Dilepton production at SIS energies

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- Motivation
- Dileptons
- IQMD
- BUU
- Time evolution of spectral functions
- Summary

Why dileptons at SIS

- measured (DLS, HADES)
- without finalstate interaction
- vector mesons decay to dileptons $\longrightarrow$ vector mesons in matter
- We hope to know the degrees of freedom (hadrons, no quark contributions)
- We may neglect temperaure effects (e.g. see Chpt)
- Path to restauration of chiral symmetry

Dilepton production

2 possibilities:

Use pp and pn contribution for HIC collisions (from data or theory)

or

separate microscopical processes (phenomenologically or from graphs) (bremsstrahlung is not well defined)

- Dalitz-decay of baryon resonances
  Wolf et al., Nucl Phys. A517 (1990) 615 (factor 1/4 missing)
  Zetenyi, Wolf, Phys. Rev, C67 (2003) 044002;
  Heavy Ion Phys. 17 (2003) 27
- Dalitz-decay of π, η and ω
- pn bremsstrahlung not negligible (M.Shafer et al., Shyam et al., Kaptari-Kampfer)
- Direct decay of vector mesons and η

Dalitz-decay of baryon resonances

QED: $$\frac{d\Gamma_{R\to Ne^+e^-}}{dM^2} = \frac{\alpha}{3\pi}\frac{1}{M^2}\Gamma_{R\to N\gamma}(M).$$

$$\Gamma_{R\to N\gamma}(M) = \frac{\sqrt{\lambda(m_*^2, m^2, M^2)}}{16\pi m_*^3}\frac{1}{n_{pol,R}}\sum_{pol}|\langle N\gamma|T|R\rangle|^2,$$

- spin-J fermion, $J \geq 3/2$: Rarita-Schwinger spinor-tensor field

$$\begin{aligned} u^{\cdots\rho_i\cdots\rho_k\cdots}(p_*,\lambda_*) &= u^{\cdots\rho_k\cdots\rho_i\cdots}(p_*,\lambda_*), \\ u^{\cdots\sigma\cdots}{}_{\sigma}{}^{\cdots}(p_*,\lambda_*) &= u^{\cdots\sigma\cdots}(p_*,\lambda_*)p_{*\sigma} = u^{\cdots\sigma\cdots}(p_*,\lambda_*)\gamma_\sigma = 0, \end{aligned}$$

EM coupling of baryon resonances

- There are 3 independent tensor structure for coupling of the nucleon and the Rarita-Schwinger spinor ($G = 1$ or γ_5):

$$\Gamma_{\mu\rho_1\cdots\rho_n} = \sum_{i=1}^{3} f_i(q^2 = M^2)\chi^i_{\mu\rho_1} p_{\rho_2} \cdots p_{\rho_n} G,$$

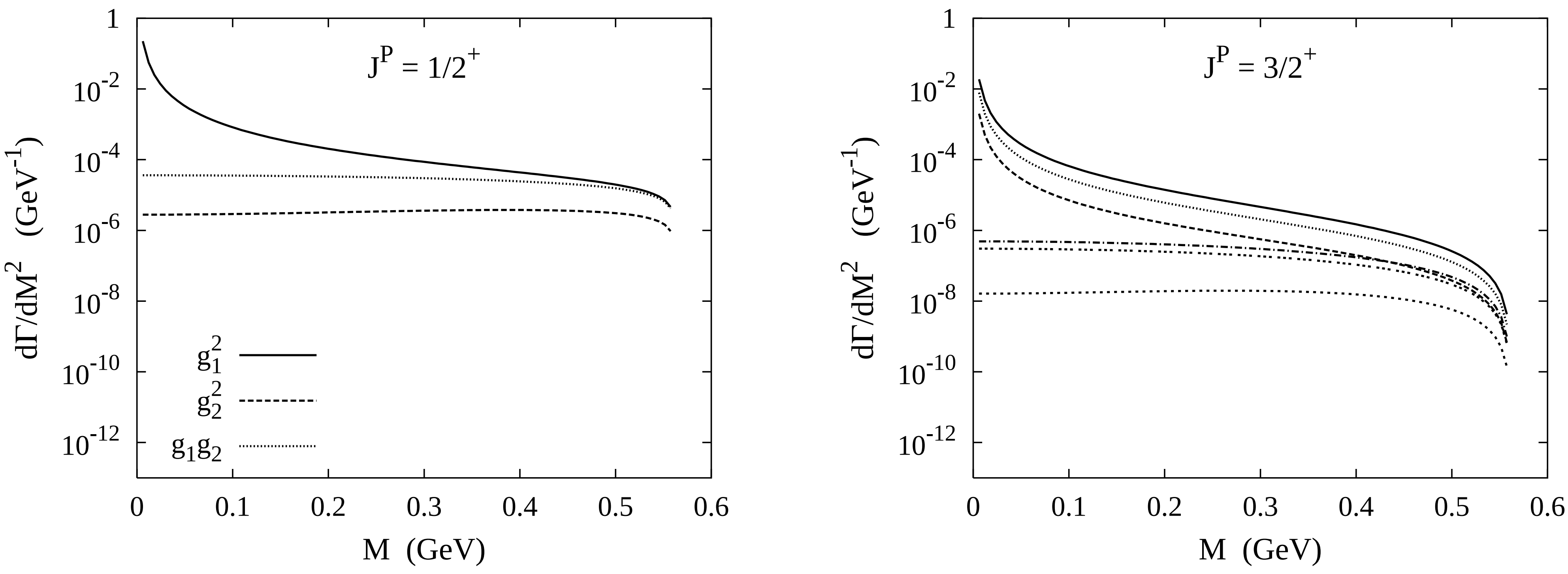
with

$$\chi^1_{\mu\rho} = \gamma_\mu q_\rho - \not{q} g_{\mu\rho},$$

$$\chi^2_{\mu\rho} = P_\mu q_\rho - (P \cdot q) g_{\mu\rho},$$

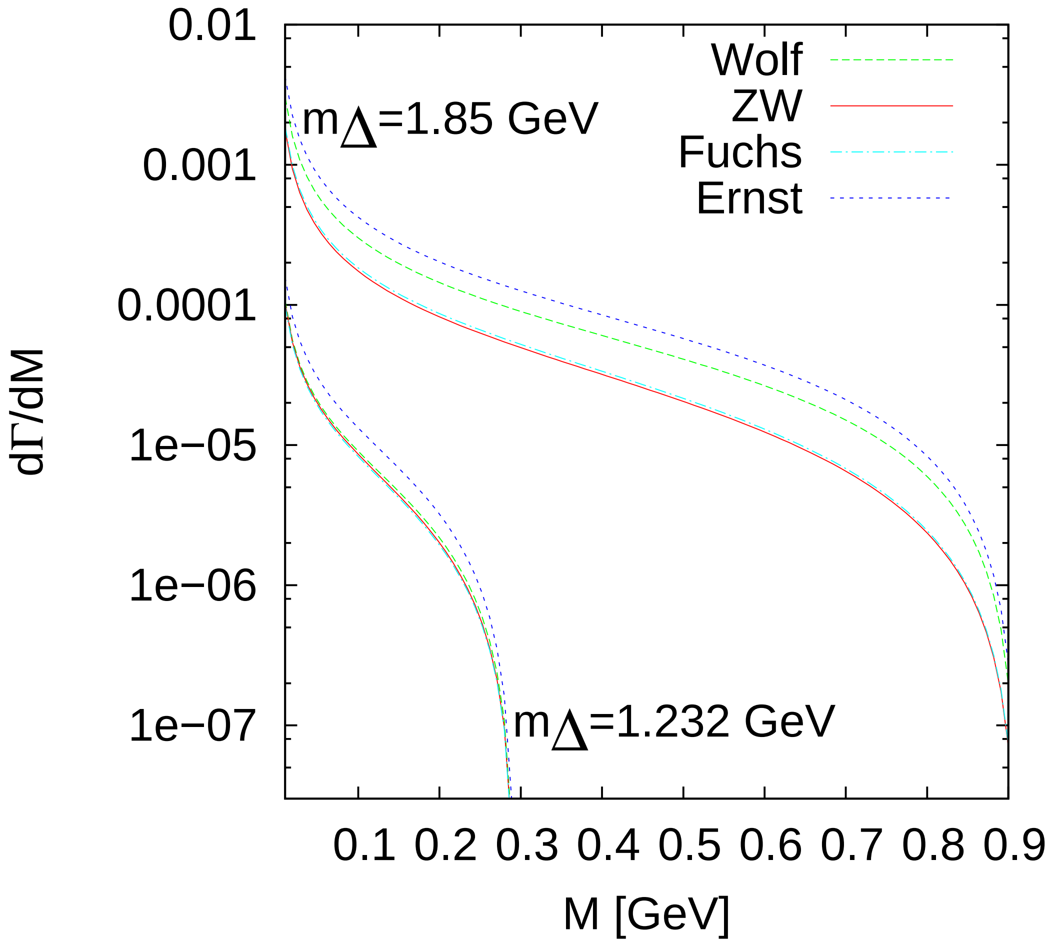
$$\chi^3_{\mu\rho} = q_\mu q_\rho - q^2 g_{\mu\rho},$$

