Dilepton Production at SIS Energies
DLS Puzzle Part II: The Δ Crisis

Janus Weil

in collab. with U. Mosel, H. van Hees, K. Gallmeister, ...

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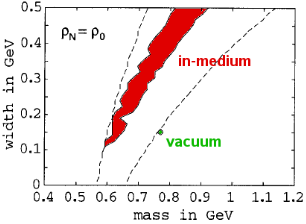
Outline

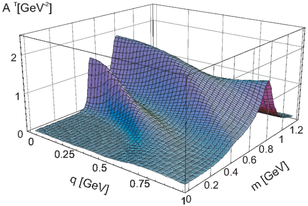
1. motivation:
   in-medium physics, "DLS puzzle"
2. the GiBUU transport model
3. dileptons from elementary reactions:
   pp, dp, pNb (at 1-4 GeV)

   [arXiv:1203.3557, EPJ A48 (2012) 111]
4. dileptons from heavy-ion collisions:
   CC, ArKCl, AuAu
   [arXiv:1211.3761]
5. conclusions

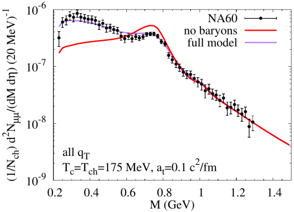
Motivation: Hadrons in Medium

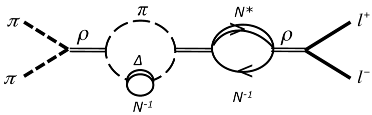
- how do vector mesons behave inside a hadronic medium?
- Brown/Rho, Hatsuda/Lee:
  mass shift (restoration of chiral sym.)
  $m_V^*(\rho)/m_V \approx 1 - \alpha(\rho/\rho_0)$,
  $\alpha \approx 0.16 \pm 0.06$
- collisional broadening (LDA):
  $\Gamma_{coll} = \rho < v_{rel}\sigma_{VN} >$
- QCD sum rules (Leupold, NPA 628, 1998)
- coupling to resonances can introduce additional structures in the spectral function (Post, 2003)
- **but:** do we even know what the ρ meson looks like in vacuum?



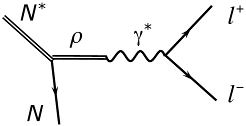


- coupling of ρ meson to baryon resonances known to be crucial for in-medium self-energies at SPS energies (Hees/Rapp)
- dominant source of collisional broadening





- should be even more important at low energies
- this coupling can even play a role in the vacuum: ρ production through baryons at low energies

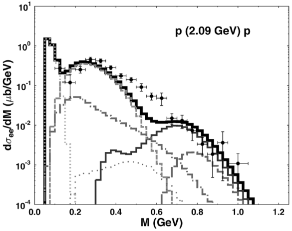


The DLS Puzzle(s)

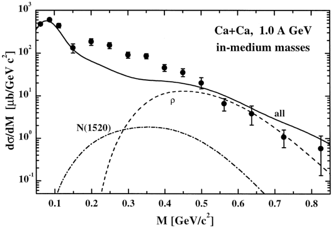
- **mid-90s**: no one can fully explain dilepton data measured by **DLS** in few-GeV regime
- data wrong? models incomplete?

- **today**: DLS data fully confirmed by new **HADES** data (better acceptance/resolution/statistics)
- there are still **two** (theory) puzzles:
  1. how to explain the elementary (N+N) dilepton spectra?
  2. are there additional 'in-medium' effects in A+A?

