Dilepton production in relativistic energies

Excited QCD 2017
Sintra 12.05.2017

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- Motivation
- Transport equations for spectral functions
- πA reactions and quantum interference in nuclear matter
- $\bar{p}$A reaction (PANDA)
- Summary

Why dileptons

- measured (DLS, HADES, CERES, NA60, STAR, ALICE)
- without final state interaction
- vector mesons decay to dileptons → vector mesons in matter
- much better then photons:
  mass can be used to distinguish between the different sources
- interesting results for p-nucleus (KEK) and nucleus-nucleus (SPS,RHIC,LHC) collisions

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
- Drell-Yan
- Open charm
- Charmonium decay

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

  S. Teis, W. Cassing, M. Effenberger, A. Hombach, U. Mosel, Gy. Wolf, Z. Phys. A359 (1997) 297-304,

  Gy. Wolf et al., Phys.Atom.Nucl. 75 (2012) 718-720

- 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
- $\frac{d\sigma^{X\to NR}}{dM_R} \sim A(M_R)\lambda^{0.5}(s, M_R^2, M_N^2)$

Spectral equilibration

- medium effects on the spectrum of hadrons (vector mesons)
- how they get on-shell (energy-momentum conservation)
- Field theoretical method (Kadanoff-Baym equation)
  B. Schenke, C. Greiner, Phys.Rev.C73:034909,2006
- Off-shell transport
  W. Cassing, S. Juchem, Nucl.Phys. A672 (2000) 417
  S. Leupold, Nucl.Phys. A672 (2000) 475
- Spectral equilibration: Markov or memory effect

Off-shell transport

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

  W. Cassing, S. Juchem, Nucl.Phys. A672 (2000) 417
  S. Leupold, Nucl.Phys. A672 (2000) 475
- testparticle approximation

Transport equations

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

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

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

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

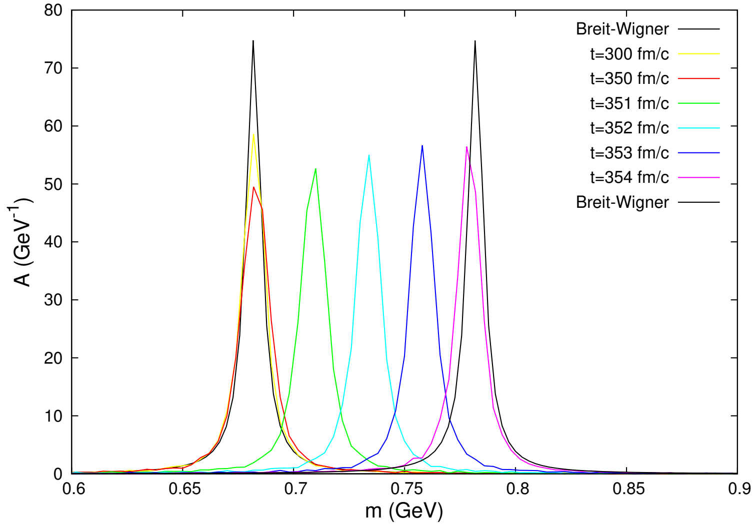
  $$C_{(i)} = \frac{1}{2\epsilon_i} \left[\frac{\partial}{\partial \epsilon_i} Re\Sigma^{ret}_{(i)} + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{Im\Sigma^{ret}_{(i)}} \frac{\partial}{\partial \epsilon_i} Im\Sigma^{ret}_{(i)} \right]$$

- the last equation for homogenous system can be rewritten as

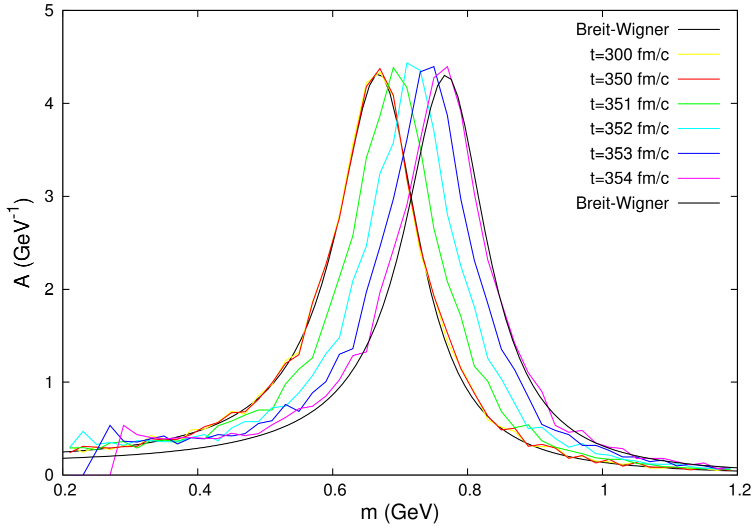
  $$\frac{dM_i^2}{dt} = \frac{d(\epsilon_i^2 - P_i^2)}{dt} = \frac{dRe\Sigma^{ret}_{(i)}}{dt} + \frac{M_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{Im\Sigma^{ret}_{(i)}} \frac{dIm\Sigma^{ret}_{(i)}}{dt}$$

Evolution of mass distribution in a box

the vector meson masses are shifted linearly with density, and change the density linearly from ρ_0 to 0 in 4 fm/c:



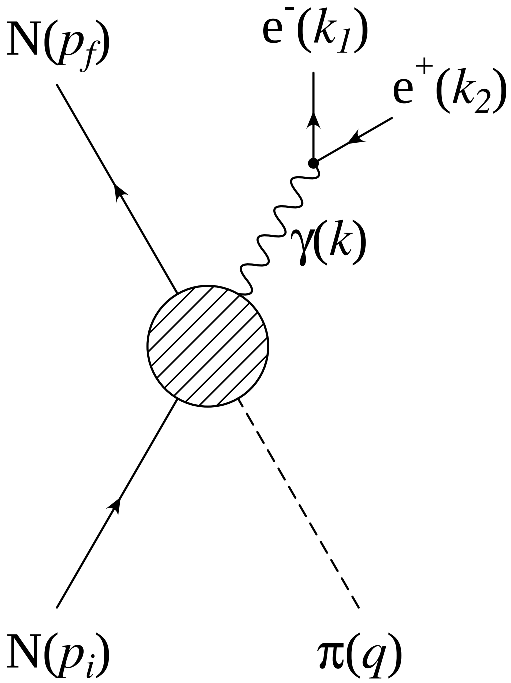
ω



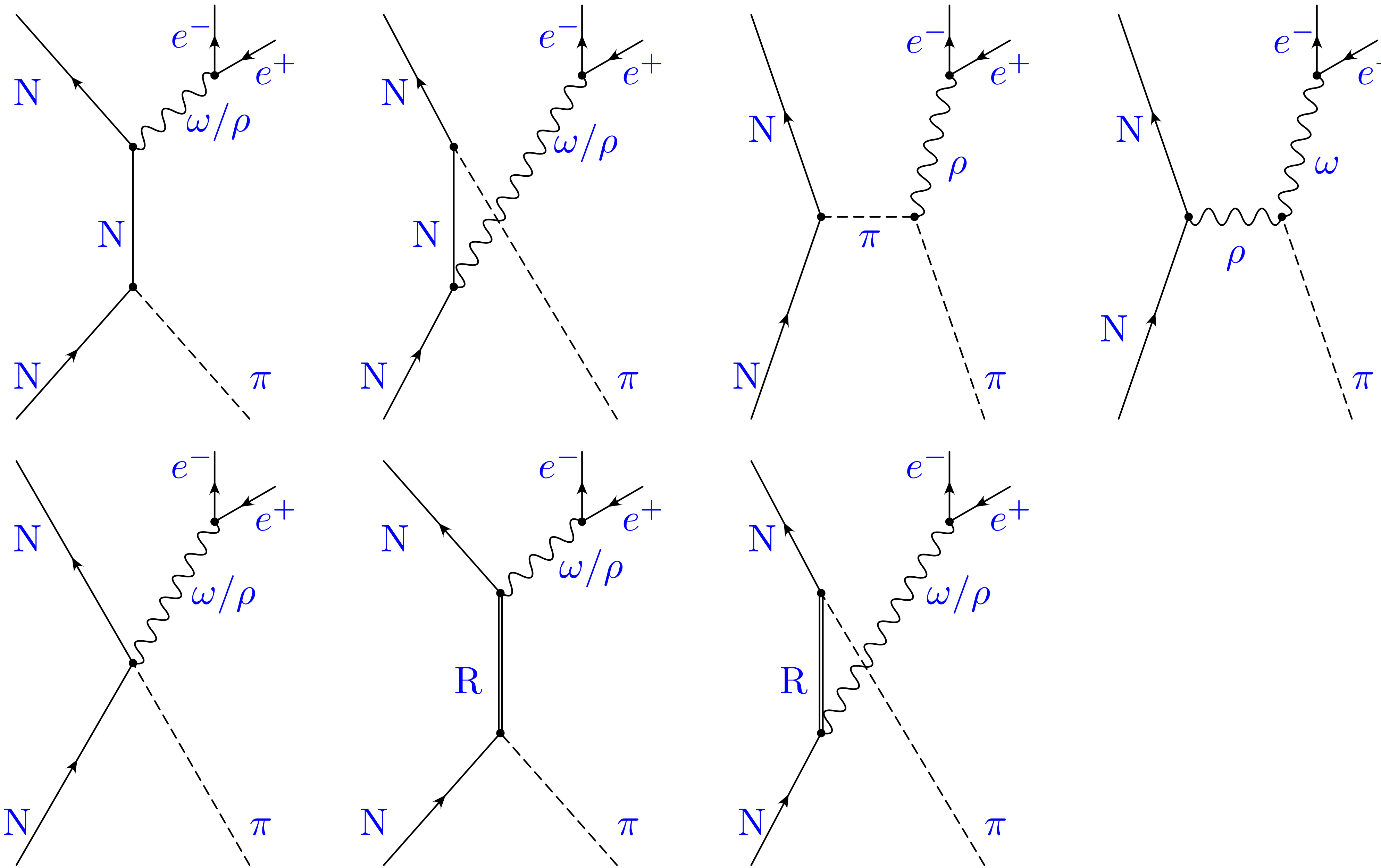
ρ

$\pi + N \to N + e^+e^-$

- Coupled-channel approaches
  K-matrix: Post-Mosel
  Bethe-Salpeter: Lutz-Wolf-Friman
- Effective field theory:
  Zétényi, Wolf,
  Phys. Rev. C86 (2012) 065209



Feynman diagrams for $\pi + N \rightarrow N + e^{+}e^{-}$



Effective Field Theory for $\pi + N \to N + e^+e^-$

$$\mathcal{L}_{\mathcal{NN}\pi} = -\frac{\mathrm{f}_{\mathrm{NN}\pi}}{\mathrm{m}_\pi}\overline{\psi}_{\mathcal{N}}\gamma_5\gamma^\mu\vec{\tau}\psi_{\mathcal{N}}\cdot\partial_\mu\vec{\pi}.$$

$$\mathcal{L}_{\omega\rho\pi} = \frac{\mathrm{g}_{\omega\rho\pi}}{2}\epsilon^{\mu\nu\alpha\beta}\partial_\mu\omega_\nu\,\mathrm{Tr}\left((\partial_\alpha\vec{\rho_\beta}\cdot\vec{\tau})(\vec{\pi}\cdot\vec{\tau})\right)$$

$$\mathcal{L}_{\mathcal{NN}\rho} = \mathrm{g}_\rho\overline{\psi}_{\mathrm{N}}\left(\vec{\not{\rho}} - \kappa_\rho\frac{\sigma_{\mu\nu}}{4\mathrm{m}_{\mathrm{N}}}\vec{\rho}^{\mu\nu}\right)\cdot\vec{\tau}\psi_{\mathrm{N}}, \quad \mathcal{L}_{\mathcal{NN}\omega} = \mathrm{g}_\omega\overline{\psi}_{\mathrm{N}}\left(\not{\omega} - \kappa_\omega\frac{\sigma_{\mu\nu}}{4\mathrm{m}_{\mathrm{N}}}\omega^{\mu\nu}\right)\psi_{\mathrm{N}}.$$

ρ_0 couples to $\bar{\psi}_N\tau_0\psi_N$ so to p and to n with different signs, while ω with the same sign

Considering $\pi^- p \to ne^+e^-$ and $\pi^+ n \to pe^+e^-$ in one channel constructive and in the other channel destructive interference

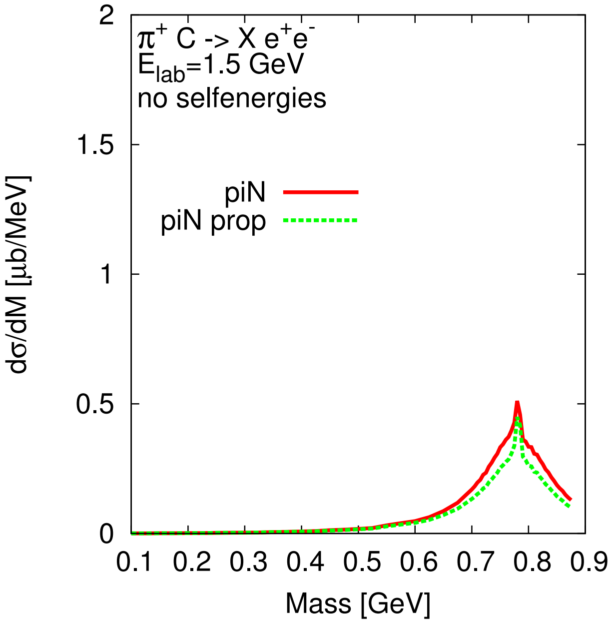
Dileptons in pion-nucleus collisions

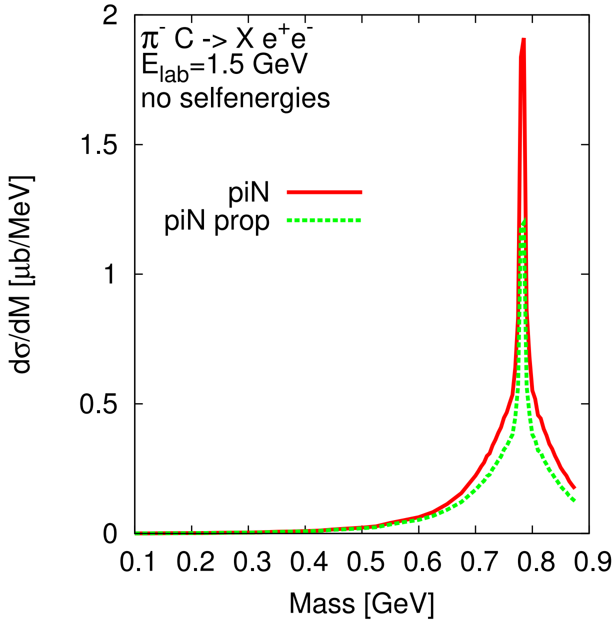
- $\dfrac{\frac{d\sigma}{dM}^{\pi^- p \to n e^+ e^-}(m_\omega)}{\frac{d\sigma}{dM}^{\pi^+ n \to p e^+ e^-}(m_\omega)} \approx 4$ because of the interference
- The effect is strong if cross secton through ρ and ω are similar
- coupling constants of ω were taken from the literature, we plan to make our fit
- The same problem was studied in M.F.M. Lutz, B. Friman, M. Soyeur, Nucl. Phys. A713 (2003) 97 and A.I. Titov, B Kämpfer, EPJ A 12 (2001) 217. They had smaller ρ cross section, so the effect was strong at lower $\sqrt{s}$
- How much of this coherence survive in a nucleus?
- In a nucleus coherence is lost if one of the vector meson collides
- Quantum measurement: collisional broadening for those ω's which will interfere with a ρ?

