Dileptons at SIS energies

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Outline

1. Motivation for electromagnetic probes $\leftrightarrow$ hadron resonances

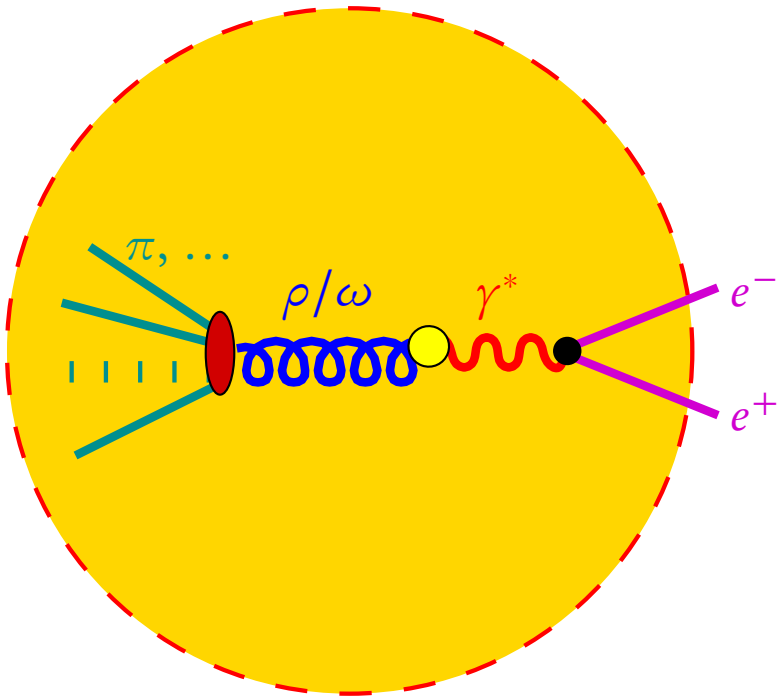
2. Resonance model at SIS energies (with J. Weil, U. Mosel)
   - The GiBUU transport model
   - Baryon-resonance model at SIS energies
   - Dileptons in pp and pNb reactions at HADES

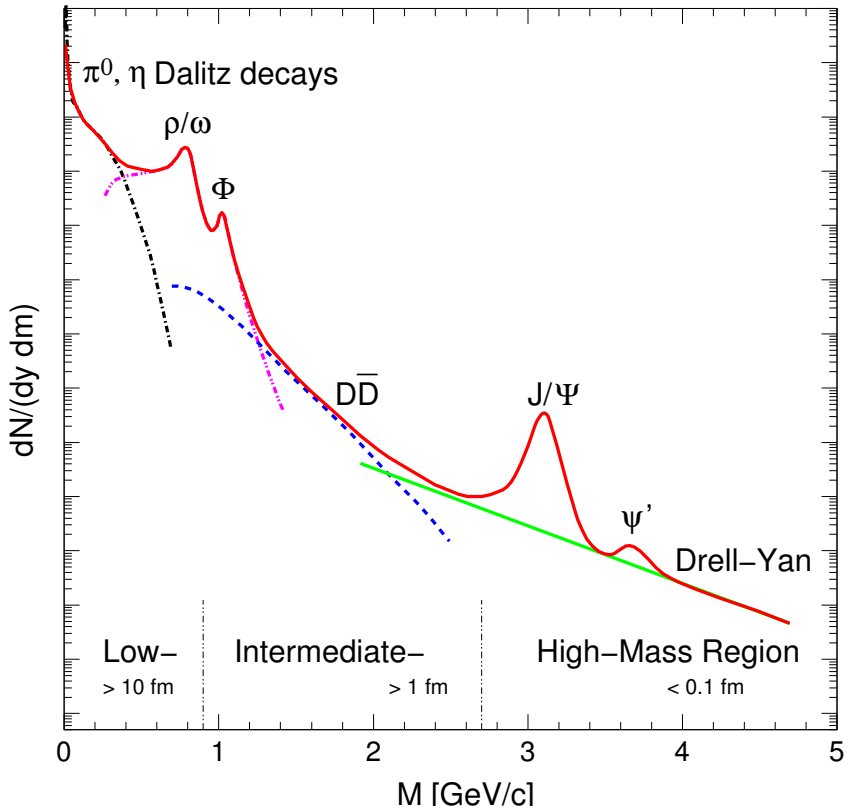
3. AA collisions with UrQMD (with S. Endres and M. Bleicher)
   - The transport model UrQMD
   - Baryon resonances and ρ-meson spectral function
   - Dileptons in CC and ArKCl at HADES

4. Conclusions and Outlook

Electromagnetic probes in heavy-ion collisions

- $\gamma, \ell^{\pm}$: no strong interactions
- reflect whole "history" of collision:
  - from pre-equilibrium phase
  - from thermalized medium QGP and hot hadron gas
  - from VM decays after thermal freezeout





[Fig. by A. Drees]

- vacuum and in-medium hadron properties needed!

[R. Rapp, J. Wambach, HvH, Landoldt-Börnstein, **I/23**, 4-1 (2010), arXiv: 0901.3289 [hep-ph]]

Electromagnetic Probes and Vector Mesons

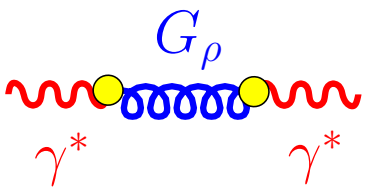
- $\ell^+\ell^-$ thermal emission rates $\Leftrightarrow$ em. current-correlation function, $\Pi_{\mu\nu}$

  [L. McLerran, T. Toimela 85, H. A. Weldon 90, C. Gale, J.I. Kapusta 91]

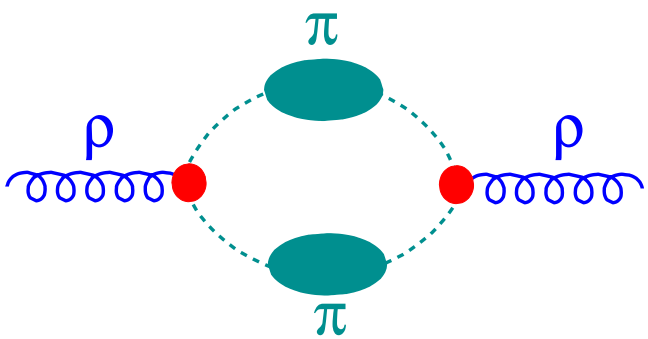
$$\frac{\mathrm{d}N_{e^+e^-}}{\mathrm{d}^4x\mathrm{d}^4q} = -g^{\mu\nu}\frac{\alpha^2}{3q^2\pi^3}\,\mathrm{Im}\,\Pi^{(\mathrm{ret})}_{\mu\nu}(q)\Big|_{q^2=M^2_{e^+e^-}} f_B(q_0)$$

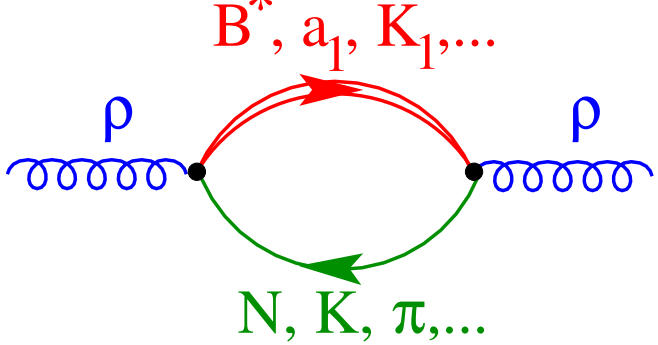
- vector-meson dominance model:

$$\Pi_{\mu\nu} =$$



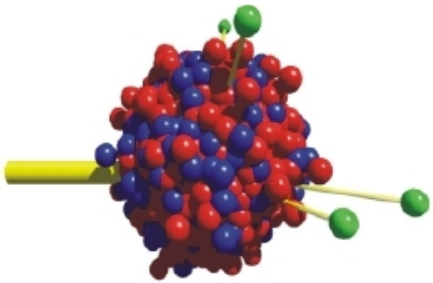
- hadronic many-body theory for vector mesons





