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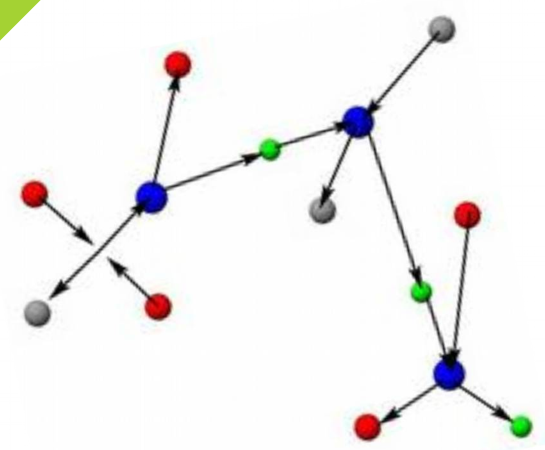
PION PRODUCTION IN THE IQMD TRANSPORT MODEL*

*** originally announced as**
« What pions tell us about the neutron skin »
But this is a spoiler ...

Christoph Hartnack
SUBATECH/ IMT Atlantique
Jörg Aichelin, University of Nantes
Yvonne Leifels and Arnaud Le Fèvre
GSI Helmholtzzentrum Darmstadt

OUTLINE



1. IQMD
1.1 The transport model
1.2 Potentials
1.3 Pion production
2. STATIC CONSIDERATIONS
2.1 P-N Asymetry
2.2 Initialisation (neutron skin)
2.3 Effects on pions
3. TIME EVOLUTION
3.1 Pions and Deltas
3.2 Mean free path
3.3 Isospin ratios
4. PION ISOSPIN RATIOS
4.1 Reaction cinematics
4.2 Asy-Eos potentials
5. MORE ON THE NEUTRON SKIN
5.1 Centrality effects
5.2 How to disentangle
6. CONCLUSION

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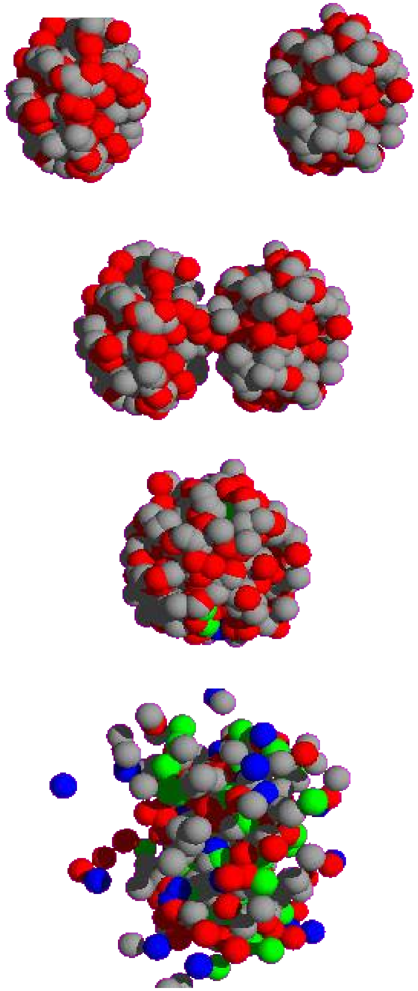
Isospin-Quantum Molecular Dynamics model

- semiclassical model with quantum features

- microscopic N-body description using 2 and 3 body potentials

- calculation of heavy ion collisions on an event-by-event-basis

- includes N, Δ, π with isospin d.o.f.



Allows for a « photo » of the high density phase and for a look inside …

Definition of the potential

$$
\begin{aligned}
V^{ij} &= G^{ij} + V^{ij}_{\rm Coul} \\
&= V^{ij}_{\rm Skyrme} + V^{ij}_{\rm Yuk} + V^{ij}_{\rm mdi} + V^{ij}_{\rm Coul} + V^{ij}_{sym} \\
&= t_1 \delta(\vec{x}_i - \vec{x}_j) + t_2 \delta(\vec{x}_i - \vec{x}_j) \rho^{\gamma-1}(\vec{x}_i) + t_3 \frac{\exp\{-|\vec{x}_i - \vec{x}_j|/\mu\}}{|\vec{x}_i - \vec{x}_j|/\mu} + \\
& \quad t_4 \ln^2(1 + t_5(\vec{p}_i - \vec{p}_j)^2)\delta(\vec{x}_i - \vec{x}_j) + \frac{Z_i Z_j e^2}{|\vec{x}_i - \vec{x}_j|} + \\
& \quad t_6 \frac{1}{\varrho_0} T_3^i T_3^j \delta(\vec{r}_i - \vec{r}_j)
\end{aligned}
$$

Bethe Weizsaecker –mass formula:

Volume term +Surface term +Coulomb term +symmetry term

(+pairing term not included)

Volume term integrated:

$$U = \alpha \cdot \left(\frac{\rho_{int}}{\rho_0}\right) + \beta \cdot \left(\frac{\rho_{int}}{\rho_0}\right)^{\gamma} + \delta \cdot \ln^2\left(\varepsilon \cdot (\Delta\vec{p})^2 + 1\right) \cdot \left(\frac{\rho_{int}}{\rho_0}\right)$$

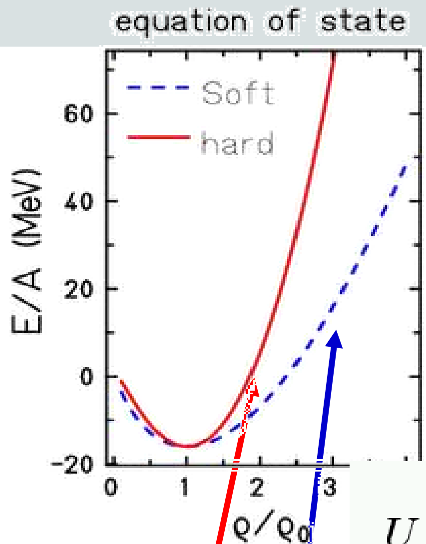
Skyrme type potential (density dependent)

Momentum dependent Interactions (mdi)

$$U_{mdi} = \delta \cdot \ln^2\left(\varepsilon \cdot (\Delta\vec{p})^2 + 1\right) \cdot \left(\frac{\rho_{int}}{\rho_0}\right)$$

« optical pot. » linear in density

THE EOS IN IQMD



- after the convolution of the Skyrme type potentials supplemented by momentum dependent interactions (mdi) for infinite saturated nuclear matter at equilibrium

$$U = \alpha \cdot \left(\frac{\rho_{int}}{\rho_0}\right) + \beta \cdot \left(\frac{\rho_{int}}{\rho_0}\right)^{\gamma} + \delta \cdot \ln^2\left(\varepsilon \cdot (\Delta\vec{p})^2 + 1\right) \cdot \left(\frac{\rho_{int}}{\rho_0}\right)$$

- soft
- hard

	α (MeV)	β (MeV)	γ	δ (MeV)	$\varepsilon\ \left(\frac{c^2}{\mathrm{GeV}^2}\right)$	κ (MeV)
S	-356	303	1.17	—	—	200
SM	-390	320	1.14	1.57	500	200
H	-124	71	2.00	—	—	376
HM	-130	59	2.09	1.57	500	376
INT	-157	103	1.58	—	—	284
VH	-110	56	2.40	—	—	456

6

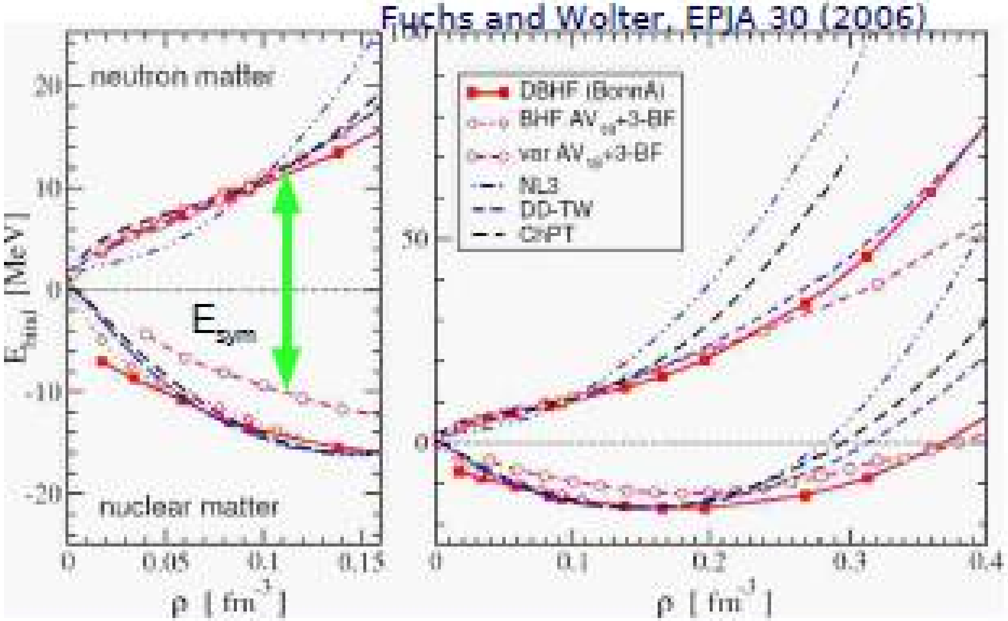
SIMILAR : ASY-EOS

Bethe Weizsäcker mass formula

$$B = a_B A - a_{surf} A^{2/3} - a_{sym} \frac{(N-Z)^2}{A} - a_C \frac{Z^2}{A^{1/3}} - E_{pair}$$

$$t_6 \frac{1}{\varrho_0} T_3^i T_3^j \delta(\vec{r}_i - \vec{r}_j)$$

Fuchs and Wolter, EPJA 30 (2006)

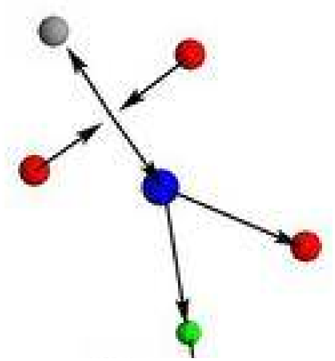


Similarly :

- **density dependence of asymetry potential**
- **One possibility :**
- **ρ^γ with**
- **γ<1 soft asy eos**
- **γ=1 linear asy eos**
- **γ>1 hard asy eos**

Pions are produced via the Δ (1232)

- **NN ↔ NΔ   Δ ↔ N π**
- **Frequent rescattering in the nucleus**
- **Use of Clebsch Gordon**
- **coeeficients**



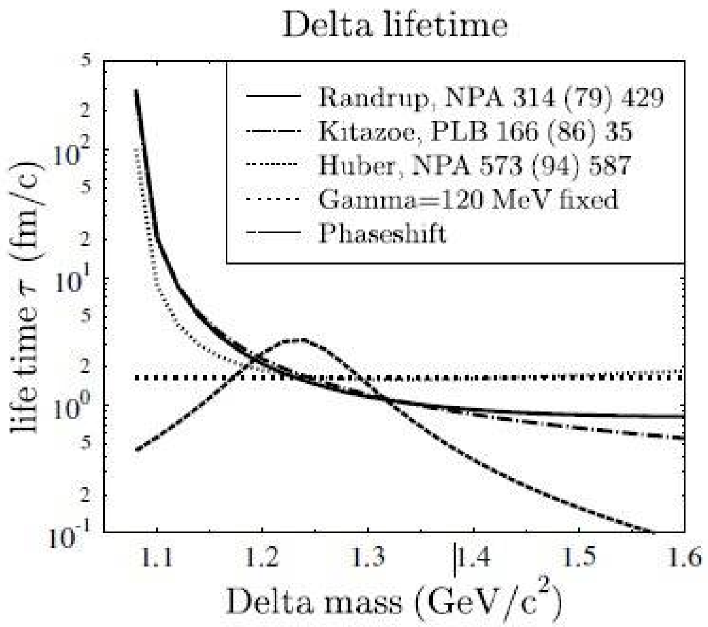
$$NN \rightarrow N\Delta$$
$$\Delta \rightarrow N\pi$$
$$N\pi \rightarrow \Delta$$
$$N\Delta \rightarrow NN$$

$$\Delta^{++} \rightarrow 1 \cdot (p + \pi^+)$$
$$\Delta^{+} \rightarrow \frac{2}{3} \cdot (p + \pi^0) + \frac{1}{3} \cdot (n + \pi^+)$$
$$\Delta^{0} \rightarrow \frac{2}{3} \cdot (n + \pi^0) + \frac{1}{3} \cdot (p + \pi^-)$$
$$\Delta^{-} \rightarrow 1 \cdot (n + \pi^-)$$