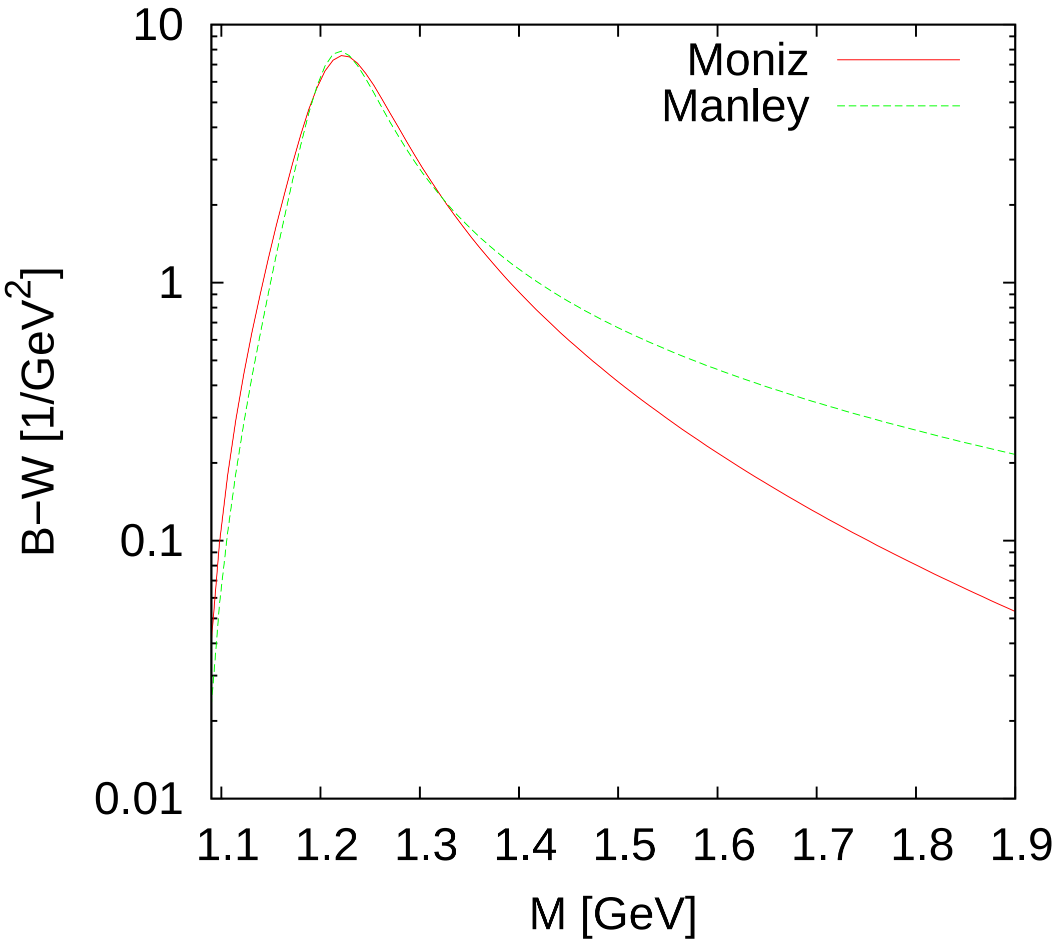
Dalitz-decay contributions



$m_* = 1.5$ GeV. The dimensionless coupling constants are set to unity.

$\Delta(1232)$





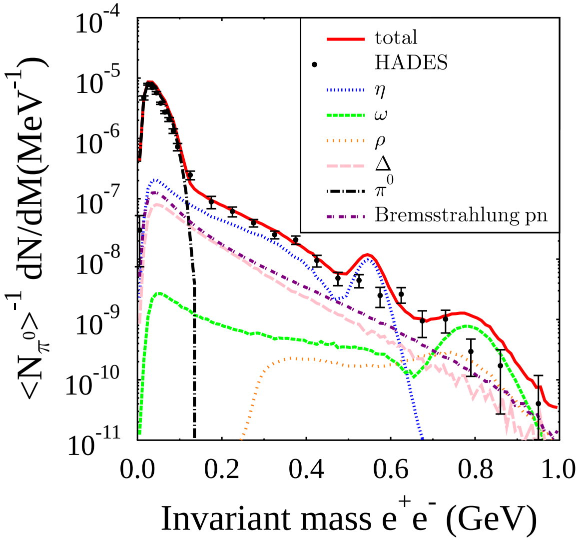
(Ernst contribution: a sign is corrected.)

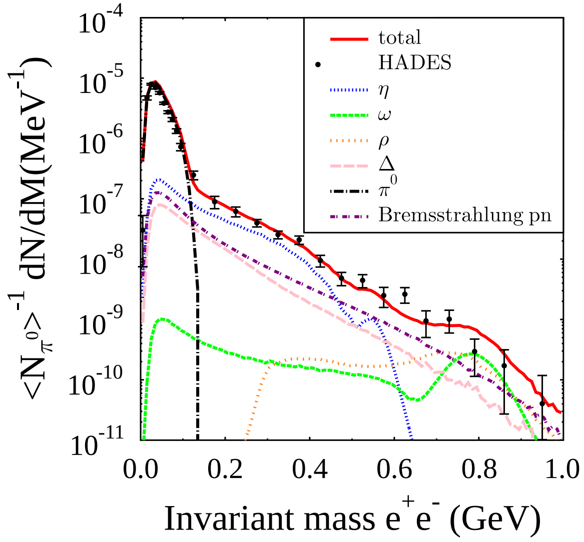
IQMD

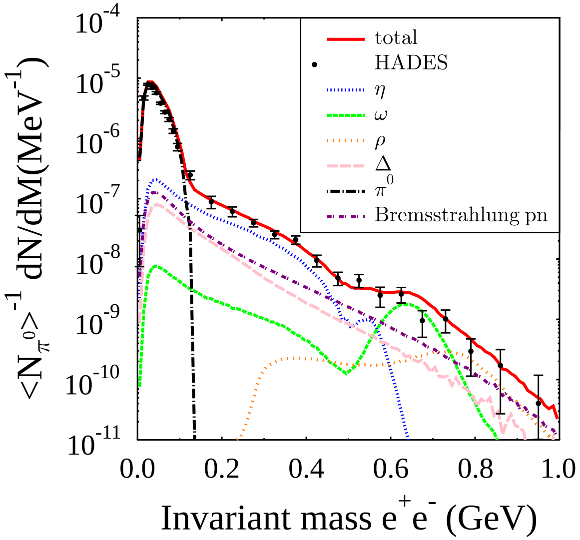
- nucleons, Δ's, π's and kaons propagate
- baryon-baryon potential: Skyrme, Yukawa, Coulomb, symmetry and a momentum dep. interaction
- very good description of the flow and pion, kaon data upto 2 GeV
- parametrization of the η, ρ and ω production cross section
- η production: two production channel, direct and via the N(1535) resonance
- correct momentum distribution of η

