

High p_T π^0 Production in p+p, Au+Au, and d+Au

Stefan Bathe

UC Riverside

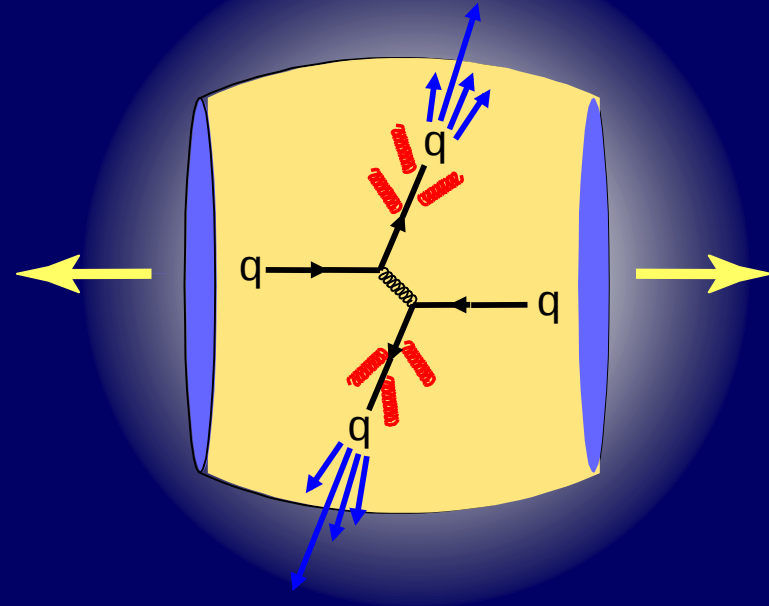
for the  Collaboration

Topics in Heavy Ion Collisions

McGill University, Montreal, Canada, June 25-28, 2003

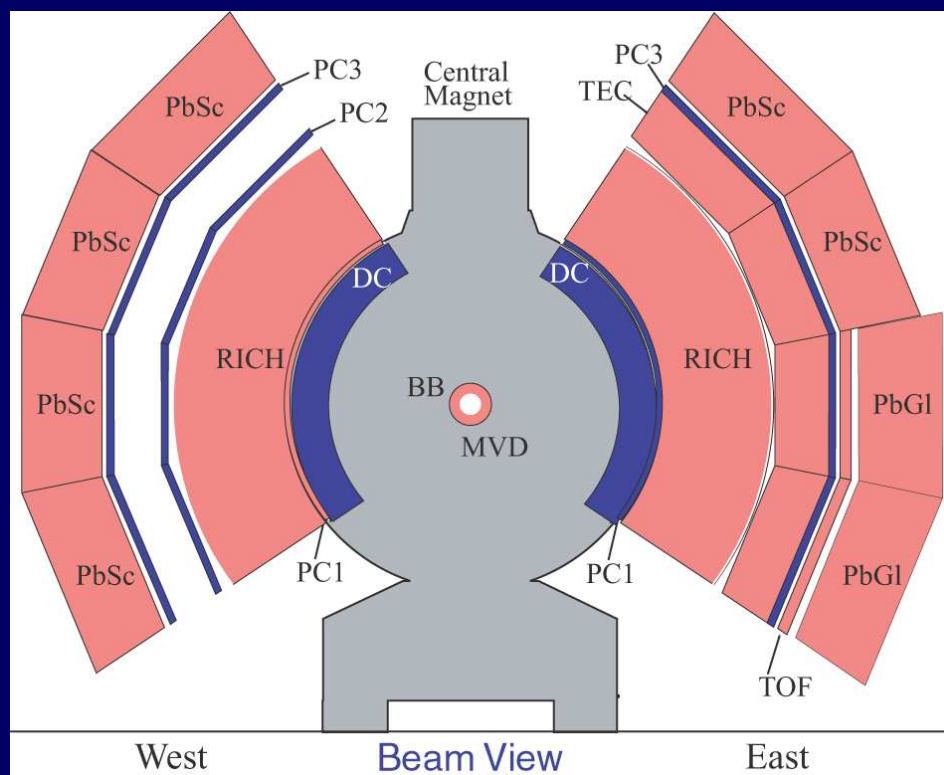
High p_T Particle Production

- High p_T particles in p+p and A+A
 - result from parton-parton scattering with high Q^2
- p+p
 - fragmentation of partons to hadrons in QCD vacuum
- A+A
 - hard scatterings in early stage
 - high p_T partons probe hot and dense nuclear matter formed in later stages



- Colored quark matter
 - partons lose energy via gluon bremsstrahlung
 - jet quenching
 - suppression of high p_T hadrons

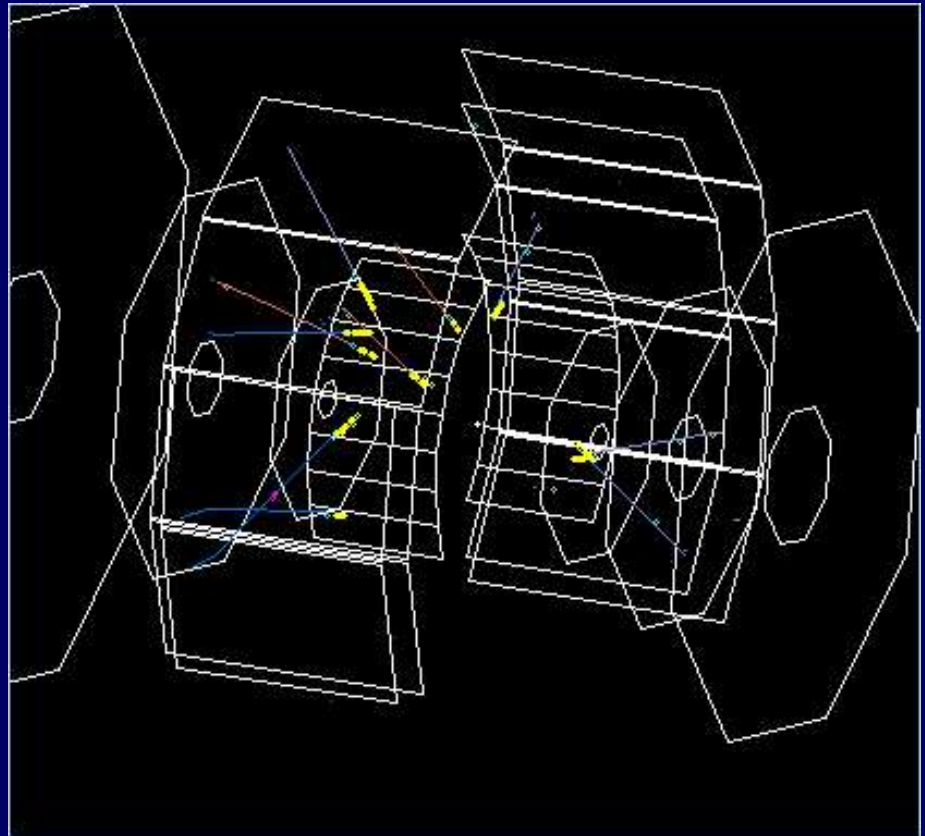
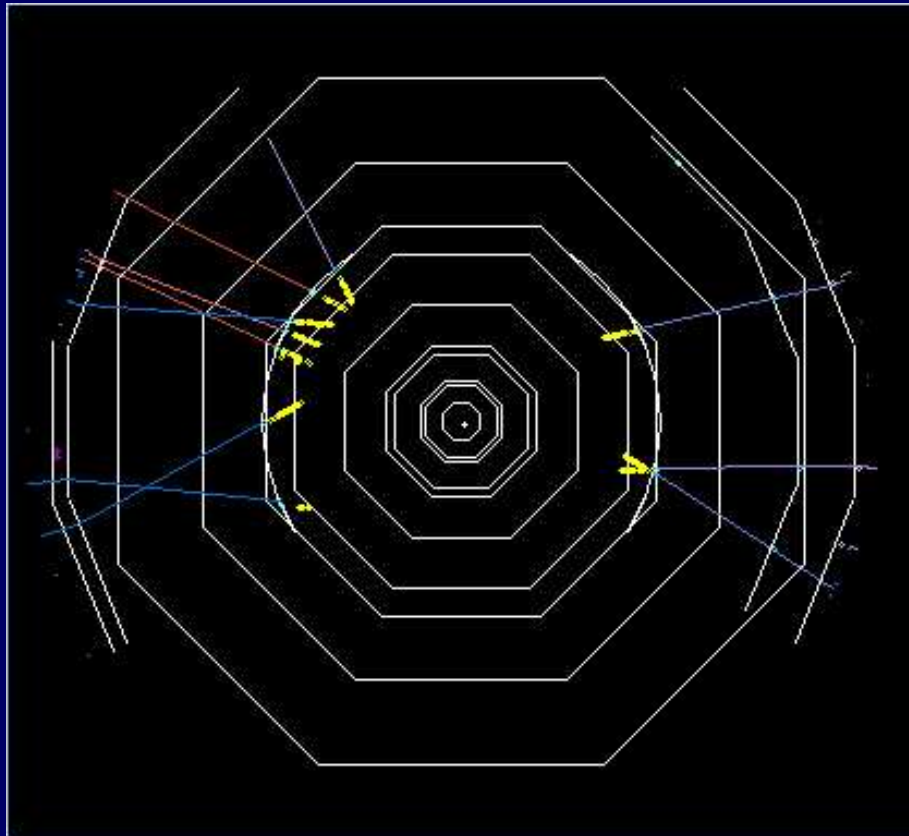
PHENIX Setup



