Resonance Production

Recent Results

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Motivation

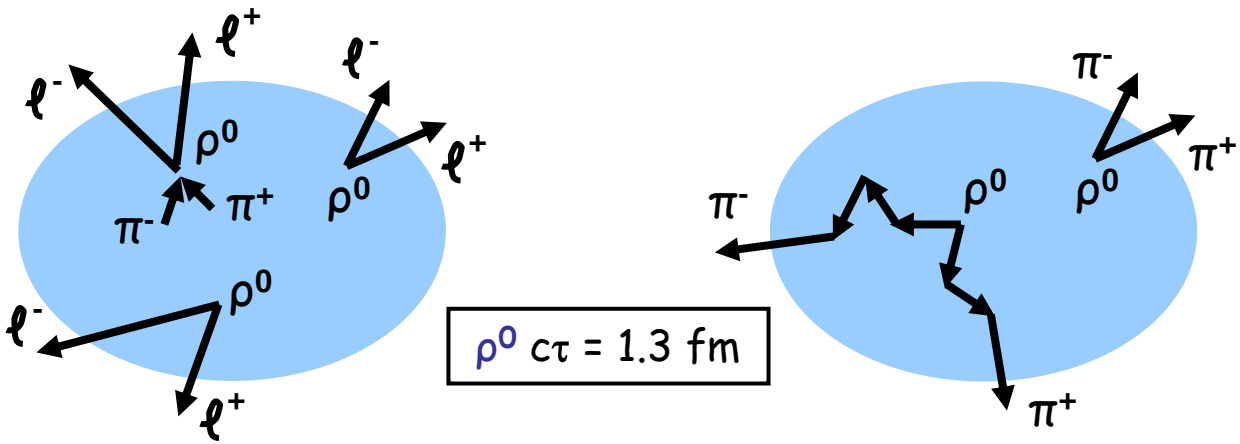
Measurements

Results

Summary

Motivation - I

- In-medium modification of mass and/or width ⇒ Chiral Symmetry Restoration, Collision Broadening or Phase Space?

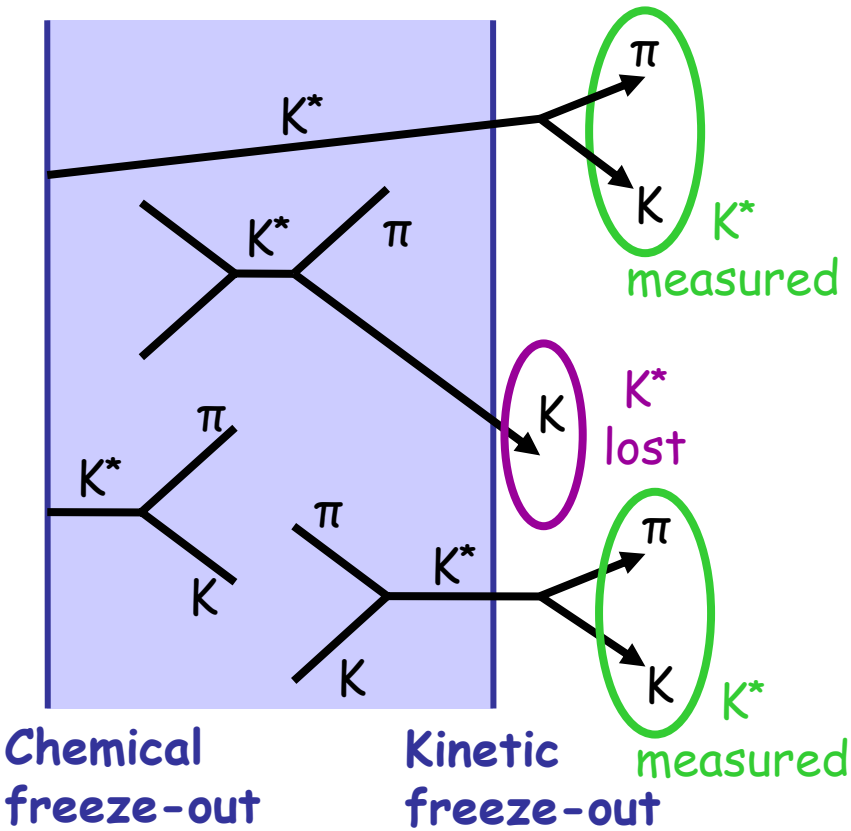


- $\rho^0(770)$ ⇒ Leptonic decay channel ⇒ probes all stages of the collision. Hadronic decay channel ⇒ probes only late stages of the collision
- Φ ⇒ Information from early time ?

Φ cτ = 44 fm

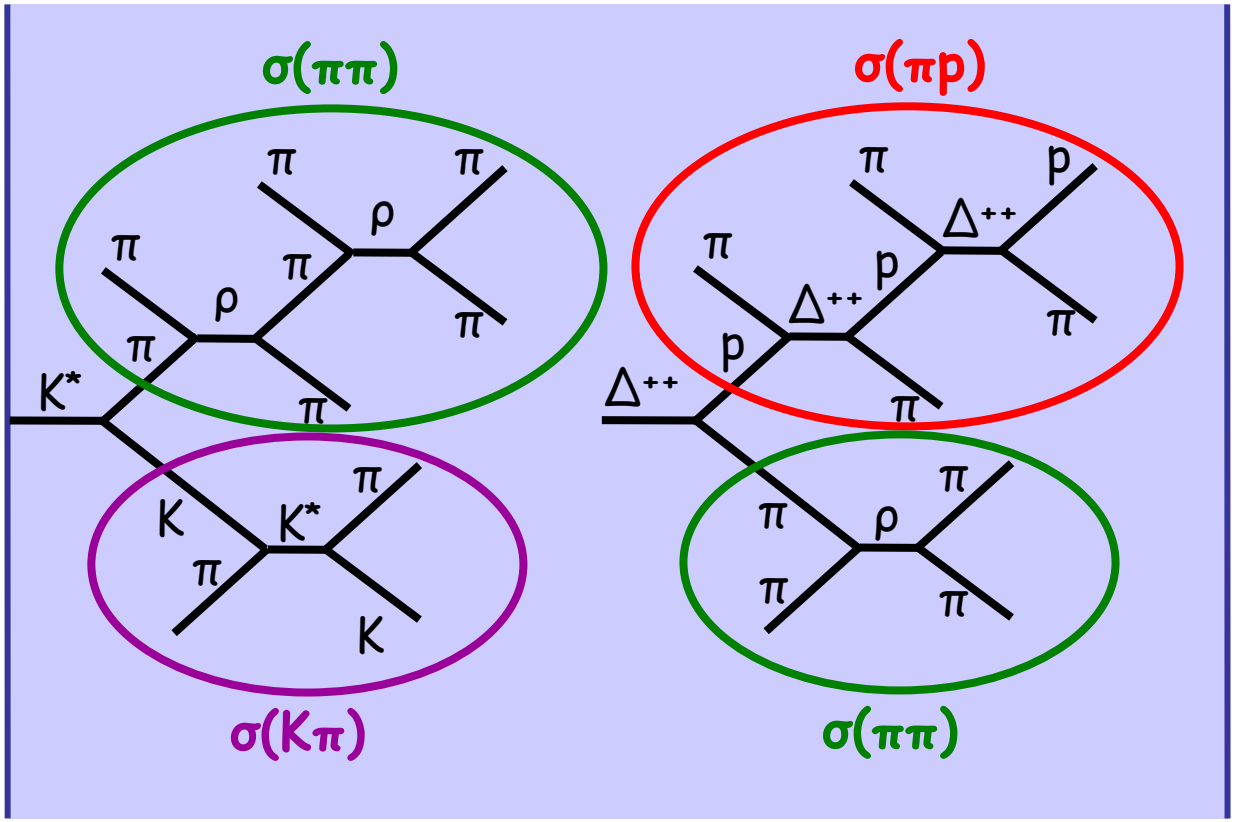
- $K^{*0}(892)$ ⇒ Regeneration and daughter rescattering ⇒ time scale ?

Motivation - II



- If resonance decays before kinetic freeze-out ⇒ not reconstructed due to rescattering of daughters
- K^{*0} ($c\tau$ = 4 fm) survival probability ⇒ time between chemical and kinetic freeze-out, source size and p_T of K^{*0}
- Chemical freeze-out ⇒ elastic interactions $\pi K \rightarrow K^{*0} \rightarrow \pi K$ regenerate $K^{*0}(892)$ until kinetic freeze-out
- K^{*0}/K may reveal time between chemical and kinetic freeze-out
- Λ^*/Λ, Δ^{++}/p, ρ^0/π, f_0/π ?

Motivation - III



Chemical freeze-out

Kinetic freeze-out

- K^{*0} regeneration ⇒ σ(Kπ)
- K^{*0} daughter rescattering ⇒ σ(ππ)
- σ(ππ) >>>> σ(Kπ)
- σ(pπ) > σ(ππ)
- Hadronic cross-sections ⇒ Change yields of K^*, Λ^*, Δ^{++}, ρ^0, f_0

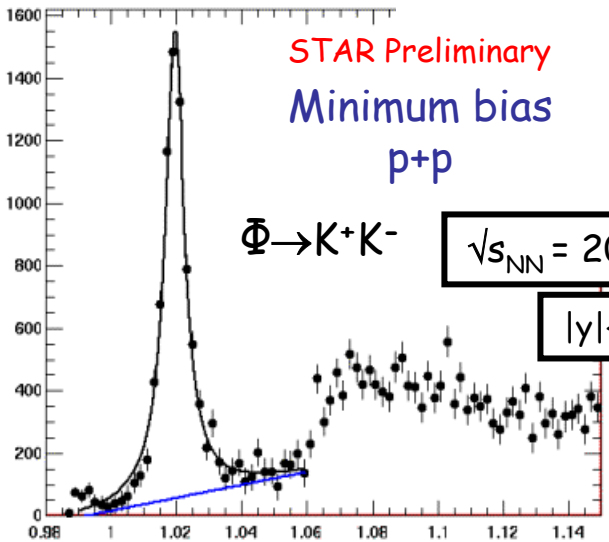
⇒ Probe dynamics between chemical and kinetic freeze-out

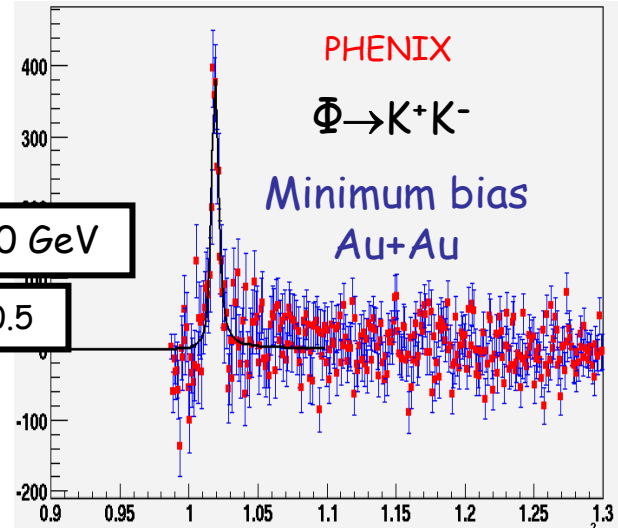
Resonance Production – Hadronic Channel

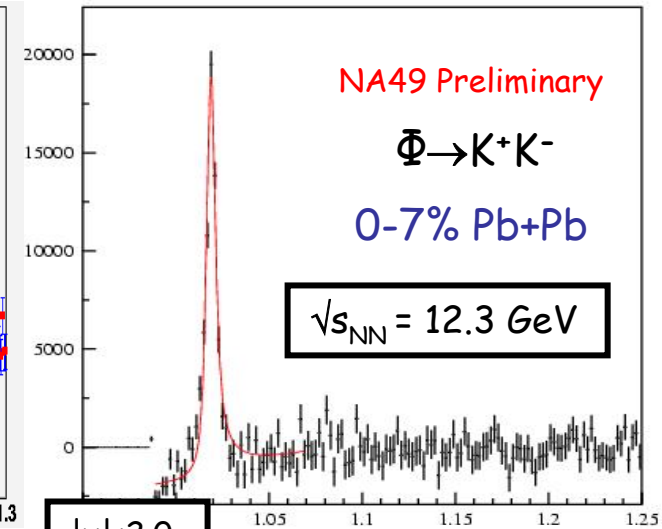
$\rho^0(770) \rightarrow \pi^+ \pi^-$	B.R. ~1	$c\tau$ = 1.3 fm
$\Delta^{++}(1232) \rightarrow p\ \pi^+$	B.R. ~1	$c\tau$ = 1.6 fm
$f_0(980) \rightarrow \pi^+ \pi^-$	B.R. 2/3	$c\tau$ = 2.6 fm
$K^{*0\pm}(892) \rightarrow \pi\ K$	B.R. 2/3	$c\tau$ = 4 fm
$\Sigma(1385) \rightarrow \Lambda\ \pi$	B.R. 0.88	$c\tau$ = 5.5 fm
$\Lambda(1520) \rightarrow p\ K$	B.R. 0.45	$c\tau$ = 12.6 fm
$\Phi(1020) \rightarrow K^+ K^-$	B.R. 0.49	$c\tau$ = 44 fm

Life Time

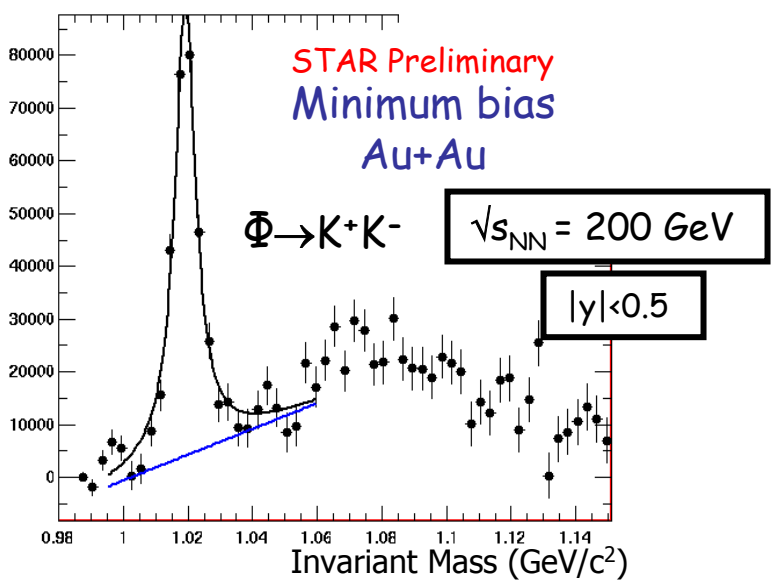
Raw Invariant Mass Distribution from Data -I

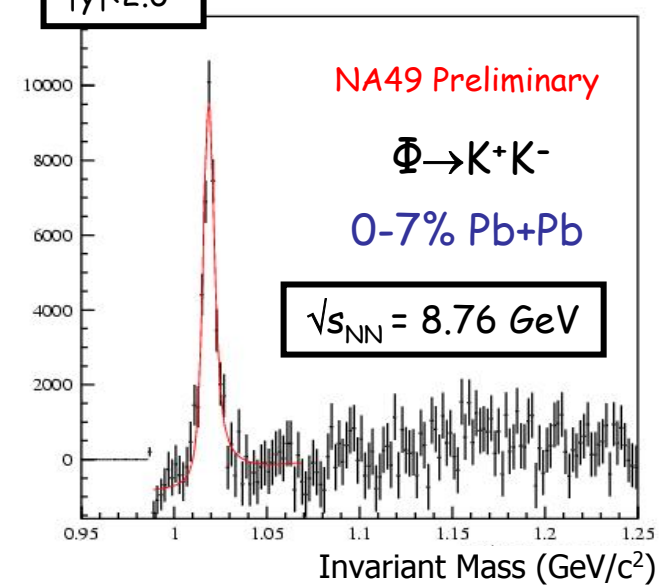




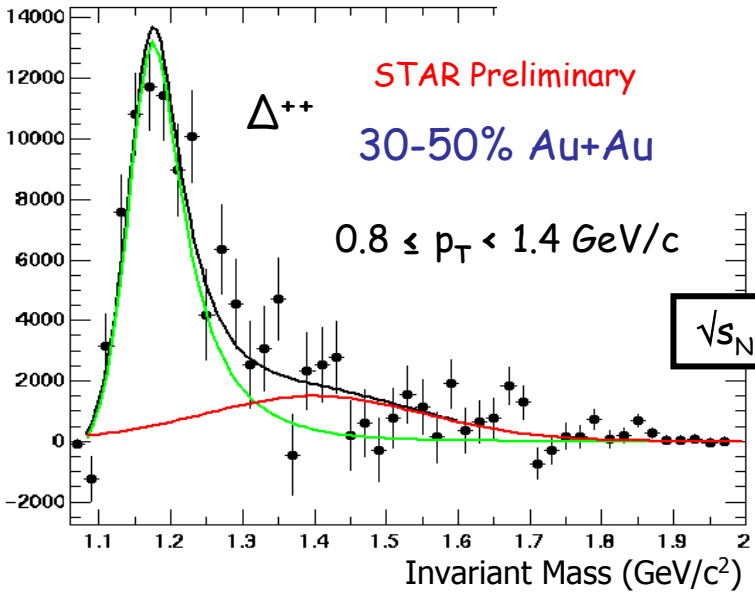


Statistical error only





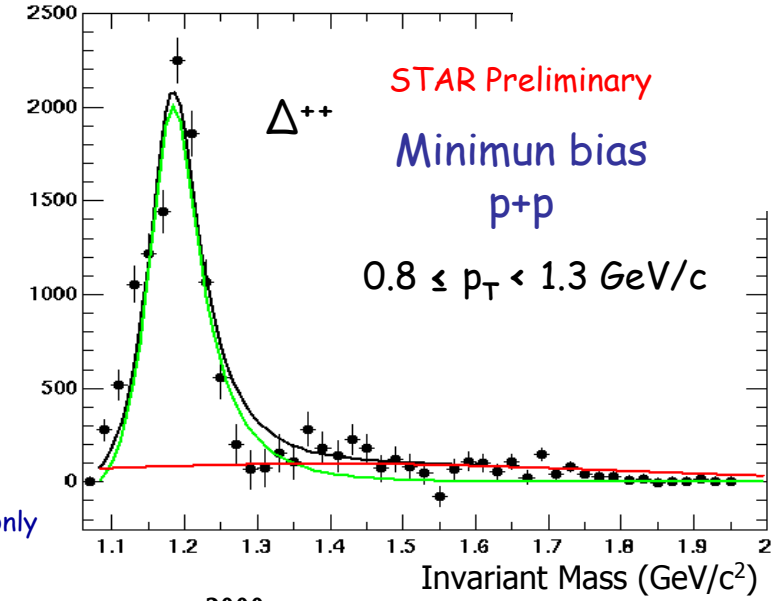
Raw Invariant Mass Distribution from Data -II

