Deducing in-medium properties of hadrons

The GiBUU transport model

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European Graduate School
Complex Systems of Hadrons and Nuclei
Copenhagen - Gießen - Helsinki - Jyväskylä - Torino

Motivation

- **Aim** to observe hadrons within a nuclear medium
- **Problem:** Link between experiments and underlying physics often unclear
  - Distinguish profane and extraordinary effects
- **Simulation of the whole reaction process**
  - Full coupled channel approach
  - Include detector acceptances
  - Transport hadronic matter through space-time, from reaction zone to detector
- **R&D phase before experiments**
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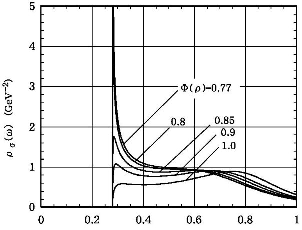
Example: The σ-meson



mass[GeV]

Shift of spectral strength to lower masses and a more narrow width in the Medium

e.g. Bernard et al. [Phys Rev Lett 59 (1989)],

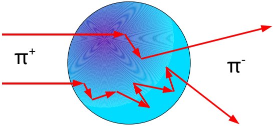
Hatsuda et al [Phys Rev Lett B367 (1999)]

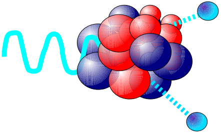
Experiment

- $\pi\pi$ photoproduction
  In-medium shift of the σ meson or just pion FSI?

Outline

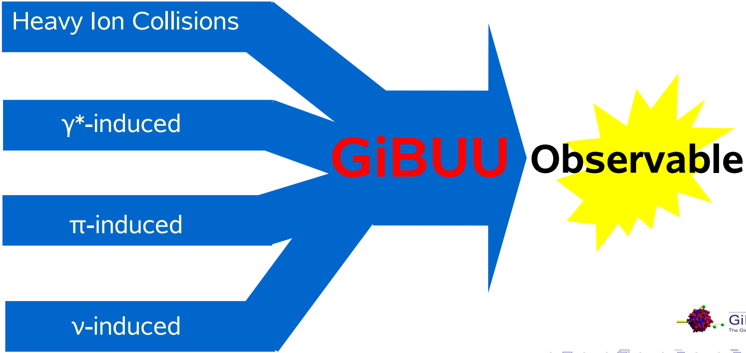
- The GiBUU transport model
- Applications
  1. π-benchmarks: DCX, . . .
  2. $\pi\pi$ photo-production
  3. ω photo-production
  4. e^- induced processes
- Summary & Outlook





The GiBUU transport model: Introduction

- Universal framework for various observables
  - Heavy-ion-collisions
  - Photon-, electron-, pion- and neutrino-induced processes
  - Gives hadronic multiplicities and also dilepton yields (e.g. for g7 at JLab)



The BUU equation

$$\frac{df_1^X(\vec{r}, p, t)}{dt} = I_{coll}\left(f_1^X, f_1^a, f_1^b, \ldots\right)$$

Offshell-transport

The collision term

- Full coupled channel problem
- Resonance model (Manley [Phys Rev C29 (1984)], PDG)
  - 61 baryons and 21 mesons in the code
- Background terms $\sigma_{\text{bg}} = \sigma_{\text{exp}} - \sigma_{\text{Res}}$
- Total cross sections as incoherent sums

Medium modifications

- Fermi motion
- Pauli Blocking
- Width modification
  - Collisional broadening

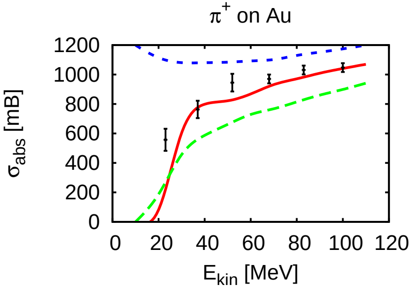
    Δ: Oset et al., NPA 468 (1987) 631; baryons: OB et al., nucl-th0707-0232
- Potentials
  - Coulomb potential
  - Baryons
    - Momentum dependend mean-field

      (Welke et al, Phys Rev C38 (1988) 2101)
    - $V_\Delta = \frac{2}{3} V_{\text{nucleon}}$

π benchmarks

Testing the model for pion FSI

- Pion absorption data
- Pion reaction cross sections
- Full width in comparison to optical model results
  ⇒ EPJ A29(2) (2006)
- Pion DCX



Data: Ashery et al. PRC 23,5(1981)

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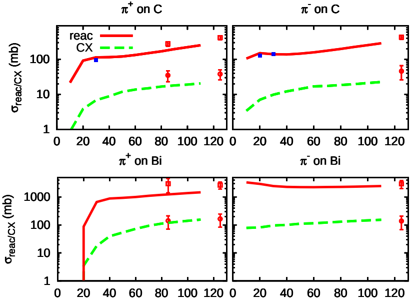

Data: Friedman et al., PLB257 (1991); Ashery et al. PRC 23,5(1981)

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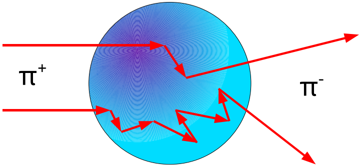
???

DCX: Introduction

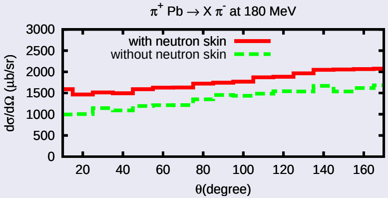
- **Sensitive test** for multiple scattering theory



- Extensive data sets for $E_{kin} = 120 - 270$ MeV, i.e. LAMPF
- Hüfner and Thies (1979): Qualitative agreement
- Vicente, Oset and Salcedo (1989): Focus on $\pi\pi$ production

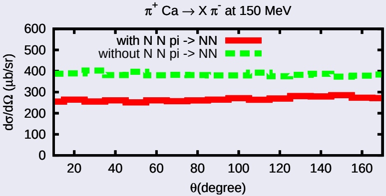
Sensitivity to model details

Neutron skins



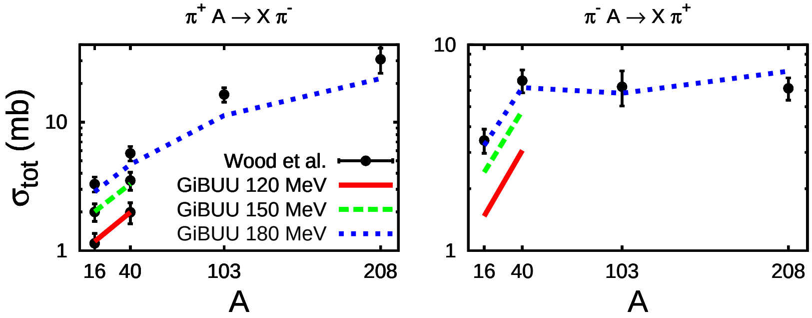
Process highly sensitive to surface effects → Access to surface properties ?!

