Electromagnetic Probes in Heavy-Ion Collisions II

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September 5, 2012

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FIAS Frankfurt Institute for Advanced Studies

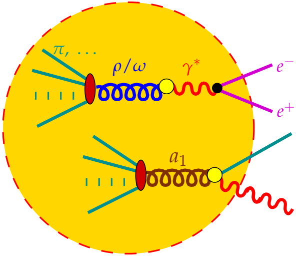
HIC for FAIR Helmholtz International Center

Outline

1. Electromagnetic probes and vector mesons
   - Relation to chiral symmetry
2. Elementary vacuum cross sections: hadrons $\rightarrow \ell^+\ell^-$
   - chiral symmetry constraints
   - Electrodynamics of pions and ρ mesons (VMD model)
   - Dalitz decays of hadron resonances
3. Dileptons in pp and pA collisions at SIS energies
   - The Transport Model GiBUU
   - Baryon-resonance model at SIS energies
   - Dileptons in pp and pNb reactions at HADES
4. Conclusions and Outlook

Why Electromagnetic Probes?

- $\gamma, \ell^{\pm}$: only e. m. interactions
- whole matter evolution



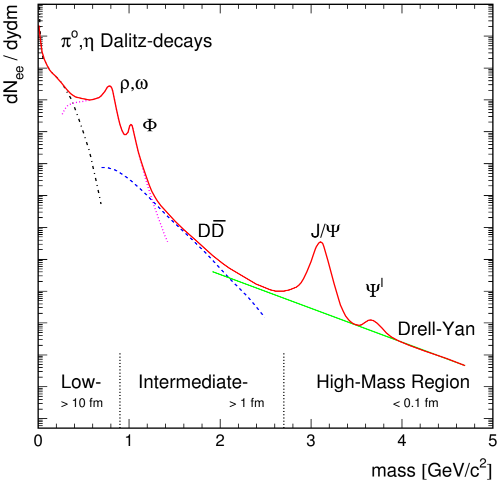


Fig. by A. Drees (from [RW00])

Vector Mesons and electromagnetic Probes

- photon and dilepton thermal emission rates given by same electromagnetic-current-correlation function ($J_\mu = \sum_f Q_f \overline{\psi_f} \gamma_\mu \psi_f$)

$$\Pi^{<}_{\mu\nu}(q) = \int \mathrm{d}^4 x \exp(\mathrm{i} q \cdot x) \left\langle J_\mu(0) J_\nu(x) \right\rangle_T = -2 n_B(q_0) \,\mathrm{Im}\, \Pi^{(\mathrm{ret})}_{\mu\nu}(q)$$

$$q_0 \frac{\mathrm{d}N_\gamma}{\mathrm{d}^4 x \mathrm{d}^3 \vec{q}} = -\frac{\alpha_{\mathrm{em}}}{2\pi^2} g^{\mu\nu} \,\mathrm{Im}\, \Pi^{(\mathrm{ret})}_{\mu\nu}(q) \Big|_{q_0 = |\vec{q}|} f_B(p_0)$$

$$\frac{\mathrm{d}N_{e^+ e^-}}{\mathrm{d}^4 x \mathrm{d}^4 k} = -g_{\mu\nu} \frac{\alpha^2}{3 q^2 \pi^3} \,\mathrm{Im}\, \Pi^{(\mathrm{ret})}_{\mu\nu}(q) \Big|_{q^2 = M^2_{e^+ e^-}} f_B(p_0)$$

- Caveat: NOT manifestly Lorentz covariant $\Leftrightarrow$ heat-bath rest frame!
- to lowest order in α: $4\pi\alpha \Pi_{\mu\nu} \simeq \Sigma^{(\gamma)}_{\mu\nu}$
- derivable from underlying thermodynamic potential, Ω!