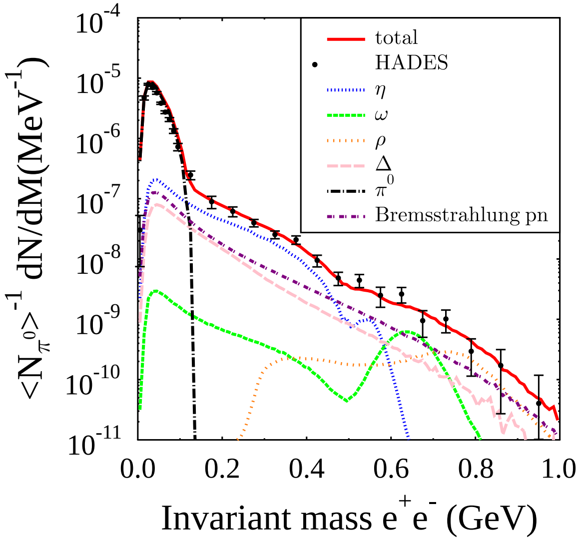
C + C 2 GeV

$np \to np\omega = 5pp \to pp\omega$ $\quad$ $np \to np\omega = pp \to pp\omega$









$$M_\omega = M_\omega^o(1 - 0.13\rho/\rho_o)$$

Summary of IQMD

- data not precise enough to observe vector meson modification in matter
- Simple model with very precise meson production
- no vector meson and eta rescattering
- mesons decay at creation
- no low mass ρ production except $\pi^+\pi^-$ annihilation
- difficult to extrapolate to medium

Why off-shell transport

- medium effects on the spectrum of vector mesons
  — indication of mass shift of longliving ω's
- how they get on-shell (energy-momentum conservation)
- if it is broad, even the local density approximation has no precise meaning

Off-shell transport

- Kadanoff-Baym equation for retarded Green-function
  Wigner-transformation, gradient expansion
- transport equation for $F_\alpha = f_\alpha(x,p,t)A_\alpha$
  $A(p) = -2ImG^{ret} = \frac{\hat{\Gamma}}{(E^2 - \mathbf{p}^2 - m_0^2 - \mathrm{Re}\Sigma^{ret})^2 + \frac{1}{4}\hat{\Gamma}^2},$

  Cassing, Juchem (2000) and Leupold (2000)
- testparticle approximation

Transport equations

- $$\frac{d\vec{X}_i}{dt} = \frac{1}{1-C_{(i)}} \frac{1}{2\epsilon_i} \left[2\,\vec{P}_i + \vec{\nabla}_{P_i} Re\Sigma^{ret}_{(i)} + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \vec{\nabla}_{P_i} \Gamma_{(i)} \right]$$

  $$\frac{d\vec{P}_i}{dt} = -\frac{1}{1-C_{(i)}} \frac{1}{2\epsilon_i} \left[\vec{\nabla}_{X_i} Re\Sigma^{ret}_{i} + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \vec{\nabla}_{X_i} \Gamma_{(i)} \right]$$

  $$\frac{d\epsilon_i}{dt} = \frac{1}{1-C_{(i)}} \frac{1}{2\epsilon_i} \left[\frac{\partial Re\Sigma^{ret}_{(i)}}{\partial t} + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \frac{\partial \Gamma_{(i)}}{\partial t} \right]$$

- where $C_{(i)}$ renormalization factor

  $$C_{(i)} = \frac{1}{2\epsilon_i} \left[\frac{\partial}{\partial \epsilon_i} Re\Sigma^{ret}_{(i)} + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \frac{\partial}{\partial \epsilon_i} \Gamma_{(i)} \right]$$

  dangerous, $C_{(i)}$ can be 1

  if $C_{(i)} > 0.5$ we use $\frac{1}{1-C_{(i)}} = 1.33(1 + C_{(i)})$

  However $C_{(i)} = 0$ do not change the results substantially

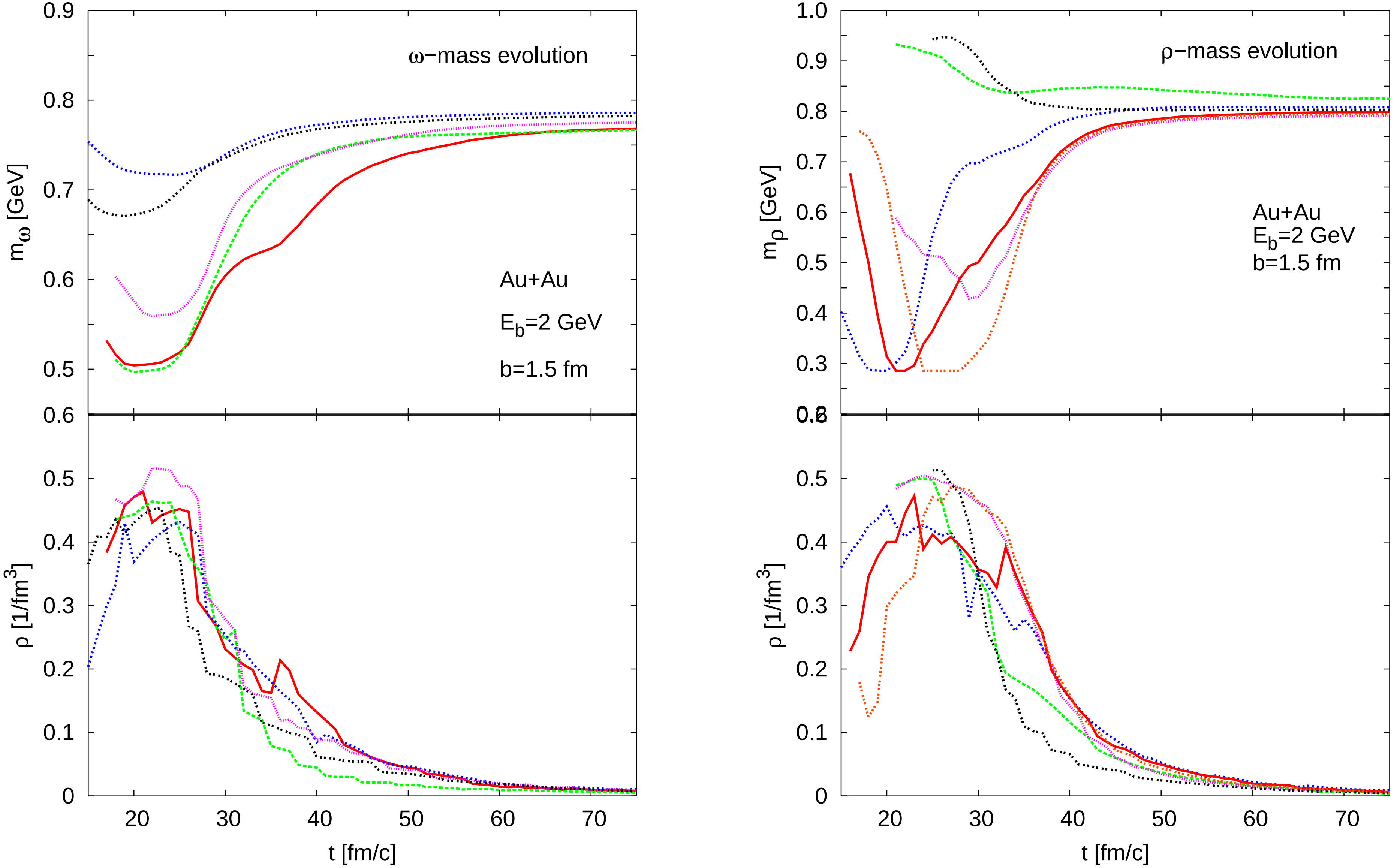
- the last equation can be rewritten as

  $$\frac{dM_i^2}{dt} = \frac{M_i^2 - M_0^2}{\Gamma_{(i)}} \frac{d\Gamma_{(i)}}{dt}$$

