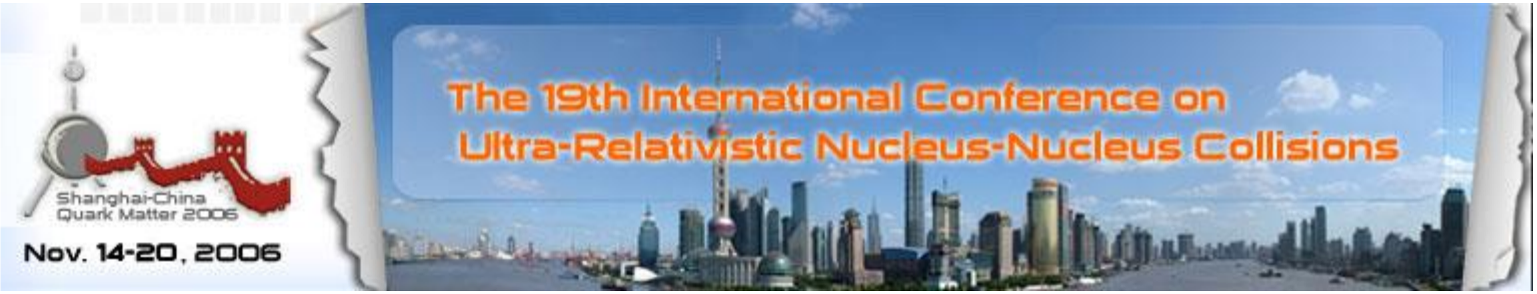
Heavy-Ion Meeting (Dec. 16, 2006)

Summary of Quak Matter 2006
-Experimental Part-

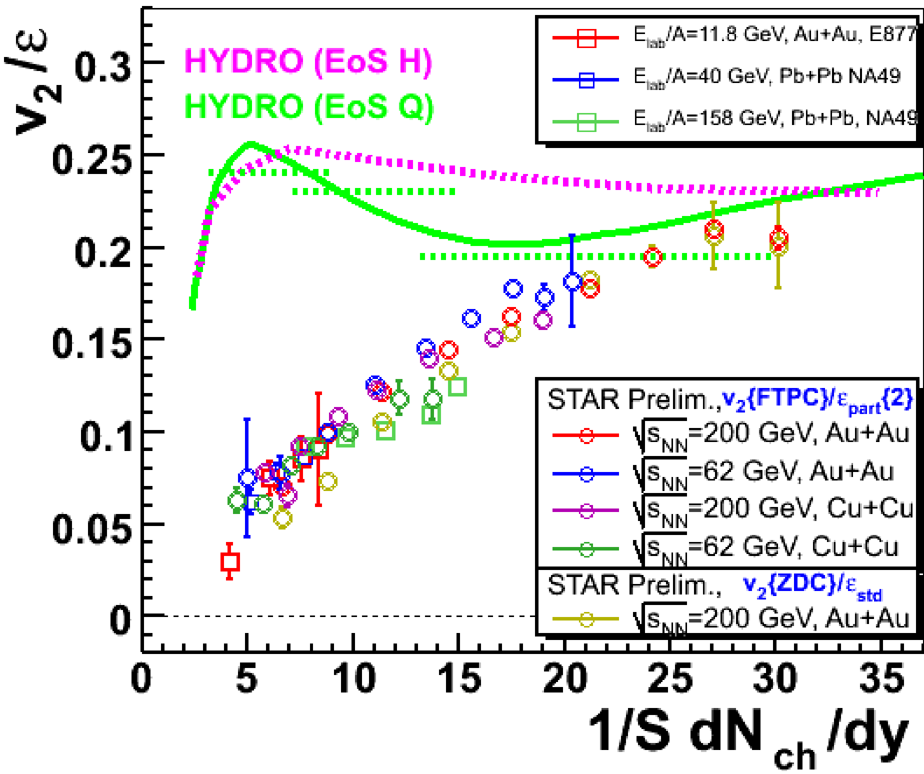


Byungsik Hong
Korea University

This file contains the collection of interesting experimental physics topics presented during the Quark Matter 2006. The priority was completely biased by the speaker's taste.

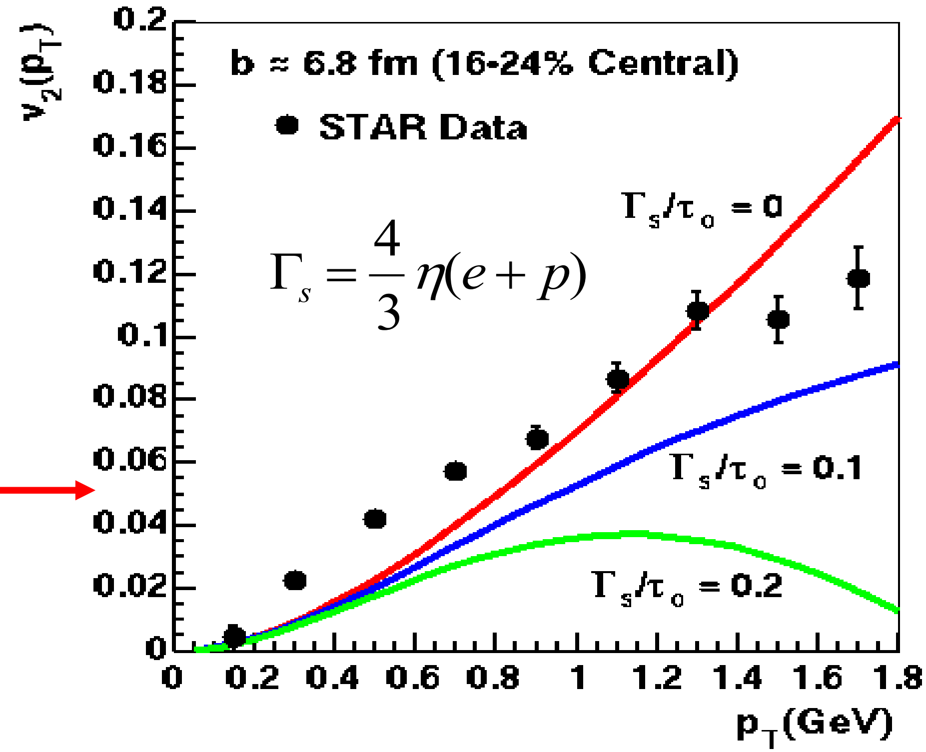
Hadron Production and Flow

Elliptic flow



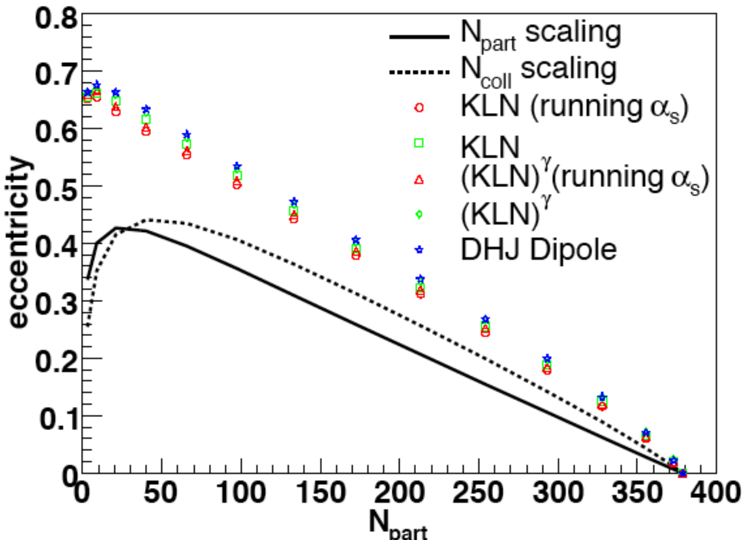
Consistent with v_2/ε scaling for all energies and collision systems.

- v_2/ε approaches the limit of ideal hydrodynamics.
- Viscosity reduces v_2.
- Viscosity needs to be small in order to explain data.

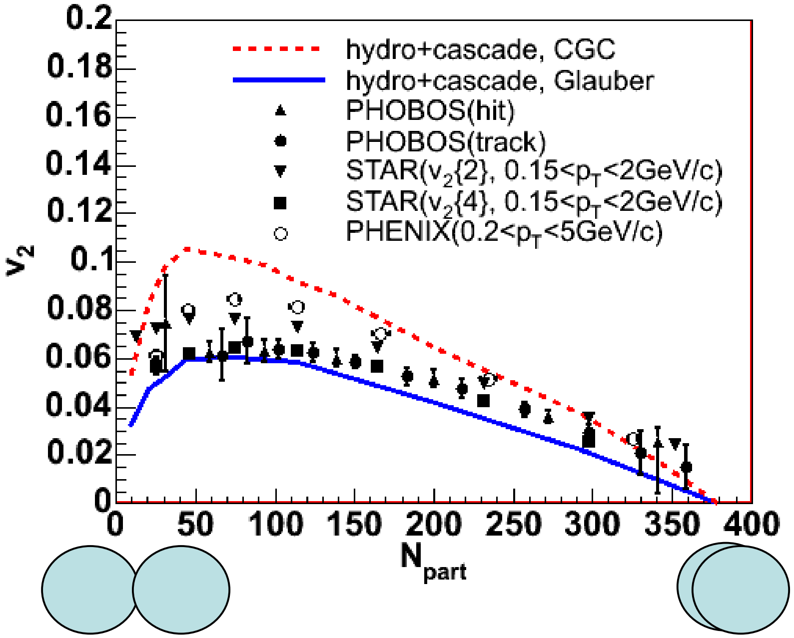


D. Teaney, PRC 68 034913 (2003)

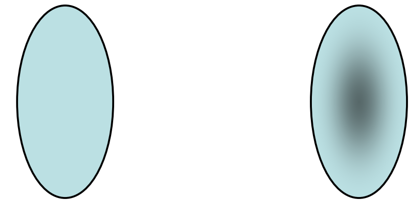
Is “perfect liquid” a unique explanation?



A. Adil, et al. nucl-th/0605012 (2006)



T. Hirano, RHIC & AGS Users Mtg 06



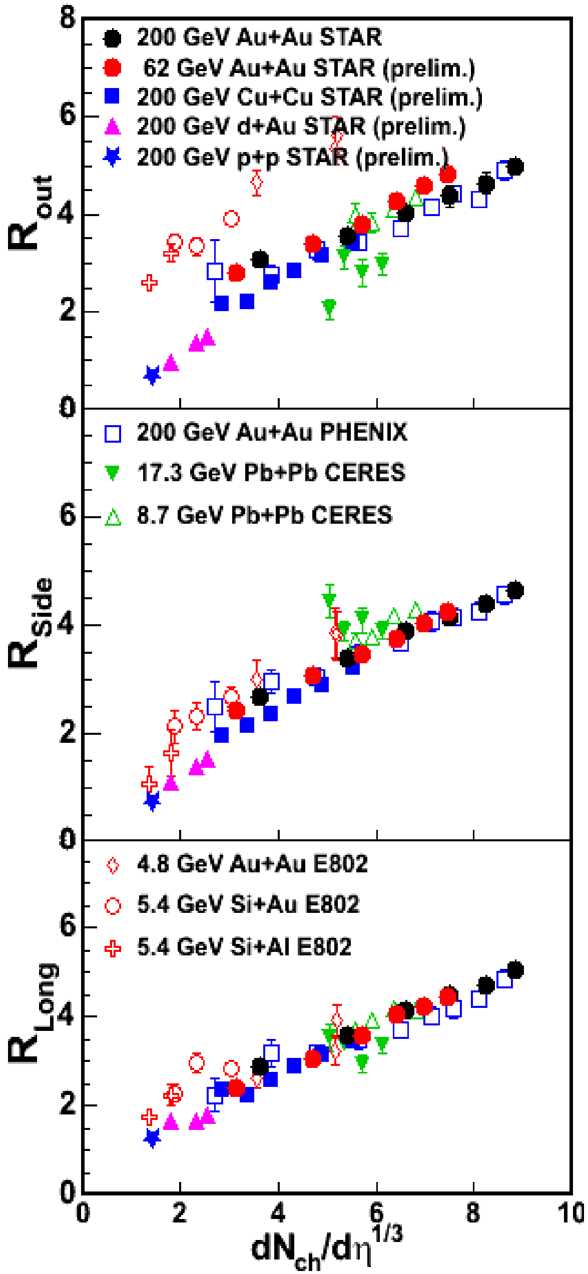
CGC Glauber

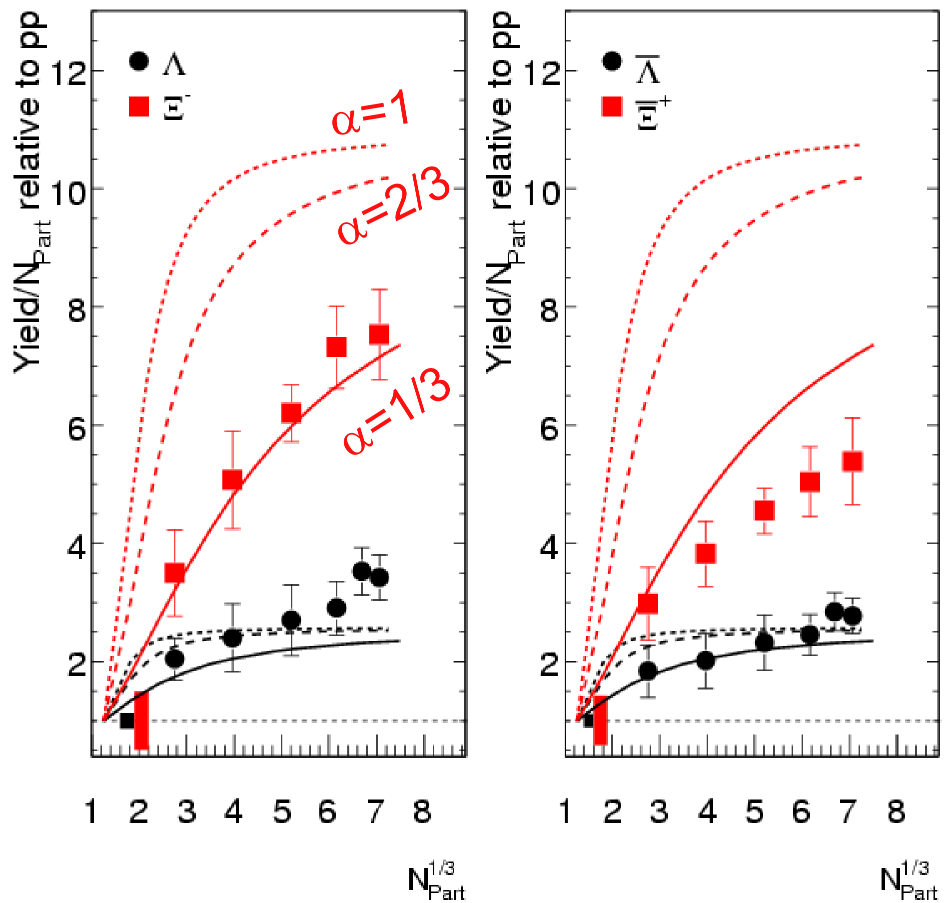
$$\varepsilon_{CGC} > \varepsilon_{Glauber}$$

- Is it Glauber + perfect liquid or, CGC + viscous matter?
- It is important to understand **the initial condition !**

Scaling of soft physics

$$V = \left(\frac{N_{Part}}{2}\right)^{\alpha} V_0$$

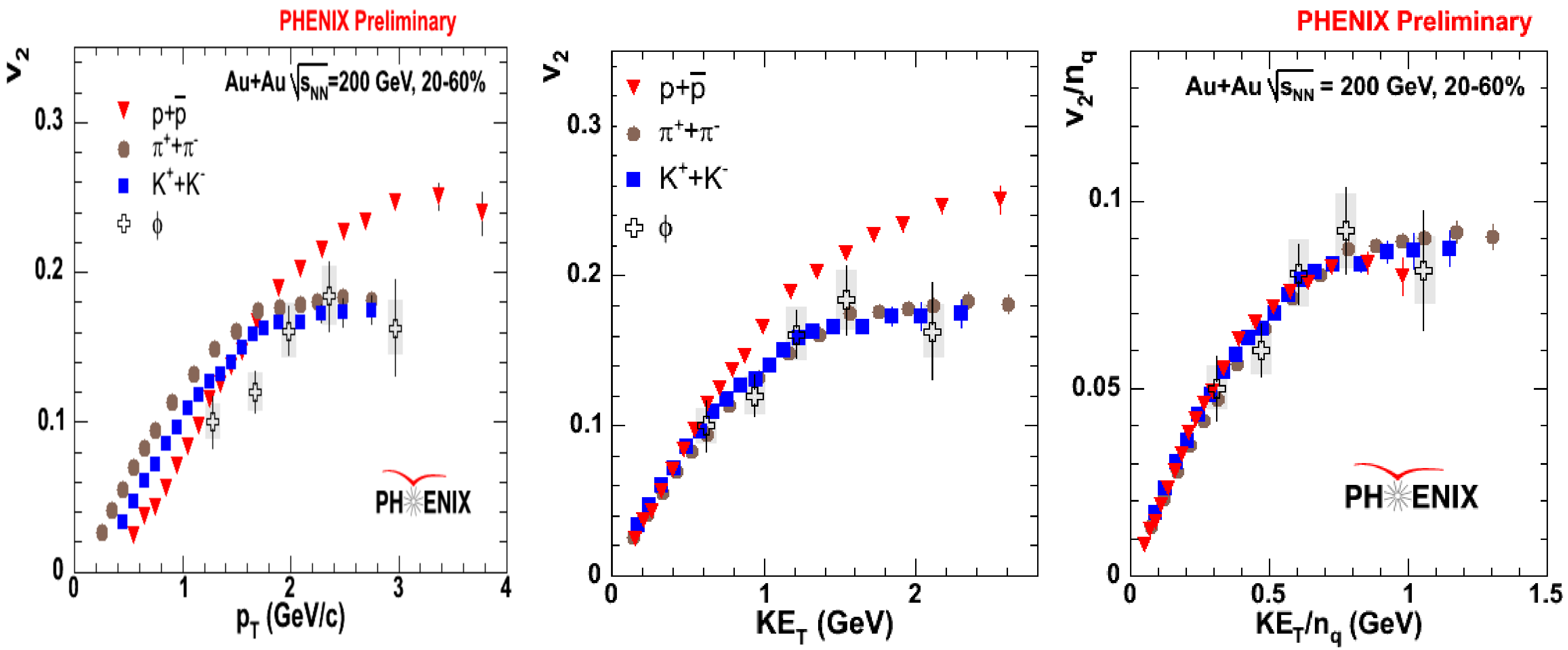




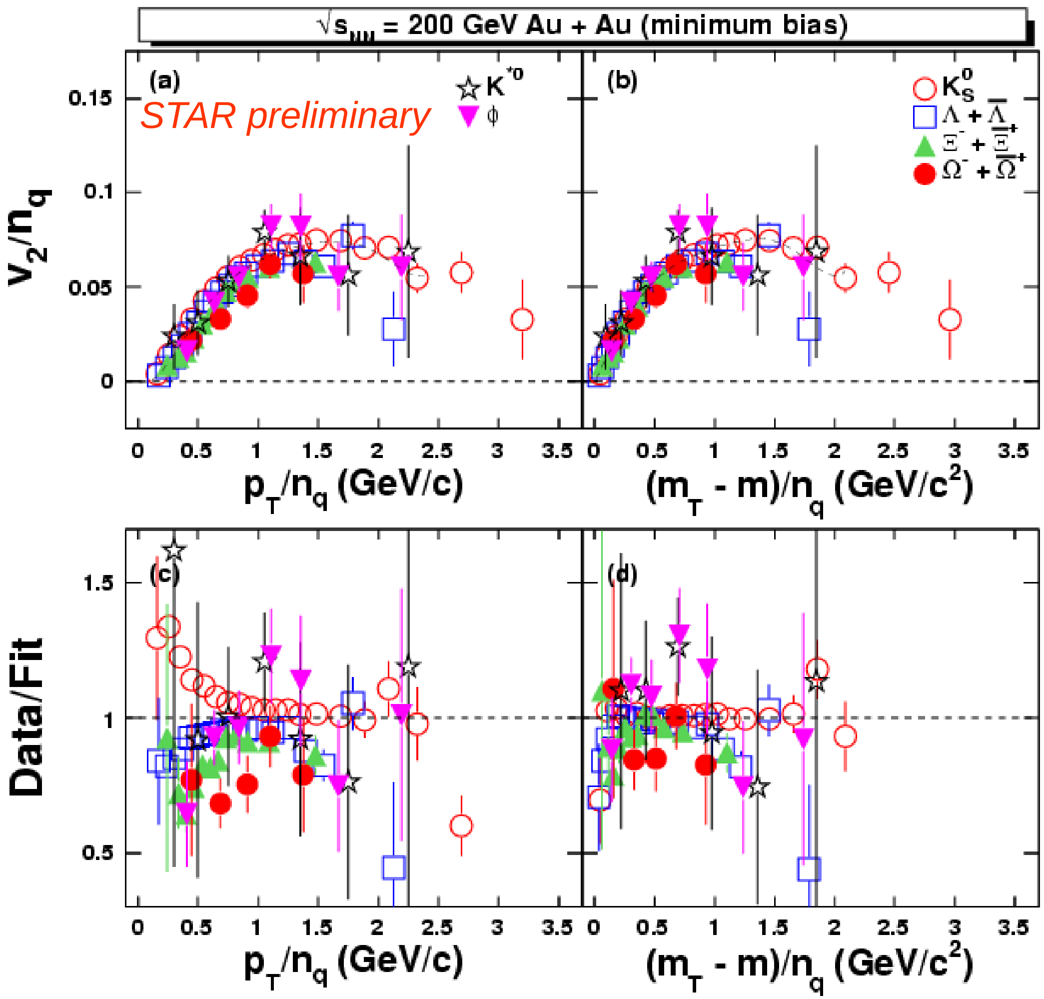
Evidence from HBT and Strangeness production shows that length plays an important role in soft physics.

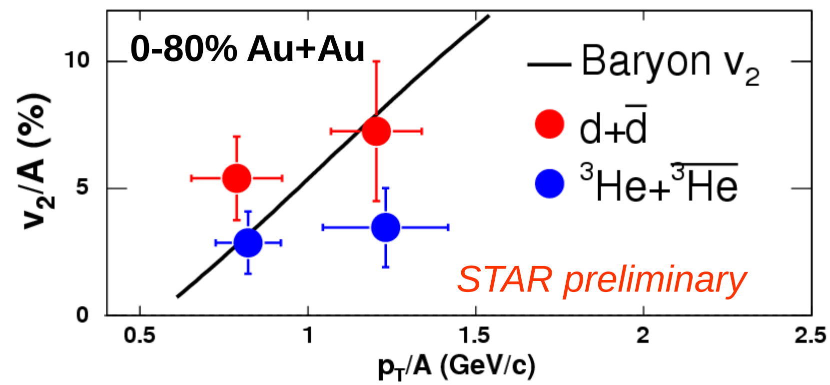
v_2 of light quarks

When the mass effect removed by m_T-m, only the quark number ratio shows up!
Is mass ordering of v_2 at low p_T generated during or after hadronization?
Feed-down for pion is visible in p_T, but not in m_T-m, because
p_T(daughter) < p_T(parent) , but m_T-m(daughter) ~ m_T-m(parent) …
Decay kinematical effect is masked by the p_T to m_T-m transformation.



v_2 of strange hadrons



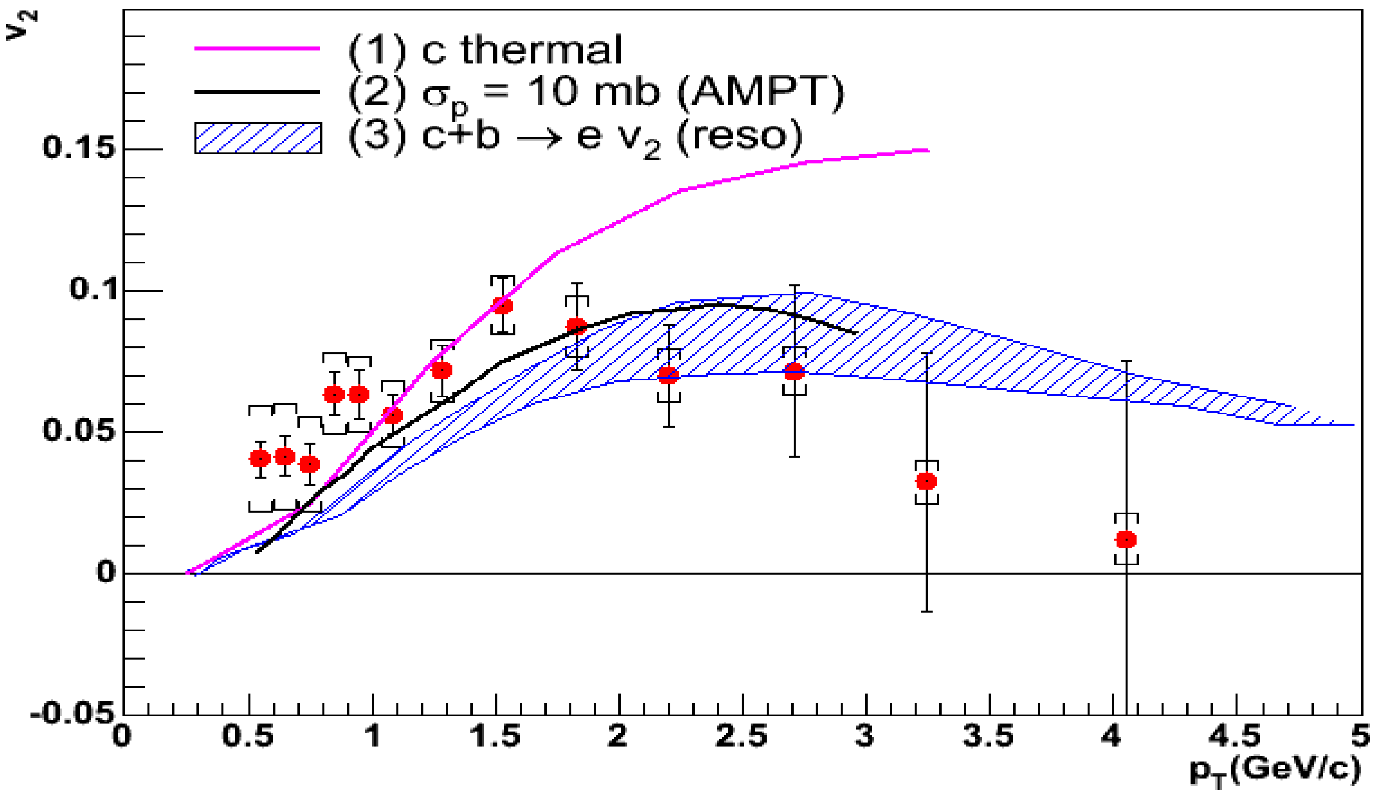


Intermediate p_T ($0.7<p_T/n<2GeV/c$)

- **K_S K* ϕ Λ Ξ Ω v_2: follow NQ scaling.**
- **Heavy particle: d follows A scaling, ^{3}He follows A scaling at low p_T, maybe deviate at higher p_T→need more statistics.**

Early freeze-out effect of multi-strangeness hadrons seen in spectra analysis with radial flow does not show up here in v_2 analysis, this is an indication that v_2 is already built up in early stage.

v_2 of charm quarks



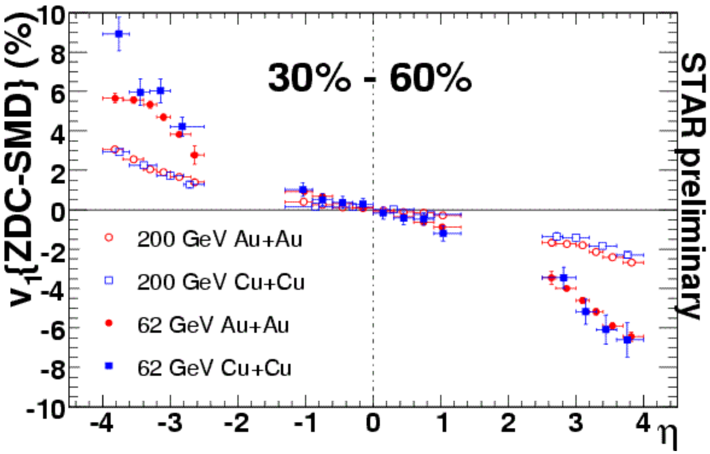
(1) Consistent with c-quark thermalization **[Phys.Lett. B595 202-208]**

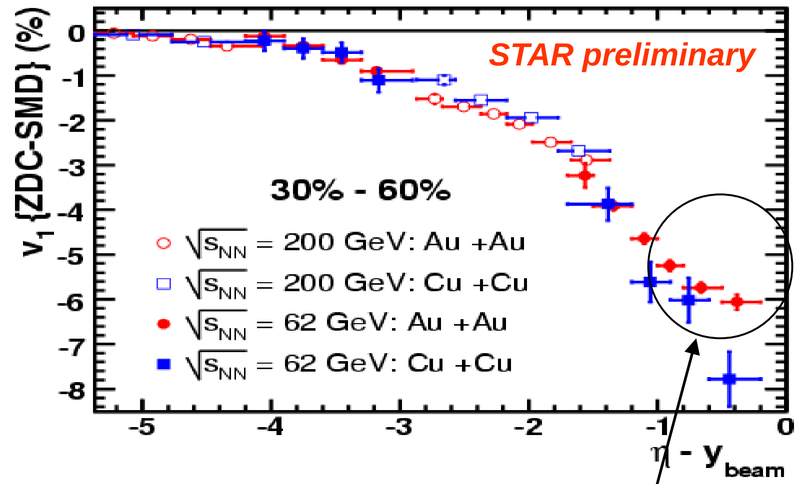
(2) Large cross section is needed in AMPT ~10 mb **[PRC72,024906]**

(3) Resonance state of D & B in sQGP **[PRC73,034913]**

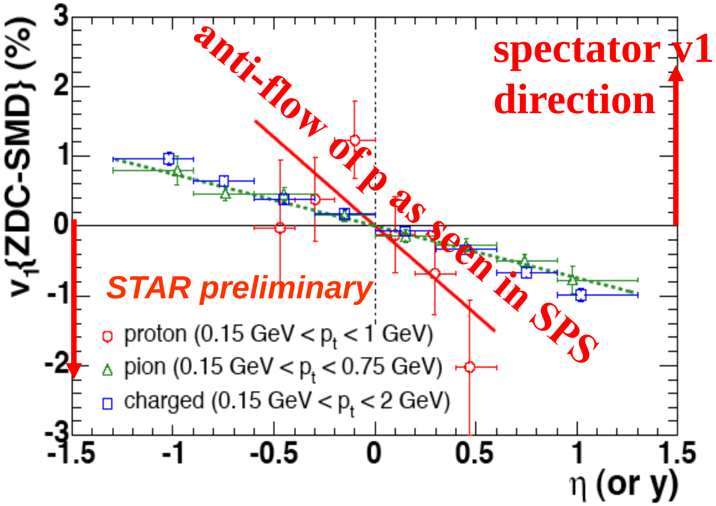
➔ indicates quark level thermalization & strong coupling

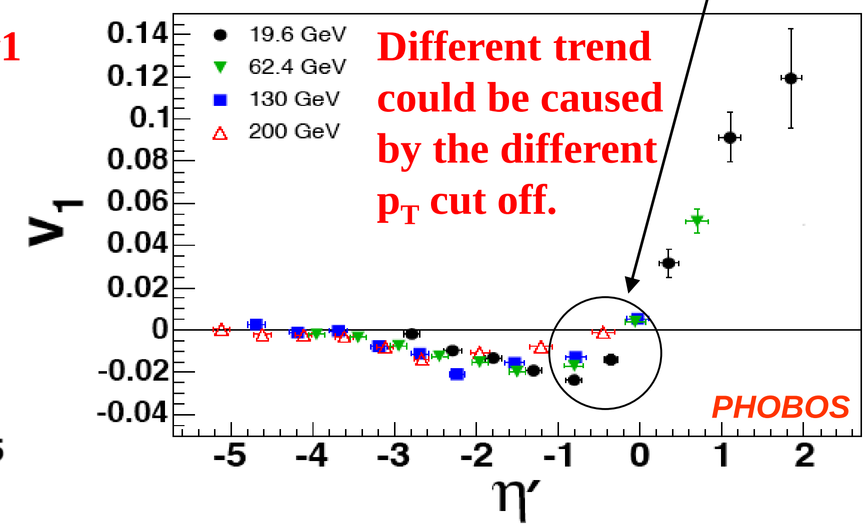
v_1 of charged hadrons





v_1 depends on energy, not on system size.