Vector Mesons and chiral symmetry

- vector and axial-vector mesons $\leftrightarrow$ respective current correlators

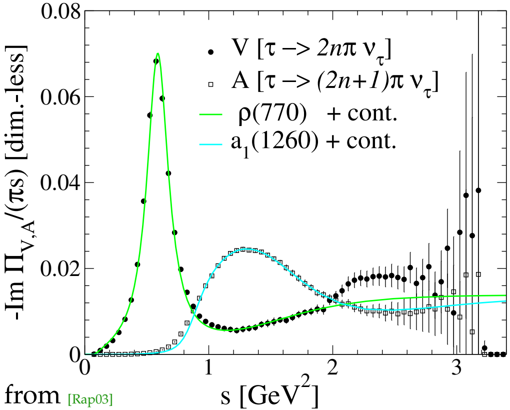
$$\Pi^{\mu\nu}_{V/A}(p) := \int \mathrm{d}^4 x \exp(\mathrm{i}px) \left\langle J^{\nu}_{V/A}(0) J^{\mu}_{V/A}(x) \right\rangle_{\text{ret}}$$

- Ward-Takahashi Identities of χ symmetry $\Rightarrow$ Weinberg-sum rules

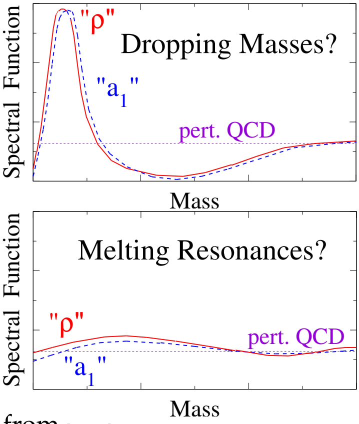
$$f_\pi^2 = -\int_0^\infty \frac{\mathrm{d}p_0^2}{\pi p_0^2} [\mathrm{Im}\,\Pi_V(p_0,0) - \mathrm{Im}\,\Pi_A(p_0,0)]$$

- spectral functions of vector (e.g. ρ) and axial vector (e.g. a_1) directly related to order parameter of chiral symmetry!

Vector Mesons and chiral symmetry



from [Rap03]



from [Rap05]

Chiral-symmetry constraints

- different realizations of chiral symmetry
- equivalent only on shell ("low-energy theorems")
- model-independent conclusions only in low-temperature/density limit (chiral perturbation theory) or from lattice-QCD calculations
- QCD sum rules (see Lect. I):
  allow for dropping-mass or melting-resonance scenario
- use phenomenological hadronic many-body theory (HMBT) to assess medium modifications of vector mesons
  - build models with hadrons as effective degrees of freedom
  - based on (chiral) symmetries
  - constrained by data on cross sections, branching ratios,... in vacuum
  - in-medium properties assessed by many-body (thermal) field theory

Example: vector-meson dominance model

- early model for electromagnetic interaction of charged pions
  [Sak60, KLZ67, GS68, Her92, Hee00]
- QED like U(1)-gauge model with massive vector meson for ρ_0 and $\pi^\pm$
- Stückelberg: introduce auxiliary scalar field for free vector mesons:

$$\mathscr{L}_\rho = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} m^2 V_\mu V^\mu + \frac{1}{2} (\partial_\mu \varphi)(\partial^\mu \varphi) + m \varphi \partial_\mu V^\mu$$

- gauge invariant under local transformation

$$\delta V_\mu(x) = \partial_\mu \chi(x), \quad \delta\varphi = m\chi(x)$$

- usual way of gauge fixing using gauge condition

$$\partial_\mu V^\mu = -\xi m \varphi$$

- effective Lagrangian of free ρ meson, Stückelberg and FP ghosts

$$\mathscr{L}_{\rho,\text{gf}} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{m}{2} V_\mu V^\mu - \frac{1}{2\xi} (\partial_\mu V^\mu)^2 + \frac{1}{2} (\partial_\mu \varphi)(\partial_\mu \varphi) - \frac{\xi m^2}{2} \varphi^2$$
$$+ (\partial_\mu \eta^*)(\partial_\mu \eta) - \xi m^2 \eta^* \eta$$

