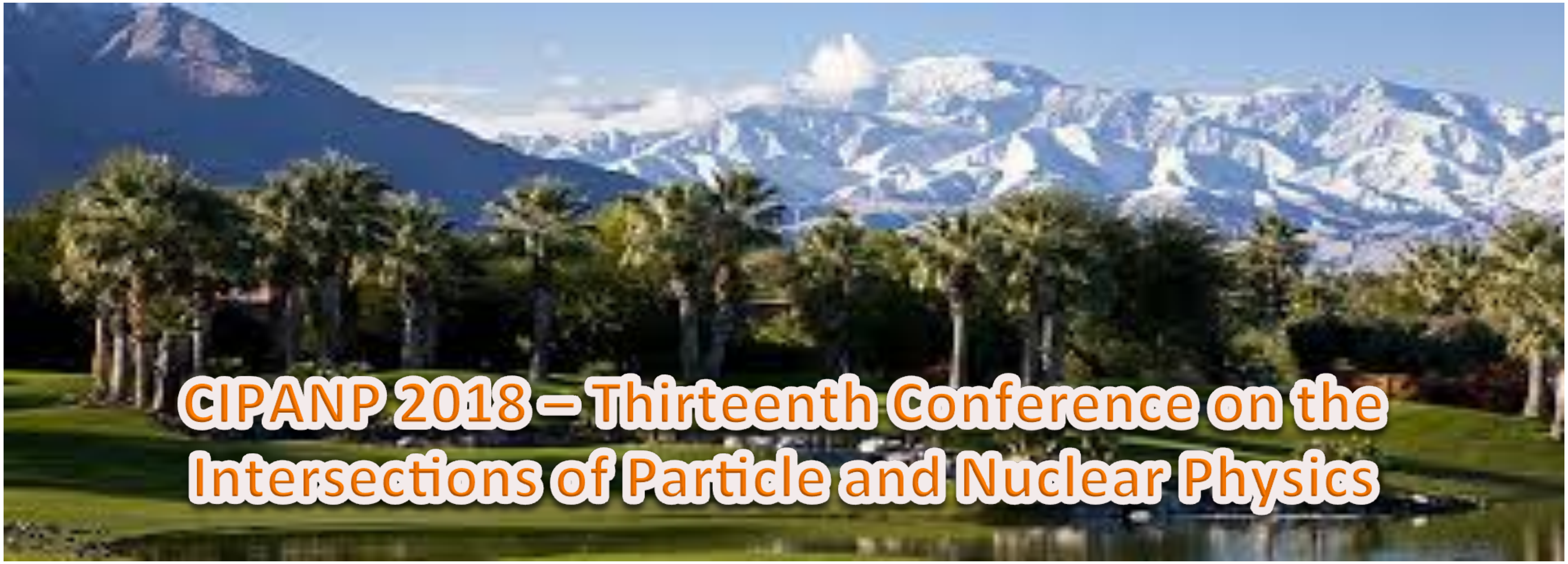
Nuclear PDF, small x physics results at RHIC

Xuan Li (LANL)



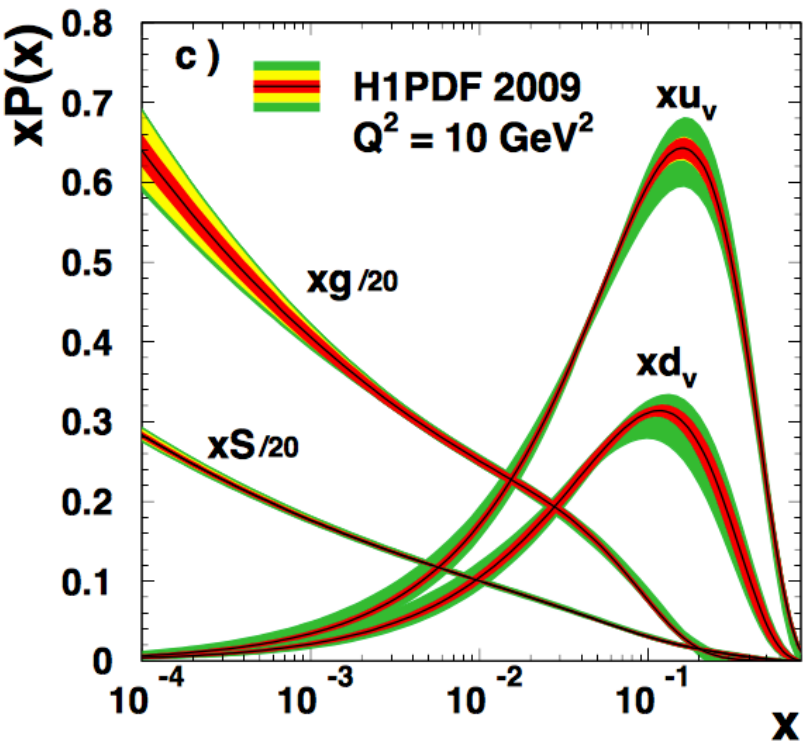
Outline

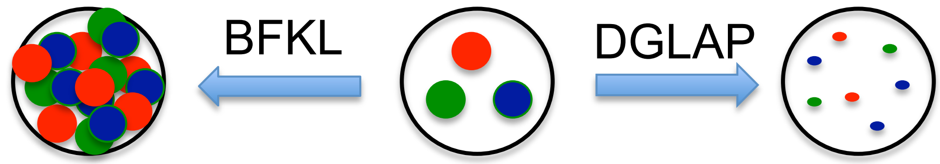
- Motivation.
- Study the nuclear gluon PDF in the low x region at RHIC:
  - forward π^0 and correlations.
- Study the nuclear dependence in p+A, d+A and ^{3}He+A collisions:
  - Ridge in long-range correlations.
- New and future measurements:
  - Mid-rapidity π^0 and direct γ, near-forward charged hadron nuclear modification measurements.
  - EIC
- Summary & Outlook

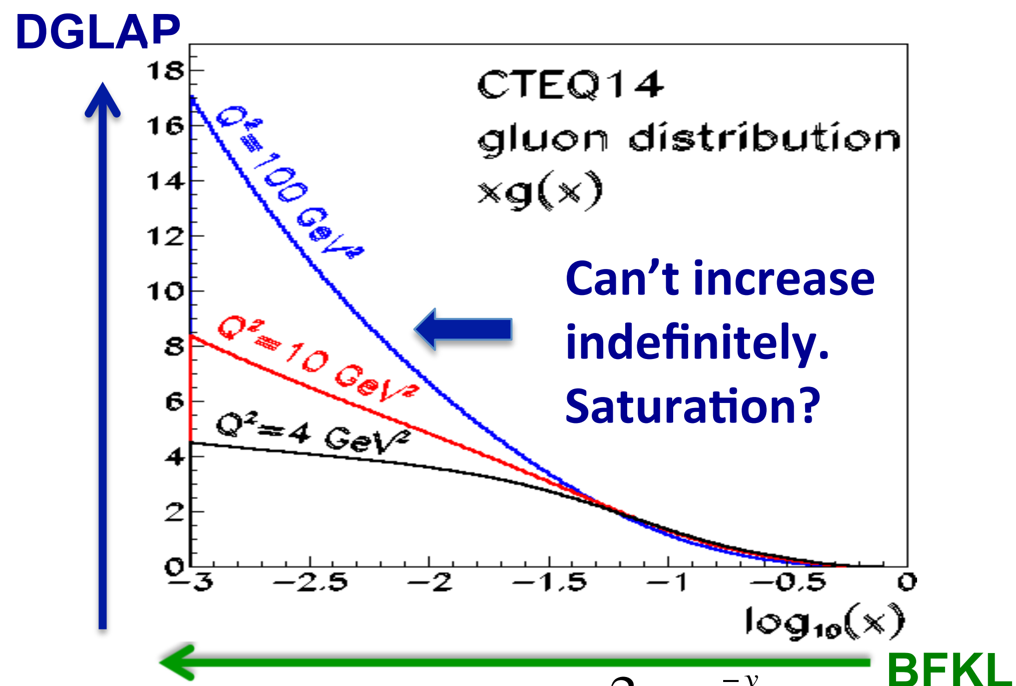
Little known of sea quark and gluon PDF at low x

- Nucleon parton PDF has been well determined in the momentum fraction range of $10^{-4}<x<0.3$ at HERA.

H1 Collab., Eur. Phys. J. C 64 (2009) 561



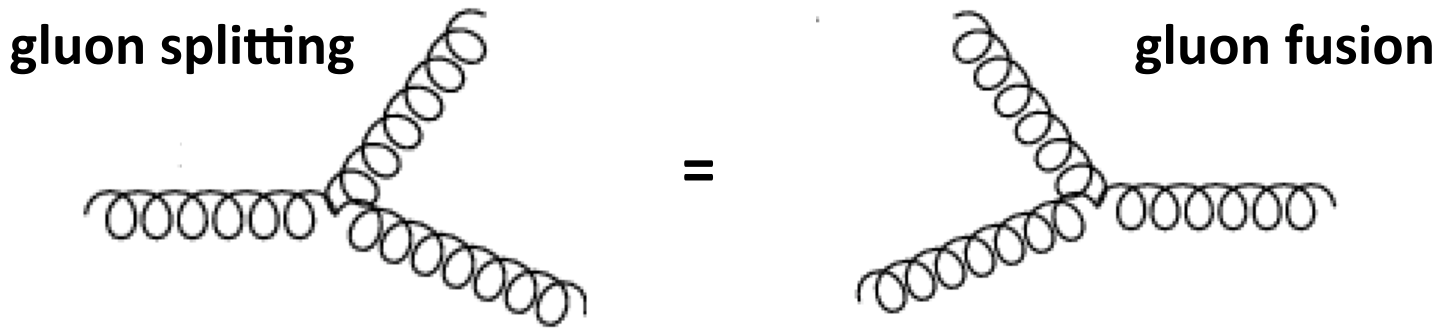


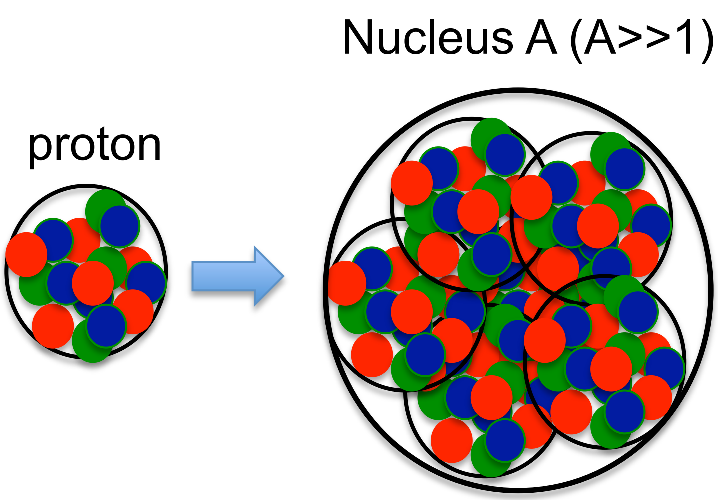


- Nucleon gluon PDF increases rapidly as x ($\approx \frac{2p_T e^{-y}}{\sqrt{s}}$) decreases at a fixed Q^2 value.

From nucleon to nucleus

- Beyond linear evolution, when gluon recombination balances gluon splitting, saturation is realized.





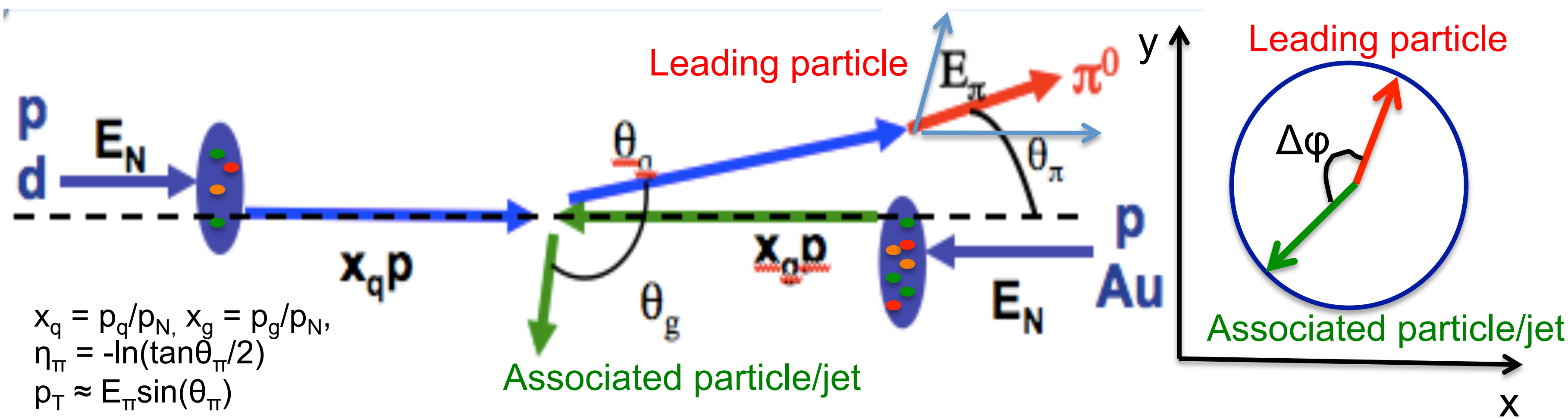
- Nuclear (mass number A) gluon density ≈ $A^{1/3}$ × nucleon gluon density at a given x.
- Leading to the expectation saturation scale $Q_s^2 \approx A^{1/3}\, x^{\beta}$. [Phys.Rev.D 78(2008)014016].

How to probe low x gluons

- Low x require low p_T, forward rapidity and large √s.