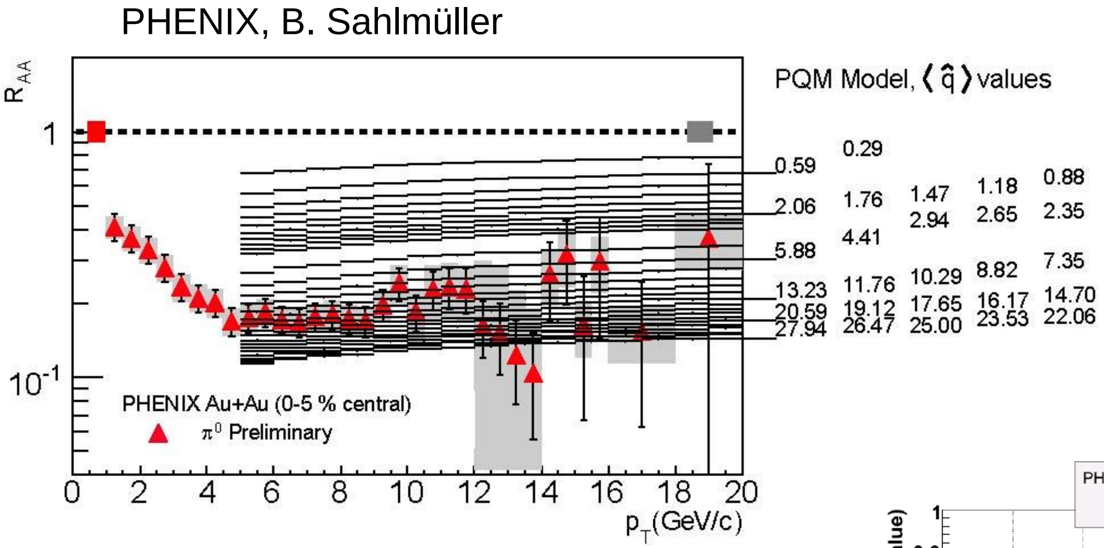


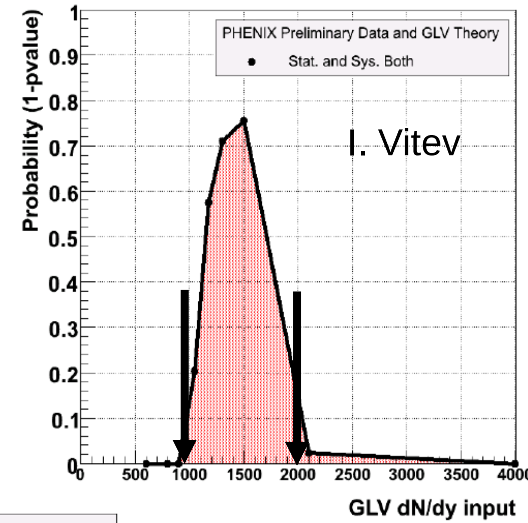


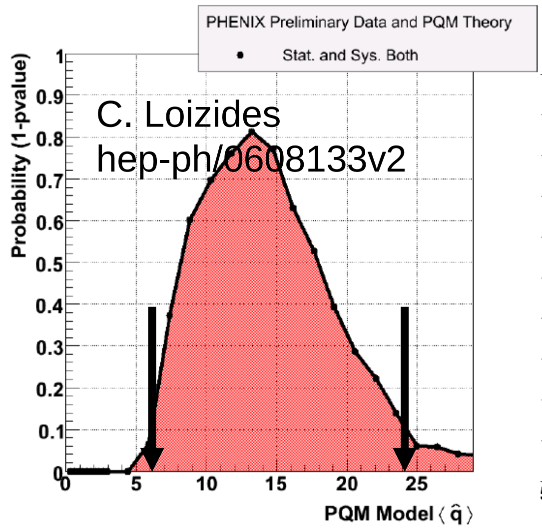
First order phase transition?

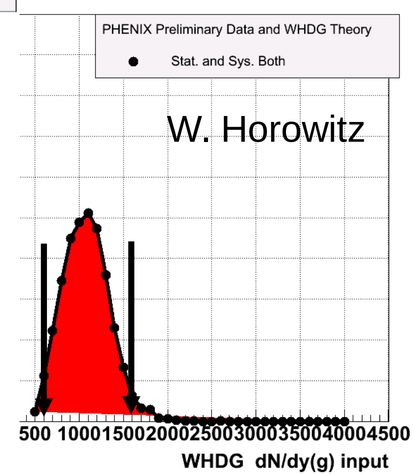
Light Quark Energy Loss

Light quark energy loss









Use R_{AA} to extract medium density:

I. Vitev: $1000 < dN_g/dy < 2000$

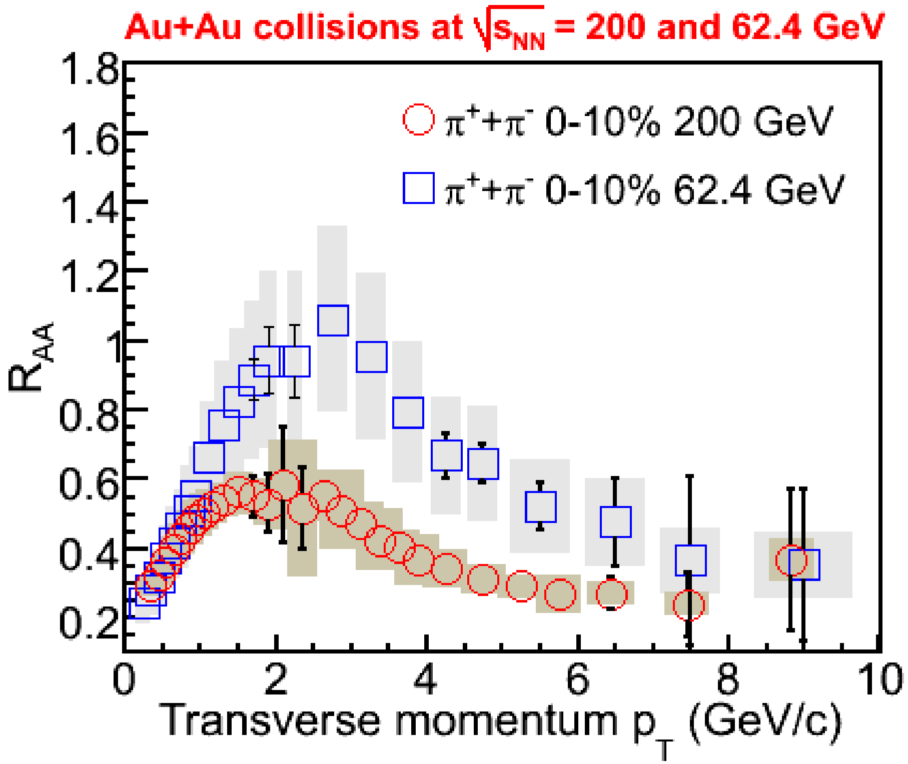
W. Horowitz: $600 < dN_g/dy < 1600$

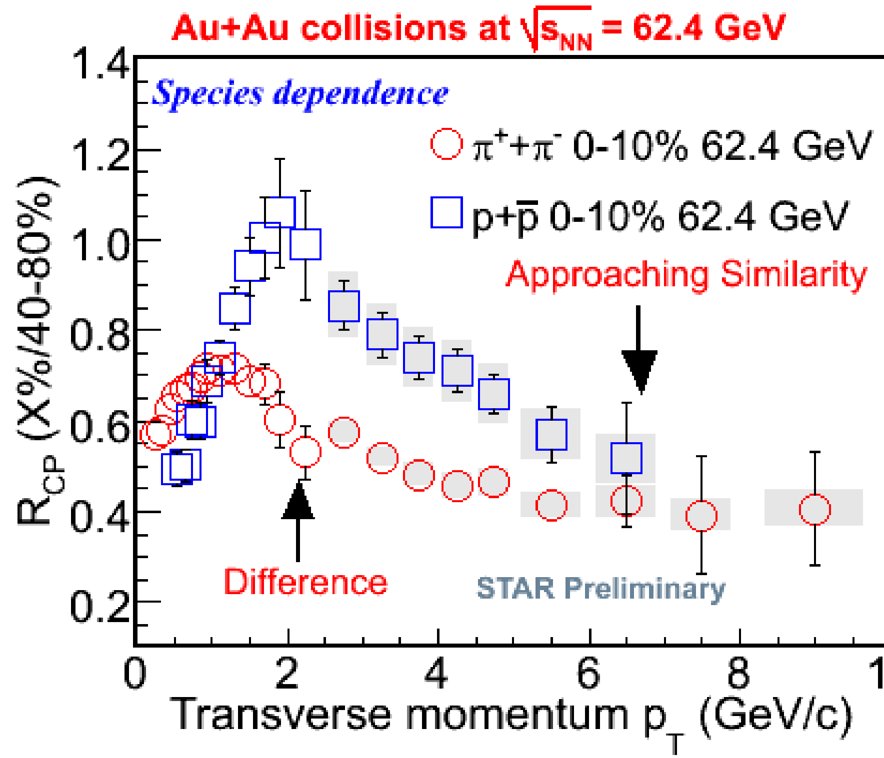
C. Loizides: $6 < \hat{q} < 24$ GeV²/fm

Statistical analysis to make optimal use of data

Caveat: R_{AA} folds geometry, energy loss and fragmentation

Energy dependence of R_{AA} (R_{CP})

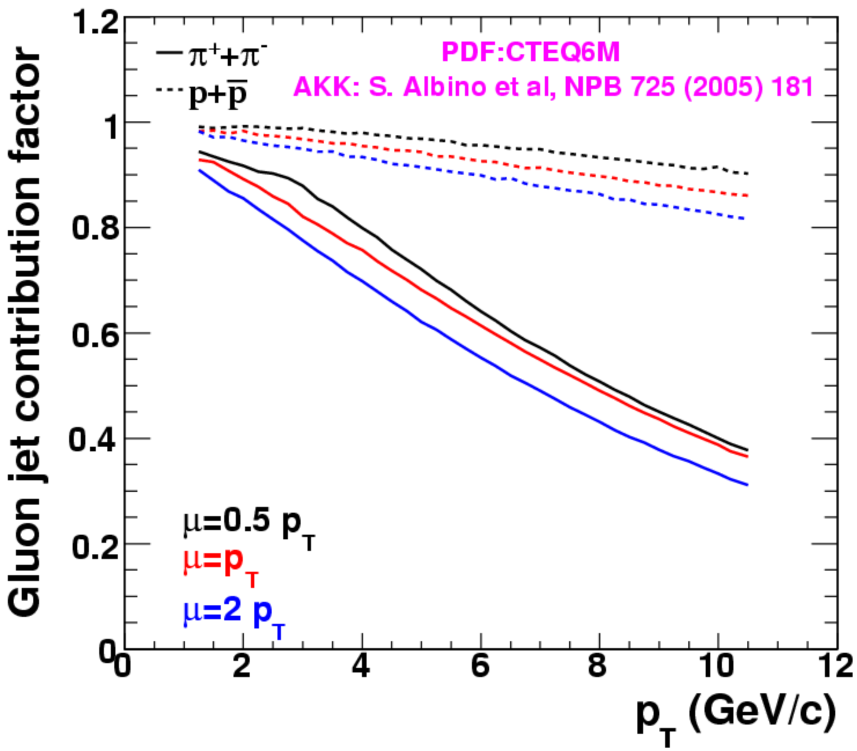


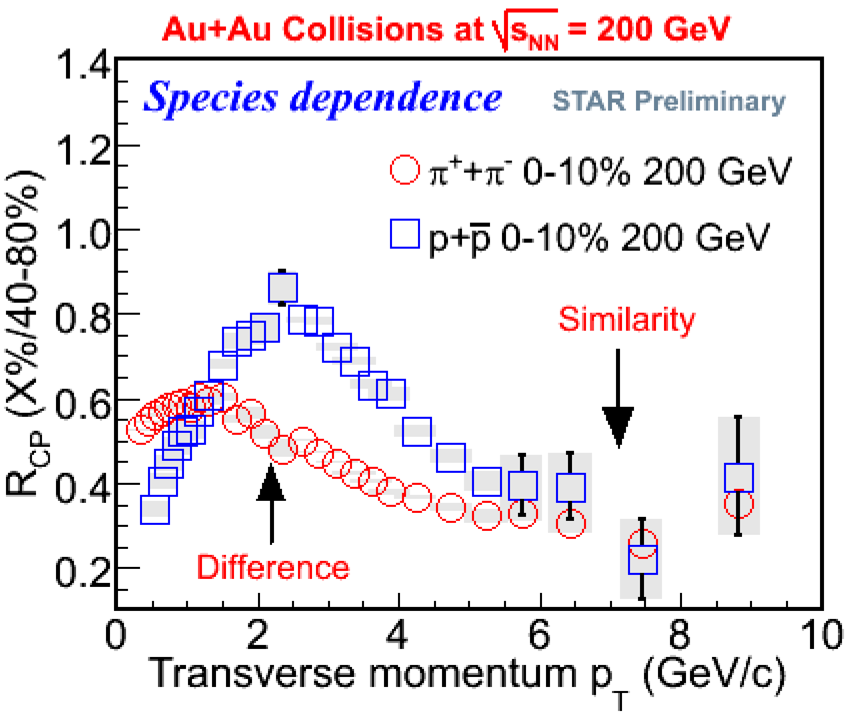


Steeper initial jet spectra ?
Or Color charge dependence ?
At same p_T : ~ 3 difference in x_T.
Q. Wang and X.N. Wang, PRC 71, 014903 (2005)

At 1.5 < p_T < 6 GeV/c: R_{CP}(p+pbar) > $R_{CP}(\pi)$
At p_T > 6 GeV/c, R_{CP}(p+pbar) ~ $R_{CP}(\pi)$
Similar to 200 GeV Au+Au collisions.

Gluon vs quark energy loss





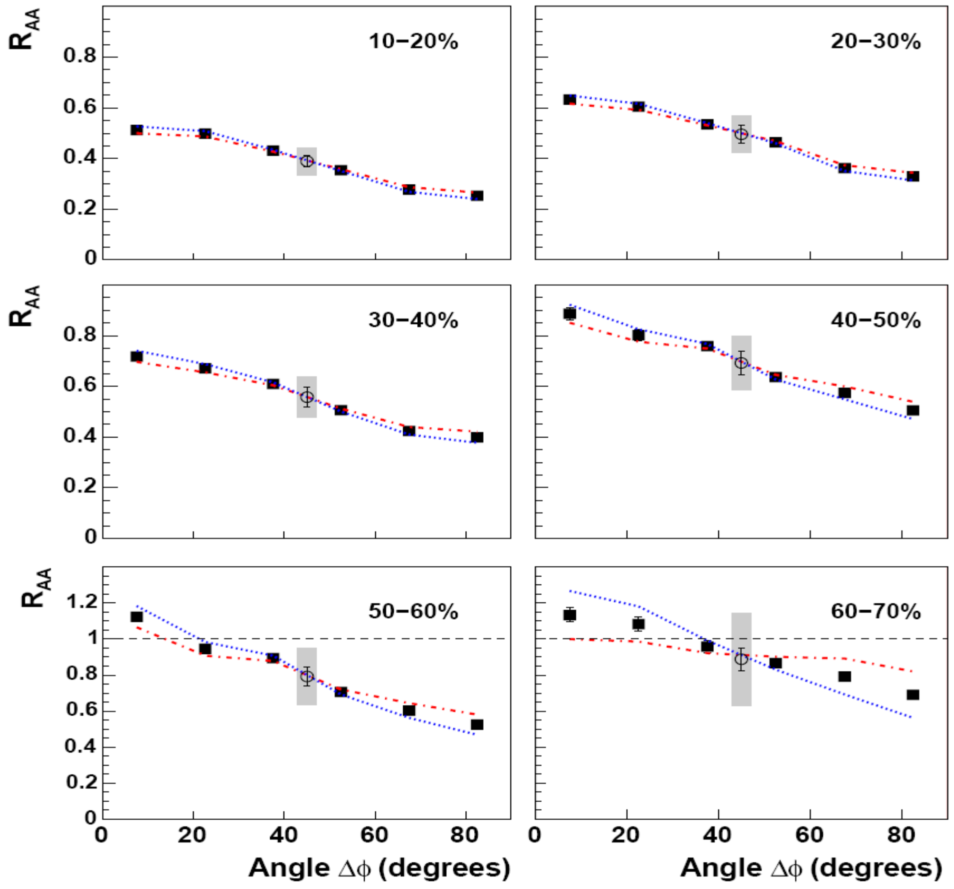
90% of p from gluons
40% of π from gluons

STAR : PRL 97, 152301 (2006)

- Protons are expected to have a larger contribution from gluons compared to pions => larger energy loss
- But above $p_T \sim 6$ GeV/c – the same suppression pattern !

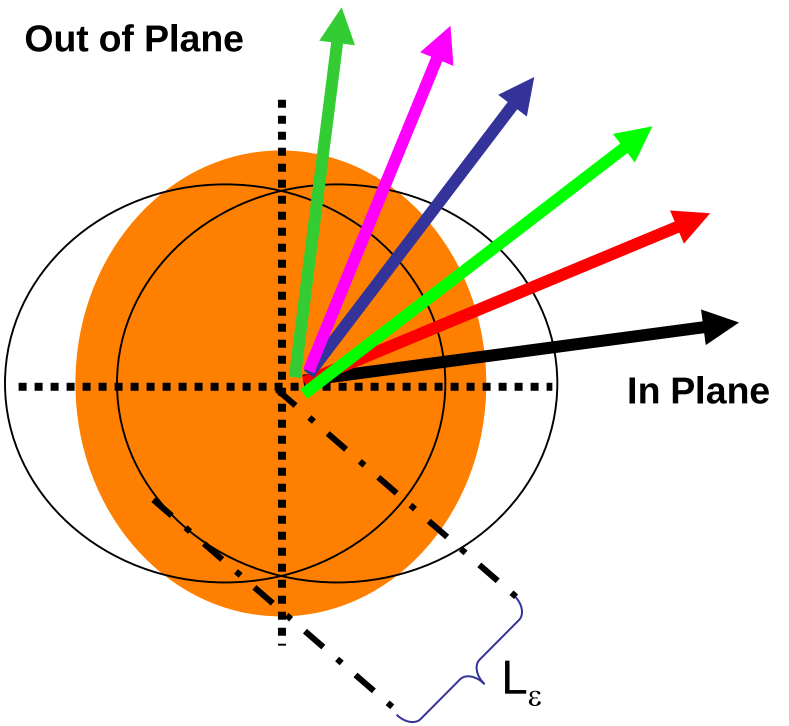
R_{AA} vs reaction plane

Au+Au collisions at 200GeV (PHENIX)



3<p_T<5 GeV/c

nucl−ex/0611007
(submitted to Phys. Rev. C.)

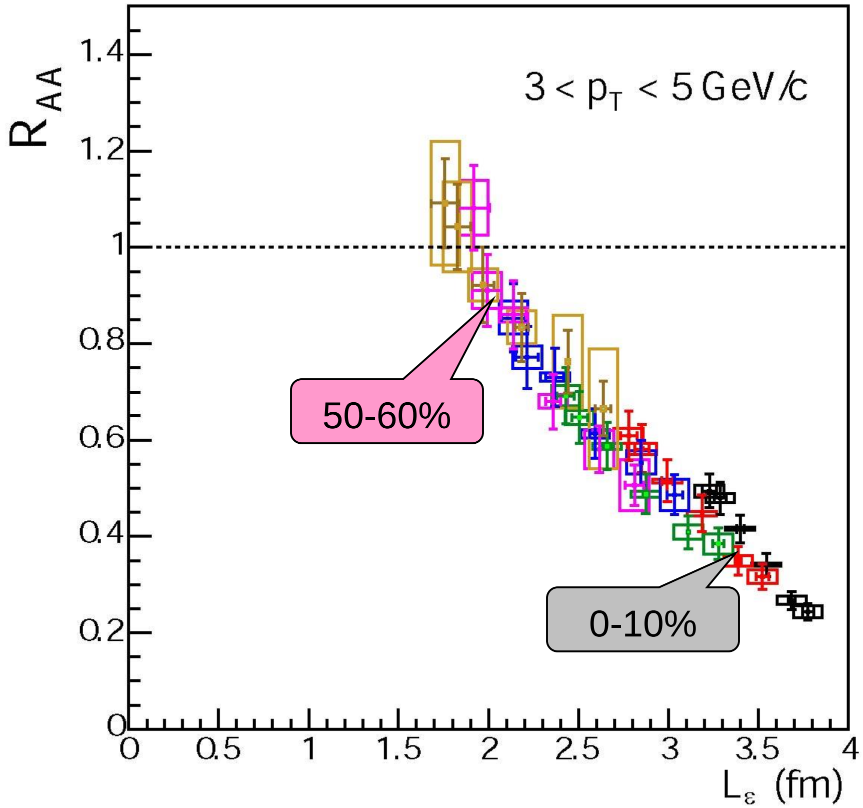


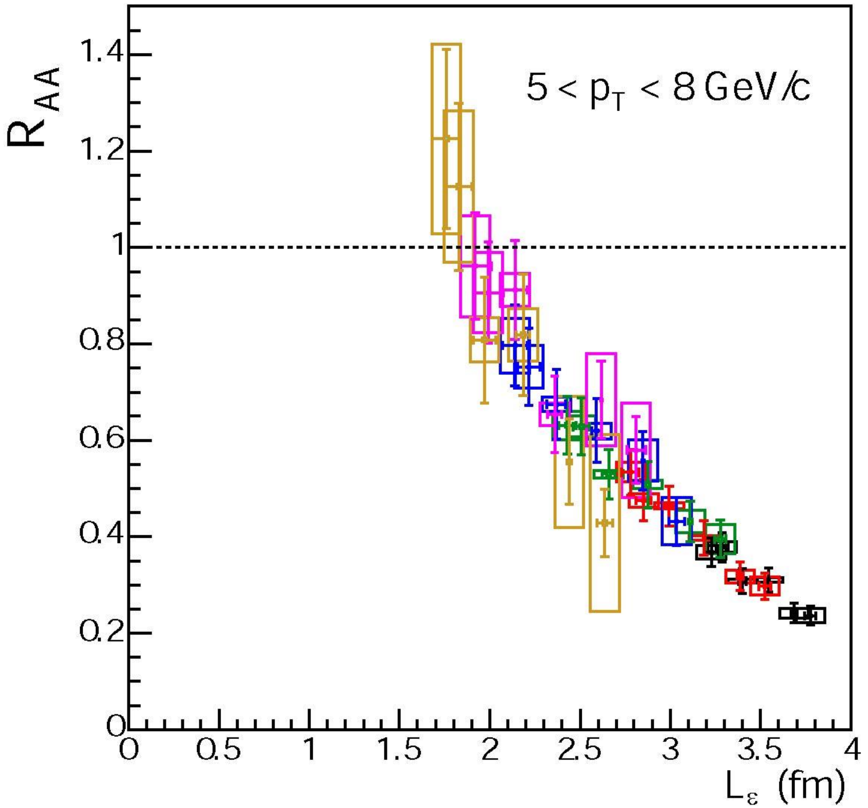
In plane emission shows no energy loss in peripheral bins.

R_{AA} : L_ε dependence

nucl−ex/0611007
(submitted to Phys. Rev. C.)

Au+Au collisions at 200GeV





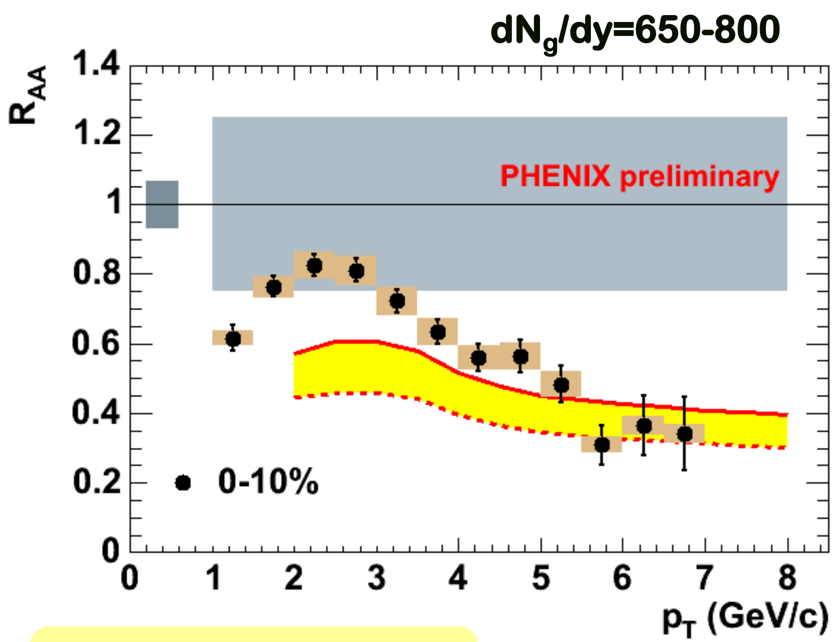
L_ε = matter thickness calculated in Glauber model

Little/no energy loss for L_e < 2 fm ⇒ Formation time effect?
V. Pantuev hep-ph/0506095

R_{AA} – energy dependence

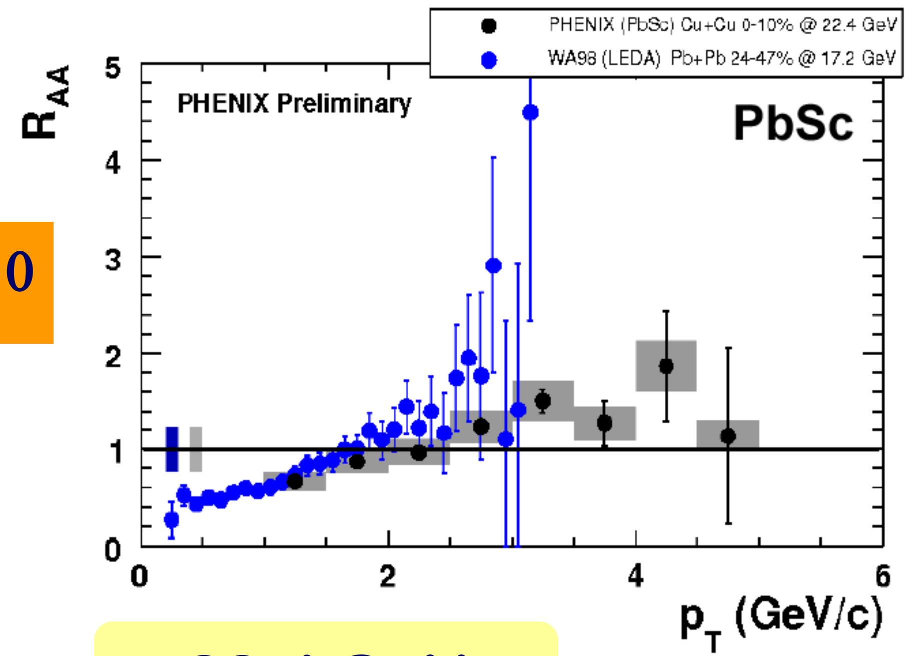
Au+Au

Vitev nucl-th/0404052



π^0

Cu+Cu

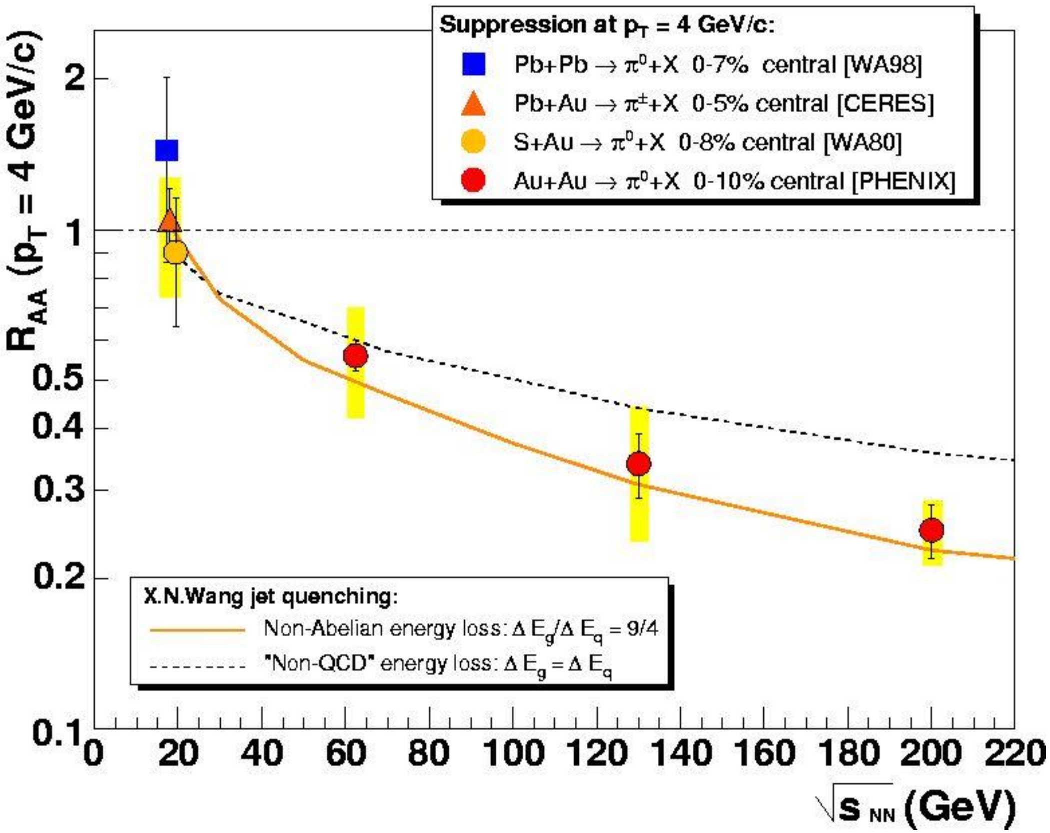


62 GeV

22.4 GeV

- Supression (and dN_g/dy) decreases as we go down in energy – consistent with SPS data

Energy dependence of E_{loss}



nucl-ex/0504001

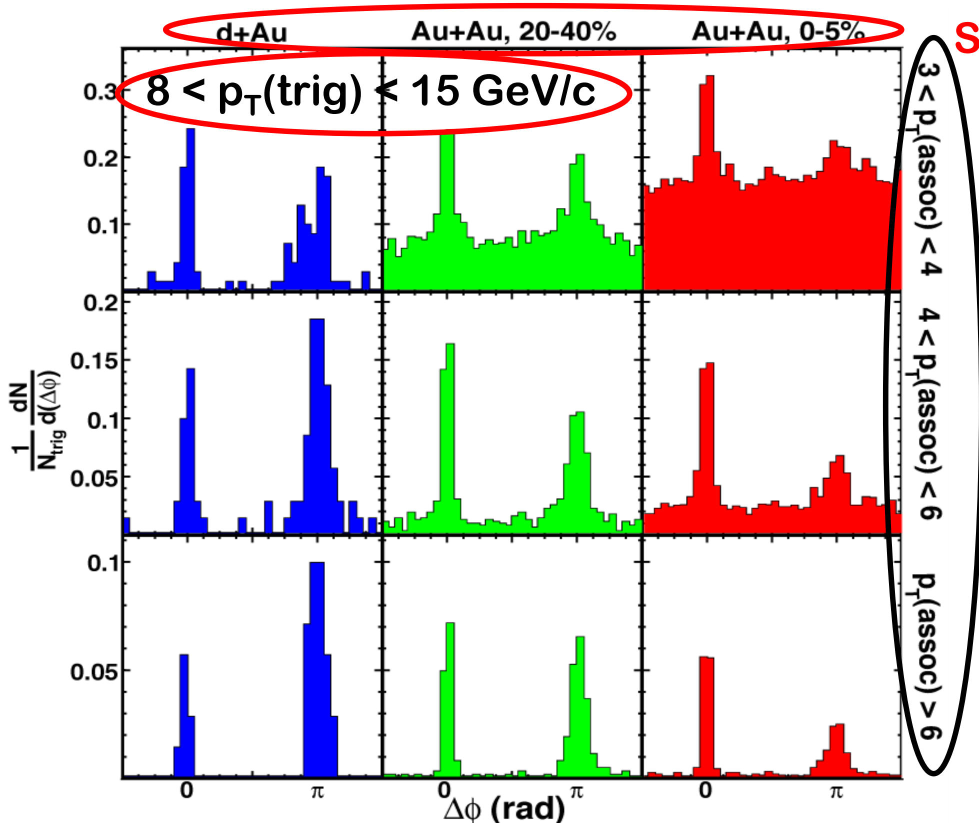
π^0

R_{AA} at 4 GeV: smooth evolution with $\sqrt{s_{NN}}$

Data is better described by Non-Abelian energy loss.

Jet Correlations

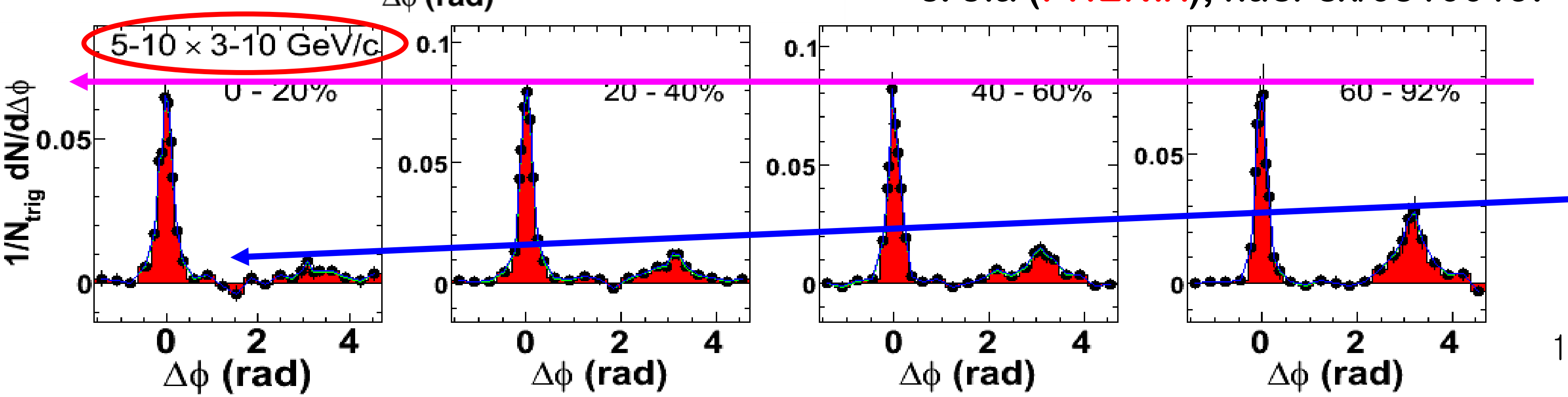
Punch-through at high p_T



STAR, PRL 97 (2006) 162301.

