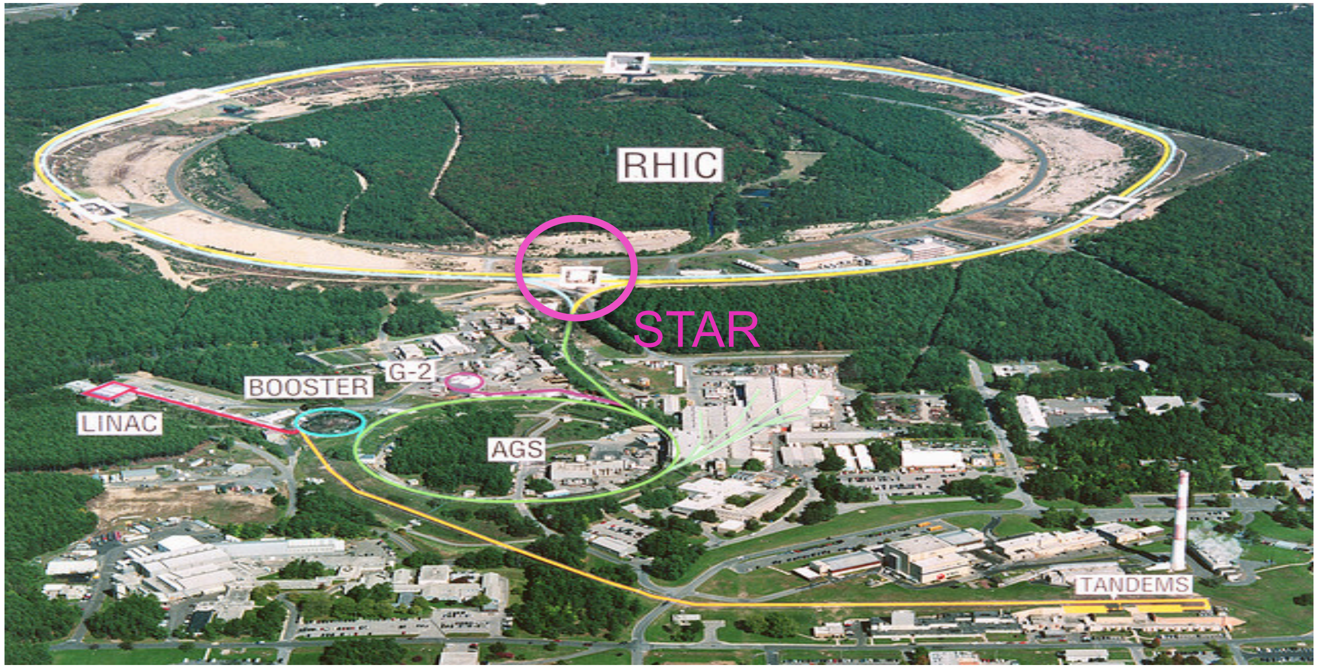
Forward+near-forward azimuthal correlations in p+p and d+Au collisions at $\sqrt{s_{NN}}$ = 200GeV at STAR



Xuan Li for the STAR Collaboration

Temple University

Outline

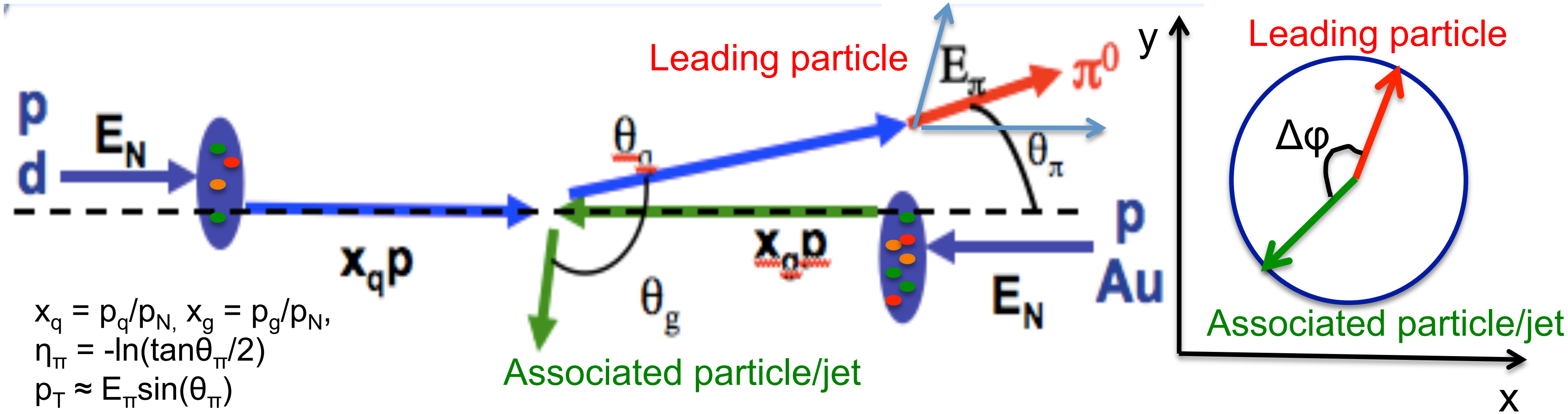
- Motivation
  - How sharp is the transition from dilute parton gas to saturated parton density: eg. Color Glass Condensate (CGC)?
- Forward+near-forward correlations at STAR
  - Near-forward jet-like cluster reconstruction
  - Forward π^0 + near-forward jet-like cluster azimuthal correlations
  - Correlations in p+Au approach comparison with d +Au results
- Summary & Outlook

How to probe low x gluons

- Forward particle production.

Parton distribution function ⊗ Hard parton scattering ⊗ Partons fragment into hadrons

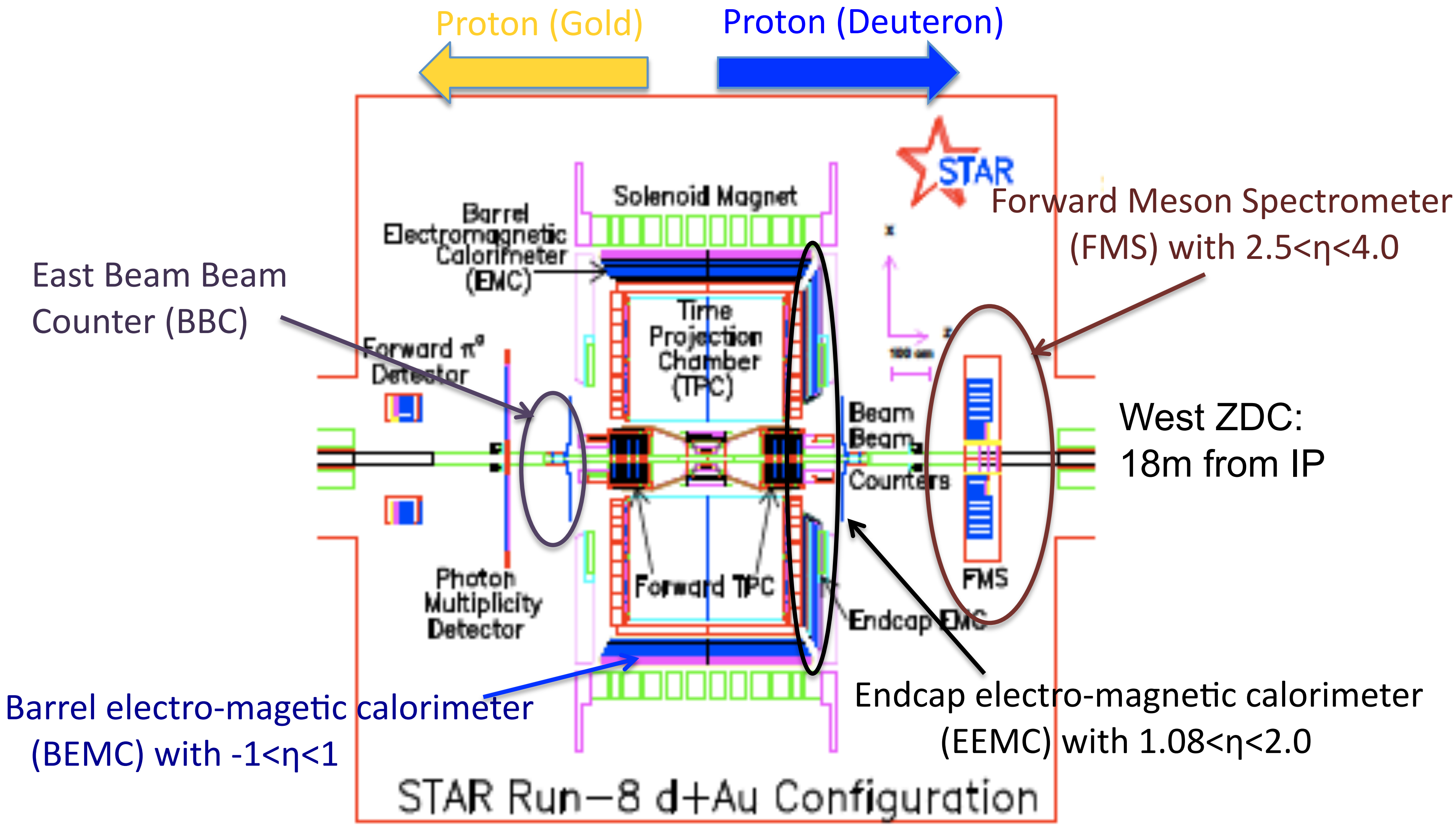
- The factorization mechanism is taken as universal and applied in nucleon (nucleus)+ nucleon (nucleus) collisions.



- 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 Detector setup

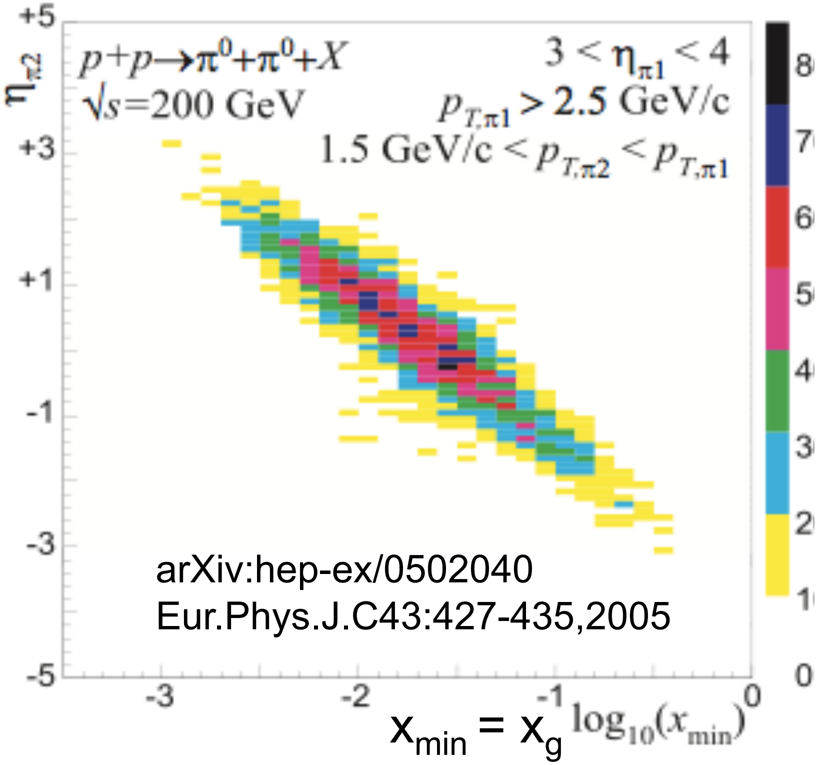
- The schematics of STAR in RHIC run8.

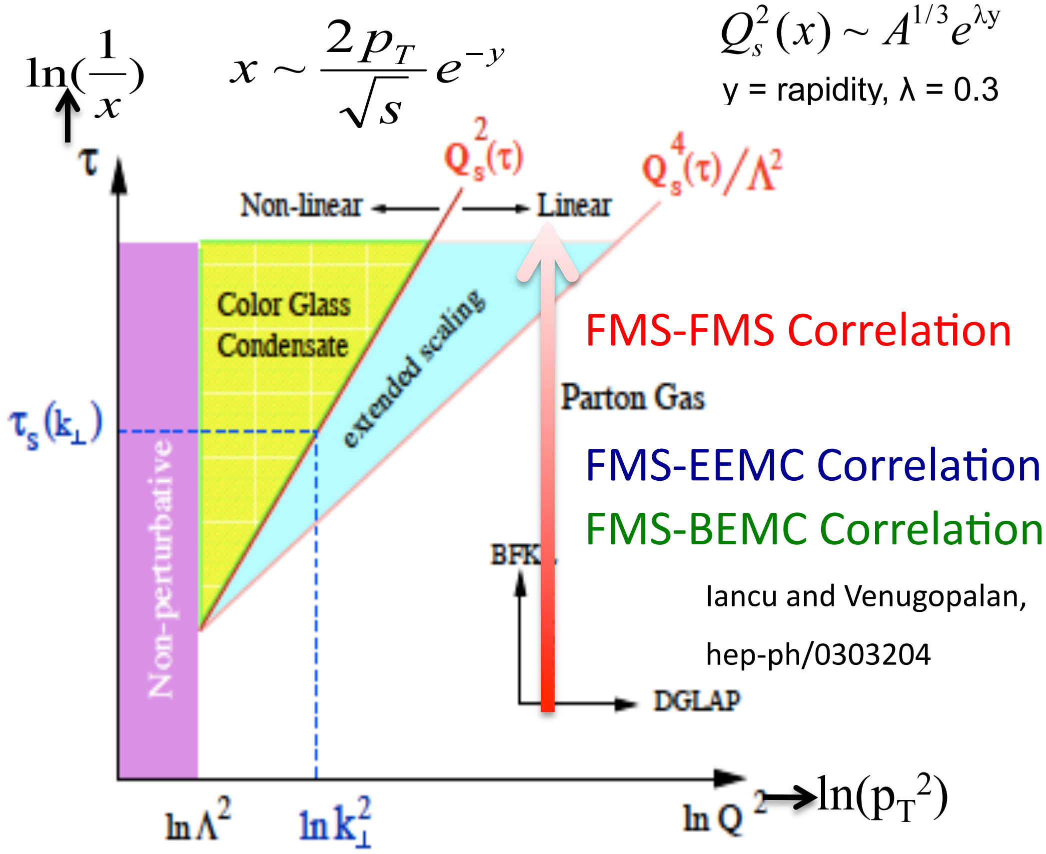


- We use the data of run8 p+p and d+Au collision at $\sqrt{s} = 200$GeV.

The soft gluon x is related to associated particle in correlations

PYTHIA simulation



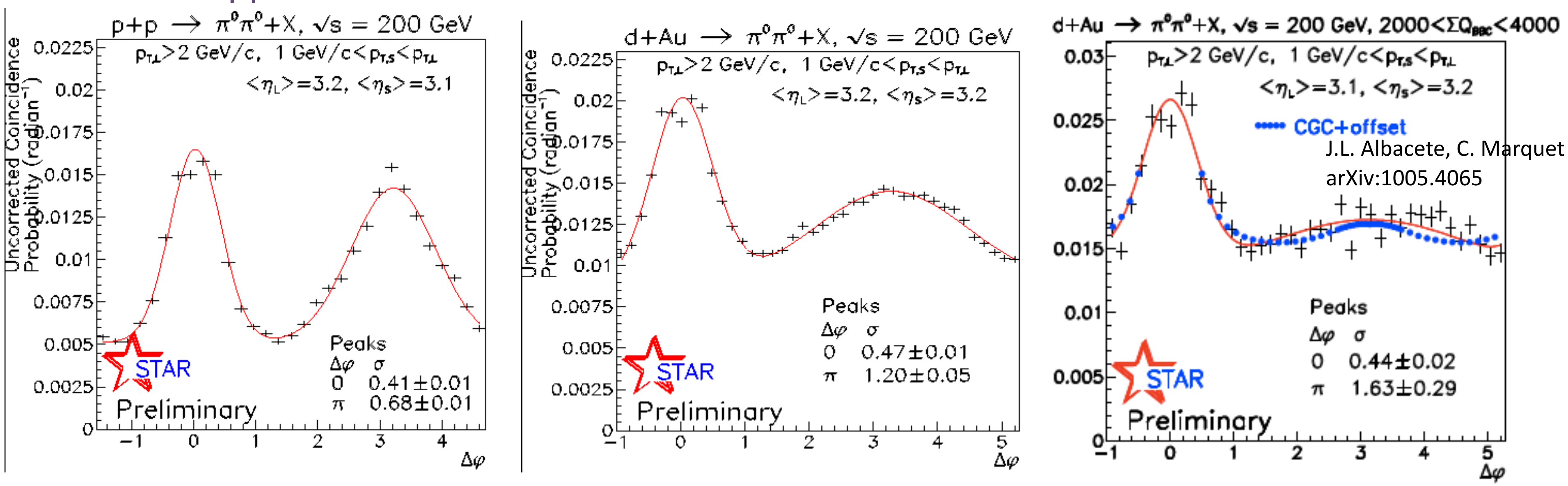


- The pseudo-rapidity of the associated particle is strongly correlated with soft gluon x in the asymmetric parton scattering.

