Critical Review of J/ψ Suppression and Future Prospects

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IN THE CITY OF NEW YORK

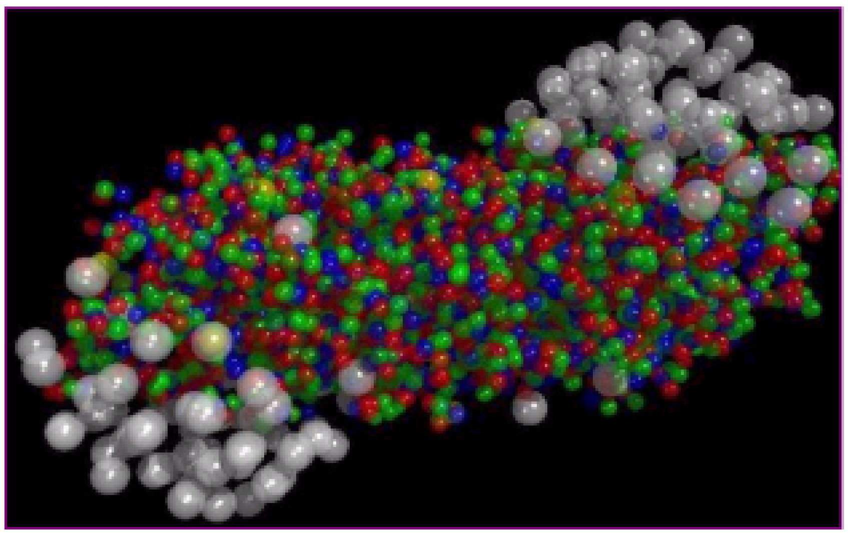
Gordon Conference
QCD in Extreme Conditions:
High Temperature, High Density, and Small-x
July 22 - 27, 2001 Newport, RI

CERN Press Release

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

Organisation Européenne pour la Recherche Nucléaire
European Organization for Nuclear Research

New State of Matter created at CERN

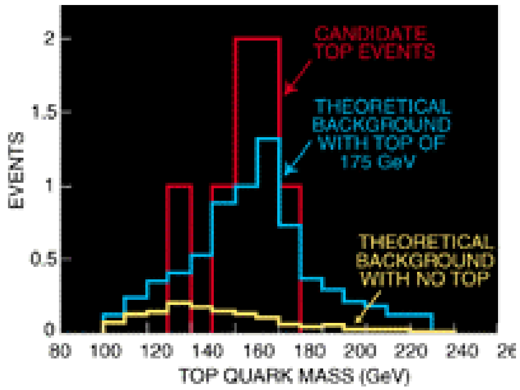


At a special seminar on 10 February, spokespersons from the experiments on CERN* 's Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

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.

Top Quark Standard

March 2, 1995



"Both CDF and D0 report a probability of less than one in 500,000 that their top quark candidates could be explained by background alone."

Followed by simultaneous publication in Physical Review Letters and accompanying detailed articles for review.

- It is unrealistic to expect a statement like "there is a probability of less than one in 500,000 that these data are explained by non-plasma models alone."
- However, the same level of scrutiny is expected given the scientific importance.
- There is no scientific paper on the CERN conclusions. However, on J/ψ suppression there are specific conclusions in the literature.

J/ψ Evidence

NA50 Publications

Evidence for deconfinement of quarks and gluons

from the J/psi suppression pattern
measured in Pb-Pb collisions at the CERN-SPS
Physics Letters B, in print; CERN-EP-2000-013 PS file

Dimuon and charm production in nucleus-nucleus collisions at the CERN-SPS
Euro. Phys. J. C, in print; CERN-EP-2000-012 PS file

Low mass dimuon production in proton and ion induced interactions at the SPS
European Physics Journal C13 (2000) 69; CERN-EP / 99-112-Rev PS file

Observation of a threshold effect

in the anomalous J/psi suppression
Physics Letters B450 (1999) 456; CERN-EP / 99-13 PS file

Observation of Fission in Pb-Pb Interactions at 158 A GeV
Physical Review C59 (1999) 876 Text (PS file) and Figures (PS file)

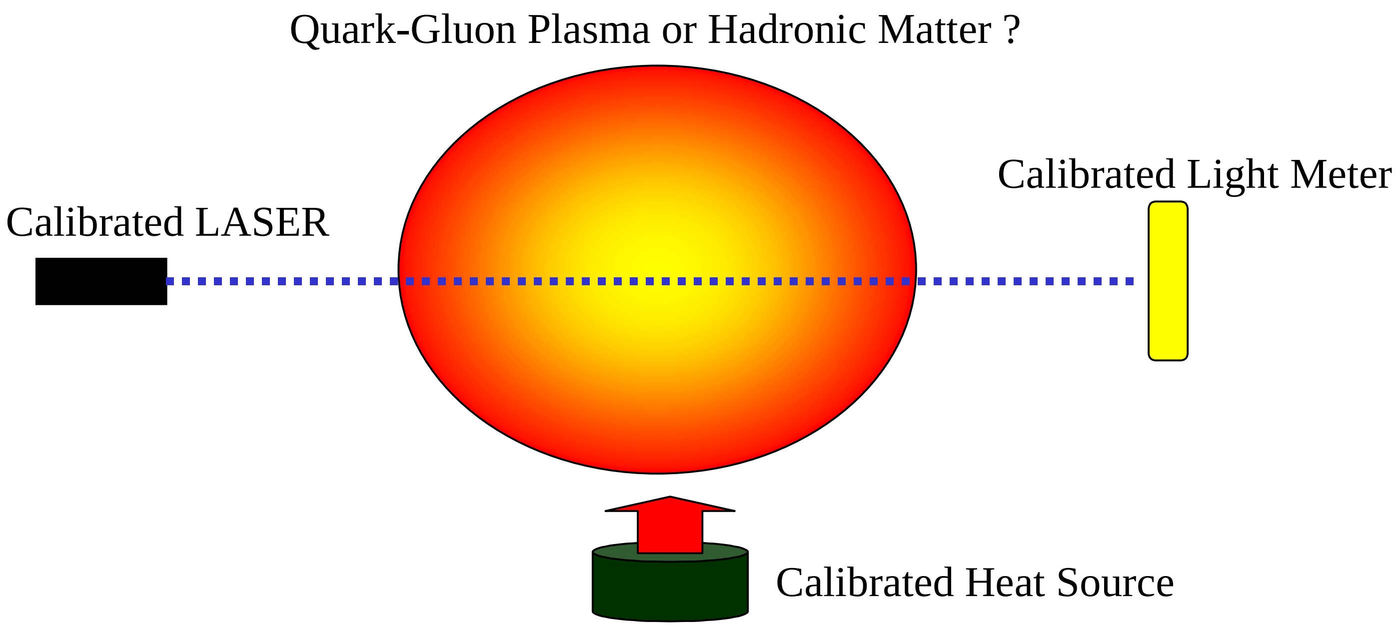
J/psi, psi' and Drell-Yan production in pp and pd interactions at 450 GeV/c
(NA51 Collaboration)
Physics Letters B438 (1998) 35 PS file

The quartz-fiber Zero-Degree Calorimeter for the NA50 experiment at CERN SPS
Nuclear Instruments and Methods in Physics Research A411 (1998) 1

Anomalous J/Psi suppression

in Pb-Pb interactions at 158 GeV/c per nucleon
Physics Letters B410 (1997) 337 PS file

A Good Experiment



Plasma or not: Confined media are essentially transparent to J/ψ's, while deconfined media are J/ψ opaque

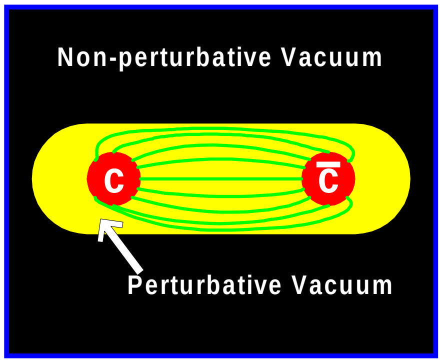
Calibrated Heat Source: Energy density/temperature varied through collision energy and centrality

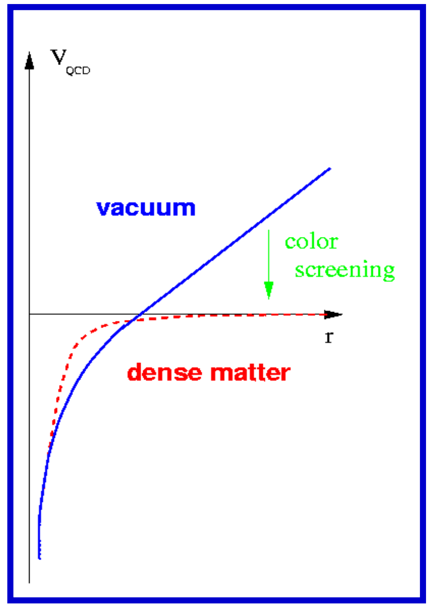
Calibrated LASER: Initial charm production and the formation of bound states

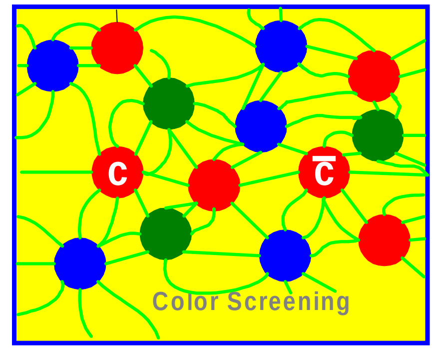
Calibrated Light Meter: Experimental measurement of J/ψ and vector meson states

What happens in a Plasma?

Long range confining potential is screened in a plasma state





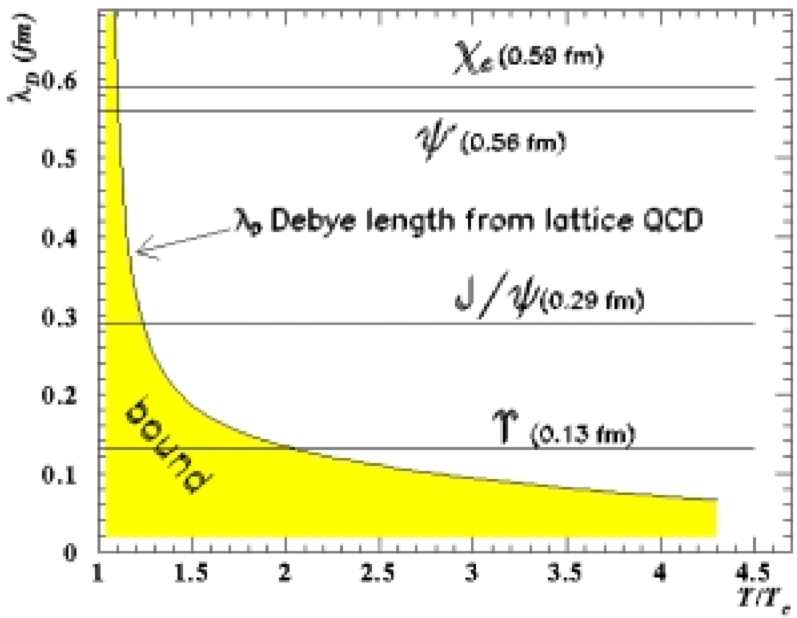


Alternative viewpoint is that semi-hard gluons are required for J/ψ breakup

QCD 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.