- elementary processes $\Leftrightarrow$ cut self-energy diagrams

The GiBUU Model



GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- Boltzmann-Uehling-Uhlenbeck (BUU) framework for hadronic transport
- reaction types: pA, πA, γA, eA, νA, AA
- open-source modular Fortran 95/2003 code
- version control via Subversion
- publicly available realeases: http://gibuu.physik.uni-giessen.de
- Review: [O. Buss et al, Phys. Rept. 512, 1 (2012)]

The Boltzmann-Uehling-Uhlenbeck Equation

- time evolution of phase-space distribution functions

$$[\partial_t + (\vec{\nabla}_p H_i) \cdot \vec{\nabla}_x - (\vec{\nabla}_x H_i) \cdot \vec{\nabla}_p] f_i(t, \vec{x}, \vec{p}) = I_{\text{coll}}[f_1, \ldots, f_i, \ldots, f_j]$$

- Hamiltonian H_i
  - selfconsistent hadronic mean fields, Coulomb potential, "off-shell potential"
- collision term I_{coll}
  - two- and three-body decays/collisions
  - multiple coupled-channel problem
  - resonances described with relativistic Breit-Wigner distribution

$$\mathcal{A}(x,p) = -\frac{1}{\pi} \frac{\text{Im}\,\Pi}{(p^2 - M^2 - \text{Re}\,\Pi)^2 + (\text{Im}\,\Pi)^2}; \quad \text{Im}\,\Pi = -\sqrt{p^2}\Gamma$$

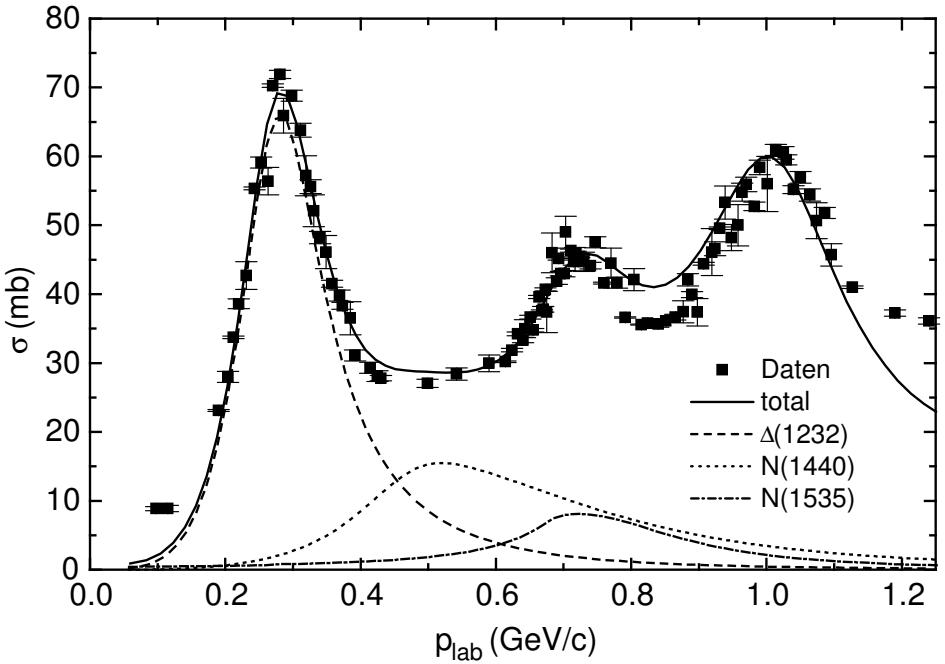
  - off-shell propagation: test particles with off-shell potential

Resonance Model

- reactions dominated by resonance scattering: $ab \to R \to cd$
- Breit-Wigner cross-section formula

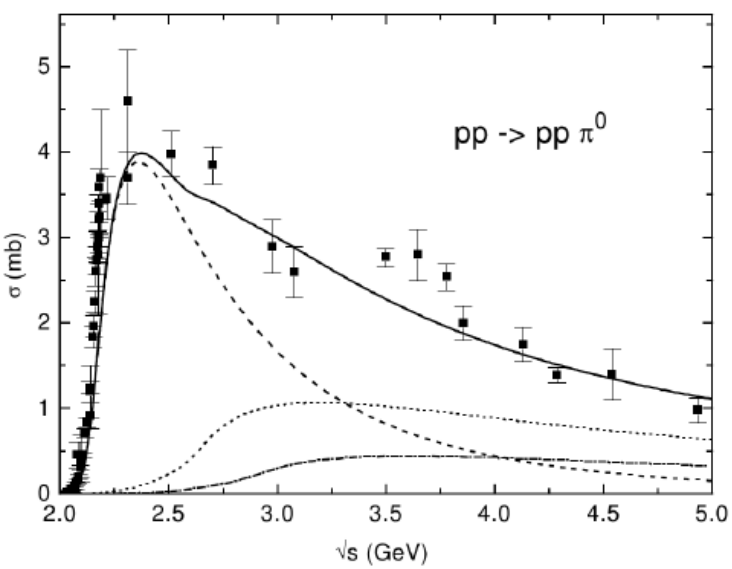
$$\sigma_{ab\to R\to cd} = \frac{2s_R+1}{(2s_a+1)(2s_b+1)} \frac{4\pi}{p_{\text{lab}}^2} \frac{s\Gamma_{ab\to R}\Gamma_{R\to cd}}{(s-m_R^2)^2 + s\Gamma_{\text{tot}}^2}$$

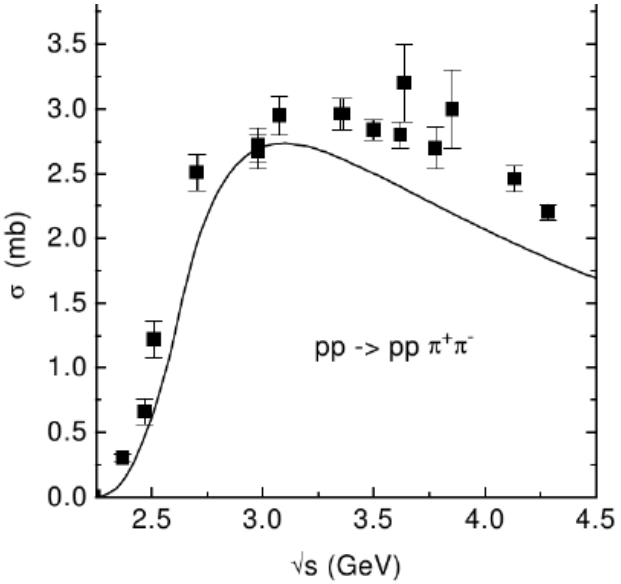
- applicable for low-energy nuclear reactions $E_{\text{kin}} \lesssim 1.1$ GeV
- example: $\sigma_{\pi^- p\to\pi^- p}$ [Teis (PhD thesis 1996), data: Baldini et al, Landolt-Börnstein **12** (1987)]

