

# Propagation of spectral functions and dilepton production at SIS energies

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Oct. 5, 2010

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

Reference: The Open Nuclear and Particle Physics Journal Vol.3 2010

## 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

- $NN \rightarrow \dots \rightarrow NNe^+e^-$  (measurable)
- $\pi^+\pi^-$  annihilation (measurable and theoretically well understood)
- $\pi N \rightarrow N\rho(\omega, \eta) \rightarrow Ne^+e^-$  measurable or calculable from measured quantities
- other secondaries ( $\pi N$  bremsstrahlung, or  $N\Delta \rightarrow NR \rightarrow NNe^+e^-$ )

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

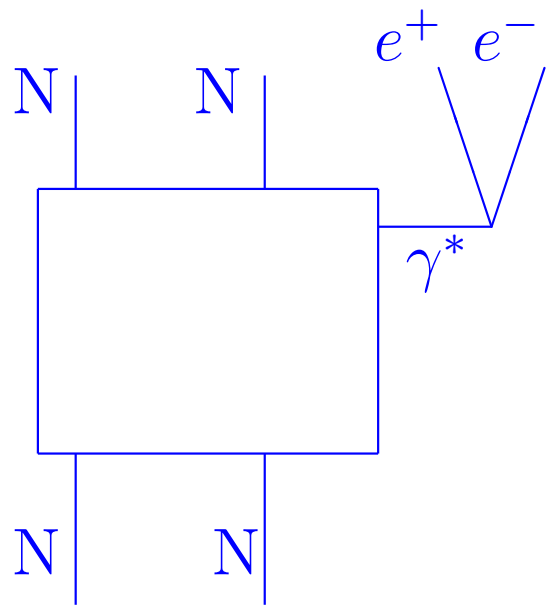
Problem:

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

## Dilepton production in NN

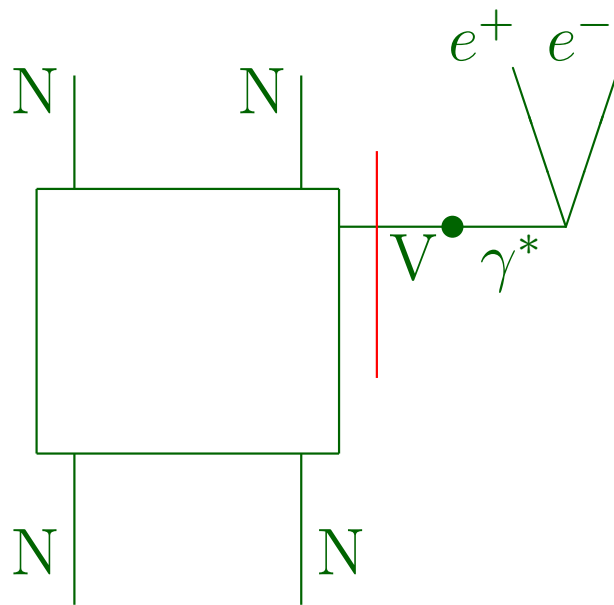
- Direct decay of vector mesons and  $\eta$
- Dalitz-decay of  $\pi$ ,  $\eta$  and  $\omega$
- Dalitz-decay of baryon resonances  
Zetenyi, Wolf, Phys. Rev, C67 (2003) 044002;  
Heavy Ion Phys. 17 (2003) 27
- pn bremsstrahlung (not negligible)

# Dilepton Channels in NN



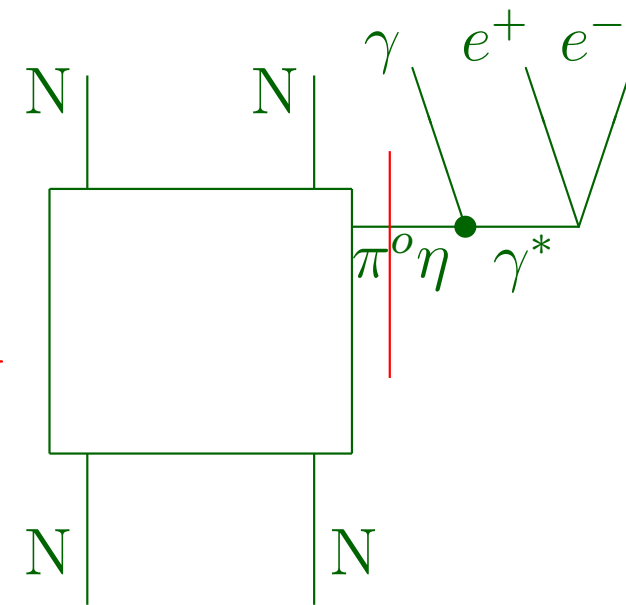
NN tot.

$\approx$

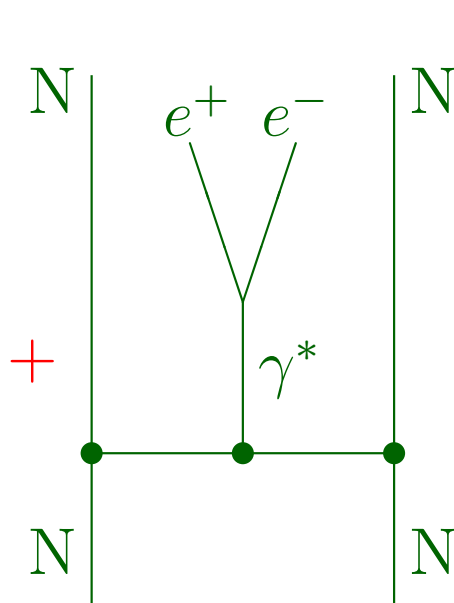


$\rho/\omega$  decay

+

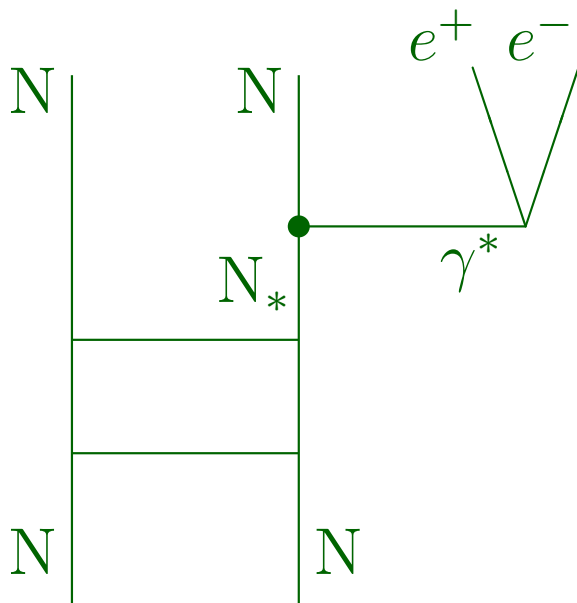


Dalitz-decay of  $\pi^0/\eta$  decay

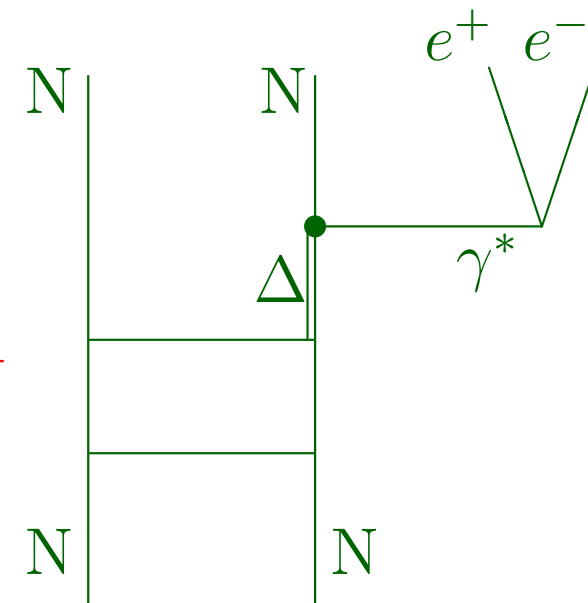


bremsstrahlung

+



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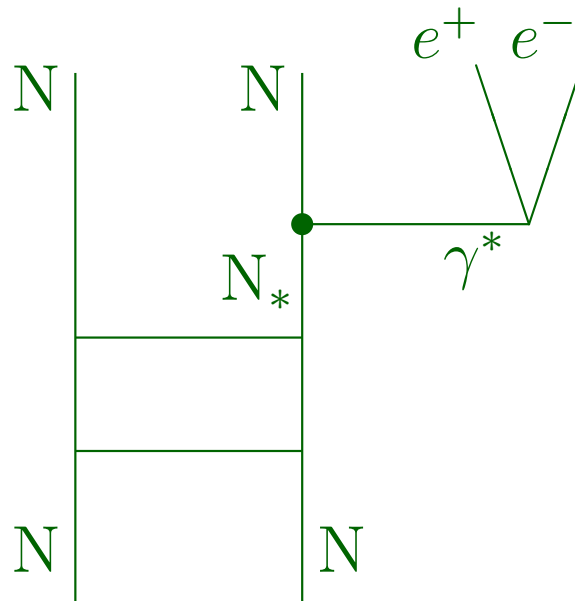


