# Possible Medium Modification of Resonances at RHIC

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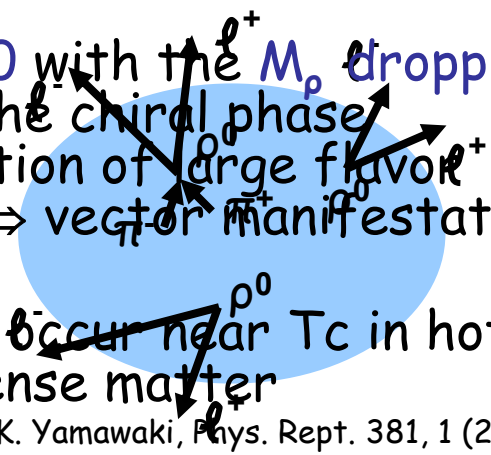
Motivation
Measurements
Discussion
Summary

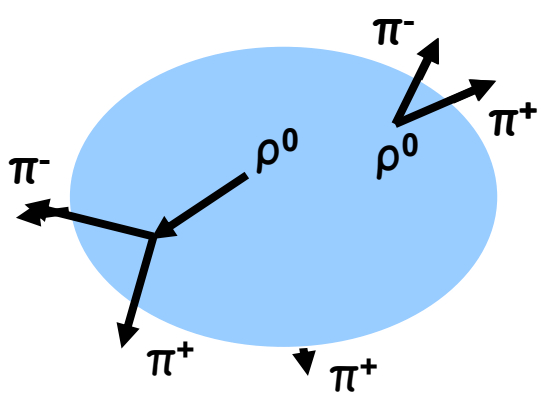
# Motivation

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

R. Rapp and J. Wambach, Adv. Nucl. Phys. 25, 1 (2000); G. E. Brown and M. Rho, Phys. Rev. Let. 66 2720 (1991); P. Braun-Munzinger, GSI Internal Report

- $\Gamma_\rho \rightarrow 0$ with the $M_\rho$ dropping near the chiral phase transition of large flavor QCD ⇒ vector manifestation (VM)
- VM ⇒ occur near Tc in hot and dense matter




M. Harada and K. Yamawaki, Phys. Rept. 381, 1 (2003)

$\rho^0 \rho^0 \tau = 1.3$ fm

- Leptonic decay channel ⇒ probes all stages of the collision
- Hadronic decay channel ⇒ probes only late **stages of the collision**

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# Resonance Production – Hadronic Channel

## For this Talk:

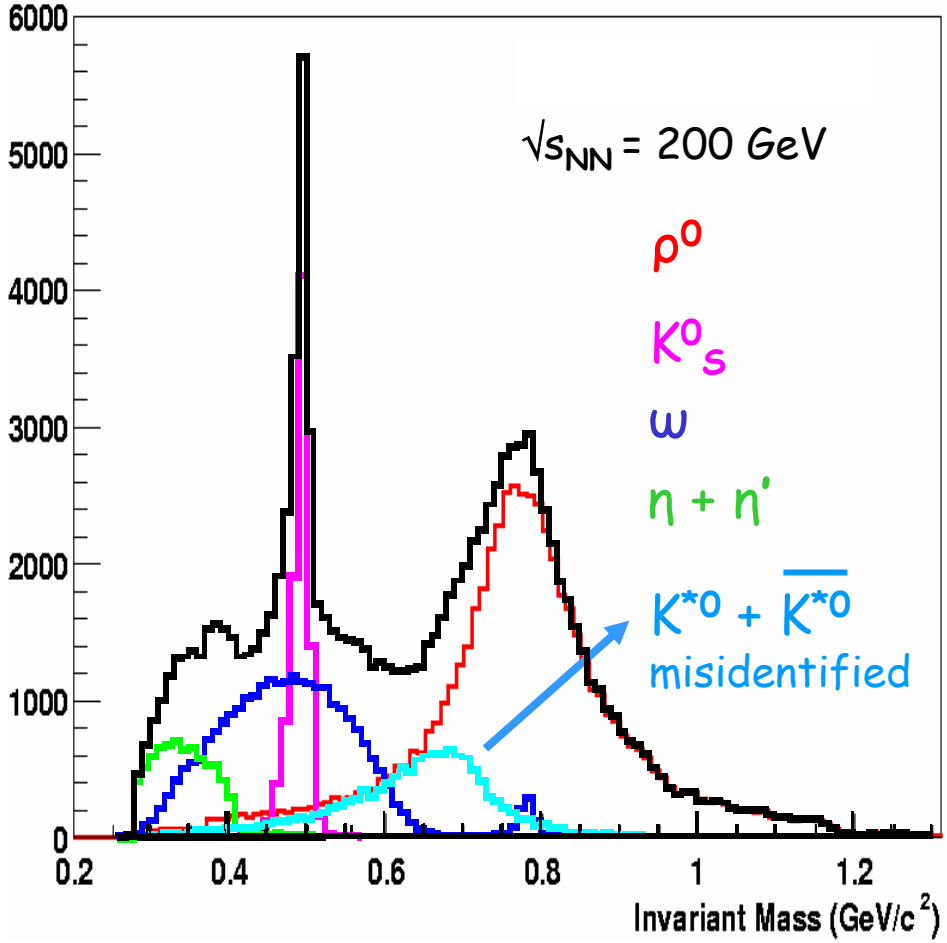
| | | |
|---|---|---|
| $\rho^0(770) \rightarrow \pi^+ \pi^-$ | B.R. ~1 | $c\tau$ = 1.3 fm |
| $\Delta^{++}(1232) \rightarrow p\, \pi^+$ | B.R. ~1 | $c\tau$ = 1.6 fm |
| $\rho^0(770) \rightarrow \pi^+ \pi^-$ | B.R. ~1 | $c\tau$ = 1.3 fm |
| $f_0(980) \rightarrow \pi^+ \pi^-$ | B.R. 2/3 | $c\tau$ = 2.6 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 |
| $K^{*0\pm}(892) \rightarrow \pi\ K$ | B.R. 2/3 | $c\tau$ = 4 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 |

Mainly

Life Time

pp, dAu, and Au+Au collisions

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




- HIJING events with a realistic simulation of detector 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 $(\pi^+ \pi^-)\, \rho^0$

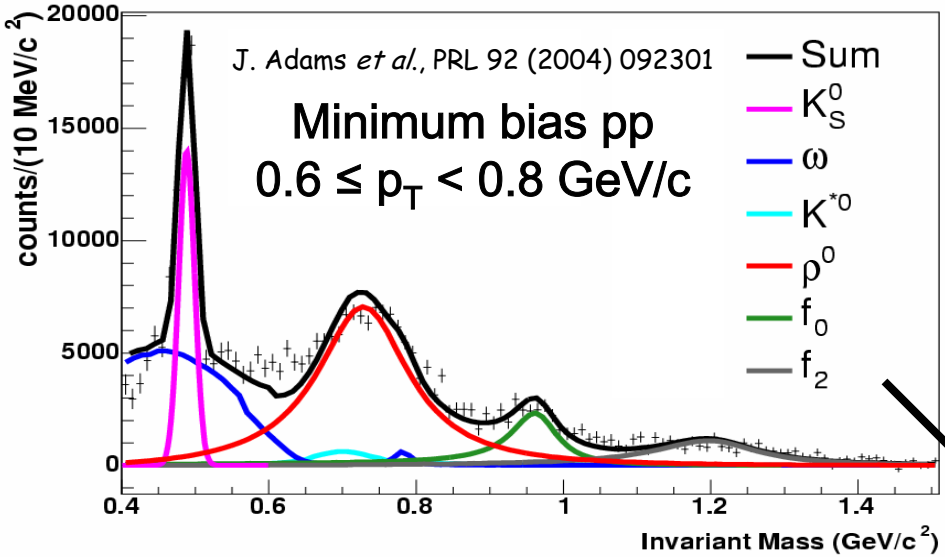
  $K^*(892)^0 \rightarrow K\ \pi$ with $K$ misidentified as $\pi$

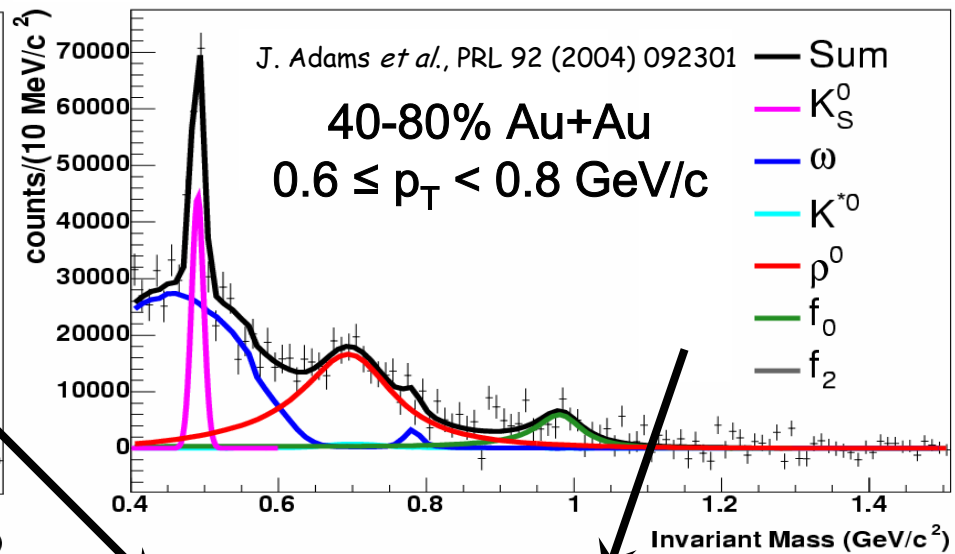
- Use $\omega$ and $K^{*0}$ shape from HIJING to fit the data