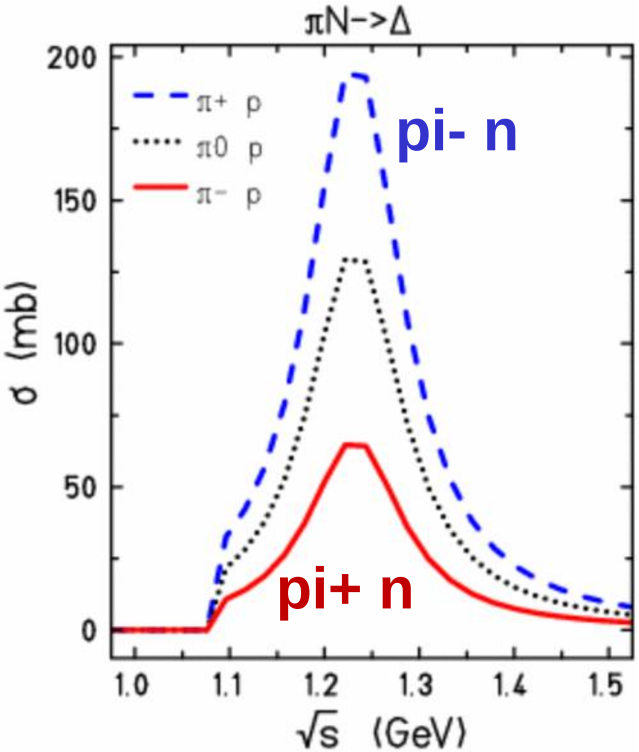
$$\sigma(pp \rightarrow n\Delta^{++}) = 3\sigma(pp \rightarrow p\Delta^{+}) = \frac{3}{4}\sigma_{\text{inelastic}}$$

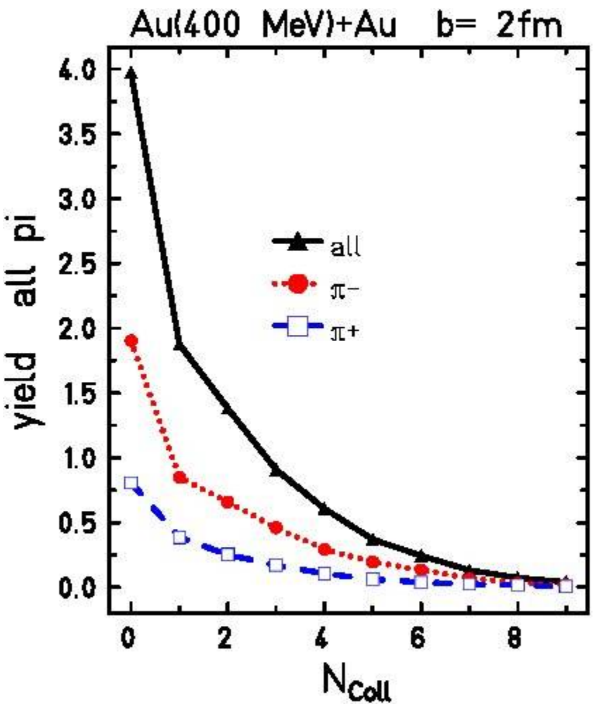
BASIC ASSUMPTIONS

- Inverse channel by detailed balance with spectral function corrections (Danielewicz and Bertsch)
- Decay of the Δ with mass-dependence width (Kitazoe, Randrup or phaseshift)
- Effects of lifetime parametrization and det.bal spectral function corrections in the order of 10% for pion yields

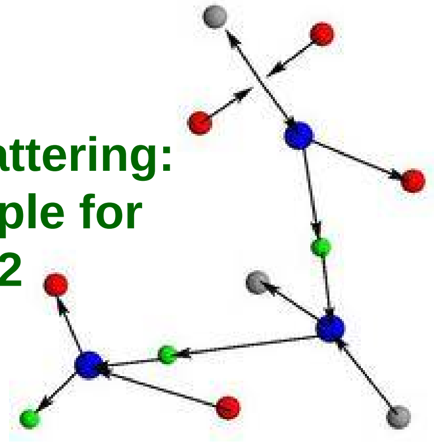


PION RESCATTERING





Rescattering: Example for N_C=2

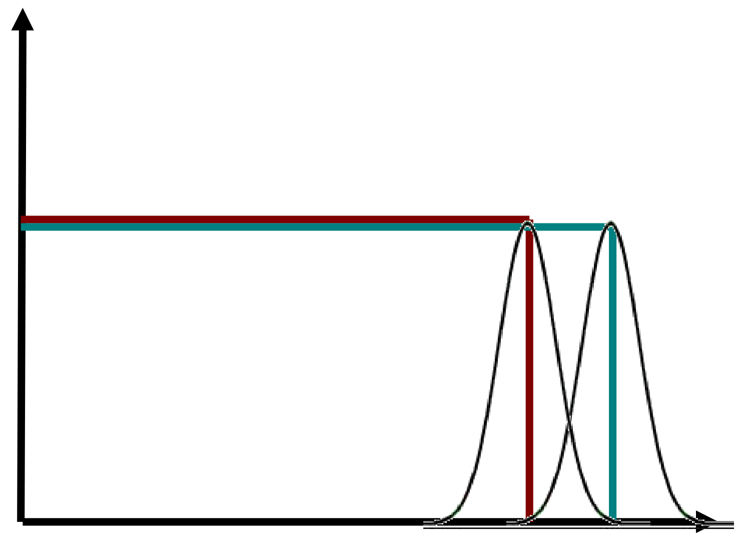


Isospin-asymetry already in the cross sections :
P-N asymetry will yield different rescattering of π- and π+

How do I distribute A nucleons (P<N) in a box ?
Two exemplaric solutions (centroides of Gaussians):

