J/Ψ and Open Charm Production in Heavy Ion Collisions

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DNP'03 Workshop on QCD, Confinement and Heavy Ion Physics

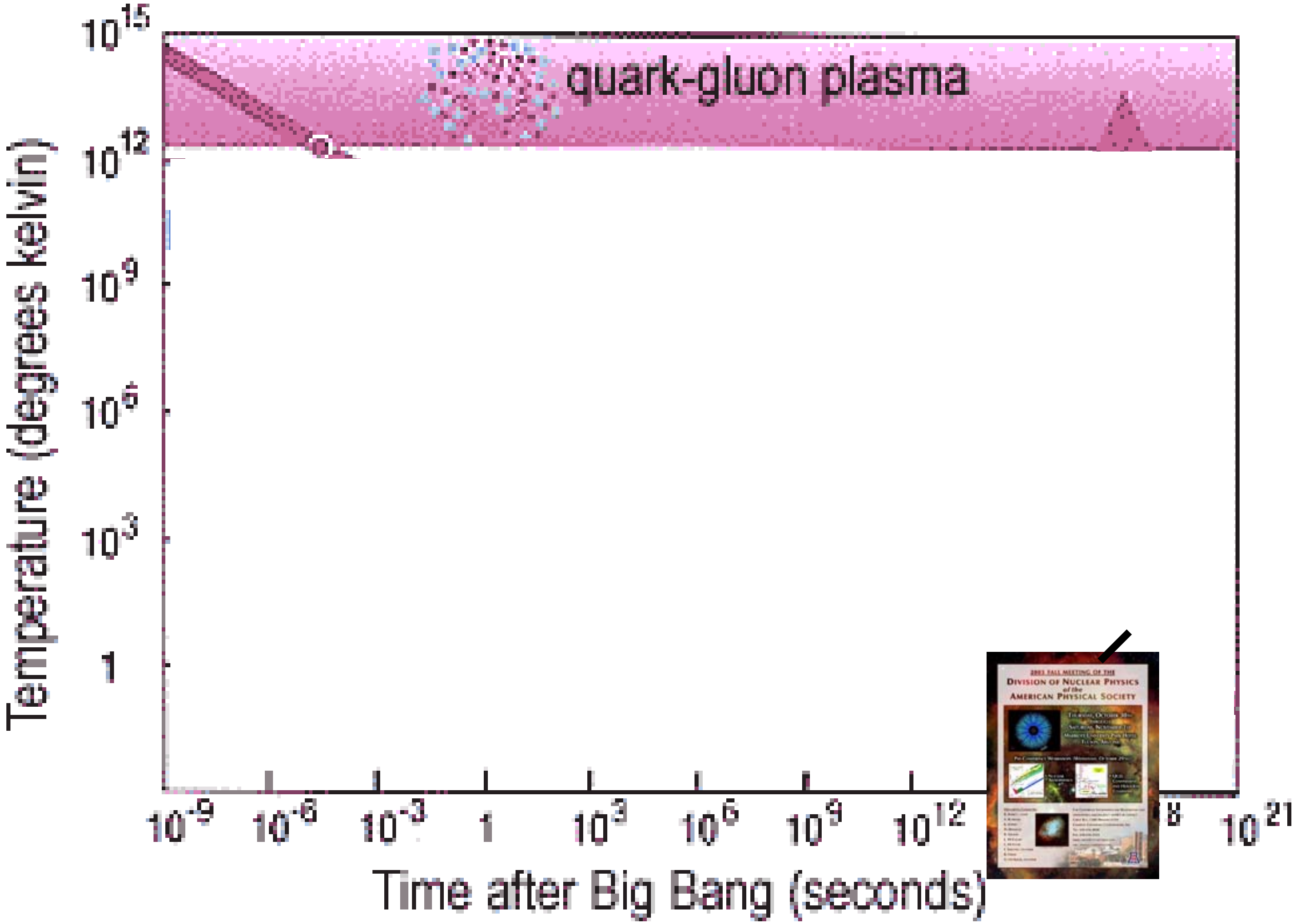
10/29/2003

Outline

- Motivation
  - Why heavy ion collisions?
  - Why J/Ψ and charm?
- Experimental Basics
  - Collision geometry
  - NA38/NA50, E772/E866, PHENIX overview
- Open charm production
- Closed charm production
- Outlook

- Motivation

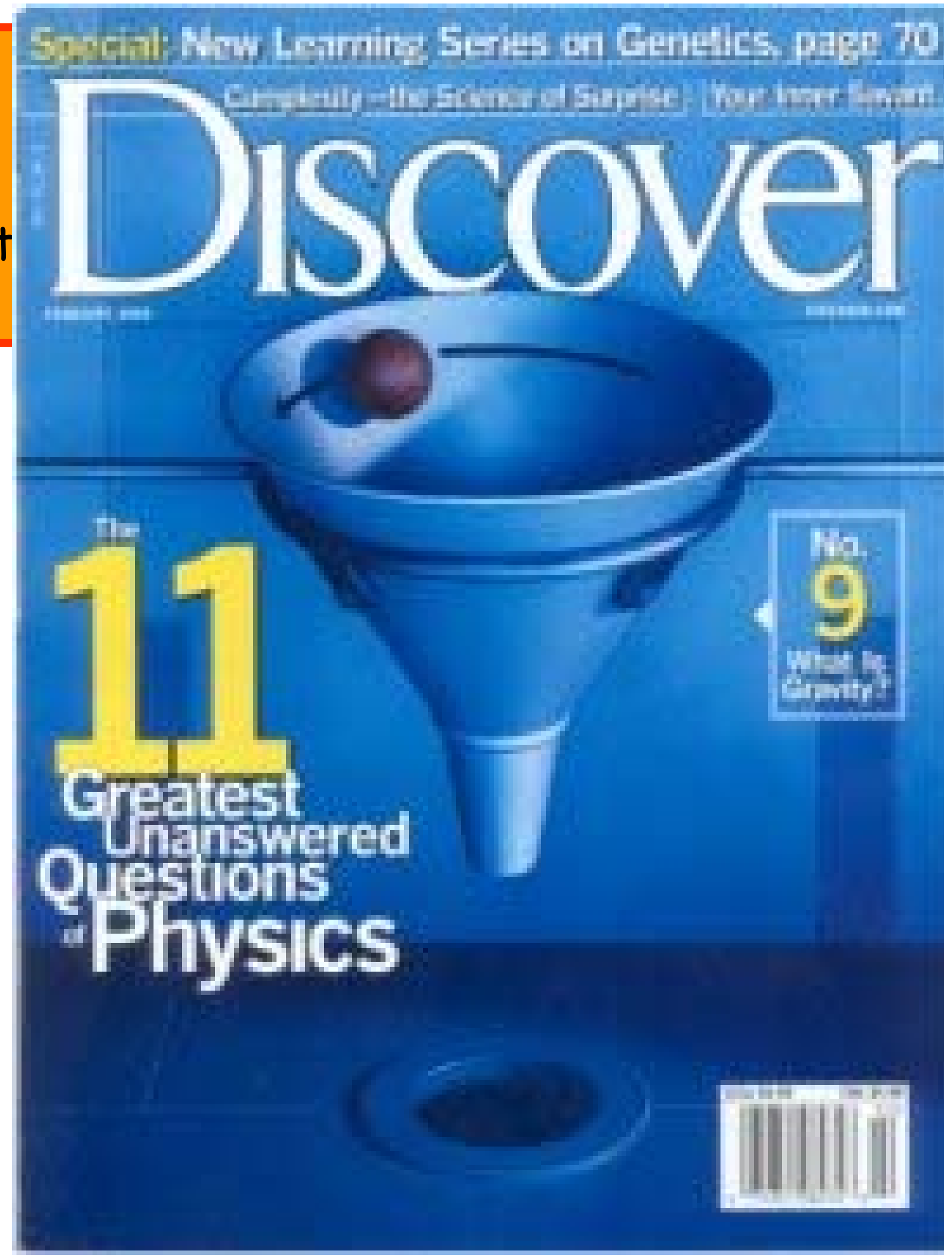
Re-creating the Big Bang in the Lab



Connecting Quarks with the Cosmos…

Stolen from title of 2001
Committee on the Physics

"Connecting Quarks with t
Eleven Science Questions



No.

7

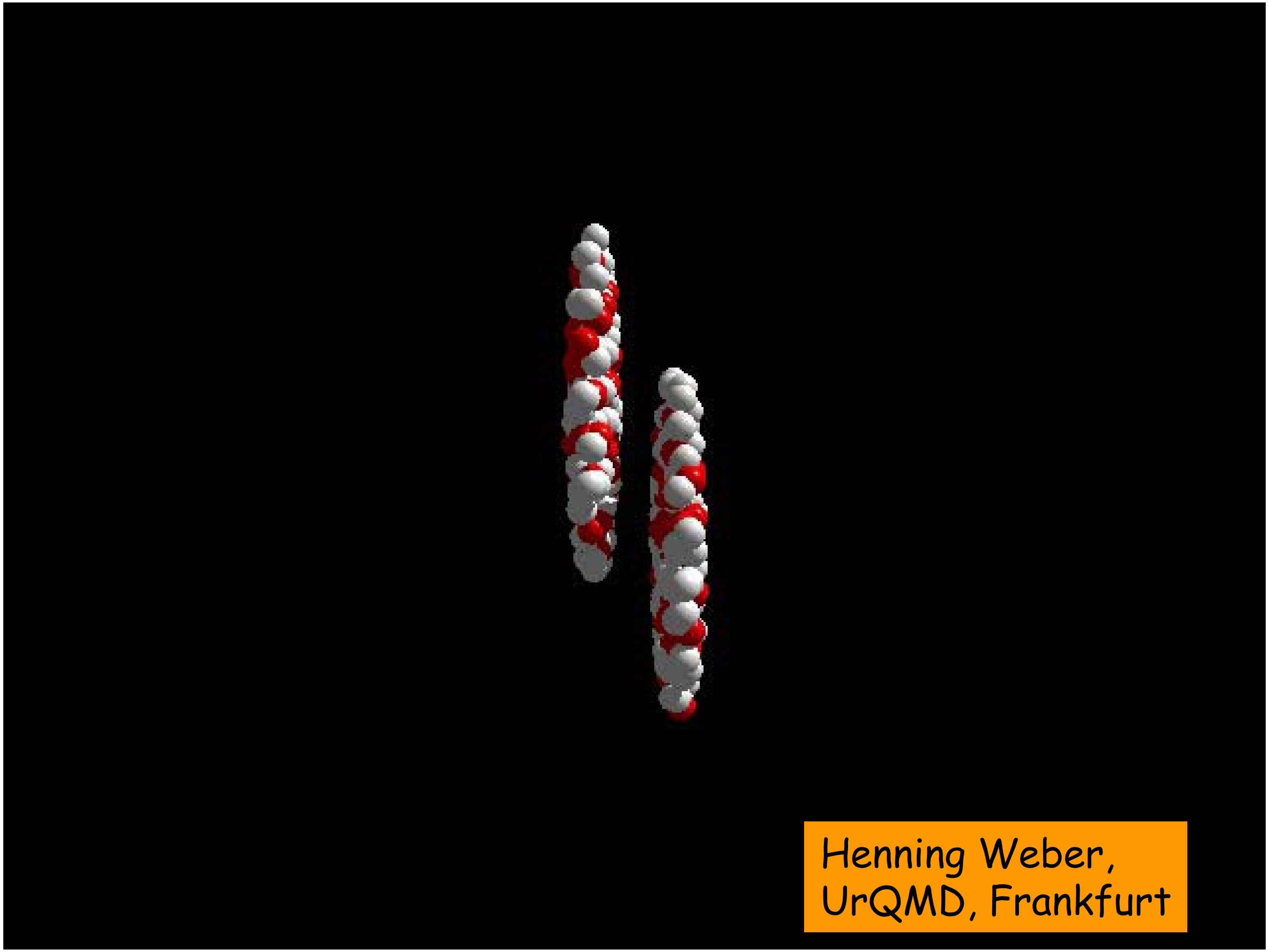
Are there new states of matter at ultrahigh temperatures and densities?

But Why Heavy Ions?

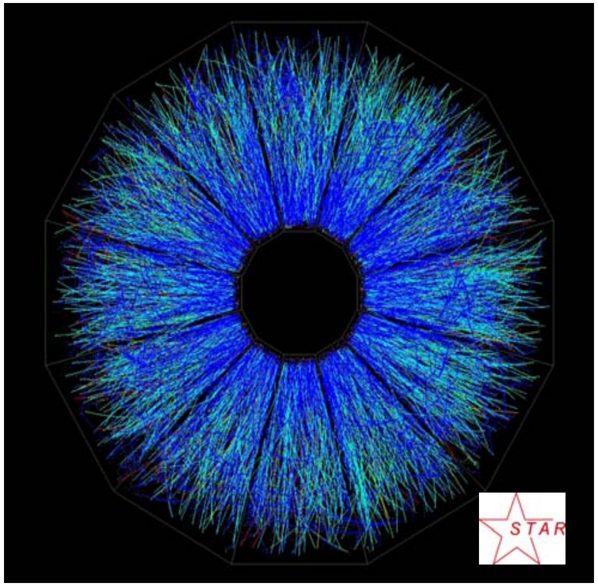
- The highest energy densities are achieved in e^+e^- collisions.
  - Energy density is not enough.
- Heavy ion collisions provide sufficient energy density over a “large” volume.
  - Conditions for a phase transition must prevail for a length of time sufficient for created particles to probe these conditions.
- Heavy ion collisions are not enough.
  - Detailed knowledge of our expectations if a phase transition is not achieved is necessary for proper interpretation of heavy ion collision results (a “control” experiment).
  - pp, pA and aa collisions are also needed.

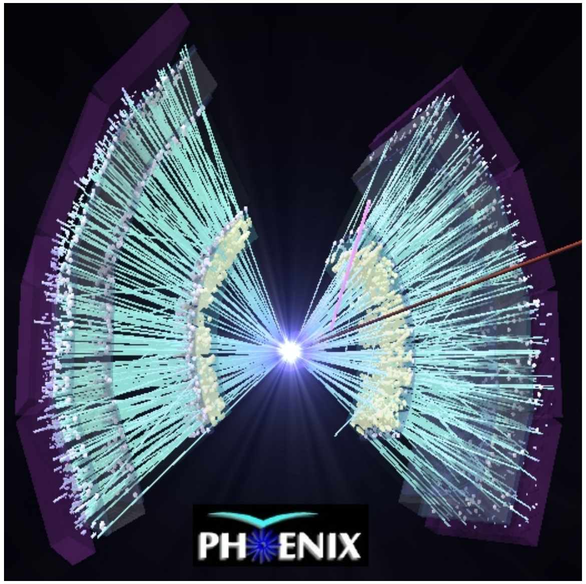
- Experimental Basics

Pixar View of a Heavy Ion Collision



Detector Views of a Heavy Ion Collision

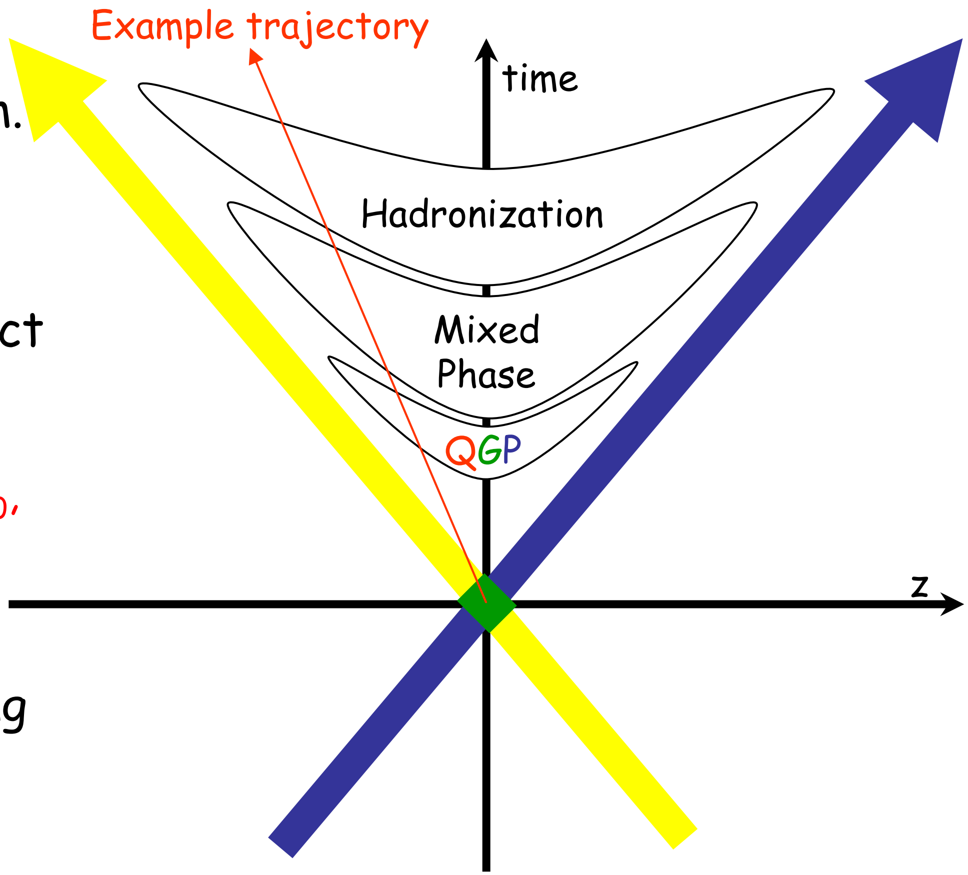




- For $\sqrt{s_{NN}}$ = 200 GeV AuAu heavy-on collisions dN/dY ~ 600.
- For scale - this is somewhere between 350 and 1000 simultaneous proton-proton collisions!
- Beauty is in the eye of the beholder - some would call this a mess!

