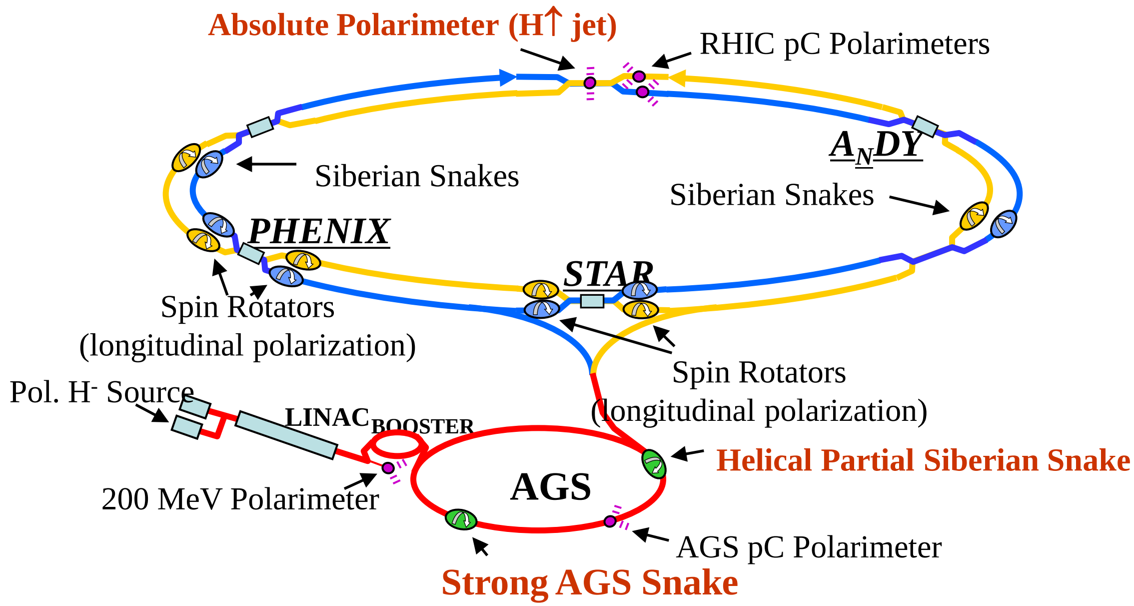
Forward Di-hadron Correlations in dAu Collisions at RHIC



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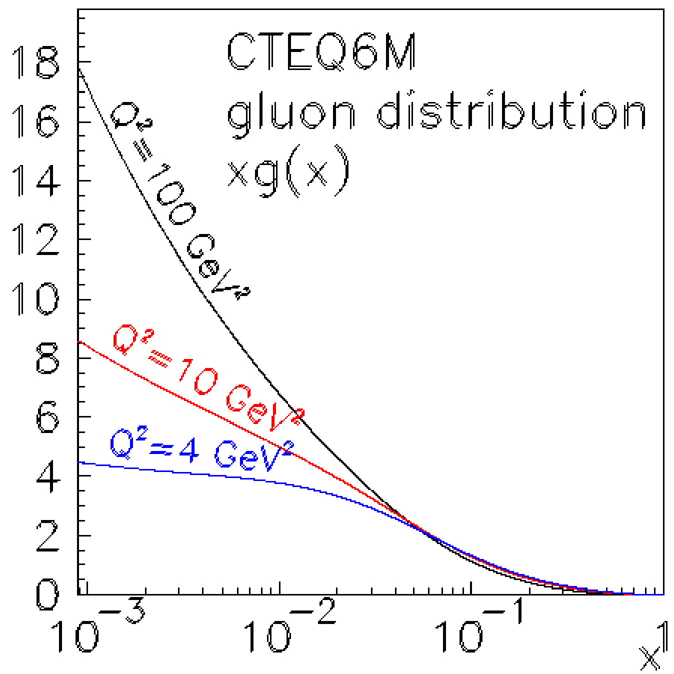
Brookhaven National Laboratory

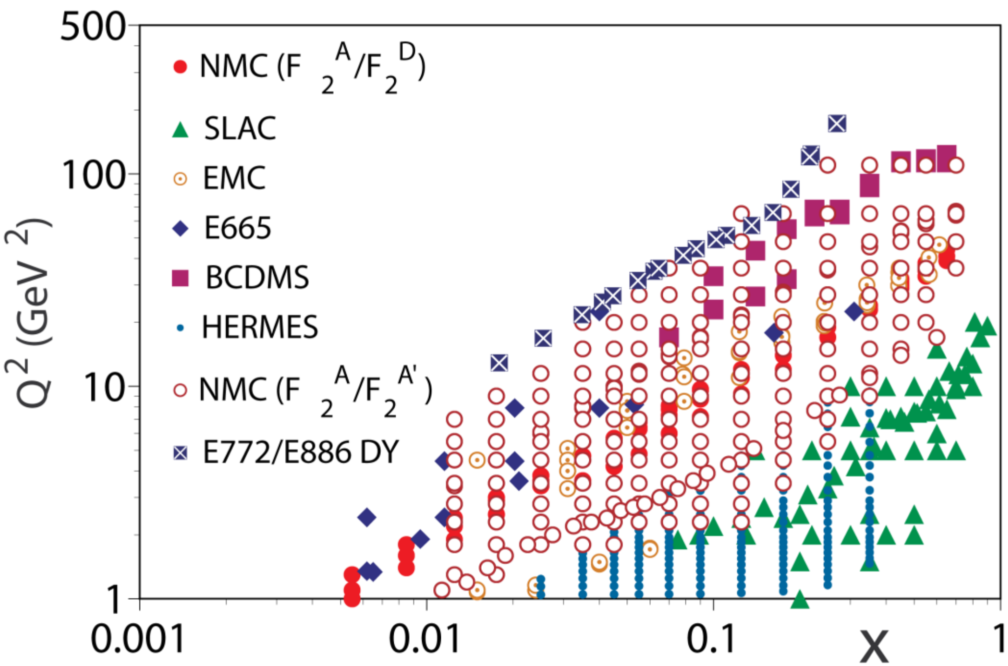
High p_T Physics at LHC, Wuhan

21 October 2012

Deep Inelastic Scattering from Nuclear Targets

Kinematic Coverage Restricted to Fixed Target Experiments (no EIC, yet)

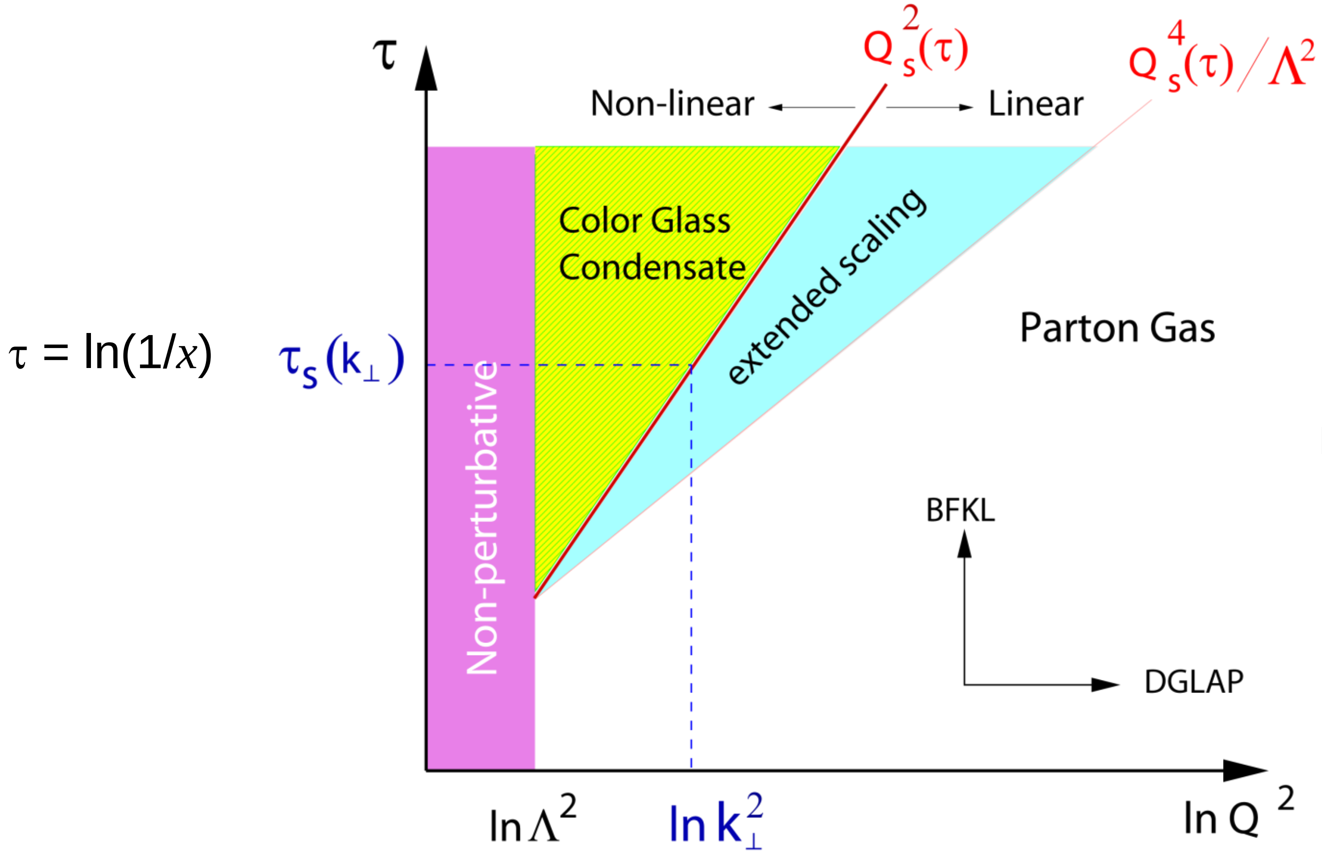




From Hirai, Kumono, Nagai PRC **70** (2004) 044905, and references therein

- Growth of gluon distribution at low-x within the proton cannot continue forever
- Gluon density in nucleus only known to x~0.02 since $g(2x) \sim \partial F_2(x,Q^2)/\partial \ln(Q^2)$

Gluon Saturation and the Color Glass Condensate

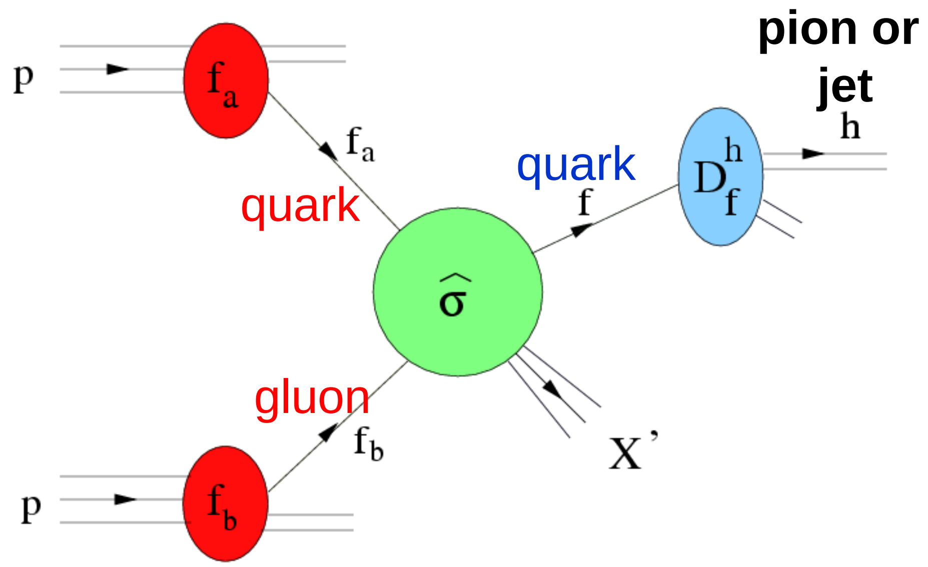


Iancu, Venugopalan
hep-ph/0303204

- Does the low-x gluon density saturate, and is this a high-energy phase of matter?
- Would a Color Glass Condensate be universal for both nuclear DIS and hadronic probes of nuclei at high energy?