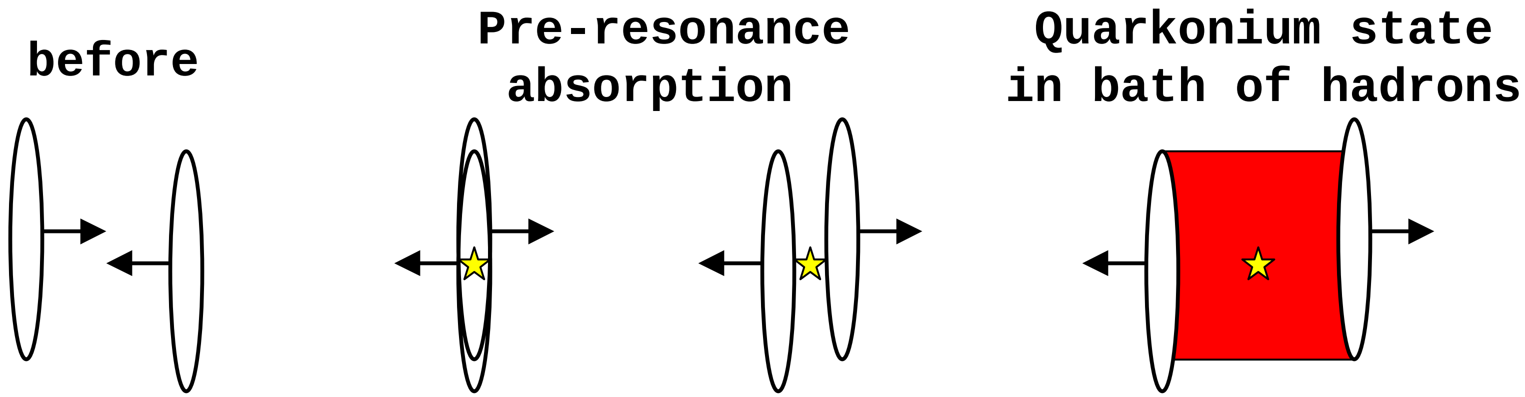


state	J/ψ	χ_c	ψ'	Υ(1s)	χ_b	Υ(2s)	χ_b'	Υ(3s)
Mass [GeV}	3.096	3.415	3.686	9.46	9.859	10.023	10.232	10.355
B.E. [GeV]	0.64	0.2	0.05	1.1	0.67	0.54	0.31	0.2
T_d/T_c	---	0.74	0.15	---	---	0.93	0.83	0.74

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

What happens in confined matter?

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

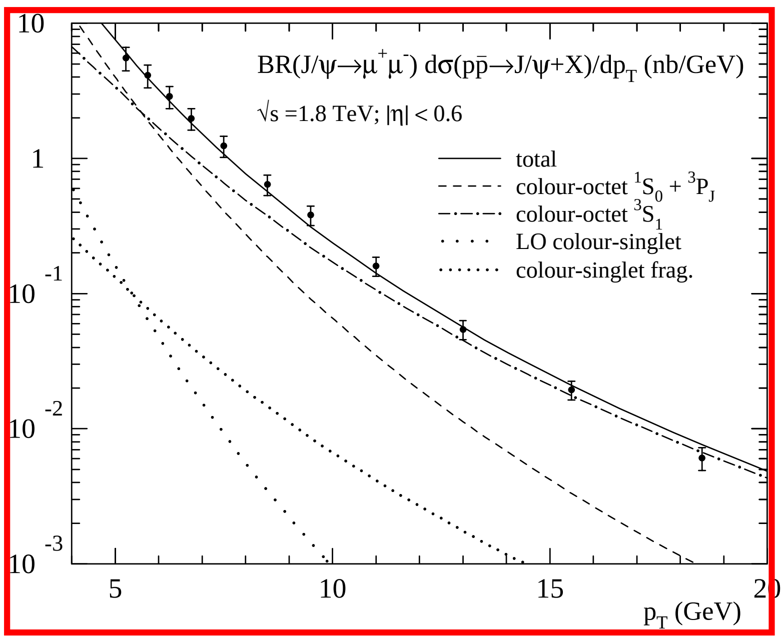


(1) break-up by nucleons in the colliding nuclei can be studied using p-A collisions

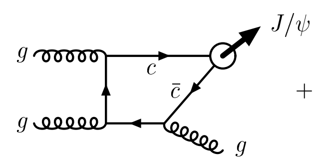
(2) break-up by co-moving hadrons in the produced **fireball** is calculated to be small, <u>but calculations vary a lot!</u>

Understanding Production

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

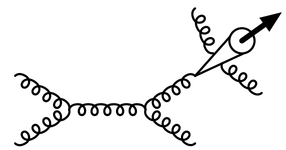


(a) leading-order colour-singlet: $g + g \to c\bar{c}[^3S_1^{(1)}] + g$



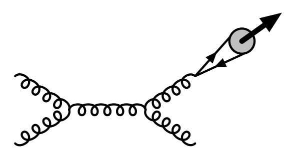
$+\dots \qquad \sim \alpha_s^3 \frac{(2m_c)^4}{p_t^8}$

(b) colour-singlet fragmentation: $g + g \to [c\bar{c}[^3S_1^{(1)}] + gg] + g$



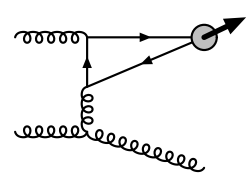
$+\dots \qquad \sim \alpha_s^5 \frac{1}{p_t^4}$

(c) colour-octet fragmentation: $g + g \to c\bar{c}[^3S_1^{(8)}] + g$



$+\dots \qquad \sim \alpha_s^3 \frac{1}{p_t^4} v^4$

(d) colour-octet t-channel gluon exchange: $g + g \to c\bar{c}[^1S_0^{(8)}, {}^3P_J^{(8)}] + g$



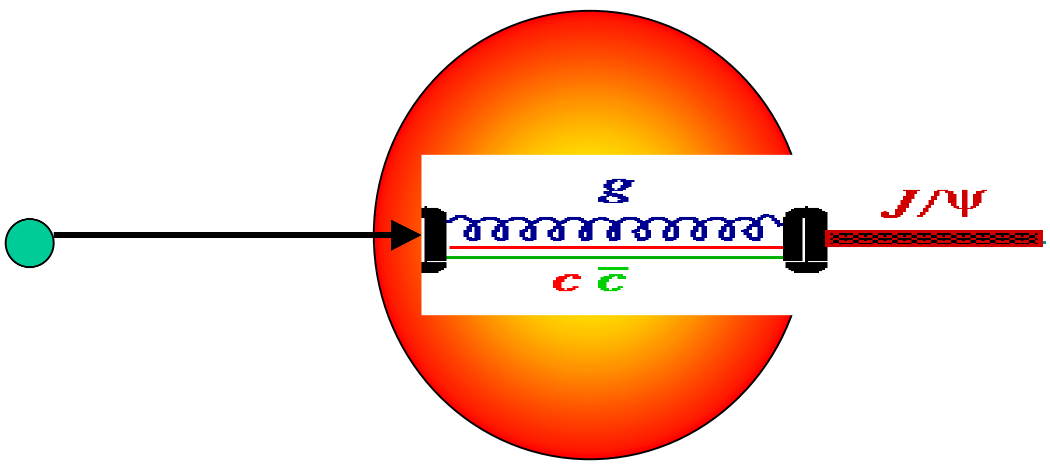
$+\dots \qquad \sim \alpha_s^3 \frac{(2m_c)^2}{p_t^6} v^4$

p+A Control Experiment

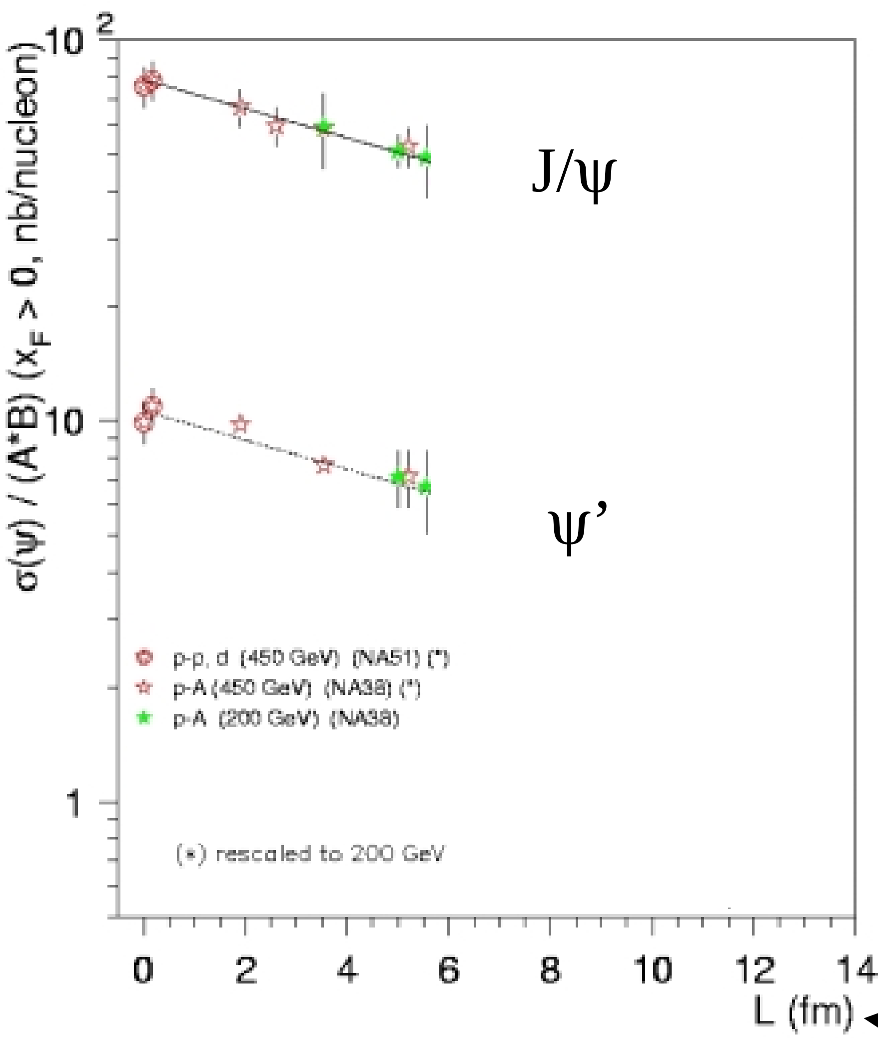
The octet state can break-up with nucleons in the colliding nuclei with $\sigma_{ccg\text{-}N}$~ 6-7 mb and for the singlet state $\sigma_{cc\text{-}N}$~2 mb.

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 $\gamma\tau > \tau_{crossing}$



The L Plot



Early p-A data from NA38, NA51at CERN and E772 at FNAL indicate similar break-up for J/ψ and ψ' consistent with Color Octet Model pre-cursor state.

$$\sigma_{c\bar{c}g-N} = 7.2 \pm 0.6mb$$

path through the nucleus

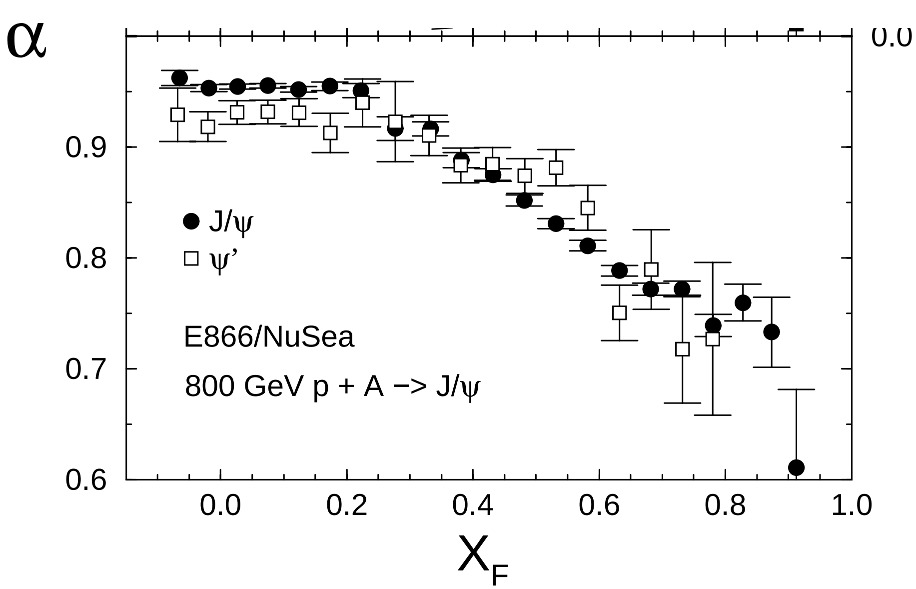
E866/NUSEA at FNAL

The full picture is much richer or more complex depending on your viewpoint.