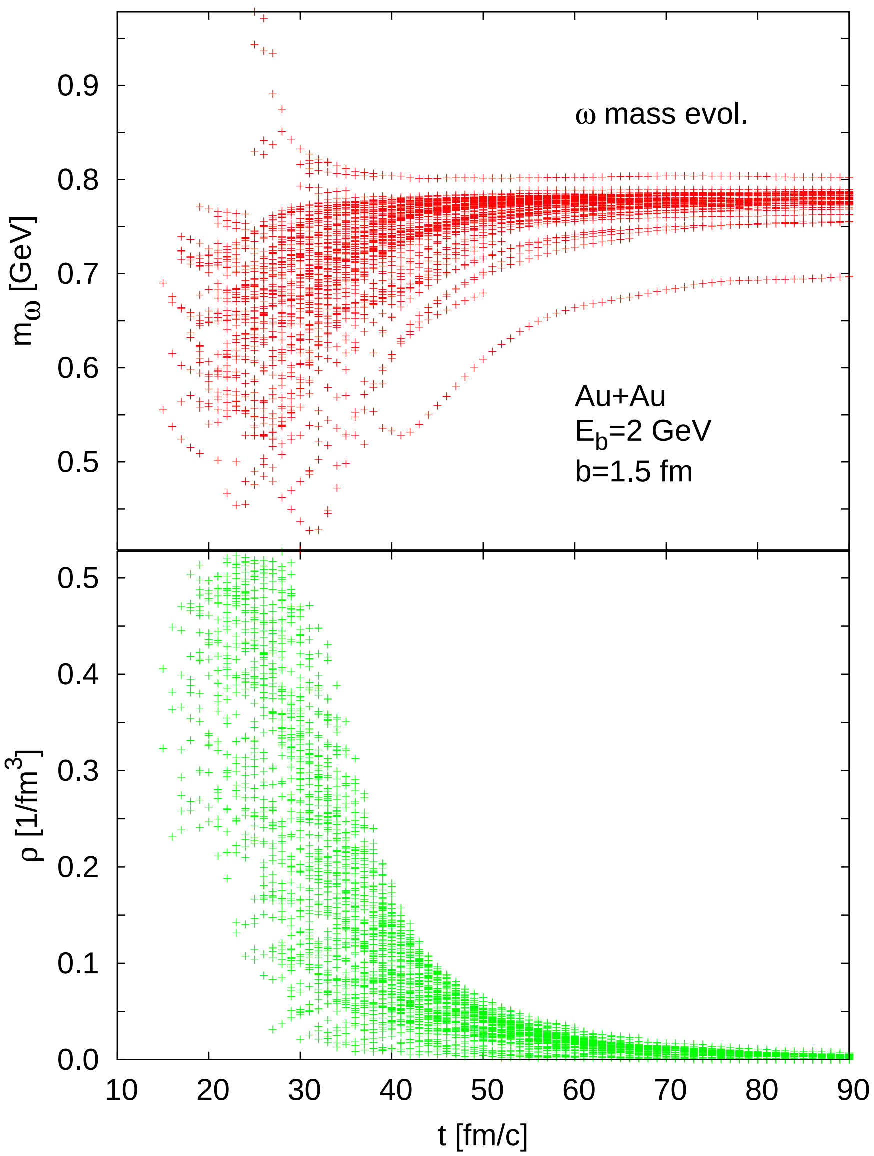
Medium effects

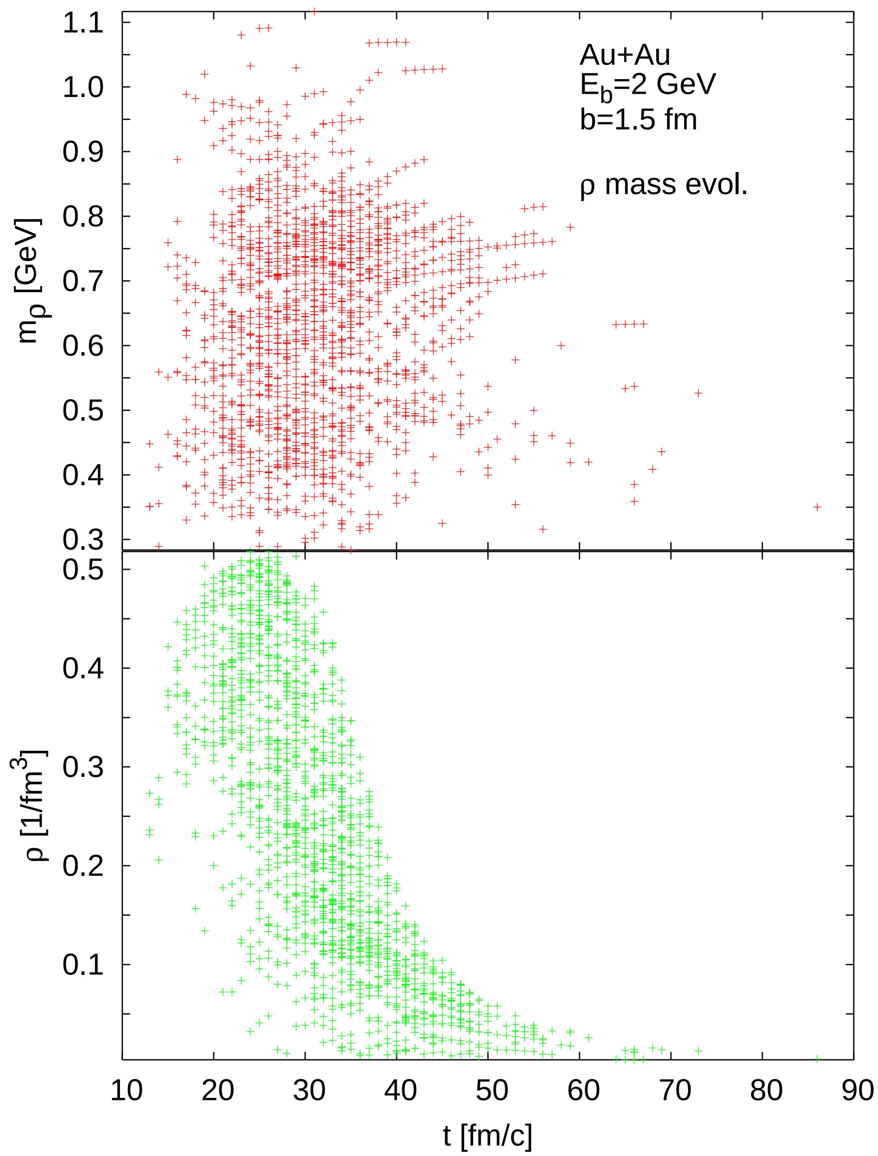
- imaginary part (collisional broadening):
  $\Gamma = \Gamma_{vac} + n v \sigma \gamma$
- real part (mass shift)
  $M = M_{vac} + n/n_o \Delta M$
  $\Delta M_\omega = -50$ MeV, $\Delta M_\rho = -120$ MeV
- danger of double counting
  collision term already contains partly the mixing of mesons with resonance-hole excitations
  but sum up only to finite order