Same density

ρ

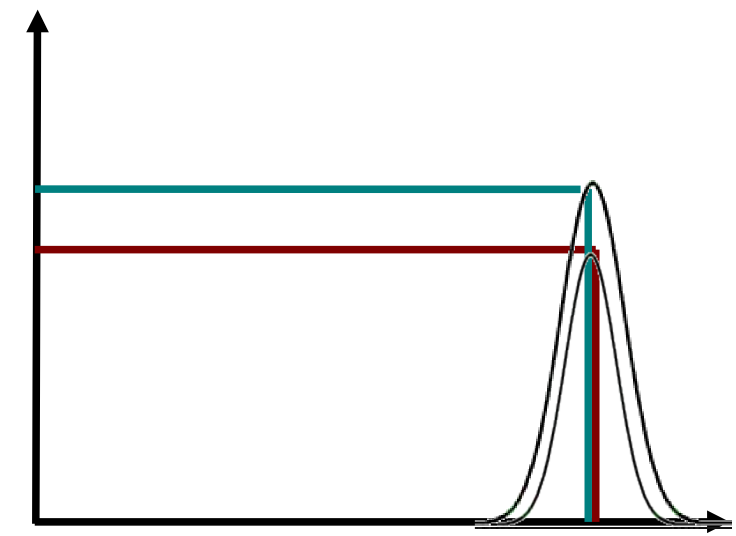


R

$R_P<R_N$

Same radius

ρ

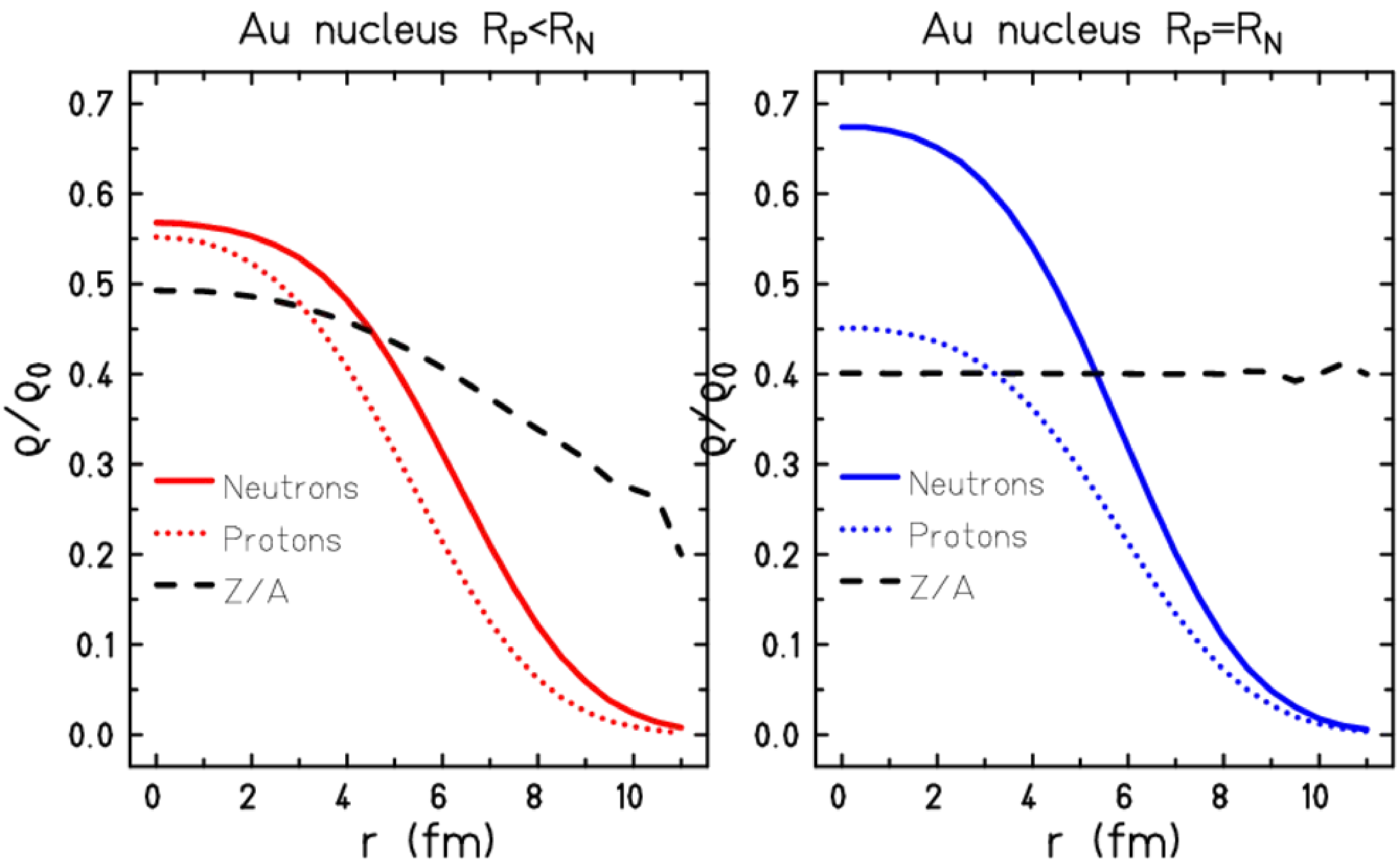


R

$R_P=R_N$

STATIC CONSIDERATIONS

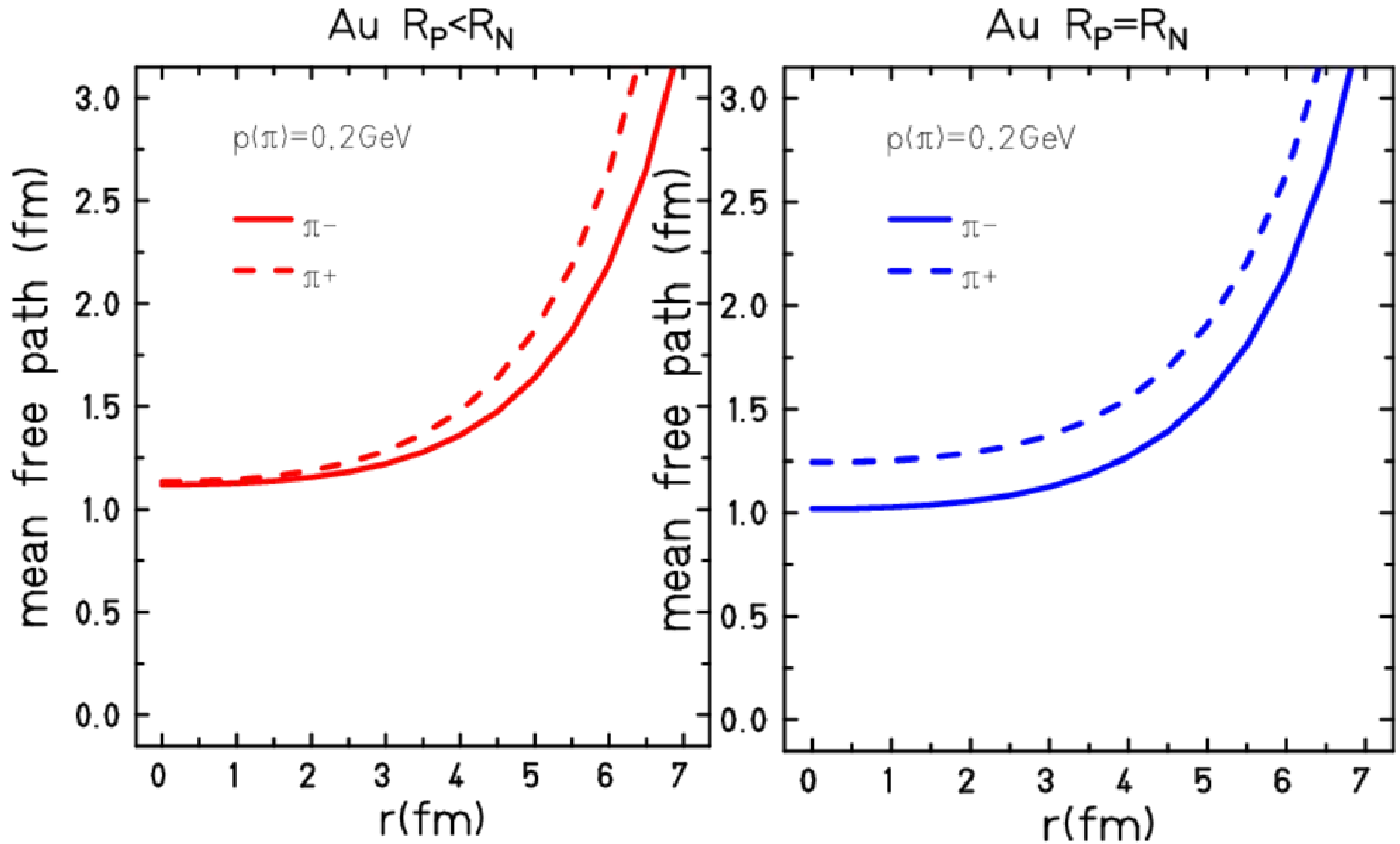
- **Initialisation with smoothing from Gaussians**



Z/A depends on R

STATIC CONSIDERATIONS

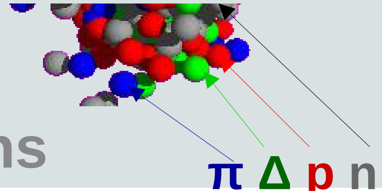
- **Mean free path of a 200 MeV pion**

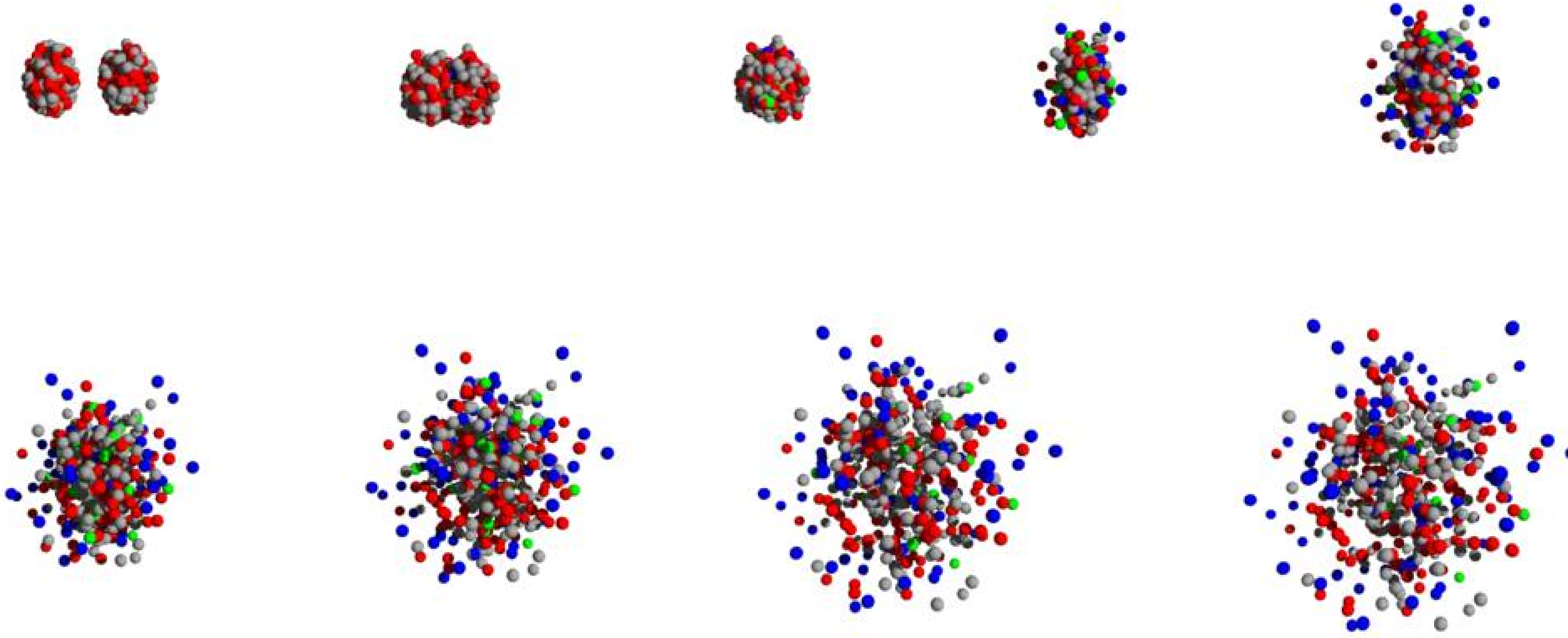


Different mean free path for π- and π+

TIME EVOLUTION

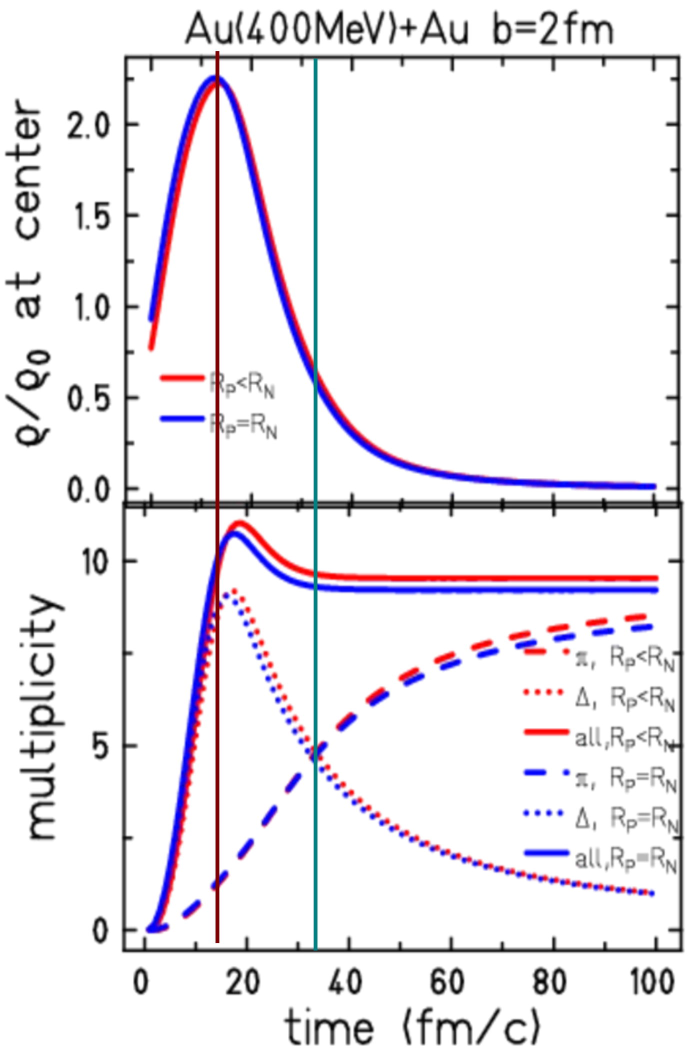
- Au+Au 1500 MeV central collisions





TIME EVOLUTION

- Central density and particle yields

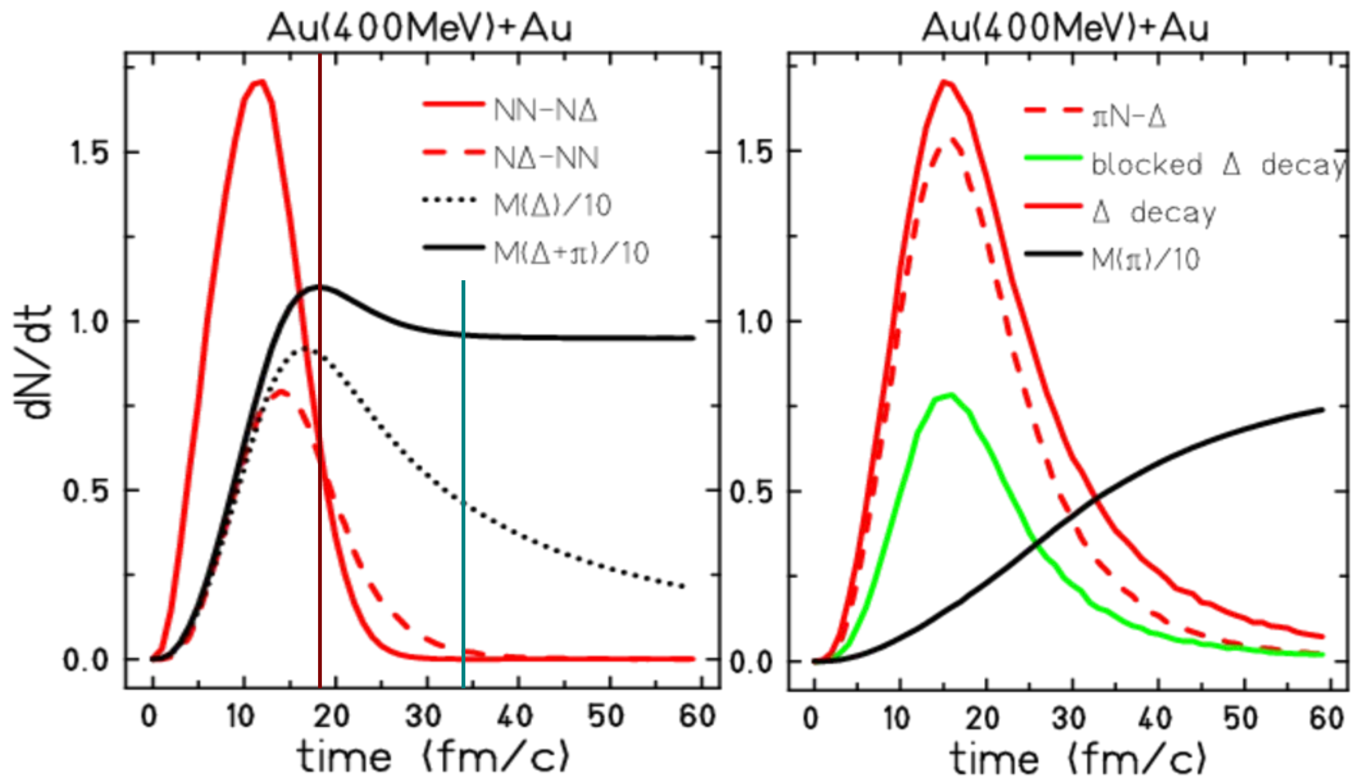


Maximum density independent of chosen initialisation

- **Deltas dominate the total yield during the compression phase**
- **Final pion number determined at the end of the compression phase**
- **Diminuation of total yield only possible via Delta absorption**

