QCD in the Heat Bath: Results from PHENIX

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Overheard at APS ~1992:

- During a plenary RHI talk at APS, I wound up seated among "real" plasma physicists who made numerous comments about us:
  - "These guys are stupid…"
    - Always a possibility.
  - "…why don't they just shoot a laser through it and then they'd know if its plasma for sure!"
    - Visible light laser…bad idea.
    - Calibrated probe through QGP…good idea…
    - …but not new. (Wang, Gyulassy, Satz …)

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The "Calibrated" Plasma Probe

- Hard scattering processes and products:
  - Occur at short time scales.
  - Are "calculable" (even by experimentalists) in simple models (e.g. Pythia) with appropriate fudging:
    - Intrinsic k_T
    - K scaling factor.
  - Find themselves enveloped by the medium
  - Are "visible" at high p_T despite the medium
  - Promise to be our laser shining (or not) through the dense medium created at RHIC.

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QCD and the Heat Bath

- I will make the following artificial divisions:
  - QCD
    - Charged Hadron + Neutral pion spectra at high p_T.
    - Heavy quark production measured via electrons at high p_T.
    - J/Ψ, γ_{direct}, $\mu^+\mu^-$ coming in the future…
  - Heat Bath
    - Multiplicity, E_T, …
    - Identified hadrons
      - Singles, pairs
      - Flow, Hadro-chemistry
    - Caveat:
      - Short mean free path means that the view of the heat bath is heavily influenced by the latest stage prior to breakup.
      - Yet, initial state information (azimuthal anisotropy) is apparent.
  - Controlling parameter
    - Nature's variation of the "centrality" controls the heat bath.
    - Size/Energy variation is better, but not yet available.

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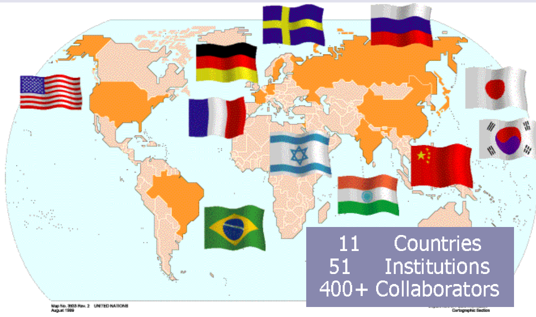
Pioneering High Energy Nuclear Interaction eXperiment



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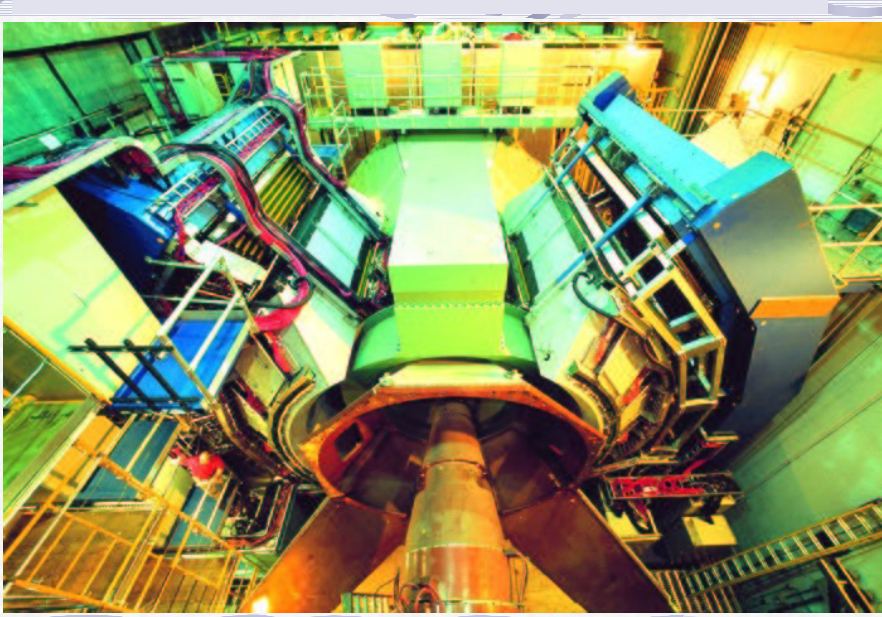
PHENIX from Above



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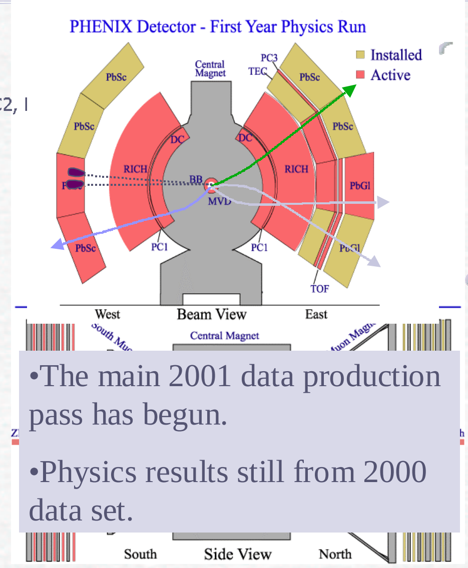
PHENIX Setup During Year 2001 Run

- West Arm
  - tracking:
    - DC,PC1, PC2, I
  - electron ID:
    - RICH,
    - EMCal
  - Photons
    - EMCal
- South Arm
  - tracking:
    - MuTr
  - muon ID:
    - MuID



•The main 2001 data production pass has begun.

•Physics results still from 2000 data set.

- East Arm
  - tracking:
    - DC, PC1, TEC, PC3
  - hadron& electron ID:
    - RICH,TEC, TOF, EMC
  - photons:
    - EMCal
- Other Detectors
  - Vertex & centrality:
    - ZDC, BBC,
    - MVD

accumulated ~200 10^6 Au-Au

full heavy ion program and first spin physics including electron & muon pairs

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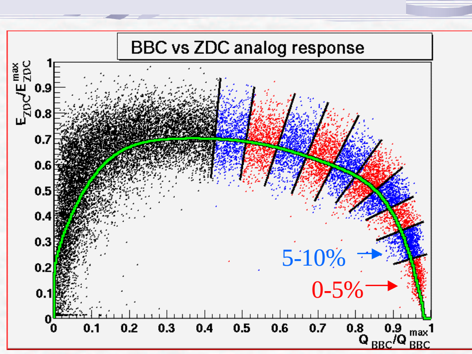
Centrality Determination