Evolution of masses

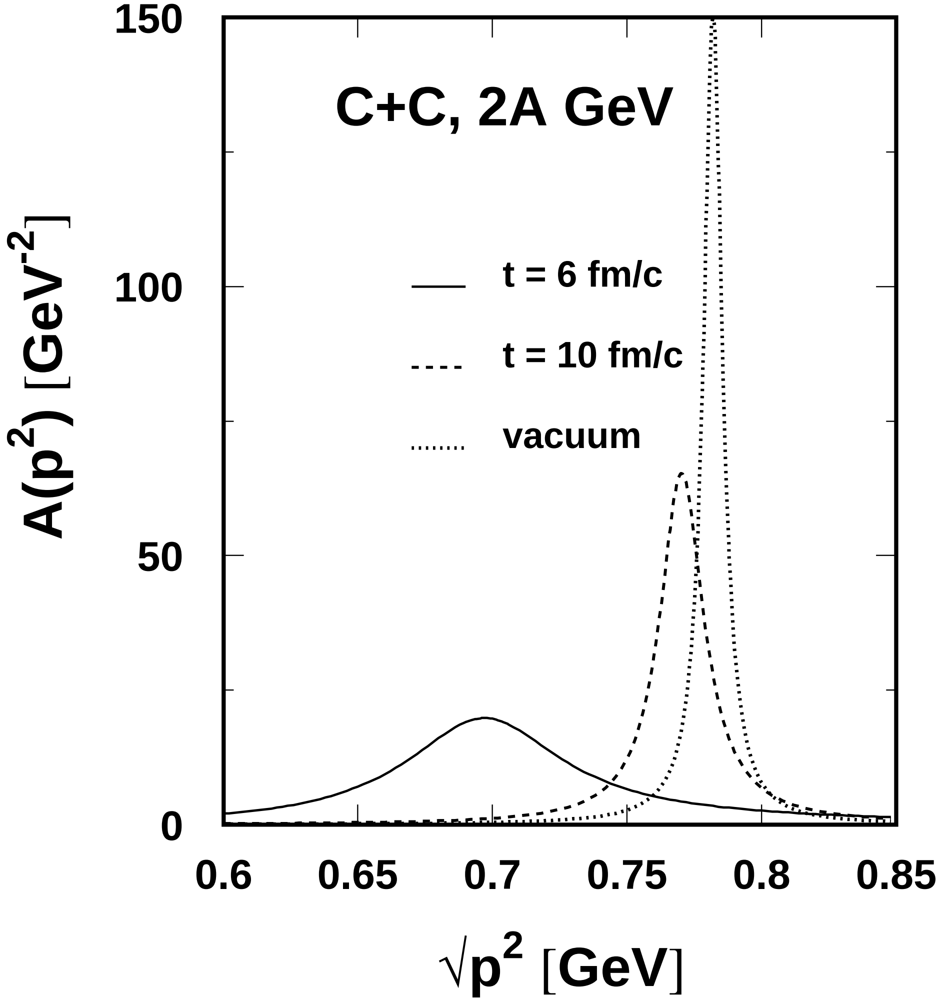


Evolution of masses

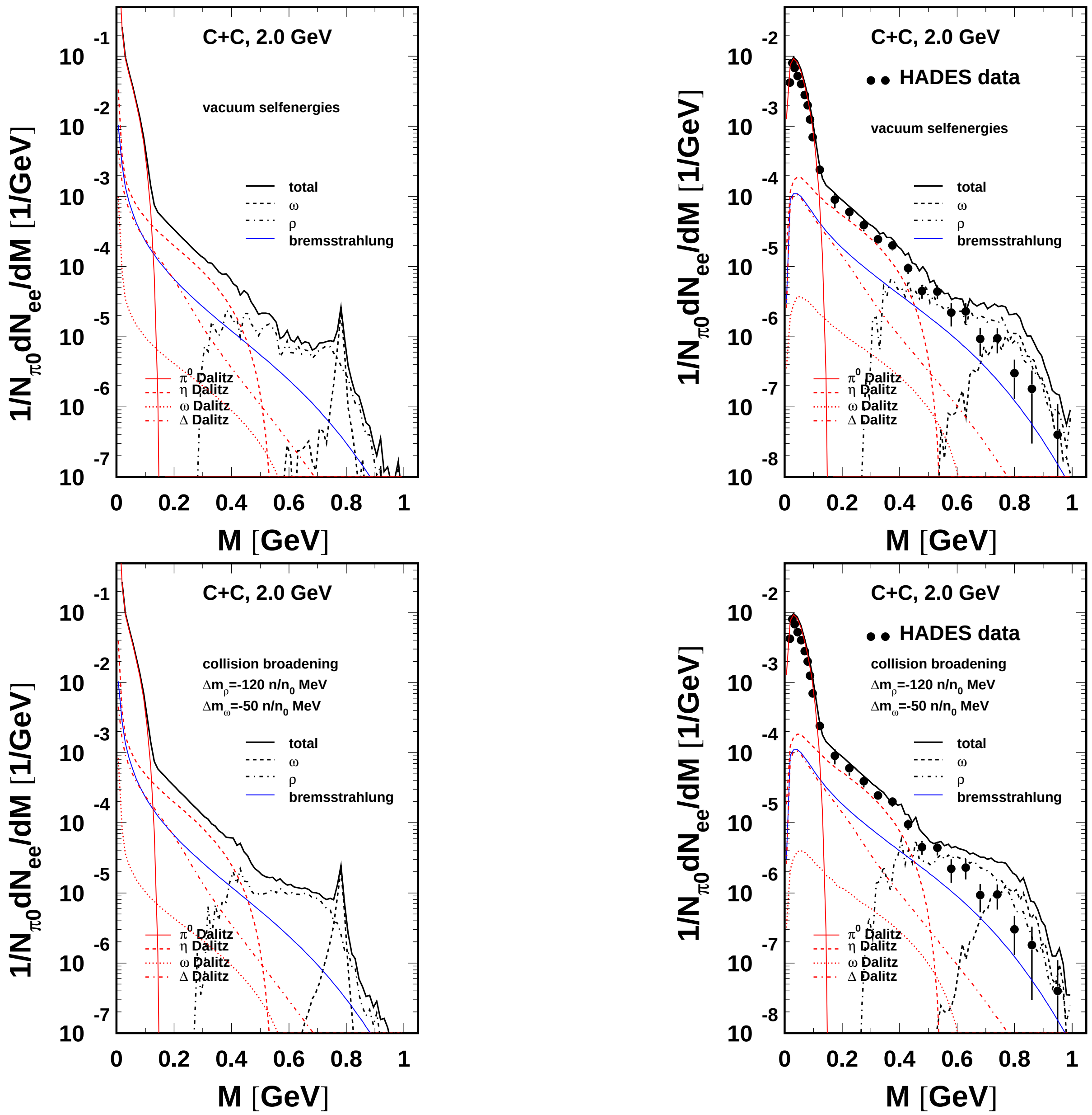




Evolution of the ω spectrum

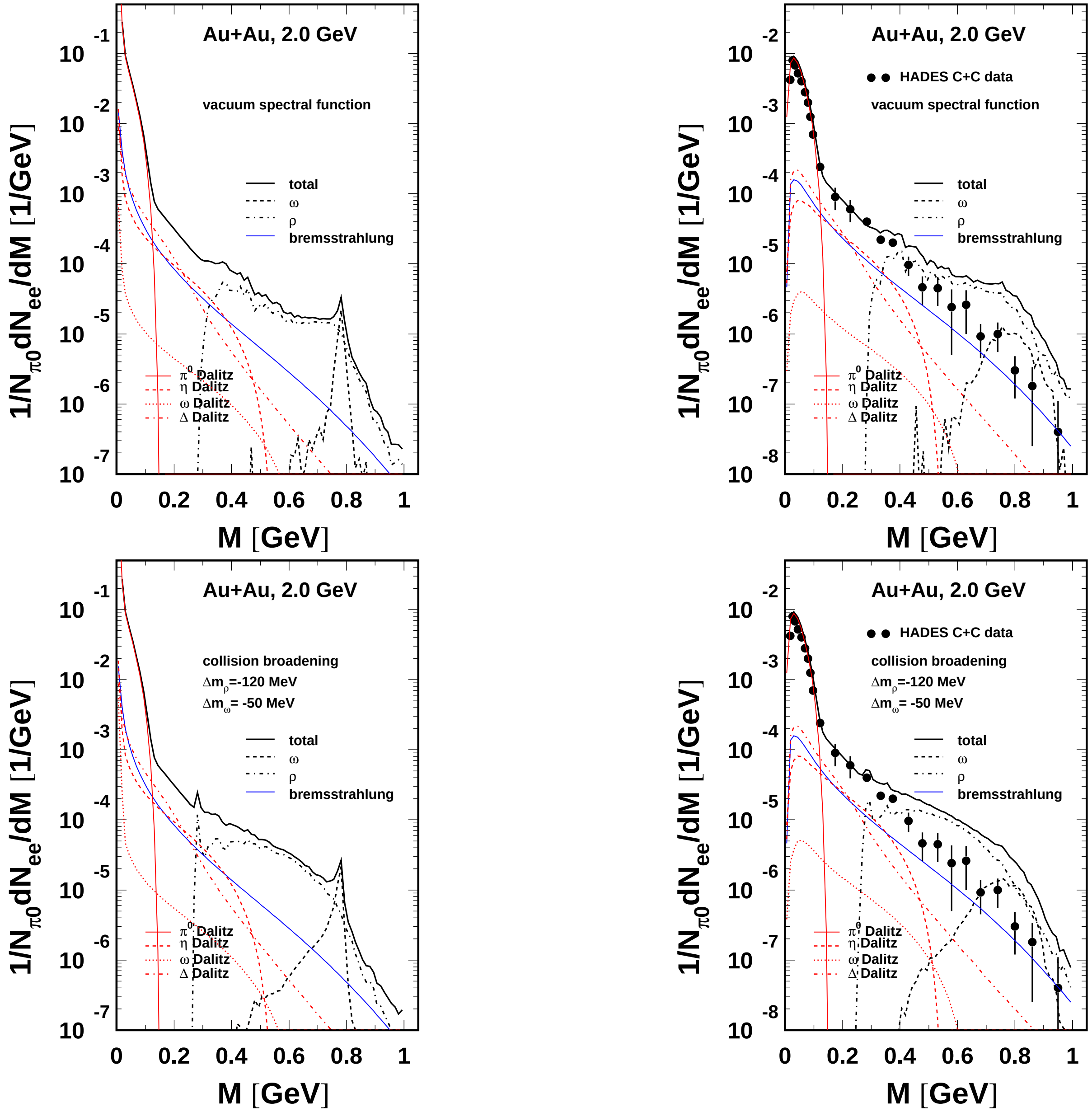


C + C 2 GeV



C+C, 2.0 GeV
vacuum selfenergies
total
ω
ρ
bremsstrahlung
π0 Dalitz
η Dalitz
ω Dalitz
Δ Dalitz
1/Nπ0dNee/dM [1/GeV]
M [GeV]
C+C, 2.0 GeV
HADES data
vacuum selfenergies
total
ω
ρ
bremsstrahlung
π0 Dalitz
η Dalitz
ω Dalitz
Δ Dalitz
1/Nπ0dNee/dM [1/GeV]
M [GeV]
C+C, 2.0 GeV
collision broadening
Δmρ=-120 n/n0 MeV
Δmω=-50 n/n0 MeV
total
ω
ρ
bremsstrahlung
π0 Dalitz
η Dalitz
ω Dalitz
Δ Dalitz
1/Nπ0dNee/dM [1/GeV]
M [GeV]
C+C, 2.0 GeV
HADES data
collision broadening
Δmρ=-120 n/n0 MeV
Δmω=-50 n/n0 MeV
total
ω
ρ
bremsstrahlung
π0 Dalitz
η Dalitz
ω Dalitz
Δ Dalitz
1/Nπ0dNee/dM [1/GeV]
M [GeV]

Au + Au 2 GeV



Au+Au, 2.0 GeV
vacuum spectral function
total
ω
ρ
bremsstrahlung
π^0 Dalitz
η Dalitz
ω Dalitz
Δ Dalitz
HADES C+C data
collision broadening
Δm_ρ=-120 MeV
Δm_ω= -50 MeV
$1/N_{\pi 0} dN_{ee}/dM$ [1/GeV]
M [GeV]

Summary

- BUU with off-shell propagation
- The in-medium modification of vector mesons is contraversal
- several theoretical uncertainties
- needs of precise data in
  - pp, pn collision with angular distribution (for separating different contribution)
  - CC and Au+Au 1 AGeV and 2AGeV
- Full calculation of all the contribution also with angular dependence for pp and pn

BUU

