

DILEPTON PRODUCTION AT SIS ENERGIES WITH THE GiBUU TRANSPORT MODEL

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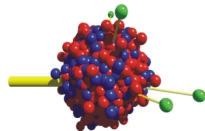
(in collab. with H. van Hees & K. Gallmeister)

FAIRNESS

Kreta, 08.09.2012



- 1 motivation: in-medium physics
- 2 the GiBUU transport model
- 3 dileptons from elementary reactions:
 $p + p$, $d + p$
 $p + \text{Nb}$
arXiv:1203.3557 [nucl-th], accepted by EPJ
- 4 dileptons from heavy-ion collisions:
 $C + C$
 $\text{Ar} + \text{KCl}$
- 5 conclusions

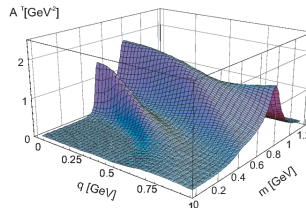
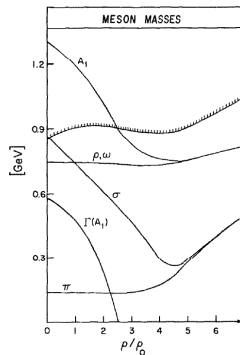


GiBUU

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):
 $\Gamma_{coll} = \rho \langle v_{rel} \sigma_{VN} \rangle$
- QCD sum rules (Leupold, NPA 628, 1998)
- coupling to resonances can introduce additional structures in the spectral function (Post, 2003)

V. Bernard, U.-G. Meissner / Vector and axial-vector mesons



THE DILEPTON COCKTAIL

hadronic sources contributing to the dilepton spectrum:

direct decays

- $\rho^0 \rightarrow e^+ e^-$
- $\omega \rightarrow e^+ e^-$
- $\phi \rightarrow e^+ e^-$
- $(\eta \rightarrow e^+ e^-)$



Dalitz decays

- $\pi^0 \rightarrow e^+ e^- \gamma$
- $\eta \rightarrow e^+ e^- \gamma$
- $\omega \rightarrow \pi^0 e^+ e^-$
- $\Delta \rightarrow N e^+ e^-$
- $(R \rightarrow N e^+ e^-)$

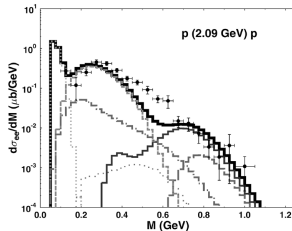
other contributions

- Bremsstrahlung:
 $NN \rightarrow N N e^+ e^-$, $\pi N \rightarrow \pi N e^+ e^-$

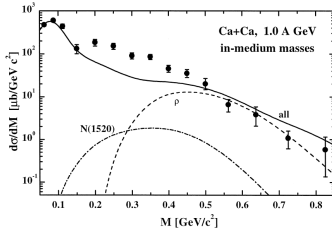
THE DLS PUZZLE(S)

- **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)

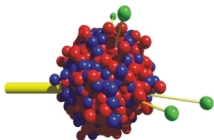


THE GiBUU TRANSPORT MODEL

- 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

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

- 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: PYTHIA 6.4
- O. Buss et al., Phys. Rep. 512 (2012),
<http://gibuu.physik.uni-giessen.de>

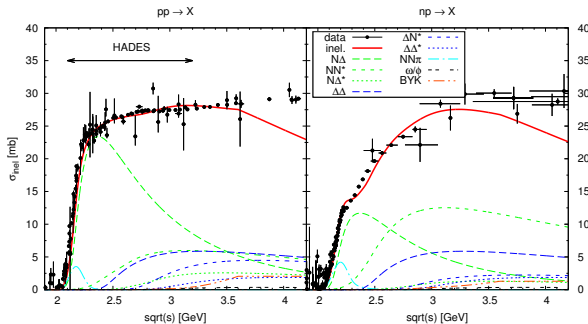


GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

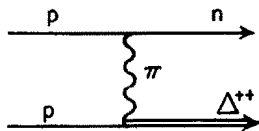
RESONANCE MODEL

- assumption: inel. NN cross section is dominated by Res. production (at low energies)
- $NN \rightarrow NR, \Delta R$ ($R : \Delta, 7 N^*$ and $6 \Delta^*$ 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 $\sqrt{s} \approx 3.5 \text{ GeV}$



