Effects of resonance widths on particle spectra and anisotropies

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From QCD matter to hadrons

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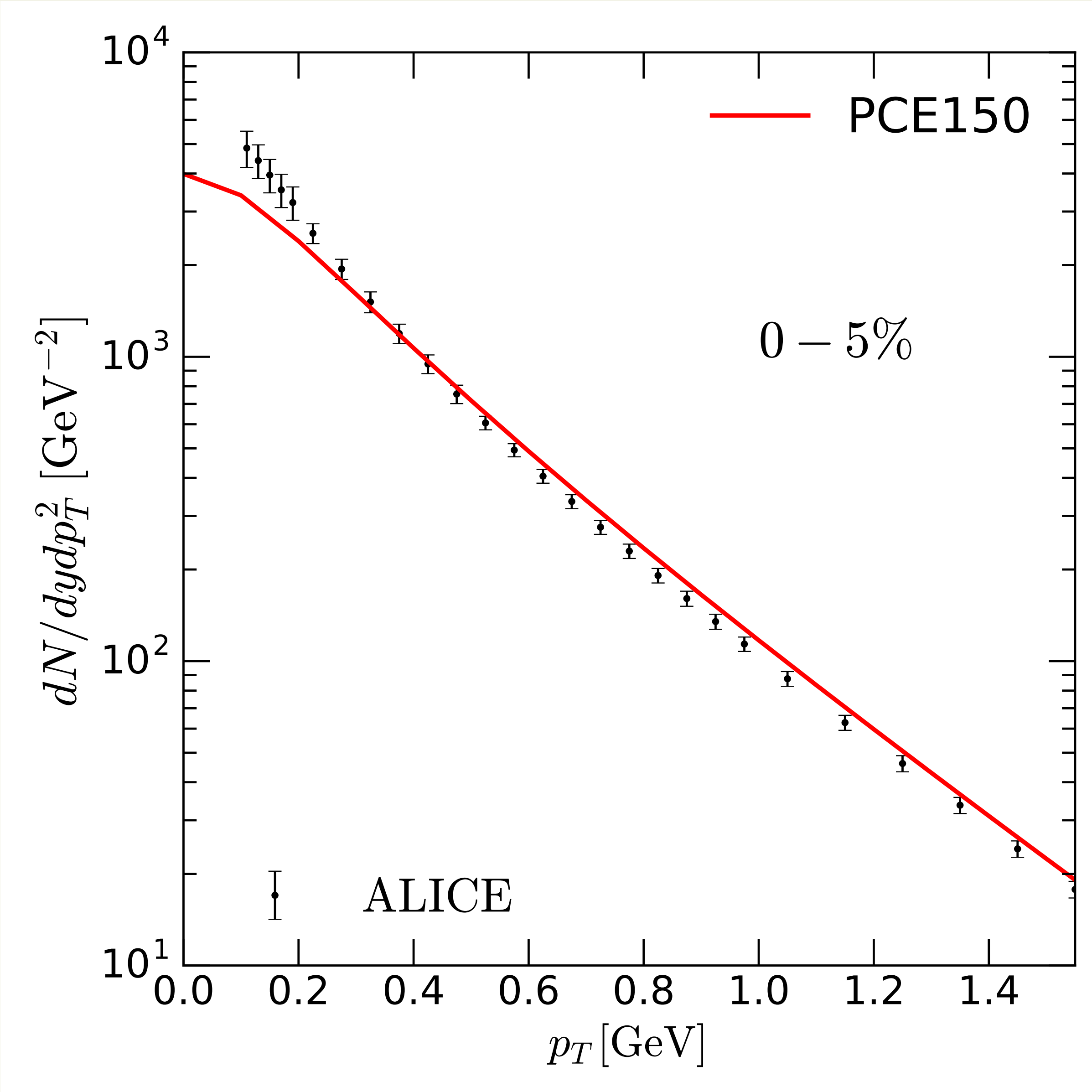
in collaboration with
Pok Man Lo
and M. Marczenko, K. Redlich, C. Sasaki

Pion p_T spectrum at LHC (Pb+Pb at $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$)



- **viscous hydro**
- **initial state:**

pQCD+saturation

- $\tau_0 \approx 0.2\mathrm{fm}/c$

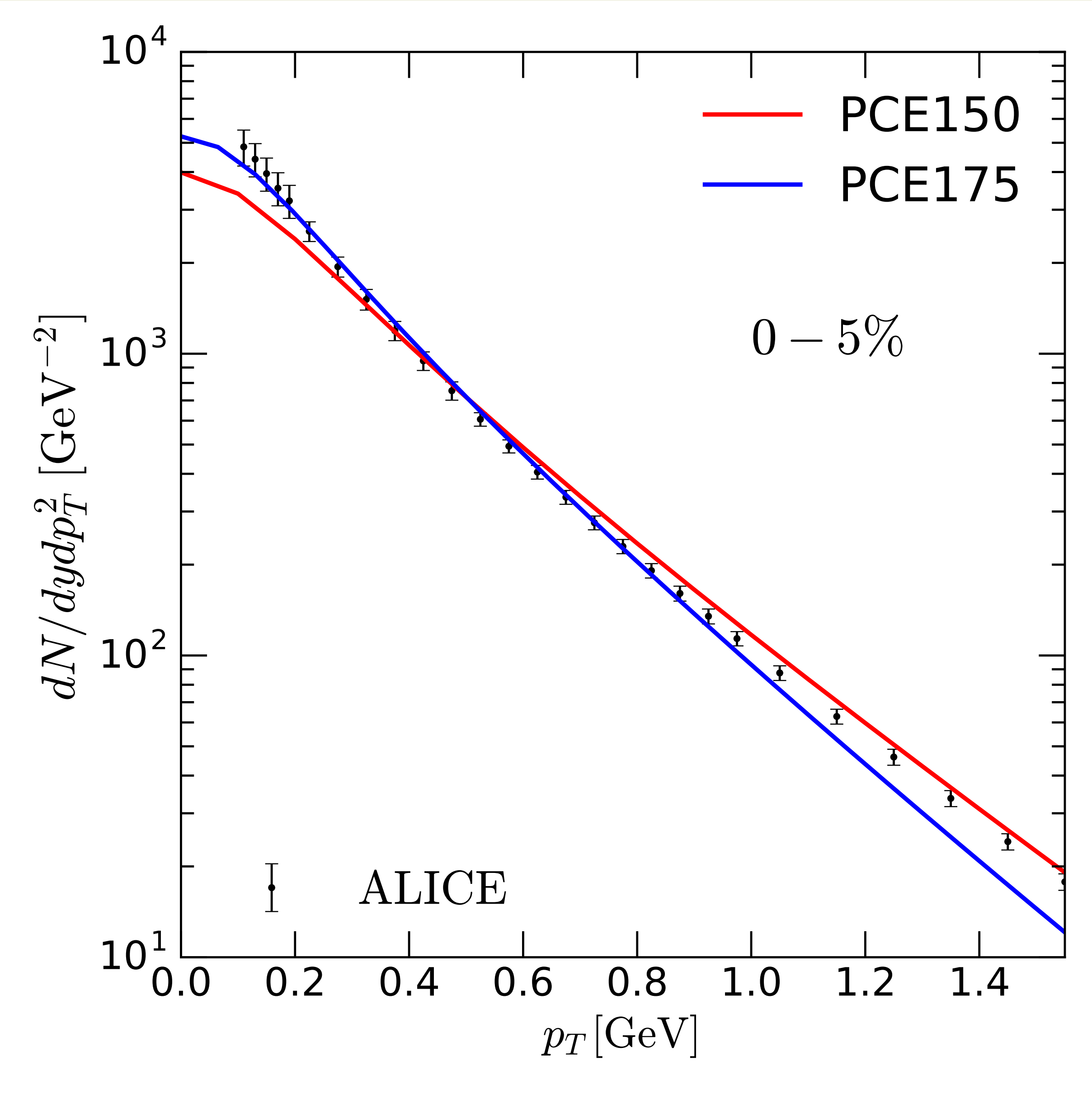
PCE150:

fit to π, K, p yields

no fit to spectrum

©H. Niemi

Pion p_T spectrum at LHC (Pb+Pb at $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$)



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- **initial state:** **pQCD+saturation**
- $\tau_0 \approx 0.2\mathrm{fm}/c$

PCE150:
fit to π, K, p yields
no fit to spectrum

PCE175:
no fit to yields
fits the spectrum

©H. Niemi

- **need more resonances**

- **yield proportional to Boltzmann factor**

$$N \propto \exp\left(-\frac{m}{T}\right)$$

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- **resonance mass?**

- **usually no width, i.e. resonances have their pole mass**

effect of Breit-Wigner width on number density:

$$n = \int \mathrm{d}^3\mathbf{p}\, f(p)$$
$$\Rightarrow n = \int \mathrm{d}^3\mathbf{p} \int \mathrm{d}m^2 \frac{\mathrm{d}\rho}{\mathrm{d}m^2} f(p,m)$$

where

$$\frac{\mathrm{d}\rho}{\mathrm{d}m^2} = \frac{1}{N}\frac{m_R\Gamma}{(m^2-m_R^2)^2+m_R^2\Gamma^2},$$

with normalisation

$$N = \int_{m_0}^{\infty} \mathrm{d}m^2 \frac{m_R\Gamma}{(m^2-m_R^2)^2+m_R^2\Gamma^2}$$

For ρ^0 $m_R = 775.26\,\mathbf{MeV}$ **and** $\Gamma = 147.8\,\mathbf{MeV}$

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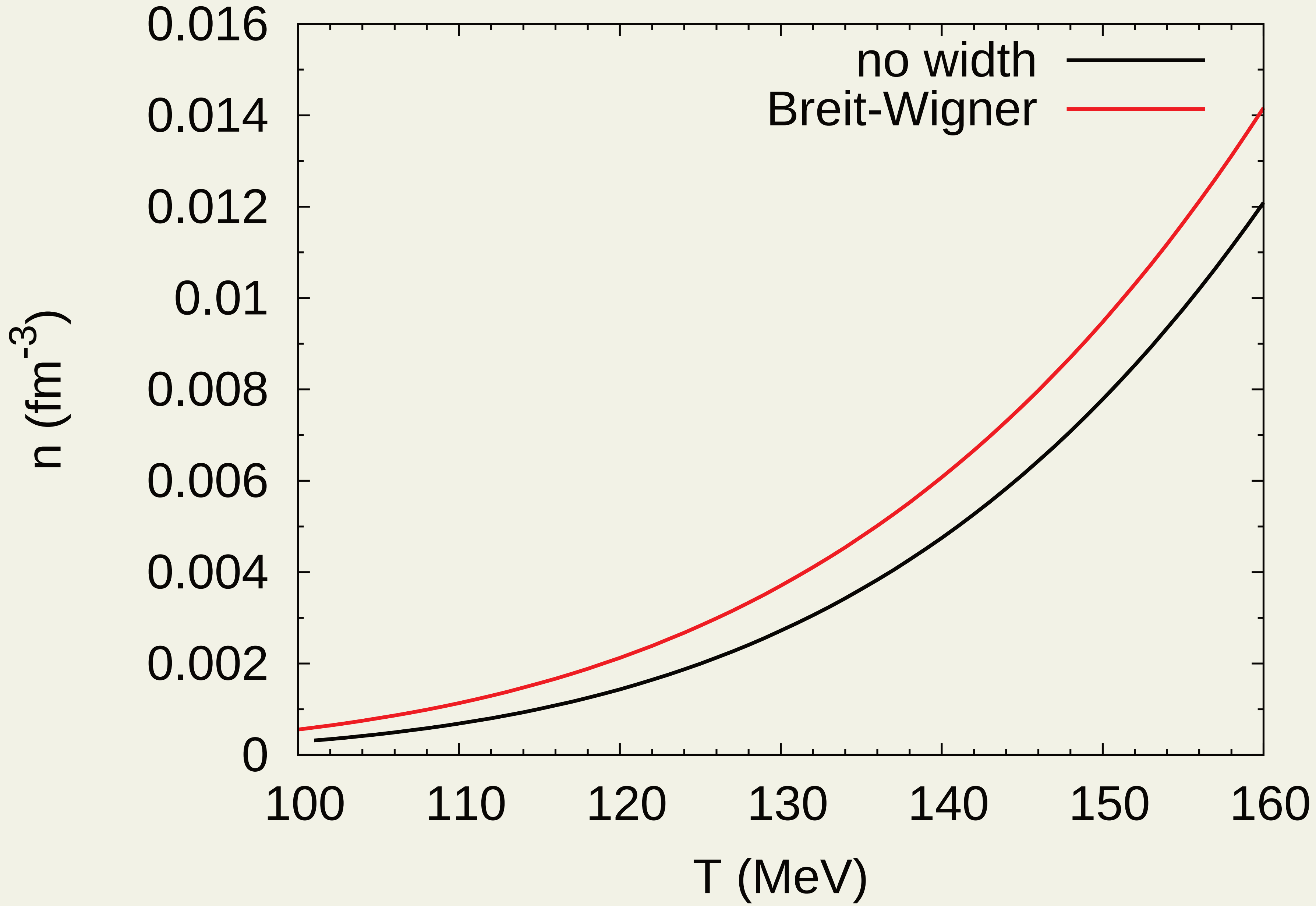
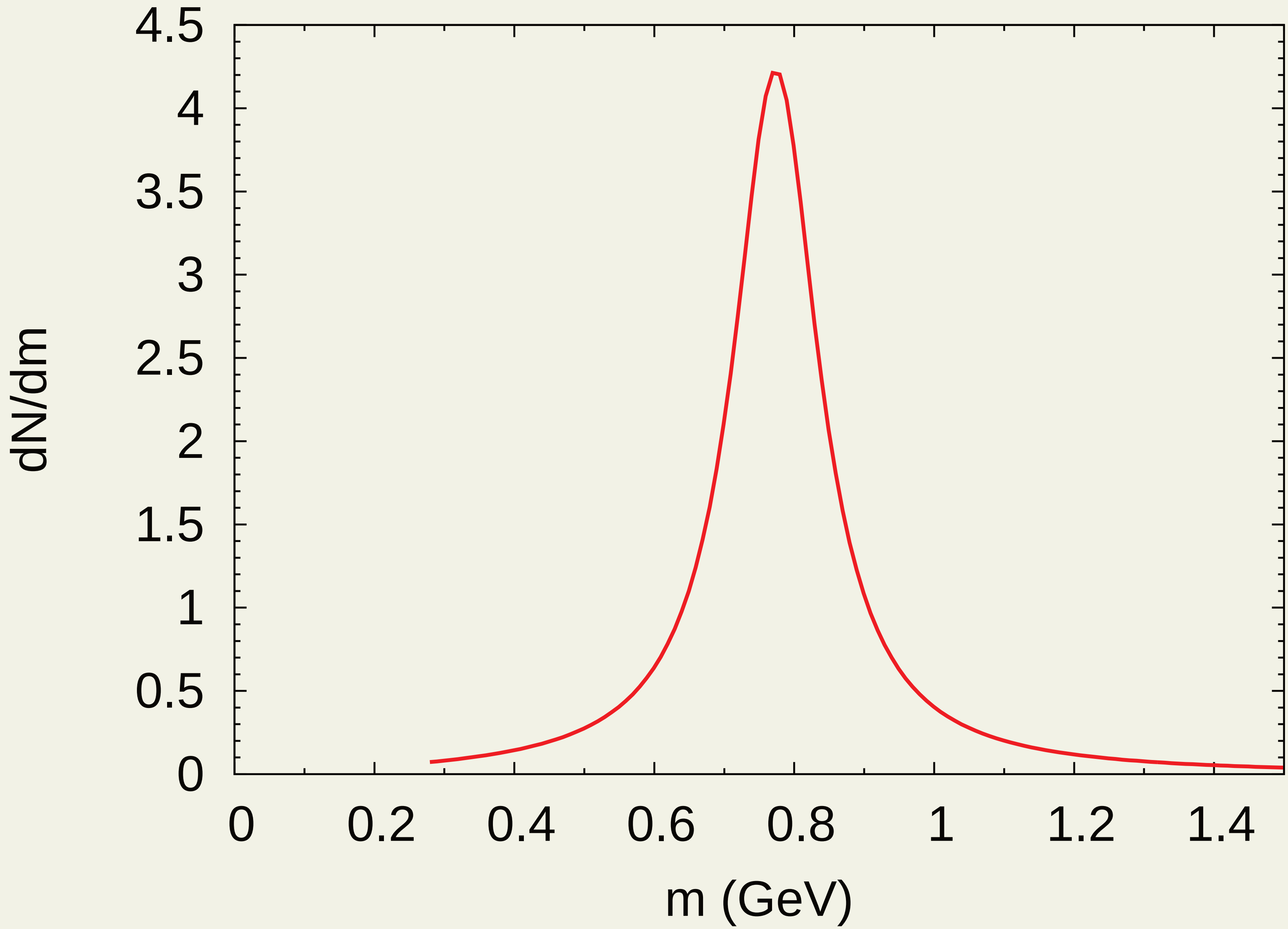
ρ-density

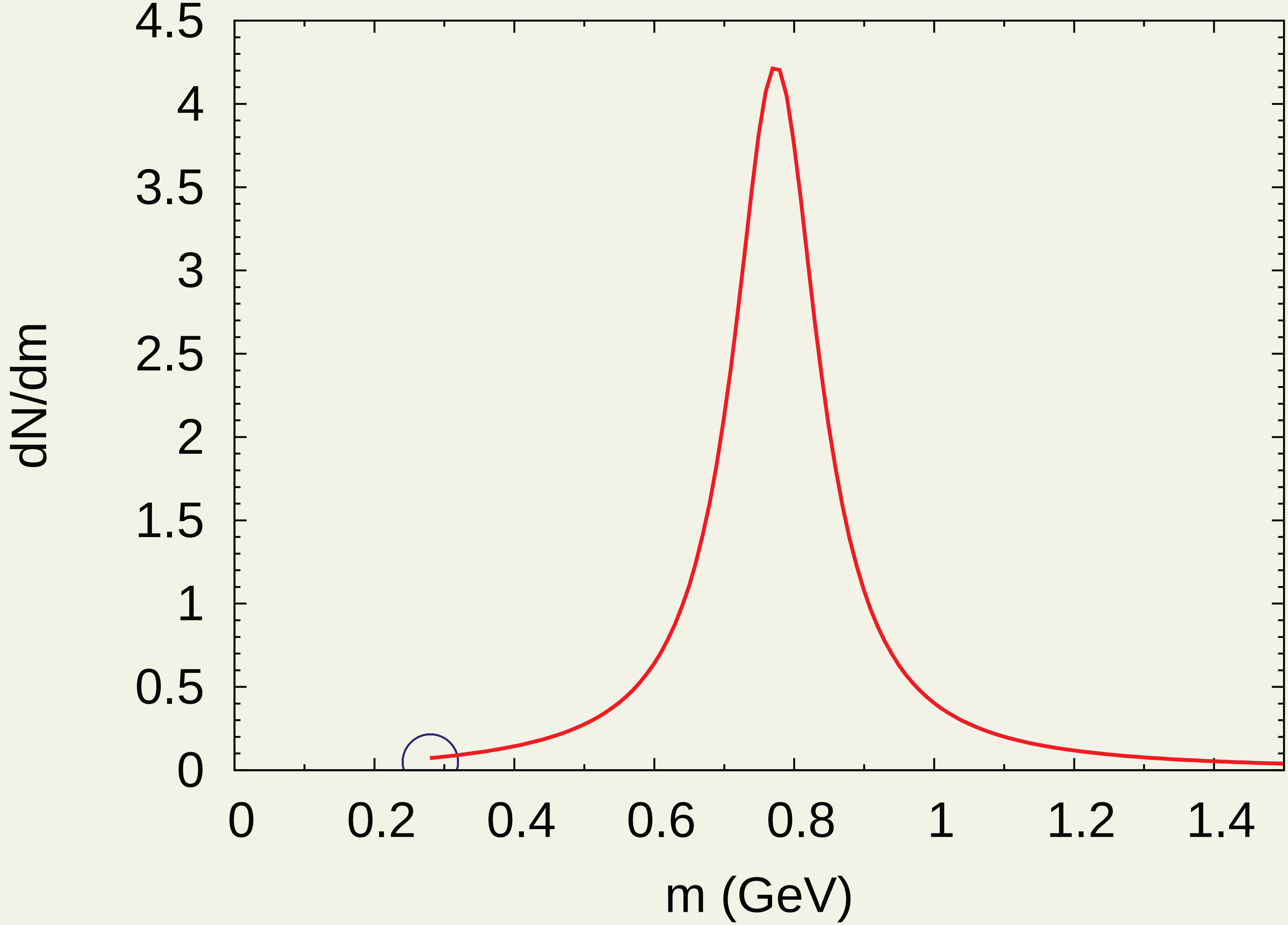


0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
100
110
120
130
140
150
160
n (fm-3)
T (MeV)
no width
Breit-Wigner

