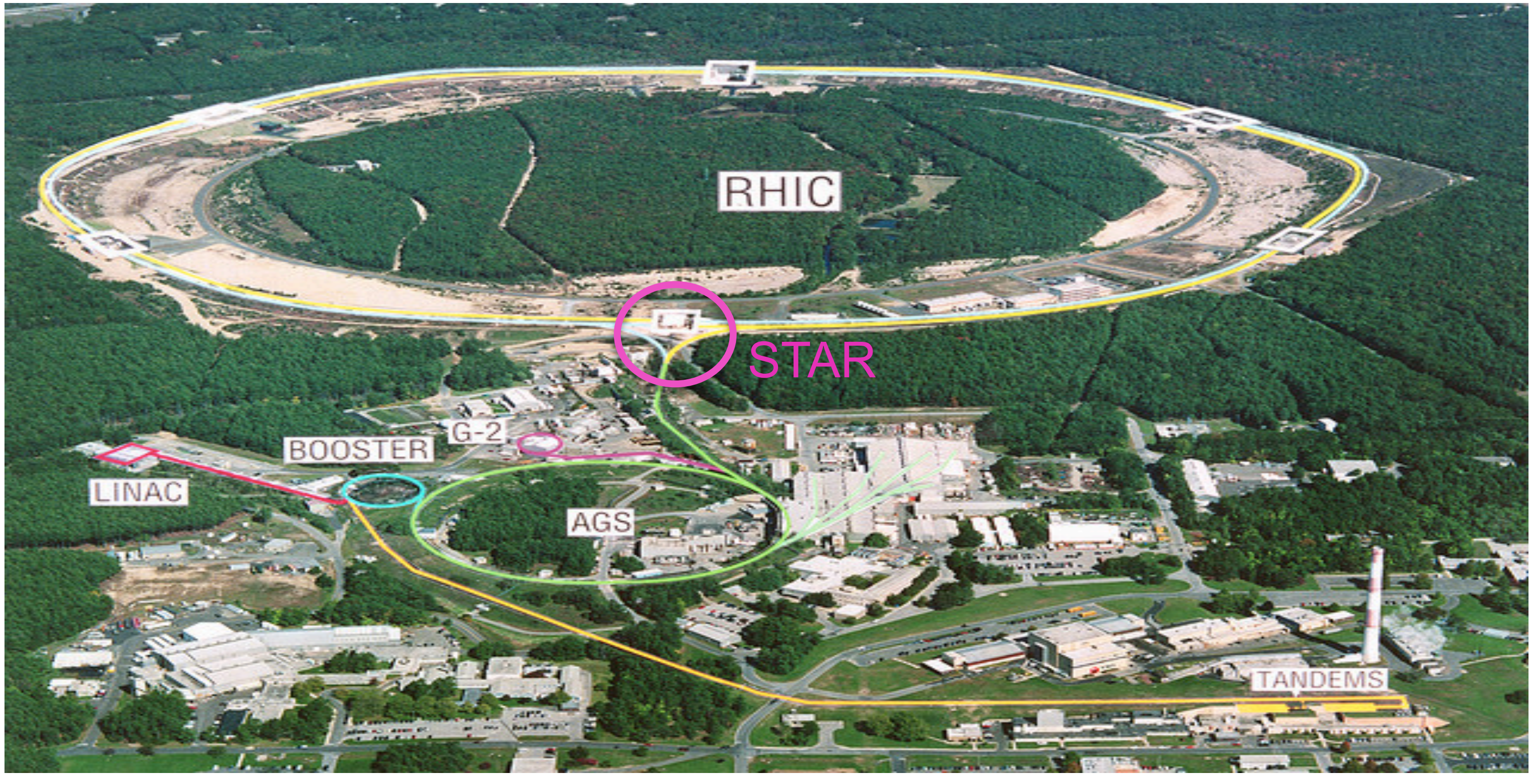
Forward di-hadron correlations at STAR



Forward physics at RHIC workshop

July 30th, 2012

Xuan Li, Temple University

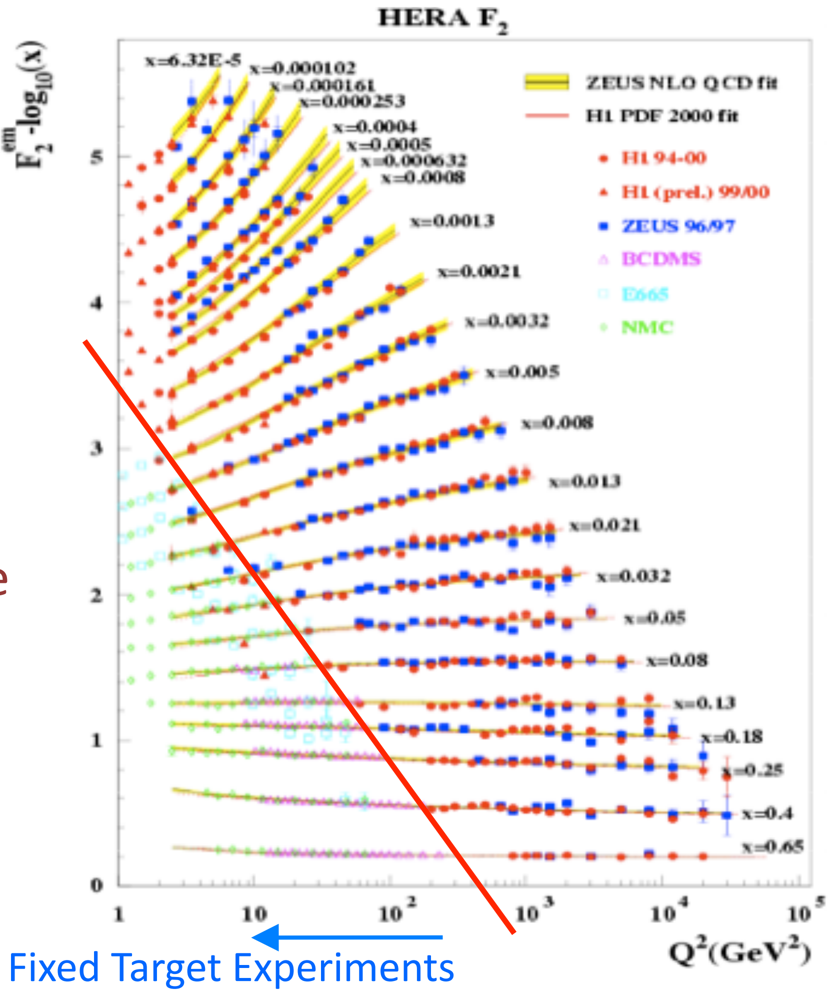
Outline

- Introduction
  - Motivation
- Are there differences between gluon distribution functions inside the proton and a larger nucleus?
- Low x physics studies at STAR through measurements of forward di-hadron correlations.
  - Forward π^0 + mid-rapidity π^0 or h.
  - Forward π^0 + forward π^0
  - Forward π^0 + near-forward jet-like cluster.
- Summary & Outlook

What does the nucleon parton distribution look like?

- The nucleon quark distribution is well known.

- Rapid rise of the gluon density at low-x evident from $\partial F_2(x,Q^2)/\partial \ln Q^2$.
- $xg(x) \approx \partial F_2(x,Q^2)/\partial \ln Q^2$
- $F_2(x,Q^2)$ is the structure function at fixed x.

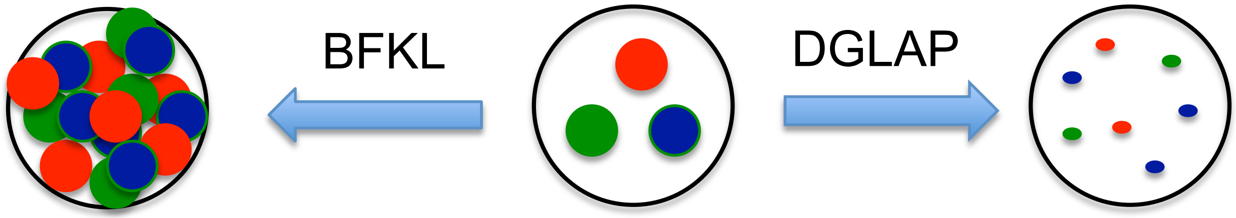


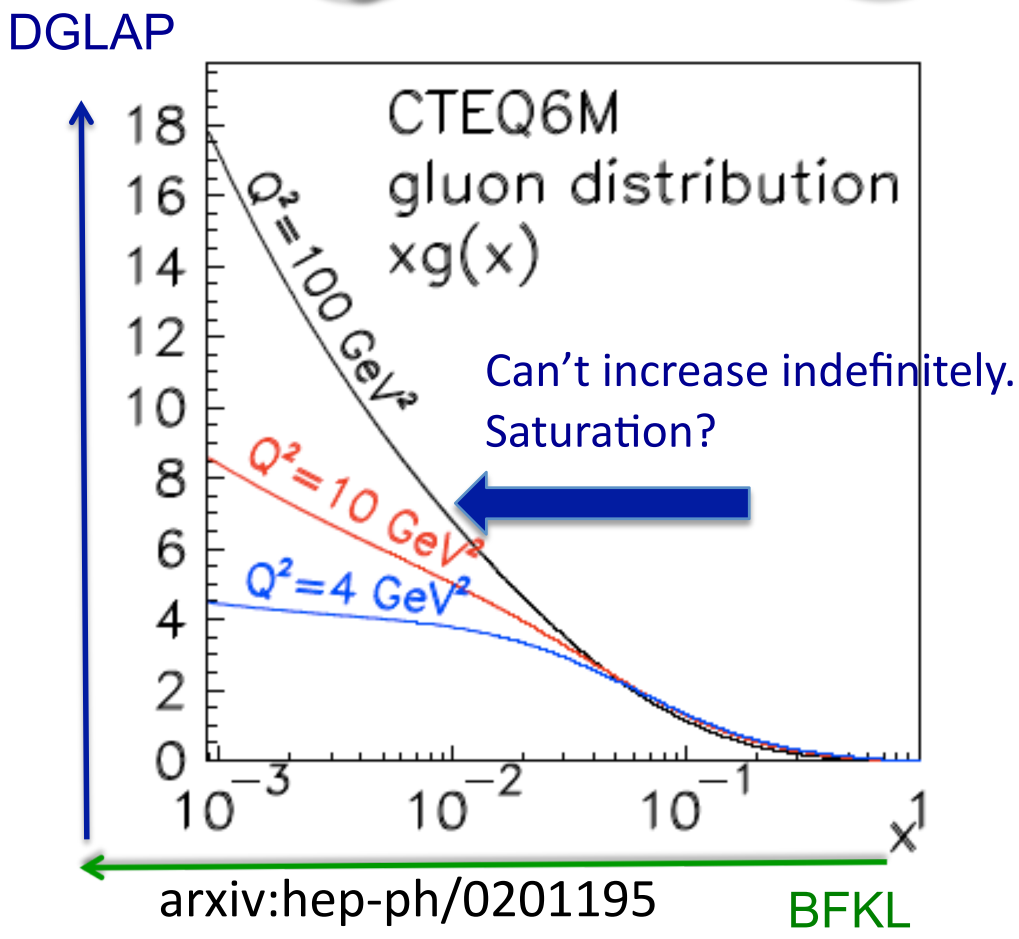
E. Rizvi, talk presented at the "International Euro Physics Conference on High Energy Physics", July 2003

- The nucleon gluon density is derived from the structure function (x, Q^2) and is well known in the $0.0001<x<0.3$.

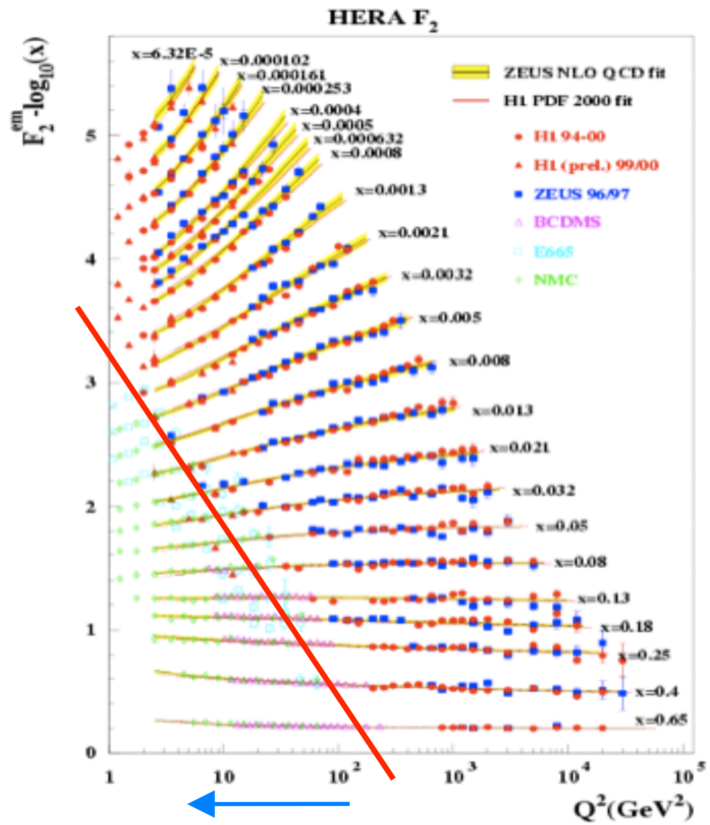
What does the nucleon parton distribution look like?

- The nucleon quark distribution is well known.





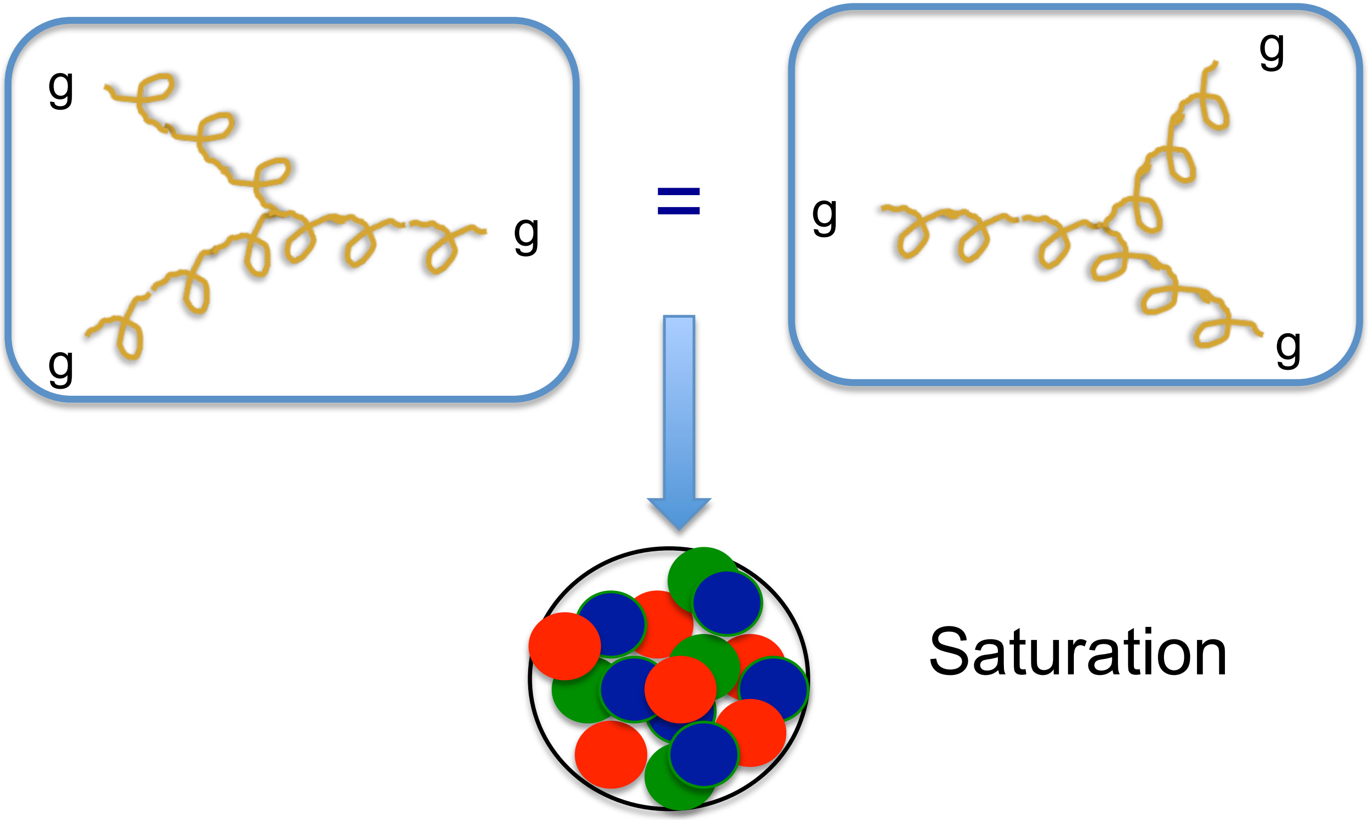
arxiv:hep-ph/0201195



Fixed Target Experiments

What is the saturation state?