$\Delta$ -Dalitz

# Bremsstrahlung calculations

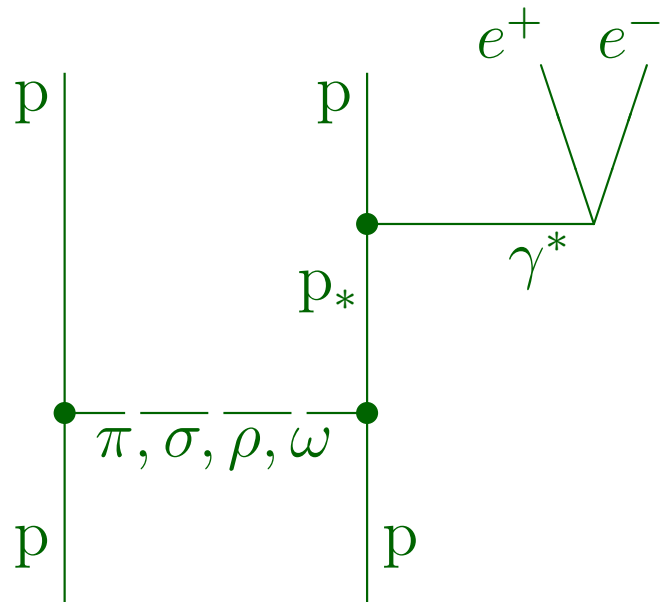
Soft photon approximation

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

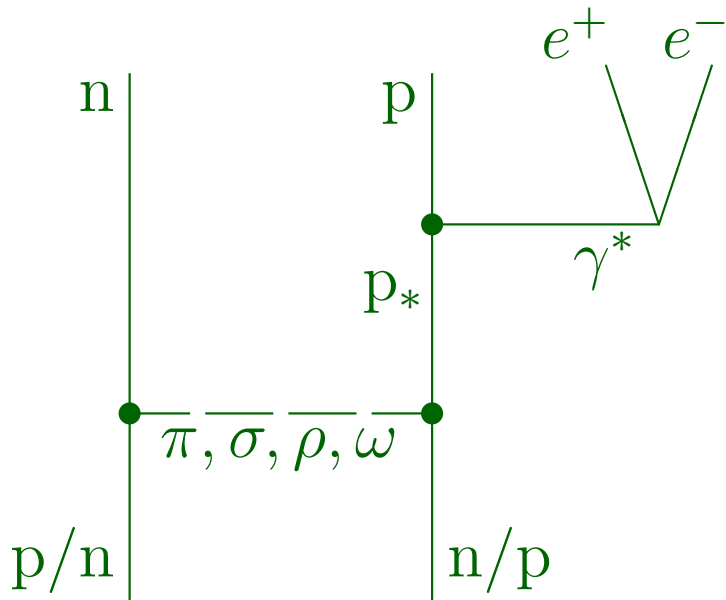


# T-matrix calculations

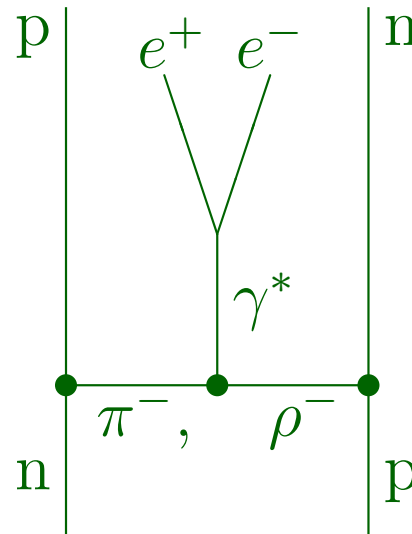
pp:

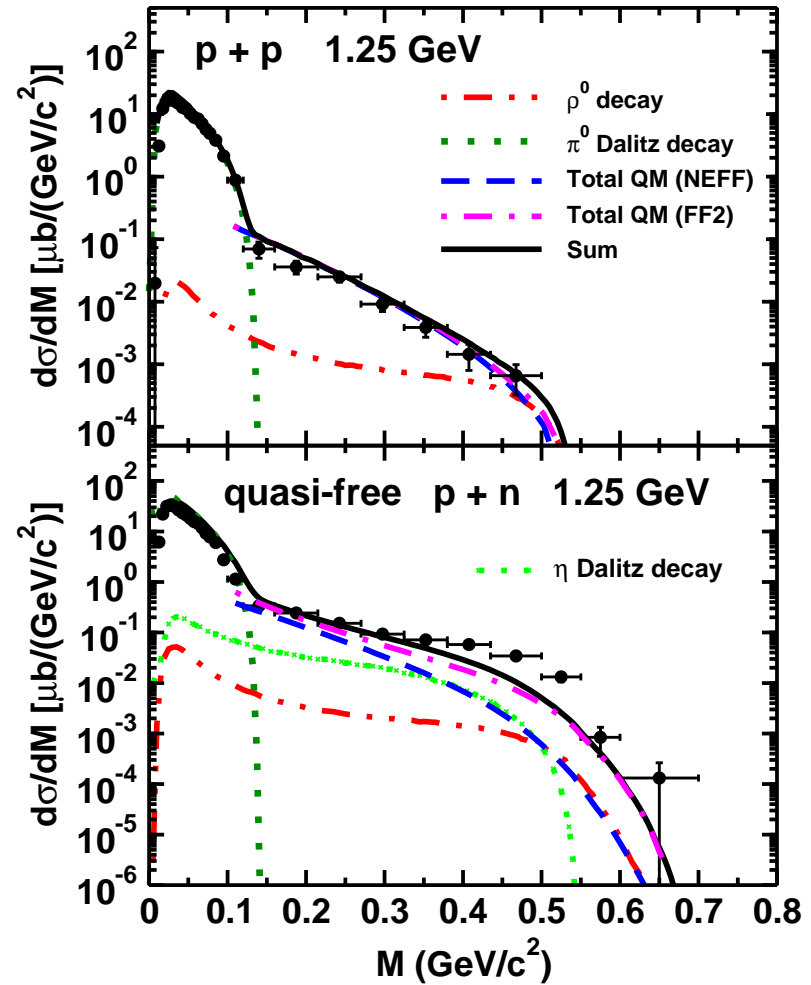
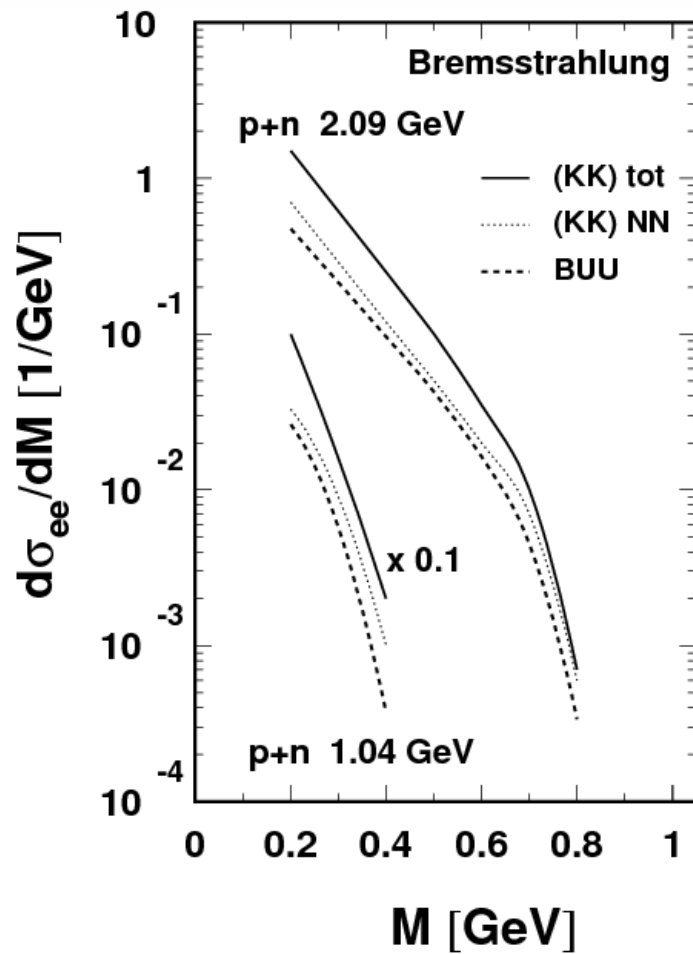


pn:



+





- L.P. Kaptari, B. Kämpfer, Nucl. Phys. A **764** (2006) 338.
- R. Shyam, U. Mosel, Phys. Rev. **C67** (2003) 065202, **C79** (2009) 035203, nucl-th:1006.3873



## 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

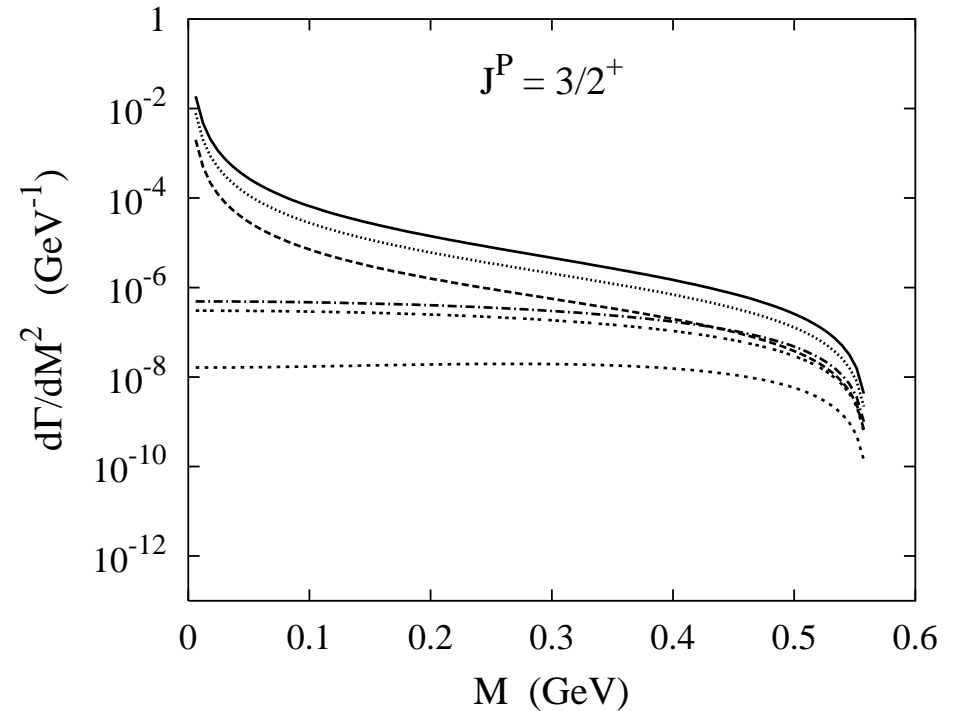
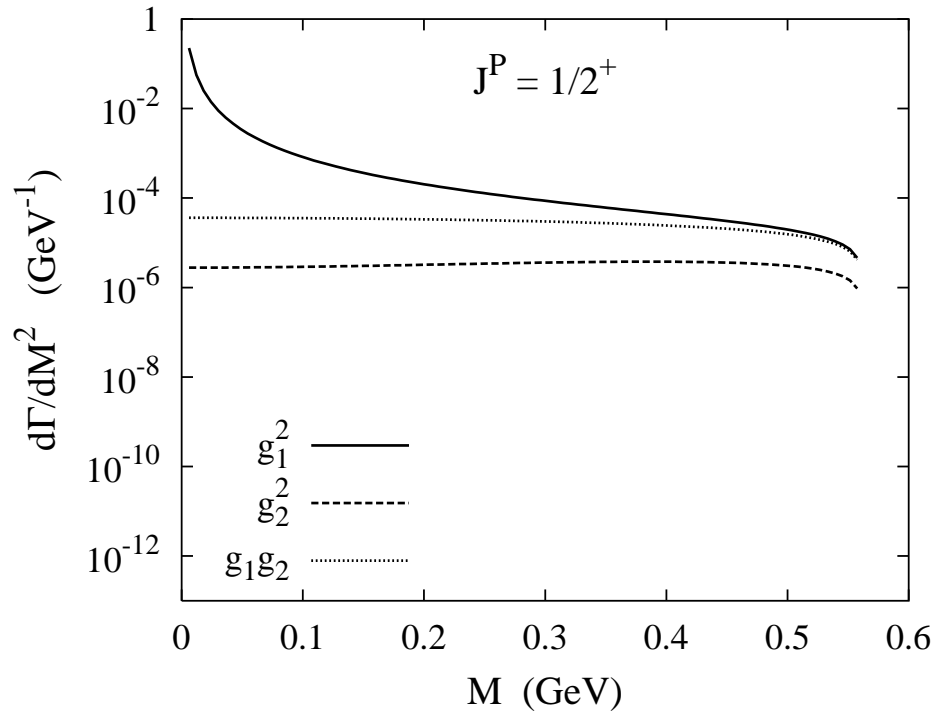
- There are 3 independent tensor structures (for  $S \geq 3/2$ ) for coupling of nucleon and Rarita-Schwinger spinors ( $G = 1$  or  $\gamma_5$ ):

