# Low-x measurements at STAR

Hank Crawford UCB/SSL

- Program goals for low-x
- X of parton interactions inferred from $\pi^0\pi^0$ and $\pi^0$h correlations through NLO pQCD
- Experimental investigation of pp and dAu correlations at x~0.1-0.001
- Comparison to theory
- DY extension to lower x

# Program

Investigate internal structure of proton

Determine nuclear gluon densities at low x
to understand energy densities in RHI collisions

See color force effects in $A_N$ for $\pi^0$ vs $\gamma^*$

All are sensitive to low-x parton distributions

Note: NLO pQCD based on fragmentation functions and fits to global data in theoretical framework is the tool to understand the dynamics
Pythia is "tuned" to reproduce experimental data – an excellent tool but susceptible to tweekers

# Structure Functions

looking inside a nucleon or nucleus w/ leptons (and quarks?)

$d\sigma/d\Omega = (d\sigma/d\Omega)_{point} |F(\mathbf{q})|^2$ (note-unpolarized)

$d\sigma/d\Omega)_{point} = d\sigma/d\Omega)_{Mott} = (Z\alpha)^2E^2(1-v^2\sin^2(\Theta/2))/4k^4\sin^4\theta/2$

static charge target

For static target, F(**q**) = Fourier transform of charge distribution

F2 derived from electromagnetic probes of nuclear targets that recoil and react

– Are the resulting pdfs universal (ie, hold for strong force as well as em)?

$2xF1(x) \approx F2(x) = x\Sigma e_f^2 f_f(x)$; $x = Q^2/(2M\nu)$; $\nu=(p.q)/M$

callan-gross $f_f(x)$ is probability to have f-flavor parton with fraction of protons momentum x

FL = F2-2xF1 : gets large at low x

We are interested in what the inside of a proton looks like –

do we start with Thomson's atom?

# Pdf – simple

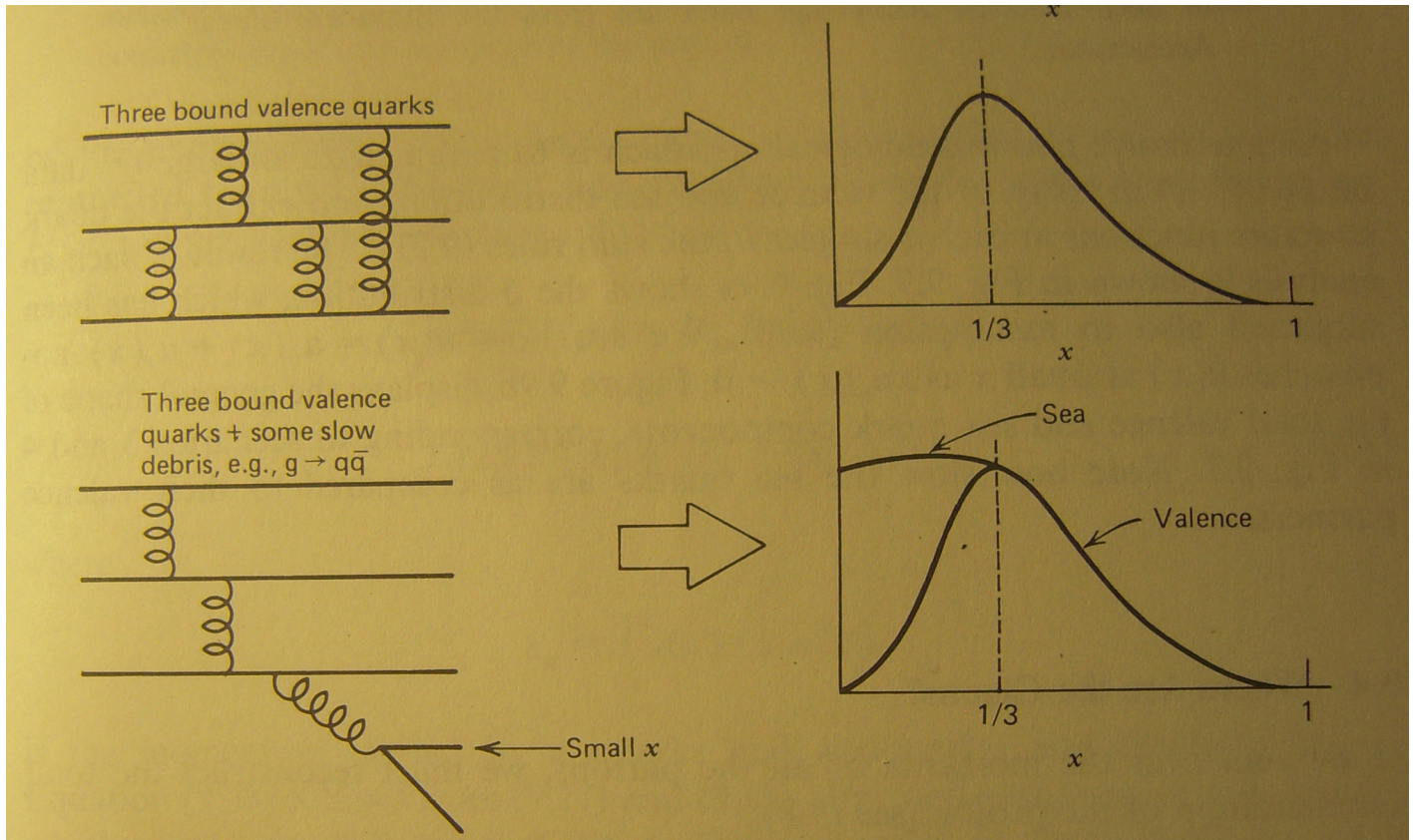
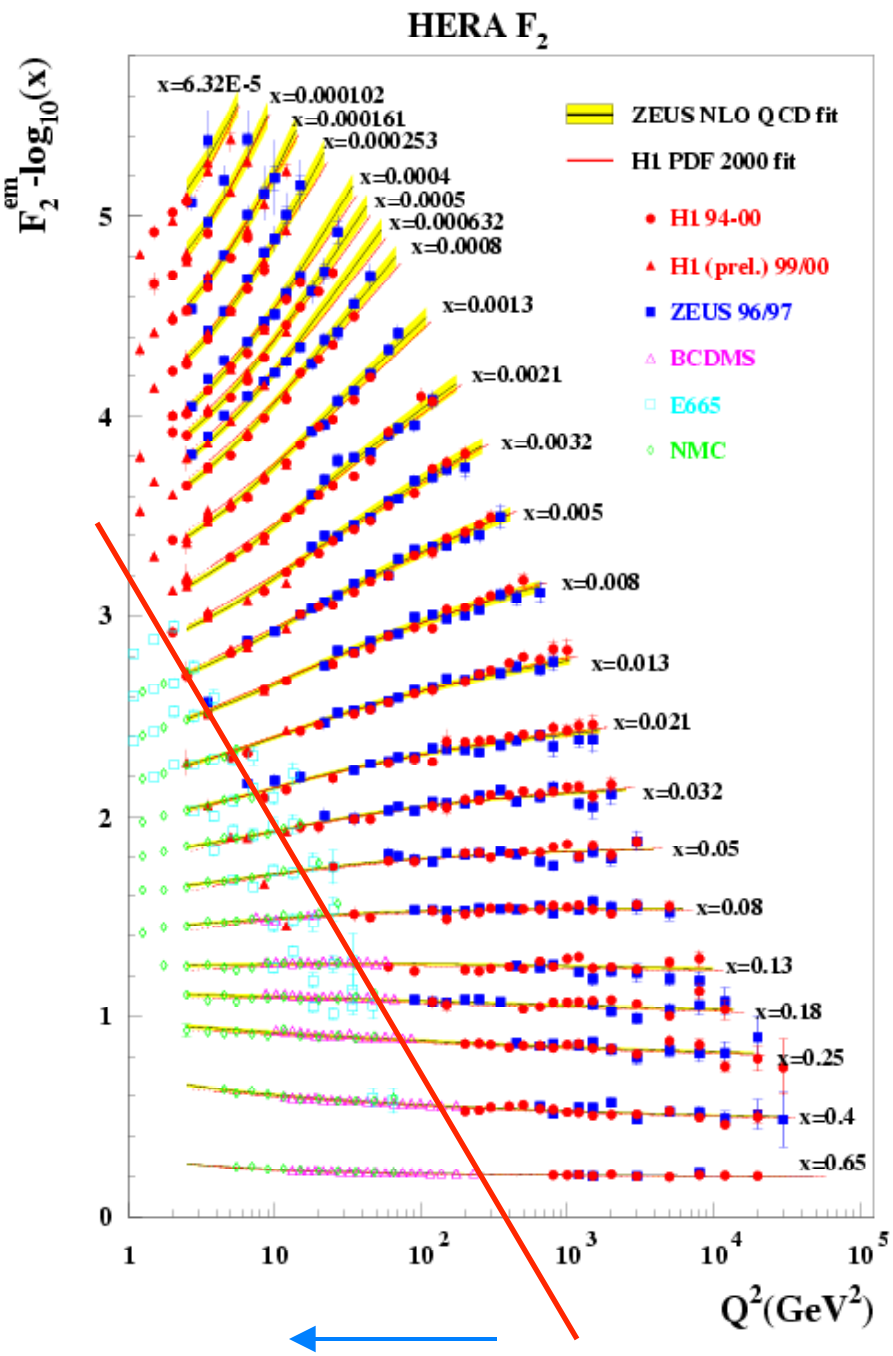



**Fig. 9.7** The structure function pictured corresponding to different compositions assumed for the proton.

From Halzen and Martin, "Quarks and Leptons", 1984, p201




Fixed Target Experiments

# World Data for (unpolarized) DIS

Note remarkable scaling at x > 0.1

Combination of fixed-target experiments and results from the HERA collider (DESY) provides a precise determination of the x and $Q^2$ dependence of the $F_2$ structure function.

Summary plot from arXiv:hep-ex/0507024, and references therein.

Extracting g(x) from em pdf:
Prytz eqn: d(F2)/d(lnQ2)≈g(2x)

# Evolution equations

see Pythia 6.321 Manual

A hard scattering, e.g. in deeply inelastic leptoproduction, will probe the hadron at a given instant. The probe, i.e. the virtual photon in the leptoproduction case, is able to resolve fluctuations in the hadron up to the $Q^2$ scale of the hard scattering. Thus probes at different $Q^2$ values will seem to see different parton compositions in the hadron. The change in parton composition with $t = \ln(Q^2/\Lambda^2)$ is given by the evolution equations

$$\frac{\mathrm{d}f_b(x,t)}{\mathrm{d}t} = \sum_{a,c} \int \frac{\mathrm{d}x'}{x'} f_a(x',t) \frac{\alpha_{abc}}{2\pi} P_{a\to bc}\left(\frac{x}{x'}\right) . \tag{187}$$

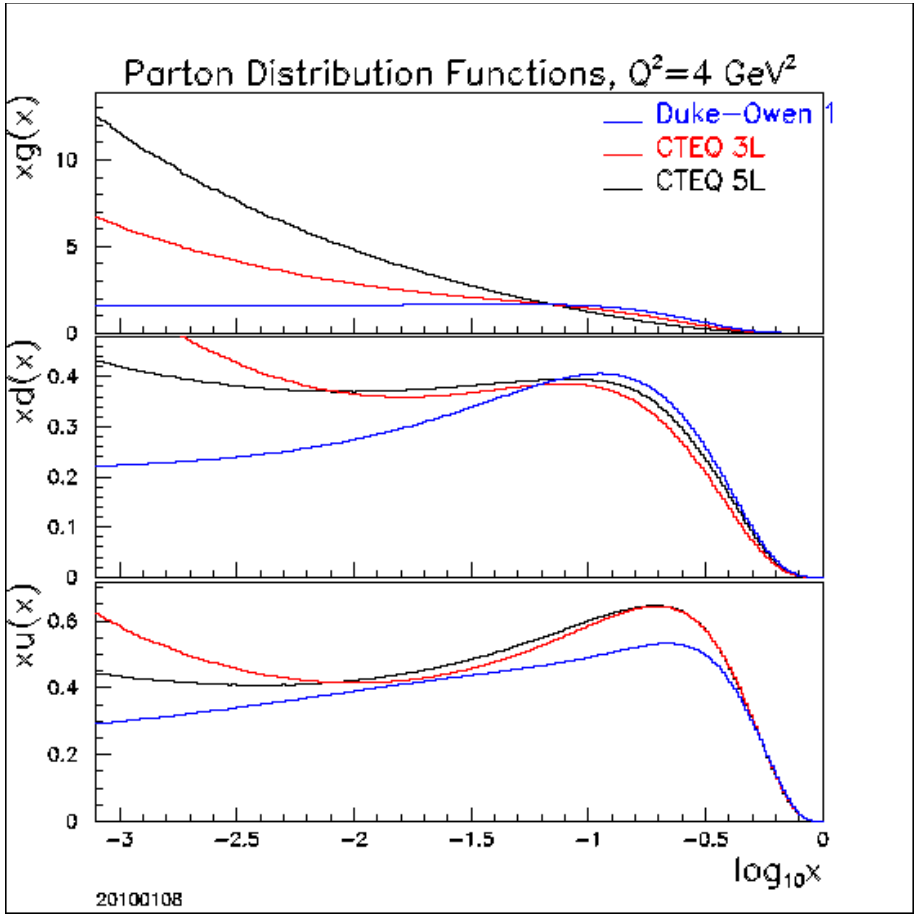
Here the $f_i(x,t)$ are the parton-distribution functions, expressing the probability of finding a parton $i$ carrying a fraction $x$ of the total momentum if the hadron is probed at virtuality $Q^2$. The $P_{a\to bc}(z)$ are given in eq. (164). As before, $\alpha_{abc}$ is $\alpha_s$ for QCD shower and $\alpha_{em}$ for QED ones.

The splitting kernels $P_{a\to bc}(z)$ are

$$\begin{aligned}
P_{q\to qg}(z) &= C_F \frac{1+z^2}{1-z} , \\
P_{g\to gg}(z) &= N_C \frac{(1-z(1-z))^2}{z(1-z)} , \\
P_{g\to q\bar{q}}(z) &= T_R \left(z^2 + (1-z)^2\right) , \\
P_{q\to q\gamma}(z) &= e_q^2 \frac{1+z^2}{1-z} , \\
P_{\ell\to \ell\gamma}(z) &= e_\ell^2 \frac{1+z^2}{1-z} ,
\end{aligned} \tag{164}$$

with $C_F = 4/3$, $N_C = 3$, $T_R = n_f/2$ (i.e. $T_R$ receives a contribution of 1/2 for each allowed $q\bar{q}$ flavour), and $e_q^2$ and $e_\ell^2$ the squared electric charge (4/9 for u-type quarks, 1/9 for d-type ones, and 1 for leptons).