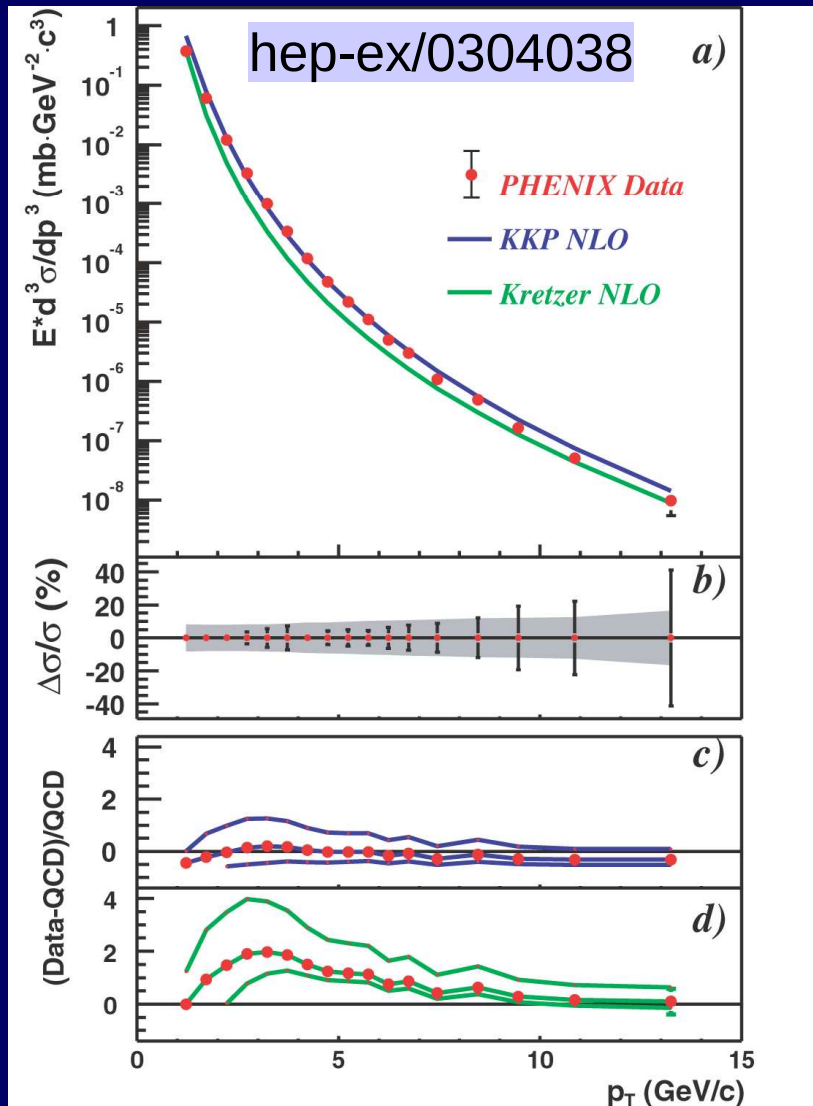
PHENIX Central Arms
 $|\eta| < 0.35$

- π^0 via $\pi^0 \rightarrow \gamma\gamma$
 - EMCal
 - Lead Scintillator (PbSc)
 - Lead Glass (PbGl)
- Charged hadrons
 - Drift Chamber (DC)
 - Pad Chamber (PC)
- Event characterization, vertex
 - Beam Beam Counter (BBC)
 - $3.0 < |\eta| < 3.9$
 - Zero Degree Calorimeter (ZDC)

p+p Collision at $\sqrt{s} = 200$ GeV

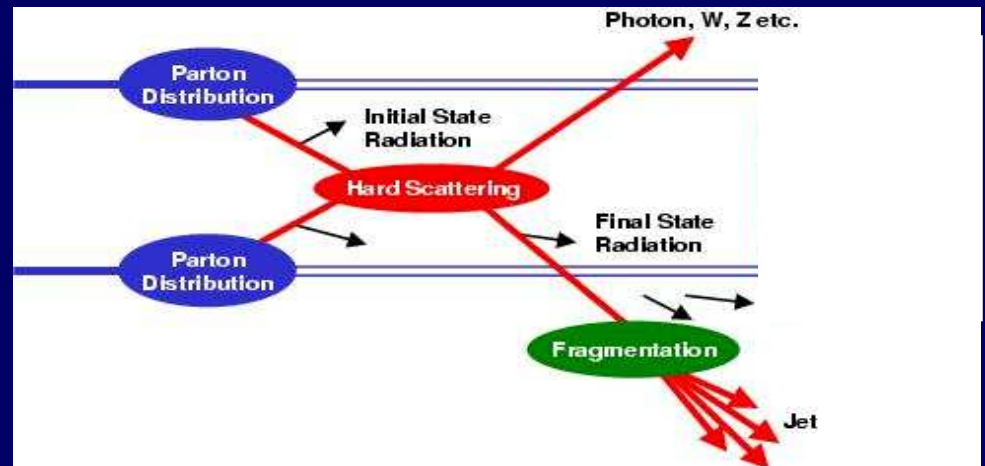


π^0 Production in p+p



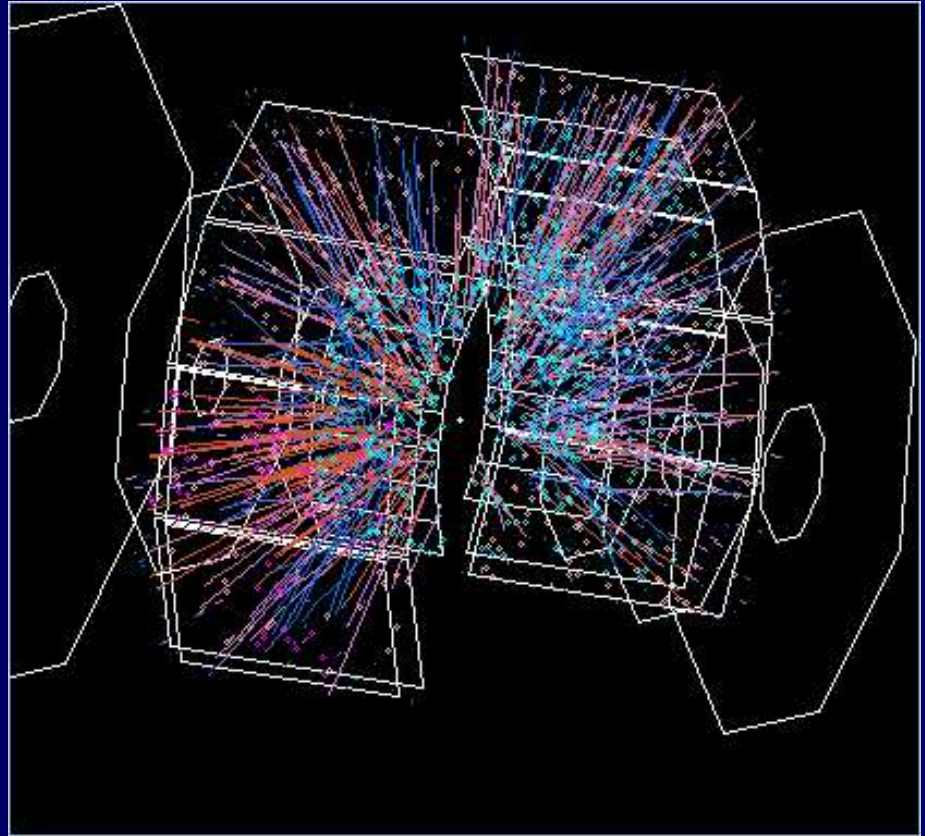
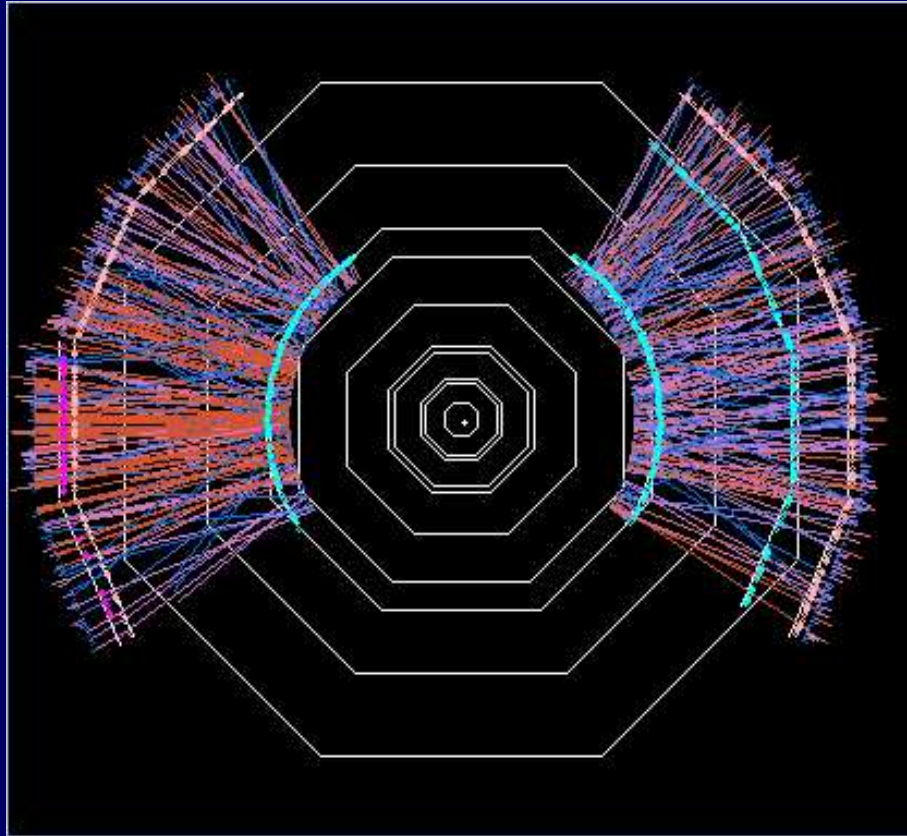
- Good agreement with NLO pQCD
 - Factorization theorem:

$$\sigma_{AB \rightarrow hX} \propto f_{a/A}(x_a, Q_a^2) \otimes f_{b/B}(x_b, Q_b^2) \otimes \sigma_{ab \rightarrow cd} \otimes D_{h/c}(z_c, Q_c^2)$$



- Constrains Fragmentation Function $D(\text{Gluon-}\pi)$
- Reference for Au+Au spectra

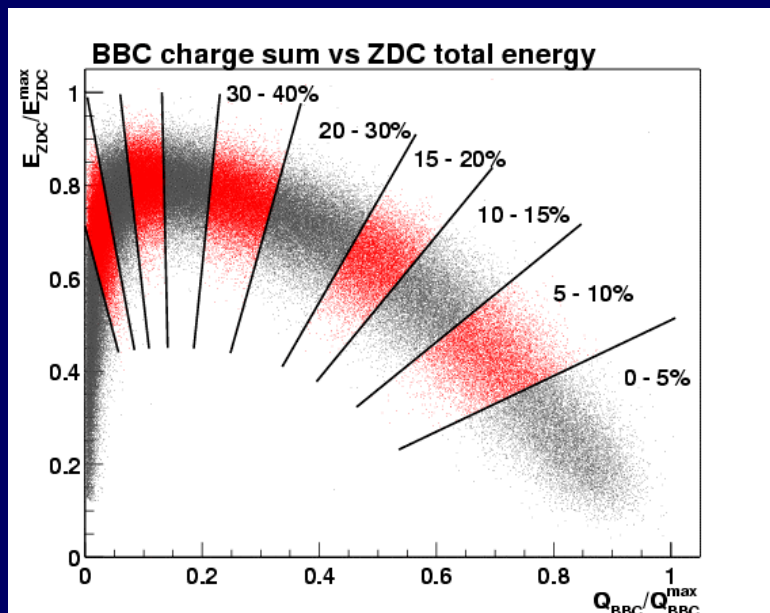
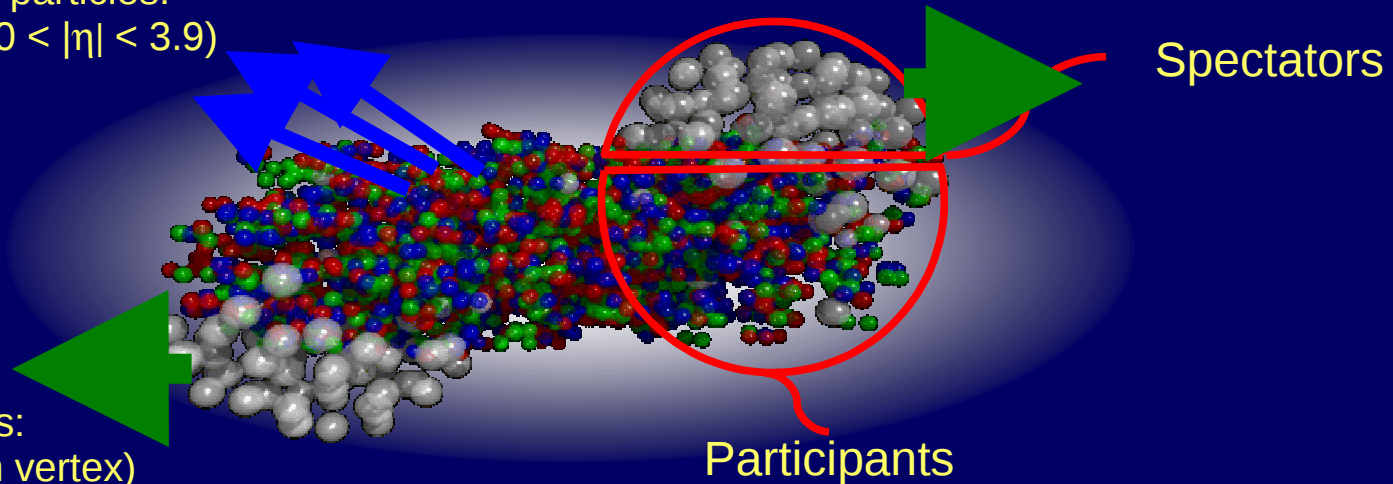
Au+Au Collision at $\sqrt{s_{NN}} = 200$ GeV



Centrality Selection in Au+Au

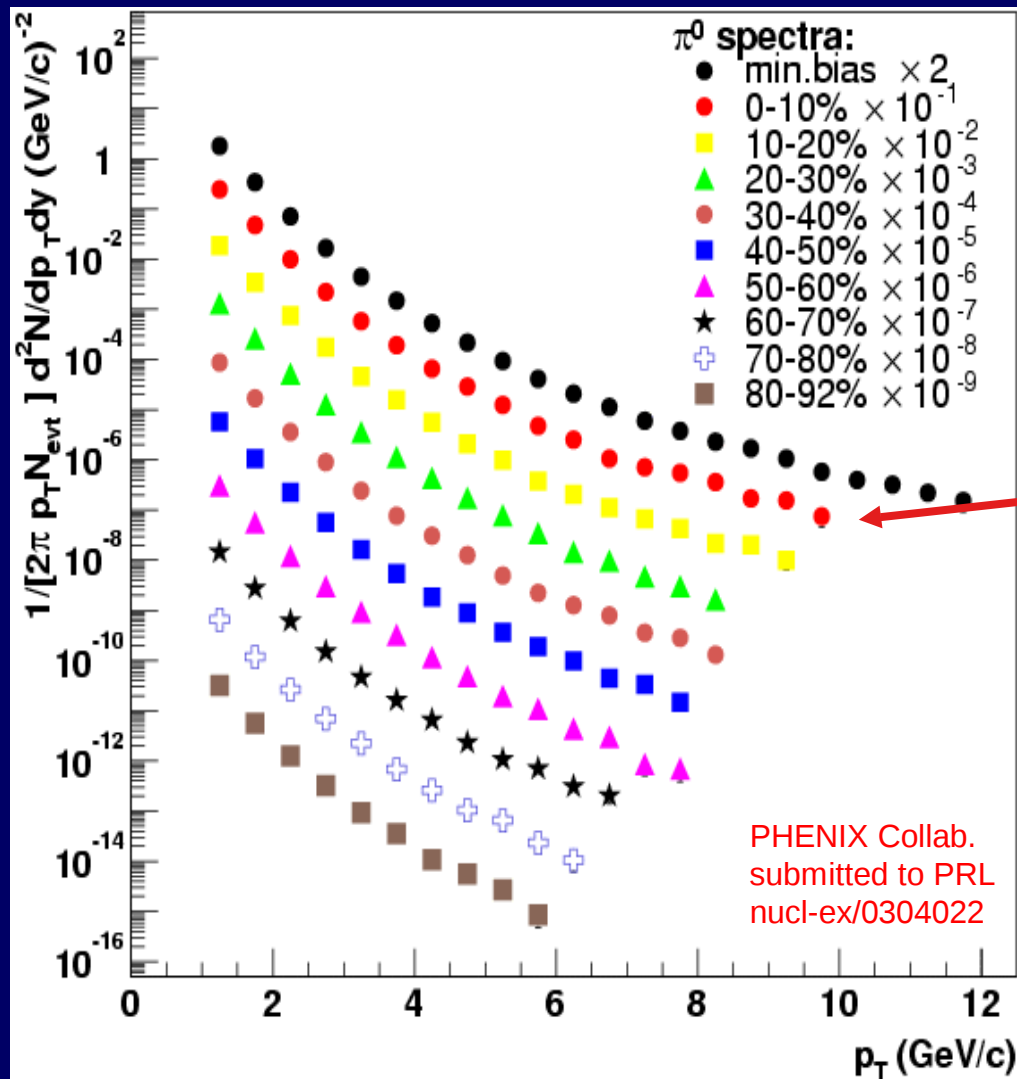
charged particles:
BBC ($3.0 < |\eta| < 3.9$)

spectator neutrons:
ZDC (~ 18 m from vertex)



