Dilepton production at SIS energies with the GiBUU transport model

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

Lunch Club Seminar
Giessen, 11.05.2012

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research

Outline

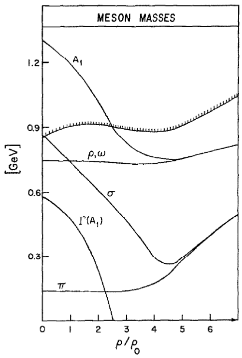
1. motivation: in-medium physics
2. the GiBUU transport model
3. dileptons from elementary reactions:
   p + p, d + p
   p + Nb

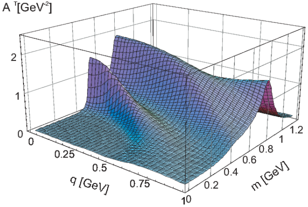
   see arXiv:1203.3557 [nucl-th]
4. dileptons from heavy-ion collisions:
   C + C
   Ar + KCl
5. conclusions

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)

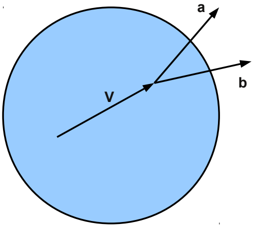
V. Bernard, U.-G. Meissner / Vector and axial-vector mesons





How to study in-medium effects?

- basic idea: observe decays $V \to ab$ inside the medium
- reconstruct in-medium mass from invariant mass of decay products: $m_V^* = \sqrt{(p_a + p_b)^2}$

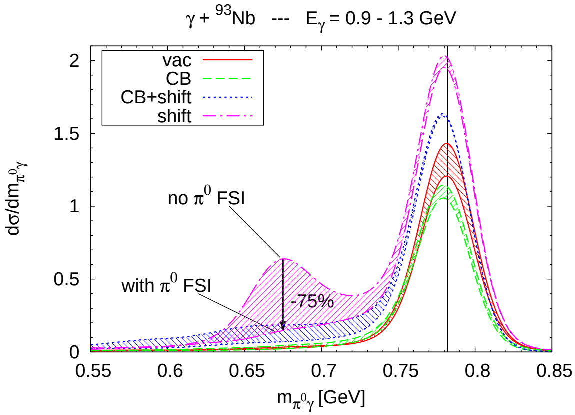


we need:

- reasonably large medium ('cold' nucleus or 'fireball' from HIC)
- short meson lifetime + low momentum
- FSI of decay products should be small

Why Dileptons? No FSI!

- drawback of hadronic decay modes: strong final-state interaction of the decay products
- example: $\omega \to \pi^0\gamma$ (measured by CBELSA/TAPS in photoproduction experiments)



The Dilepton Cocktail

hadronic sources contributing to the dilepton spectrum:

direct decays:

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

Dalitz decays:

- $\pi^0 \to e^+e^-\gamma$
- $\eta \to e^+e^-\gamma$
- $\omega \to \pi^0 e^+e^-$
- $\Delta \to Ne^+e^-$
- $R \to Ne^+e^-$

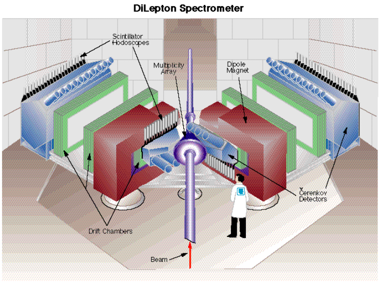
other contributions:

- NN-Bremsstrahlung: $NN \to NNe^+e^-$
- Bethe-Heitler process: $\gamma N \to Ne^+e^-$ (only in photoproduction)
- ...

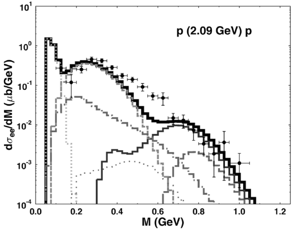
THE DLS PUZZLE(S)

1. how to explain the elementary (N+N) DLS dilepton spectra?
2. are there additional medium effects in A+A?