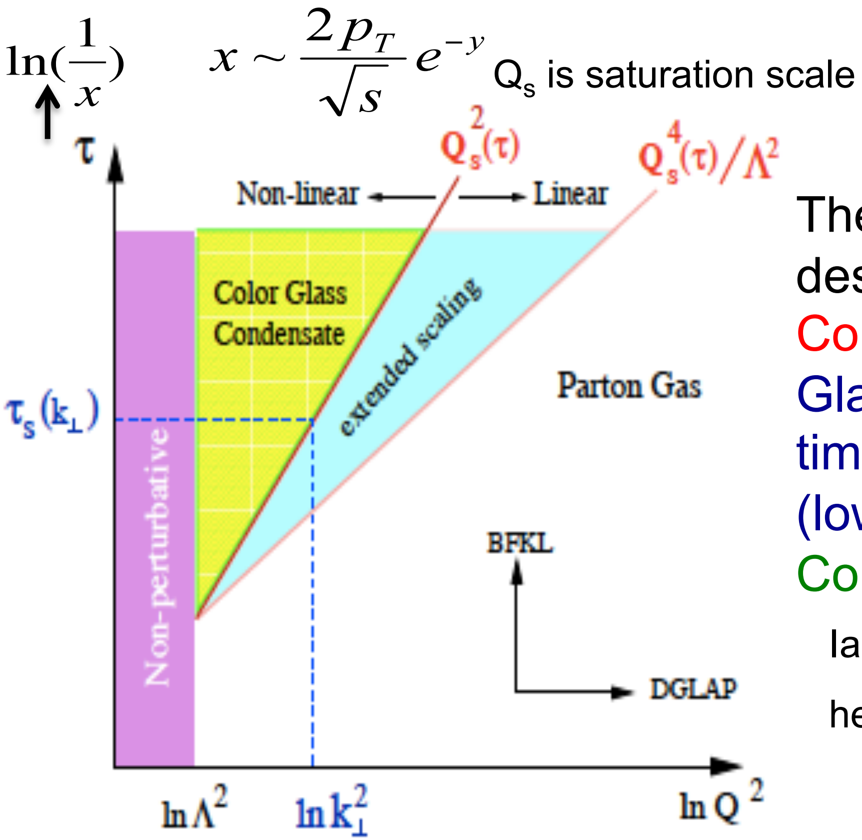
- When gluon recombination balances gluon splitting, saturation is realized.



- The nucleon gluon saturation is expected to be at $x<0.0001$ region.

What is the saturation state?

- When gluon recombination balances gluon splitting, saturation is realized.



The Color Glass Condensate (CGC) describes the saturation state,

Color: gluons carry color charge.

Glass: fast source (larger x) has a normal time scale $1/Q_s$, they emitted slow parton (lower x) with a dilation time scale.

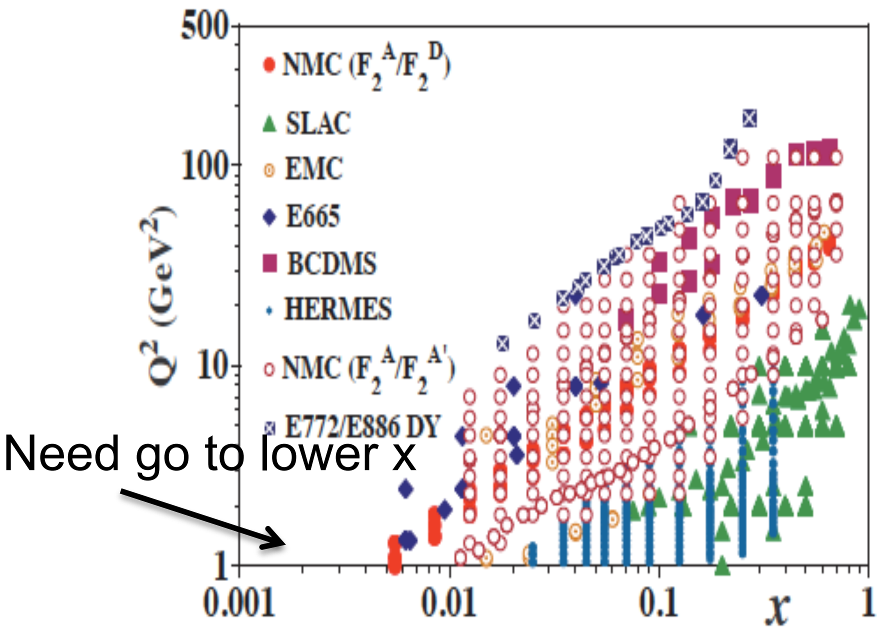
Condensate: high gluon density.

Iancu and Venugopalan,

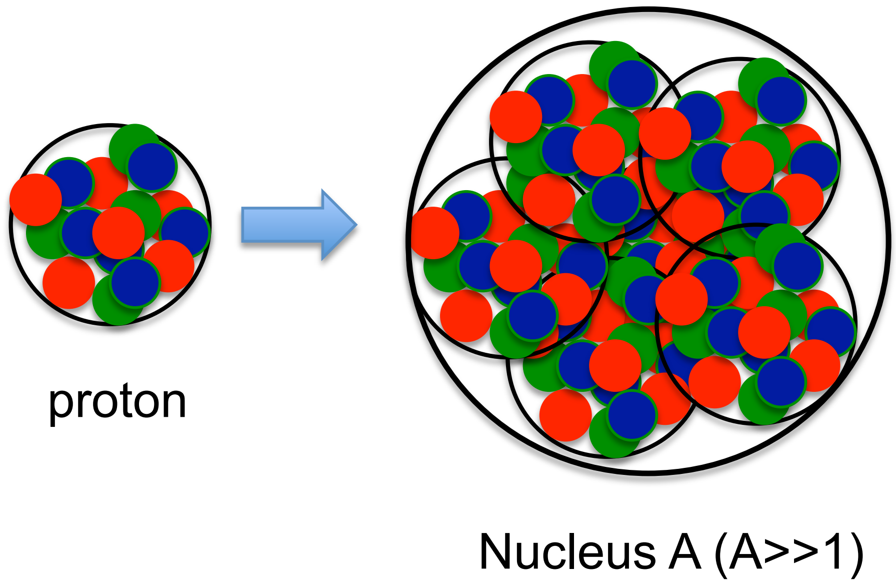
hep-ph/0303204

How about a larger nucleus?

- Fixed target experiments derived the nuclear gluon density only at 0.02<x<0.3.



Current fixed target results
[Phys. Rev. C70 (2004)044905]

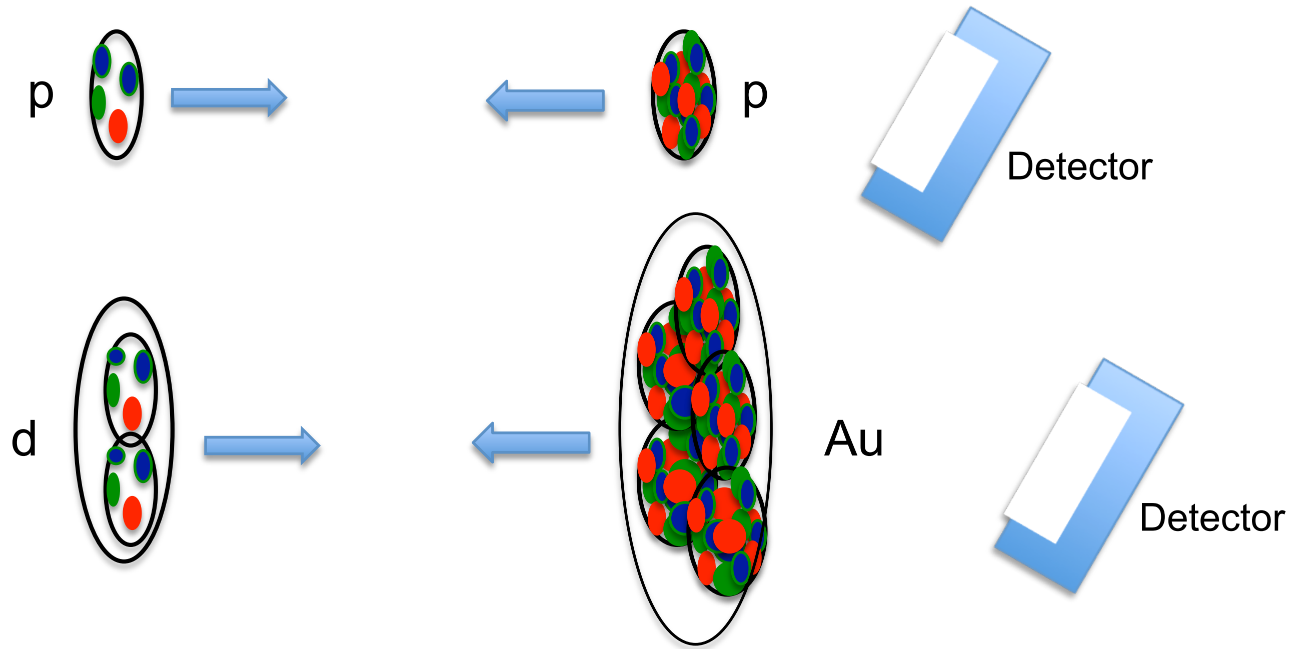


- Nuclear (mass number A) gluon density ≈ $A^{1/3}$ × nucleon gluon density at a given x, leading to the expectation $Q_s^2 \approx A^{1/3} x^{\beta}$. [hep-ph/0304189]
For example, for Au nucleus, the saturation is expected at x≈0.001.

How to probe low x gluons

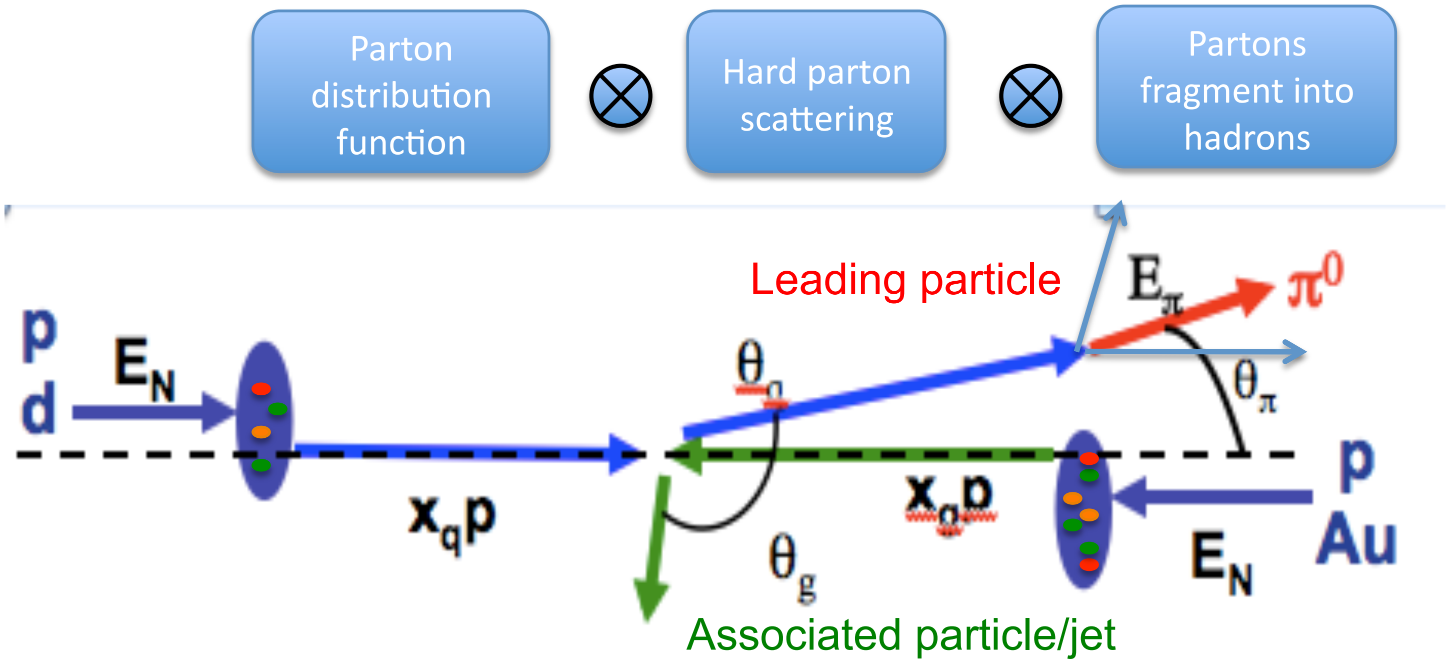
- Forward inclusive production.

RHIC is a hadron collider including p+p and d+Au collisions.



How to probe low x gluons

- Forward inclusive production.