RESONANCE PRODUCTION

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



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

$$\sigma_{NN \rightarrow NR} = \frac{C_I}{p_{is}} \frac{|\mathcal{M}_{NR}|^2}{16\pi} \int d\mu \mathcal{A}_R(\mu) p_F(\mu)$$

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

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

HADRONIC DECAYS

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

		M_0	Γ_0	$ \mathcal{M}^2 /16\pi$ [mb GeV ²]		branching ratio in %						
	rating	[MeV]	[MeV]	NR	ΔR	πN	ηN	$\pi\Delta$	ρN	σN	πN^* (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

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

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

DILEPTON DECAYS

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

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

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

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

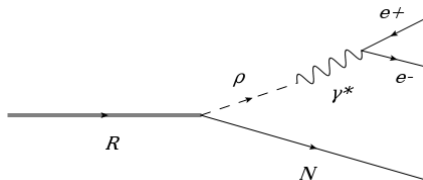
- $\Delta \rightarrow N e^+e^-$ [Krivoruchenko, Phys.Rev.D65, 2002]:

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

- important: form factors well restricted for π^0 , η and ω , but completely unknown for Δ !
- available models for Delta FF: Wan/Iachello [Int.J.Mod.Phys.A20, 2005], Ramalho/Pena [Phys.Rev.D85, 2012]

DILEPTON DECAYS OF BARYONIC RESONANCES

- how to treat $R \rightarrow Ne^+e^-$?
- option 1: do Dalitz decay (as for Δ), with proper form factor!
- option 2: do **two-step decay** $R \rightarrow \rho N \rightarrow e^+e^- N$



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

- soft-photon approximation

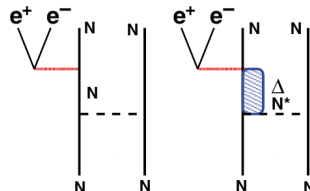
[Gale/Kapusta, PRC40, 1989]:

$$\frac{d\sigma_{pn \rightarrow p n e^+ e^-}}{dM dE d\Omega} = \frac{\alpha^2}{6\pi^3} \frac{q}{ME^2} \bar{\sigma}(s) \frac{R_2(s_2)}{R_2(s)},$$

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

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

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

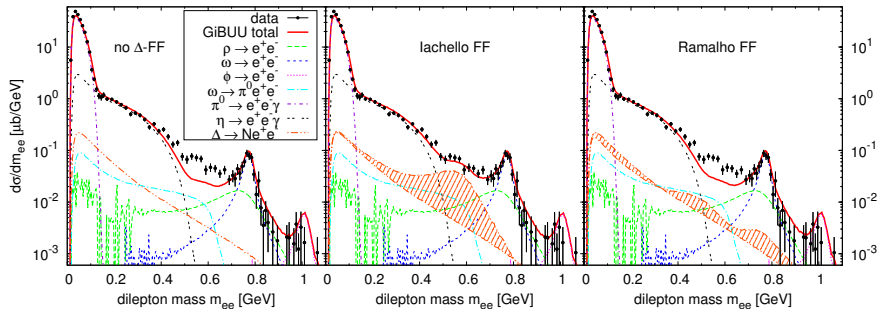


- used for NN , πN
- NN : pn only (destr. interference in pp not treated)
- OBE: Kaptari-Kämpfer [NPA764, 2006],
Shyam-Mosel [PRC82, 2010]
- no electromagnetic form factors (!)