# PDFs before and after HERA



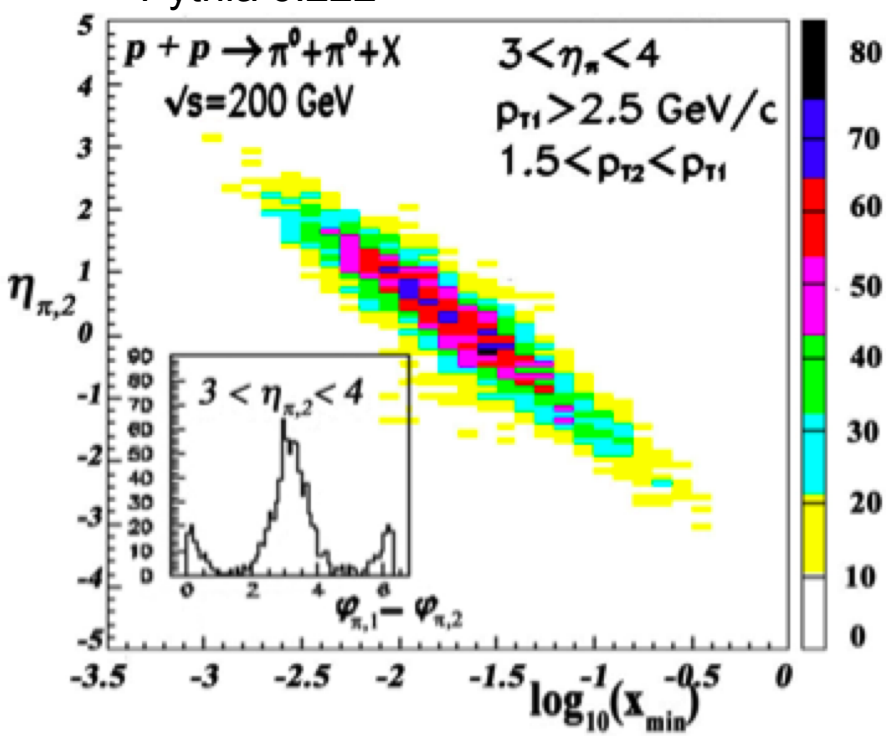

At RHIC $Q^2 \sim p_T^2$
Our $p_T \sim 2$ GeV
Is sensitive to
$0.001 < x < 0.01$

Note the large changes in xg(x) at low x

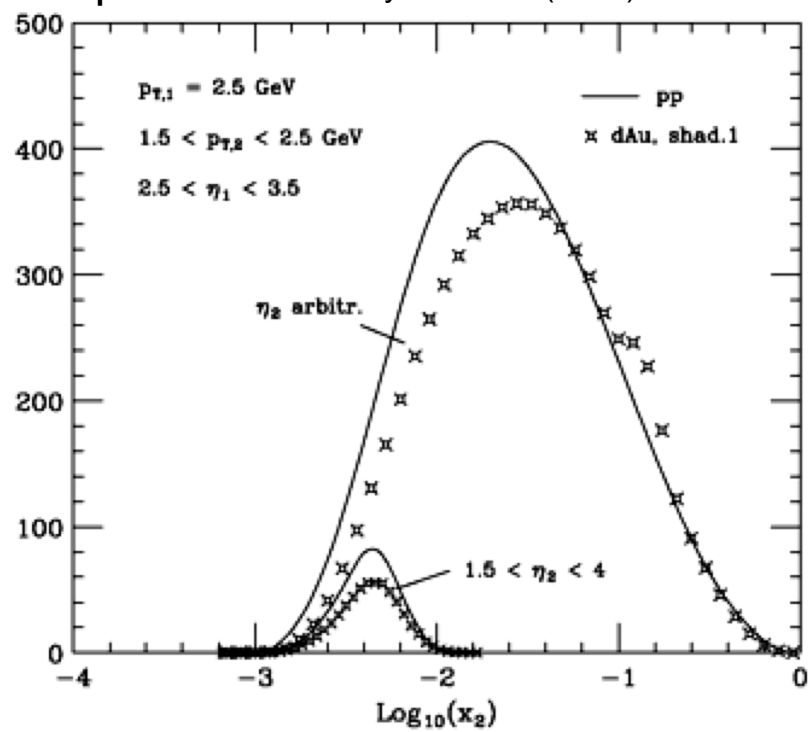
in range .01-.001 we can already contribute

# X1 and X2
# momentum fractions of interacting partons

Pythia 6.222

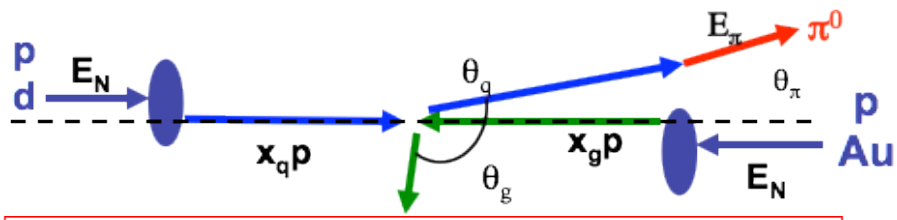


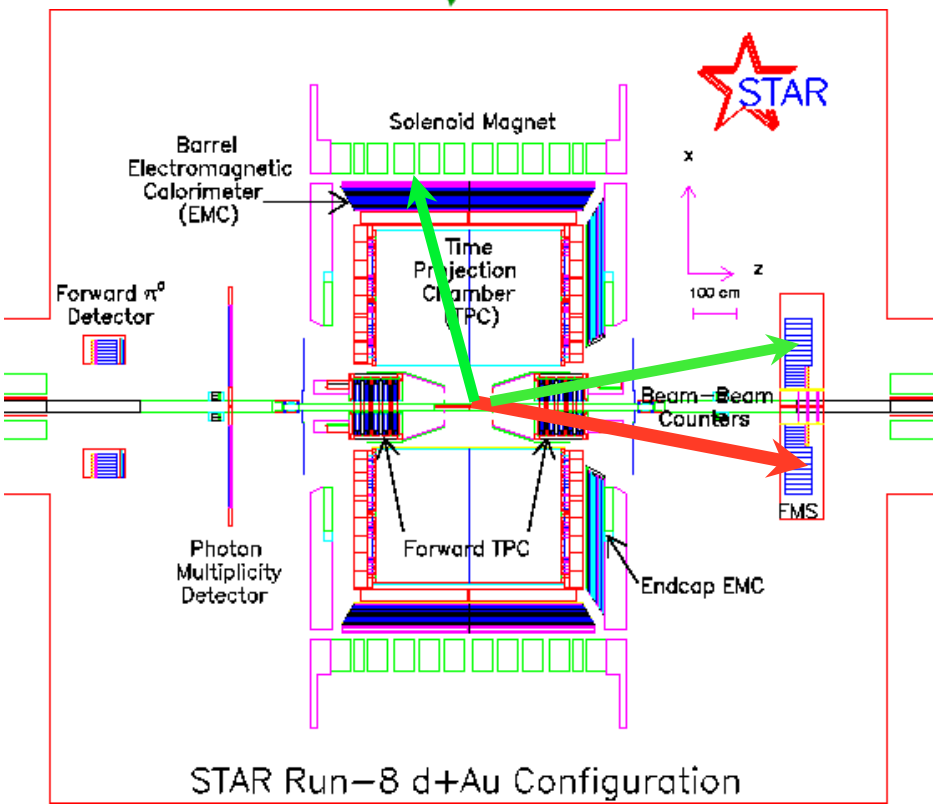

pQCD : GSV PhysLetB 603(2004)173



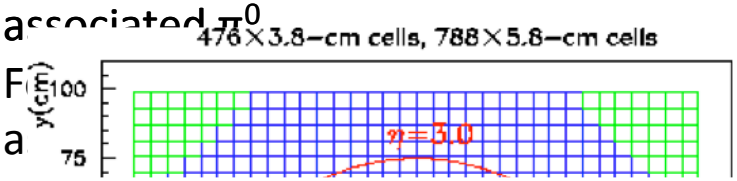

Get x from correlations between a trigger or leading particle ( a $\pi^0$ in the FMS) and a subleading particle (a TPC track hadron, or a BEMC $\pi^0$, or another FMS $\pi^0$)

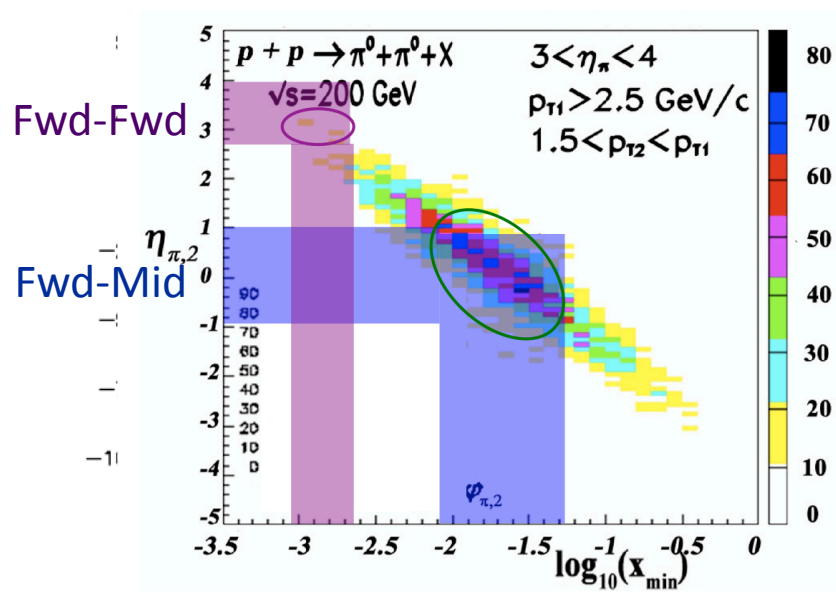
# 2-body kinematics at STAR



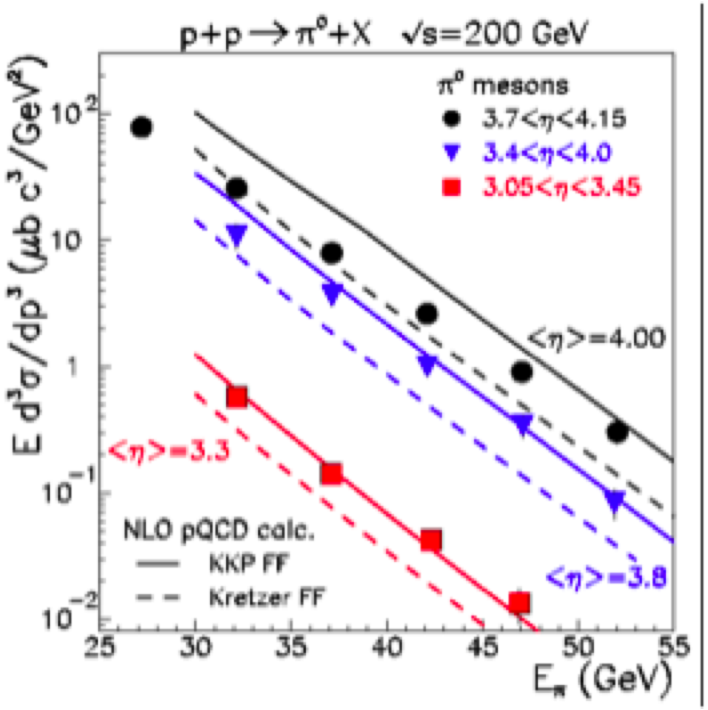

- Forward Meson Spectrometer (FMS)
- trigger $\pi^0$
- 2m*2m Projection Chamber (TPC)
- associated $h^\pm$
- Barrel EM Calorimeter (EMC)
- associated $\pi^0$
- F
- a

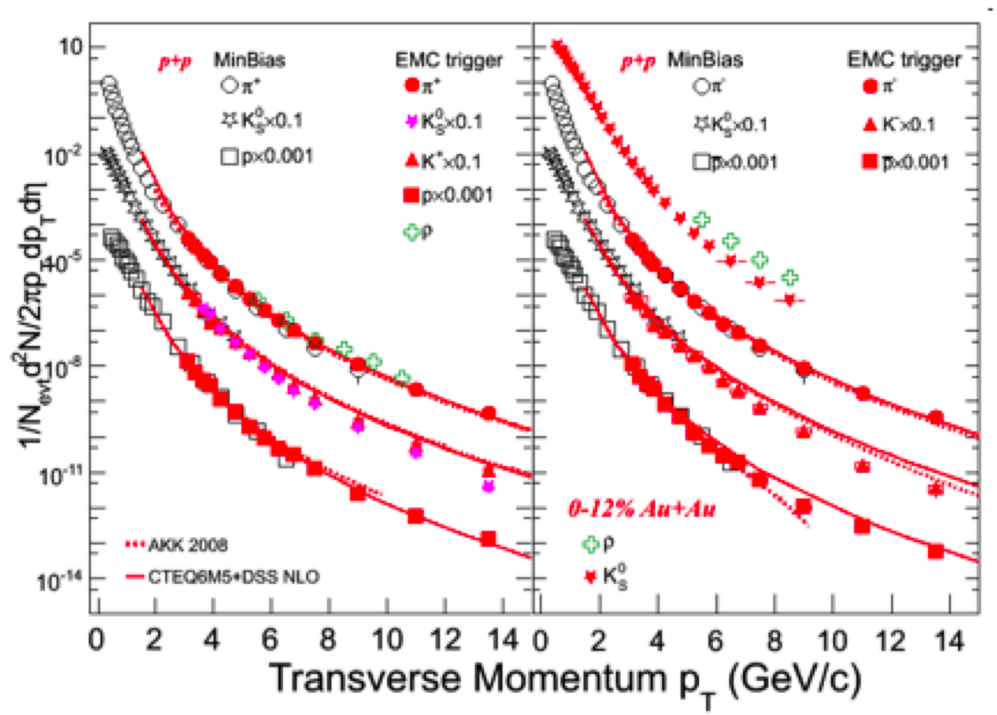


# NLO pQCD

Cross sections agree with NLO pQCD down to pT~2 GeV/c
over a wide range of pseudorapidity, 0<η<3.8, at sqrts=200 GeV




PRL 97 2006 152302 nucl-ex/0602011

Our $\pi^0$ data is used in "Global analysis of fragmentation functions for pions and kaons and their uncertainties" , D. de Florian, R. Sassot, M. Stratmann, Phys. Rev. D76 (2007) 114010.