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

with

$$\begin{aligned}\chi_{\mu\rho}^1 &= \gamma_\mu q_\rho - \not{q} g_{\mu\rho}, \\ \chi_{\mu\rho}^2 &= P_\mu q_\rho - (P \cdot q) g_{\mu\rho}, \\ \chi_{\mu\rho}^3 &= q_\mu q_\rho - q^2 g_{\mu\rho},\end{aligned}$$

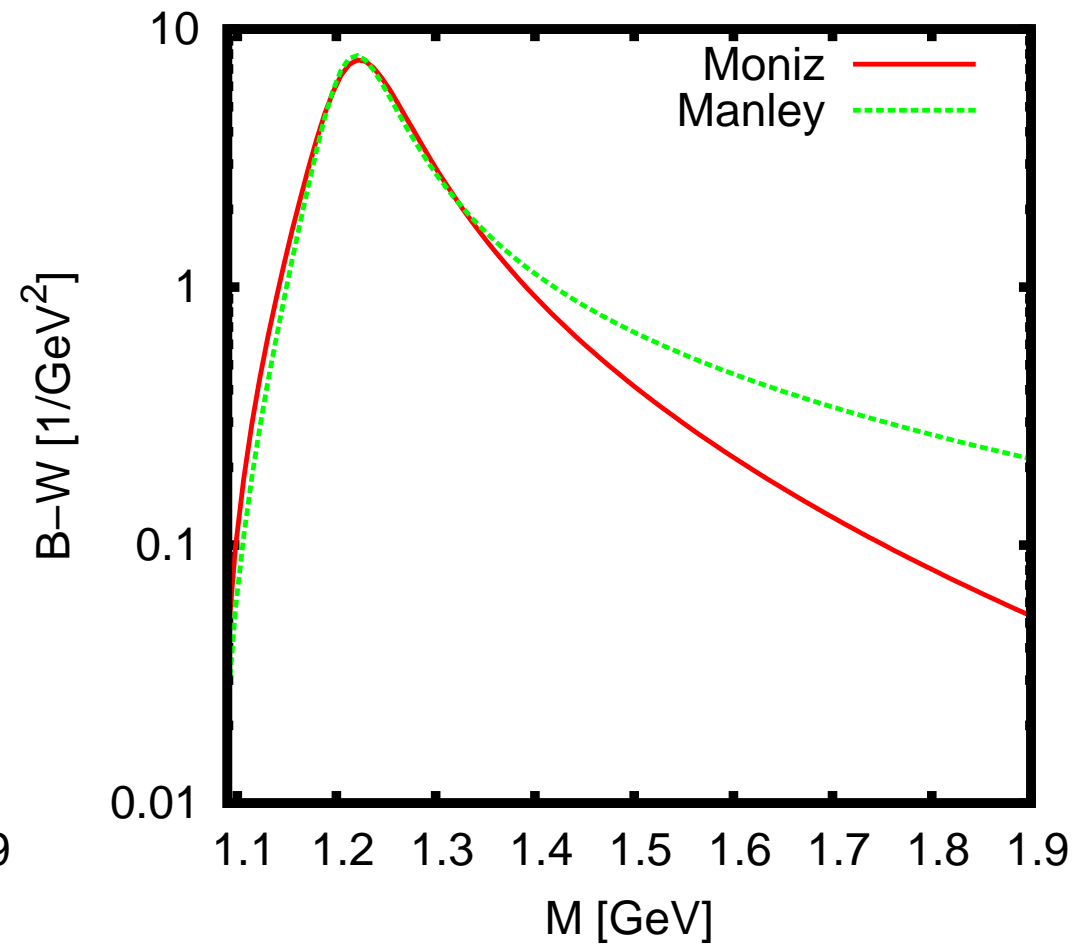
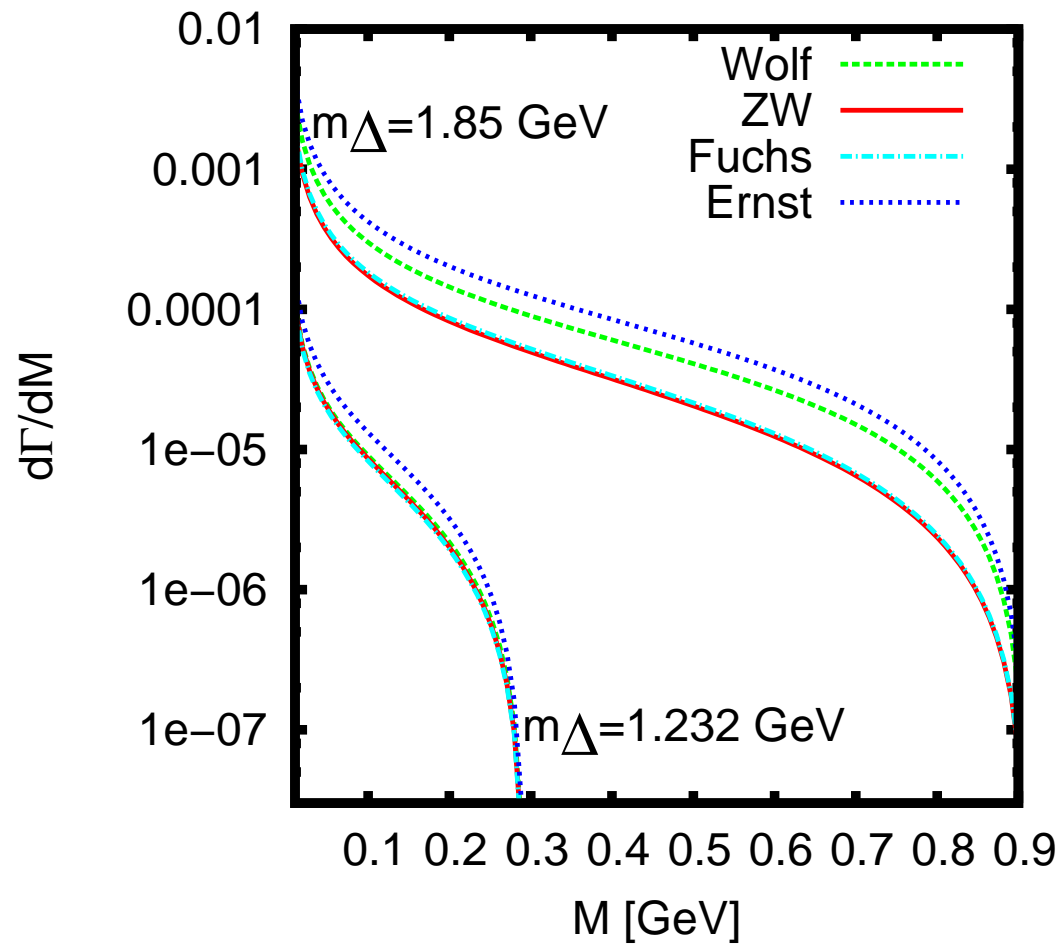
# Dalitz-decay contributions



$m_* = 1.5$  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.

# $\Delta(1232)$



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

## Summary of elementary dilepton production

- 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.