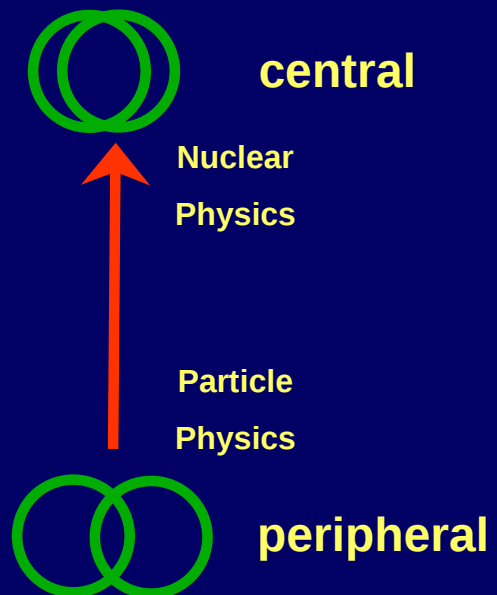
- Centrality characterized by
 - N_{part} : Number of nucleons which suffered ≥ 1 collision
 - N_{coll} : Number of inelastic nucleon-nucleon collisions
- N_{part} and N_{coll} from Glauber calculations

π^0 Production in Au+Au



- NN-reference needed

central spectra up to 10 GeV/c



Nuclear Modification Factor R_{AA}

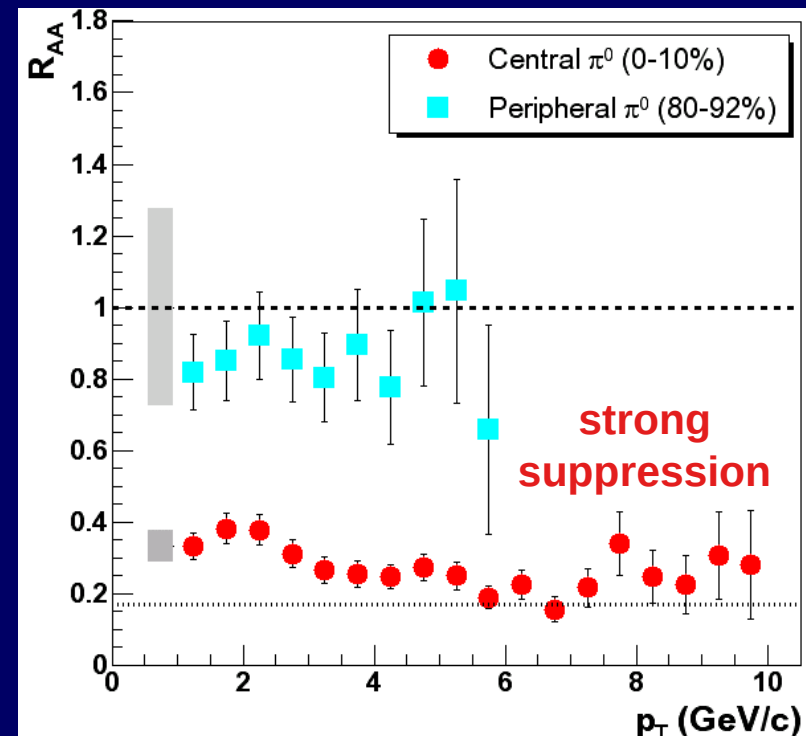
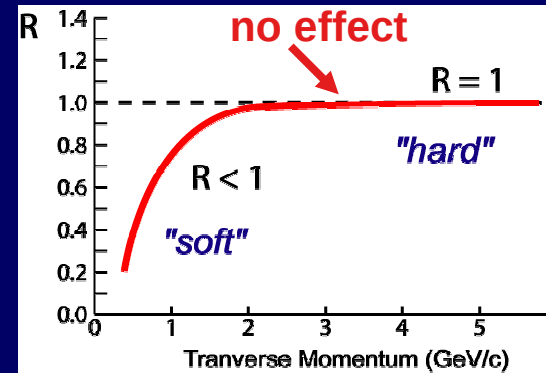
- Hard processes
 - yield scales with N_{coll}
 - reason:
 - small cross section
 - incoherent superposition

- Nuclear Modification Factor R_{AA}

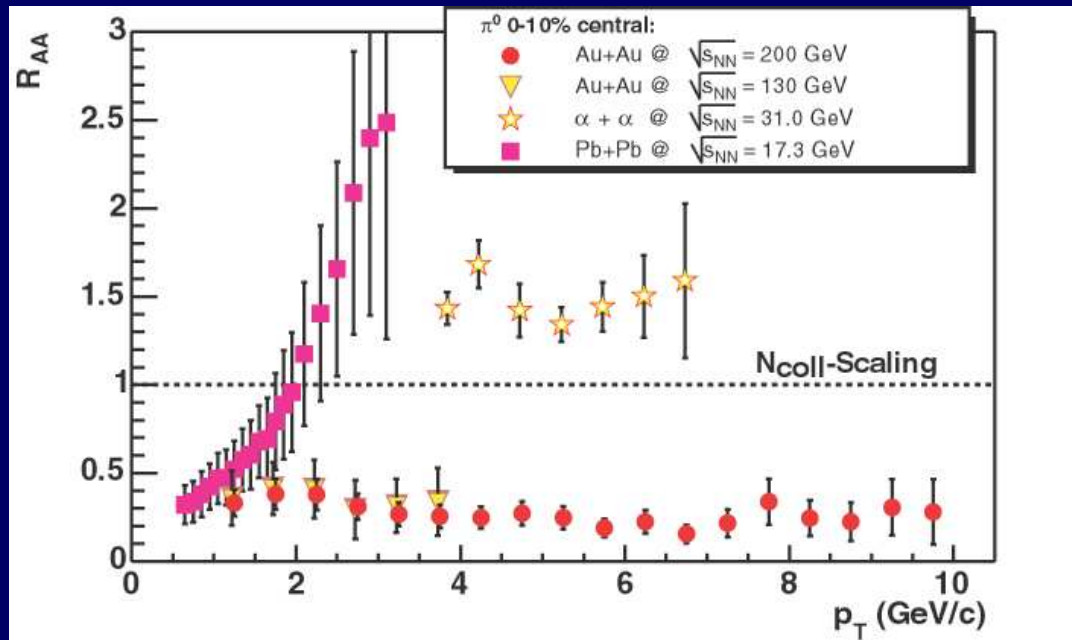
$$R_{AA} = \frac{dN_{AA}^{\pi^0} / dp_T}{T_{AA} d\sigma_{NN}^{\pi^0} / dp_T}$$

