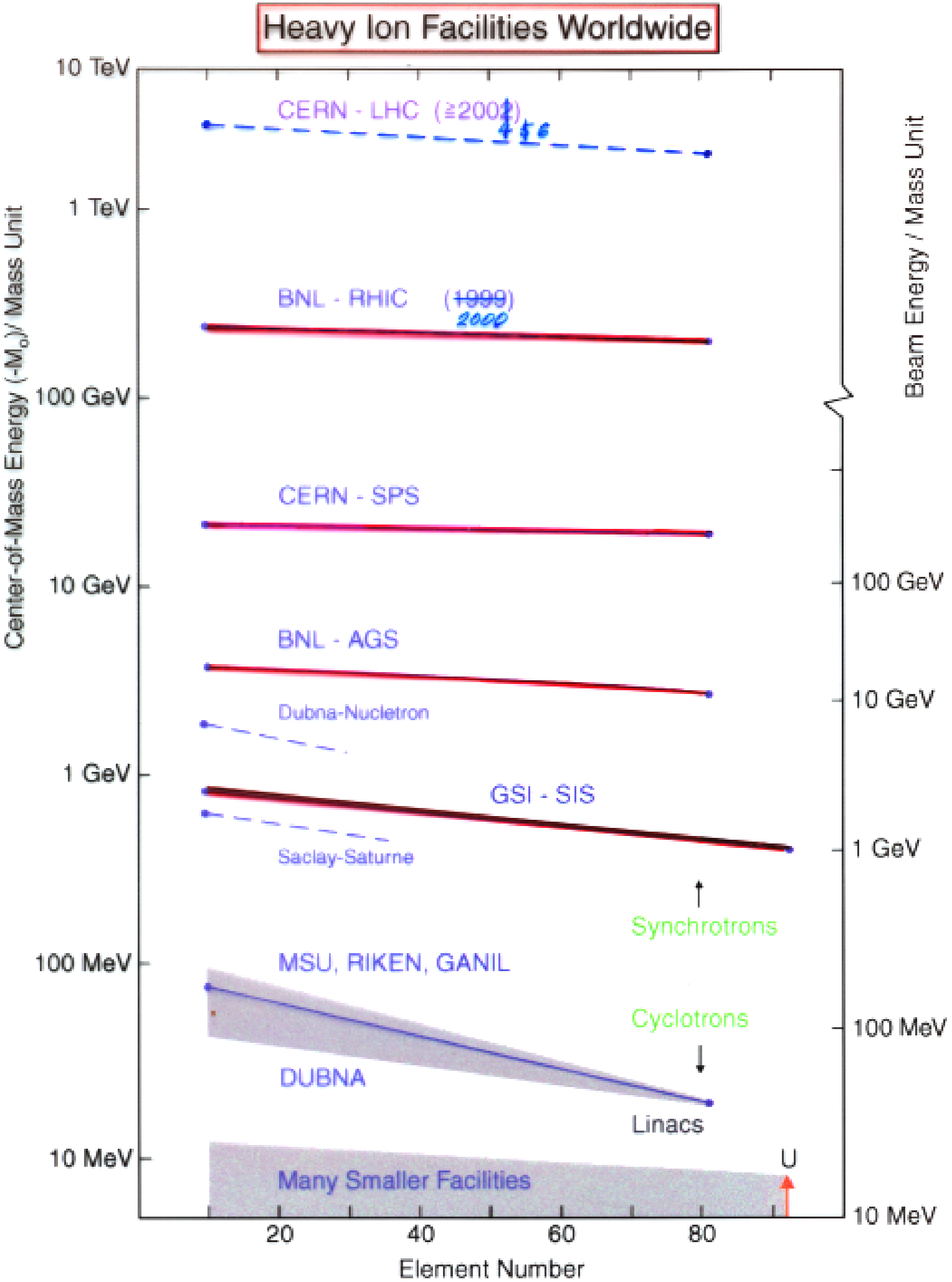
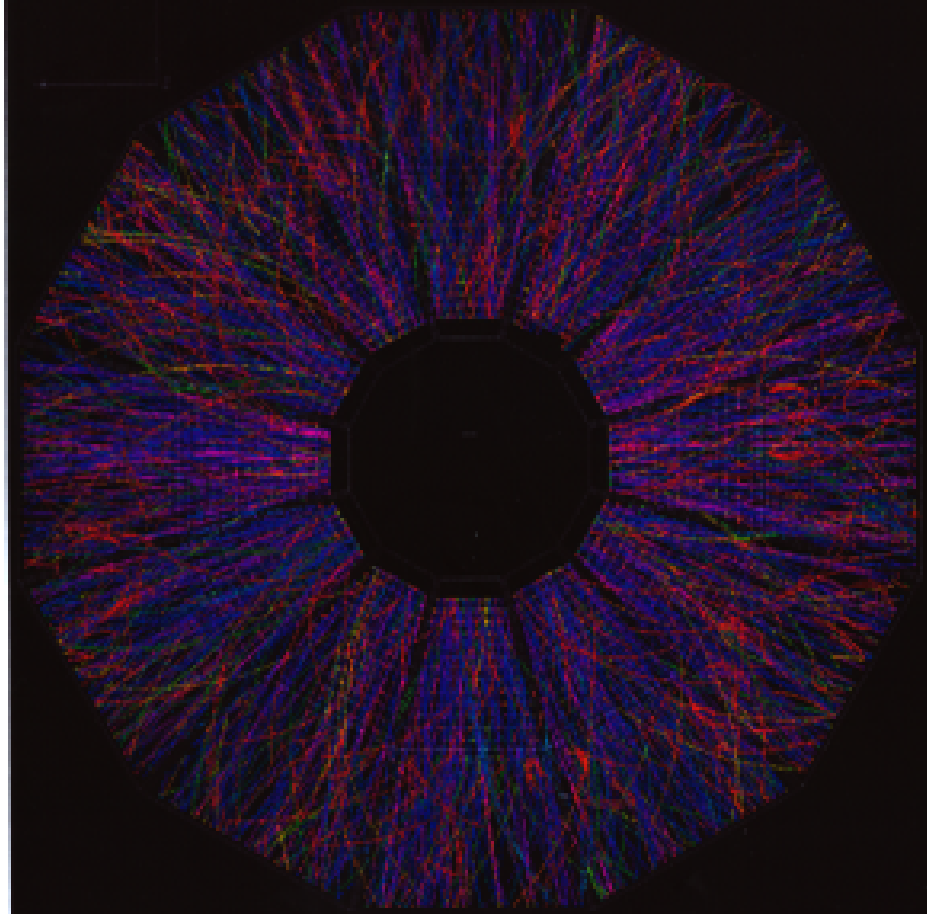
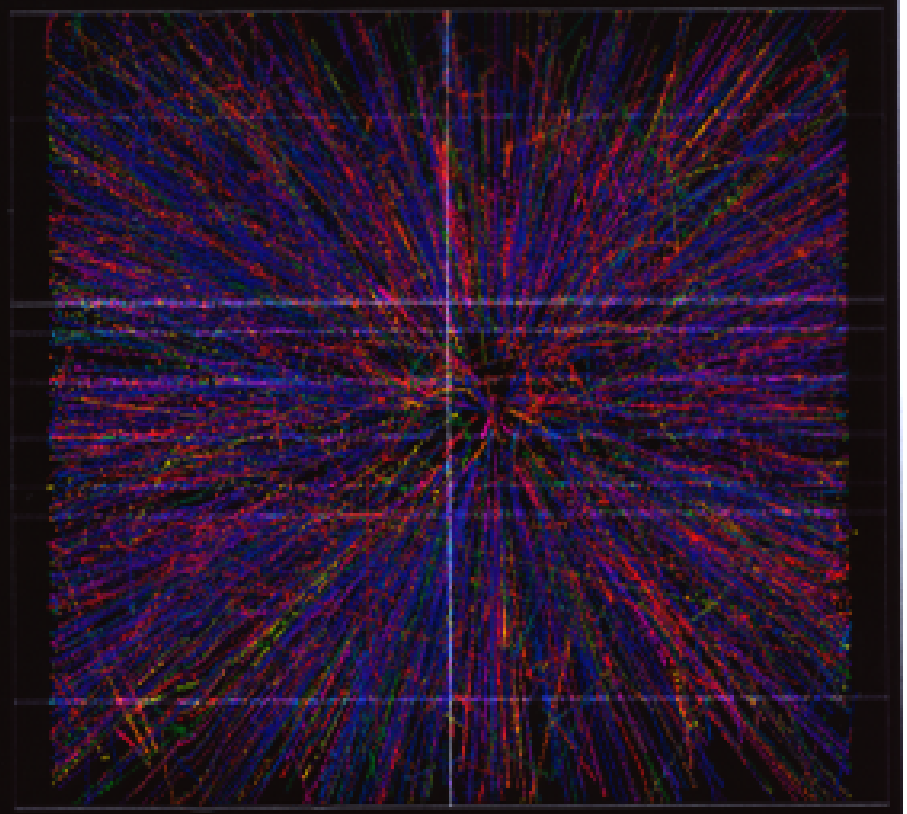

Heavy Ion Facilities Worldwide
10 TeV
1 TeV
100 GeV
10 GeV
1 GeV
100 MeV
10 MeV
Center-of-Mass Energy (-M$_o$)/ Mass Unit
Beam Energy / Mass Unit
CERN - LHC (≥2002)
BNL - RHIC (1999)
2000
CERN - SPS
BNL - AGS
Dubna-Nucletron
GSI - SIS
Saclay-Saturne
Synchrotrons
MSU, RIKEN, GANIL
Cyclotrons
DUBNA
Linacs
Many Smaller Facilities
U
20
40
60
80
Element Number

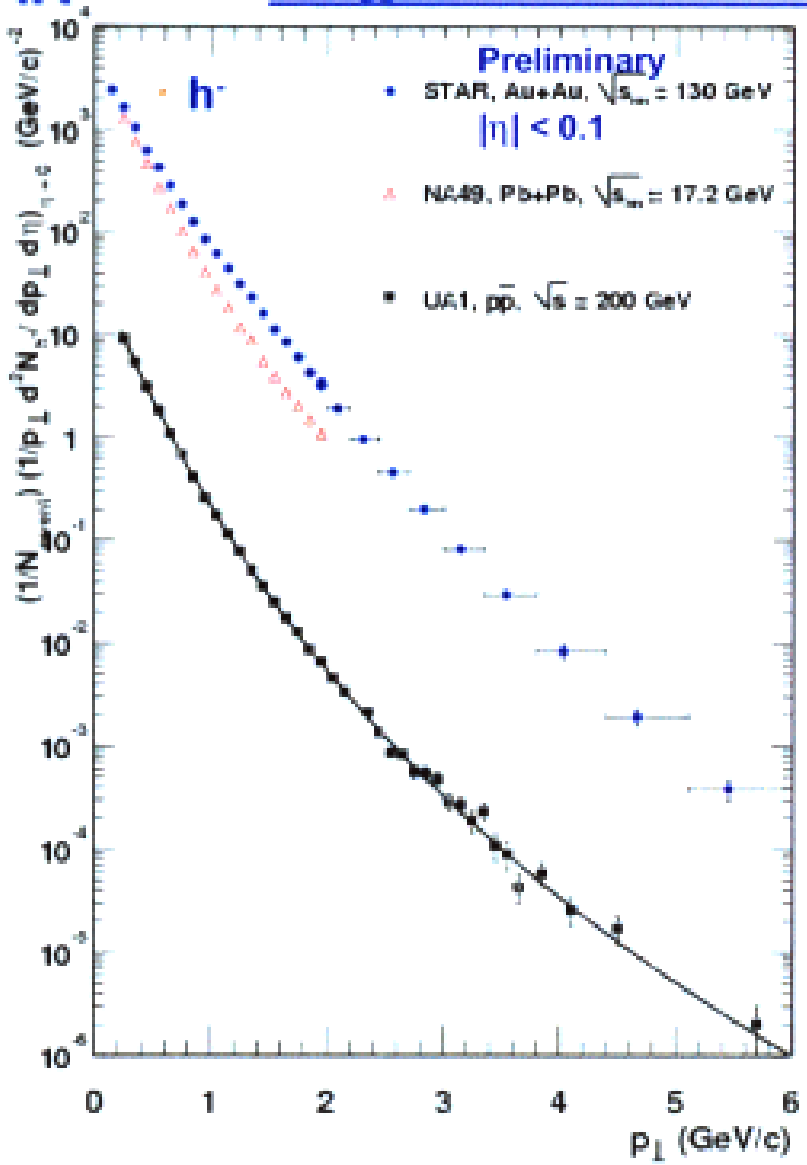
TPC Performance



colors ~ momentum: low - - - high



Negative Hadrons: p_t - distributions



Power Law

$A\,(1 + p_t/p_0)^{-n}$

$p_0 = 2.74 \pm 0.11$ GeV/c

$n = 13.65 \pm 0.42$

STAR

$\langle p_t \rangle = 0.514 \pm 0.012$ GeV/c

NA49

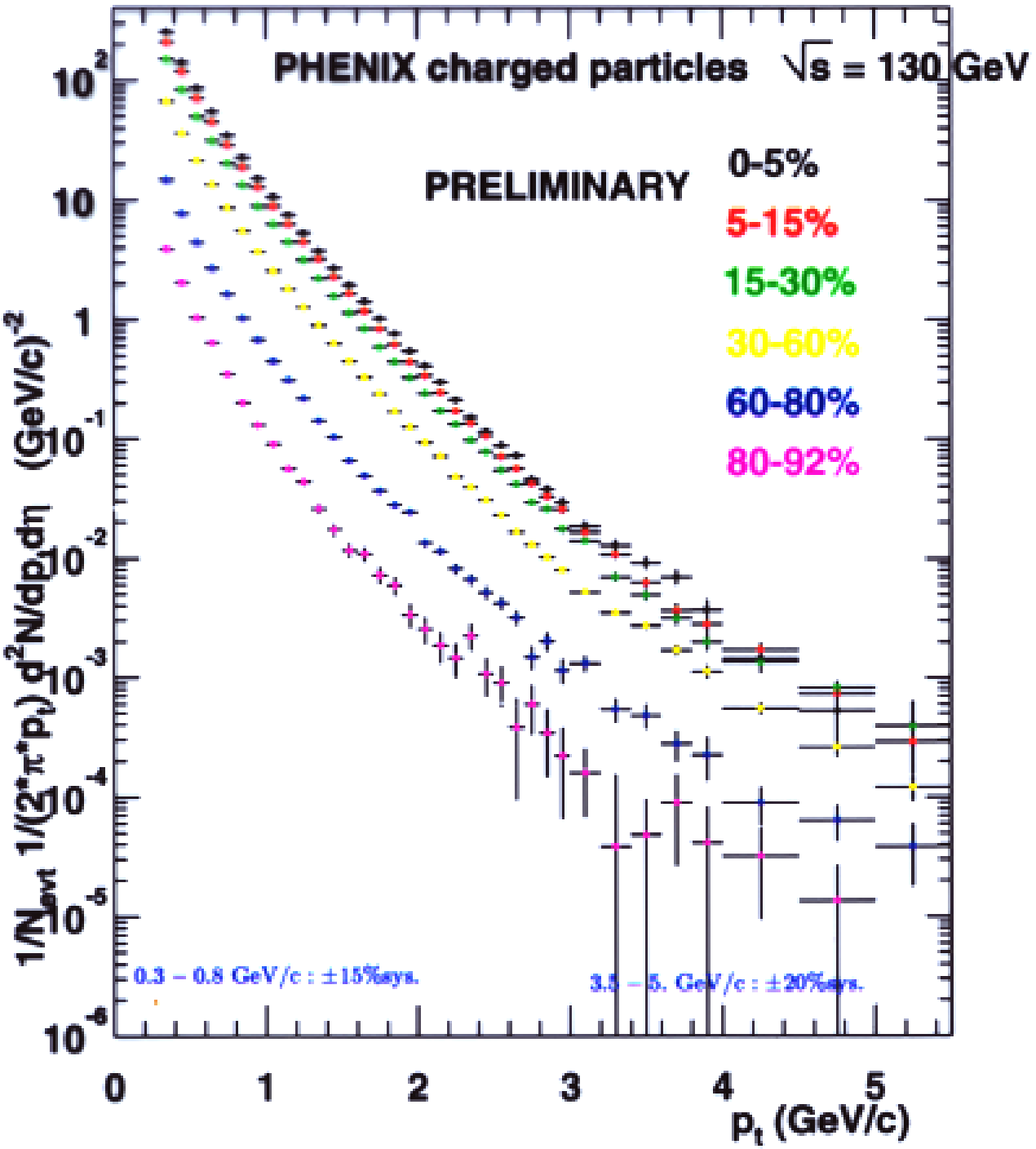
$\langle p_t \rangle = 0.414 \pm 0.004$ GeV/c

UA1

$\langle p_t \rangle = 0.392 \pm 0.003$ GeV/c

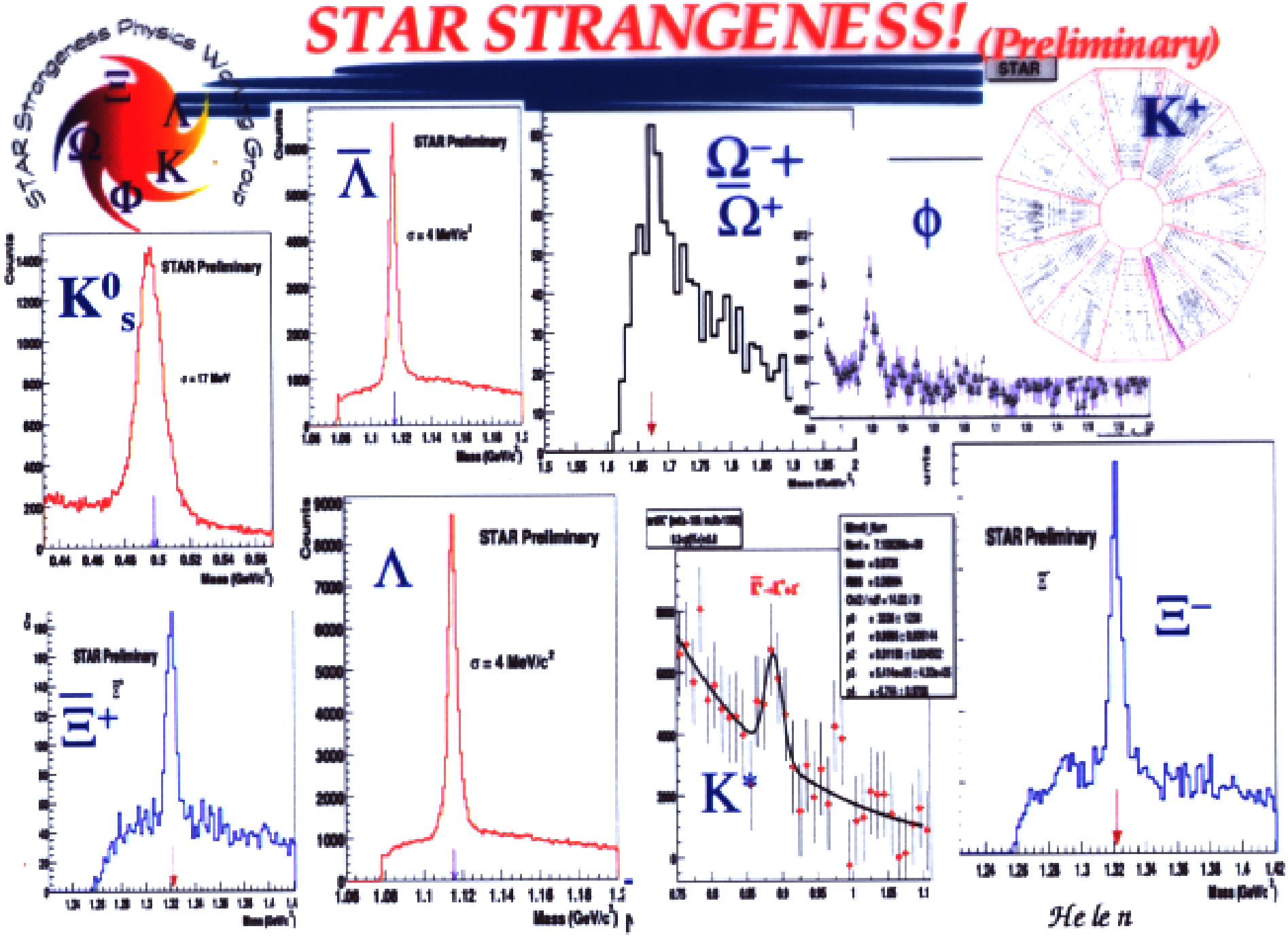
J.W. Harris for STAR at QM2001

Momentum Distributions



Absolute Normalization : ±20%sys.

