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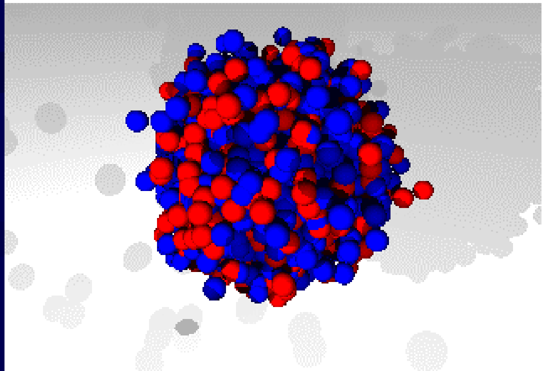

Low-energy pions in nuclear matter

... within a Boltzmann-Uehling-Uhlenbeck transport model

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„In-Medium Hadron Physics“
Giessen, November 2004

Outline

- Motivation
  - 2π correlations in experiment by TAPS (Metag, Messchendorp, Schadmand et al)
- Part I: Low-energy pions in a BUU transport simulation
  - diploma thesis at JLU Giessen, May 2004
    - http://theorie.physik.uni-giessen.de/html/diploma_theses.html
- Part II: ππ photoproduction off complex nuclei
  - P. Mühlich, L. Alvarez-Ruso, O. Buß, U. Mosel
    - Phys.Lett.B595:216-222, 2004
- Conclusions and Outlook

Motivation

Motivation:
2π correlations with TAPS

- Photoproduction off complex nuclei with 400-460 MeV γ's at TAPS@MAMI
  - Metag, Messchendorp,Schadmand et al
  - Phys. Rev. Letters 89(2002)222303
- Excitation of the "f0(600)" (L=0,I=0) resonance, which is called σ-meson.
  - Possible Final states : $\sigma \to \pi^0 \pi^0$, $\sigma \to \pi^+ \pi^-$
    - σ decays already inside the nuclear medium into a π π final state.
    - Key idea : Observe the invariant mass in the $\pi^0 \pi^0$ channel, to analyze the modification of the σ resonance in the medium.
    - Prediction: The mass of the σ resonance is shifted down
      - e.g Chanfray et al : Phys.Lett.B256 (1991) , Roca et al: Phys.Lett.B541(2002) , ...
- Problem
  - Ordinary final state interactions of pions in the media.

Part I

Pions in a Boltzmann-Uehling-Uhlenbeck (BUU) transport simulation

The BUU model

- **Transport model derived in 1930‘s based on classical Boltzmann equation**
  - Utilized by Bertsch & Kruse in the early 1980‘s to model heavy ion collisions
    - Phys Rev C29(1984),673
  - Related by limiting procedure to full Kadanov-Baym equations (Quantum mechanical transport equations)
  - Allows full coupled channel calculations
- **Off-Shell transport incorporated in the late 90‘s**
  - e.g. Effenberger, Leupold, Cassing, Mosel at JLU Giessen (Phys.Rev.C60:051901,1999)
- **Usage of basically the <u>same code</u> in heavy-ion collisions, photon-nucleus and electron-nucleus processes**

$$\frac{df}{dt} = \partial_t f(\vec{p},\vec{r}) + \nabla_{\vec{p}} H \ \nabla_{\vec{r}} f(\vec{p},\vec{r}) - \nabla_{\vec{r}} H \ \nabla_{\vec{p}} f(\vec{p},\vec{r}) = I_{coll}$$

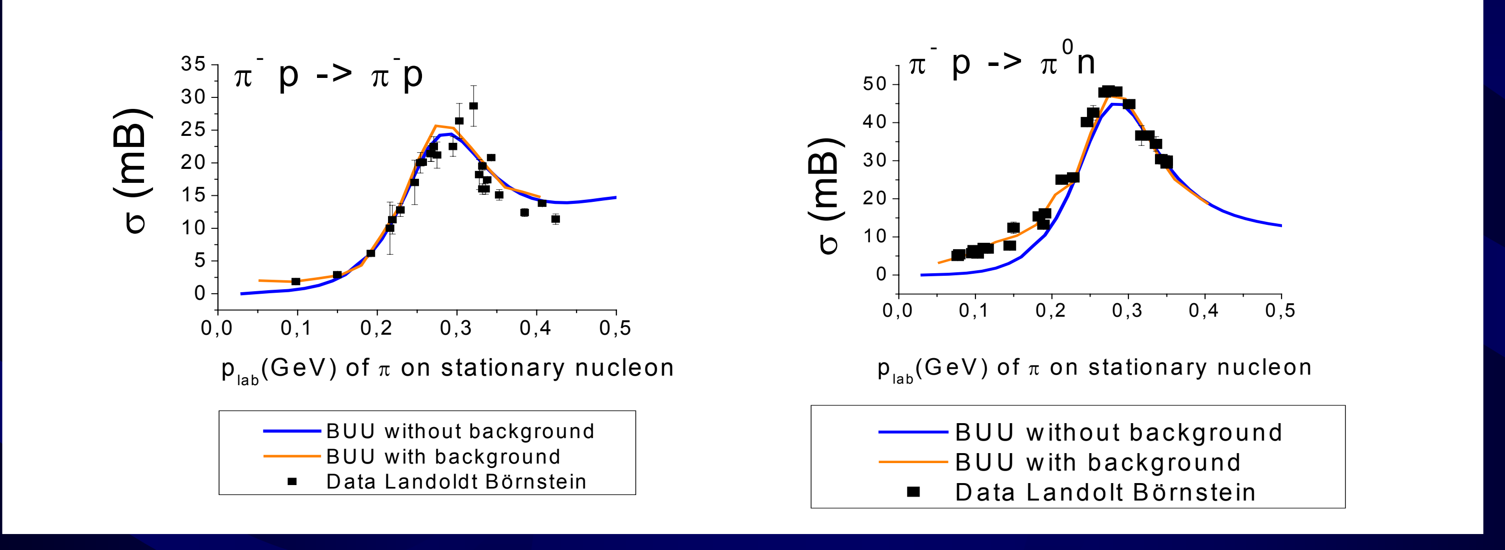
Some earlier works...

- Salcedo, Oset et al
  - NPA 484 (1988)
  - „Computer simulation of inclusive pion nuclear reactions“
  - 85 MeV<E_{kin}< 300 MeV
  - Only pions as degrees of freedom in simulation
- Engel, Cassing, Mosel, Schäfer and Wolf
  - NPA 572 (1994), 657
  - „Pion nucleus reactions in a microscopic transport model“
  - 85 MeV<E_{kin}< 315 MeV
  - Precessor model of the actual BUU code
- ...

The collisions: Elastic scattering

Two channels:

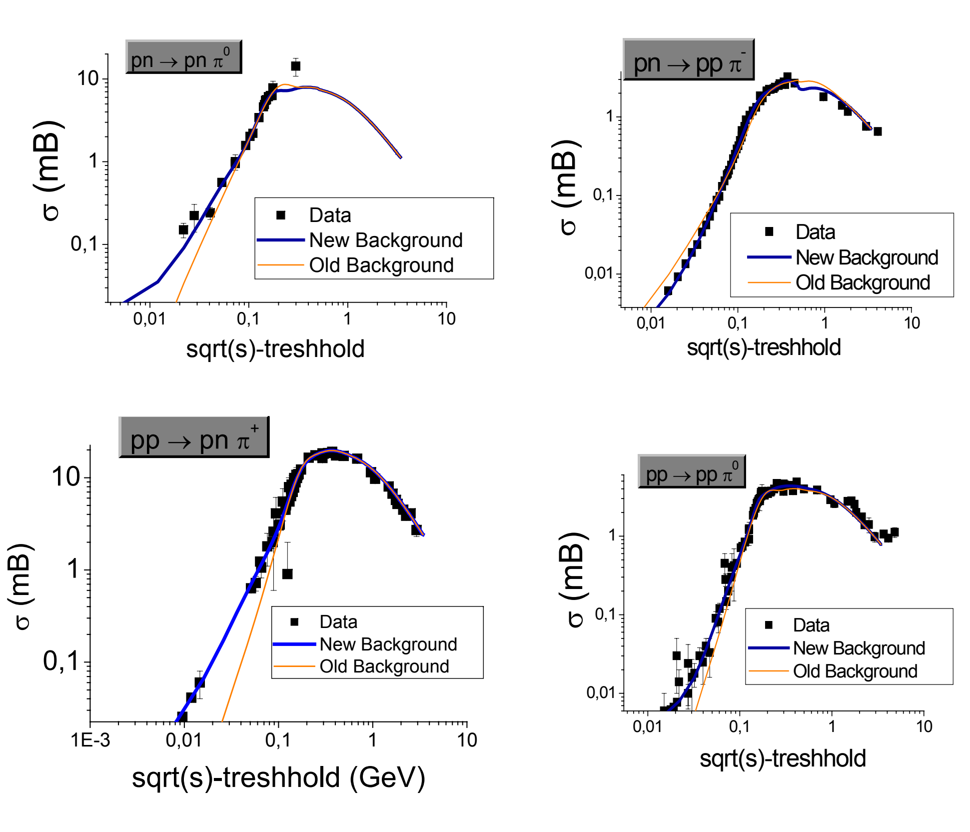
1. N π → R → N π
2. Non resonant background (not necessary in I=3/2 channel)
   - Fitted to match experimental cross sections