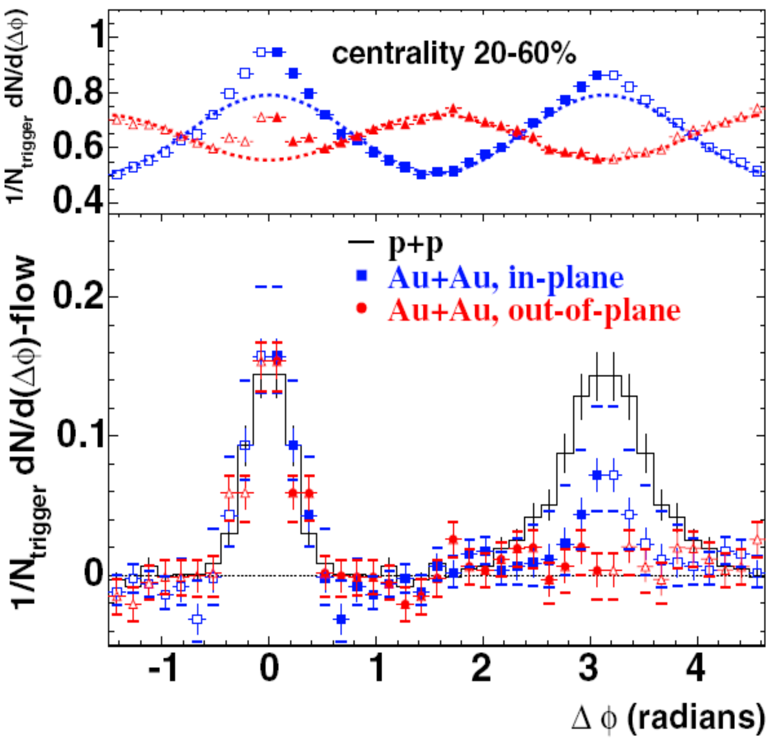
- clear away-side peak dijets
- little modification on near side
- suppression of away-side yield
- but little modification to away-side shape

J. Jia (PHENIX), nucl-ex/0510019.

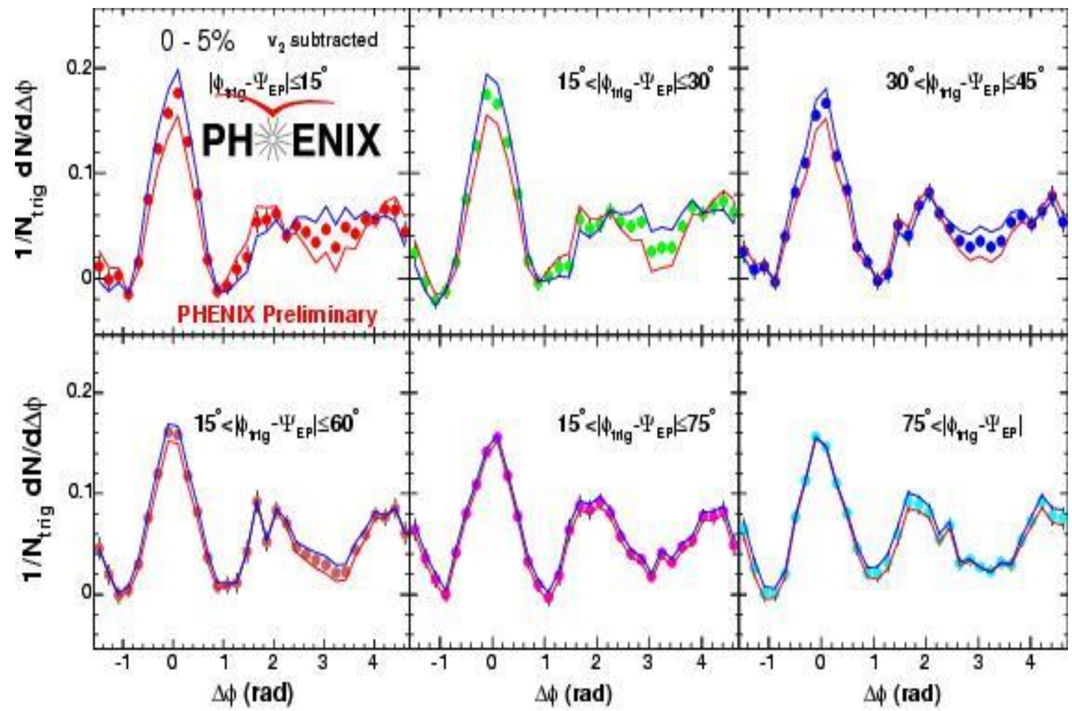


Reaction plane dependence

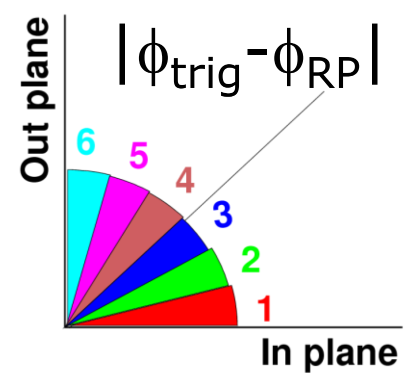
STAR, PRL93 (2004) 252301.



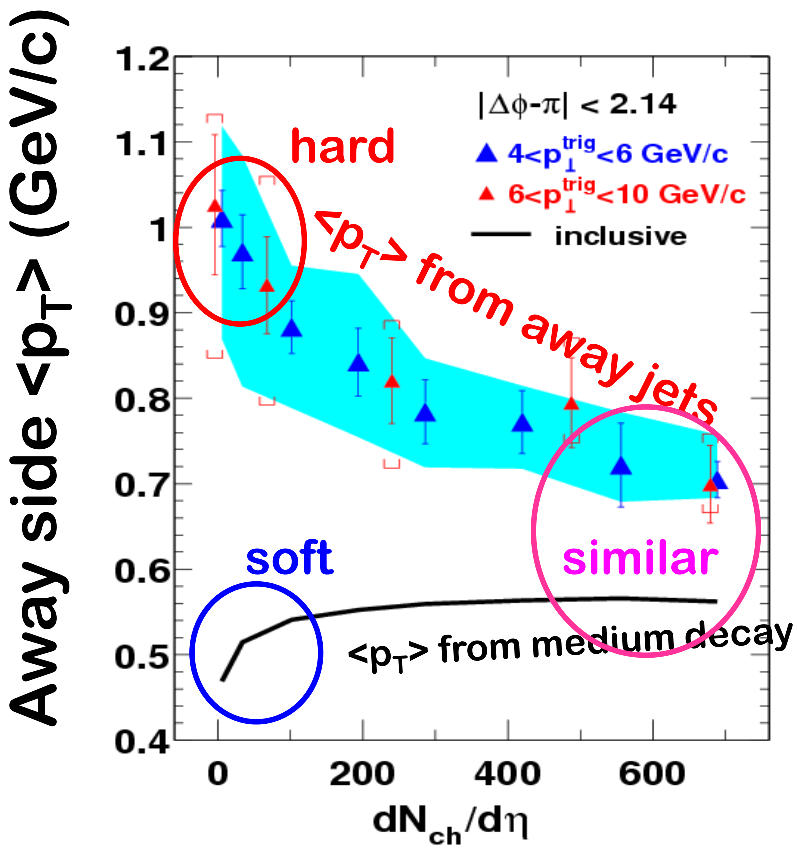
PHENIX, nucl-ex/0510019.

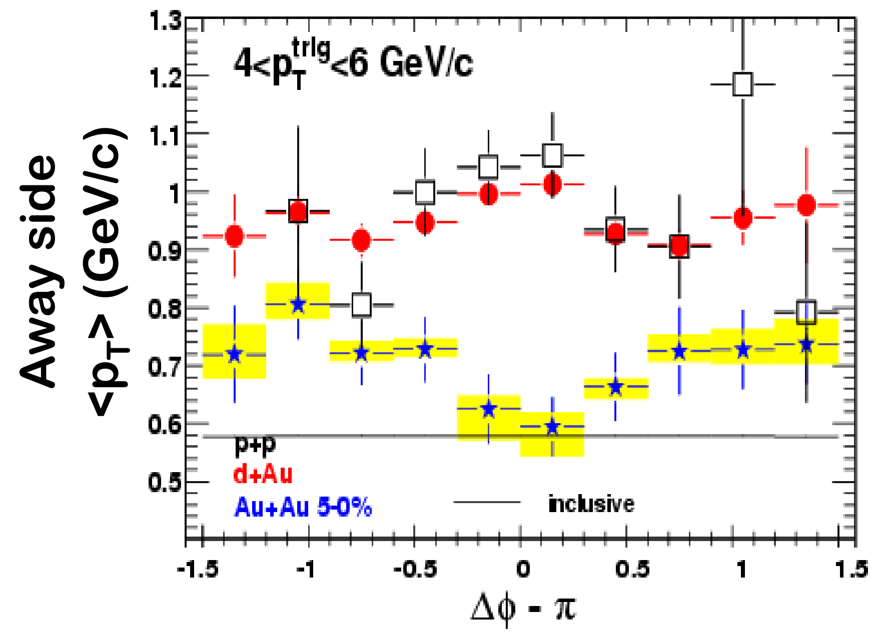


jet shape w.r.t. the reaction plane
geometrical effect of the almond shape
This effect itself is a one of v_2 sources,
which will be an important effect at LHC.
This should also lead different v_2 between bulk and jet.



Softened away-side peak at low p_T





hard-soft: approach
thermalization.

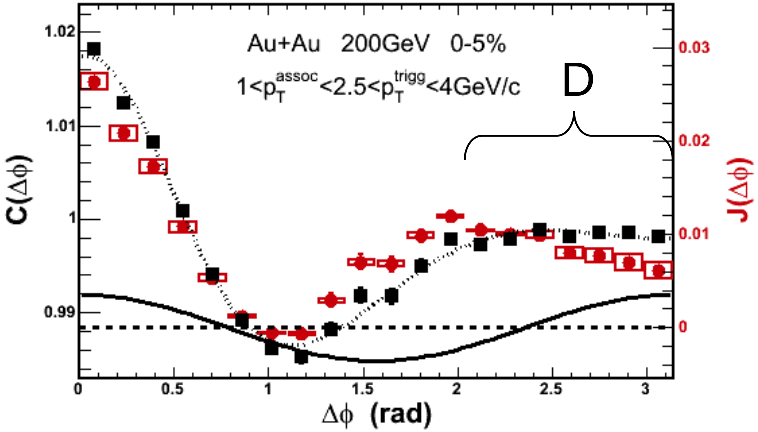
soft-soft (larger x-section):
higher degree of
thermalization.

$<p_T>$ is dipped at π.

Hadrons in the double-hump are harder:
shock wave push?

Jet shapes

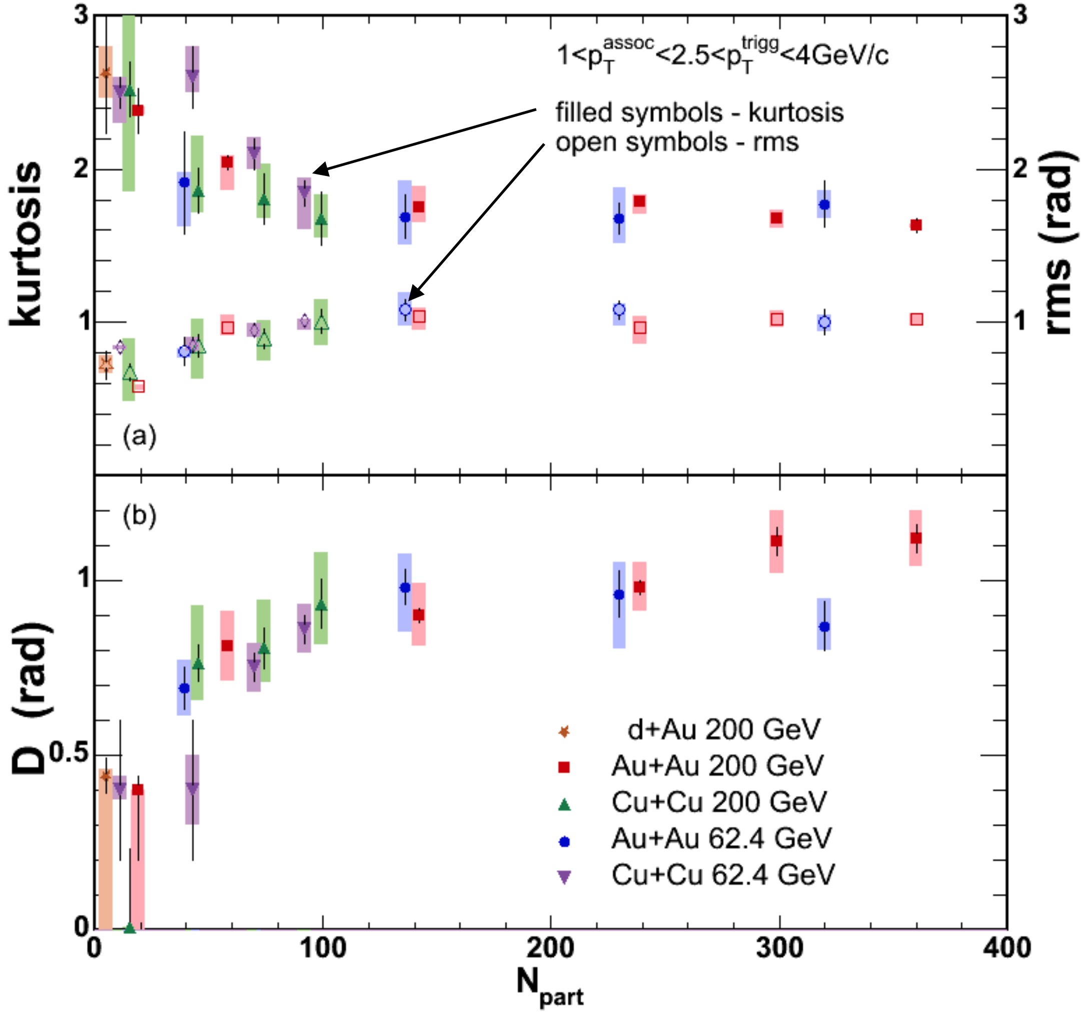
nucl-ex/0611019
(submitted to Phys.Rev.Lett.)



$$\mu_n = \left\langle (\Delta\varphi - \pi)^n \right\rangle$$

$$rms = \sqrt{\mu_2}$$

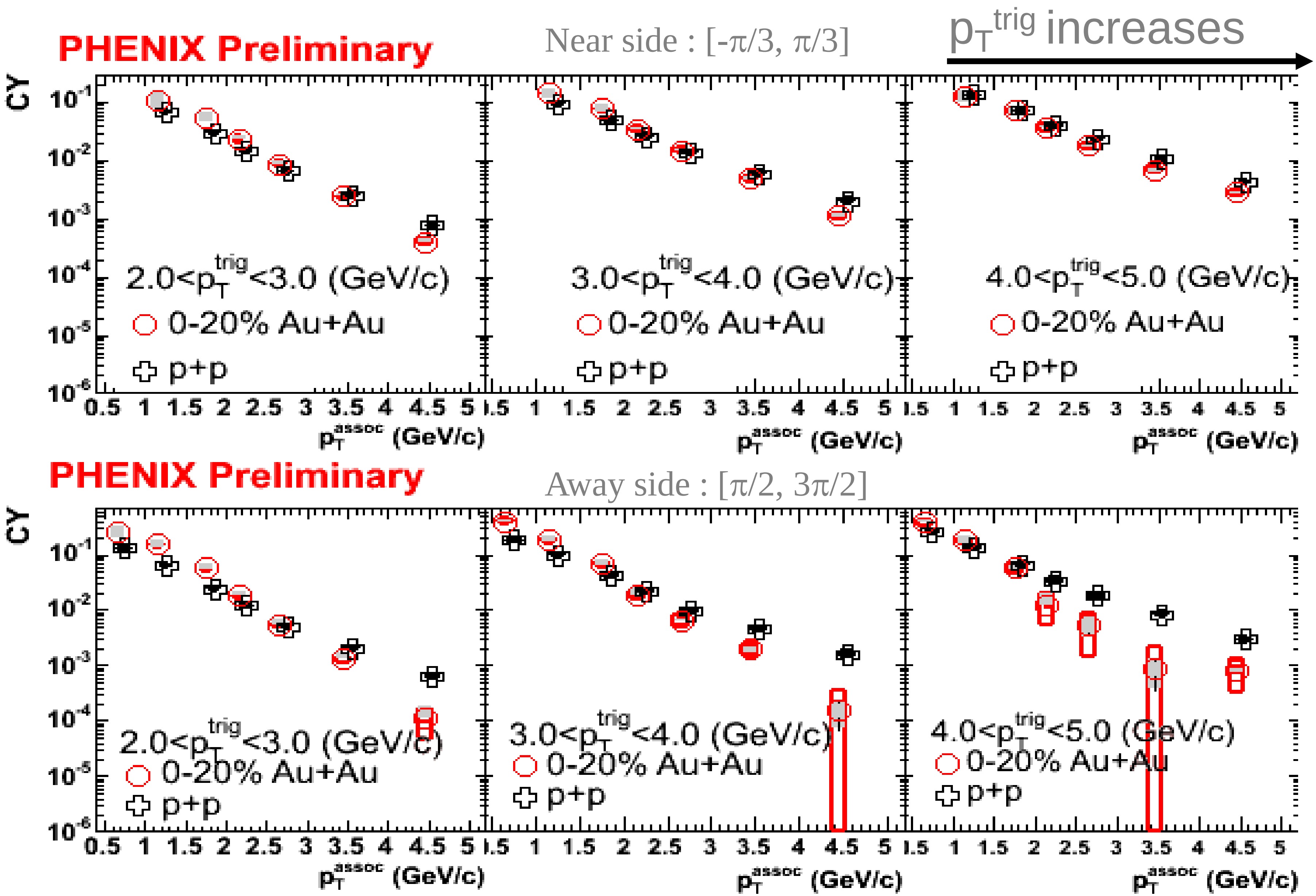
$$kurtosis = \mu_4 / \mu_2^2$$



rms, kurtosis and D also independent of p_T of associated hadrons - poses challenge to color Cerenkov models

Nearside vs awayside

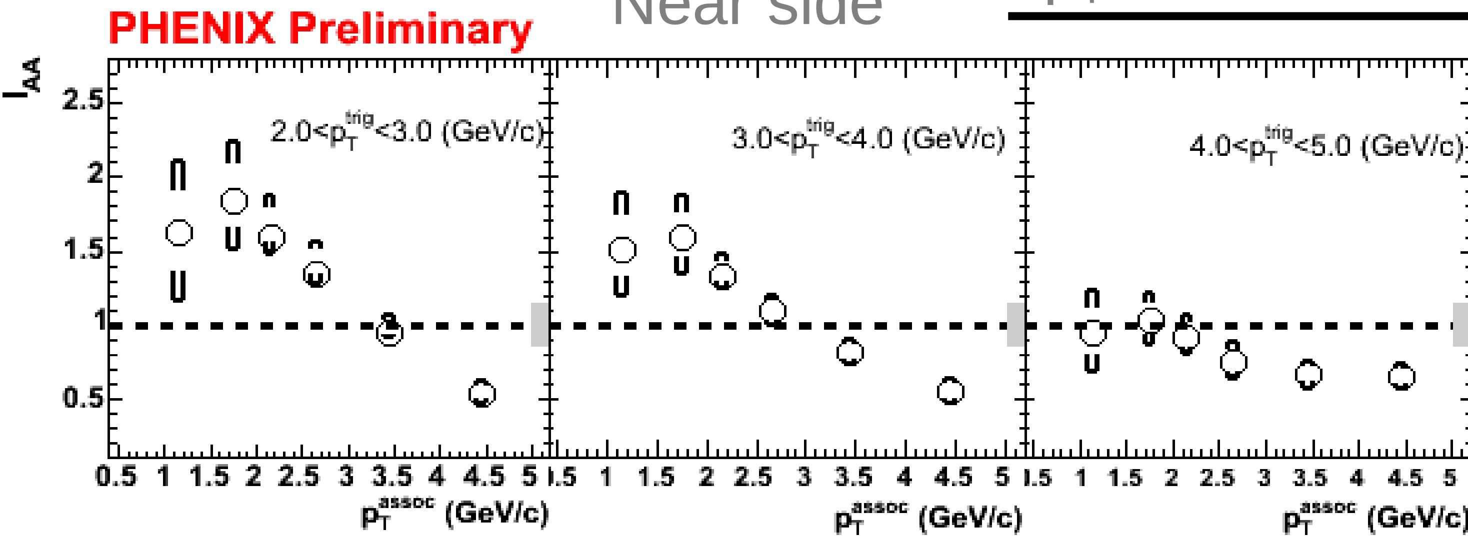
$CY = dN^{pair}/d\phi/N^{trig}$



$I_{AA} = CY_{AA}/CY_{PP}$

Near side

p_T^{trig} increases →

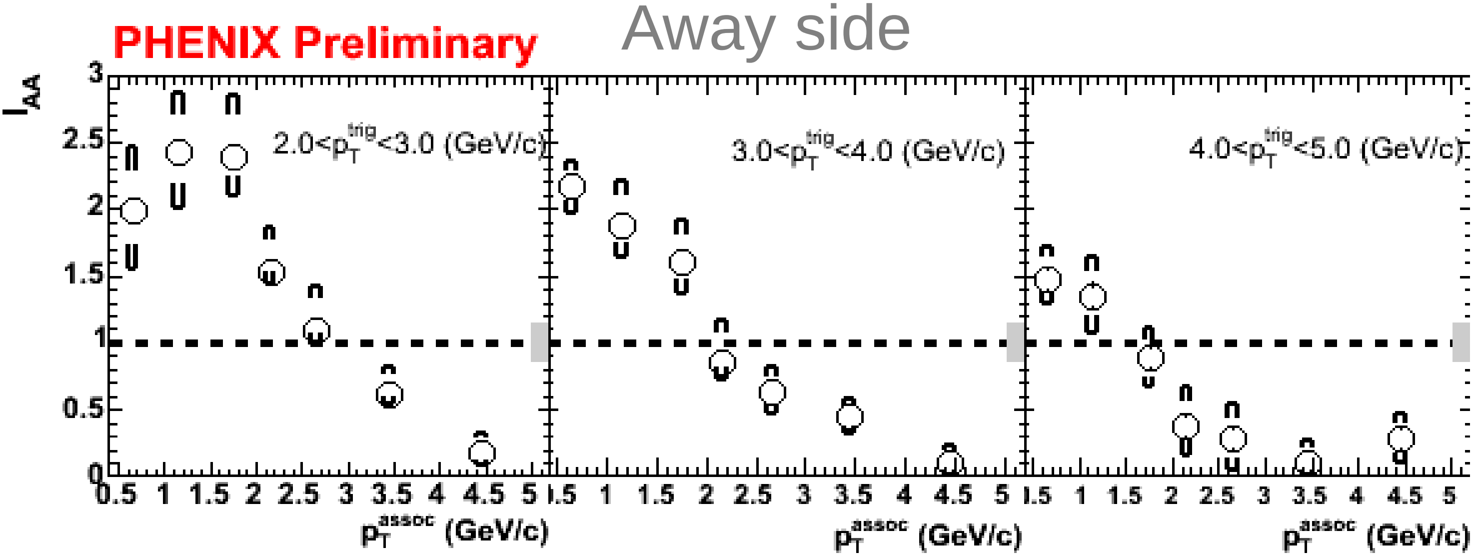


Increase p_T^{trig}

↓

Decrease Modification
Smaller enhancement in low p_T^{assoc}

Away side



Increase p_T^{trig}

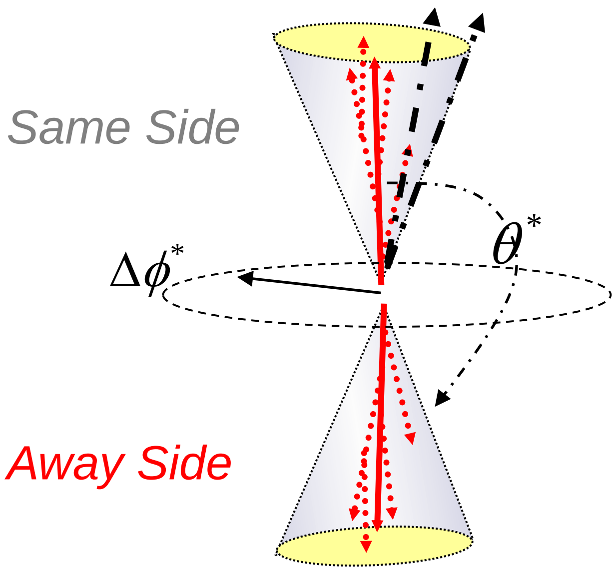
↓

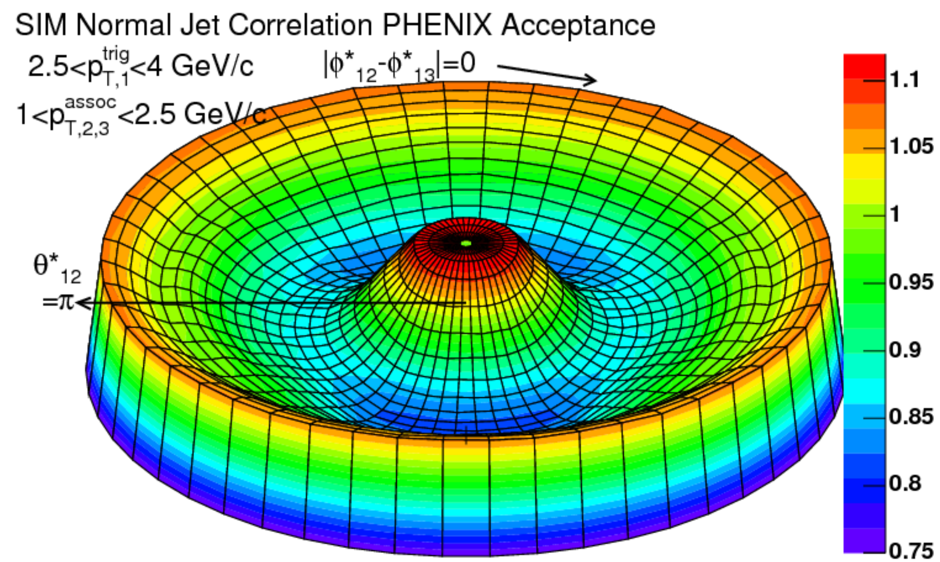
Increase Modification
Stronger suppression in high p_T^{assoc} less enhancement in low p_T^{assoc}

3-Particle Correlations

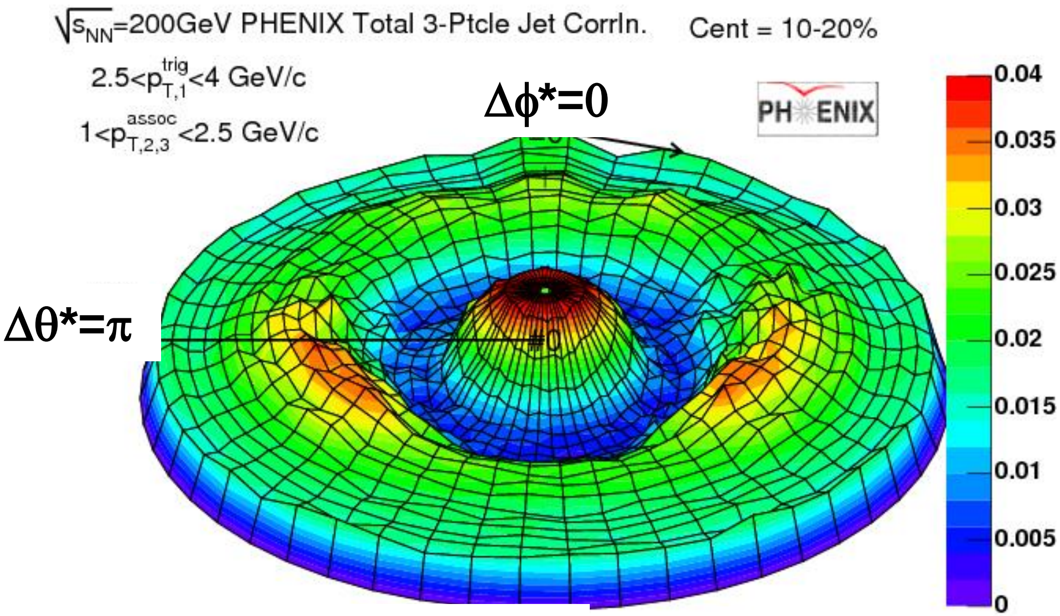
θ^* : polar angle of the first associated particle, $\theta^{*}{}_{1}{}^{assoc}$

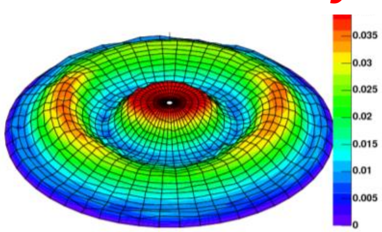
$\Delta\phi^*$: $\phi^{*}{}_{1}{}^{assoc}$ $-\phi^{*}{}_{2}{}^{assoc}$





Correlation Topologies

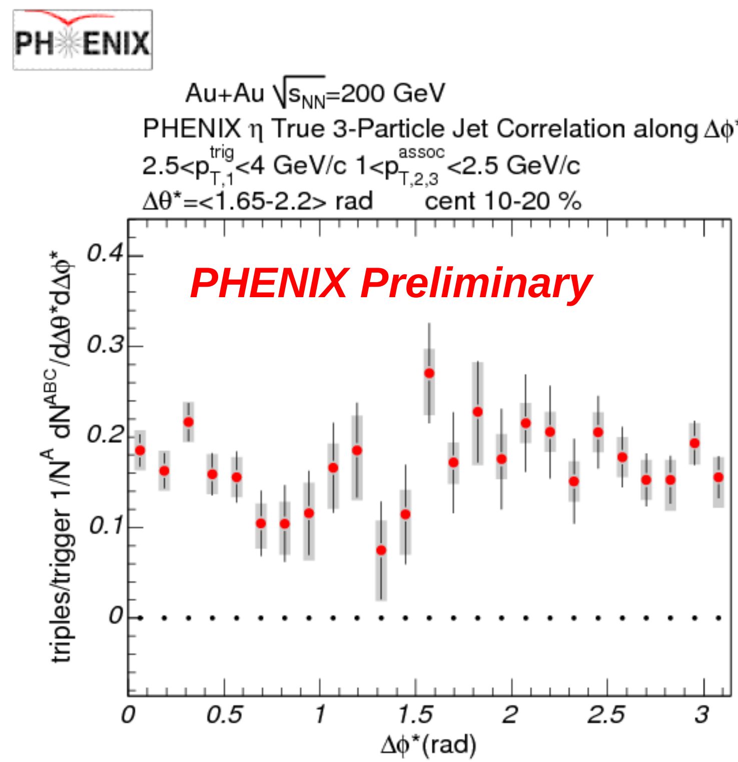




Cone Jet

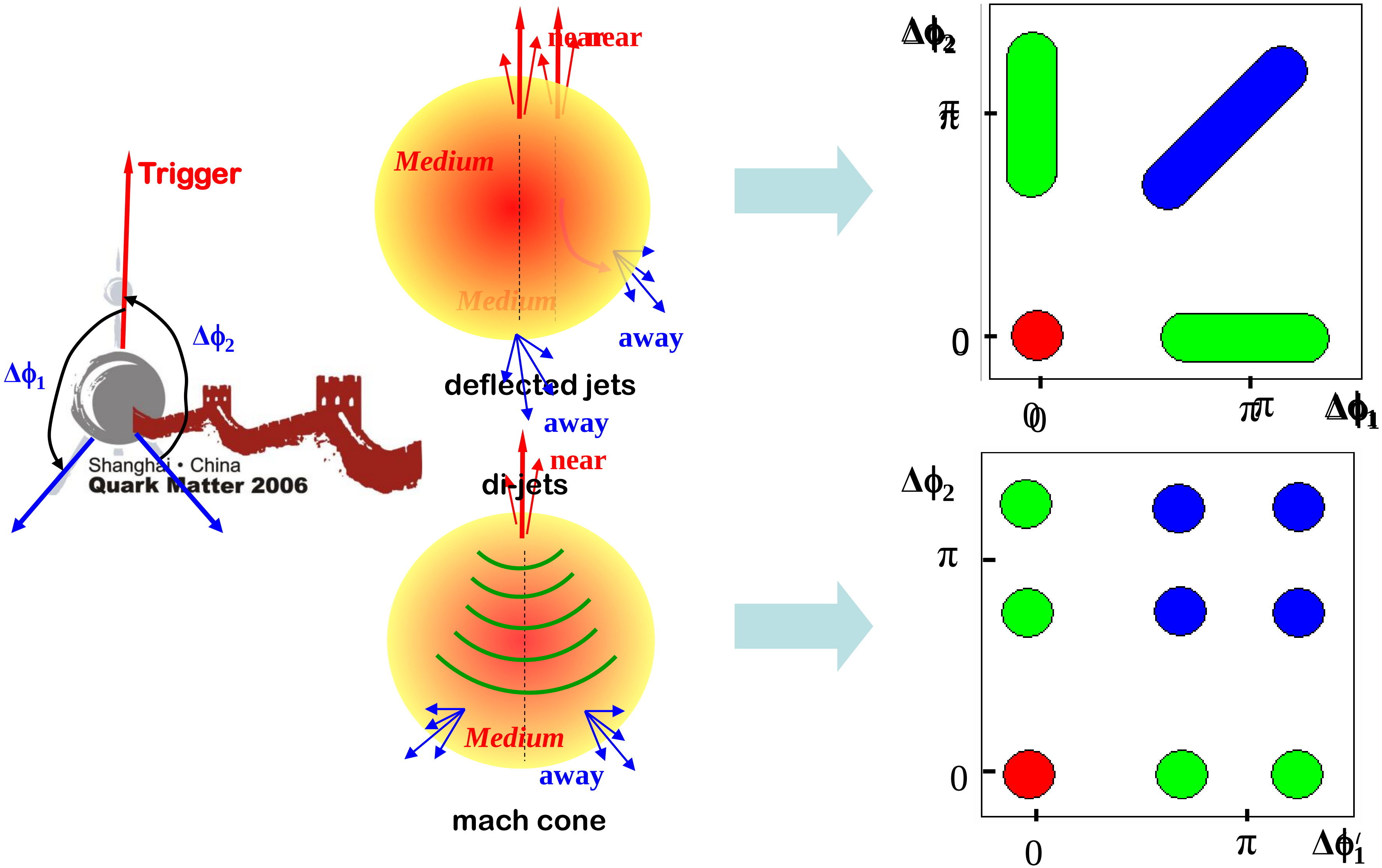
(medium excitation)

