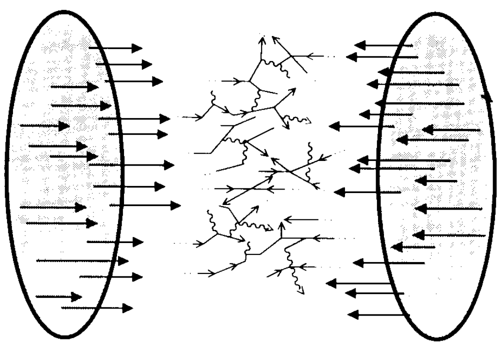
Relativistic Heavy Ion Physics:

Heavy Quarks and Quarkonia



CTEQ Summer School
Lecture #2 - June 8, 2002

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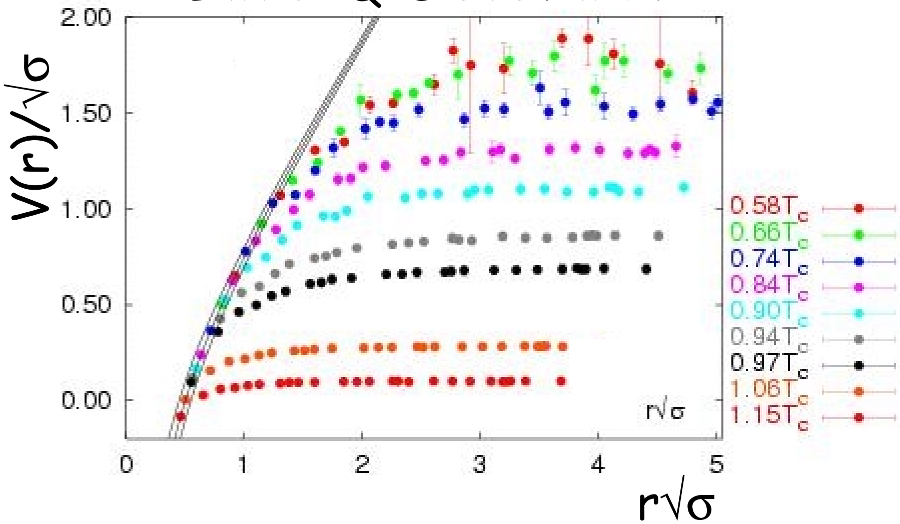
IN THE CITY OF NEW YORK

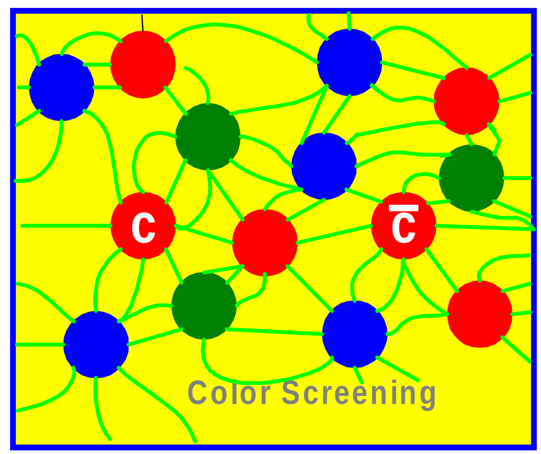
University of Colorado, Boulder

Studying Quark Deconfinement

Lattice QCD results show that the confining potential between heavy quarks is screened at high temperature.

Lattice QCD calculation



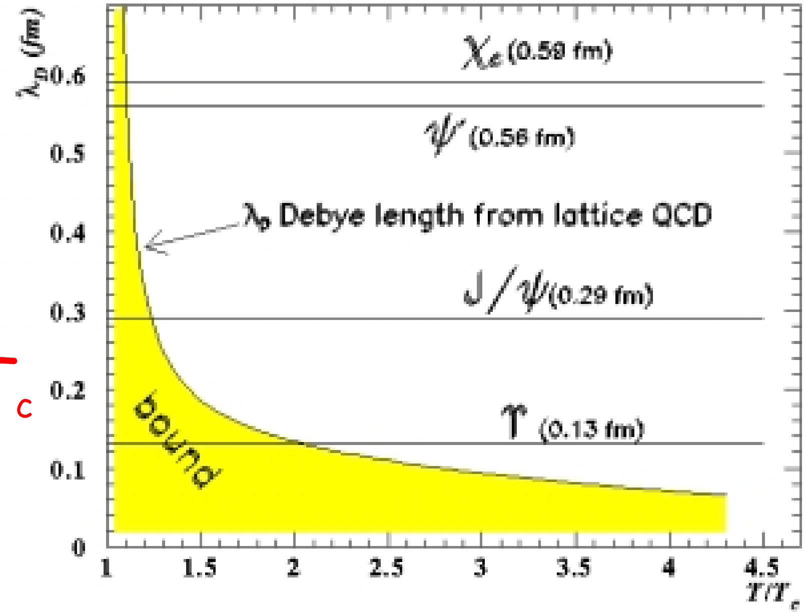


This screening should suppress bound states such as J/ψ.

Thermometer

Different states "melt" at different temperatures due to different binding energies.

The ψ' and χ_c melt below or at T_c the J/ψ melts above T_c and eventually the Υ(1s) melts.



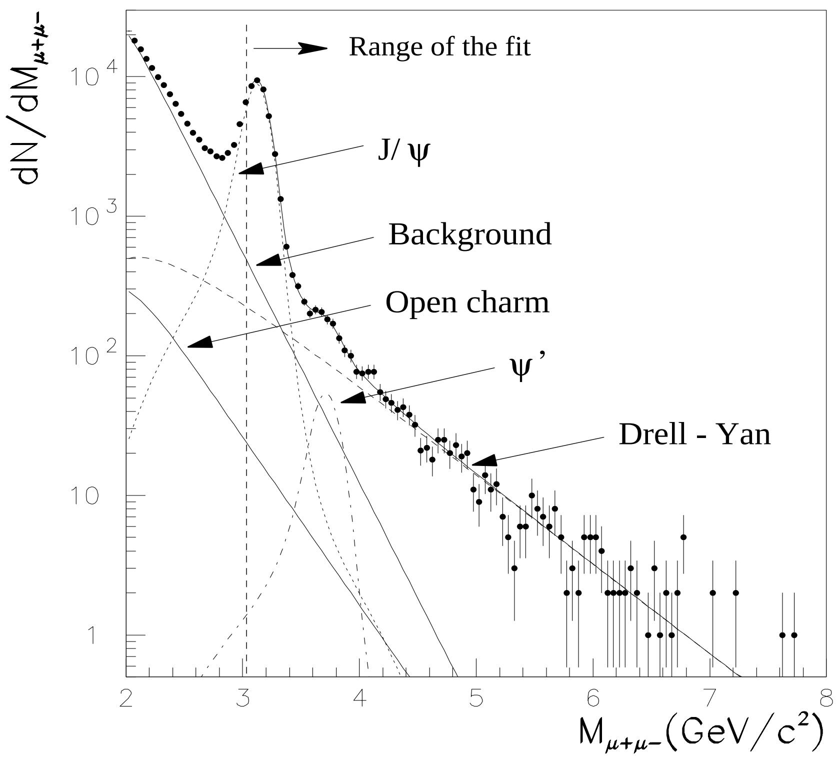
state	J/ψ	χ_c	ψ'	Υ(1s)	χ_b	Υ(2s)	χ_b'	Υ(3s)
Mass [GeV}	3.096	3.415	3.686	9.46	9.859	10.023	10.232	10.355
B.E. [GeV]	0.64	0.2	0.05	1.1	0.67	0.54	0.31	0.2
T_d/T_c	---	0.74	0.15	---	---	0.93	0.83	0.74

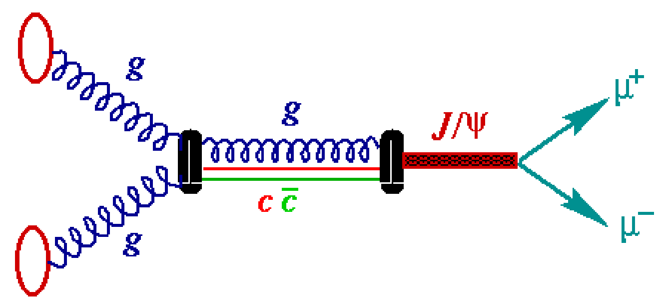
hep-ph/0105234 - "indicate ψ' and the χ_c dissociate below the deconfinement point."

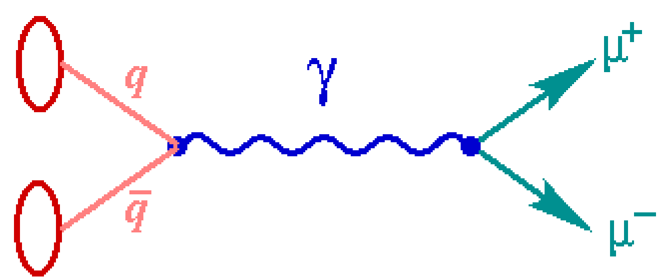
Drell-Yan Baseline

At CERN-SPS energies, Drell-Yan dominates the dimuon invariant mass spectrum above the J/ψ and ψ'.

Drell-Yan provides a good baseline for J/ψ suppression that should scale with binary collisions since the photon does not interact with the medium.



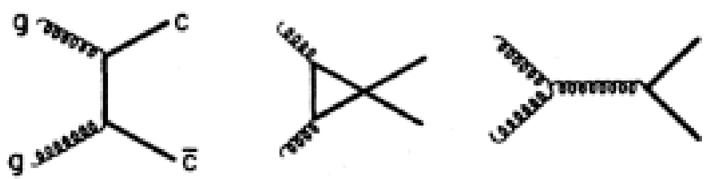


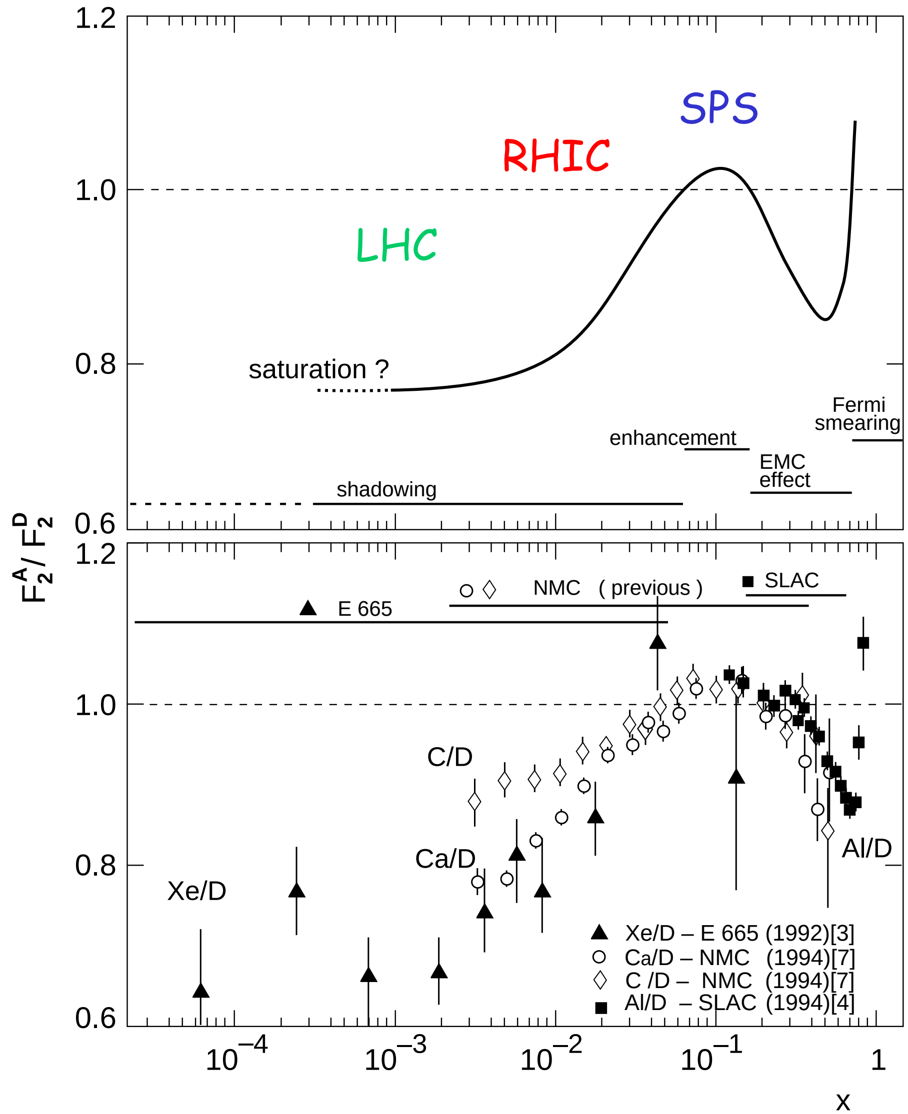


Charm Normalization

At RHIC, Drell-Yan is not easily measured because it is dominated by leptons from open charm above the ψ′.