TIME EVOLUTION

- Channels for production and absorption of Δ & π

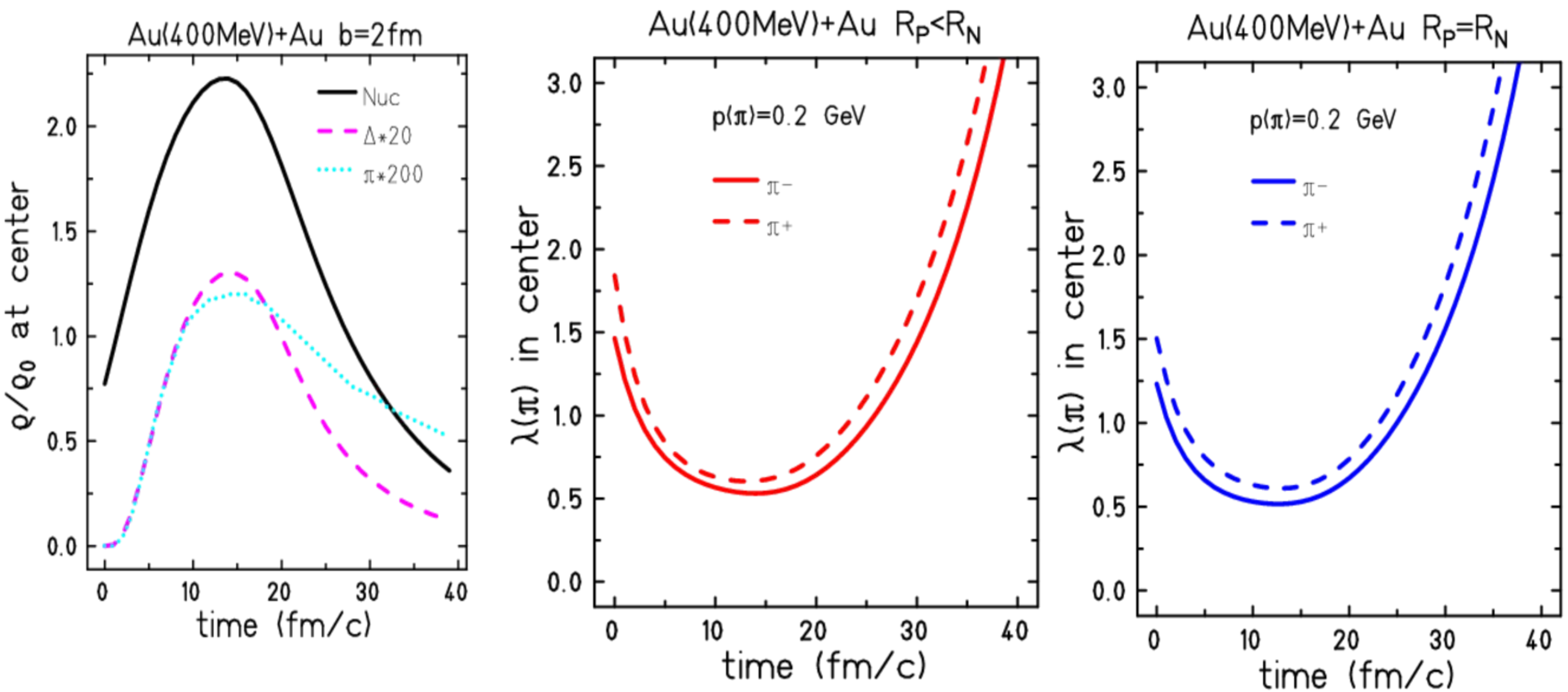


- **Maximum reached when Δ absorption dominates over production**
- **Total yield stabilized when absorption stops.**

Number of free pions grows slowly due to strong interplay between Δ decay and π absorption

TIME EVOLUTION

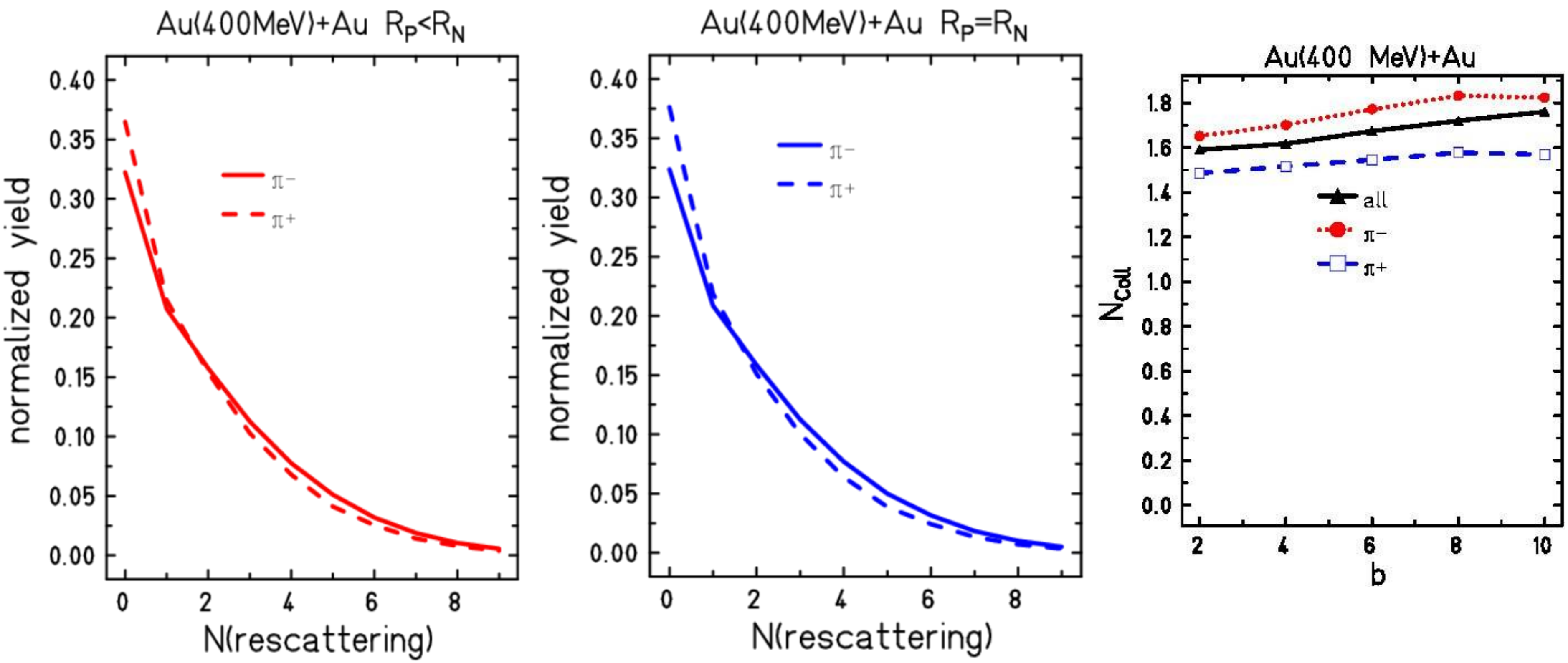
- **Mean free path of the pions**



Positive and negative pions will show different rescattering.

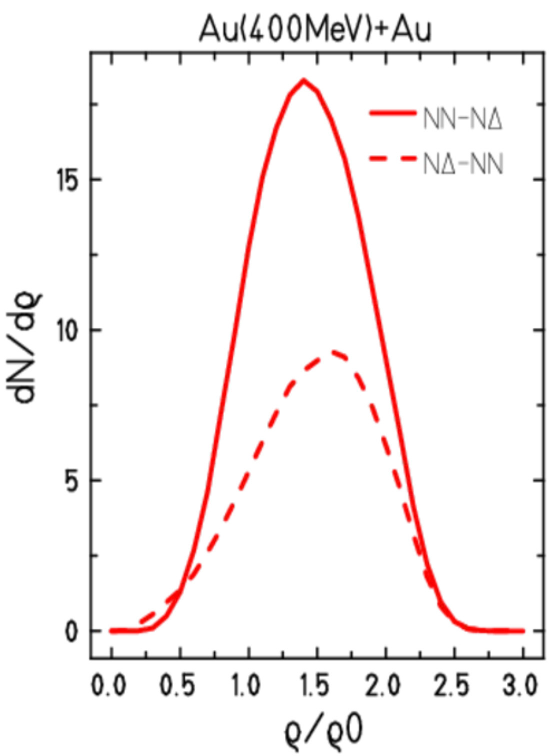
TIME EVOLUTION

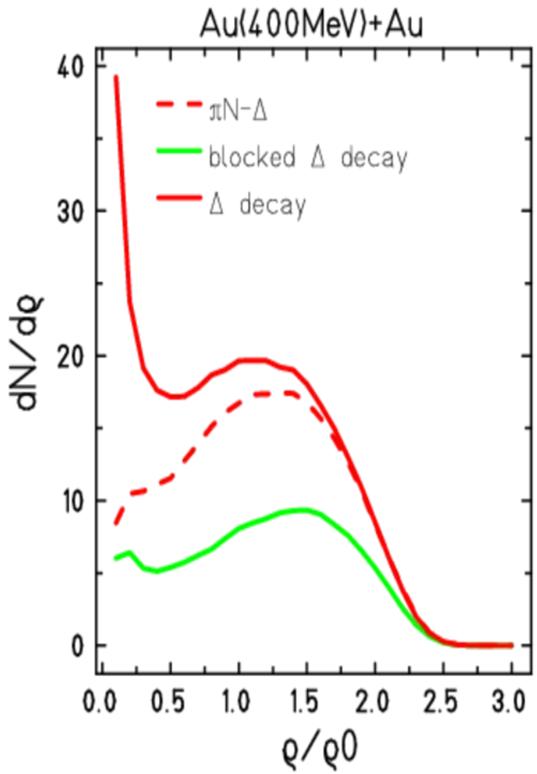
- Different rescattering for pi- and pi+