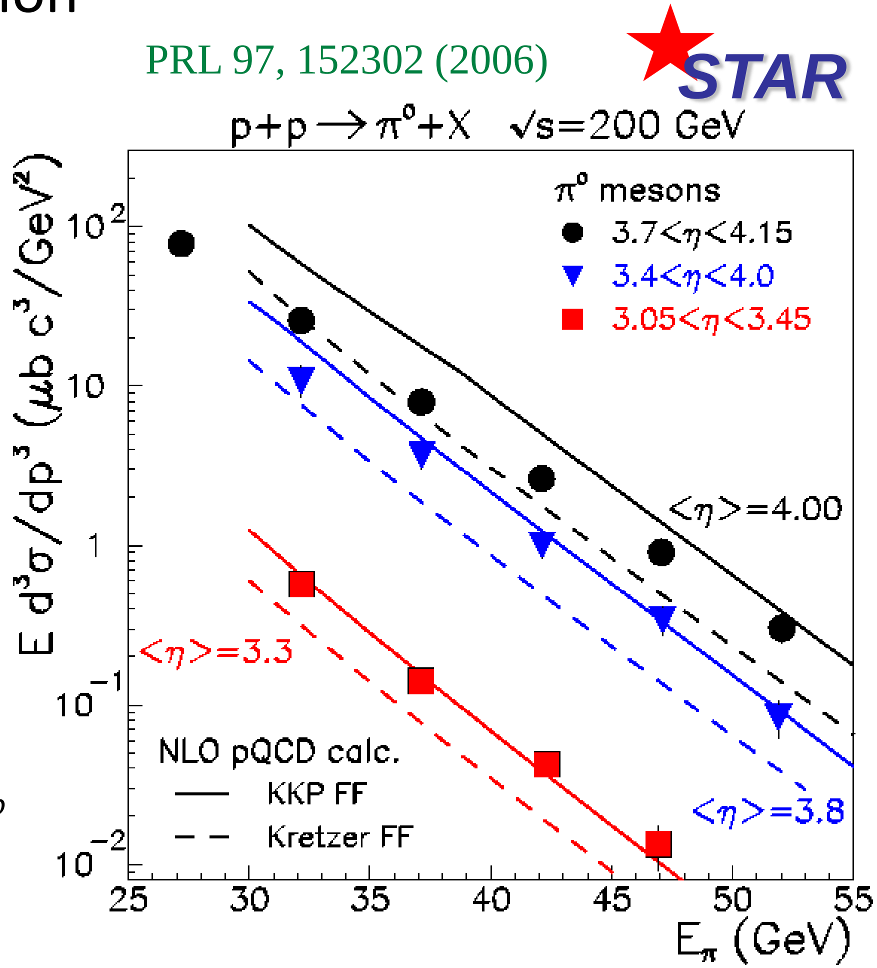
Probing Low-x Gluons in Forward Production

Factorization



$$d\sigma_\pi = \sum_{a,b,c} \int dx_a \int dx_b \int dz_c \; f_a(x_a) f_b(x_b) D_c^\pi(z_c) d\hat{\sigma}_{ab}^c$$

PRL 97, 152302 (2006)

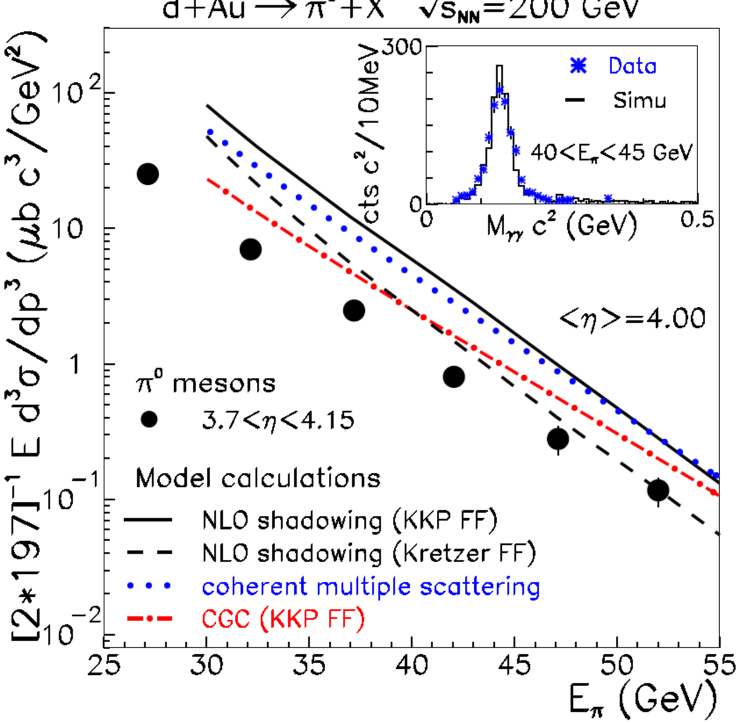


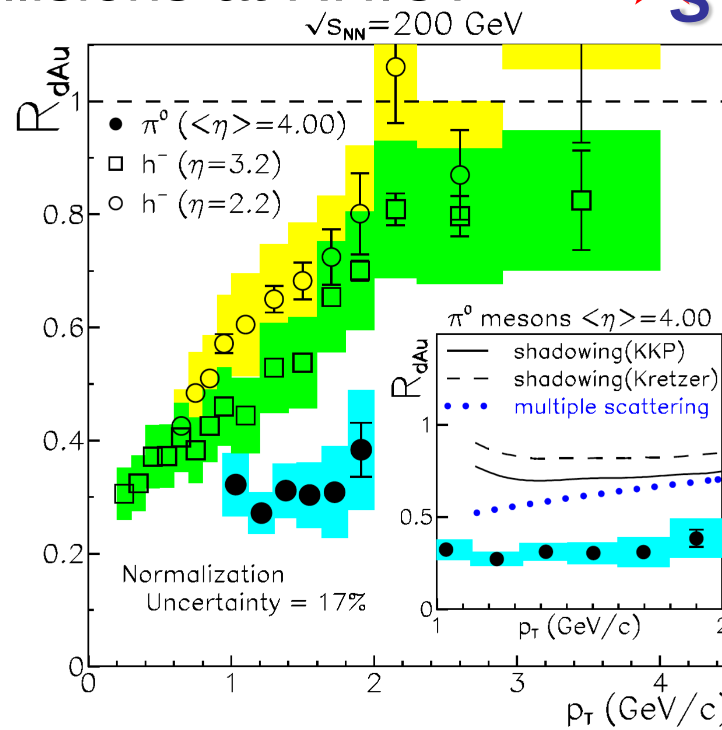
p+p forward π cross-section is consistent with NLO pQCD calculations

Does this work for d+Au? (if so, then use as probe of low-x gluons)

Hints of Gluon Saturation from Large-Rapidity Particle Production in d+Au Collisions at RHIC?

STAR





$$R_{dAu} = \frac{\sigma_{inel}^{pp}}{\langle N_{bin}\rangle \sigma_{hadr}^{dAu}} \frac{\sigma(dAu \to \pi)}{\sigma(pp \to \pi)}$$

d+Au→π^0+X cross sections at $\sqrt{s_{NN}}$ = 200 GeV and <η>=4.0 [STAR, Phys.Rev.Lett. **97** (2006) 152302]

NLO pQCD calculations using gluon shadowing [Guzey, Strikman and Vogelsang PLB **603** (2004) 173]

CGC model calculation [Dumitru, Hayashigaki, Jalilian-Marian, Nucl.Phys. **A770** (2006) 57]

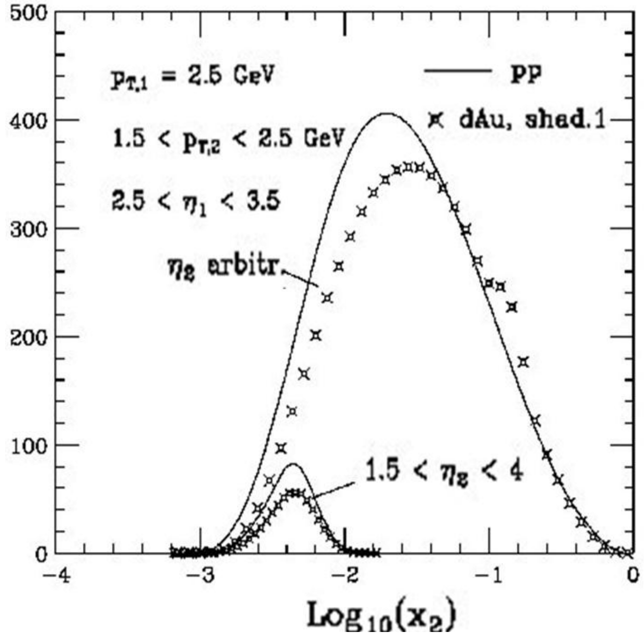
- Large-rapidity d+Au cross sections are suppressed
- Data are best described by CGC model calculation
- Many other possible explanations of suppression

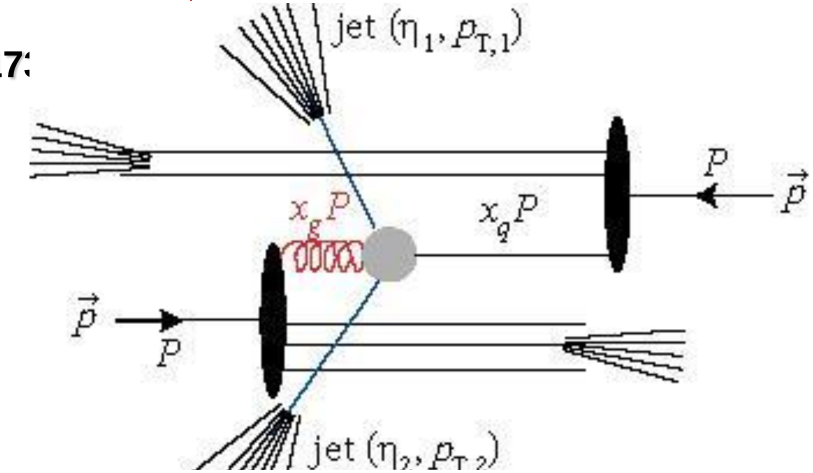
Forward Production

Inclusive and particle correlations

$$x_+ \approx \frac{p_T}{\sqrt{s}}\left(e^{+\eta_1} + e^{+\eta_2}\right) \xrightarrow[\eta_1 \gg \eta_2]{} x_F$$

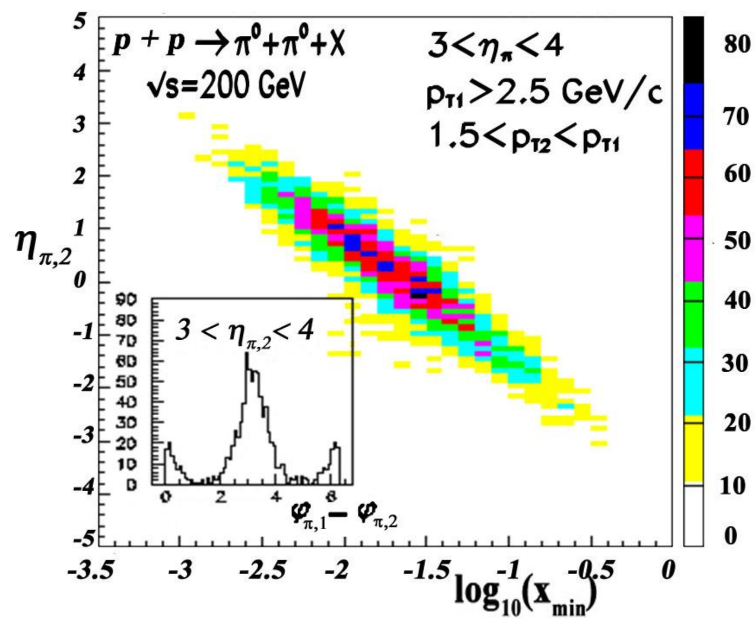
Guzey, Strikman and Vogelsang, PLB603 (2004) 17





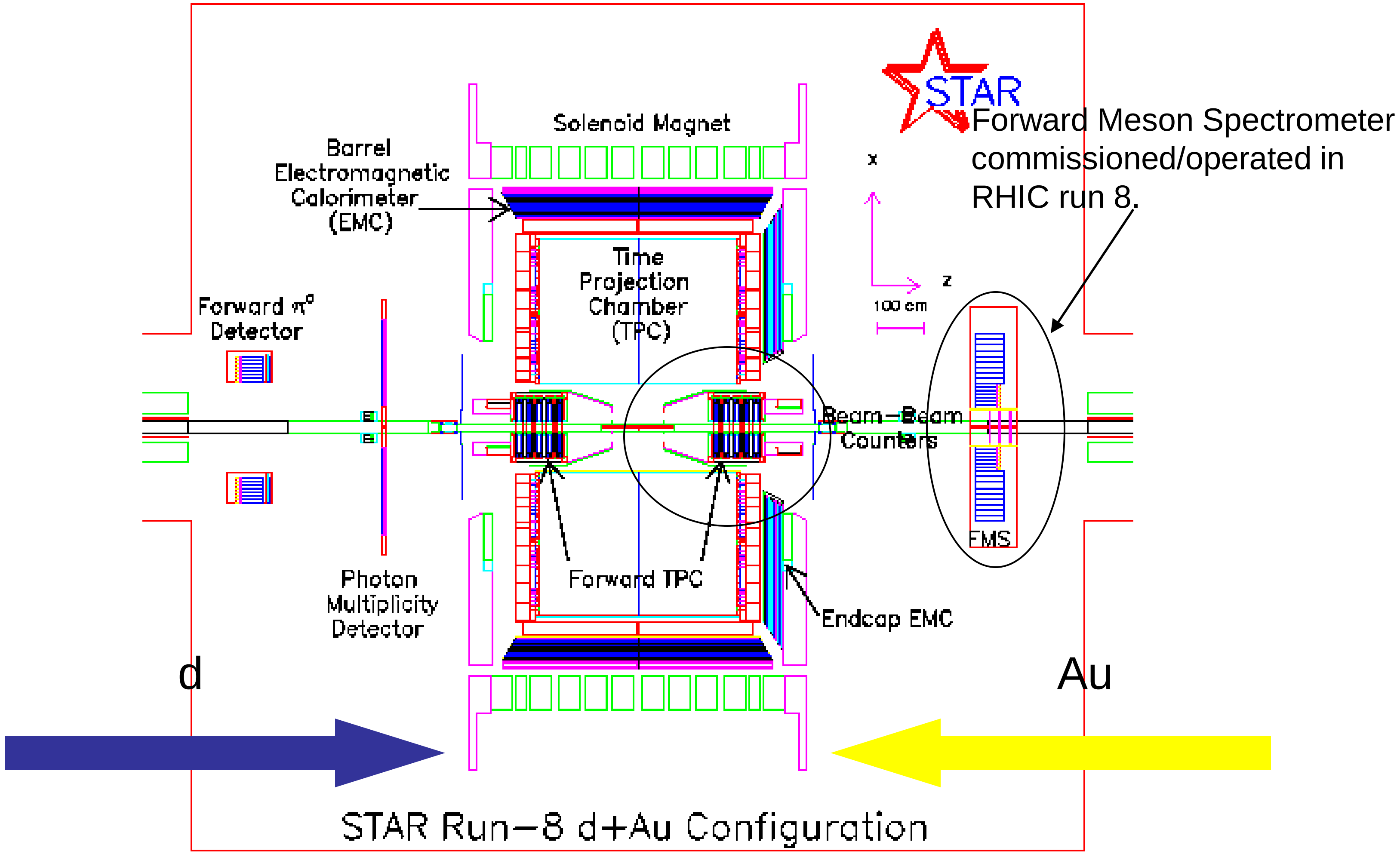
$$x_- \approx \frac{p_T}{\sqrt{s}}\left(e^{-\eta_1} + e^{-\eta_2}\right) \xrightarrow[\eta_1 \gg \eta_2]{} x_F e^{-(\eta_1+\eta_2)}$$

- constrain x_{gluon} probed by high-x quark by detection of second hadron serving as jet surrogate.
- span broad pseudorapidity range (-1<η<+4) for second hadron ⇒ span broad range of x_{gluon}
- provide sensitivity to higher p_T for forward π^0 ⇒ reduce 2→3 (inelastic) parton process contributions thereby reducing uncorrelated background in $\Delta\phi$ correlation.



