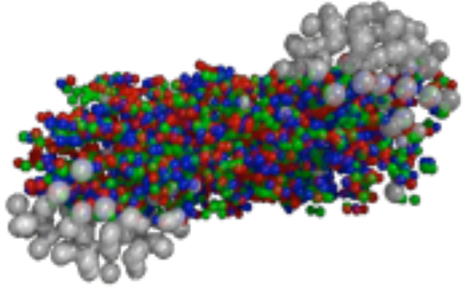
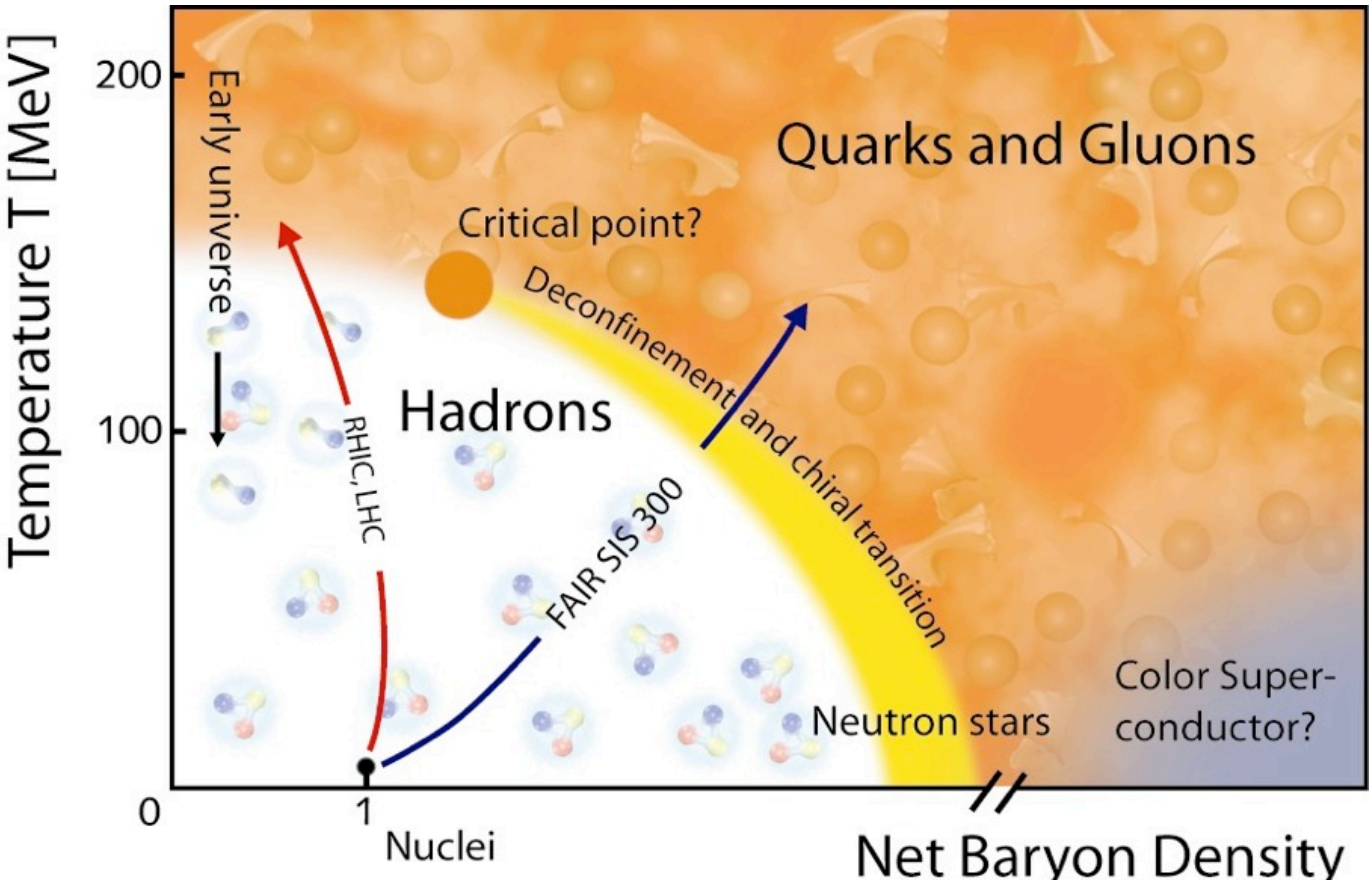
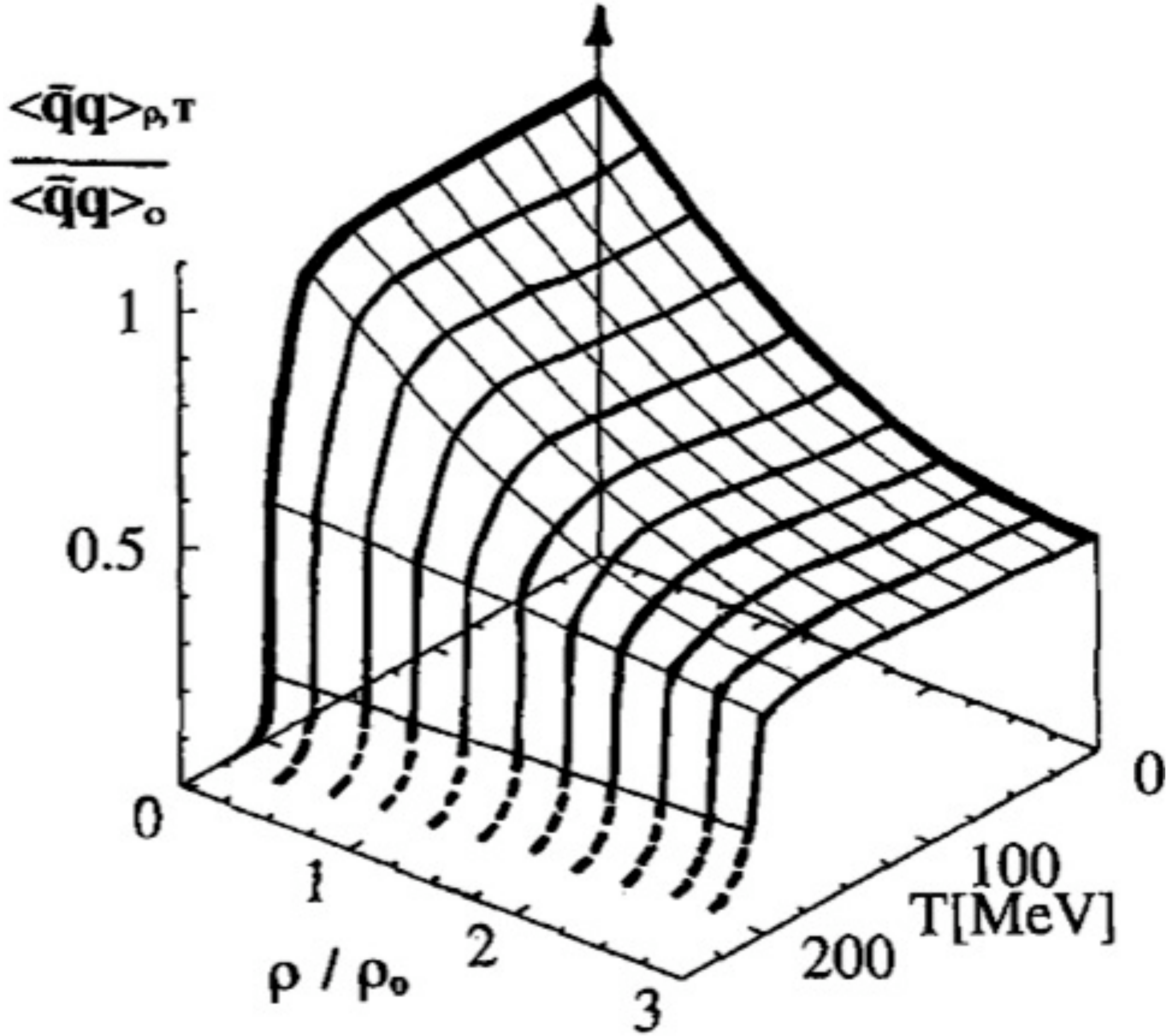
Phasediagram of QCD