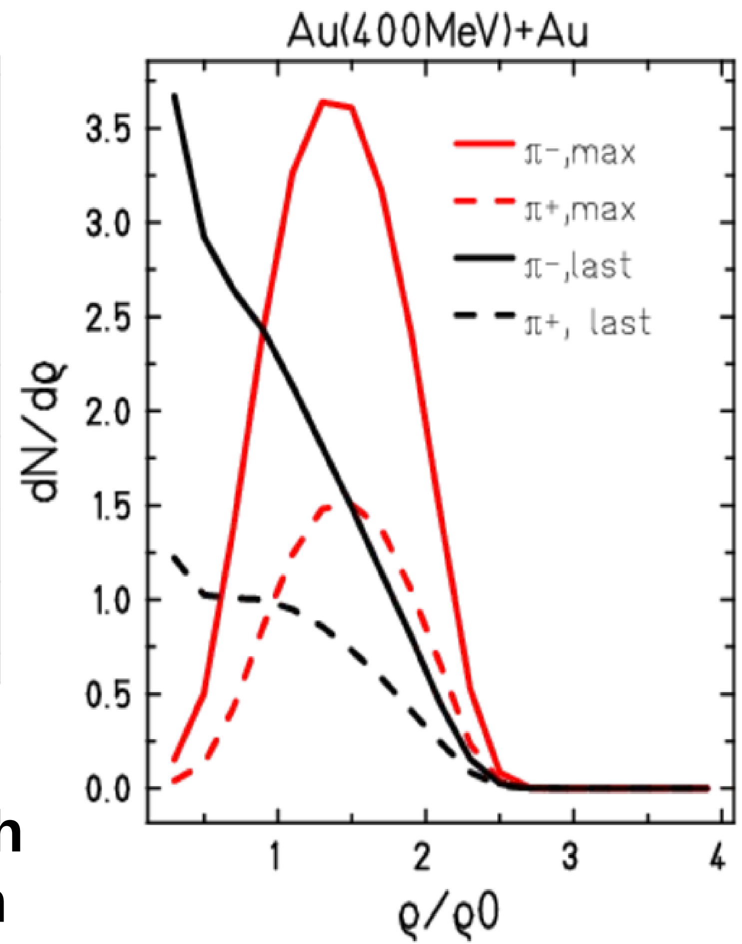


TIME EVOLUTION

- **Pions initiated at high density but freeze out at low ρ**



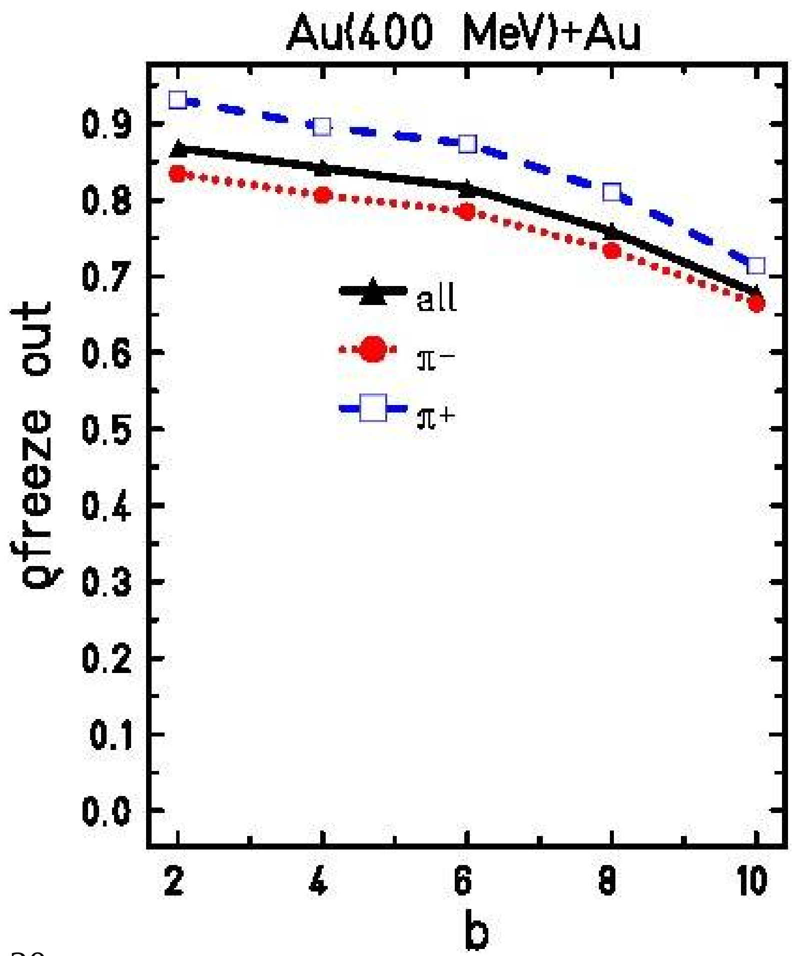


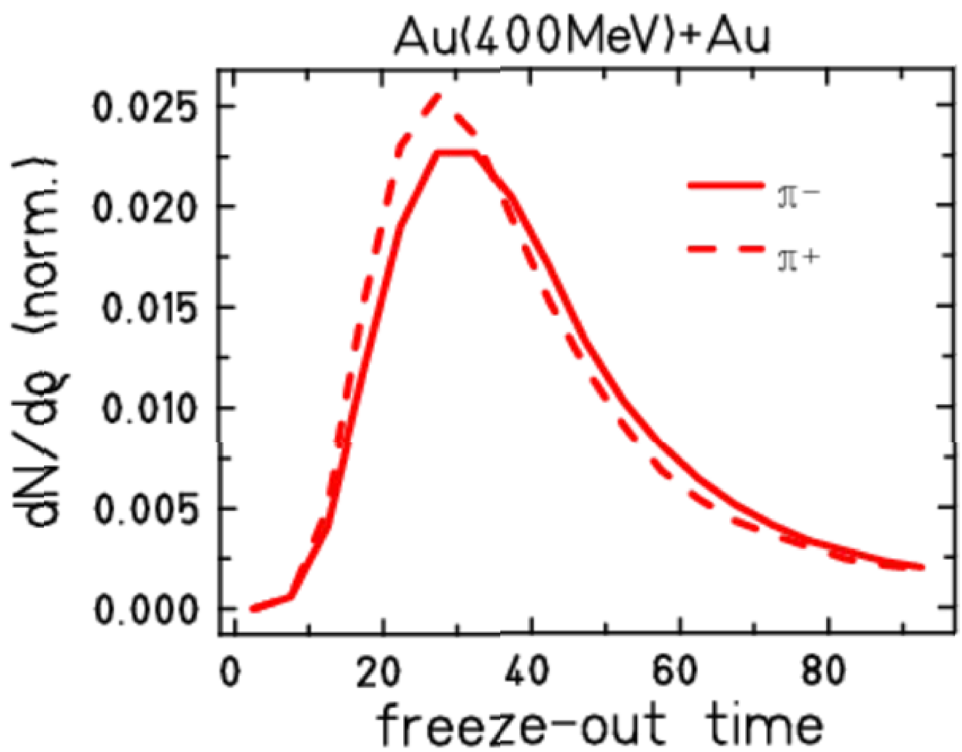


Rescattering washes out every high density signal, final pion stem from low densities

TIME EVOLUTION

- **Freeze out time**

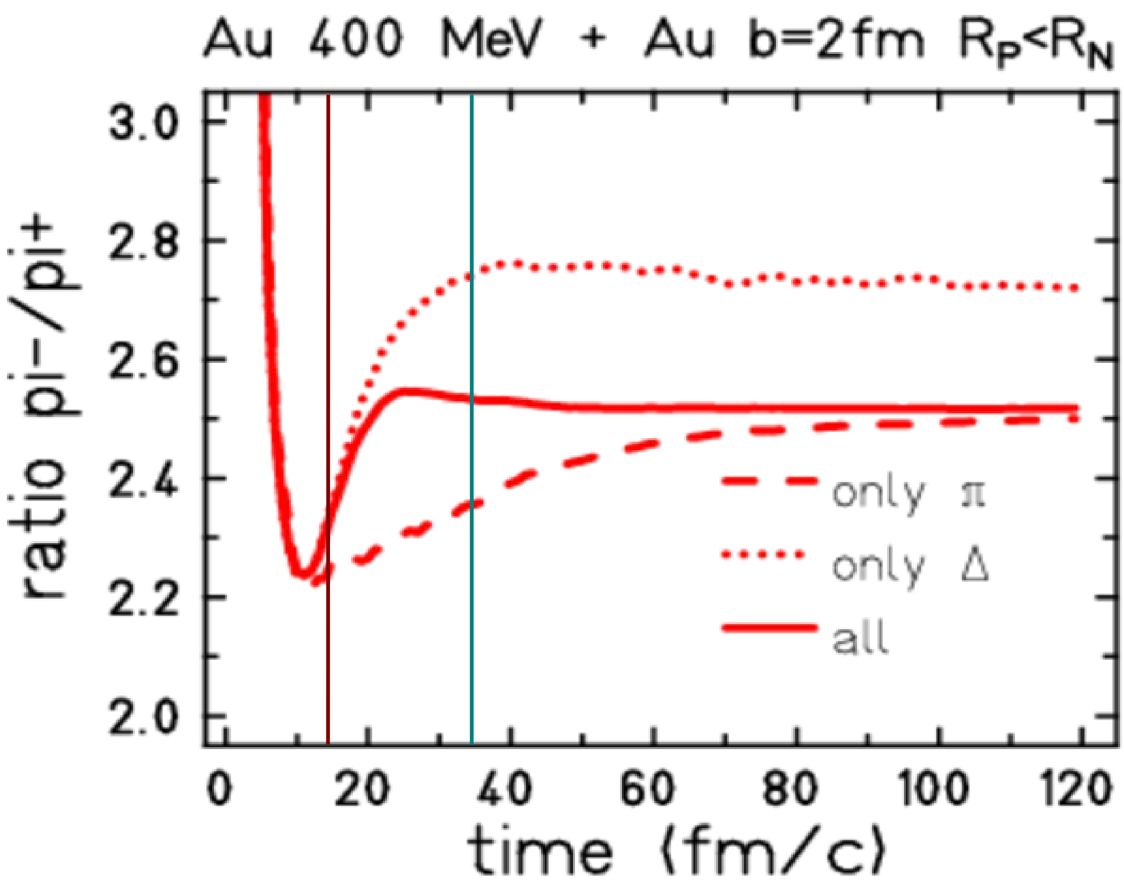


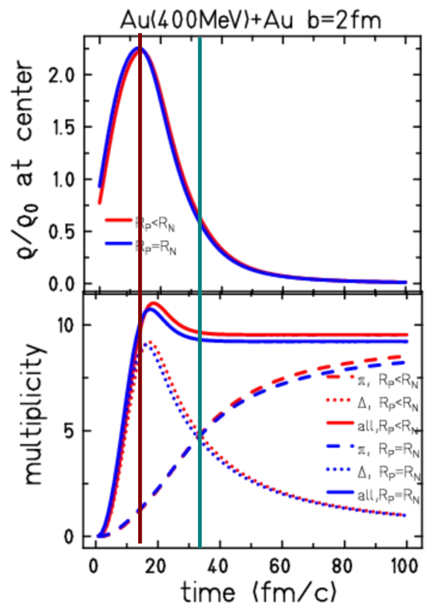


π- freeze out at lower densities and at later times than π+

TIME EVOLUTION

- **Evolution of the pion isospin ratio**





π- stay longer in the Δ than π+.

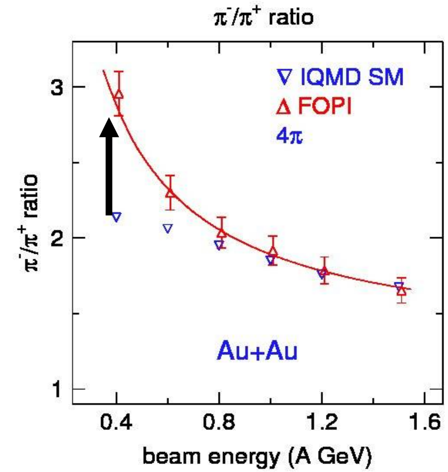
Final ratio determined during expansion phase

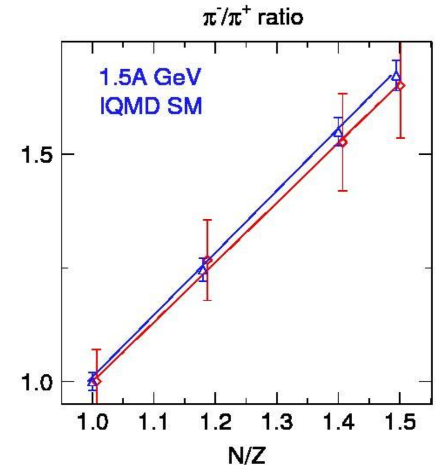
PION RATIOS

- Motivation for the pion ratios

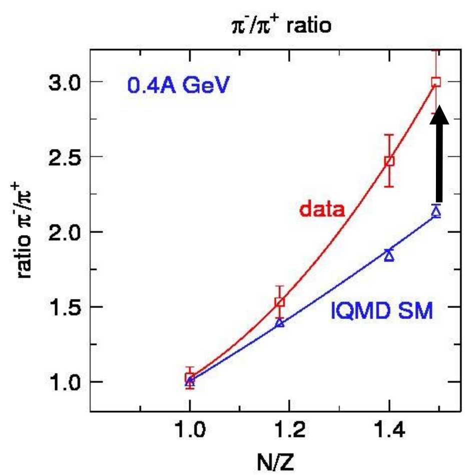
Comparison of IQMD

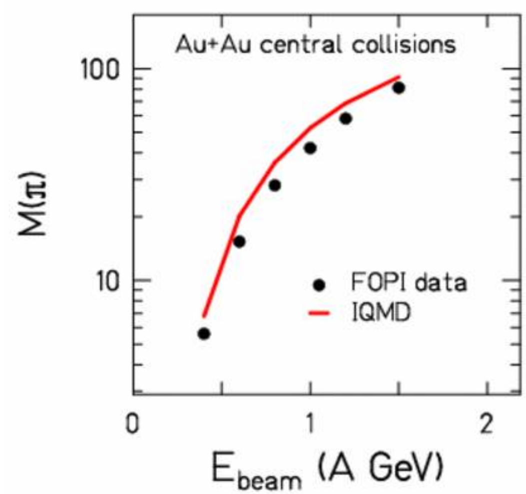
- **with FOPI data**
    - **In principle a great success, but one problem**
  - *W. Reisdorf and the FOPI Collaboration Nuclear Physics A 848 (2010) 366–427*