Min bias pp data:
PLB 637 (2006) 161
Hi-$p_T$ data: Xu Y. QM09

Fits to “raw” data

# Pythia GSTAR vs Clusters in data

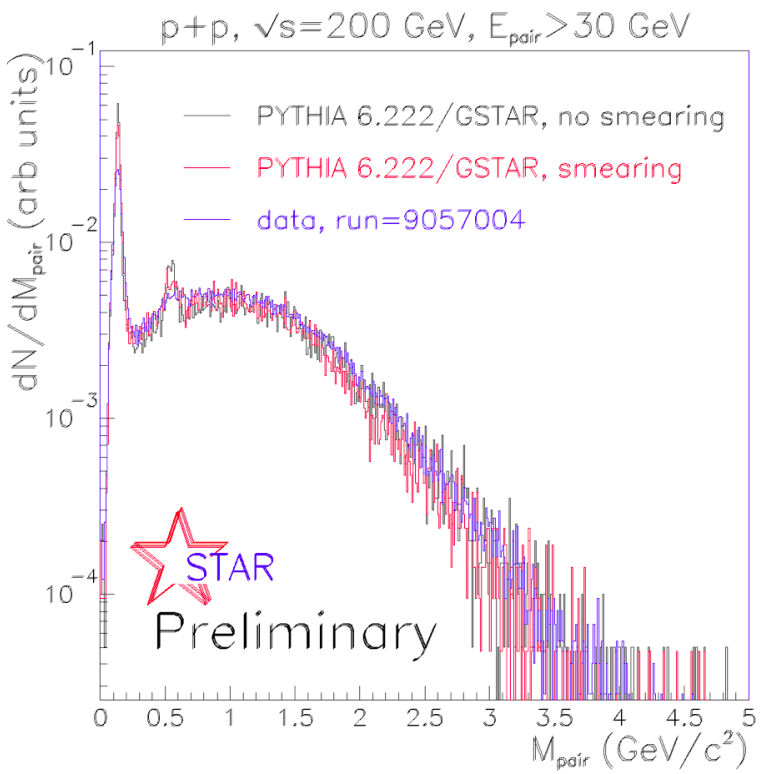
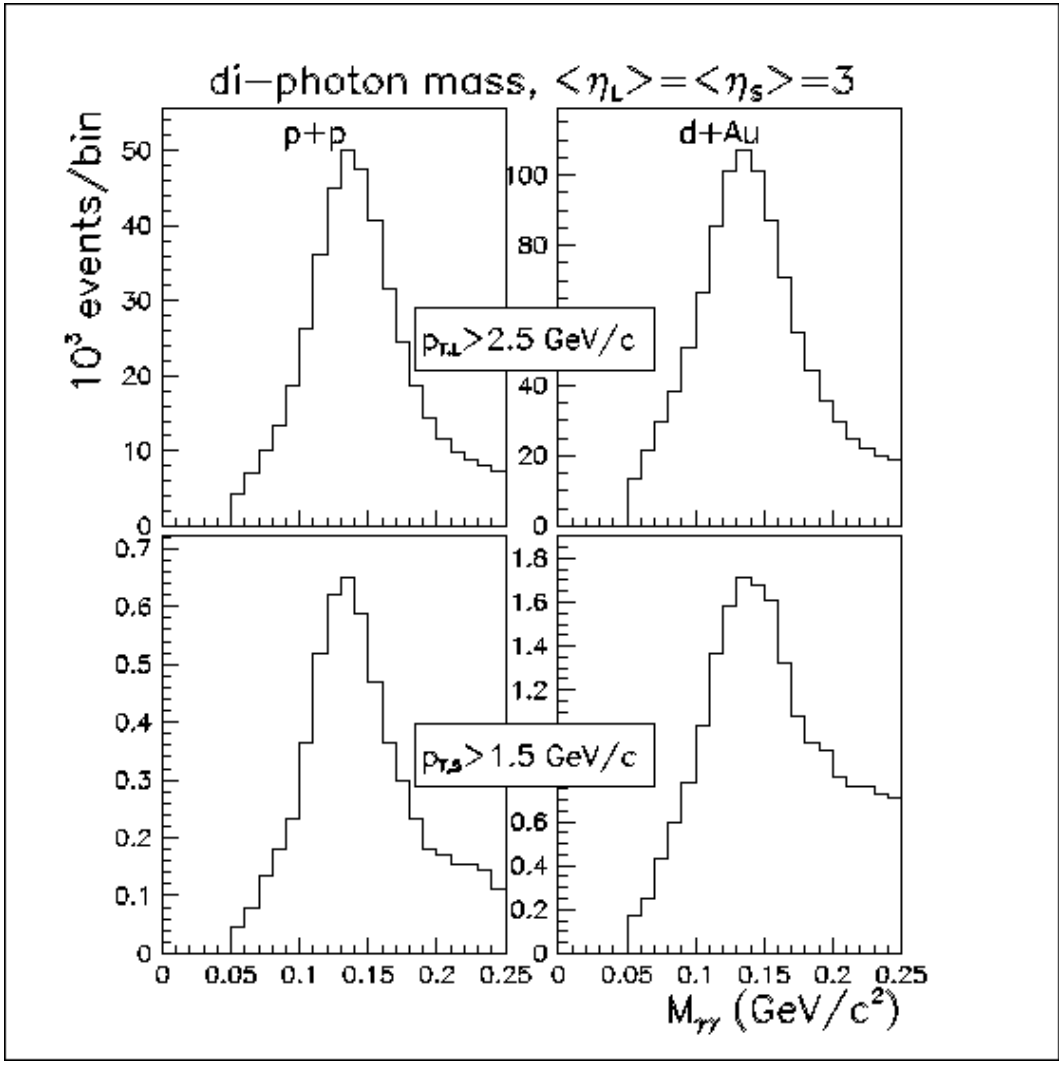



**Fig. 4** Intercomparison of cluster pair invariant mass from data (blue) to full PYTHIA/GEANT simulations from the Forward Meson Spectrometer. In general, most aspects of the p+p data are present in the PYTHIA/GEANT reconstructions [8].

arXiv:0906.23332

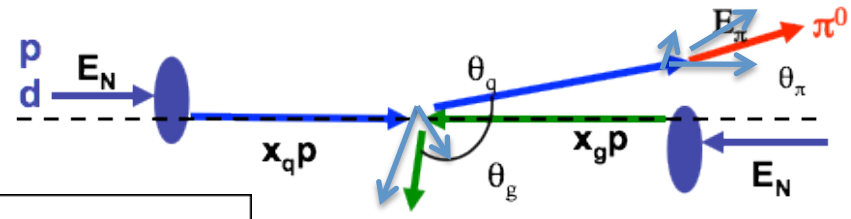
Pythia 6.222 agrees well with our data

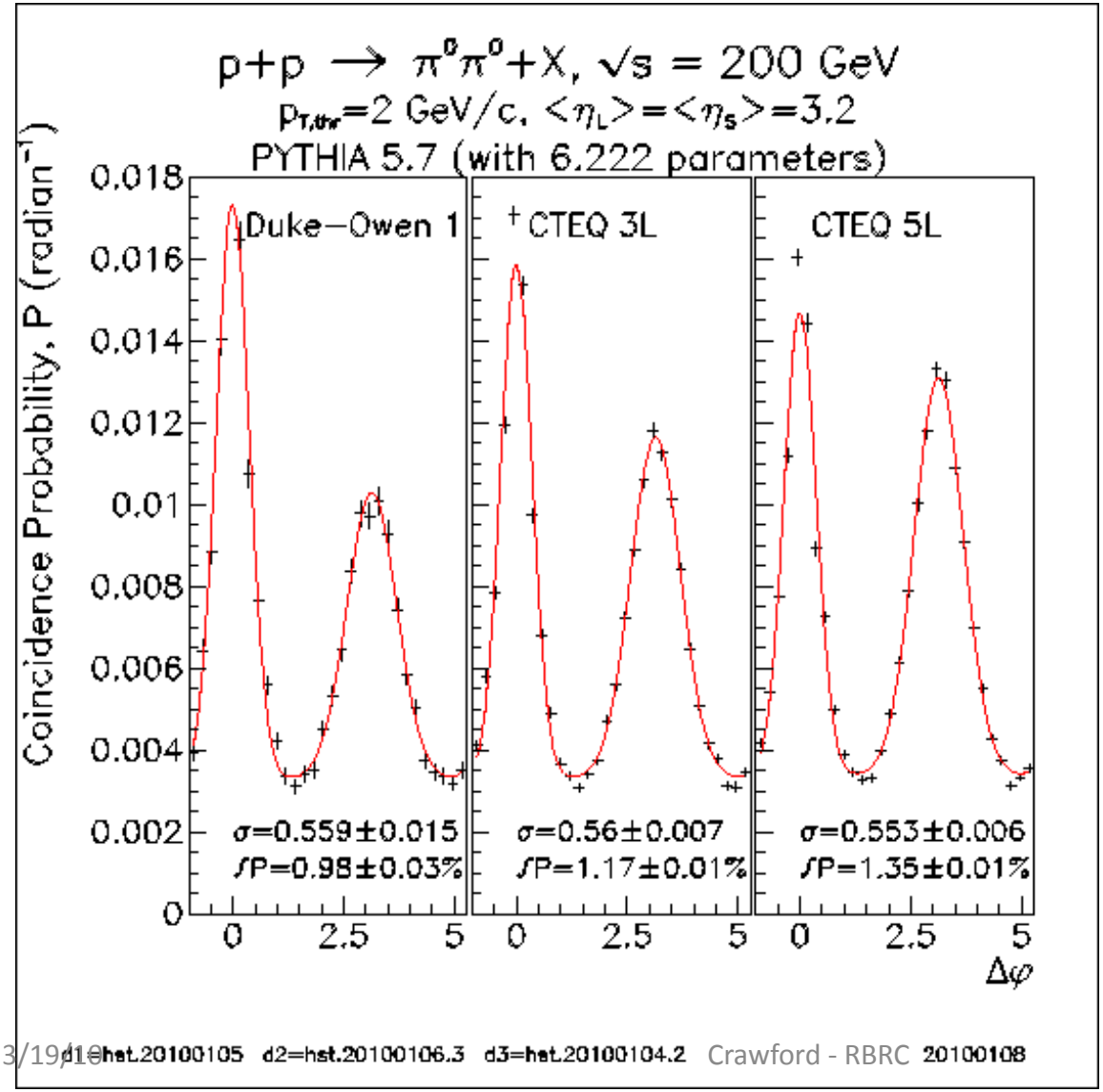
# General $\pi^0$ reconstruction




Typical mass
Cuts in analysis
$0.1<M_{\gamma\gamma}<0.2$ are
Identified as $\pi^0$

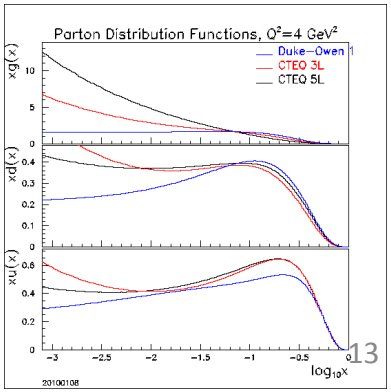
# Pythia Pdf sensitivity



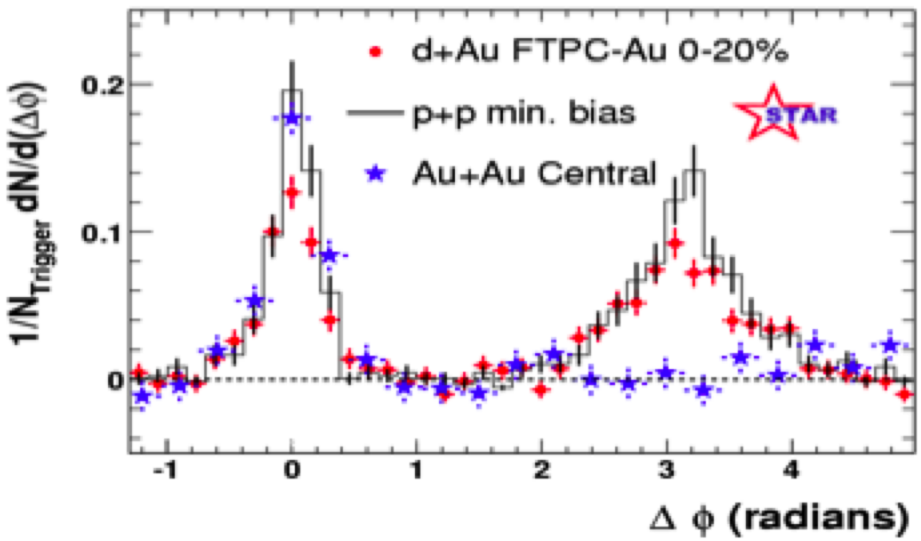




Our signal:
Same side and away side peaks and widths

(and composition)



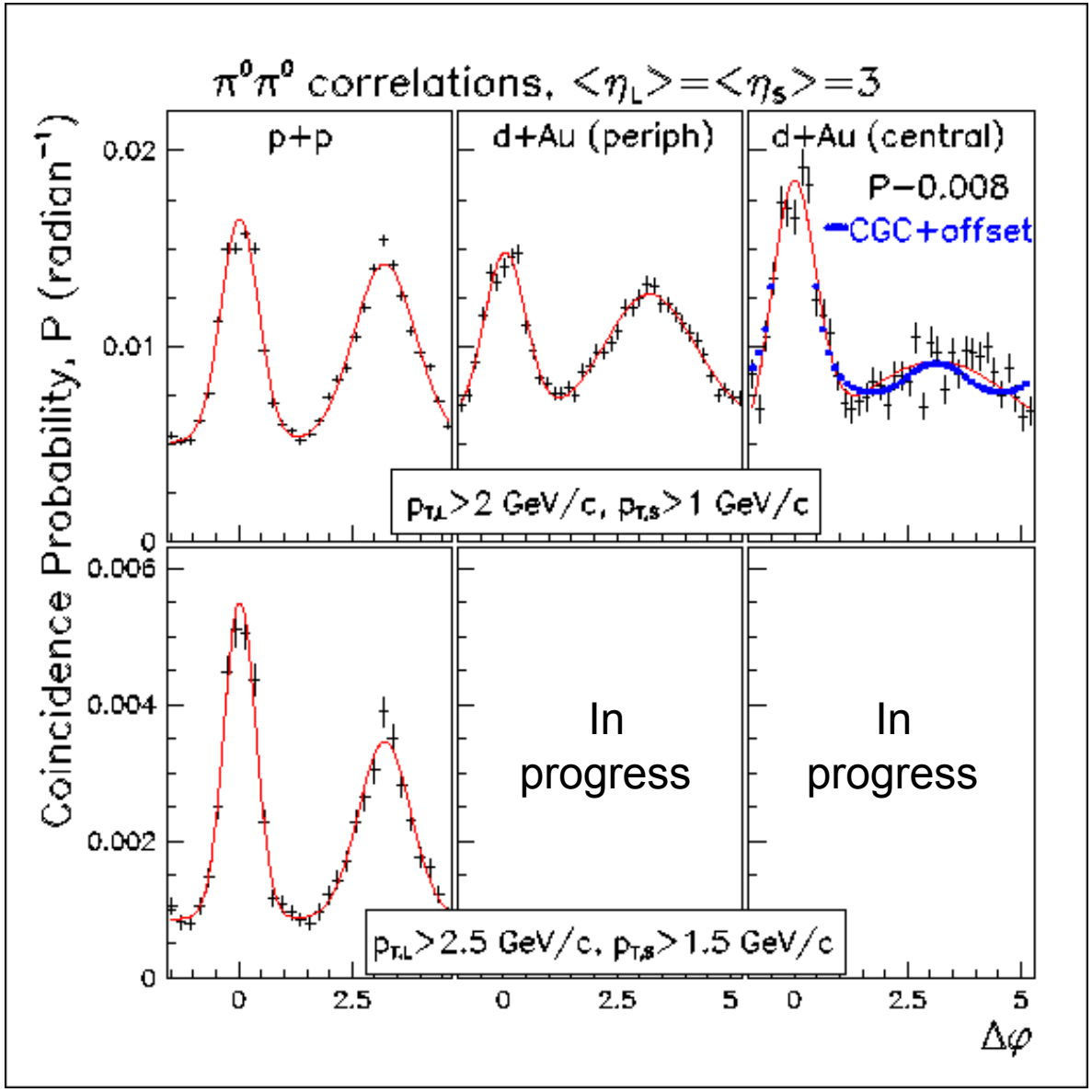
# First data – run 3




Away-side peak is gone in central AuAu collisions
Suppression as a function of "b"