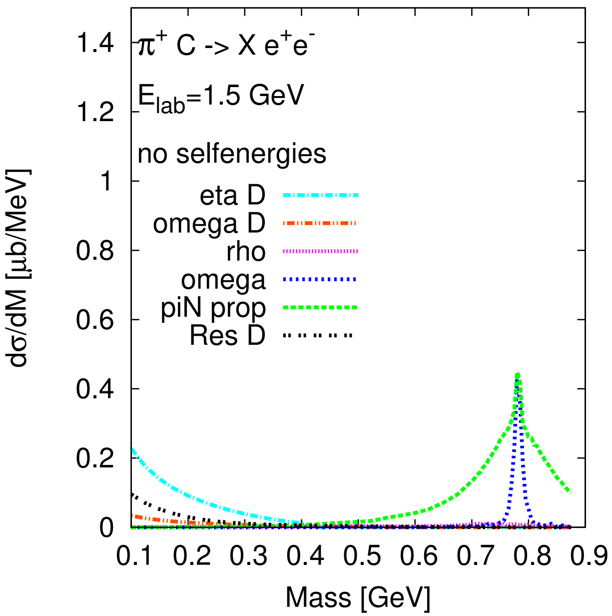
Simulation of π A collisions

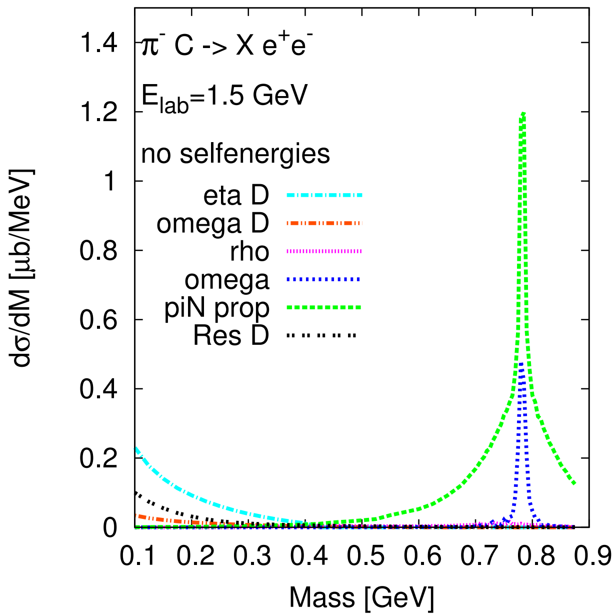
- Same as usually except for $\pi N \to N e^+ e^-$
- in case of a πN collision several "doublets" are created.
  (The original π and N do not change their state.)
  A doublet consists of 2 perturbative particles ρ and ω with their cross sections and the "cross section" of the interference term. ρ and ω are created with the same position, momentum and mass.
- They propagate, decay and can be absorbed. The interference term contribute only if none of them collide or is absorbed.
- Propagation: perturbative ρ's and ω's propagate in the surounding medium
- Absorption: ρ's and ω's can be absorbed by a nucleon

π C, 1.5 GeV, no selfenergies, Preliminary results

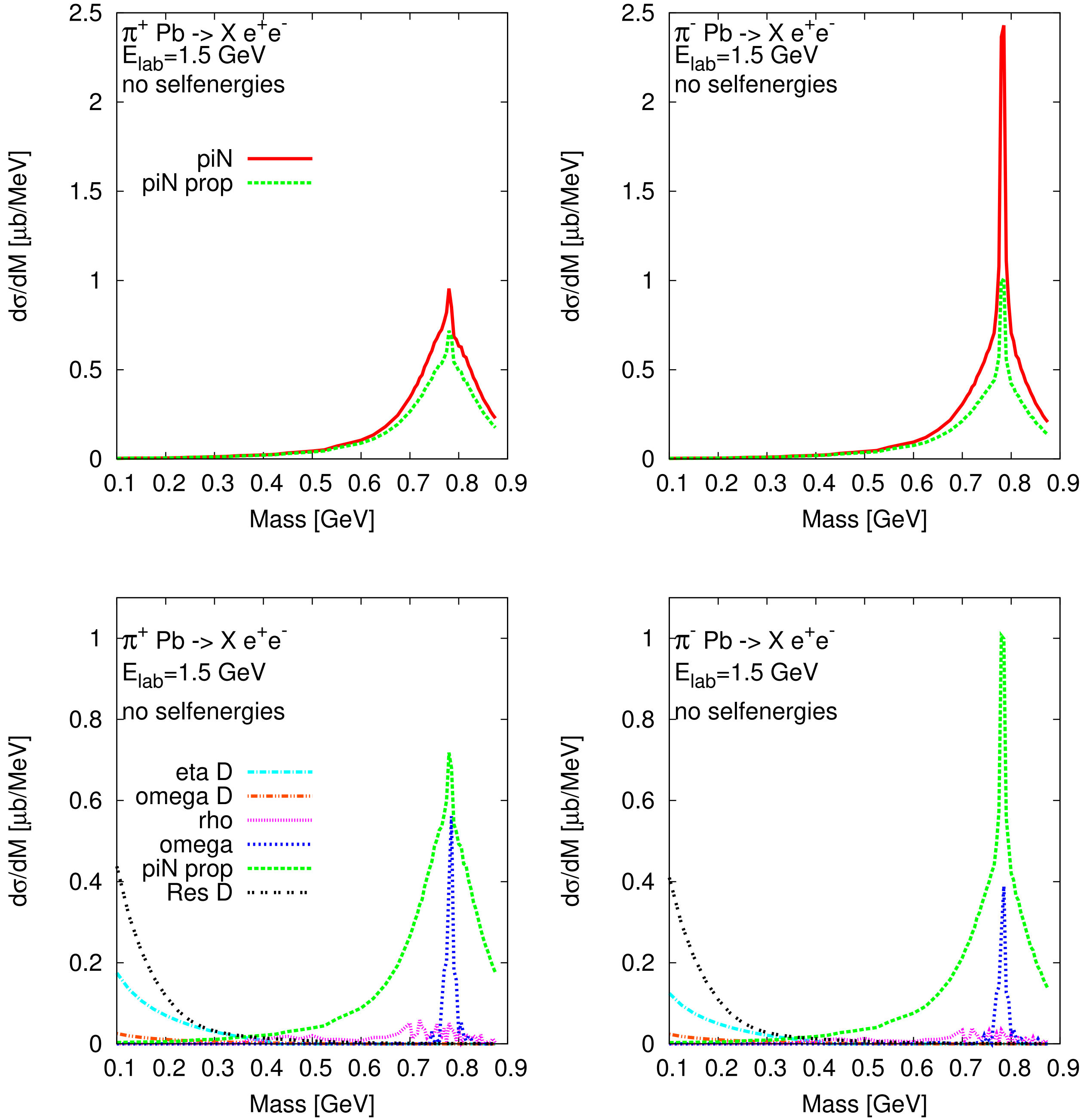








π Pb, 1.5 GeV, no selfenergies, Preliminary results



Dileptons in pion-nucleus collisions

- $$\frac{\frac{d\sigma}{dM}^{\pi^- p \to n e^+ e^-}(m_\omega)}{\frac{d\sigma}{dM}^{\pi^+ n \to p e^+ e^-}(m_\omega)} \approx 4$$
  $$\frac{\frac{d\sigma}{dM}^{\pi^- C^{12} \to X e^+ e^-}(m_\omega)}{\frac{d\sigma}{dM}^{\pi^+ C^{12} \to X e^+ e^-}(m_\omega)} \approx 2.9$$
  $$\frac{\frac{d\sigma}{dM}^{\pi^- Pb^{207} \to X e^+ e^-}(m_\omega)/N_p}{\frac{d\sigma}{dM}^{\pi^+ Pb^{207} \to X e^+ e^-}(m_\omega)/N_n} \approx 2.0$$

  In case of complete decoherence these ratios should be 1.

- Experimentally the decoherence can be observed in strongly interacting matter.

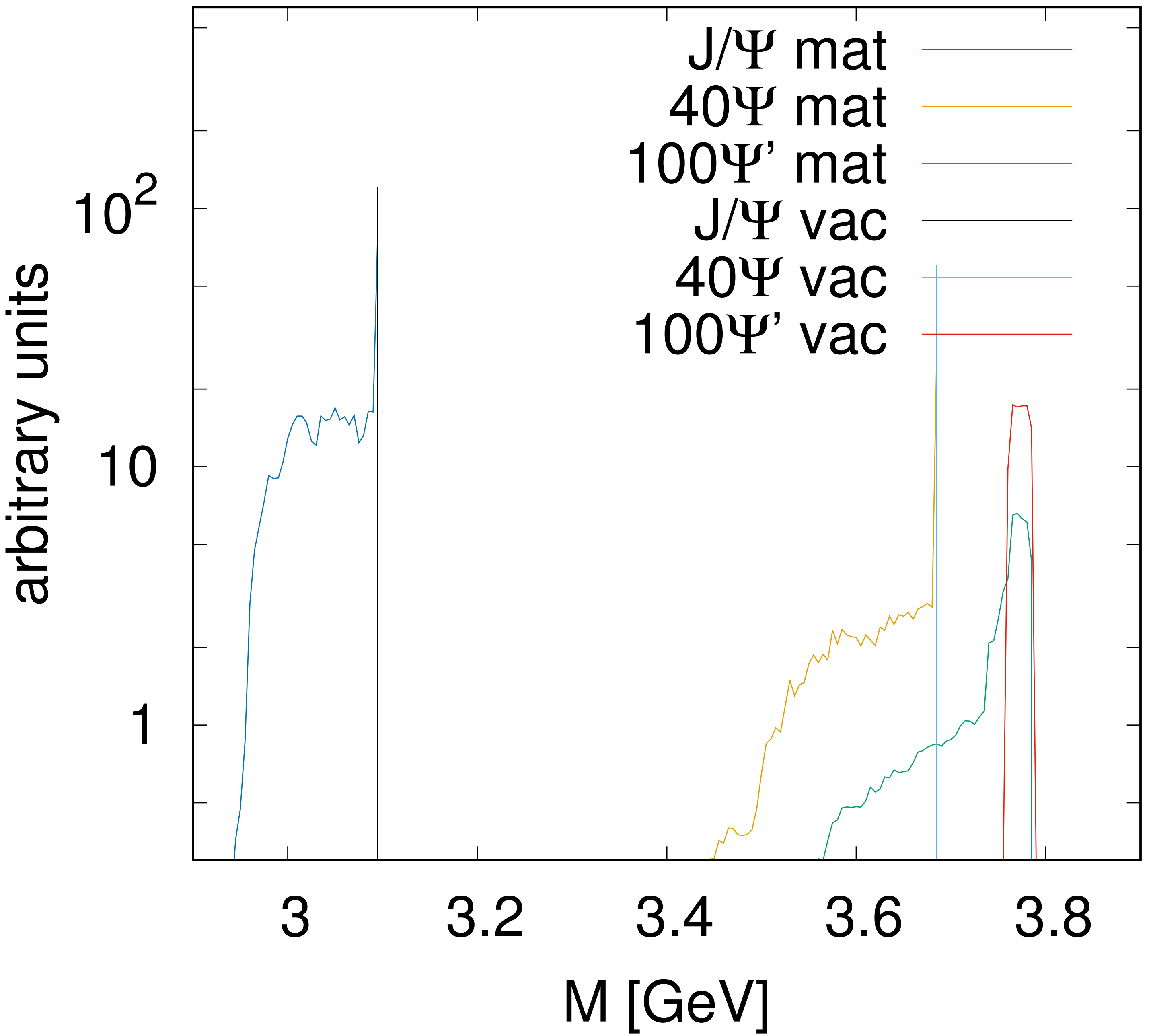
- Is an interference with its pair a measurement? Collisional broadening?