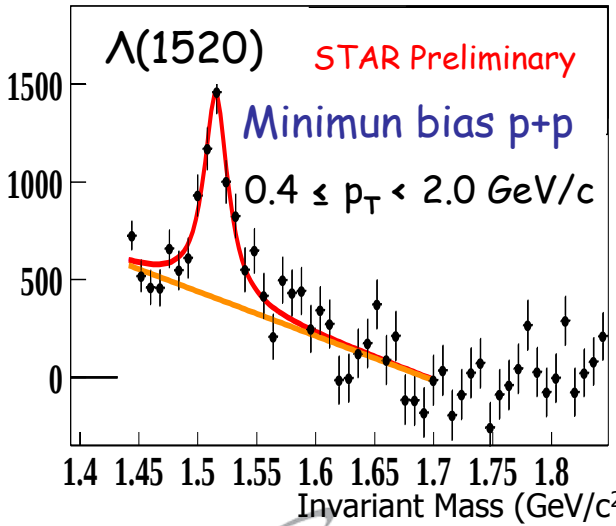


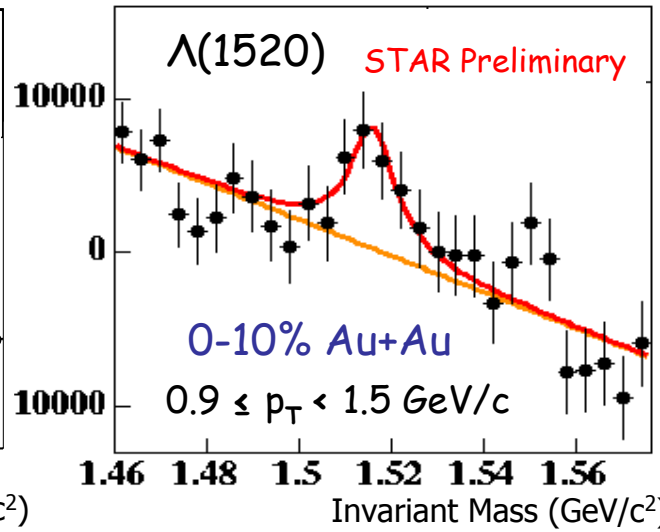
$\sqrt{s_{NN}}$ = 200 GeV

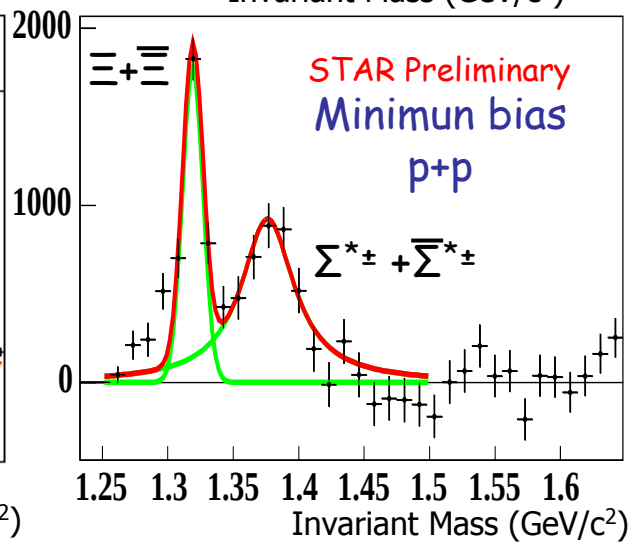
|y|<0.5

Statistical error only

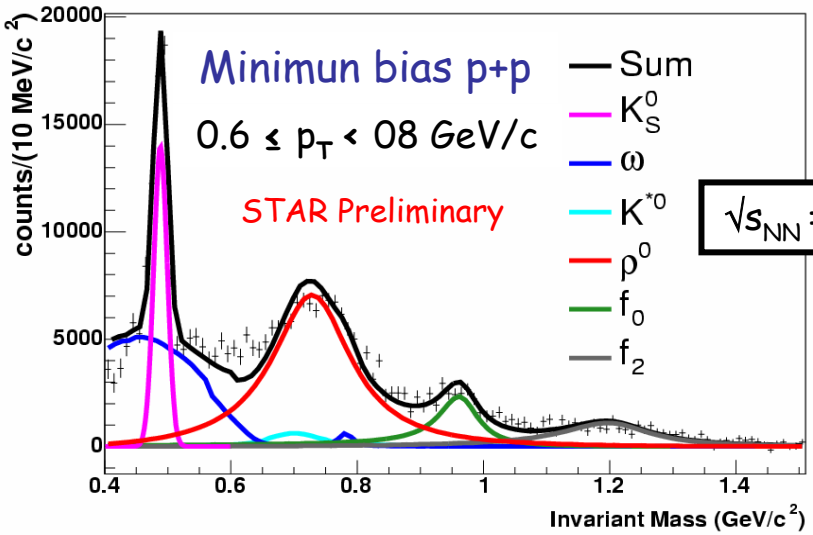








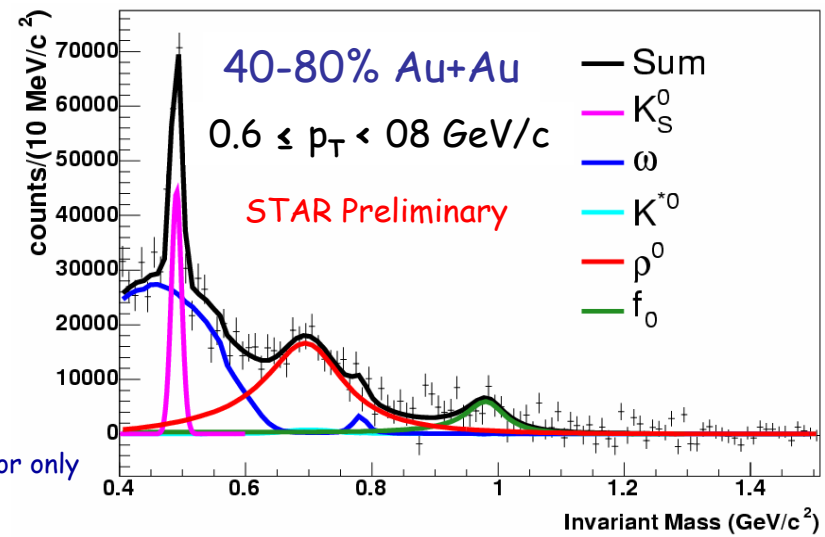
Raw Invariant Mass Distribution from Data -III

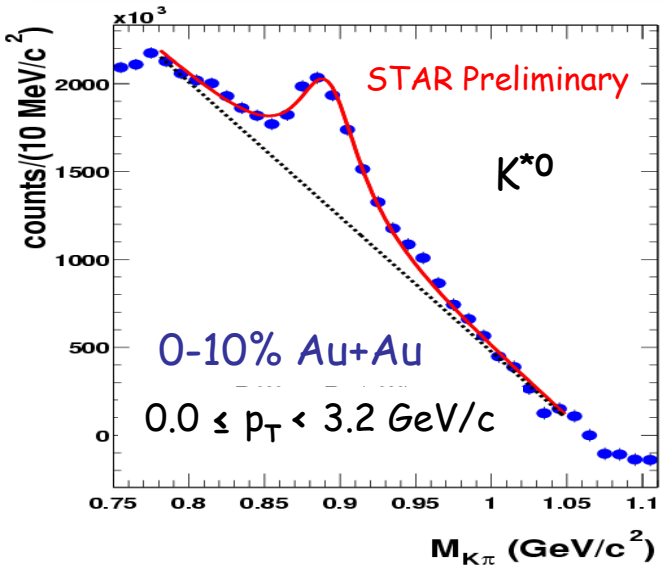


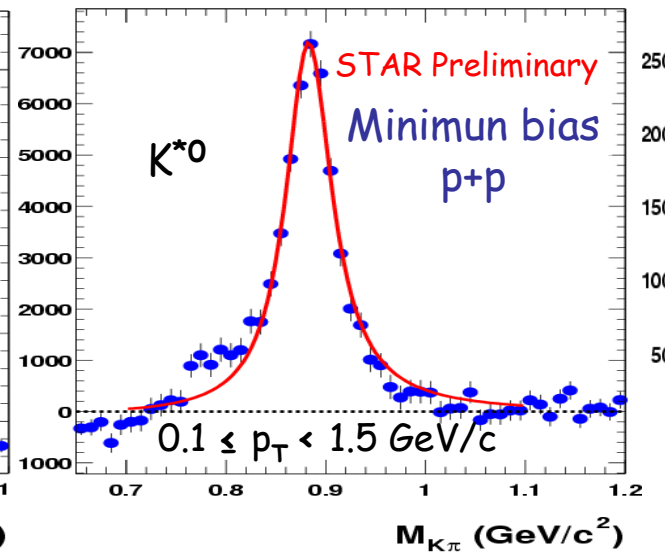
$\sqrt{s_{NN}}$ = 200 GeV

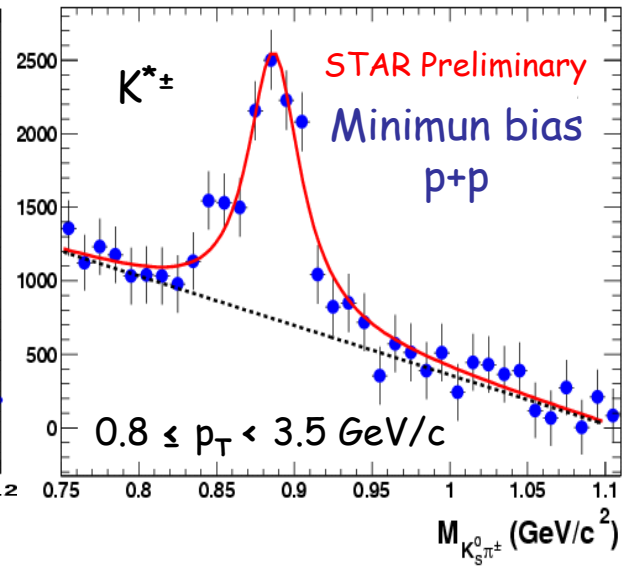
|y|<0.5

Statistical error only



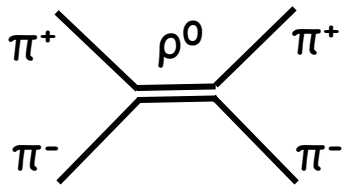






Phase Space

$$\text{Phase Space} = \frac{M}{\sqrt{M^2 + p_T^2}}\, e^{\frac{-\sqrt{M^2 + p_T^2}}{T}}$$



- M = Invariant Mass; p_T = transverse momentum; T = Temperature
- pp ⇒ particle composition reasonably reproduced by statistical model ⇒ T = 160 MeV

  F. Becattini, Nucl. Phys. *A* **702**, 336 (2002); Z. Phys. *C* **69**, 485 (1996); F. Becattini and U. Heinz, Z. Phys. *C* **76**, 269 (1997)
- Au+Au ⇒ between chemical and kinetic freeze-out ⇒ resonances formed until particles too far apart ⇒ resonances emitted
  T = 120 MeV

  E.V. Shuryak and G.E. Brown, Nucl. Phys. *A* 717 (2003) 322

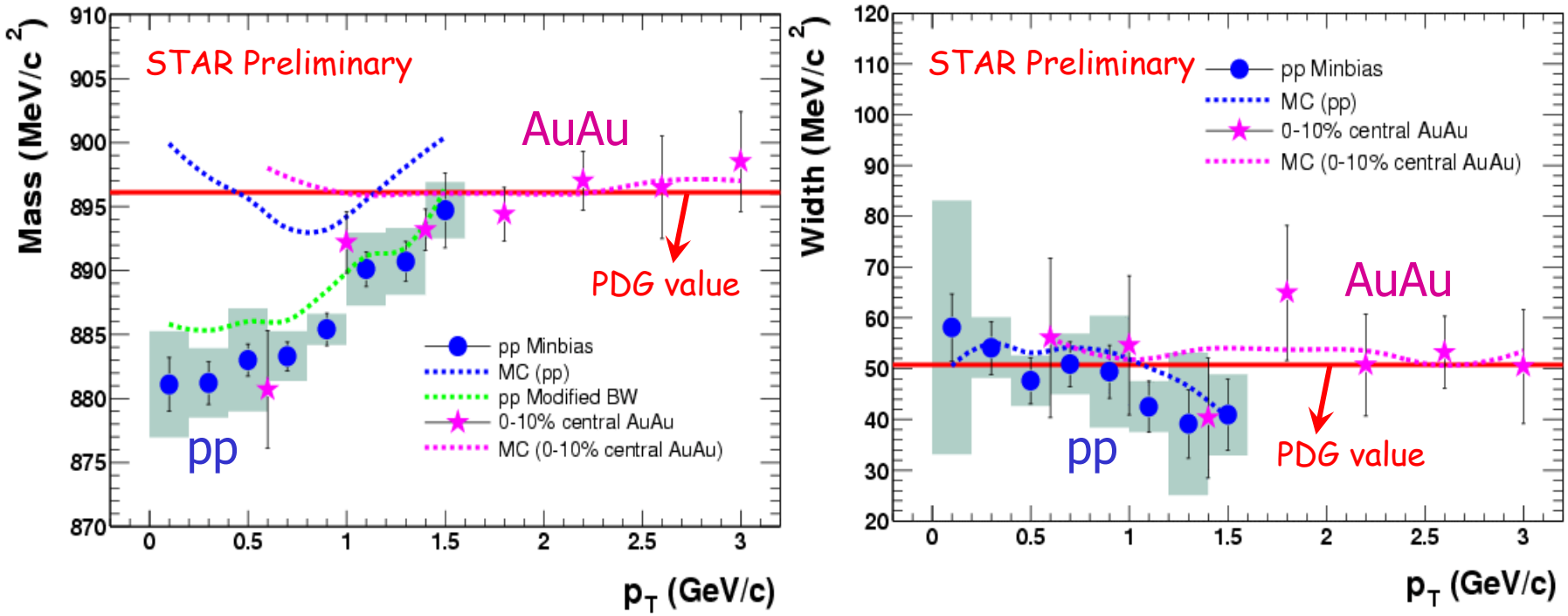
$$BW(M) = \frac{\Gamma(M)}{(M^2 - M_\rho^2)^2 + M_\rho^2\,\Gamma(M)^2} \qquad \Gamma(M) = \Gamma_\rho \left[\frac{M^2 - 4m_\pi^2}{M_\rho^2 - 4m_\pi^2}\right]^{\frac{3}{2}} \frac{M_\rho}{M}$$

P. Braun-Munzinger *et.al.*, CERES Int. Note, March 2000, unpublished; E.V. Shuryak and G.E. Brown, Nucl. Phys. *A* 717 (2003) 322; P.K. Kolb and M. Prakash, nucl-th/0301007; H.W. Barz *et al.*, Phys. Lett. B 265, 219 (1991); R. Rapp, hep-ph/0305011.