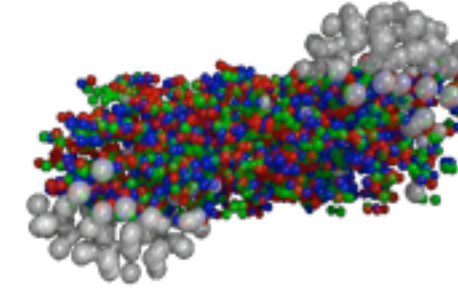


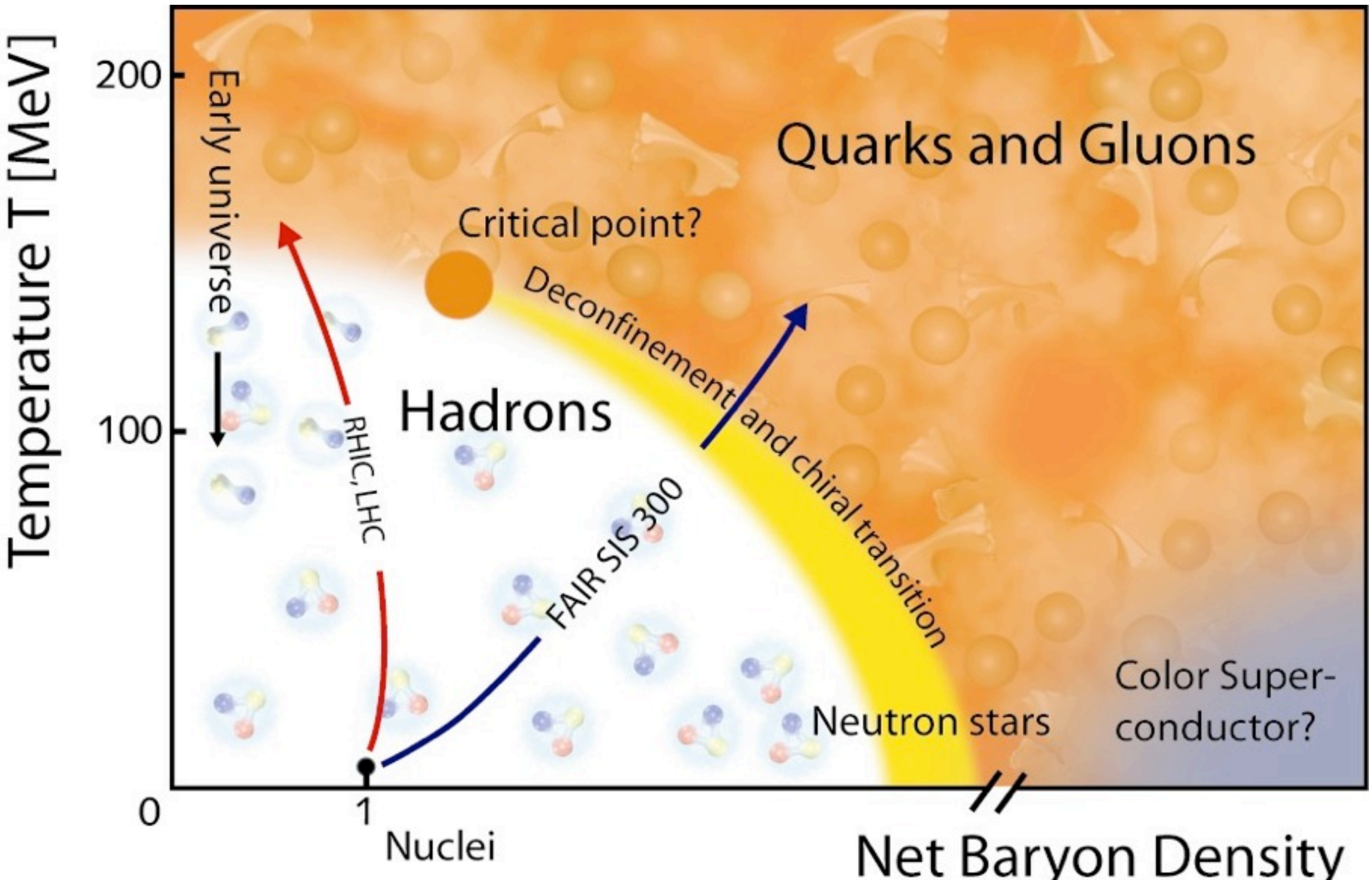


Chiral symmetry and density

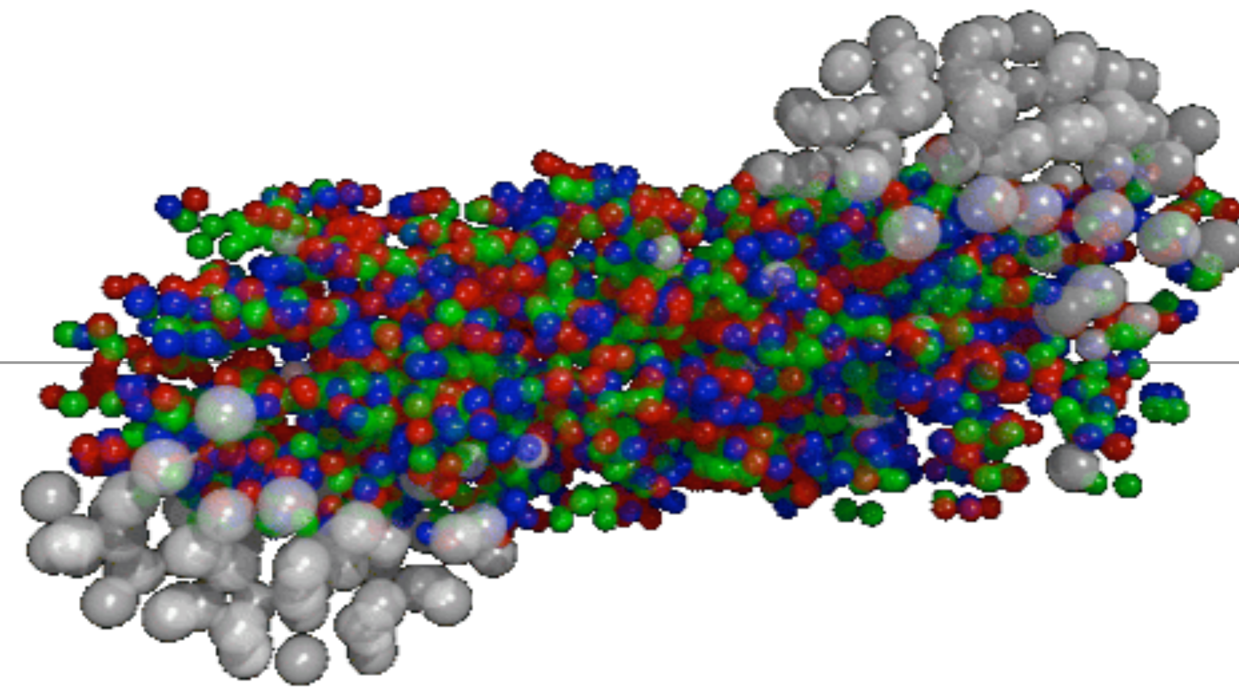


Phasediagram of QCD

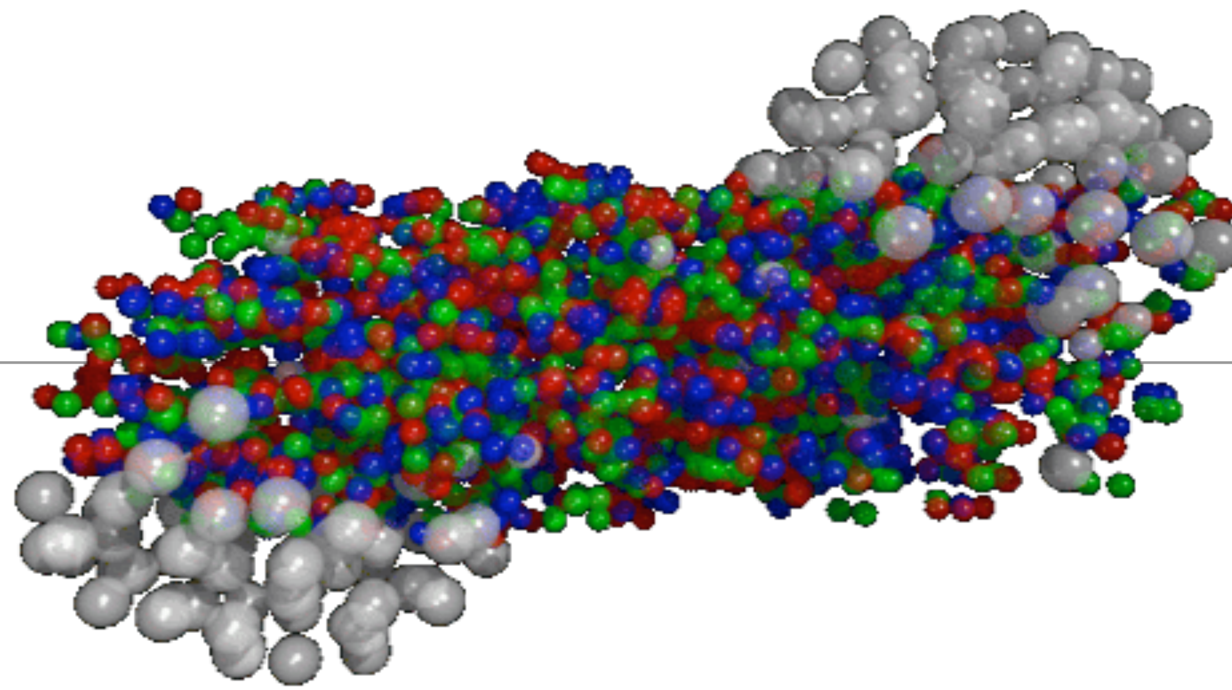


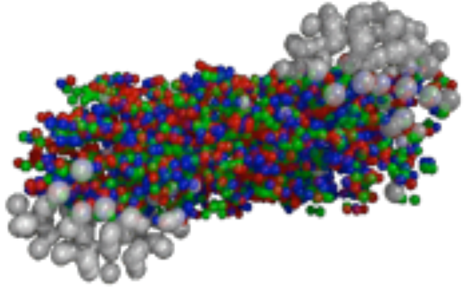


Measuring high μ_B with resonances/ dileptons



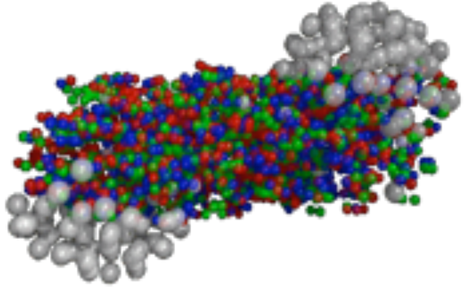
What you need to know to make people uneasy at dilepton meetings





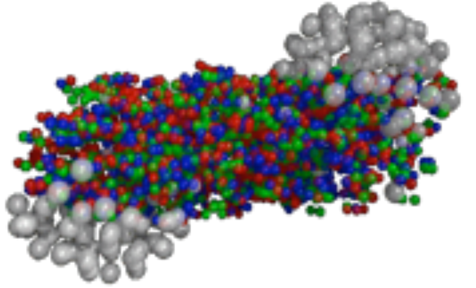
Check density

- Several physical effects are density driven, e.g.
  - vector meson spectral function broadening
  - chiral phase transition
  - QGP phase transition
  - quarkyonic matter
  - ...



Motivation

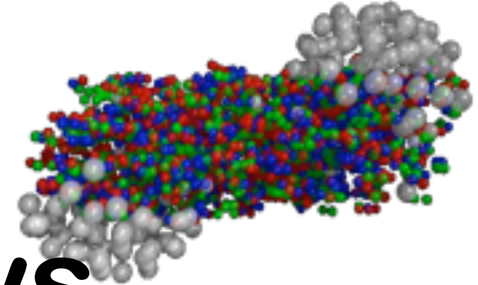
- Before including those density-driven effects into theoretical models one should check:
    - the maximum density which is reached in heavy ion collisions
    - the behaviour of the system without any medium effects
    - from what stage is the information one can gather experimentally from? and how?



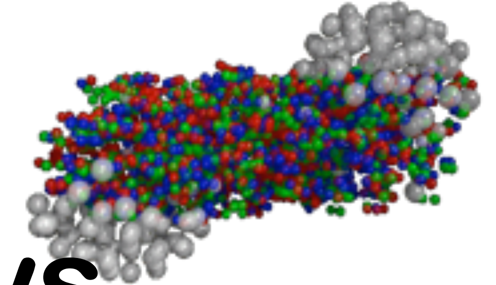
Outline

- **Quick UrQMD reminder**
- **Resonance kinematics**
  - **How deep can we look into heavy ion collisions using resonances/ dileptons?** (does high transverse momentum change anything?)
  - **Baryons @ low energies**
  - **a_1**
  - **Hadronic cocktail and what we learn from it**

Dileptonic and hadronic decays



Dileptons	Hadrons
do not interact strongly with the surrounding medium	suffer from final state interactions
originate from various sources in various mass regions (note: Dalitz decays)	originate from various sources in various mass regions
Typical branching ratios on the order of 10^{-4} - 10^{-5}	Typical branching ratios on the order of 0.1 - 1
when measured reflect the integrated collision history	when measured reflect the late stage (after freezeout) of the collision



