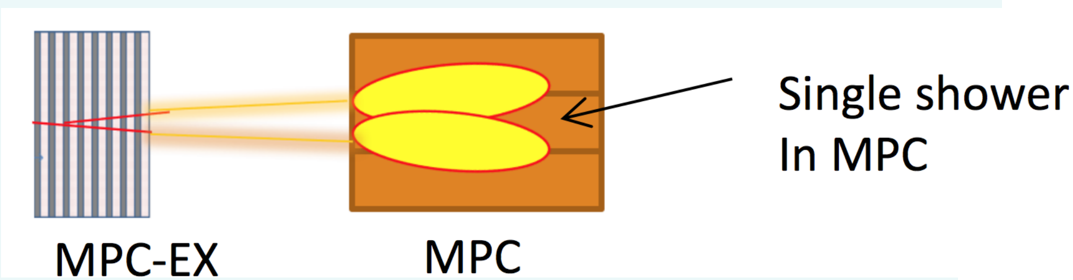
Muon Piston Calorimeter(MPC) + Pre-Shower (MPC-ex)

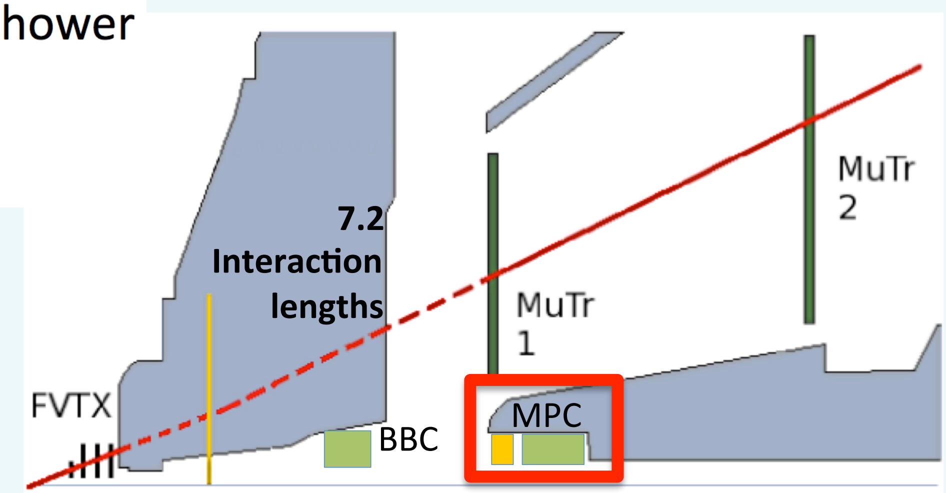
arXiv:1301.1096





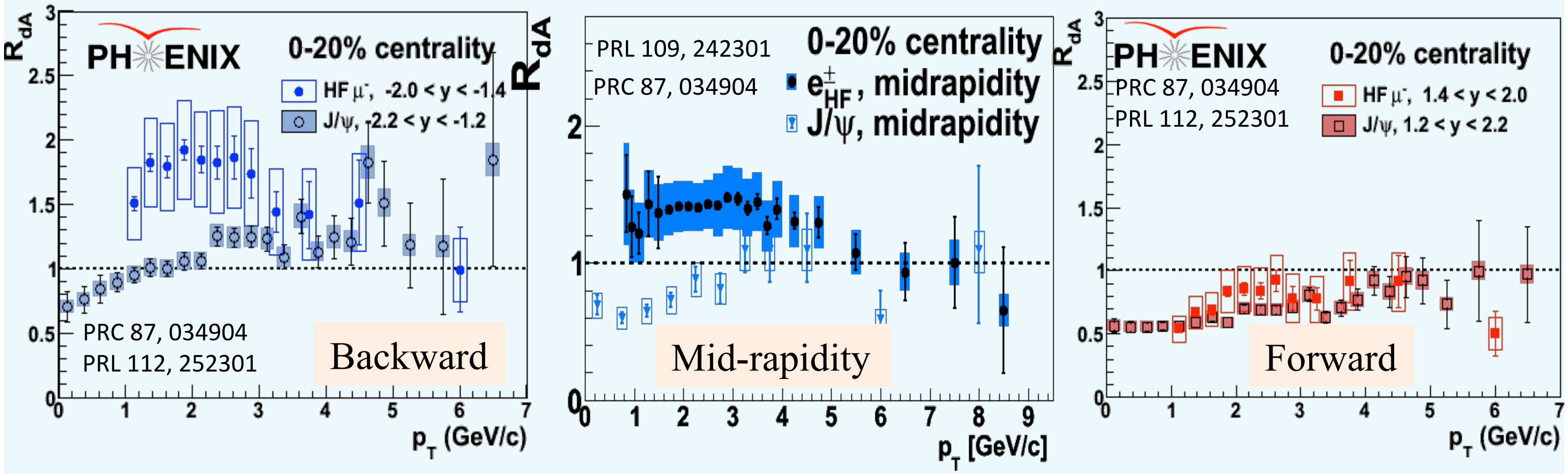






MPC-ex helps to measures high p_T π^0

p(d)A: Heavy Flavor



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

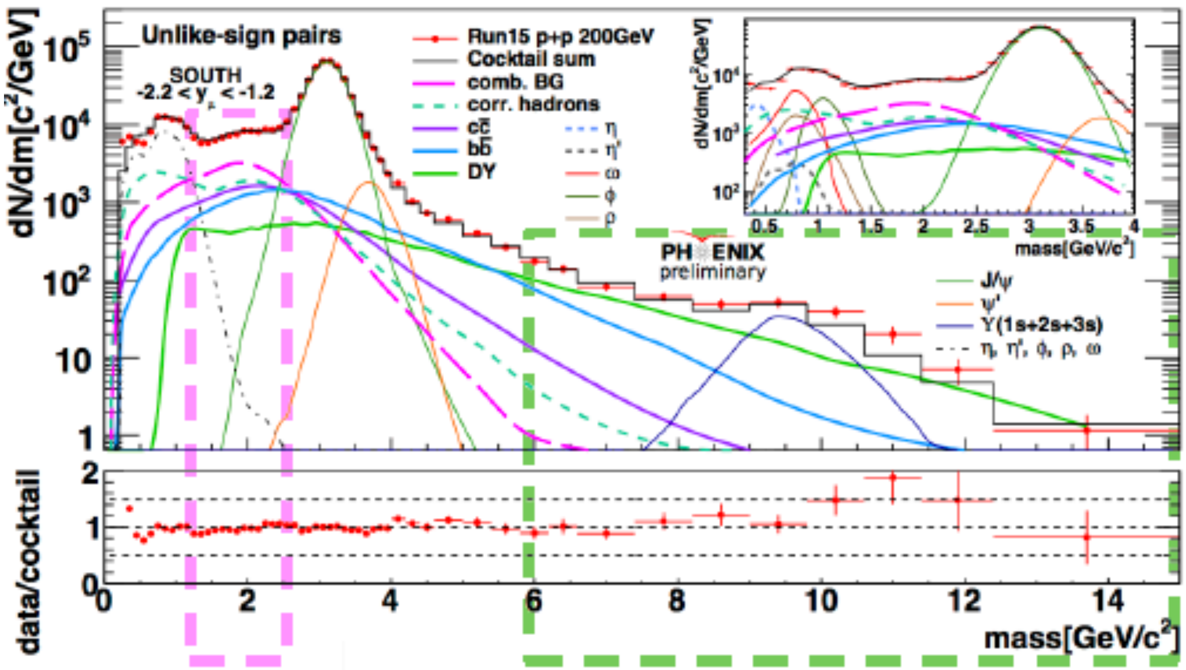
Similar to light hadrons

Parton scattering, shadowing, energy loss, etc.