$$N_{\text{coll}} = \sigma_{NN}^{\text{inel}} \cdot T_{AA}$$

- In the absence of nuclear effects: $R_{AA}=1$ at high p_T



R_{AA} for π^0 in Central Collisions



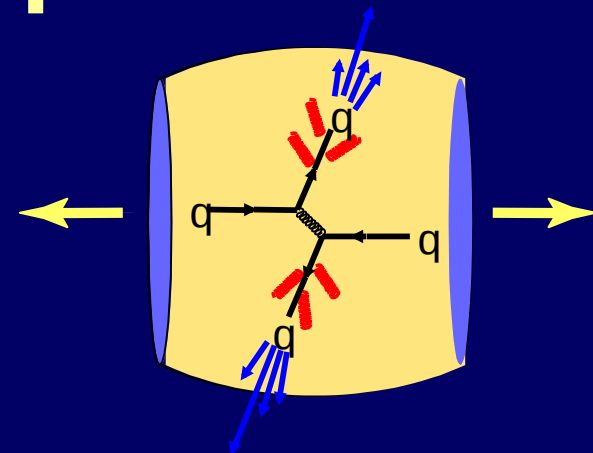
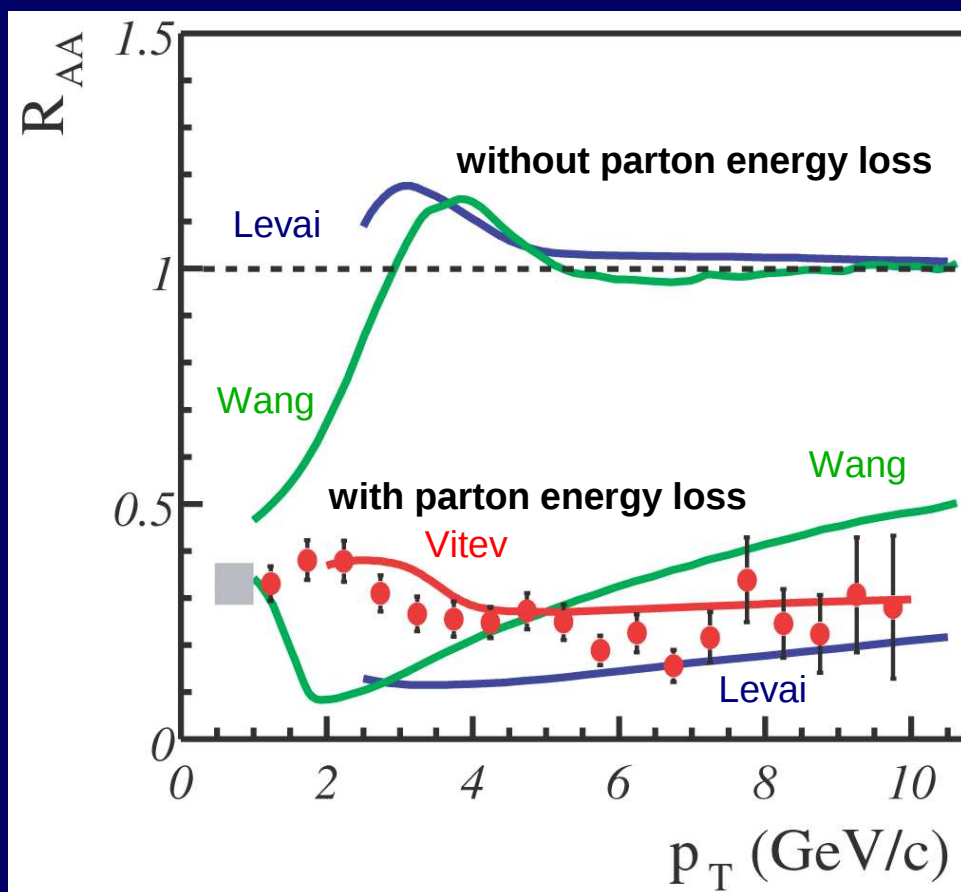
- Cronin Effect at lower energies
- Expectation
 - $R_{AA} > 1$
- Observed
 - factor 4-5 suppression at 130 and 200 GeV

A.L.S. Angelis PLB 185, 213 (1987)
 WA98, EPJ C 23, 225 (2002)
 PHENIX, PRL 88 022301 (2002)
 PHENIX submitted to PRL,
 nucl-ex/0304022

$$R_{AA} = \frac{dN_{AA}^{\pi^0} / dp_T}{T_{AA} d\sigma_{NN}^{\pi^0} / dp_T}$$

Jet Quenching?

Comparison with model calculations with and without parton energy loss:



- π^0 suppression described by models with parton energy loss
- Additional nuclear effects needed to describe p_T dependence
- Other explanations not ruled out at this stage

Initial ↔ Final State Effects

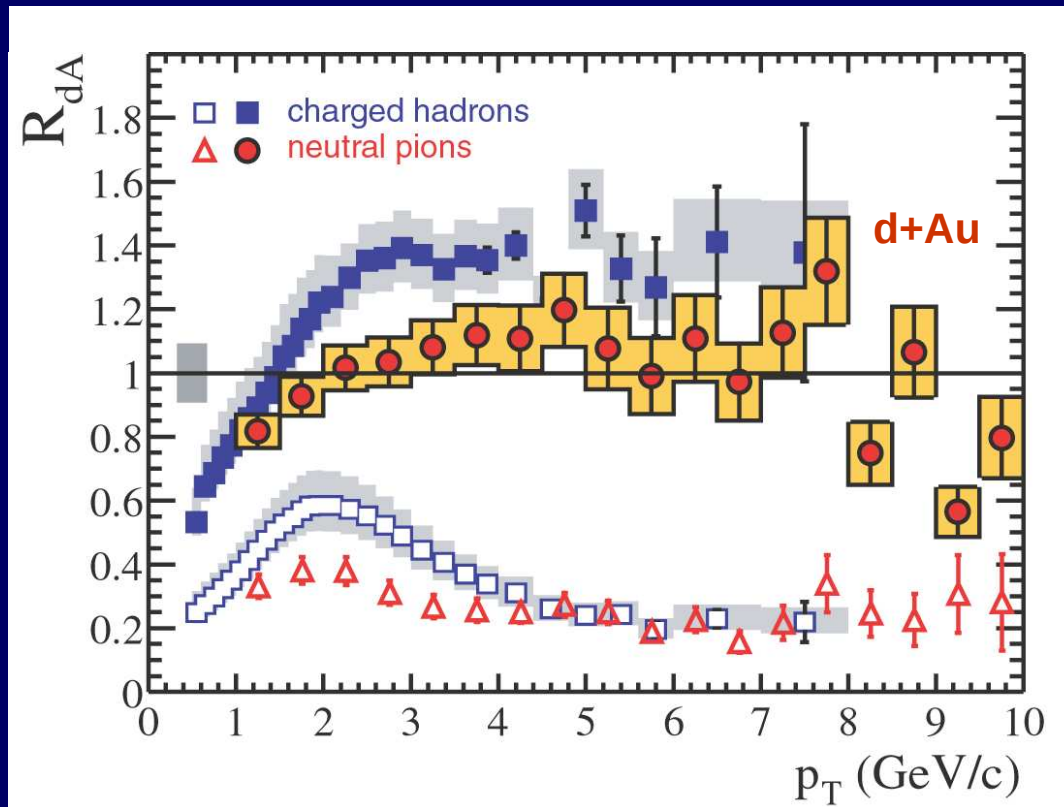
- Initial state effects
 - lead to $R_{AA} \neq 1$ at high p_T
 - but are not related to properties of hot and dense nuclear matter
- Possibilities
 - Initial state multiple soft scatterings
(Cronin effect)
 $R_{AA} > 1$
 - Modifications of nuclear structure functions in nuclei
(Shadowing)
 $R_{AA} < 1$
 - gluon saturation
(Color Glass Condensate)
 $R_{AA} < 1$?
- Final state effects
 - dense partonic medium
parton energy loss (and recombination)
 - dense hadronic medium
hadronic energy loss

d+Au: The Control Experiment



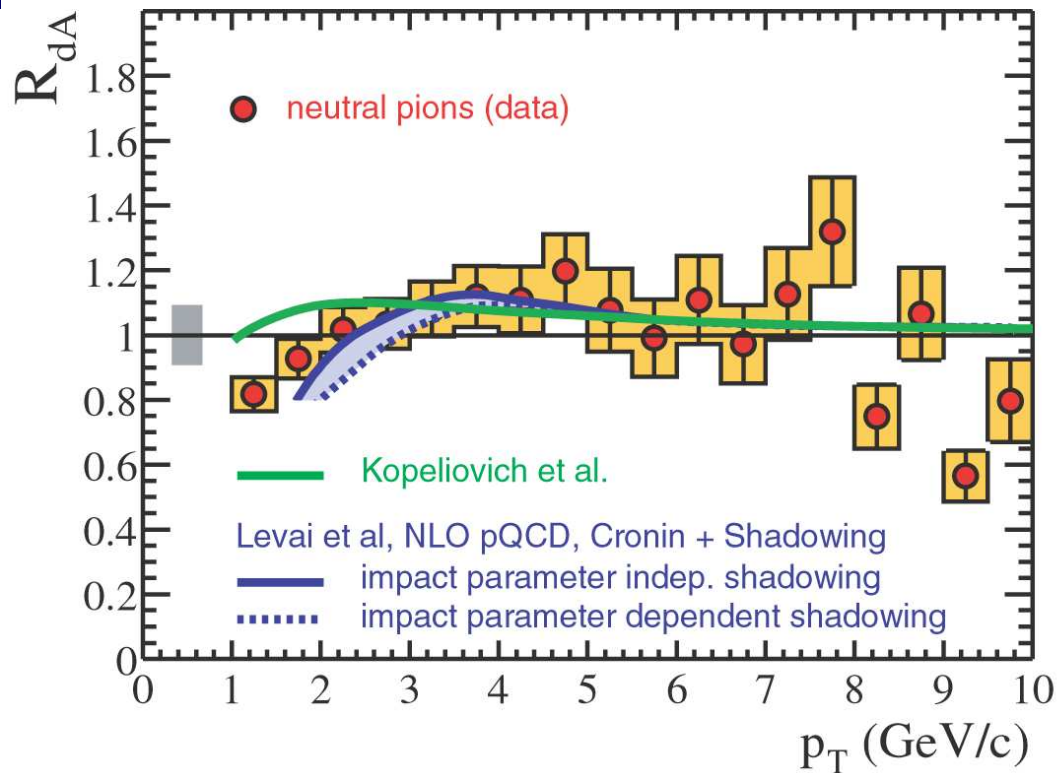
- Initial state nuclear **effects** present in **both** A+A and N+A collisions
- Final state medium **effects only** present in A+A collisions

R_{AA} in d+Au (R_{dA})