$\bar{p}$A at PANDA energies

- J/Ψ, Ψ(3686), Ψ(3770)
- mass and width linearly depend on density:
  S.H. Lee, nucl-th/0310080
  at normal nuclear density:

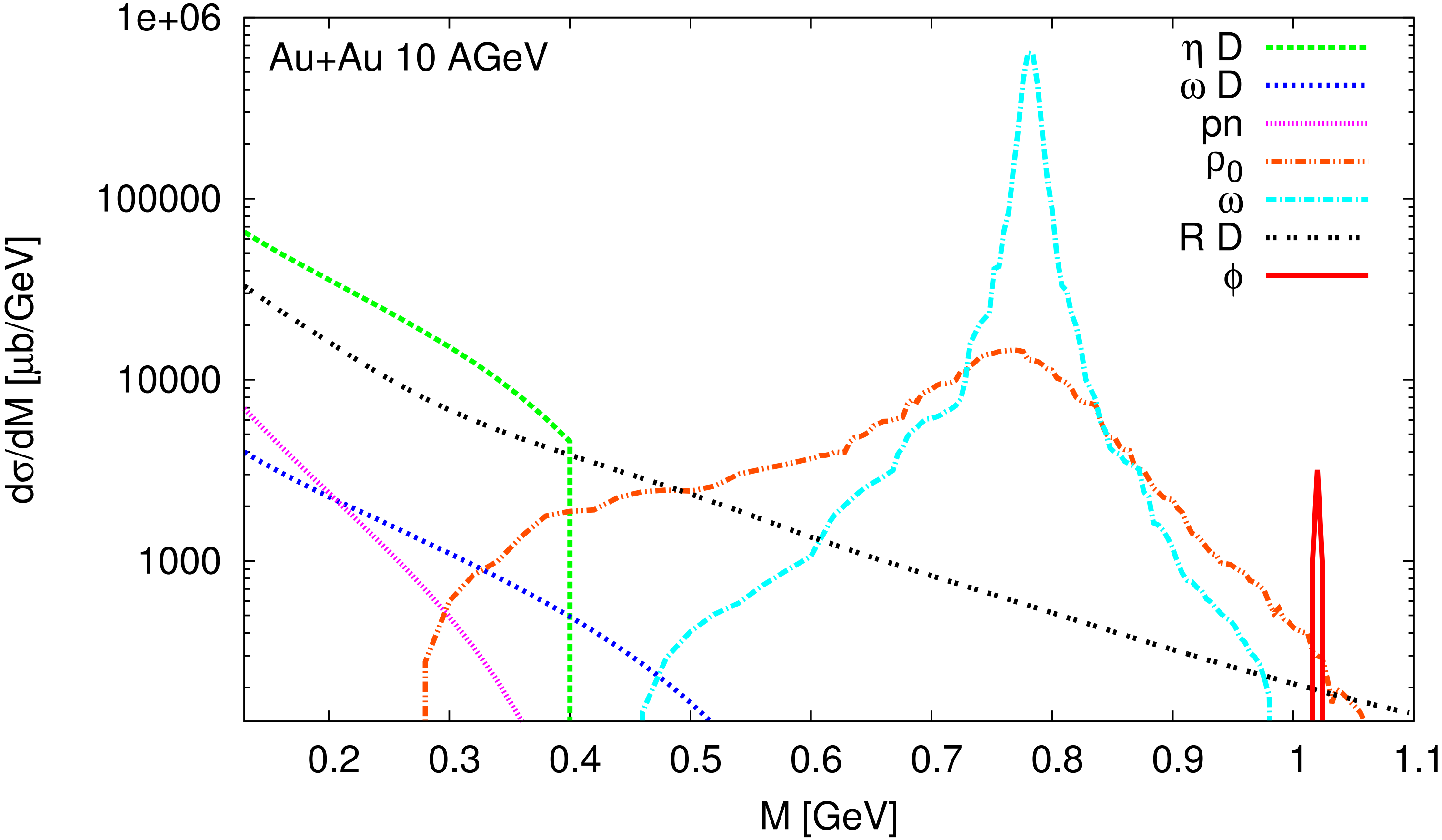
Charmonium	Mass shift	width
J/Ψ	-15 MeV	Γ_0+20 MeV
Ψ(3686)	-100 MeV	Γ_0+20 MeV
Ψ(3770)	-140 MeV	Γ_0+20 MeV

$\bar{p}$Au at 10 GeV/c (preliminary)



Background is missing

Au+Au at 10 AGeV/c (CBM, NICA)



No in-medium effects

Summary

- Dilepton production in πN and πA an unique way to study quantum interference inside strongly interacting matter by measuring on nucleon, on light and on heavy nuclei.
- Dilepton production in $\bar{p}$A provides us the possibility to study charmonium spectral function in matter.
- Calculation of the background is missing
- special kinematics can enhance the effect

Dilepton production in Heavy ion Collisions

Sources of low mass dileptons

- $NN \to \ldots \to NNe^+e^-$ (measurable)
- vector meson decay (can be created also in $\pi^+\pi^-$ annihilation)
- other secondaries (πN, or NΔ(NR)$\to$ NNe^+e^-)

Strategy 1: put the measured $NN \to NNe^+e^-$, $\rho(\omega.\phi) \to e^+e^-$ and the estimated cross secton for the secondaries to a transport and obtain the HIC result.