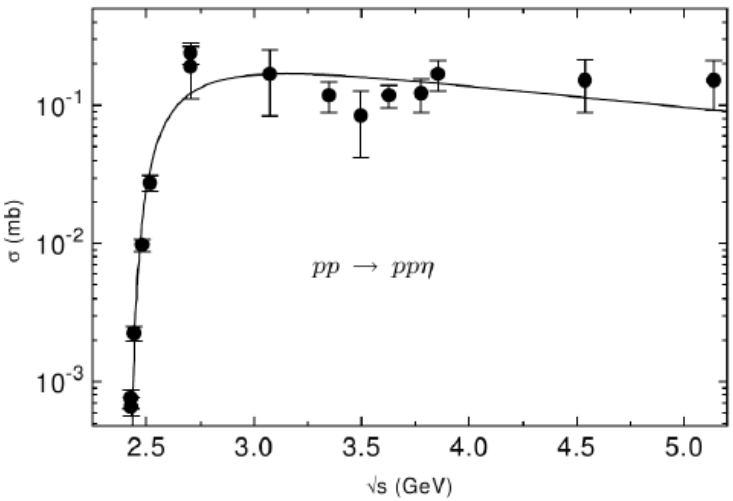


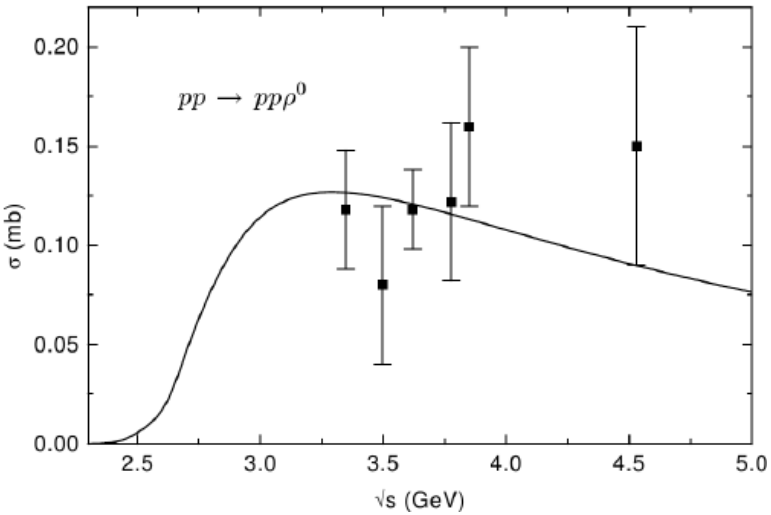
Resonance Model

- further cross sections









Extension to HADES energies

- keep same resonances (parameters from Manley analysis)

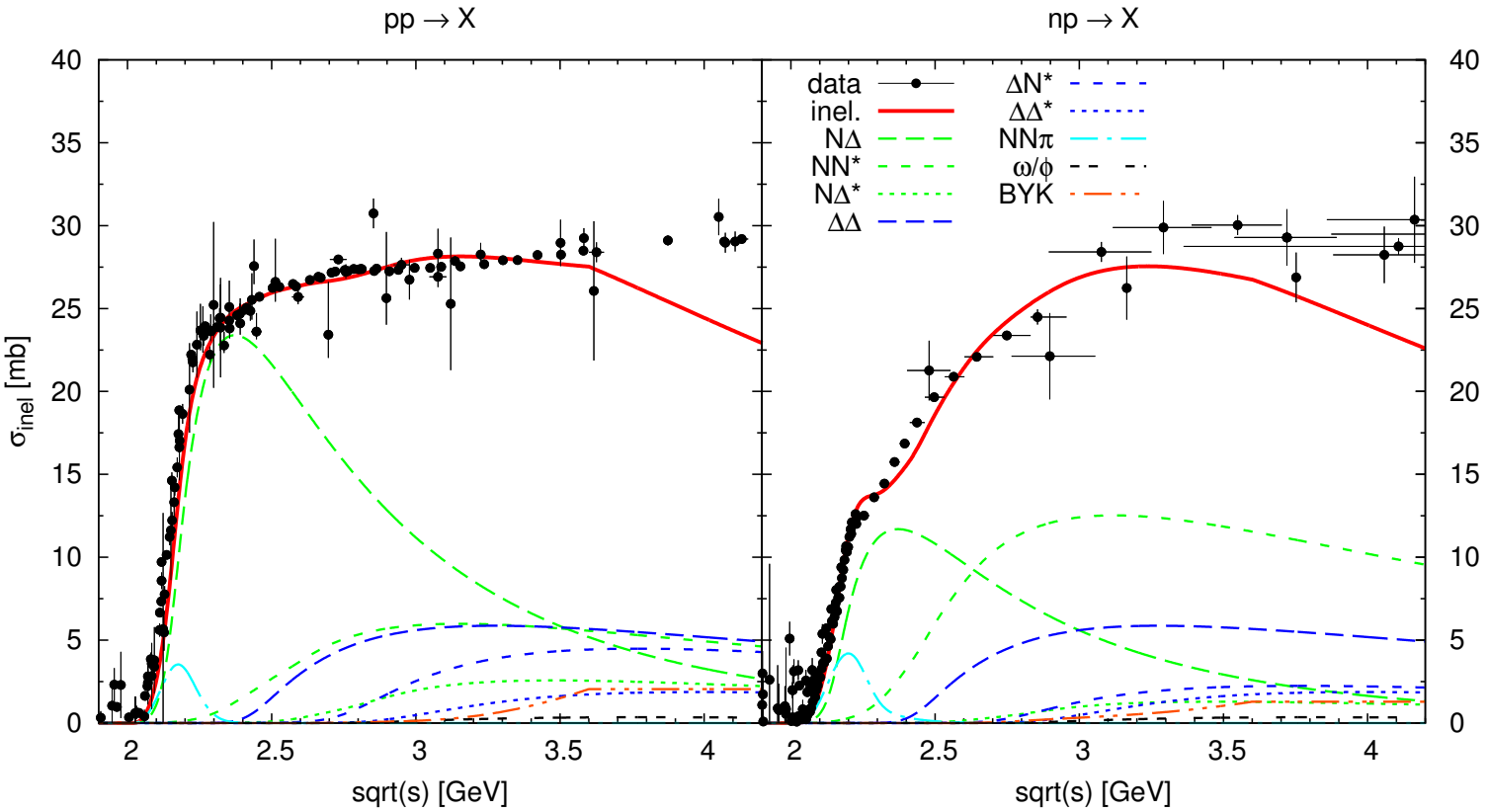
	rating	M_0 [MeV]	Γ_0 [MeV]	$\lvert\mathcal{M}^2\rvert/16\pi$ [mb GeV^2] NR	ΔR	branching ratio in % πN	ηN	$\pi\Delta$	ρN	σN	$\pi N^*(1440)$	$\sigma\Delta$
$P_{11}(1440)$	****	1462	391	70	—	69	—	22_P	—	9	—	—
$S_{11}(1535)$	***	1534	151	8	60	51	43	—	$2_S + 1_D$	1	2	—
$S_{11}(1650)$	****	1659	173	4	12	89	3	2_D	3_D	2	1	—
$D_{13}(1520)$	****	1524	124	4	12	59	—	$5_S + 15_D$	21_S	—	—	—
$D_{15}(1675)$	****	1676	159	17	—	47	—	53_D	—	—	—	—
$P_{13}(1720)$	*	1717	383	4	12	13	—	—	87_P	—	—	—
$F_{15}(1680)$	****	1684	139	4	12	70	—	$10_P + 1_F$	$5_P + 2_F$	12	—	—
$P_{33}(1232)$	****	1232	118	OBE	210	100	—	—	—	—	—	—
$S_{31}(1620)$	**	1672	154	7	21	9	—	62_D	$25_S + 4_D$	—	—	—
$D_{33}(1700)$	*	1762	599	7	21	14	—	$74_S + 4_D$	8_S	—	—	—
$P_{31}(1910)$	****	1882	239	14	—	23	—	—	—	—	67	10_P
$P_{33}(1600)$	***	1706	430	14	—	12	—	68_P	—	—	20	—
$F_{35}(1905)$	***	1881	327	7	21	12	—	1_P	87_P	—	—	—
$F_{37}(1950)$	****	1945	300	14	—	38	—	18_F	—	—	—	44_F