The collisions : Pion absorption

- Use detailed balance to describe $N\,N\,\pi \Rightarrow N\,N$ by the inverse process
- <u>Two channels for $N\,N\,\pi \Rightarrow N\,N$:</u>

  1. $N\,N \Rightarrow N\,R \Rightarrow N\,N\,\pi$
  2. Nonresonant background
     - Fitted to match experimental crosssection for elementary processes



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Most important medium modifications in the model

- Pauli blocking of final states if Δ decays
- Delta receives collisional width (new decay channels in medium)
- Potential (Skyrme type with momentum dependence)
- Off-Shell propagation

M. Effenberger,

Diploma thesis 1996

Δ

- Pauli blocking of final states if π is absorbed
- Potential derived from self energy

π

•Potential (Skyrme type with momentum dependence)

•Pauli blocking

N

The Δ Width

Studied by M. Effenberger, Diploma thesis 1996

- Problem : Missing Δ NN $\rightarrow$ NNN process.
- Correct collisional width introduced according to Oset et al, NPA 468(1987), 631-652
- Technical: No explicit Δ N $\rightarrow$ N N process, solved via decay of the Δ´s.

Δ

The Δ Potential

Phenomenology: $V_\Delta \simeq$ -30 MeV (e.g. Ericson-Weise: "Pions and nuclei", page 248)

Momentum independent nucleon potentials are roughly 50 MeV strong.

Therefore we model the Δ potential by

$$V_\Delta = \frac{2}{3} V_{nucleon}$$

Therefore we also assume same momentum dependence

Δ

The Nucleon Potential

Welke et al, Phys Rev. C38 (1988)

Medium-momentum-dependend potential with K=290 MeV. Also other options possible!

Fixed in momentum dependence by:

$$
\begin{aligned}
V_{nucleon}(p=0,\rho=\rho_0) &= -75 MeV \\
V_{nucleon}(p=0,\rho=\rho_0) &= -75 MeV \\
V_{nucleon}(p=\infty,\rho=\rho_0) &= 30.5 MeV
\end{aligned}
$$

N

Effective Hamiltonian for the pion used in BUU

p_π<140 MeV:

Low energy model for the self energy Π

(Nieves et al, NPA 554 (1993)**)**

- Valid for low momentum
- Evaluate self energy at vacuum energy
- Good approximation at low energies

$$H_{eff} \equiv \sqrt{m^2 + \vec{p}^{\,2} + \Re\left(\Pi\left(m^2 + \vec{p}^{\,2}\right)\right)} + V_C$$

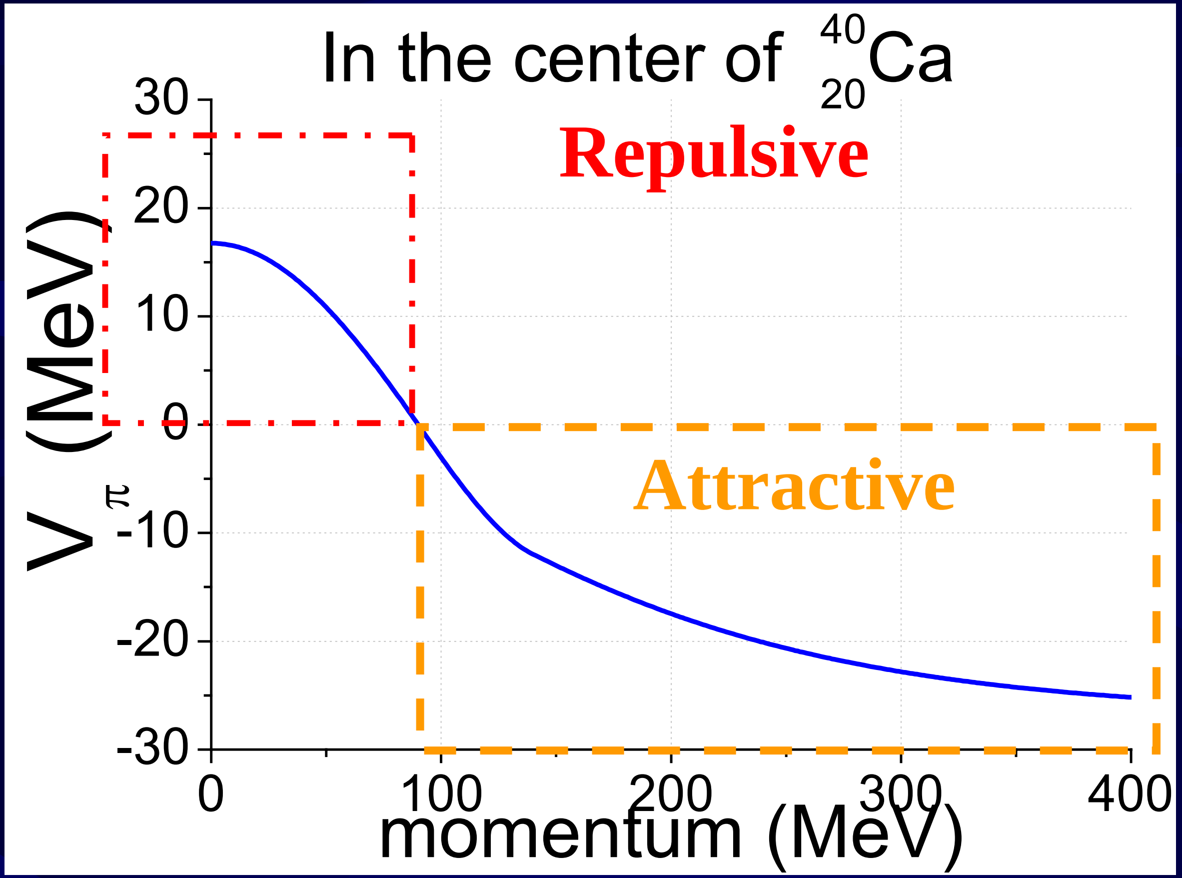
p_π ≥140 MeV:

Use simple delta hole model

- Solve dispersion relation analytically p=p(ω)
- Derive spectral function ρ(ω,p)
  - Result: Two branches in ρ(ω,p)
    - W. Ehehalt
      - Diploma thesis 1992
    - P. Henning,
      - Phys.Rep. 253 (1995)