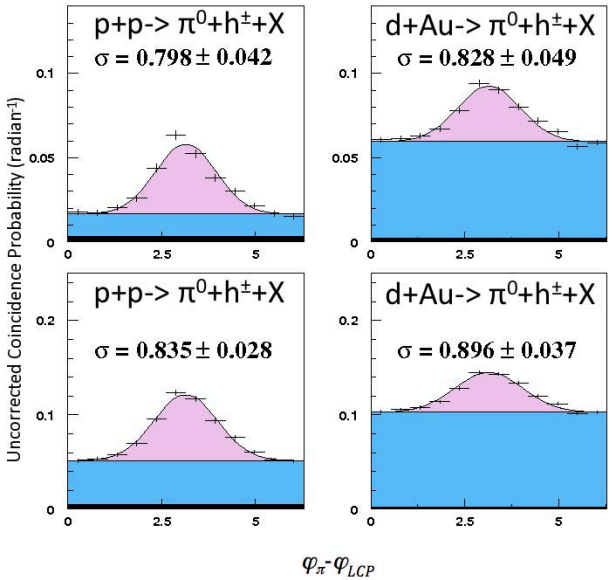
# FMS-FMS Data

Blue is from Marquette
See below

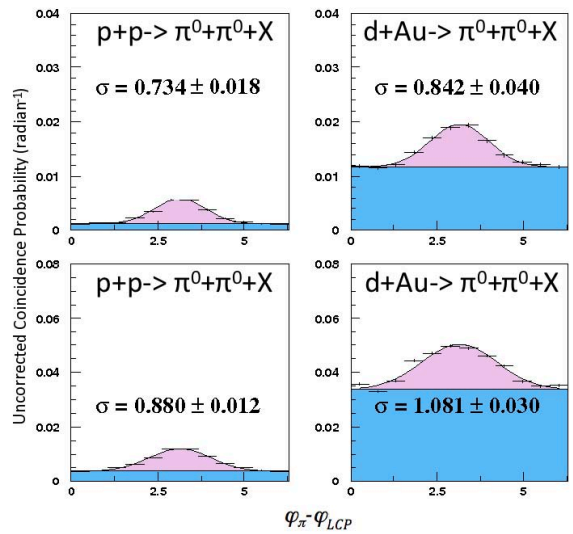


# Spanning -1<η<4.1 with FMS trigger

# $\pi^0$h-mid, $\pi^0\pi^0$-mid, $\pi^0\pi^0$-fwd

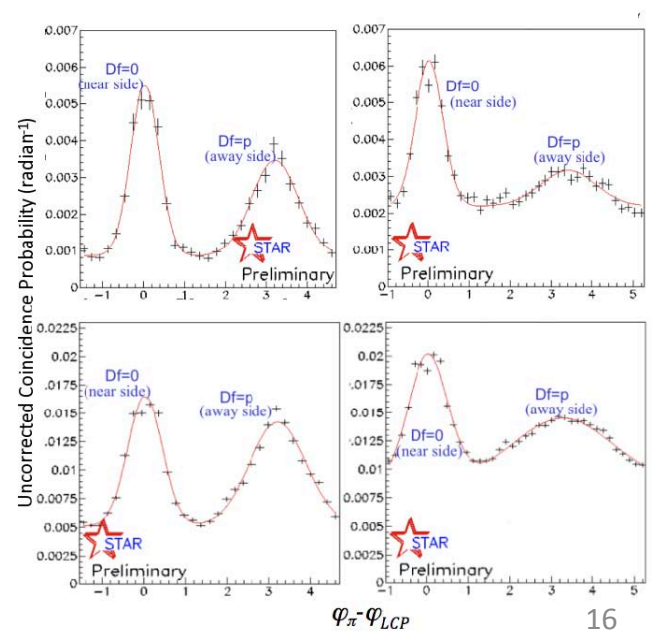



Made possible by STAR coverage



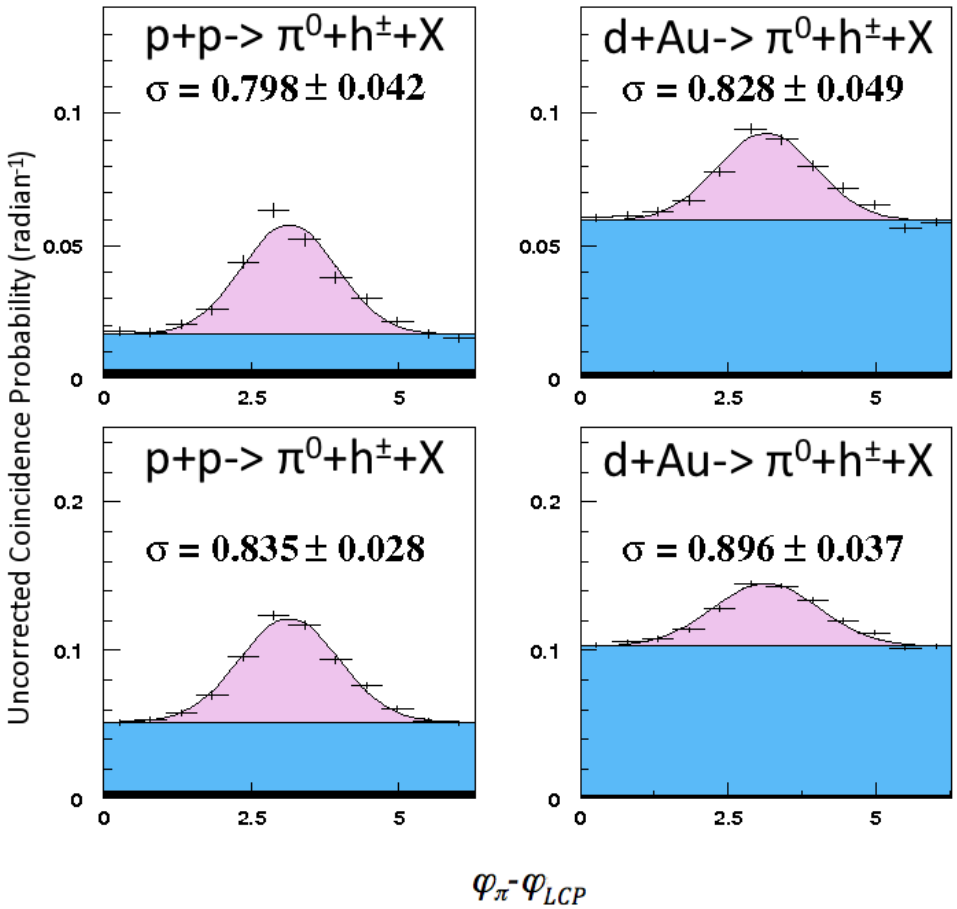

Centrality averaged

2 trigger $p_T$s each



# FMS-TPC: $\pi^0_{FWD}$-$h_{MID}$ $p_T$ dependence

p+p STAR PRELIMINARY d+Au




$p_T^{(FMS)}$>2.5GeV ; $p_T^{(TPC)}$>1.5GeV

$p_T^{(FMS)}$>2.0GeV ; $p_T^{(TPC)}$>1.0GeV

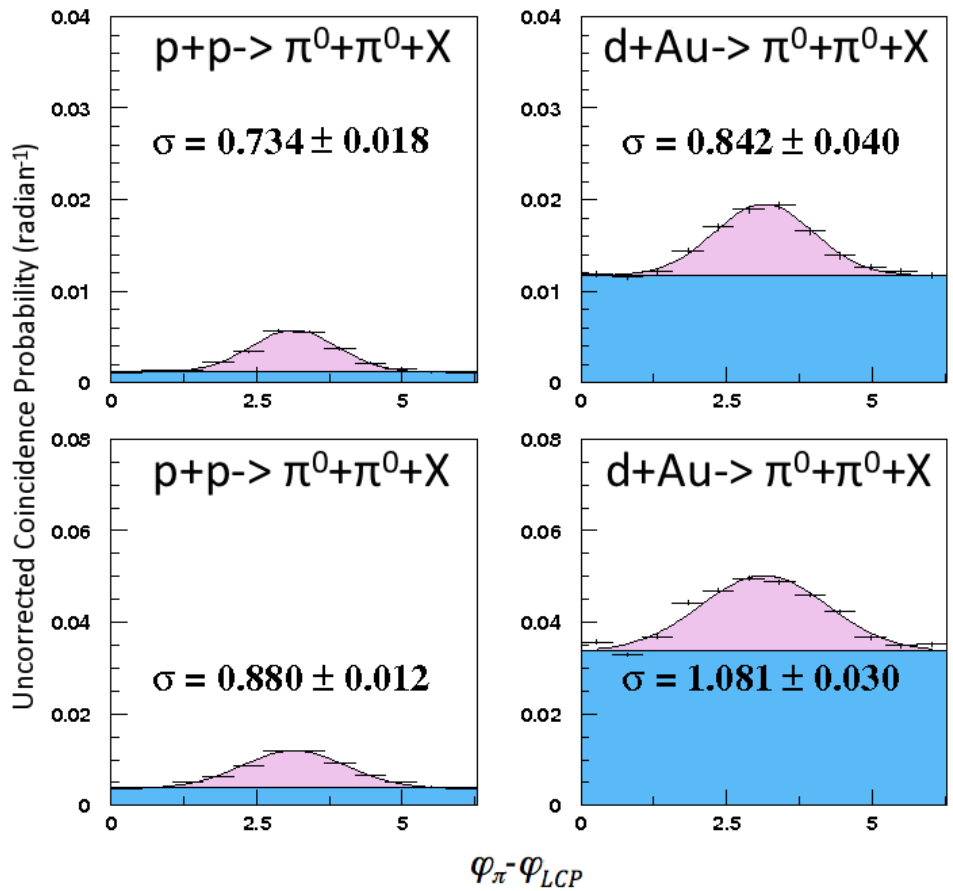
dAu ≈ pp

# FMS-BEMC: $\pi^0_{FWD}$-$\pi^0_{MID}$ $p_T$ dependence

$p_T^{(FMS)}$>2.5GeV ; $p_T^{(bEMC)}$>1.5GeV

$p_T^{(FMS)}$>2.0GeV ; $p_T^{(bEMC)}$>1.0GeV

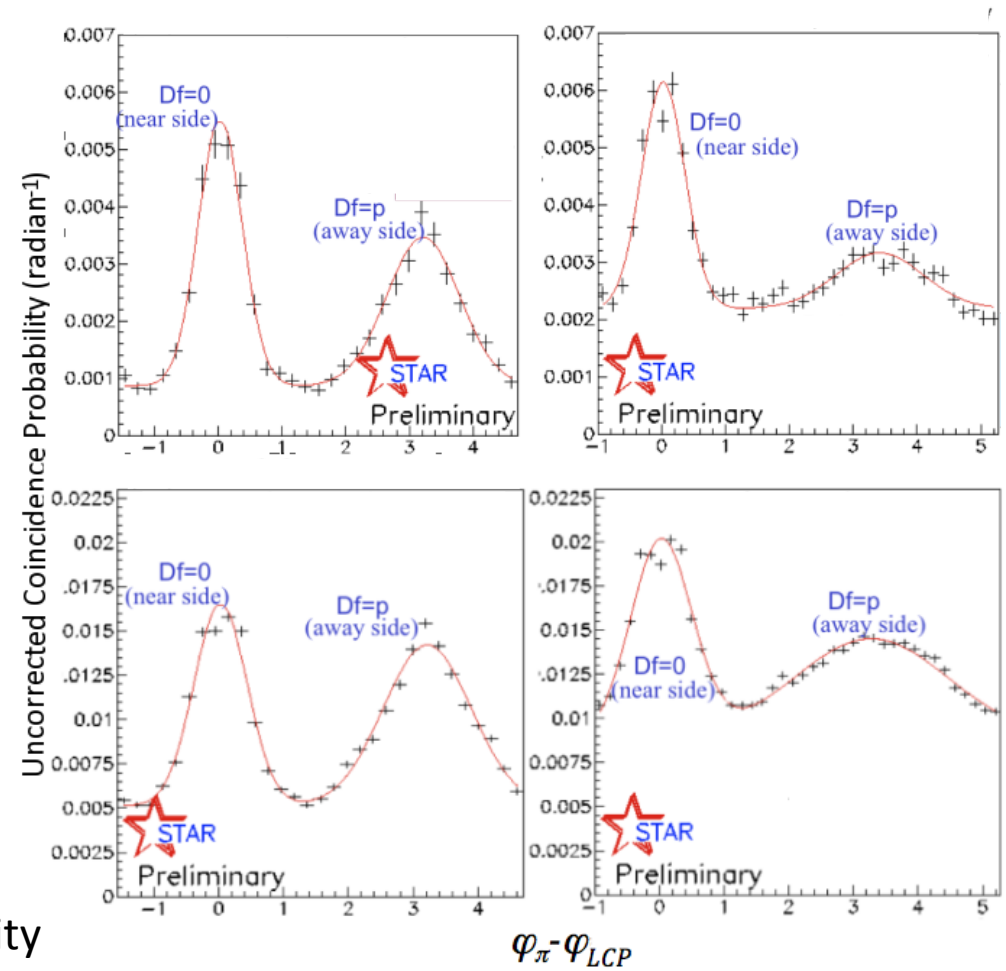
Gaussian+constant fit to away-side dAu significantly broader than pp



# FMS-FMS : $\pi^0$-$\pi^0$ $p_T$ dependence

$p_{TL}^{(FMS)}$>2.5GeV; $p_{TS}^{(FMS)}$>1.5GeV

$p_{TL}^{(FMS)}$>2.0GeV; $p_{TS}^{(FMS)}$>1.0GeV



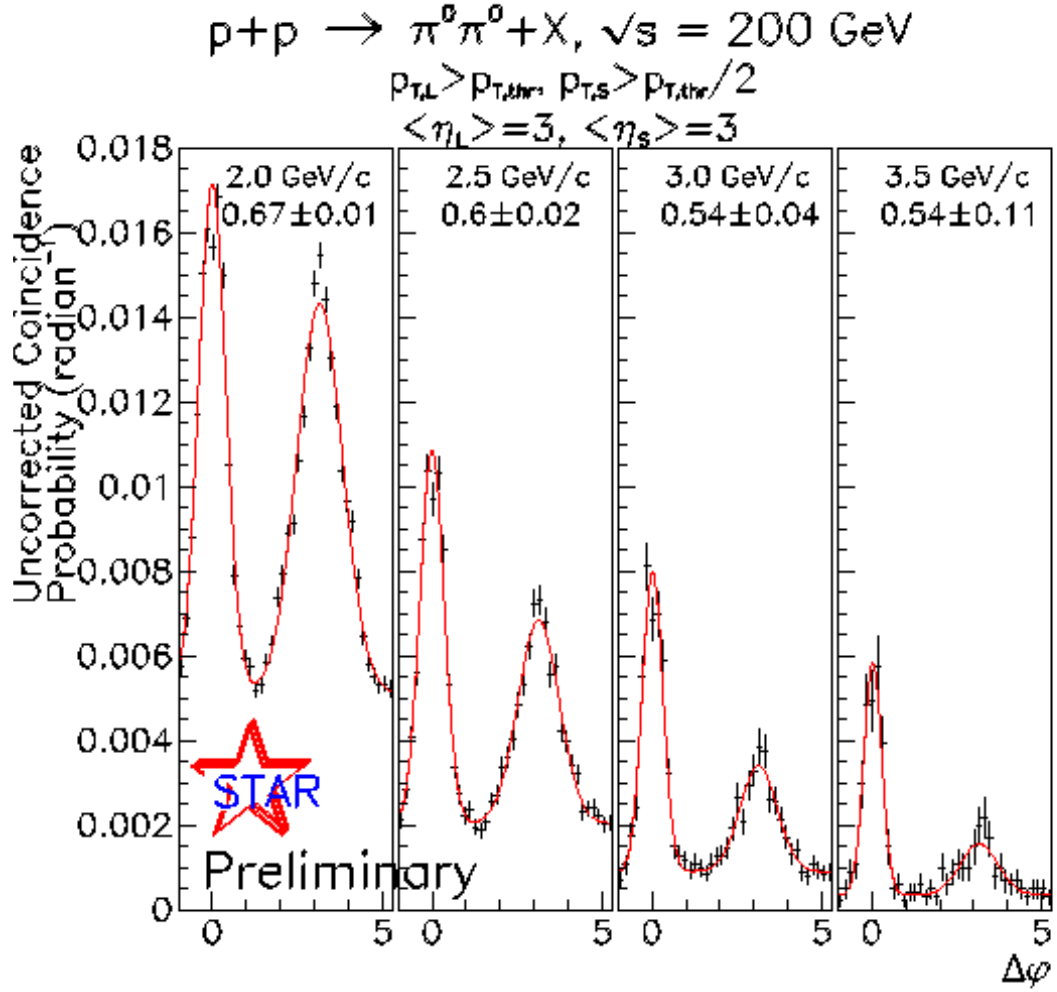

dAu much broader than pp

In addition to $p_T$, we can cut on centrality

# Scanning pt

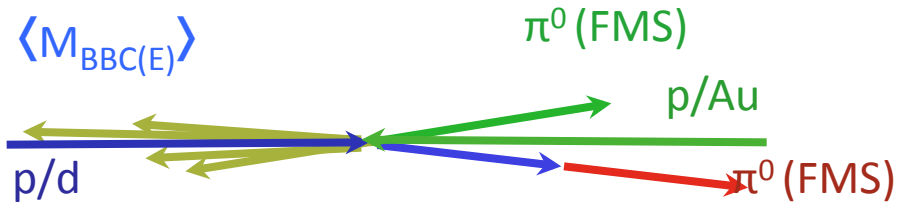
**Normalized to number of events with leading $P_T(\pi^0)$> 2.0 GeV**