- ZDC measures neutral energy (principally free spectator neutrons) along collision axis.
- BBC measures produced charged particles within η=+/-(3.0-3.9).
- Their joint response is divided into centrality slices :
  - Each colored band is 5%.
  - Central is at lower right.
- The PHENIX trigger accepts 92% of minimum bias events.
- A Glauber calculation was used to deduce the numbers of participants (N_{part}) and binary collisions (N_{binary}) for each centrality.



cross section fraction	N_{part}	N_{binary}
0-5	348 ± 10	1009 ± 91
5-15	271 ± 9	712 ± 65
15-30	180 ± 7	406 ± 42
30-60	79 ± 5	131 ± 22
60-92	14 ± 3	14 ± 5

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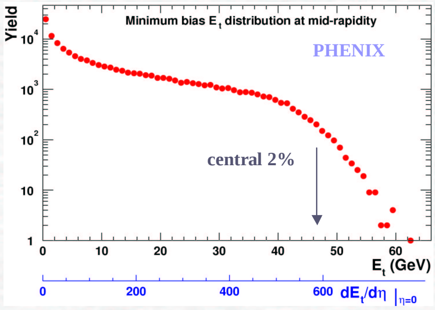
Transverse Energy Production



- Transverse Energy production yields Bjorken Estimate for Energy Density as:

$$\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{c\tau}\left(\frac{dE_T}{d\eta}\right)$$

- For τ=1.0 fm/c, this yields ~4.6 GeV/fm^3!
- ε well above estimated critical value ε_c~0.6-1.2 GeV/fm^3

ε ~ 1.5X higher than at CERN

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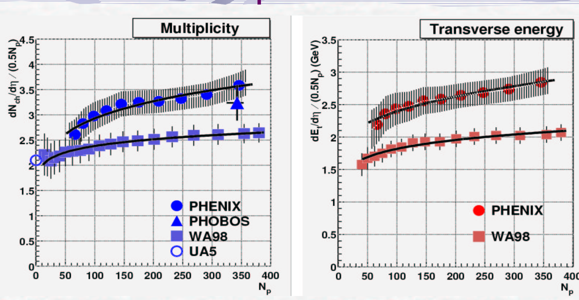
Multiplicity and E_T vs. N_{part}

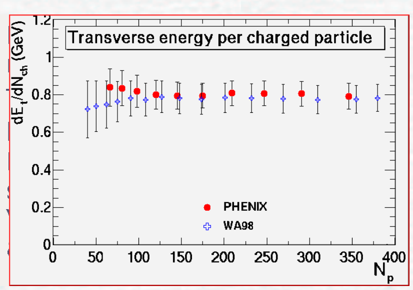
- Multiplicity and E_T both rise faster than linearly with the number of participants.
- This has been parameterized as:

soft hard

$$\frac{dN_{ch}}{d\eta} = A * N_{part} + B * N_{binary}$$



- The "Binary Scaling" contribution varies ,
  ~25% in peripheral collisions
  ~50% in central collisions
- $<E_T>/<N_{ch}>$ ~ constant with centrality



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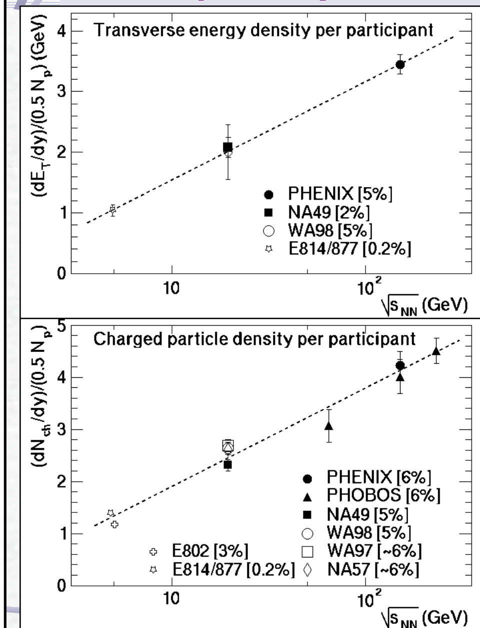
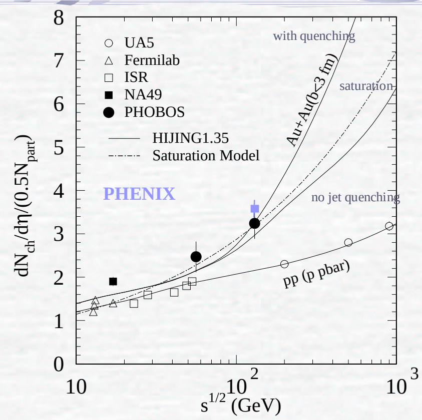
Multiplicity and E_T vs. $\sqrt{s}$





- N_{ch} and E_T evolution very well described by *ln(√s)*
- Saturation model also quite reasonable here (and especially with the PHOBOS result…).

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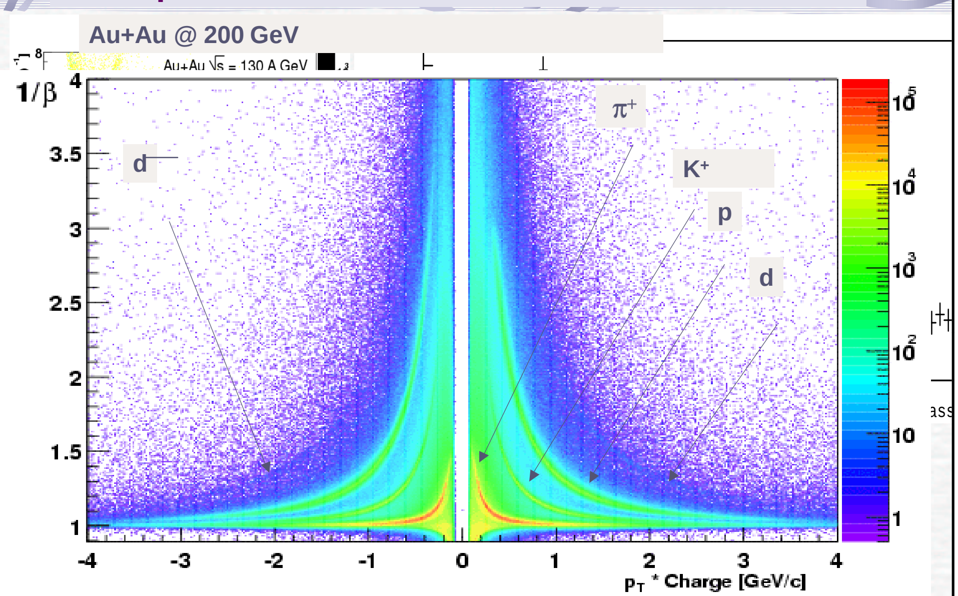
Composition of the Heat Bath: PID



