Extracting in-medium properties for vector mesons from dilepton spectra

Elvira Santini

D. Cozma, Amand Faessler, C. Fuchs, M.I. Krivoruchenko, B.V. Martemyanov

Eberhard Karls
Universität
Tübingen

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Historical overview and current status

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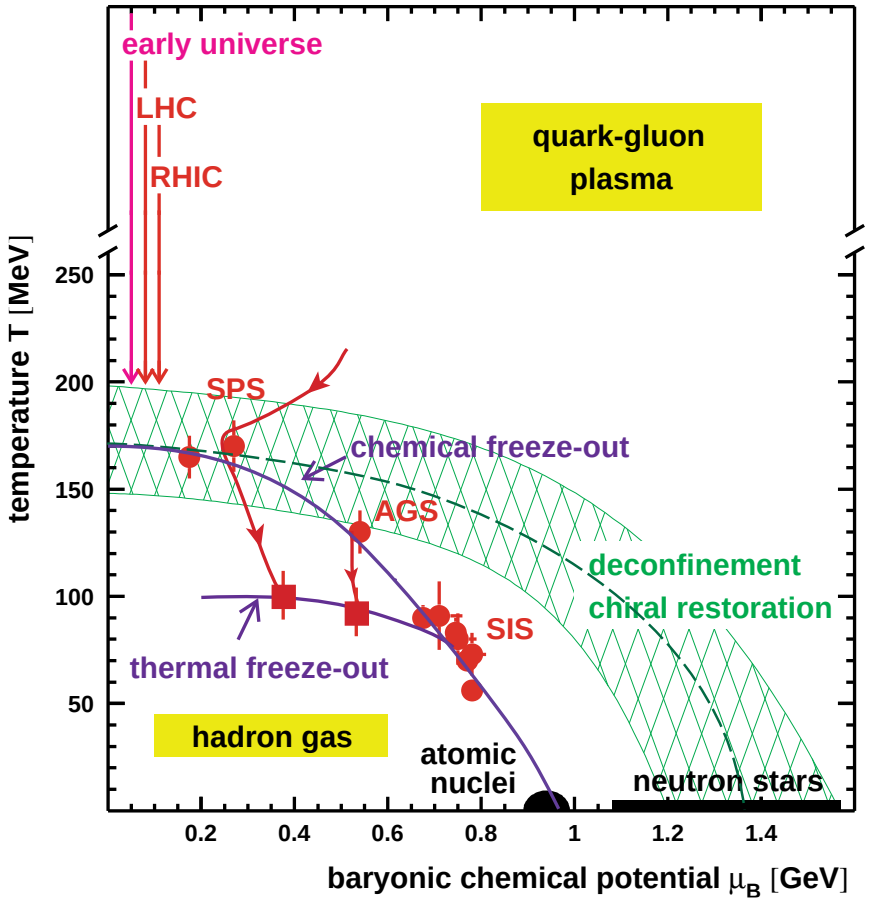
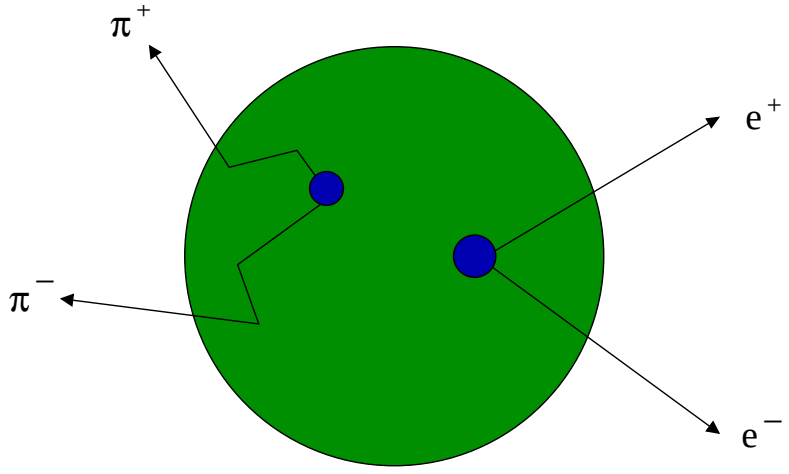
Theoretical description of e^+e^- production in HIC at 1-2 AGeV

- Summary

Why dileptons?





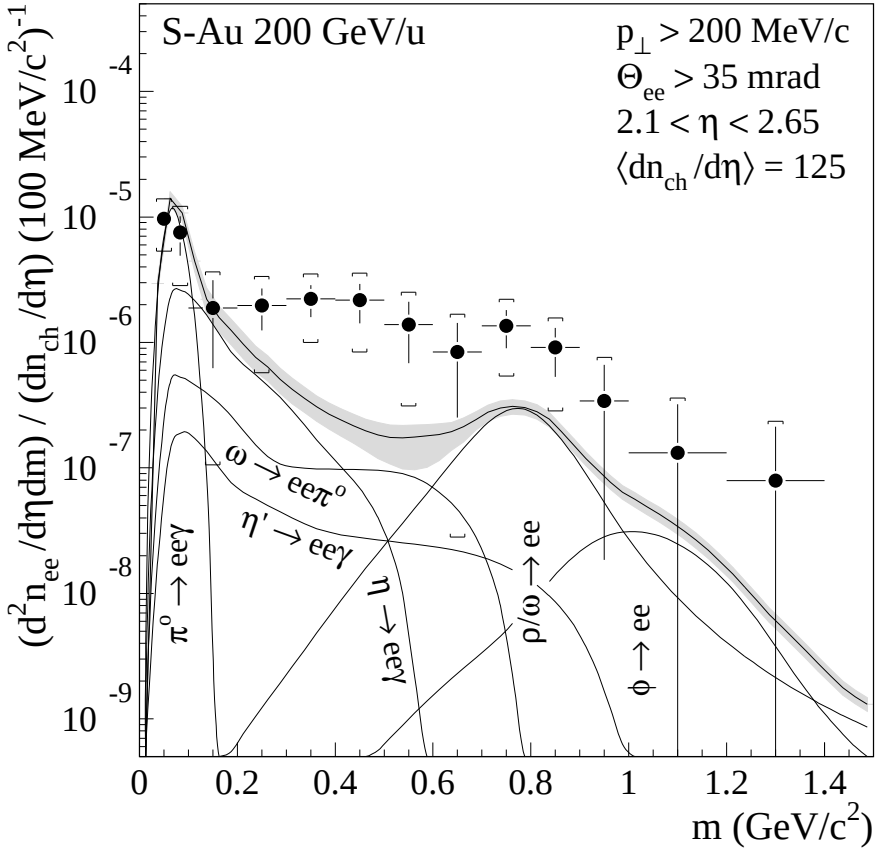
l^+l^- $\longrightarrow$ Tool to investigate medium effects on hadron properties

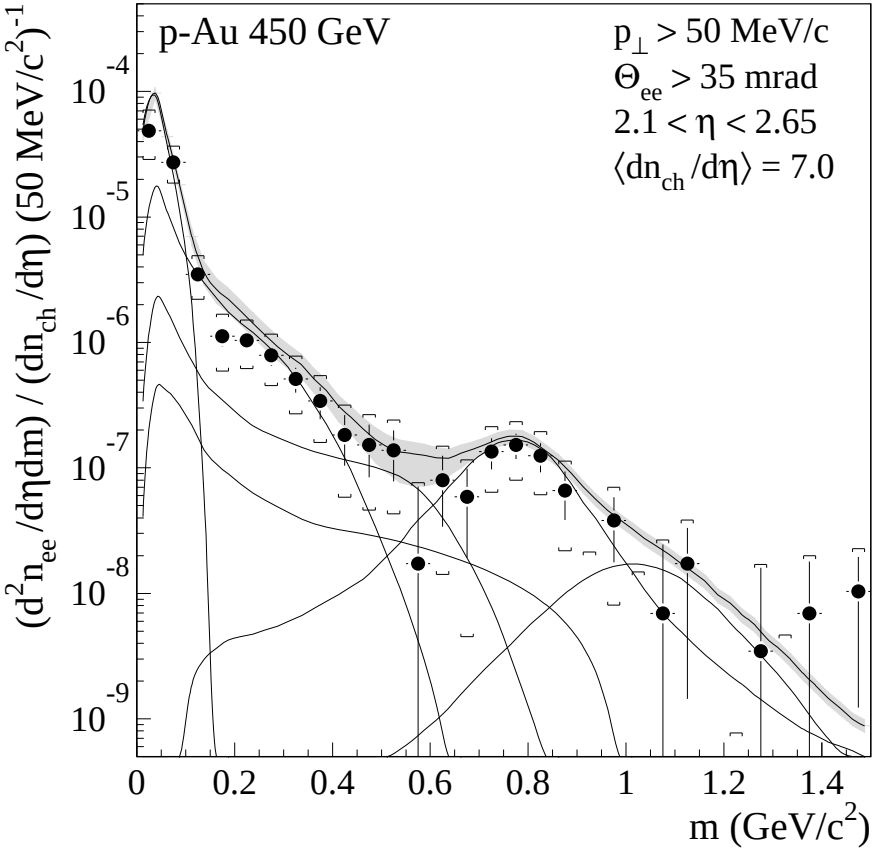
PART I

Dileptons and vector mesons:

Historical overview and current status

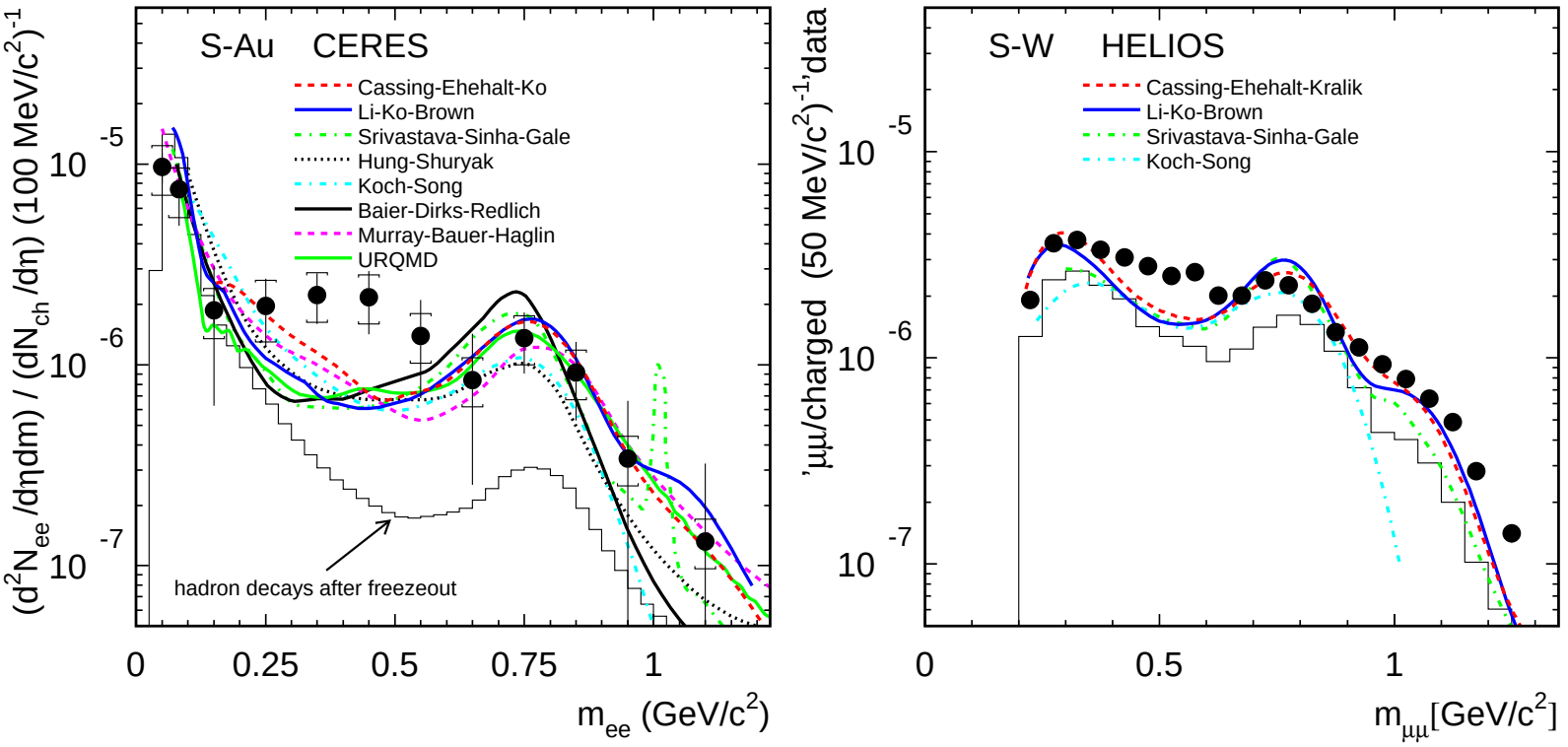
CERES Coll.@CERN [G.Agakichiev *et al.*, **PRL75**(1995)1272]





- HELIOS-3 Coll.: similar enhancement of low-mass dilepton over the cocktail [M.Masera *et al.*, **NPA590**(1995)93c]

Adding $\pi^+\pi^- \to l^+l^-$: **not enough** when using vacuum meson properties!