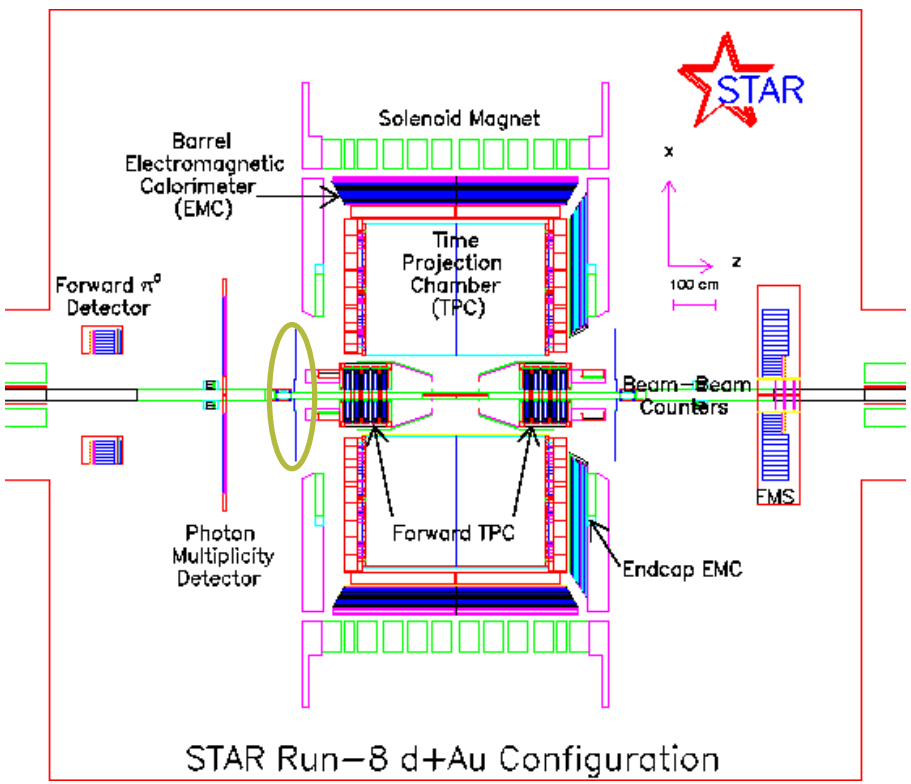
**No efficiency corrections (may have some ϕ dependence)**

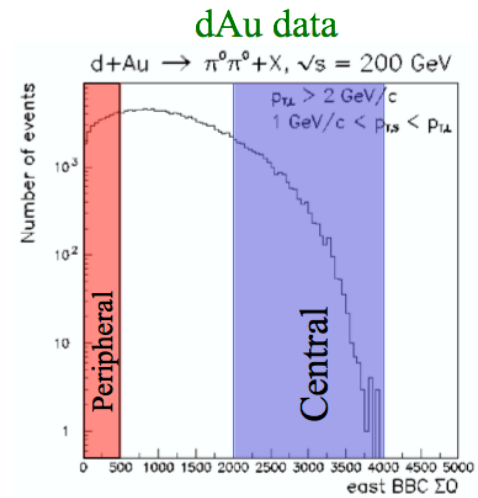



**Wider range $p_T$ scan ($p_T^{Trig}$ =2.0 to 3.5GeV, $p_T^{Asso}$ = $p_T^{Trig}$ /2) for dAu is coming**

# Centrality dependence of correlations

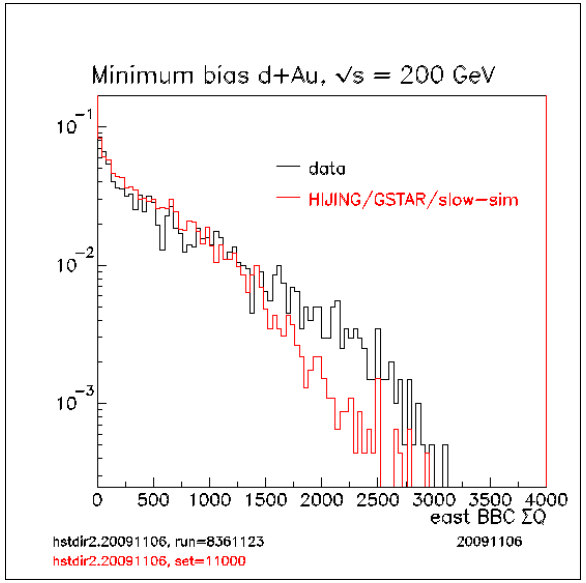


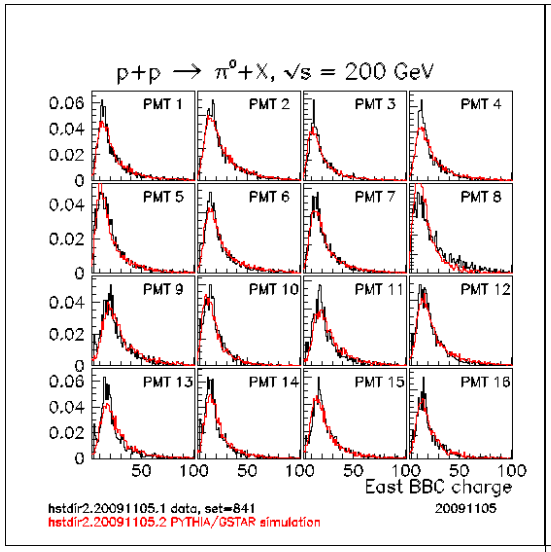



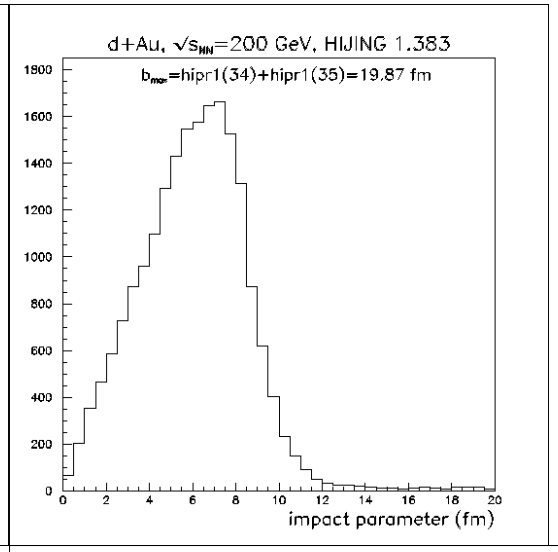




- Saturation expected more when thick part of the nucleus is probed
- Centrality selection through Au-side multiplicity
- Selection: charge sum from east (Au side: $-5.0 < \eta_{BBC} < -3.4$) BBC phototubes

# Impact parameter b in Hijing

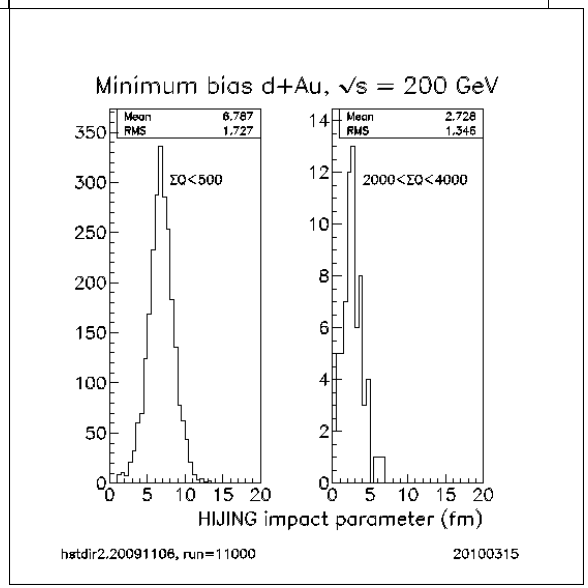


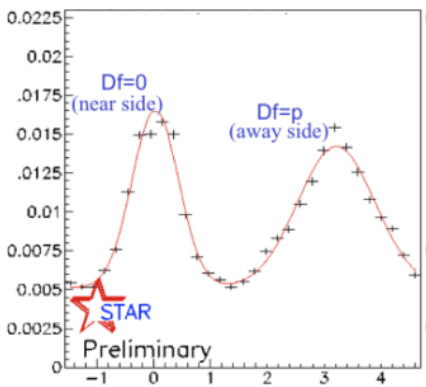

$\Sigma Q_{BBCE}$

| min | max | <b> (fm) | RMS.b (fm) |
|---|---|---|---|
| 0 | 500 | 6.8 | 1.7 |
| 2000 | 4000 | 2.7 | 1.3 |

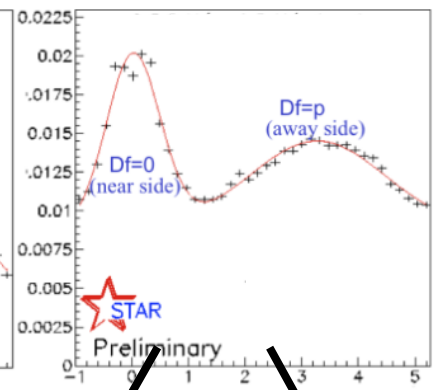


# Centrality dependence of correlations

p+p




d+Au

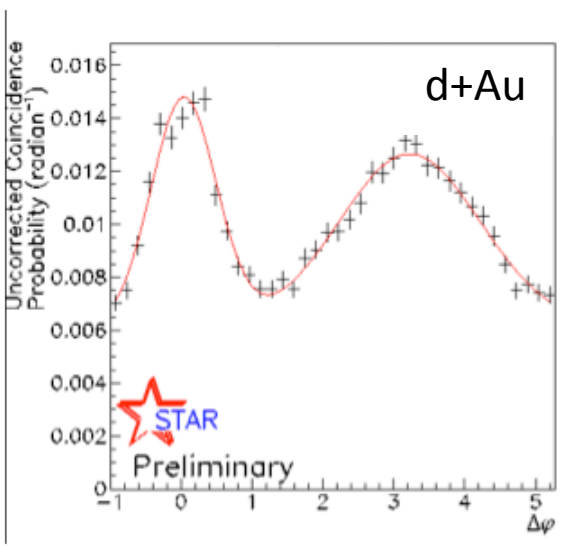


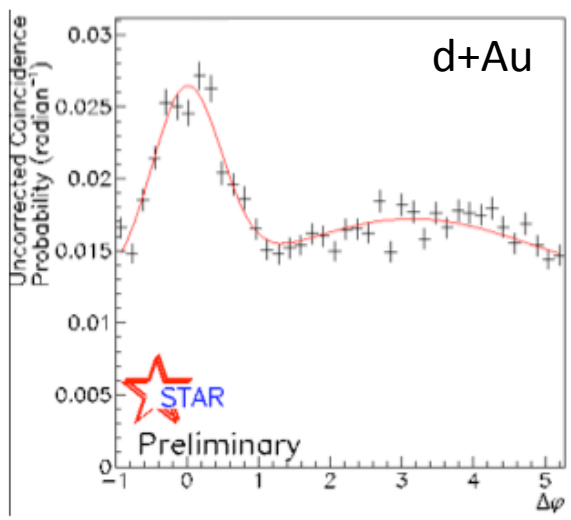

$p_{TL}^{(FMS)}$>2.0GeV
$p_{TS}^{(FMS)}$>1.0GeV

$\varphi_\pi - \varphi_{LCP}$

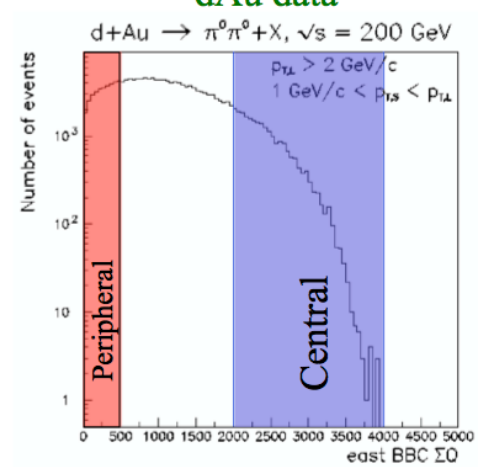
peripheral

central



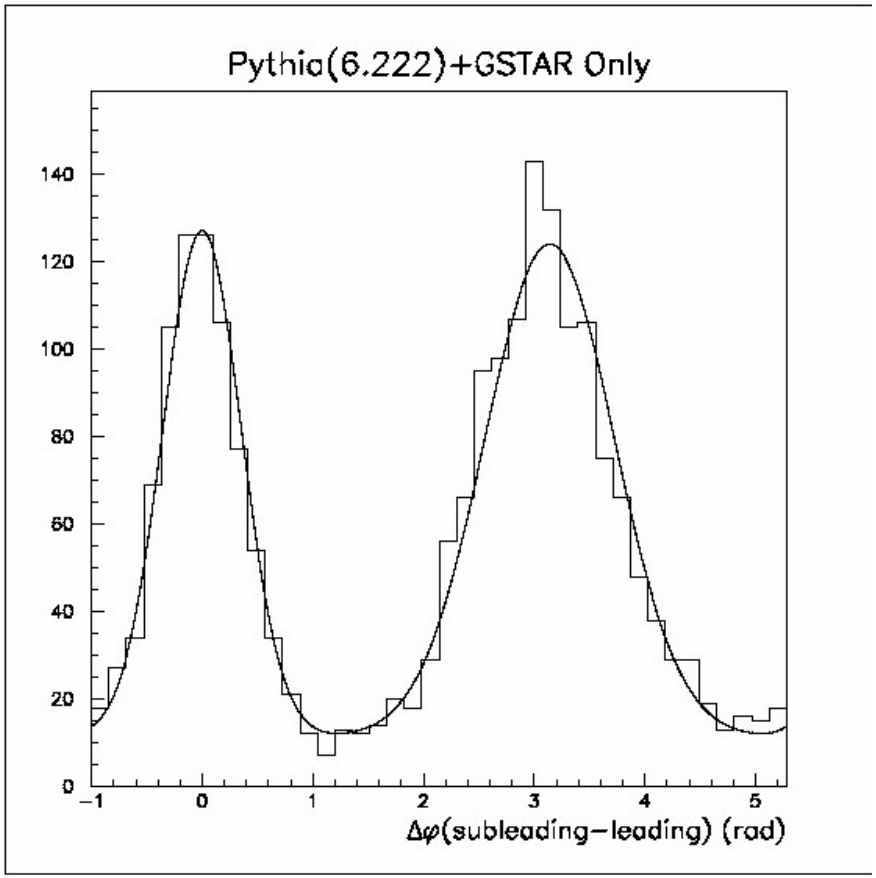



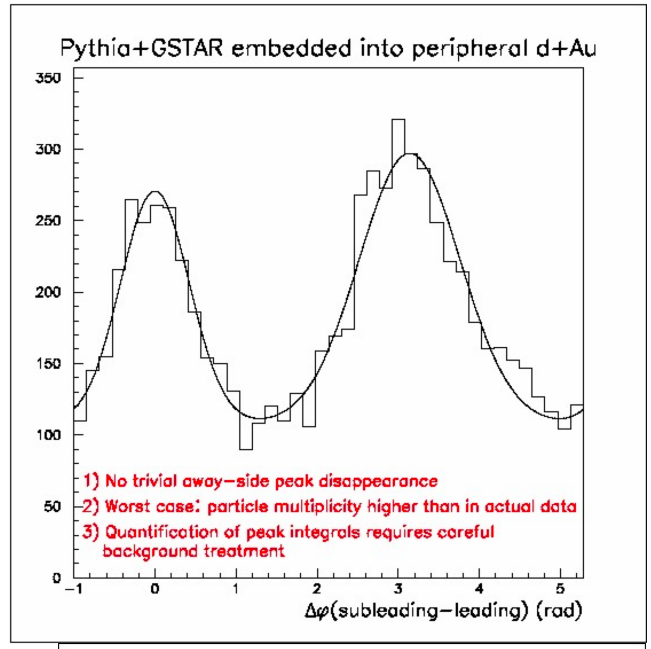

dAu data

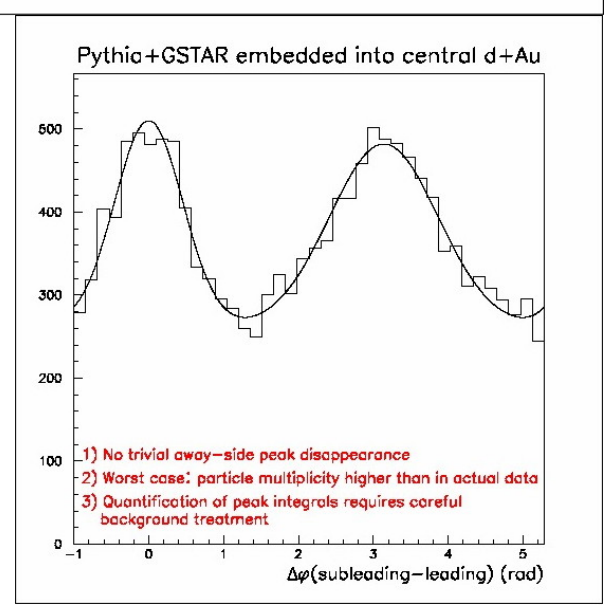



- Near-side peak similar p+p vs. d-Au
- Away-side signal changing with centrality:
- Peripheral d+Au collisions similar to p+p
- Central d+Au collision show strong suppression