However at x_F = xx the J/ψ and ψ' should be formed outside the nucleus. Why do the values of α not agree?

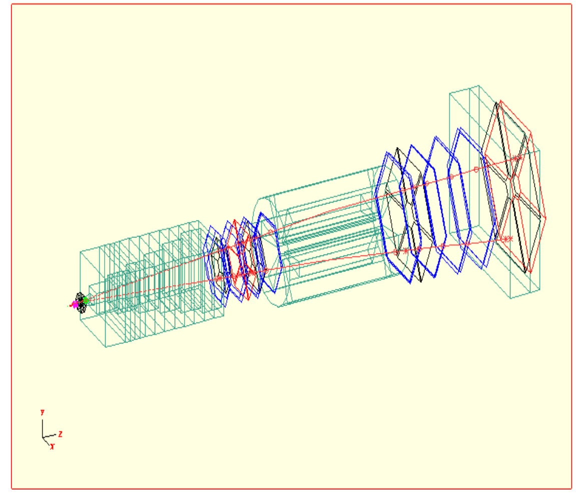
Different physics at high $x_{F.}$

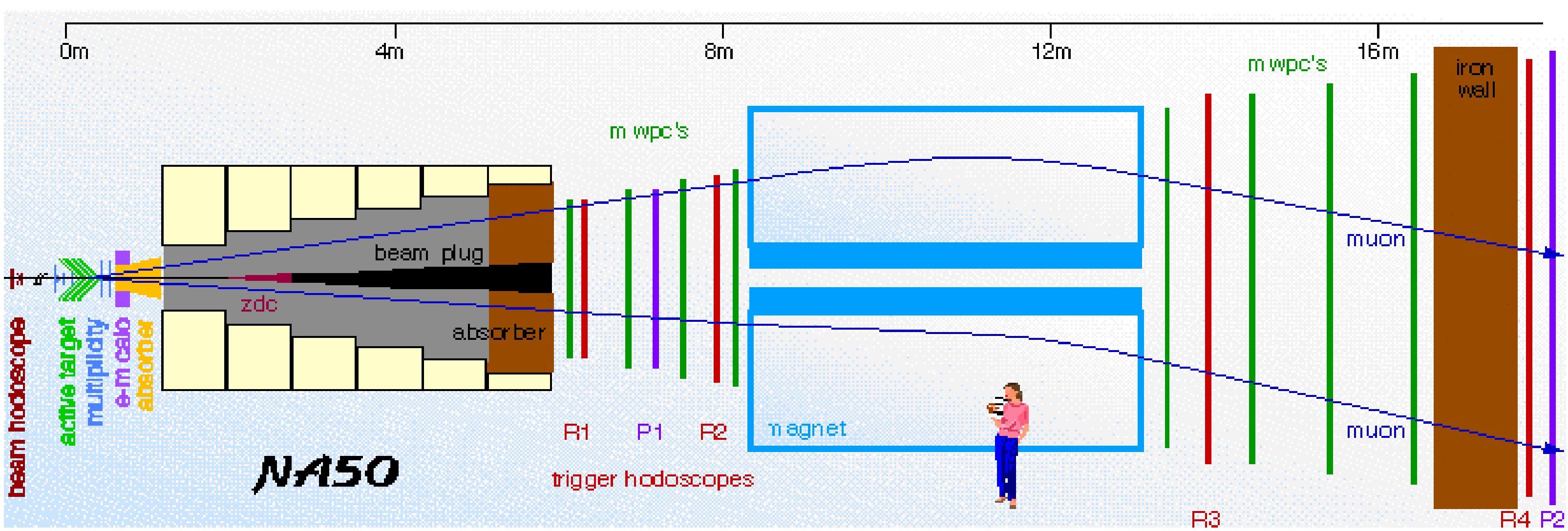
$$\sigma_{pA \to J/\psi} = \sigma_{pp \to J/\psi} \times A^{\alpha}$$



NA50: “Calibrated Light Meter”

- Excellent muon identification
- Triggering using hodoscopes
- High flux of incident beam
  - ~ 5 x 10^7 ions / spill
- Large Data Sample
  - ~ 2 x 10^5 J/ψ

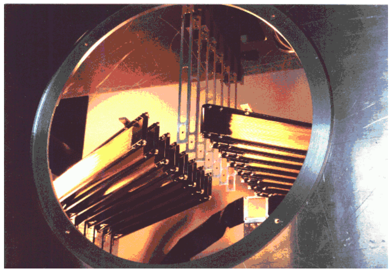




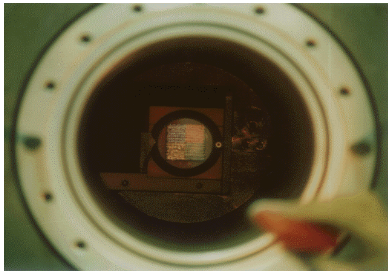
NA50 Pictures

Muon Spectrometer

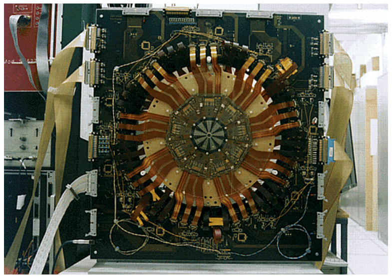
Active Target



Zero Degree Calorimeter

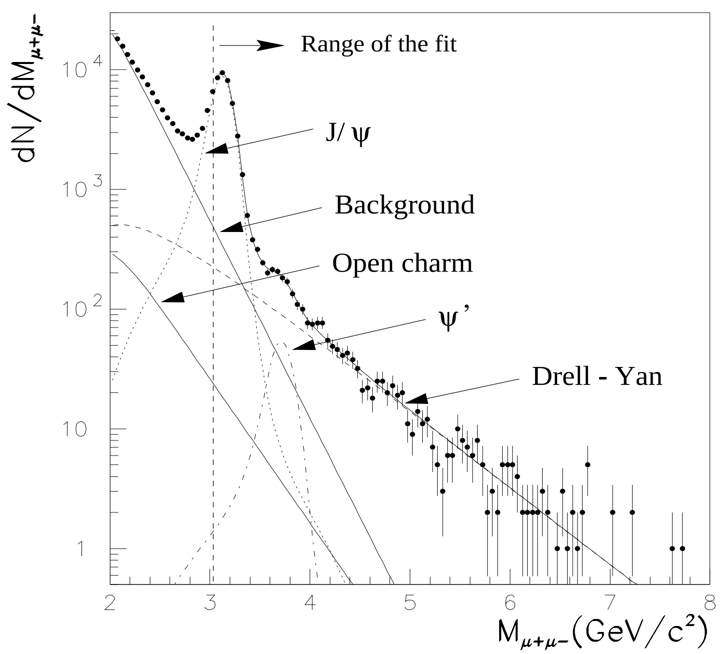


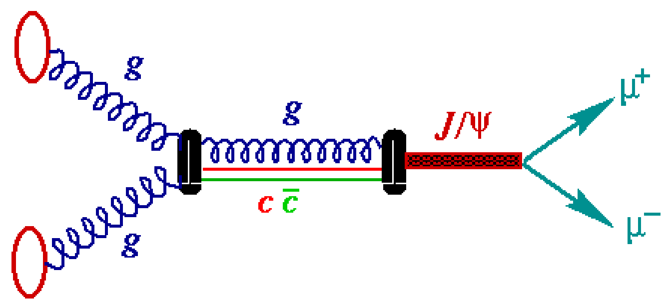
Multiplicity Detector

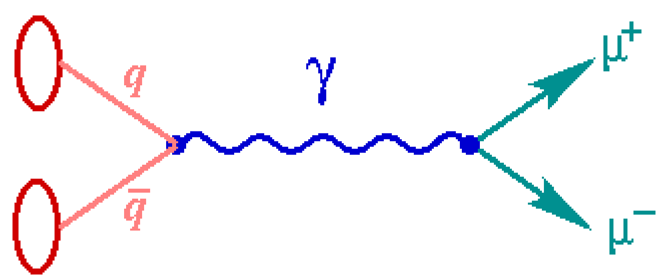


Calibrating the Laser

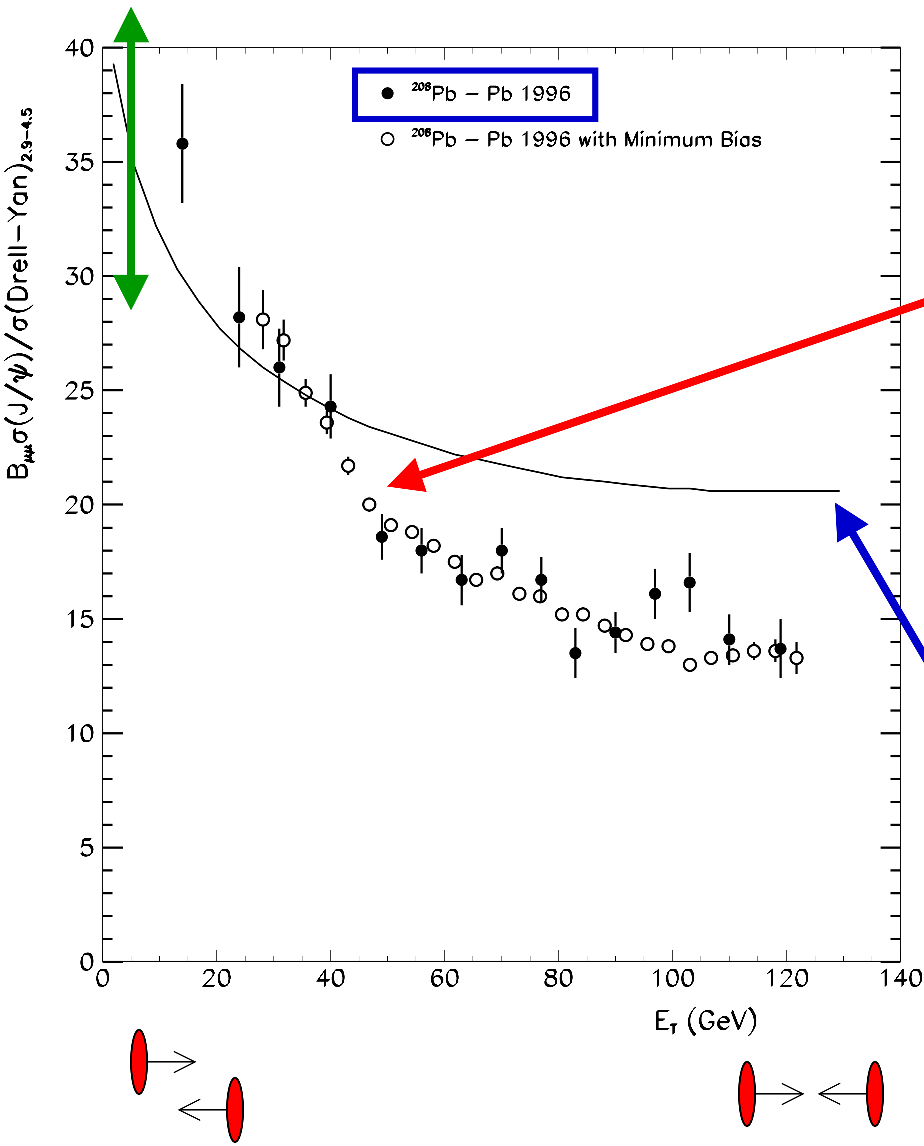
NA50 measures the J/ψ yield. However, there is no measurement of the charm cross section. Therefore they use Drell-Yan as a calibration of the hard production.
Drell-Yan is indifferent to traversing a quark-gluon plasma or hadronic fireball and thus provides a standard candle.