Example: vector-meson dominance model

- so far: free ρ meson and free ghosts
- ghosts only relevant for ideal gas thermodynamics
  - V^{μ}: four bosonic field degrees (3 transverse with mass m, 1 longitudial with mass $\sqrt{\xi}m$)
  - φ: 1 bosonic Stückelberg ghost with mass $\sqrt{\xi}m$
  - η^*, η: 2 pseudofermionic Faddeev Popov fields with mass $\sqrt{\xi}m$
  - in partition sum: 3 bosons with mass m + 2 bosons with mass $\sqrt{\xi}m$ − 2 FP ghosts with mass $\sqrt{\xi}m \Rightarrow$ effectively three bosons with mass m
  - partition sum independent of gauge parameter, ξ!
  - $\xi \to \infty$: "unitary gauge" $\to$ only three bosonic ρ-degrees of freedom!
- Coupling to pions: obey gauge invariance! (like scalar QED)

$$\mathscr{L}_{\pi} = (\mathrm{D}_{\mu}\pi)^{*}(D^{\mu}\pi) - m_{\pi}^{2}|\pi|^{2} - \frac{\lambda}{8}|\pi|^{4}$$

- $\mathrm{D}_{\mu} = \partial_{\mu} + \mathrm{i}gV_{\mu}$; g: $\rho\pi\pi$ coupling

Example: vector-meson dominance model

- add photons: $\mathrm{D}_\mu = \partial_\mu + \mathrm{i} g V_\mu + \mathrm{i} e A_\mu$
- Lagrangian for photons: usual gauge fixed QED
- additional direct $\rho\gamma$ mixing [KLZ67]

$$\mathscr{L}_{\rho\gamma} = -\frac{e}{2 g_{\rho\gamma}} V_{\mu\nu} A^{\mu\nu}$$

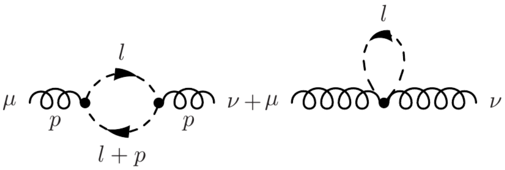
- classical field equations: $\Rightarrow$ electromagnetic current

$$j_{\text{em}}^{\nu} = \partial_\mu A^{\mu\nu} = \mathrm{i} e \left(1 - \frac{g}{g_{\rho\gamma}}\right) \pi \overleftrightarrow{\mathrm{D}}^{\nu} \pi^* + \frac{e}{g_{\rho\gamma}} m^2 V^\mu + \frac{e^2}{g_{\rho\gamma}^2} \partial_\mu A^{\mu\nu}$$

- for $g_{\rho\gamma} = g$: $j_{\text{em}}^{\nu} = \frac{e}{g} m^2 V^\nu + \mathcal{O}(e^2)$: $\Rightarrow$ "vector-meson dominance"

Example: vector-meson dominance model

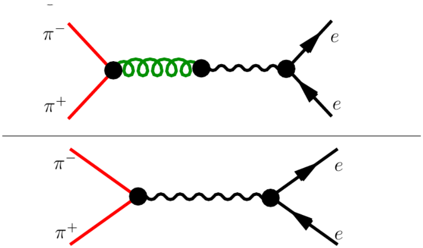
- calculate ρ selfenegy

$i\Sigma_\rho^{\mu\nu}(p) =$ 

- transversality from gauge invariance:

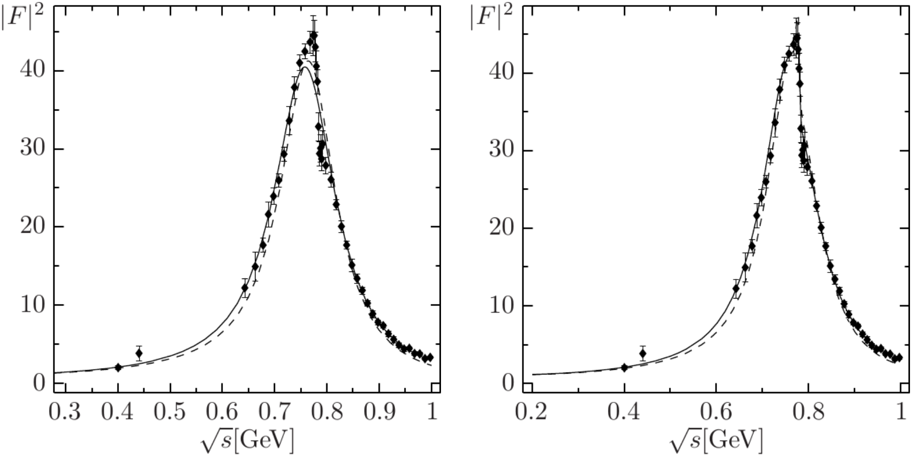
$$\Sigma_\rho^{\mu\nu}(q) = \left(q^2 g^{\mu\nu} - q^\mu q^\nu\right) \tilde{\Sigma}(q^2)$$

- electromagnetic form factor of pions

$F(k^2) =$ 

Example: vector-meson dominance model

- fit to observables: em. form factor of π

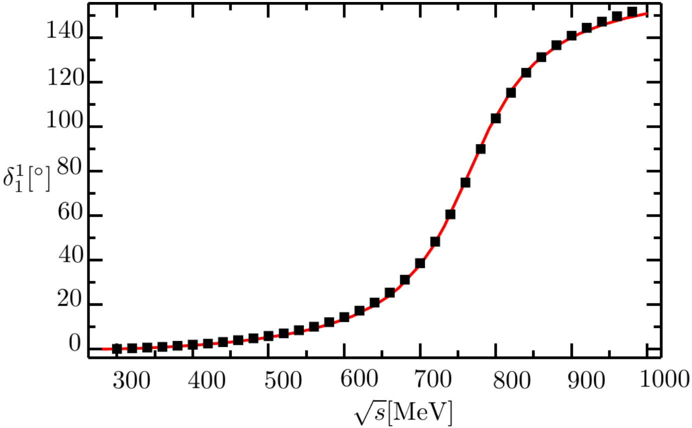


- best fit: $g = 5.683, g_{\rho\gamma} = 5.171, m_\rho = 765\ \mathrm{MeV}/c^2$
  strict VMD: $g = g_{\rho\gamma} = 5.38, m_\rho = 770\ \mathrm{MeV}/c^2$
  data: [B+85]

Example: vector-meson dominance model

- $\pi\pi \to \pi\pi$ phase shift in $I = 1$ channel

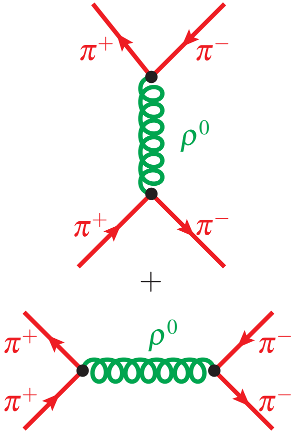
$$\delta_1^1 = \arccos \frac{\mathrm{Re}\, G_\rho}{|G_\rho|}$$

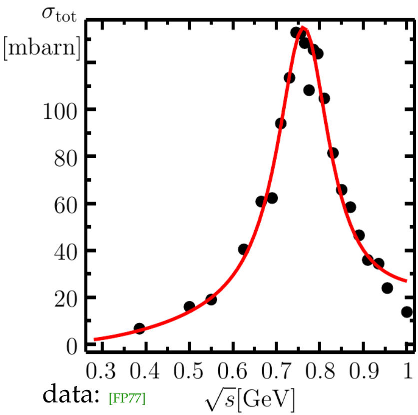


data: [FP77]