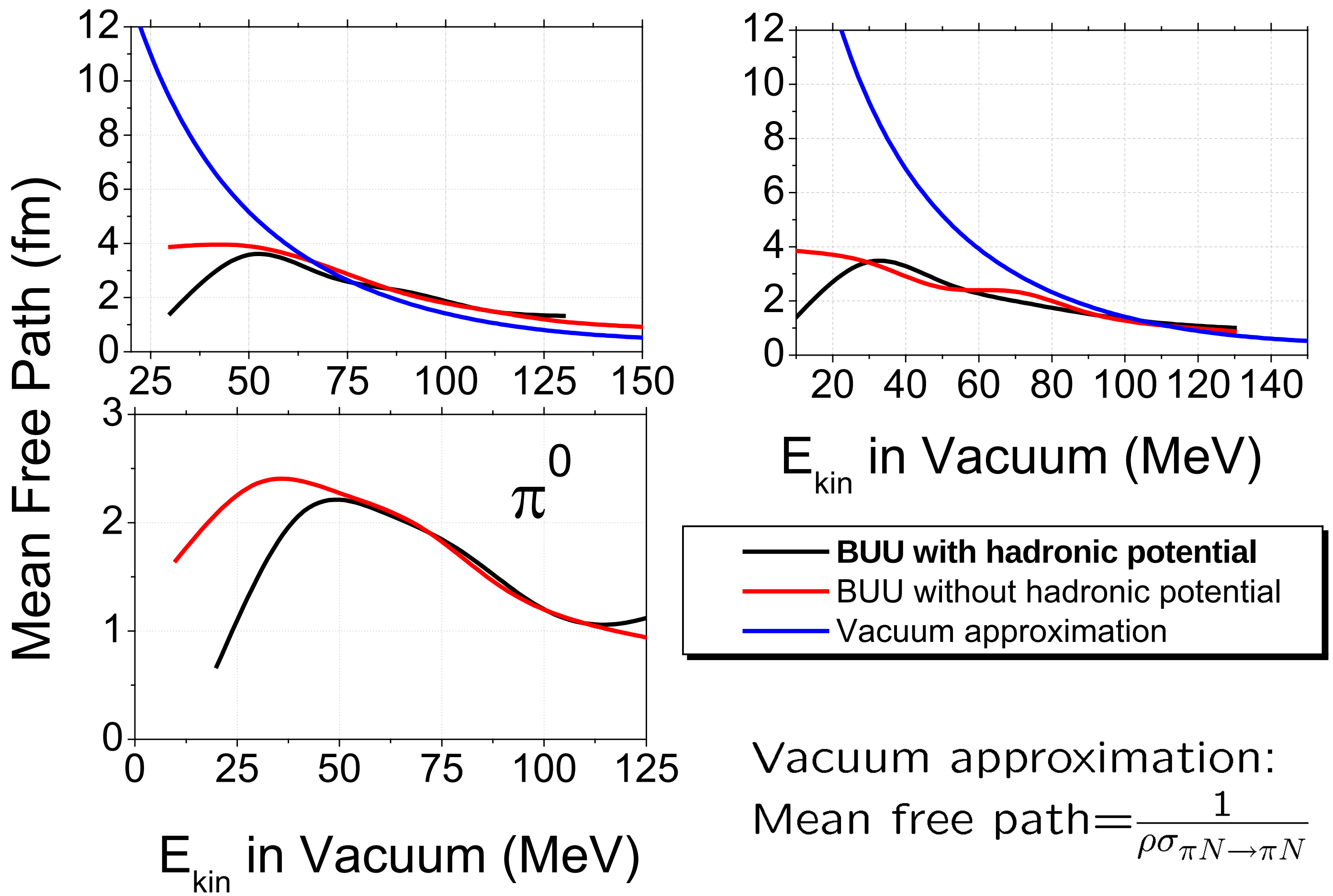
$$\begin{aligned} H_{eff} \equiv\ & Z_{\Delta-\text{hole}-\text{branch}}\, E_{\Delta-\text{hole}-\text{branch}} \\ & + Z_{\pi-\text{branch}}\, E_{\pi-\text{branch}} + V_C \end{aligned}$$

$$V_\pi = H_{eff} - H_{vacuum}$$



Results I :
Mean free path in BUU

Mean free path



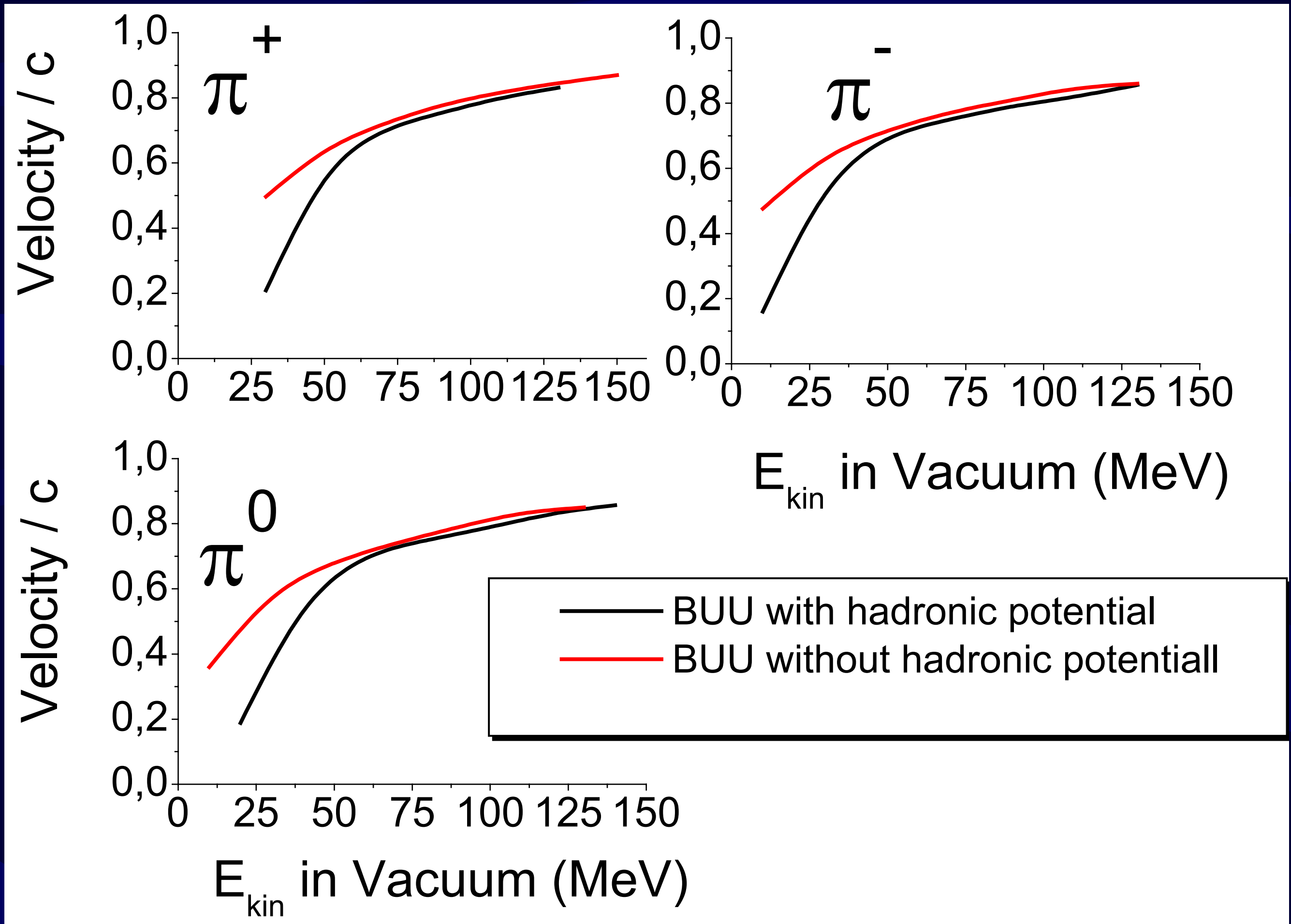
Vacuum approximation:

Mean free path$=\frac{1}{\rho\sigma_{\pi N\to\pi N}}$

$\Rightarrow$ NN$\leftrightarrow$ N N π is important

- Minor impact of potential at large energies
- Steep decrease at low energies $\rightarrow$ problems with tunneling?!

Velocity modification



Comparison to result with optical model

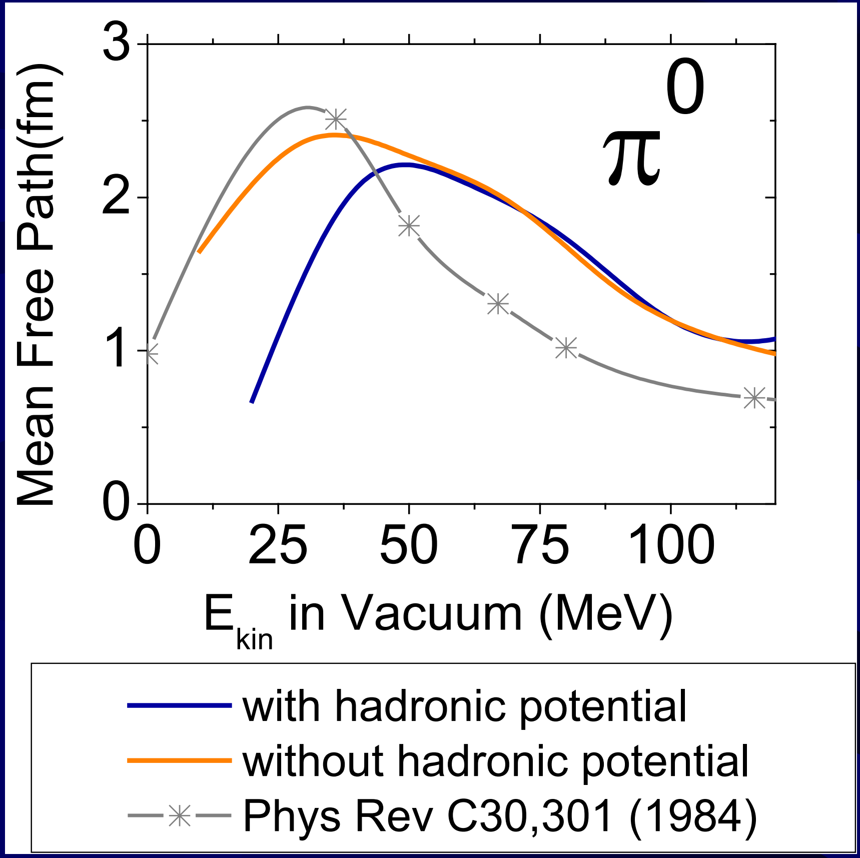
- Optical potential based on analysis of scattering experiments
- Determine mean free path with

$$\Psi_\pi = e^{ikr} \text{ with } k \in \mathbf{C}.$$

$$\Rightarrow I(r) \sim \Psi_\pi^\star \Psi_\pi = e^{-\frac{r}{\lambda}} \text{ with } \lambda = \frac{1}{2\Im(k)}$$