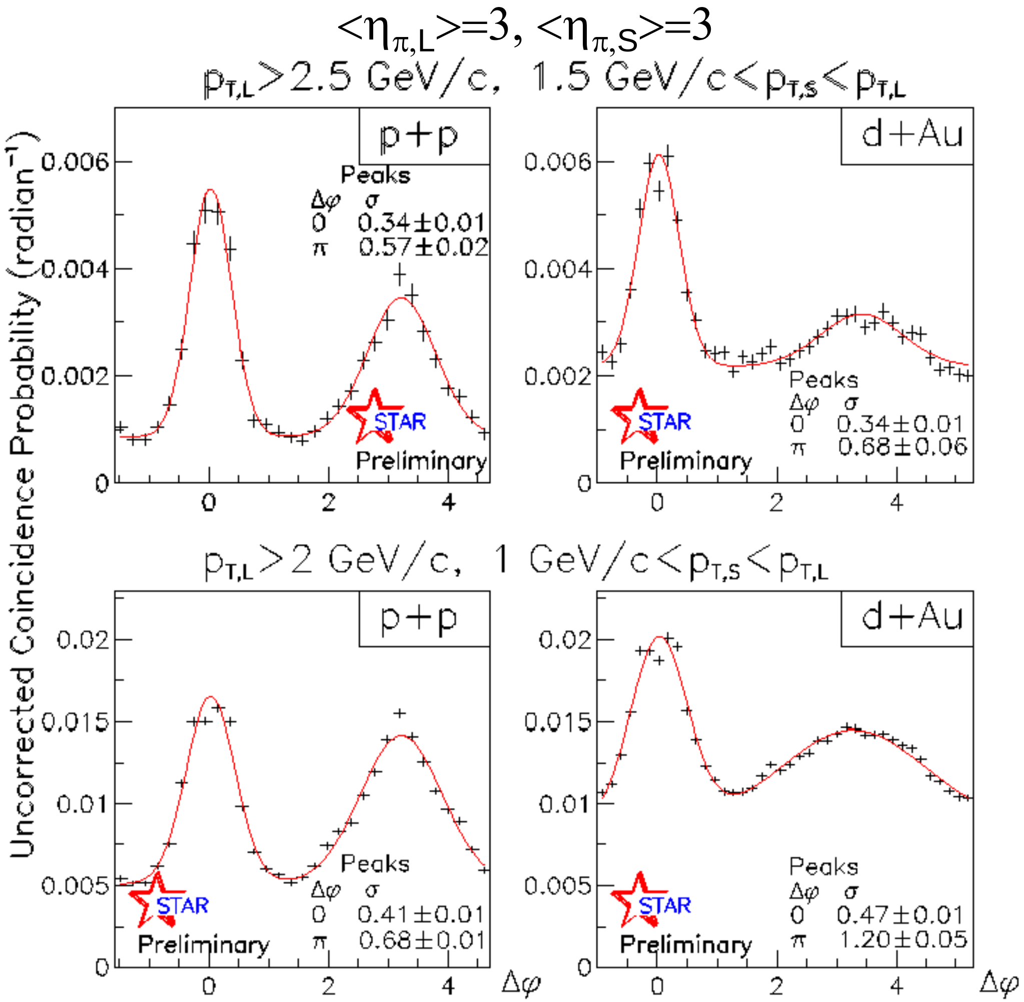
PYTHIA Simulation

STAR Detector

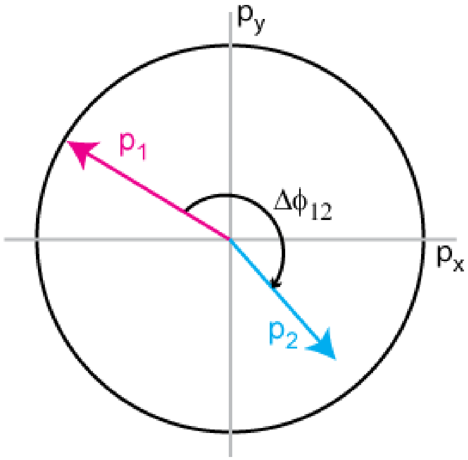


- STAR and PHENIX are primarily instrumented near mid-rapidity
- Forward direction can be viewed at STAR, but instrumentation is limited and is not fully compatible with high luminosity polarized p+p collisions

Forward di-pion azimuthal correlations

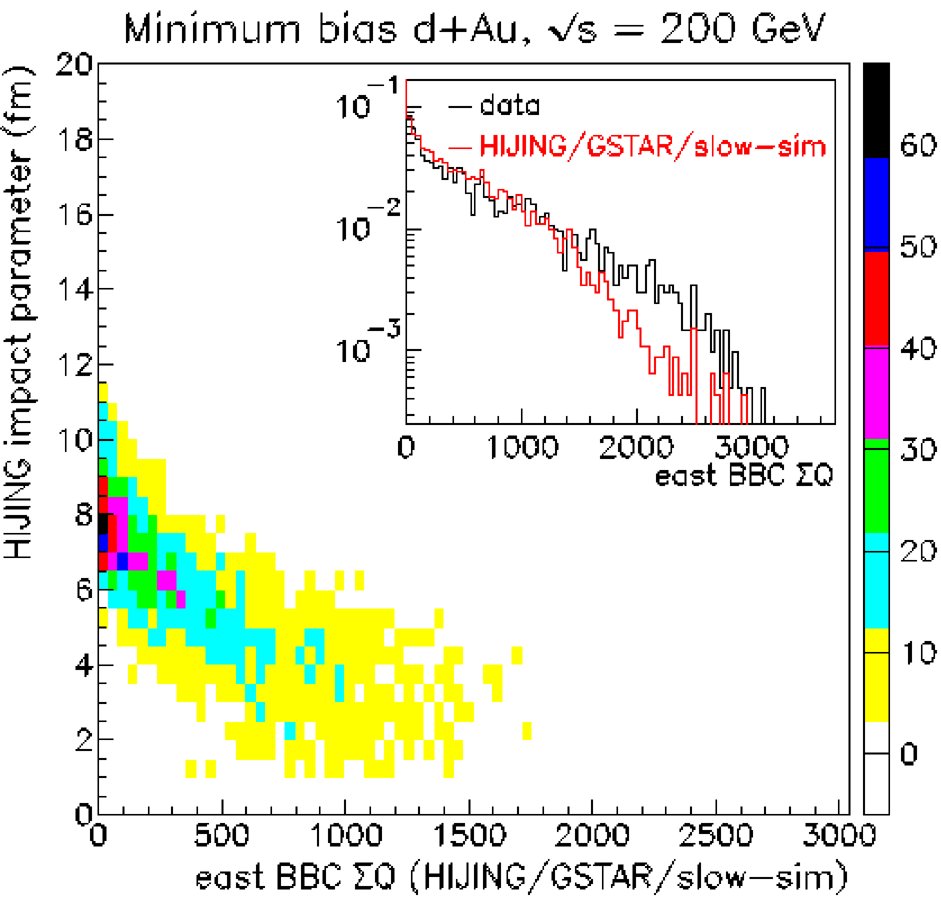


arXiv:1005.2378

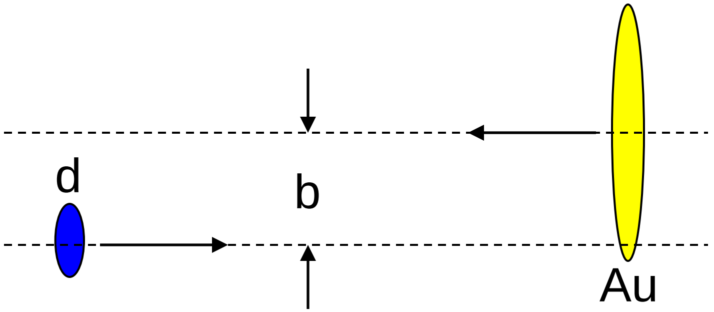


- Forward π^0 pairs probe the lowest x. From 2→2 scattering: ~0.001<x<0.005
- Forward π^0 pairs are detected via 4 γ
- Jet-like correlations for p+p consistent with NLO pQCD description of inclusive forward π^0 cross section
- Significant broadening observed in d+Au relative to p+p

Centrality Definition



arXiv:1005.2378

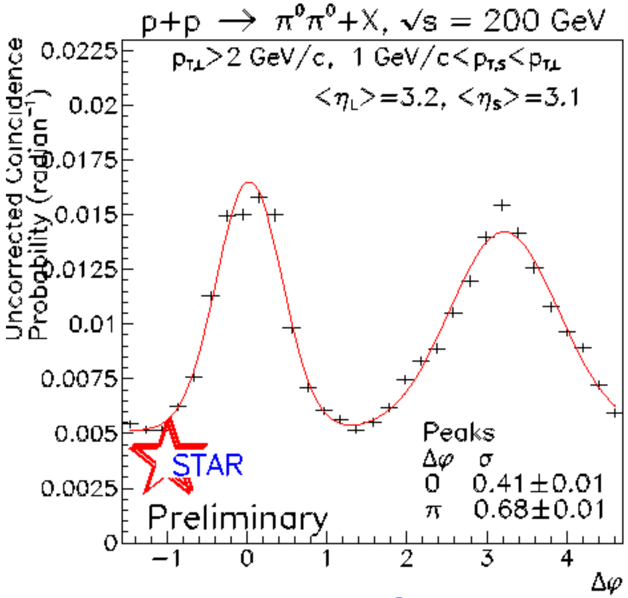


- relate particle production in Au beam direction (5 < -η < 3) to impact parameter for collision through a model (HIJING)
- Observe maximum of ~50 minimum-bias equivalent particles in Au beam direction
- Define…
  - **peripheral**: ΣQ<500 (<b>~7 fm)
  - **central**: 2000< ΣQ<4000 (<b>~2.7 fm)

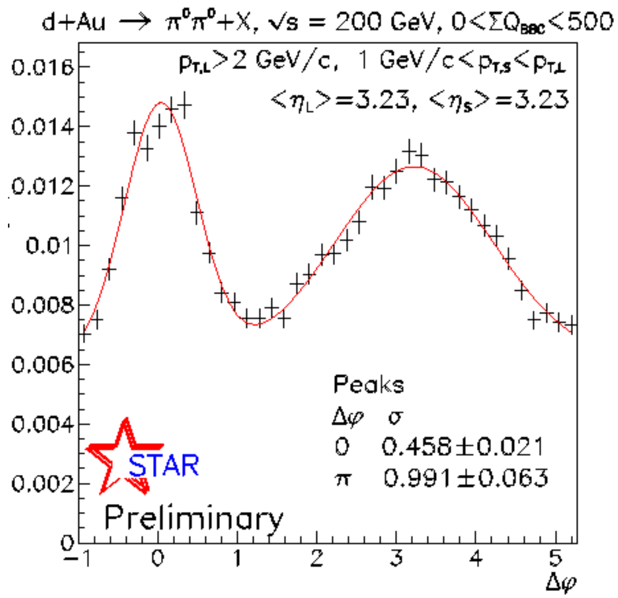
Centrality dependence of forward di-pion correlations

Leading P_T $\pi^0 > 2$ GeV

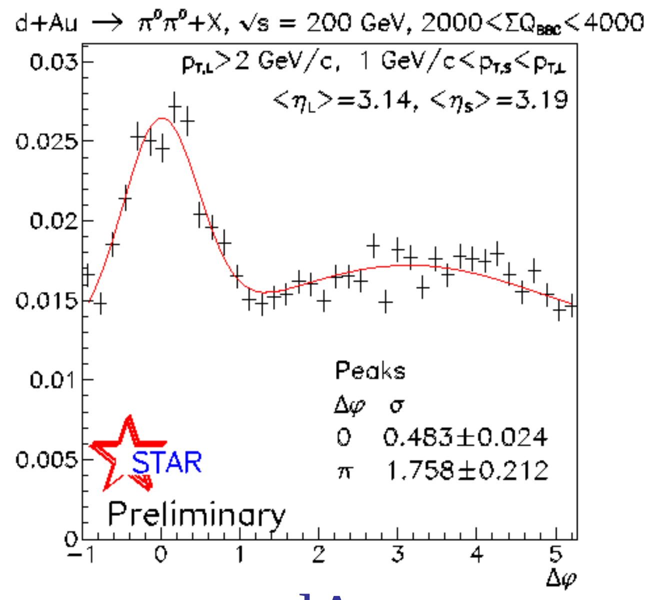
arXiv:1005.2378



pp data



dAu
peripheral



dAu
central

- Away-side peaks evident in peripheral dAu and pp.
- Away-side peaks in peripheral dAu are roughly 50% wider than in pp.
- Significant dependence on centrality is evident in azimuthal decorrelation.