- production channels in Teis: $NN \to N\Delta$, $NN \to NN^*, N\Delta^*$, $NN \to \Delta\Delta$
- extension to $NN \to \Delta N^*, \Delta\Delta^*$, $NN \to NN\pi$, $NN \to NN\rho, NN\omega, NN\pi\omega, NN\phi$, $NN \to BYK$ $(B = N, \Delta,\ Y = \Lambda, \Sigma)$

[J. Weil, HvH, U. Mosel, arXiv:1203.3557[nucl-th]]

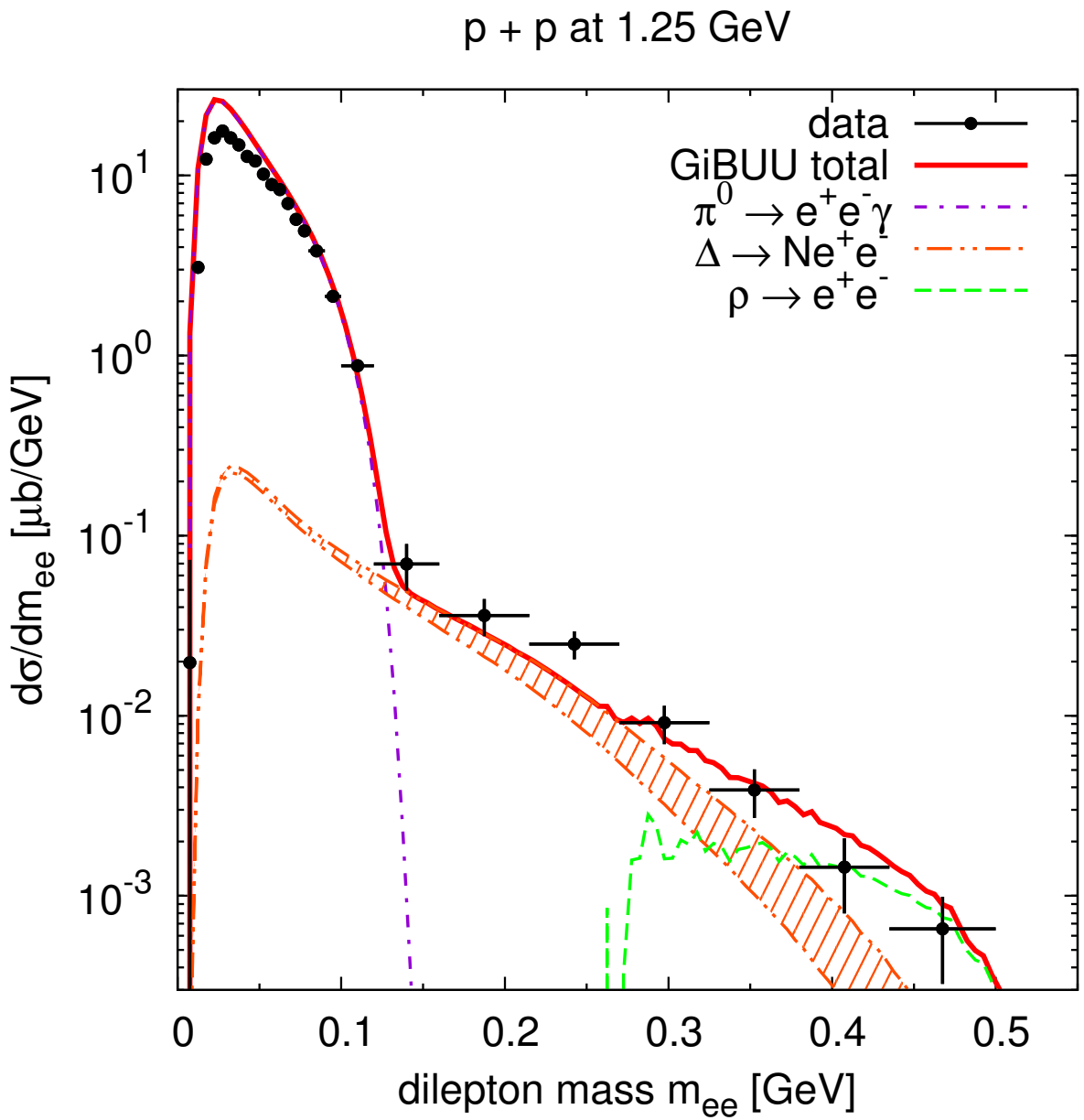
Extension to HADES energies

- good description of total pp, pn (inelastic) cross section

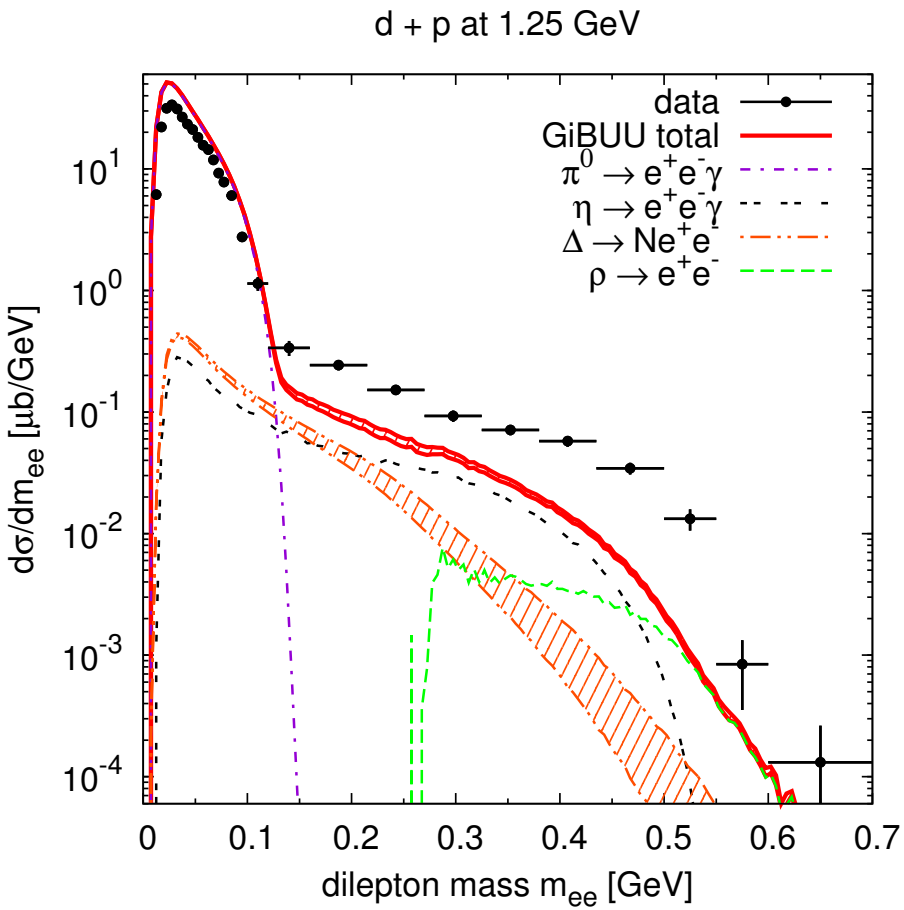


- dilepton sources
  - Dalitz decays: $\pi^0, \eta \to \gamma \ell^+\ell^-$; $\omega \to \pi^0 \ell^+\ell^-$, $\Delta \to N\ell^+\ell^-$
  - $\rho, \omega, \phi \to \ell^+\ell^-$: invariant mass $\ell^+\ell^-$ spectra $\Rightarrow$ spectral properties of vector mesons

p p at HADES ($E_{\mathrm{kin}} = 1.25$ GeV)