- Final state effects minimal in d+Au
- **No suppression in d+Au**
- **Initial state effects ruled out as explanation for suppression in Au+Au**

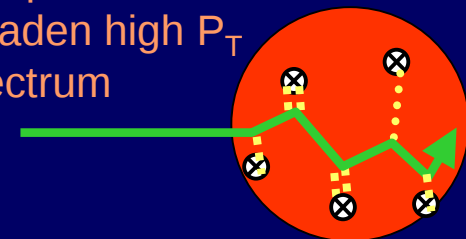
π^0 in d+Au: Data $\longleftrightarrow$ Theory



- Data well reproduced by
 - NLO pQCD calculation, plus
 - phenomenological model of Cronin effect, plus
 - Shadowing

Cronin Effect:

Multiple Collisions
broaden high P_T
spectrum



Levai et al., nucl-th/0306019

Kopeliovich et al., hep-ph/0201010

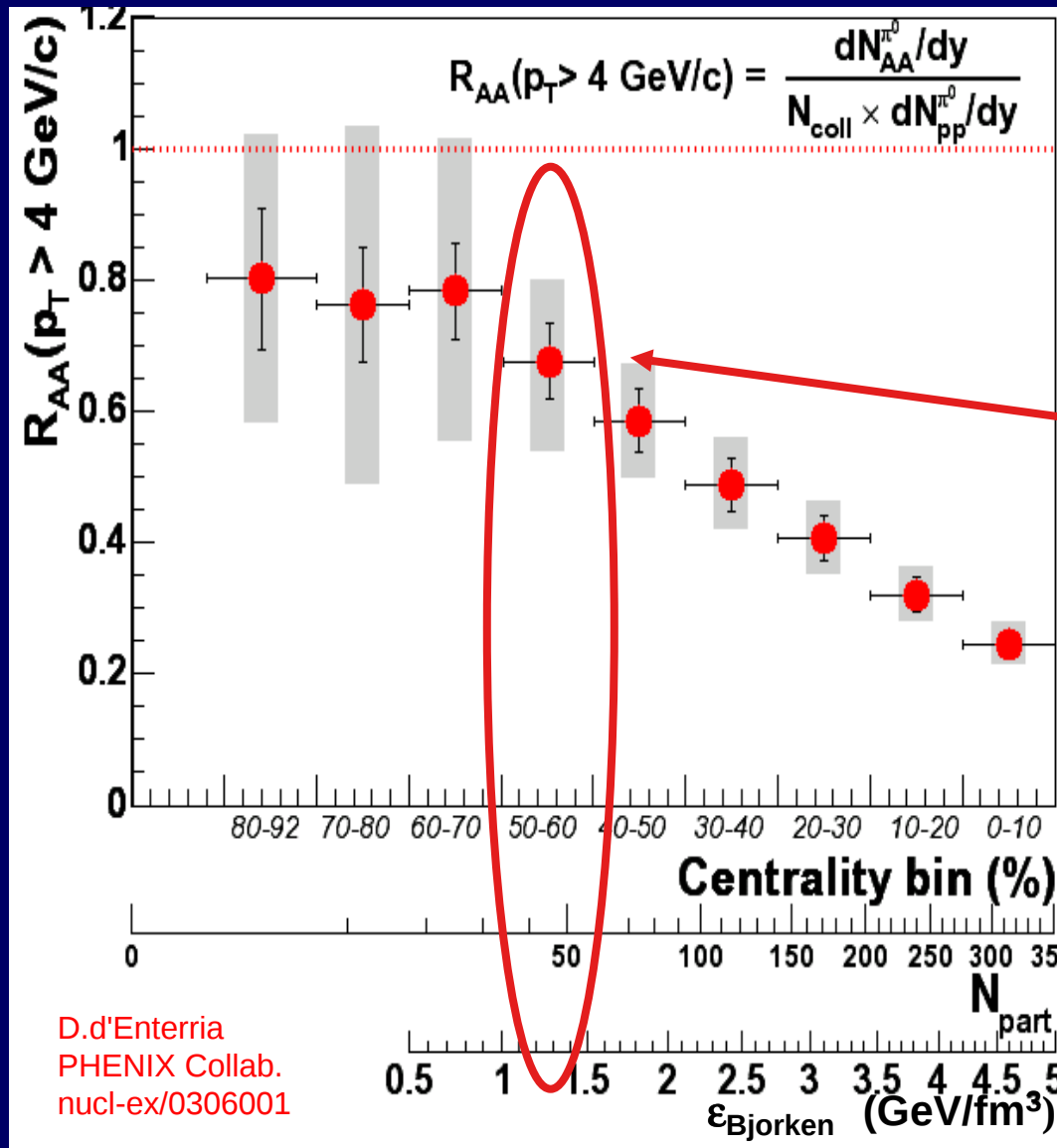
Summary

- **Strong suppression** of high p_T particle production **in central Au+Au** at $\sqrt{s_{NN}} = 200$ GeV with respect to N_{coll} scaled p+p reference
- **No suppression in 200 GeV d+Au**
- **Suppression in Au+Au is caused by** properties of created **hot and dense medium**



Backup Slides

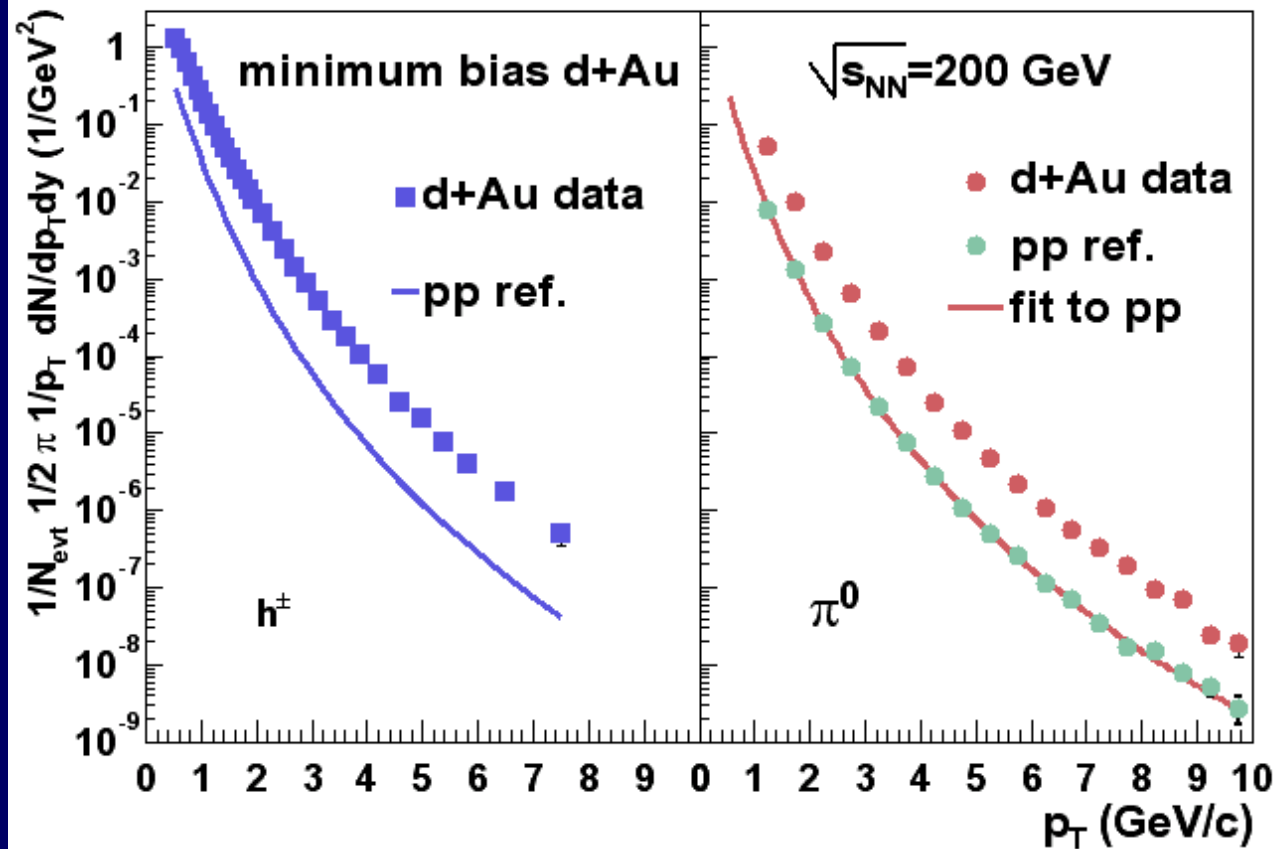
Centrality Dependence of Suppression



- Peripheral (60-92%) consistent with N_{coll} scaling
- $R_{AA} < 1$ (2σ) for 50-60%
 - $N_{\text{part}} \sim 50 \pm 15$
 - $\epsilon_{\text{Bjorken}} \sim 1.2 \text{ GeV/fm}^3$
- Gradual or abrupt suppression not conclusive at this point