Pb+Pb Results for (J/ψ)/DY



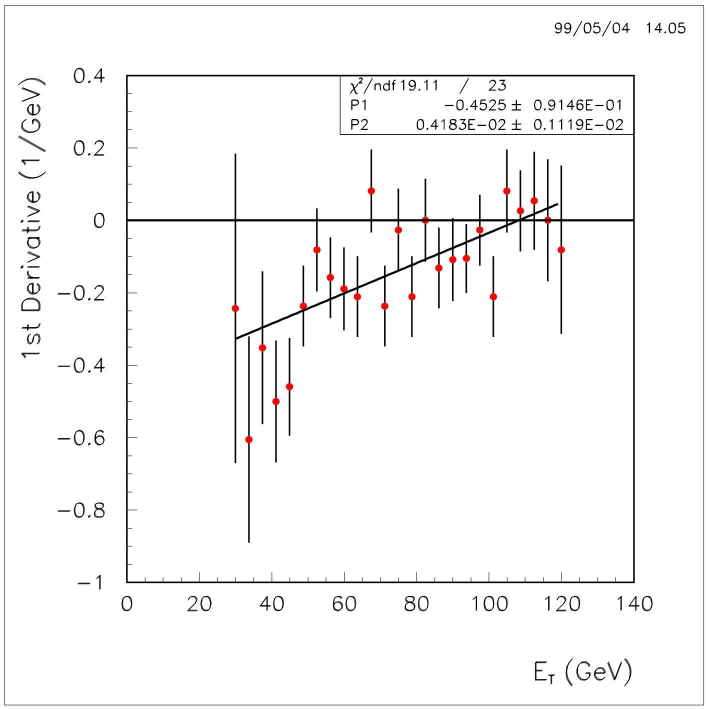
"A clear onset of the anomaly is observed. It excludes models based on hadronic scenarios since only smooth behavior with **monotonic derivatives** can be inferred from such calculations"

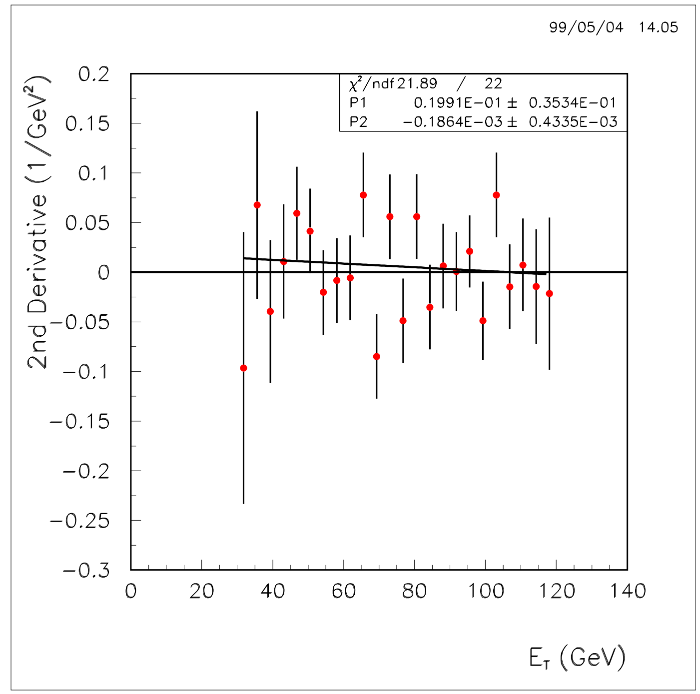
Phys. Lett. B 450, 456 (1999).

Model calculation assumes:

- charm production scales as DY
- color octet is absorbed by nucleons with σ = 7 mb
- no absorption with comovers π,ρ

Non-Monotonic Derivatives?

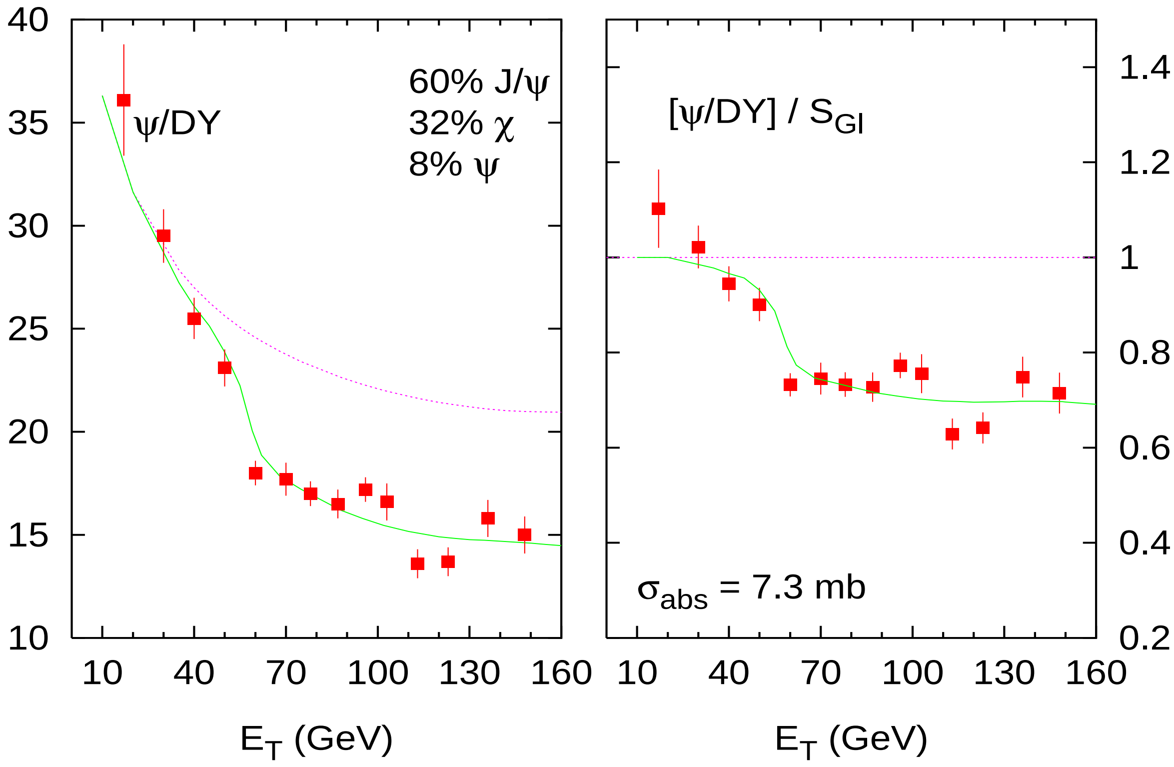




Not only are the derivatives monotonically changing, but the first derivative is linearly changing with a χ^2/dof = 19.1/23. There is an interesting suppression relative to the model, but the statement about non-monotonic derivatives is just wrong.

Plasma Theory

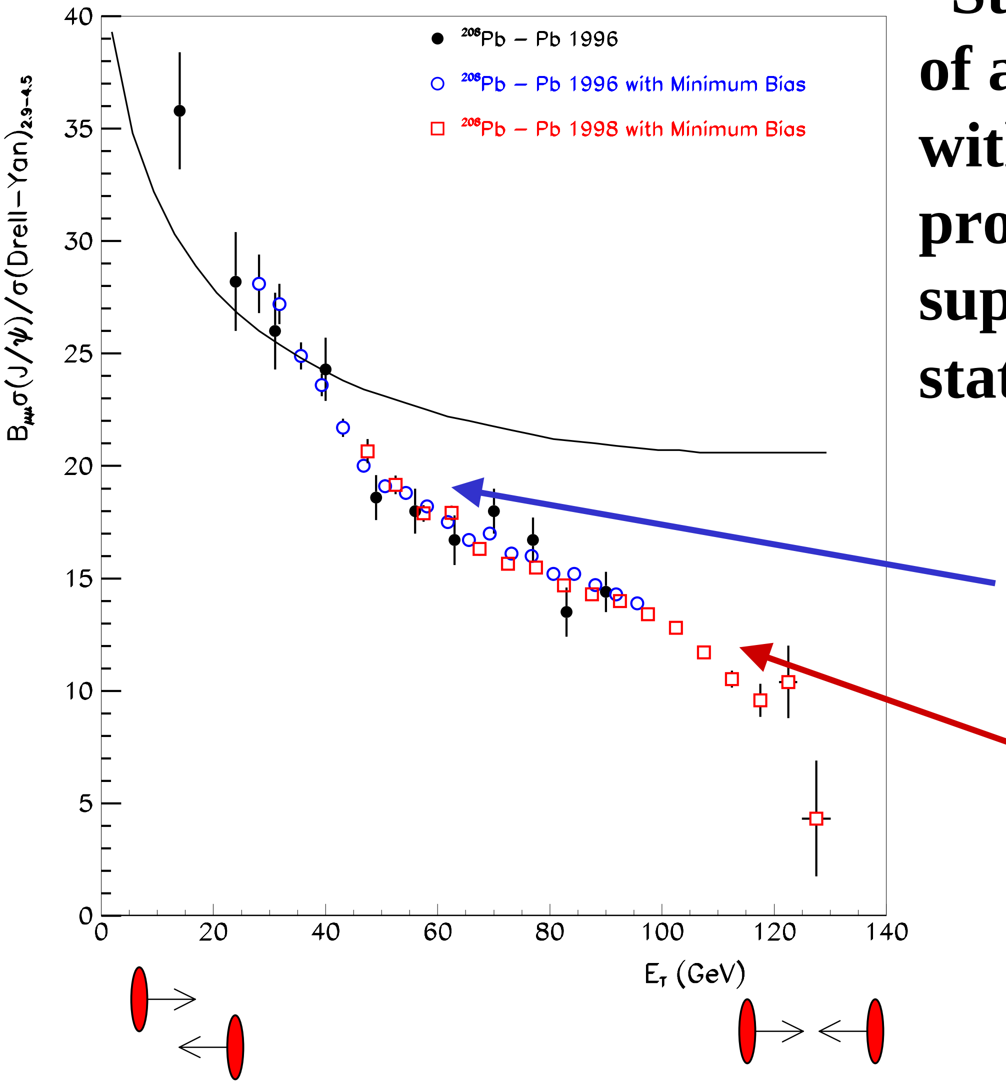
Invoking a model of bubble nucleation, one is able to reproduce the suppression. **This implies a first order phase transition.** Or what about second order with finite volume effects?