$NN\pi \rightarrow NN$



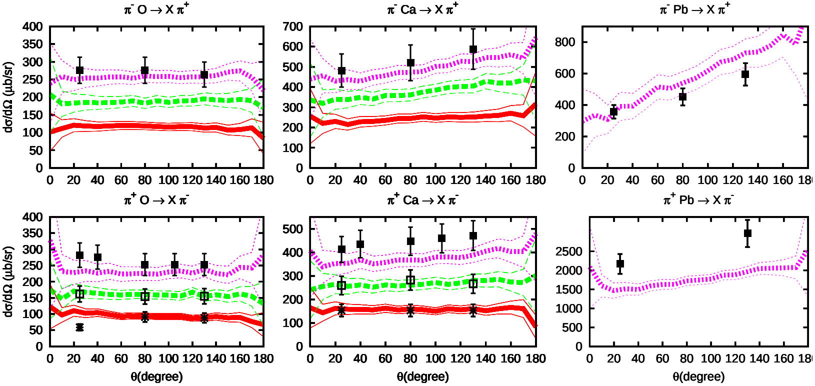
$NN\pi \rightarrow NN$ is important

Total Xsections



Data: Wood et al., Phys Rev C46,5 (1992) 1903

Scattering angles

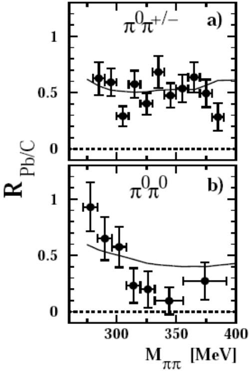


$T_\pi = 120, 150, 180$ MeV

$\pi\pi$ photoproduction off nuclei

Experimental findings

$$R_{Pb/C} \sim \sigma_{Pb}/\sigma_C = \sigma(High\ \rho_{eff})/\sigma(low\ \rho_{eff})$$



"non-σ-channel"

"σ channel"

J. G. Messchendorp et al., Phys. Rev. Lett. 89 (2002)

Theoretical descriptions

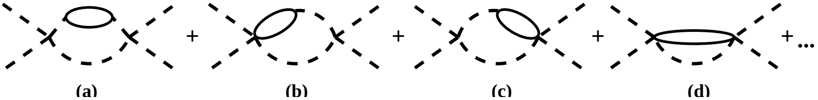
- Linear σ model, NJL: σ-meson as chiral partner of the pion
  Expect lowering of the mass due to chiral symmetry restauration in the medium

  Bernard et al. PRL 59(1987); Hatsuda et al. PRL 82 (1999)

- σ as dynamically generated pole in the $\pi\pi$ scattering amplitude

  Oller, Oset et al., PRD 59 (1999)

  Shift due to strong *P*-wave couplings



Roca et al., Phys. Lett. B541 (2002)

- Incoherent final state rescattering of the pions

Our Model

Initial state

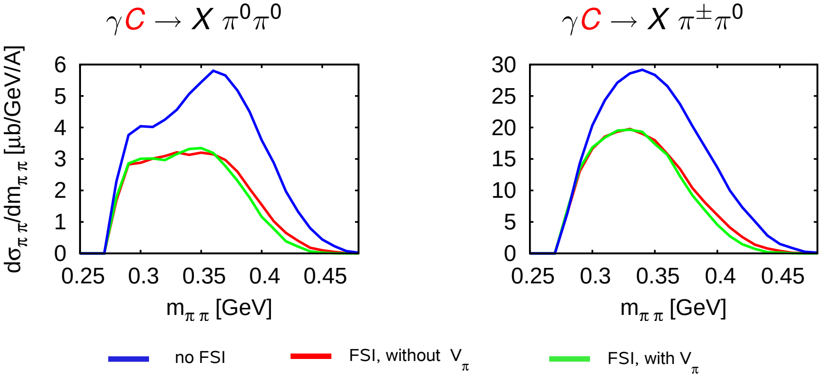
- Microscopic model for $\gamma N \to N'\pi\pi$ as event generator

  Tejedor, Oset, NPA 600 (96); Nacher et al , NPA 695 (01)
- Total cross sections scaled to match experiment
- No medium modifications in the propagators
- Consider Fermi motion of nucleons

Final State

Final state by GiBUU transport model

Mass distribution, 400 MeV $< E_\gamma <$ 500 MeV



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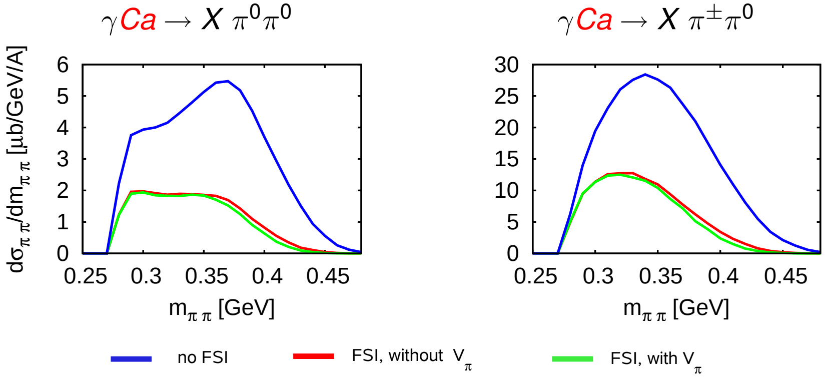