Δφ* Azimuthal Section:

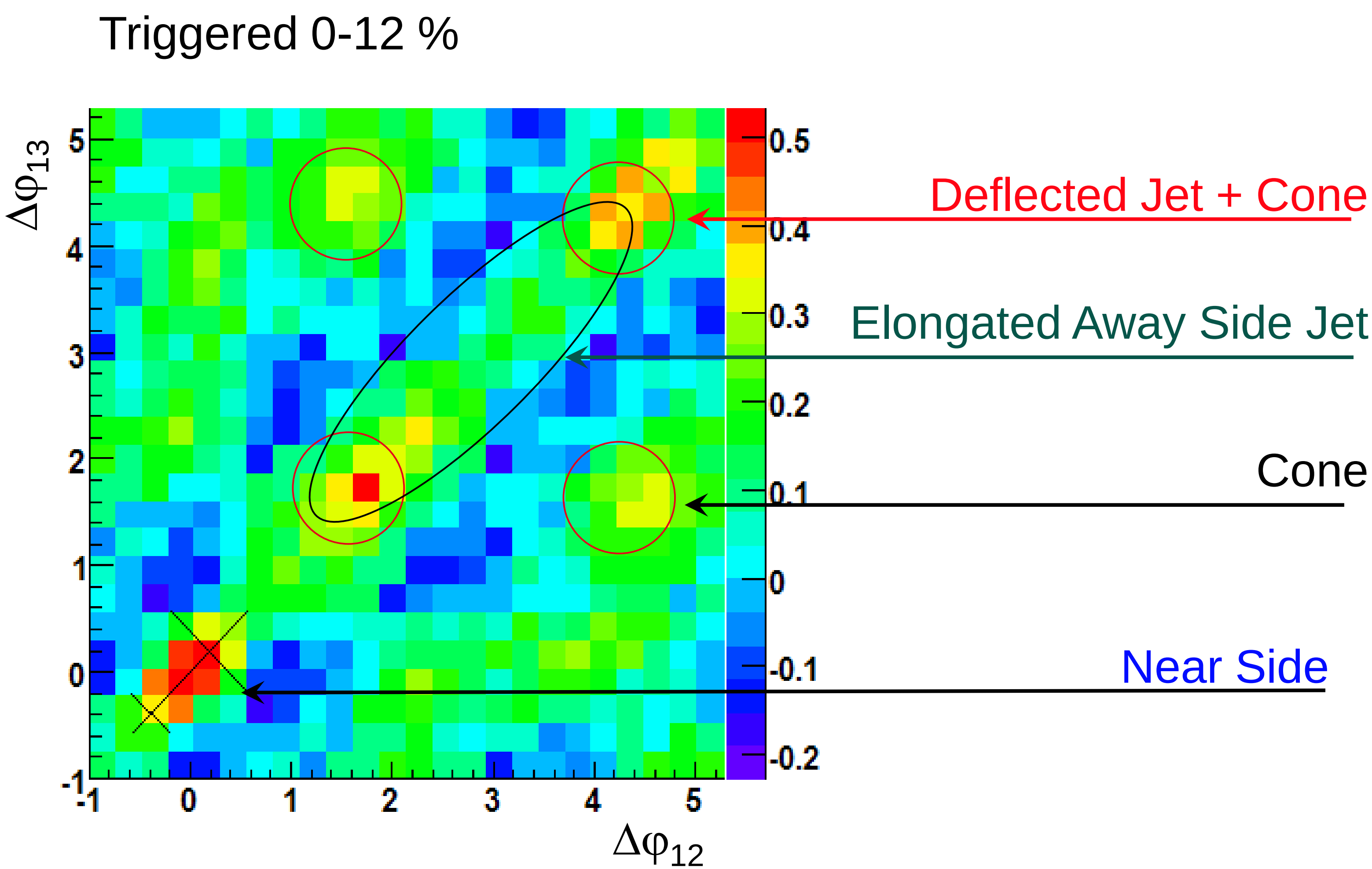


How to discriminate various possibilities?

Need 3-particle correlation to discriminate different physics mechanisms.

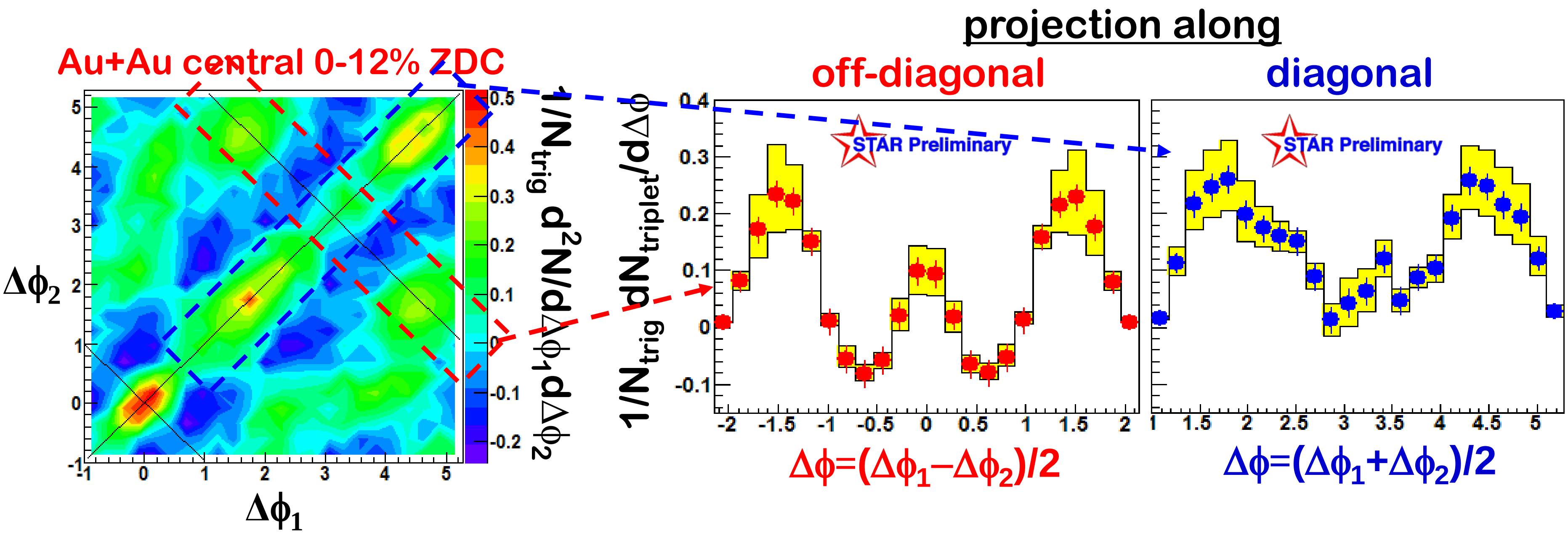


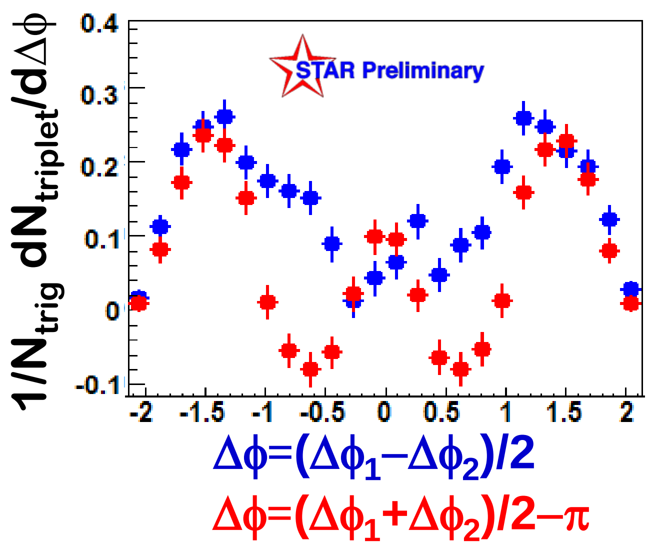
Jet-flow subtraction in Au+Au



Diagonal and Off-diagonal structures are suggestive of ***conical emission***.

ZDC central 12% Au+Au



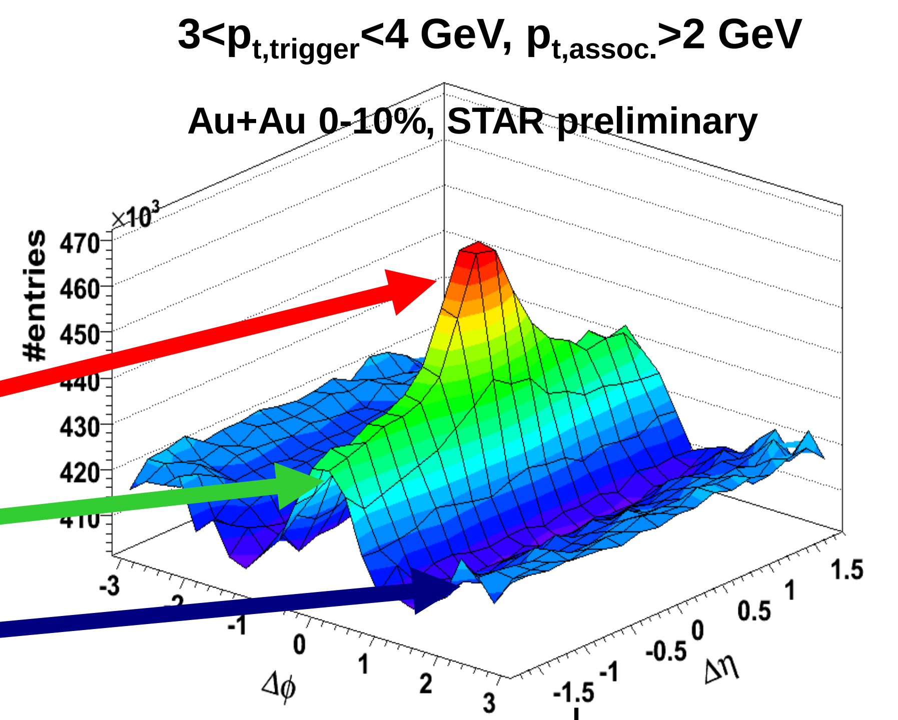


Diagonal and Off-diagonal structures
are suggestive of ***conical emission***.

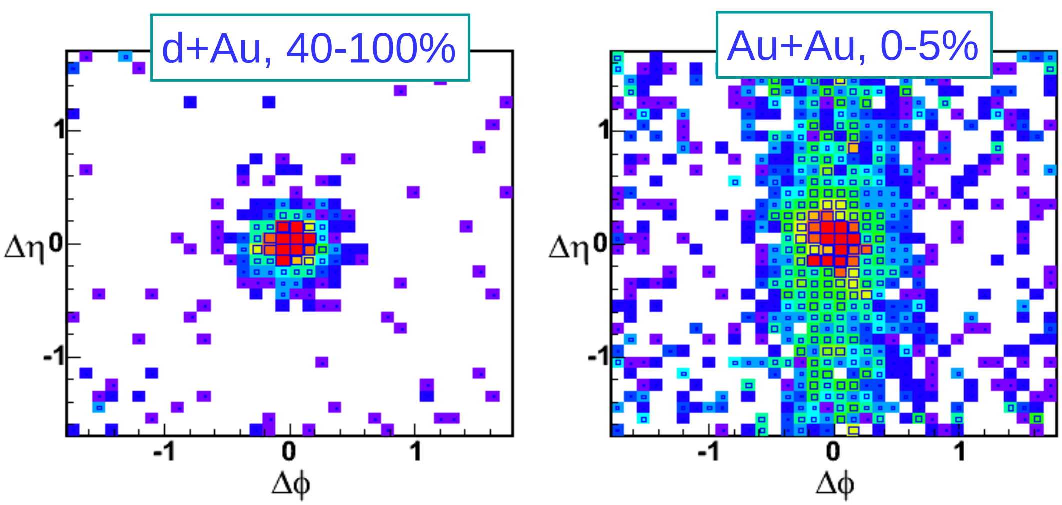
Near-side jet

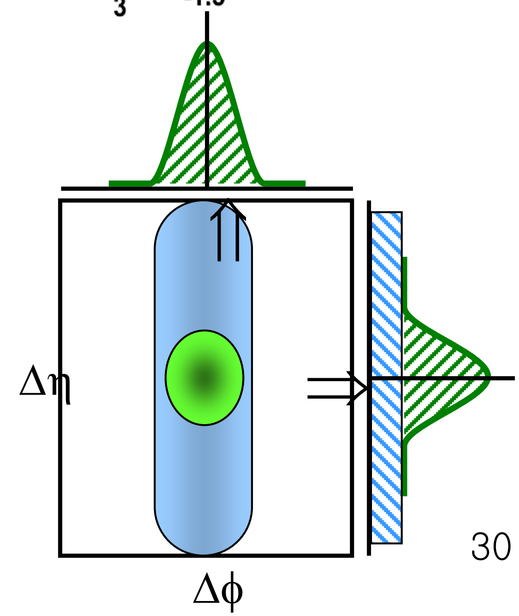
STAR, nucl-ex/0509030

- Near-side long range correlation in $\Delta\eta$
- Components
  - **near-side jet peak**
  - **near-side ridge**
  - **Away-side jet & v_2 modulation**



3 < p_T(trig) < 6 GeV, 2 < p_T(assoc) < p_T(trig)

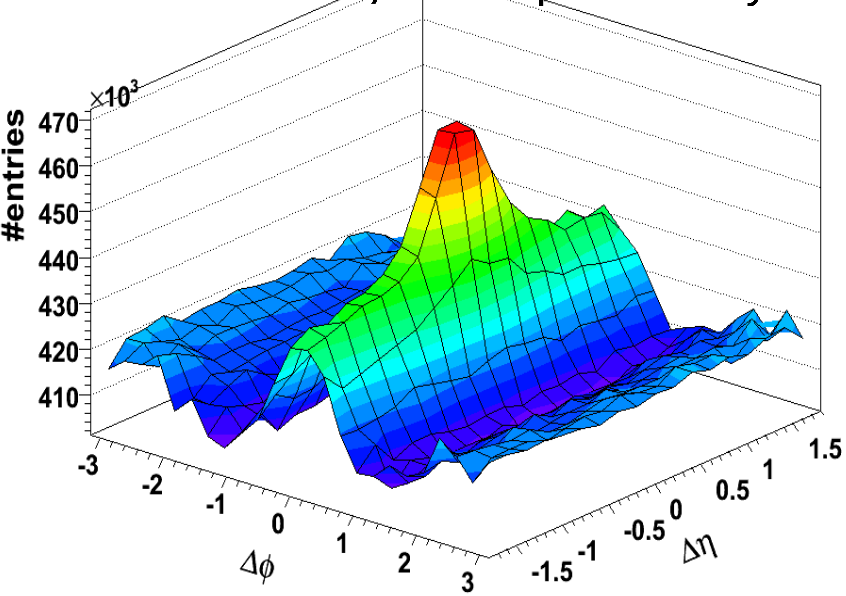


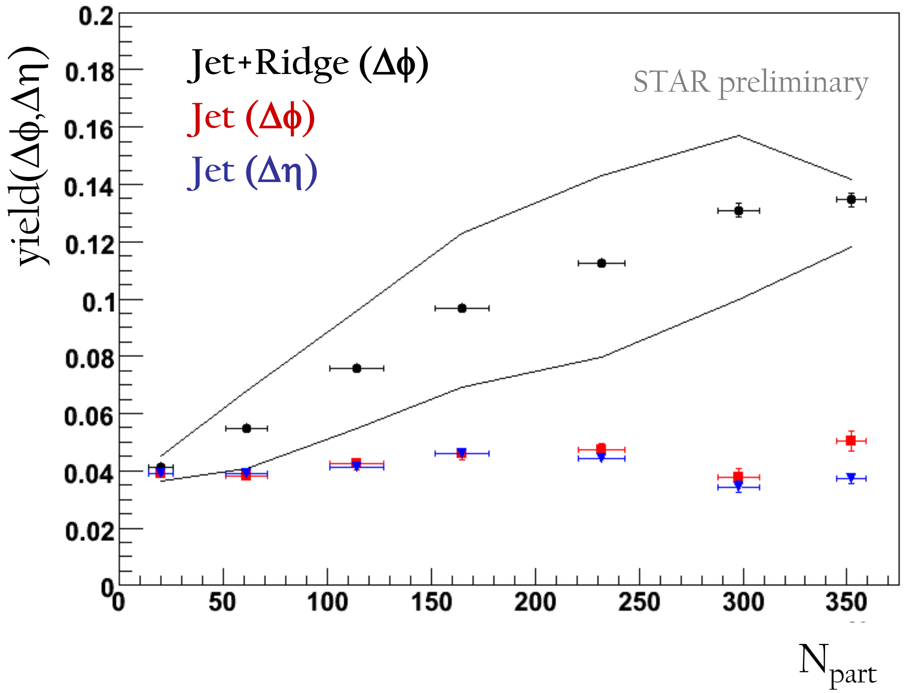


Ridge+jet yield vs centrality

3<$p_{t,trigger}$<4 GeV, $p_{t,assoc.}$>2 GeV

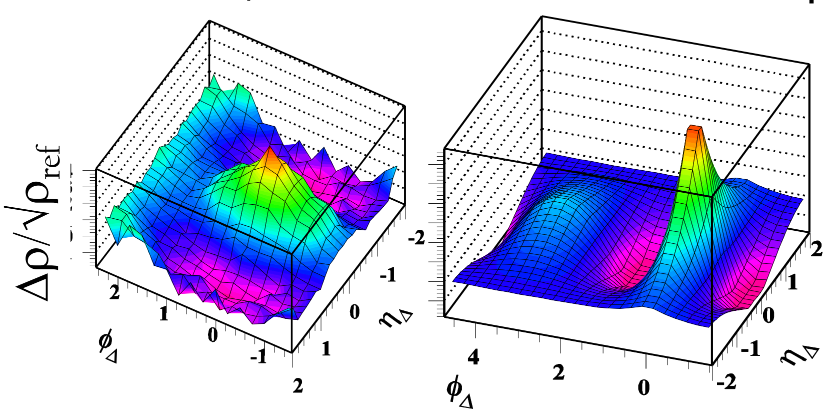
Au+Au 0-10%, STAR preliminary





"Jet" yield constant with N_{part}

p+p low p_T Au+Au. low p_T



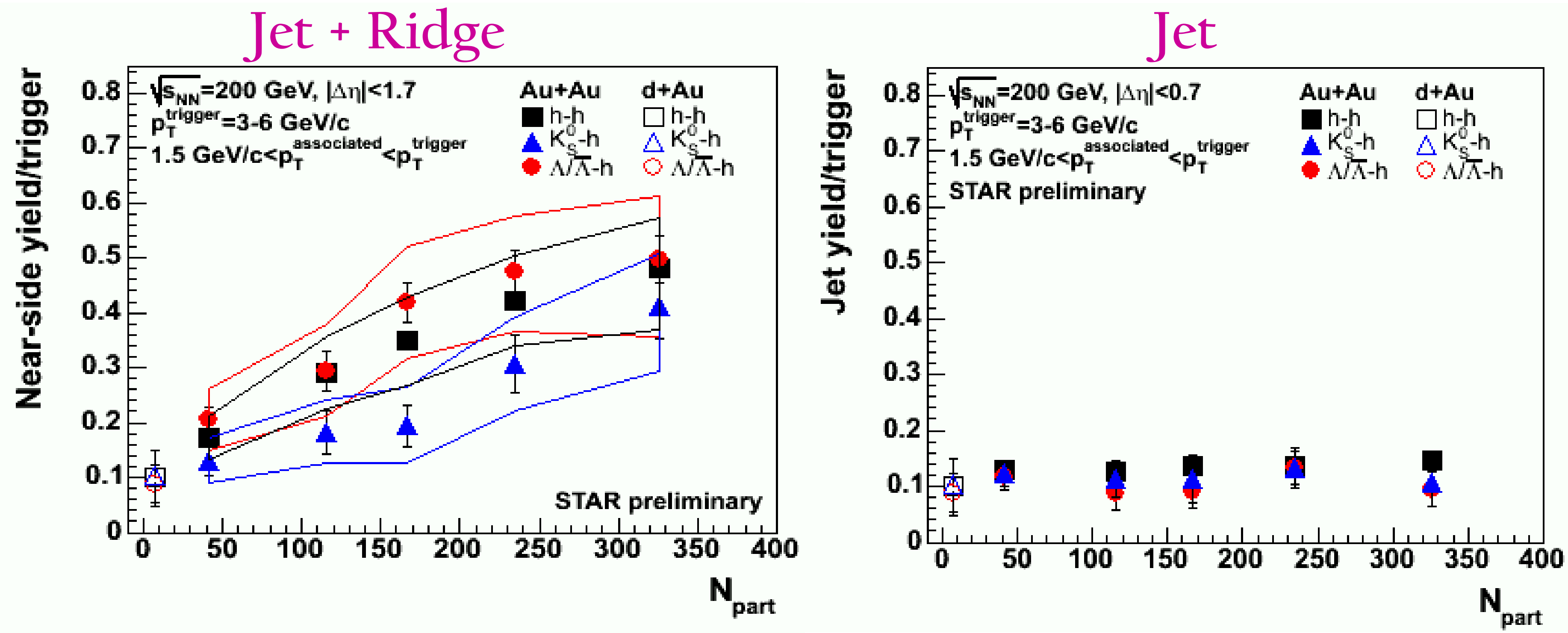
PRC 73, 064907 (2006)

Reminder from p_T<2 GeV:

η elongated structure already in minbias Au+Au

φ elongation in pp → to η elongation in Au+Au

Λ, K^0_s near-side associated yield vs centrality in Au+Au



Charged hadrons: ridge yield increased vs. N_{part}

Λ,K^0_s both have increase of near-side yield with centrality in Au+Au

Λ, K^0_s: ratio of yields in central Au+Au/d+Au ~ 4-5

ridge yield of K^0_S < ridge yield of Λ

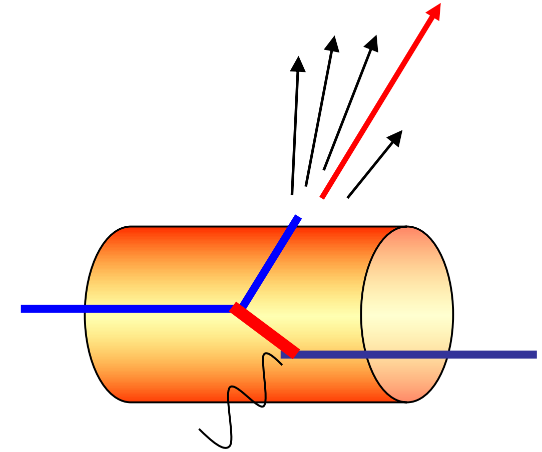
-> "ridge" yield increases with centrality

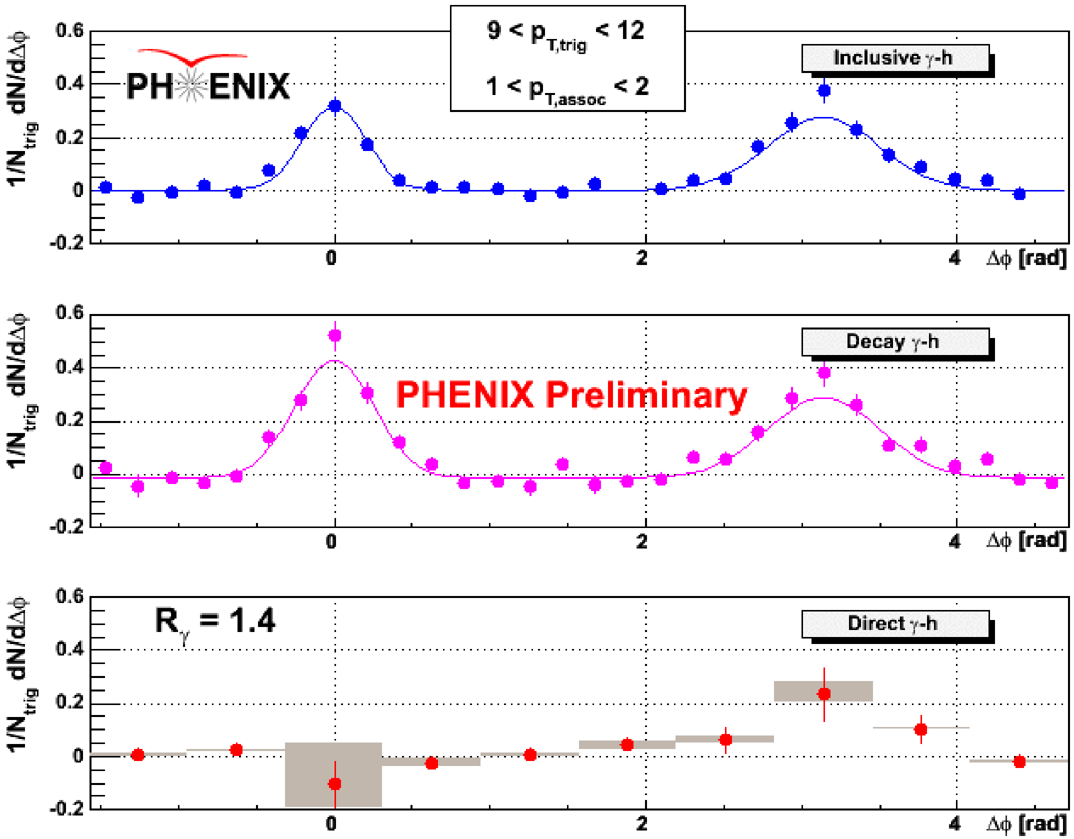
-> "jet" yield is constant vs Npart

same yield as in d+Au

γ-jet correlations

p+p collisions at 200 GeV





1 Inclusive γ-h

$$Y_{inclusive-h} = \left(\frac{\gamma_{decay}}{\gamma_{inclusive}}\right) Y_{decay-h} + \left(\frac{\gamma_{direct}}{\gamma_{inclusive}}\right) Y_{direct-h}$$

2 Decay γ-h contribution (via π^0-hadron)

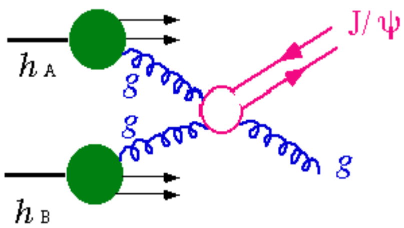
3 Direct γ-h !

$$Y_{direct-h} = \frac{1}{1-1/R}\left(Y_{inclusive-h} - \frac{1}{R} Y_{decay-h}\right) \quad R = \frac{\gamma_{inclusive}}{\gamma_{decay}}$$

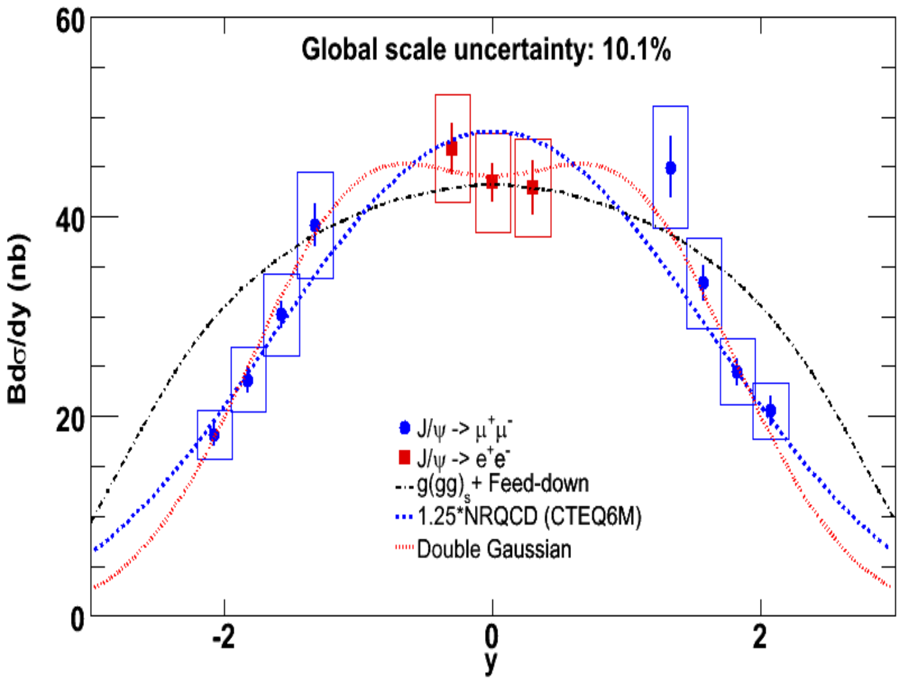
Heavy Flavor

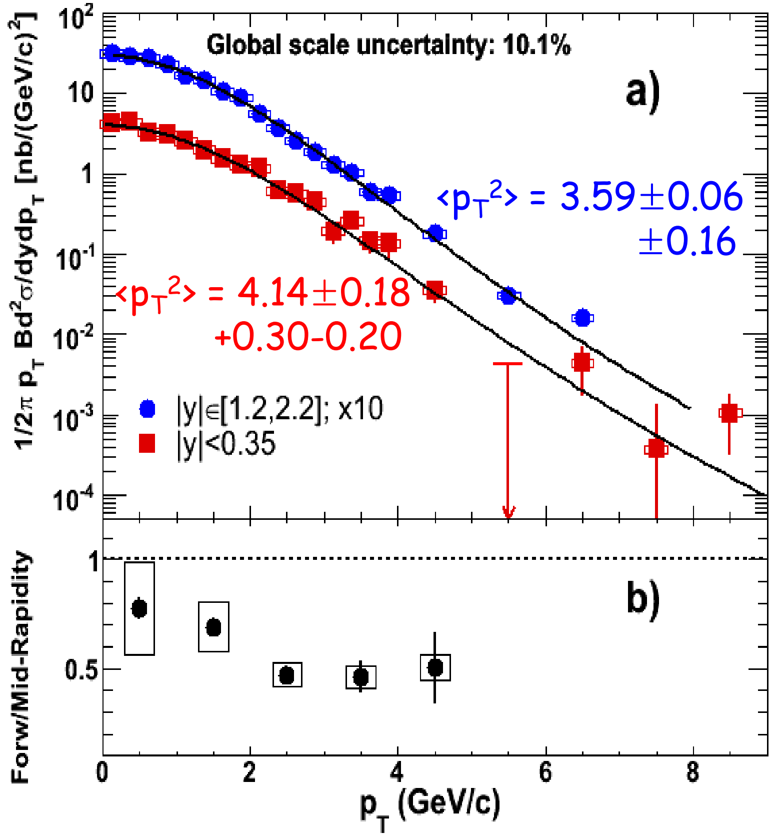
J/Ψ in p+p collisions

Gluon fusion dominates (NLO calculations add more complicated diagrams, but still mostly with gluons)



Improved Run-5 pp reference data



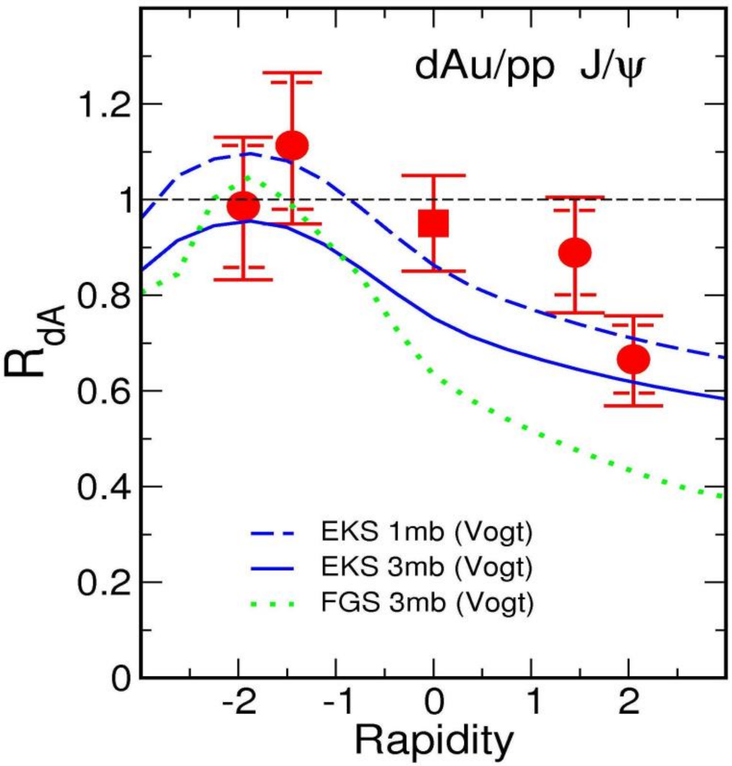


hep−ex/0611020 (submitted to Phys. Rev. Lett.)