D. Kharzeev, Nucl. Phys. A638, 279a (1998).

New Data: Sequential Suppression

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

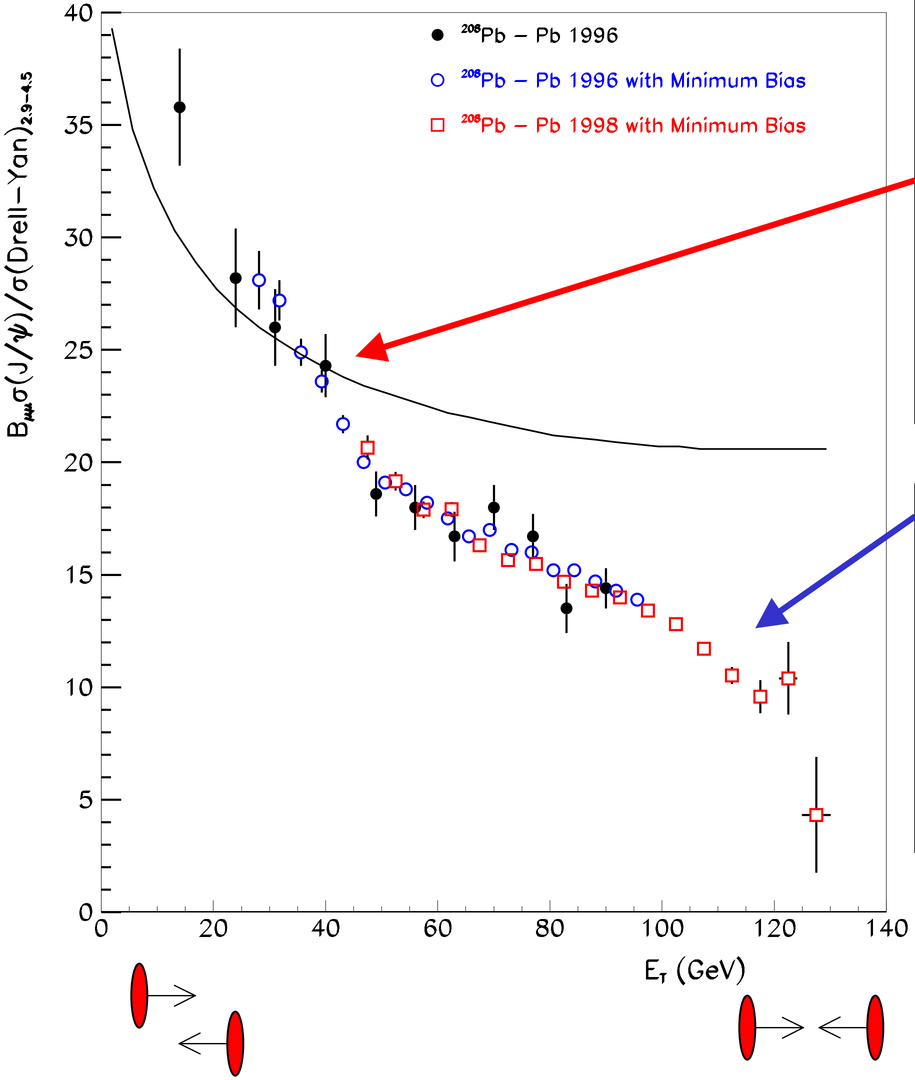
Discontinuity due to χ_c melting

Drop due to J/ψ melting

Using Drell-Yan as control*

What changed?

NA50 at the CERN-SPS

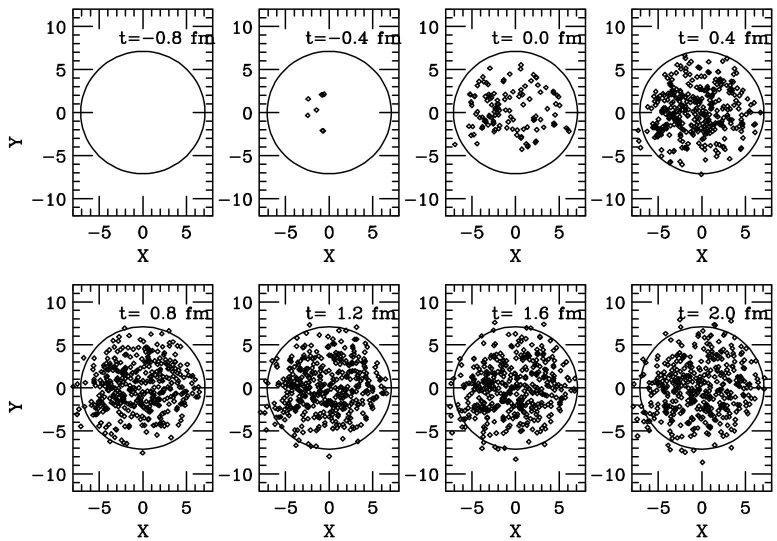


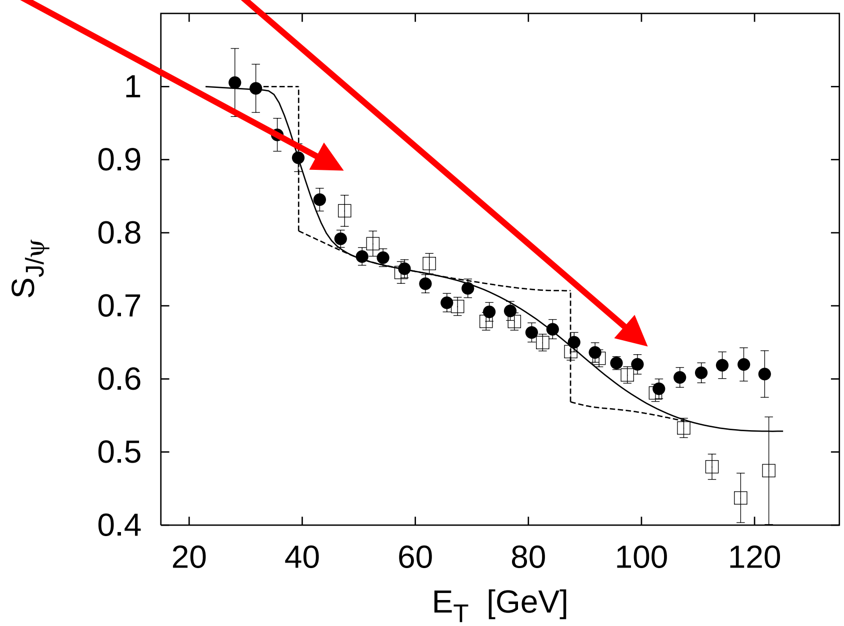
<u>1998 data not included on plot:</u>
With a 7% target in 1998 there was a "high contamination of Pb-air interactions, [but is] found to be negligable for E_T > 40 GeV. Since the main goal of the 1998 run is to study the suppression pattern in central Pb-Pb collisions, we have limited the analysis to E_T > 40 GeV."

<u>1996 data not included on plot:</u>
"With a 30% target, it is conceivable that a spectator fragment from a first peripheral collision reinteracts downstream, resulting in measured values of E_T and E_{ZDC} typical of central collisions."

Percolation

Percolation model of H. Satz looks at localized parton densities and above a critical density assumes a first order phase transition (similar to bubble production). Sequential melting of χ_c and J/ψ seen.



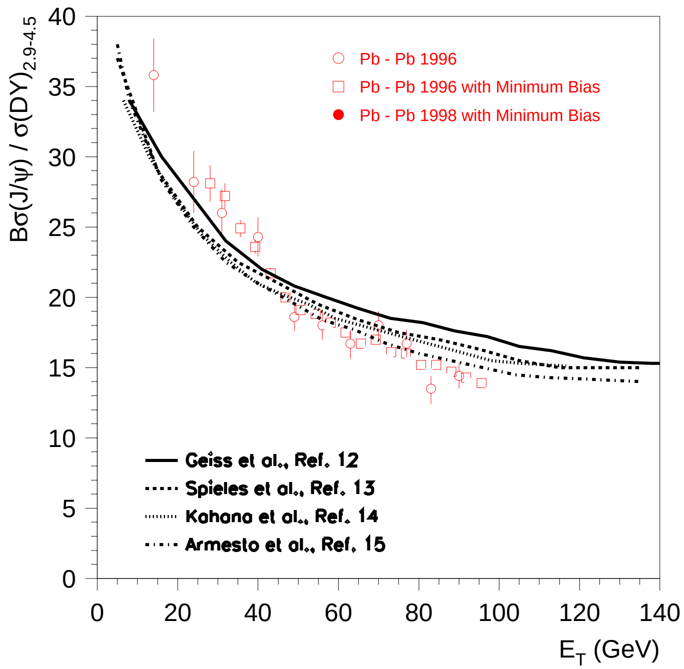


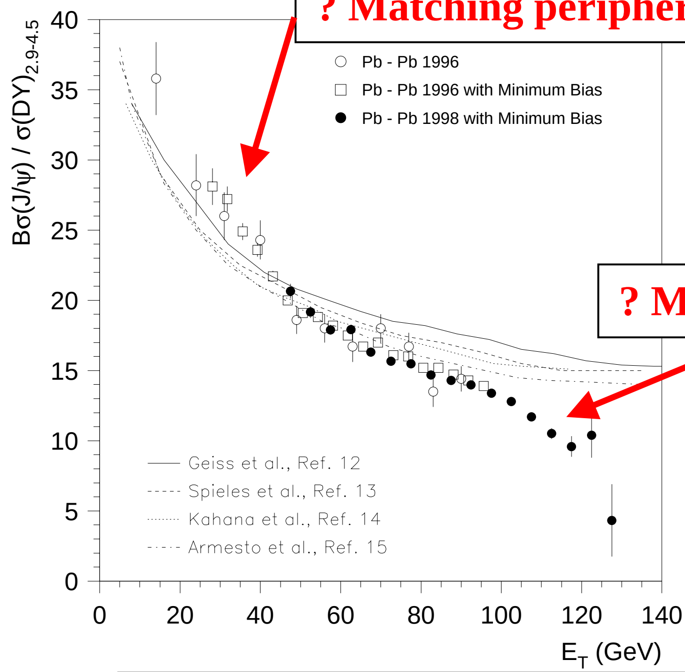
H. Satz: hep-ph/9908339

“Hadronic” Models

There is expected “hadronic” suppression of J/ψ due to:

- pre-resonance absorption on target and projectile nucleons
  - * remember how well this is understood from E866 data
- final state interactions with π , ρ , etc.
  - * cross sections not well known





? Matching peripheral data

? Matching central data

? Consistent with p+A,S+U and p+A (*Fermilab)

Figure 6: Comparison between our data and several conventional calculations of J/ψ suppression.

Figure 6: Comparison ... suppression.

The Emperor's New "Calibrated Laser"

We want to know what fraction of charm quark pairs form J/ψ.

Best Calibrated LASER

Thus we would like to measure D mesons via displaced vertices. Since we cannot do that we might assume that charm production scales as hard processes do with the number of binary collisions (or the nuclear thickness function T_{AB}).

Next Best Calibrated LASER

Drell-Yan was thought to be a good model, though it reflects the q-qbar distribution, and not the gluons that dominate charm production. Also statistics in NA50 were somewhat lacking.

Next to the Next Best Calibrated LASER

Thus NA50 uses a Glauber model to calculate Nbinary.
Why does NA50 call this "Drell-Yan Minimum Bias"?

