Lepton Physics at RHIC

M. J. Tannenbaum
BNL

VII Workshop on Non-Perturbative QCD
Villefranche-sur-Mer, La Citadelle
January 2003

Results on physics at RHIC using outgoing leptons will be presented from Au+Au collisions at nucleon-nucleon c.m. energies $\sqrt{s_{NN}} =$ 130 GeV and 200 GeV, and from p-p collisions at $\sqrt{s_{NN}} = 200$ GeV. Introduction and motivation will be presented both from the theoretical and experimental perspectives. Topics include open charm production via single $e^{\pm}$, $J/\Psi \rightarrow e^+ + e^-$, $\mu^+ + \mu^-$, leptonic decay of vector mesons and the dilepton continuum.

Quantum Chromo Dynamics
QCD

- QCD is the theory of the strong interaction
- The force between a quark and an antiquark is free and coulomb-like at short distances but is string-like at large r

$$\boxed{V = -\frac{4}{3}\frac{\alpha_s}{r} + \sigma r}$$

- The coulomb-like part leads to narrow bound states
- The string-like tension leads to confinement

- Narrow bound states of heavy quarks, c, b, were discovered in 1970's via large branching ratios to di-leptons $\sim 10^{-2}$
- c.f. $\sim 10^{-4}$ for light quark vector mesons ρ, ω.

Best Lepton Pair data c. 1977

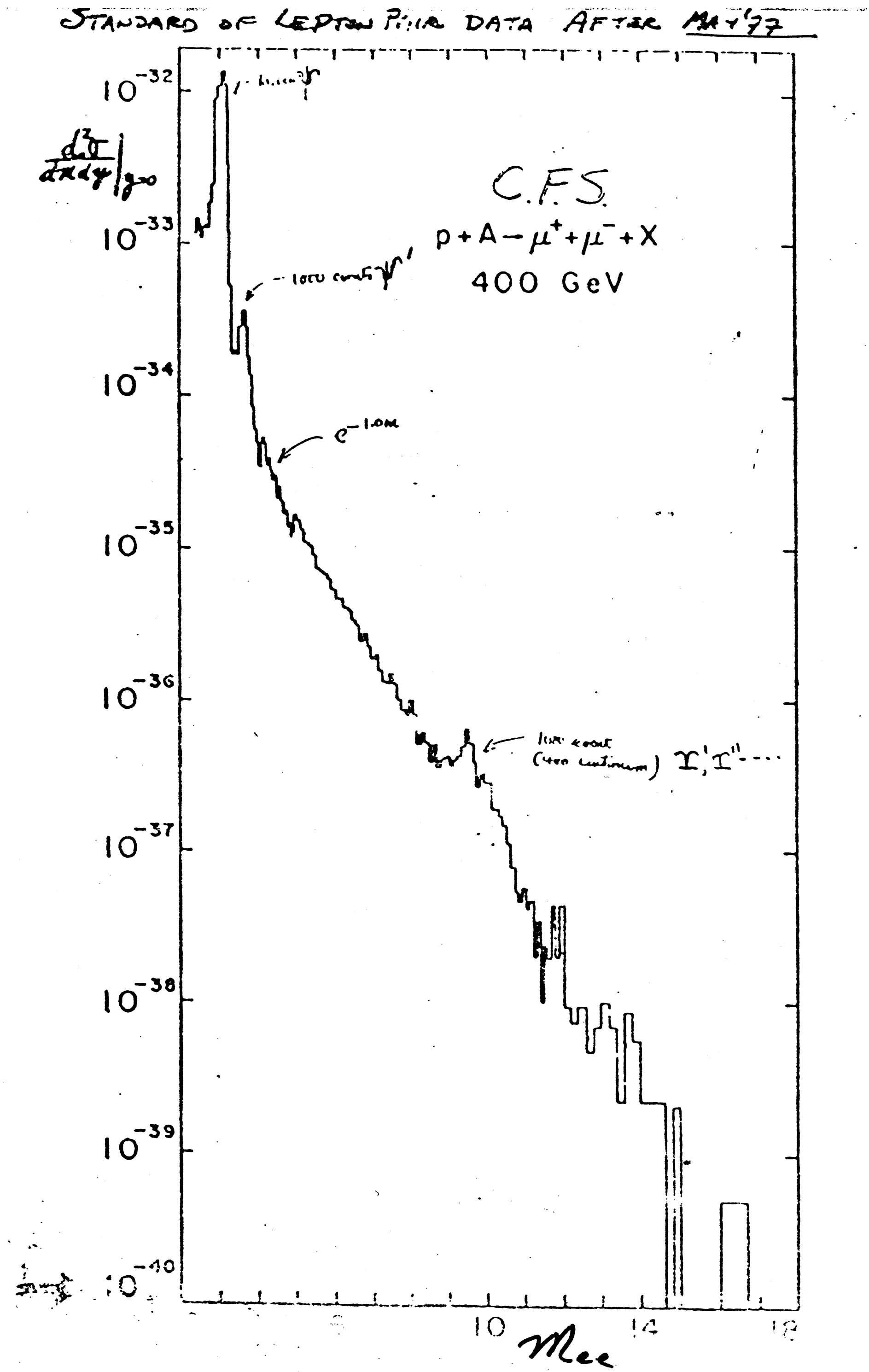
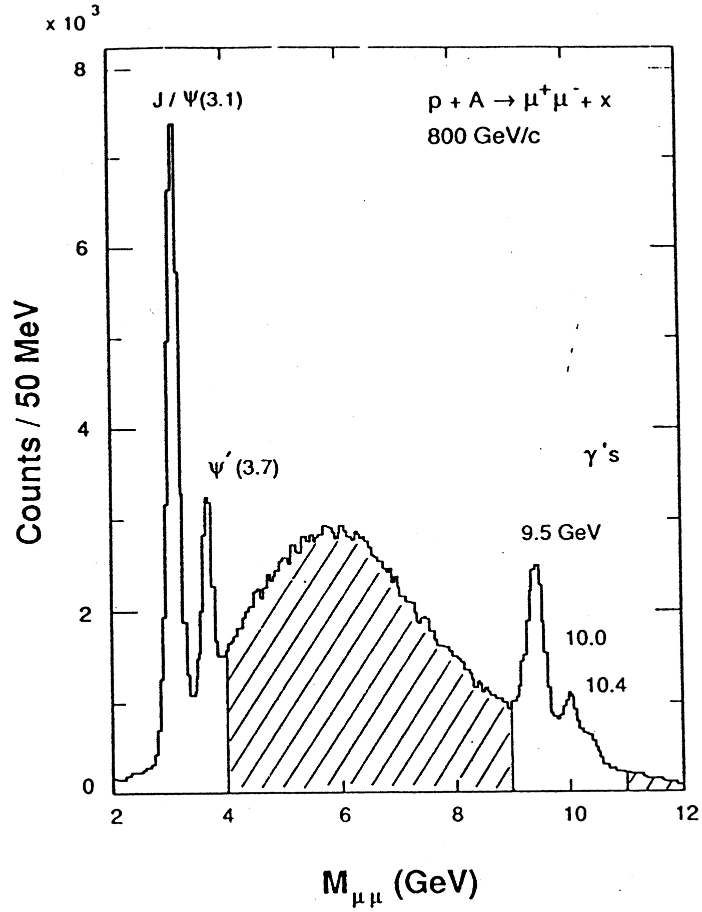


Figure 1: Lederman's spectrum of di-muon invariant mass at mid-rapidity

Recent State of the Art FNAL



Bound States follow the QCD potential Model

VOLUME 34, NUMBER 6 PHYSICAL REVIEW LETTERS 10 FEBRUARY 19

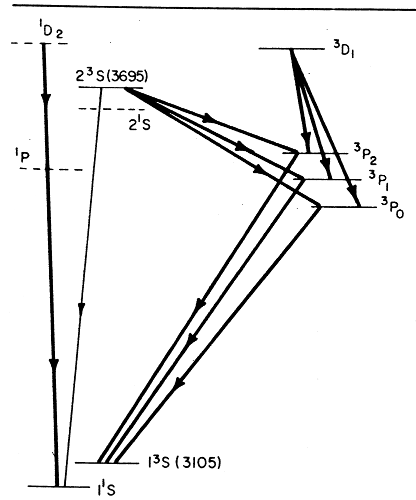


FIG. 1. The spectrum of charmonium. The vertical

TABLE I. γ ray widths.[a]

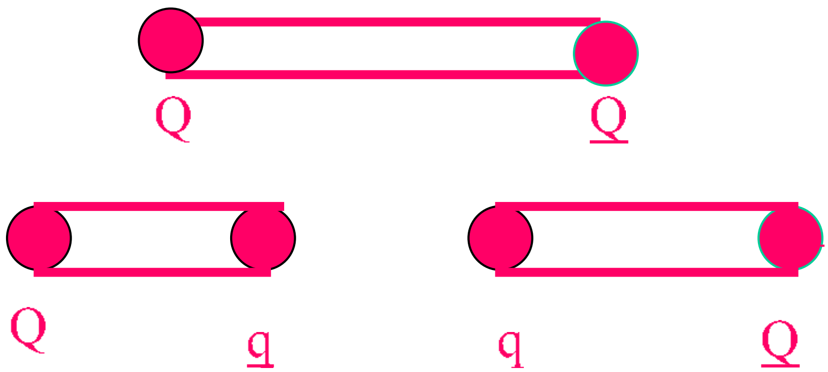
Transition	Γ_γ	Γ_γ (keV)
$2\,^3S \to {}^3P_2$	$5I_1\alpha k^3$	120
$\to {}^3P_1$	$3I_1\alpha k^3$	70
$\to {}^3P_0$	$1I_1\alpha k^3$	25
${}^3P_2 \to 1\,^3S$	$I_2\alpha k^3$	240
${}^3P_1 \to 1\,^3S$	$I_2\alpha k^3$	240
${}^3P_0 \to 1\,^3S$	$I_2\alpha k^3$	240
${}^1P_1 \to 1\,^1S$	$I_2\alpha k^3$	240
${}^3D_1 \to {}^3P_2$	$1I_3\alpha k^3$	7
$\to {}^3P_1$	$15I_3\alpha k^3$	110
$\to {}^3P_0$	$20I_3\alpha k^3$	150
$2\,^3S \to 1\,^1S$	$I_4\alpha k^7$	~1

[a]In the second column $1/\alpha = 137$, k is the energy of the transition, and I_n is a radial integral. The last column is based on our wave functions and energy differences, with fine-structure splittings and S–D mixing ignored.

P multiplet lies about 230 MeV below that of the $2S$ levels. This energy difference is not very sensitive to our choice of parameters: It decreases to 160 MeV if α_s and m_c assume the

Charmonium becomes Open Charm

• The force between a quark and an antiquark is free and coulomb-like at short distances but is string-like at large r



• The string-like tension leads to confinement BUT

• At larger r, the string tension limit is exceeded

• the string breaks forming a q q pair which binds to QQ

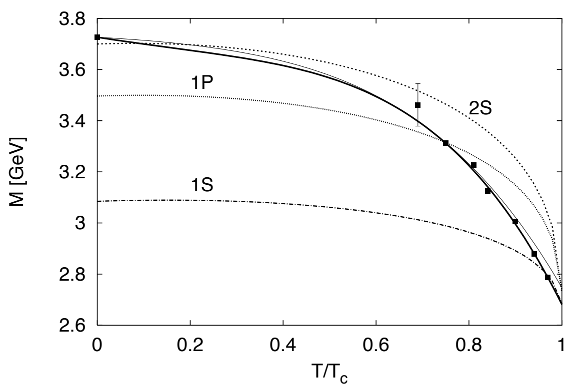
• making a D=Qq D=Qq open charm (Beauty) pair.

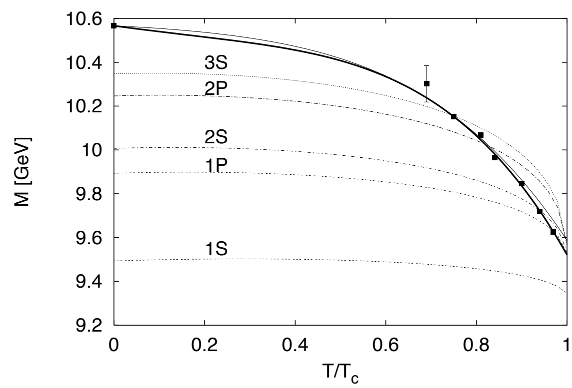
$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \sigma r$$

- $V(r \to \infty) = 2M_D$ for $T = 0$

High Temperature $T \rightarrow T_c$

- $\sigma \rightarrow 0$ as $T \rightarrow T_c$, $2M_D \rightarrow 0$
- Excited quarkonia dissociate to open charm, beauty

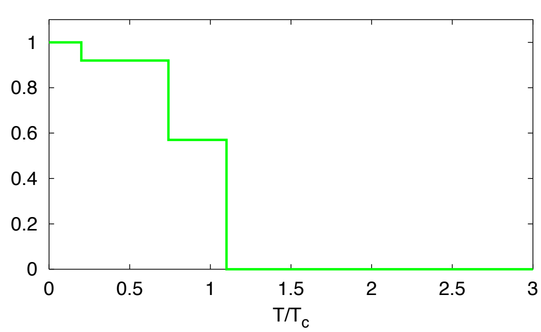




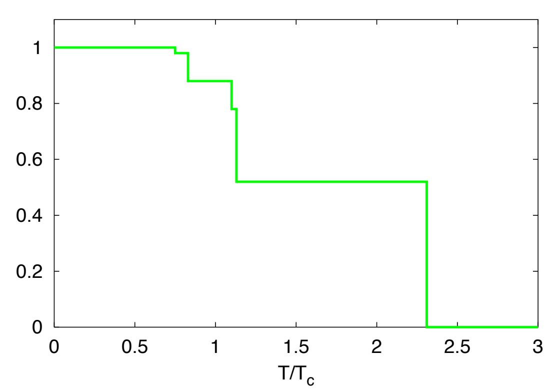
- 'Like' Chiral Symmetry Restoration

Tightest bound quarkonia survive at T_c but

- $\alpha_s(T) \Downarrow$ as $T \Uparrow$ but $\alpha_s(T_c)$ is finite $\Rightarrow$ Quarkonia can exist above T_c.
- BUT attractive potential is 'Debye screened' in QGPlasma $\Rightarrow$ Dissociation of Quarkonia in QGP = Deconfinement!



χ_c, ψ', J/ψ

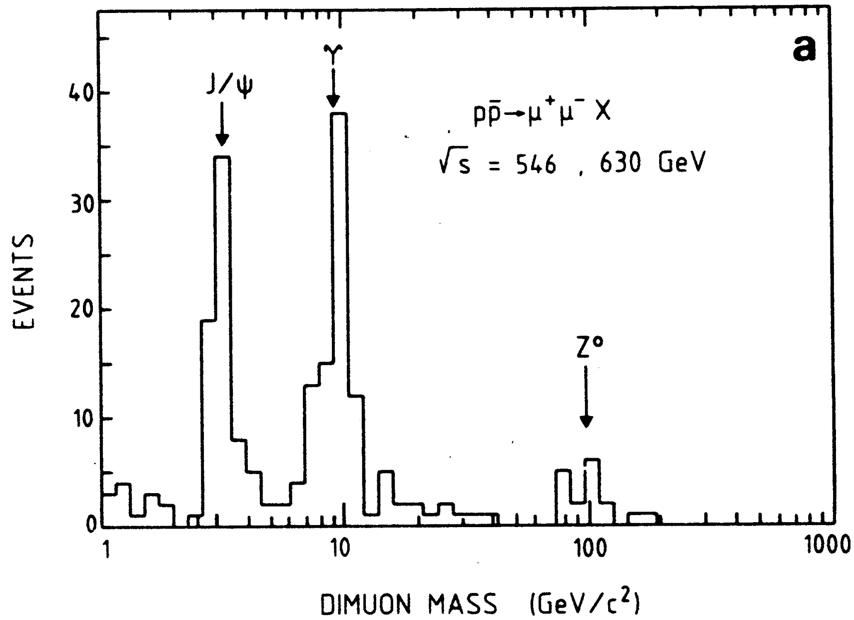


Υ'', χ_b', Υ', χ_b, Υ

[H. Satz, et al., Phys. Lett. B**178**, 416 (1986), Phys. Lett. B**514**, 57 (2001), Phys. Rev. D**64**, 094015 (2001)]

QUARKONIA
The Road To Success in HEP

,ETTERS B 5 March 1987



$p_T(\mu) \geq 3$ GeV/c, UA1 Phys. Lett. B**186**, 237 (1987)

The Road To Success in HIP

The Physics of Open Charm (Beauty)

- Produced via $g+g \longrightarrow c+\bar{c}$ so measures gluon structure function.
- charm and J/ψ both suppressed $\Rightarrow$ Shadowing in Gluon Structure Fn.
- Large mass scale $\Rightarrow$ sensitive to initial T
- Large mass scale $\Rightarrow$ energy loss in QGP is less than for light quarks $\Rightarrow$ less suppression of c jets than light quark jets due to 'jet quenching' in hot (deconfined) medium ['Dead Cone Effect', Y. L. Dokshitzer and D. E. Kharzeev, Phys. Lett. B**519**, 199 (2001)]

But a Key reason to study Charm is Experimental

- Large semi-leptonic branching ratio $\sim$ 7-17% per lepton (e, μ)
- Large mass $\Rightarrow \sim 1$ GeV leptons ($\gg \langle p_T \rangle$)
- Lepton I.D. in large hadronic and photonic background is an experimental challenge **BUT**
- Charm via single lepton measurement has **NO Combinatoric Background** $\Rightarrow$ same difficulty in p-p and A+A collisions.

Why (Some) Experimentalists Study Leptons at High p_T From Hadron Collisions

They indicate weak ($e^{\pm}\nu$) or EM decays (e^+e^-)

$\Rightarrow$ Long Lived Particles $\tau \gg 1$ fm/c (3.3×10^{-23} sec)

- Originally (1964) inspired by the search for the Intermediate W boson of weak interactions in p-p collisions.
  - "Zichichi" Signature [Proc. 12th ICHEP, Dubna, 1964, p35 (footnote)] hadron spectra fall like e^{-6p_T}, decay lepton spectra fall faster and can be calculated, upon which the decay $W \rightarrow e+\nu$ from heavy W produced at rest (mid-rapidity) would give a (jacobean) peak at $p_{T_e} = M_W/2$

That's Actually How the $W^{\pm}$ was discovered in 1983!

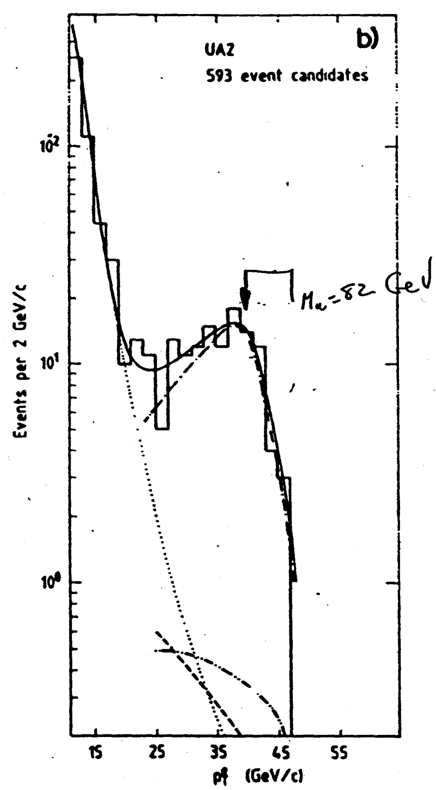


Figure 2: $W^{\pm} \rightarrow e^{\pm} + X$ from UA2 c. 1984

However Great Excitement in 1974
Discovery of prompt electrons in p-p collisions
$e^{\pm}/\pi^{\pm} \sim 10^{-4}$, $p_T \geq 1.3$ GeV/c—no peak

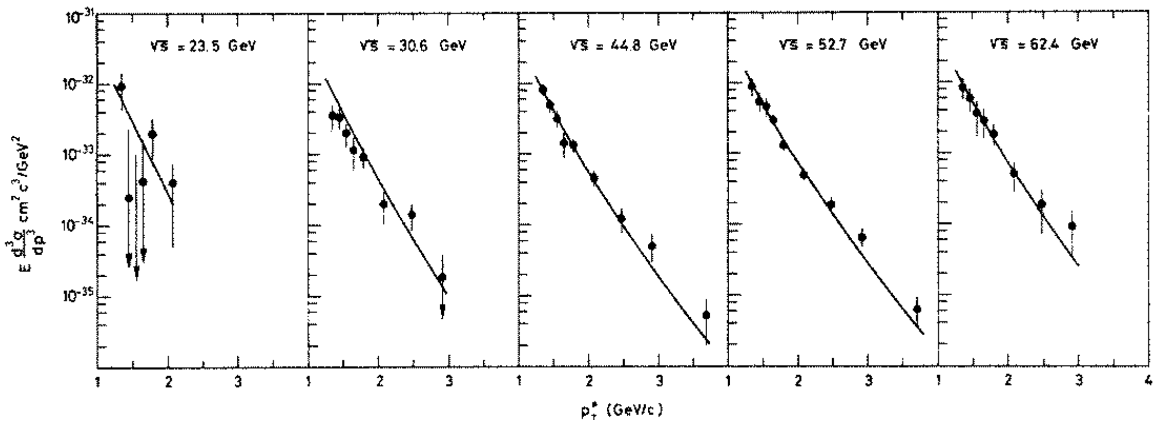


Figure 3: Invariant cross section for $(e^+ + e^-)/2$ vs p_T for 5 values of $\sqrt{s}$ at the CERN-ISR compared to fits (solid lines) to corresponding data for $(\pi^+ + \pi^-)/2$ [CCRS, Phys. Lett. B**53**, 212 (1974), Nucl. Phys. **B113**, 189 (1976)]

- Discovered before J/ψ
- Not due to J/ψ but $\langle p_T \rangle|_{J/\Psi}$ is a key issue.