# Embedding Study



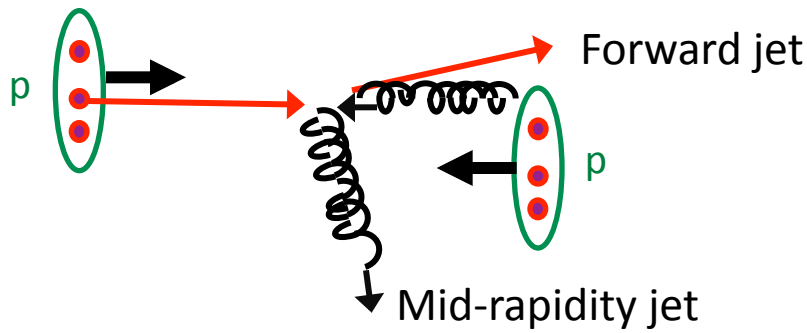




Correlation preserved even with mean multiplicity from embedding > multiplicity for triggered dAu data

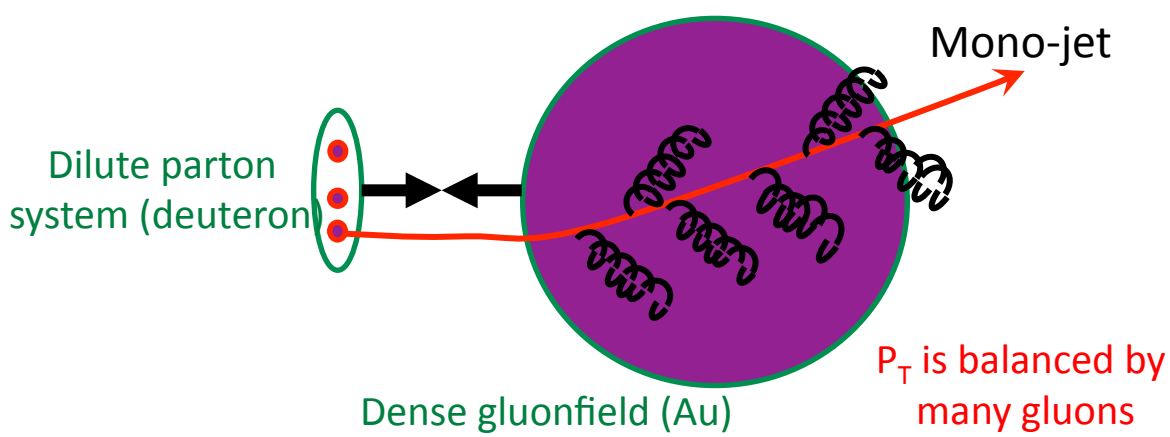
# Back-to-back Angular Correlations

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

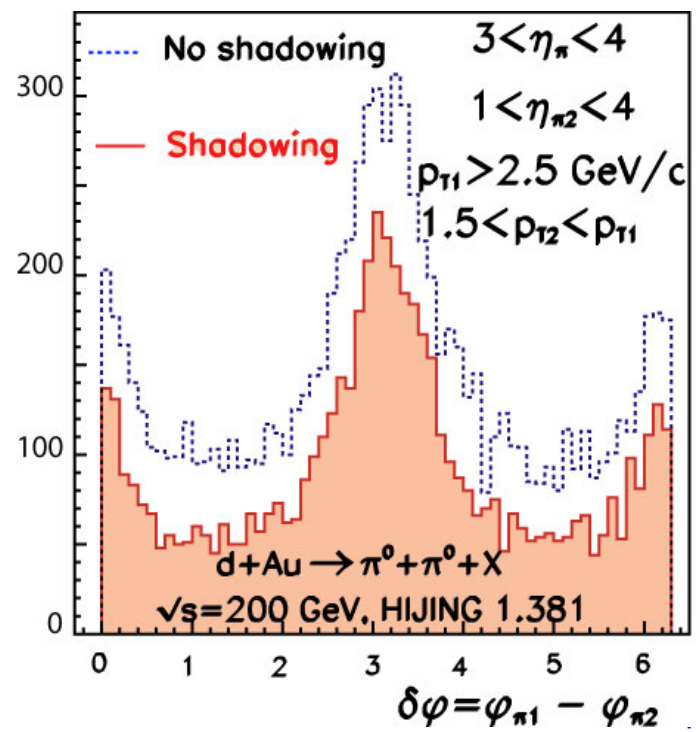



With high gluon density

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

A.Ogawa

# Comparison w/ Marquette

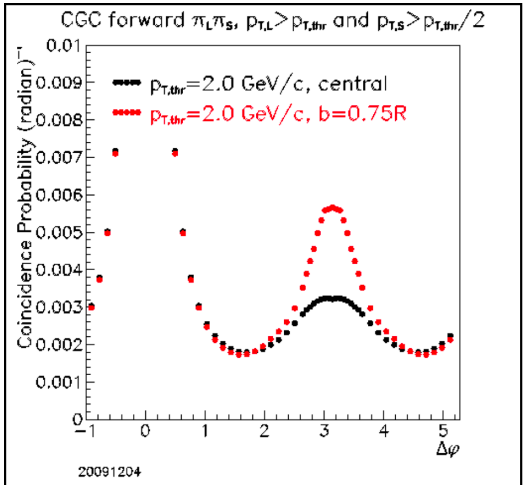



**Fig. 2b** Theoretical predictions in the framework of [1] for the centrality dependence of azimuthal correlations for d+Au collisions

CGC with $Q_0^2$=1.5 GeV$^2$

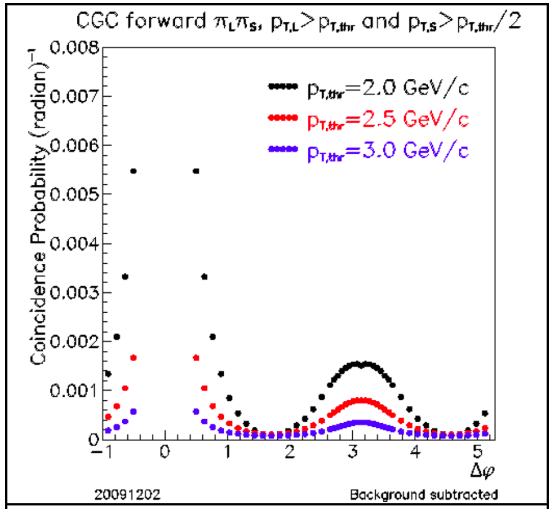
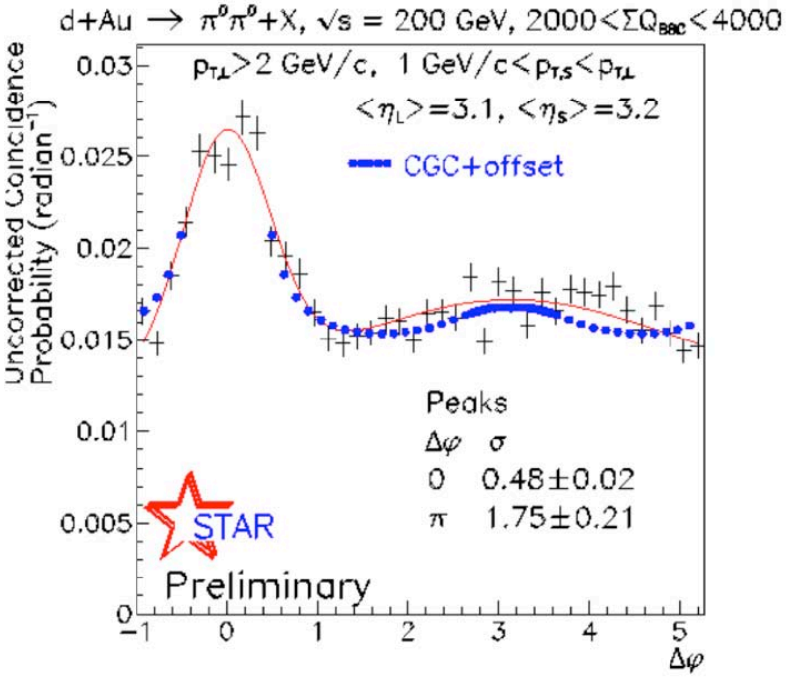



**Fig. 2a** Theoretical predictions in the framework of [1] for the $p_T$ dependence of azimuthal correlations for central d+Au collisions.




CM doing b strips to make better comparison

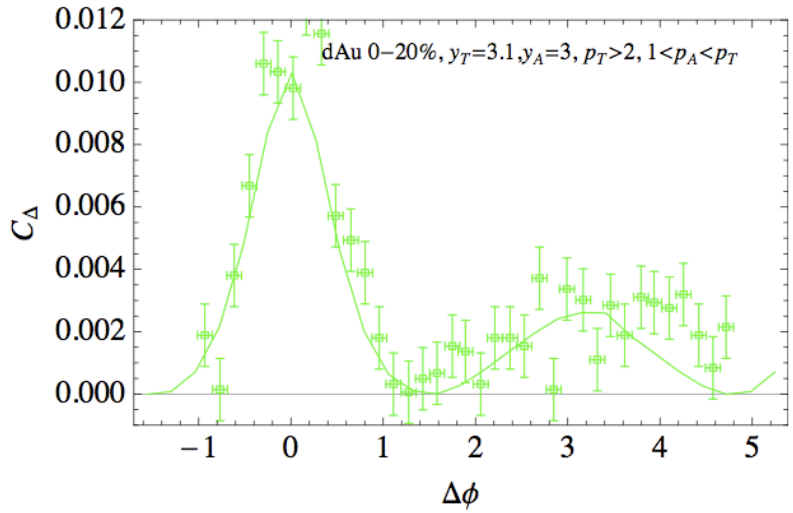
Cyrille Marquet: arXiv:0708.0231
Nucl.Phys.A796:41-60,2007

b=0

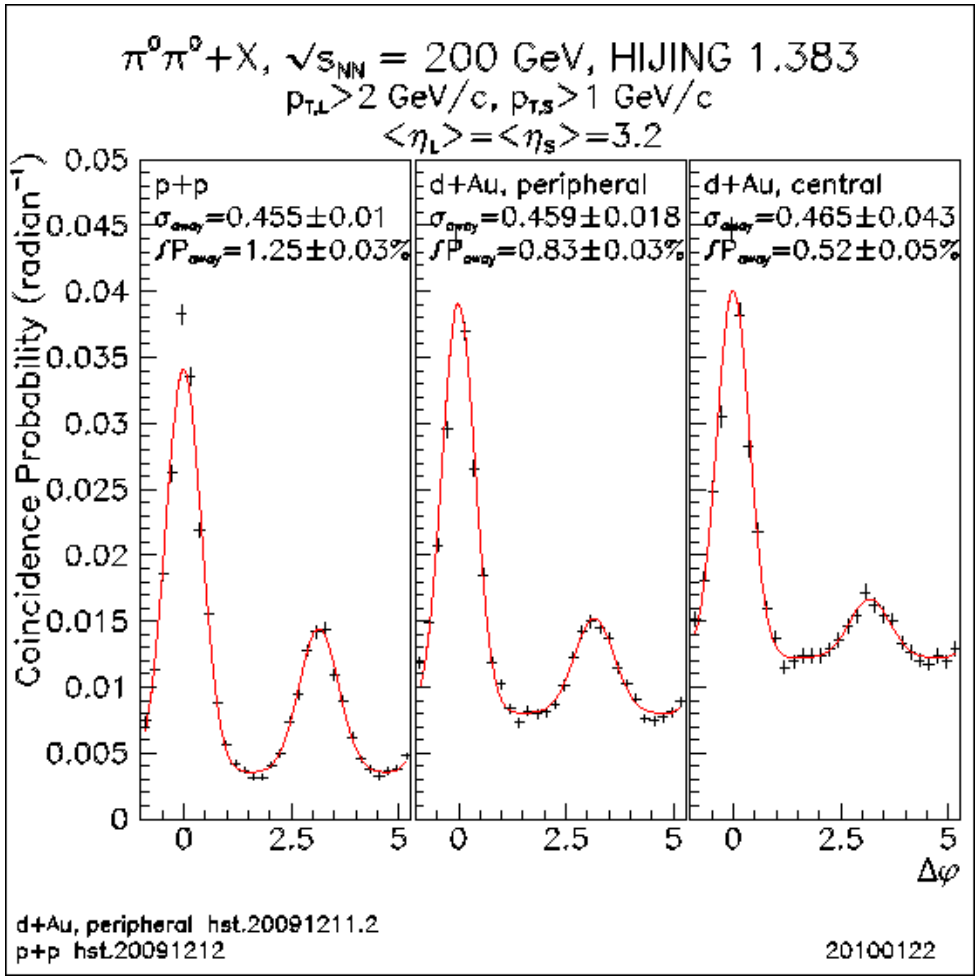
# Comparison with Tuchin

Kirill Tuchin: arXiv:0912.5479v1
normalized to peak height

CGC with $Q_0^2 \sim 1.5\ \mathrm{GeV}^2$

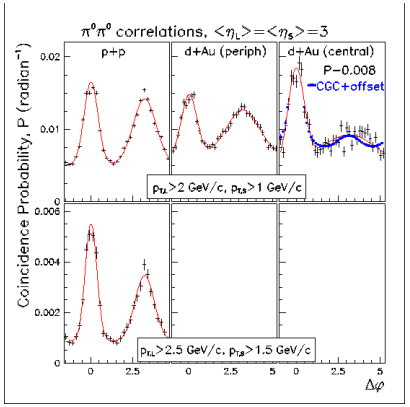


# Comparison to Hijing

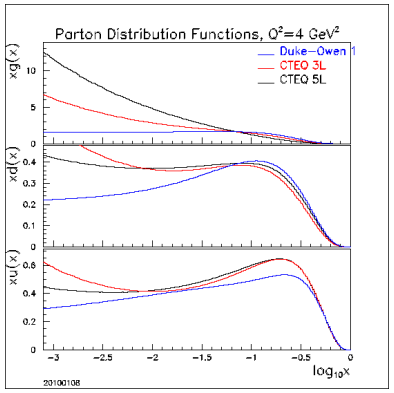



Does not reproduce data

Run8 data (see#16)