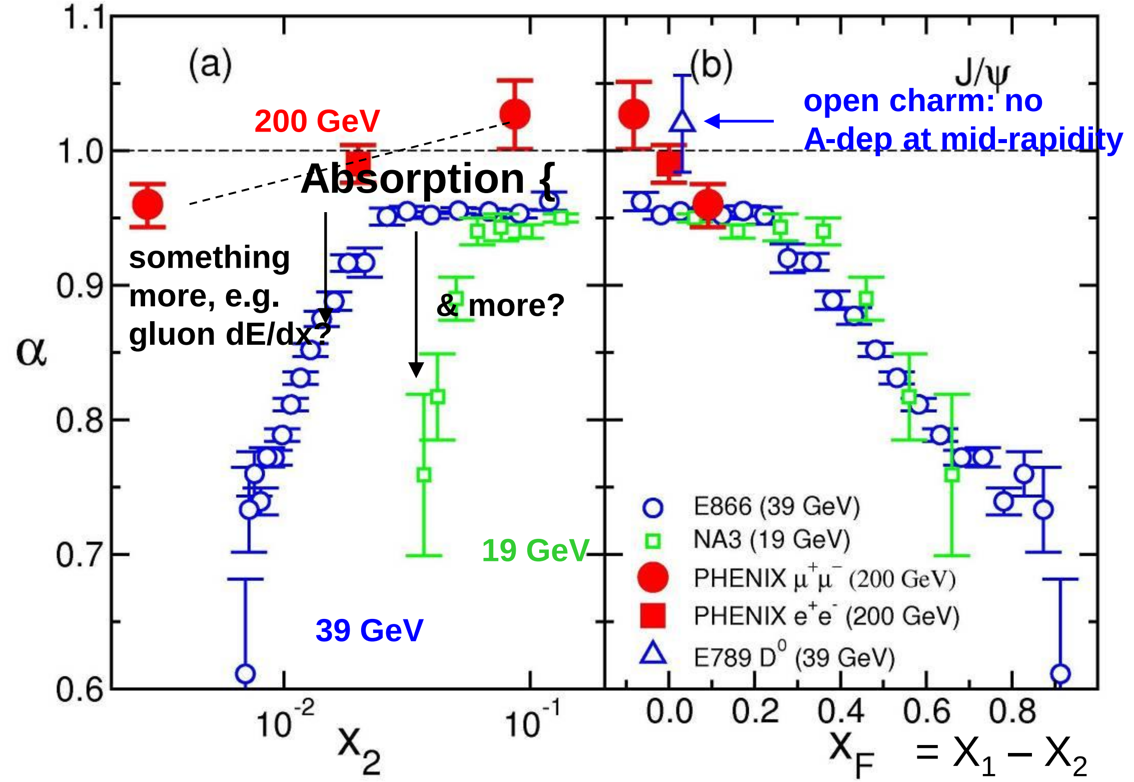
J/Ψ in d+Au collisions

$$\sigma_A = \sigma_N A^{\alpha}$$

PHENIX, PRL 96, 012304 (2006)



J/ψ for different √s collisions



Data favors weak shadowing & absorption

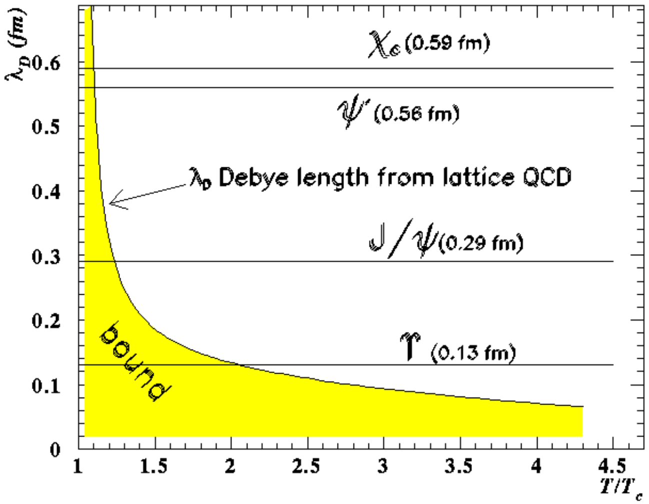
- With limited statistics difficult to disentangle nuclear effects
- Need another d+Au run!

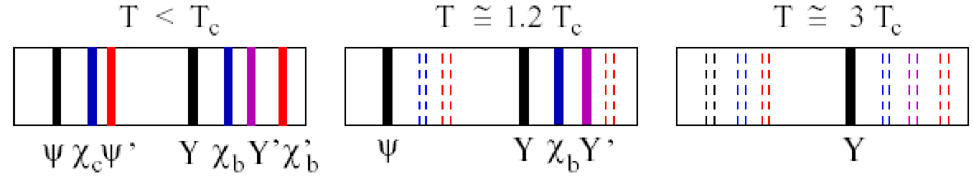
Not universal vs x_2 as expected for shadowing, but does scale with x_F, why?

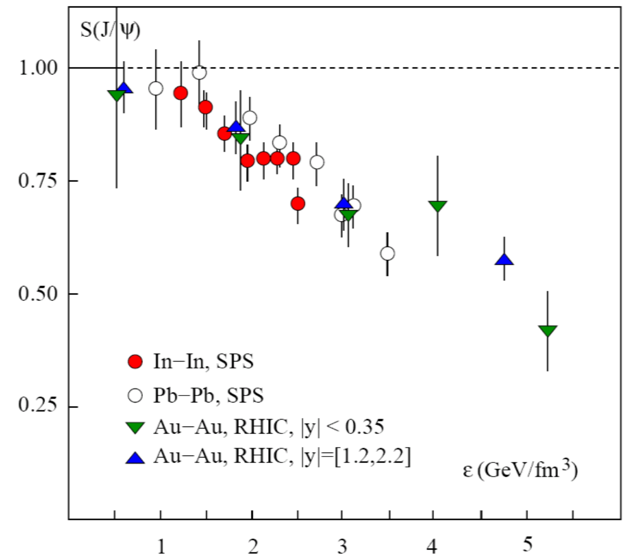
- Initial-state gluon energy loss?
- Sudakov suppression (energy conservation)?

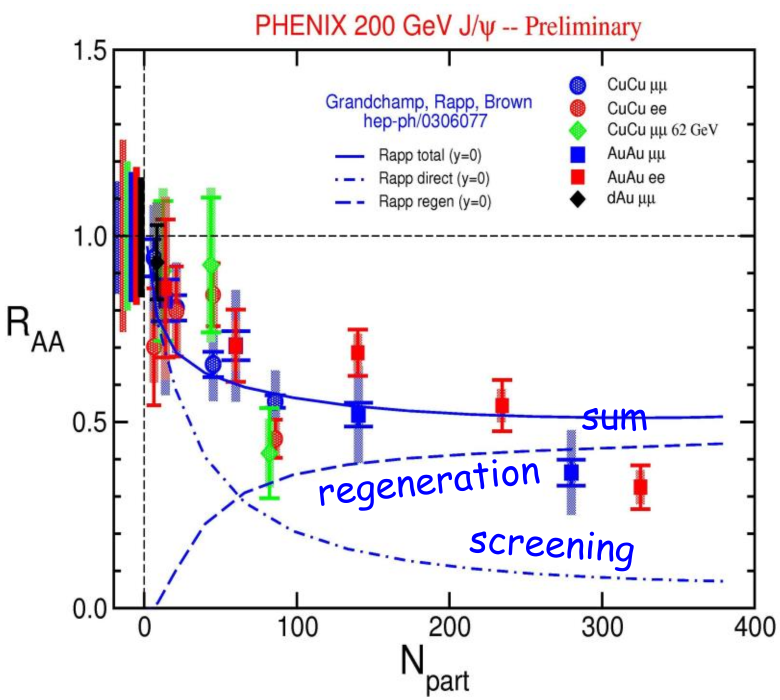
J/Ψ in Au+Au collisions

from H. Satz, hep-ph/0609197







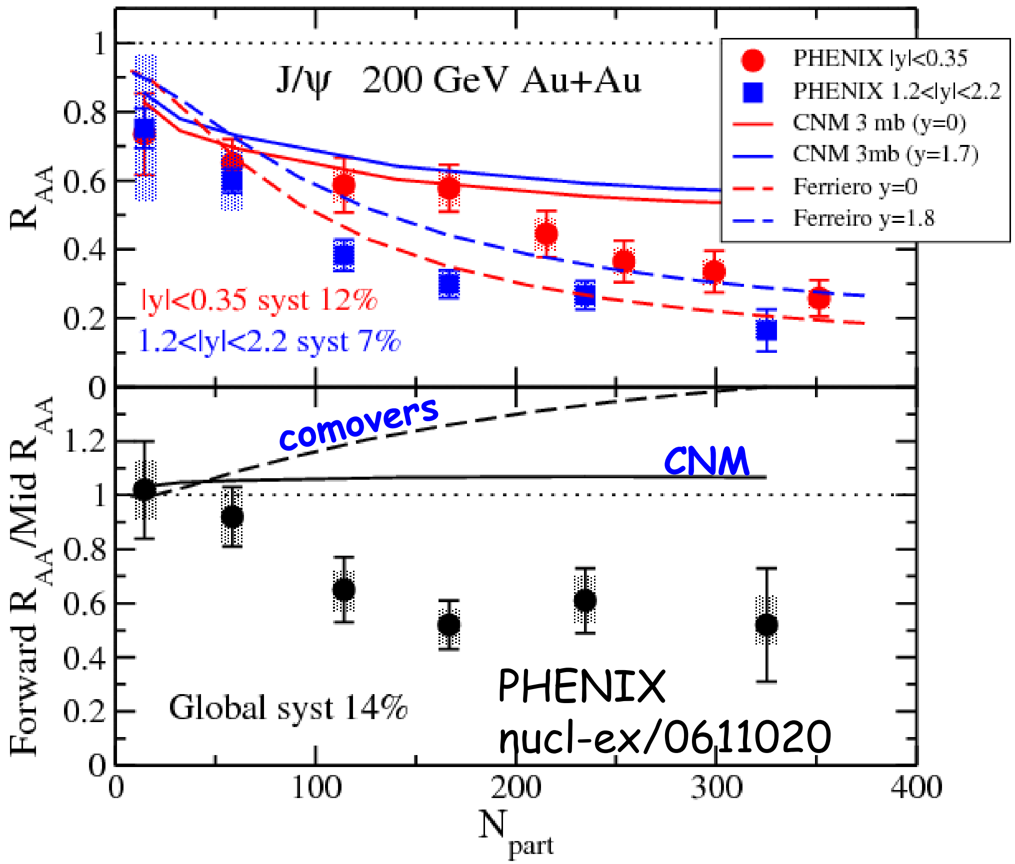


-Survival probability corrected for normal absorption

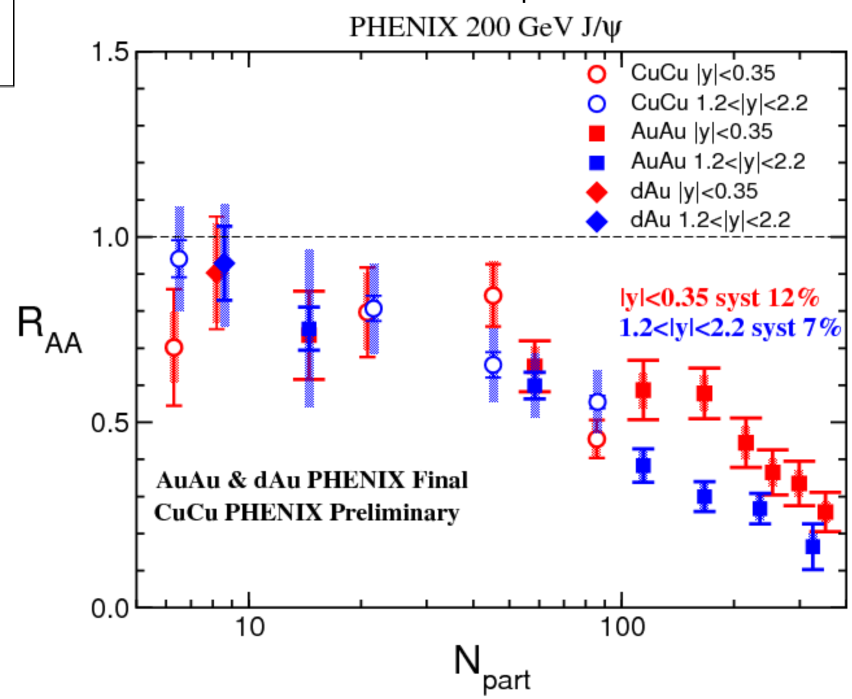
-On the other hand, recent lattice calculations suggest J/ψ not screened after all. Suppression only via feed-down from screened χ_C & ψ'

J/Ψ in Au+Au collisions

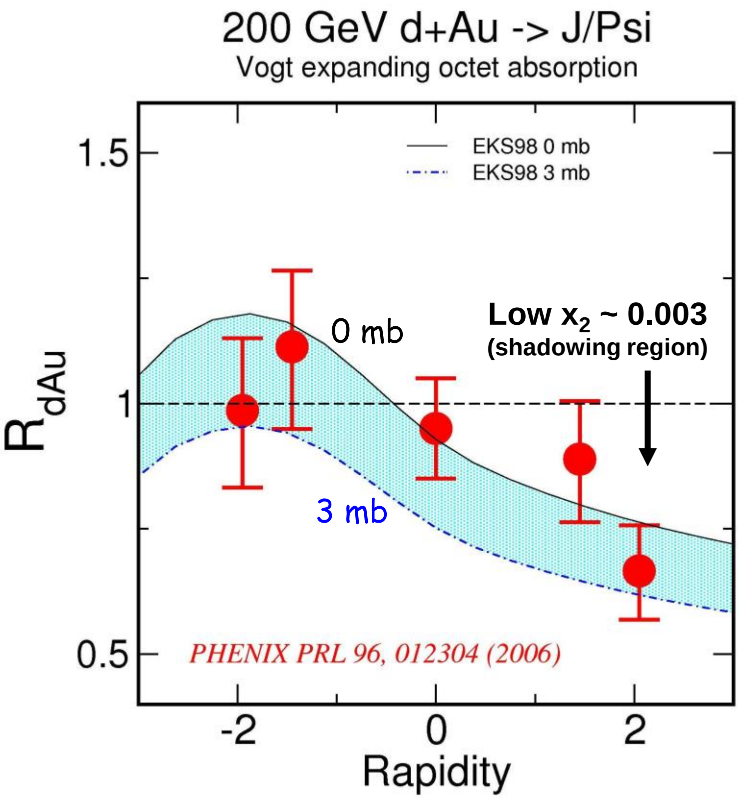
- Most central collisions suppressed to ~0.2
- Forward suppressed more than mid-rapidity
  - saturation of forward/mid suppression ratio rapidity @ ~0.6 for N_{part} ≥ 100?
  - trend opposite to that of CNM (solid lines) and comover (dashed) models

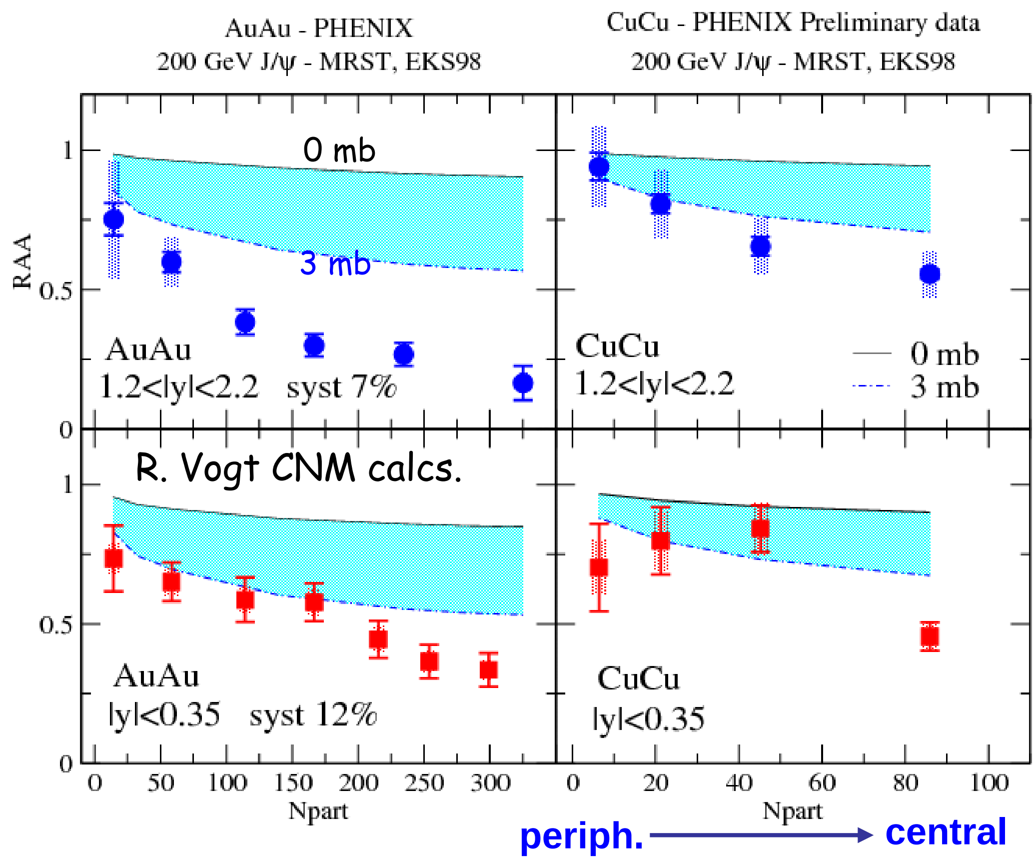


Also CuCu preliminary results (open circles) follow AuAu trend vs centrality for N_{part} below ~100



J/Ψ in Au+Au collisions

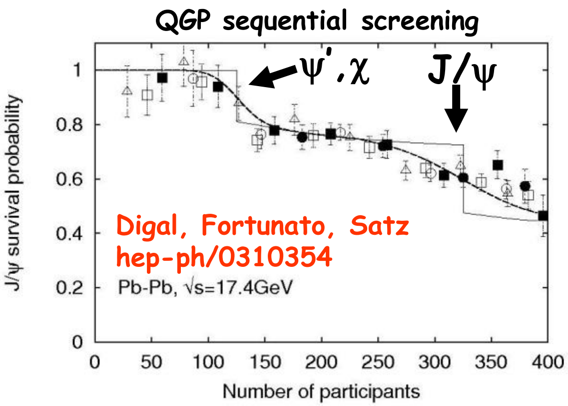


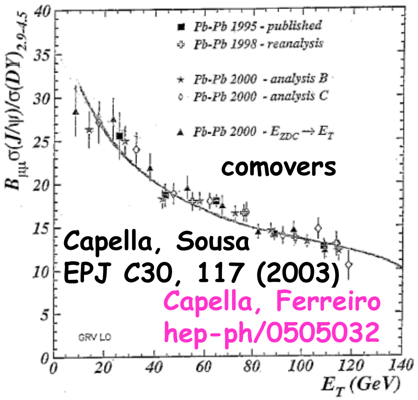


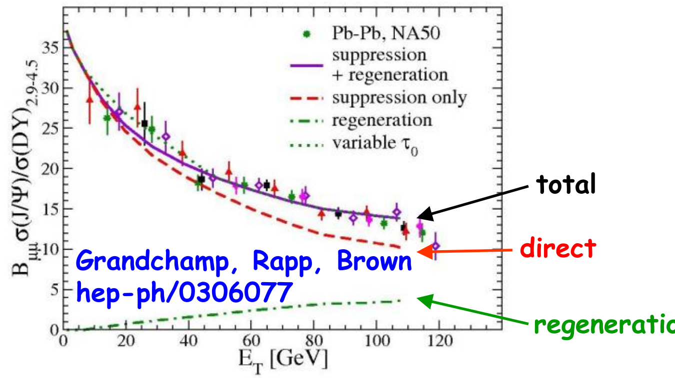
- **CNM calculations with shadowing & absorption – R. Vogt, nucl-th/0507027**
- **Present d+Au data probably only constrains absorption to σ_{ABS} ~ 0-3 mb**

- **AuAu suppression is stronger than CNM calculations predict especially for most central mid-rapidity & at forward rapidity**

Models w/o regeneration





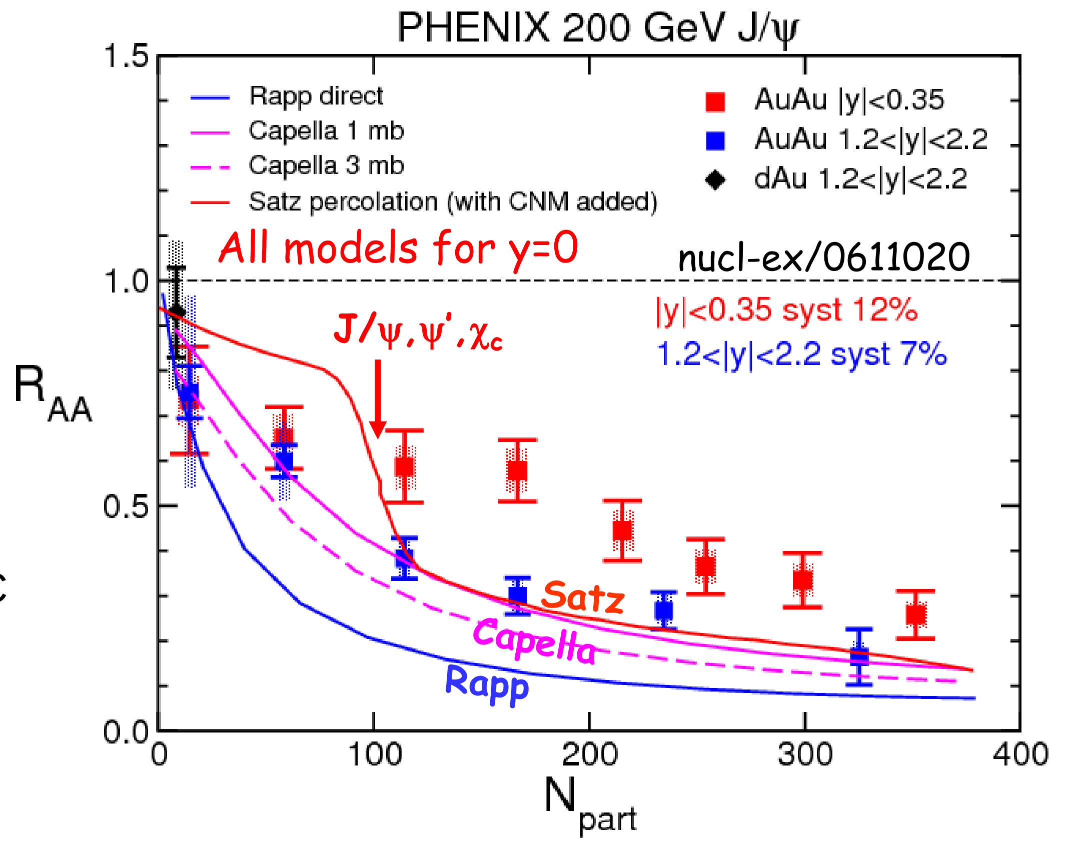


Models that reproduce NA50 results at lower energies (above):

- Satz - color screening in QGP (percolation model) with CNM added (EKS shadowing + 1 mb)
- Capella – comovers with normal absorption and shadowing
- Rapp – direct production with CNM effects (without regeneration)

But predict too much suppression for RHIC mid-rapidity (at right)!

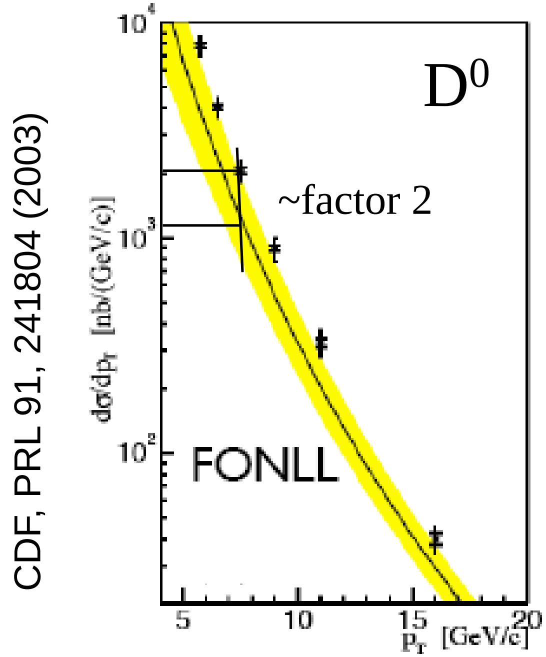
Need regeneration models! (M. Leitch's talk)

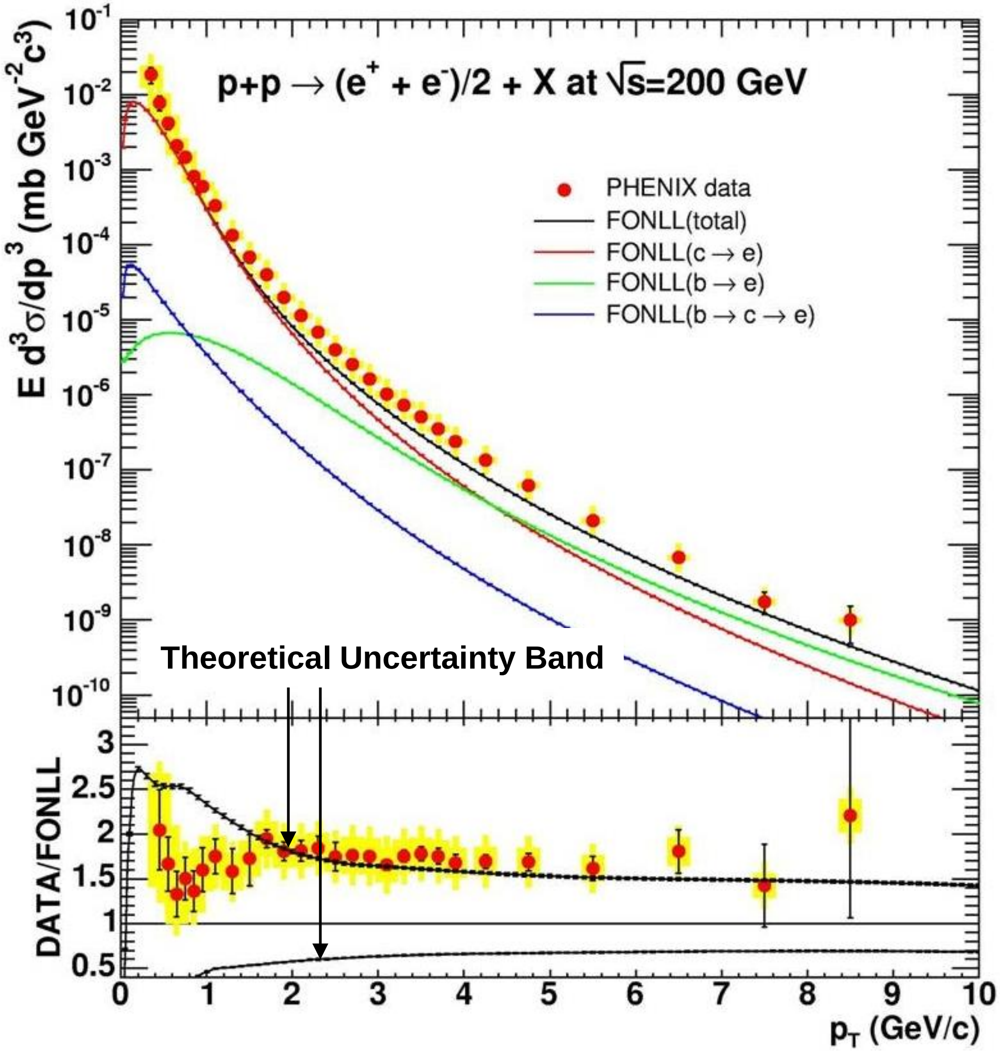


PHENIX non-photonic electrons

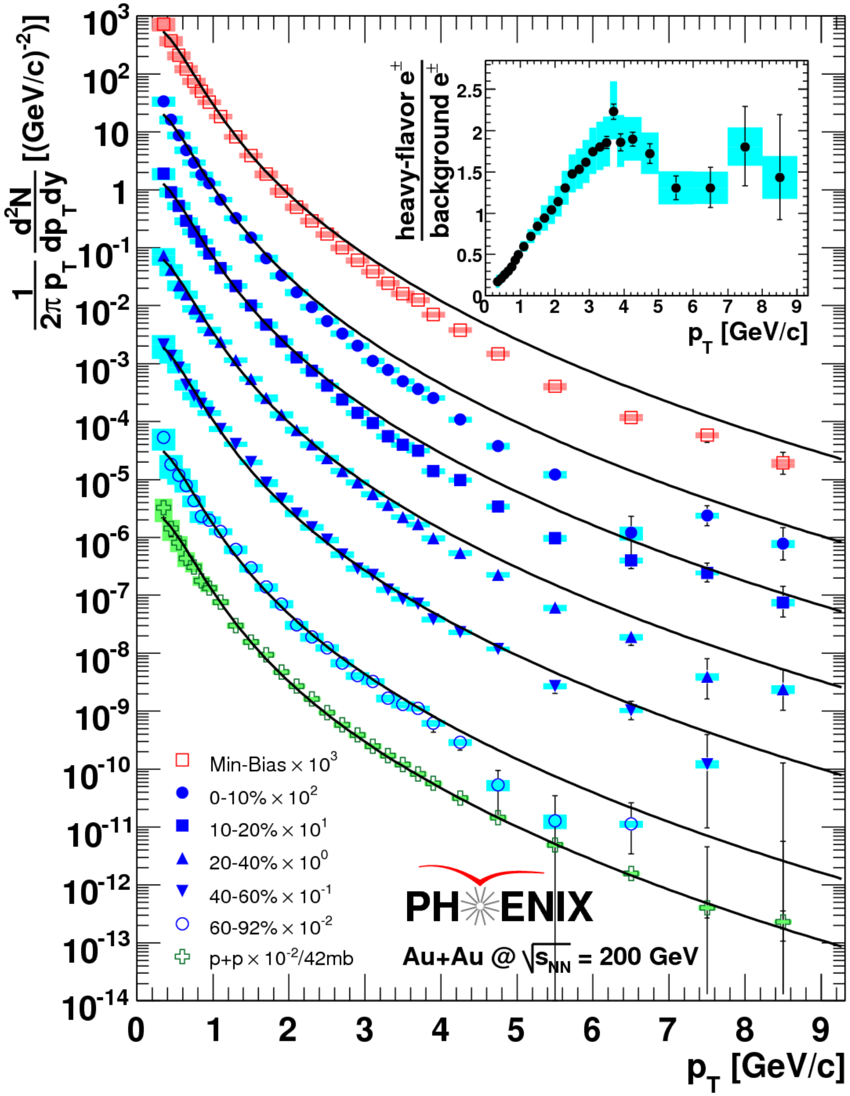
hep−ex/0609010
(accepted by Phys. Rev. Lett.)