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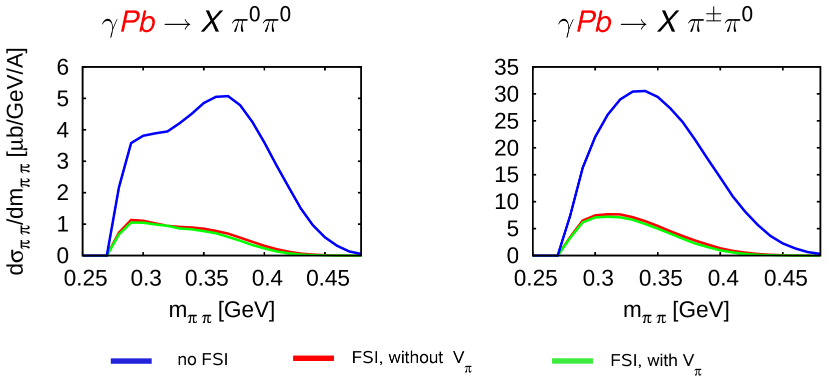
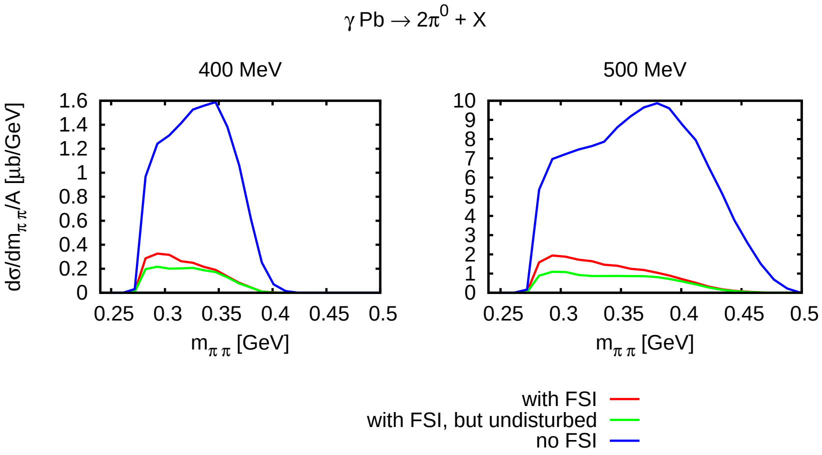
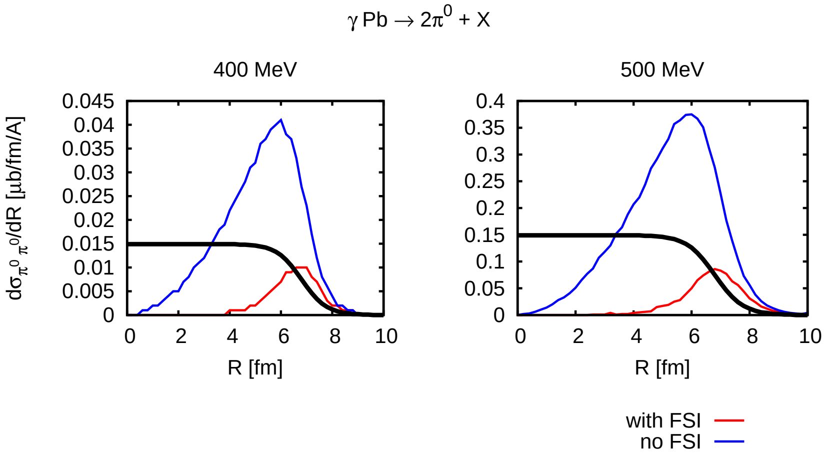


Final state effects - details



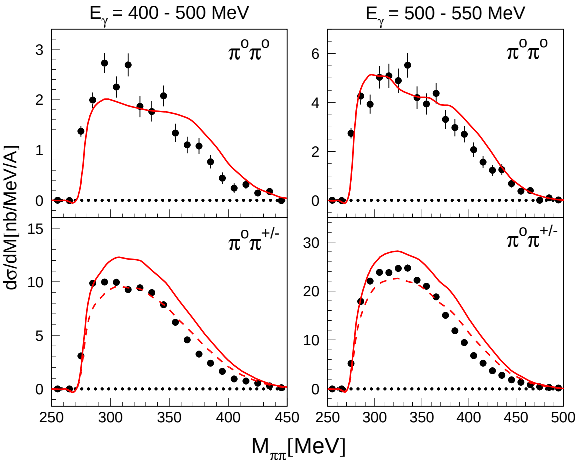
Rescattering leads to enhancement at low masses

Production places



Mostly surface → low effective densities

Latest experimental results: $\gamma Ca \to X\pi\pi$



F. Bloch, B. Krusche et al., EPJ A32:219,2007.

$\Rightarrow$ Data also compatible with FSI effects.

Uncertainties

- Elementary data
  - Problem due to uncertain $\gamma n \to X$ cross sections.
  - Errors up to 20% solely due to elementary input
  - CB-ELSA TAPS: new data on deuterium
- Final state interactions
  - Possibility to suppress extreme low-energetic pions ?!

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ω photoproduction

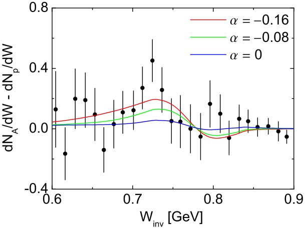
ω photoproduction: $\gamma A \to (\omega \to \pi^0\gamma)X$

Determine ω self energy via comparison of BUU and experiment

Parametrization of real part

$$m^\star_\omega = m^0_\omega \left(1 + \alpha \frac{\rho}{\rho_0}\right)$$

Invariant mass reflects $\mathcal{A}$:



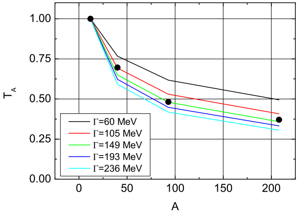
$\Rightarrow \alpha \simeq -\mathbf{0.16}$

theory: P. Muehlich et al., NP A780:187-205
data: D. Trnka et al., PRL 94:192203

Parametrization of imaginary part

$$\Gamma^\star_\omega = K \rho v_{rel} \sigma_{\omega N}$$

Transparency $T_A \sim \sigma_{\gamma A}/\sigma_{\gamma^{12}C} \to$ absorption strength $\leftrightarrow$ lifetime $\leftrightarrow$ inelastic width



$\mathbf{K \simeq 1.75} \Rightarrow \Gamma(p = 1\,GeV) \simeq 150$ MeV

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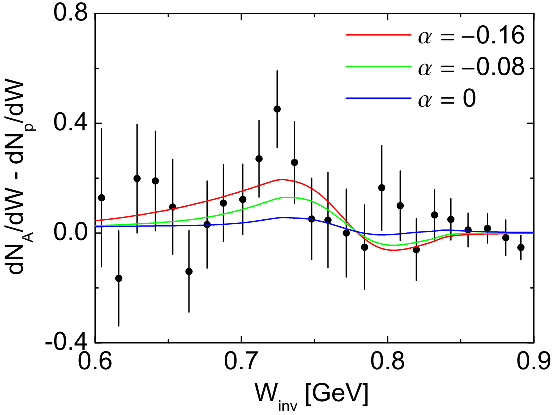

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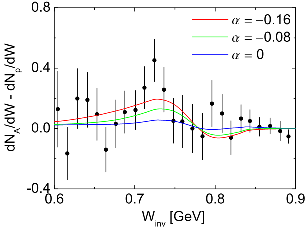

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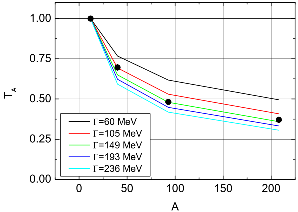

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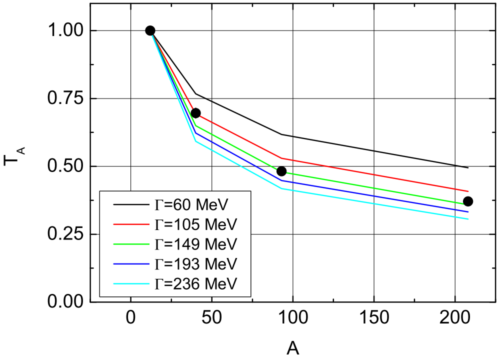
$E_\gamma = 1.2 - 2.2$ GeV



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data: D. Trnka et al., preliminary (talks tommorow afternoon!!)