Uses Duke-Owen Which predates HERA



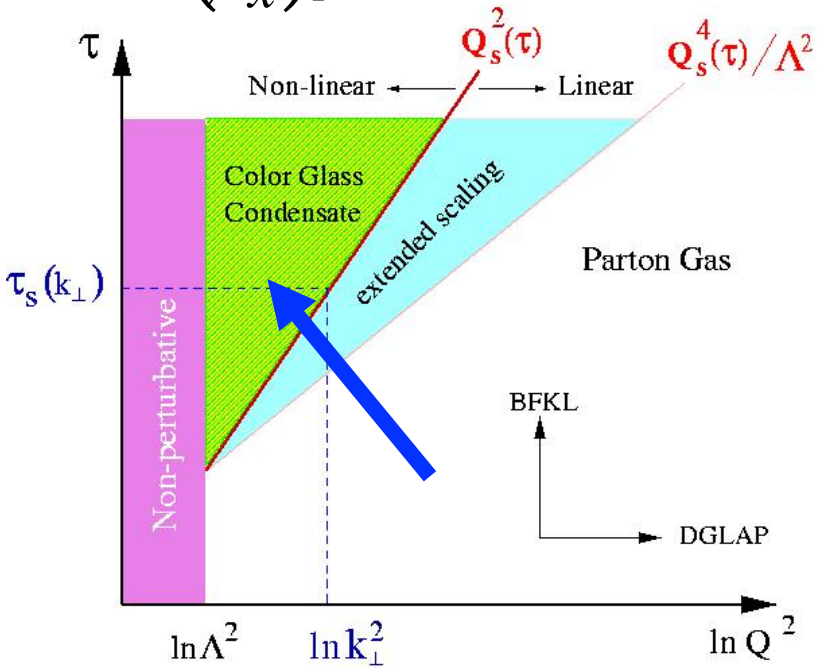

Also have uRQMD

(See#14)

# Forward rapidity d+Au

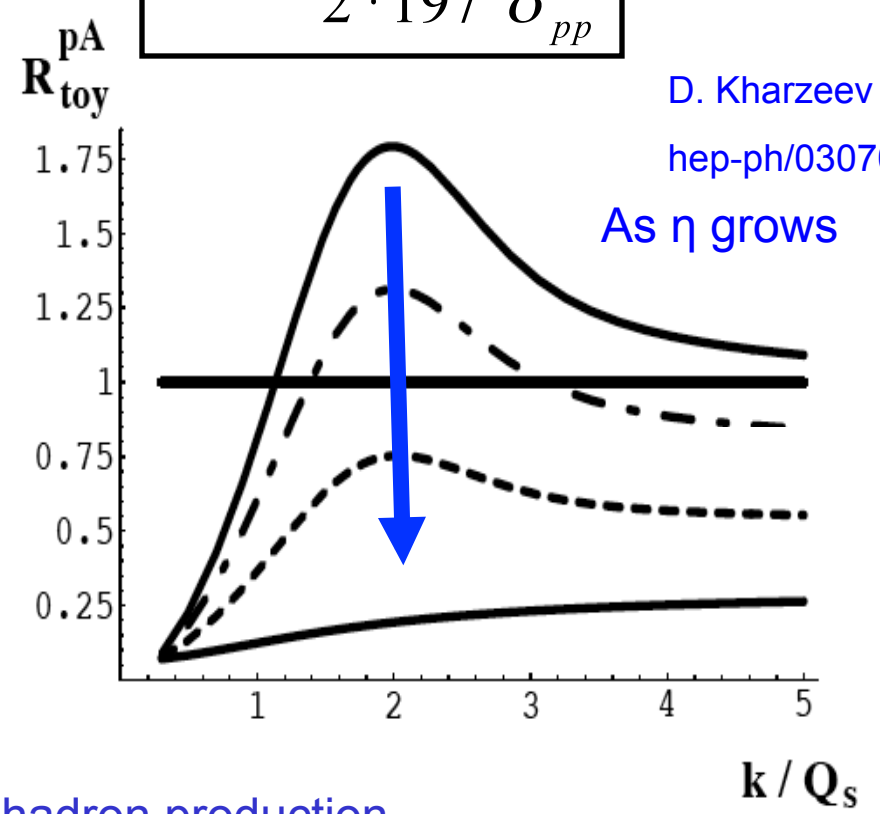
## Expectations from Color Glass Condensate

$$\tau = \ln\left(1/x\right)$$ τ related to rapidity of produced hadrons.




Iancu and Venugopalan, hep-ph/0303204

$$R_{dAu} = \frac{1}{2*197}\frac{\sigma_{dAu}}{\sigma_{pp}}$$



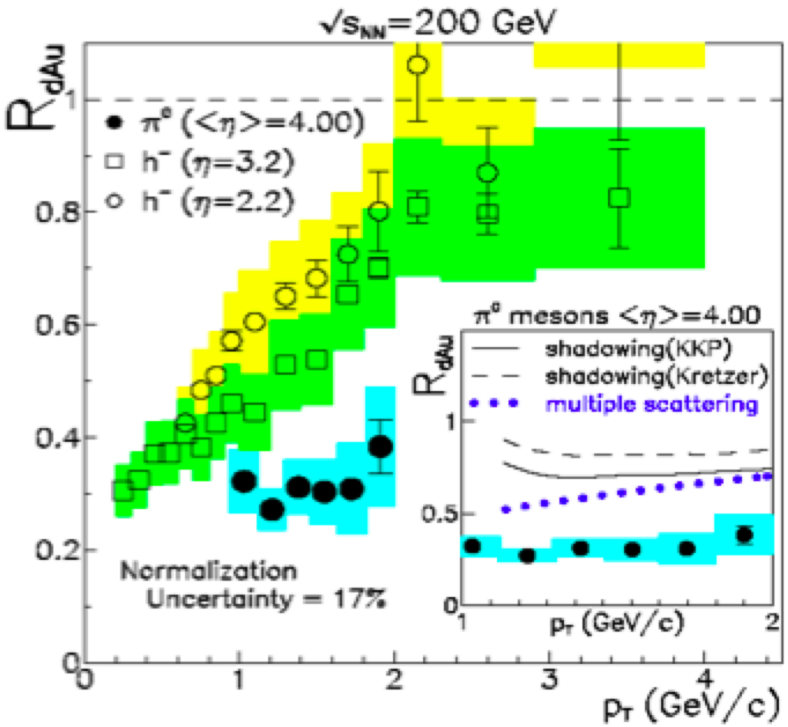

D. Kharzeev

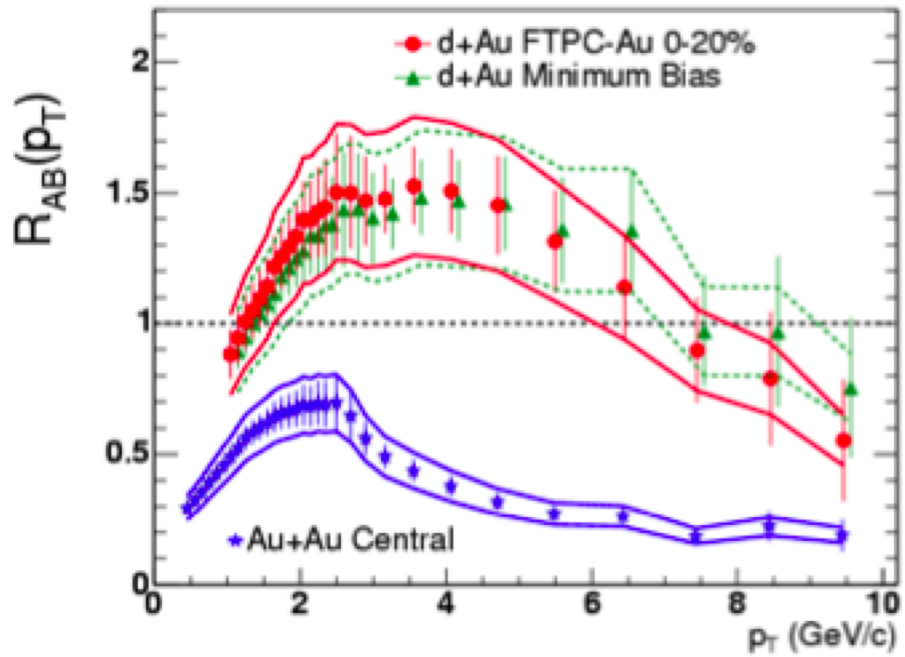
hep-ph/0307037

As η grows

CGC expects suppression of forward hadron production

# Suppression: $R_{dAu}$



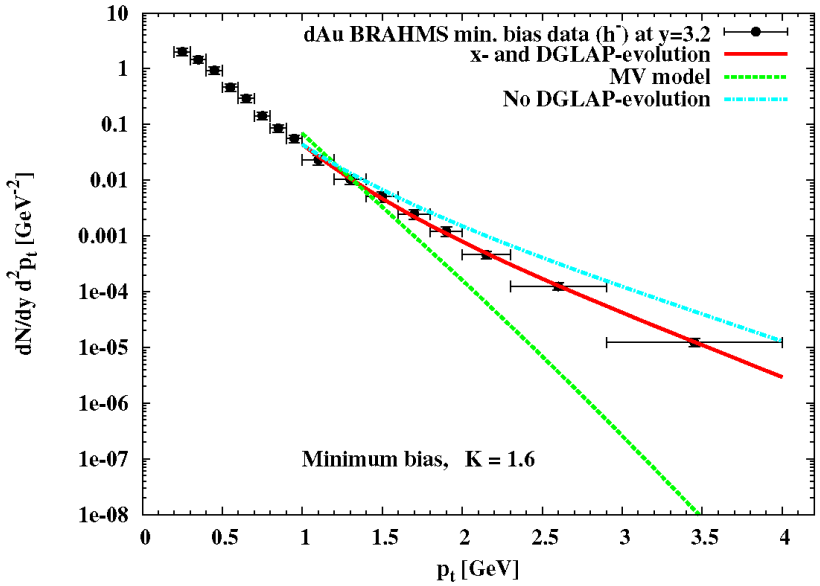




Note that overall π production is suppressed below 3 GeV in dAu compared to pp

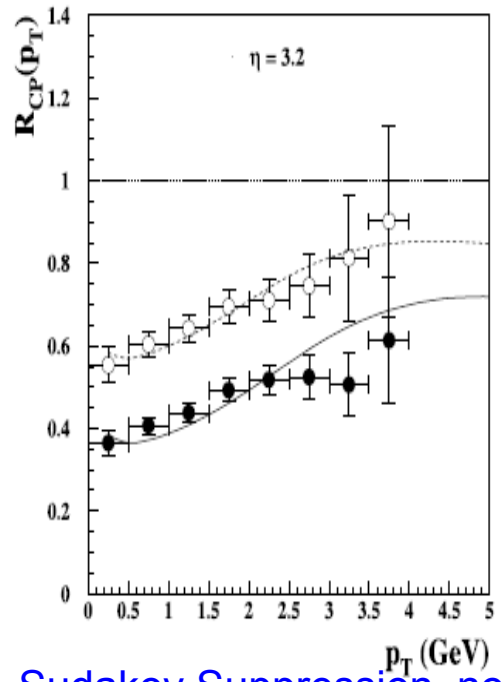
# Is saturation really the explanation?

η = 3.2

Dumitru, Hayashigaki Jalilian-Marian
NP A765, 464




A CGC calc. gives a very good description of the pT dependence



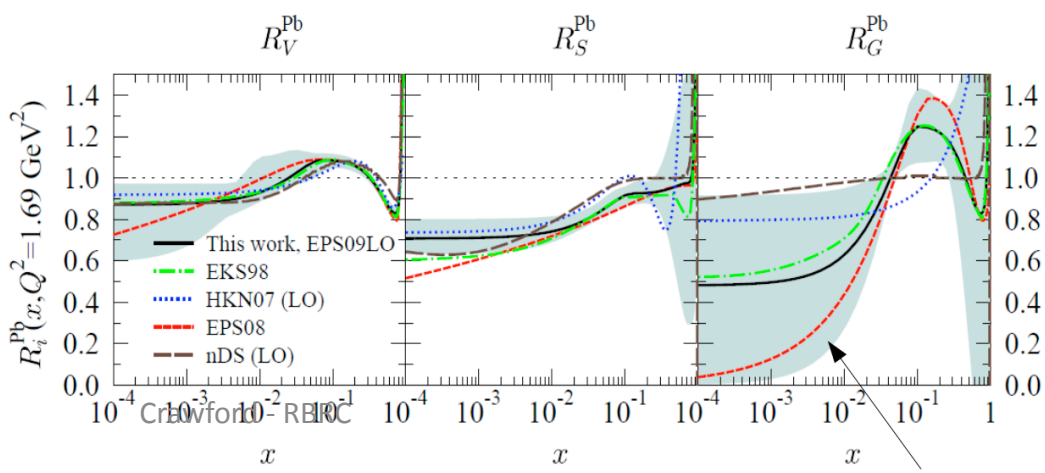

BRAHMS

PRL 93, 242303

B.Kopeliovich
et. al.
PRC72 054606

Sudakov Suppression, not low-x phenomena
Reproduce $p_T$ trend and centrality dependence.