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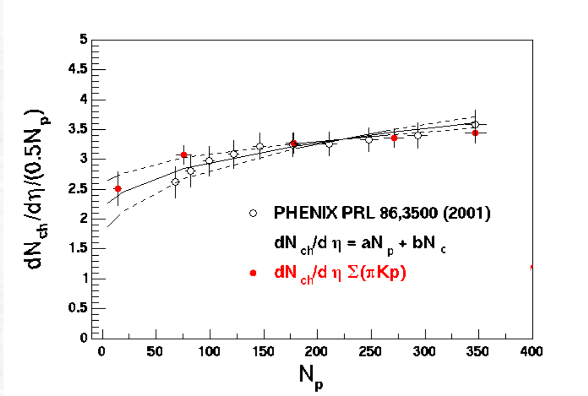
Yield vs. Centrality



x1.2

x1.7

- Yield per participant for all species rises with N_{part}.
- Not surprising since the total N_{ch} rises faster than N_{part}.
- Integral of π, K, p yields in excellent agreement with $dN_{ch}/d\eta$ result.

Surprising to me:

- Yields of K+, K-, p, p-bar rise faster with N_{part} than pion yields.
- The "faster than N_{part}" character of N_{ch} production also involves a change in relative species abundances favoring K and nucleon production!

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Net and Total Baryon Density

- Typically we have measure and quote "net baryon" density (b—bbar).
- Some physical processes will more naturally depend upon the "total baryon" density:
  - e.g. medium modifications to mesons are predicted to be same for baryonic and anti-baryonic dense matter (Rapp).
- Here we calculate both densities:

	SPS (Pb-Pb)	RHIC (Au-Au)
$p - \bar{p}$	33.5	8.6
Participating nucleons $(p - \bar{p})$ A/Z	85	21.4
$dN(\bar{p})/dy$	6.2	20.1
Produced baryons $(p, \bar{p}, n, \bar{n})$	24.8	80.4
Total baryon density	110	102

Caveat:

We don't measure neutrons!

Assume:
--$(n+p)_{part}$=A/Z
--$n_{prod} = p_{prod}$

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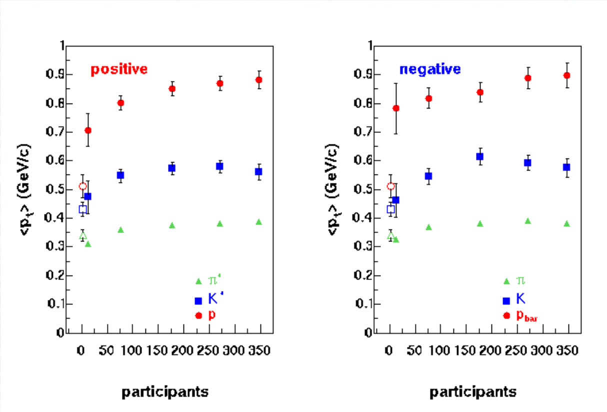
$<p_T>$: Energy Distribution in Bath



- $<p_T>$ variation with centrality roughly the same for all species:
  - ~20% rise.
- π and K close to pp production for peripheral collisions.
- Proton differs from pp significantly at most peripheral bin.

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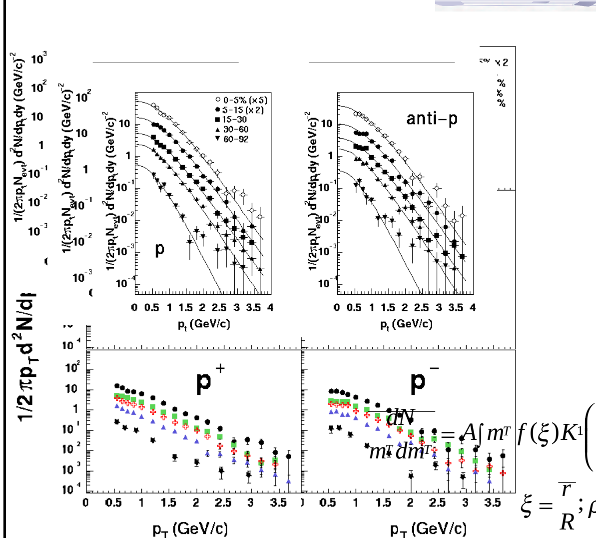
Hadron Spectra



- Hadron spectra stiffen with increasing hadron mass.
- Well known consequence of collective motion in the final state.
- Spectra well fitted by "flowing thermal Ansatz:

$$\frac{dN}{m_T dm_T} = A\int m_T f(\xi) K_1\left(\frac{m_T\cosh(\rho)}{T_{FO}}\right) I_0\left(\frac{p_T\sinh(\rho)}{T_{FO}}\right)\xi d\xi$$

$$\xi = \frac{r}{R};\ \rho = \tanh^{-1}(\beta_s \xi^n)$$

$$\beta_s \equiv SurfaceVelocity$$

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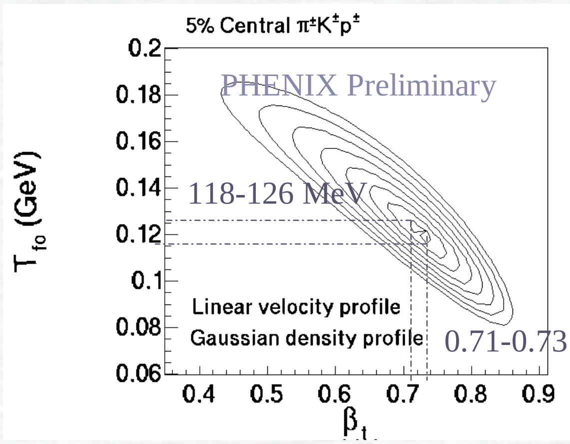
Thermal Fit Error Contours



- For each T_{FO} and β, a best fit and χ^2 are found.
- X^2_{min}/dof = 34/40.
- Contours show 1σ, 2σ, 3σ…
- Similar T to CERN, higher flow velocity.

Although the result of such a technique is only as good as the assumed functional form, the differences between experiments can be quite instructive.