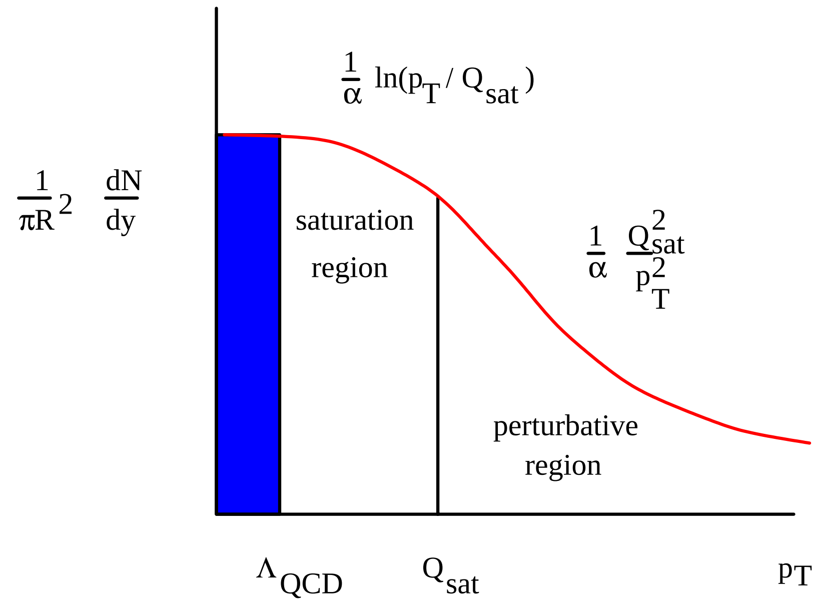
Shadowing of initial state partons means that one must compare J/ψ production with something that couples directly to the gluons (eg. Charm, Beauty).



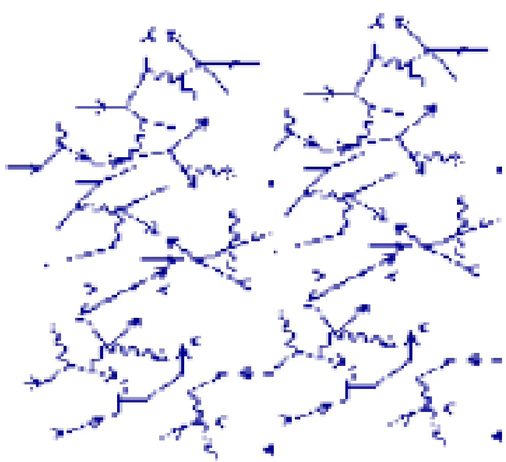


More Charm Interest

In addition, total charm production may be affected not just in a factorized shadowing picture, but from the saturation of gluons in a Color Glass Condensate.



Is there thermal or simple secondary scattering charm production after the initial parton-parton scattering?

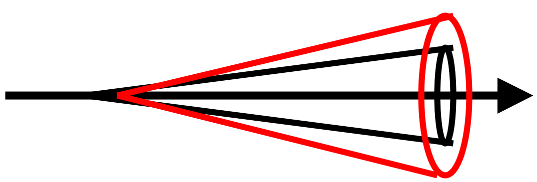


Could large thermal charm production lead to J/ψ enhancement via c-cbar coalescence?

Charm and Jets

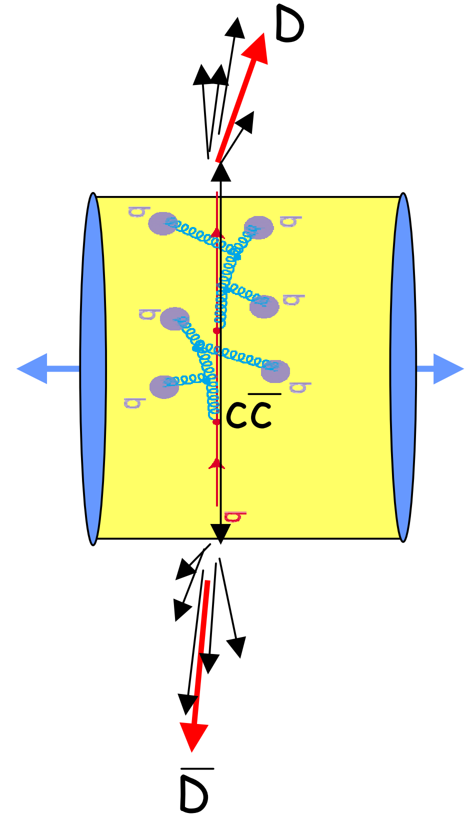
Radiative quark energy loss is qualitatively different for heavy and light quarks.

More massive charm quarks move slower and this leads to suppression of co-linear gluon emission (“dead-cone” effect)



Suppression of Suppression = NO Suppression

Predict enhanced **D/π** ratio



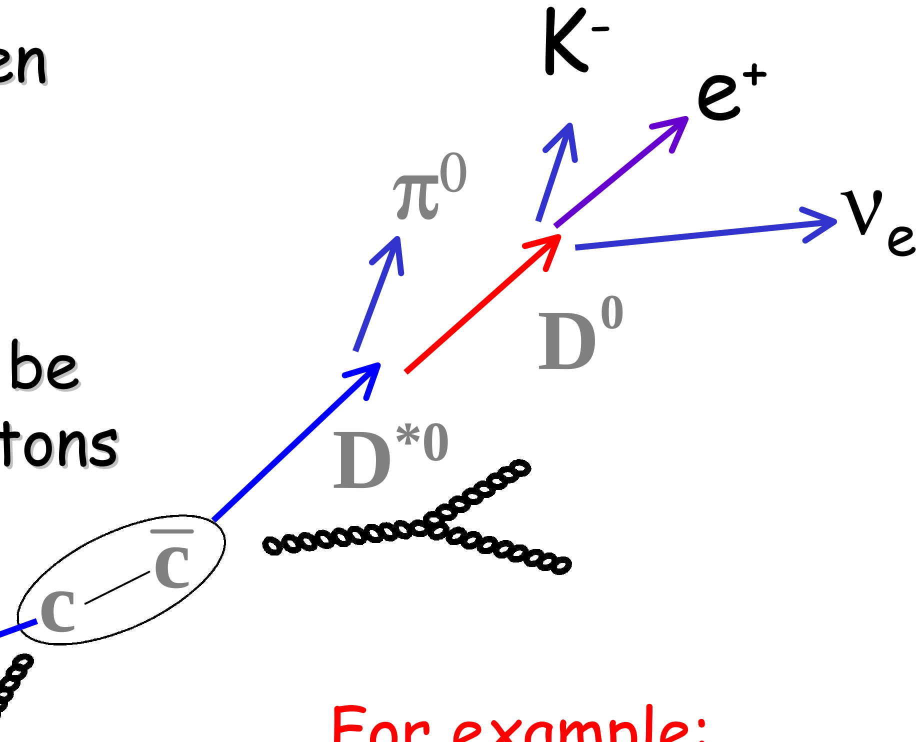
Y.L.Dokshitzer and D.E. Kharzeev, hep-ph/0106202

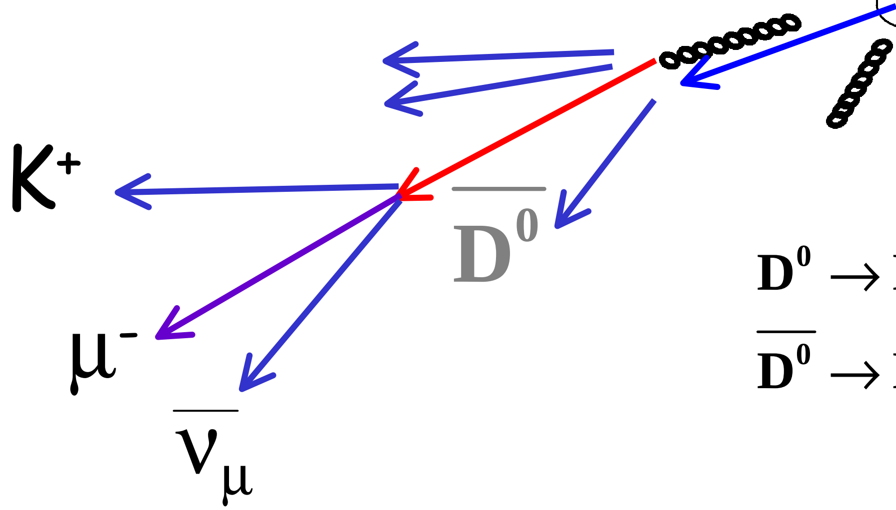
Charm Diagram

Direct reconstruction of open charm is ideal, but difficult.

$$\left(\mathbf{E.g.}\ D^0 \to K^-\pi^+\right)$$

Open charm and bottom can be measured through single leptons and lepton pairs.





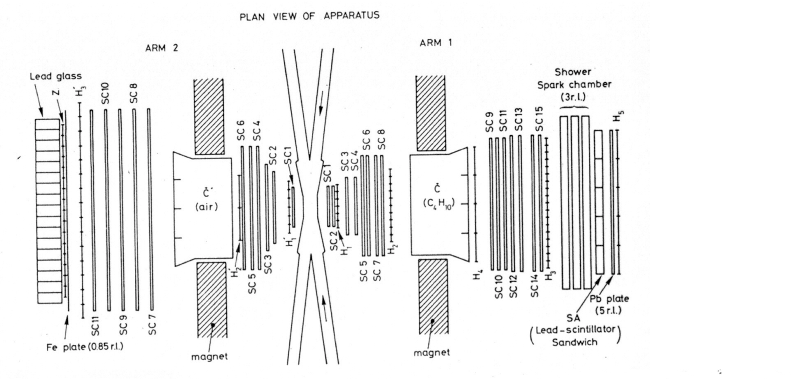
$$D^0 \to K^-\ell^+\nu_e$$

$$\overline{D^0} \to K^+\ell^-\overline{\nu_\ell}$$

For example:

$$\left\{\begin{array}{l} D^0\overline{D^0} \to e^+e^-K^+K^-\nu_e\overline{\nu_e} \\ D^0\overline{D^0} \to e^-\mu^+K^+K^-\overline{\nu_e}\nu_\mu \\ D^0\overline{D^0} \to \mu^+\mu^-K^+K^-\nu_\mu\overline{\nu_\mu} \end{array}\right.$$

Charm via Electrons



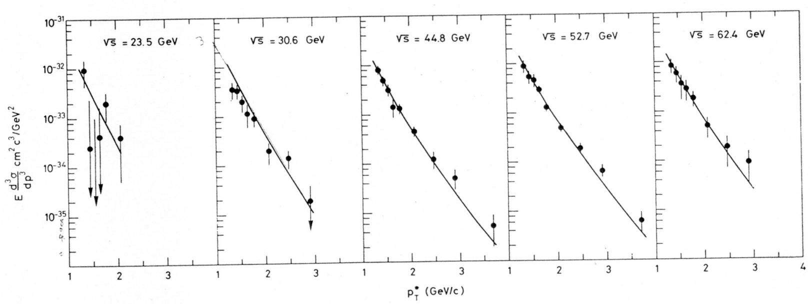


Fig. 7. The charge-averaged invariant cross section for electron production, plotted as a function of the c.m. momentum p_T^* for five values of $\sqrt{s}$. The curve represents a fit of the charge-averaged pion data of the BS Collaboration [22], and has been multiplied by 10^{-4}.

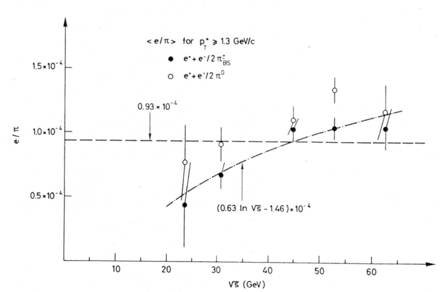


Fig. 9. The ratio of the invariant cross sections of electrons to pions of $p_T^* \geq 1.3$ GeV/c plotted as a function of c.m.s. energy $\sqrt{s}$. The pion data were obtained from the work of the British-Scandinavian Collaboration [22] (solid points) and from the spectrum of selected conversions measured in this experiment (open points). The two curves shown are fits to the solid points.

High p_T single electrons were observed at the ISR in the early 1970's

F. W. Busser et al., PLB 53, 212
F.W.Busser et al., NPB 113, 189

These electrons were later interpreted as a signal from semi-leptonic decays of open charm

I.Hunchlife and C.H.Llewellyn Smith, PLB 61,472
M. Bourquin and J.-M.Gaillard, NPB 114,334

Direct D Reconstruction

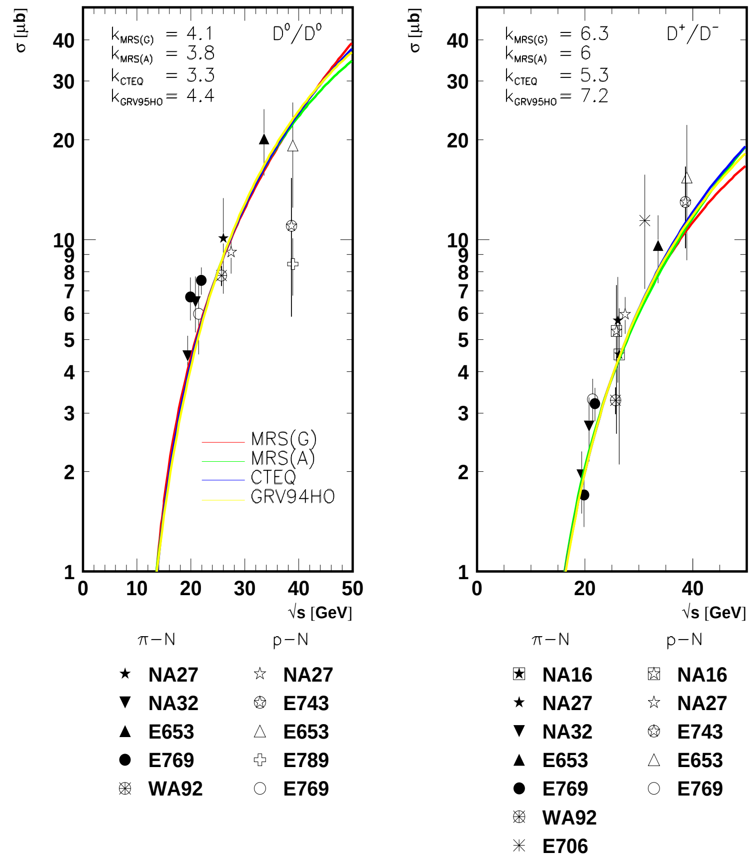
Direct charm measurement in hadron-hadron collisions has proved to be quite challenging.