K^{*0} Mass and Width

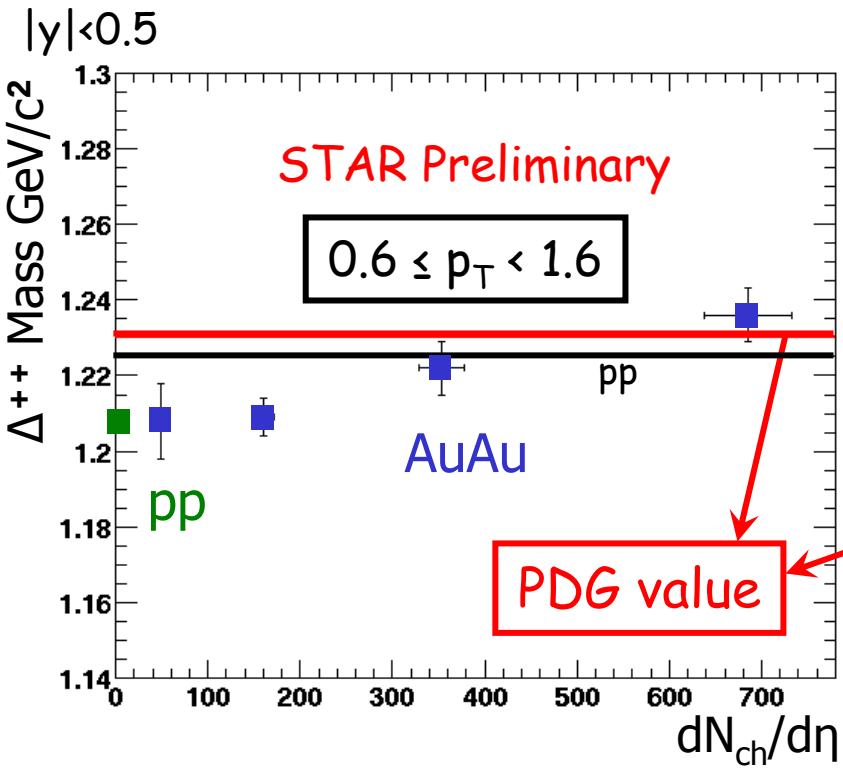
$|y|<0.5$

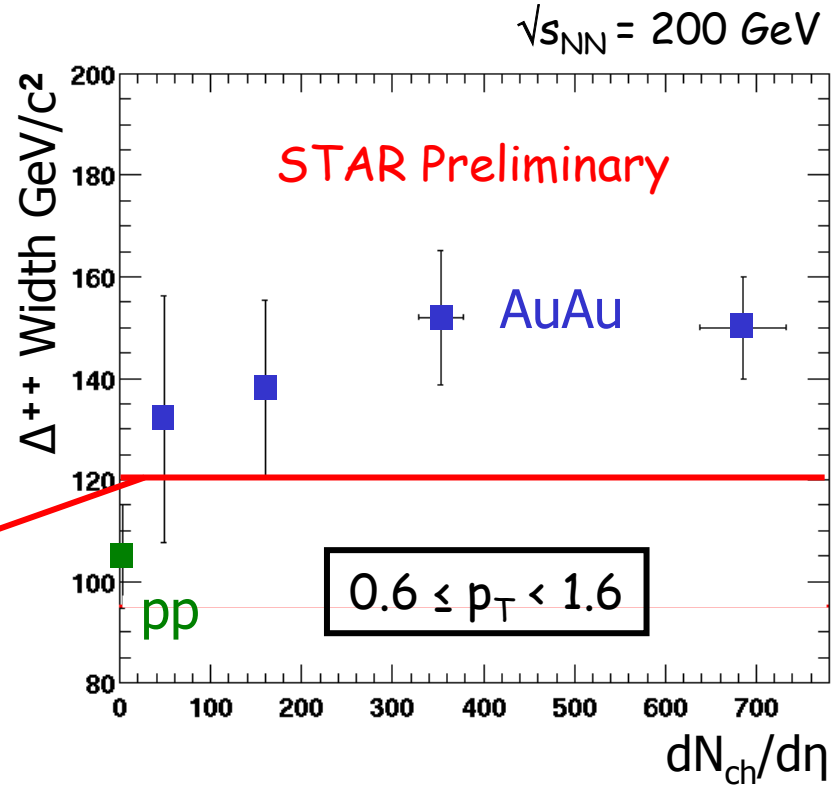
$\sqrt{s_{NN}} = 200$ GeV



- K^{*0} mass ⇒ shifted in p+p and Au+Au at low p_T
- K^{*0} width ⇒ agrees with the MC (GEANT) calculation
- Systematic and statistical error added in quadrature

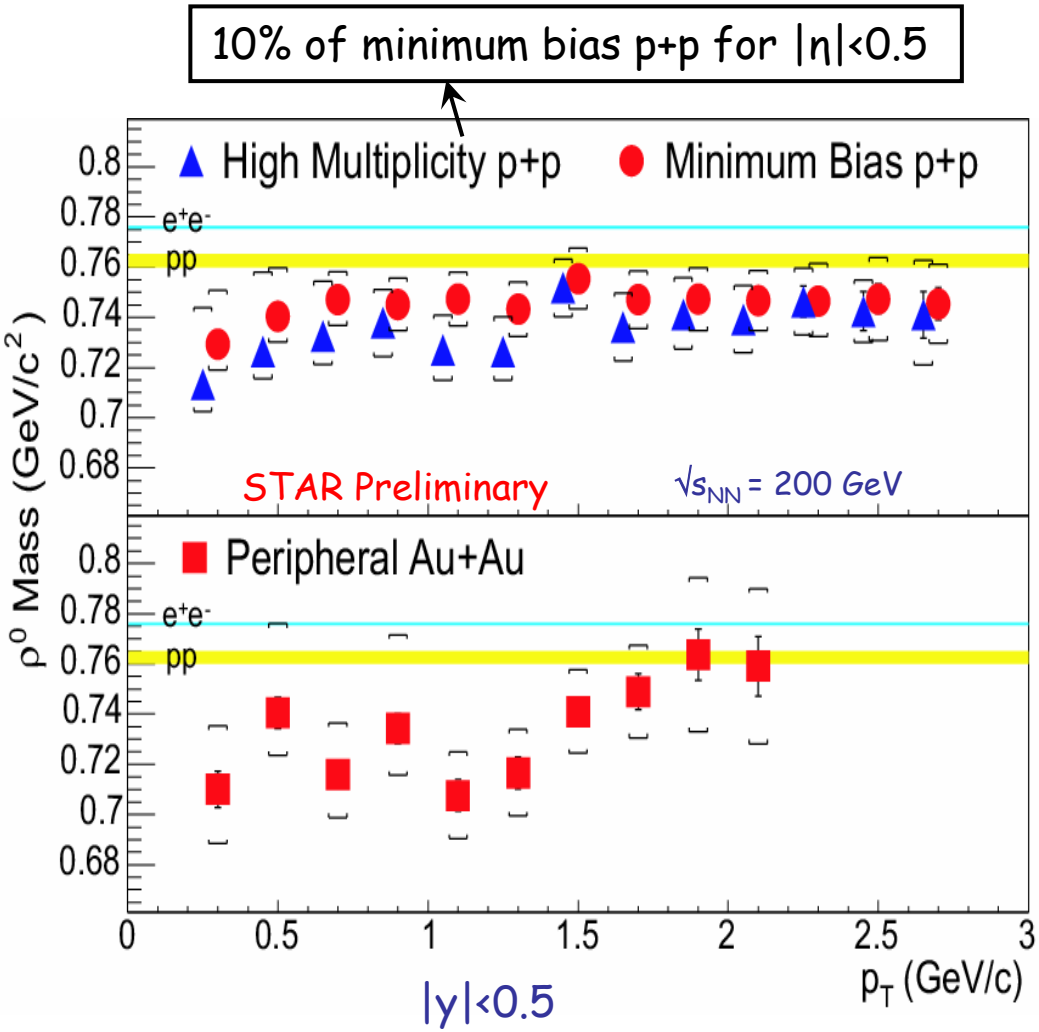
Δ^{++} Mass and Width





- p+p at $\sqrt{s}$ = 27.5 GeV $\Rightarrow$ $M_{\Delta^{++}}$ = 1225 ± 2 MeV/c^2
- Δ^{++} mass $\Rightarrow$ lower in p+p and Au+Au at low N_{ch}
- Δ^{++} mass $\Rightarrow$ increases with increasing N_{ch}
- Statistical errors only

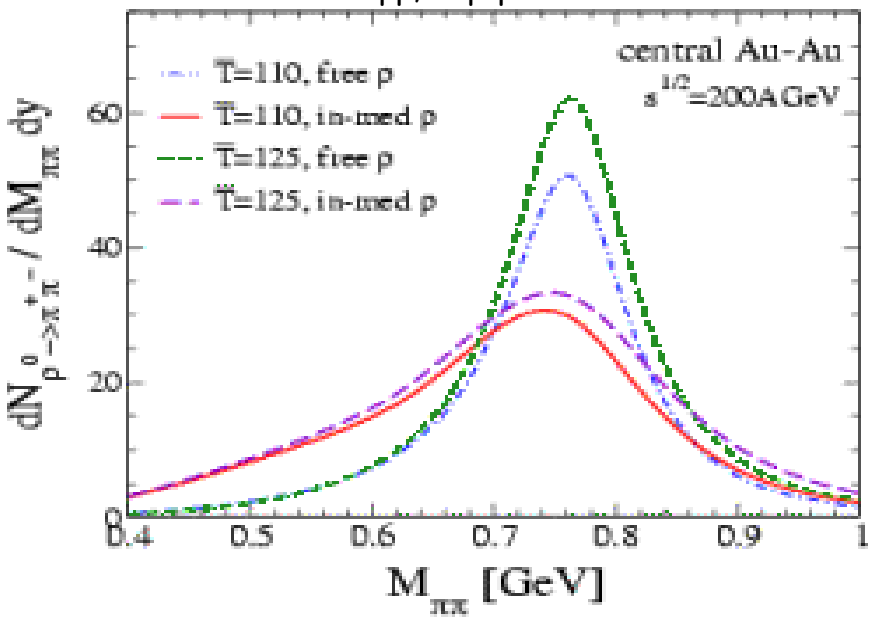
ρ^0 Mass



- p+p at $\sqrt{s}$ = 27.5 GeV ⇒ M_ρ = 762.6 ± 2.6 MeV/c^2
- PDG average hadroproduced ρ^0 ⇒ M_ρ = 769.0 ± 0.9 MeV/c^2
- PDG average e^+e^- ρ ⇒ M_ρ = 775.9 ± 0.5 MeV/c^2
- ρ^0 mass p_t dependent and lower than previous p+p measurement in both p+p and peripheral Au+Au collisions
- ρ^0 mass high multiplicity p+p lower than minimum bias p+p ⇒ multiplicity dependent
- Systematic errors ⇒ common and correlated between p+p and peripheral Au+Au
- ρ^0 width ⇒ no sensitivity for systematic study

Possible Explanations for Mass Shift - I

R. Rapp, hep-ph/0305011



- **1. Dynamical effect** ⇒ ρ^0 interactions at late stages of the collision
  - nucleons, hyperons and baryon resonances
  - pions, kaons and ρ^0-mesons
  - t-channel exchanges

⇒ Distortion of the ρ^0 spectral shape ⇒ mass shift and/or broadening

E.V. Shuryak and G.E. Brown, Nucl. Phys. A 717 (2003) 322

Name/Mass	*Width*	*Branching*	Mass Shift
$a_1(1260)$	400	0.6	-19
$a_2(1320)$	104	0.7	-15
$K_1(1270)$	90	0.4	+1.6
$K_2(1430)$	100	0.087	-0.4
$N^*(1520)$	370	0.2	10

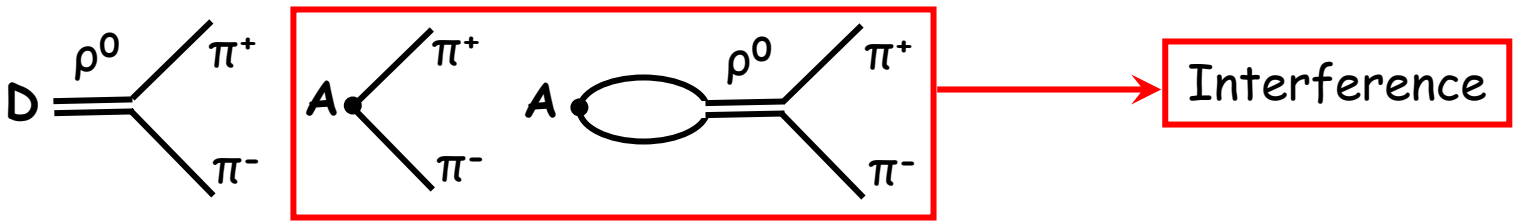
-23 MeV/c^2 shift in the ρ^0 mass

-38 MeV/c^2 shift in the ρ^0 mass due to t-channel attraction

Δ^{++} ⇒ different from ρ^0 ⇒ mass should increase! (prediction)

Possible Explanations for Mass Shift - II

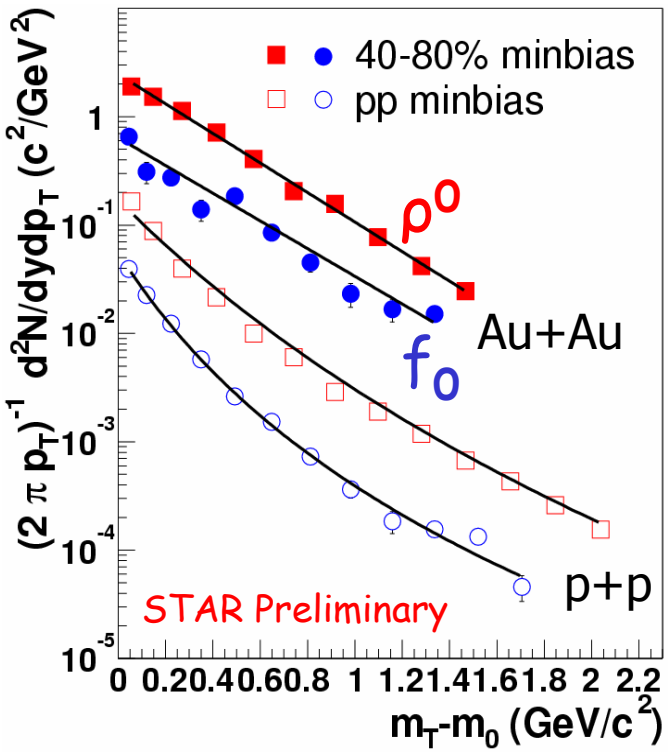
- 2. Interference between various $\pi^+\pi^-$ scattering channels can effectively distort the line shape of resonances
  R. Longacre, nucl-exp/0305015



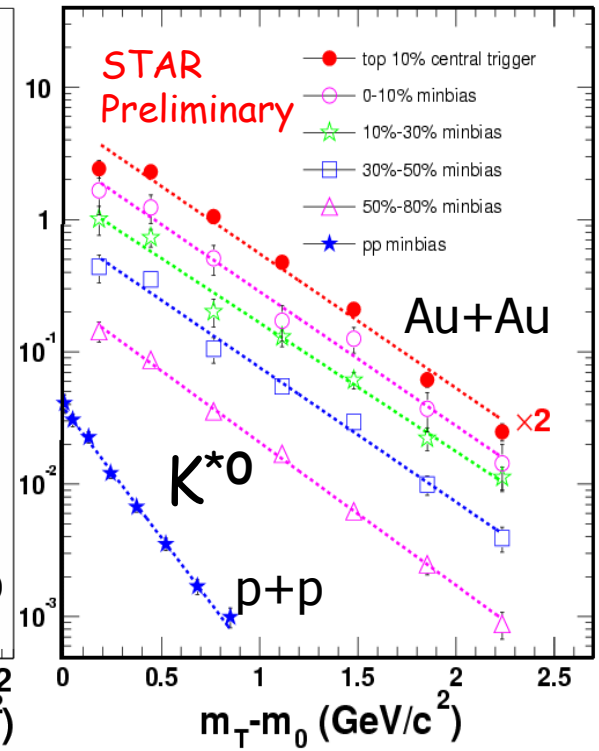
- 3. Bose-Einstein correlations between ρ^0 decay daughters and pions in the surrounding matter can also distort the resonance shape
  G.D. Lafferty, Z. Phys. C 60, 659 (1993); R. Rapp, hep-ph/0305011; S. Pratt *et al.*, nucl-th/0308087.