Example: vector-meson dominance model

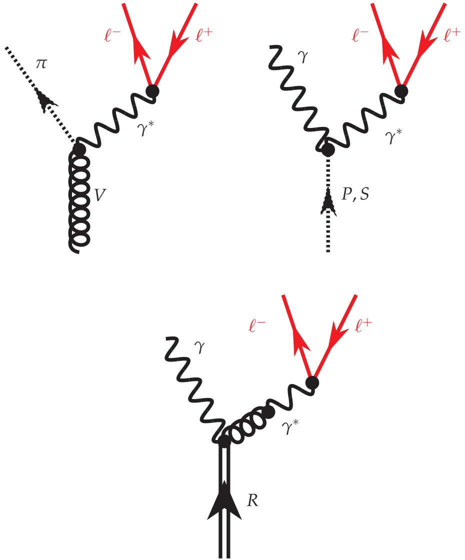
- $\pi\pi \to \pi\pi$ total cross section



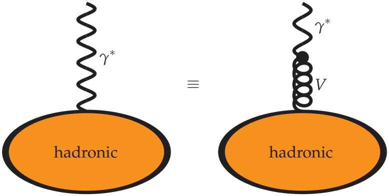


data: [FP77]

Dalitz decays



- Dalitz decay:
  1 particle $\rightarrow$ 3 particles
- V: $\omega \rightarrow \pi + \gamma^* \rightarrow \pi + \ell^+ + \ell^-$
- P, S:
  $\pi, \eta \rightarrow \gamma + \gamma^* \rightarrow \gamma + \ell^+ + \ell^-$
- R: Baryon resonances
  $\Delta, N^* \rightarrow N + V \rightarrow N + \gamma^* \rightarrow N + \ell^+ + \ell^-$
- vector-meson dominance



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 on hadronic transport (GiBUU): [BGG+12]

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

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

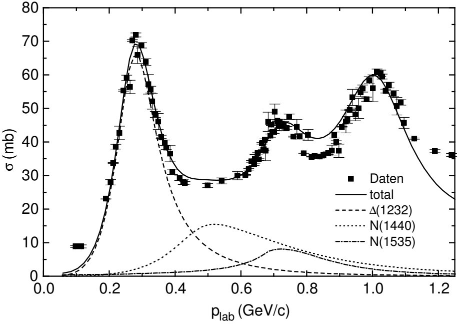
  - off-shell propagation: test particles with off-shell potential

Resonance Model

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

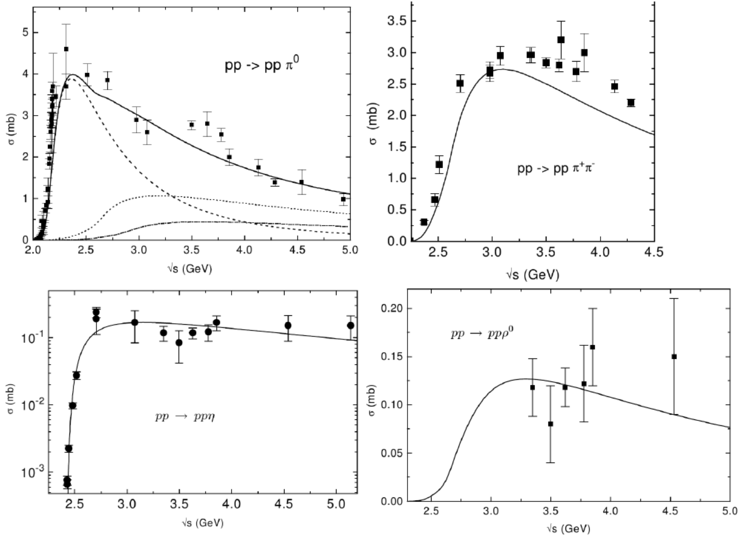
$$\sigma_{ab \to R \to cd} = \frac{2s_R + 1}{(2s_a + 1)(2s_b + 1)} \frac{4\pi}{p_{\text{lab}}^2} \frac{s\Gamma_{ab \to R}\Gamma_{R \to cd}}{(s - m_R^2)^2 + s\Gamma_{\text{tot}}^2}$$