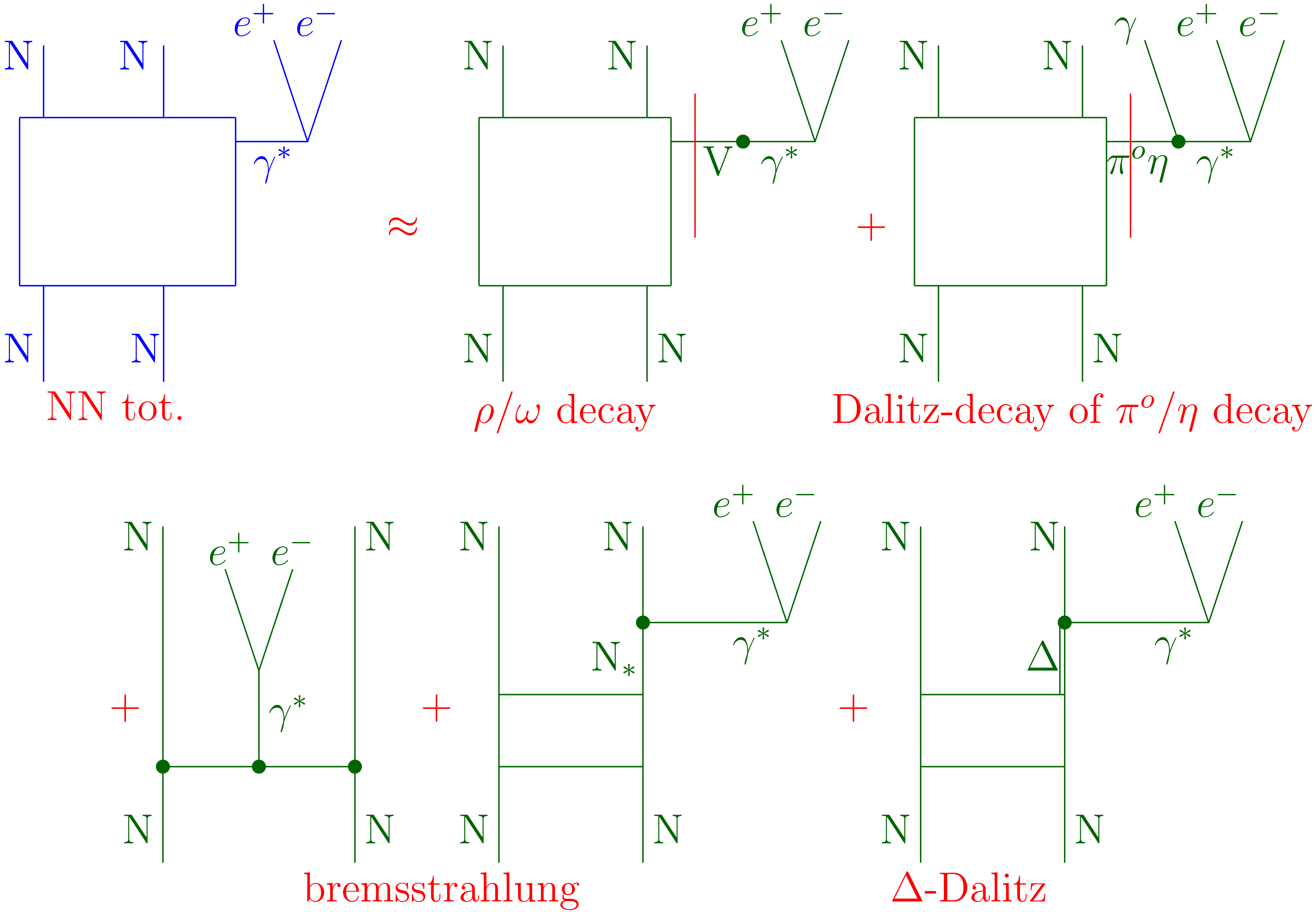
Problem:

Hunted in-medium effects are buried in the $NN \to NNe^+e^-$ cross section and in the properties of the vector mesons.

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

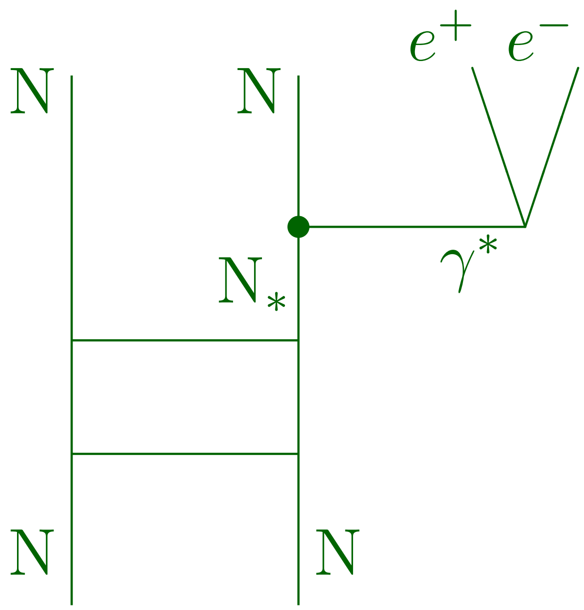
Dilepton Channels in NN



Bremsstrahlung calculations

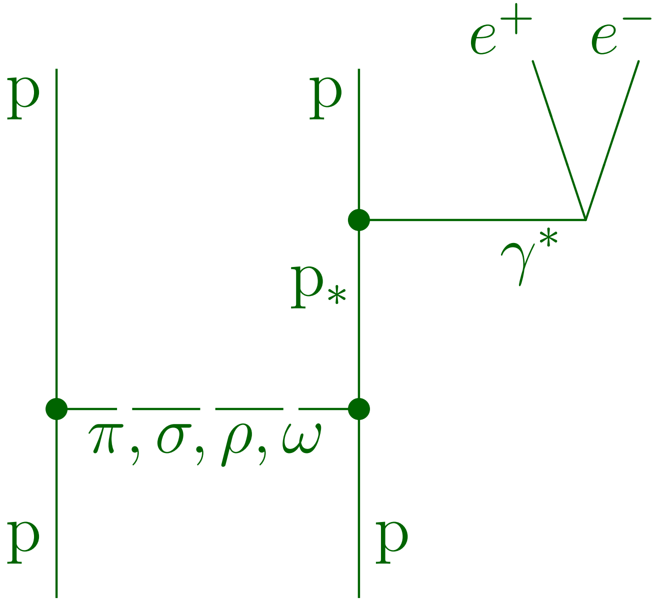
Soft photon approximation

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

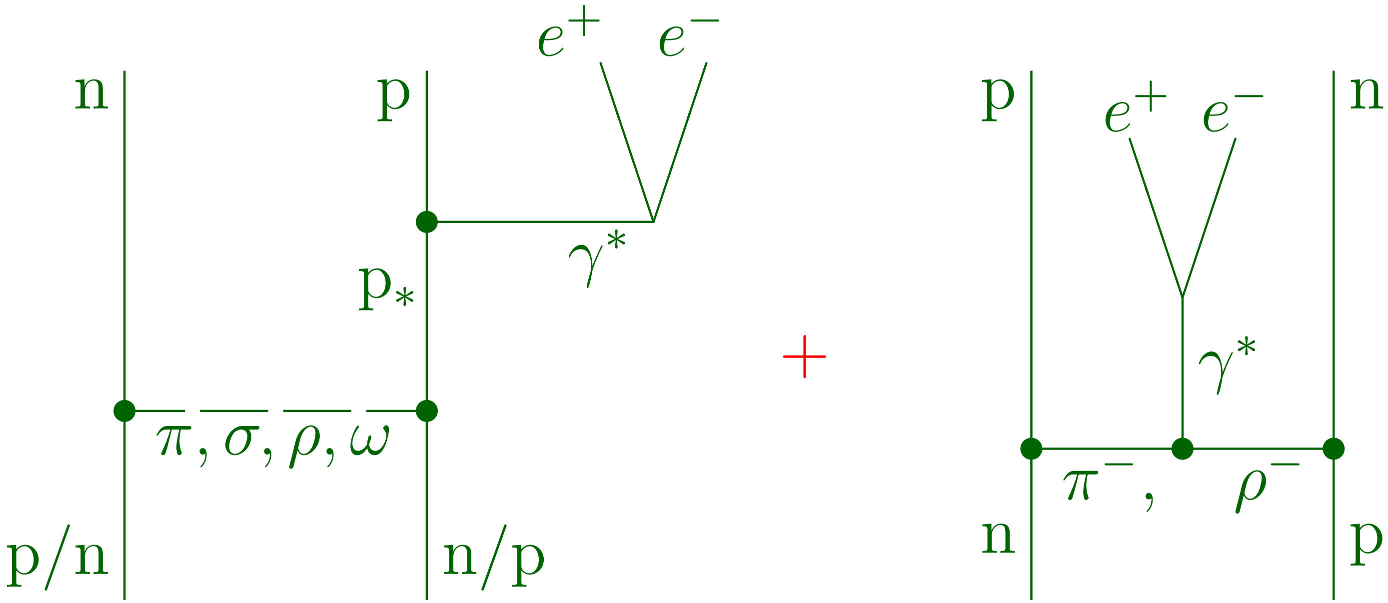


T-matrix calculations

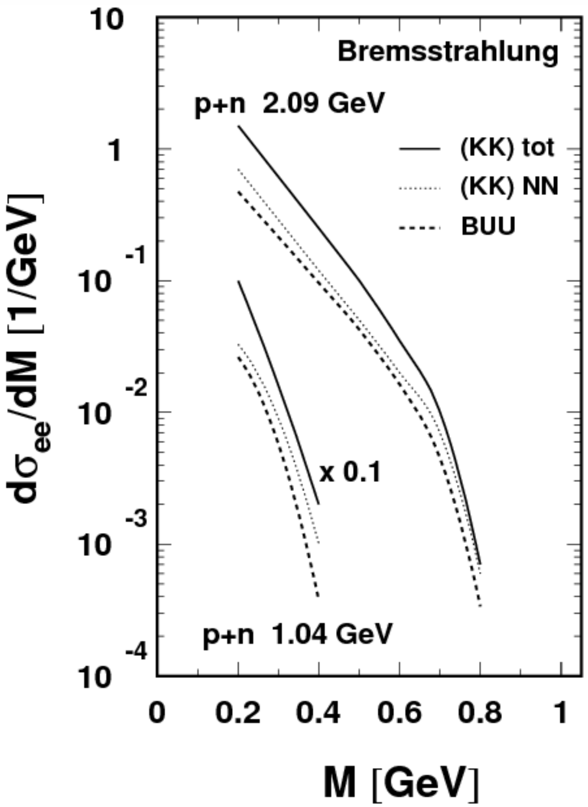
pp:



pn:



- L.P. Kaptari, B. Kämpfer, Nucl. Phys. A **764** (2006) 338.
- R (2009) 035203



Dalitz-decay of baryon resonances

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

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

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

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

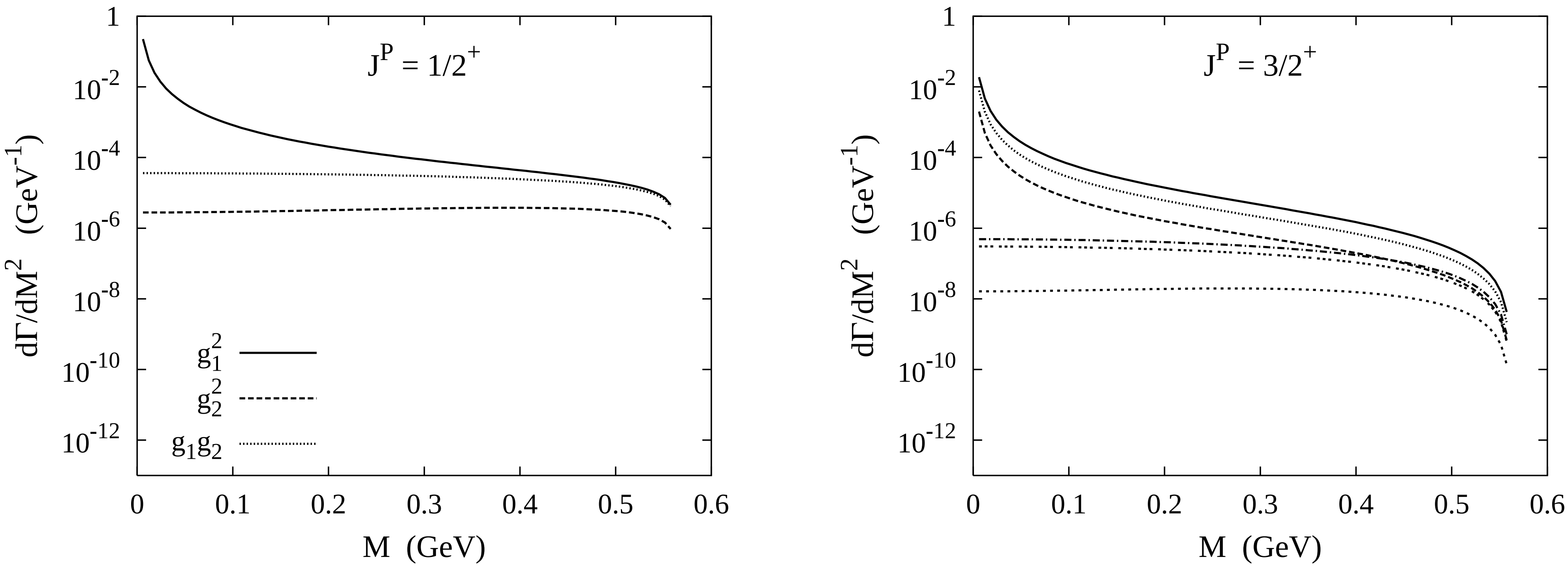
with

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

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

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

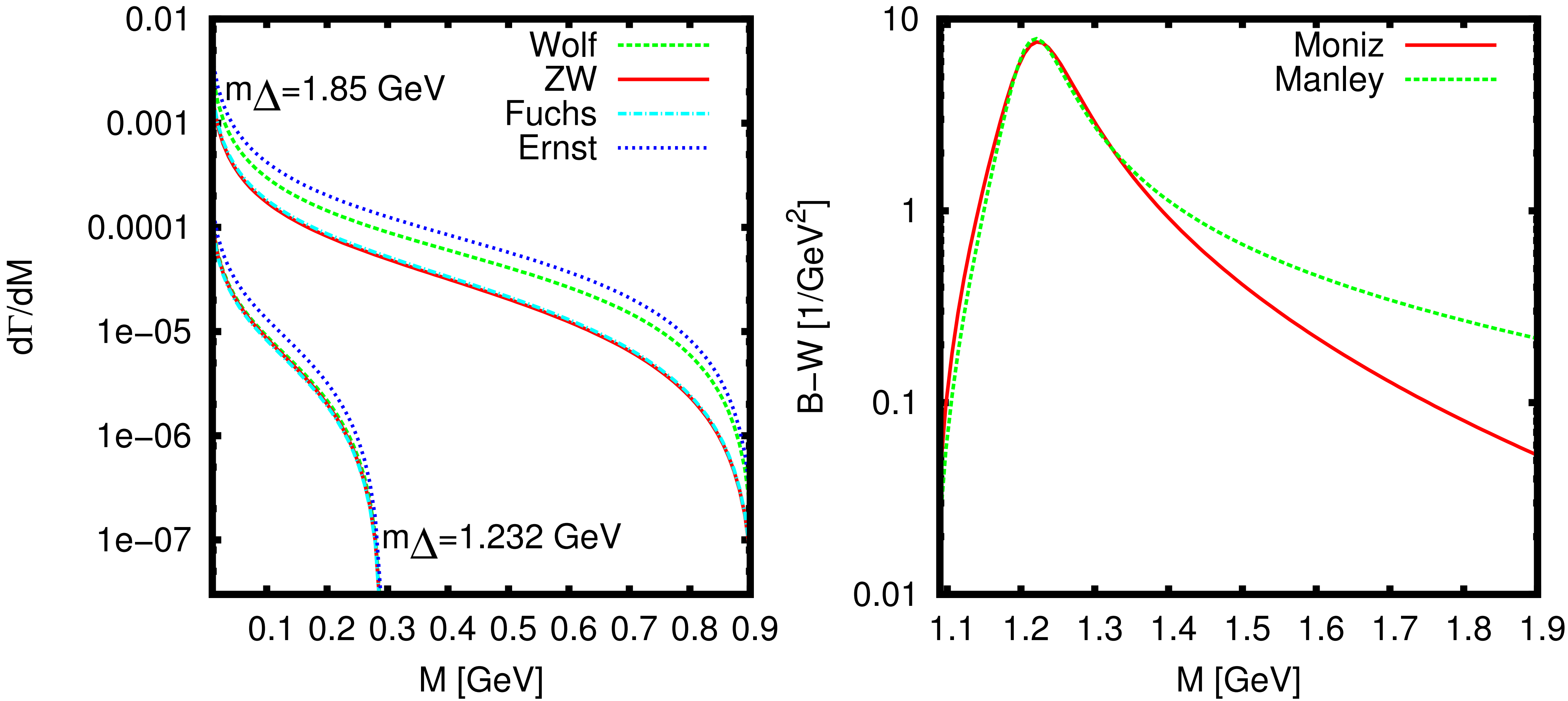
Dalitz-decay contributions



$m_* = 1.5$ GeV. 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 already negligible.