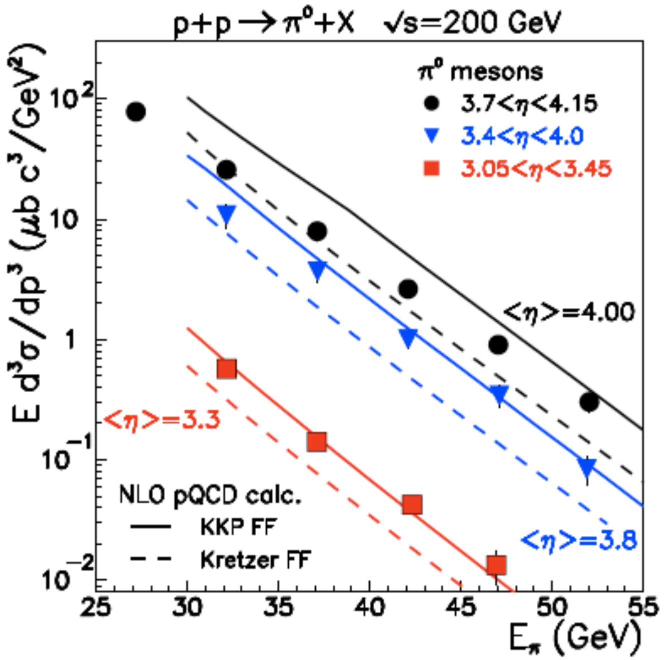


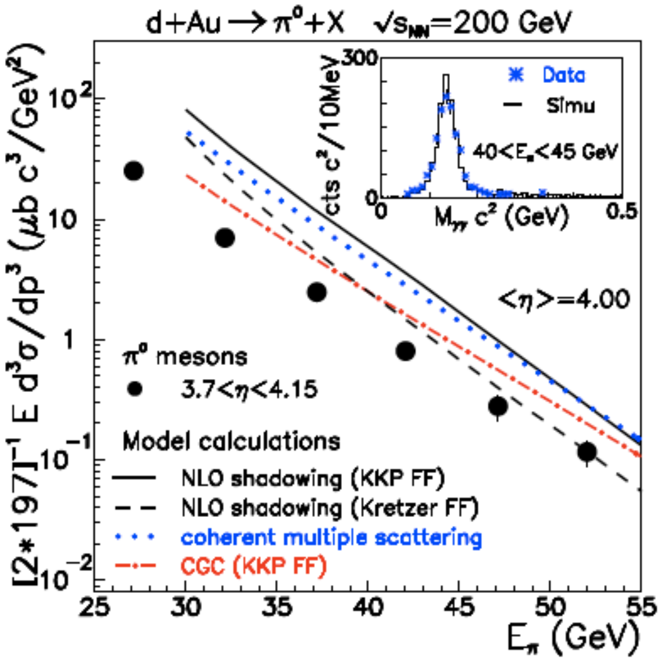
$x_q = p_q/p_N,$
$x_g = p_g/p_N,$
$\eta_\pi = -\ln(\tan\theta_\pi/2)$
$p_T \approx E_\pi \sin(\theta_\pi)$

- The factorization mechanism is taken as universal and applied in nucleon (nucleus)+ nucleon (nucleus) collisions.
- Large rapidity ($\eta_\pi \sim 4$) inclusive π production and correlations **probes asymmetric partonic collisions.**
- Mostly **high-x_q valence quark (x>0.2)** + **low-x_g gluon (x<0.01).**

How to probe low x gluons

- Forward inclusive π^0 production measurements.



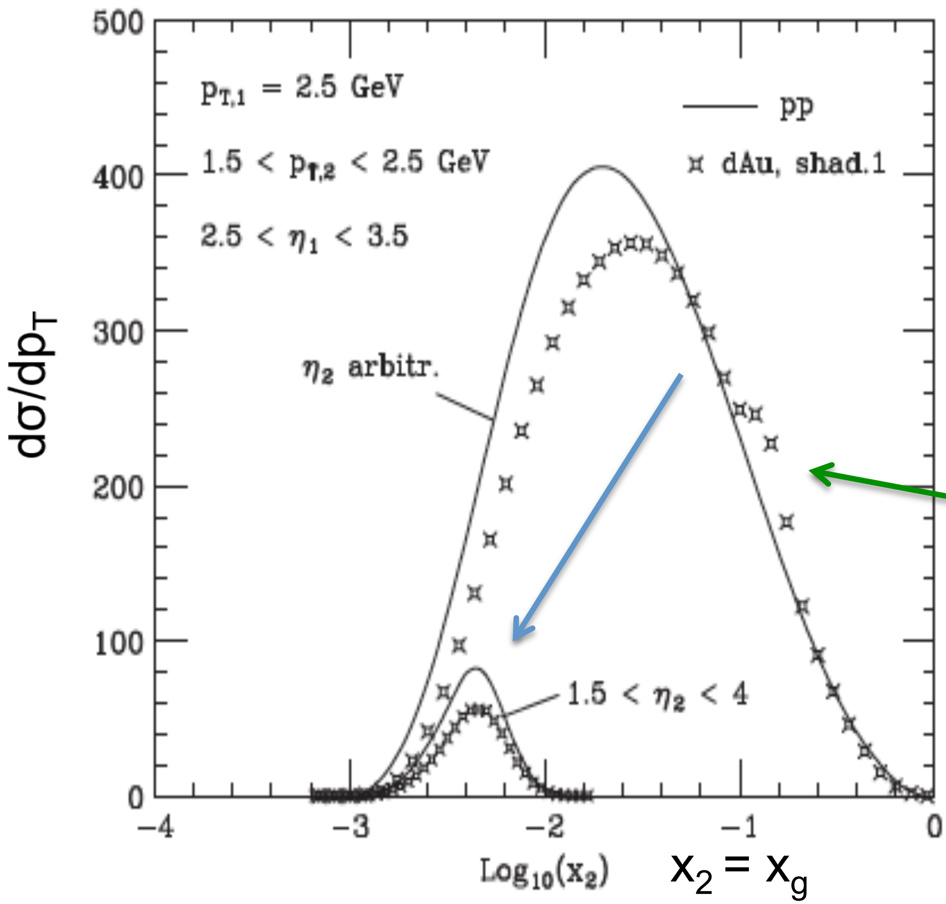


Phys. Rev. Lett. 97.152302

- pp data is in agreement with perturbative QCD.
- Suppression of forward inclusive particle in dAu data is better described by the Color Glass Condensate (CGC).
- But …

How to probe low x gluons

- Inclusive π^0 to correlated π^0-π^0.



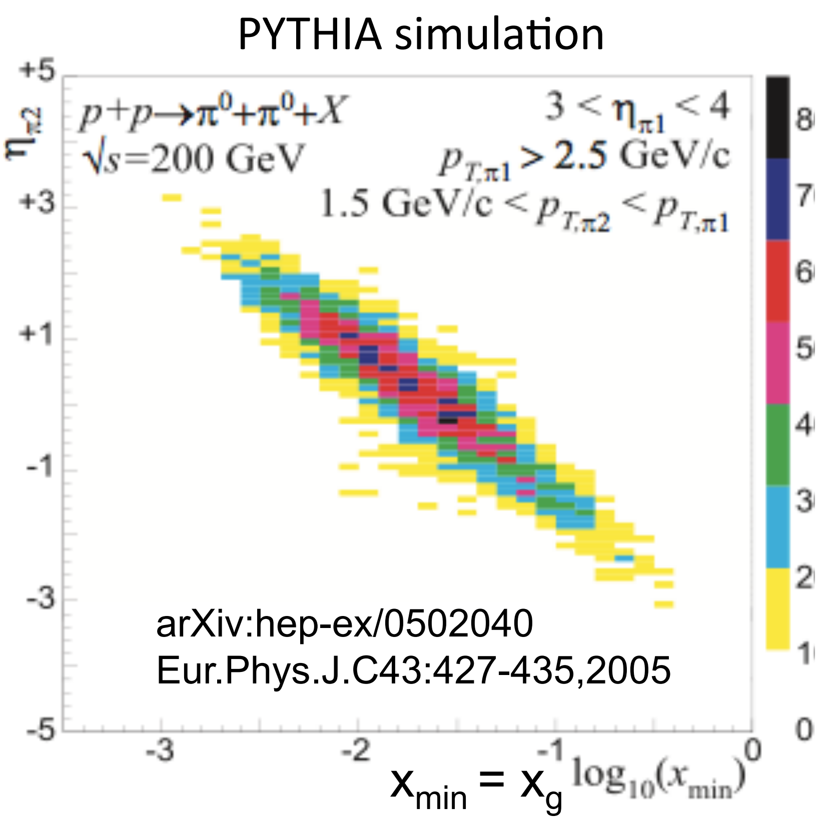
- From inclusive π^0 to π^0-π^0 correlations.
- Inclusive π^0 integrated x.
- Correlated π^0-π^0 allows us selection x.

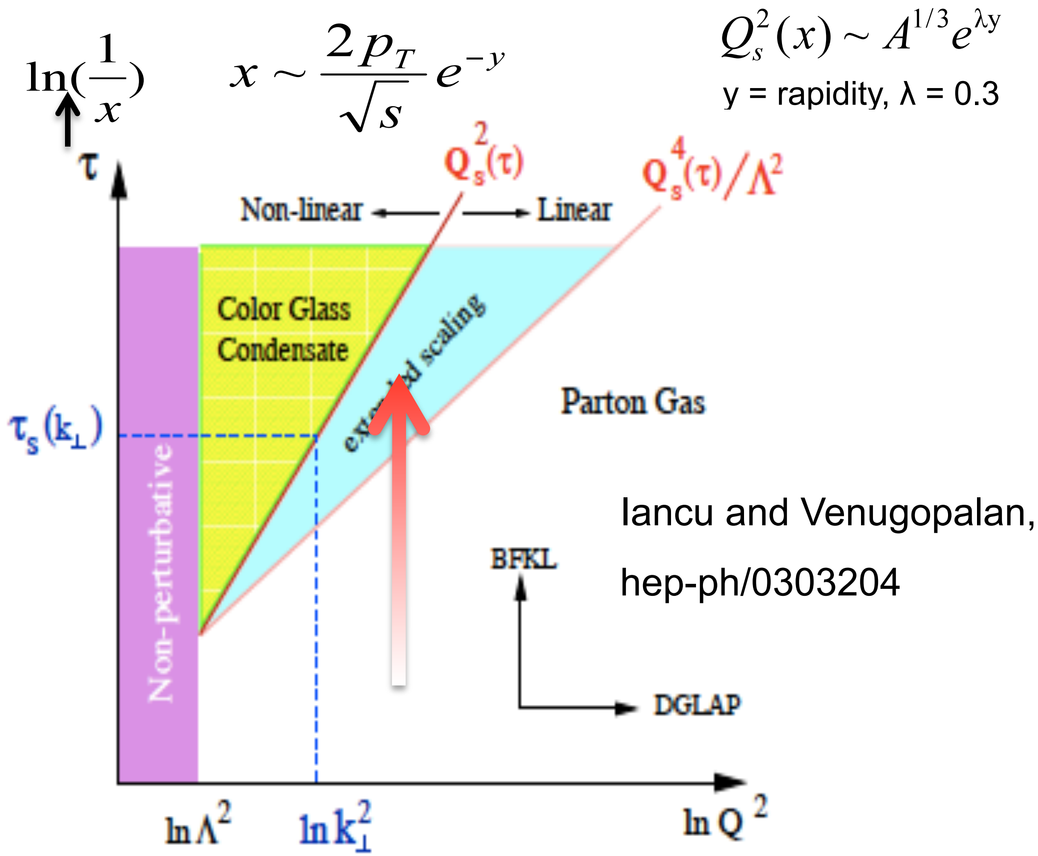
Anti-shadowing related with the EMC effect.

Phys. Lett. B603 (2004) 173

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

The soft gluon x is related to associated particle in correlations

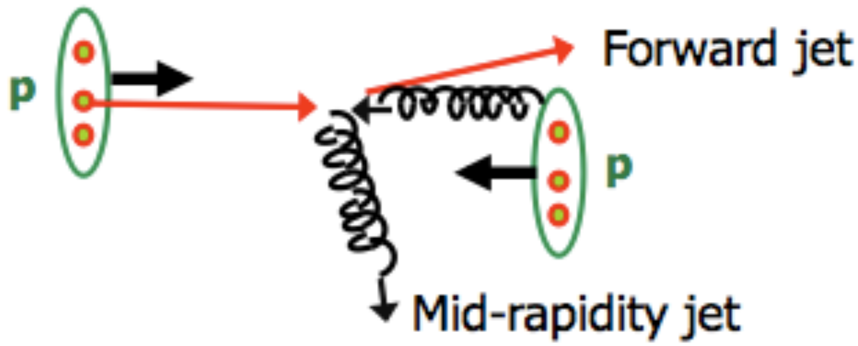




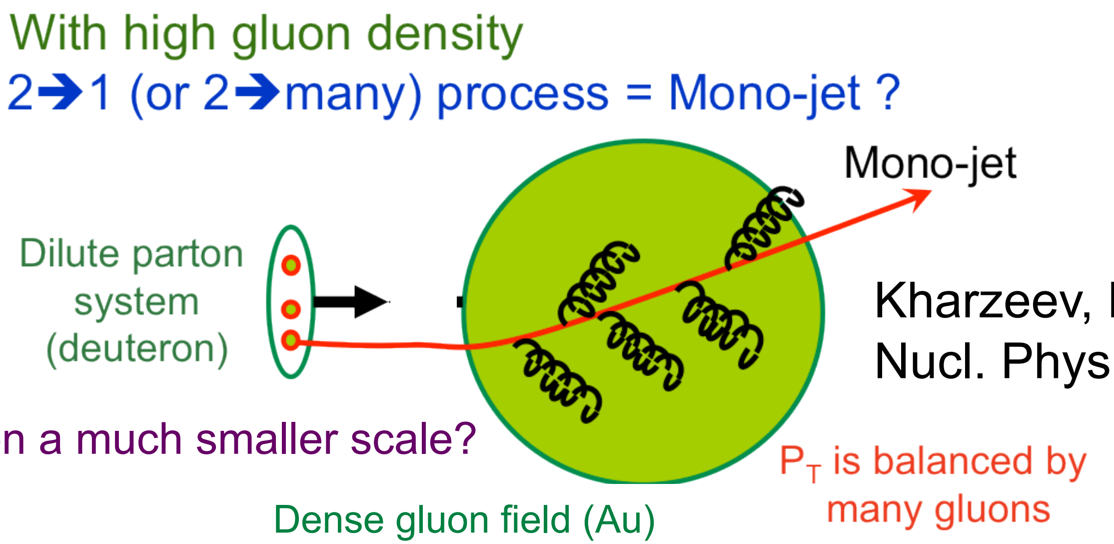
- At fixed low Q^2 ($>\Lambda^2$), the gluon density increases rapidly as x decreases. The state transfers from dilute parton gas to Color Glass Condensate (CGC).

Back to back 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 ?



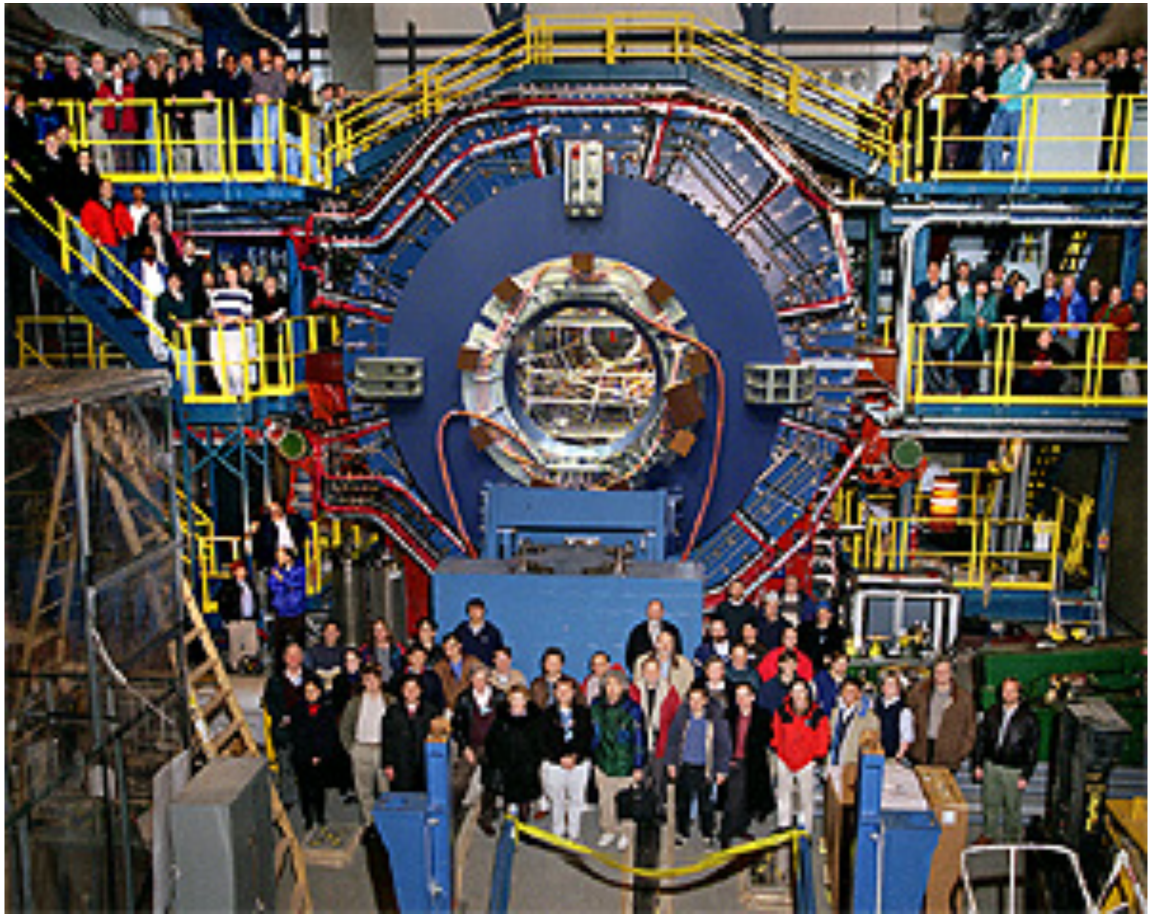
Kharzeev, Levin, McLerran Nucl. Phys. A748 (2005) 627

Mossbauer effect on a much smaller scale?