UrQMD, Ernst et al., PRC 58 (1998)



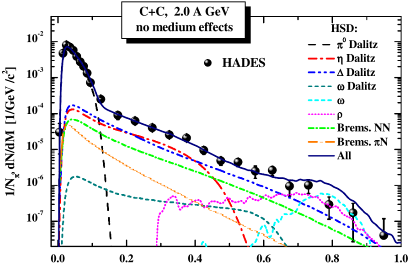
HSD, Bratkovskaya et al., PLB 445 (1999)

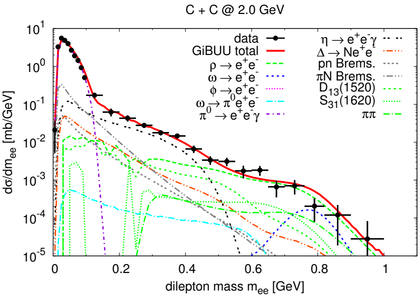


Starting points for a solution

1. early observation (Winckelmann et al, PRC 51, 1995):
   "The ρ mass spectrum is strongly distorted due to phase space effects, populating dominantly dilepton masses below 770 MeV." (already in pp, due to production via baryon resonances. Unfortunately mostly ignored in later works!)

2. later claim (Bratkovskaya et al, NPA 807, 2008):
   "We find that the DLS puzzle [...] may be solved when incorporating a stronger bremsstrahlung contribution in line with recent OBE calculations." (and: a stronger Δ contribution)





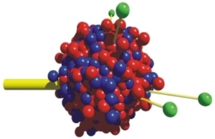
- both HSD and GiBUU describe the data quite well
- but: with a rather different cocktail composition!
- Δ channel is very strong in HSD, but almost negligible in GiBUU
- ⇒ the "Δ crisis"!

The GiBUU Transport Model

- BUU-type hadronic transport model
- unified framework for various types of reactions (γA, eA, νA, pA, πA, AA) and observables
- BUU equ.: space-time evolution of phase space density

$$\left(\partial_t + (\nabla_{\vec{p}} H_i)\nabla_{\vec{r}} - (\nabla_{\vec{r}} H_i)\nabla_{\vec{p}}\right) f_i(\vec{r}, t, \vec{p}) = I_{coll}[f_i, f_j, ...]$$

- Hamiltonian H_i:
  - hadronic mean fields, Coulomb, “off-shell potential”
- collision term I_{coll}:
  - decays and scattering processes (2- and 3-body)
  - low energy: resonance model, high energy: string fragment.
- O. Buss et al., Phys. Rep. 512 (2012), http://gibuu.physik.uni-giessen.de

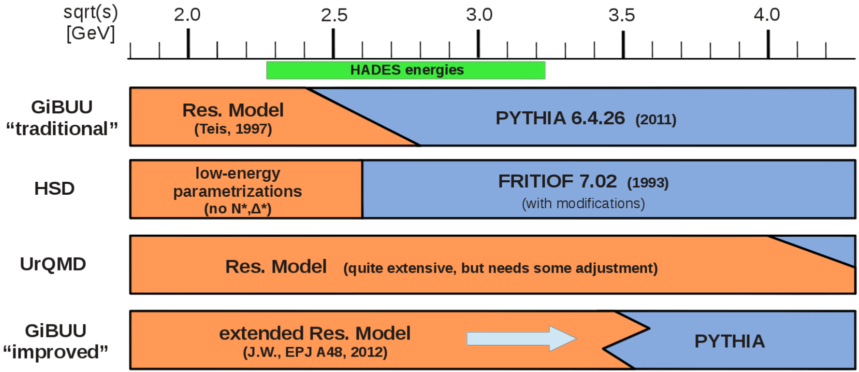


GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

Modeling collisions in the few-GeV regime

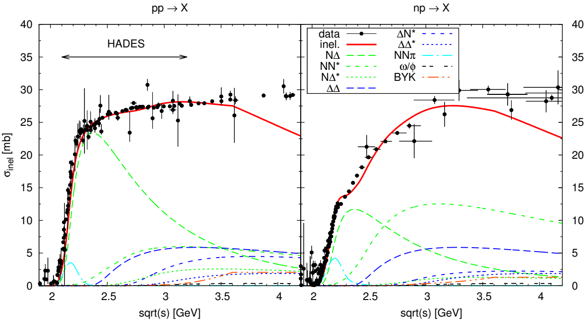
- baryon-baryon collisions at low energies: resonance models vs. string fragmentation



- HADES energy range is clearly in the resonance regime!
- we need one consistent model for the whole energy range!