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

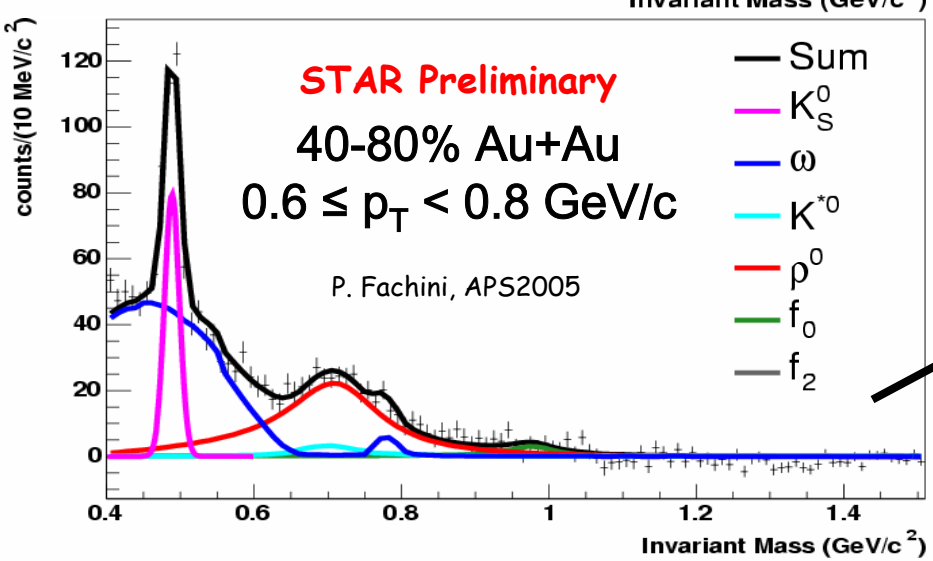
# Measurements at RHIC

# Raw Invariant Mass Distribution from Data




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

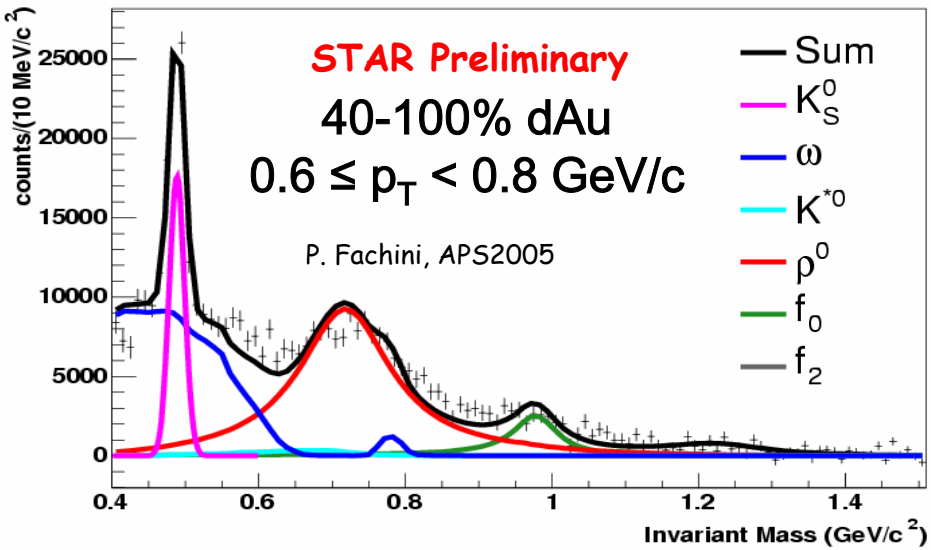


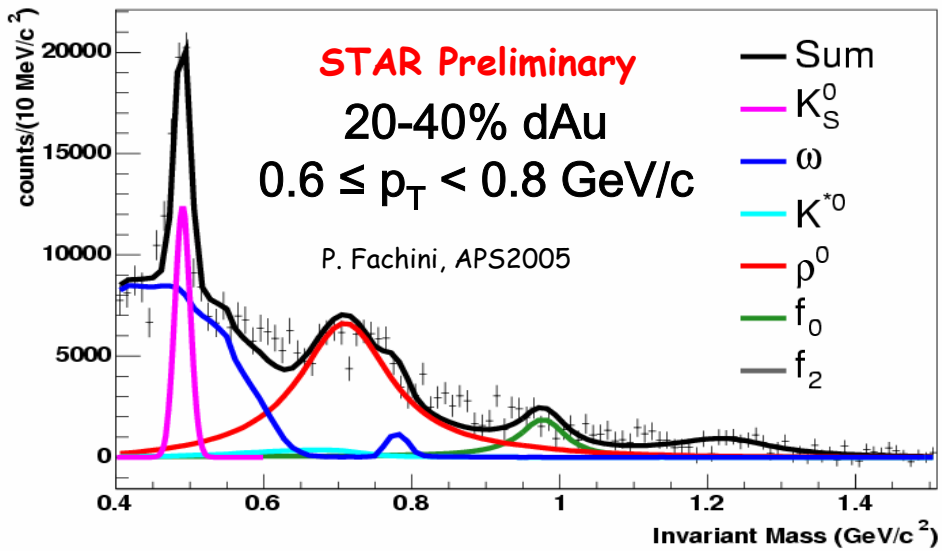

$\sqrt{s_{NN}}$ = 62 GeV

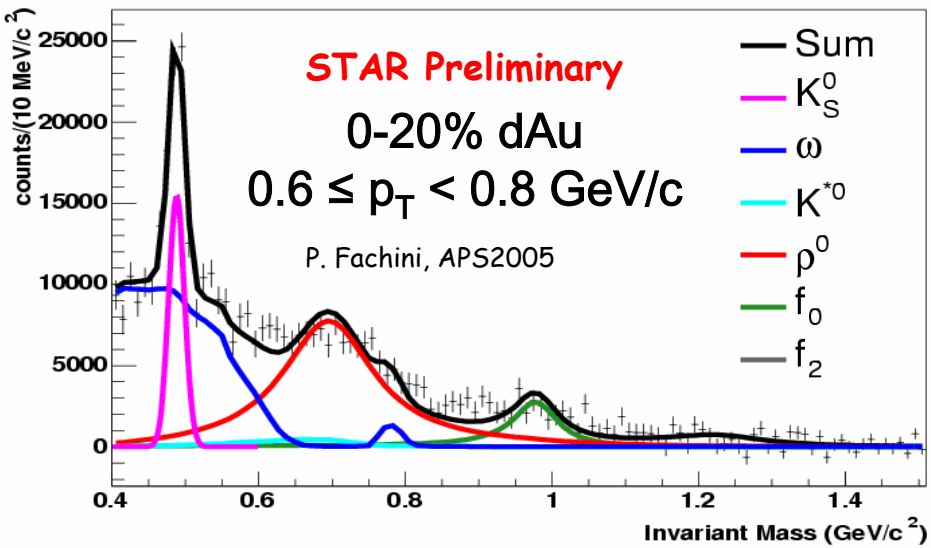
Background subtracted ⇒ like-sign

|y|<0.5

# Raw Invariant Mass Distribution from Data



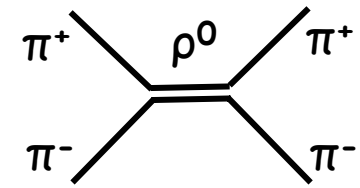




- Background subtracted ⇒ like-sign
- Different centralities dAu
- $\sqrt{s_{NN}}$ = 200 GeV
- |y|<0.5

# 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 = Inverse Slope
- pp ⇒ particle composition reasonably reproduced by statistical model ⇒ T = 160 MeV ⇒ also dAu

  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

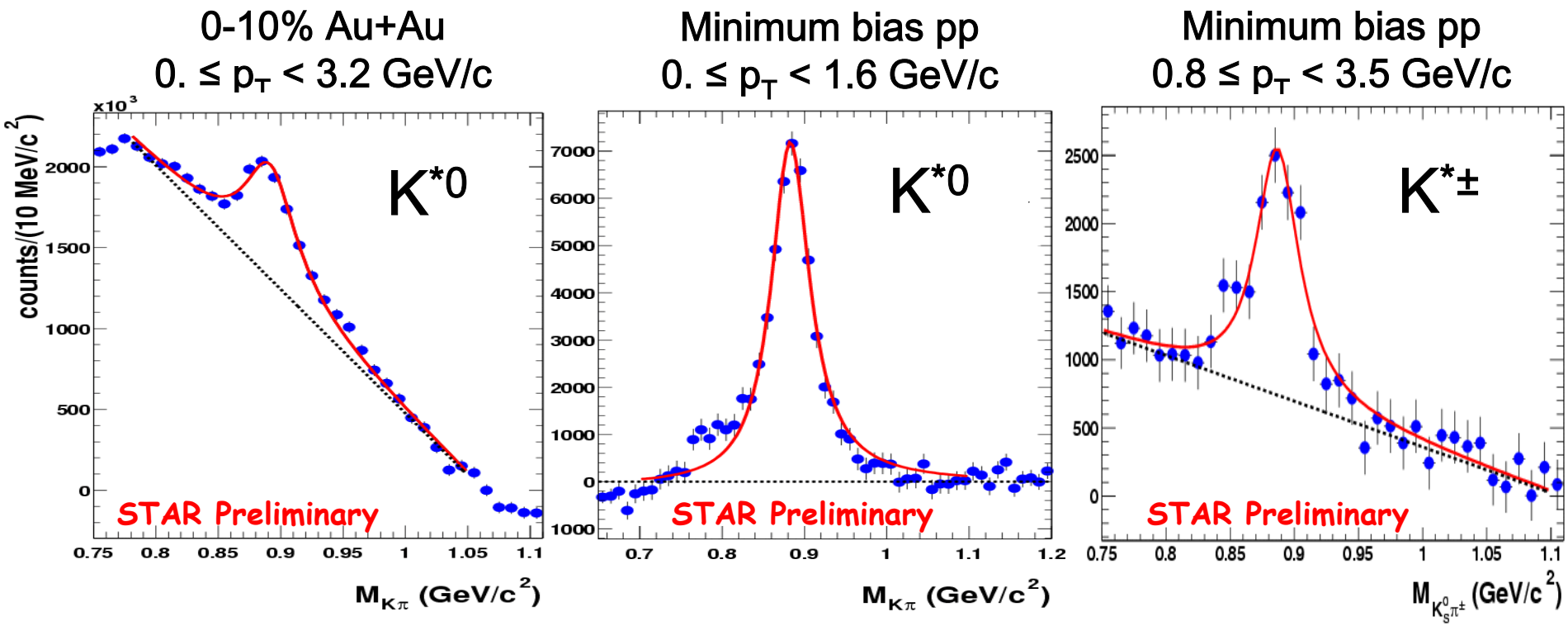
  E.V. Shuryak and G.E. Brown, Nucl. Phys. A 717 (2003) 322

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

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.