CGC predicts suppression of back-to-back correlation.

What we use to probe low x gluons

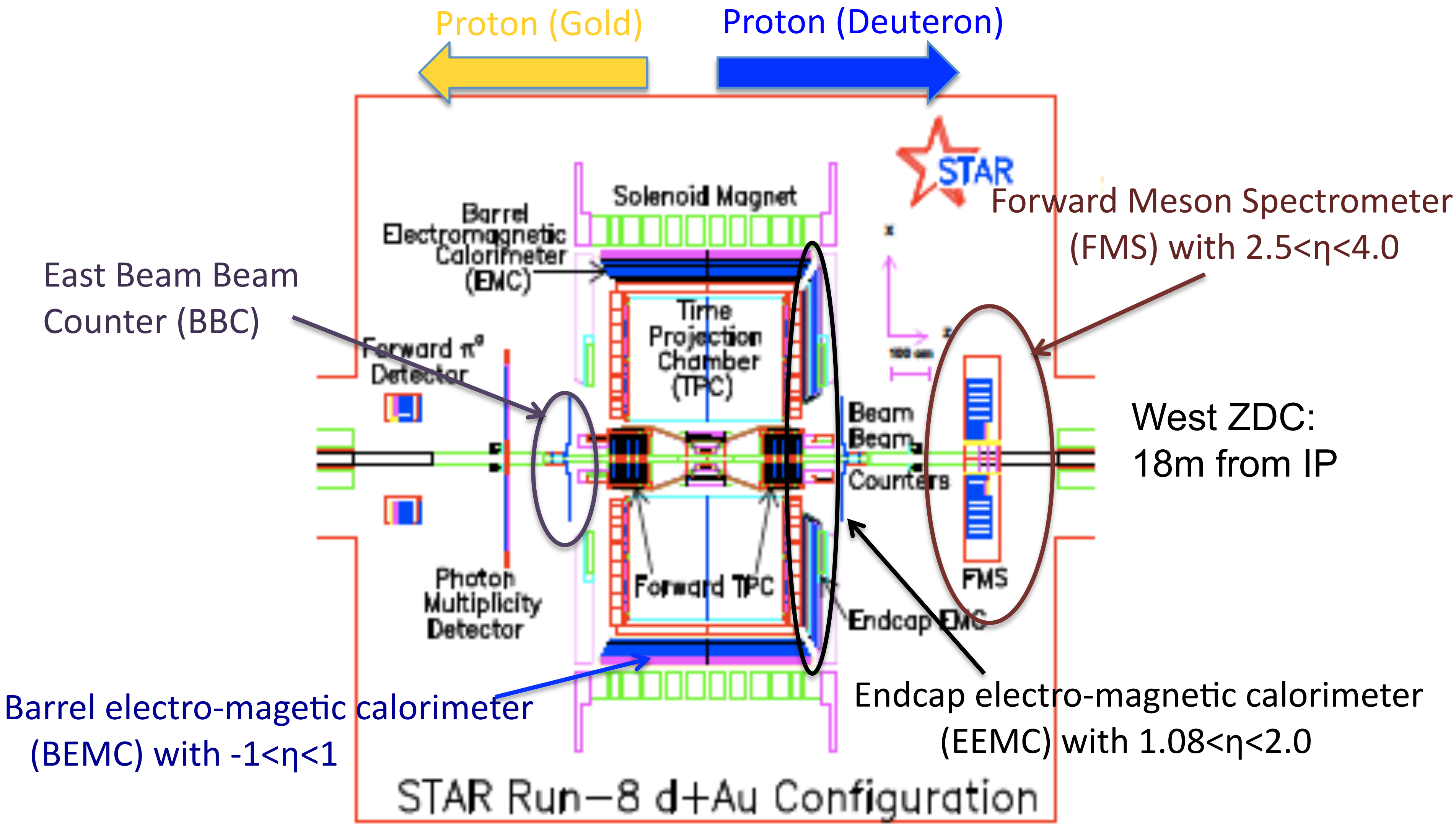
- The Solenoid Tracker at RHIC (STAR) is located at the 6 o'clock position of RHIC.



Beam view

STAR Detectors

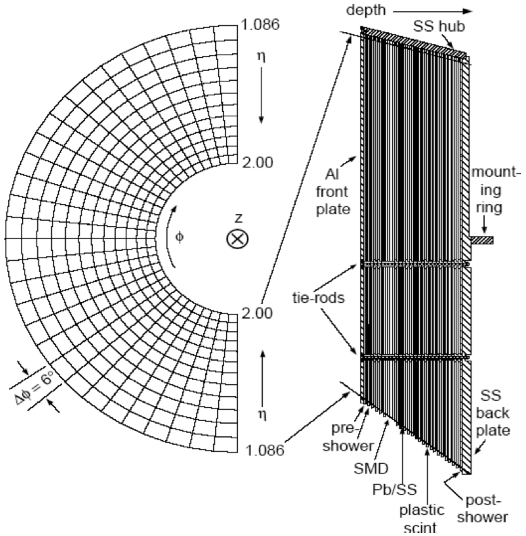
- The schematics of STAR in RHIC run8.

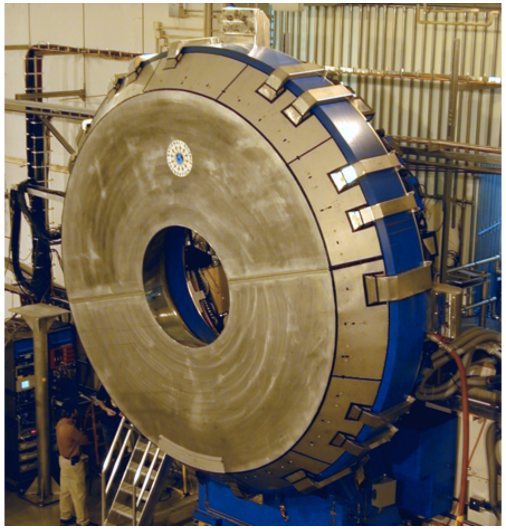


- We use the data of run8 p+p and d+Au collision at $\sqrt{s} = 200$GeV.

STAR Detectors

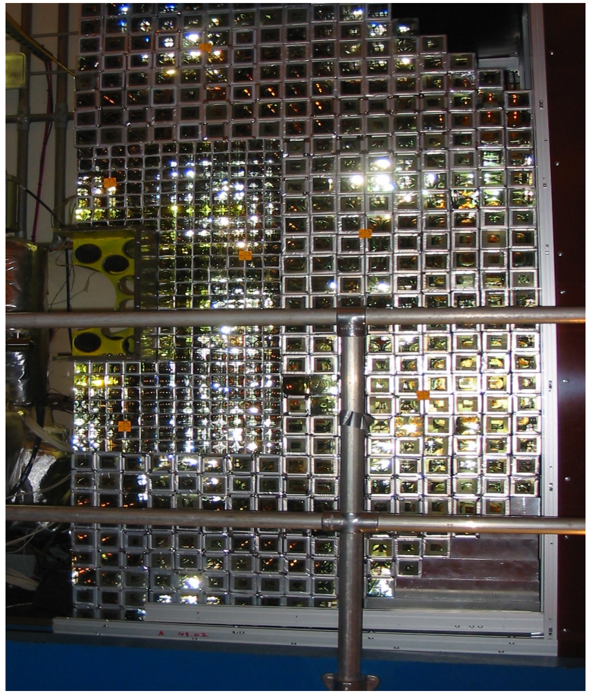
- The detectors of STAR used for correlations.





EEMC measuring range $1<\eta<2$

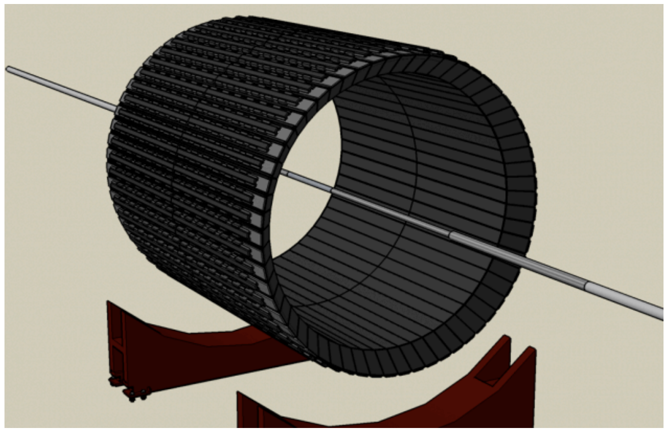
Tower range $\Delta\phi=0.1$, $\Delta\eta=0.057\text{-}0.099$



Front view of north half of FMS.

FMS measuring range $2.5<\eta<4$.

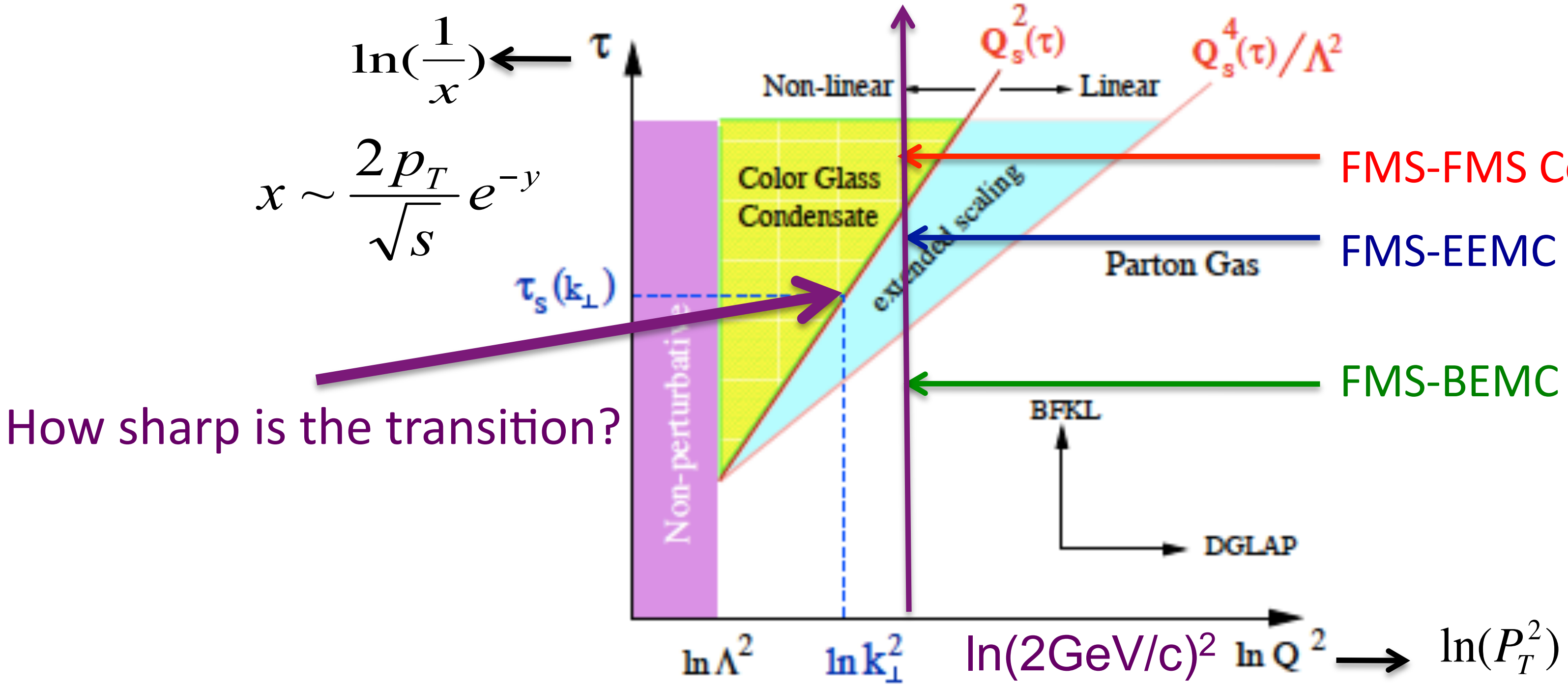
$\Delta\phi=0.058$, $\Delta\eta=0.1$ for large cells.



BEMC measuring range $-1<\eta<1$. Tower range $\Delta\phi=0.05$, $\Delta\eta=0.05$.

Rapidity dependence of azimuthal correlations

- At fixed low Q^2 ($>\Lambda^2$), the gluon density increases rapidly as x decreases.