## Cross sections

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

Meson absorption cross sections are given by

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

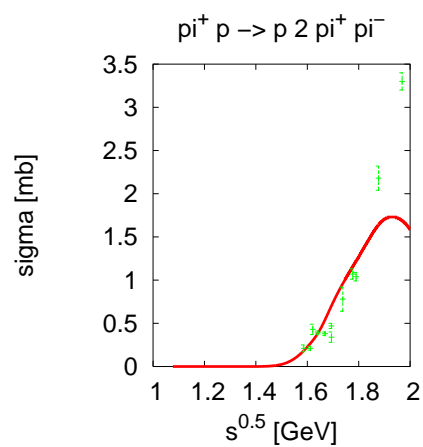
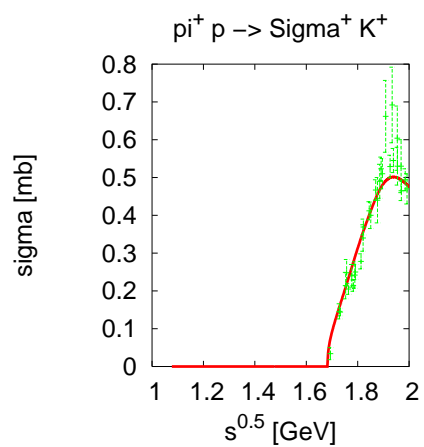
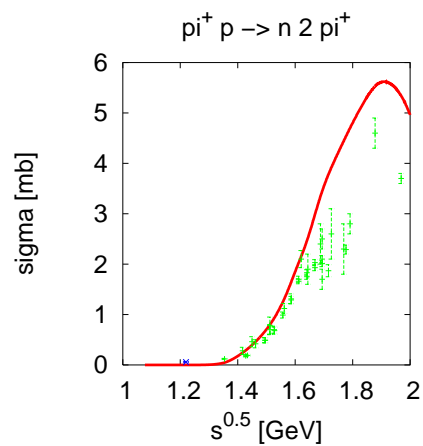
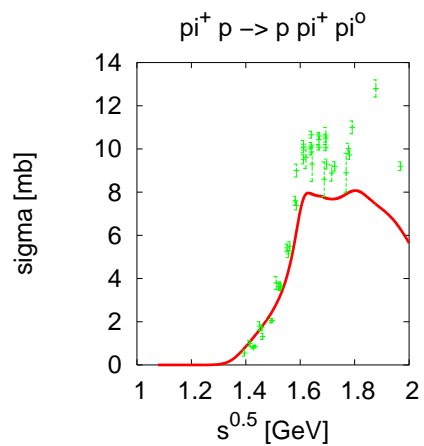
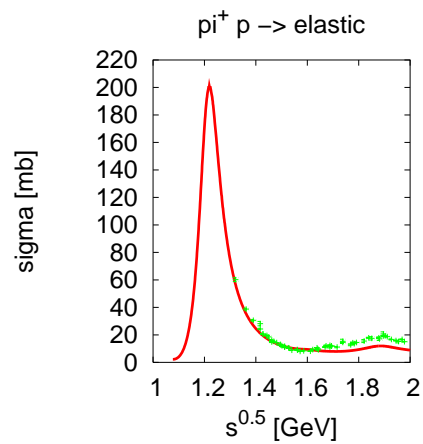
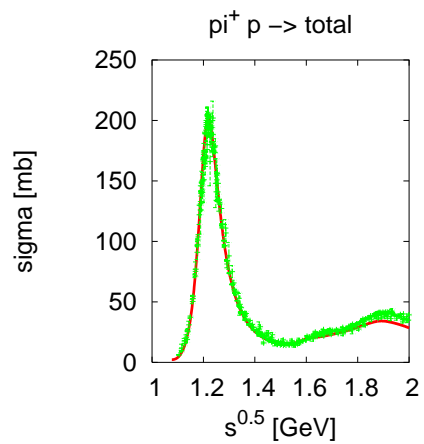
Baryon resonance parameters: mass, width, branching ratios are fitted by describing the meson production channels in  $\pi N$  collisions:

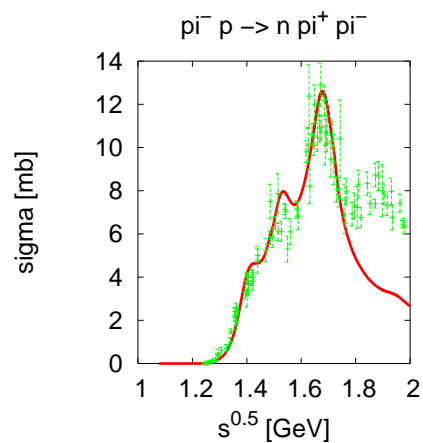
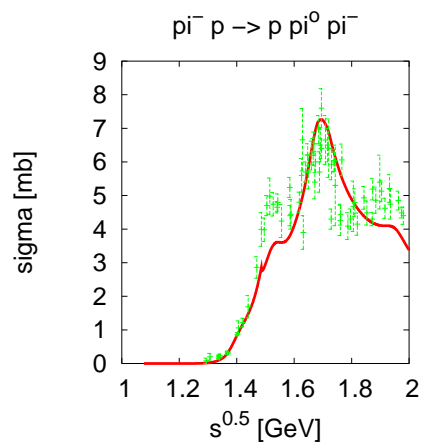
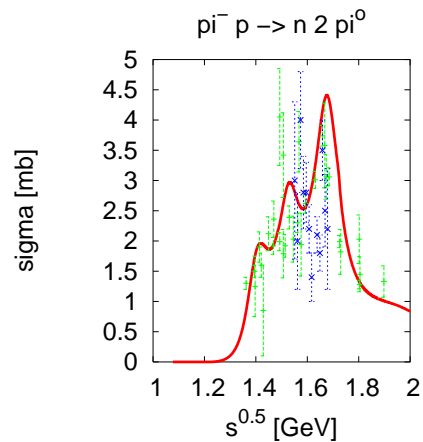
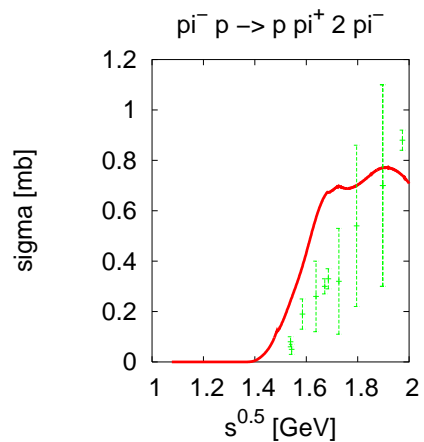
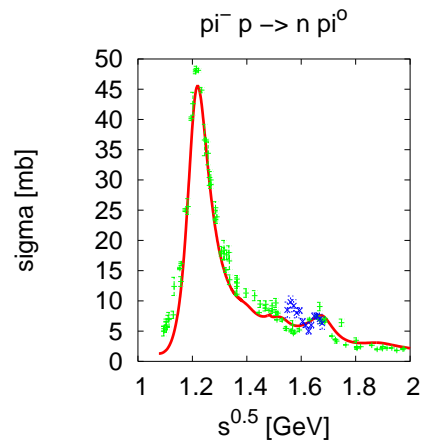
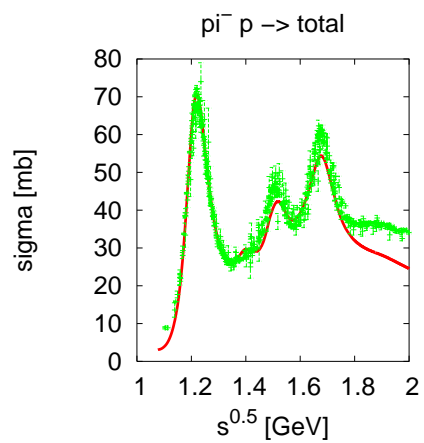
$$\sigma_{\pi N \rightarrow NM} = \sum_R \sigma_{\pi N \rightarrow R} \frac{\Gamma_{R \rightarrow NM}}{\Gamma_{tot}}$$

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

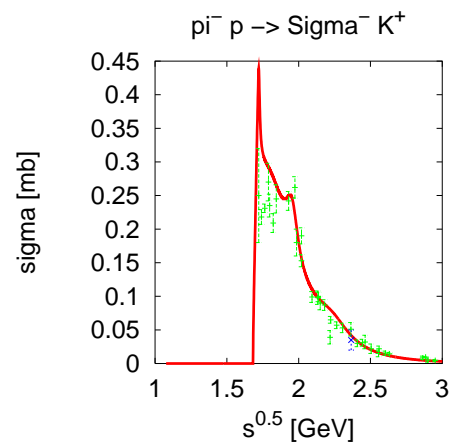
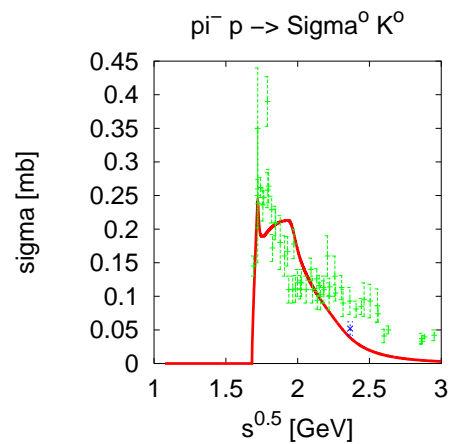
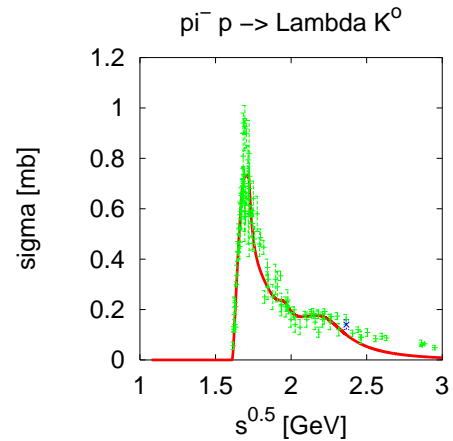
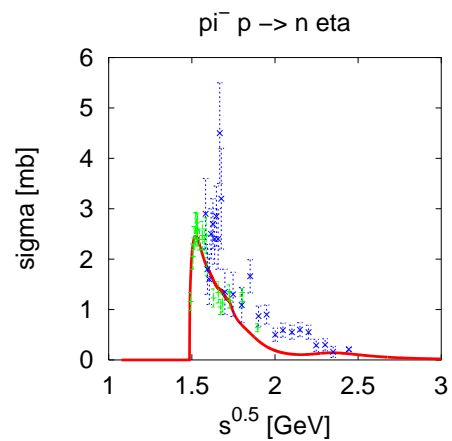
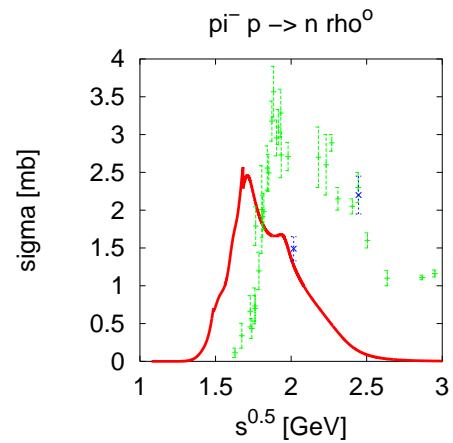
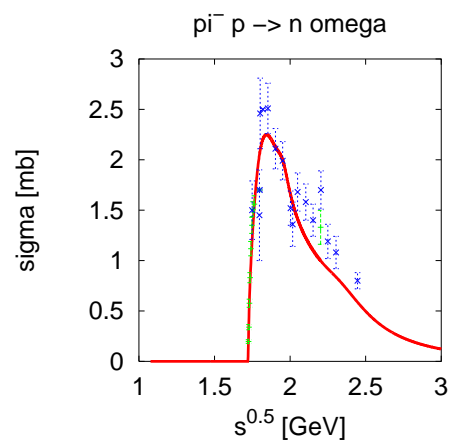
$$\sigma_{NN \rightarrow NM} = \sum_R \sigma_{NN \rightarrow NR} \frac{\Gamma_{R \rightarrow NM}}{\Gamma_{tot}}$$