# Raw Invariant Mass Distribution from Data

J. Adams *et al.*, nucl-ex/0412019 to be published PRC

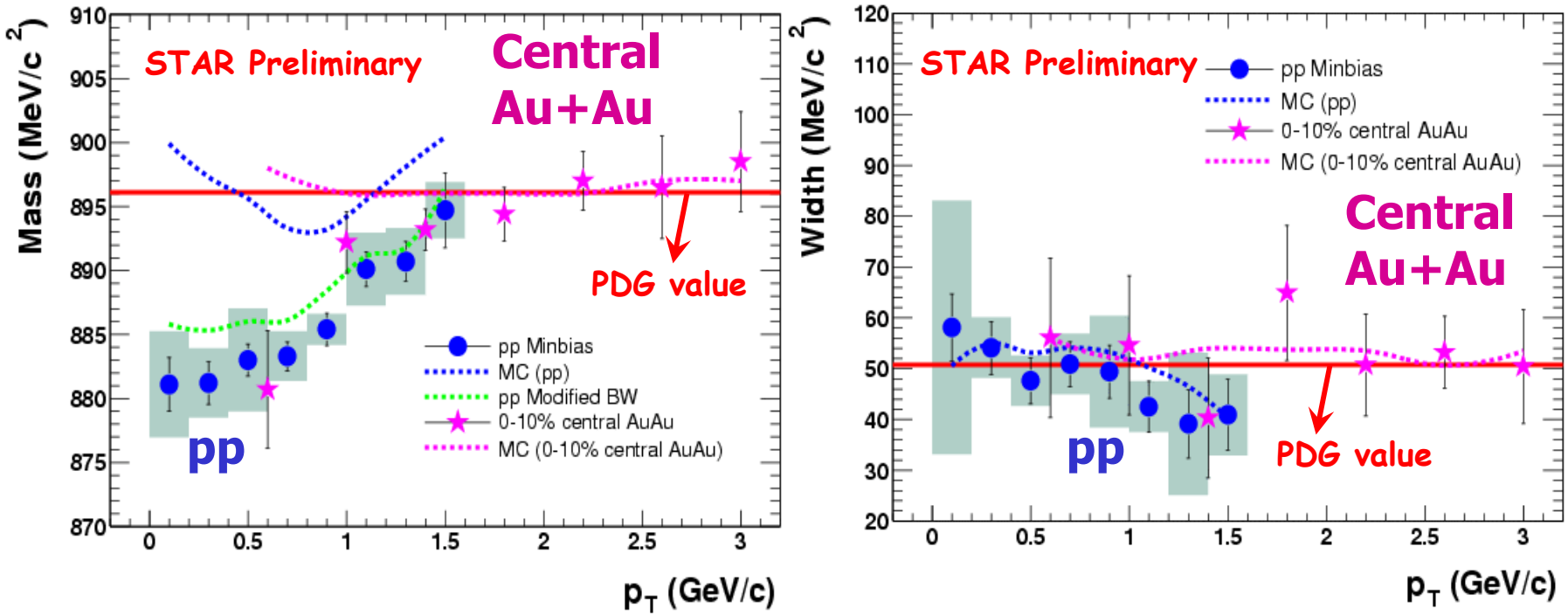



- Background subtracted ⇒ mixed-event
- $\sqrt{s_{NN}}$ = 200 GeV and |y|<0.5

# $K^{*0}$ Mass and Width ⇒ pp and Au+Au $\sqrt{s_{NN}}$ = 200 GeV

J. Adams *et al.*, nucl-ex/0412019 to be published PRC

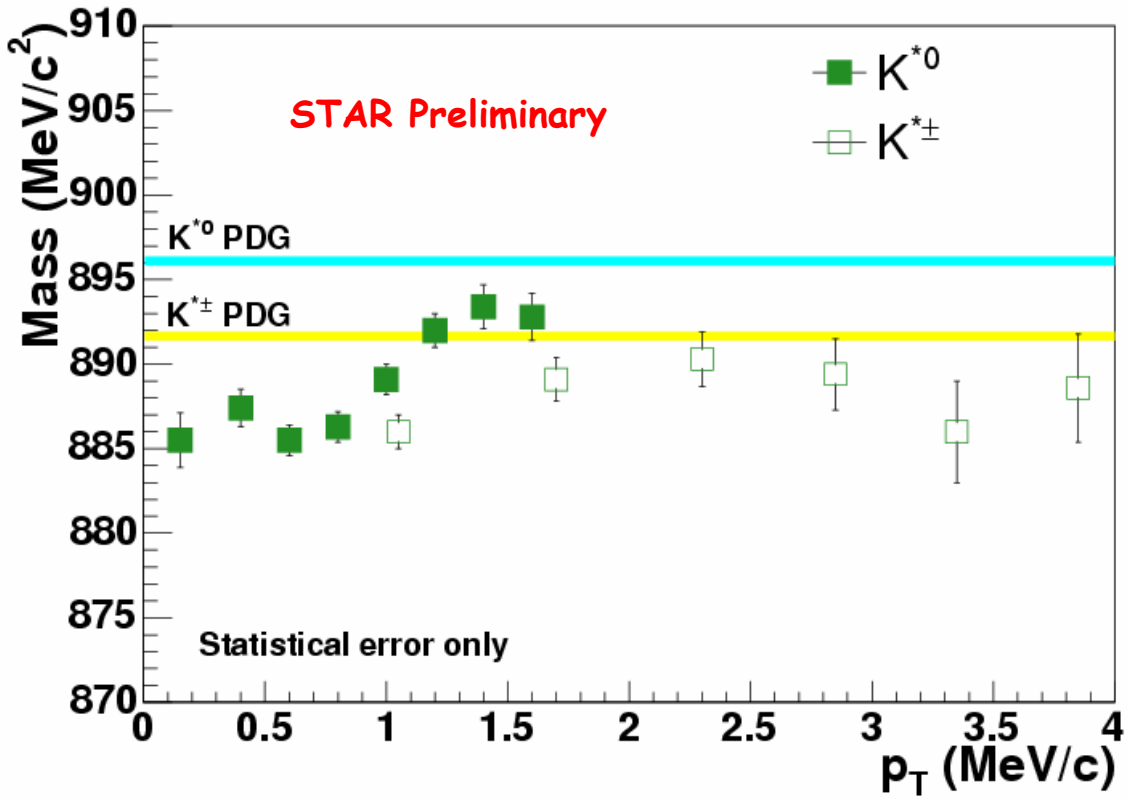
|y|< 0.5




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

# $K^{*0}$ and $K^{*\pm}$ Mass ⇒ Minimum bias dAu $\sqrt{s_{NN}}$ = 200 GeV

P. Fachini, APS2005

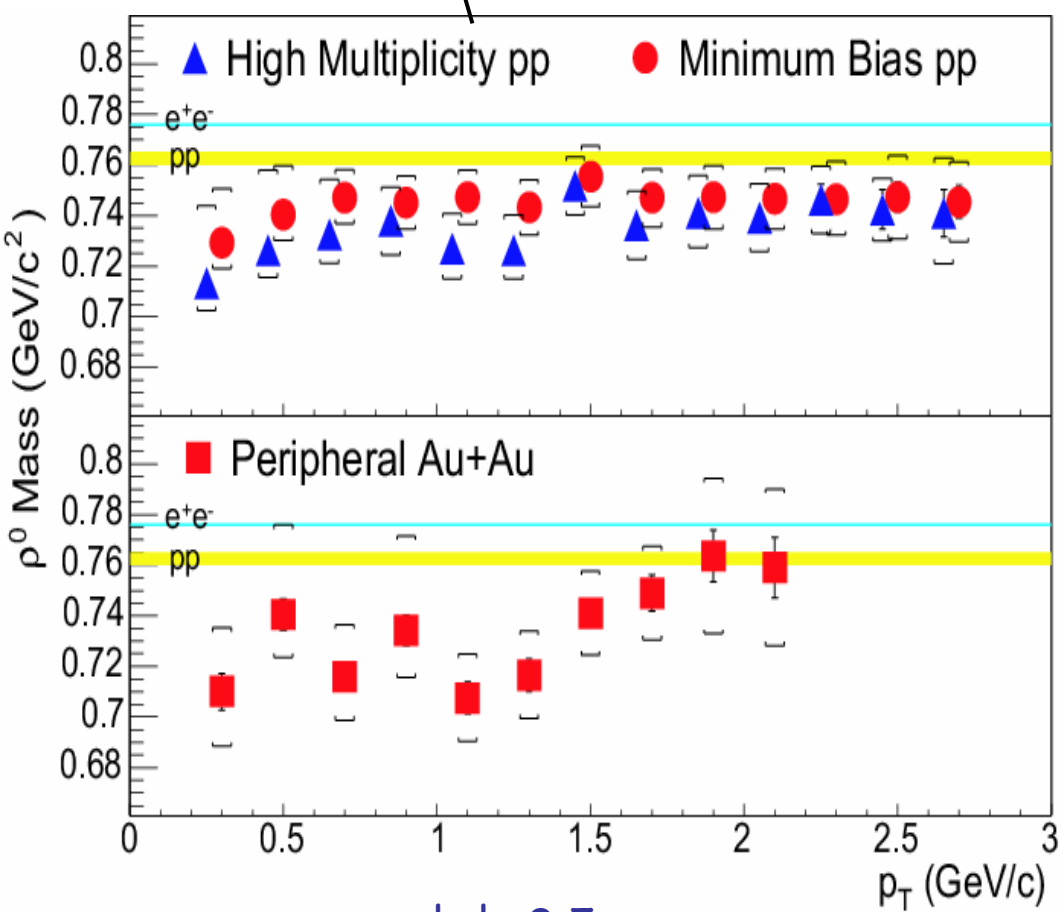



- $K^{*0}$ mass ⇒ shifted in dAu at low $p_T$
- $K^{*\pm}$ mass ⇒ agreement with PDG in dAu at high $p_T$

# $\rho^0$ Mass ⇒ pp and Au+Au $\sqrt{s_{NN}}$ = 200 GeV

J. Adams *et al.*, PRL 92 (2004) 092301

10% of minimum bias p+p for |η|< 0.5




|y|< 0.5

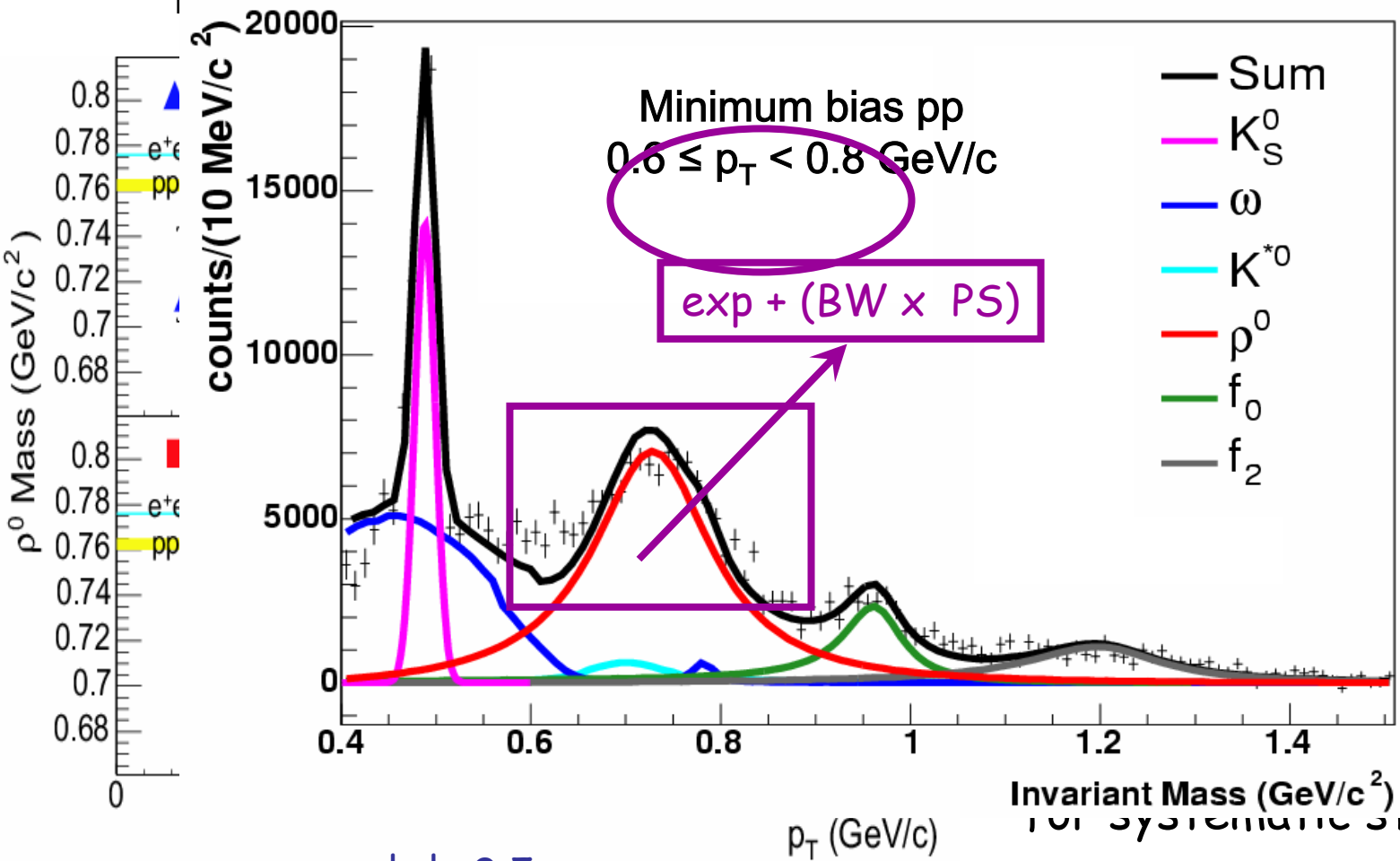
$e^+e^-$ ⇒ PDG average from **EXCLUSIVE** ρ measurements ⇒ **ρ mass in vacuum ⇒ 775.9 ± 0.5 MeV/c²**

pp ⇒ $\sqrt{s}$ = 27.5 GeV only pp measurement PDG ⇒ **INCLUSIVE** ρ measurement ⇒ **NOT** the ρ mass in vacuum

# $\rho^0$ Mass ⇒ pp and Au+Au $\sqrt{s_{NN}}$ = 200 GeV

J. Adams *et al.*, PRL 92 (2004) 092301

10% of minimum bias p+p for |η|< 0.5

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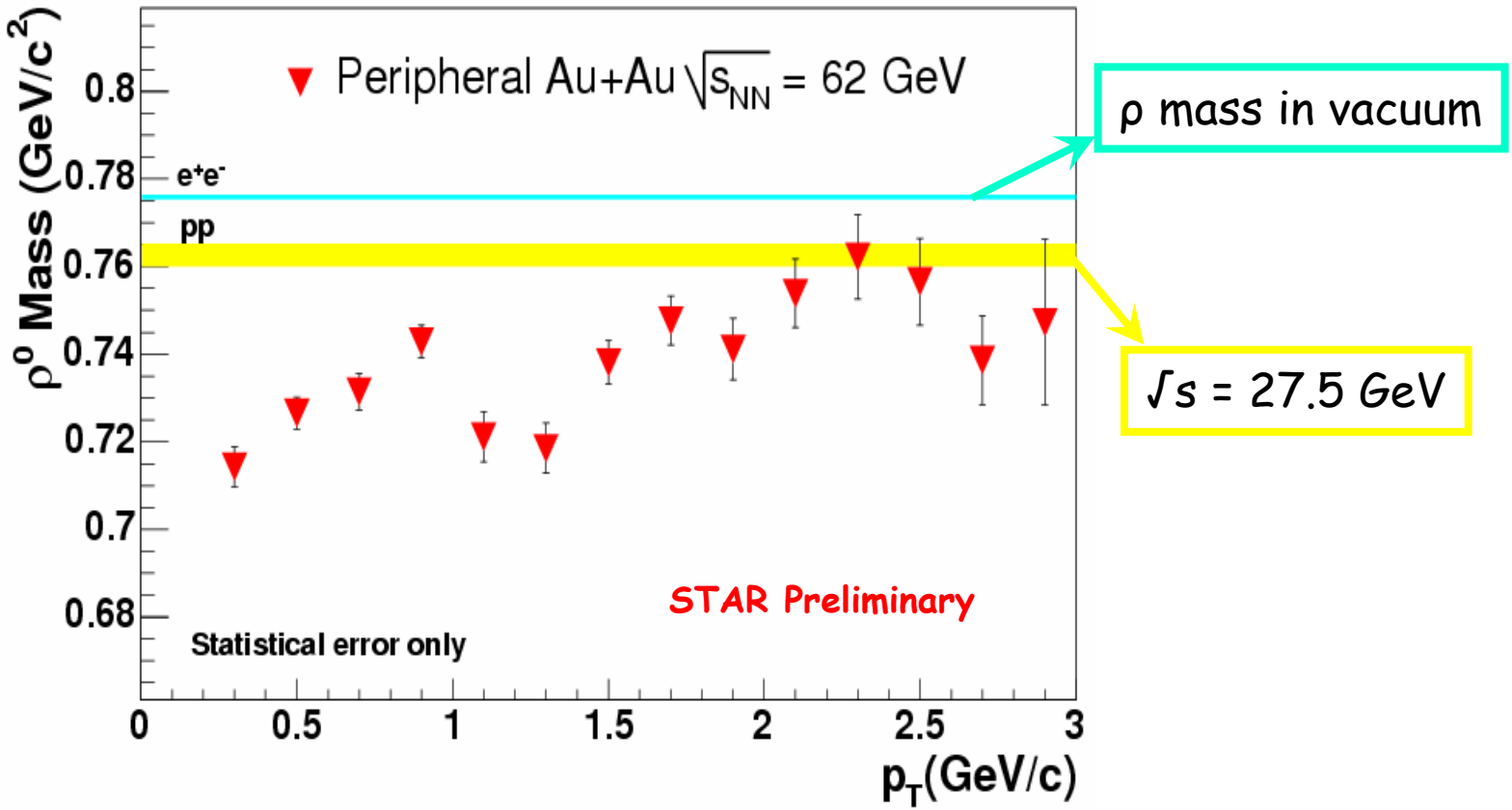
|y|< 0.5