Dileptonic and hadronic decays

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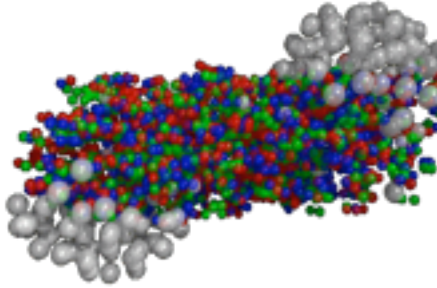
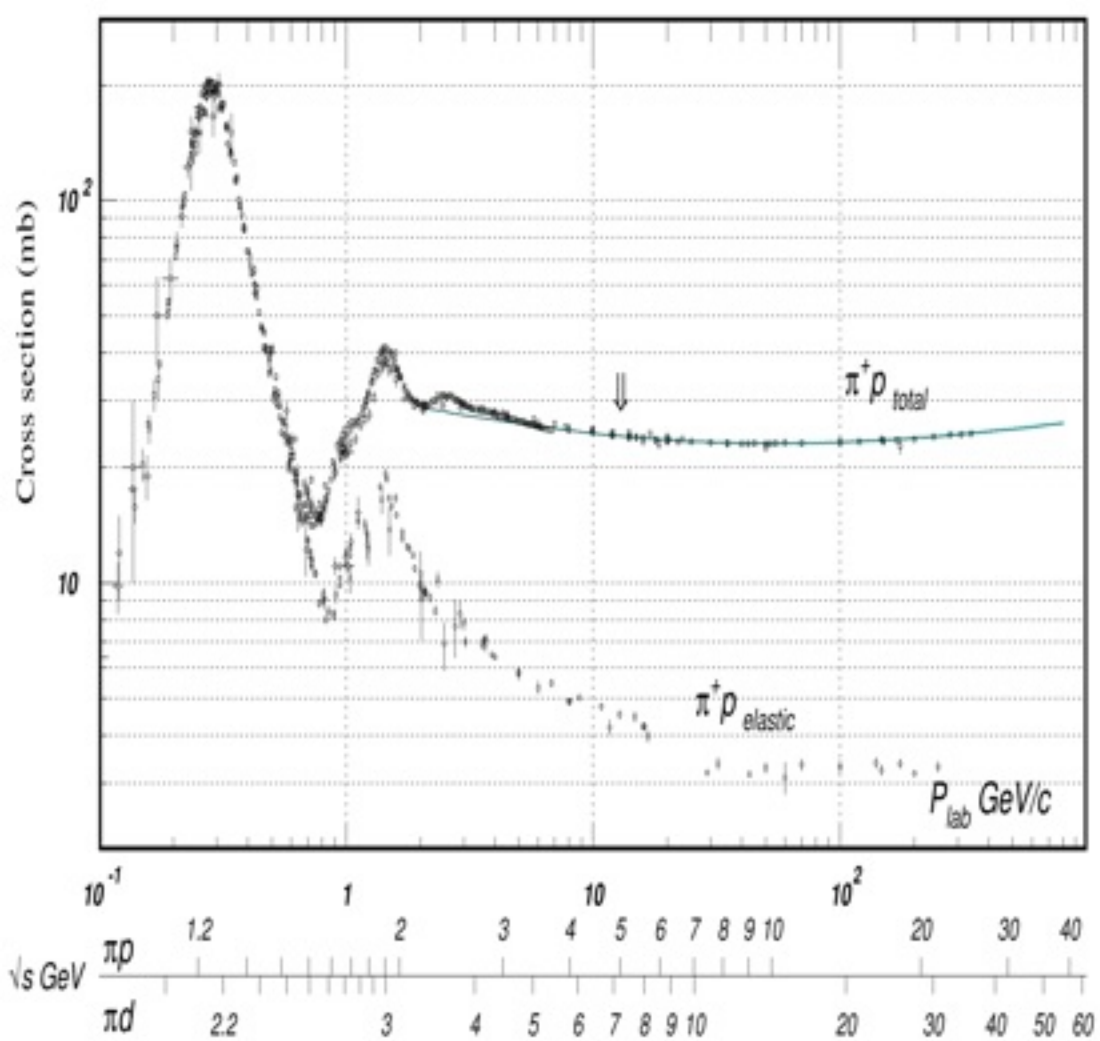


Measuring resonances

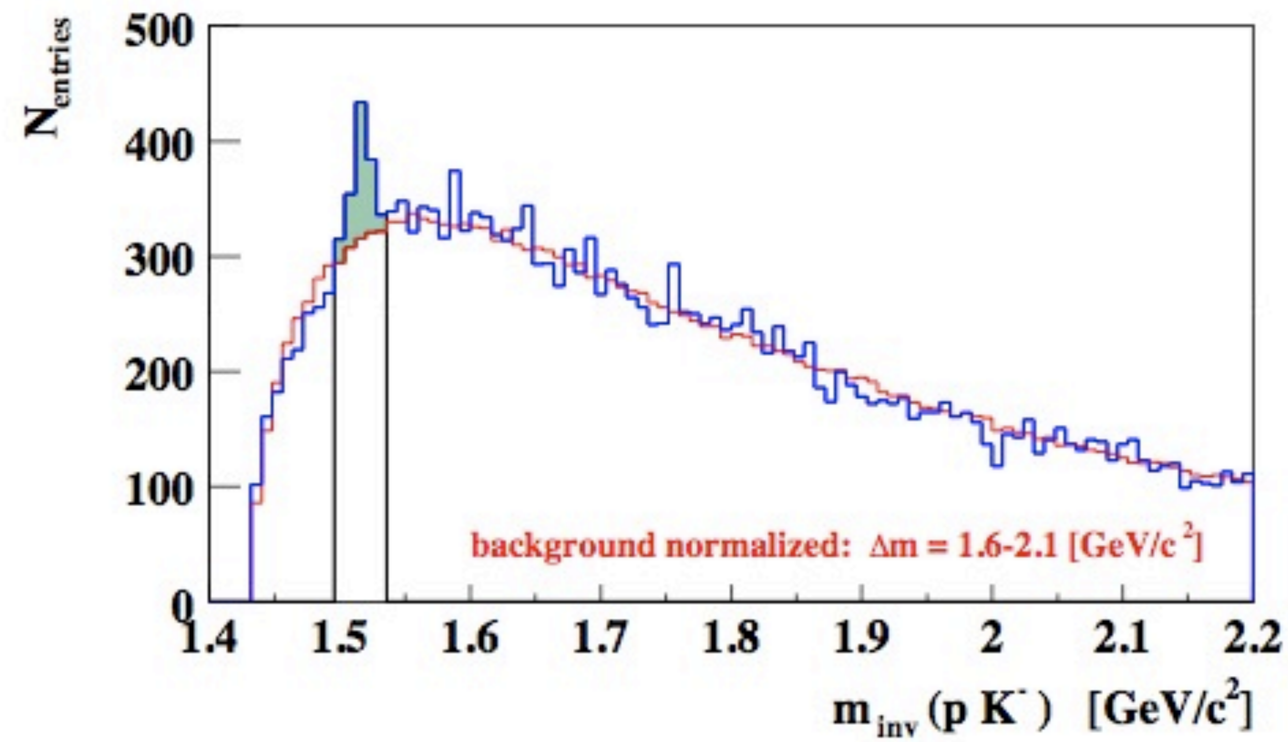
- Resonances decay on timescales of fm ⇒ cannot be measured directly

- Resonances are measured via their decay products, cross section follows a Breit-Wigner law



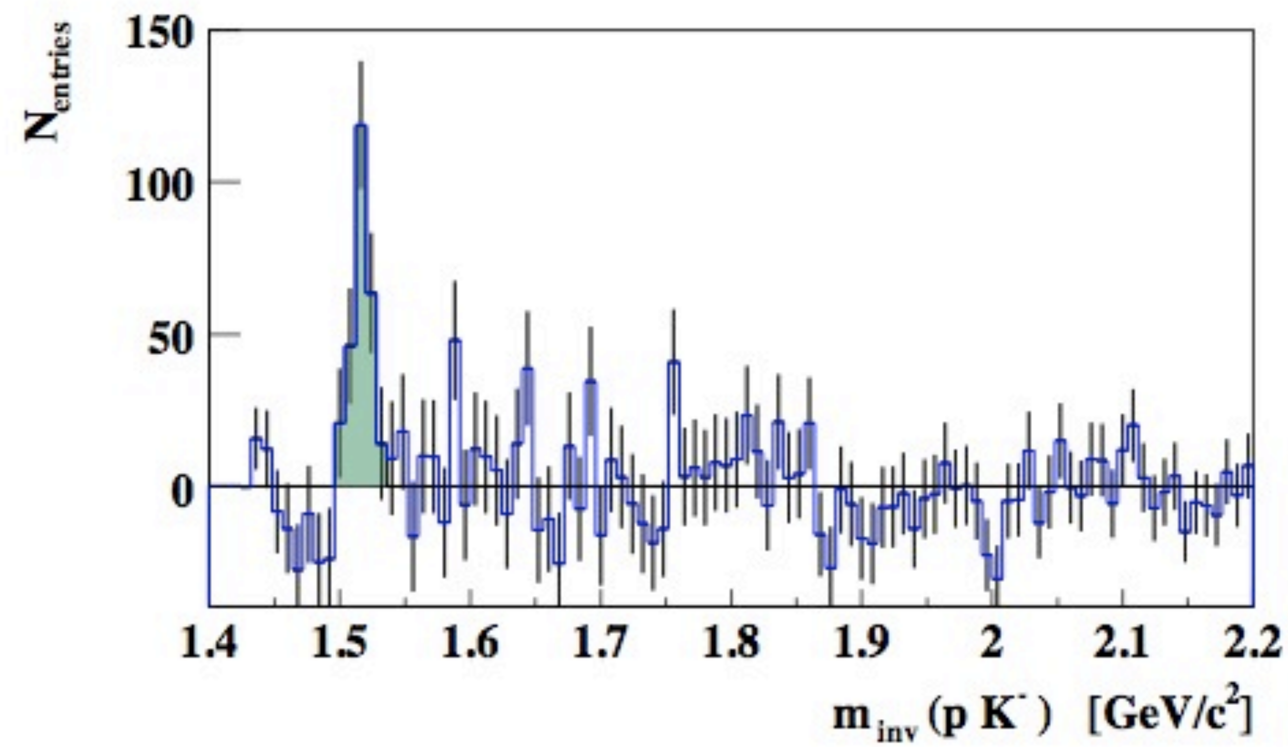
Measuring resonances in p+p

Correlate all protons and
kaons in the event,
plot invariant mass.