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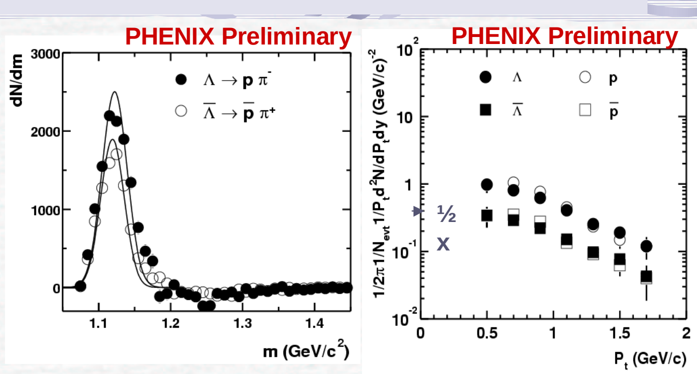
Lambda comes to PHENIX

Not a new particle, but new to PHENIX!



- Size matters.
- With physically large B-field volume and physically short cτ, Lambda measurement in PHENIX
- Likely more to come…

- $m_\Lambda \sim m_p$
- Should have similar thermo and does!

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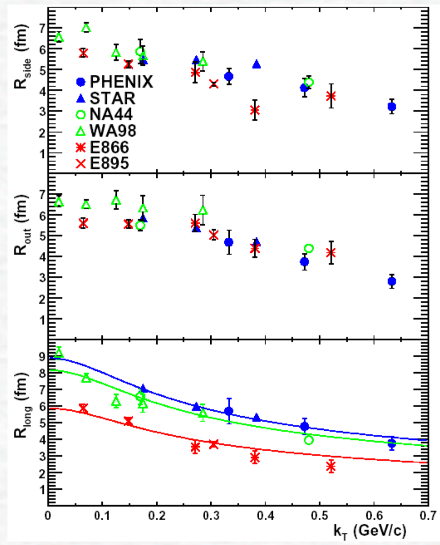
HBT

- HBT correlations also reflect underlying collective flow velocities via the k_T dependence of the radius parameter.
- World systematics of HBT nearly universal trend of R_{out}, R_{side}???
- $R_{out} \sim R_{side}$???
- Only R_{long} variation with $\sqrt{s}$???
- A real dilemma.



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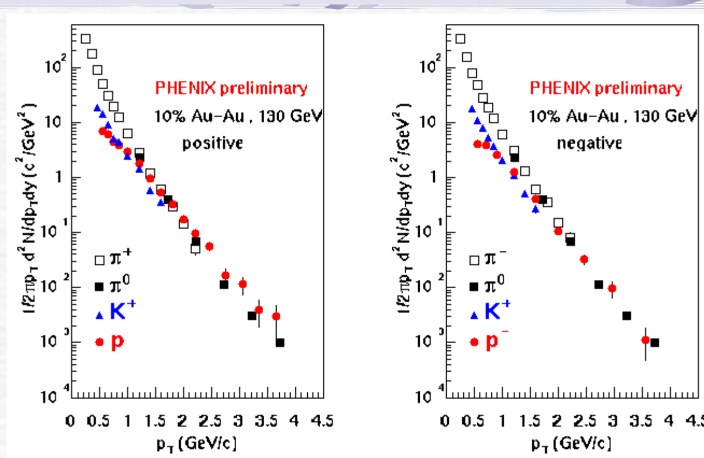
What's the composition of $h^+ + h^-$?

- PID for charged hadrons run out prior to the p_T required for hard processes.
- Plots w/o renormalization show the species content of hadrons leading into our high p_T probe particles.



The stiff slopes (and increased yield) of nucleons cause the high p_T spectrum to be more than 50% nucleons!

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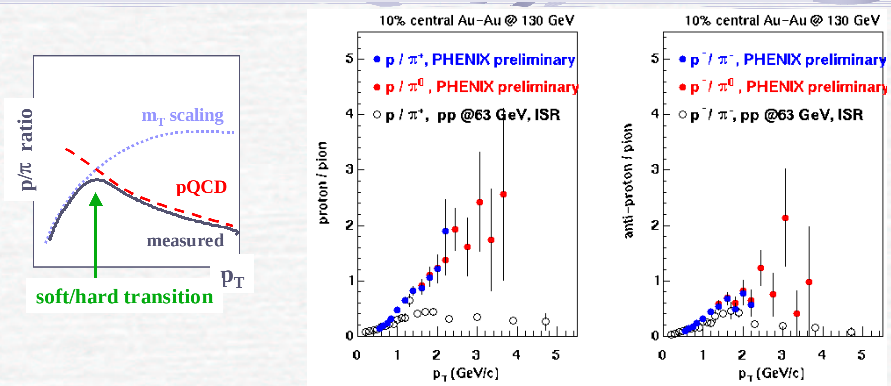
Where does hard scattering begin?



- Initial state Hard scattering should produce a p/π ratio which falls with p_T.
- m_T scaling (flow) will producing a rising p/π.
- ISR: Onset of hard processes noted above 2 GeV/c.
- RHIC: No clear onset of hard scattering is found in the data up to p_T = 3 GeV/c !!

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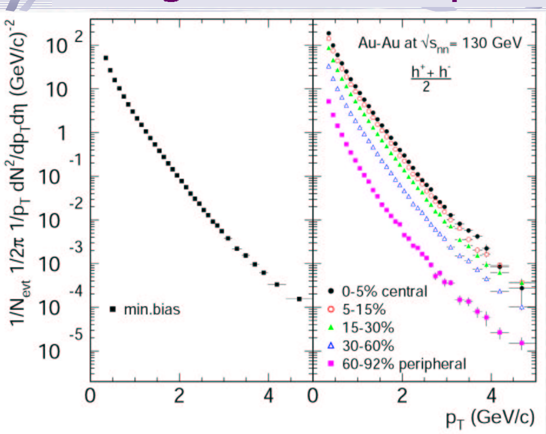
Charged Hadron Spectra to High p_T



To quantify the shape evolution we can use either pp data or peripheral collisions.

- Charged hadron spectra in bins of centrality show a gradual loss in concavity as they evolve from peripheral to central collisions.
- The loss in concavity is opposite to the effect one might expect comes from the known stiff proton contribution.
- The protons have a significantly higher slope than pions and become the majority contributor in the range 2-3 GeV/c.

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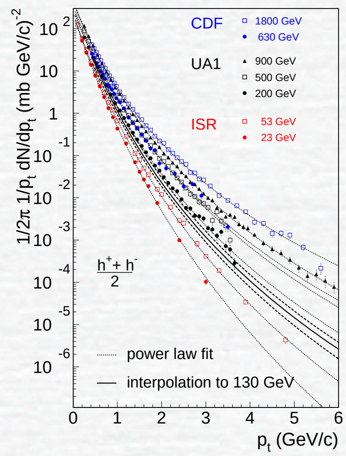
Interpolation of pp Data

- Unfortunately, no pp data at √s=130 GeV exist.
- We choose to interpolate using ISR, UA1, and CDF data.
- The data establish the parameters of the "Power Law Fit" as a function of √s.

$$\frac{1}{2\pi p_T}\frac{d^2\sigma}{d\eta dp_T} = \frac{A}{\left(1+\frac{p_T}{p_0}\right)^n}$$

- These are smoothly interpolated to produce the solid curve in the figure.