$$\epsilon_{Bj} = \frac{dE_T}{dy} \frac{1}{\tau_0 \pi R^2}$$

d+Au Spectra

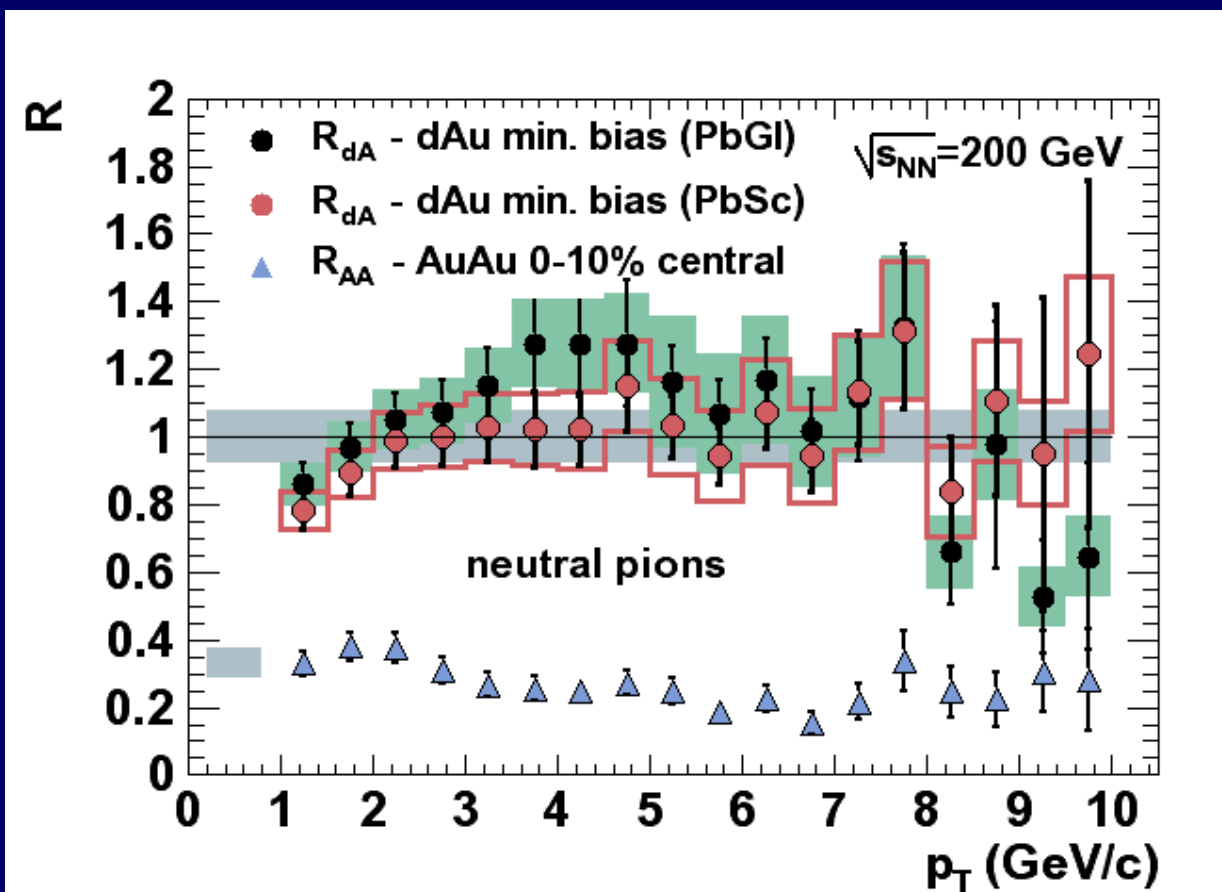


- Final spectra for charged hadrons and identified pions.
- Data span 7 orders of magnitude.

R_{AA} vs. R_{dA} for Identified π^0

d+Au

Au+Au



Initial State
Effects Only

Initial + Final
State Effects

Systematic Errors (1σ)

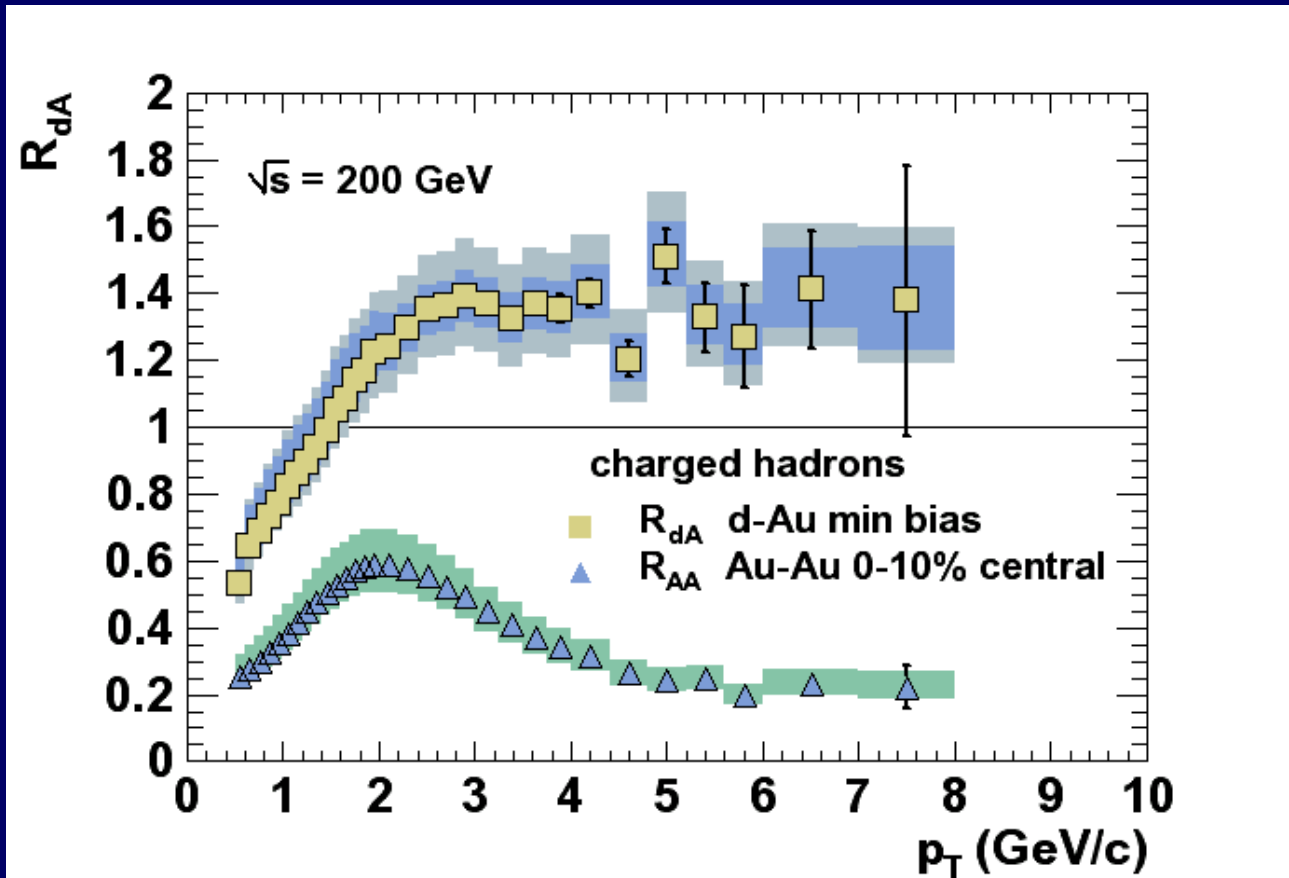
	p_T indep.	2 GeV	6 GeV	10 GeV	type
Peak extraction	5.0%(5.0%)				A
geometric acc.		3.0%(3.0%)	2.0%(2.0%)	2.0%(2.0%)	B
π^0 reconstr. Eff.		4.0%(4.0%)	4.0%(4.0%)	4.5%(4.5%)	B
Energy scale		4.0%(4.0%)	9.0%(9.0%)	11.0%(11.0%)	B
Trigger eff.		-	5.0%(10.0%)	3.0%(3.0%)	B
G1 Norm. Scale	5.0%(5.0%)				C
Conv. Correction	2.8%(2.8%)				C
Total error		10%(10%)	14%(16%)	15%(15%)	

PbSc (PbGl)