STAR STRANGENESS! (Preliminary)



Helen

STAR Talks at Quark Matter

- PHYSICS
  - "Anisotropic Flow .....", R. Snellings
  - "First Results on Strangeness Production .....", H. Caines
  - "HBT Interferometry ..... ", F. Laue
  - "Charged Particle Spectra .....", Manuel Calderon
  - "Particle Ratios .....", H. Huang
  - "Anti-Nucleus Production .... ", D. Hardtke
  - "Resonance Studies ..... ", Z. Xu
  - "High Pt Spectra ..... ", J. Dunlop
  - "Two-particle Transverse Mass Correlation Analysis .....", J. Reid

- INSTRUMENTATION
  - "The STAR Time Projection Chamber", F. Retiere
  - "The STAR RICH Detector", B. Lasiuk

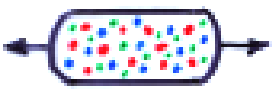
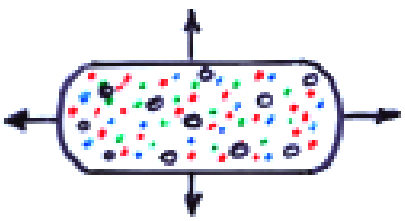
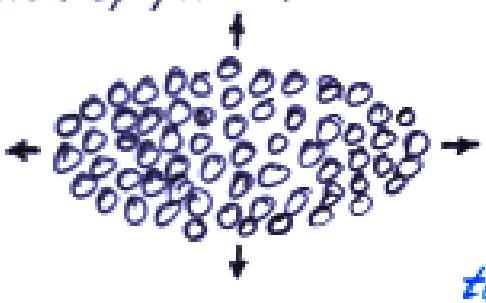
STAR Poster Presentations at Quark Matter

- STRANGENESS
  - "Calculating the Efficiency of Singly-Strange Hadrons in the STAR TPC" - M. Lamont
  - "Strange Particle Correlation Studies with the STAR Detector" - T. Humanic
  - "Kaon Reconstruction via One-Prong Decays in the STAR TPC" - W. Deng
  - "Multiply-Strange Baryon Production in Au + Au..." - C. Lansdell
- HBT
  - "HBT Event-by-Event" - D. Flierl
  - "Results from Three Particle Interferometry at STAR" - R. Willson
  - "Correlations of Non-identical Particles in Au + Au..." - A. Kisiel
  - "Pion Interferometry Relative to the Reaction Plane" - R. Wells
  - "Proton-proton and Anti-proton-Anti-proton Correlations" - M. Lopez-Noriega
  - "Pion Phase Space Density from STAR HBT Analysis" - J. Cramer
- SPECTRA
  - "Photon Production in Au + Au Collisions" - I. Johnson
  - "Parity and CP Violation Studies at RHIC" - E. Finch
  - "Systematic Studies of Numbers of Participants in Au + Au Collisions at RHIC Using STAR Data" - Y. Chen
- EVENT-BY-EVENT
  - Azimuthal and pseudo-rapidity correlations of high p_t particles - S. Chattopadhyay
  - Event-by-Event fluctuations of mean p_t - Z. Ahammed
- PERIPHERAL
  - Peripheral collisions with STAR - F. Meissner
- INSTRUMENTATION
  - "The Hardware Controls System for the STAR Experiment"
  - "Laser Calibration System for the STAR TPC"
  - "Performance of the Partial STAR SVT in the RHIC 2000 Run"
  - The STAR Trigger System - Z. Milosevich
  - The Hardware Controls System for the STAR Experiment - Dennis Reichhold

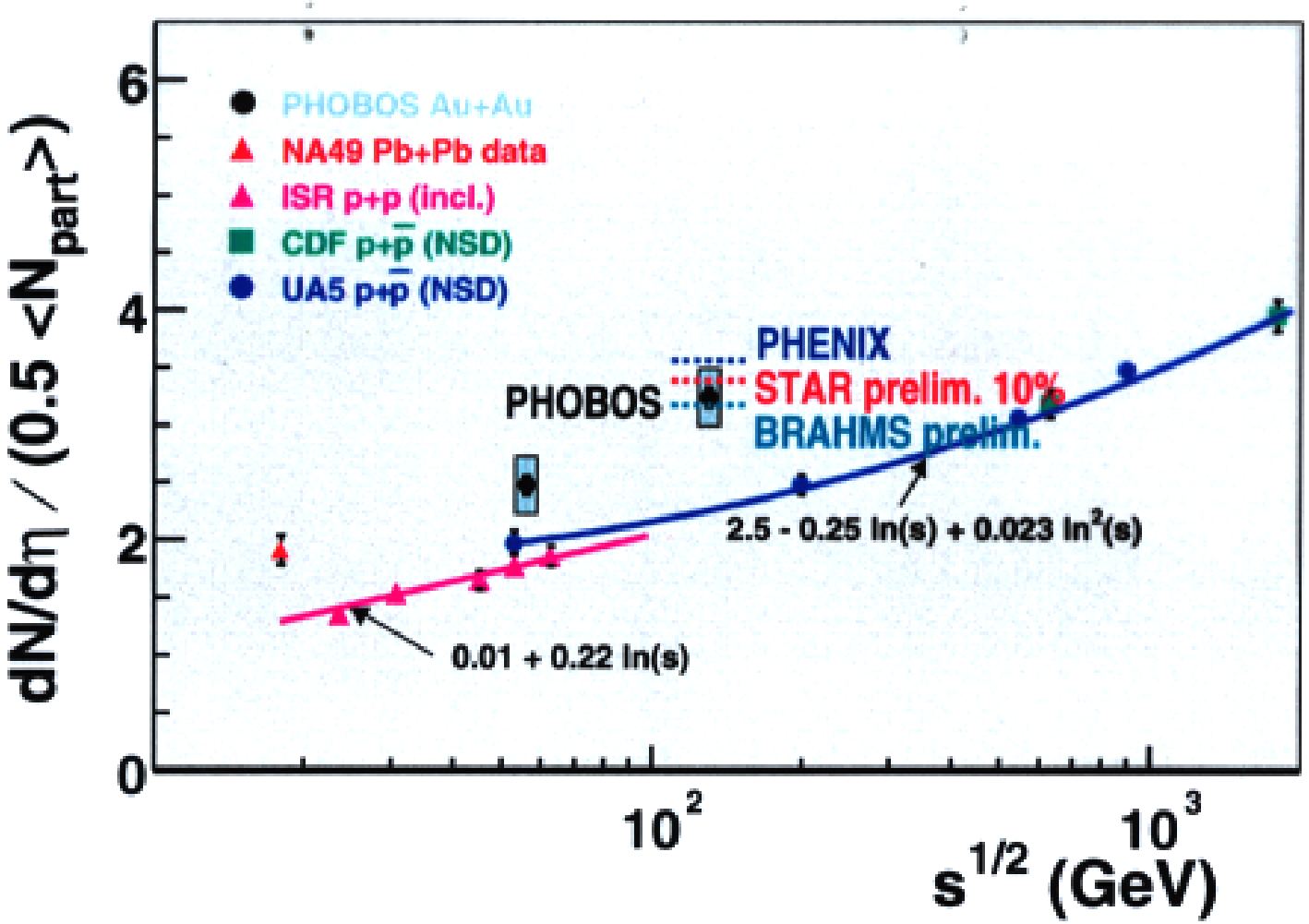
Relevant Posters

- P201 S. Adler The PHENIX Timing System
- P205 S. Botelho The PHENIX Time Expansion Chamber at RHIC
- P208 M. Chiu The PHENIX Data Acquisition System
- P211 L. Ewell The PHENIX Online Computing System
- P212 S.V. Greene The Design and Performance of the PHENIX Pad Chambers
- P213 A. Hansen The PHENIX Multiplicity Vertex Detector
- P214 A. Hoover, M. Liu The PHENIX South Muon Tracking System
- P215 J. Lajoie The PHENIX Muon Identifier Local Level-1 Trigger System
- P217 Y. Mao The PHENIX Muon Identifier Subsystem
- P219 Y. Micke Performance of the Time-of-Flight Counter in PHENIX
- P221 G. Mishra The PHENIX Event Builder
- P222 P. Nilsson The Readout System for the PHENIX Pad Chambers
- P223 E. O'Brien Charged Particle Tracking in PHENIX
- P226 T. Sakaguchi Performance of the PHENIX Ring Imaging Cherenkov Detector
- P229 T. Sugitate Performance of the Beam-Beam Counter in PHENIX
- P230 H. Torii Performance of the PHENIX EM Calorimeter in PHENIX

Quark Matter Formation at SPS/RHIC Energies

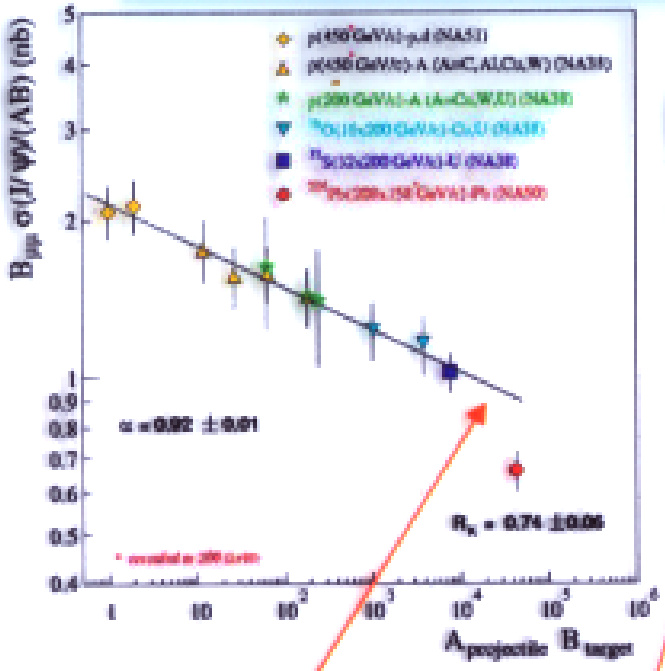
system evolution	evidence	
collision		
↓		S R
	energy density ε_i = 3 - ? / 5 - 15 GeV/fm^3	
	temperature T_i > 200/220 - 300 MeV	
quark matter formation	• J/ψ suppression	S
	• Jet quenching	R
↓ 	• thermal photons/dileptons	S
	• strangeness enhancement	S/R
early expansion of fireball	• strong radial and elliptic flow	R
↓		
hadronisation at phase boundary in chemical equilibrium	temperature T_c = 170 MeV	
	chem. potential μ_B = 0.27/0.02 MeV	
	• thermal analysis of hadron yields (incl. memory effects)	S/R
		
chiral transition at phase boundary	• excess in low mass lepton pairs	S
↓		
expansion of fireball	• radial and elliptic flow	S
↓ 		
	temperature T_f ~ 120 MeV	
thermal freeze-out	• single particle spectra	S/R
	• HBT correlations	S/R

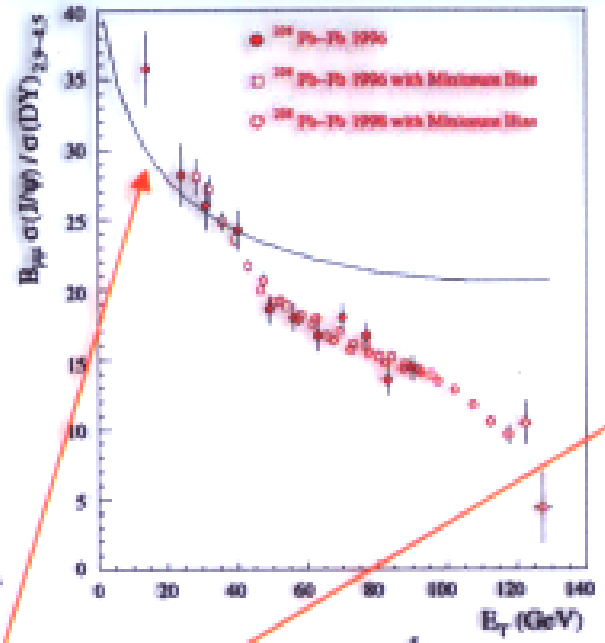
Energy dependence

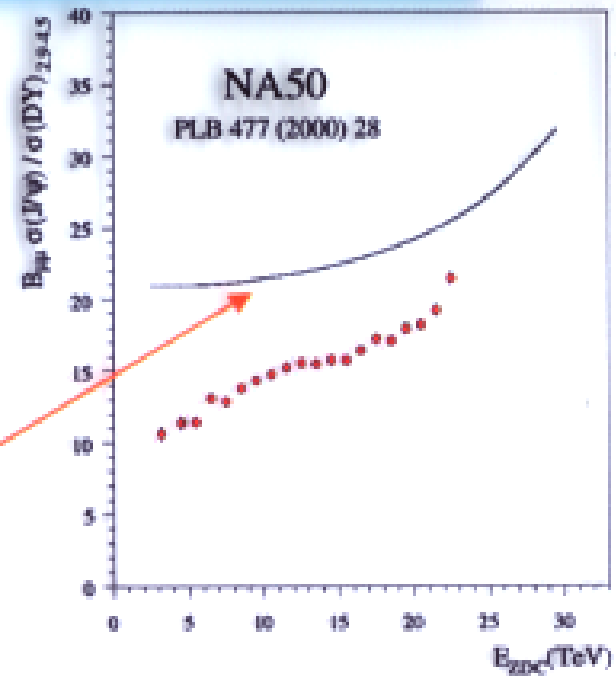


C. Lourenco

Anomalous J/ψ suppression in Pb-Pb collisions

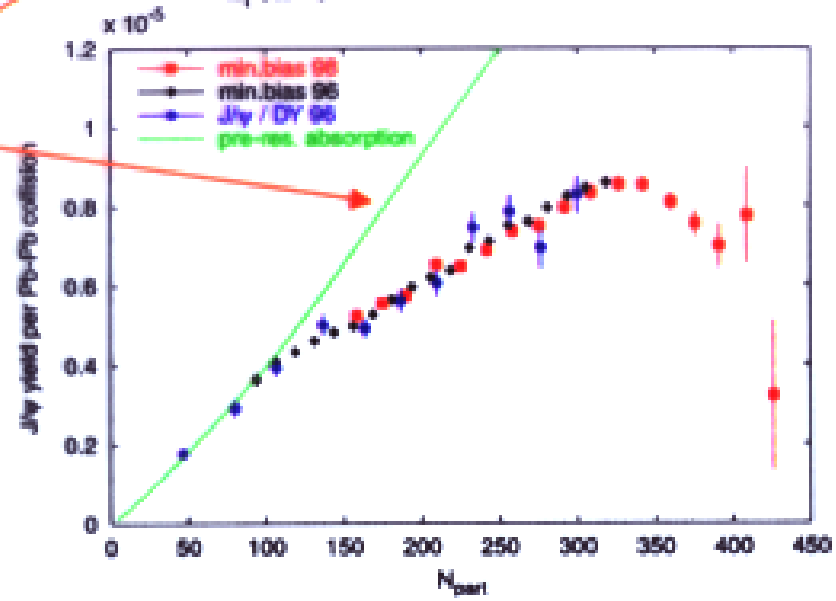






Normal nuclear absorption

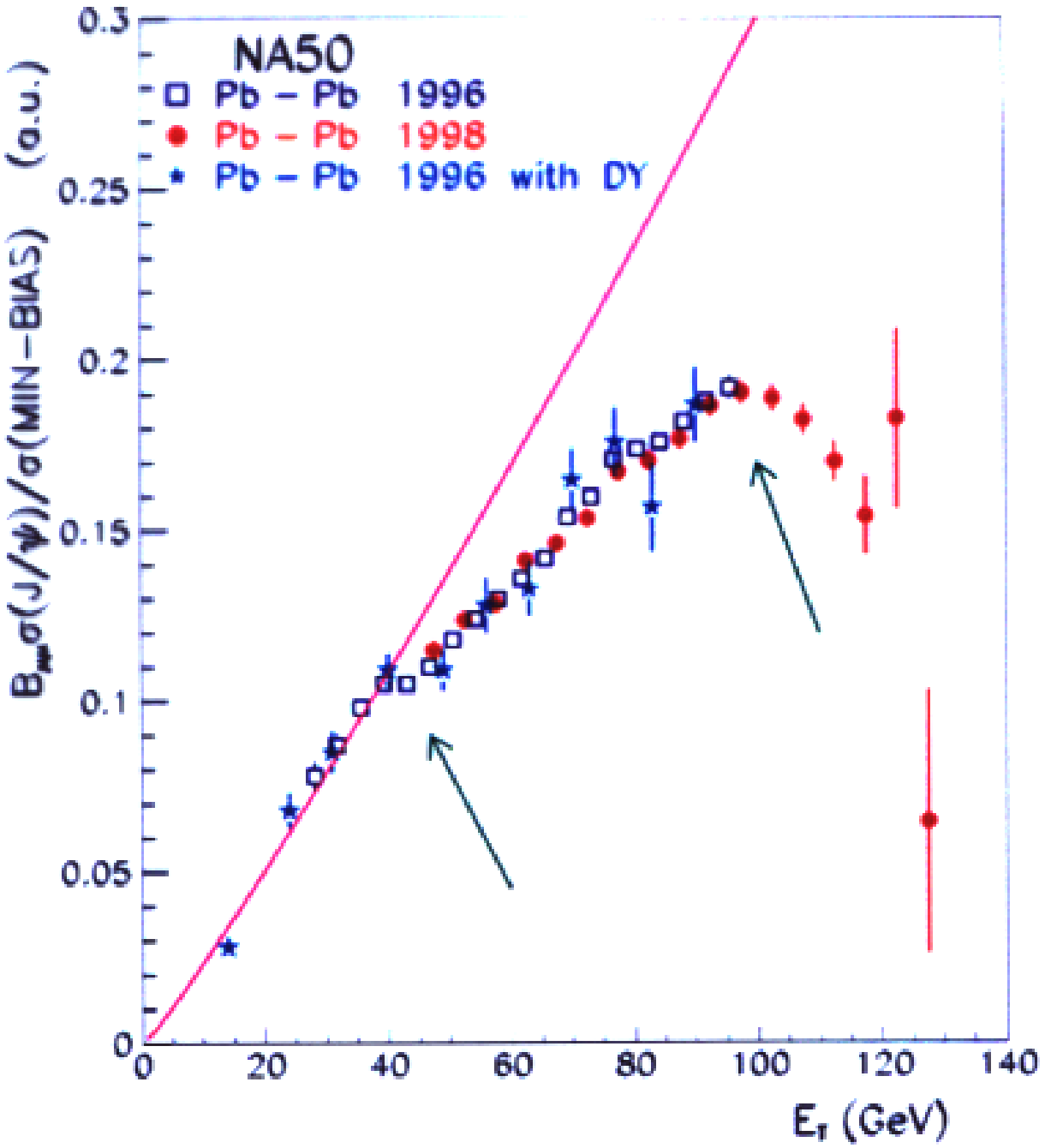
$\sigma_{abs} = 6.4 \pm 0.8$ mb



J/ψ "anomalous" suppression when :