They normalize to the Drell-Yan measured yield. The Red Herring

Glauber Modeling

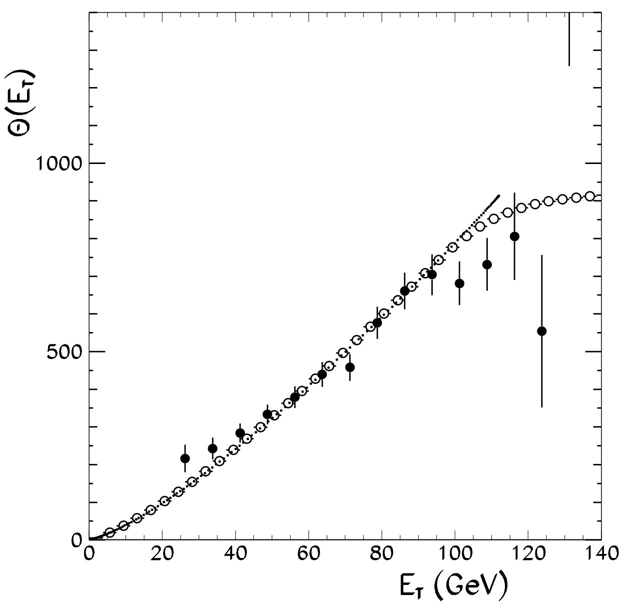
Simple Glauber model that assumes:

$E_T = A \times N_{participants}$

$DY = B \times N_{binary}$

E_T resolution = 94% /$\sqrt{(E_T)}$ - empirically determined!

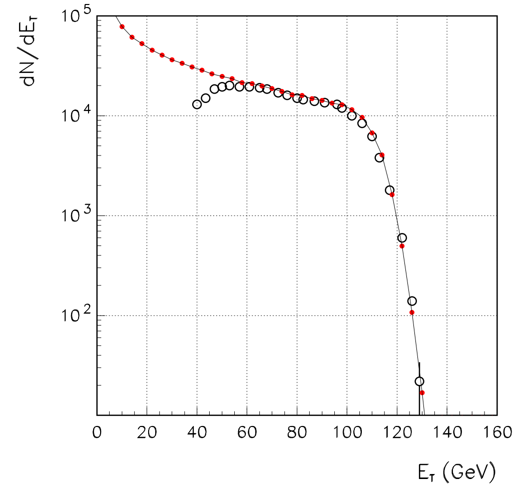
Compare model to Drell-Yan data. Not bad although note the disagreement below 40 GeV and above 100 GeV.

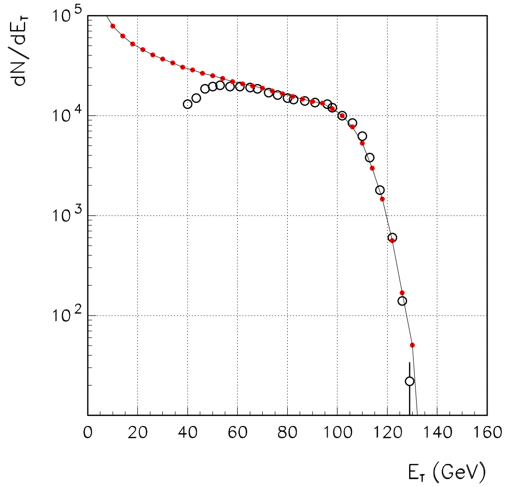


This plot is from older data set. I emailed NA50 to ask what resolution value is used for most recent calculation. No reply.

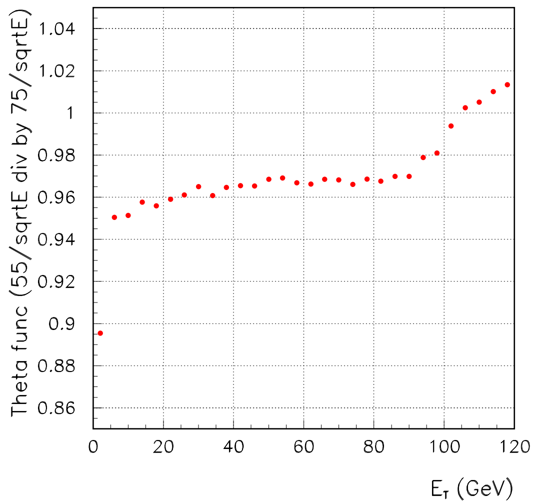
My Glauber Model

We find good agreement with their data in the ET resolution range 55-75% /√(E_T)





Ratio of calculated N_b versus E_T

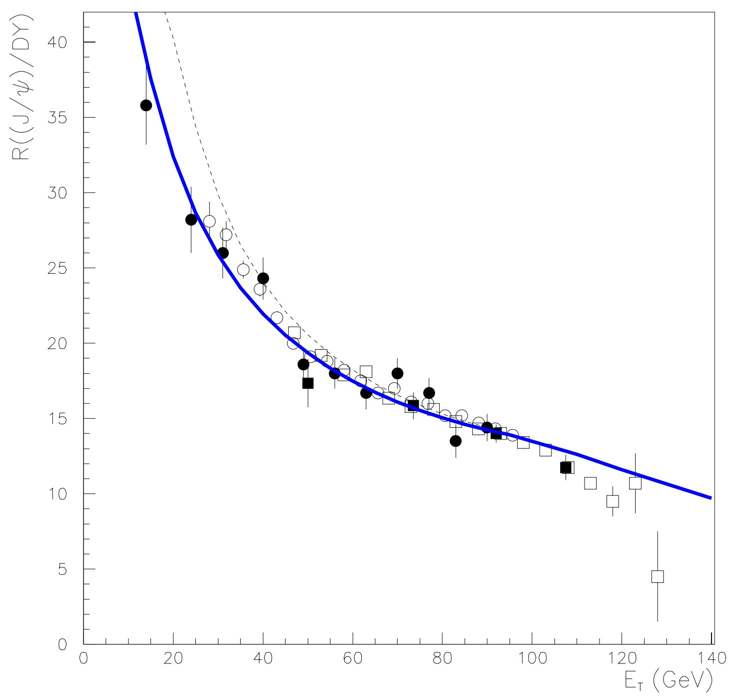


Easy to create an inflection point exactly they see it.

Amazing to have a discovery paper with no mention of systematic errors (double check that in their paper).

More Hadronic Models

Different modeling of E_T production and detector response may play a significant role. Recent speculation that trigger bias due to autocorrelation of J/ψ and E_T could account for the second suppression.



Other models attempt to fit by varying the J/ψ - comover breakup cross section.

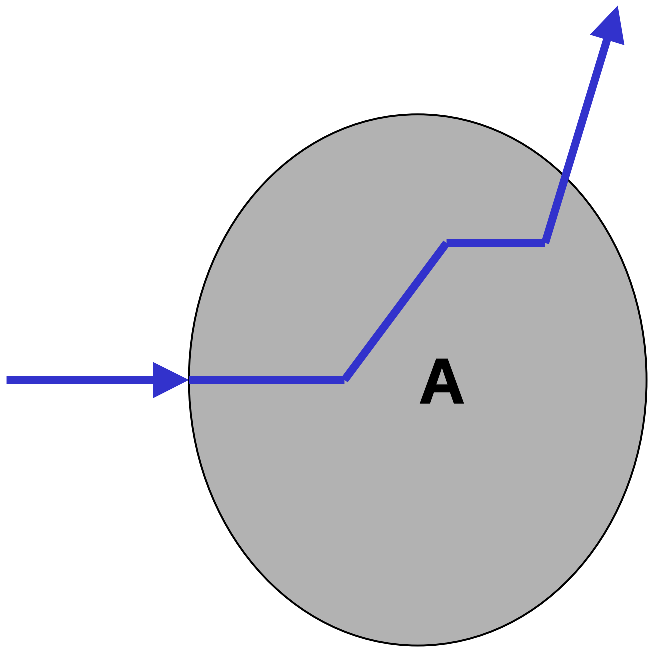
Fact: If you arbitrarily change the co-mover density as a function of E_T you can fit any arbitrary data set.

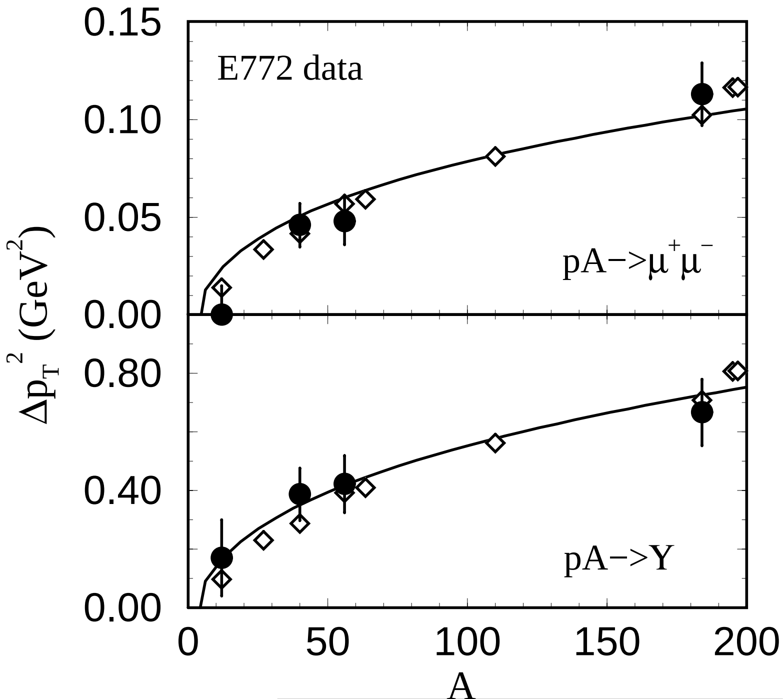
(Capella, Ferreiro and Kaidolov, hep-ph/0002300)

Transverse Momentum

Prior collisions broaden the transverse momentum spectrum ("Cronin effect")

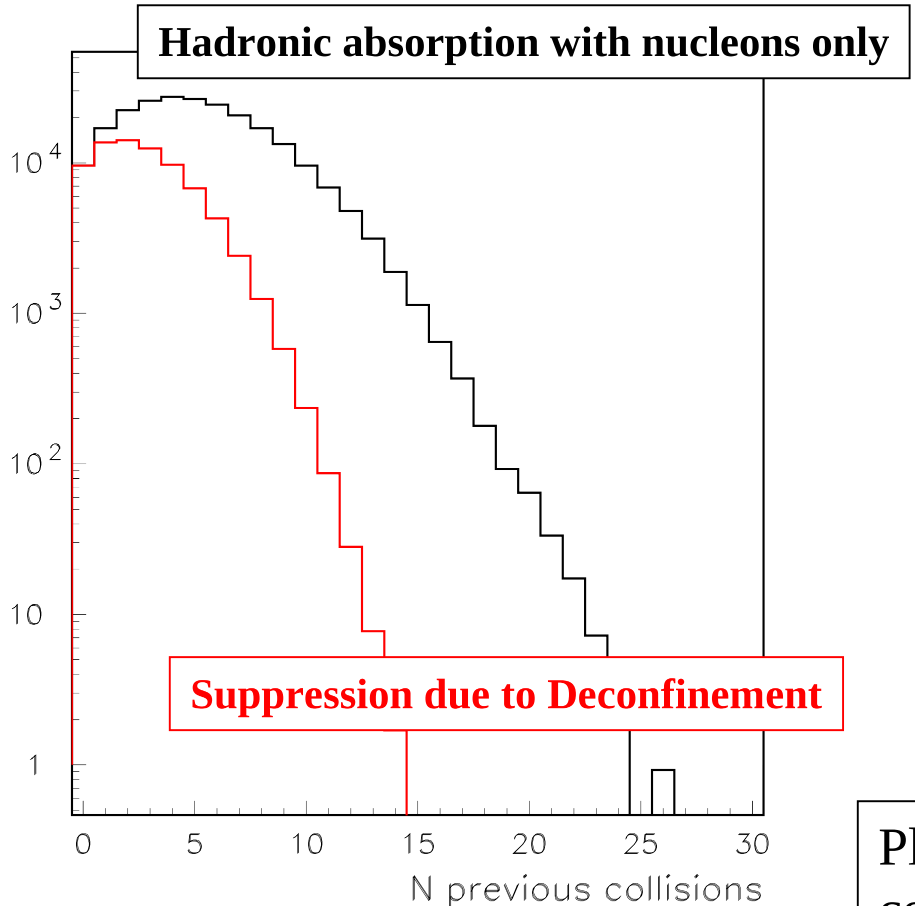
$$\langle p_t^2 \rangle_N = \langle p_t^2 \rangle_{pp} + (N-1)\ \Delta p_t^2$$