Parton distribution function $\otimes$ Hard parton scattering $\otimes$ Partons fragment into hadrons

- The factorization mechanism is taken as universal and applied in nucleon (nucleus)+ nucleon (nucleus) collisions.

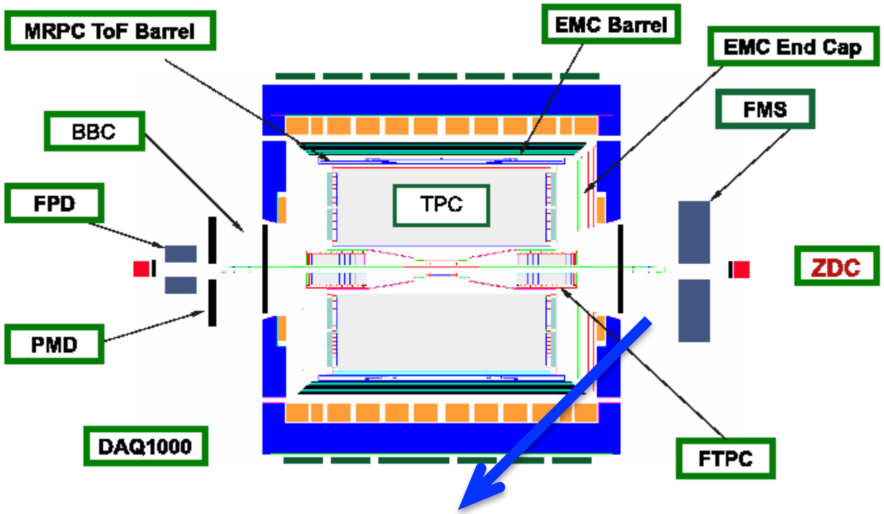


$x_q = p_q/p_N$, $x_g = p_g/p_N$,
$\eta_\pi = -\ln(\tan\theta_\pi/2)$
$p_T \approx E_\pi \sin(\theta_\pi)$

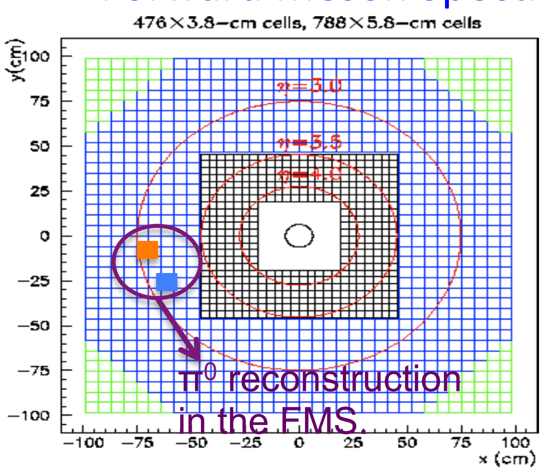
- Large rapidity (η_π~4) inclusive π production and correlations **probe asymmetric partonic collisions.**
- Mostly **high-x_q valence quark (x>0.2)** + **low-x_g gluon (x<0.01).**
- **Forward back-to-back correlations can probe low x gluon.**

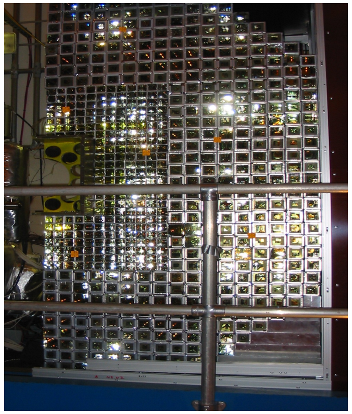
STAR and PHENIX detectors

- STAR has detector spans $-1<\eta<4.5$ with full azimuthal coverage.

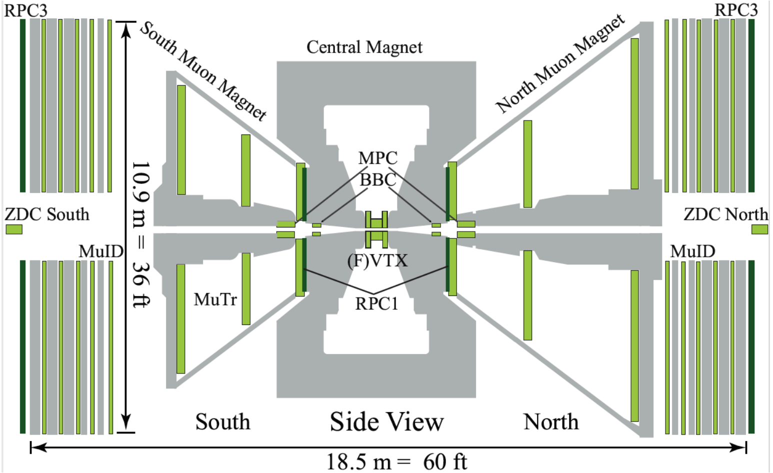


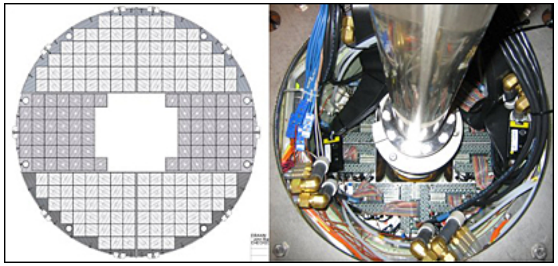
- Forward Meson Spectrometer ($2.5<\eta<4.5$)



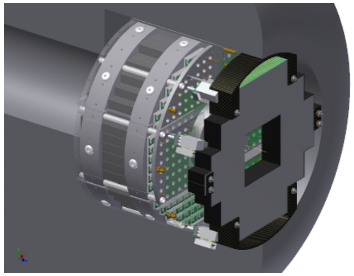


- PHENIX has detector spans $|\eta|<0.3$, $1<|\eta|<3$ and $3.1<|\eta|<3.9$.





Muon Piston Calorimeter ($3.1<|\eta|<3.9$).



- Upgrade with MPC-EX in 2015.

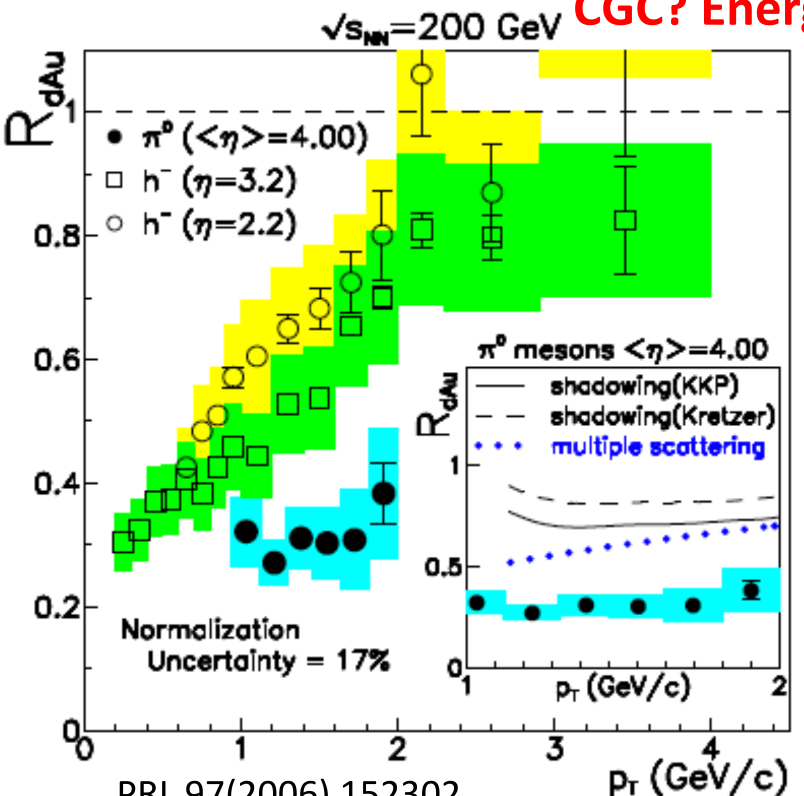
Access low x gluons with forward hadron and correlation studies

Significant nuclear modification of forward π^0 within Au nuclei

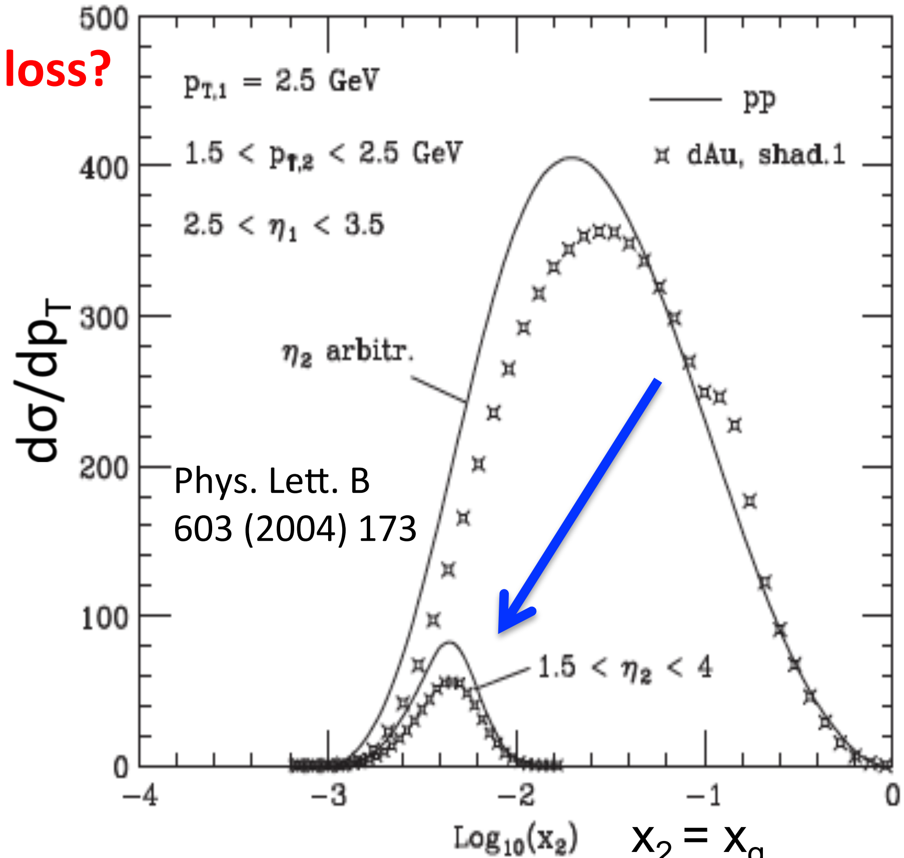
Significant nuclear modification beyond the shadowing prediction.

Correlated π^0-π^0 allows us to select x.

CGC? Energy loss?



PRL 97(2006) 152302



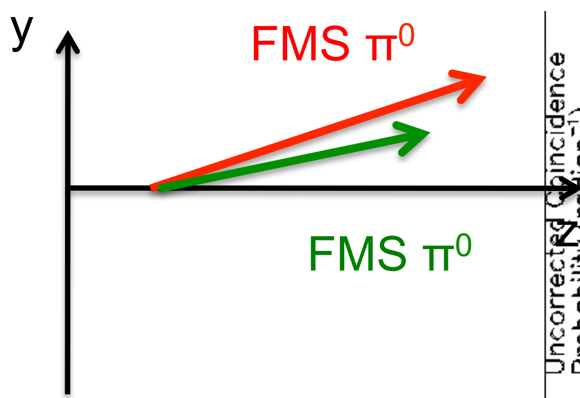
Phys. Lett. B 603 (2004) 173

$x_2 = x_g$

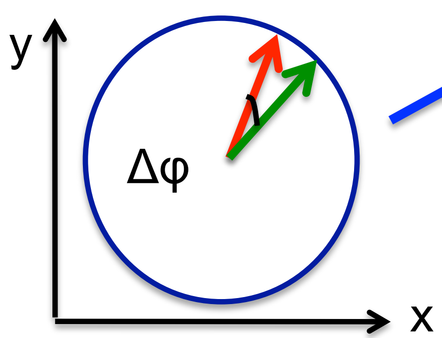
Forward π^0-forward π^0 correlations are more sensitive to low x gluons than inclusive production.

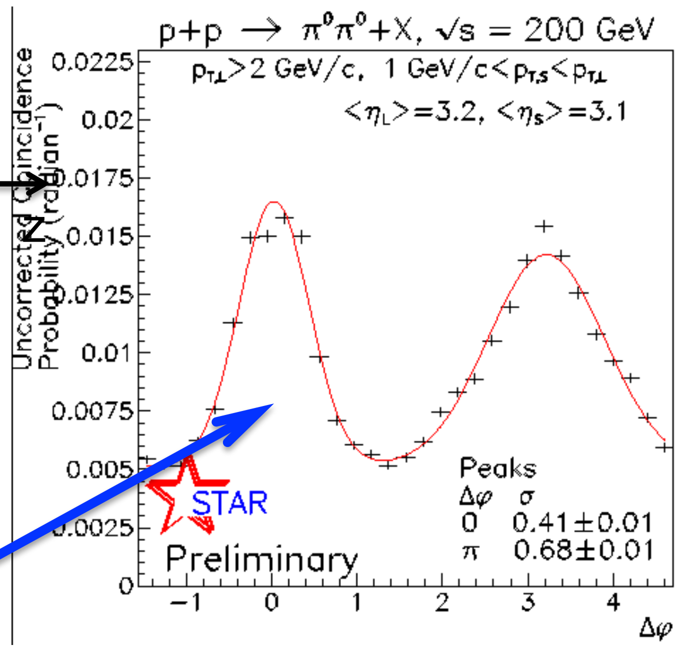
Forward-forward rapidity correlation at STAR

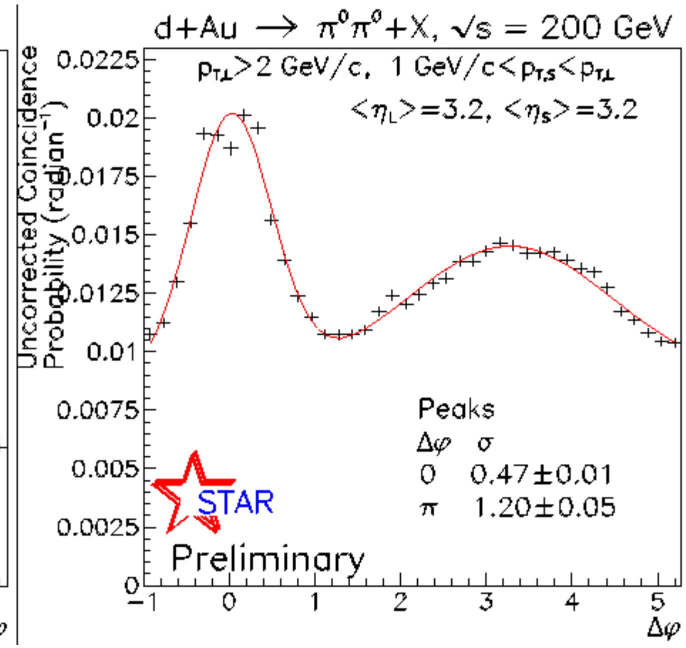
- Most Forward-Forward azimuthal correlations at RHIC can probe gluon density at 0.0009 < x < 0.005.