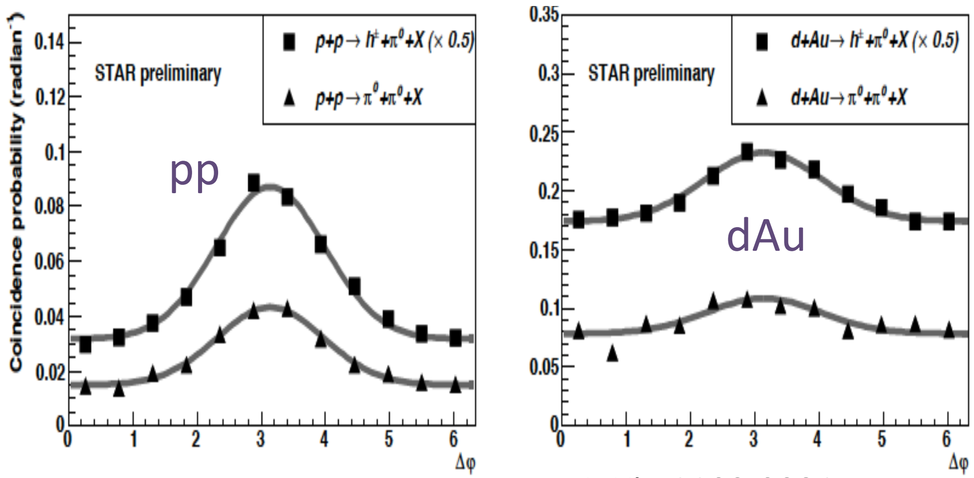
Existing STAR forward di-hadron measurements

—— forward-forward, forward-mid correlations

pp ArXiv:1108.3989 dAu Central dAu



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

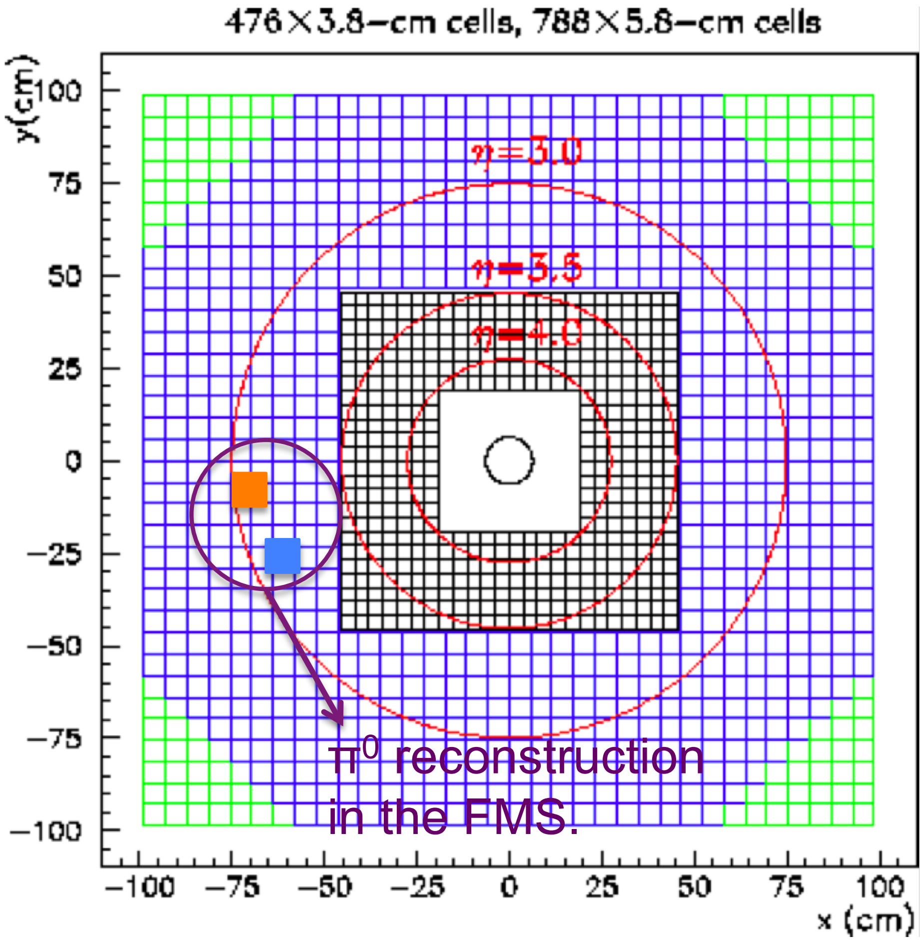


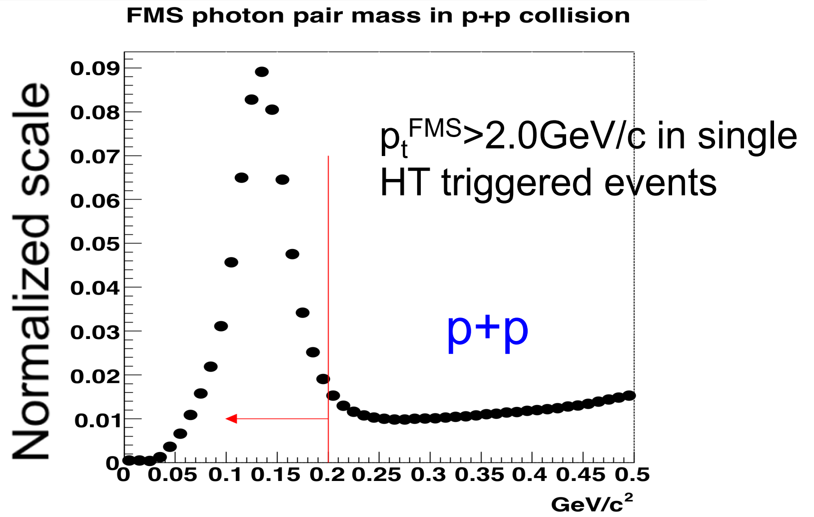
ArXiv:1102.0931

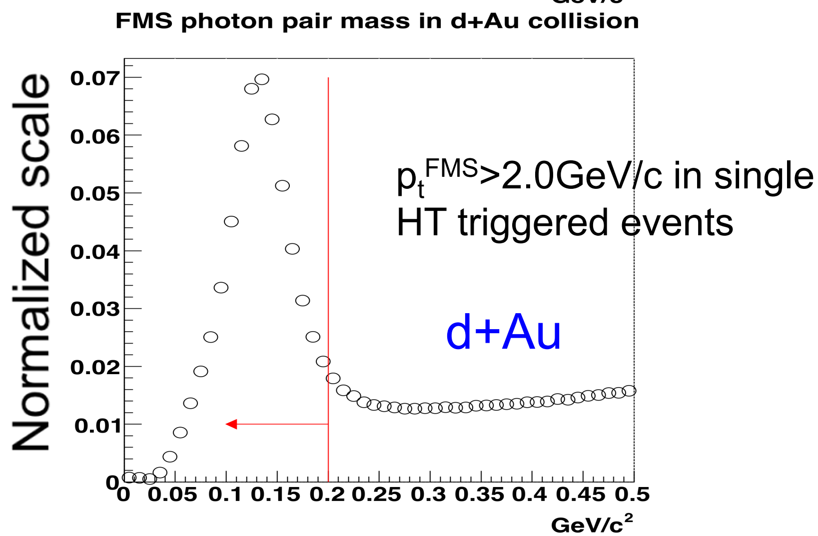
- Forward-forward: significant broadening from p+p to d+Au in back-to-back peak. Suppression in central d+Au.
- Forward-mid: No significant broadening from p+p to d+Au.
- Higher pedestal in d+Au than in p+p.

π^0 reconstruction in the FMS

- Leading forward π^0 is reconstructed in the most forward detector — FMS with HT trigger.





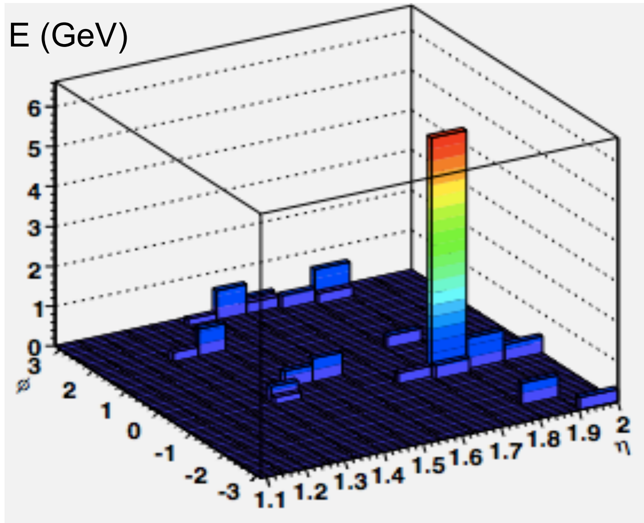


- There are clear π^0 peaks in the FMS during p+p and d+Au collisions.

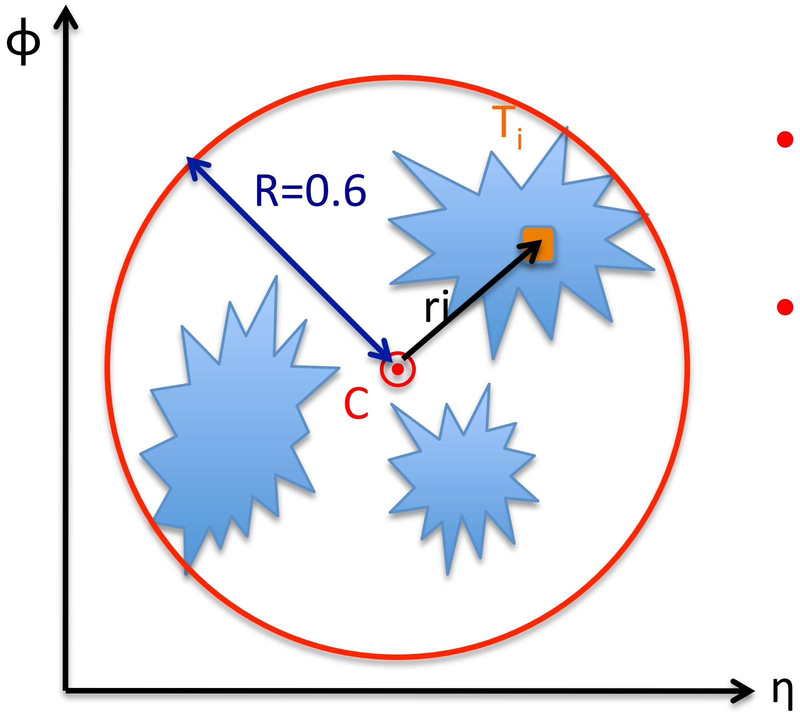
Jet-like cluster reconstruction in the EEMC

- The jet-like cluster are reconstructed based on cone algorithm.

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.



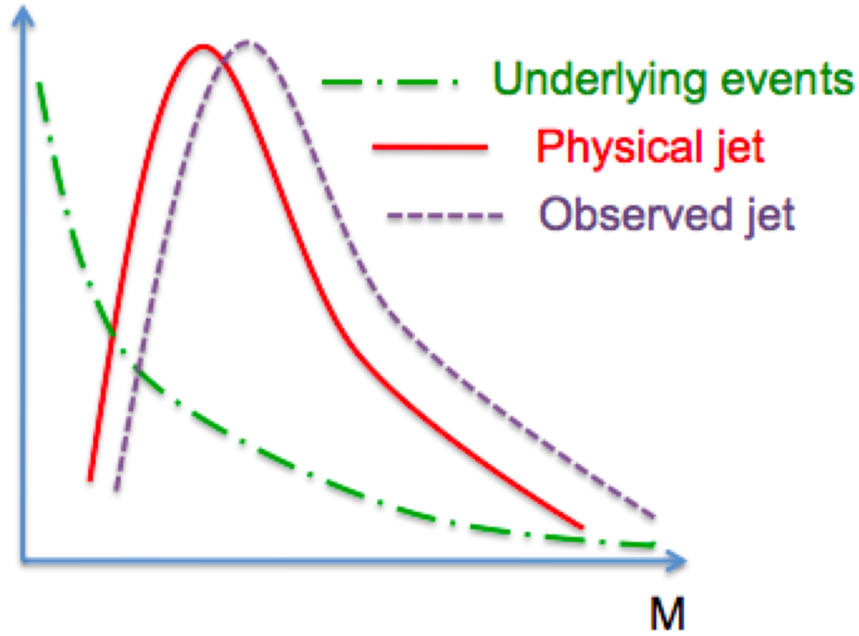
The EEMC energy deposition is jetty.

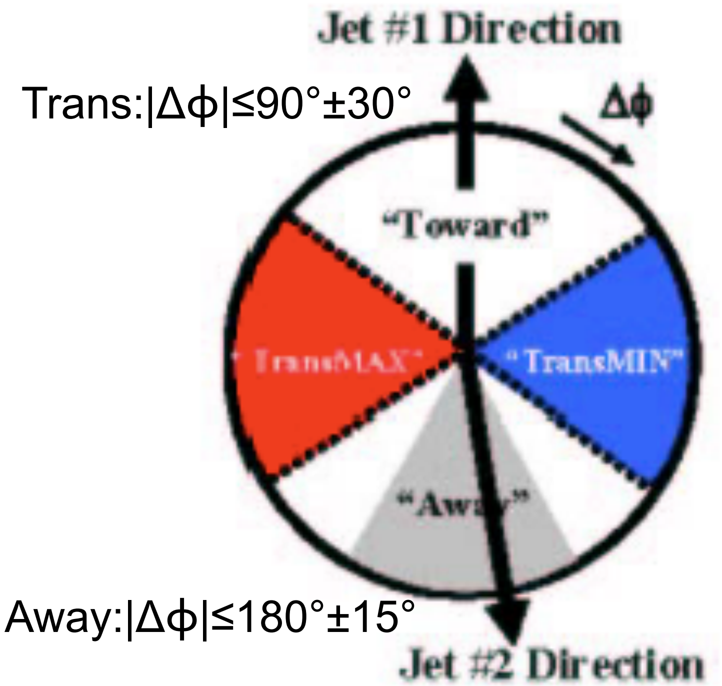


- Energy E_{jet}: $E_{jet} = \Sigma E_{Ti}$, E_{Ti} is the energy of tower i.
- Mass M_{jet}: (1) Assuming tower hits are zero mass. Projecting T_i energy to its center to get the momentum vector of the tower p_{Ti}. (2) The jet-like momentum vector $p_{jet} = \Sigma p_{Ti}$. (3) M_{jet} =sqrt(E_{jet}^2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

What is the underlying events

- Underlying event can shift physical jet to observed jet.
- Underlying events: Initial and final state interactions ("color and spectator baggage") [ISMD05, Rick Field].