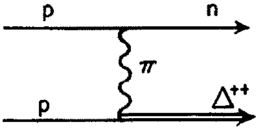
Resonance Model

- assumption: inel. NN cross section is dominated by production and decay of baryonic resonances
- $NN \rightarrow NR, \Delta R$ (R : Δ, 7 N^* and 6 Δ^* states)
- based on Teis RM [Z. Phys. A 356, 1997] with several extensions
- all π, η and ρ mesons produced via R decays (ω, ϕ: non-res.)
- good descr. of total NN cross sections up to $\sqrt{s} \approx 3.5 GeV$



Resonance Production

- $NN \to N\Delta$: OBE model [Dmitriev et al, NPA 459 (1986)]



- other resonances produced via phase-space approach (constant matrix elements):

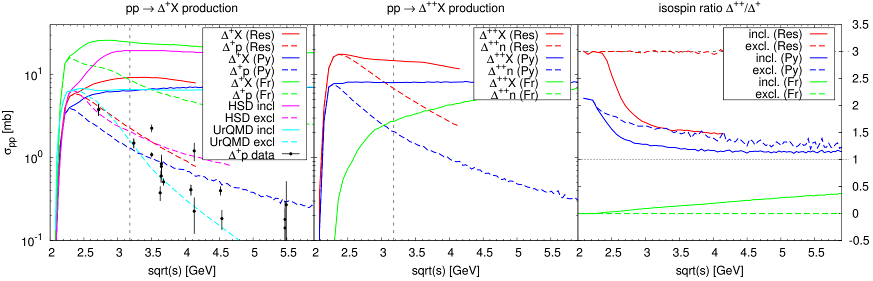
$$\sigma_{NN\to NR} = \frac{C_I}{p_i s} \frac{|\mathcal{M}_{NR}|^2}{16\pi} \int \mathrm{d}\mu \mathcal{A}_R(\mu) p_F(\mu)$$

$$\sigma_{NN\to \Delta R} = \frac{C_I}{p_i s} \frac{|\mathcal{M}_{\Delta R}|^2}{16\pi} \int \mathrm{d}\mu_1 \mathrm{d}\mu_2 \mathcal{A}_\Delta(\mu_1) \mathcal{A}_R(\mu_2) p_F(\mu_1, \mu_2)$$

- lately: introduced angular distributions $d\sigma/dt = b/t^a$, $a \approx 1$ ($\to$ A. Dybczak)

Δ production cross section

- only exclusive Δ^+ production constrained by data
- resonance models (UrQMD/GiBUU) agree roughly on inclusive production
- but: inclusive cross section much larger in HSD/FRITIOF
- string models do not obey isospin relations!



lesson: don't trust string fragmentation models at low energies!

Hadronic decays

- all resonance parameters, decays modes and width parametriz. taken from: Manley/Saleski, Phys. Rev. D 45 (1992)
- Manley: PWA including $\pi N \to \pi N$ and $\pi N \to 2\pi N$ data
- important point: **consistency**! (coupled-channel constraints)

	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

$$\Gamma_{R\to ab}(m) = \Gamma^0_{R\to ab}\frac{\rho_{ab}(m)}{\rho_{ab}(M^0)}$$

$$\rho_{ab}(m) = \int \mathrm{d}p_a^2\mathrm{d}p_b^2\mathcal{A}_a(p_a^2)\mathcal{A}_b(p_b^2)\frac{p_{ab}}{m}B^2_{L_{ab}}(p_{ab}R)\mathcal{F}^2_{ab}(m)$$