R.Rapp,J.Wambach, **ANP25**(2000)1 and references therein

$\Rightarrow$ One needs to consider $\boxed{\pi^+\pi^- \to \rho^* \to l^+l^-}$

In-medium scenarios

- 'dropping' mass scenario

Effective Lagrangian+mean field:

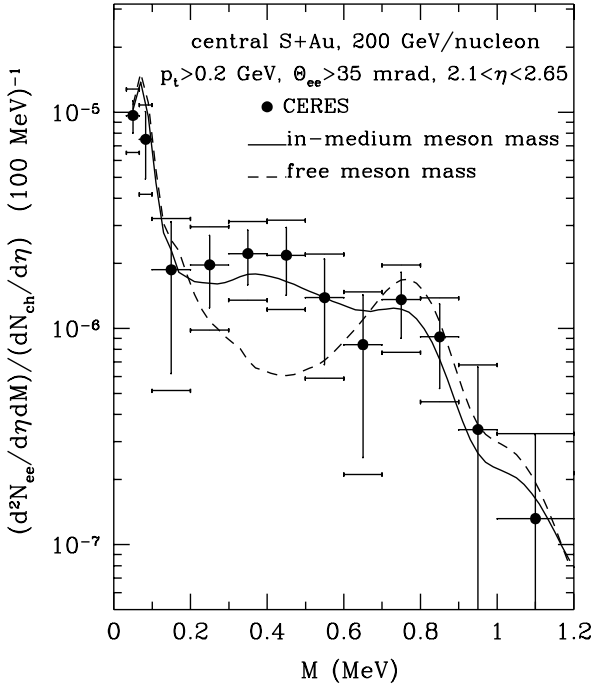
[Brown,Rho,**PRL66** (1991) 2720]

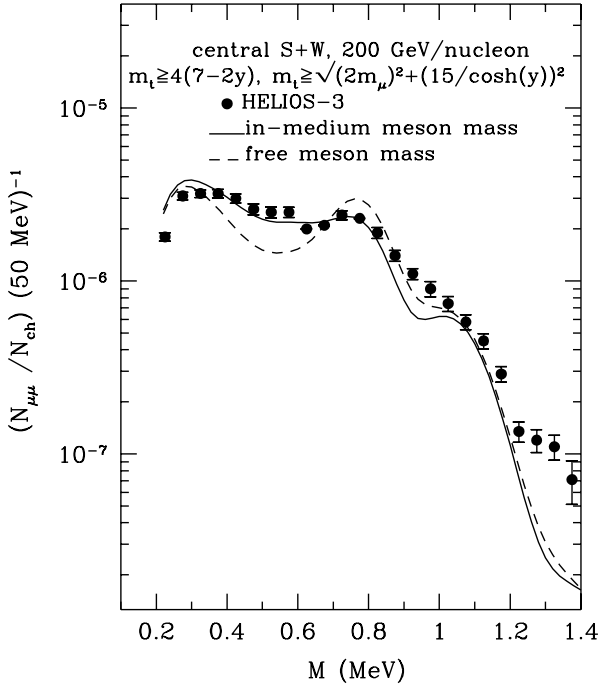
$$\frac{m_V^\star}{m_V} = \frac{m_N^\star}{m_N} = \frac{f_\pi^\star}{f_\pi} \sim 0.8 \text{ at } \rho_0$$

QCD sum rules:

[Hatsuda,Lee, **PRC46** (1992) R34]

$$\frac{m_V^\star}{m_V} = 1 - \alpha \frac{\rho_B}{\rho_0} \qquad \alpha \sim 0.16 \pm 0.06$$

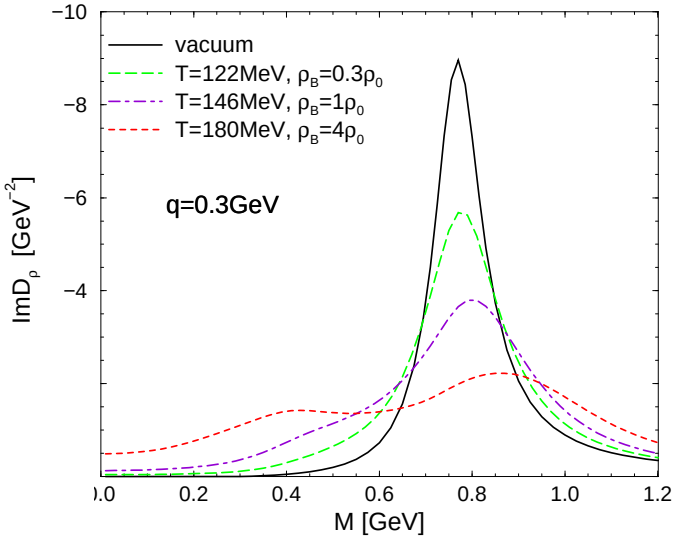


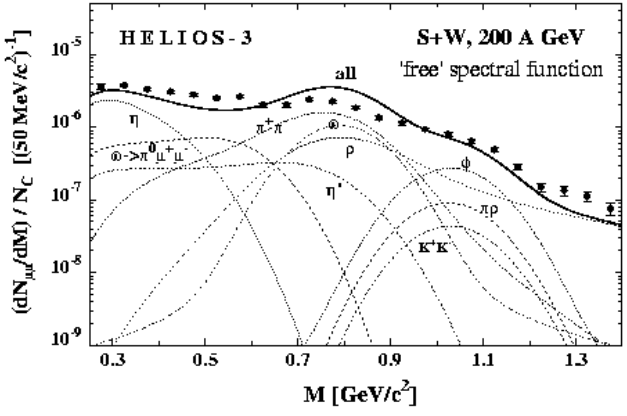


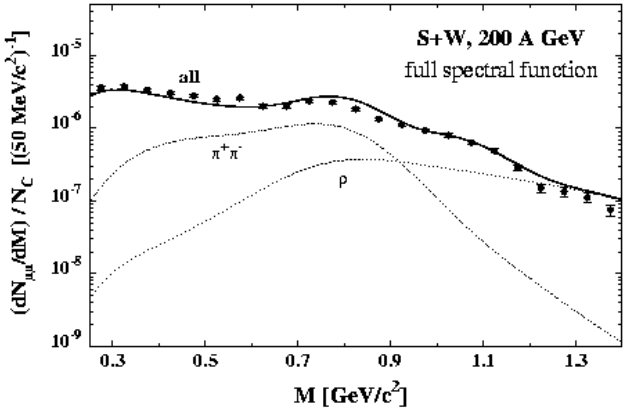
G.Q.Li,C.M.Ko,
G.E.Brown,H.Sorge,
NPA611 (1996) 539

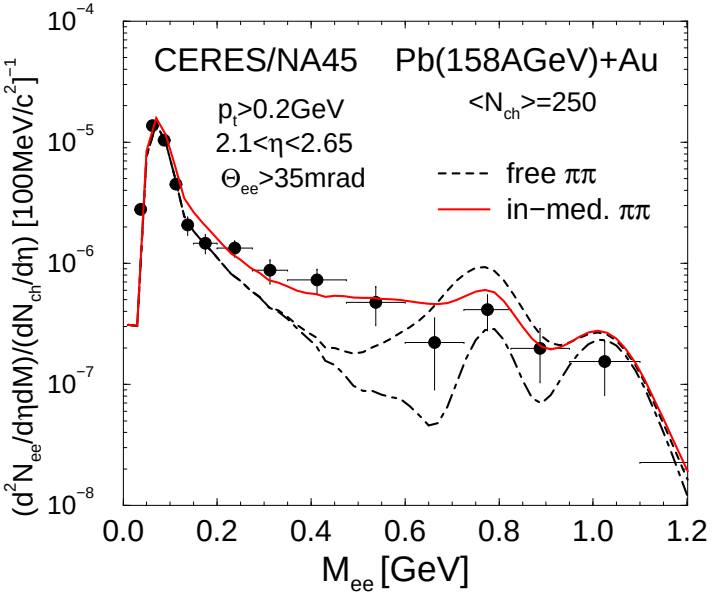
- ’complex’ spectral functions
  [R.Rapp,J.Wambach, **ANP25**(2000)1]

$$D_\rho^{L,T} = [M^2 - (m_\rho^{(0)})^2 - \Sigma_{\rho\pi\pi}^{L,T} - \Sigma_{\rho M}^{L,T} - \Sigma_{\rho B}^{L,T}]^{-1}$$









W.Cassing *et al.*,
PRC53 (1998) 916

NA60@CERN:

- evidence for no mass shift of the ρ in In+In@158 AGeV

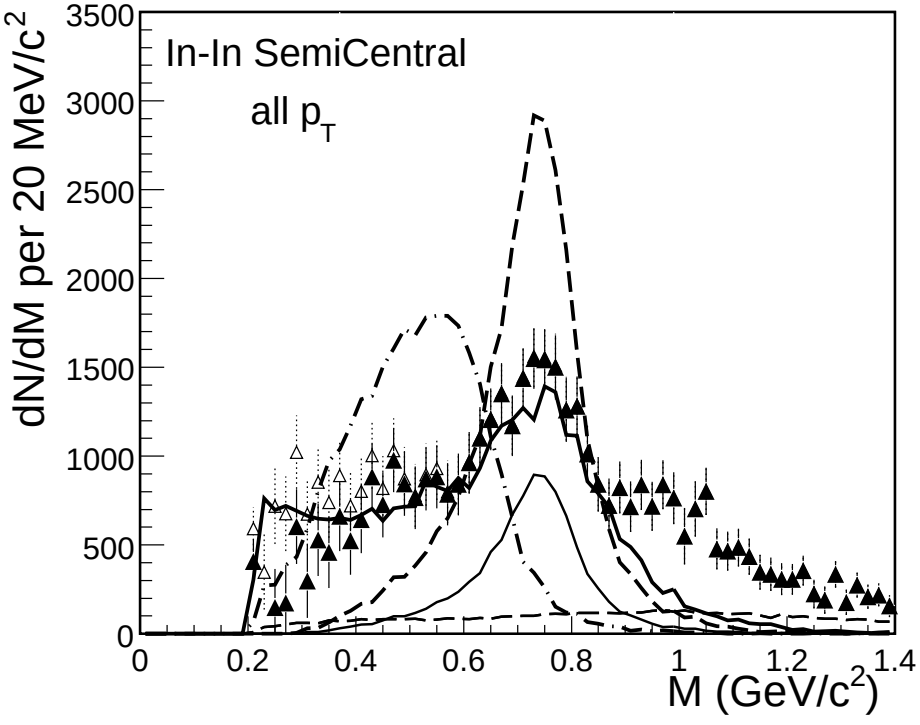
  [R. Arnaldi *et al.*, PRL**96**, 162302 (2006)]

- data in favour of “complex” spectral functions

dashed : vacuum

thick solid : R.Rapp spf

dash-dotted : Brown-Rho scaling



“The ρ spf shows a strong broadening but essentially no mass shift.
This may rule out theoretical models linking hadron masses

directly to the chiral condensate.”

NA60@CERN:

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H. van Hees and R. Rapp,

PRL**97**, 102301 (2006)

“The ρ spf shows a strong broadening but essentially no mass shift.
This may rule out theoretical models linking hadron masses

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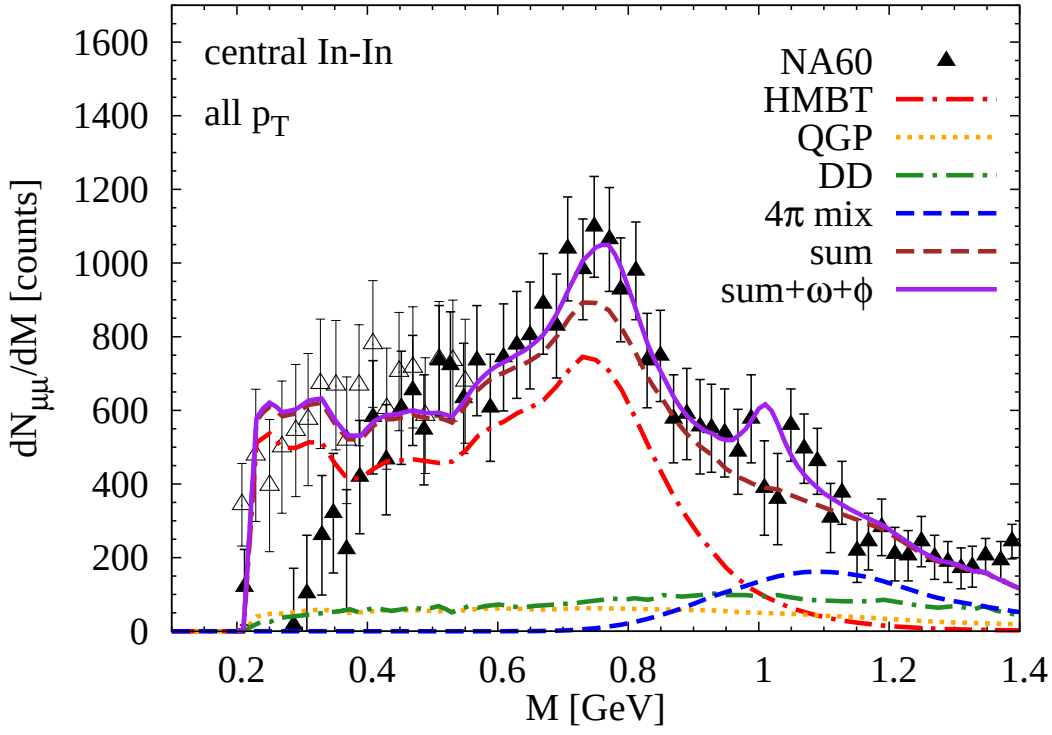
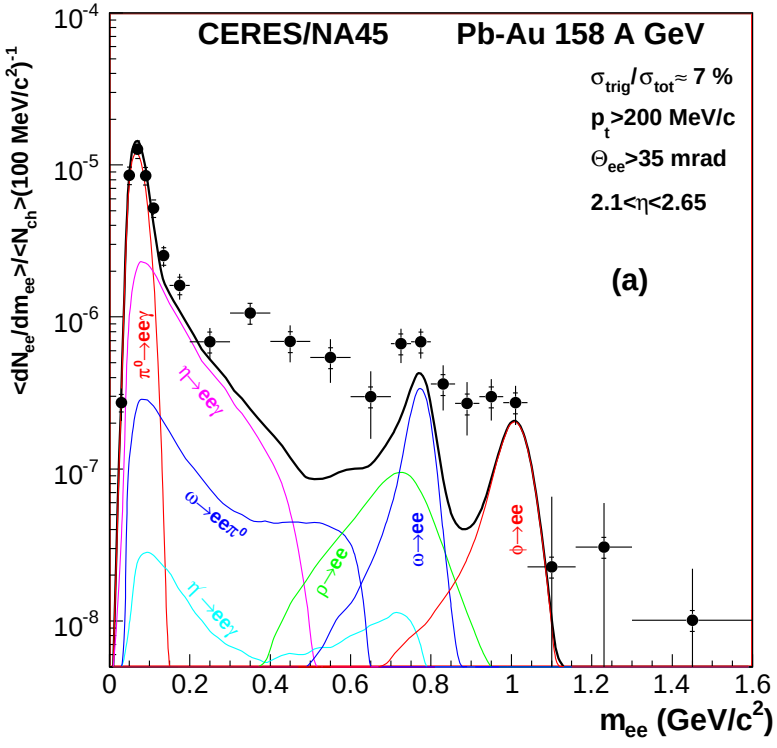
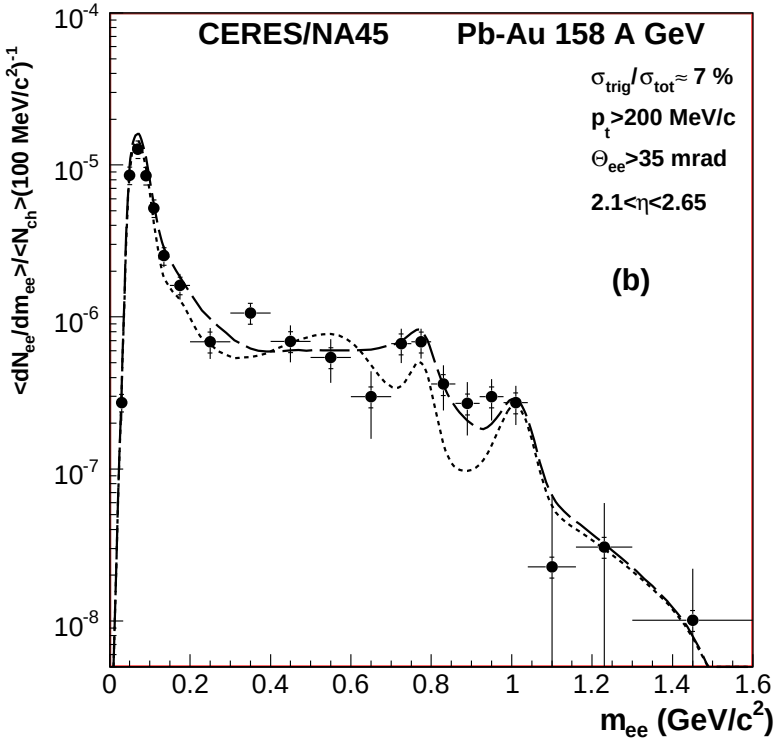