Breit-Wigner



Breit-Wigner



Mass dependent width

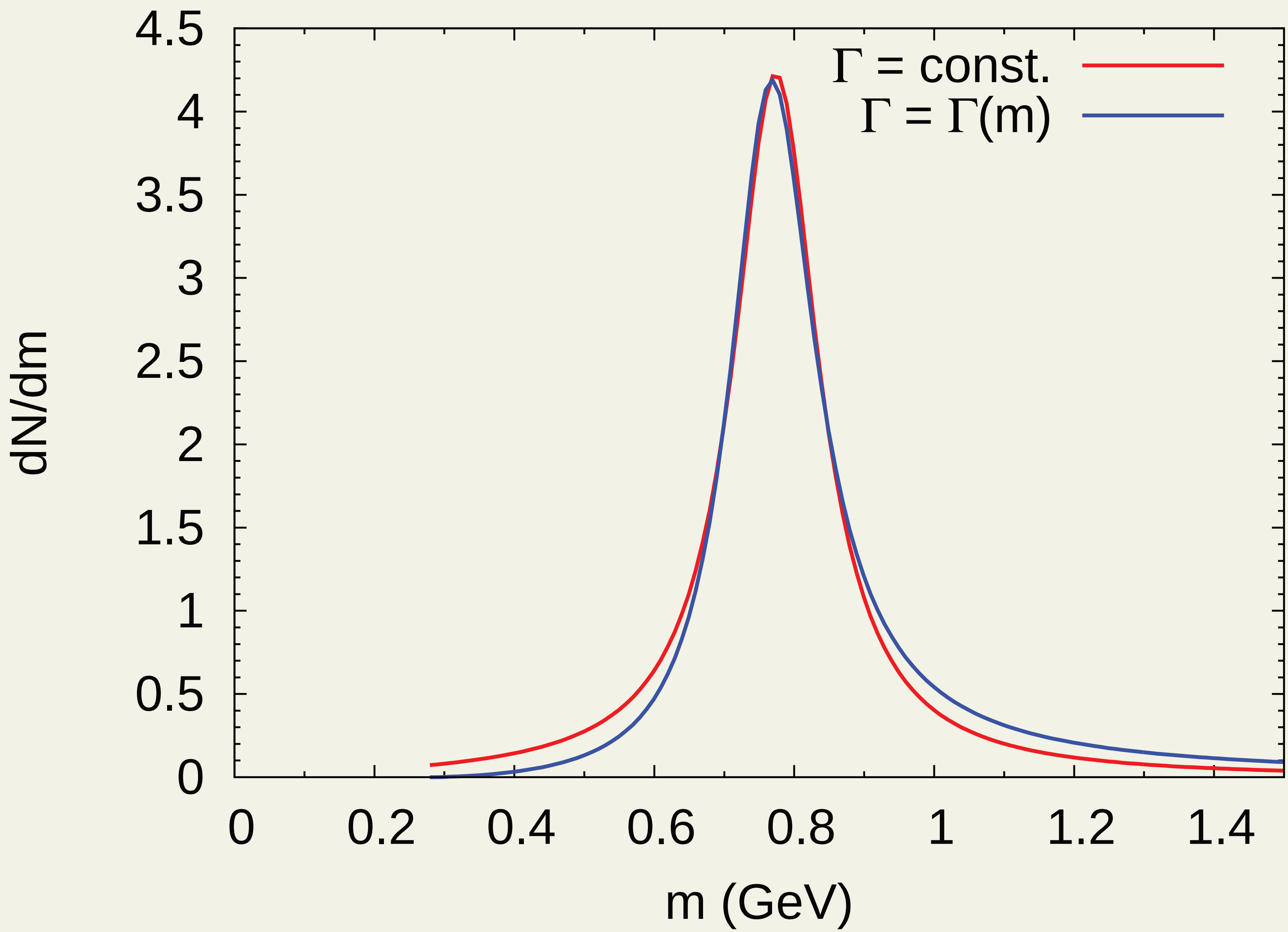
$$\frac{\mathrm{d}\rho}{\mathrm{d}m^2} = \frac{1}{N}\frac{m_R\,\Gamma(m)}{(m^2 - m_R^2)^2 + m_R^2\Gamma(m)^2},$$

with width

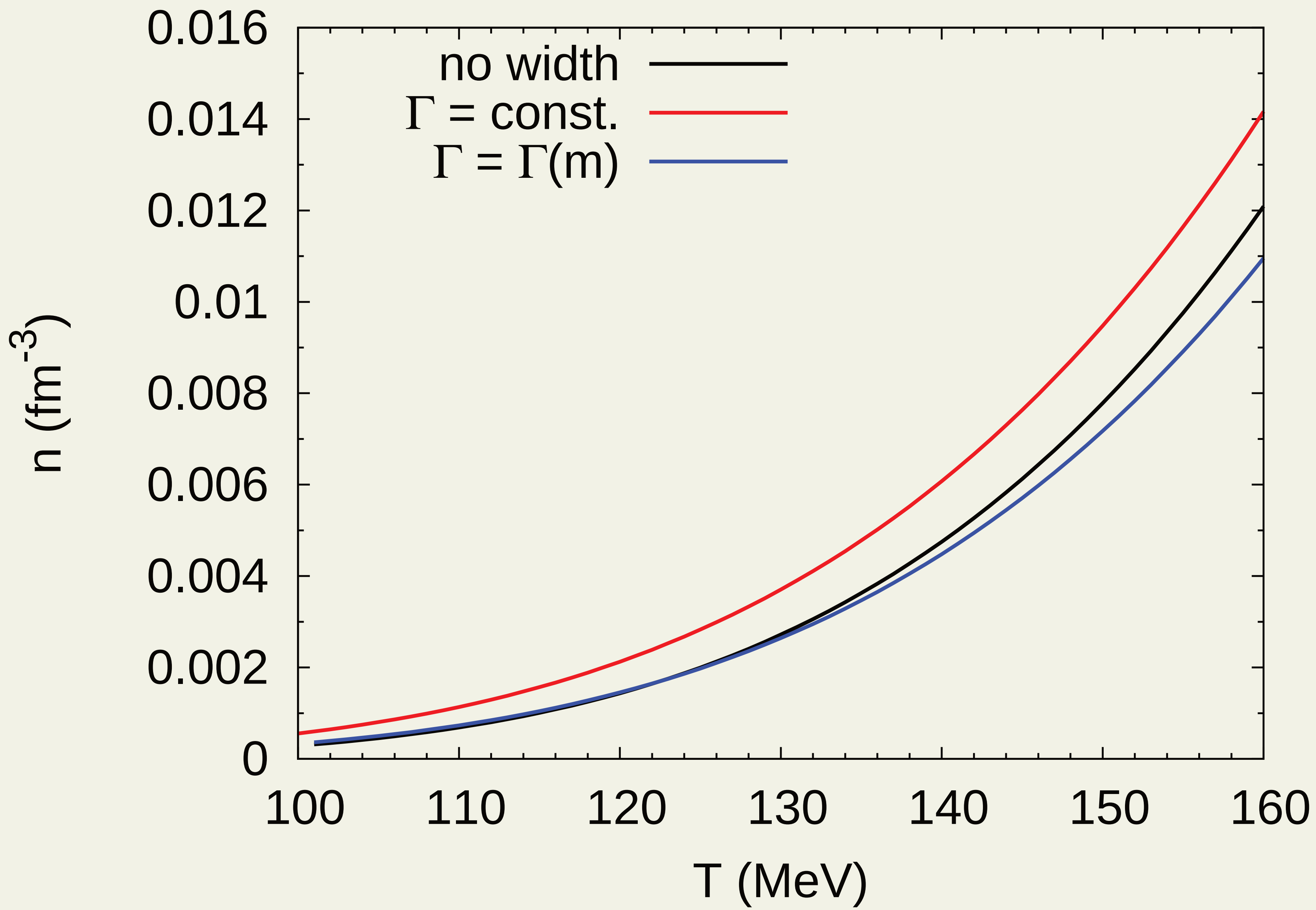
$$\Gamma(m) = \frac{1}{2}\frac{p_{\mathrm{CMS}}^3 r_0^2}{1 + p_{\mathrm{CMS}}^2 r_0^2}$$

where $r_0 = 6.3$ **GeV**$^{-1}$

Breit-Wigner



ρ-density



0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
n (fm^-3)
no width
Γ = const.
Γ = Γ(m)
100
110
120
130
140
150
160
T (MeV)

relativistic Breit-Wigner

$$\frac{\mathrm{d}\rho}{\mathrm{d}m^2} = \frac{1}{N}\frac{m_R\,\Gamma(m)}{(m^2-m_R^2)^2+m_R^2\Gamma(m)^2}$$

or:

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But if $\Gamma(m) \propto m$ at large m,

$$N = \int_{m_0}^{\infty} \mathrm{d}m^2 \frac{m\,\Gamma(m)}{(m^2 - m_R^2)^2 + m^2\Gamma(m)^2} = \infty$$

Particle Data Group about ρ:

```
...the line shape does not correspond to
a relativistic Breit-Wigner function...but
requires some additional shape parameter
```

Garbage in, garbage out

Dashen-Ma-Bernstein: Phys. Rev. 187, 345 (1969)

If interactions mediated by $narrow$ resonances, properties of interacting hadron gas are those of noninteracting hadron-resonance gas

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Dashen-Ma-Bernstein: S-matrix formulation of statistical mechanics:

$\Rightarrow$ **Second virial coefficient can be evaluated in terms of scattering phase shift (as far as interaction is manifested in elastic scattering)**

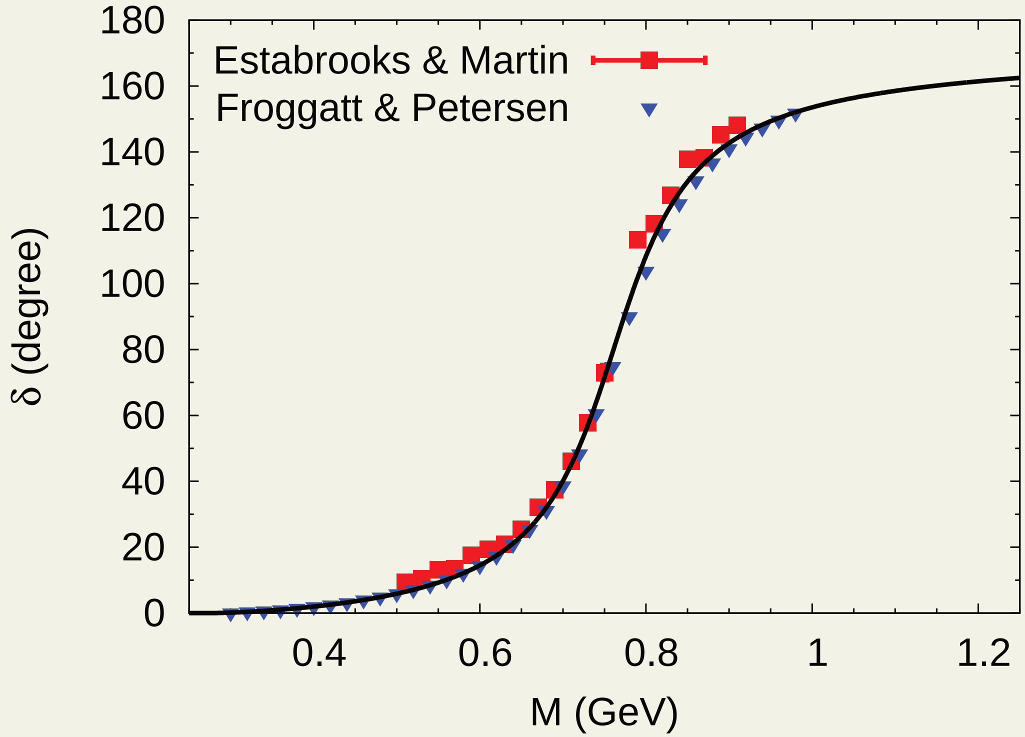
$\Rightarrow$ **relativistic Beth-Uhlenbeck form**

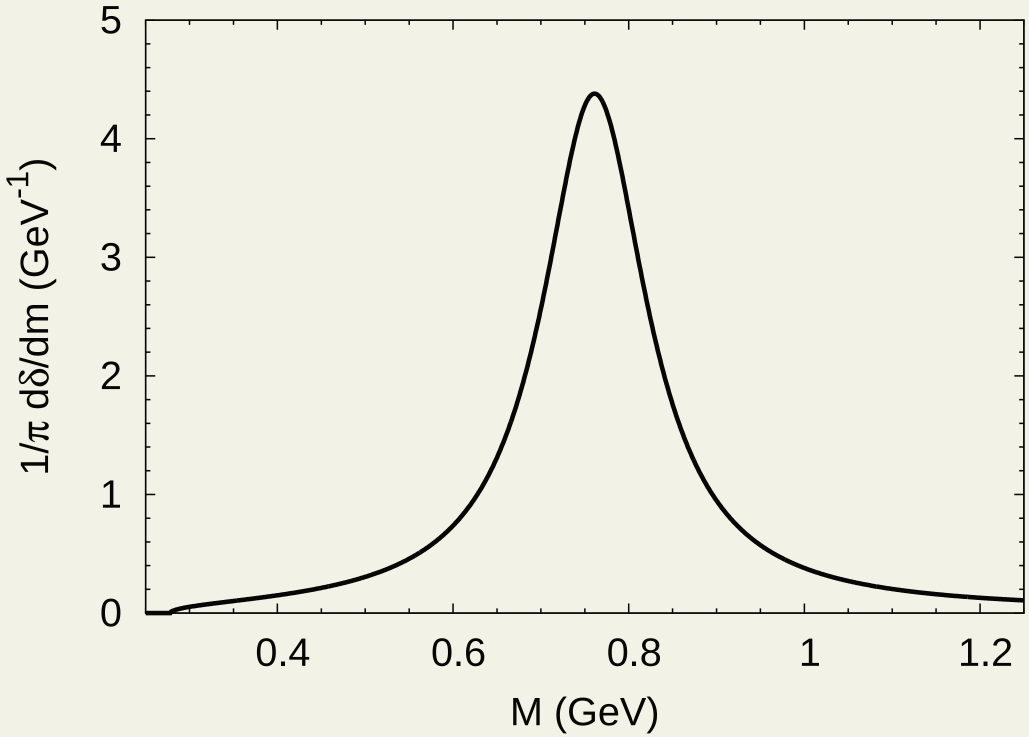
S-matrix

- **effects of interactions expressed in terms of scattering phase shifts**

$$n = \int \mathrm{d}^3\mathbf{p} \int \mathrm{d}m \frac{\mathrm{d}\rho}{\mathrm{d}m} f(p,m) \qquad \text{with} \qquad \frac{\mathrm{d}\rho}{\mathrm{d}m} = \frac{1}{\pi}\frac{\mathrm{d}\delta}{\mathrm{d}m}$$

- $\pi\pi$ **scattering, P-wave, i.e.** ρ **resonance**





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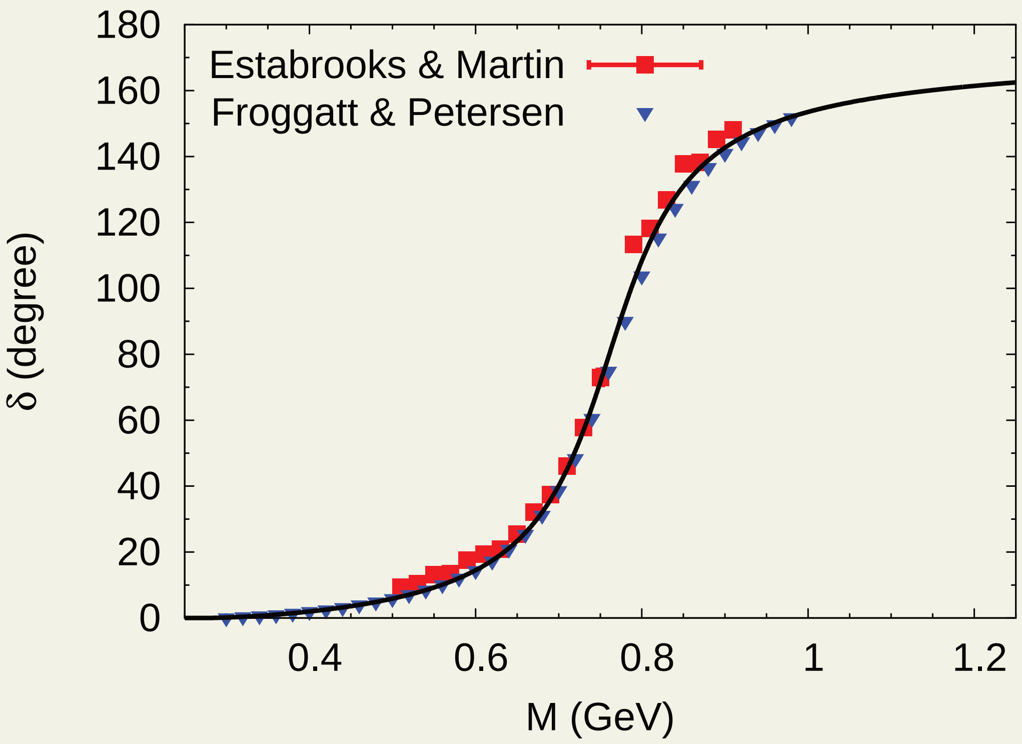

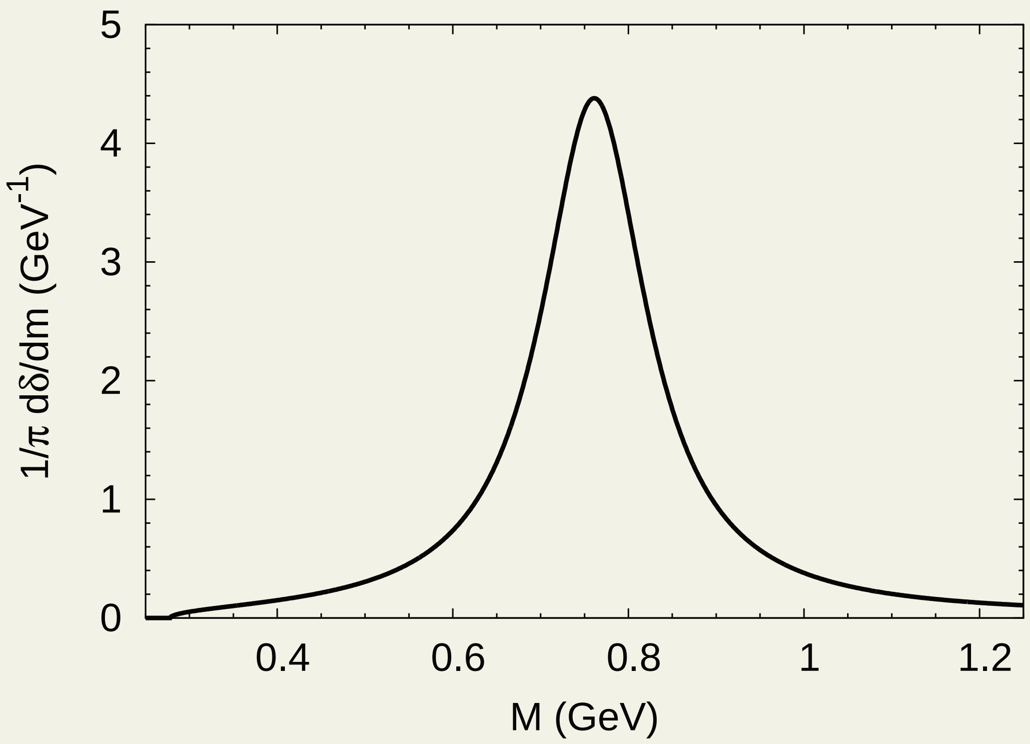

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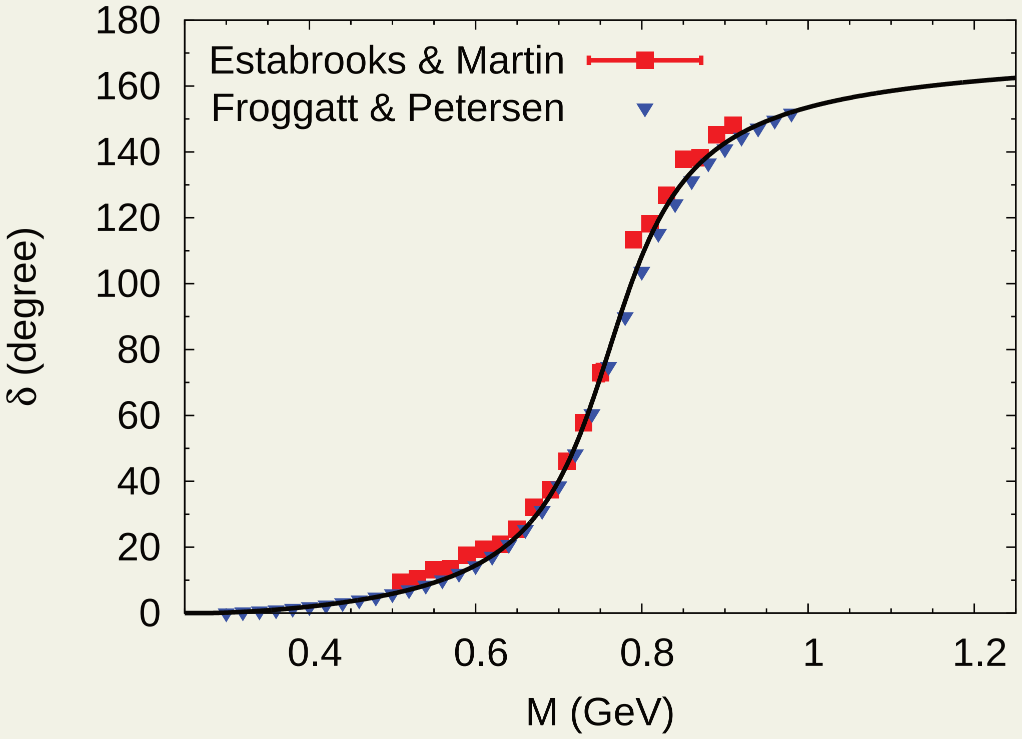