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

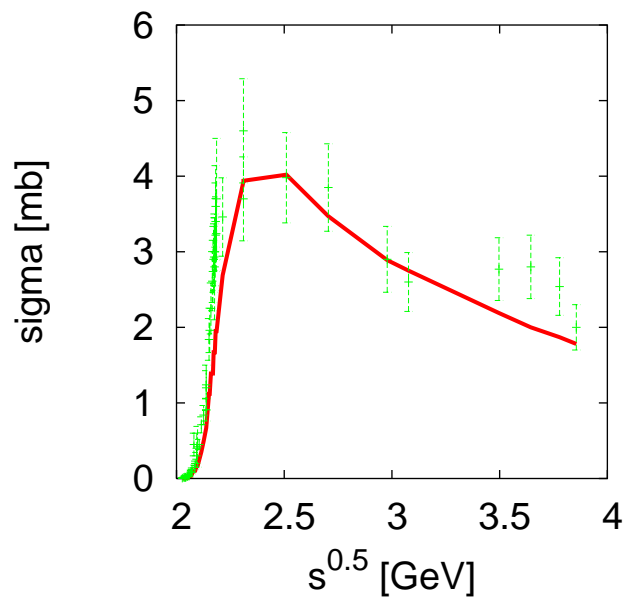




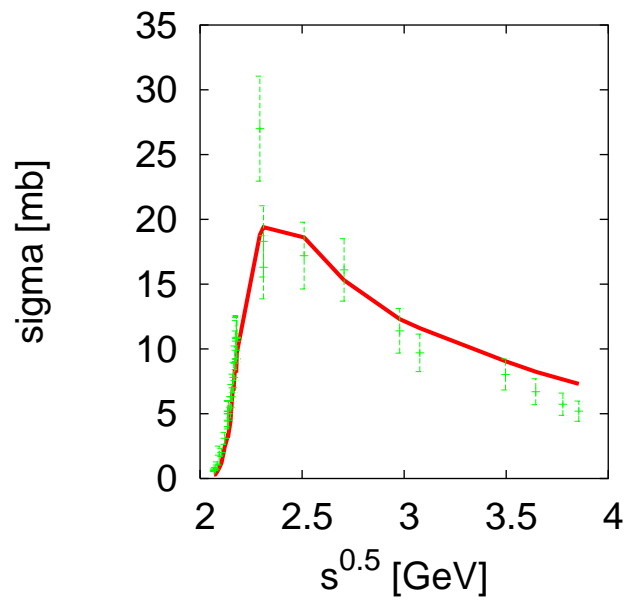




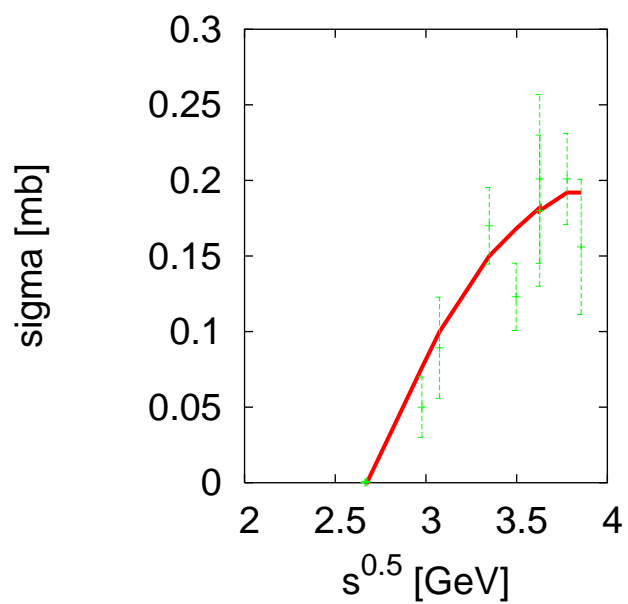
pp→pp pi<sup>0</sup>



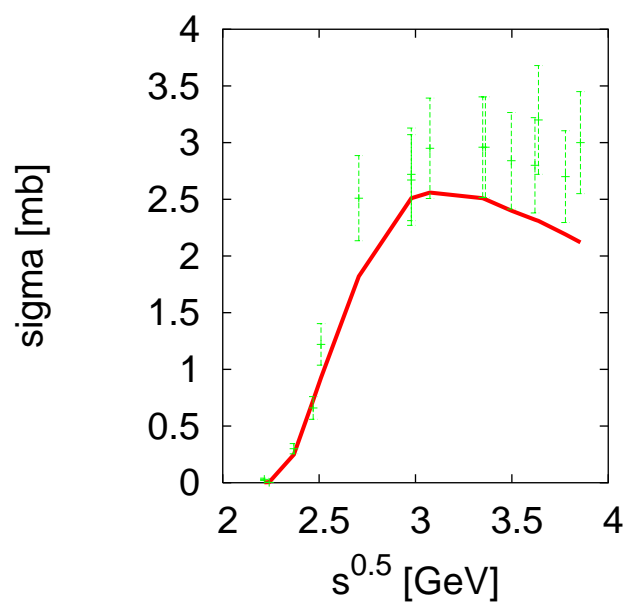
pp→pn pi<sup>+</sup>



pp→pp omega



pp→pp pi<sup>+</sup> pi<sup>-</sup>



## Why off-shell transport

- medium effects on the spectrum of vector mesons
  - indication of mass shift of longliving  $\omega$ '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  $F_\alpha = f_\alpha(x, p, t)A_\alpha$

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

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)

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

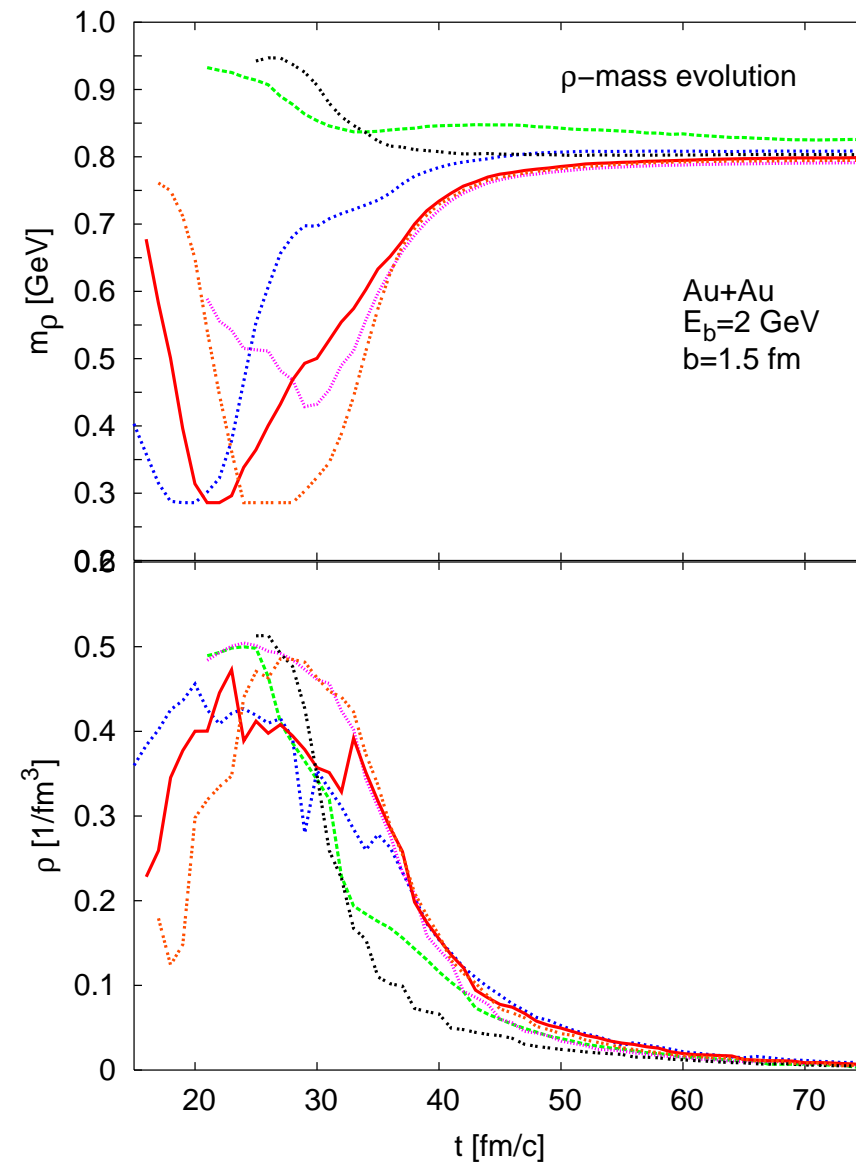
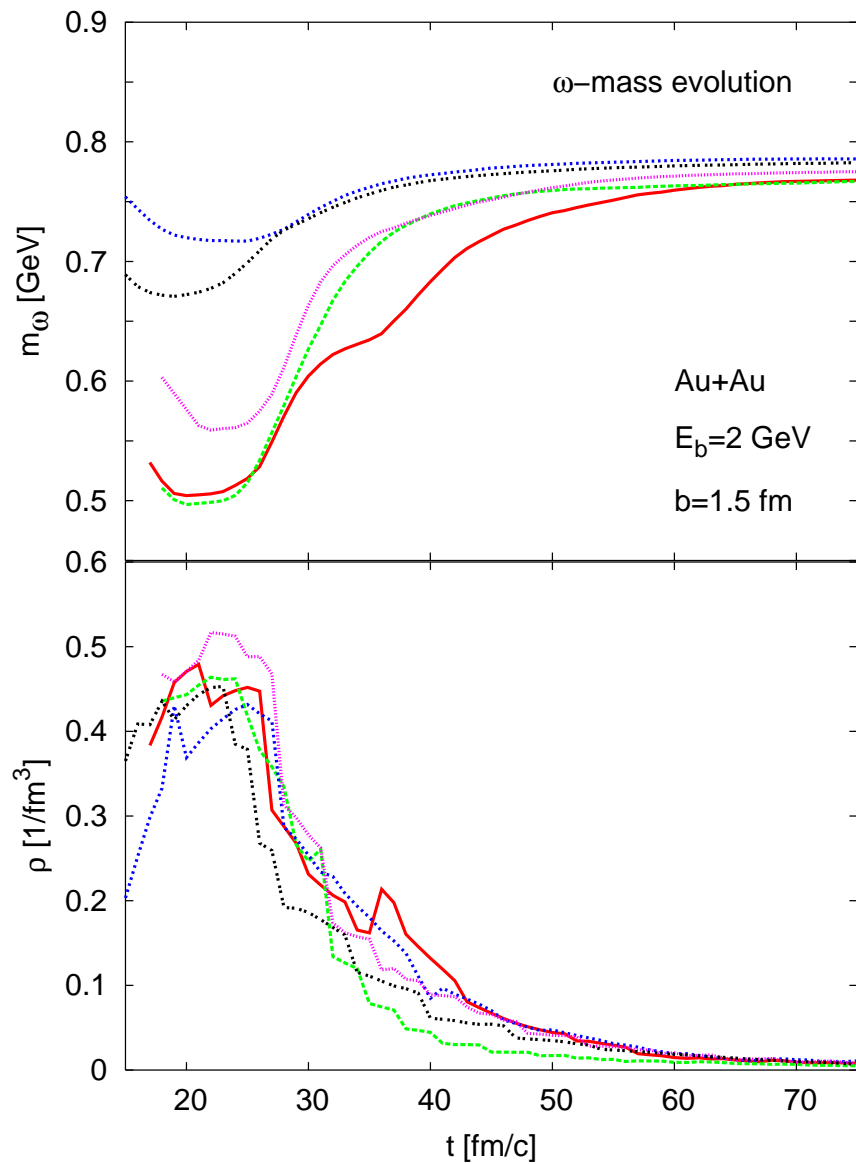
$$\Delta M_\omega = -50 \text{ MeV}, \Delta M_\rho = -120 \text{ MeV}$$

