

Dilepton production at SIS energies

Zimányi Winter School

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- Motivation
- Dileptons
- Time evolution of spectral functions
- Dilepton production at HADES
- Summary

Why dileptons

- measured (DLS, HADES)
- without finalstate interaction
- vector mesons decay to dileptons \rightarrow vector mesons in matter

Dilepton production in Heavy ion Collisions

Sources of dileptons

- $NN \rightarrow \dots \rightarrow NN e^+ e^-$ (measurable)
- $\pi^+ \pi^-$ annihilation (measurable and theoretically well understood)
- other secondaries (πN , or $N\Delta \rightarrow NR \rightarrow NN e^+ e^-$)

Strategy 1: put the measured $NN \rightarrow NN e^+ e^-$, $\pi^+ \pi^- \rightarrow e^+ e^-$ and the estimated cross section for the secondaries to a transport and obtain the HIC result.

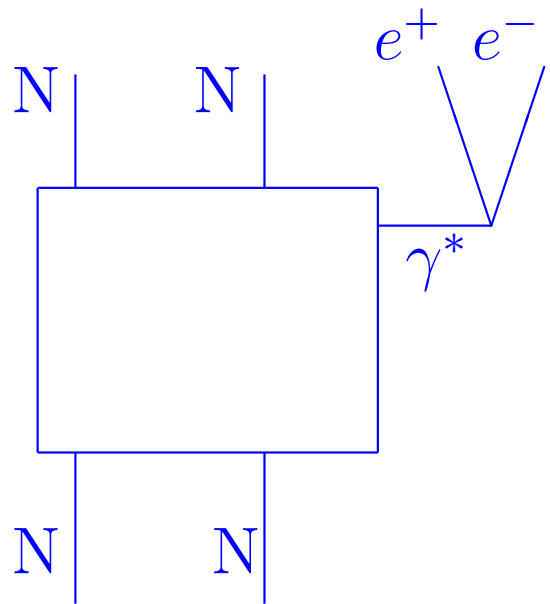
Problem:

Hunted in-medium effects are buried in the $NN \rightarrow NN e^+ e^-$ cross section

Dilepton production in NN

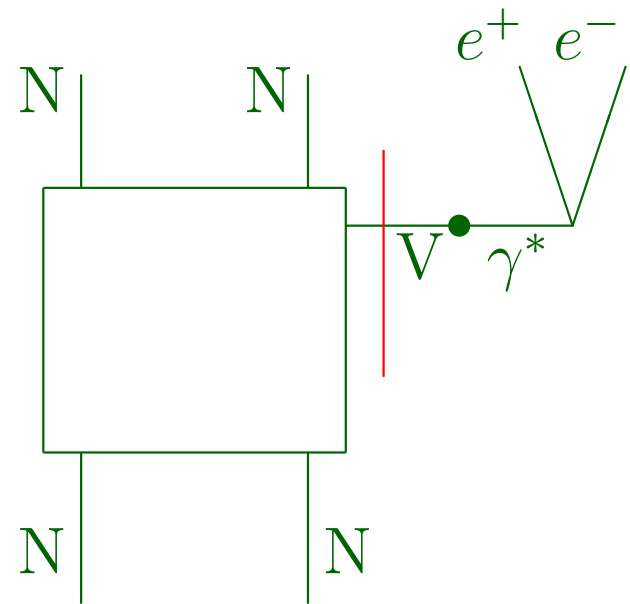
- Direct decay of vector mesons and η
- Dalitz-decay of π , η and ω
- Dalitz-decay of baryon resonances
Zetenyi, Wolf, Phys. Rev, C67 (2003) 044002;
Heavy Ion Phys. 17 (2003) 27
- pn bremsstrahlung not negligible

Dilepton Channels in NN



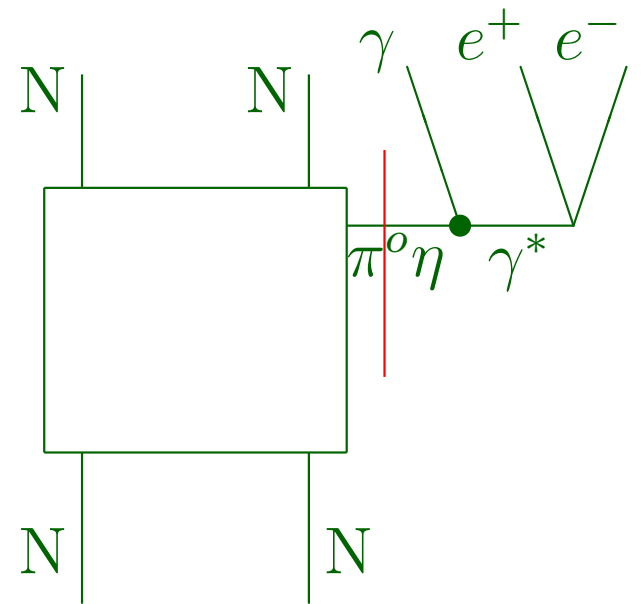
NN tot.

\approx

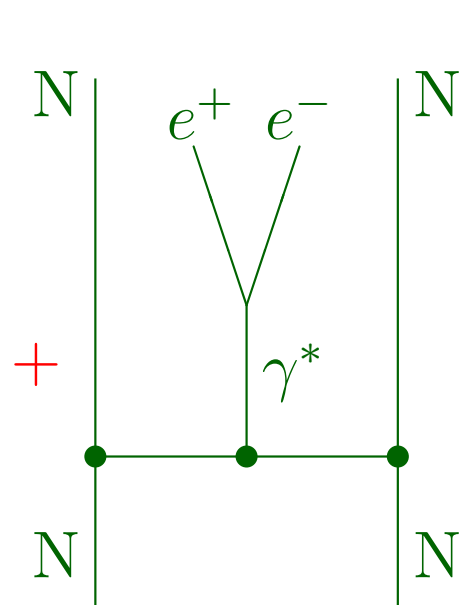


ρ/ω decay

+

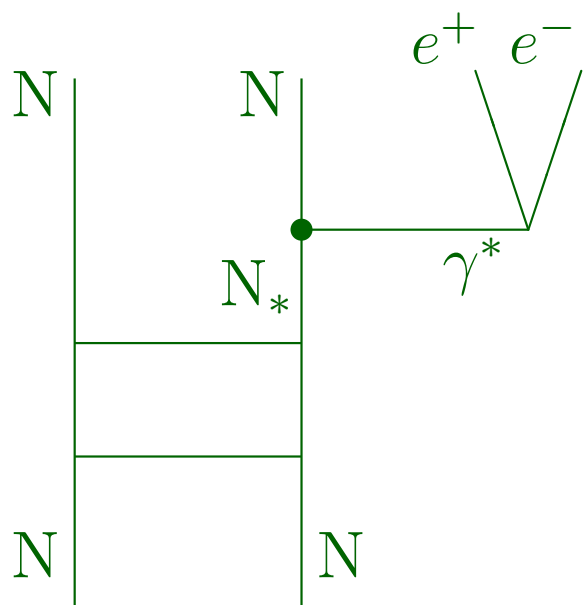


Dalitz-decay of π^0/η decay

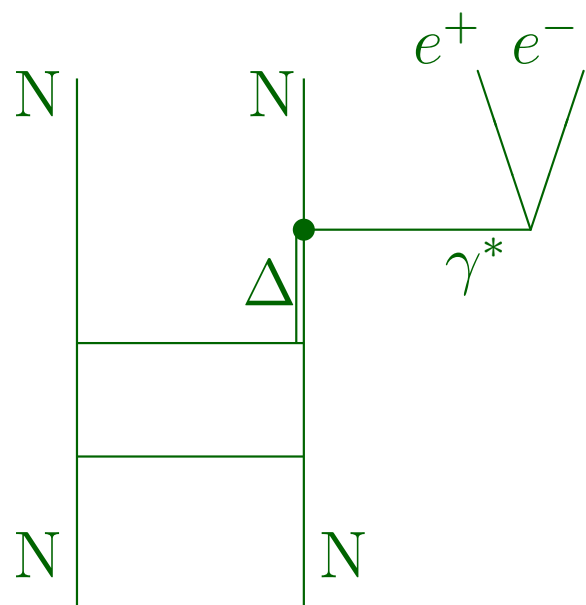


bremsstrahlung

+



+

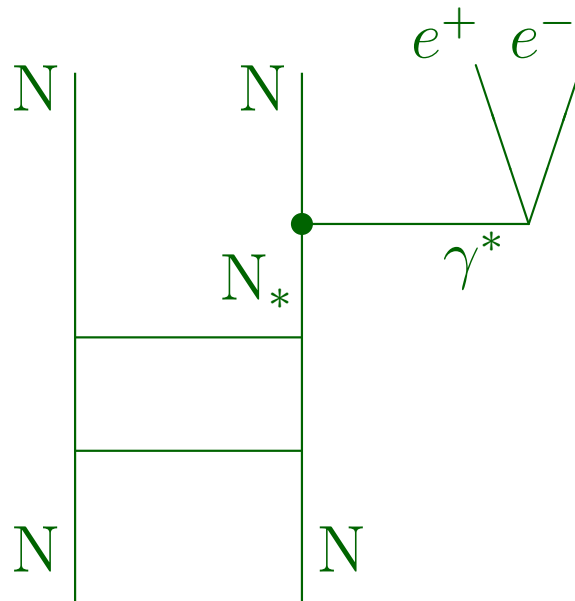


Δ -Dalitz

Bremsstrahlung calculations

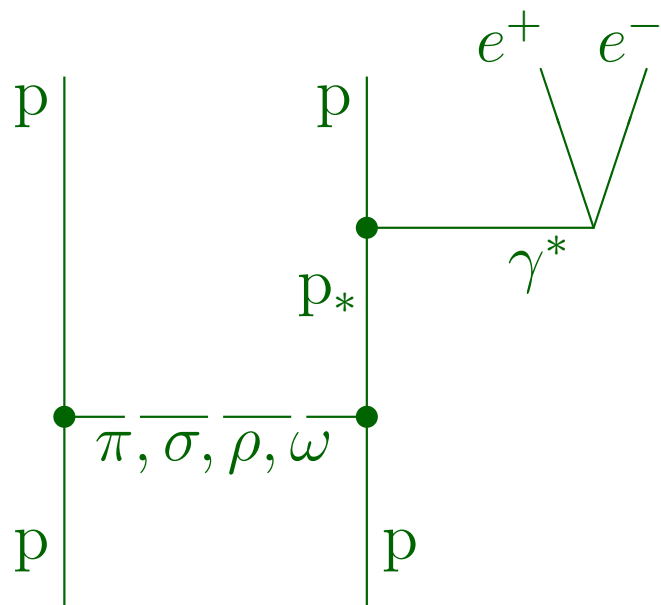
Soft photon approximation

$$\frac{d\sigma}{dM} = \frac{\sigma}{M} \frac{\alpha^2}{6\pi^3} \int \frac{d^3q}{q_0^3} \frac{R_2(\bar{s})}{R_2(s)}.$$