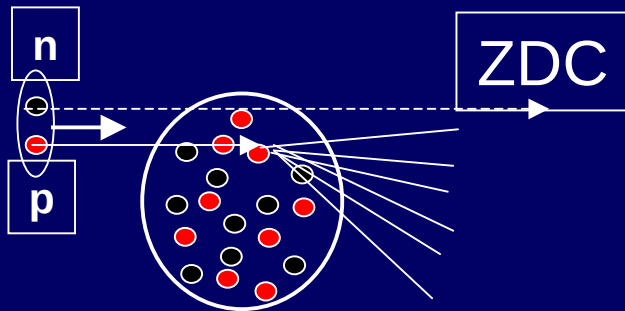
Charged Hadron Results

d+Au

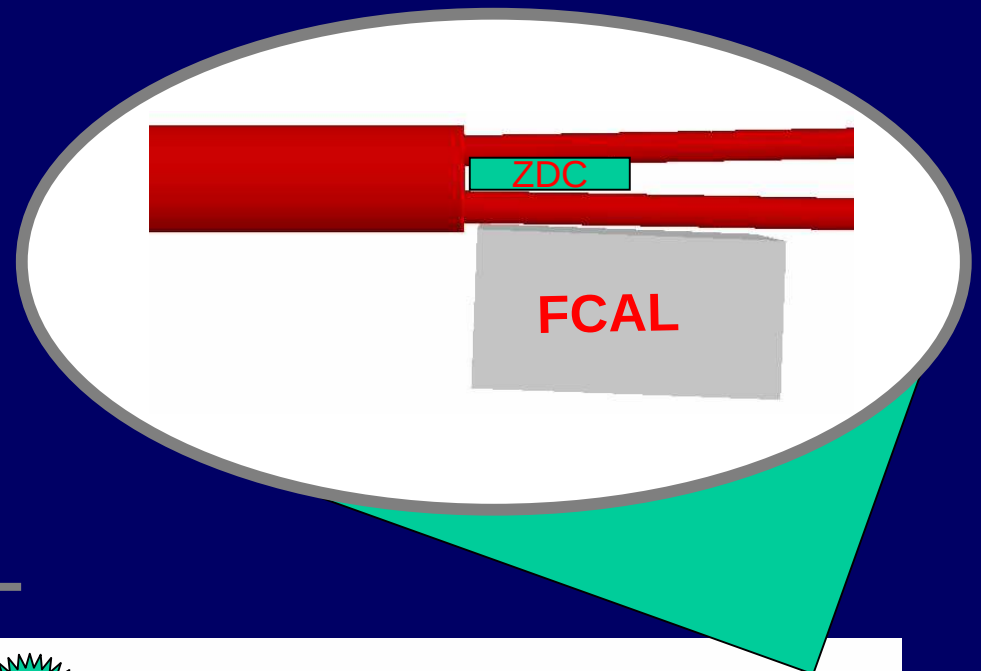
Au+Au



First grasp at centrality selection in dAu



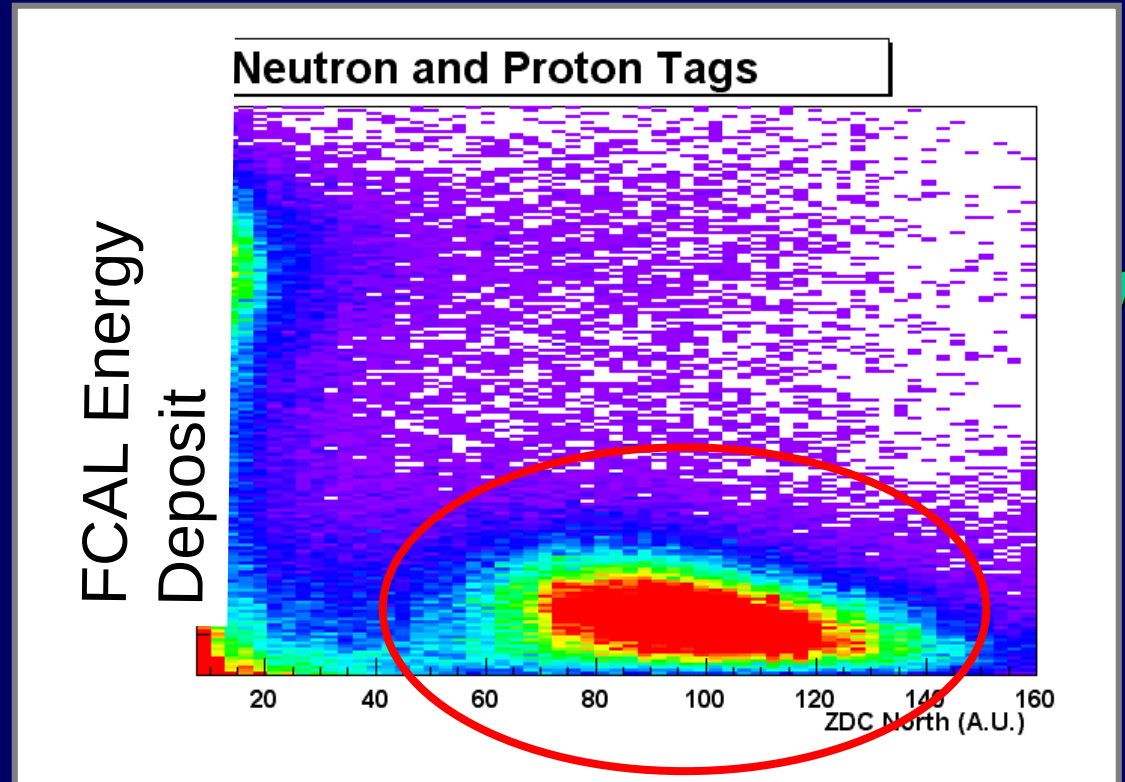
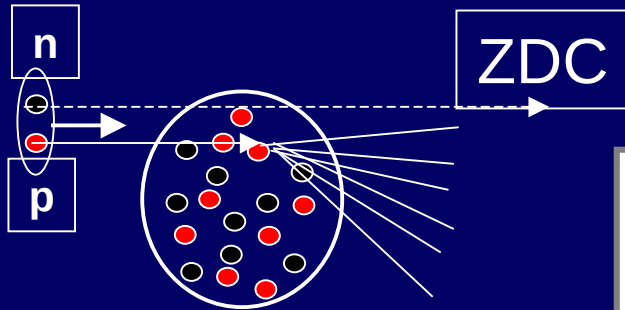
Neutron tagged events are enhanced in very-peripheral collisions



18 m

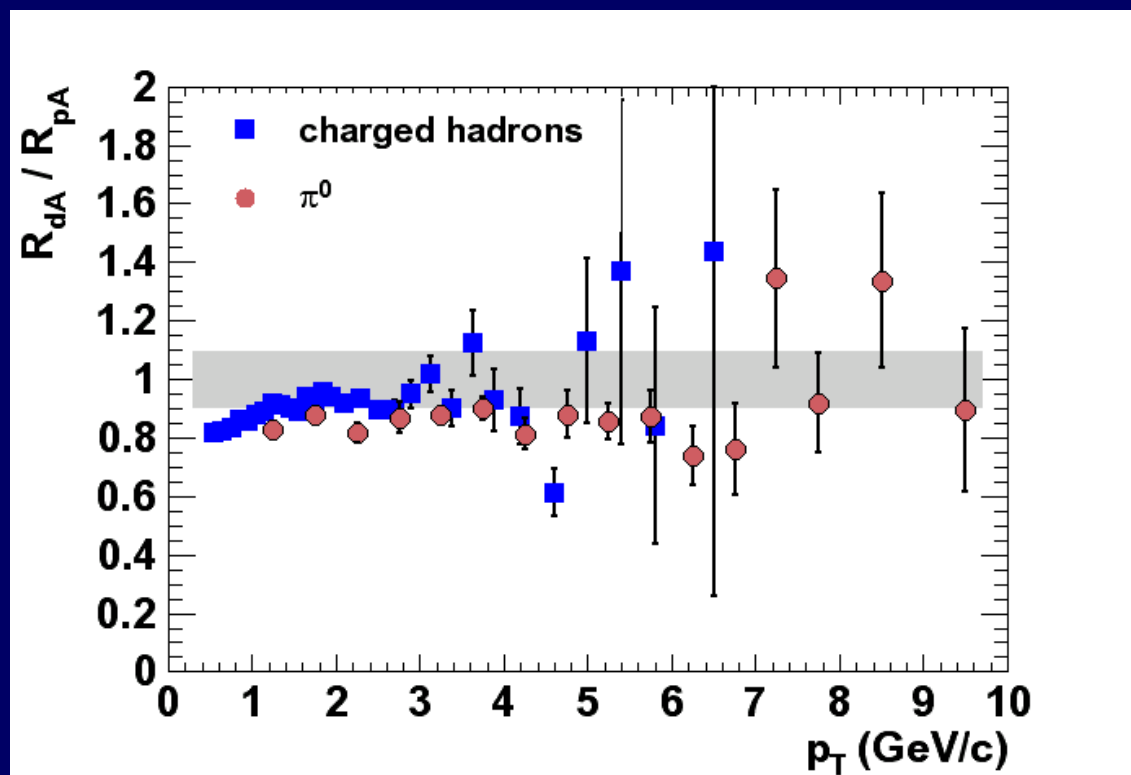


First grasp at centrality selection in dAu



$$R_{dA} / R_{pA}$$

Comparison of very-peripheral events ($\langle N_{\text{coll}} \rangle = 3.6 \pm 0.4$)
to minimum bias events ($\langle N_{\text{coll}} \rangle = 8.5 \pm 0.7$)



Data indicates no centrality dependence