Ratio:
1.72 +/-0.02 (stat) +/- 0.19 (sys)
(0.3 < p_T < 9.0 GeV/c)





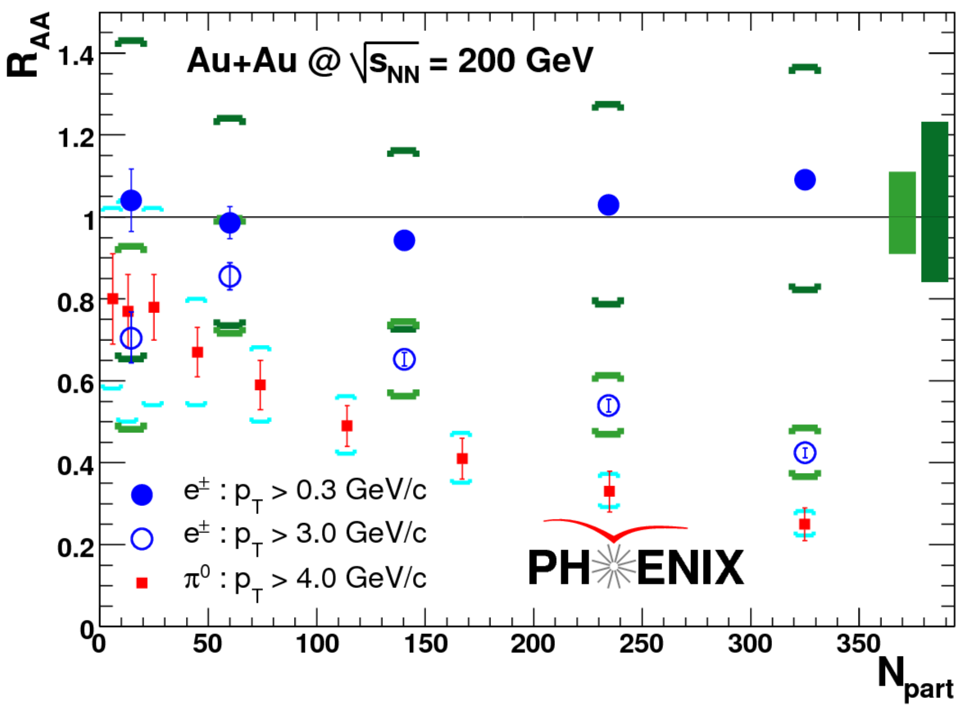
Heavy flavor in Au+Au



nucl-ex/0611018
(submitted to Phys. Rev. Lett.

No suppression at low p_T

Suppression observed for p_T>3.0 GeV/c, smaller than for light quarks.



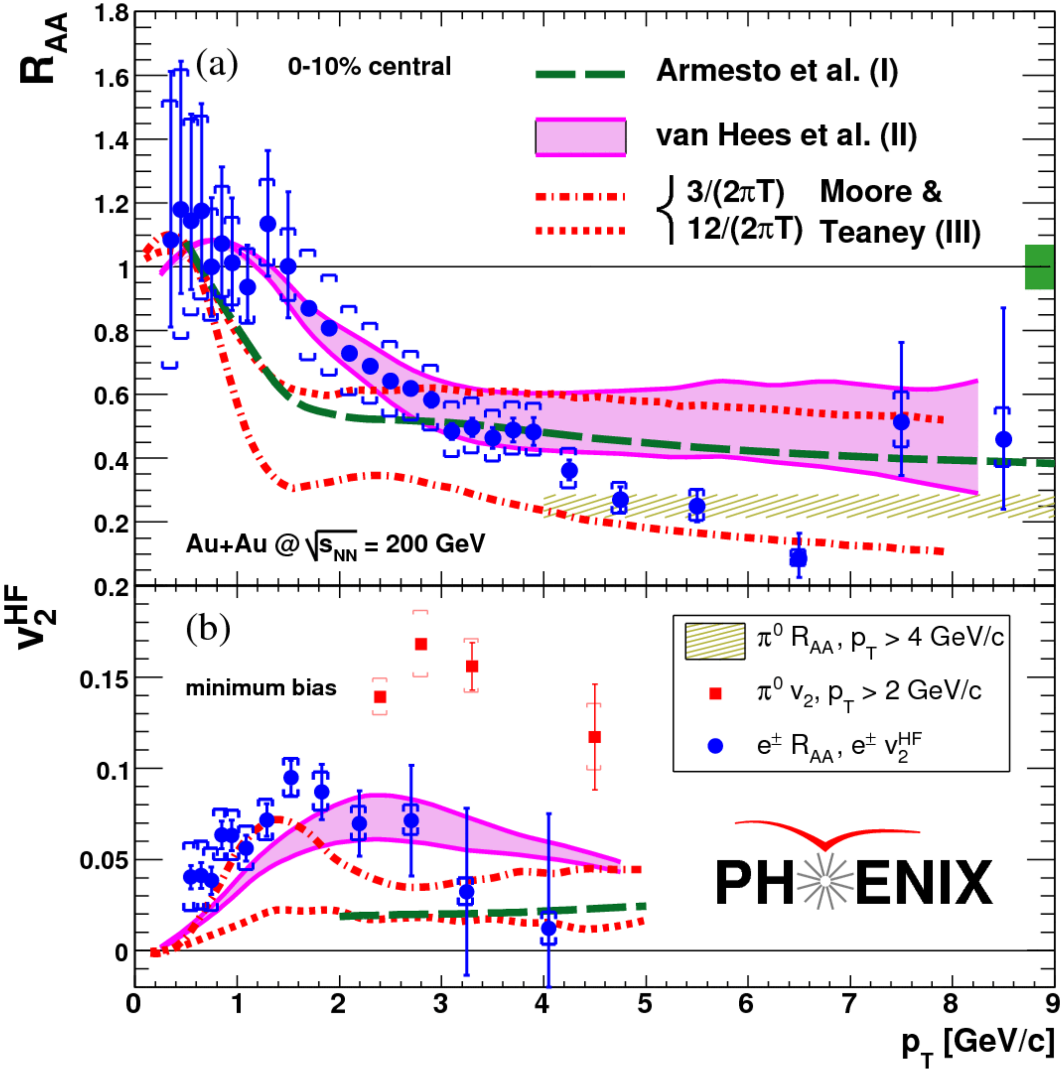
Heavy quark energy loss and flow

nucl-ex/0611018
(submitted to Phys. Rev. Lett.)

Radiative energy loss only fails to reproduce v_2^{HF}.

Heavy quark transport model has reasonable agreement with both R_{AA} and v_2^{HF}.

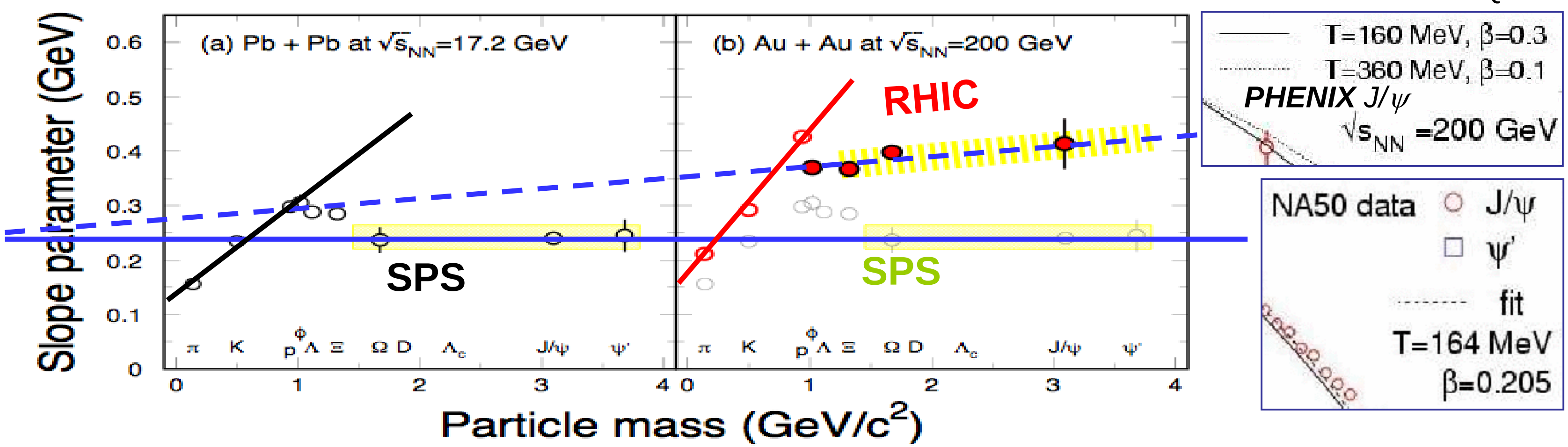
Small relaxation time τ or diffusion coefficient D_{HQ} inferred for charm.

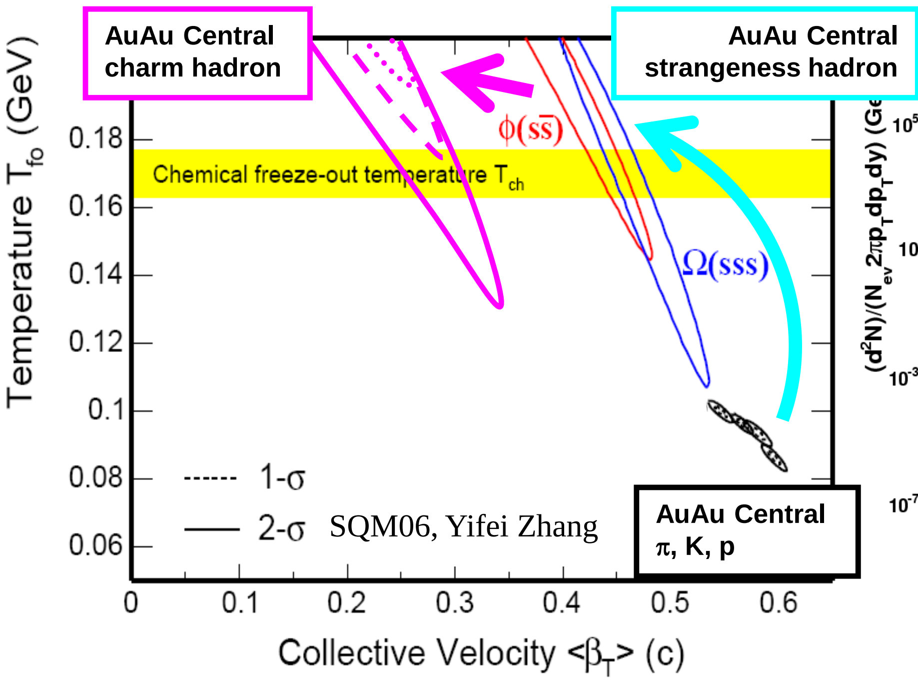


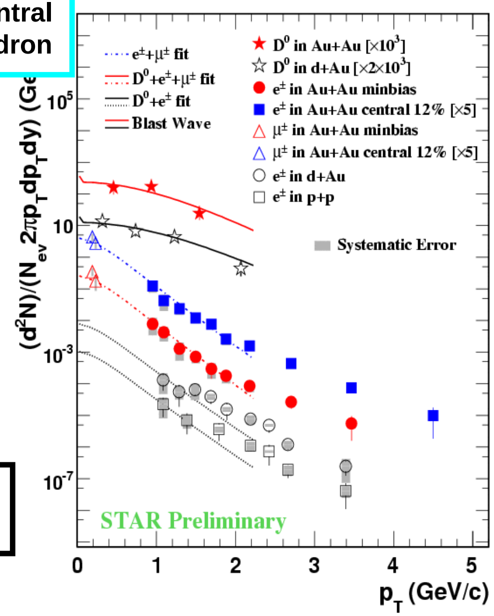
Charm quark collectivity

N. Xu, SQM 2006, PHENIX (π, K, p, J/ψ): PRC69, 034909(04), QM05; STAR (ϕ, Ξ, Ω): QM05

PBM et. al. QM06

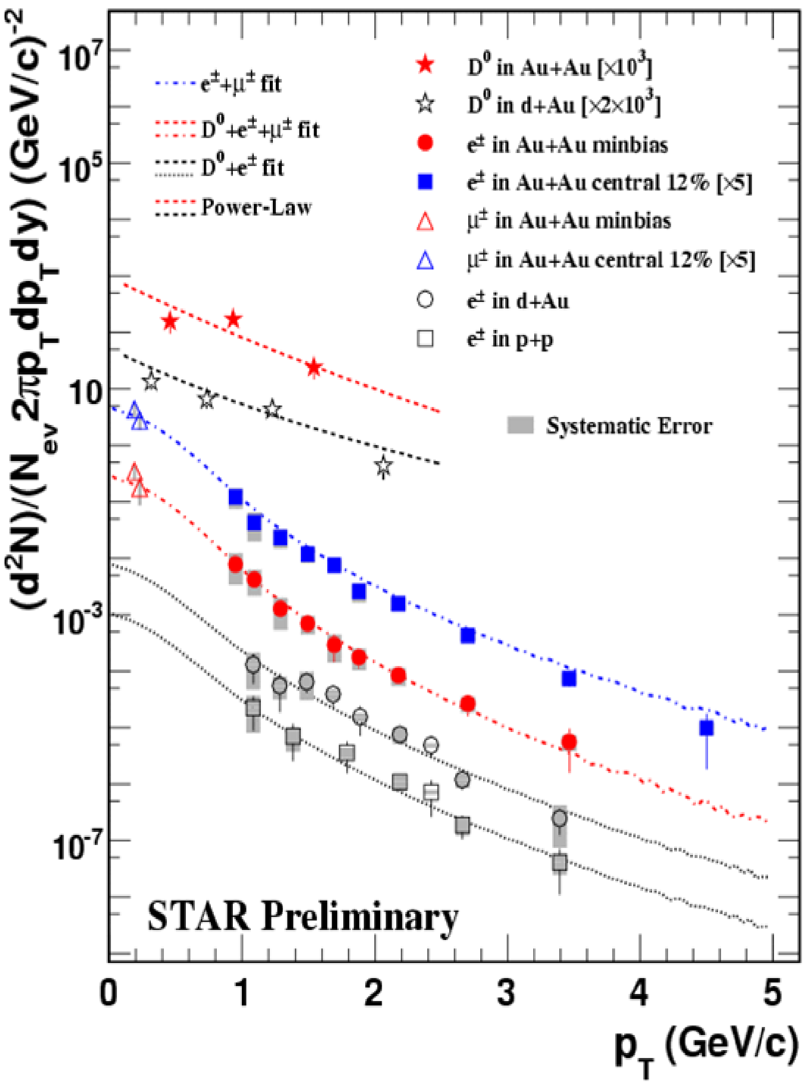




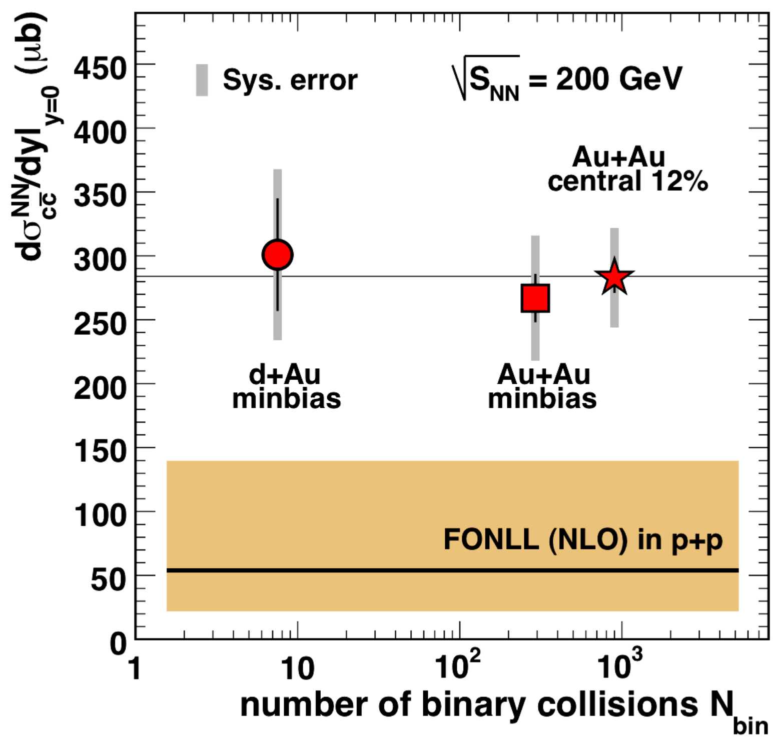


J/ψ would need re-generation, both J/ψ and open charm spectra are consistent with small transverse radial flow, which might be built up during partonic stage…

$d\sigma^{NN}{}_{cc}/dy$ from p+p to A+A

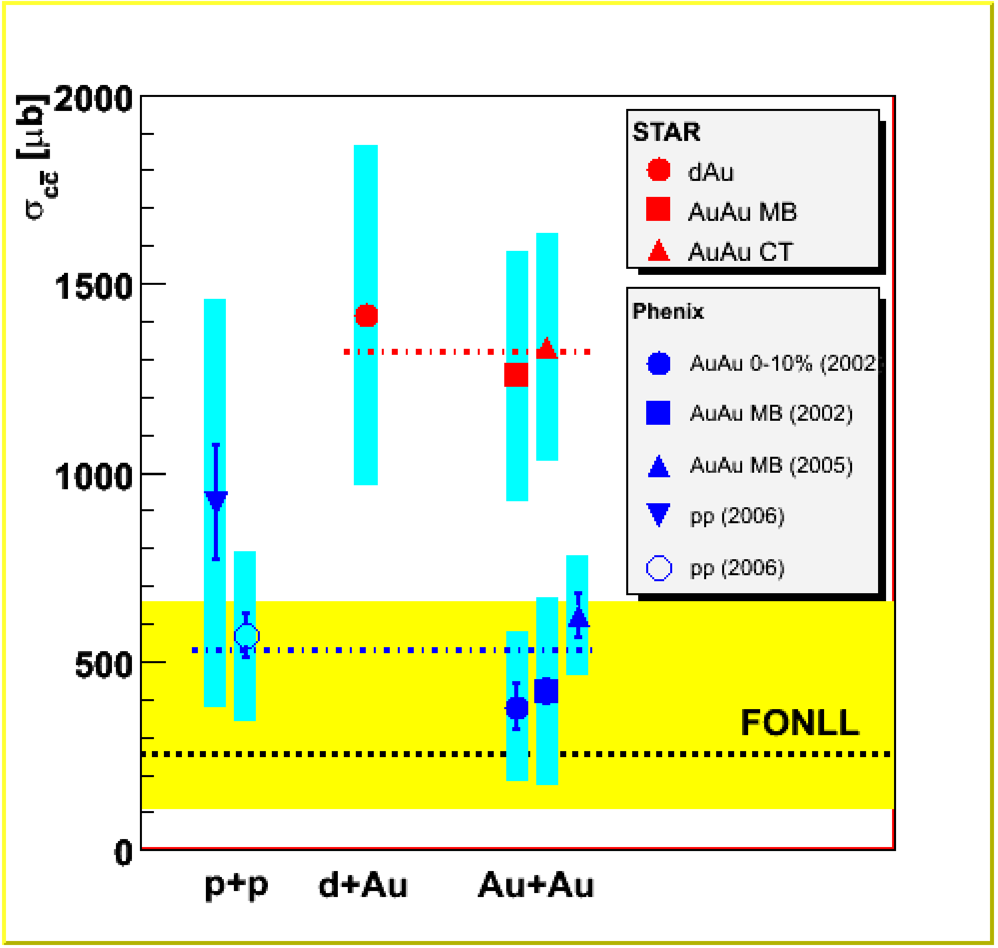


- D^0, $e^{\pm}$, and $\mu^{\pm}$ combined fit
- Advantage: Covers ~95% of cross section
- Mid-rapidity $d\sigma^{NN}{}_{cc}/dy$ vs N_{bin}
- $\sigma^{NN}{}_{cc}$ follows binary scaling
  - Charm production from initial state as expected
- Higher than FONLL prediction in pp collisions.



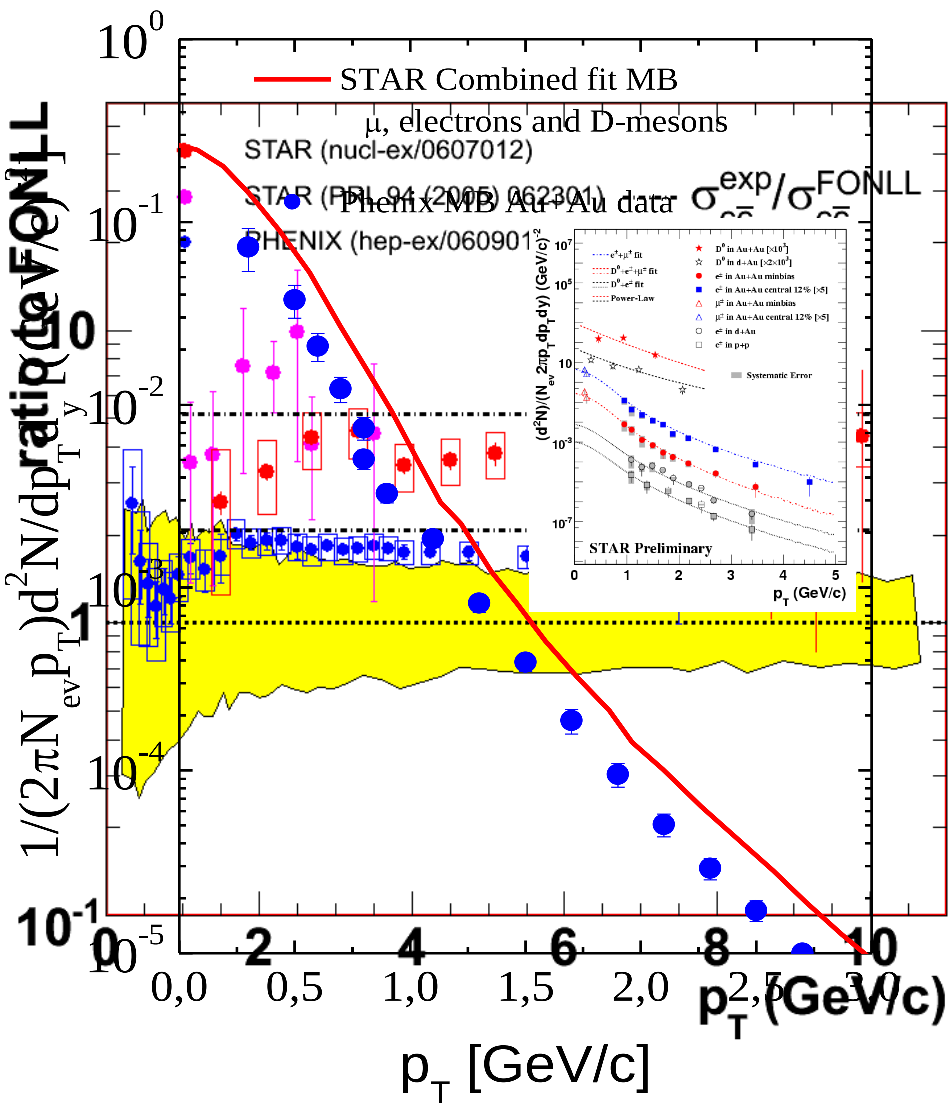
Discrepancy in total cross section

- FONLL as baseline
  - Large uncertainties due to quark masses, factorization and renormalization scale
- Phenix about a factor of 2 higher but consistent within errors
  - Only electrons but less background
- STAR data about a factor of 5 higher
  - More material but it is the only direct measurement of D-mesons
    - 95% of the total cross section is measured



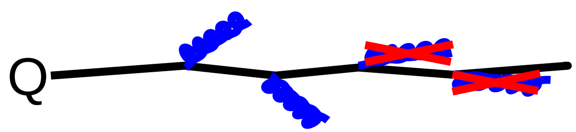
What about the spectral shape?

- FONLL describes the shape well
- Experiments do not agree to each other
  - Low material in Phenix
    - Less electron background to subtract
  - Direct measurement of D-mesons at STAR and low-p_T
- Is this shown only at high-p_T?



Open heavy flavors–EL in Medium

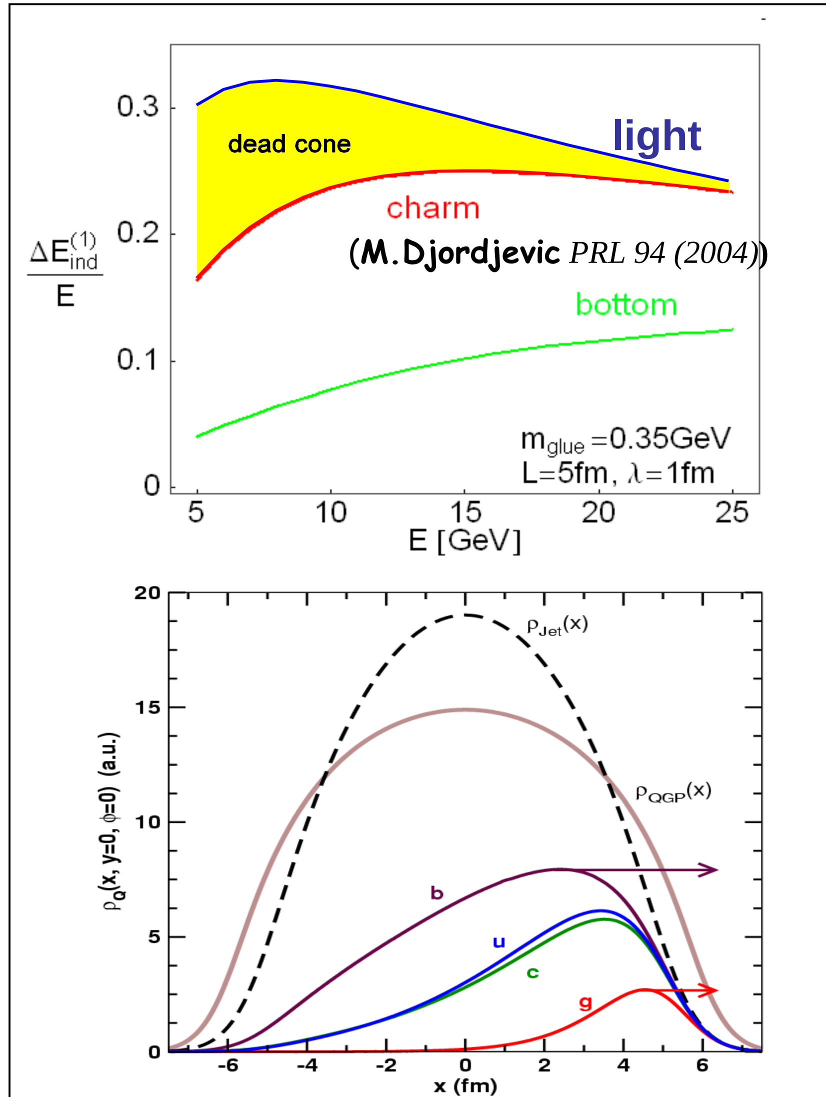
- In vacuum, gluon radiation suppressed at $q < m_Q/E_Q$
  - "dead cone" effect implies lower energy loss (Dokshitzer-Kharzeev, '01)



  - energy distribution w dI/dw of radiated gluons suppressed by angle-dependent factor

- Smaller energy loss would probe inside the medium

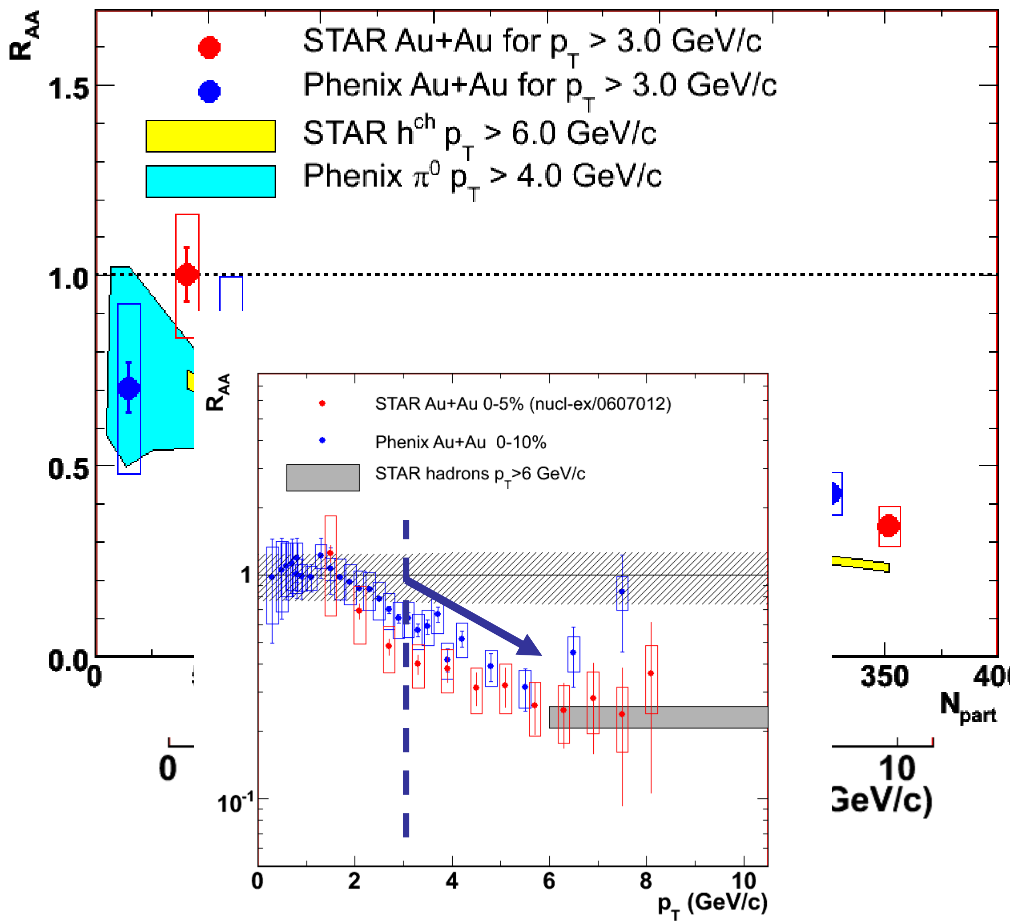
- Collisional E-loss: qg → qg, qq → qq
  - dE/dx ∝ ln p - small?