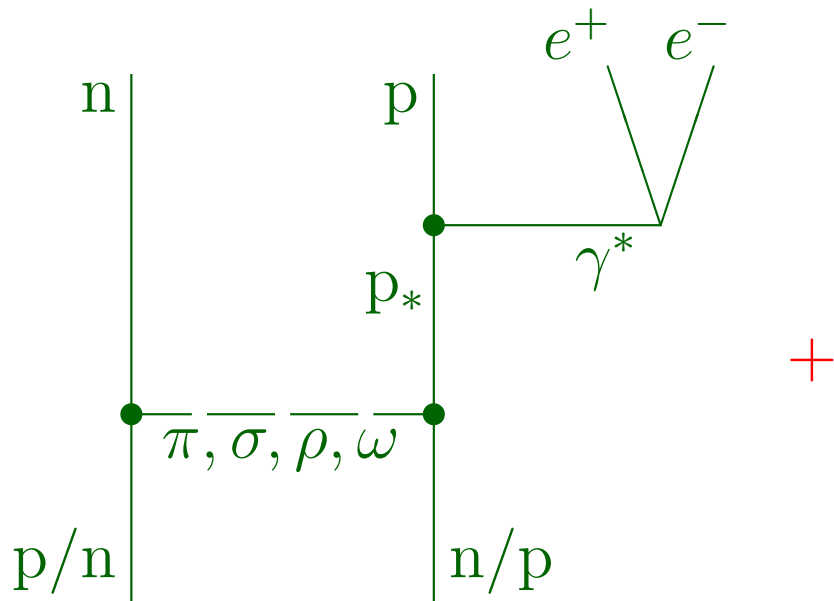


T-matrix calculations

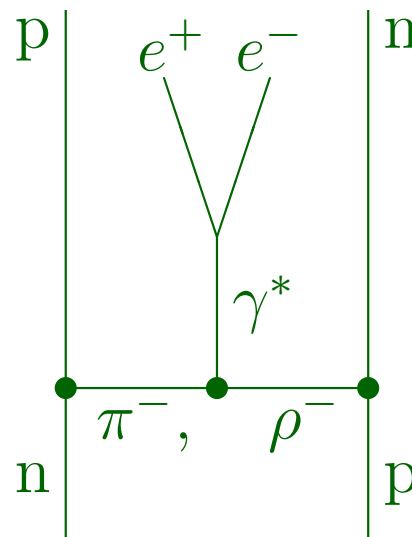
pp:



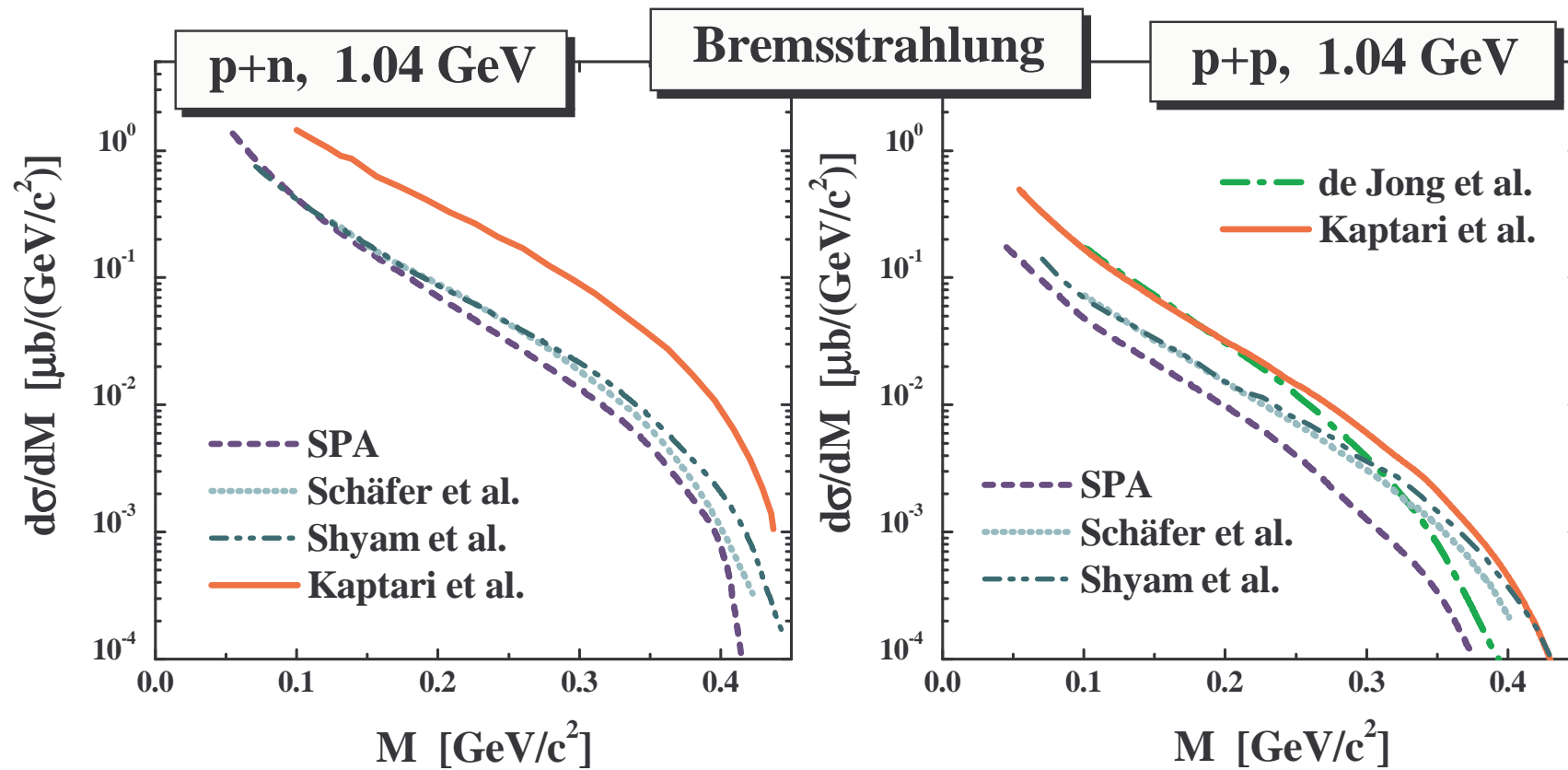
pn:



+



- L.P. Kaptari, B. Kämpfer, Nucl. Phys. A **764** (2006) 338.
- R. Shyam, U. Mosel, Phys. Rev. C **67** (2003) 065202, C **79** (2009) 035203



Dalitz-decay of baryon resonances

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

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

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

$$u^{\dots \rho_i \dots \rho_k \dots}(p_*, \lambda_*) = u^{\dots \rho_k \dots \rho_i \dots}(p_*, \lambda_*),$$

$$u^{\dots \sigma \dots}_{\sigma} (p_*, \lambda_*) = u^{\dots \sigma \dots}(p_*, \lambda_*) p_{*\sigma} = u^{\dots \sigma \dots}(p_*, \lambda_*) \gamma_{\sigma} = 0,$$

EM coupling of baryon resonances

- There are 3 independent tensor structures (for $S \geq 3/2$) for coupling of nucleon and Rarita-Schwinger spinors ($G = 1$ or γ_5):