# $\rho^0$ Mass $\Rightarrow$ 40-80% Au+Au $\sqrt{s_{NN}}$ = 62 GeV

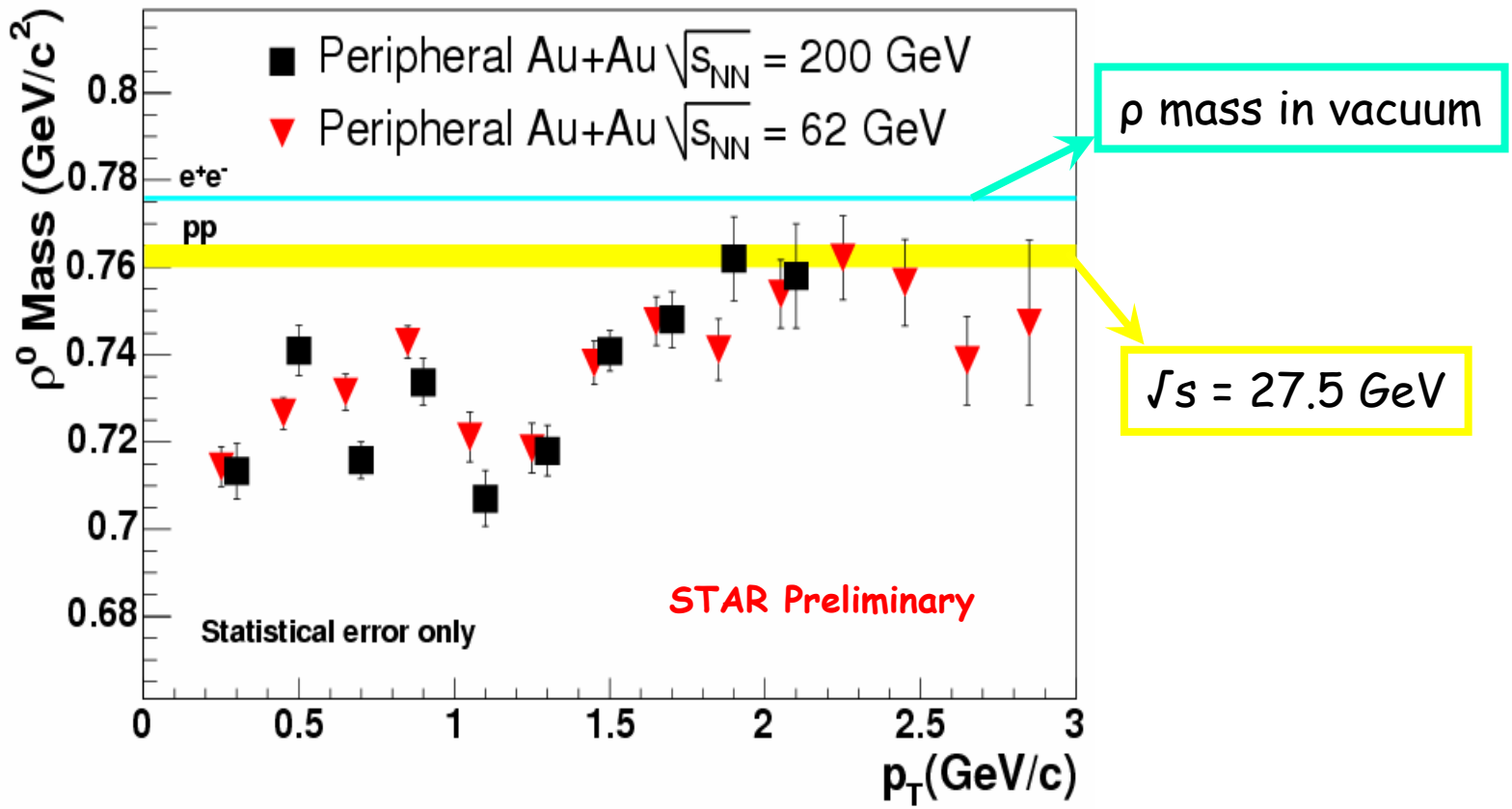
P. Fachini, APS2005




- $\rho^0$ mass $\Rightarrow$ $p_t$ dependent and lower than previous pp measurement below 2 GeV within statistical error

# $\rho^0$ Mass $\Rightarrow$ 40-80% Au+Au $\sqrt{s_{NN}}$ = 62 GeV

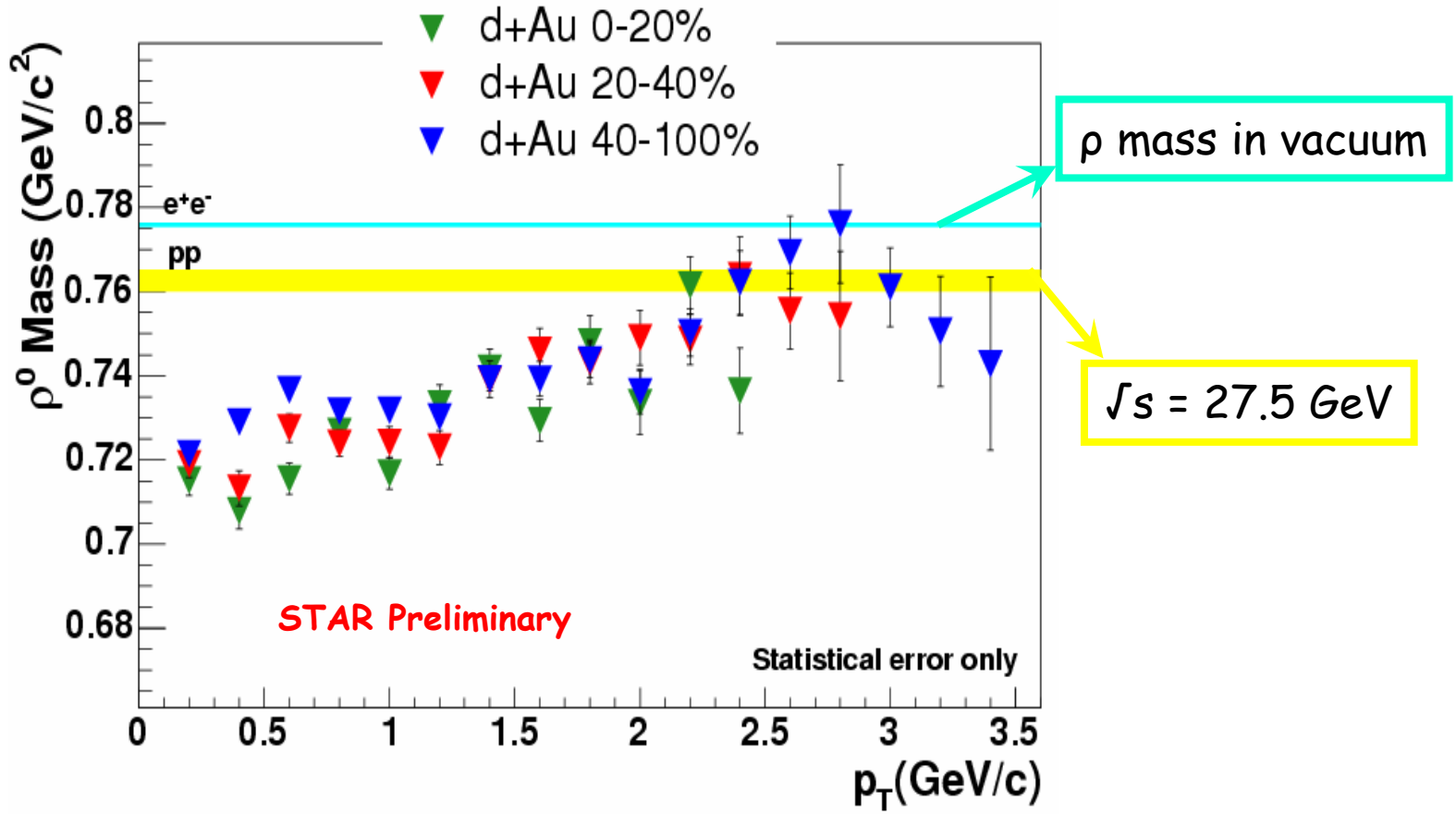
P. Fachini, APS2005




- $\rho^0$ mass $\Rightarrow$ peripheral Au+Au $\sqrt{s_{NN}}$ = 62 GeV and $\sqrt{s_{NN}}$ = 200 GeV comparable

# $\rho^0$ Mass $\Rightarrow$ dAu $\sqrt{s_{NN}}$ = 200 GeV

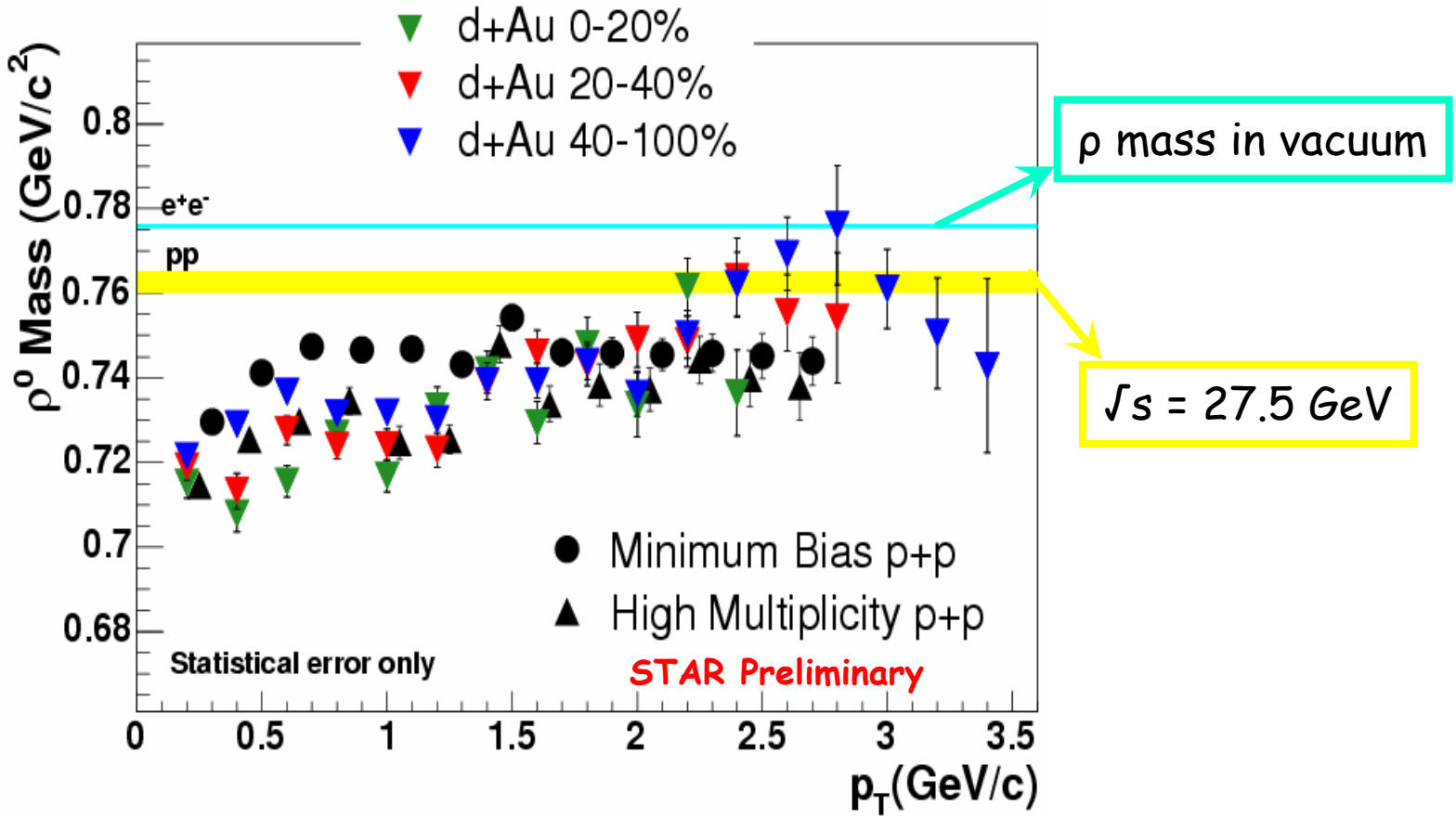
P. Fachini, APS2005




- $\rho^0$ mass $\Rightarrow$ $p_t$ dependent and lower than previous pp measurement below 2 GeV within statistical error