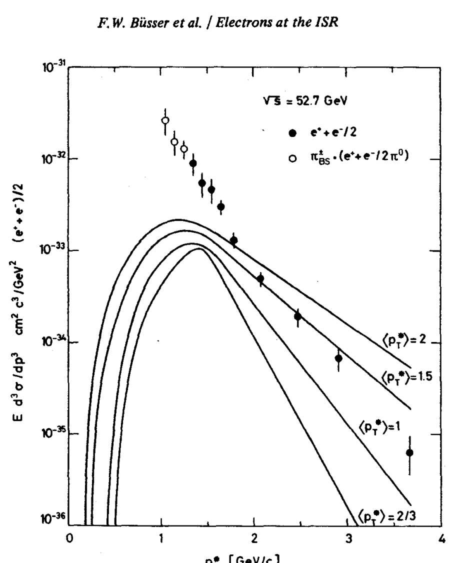


Figure 4: CCRS calculation of $e^{\pm}$ from J/ψ as a function of $\langle p_T \rangle$ of the J/ψ

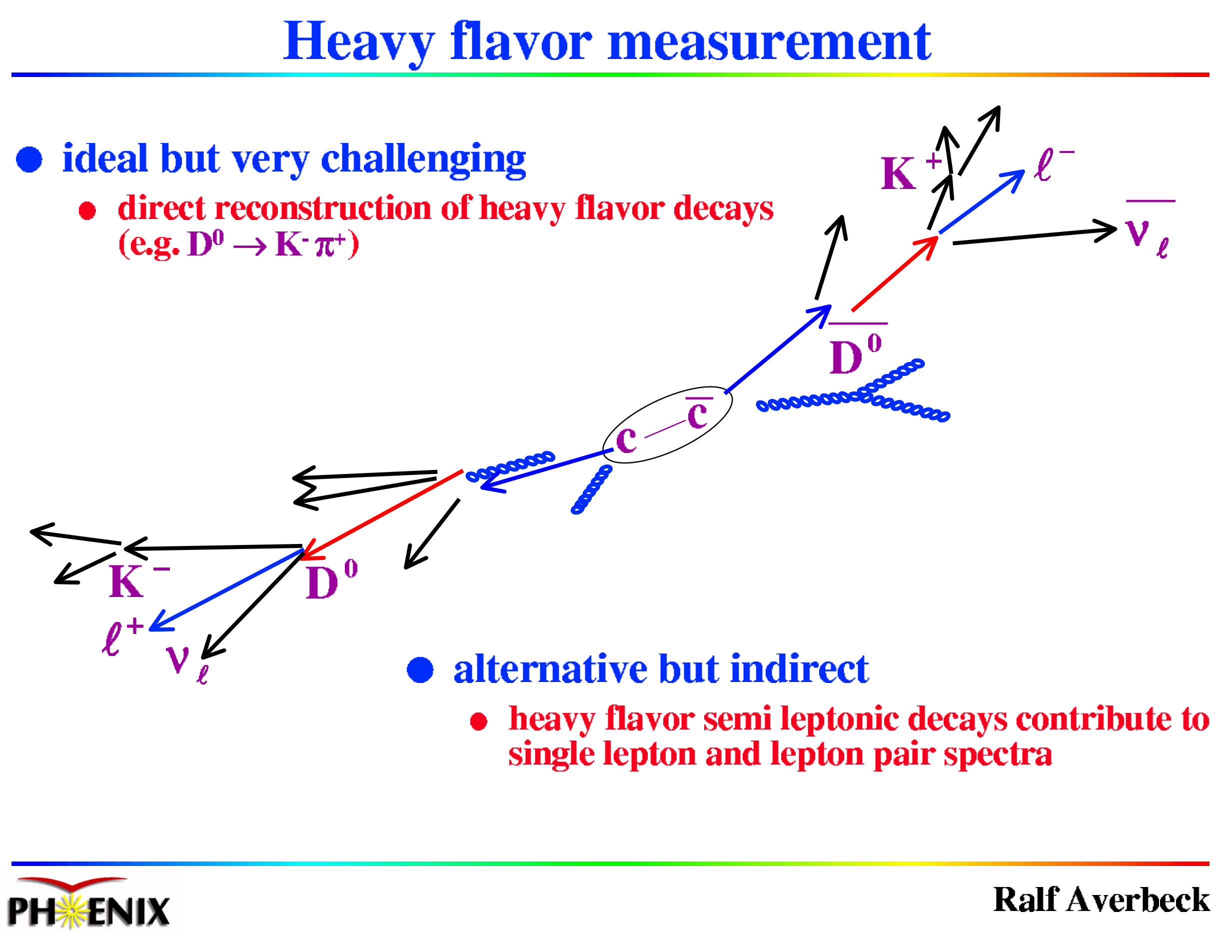
1976—Prompt Electrons = Open Charm

• Some previous (and even post) spurious results: MJT in 1974 "All those who try to measure direct leptons become the world's experts in η Dalitz Decay ($\eta \rightarrow \gamma + e^+ + e^-$)"

• First suggestion of direct photons in p-p collisions as the source of prompt leptons [G. R. Farrar and S. C. Frautschi, Phys. Rev. Lett. **36**, 1017 (1976), and others] well before pQCD predicts $g + q \rightarrow \gamma + q$ "Inverse QCD compton effect"

• 1976—Finally explained as evidence for open charm. [I. Hinchliffe and C. H. Llewellyn Smith, Phys. Lett. B**61**, 472 (1976); M. Bourquin and J.-M. Gaillard, Nucl. Phys. **B114**, 334 (1976) (The original "Coctail Model")]

The 'modern' view



Experimental Issues
Real Backgrounds, Falling Spectra
Photons from $\pi^0 \to \gamma + \gamma$ follow the π^0 curve down by a factor of $2/(n-1)$

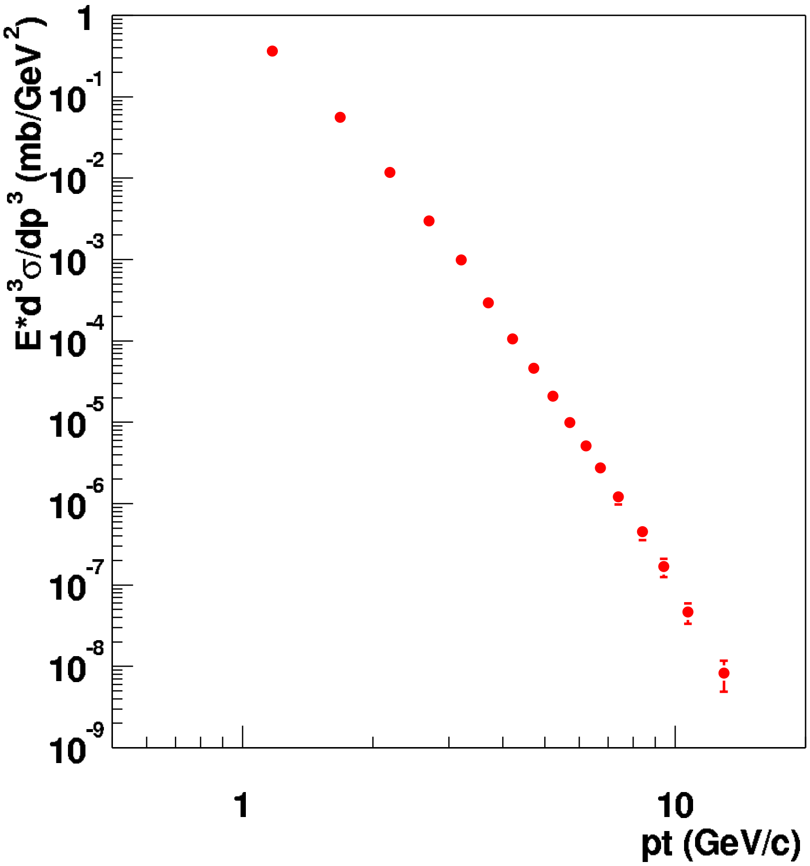


Figure 5: PHENIX π^0 spectrum for $\sqrt{s} = 200$ GeV p-p collisions

$$\frac{dn_{\pi^0}}{p_T dp_T} \propto p_T^{-n}$$

where $n \sim 8$, so $\gamma|_{\pi^0}/\pi^0 \sim 1.2 \times 2/7 = 0.34$ and the factor 1.2 includes $\eta \to \gamma + \gamma$ (estimated).

• This assumes that e.g. one 10 GeV photon and two 5 GeV photons (a 10 GeV π^0) measure at exactly the same energy in the experiment $\Rightarrow$ **nonlinearity** is a big experimental issue for photons.

PHENIX π^0 spectra at $\sqrt{s_{NN}} = 200$ GeV

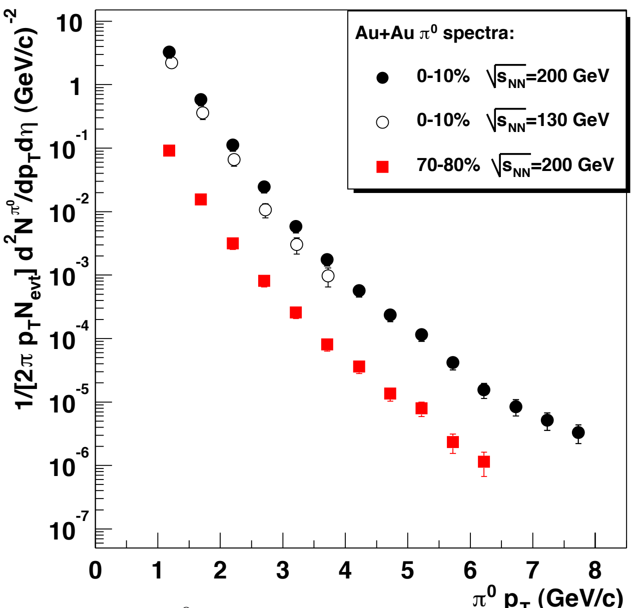
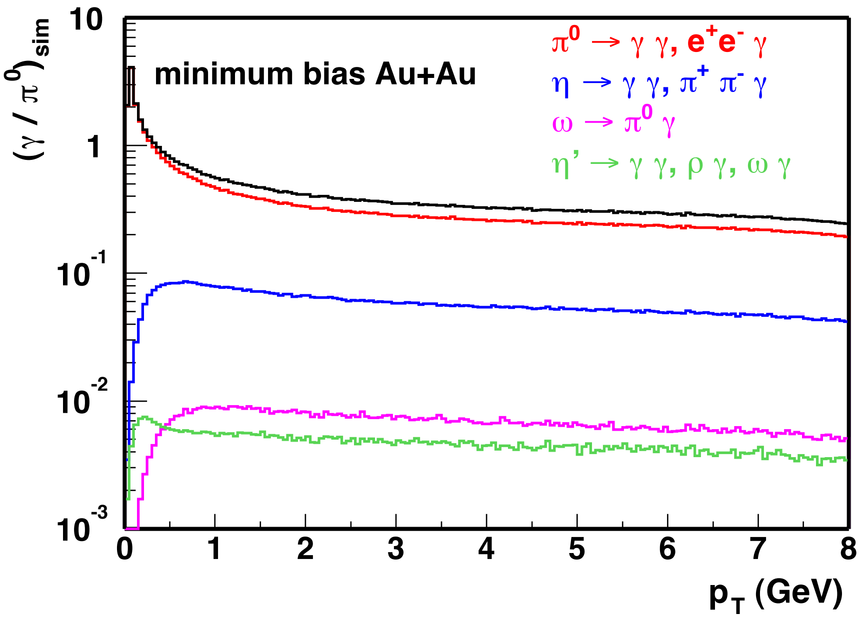


Figure 6: PHENIX QM02 π^0 spectra in Au+Au peripheral and central collisions

- The inclusive γ spectrum **calculated** from the above π^0 spectrum shown below as $\gamma|_{\pi^0}/\pi^0$.



- Note that $\gamma|_{\pi^0}/\pi^0 \sim$ constant for $p_T \geq 3$ GeV/c consisistent with power law with $n \sim 8$ for π^0 (and assumed for other particles).

PHENIX inclusive γ spectrum

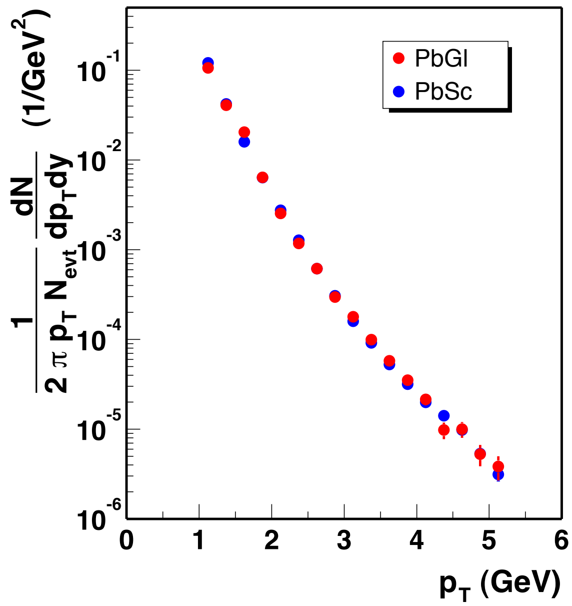
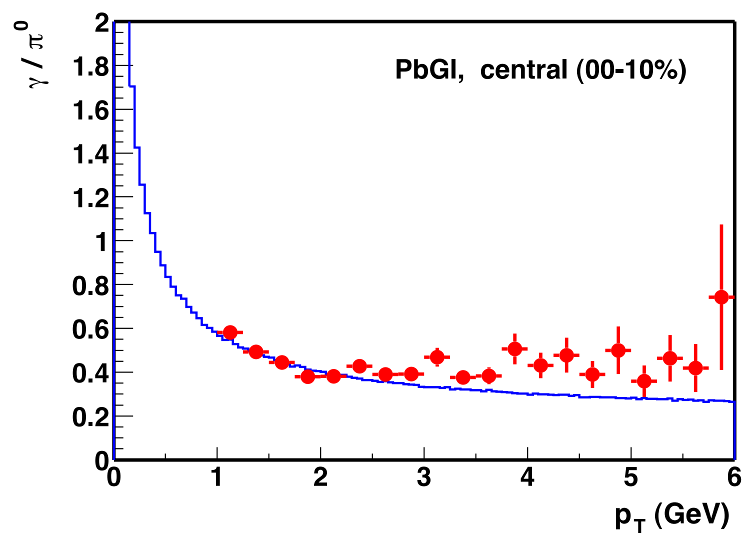


Figure 7: PHENIX QM02 inclusive γ spectrum in Au+Au central collisions at $\sqrt{s_{nn}} = 200$ GeV **statistical errors only**

- Are the γ direct or all from decays? Hard to compare two 6-7 order log plots. Analysis is best in $\gamma/\pi^0_{meas}/\gamma/\pi^0_{decays}$



- Background from n, $\bar{n}$? Possible non-linearity? η/π^0 ratio? ...

QM02 inclusive γ results
PHENIX

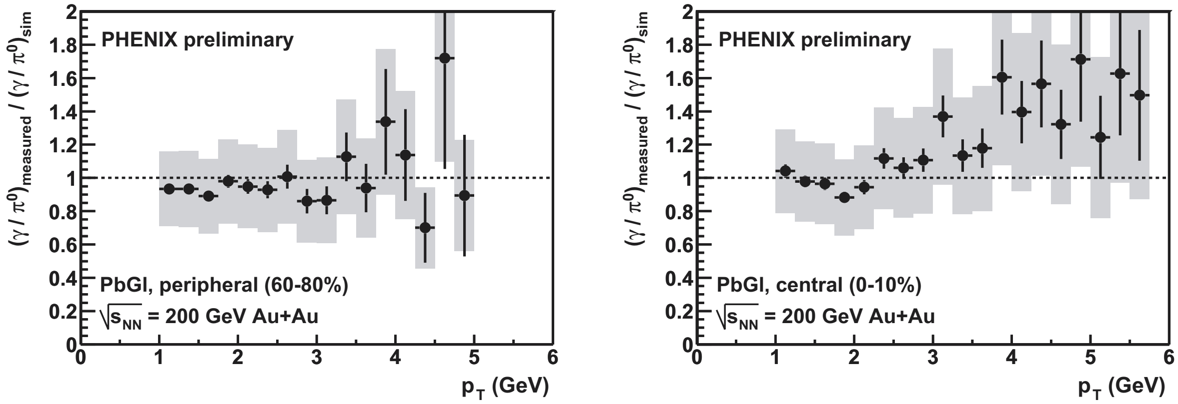


Figure 8: PHENIX QM02 $\gamma/\pi^0|_{meas}/\gamma/\pi^0|_{decays}$ vs. $p_T$in Au+Au collisions at $\sqrt{s_{nn}} = 200$ GeV **Systematic Errors Included**

STAR

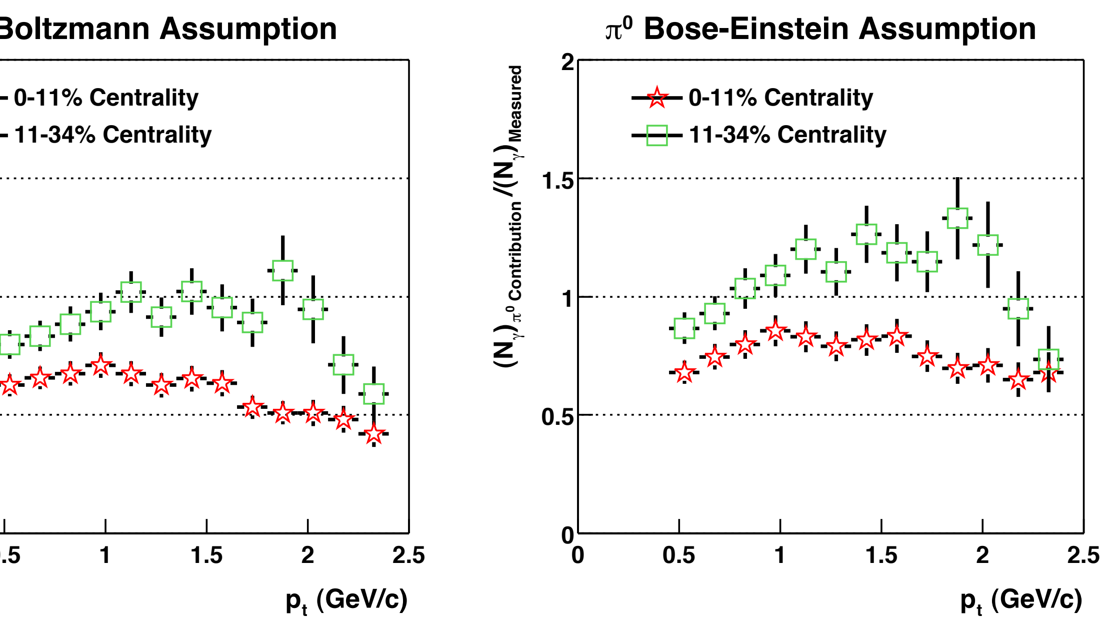


Figure 9: STAR QM02 $\gamma/\pi^0|_{\pi^0}/\gamma/\pi^0|_{meas}$ **Systematic Errors Included**

- Ratio is upside-down!
- Background from n, $\bar{n}$? Background from η, ω, $\eta^{'}$?
- Shape of π^0 spectrum!?
- Non-linearity not an issue—measured via conversions.

All Inclusive Photons create Background e^+e^- pairs

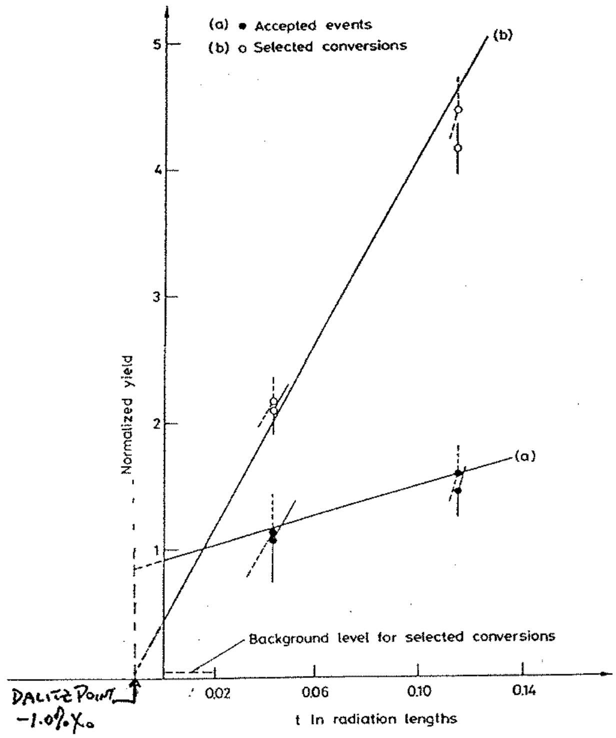


Figure 10: CCRS yield of inclusive electrons vs total external radiation length t/X_0 for (b) selected conversions (extrapolates to zero at the "Dalitz point") and (a) Accepted events with prompt electrons (non-zero intercept at Dalitz point). Yields are relative, normalized to 1 at the standard thickness $t/X_0 = 0.16$

- Probability of internal and external conversion per γ

$$\frac{e^-|_\gamma}{\gamma} = \frac{e^+|_\gamma}{\gamma} = \frac{\delta_2}{2} + \frac{t}{\frac{9}{7}X_0} \equiv \delta_{eff}$$

where $\delta_2/2 =$ Dalitz (internal conversion) branching ratio per photon $= 0.6\%\ \pi^0$, 0.8% for $\eta \to \gamma\gamma$.