CERES(2)@CERN:

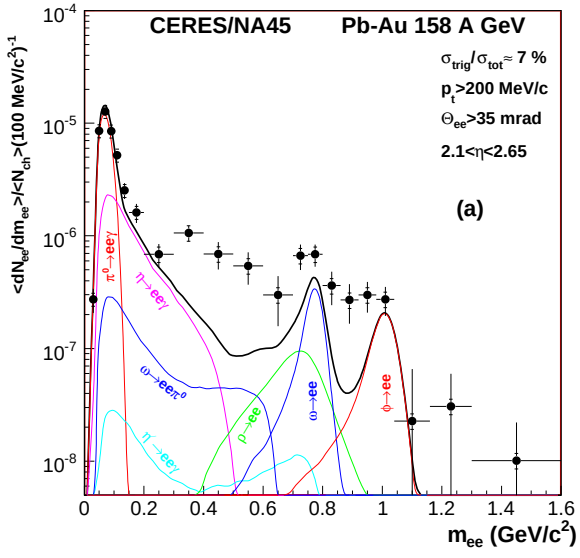
- new data set for Pb-Au@158 AGeV
  (improved mass resolution in the resonance region)
- data in favour of “complex” spectral functions

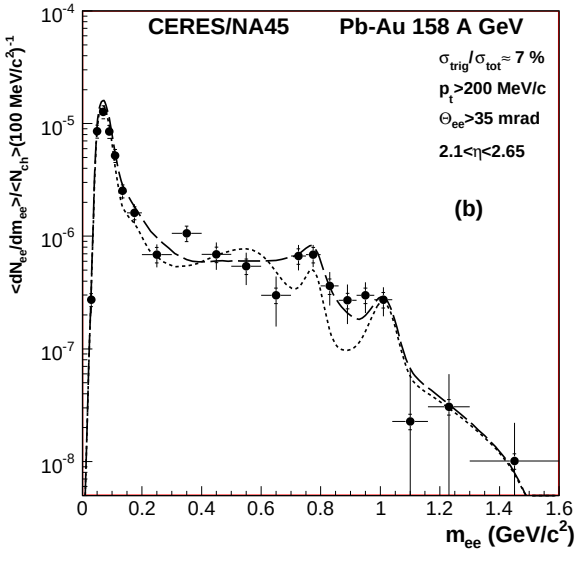
[D. Adamova *et al.*, nucl-ex/0611022]

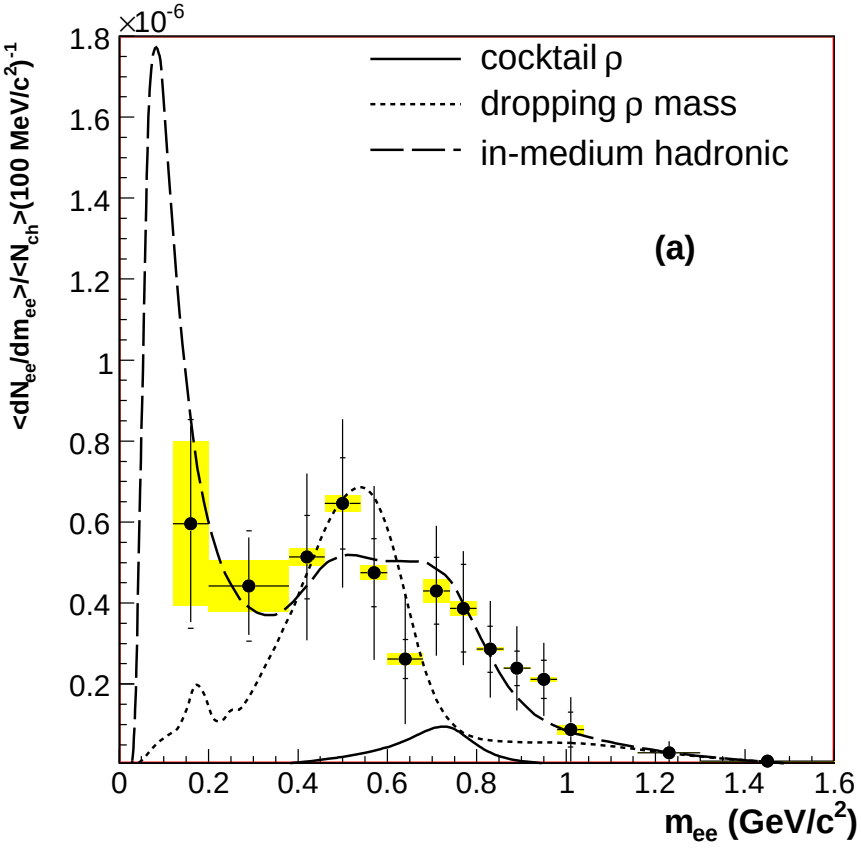




CERES(2)@CERN:

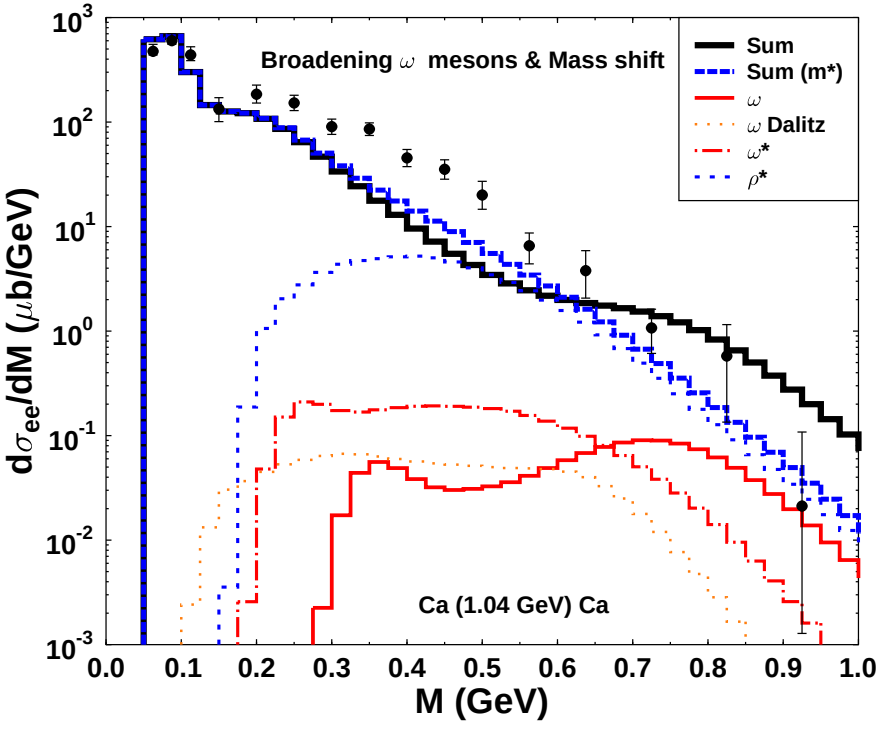

CERES/NA45
Pb-Au 158 A GeV
$\sigma_{trig}/\sigma_{tot} \approx 7$ %
p_t>200 MeV/c
Θ_{ee}>35 mrad
2.1<η<2.65
(a)
$\pi^0 \to ee\gamma$
$\eta \to ee\gamma$
$\omega \to ee\pi^0$
$\eta' \to ee\gamma$
$\rho \to ee$
$\omega \to ee$
$\phi \to ee$
$<dN_{ee}/dm_{ee}>/<N_{ch}>(100\ MeV/c^2)^{-1}$
m_{ee} (GeV/c^2)

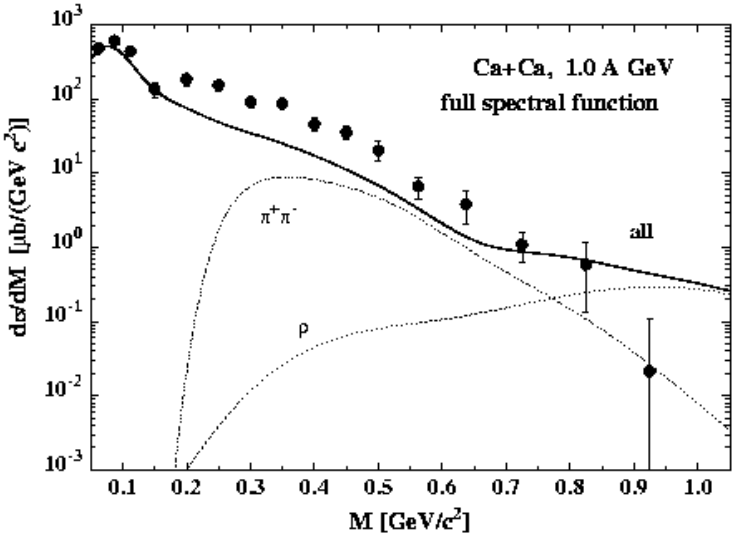

CERES/NA45
Pb-Au 158 A GeV
$\sigma_{trig}/\sigma_{tot} \approx 7$ %
p_t>200 MeV/c
Θ_{ee}>35 mrad
2.1<η<2.65
(b)
$<dN_{ee}/dm_{ee}>/<N_{ch}>(100\ MeV/c^2)^{-1}$
m_{ee} (GeV/c^2)

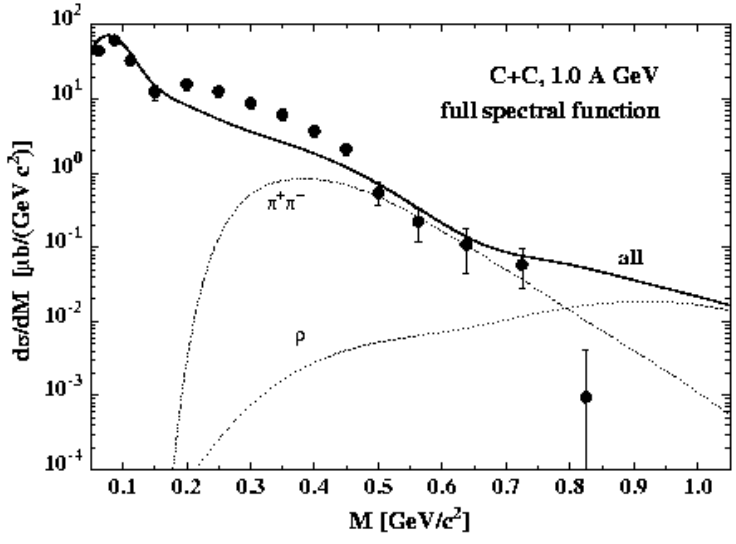

$\times 10^{-6}$
cocktail ρ
dropping ρ mass
in-medium hadronic
(a)
$<dN_{ee}/dm_{ee}>/<N_{ch}>(100\ MeV/c^2)^{-1}$
m_{ee} (GeV/c^2)

1 A GeV $\Rightarrow$ DLS Coll.@BEVELAC:

in contrast to URHIC
spectral function and/or
ρ dropping mass
don't help







C. Ernst *et al.*, **PRC58**(1998)447

E.L.Bratkovskaya *et al.*, **NPA634**(1998)168

1 A GeV $\Rightarrow$ DLS Coll.@BEVELAC:

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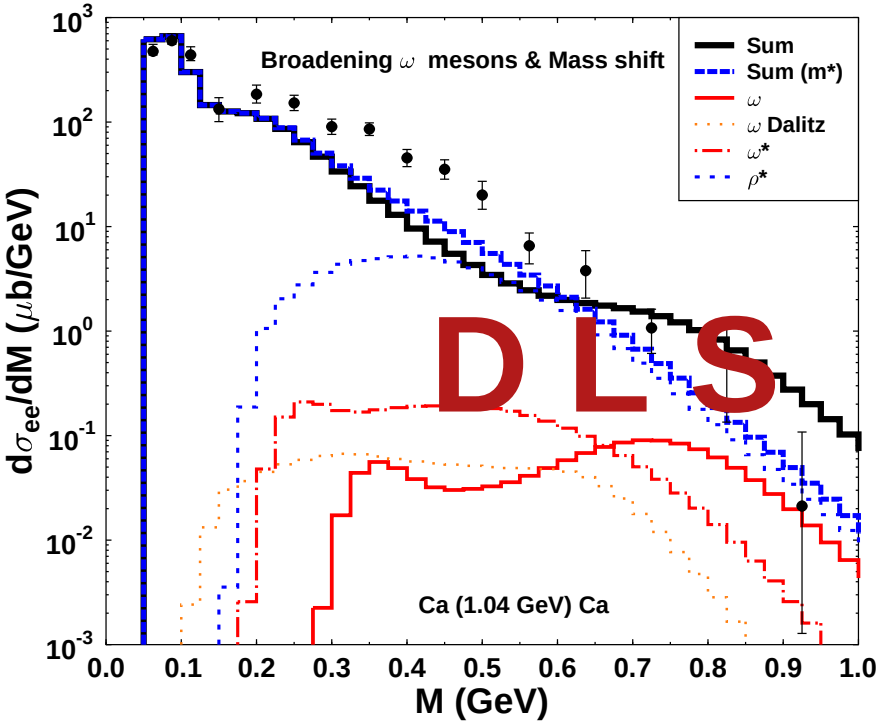
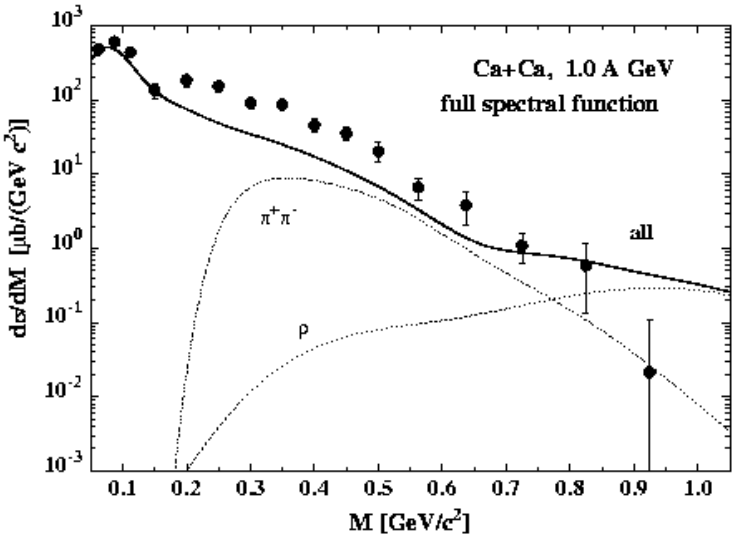
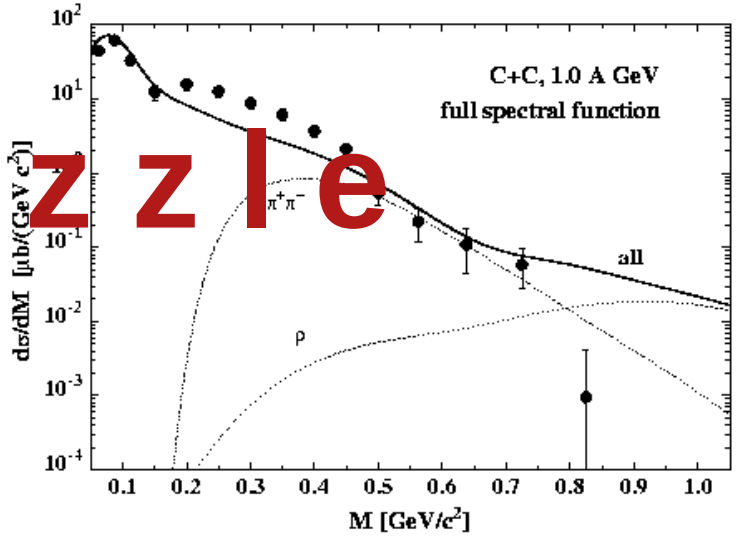