- Boltzmann-Ühling-Uhlenbeck equation

$$\frac{\partial F}{\partial t} + \frac{\partial H}{\partial \mathbf{p}}\frac{\partial F}{\partial \mathbf{x}} - \frac{\partial H}{\partial \mathbf{x}}\frac{\partial F}{\partial \mathbf{p}} = \mathcal{C}, \quad H = \sqrt{(m_0 + U(\mathbf{p},\mathbf{x}))^2 + \mathbf{p}^2}$$

- potential: momentum dependent, soft: K=215 MeV
  $U^{nr} = A\frac{n}{n_0} + B\left(\frac{n}{n_0}\right)^\tau + C\frac{2}{n_0}\int \frac{d^3p'}{(2\pi)^3}\frac{f_N(x,p')}{1+\left(\frac{\mathbf{p}-\mathbf{p}'}{\Lambda}\right)^2},$

  Teis et al., Z. Phys. 1997

- testparticle method
  $F = \sum_{i=1}^{N_{test}} \delta^{(3)}(\mathbf{x} - \mathbf{x}_i(t))\delta^{(4)}(p - p_i(t)).$

Collision term

- NN $\leftrightarrow$ NR, NN $\leftrightarrow$ $\Delta\Delta$
- baryon resonance can decay via 9 channels
  R $\leftrightarrow$ Nπ, Nη, Nσ, Nρ, Nω, $\Delta\pi$, N(1440)π, KΛ, KΣ
- 24 baryon resonances + Λ and Σ baryons
  $\pi, \eta, \sigma, \rho, \omega$ and kaons
- $\pi\pi \leftrightarrow \rho$, $\pi\pi \leftrightarrow \sigma$, $\pi\rho \leftrightarrow \omega$
- for resonances: energy dependent with
- $\frac{d\sigma^{X\to NR}}{dM_R} \sim A(M_R)\lambda^{0.5}(s, M_R^2, M_N^2)$

Cross sections

Elastic baryon-baryon cross section is fitted to the elastic pp data

Meson absorption cross sections are given by

$$\sigma_{\pi N \to R} = \frac{4\pi}{p^2}(spin factors)\frac{\Gamma_{in}\Gamma_{tot}}{(s - m_R^2) + s\Gamma_{tot}^2}$$