- $E_T > 40$ GeV ; $E_{ZDC} < 24$ TeV (?)
- $N_{part} > 100$; $L > 8$ fm ; $b < 8$ fm

ψ/Minimum Bias as a function of E_T



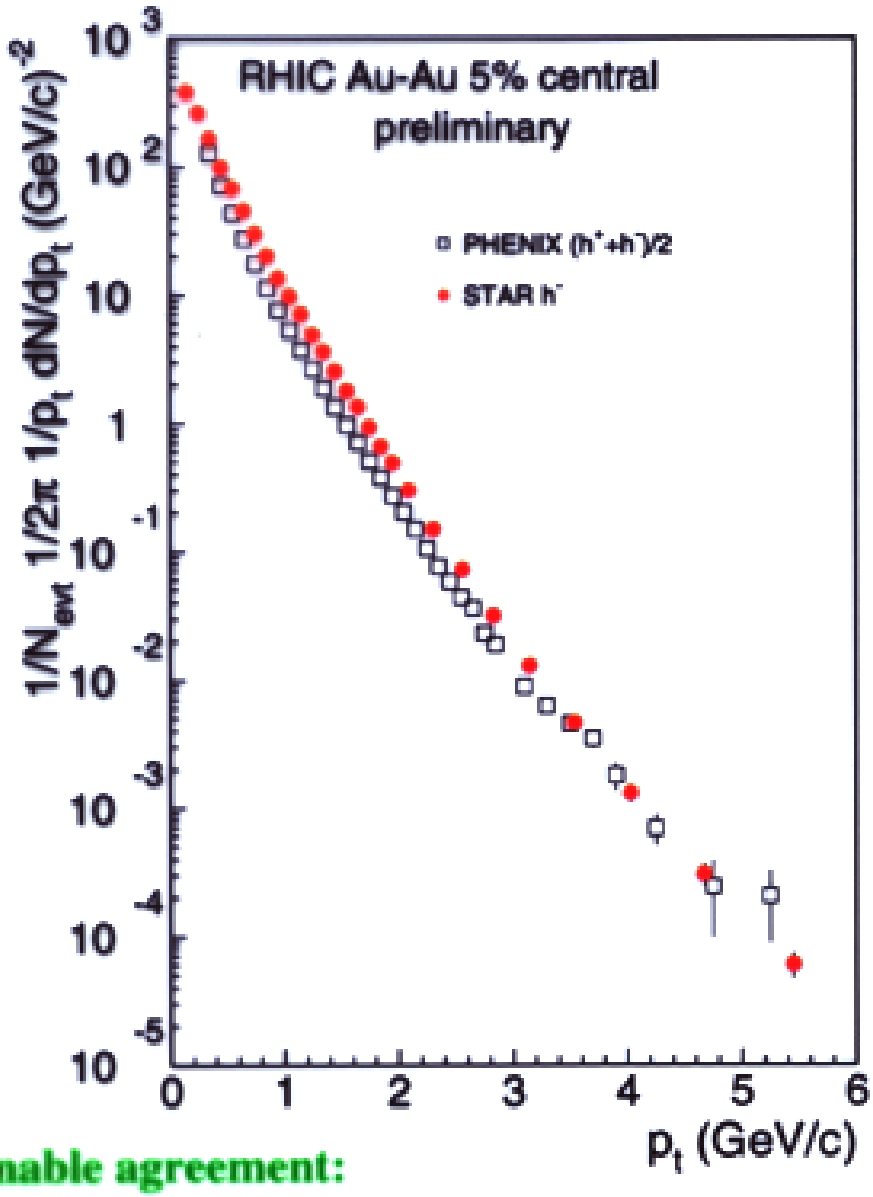
Solid line: Absorption Model with $\sigma_{abs} = 6.4 \pm 0.8\ mb$ as obtained from fit to p-A and S-U data (NA38 + NA51) with full calculation

Pattern exhibits 2 "accidents"

Inclusive p_t Spectra of charged Particles

J.C. Dunlop, STAR
F. Messer, PHENIX

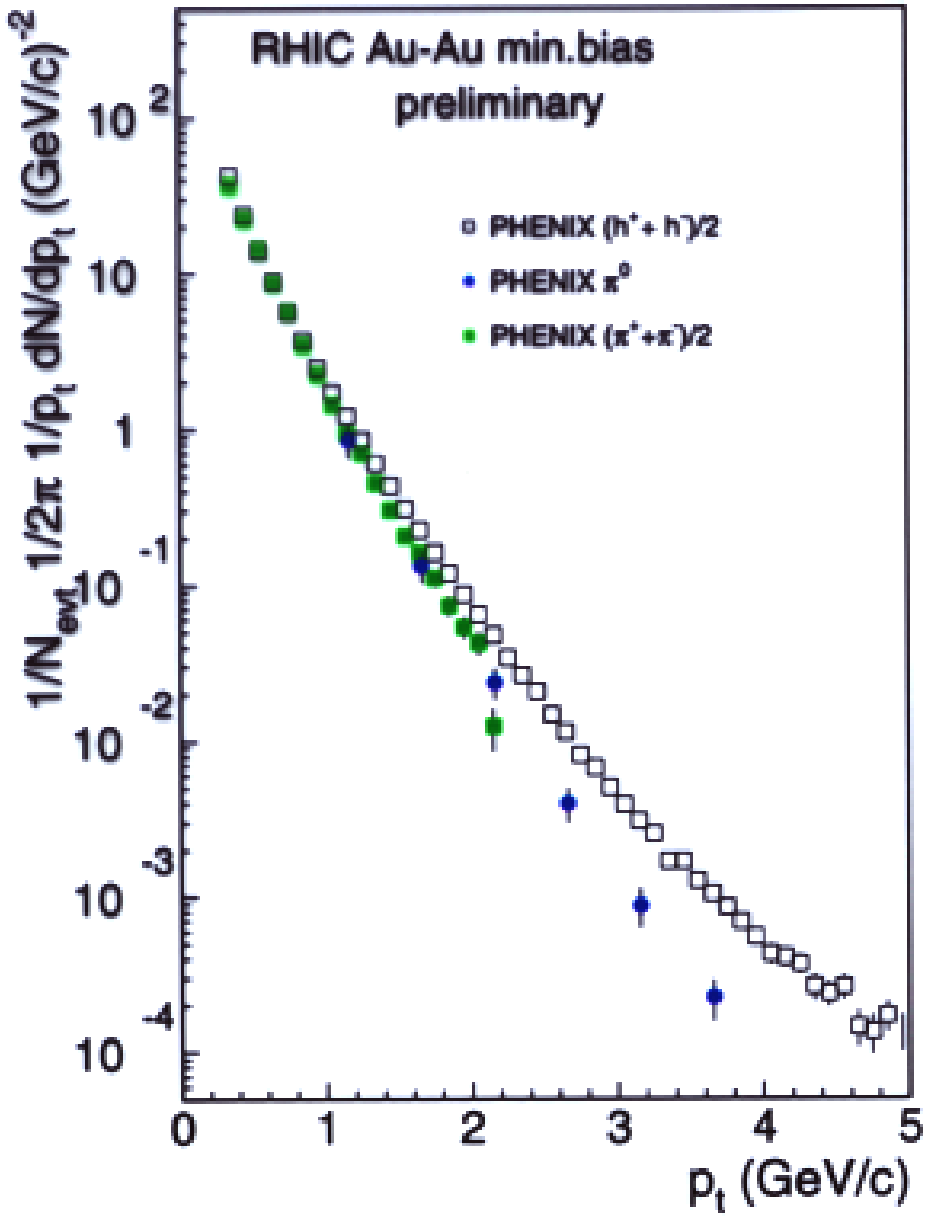
- **first high p_t data from RHIC:**
  - p_t range to 6 GeV, covering >6 orders of magnitude
  - well above what was reached at the SPS



- **reasonable agreement:**
  - small differences in shape and yield
  - centrality selection …

Inclusive p_t Spectra of Pions

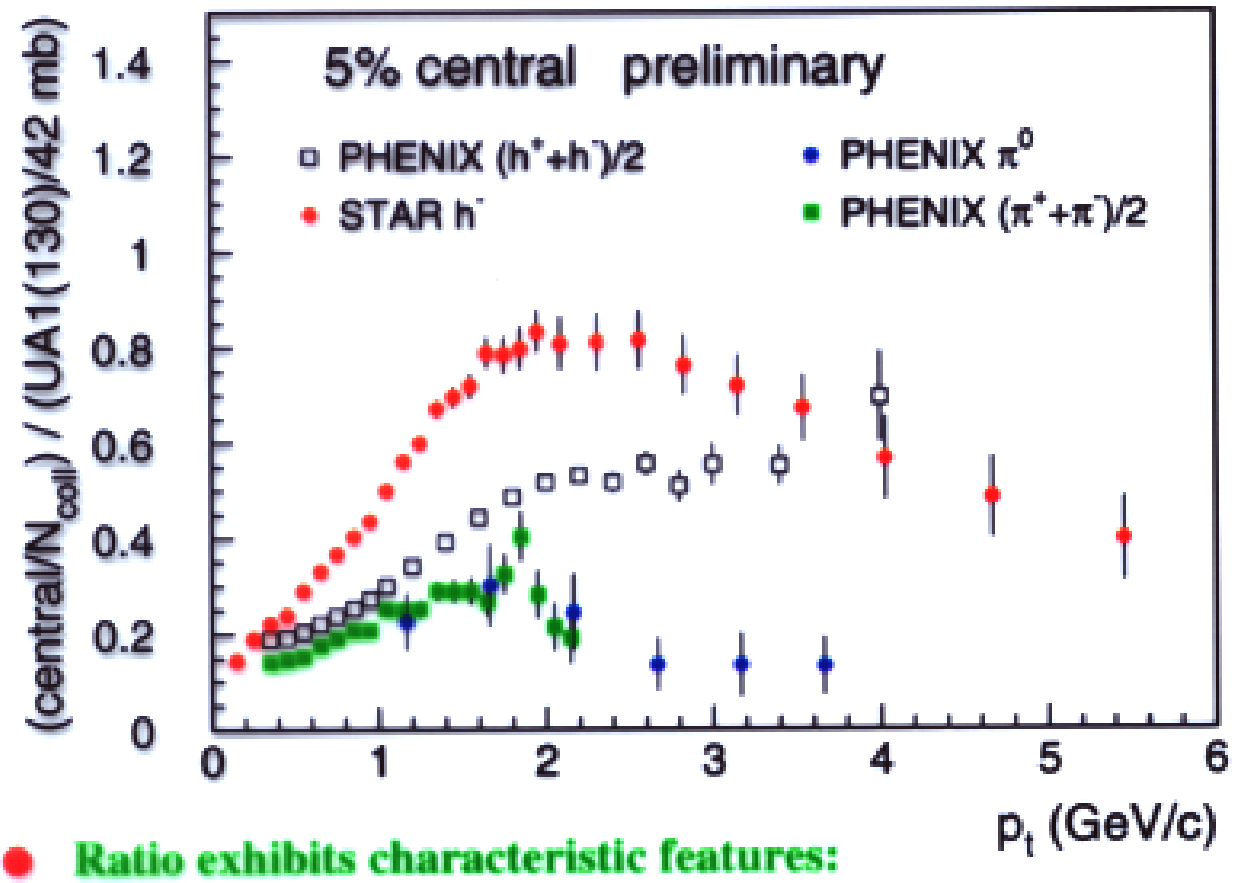
G. David, PHENIX
F. Messer, PHENIX
J.Velkovska, PHENIX



- π^0 from 1 to 4 GeV
- good agreement with h^- below 2 GeV
- agreement in shape with $\pi^\pm$ from 0.3 to 2.2 GeV

Comparison to central Au-Au to p-p

- **Use identical p-p parameterization for all data sets**
  - normalize data to number of binary collisions
  - divide by p-p parameterization UA1(130)/42 mb

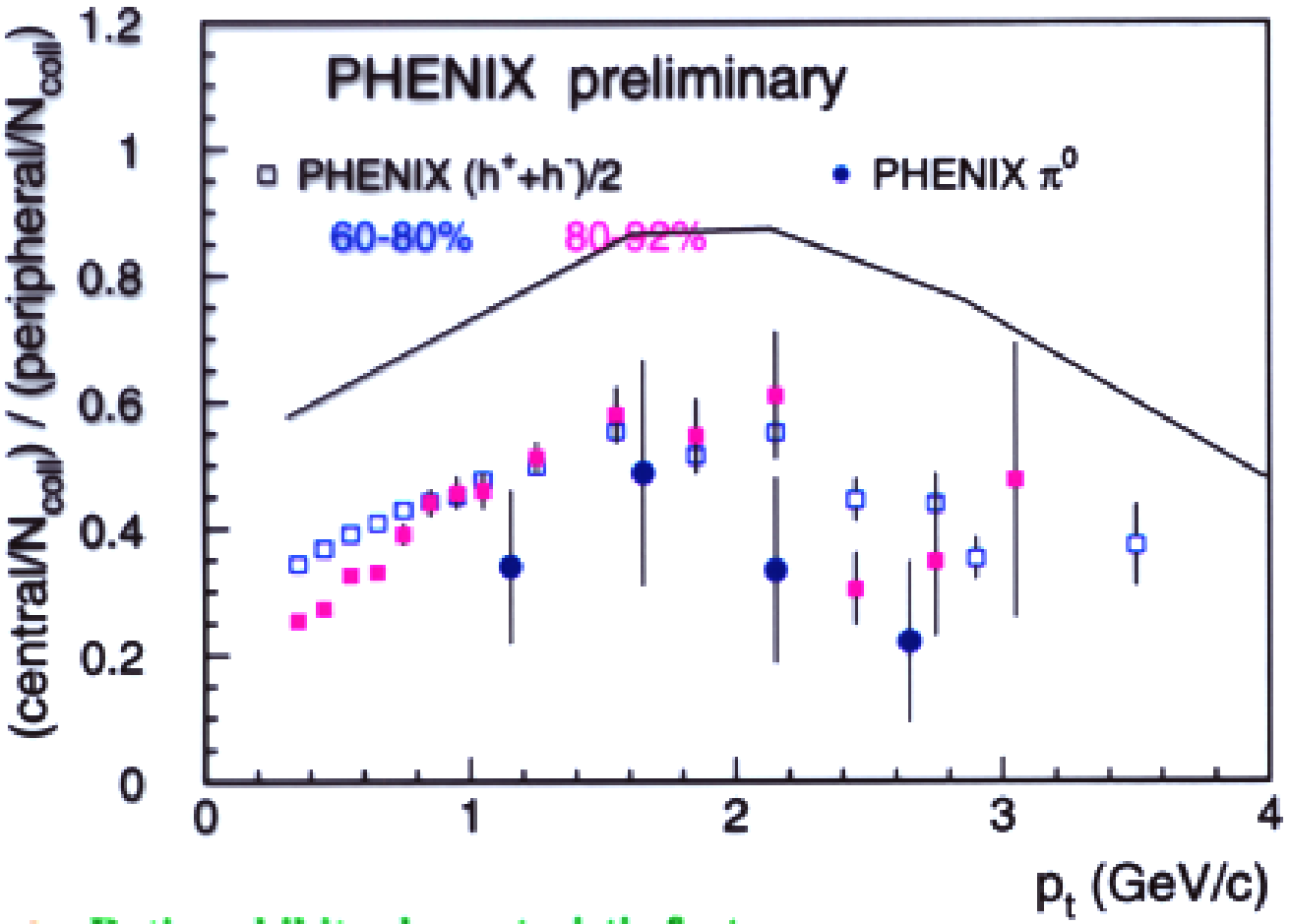


- **Ratio exhibits characteristic features:**
  - increases up to ~ 2 GeV
  - saturates at $R_{AA} < 1$
  - decrease at high p_t

- **Issues: large systematic error ~ 30%**
  - data: normalization, differences in shape, centrality selection, p/ p contribution ..
  - systematic uncertainty of p-p parameterization

Ratio Central/Peripheral

- normalize central and peripheral to number of collisions
- different systematic errors:
  - many experimental errors cancel
  - systematic uncertainty ~60% on N_{coll}



- Ratio exhibits characteristic features:
  - increases up to ~ 2 GeV
  - saturates at $R_{AA} < 1$
  - decrease at high p_t

within systematic errors:

$R_{AA} < 1$

X.N. Wang
QM 2001
Au + Au
$\sqrt{s_{NN}}$ = 130 GeV
dE/dx = 0
dE/dx = 0.25 GeV/fm
STAR h^- (Preliminary)
PHENIX h (Preliminary)
pp ..... $\sqrt{s_{NN}}$ = 200 GeV
p+pbar → $(h^+ + h^-)/2$
UA1 $\sqrt{s_{NN}}$ = 200 GeV
p_T (GeV/c)
$dE/dy\,d^2p_T\,d\phi/p_T$ (c^2 mbGeV)