DLS puzzle



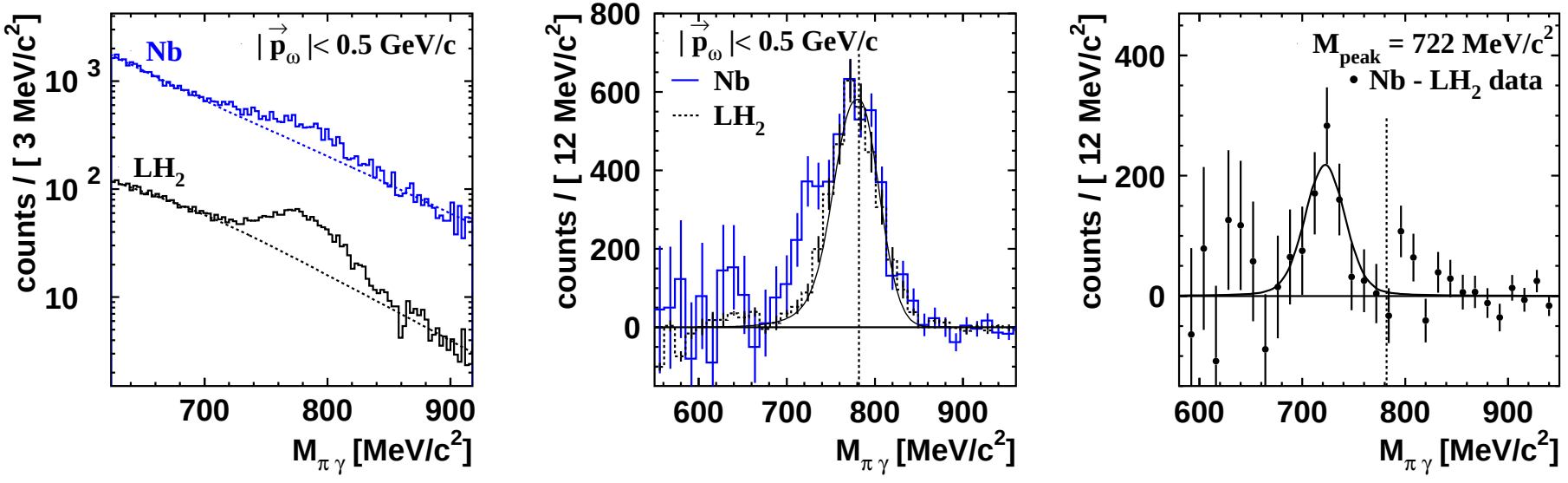


C. Ernst *et al.*, **PRC58**(1998)447

E.L.Bratkovskaya *et al.*, **NPA634**(1998)168

γ-A and p-A reactions

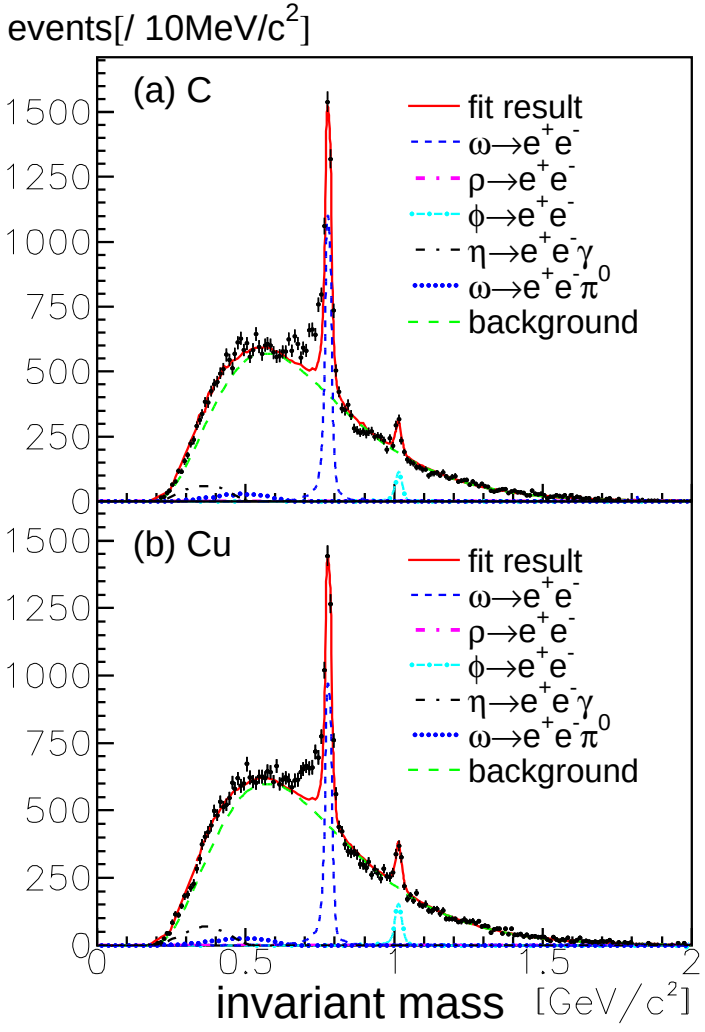
TAPS : $\gamma + A \rightarrow \omega + X \rightarrow \pi^0\gamma + X'$



D. Trnka *et al.*, **PRL94**(2005)192303

γ-A and p-A reactions

E325@KEK : $p + A \rightarrow V + X \rightarrow e^+e^- + X'$ (V=ρ, ω, ϕ)

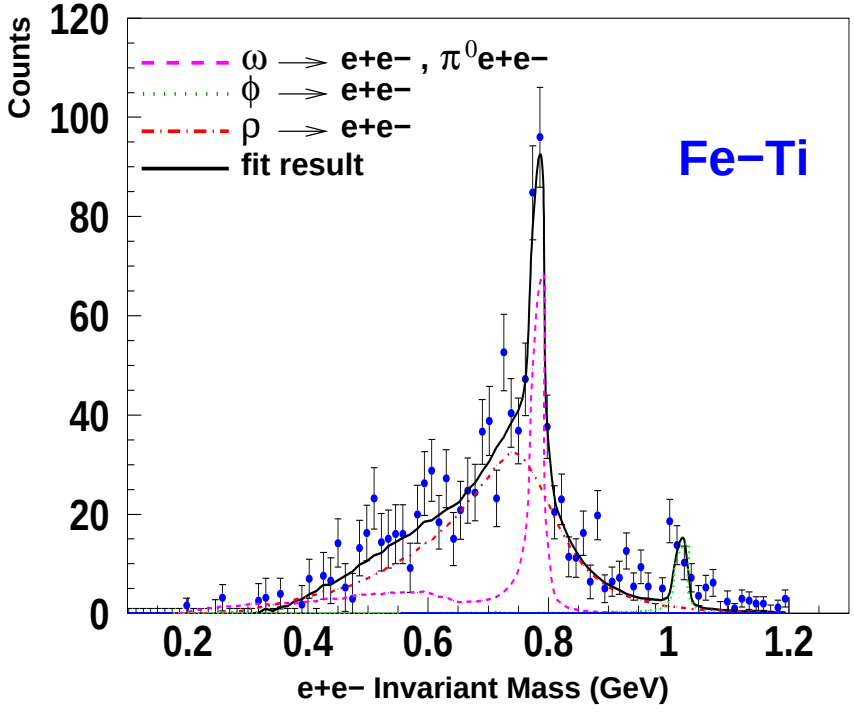


M. Naruki *et al.*,

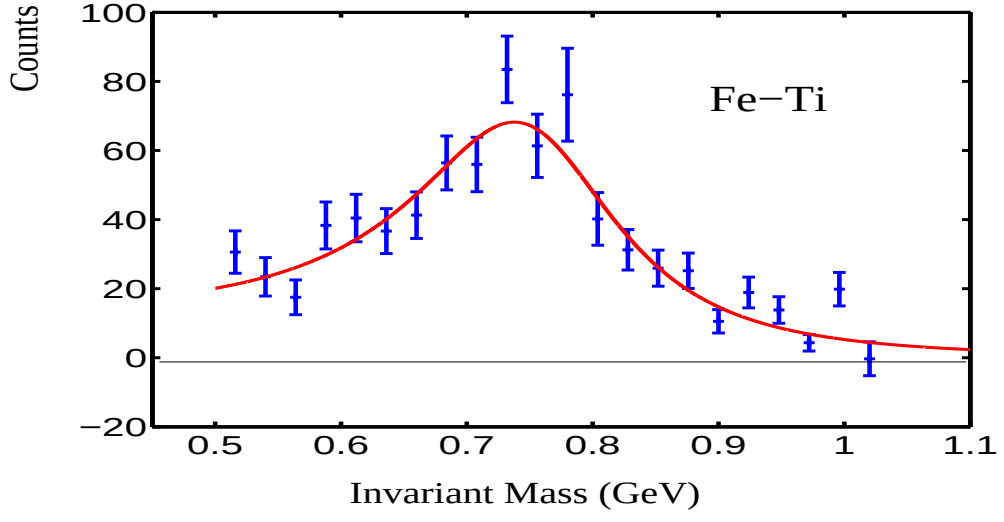
PRL96(2006)092301

γ-A and p-A reactions

CLAS@JLab : $\gamma + A \rightarrow V + X \rightarrow e^+e^- + X'$ (V=ρ, ω, ϕ)



ρ meson



R. Nasseripour *et al.*, nucl-ex/0707.2324

γ-A and p-A reactions

TAPS : $\gamma + A \to \omega + X \to \pi^0\gamma + X'$

E325@KEK : $p + A \to V + X \to e^+e^- + X'$ (V=ρ, ω, ϕ)

CLAS@JLab : $\gamma + A \to V + X \to e^+e^- + X'$ (V=ρ, ω, ϕ

Exp.	ρ		ω	
	α	$\mathbf{\Gamma}$ [MeV]	α	$\mathbf{\Gamma}$ [MeV]
TAPS			0.14	55
E325	$0.092^{\pm 0.002}$	$\Gamma^{\rm vac}$	$0.092^{\pm 0.002}$	$\Gamma^{\rm vac}$
CLAS	$0.02^{\pm 0.02}$	$176.4^{\pm 9.5}$ (C), $217.7^{\pm 14.5}$ (Fe)		

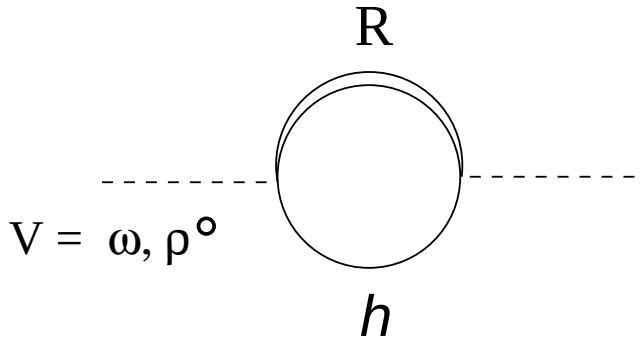
PART II

In-medium spectral functions of ρ and ω mesons

In-medium spectral functions

- **Self-energy**

$$\Sigma_N = -\int A_{VN}\, 2\cdot 2 \frac{d^3p_N}{2E(2\pi)^3} \quad \sim$$



$$A_{VN} = -\sum_R \frac{(2J_R+1)}{2\cdot 3}\frac{8\pi s}{k}\frac{\Gamma_{RNV}(s)}{s - M_R^2 + i\sqrt{s}\Gamma_R^{tot}(s)} \qquad \left(n_B = \frac{2}{3\pi^2}p_F^3\right)$$

$$\Gamma_{RNV}(s) = \frac{k}{8\pi s}\frac{2(\overbrace{A_{3/2}^2 + A_{1/2}^2 + S_{1/2}^2}^{\Sigma_N^T\ ,\ \Sigma_N^L})}{(2J_R+1)} \qquad \Sigma_N = \frac{2\Sigma_N^T + \Sigma_N^L}{3}$$

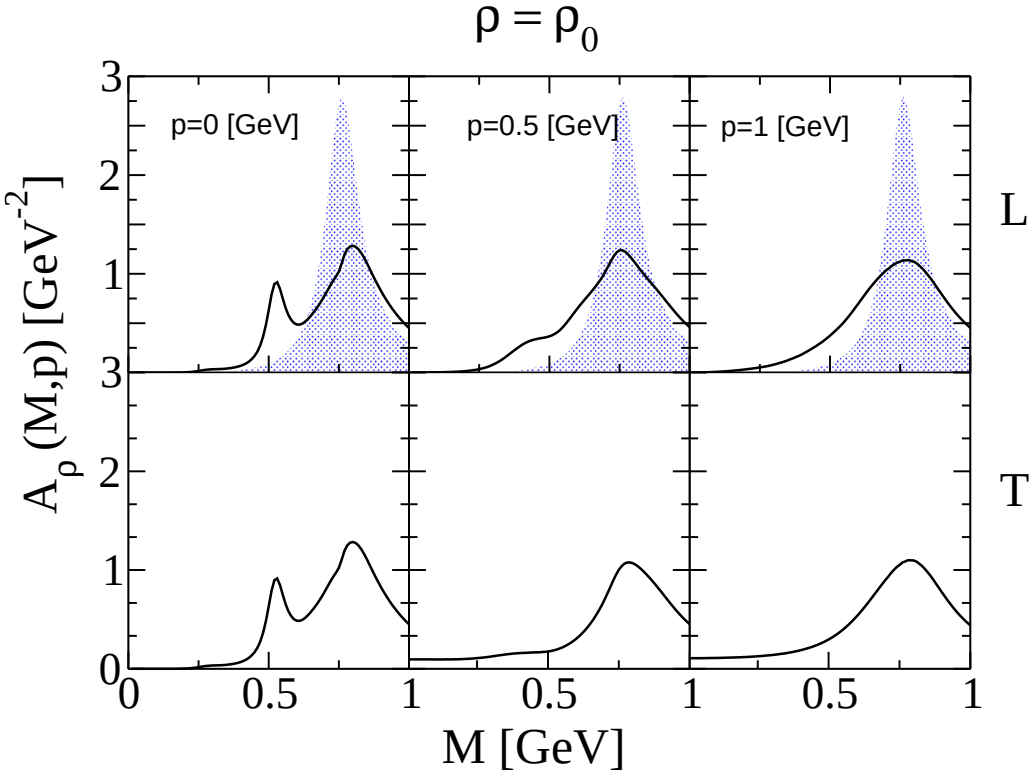
$$\Sigma = \Sigma_N + \Sigma_0 \qquad \Sigma_0 = -im_\rho\Gamma_V^{tot}(m)$$