Using D* reconstruction and displaced vertex measurements have allowed observations at FNAL and CERN.

Extrapolation of p-p data at lower energies to RHIC 130 GeV yields

$$\sigma_{cc} = 380 \pm 120\ \mu b$$

Systematic error should probably be somewhat larger.



Measuring Charm

PHENIX recorded 2 million Au-Au events in Run I, and can thus address charm production via single electrons.

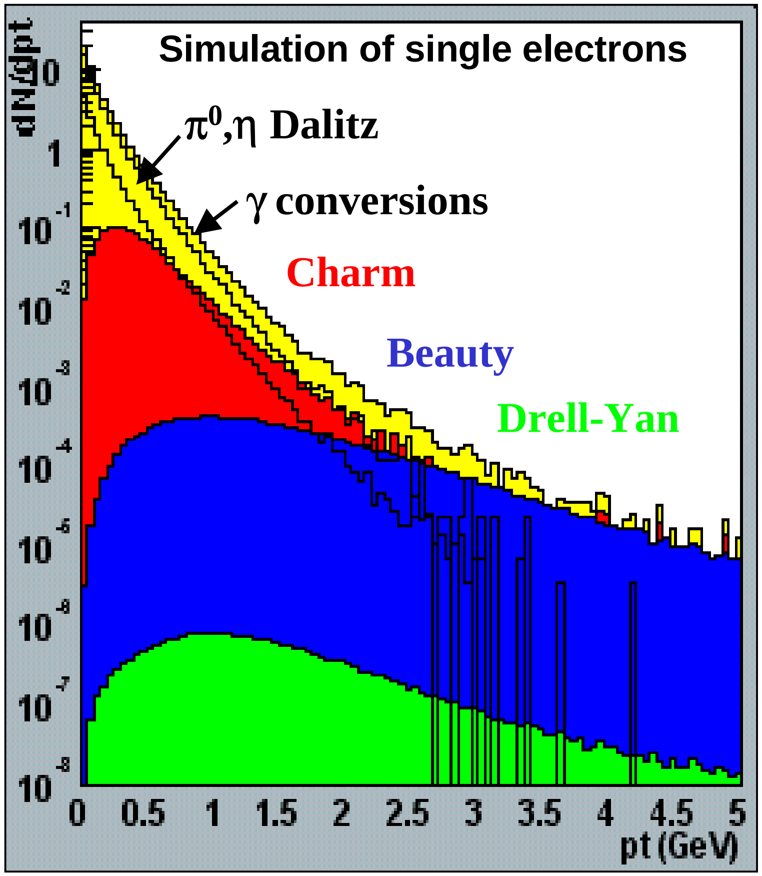
$D^0 \rightarrow K^- \; e^+ \nu_e$

$B^0 \rightarrow D^- \; e^+ \nu_e$

One must account for contributions:

π^0, η Dalitz
γ conversions

Remaining signal is then from
- open charm and open beauty
- Drell-Yan
- thermal production
- new physics

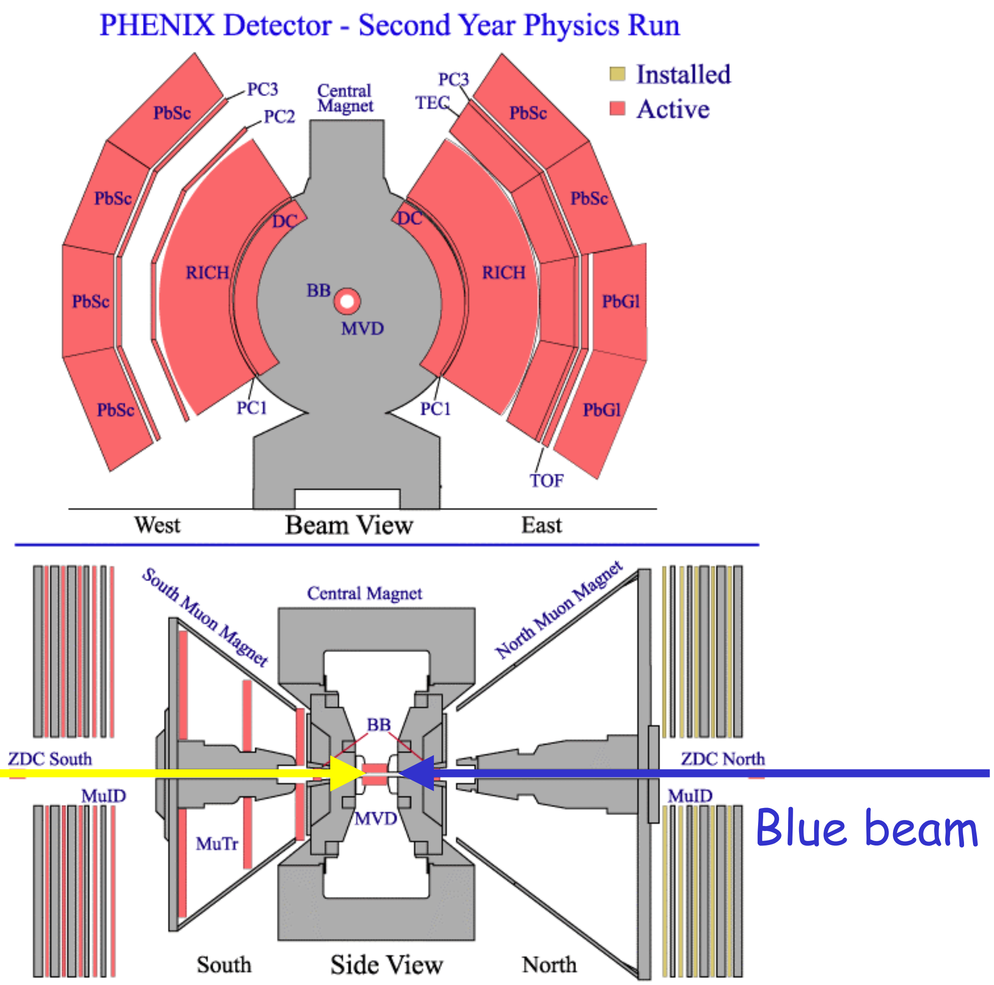


PHENIX
Pioneering High Energy Ion eXperiment

Designed to measure electrons, muons, photons and hadrons.

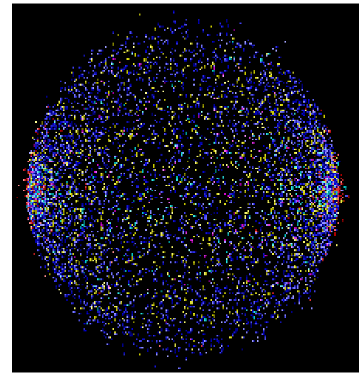
Complex set of four separate particle spectrometers.

This requires many different types of detector technologies and an integrated electronics readout.



Electron Needle in a Hadron Haystack

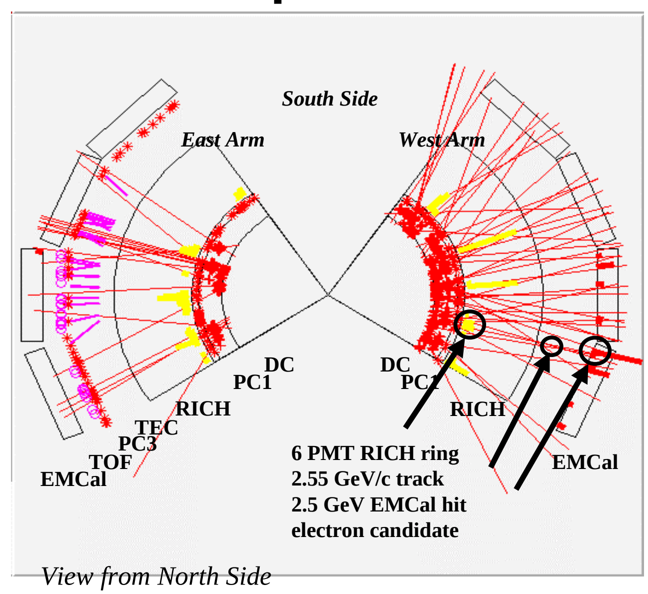
PHENIX is designed to find
1 electron out of 10,000 pions !



Electron identification:

- track reconstructed
  (momentum p)
- ring found in Ring Imaging Cherenkov Counter
  (velocity threshold)
- energy cluster found in Electro-magnetic Calorimeter
  (energy E)

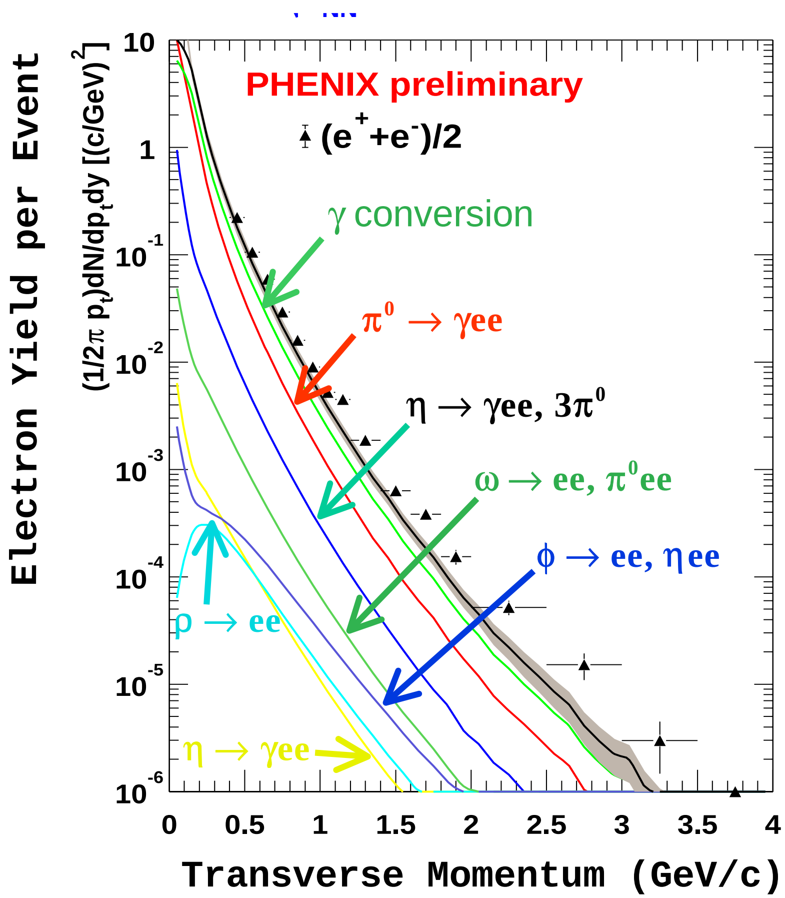
PHENIX Spectrometer



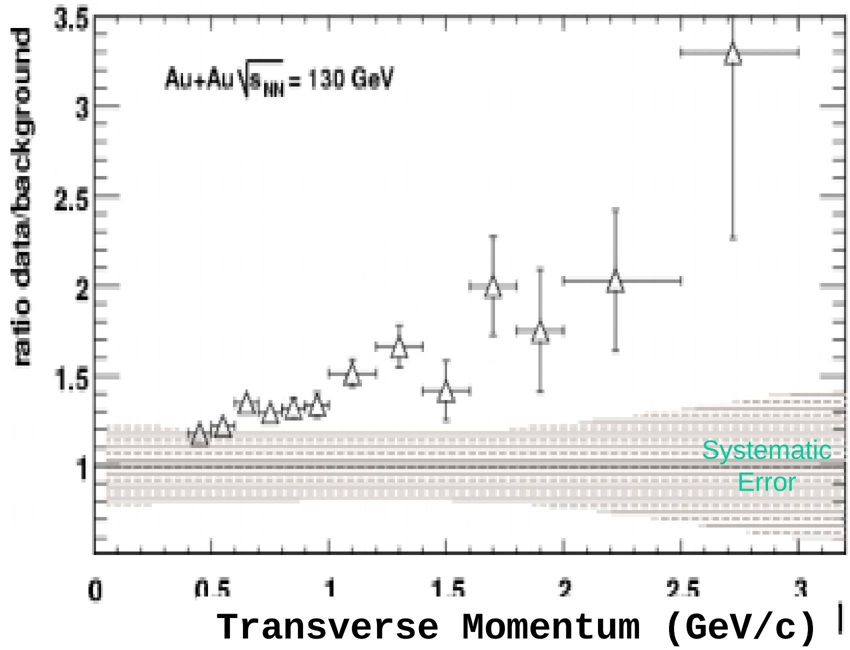
PHENIX Picture

Total Electron Yield

Many electrons are from light hadron decays, and must be subtracted off to see the charm contribution.