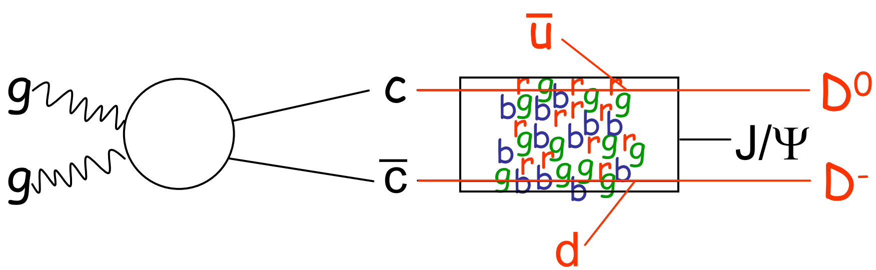
Space-time View of a Heavy Ion Collision

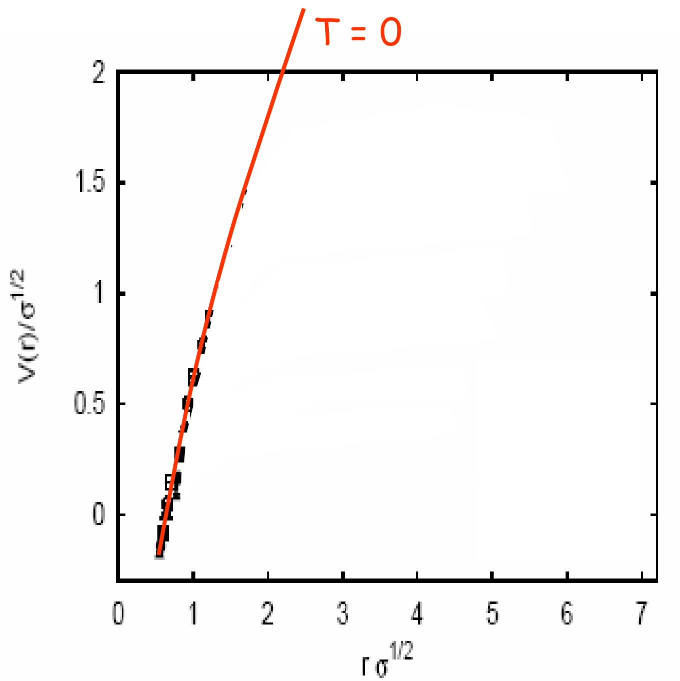
- Not only is it difficult to measure these collisions, it is also difficult to interpret them.
- Most of the collision products are hadronic in nature. The strong interaction is strong enough that they will re-interact prior to leaving the collision zone.
  - To have λ_{mfp} > 10fm @ $\rho = 20\rho_0$, σ < 0.35 mb.
- Note, this "problem" can be a virtue: "jet suppression" analyses rely on jets interacting with and probing the created medium.



Color Screening and the QGP

- Matsui and Satz (Phys. Lett. **B178**, 416.) first articulated the consequences of color screening on quarkonium production.
- c,c-bar pairs are primarily produced through gluon fusion early in the collision.
- Most often the c and c-bar quarks pair off with a light quark and exit the system as D-mesons.
- Occasionally the c and c-bar pair up with their primordial partner. Due to the attractive strong-force potential they can form bound states like the J/Ψ through a non-perturbative process.
- If the bound state is formed in, or passes through, a QGP, the free color charges will screen that potential (in a manner completely analogous to Debye screening in a Coulomb plasma).
- In this case the J/Ψ will melt (or never form in the first place) and the c and c-bar quarks will again leave the system as D-mesons, having found a ubiquitous light quark.





S. Digal, P. Petreczky, H. Satz, Phys. Lett. **B514**, 57.

An unambiguous signature…

- They carefully outlined the conditions that needed to be met for an observed suppression to be an unambiguous signature of QGP formation.
- We will see that two of these assumptions have turned out to be violated.

To assure that this J/ψ suppression in nuclear collisions indeed constitutes an observable signature of plasma formation, we must answer a number of questions:

(i) Can the J/ψ escape from the production region before plasma formation?

(ii) At what temperature does $r_D(T)$ fall below $r_{J/\psi}(T)$, and how does $r_{J/\psi}(T)$ behave as function of T? The large mass gives the J/ψ a smaller radius than that of conventional mesons, and sufficiently small hadrons could survive deconfinement as Coulombic bound states until much higher temperatures.

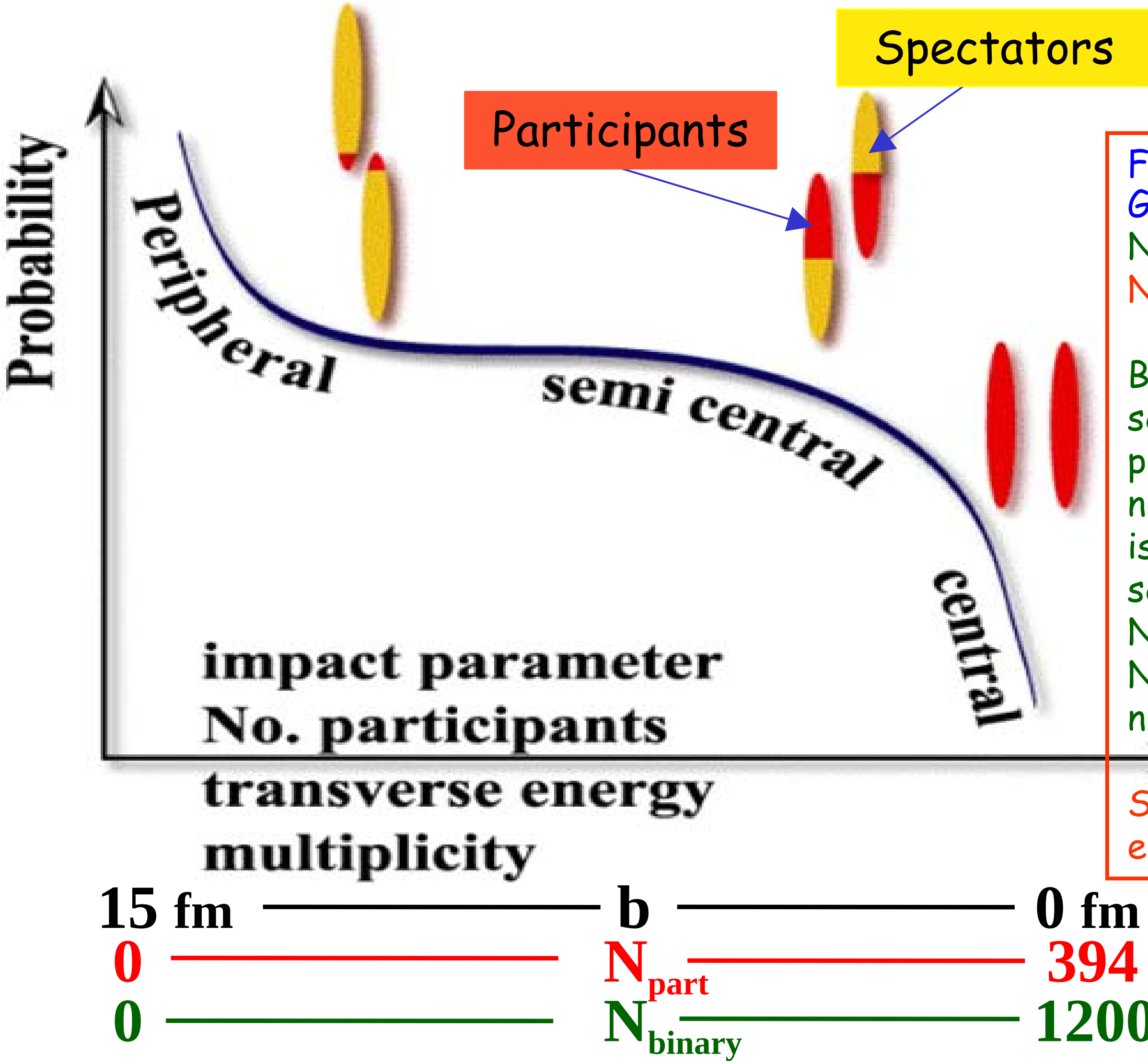
(iii) Are there competitive non-plasma J/ψ suppression mechanisms?

(iv) Could the J/ψ suppression in the plasma be compensated in the transition or hadronization stage?

(v) Could enhanced non-resonant production of lepton pairs ("thermal dileptons") prevent the observation of the J/ψ? In this case, we could not study deconfinement directly, although plasma formation would still be the cause for not seeing J/ψ's. We will now take up these questions.

- Experimental Basics

Collision Geometry and Centrality

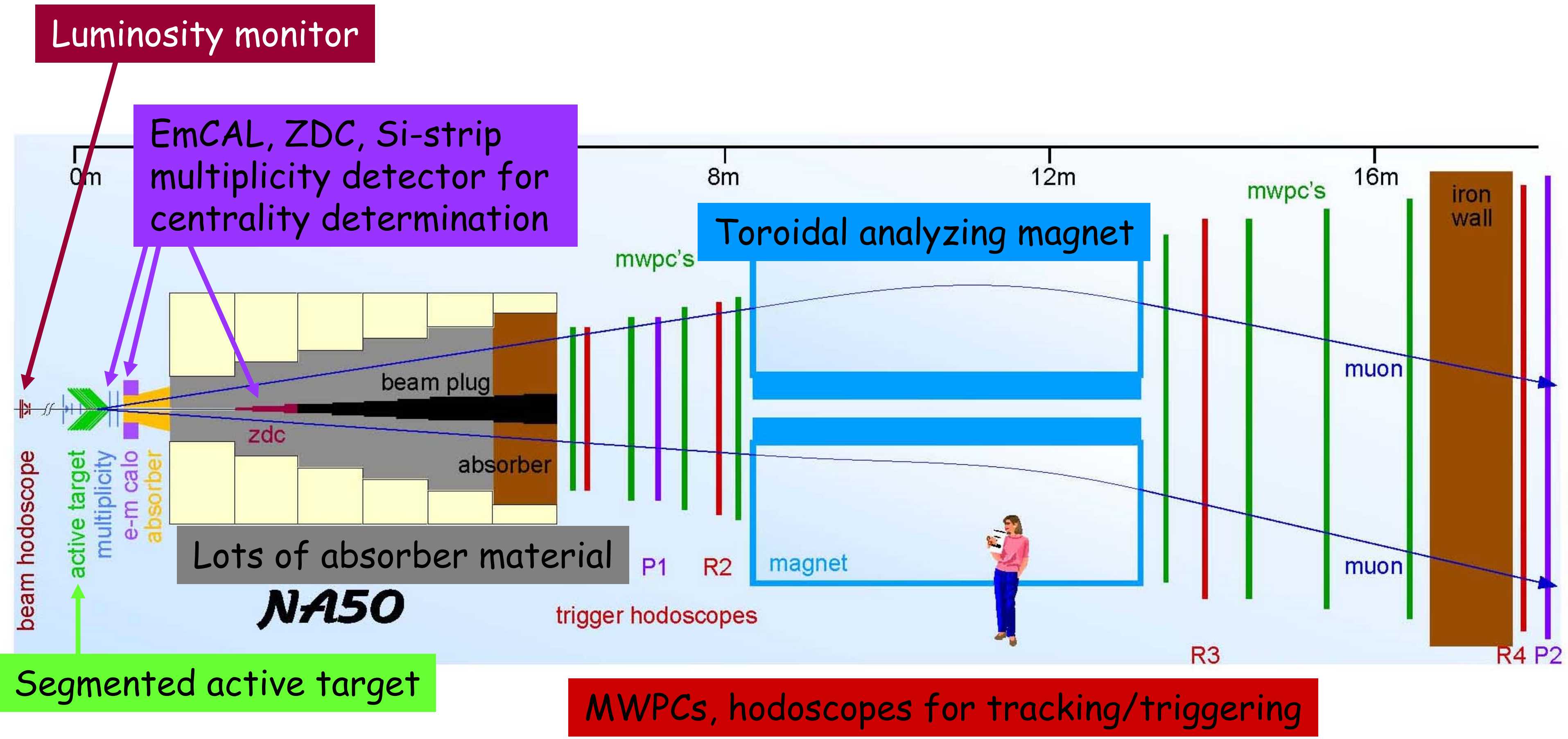


For a given impact parameter, Glauber model predicts:
N_{binary} (# binary collisions), and
N_{part} (# participants)

Because the cross-section for a hard-scattering event is small, the probability for any participating nucleon to have two such interactions is very small and such interactions will scale with N_{binary}.
Note: averaging over all centralities N_{binary} is the product of the nucleon numbers (AB, or A for pA collisions)

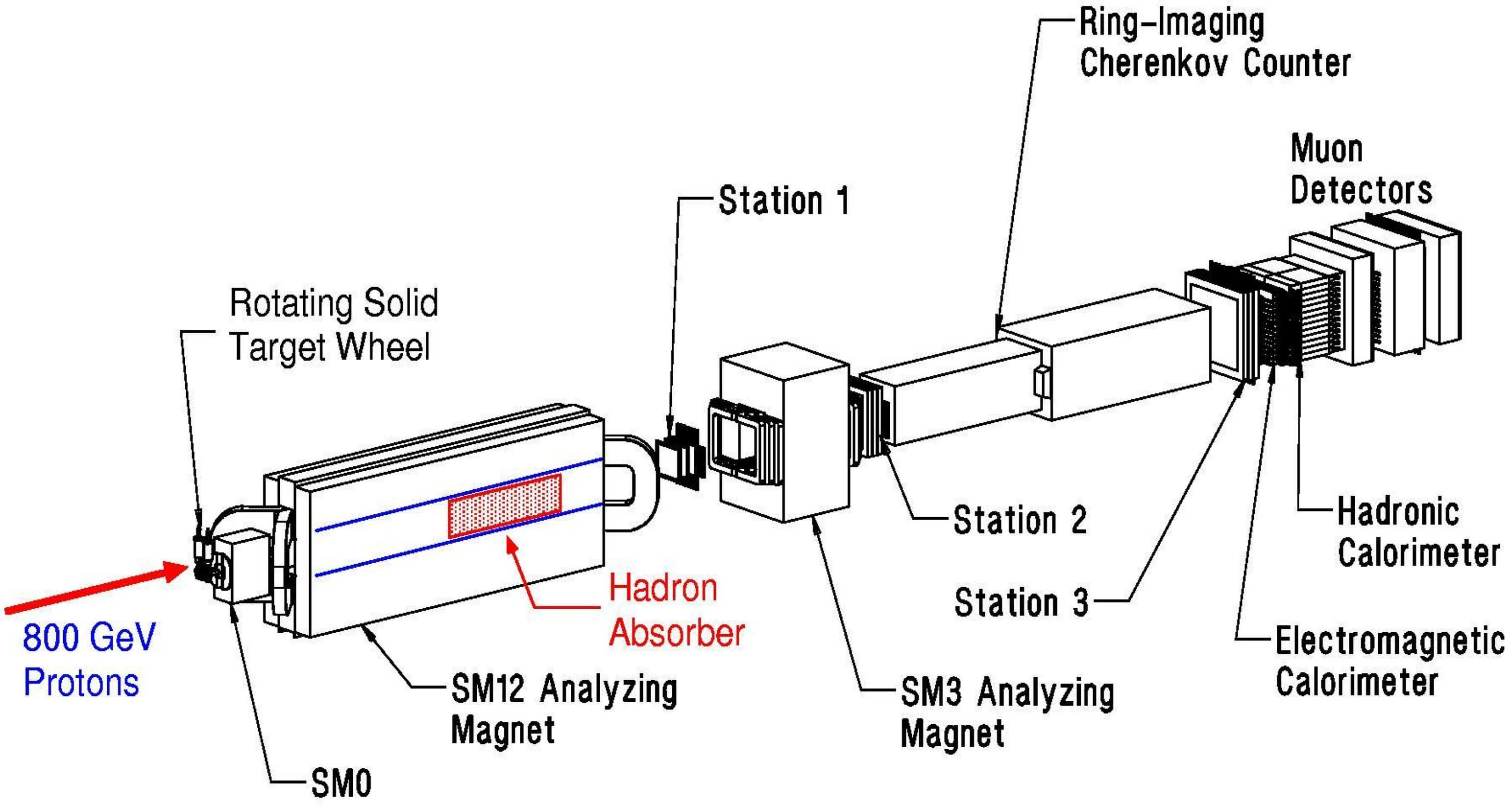
Soft collisions, on the other hand, are expected to scale as N_{part}.