Near side correlation





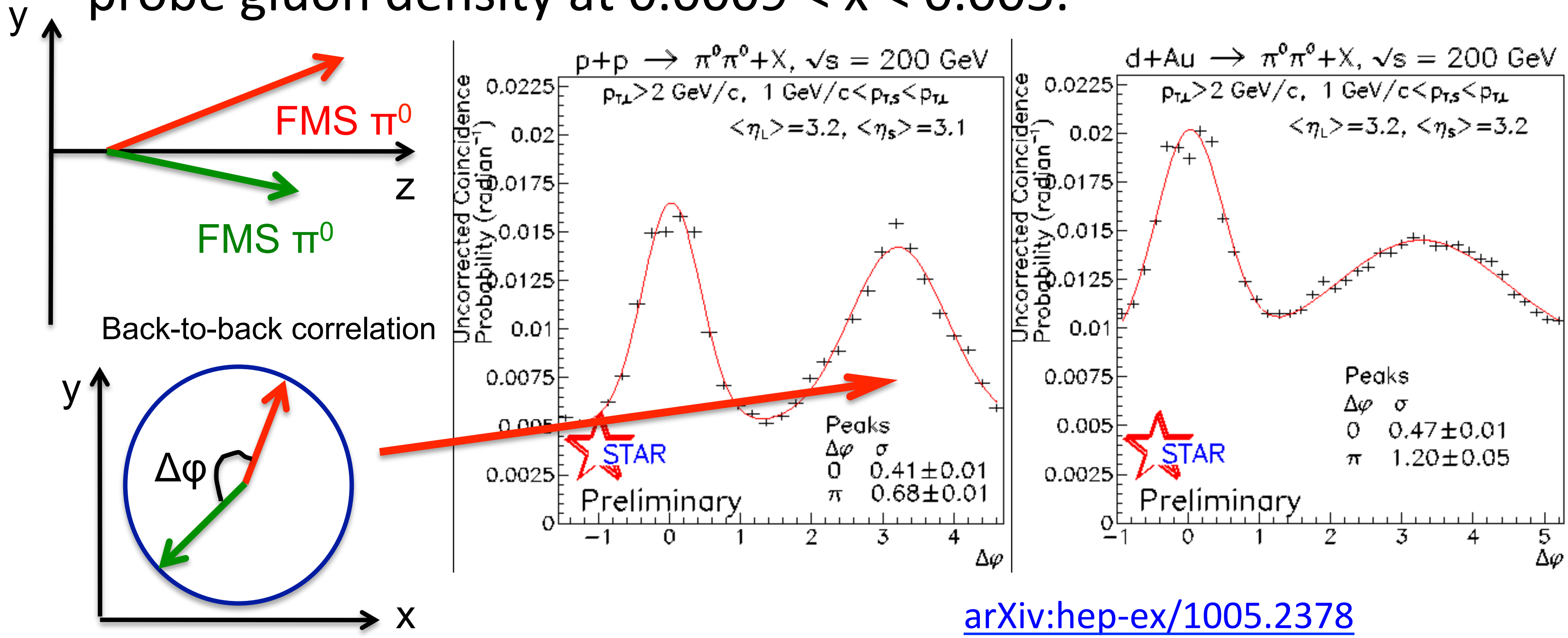


arXiv:hep-ex/1005.2378

- Similarity of near side peak in pp and dAu data indicate similar initial jet shape in proton and gold nuclei.

Forward-forward rapidity correlation at STAR

- Most Forward-Forward azimuthal correlations at RHIC can probe gluon density at $0.0009 < x < 0.005$.

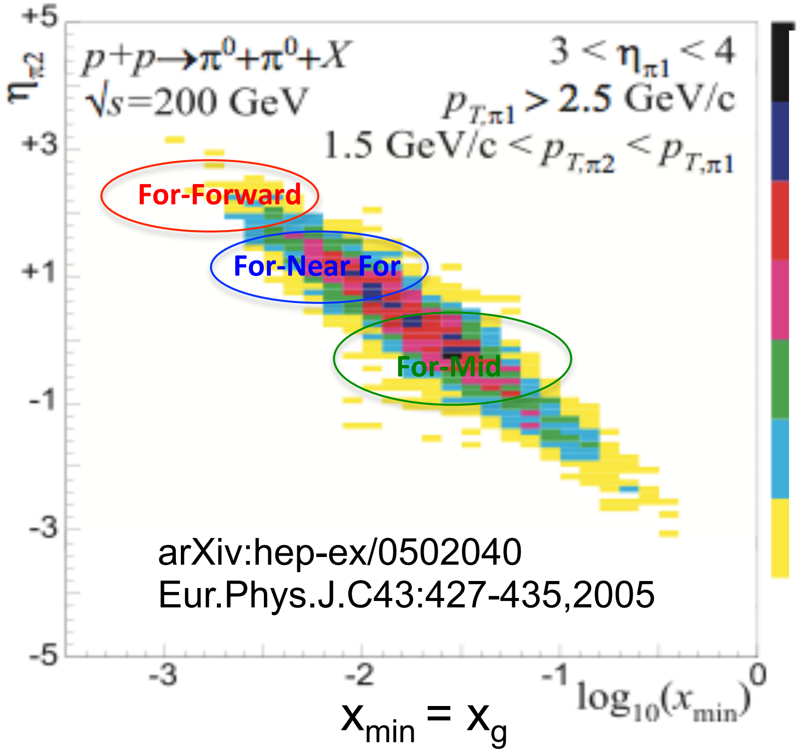


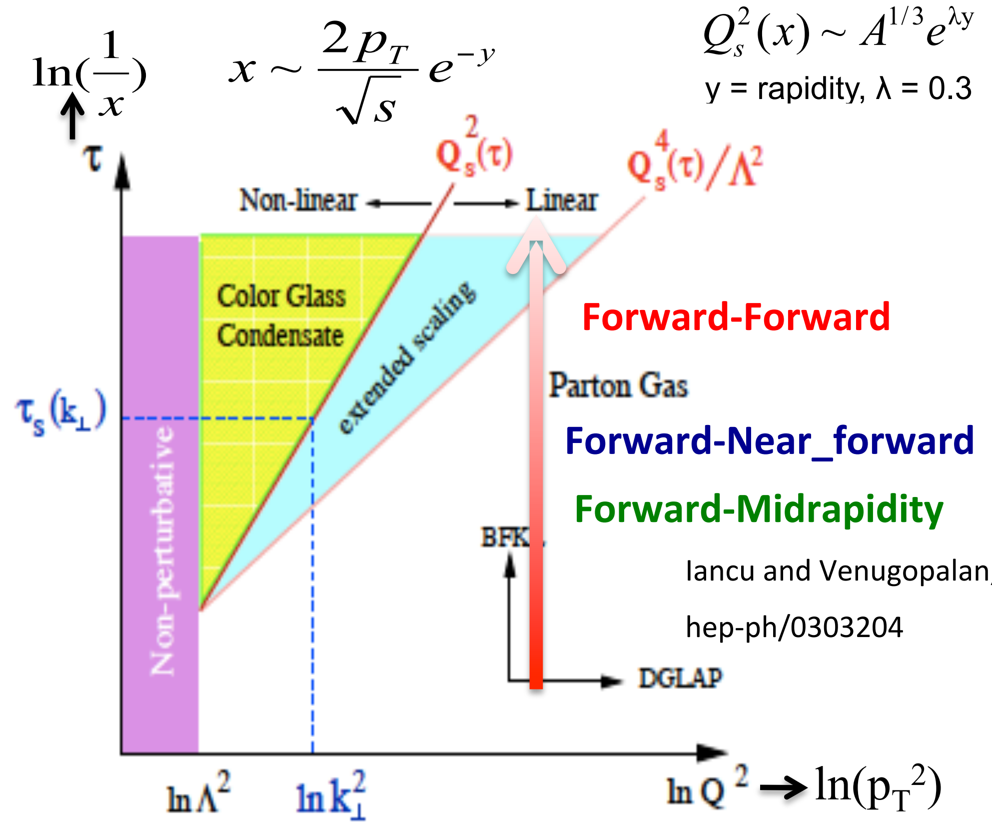
arXiv:hep-ex/1005.2378

- Significant broadening from pp to dAu in the away side peak indicates prominent nuclear modification of the gluon PDF inside the Au nuclei at low x region.

Access different x region of soft gluon through rapidity scan

PYTHIA simulation

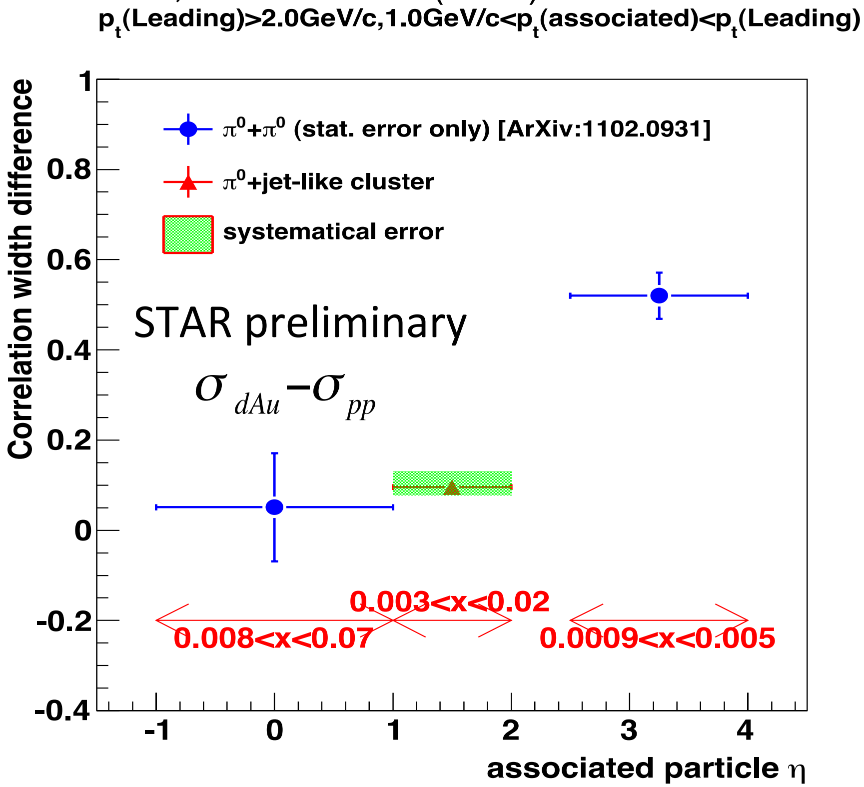




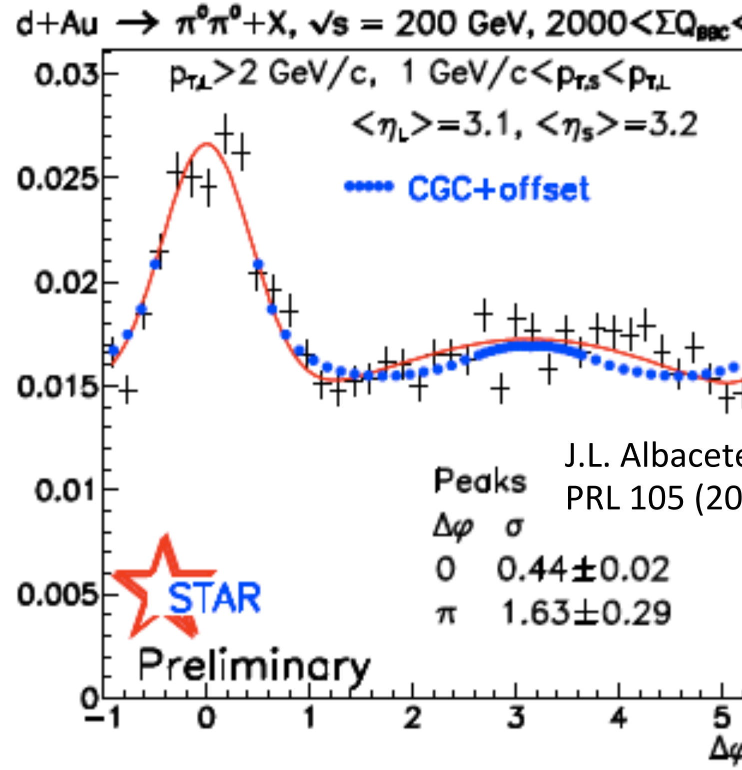
- **The pseudo-rapidity of the associated particle** is strongly correlated with **soft gluon x** in the asymmetric parton scattering mostly **high-x_q valence quark (x>0.2)** + **low-x_g gluon (x<0.01).**