X.N. Wang

dE/dx and Hadron Spectra

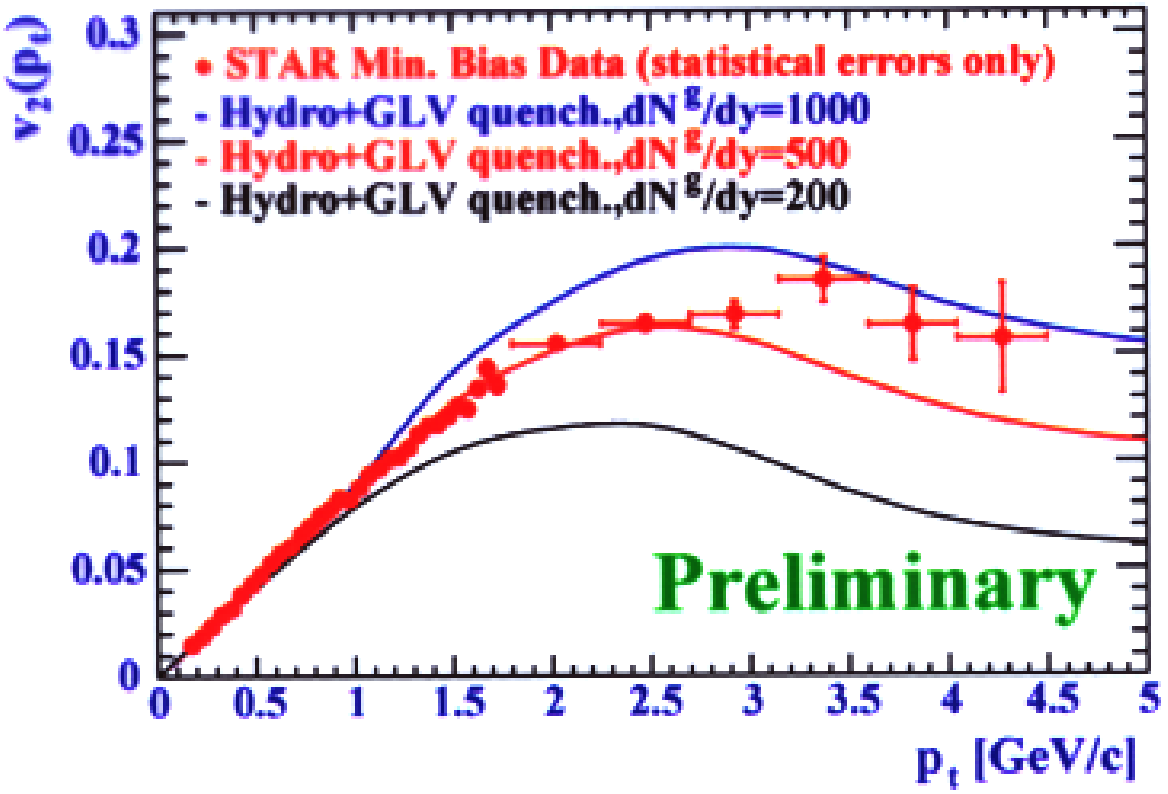
$$\langle N \rangle_{bin} \equiv \int d^2b\, T_{AB}(b)$$

$$\int d^2b\, T_{AB}(b) \frac{d\sigma^{NN}}{dyd^2p_T} = \frac{d\sigma^{AB}}{dyd^2p_T}$$

Charged particle anisotropy
$0 < p_t < 4.5$ GeV/c

Raimond Snellings, STAR

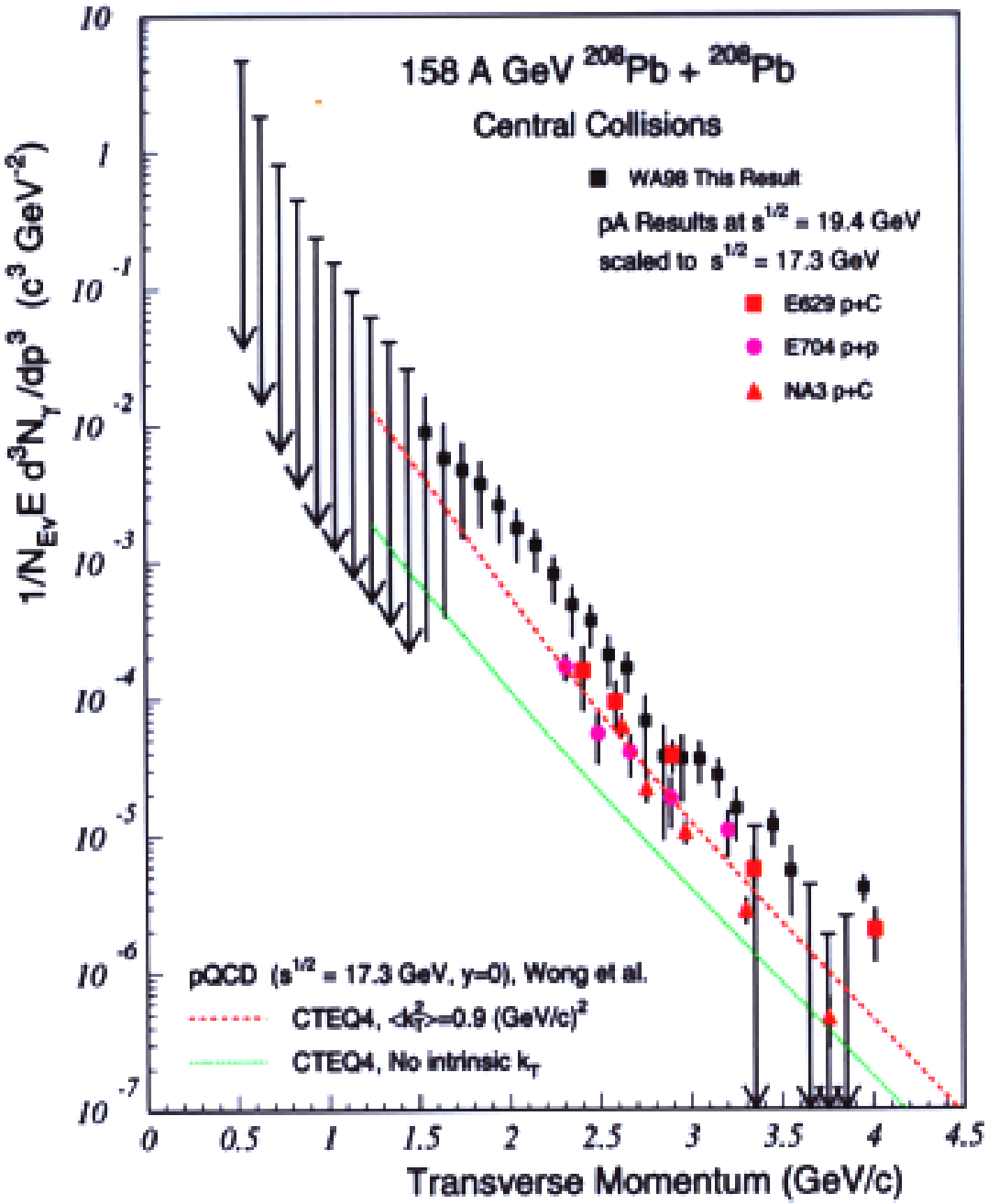
- STAR data: only statistical errors plotted. Systematic error 10% - 20% for $p_t = 2 - 4.5$ GeV/c
- Hydro+GLV: M. Gyulassy, I. Vitev and X.N. Wang, nucl-th/0012092



- azimuthal angular correlation measured by v_2:
  - hydrodynamic behavior up to ~1.5 GeV
  - followed by saturation
- comparison to a recent theoretical calculation
  - compatible with jet quenching scenario
  - sensitivity to initial conditions

A. Lebedev / WA 98

Direct Photons



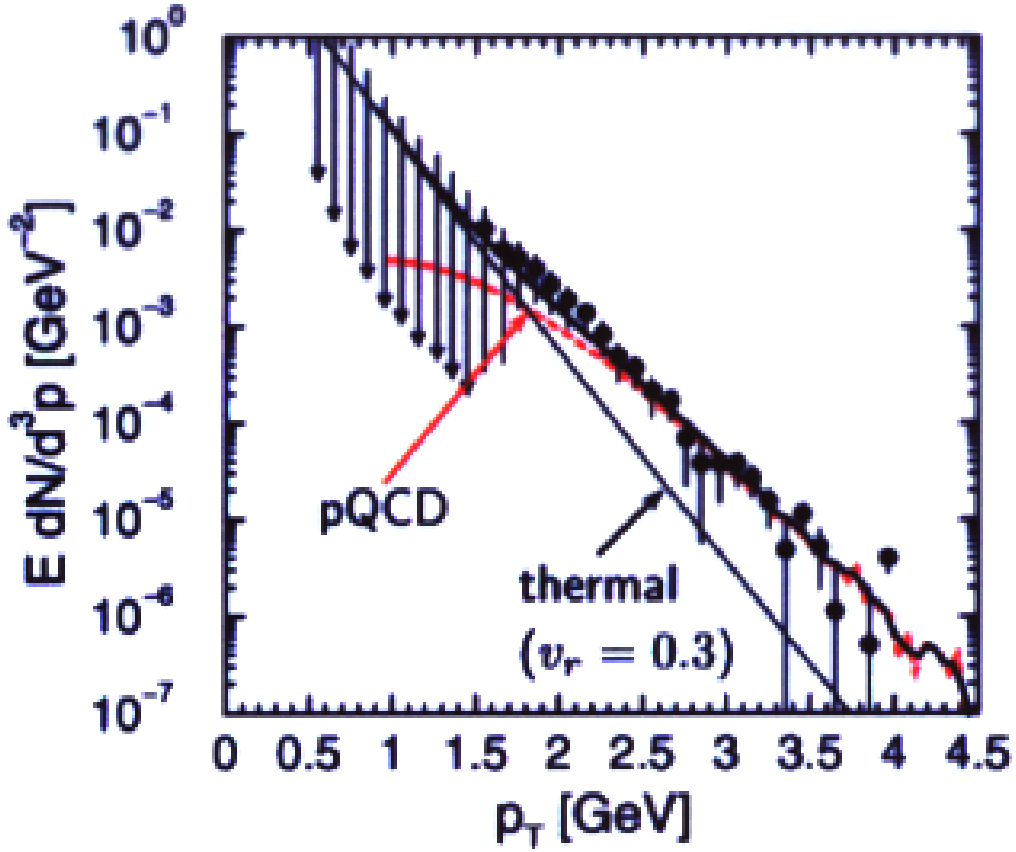
- Comparison to pA:
  - correct for number of nucleon-nucleon collisions.
  - assume invariant yield has form $f(x_T)/s^2$ where $x_T = 2P_T/s^{1/2}$

- WA98:
  Phys. Rev. Lett., v.85(2000), p.3595

- Similar spectrum shape, but factor of 2-3 enhanced yield for Pb+Pb

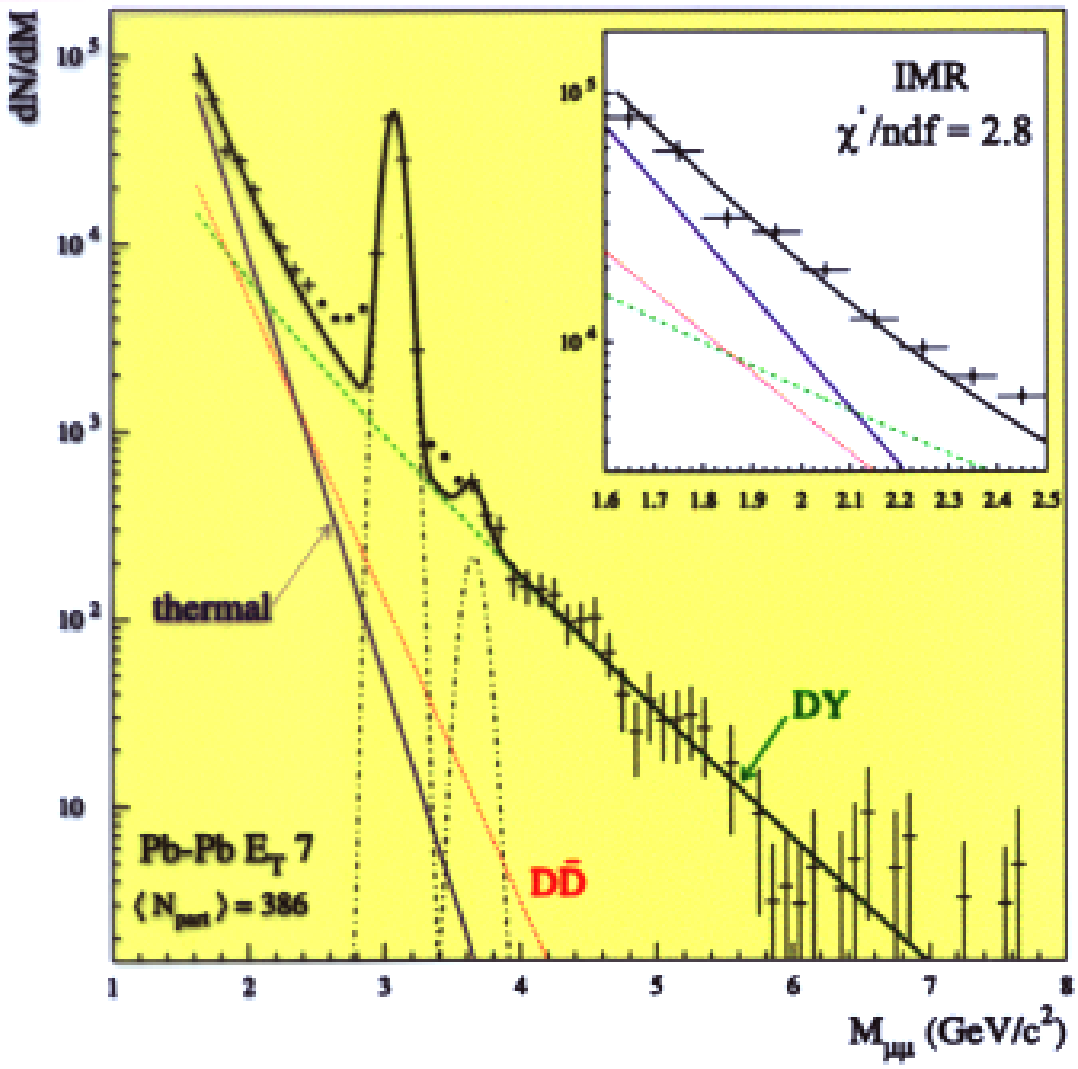
- NLO pQCD calculations underpredict direct photon yield.

WA98: central Pb(158 AGeV) + Pb $\rightarrow X + \gamma$



CERES + NA50 + WA98: $\langle T \rangle = 170$ MeV $\quad N_{\rm eff} = \int dt V(t) = 3.3 \times 10^4$ fm^4

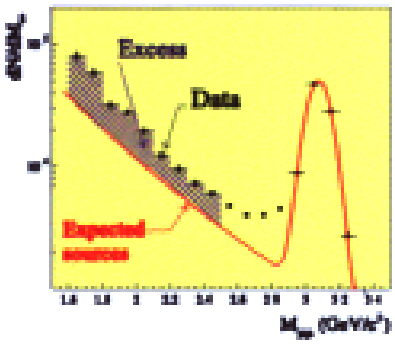
Thermal dimuons



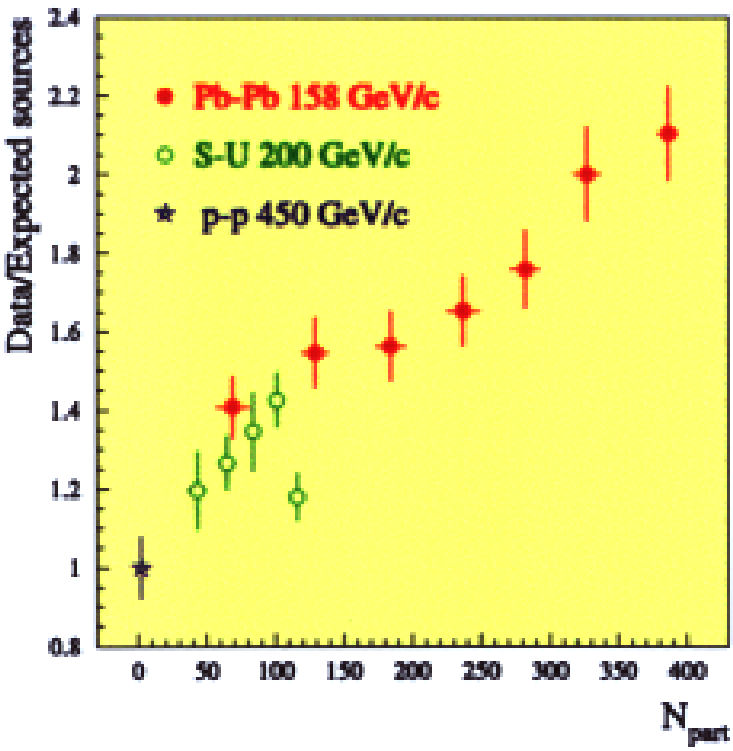
→ the IMR excess can be well accounted for by **thermal radiation** when combined with **DY** and **open charm**

data/expected sources

- quantify the difference between data and expected sources



plot **data/expected sources** vs N_{part} in $1.6 < M < 2.5$ GeV/c^2



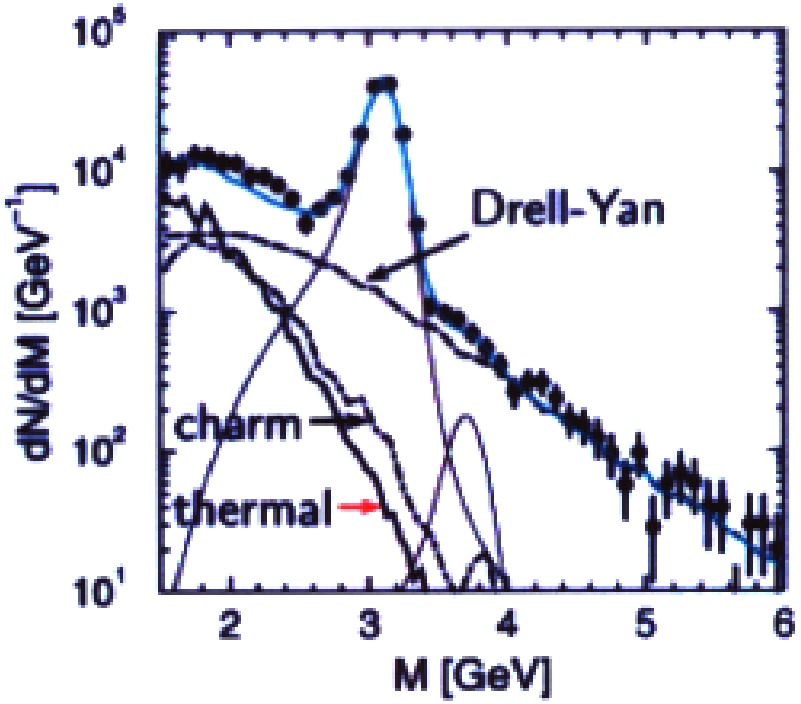
- the IMR **excess increases** as a function of **centrality**