NA38/NA50



Luminosity monitor
EmCAL, ZDC, Si-strip multiplicity detector for centrality determination
Toroidal analyzing magnet
0m
8m
12m
16m
mwpc's
mwpc's
iron wall
beam plug
zdc
absorber
muon
muon
beam hodoscope
active target
multiplicity
e-m calo
absorber
Lots of absorber material
NA50
P1
R2
magnet
trigger hodoscopes
R3
R4 P2
Segmented active target
MWPCs, hodoscopes for tracking/triggering

E772/E866

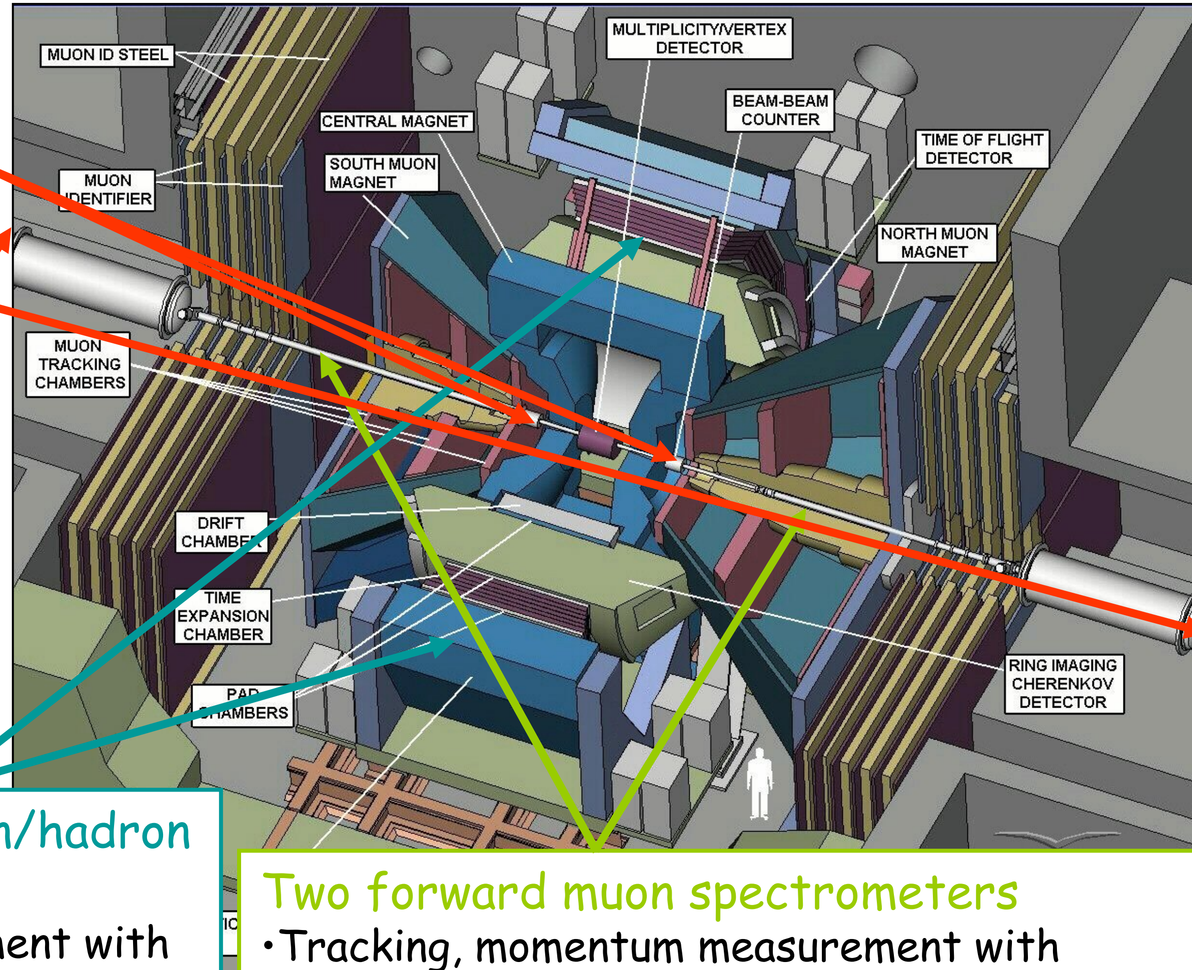


Ring-Imaging
Cherenkov Counter
Muon
Detectors
Station 1
Rotating Solid
Target Wheel
Station 2
Hadronic
Calorimeter
Hadron
Absorber
Station 3
800 GeV
Protons
Electromagnetic
Calorimeter
SM12 Analyzing
Magnet
SM3 Analyzing
Magnet
SM0

PHENIX

Two sets of forward-rapidity detectors for event characterization

- Beam-beam counters measure particle production in $3.0<|\eta|<3.9$. Luminosity monitor + vertex determination.
- Zero-degree calorimeters measure forward-going neutrons.
- Correlation gives centrality



Two central electron/photon/hadron spectrometers:

- Tracking, momentum measurement with drift chamber, pixel pad chambers
- e ID with E/p ratio in EmCAL + good ring in RICH counter.

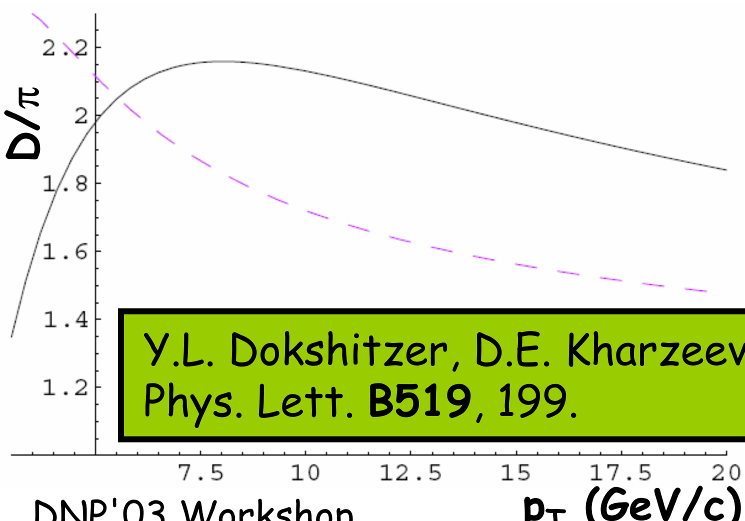
Two forward muon spectrometers

- Tracking, momentum measurement with cathode strip chambers
- μ ID with penetration depth / momentum match

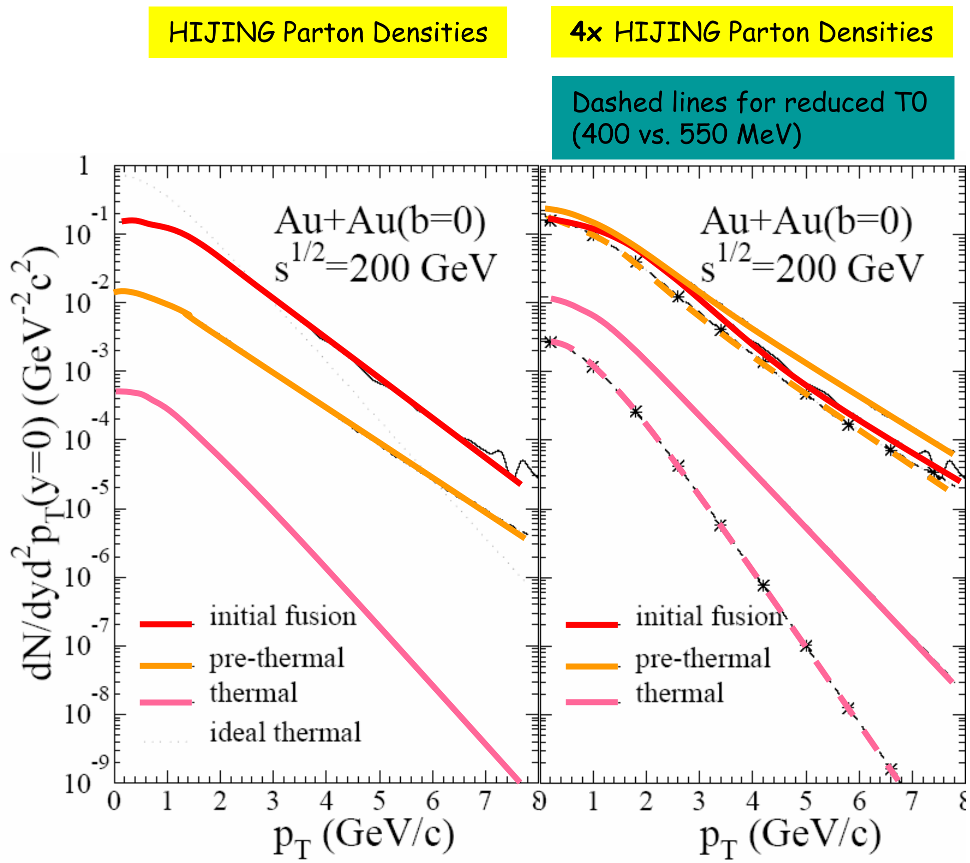
- Open Charm Production

Charming Aspects of Heavy Flavor Production

- Production mainly via *gg* fusion in earliest stage of collision.
  - Sensitive to initial gluon density.
- Possible additional thermal production at very high temperature.
  - Sensitive to initial temperature.
- Energy loss by gluon radiation? → softening of D(B)-meson spectra?
  - Sensitive to state of nuclear medium.



Y.L. Dokshitzer, D.E. Kharzeev
Phys. Lett. **B519**, 199.



P. Levai, B. Müller, X. N. Wang
Phys. Rev. **C51**, 3326.

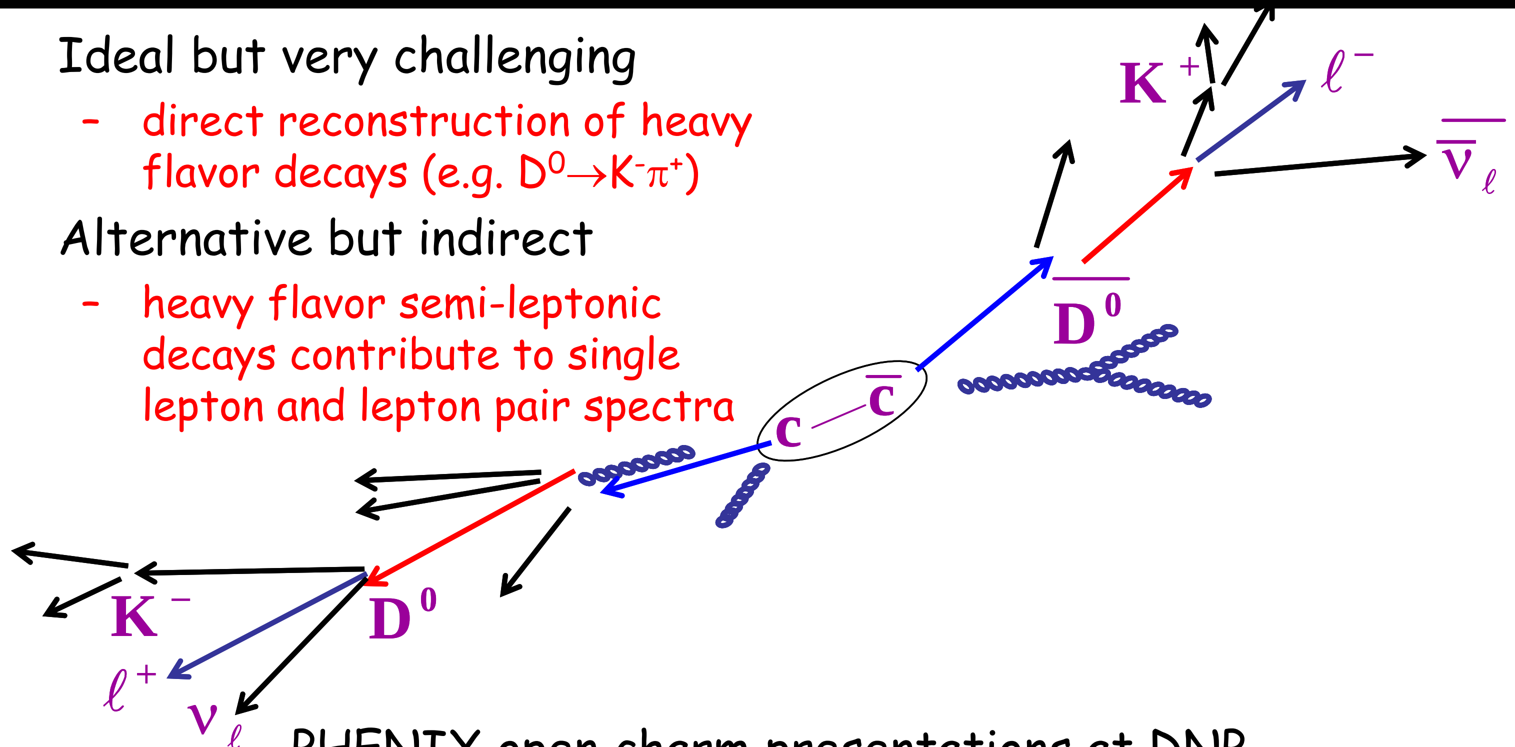
Understanding the J/Ψ Baseline

- Drell-Yan (DY) was an appealing J/Ψ normalization process.
  - Identical detector acceptance.
  - Any deviation expected to signal QGP formation.
- J/Ψ and Open Charm (OC) produced through same initial processes (unlike DY).

  $\Rightarrow$ Normalization to OC reduces sensitivity to medium-effects unrelated to screening:
  - Shadowing
  - Initial state energy loss
  - Thermal charm enhancement

Charm Measurements

- Ideal but very challenging
  - direct reconstruction of heavy flavor decays (e.g. $D^0 \rightarrow K^- \pi^+$)
- Alternative but indirect
  - heavy flavor semi-leptonic decays contribute to single lepton and lepton pair spectra



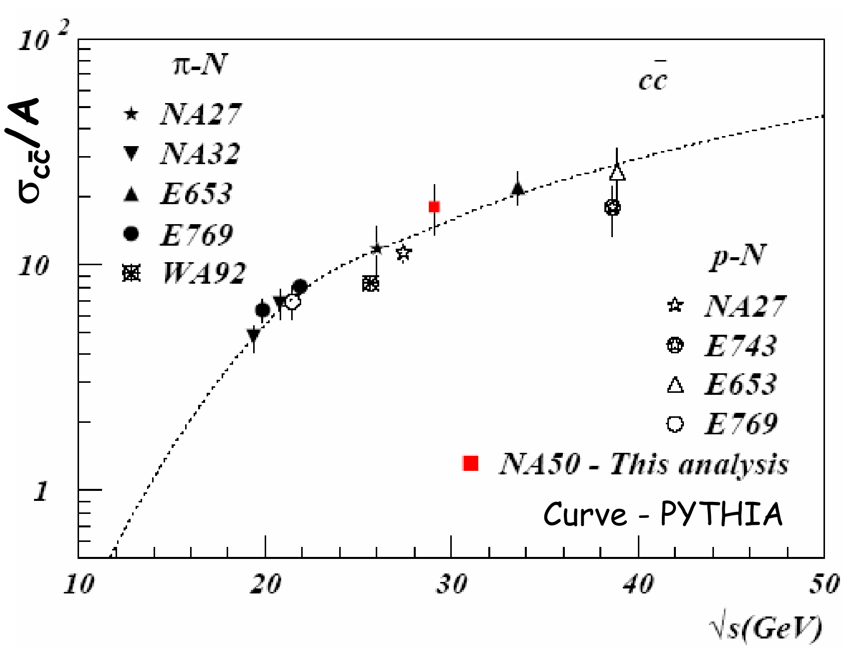
PHENIX open charm presentations at DNP

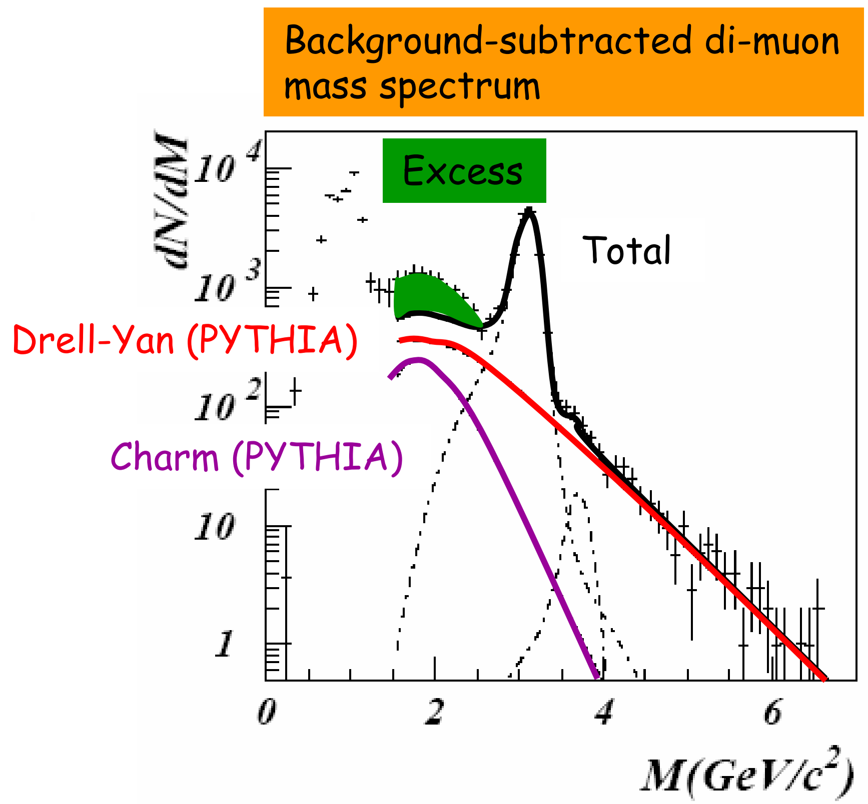
Sergey Butsyk (GC.010): Single Electron Production in pp Collisions (cocktail technique)
Xinhua Li (GC.011): Single Electron Production in pp Collisions (eγ coincidence technique)
Andrew Glenn (DG.011): Single Muon Production in AuAu Collisions
Ming Liu (CC.004): Single Muon Production in dAu Collisions

NA50 - Charm Enhancement?

- NA50 measures charm by looking for di-muon pairs in excess of expectation for $\phi < M_{\mu\mu} < J/\Psi$.
- For pA collisions they find agreement with PYTHIA scaled by N_{binary}.
- For SU and PbPb collisions an excess is observed.

M.C. Abreu *et al.*,
Eur. Phys. J. **C14**, 443.

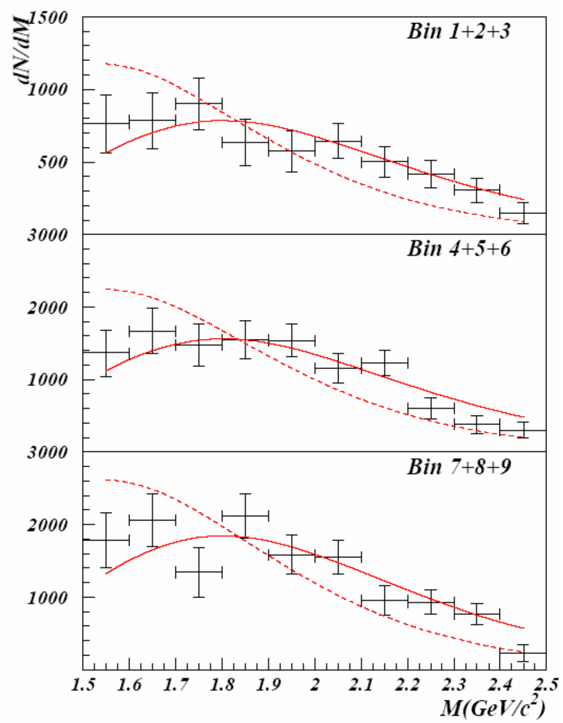




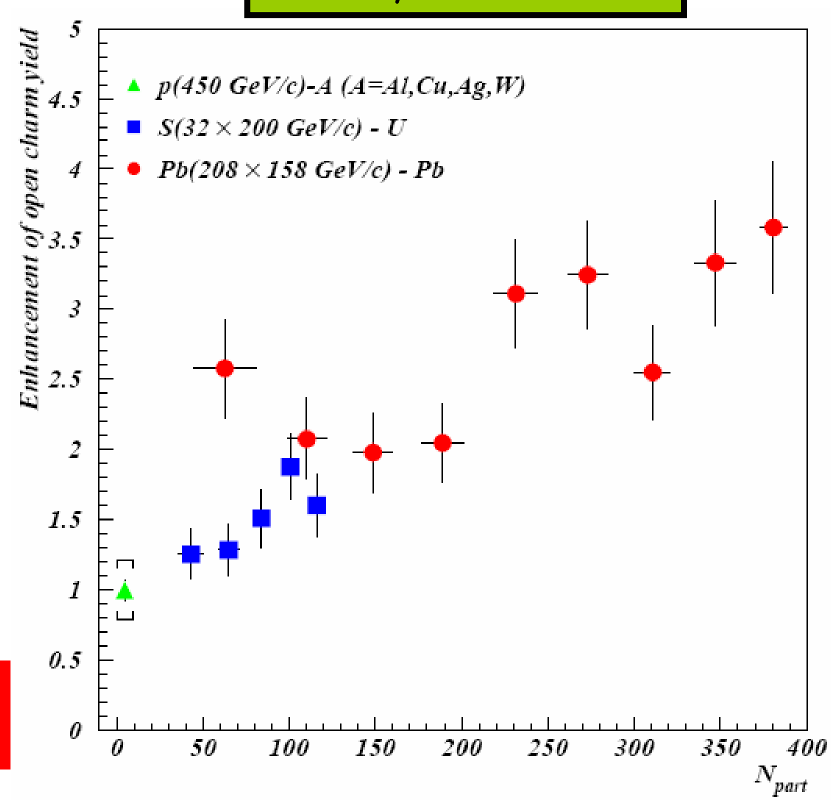
NA50 - Charm Enhancement? II

- The excess is shown for different PbPb centrality bins with best-fit curves with shapes corresponding to the charm spectrum and the combinatorial background spectrum.
- If all the excess is attributed to additional charm production this excess increases linearly with N_{part}.