Dilepton decays

- $V \to e^+e^-$ (with $V = \rho, \omega, \phi$) via strict VMD: $\Gamma(\mu) \propto \mu^{-3}$
- $P \to \gamma e^+e^-$ (with $P = \pi^0, \eta, \eta'$) [Landsberg, Phys.Rep.128, 1985]:

$$\frac{d\Gamma}{d\mu} = \frac{4\alpha}{3\pi}\frac{\Gamma_{P\to\gamma\gamma}}{\mu}\left(1 - \frac{\mu^2}{m_P^2}\right)^3 |F_P(\mu)|^2,$$

- $\omega \to \pi^0 e^+e^-$ [Landsberg]:

$$\frac{d\Gamma}{d\mu} = \frac{2\alpha}{3\pi}\frac{\Gamma_{\omega\to\pi^0\gamma}}{\mu}\left[\left(1 + \frac{\mu^2}{\mu_\omega^2 - m_\pi^2}\right)^2 - \frac{4\mu_\omega^2\mu^2}{(\mu_\omega^2 - m_\pi^2)^2}\right]^{3/2} |F_\omega(\mu)|^2$$

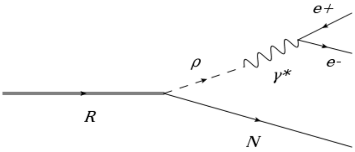
- $\Delta \to Ne^+e^-$ [Krivoruchenko, Phys.Rev.D65, 2002]:

$$\frac{d\Gamma}{d\mu} = \frac{2\alpha}{3\pi\mu}\frac{\alpha}{16}\frac{(m_\Delta + m_N)^2}{m_\Delta^3 m_N^2}\sqrt{(m_\Delta + m_N)^2 - \mu^2}\left[(m_\Delta - m_N)^2 - \mu^2\right]^{3/2} |F_\Delta(\mu)|^2$$

- important: form factors well restricted for π^0, η and ω, but completely unknown for Δ!
- we use Delta FF model of Ramalho/Pena [Phys.Rev.D85, 2012]

Dilepton decays of baryonic resonances

- how to treat $R \to Ne^+e^-$?
- option 1: do Dalitz decay (as for Δ), with proper form factor! (fixed at photon point, 'extrapolate' to $q^2 > 0$)
- option 2: do **two-step decay** $R \to \rho N \to e^+e^-N$ (using 'hadronic' info from PWA)



- consequence: dilepton contributions from all N^* and Δ^* resonances, which have a ρ coupling
- and: we get an 'implicit' form factor from decay kinematics

Bremsstrahlung

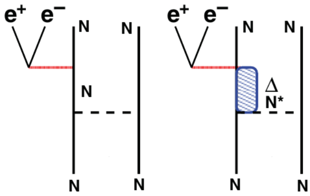
- soft-photon approximation
  [Gale/Kapusta, PRC40, 1989]:

$$\frac{\mathrm{d}\sigma_{pn\to pne^+e^-}}{\mathrm{d}M\mathrm{d}E\mathrm{d}\Omega} = \frac{\alpha^2}{6\pi^3}\frac{q}{ME^2}\bar{\sigma}(s)\frac{R_2(s_2)}{R_2(s)} ,$$

$$\bar{\sigma}(s) = \frac{s-(m_1+m_2)^2}{2m_1^2}\sigma_{el}^{pn}(s) ,$$

$$R_2(s) = \sqrt{1-(m_1+m_2)^2/s} ,$$

$$s_2 = s + M^2 - 2E\sqrt{s} ,$$

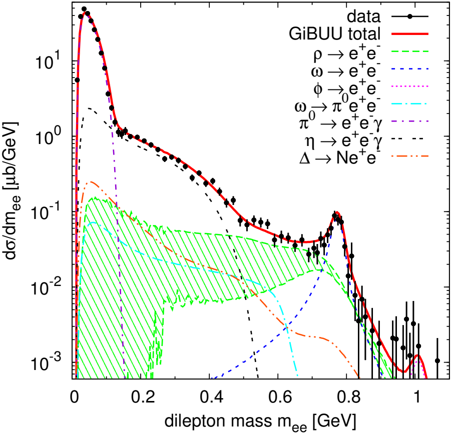


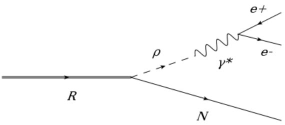
- used for NN, πN
- NN: pn only (destr. interference in pp not treated)
- OBE: Kaptari-Kämpfer [NPA764, 2006],
  Shyam-Mosel [PRC82, 2010]