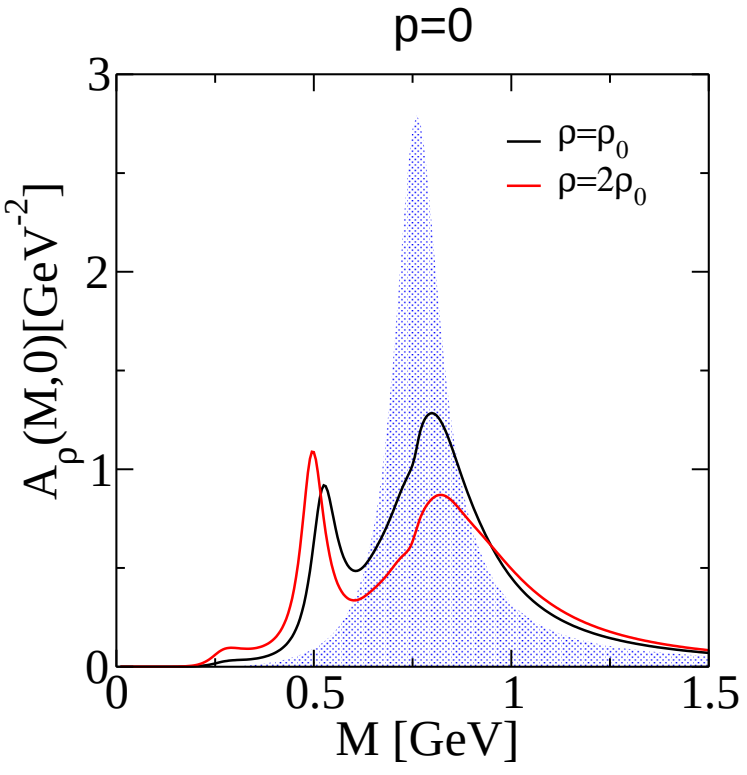
Included resonances

N^*	J^P	$L_{2I\,2J}$	Δ	J^P	$L_{2I\,2J}$
$N^*(1535)$	$\frac{1}{2}^-$	S_{11}	$\Delta(1620)$	$\frac{1}{2}^-$	S_{31}
$N^*(1650)$	$\frac{1}{2}^-$	S_{11}	$\Delta(1700)$	$\frac{3}{2}^-$	D_{33}
$N^*(1520)$	$\frac{3}{2}^-$	D_{13}	$\Delta(1232)$	$\frac{3}{2}^+$	P_{33}
$N^*(1440)$	$\frac{1}{2}^+$	P_{11}	$\Delta(1905)$	$\frac{5}{2}^+$	F_{35}
$N^*(1720)$	$\frac{3}{2}^+$	P_{13}	$\Delta(1950)$	$\frac{7}{2}^+$	F_{37}
$N^*(1680)$	$\frac{5}{2}^+$	F_{15}			

ρ-meson spectral function

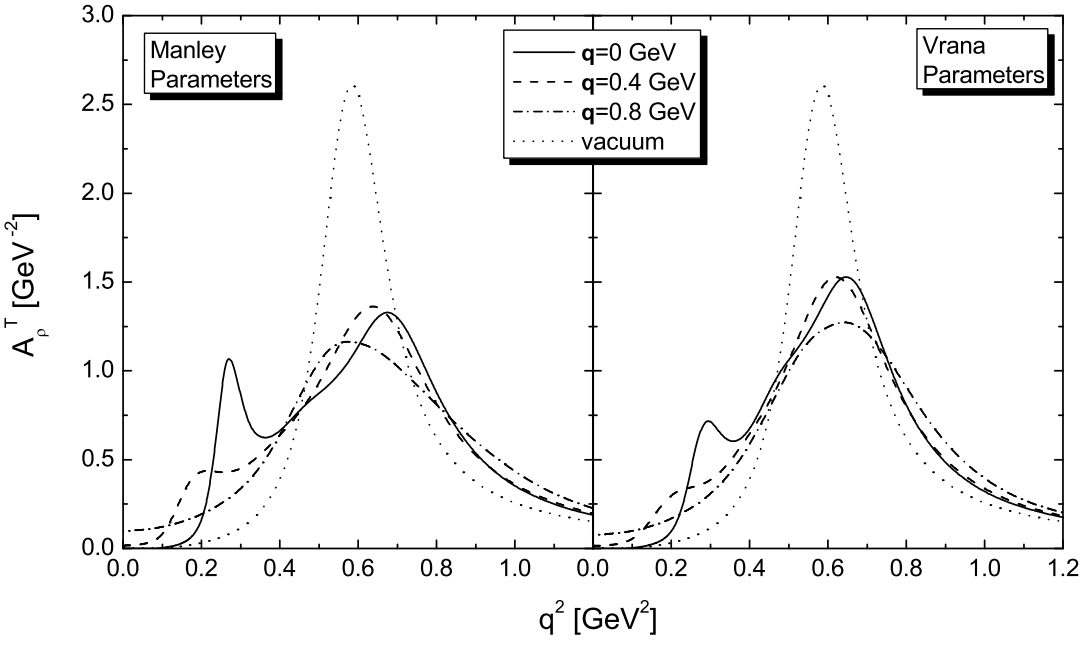
$$A_{\rho/\omega}(p, n_B) = -\frac{1}{\pi} \mathrm{Im} \left\{ \frac{1}{p^2 - m^2_{\rho/\omega} - \Sigma(p, n_B)} \right\} \qquad (p^2 = M^2)$$



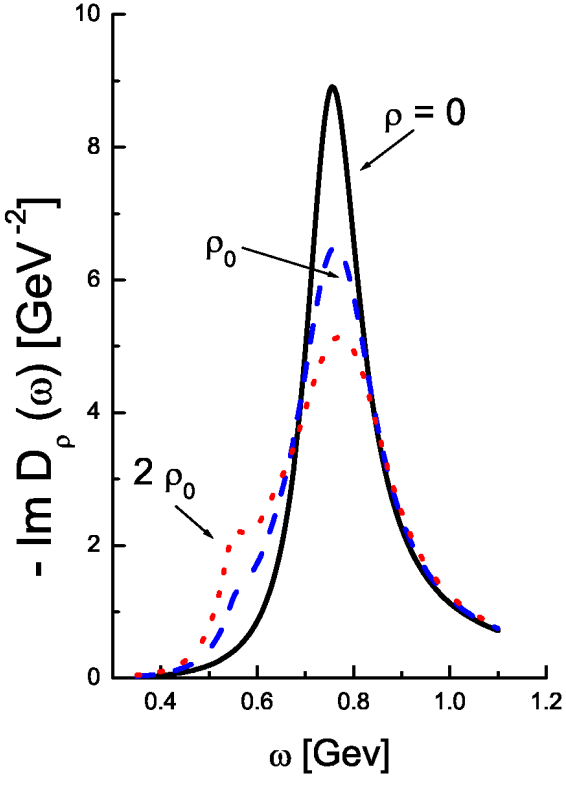


$$A_{VN} = -\sum_R C(J_R, s, k) \frac{\Gamma_{RNV}(s)}{s - M_R^2 + i\sqrt{s}\Gamma_R^{tot}(s)}$$

Other groups



M.Post,S.Leupold,U.Mosel **NPA741**(2004)81



M.F.M.Lutz,Gy.Wolf,B.Friman

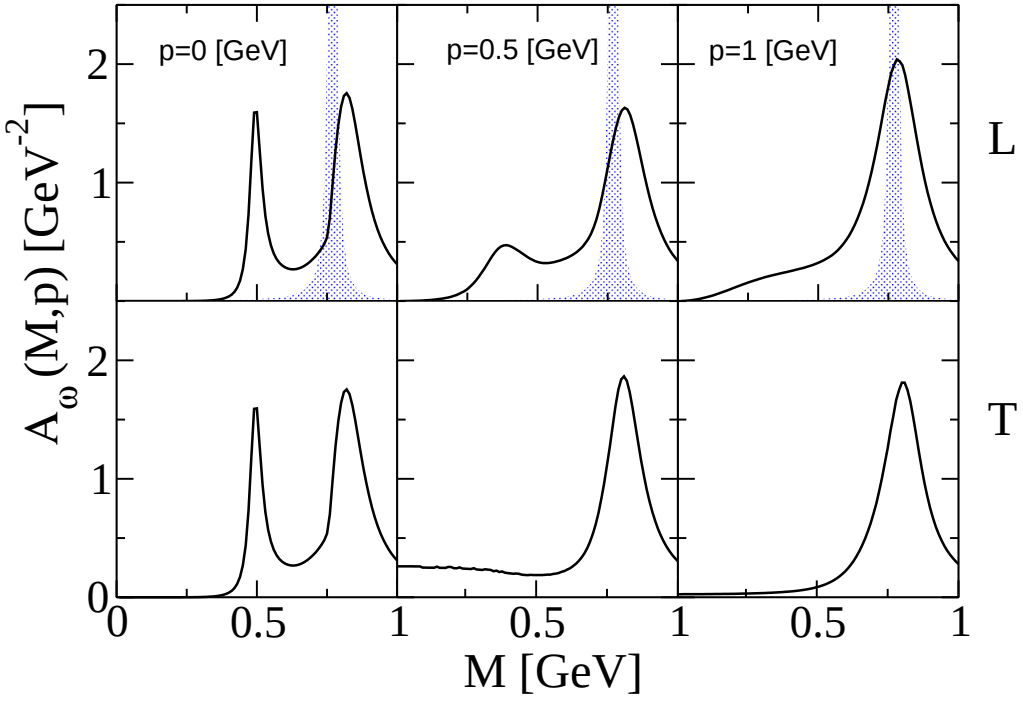
NPA706(2002)431

$N^\star(1520)$: $\Gamma_{N\rho} \sim 26$ MeV(Post *et al.*), $\Gamma_{N\rho} \sim 2$ MeV(Lutz *et al.*)

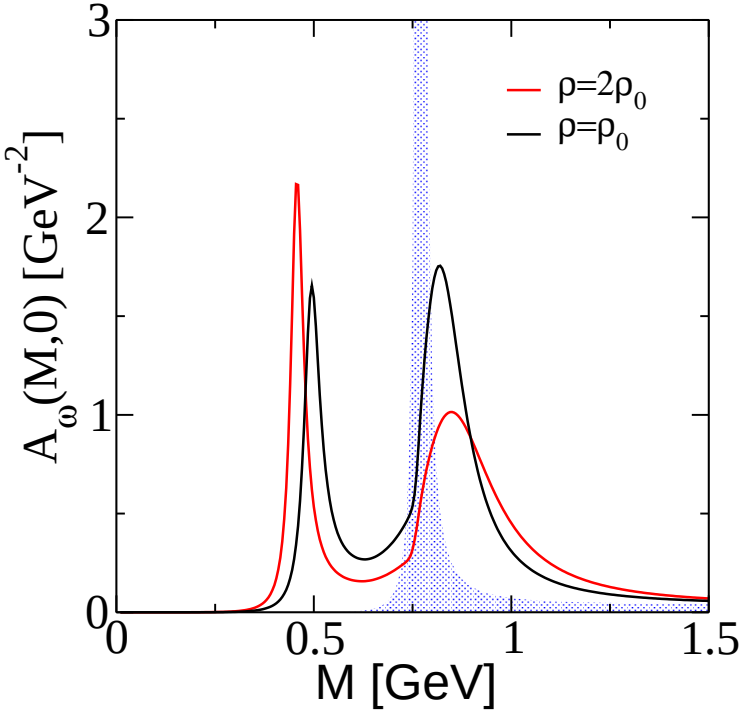
ω-meson spectral function

$$A_{\rho/\omega}(p, n_B) = -\frac{1}{\pi} \mathrm{Im} \left\{ \frac{1}{p^2 - m^2_{\rho/\omega} - \Sigma(p, n_B)} \right\} \qquad (p^2 = M^2)$$

$\rho = \rho_0$

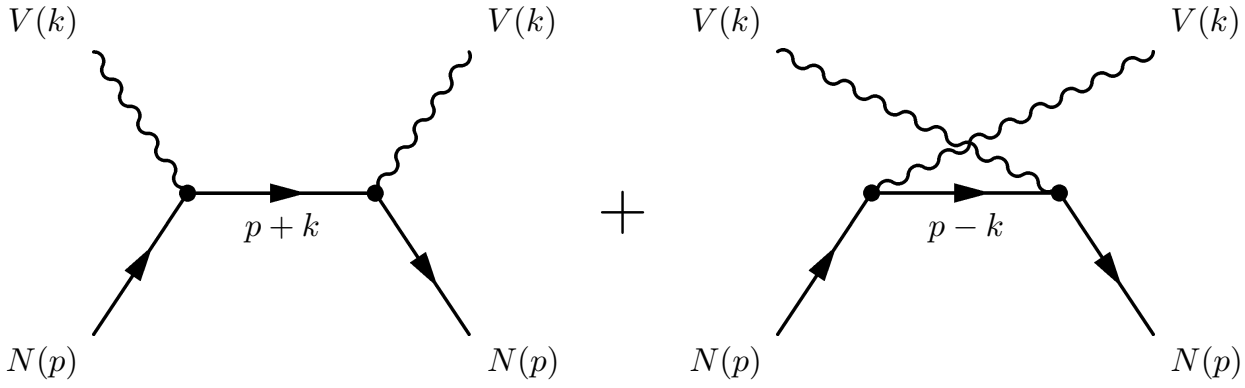


p=0



Non-resonant contributions

- Compton scattering contribution



$$\delta\mathcal{L}_{\omega NN} = g_{\omega NN}\bar{\psi}\gamma^{\mu}\psi A_{\mu}^{(\omega)}$$

$$\delta\mathcal{L}_{\rho NN} = \frac{g_{\rho NN}}{2m_N}\bar{\psi}\sigma^{\mu\nu}\psi F_{\mu\nu}^{(\rho)}$$