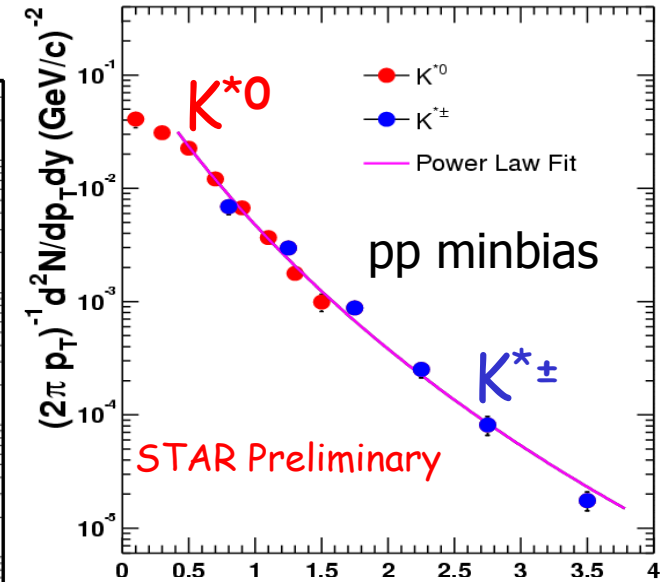
Spectra - I

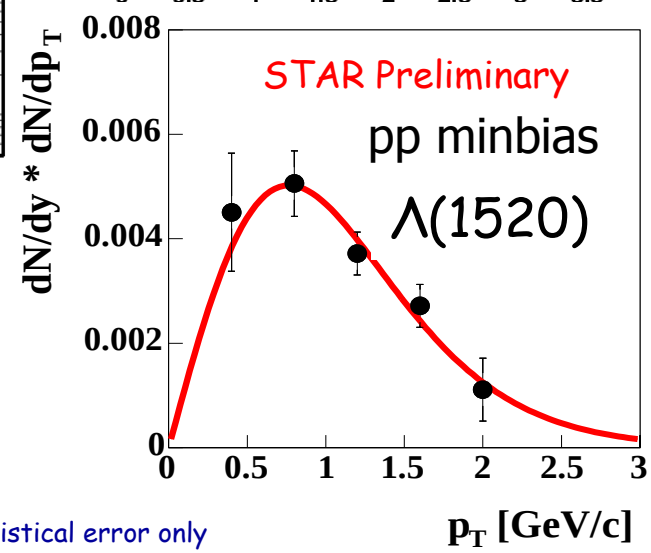
$\sqrt{s_{NN}}$ = 200 GeV



|y|<0.5



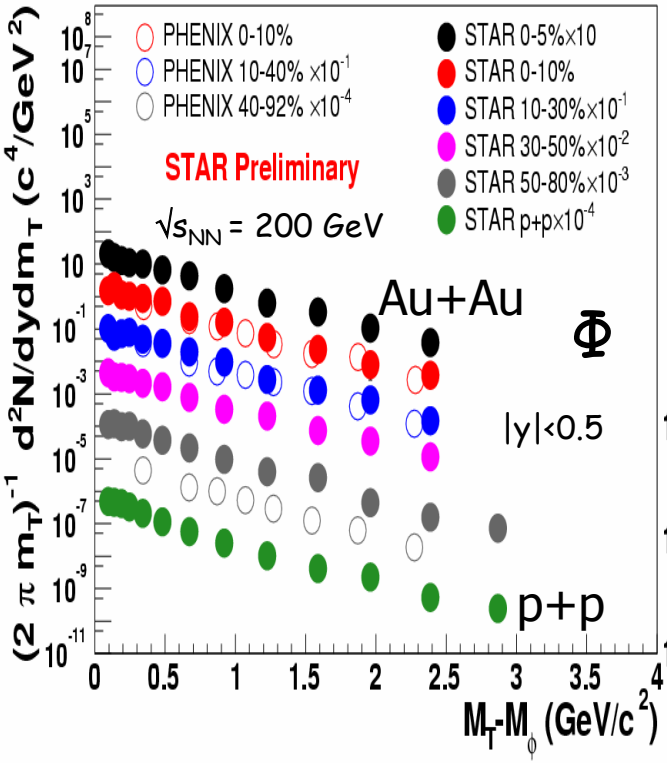


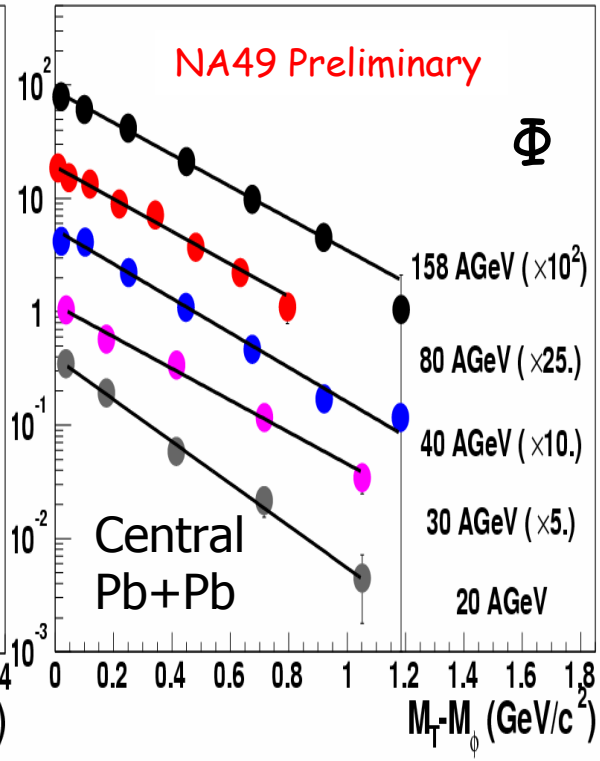


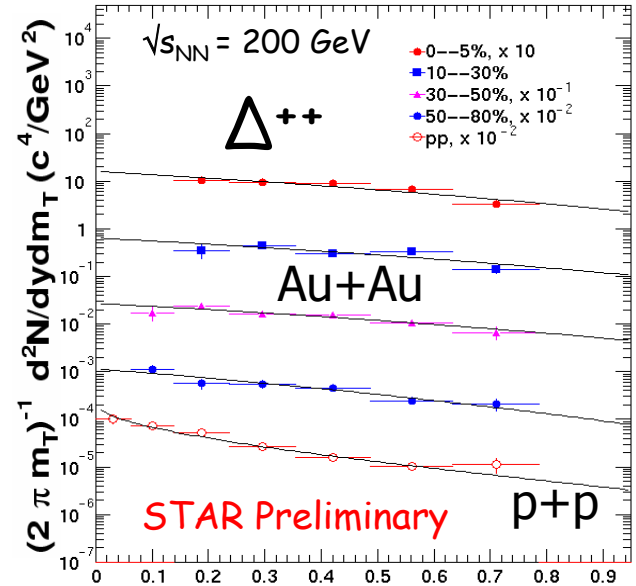
- Au+Au and K^{*0}, Λ(1520) p+p ⇒ spectra fit to exponential in m_T-m_0
- p+p ⇒ spectra fit to power-law

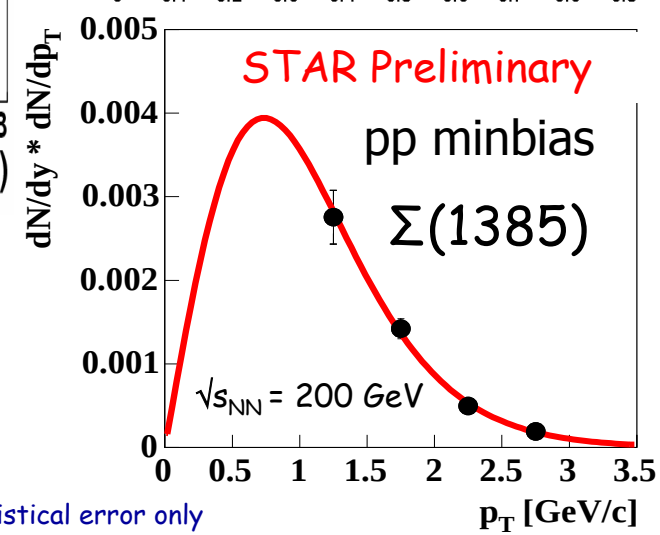
Statistical error only

Spectra - II





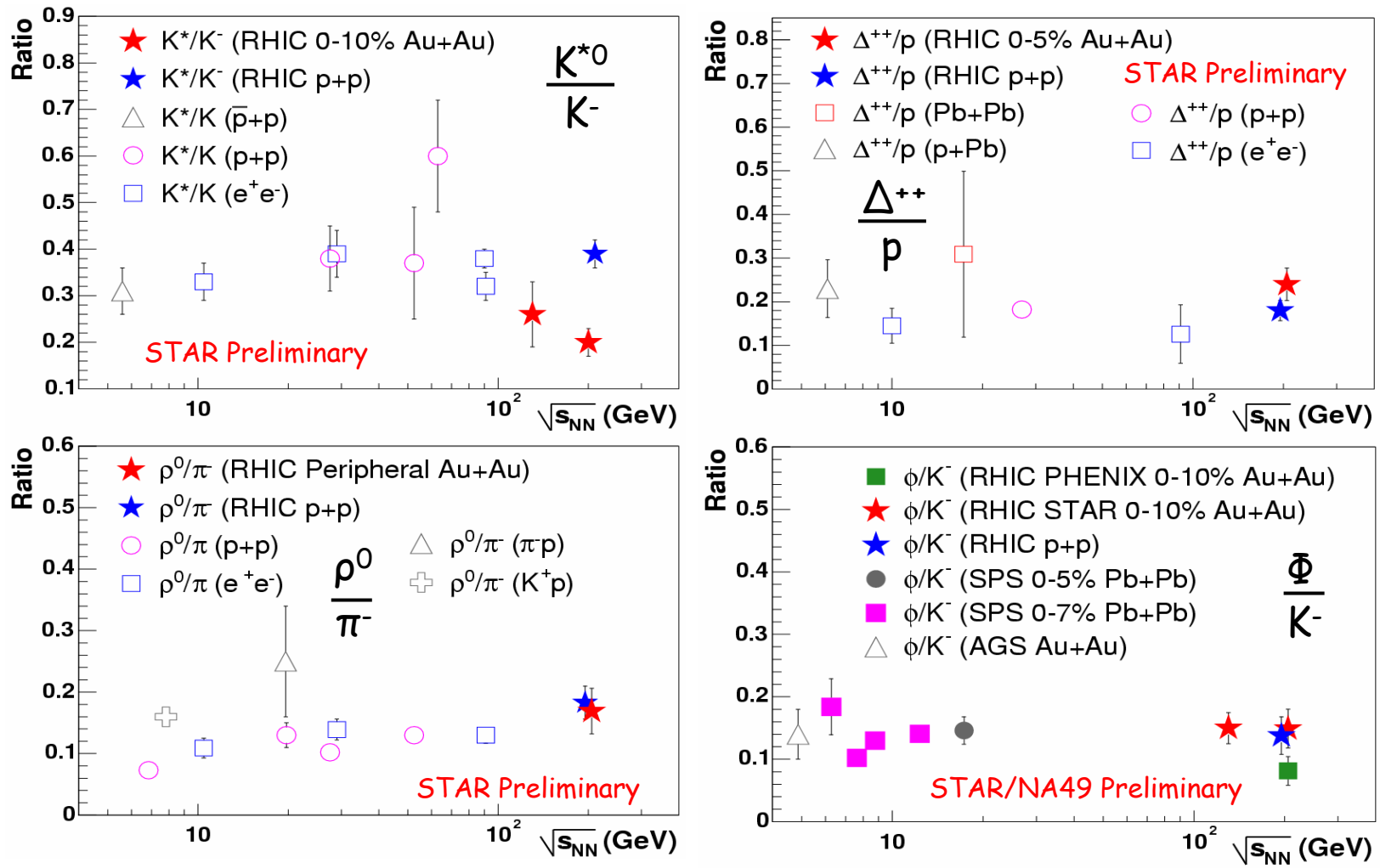




- Au+Au and Σ(1385) p+p ⇒ spectra fit to exponential
- p+p ⇒ spectra fit to power-law

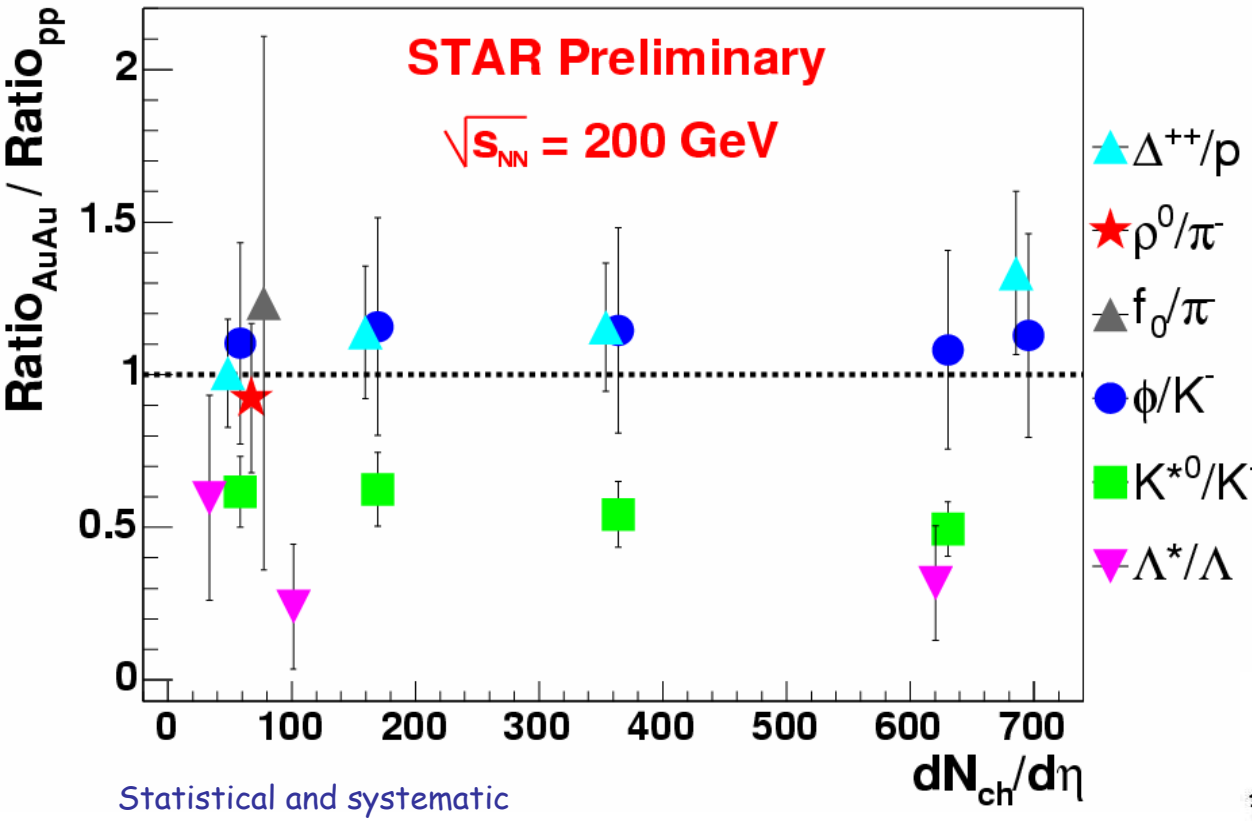
Statistical error only

Particle Ratios – Beam Energy Dependence



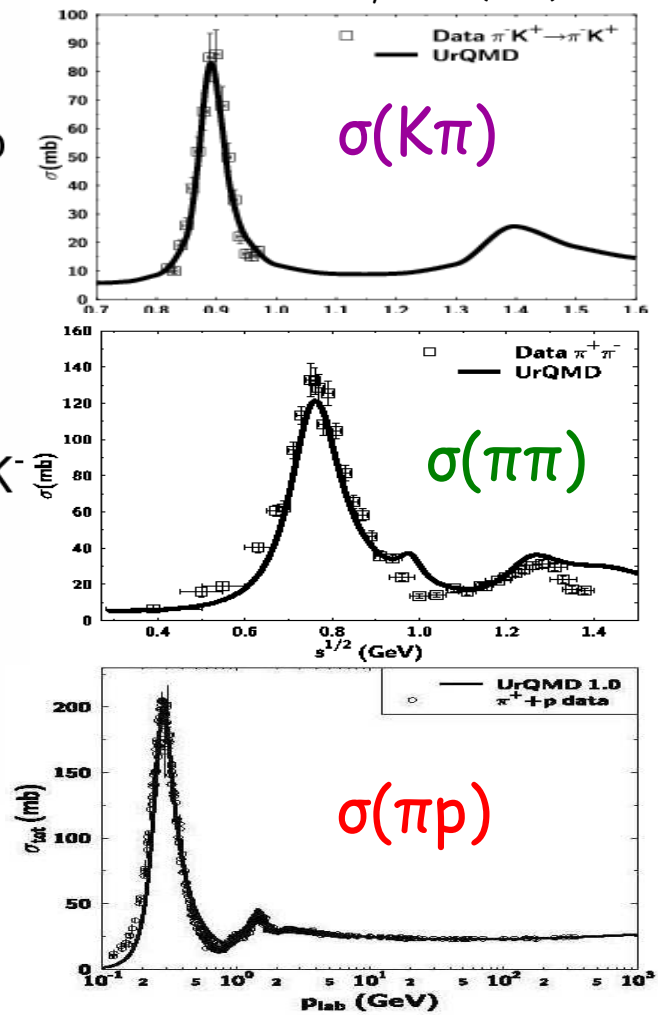
⇒ No strong energy and system size dependence (except K^{*0}/K^-)

Particle Ratios – Multiplicity Dependence



Statistical and systematic errors added in quadrature

M. Bleicher *et al.* J. Phys. G 25 (1999) 1859



- Φ/K^- independent of centrality ⇒ Φ not produced via kaon coalescence ?
- Cross-section ⇒ regeneration or rescattering ?