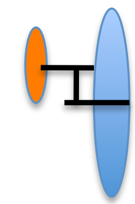
Rapidity and centrality dependence of forward di-hadron correlations at STAR

STAR, NPA 904–905 (2012) 823c–826c



Forward-forward in central d+Au

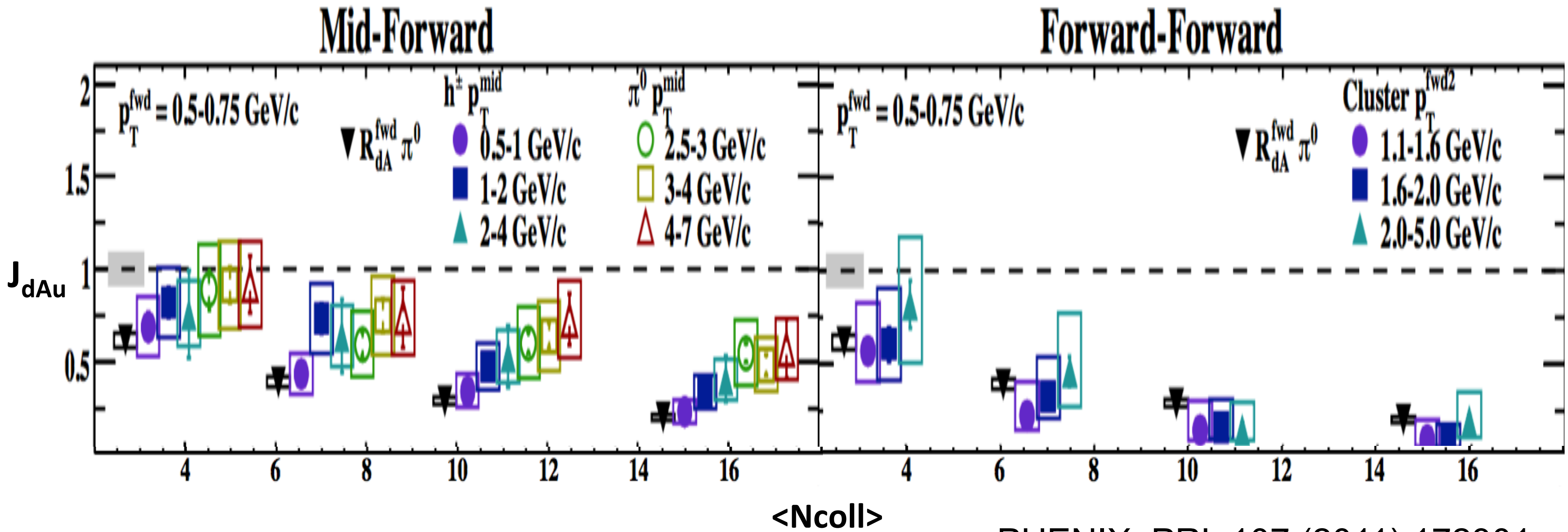




J.L. Albacete, C. Marquet
PRL 105 (2010) 162301

- Clear rapidity dependent broadening of away side peak in the forward di-hadron correlations at STAR.
- Suppression of the forward-forward away-side in central d+Au is consistent with the CGC calculations.

Rapidity, p_T and centrality dependence of forward di-hadron correlations at PHENIX

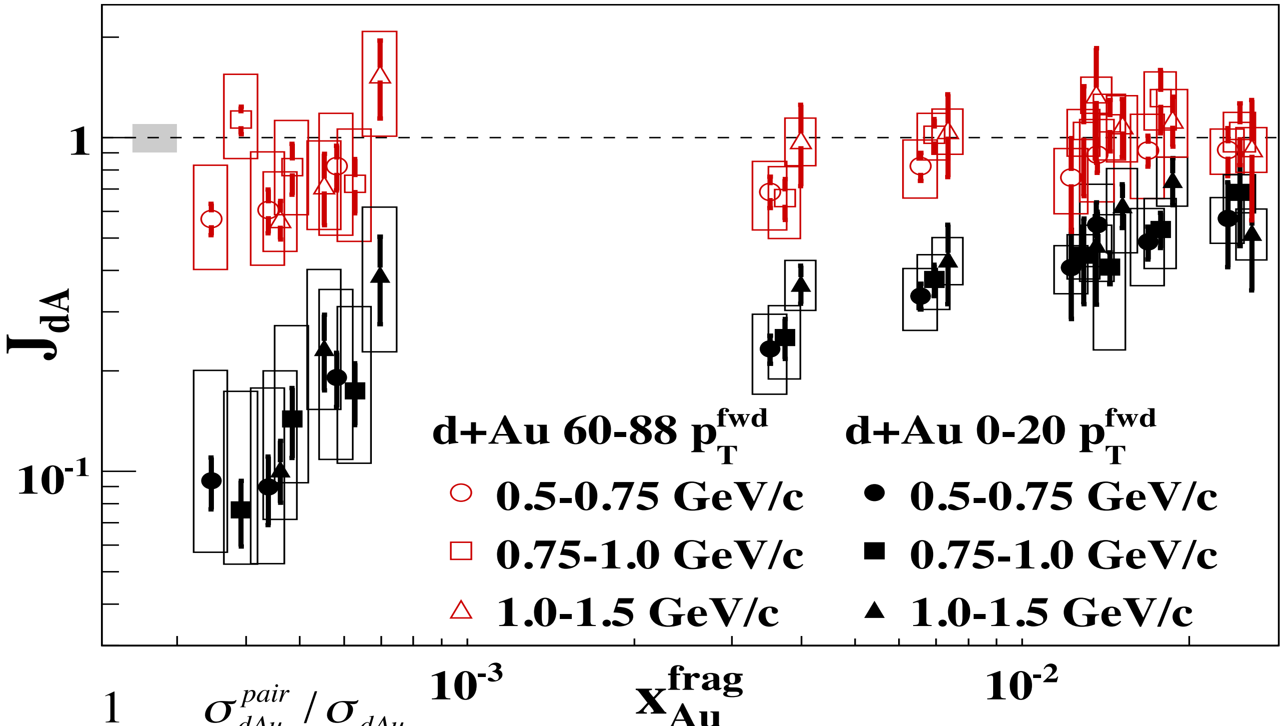


PHENIX, PRL 107 (2011) 172301

$$J_{dAu} = \frac{1}{<N_{coll}>} \frac{\sigma_{dAu}^{pair} / \sigma_{dAu}}{\sigma_{pp}^{pair} / \sigma_{pp}}$$

- Clear rapidity, p_T and centrality dependent broadening and suppression of the away side peak in the di-hadron correlations at PHENIX.

Rapidity, p_T and centrality dependence of forward di-hadron correlations at PHENIX



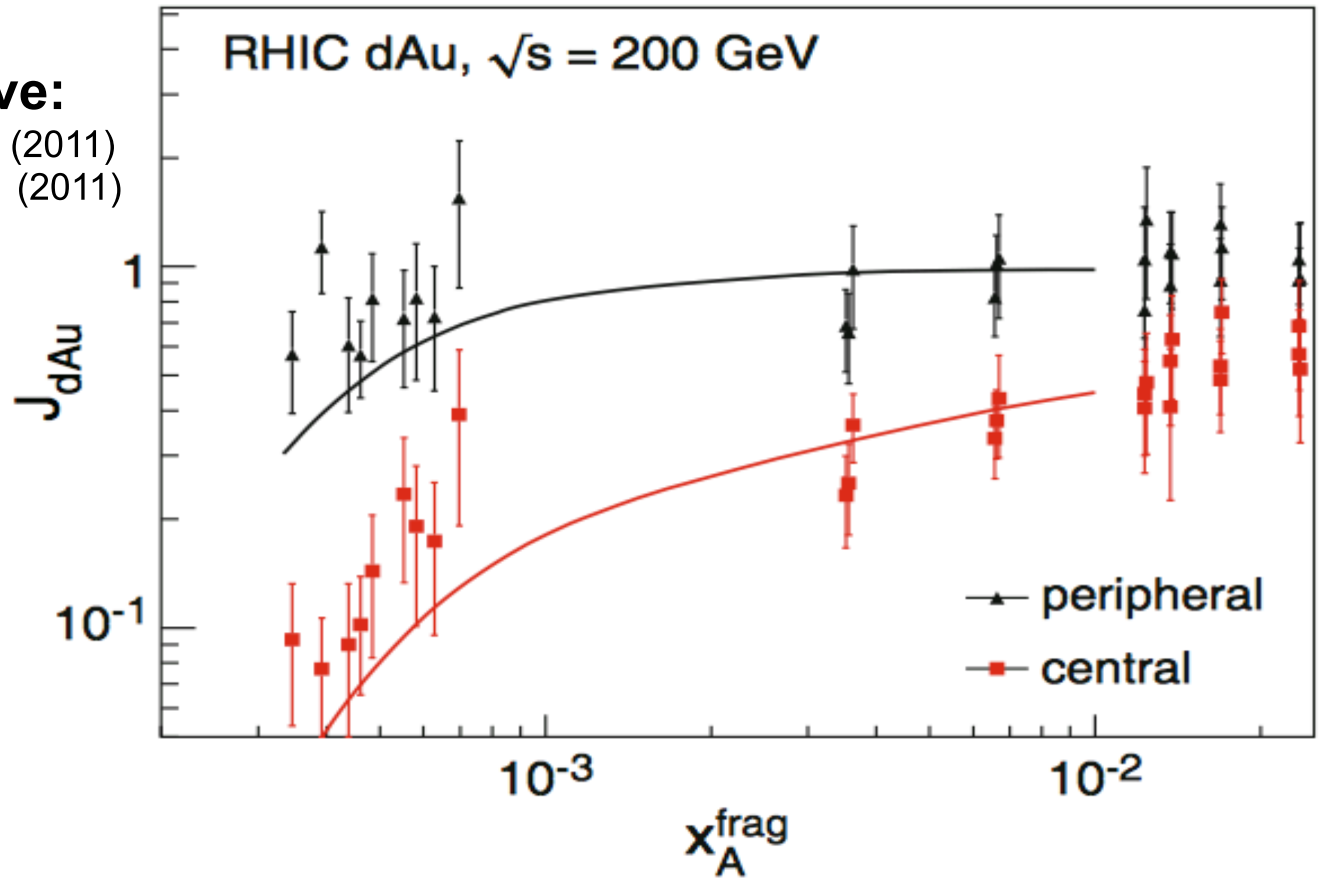
$$J_{dAu} = \frac{1}{<N_{coll}>} \frac{\sigma_{dAu}^{pair} / \sigma_{dAu}}{\sigma_{pp}^{pair} / \sigma_{pp}}$$

PHENIX, PRL 107 (2011) 172301

- Largest suppression of forward di-hadron correlation with lowest p_T observed at PHENIX in central d+Au collisions and is centrality dependent.

Rapidity, p_T and centrality dependence of forward di-hadron correlations at PHENIX

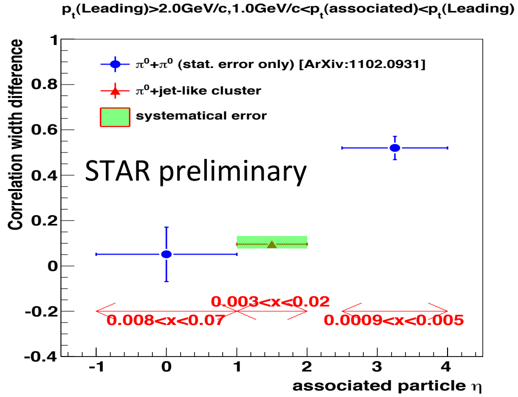
CGC curve:
PRD 83, 105005 (2011)
PRL 106, 022301 (2011)



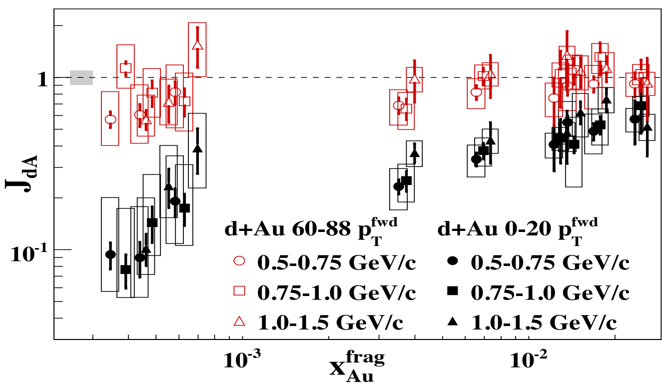
- The centrality dependent suppression of forward di-hadrons is consistent with CGC predictions.