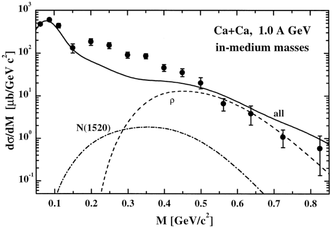
(still unsolved in 2012 ...)



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

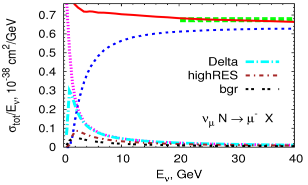
$$\left(\partial_t + (\nabla_{\vec{p}} H_i)\nabla_{\vec{r}} - (\nabla_{\vec{r}} H_i)\nabla_{\vec{p}}\right) f_i(\vec{r}, t, \vec{p}) = I_{coll}[f_i, f_j, ...]$$

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

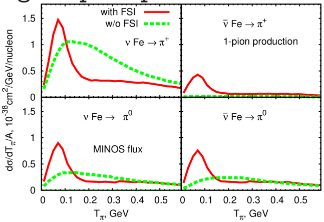
GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

Neutrinos in GiBUU

$\nu A \rightarrow \ell X$



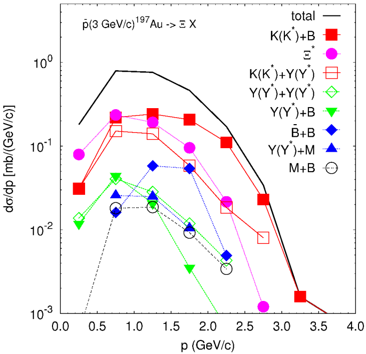
e.g. 1-pion production on Fe



O. Lalakulich, arXiv:1203.2935

Strangeness production in $\bar{p}A$ reactions

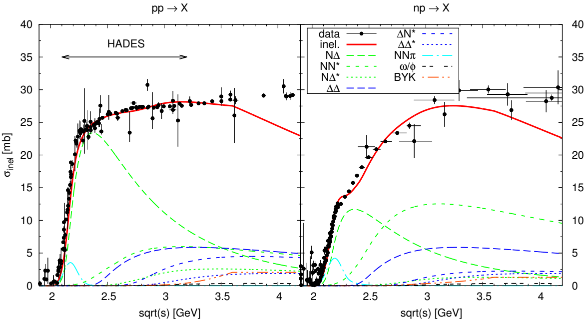
Predictions for PANDA



A. Larionov, arXiv:1202.0748

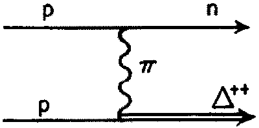
Resonance Model

- assumption: inel. NN cross section is dominated by Res. production (at low energies)
- $NN \rightarrow NR, \Delta R$ (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):

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

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

Hadronic decays

all resonance parameters and decays taken from:
Manley/Saleski, Phys. Rev. D 45 (1992)

		M_0	Γ_0	$\lvert\mathcal{M}^2\rvert/16\pi$ [mb GeV^2]		branching ratio in %						
	rating	[MeV]	[MeV]	NR	ΔR	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 $P = \pi^0, \eta, \eta'$) from Landsberg (1985):

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

- $\omega \to \pi^0 e^+e^-$ (Bratkovskaya et al., 1997):

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

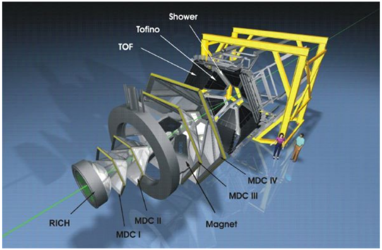
- $\Delta \to Ne^+e^-$ (Krivoruchenko et al., 2002):