M.C. Abreu *et al.*,
Eur. Phys. J. **C14**, 443.



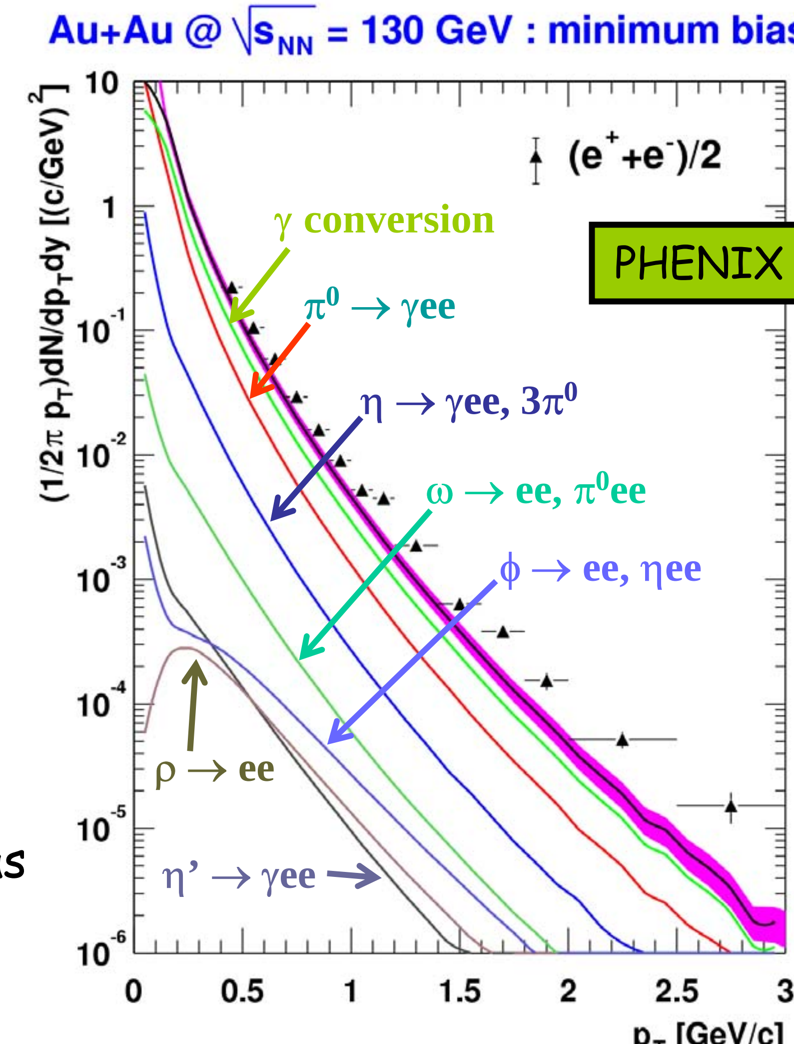
Decreasing centrality



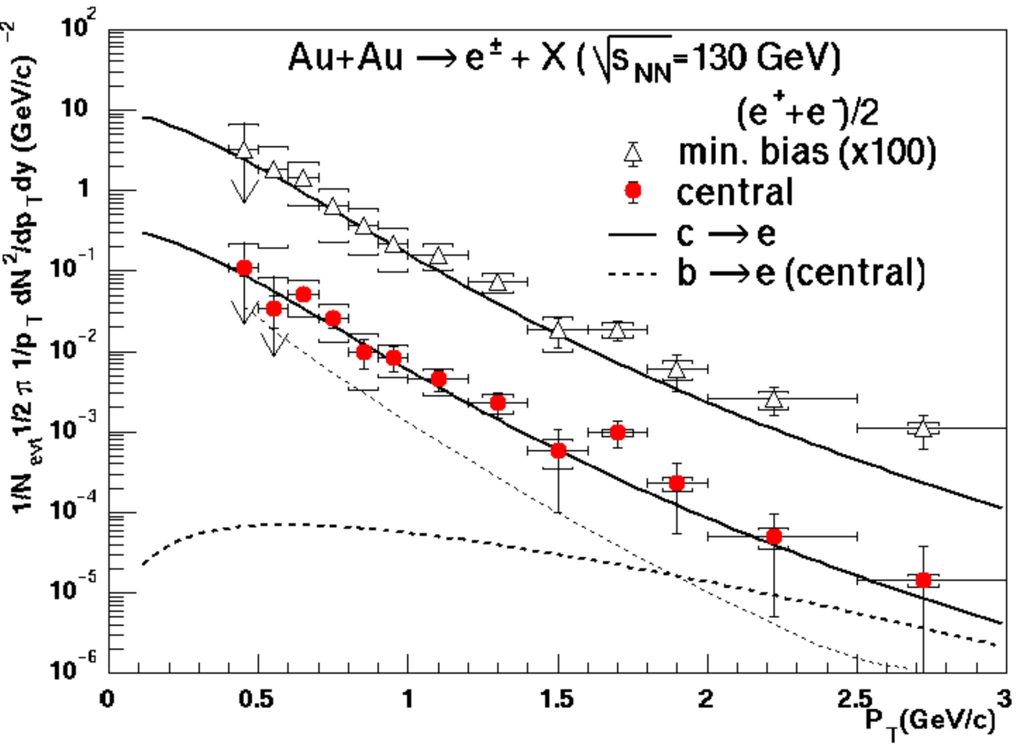
Solid line – charm shape
Dotted line – combinatorial background shape

PHENIX Charm Measurements: Cocktail Method

- Light hadron cocktail input:
  - π^0 (dominant source {~80 %} at low p_T)
    - p_T spectra from PHENIX π^0, $\pi^\pm$ data
  - Other hadrons
    - m_T scaling: $p_t \rightarrow \sqrt{p_t^2 + m_h^2 - m_\pi^2}$
    - Relative normalization to π at high p_T:
      - $\eta/\pi = 0.55$, $\eta'/\pi = 0.25$, $\rho/\pi = \omega/\pi = 1.0$ (from SPS, FNAL and SPS data)
      - $\phi/\pi = 0.4$ (agrees with STAR's inclusive $\phi/h^- = 0.02$)
  - Photon conversions
    - Material in PHENIX acceptance
    - p dependent conversion probability
  - Main systematic errors (band)
    - Pion spectra
    - Ratio η/π^0
    - Ratio conversion/Dalitz (material)
- Excess above cocktail, increasing with p_T, as expected from charm decays!



$\sqrt{s_{NN}}$ = 130 GeV AuAu Single Electron Data



Phys. Rev. Lett. **88**, 192303

Compare single electron excess above background with the expected charm contribution by scaling PYTHIA spectra by N_{binary}:

$$\frac{dN^{AuAu}_{c\to e}}{dp_3} \stackrel{?}{=} N_{binary} \frac{dN^{PYTHIA}_{c\to e}}{dp_3}$$

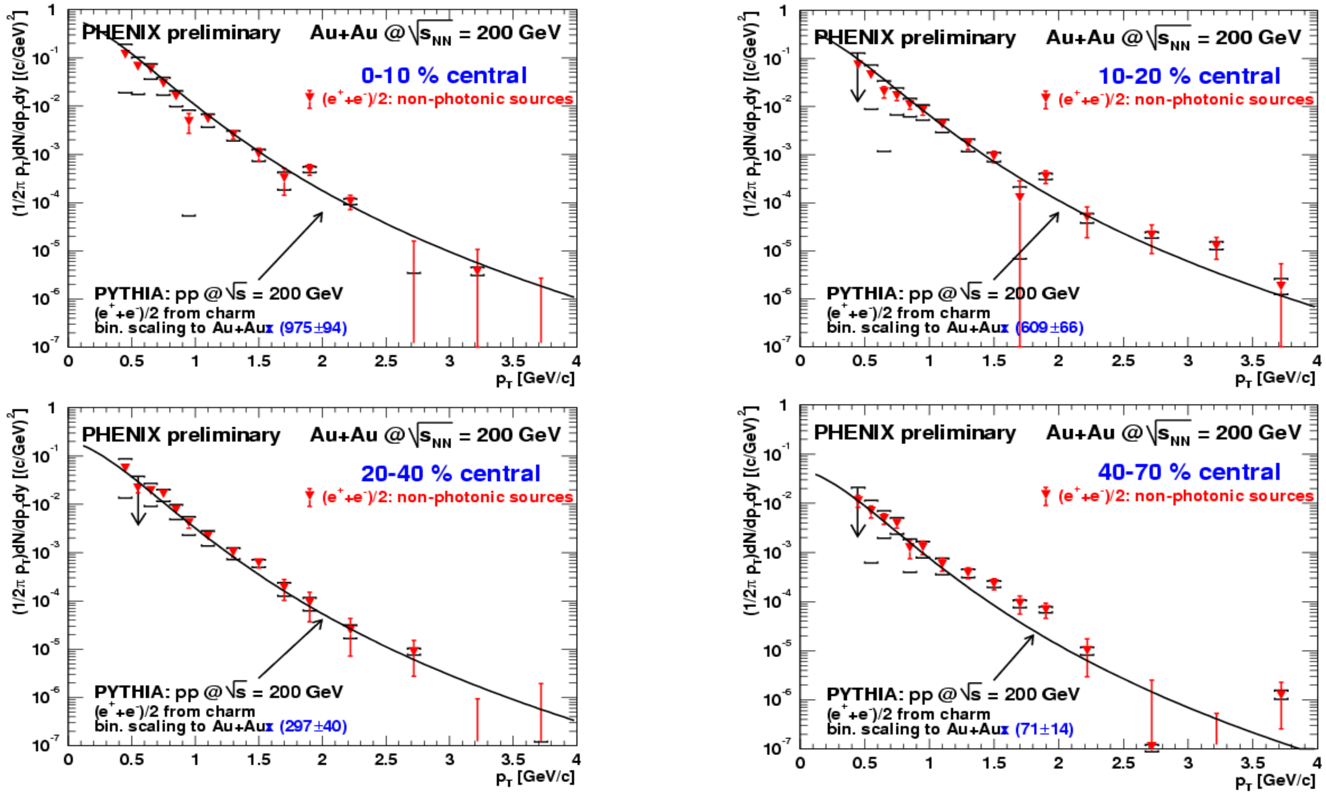
Reasonable agreement over entire spectrum.

To quantify the entire excess is attributed to semi-leptonic charm decay, the excess in different centrality bins is integrated and scaled by N_{binary} to obtain:

$$\sigma_{cc}^{0\text{-}10\%} = 380 \pm 60\ (\text{stat}) \pm 200\ (\text{sys})\ \mu\text{b},$$

$$\sigma_{cc}^{0\text{-}92\%} = 420 \pm 33\ (\text{stat}) \pm 250\ (\text{sys})\ \mu\text{b}$$

Centrality Dependence

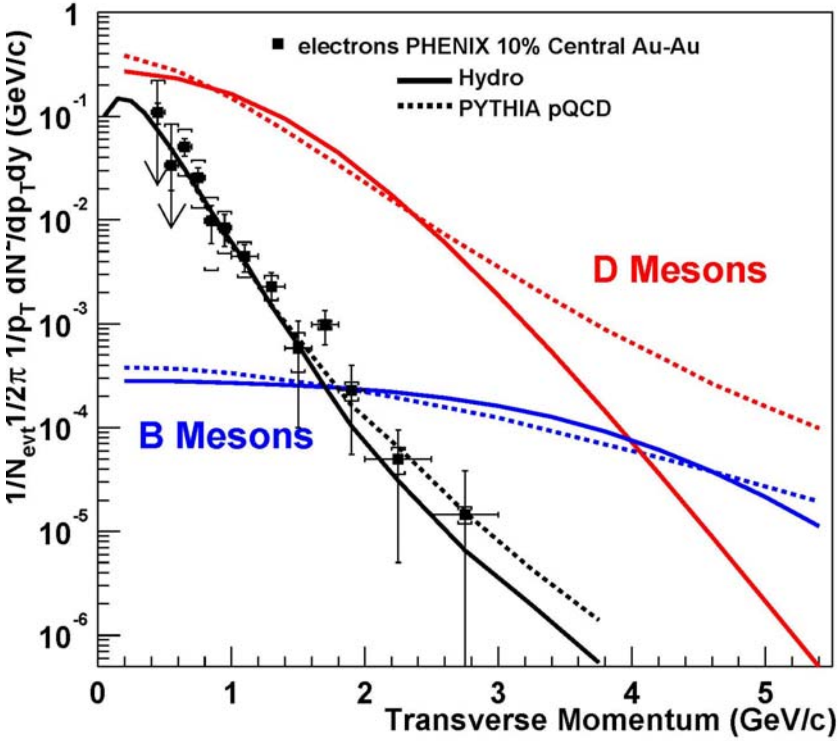


- PHENIX data consistent with the PYTHIA charm spectrum scaled by number of binary collisions in all centrality bins!

- Dominant systematic errors from:
    - Using PYTHIA charm spectrum – pp data is being analyzed
    - Relying on Monte Carlo for material calculation - special runs w/ γ-converter being analyzed

Does Charm Flow at RHIC?

- Previous slides showed that PHENIX open charm data are consistent with PYTHIA scaled by N_{binary}
  - No interaction with the produced medium.
- It has also been shown that these data are also consistent with the completely opposite dynamical picture
  - Zero mean-free-path hydrodynamics



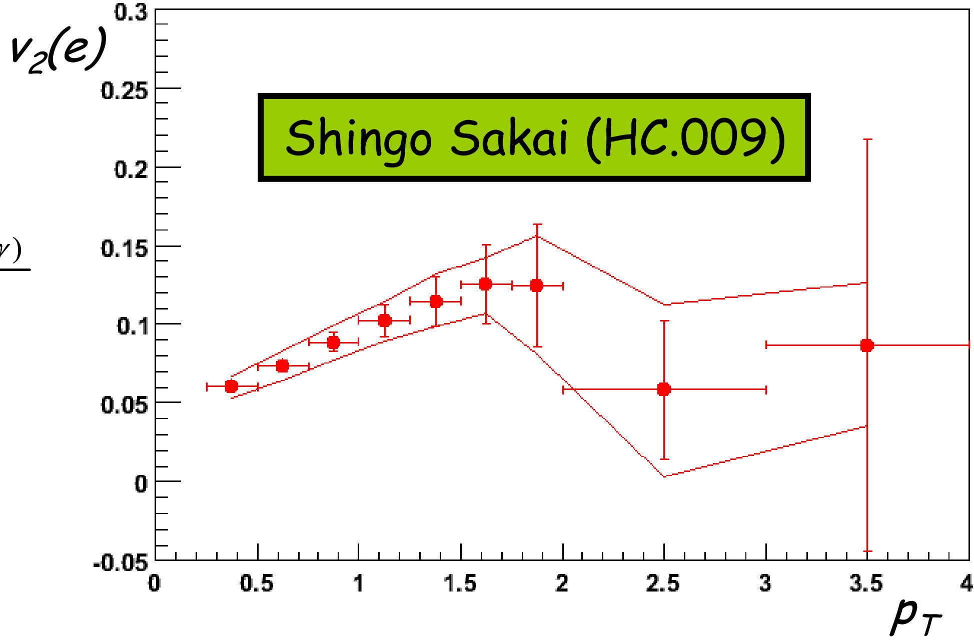
Batsouli *et al.*, Phys. Lett. **B557**, 26

Electrons do…

- What is needed to estimate charmed electron flow, $v_2(c)$?

$$\frac{dN^e}{d\phi} = \frac{dN^\gamma}{d\phi} + \frac{dN^c}{d\phi} \Rightarrow v_{2(c)} = \frac{v_{2(e)} - r v_{2(\gamma)}}{1-r}$$

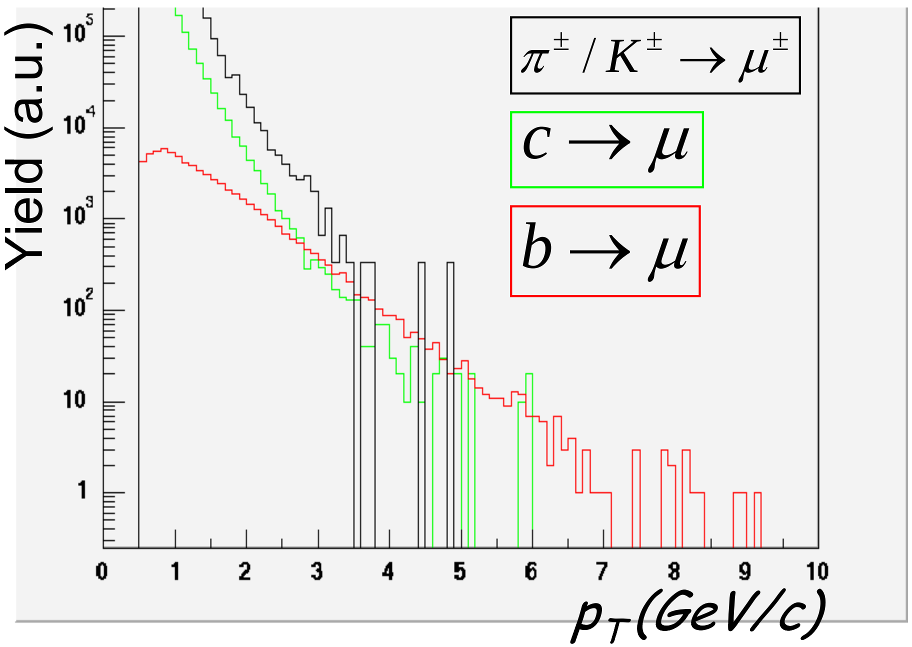
  - Charm yield relative to inclusive electron yield at $\sqrt{s_{NN}}$ = 200 GeV ($r = N_\gamma / N_e$)
  - $v_2(\gamma)$ – flow of electrons originating photonic source
  - Study $v_2^{D\to eX}$ (due to large Q value)



Charm in PHENIX Muon Arms

- Single muon production provides information on charm production in a manner similar to the central-arm single-electron production.
- Primary source of background is light hadronic (π, K) decay.
- In addition (not shown) hadrons that punch through a part (or all) of the MuID absorber and are subsequently mis-identified as muons are a significant source of background.
- Somewhat trickier than central arm measurement because main sources of background are not directly measured.