Electron R_{AA} from d+Au to Au+Au

- Use of non-photonic electron spectra as proxy for energy loss study
- R_{AA} show increasing suppression from peripheral to central Au+Au
  - First evidence of heavy quark EL
  - Differences between STAR and PHENIX disappear in R_{AA}
- Is it smaller than for light-quark hadrons?
- For various model comparisons, see Suaide's talk
  - Bottom would be more important (larger collisional energy loss and larger dead cone effect)
  - Collisional dissociation (heavy quarks fragment inside the medium and are suppressed by dissociation)

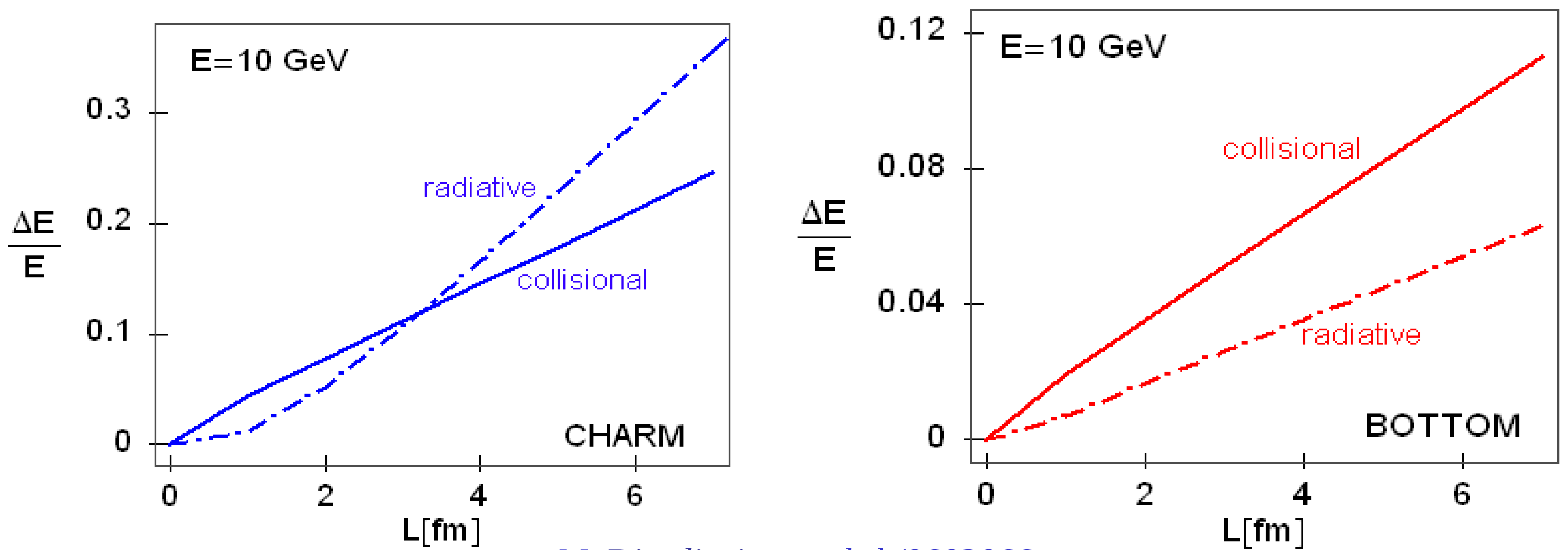
PHENIX nucl-ex/0611018
STAR nucl-ex/0607012



Collisional EL for heavy quarks

- Collisional and radiative energy losses are comparable!
  - M.G.Mustafa,Phys.Rev.C72:014905
  - A. K. Dutt-Mazumder et al.,Phys.Rev.D71:094016,2005

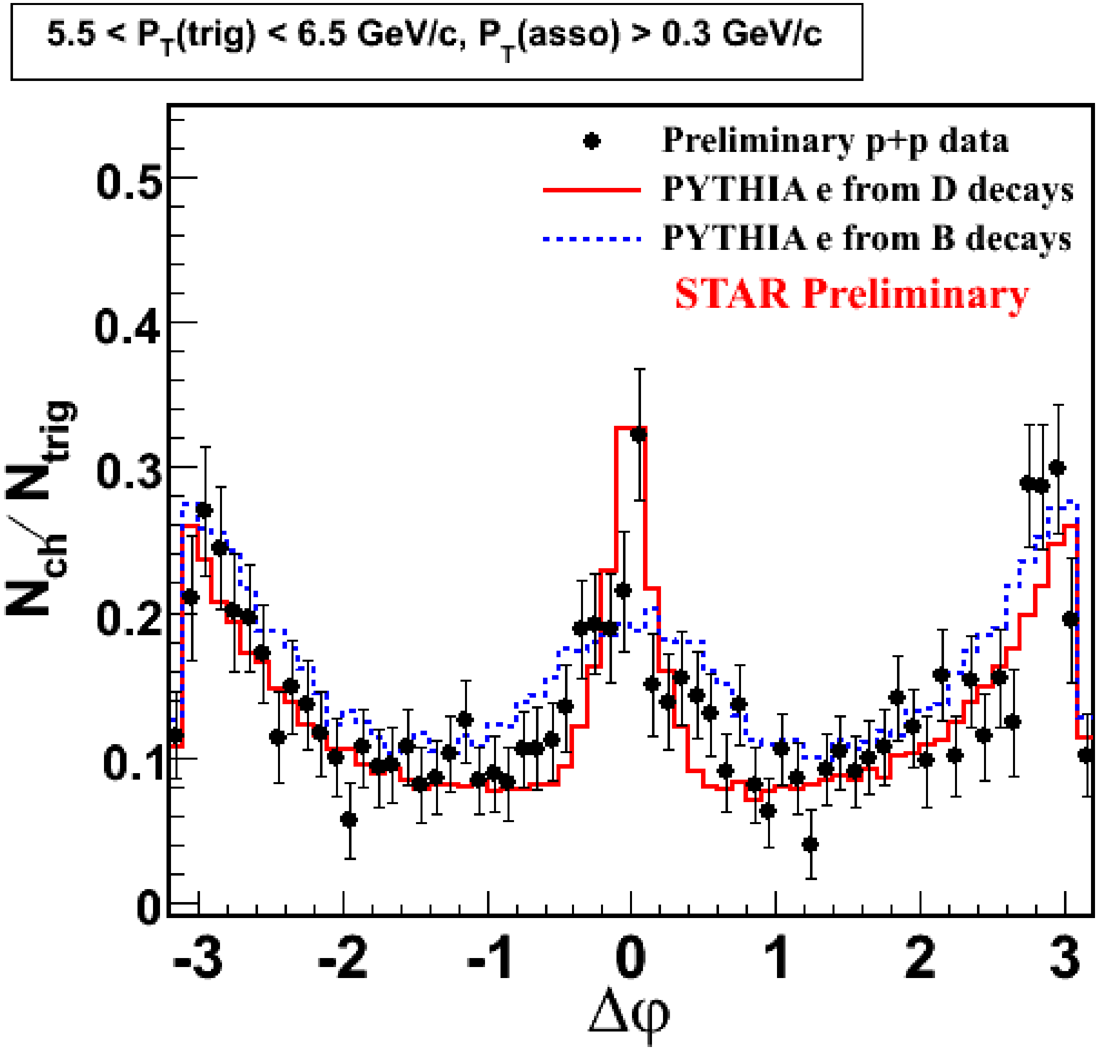
- Should strongly affect heavy quark R_{AA}



M. Djordjevic, nucl-th/0603066

e-h azimuthal correlations in pp

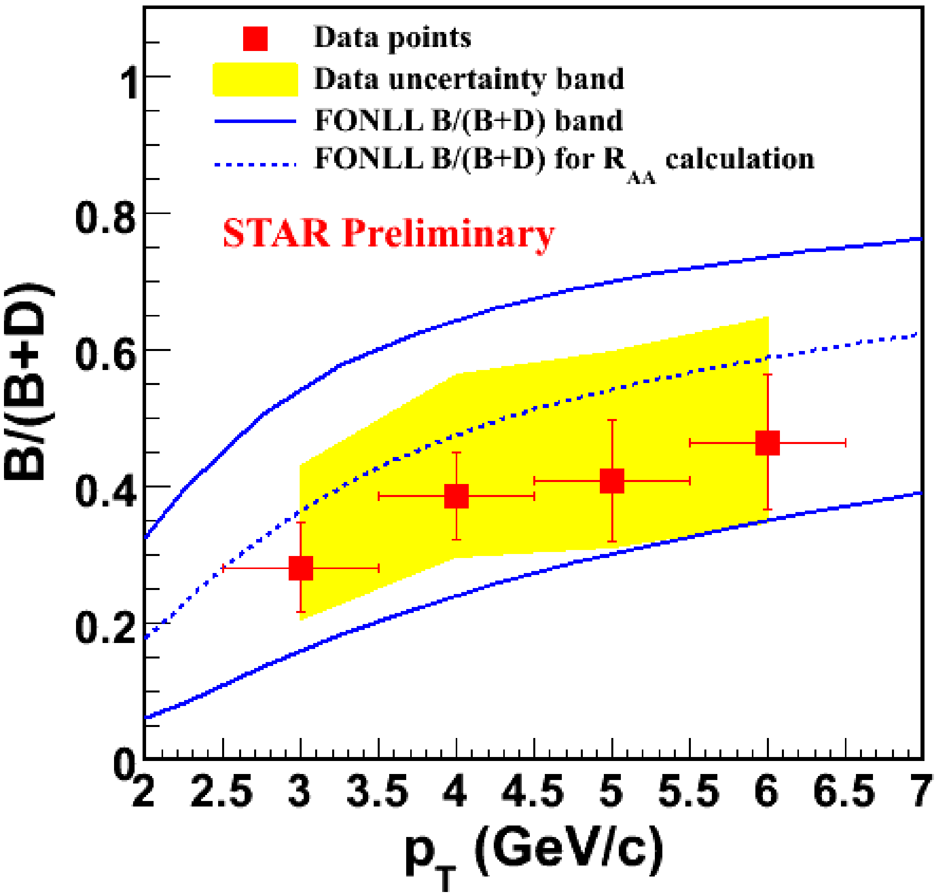
What is the fraction of B mesons, B/(D+B)?



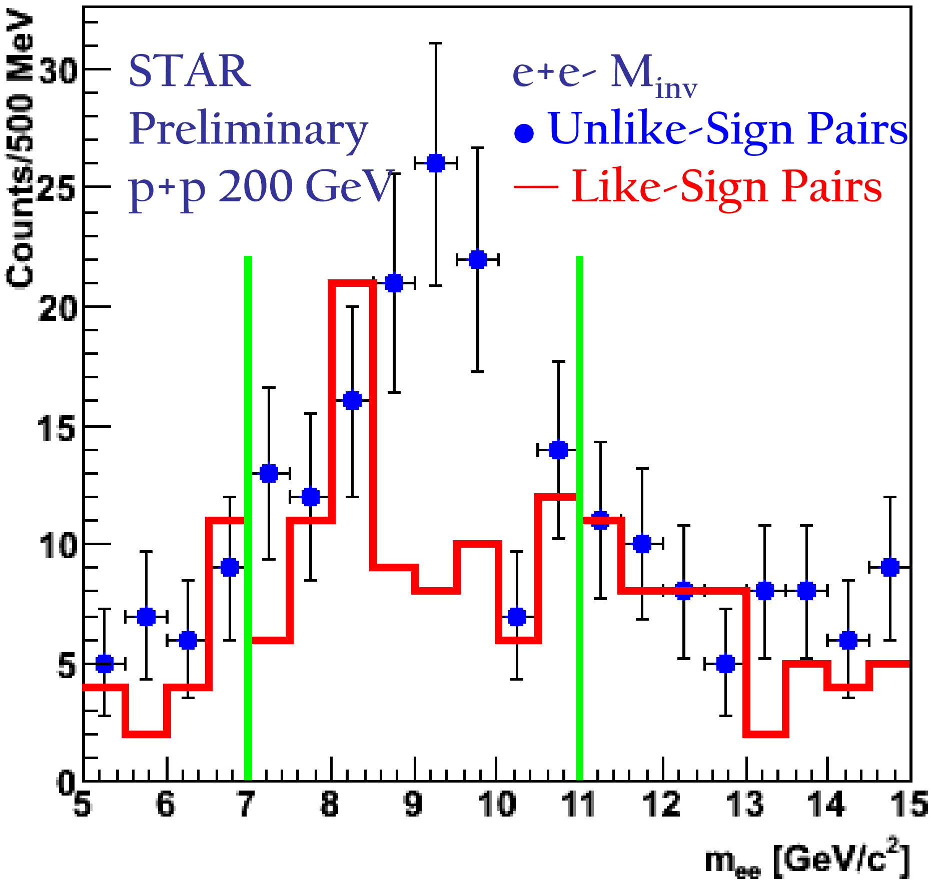
B in NP electrons vs p_T

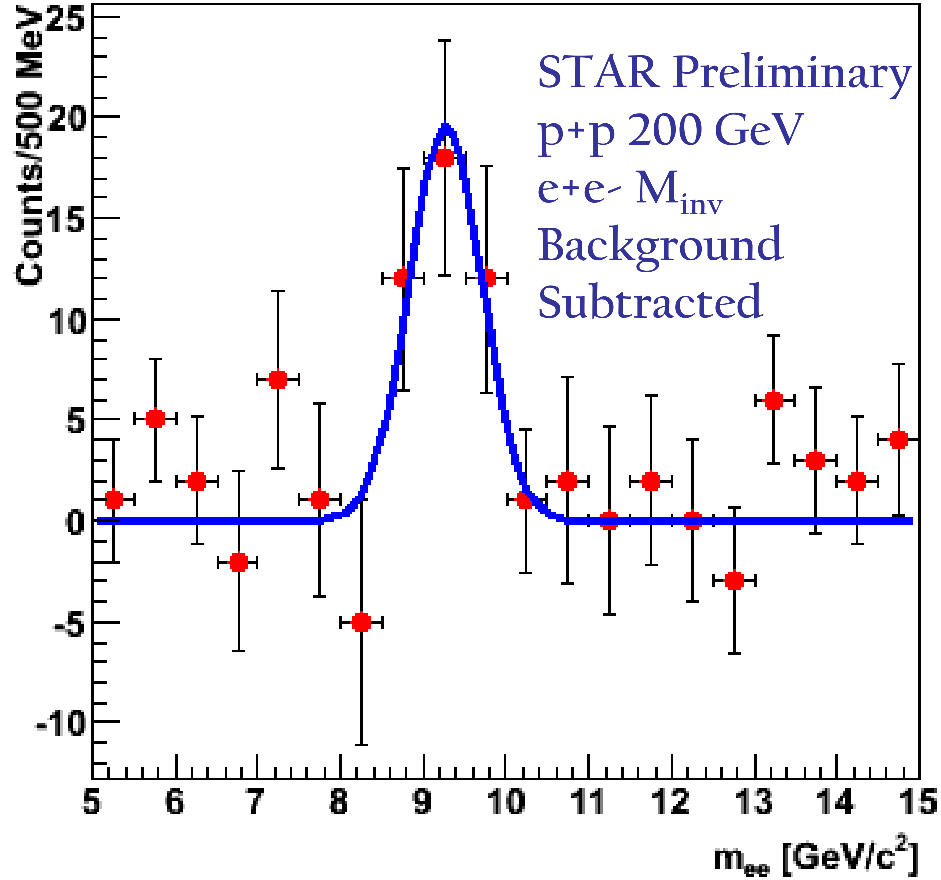
- Non-zero B contribution
- Contribution consistent with FONLL
  - Model dependent (PYTHIA)
  - Depends on kinematics of D and B decay (not on the fragmentation)
- Dominant systematic uncertainty:
  - photonic background rejection effici ency
  - Additional uncertainties under study

p+p 200 GeV



More beauty: Υ signal in pp

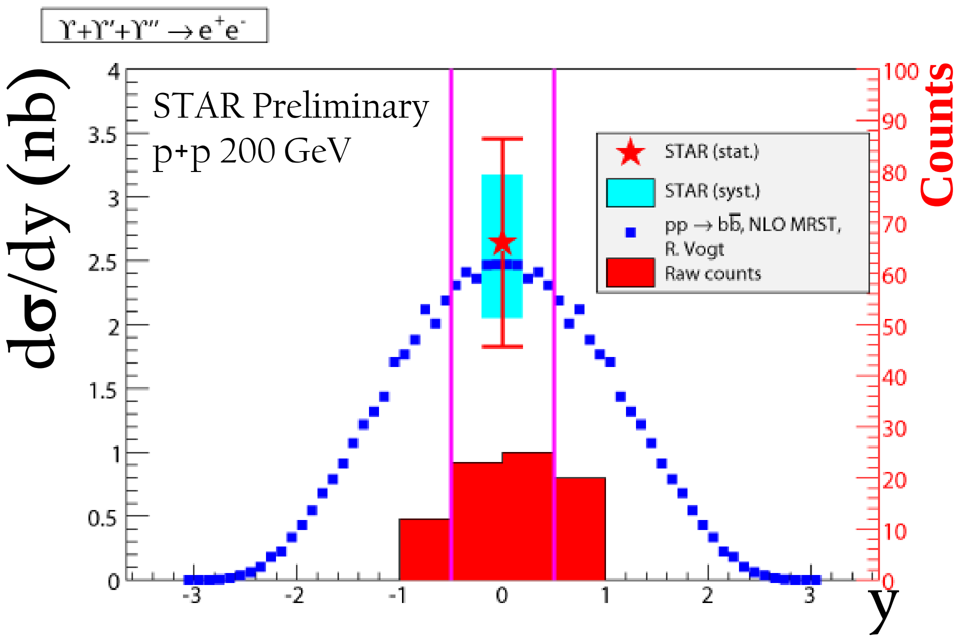




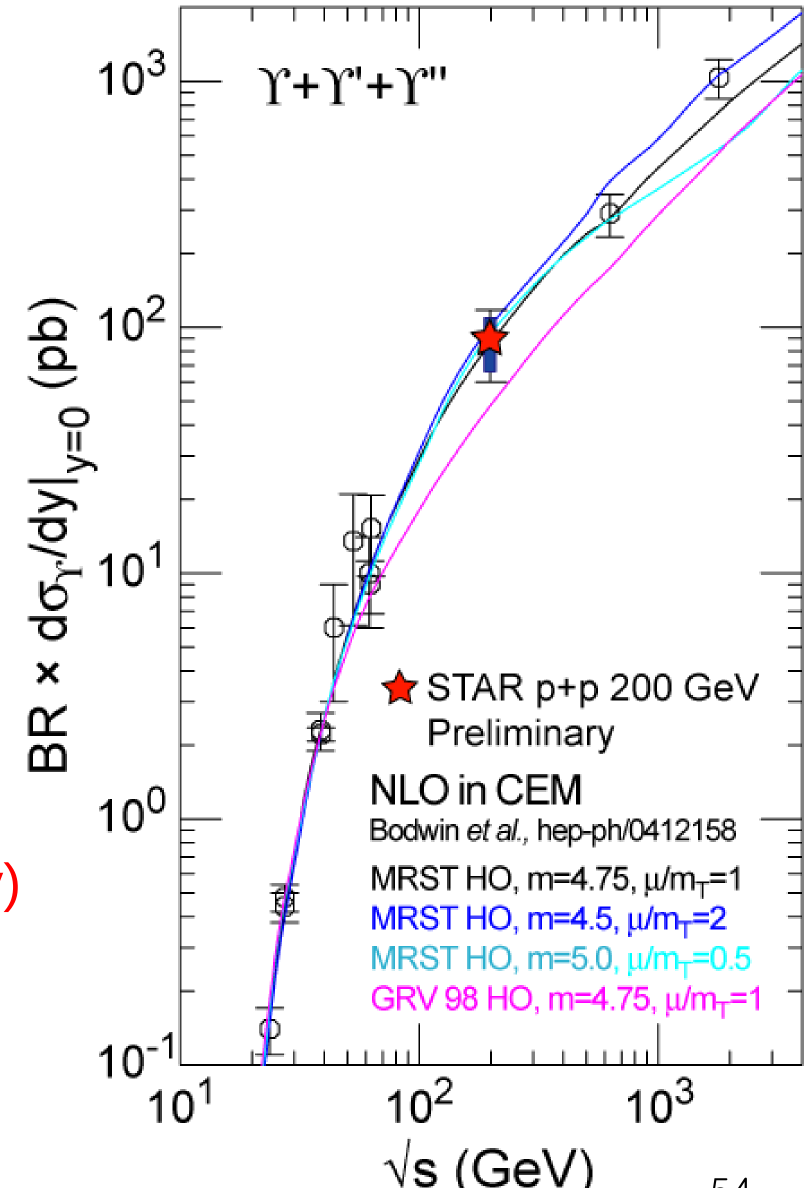
- Large dataset sampled in Run VI
  - Luminosity limited trigger
  - Analyzed 5.6 pb^{-1}, with corrections.
- Measure Υ(1s+2s+3s) dσ/dy at y=0

$$\int \mathfrak{L}\, dt = 9\, pb^{-1}$$

Mid-rapidity ϒ(1s+2s+3s) Cross section

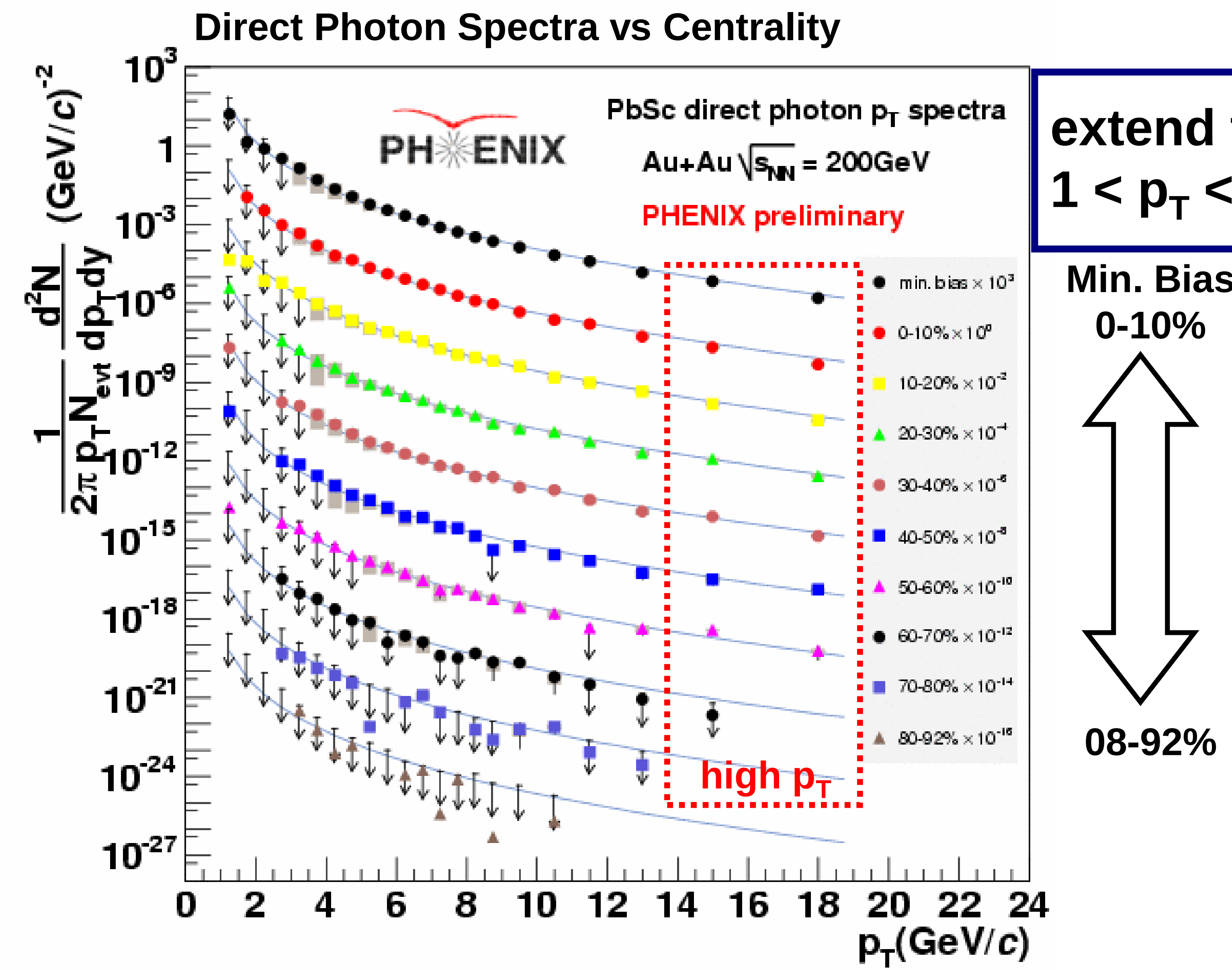


- Integrate yield at mid-rapidity: |y|<0.5
- ϒ(1s+2s+3s) BR * dσ/dy
  - 91 ± 28 $_{stat}$ ± 22 $_{syst}$ pb^{-1} (Preliminary)
- Consistent with NLO pQCD calculations at midrapidity.
- Trigger ready for next run and RHIC II: luminosity limited



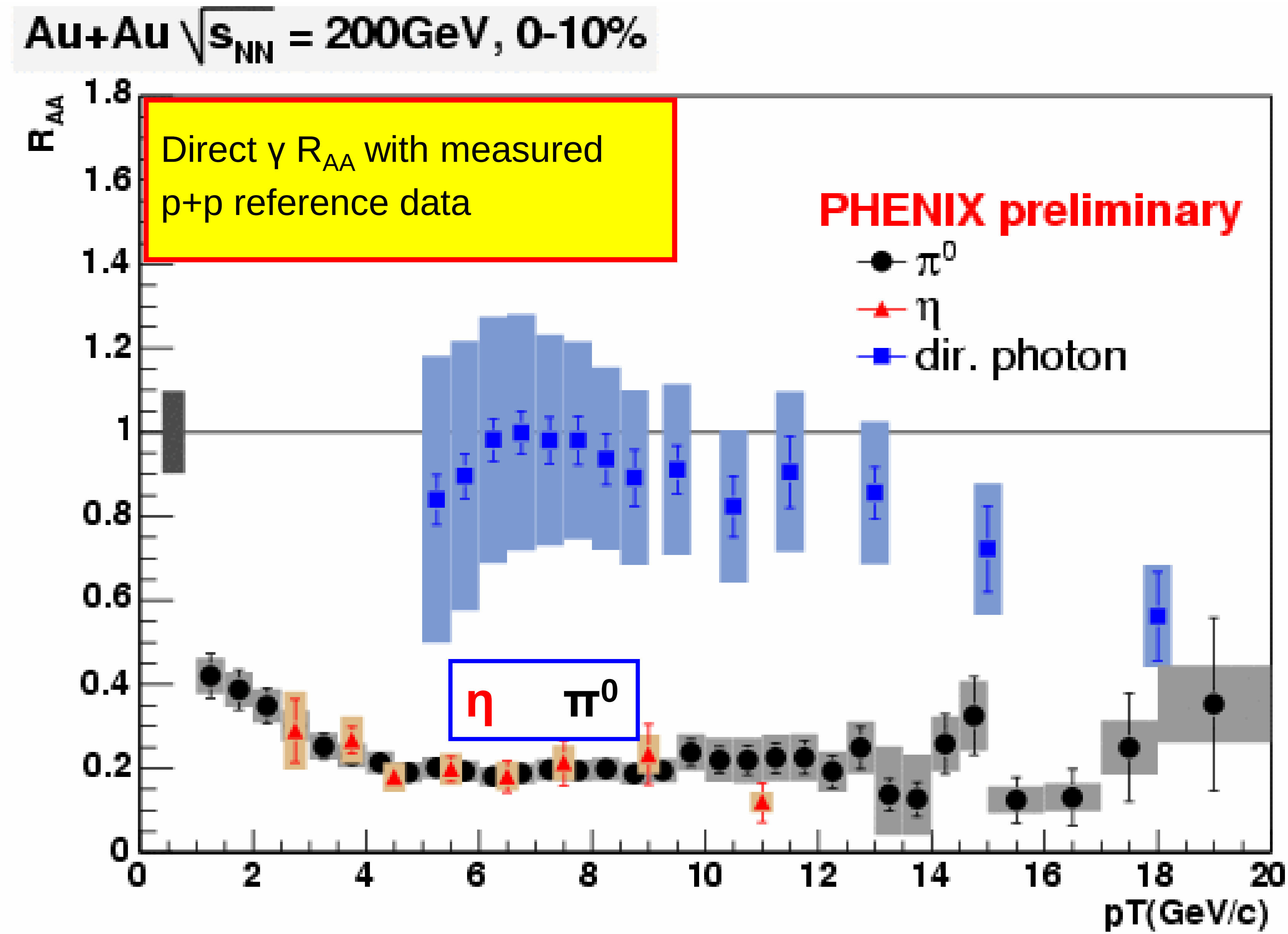
Direct Photons

Direct photons

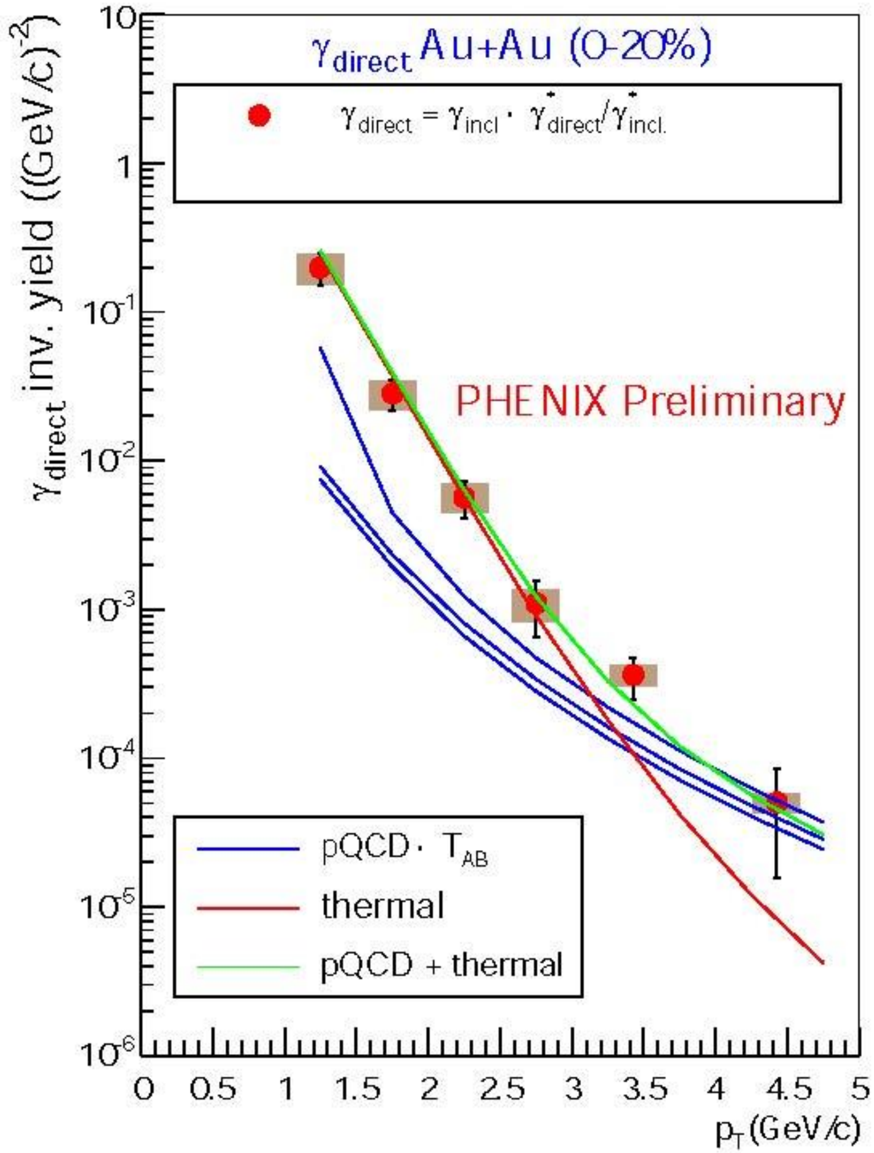


extend to high p_T
$1 < p_T < 20$ GeV

Direct γ R_{AA} at 200 GeV



Direct photons at low p_T



QM 2005: Data consistent with thermal+ NLO pQCD

pQCD uncertain at low p_T
Gordon and Vogelsang
Phys. Rev. D48, 3136 (1993)

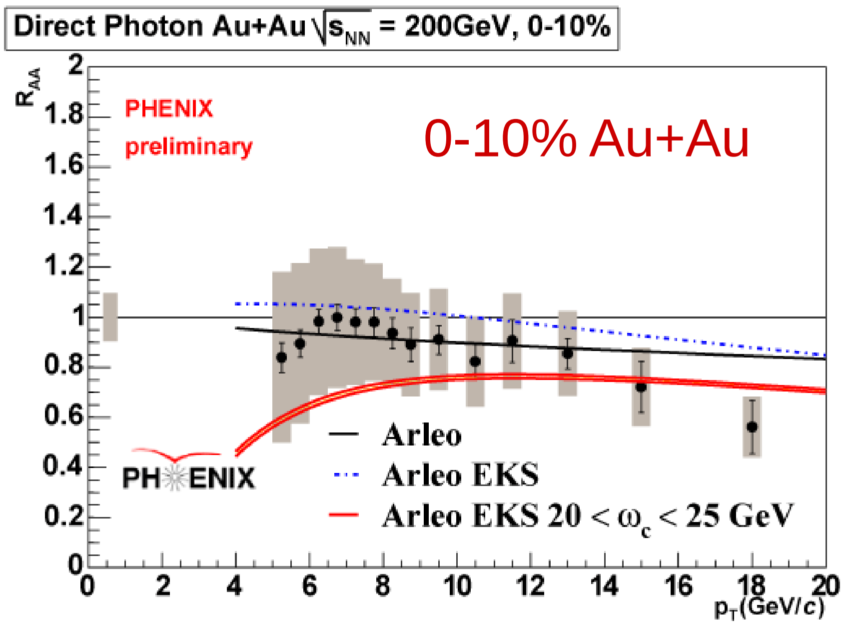
Thermal d'Enterria, Perresounko
Eur.Phys.J.C46:451-464,2006

(a) New experimental method for the measurement of direct photons

➔ external conversion from beam pipe

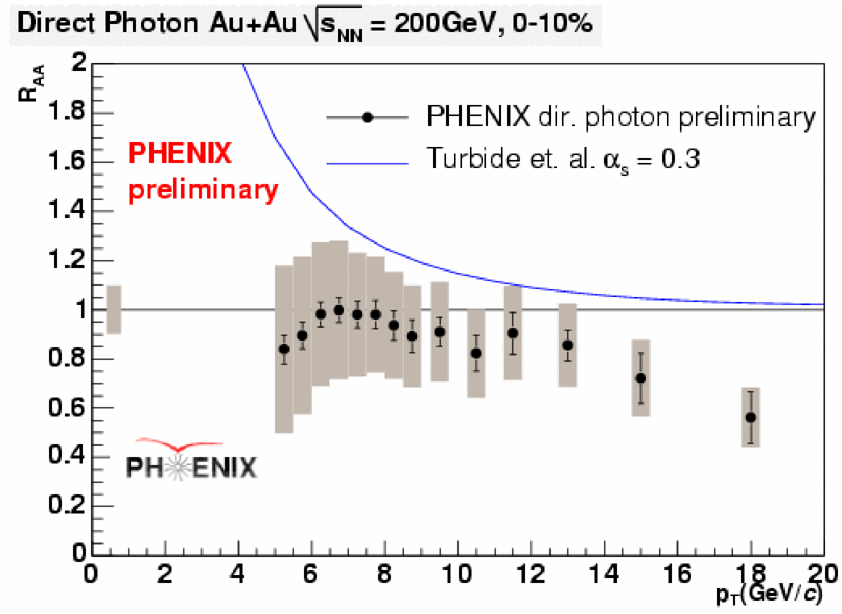
(b) pp and d+Au reference data: work in progress.