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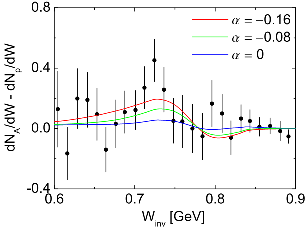

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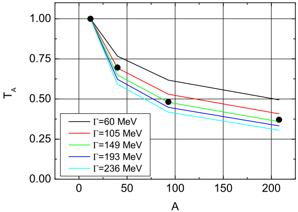

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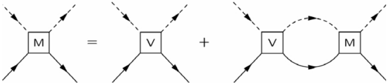
ω meson in nuclear matter

Microscopic determination of ω in-medium self energy

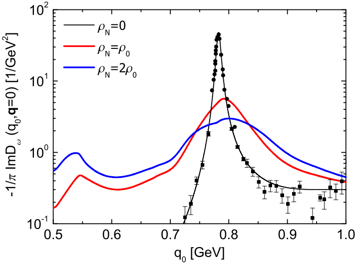
P. Muehlich et al., NP A780:187-205

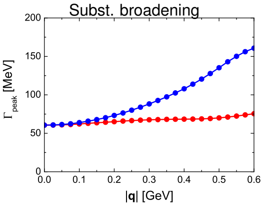
Low density theorem: $\Pi_\omega^{med} = \rho T_{\omega N \to \omega N}$

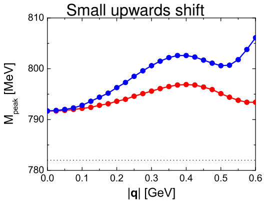
Forward scattering amplitude: K-matrix solution of Bethe-Salpeter eq.



Spectral function at $p = 0$







At present: Contradiction of theory and experiment

e^- induced processes

e^- induced processes in the resonance region

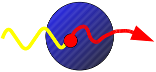
Motivation

- Properties of the nucleon in the medium
  - Collisional broadening
  - Effective model for the nuclear ground state
- Resonance excitations in the medium
  - Melting of the resonances
- Connection to high energy electron scattering
  - K. Gallmeister: "Time dependence of hadronization" (friday 11:25)
  - Bloom Gilman duality
- e^- as benchmark for ν induced processes

arXiv:0707.0232 [nucl-th], in press

Our model for the initial vertex

- Impulse approximation
- In-medium kinematics (i.e. potentials included)



Quasi-elastic scattering

$$J^\mu_{\mathrm{QE}} = F_1\gamma^\mu + \frac{i}{2m_0}F_2\sigma^{\mu\nu}q_\nu + \frac{F_1(m_i - m_f)}{q^2}q^\mu$$

- Assume $F_1(Q^2)$, $F_2(Q^2)$ same as in vacuum (BBBA05)

Pion production

$$J^\mu_\pi = \sum_{i=1}^{6} A_i M^\mu_i$$

- MAID (Tiator et al.)

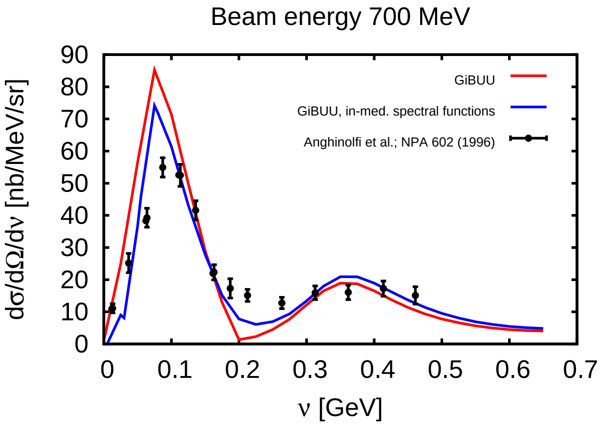
Resonance production

FF $\Leftrightarrow$ MAID helicity amplitudes

Δ, $P_{11}(1440)$, $D_{13}(1520)$, $S_{11}(1535)$, $S_{31}(1620)$, $S_{11}(1650)$, $D_{15}(1675)$, $F_{15}(1680)$, $D_{33}(1700)$, $P_{13}(1720)$, $F_{35}(1905)$, $P_{31}(1910)$, $F_{37}(1950)$

Results: Inclusive cross sections off ¹⁶O

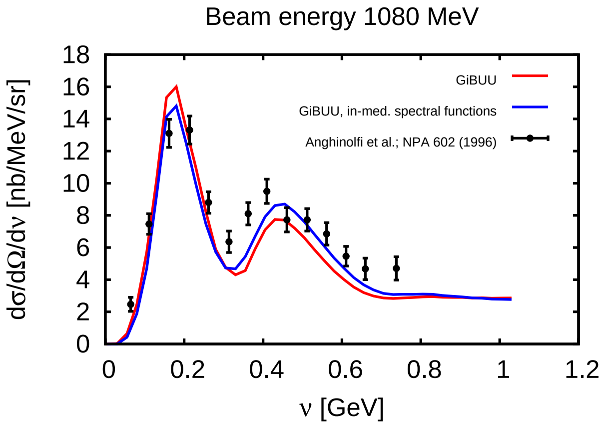
$Q^2 \leqslant 0.137\ \mathrm{MeV}^2$



Data: M. Anghinolfi et al., NPA 602 (1996); ADONE(Frascati)

Results: Inclusive cross sections off ^{16}O

$Q^2 \leqslant 0.328\ \mathrm{MeV}^2$



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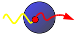
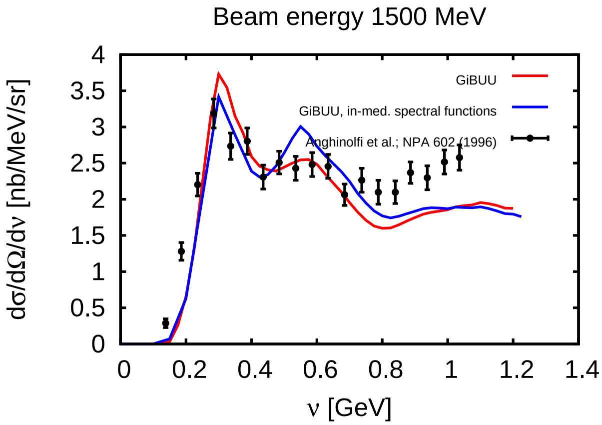


Results: Inclusive cross sections off ^{16}O

$Q^2 \leqslant 0.632\ \mathrm{MeV}^2$



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Summary & Outlook

- e^- scattering
  - Satisfying description of total inclusive cross sections
  - Outlook : Pion production

http://gibuu.physik.uni-giessen.de

Summary & Outlook

- π-benchmarks
  - Pion DCX described successfully for $E_{kin} \gtrsim 30$ MeV
  - Large influence of neutron skins ($\rightarrow$ PREX)
- $\pi\pi$ photoproduction
  - New analysis also compatible to FSI interpretation
  - Pions stem from surface, small effective density
- ω photoproduction
  - Theory ($m_\omega \uparrow$) and experiment($m_\omega \downarrow$) contradict
- e^- scattering
  - Satisfying description of total inclusive cross sections
  - Outlook : Pion production

http://gibuu.physik.uni-giessen.de

Thank you!