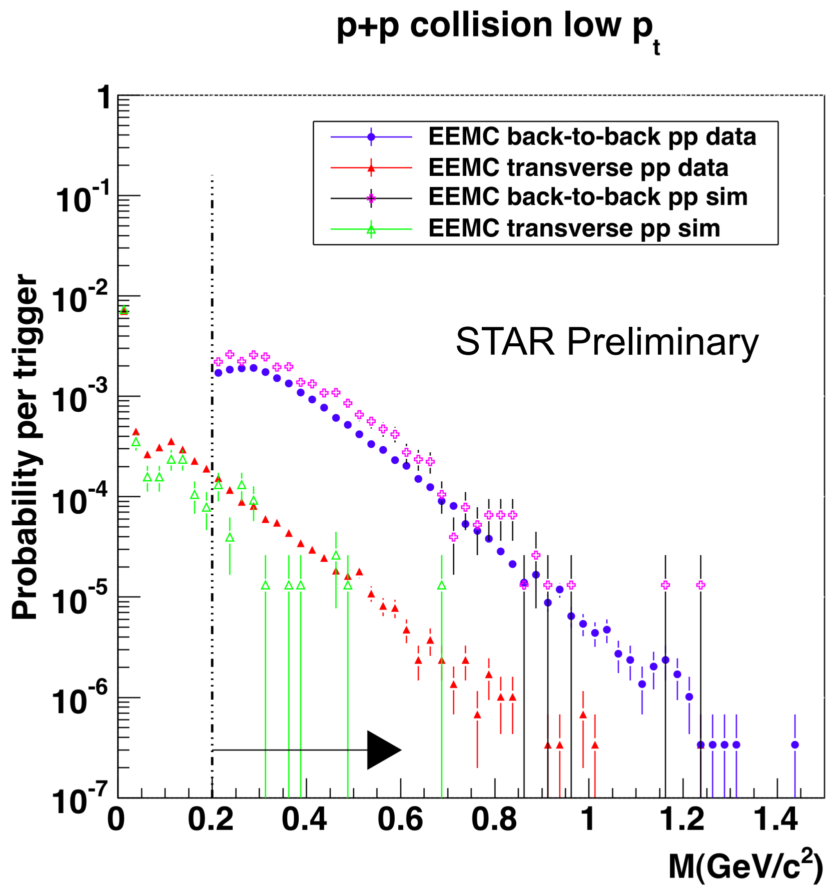


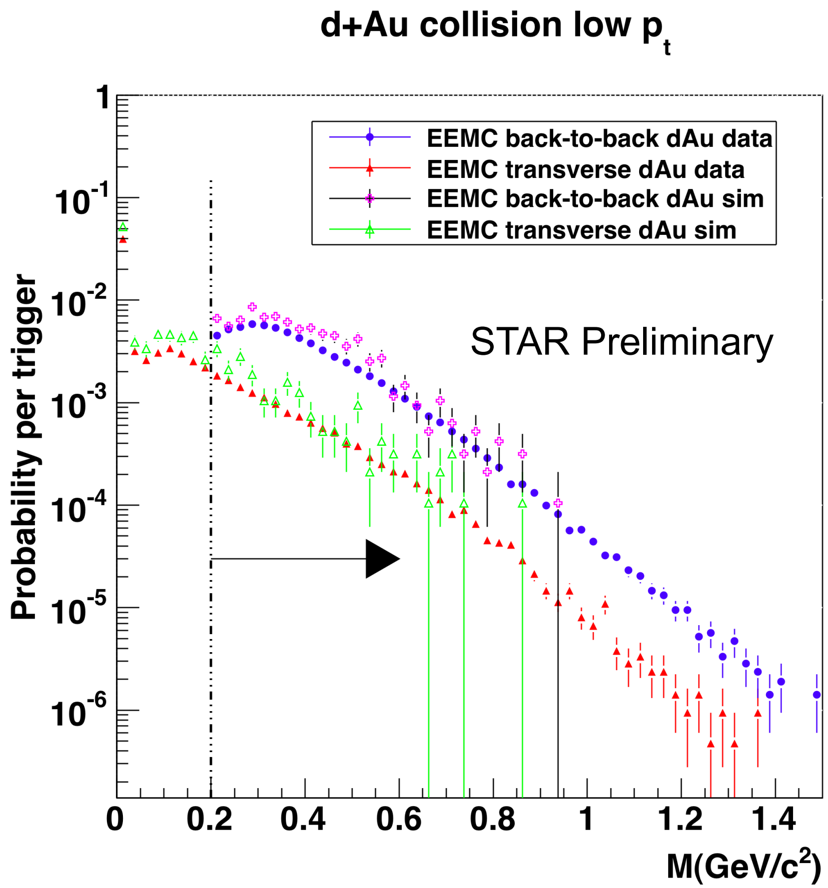
In back to back correlation (away side jet must remain [5π/6,7π/6]), define jet #1 direction is ϕ =0, then the regions [π/3,2π/3]and [4π/3,5π/3] are the underlying event study areas (transverse region).

The mass spectrum of the back-to-back jet-like cluster and the underlying events in the EEMC

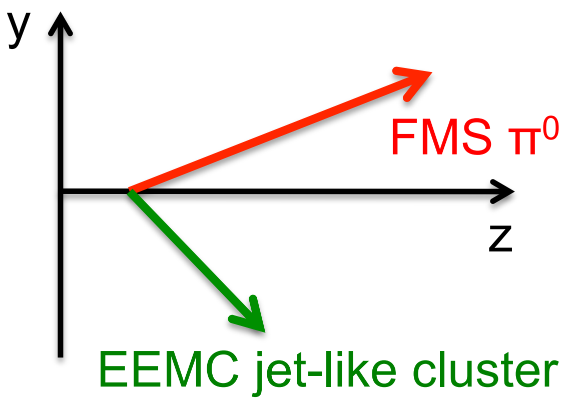
- Data and simulation comparison under the condition: FMS π^0 (p_t^{FMS}>2.0GeV/c), the back-to-back EEMC jet-like cluster(1.0GeV/c<p_t^{EEMC}<p_t^{FMS},M>0.2GeV/c^2) and the underlying events (no M cut and no p_t cut).

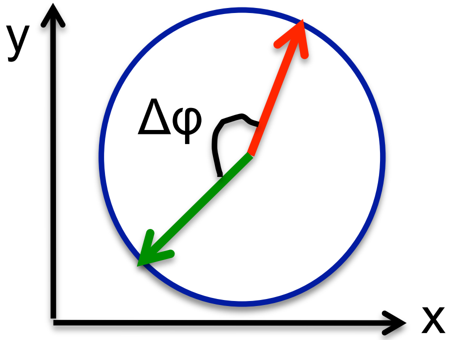
500MeV tower threshold



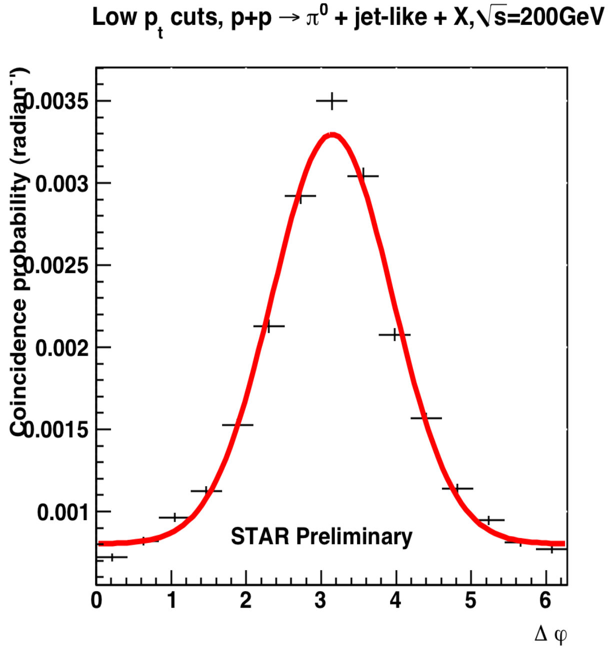


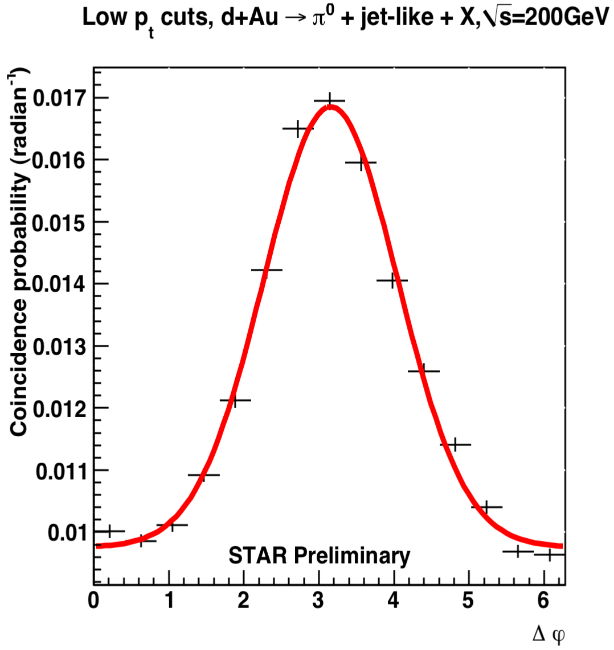
FMS (π^0)-EEMC (jet-like cluster) correlations (Low p_t)





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





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

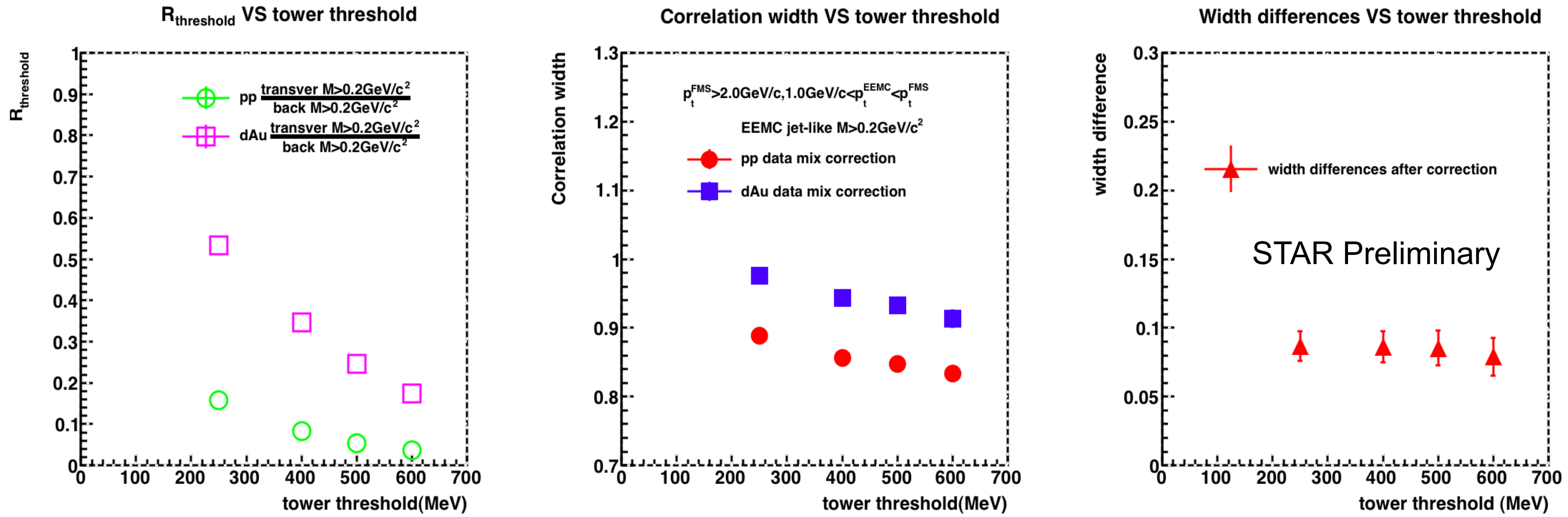
- $\sigma_{pp} = 0.80 \pm 0.01$, $\sigma_{dAu} = 0.89 \pm 0.02$
- $A_{1pp} = 0.005$, $A_{1dAu} = 0.016$
- $b_{pp} = 0.0008$ and $b_{dAu} = 0.0097$

- To suppress underlying event contribution, we use 600MeV tower threshold for the EEMC and 0.4GeV/c^2 as the lower mass limit for the reconstructed jet-like cluster.
- $\sigma_{dAu} - \sigma_{pp} = 0.10 \pm 0.02^{+0.04}_{-0.02}$ Significant broadening from p+p to d+Au.

The correlation results on the tower threshold dependence

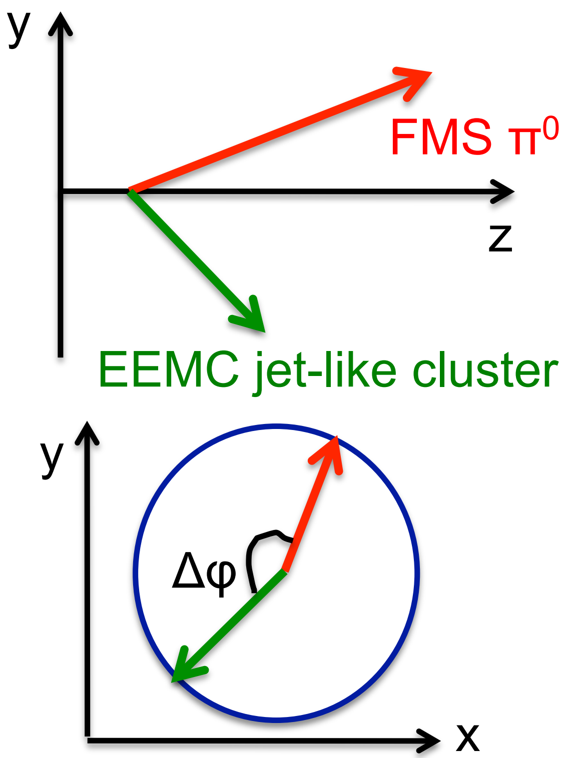
- The EEMC tower thresholds are selected from 250MeV, 400MeV, 500MeV to 600MeV. Results are after mixed event corrections. Fit function is $G(x) = b + \frac{A_1}{\sqrt{2\pi}\sigma}\exp(\frac{1}{2}(\frac{x-A_2}{\sigma})^2)$, σ is defined as width.

$$R_{threshold} = \frac{\int_{0.2GeV/c^2}^{\infty} dN/dM_{underly}}{\int_{0.2GeV/c^2}^{\infty} dN/dM_{jet}}$$

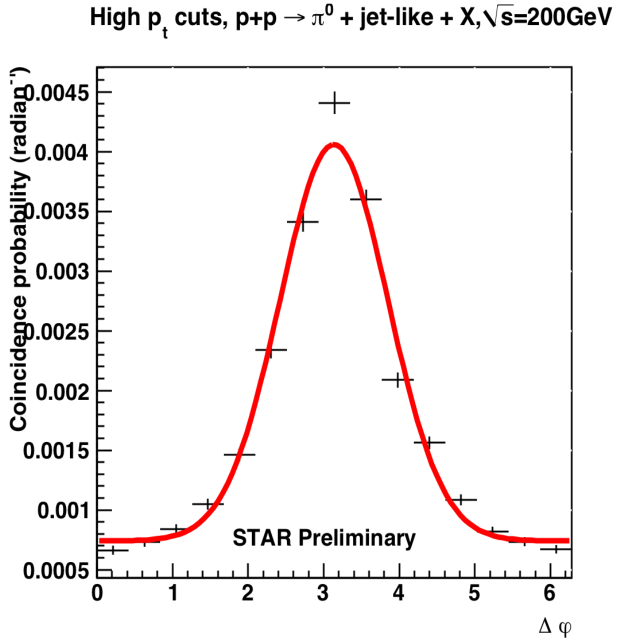


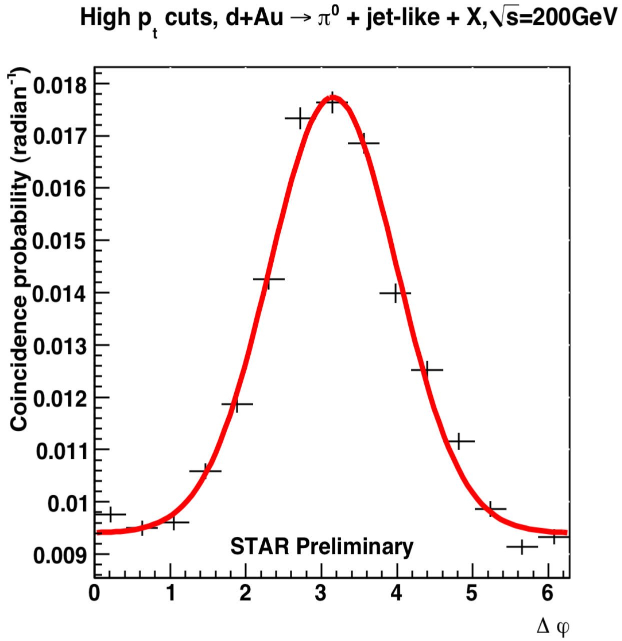
- The different tower thresholds do not impact on the width differences between pp and dAu much.