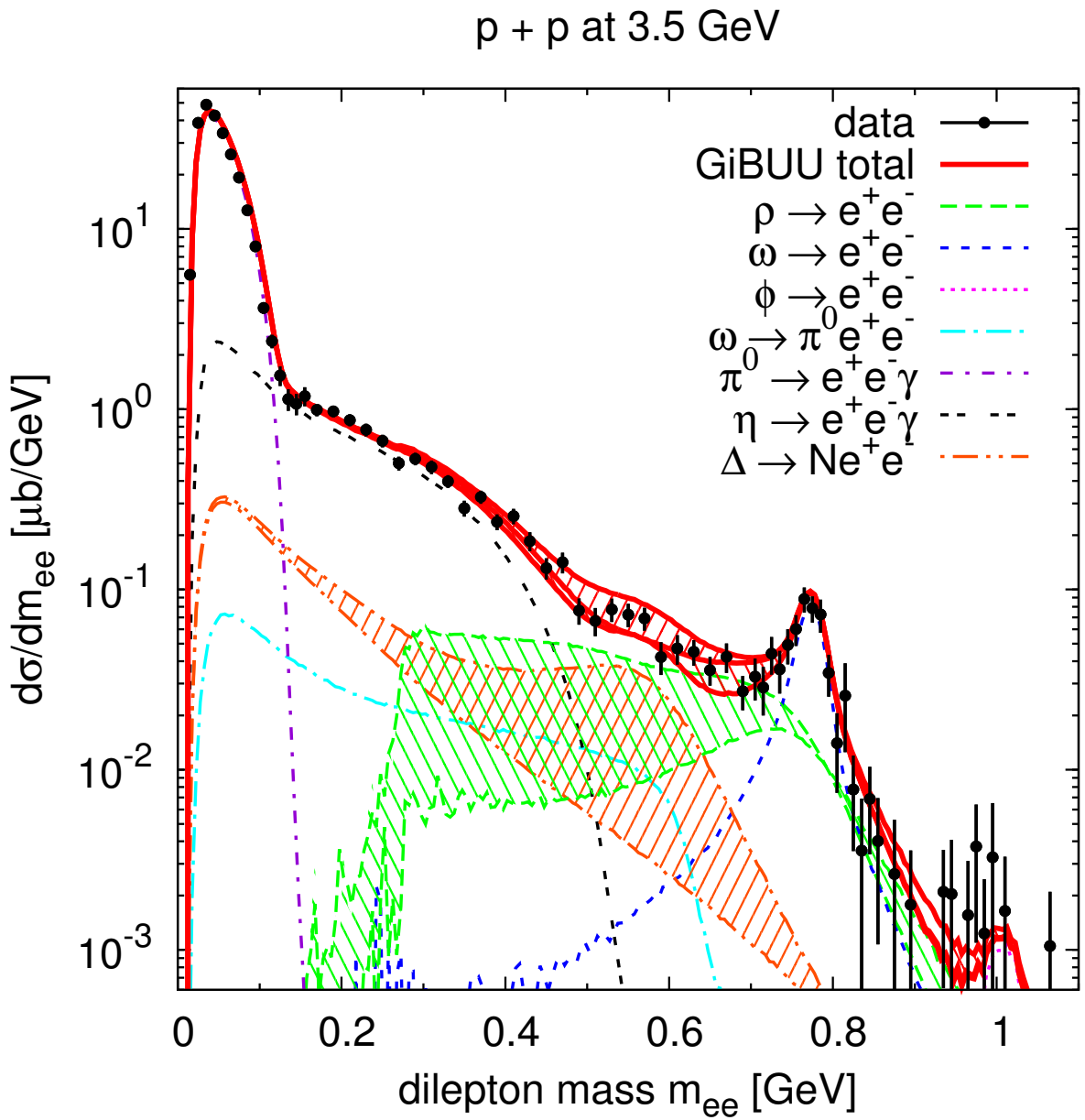


d p at HADES ($E_{\mathrm{kin}} = 1.25$ GeV)

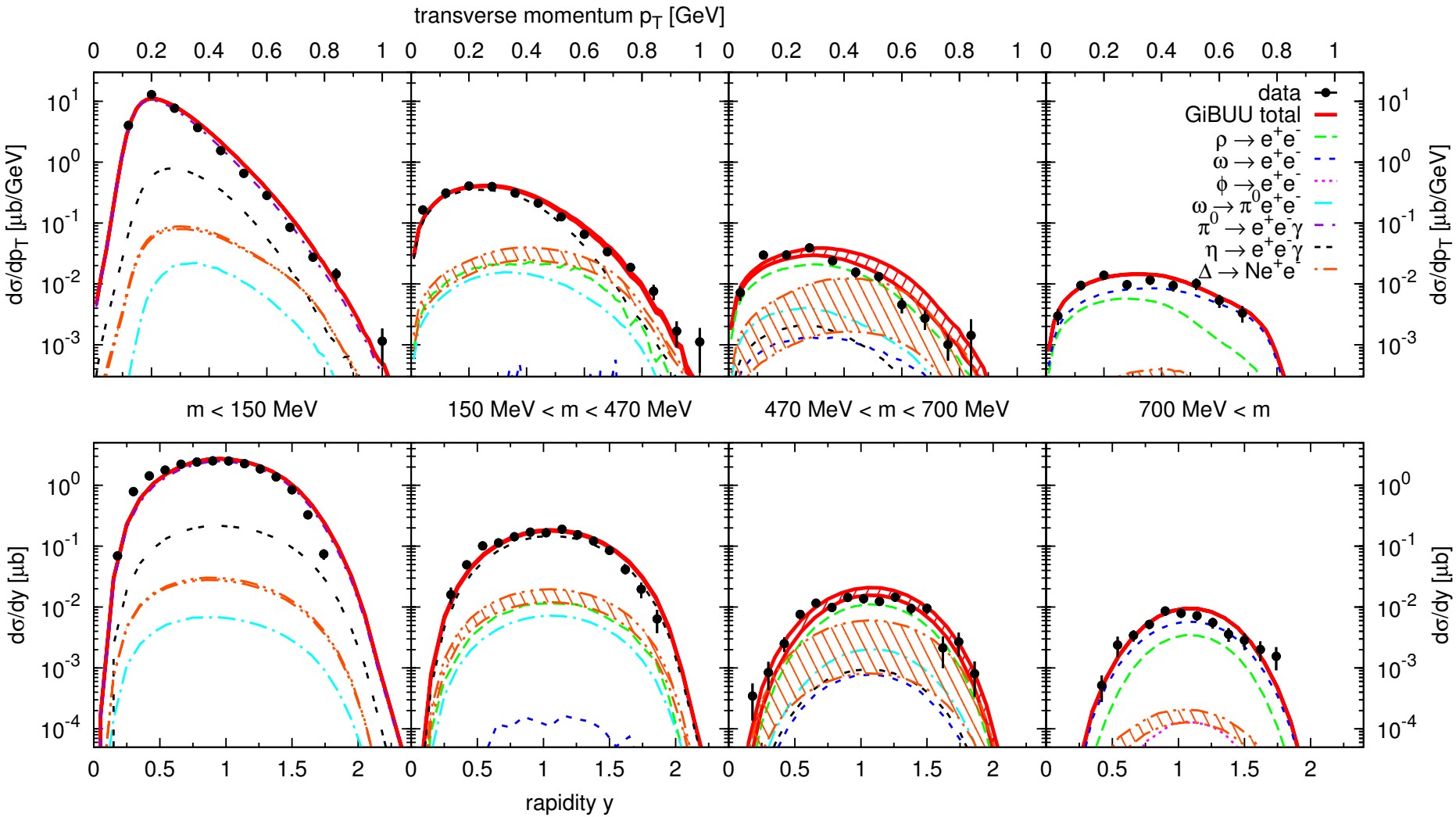


- triggered on forward protons $\rightarrow$ quasifree np scattering
- model uncertainties:
  - ρ production through $D_{13}(1525)$ (isospin symmetric?)
  - $S_{11}(1535)$ [enhanced in np; (from η production)]
  - d-wave function treatable as quasiclassical "distribution"?