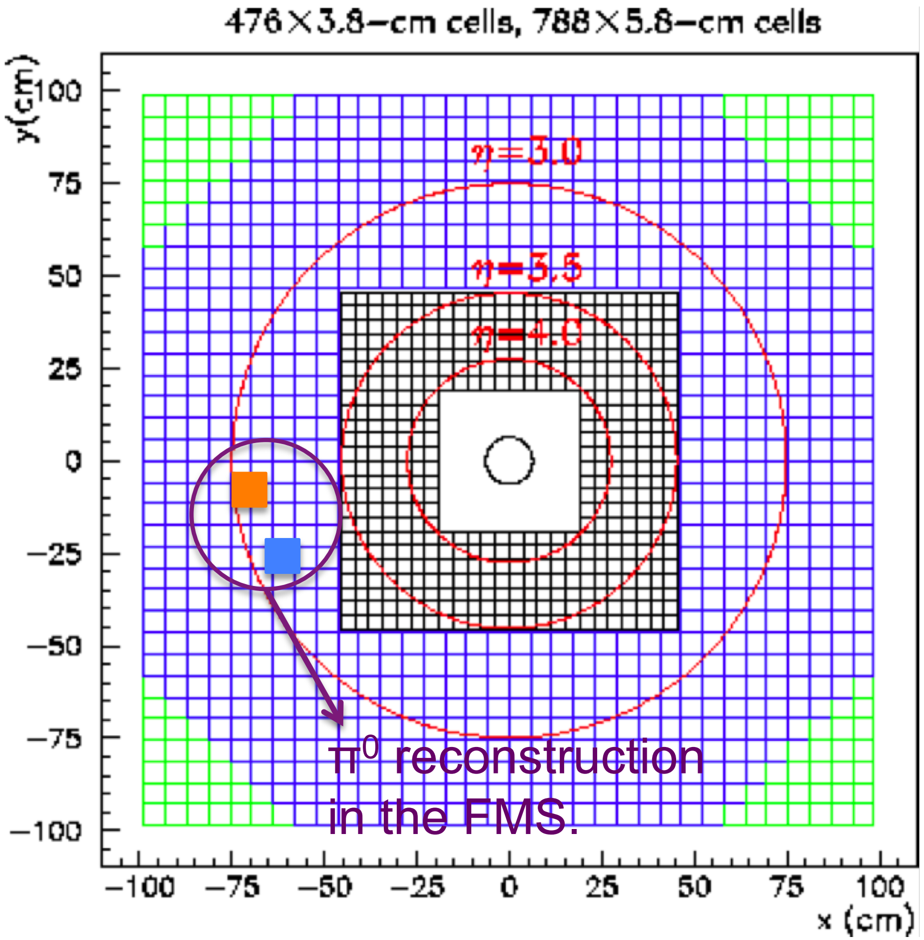


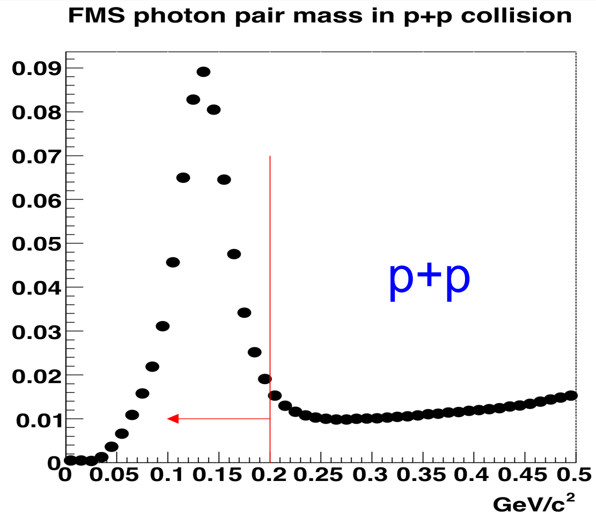
Iancu and Venugopalan, hep-ph/0303204

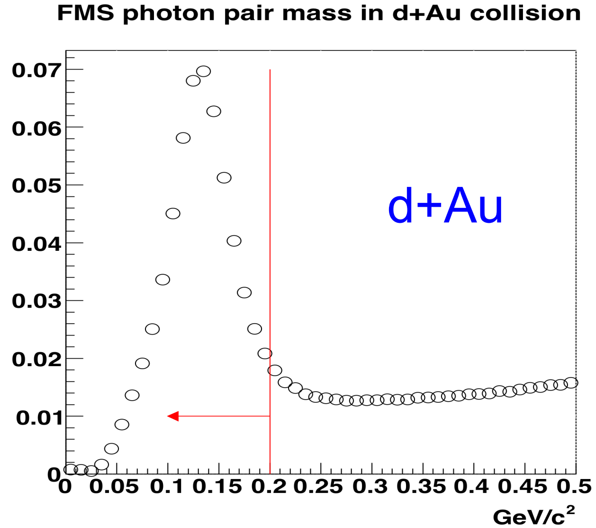
- Nearly continuous EM system (spans $-1<\eta<4$) at STAR provides acceptance for azimuthal correlations at different pseudo-rapidity.

π^0 reconstruction in the FMS

- The triggered particle is π^0 reconstructed in the most forward detector — FMS.



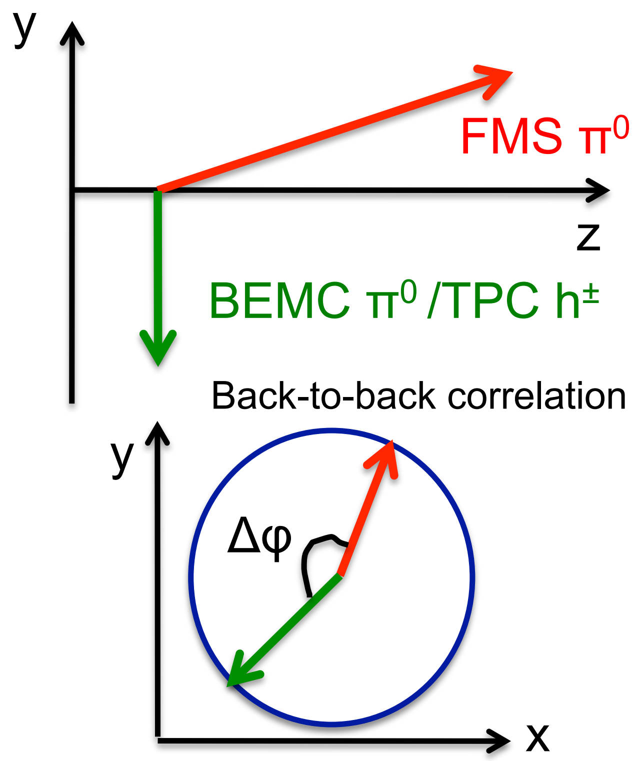




- There are clear π^0 peaks in the FMS during p+p and d+Au collisions.

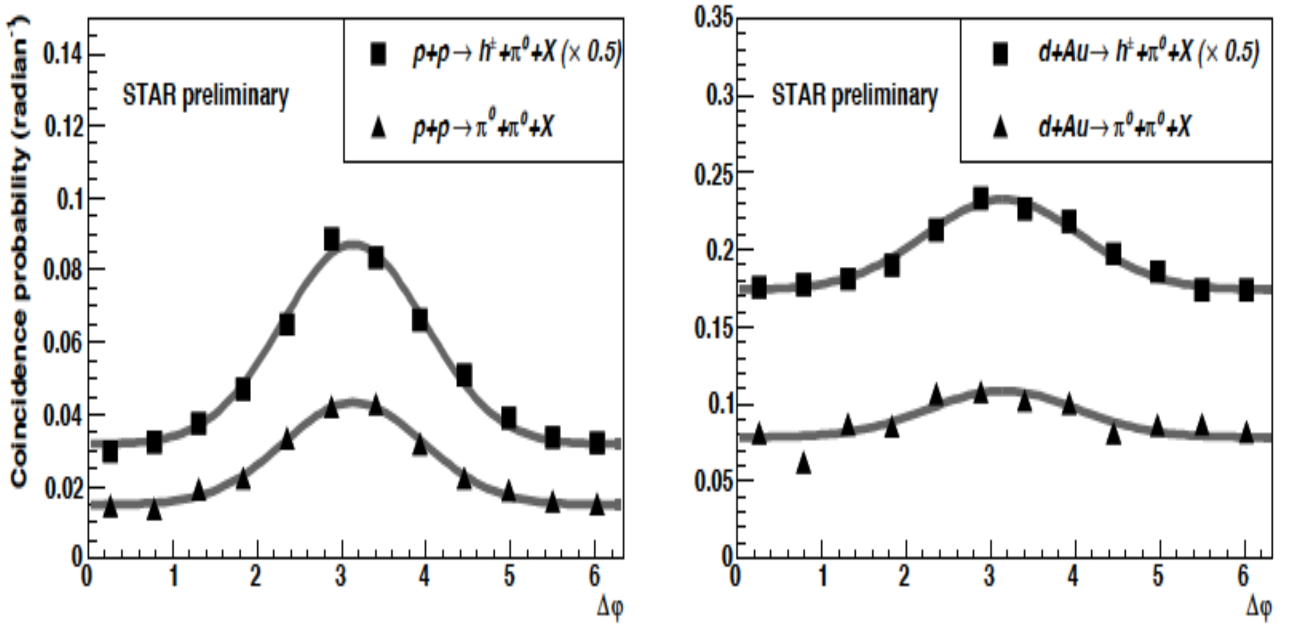
Forward-mid rapidity correlations

- FMS-BEMC(TPC) azimuthal correlations probe nuclei gluon density at $0.008 < x_{BJ} < 0.07$.



E. Braidot (arXiv:1102.0931)

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



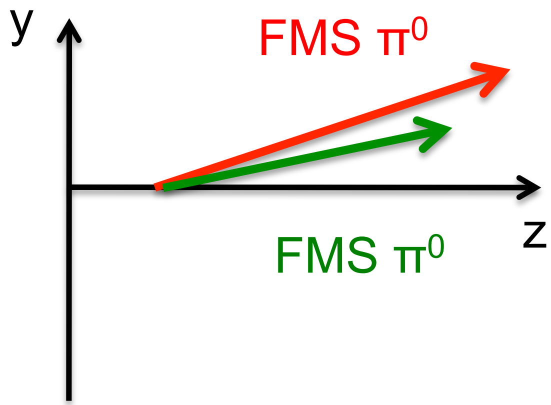
σ_{up}=0.846±0.025, b_{up}=0.063±0.001
σ_{low}=0.829±0.045, b_{low}=0.015±0.001

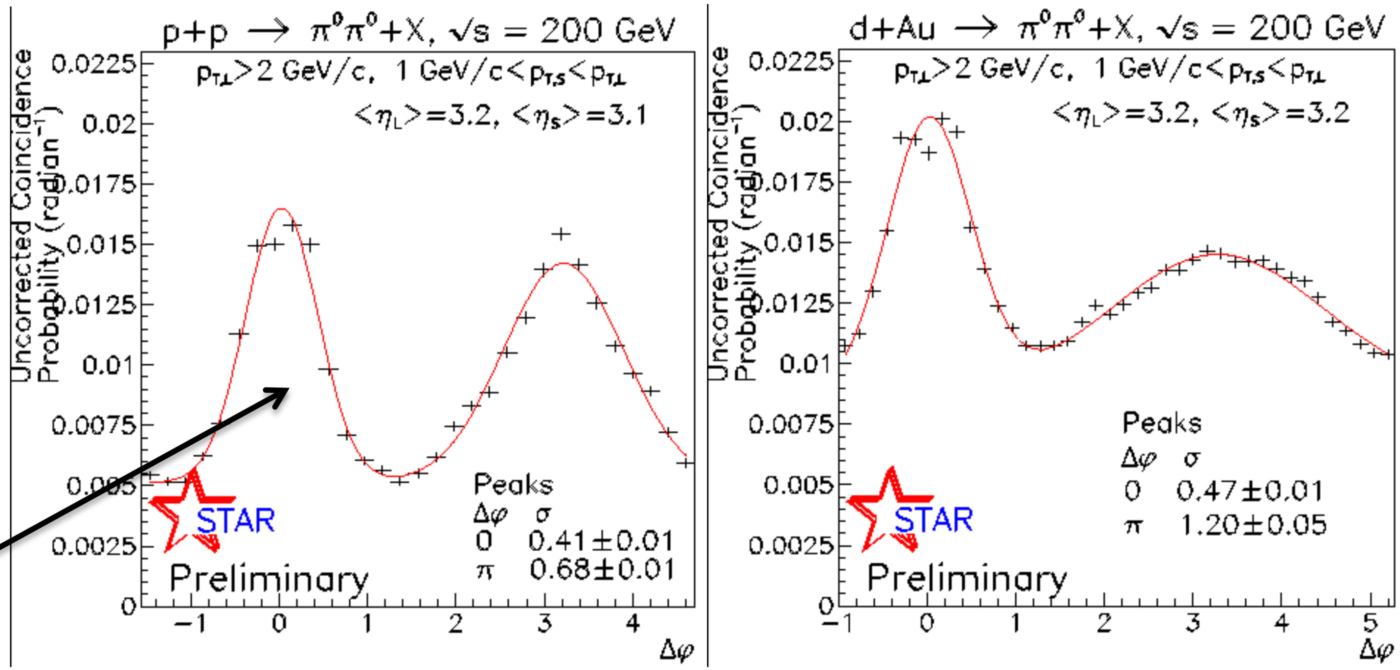
σ_{up}=0.915±0.025, b_{up}=0.348±0.002
σ_{low}=0.880±0.111, b_{low}=0.078±0.002

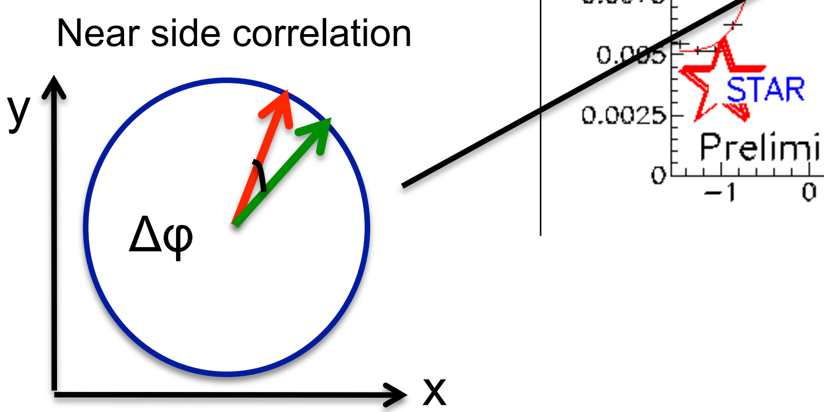
- Higher pedestal in d+Au than in p+p.
- No significant broadening from p+p to d+Au.
- Similar away-side correlation strength.

Forward-forward rapidity correlation

- FMS-FMS azimuthal correlations probe gluon density at 0.0009 < x < 0.005.





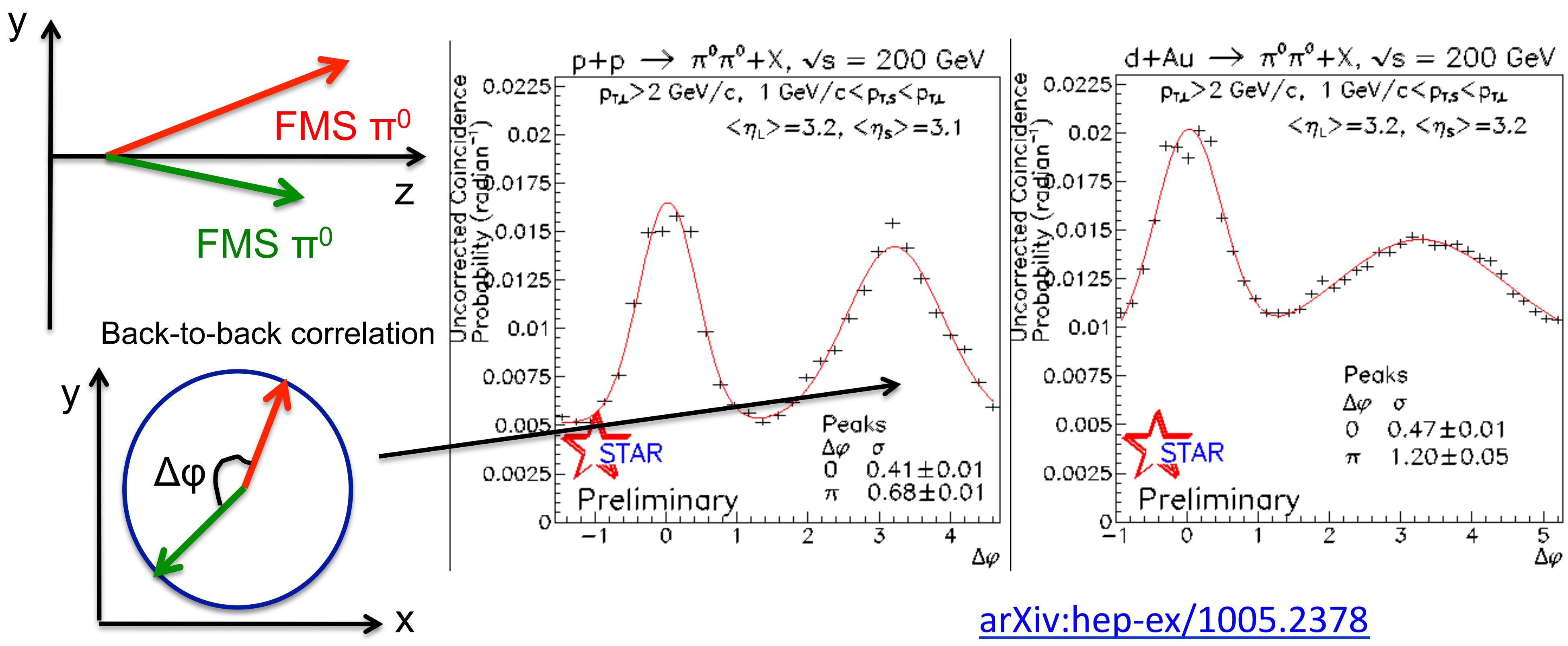


arXiv:hep-ex/1005.2378

- Similarity of near side peak in pp and dAu data.
- There is significant broadening from pp to dAu in forward-forward rapidity azimuthal correlations in the away side peak.