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

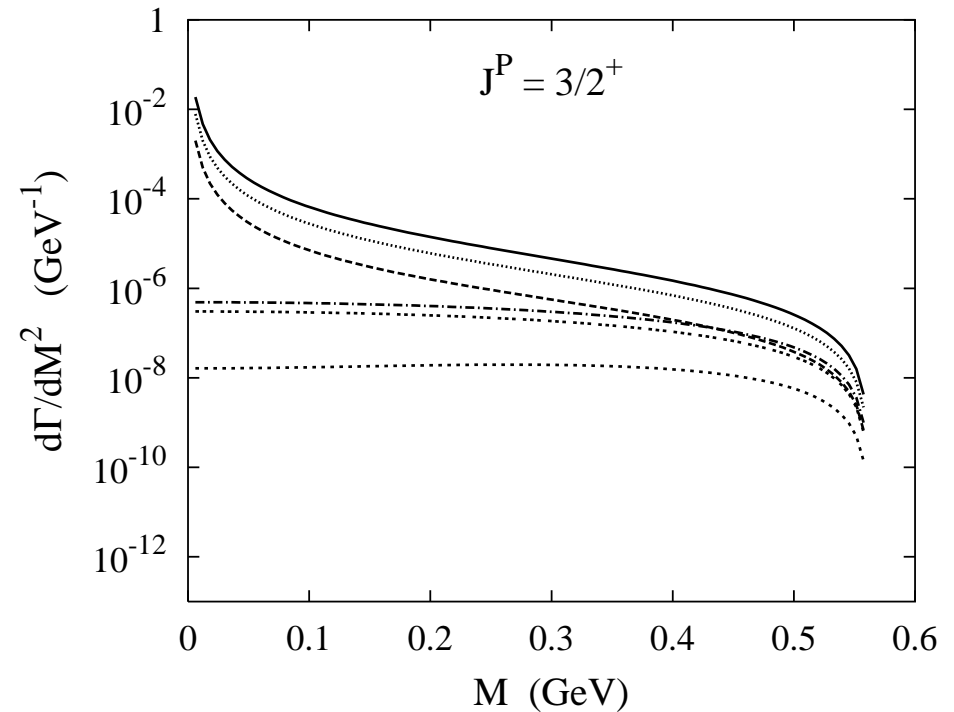
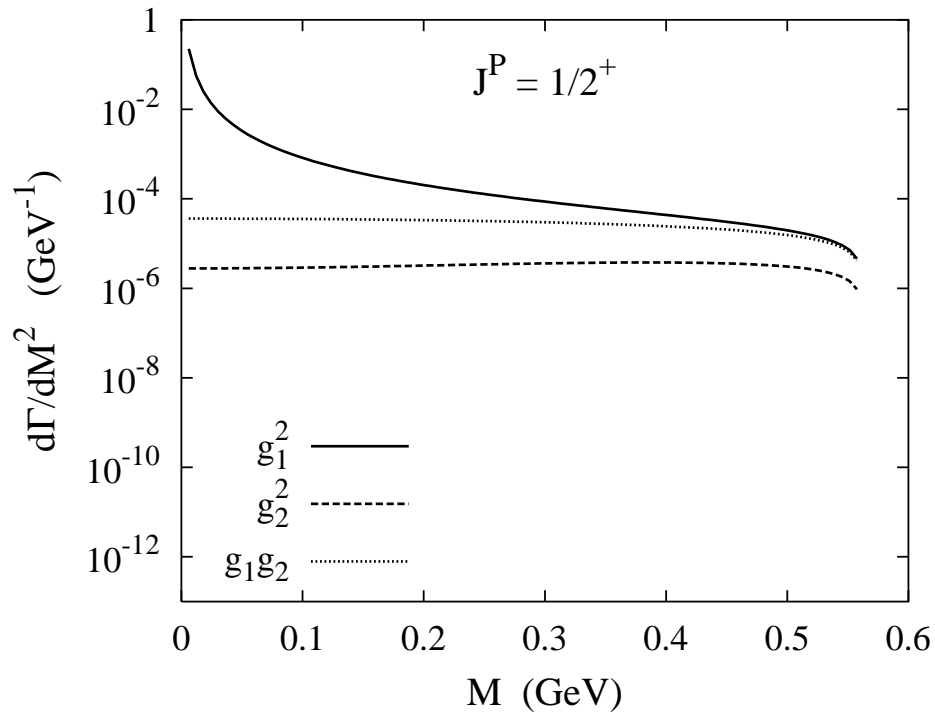
with

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

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

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

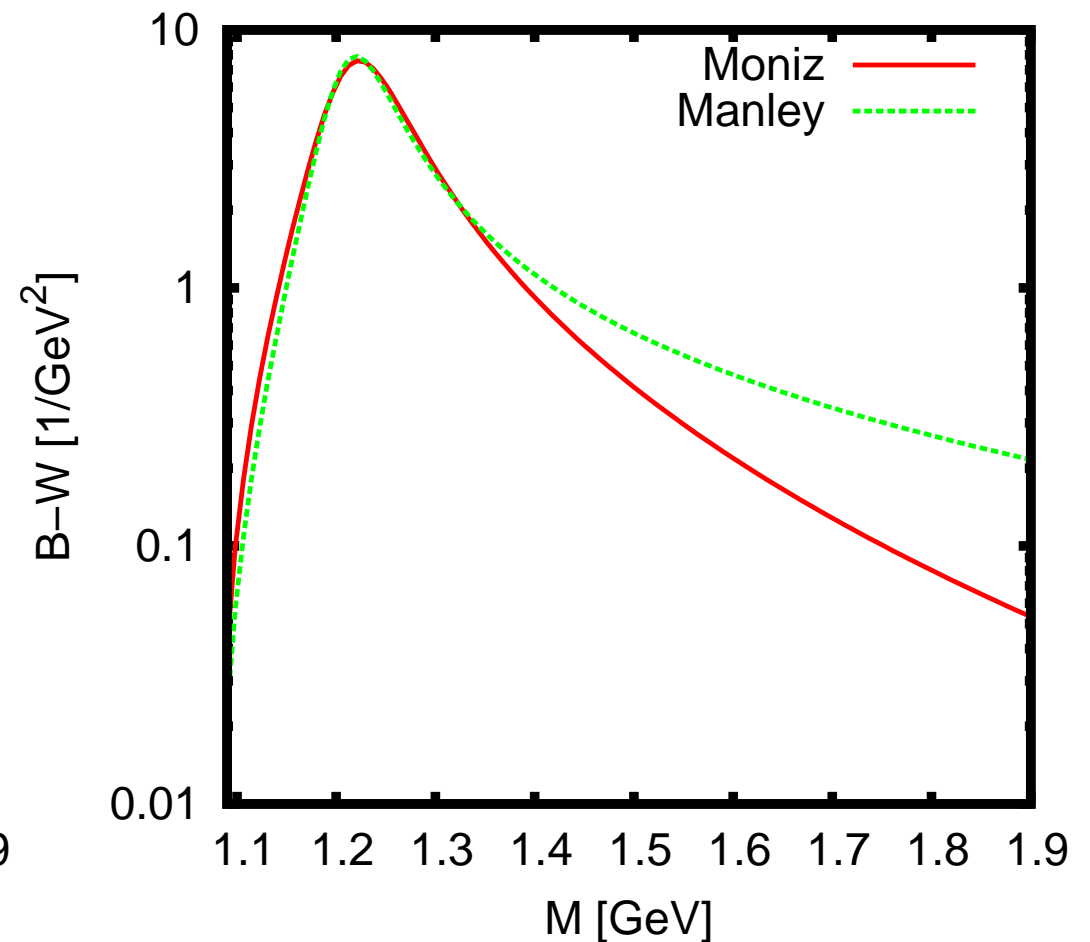
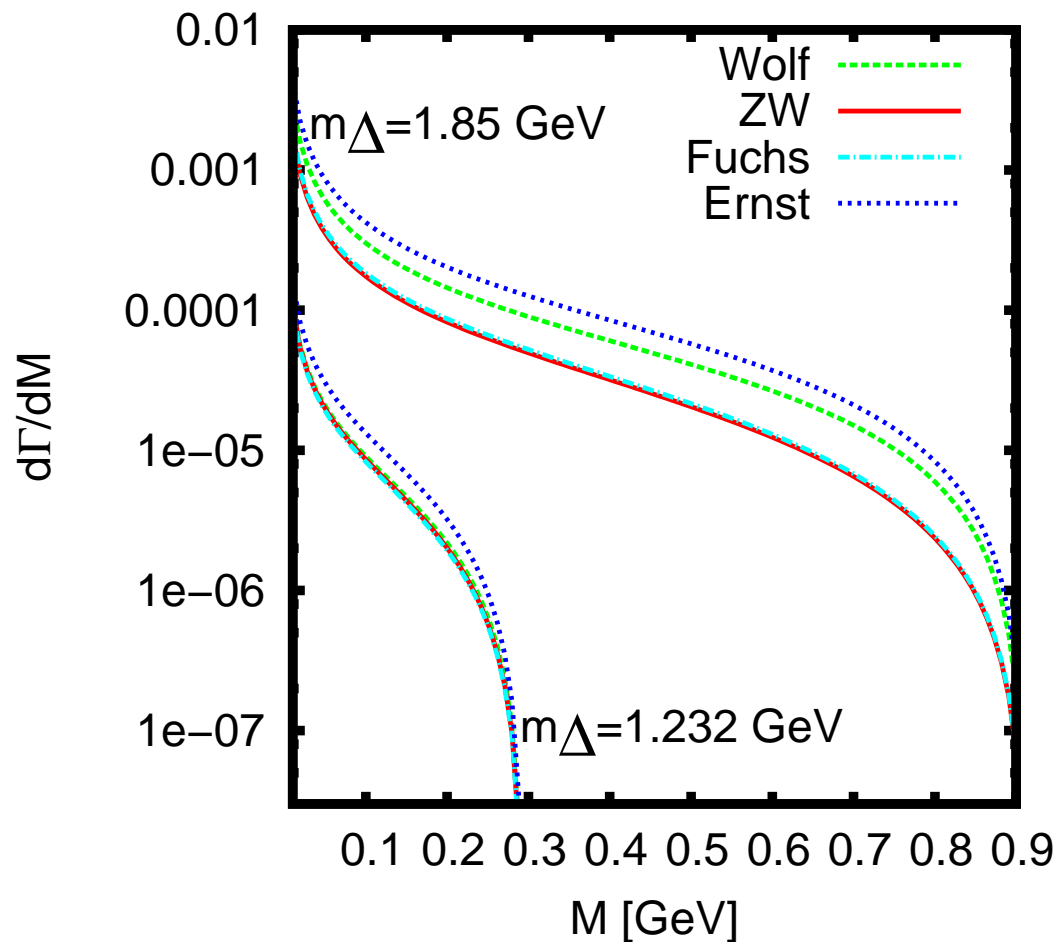
Dalitz-decay contributions



$m_* = 1.5$ GeV. Dimensionless coupling constants are set to 1.

In the $S = 1/2$ case g_2 and in the $S \geq 3/2$ case g_3 cannot be fixed at $M=0$, since their contributions there are identically 0.

$\Delta(1232)$



Δ properties are fixed around the resonance region, but because of its very strong electromagnetic coupling it dominates the Dalitz-decay spectrum at high masses (~ 1.7 GeV), although for pion production its effect is already negligible.

Summary of elementary dilepton production

- There is no good bremsstrahlung calculation (describes pp and pn at the same time).
- Delta-Dalitz decay contribution is very uncertain, too
- Complete $NN \rightarrow NN e^+ e^-$ calculation is needed with angular dependence and compare with experimental data for pp and pn. Deduce the relative strengths. Then put into transport.