- danger of double counting

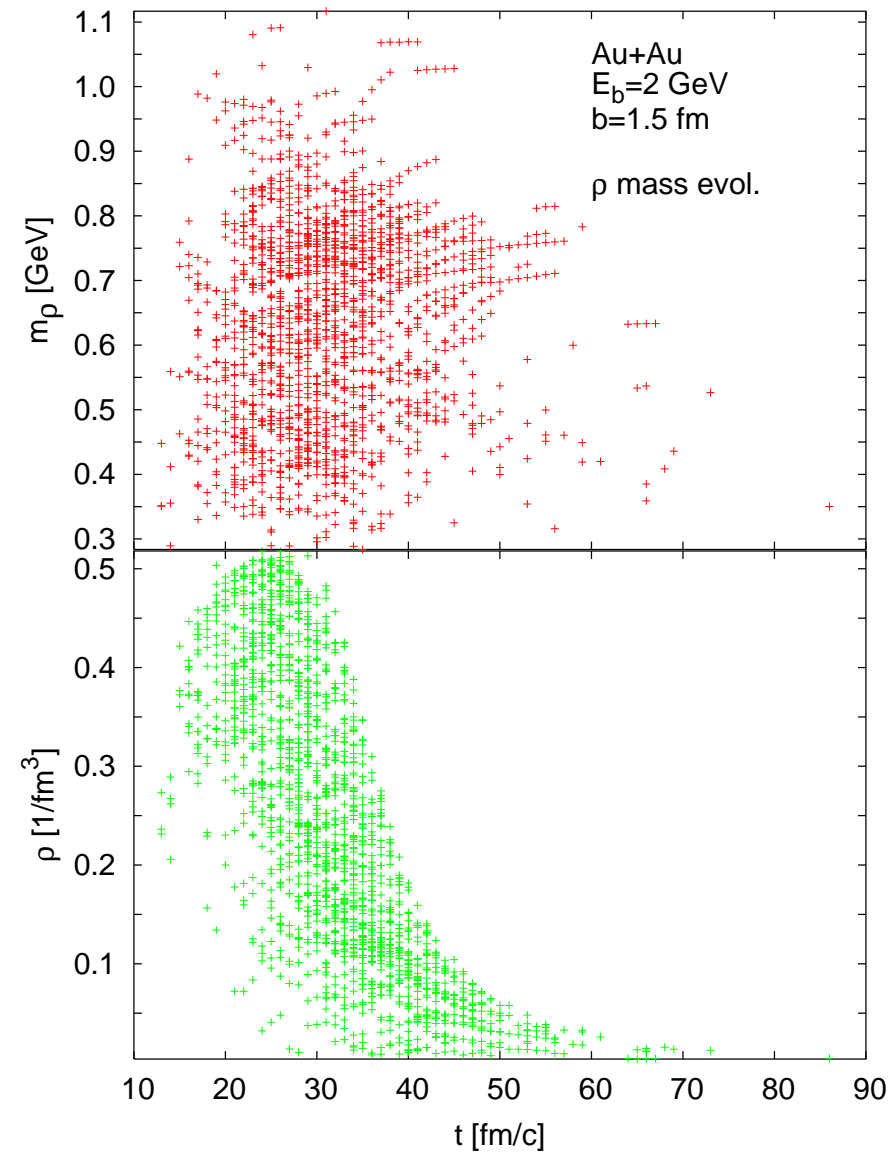
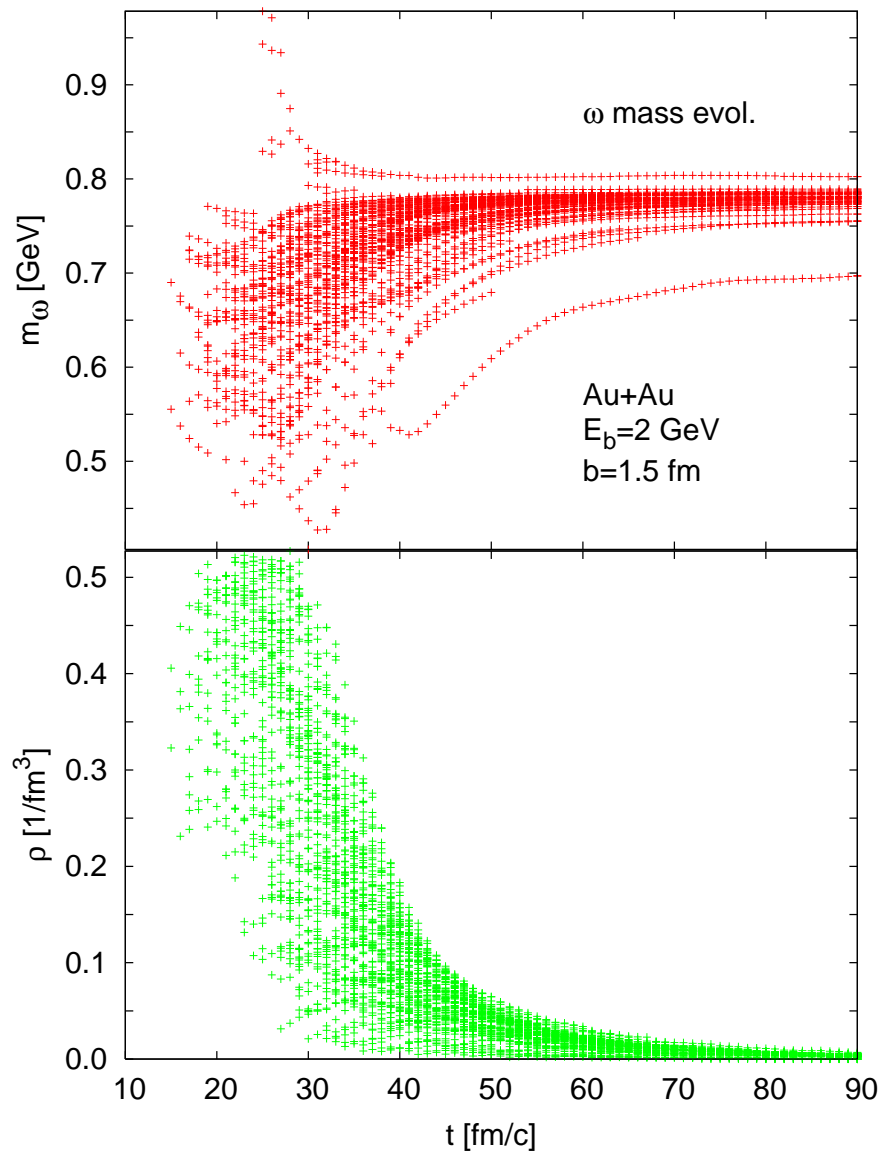
collision term already contains partly the mixing of mesons with resonance-hole excitations