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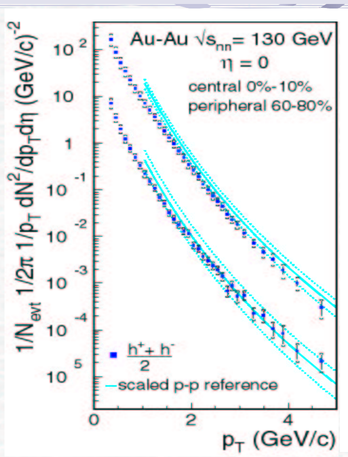
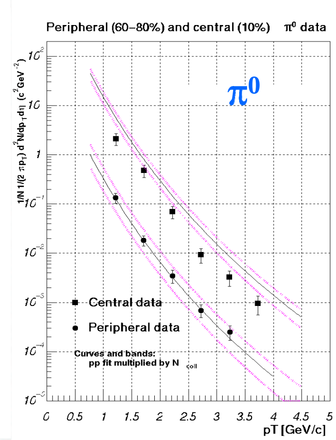
Spectral comparison

- Good fit to peri-collisions using interpolated power law.
- Power Law overpredicts the central collisions





The discrepancy between the neutral pions and the interpolated power law is more severe than for the charged hadrons.

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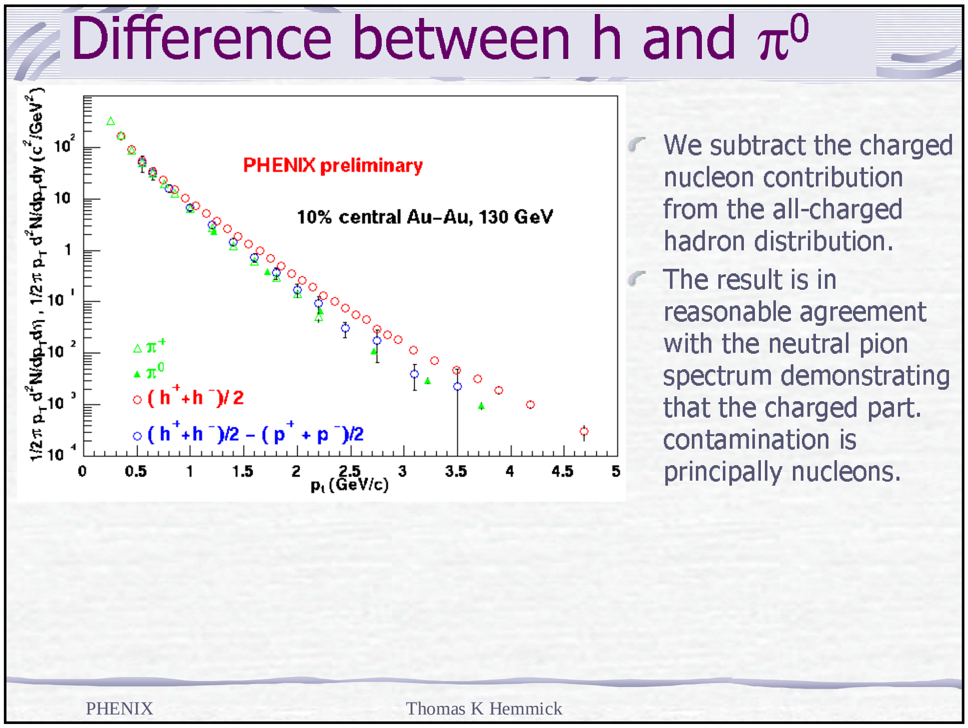
Difference between h and π0
PHENIX preliminary
10% central Au-Au, 130 GeV
π+
π0
(h+ + h−)/2
(h+ + h−)/2 − (p+ + p−)/2
pt (GeV/c)
We subtract the charged nucleon contribution from the all-charged hadron distribution.
The result is in reasonable agreement with the neutral pion spectrum demonstrating that the charged part. contamination is principally nucleons.
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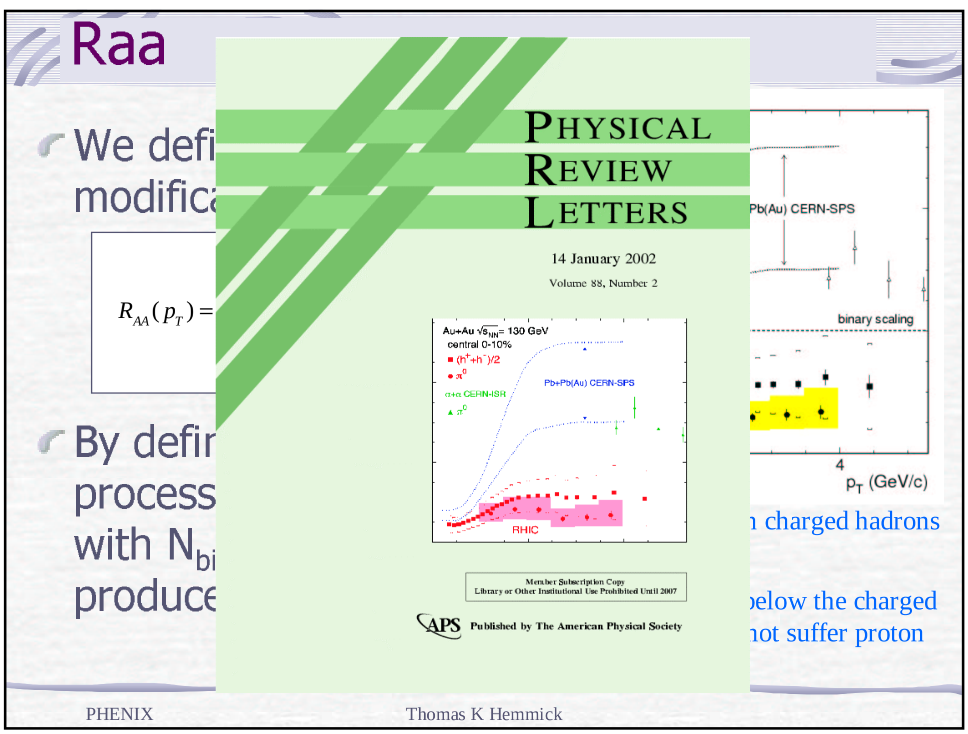
Raa
We defi
modifica
By defin
process
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produce
PHYSICAL
REVIEW
LETTERS
14 January 2002
Volume 88, Number 2
Au+Au √sNN = 130 GeV
central 0-10%
(h+ + h−)/2
π0
Pb+Pb(Au) CERN-SPS
α+α CERN-ISR
RHIC
APS Published by The American Physical Society
Pb(Au) CERN-SPS
binary scaling
pT (GeV/c)
n charged hadrons
below the charged
not suffer proton
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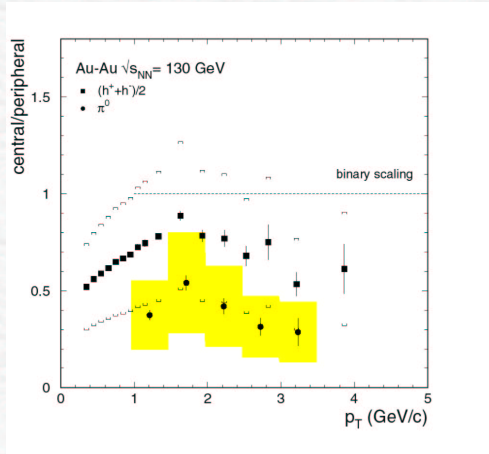
R_{AA}--Peripheral