p p at HADES ($E_{\mathrm{kin}} = 3.5$ GeV)

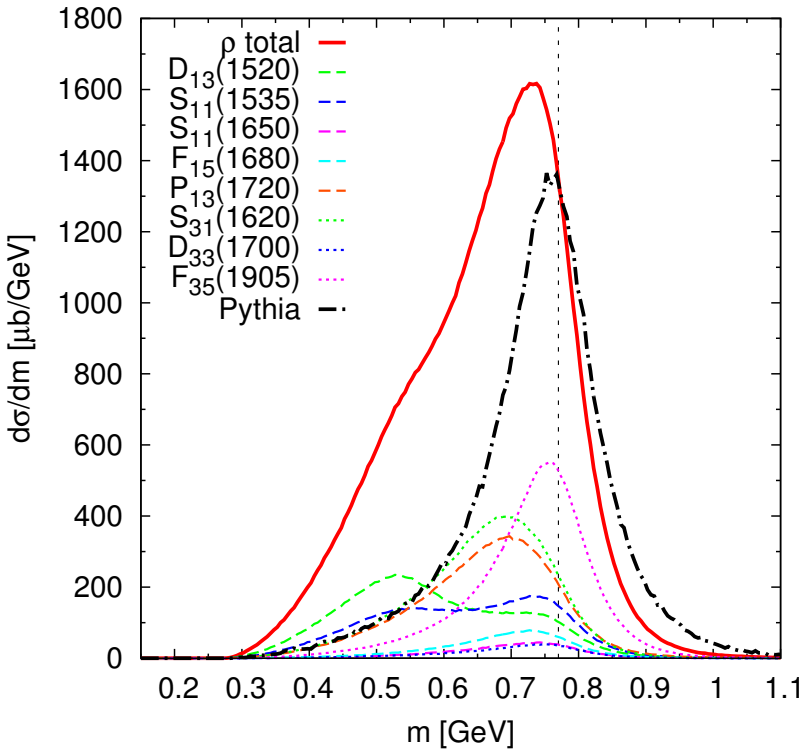


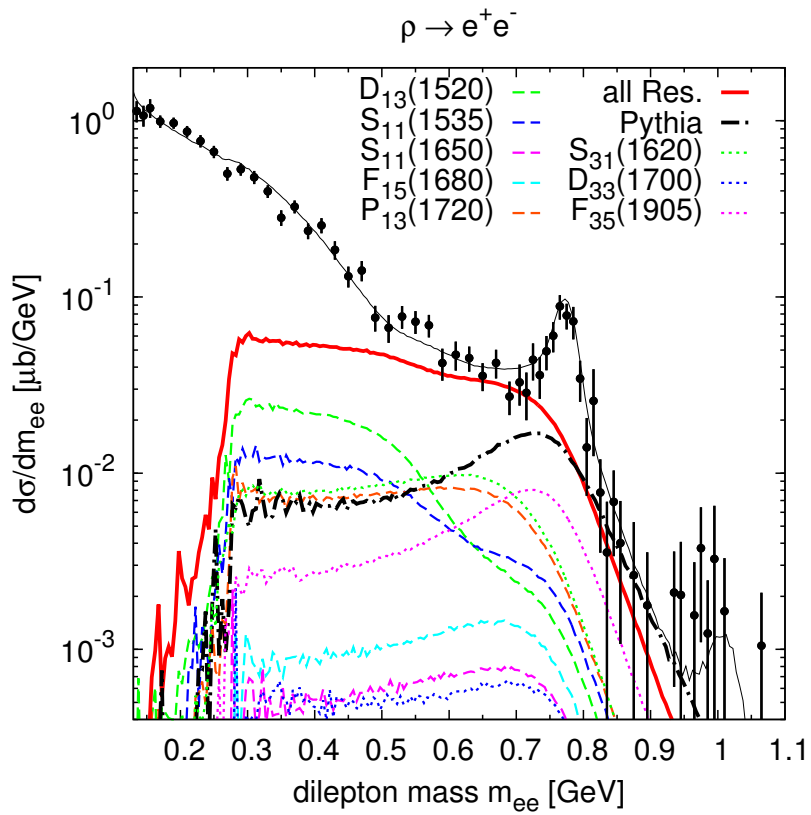
p p at HADES ($E_{\mathrm{kin}} = 3.5$ GeV)



"ρ meson" in pp

- production through hadron resonances
  $NN \to NR \to NN\rho$, $NN \to N\Delta \to NN\pi\rho$





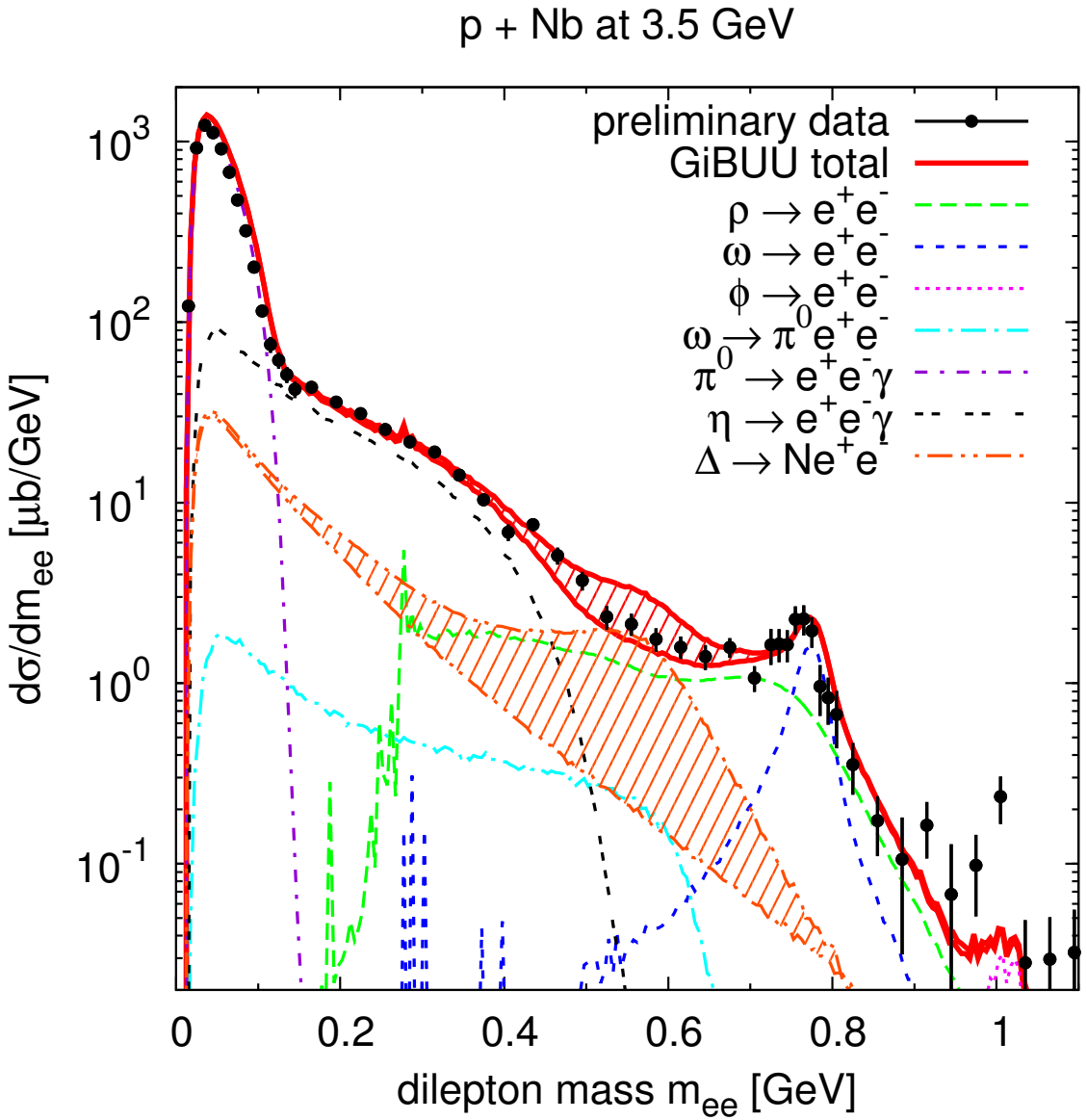
- "ρ"-line shape "modified" already in elementary hadronic reactions
- due to production mechanism via resonances