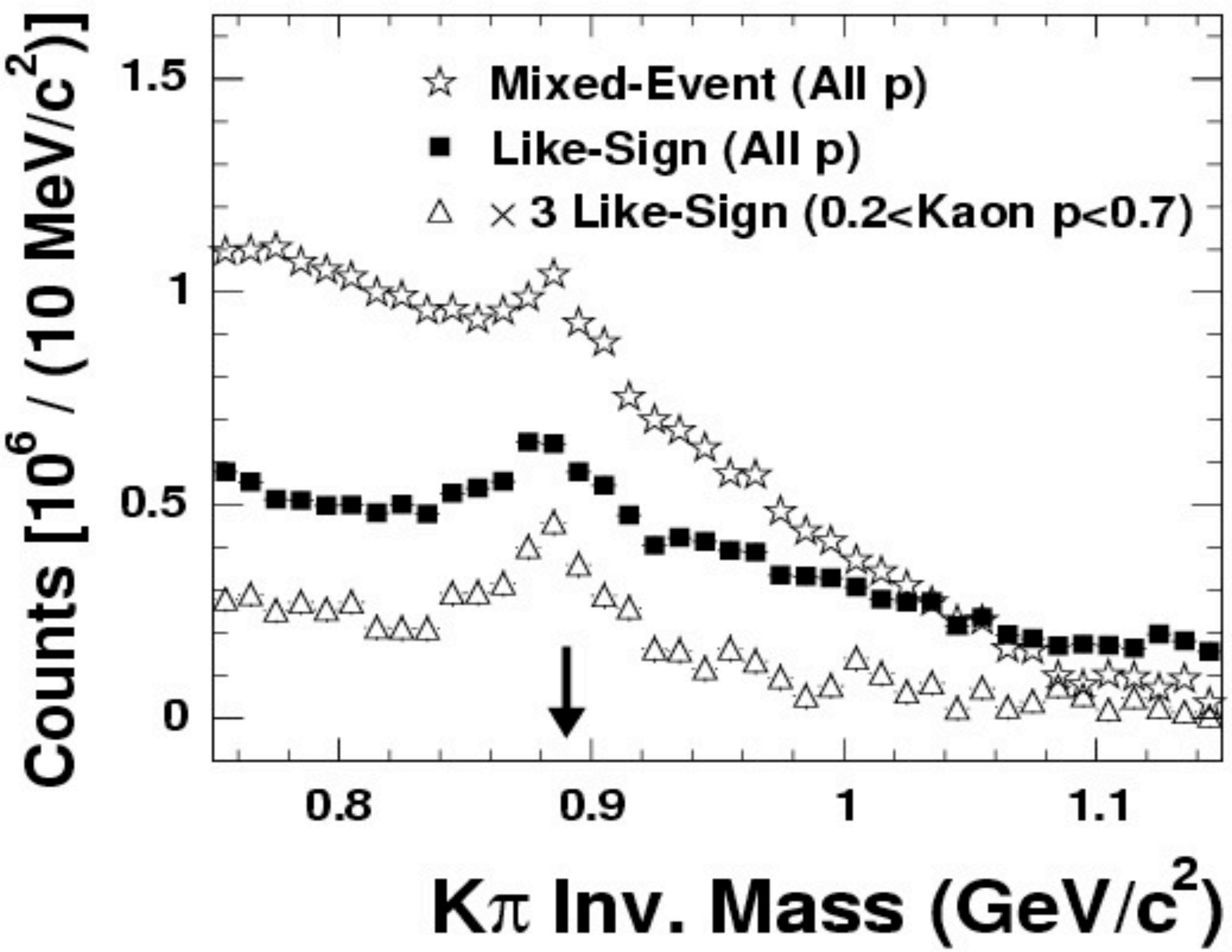
Lots of uncorrelated pairs
→ background subtraction
needed

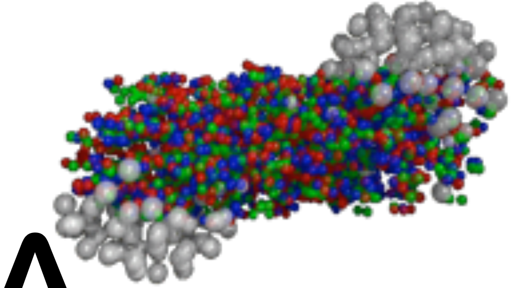
Still a visible peak,
but not as clear as before.



Measuring resonances in A+A

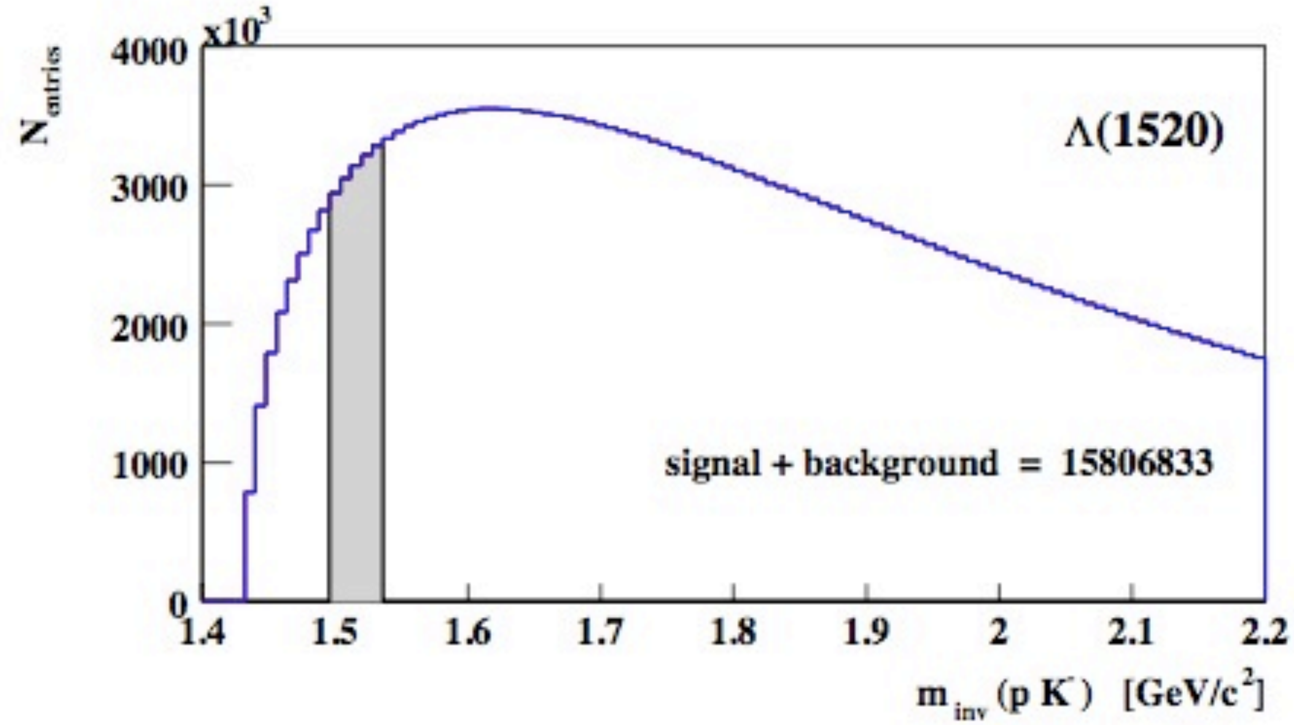
Different methods to subtract the background lead to slightly different results.



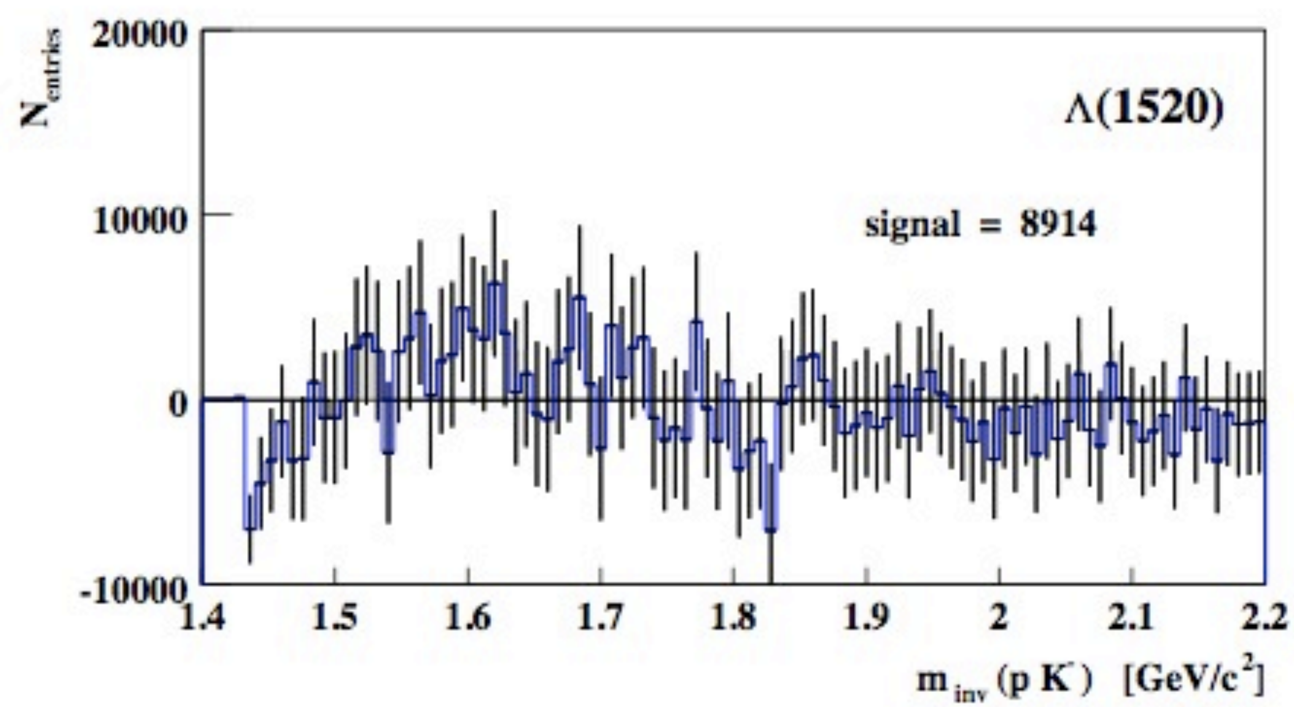


Measuring resonances in A+A

Correlate all protons and
kaons in the event,
plot invariant mass.

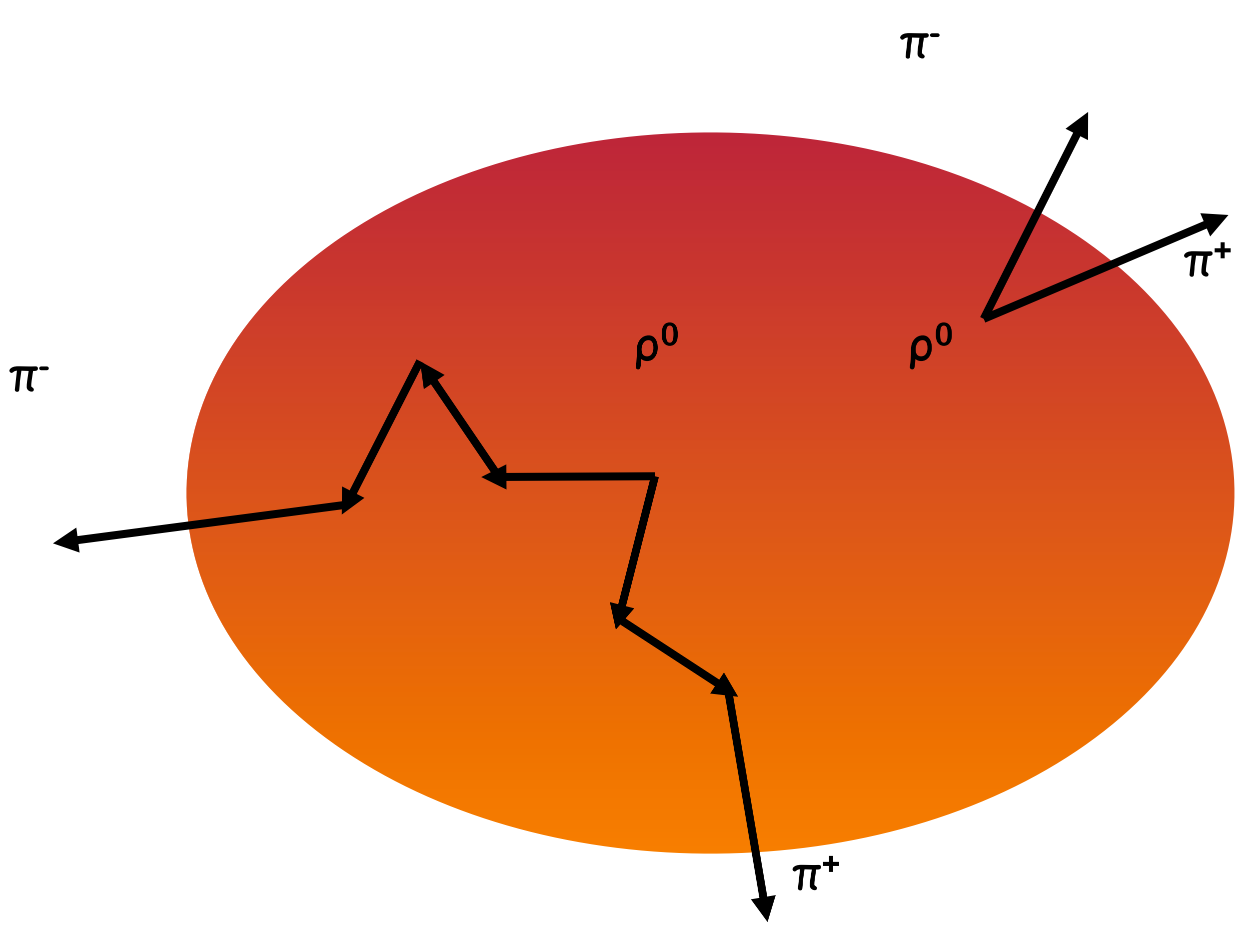


Peak?