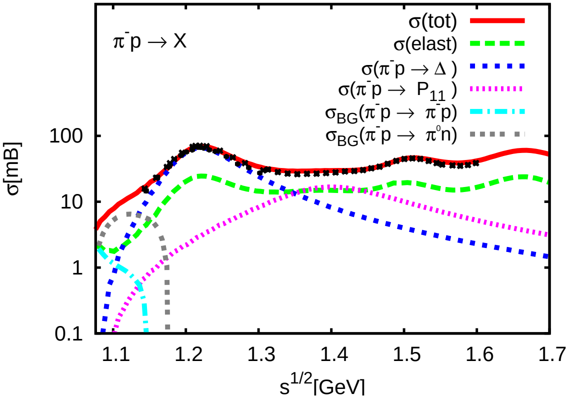
Deutsche Forschungsgemeinschaft

DFG

Pions - details

Pion-nucleon scattering

$$\sigma_{\pi N\to\pi N} = \sigma_{\pi N\to R\to\pi N} + \sigma^{BG}_{\pi N\to\pi N}$$



Data

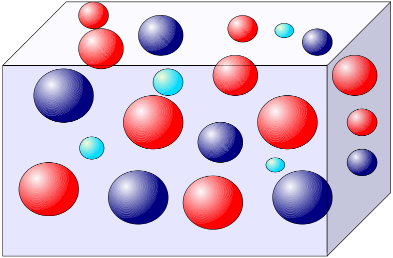
- Carter et al. [Nucl Phys B26 (1971)]
- Davidson et al. [Phys Rev D6 (1971)]
- Kriss et al [Phys Rev C59 (1999)]

Pions in nuclear matter

Pions in nuclear matter

Basic checks

- Size of box: $(12\mathrm{fm})^3$
- Continuous boundary conditions
- Pions initialized within radius of $3.5\mathrm{fm}$ in *xy*-plane at origin
- $\Delta t = 0.25\frac{fm}{c}$, $T = 2.5\frac{fm}{c}$
- 300 parallel ensembles with 100 pions/ensemble
- 6 sequential

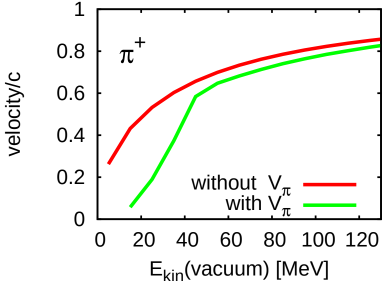


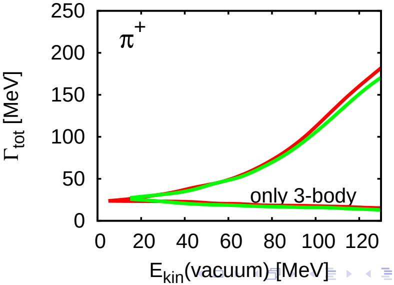
Mean free path

- Mean free path interesting model parameter
- Discrepancies in the literature

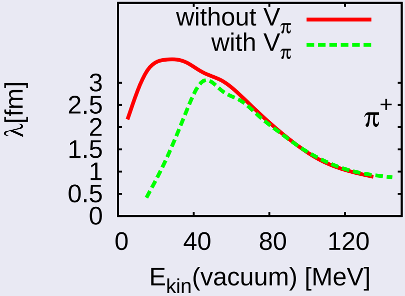
$$\lambda = \frac{v}{\Gamma}$$

Decrease of velocity due to repulsive potential

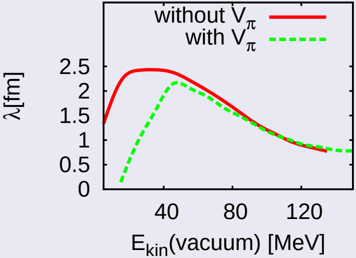




π^+ meson



π^0 meson



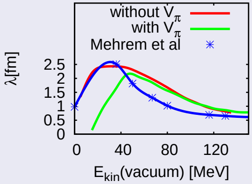
- Semiclassical treatment causes problems for $E_{kin} \lesssim 20\,\mathrm{MeV}$
- Classical not allowed region in phase space
- Importance of tunneling

Comparison to other calculations

Optical Model

- Use QM-solution of dispersion relation

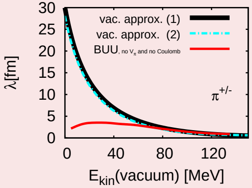
$$\lambda = \frac{1}{2\Im(p)}$$



Vacuum approximation

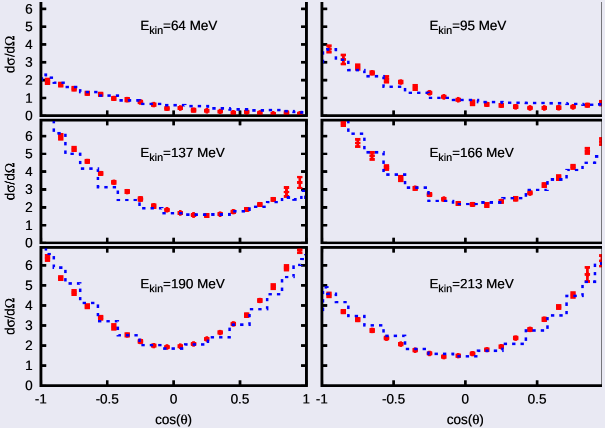
$$\lambda = \frac{1}{\rho\sigma_{\pi N\to X}} \quad (1)$$

$$\lambda = \frac{1}{4\int_{p_F}\sigma_{\pi N\to X}(s)\frac{d^3p}{(2\pi)^3}} \quad (2)$$



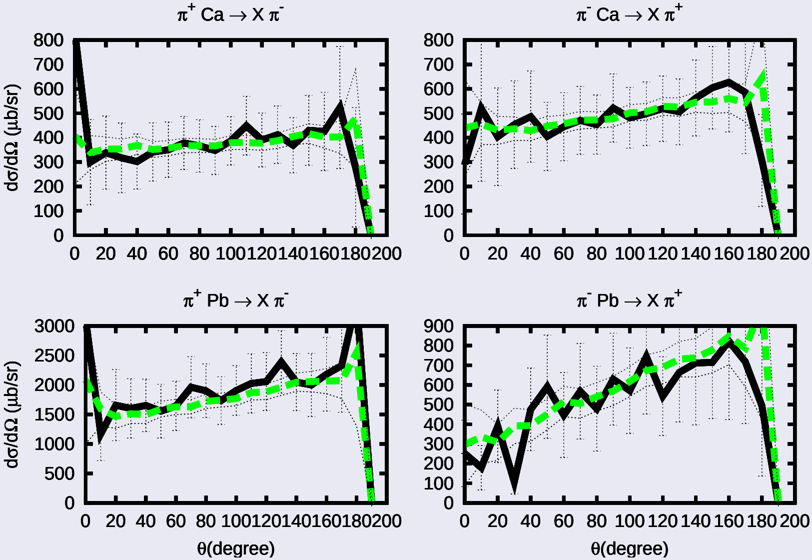
DCX - details

Elementary DCX



$\pi^- p \to \pi^0 n$ angular distribution in CM frame; data from CB: Sadler et al. (2004)