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



$P_T(FMS) > 2.5$ GeV/c ; 1.5 GeV/c < $P_T(EEMC) < P_T(FMS)$





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

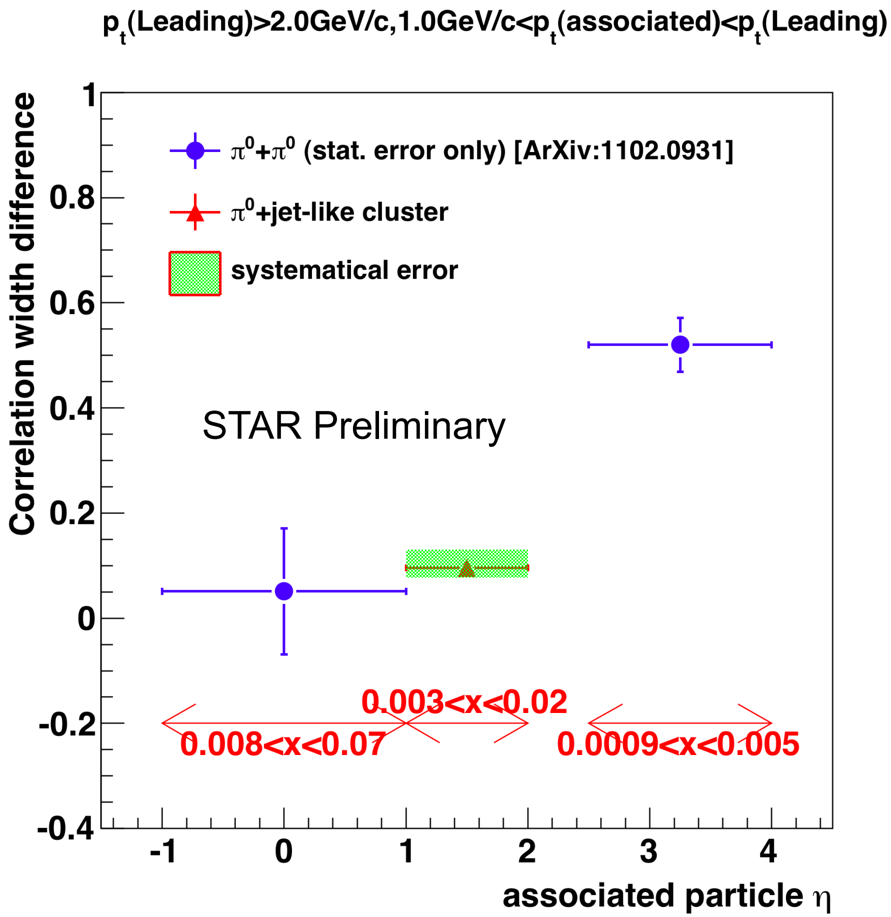
- $\sigma_{pp} = 0.71 \pm 0.01$, $\sigma_{dAu} = 0.84 \pm 0.02$
- $A_{1pp} = 0.006$, $A_{1dAu} = 0.018$
- $b_{pp} = 0.0007$, $b_{dAu} = 0.0094$

- To suppress underlying event contribution, we use 600MeV tower threshold for the EEMC and 0.4GeV/c^2 as the lower mass limit for the reconstructed jet-like cluster.
- $\sigma_{dAu} - \sigma_{pp} = 0.13 \pm 0.02^{+0.03}_{-0.02}$ Significant broadening from p+p to d+Au.

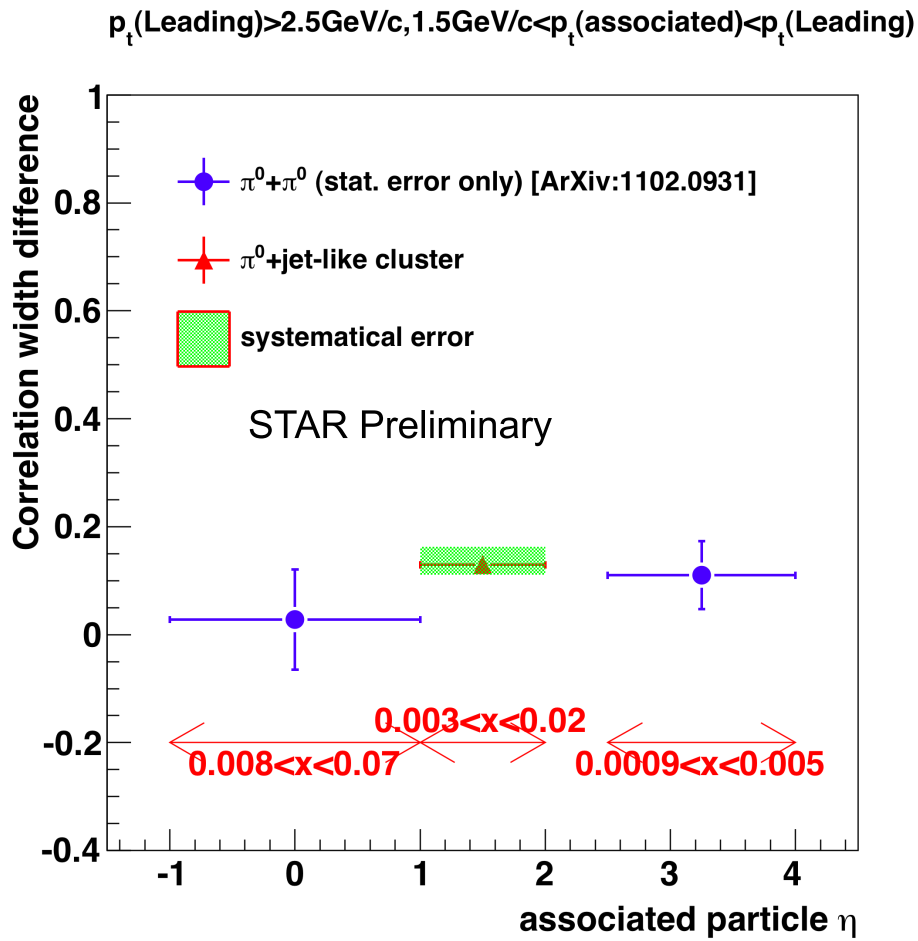
Summary on the correlation peak

- Compare the width differences from p+p to d+Au collisions for different di-hadron correlations.

Low p_t

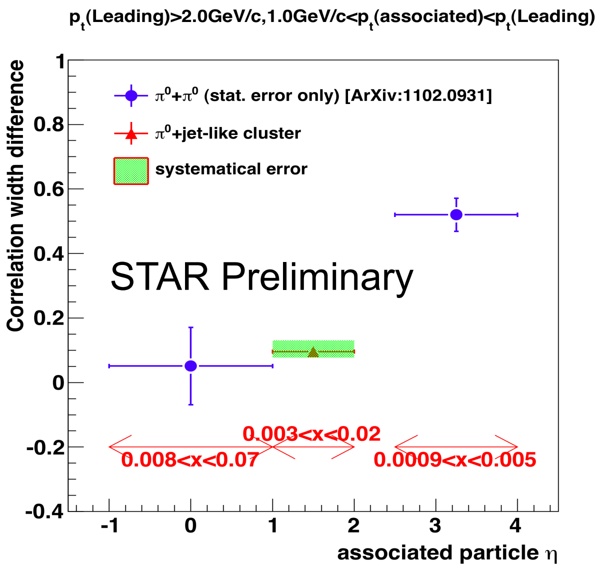


High p_t

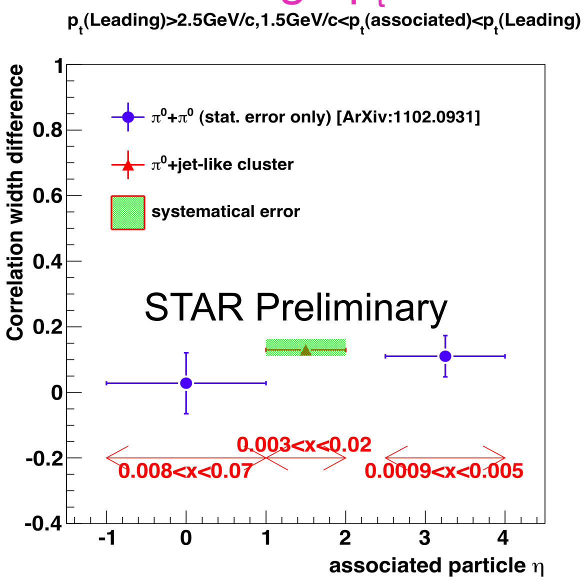


Summary on the correlation peak

Low p_t

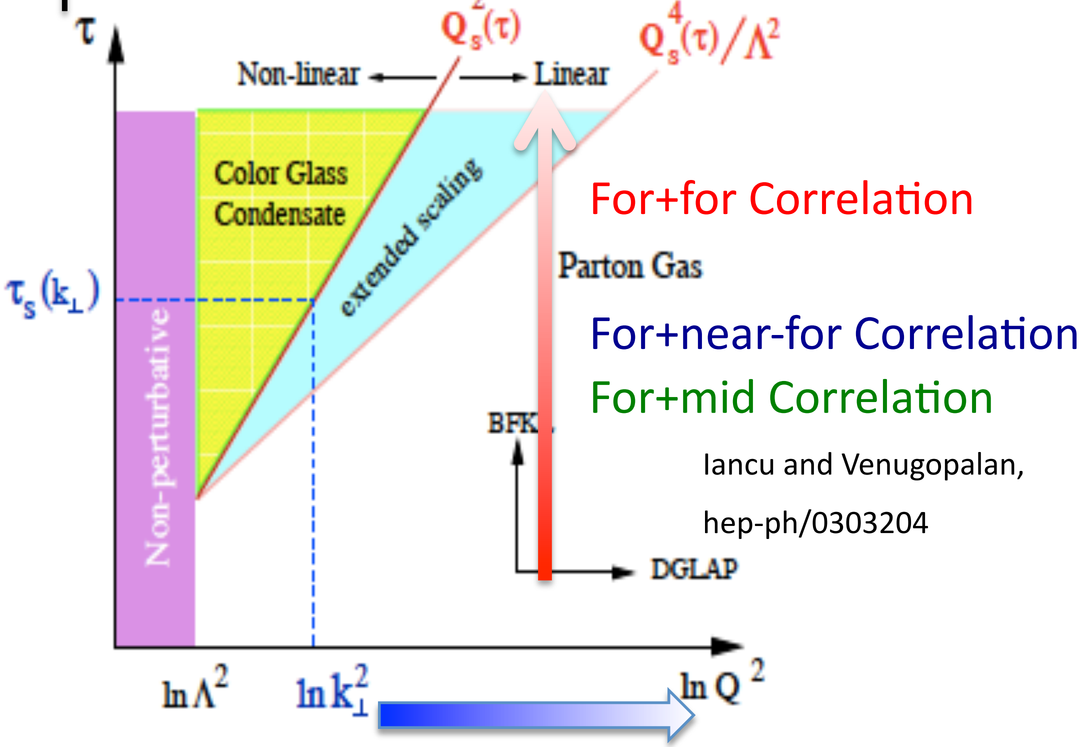


High p_t



$\ln(\frac{1}{x})$ $\quad x \sim \frac{2p_T}{\sqrt{s}} e^{-y}$ $\quad Q_s^2(x) \sim A^{1/3} e^{\lambda y}$

y = rapidity, λ = 0.3

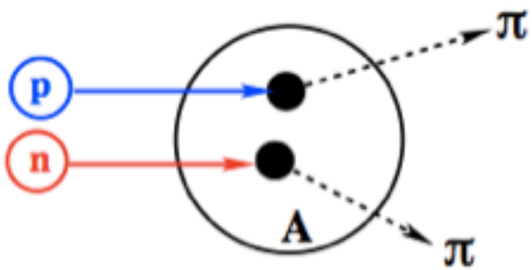


Iancu and Venugopalan, hep-ph/0303204

Not only x dependence but also Q^2 dependence.

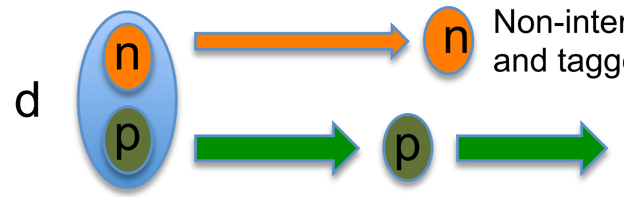
- Evolution of results in assoc particle η is consistent with a smooth transition from dilute parton system to Color Glass Condensate state (or saturation).

Tagging Spectator Neutrons from Deuteron Beam as p+Au approach



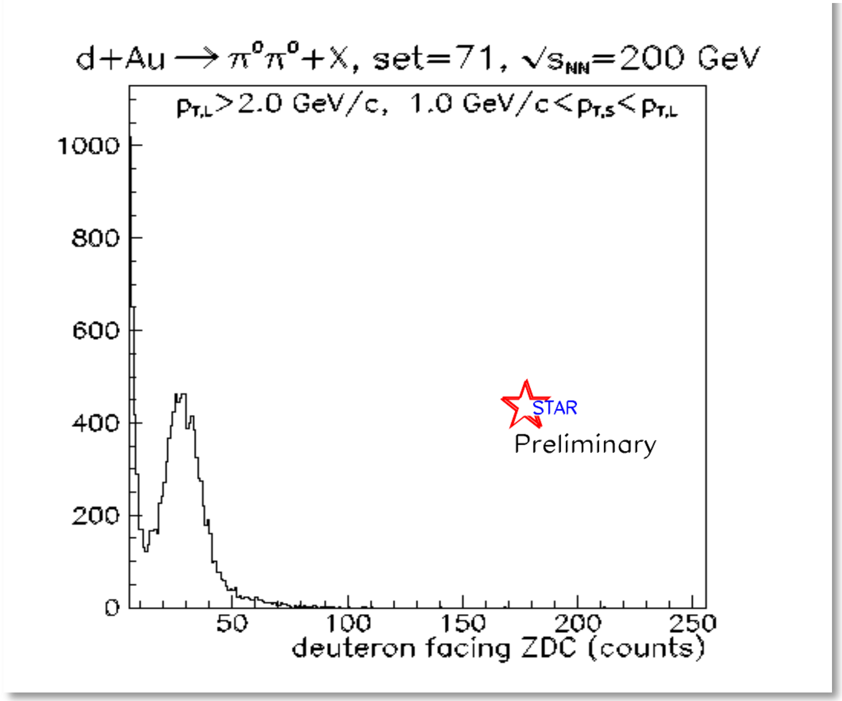
M. Strikman, W.Vogelsang
Phys.Rev.D 83,034029, 2011

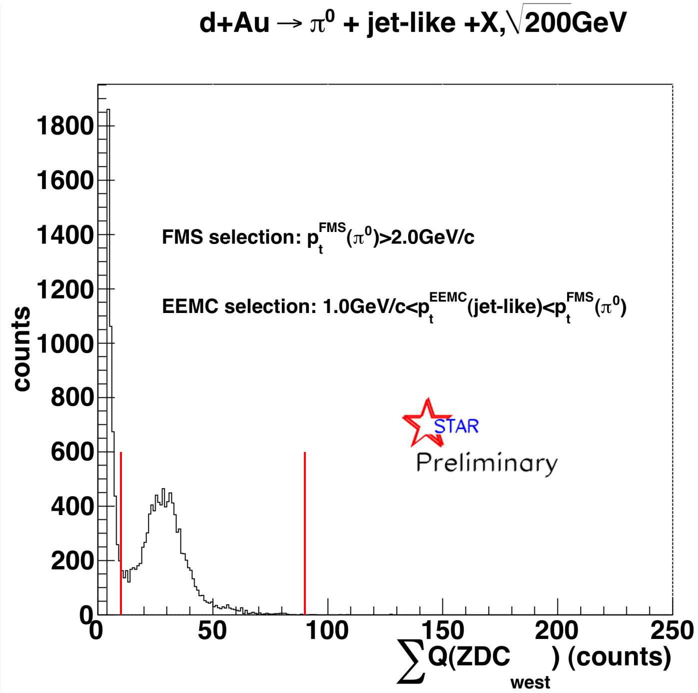
Independent double parton scattering only contributes to the correlation pedestal.



Tag non-interacting neutron in deuteron in d+Au collision as p+Au approach.