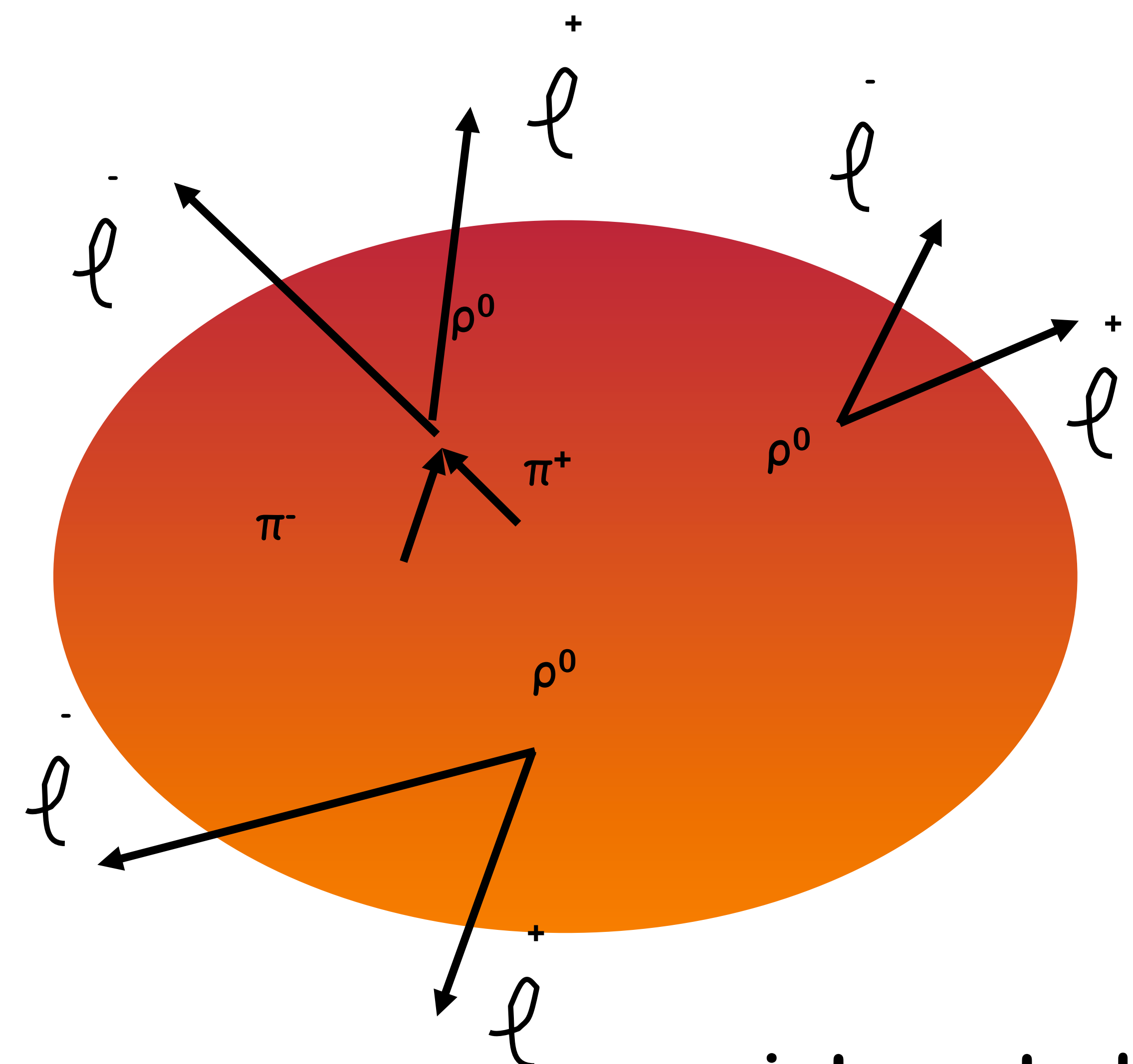
Dileptonic and hadronic decays

hadronic decay

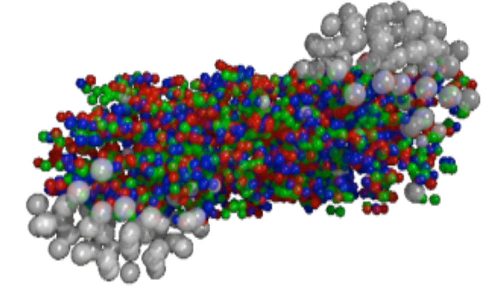


late stage

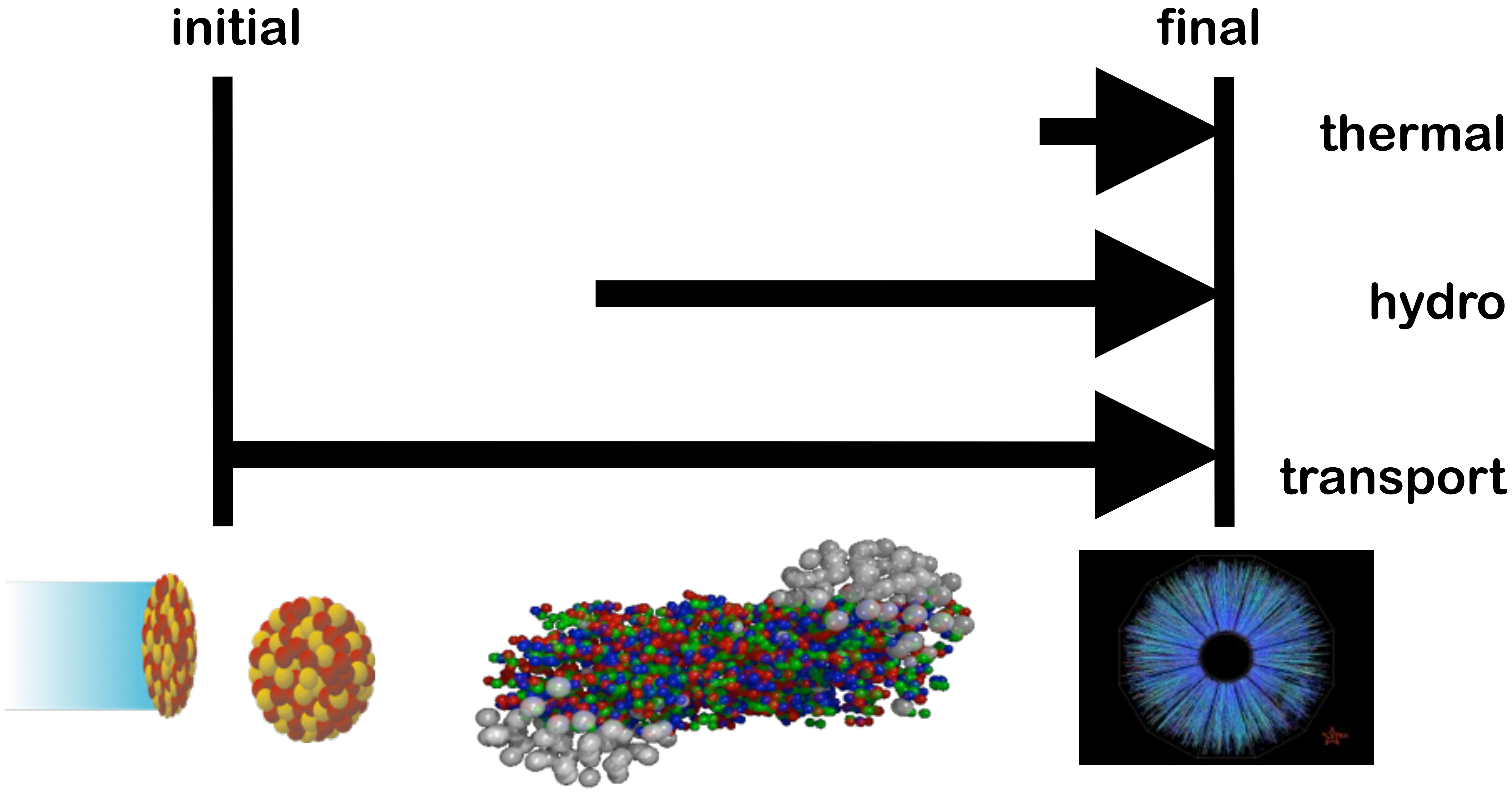
leptonic decay

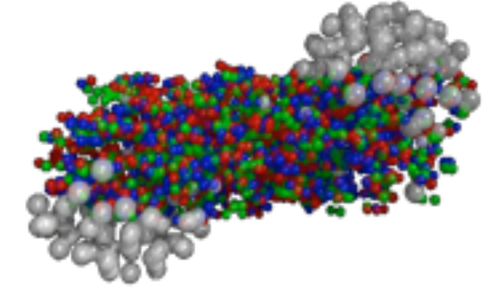


integrated collision



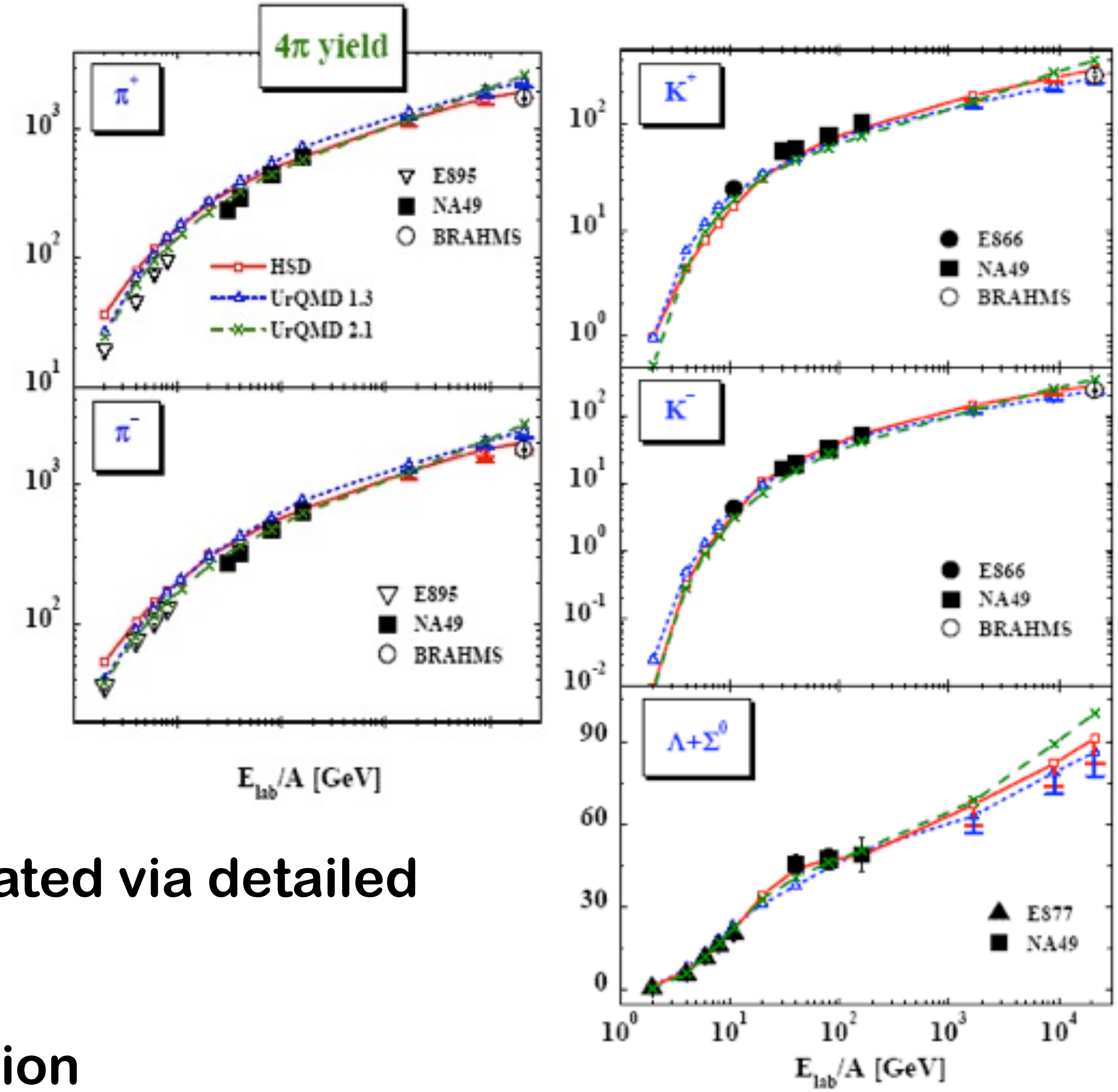
Model selection





The tool - UrQMD

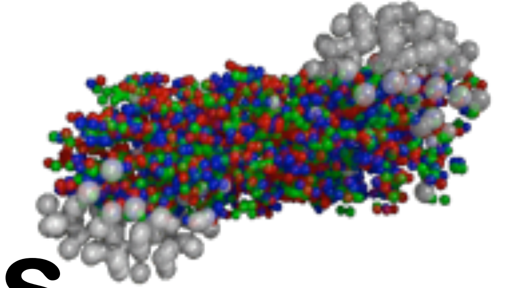
- Ultra Relativistic Quantum Molecular Dynamics
- Non equilibrium transport model
- All hadrons and resonances up to 2.2 GeV included
- Particle production via string excitation and -fragmentation
- Cross sections are fitted to available experimental data or calculated via detailed balance or the additive quark model
- Does account for canonical suppression



No explicit implementation of in-medium modifications!

Phys.Rev.C69:054907,2004

Phys.Rev.C74:034902,2006



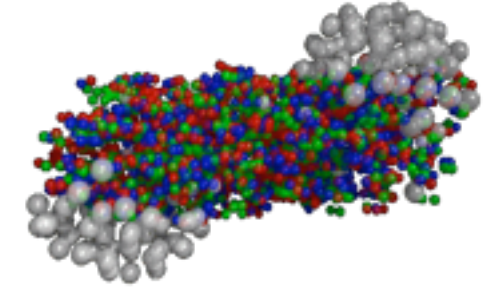