Results: elementary reactions

- if we want to investigate in-medium effects, we better make sure we understand the dilepton signal from elementary NN collisions ("in the vacuum")
- this is not a trivial task and represents the most important prerequisite for understanding the heavy-ion collisions
- HADES has measured:
  p+p at $E_{kin} = 1.25$, 2.2 and 3.5 GeV
  d+p at $E_{kin} = 1.25$ GeV
- all simulation results filtered through HADES acceptance filter
- opening angle cut: $\theta_{ee} > 9^\circ$
- lepton momentum cut: $p_e^{min} < p_e < p_e^{max}$

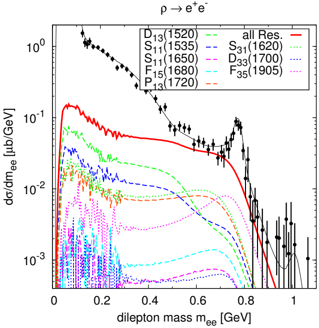
- using resonance model
- important: ρ production via baryonic resonances
- $R \to \rho N \to e^+ e^- N$
- low-mass part enhanced by light resonances (and $1/m^3$ factor from dilepton decay width)
- same effect seen in UrQMD

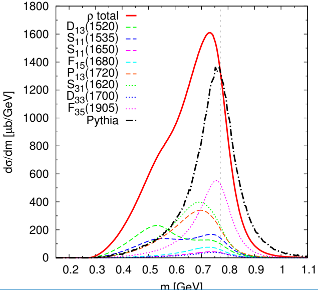




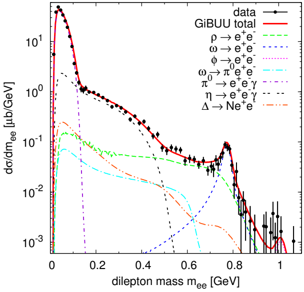
p+p at 3.5 GeV: resonance contributions

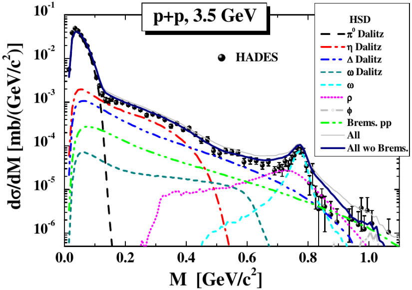
- ρ channel is given by a mix of several resonance contributions
- shape depends on the mass of the resonance (phase space of decay)
- contributions of single resonances not well constrained, but good agreement in total
- cross check from πN mass spectra needed
- the same ρNR coupling that dominates in-medium self-energy is responsible for a 'modified' ρ already in pp collisions!