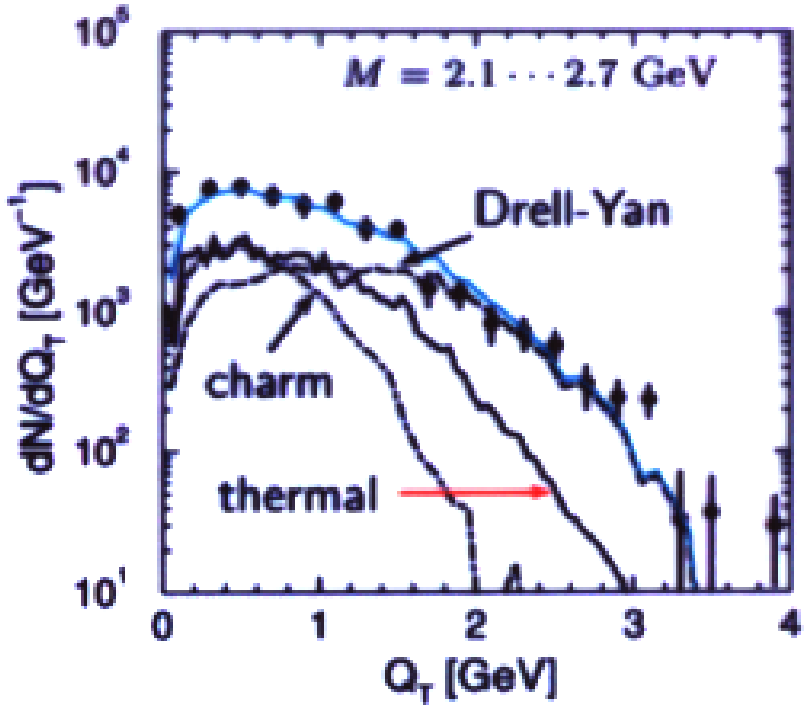
Thermal dimuons

- model developped by Rapp and Shuryak
  [Phys.Lett.B473(2000)13]

  - $\mu\mu$ yield based on $q\bar{q}$ annihilation rate
  - integration over space-time history
  - central collisions only
  - parameters :
    - fireball lifetime : 14 fm/c
    - initial temperature : $T_i = 192$ MeV
  - explicit introduction of a QGP phase
    - critical temperature : $T_c = 175$ MeV
  - no free parameters

NA50: central Pb(158 AGeV) + Pb $\rightarrow X + \mu^+\mu^-$

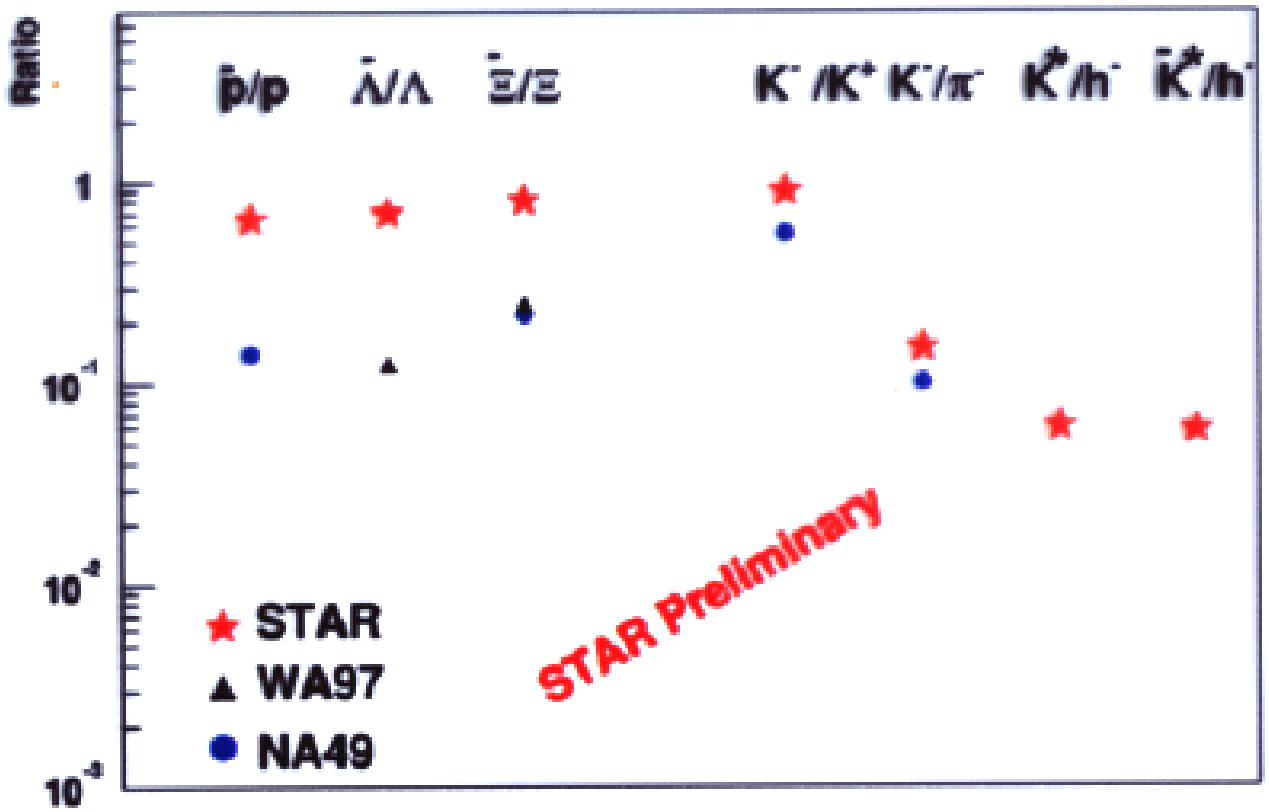




no charm enhancement needed

flow

Ratios Compared to SPS



$\bar{p}/p$ = 0.61 ± 0.03 (stat.) ± 0.06 (sys.)

$\bar{\Lambda}/\Lambda$ = 0.73 ± 0.03 (stat.)

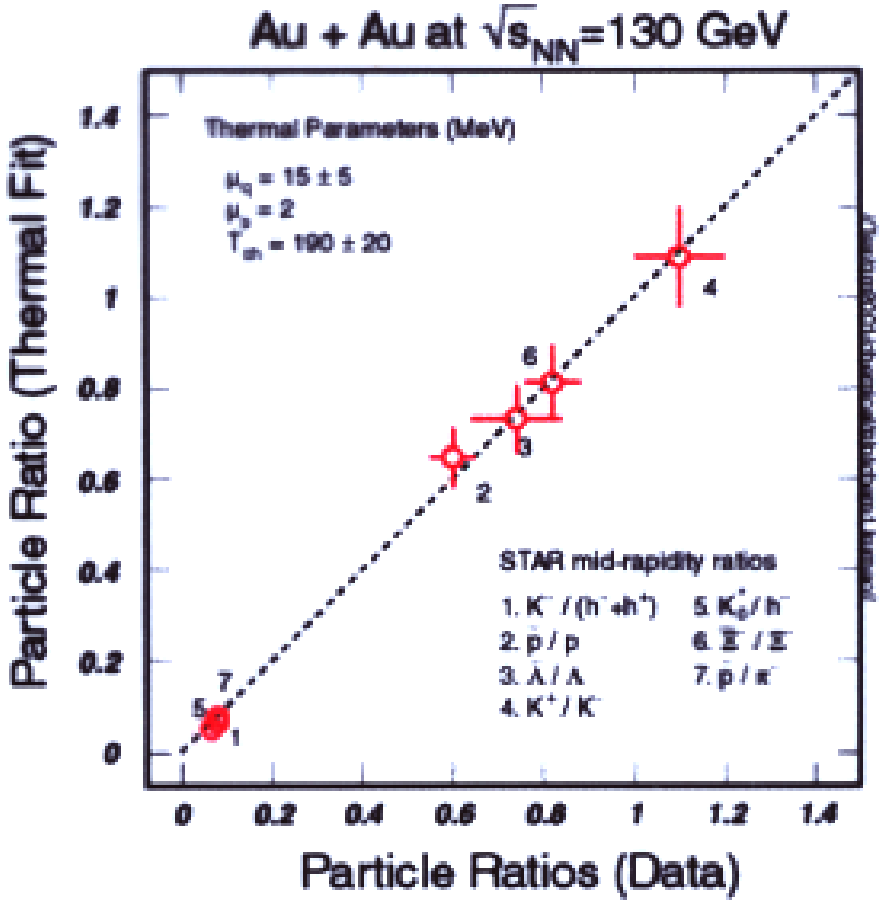
$\bar{\Xi}/\Xi$ = 0.82 ± 0.08 (stat.)

K^+/K^- = 1.12 ± 0.01 ± 0.06

→ Quark Coalescence

J.W. Harris for STAR at QM2001

Chemical Fit Results



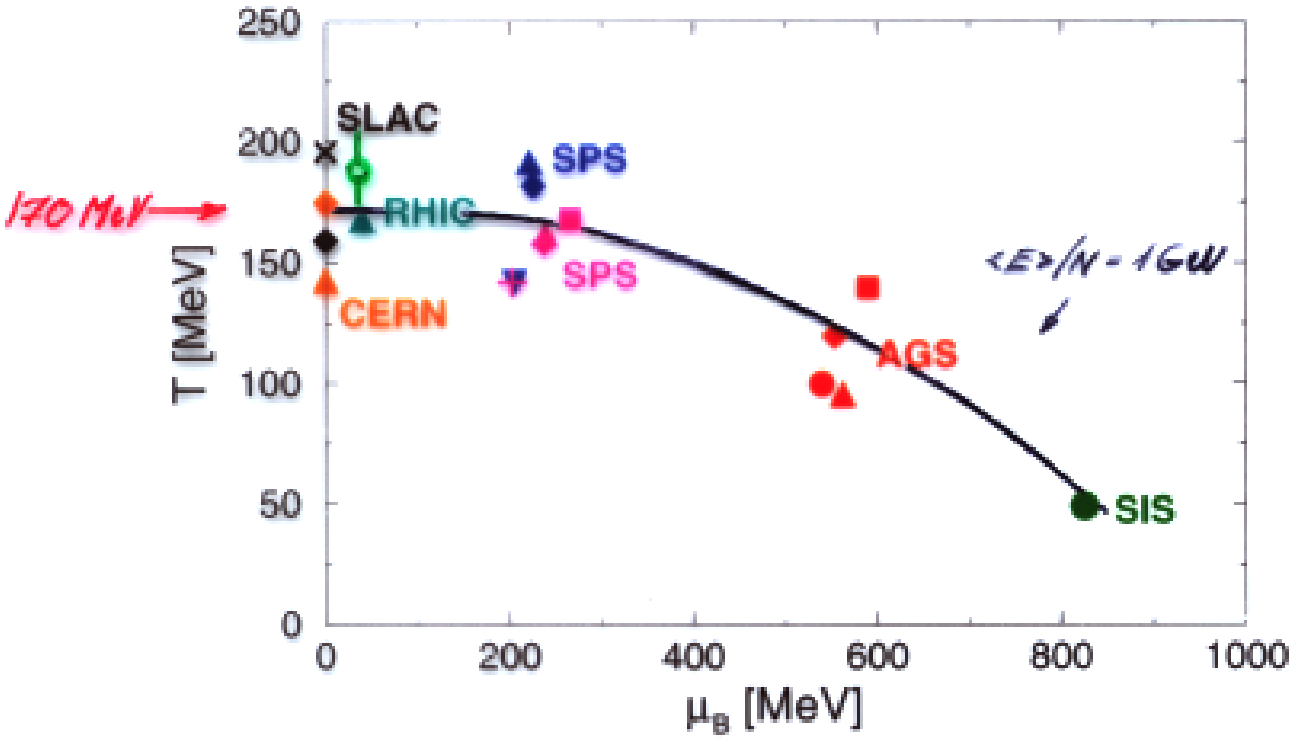
- **Thermal fit to preliminary data:**

  T_{ch} = 190 MeV
  μ_q = 20 MeV
  μ_s ≤ 4 MeV

- **Not a 4π-yields fit!**

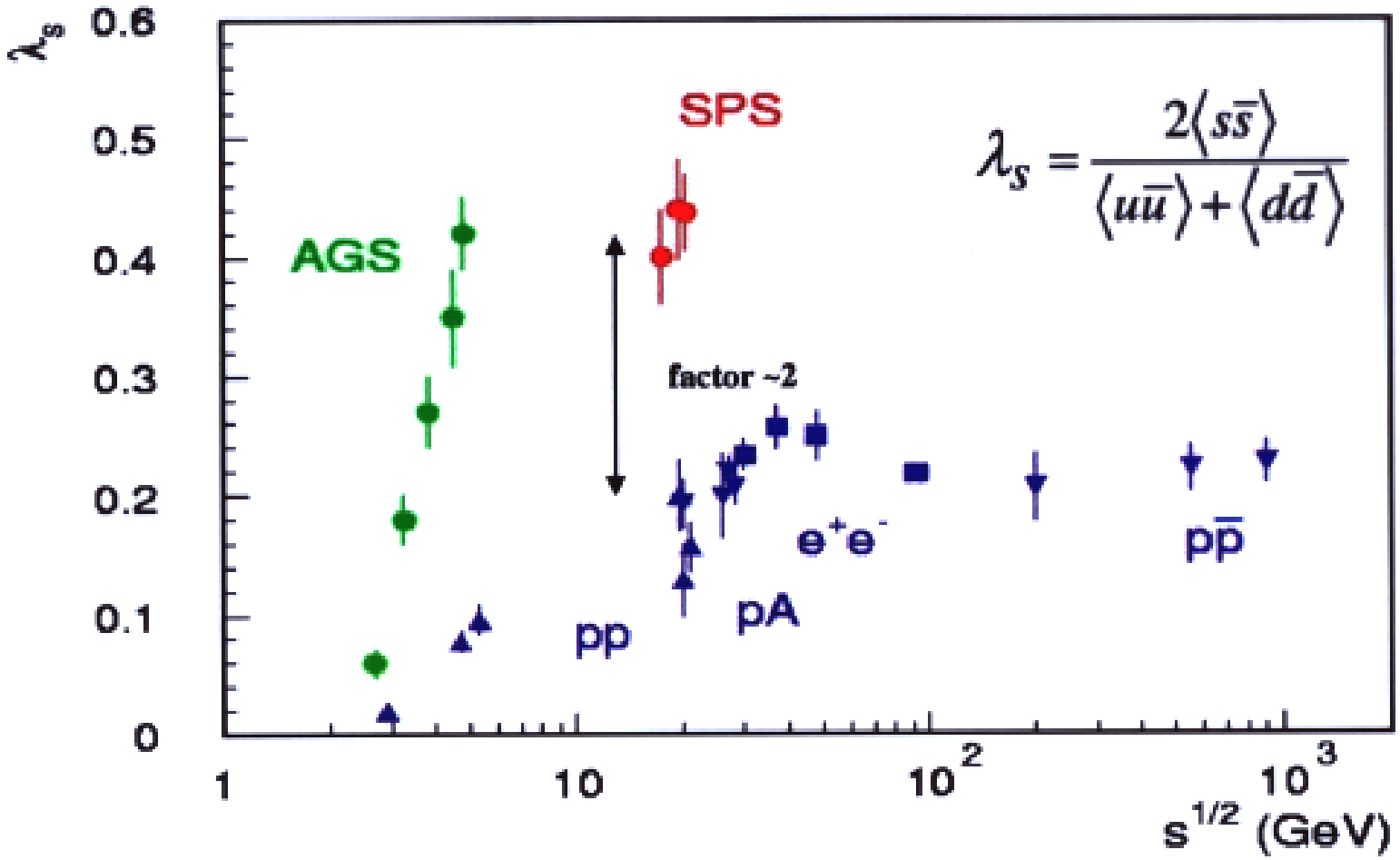
  $\gamma_s \equiv 1$
  $\chi^2 \equiv 1.4$

D. Rischke



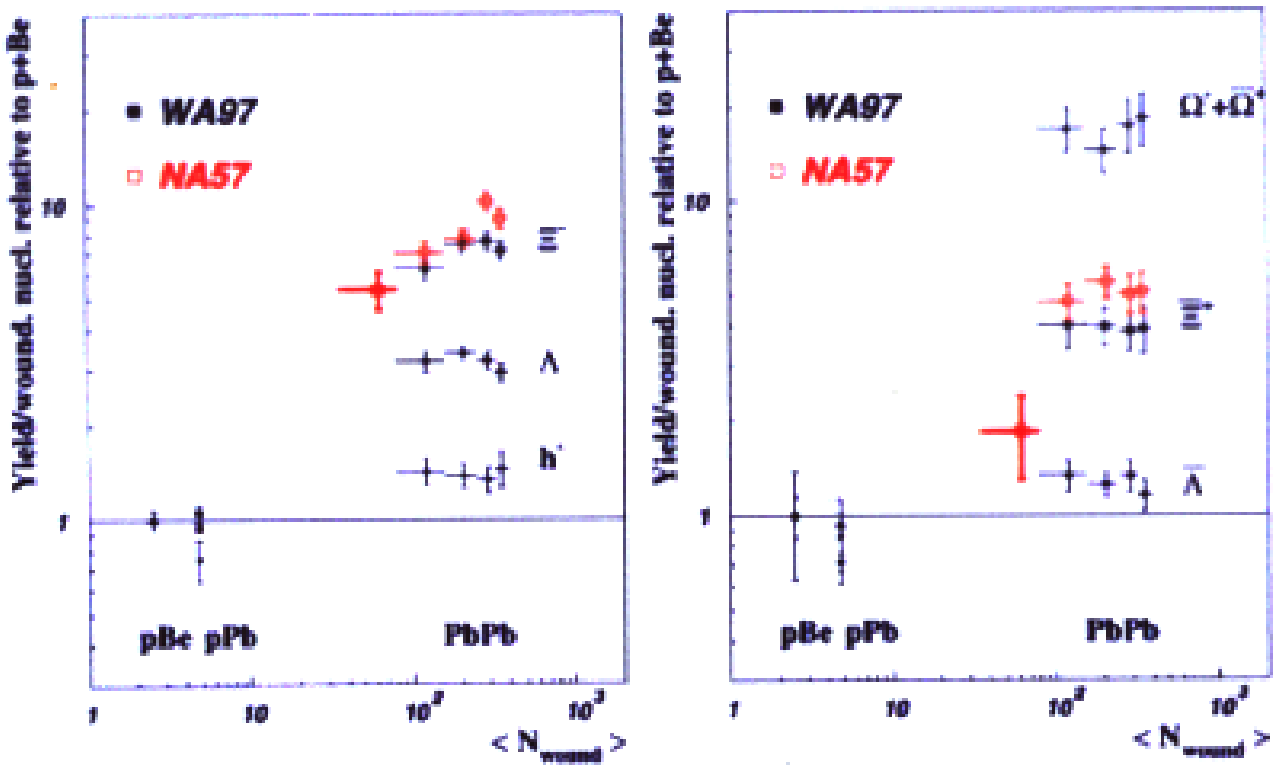
Au+Au, 2.3 AGeV	● [1] Cleymans et al., PRC 59 (99) 1663
	■ [2] Yen et al., JPG 24 (98) 1777
	◆ [3] Becattini et al., hep–ph/0002267
Au+Au, 5 AGeV	▲ [4] Kabana et al., hep–ph/0010247
	● [5] Cleymans et al., PLB 388 (96) 5
	◆ [6] Becattini, JPG 23 (97) 1933
S+S, 20 AGeV	▼ [7] Sollfrank, EPJC 9 (9) 159
	▲ [8] Panagiotou et al., PRC 53 (96) 1353
	■ [9] Braun–Munzinger et al., PLB 465 (9) 15
Pb+Pb, 17 AGeV	◆ [3]
	▲ [4]
	+ [10] Letessier et al., IJMPE 9 (00) 107
Au+Au, 130 AGeV	▲ [4]
	◆ [11] Becattini et al., ZPC 74 (97) 319
p–pbar, 900GeV	▲ [4]
e^+e^-, 29GeV	× [12] Hoang et al., ZPC 38 (88) 603
	◆ [13] Becattini et al., hep–ph/0010221