Time between Chemical and Kinetic Freeze-out

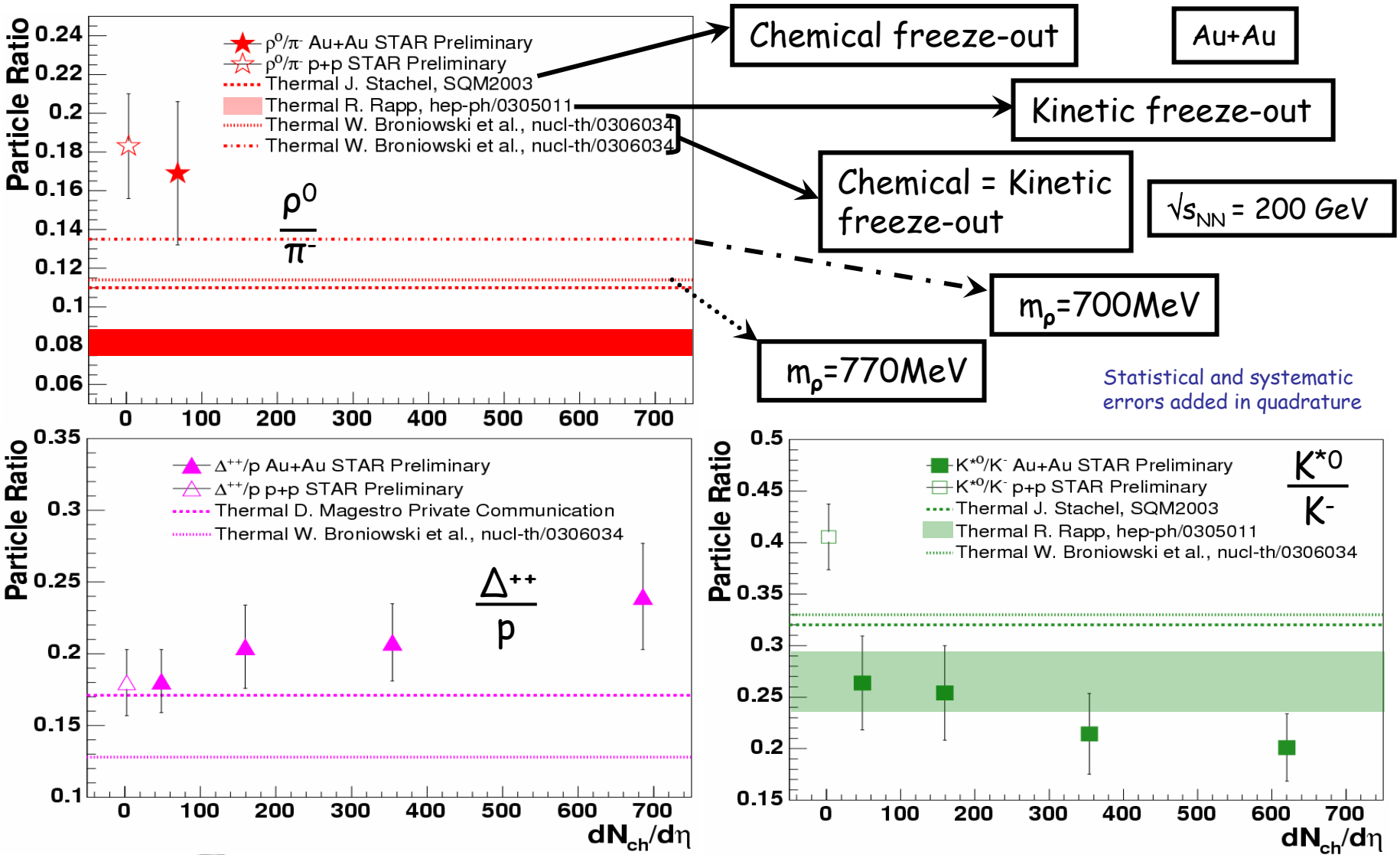
- If rescattering is the dominant process,

$$N(\Delta t) = N_0 \, e^{-\frac{t}{c}}$$

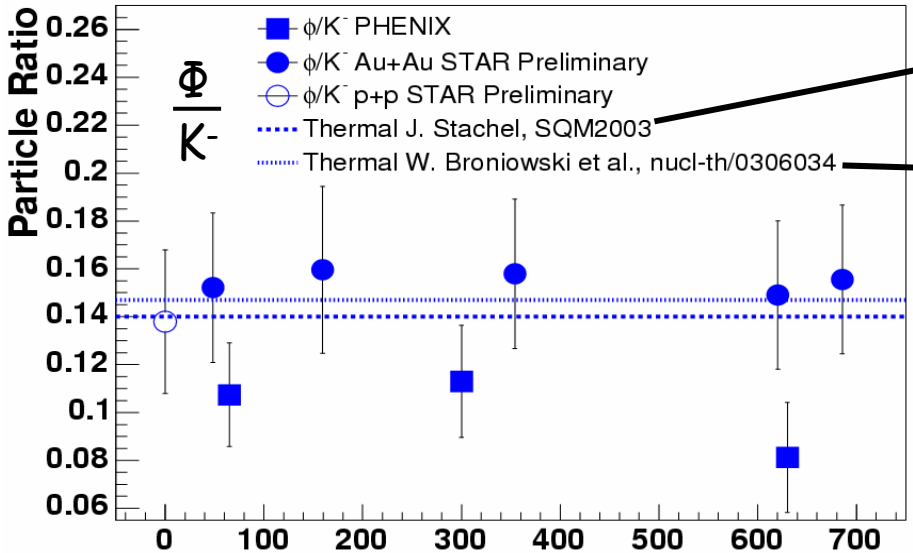
$$e^{-\frac{\Delta t}{c}} = \frac{\left(\frac{K^{*0}}{K^-}\right)_{Au+Au}}{\left(\frac{K^{*0}}{K^-}\right)_{p+p}} = \frac{0.205}{0.385}$$

- And the time between chemical and kinetic freeze-out should be $\Delta t \sim 3$ fm
- If regeneration is the dominant process, $\Delta t > 3$ fm

Thermal Models - I



Thermal Models - II



Chemical freeze-out

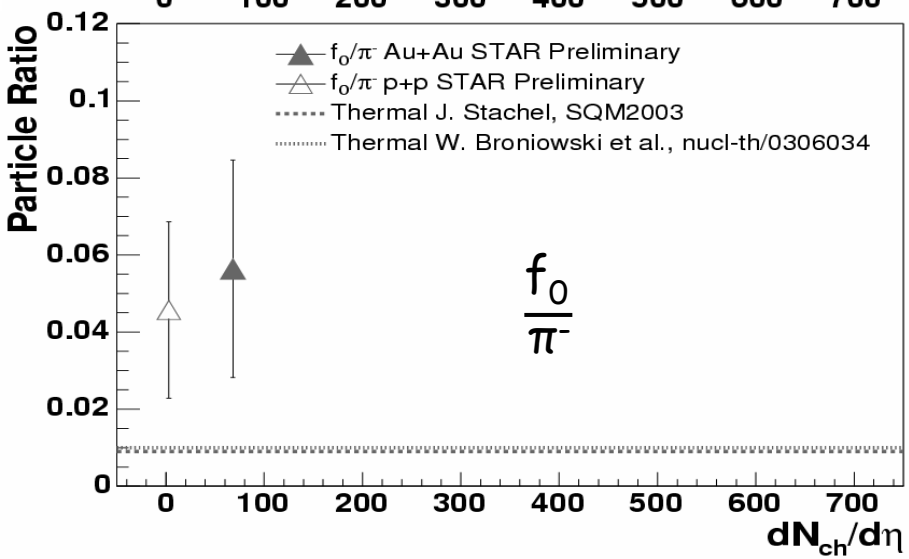
$\sqrt{s_{NN}}$ = 200 GeV

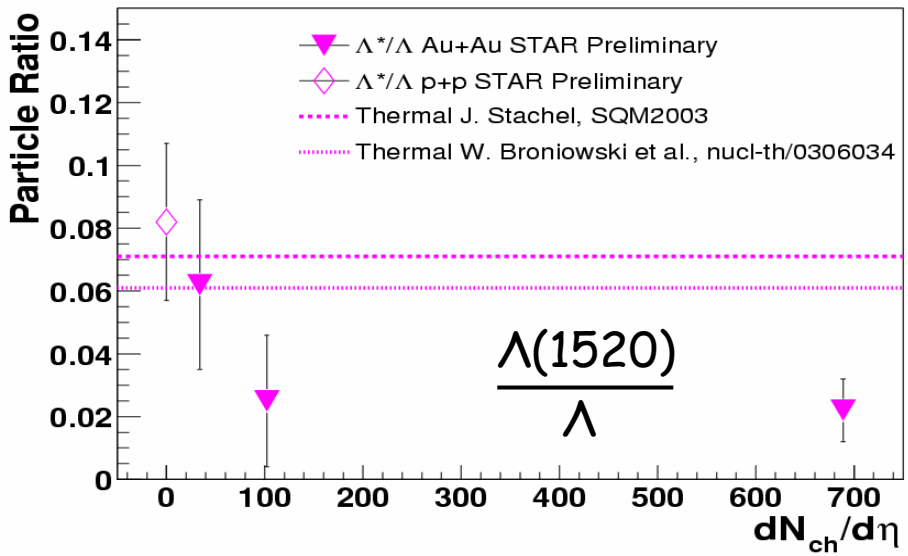
Chemical freeze-out = Kinetic freeze-out

Au+Au

- Thermal calculations ⇒ Do not reproduce ratios of short-lived resonances

Statistical and systematic errors added in quadrature





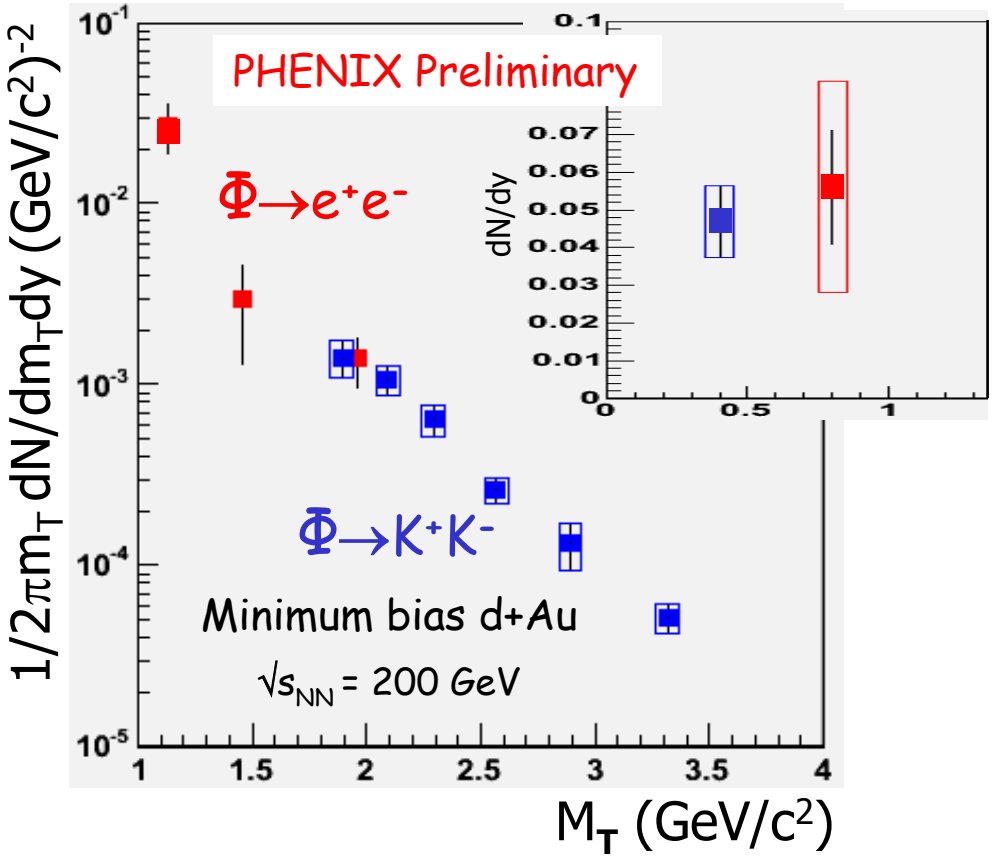
Summary

- Significant resonance production measured from hadronic interactions
- ρ^0, K^{*0} and Δ^{++} $\Rightarrow$ mass shift observed in p+p and Au+Au collisions even after phase space correction
- Δ^{++} $\Rightarrow$ width broadening in central Au+Au collisions
- Mass shift expected due to in-medium modifications, interference and Bose-Einstein correlations ?
- Φ/K^- independent of centrality $\Rightarrow$ Φ not produced via kaon coalescence ?
- Short-lived resonances $\Rightarrow$ Regeneration and daughter rescattering $\Rightarrow$ driven by hadronic cross-sections ?
- Resonances can provide information on the collision dynamics

Outlook

- What's next?
  - We need:
    - Systematic study of K^{*0} and Δ^{++} mass and width in Au+Au
    - ρ^0 in central Au+Au
    - $\Lambda(1520)$, $\Sigma(1385)$, $\Xi(1530)$… Other higher state resonances…
    - High-p_T and v_2 measurements of resonances
    - Leptonic Channel
      - Φ, ρ, ω…
      - Φ, ρ $\Rightarrow$ Comparison between leptonic and hadronic channels in Au+Au!!!
  - Requires
    - Large statistics $\Rightarrow$ RUN 4 @RHIC
    - RHIC Upgrades
      - Low mass dileptons $\Rightarrow$ PHENIX
      - TOF $\Rightarrow$ STAR

Outlook


PHENIX Preliminary
Φ→e⁺e⁻
Φ→K⁺K⁻
Minimum bias d+Au
√s_NN = 200 GeV
1/2πm_T dN/dm_T dy (GeV/c²)⁻²
M_T (GeV/c²)
dN/dy

Experimental References

H. Zhang ⇒ $\rho^0(770)$, $K^*(892)$, $\Delta^{++}(1232)$ STAR ⇒ Poster QM2004

S. Salur ⇒ $\Sigma(1385)$ STAR ⇒ Poster QM2004

C. Markert ⇒ $\Lambda(1520)$ STAR ⇒ Talk QM2004

J. Ma ⇒ $\Phi(1020)$ STAR ⇒ Poster QM2004

L. Gaudiche ⇒ $\Lambda(1520)$ STAR ⇒ SQM2003

P. Fachini ⇒ $f_0(980)$ STAR ⇒ SQM2003

R. Seto ⇒ $\Phi(1020)$ PHENIX ⇒ Talk QM2004

D. Mukhpadhyay ⇒ $\Phi(1020)$ PHENIX ⇒ QM2002

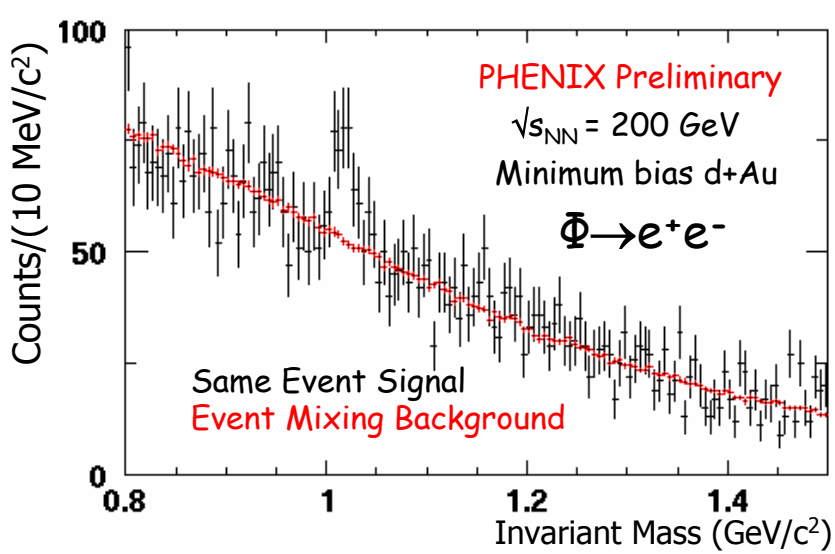
C. Maguirre ⇒ $\Phi(1020)$ PHENIX ⇒ Poster QM2004