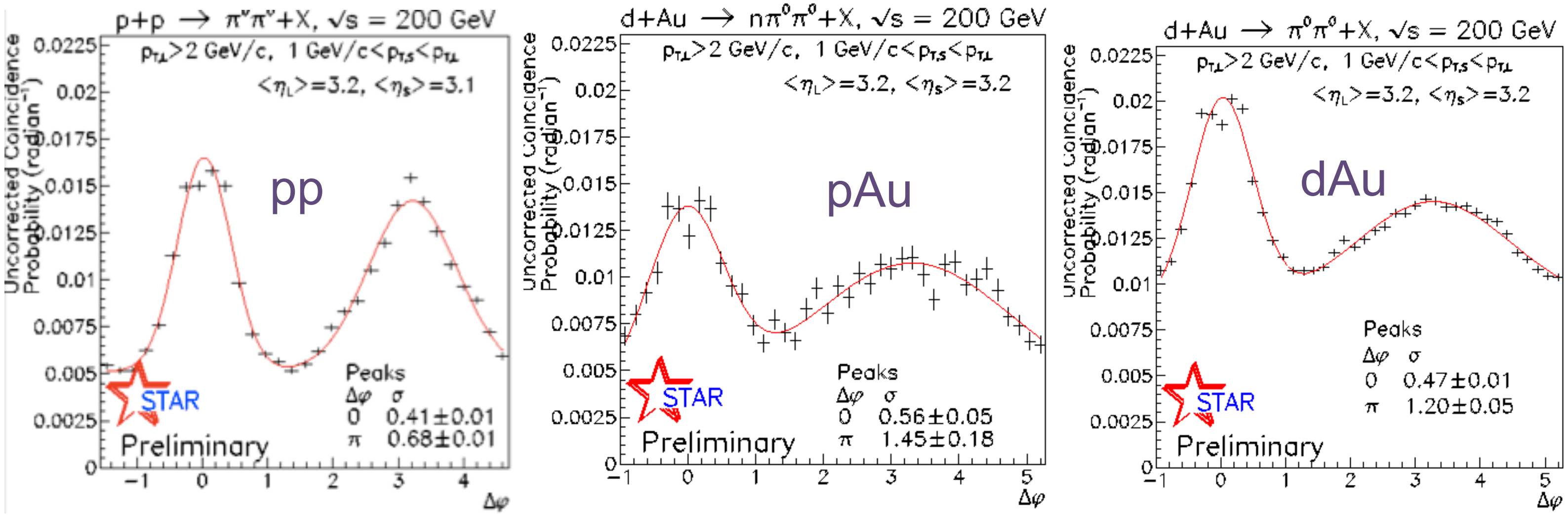
Deuteron-facing (West) ZDC Response





- Clear neutron peak in deuteron-facing ZDC in d+Au collisions.

Results in p+Au approach

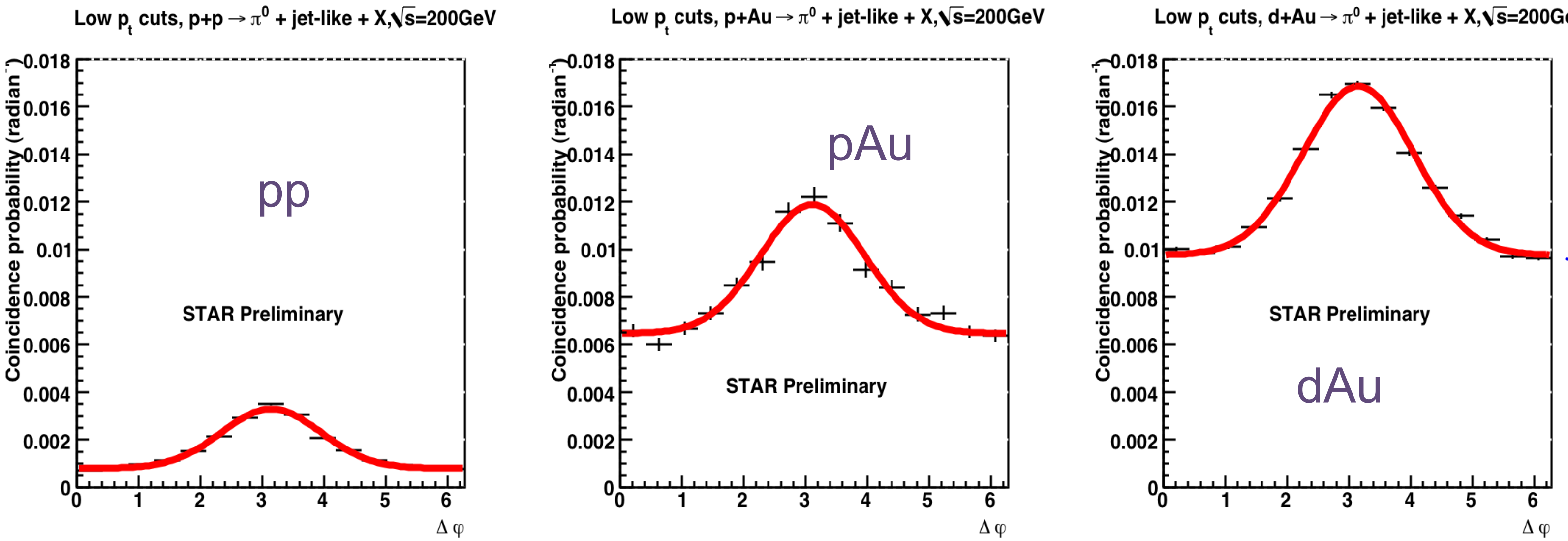


FMS π^0 - FMS π^0 correlations

p_t^{FMS1}>2.0GeV/c.

1.0GeV/c<p_t^{FMS2}< p_t^{FMS1}

ArXiv:1109.0649



FMS π^0 – EEMC jet-like cluster correlations

p_t^{FMS}>2.0GeV/c.

1.0GeV/c<p_t^{EEMC}< p_t^{FMS}.

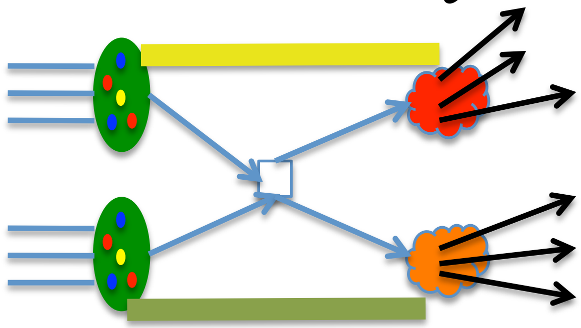
- Multi-parton interactions appear to contribute to the pedestal in d+Au collisions but less significantly to p+Au collisions.

Summary

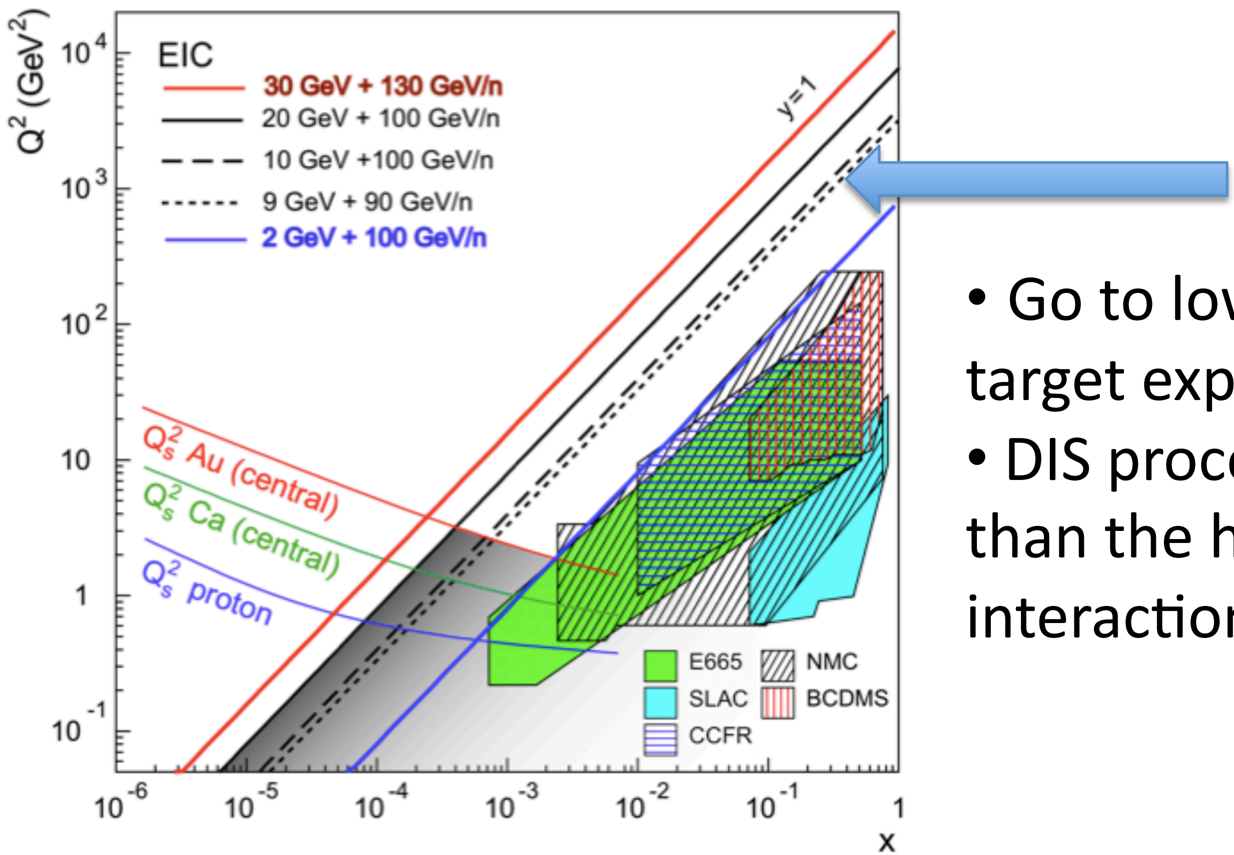
- Significant broadening from p+p to d+Au collisions for the FMS π^0 – EEMC jet-like cluster correlation peak width.
- Comparisons of p+Au to d+Au suggest independent double parton scattering is present in d+Au, affecting only the azimuthal correlation pedestal.
- The rapidity dependences of the correlations 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)?

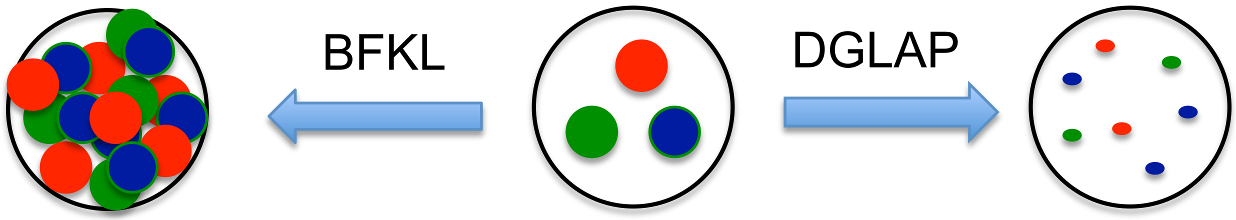


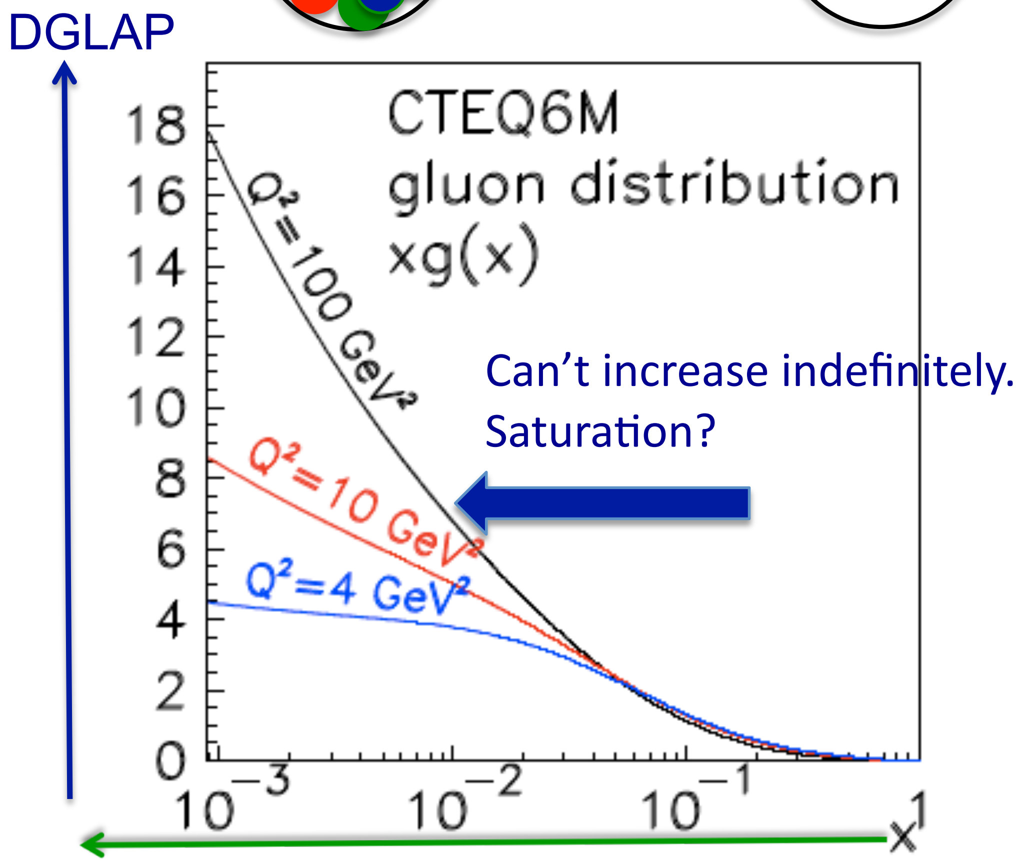
- Go to lower x than fixed target experiment.
- DIS process is much cleaner than the hadron-hadron interaction.

Backup

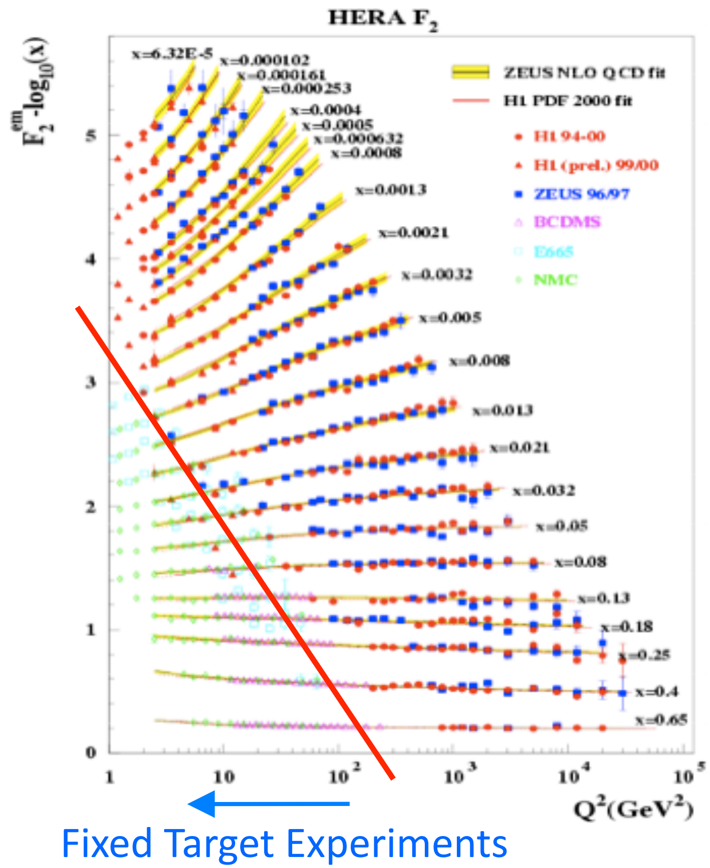
What does the nucleon parton distribution look like?

- The nucleon quark distribution is well known.