Isn't this inconsistent with the previous slide ? (2.2 vs 2.5)





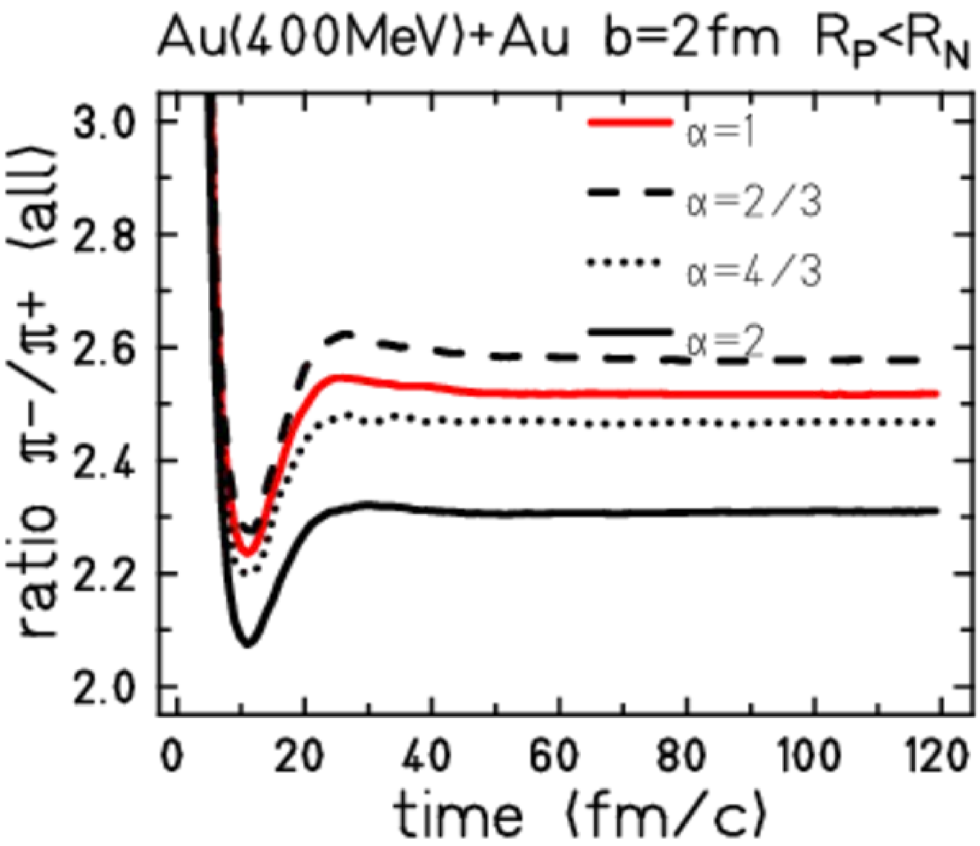
PION RATIO : WHAT SHOULD ONE EXPECT ?

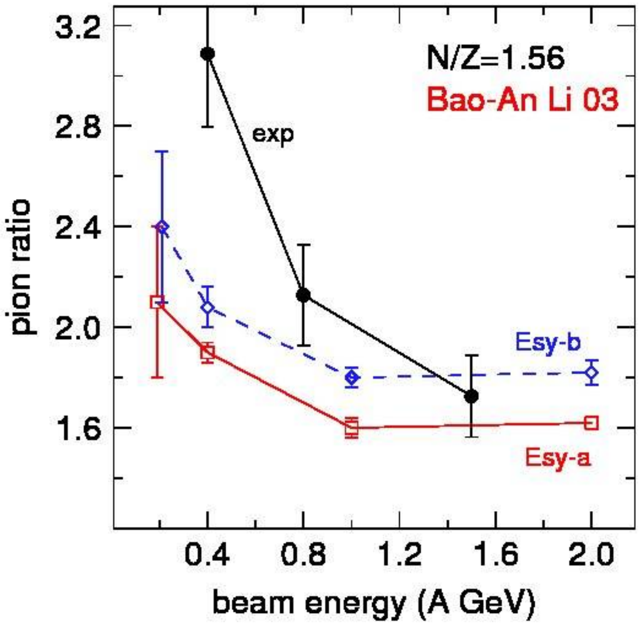
- If every particle could collide with everybody

charge tot	158	394	masse	Z=	79	A=	197
neutrons	236	0,401	Z/A				
Combinat.	pure	inel co	wgtd	D-	D0	D+	D++
pp	0,16	1	0,211			0,05	0,16
nn	0,358	1	0,472	0,35	0,12		
pn	0,482	0,5	0,317		0,16	0,16	
	wgt.mn	0,759	total	0,35	0,28	0,21	0,16
pi-/pi+		pi-	0,445	0,35	0,09		
1,9520936		pi0	0,327		0,19	0,14	
		pi+	0,228			0,07	0,16

PION RATIOS

- Effect of the asy eos



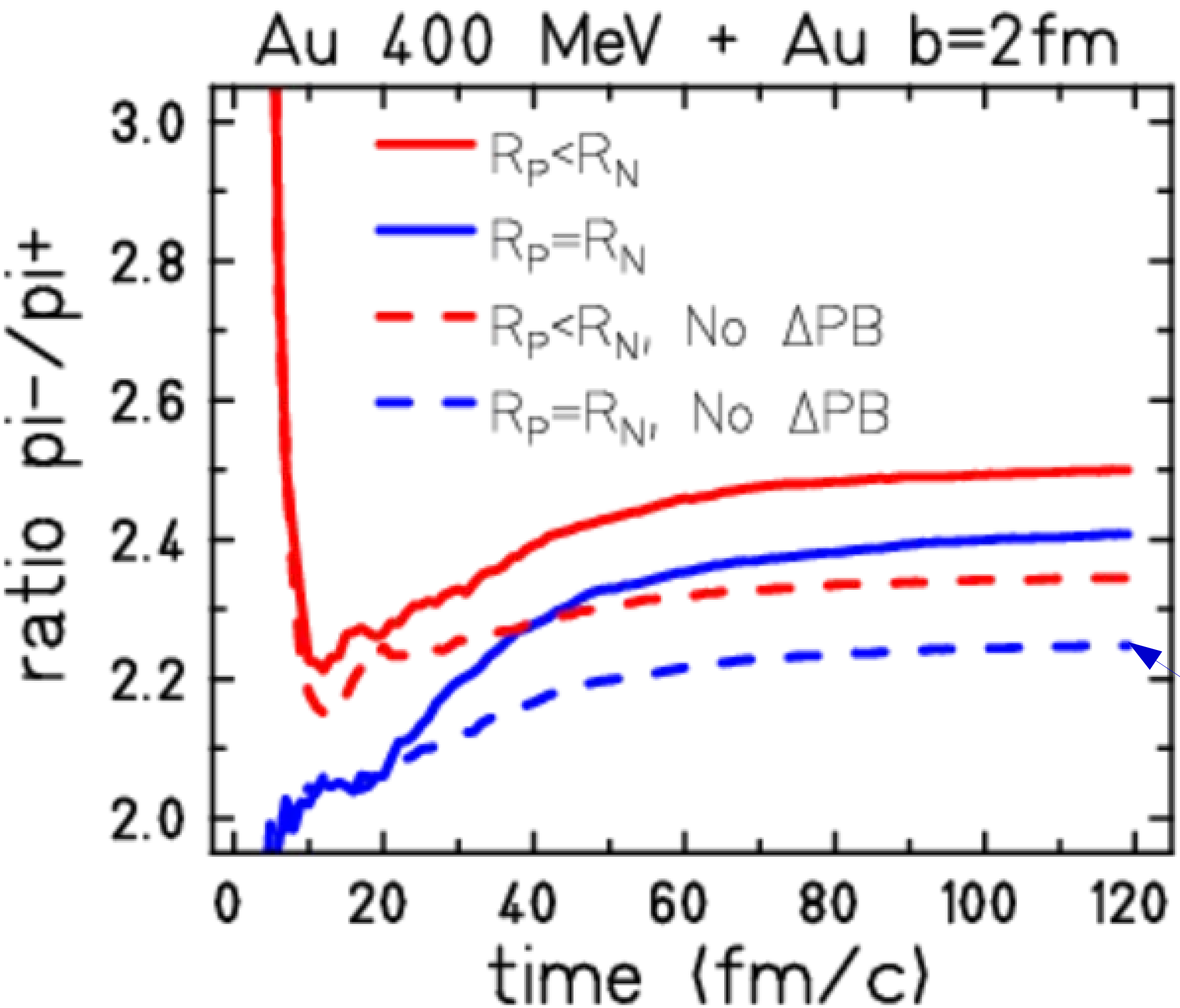


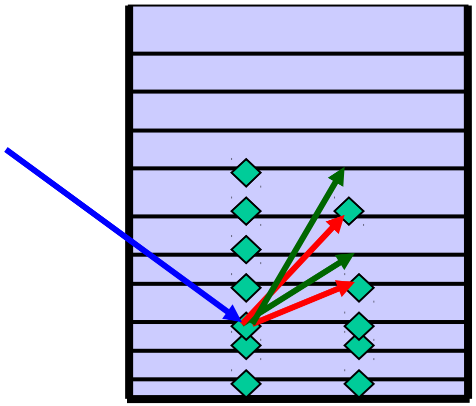
Triggered a lot of propositions for using π-ratios for studying the eos for asymetric matter.

However dependences quite weak and other effects may dominate….

PION ISOSPIN RATIOS

- Effects of initialization and Δ Pauli blocking





Effect is of about the same size than effect of asy-eos

Used for comparison with FOPI

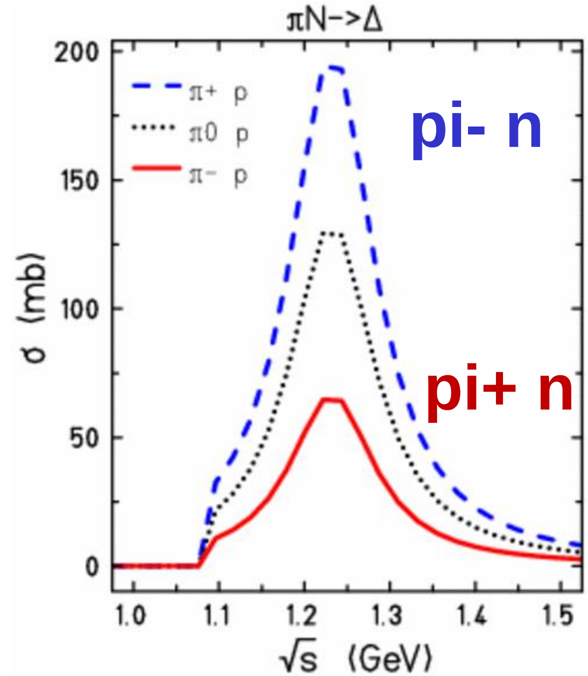
PION RATIOS

- **Explaining effect of neutron skin and Δ Pauli bl.**

- **In neutron dominated matter the π- has a higher chance to rescatter than the π+**

- **However, the produced Δ- produces completely π-, while the produced Δ+ produces preferentially π0: π+ is preferentially destroyed**