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 $F_\alpha = f_\alpha(x, p, t)A_\alpha$

$$A(p) = -2\text{Im}G^{ret} = \frac{\hat{\Gamma}}{(E^2 - \mathbf{p}^2 - m_0^2 - \text{Re}\Sigma^{ret})^2 + \frac{1}{4}\hat{\Gamma}^2},$$

Cassing, Juchem (2000) and Leupold (2000)

- testparticle approximation

Transport equations

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

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

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

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

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

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):

$$\Gamma = \Gamma_{vac} + nv\sigma\gamma$$

- real part (mass shift)

$$M = M_{vac} + n/n_o\Delta M$$

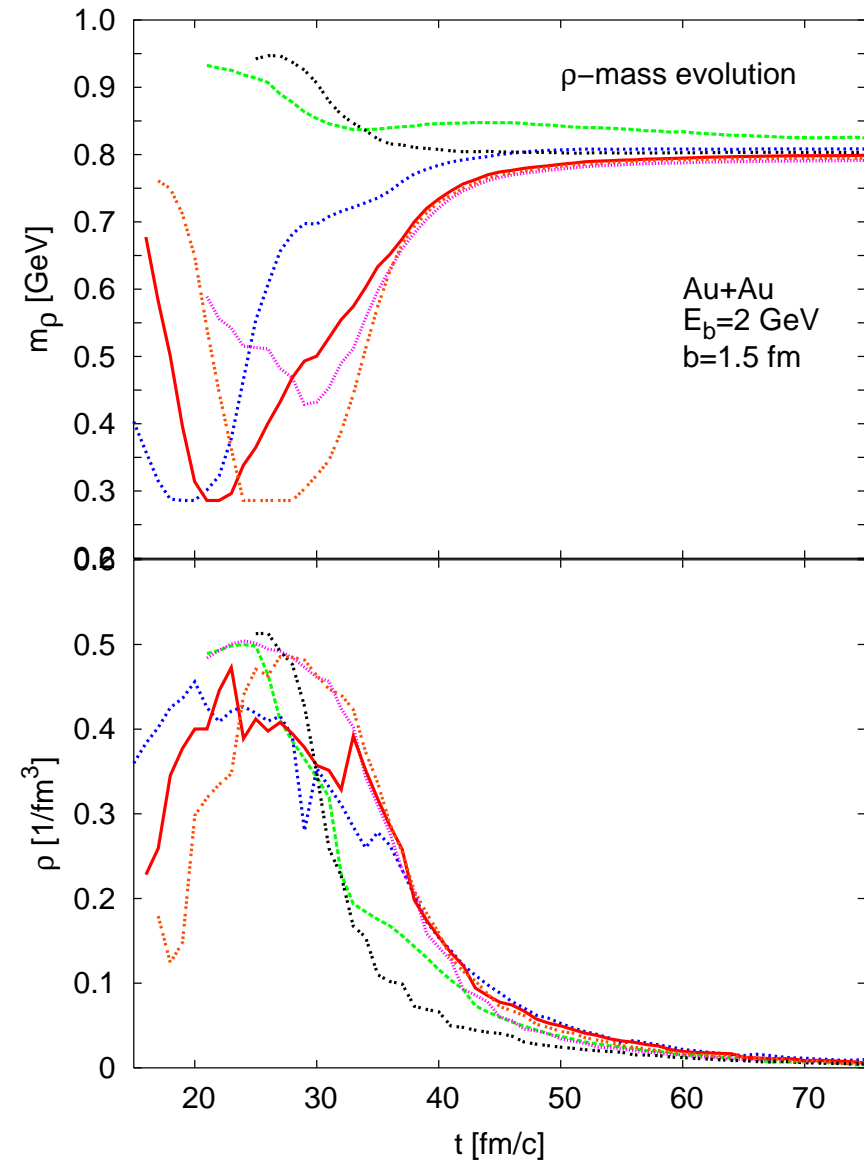
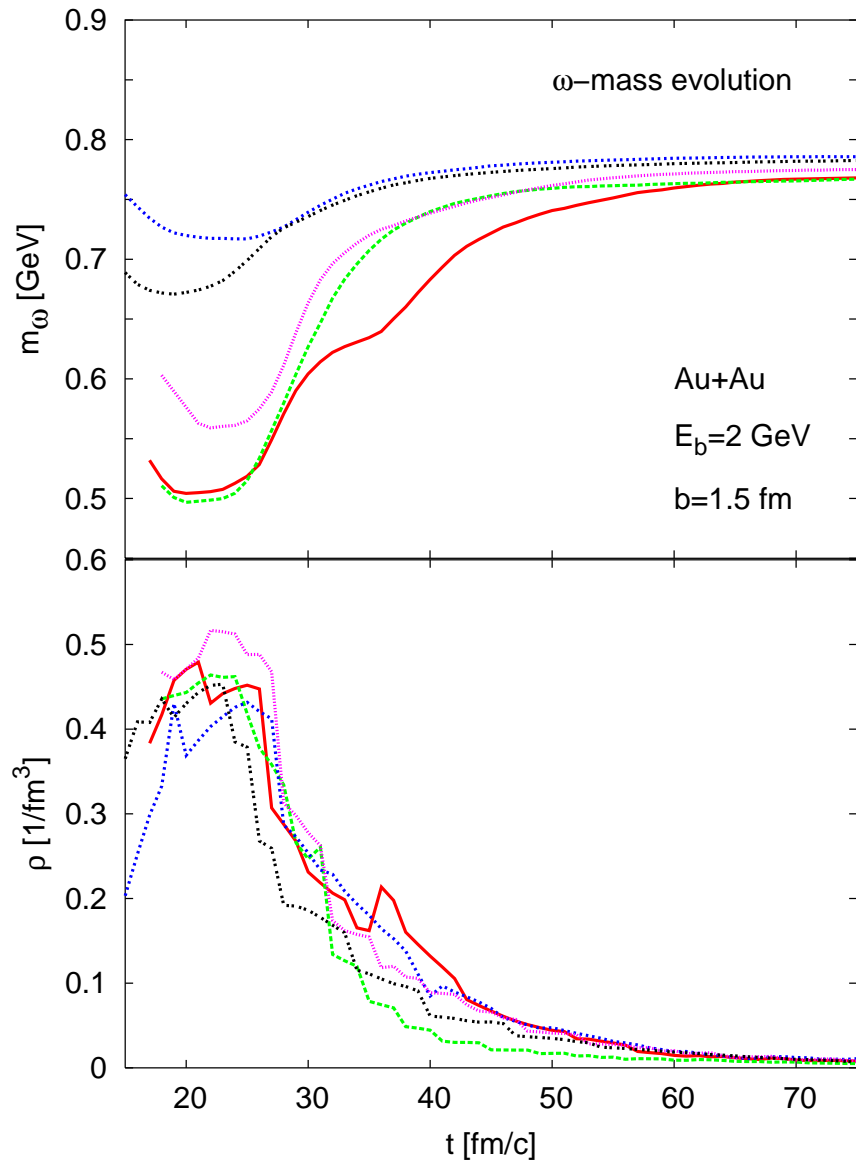
$$\Delta M_\omega = -50 \text{ MeV}, \Delta M_\rho = -120 \text{ MeV}$$

- danger of double counting

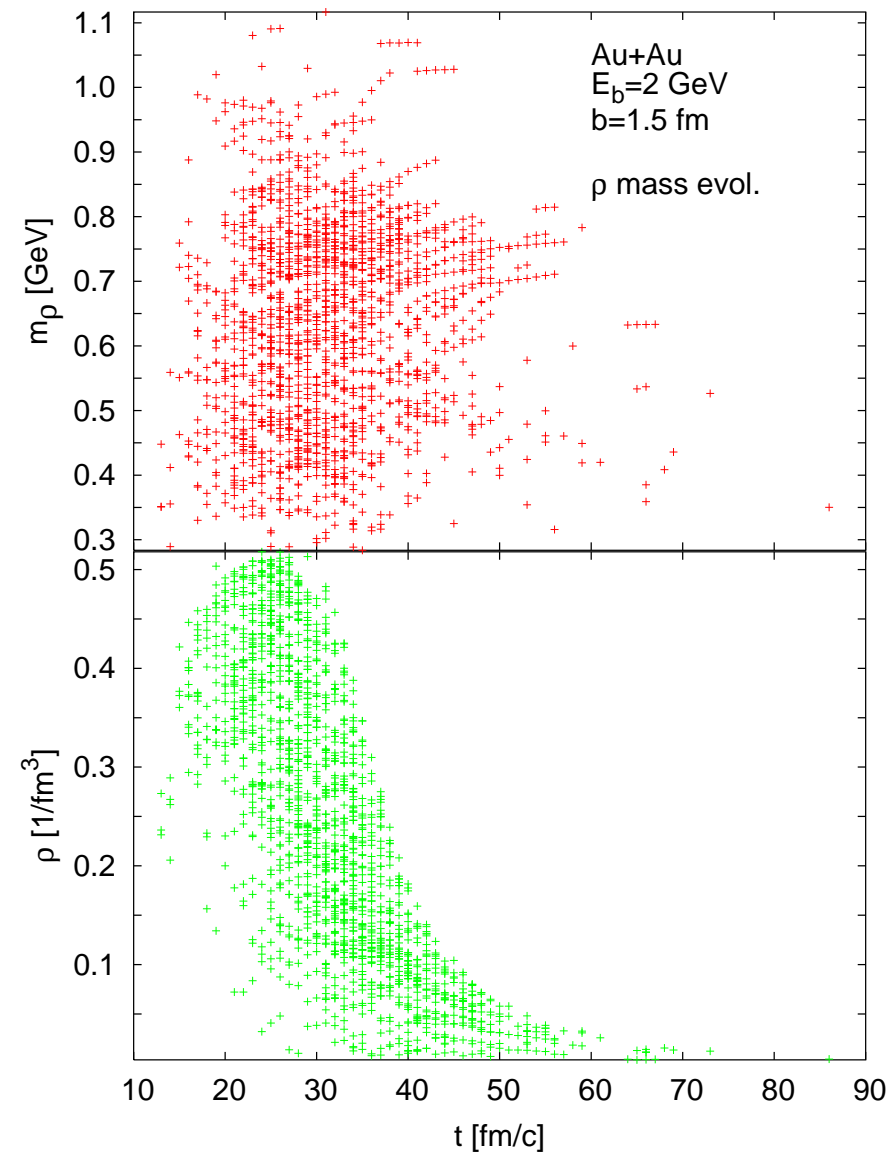
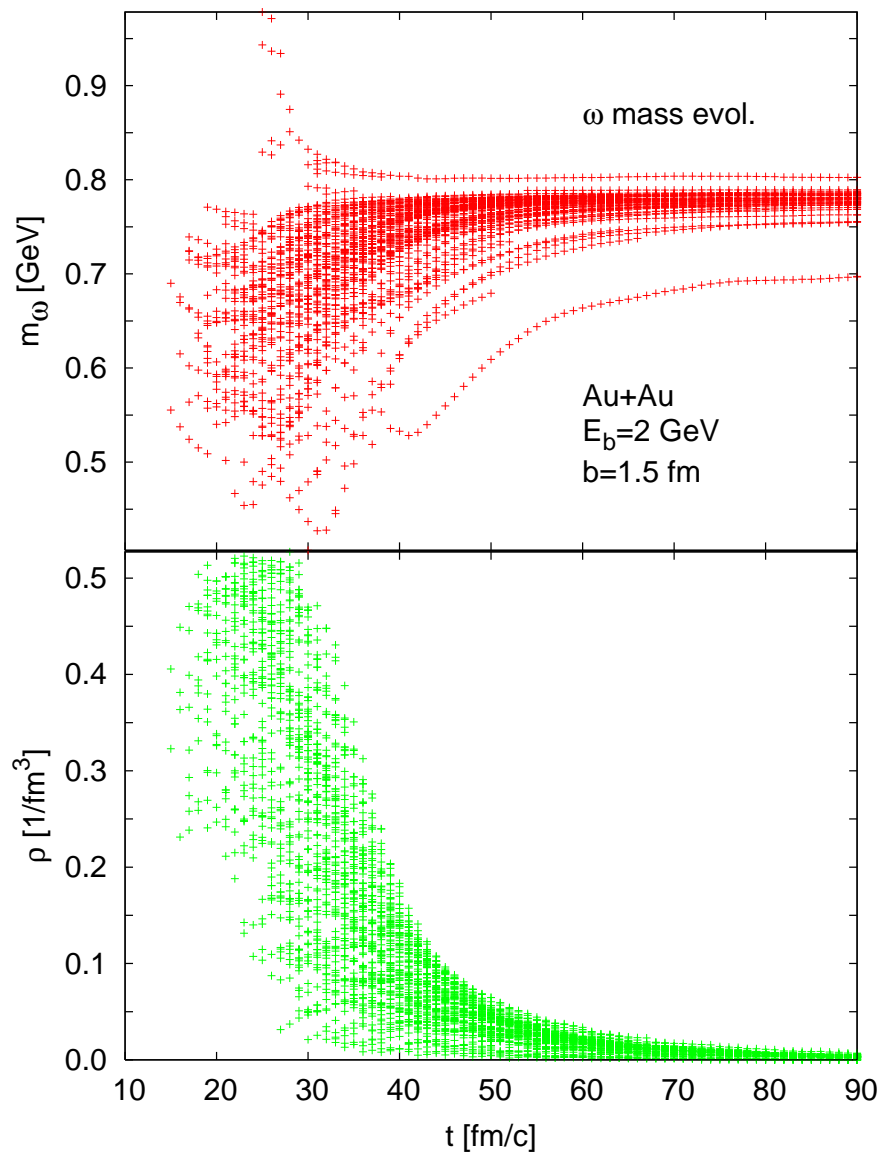
collision term already contains partly the mixing of mesons with resonance-hole excitations