- We can also reference R_{AA} using measured peripheral collisions to avoid the systematic error in the pp interpolation.



Again, the central data drops below 1.0 and shown no Cronin!

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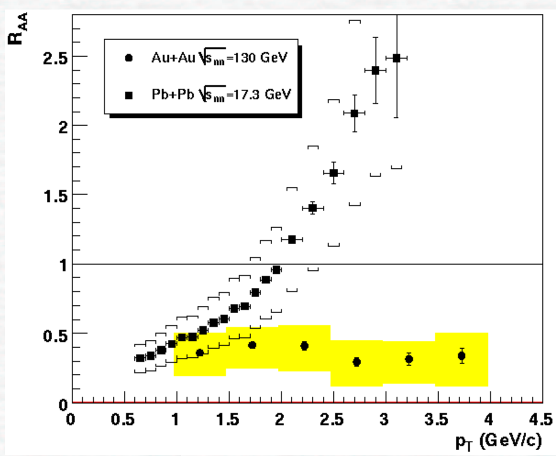
R_{AA}—π^0 at RHIC and CERN



WA98 measurements of R_{AA} for π^0 show a dramatically different behavior than at RHIC.

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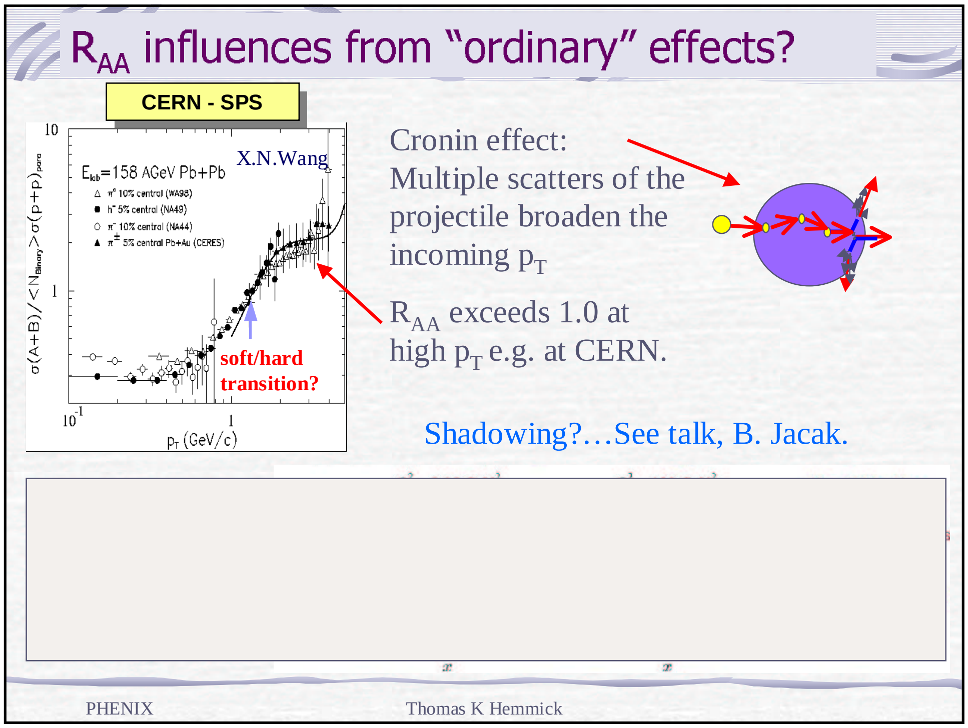
RAA influences from "ordinary" effects?
CERN - SPS
X.N.Wang
Elab=158 AGeV Pb+Pb
soft/hard transition?
pT (GeV/c)
Cronin effect:
Multiple scatters of the projectile broaden the incoming pT
RAA exceeds 1.0 at high pT e.g. at CERN.
Shadowing?…See talk, B. Jacak.
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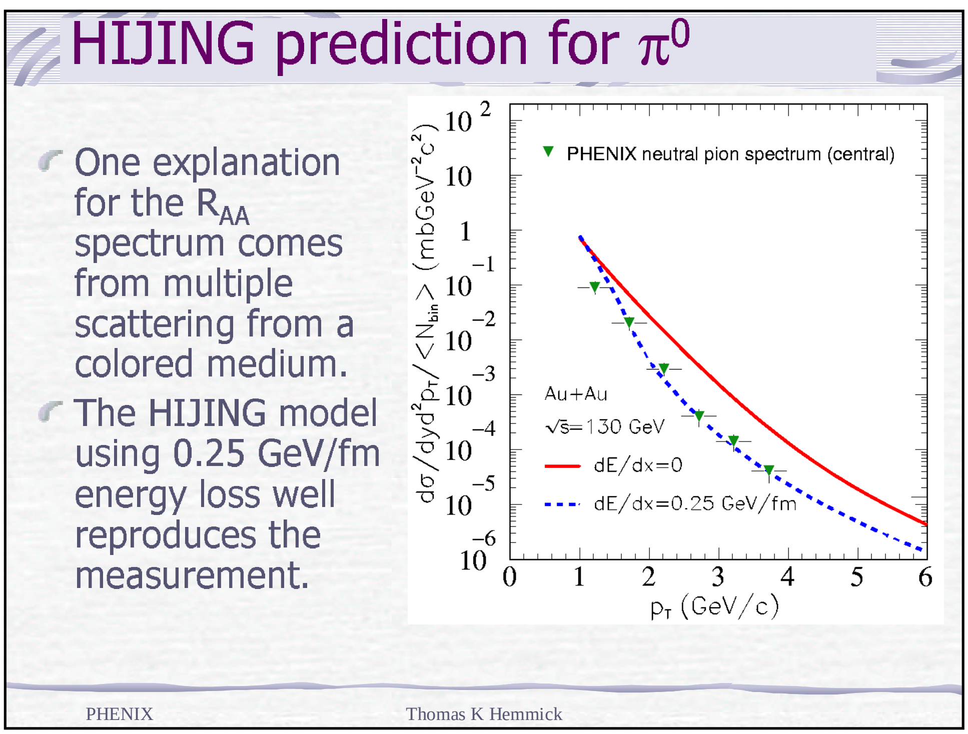
HIJING prediction for π0
One explanation for the RAA spectrum comes from multiple scattering from a colored medium.
The HIJING model using 0.25 GeV/fm energy loss well reproduces the measurement.
PHENIX neutral pion spectrum (central)
Au+Au
√s=130 GeV
dE/dx=0
dE/dx=0.25 GeV/fm
pT (GeV/c)
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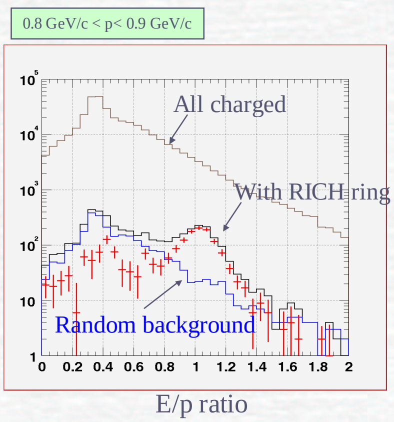
Electron Identification