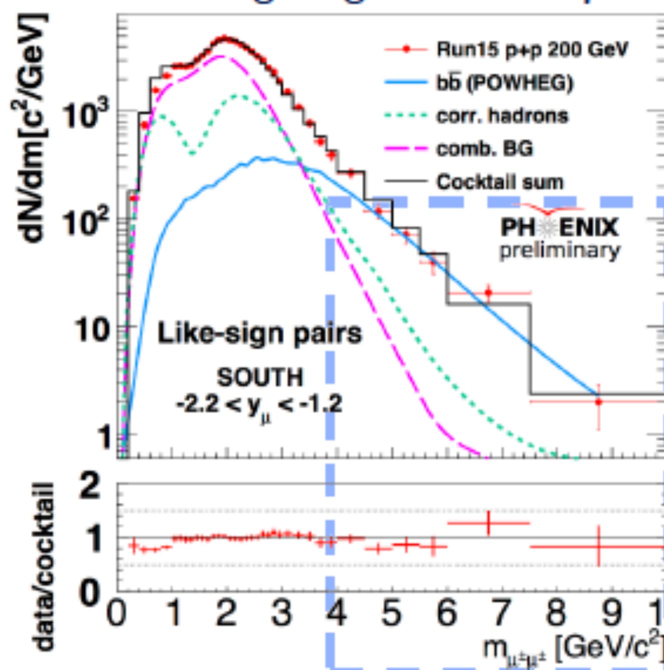
J/ψ breakup

Decomposing di-muon cocktail

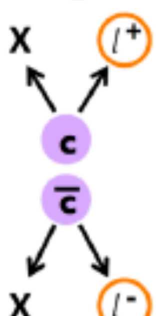
Opposite charge-sign di-muon pairs

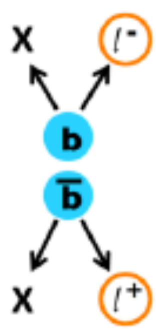


Same charge-sign di-muon pairs

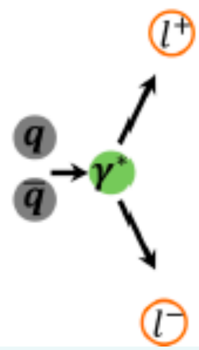


Charm highest S/B

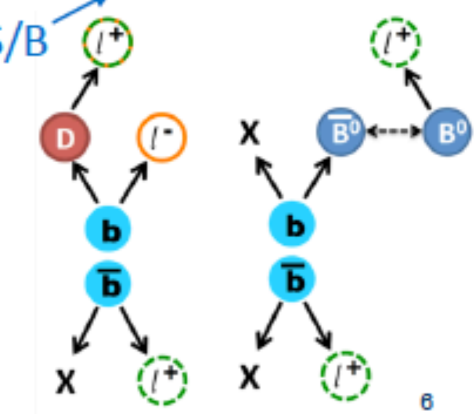




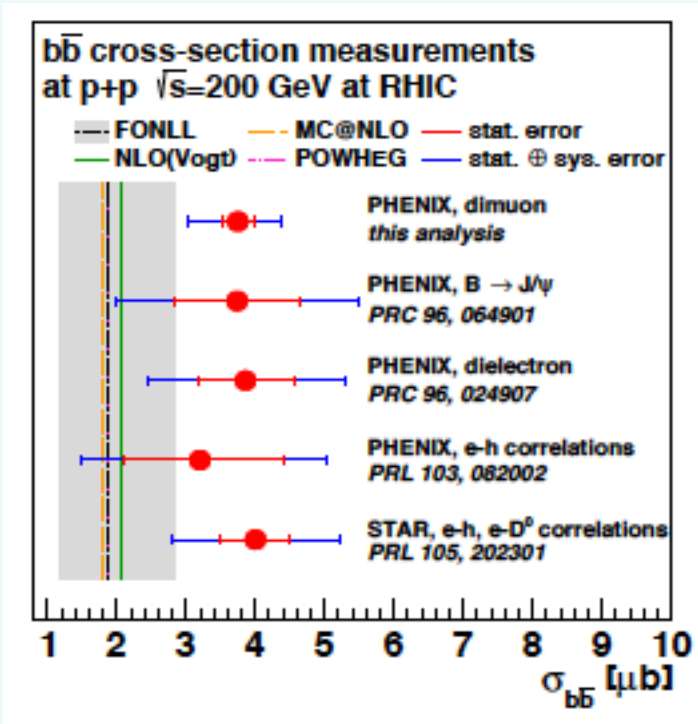
DY highest S/B

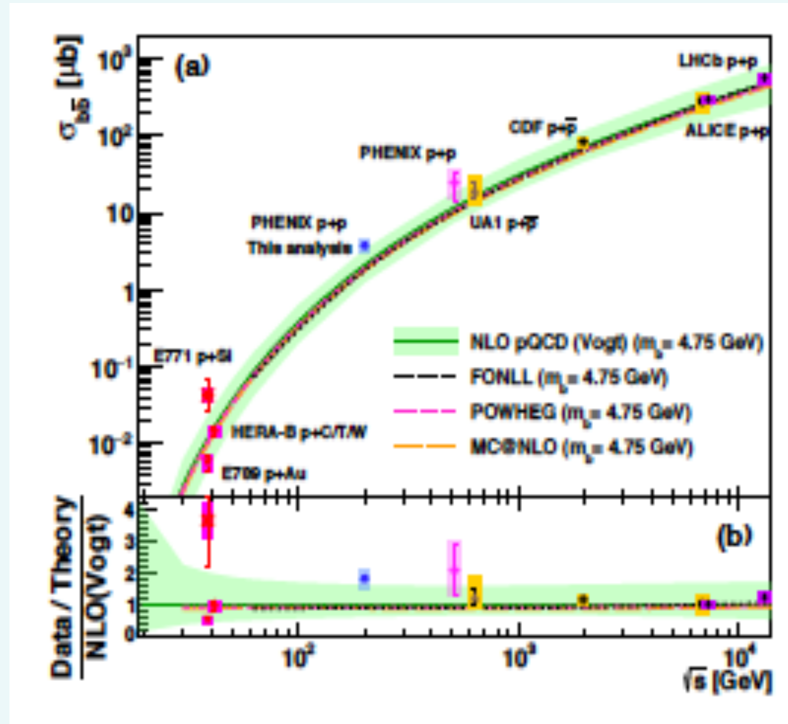


Bottom highest S/B



pp $\rightarrow b\bar{b} + X$





Theory underestimates RHIC data by a factor of ~2
Unlike higher energy LHC data

Cold nuclear matter effects at forward/backward

PH✳ENIX

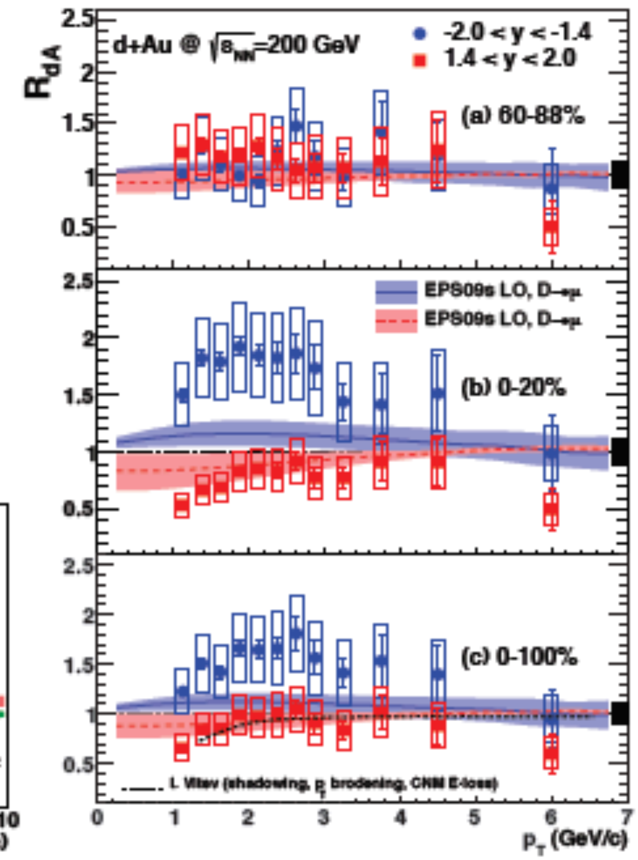
- EPPS16 predicts a constant R_{pA} as a function of pair p_T

- Common mechanism behind modifications for charm/charged hadrons?

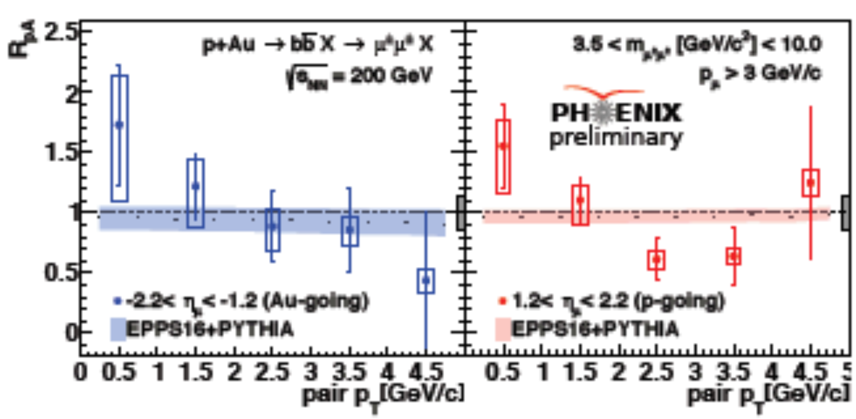
Multiple scattering of partons within nuclear medium?
- collisional energy loss/angular broadening

single μ from charm+botton

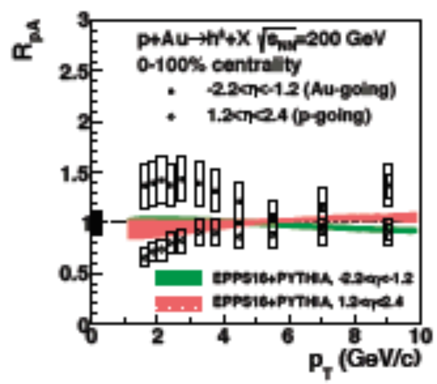
PhysRevLett.112.252301



μμ from bottom $(<p_{T,\mu}>\sim 2.5$ GeV/c)