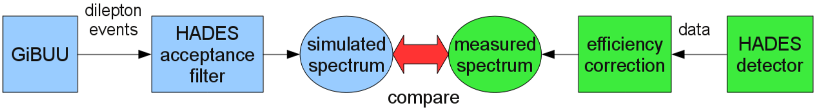
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\mu} = \frac{2\alpha}{3\pi\mu} \frac{\alpha}{16} \frac{(m_\Delta + m_N)^2}{m_\Delta^3 m_N^2} \sqrt{(m_\Delta + m_N)^2 - \mu^2} \left[(m_\Delta - m_N)^2 - \mu^2\right]^{3/2} |F_\Delta(\mu)|^2$$

- but no $N^* \to Ne^+e^-$ or $\Delta^* \to Ne^+e^-$! (to avoid double counting)

The HADES detector at GSI

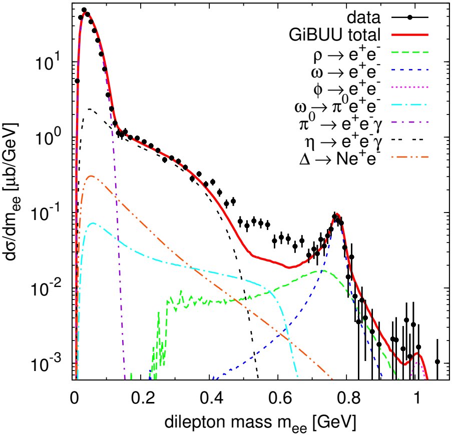
- "High Acceptance Di-Electron Spectrometer"
- pp, pA, AA $\to e^+e^-X$
- SIS: few-GeV regime ($\sqrt{s} < 4$ GeV)
- mass resolution: $\sim$ 15 MeV
- polar angle: $15^\circ < \theta < 85^\circ$
- opening angle cut: $\theta_{ee} > 9^\circ$
- better acceptance/resolution/statistics than DLS





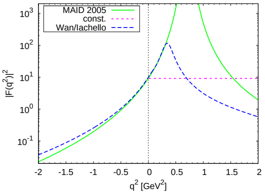
- if we want to investigate in-medium effects, we better make sure we understand the dilepton signal from elementary collisions (in the vacuum)
- this is not a trivial task and represents the most important prerequisite for understanding the heavy-ion collisions
- HADES has measured:
  p+p at $E_{kin} = 1.25$, 2.2 and 3.5 GeV
  d+p at $E_{kin} = 1.25$ GeV

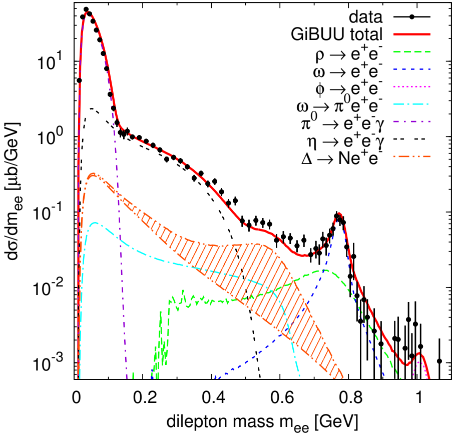
- first try: using PYTHIA string model
- some tuning needed
- 'gap' at intermediate masses
- question: which process could fill this gap?



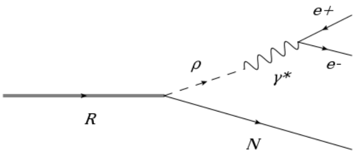
p+p at 3.5 GeV

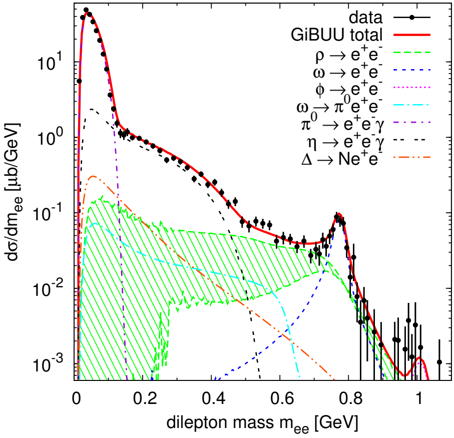
- use em. transition form factor for Δ Dalitz decay
- naive VMD form factor would overshoot the data
- two-component quark model by Wan/Iachello seems to give a good fit
  [Int. J. Mod. Phys. A 20 (2005)]
- but: is this really a proper model of the Δ FF?