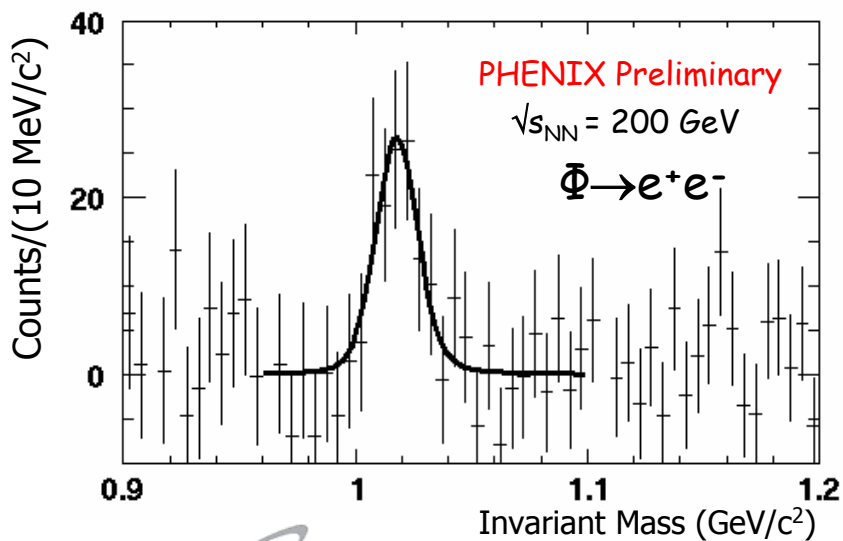
Marek Gazdzicki ⇒ $\Phi(1020)$ NA49 ⇒ Talk QM2004

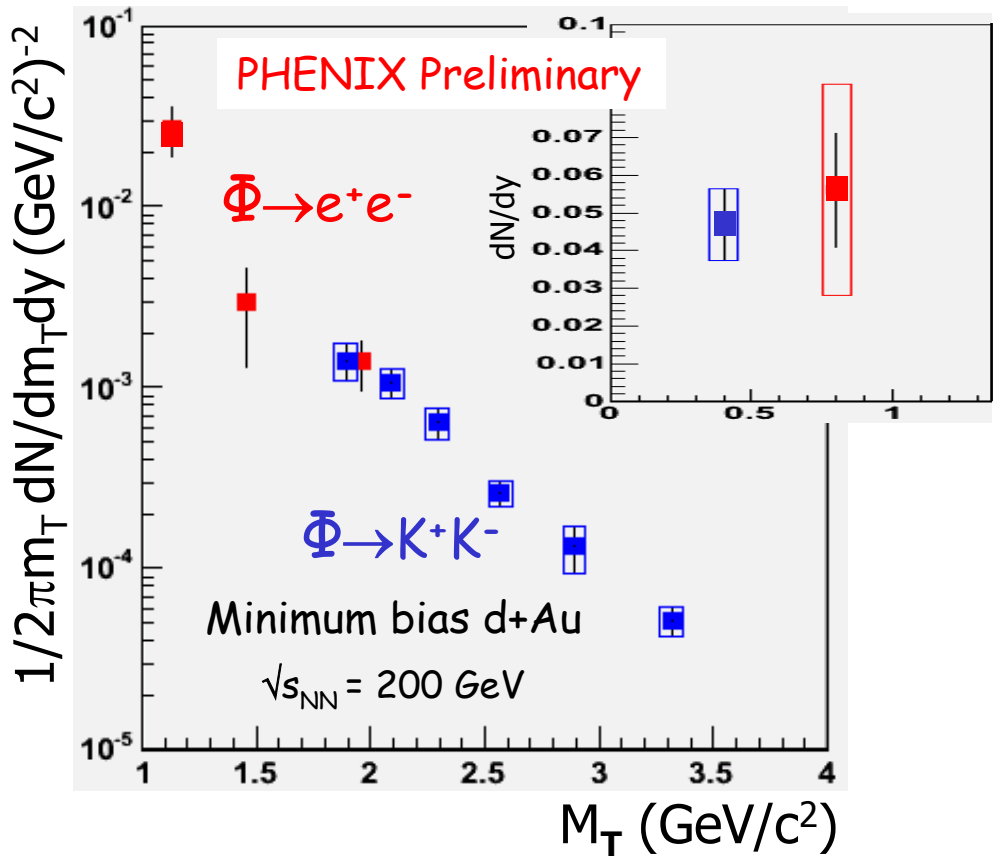
V. Friese ⇒ $\Phi(1020)$ NA49 ⇒ SQM2003

Back-up Slides

$\Phi \rightarrow e^+e^-$ and $\Phi \rightarrow K^+K^-$ in d+Au



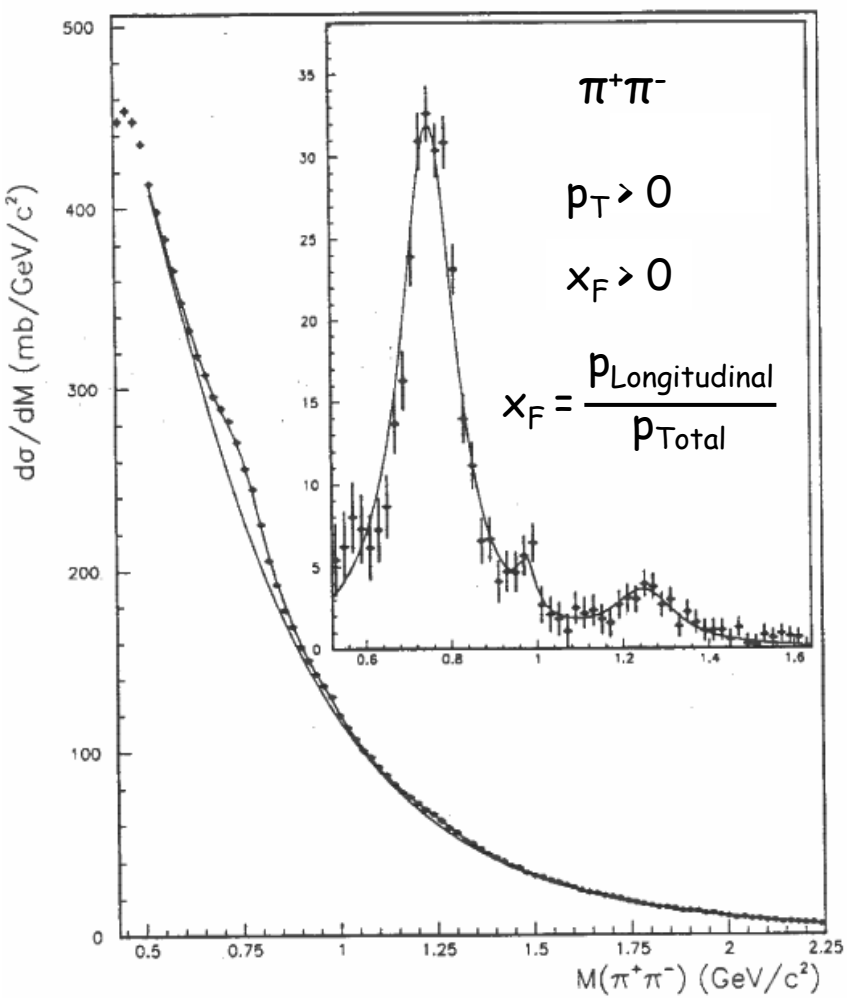




- $\Phi \rightarrow e^+e^-$ and $\Phi \rightarrow K^+K^-$ consistent in d+Au at $\sqrt{s_{NN}}$ = 200 GeV
- What about Au+Au ?

ρ^0-meson Measured in pp ⇒ NA27

M. Aguilar-Benitez, Z. Phys. C 50 (1991) 405



- $\sqrt{s}$ = 27.5 GeV
- The ρ^0 mass obtained by fitting same event distribution of $\pi^+\pi^-$ to

$$BG + PS \times BW = BG + BG \times BW = BG(1 + BW)$$

BW = Breit-Wigner; BG = Background; PS = Phase Space

$$BW(M) = \frac{1}{p^*} \times \frac{\Gamma(M)}{(M^2 - M_\rho^2)^2 + M_\rho^2\,\Gamma(M)^2}$$

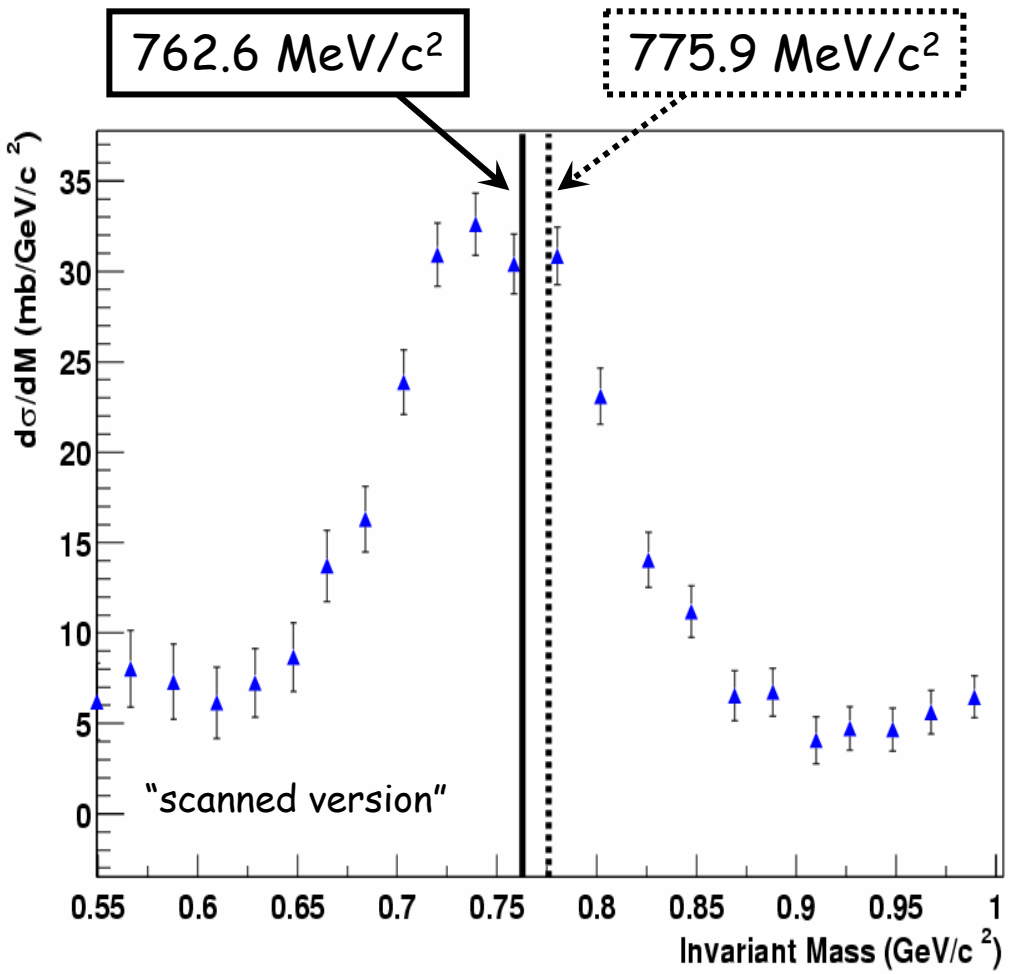
$$PS = BG = BG(p^*) = a1\left(\frac{p^*}{M}\right)^{a2} \times e^{-a3 \cdot p^* - a4 \cdot p^{*2}}$$

$$\Gamma(M) = \Gamma_\rho \left[\frac{M^2 - 4m_\pi^2}{M_\rho^2 - 4m_\pi^2}\right]^{\frac{3}{2}} \frac{M_\rho}{M}$$

$$p^* = \frac{2M}{(M^2 - 4m_\pi^2)^{1/2}}$$

ρ^0-meson Measured in pp ⇒ NA27

M. Aguilar-Benitez, Z. Phys. C 50 (1991) 405

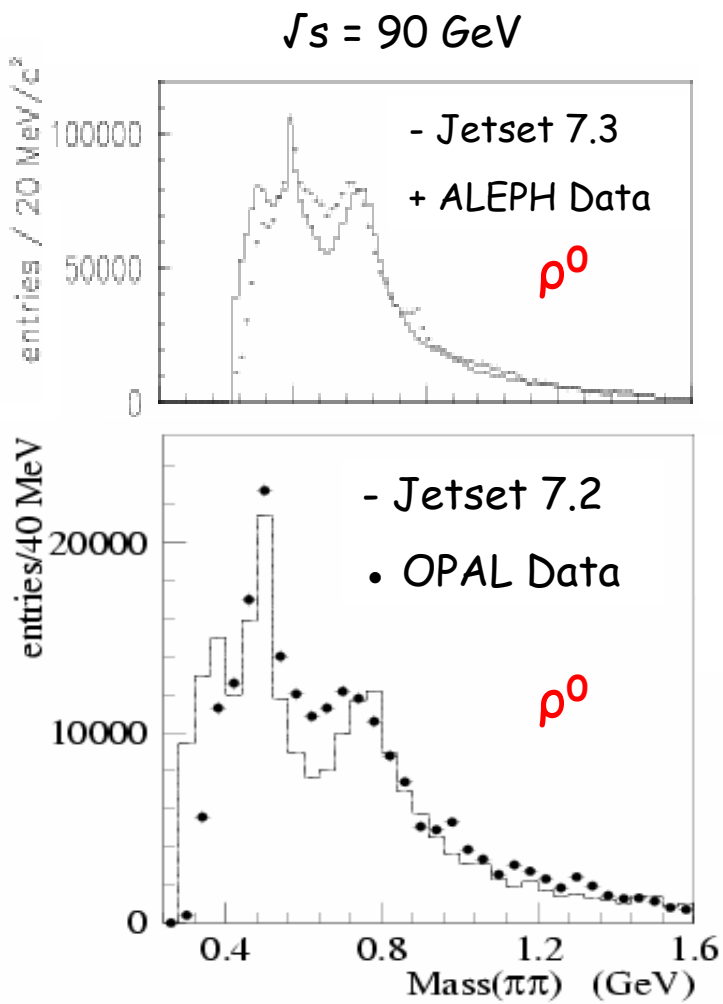


- CERN ⇒ $\sqrt{s}$ = 27.5 GeV
- ρ^0 mass = 762.6 ± 2.6 MeV/c^2 ⇒ only pp measurement used in average by PDG
- PDG average "other reactions" hadroproduced ⇒ ρ^0 mass = 769.0 ± 0.9 MeV/c^2
- PDG average e^+e^- ⇒ ρ mass = 775.9 ± 0.5 MeV/c^2

⇒ **The position of the ρ^0 peak is clearly below reported value**

ρ^0-meson Measured in $e^+e^- \Rightarrow$ LEP

P. D. Acton *et al.*, Z. Phys. C 56 (1992) 521; G. Abbiendi *et al.*, Eur. Phys. J. C 5 (1998) 411; P. Abreu *et al.*, Phys. Lett. B 298 (1993) 236; D. Buskulic *et al.*, Z. Phys. C 69 (1996) 379; G. D. Lafferty, Z. Phys. C 60 (1993) 659, private communication



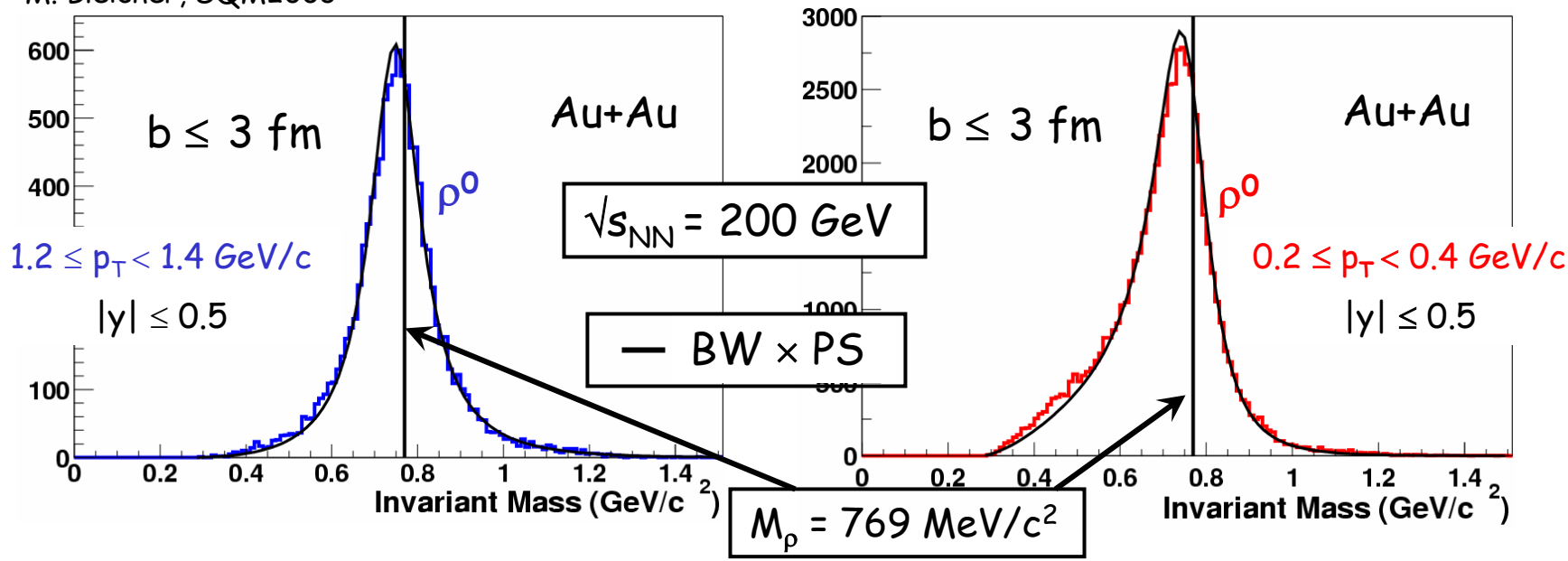
- OPAL $\Rightarrow$ ρ^0 mass shifted by ~70 MeV/c^2 at low x_p and no shift at high x_p (x_p ~1)

$$x_p = \frac{E(\text{meson})}{E(\text{beam})}$$

- OPAL $\Rightarrow$ -10 to -30 MeV/c^2 shift in the position of the maximum of the resonance $\rho^\pm$ $\Rightarrow$ consistent with ρ^0 measurement
- DELPHI $\Rightarrow$ $0.1 < x_p < 0.4$ $\Rightarrow$ ρ^0 peak fit to (BWxBG) + BG $\Rightarrow$ ρ^0 mass = 757 ± 2 MeV/c^2 $\Rightarrow$ five standard deviations below PDG value
- ALEPH $\Rightarrow$ same ρ^0 mass shift observed by OPAL