- Must keep external $t/\frac{9}{7}X_0$ comparable $\sim 0.6\%$ to avoid additional background from external conversions.

- But can add small external converter in test run to determine whether $e^-/\gamma \to 0$ at "Dalitz Point" $-\frac{9}{7}\delta_2/2 \sim 0.8 - 1.0\%$ in units of radiation lengths, **insensitve** to the η/π^0 ratio. Converter curve measures the photonic background!

Effect of Falling Spectra

- Still assuming the p_T^{-n} power law for the π^0 and thus decay γ Spectra:

$$\left.\frac{e^-}{\pi^0}\right|_{\pi^0}(p_T) = \left.\frac{(e^- + e^+)}{2\pi^0}\right|_{\pi^0}(p_T) = \delta_{eff}\times\frac{2}{(n-1)^2} > 0.6\%/7^2 = 1.2\times10^{-4}$$

- Need $\sim 10^4$ rejection against $\pi^\pm$ just to be able to see the $e^\pm$ background from π^0 Dalitz. $\Rightarrow$ some experimental discussion.

For the record, it's actually easier in Au+Au at RHIC

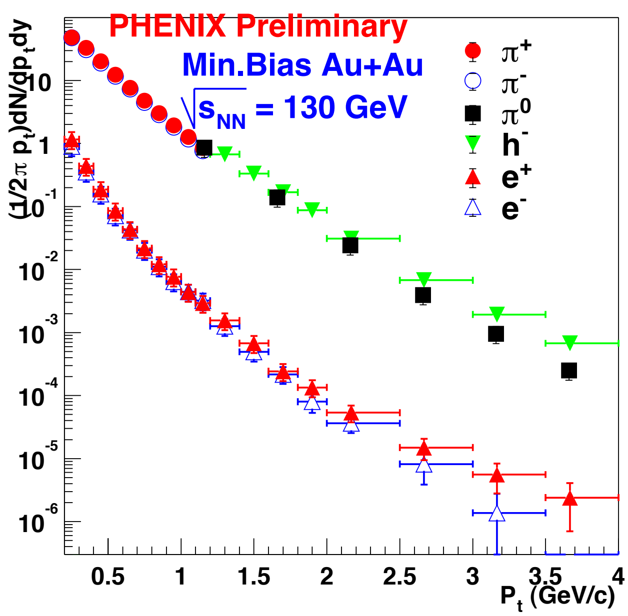
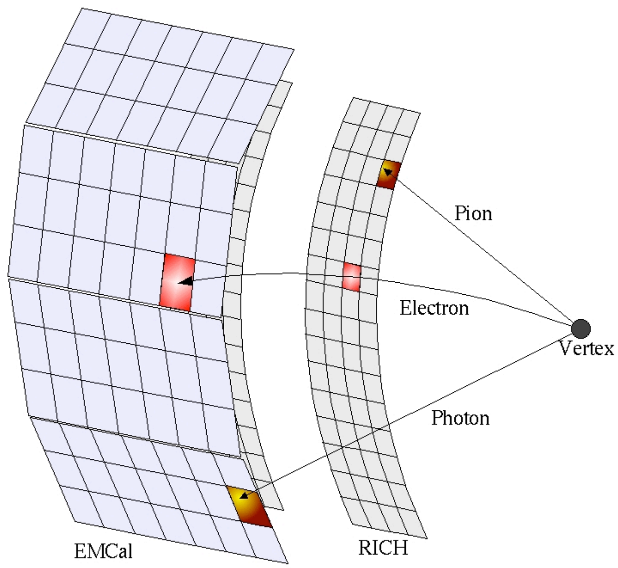
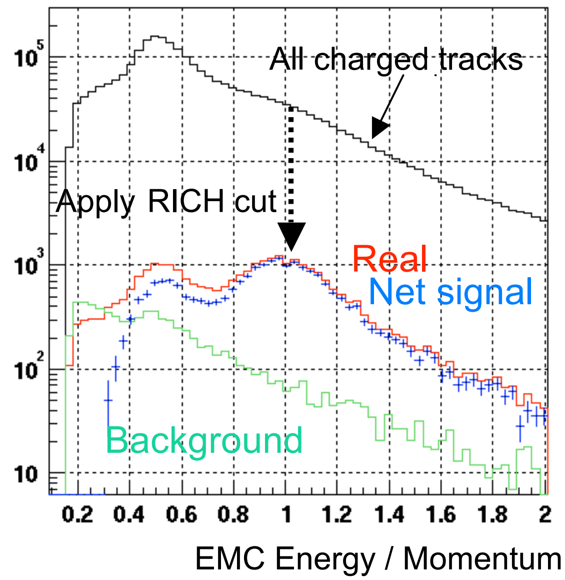


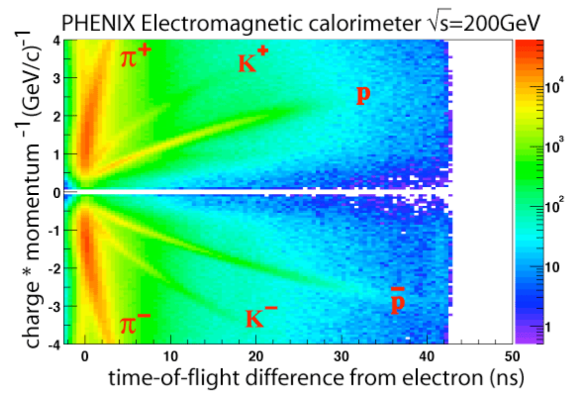
Figure 11: PHENIX inclusive $\pi^\pm$, π^0, h^-, $e^\pm$ p_T spectra in minimum bias Au+Au collisions at $\sqrt{s_{nn}} = 130$ GeV

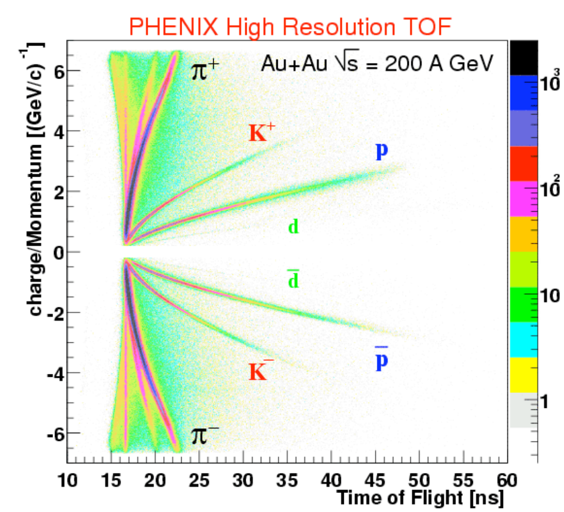
- $e/\pi \sim 1/500 = 2\times10^{-3} \gg 1.2\times10^{-4}$
- Measured Conversions/Dalitz $= 1.8 \pm 0.2$
- Since π are suppressed at high p_T, suggests that charm is not suppressed ...

Detecting electrons means detecting all particles=PHENIX



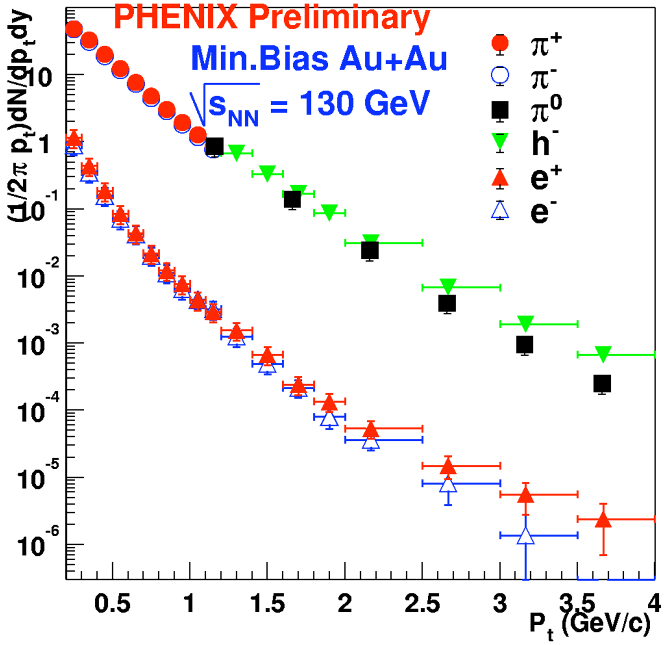


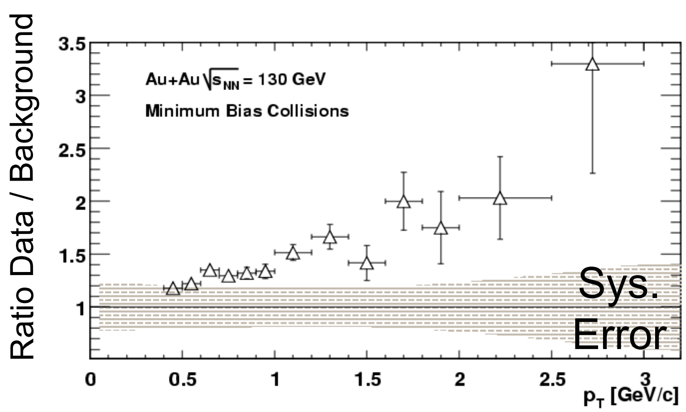


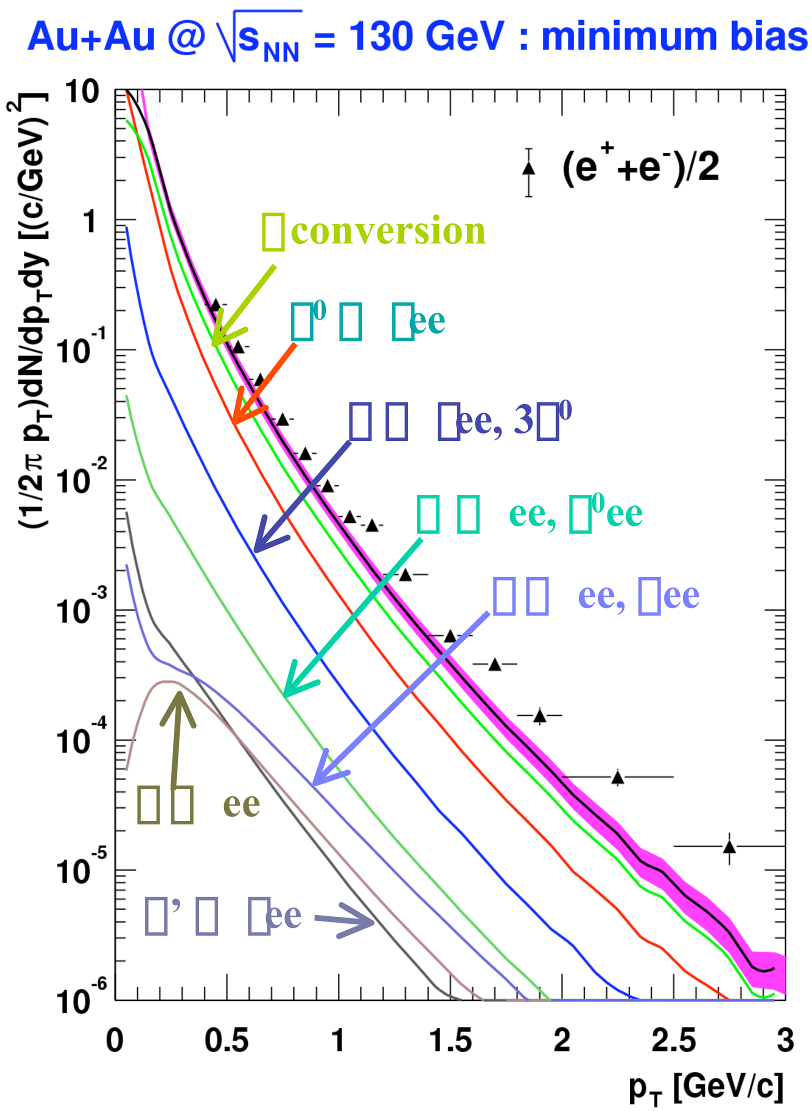


- ElectroMagnetic Calorimeter measures Energy of photons and electrons
  - reconstructs π^0 from 2 photons. Measures decent Time of Flight
  - hadrons deposit Minimum Ionization, or higher if they interact
- For electron ID require RICH (cerenkov) and matching energy in EMCal
  - Electron and photon energy can be matched to < 1%--No nonlinearity problem
- momentum +TOF=charged particle ID
- High Resolution TOF completes the picture giving excellent charged hadron PID

PHENIX--charm via single e$^\pm$ in Au+Au



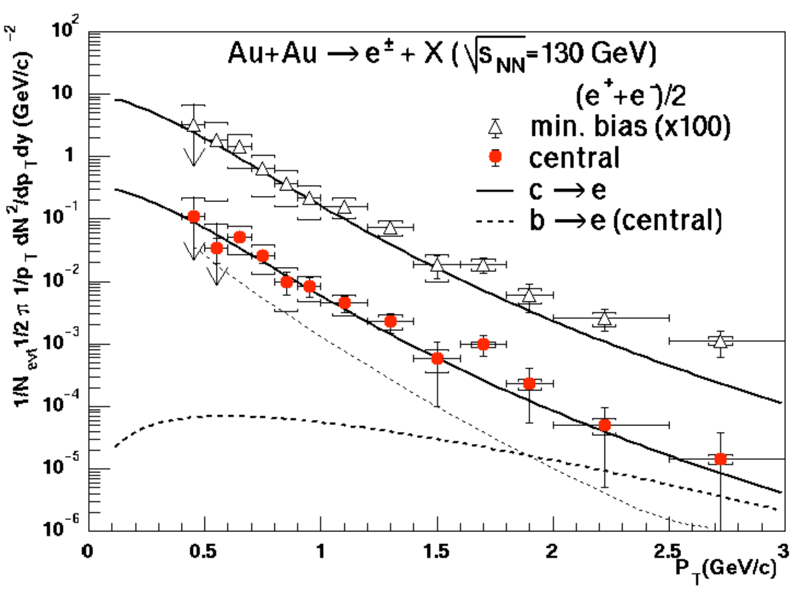


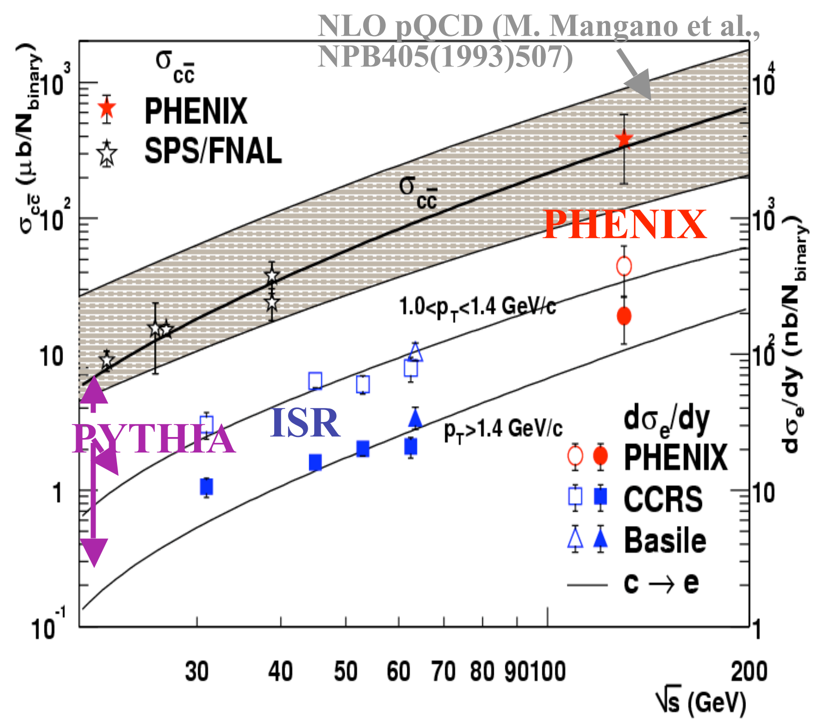


- main systematic errors (band)
  - –pion spectra, ratio □/□^{0}, ratio conversion/Dalitz (material) □ Need converter run

PHENIX--charm via single e$^{\pm}$ in Au+Au 130 cont'd

- Min bias and central Au+Au p_T distributions are consistent with pointlike nbinary scaling from pythia (p-p)
- consistent with ISR and NLO pQCD in measured dσ_e/dy and total deduced charm cross section.





To go from p-p to A+A collisions: We know from DIS that Hard Scattering is Point-Like

E. Gabathuler, Total cross-section

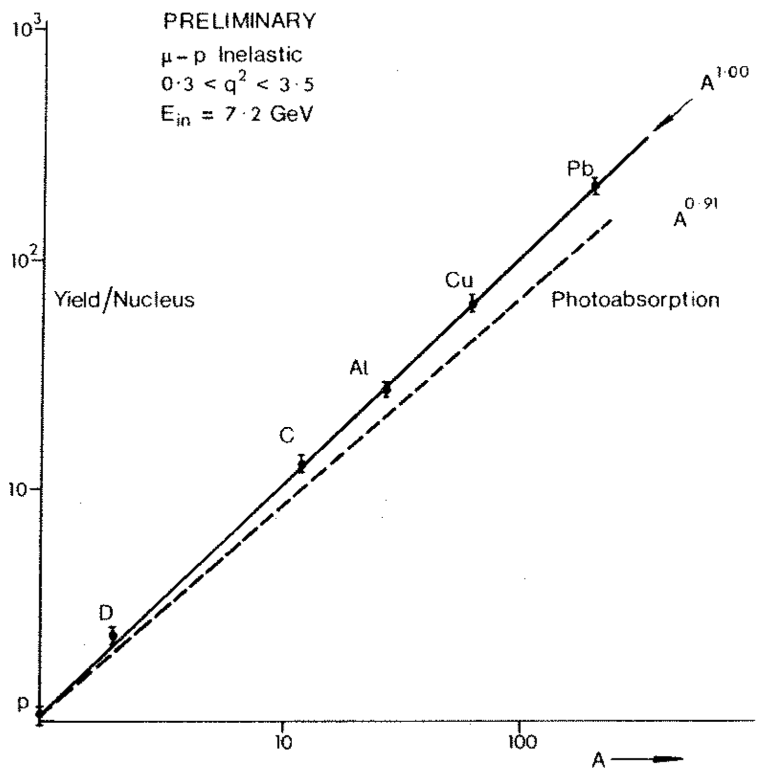


Fig. 14. The *A* dependence of the inelastic muon cross-section as presented by Tannenbaum (see discussion).

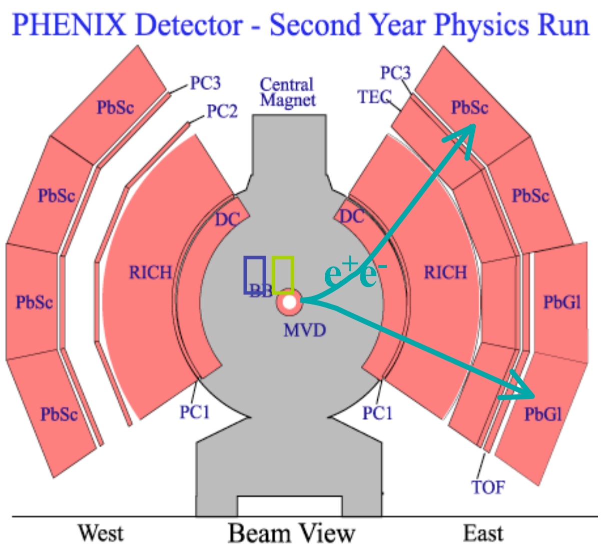
AGS $\mu - A$ scattering data, from E. Gabathuler's talk, [Proc. 6th Int. Symposium on Electron and Photon Interactions at High Energies, Bonn (1973)].