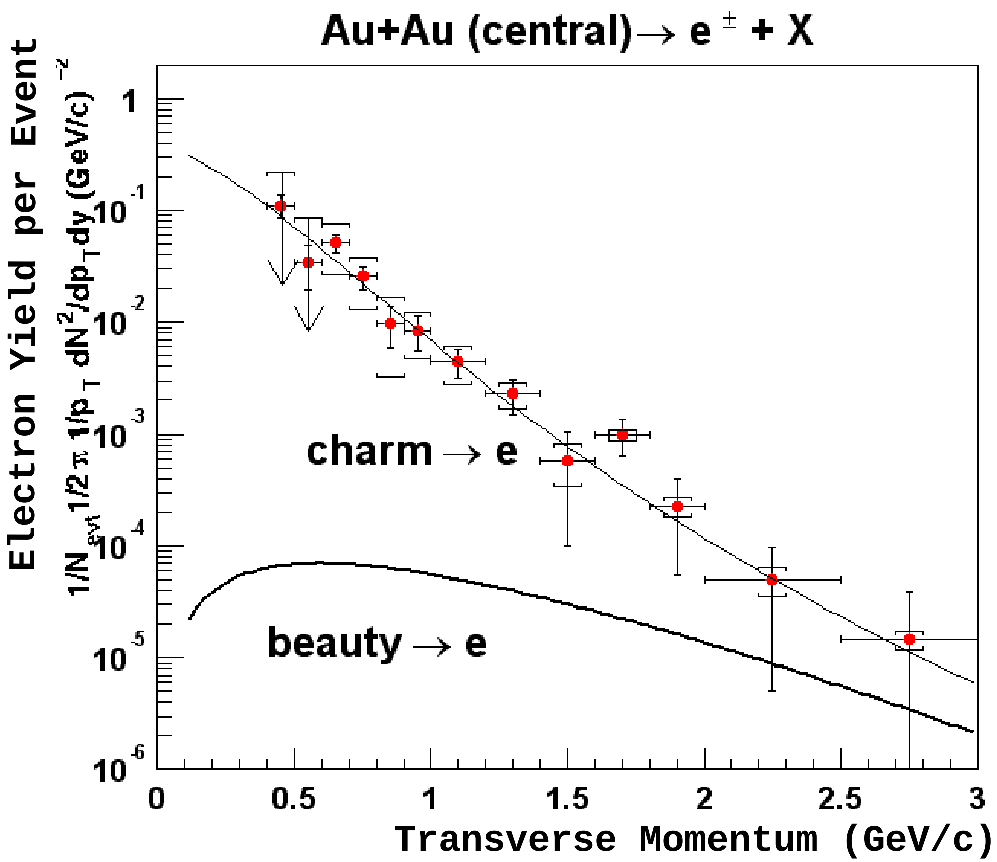


$$ratio = \frac{All.Electrons}{"Background"\ Electrons}$$



Charm Results

Clear remaining electron signal observed that appears consistent with semi-leptonic decays of charmed D mesons.

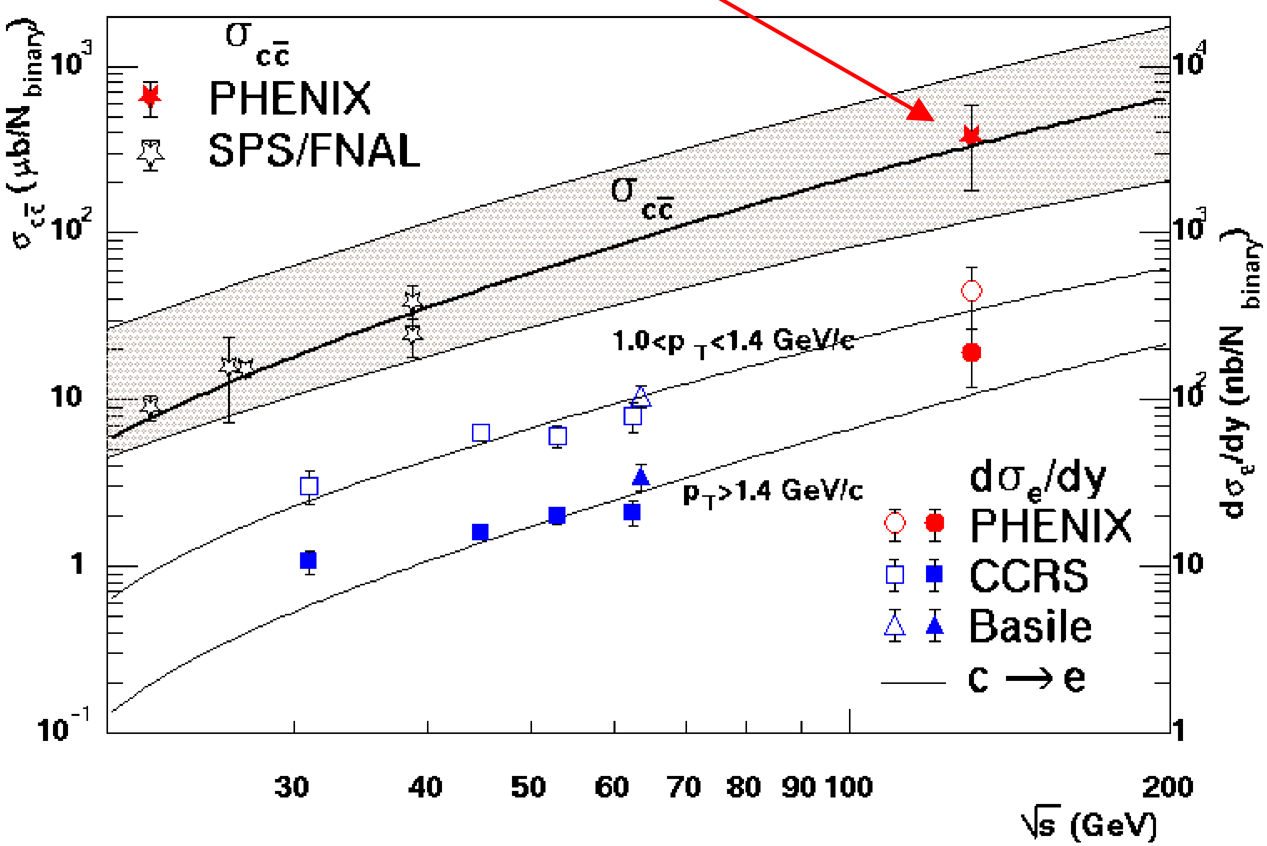


PYTHIA model is tuned to match lower energy charm production data.

PYTHIA shows good agreement with charm production that scales with the number of binary collisions.

Binary Scaling

Surprisingly good agreement with assumption of binary collision scaling and extrapolated proton-proton charm cross section at 130 GeV.



Charm Cross Section

We estimate the charm yield by assuming that all single electrons above "background" are from D mesons.

Neglect other possible sources such as thermal dileptons, etc.

By fitting the single electron distribution, we obtain:

Centrality	N_{binary}	$d\sigma_{cc}/dy\|_{y=0}(\mu b)$	$\sigma_{cc}(\mu b)$
0-10%	905±64	97±13±49	380±60±200
0-92%	246±16	107±8±63	420±33±250

Data is consistent with binary scaling (no nuclear or medium effects), but with large uncertainties.

Errors - statistical uncertainty (±14%), fitting range (±18%), background subtraction (±44%), PYTHIA k_T (±11%), D^+/D^0 (±13%).

Additional uncertainty in the total charm cross section from PDF in the charm rapidity distribution.

Proton-Nucleus Studies

D meson production in proton-Nucleus and π-Nucleus collisions at lower energies is consistent with binary collision scaling (α = 1).

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

E769 250 GeV π± PRL 70,722 (1993)

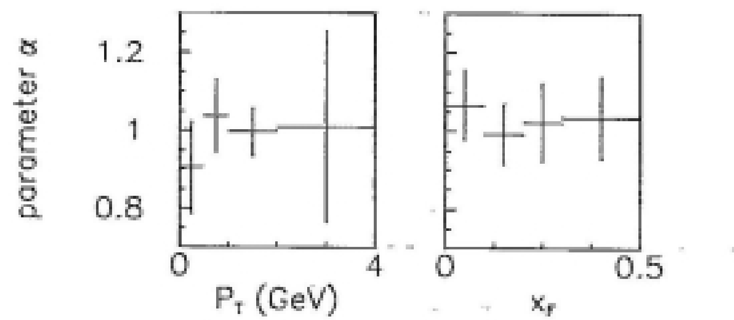


FIG. 4. Dependence of the parameter α on P_T and x_F for D^+ and D^0.

WA82 340 GeV π⁻ PRB 284,453 (1992)

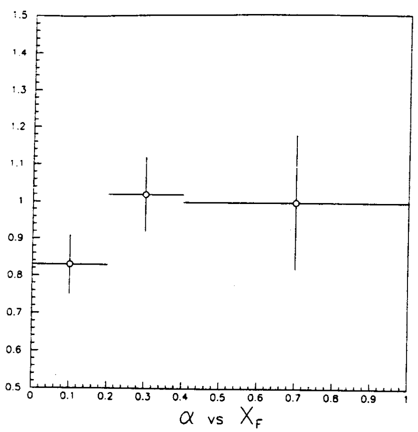
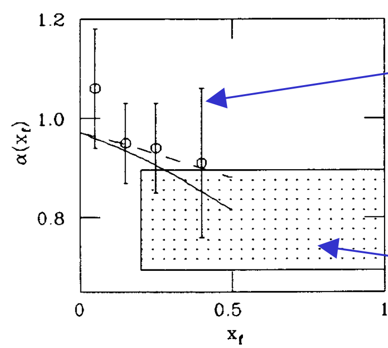


Fig. 4. The parameter α for charm production as measured in three x_F intervals.

Vogt et al., NP 383,643 (1992)



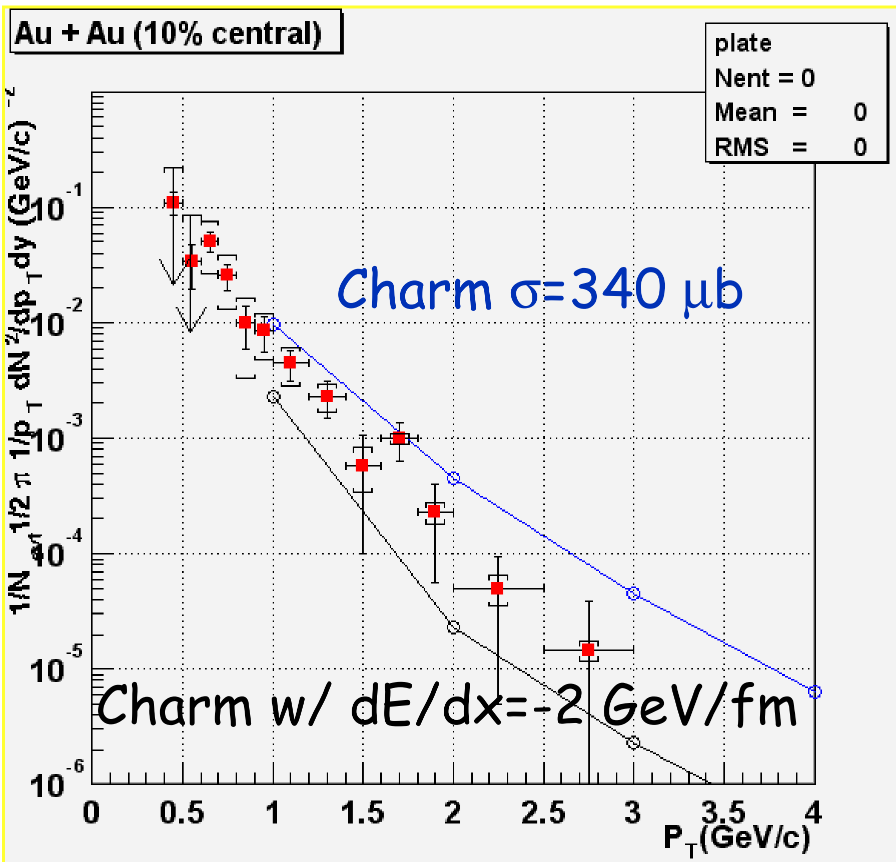
E769 250 GeV π

WA78 320 GeV π (Beam dump)

Fig. 14. We show $\alpha(x_f)$ for π^-A interactions at 300 GeV as calculated in our model. The dashed curve shows delta function fragmentation, the solid curve, the Peterson function. These results are compared to those for $D^{\pm}$ mesons produced by 250 GeV π^-A interactions [3] and the effective α found by the WA78 beam dump experiment [23], indicated by the band with $\langle x_f \rangle = 0.31$.

Theoretical Calculation

Theoretical prediction for electrons from charm.
Inclusion of energy loss at the same scale as for light quarks.



Z.Lin, R. Vogt, X-N. Wang PRC 57 (1998)

Why is the calculation with no energy loss different from the PYTHIA result?

Different fragmentation function used in calculation.