Strangeness production



N. Carrer / NA 57

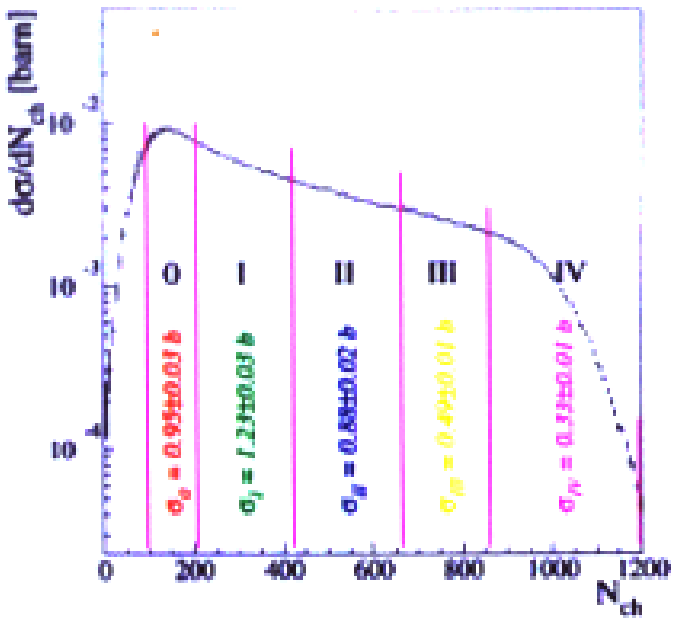
Yields per participant

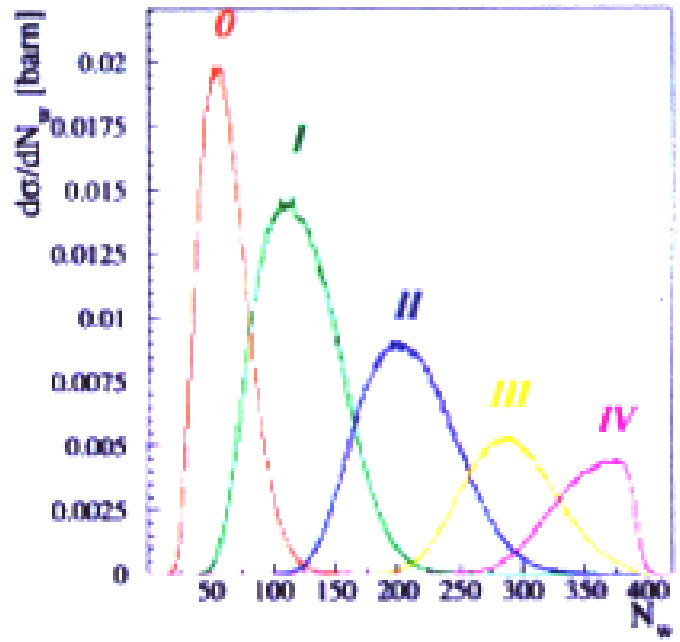


- Yield per N_{wound} rises from $\langle N_{wound} \rangle = 62 \rightarrow 121$ both for Ξ^- and for $\bar{\Xi}^+$
  - 2.6 for $\bar{\Xi}^+$ (3.5 σ effect)

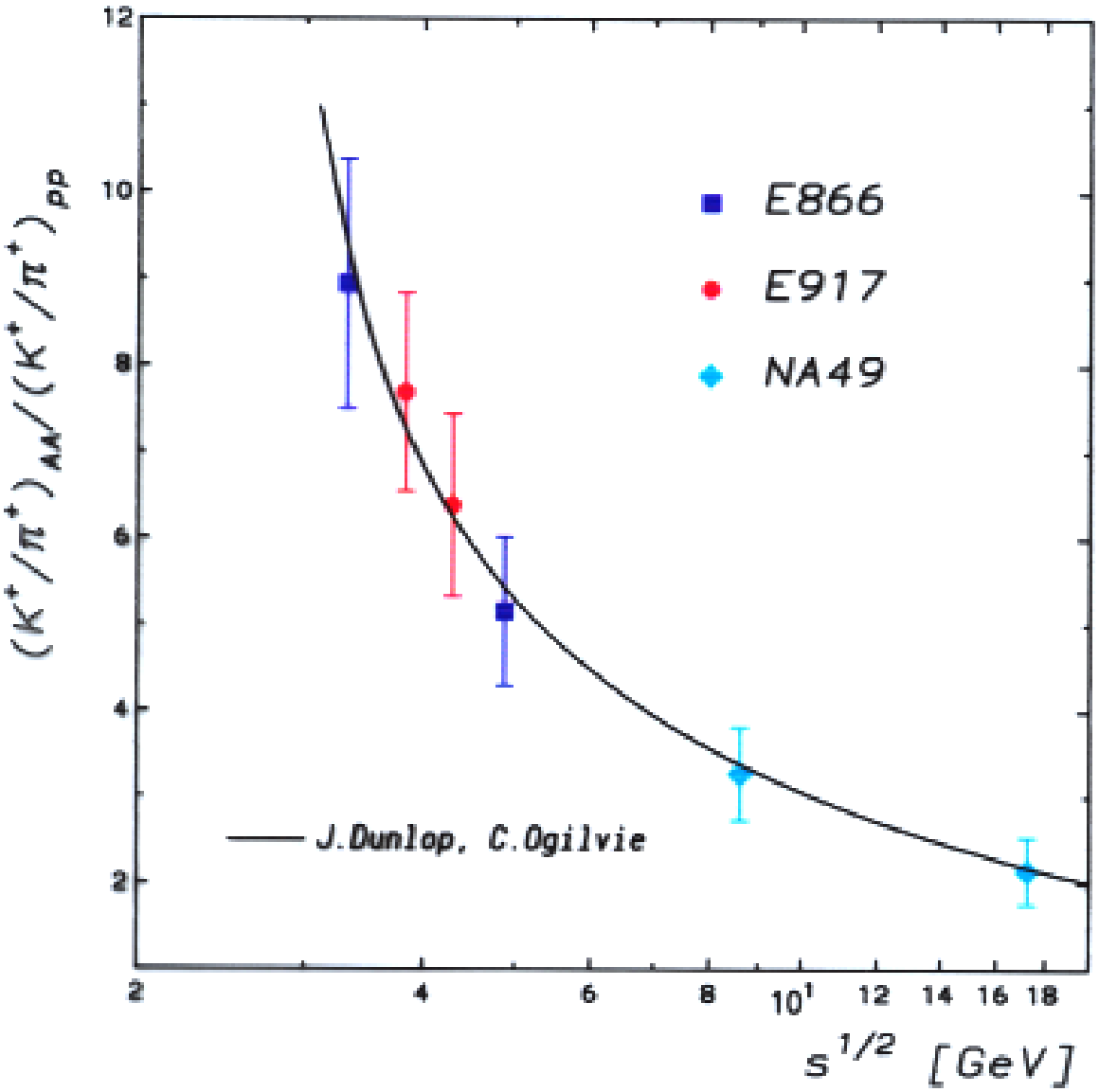
N. Carrer / NA 57

Centrality

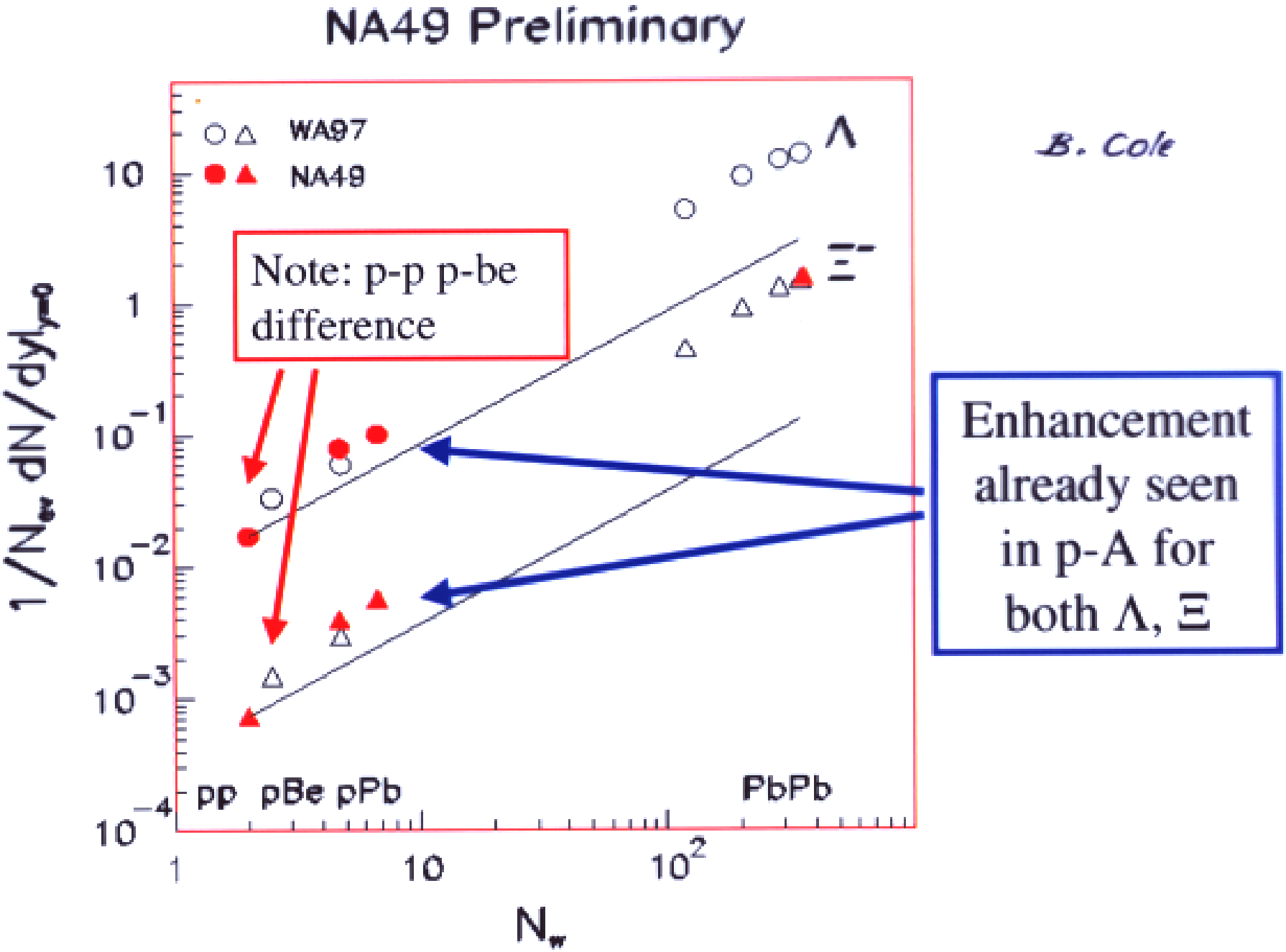


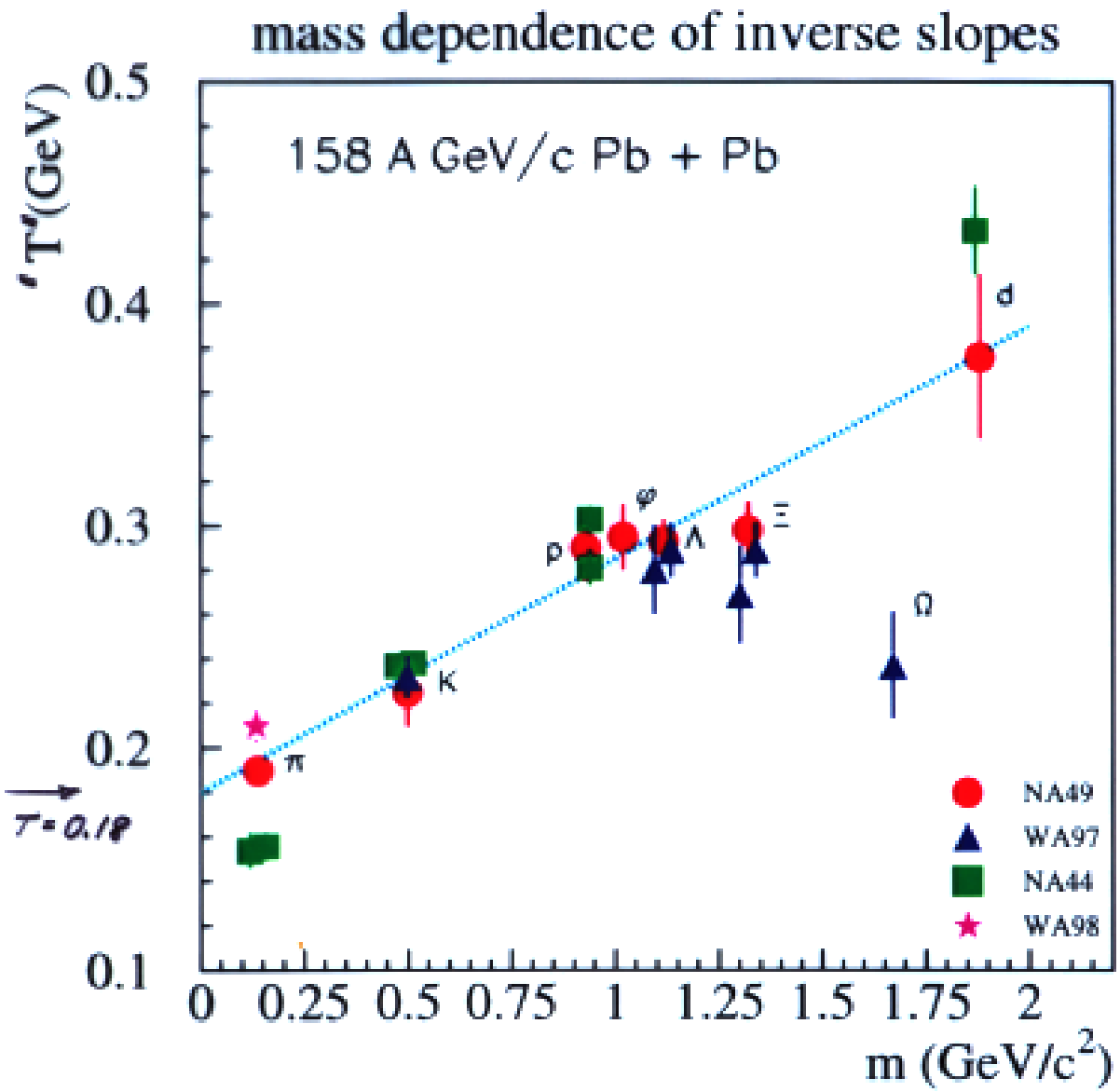


- Centrality selection → charged part. multiplicity (MSD)
- N_{wound} from Xsections for each class (Glauber model)
  - In WA97 N_{wound} from WNM (δN_{wound} at most 3%)
- NA57: most peripheral bin → $\langle N_{wound} \rangle = 62$


12
10
8
6
4
2
2
4
6
8
10¹
12
14
16
18
$(K^+/\pi^+)_{AA}/(K^+/\pi^+)_{pp}$
$s^{1/2}$ [GeV]
E866
E917
NA49
J.Dunlop, C.Ogilvie