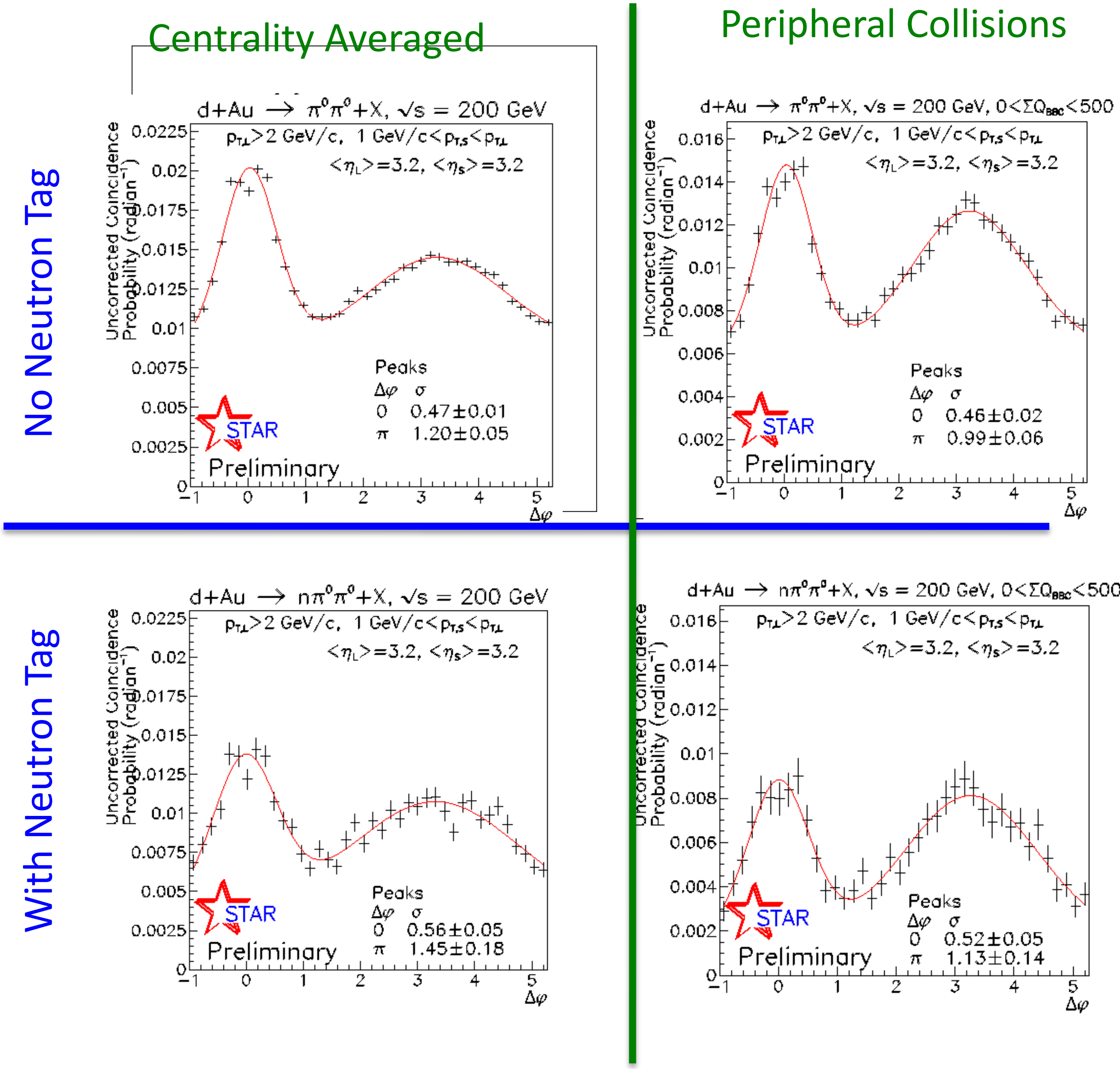
Forward Di-Pion Azimuthal Correlations with Neutron Tag

- Inclusion of west ZDC spectator neutron condition reduces the pedestal
- Pedestal from d+Au correlations with neutron tag are quantitatively consistent with pedestal in p+p correlations
- Little impact on peak heights or widths with spectator neutron condition

- Some theorists have argued that multi-parton interactions will affect the pedestal level

  (Strickman, Vogelsang arXiv: 1009.6123)

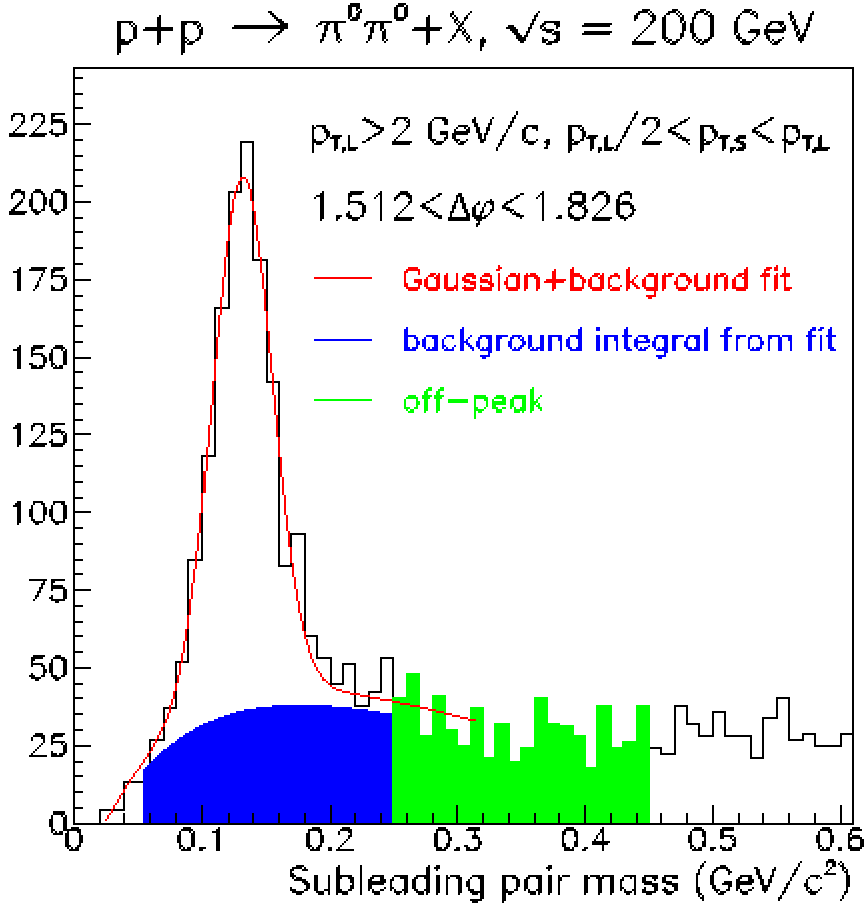
- Multi-parton interactions appear to contribute to the pedestal in d+Au collisions but not p+Au collisions
- Other basic aspects of the azimuthal correlations appear to be unchanged between d+Au and p+Au collisions

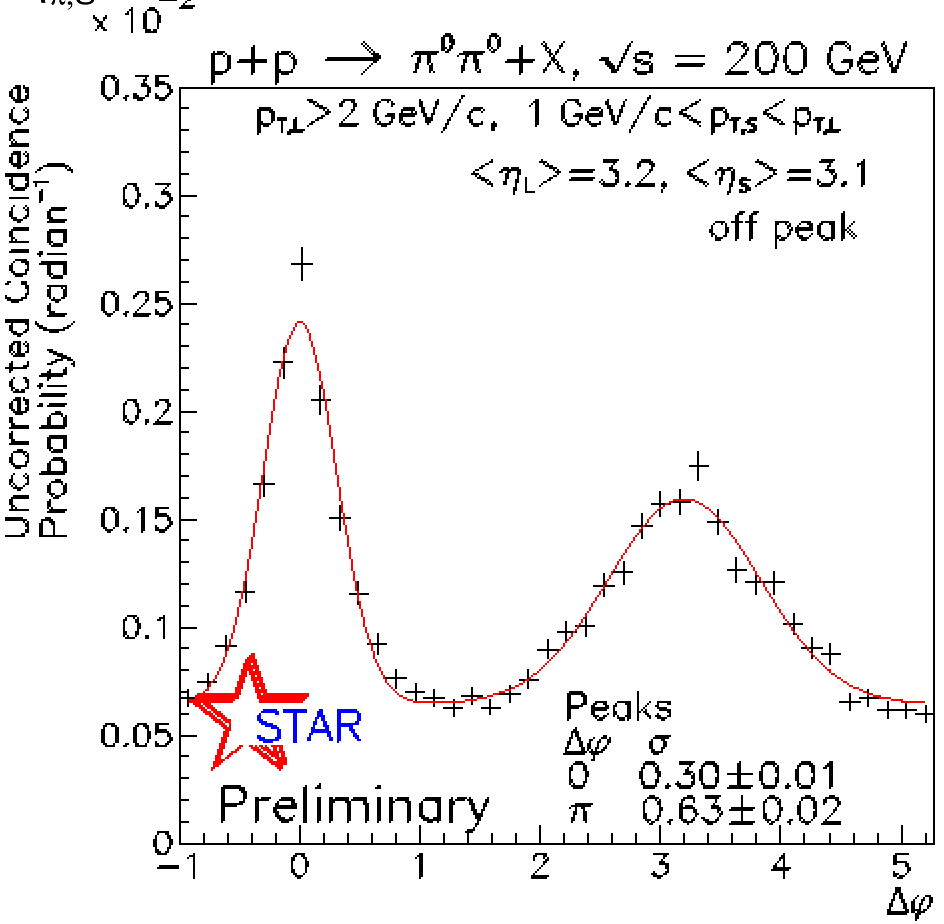


Corrections-I

Off-mass-peak background subtractions

$<\eta_{\pi,L}>=3,\ <\eta_{\pi,S}>=3.2$

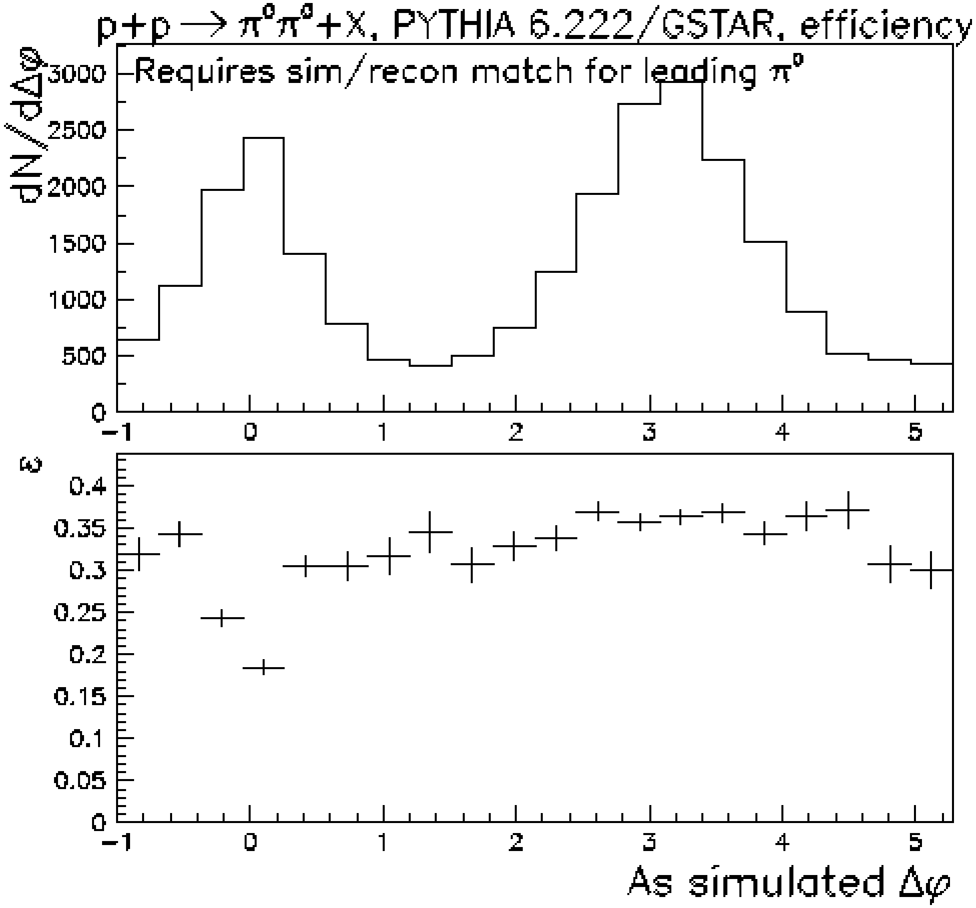




- off mass peak azimuthal correlations show jet-like structures similar to on-peak
- Fit background under mass peak to scale off-peak yields for subtraction

Corrections-II

Efficiency corrections



$p_{T,L}$>2 GeV/c $p_{T,S}$>1 GeV/c

$\langle\eta_{\pi,L}\rangle=3$, $\langle\eta_{\pi,S}\rangle=3$

$$P(\Delta\phi) = \frac{\left.\frac{dN}{d\Delta\phi}\right|_{onpeak} - b(\Delta\phi)\left.\frac{dN}{d\Delta\phi}\right|_{offpeak}}{nd\varepsilon(\Delta\phi)}$$