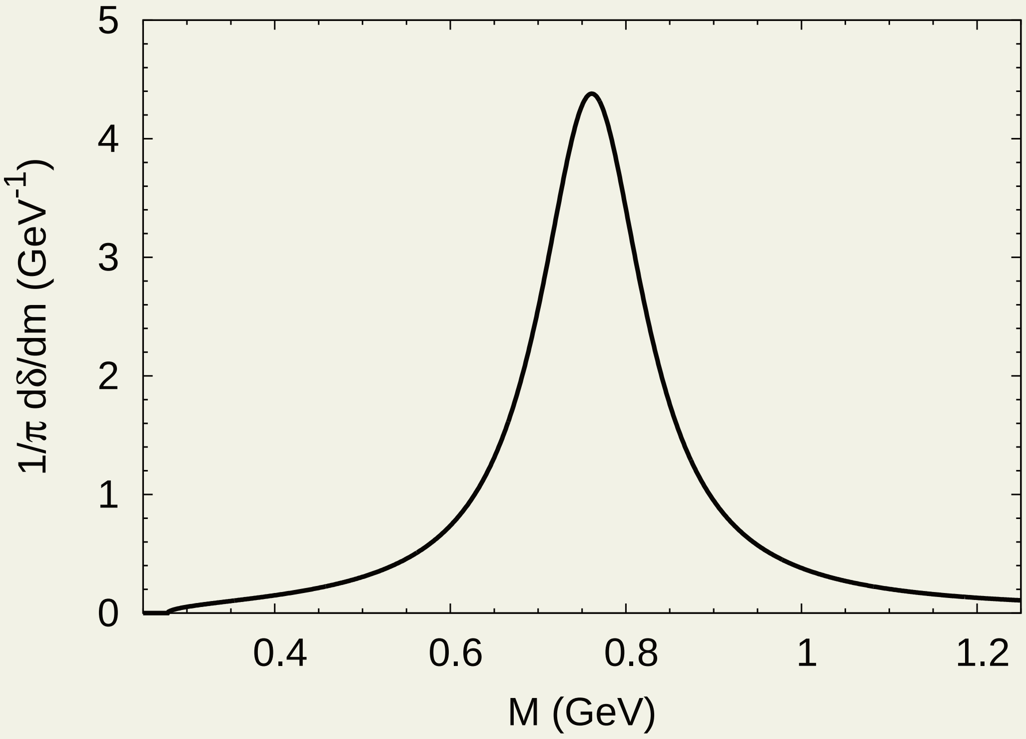

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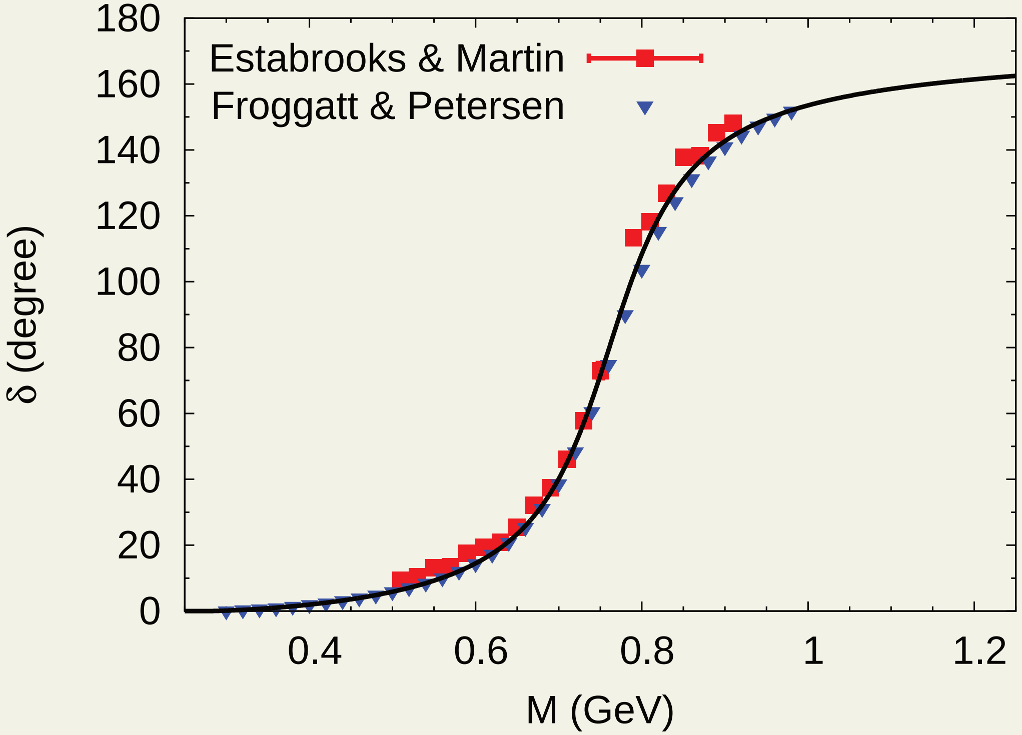

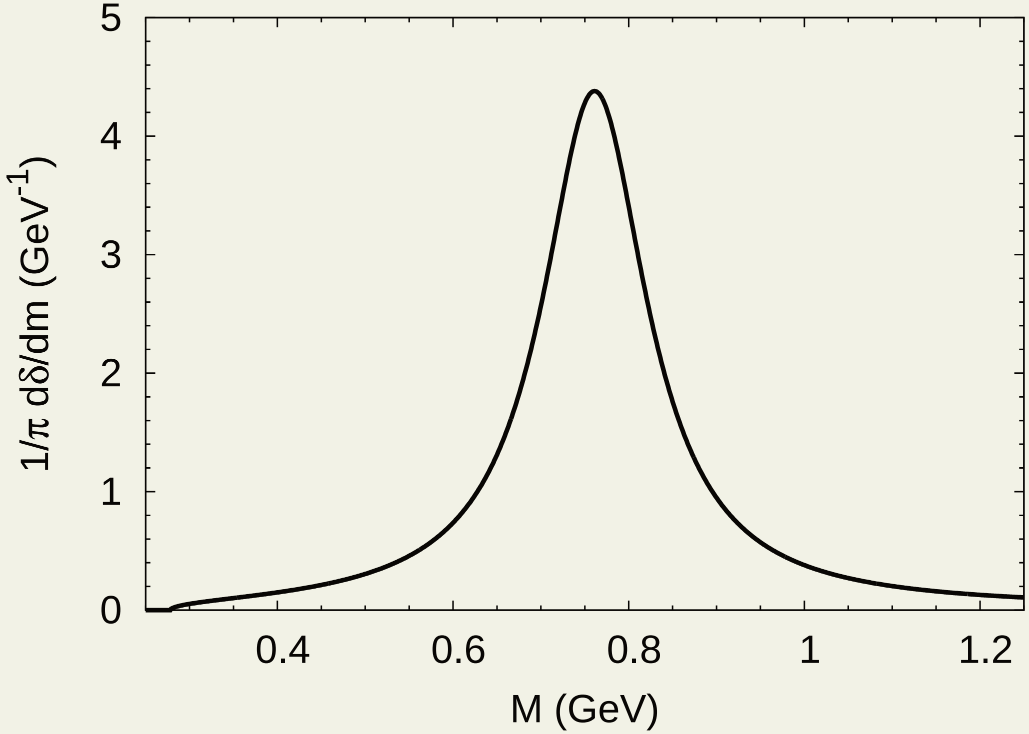

S-matrix

- **effects of interactions expressed in terms of scattering phase shifts**

$$n = \int d^3\mathbf{p} \int dm \frac{d\rho}{dm} f(p,m) \qquad \text{with} \qquad \frac{d\rho}{dm} = \frac{1}{\pi}\frac{d\delta}{dm}$$

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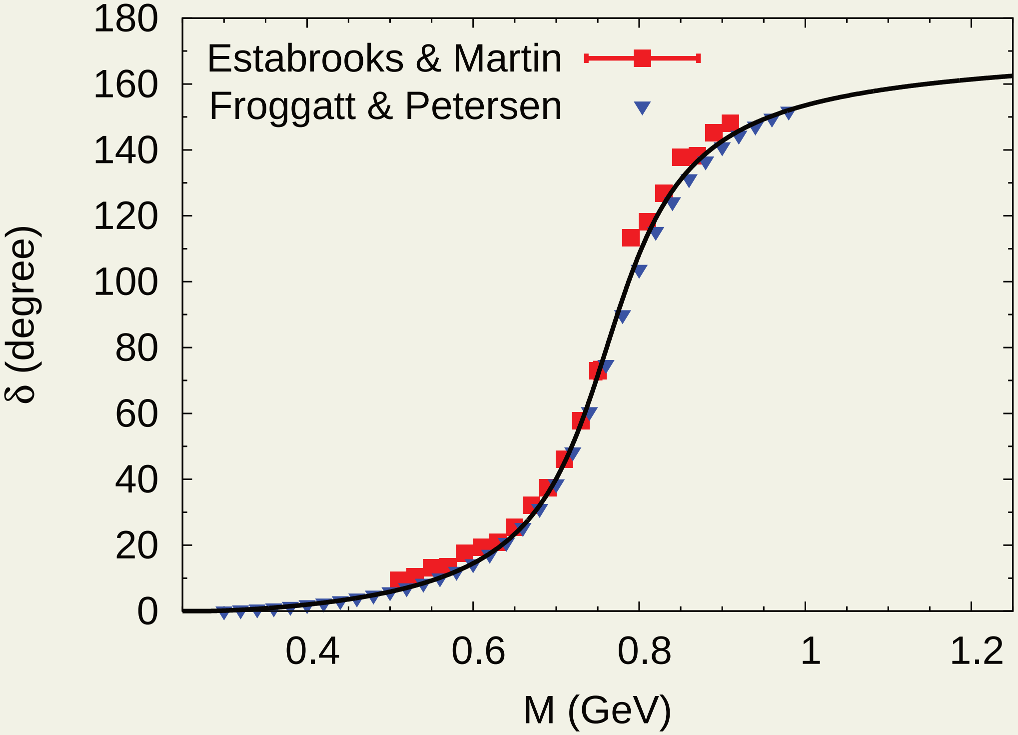

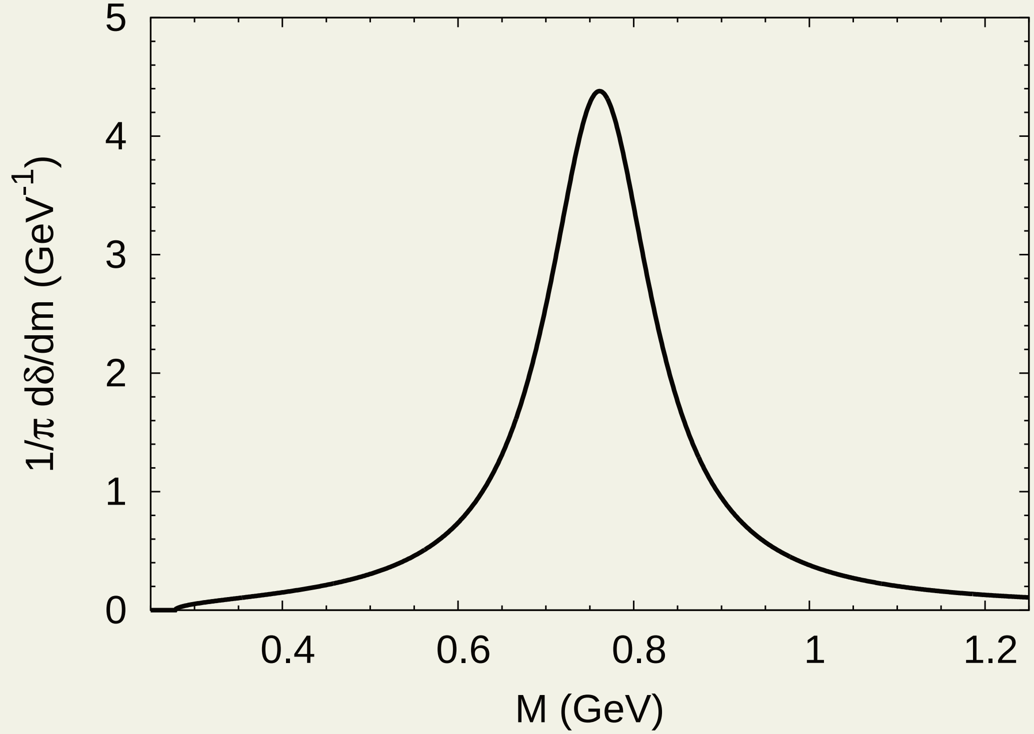

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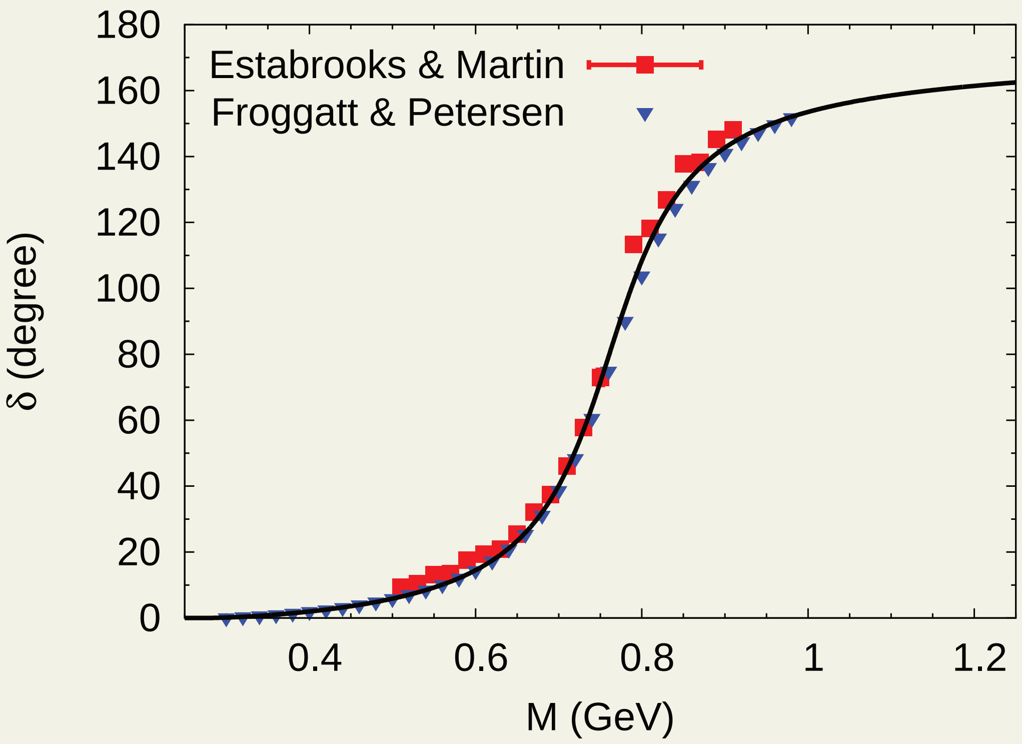
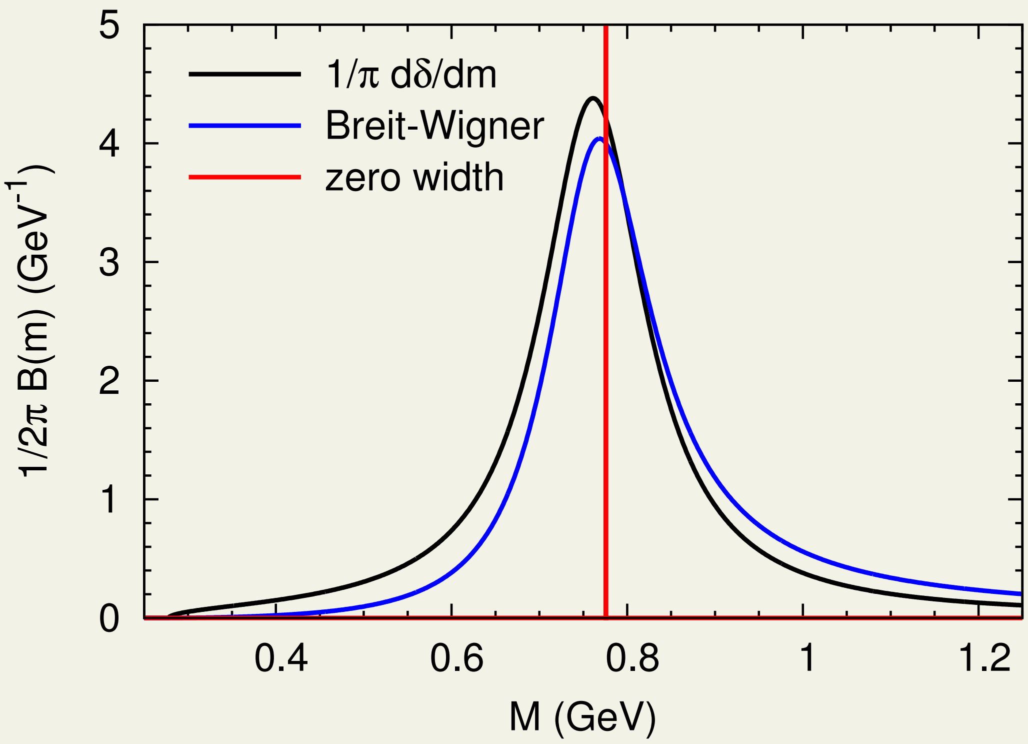
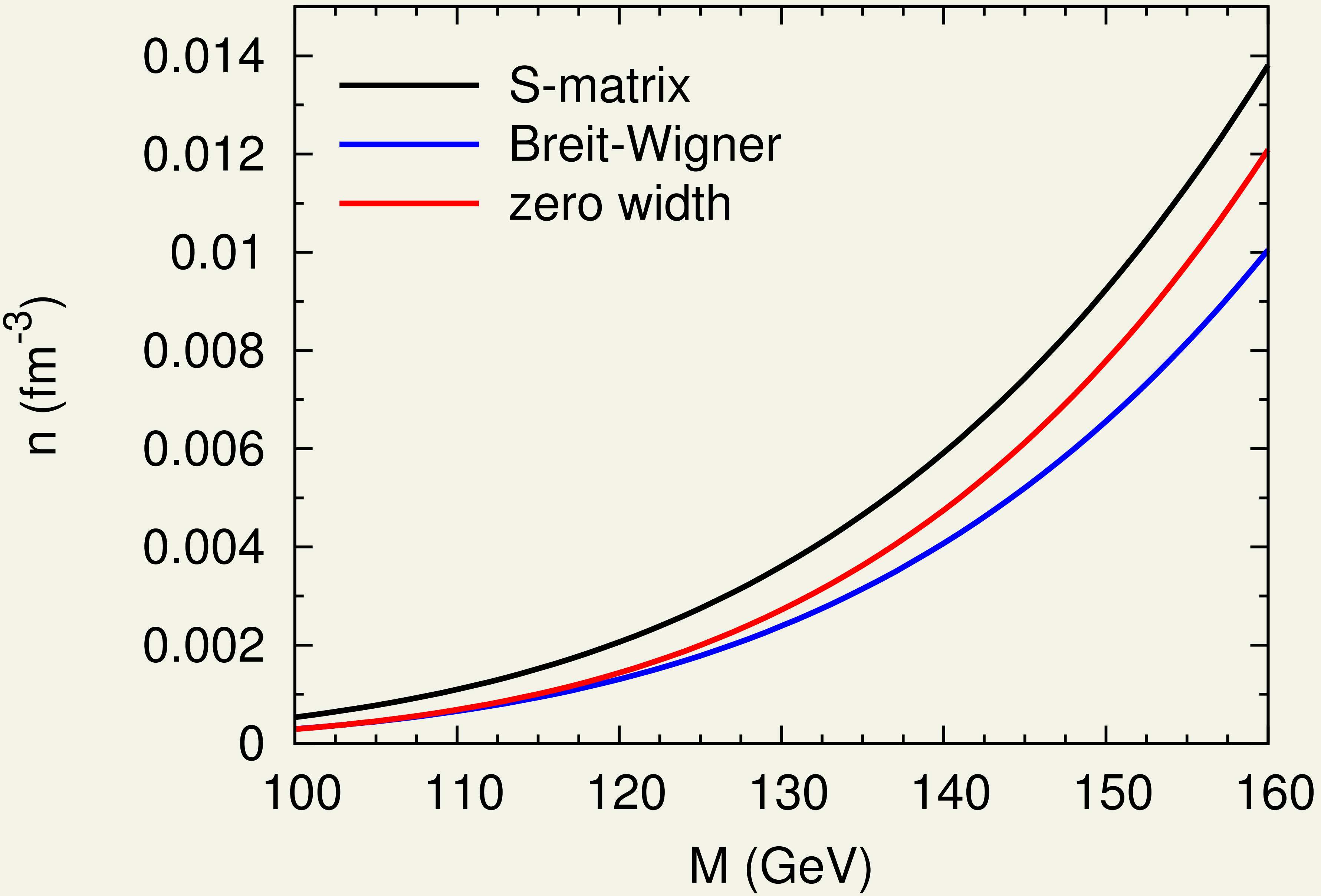