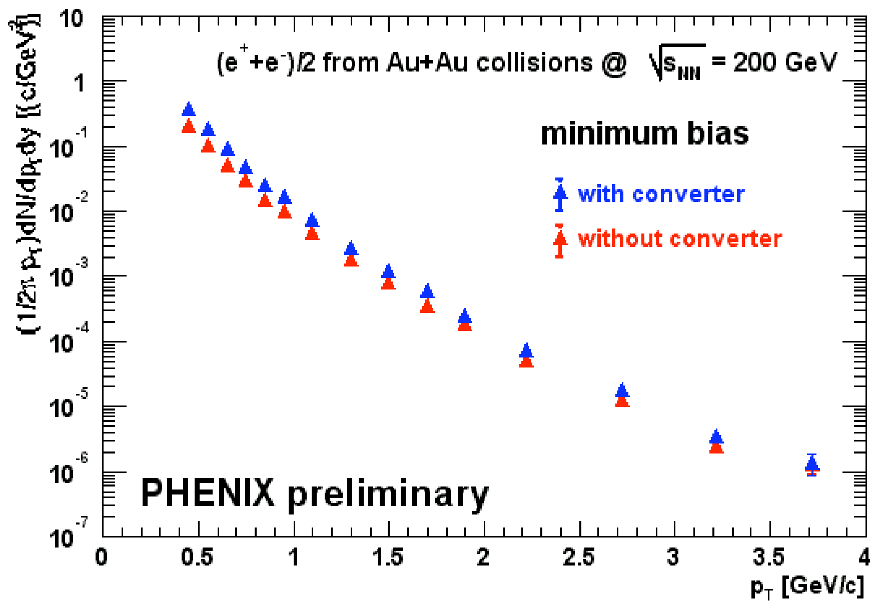
♡ DIS is pointlike $A^{1.00}$ even at modest q^2—no shadowing.

♡ Photoproduction is shadowed—$A^{0.91}$

♡ In the region of hard scattering ($p_T > 2$ GeV/c) scaling from p-p to nuclear collisions should be simply proportional to the relative number of point-like encounters, corresponding to A (p+A), $A \times B$ (A+B) for the total rate and to T_{AB}, the overlap integral of the nuclear profile functions, as a function of centrality.

QM02 PHENIX 200 GeV charm via e$^{\pm}$





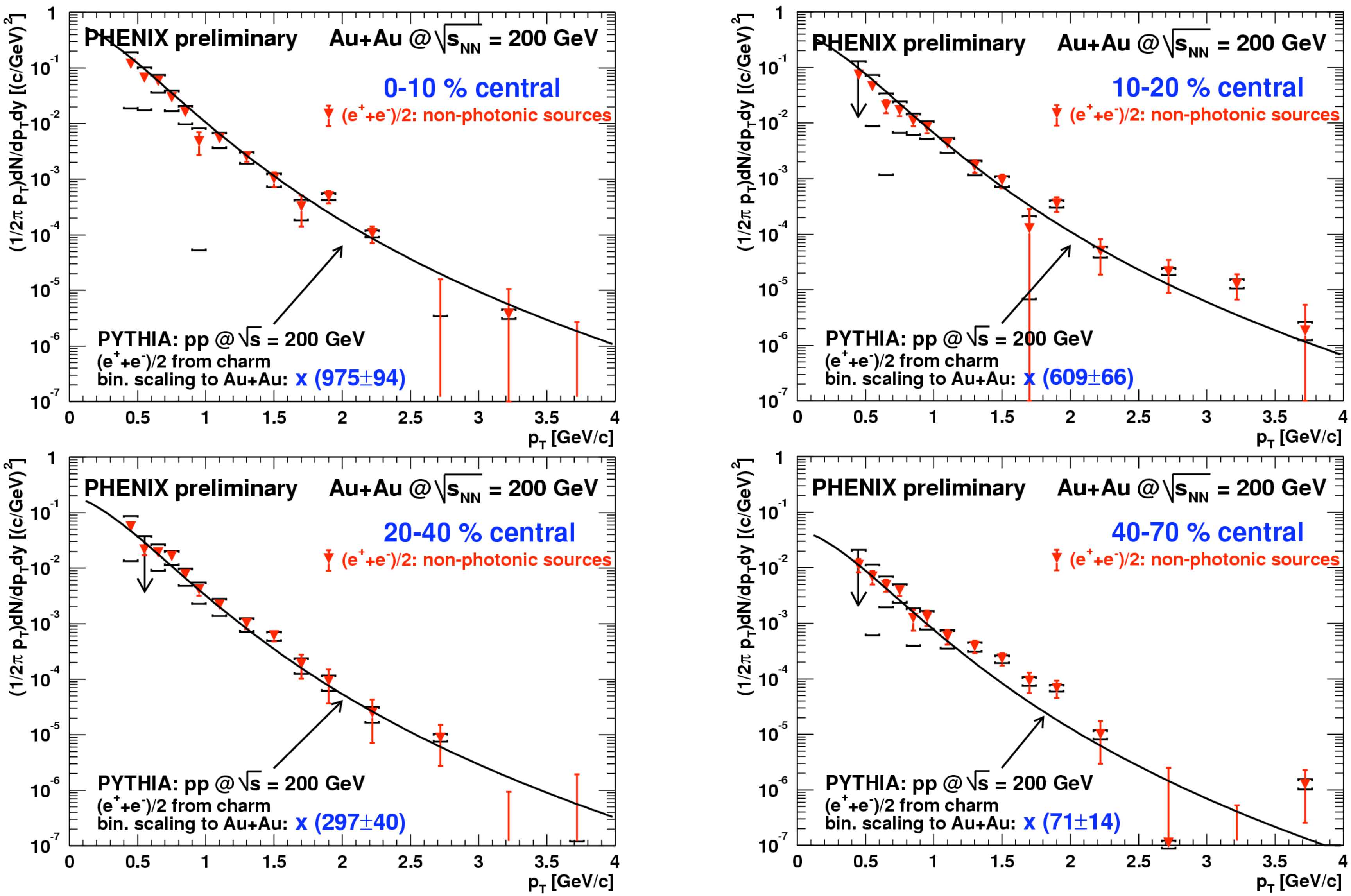
- **Some data with 1.7 % X_0 converter added**
- **converter only affects photonic component**

- **converter effect is much greater at low pT, indicating**
  - **relatively much larger photonic component at low pT**
  - **relatively smaller phtonic (i.e. larger non-photonic) component at higher pT (i.e. charm)**

Reduced systematic erros.

Single e p_T distribution vs Centrality

Consistent with binary (pointlike) scaling □ charm is not suppressed



Conclusions from single e± measurement

- e± from charm decays measured by PHENIX in Au+Au collisions at RHIC
- e± yields and spectral shapes
- consistent with PYTHIA calculations for pp:

  σ_{cc} = 330 (650) μb at 130 (200) GeV)
- scaled to Au+Au by number of binary collisions
- NA50: factor ~3 charm enhancement inferred at SPS

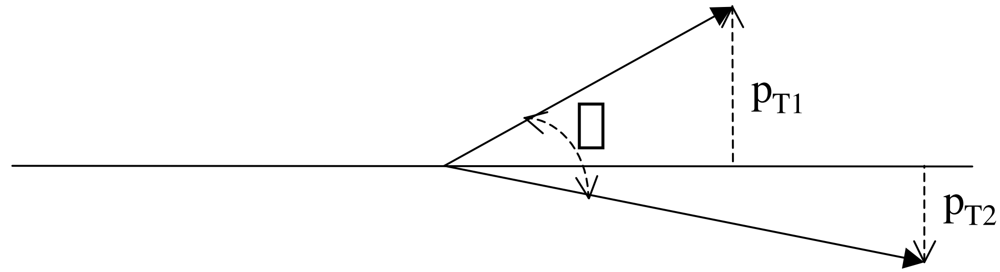
  from μ+ μ- pair enhancement (will discuss later)
  - no enhancement observed at RHIC in inclusive charm production.
- RHIC: factor 3-4 suppression of high p_T hadrons relative to binary scaling
  - no suppression observed in e± from charm decays---follows binary scaling

    Seems to IMPLY
    - normal gluon structure function in initial state

      ⇒ no saturation, no large shadowing
    - possibly less energy loss of heavy quarks in dense medium:

      "dead cone effect"? (Y. Dokshitzer, D. Kharzeev: hep-ph/0106202)

Lepton Pairs---Kinematics, Notation



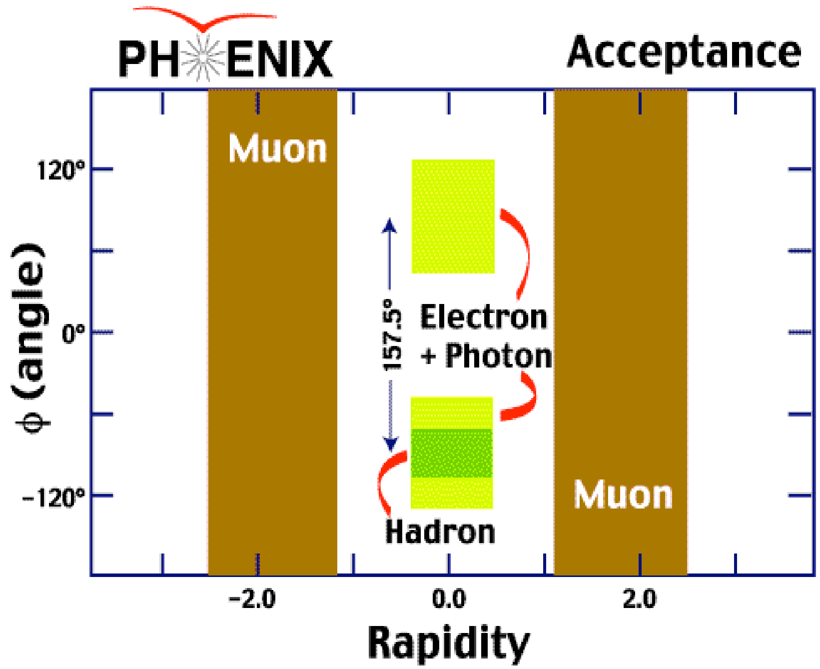
- $\vec{p}_T = \vec{p}_{T1} + \vec{p}_{T2}$ $\qquad$ $\vec{p}_L = \vec{p}_{L1} + \vec{p}_{L2}$
- $m^2 = m_1^{\,2} + m_2^{\,2} + 2(E_1E_2 - p_1p_2 \cos □)$
- $y = \frac{1}{2}\ln[(E+p_L)/m_T]$

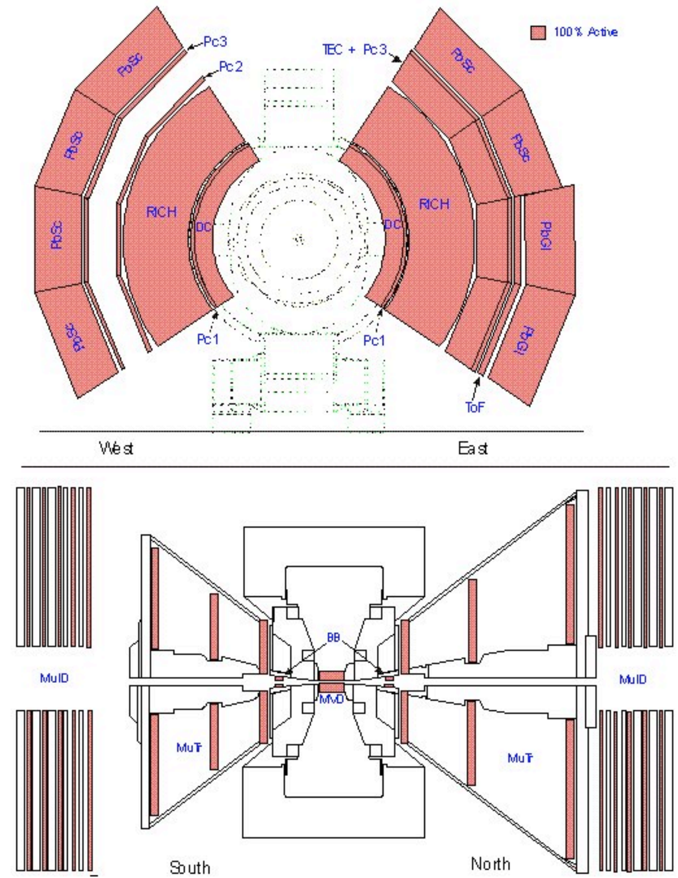
□*, □*, azimuthal and polar angles of the pair in its cm system

- simple if pT=0, more complicated pT≠0 collins-soper-sterman

[J. C. Collins, D. E. Soper and G. Sterman, NP**B250**, 199 (1985)]

Acceptance is geometrical but:



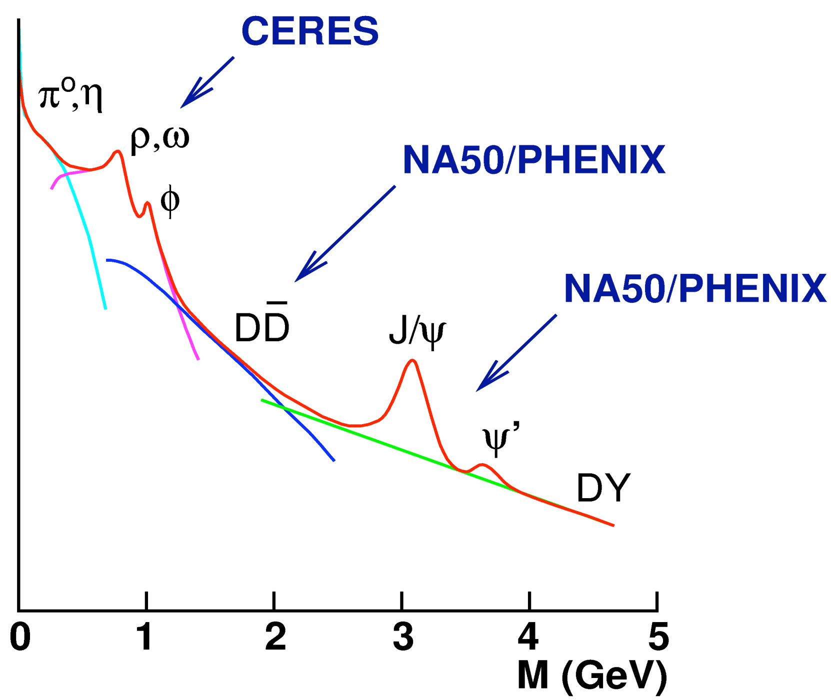


Acceptance (geometrical)= prob. to fall on detector for given p_T y m

- an average over □*, □*, (sometimes over p_T, y)---can be model dependent (e.g. if averaged -3<y<3, is y distribution flat?)

Efficiency=detection prob for lepton pair or lepton in acceptance

Survey of Physics Topics using lepton pairs



MJT Physics topics using e^+e^- 11/96

Topic	Method	Comment
π^0	external conversions (+Dalitz) $m_{e^+e^-} \leq m_{\pi^0}$	Inclusive γ
η	$140 \leq m_{e^+e^-} \leq 400$ MeV/c^2	Dalitz decay
Direct γ	$400 \leq m_{e^+e^-} \leq 600$ MeV/c^2	Internal Conversion
ρ^0	$600 \leq m_{e^+e^-} \leq 900$ MeV/c^2	Lose money on every sale...
ω^0	$m_{e^+e^-} \simeq 782 \pm 8$ MeV/c^2	Should work (?)
ϕ	$m_{e^+e^-} \simeq 1019 \pm 4$ MeV/c^2	compare K^+K^-
Charm	$e^{\pm}$ inclusive $p_T \geq 1.1$ GeV/c	No combinatoric bkg.
$c-\bar{c}$	$1.6 \leq m_{e^+e^-} \leq 5$ GeV/c^2	Jet Quenching
$c-\bar{c}$	$1.6 \leq m_{e^{\pm}\mu^{\mp}} \leq 5$ GeV/c^2	Jet Quenching Msmt. Charm bkg for D-Yan
Drell-Yan	$4.0 \leq m_{e^+e^-}$ GeV/c^2	QCD Sanity check
J/Ψ	$m_{e^+e^-} \simeq 3097 \pm 0.09$ MeV/c^2	QGP or Bust Inclusive, Central $(AB)^\alpha$ p_T dependence
Ψ'	$m_{e^+e^-} \simeq 3686 \pm 0.3$ MeV/c^2	Rate Limit ?
Υ	$9.6 \leq m_{e^+e^-} \leq 10.6$ GeV/c^2	*Rate Limit*

MJT Physics topics using e^+e^- 11/96

Topic	Method	Comment
π^0	external conversions (+Dalitz) $m_{e^+e^-} \leq m_{\pi^0}$	Inclusive γ
η	$140 \leq m_{e^+e^-} \leq 400$ MeV/c^2	Dalitz decay
Direct γ	$400 \leq m_{e^+e^-} \leq 600$ MeV/c^2	Internal Conversion
ρ^0	$600 \leq m_{e^+e^-} \leq 900$ MeV/c^2	Lose money on every sale...
ω^0	$m_{e^+e^-} \simeq 782 \pm 8$ MeV/c^2	Should work (?)
ϕ	$m_{e^+e^-} \simeq 1019 \pm 4$ MeV/c^2	compare K^+K^-
Charm	$e^\pm$ inclusive $p_T \geq 1.1$ GeV/c	No combinatoric bkg.
$c - \bar{c}$	$1.6 \leq m_{e^+e^-} \leq 5$ GeV/c^2	Jet Quenching
$c - \bar{c}$	$1.6 \leq m_{e^\pm\mu^\mp} \leq 5$ GeV/c^2	Jet Quenching Msmt. Charm bkg for D-Yan
Drell-Yan	$4.0 \leq m_{e^+e^-}$ GeV/c^2	QCD Sanity check
J/Ψ	$m_{e^+e^-} \simeq 3097 \pm 0.09$ MeV/c^2	QGP or Bust Inclusive, Central $(AB)^\alpha$ p_T dependence
Ψ'	$m_{e^+e^-} \simeq 3686 \pm 0.3$ MeV/c^2	Rate Limit ?
Υ	$9.6 \leq m_{e^+e^-} \leq 10.6$ GeV/c^2	*Rate Limit*

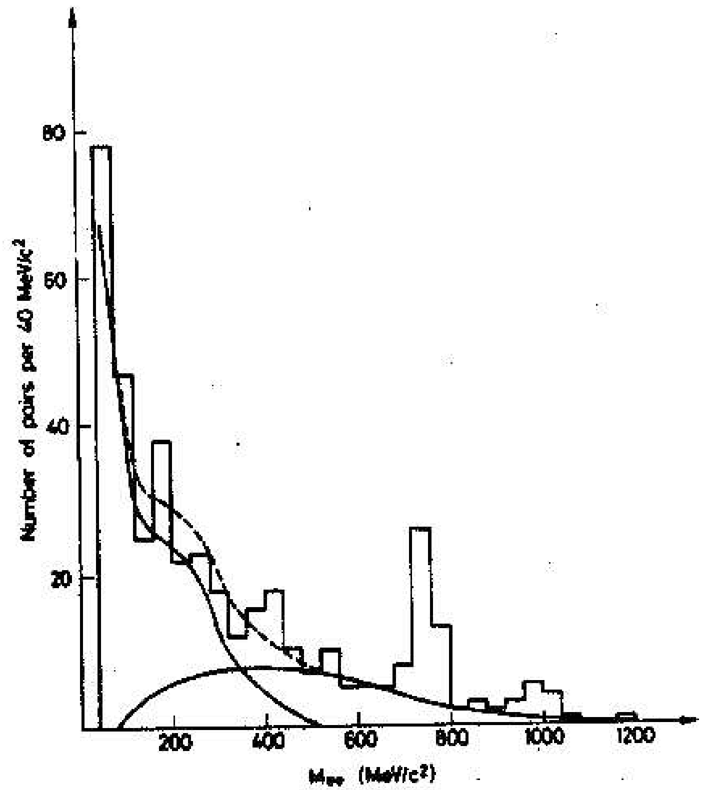
Low Mass Pairs---ISR best data 1979

[A. Chilingarov, et al., Nucl. Phys. B151, 29 (1979)]

•ISR `same side' low mass e+ e- pair production with the condition $p_T \geq 1.6$ GeV/c+0.5 m(GeV/c^2) η and ρ ω $e^+ e^-$ peaks are clear. Solid curve for m≤500 MeV/c^2 is $\pi^0 \to \gamma$ Dalitz decay. Other solid curve for m ≥ 100 MeV/c^2 is c c production with 73μb cross section.

•Sum of 2 solid curves (dashed curve) seems to explain excess pairs in the range 400< m< 600 MeV/c^2 where there is no known source of Dalitz decay.

•Also, excess could be explained by internal conversion of direct photon with γ/π=3.8% at p_T=1.9 GeV/c, but this would scale like 1/m to lower masses in disagreement with data



These expt's are tricky: continuing ``low mass pair anomaly'' results in the period 1976-91 explained by wrong assumption for □/□^{0} ratio!!!!!!!