- Determine k by solving K.-G. equation in momentum space

$$(E + V_{opt}(E,k))^2 = k^2 + m^2$$



Mehrem, Radi, Rasmussen

Phys Rev C30,301 (1984)

Mehrem, Radi, Rasmussen

Phys Rev C30,301 (1984)

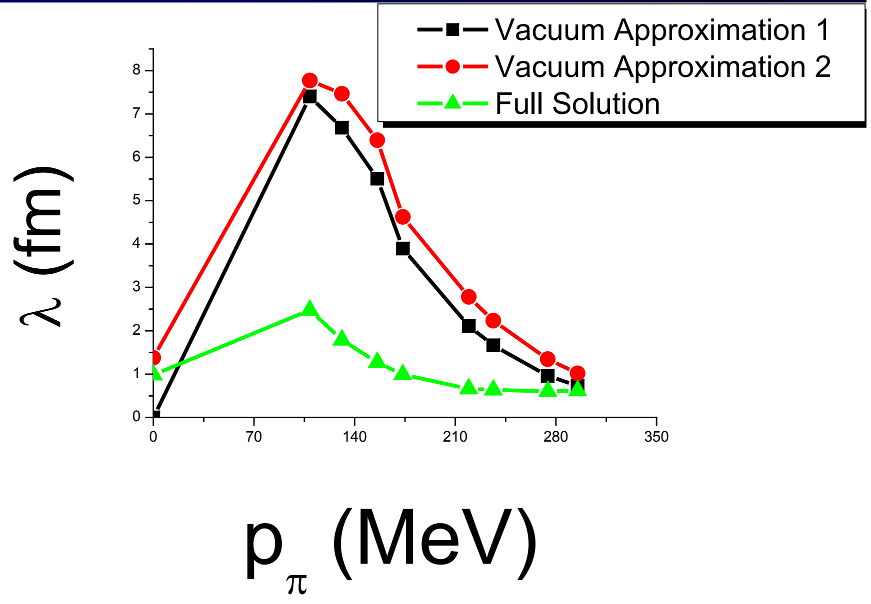
Old knowledge

- Solving the dispersion relation is (in some cases) the key
- Vacuum approximations faulty :

$$\lambda \simeq -\frac{p}{Im\left(2\sqrt{p^2+m^2}V_{opt}(p,\omega=\sqrt{p^2+m^2})\right)}$$

$$\lambda \simeq -\frac{p}{2\sqrt{p^2+m^2}Im\left(V_{opt}(p,\omega=\sqrt{p^2+m^2})\right)}$$

- Much too high results when evaluating the mean free path with a given optical potential and the vacuum dispersion relations.



The Message

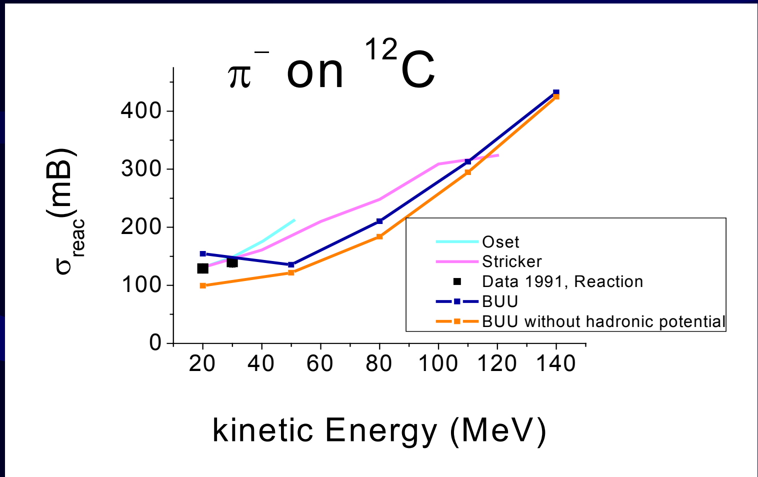
1. Not straight-forward how to define the classical mean free path out of optical models

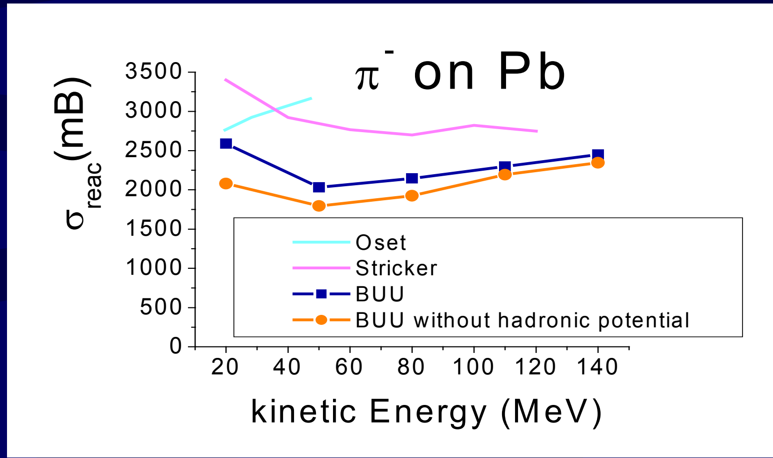
2. More than one branch possible in microscopic calculations: Averaging ???

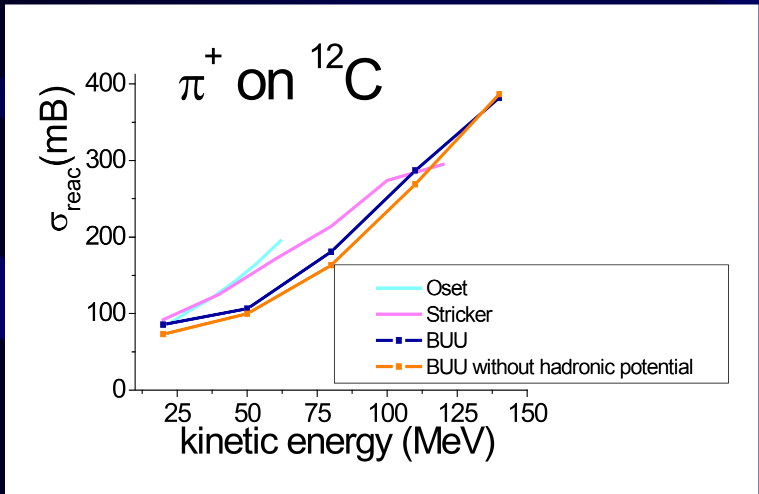
3. Microscopic models valid in vacuum approximation ?!