D Meson Contributions

The three types of D mesons that contribute single electrons are:

name	b.f. $D \rightarrow eX$	percentage contribution to electrons in PYTHIA
D^+	17.2%	21.6%
D^0	7.7%	66.8%
D^+_S	8.0%	11.6%

Note that most all excited charm mesons do not decay semi-leptonically, but only contribute via sequential decay

D^{*+}	$D^0 \pi^+$	68.3%
	$D^+ \pi^0$	30.6%
	$D^+ \gamma$	1.1%
D^{*0}	$D^0 \pi^0$	61.9%
	$D^0 \gamma$	38.1%

$D^+/D^0 = 0.32$ (PYTHIA) gives an average b.f. $D \rightarrow eX$ of **9.7%**

PHENIX paper uses $D^+/D^0 = 0.65 \pm 0.35$ which gives b.f. $D \rightarrow eX$ of **11.0%**

Theory prediction of Lin, Vogt, Wang uses b.f. $D \rightarrow eX$ of **12.0%**

Fragmentation Functions

Lund symmetric fragmentation function (PYTHIA default)

$$f(z) = c \cdot \frac{1}{z} \cdot z^{a_\alpha} \cdot \left(\frac{1-z}{z}\right)^{a_\beta} \cdot \exp\left(-\frac{bm_T^2}{z}\right)$$

Quark mass dependence is in the m_T

Bowler modification "since LUND predicts a somewhat harder B meson spectrum than observed in data."

$$f(z) = c \cdot \frac{1}{z^{1+R_Q bm_Q^2}} z^{a_\alpha} \cdot \left(\frac{1-z}{z}\right)^{a_\beta} \cdot \exp\left(-\frac{bm_T^2}{z}\right)$$

Other options are:

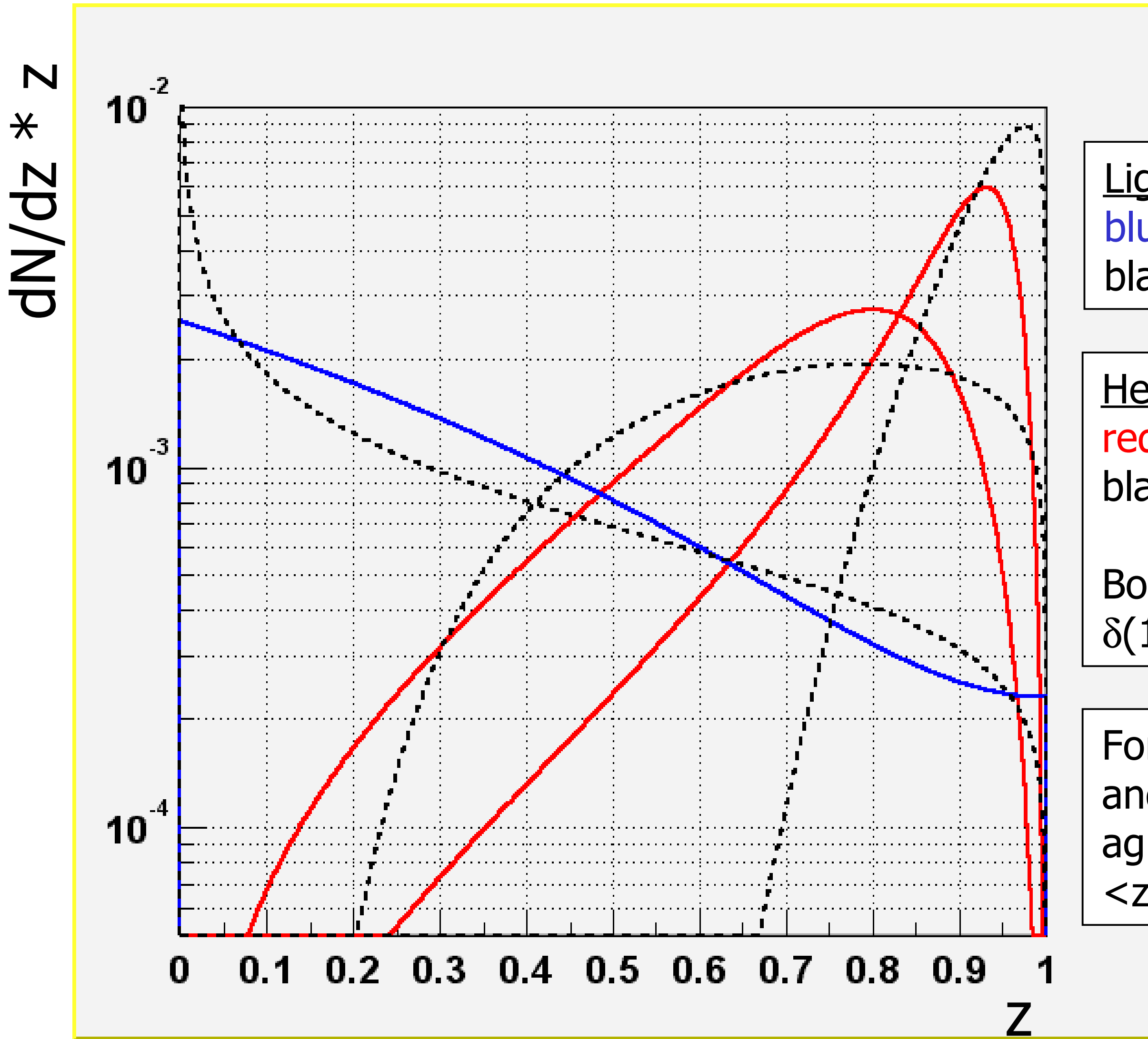
Field-Feynman (for light quarks)

$$f(z) = 1 - a + 3a\left(1-z\right)^2)$$

Peterson (for heavy quarks)

$$f(z) = c \cdot \frac{1}{z\left(1 - \frac{1}{z} - \frac{\varepsilon_Q}{1-z}\right)^2}$$

Comparing Functions



Light quarks (u,d)
blue = Fields-Feynman
black dash = Lund fragmentation

Heavy quarks (c,b)
red = Peterson function
black dash = Lund fragmentation

Bowler correction not shown
$\delta(1-z)$ is obvious

For charm quarks, the Peterson and Lund fragmentation roughly agree and give an average $\langle z \rangle \sim 0.8$.

Intrinsic Charm

For example, in R. Vogt, Brodsky, Hoyer, "Systematics of Charm Production", Nucl. Phys. B383, 643 (1992), they discuss a model where large x_F D mesons are dominantly produced by intrinsic charm pairing with co-moving valence quarks.

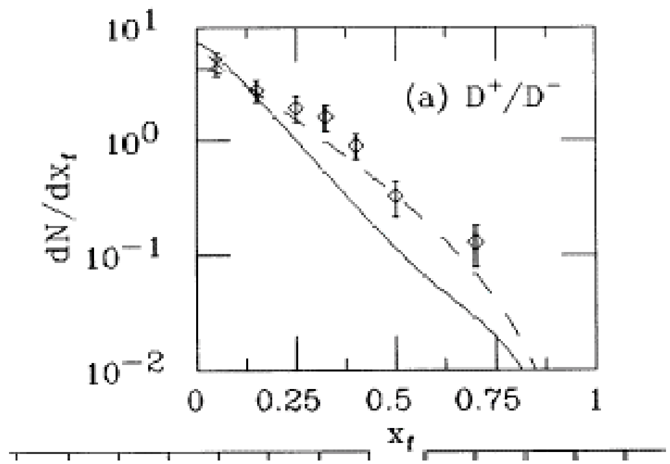
π^- ($\bar{u}$ d)

D^+ (c $\bar{d}$)

D^- ($\bar{c}$ d)

Charm quark is not slowed down in combining with nearby d quark. Thus more D^- than D^+ at high x_F.

π^- + A at 250 GeV



Dashed = δ(1-z) function
Solid = Peterson function

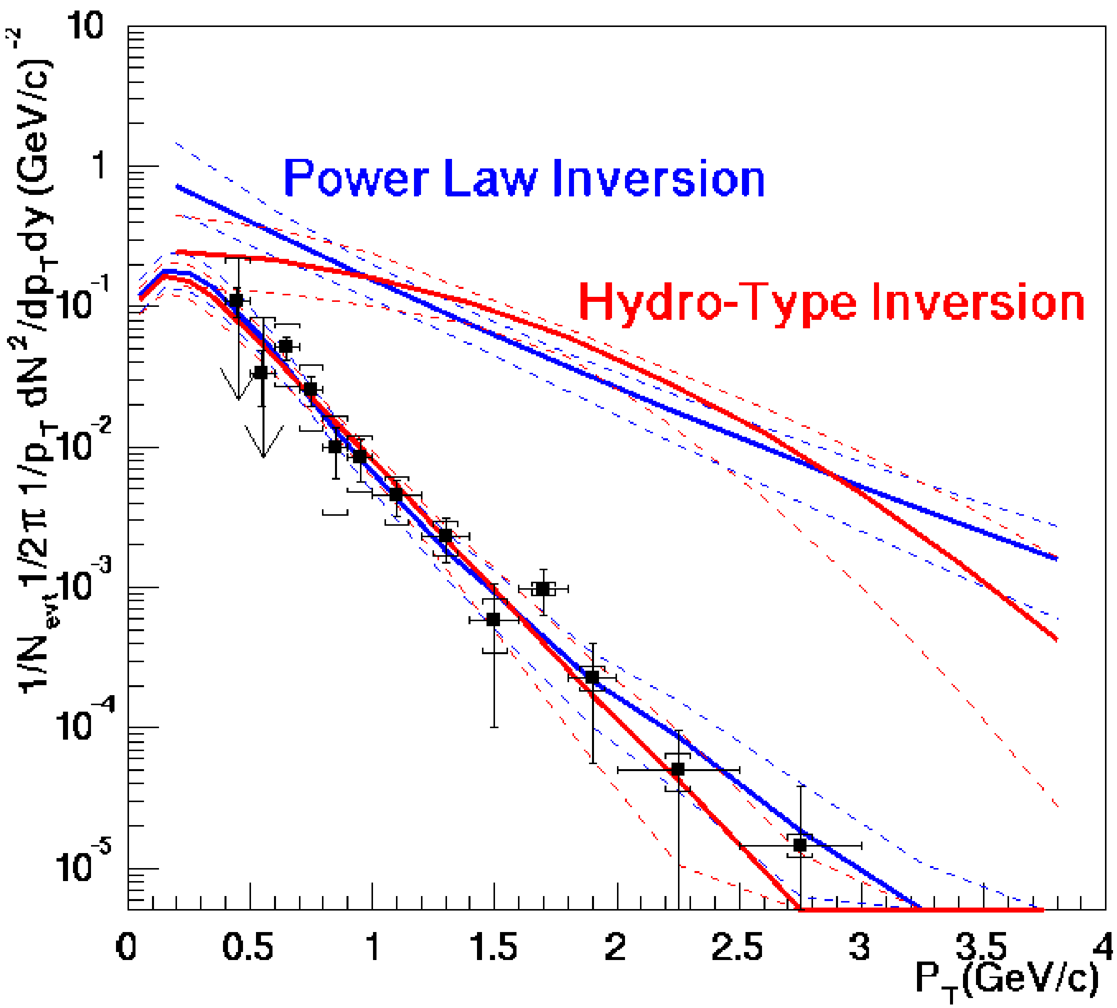
Electron Inversion

Going beyond the PHENIX data, one can invert the single electrons to calculate a D meson spectrum.

1) Power Law Form

2) Guassian Form

Both forms are agree with limited statistics PHENIX data from Run1.

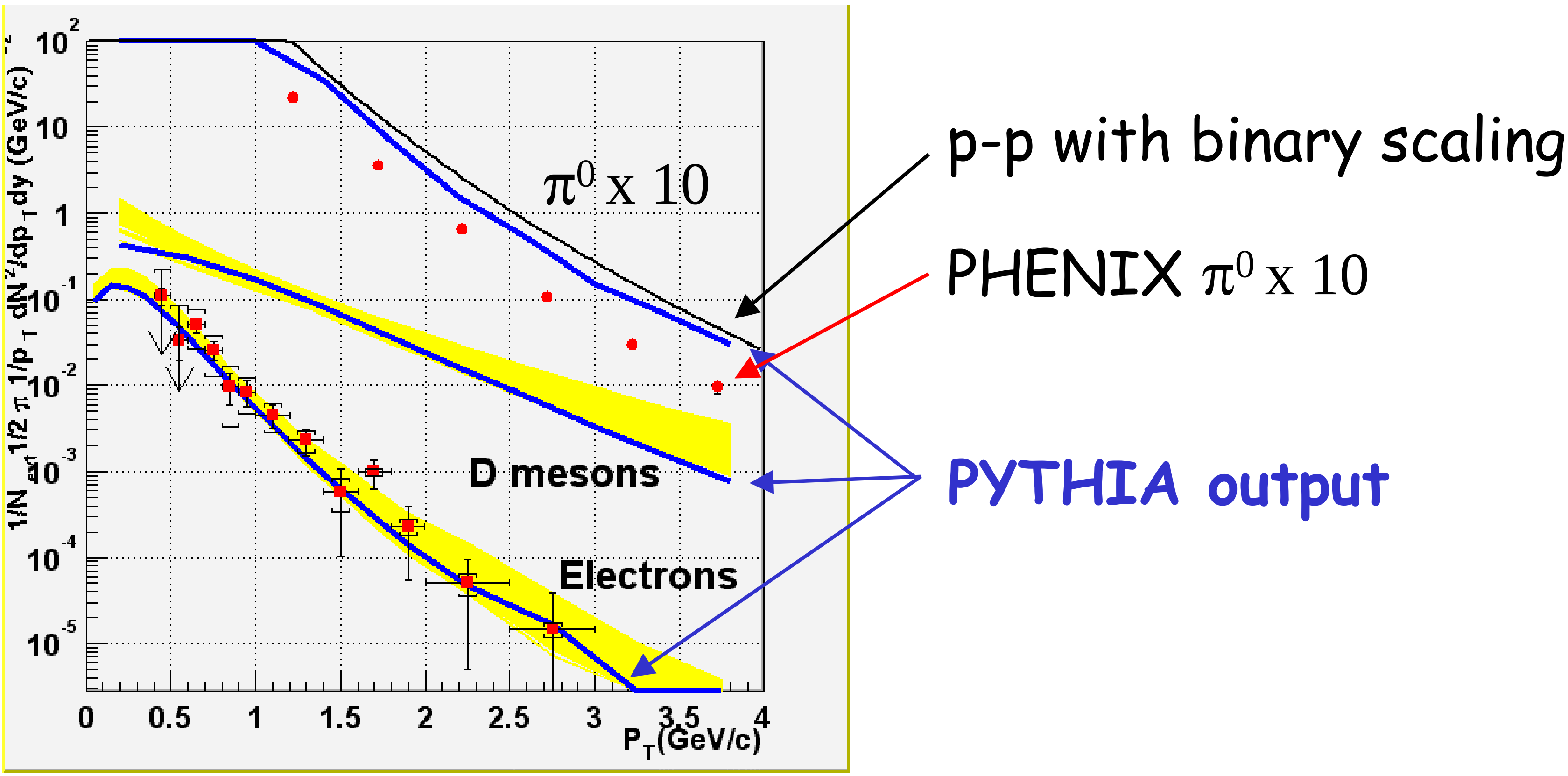


Work withSean Kelly

D/π ?