Summary of elementary dilepton production

- There is no good bremsstrahlung calculation (describes pp end pn at the same time).
- Delta-Dalitz decay contribution is very uncertain, too
- Complete NN$\rightarrow$ NNe^+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

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

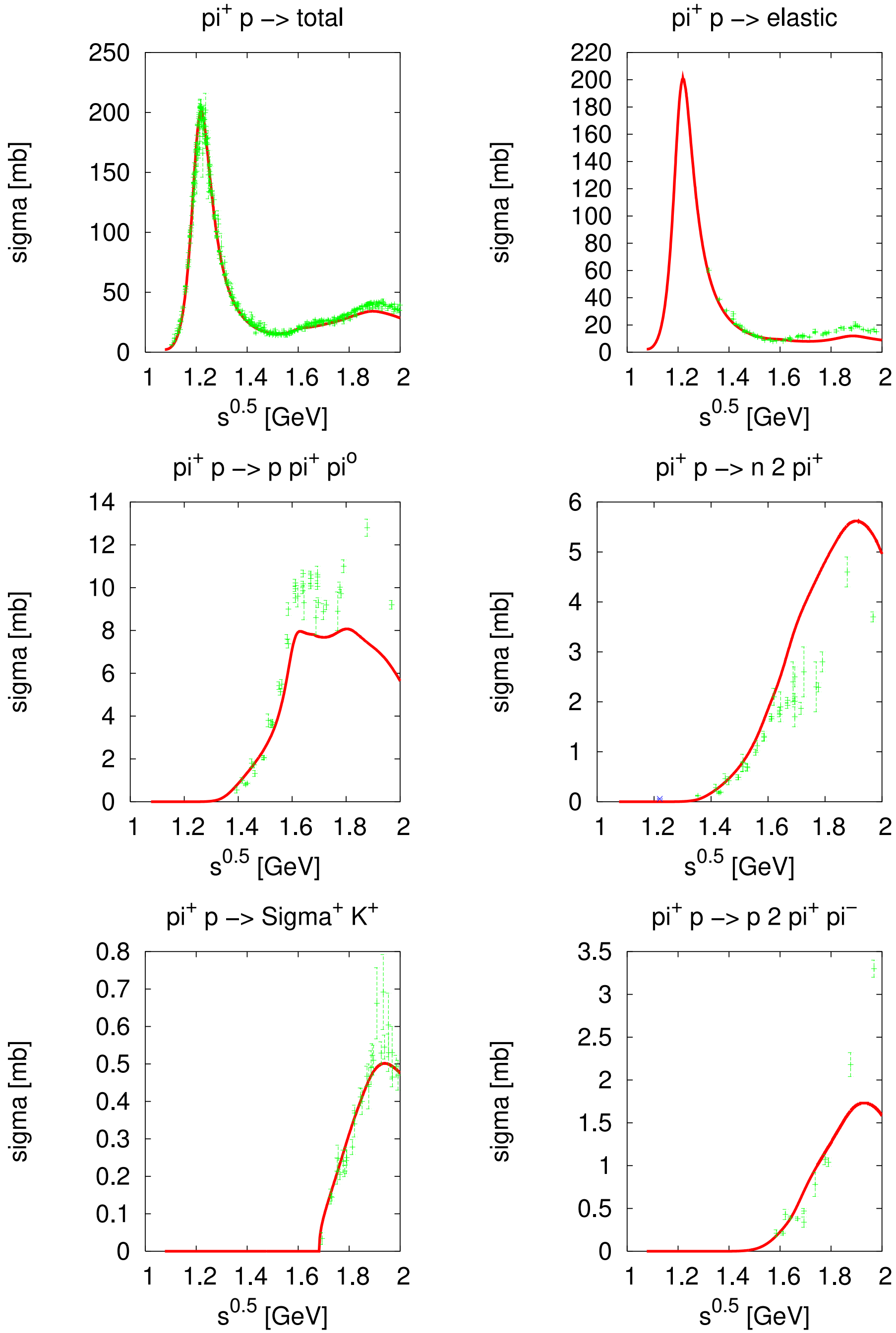
Baryon resonance parameters: mass, width, branching ratios are fitted by describing the meson production channels in πN collisions:

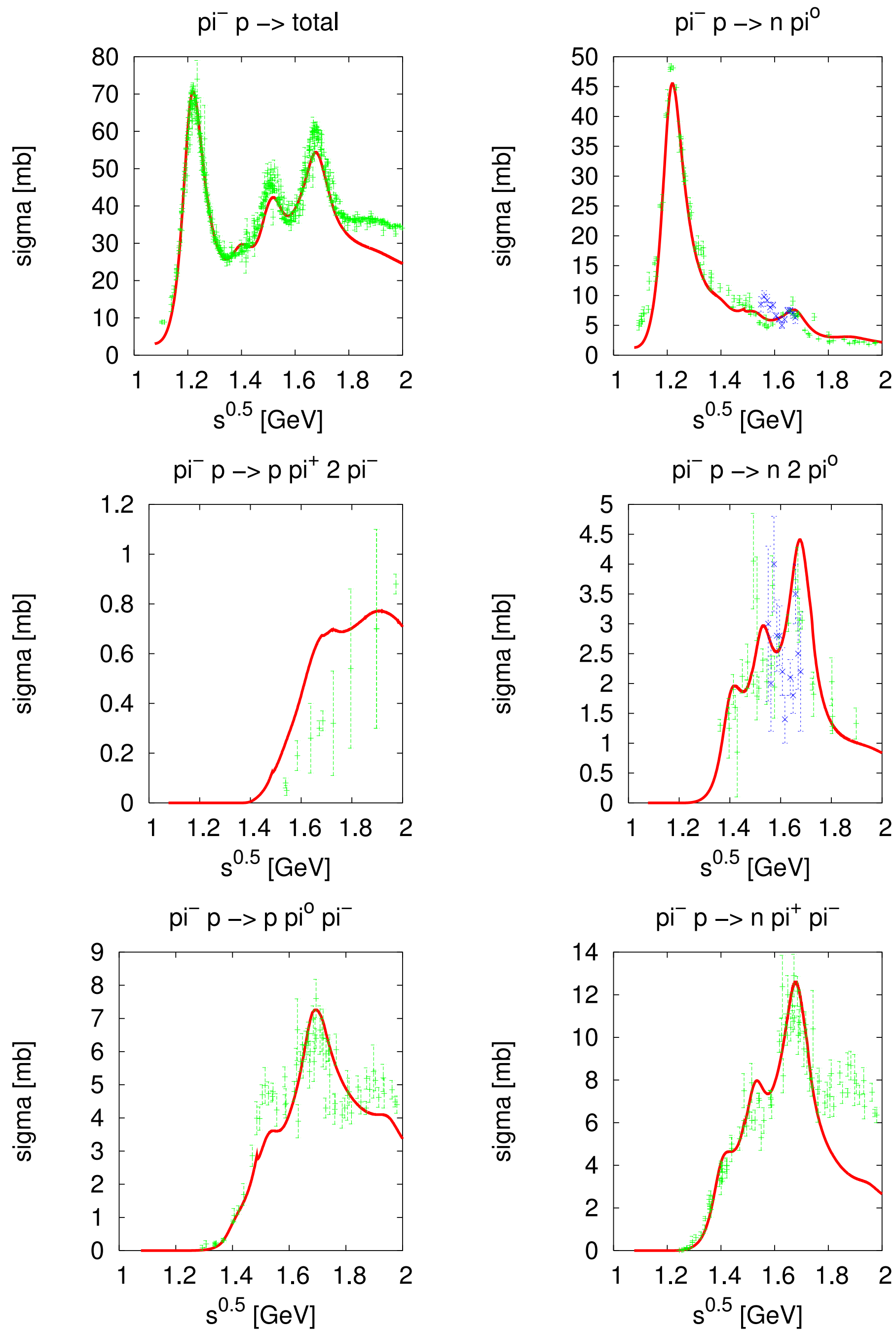
$$\sigma_{\pi N \to NM} = \sum_R \sigma_{\pi N \to R}\frac{\Gamma_{R \to NM}}{\Gamma_{tot}}$$