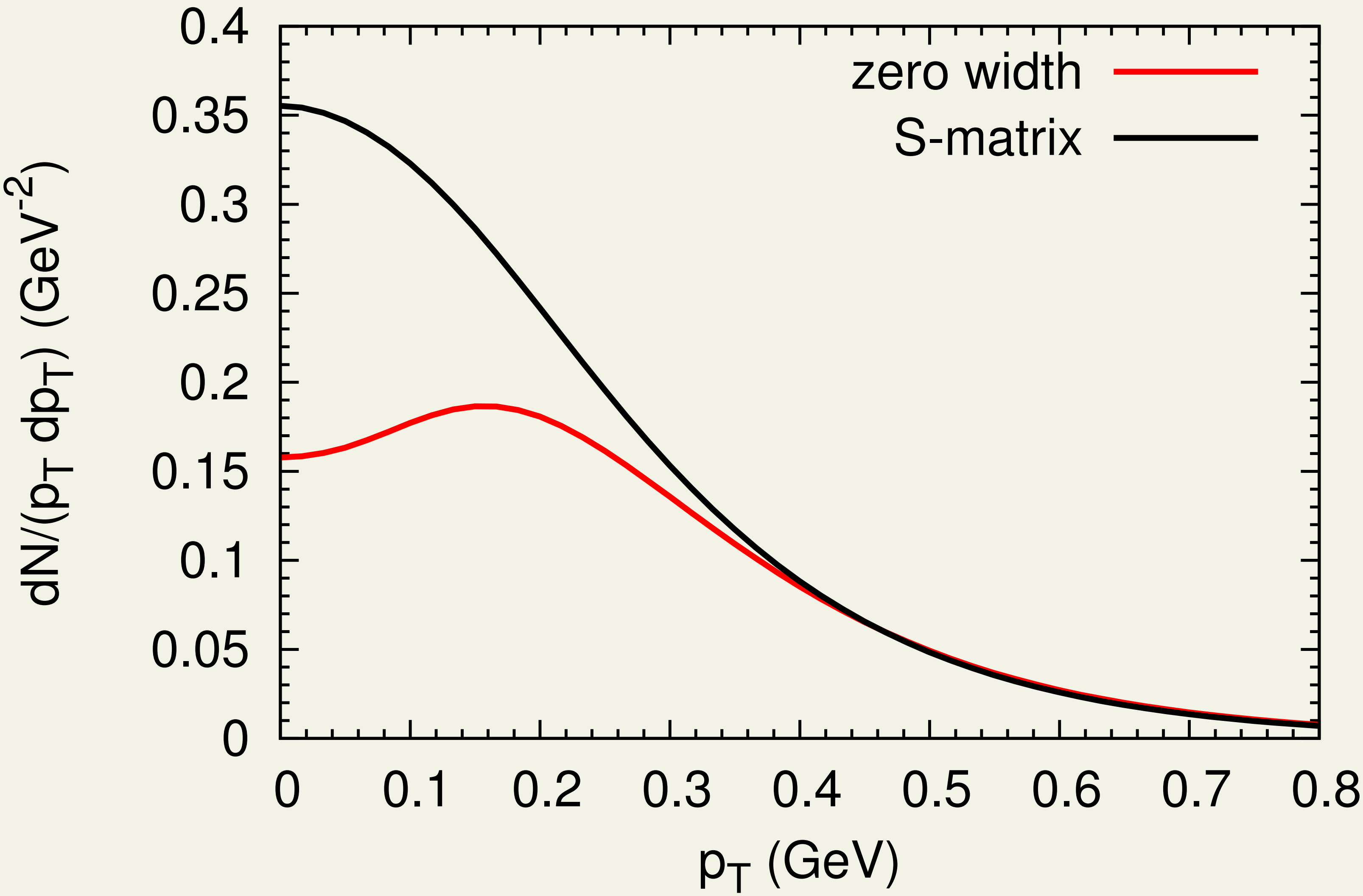


ρ-density



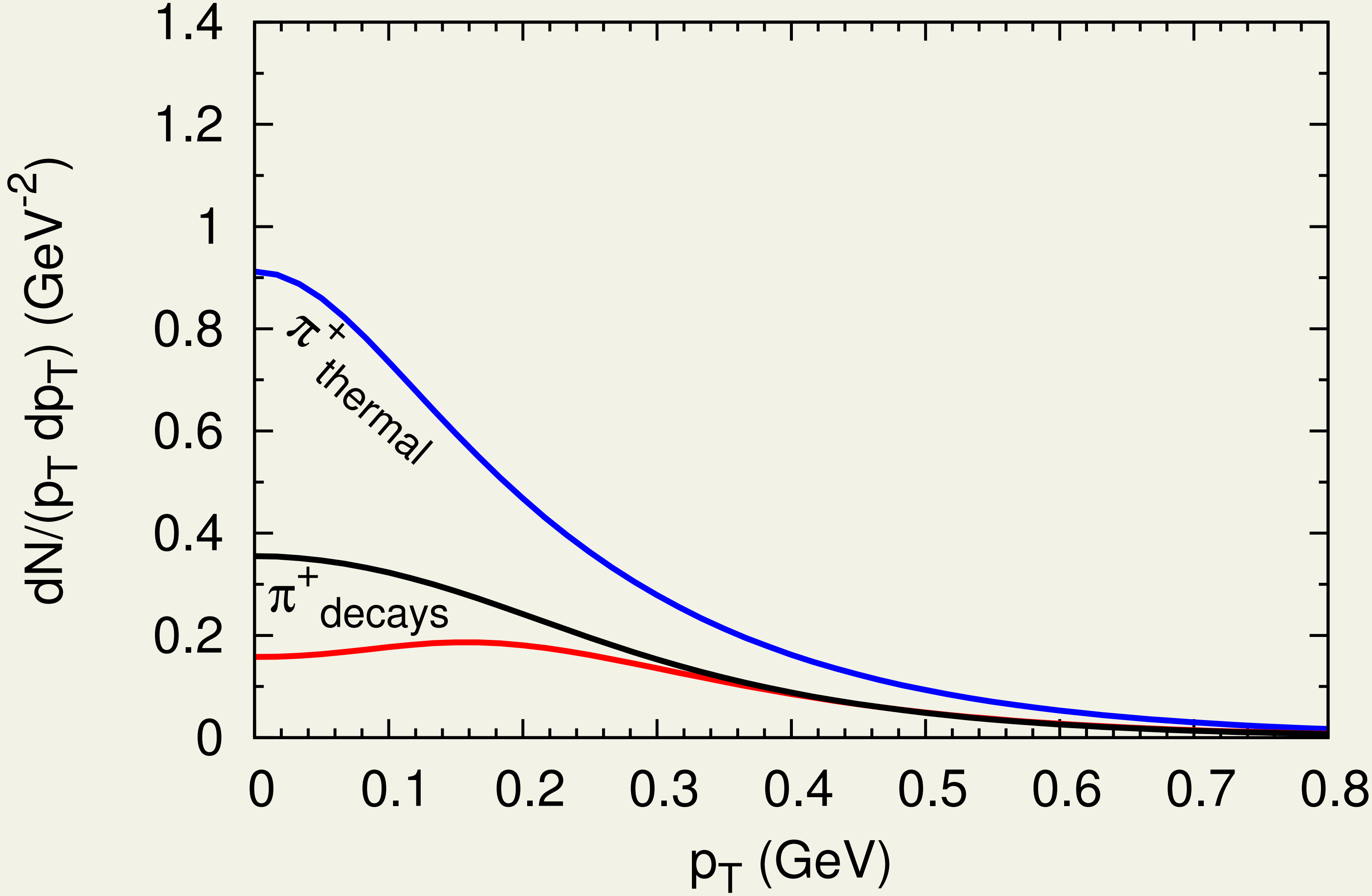
S-matrix
Breit-Wigner
zero width
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
n (fm^{-3})
100
110
120
130
140
150
160
M (GeV)

Pions from ρ decays



- **static source,** $T = 155\,\mathrm{MeV}$

Thermal pions + pions from ρ decays



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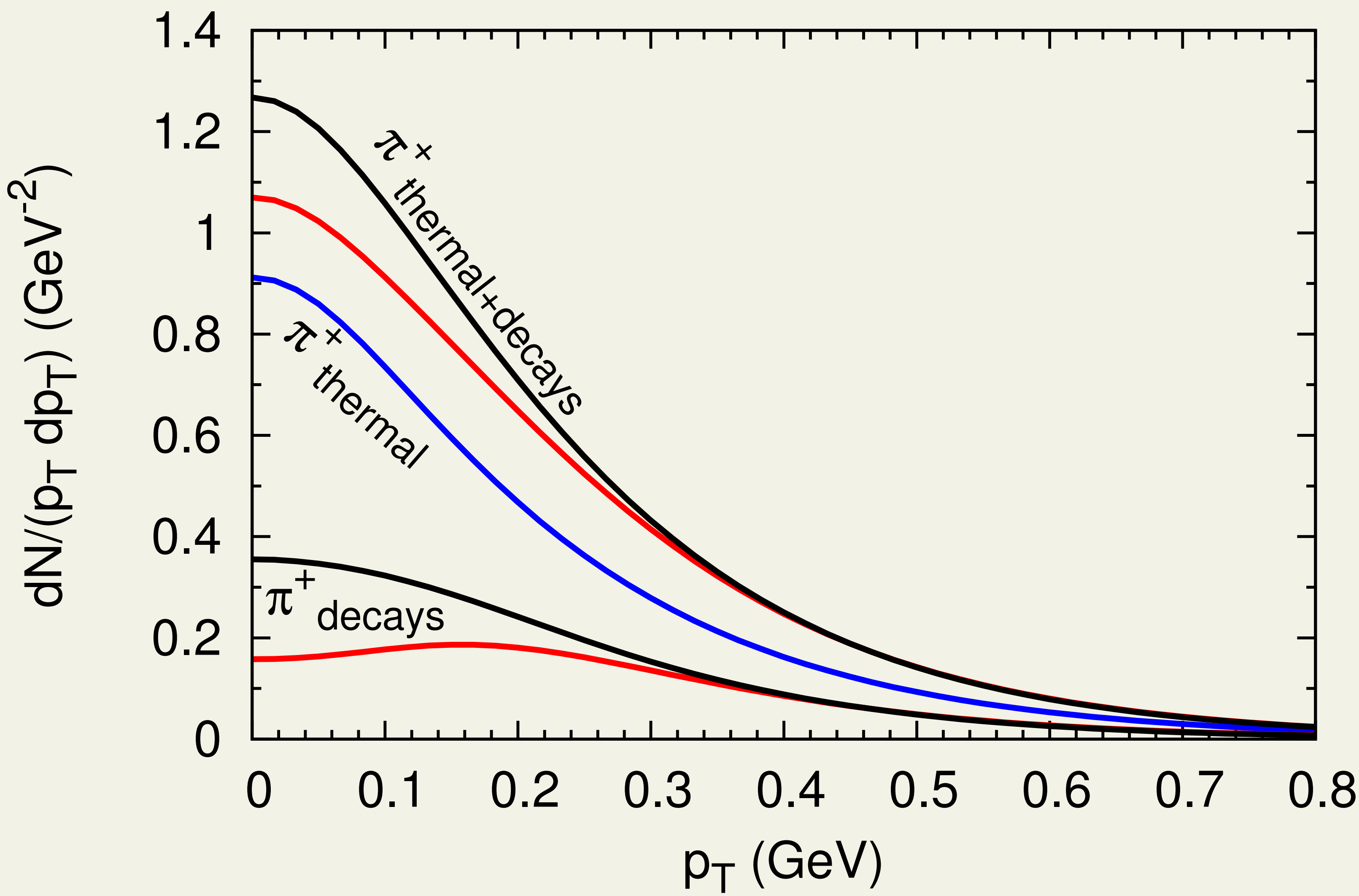
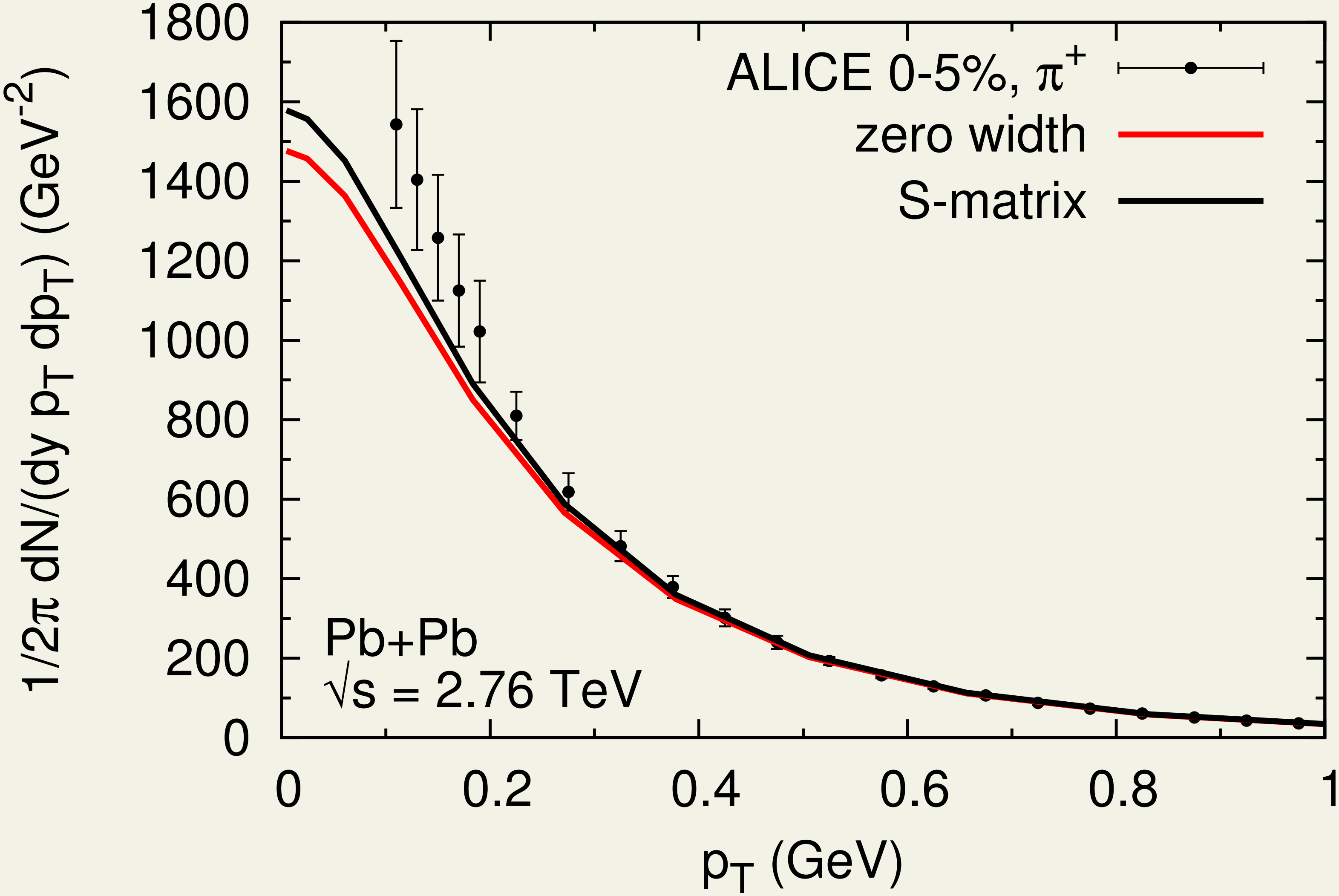


- **static source,** $T = 155\,\mathrm{MeV}$

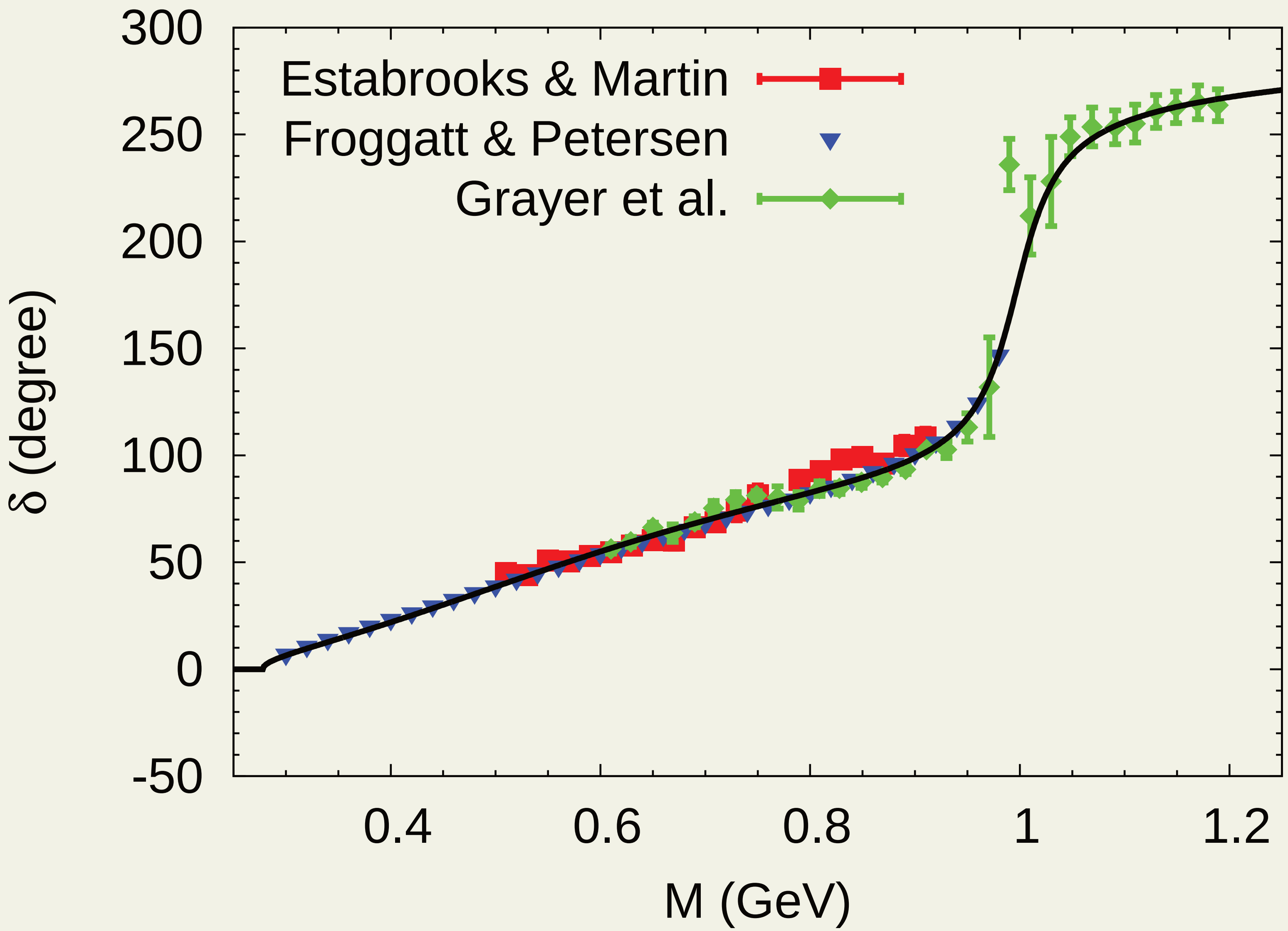
Pions from blast wave



- $\tau = 14.1\,\mathrm{fm}$
- $R = 10\,\mathrm{fm}$
- $v_{max} = 0.8$

- **all resonances up to 2 GeV**
- **S-matrix for rhos**
- **zero width for everything else**