Full versus parallel Ensemble



Scaling: DCX as simple 2-step process

Idea

- Surface process
  $\Rightarrow \sigma \sim A^{2/3}$
- Assume two-step process

$$\sigma \sim \frac{Q(Q-1)}{(A-Q)(A-1)} A^{2/3}$$

$Q = N$ for π^-
$Q = Z$ for π^+

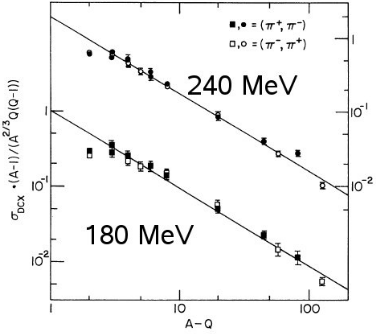


FIG. 3. Total inclusive cross sections at 240 MeV (upper

Gram et al., Phys. Rev. Lett. 62(1989)

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So simple?

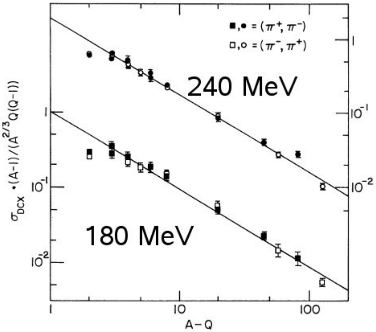

FIG. 3. Total inclusive cross sections at 240 MeV (upper

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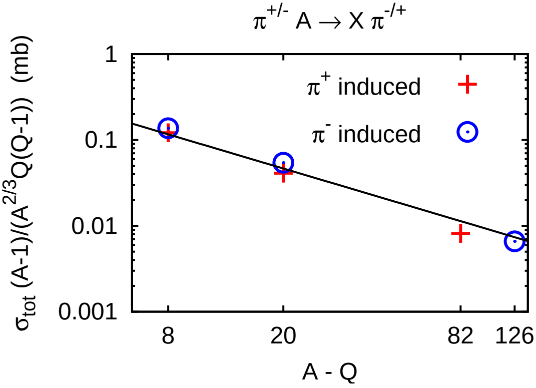
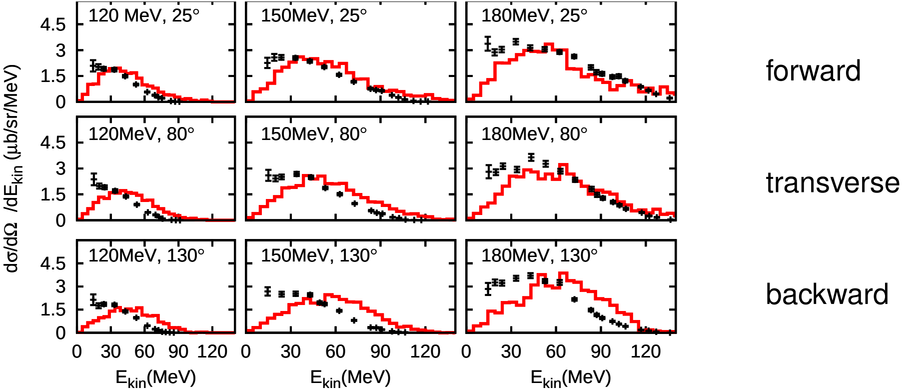
Scaling



$\Longrightarrow$ It seems so easy, since medium effects (e.g. Coulomb, skins) cancel each other.