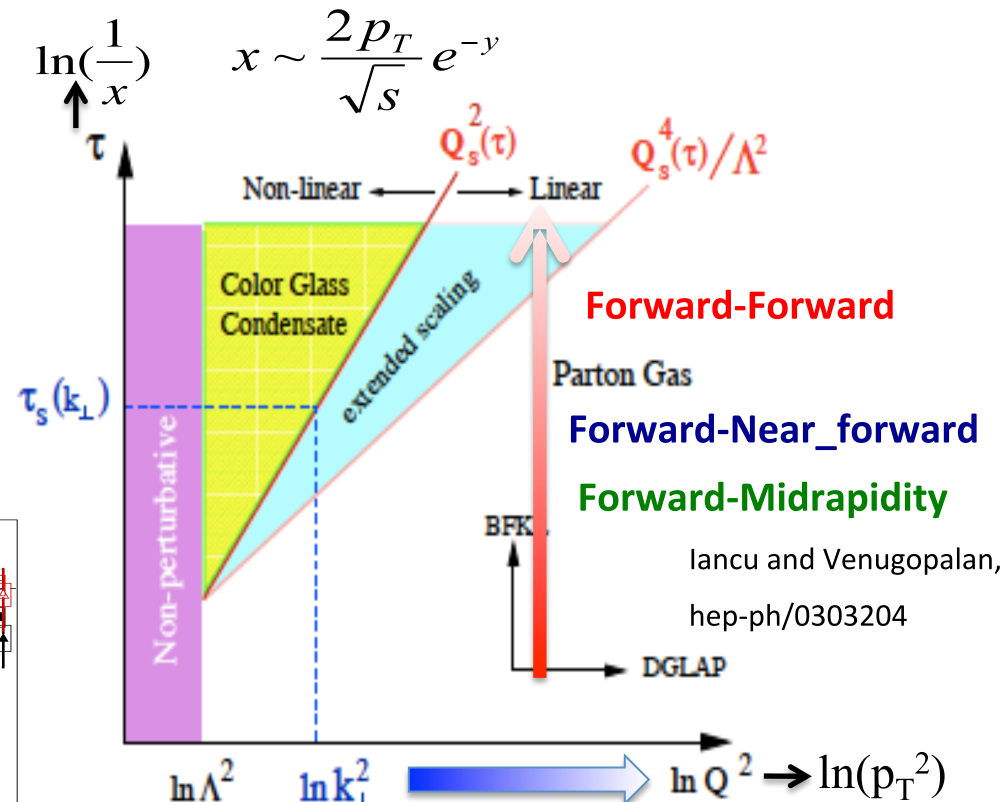
Rapidity dependent away side broadening

STAR, NPA 904–905,823c–826c



PHENIX, PRL 107 (2011) 172301



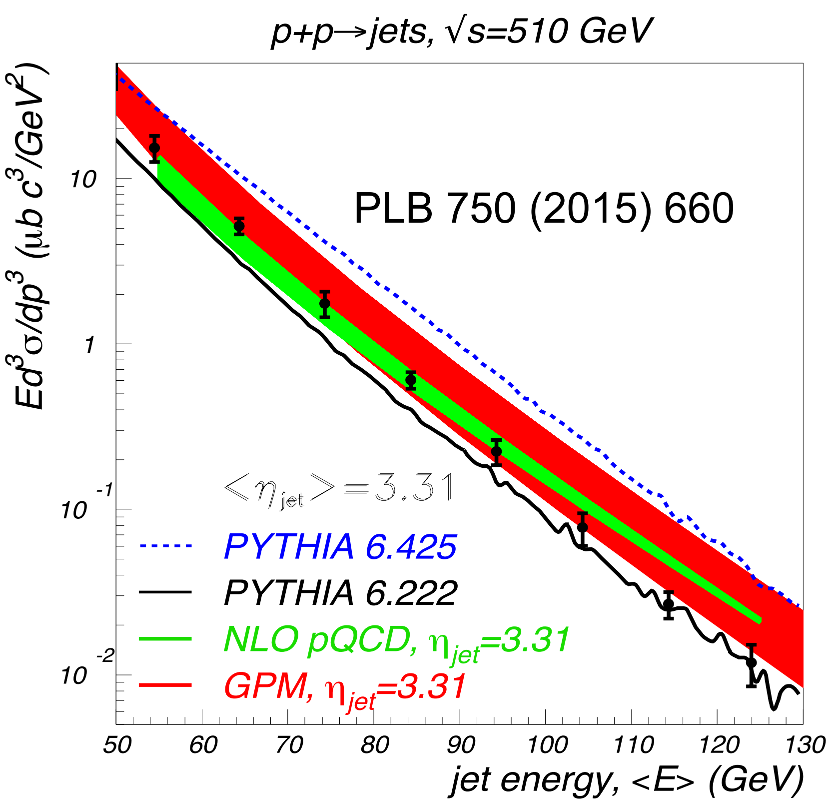


Not only x dependence but also Q^2 dependence.

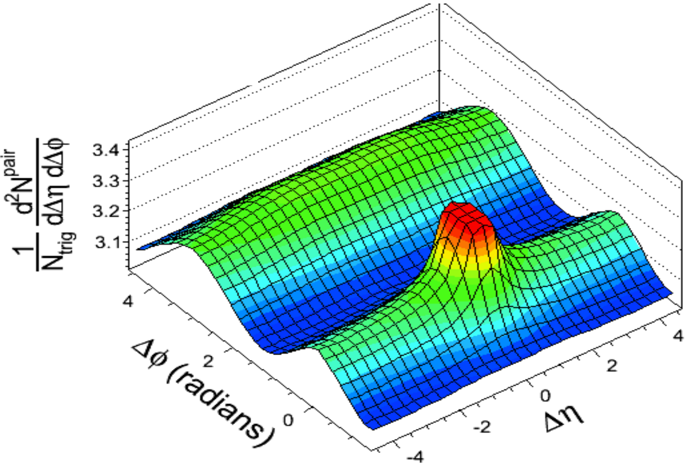
- A large change in the width difference with a small p_T variance indicates a cross over of the dense gluon state boundary.
- A smooth transition from dilute parton system to dense gluon state (or saturation).

Challenges and ongoing/new analysis to access low x gluons

- Timing in the correct trigger is critical for final results.
- High particle density in the forward rapidity causing non-uniform gain of EMCal which is the biggest challenge for experiments.



- New p+Al/Au and d+Au data taken in 2015/2016 provide opportunities to study the A dependence of nuclear gluon PDF.
- New observables:
  - forward di-jets and γ+jet will help reduce the fragmentation impacts.
  - Bottom production and Drell-Yan process can directly access low x gluons.



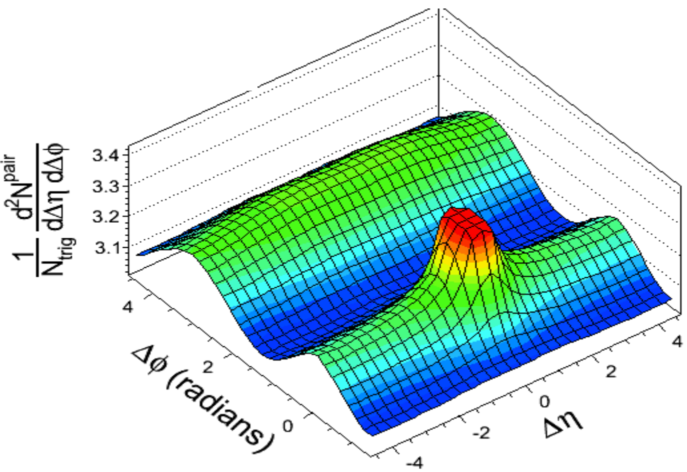
CMS pPb
PLB 718 (2013) 795

Ridge in p/d/^{3}He+A collisions?

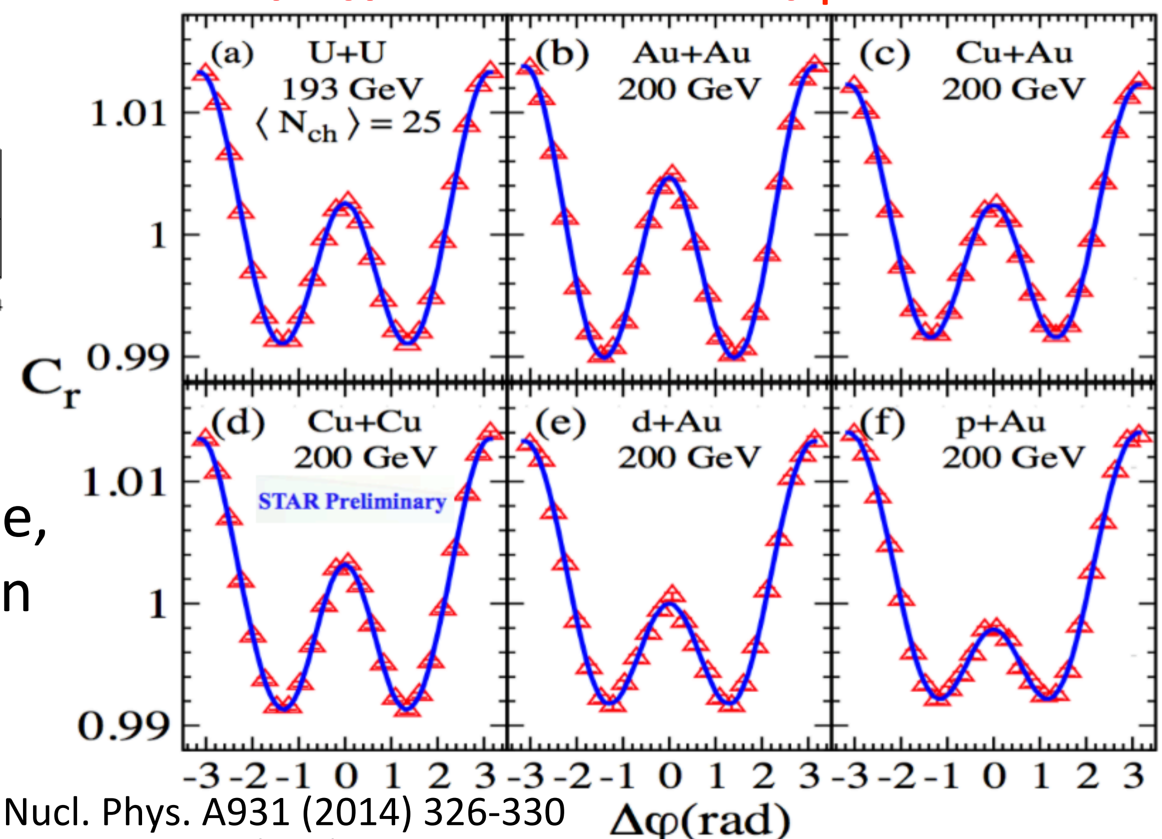
- **Due to dense gluon medium?** arXiv:1805.08847
- **From initial state interactions?** T. Trainor 2013 *JPCS.* **420** 012026
- **From small QGP droplet?** arXiv:1206.0148

Ridge of long range correlation in both Heavy Ion and small system at STAR

- Near-side peak in long range correlations in p/d+Au collisions with small p_T is due to dense gluon density, geometry structure or small QGP droplet formation?



$|\Delta\eta|>0.7$ 0.2 GeV/c<p_T<4GeV/c



- With smaller amplitude, clear ridge measured in p+Au and d+Au collisions at STAR.

Nucl. Phys. A931 (2014) 326-330

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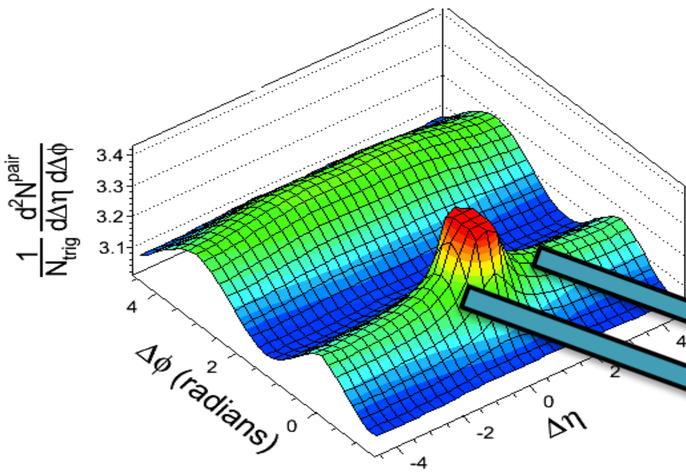

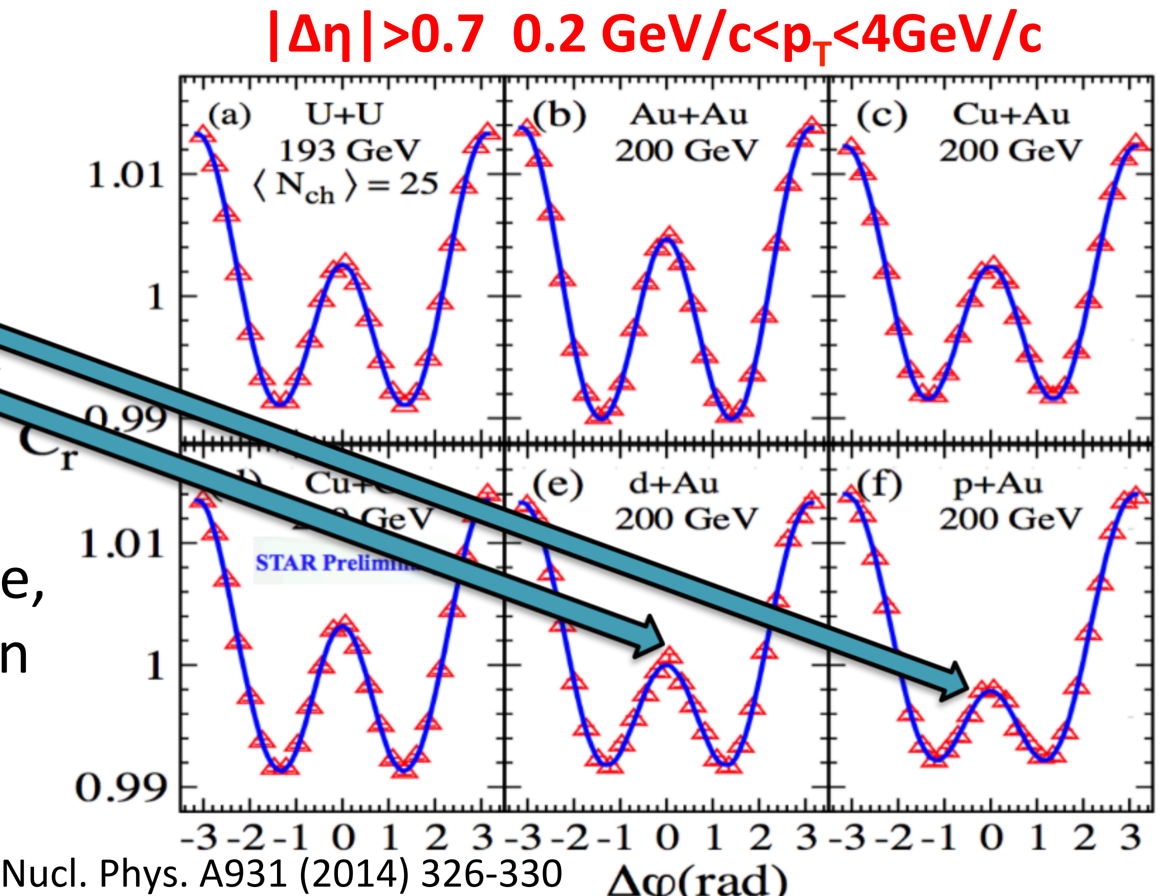

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Nucl. Phys. A931 (2014) 326-330