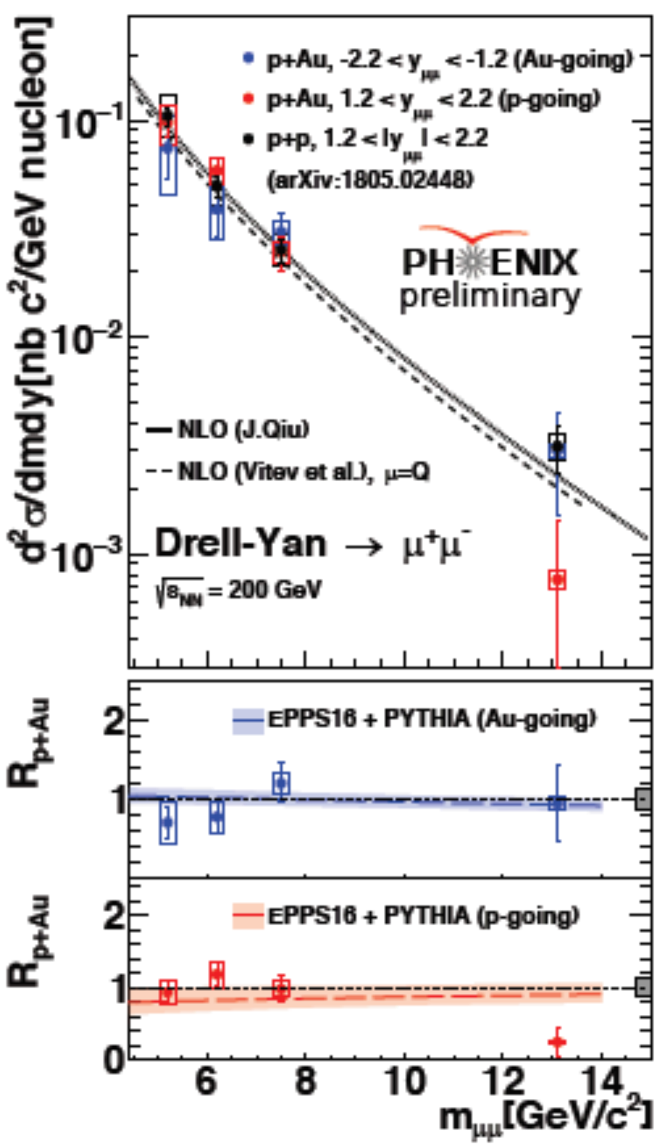


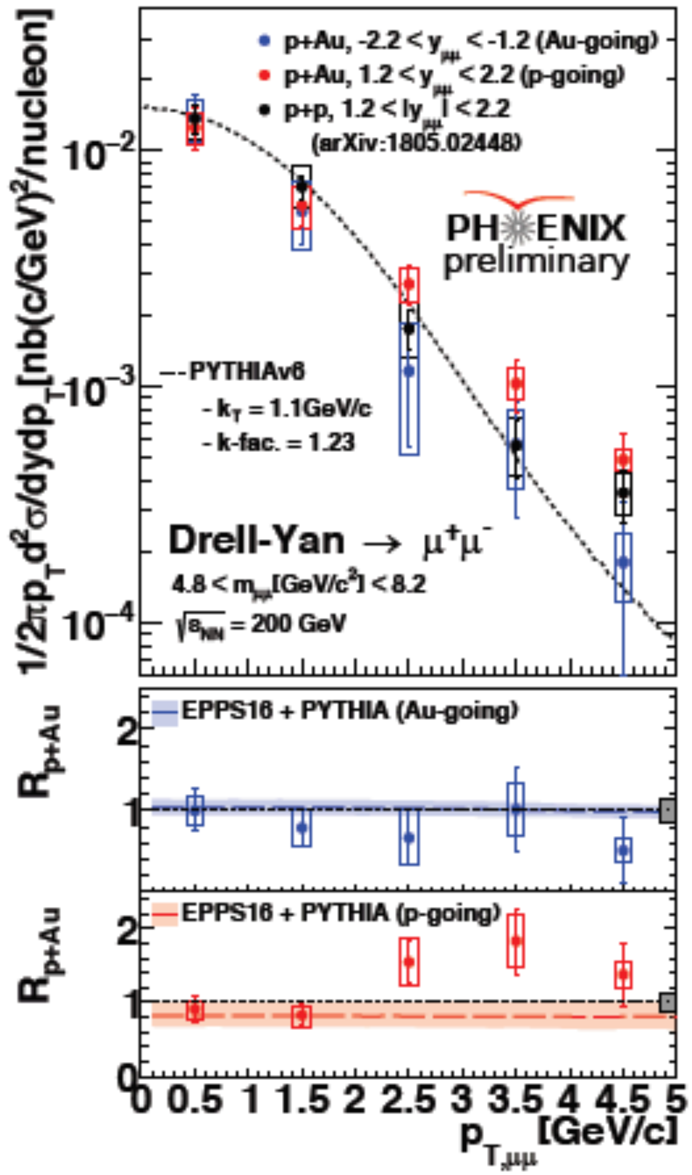
charged hadrons

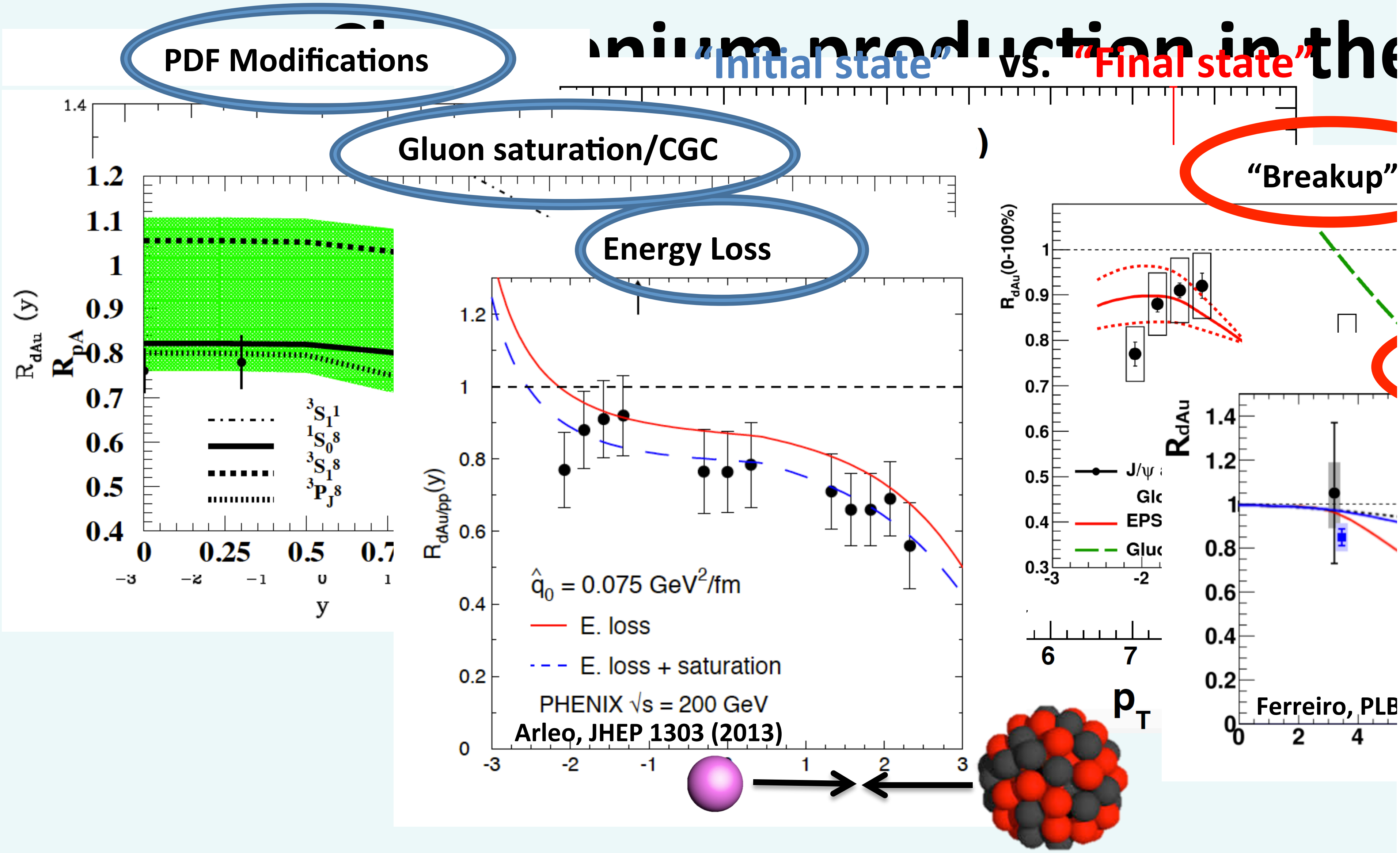


p+Au Drell-Yan cross-section

- **Not affected by final state interactions**
  - **clean probe of initial state effects**
- **R_{p+Au} are consistent with unity and EPPS16.**
- **R_{p+Au} (p-going, p_T>2 GeV/c) has a small tendency to lie above unity.**