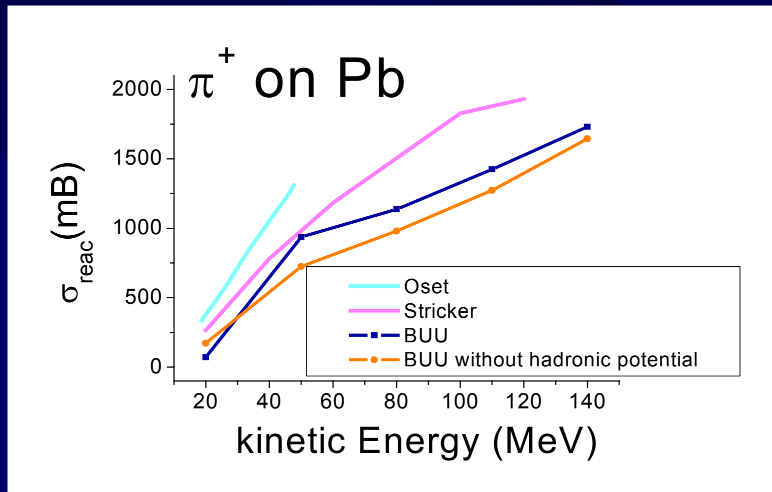
Results II:
Pion on nucleus

Quantum vs. BUU





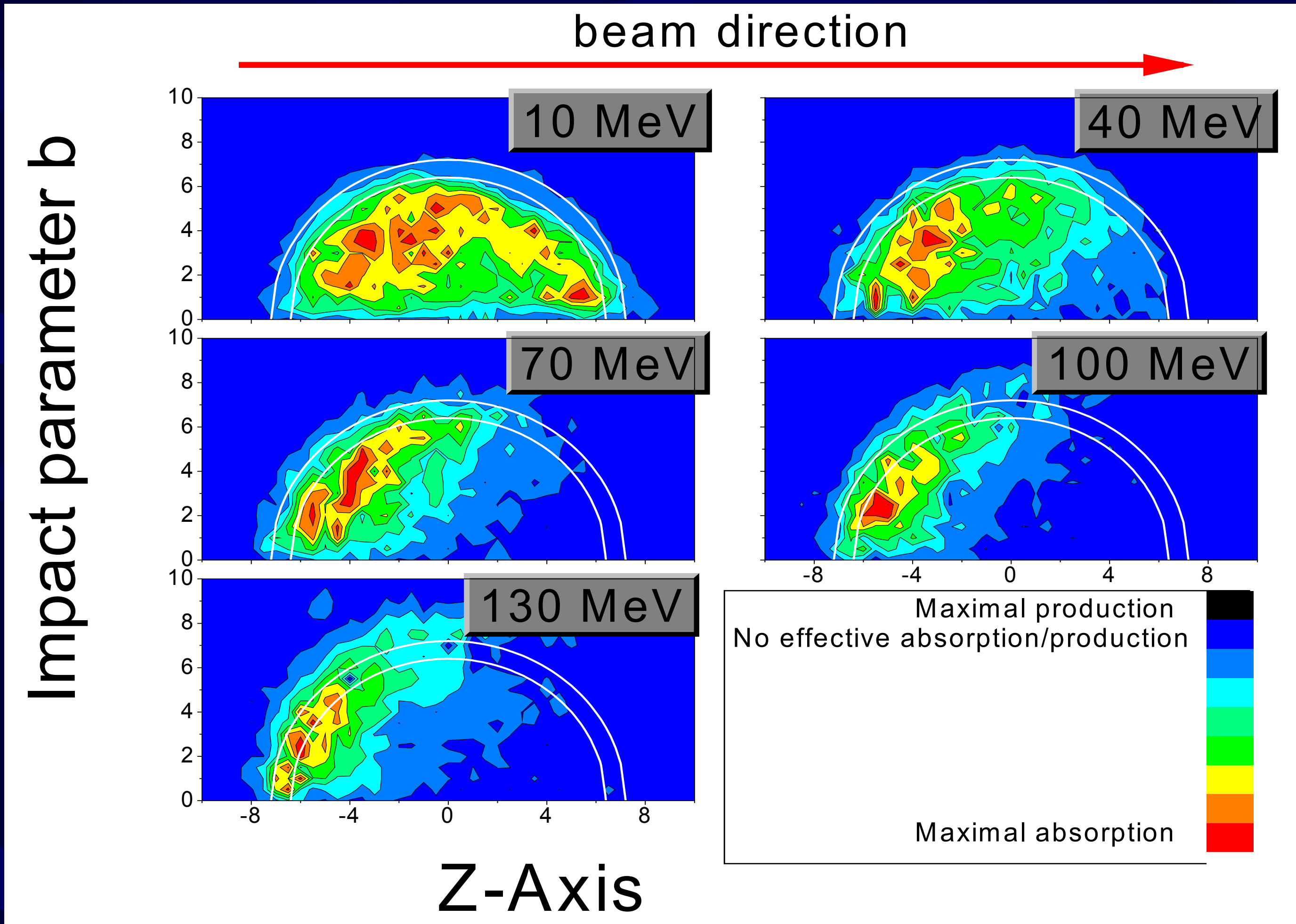




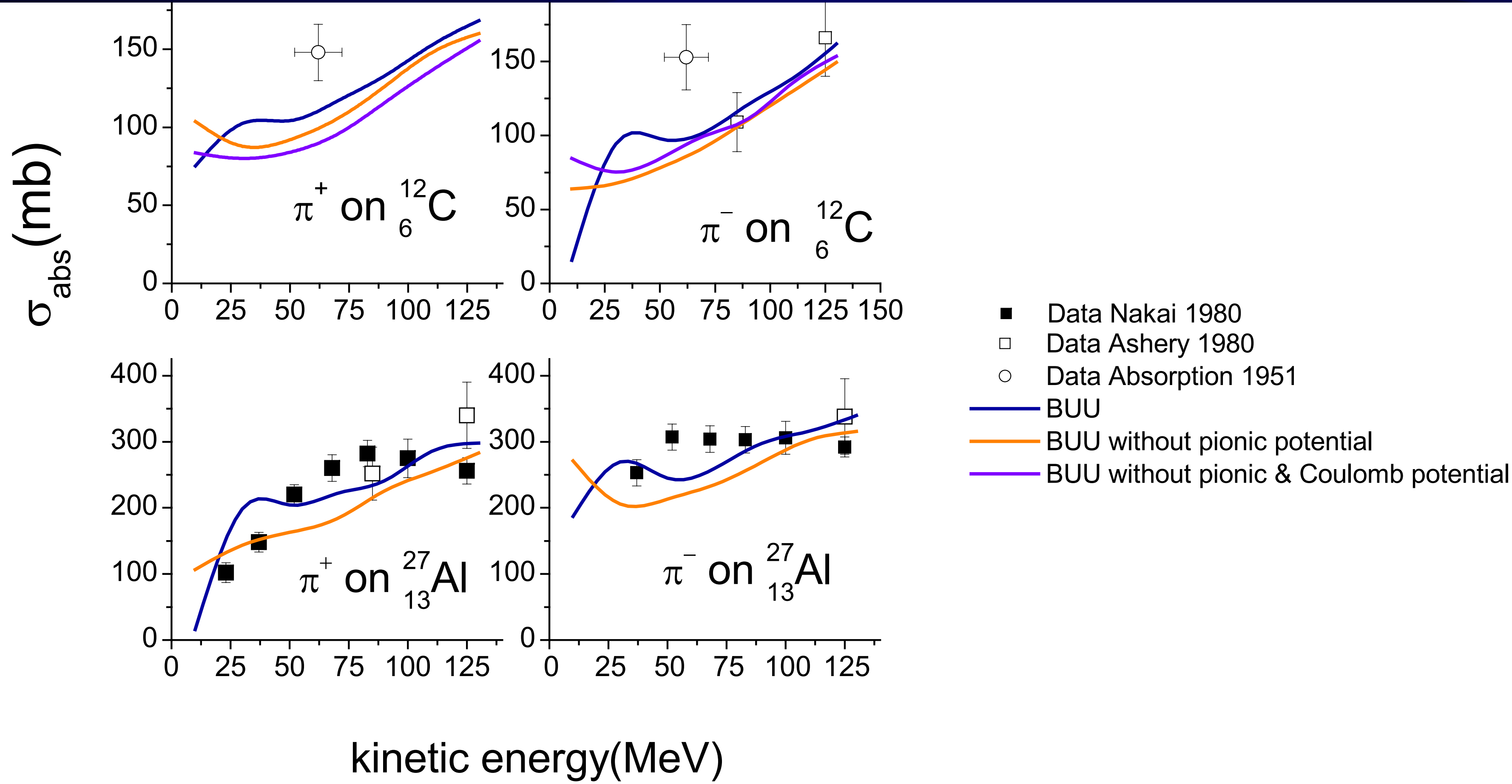
Results III : Pion absorption

Place of absorption:

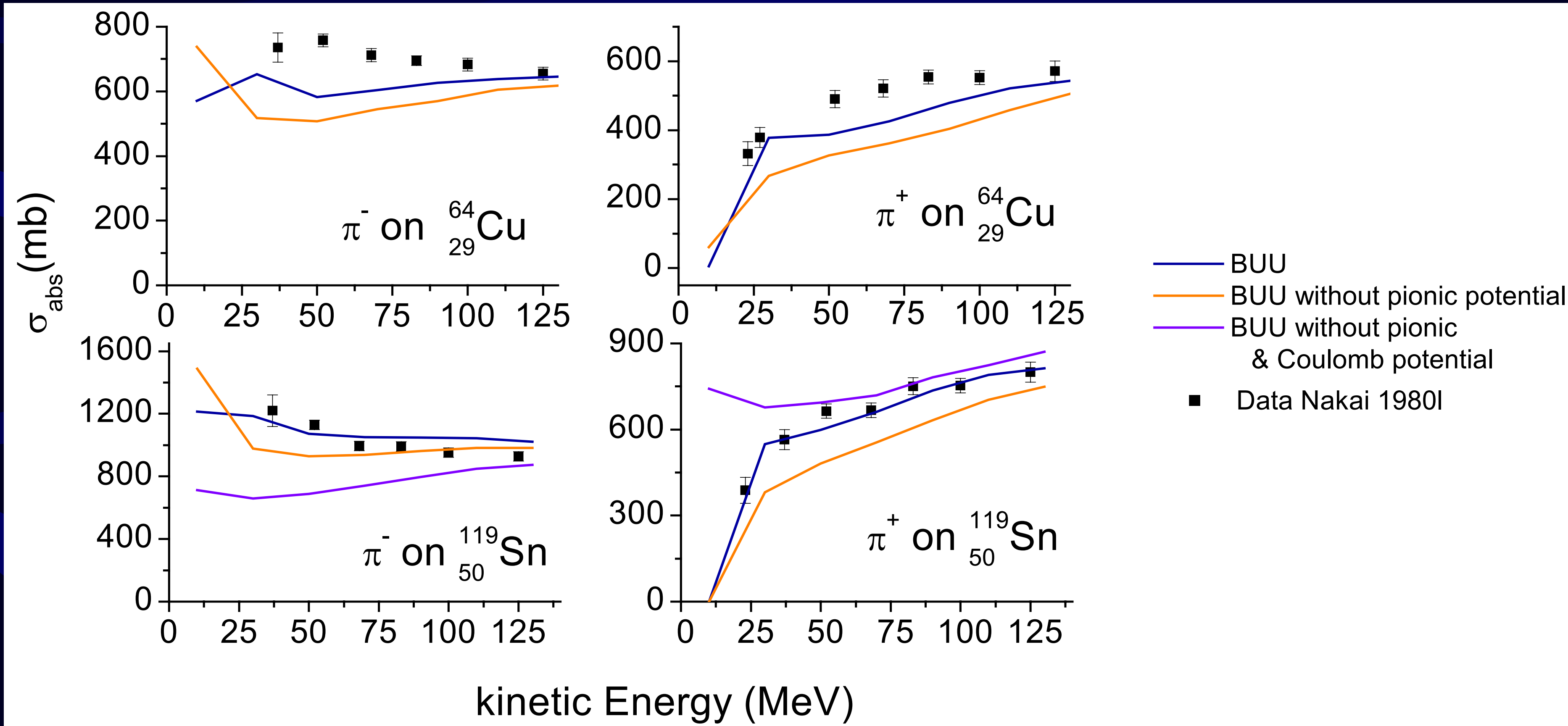
π^- on Pb, without optical potential



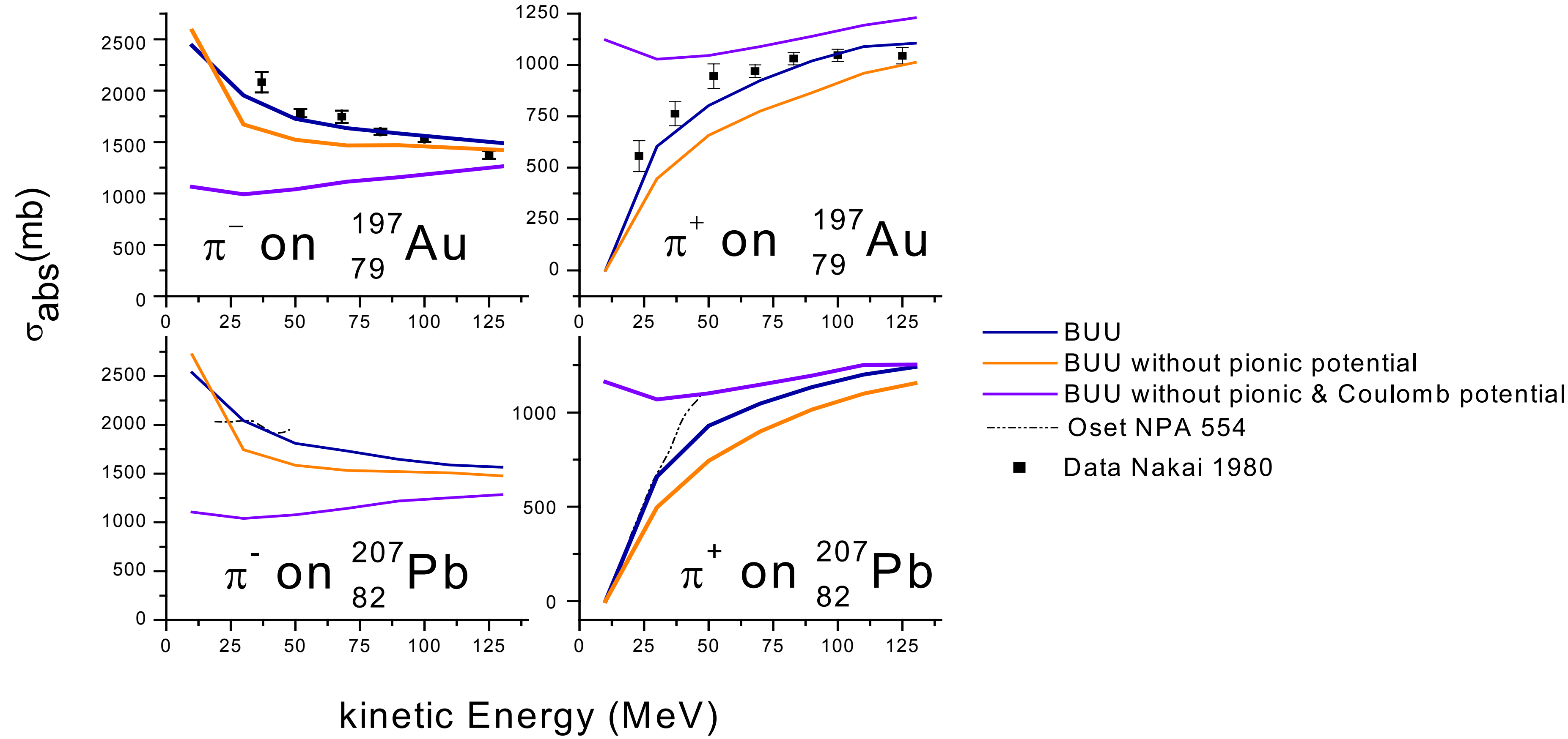
Absorption: BUU – light nuclei



Absorption: BUU –medium size nuclei



Absorption:
BUU – heavy nuclei



Conclusions Part I

- Sizeable impact of pion potential in absorption experiment
- Absorption is described in a good manner
- Decay width compatible to optical model results
- Important how to define a Mean Free Path
  - Some discrepancies in literature

Part II

Photo induced :
$\gamma A \rightarrow A' \pi \pi$

Pascal Mühlich, Luis Alvarez-Ruso, Oliver Buß, U. Mosel

Why is γ A $\rightarrow$ A' π π interesting?

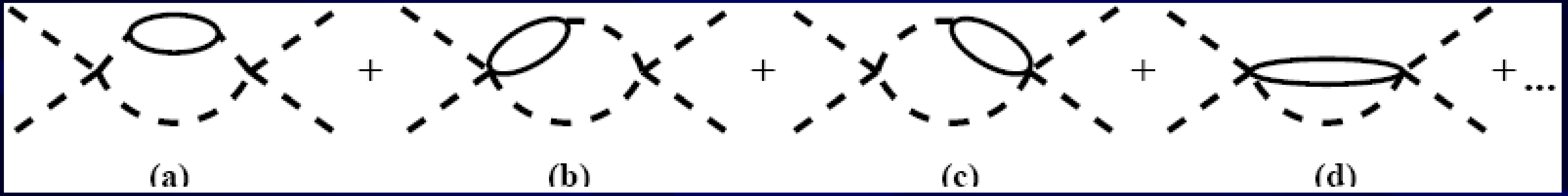
- As intermediate process: $\sigma \rightarrow \pi\ \pi$
- Prediction of lower σ mass in medium, therefore shift of $d\sigma/dm_{\pi\pi}$ spectra expected.

Different models:

– Linear σ model includes σ -meson as chiral partner of the pion
  - Expect lowering of the mass due to chiral symmetry restauration in the medium
– Dynamically generated pole in the π π scattering amplitude
  - Oller, Oset et al, PRD 59 (1999)
  - In the medium shift to lower masses due to strong p-Wave couplings of pions to ph – and Δh-states.

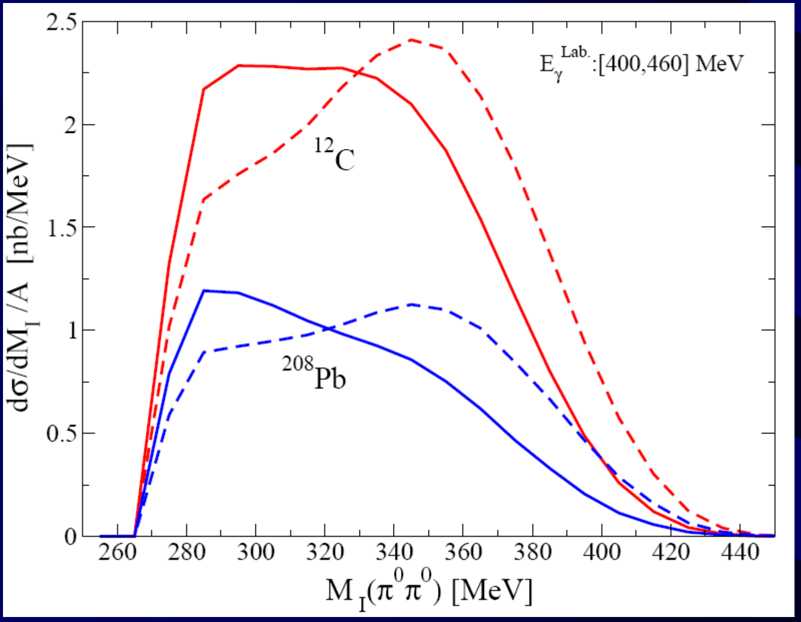
Roca, Oset, Vicente Vacas

Phys.Lett.B541:77-86,2002



Strong particle-hole couplings in the 2π – final rescattering term.