# $\rho^0$ Mass $\Rightarrow$ dAu $\sqrt{s_{NN}}$ = 200 GeV

P. Fachini, APS2005




- $\rho^0$ mass $\Rightarrow$ dAu and high multiplicity pp $\sqrt{s_{NN}}$ = 200 GeV comparable

# Previous Measurements

# What about previous measurements???

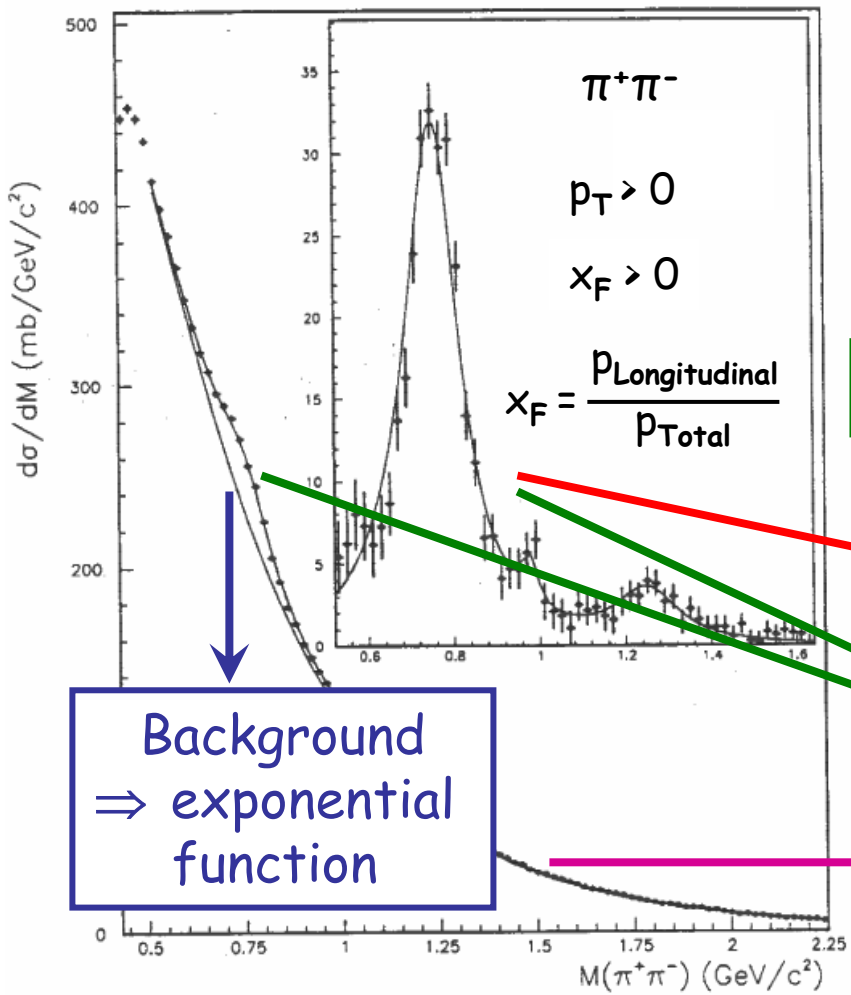
- $K^{*0}$ ⇒ no detailed mass measurements ⇒ mass integrated in $p_T$, $x_F$, $x_p$ ⇒ previous experiments agree PDG value
- STAR measurement ⇒ $K^{*0}$ mass shifted ~10 MeV/$c^2$ in minimum bias pp for $p_T$ < 1 GeV/c

- $\rho$ ⇒ no detailed mass measurements ⇒ mass integrated in $p_T$, $x_F$, $x_p$
- STAR measurement ⇒ $\rho^0$ mass shifted ~40 MeV/$c^2$ in minimum bias pp
- Previous $\rho^0$ mass measurements ⇒ NA27, OPAL, DELPHI, and ALEPH

- **NOTE:** Previous experiments interested in cross-sections and **NOT** in mass!

# $\rho^0$-meson Measured in pp ⇒ NA27

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




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

BG + PS x BW = BG + BGxBW = BG(1 + BW)

PS = BG

BW = Breit-Wigner

BG = Background

PS = Phase Space

Signal $\pi^+\pi^-$ distribution after background subtraction

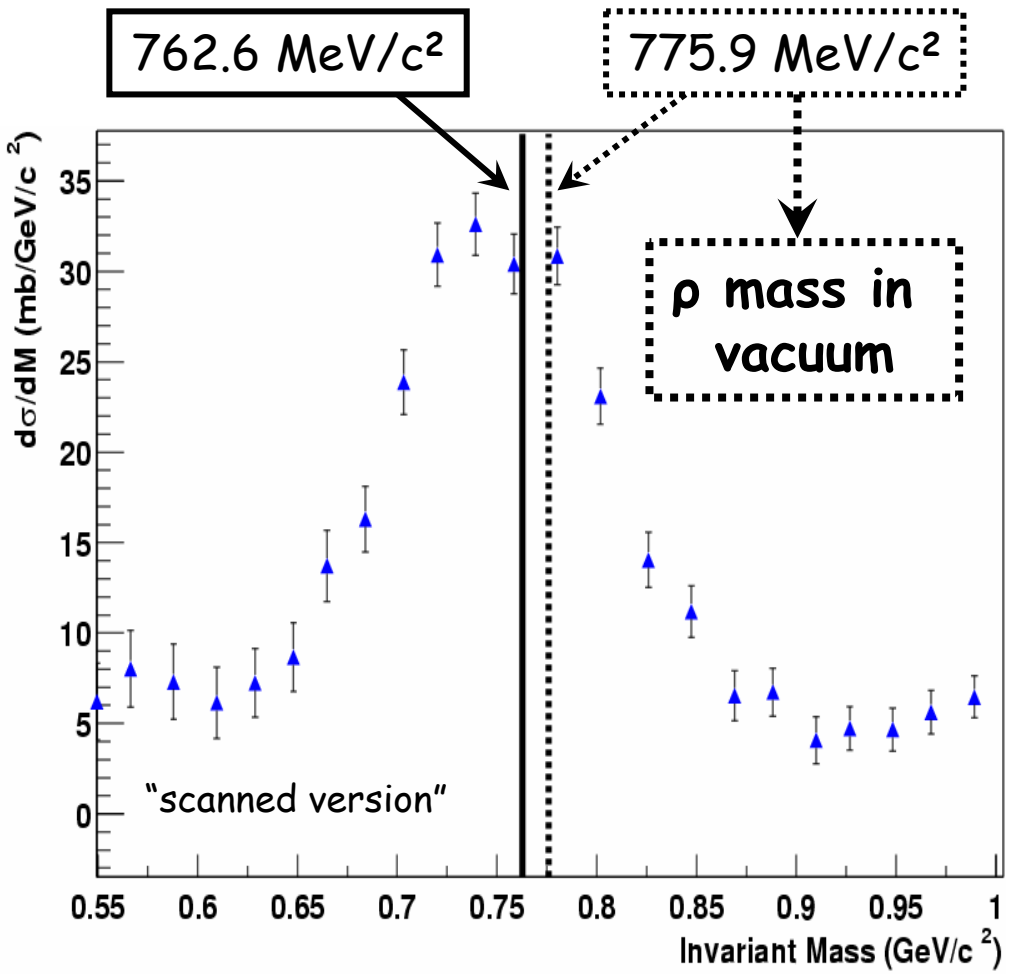
Signal

Background ⇒ exponential function

Same event distribution $\pi^+\pi^-$

# $\rho^0$-meson Measured in pp ⇒ NA27

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

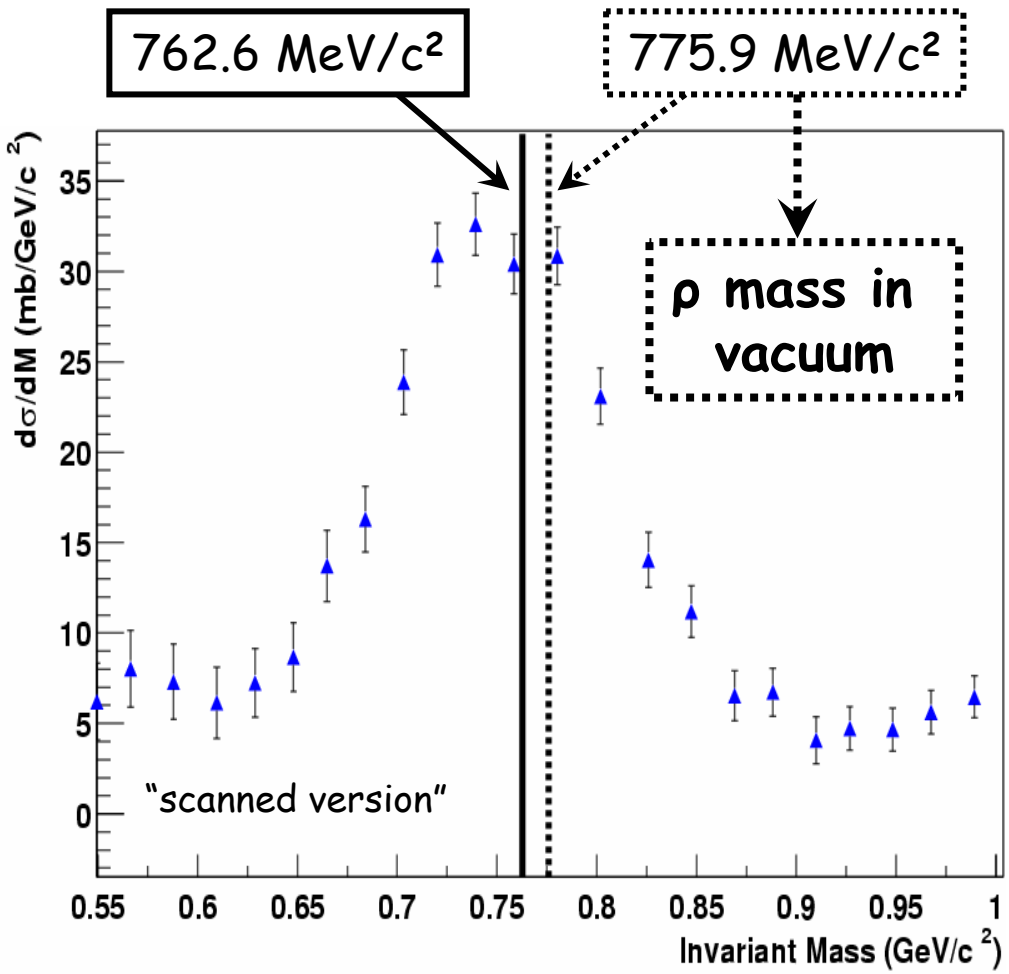



- CERN ⇒ $\sqrt{s}$ = 27.5 GeV
- $\rho^0$ mass = 762.6 ± 2.6 MeV/c² ⇒ only pp measurement used in average by PDG
- PDG average "other reactions" hadroproduced ⇒ $\rho^0$ mass = 769.0 ± 0.9 MeV/c²
- PDG average $e^+e^-$ (exclusive) ⇒ ρ mass = 775.9 ± 0.5 MeV/c²

⇒ **The position of the $\rho^0$ peak is clearly below reported value**

# $\rho^0$-meson Measured in pp ⇒ NA27

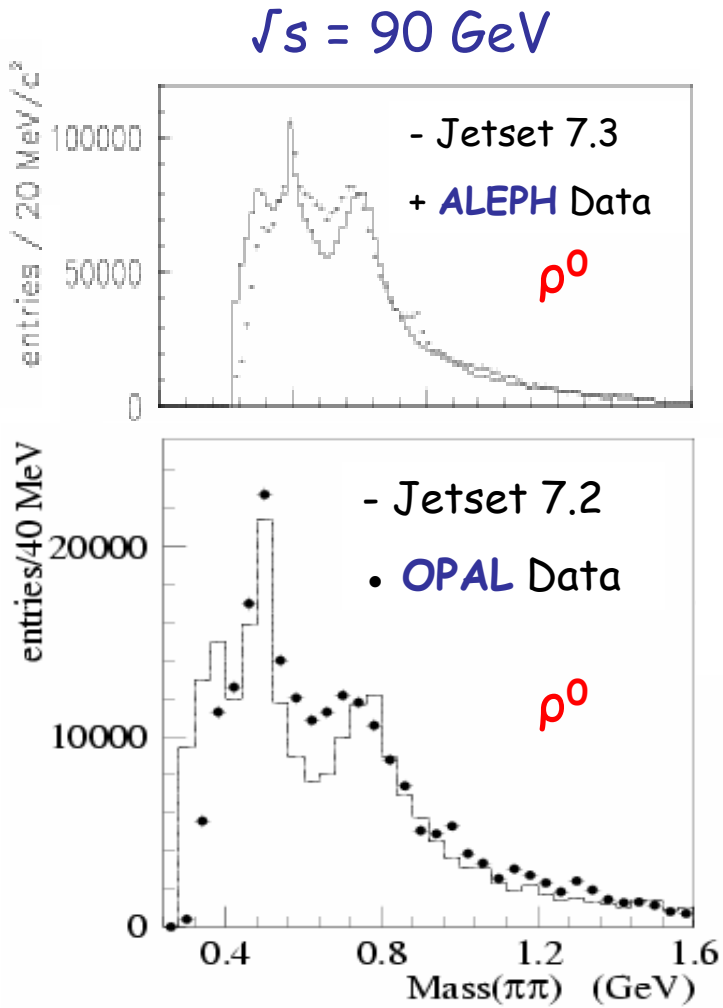
M. Aguilar-Benitez *et al.*, Z. Phys. C 50, 405 (1991)