p Nb at HADES (3.5 GeV)

- medium effects built in transport model
  - binding effects, Fermi smearing, Pauli blocking
  - final-state interactions
  - production from secondary collisions
- sensitivity to additional in-medium modifications of vector mesons?

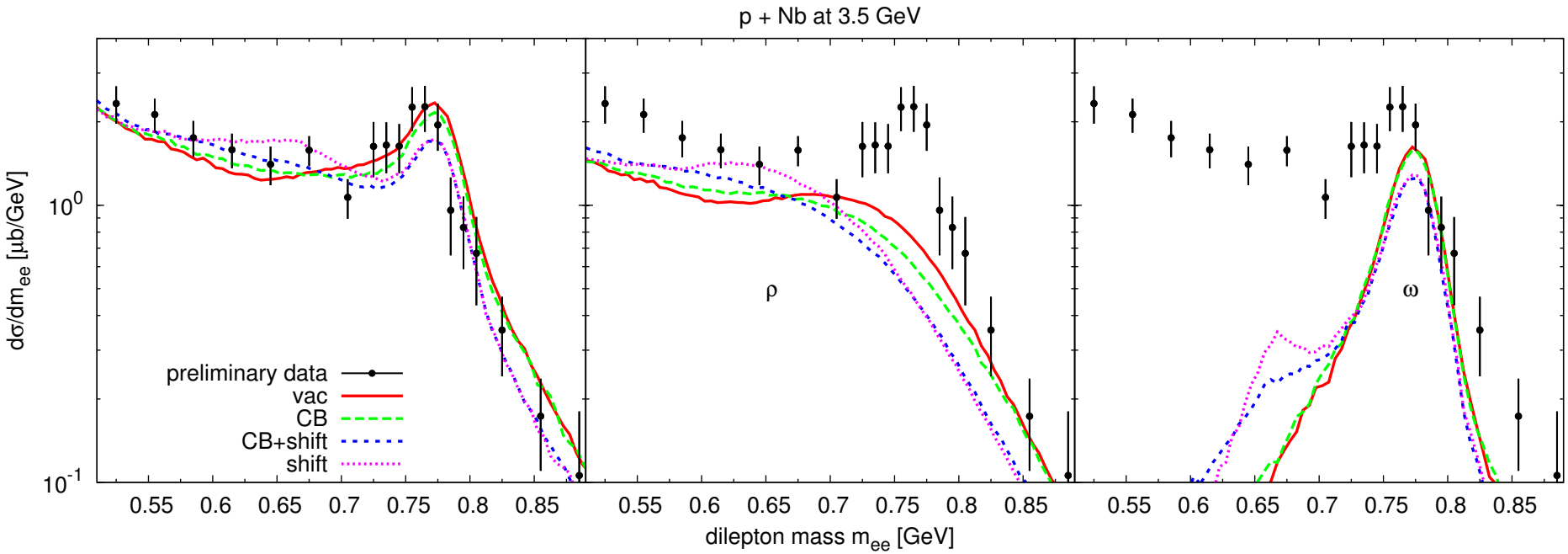
p Nb at HADES (3.5 GeV)

- with vacuum spectral functions:



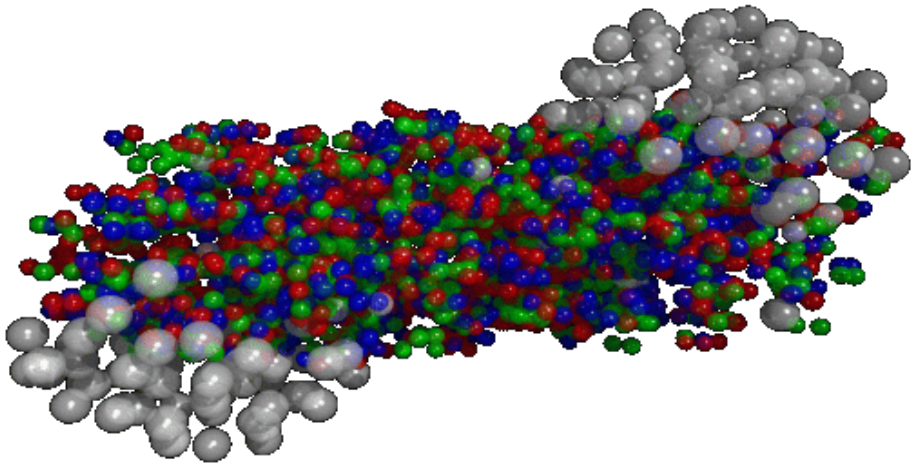
p Nb at HADES (3.5 GeV)

- with medium modified spectral functions:



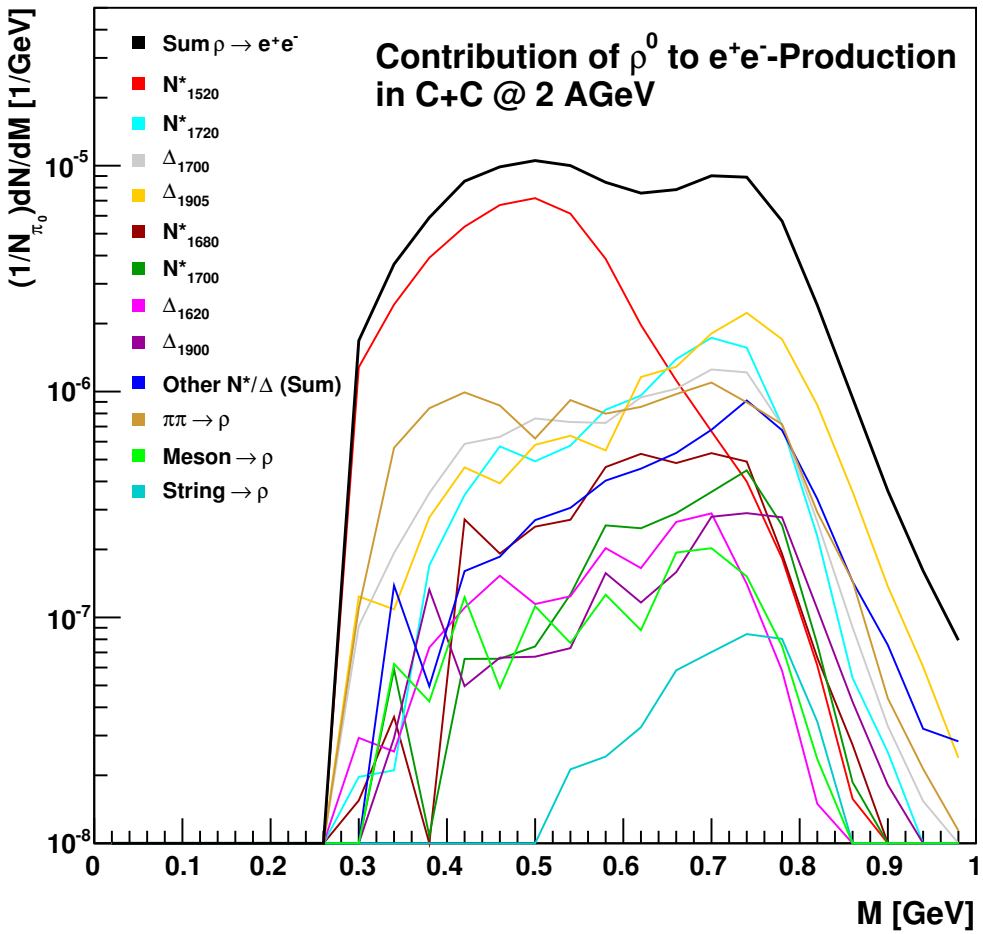
- no definite hint for medium modifications in p Nb