$\Longrightarrow$ σ gets lighter and more narrow in the medium



Our approach

- Initialization
  - Elementary 2π photo-production
    - Tejedor, Oset, NPA 600 (96)
    - Nacher et al , NPA 695 (01)
  - Vacuum cross sections, no medium modifications in this place

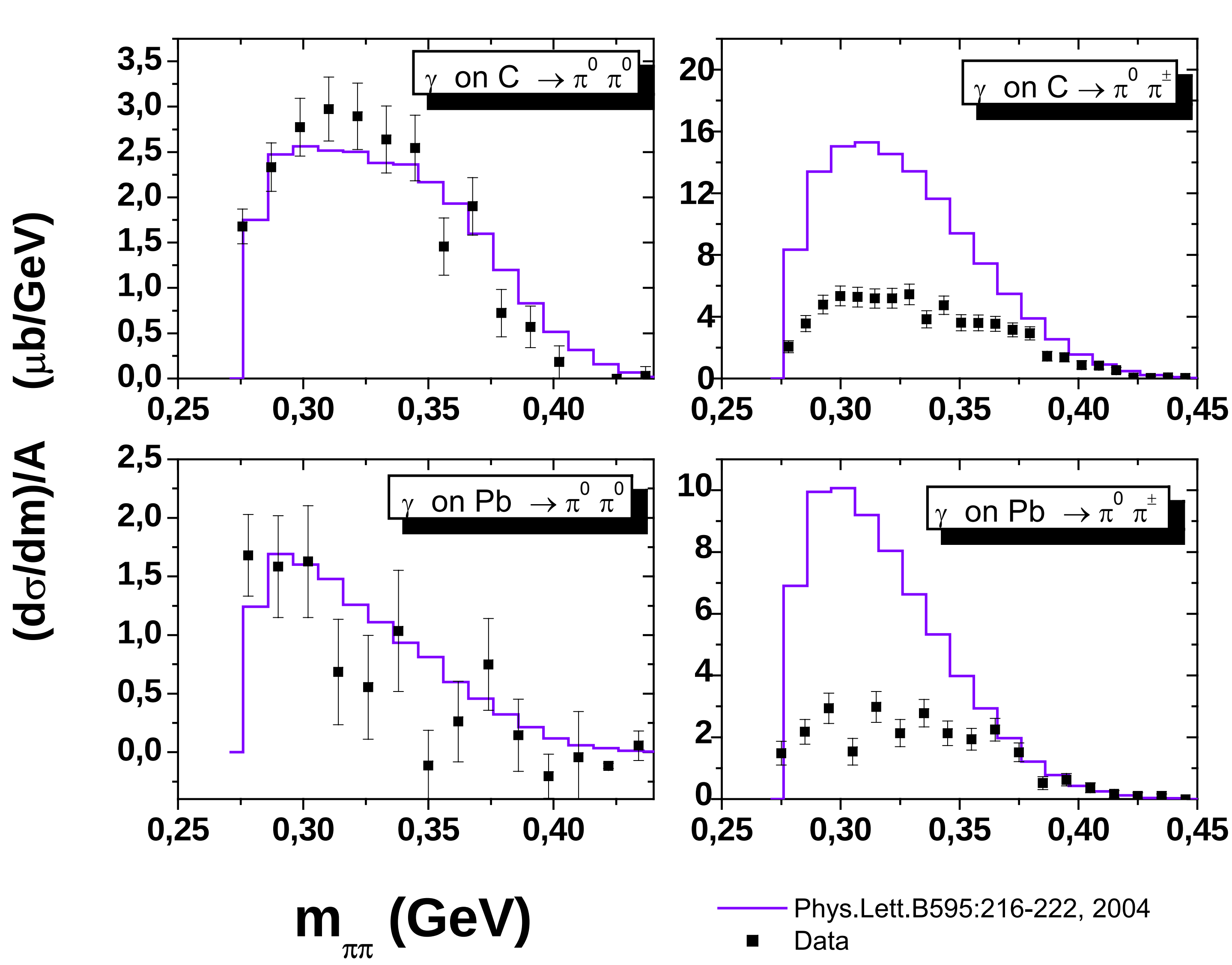
Final State 1

- Standard BUU
- With propagation and medium-modification of the resonances
- Neglect π N$\rightarrow$ π π N
- Paper in preparation

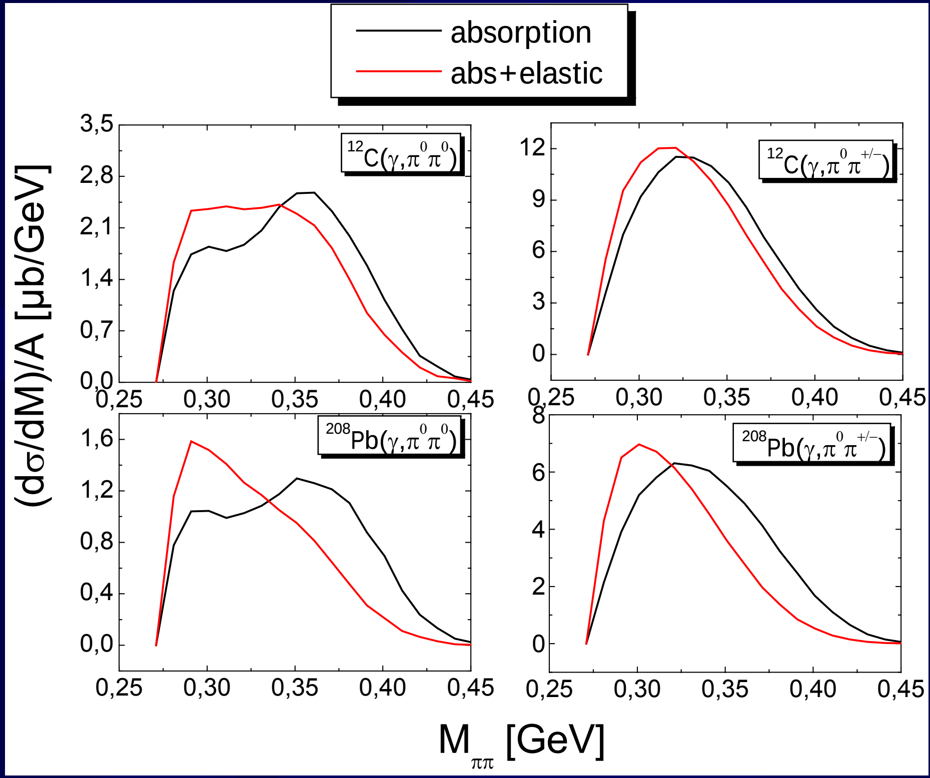
Final State 2

- Absorption by optical model
  - Nieves et al, NPA 554 (1993)
  - Garcia-Recio et al, NPA 526 (1991)
- Elastic scattering according to BUU prescription
- No resonances in the simulation, but the correct angular distribution for πN (SAID)
- Neglect π N$\rightarrow$ π π N
- Phys.Lett.B595:216-222, 2004

Here: Final State 2.