but sum up only to finite order

# Evolution of masses

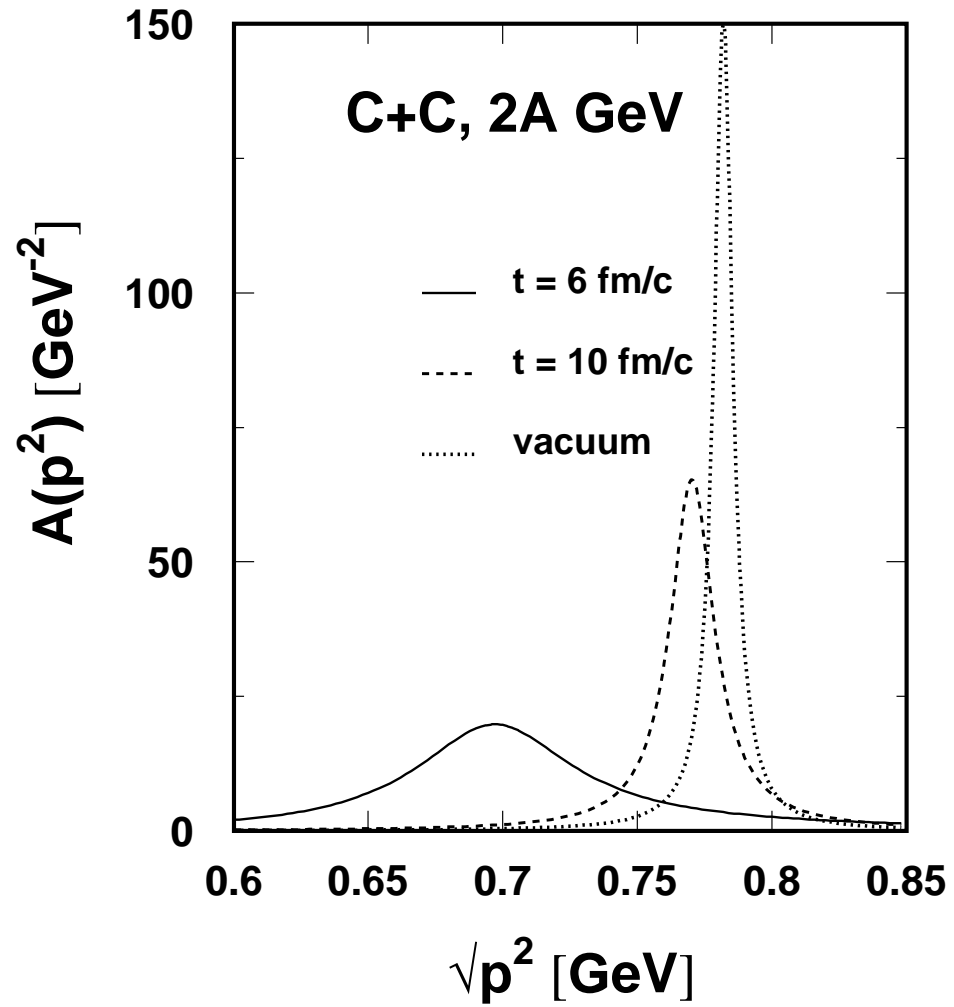


# Evolution of masses

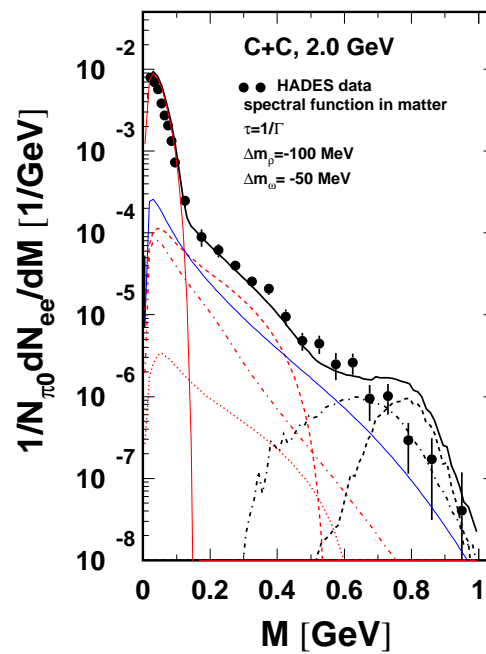
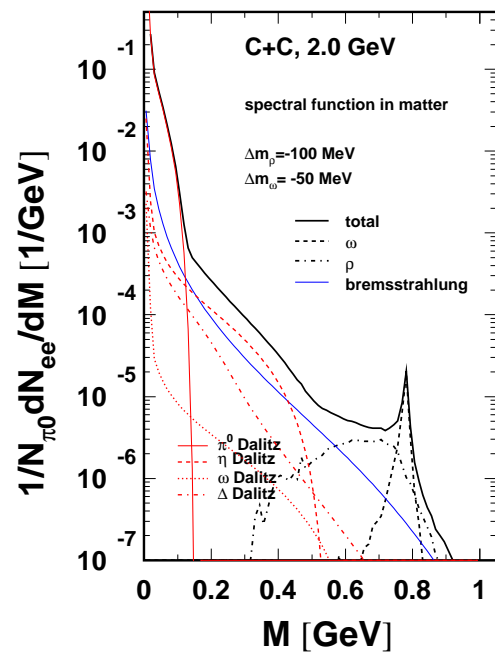
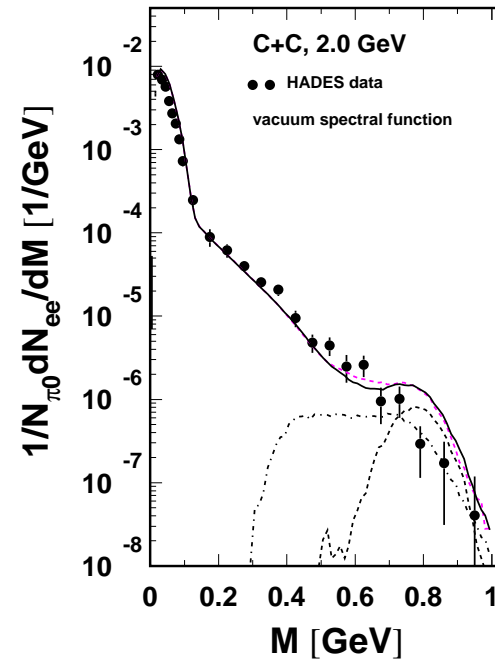
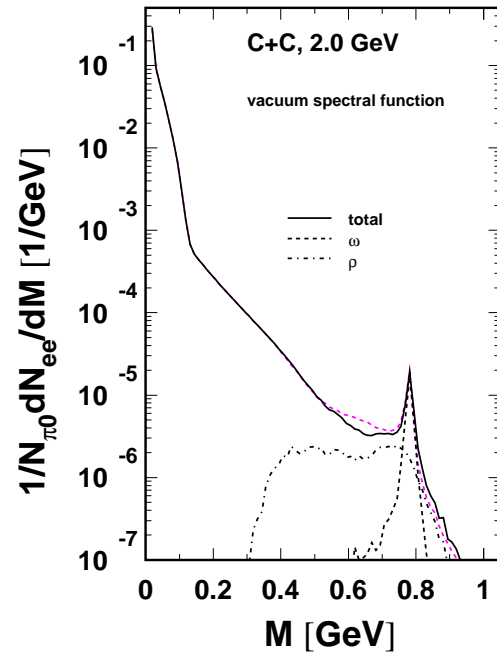