RESULTS: ELEMENTARY REACTIONS

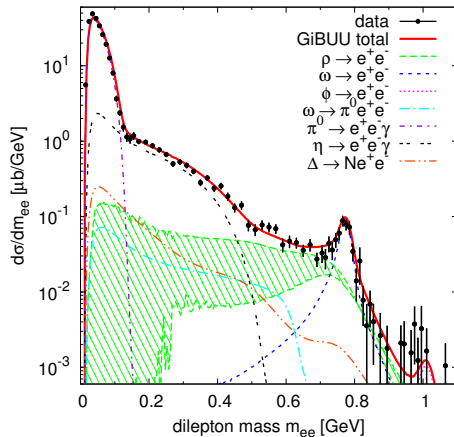
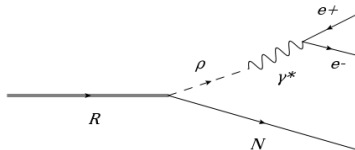
- if we want to investigate in-medium effects, we better make sure we understand the dilepton signal from elementary NN collisions (“in the vacuum”)
- this is not a trivial task and represents the most important prerequisite for understanding the heavy-ion collisions
- HADES has measured:
 - p+p at $E_{kin} = 1.25, 2.2$ 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: $p_e^{min} < p_e < p_e^{max}$

- first try: using PYTHIA string fragmentation model
[J.W., arXiv:1105.0314[nucl-th], 2011], [Agakishiev, EPJA48, 2012]
- some tuning needed
- 'gap' at intermediate masses
- lachello FF: improves agreement in mass spectrum, but fails in p_T
- Ramalho FF: gap persists



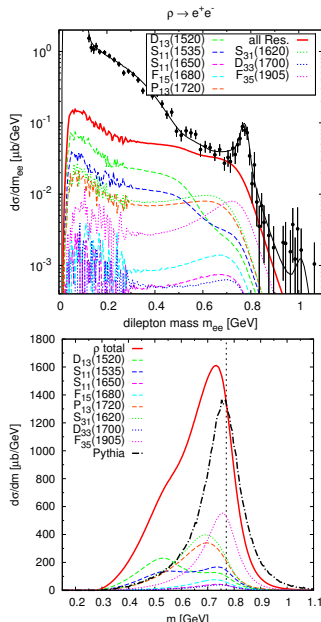
P+P AT 3.5 GeV

- now: use resonance model
- ρ production via baryonic resonances
- $R \rightarrow \rho N \rightarrow e^+ e^- N$
- low-mass part enhanced by light resonances (and $1/m^3$ factor from dilepton decay width)

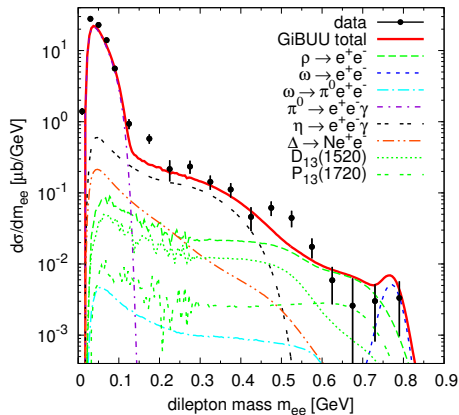


P+P AT 3.5 GeV: RESONANCE CONTRIBUTIONS

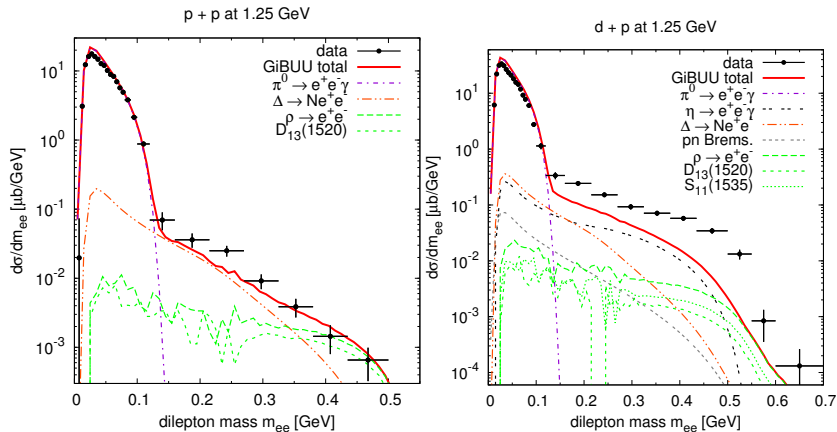
- ρ channel is given by a mix of several resonance contributions
- shape depends on the mass of the resonance and angular momentum of the decay
- contributions of single resonances not well constrained, but good agreement in total
- cross check from πN mass spectra needed! ($\rightarrow$ A. Dybczak)



- again: resonance production gives improvement over phase-space ρ
- but: data suggest that relative strengths of resonance contributions are not quite right
- $D_{13}(1520)$ underestimated, $P_{13}(1720)$ overestimated?