P – coincidence probability

b = N_{back} / $N_{offpeak}$ from pair mass

n – number of leading pions

d – bin width

The figure shows the efficiency…

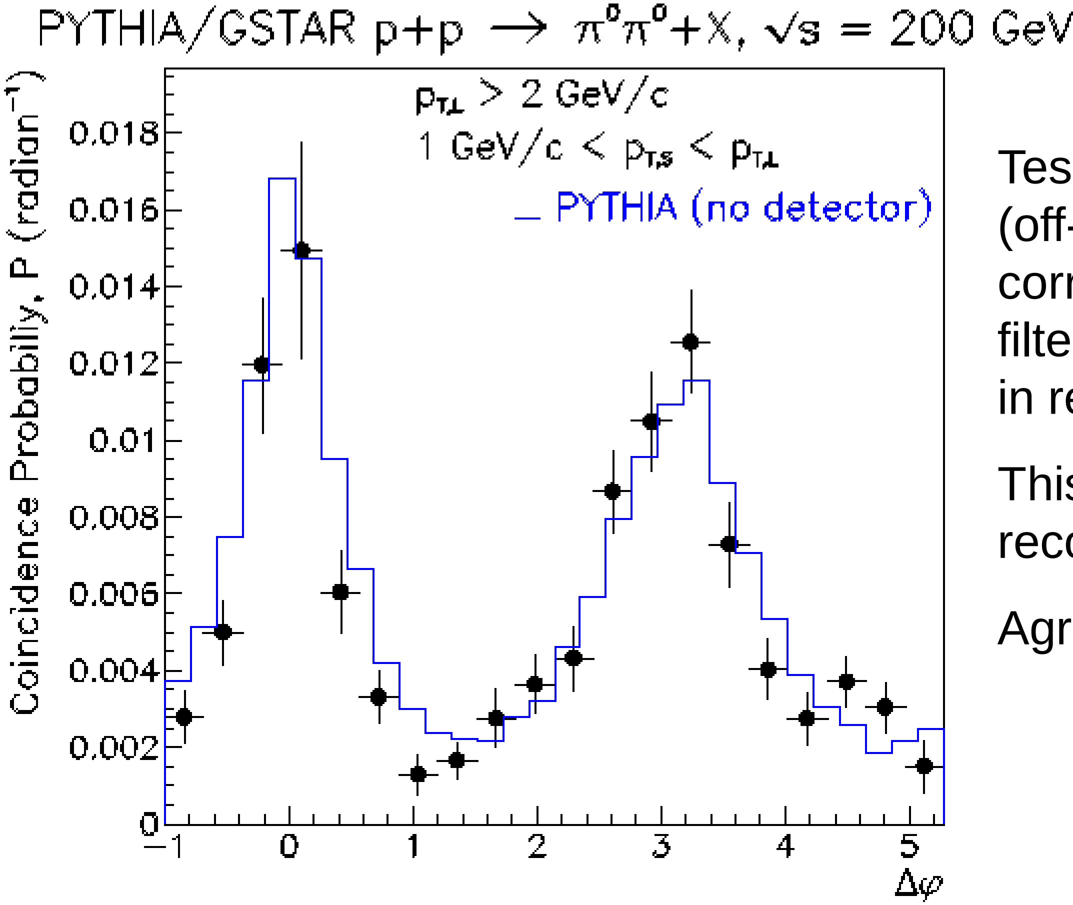
$$\boldsymbol{\varepsilon(\Delta\phi) = N_1(\Delta\phi) / N_2(\Delta\phi)}$$

N_2 = subleading π^0 from PYTHIA

N_1 = subleading π^0 from PYTHIA+GEANT with PYTHIA γ matching reconstructed clusters

Model Test of Corrections for p+p

$<\eta_{\pi,L}>=3, <\eta_{\pi,S}>=3$



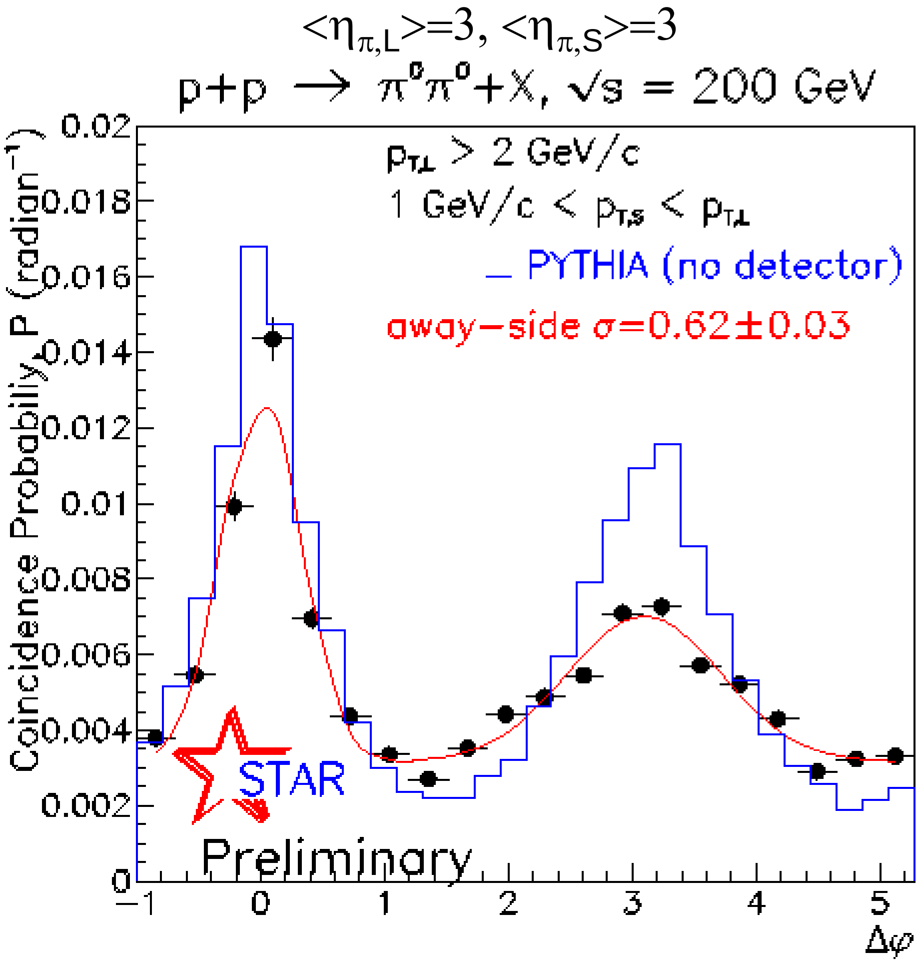
Test ε and full correction procedure (off-peak subtractions and efficiency corrections) by applying it to inclusive filtered PYTHIA/GEANT events used in reconstruction.

This tests that correction method can recover a model input.

Agreement to within statistics

p+p Coincidence Probability

Applying background and efficiency corrections



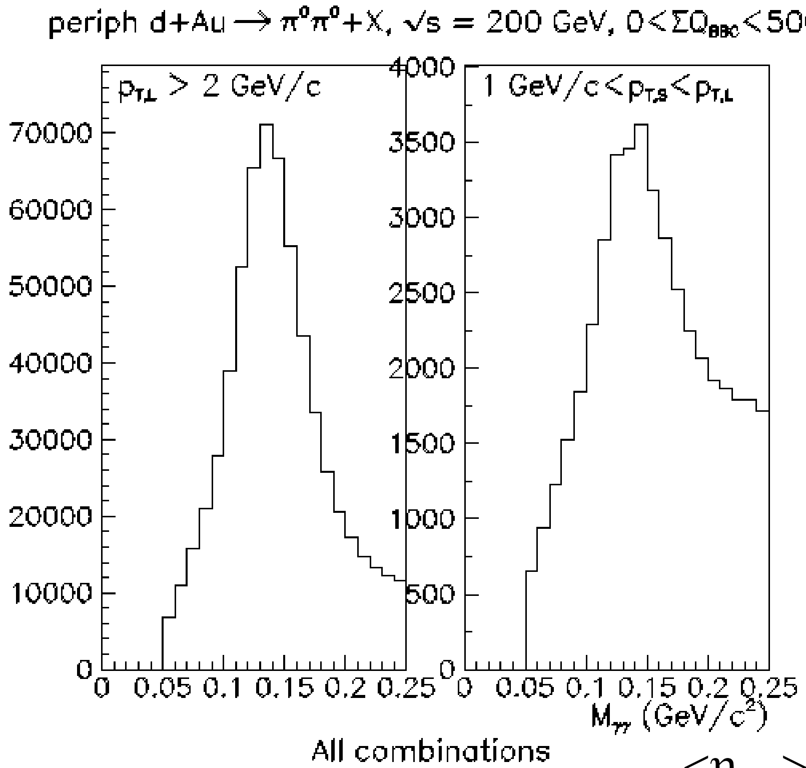
PYTHIA 6.222

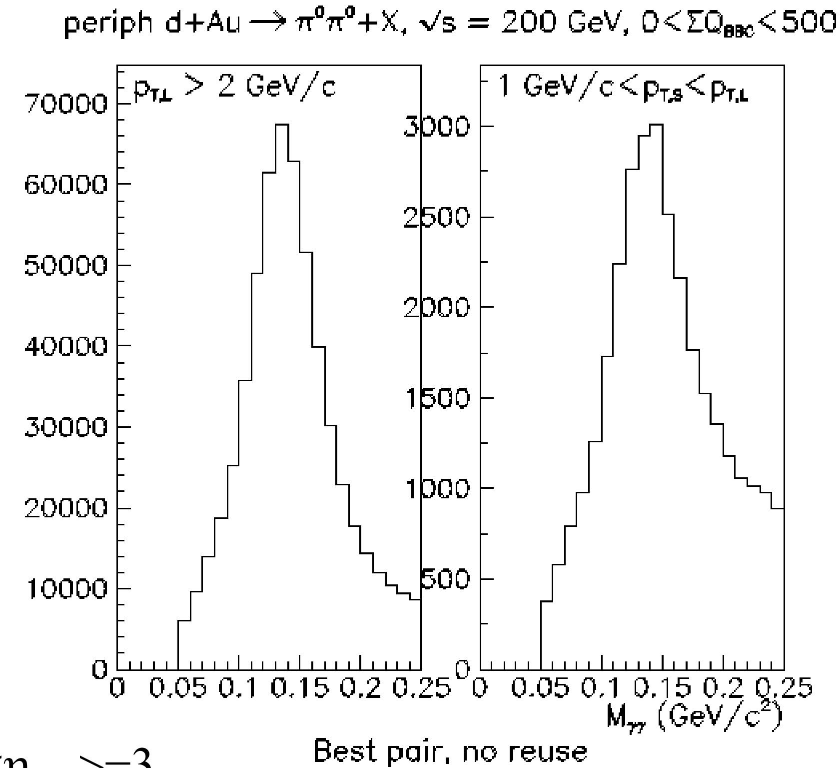
Apply off-mass-peak subtraction and efficiency correction to p+p data

Conclusions:

- Away-side peak width comparable to uncorrected azimuthal correlatons
- Near-side peak agrees with PYTHIA
- Away-side peak broader than PYTHIA
- Pedestal appears larger than PYTHIA

Status of corrected dAu coincidence probability





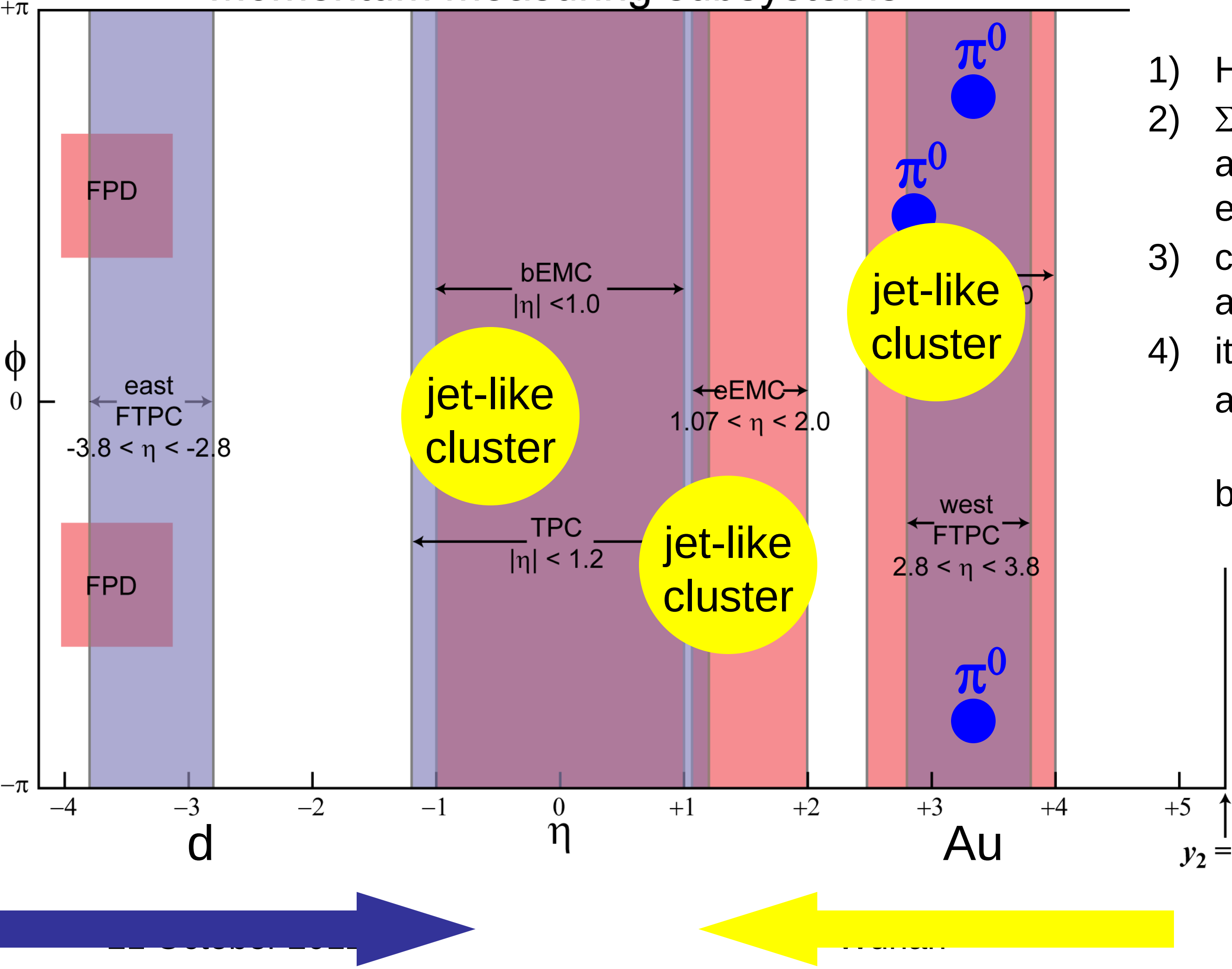
$<\eta_{\pi,L}>=3$, $<\eta_{\pi,S}>=3$

- Background subtractions particularly for peripheral dAu are still not robust, likely because "off-peak" azimuthal correlations are similar in shape to $\pi^0\pi^0$ azimuthal correlations ("jet-like" correlations, see below…)
- Attempts have been made to reduce the combinatoric background via "no reuse" of photon clusters near the neutral pion peak. Despite this reduction, azimuthal correlations for peripheral dAu remain quite sensitive to the background subtraction.