- 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



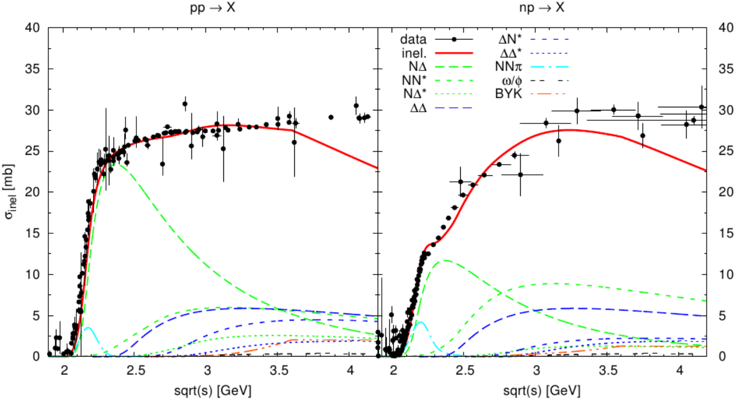
- [WHM12]
- keep same resonances (parameters from Manley analysis)

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

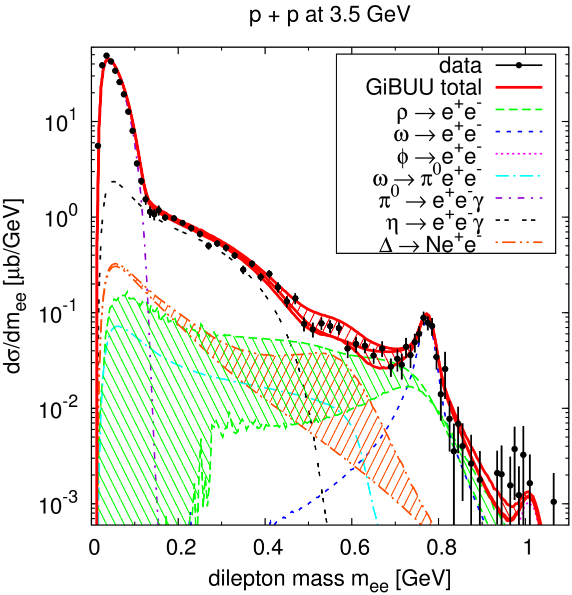
Extension to HADES energies

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

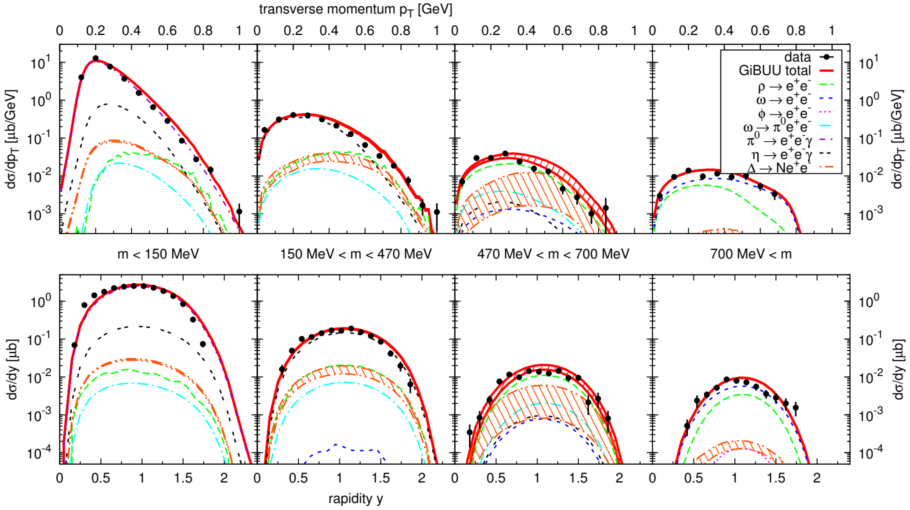


- dilepton sources
  - Dalitz decays: $\pi^0, \eta \to \gamma \ell^+ \ell^-$; $\omega \to \pi^0 \ell^+ \ell^-$, $\Delta \to N \ell^+ \ell^-$