- **Additionally the Pauli blocking will penalize channel producing n, i.e the production of π+ will be still more suppressed.**



$$\Delta^{++} \rightarrow 1 \cdot (p + \pi^+)$$

$$\Delta^{+} \rightarrow \frac{2}{3} \cdot (p + \pi^0) + \frac{1}{3} \cdot (n + \pi^+)$$

$$\Delta^{0} \rightarrow \frac{2}{3} \cdot (n + \pi^0) + \frac{1}{3} \cdot (p + \pi^-)$$

$$\Delta^{-} \rightarrow 1 \cdot (n + \pi^-)$$

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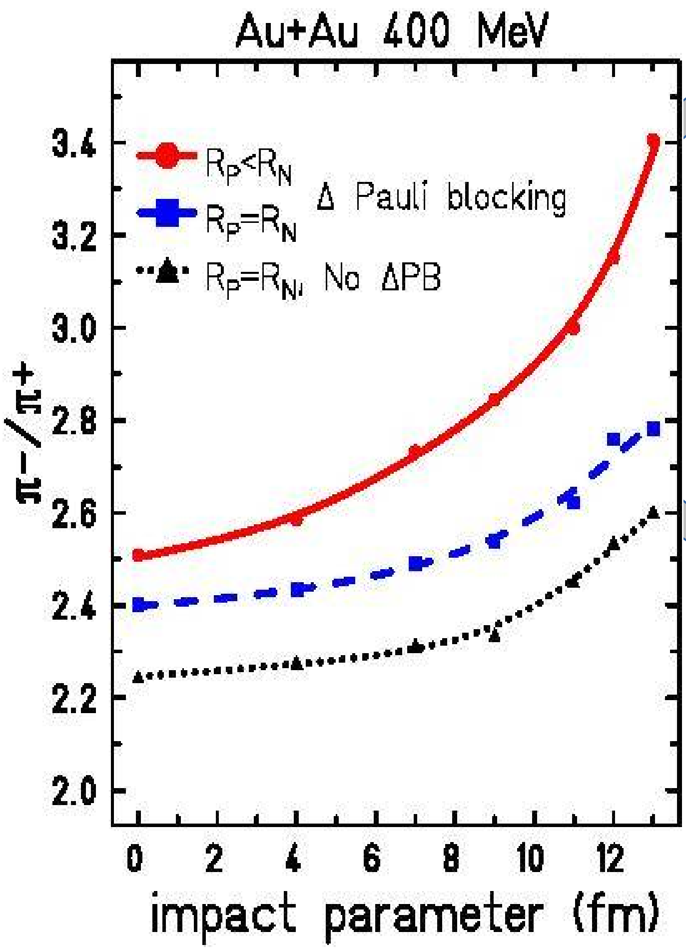
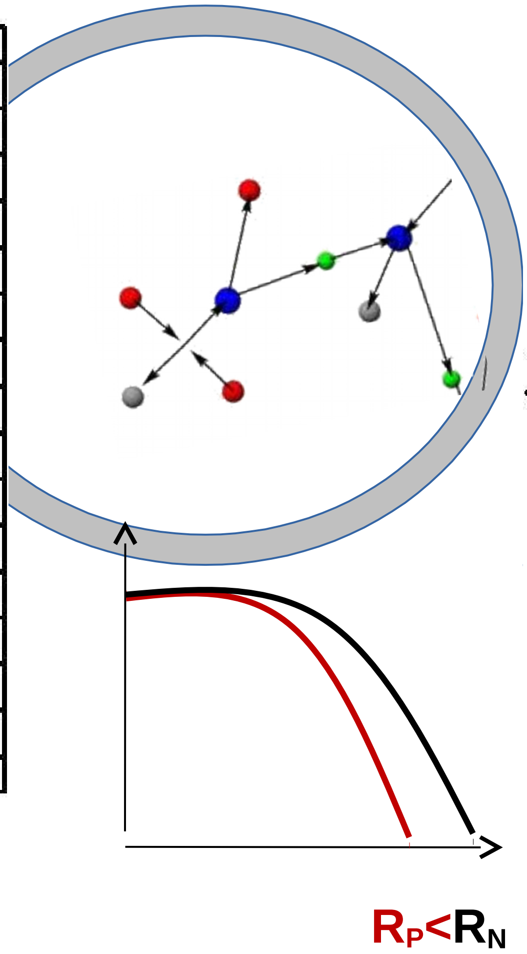
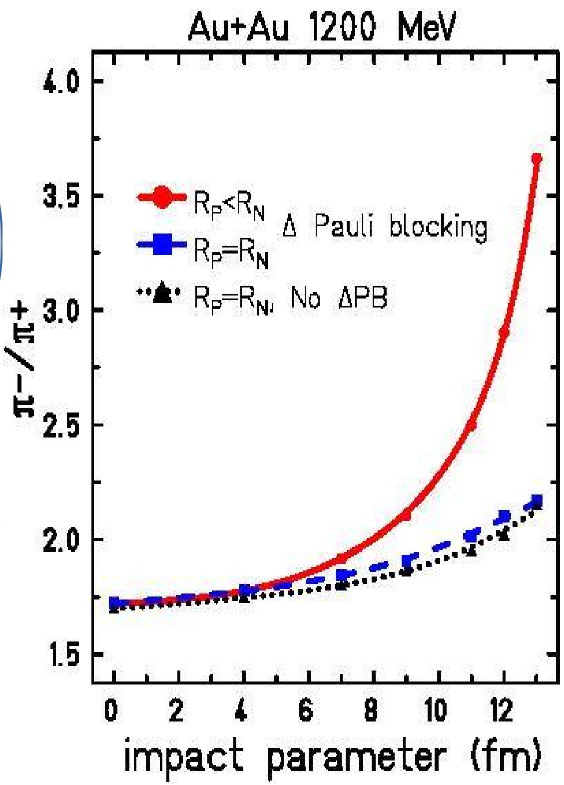
PION RATIOS

- How to disentangle other effects ?

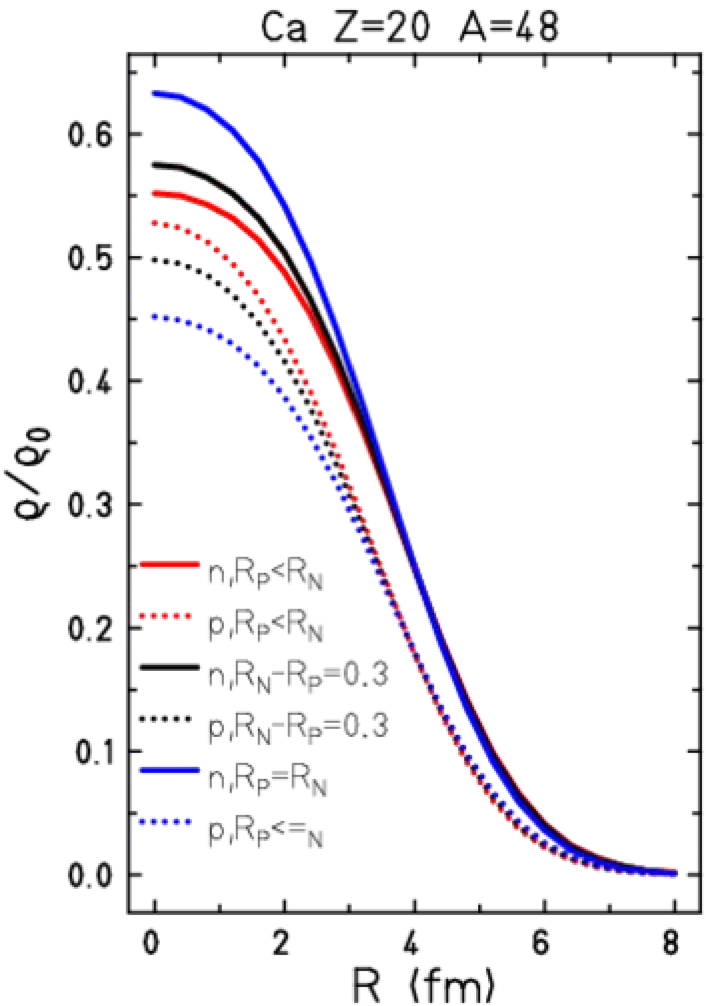


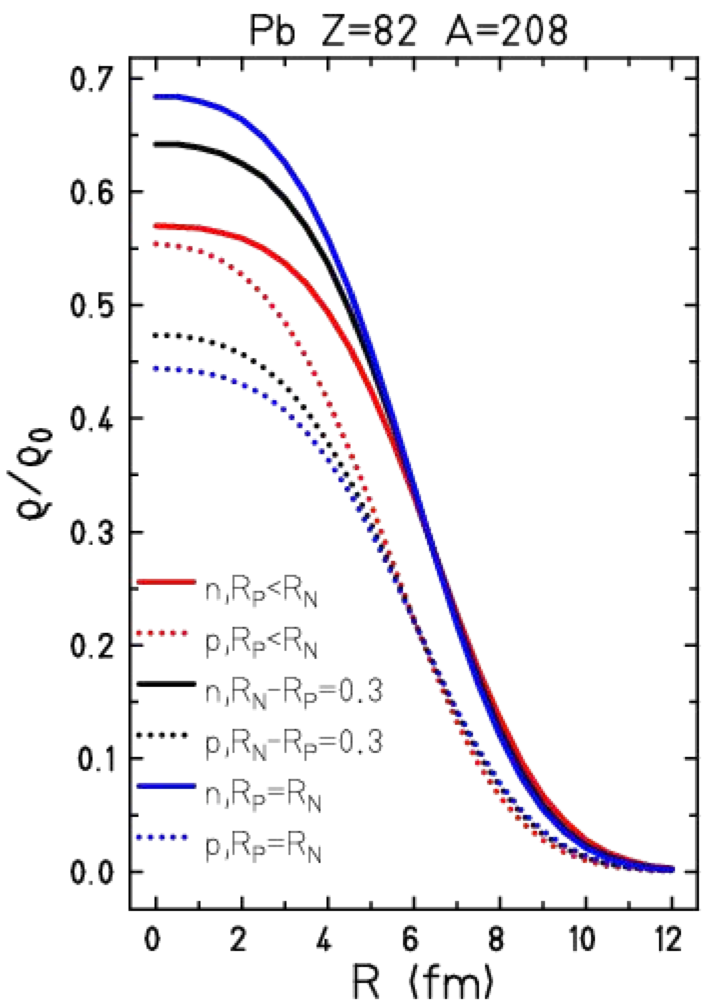




MORE TOWARDS NEUTRON SKIN

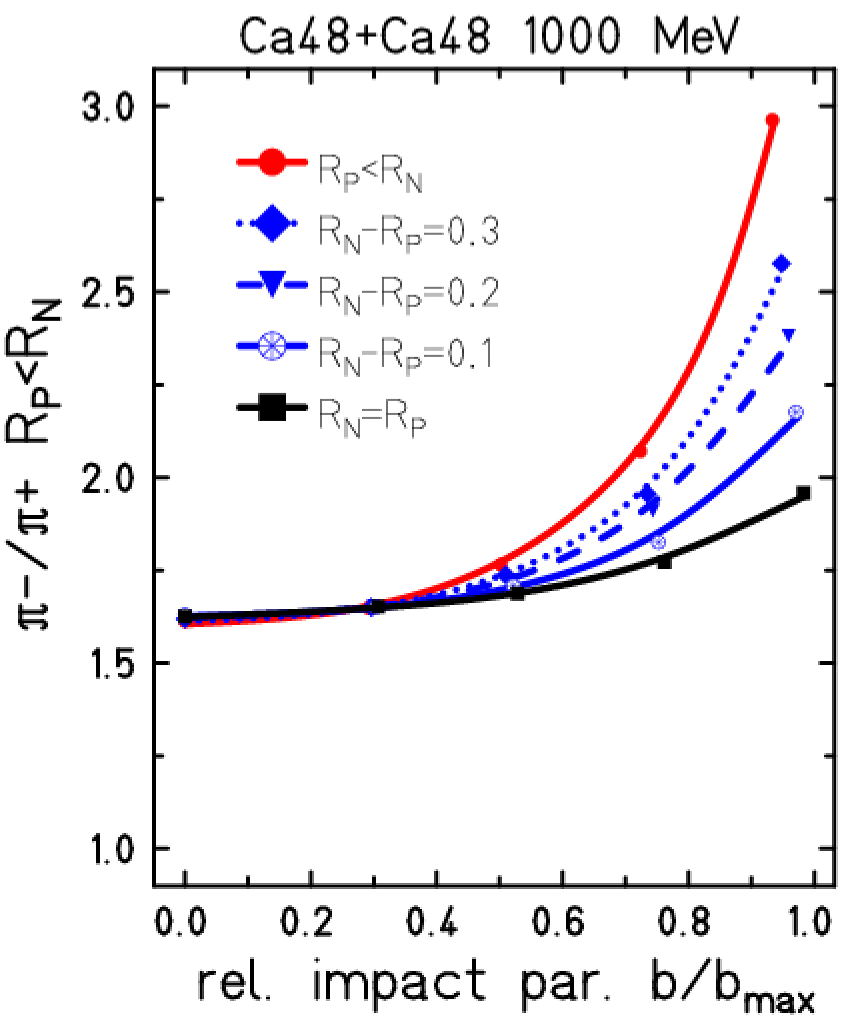
- Take more « spherical systems »