Quantum Molecular Dynamics

Nucleon = Gaussian Wave-Packet

$$\phi_i(\vec{x};\vec{q}_i,\vec{p}_i,t) = \left(\frac{2}{L\pi}\right)^{3/4} \exp\left\{-\frac{2}{L}(\vec{x}-\vec{q}_i(t))^2 + \frac{1}{\hbar}\mathrm{i}\vec{p}_i(t)\vec{x}\right\}$$

N-Body-State = product of coherent states

$$\Phi = \prod_i \phi_i(\vec{x},\vec{q_i},\vec{p_i},t)$$



QMD

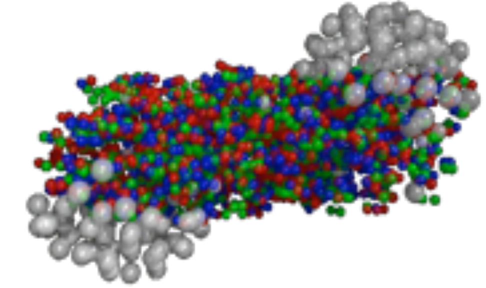
Lagrangian Density

$$\mathcal{L} = \sum_i \left[-\dot{\vec{q}}_i \, \vec{p}_i - T_i - \frac{1}{2} \sum_{j \neq i} \langle V_{ik} \rangle - \frac{3}{2Lm} \right]$$

Equations of motion

$$\dot{\vec{q}}_i = \frac{\vec{p}_i}{m} + \nabla_{\vec{p}_i} \sum_j \langle V_{ij} \rangle = \nabla_{\vec{p}_i} \langle H \rangle$$

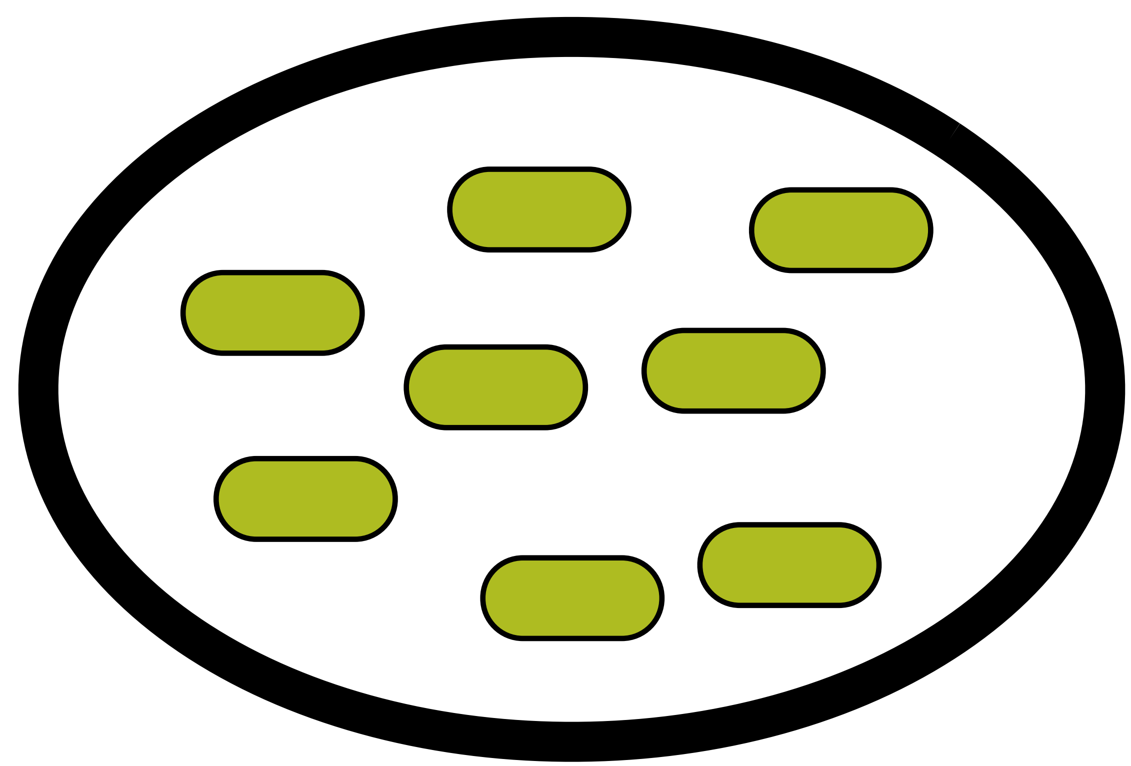
$$\dot{\vec{p}}_i = -\nabla_{\vec{q}_i} \sum_{j \neq i} \langle V_{ij} \rangle = -\nabla_{\vec{q}_i} \langle H \rangle .$$