Forward-forward rapidity correlation

- FMS-FMS azimuthal correlations probe gluon density at $0.0009 < x < 0.005$.

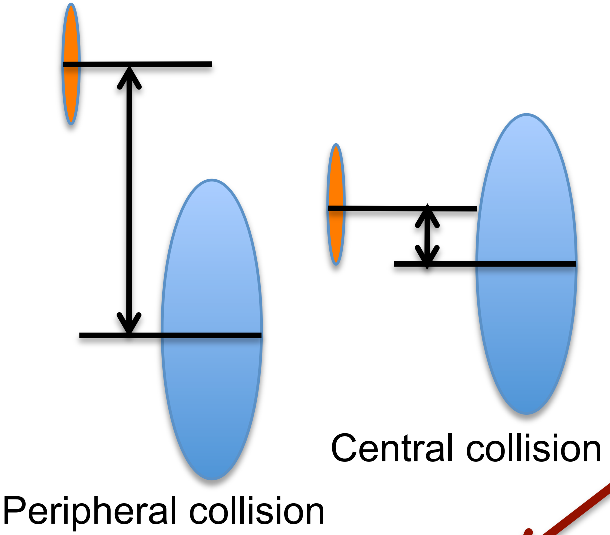


arXiv:hep-ex/1005.2378

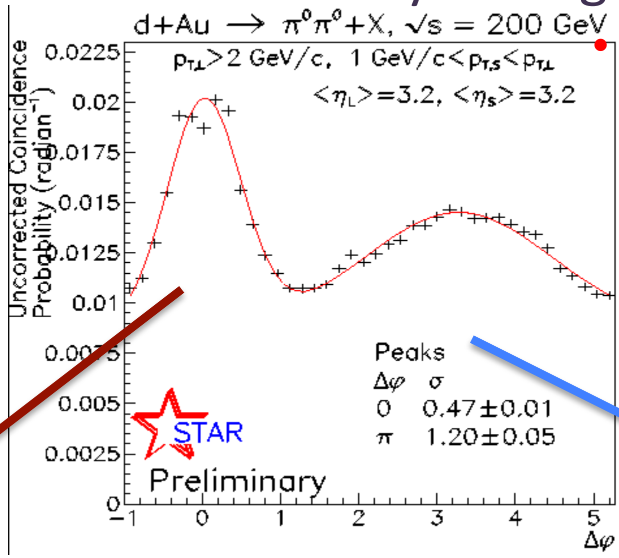
- Similarity of near side peak in pp and dAu data.
- There is significant broadening from pp to dAu in forward-forward rapidity azimuthal correlations in the away side peak.

Forward-forward rapidity correlation

- Centrality cut on the dAu data.

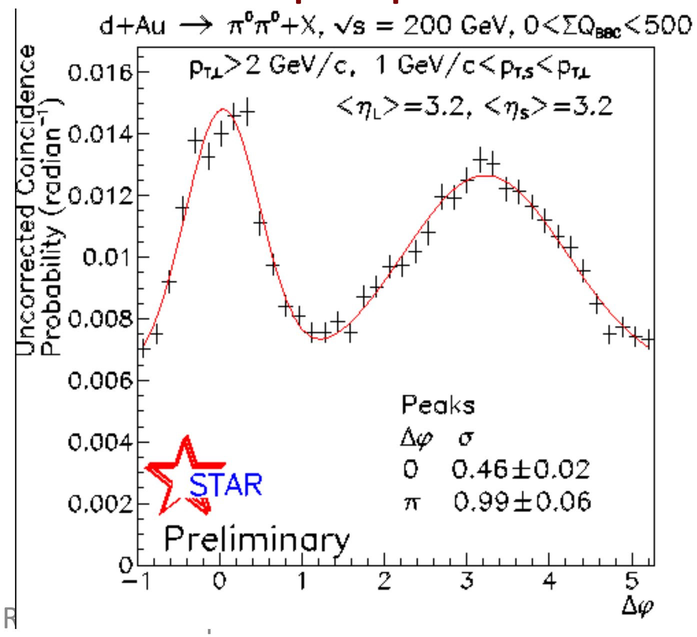


dAu centrality averaged

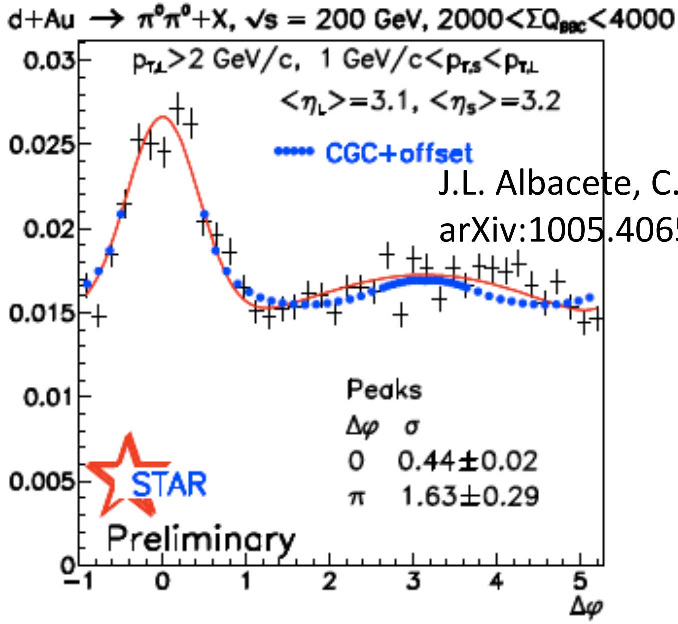


The suppression of the height of the away side peak in the central dAu collisions suggests forward-forward correlations at low x are consistent with gluon saturation in nuclei at RHIC.

dAu peripheral



dAu central

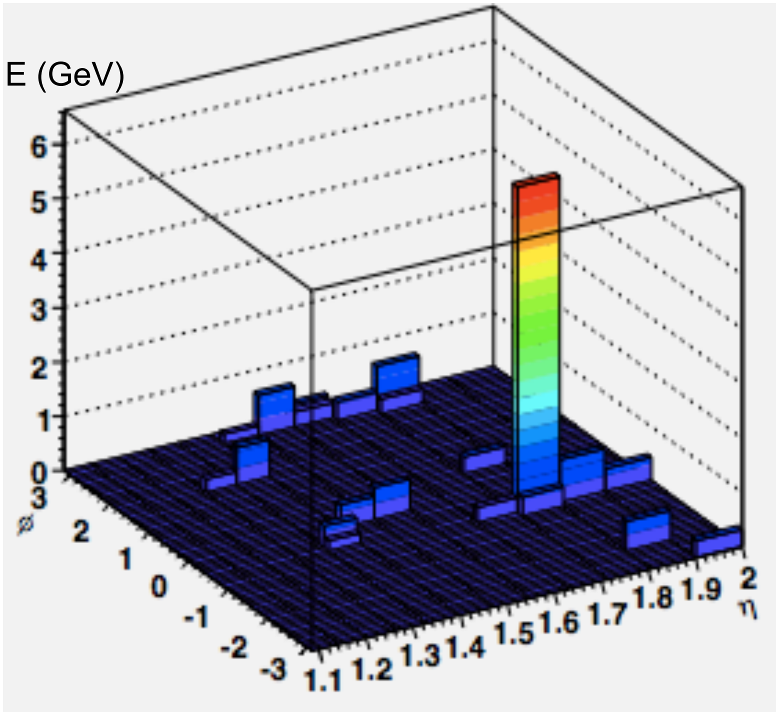


J.L. Albacete, C. Marquet arXiv:1005.4065

The event reconstruction in the EEMC

- The event is reconstructed based on the energy deposition in the EEMC.

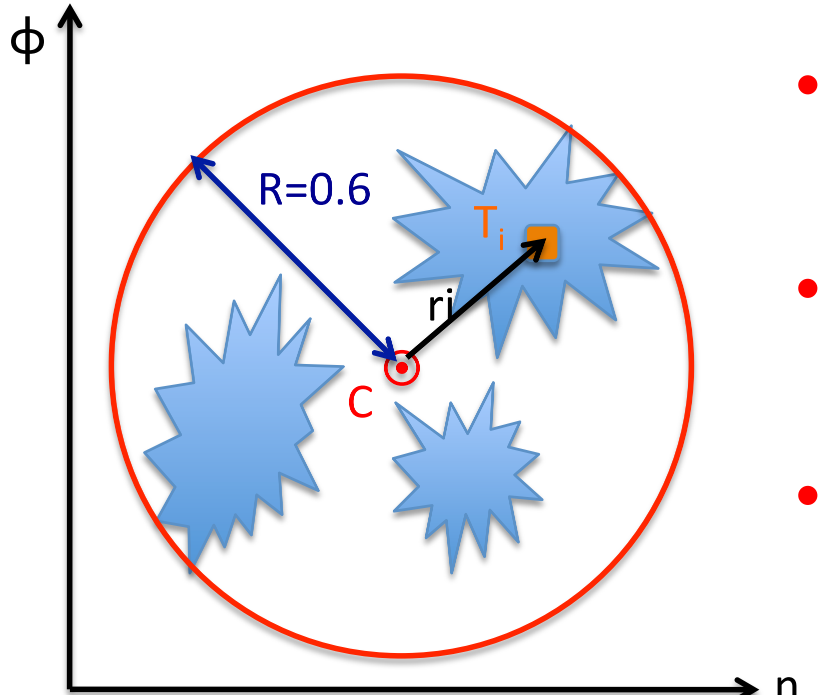
One event of the energy deposition in the EEMC with FMS π^0 trigger (p_t>2.0GeV/c) in p+p collision at $\sqrt{s}$ = 200GeV.



- The π^0 usually is the leading particle inside a jet measured in the EM calorimeter.
- The initial gluon state is independent of the final fragmentation process. Jet-like clusters can be surrogates of fragment partons.

Jet-like cluster are reconstructed with cone algorithm

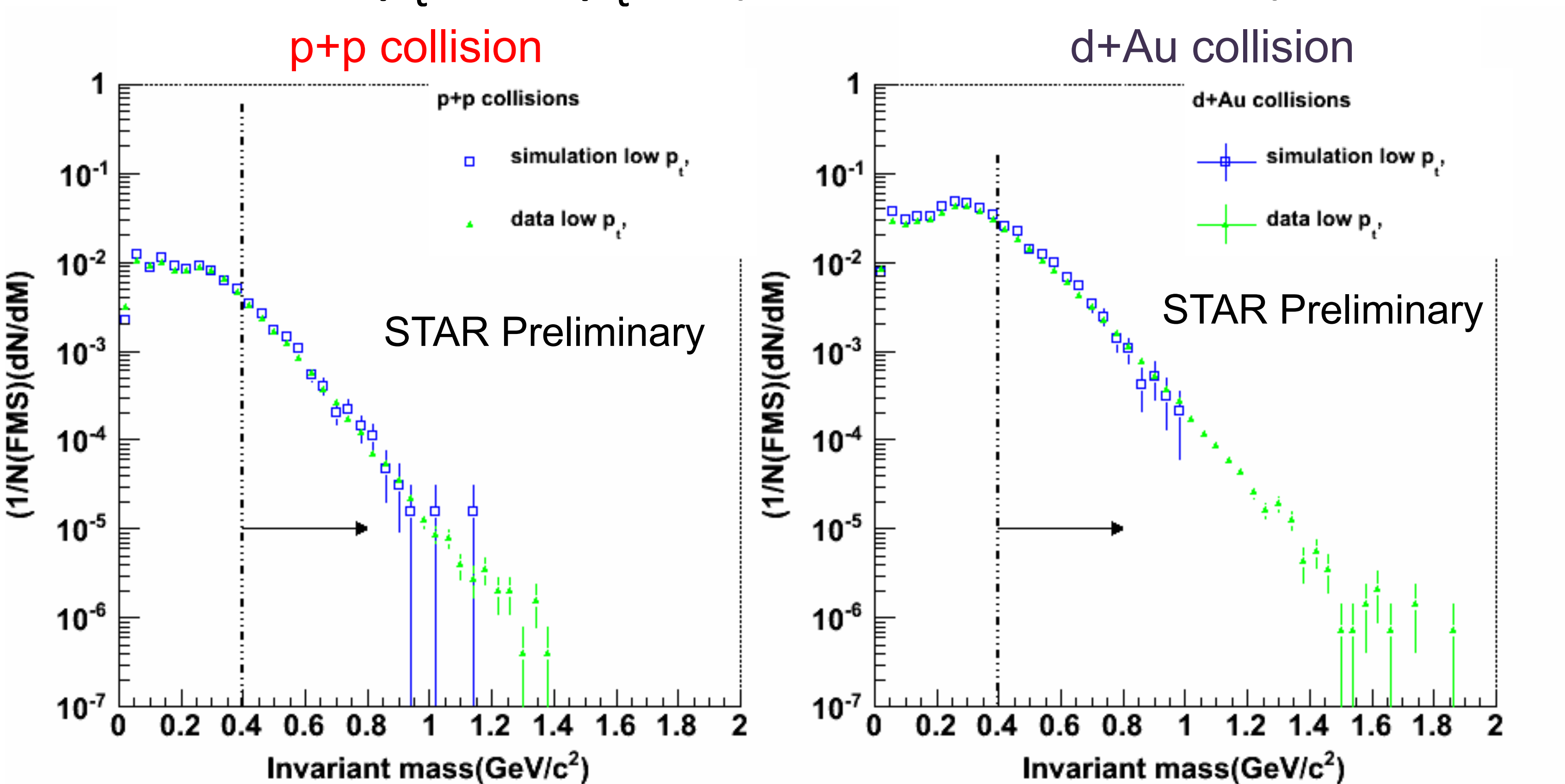
- Energy E_{jet}: $E_{jet} = \Sigma E_{Ti}$, E_{Ti} is the energy of tower i.
- Mass M_{jet}: (1) Assuming hits of towers are zero mass. Projecting T_i energy to its center to get the momentum vector of the tower p_{Ti}.
- (2) The jet-like momentum vector $p_{jet} = \Sigma p_{Ti}$.
- (3) $M_{jet} = \mathrm{sqrt}(E_{jet}^2 - P_{jet}^2)$.



- Jet-like cluster pseudo-rapidity η: based on the jet-cluster center.
- Jet-like cluster polar angle ϕ: based on the jet-like cluster center.
- P_t of jet-like cluster: based on the jet-like cluster center.