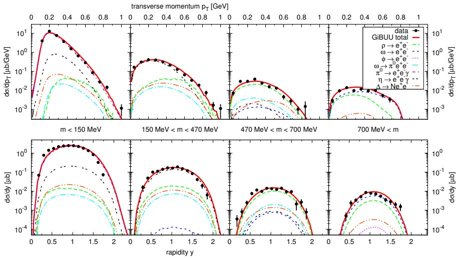


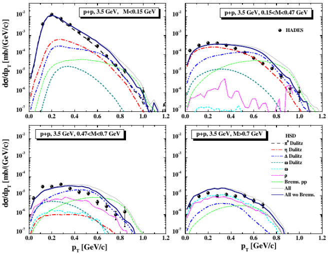


p+p at 3.5 GeV: comparison to HSD



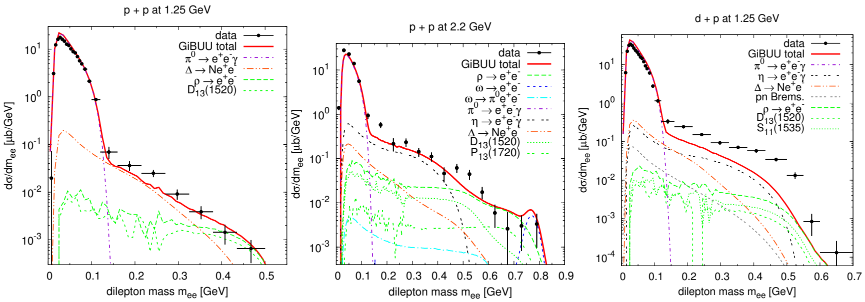






HSD fails to describe p_T data due to large Δ and Bremsstr. contr.!

OTHER ELEMENTARY COLLISIONS



- p+p at 1.25 and 2.2 GeV rather well described
- d+p misses factor 2-10
- reason not completely clear, OBE models might help
- isopsin effects not completely understood?

In-medium effects in p+A and A+A

constrained by NN spectra:

- basic cocktail composition (in 'vacuum')
- particle production from NN
- form factors (limited)
- ρ spectral distribution in vacuum (non-trivial!)

additional effects:

- secondary collisions:
  - $mB \to X$: meson absorption, secondary production ($\pi N \to R$)
  - $mm \to X$: most importantly $\pi\pi \to \rho$
- modifications of spectral functions:
  - collisional broadening: $\Gamma_{tot} = \Gamma_{dec} + \Gamma_{coll}$
  - mass shifts? $m^* = m \cdot (1 - \rho/\rho_0)$
  - may be important for: ρ meson, baryonic resonances

Off-Shell Transport

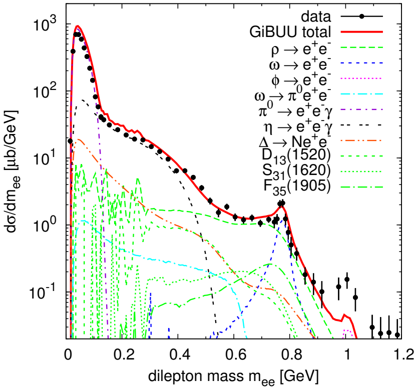
- off-shell EOM for test particles
  [Cassing/Juchem (NPA 665, 2000), Leupold (NPA 672, 2000)]:

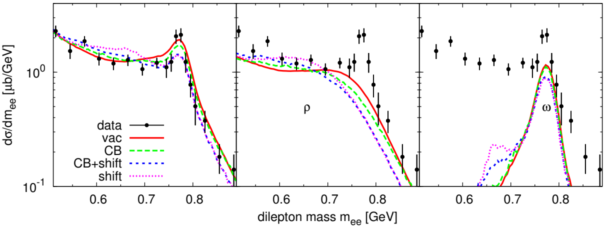
$$
\begin{aligned}
\dot{\vec{r}}_i &= \frac{1}{1-C_i}\frac{1}{2E_i}\left[2\vec{p}_i + \frac{\partial}{\partial \vec{p}_i} Re(\Sigma_i) + \chi_i \frac{\partial \Gamma_i}{\partial \vec{p}_i}\right] , \\
\dot{\vec{p}}_i &= -\frac{1}{1-C_i}\frac{1}{2E_i}\left[\frac{\partial}{\partial \vec{r}_i} Re(\Sigma_i) + \chi_i \frac{\partial \Gamma_i}{\partial \vec{r}_i}\right] , \\
C_i &= \frac{1}{2E_i}\left[\frac{\partial}{\partial E_i} Re(\Sigma_i) + \chi_i \frac{\partial \Gamma_i}{\partial E_i}\right] , \\
\chi_i &= \frac{m_i^2 - M^2}{\Gamma_i} , \quad \frac{d\chi_i}{dt} = 0
\end{aligned}
$$