Transport Model - UrQMD

M. Bleicher, SQM2003

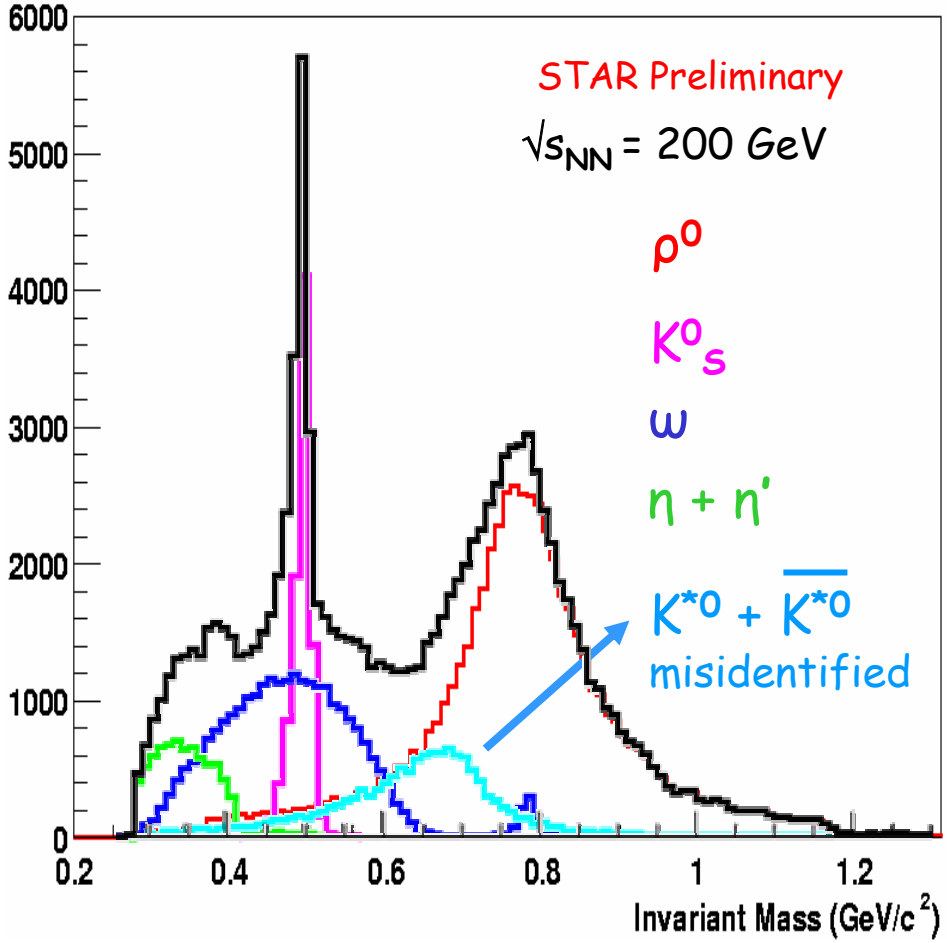


- UrQMD ⇒ Only imaginary part ⇒ No in-medium modification
- Central Au+Au ⇒ ρ^0 mass shifted ~30 MeV at low p_T
- ρ^0 shape reproduced by p-wave Breit-Wigner × Phase Space
  - $M_\rho = 765.6 \pm 0.4$ MeV/c^2 for $0.2 \le p_T < 0.4$ GeV/c
  - $M_\rho = 761.2 \pm 0.9$ MeV/c^2 for $1.2 \le p_T < 1.4$ GeV/c
  - $M_\rho = 769$ MeV/c^2 input

$\Gamma = 150$ MeV

$\pi^+\pi^-$ Invariant Mass Distribution from Monte Carlo

P. Fachini, SQM2003



- HIJING events with a realistic simulation of TPC response

  $\rho^0(770) \rightarrow \pi^+ \pi^-$

  $K^0_s \rightarrow \pi^+ \pi^-$

  $\omega(782) \rightarrow (\pi^+ \pi^-)\, \pi^0$ and $\pi^+ \pi^-$

  $\eta \rightarrow (\pi^+ \pi^-)\, \pi^0$ and $(\pi^+ \pi^-)\, \gamma$

  $\eta' \rightarrow (\pi^+ \pi^-)\, \eta$ and $(\pi^+ \pi^-)\, \rho^0$

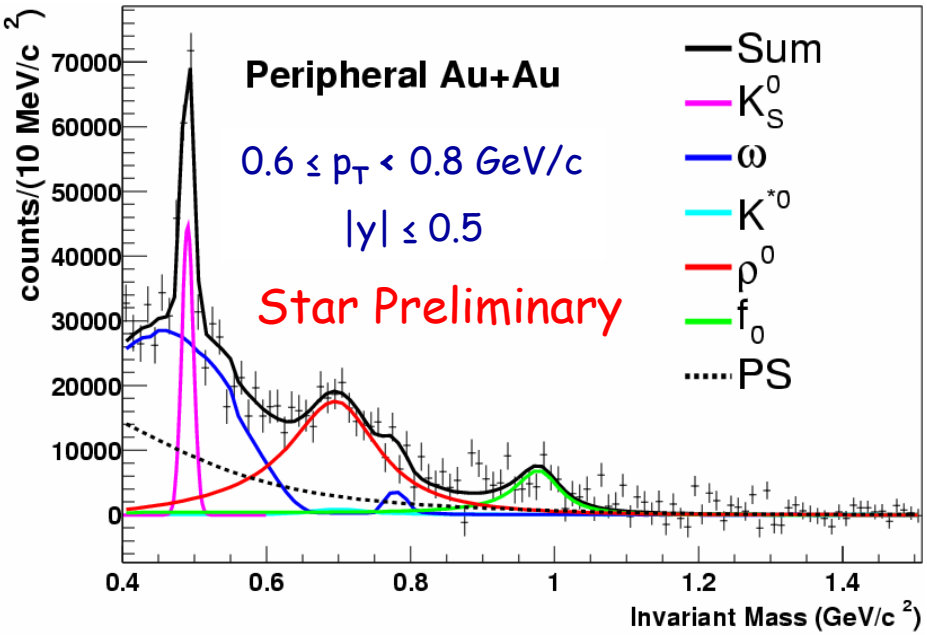
  $K^*(892)^0 \rightarrow K\ \pi$ with K misidentified as π

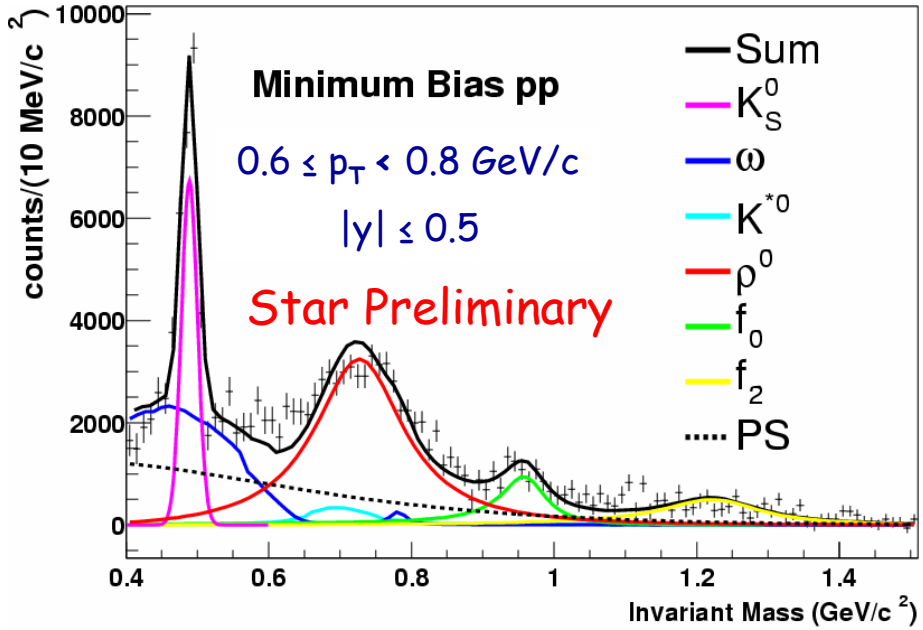
- Use ω and K^{*0} shape from HIJING to fit the data

- K^{*0} signal is fixed using our measurement

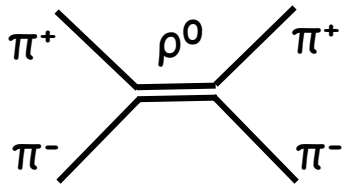
$\pi^+\pi^-$ Raw Invariant Mass Distribution from Data

J. Adams *et al.* nucl-exp/0307023



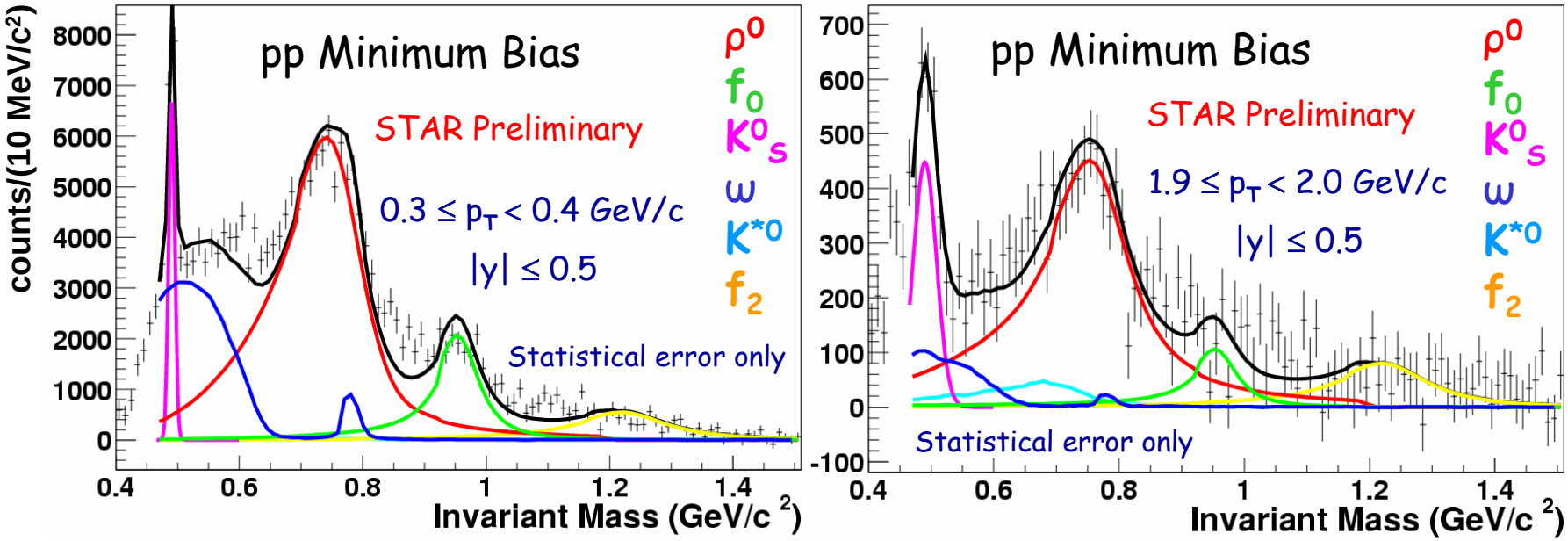


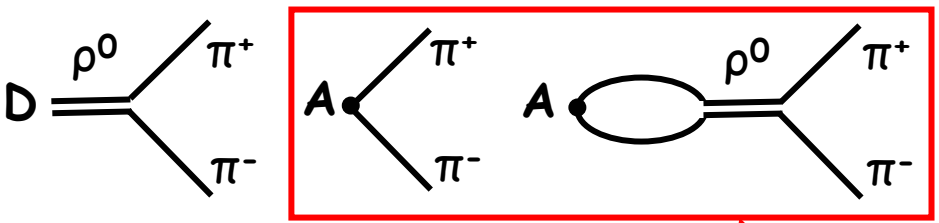
$$\text{Phase Space} = \frac{M}{\sqrt{M^2 + p_T^2}}\, e^{\frac{-\sqrt{M^2 + p_T^2}}{T}}$$



Partial-Wave Analysis

P. Fachini, SQM2003 and R. Longacre, nucl-exp/0305015



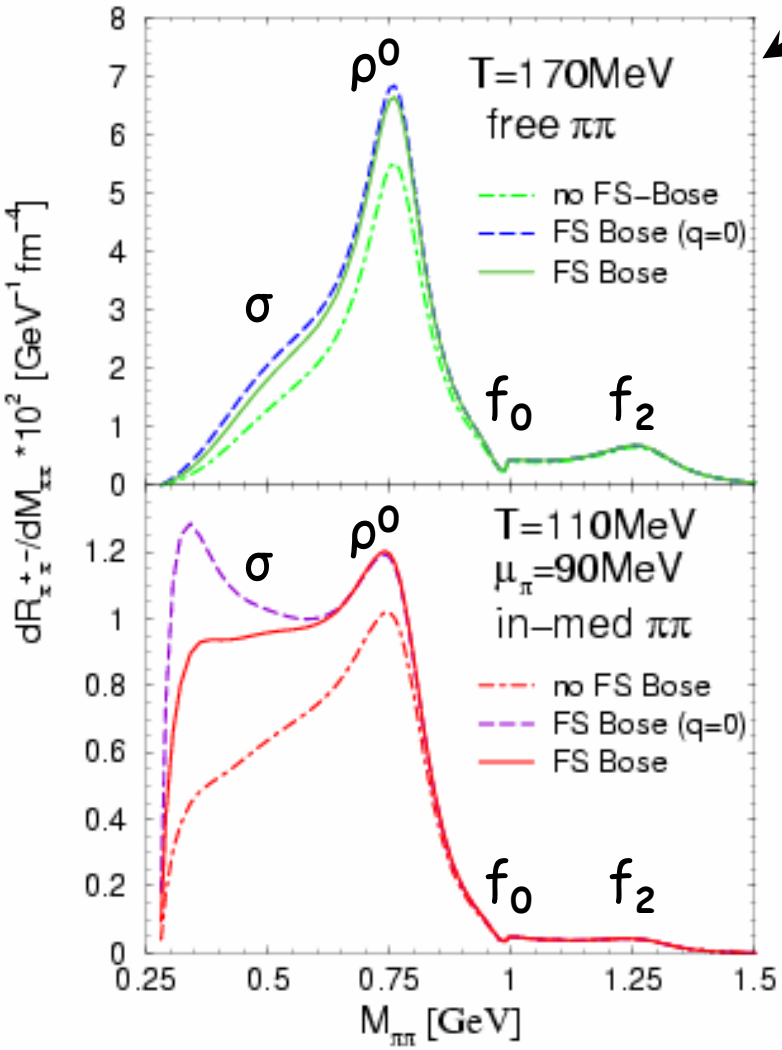


Interference

- Partial-wave analysis + $\pi^+\pi^-$ scattering reproduce ρ^0 mass measured in minimum bias pp
- M_ρ = 779.1 MeV/c²
  Γ = 150 MeV/c²
- Distance of interaction in $\pi^+\pi^-$ scattering ⇒ 1/3 fm