A broader view of correlations

η-dependence of forward π^0+jet-like correlations

Momentum measuring subsystems



Cone jet finder:

1) High tower taken as a seed;
2) ΣE_i in cone of $R = \sqrt{\Delta\eta^2 + \Delta\varphi^2} = 0.6$ about high tower, with tower energy thresholds of E_{thr}
3) compute energy-weighted average $\langle\eta\rangle, \langle\varphi\rangle$
4) iterate until convergence...
   a) ΣE_i in cone of radius R about $\langle\eta_N\rangle, \langle\varphi_N\rangle$
   b) compute energy-weighted average $\langle\eta_{N+1}\rangle, \langle\varphi_{N+1}\rangle$

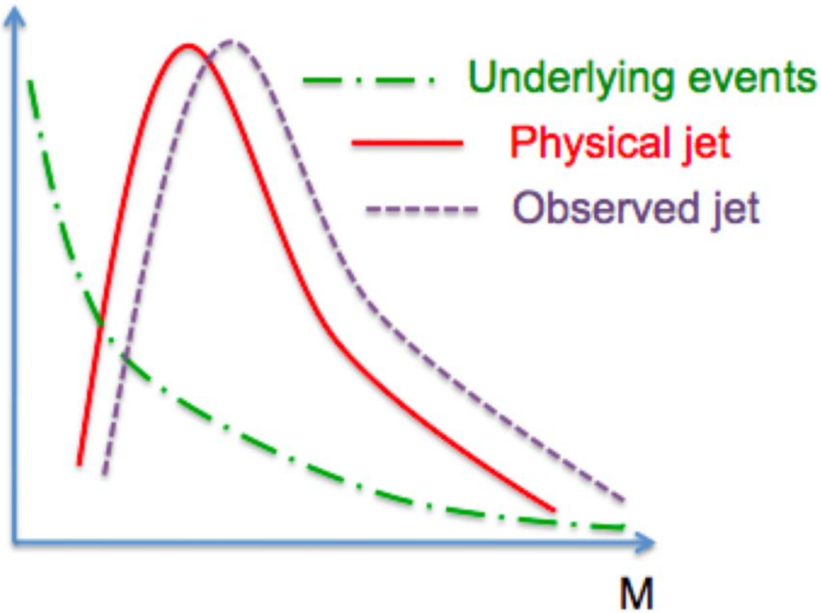
⇒ jet-like clusters

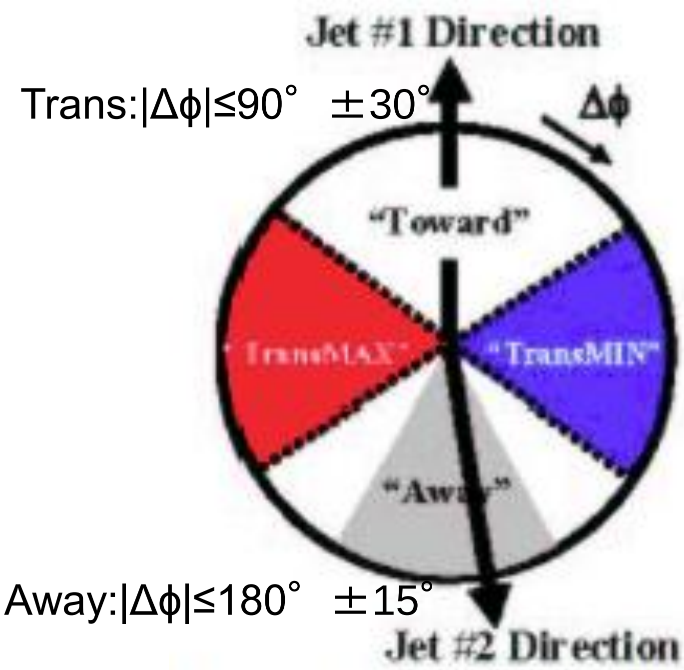
These are not jets, since only EM calorimeter response is considered and p_T is small.

Studies relating jet-like clusters to partons are underway…

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].



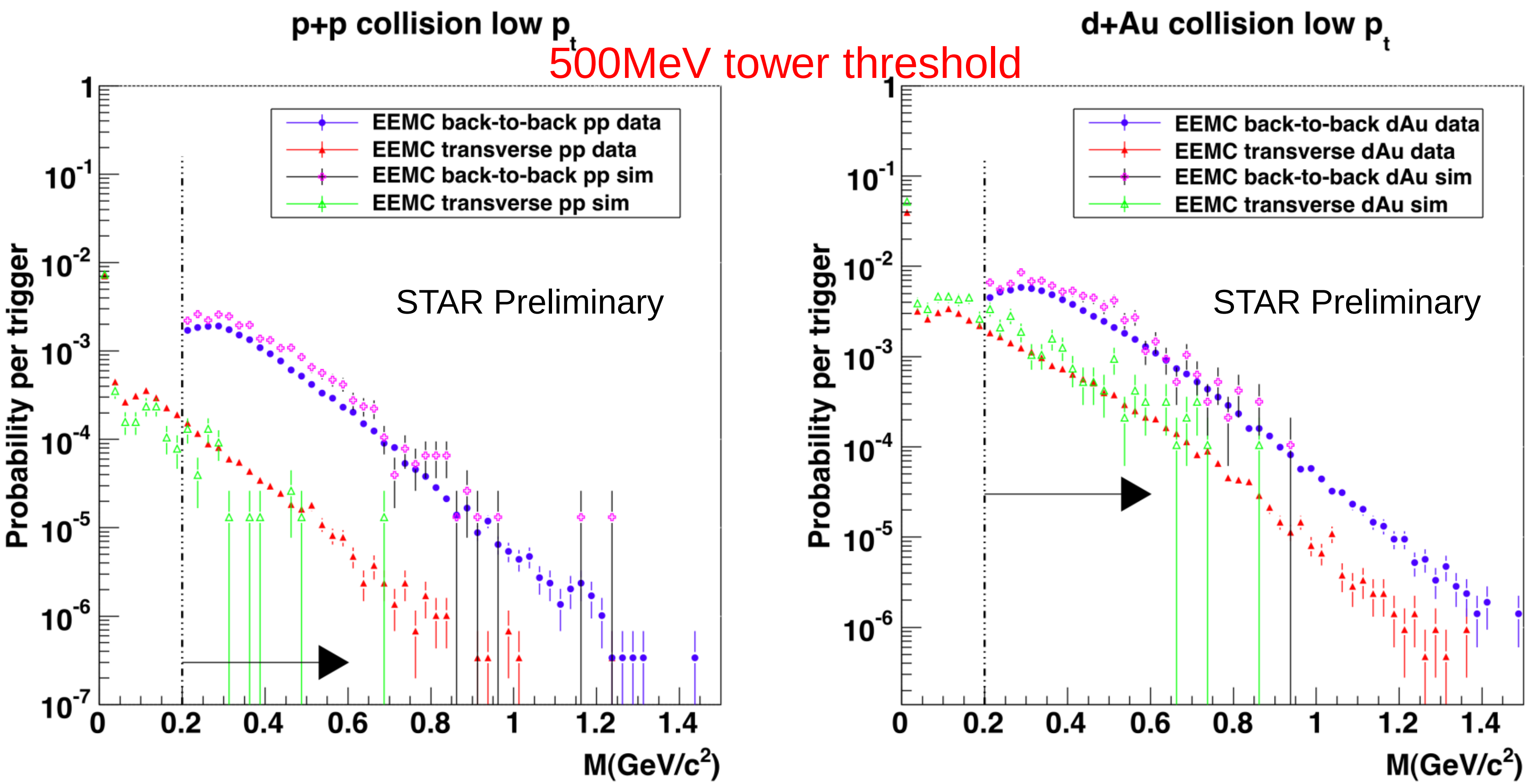


In back to back correlation (away side jet must remain [5π/6,7π/6]), define jet #1 direction is ϕ =0, then the regions [π/3,2π/3]and [4π/3,5π/3] are the underlying event study areas (transverse region).

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

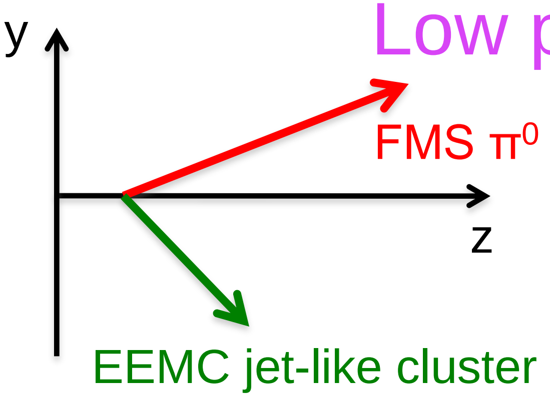
Compare data and simulation using the conditions:

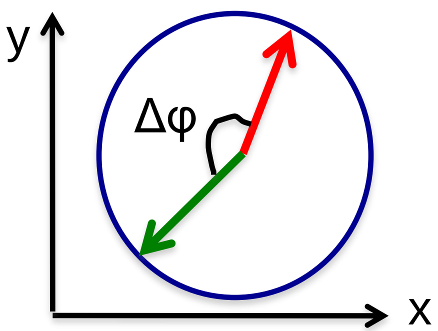
- FMS π^0 with p_t^{FMS}>2.0GeV/c;
- For back-to-back EEMC jet-like cluster require 1.0GeV/c<p_t^{EEMC}<p_t^{FMS} and M>0.2GeV/c^2;
- No additional requirements for underlying events



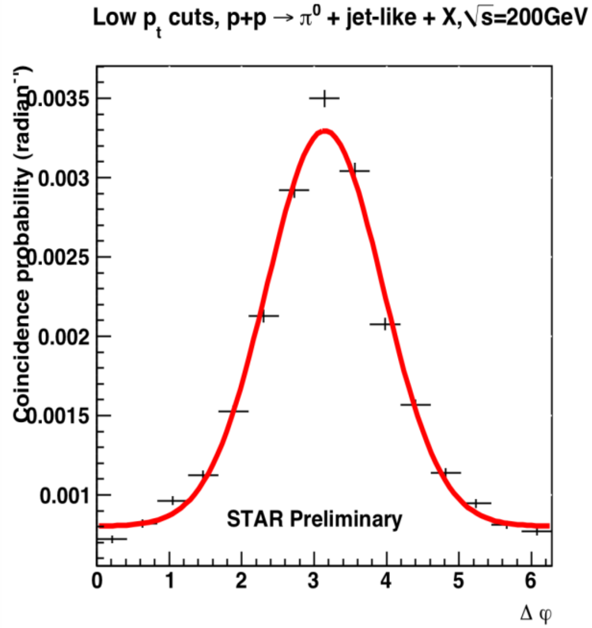
FMS (π^0)-EEMC (jet-like cluster) correlations

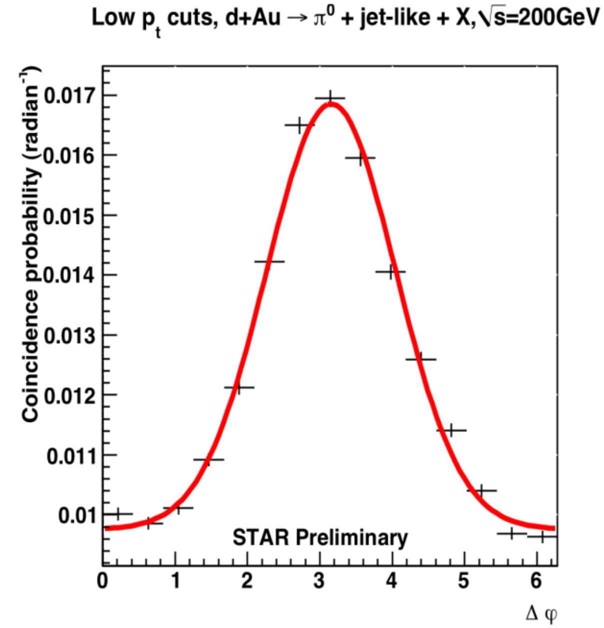
Low p_t with $<\eta_{\pi L}>=3$, $<\eta_{jet\text{-}like}>=1.5$





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





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

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

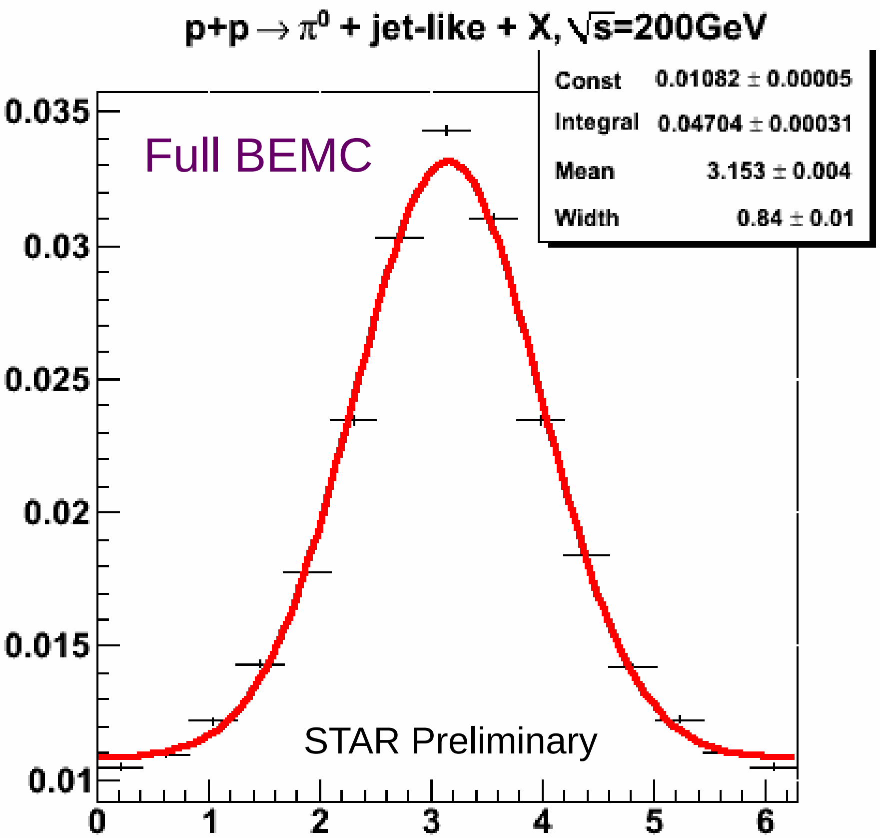
- To suppress underlying event contribution, we use 600MeV tower threshold for the EEMC and 0.4GeV/c^2 as the lower mass limit for the reconstructed jet-like cluster.
- $\sigma_{dAu} - \sigma_{pp} = 0.10 \pm 0.02^{+0.04}_{-0.02}$ Significant broadening from p+p to d+Au.