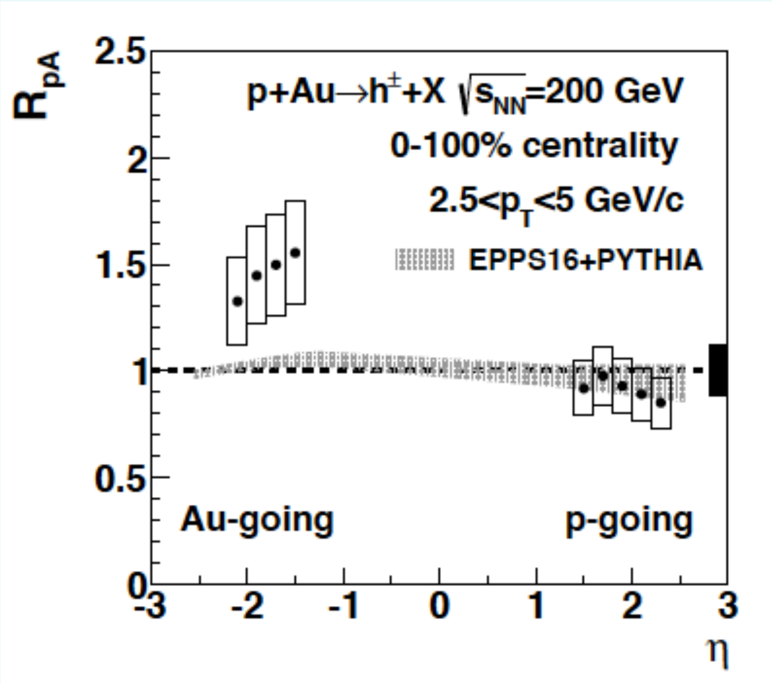




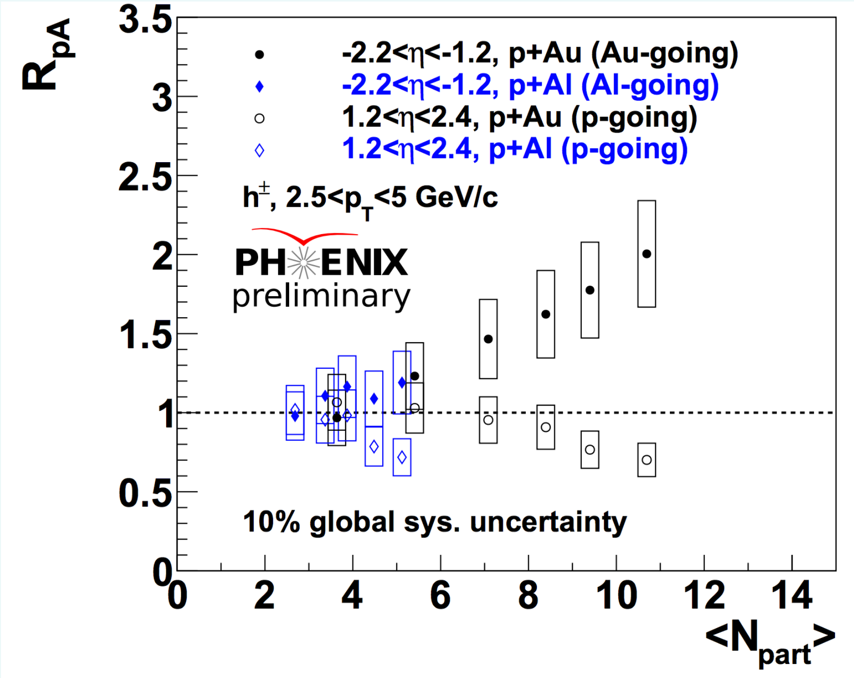


"Initial state" vs. "Final state"
PDF Modifications
Gluon saturation/CGC
Energy Loss
"Breakup"
R_{dAu} (y)
R_{pA}
$^3S_1{}^1$
$^1S_0{}^8$
$^3S_1{}^8$
$^3P_J{}^8$
y
$R_{dAu/pp}(y)$
$\hat{q}_0$ = 0.075 GeV^2/fm
E. loss
E. loss + saturation
PHENIX $\sqrt{s}$ = 200 GeV
Arleo, JHEP 1303 (2013)
R_{dAu}(0-100%)
EPS
p_T
R_{dAu}
Ferreiro, PLB

pA



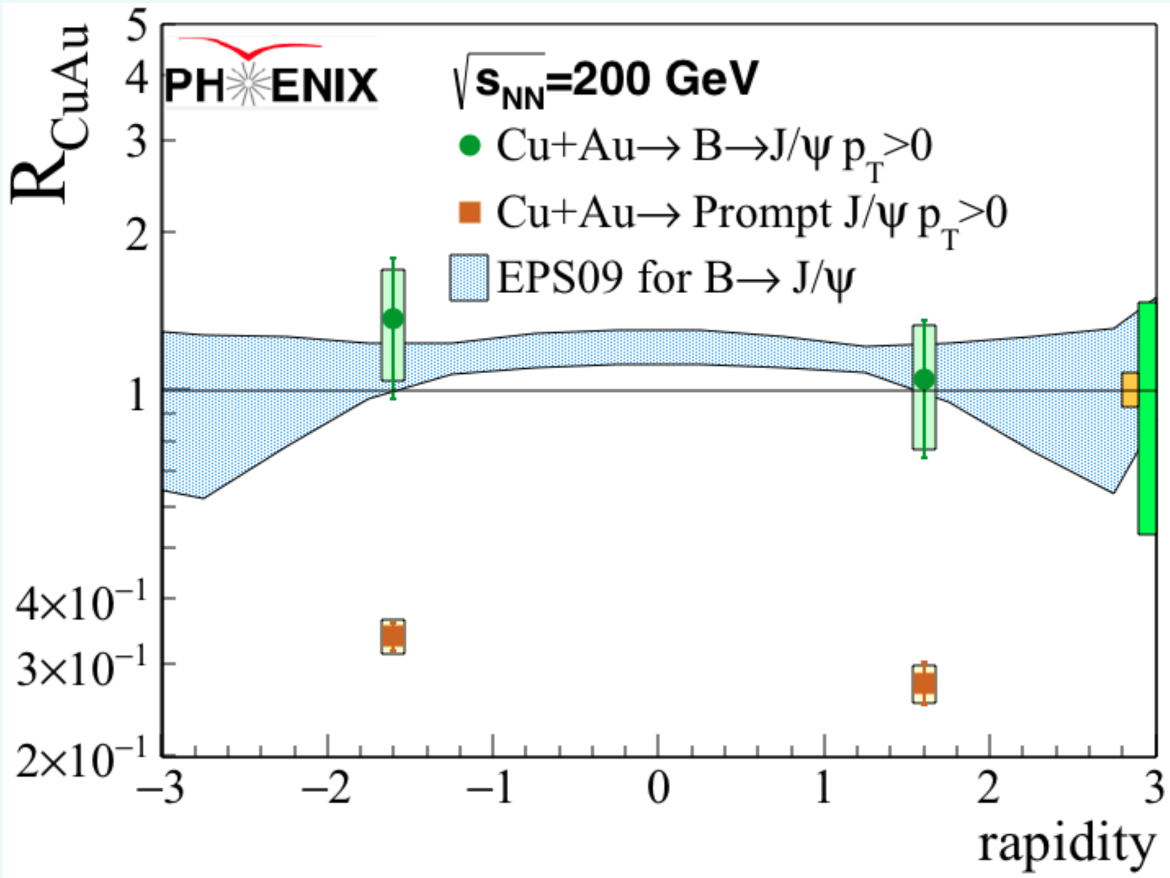
R_{pA}
p+Au→h$^{\pm}$+X $\sqrt{s_{NN}}$=200 GeV
0-100% centrality