but sum up only to finite order

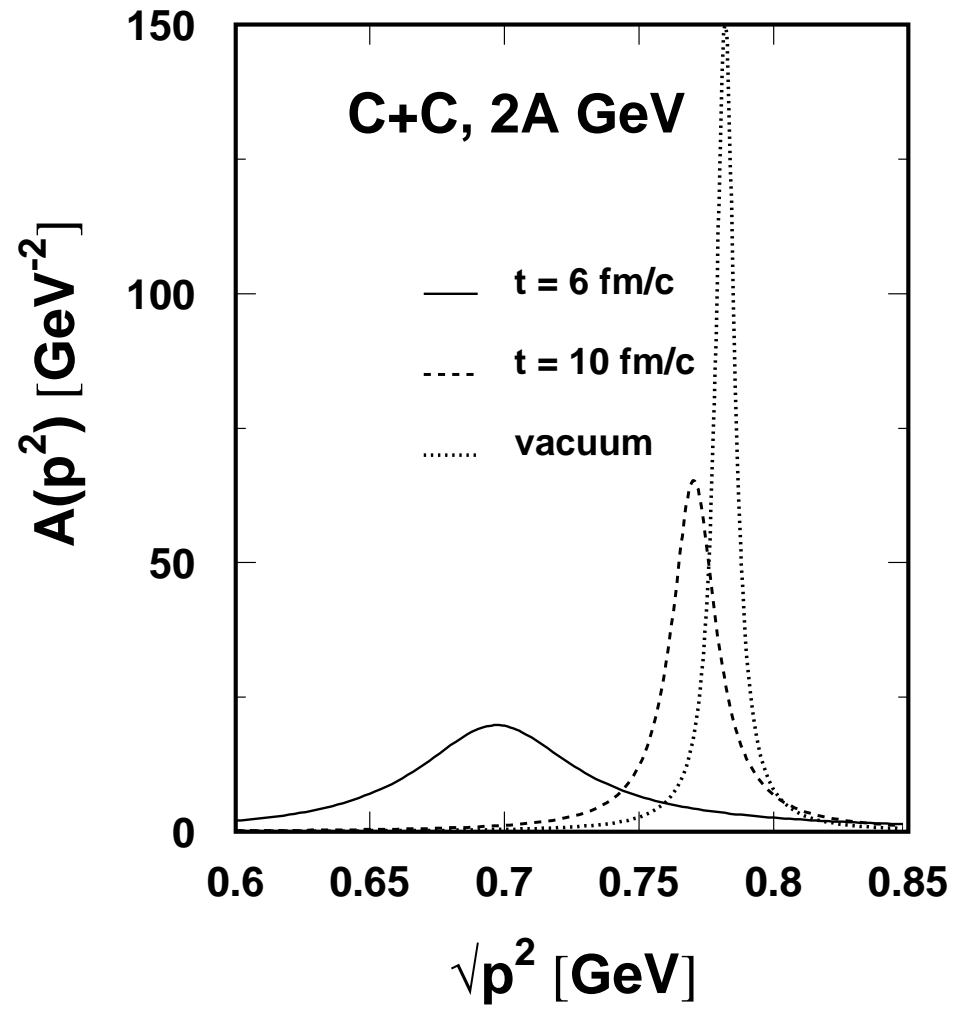
Evolution of masses



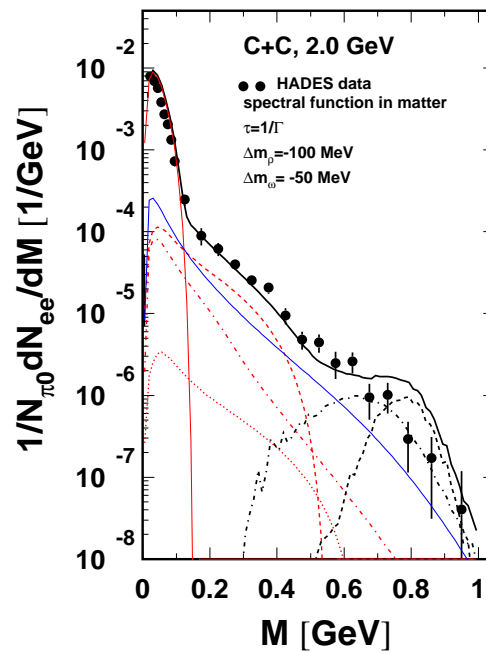
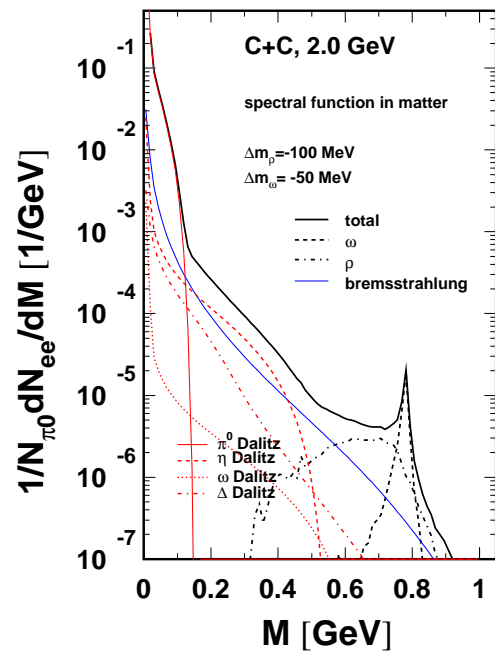
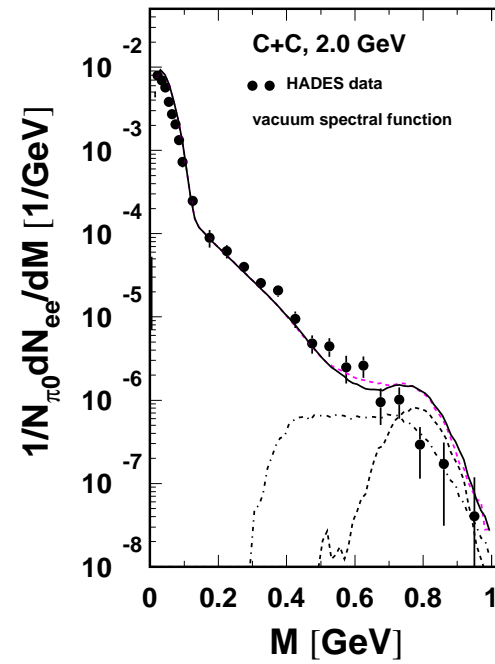
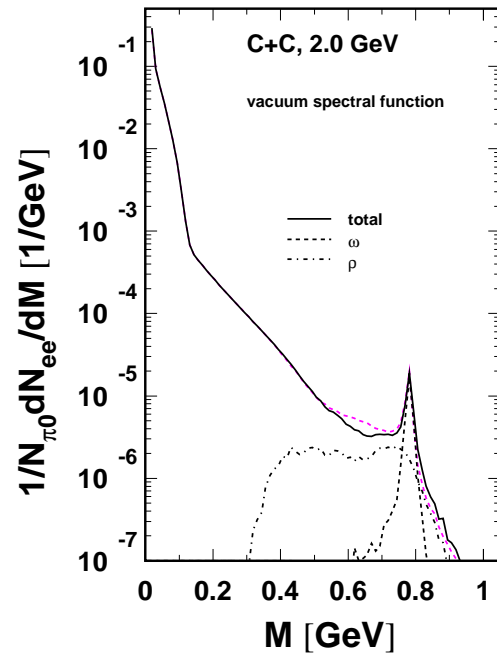
Evolution of masses