$g_{\omega NN}, g_{\rho NN}$: BONN OBE model

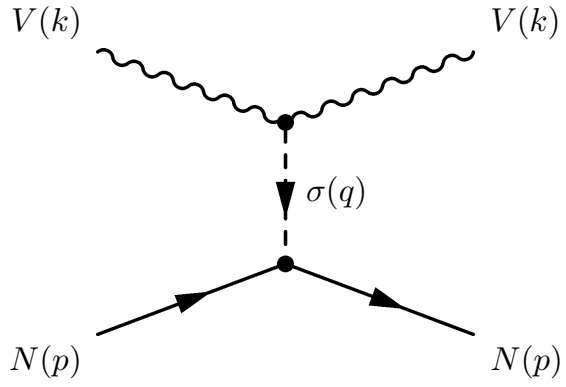
[Machleidt, **PRC63**(2001)024001]

$$\Sigma^{\mathrm{Compt}} = -2\cdot 2\int \frac{d^3p_N}{2E_p(2\pi)^3}\,\mathcal{M}^{\mathrm{Compt}}$$

- σ-exchange contribution

$$\delta\mathcal{L}_{VV\sigma} = \frac{g_{VV\sigma}}{m_\sigma} F^{\mu\nu}_{(V)} F^{(V)}_{\mu\nu} \sigma$$

$$\delta\mathcal{L}_{NN\sigma} = g_{NN\sigma} \bar{\psi}\psi\sigma$$



$g_{NN\sigma}$: BONN OBE model

[Machleidt, **PRC63**(2001)024001]

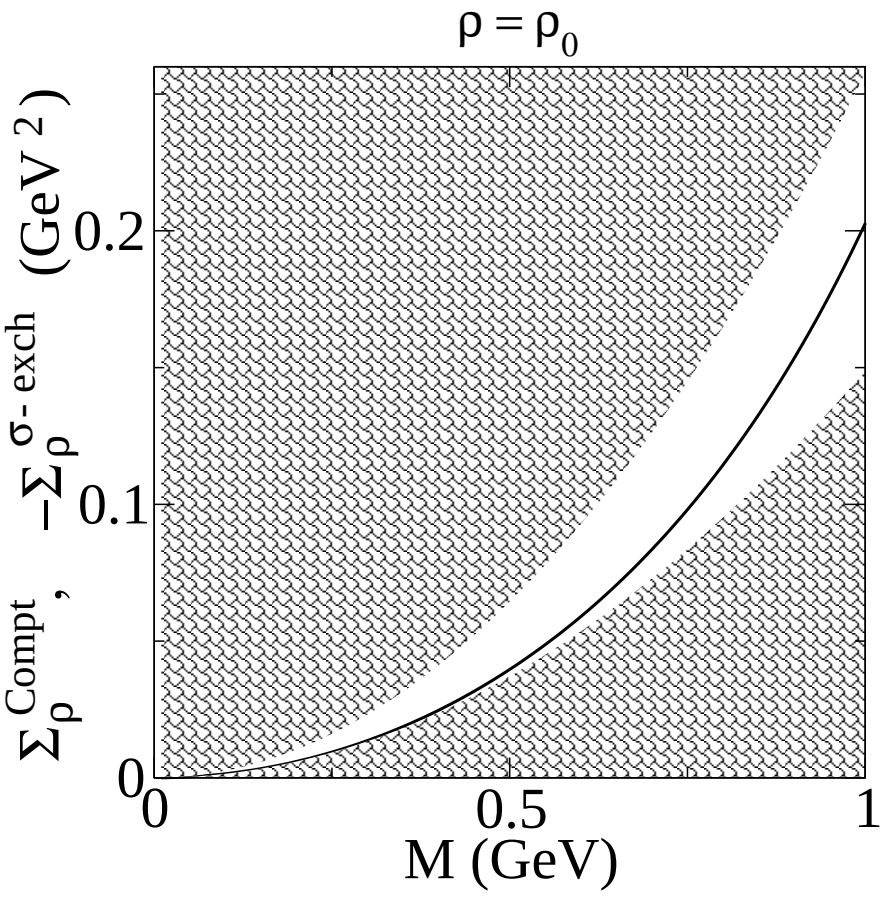
$g_{\rho\rho\sigma}$: from $\rho^0 \to \pi^+\pi^-\pi^+\pi^-$

assuming $\rho^0 \to \rho^0\sigma \to \pi^+\pi^-\pi^+\pi^-$

$B(\rho^0 \to \pi^+\pi^-\pi^+\pi^-) = (1.8 \pm 0.9) \times 10^{-5}$

$g_{\omega\omega\sigma}$: $3\, g_{\rho\rho\sigma}$

ρ meson



For the mean values of B
$\Sigma_\rho^{\mathrm{Compt}}$ and $\Sigma_\rho^{\sigma-\mathrm{exch}}$
almost cancel completely

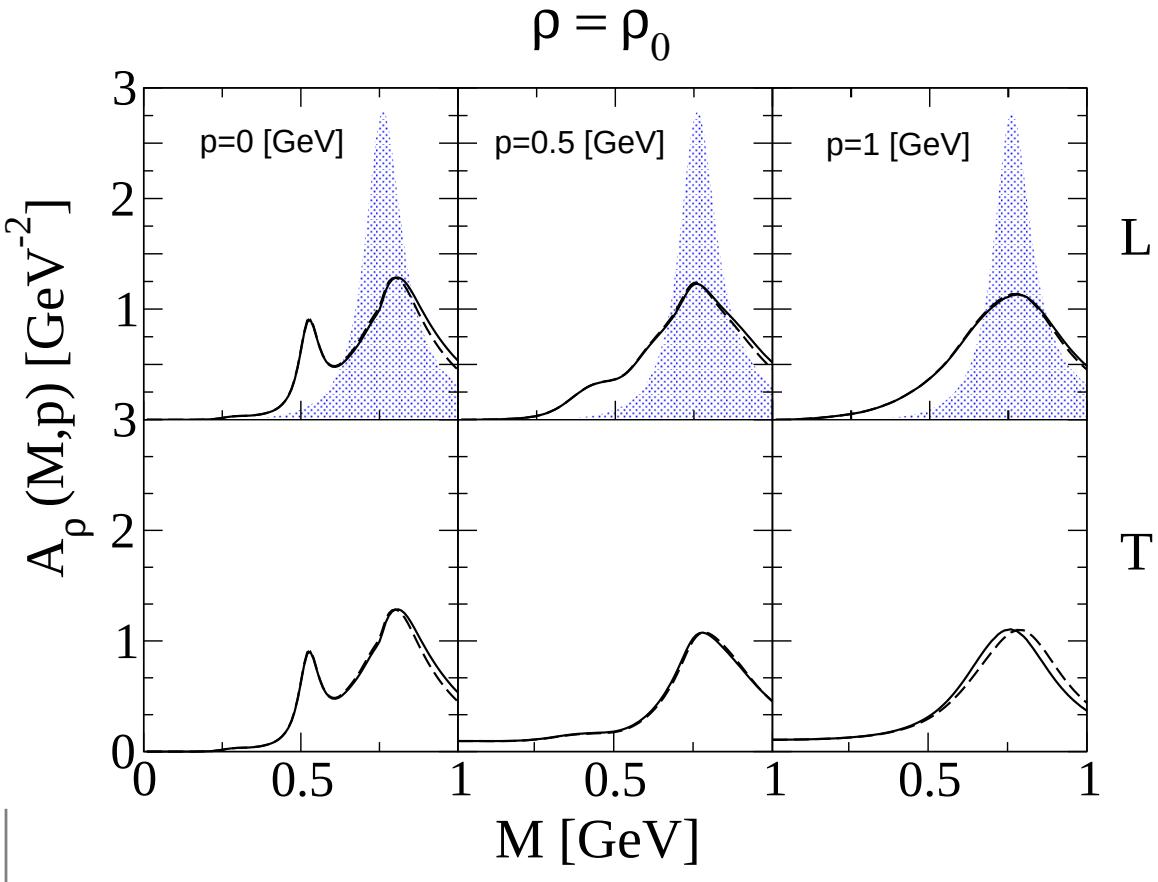
small changes in the ρ spectral function

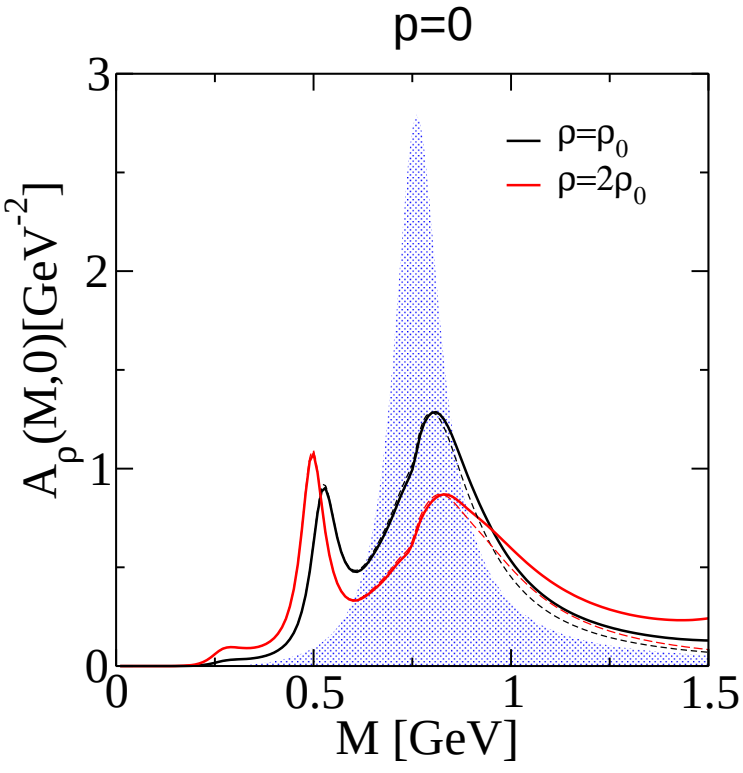
Error band: $B(\rho^0 \to \pi^+\pi^-\pi^+\pi^-) = (1.8 \pm 0.9) \times 10^{-5}$

ρ-meson spectral function

– – $\Sigma_0 + \Sigma^{\mathrm{Res}}$

— $\Sigma_0 + \Sigma^{\mathrm{Res}} + \Sigma^{\mathrm{Compt}} + \Sigma^{\sigma-\mathrm{exch}}$

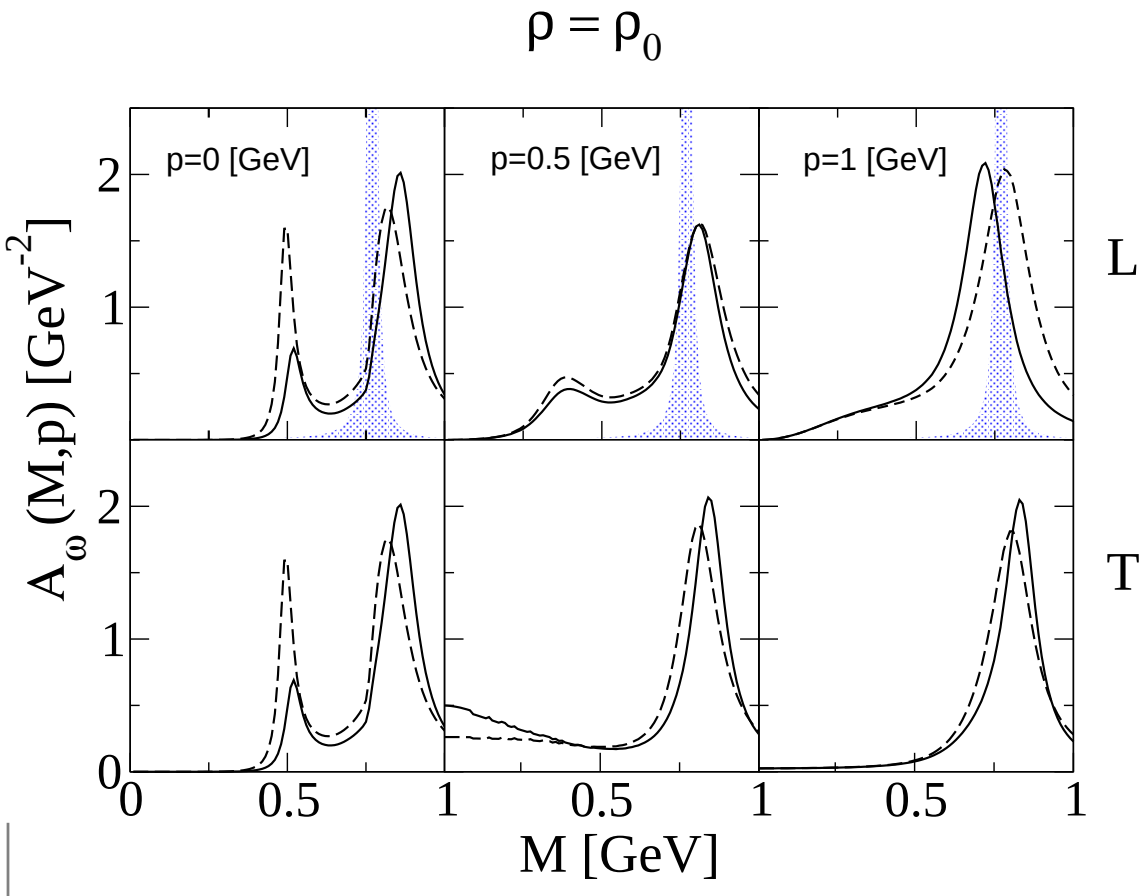


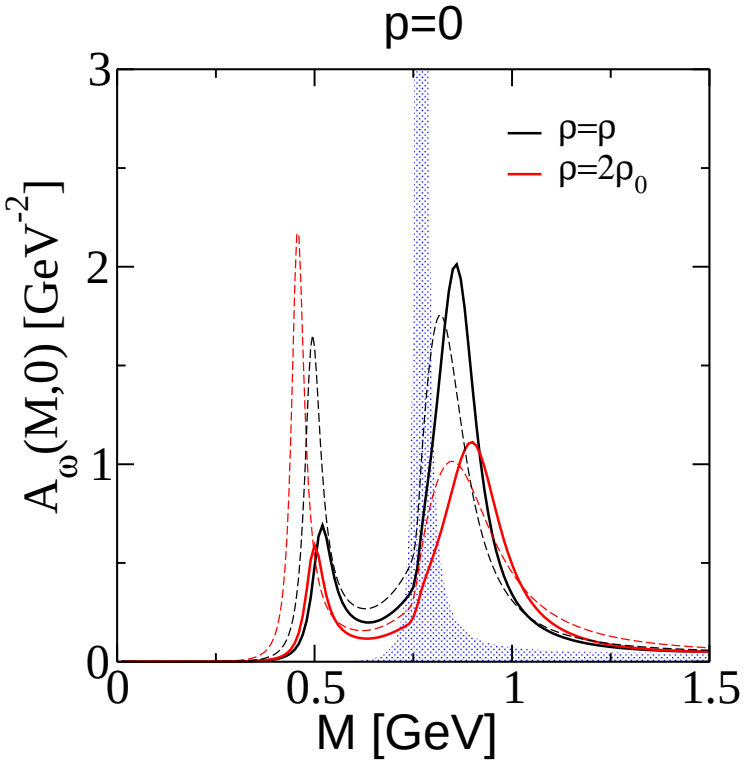


ω-meson spectral function

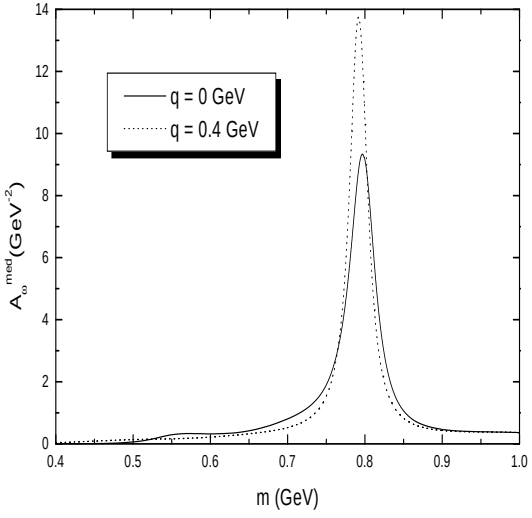
– – $\Sigma_0 + \Sigma^{\mathrm{Res}}$

— $\Sigma_0 + \Sigma^{\mathrm{Res}} + \Sigma^{\mathrm{Compt}} + \Sigma^{\sigma-\mathrm{exch}}$