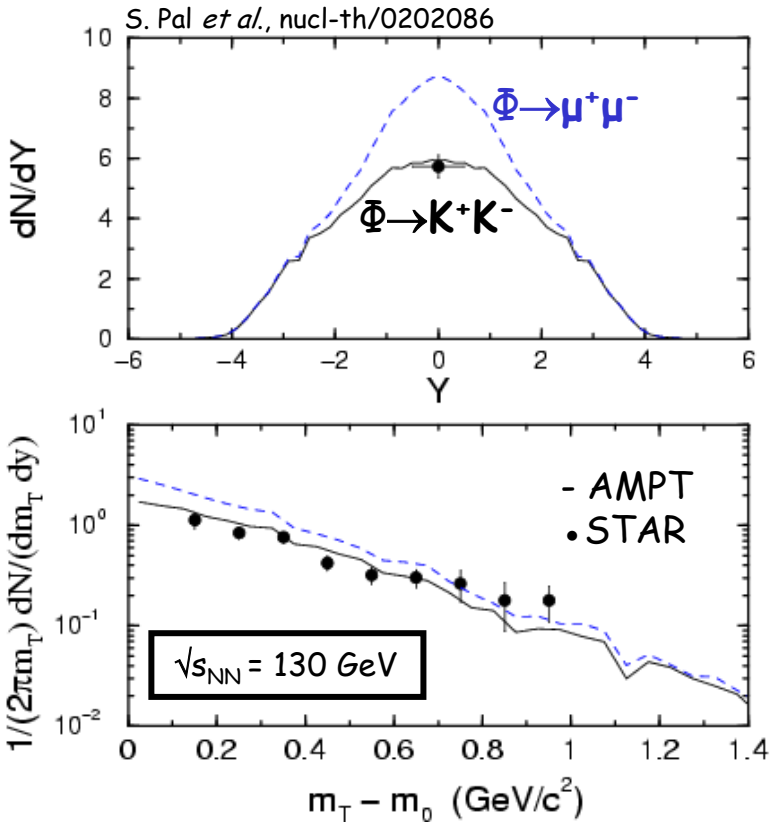
Bose-Einstein Correlations

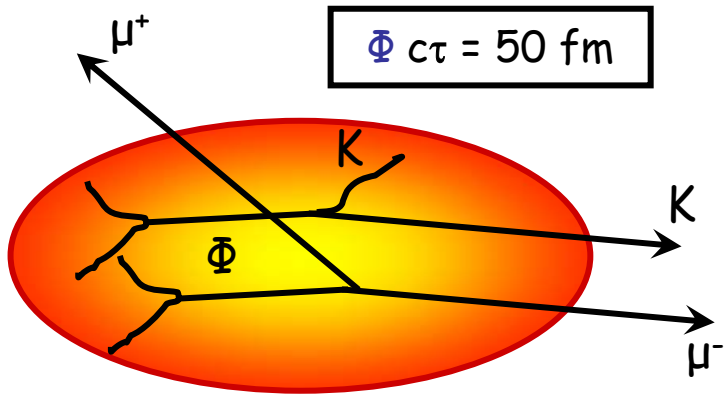
G.D. Lafferty, Z. Phys. C 60, 659 (1993); R. Rapp, hep-ph/0305011; S. Pratt *et al.*, nucl-th/0308087

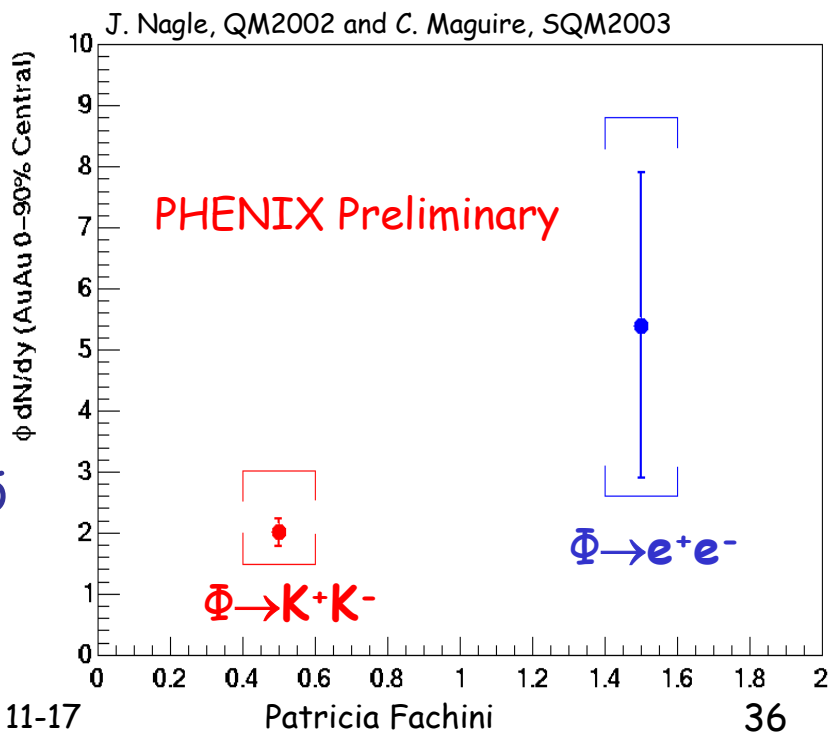


- Bose-Einstein correlations between ρ^0 decay daughters and pions in the surrounding matter⇒ distortion of the ρ^0 spectral shape
- LEP ⇒ Bose-Einstein correlations used to explain the ρ mass shift observed ⇒ need large values of Bose-Einstein parameters
- In-medium $\pi\pi$ in Au+Au at RHIC ⇒ adding Bose-Einstein correlations
  - ρ^0 peak shifted downward 5-10 MeV/c^2
  - Rate increases ~20% around ρ^0 mass region
  - More pronounced σ shoulder

Φ yield

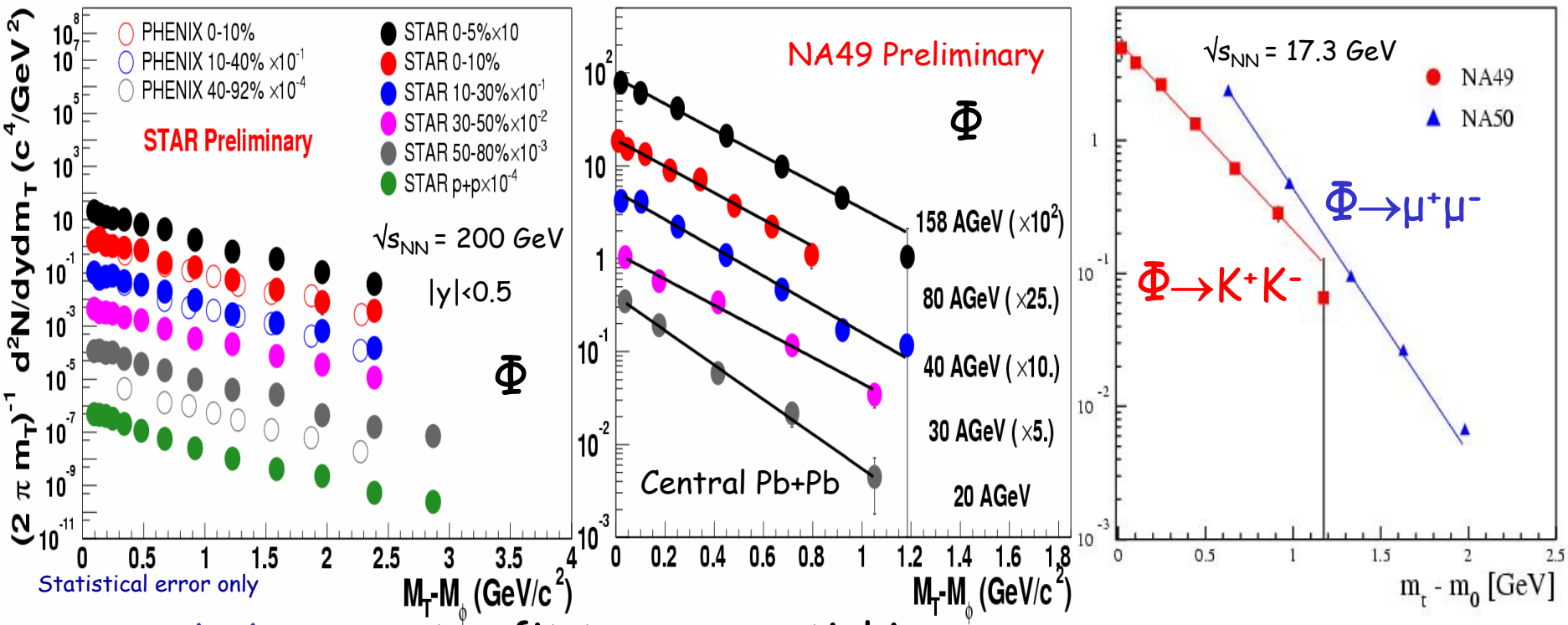






- AMPT: $(\Phi\rightarrow\mu^+\mu^-)/(\Phi\rightarrow K^+K^-) = 1.5$
- Experiment comparison ⇒ need more statistics!

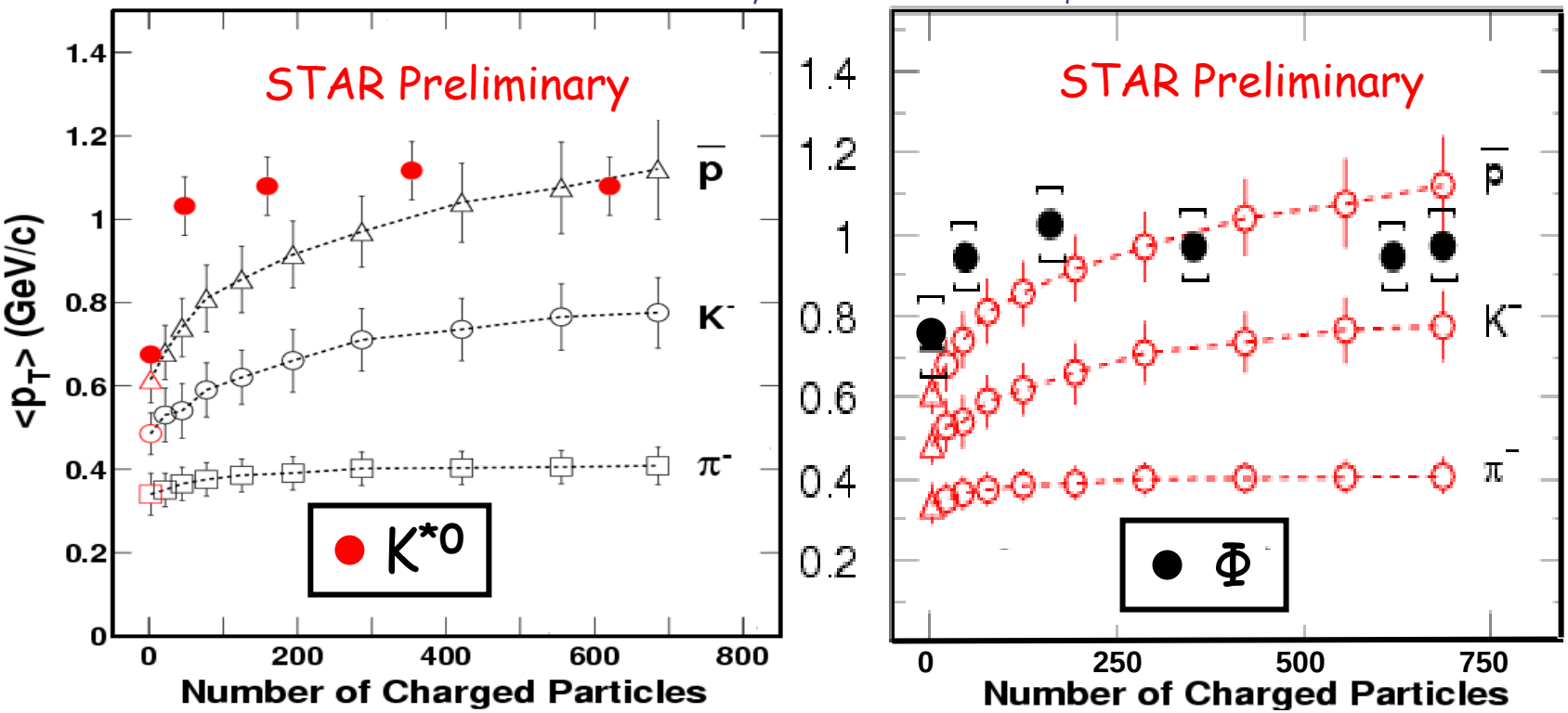
Spectra - Φ



- A+A ⇒ spectra fit to exponential in m_T-m_0
- p+p ⇒ spectra fit to power-law
- SPS ⇒ Strong differences in slope and yield between hadronic channel (NA49) and dimuon channel (NA50)
- Need $\Phi \rightarrow e^+e^-$ at RHIC in Au+Au !

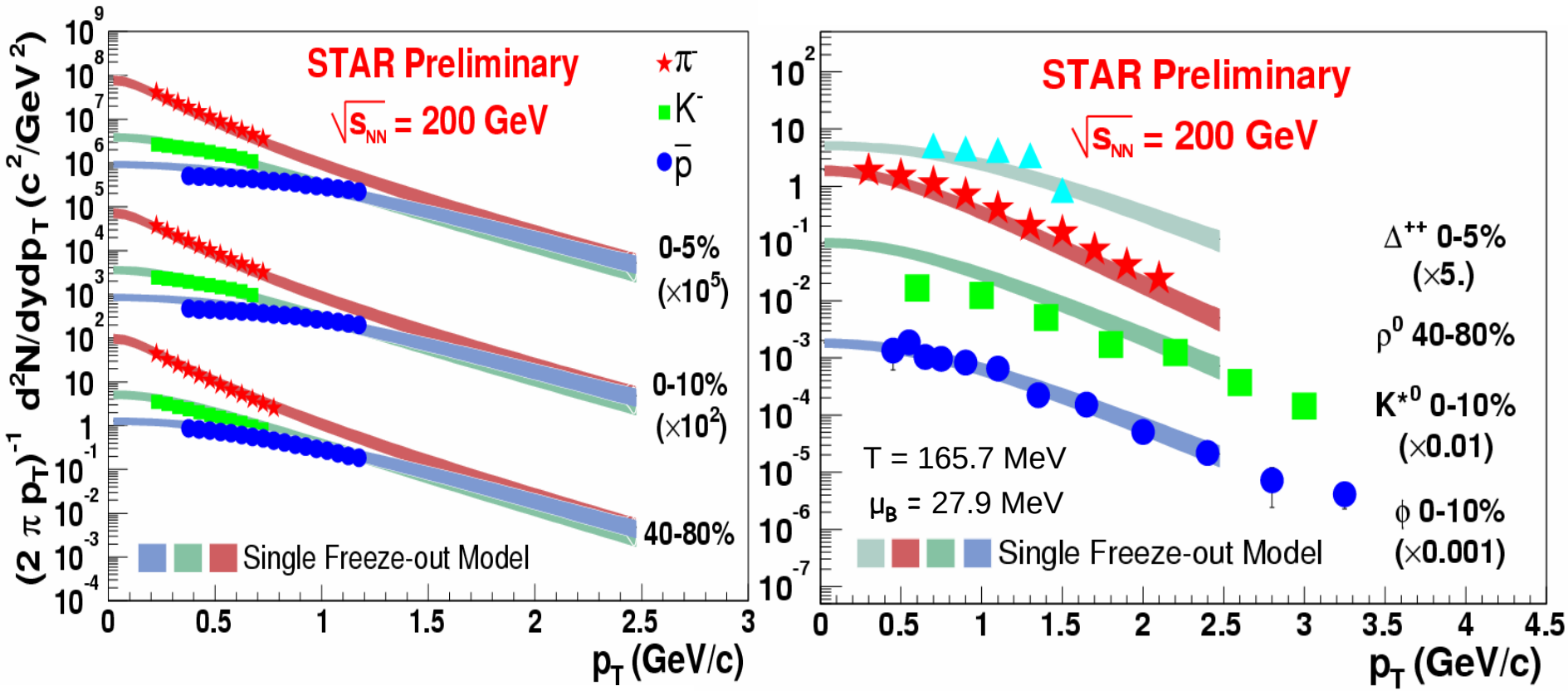
$\langle p_T \rangle$ Charged Particle Dependence

Statistical and systematic errors added in quadrature



- π^-, K^-, $\bar{p}$ ⇒ $\langle p_T \rangle$ increase for increasing mass ⇒ expected hydro type collective flow
- Φ and K^{*0} ⇒ Behave different ⇒ No centrality dependence

Thermal Model – Single Freeze-Out



- Fit π^-, K^-, $\bar{p}$ spectra ⇒ then get the resonance spectra
- Single freeze-out thermal model ⇒ Reasonable description spectra shape for ρ^0, Δ^{++}, and Φ ⇒ What about K^{*0} ?