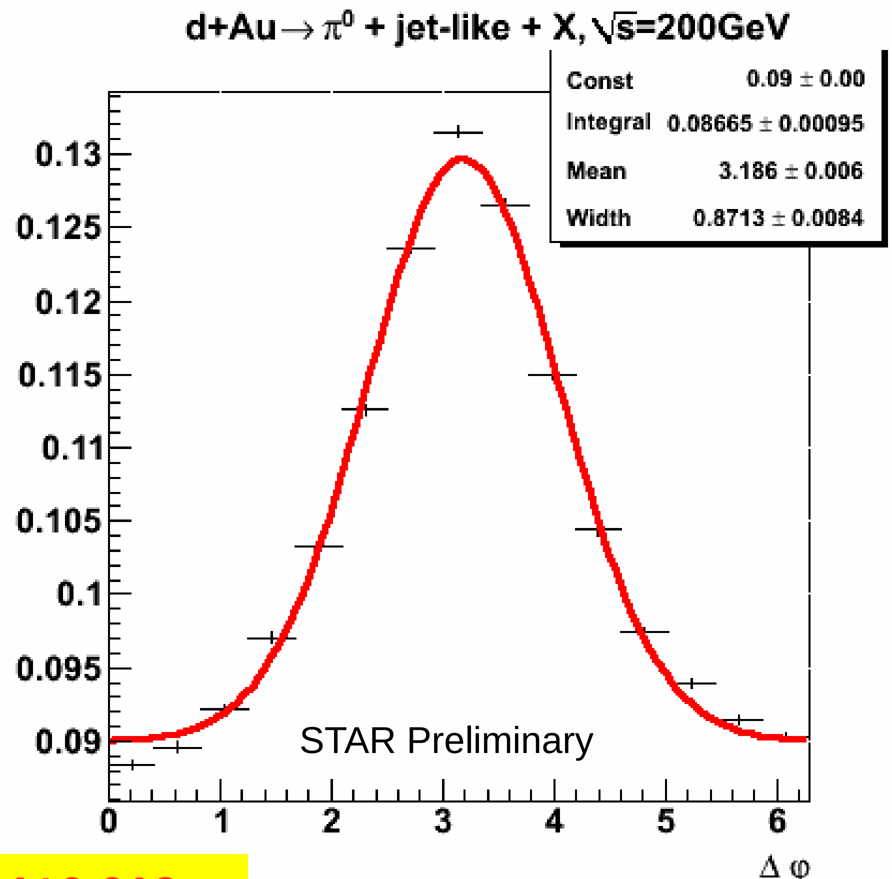
FMS (π^0)-BEMC (jet-like cluster) correlations

Low p_t with $<\eta_{\pi L}>=3$, $<\eta_{jet\text{-}like}>=0$

- FMS π^0 $p_t^{FMS}>2.0$GeV/c. With 400MeV tower threshold, cone R=0.6, BEMC jet-like cluster ($M>0.2$GeV/c^2) $-0.9<\eta<0.9$, $1.0\text{GeV/c}<p_t^{EEMC}<p_t^{FMS}$.

After mixed event correction



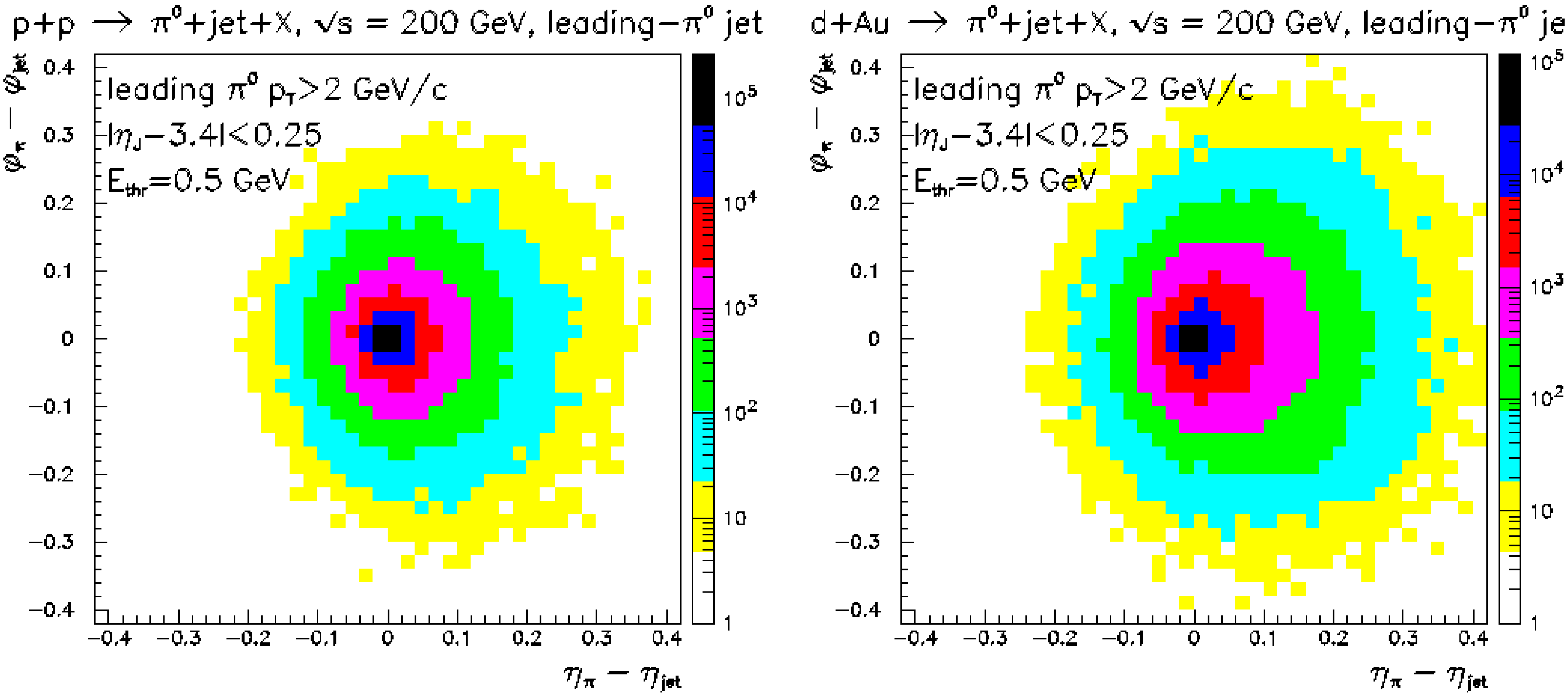


$\sigma_{dAu} - \sigma_{pp} = 0.031 \pm 0.013$

Xuan Li

Forward Jet-Like Clusters-I

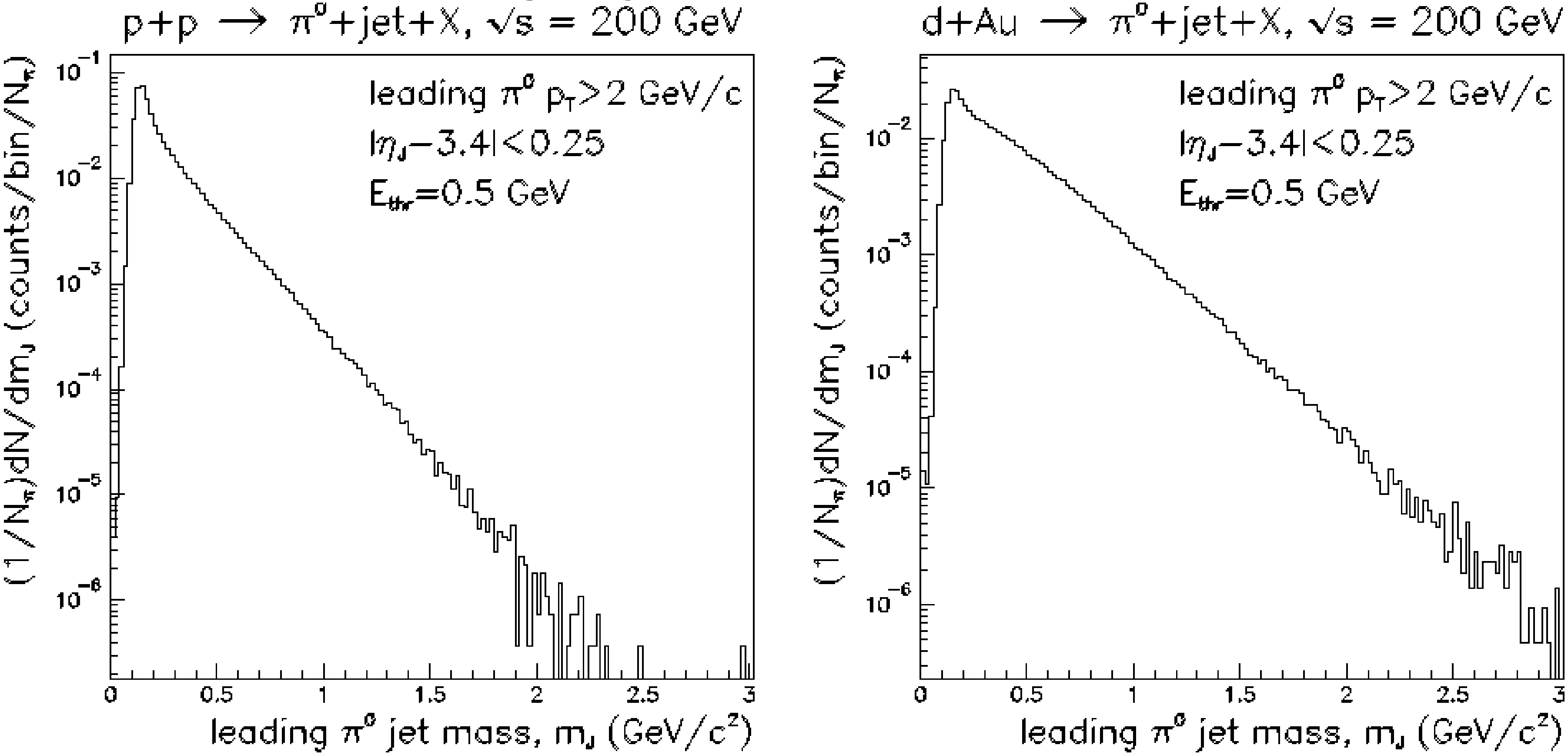
Leading π^0 jet-like cluster direction in FMS



- Leading neutral pion determines jet-like cluster direction for both p+p and d+Au
- Use the direction correlation to exclude leading-pion jet-like cluster, since correlation is mostly trivial (i.e., $\eta_{jet} = \eta_\pi$ and $\varphi_{jet} = \varphi_\pi$)
- Requirement $|\eta_{jet} – 3.4| < 0.25$ centers jet-like cluster within the acceptance

Forward Jet-Like Clusters-II

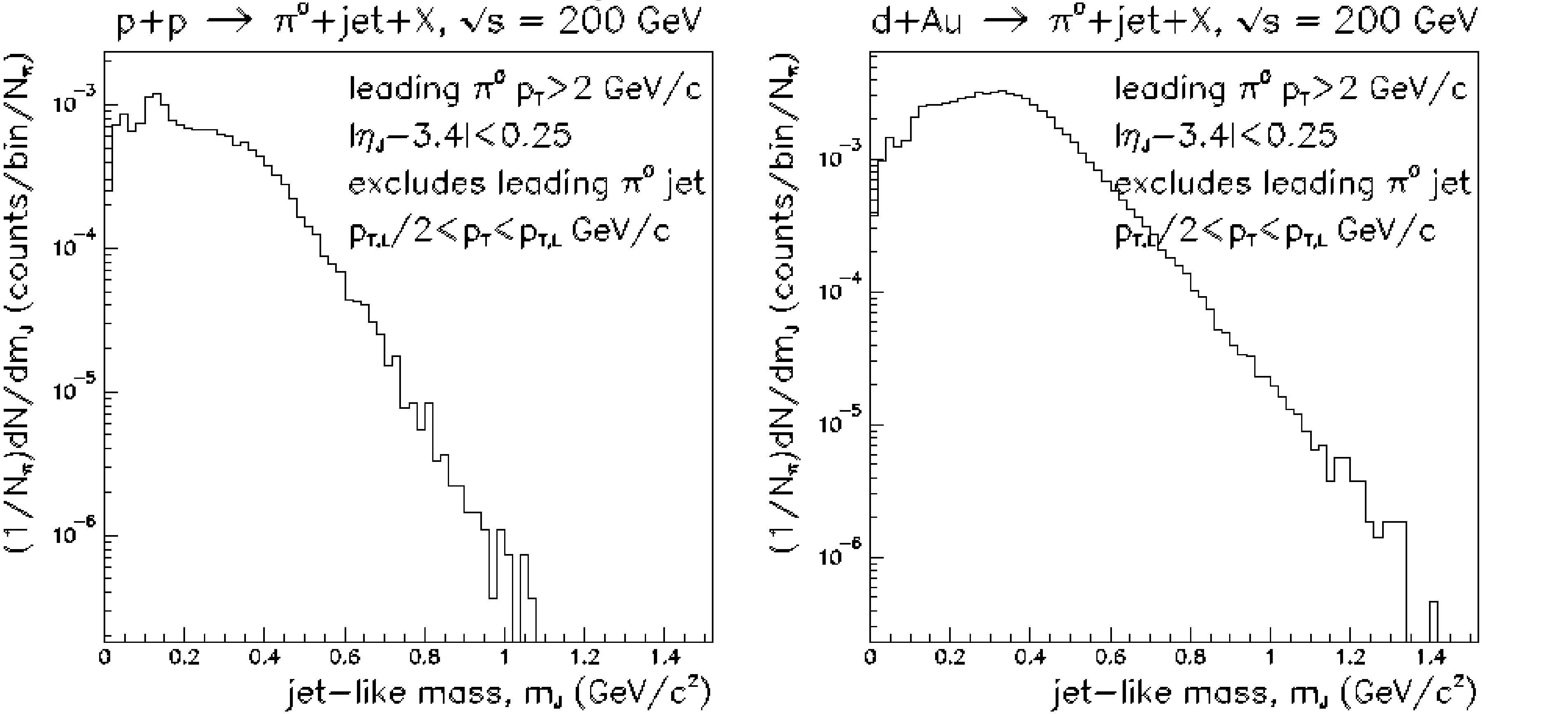
Leading π^0 jet-like cluster mass in FMS