- Ideally ⇒ phase space should have accounted for the shift in the $\rho^0$ peak ⇒ mass from the fit to the peak ⇒ ρ mass in vacuum ⇒ ρ mass = 775.9 ± 0.5 MeV/c² ⇒ PDG average $e^+e^-$ (exclusive)
- However ⇒ $\rho^0$ mass = 762.6 ± 2.6 MeV/c² ⇒ **Phase Space does not explain the shift of the $\rho^0$ peak!**

# $\rho^0$-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 $\Rightarrow$ $\rho^0$ mass shifted by ~70 MeV/c² at low $x_p$ and no shift at high $x_p$ ($x_p$ ~1)

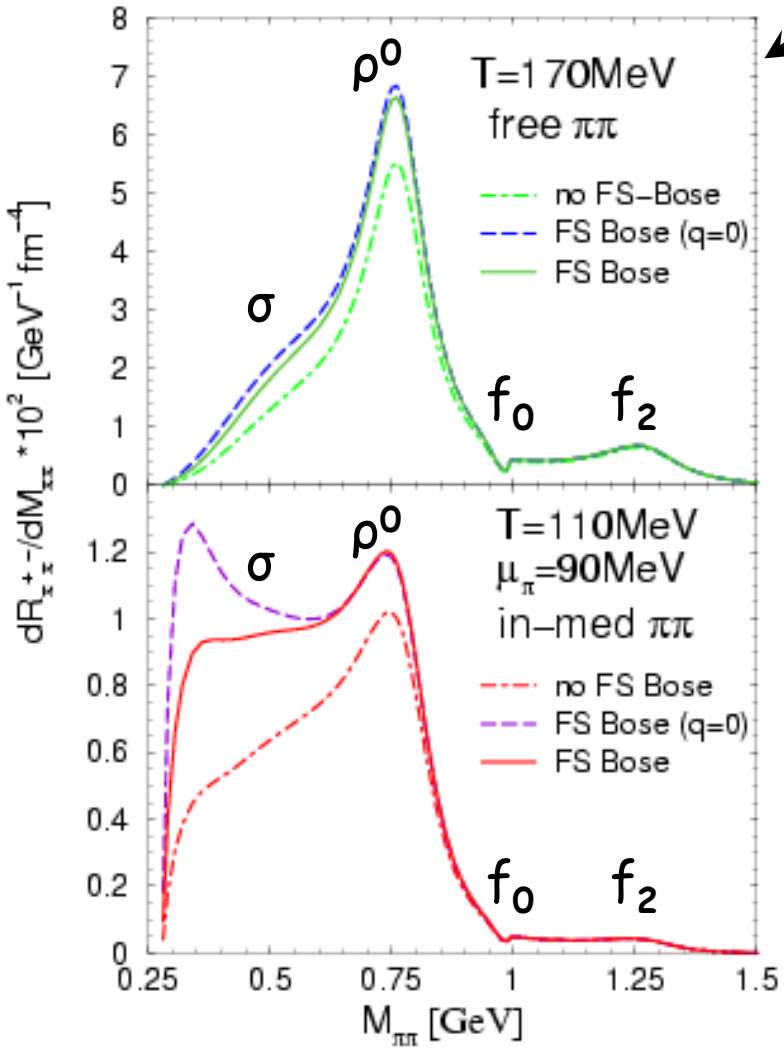
$$x_p = \frac{E(\text{meson})}{E(\text{beam})}$$

- OPAL $\Rightarrow$ -10 to -30 MeV/c² shift in the position of the maximum of the resonance $\rho^\pm$ $\Rightarrow$ consistent with $\rho^0$ measurement
- DELPHI $\Rightarrow$ $0.1 < x_p < 0.4$ $\Rightarrow$ $\rho^0$ peak fit to (BWxBG) + BG $\Rightarrow$ $\rho^0$ mass = 757 ± 2 MeV/c² $\Rightarrow$ five standard deviations below PDG value
- ALEPH $\Rightarrow$ same $\rho^0$ mass shift observed by OPAL

# Possible Explanations Mass Shift

# Possible Explanations for Mass Shift - I

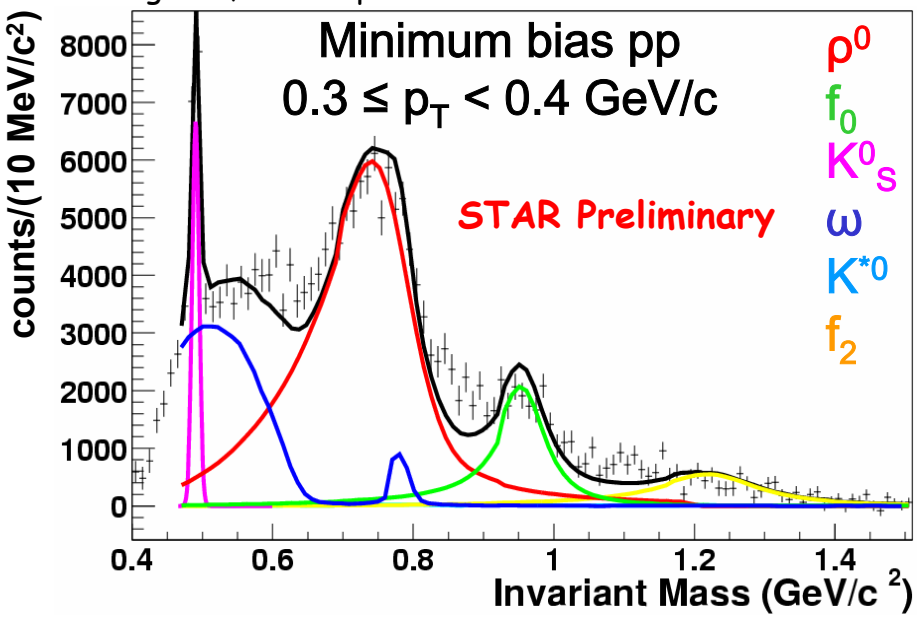
G.D. Lafferty, Z. Phys. C 60, 659 (1993); R. Rapp, Nucl.Phys. A725, 254 (2003); S. Pratt *et al.*, Phys.Rev. C68, 064905 (2003)

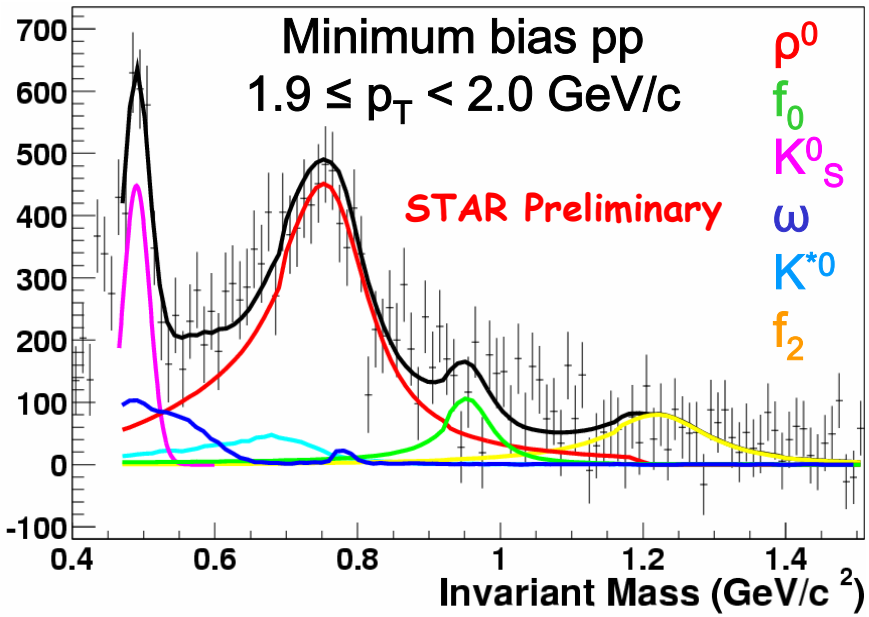


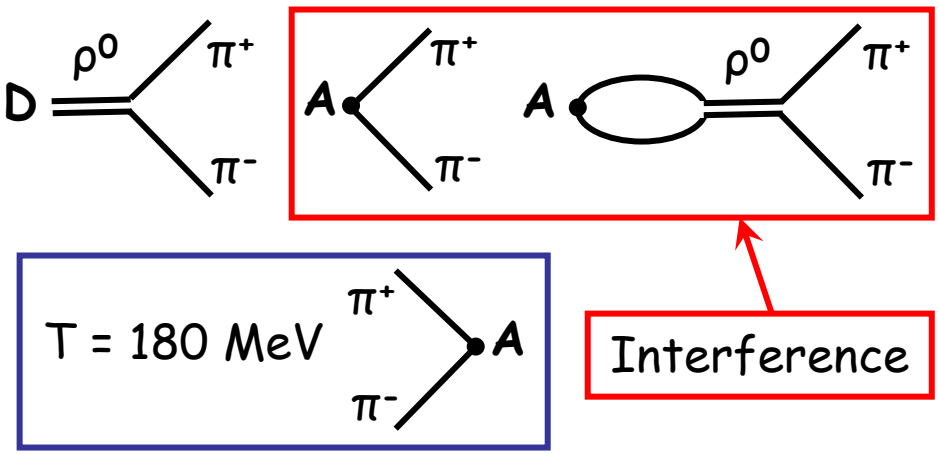

- **1. Bose-Einstein correlations** between $\rho^0$ decay daughters and pions in the surrounding matter ⇒ distortion of the $\rho^0$ spectral shape
- LEP ⇒ Bose-Einstein correlations used to explain the $\rho$ mass shift observed ⇒ need large values of Bose-Einstein parameters
- In-medium $\pi\pi$ in Au+Au at RHIC ⇒ adding Bose-Einstein correlations
  - $\rho^0$ peak shifted downward 5-10 MeV/c²
  - Rate increases ~20% around $\rho^0$ mass region
  - More pronounced $\sigma$ shoulder

# Possible Explanations for Mass Shift - II

R. Longacre, nucl-exp/0305015



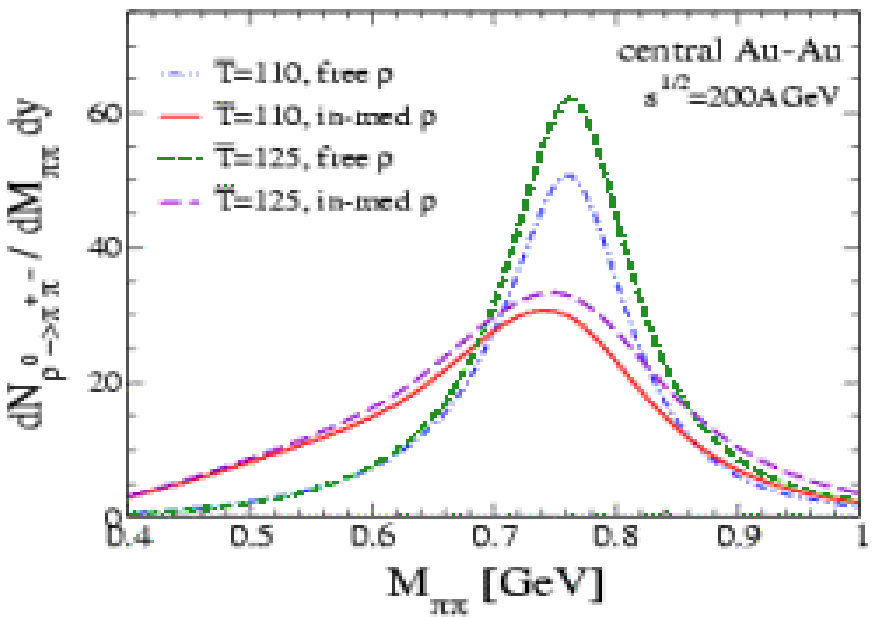




- **2. Interference** ⇒ Partial-wave analysis + $\pi^+\pi^-$ scattering
- $M_\rho$ = 779.1 MeV/c²
  $\Gamma$ = 150 MeV/c²
- Distance of interaction in $\pi^+\pi^-$ scattering ⇒ 1/3 fm