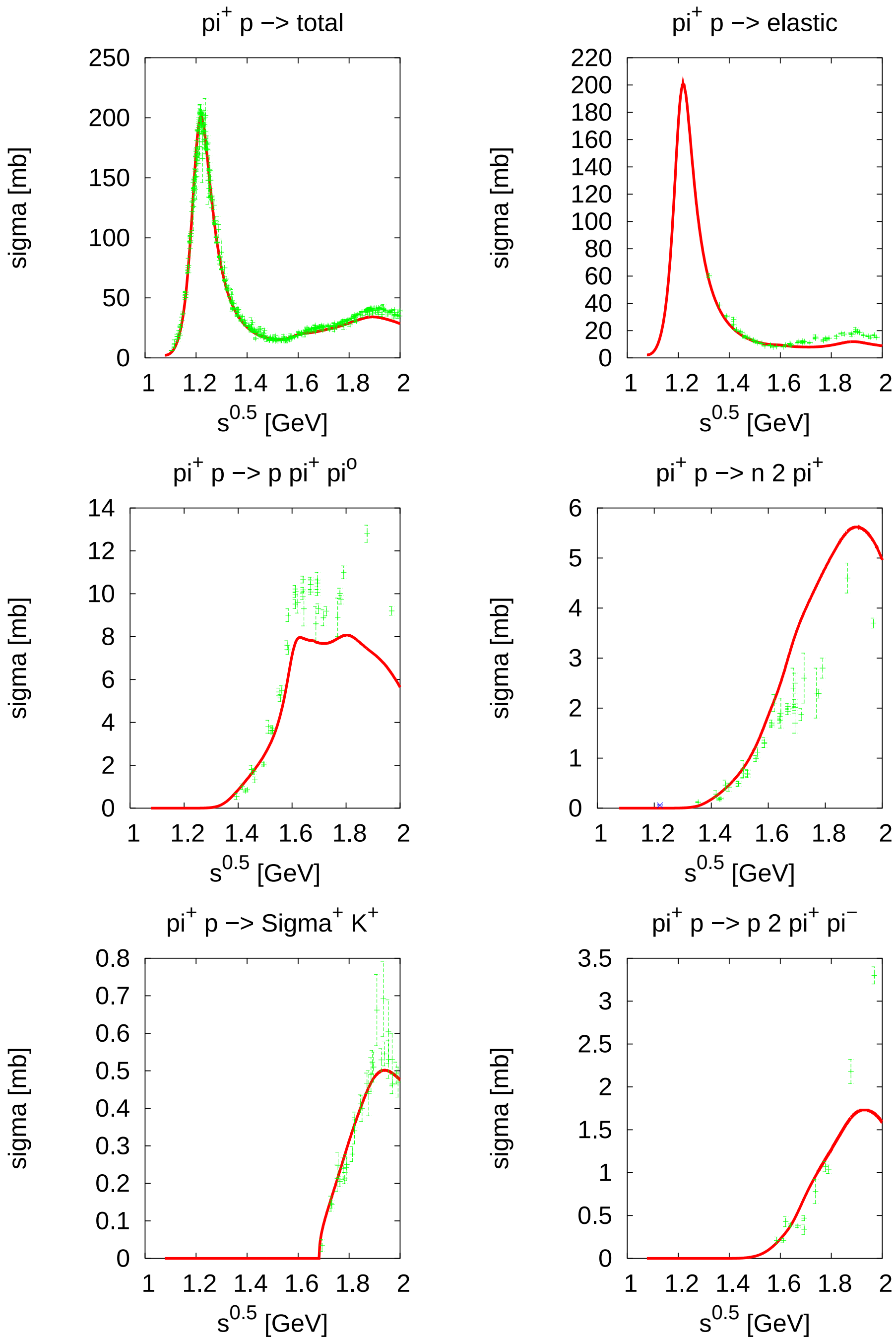
Baryon resonance parameters: mass, width, branching ratios are fitted by describing the meson production channels in πN collisions:

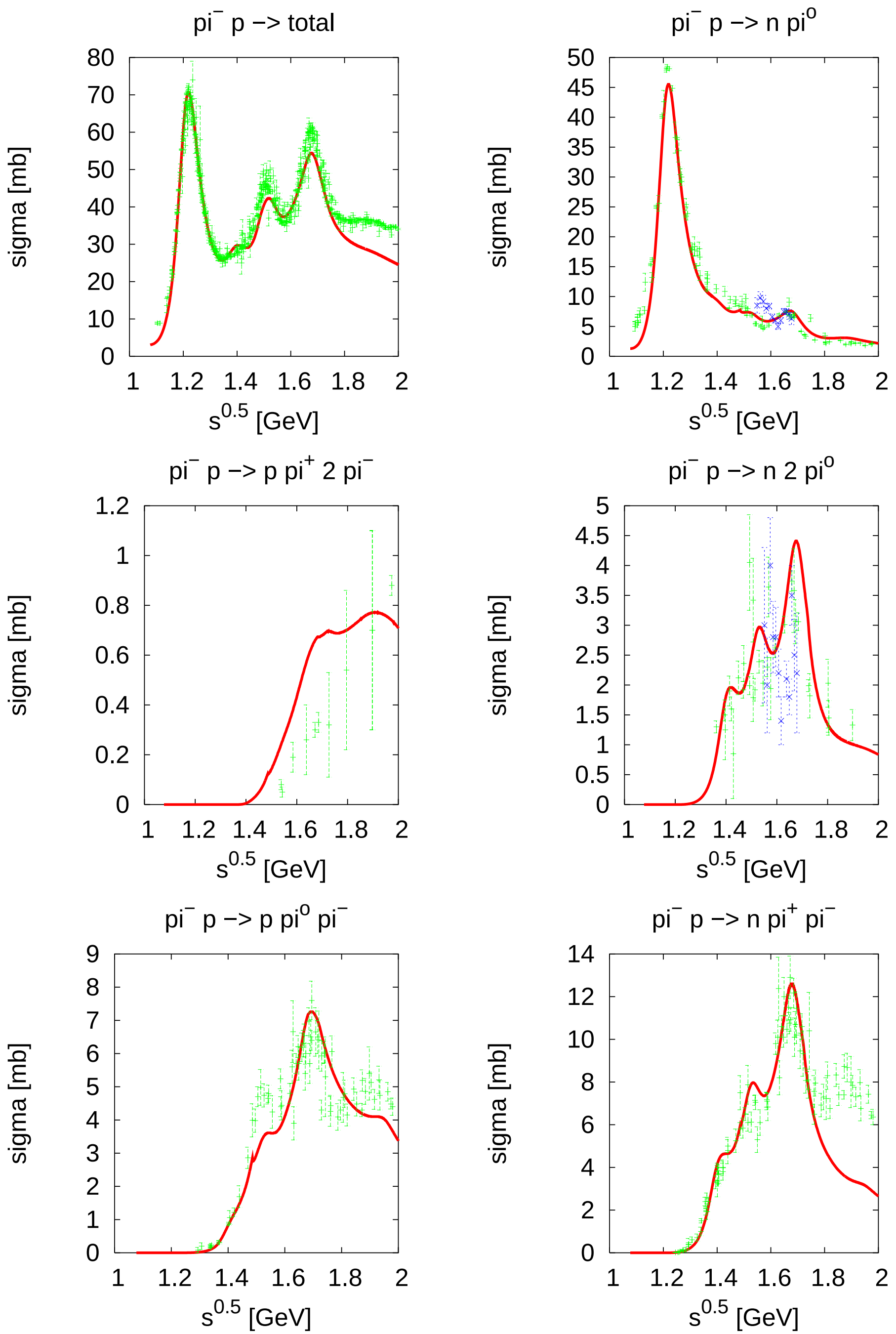
$$\sigma_{\pi N \to NM} = \sum_R \sigma_{\pi N \to R} \frac{\Gamma_{R \to NM}}{\Gamma_{tot}}$$