P+P / D+P AT 1.25 GeV



- p+p overall well described, d+p misses factor 2-10
- reason not completely clear, OBE models might help
- isospin 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:
 - $mB \rightarrow X$: meson absorption, secondary production ($\pi N \rightarrow R$)
 - $mm \rightarrow X$: most importantly $\pi\pi \rightarrow \rho$
- 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 EOM for test particles

[Cassing/Juchem (NPA 665, 2000), Leupold (NPA 672, 2000)]:

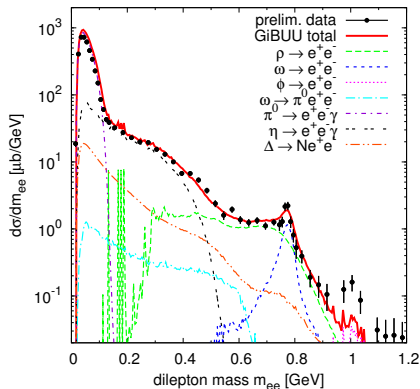
$$\begin{aligned}\dot{\vec{r}}_i &= \frac{1}{1 - C_i} \frac{1}{2E_i} \left[2\vec{p}_i + \frac{\partial}{\partial \vec{p}_i} \text{Re}(\Sigma_i) + \chi_i \frac{\partial \Gamma_i}{\partial \vec{p}_i} \right], \\ \dot{\vec{p}}_i &= -\frac{1}{1 - C_i} \frac{1}{2E_i} \left[\frac{\partial}{\partial \vec{r}_i}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

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

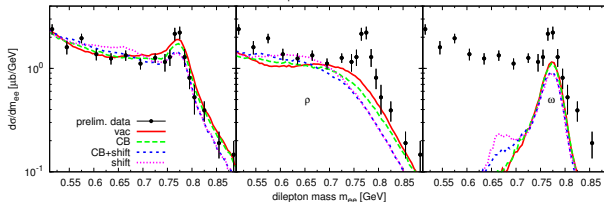
P + ^{93}Nb AT 3.5 GeV

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

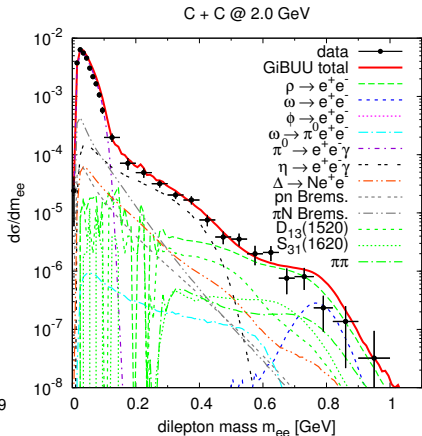
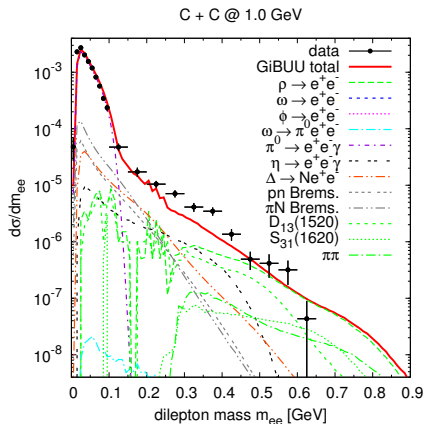
p + Nb at 3.5 GeV