Single muon p_T distribution for PYTHIA pp collisions @ √s=200 GeV



- J/Ψ production

PHENIX J/Ψ Results

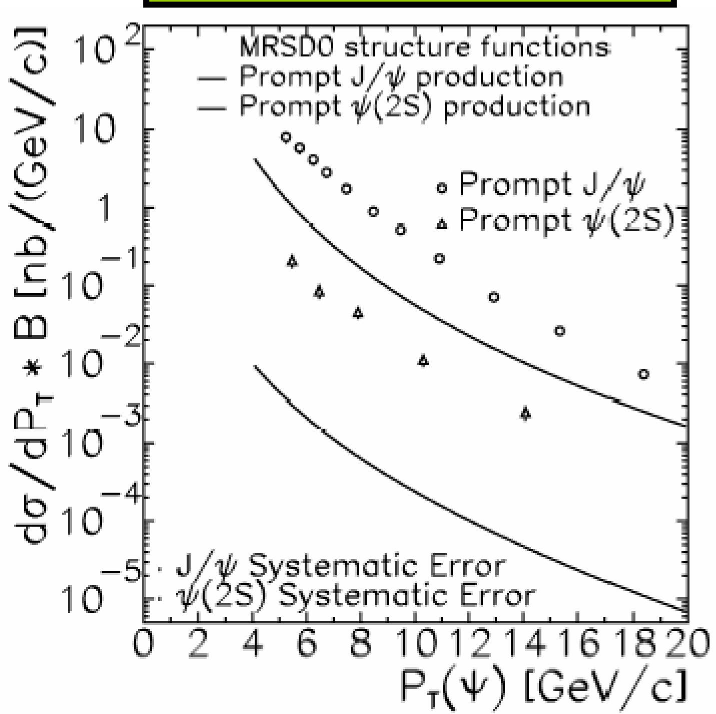
PHENIX J/Ψ presentations at DNP

Sasha Lebedev	(DG.008)	J/Ψ and χ_c in dAu Collisions
Xiaorong Wang	(DG.013)	J/Ψ Polarization in pp and dAu Collisions
Chun Zhang	(DG.007)	J/Ψ x_F *and* p_T Dependence in dAu Collisions
Sean Kelly	(DG.006)	J/$\Psi \rightarrow \mu\mu$ Measurements in PHENIX
Jane Burward-Hoy	(DG.004)	J/Ψ Centrality Dependence in dAu Collisions

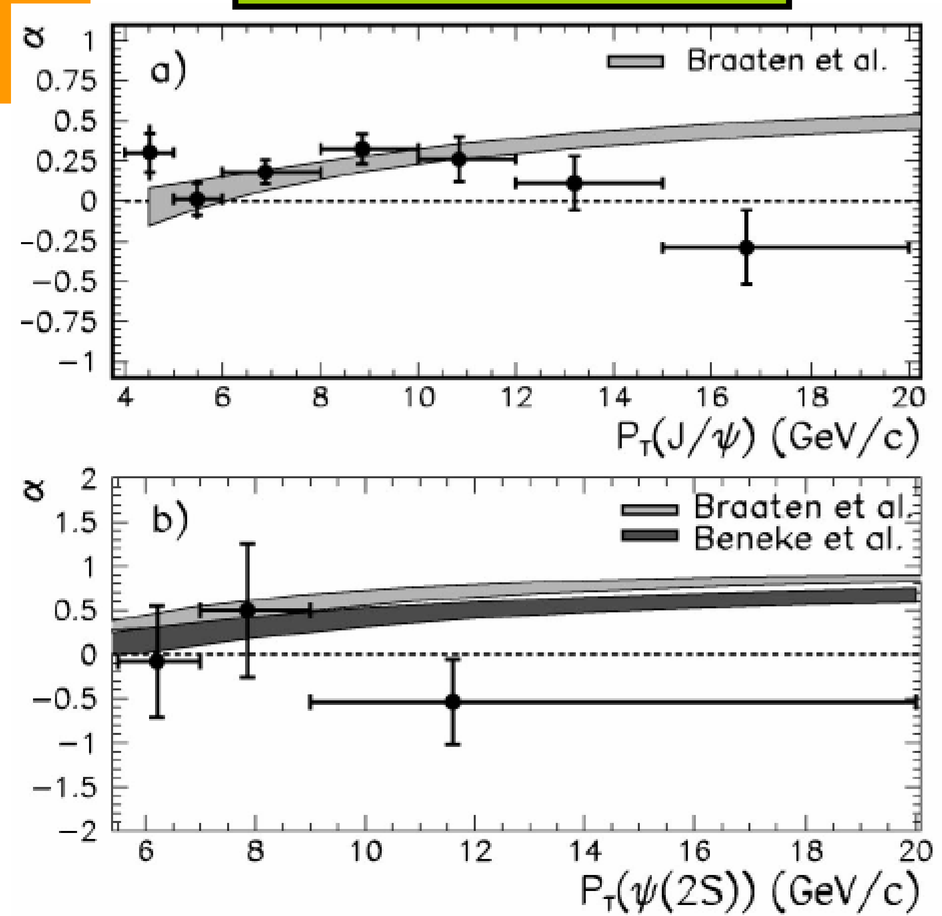
CDF pp ($\sqrt{s}$ = 1.8 TeV) results

- Color singlet model underpredicts high-p_T yield.
- Color octet model overpredicts transverse polarization at high p_T.

F. Abe *et al.*,
Phys. Rev. Lett. **79**, 572.

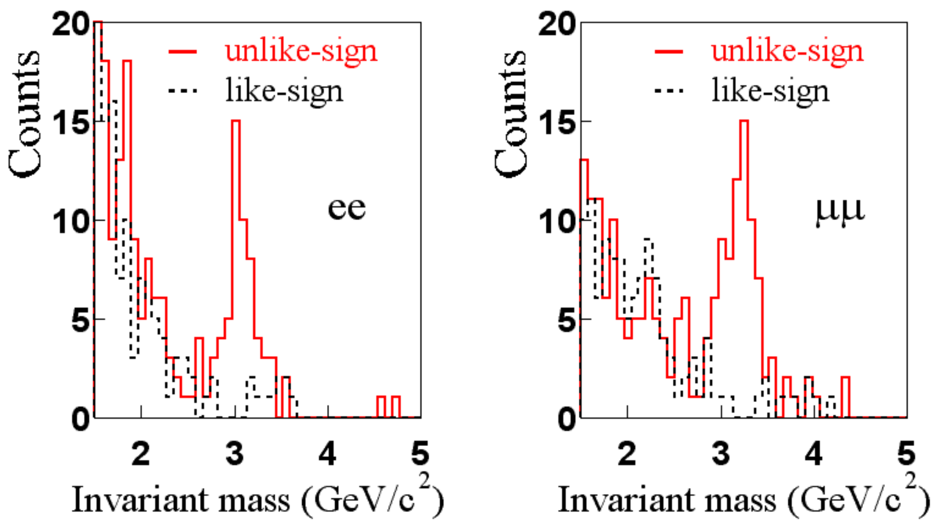


T. Affolder *et al.*,
Phys. Rev. Lett. **85**, 2886.

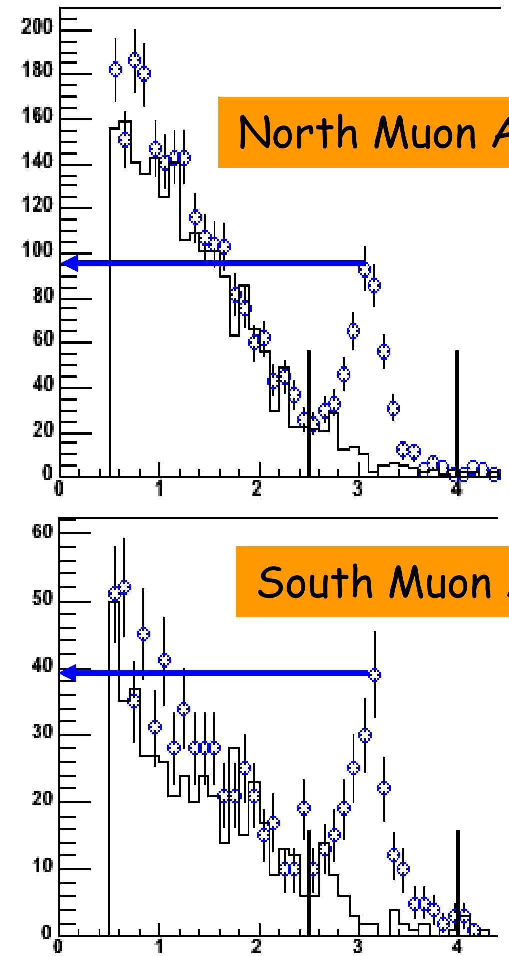


PHENIX pp ($\sqrt{s}$ = 200 GeV) Results

Run-2: hep-ex/307019



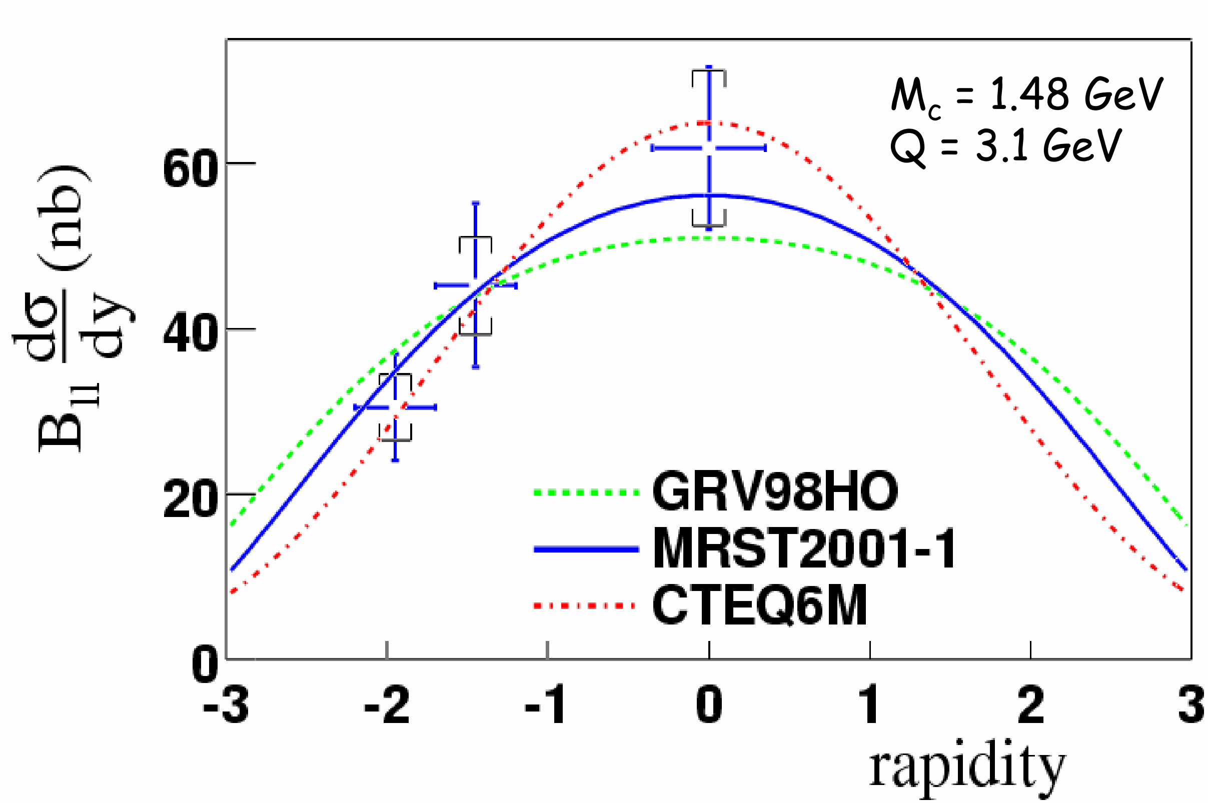
Run-3 Preview



- J/Ψ seen in both central and muon arms.
- Resolutions in agreement with expectations.

Rapidity Distribution

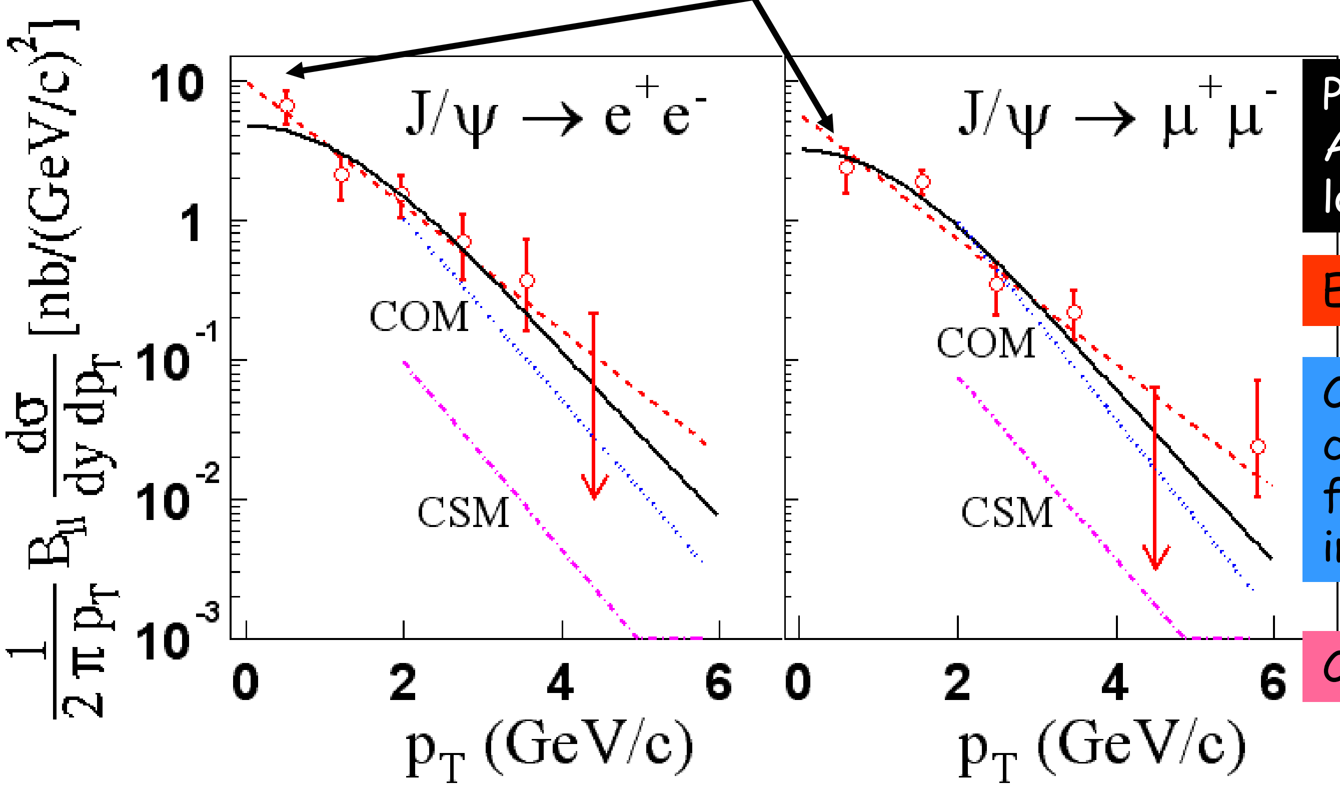
Data: hep-ex/307019
Curves: H. Sato



- Integrated cross-section : 3.98 ± 0.62 (stat) ± 0.56 (sys) ± 0.41(abs) μb
- Estimated B decay feed down contribution : < 4% (@ 200 GeV)
- Some sensitivity to PDFs with additional statistics

p_T Distribution

Note: sensitivity down to $p_T = 0$.