PHENIX D/π is a factor of 2-3 larger than from PYTHIA model tuned to lower energy charm data.

We <u>must</u> replace PYTHIA with PHENIX p-p data for π and D with Run 2 data ! Then we will see.

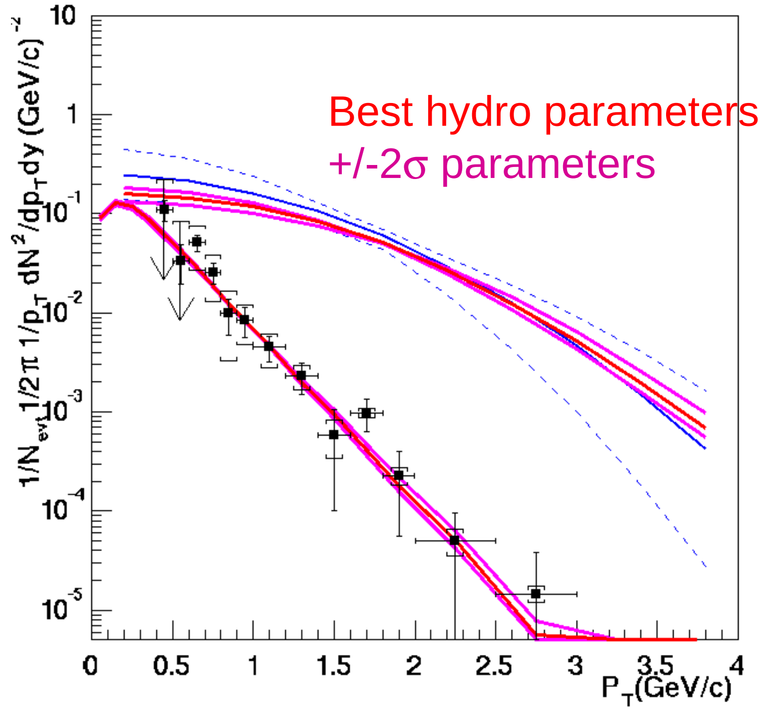


Hydrodynamics? Or Fragmentation

If we assume that there is large pressure build up in the partonic phase, charm quarks may participate in hydrodynamic expansion. This could also happen in the hadronic stage via D meson scattering.

Simply taking the hydrodynamic model parameters from matching the PHENIX π, K, p, one calculates the D meson p_T spectra.

We then calculate the single electrons and find good agreement.
Remember there is a free normalization.

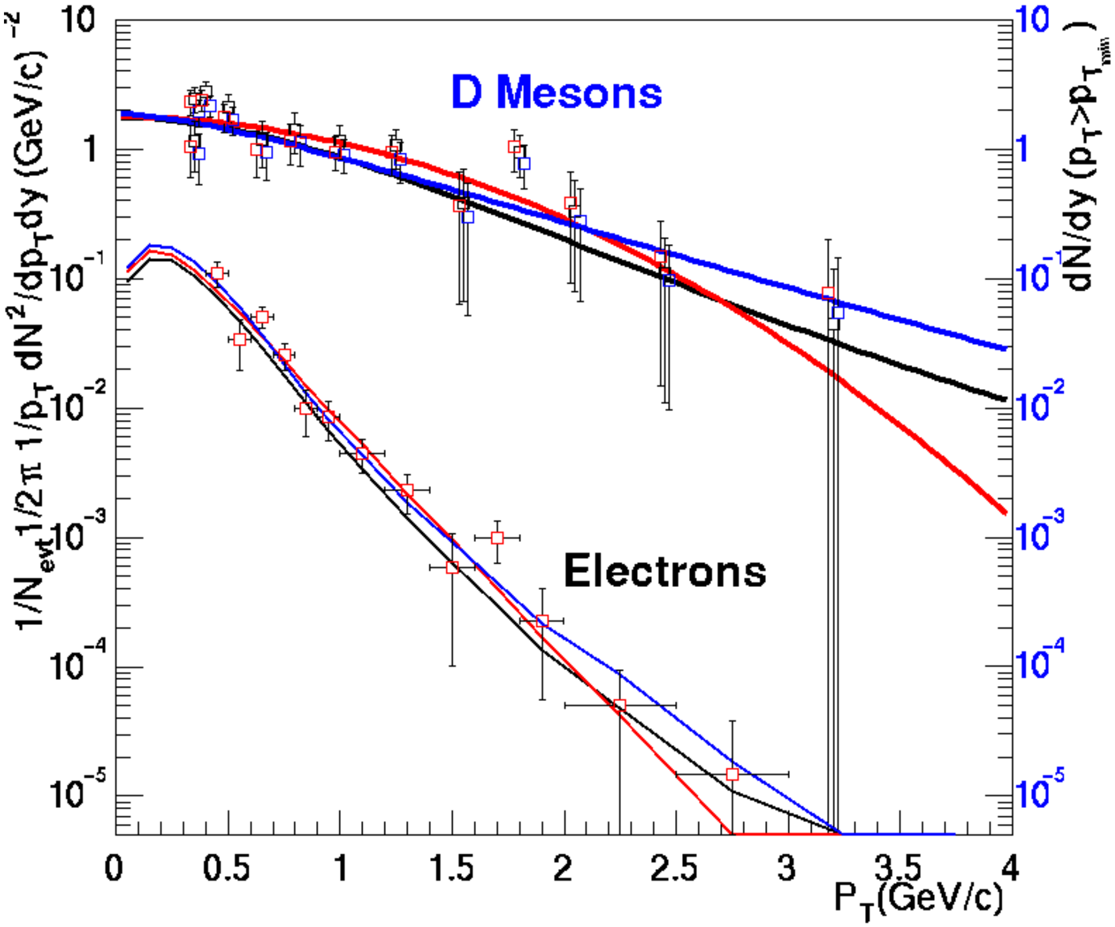


Work with Sotiria Batsouli

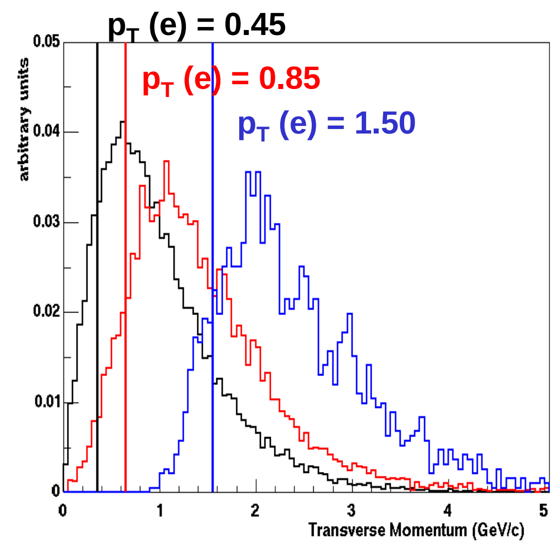
Alternate Inversion Method

One can invert the electrons point by point to a D meson yield integrated above some p_T minimum.

Much greater statistics from Run 2 should help discriminate between these models.



Distribution of D mesons that contribute to different electron bins.



Many Lepton Channels

Future measurements of single leptons at higher momentum will have large contributions from Beauty decays.

Also correlated leptons provide additional constraints and very different backgrounds.

Finally, future RHIC upgrades with inner silicon detectors may allow for displaced vertex measurements to tag the heavy meson decays.

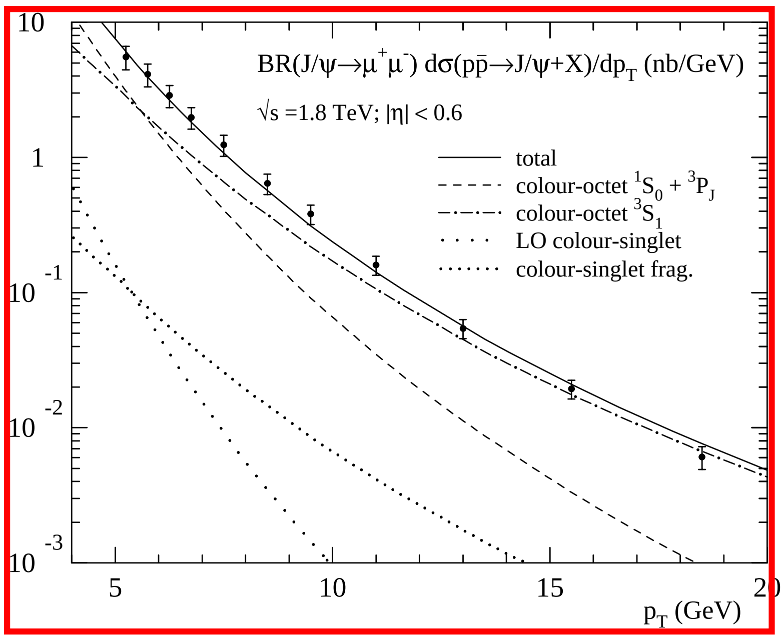
$$D^0 \rightarrow K^- \ \pi^+$$
$$D^0 \rightarrow K^- \ e^+ \nu_e$$
$$D^0 \rightarrow K^- \ \mu^+ \nu_\mu$$

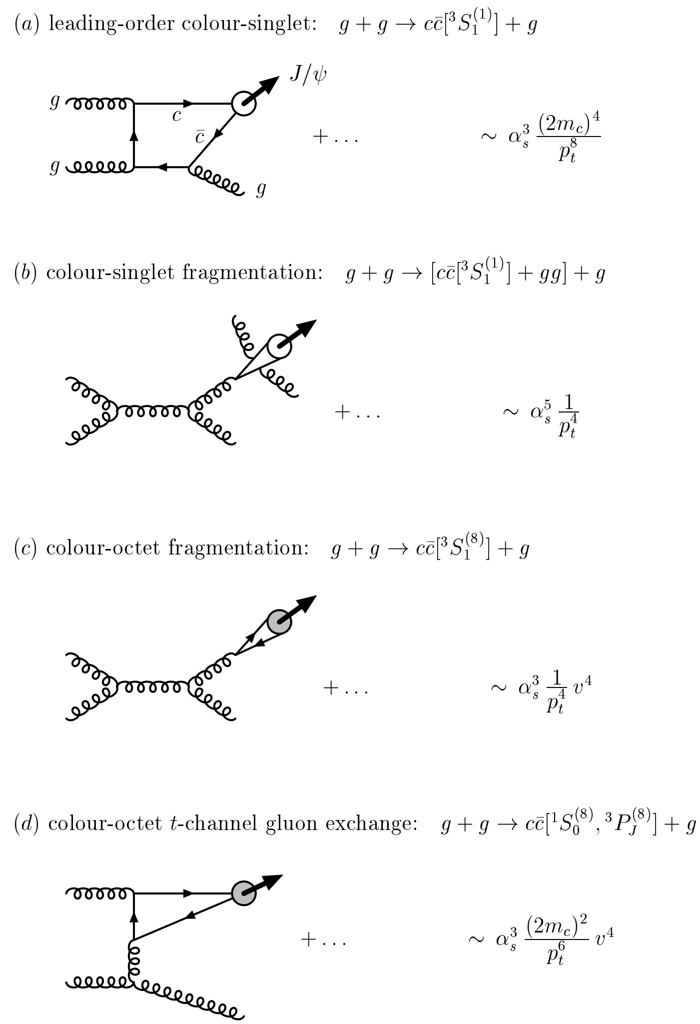
$$B^0 \rightarrow D^- \ \pi^+$$
$$B^0 \rightarrow D^- \ e^+ \nu_e$$
$$B^0 \rightarrow D^- \ \mu^+ \nu_\mu$$

$$D^0\overline{D^0} \rightarrow \mu^+\mu^- \ K^+ K^- \nu_\mu \nu_\mu$$
$$D^0\overline{D^0} \rightarrow e^+e^- \ K^+ K^- \nu_e \nu_e$$
$$D^0\overline{D^0} \rightarrow \mu^+e^- \ K^+ K^- \nu_e \nu_\mu$$

J/ψ Production

Quarkonium states are not directly produced, but have pre-cursor states. Color Octet Model (COM) necessary to explain J/ψ production at high p_T measured by **CDF** at the Tevatron.