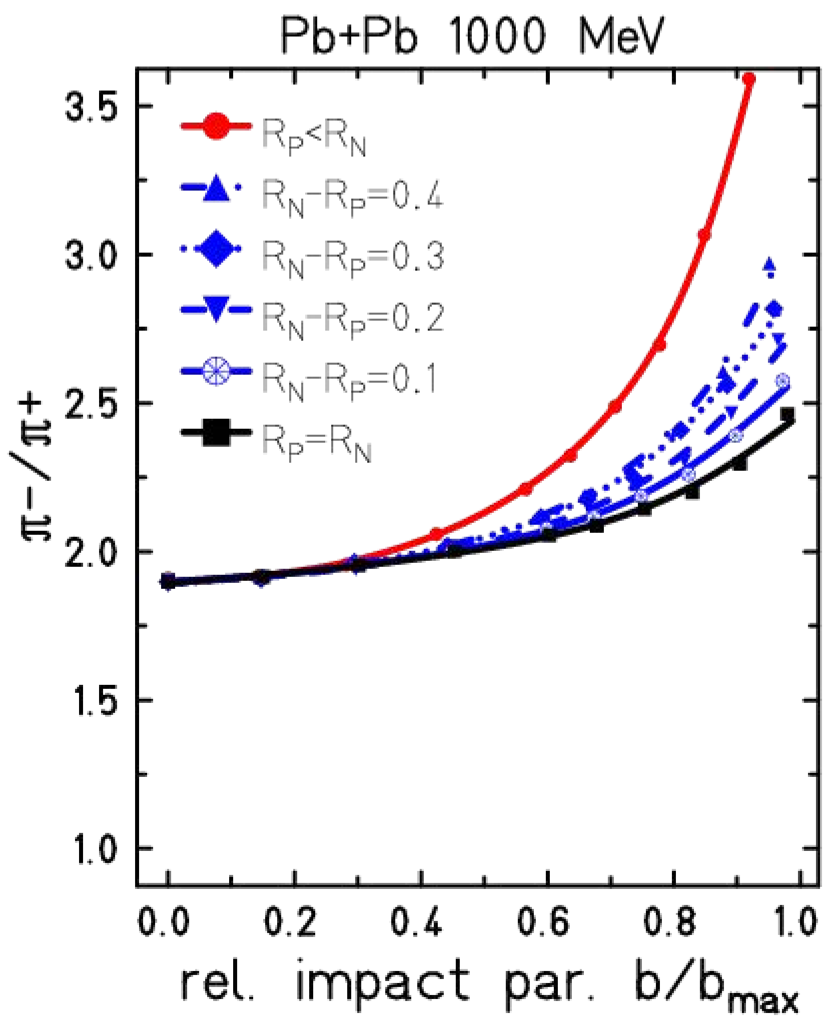




MORE TOWARDS NEUTRON SKIN

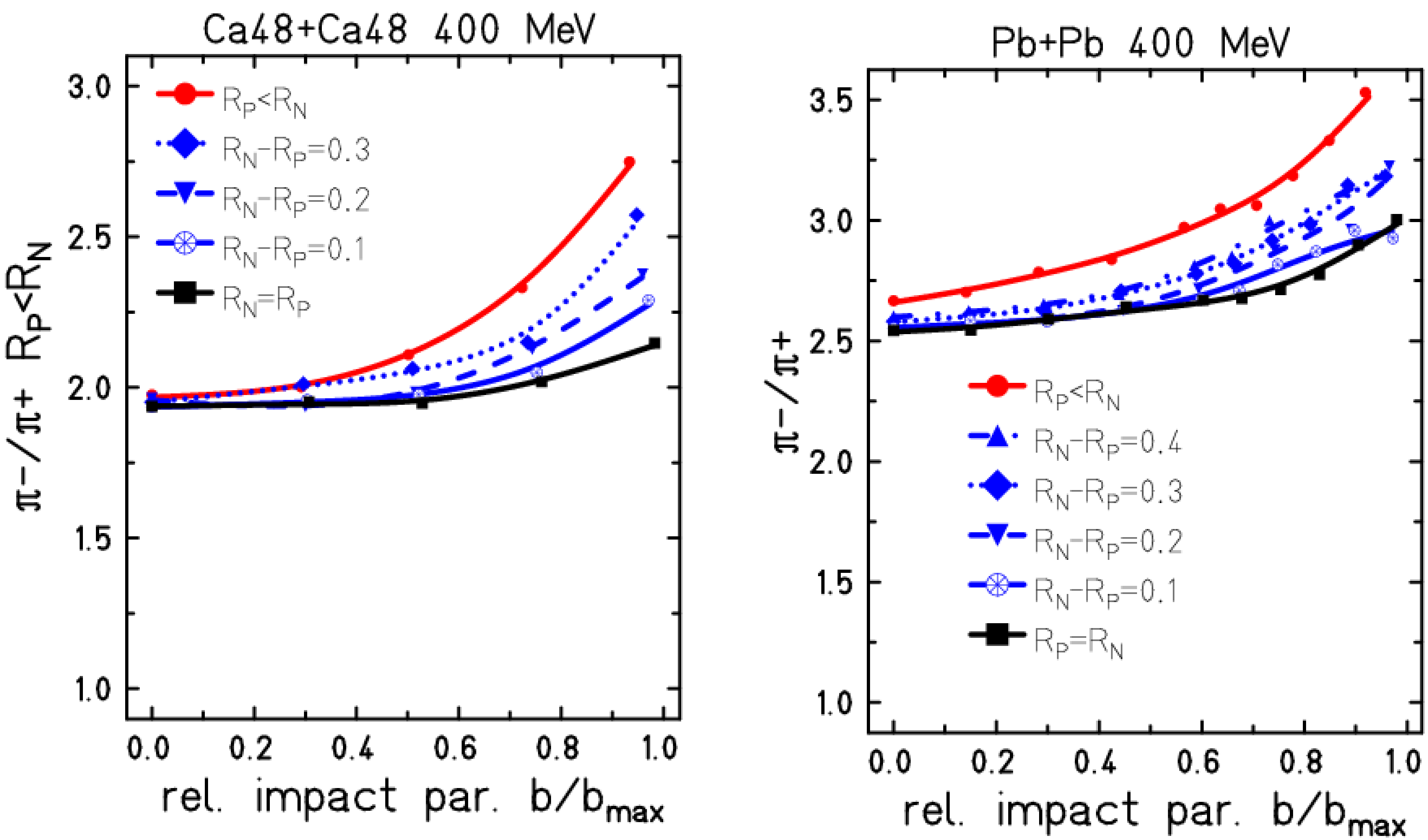
- For neutron skin look at 1000 MeV





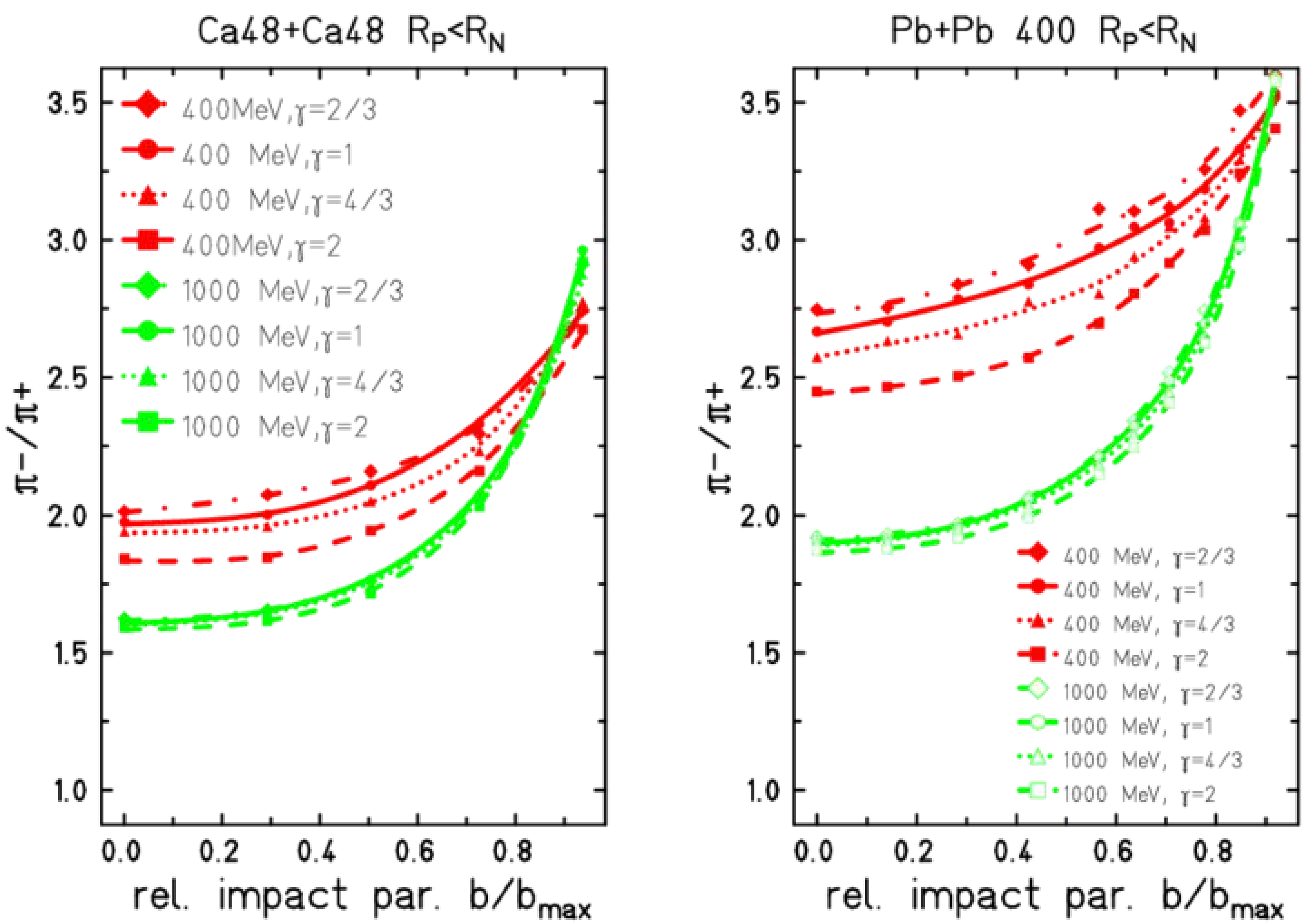
MORE TOWARDS NEUTRON SKIN

- The centrality will also show up at 400 MeV

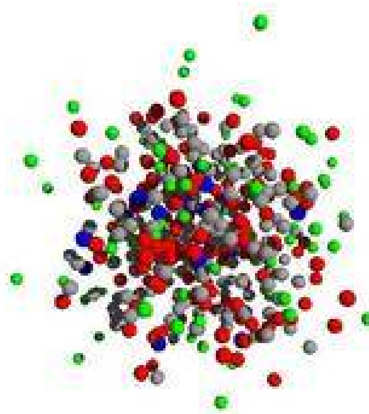


MORE TOWARDS NEUTRON SKIN

- Afterwards look for other effects : asy eos etc



CONCLUSION



1. PIONS AND DELTAS

1.1 Frequent rescattering of pions
1.2 Differences pi- and pi+
1.3 Delta dominant at high densities
1.4 Final pions from low densities
1.5 No real signal for compression

2. ISOSPIN RATIOS

2.1 Differences pion/Delta
2.2 importance of initialisation
2.3 Importance of Δ Pauli bl.
2.4 Influence of rescattering
2.5 Influence of asy eos of same order

3. HOW TO DISENTANLE

3.1 Take large& intermediate systems
3.2 Large impact parameters
3.3 Different energies 400 & 1000 MeV

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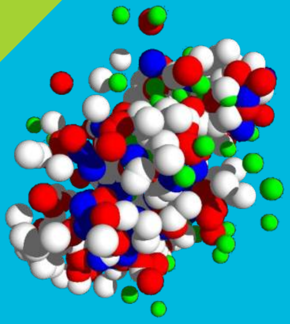
THANK YOU



If we shadows have offended,
Think but this, and all is mended,
That you have but slumber'd here
While these visions did appear.
And this weak and idle theme,
No more yielding but a dream
Gentles, do not reprehend:
if you pardon, we will mend.

W. Shakespeare: A midsummer night's dream

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