Data & simulation comparison for EEMC jet-like cluster mass

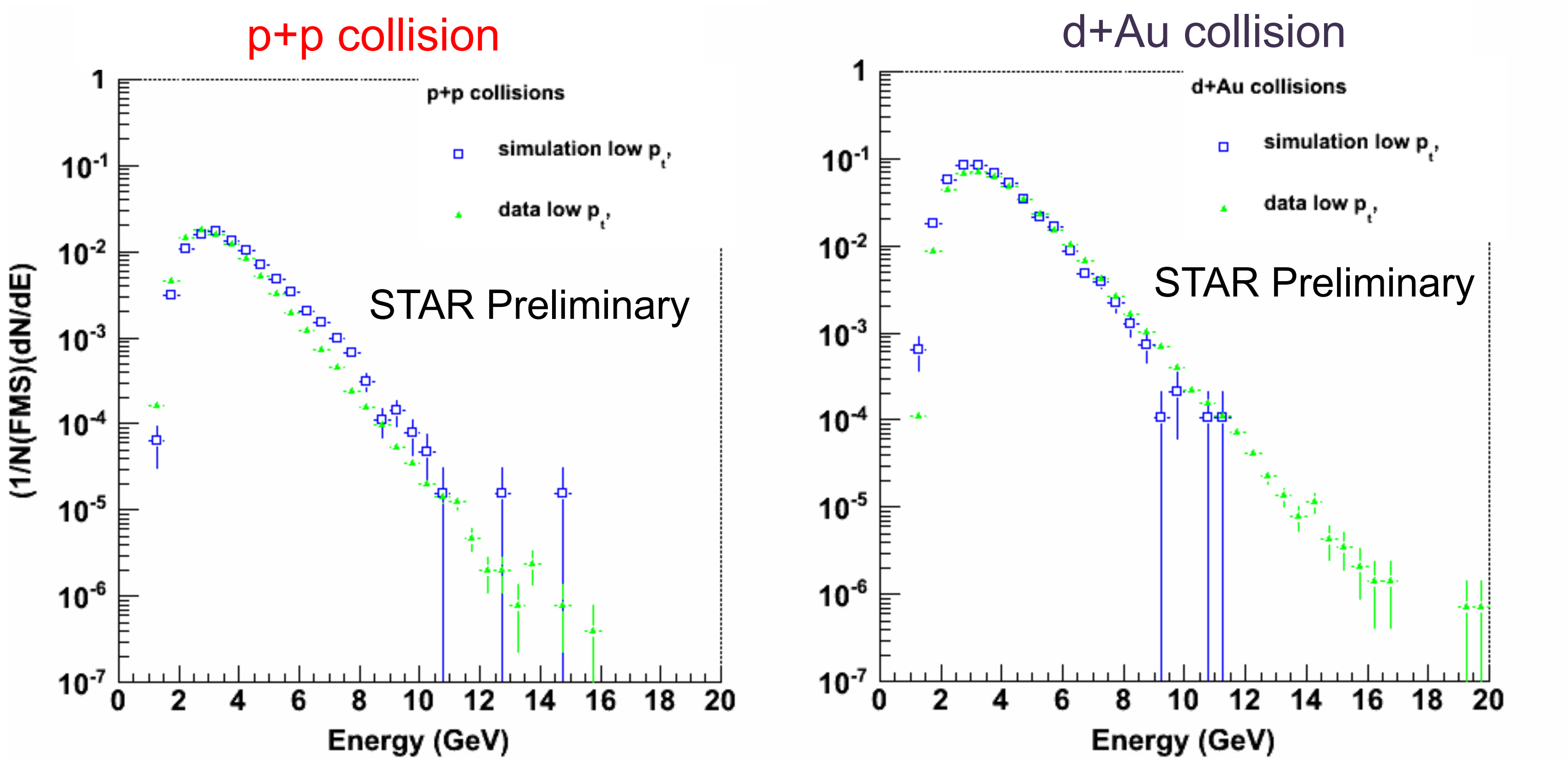
- Cuts: EEMC tower threshold 600MeV. p_t^{FMS}>2.0GeV/c, 1.0GeV/c<p_t^{EEMC}<p_t^{FMS} (Data & simulation)



- Good agreement between data and simulation in both p+p and d+Au collisions.

Data & simulation comparison for EEMC jet-like cluster energy

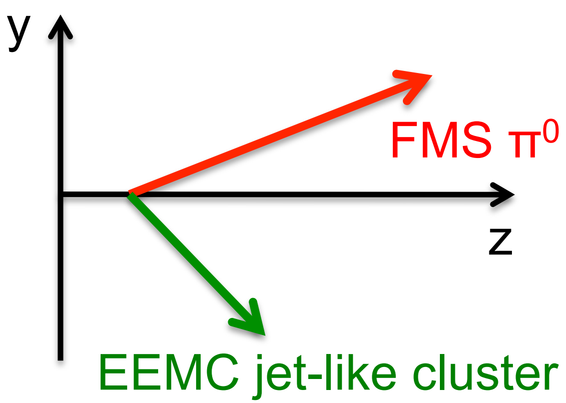
- Cuts: EEMC tower threshold 600MeV. p_t^{FMS}>2.0GeV/c, 1.0GeV/c<p_t^{EEMC}<p_t^{FMS} (Data & simulation)

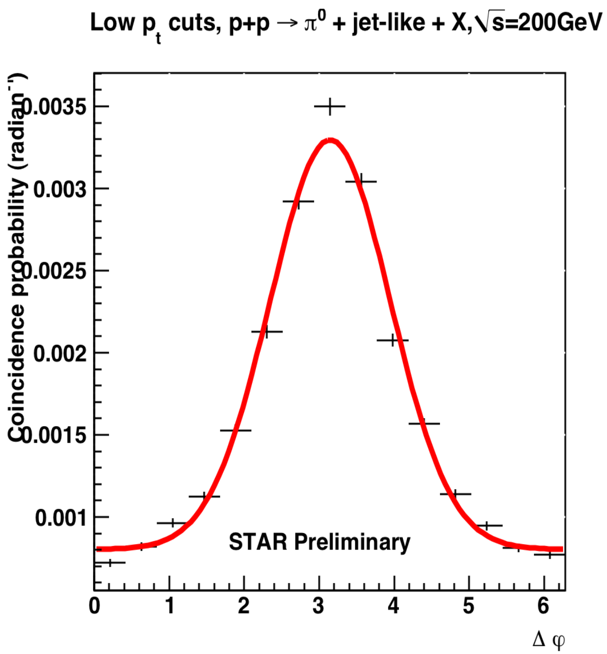


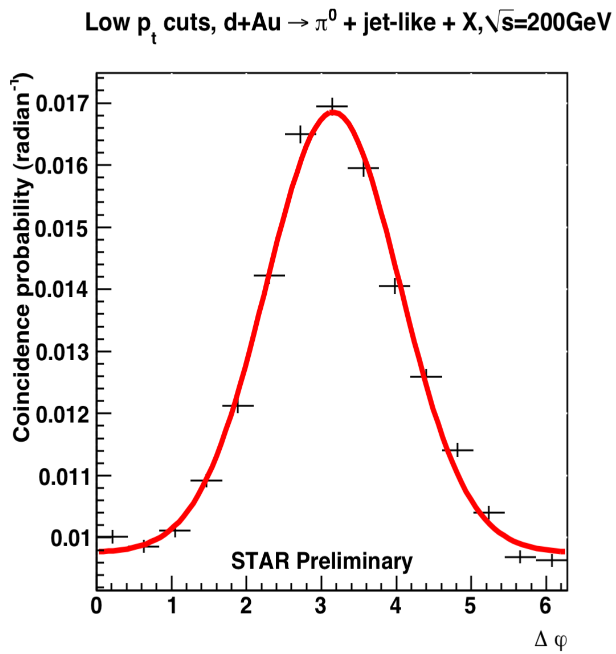
- Good agreement between data and simulation in both p+p and d+Au collisions.

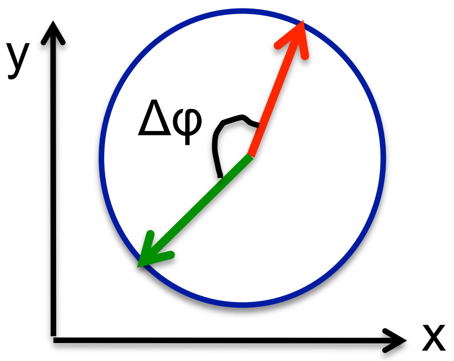
FMS (π^0)-EEMC (jet-like cluster) correlations

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









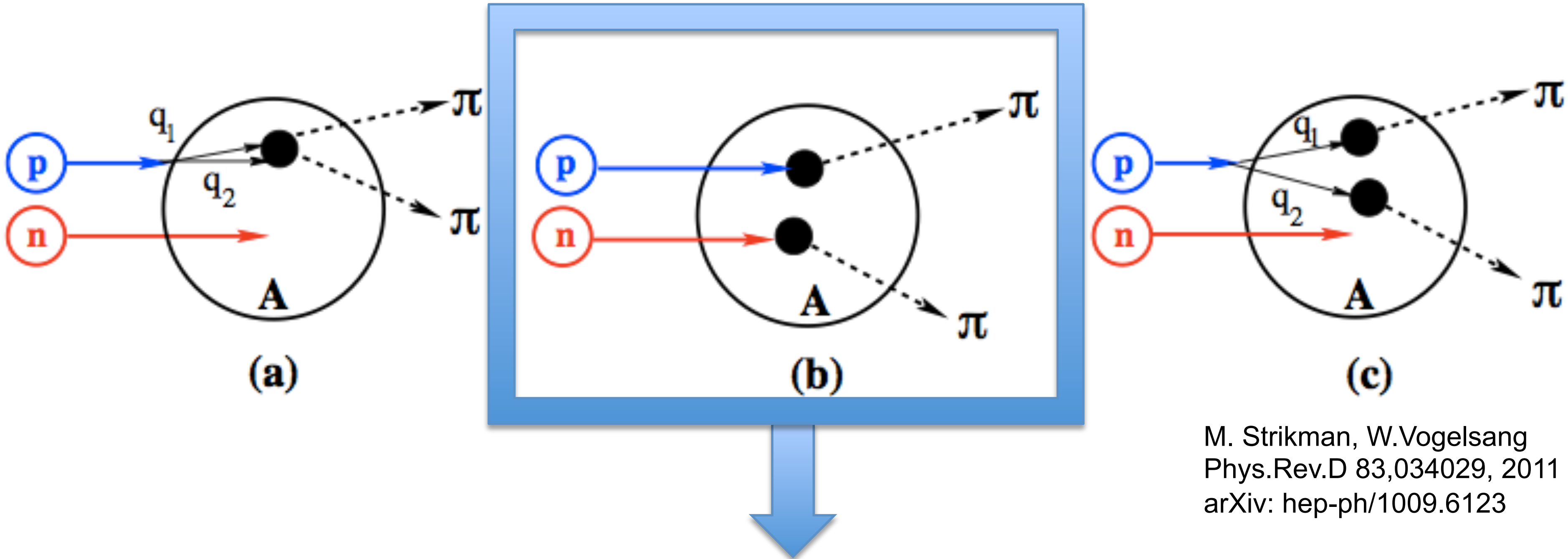
- EEMC tower threshold 600MeV, EEMC jet-like cluster M>0.4GeV/c^2.
- σ_{pp} = 0.7978 ± 0.0120, σ_{dAu}= 0.8935± 0.0157
- b_{pp}= 0.00080 and b_{dAu}= 0.00970

Fit function: $G(x) = b + \frac{A_1}{\sqrt{2\pi}\sigma}\exp(\frac{1}{2}(\frac{x - A_2}{\sigma})^2)$

- σ_{dAu}-σ_{pp} = 0.0957 ± 0.0200. There is significant broadening from p+p to d+Au collisions for the correlation peak width.

Theory predictions on the pedestal

- From leading twist to double parton scattering.



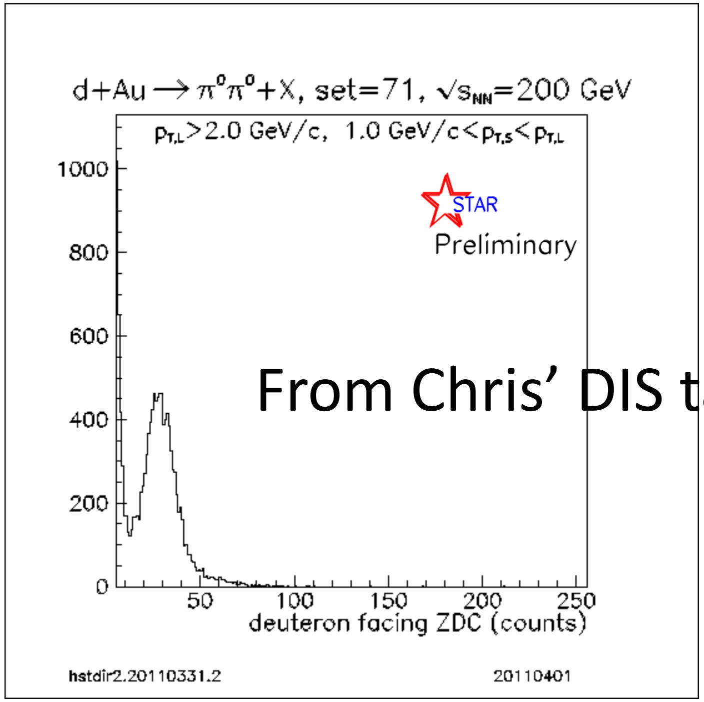
M. Strikman, W.Vogelsang
Phys.Rev.D 83,034029, 2011
arXiv: hep-ph/1009.6123

- The contribution from (b) can be studied by comparing the pedestal (uncorrelated part) of the correlations in d+Au and p+Au collisions.
- A deuteron beam facing neutron tag is used in d+Au collisions as a p+Au approach.