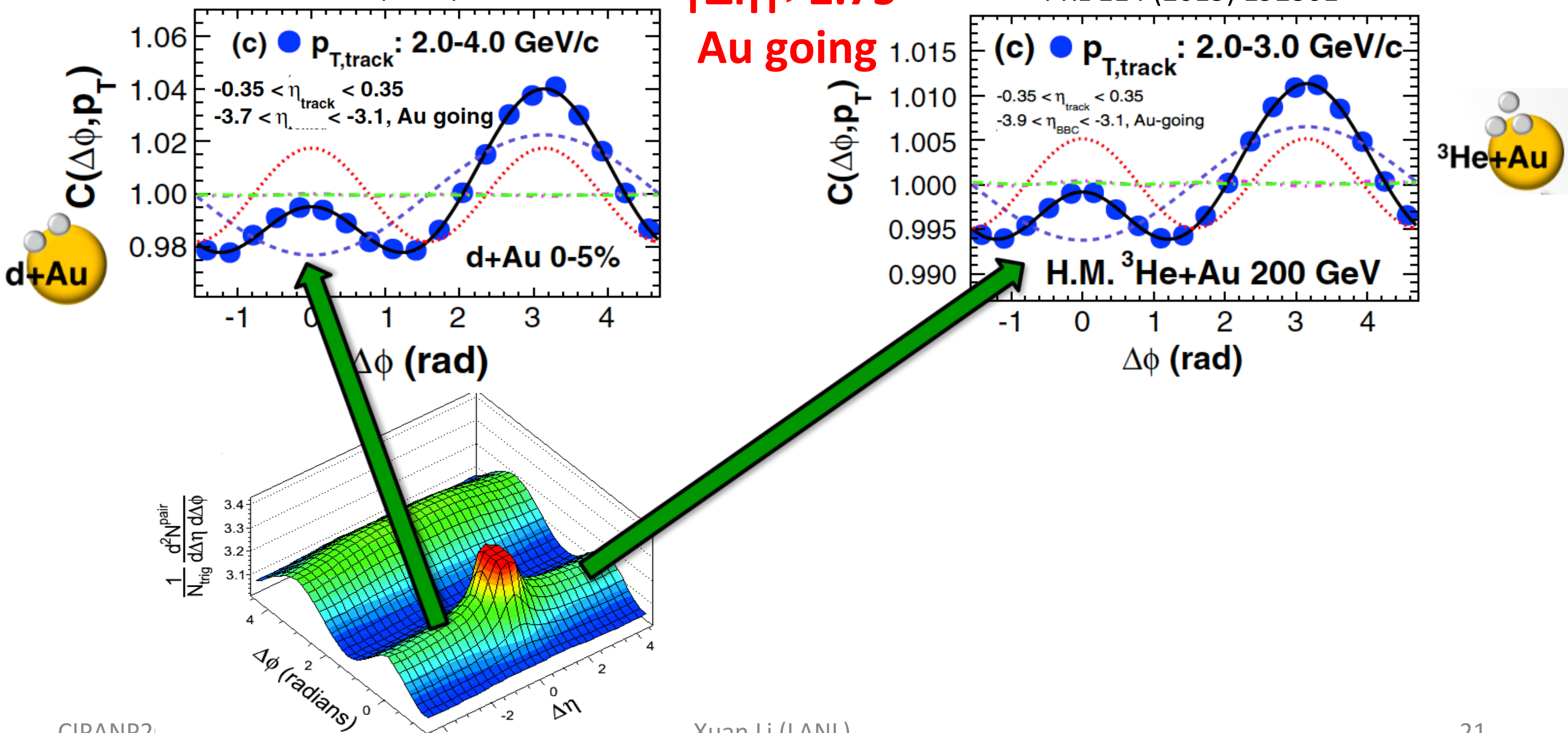
Ridge of long range correlation in central d/^{3}He+A but not in p+A at PHENIX

- Near-side peak in long range correlations in p/d+Au collisions with small p_T is due to dense gluon density, geometry structure or small QGP droplet formation?

PRL 114 (2015) 192301

|Δη|>2.75
Au going

PRL 114 (2015) 192301



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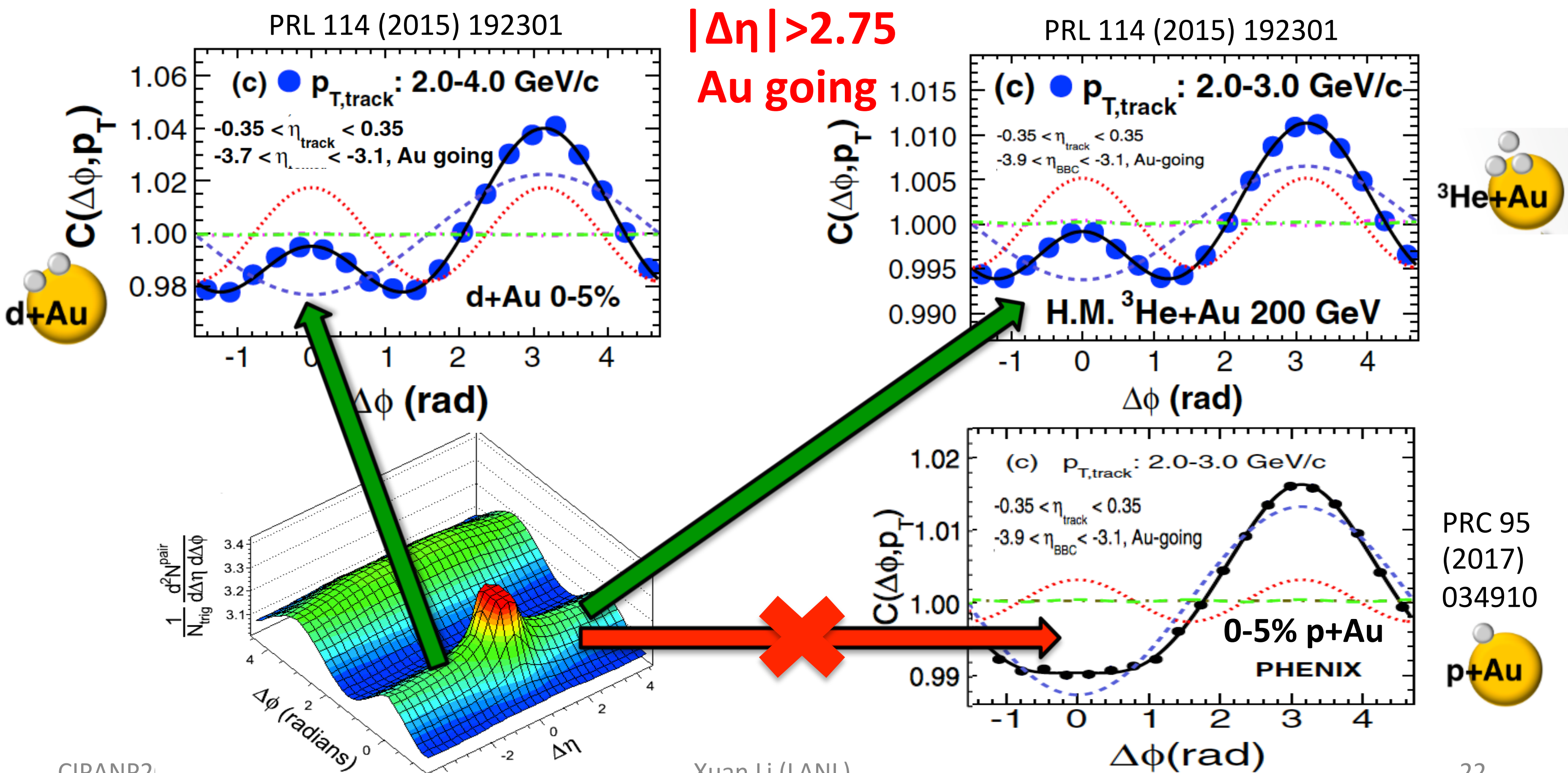
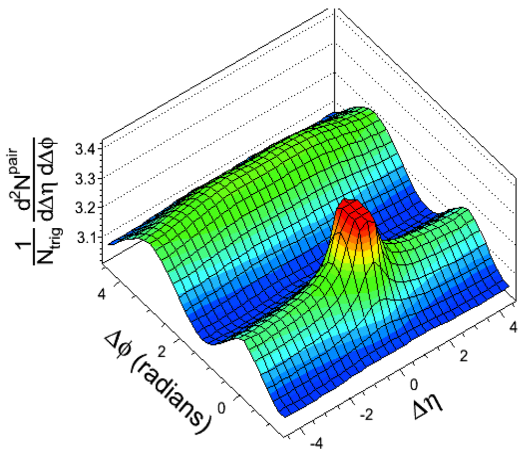
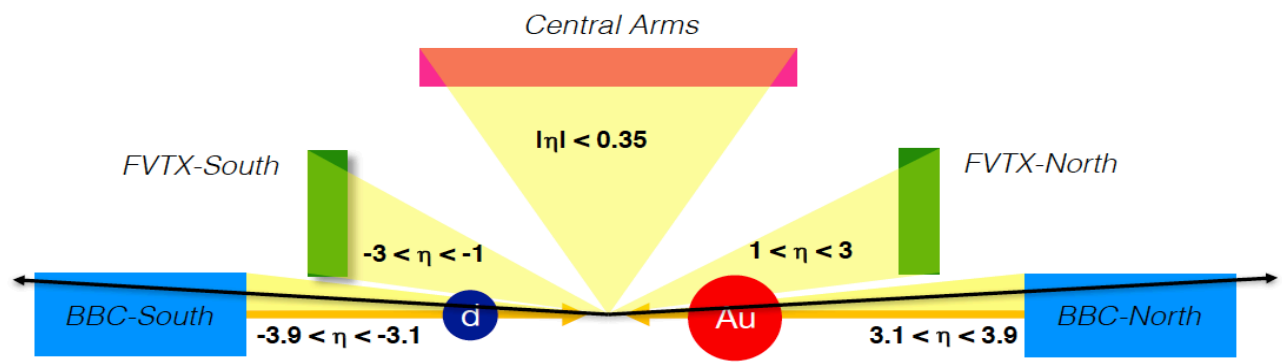
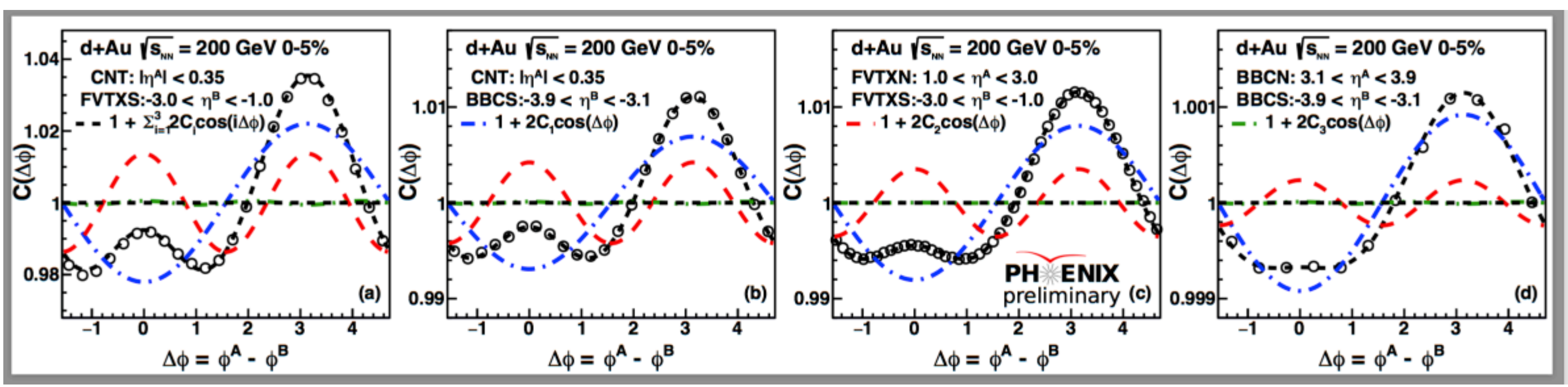


Rapidity dependence of Ridge in central d+Au

- Ridge evolves with Δη in central d+Au collisions like what has been observed at the LHC.