- pp measurement, [K. J. Anderson et al, PR37, 799 (1976)]
They noted □ dalitz could explain effect if □/(□+□)=60%
- Quark Matter conference `highlights' from 1984, H. J. Specht, until 1991 U. Goerlach, when they use correct □/□ !!!!!
- Final publication Helios Collab., Eur. Phys. J. **C13**, 433 (2000)

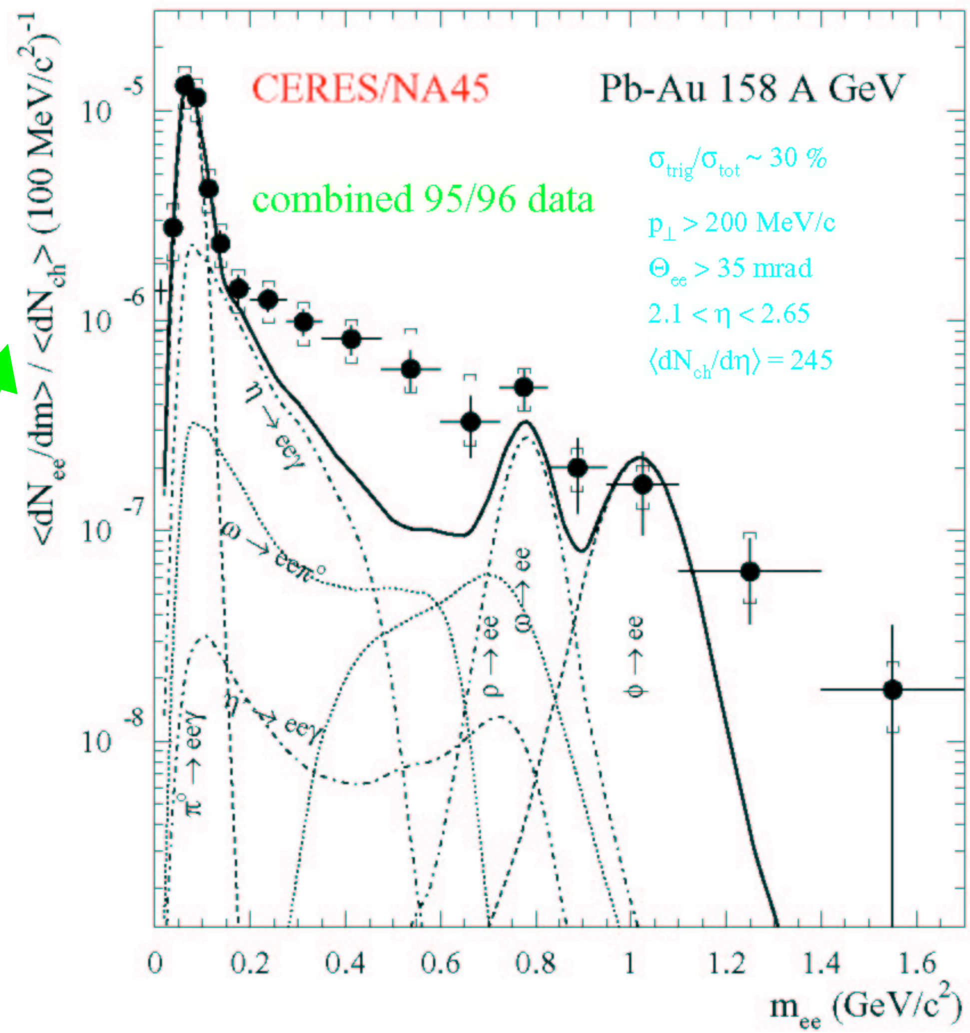
- However `low mass anomaly' persists in more recent CERES experiment at SpS fixed target.

CERES--low mass pairs at CERN-SpS

[CERES Collaboration, G. Hering, et al, nucl-ex/0203004]

- Excess in $0.2<m<0.6$ GeV/c^2
- source of many theoretical fantasies.
- Authors claim it's not charm?
- Huge background subtraction.
- Strange way to quote msmt, not centrality based

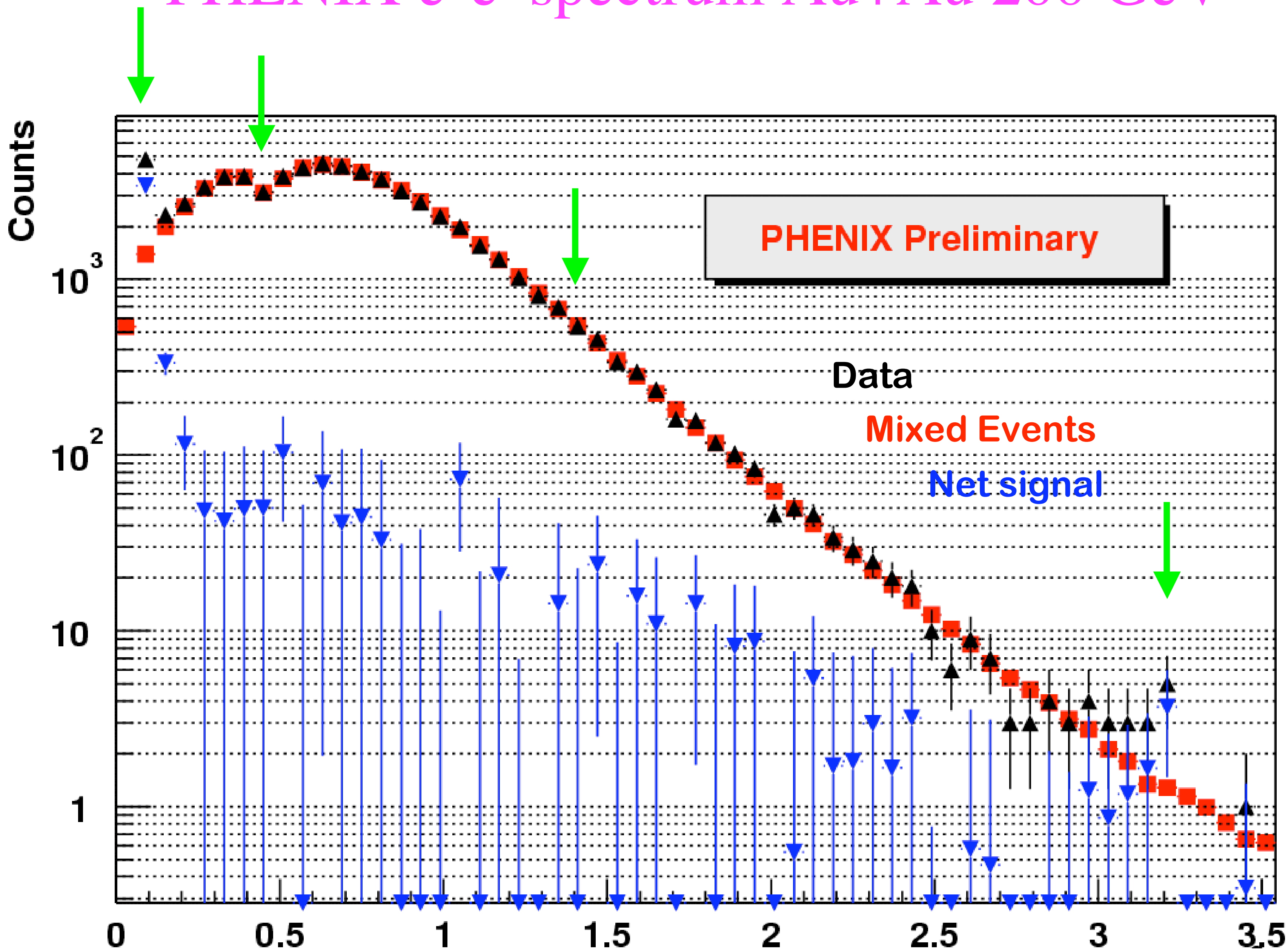
?



On to the RHIC data

RHIC data

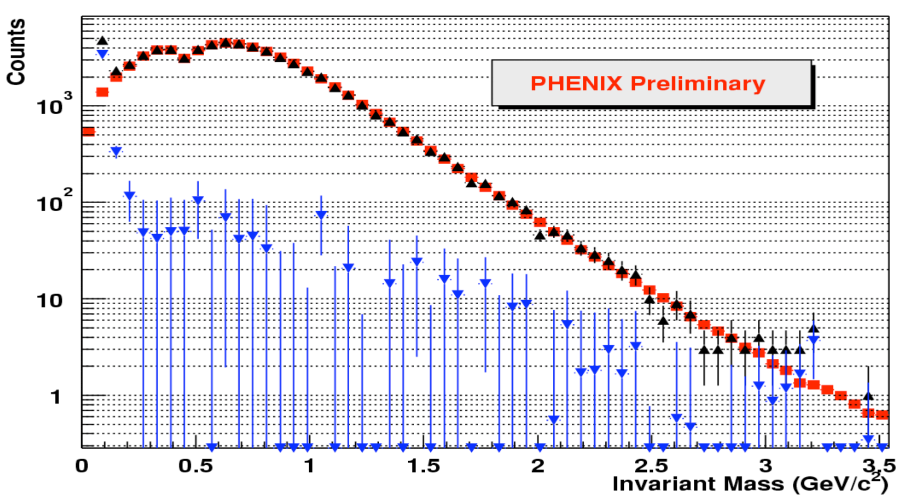
PHENIX e^+e^- spectrum Au+Au 200 GeV



PHENIX e^+e^- spectrum at RHIC 200 GeV Au+Au

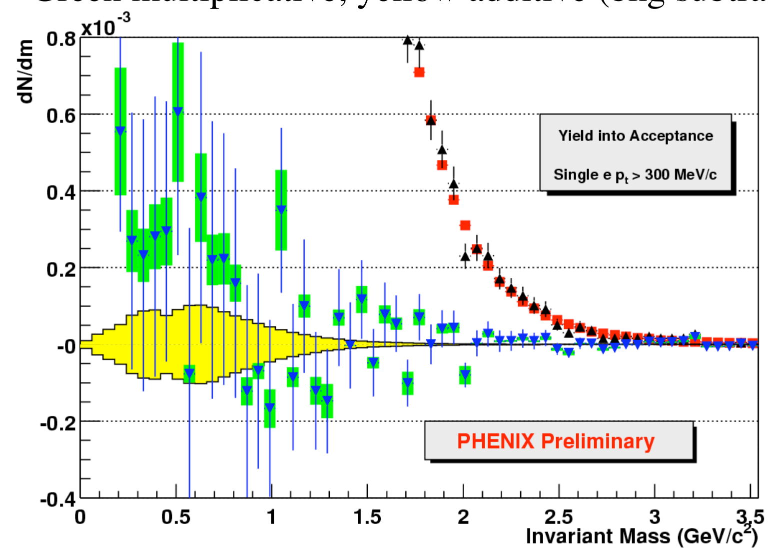
- The huge $e^\pm$ rate from conversions gives a HUGE random $e^+ e^-$ background. In general $Ne^+ \neq Ne^-$
- $(P_{e+} + P_{e-})^2 = P_{e+}P_{e+} + P_{e-}P_{e-} + 2P_{e+}P_{e-}$
- Background subtraction by mixed e+ e- events with normalization $N_{e+e-} = 2\sqrt{N_{e+e+}\, N_{e-e-}}$

Real and **Mixed** e^+e^- Distribution

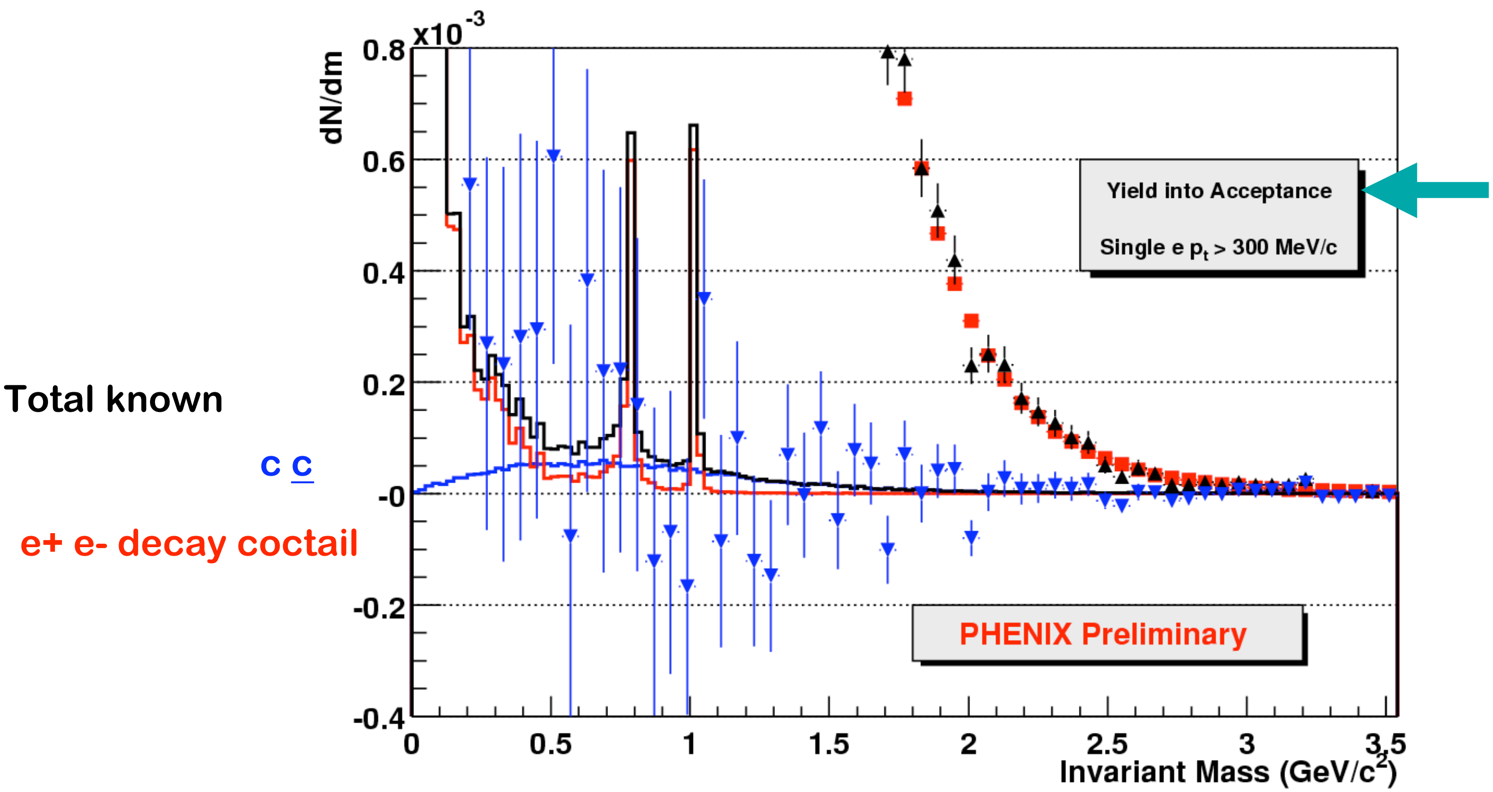


Real - **Mixed** with systematic errors

Green multiplicative, yellow additive (bkg subtraction)



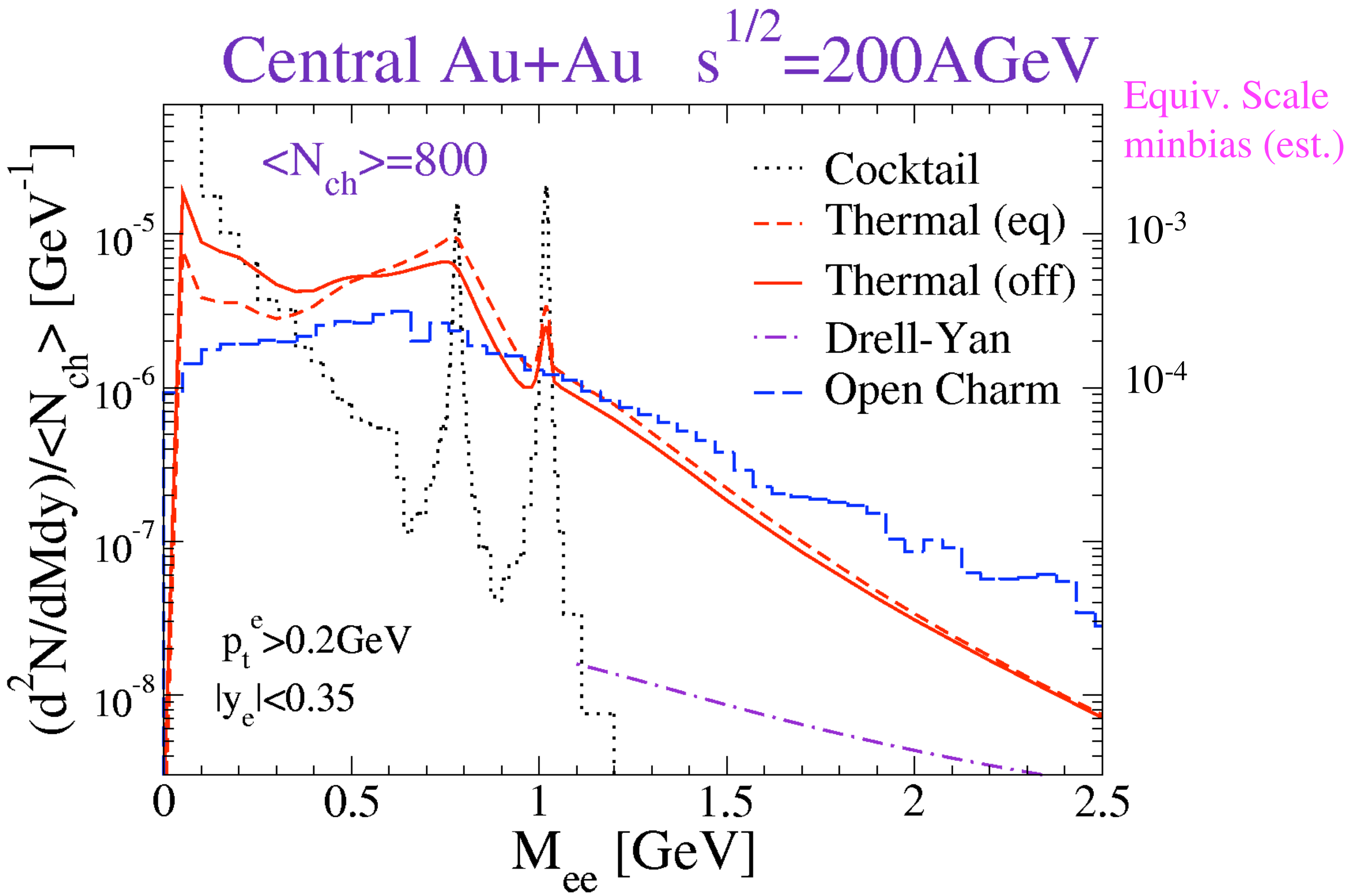
PHENIX intermediate mass results



•Need less background (i.e. Dalitz rejection) or more data before we can say anything serious

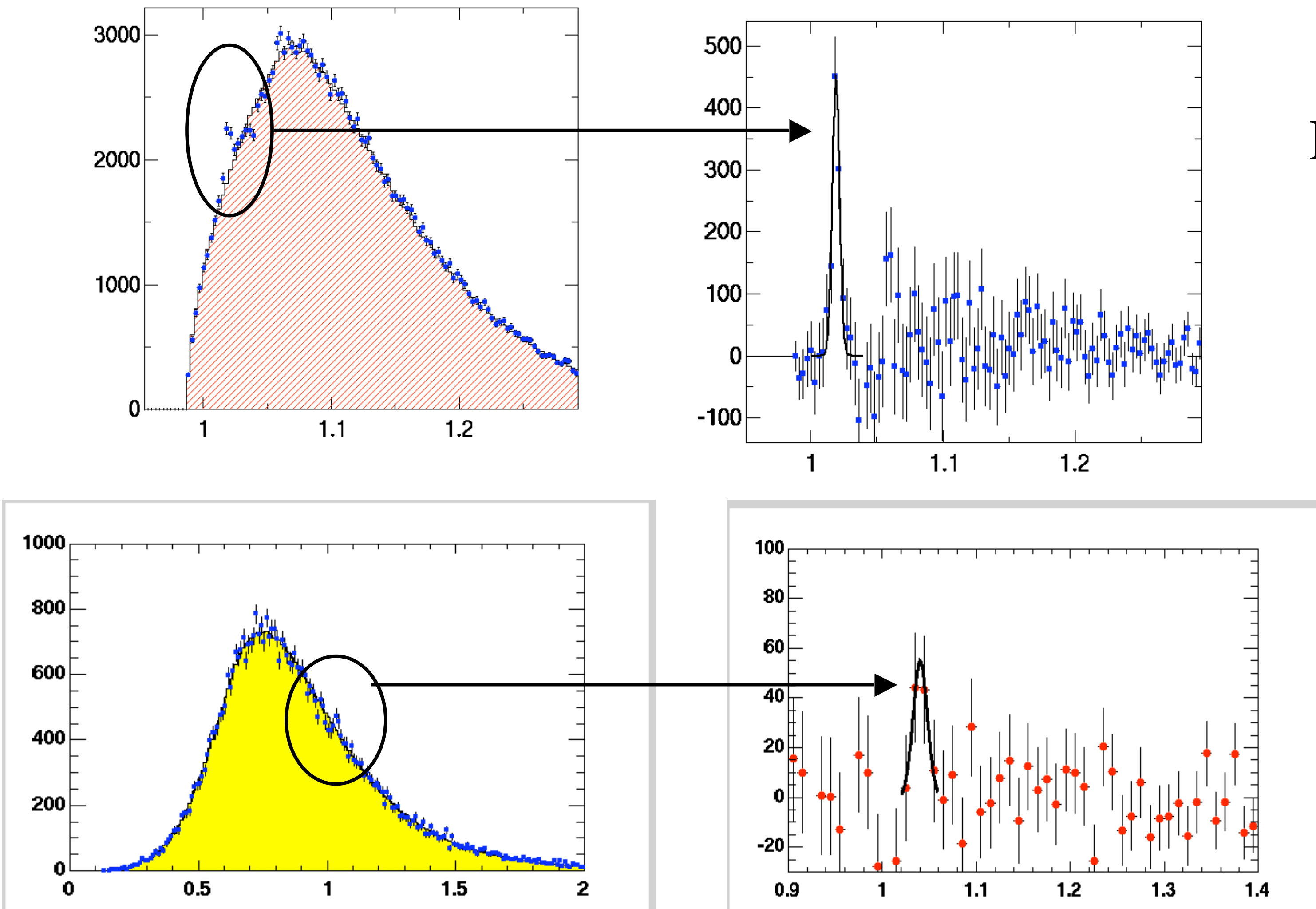
This is the mass range for thermal pairs

[Ralf Rapp, PRC63, 054907 (2001), also nucl-th/0204003]



[More classical reference: K. Kajantie, et al (KKMM) PR**D34**, 2746 (1986)]

Vector Meson Interlude---PHENIX phi-> KK ee



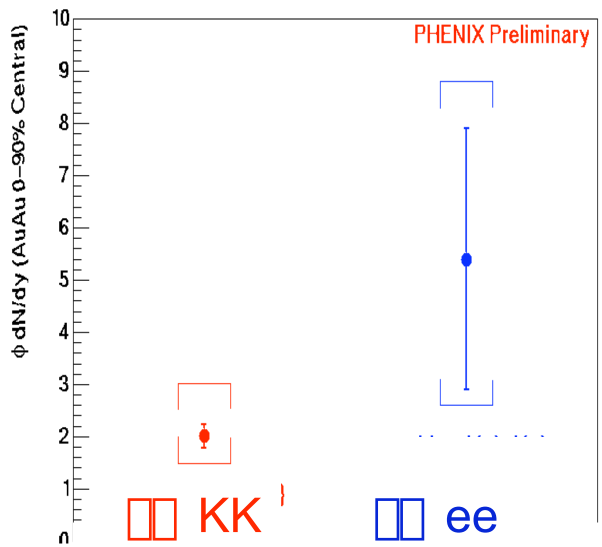
$K^+ K^-$

$e^+ e^-$

PHENIX--phi comparison
Do observed branching ratios change?