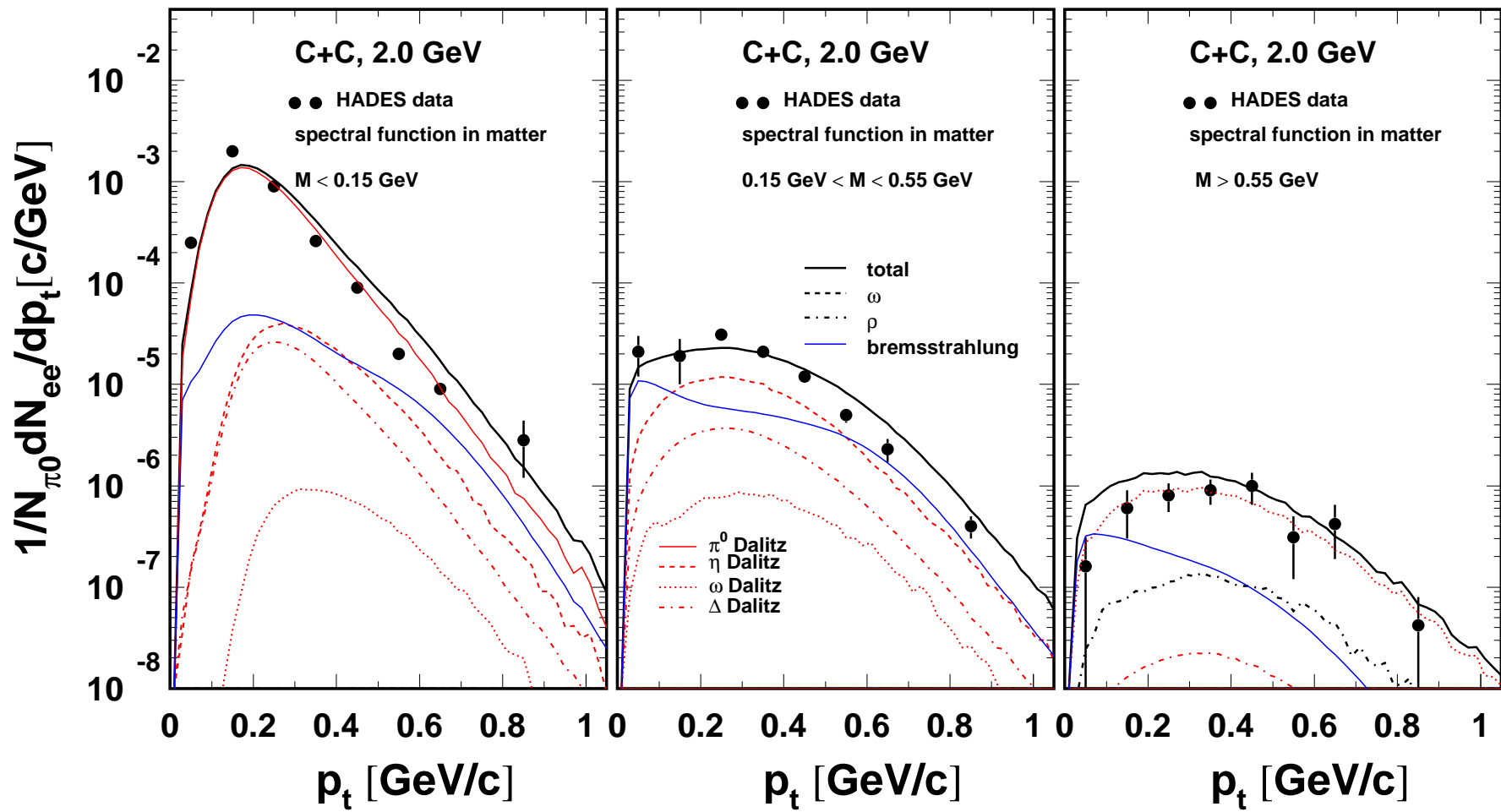


# Evolution of the $\omega$ spectrum

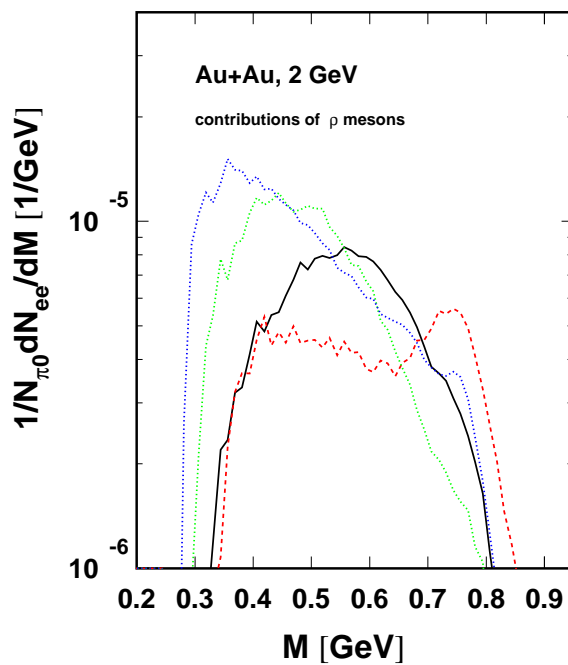
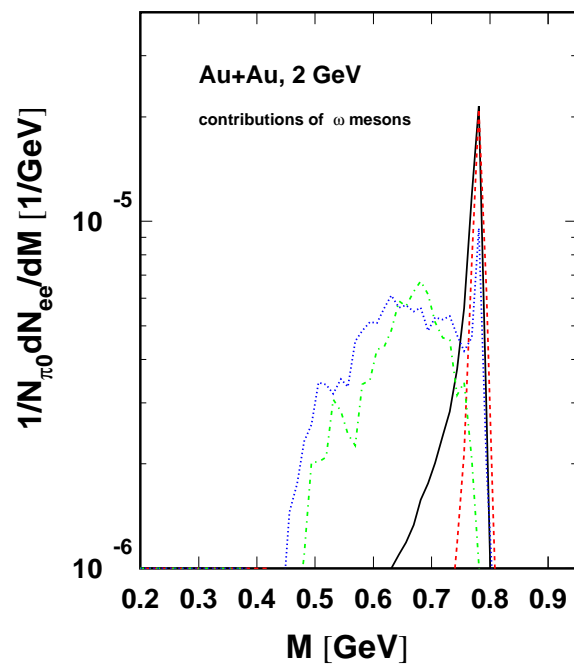
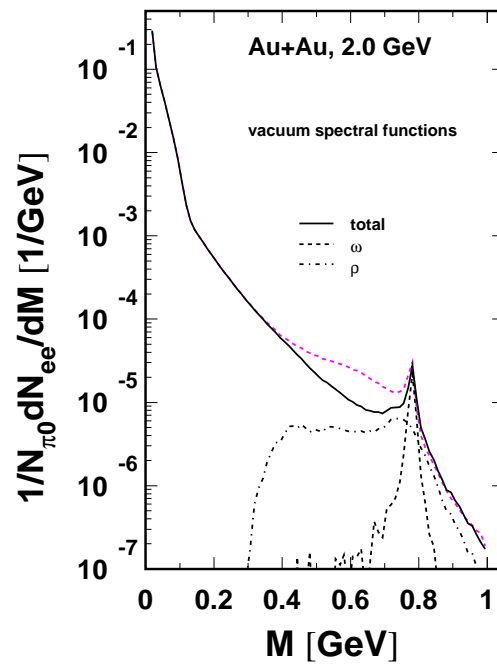
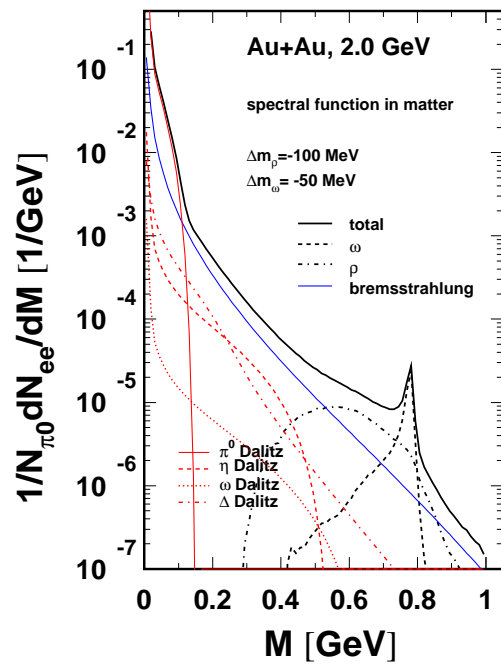


# C + C 2 GeV





# Au + Au 2 GeV

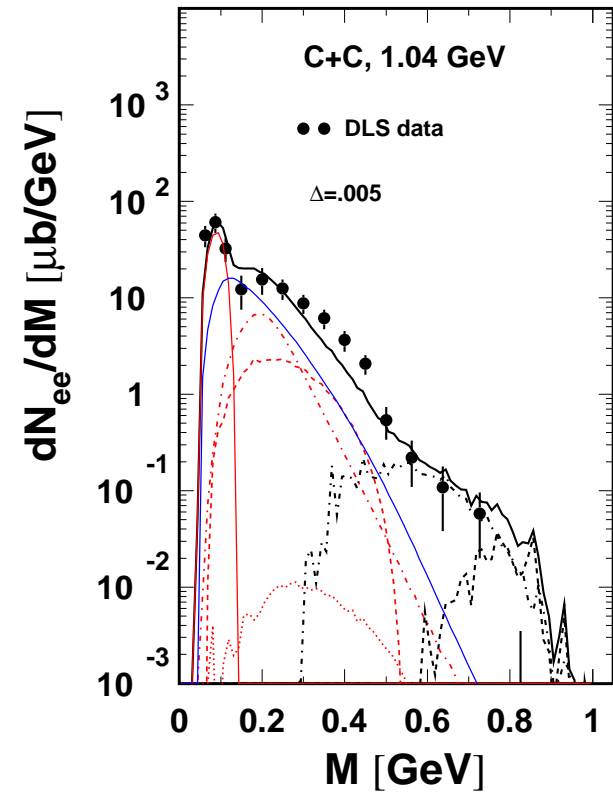
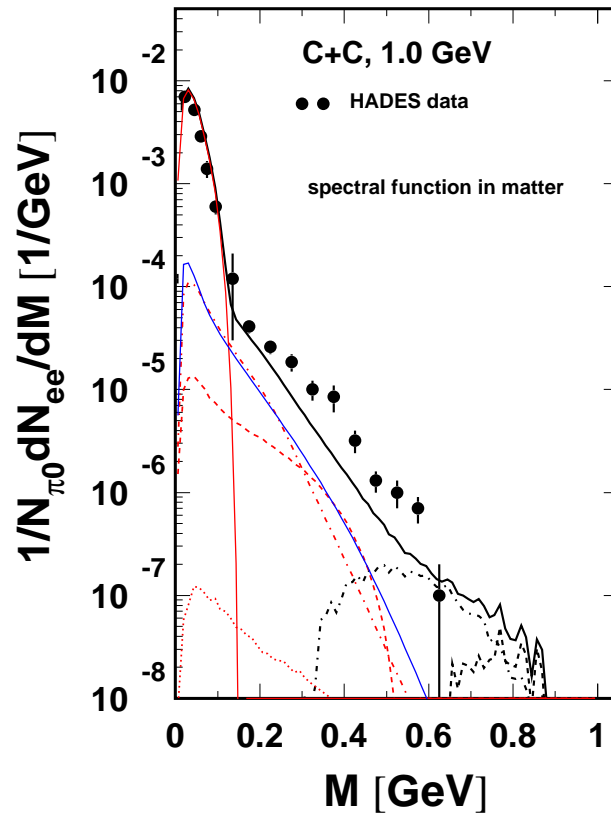
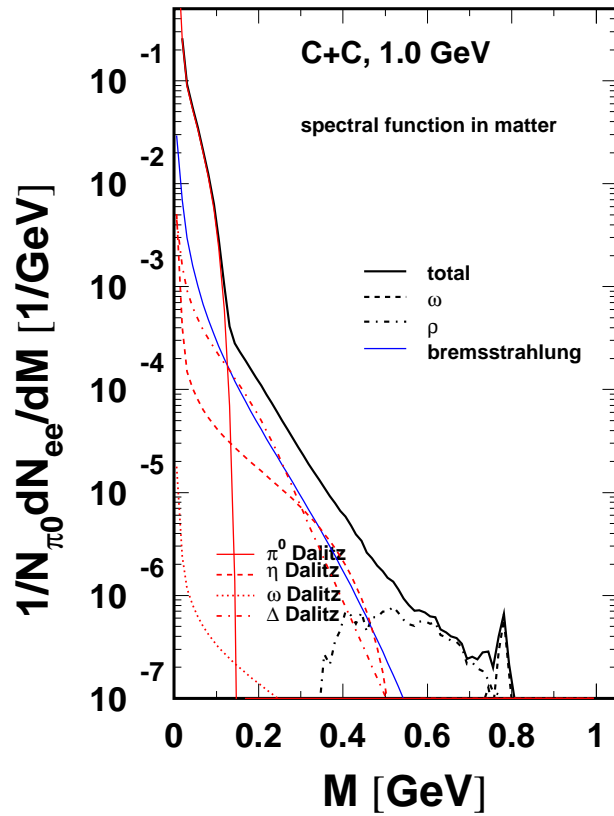


Vacuum

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