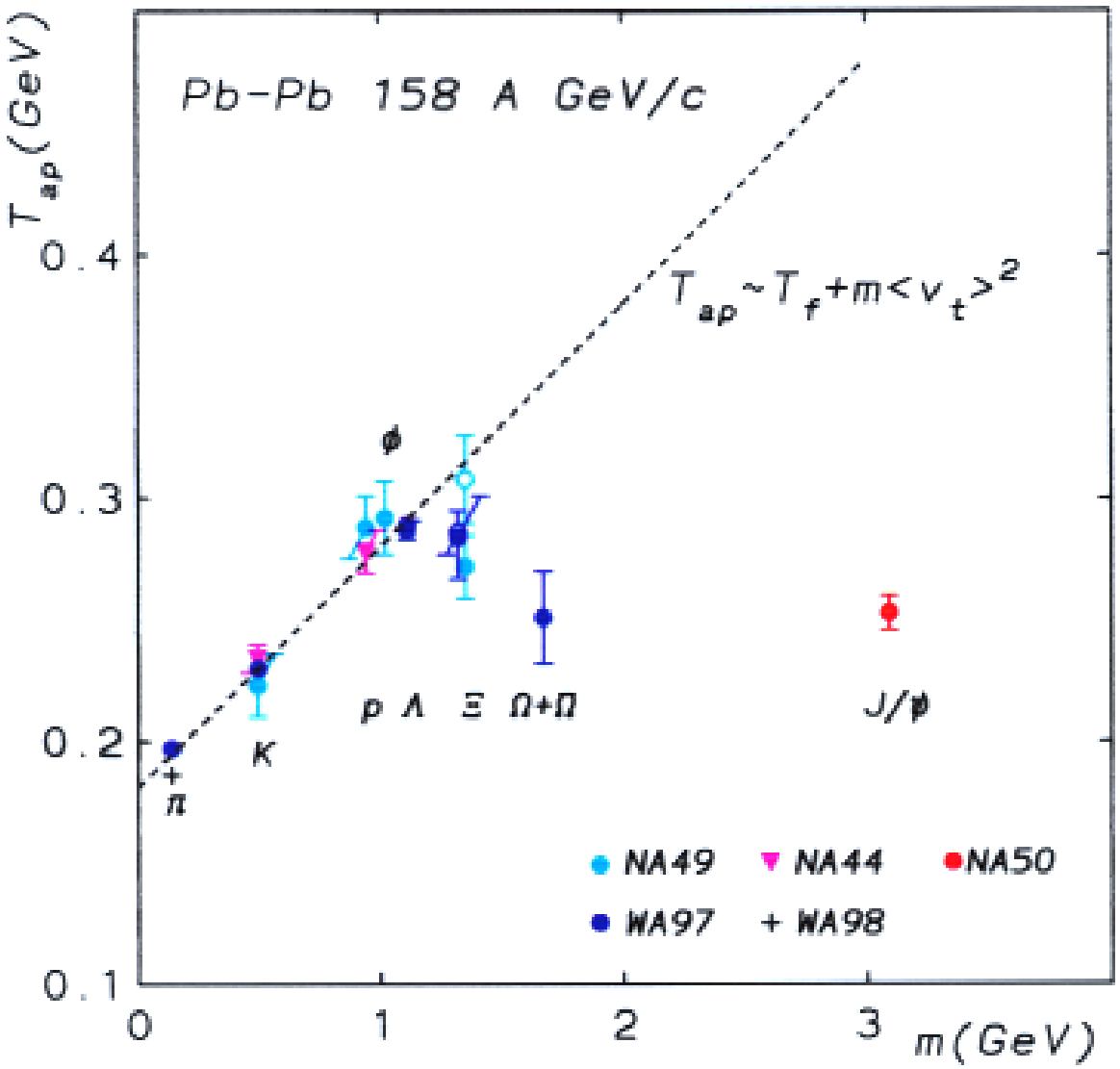
NA49 Wounded-Nucleon Analysis





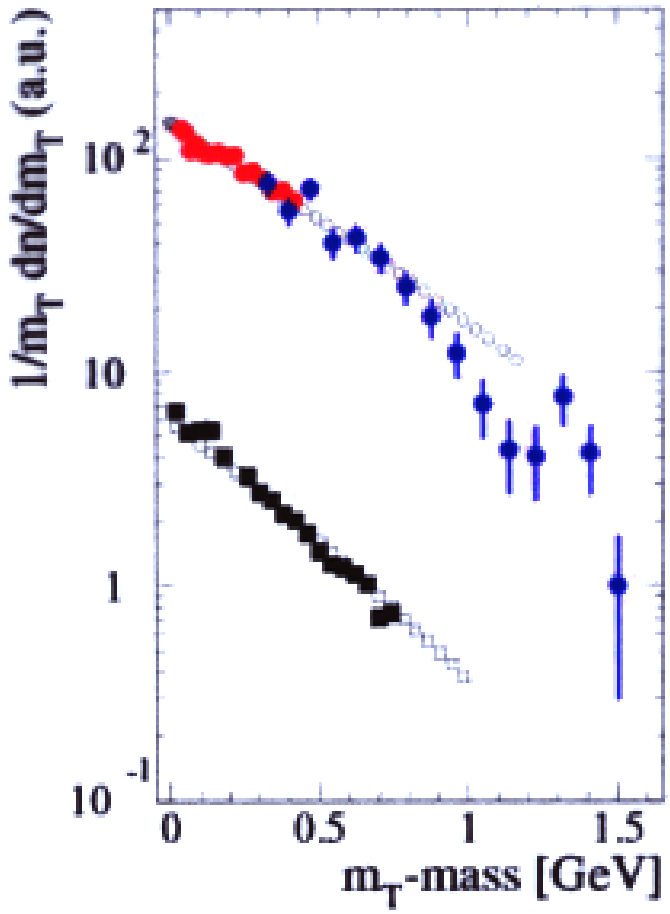
"spirit" of plot: $p_T = p_T^{thermal} + m\gamma_T v_T/c$

C. Redlich


Pb-Pb 158 A GeV/c
T_{ap}(GeV)
$T_{ap} \sim T_f + m\langle v_t \rangle^2$
0.4
0.3
0.2
0.1
0
1
2
3
m(GeV)
ϕ
p
Λ
Ξ
$\Omega+\bar{\Omega}$
J/ψ
K
π^+
NA49
NA44
NA50
WA97
+ WA98

Nu Xu

Comparison



● PHENIX, top 15% (J. Velkovska)

● STAR, top 6%

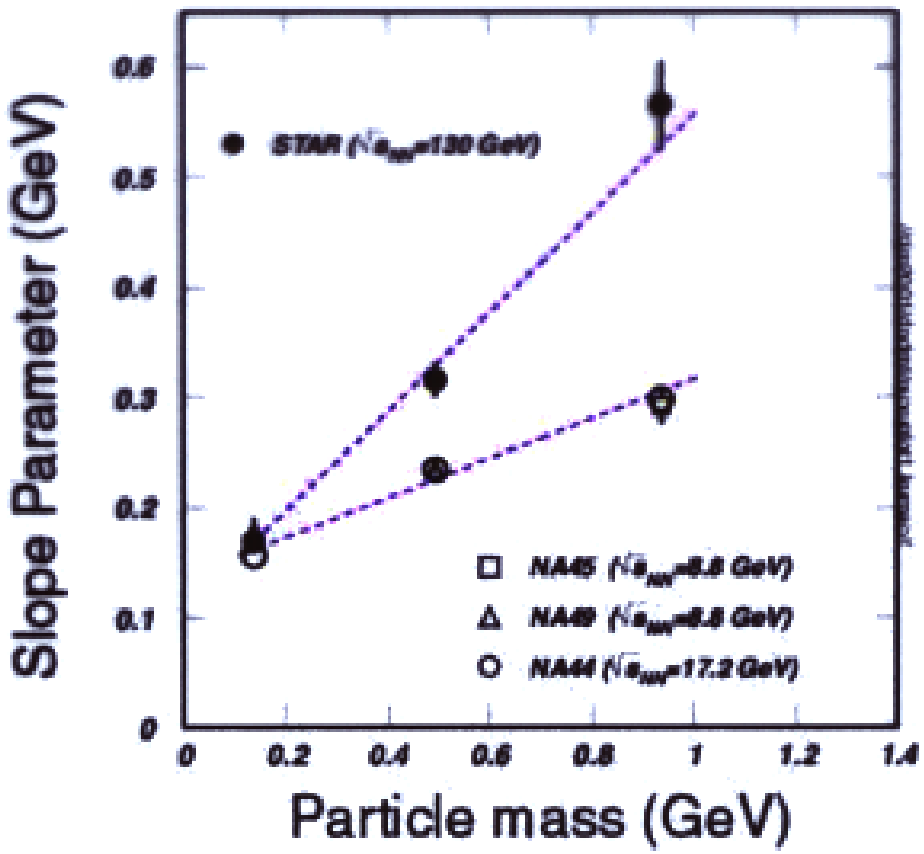
○ T= 100 MeV, <β>=0.6*c*

■ NA44 SPS Pb+Pb, top 4%

□ *T* = 110 MeV, < β>=0.45*c*

Nu Xu

SPS Comparison

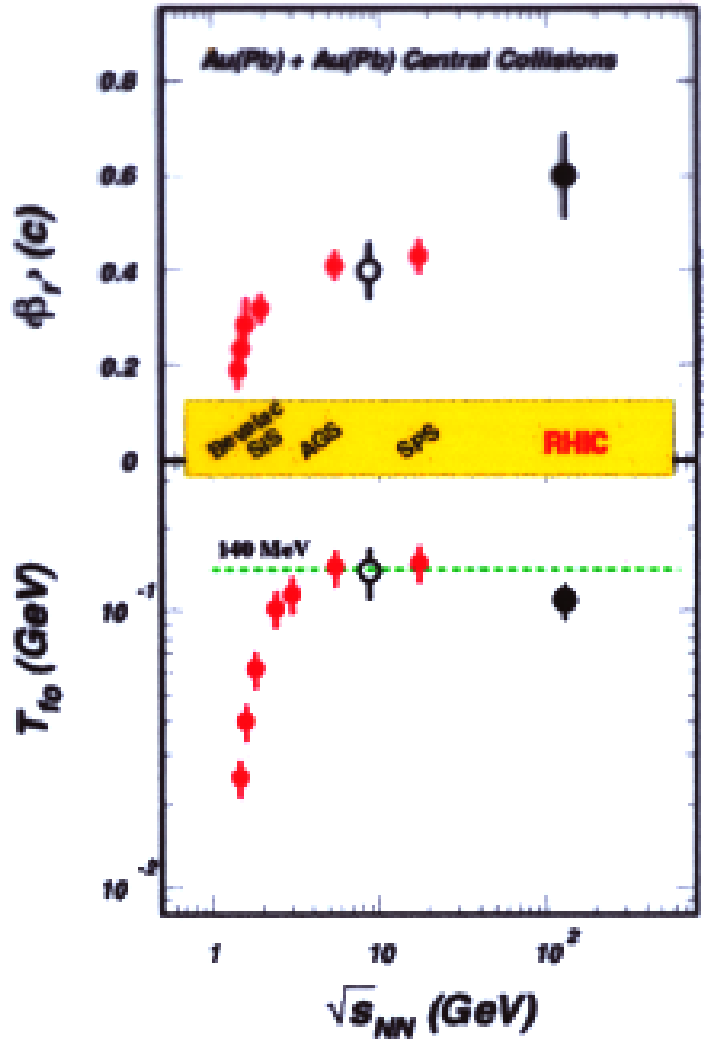


- Slope parameters of pion and kaon overlap at 40 and 158 AGeV central collisions
  - *similar strength of flow ?*
- Stronger mass dependence at RHIC than SPS
  - *stronger flow ?*
- *Slope parameter change with fitting region -> strong flow behavior!*
- NA50 J/ψ slope = 233 MeV! (P.Bordalo)

Phenix ($0.8 < p_t < 1.75$ GeV/c) / STAR ($0.2 < p_t < 1$ GeV/c)

Nu Xu

Kinetic Freeze-out Systematic



1) At RHIC, in central Au+Au collisions:

$\beta_r \cong 0.6$ c

$T_{fo} \cong 0.1$ GeV

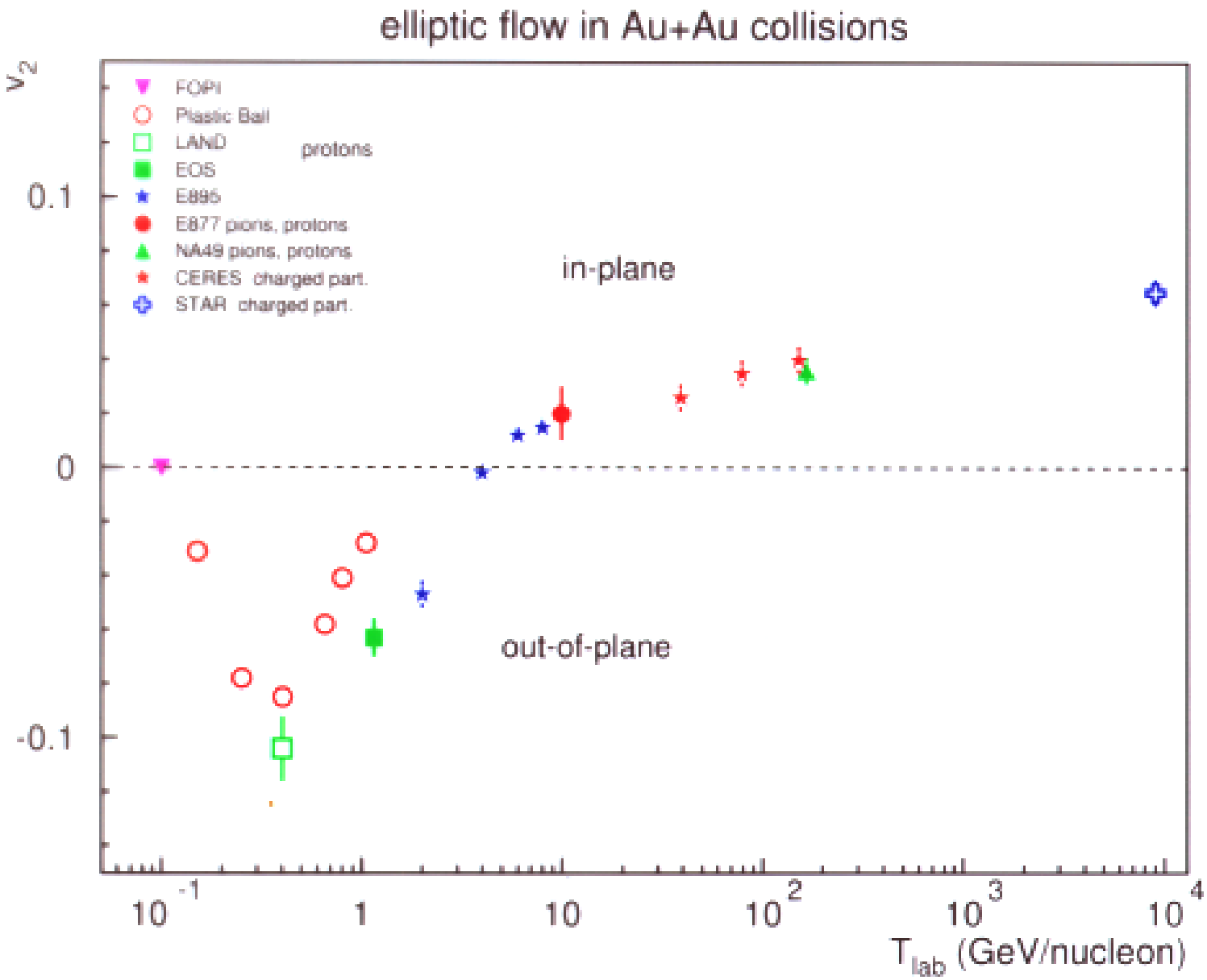
2) A jump(?) in the collective velocity parameter compared to results from lower energy collisions.

The large value of β_r at RHIC is consistent with the v_2 and the strong m_t-dependence of the π HBT measurements!

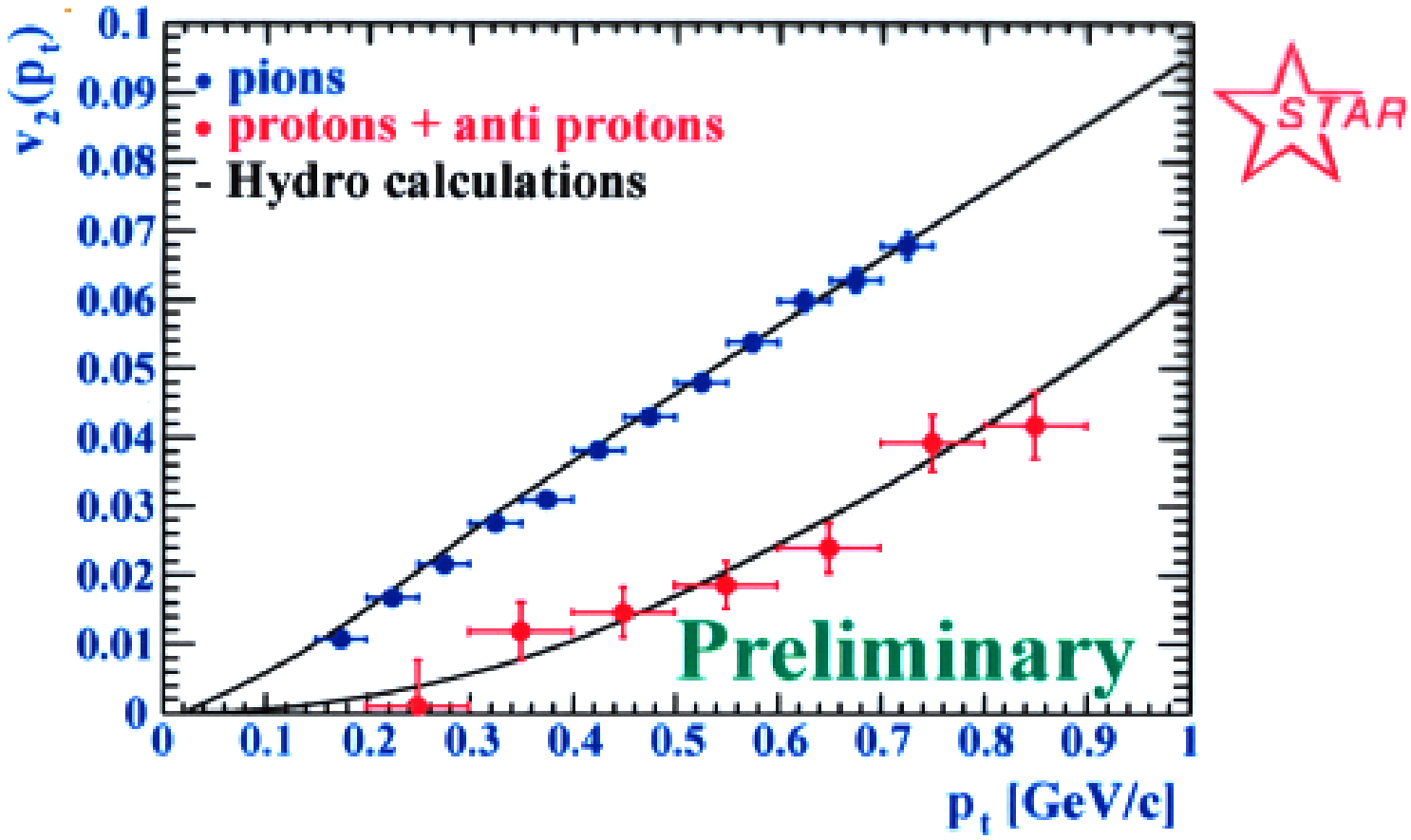
3) T_{fo} behavior in (1-10 GeV) predicted by Stocker et al. in 1981;

4) Energy scan need to check if this is a jump or smooth rise.