The UrQMD transport model



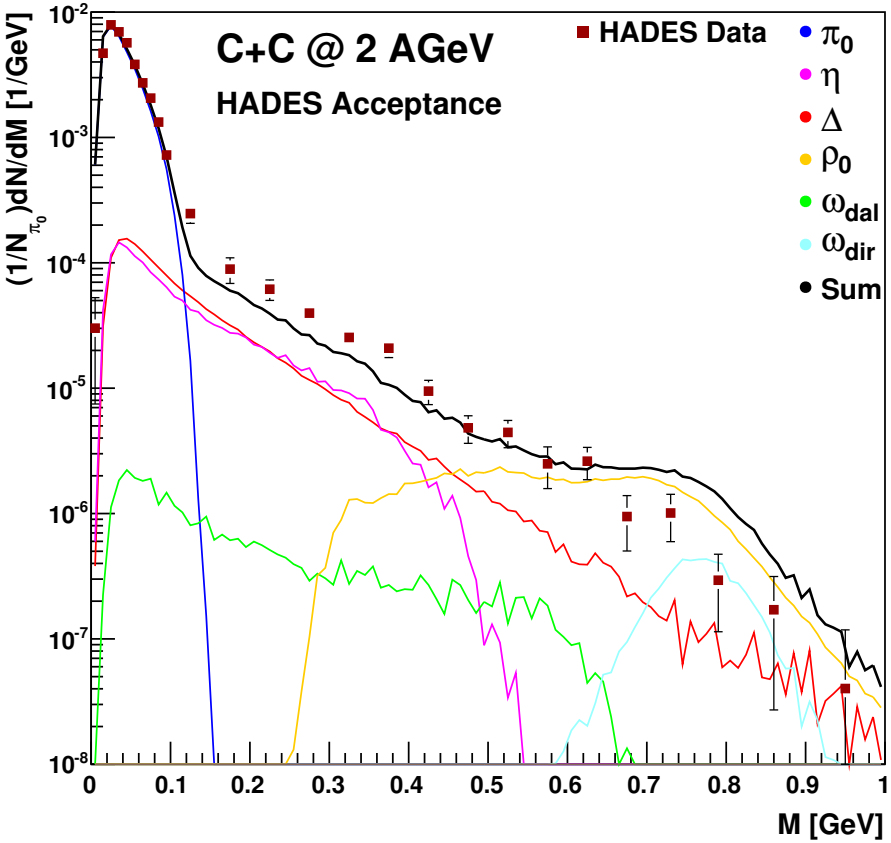
- BUU approach: Ultarelativistic Quantum Molecular Dynamics
- includes hadrons and hadron resonances up to 2.2 GeV
- particle production via string excitation and fragmentation
- constrained by available cross-section data
- no in-medium modifications
- open source! urqmd.org

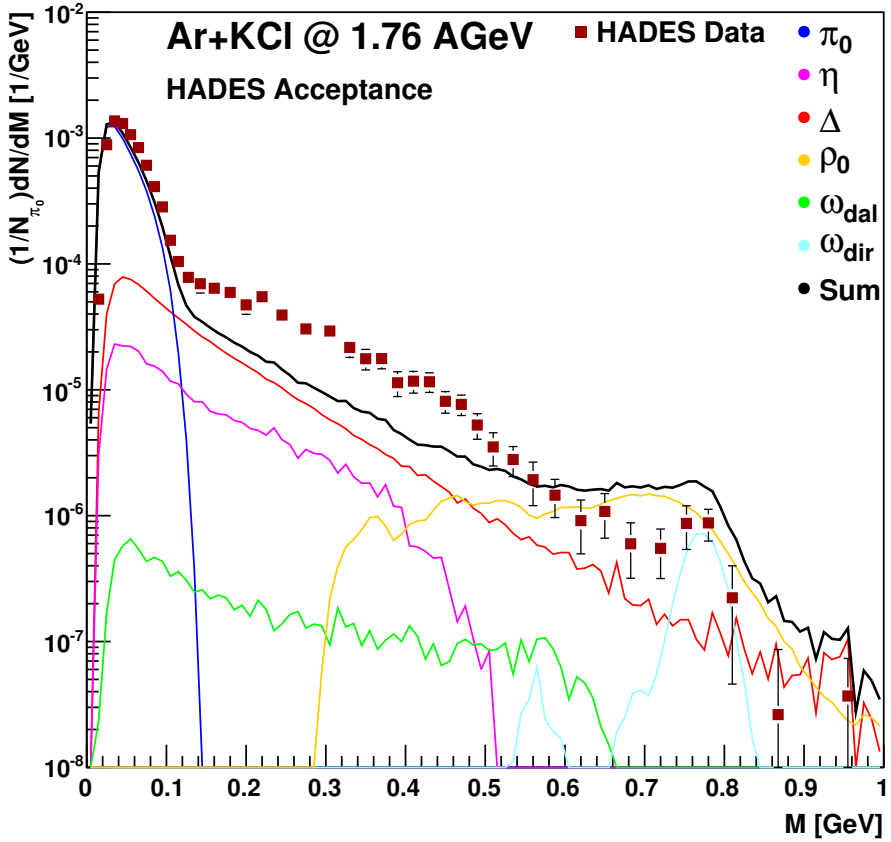
Baryon resonances and the ρ in UrQMD



- same principle as in the calculation with GiBUU
- different distribution of strength to channels
- uncertainty in empirical input!
- Important Caveat: never mix contributions from different models!

UrQMD vs. HADES in AA collisions (preliminary)





- overestimates ρ around the peak
- need better pp, np before sensitive in-medium modifications

Conclusions and Outlook

- dilepton spectra $\Leftrightarrow$ in-medium em. current correlator
- Vector meson in baryonic reactions
  - spectral form already "modified" in NN reactions compared to RPP
  - due to creation through baryon resonances
  - not uniquely constrained by cross-section/branching-ratio data
  - opportunity for pion beam at GSI/HADES and/or FAIR/CBM?!?
  - NB: same mechanism also crucial at higher energies (SPS, RHIC, LHC)!
- GiBUU
  - pp, np (dp) with resonance model for all HADES energies
  - np/dp still a problem?
  - p Nb fine
  - AA work in progress
- UrQMD (preliminary)
  - same baryon-resonance approach
  - "cocktail" different, but total result comparable
  - pretty good in describing AA data from HADES
  - sensitivity to medium effects under investigation!