p + Nb at 3.5 GeV

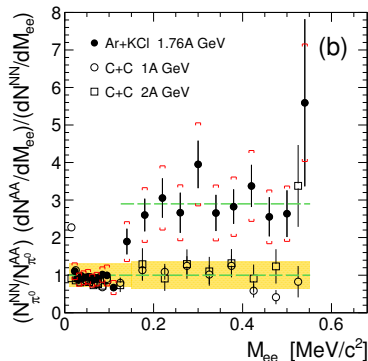
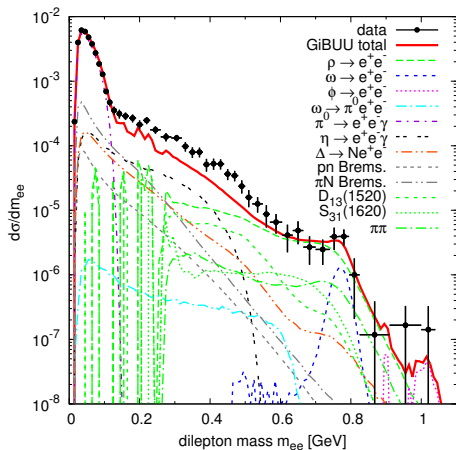


$^{12}\text{C} + ^{12}\text{C}$ AT 1.0 AND 2.0 GeV



- 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 ($\leftrightarrow$ “deuteron problem”?)

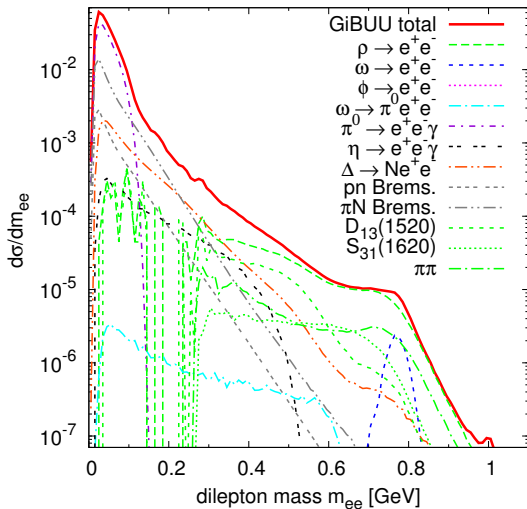
$^{40}\text{Ar} + ^{39}\text{K}^{35}\text{Cl}$ AT 1.76 GeV



- 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

$^{197}\text{Au} + ^{197}\text{Au}$ AT 1.25 GeV

- “prediction”, waiting for data



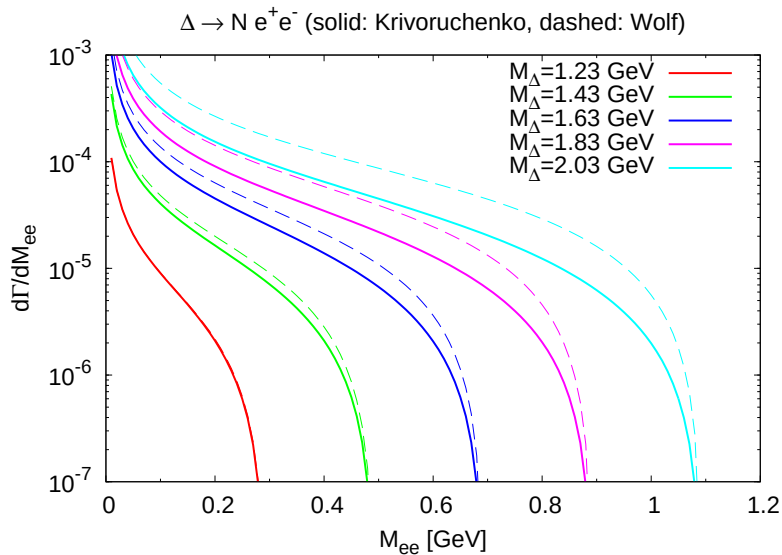
CONCLUSIONS

- ① elementary $p+p$ reactions well understood
with resonance model description
(higher resonances are important!)
- ② some problems remaining in $d+p$ (at low energy)
- ③ $p+Nb$: good agreement with data
(moderate medium modifications)
- ④ heavy-ion reactions:
minor deviations in $C+C$
investigation of medium effects in $ArKCl$ (VM + Res)
waiting for $Au + Au$ data