- Jet-like cluster mass is computed by assuming all incident particles are massless
- Resulting jet-like cluster mass is dominated (78% for p+p and 50% for d+Au) by π^0
- Jet-like cluster acceptance requirement reduces probability, since neutral pion is small compared to R=0.6 cone

Forward Jet-Like Clusters-III

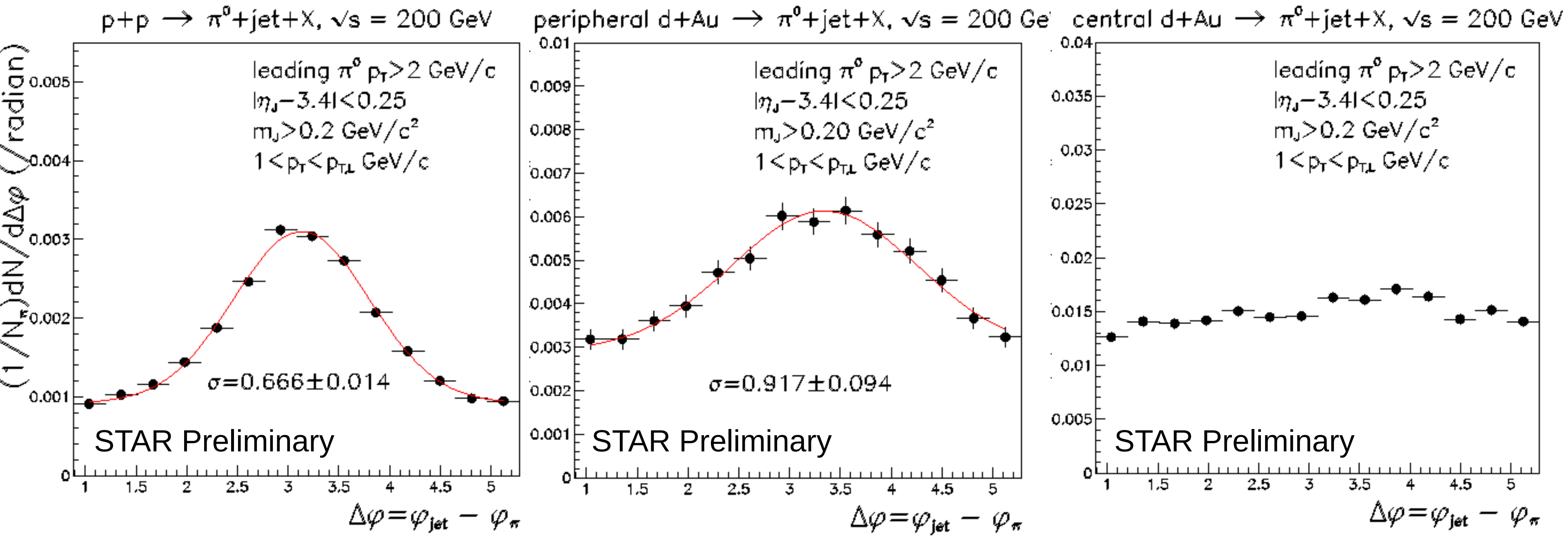
Associated jet-like cluster mass in FMS



- Jet-like cluster mass is computed by assuming all incident particles are massless
- Resulting jet-like cluster mass is mostly (58% for p+p and 32% for d+Au) from π^0
- Mass distributions are comparable at $<\eta_J>$=1.5 and 3.4
- The d+Au$\rightarrow\pi^0$+jet illustrates background subtraction issues for d+Au$\rightarrow\pi^0+\pi^0$

Forward Jet-Like Clusters-IV

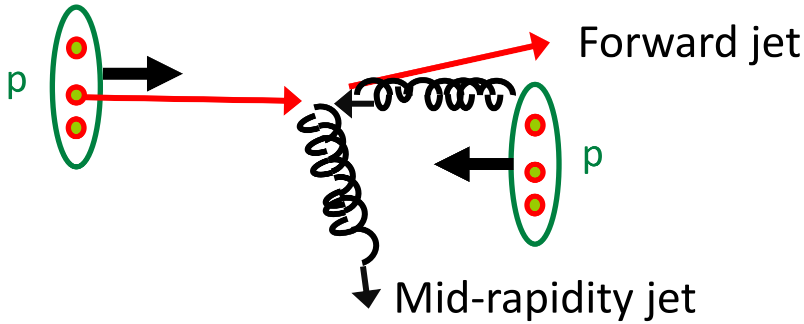
Centrality dependence of π^0+jet-like cluster azimuthal correlations in FMS



- Mixed-event corrections applied, resulting in ~15% bin-to-bin changes
- Use beam-beam counter facing Au beam to select peripheral (ΣQ<250) and central (2000<ΣQ<4000) collisions
- No evidence of away-side peak for central d+Au collisions

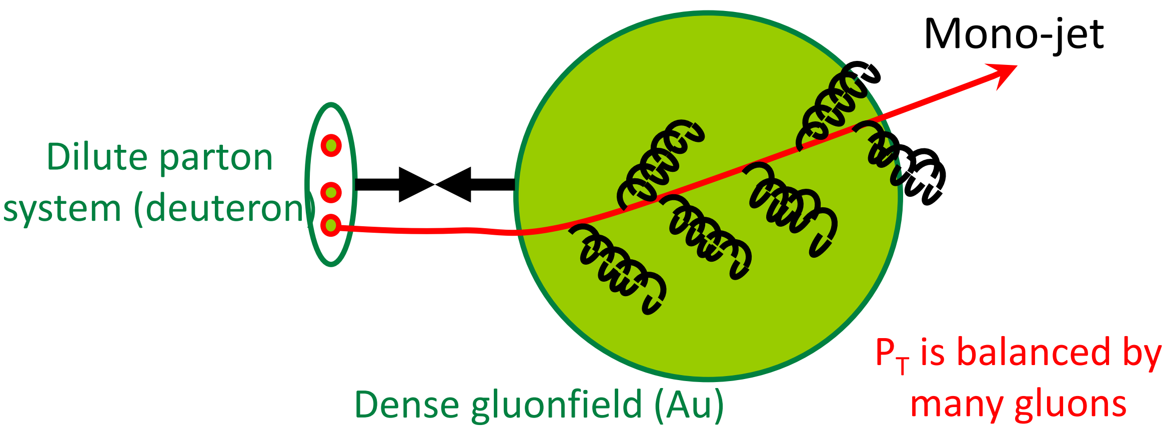
Back-to-back Angular Correlations

pQCD 2➔2 process =back-to-back di-jet (Works well for p+p)

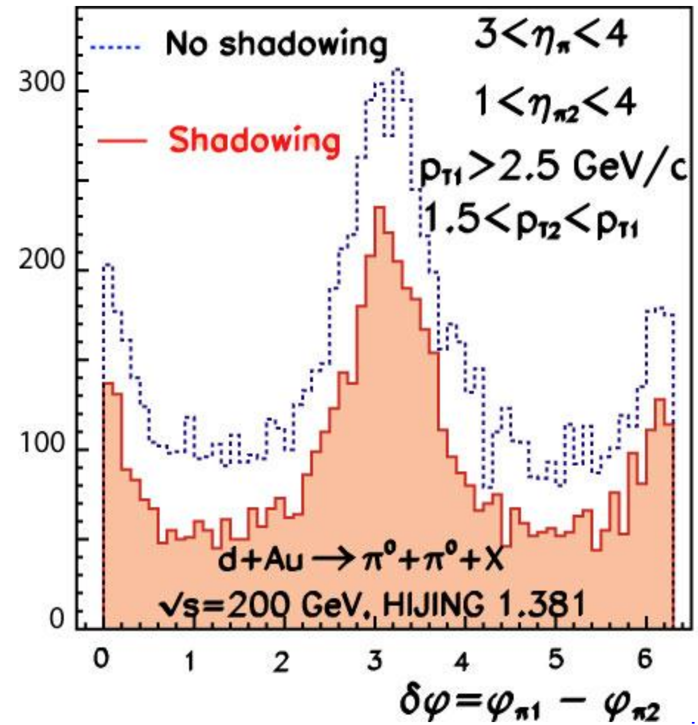


With high gluon density

2➔1 (or 2➔many) process = Mono-jet ?



d+Au in HIJING



CGC predicts suppression of back-to-back correlation

Conventional shadowing changes yield, but not angular correlation

Conclusions

- Forward di-pions show evidence of significant broadening of azimuthal correlations in d+Au relative to p+p, qualitatively consistent with expectations of gluon saturation.

- Azimuthal correlations between a leading forward pion and jet-like objects enable study of a broad rapidity range spanning $-1<\eta<4$
  - p+p correlations become narrower as η increases
  - d+Au correlations become broader as η increases

    Studies relating jet-like cluster energy to parton energy are underway

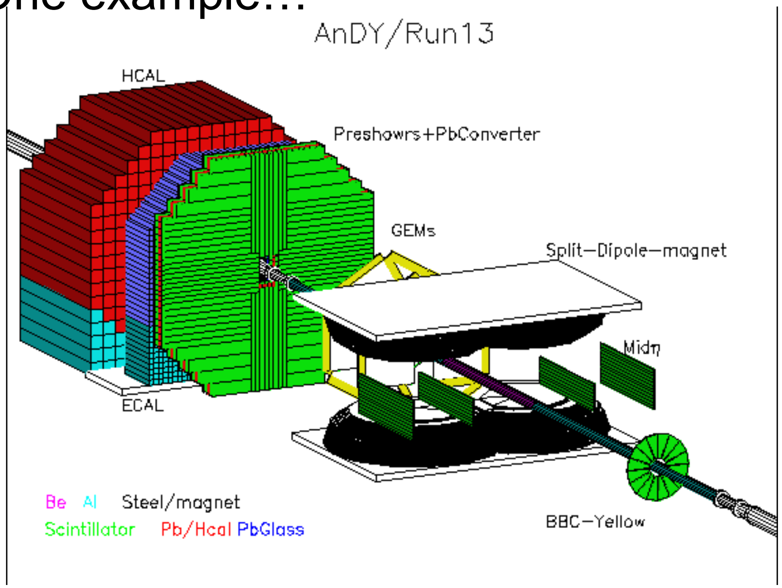
- Centrality dependence of both forward di-pions and forward pion + jet-like clusters in d+Au show correlations for peripheral collisions but not for central collisions.

Pronounced cold nuclear matter effects in the forward direction

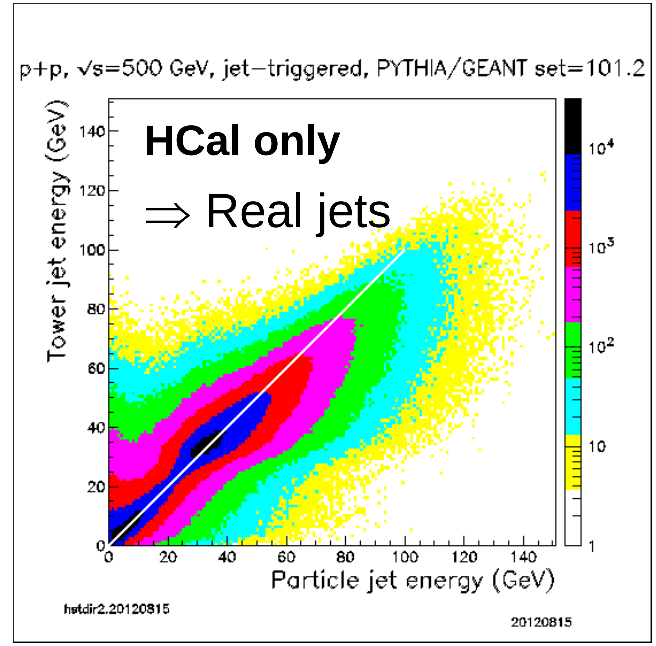
Outlook

Improved forward instrumentation at RHIC

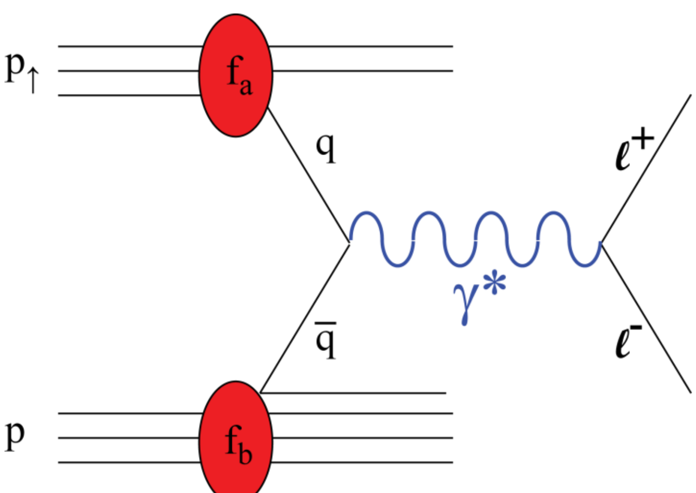
One example…



GEANT model of proposed A_NDY apparatus (run-13)



Correlation between particle jet energy and tower jet energy



With sufficient background rejection, forward Drell-Yan production becomes accessible