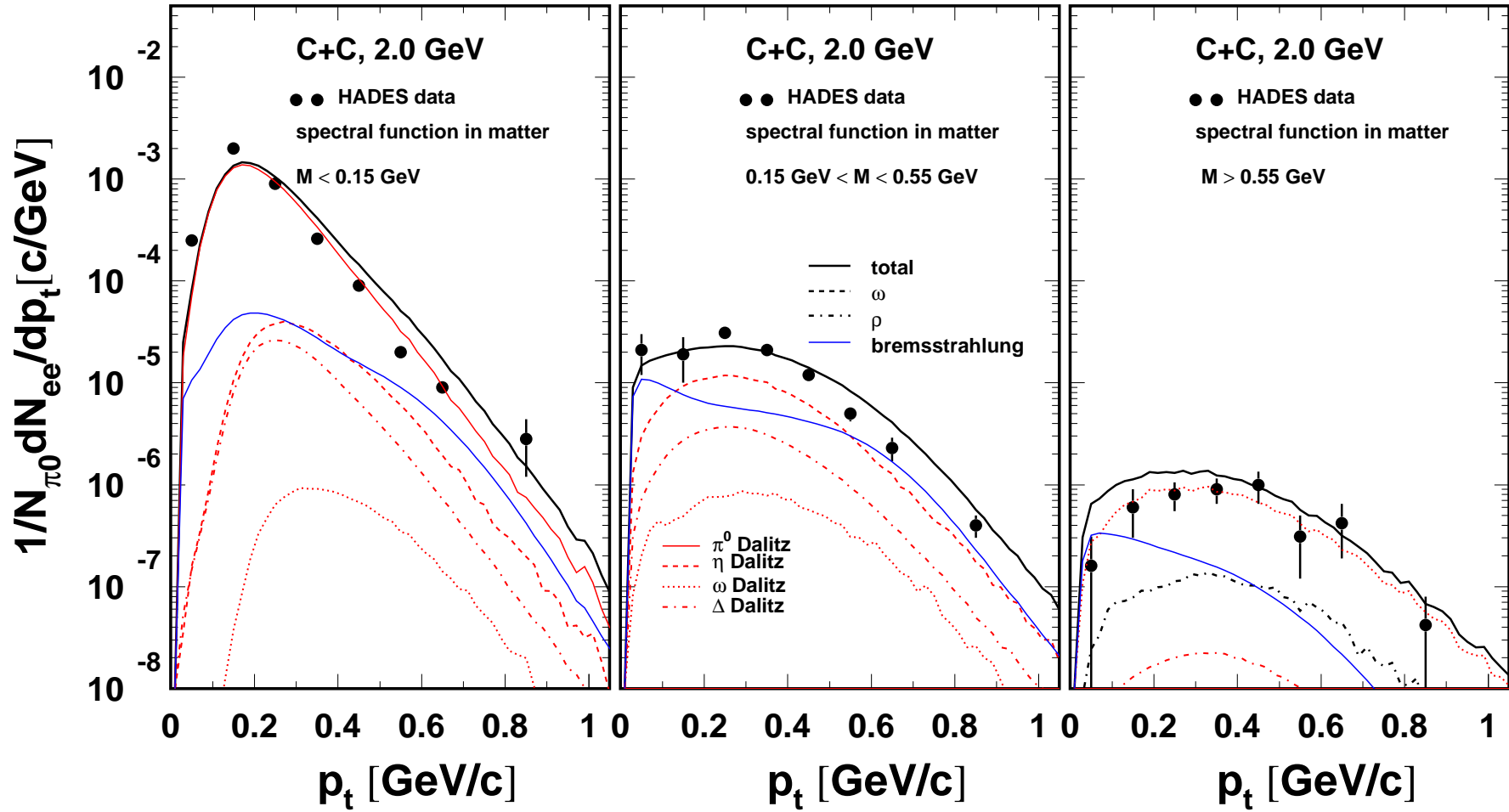


Evolution of the ω spectrum

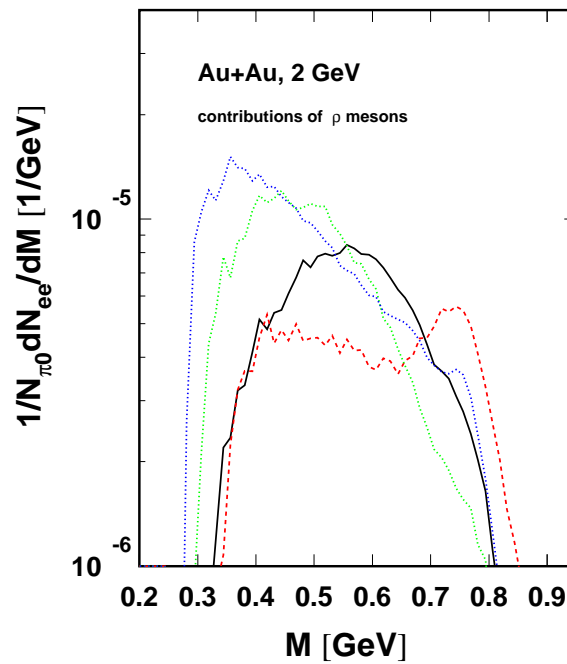
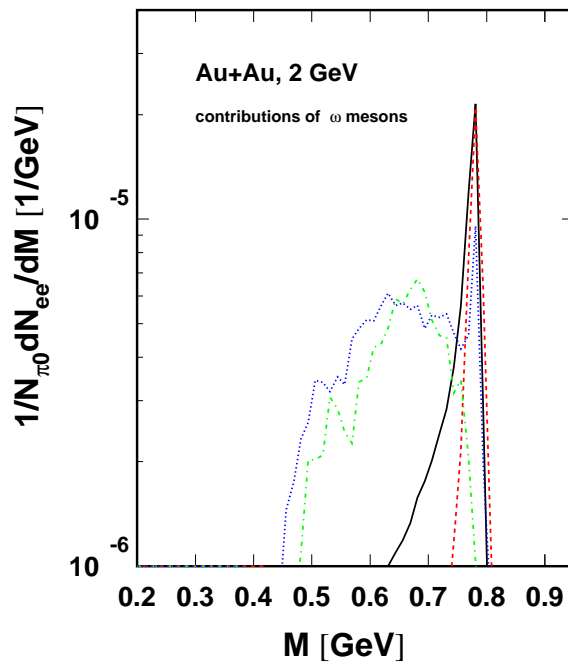
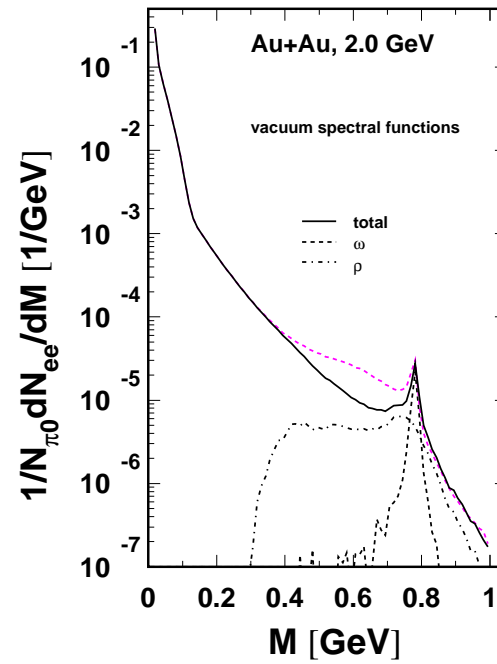
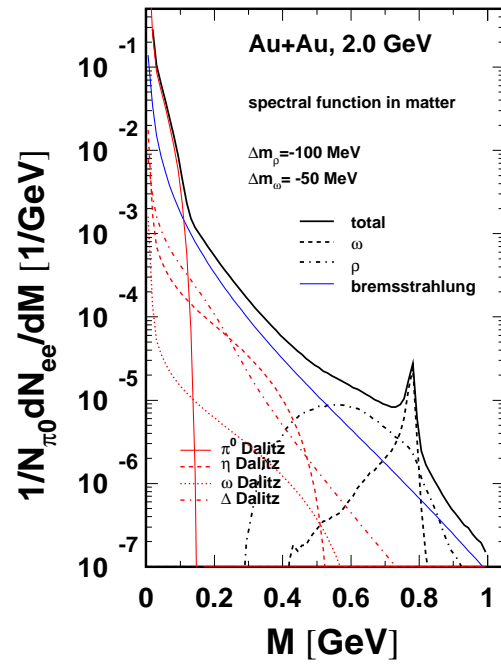