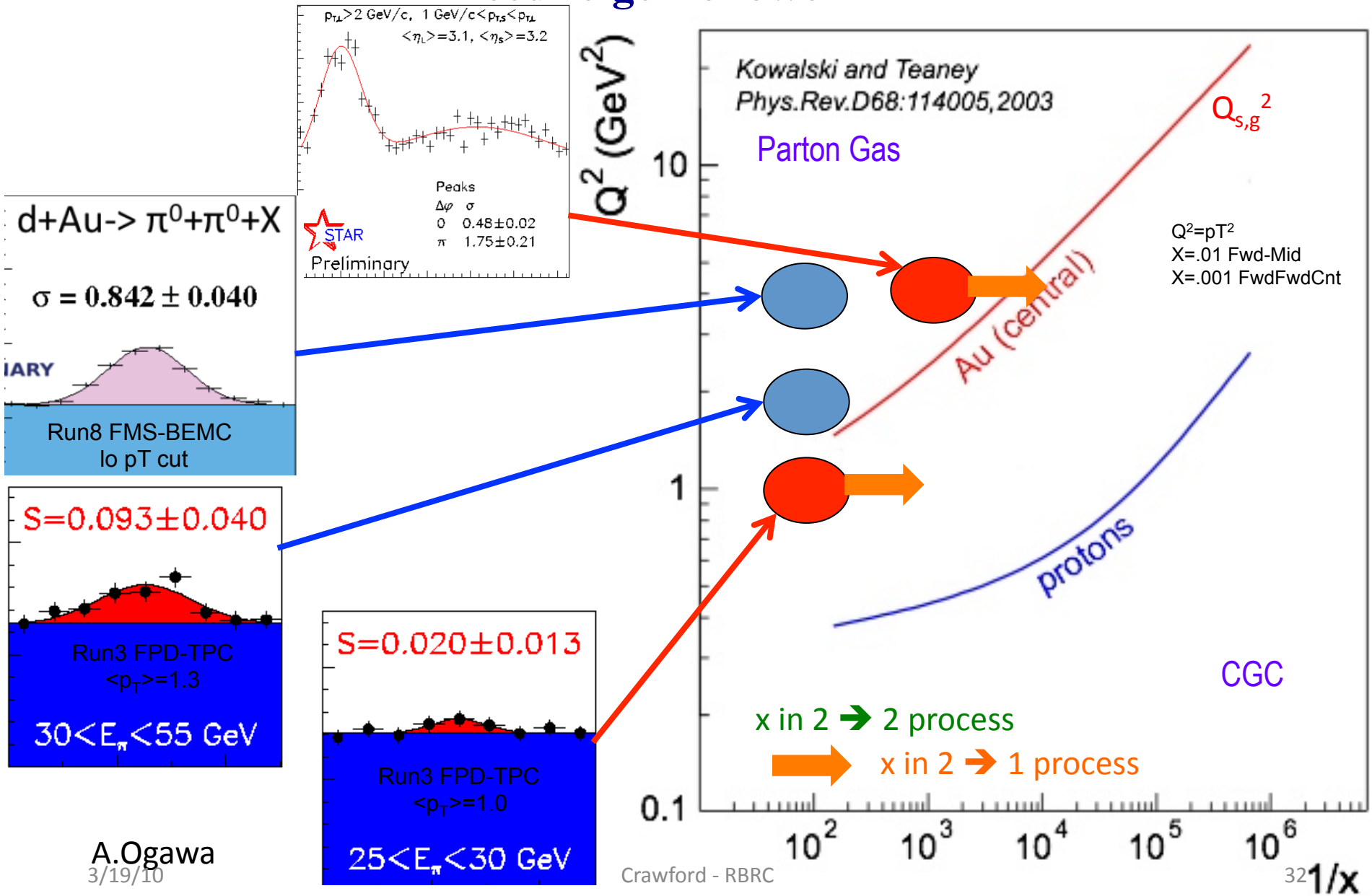
Paukkunen et al (QM09)
EPS09




A.Ogawa

# Mapping Saturation Scales

## need to get to lower x



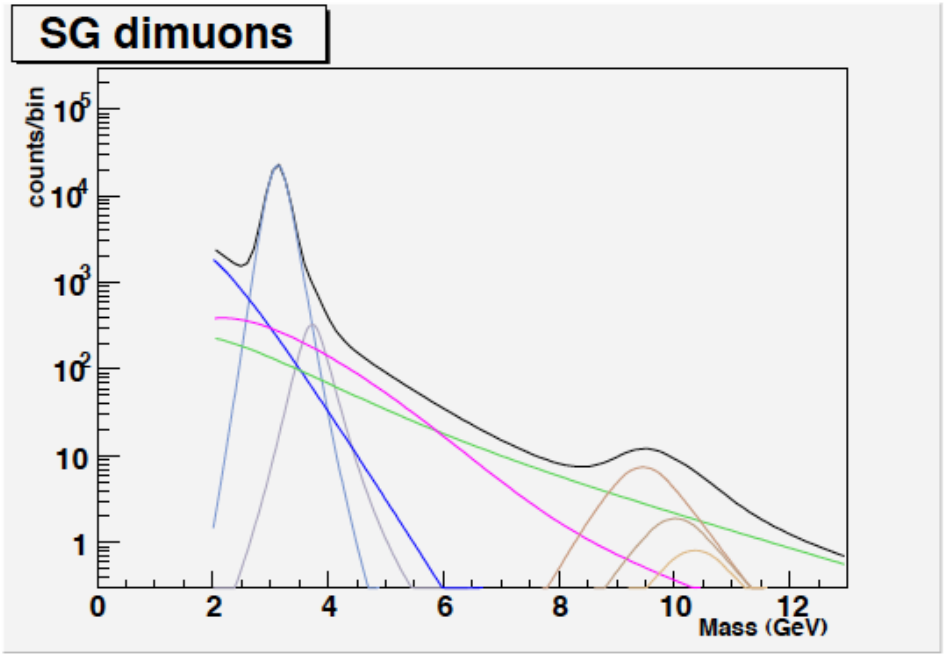

A.Ogawa

# DY for lower x

- Drell-Yan qqbar -> $\gamma^*$-> e+e- OR $\mu+\mu-$
  - $x_F = x1 - x2$
  - $M^2 = x1 \bullet x2 \bullet s$ where $s = (E_{CM})^2$
  - $x2 = -xF +/- \text{sqrt}(x_F^2+4M^2/s)$
  - $x2 = M^2/x_F/s$
    - 250 GeV p on 100 GeV Au
    - For 250 GeV p on 100 GeV Au, get
    - $S^2 = E^2 - p^2 = (250+100)^2 - (250-100)^2 \approx 316$ GeV
    - For $M(\gamma^*)=3.2$
      - => $x2 = 10^{-4}$

      Lower M* => lower x2

# DY M* range




Above J/ψ the Primary bkgd Is ϒ

Figure 7: *Dimuon invariant mass $dN^{\mu^+\mu^-}/dM$ cocktail distributions in the PHENIX muon spectrometer acceptance, from full PYTHIA plus PHENIX detector simulations. Black = Total, Light-Blue = $J/\Psi$, Light-Gray = $\Psi'$, Blue = $c\bar{c}$, Magenta = $b\bar{b}$, Green = Drell-Yan, Light-Brown = three Upsilon states.*

# Forward J/ψ -> $e^+e^-$ ->M( J/ψ) measured in FMS at STAR

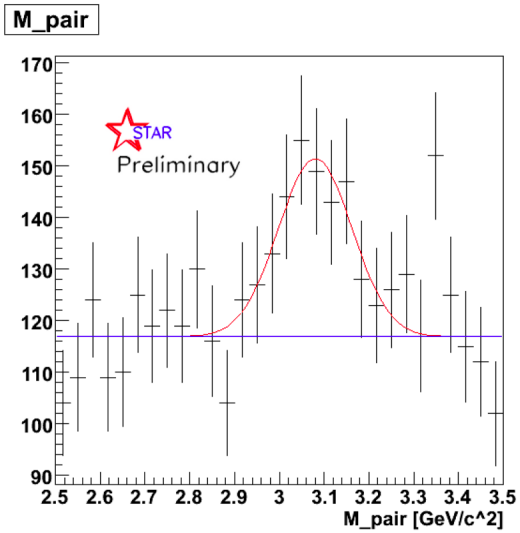



**Fig. 8** Reconstructed mass from pairs of clusters observed at forward rapidity with the FMS. Each cluster is subjected to an isolation cut, to reduce backgrounds from neutral pion decay and jet production. A further requirement is imposed on the transverse momentum of the cluster. The Gaussian peak is consistent with observation of J/ψ produced with $\langle x_F \rangle = 0.67$. The $x_F$ dependence of J/ψ production in p+p collisions could come from large-x intrinsic heavy components in the proton wavefunction [12].

# DY $A_N$ motivator

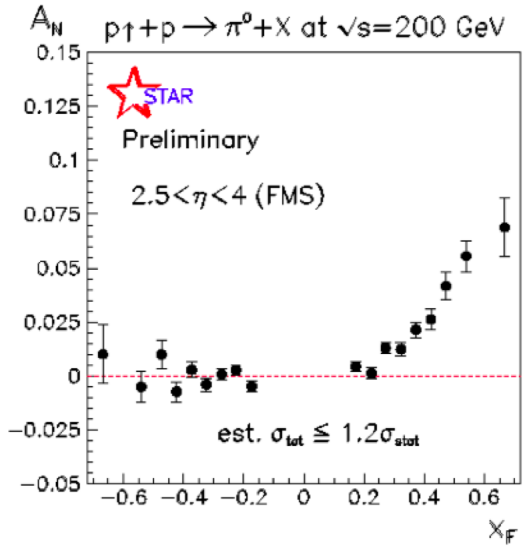



**Fig. 5b** Feynman $x$ dependence of the analyzing power for $\pi^0$ production from the FMS. These results integrate over a different pseudorapidity range from published results [4].

qg interaction leaves different Color field than qqbar leaves.

Apparently more robust calculations concerning color interaction are possible with DY measurements; Color-induced phase differences suggest that $A_N$(DY) is of different sign than $A_N(\pi^0)$

# DY spectrum

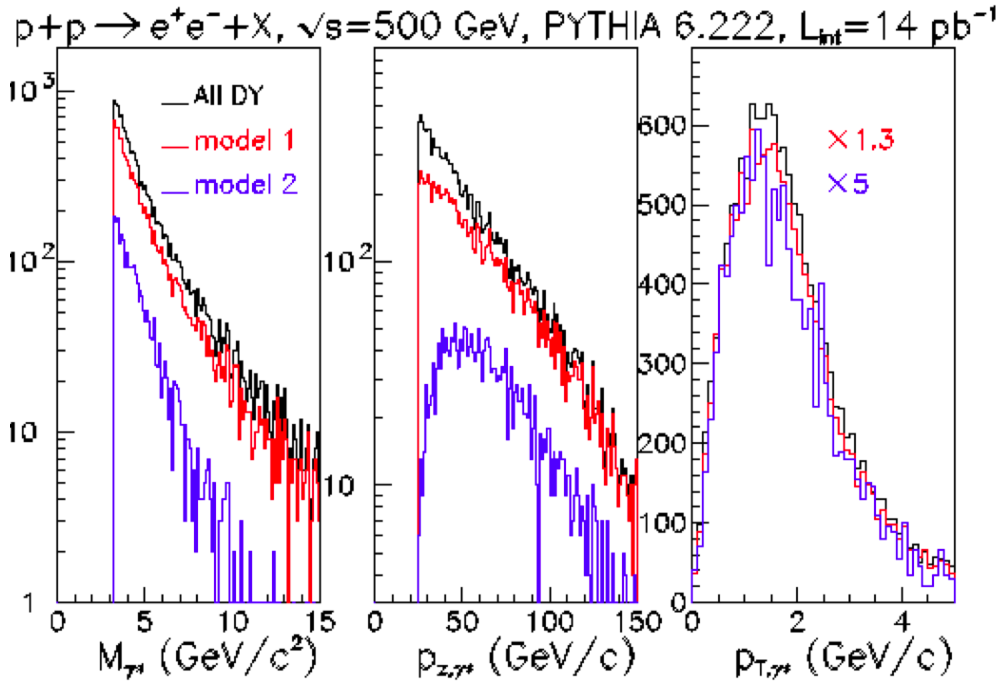
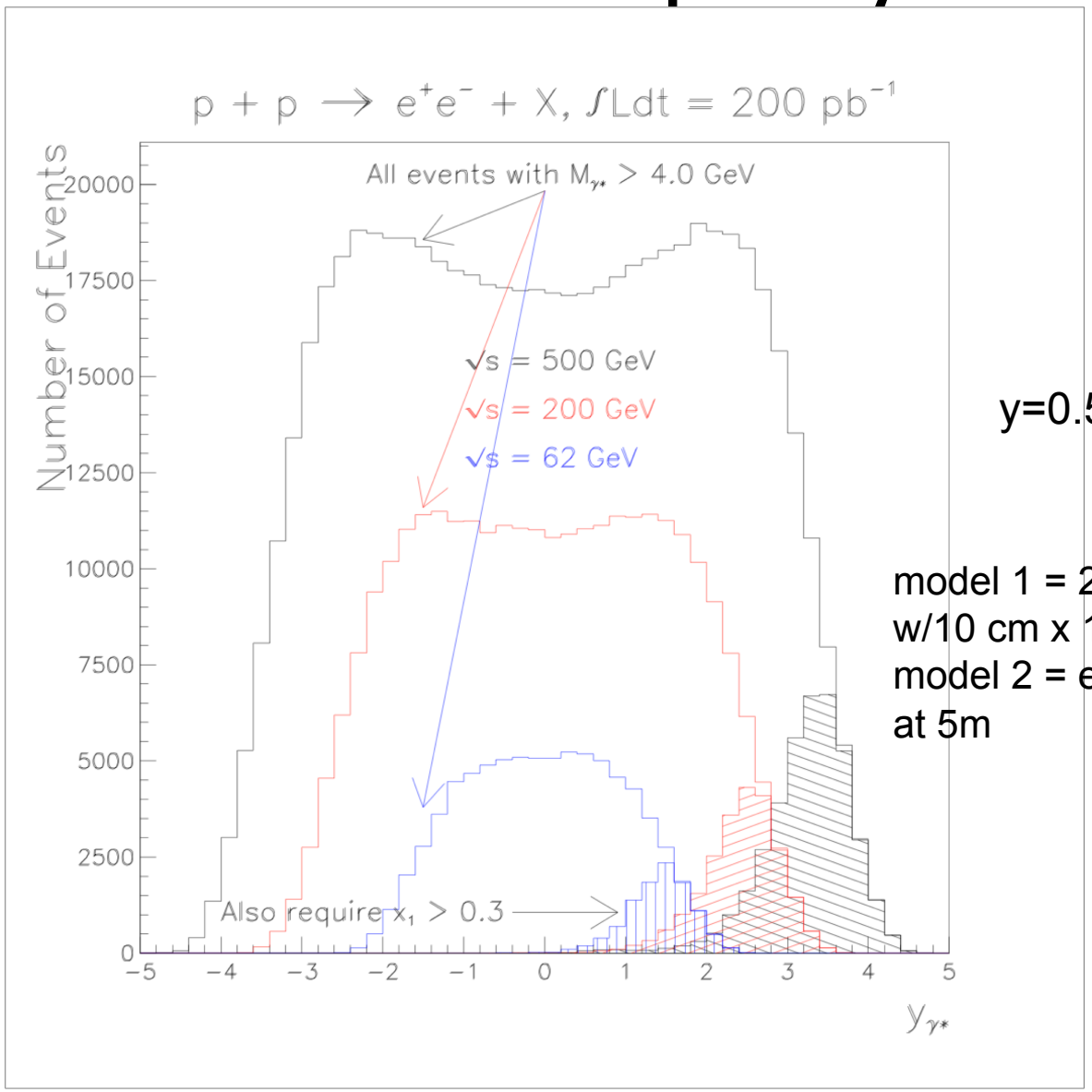



**Fig. 5** Kinematic distributions for the virtual photon. Model 1 would be a final facility and model 2 is the first stage of the proposed feasibility test for studying DY production at RHIC.

model 1 = 2x2 $m^2$ EM+H at 10m w/10 cm x 10 cm hole
model 2 = existing FHC + EM at 5m

# DY Yield vs rapidity




$y=0.5*\ln((E+p_z)/(E-p_z))$

model 1 = 2x2 $m^2$ EM+H at 10m w/10 cm x 10 cm hole
model 2 = existing FHC + EM at 5m

L.Bland

# DY test plan

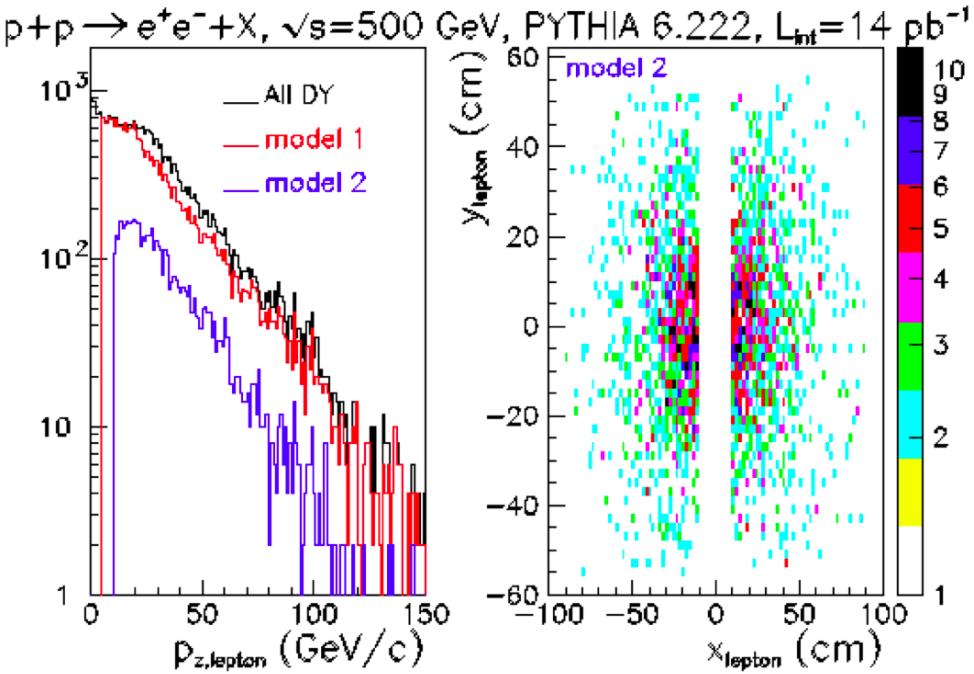



**Fig. 10** Kinematic distributions for the electron and positron decay products of the virtual photon. Model 1 would be a final facility and model 2 is the first stage of the proposed feasibility test for studying DY production at RHIC.

# DY plan

First – calorimetry (E + H) with charged/neutral selection
we have already seen the J/ψ this way
and that was without any hadron calorimeter

Add tracking if needed

Use all fast detectors and electronics – run at 10 MHz

Determine sign of $A_N$ and requirements for
DY study of x distribution

# Outlook

Complete efficiency studies and publish $\pi^0$h and $\pi^0\pi^0$ correlation results for pp and dAu

Complete FMS-EEMC correlations to fill $1<\eta_2<2$ in study of rapidity dependence

Complete J/ψ measurements

Measure $A_N$(DY) above J/Ψ to see color force

Measure P(x) at $x\sim10^{-4}$ for $M(\gamma^*)>3.2$ GeV

# backup