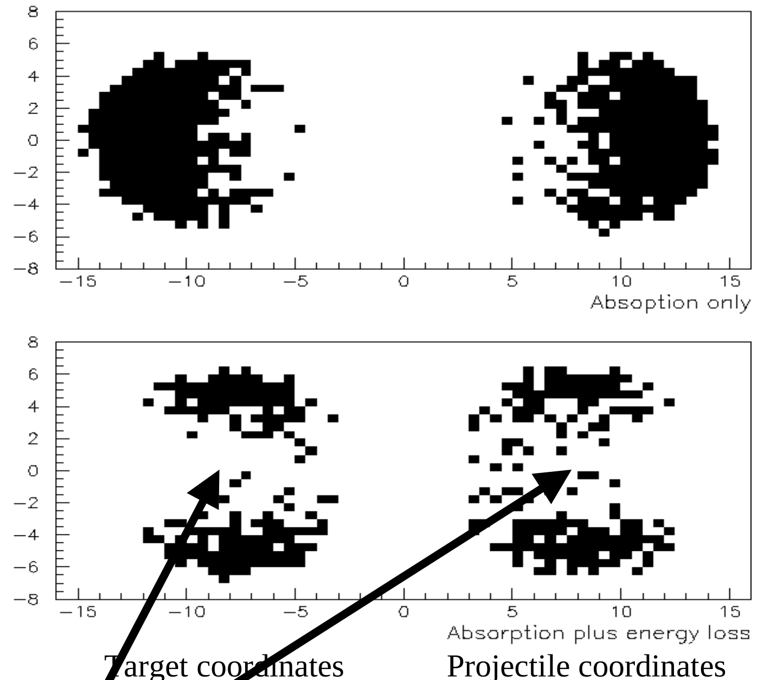




S. Gavin et al., hep/9610432v2

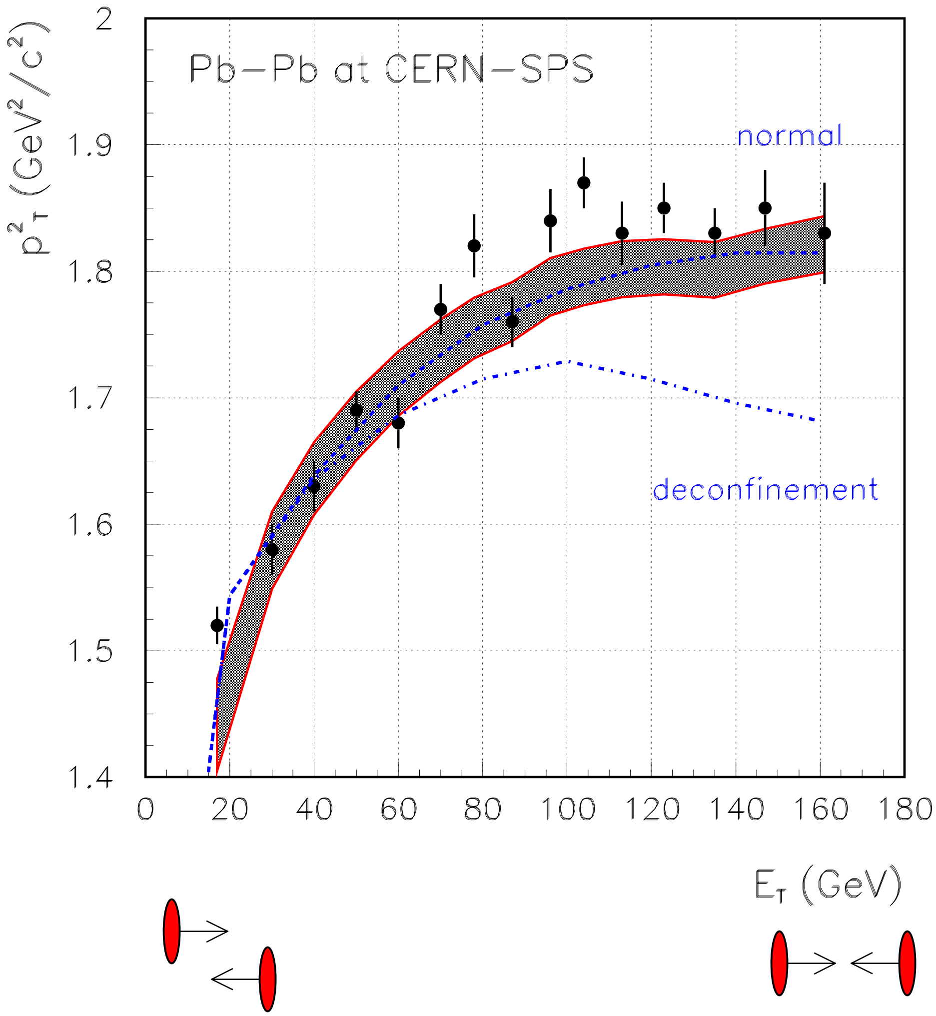
Number of Previous Collisions





Plasma breaks up J/ψ formed at the core of the collision, which are the ones most likely to have the largest number of previous collisions (N)

Data and Predictions



There is much more information in the full p_T spectra, which has not been shown.

Early predictions had suppression at low p_T, since these objects spend more time in the plasma.

Opposite effect of that shown here.

D.Kharzeev, M.Nardi, H.Satz, Phys. Lett. B405, 14 (1997).
JLN, M. Bennett, Phys. Lett. B465, 21 (1999).

CERN Press Release

Lattice QCD predicts a phase transition at $\varepsilon_c \sim 0.6$ GeV/fm^3 or $T_C \sim 170$ MeV.

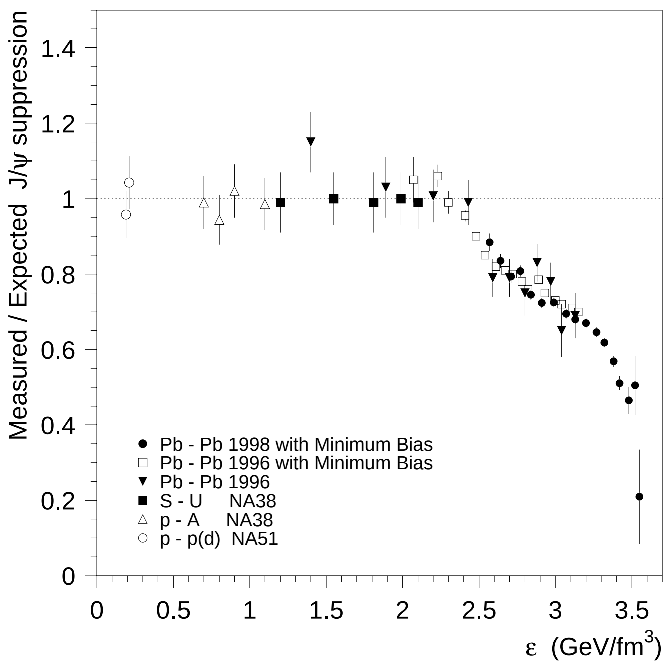
- S + S collisions reach $\varepsilon \sim 1$ GeV/fm^3
- Plasma formation seen via strangeness enhancement

Above $\varepsilon \sim 2$ GeV/fm^3 the χ_c state melts

- Percolation model indicates strong 1st order transition

Above $\varepsilon \sim 3$ GeV/fm^3 the J/ψ state melts

- Most central Pb + Pb collisions reach $\varepsilon \sim 3.5$ GeV/fm^3 or T ~ 240 MeV



Multiple Nucleations

Think of picture with scattering from semi-hard gluons…

Is this really possible?

I strongly believe that the “discontinuities” in the NA50 data have nothing to do with the physics of deconfinement. However, the overall suppression in the yield might.

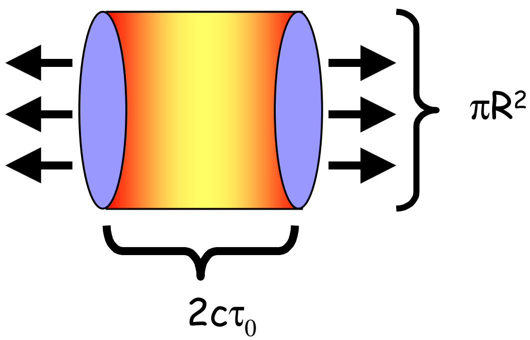
Contradiction between CERN conclusion and J/y picture
Contradiction between J/y physics picture and nucleation model to make transition sharp….

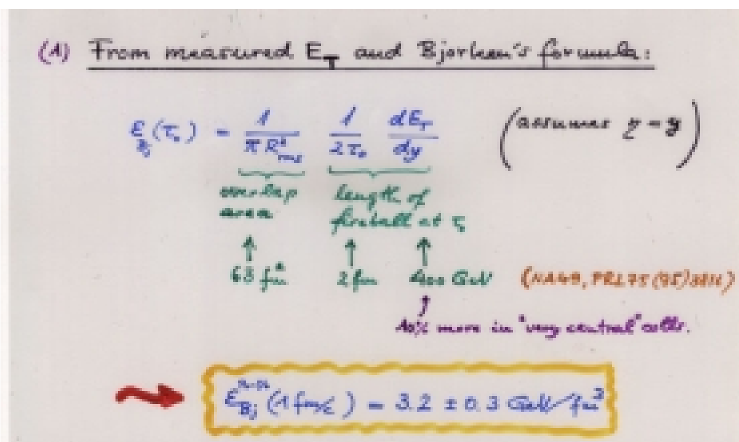
Estimating Energy Density

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

Need to measure transverse energy (E_T)

Need to estimate the time to thermalize the system (τ_0 ~ 1.0 fm/c)





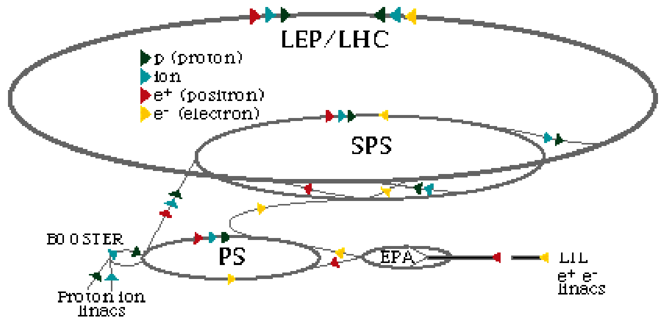
Interesting that Heinz uses wrong formula. People say it can be absorbed in tau, but two mistakes is never good

J.D. Bjorken, Phys. Rev. D27, 140 (1983).

* Note there is a trivial factor of 2 error in this reference that is corrected here.

Is RHIC easier?