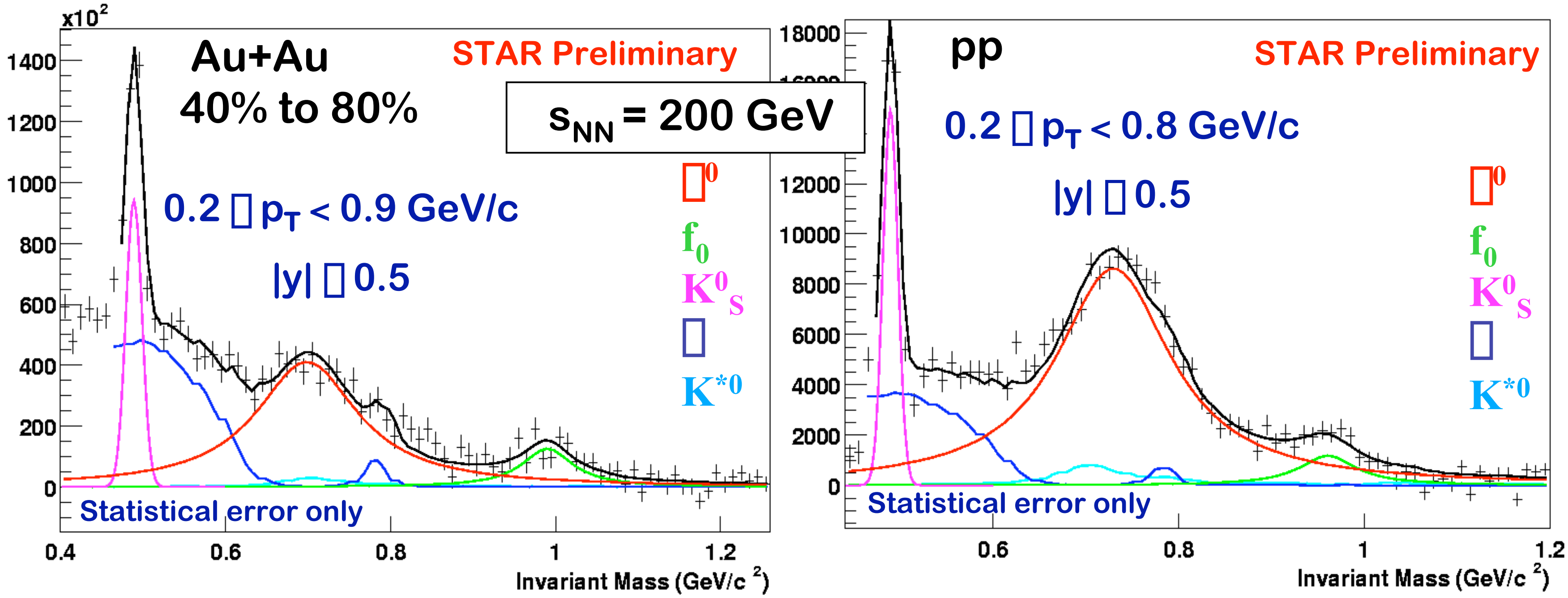
$$\phi \to e^+e^-: \quad \frac{\mathrm{dN}}{\mathrm{dy}} = 5.4 \pm 2.5(stat)^{+3.4}_{-2.8}(sys)$$

$$\phi \to K^+K^-: \quad \frac{\mathrm{dN}}{\mathrm{dy}} = 2.01 \pm 0.22(stat)^{+1.01}_{-0.52}(sys)$$



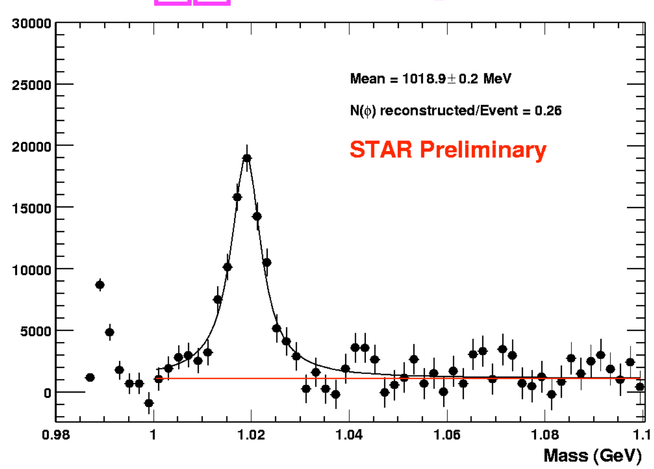
•Cross sections are consistent using `vaccuum' branching ratios⇒ No medium effect (yet?)

STAR□$^+$□$^-$



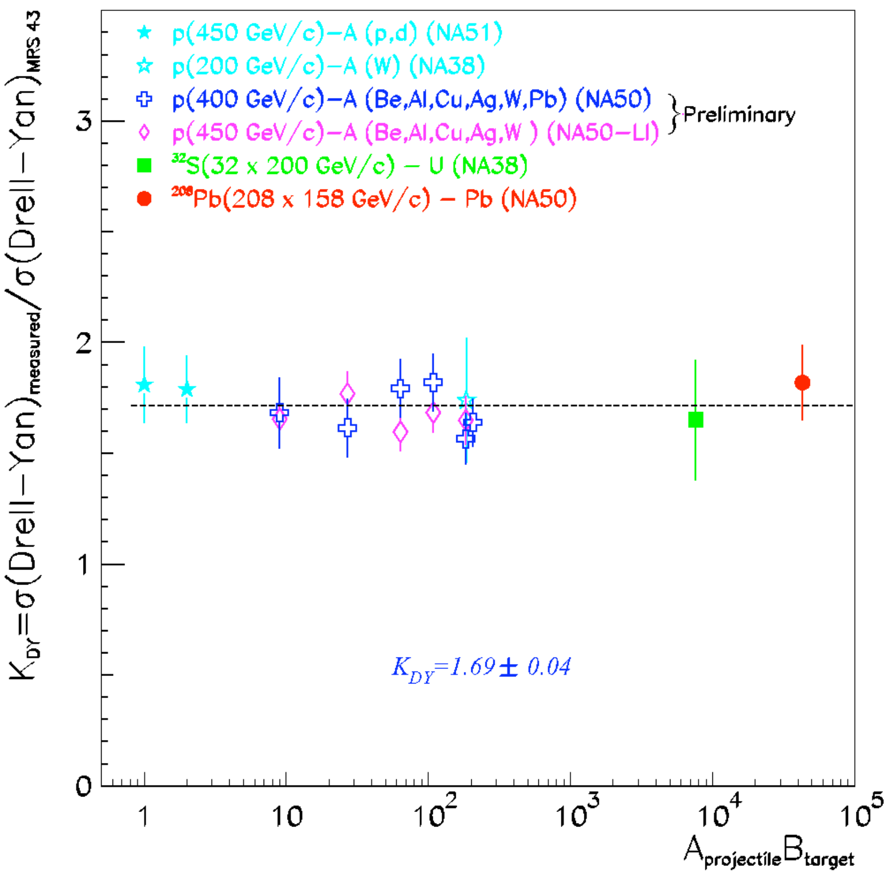
•Even □□ □$^+$□$^-$ is hard, long wait for □□ $e^+ e^-$ but great hadron gas signature

For the record: STAR □□ K^+K^- [PRC **65**, 04190(R) (2002)]

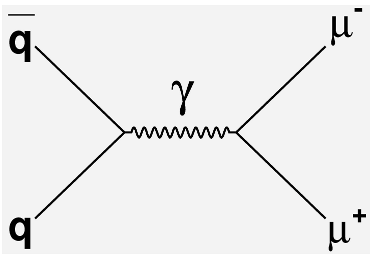


Drell-Yan production is pointlike
Scales like AB or T_{AB} (ncoll)

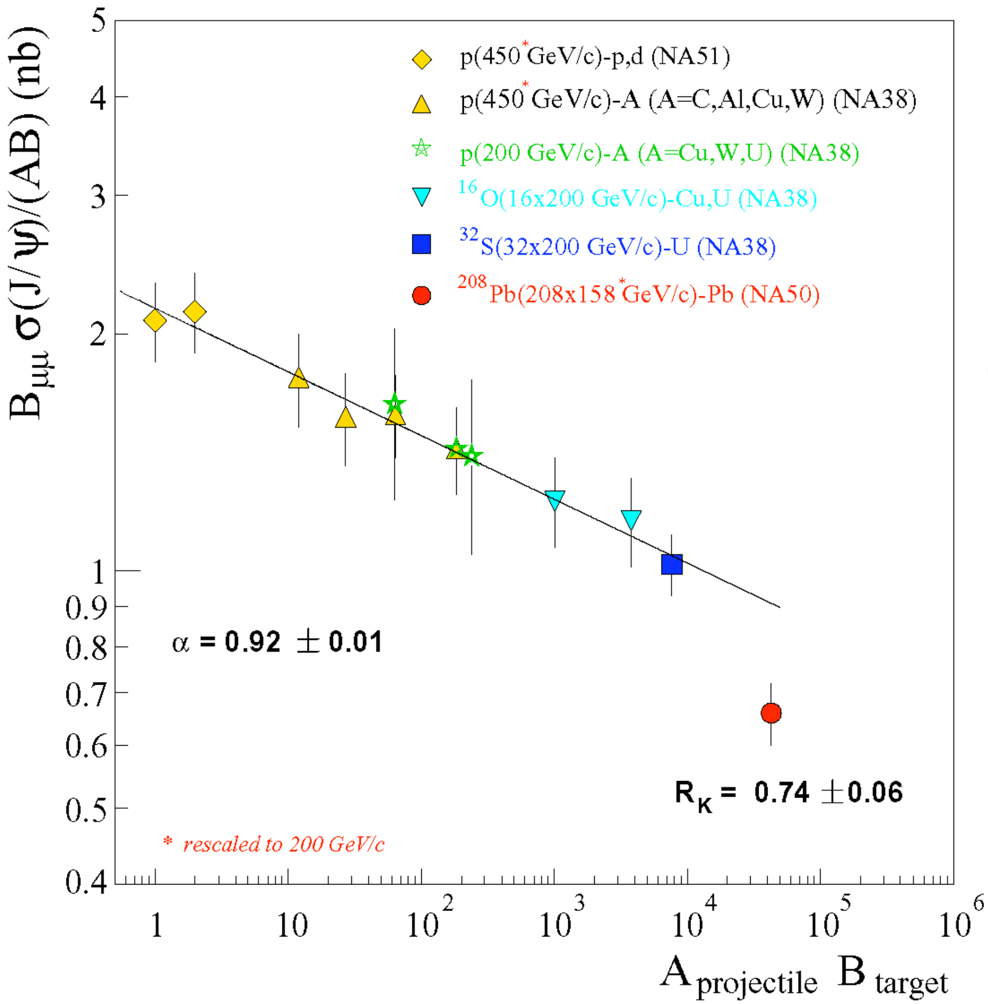
Drell-Yan: Experimental K factor

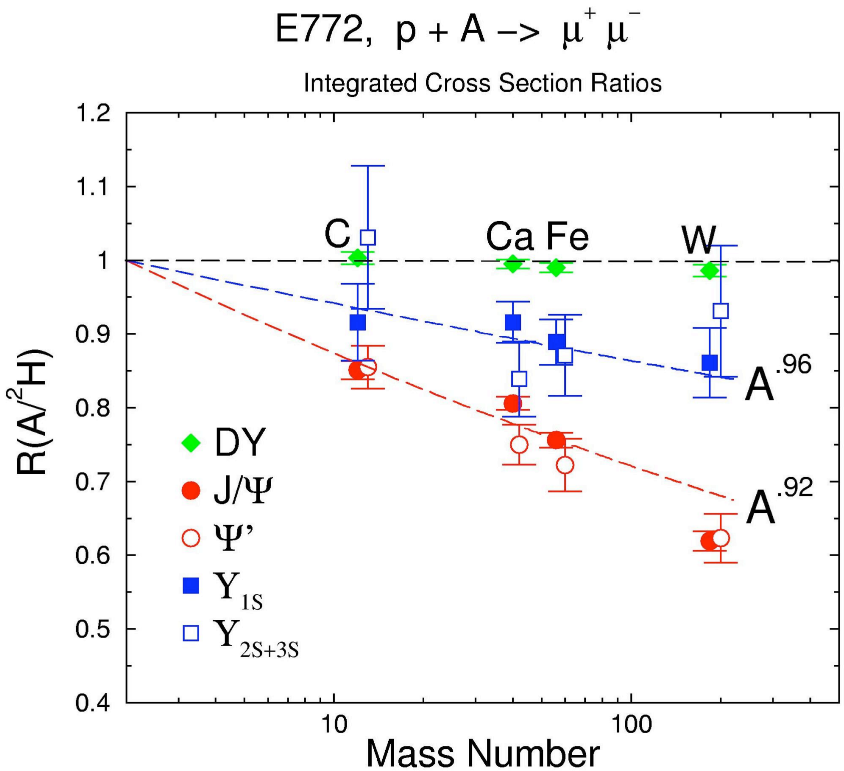


Drell-Yan Process



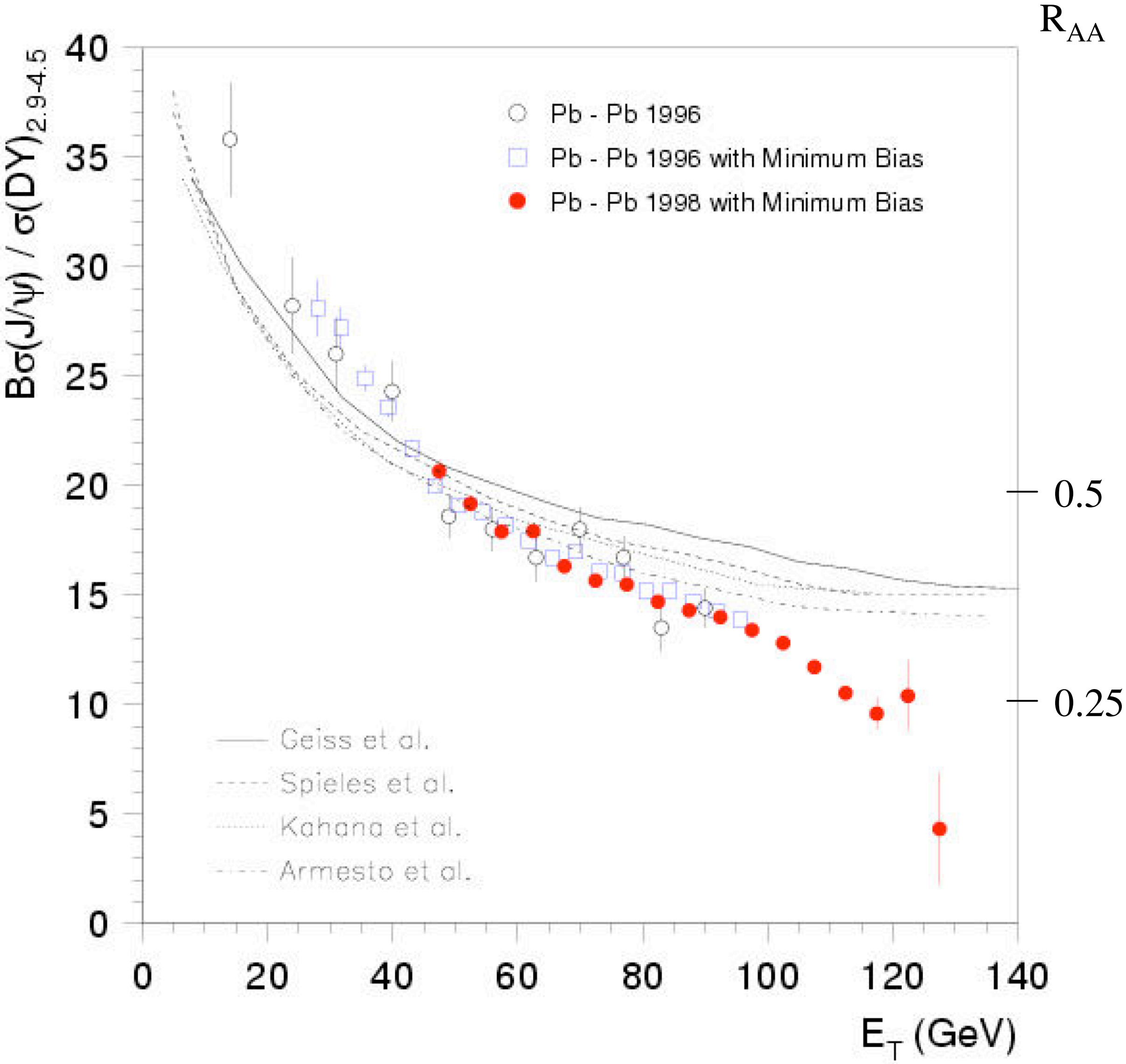
J/ψ and Drell-Yan production-summary





- DY is pointlike
- J/ψ is hadronic
- Complicates suppression issue

NA50 J/ Suppression at CERN 1988-2000

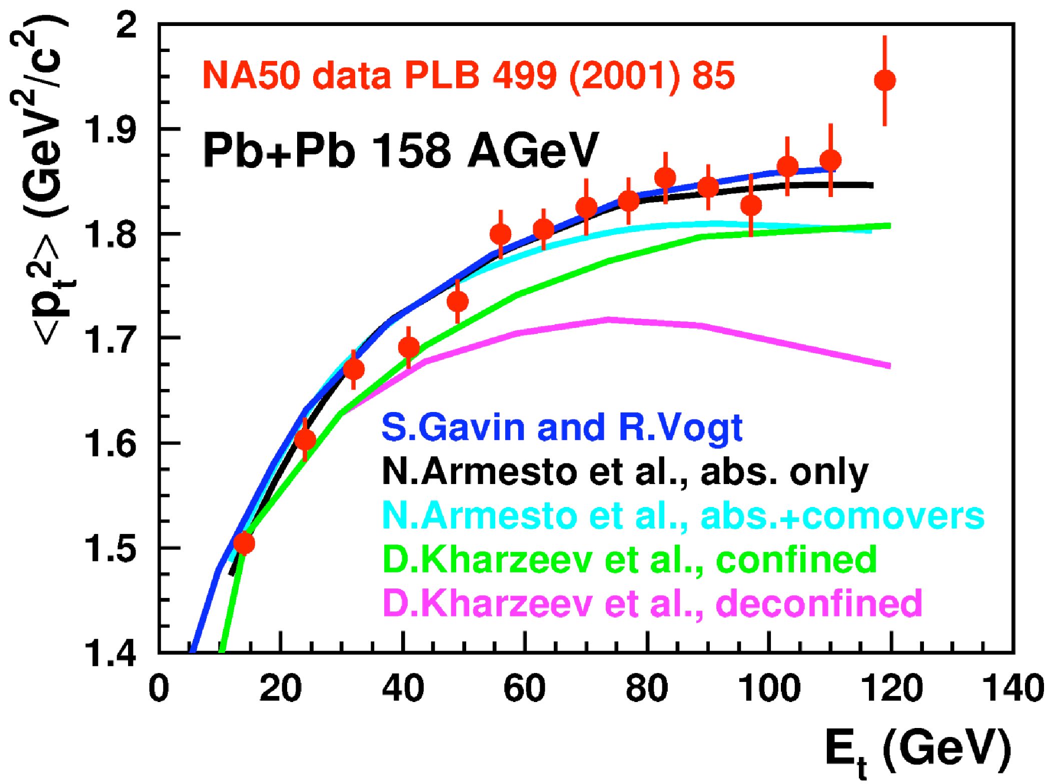


- Is it normal $T_{AB}^{0.92}$?
- Plus comovers?
- Discontinuities?
- $_c$ + suppression?
- J/ suppression?
- pT dependence is relevant