S-wave $\pi\pi$ scattering



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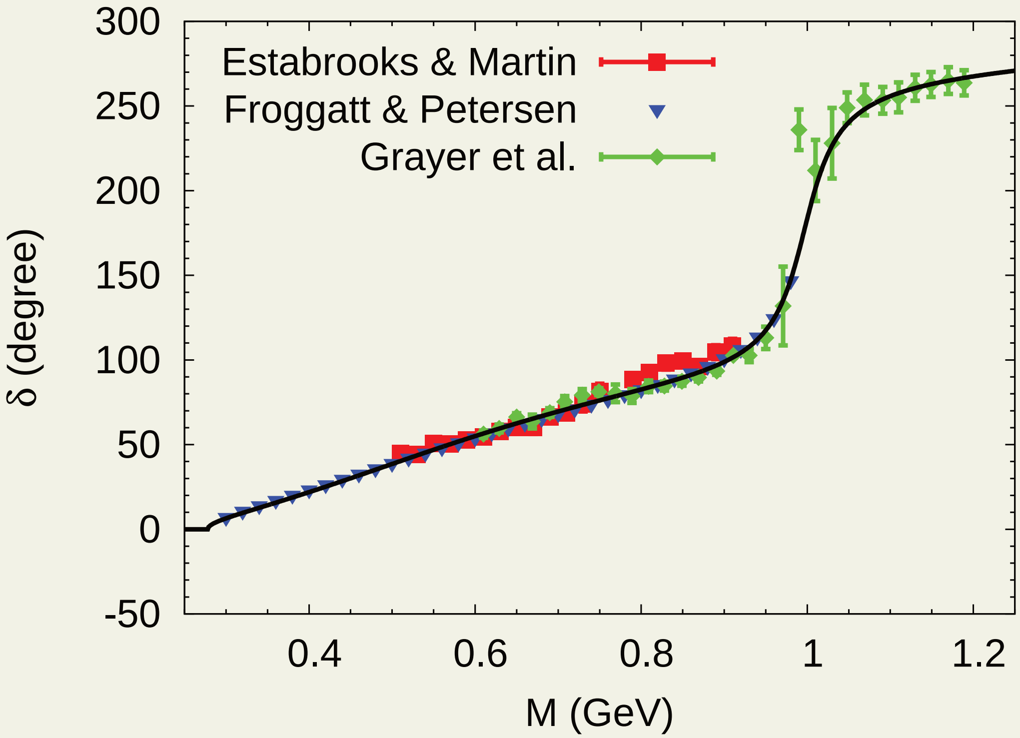
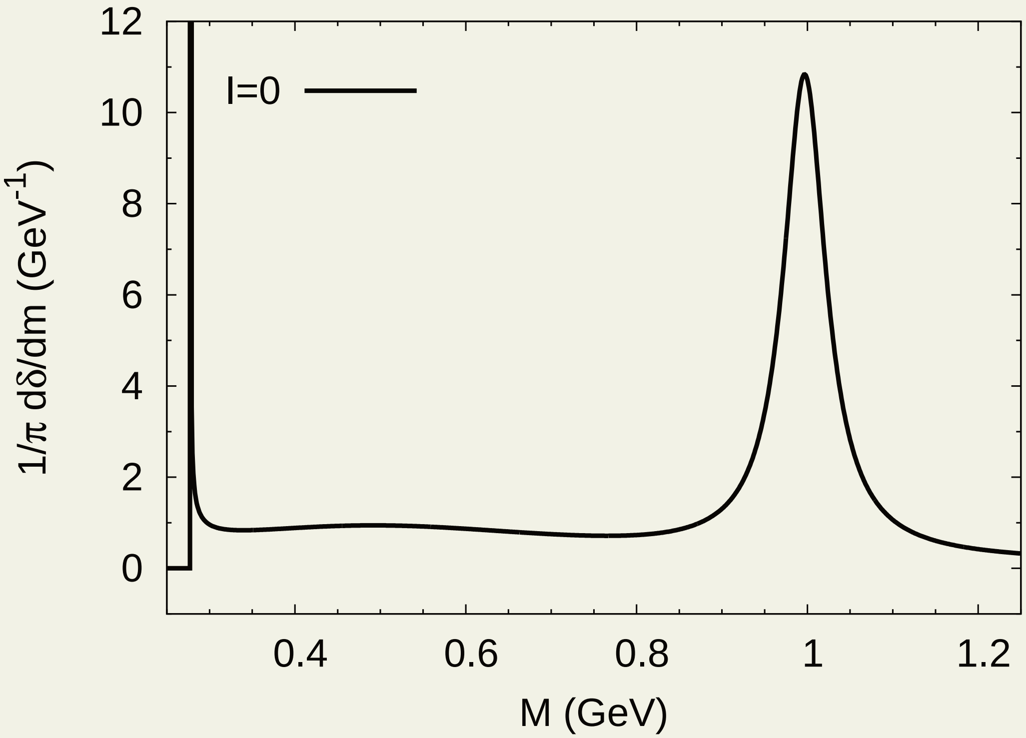
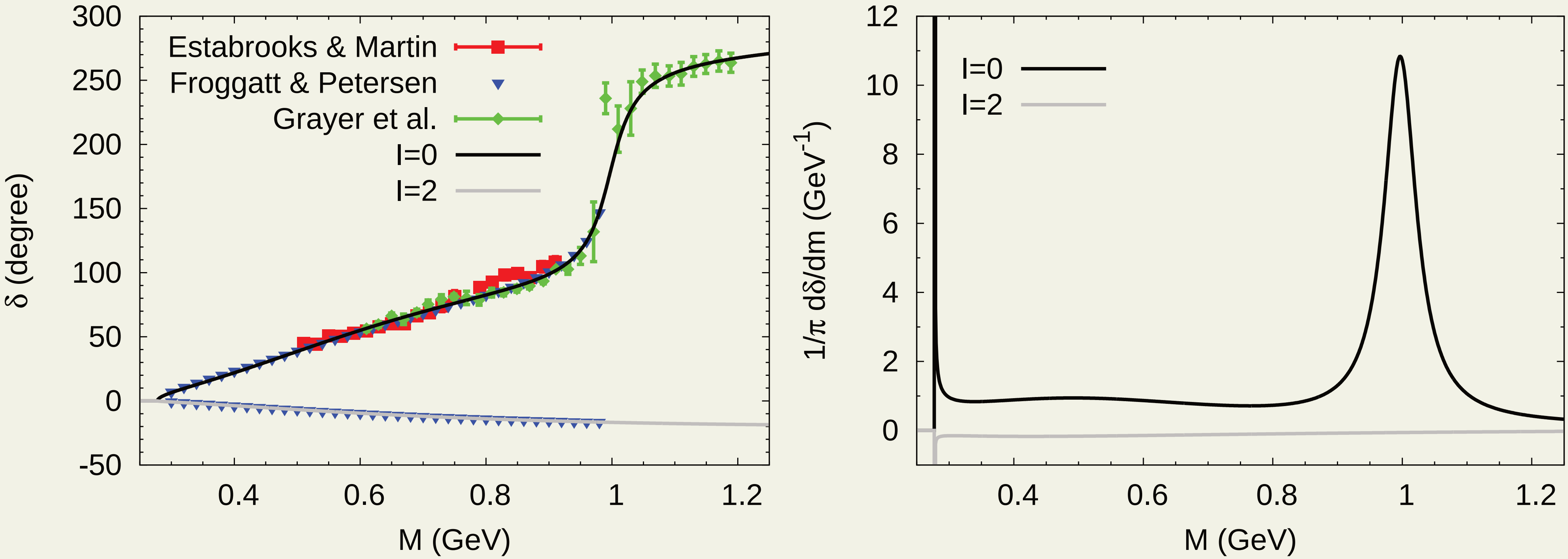




S-wave $\pi\pi$ scattering



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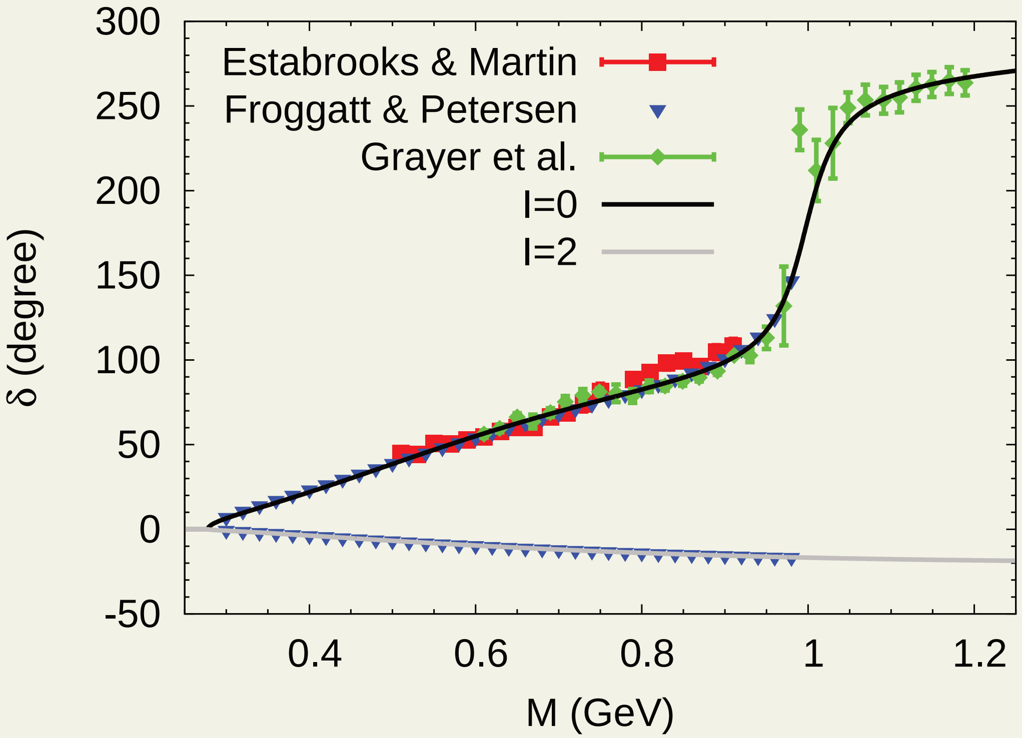
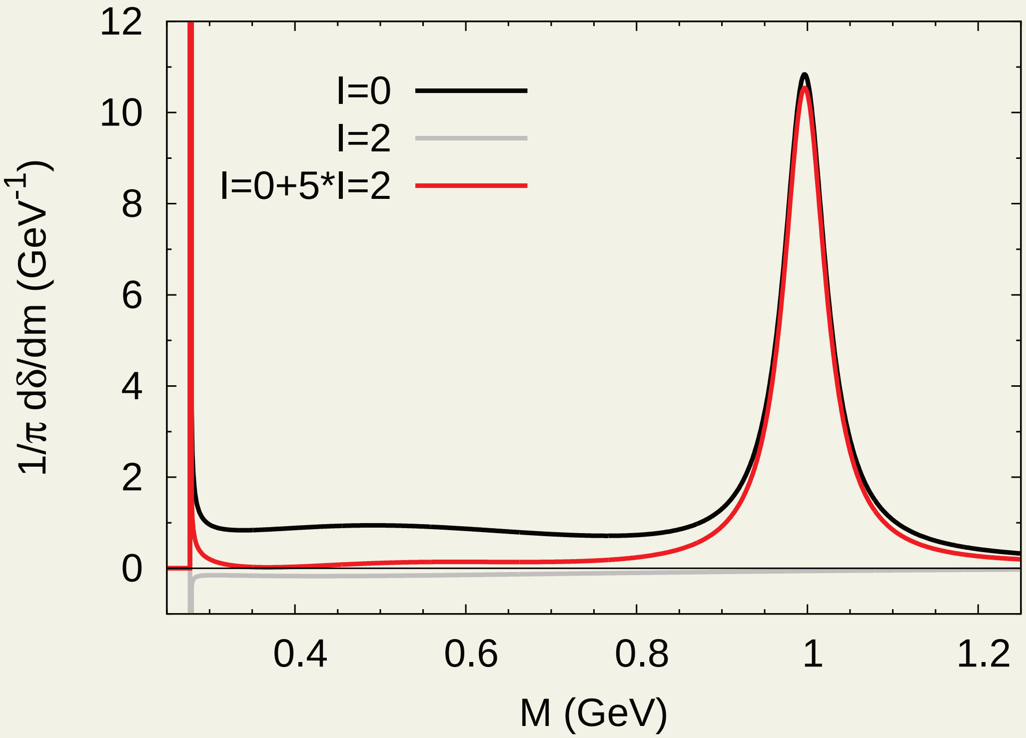
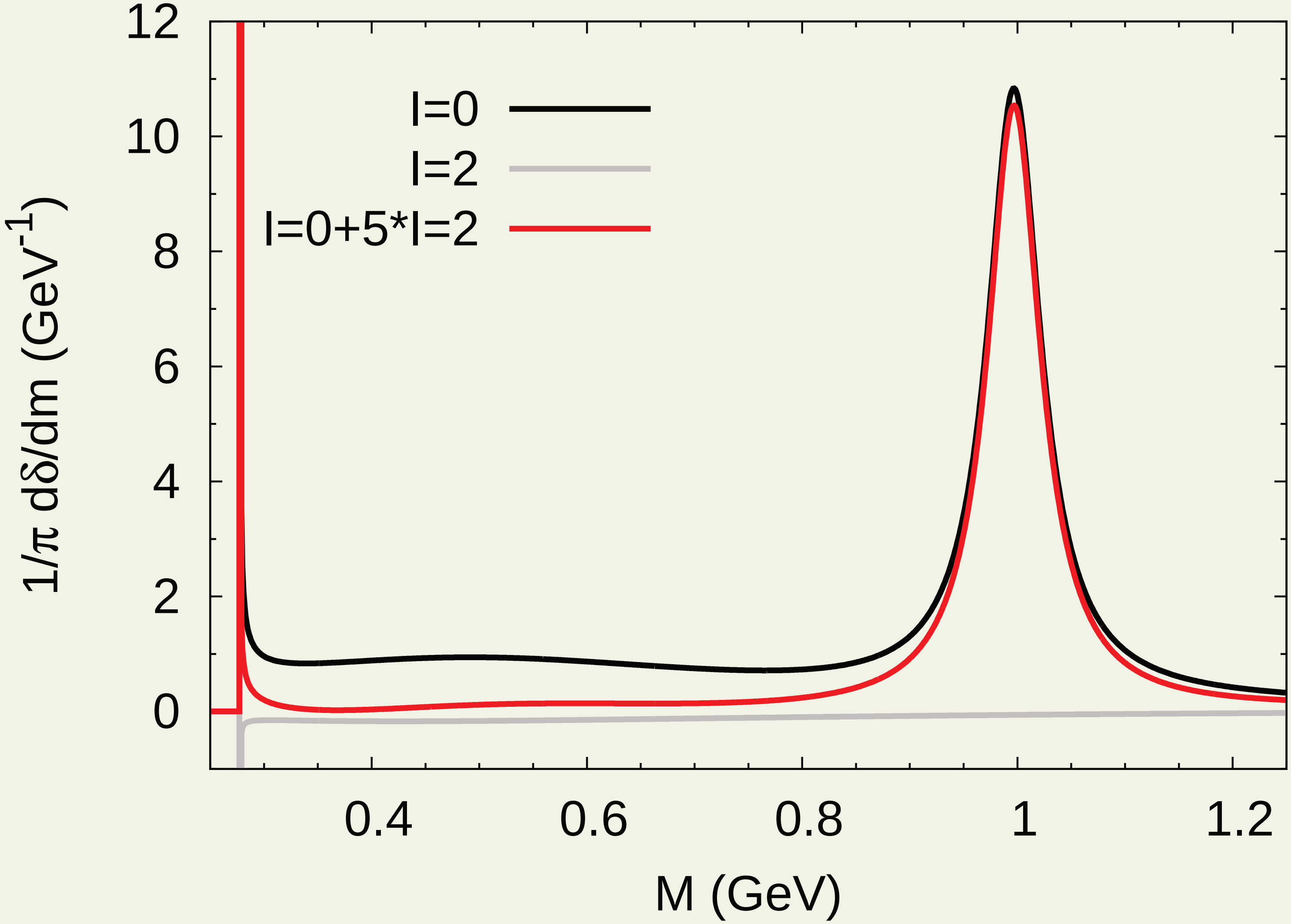




as advocated by

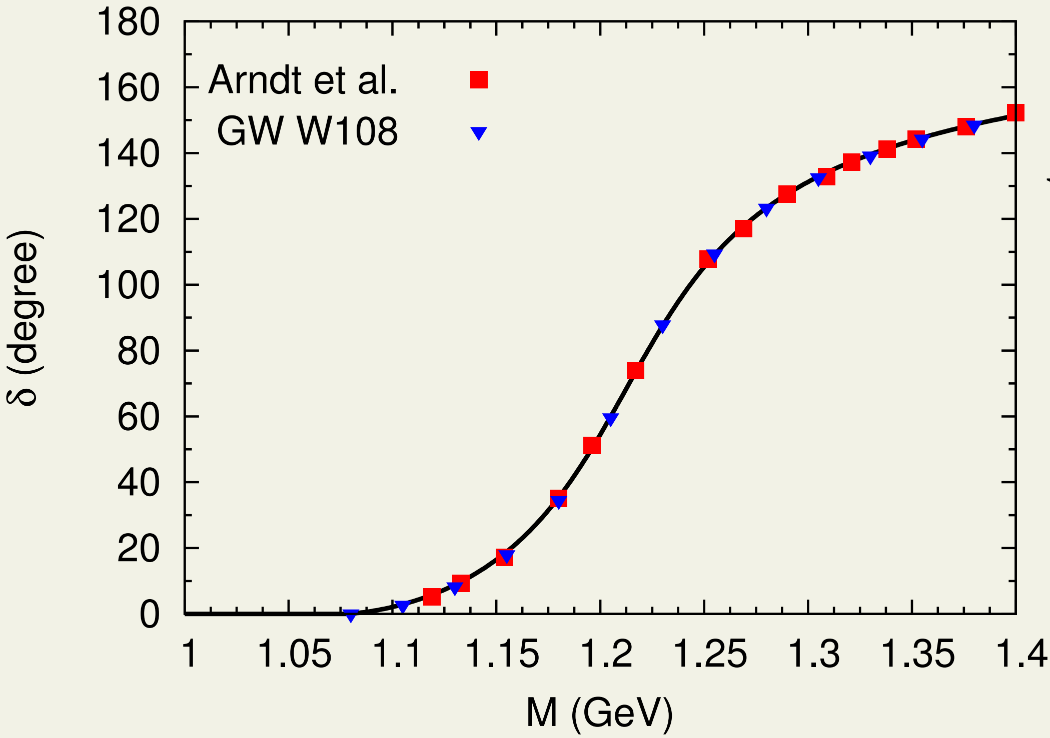
- **Broniowski, Giacosa & Begun, PRC92, 034905 (2015)**
- **Prakash & Venugopalan, NPA546, 718 (1992)**