C + C 2 GeV





Au + Au 2 GeV

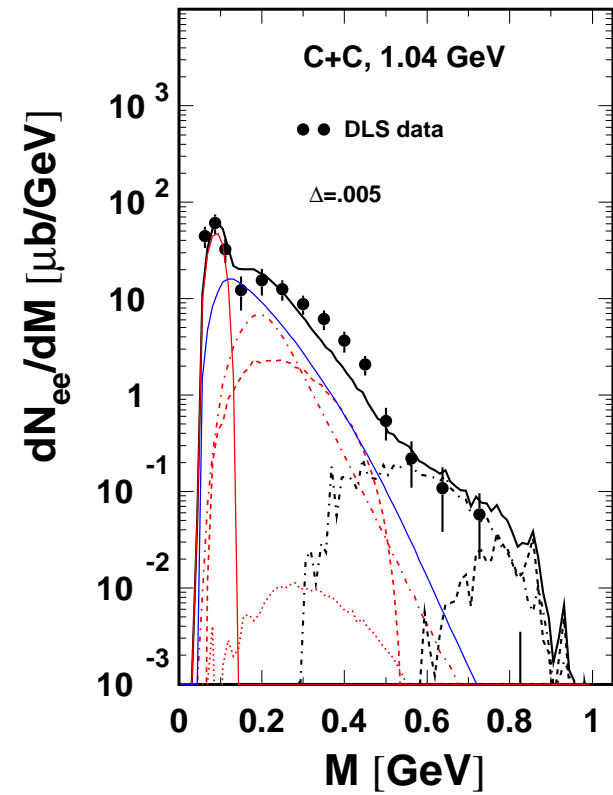
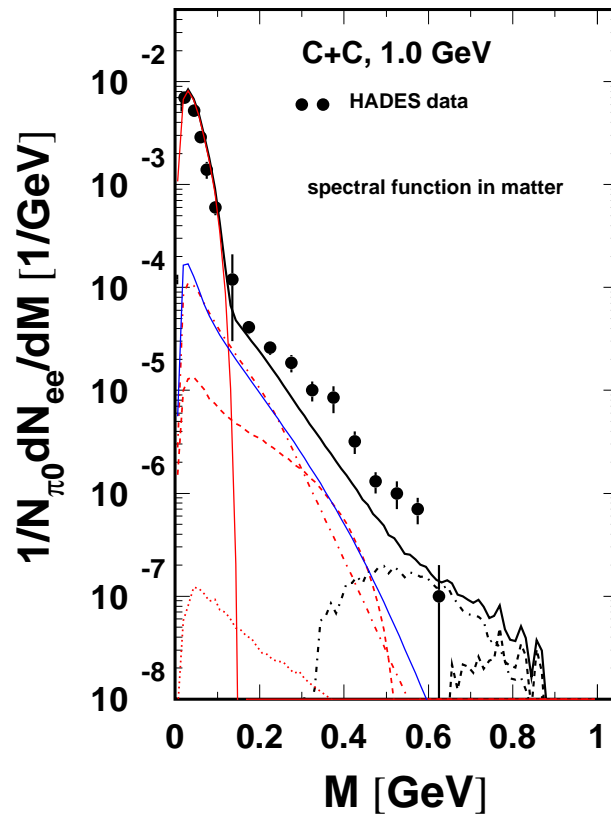
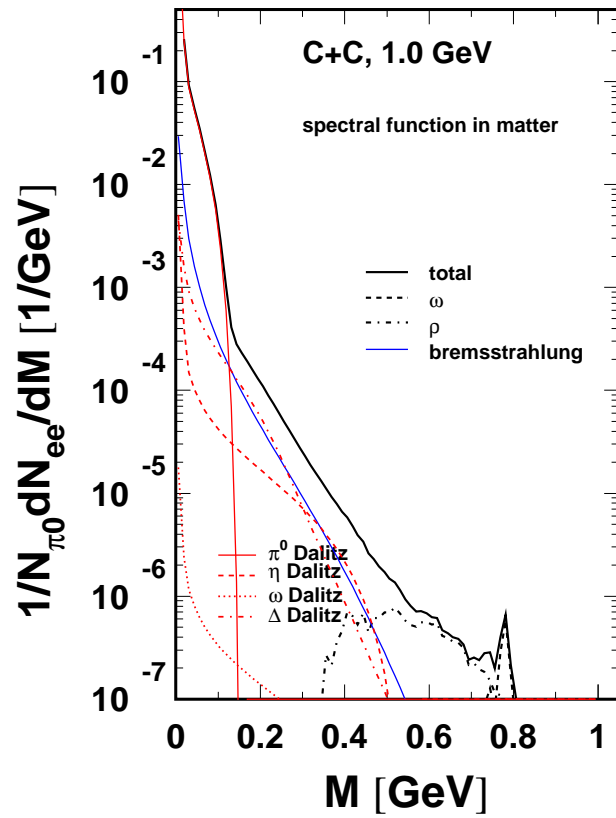


Vacuum

Matter

Static

C + C 1 AGeV



Summary

- BUU with off-shell propagation
- several theoretical uncertainties
- needs of precise data in
 - pp, pn collision (bremsstrahlung, resonance-Dalitz decay)
 - Au+Au 1 GeV and at the highest available energy

- 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

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

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
 $R \leftrightarrow N\pi, N\eta, N\sigma, N\rho, N\omega, \Delta\pi, N(1440)\pi, K\Lambda, K\Sigma$
- 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
- $\frac{d\sigma^{X \rightarrow NR}}{dM_R} \sim A(M_R) \lambda^{0.5}(s, M_R^2, M_N^2)$

Cross sections

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

Meson absorption cross sections are given by

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

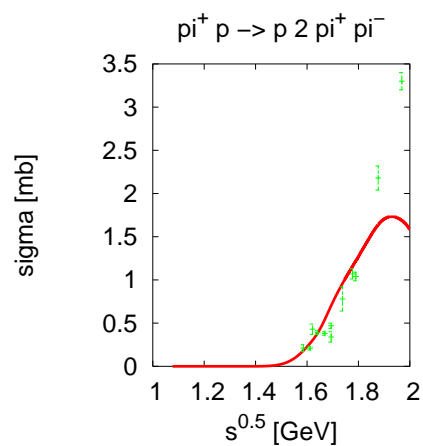
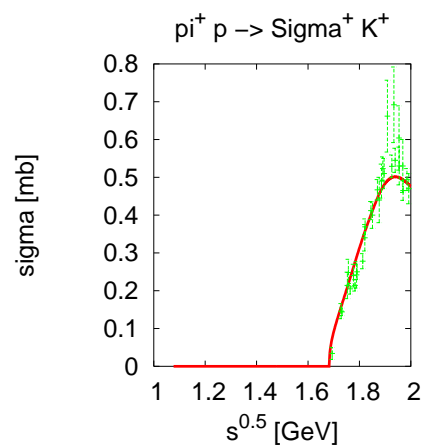
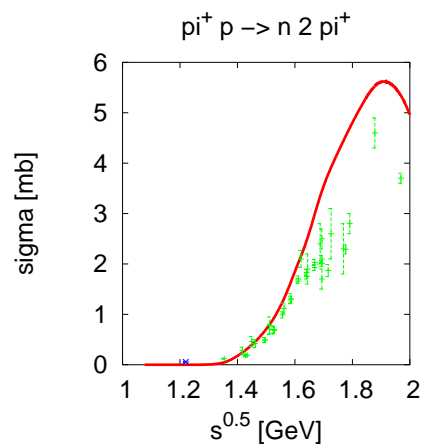
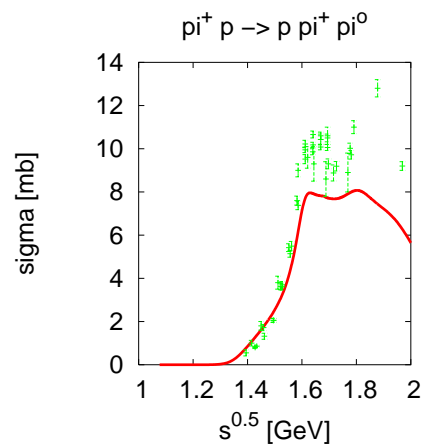
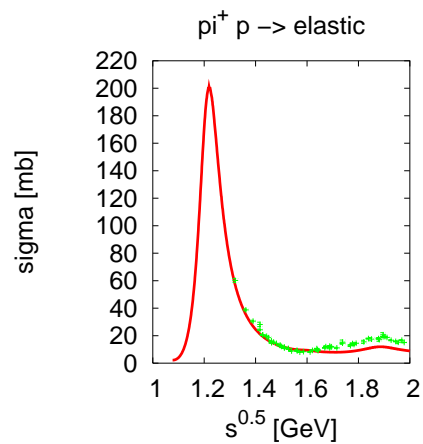
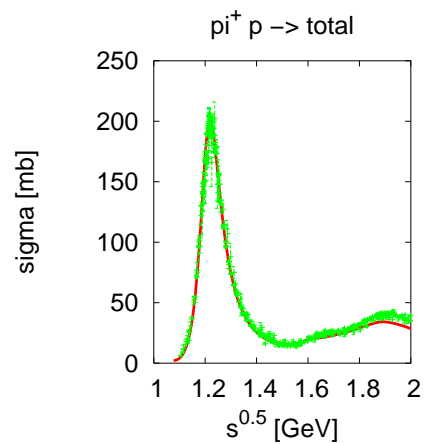
Baryon resonance parameters: mass, width, branching ratios are fitted by describing the meson production channels in πN collisions:

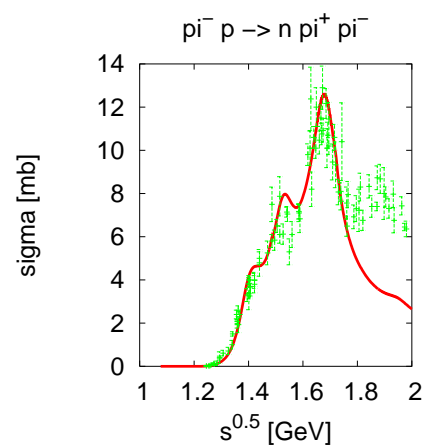
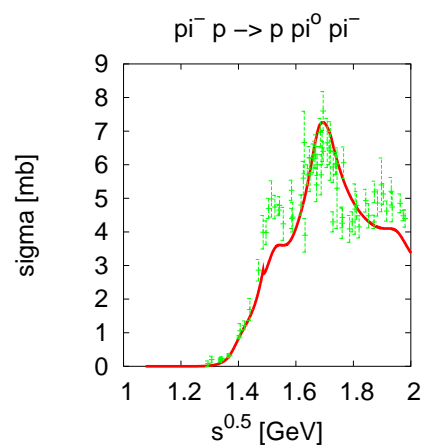
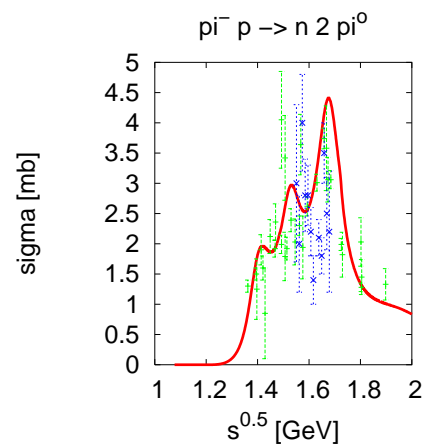
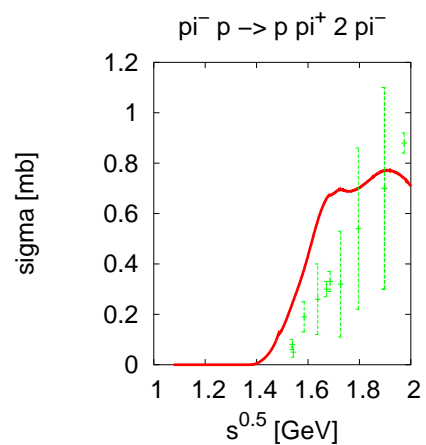
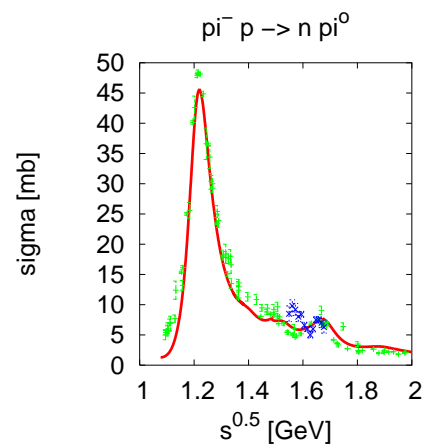
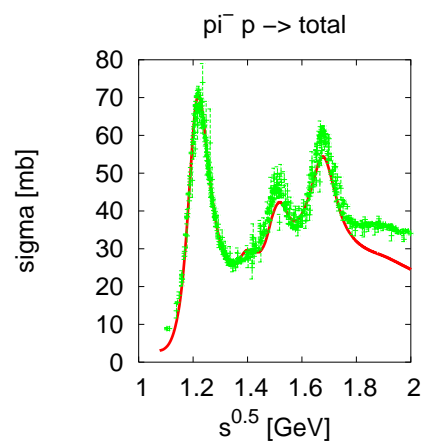
$$\sigma_{\pi N \rightarrow NM} = \sum_R \sigma_{\pi N \rightarrow R} \frac{\Gamma_{R \rightarrow NM}}{\Gamma_{tot}}$$

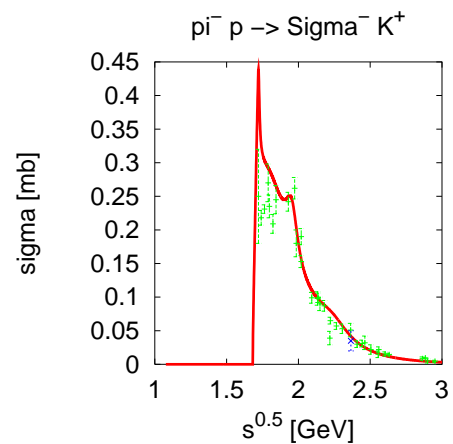
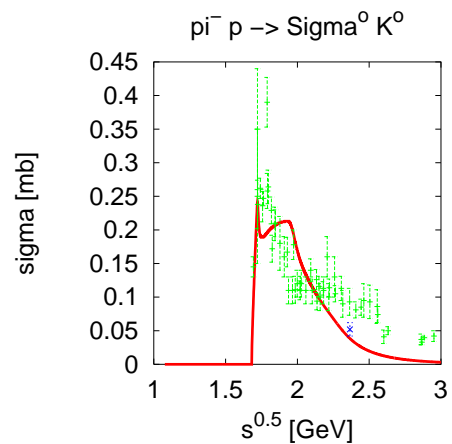
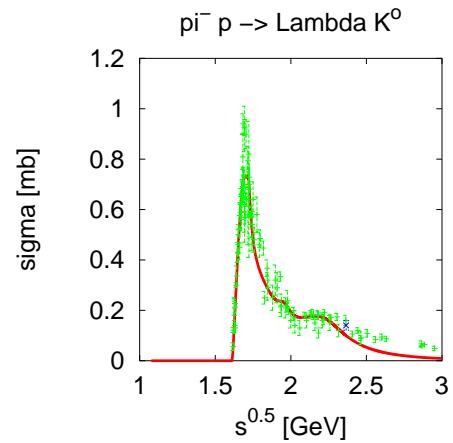
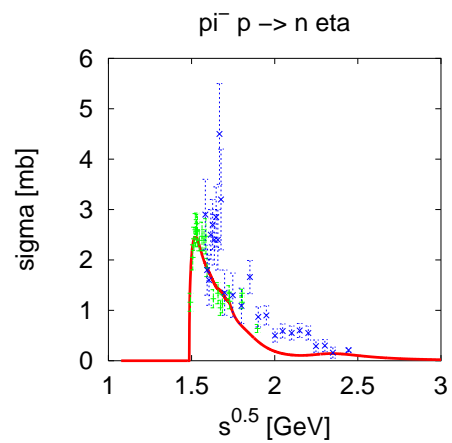
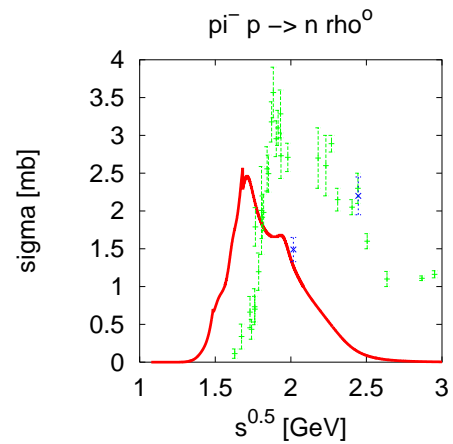
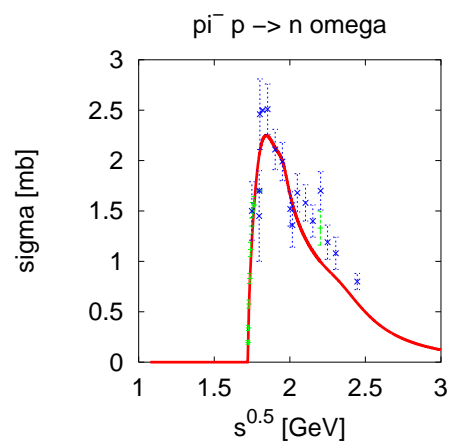
Resonance production cross section $NN \rightarrow NR$ is given by the fit of

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

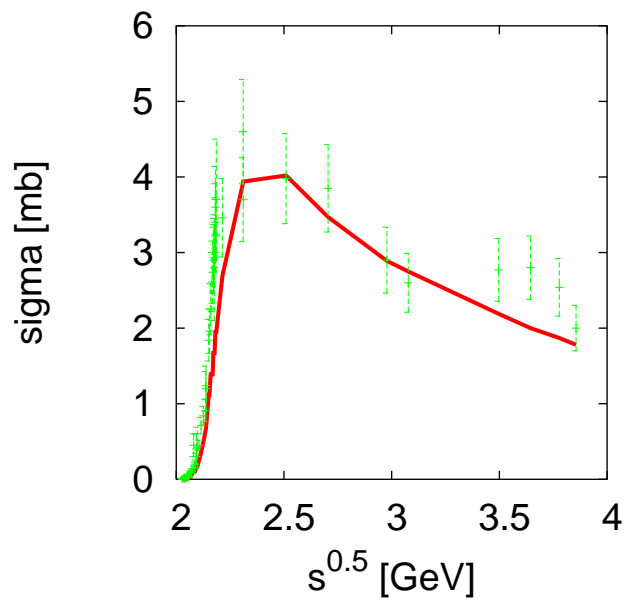
27 baryons, 6 mesons. Fit is done by the Minuit package (CERN)



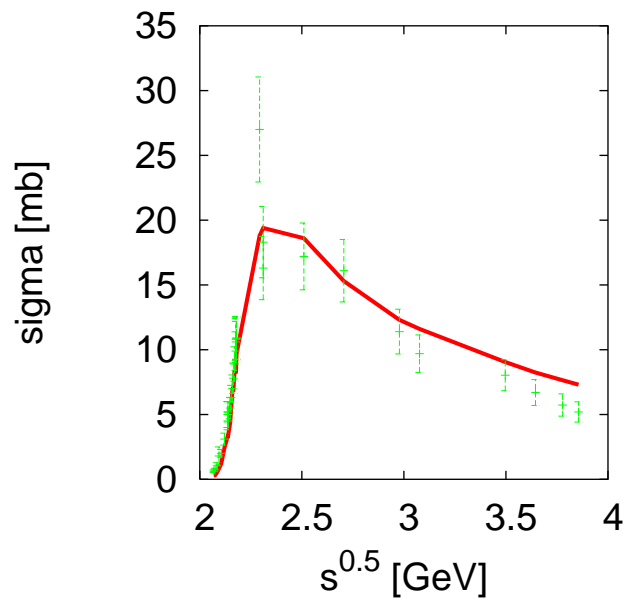




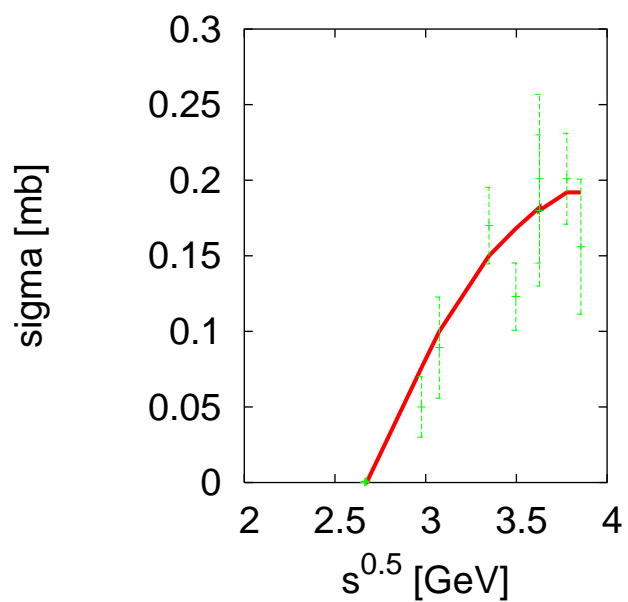
pp→pp pi⁰



pp→pn pi⁺



pp→pp omega



pp→pp pi⁺ pi⁻