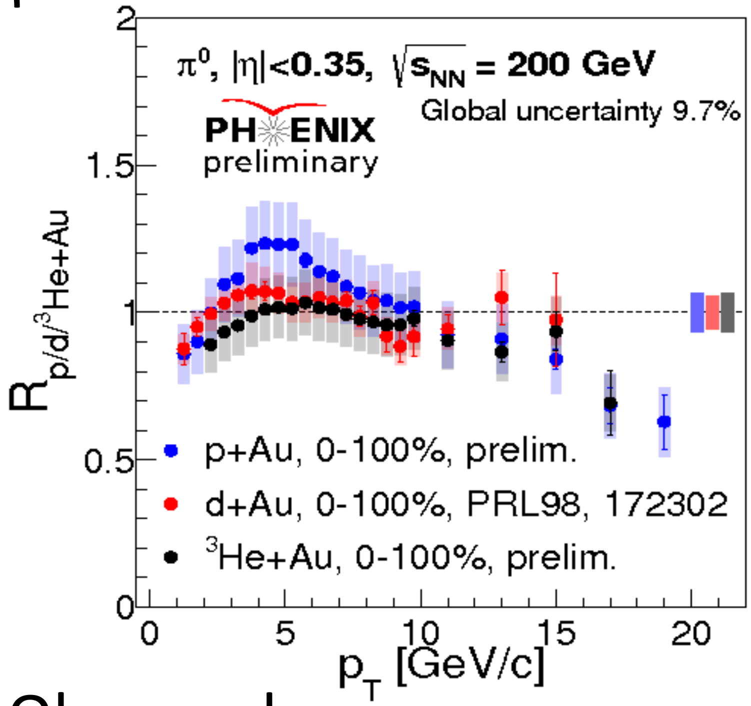


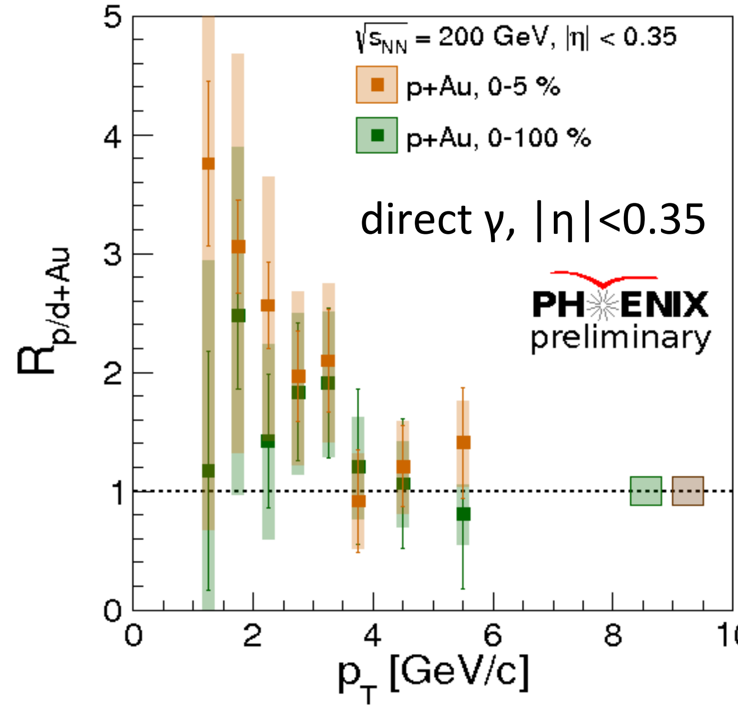
New and future measurements

- need to subtract other cold nuclear matter effects to understand the nuclear PDF

Mid-rapidity π^0 $R_{p/d/He+Au}$ and direct γ R_{p+Au}

- Access intermediate x gluons with mid-rapidity π^0 and direct γ measurements.

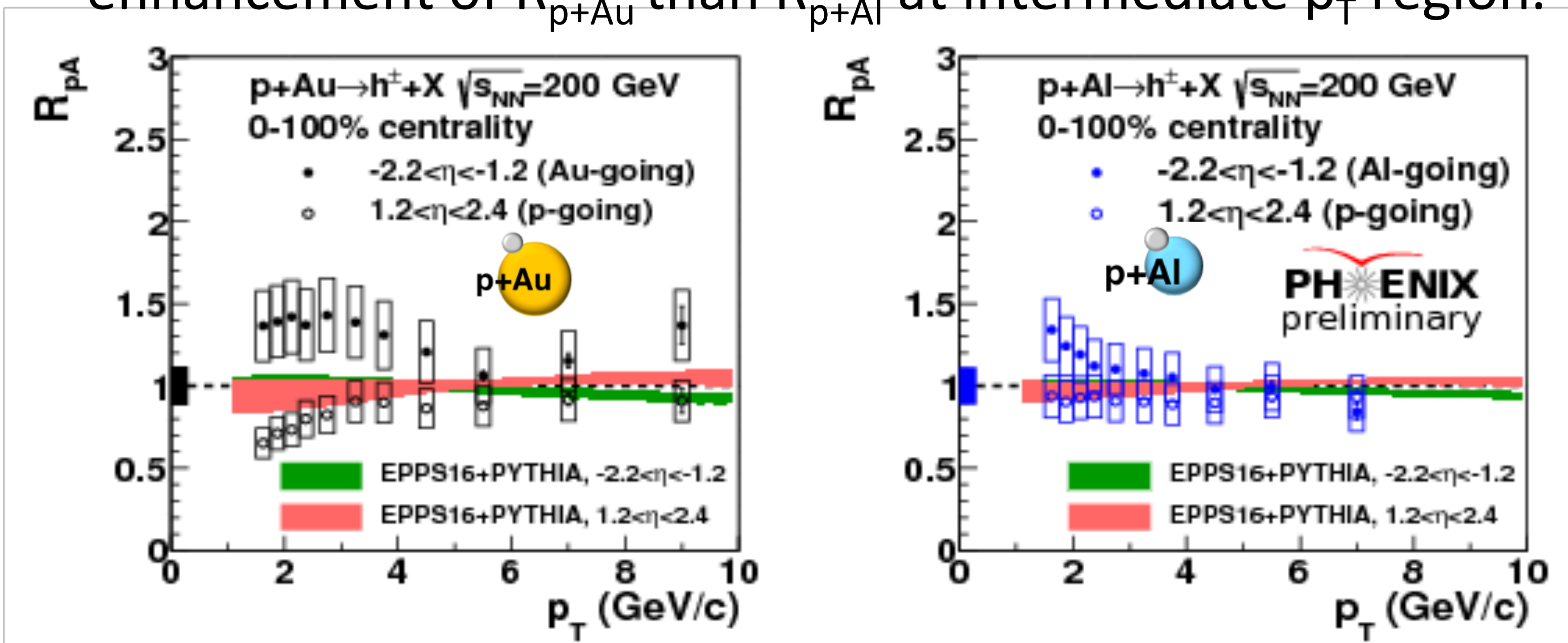




- Observed:
  - Cronin effect in the intermediate p_T region and energy loss in the high p_T region for π^0 $R_{p/d/He+Au}$.
  - Indication of thermal photon or hot hadron gas formation at low p_T in p+Au collisions.

Near-forward/backward charged hadron $R_{p+Au/Al}$

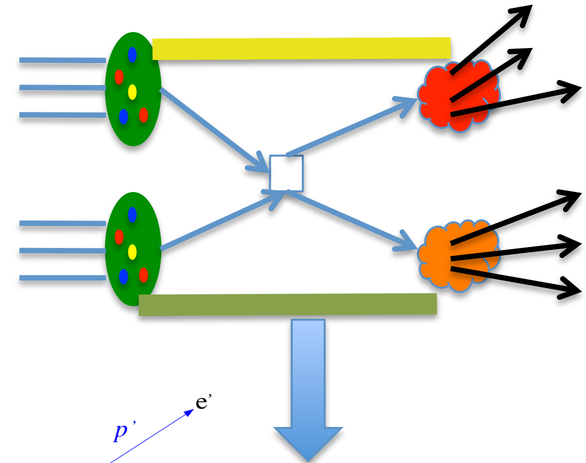
- At positive rapidity (p going direction), larger suppression of R_{p+Au} than R_{p+Al} at low p_T region.
- At negative rapidity (A going direction), likely larger enhancement of R_{p+Au} than R_{p+Al} at intermediate p_T region.



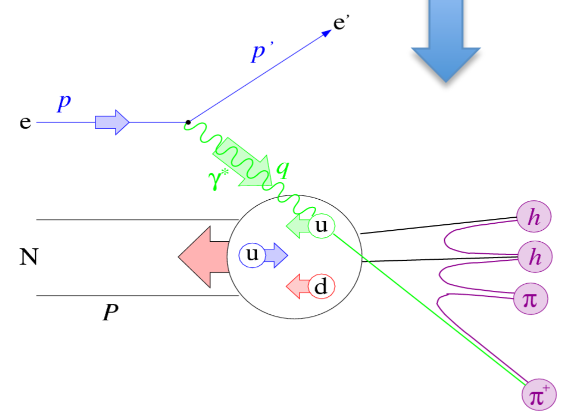
- Is the enhancement in the A going direction due to multiple particle scattering? Need theory interpretation.

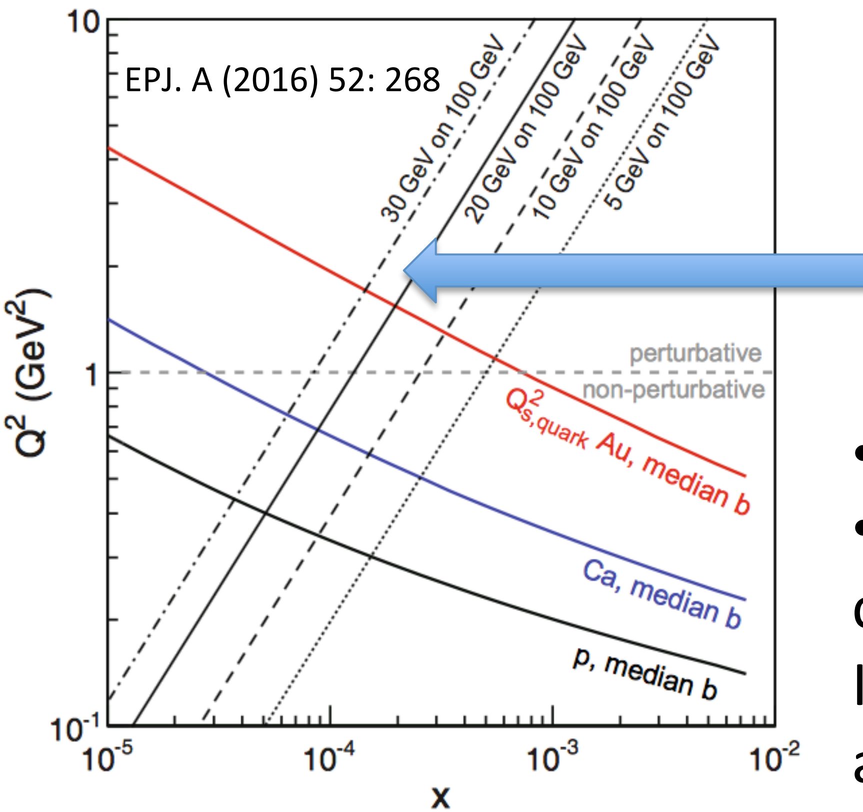
Future nuclear PDF studies at low x

- The final state hadrons in hadron/nuclei collisions are complex objects that can include not only color interactions from initial states but also from final states.



- A Electron Ion Collider (EIC)?





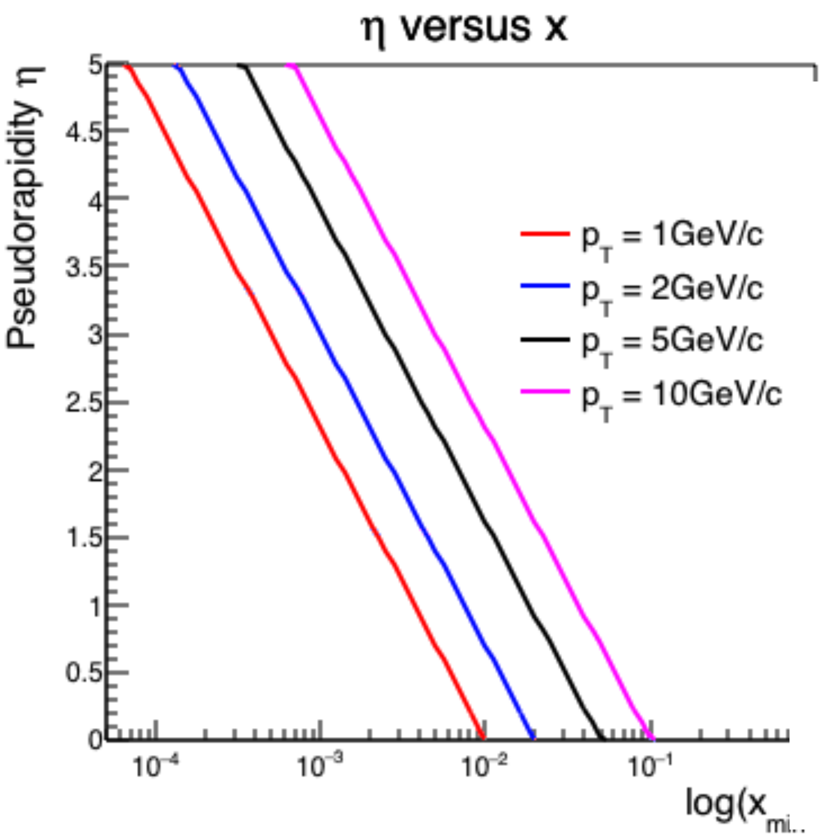
- Go to lower x at EIC.
- Inclusive DIS process is much cleaner than the hadron-hadron Interaction but can not directly access gluons.