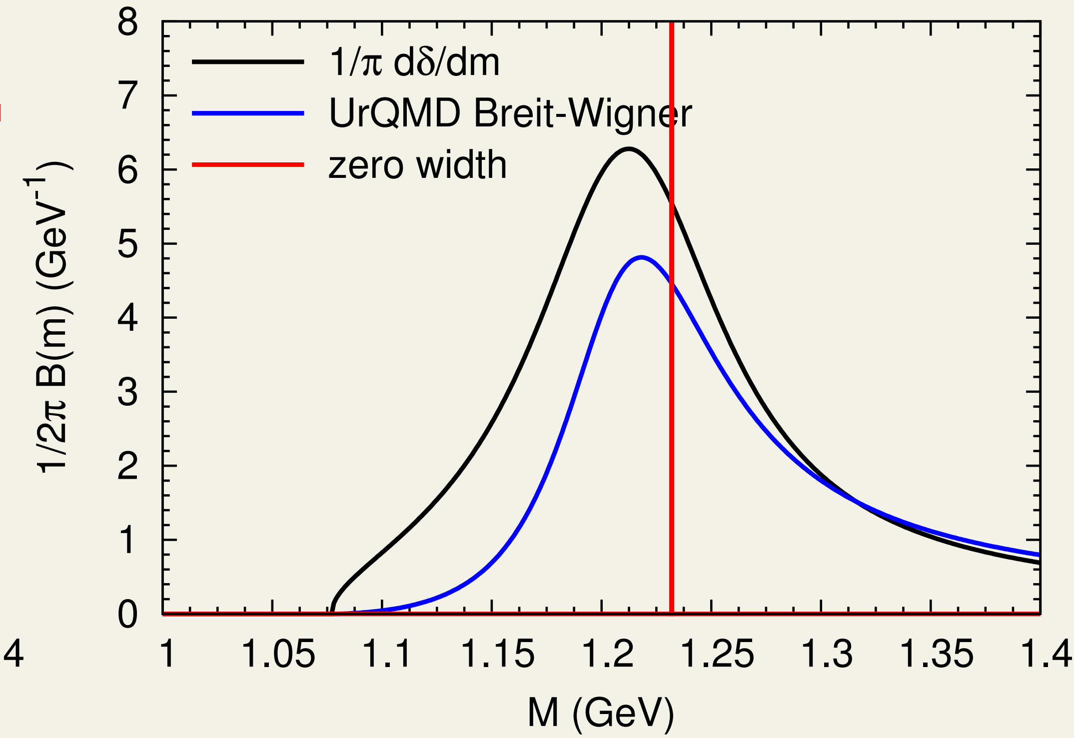
S-wave $\pi\pi$ scattering



- $f_0(980)$ **nicely described**

P_{33} πN scattering, a.k.a. Δ





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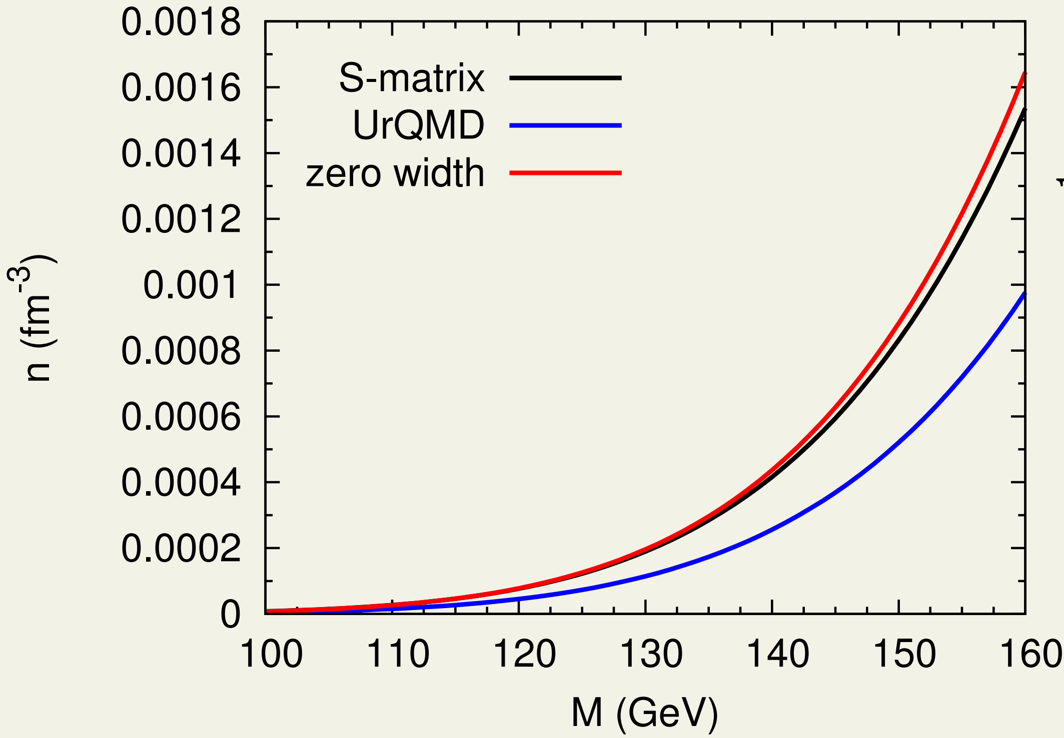
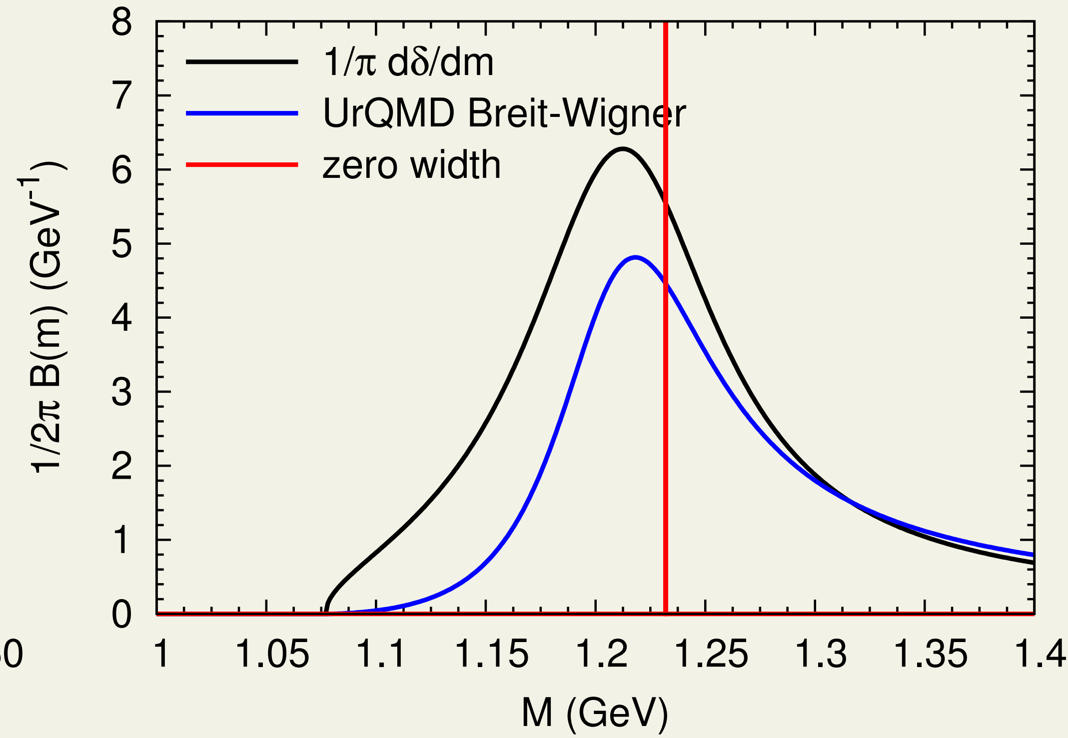
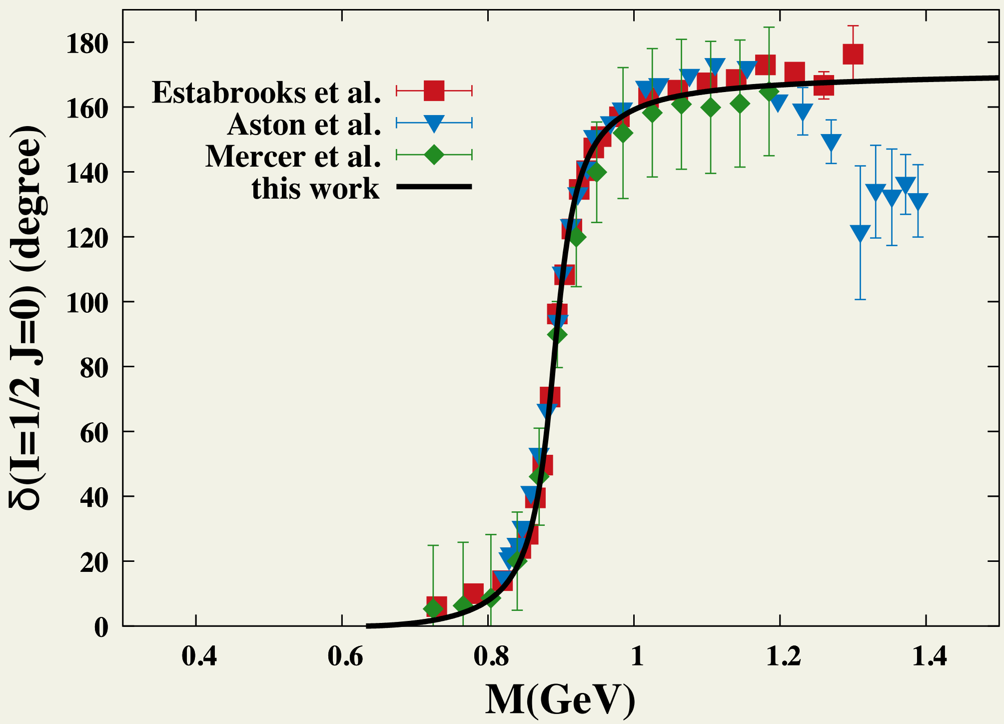
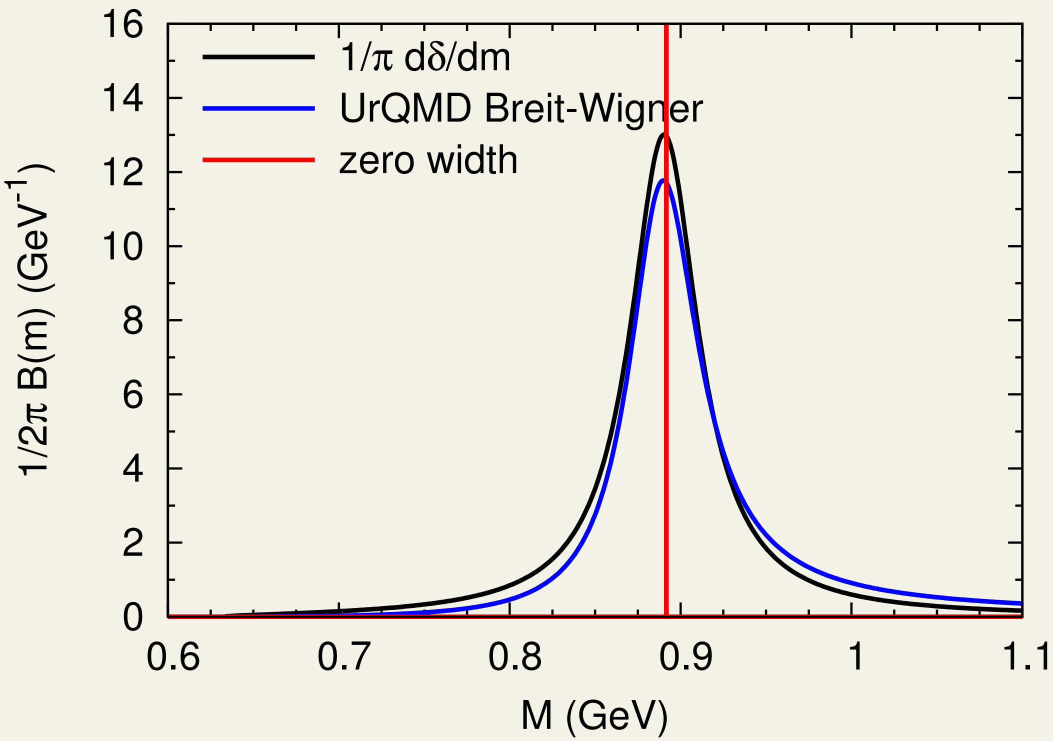