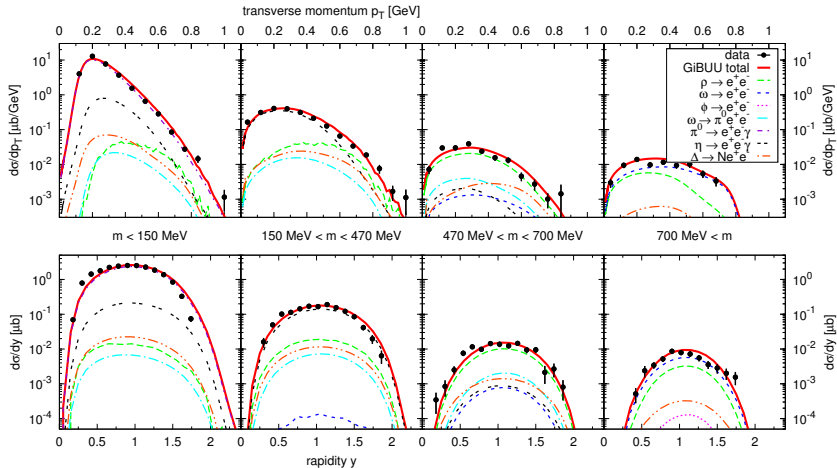
⇒ **we are close to understanding the elementary data,
more investigation of medium effects needed!**

Back-Up Slides

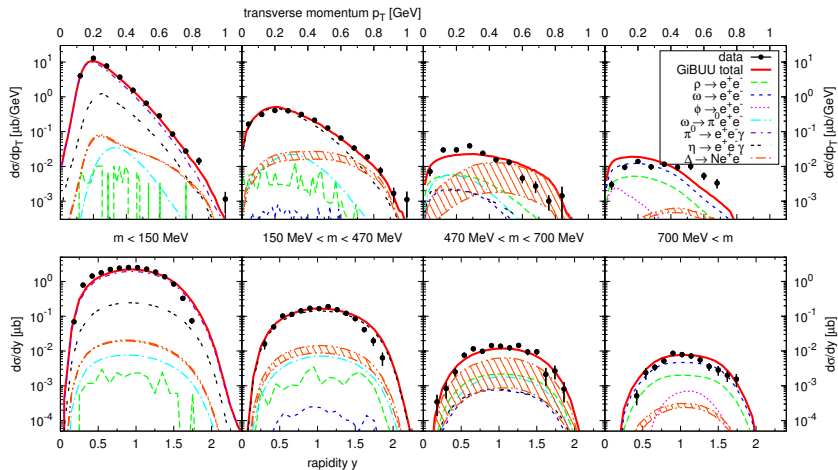
Δ DALITZ DECAY



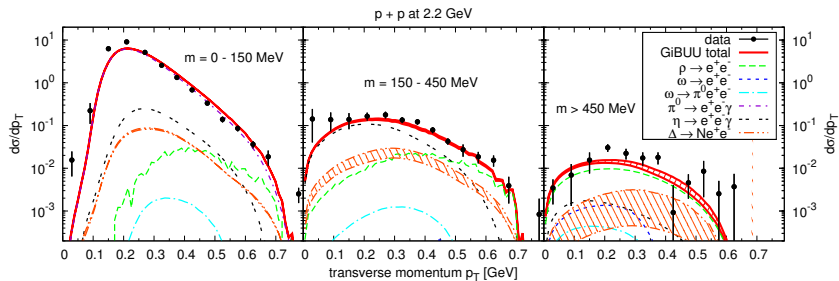
P + P @ 3.5: p_T AND RAPIDITY (RES. MODEL)