# Possible Explanations for Mass Shift - III

R. Rapp, Nucl.Phys. A725, 254 (2003)




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

⇒ Distortion of the $\rho^0$ 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/c² shift in the $\rho^0$ mass

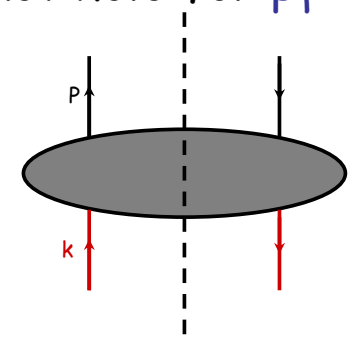
-38 MeV/c² shift in the $\rho^0$ mass due to t-channel attraction

# Possible Explanations for Mass Shift - IV

S. Kretzer, Acta Phys.Polon.B36, 179 (2005)

- Previous explanations for mass shift ⇒ should not hold for $p_T$ >~ 2.0 GeV in pp ⇒ fragmentation

$$\int_{\frac{M^2}{z}}^{\hat{s}} dk^2 \int_0^{\frac{1-z}{z}(k^2-\frac{M^2}{z})} dk_\perp^2$$




- **4. Fragmentation Function** ⇒ Qualitative (dual) features ⇒
  - Heavier hadrons come with a harder FF
  - Heavier hadrons suppressed
  - Short-lived resonances shifted to lower mass

$$\partial\left[\mathrm{BW}(M_\rho^2,\Gamma_\rho^2,P^2)\times\int_{\frac{P^2}{z}}^{\hat{s}}\frac{dk^2}{k^2}\right]/\partial P = 0$$

$$\Rightarrow P = M_\rho - \mathcal{O}\,(1 - \text{a few} \times 10\ \text{MeV})$$

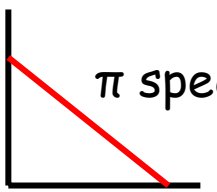
**"Partonic Phase Space"**

- And slowly approaching $M_\rho$ with increasing $p_T$

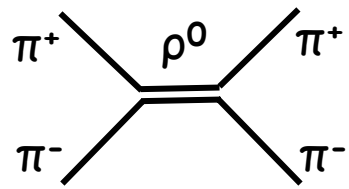
# Discussing Phase Space

# What is the meaning of Phase Space in Au+Au?

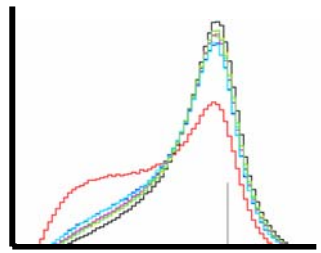
- Hadrons scattering ⇒ forming resonances ⇒ modifying mass distributions




⇒



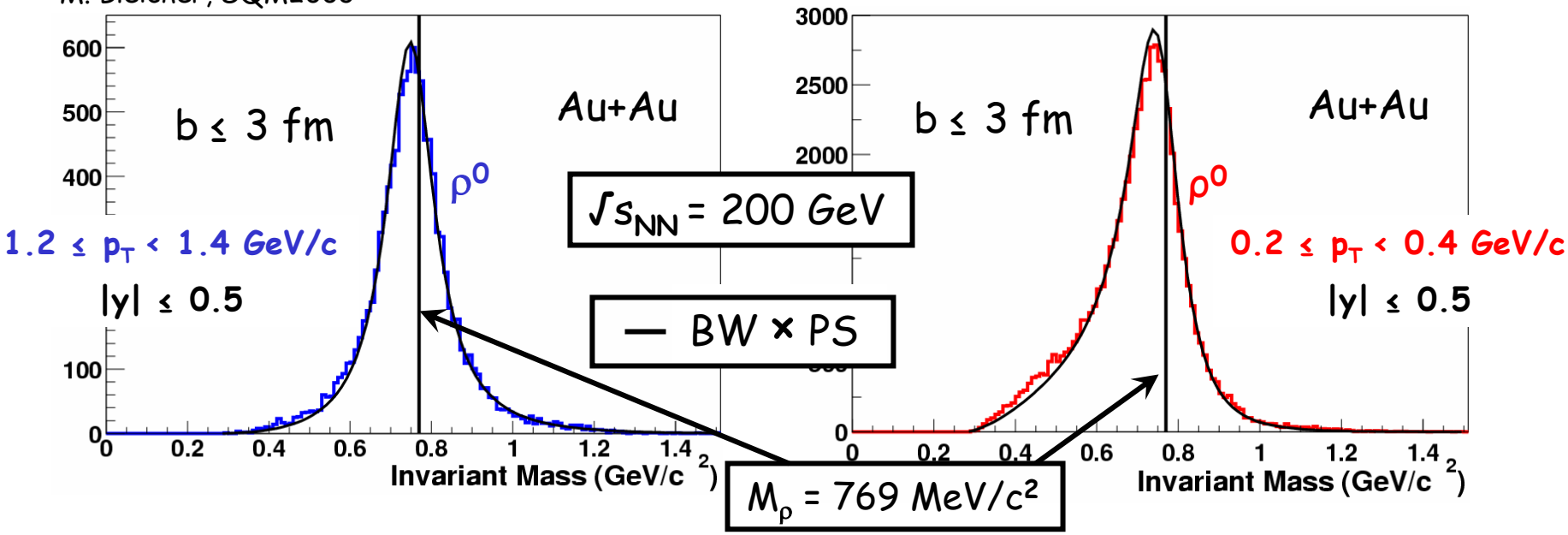

⇒ Γ = 150 MeV ⇒



- **Check** ⇒ Transport Model Calculations ⇒ UrQMD

# Transport Model - UrQMD

M. Bleicher, SQM2003




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

# What is the meaning of Phase Space in pp?

- Only few particles produced ⇒ unlike many final-state interactions
- Multiparticle production ⇒ invariant particle spectra typically exponential in $p_T$ ($m_T$).
- Reason exponential behavior ⇒ multiparticle production saturates available phase space ⇒ **no need to be thermodynamically equilibrated** ⇒ valid for pp and $e^+e^-$.
- Resonance mass ⇒ multiparticle production saturates available phase space ⇒ distortion invariant mass distribution?

# Phase Space in pp ⇒ **Possibility I**

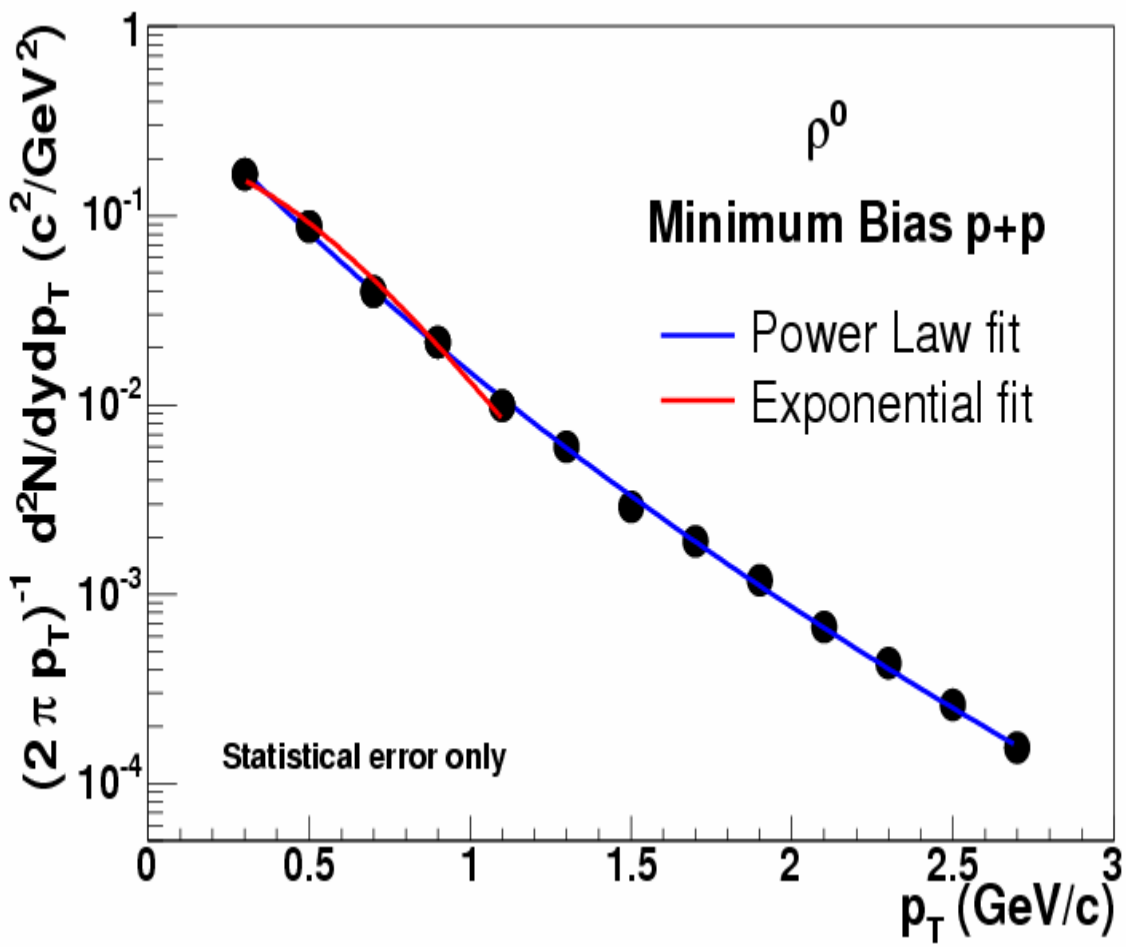
- Multiparticle production saturates available phase space

⇒ particle spectra $\sim e^{-\frac{p_T}{T}}$

⇒ mass distribution $\sim BW \times e^{-\frac{p_T}{T}}$

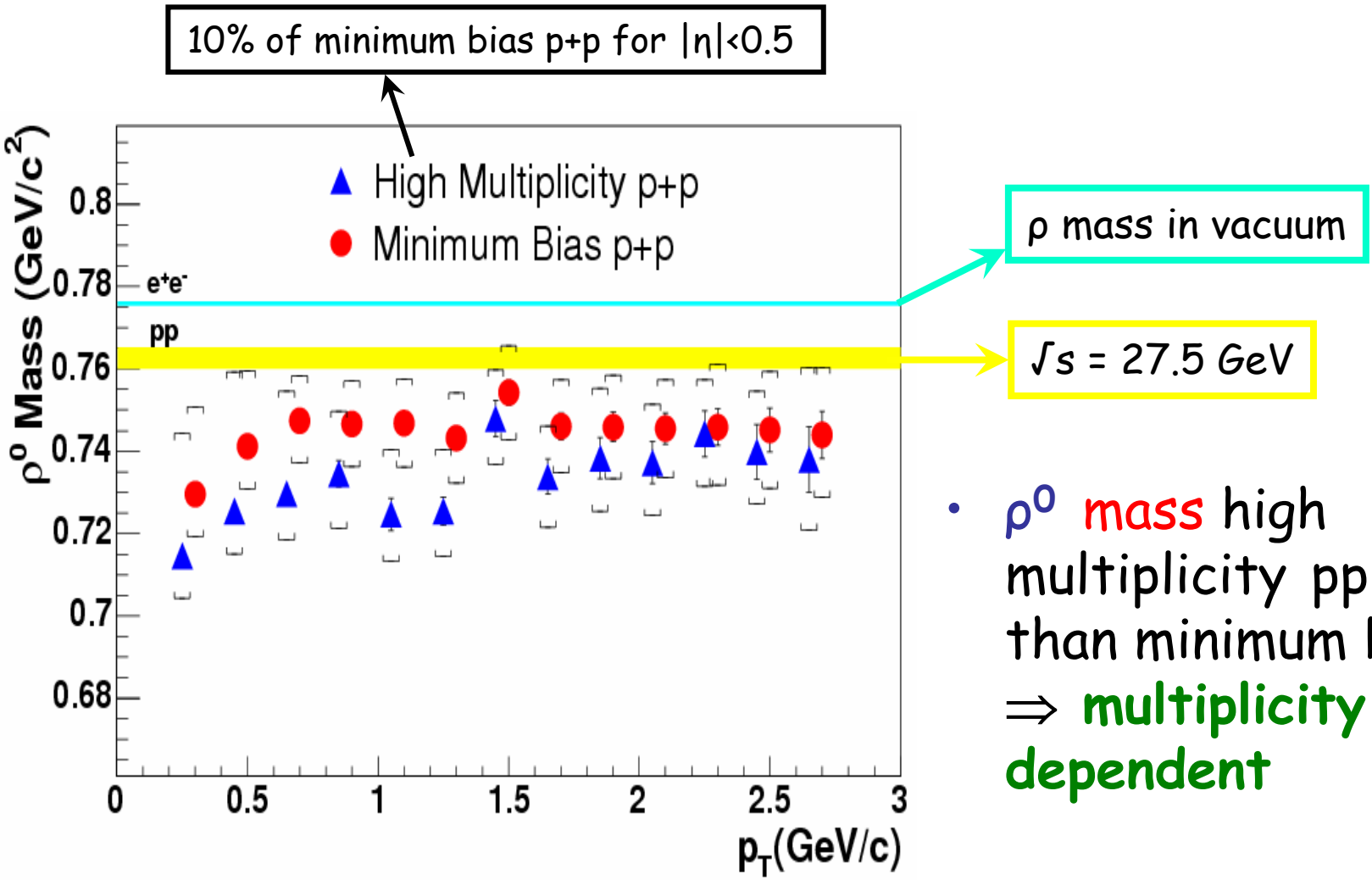
- Spectra and mass measurements consistent with this picture?
- What about quantum mechanics?