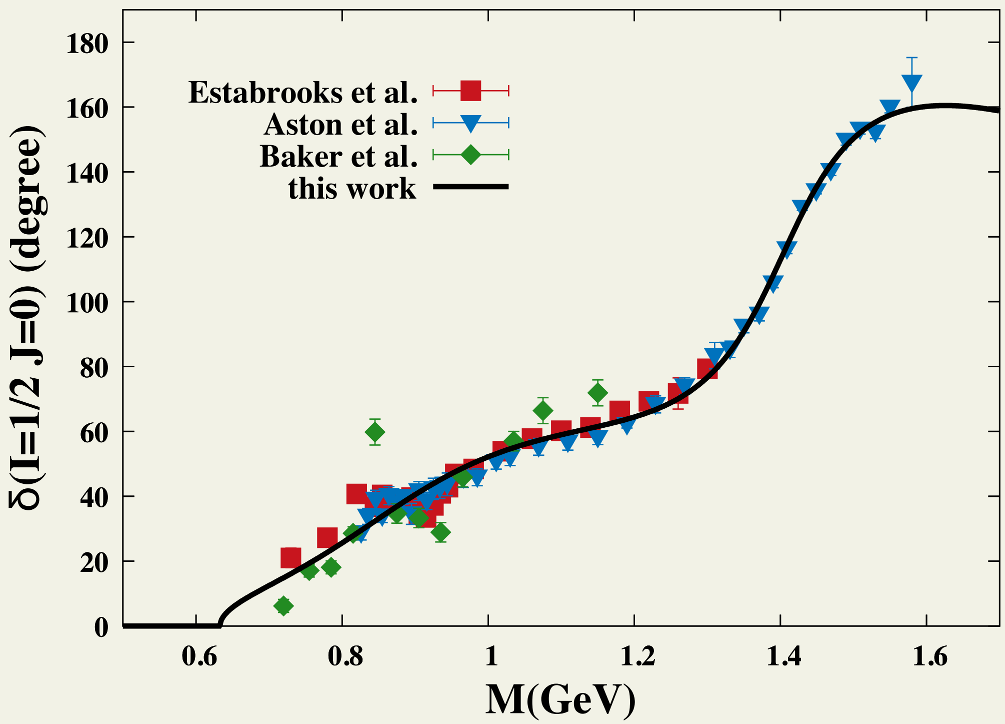


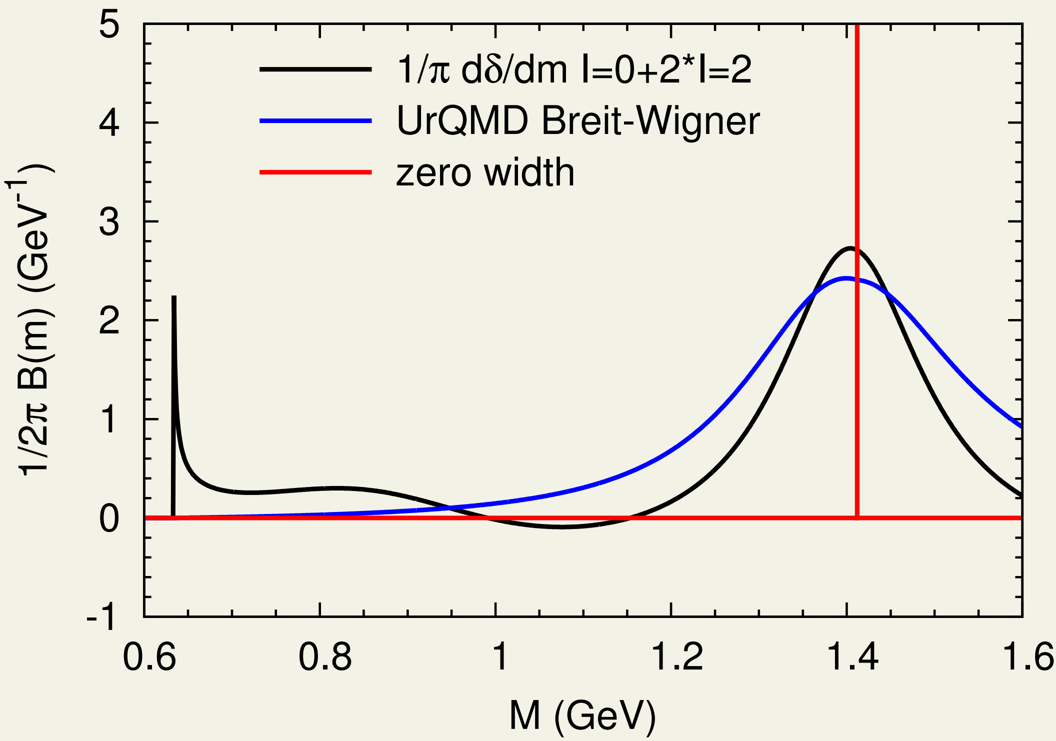
P-wave πK scattering, $K^*(892)$



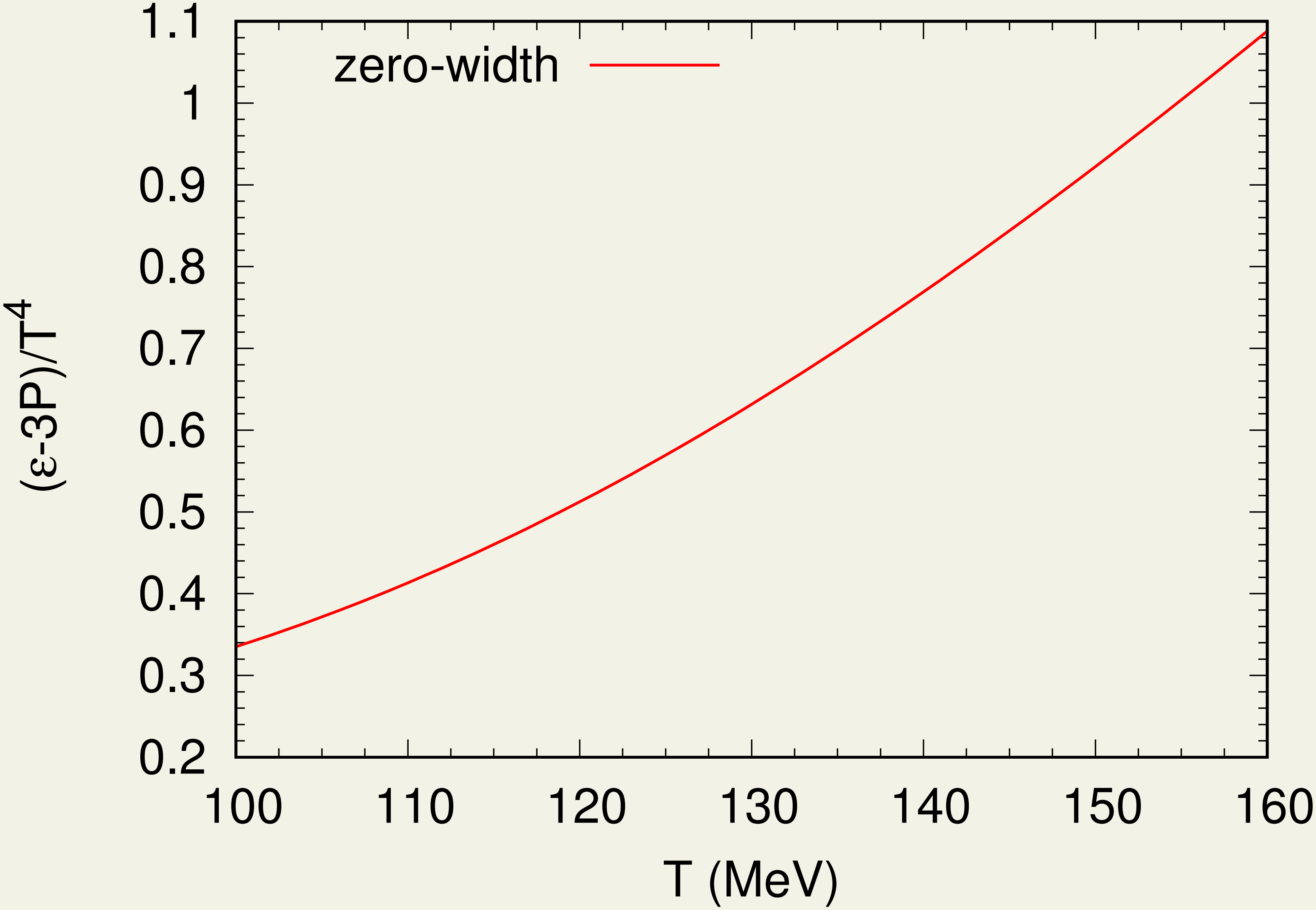


S-wave πK scattering, $K_0^*(1430)$

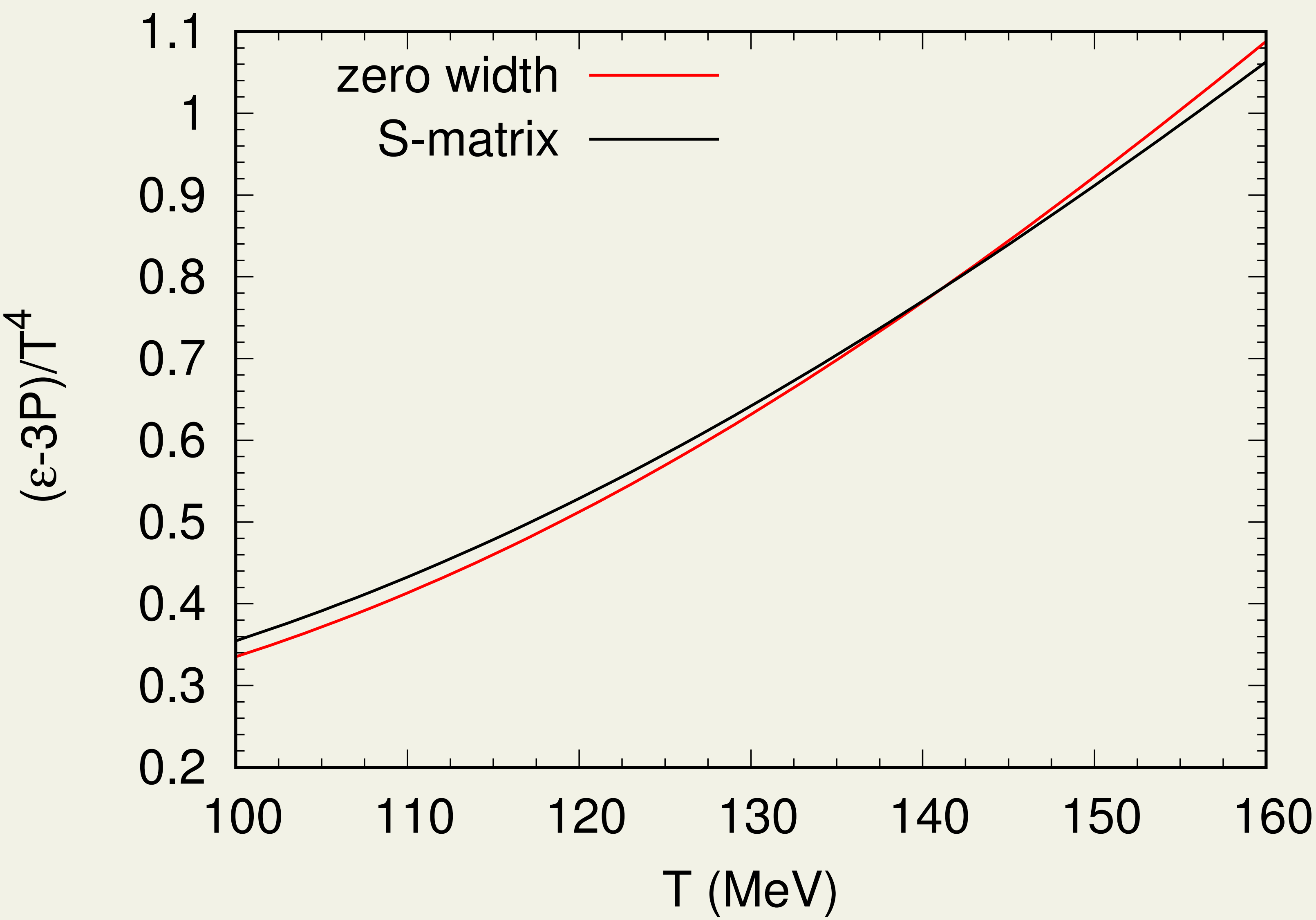




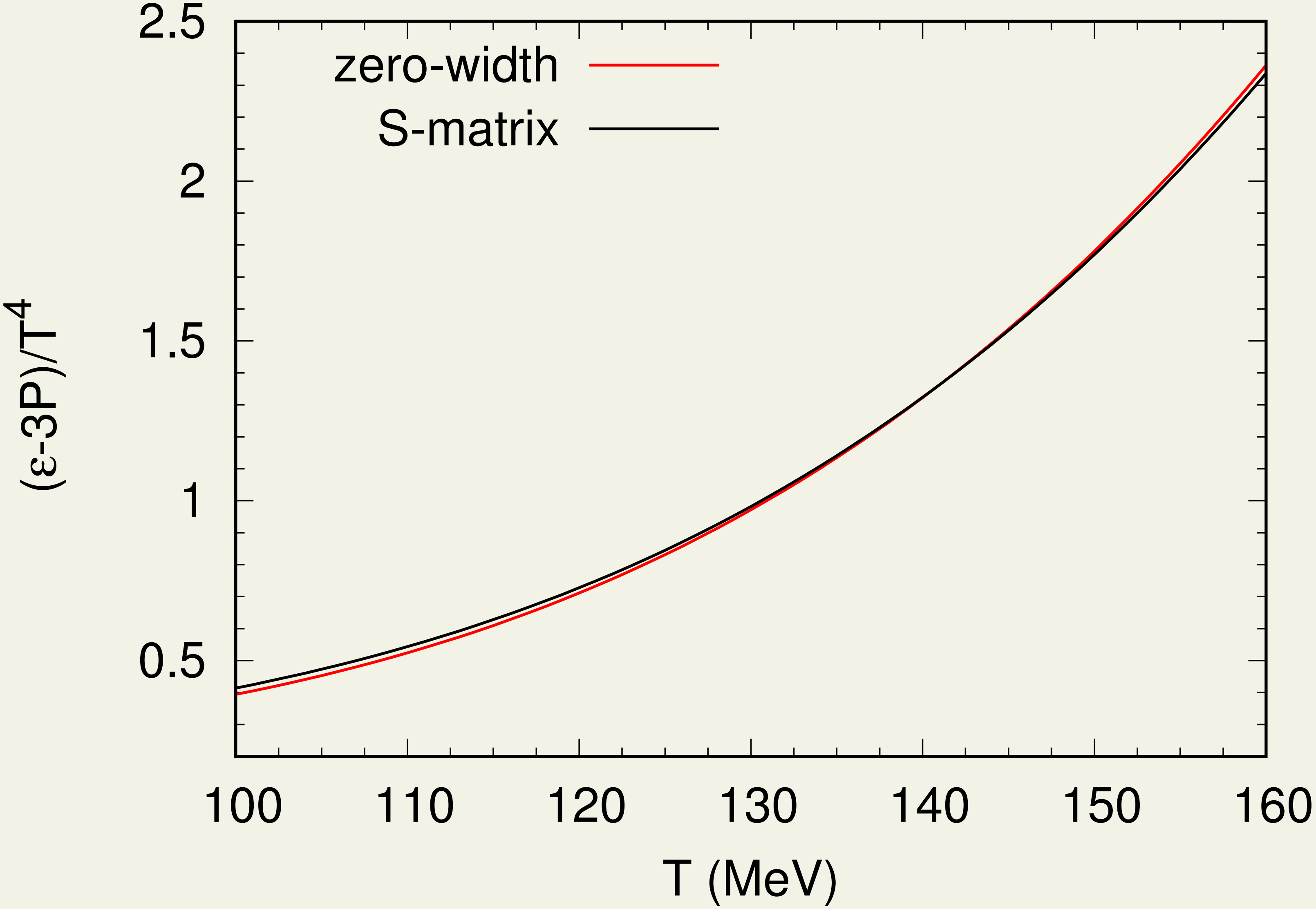
π, K, N, ρ, $f_0(980)$, K^*, $K_0^*(1430)$, Δ



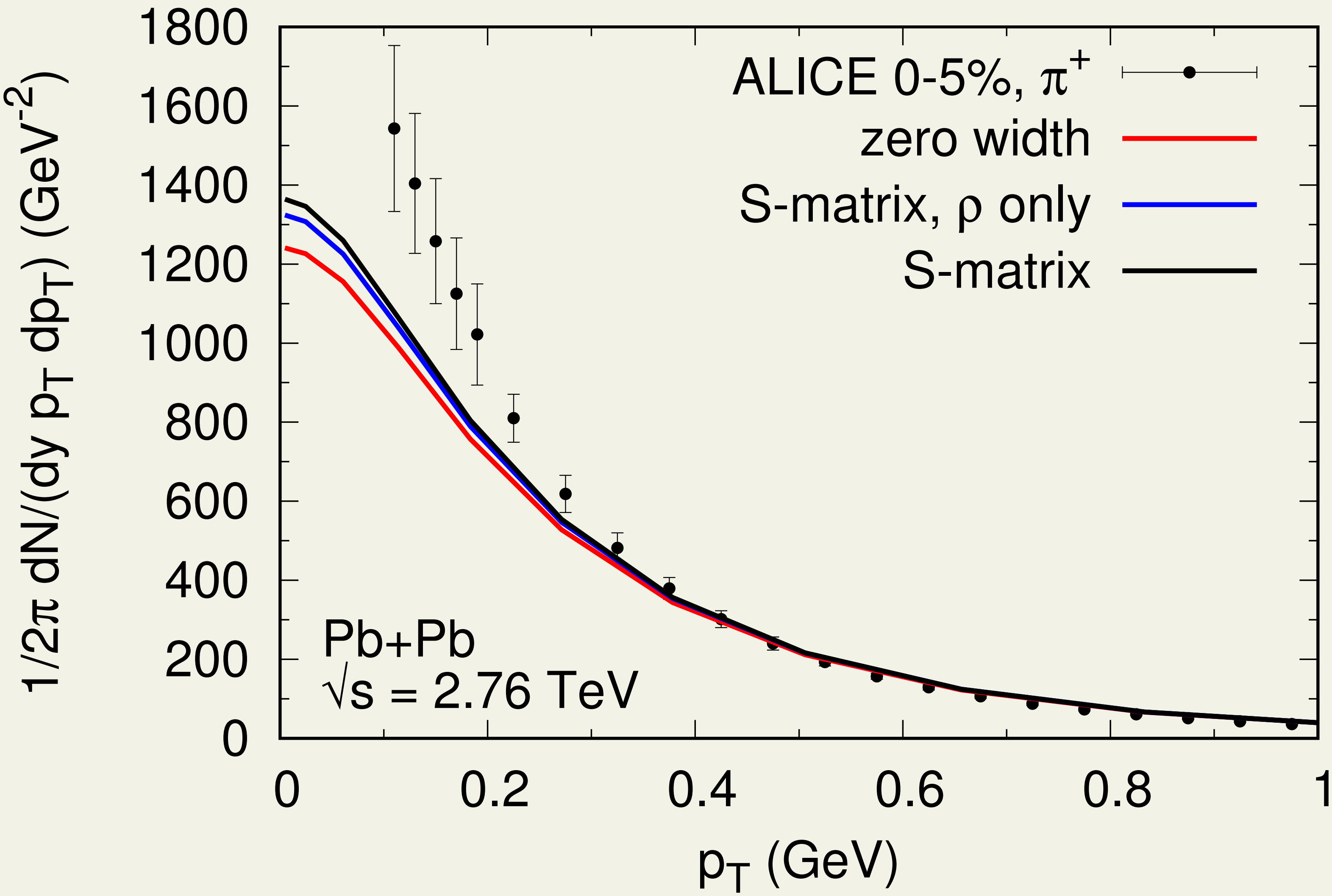
π, K, N, ρ, $f_0(980)$, K^*, $K_0(1430)$, Δ



the whole zoo

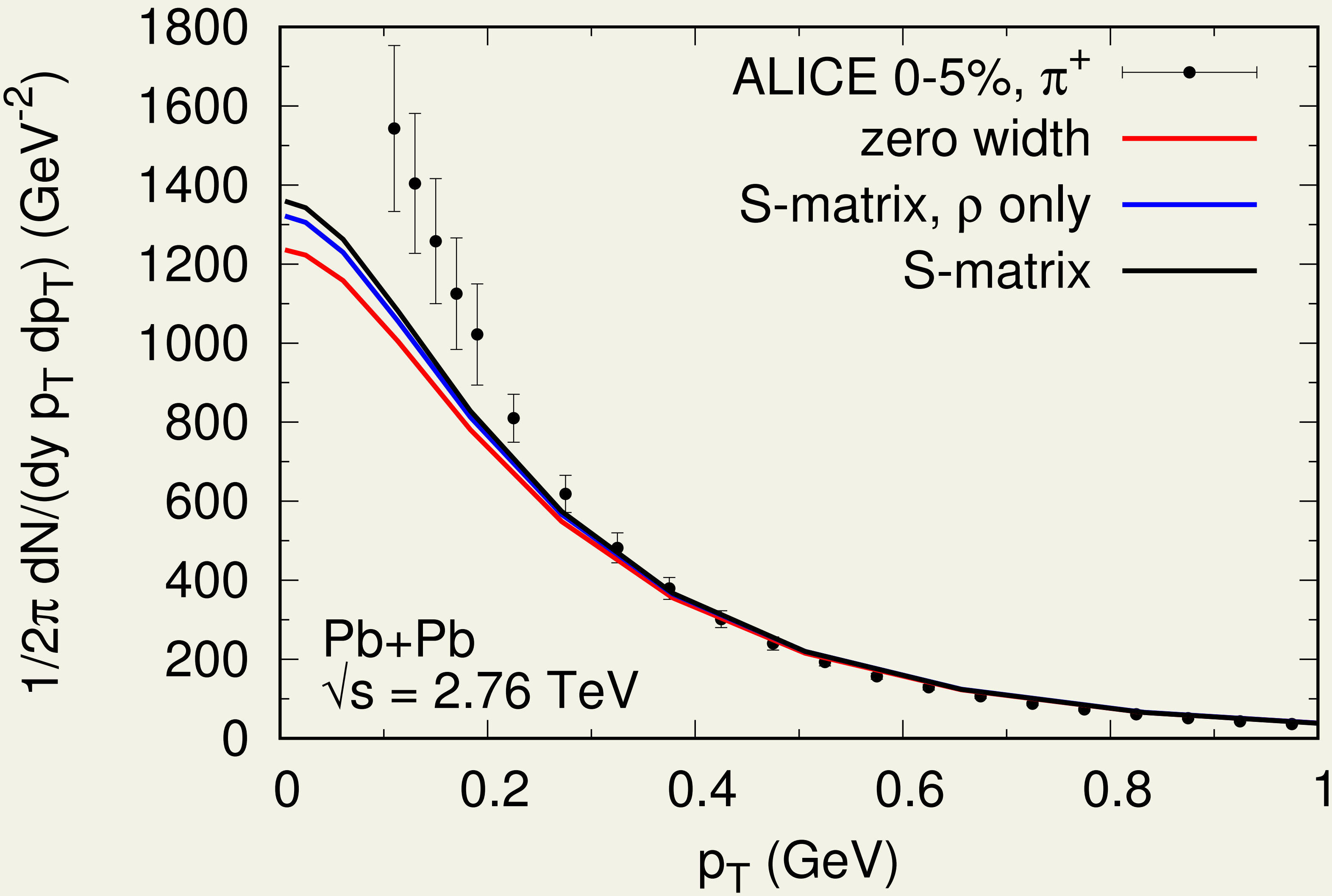


Ideal hydro, $T = 150$ MeV



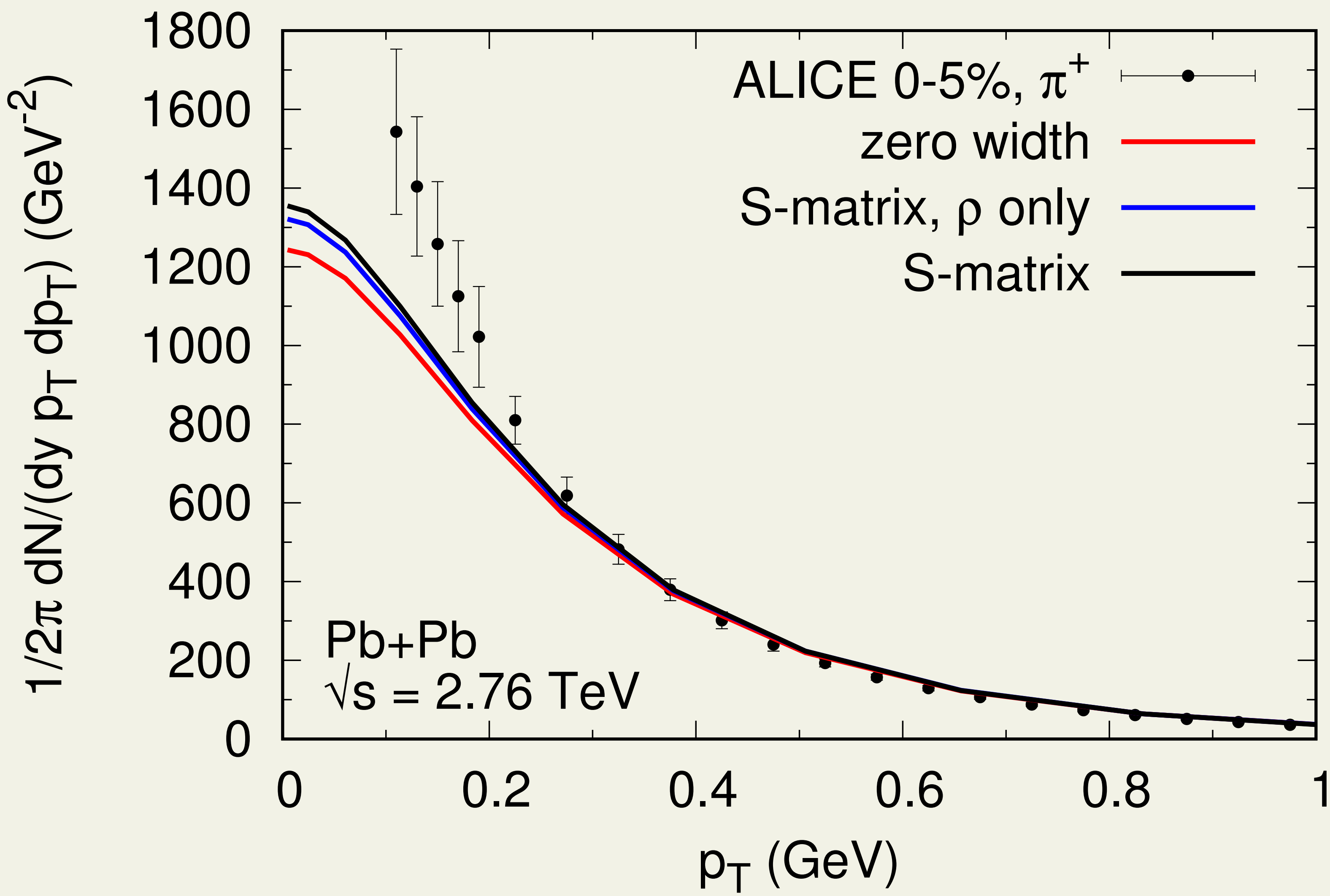
- **all resonances up to 2 GeV**
- **S-matrix for** ρ, Δ, $f_0(980)$, $K^*(892)$, $K_0^*(1430)$
- **zero width for everything else**