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

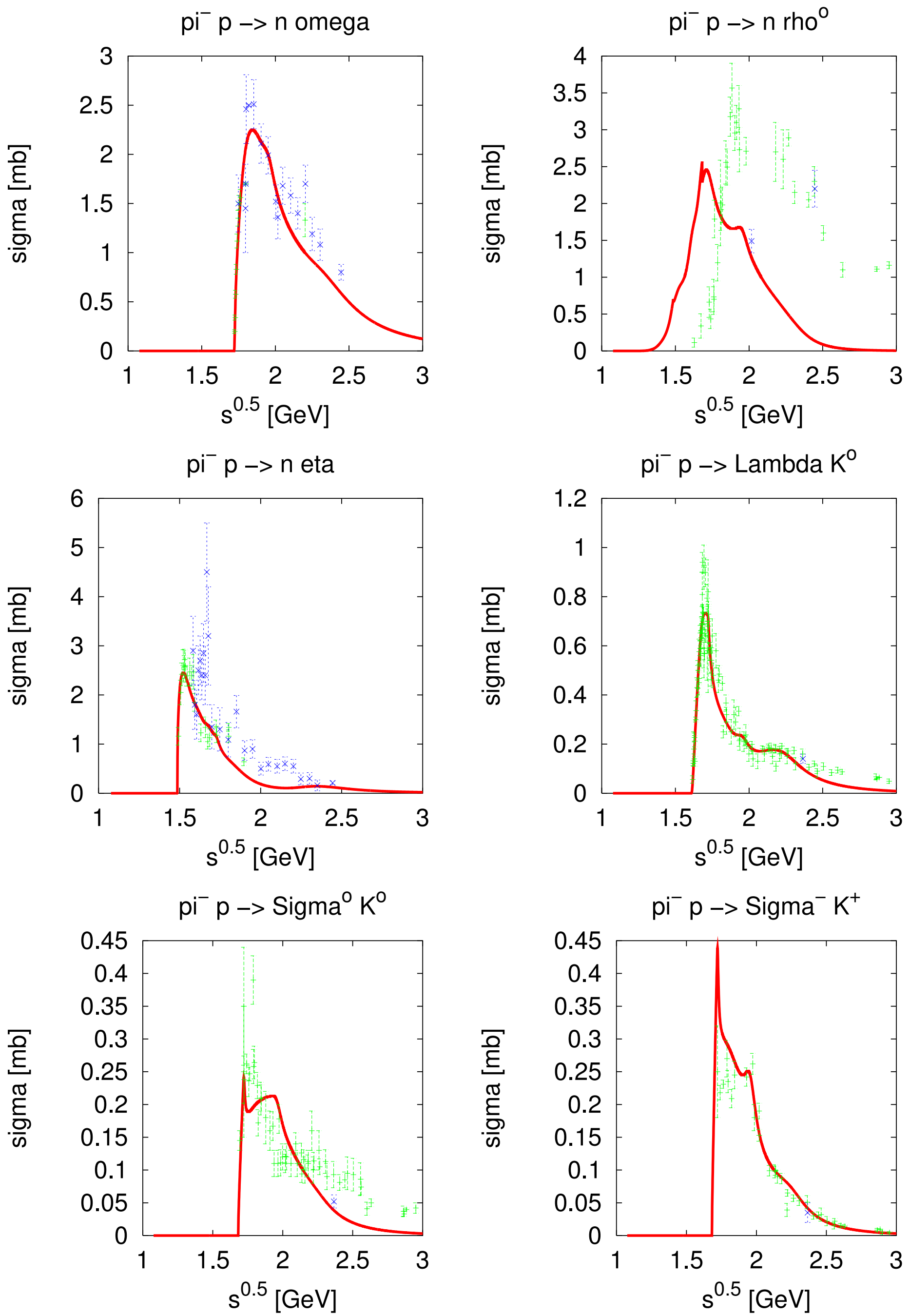
$$\sigma_{NN \to NM} = \sum_R \sigma_{NN \to NR}\frac{\Gamma_{R \to NM}}{\Gamma_{tot}}$$

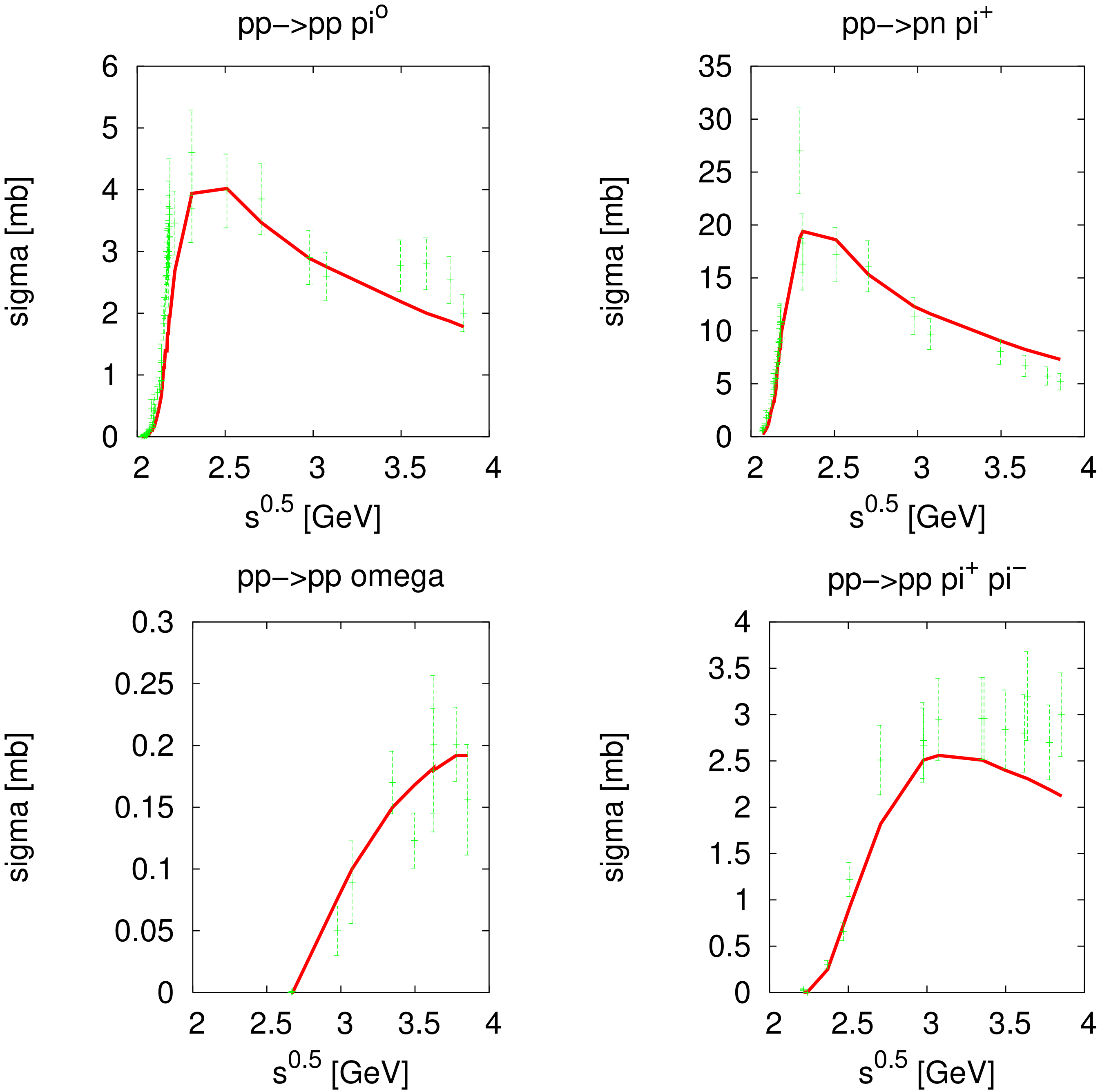
27 baryons, 6 mesons. Fit is done by the Minuit package (CERN)


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^o
pi⁻ p -> p pi⁺ 2 pi⁻
pi⁻ p -> n 2 pi^o
pi⁻ p -> p pi^o pi⁻
pi⁻ p -> n pi⁺ pi⁻
sigma [mb]
s^0.5 [GeV]


pi⁻ p -> n omega
pi⁻ p -> n rho°
pi⁻ p -> n eta
pi⁻ p -> Lambda K°
pi⁻ p -> Sigma° K°
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]

Kadanoff-Baym Equation

Schwinger-Dyson equation:

$$G = G_0 + G_0 \Sigma G$$

$$\begin{aligned}
G^{11}(1,2) &= G^T(1,2) = \langle T(\phi(1)\phi(2))\rangle \\
G^{22}(1,2) &= G^{AT}(1,2) = \langle \tilde{T}(\phi(1)\phi(2))\rangle \\
G^{21}(1,2) &= G^{<}(1,2) = \langle \phi(2)\phi(1)\rangle \\
G^{12}(1,2) &= G^{>}(1,2) = \langle \phi(1)\phi(2)\rangle \\
G^{r}(1,2) &= \theta(t1-t2)(G^{>}(x1,t1;x2,t2) - G^{<}(x1,t1;x2,t2)) \\
G^{a}(1,2) &= \theta(t2-t1)(G^{<}(x1,t1;x2,t2) - G^{>}(x1,t1;x2,t2))
\end{aligned}$$

After some manipulation: *Kadanoff-Baym equation*:

$$\begin{aligned}
(i\hbar\partial_{t1} - H_0(1))G^{<}(1,2) &= \int d3\,\Sigma^r(1,3)G^{<}(3,2) + \int d3\,\Sigma^{<}(1,3)G^{a}(3,2) \\
(i\hbar\partial_{t1} - H_0(1))G^{r}(1,2) &= \delta^4(1,2) + \int d3\,\Sigma^r(1,3)G^{r}(3,2)
\end{aligned}$$

Wigner-transformation

- Retarded propagator is not a distribution function
- Wigner transform:

$$r = x1 - x2 \qquad , \qquad R = x1 + x2$$

R (center of mass) dependence of propagators and selfenergies are weaker than the r dependence

$$G^r(R,P) = \int d^4r\, G^r(X+r, X-r)$$

- Gradient expansion in r. Neglect all terms with more than one derivative in R
- transport equation for $F_\alpha = iG^<(R,P) = f_\alpha(x,p,t)A_\alpha$

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

Cassing, Juchem (2000) and Leupold (2000)

- testparticle approximation