  - $\rho, \omega, \phi \to \ell^+ \ell^-$: invariant mass $\ell^+ \ell^-$ spectra ⇒ spectral properties of vector mesons
  - for details, see [WHM12]

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

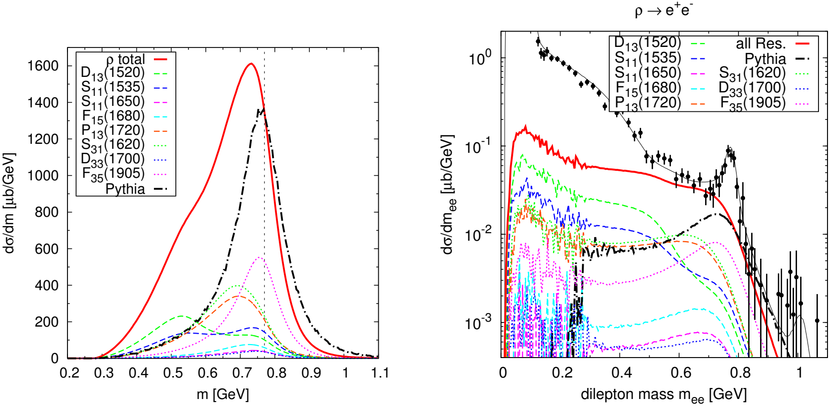


p p at HADES ($E_{kin} = 3.5$ GeV)



“ρ meson” in pp

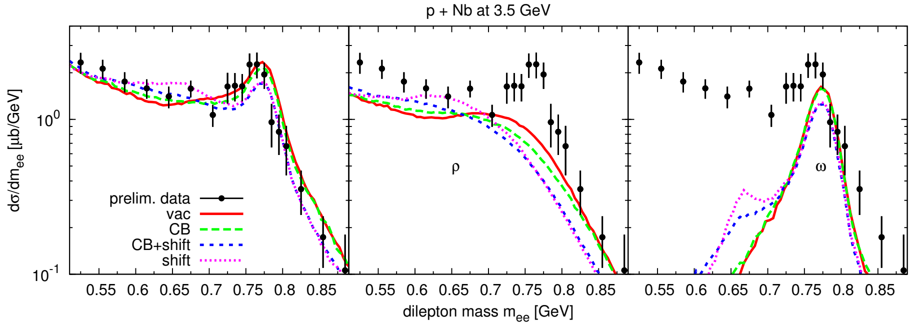
- production through hadron resonances
  $NN \to NR \to NN\rho$, $NN \to N\Delta \to NN\pi\rho$