Ideal hydro, $T = 120$ MeV, $T_{\rm chem} = 150$ MeV



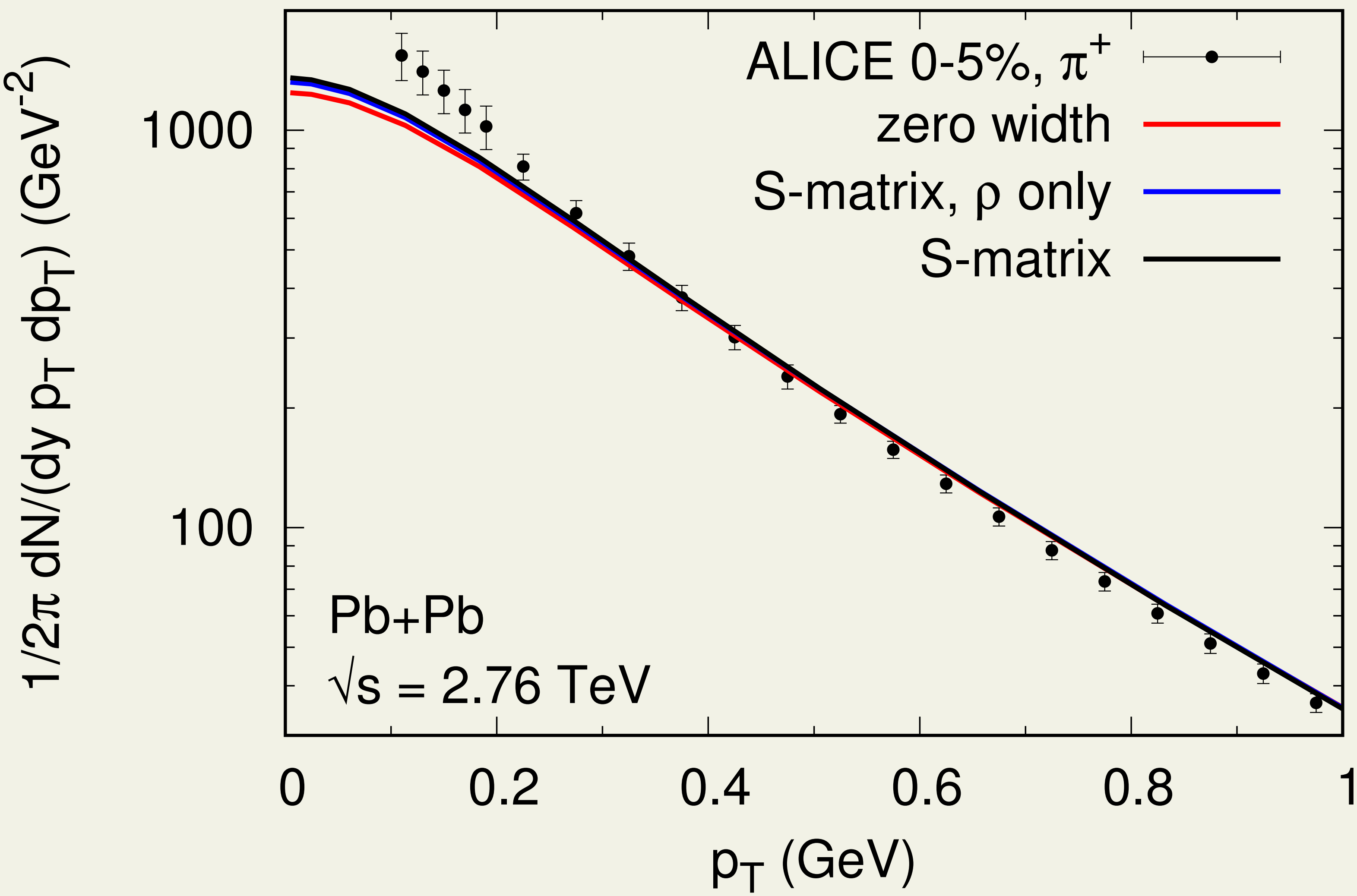
- **all resonances up to 2 GeV**
- **S-matrix for** ρ, Δ, $f_0(980)$, $K^*(892)$, $K_0^*(1430)$
- **zero width for everything else**

Ideal hydro, $T = 100$ MeV, $T_{\text{chem}} = 150$ MeV



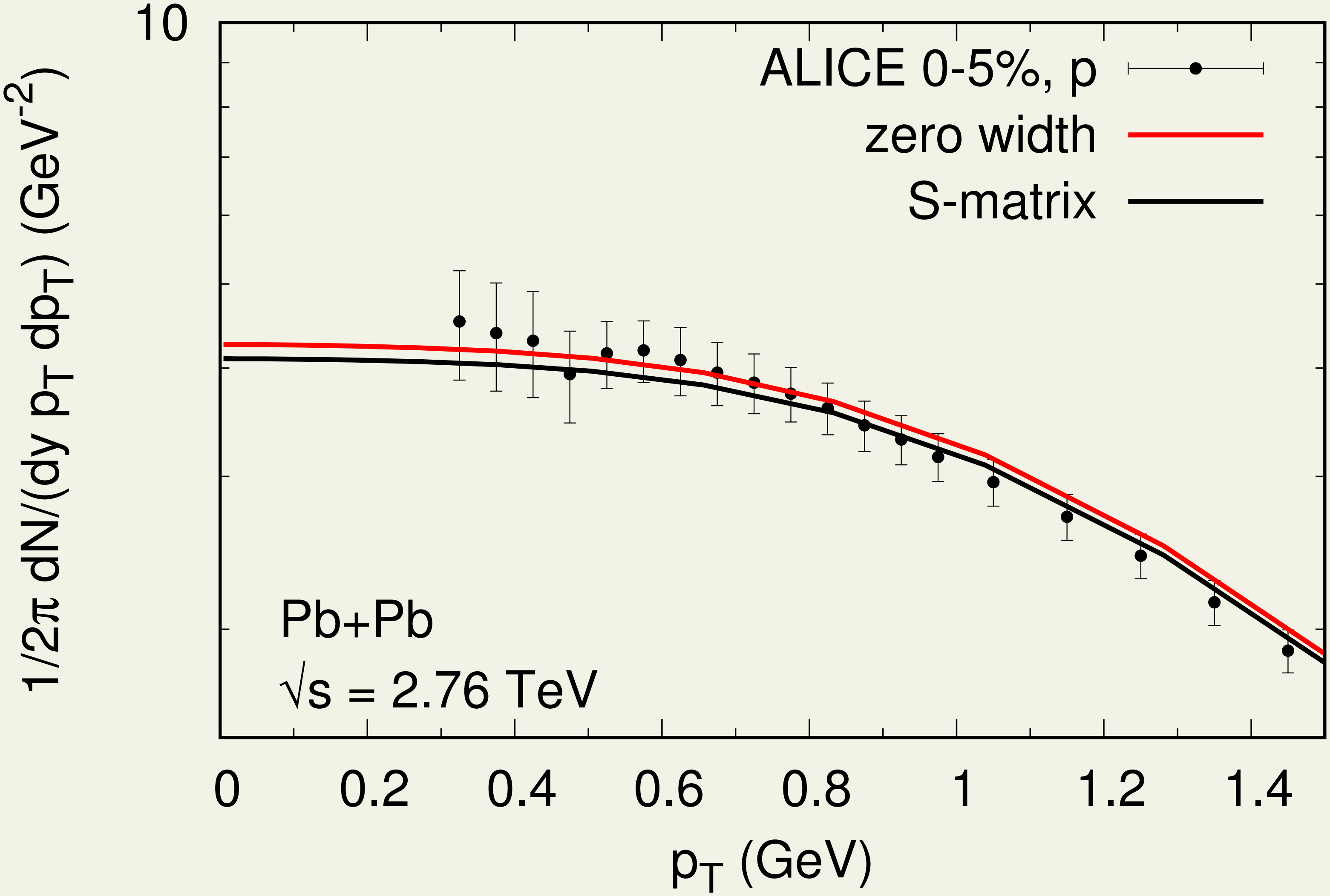
- **all resonances up to 2 GeV**
- **S-matrix for** ρ, Δ, $f_0(980)$, $K^*(892)$, $K_0^*(1430)$
- **zero width for everything else**

Ideal hydro, $T = 100$ MeV, $T_{\text{chem}} = 150$ MeV



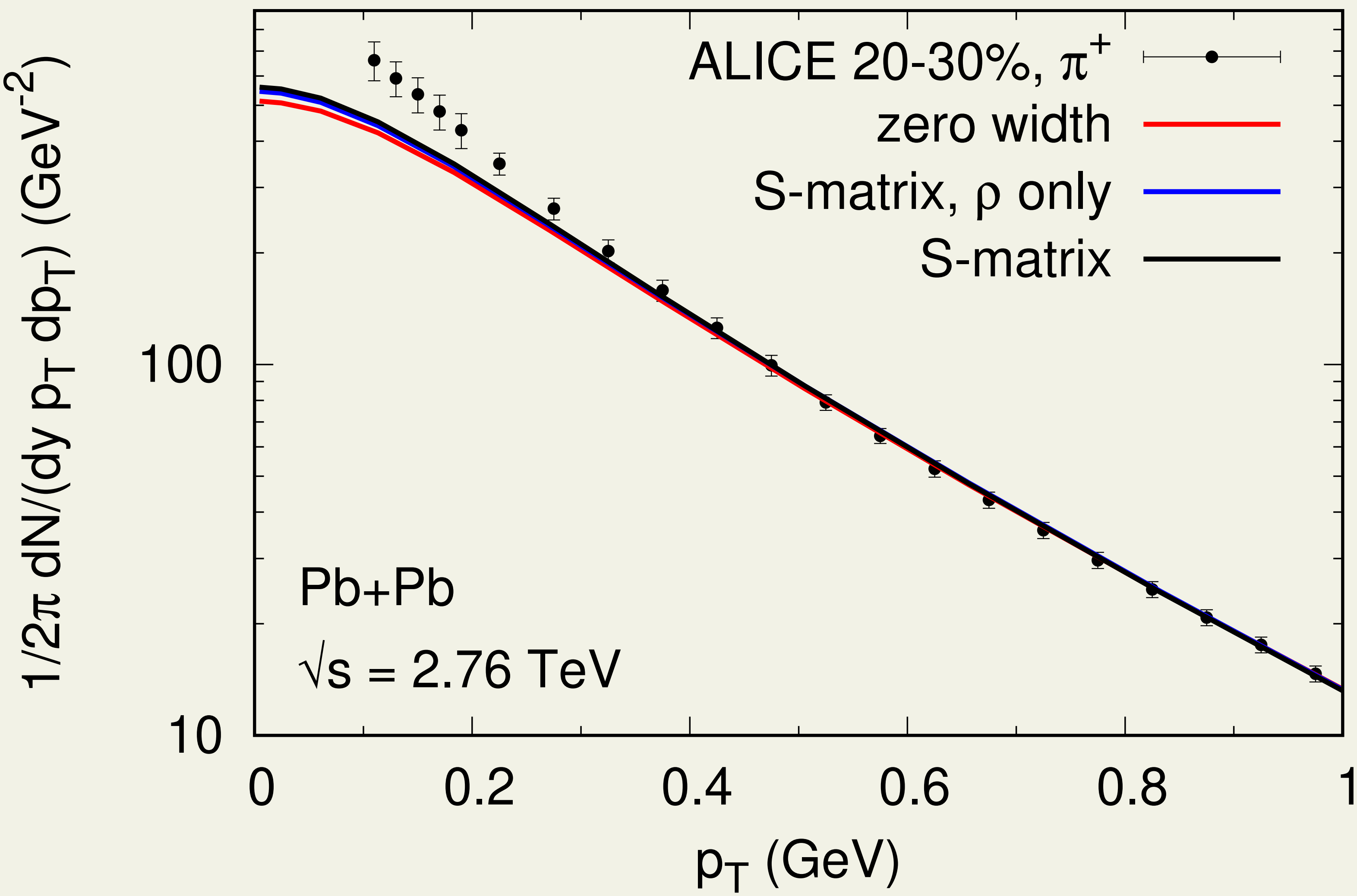
- **all resonances up to 2 GeV**
- **S-matrix for** ρ, Δ, $f_0(980)$, $K^*(892)$, $K_0^*(1430)$
- **zero width for everything else**

Ideal hydro, protons, $T = 100$ MeV, $T_{\rm chem} = 150$ MeV



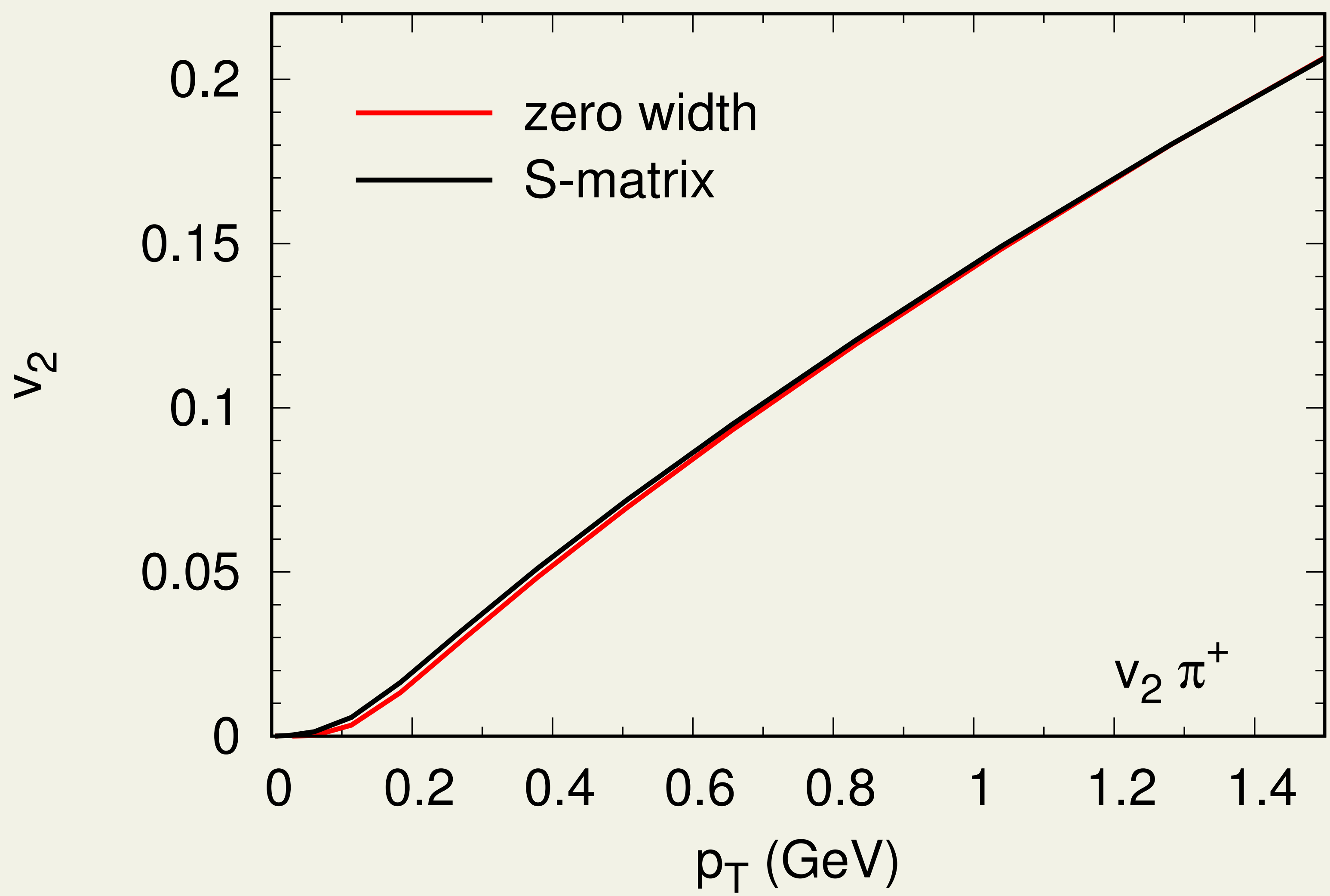
- **all resonances up to 2 GeV**
- **S-matrix for** ρ, Δ, $f_0(980)$, $K^*(892)$, $K^*_0(1430)$
- **zero width for everything else**

Ideal hydro, $T = 100$ MeV, $T_{\text{chem}} = 150$ MeV



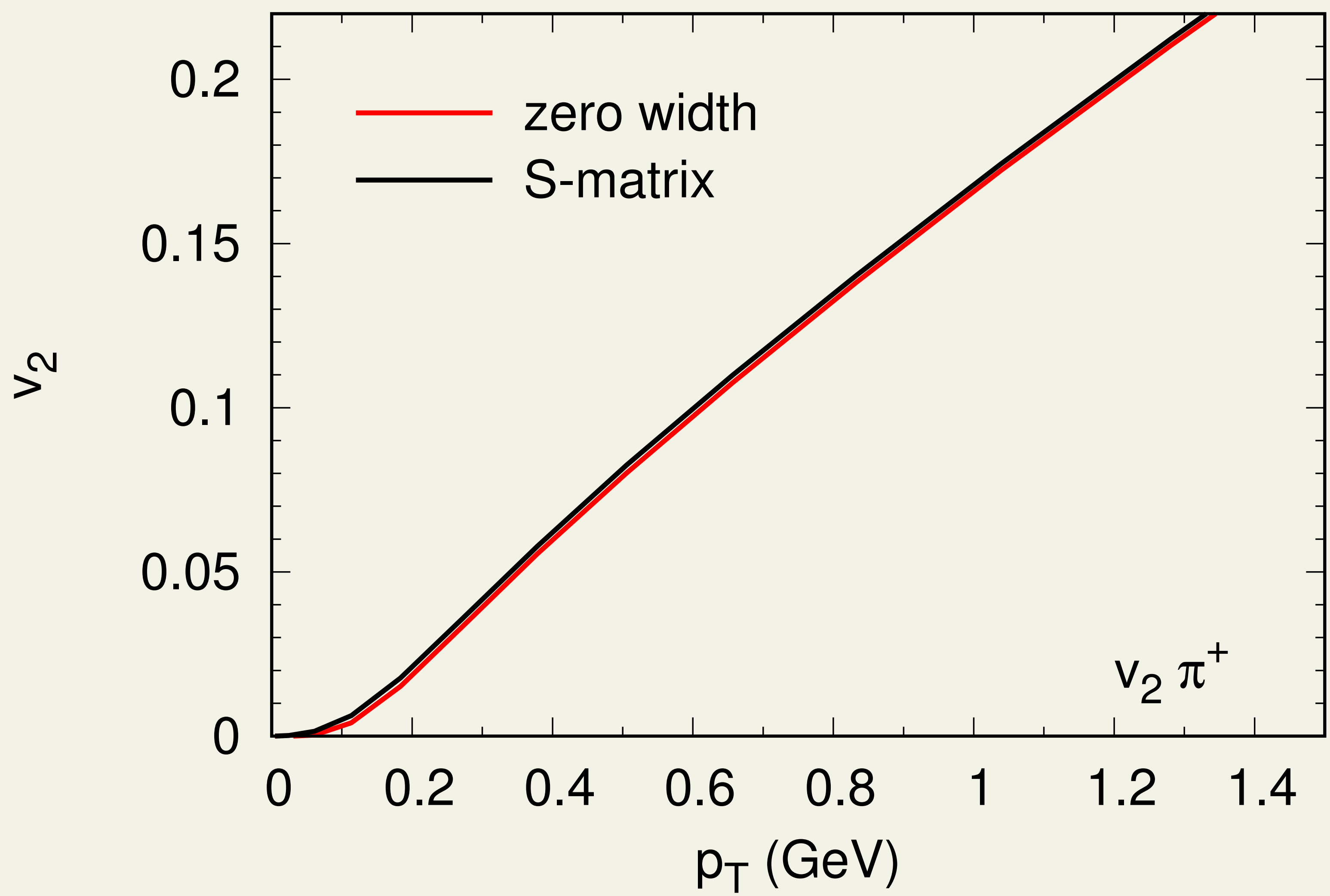
- **all resonances up to 2 GeV**
- **S-matrix for** ρ, Δ, $f_0(980)$, $K^*(892)$, $K_0^*(1430)$
- **zero width for everything else**

Ideal hydro, $v_2(p_T)$ of pions, $T = 150$ MeV



- all resonances up to 2 GeV
- S-matrix for ρ, Δ, $f_0(980)$, $K^*(892)$, $K_0^*(1430)$
- zero width for everything else

Ideal hydro, $v_2(p_T)$ of pions, $T = 100$ MeV, $T_{\rm chem} = 150$ MeV



- **all resonances up to 2 GeV**
- **S-matrix for ρ, Δ, $f_0(980)$, $K^*(892)$, $K_0^*(1430)$**
- **zero width for everything else**

Summary

- **Resonance widths change the low-p_T distribution of pions**

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  - **Improves the fit to low p_T data**

- **Effect on $v_2(p_T)$ small**

♻ **This talk consisted of 100% recycled electrons**