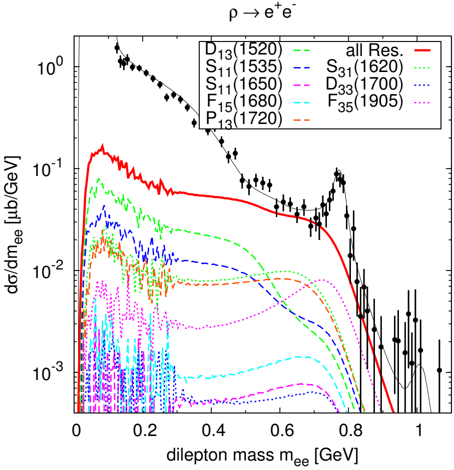
- now: use resonance model
- ρ production via baryonic resonances
- $R \to \rho N \to e^+ e^- N$
- low-mass part enhanced by light resonances (and $1/m^3$ factor from dilepton decay width)





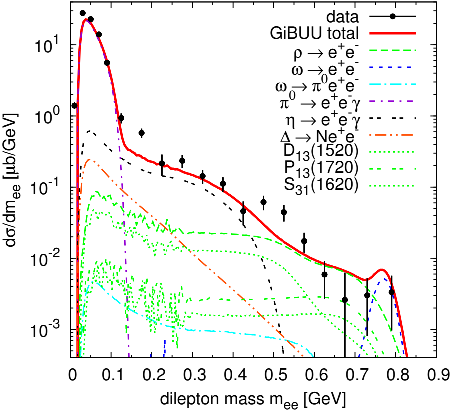
p+p at 3.5 GeV: resonance contributions

- 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!

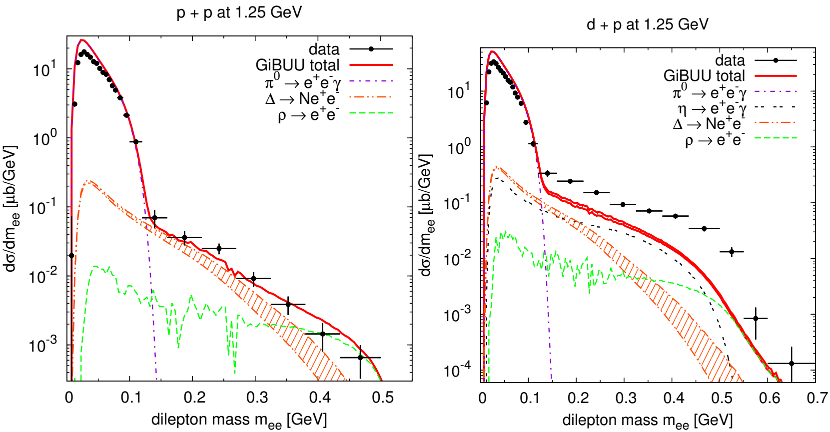


p+p at 2.2 GeV

- 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?