Phenomenological fit A(1+PT/B)2)-6 taken from lower-energy analyses

Exponential fit

Color Octet Model calculation doesn't include fragmentation contributions important for $p_T > 5$ GeV/c

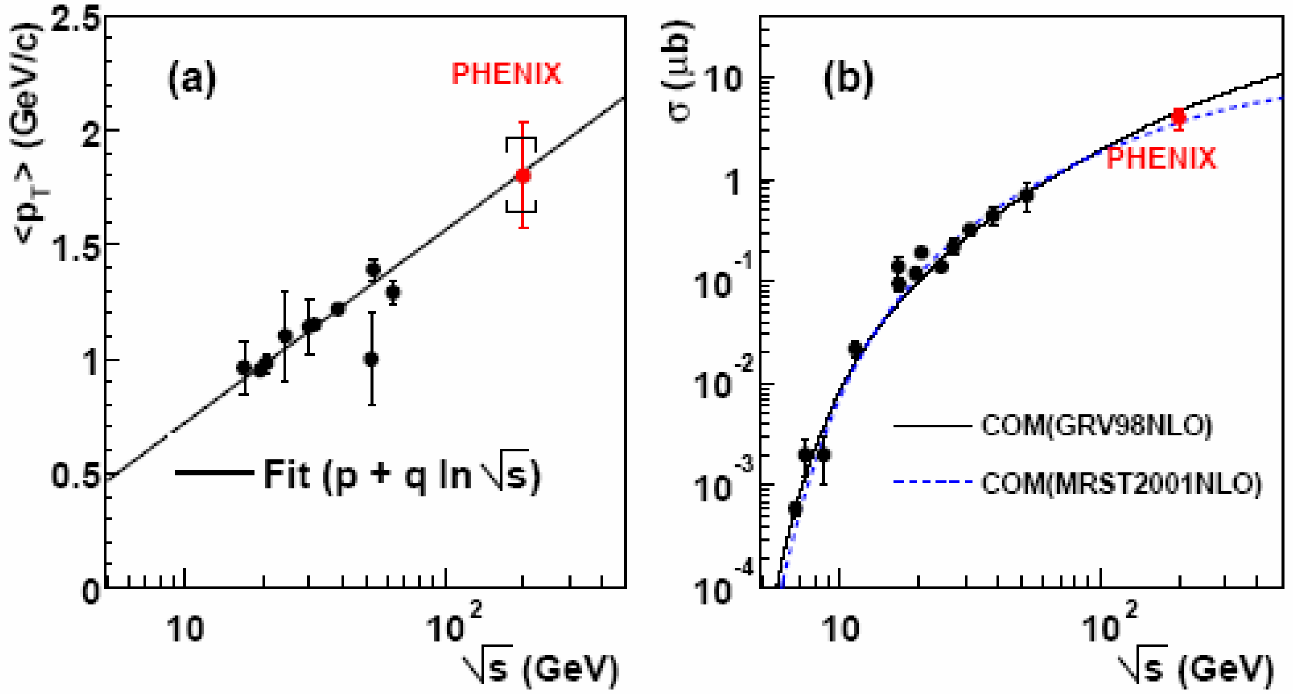
Color Singlet Model

Combination of electron and muon results gives:
$\langle p_T \rangle$ = 1.80 ± 0.23 (stat) ± 0.16 (sys) GeV/c

hep-ex/307019

Color Singlet Model

√s Scaling



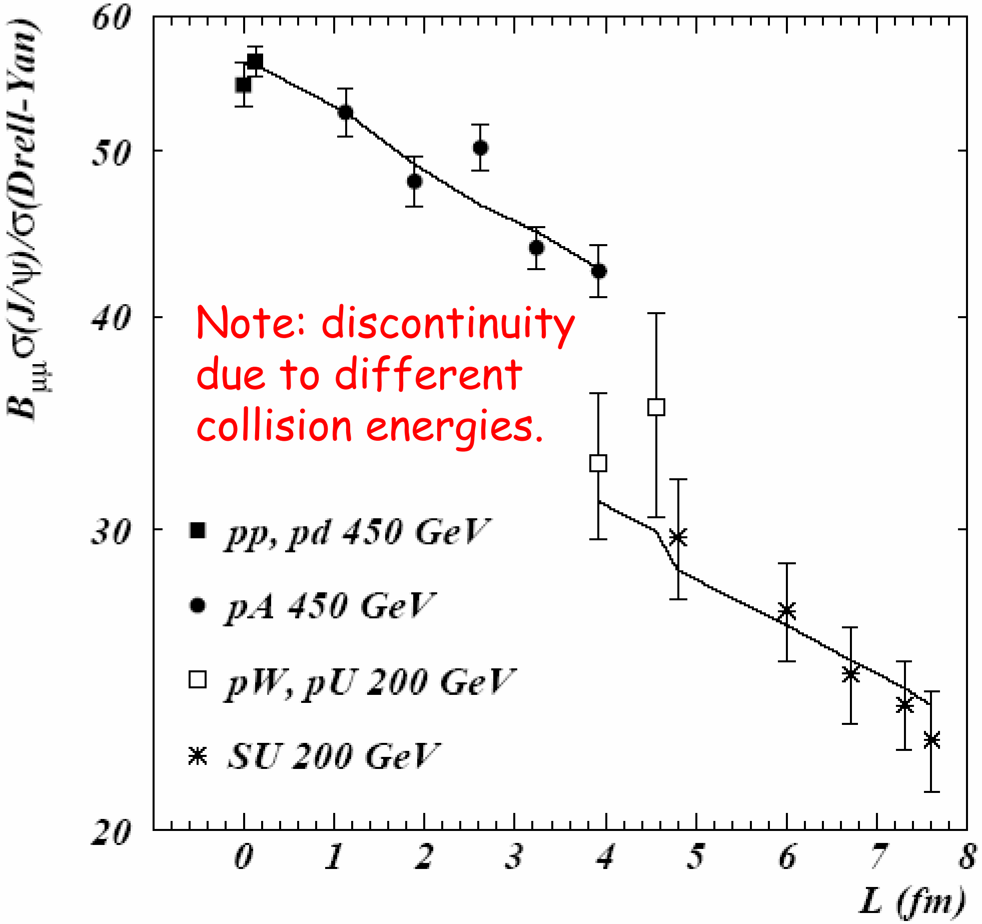
- Phenomenological fit for average p_T; p = 0.531, q= 0.188
- Cross-section well described by Color Evaporation Model.

NA38/NA50 pA Results

- Calculate ratio of J/Ψ production to Drell-Yan.
  - Many systematic errors cancel in the ratio.
- For each collision type, calculate average length of nuclear material, L, that will pass over the J/Ψ.
- Data would be flat if N_{binary} scaling was true.
- Glauber model fit to all data yields:

$$\sigma_{abs}^{J/\Psi} = 4.1 \pm 0.6 mb$$

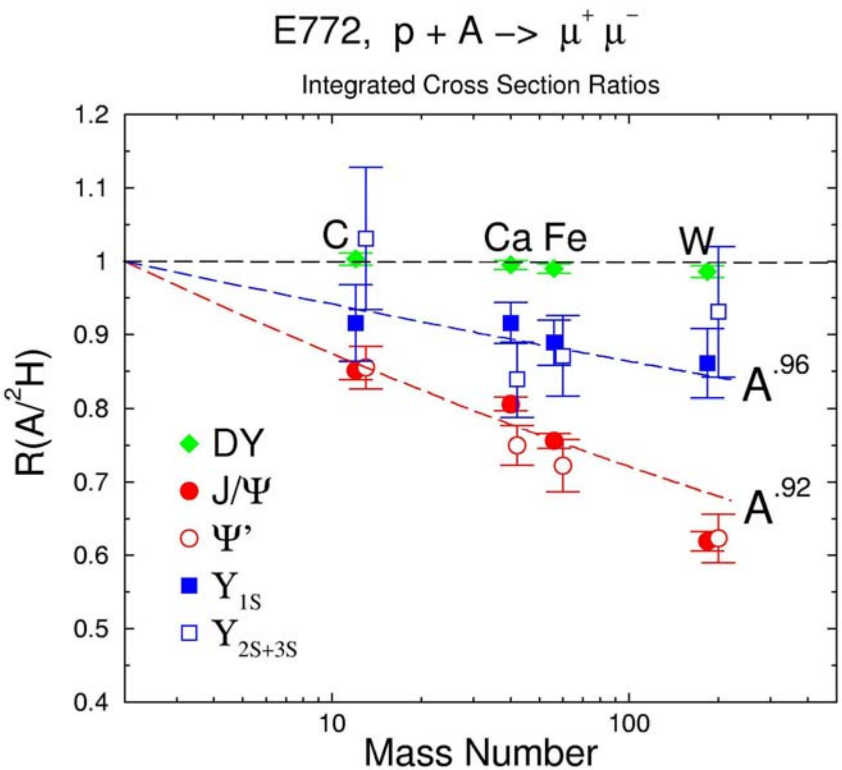
B. Alessandro *et al.*, Phys. Lett. **B553**, 167.

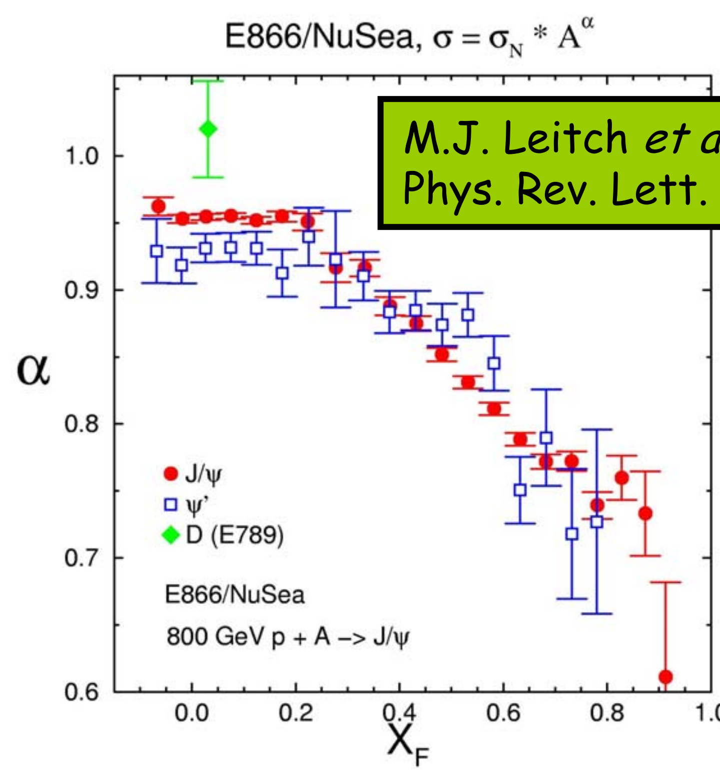


E772/E866 Results

Mass scaling:
- Power-law scaling observed in pA Collisions: $\sigma_{pA} = \sigma_{pp} A^{\alpha}$.
- $\alpha_{\Upsilon} > \alpha_{\Psi}$
- DY has $\alpha = 1$

X_F scaling:
- J/Ψ and Ψ' similar at large x_F where they both correspond to a cc traversing the nucleus
- Ψ' absorbed more strongly than J/Ψ near mid-rapidity ($x_F \sim 0$) where the resonances are beginning to be hadronized in nucleus
- Open charm not suppressed (at $x_F \sim 0$)

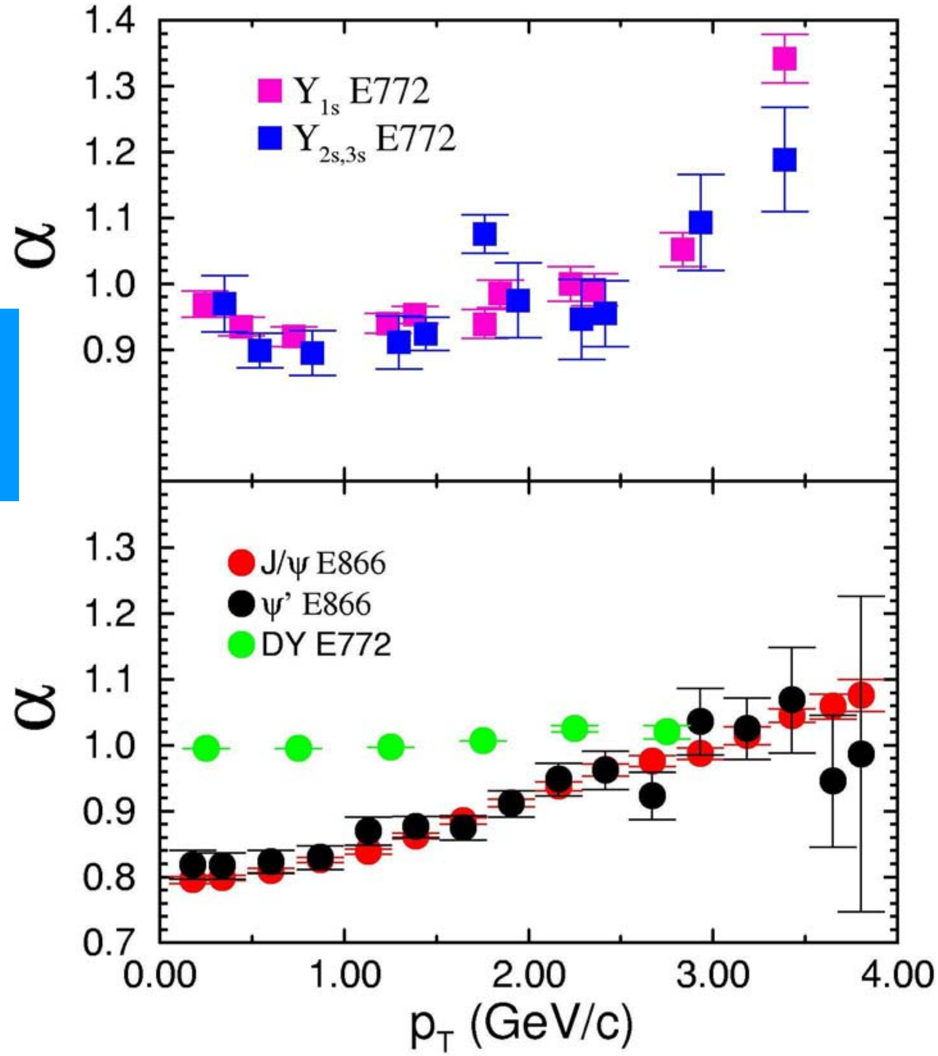




M.J. Leitch *et al.*, Phys. Rev. Lett. **84**, 3256.

DM Alde *et al.*, Phys. Rev. Lett. **66**, 133; Phys. Rev. Lett. **66**, 2285.

E772/E866 Results, cont.



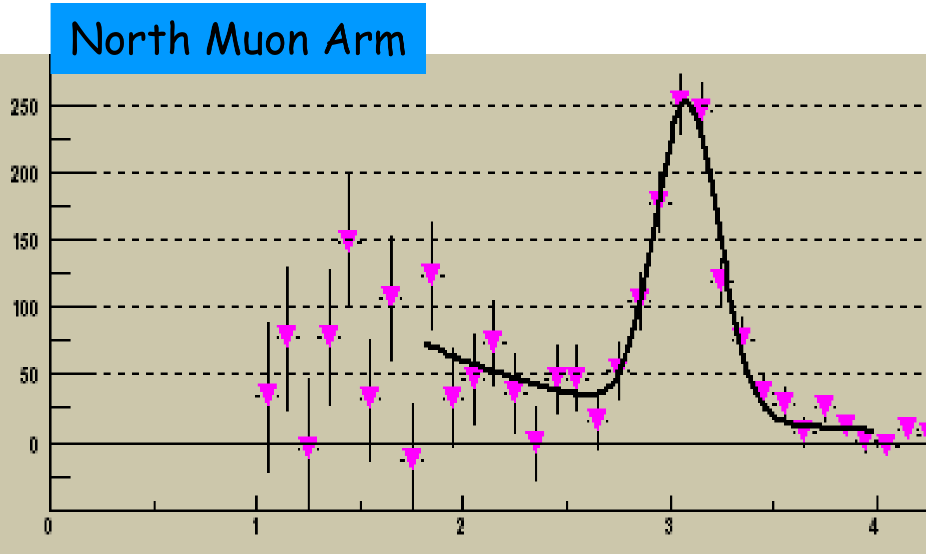
p_T scaling:

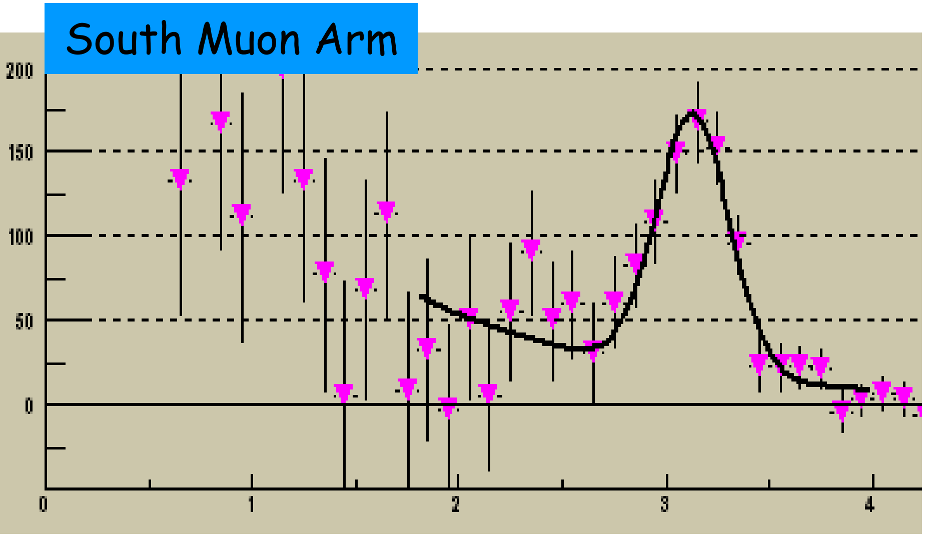
- p_T broadening is observed
- The shape of α vs. p_T is x_F independent

E772: DM Alde *et al.*, Phys. Rev. Lett. **66**, 133; Phys. Rev. Lett. **66**, 2285.