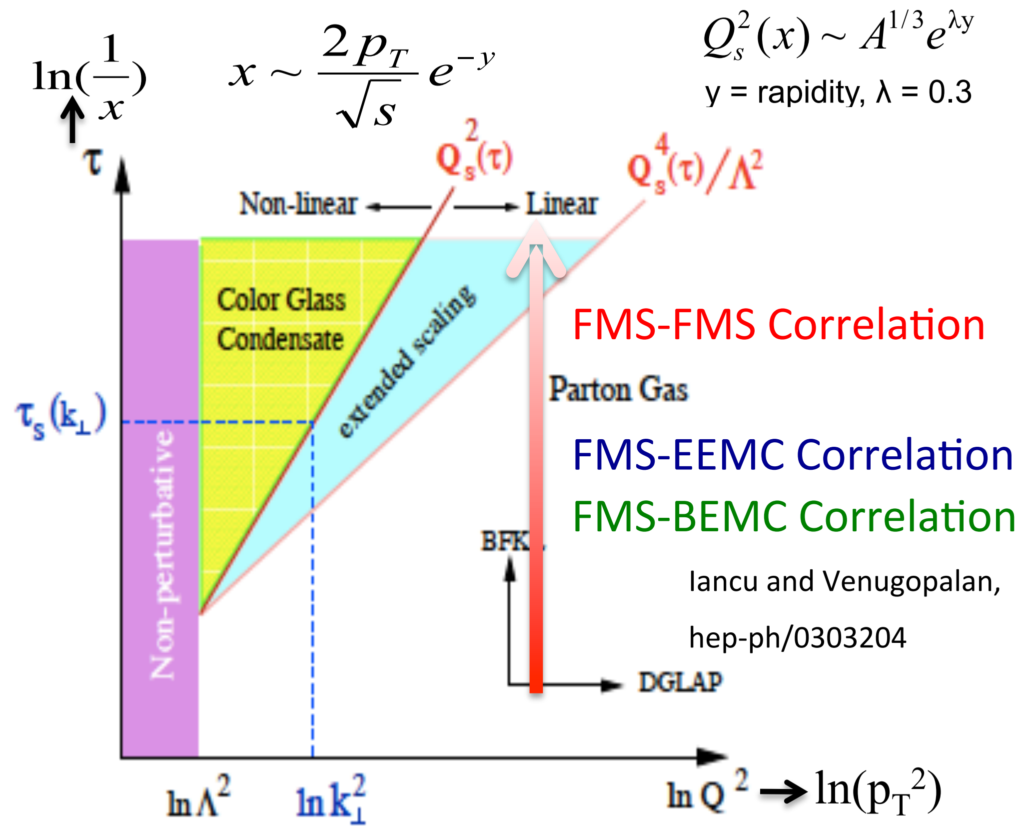
Summary and Outlook

- RHIC is the ideal place to study nuclear gluon PDF at low x region.
- Significant nuclear modification of forward π^0 and correlations measured in d+Au collisions at STAR and PHENIX. Suppression in central d+Au collisions is consistent with CGC prediction.
- To extract the nuclear PDF information, need to consider the geometry structure of p+A, d+A and ^{3}He+A collision systems, the multiple particle scattering effects, energy loss and etc.
- Ongoing rapidity dependent hadron, heavy flavor and correlation studies will provide further constrains on the nuclear PDF.
- Continue to explore the nuclear PDF in the low x region at the Electron Ion Collider.

Backup

The soft gluon x is related to associated particle in correlations

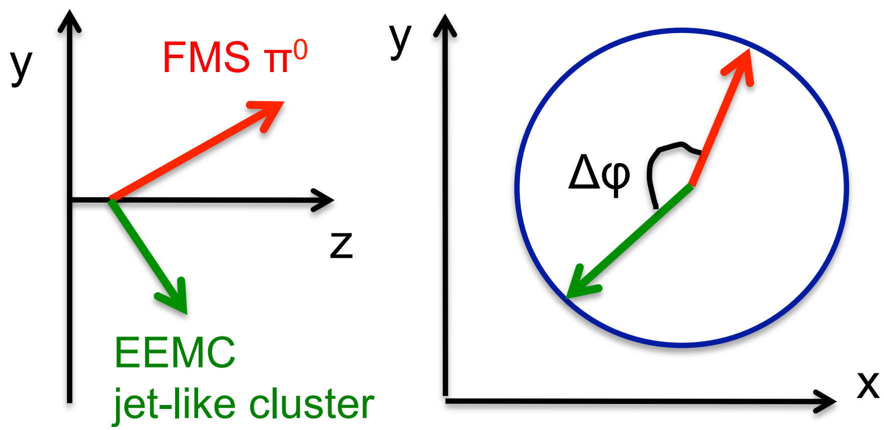




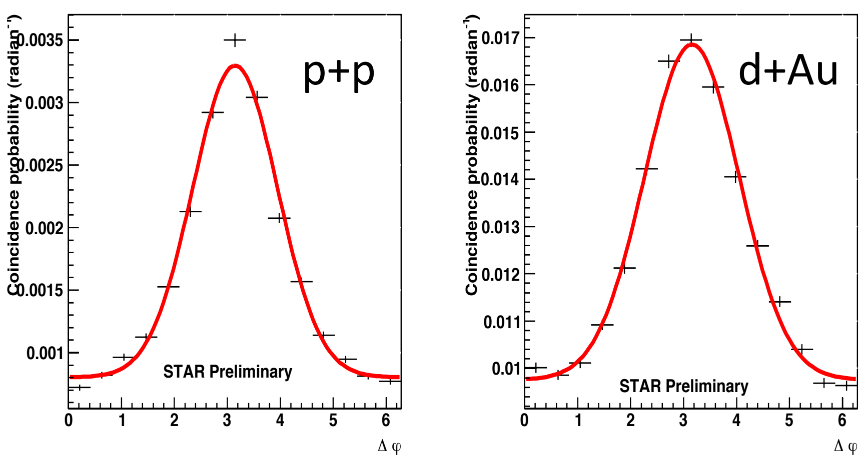
- **The pseudo-rapidity of the associated particle** is strongly correlated with **soft gluon x** in the asymmetric parton scattering mostly **high-x_q valence quark (x>0.2)** + **low-x_g gluon (x<0.01).**

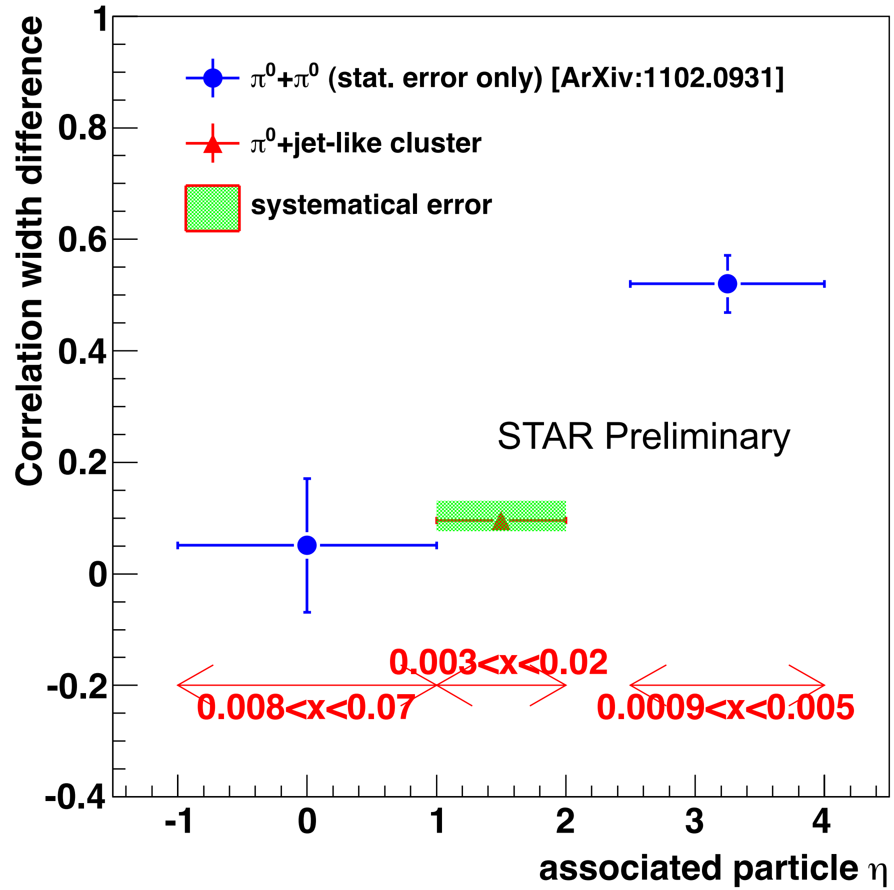
Summary on the correlation peak

- Compare the width differences of the away side-peak between p+p to d+Au collisions for different di-hadron correlations.



P_T(FMS) > 2.0 GeV/c ; 1.0 GeV/c < P_T(EEMC) < P_T(FMS)





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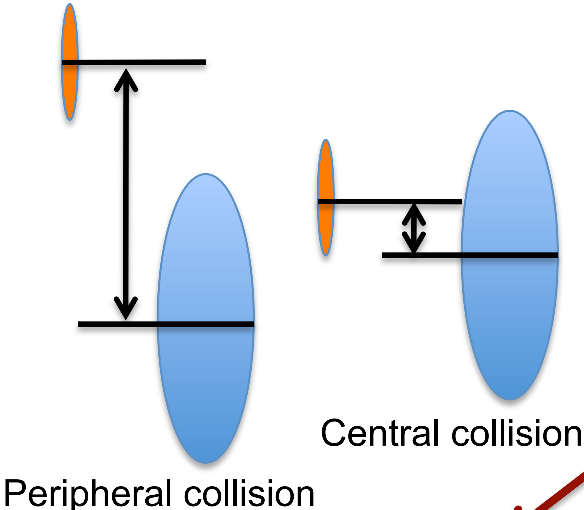
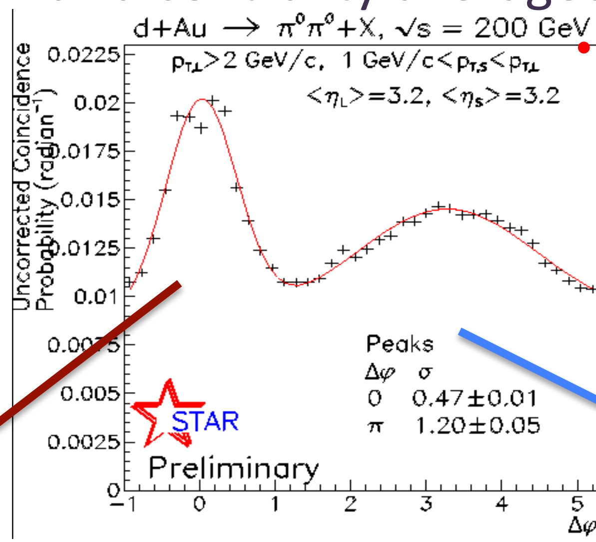
Forward-forward rapidity correlation

- Centrality cut on the dAu data.

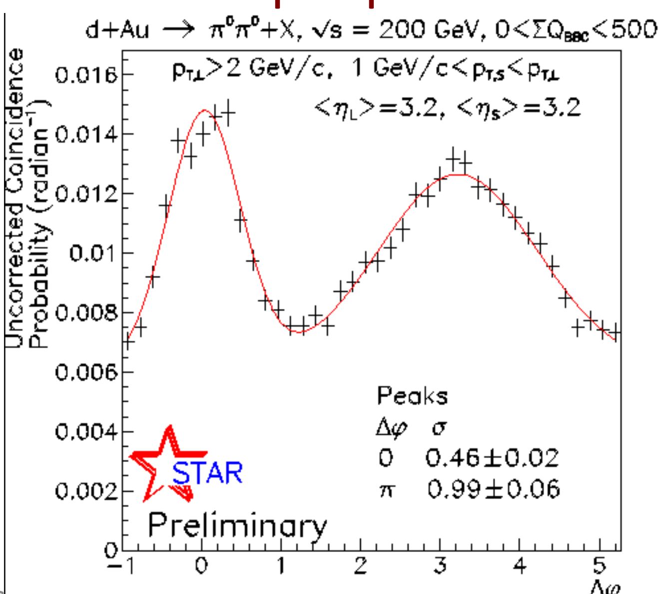


dAu centrality averaged

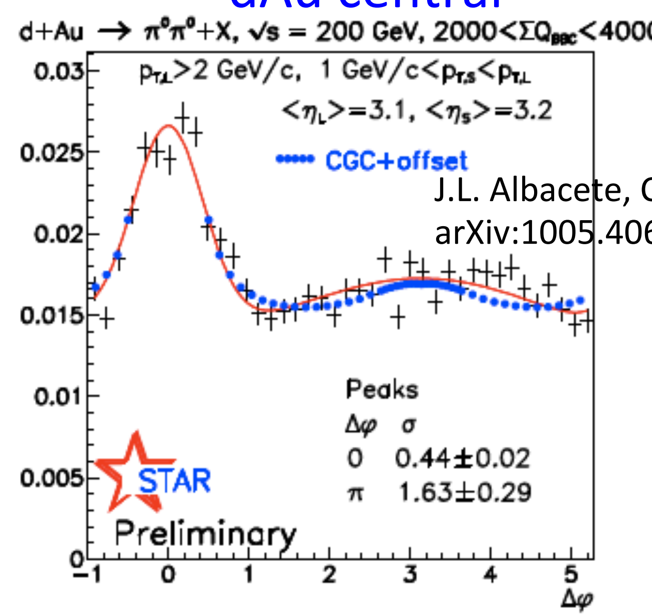


The suppression of the height of the away side peak in the central dAu collisions suggests forward-forward correlations at low x are consistent with gluon saturation in nuclei at RHIC.

dAu peripheral



dAu central



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