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

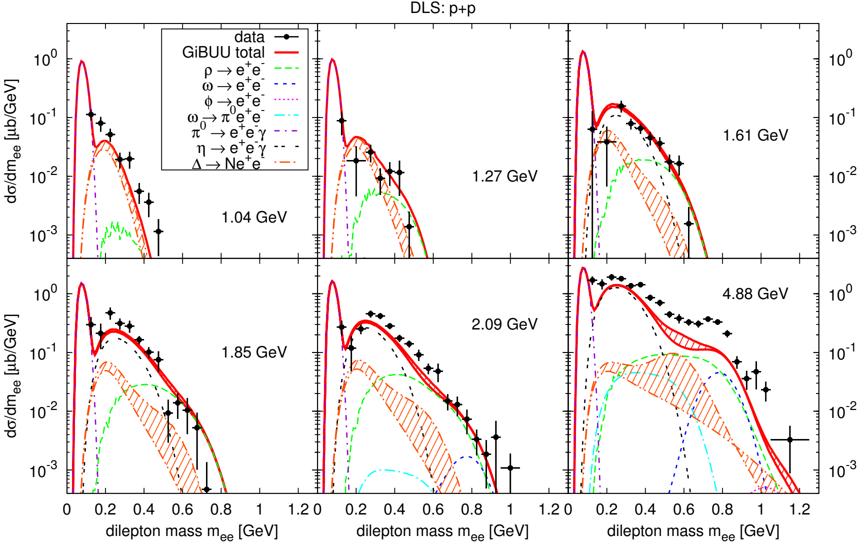
p Nb at HADES (3.5 GeV)

- medium effects built in transport model
  - binding effects, Fermi smearing, Pauli blocking
  - final-state interactions
  - production from secondary collisions
- sensitivity on medium effects of vector-meson spectral functions?



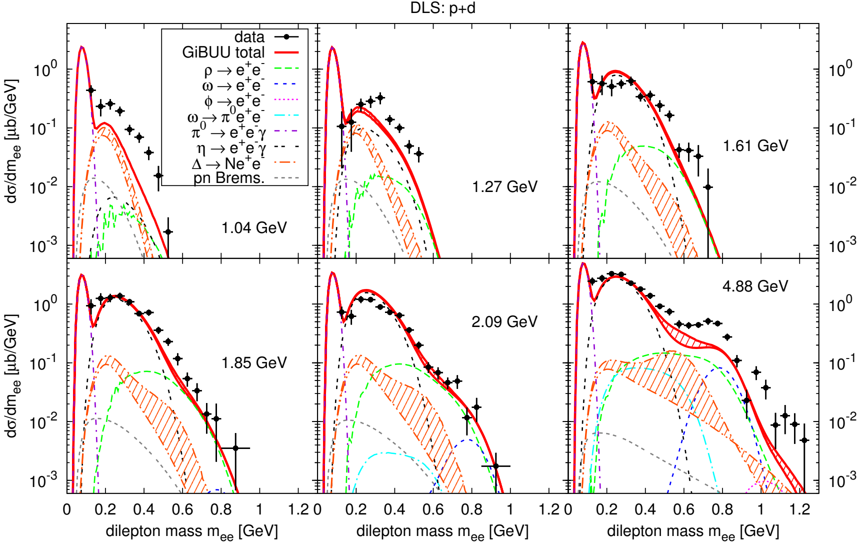
Comparison to old DLS data (pp)

- HADES data consistent with DLS data
- checked by comparing HADES data within DLS acceptance



Comparison to old DLS data (pd)

- HADES data consistent with DLS data
- checked by comparing HADES data within DLS acceptance



Conclusions and Outlook

- dilepton spectra $\Leftrightarrow$ in-medium em. current correlator
- effective hadronic models for dilepton sources
  - vector-meson dominance model (VMD)
  - low-mass region $0 \leq M \lesssim 1$ GeV: $j_{\text{em}}^{(\text{had})\mu} \propto V^{\mu}$ $(V \in \{\rho, \omega, \phi\})$
  - direct relation between dilepton signal and VM spectral functions
  - interactions with mesons and baryons
  - models constrained by phenomenology in pp, pn, pA
  - medium modifications predicted by finite-temperature QFT
- Elementary reactions at SIS energies
  - GiBUU for pp, pn with resonance model for all HADES energies
  - pn still a problem?
  - p Nb, AA work in progress

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