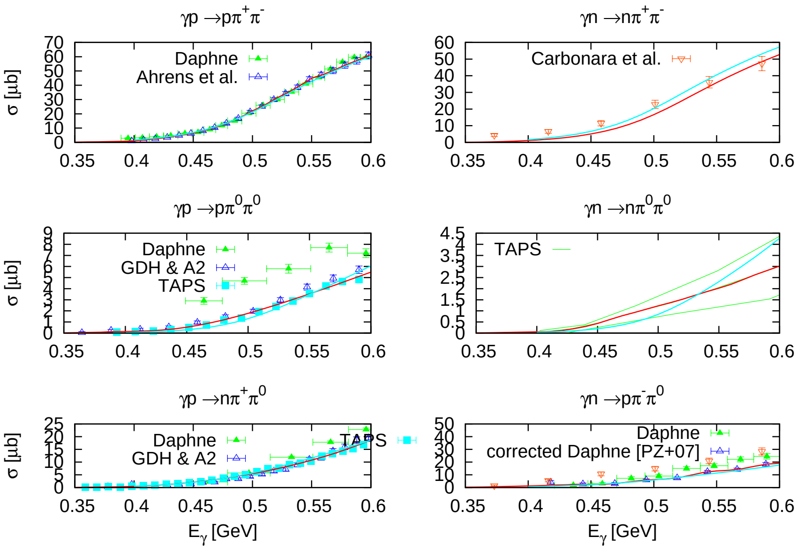
Energy distribution

$\pi^+ O \to X\pi^-$

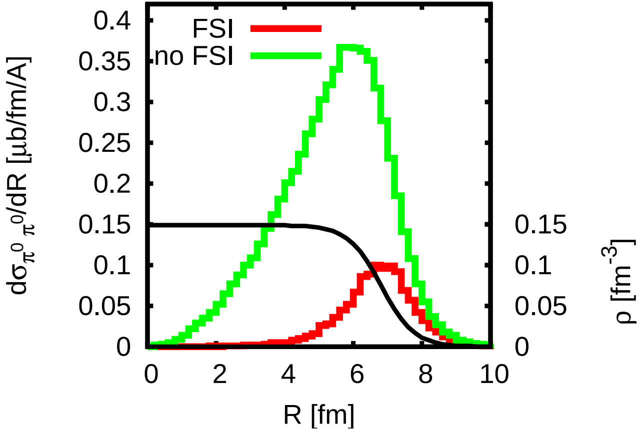


$\pi\pi$ production - details

Elementary cross sections

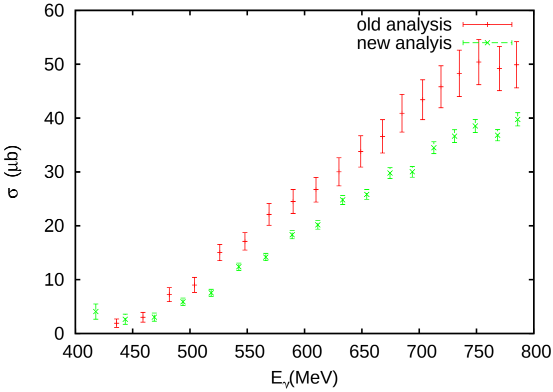


Production places

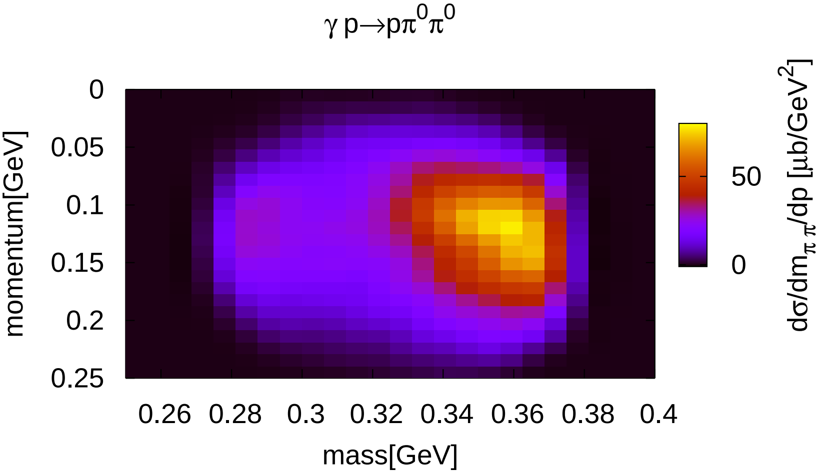


$E_\gamma = 500\ \mathrm{MeV}$

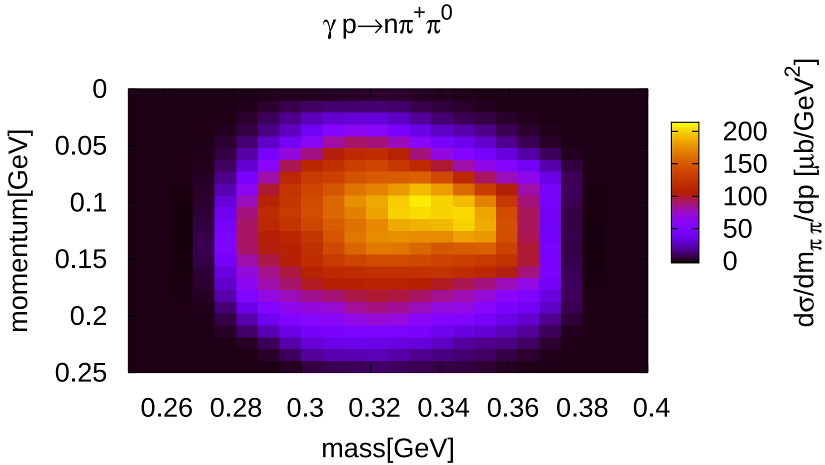
$\gamma n \longrightarrow p\pi^-\pi^0$



Zabrodin et al., P. Pedroni



$E_\gamma = 450$ MeV



$E_\gamma = 450$ MeV

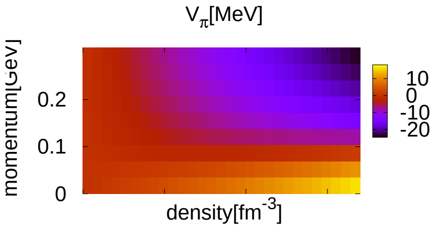
The hadronic potential for the π meson

$p < 80$ MeV — Optical model — $V_{opt} = \frac{\Pi(\omega_{vac})}{2\omega_{vac}}$

Nieves NPA 554,554 (1993)

$p > 140$ MeV — First Order Delta-Hole — $V_{opt} = \sum_i Z_i V(\omega_i)$

$140 > p > 80$ — Interpolation



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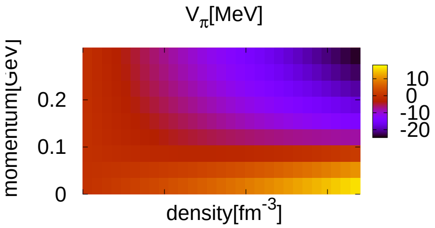

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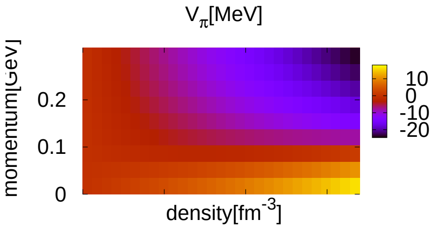
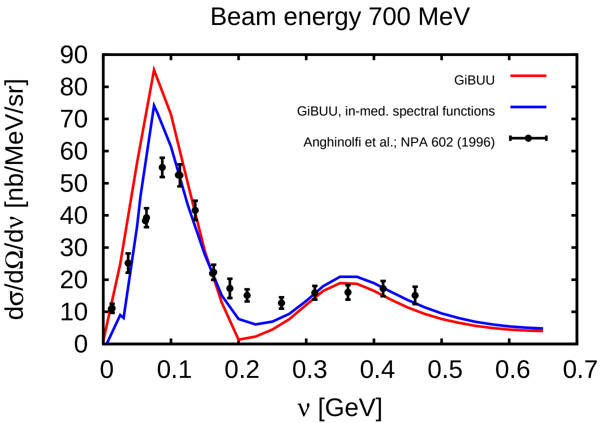


e^- scattering - details

Results: Inclusive cross sections off ^{16}O

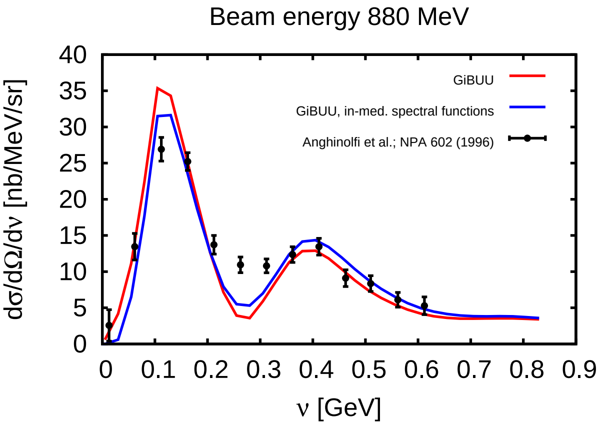
$Q^2 \leqslant 0.137\ \mathrm{MeV}^2$



Data: M. Anghinolfi et al., NPA 602 (1996); ADONE(Frascati)