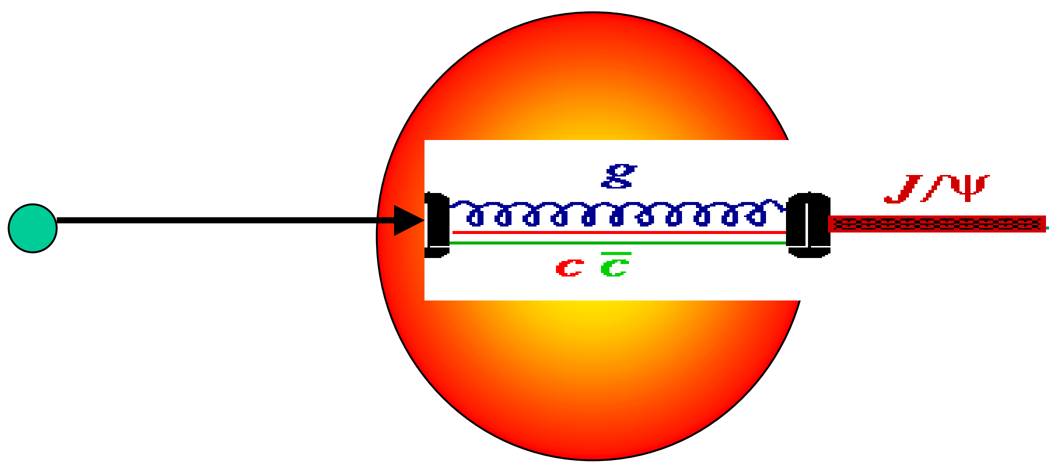
F. Abe et al., Phys. Rev. Lett. 79, 3867 (1997).
Kramer, hep-ph/0106120

Nuclear Absorption

The octet state can break-up with nucleons in the colliding nuclei with $\sigma_{ccg\text{-}N} \sim 6\text{-}7$ mb and for the singlet state $\sigma_{cc\text{-}N} \sim 2$ mb

After a proper time $\tau_{c\bar{c}g} \approx \left(2m_c\Lambda_{QCD}\right)^{-1/2} \approx 0.3\, fm/c$
the J/ψ or ψ' state is formed. After that the break-up cross section for the ψ' is larger due to the lower binding energy.

J/ψ and ψ' should have similar absorption if $\gamma\tau_{ccg} > \tau_{crossing}$



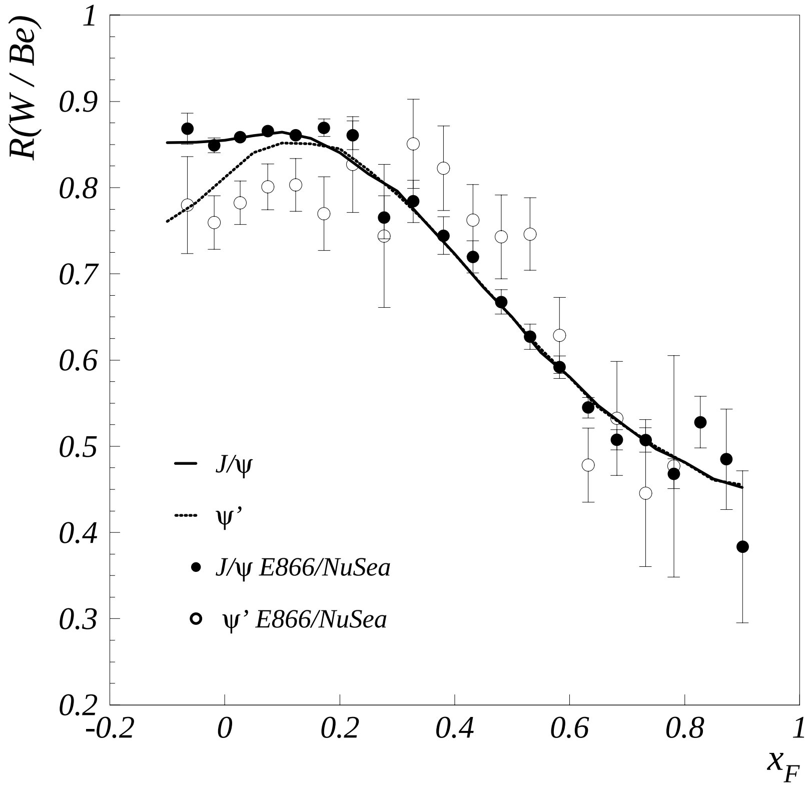
Proton-Nucleus Modeling

- Model includes both octet and singlet state contributions.
- Require $\tau_{8\text{-}1}$ = **0.02 fm/c**, much smaller than expected !
- Still shows disagreement with E866 data.

- Energy dependent breakup

$$\sigma_{(\bar{c}c)_8 N} = \sigma \cdot \left(\frac{\sqrt{s}}{10GeV} \right)^{0.4}$$

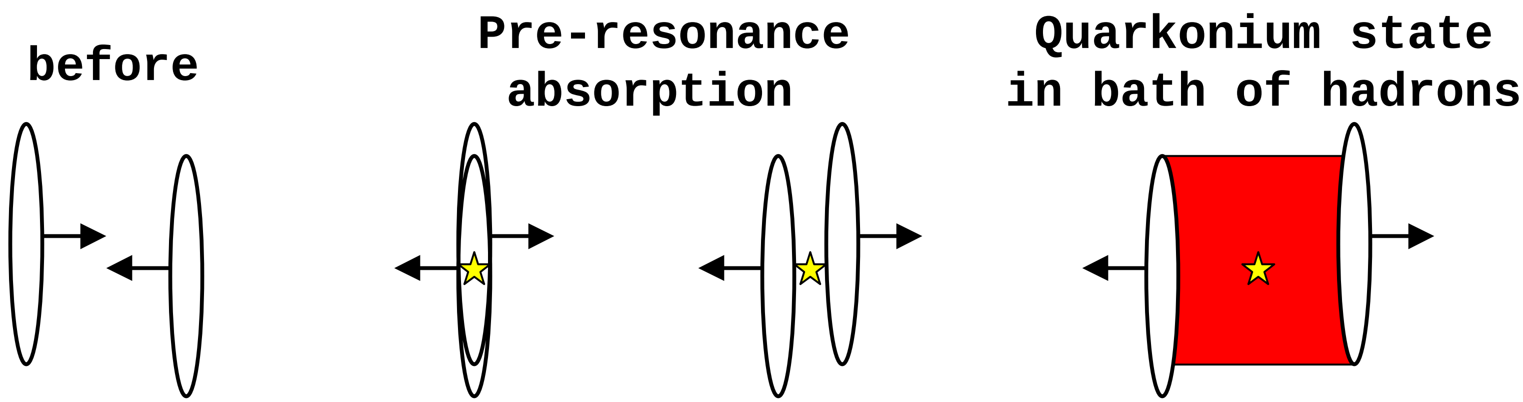
and small $\tau_{8\text{-}1}$ results in matching the large x_F observed nuclear suppression.



Arleo, Gossiaux, Gousset, Aichelin, hep-ph/9907286

Nucleus-Nucleus Collisions

We must understand the normal absorption of the J/ψ or its precursor state in normal nuclear matter.



(1) break-up by nucleons in the colliding nuclei can be studied
using p-A collisions

(2) break-up by co-moving hadrons in the produced **fireball**
is calculated to be small, <u>but calculations vary a lot!</u>

CERN Press Release 2000

http://press.web.cern.ch/Press/Release00/PR01.00EQuarkGluonMatter.html

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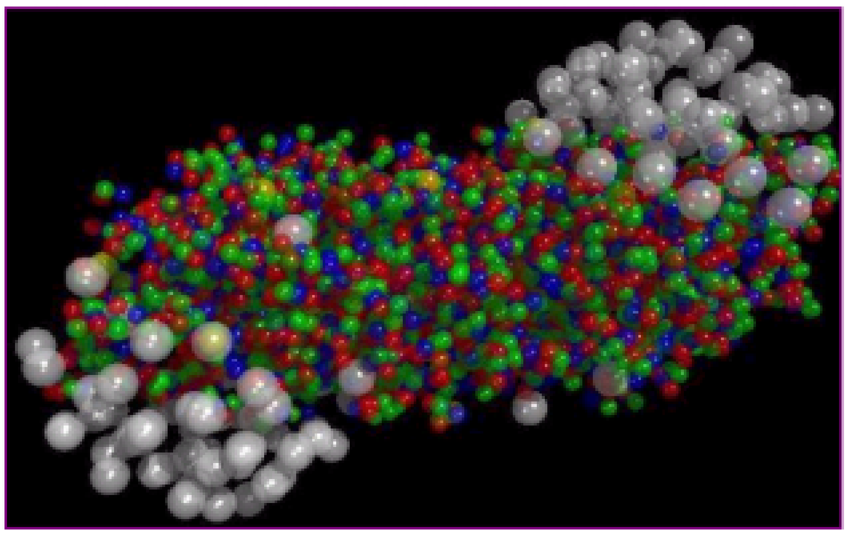
PRESS RELEASE

CERN

Organisation Européenne pour la Recherche Nucléaire
European Organization for Nuclear Research

New State of Matter created at CERN

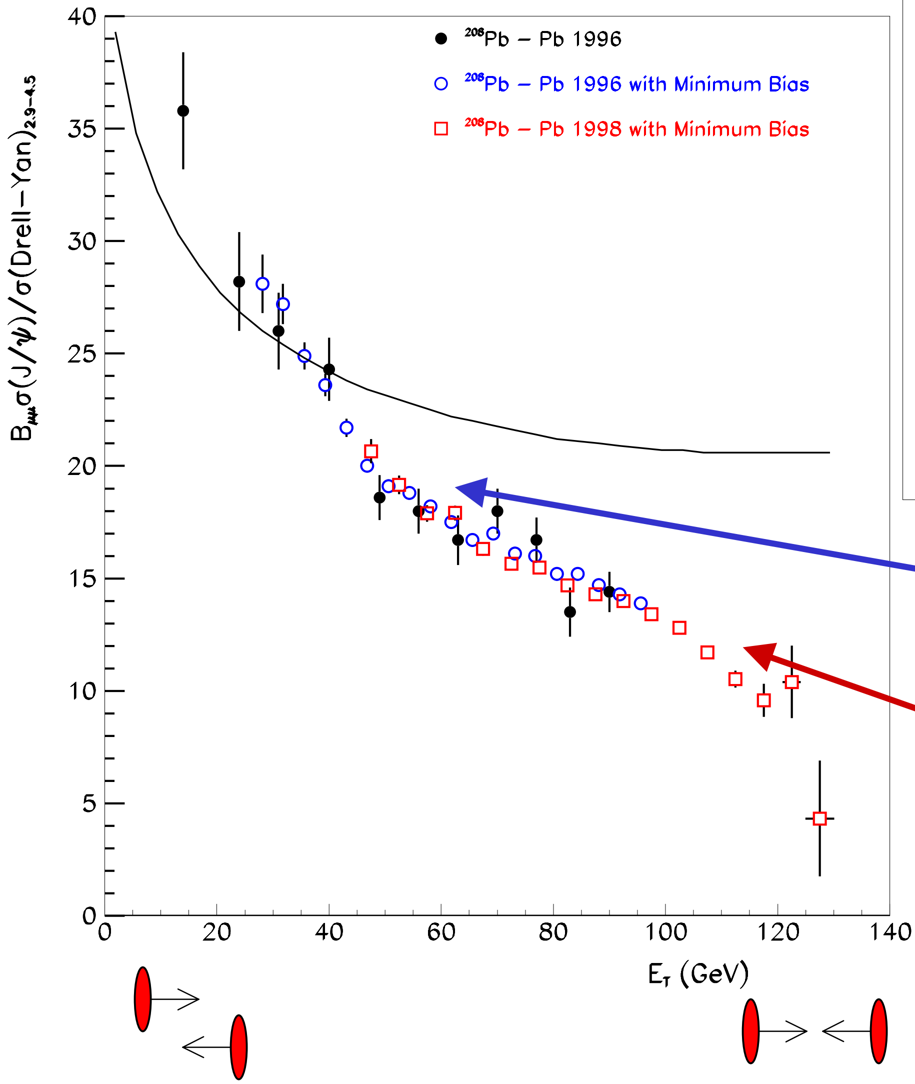


At a special seminar on 10 February, spokespersons from the experiments on CERN* 's Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

Theory predicts that this state must have existed at about 10 microseconds after the Big Bang, before the formation of matter as we know it today, but until now it had not been confirmed experimentally. Our understanding of how the universe was created, which was previously unverified theory for any point in time before the formation of ordinary atomic nuclei, about three minutes after the Big Bang, has with these results now been experimentally tested back to a point only a few microseconds after the Big Bang.

NA50 Suppression Result

NA50 at the CERN-SPS



"Strong evidence for the formation of a transient quark-gluon phase without color confinement is provided by the observed suppression of the charmonium states J/ψ, χ_c, and ψ'."