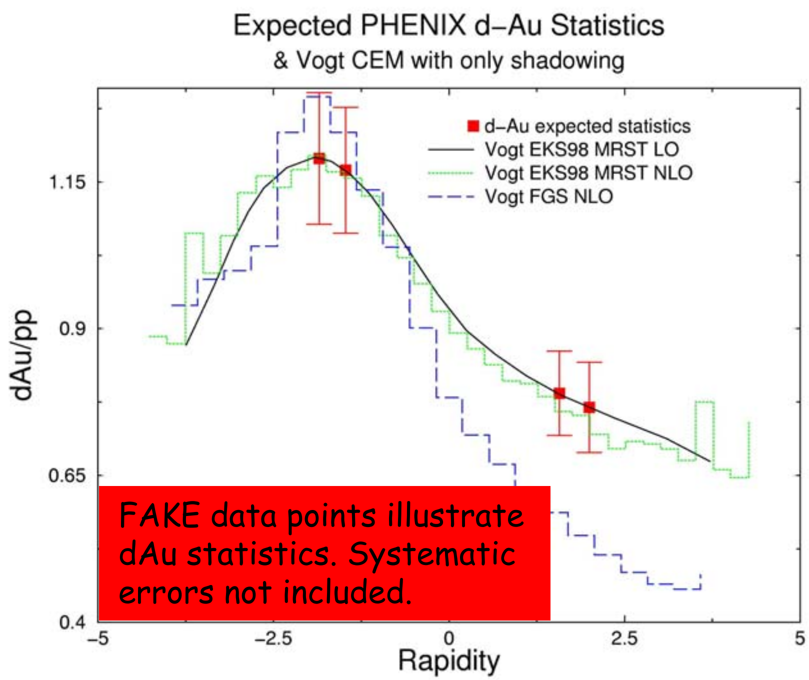
E866: M.J. Leitch *et al.*, Phys. Rev. Lett. **84**, 3256.

PHENIX dAu Preview



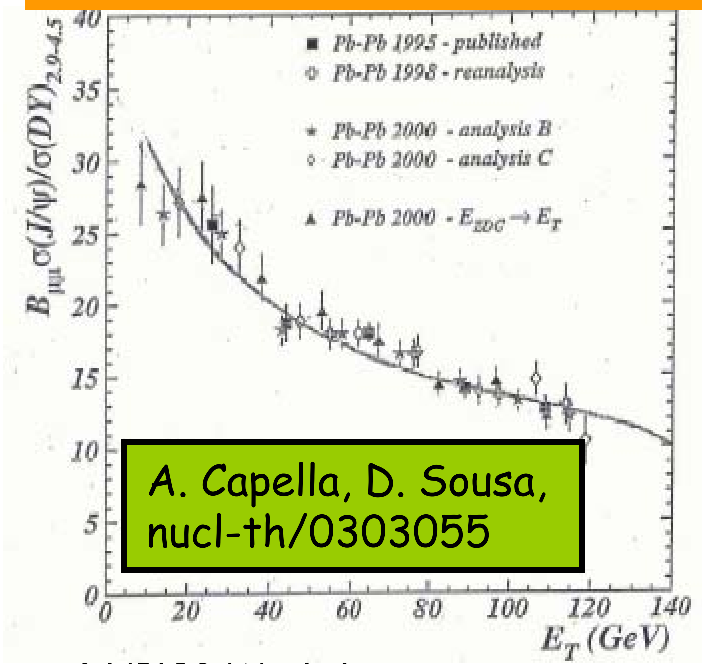


- At RHIC dA collisions are significantly easier than pA (due to *q/M* ratios).
- Note – efficiencies and acceptances not included ⇒ no interpretation possible.
- Enough data to start binning in centrality, *y*, *xF*, *pT*, etc.



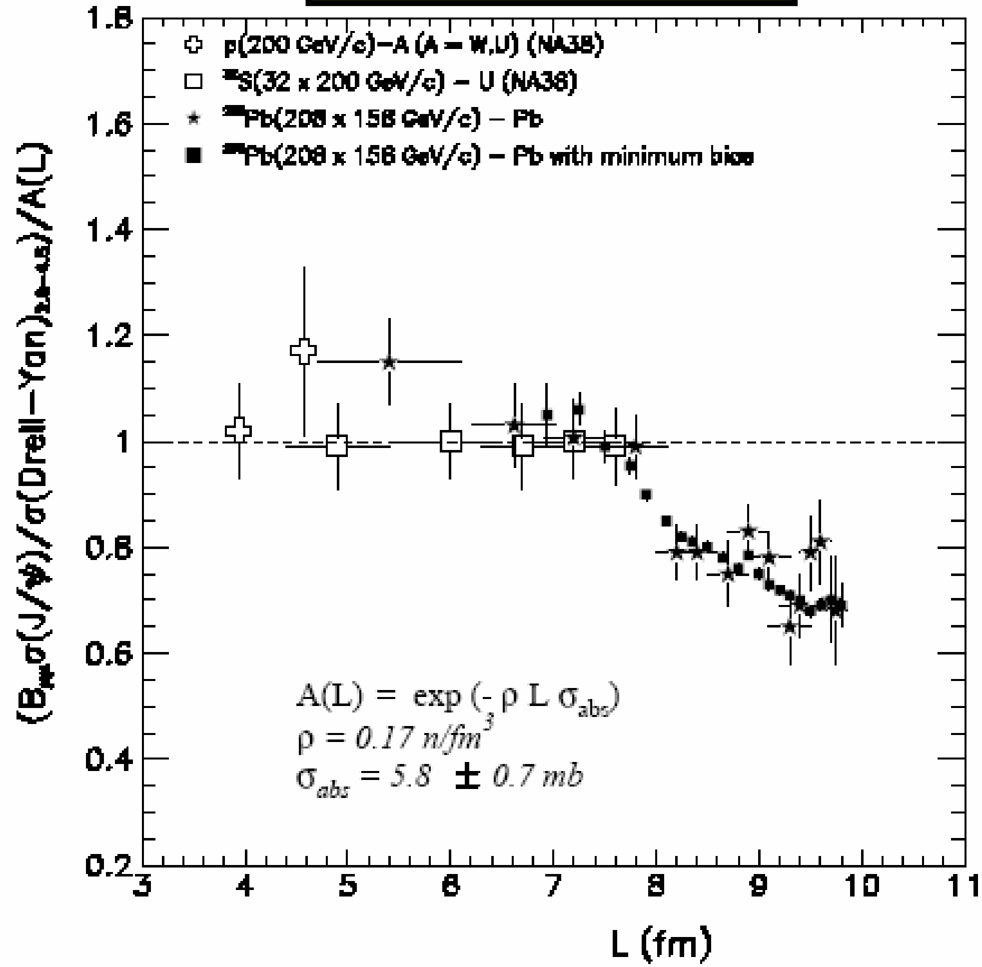
NA38/NA50 AA Results

- Absorption only in cold nuclear matter of colliding nuclei cannot explain the data.
- QGP-based models can explain the data.
- Absorption only in cold nuclear matter of colliding nuclei can also explain the data.

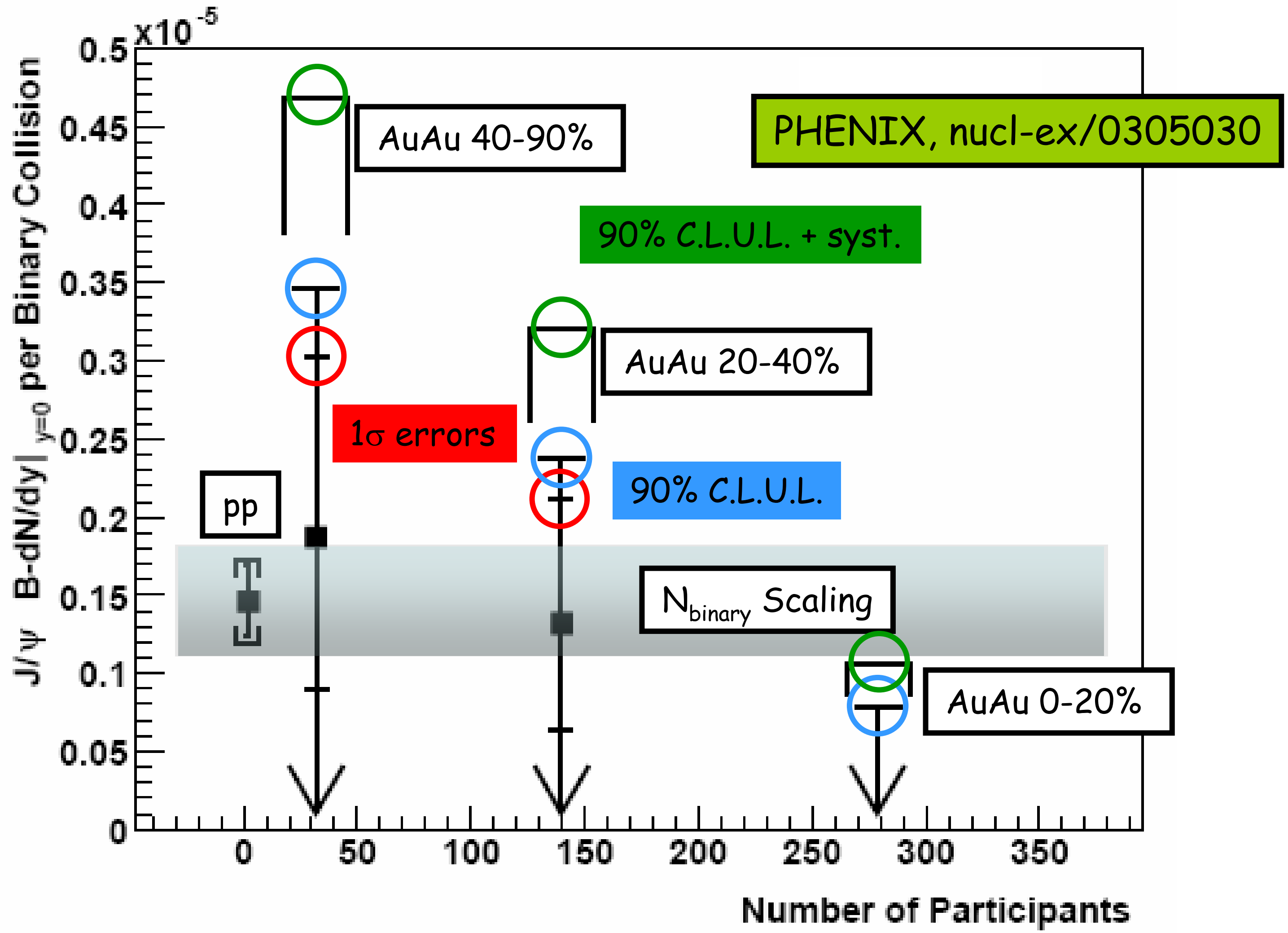


A. Capella, D. Sousa, nucl-th/0303055

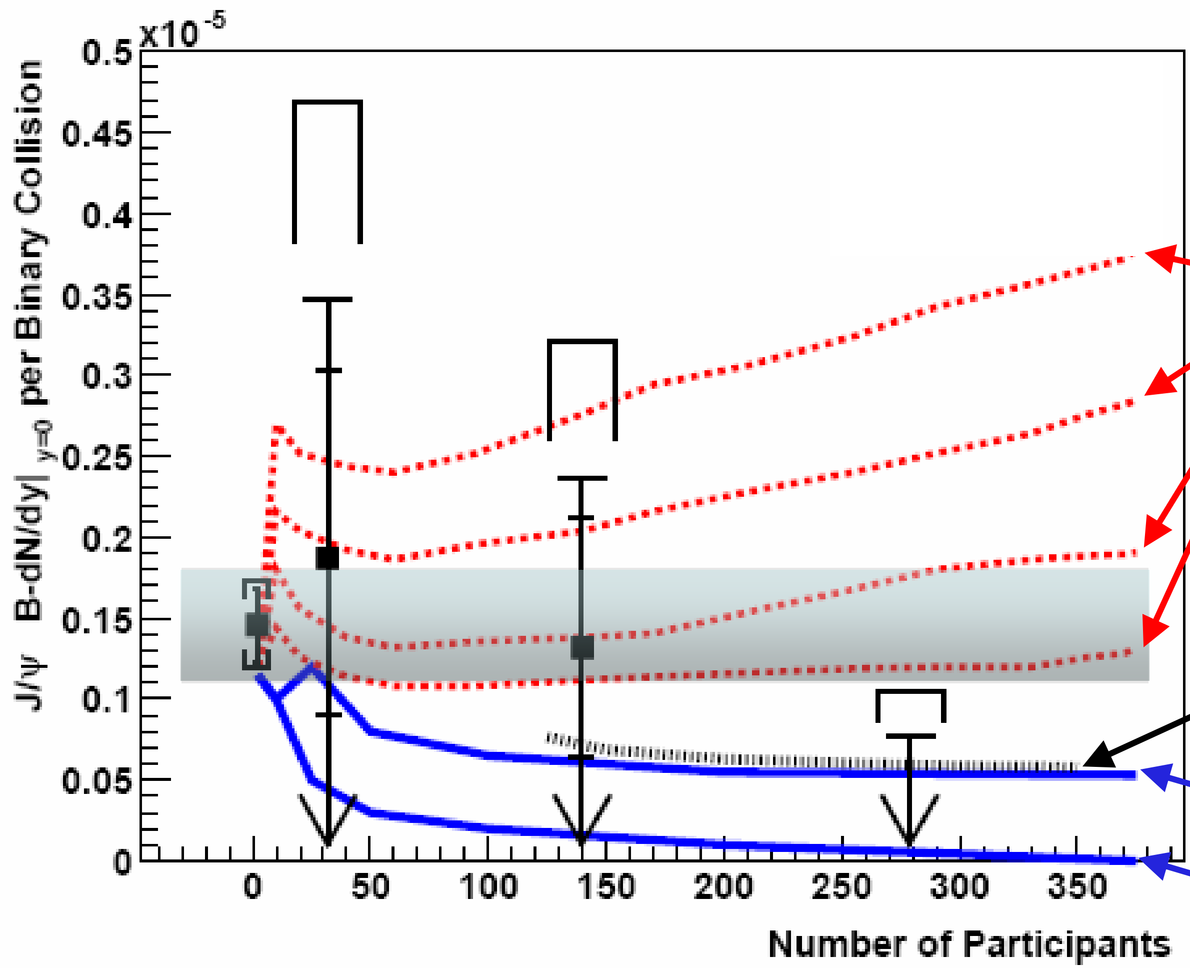
M.C. Abreu *et al.*, Phys. Lett. **B450**, 456.



PHENIX AuAu ($\sqrt{s_{NN}}$ = 200 GeV) Results



Model Comparisons



R.L. Thews, M. Schroedter, J. Rafelski, Phys. Rev. **C63**, 054905

Plasma coalescence model
T = 400 MeV, Charm Δy =
1.0
2.0
3.0
4.0

Statistical hadronization after complete screening in a QGP

A. Adronic *et al.*,
Phys. Lett. **B571**, 36-44.

Absorption (Nuclear + QGP) + final-state coalescence

Absorption (Nuclear + QGP)

L. Grandchamp, R. Rapp:
Nucl. Phys. **A709**, 415;
Phys. Lett. **B523**, 60.

No discrimination btwn models w/ suppression w.r.t N_{binary} scaling

Disfavor models w/ enhancement w.r.t N_{binary} scaling.

Where do we go from here?

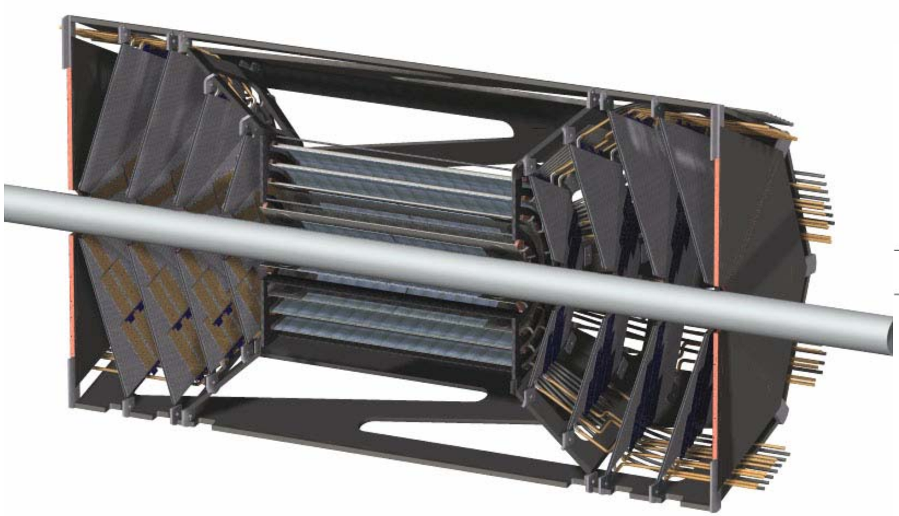
- Broad kinematic reach
  - y/p_T coverage for open charm, charmonium
  - Upsilon may be a good control measurement because it's more tightly bound ⇒ repeat above w/ charm → bottom
- pp collisions
  - Initial production mechanism
- pA collisions
  - Shadowing
  - Initial state energy loss
  - Cold medium absorption
- Light ion collisions
  - Modify path length through medium
  - Most efficient way to dial in N_{binary}.
- Energy scans
  - Modify energy density
  - More difficult (both luminosity & cross-sections fall w/ energy)

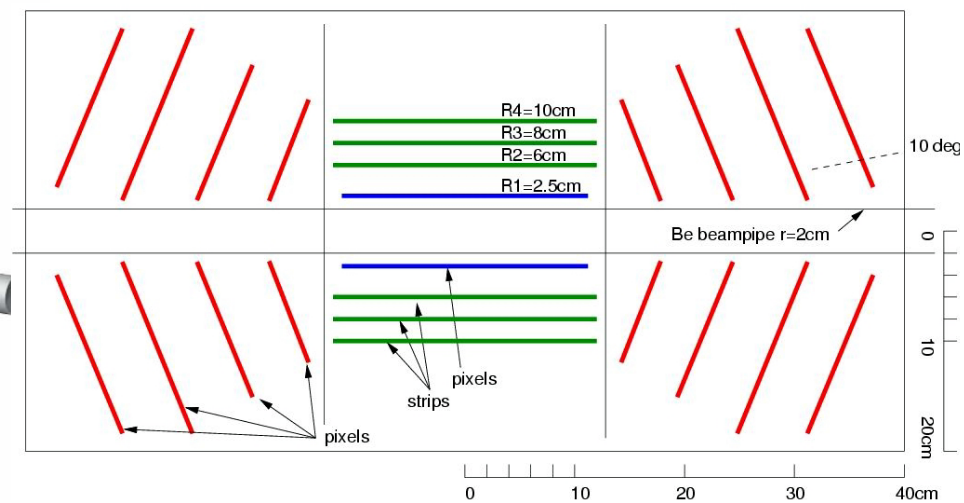
Collect enough data to limit the theorists' creativity…

- Backup Slides

PHENIX VTX

- Over the next n years RHIC will provide collisions of many nuclear species at different energies.
- In addition to the PHENIX baseline detector a Silicon Vertex Detector (VTX) is being proposed.
- Significant impact on heavy flavor measurements:
  - Reduce J/Y backgrounds and improve mass resolution
  - Extend open charm, beauty coverage to higher and lower pT thru DCA cut, direct reconstruction.
  - Push structure function measurements to smaller x values.