CERN-SPS at 17.4 GeV/u



J/ψ in PbPb: σ ~ 2 mb
Collision rate: 3 x 10^6 Hz
Running/year: 5 x 10^6 s

Bottom Line: 5 x 10^9 / year

RHIC at 200.0 GeV/u

J/ψ in AuAu: σ ~ 50 mb
Collision rate: 1 x 10^4 Hz
Running/year: 2 x 10^7 s

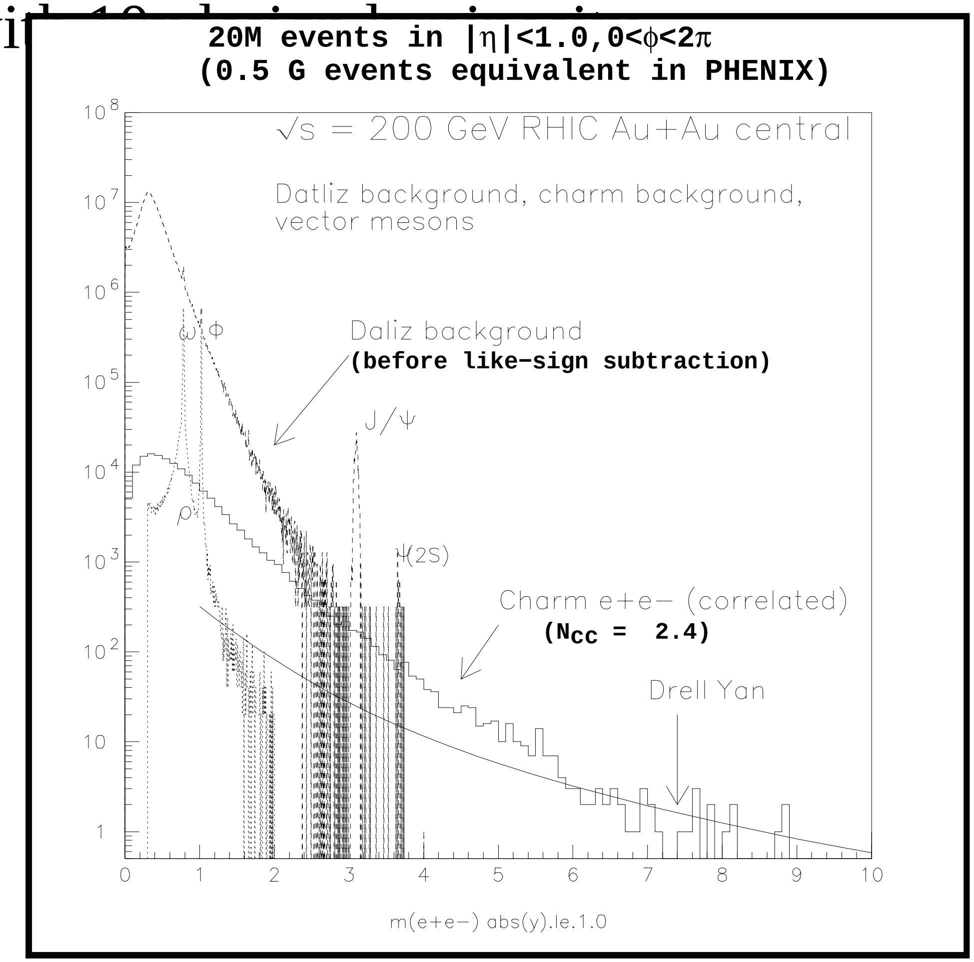
Bottom Line: 2 x 10^9 / year

* Branching fraction, acceptance, efficiency reduce the number to ~ 10^5-10^6 / year

PHENIX Measurement

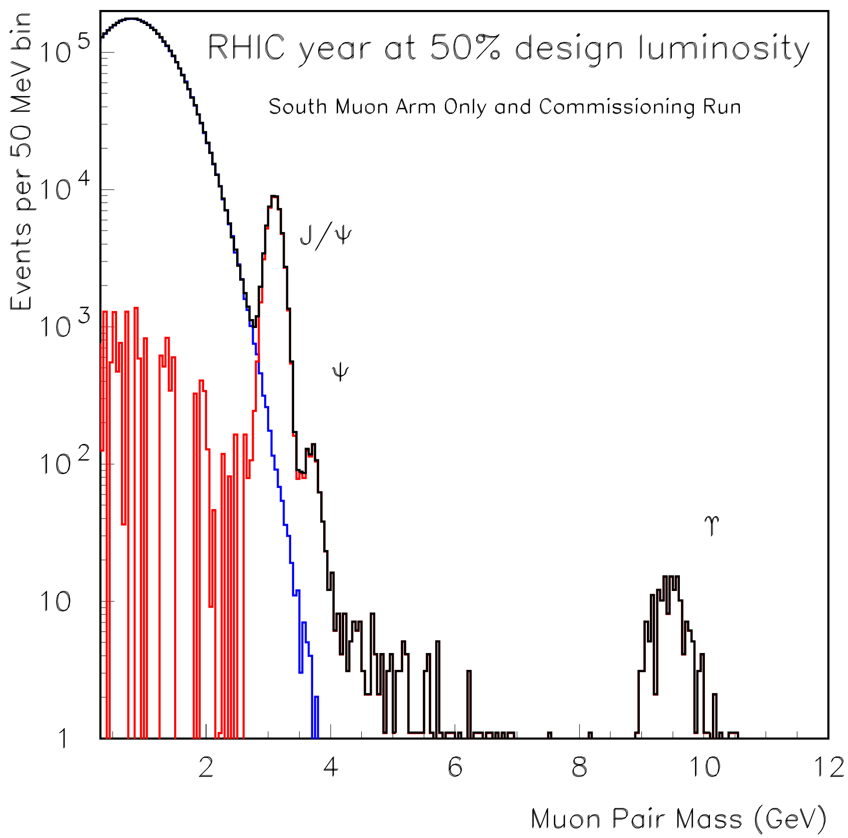
Two measurements

Show projected spectra wi

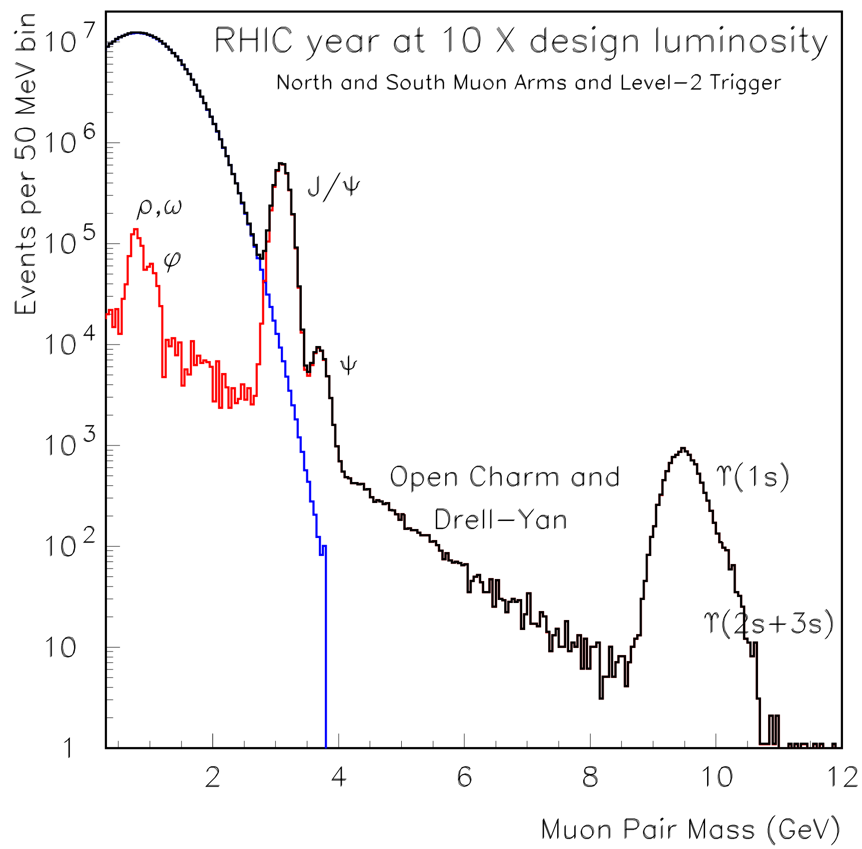


PHENIX Muon Measurement

Run 2 Results



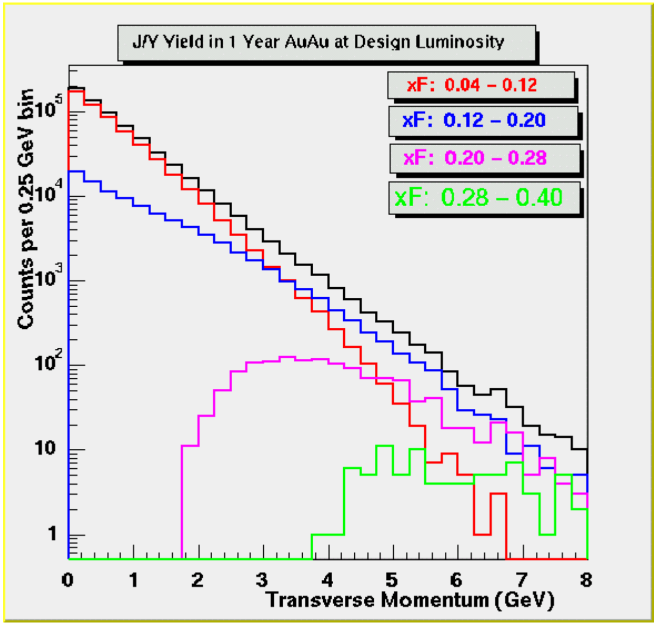
Run 4 Results

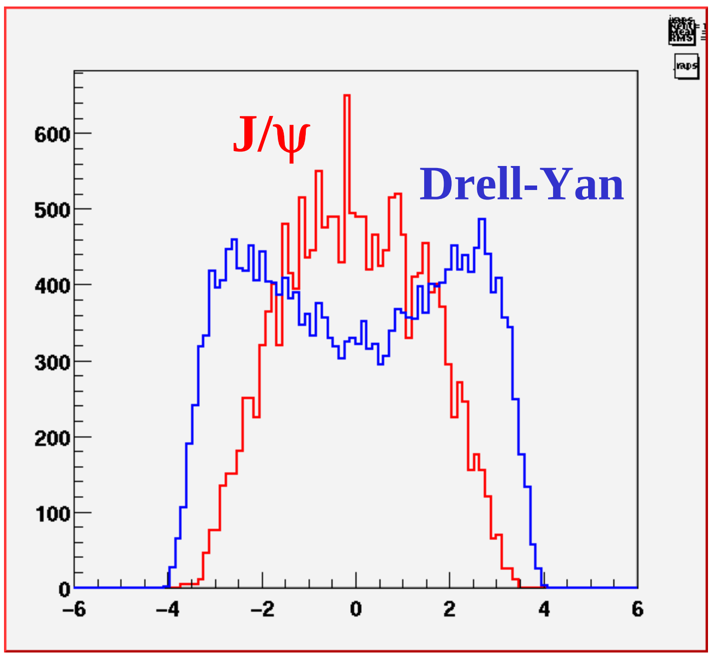


* Year 4 includes both North and South Muon Arms and Level-2 Trigger which makes possible ρ , ϕ physics and discrimination of Y states.

PHENIX can measure the p_T distribution of J/y.

At higher energies,
there is possible production
of J/y from charm-anticharm
recombination in a thermal
system and also
at LHC B-->J/y K.





Note muon versus electron acceptance and also co-mover issue in different regions. Show PHOBOS dNch/deta plot!

STAR Measurement

Need to find out what the deal is here….

Write to Peter Jacobs….Ullrich ?

Maybe mention charm!

What are the capabilities at RHIC energies

PHENIX
STAR (? - need to find out)

What are latest Pt distributions from NA50

What is the NA60 real proposal

Diagramatic View