- The Electromagnetic Calorimeter and RICH were used to select single electrons.
- Neither device has sufficient identification working alone.
- The combination shows a clear peak of signal electrons that both fire the RICH and deposit energy equal to their momentum in the EMcal.

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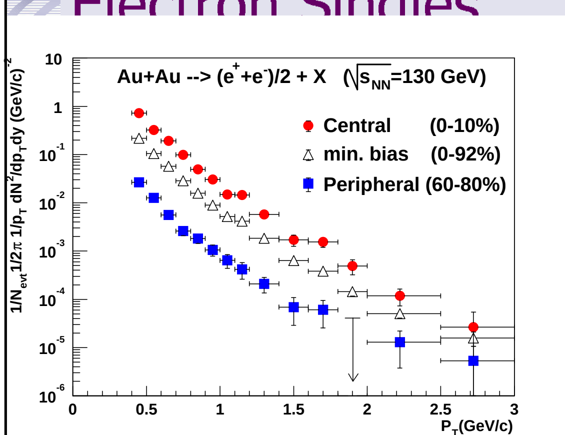
Electron Singles



Identified electron spectra are shown on the left.

Low p_T single electrons dominantly come from π^0 Dalitz decay:
$\pi^0 \to \gamma + e^+e^-$
and other neutral meson decays.

Our measurements of the π^0, π^+, π^- spectra determine this background level.

- Other backgrounds can also be modeled and subtracted as an "electron cocktail".