2.5<p_T<5 GeV/c
EPPS16+PYTHIA
Au-going
p-going
η



R_{pA}
-2.2<η<-1.2, p+Au (Au-going)
-2.2<η<-1.2, p+Al (Al-going)
1.2<η<2.4, p+Au (p-going)
1.2<η<2.4, p+Al (p-going)
h$^{\pm}$, 2.5<p_T<5 GeV/c
PHENIX
preliminary
10% global sys. uncertainty
<N_{part}>

B-meson R_{CuAu}

Phys. Rev. C 96, 064901 (2017)



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

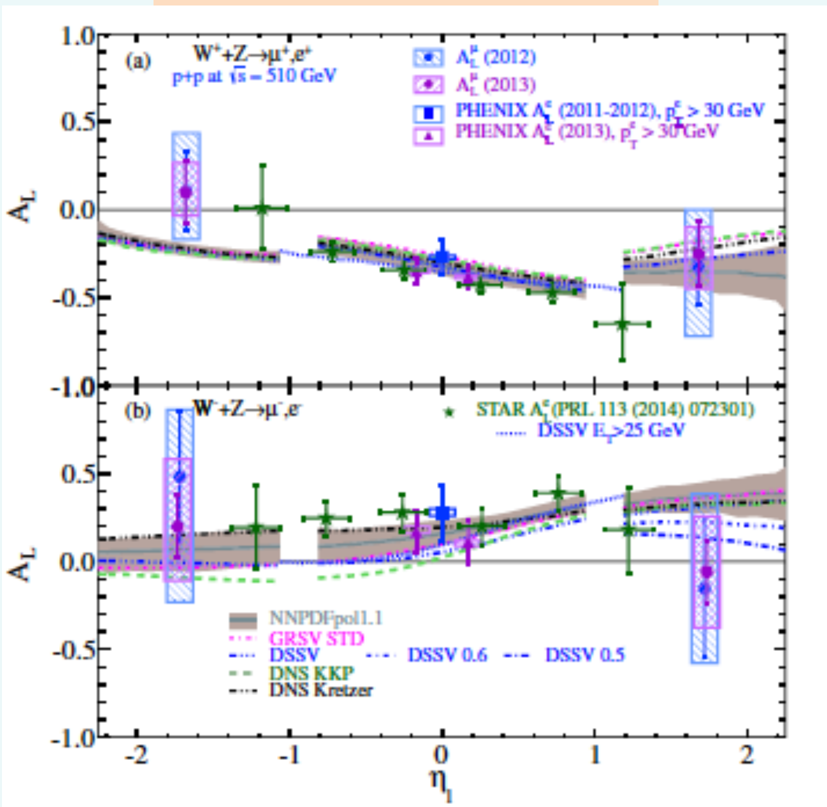
Δq-bar: W± → l±

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

e: |η|<0.35 μ: 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)