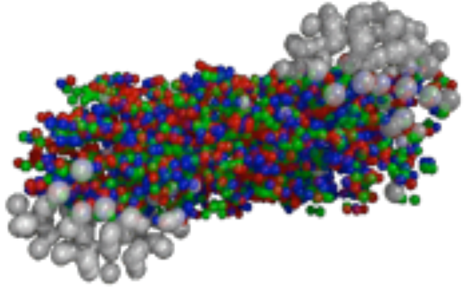


QMD

Complicated N-Body Schrödinger Problem

6 (N_P+N_T) equations



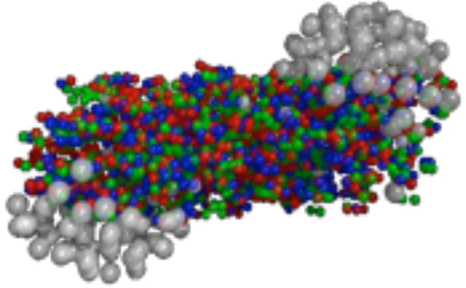


Steps in UrQMD

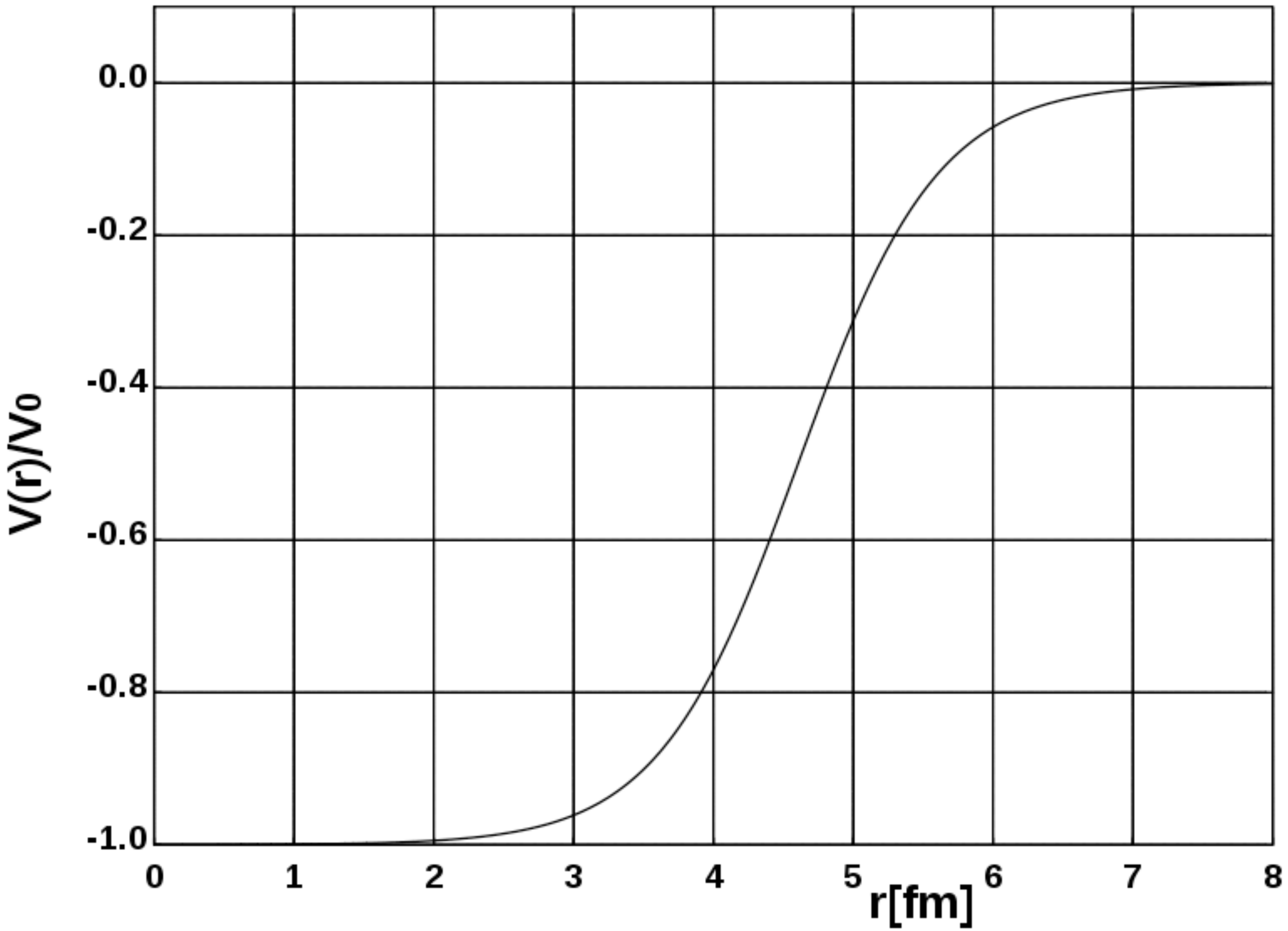
Initialization

Propagation of nuclei and produced particles

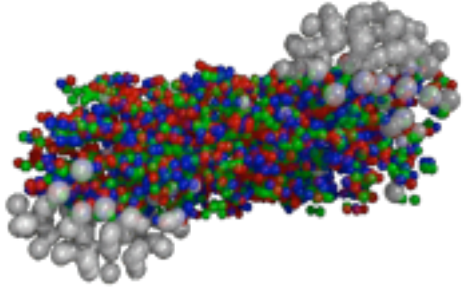
Binary scatterings



Initialization



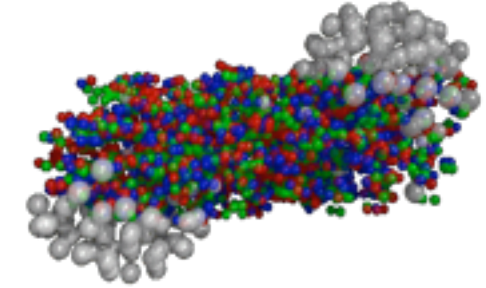
Collision criterium



When do particles collide?

1) Know cross section

2) Check collision criterium



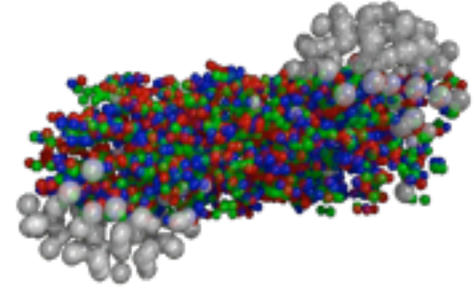
Collision criterium

When do particles collide?

1) Know cross section

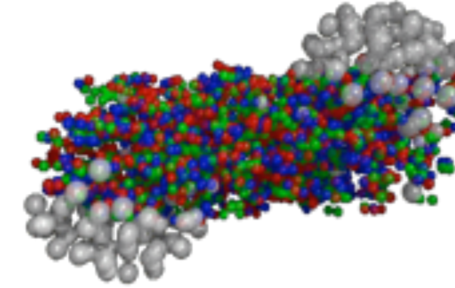
2) Check collision criterium

$$\pi d^2 \leq \sigma_{tot}$$



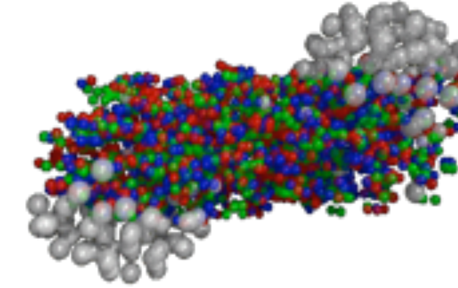
The tool - UrQMD

nucleon	Δ	Λ	Σ	Ξ	Ω
N_{938}	Δ_{1232}	Λ_{1116}	Σ_{1192}	Ξ_{1317}	Ω_{1672}
N_{1440}	Δ_{1600}	Λ_{1405}	Σ_{1385}	Ξ_{1530}	
N_{1520}	Δ_{1620}	Λ_{1520}	Σ_{1660}	Ξ_{1690}	
N_{1535}	Δ_{1700}	Λ_{1600}	Σ_{1670}	Ξ_{1820}	
N_{1650}	Δ_{1900}	Λ_{1670}	Σ_{1775}	Ξ_{1950}	
N_{1675}	Δ_{1905}	Λ_{1690}	Σ_{1790}	Ξ_{2025}	
N_{1680}	Δ_{1910}	Λ_{1800}	Σ_{1915}		
N_{1700}	Δ_{1920}	Λ_{1810}	Σ_{1940}		
N_{1710}	Δ_{1930}	Λ_{1820}	Σ_{2030}		
N_{1720}	Δ_{1950}	Λ_{1830}			
N_{1900}		Λ_{1890}			
N_{1990}		Λ_{2100}			
N_{2080}		Λ_{2110}			
N_{2190}					
N_{2200}					
N_{2250}					



The tool - UrQMD

0^{-+}	1^{--}	0^{++}	1^{++}
π	ρ	a_0	a_1
K	K^*	K_0^*	K_1^*
η	ω	f_0	f_1
η'	ϕ	f_0^*	f_1'
1^{+-}	2^{++}	$(1^{--})^*$	$(1^{--})^{**}$
b_1	a_2	ρ_{1450}	ρ_{1700}
K_1	K_2^*	K_{1410}^*	K_{1680}^*
h_1	f_2	ω_{1420}	ω_{1662}
h_1'	f_2'	ϕ_{1680}	ϕ_{1900}



Cross sections

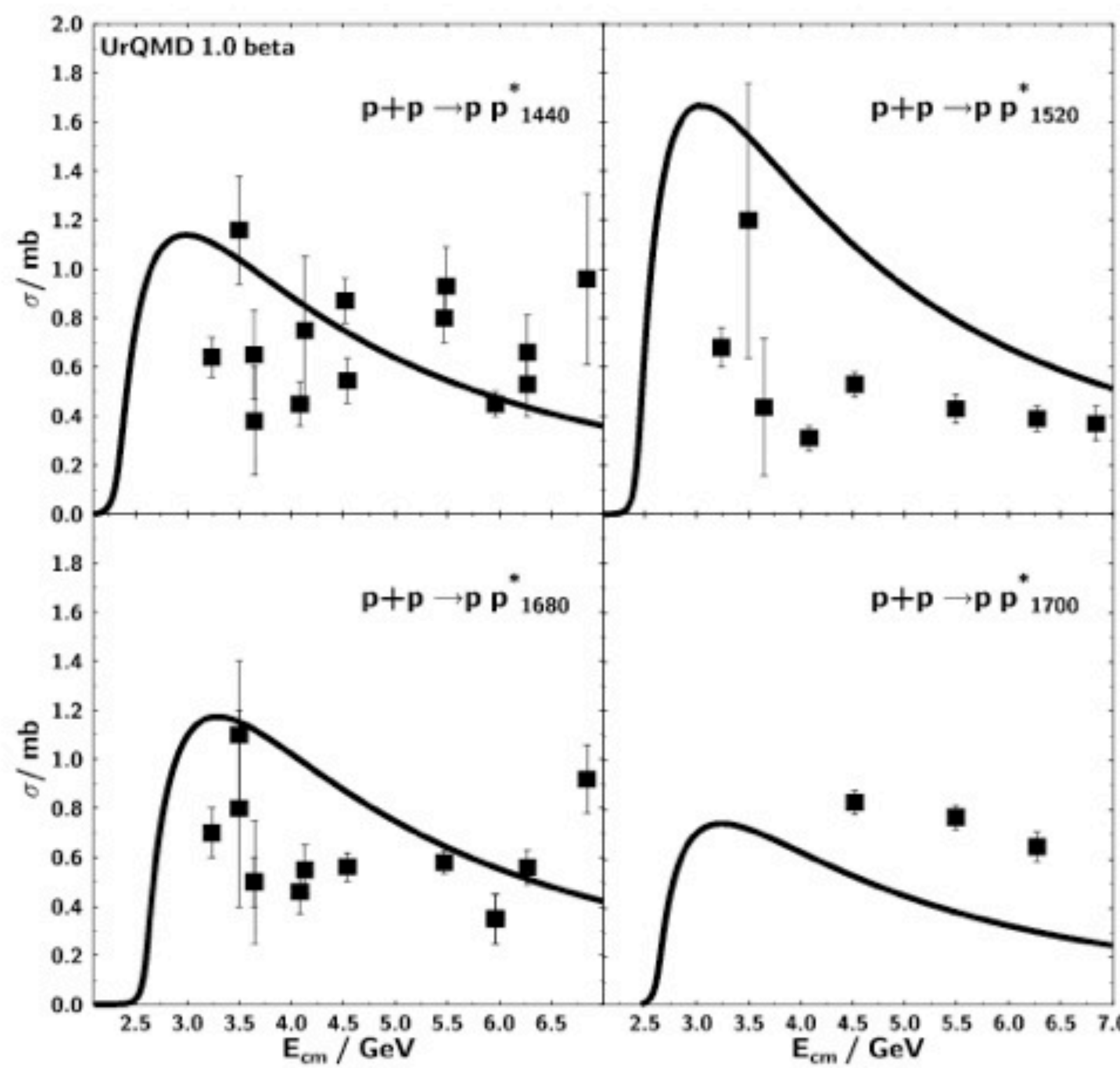
$$\sigma_{1,2\rightarrow 3,4}(\sqrt{s}) \sim (2s_3+1)(2s_4+1)\frac{<p_{3,4}>}{<p_{1,2}>}\frac{1}{\sqrt{s}}|M(m_3,m_4)|^2$$

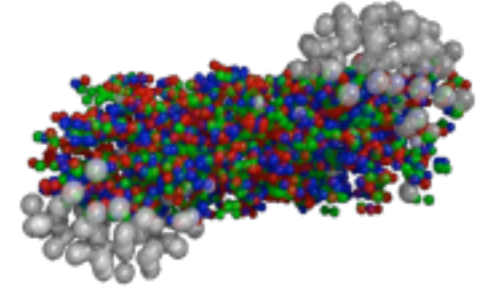
Global fit with the same kind of matrix element for 5 channels

$$NN \rightarrow NN^*, N\Delta^*, \Delta\Delta, \Delta N^*, \Delta\Delta^*$$

$$|M(m_3,m_4)|^2 = A\frac{1}{(m_4-m_3)^2(m_4+m_3)^2}$$

Data from elementary reactions are needed as an input into theory! (HADES?)