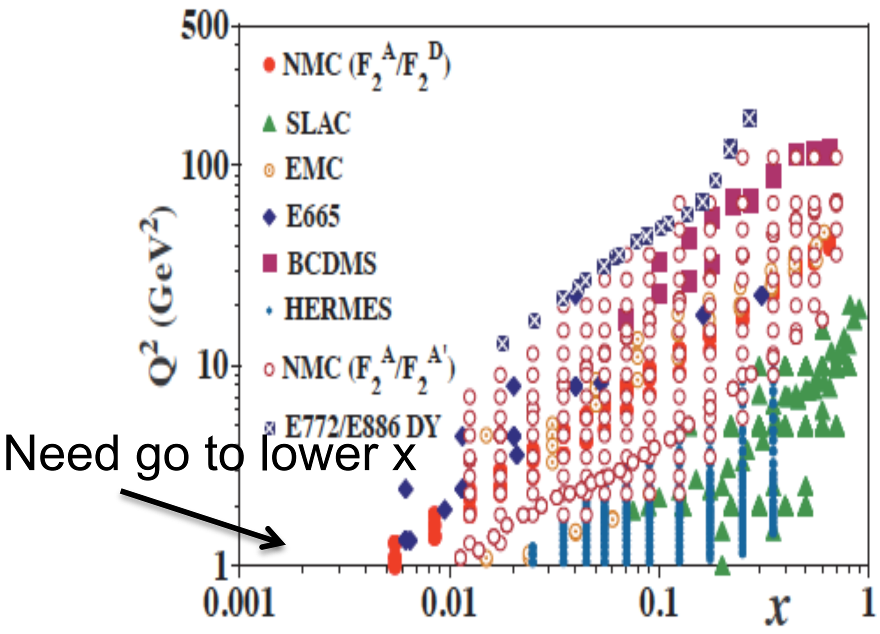


arxiv:hep-ph/0201195

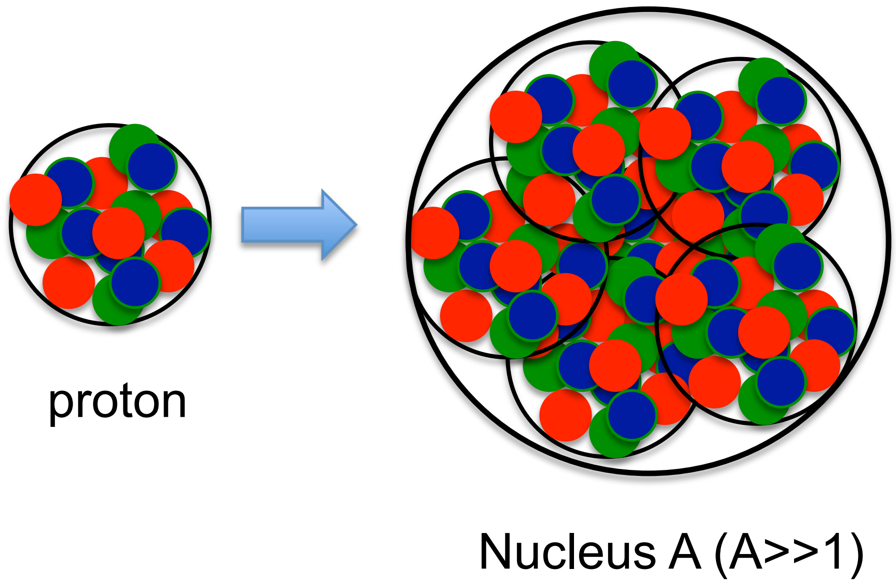


How about a larger nucleus?

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

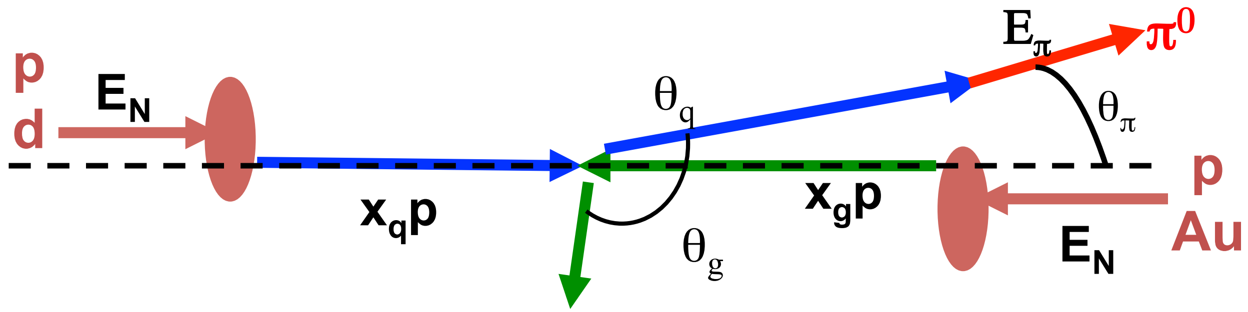


Current fixed target results
[Phys. Rev. C70 (2004)044905]



- 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.

Why do forward π^0 production in a hadron collider?



$$Q^2 \sim p_T^2 \qquad x_F \approx \frac{2E_\pi}{\sqrt{s}}$$

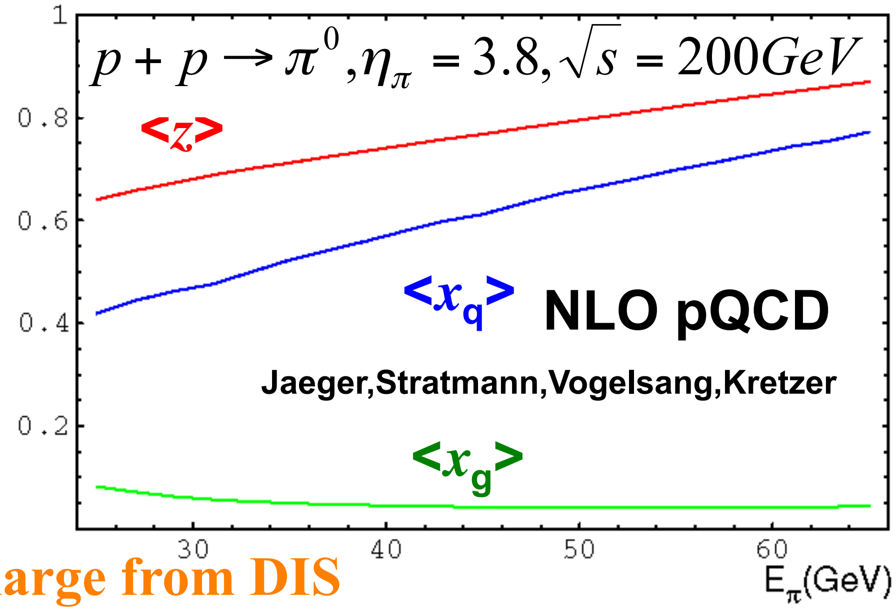
$$\sqrt{s} = 2E_N \qquad z = \frac{E_\pi}{E_q}$$

$$\eta = -\ln(\tan(\frac{\theta}{2}))$$

$$x_q \approx x_F / \langle z \rangle \qquad x_g \approx \frac{p_T}{\sqrt{s}} e^{-\eta_g}$$

(collinear approx.)

- **Large rapidity π production (η_π~4) probes asymmetric partonic collisions**
- Mostly **high-*x* valence quark** + **low-*x* gluon**
  - **$0.3 < x_q < 0.7$**
  - **$0.001 < x_g < 0.1$**
- $<z>$ nearly constant and high 0.7 ~ 0.8

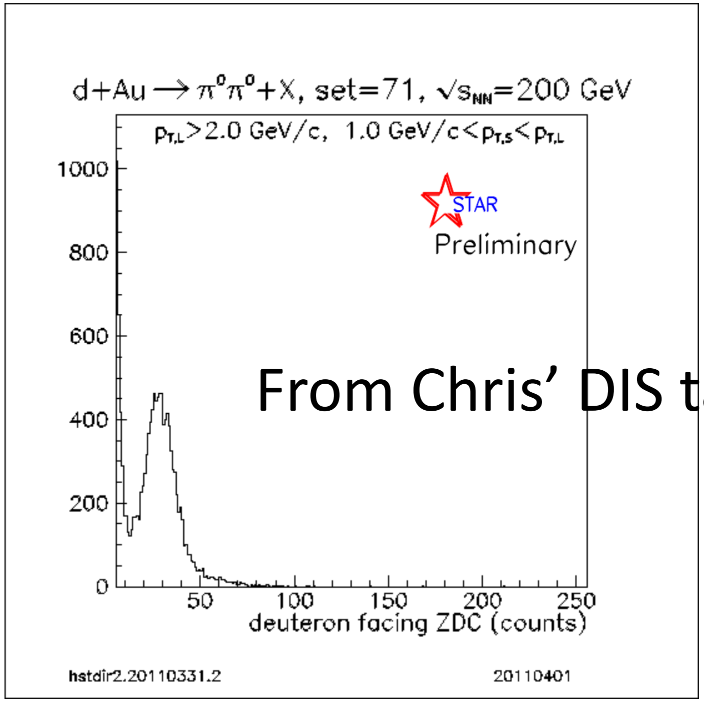


- **Large-*x* quark polarization is known to be large from DIS**
- **Directly couple to gluons ⇒ probe of low *x* gluons**

Tagging Spectator Neutrons from Deuteron Beam

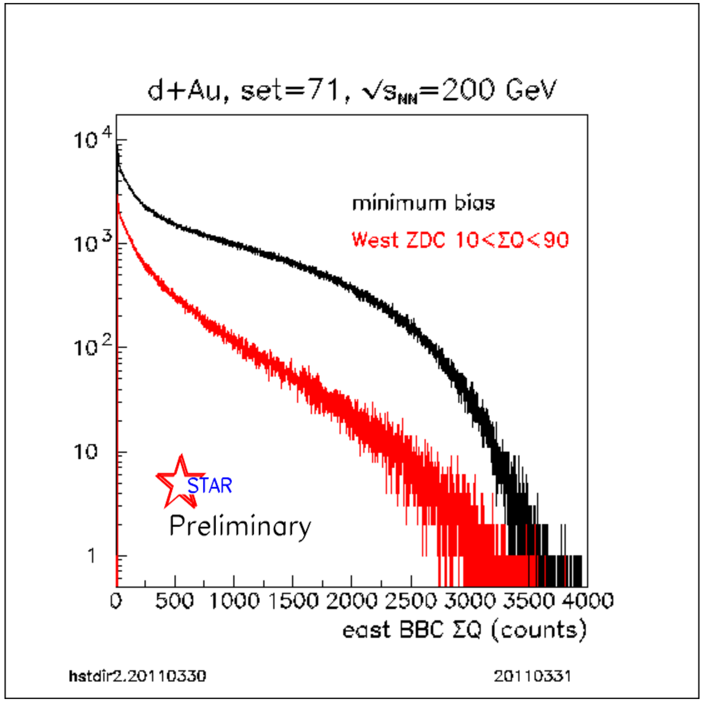
- It may also be useful to distinguish between p+Au and d+Au collisions by looking for events where the neutron in the deuteron remains intact

Deuteron-facing (West) ZDC Response



From Chris' DIS talk

Gold-facing (East) BBC Charge Sum

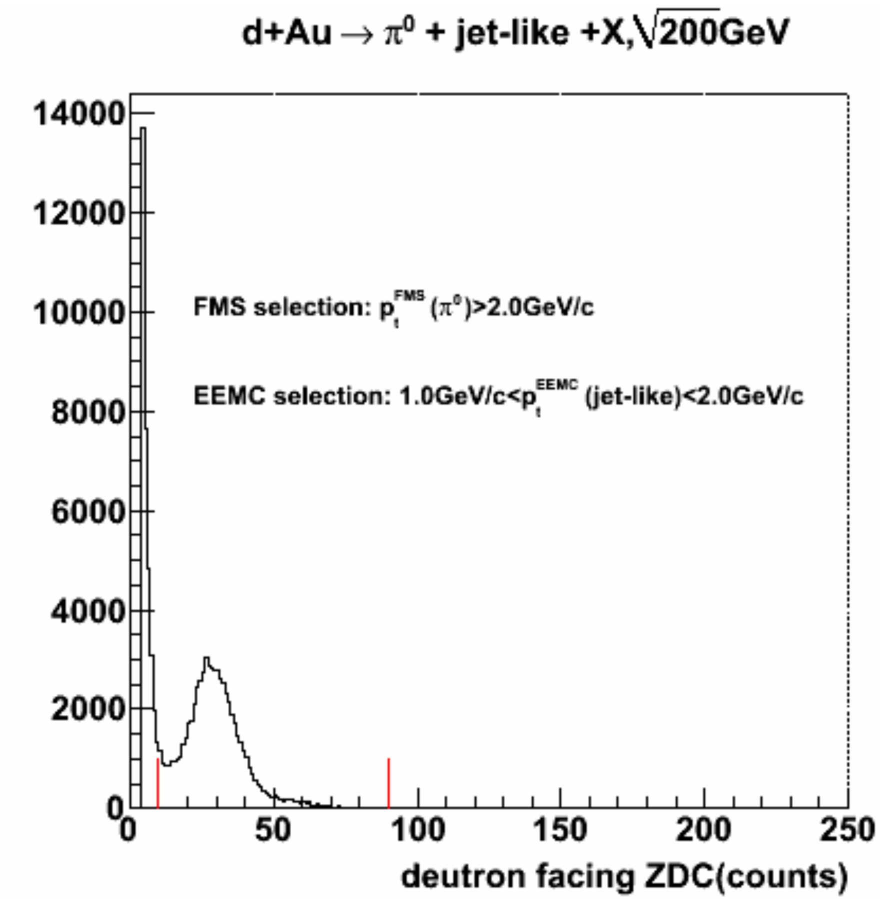


ArXiv:1109.0649

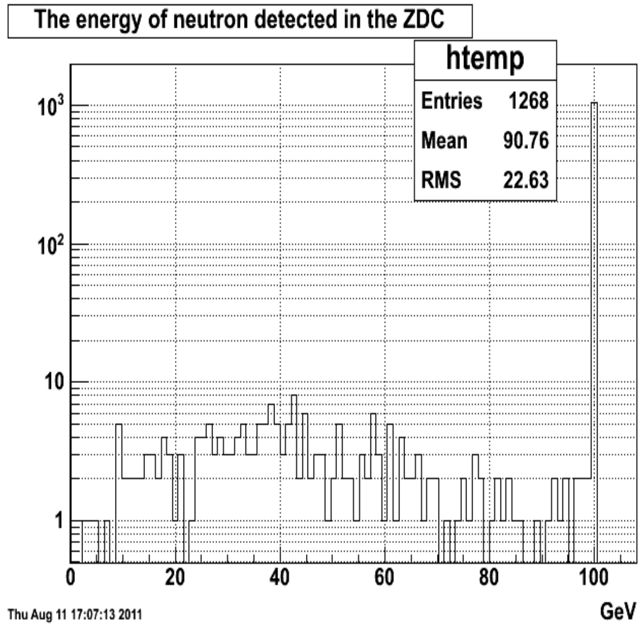
- Minimum Bias Run 8 d+Au Data
- Tag spectator neutrons using deuteron-facing (West) ZDC
- Clear single-neutron peak
- Cutting on single-neutron peak biases towards peripheral collisions

ZDC west neutron tag in deuteron beam

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



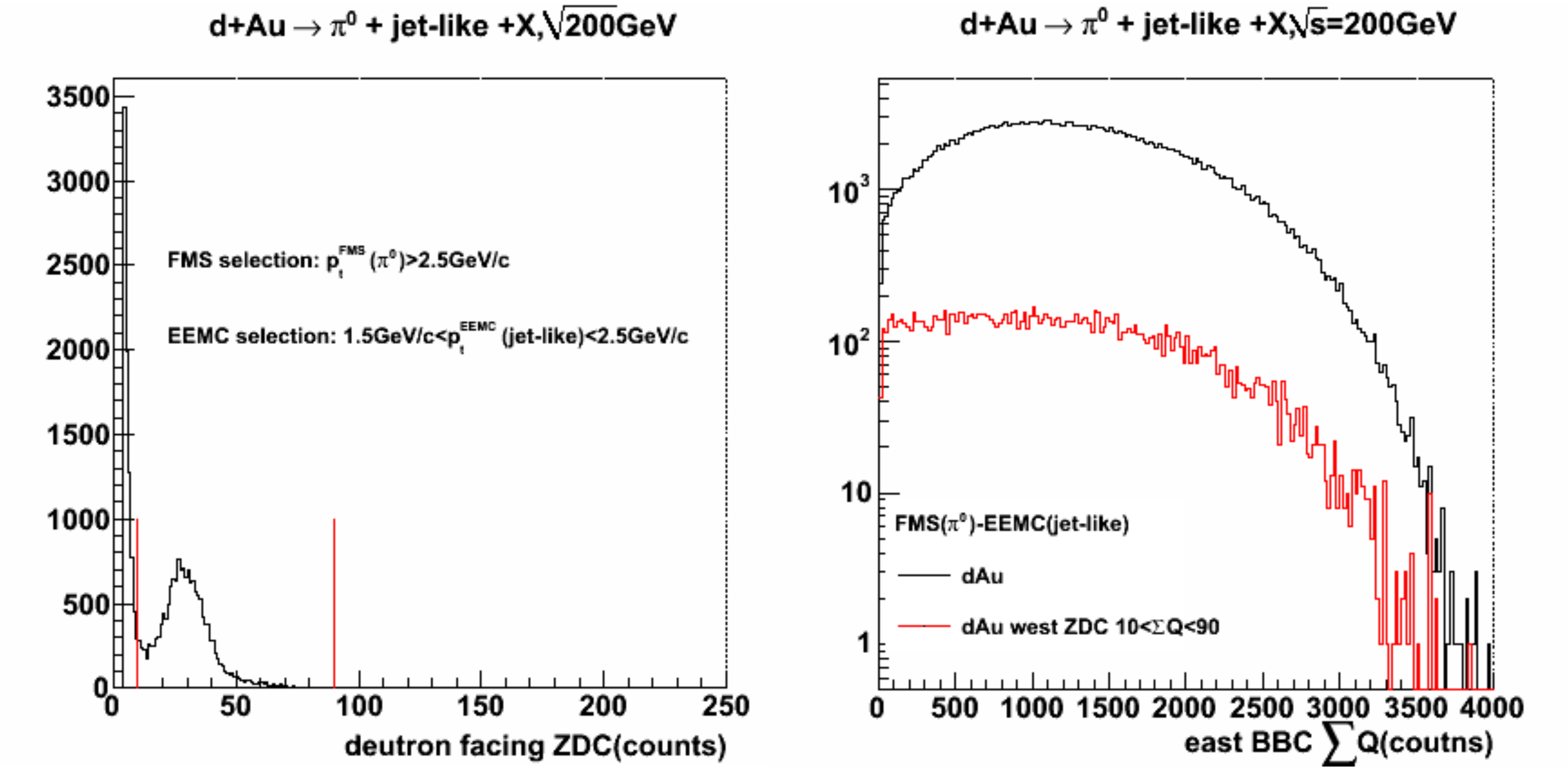
- In 200k dAu simulation with shadowing setup, using HIJING neutron and apply ZDC acceptance. With FMS π^0 p_t>2.0GeV/c trigger.