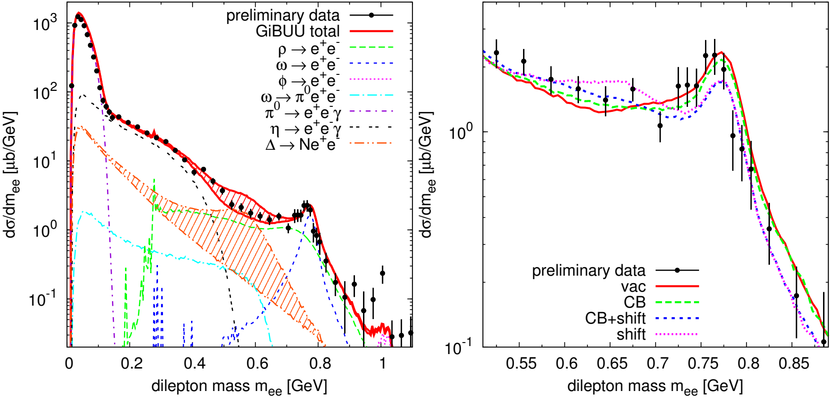


P+P / D+P at 1.25 GeV



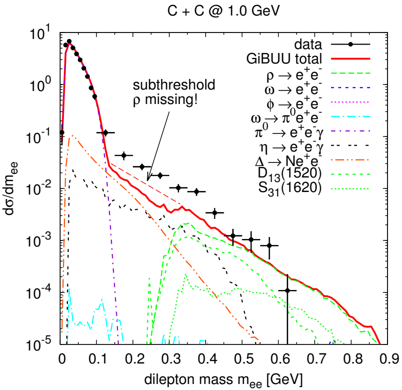
- slight deviation in pion channel (ang. distr.?)
- p+p overall well described, d+p misses factor 2-10
- reason not completely clear, OBE models might help

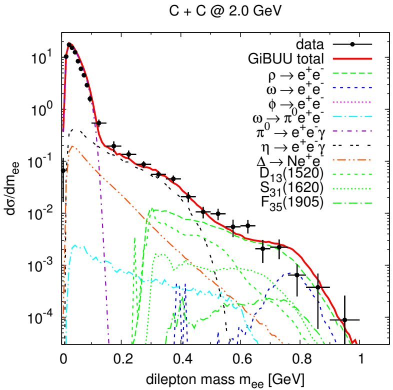
p+Nb at 3.5 GeV



- after p+p@3.5 is fixed: good overall agreement in p+Nb (without Δ FF!)
- moderate medium modifications (VM spectral functions)

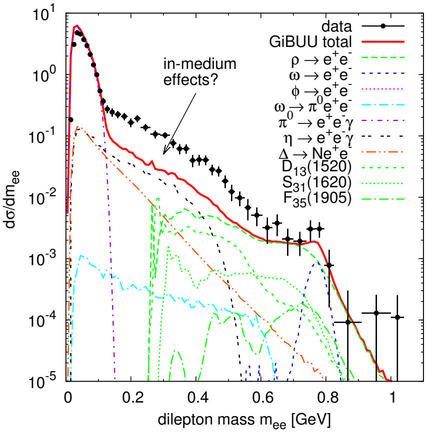
$^{12}C + {}^{12}C$ at 1.0 and 2.0 GeV

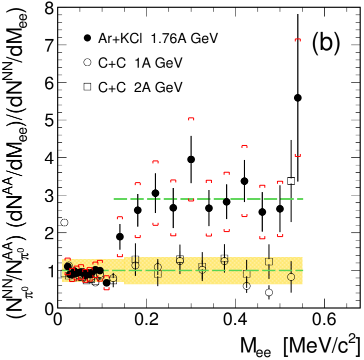




- C+C is a light system, can be described roughly by a superposition of NN collisions
- 2 GeV data well described by GiBUU
- some discrepancies at 1 GeV ("deuteron problem"?)

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





- Ar+KCl seems to show some excess over NN ($\sim$ factor 3)
- GiBUU with vacuum SF: similar discrepancy
  $\Rightarrow$ room for in-medium effects

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 energies)

3. p+Nb: good agreement with data
   (moderate medium modifications)

4. heavy-ion reactions:
   some problems in C+C at 1 GeV
   investigation of medium effects in ArKCl (VM + Res)
   $^{197}Au + ^{197}Au$ at 1.25 GeV

⇒ **both DLS puzzles still not completely solved,**
but we're getting closer (hopefully) ...