Tagging Spectator Neutrons from Deuteron Beam

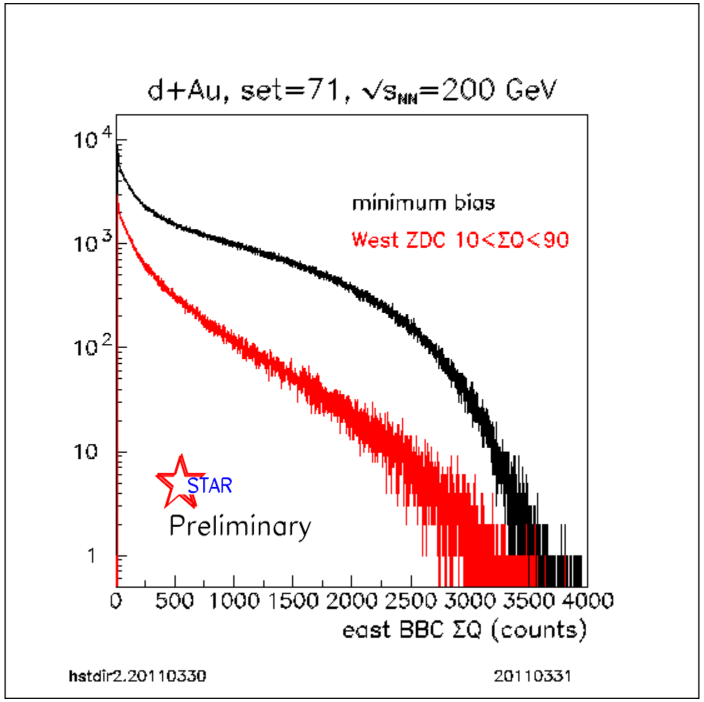
- It may also be useful to distinguish between p+Au and d+Au collisions by looking for events where the neutron in the deuteron remains intact

Deuteron-facing (West) ZDC Response



From Chris' DIS talk

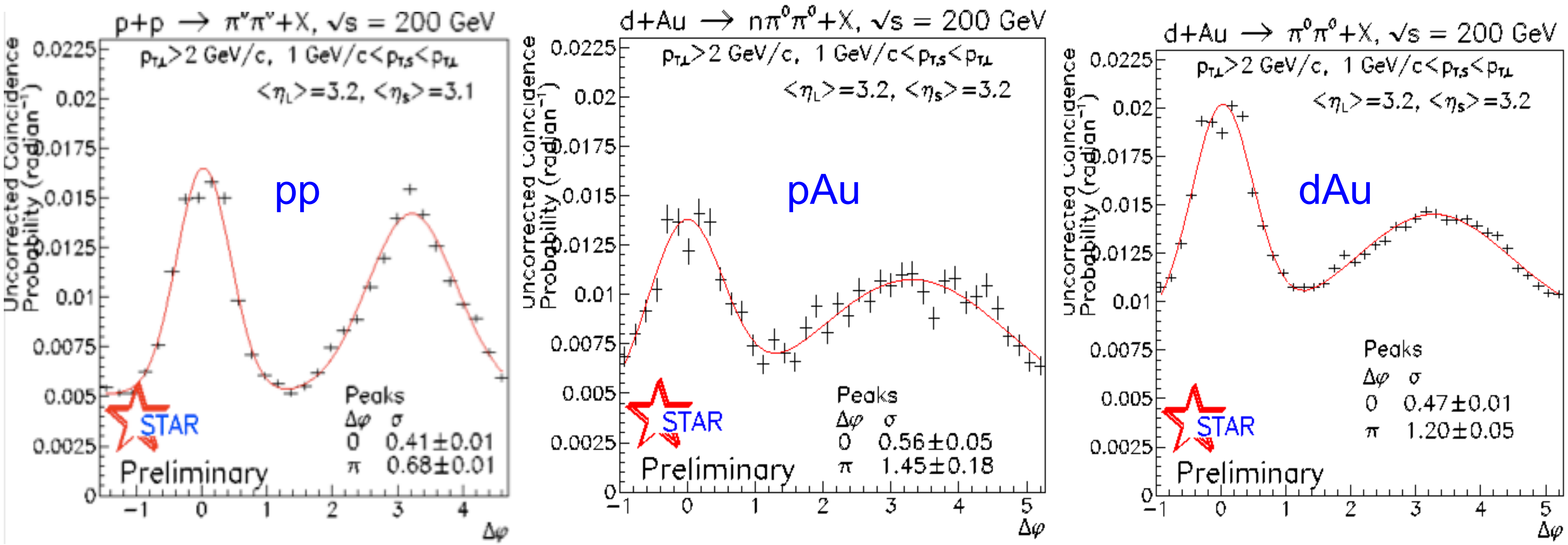
Gold-facing (East) BBC Charge Sum



- Minimum Bias Run 8 d+Au Data
- Tag spectator neutrons using deuteron-facing (West) ZDC
- Clear single-neutron peak
- Cutting on single-neutron peak biases towards peripheral collisions

What has been done in FMS-FMS correlations

- FMS-FMS π^0-π^0 correlations.

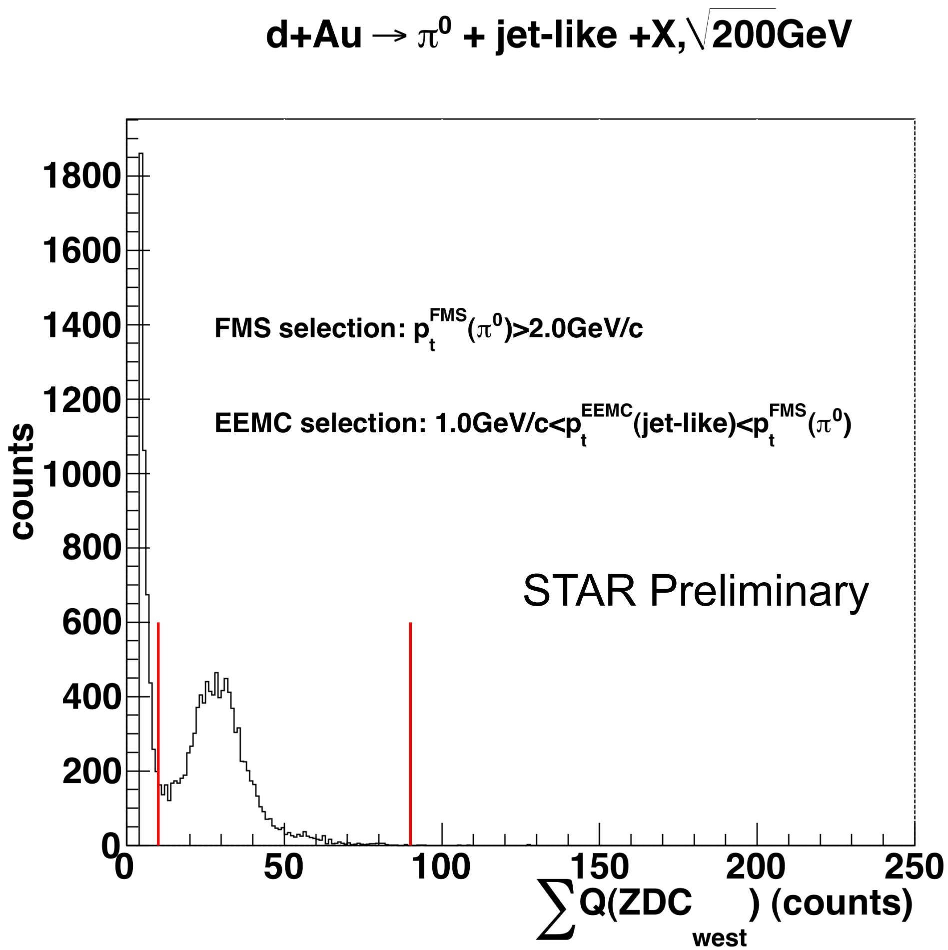


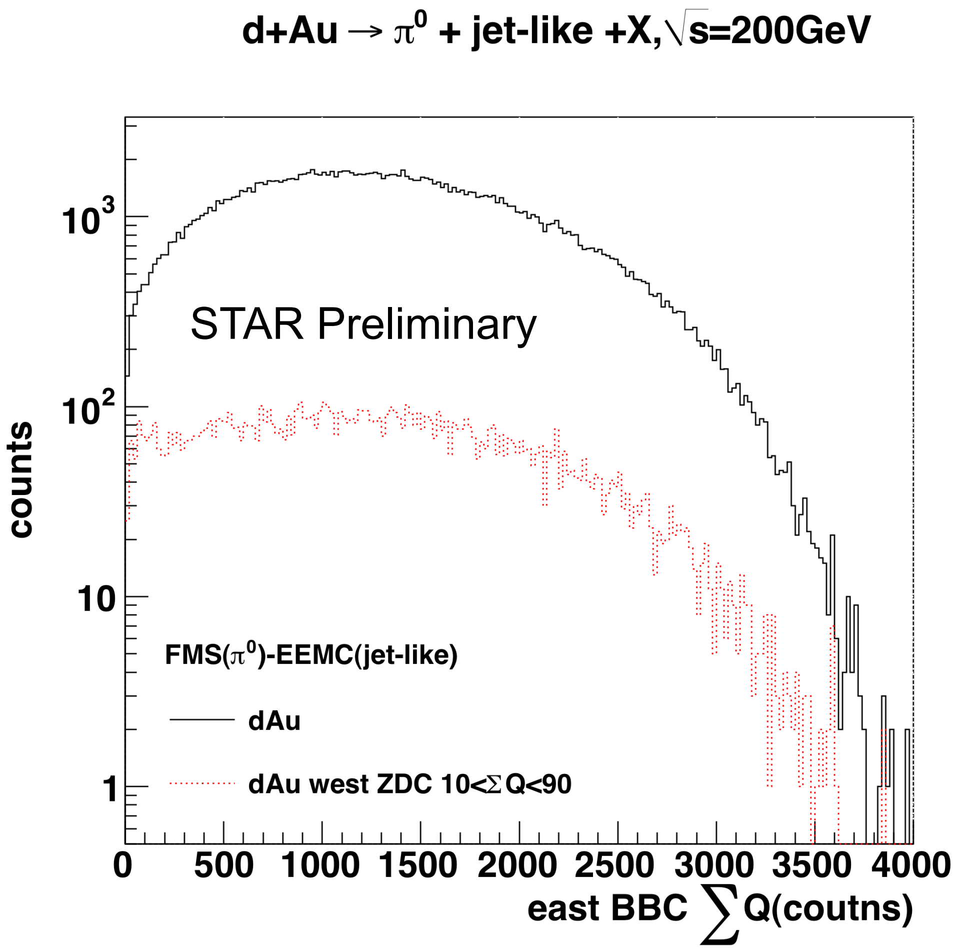
ArXiv:1109.0649

- Multi-parton interactions appear to contribute to the pedestal in d+Au collisions but less significantly to p+Au collisions.

ZDC west neutron tag in deuteron beam

- dAu FMS π^0 and EEMC jet-like coincidence.

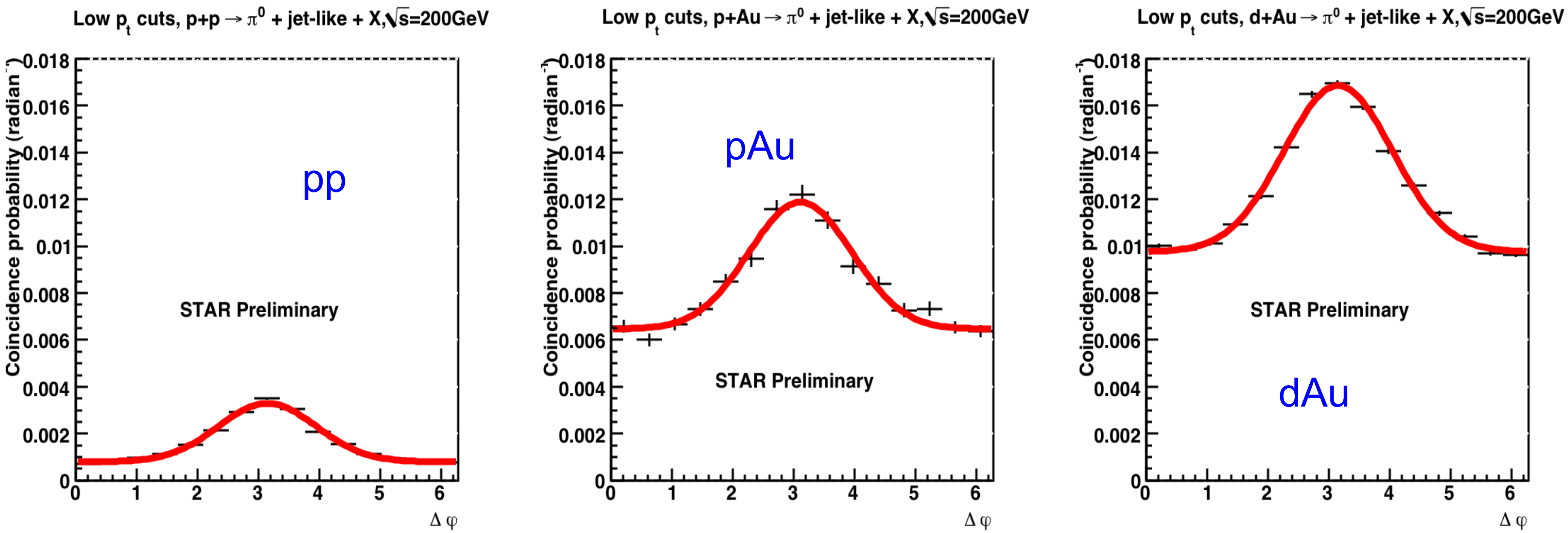




The ZDC west charge sum in forward π^0 triggered dAu looks similar like forward-forward data.

FMS-EEMC correlations in p+Au approach

- The coincidence probability of azimuthal correlation.
- P_t^{FMS}>2.0GeV/c and 1.0GeV/c<p_t^{EEMC}<p_t^{FMS} (M^{EEMC}>0.4GeV/c^2)



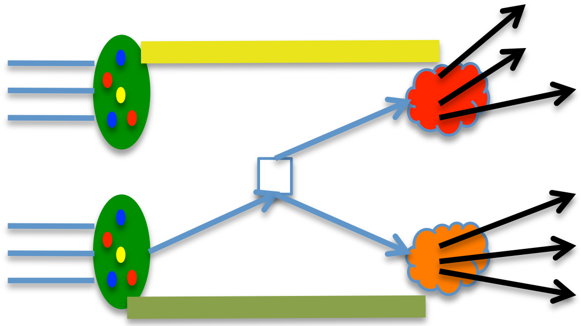
- The p+Au approach only impacts on the pedestal, the other qualities like the width of the correlation peak are analogous like in d+Au collisions.
- The independent double parton scattering contributes to FMS π^0 + EEMC jet-like cluster correlations in d+Au collisions as well.

Summary

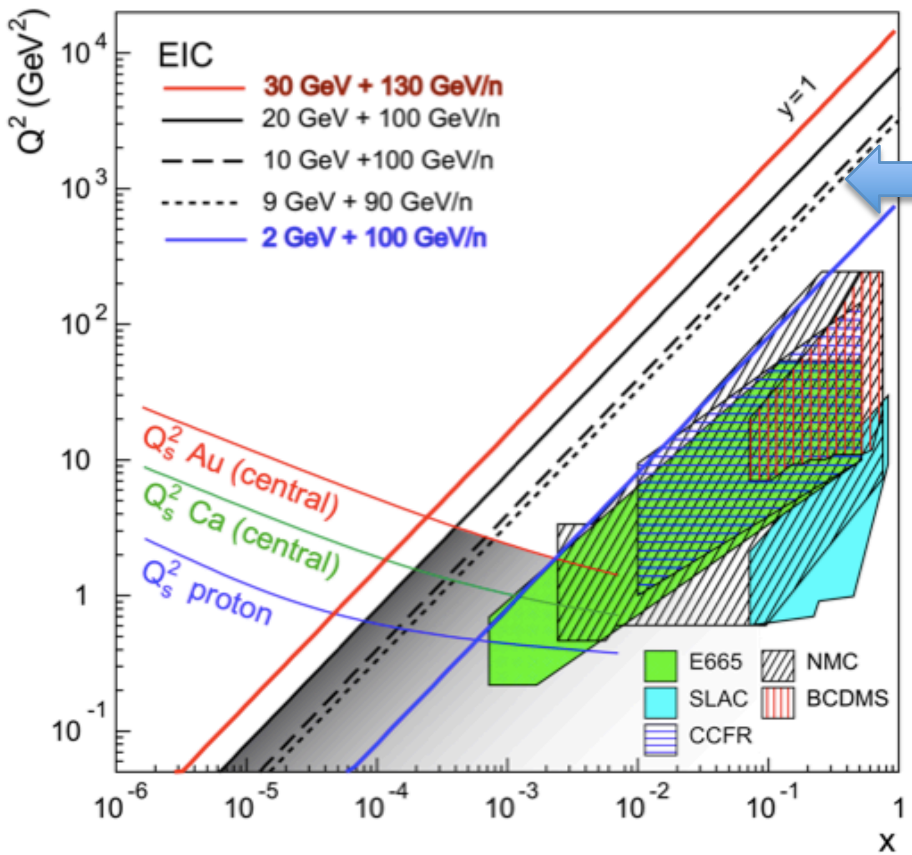
- Forward studies at RHIC provide opportunities to explore the initial state of the proton and the nuclei.
- Comparison of p+Au to d+Au suggest independent double parton scattering is present in d+Au, affecting only the azimuthal correlation pedestal.
- The rapidity dependences of the correlations suggest a smooth transition process from dilute parton gas to dense CGC state.

Outlook of nucleus gluon saturation study

The final state π^0s or jet-like clusters 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 than fixed target experiment.
- DIS process is much cleaner than the hadron-hadron interaction.