The ZDC neutron bump has photon background, but the ZDC neutron tag events are dominated by pAu collisions.

ZDC west neutron tag in deuteron beam

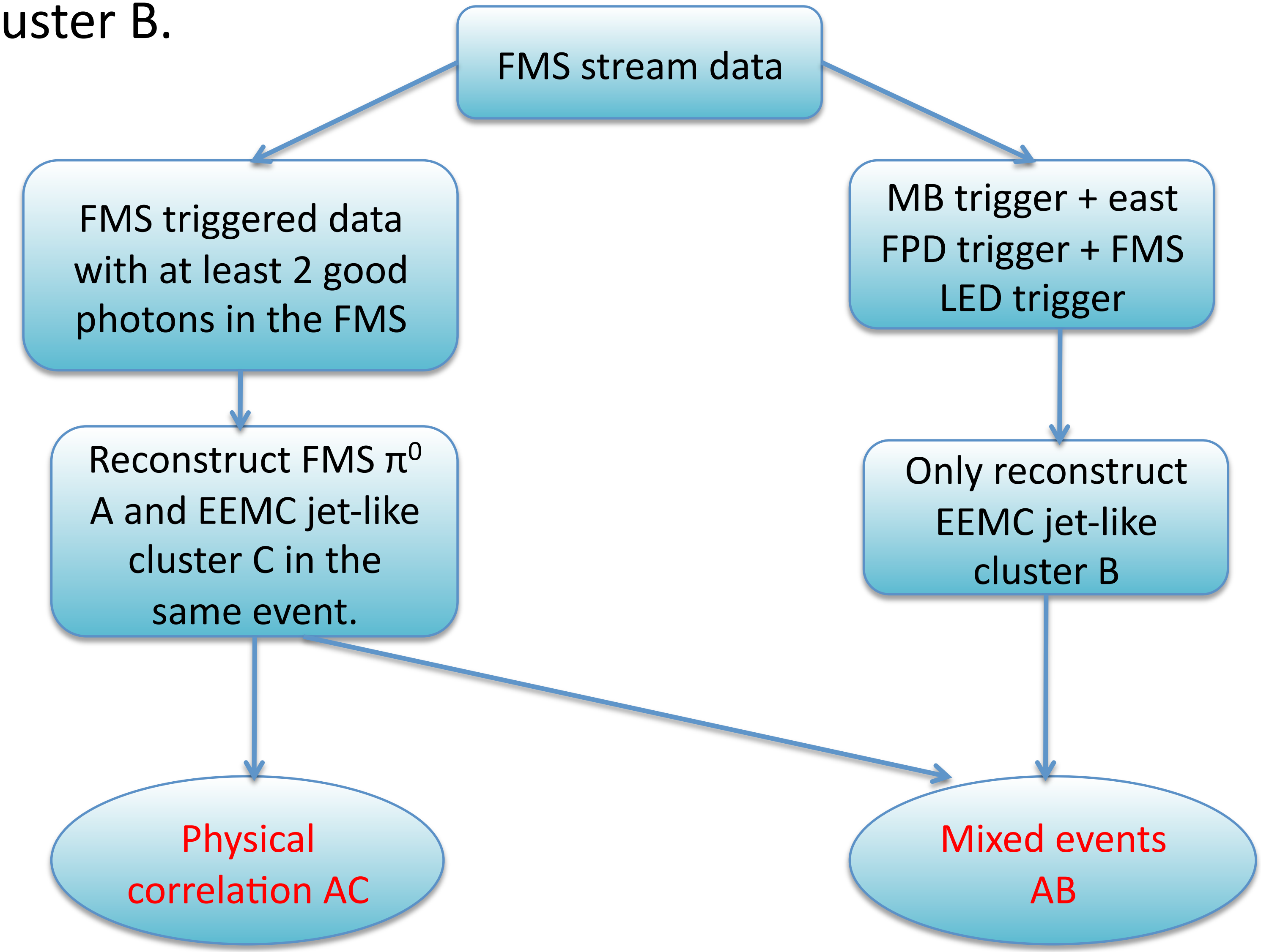
- dAu FMS π^0 and EEMC jet-like coincidence.



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

Mixed events studies

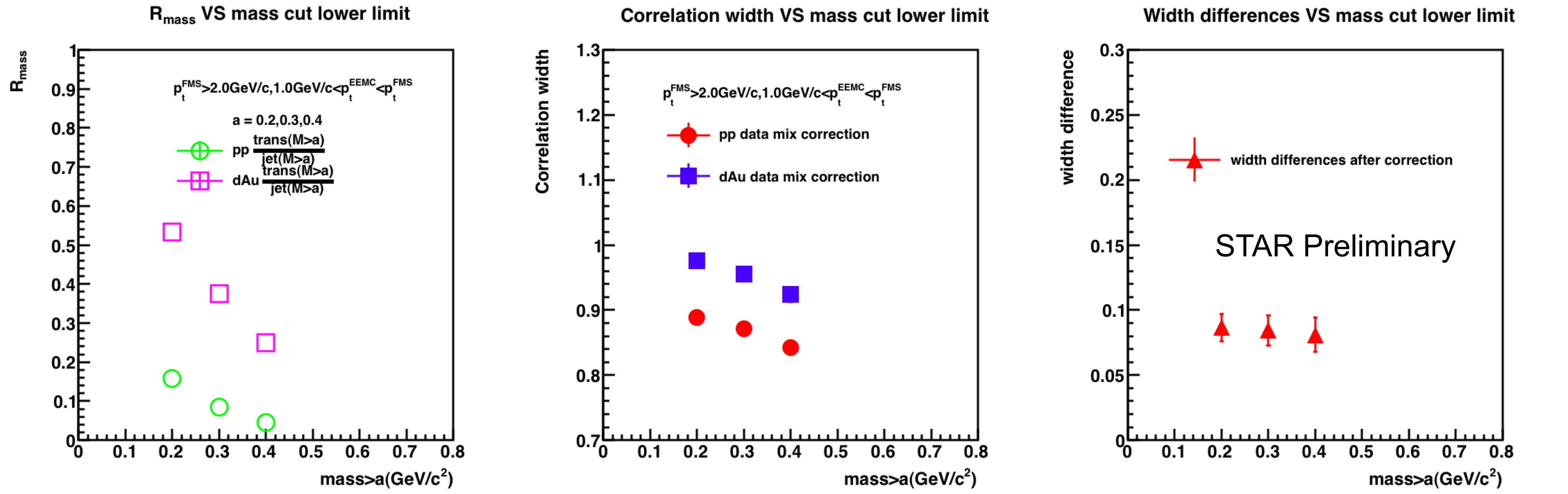
- Algorithm. The studies initially use MB data for EEMC jet-like cluster B.



The correlation results on the lower limit of the mass cut for the EEMC jet-like clusters

- The EEMC jet-like cluster lower limit of the mass cut a=0.2GeV/c², 0.3GeV/c² and 0.4GeV/c². Results are after mixed event corrections. Fit function is $G(x) = b + \frac{A_1}{\sqrt{2\pi}\sigma}\exp(\frac{1}{2}(\frac{x-A_2}{\sigma})^2)$ and σ is width.

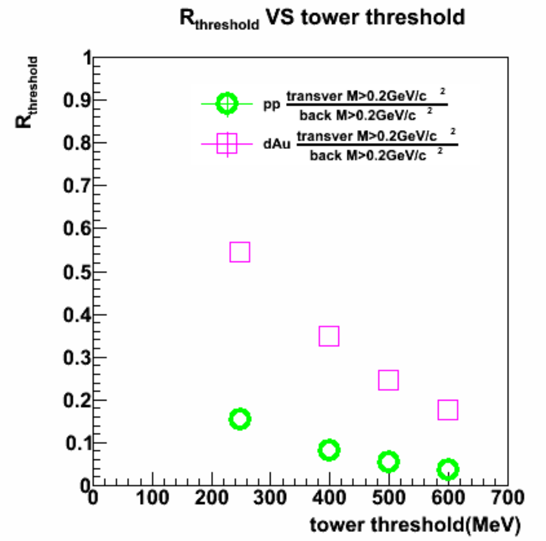
$$R_{mass} = \frac{\int_a^{\infty} dN/dM_{underly}}{\int_a^{\infty} dN/dM_{jet}}$$

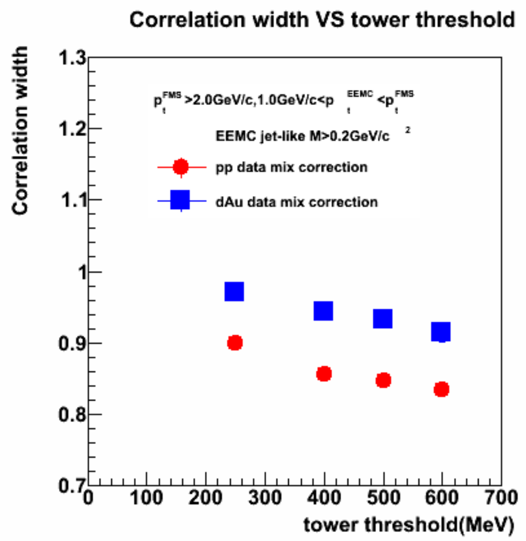


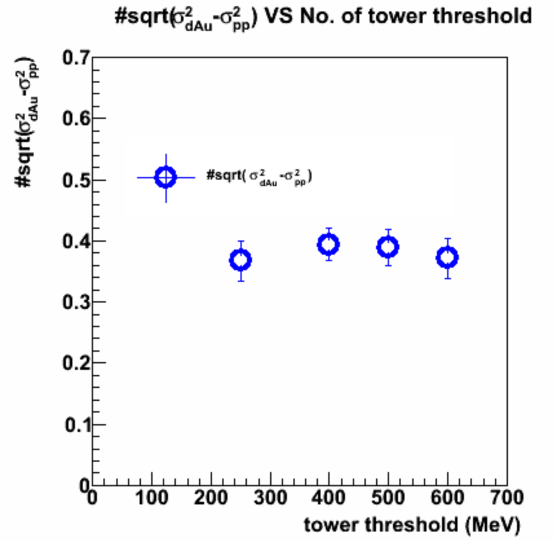
- The different mass lower limit cuts do not impact on the width differences between pp and dAu much.

Different form

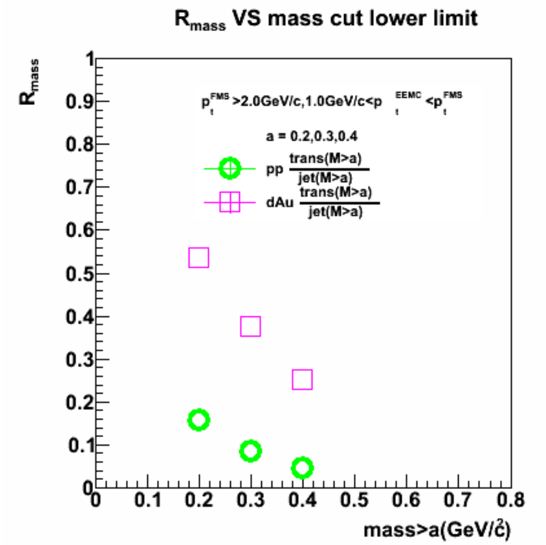
- Different EEMC tower threshold.

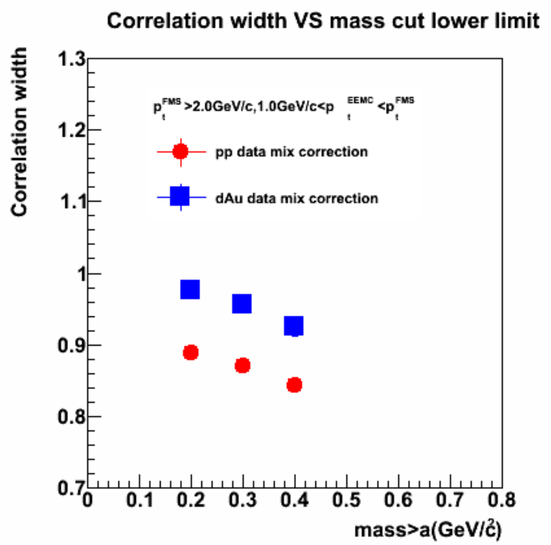


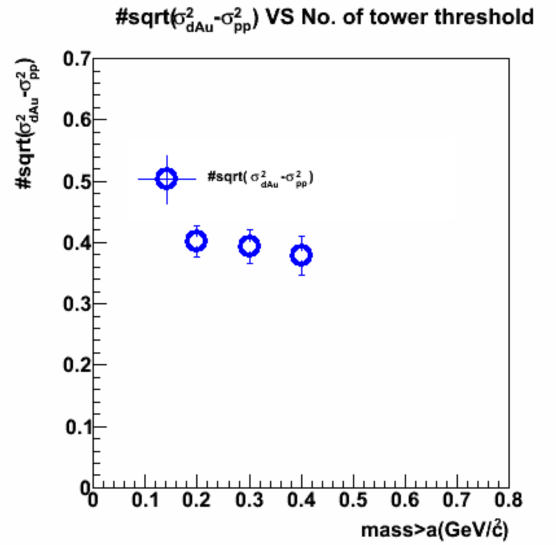




- Different low mass cut for EEMC jet-like cluster.