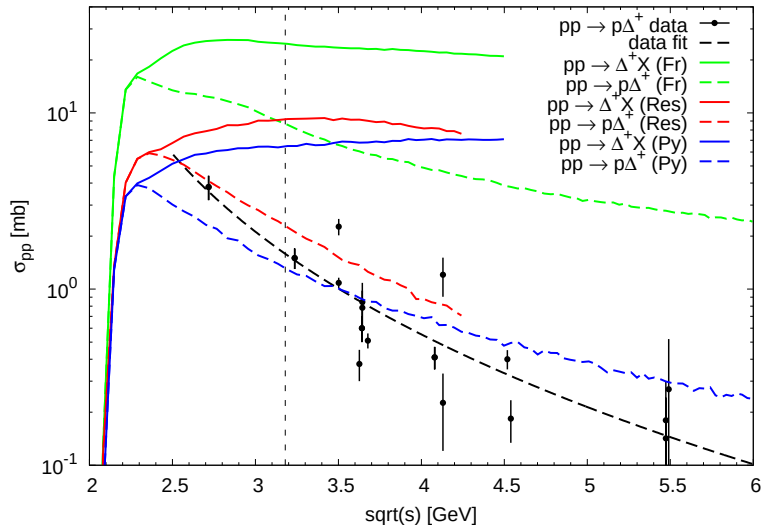
P + P @ 3.5: p_T AND RAPIDITY (PYTHIA)



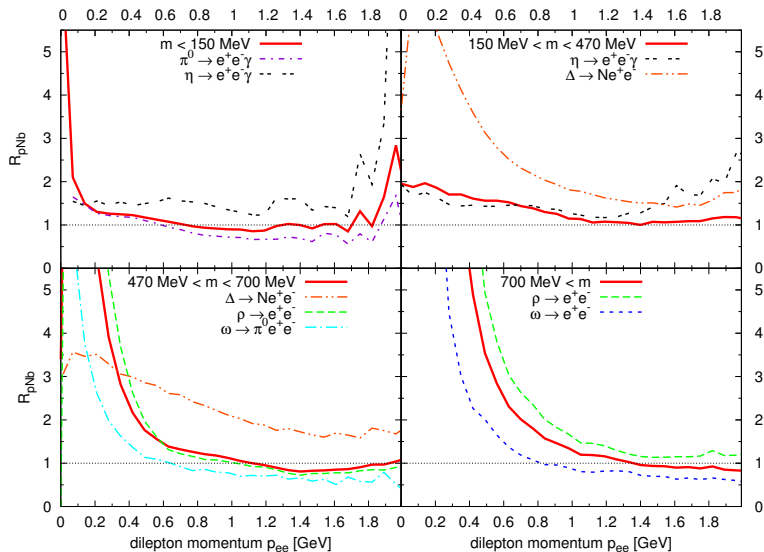
P + P @ 2.2: p_T SPECTRA



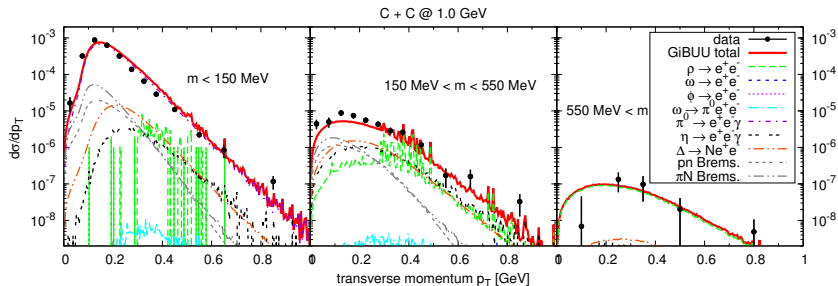
Δ^+ PRODUCTION CROSS SECTION



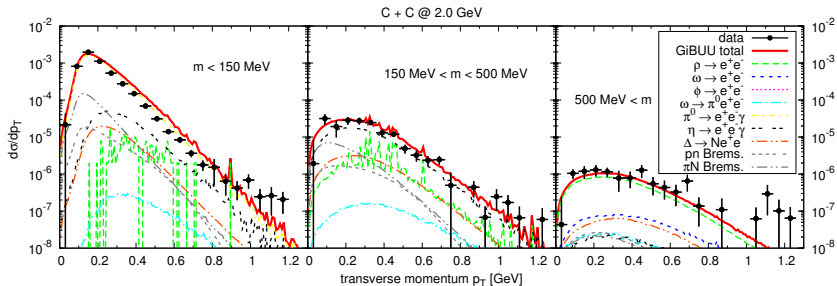
RATIO $P+NB/P+P$



C + C @ 1 GeV: p_T SPECTRA



C + C @ 2 GeV: p_T SPECTRA



$Ar + KCl @ 1.76 \text{ GeV}$: p_T SPECTRA