Model comparison



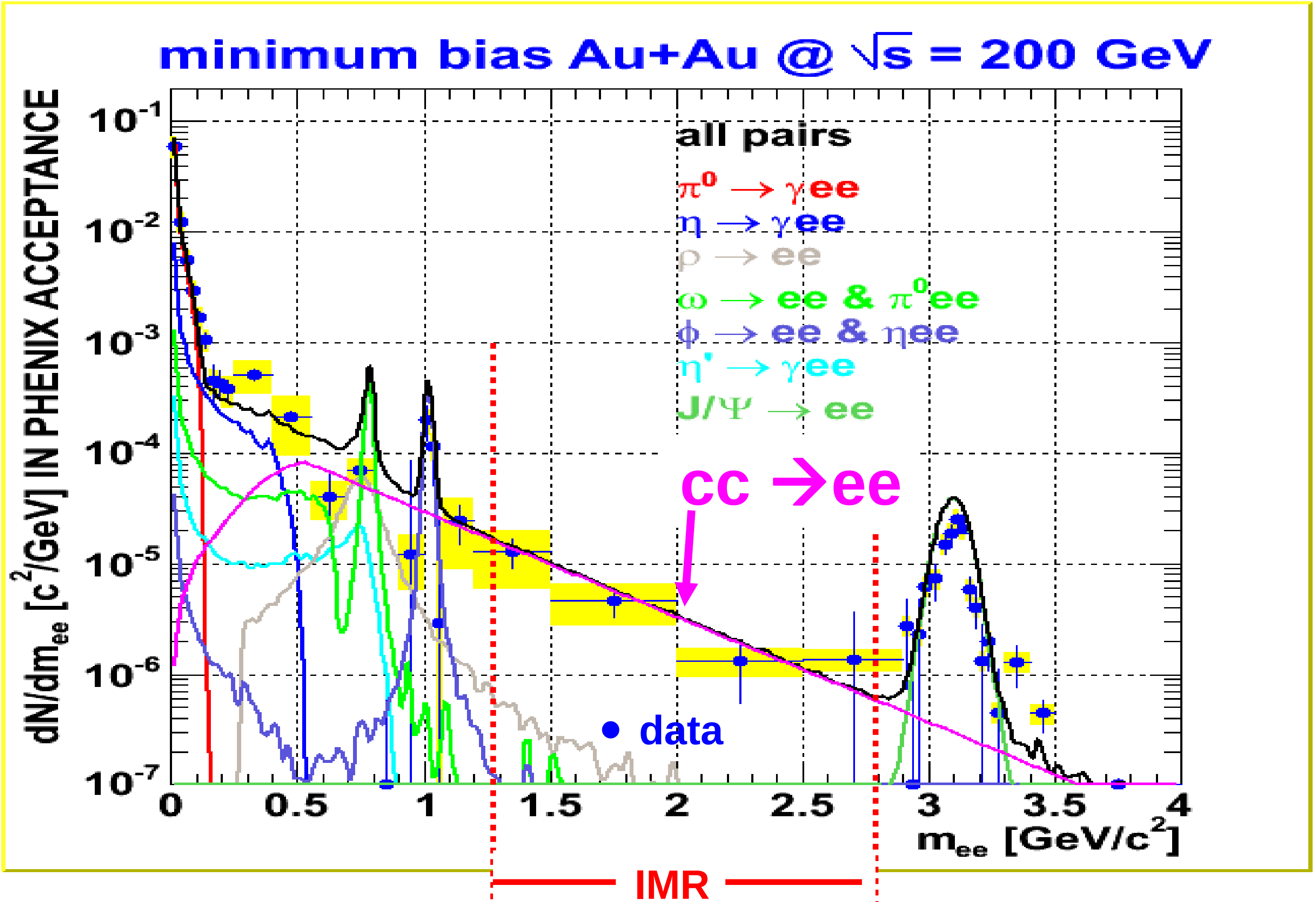
Nuclear effects + E-loss (frag γ)

Quark-γ in-medium conversions



In-Medium Effects

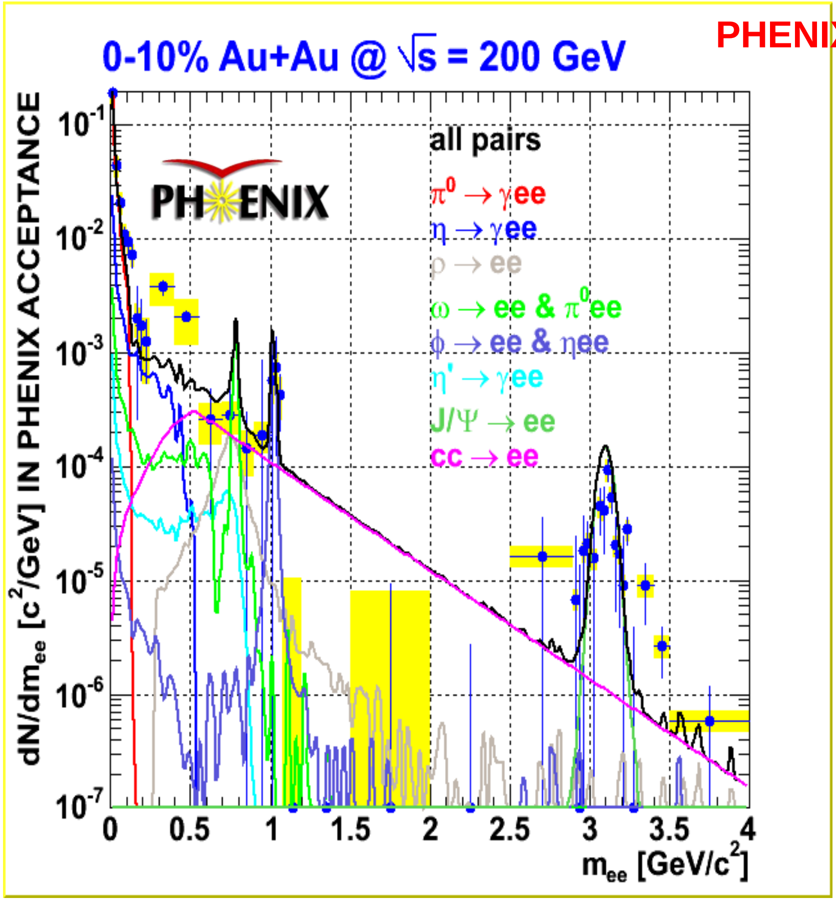
Di-lepton invariant mass spectra

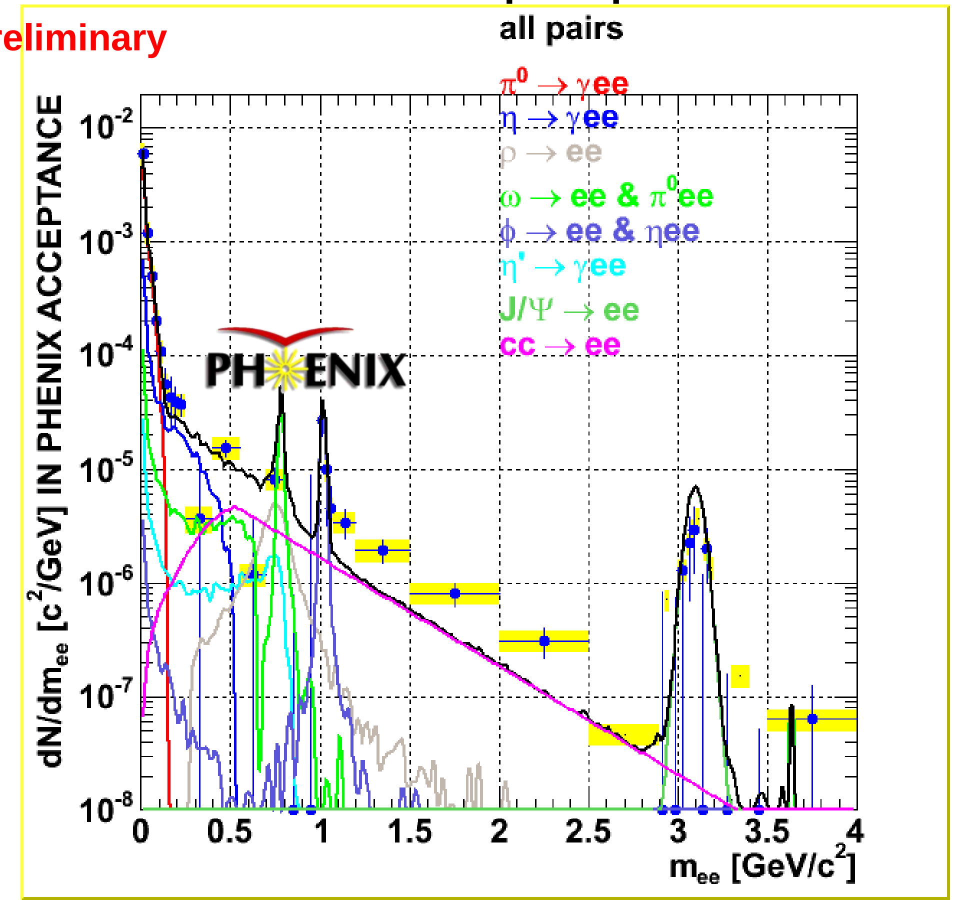


Centrality Dependence

0-10% -- central

60-100% -- peripheral

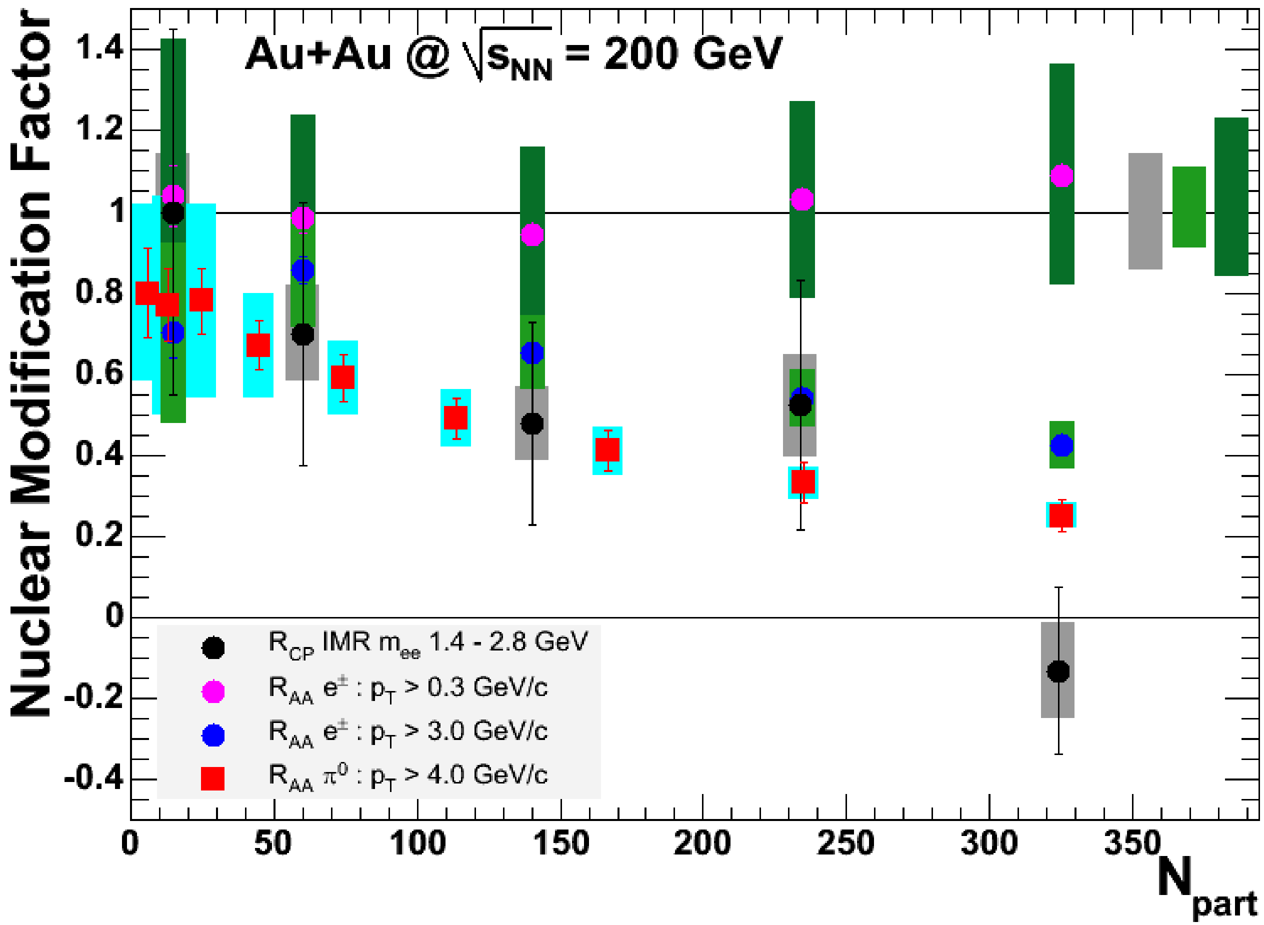




- intermediate mass region, dominated by charm decays: suppression towards central collisions, compatible with suppression pattern observed for HF electrons and J/ψ
- low mass region: hint of enhancement but uncertainties are large

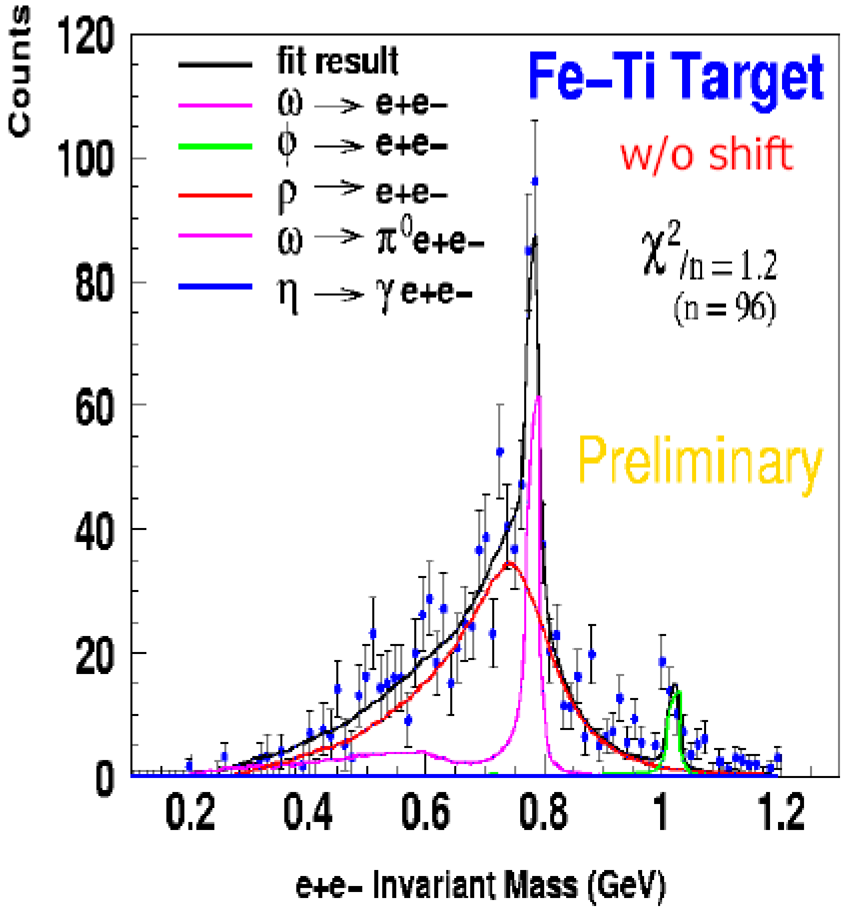
Nuclear Modification in Charm

R_{CP} for $1.4 < m_{ee} < 2.8$ GeV/c^2 in Au+Au



More experimental data

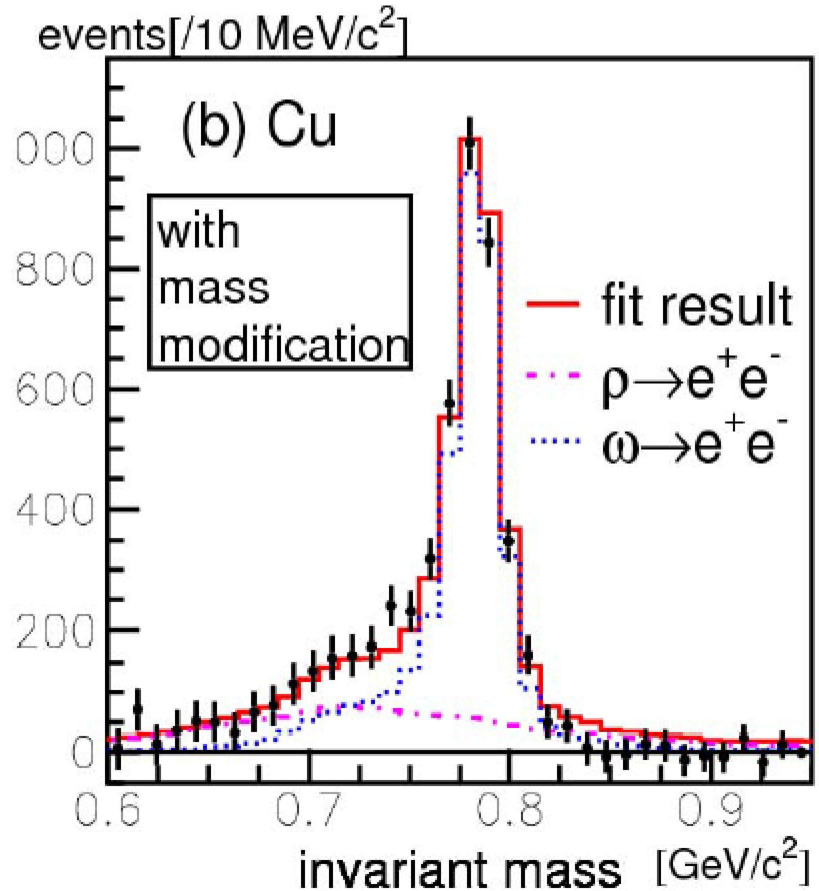
JLAB-CLAS: G7 $\gamma A \rightarrow e^+e^- + X$



ρ slightly broadened; no mass shift

No consistent picture!!

KEK-E325: p (12 GeV) A→ ρ, ω +X



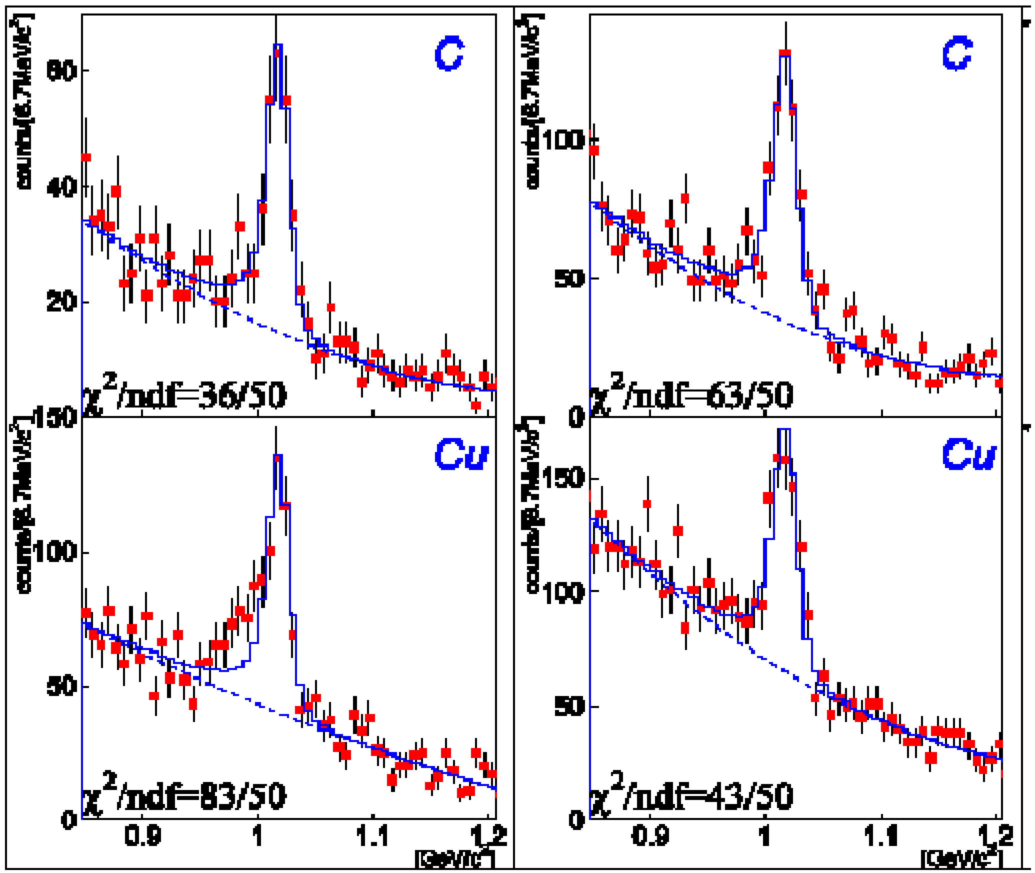
ρ shifted in mass: $m_\rho = m_0\left(1 - 0.092\frac{\rho}{\rho_0}\right)$; no broadening!!

M. Naruki et al., PRL 96 (2006) 092301

More experimental data

KEK-E325: p (12 GeV) A→ ρ, ω +X; Φ → e^+e^-

βγ<1.25 (Slow)   1.25<βγ<1.75



Target dependence

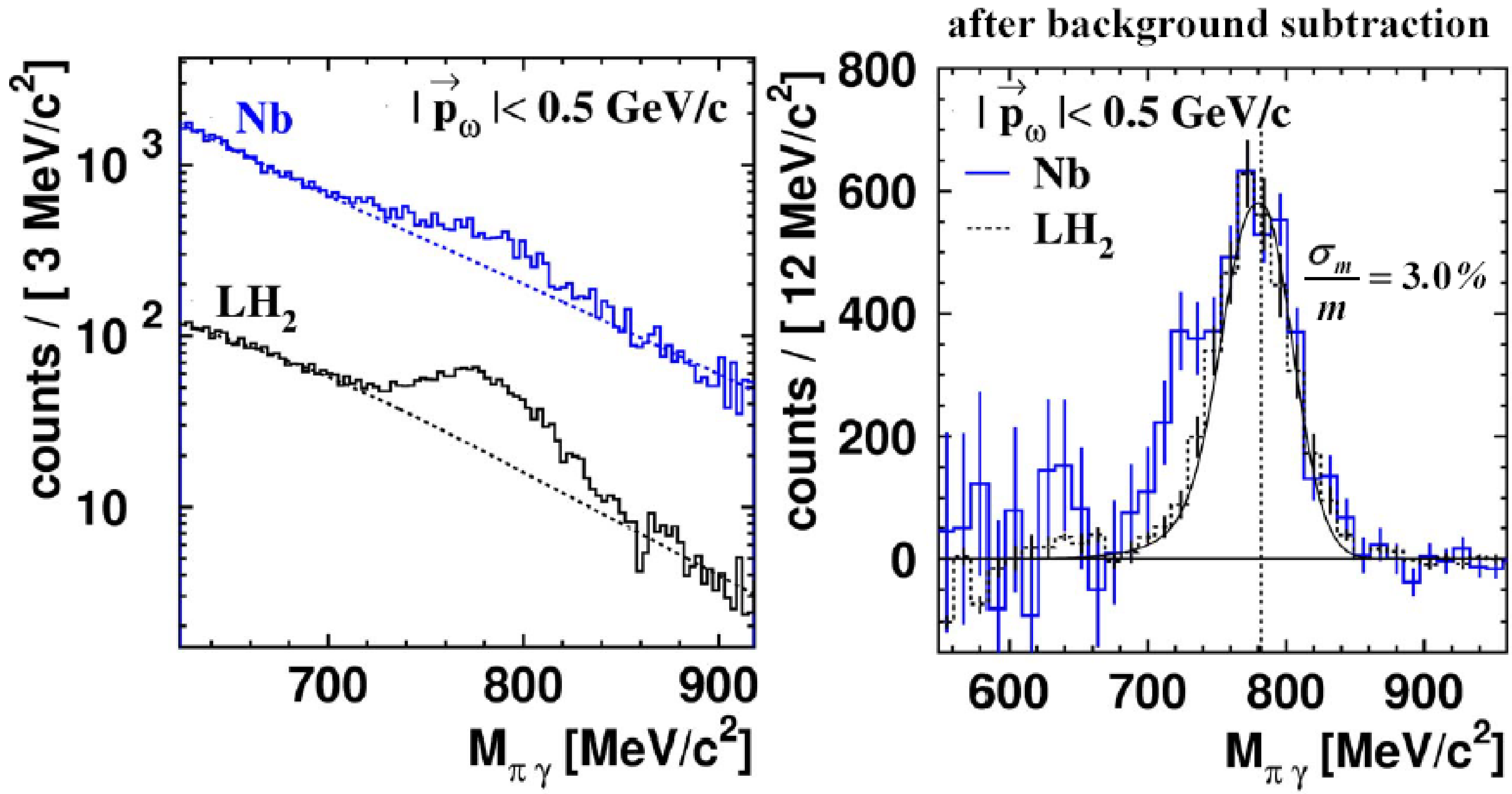
mass shift of Φ - meson for low recoil momenta in Cu: $m_\Phi = m_0\left(1 - 0.04\frac{\rho}{\rho_0}\right);$

More experimental data

TAPS@ELSA

inclusive $\omega \to \pi^0 \gamma$ signal for LH_2 and Nb target

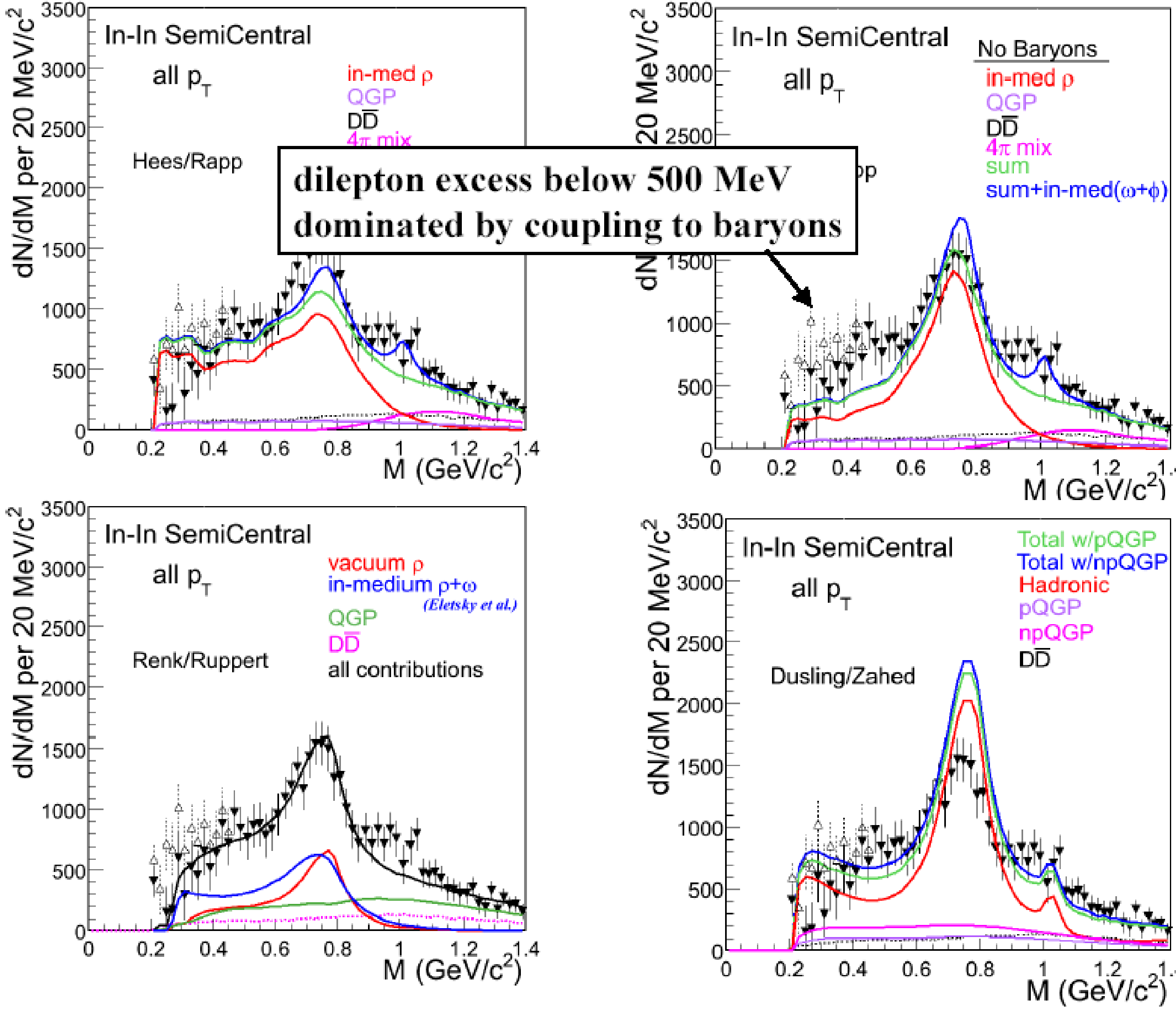
D. Trnka et al., PRL 94 (2005) 192203



difference in line shape of ω signal for proton and nuclear target

consistent with $m_\omega = m_0 (1 - \alpha\ \rho/\rho_0)$ for $\alpha = 0.13$

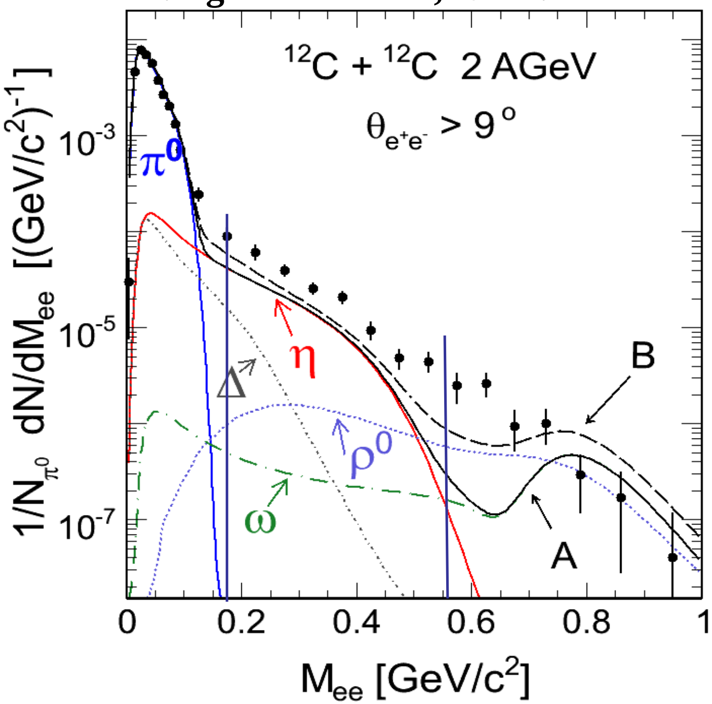
More experimental data



Dielectrons in low energy HI collisions

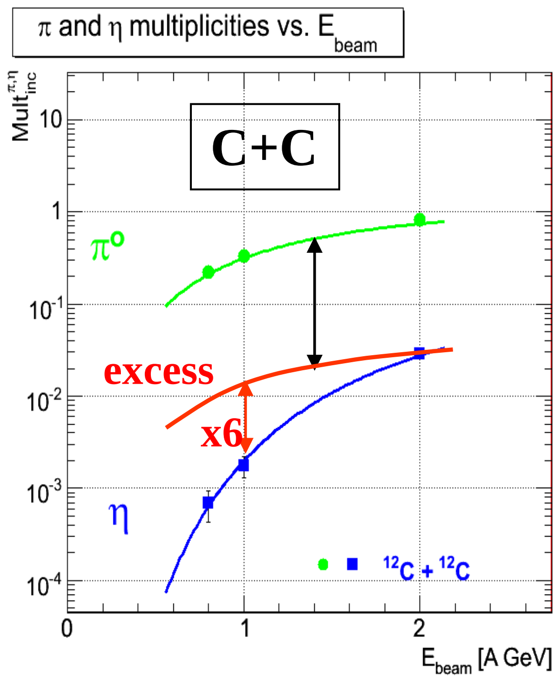
- HADES @ GSI

G. Agakichiev et al, subm. to PRL



- dielectron excess beyond expectation from decays of long lived mesons
  - total/η = 2.07 ± 0.21 ± 0.38 for $0.17 < m_{ee} < 0.55$ GeV/c^2

- scaling of excess yield
  - DLS: C+C @ 1.04 AGeV
    - total/η = 6.5 ± 0.5 ± 2.1



- excess scales with π^0, which are produced via baryon resonances (!)

Summary on in-medium effect

current status of in-medium modifications of vector mesons

	KEK	Jlab	CBELSA/TAPS	CERES	NA 60
ω	–	–	mass shift: -14% $\Gamma_\omega(\rho=\rho_0)\approx 100MeV$	–	–
ρ	mass shift: -9% no broadening	no mass shift some broadening	–	broadening favored over density dependent mass shift	no mass shift strong broadening
Φ	mass shift: -4% $\Gamma_\phi(\rho_0)=47MeV$	–	–	–	–

despite of enormous progress in the experiments no fully consistent picture as yet

Summary of summary

1. Hadron production
   - Various scaling phenomena on flow and HBT
2. Light quark energy loss
   - Energy, species, and geometry dependences
3. Jet and particle correlations
   - Reaction plane dependence
   - Detailed study on the shape of jets
   - Existence of the mach cone established
4. Heavy flavor
   - Yield suppression of heavy flavor in central AA is similar to that for light quarks
   - Discrepancy on the cross section still exist
   - First b-production estimated
5. In-medium effects
   - Complete suppression of intermediate mass region in central Au+Au collisions at RHIC
   - Mass shift and broadening of light vector mesons are still controversial even experimentally.