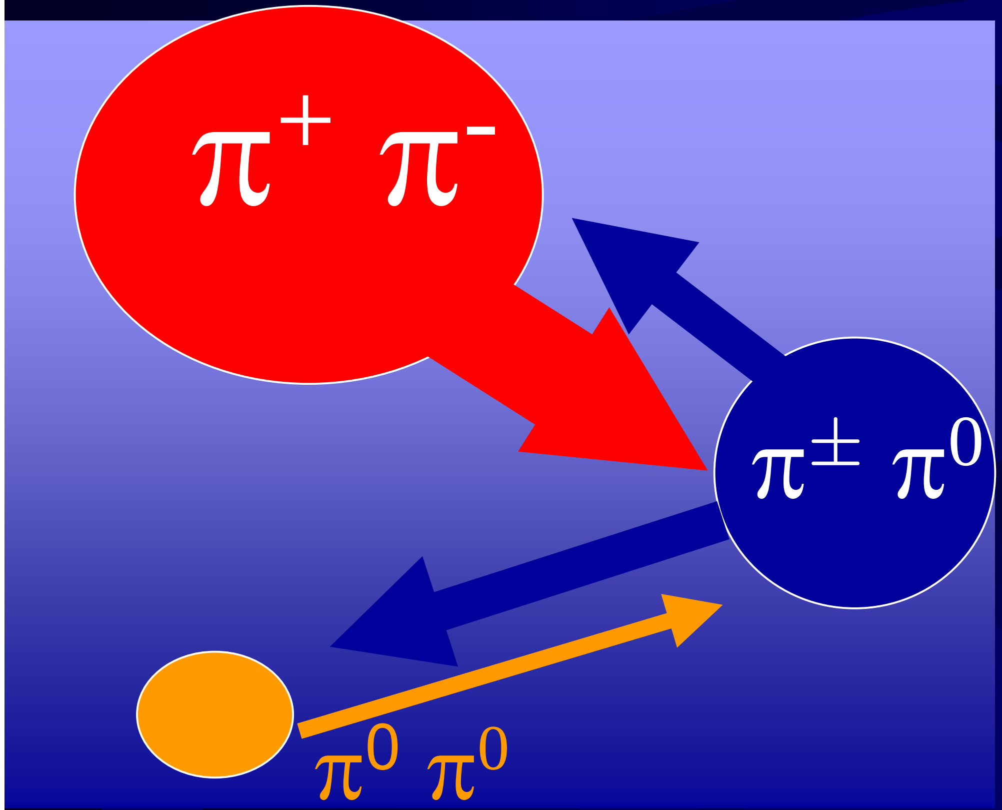


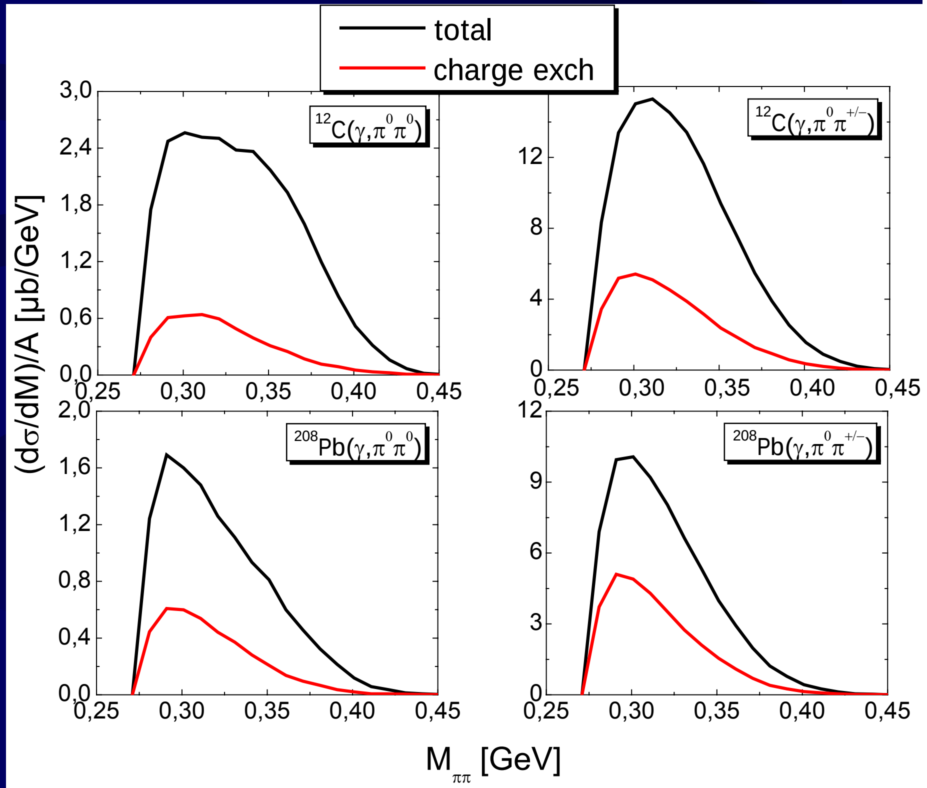
Considering quasielastic scattering in the final state



Message : Not negligible contributions due to elastic scattering. Here: Final State 2.

Considering charge exchange in the final state





Large contributions due to charge exchange, since different charge channels are not of same size in the initialization.

Here: Final State 2.

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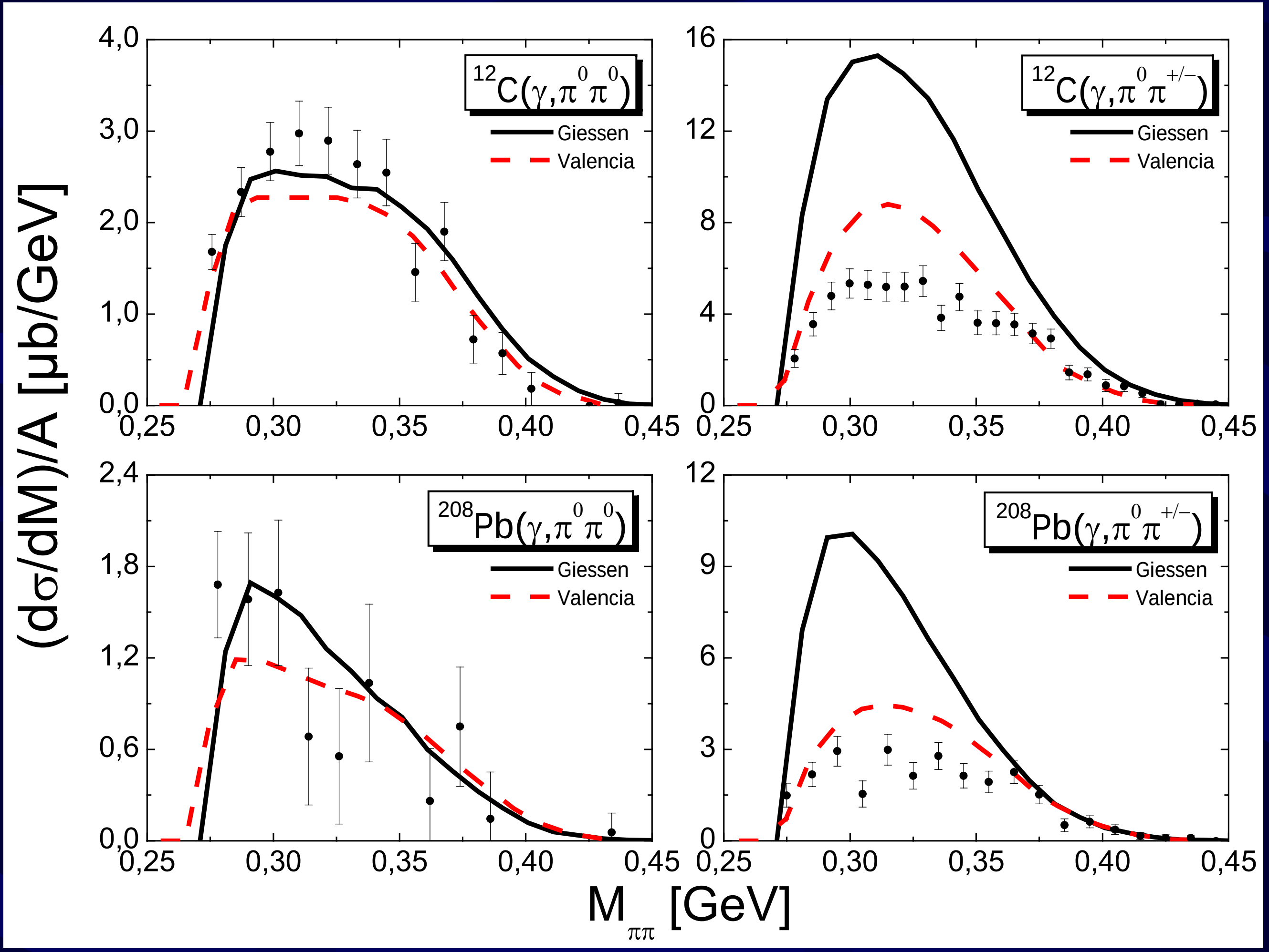
Comparison to Roca et al
Phys.Lett.B541:77-86,2002



Conclusions Part II

- Importance of ordinary final state effects
- Observed target mass dependence of the $\pi^0\,\pi^0$ channel is no unmistakable evidence of the modification of the $\pi\pi$ interaction in the medium
- Discrepancy with the data in the $\pi^0\,\pi^{\pm}$ channel is a standing problem...

Thank you …

... and thanks to:

- Prof. Dr. Ulrich Mosel
- Pascal Mühlich, Dr. Luis Alvarez-Ruso
- Dr. Jürgen Lehr

- Prof. Dr. Radhey Shyam
  - Saha Institute of Nuclear Physics, Calcutta