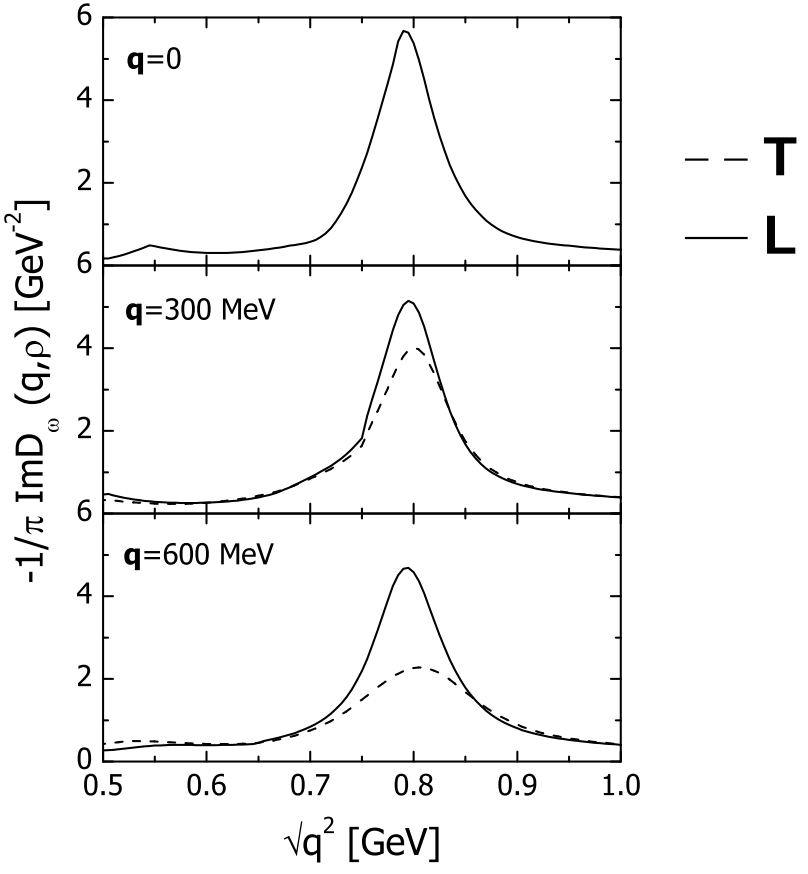


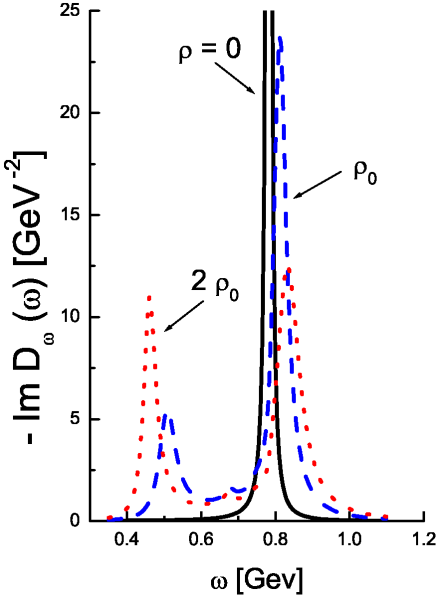
Other groups



M.Post,U.Mosel,

NPA688(2001)808





M.F.M.Lutz *et al.*,

NPA706(2002)431

P.Muehlich,V.Shklyar,S.Leupold,

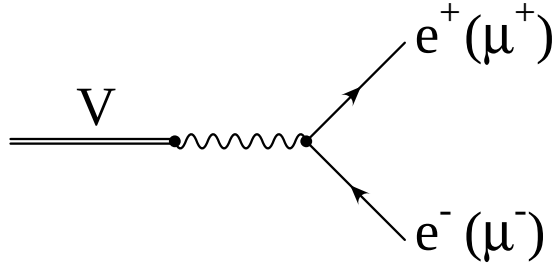
U.Mosel,M.Post,**NPA780**(2006)187

PART III

Theoretical description of e^+e^- production in HIC at 1-2 AGeV

Elementary sources for e^+e^- production

Mesonic decays



Dilepton decays of pseudoscalar (π,η,$\eta\prime$)

and vector (ρ, ω, ϕ) mesons

$$d\Gamma^{(\mathcal{M}\to Xe^+e^-)} = d\Gamma^{(\mathcal{M}\to X\gamma^\star)} M\Gamma^{(\gamma^\star\to e^+e^-)} \frac{dM^2}{\pi M^4}$$

$$M\Gamma^{(\gamma^\star\to e^+e^-)} = \frac{\alpha}{3}\left(M^2+2m_e^2\right)\sqrt{1-\frac{4m_e^2}{M^2}}$$

direct decays : $\mathcal{M}\to e^+e^-$

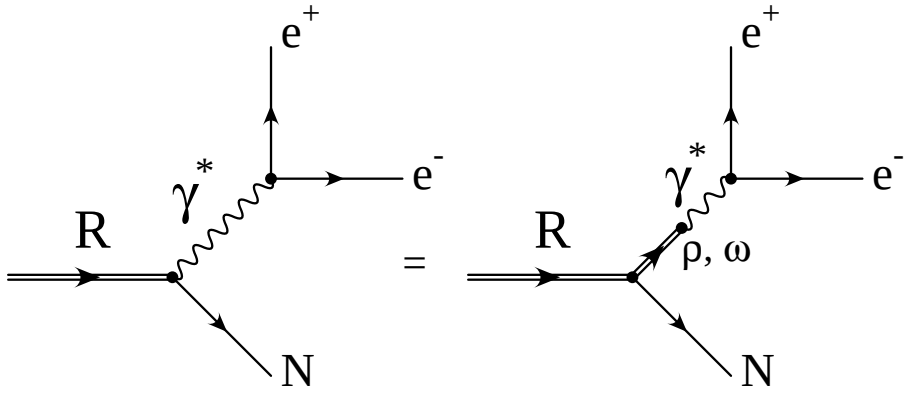
Dalitz decays : $\mathcal{M}\to \pi e^+e^-, \gamma e^+e^-, \ldots$

4-body decays : $\mathcal{M}\to \pi\pi e^+e^-$

A.Faessler, C.Fuchs and M.I.Krivoruchenko, **PRC61**(2000)035206

Resonance decays

$R \to N e^+ e^-$ decays of nucleon resonances $R = \Delta, N^\star$ with mass μ below 2 GeV and spin $J \leq \frac{7}{2}$



Vector meson dominance (VMD)

$$d\Gamma^{(R\to N e^+ e^-)} = d\Gamma^{(R\to N\gamma^\star)} M\Gamma^{(\gamma^\star\to e^+e^-)} \frac{dM^2}{\pi M^4}$$

$$d\Gamma^{(R\to N\gamma^\star)} \propto l.c. \left\{ |G_M|^2, |G_E|^2, |G_C|^2 \right\}_{c(\mu, m_N, M; l)}$$

decay modes: $\Delta \to N\rho; N^\star \to N\rho, \omega$

problems of VMD

- inconsistency between resonance meson decay and photoproduction data
- wrong asymptotics for the form factors

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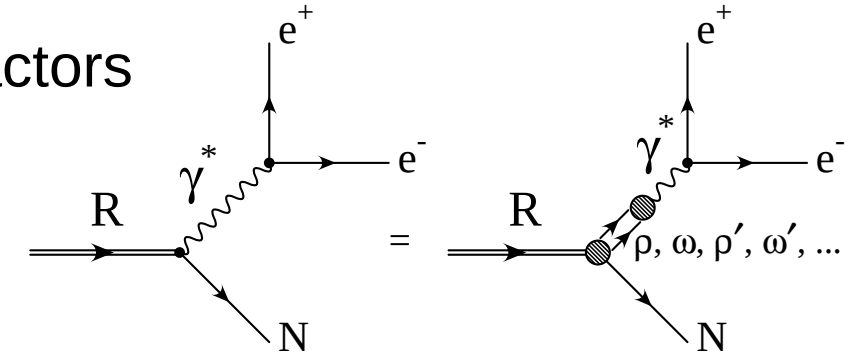


$\Rightarrow$ **Extended VMD**

ASSUMPTION: interference between ρ and ρ', ρ'', . . . , in radiative processes

$\Rightarrow$ include excited ρ', ω', ρ'', . . . , states in the transition form factors

M.I.Krivoruchenko, B.Martemyanov, A.Faessler and C.Fuchs, **AP296**(2002)299

Heavy Ion Collisions

Heavy Ion Collisions

Transport model: **Quantum Molecular Dynamics**

Monte Carlo cascade + Mean field + Pauli-blocking

- included baryon-baryon collisions:

  all elastic channels

  inelastic channels $NN \to NN^\star$, $NN \to N\Delta^\star$,
  $NN \to \Delta N^\star$, $NN \to \Delta\Delta^\star$, $NR \to NR'$

- included pion-absorption $\rightleftharpoons$ resonance-decay channels:

  $\Delta \rightleftharpoons N\pi$, $\Delta^\star \rightleftharpoons \Delta\pi$, $\Delta^\star \rightleftharpoons N_{1440}\pi$, $N^\star \rightleftharpoons N\pi$,
  $N^\star \rightleftharpoons N\pi\pi$, $(N^\star \rightleftharpoons \Delta\pi,\ N^\star \rightleftharpoons N_{1440})$

- included eta-absorption via $N^*(1535)$

  η production cross sections in C+C consistent with results from TAPS

Tübingen QMD: all 4* resonances with mass below 2 GeV included

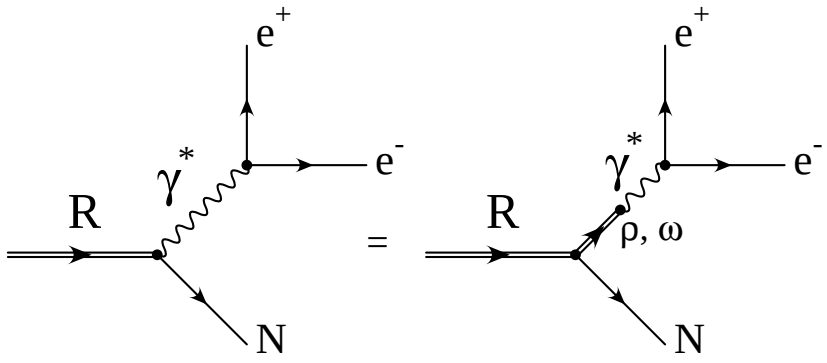
$\Rightarrow$ 10 Δ and 11 $N^\star$ resonances

Res.	$\Gamma_{\rm tot}$ [MeV]	$N\omega$	$N\rho$	$N\pi$	$N\pi\pi$	$\Delta_{1232}\pi$	$N_{1440}\pi$	$N\eta$
N_{1520}	125	0.08	26.63	75	18.75	31.25		
N_{1535}	150	2.05	4.62	82.5	7.5		7.5	52.5
N_{1720}	184	32.4	129.3	22.5	67.5	15		
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
Δ_{1232}	115		~ 0	115				
Δ_{1620}	180		16.4	45		108	27	
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$

Influence of ρ^* and ω^* on the dilepton yield

Modifications:

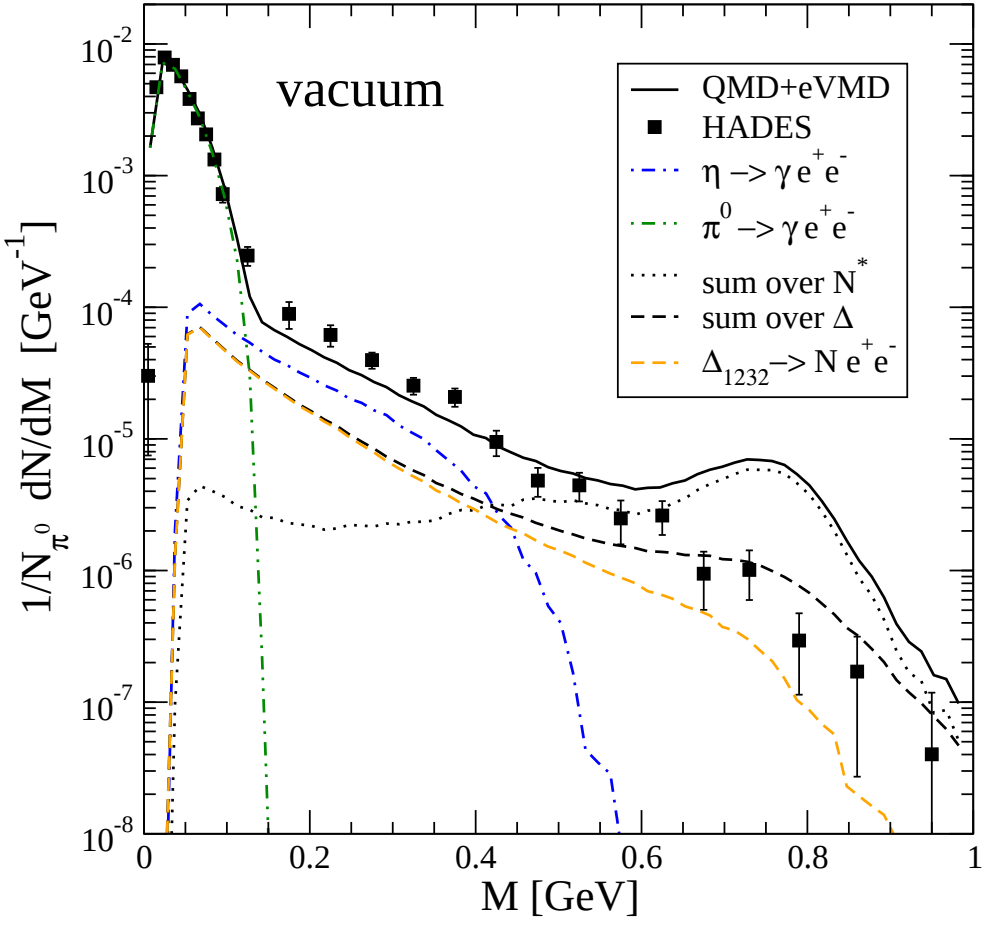
- $d\Gamma(\mu, M)^{R\to Ne^+e^-}/dM^2$

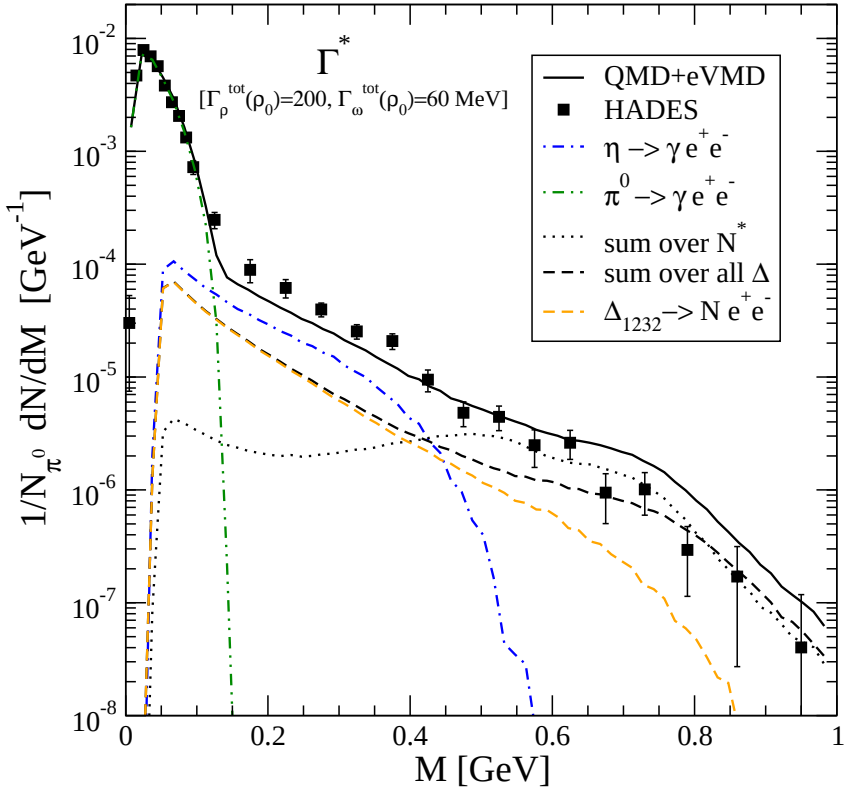


$$\frac{1}{m_\rho^2 - M^2 + \Sigma_0} \to \frac{1}{m_\rho^2 + \mathrm{Re}\Sigma - M^2 + \mathrm{Im}\Sigma}$$

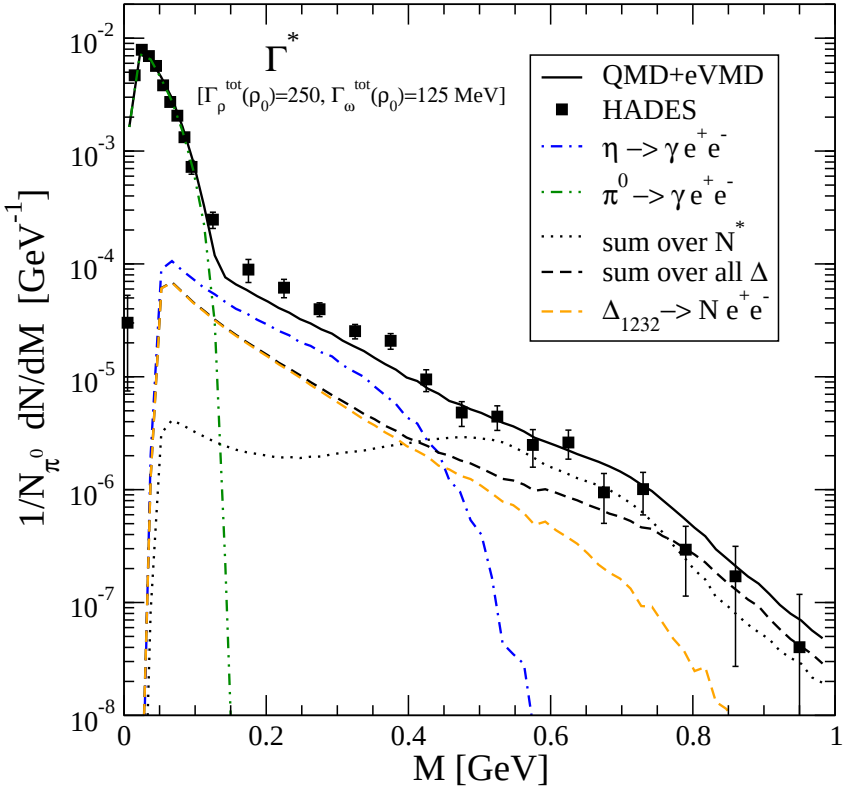
- $\Gamma(\mu)^{R\to N\rho}$, $\Gamma(\mu)^{R\to N\omega}$ $\Rightarrow$ $\Gamma(\mu)^{\mathrm{tot}}$

Comparison to HADES data



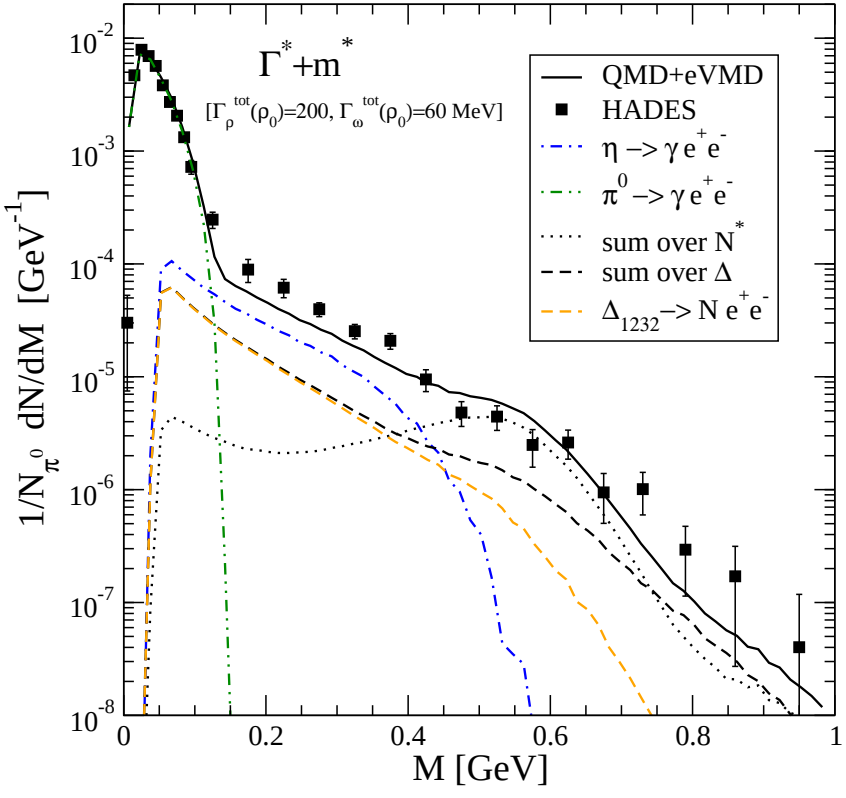


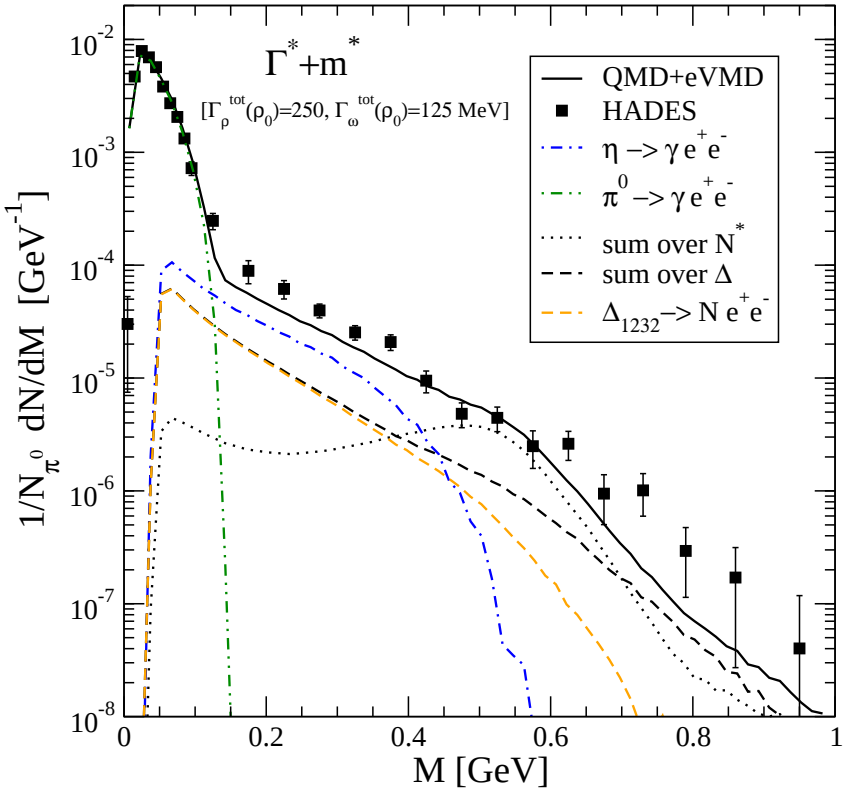
$$\Gamma_V^{tot} = \Gamma_V^{vac} + \rho/\rho_0 \Gamma_V^{coll}$$

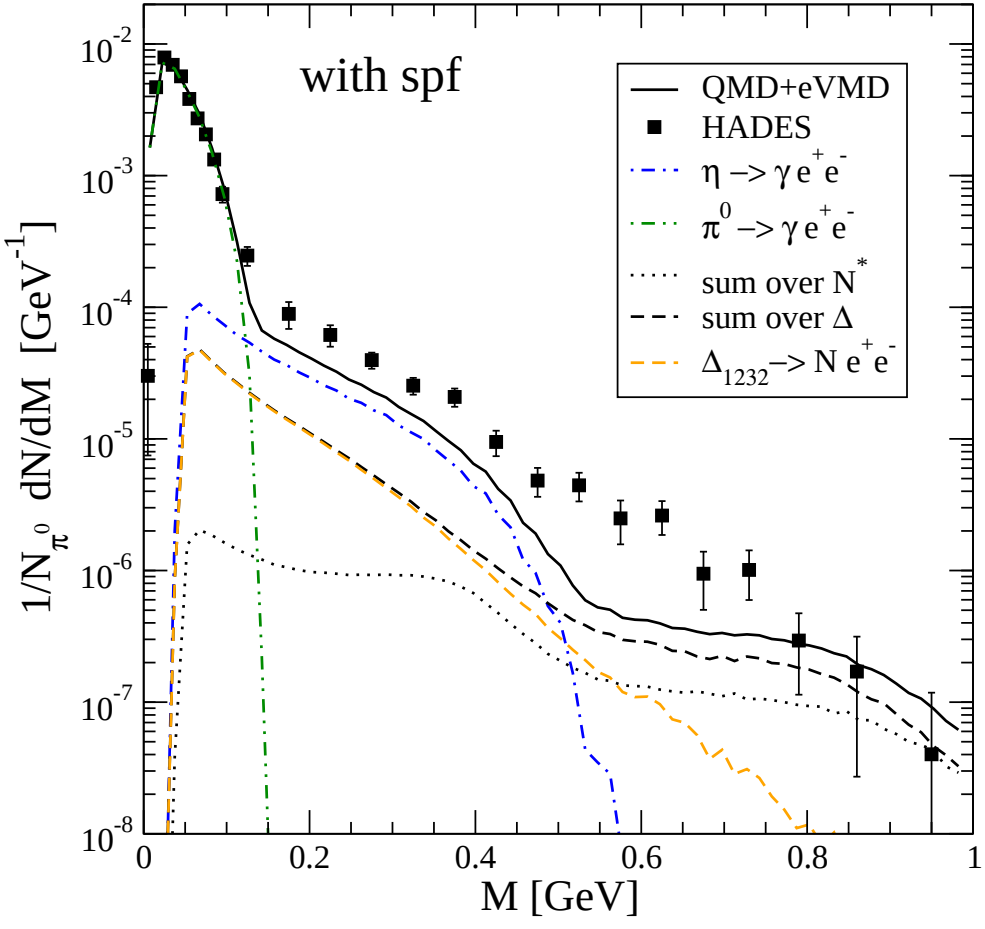


$$\Gamma_V^{\rm tot} = \Gamma_V^{\rm vac} + \rho/\rho_0 \Gamma_V^{\rm coll}$$

$$m_V^* = m_V(1 - \alpha\rho/\rho_0) \text{ with } \alpha = 0.2$$







$$\Gamma(\mu)^{R\to N\rho},\ \Gamma(\mu)^{R\to N\omega} \nearrow$$

$$\Rightarrow \quad \Gamma(\mu)^{\mathrm{tot}} \nearrow$$

Summary

- Current experimental data support modifications of ρ and ω properties in-medium
  - **UrHIC**: favour a broadening of the ρ over a dropping of its mass according to BR scaling.
  - $\gamma + A$, $p + A$: outcome not yet clear. Differrent experiments find different outcomes. Only dropping mass? Only broadening? Dropping mass AND broadening?
  - **HIC at 1-2 AGeV**: BR scaling seems to induce a lack of strength not supported by the HADES data. However, big error bars in the region of the VM peak and above: **need for better resolution**. Data nicely described by $\Gamma_V^{\rm tot}$=$\Gamma_V^{\rm vac}$+$\rho/\rho_0\Gamma_V^{\rm coll}$ with $\Gamma_\omega^{\rm tot}(\rho_0)$=125 MeV, $\Gamma_\rho^{\rm tot}(\rho_0)$=250 MeV.
    Inclusion of complex spectral functions: strong modifications of the spectral functions of the nucleon resonances are induced. ***Result not supported by experimental data***. **Problem**: In-medium modifications of VM and nucleon resonance spectral functions tight connected. Resonances and vector meson should be treated on the same footing...complex coupled channel problem!
    DLS PUZZLE: not solved by introduction of in-medium effects.

    Last ECT* conference (June '07): could be Bremsstrahlung!