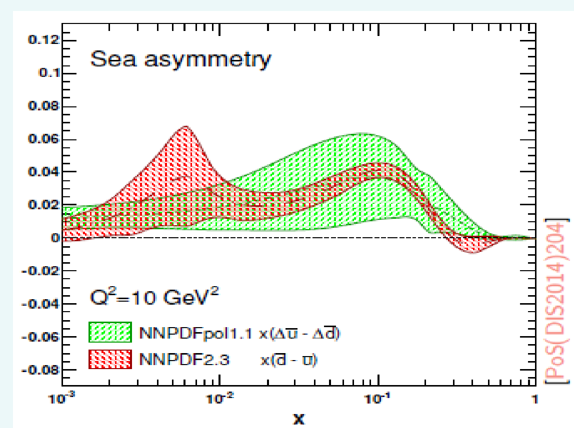
PRD 98, 032007 (2018)



Uncertainties are large due to sizable background (S/B= 0.15−0.28)

Data generally agree with current theory constraint, with some tension in backward region, leading to a preference of ubar polarization to be more positive and dbar polarization to be more negative

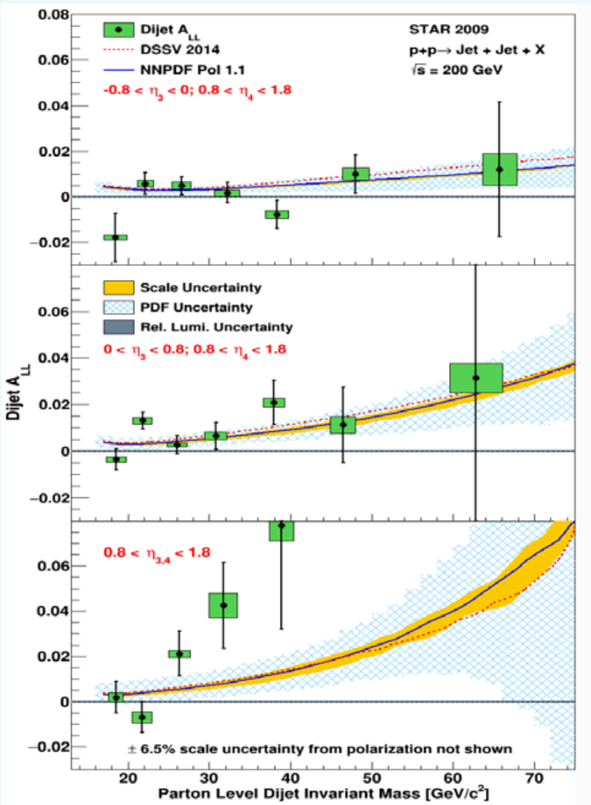
$$x(\bar{d} - \bar{u})$$
$$x(\Delta\bar{u} - \Delta\bar{d})$$