# $\rho^0$ Spectra in pp at $\sqrt{s_{NN}}$ = 200 GeV




- $\pi^-$ Minimum bias pp
  - $T_{slope}$ = 160 MeV
- $\rho^0$ Minimum bias pp
  - $T_{slope}$ ~ 180 MeV
- $\rho^0$ High Multiplicity pp
  - $T_{slope}$ ~ 180 MeV
- $\rho^0$ $T_{slope}$ **multiplicity independent**
- What about the mass?

# $\rho^0$ Mass in pp at $\sqrt{s_{NN}}$ = 200 GeV




- $\rho^0$ mass high multiplicity pp lower than minimum bias pp ⇒ multiplicity dependent

# Quantum Mechanics

- A resonance is formed when a particle and its wave packet is trapped inside a potential well elevated above the outside world
- The particle can tunnel thru the barrier and escape
- The particle has a frequency associated with the bound state of the well and its probability of being inside the well is an exponential decay
- This can be written as:

$$\Psi = \Psi_0 \, e^{-\frac{\gamma}{2}t} \, e^{-i\omega_0 t}$$

$\omega_0$ is the frequency of the bound state

$\frac{\gamma}{2}$ is the mean life time

# From Quantum Mechanics…

- Using the Fourier transformation:

$$\Psi(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \Psi(t)\, e^{i\omega t}\, dt$$

we can write:

$$\Psi(\omega) = \frac{\Psi_0}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{i(\omega - \omega_0 + i\frac{\gamma}{2})t}\, dt$$

and integrating with:

$$u = \omega - \omega_0 + i\frac{\gamma}{2}$$

# From Quantum Mechanics…

The result is :

$$\Psi(\omega) = \frac{\Psi_0}{(\omega - \omega_0 + i\frac{\gamma}{2})} \times \frac{1}{\sqrt{2\pi}} e^{iu} \Big|_{-\infty}^{\infty}$$

$$\Psi(\omega) = \frac{\frac{\gamma}{2}}{(\omega_0 - \omega - i\frac{\gamma}{2})}$$

which is a Breit-Wigner function with : $\begin{cases} \omega_0 \Leftrightarrow \text{Mass} \\ \frac{\gamma}{2} \Leftrightarrow \text{Width} \end{cases}$

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

# Phase Space in pp ⇒ **Possibility I**

- $\rho^0$ $T_{slope}$ independent of multiplicity

and

- $\rho^0$ mass **multiplicity dependent**

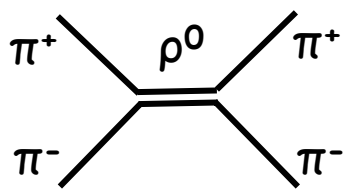
and

- Quantum Mechanics ⇒ Resonance mass distribution ⇒ **Breit-Wigner function!**

⇒ **Possibility I** ⇒ **Inconsistent!**

# Phase Space in pp ⇒ **Possibility II**

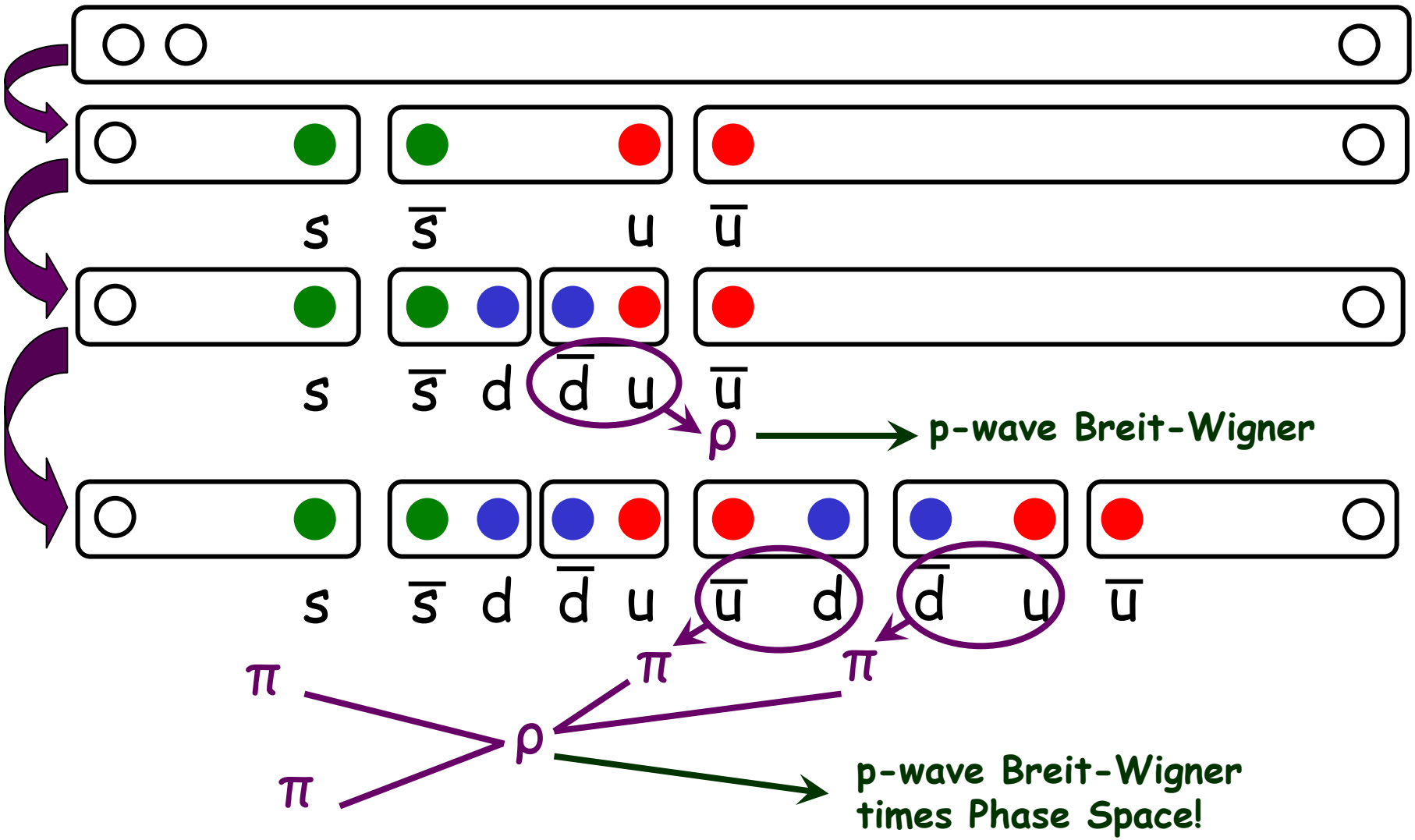
- Multiparticle production saturates available phase space ⇒ exponential particle spectra
- Hadron interactions




modify the resonance mass distribution from a Breit-Wigner function.

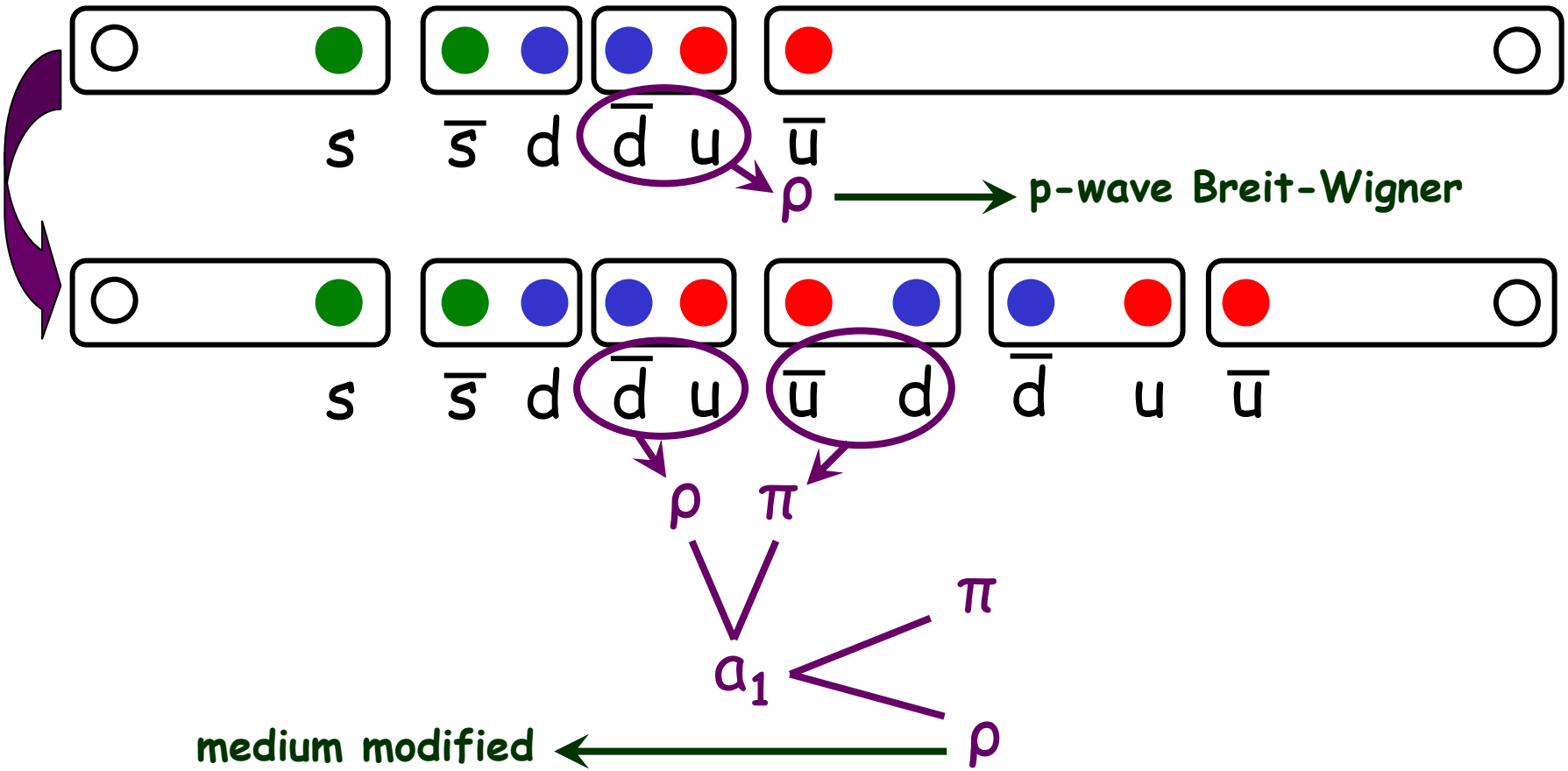
⇒ **Significant scattering interactions in pp (and $e^+e^-$)**

# pp ⇒ Particle production: String Fragmentation



# pp ⇒ Particle production: String Fragmentation

⇒ **Going even further ⇒ possible medium modifications**



# Summary - I

- $\rho^0$ and $K^{*0}$ ⇒ mass shift observed in pp, dAu, and Au+Au collisions ⇒ even **after phase space correction**
- $\rho^0$ mass shift
  - Peripheral Au+Au $\sqrt{s_{NN}}$ = 200 GeV
  - Peripheral Au+Au $\sqrt{s_{NN}}$ = 62 GeV
  - High multiplicity pp $\sqrt{s_{NN}}$ = 200 GeV
  - dAu $\sqrt{s_{NN}}$ = 200 GeV

  } ⇒ Comparable
- $\rho^0$ mass shift observed by previous experiments ⇒ NA27, OPAL, DELPHI, and ALEPH ⇒ even **after phase space correction**
- **Phase space** ⇒ does **NOT** reproduce mass shift measured

# Summary - II

- Possible explanations mass shift
  - Medium modification
  - Interference
  - Bose-Einstein correlations
  - "Partonic phase space" ⇒ high $p_T$
- Interference and Bose-Einstein ⇒ do **NOT** explain mass shift **peripheral Au+Au**, **high multiplicity pp**, and **dAu** ⇒ Medium modification ?
- **Phase space** discussion ⇒ significant scattering interactions in pp ⇒ even possible medium modification ?

⇒ Resonances can provide information on the collision dynamics