Resonance production cross section $NN \to NR$ is given by the fit of

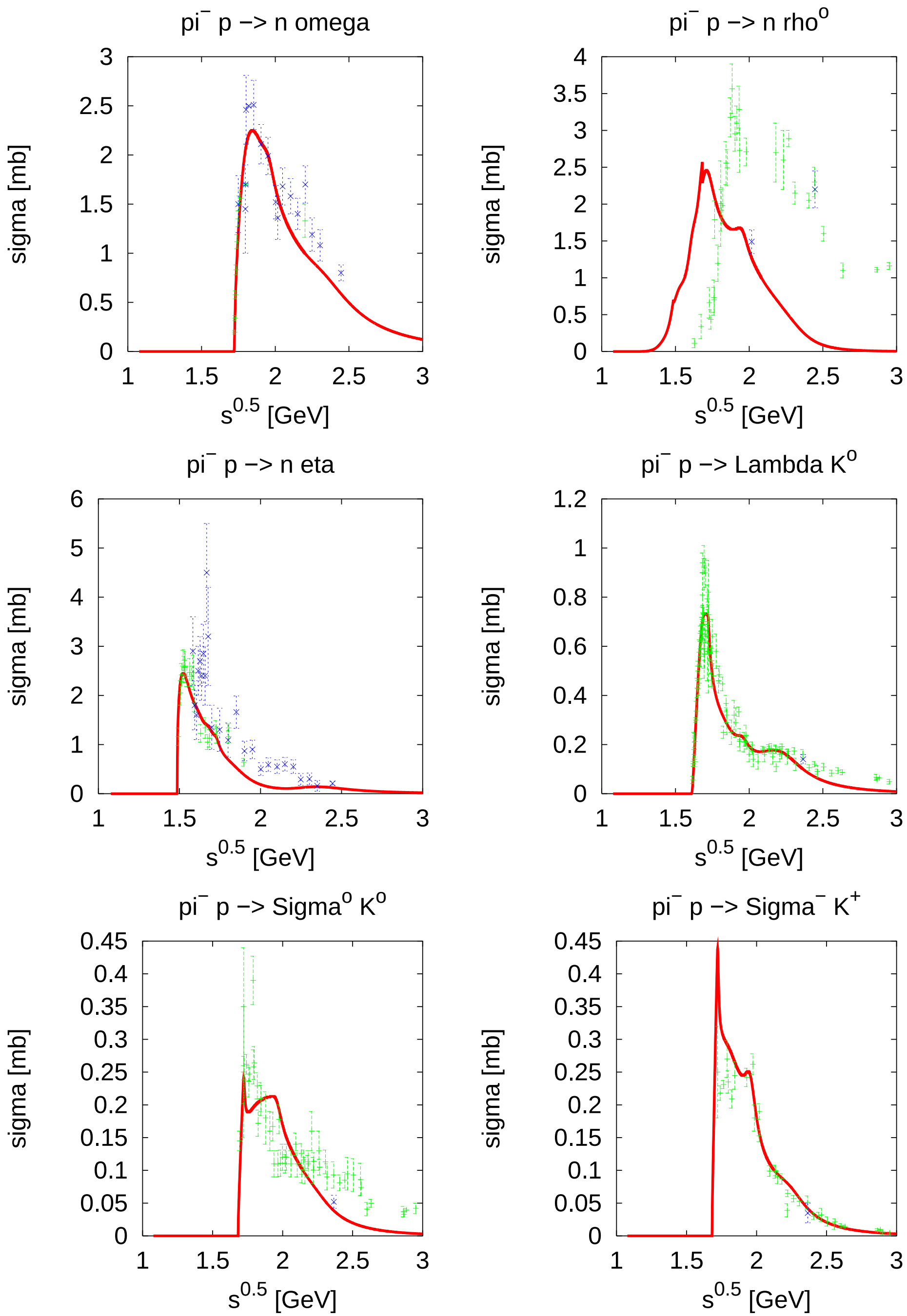
$$\sigma_{NN \to NM} = \sum_R \sigma_{NN \to NR} \frac{\Gamma_{R \to NM}}{\Gamma_{tot}}$$

27 baryons, 6 mesons. Fit is done by the Minuit package (CERN)

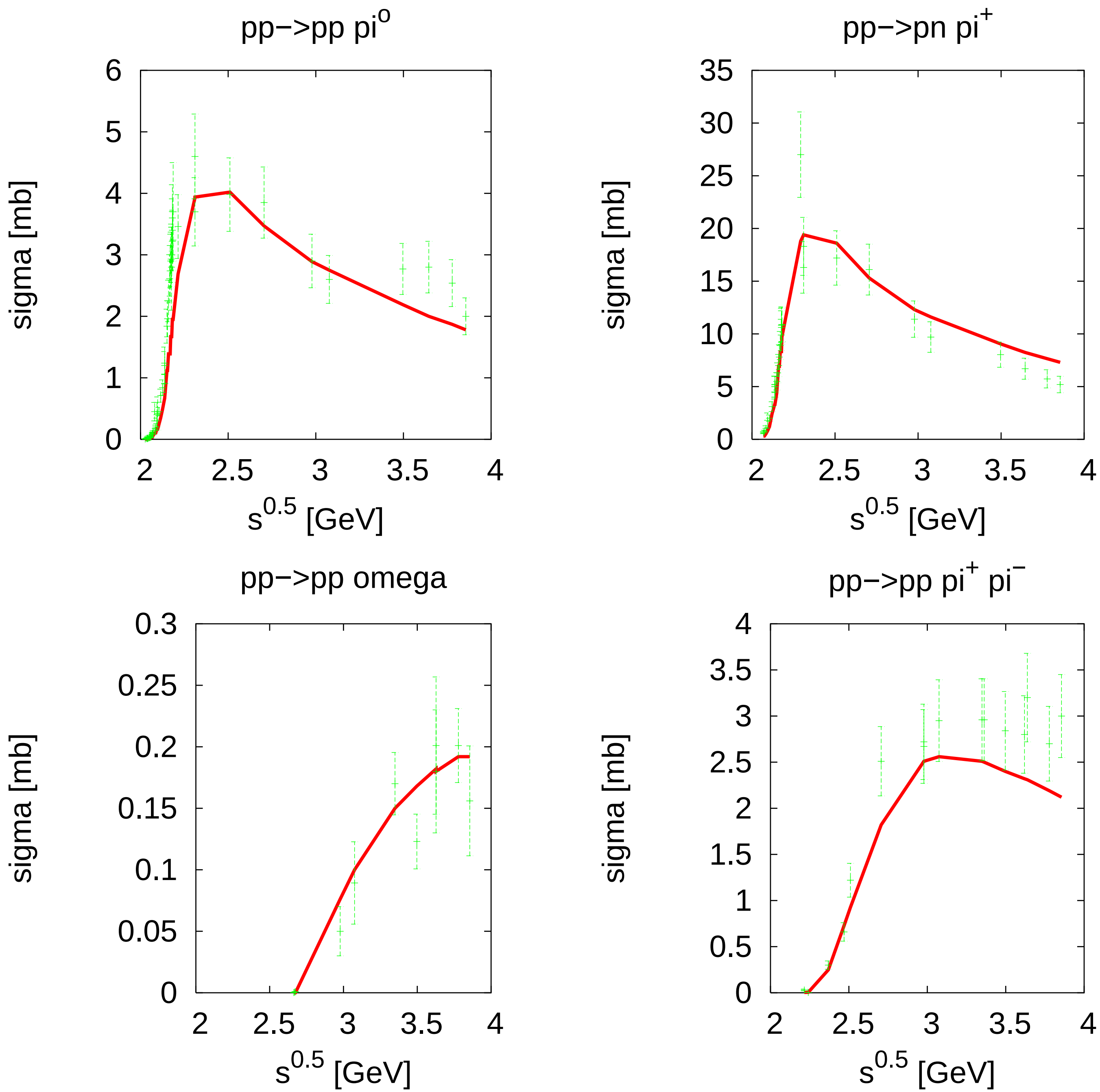

pi+ p −> total
pi+ p −> elastic
pi+ p −> p pi+ pio
pi+ p −> n 2 pi+
pi+ p −> Sigma+ K+
pi+ p −> p 2 pi+ pi−
sigma [mb]
s0.5 [GeV]



pi$^-$ p -> total
pi$^-$ p -> n pi^0
pi$^-$ p -> p pi$^+$ 2 pi$^-$
pi$^-$ p -> n 2 pi^0
pi$^-$ p -> p pi^0 pi$^-$
pi$^-$ p -> n pi$^+$ pi$^-$
sigma [mb]
s$^{0.5}$ [GeV]



pi⁻ p -> n omega
pi⁻ p -> n rho⁰
pi⁻ p -> n eta
pi⁻ p -> Lambda K⁰
pi⁻ p -> Sigma⁰ K⁰
pi⁻ p -> Sigma⁻ K⁺
sigma [mb]
s^0.5 [GeV]



pp->pp pi^{o}
pp->pn pi^{+}
pp->pp omega
pp->pp pi^{+} pi^{-}
sigma [mb]
s$^{0.5}$ [GeV]