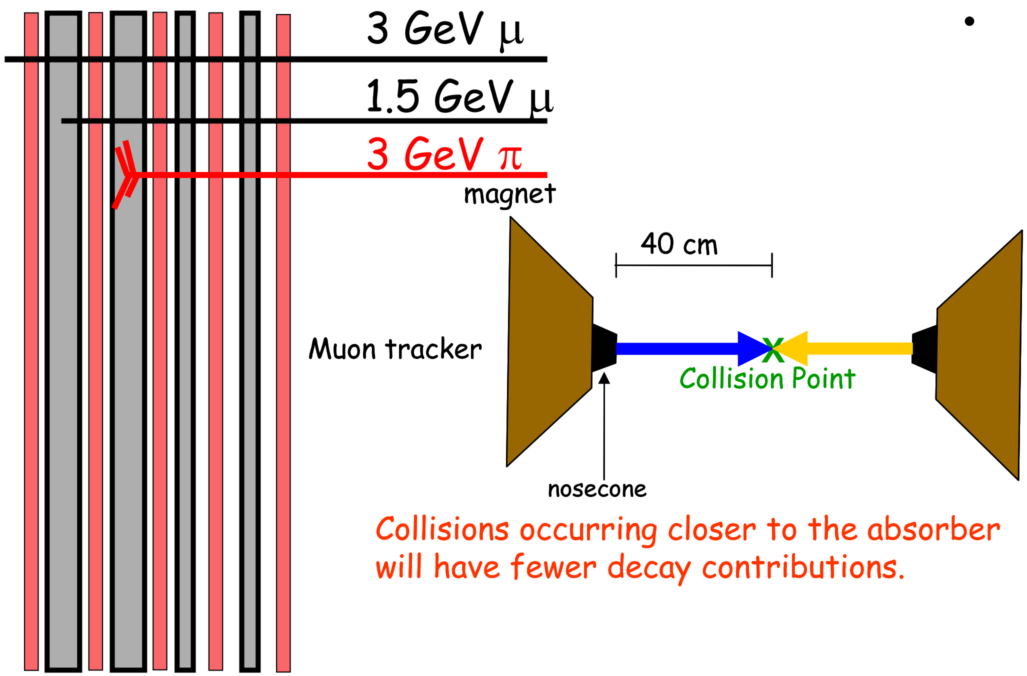


PHENIX

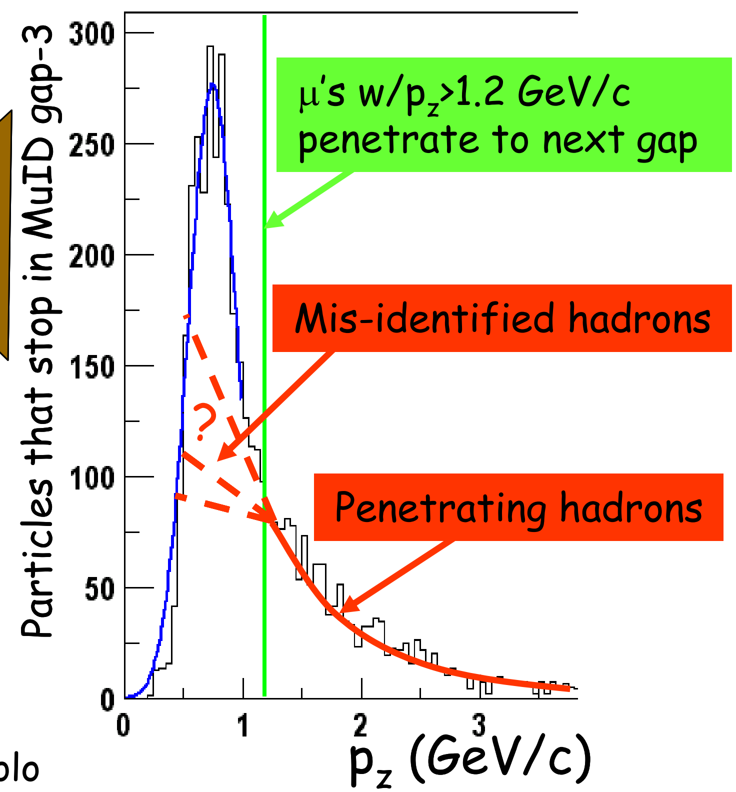
- Sophisticated multi-level trigger system and pipelined, deadtime-less readout architecture optimized to allow storage of all physics events of interest.
- Data sets include:
  - AuAu @ $\sqrt{s_{NN}}$ = 130, 200 GeV
  - pp @ $\sqrt{s}$ = 200 GeV
  - dAu @ $\sqrt{s_{NN}}$ = 200 GeV

Single Muon Backgrounds

- For π, K γcτ >> 80cm → decay probability nearly constant between nosecones.

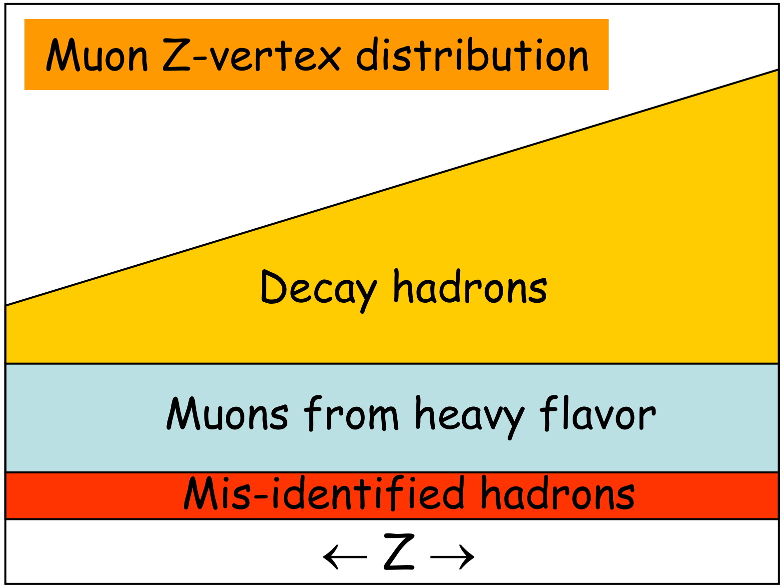


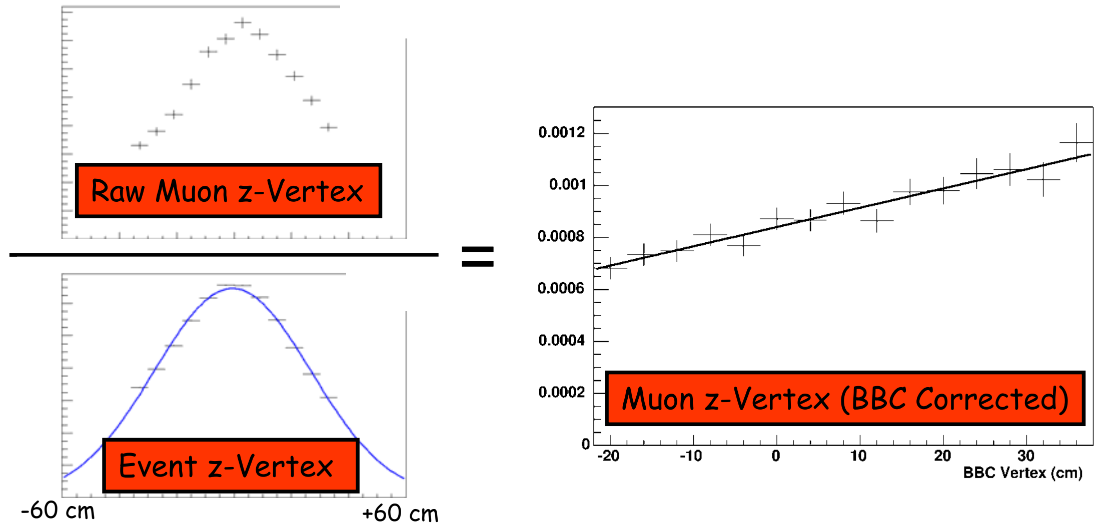
- Muons that stop in a particular gap have well-defined momentum.
- Particles with greater momentum are cleanly ID'd as hadrons.
- Some lower-momentum component sneaks in under muon peak.



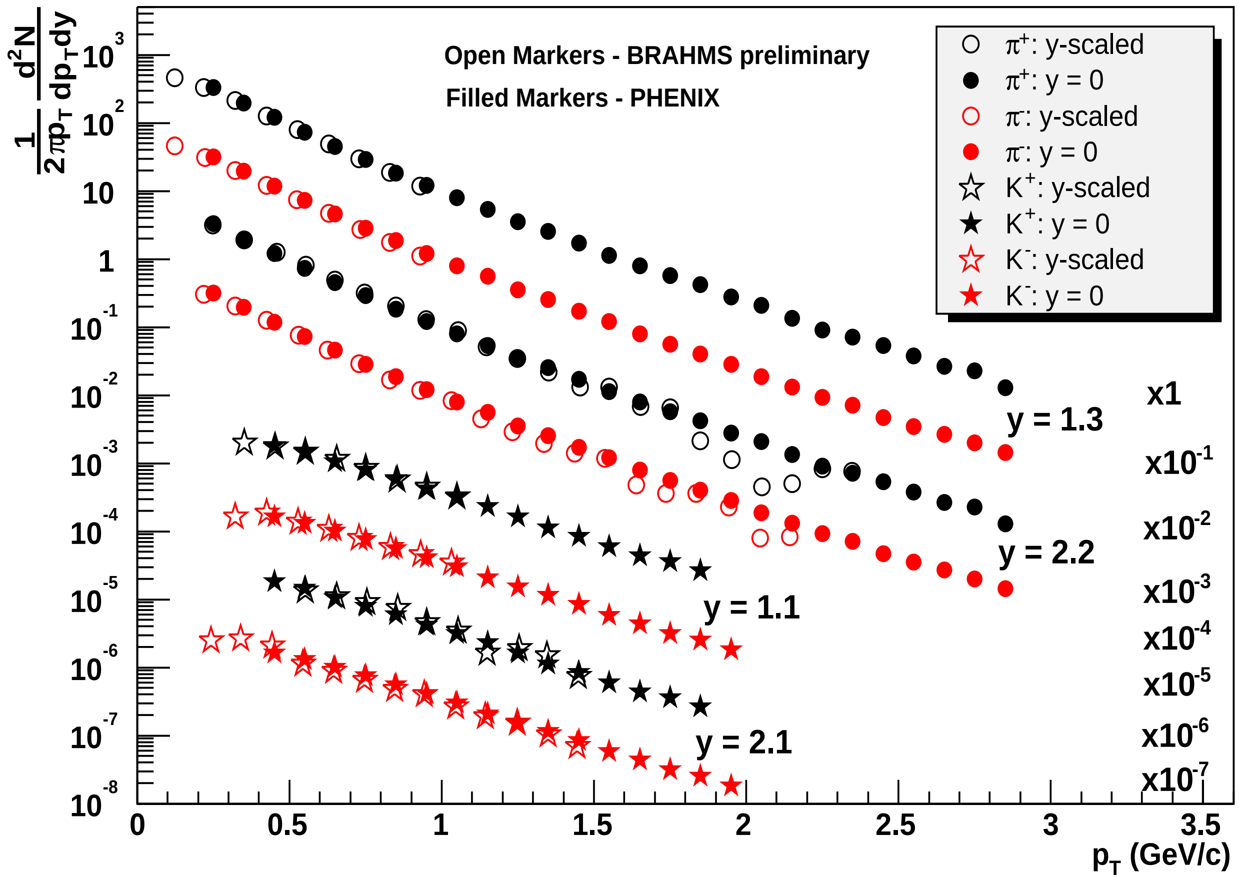
Decay Hadrons

- For decay hadrons a linear behavior is expected in muon the vertex distribution after normalizing for event vertex distribution.
- Indeed, such a behavior is observed and the initial π,K distributions can be deduced used as input to calculate mis-identified hadrons.
  - Indirect
  - Doesn't include proton contribution.



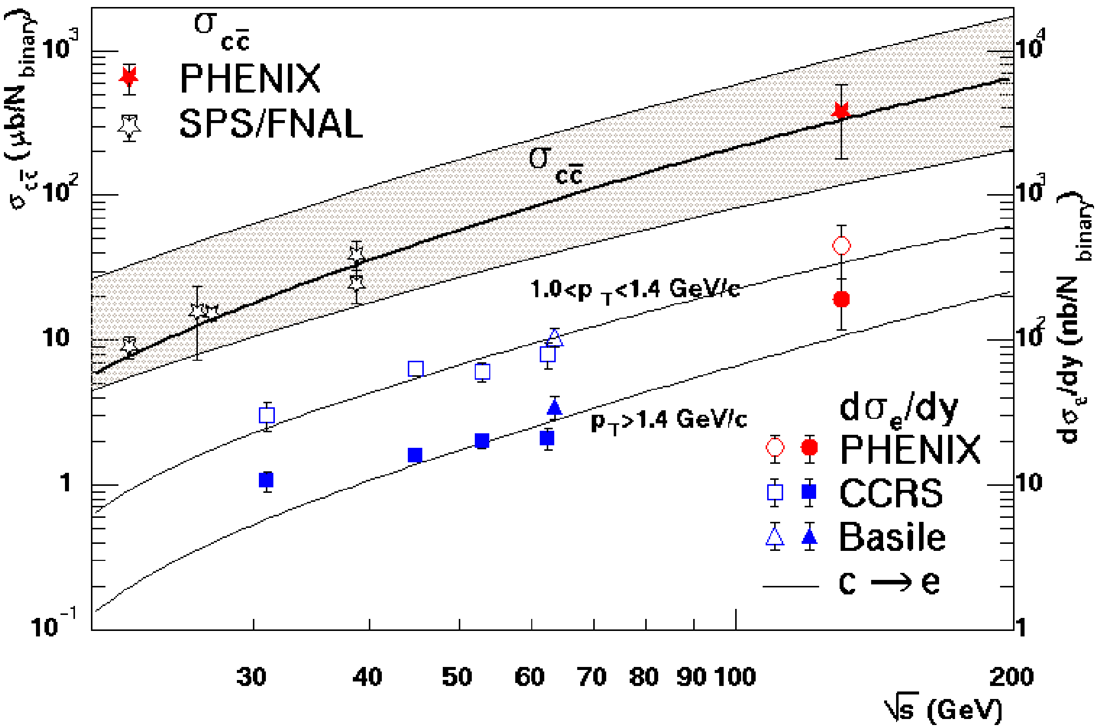


y, p_T Factorization for Hadron Input



BRAHMS data extracted from Djamel Ouerdane's thesis

Comparison with Other Experiments



Phys. Rev. Lett. 88, 192303

Cross sections for:

- single electrons resulting from charm, and
- total charm production

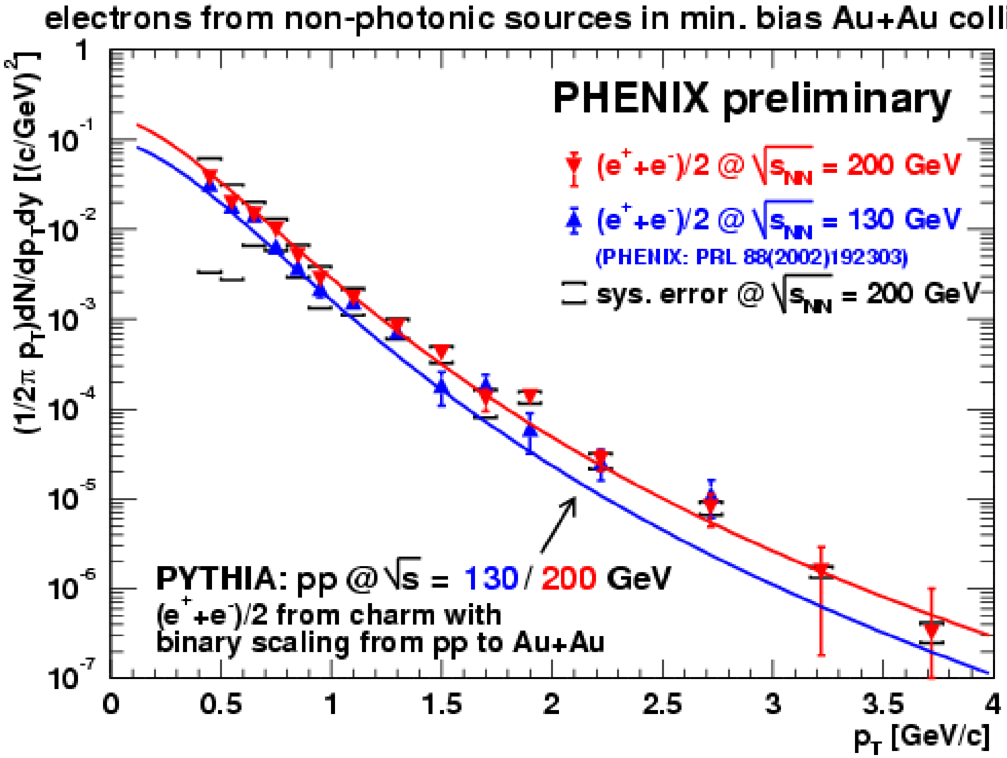
are scaled by N_{binary} and compared with:

- Solid curves: PYTHIA
- Shaded band: NLO QCD

•Assuming N_{binary} scaling, PHENIX data are consistent with √s systematics (within large uncertainties)!

•One of the main systematic uncertainties in this comparison is the pp baseline expectations for charm production, and PHENIX is analyzing these results.

$\sqrt{s_{NN}}$ = 200 GeV AuAu Single Electron Data



- The yield of non-photonic electron at 200 GeV is higher than 130 GeV and consistent with PYTHIA charm calculation:

$$(\sigma_{c\bar{c}}\ (130\ \text{GeV}) = 330\ \mu b,\ \ \sigma_{c\bar{c}}\ (200\ \text{GeV}) = 650\ \mu b)$$

- For this data set special runs with a photon converter of known thickness were collected and will reduce the systematic error on the final result.