Maurice Jacob and Ulrich Heinz

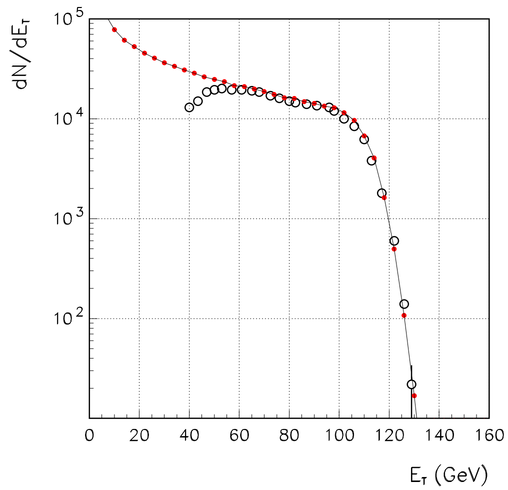
Discontinuity due to χ_c melting

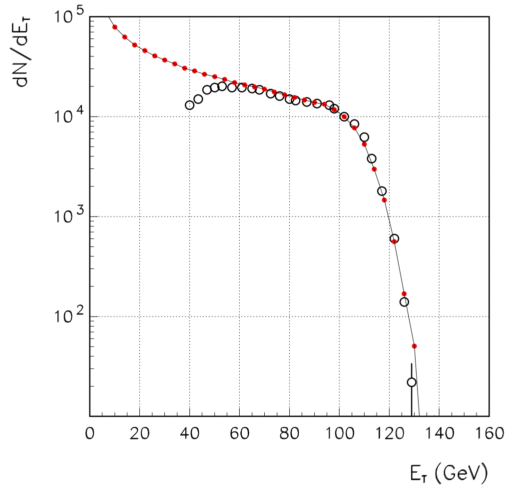
Drop due to J/ψ melting

Using Drell-Yan as control*

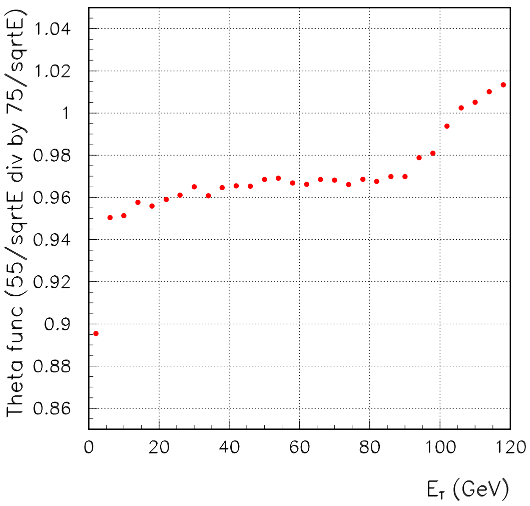
Model Bias

Mike Bennett and I find good agreement with their data in the E_T resolution range 55-75% $/\sqrt{(E_T)}$





Ratio of 55%/75% calculated N_b versus E_T



Easy to create an inflection point exactly where they see one.

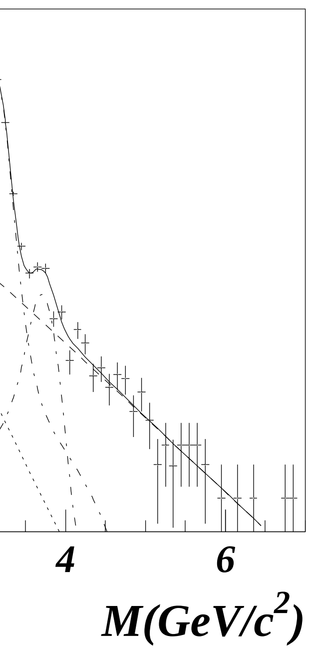
No systematic error included by NA50 for energy resolution, Glauber model parameters, transverse energy scaling.

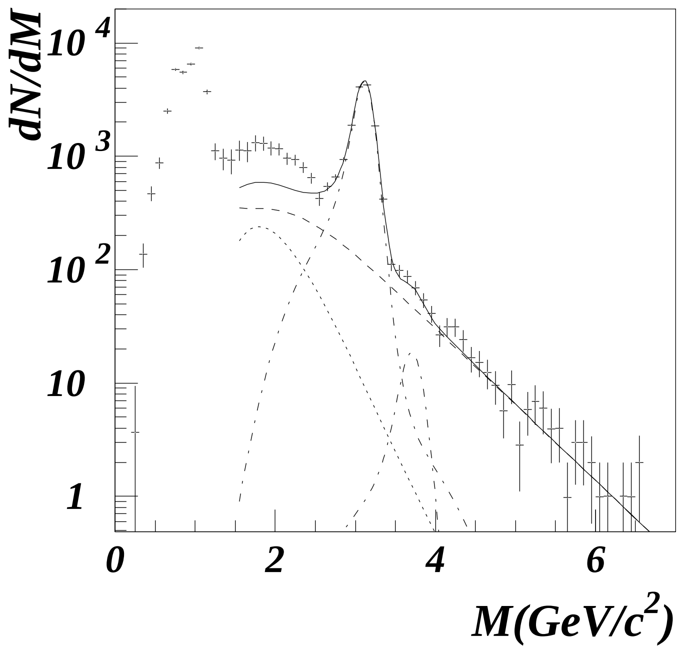
Charm Enhancement !

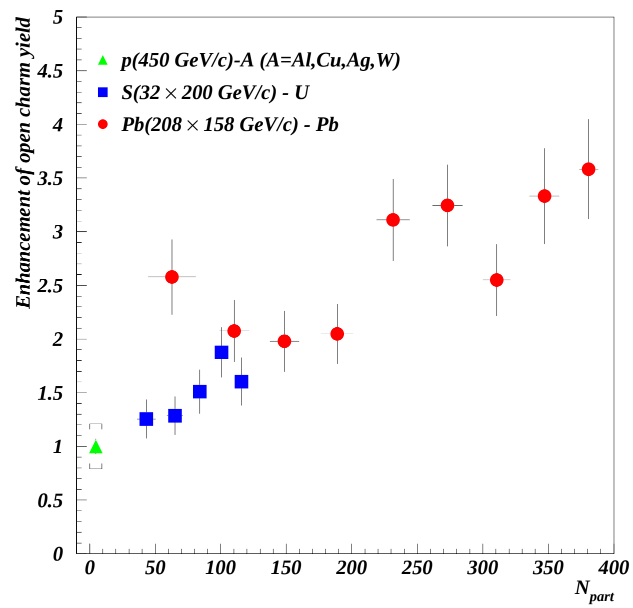
Intermediate mass region (IMR) dimuons are thought to have a large open charm contribution.

NA50 observes an enhancement of IMR relative to Drell-Yan, which scales with binary collisions.

This may imply a charm enhancement by x3.5 over binary scaling in central Pb+Pb collisions !

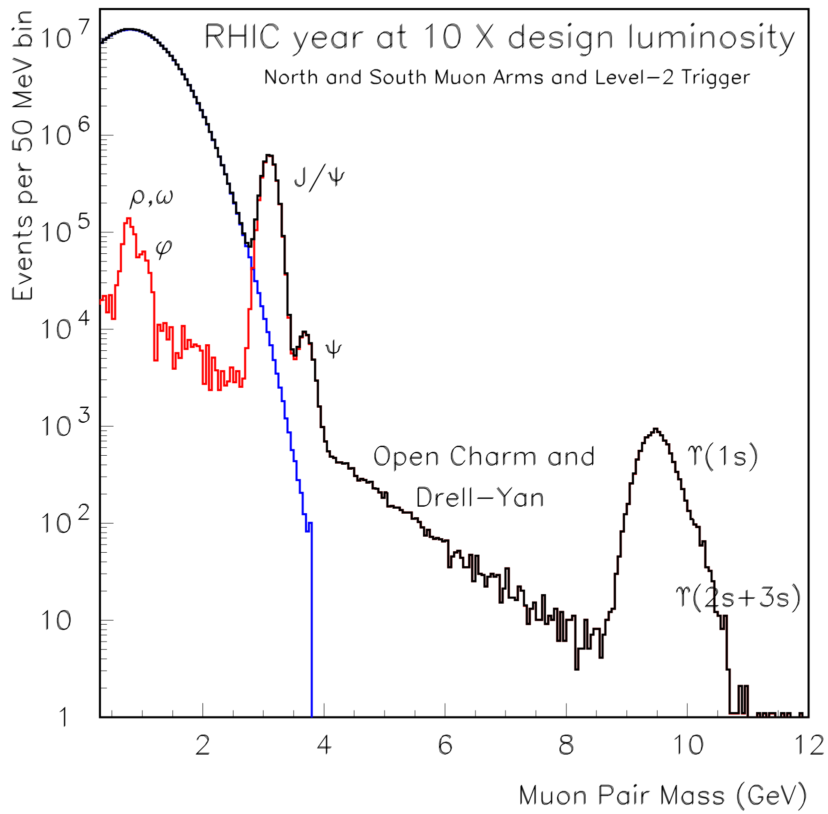




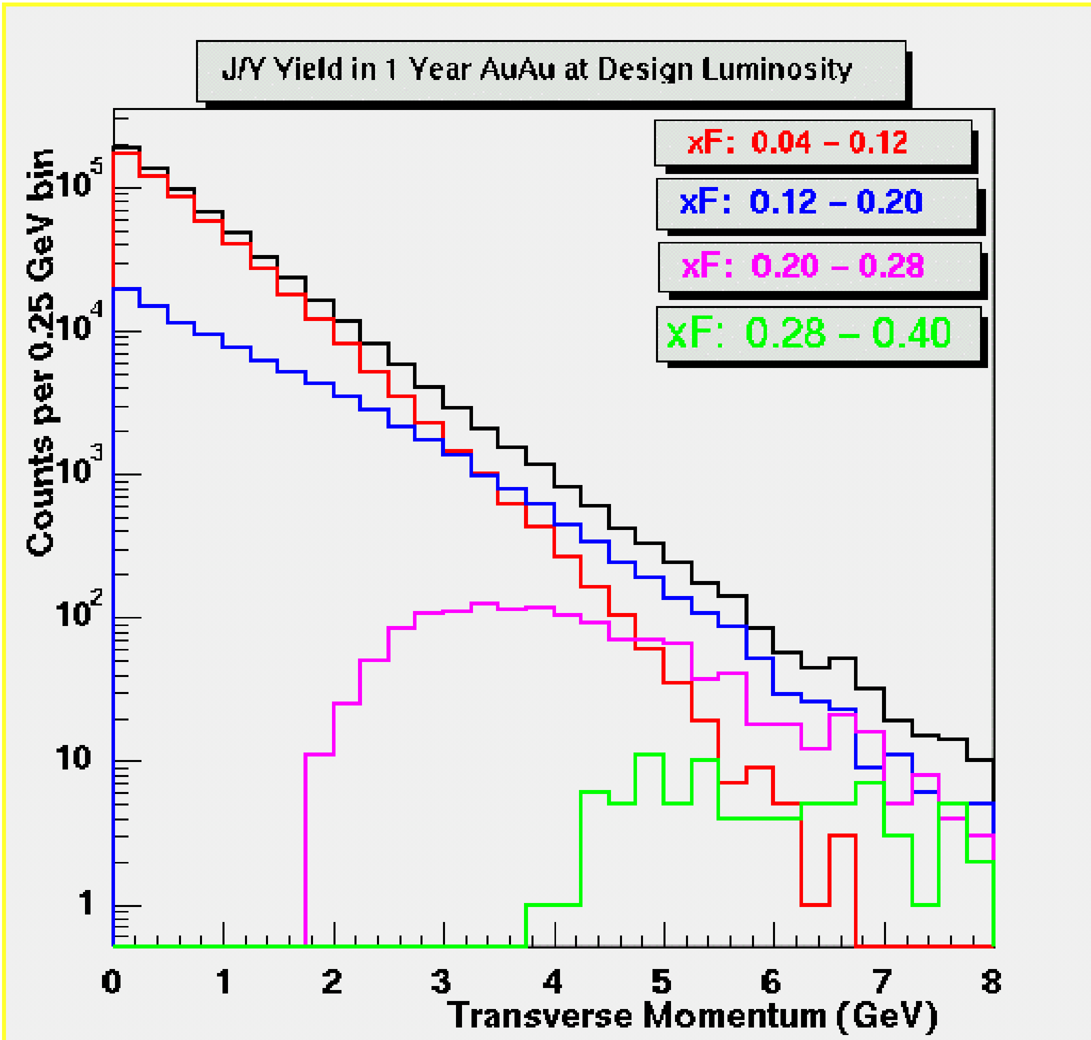


Future Measure at RHIC

At RHIC, PHENIX can measure quarkonia in the electron and muon channel. We have first low statistics data on tape. Future running at high luminosity will be required for a definitive measurement. STAR will also add a measurement in the electron channel at high p_T.



PHENIX Coverage



Conclusions, so far…

RHIC appears to be creating a hot, dense and expanding state of deconfined QCD matter

All results so far consistent (but not conclusive) with this interpretation

- initial conditions - saturated gluon distributions from color glass condensate
- energy density - exceeds lattice QCD expectations
- plasma state - large parton scattering for hydrodynamic expansion
- hard probes - parton energy loss from deconfined medium

RHIC experiments have two orders of magnitude more data in Run II. More stringent tests required of models. Polarized proton-proton data taking just completed. Exciting years ahead of physics discovery !

High Intensity Future Awaits