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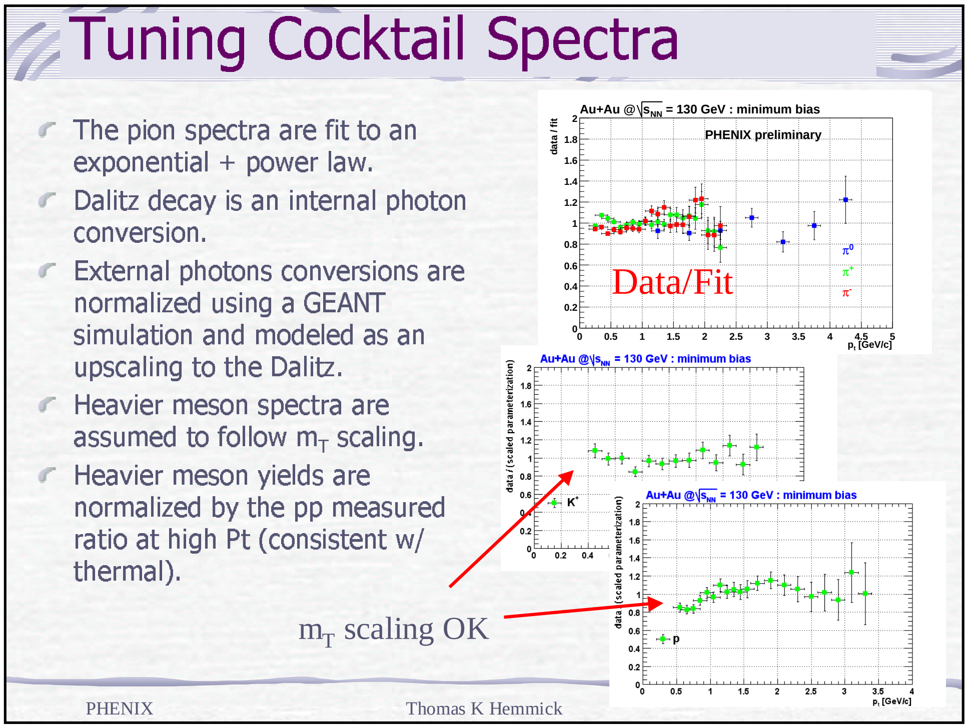
Tuning Cocktail Spectra
The pion spectra are fit to an exponential + power law.
Dalitz decay is an internal photon conversion.
External photons conversions are normalized using a GEANT simulation and modeled as an upscaling to the Dalitz.
Heavier meson spectra are assumed to follow m_T scaling.
Heavier meson yields are normalized by the pp measured ratio at high Pt (consistent w/ thermal).
m_T scaling OK
Au+Au @ $\sqrt{s_{NN}}$ = 130 GeV : minimum bias
PHENIX preliminary
Data/Fit
data / fit
p_t [GeV/c]
K
p
data / (scaled parameterization)
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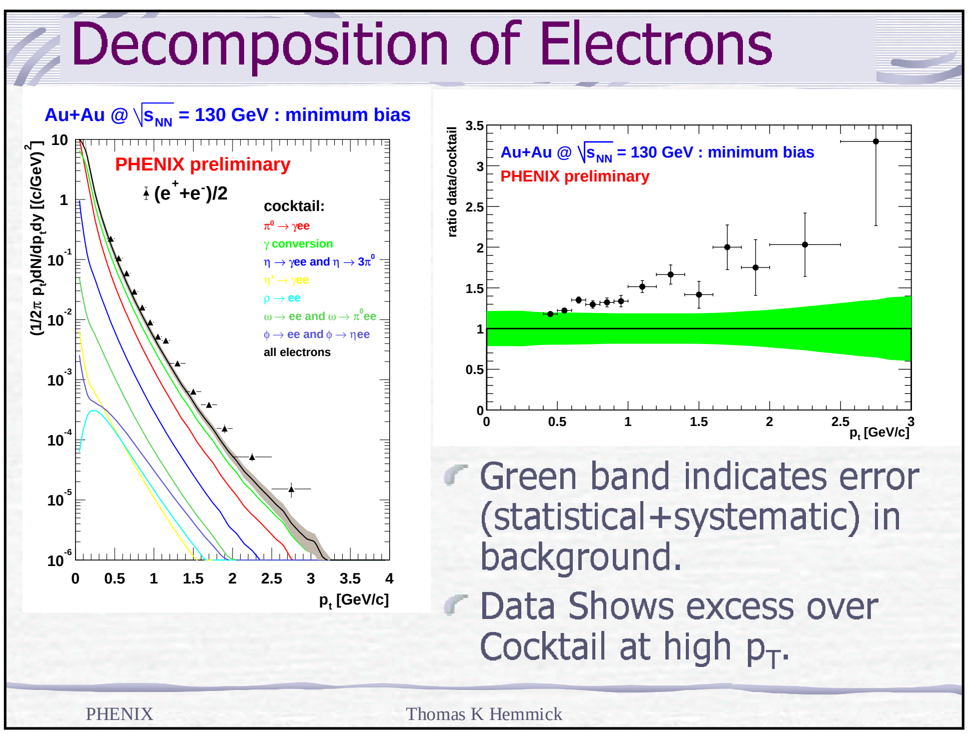
Decomposition of Electrons
Au+Au @ $\sqrt{s_{NN}}$ = 130 GeV : minimum bias
PHENIX preliminary
$(e^+ + e^-)/2$
cocktail:
$\pi^0 \to \gamma ee$
γ conversion
$\eta \to \gamma ee$ and $\eta \to 3\pi^0$
$\eta' \to \gamma ee$
$\rho \to ee$
$\omega \to ee$ and $\omega \to \pi^0 ee$
$\phi \to ee$ and $\phi \to \eta ee$
all electrons
$(1/2\pi\ p_t)dN/dp_t dy\ [(c/GeV)^2]$
p_t [GeV/c]
ratio data/cocktail
Green band indicates error (statistical+systematic) in background.
Data Shows excess over Cocktail at high p_T.
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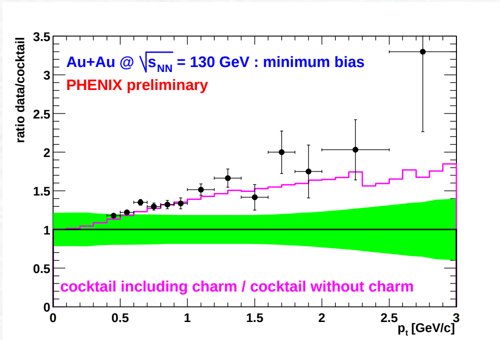
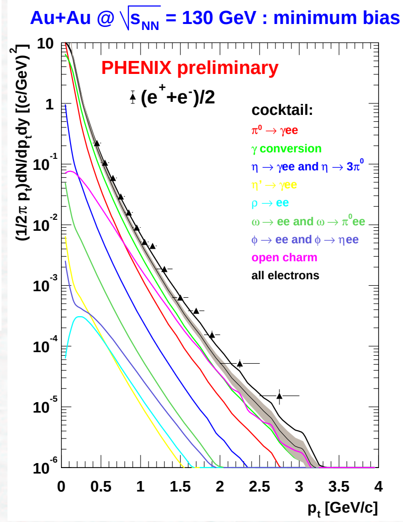
Pythia (after tuning…)





- Akiba will show detail about the tuning of Pythia to describe open charm production in pp.
- The addition of open charm decays ala' Pythia well describes the electron excess.

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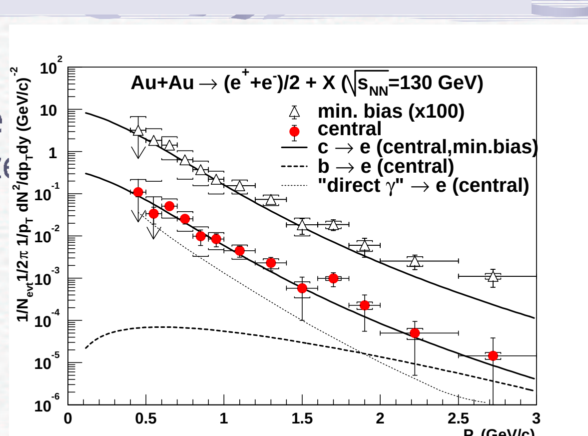
Fit the excess as charm

- The subtracted spectrum can be used to normalize the charm yield and thereby the cross section.
- The result is comparable within large error bars to the Pythia calculation.



0–10%

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Summary-1

- The RHIC medium is certainly intriguing and exciting:
  - Particle production scales faster than N_{part} possibly signaling a hard N_{binary} component.
  - Kaon and Nucleon contributions grow in percentage with centrality.
  - Low net baryon density but high total baryon density.
  - Strong radial flow implied by relative slope constants of hadrons.
  - Nucleons begin to be dominant contributors to p_T spectra above 2 GeV/c.
  - HBT R_{out}~R_{side}???
- Probes of the medium yield exciting results
  - R_{AA} below 1. Especially dramatic for identified π^0 which have no proton background.
  - Charm = Pythia within huge errors. Why?

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Summary-2

- PHENIX has produced a wealth of data and has much more in analysis.
- The RHIC era opens the Hard Scattering or QCD toolbox (Pandora box?) in RHI physics.
  - My wife usually criticises my use of new tools:

    LMH: "Don't you ever read the manual?"

    TKH: "Honey, these tools don't come with manuals!"
- Maybe during this week these months we'll write the manual for QCD in the RHIC era.

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