- needed to incorporate density-dependent self energies Σ_i, widths $\Gamma_i \sim Im(\Sigma_i)$ and spectral functions
- but: neglecting momentum dependence

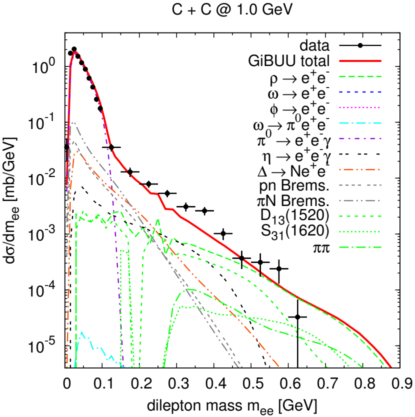
p + ^{93}Nb at 3.5 GeV

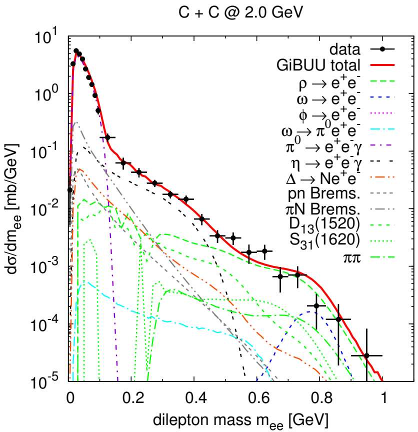
- after p+p@3.5 is fixed: good overall agreement in p+Nb
- moderate medium modifications (of VM spectral functions)





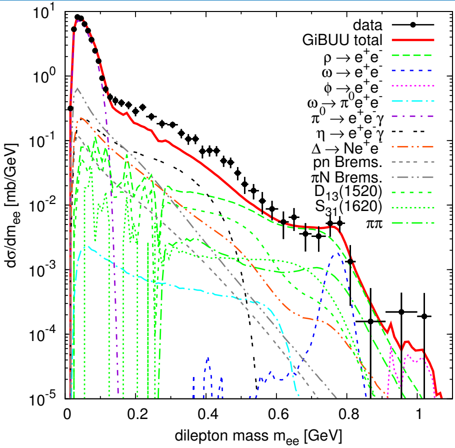
$^{12}C + ^{12}C$ at 1.0 and 2.0 GeV

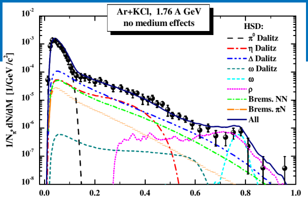


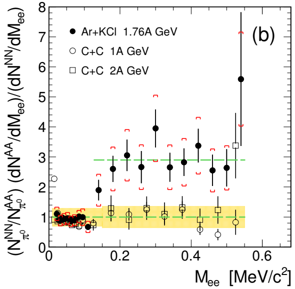


- C+C is a light system, can be described roughly by a superposition of NN collisions
- 2 GeV data well described by GiBUU
- some discrepancies at 1 GeV (↔ "deuteron problem"?)

$^{40}Ar + {}^{39}K^{35}Cl$ at 1.76 GeV







- Ar+KCl seems to show some excess over NN/CC ($\sim$ factor 3)
- GiBUU with vacuum SF: discrepancy is smaller than factor 3
  $\Rightarrow$ we get some enhancement over 'reference cocktail',
  but: still room for in-medium effects

Conclusions

1. large Δ and Bremsstrahlung contributions (as claimed by HSD) do **not** provide a proper solution of the DLS puzzle: they are in conflict with HADES data (p_T)!
2. alternative approach: significant yield from N^* and Δ^* resonances coupling to the ρ meson provides better description of the data
3. independent analysis with a third model (UrQMD!) would be helpful to settle the discrepancy between GiBUU and HSD (aka "the Δ crisis")
   $\rightarrow$ requires readjustments of UrQMD resonance model
4. more work on in-medium modifications needed