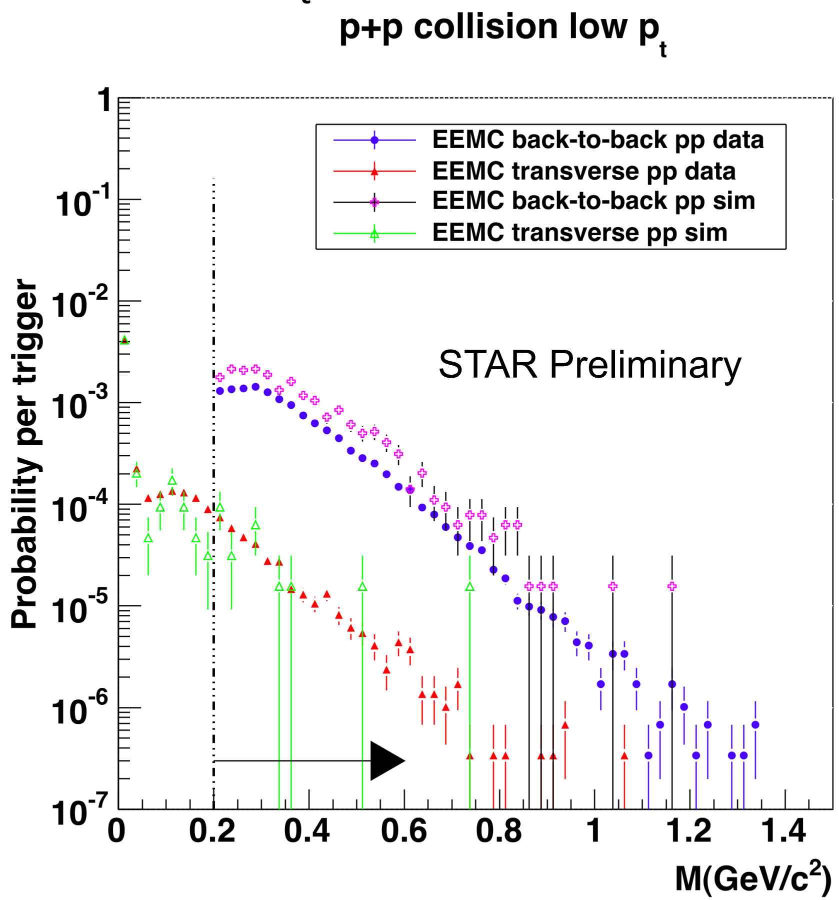


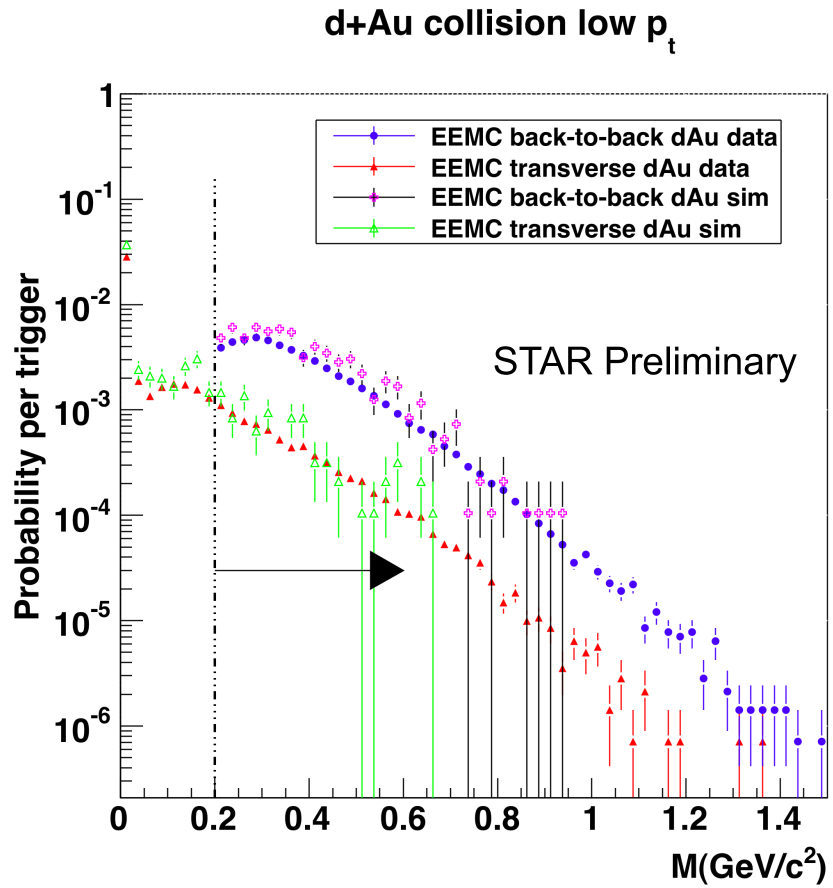




The mass spectrum of the back-to-back jet-like cluster and the underlying events in the EEMC

- Data and simulation comparison under the condition: FMS π^0 (p_t^{FMS}>2.0GeV/c), the back-to-back EEMC jet-like cluster(1.0GeV/c<p_t^{EEMC}<p_t^{FMS},M>0.2GeV/c^2) and the underlying events (no M cut and no p_t cut).   600MeV tower threshold





Systematic uncertainties on the width differences

- Systematic uncertainty sources:
  - (I) Cone radius R
  - (II) EEMC tower energy threshold
  - (III) Pseudo-rapidity cuts for the EEMC jet-like cluster
  - (IV) Mass cut lower limit for the EEMC jet-like cluster
- We change only one cut and fix the other cuts to see the systematic uncertainties.
  - Standard cuts: R=0.6, EEMC tower threshold 600MeV, jet-like cluster with $1.1<\eta<1.9$, and jet-like cluster mass lower limit 0.4GeV/c^2.

Systematic uncertainties

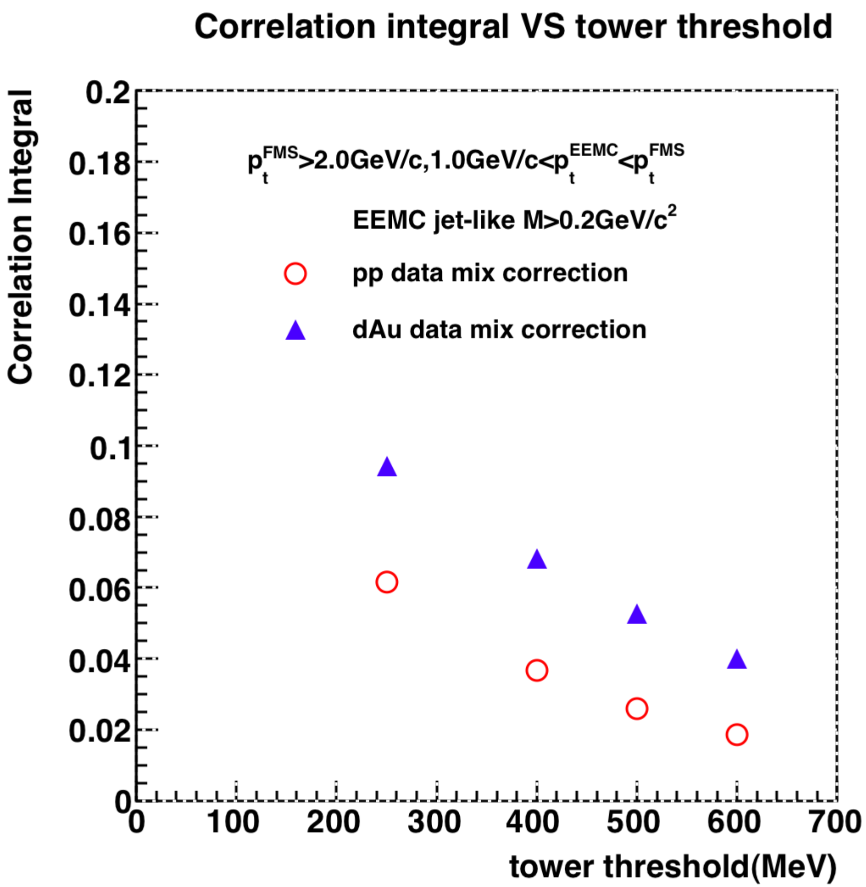
- Consider the four sources on previous slide.

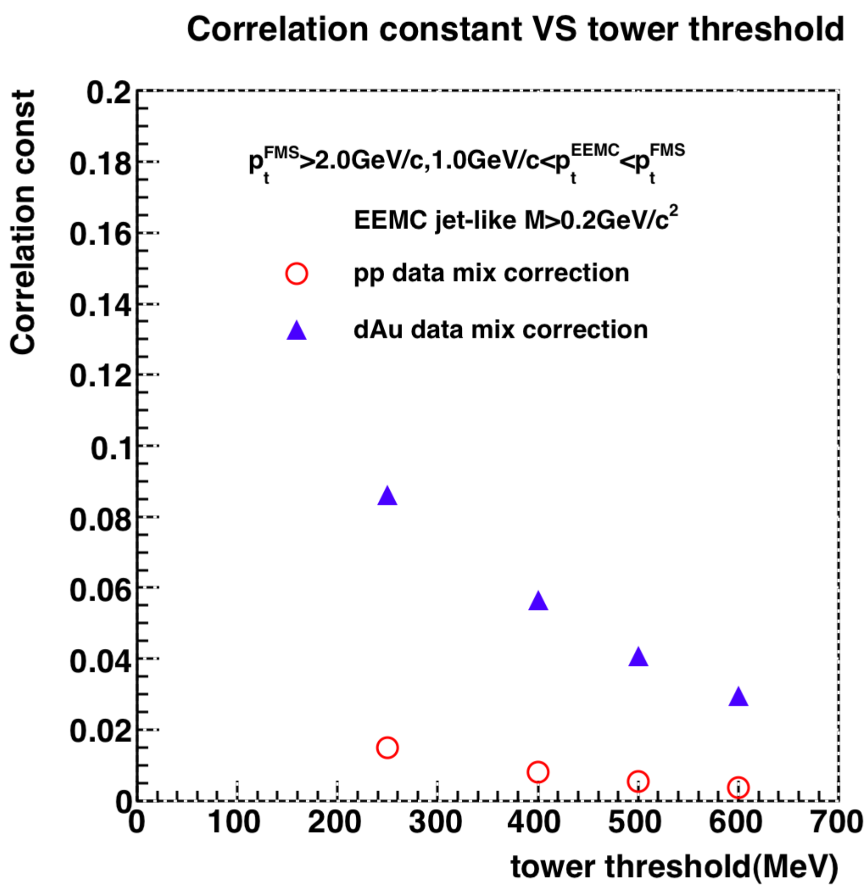
Item	Width differences $\Delta\sigma$ (low p_t)	Width differences $\Delta\sigma$ (high p_t)
standard	0.0957±0.0200	0.1295±0.0229
I	0.1163±0.0279	0.1107±0.0264
II	0.0770±0.0140	0.1242±0.0173
III	0.1308±0.0296	0.1428±0.0333
IV	0.0915±0.0224	0.1246±0.0220
systemactic	+ 0.0351 - 0.0187	+0. 0329 -0. 0188

- Based on the systematic studies shown above, the correlation width differences between p+p collisions and d+Au collisions for the coincidence probability of FMS π^0 and EEMC jet-like cluster are,
- $0.0957 \pm 0.0200^{+0.0351}_{-0.0187}$ with low pt cuts,
- $0.1295 \pm 0.0229^{+0.0329}_{-0.0188}$ with high pt cuts.

Reduce underlying event contribution impact on the fit constant value most

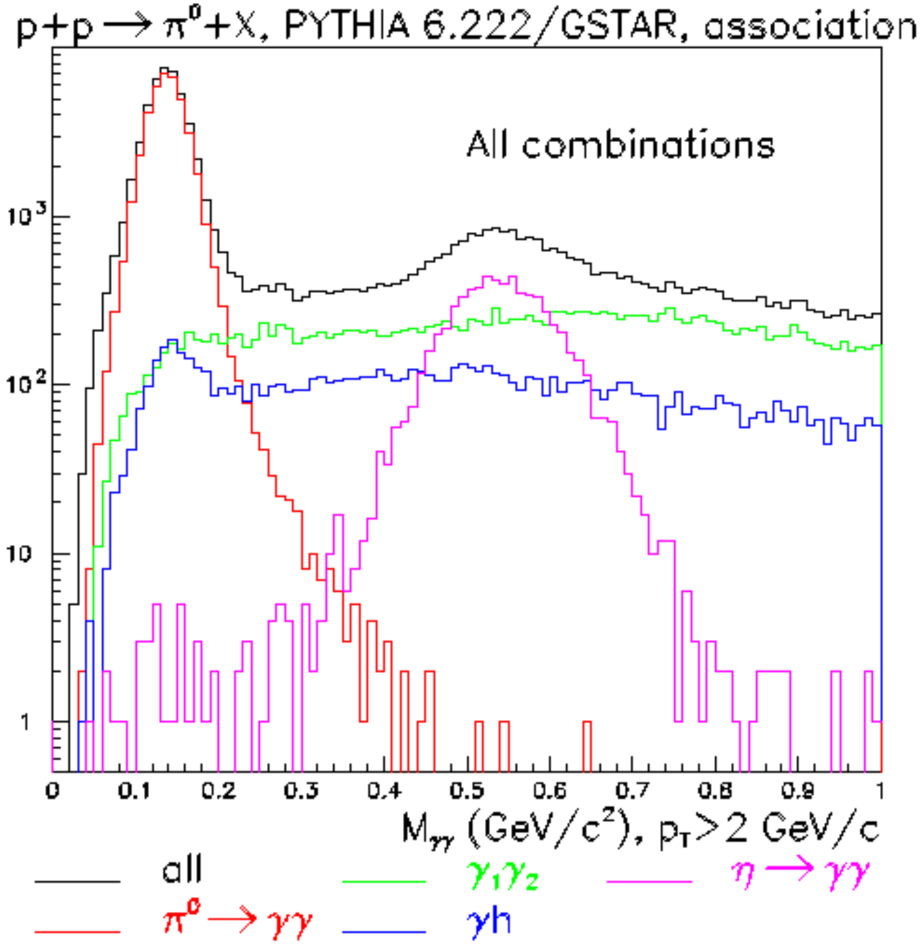
- For FMS π^0-EEMC jet-like cluster correlations.



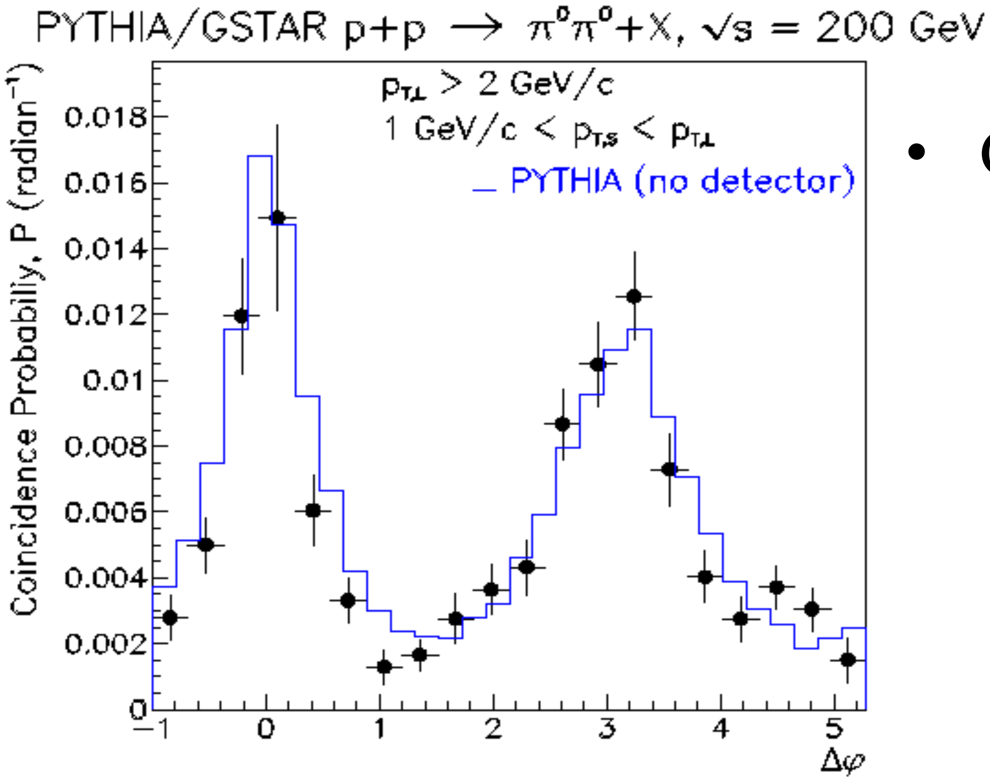


FMS π^0 background contribution

- In p+p full simulation, inclusive FMS π^0 mass.



Ongoing corrections on the forward+forward correlations



- Corrections are:
  - $\Delta\varphi$ dependent background subtraction.
  - $\Delta\varphi$ dependent efficiency correction.

- Test corrections in PYTHIA/GEANT for p+p ⟶ $\pi^0+\pi^0$.
- Good agreement with PYTHIA (no detector) information.