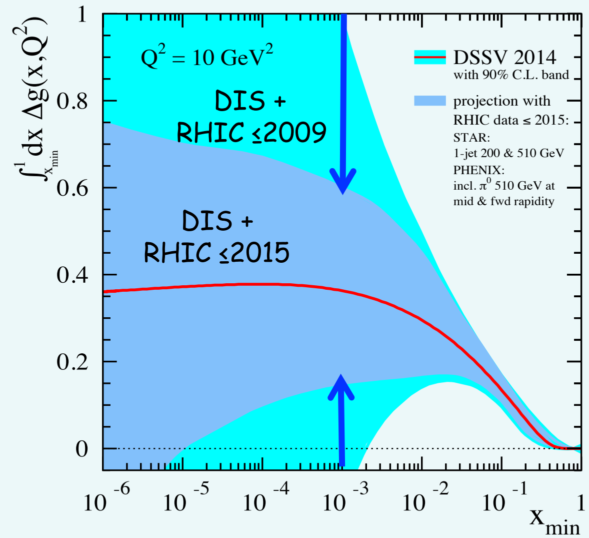


Di-jet A_{LL}: $\Delta G(x)$ to lower x

If we run at $\sqrt{s}$=500 GeV

STAR: 1805.09742

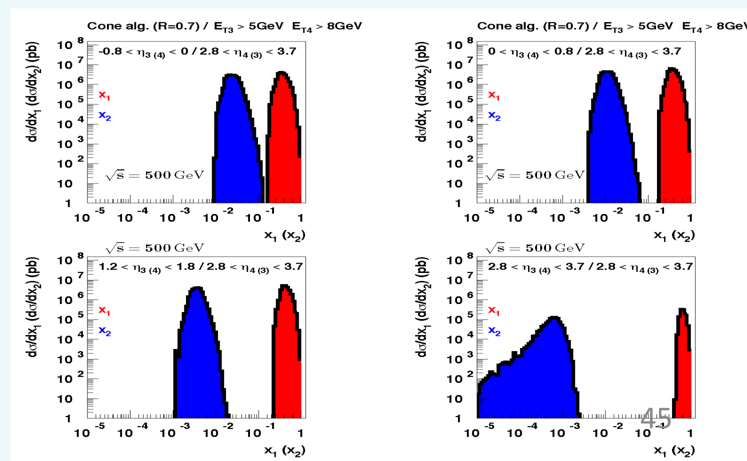




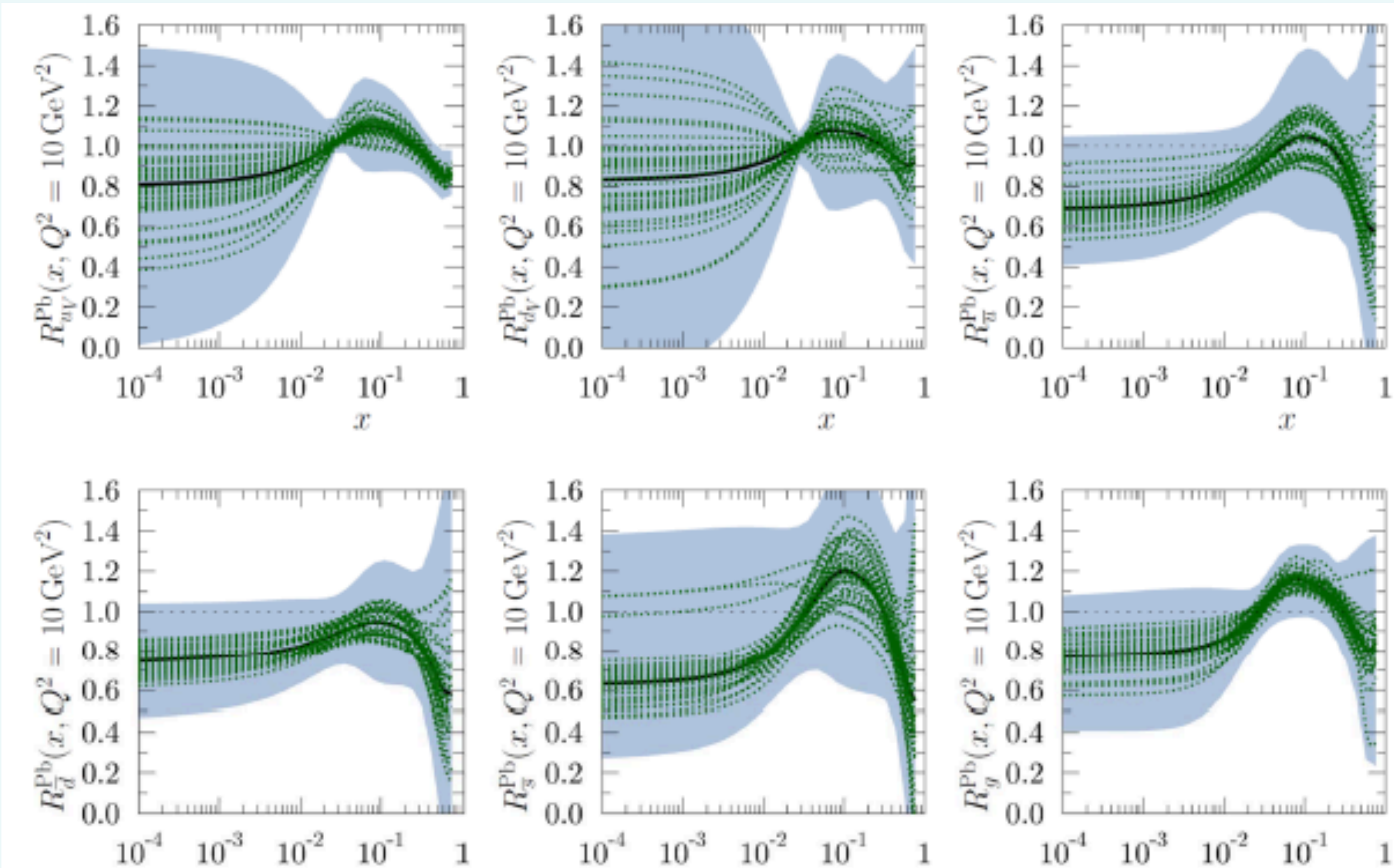
fsPHENIX will considerably improve it

Effective jet triggering and high DAQ rate

Higher rapidity => Lower x (down to ~10^{-3})



nPDF



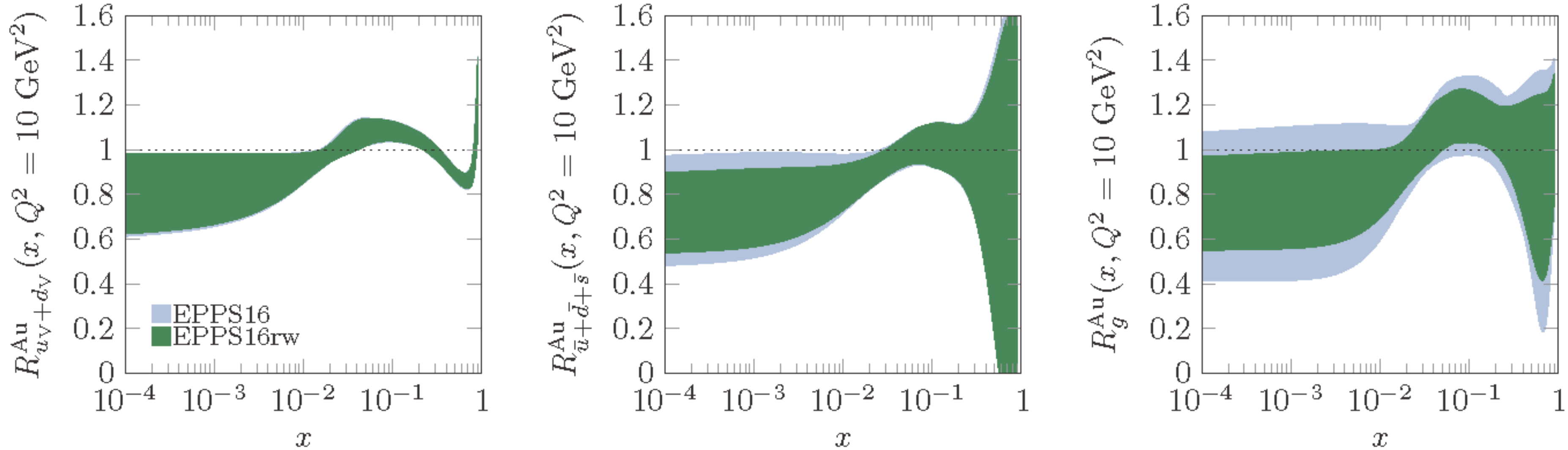
Current nPDF are mainly constrained by DIS data (affected also by final state effect)
Large uncertainty at low x

nPDF from DY

sPHENIX:

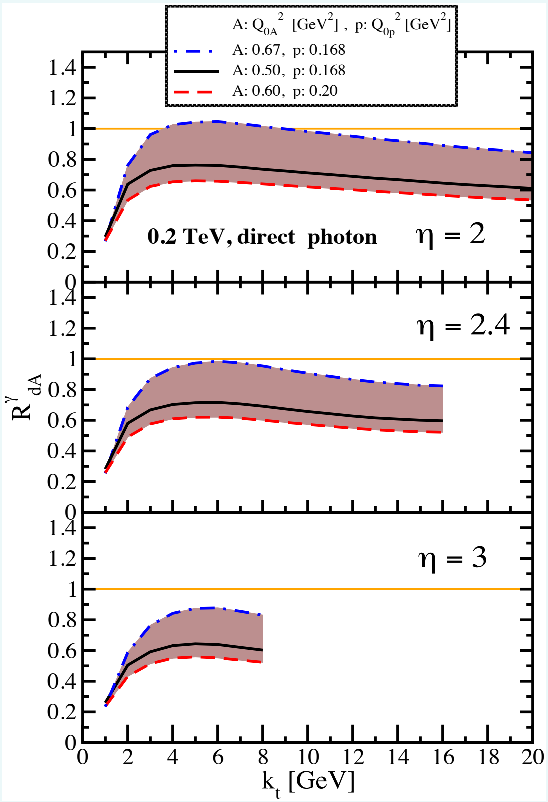
pp: 197 pb^{-1}

pAu:330 nb^{-1}

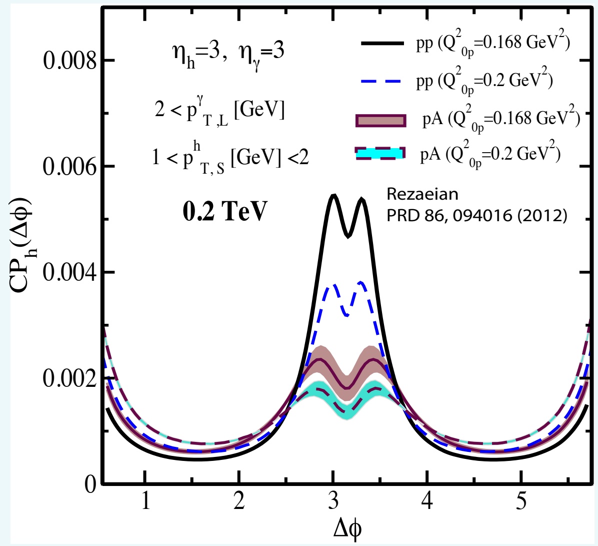


p(d)A: direct photons

CGC prediction for direct photon R_{pA}



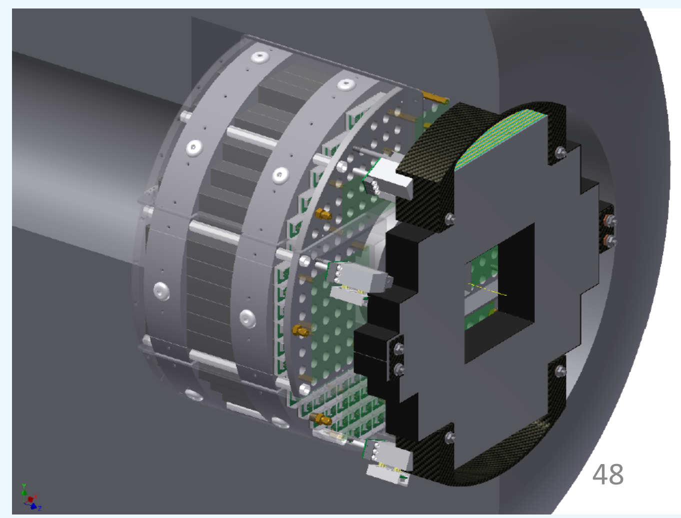
γ-h forward-forward correlations



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

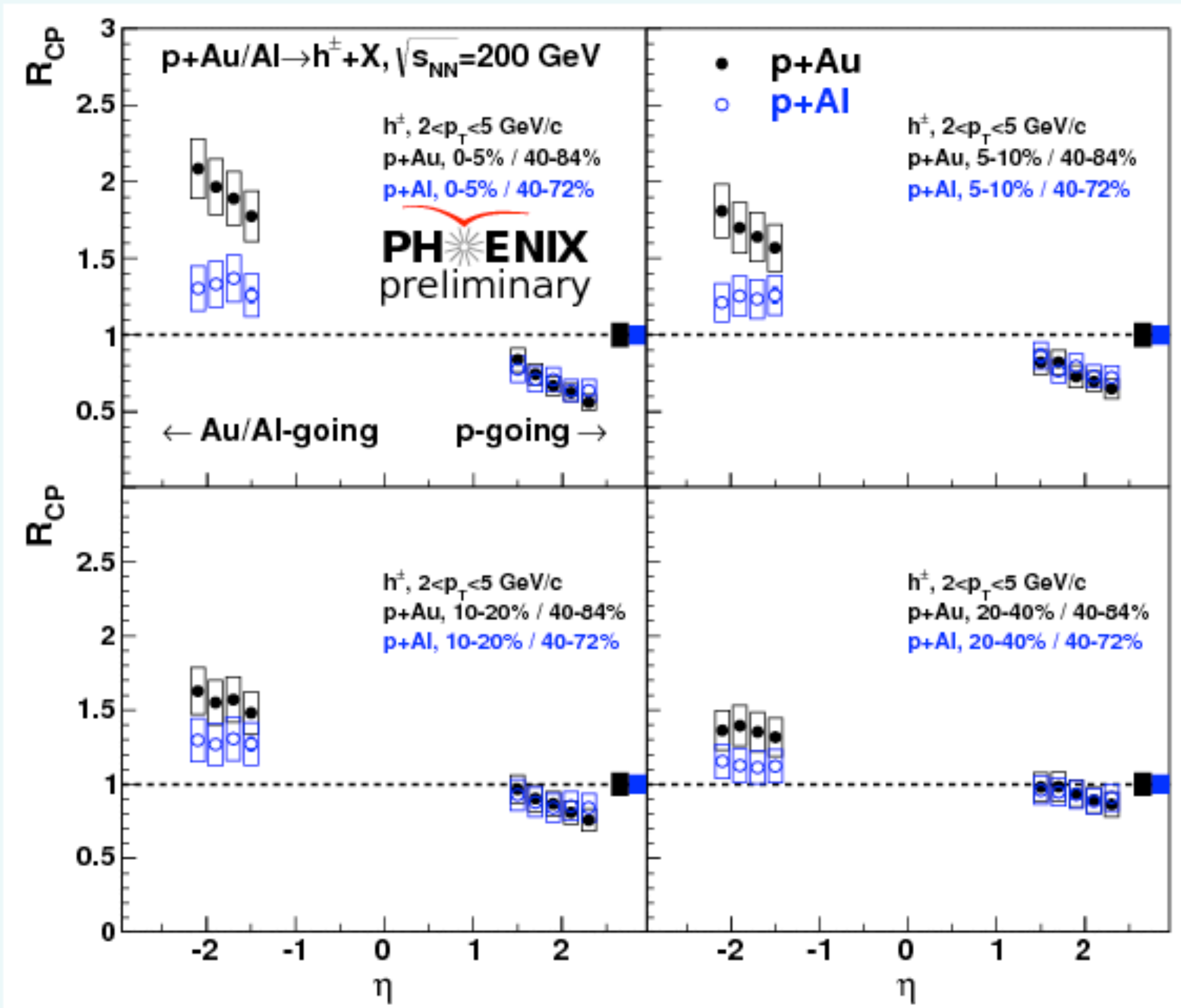
MPC-EX: EMCal + Preshower
3.1<|η|<3.8
π^0/γ separation to >80 GeV/c

Analysis of 2016 dAu data is ongoing



R_{pA}: forward-backward

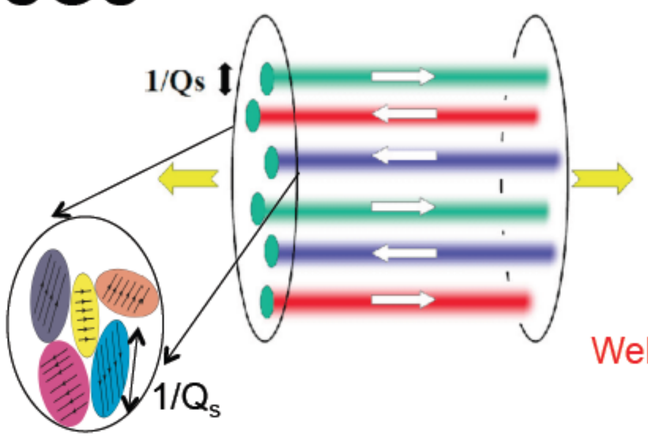
Nucleus size and rapidity dependence



From J.Jia

Examples of initial vs final state scenarios

CGC



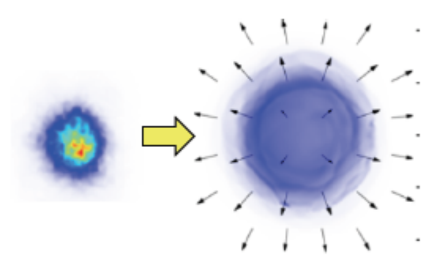
Domain of color fields of size $1/Q_s$, each produce multi-particles correlated across full η.

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