[NA50 collaboration, M.C. Abreu, et al., PL**B 477**, 28 (2000)]

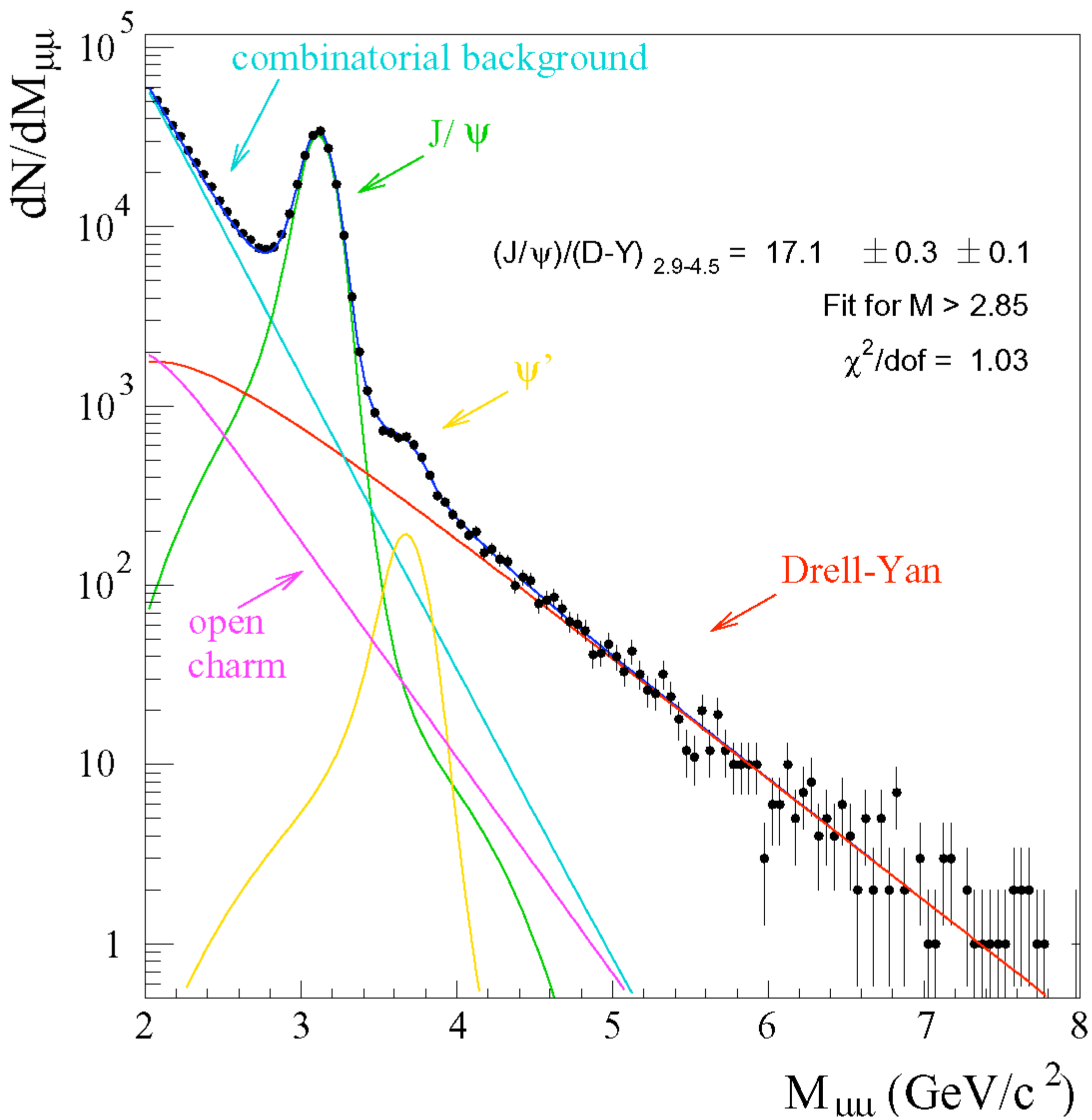
Is this QGP suppression---p_T dependence?

$J/\psi < p_t^2 >$ vs. $\mathrm{E_t}$: Model Comparison



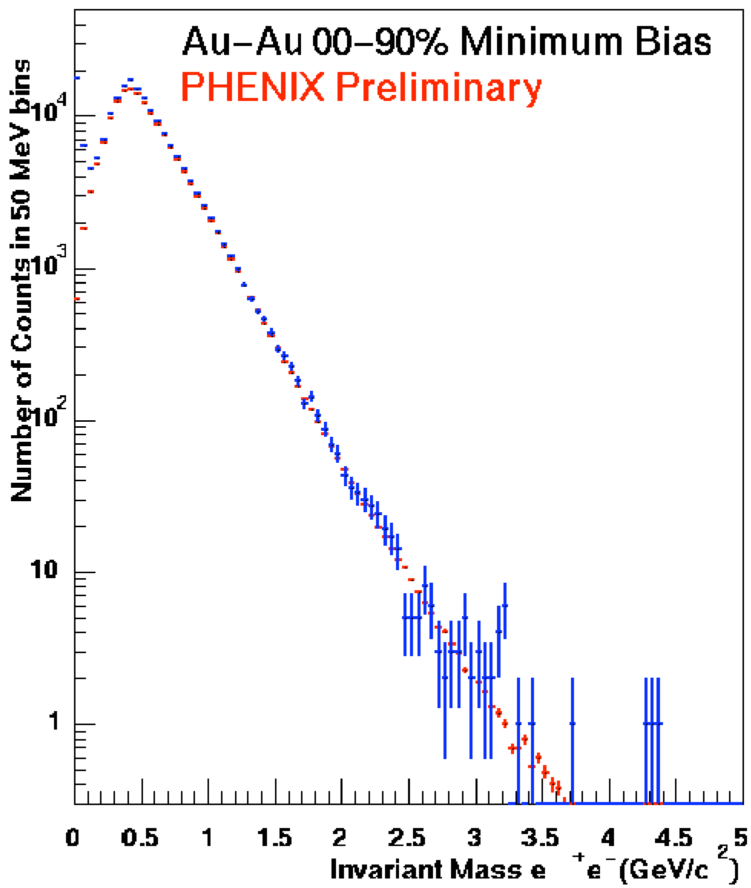
can a QGP model fit simultaneously $(J/\psi)/(\mathrm{DY})$ and $< p_t^2 >$ vs. $\mathrm{E_t}$

J/ψ Production--State of the Art NA50
CERN fixed target Pb+Pb $\sqrt{s_{NN}}=17.2$ GeV



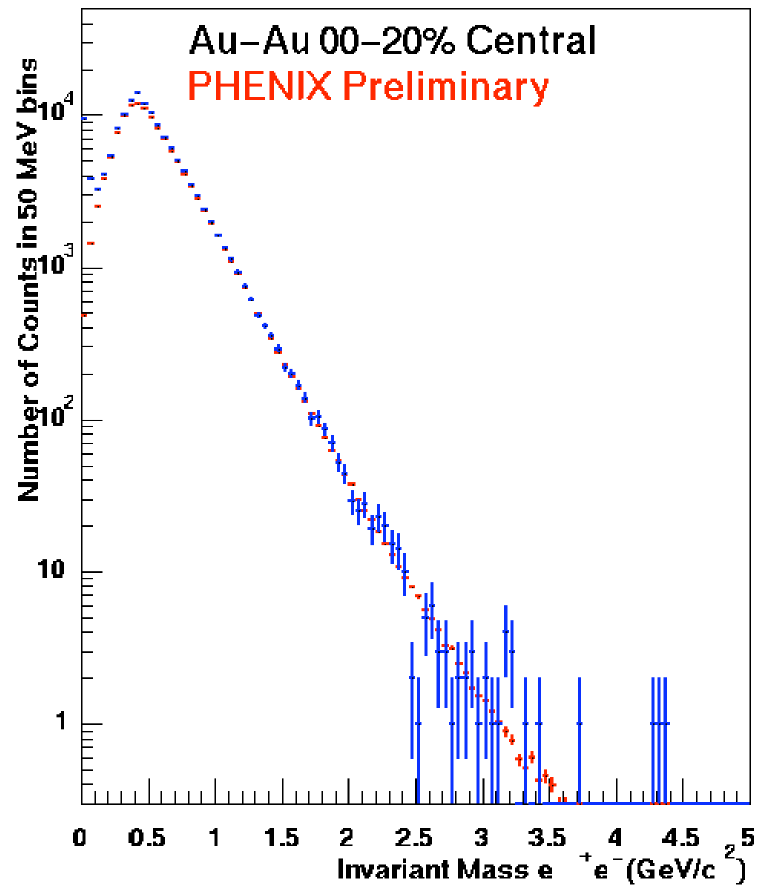
J/ψ Production--PHENIX State of the Art
RHIC Au+Au s_{NN}=200GeV J/ψ → e^+e^-

N=10.8 ± 3.2 (stat) ± 3.8 (sys)



Minimum bias

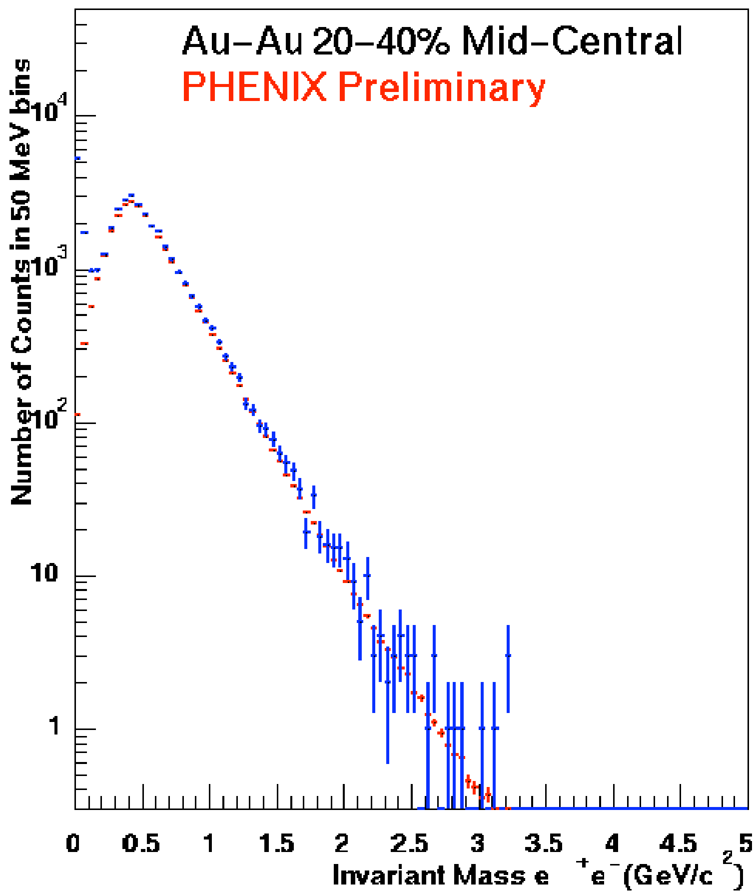
N=5.9 + ± 2.4 (stat) ± 0.7 (sys)



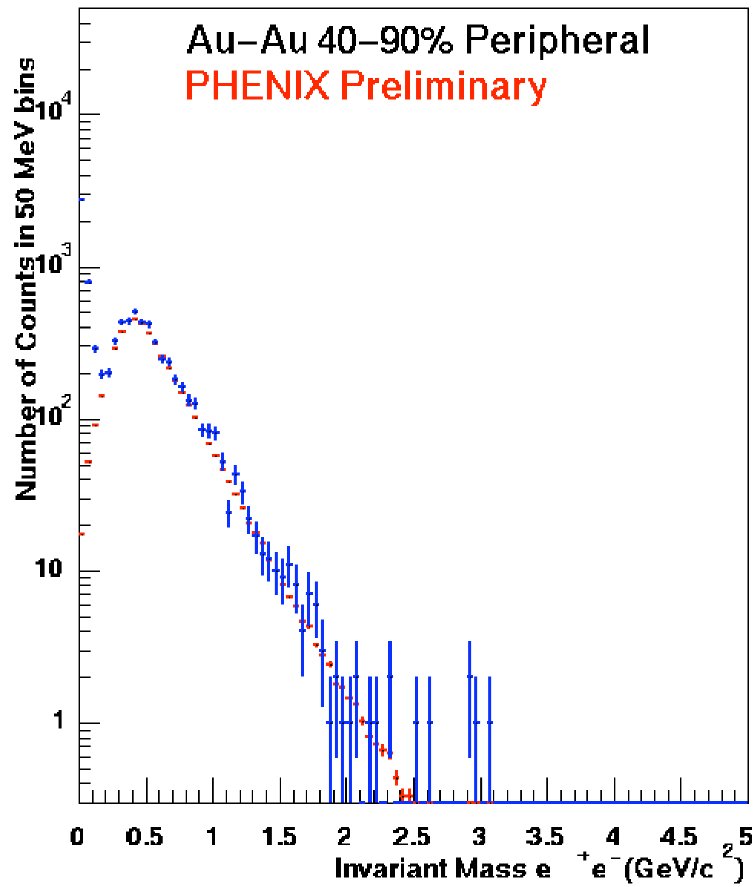
→ Versus centrality

J/ψ Production--PHENIX State of the Art
RHIC Au+Au $\sqrt{s_{NN}}$=200GeV J/ψ → e^+e^-

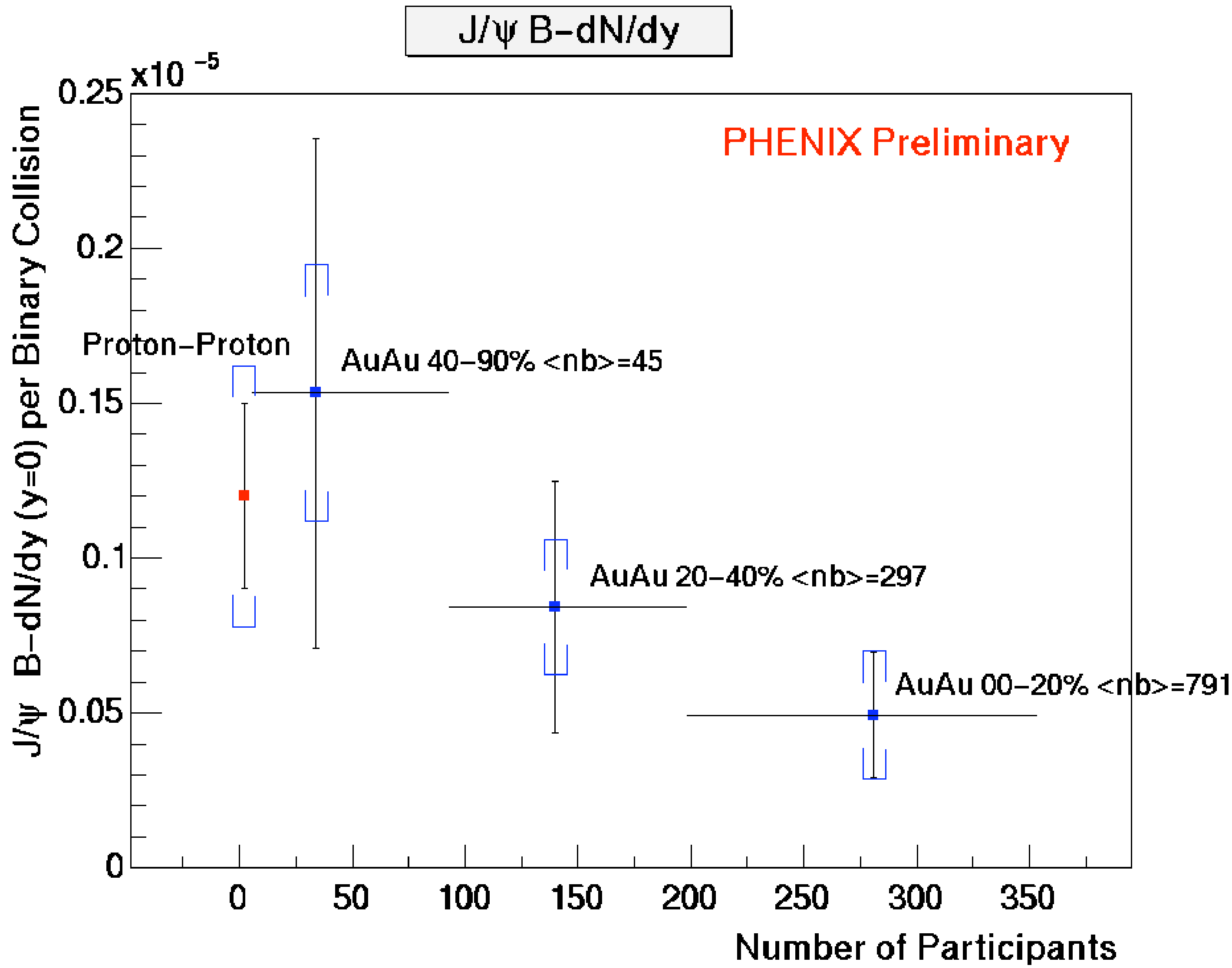
N=4.5 ± 2.1 (stat) ± 0.5 (sys)



N=3.5 ± 1.9 (stat) ± 0.5 (sys)