v_2 vs Beam Energy



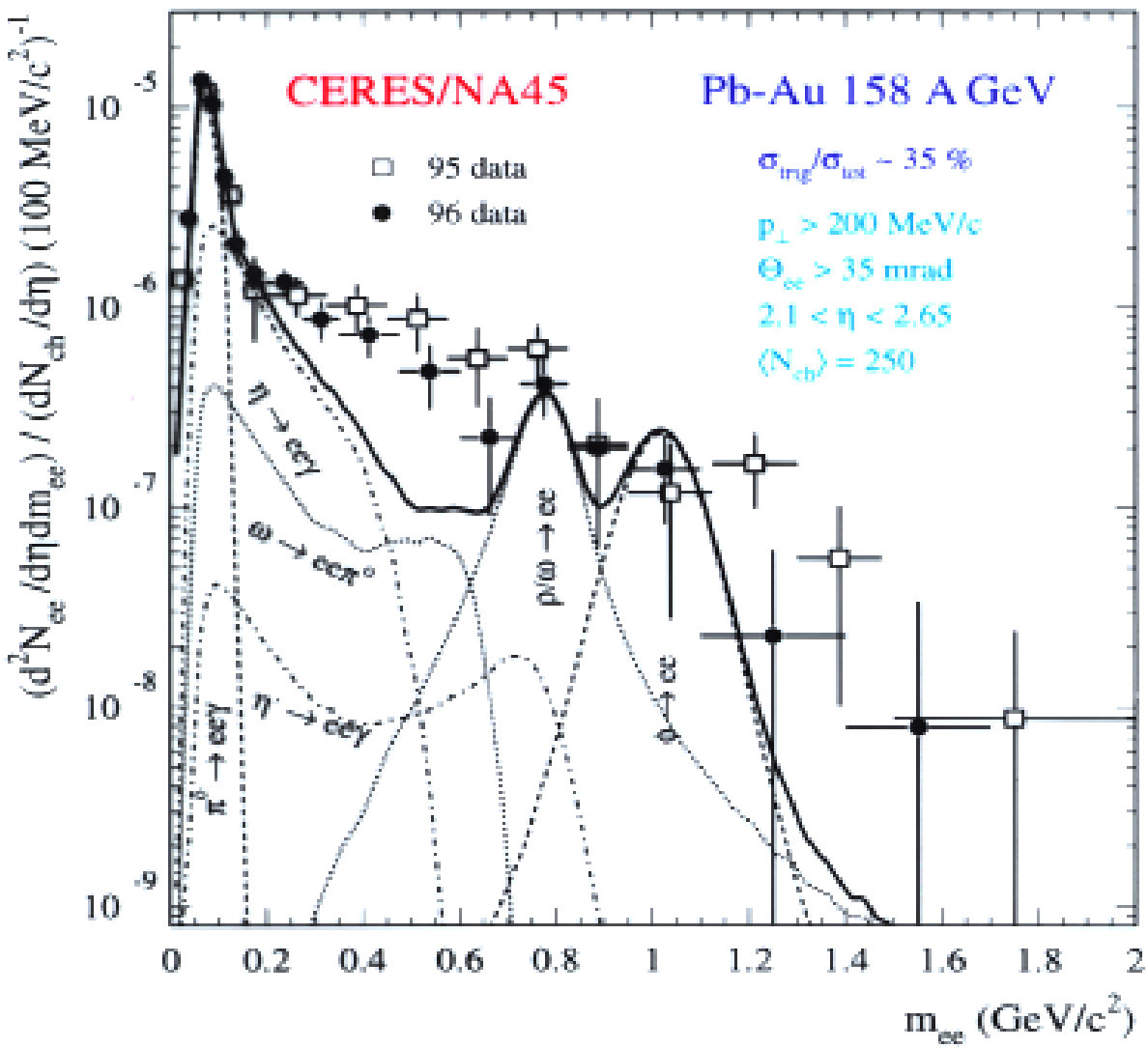
p_T dependence for π,p



- Hydro calculations: P. Huovinen, P. Kolb and U. Heinz

e^+e^- pair mass spectrum

B. Lenkeit et al., INPC Paris (98)

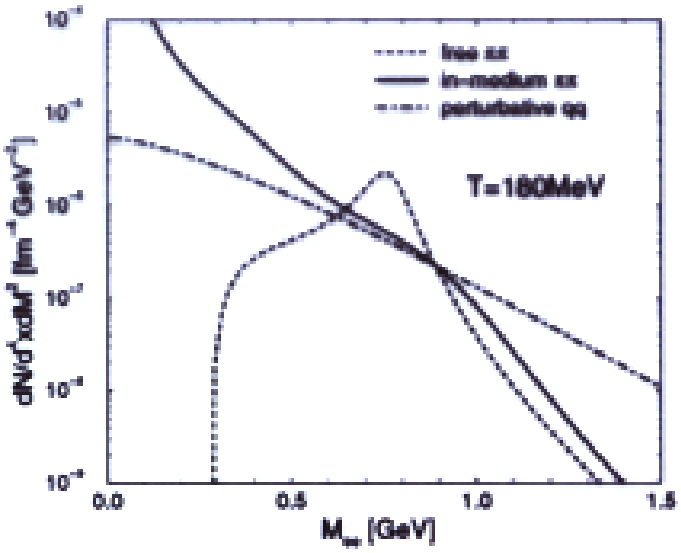


- particle ratios taken from a thermal model fitted to measured ratios in Pb-Pb ($\boldsymbol{T = 175 MeV, \mu_B = 270 MeV}$)
- rapidity and pt distributions following measured systematics in Pb-Pb
- enhancement ($0.25 < m_{ee} < 0.7$ GeV/c^2) :
  $2.6 \pm 0.5(stat.) \pm 0.6(syst.)$ (96' data set)
  $3.9 \pm 0.9(stat.) \pm 0.9(syst.)$ (95' data set)

Rapp and Wambach; hep-ph/9909229

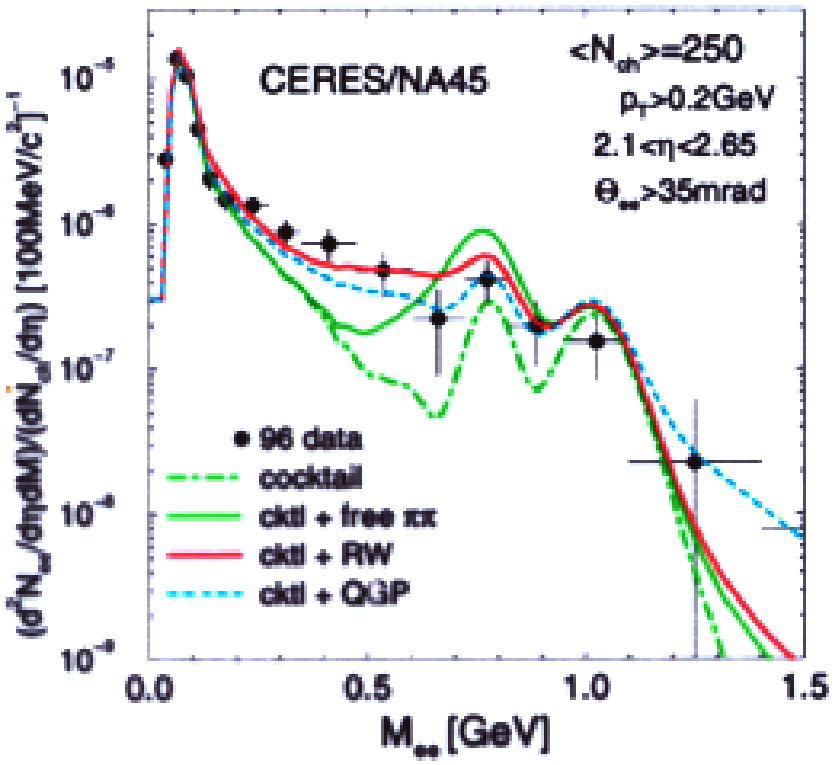
Quark-Hadron Duality ?

hadronic rates vrs. plasma rates



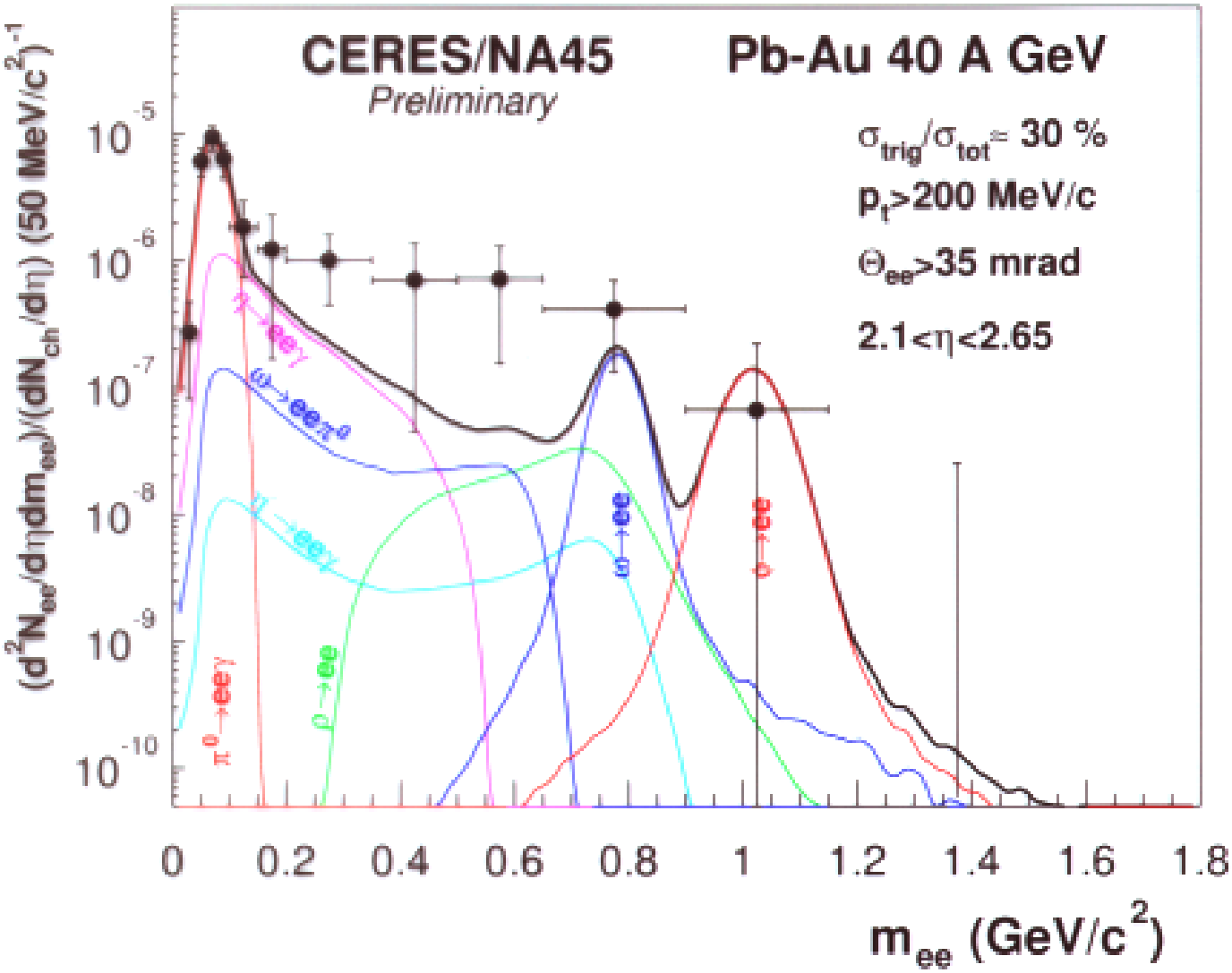
'soft dileptons' from the plasma ?

30% Central Pb(158GeV/u)+Au



S. Damjanović • K. Filimonov

Invariant Mass Spectrum



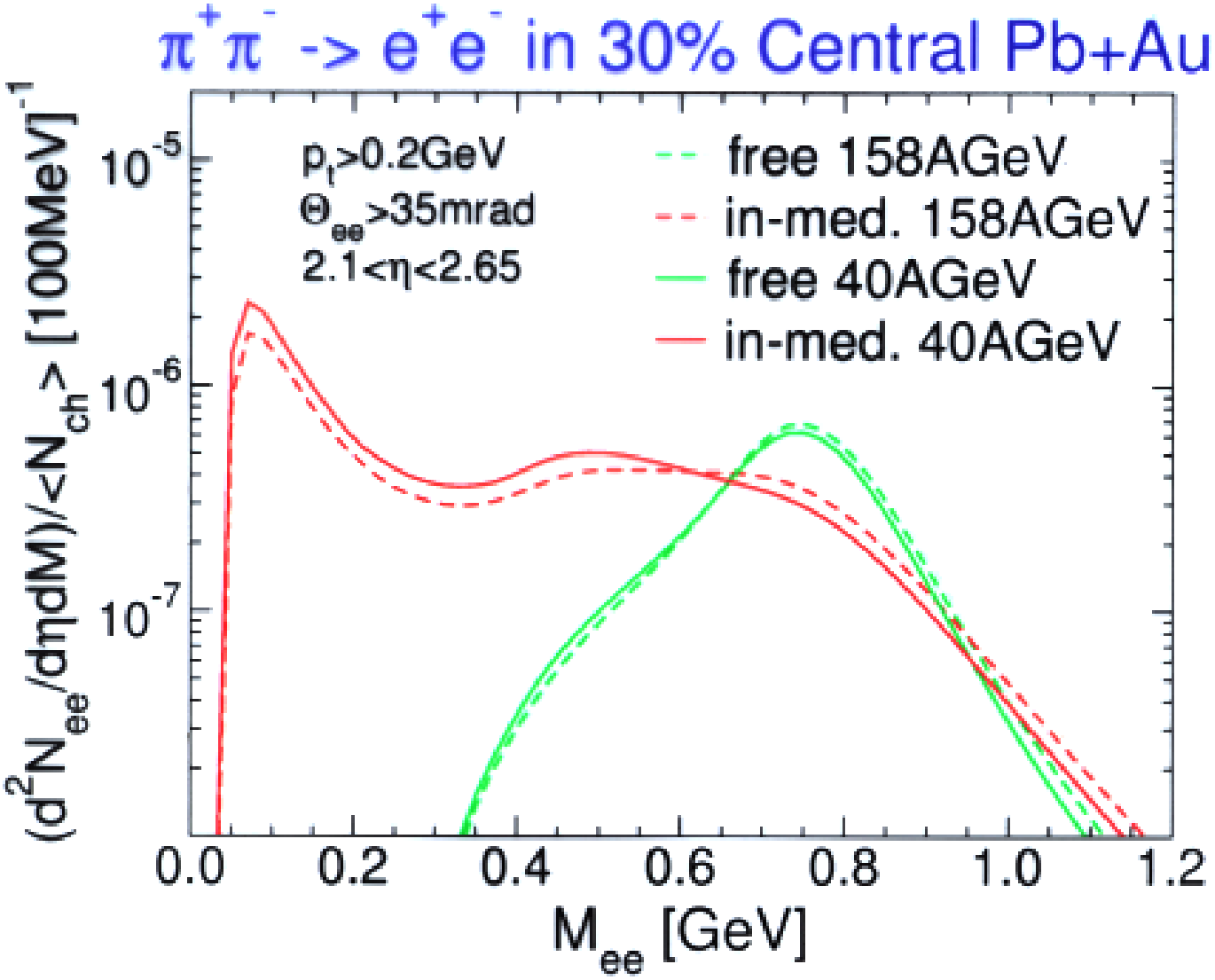
Total number of pairs for m > 0.2 GeV/c ^{2}

S=159 +- 46

Ratio Signal/Background

S/B=1/6

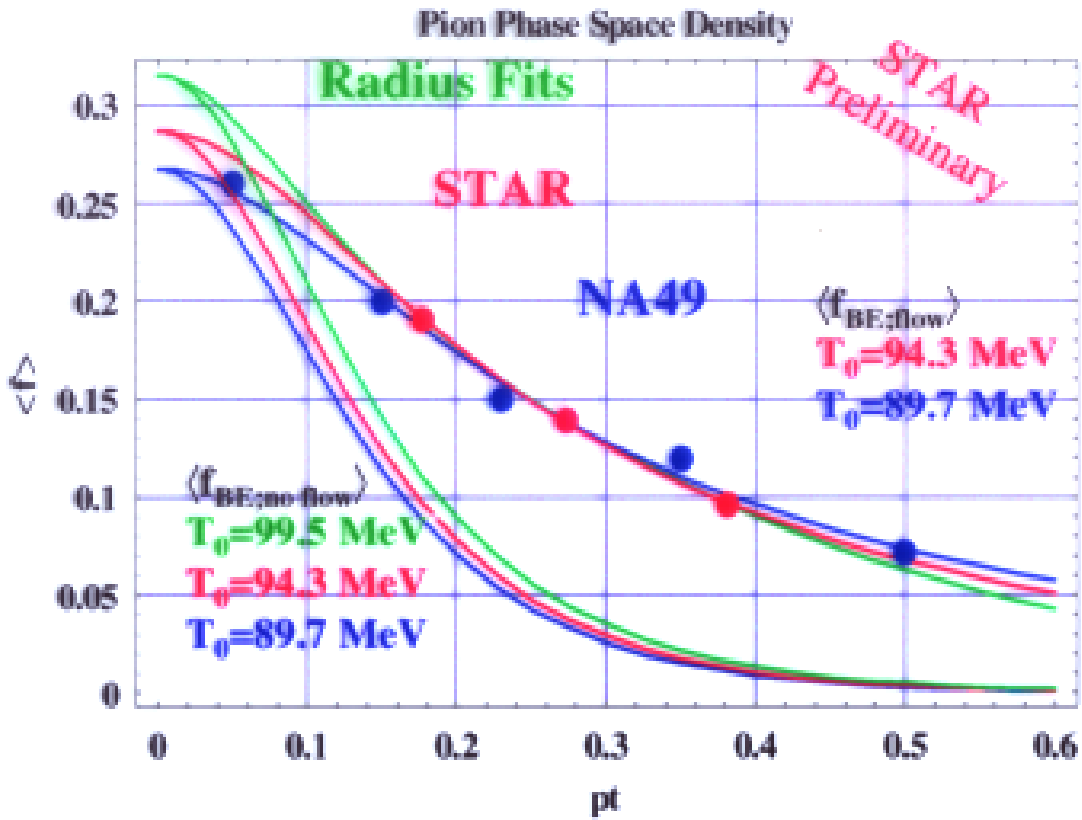
R. Rapp


$\pi^+\pi^- \to e^+e^-$ in 30% Central Pb+Au
p_t>0.2GeV
Θ_{ee}>35mrad
2.1<η<2.65
free 158AGeV
in-med. 158AGeV
free 40AGeV
in-med. 40AGeV
$(d^2N_{ee}/d\eta dM)/\langle N_{ch}\rangle$ [100MeV]$^{-1}$
10^{-5}
10^{-6}
10^{-7}
0.0
0.2
0.4
0.6
0.8
1.0
1.2
M_{ee} [GeV]

Pion Phasespace Density

pion occupation of cell in coordinate⊗momentum space:

$$\langle f \rangle(m_T) = \frac{(\hbar c)^3}{2\,E_\pi\,m_T}\,\frac{d^2N}{dy\,dm_T}\,\frac{(\lambda\,\pi)^{1/2}}{R_O\,R_S\,R_L}$$



- "Universal" phasespace density observed at SPS appears to hold at RHIC as well
- Better description by inclusion of radial flow
- Fundamental phasespace saturation may relate increases in geometry, temperature, multiplicity

Sergey Panitkin

C. Lourenco

What are we missing ?

NA49

- A detailed centrality dependence of the Pb-Pb data
- A careful comparison of the existing 40, 80 and 158 GeV data
- A solid baseline reference from hadron production in h-A collisions

NA57

- A robust p-A (and light ion) reference line
- A scan of the energy density region between p-Pb and Pb-Pb

CERES

- Improved resolution, statistics and signal to background
- A study of the excess as a function of the energy density

NA50

- Accurate low E_T Pb-Pb data to compare with the normal absorption curve
- High precision p-A data for the J/ψ and ψ' suppression patterns