Results: Inclusive cross sections off ^{16}0

$Q^2 \leqslant 0.217\ \mathrm{MeV}^2$



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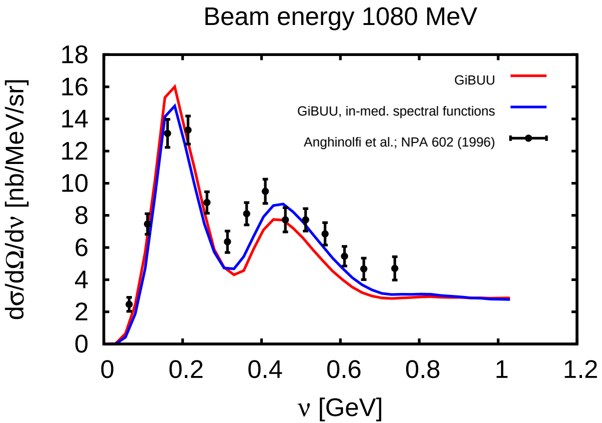

Data: M. Anghinolfi et al., NPA 602 (1996); ADONE(Frascati)

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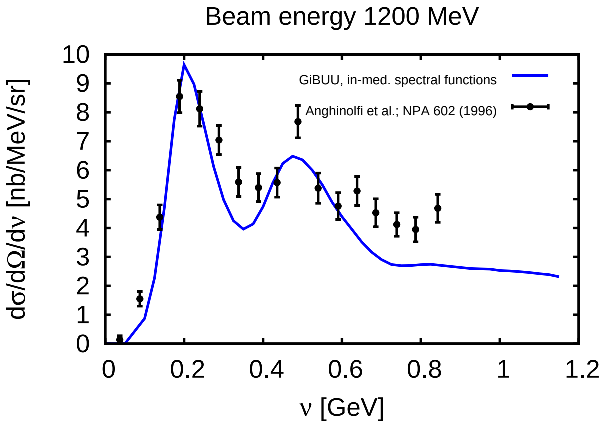

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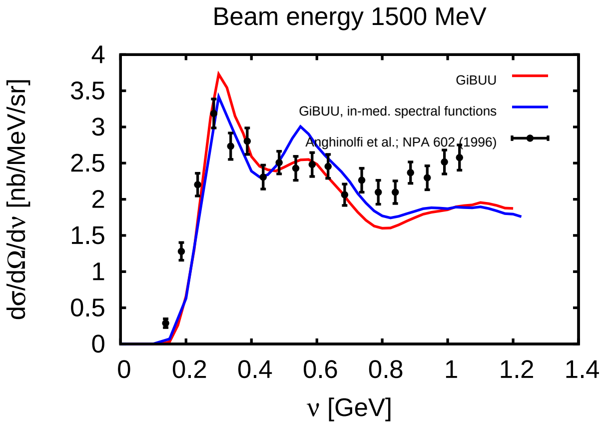

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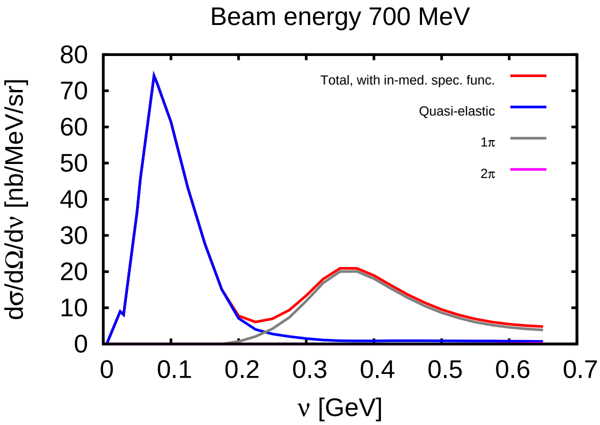

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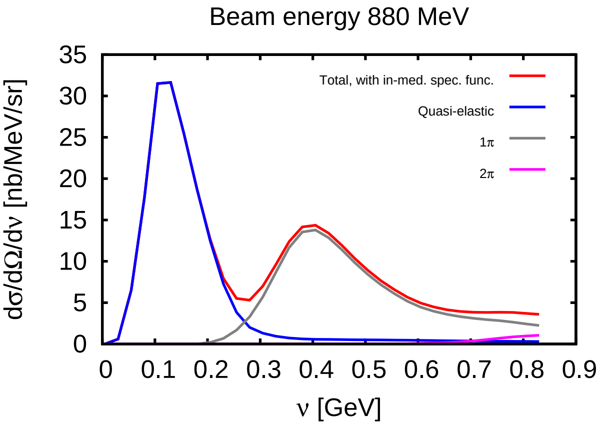

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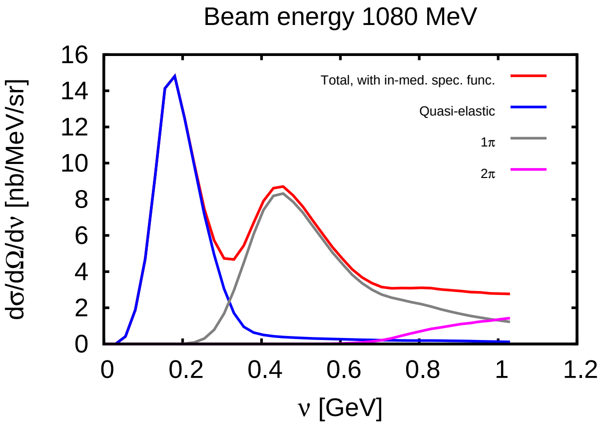

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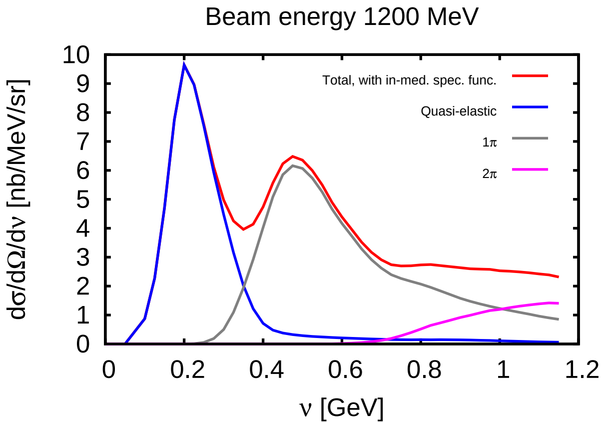

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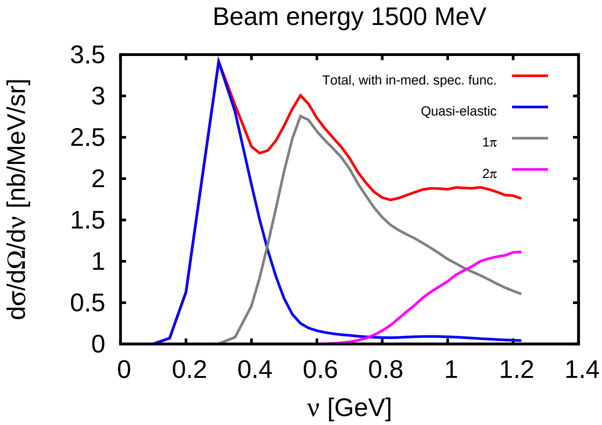

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