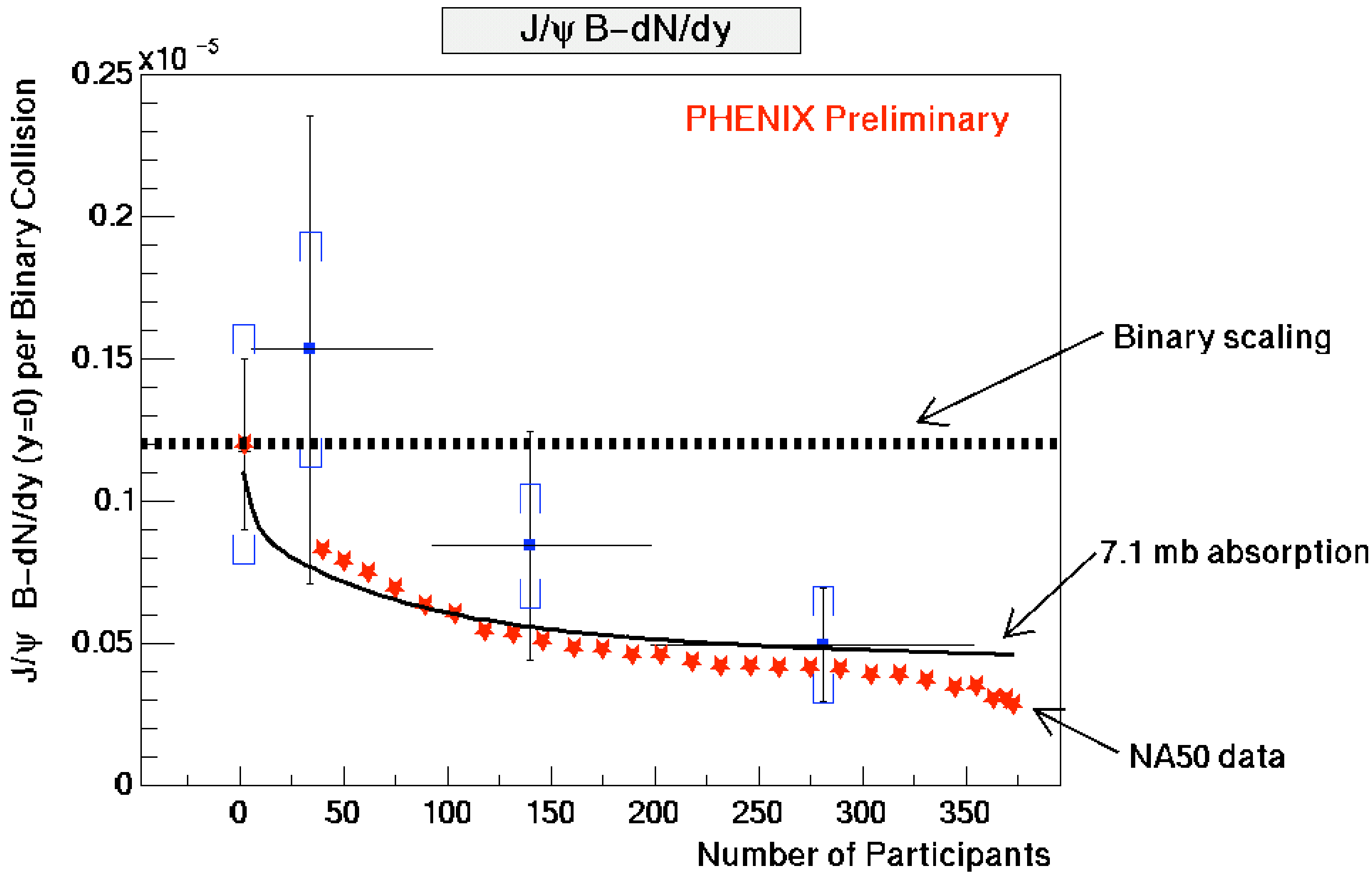


J/ψ Production--PHENIX State of the Art
RHIC Au+Au s_{NN}=200GeV J/ψ→ e^+e^-



J/ Production--PHENIX State of the Art

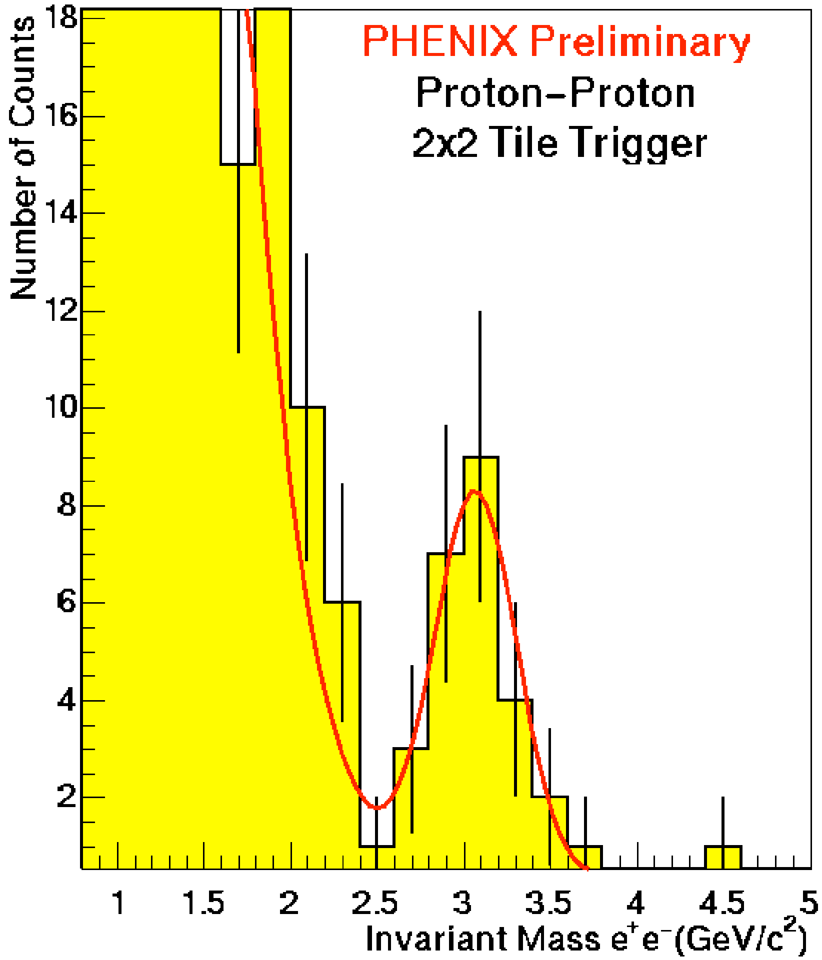
RHIC Au+Au s_{NN}=200GeV J/ e^+e^-



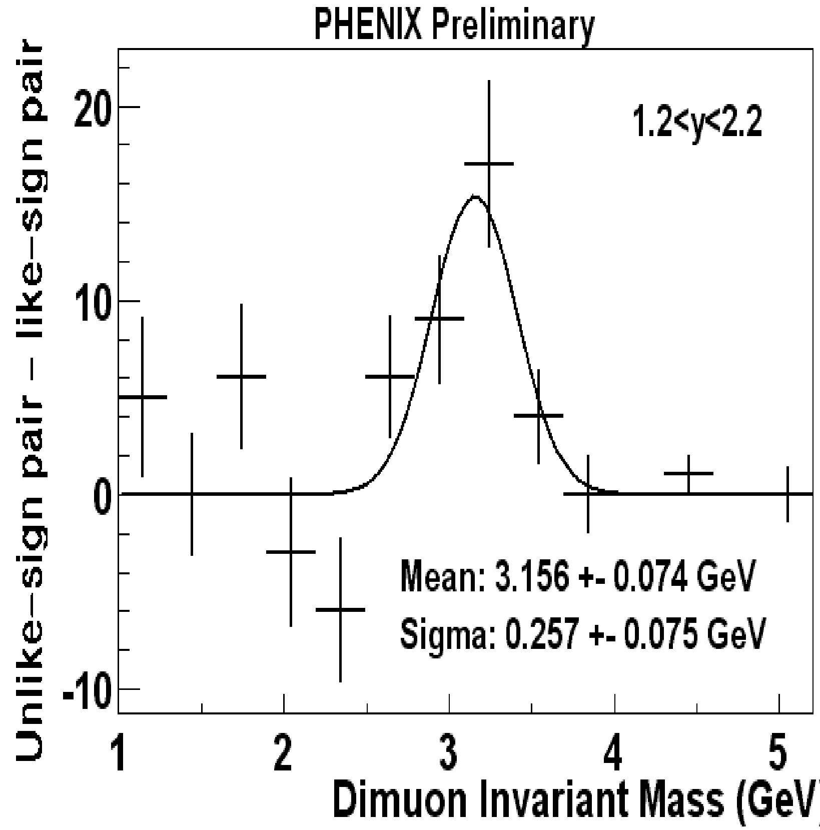
- Inconclusive, need 100-1000 times more data!
- p-p data also sparse, but more conclusive

J/ψ Production--PHENIX RHIC p-p $\sqrt{s}$=200GeV

J/$\psi \rightarrow e^+e^-$



J/$\psi \rightarrow \mu^+\mu^-$



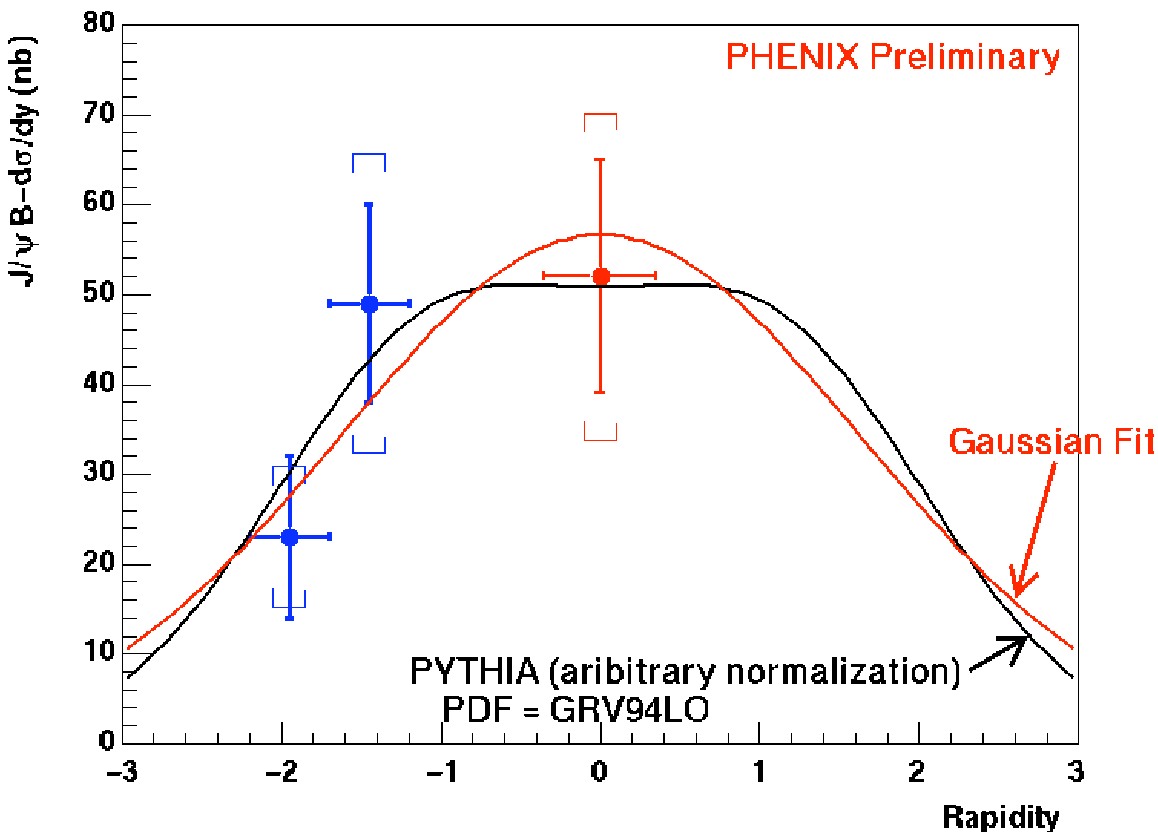
$N_{J/\psi}$=24±6(stat)±4 (sys)

$B d\sigma/dy$=52±13(stat) ±18(sys) nb

1.2<y<1.7 $N_{J/\psi}$=26±6(stat)±2.6 (sys)

1.7<y<2.2 $N_{J/\psi}$=10±4(stat)±1.0 (sys)

J/ψ B-dσ/dy and σ (p-p $\sqrt{s}$=200 GeV)

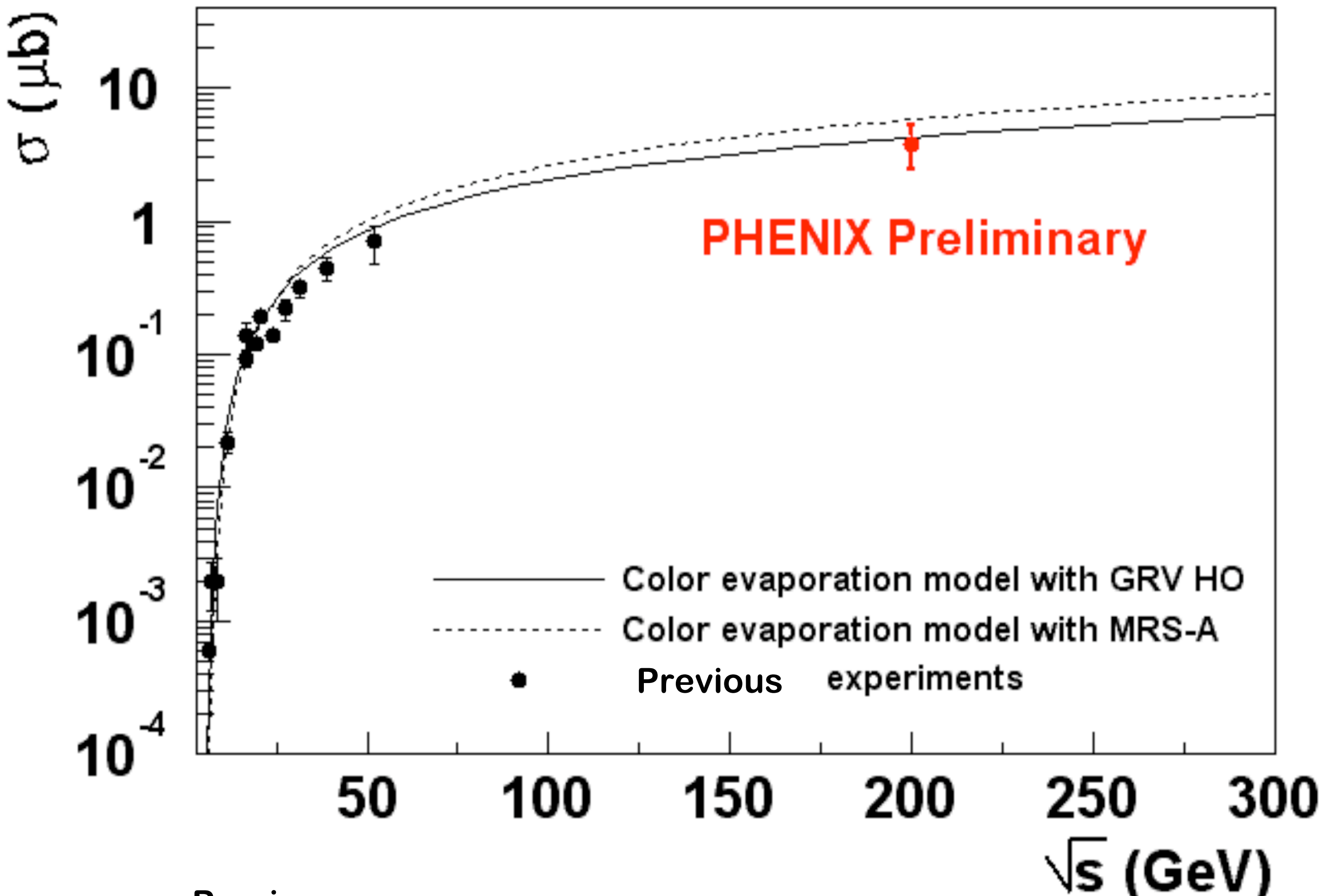


$$B \cdot \sigma(pp \rightarrow J/\psi + X) = 226 \pm 36(stat) \pm 79(sys)\ \mathrm{nb}$$

$$\sigma(pp \rightarrow J/\psi + X) = 3.8 \pm 0.6(stat) \pm 1.3(sys)\ \mu\mathrm{b}$$

J/ s dependence in p-p

RHIC/PHENIX measurement is respectable and instructive!

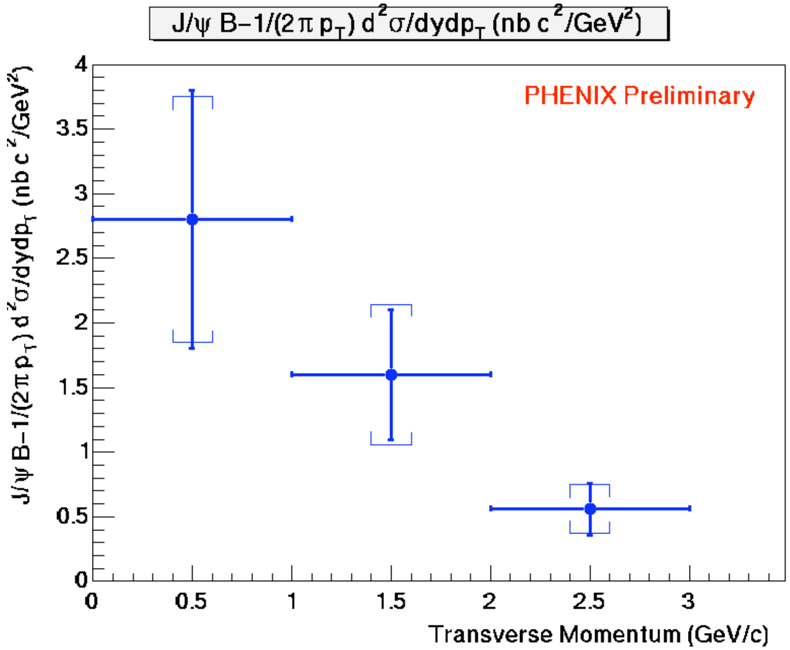


Previous

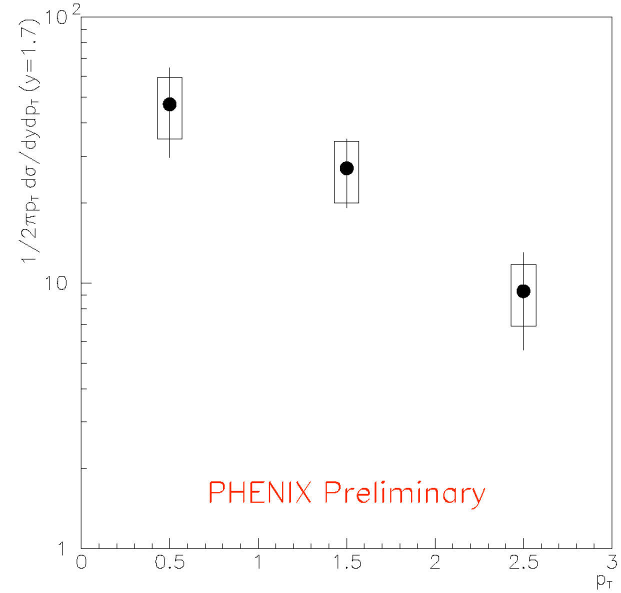
CEM predictions (Phys.Lett.B390:323-328,1997)

J/ψ $\langle p_T \rangle$ (p-p $\sqrt{s}$=200 GeV)

$J/\psi \rightarrow e^+e^-$

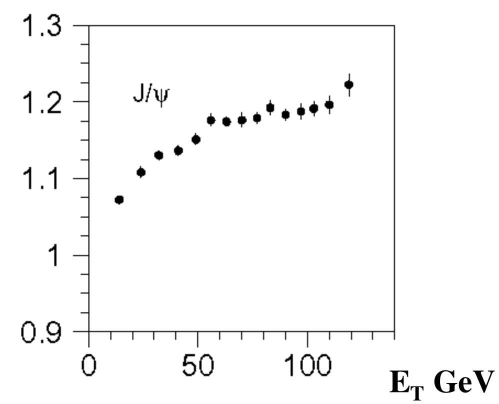


$J/\psi \rightarrow \mu^+\mu^-$



RHIC p-p $\sqrt{s}$=200 GeV $\langle p_T \rangle_{J/\psi}$ ~ 1.6--2.0 GeV/c

seems much larger than at CERN $\sqrt{s}$=17.2 GeV



$<p_T>$ vs s

Agrees with trend from lower s [Apanasevich, et al, PRD59, 074007 (1999)]

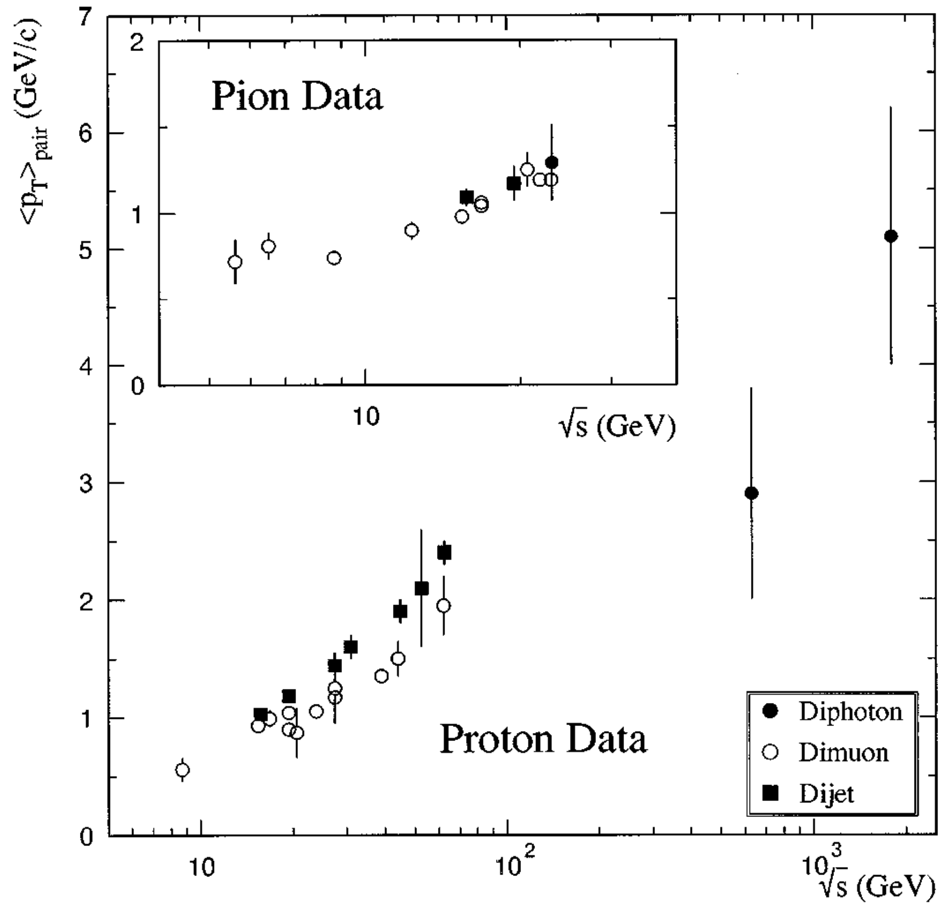


FIG. 1. $\langle p_T \rangle$ of pairs of muons, photons, and jets produced in hadronic collisions versus $\sqrt{s}$.

Conclusions--leptons/photons at RHIC

- Proof of principle established for J/□ in Au+Au
  - need a factor 100-1000 (10000) more data
- Significant result for J/□ cross section in p-p with 60 events
- charm via single $e^{\pm}$ in AuAu indicates point-like scaling
  - suggestive of difference in light and heavy quark jets
  - first measurement of charm in RHI collisions
- Low mass region, inconclusive, huge background
  - Need lots more data, or, preferably Dalitz rejection
- □, □, □ some early results, still a long way to go in $e^{+}e^{-}$
- Direct photons---systematics still under study, results this yr.

A very successful start of what
we hope should be a long and fruitful program