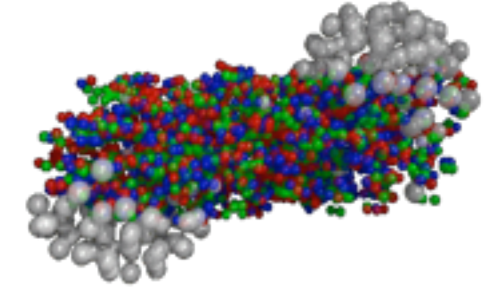
Density calculation

- **Lorentz-transform the CF density to the frame where the three-current vanishes (Eckart frame)**

$$\vec{\beta}_{CF} = \frac{\sum_{j=1}^{N} \left(\frac{\vec{p_j}}{E_j} \right) \cdot P_j}{\sum_{j=1}^{N} P_j}$$

$$\begin{pmatrix} \gamma & -\beta_x\gamma & -\beta_y\gamma & -\beta_z\gamma \\ -\beta_x\gamma & 1+(\gamma-1)\frac{\beta_x^2}{\beta^2} & (\gamma-1)\frac{\beta_x\beta_y}{\beta^2} & (\gamma-1)\frac{\beta_x\beta_z}{\beta^2} \\ -\beta_y\gamma & (\gamma-1)\frac{\beta_y\beta_x}{\beta^2} & 1+(\gamma-1)\frac{\beta_y^2}{\beta^2} & (\gamma-1)\frac{\beta_y\beta_z}{\beta^2} \\ -\beta_z\gamma & (\gamma-1)\frac{\beta_z\beta_x}{\beta^2} & (\gamma-1)\frac{\beta_z\beta_y}{\beta^2} & 1+(\gamma-1)\frac{\beta_z^2}{\beta^2} \end{pmatrix}$$

- **The zero-component of the transformed four-current is the relevant density**



Density calculation

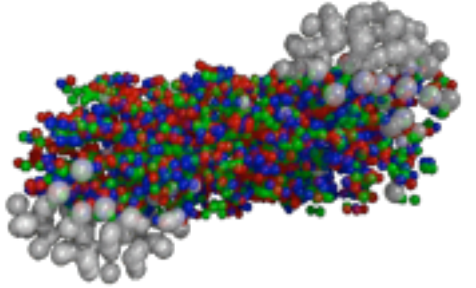
- **Local baryon density is the zeroth component of the baryon four-current** $j^\mu = (\rho_B, \vec{j})$ **when the baryon is at rest**

- **UrQMD calculates in the Computational Frame (CF), which is usually the CMS (due to symmetry)**

- $j^\mu_{CF} = (\rho_{B_{CF}}, \vec{j}_{CF})$ **can be calculated as a sum over Gaussians**

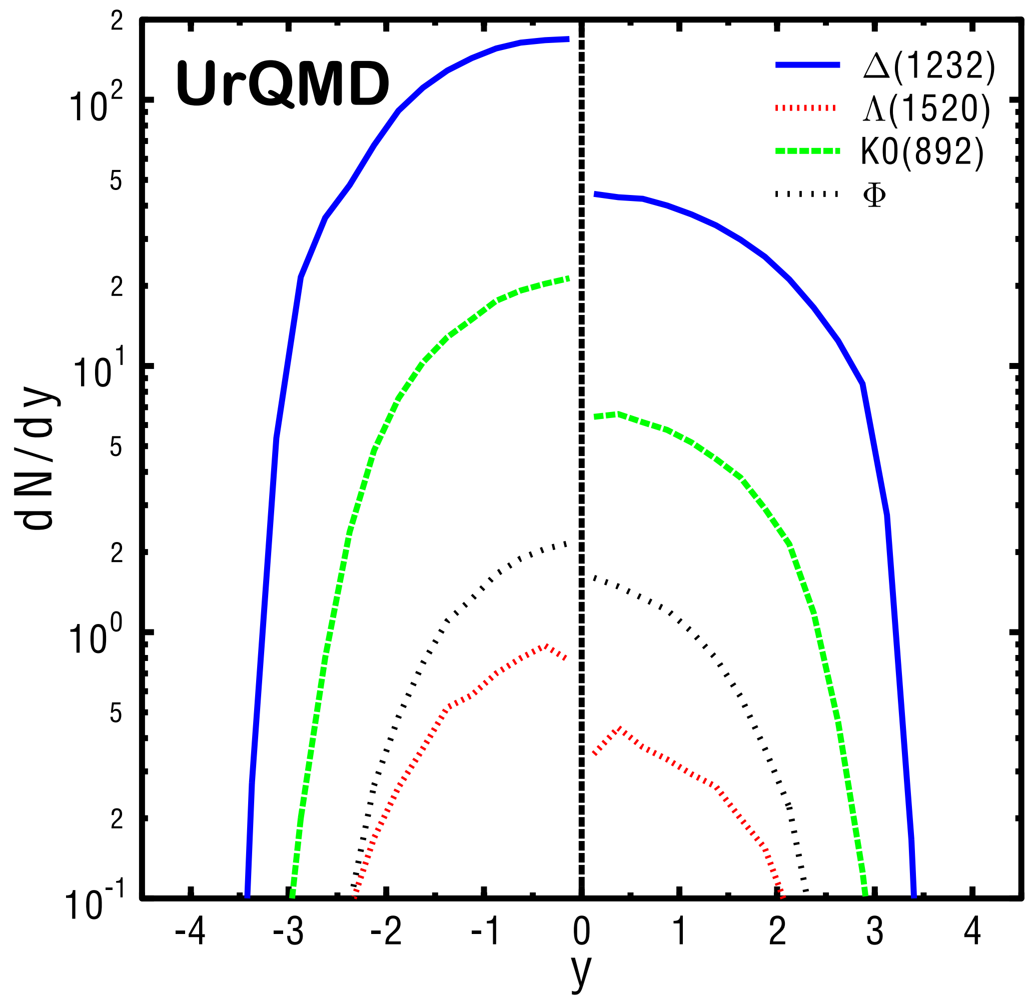
$$\rho_{CF}(\vec{r_i}) = \sum_{j=1}^{N} \left(\frac{1}{\sqrt{2\pi}\sigma}\right)^3 \gamma_z \, \mathrm{e}^{\left(-\frac{(x-x_0)^2+(y-y_0)^2+(z-z_0)^2\gamma_z^2}{2\sigma^2}\right)}$$

$$= \sum_{j=1}^{N} P_j$$

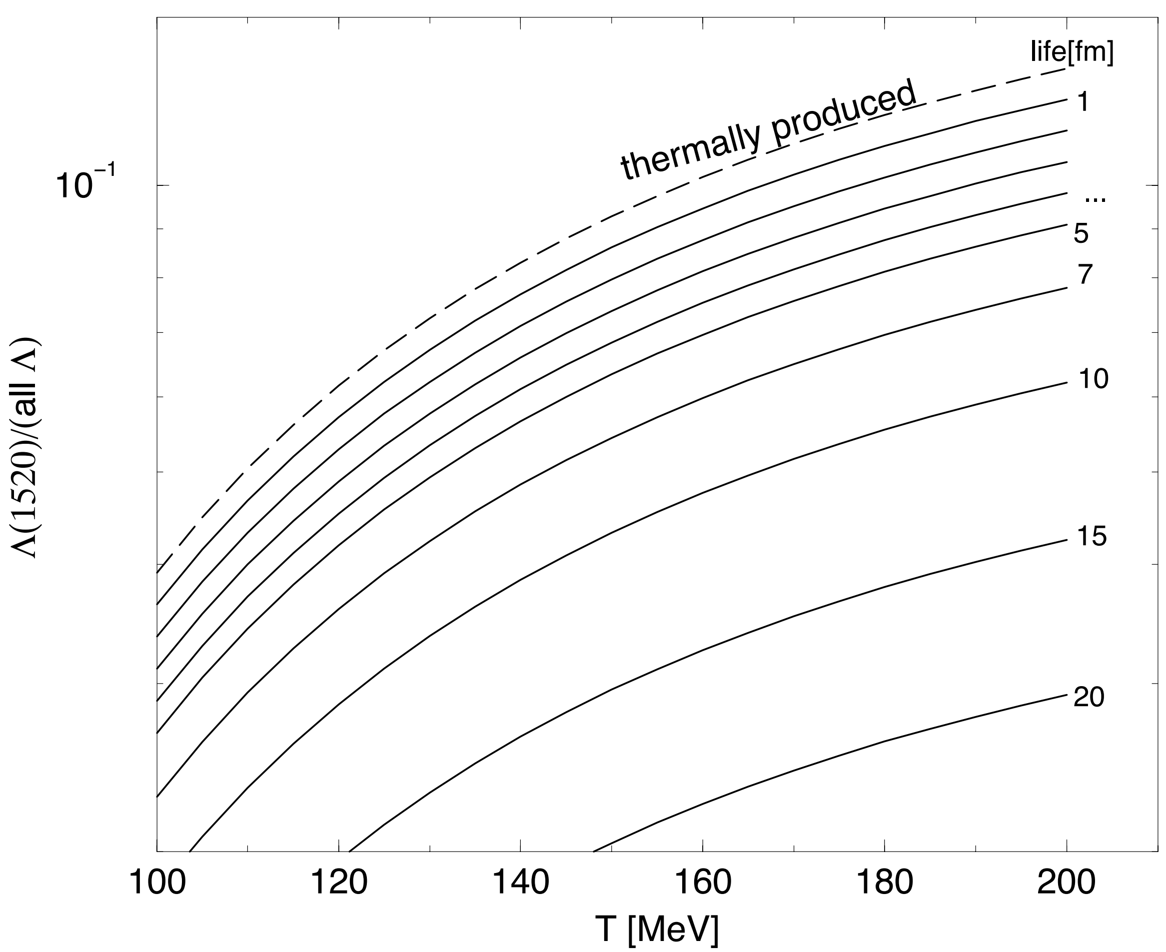


Rescattering

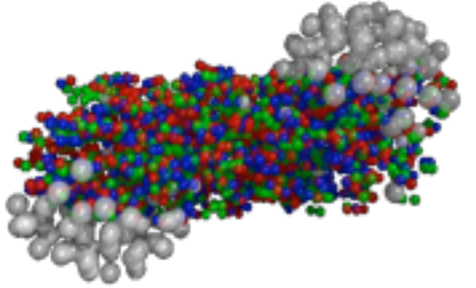
- well known effect, studied in
  - ➡ statistical hadronization models
  - ➡ transport models
  - ➡ hydrodynamical models



Bleicher, Aichelin, Phys.Lett.B530:81-87

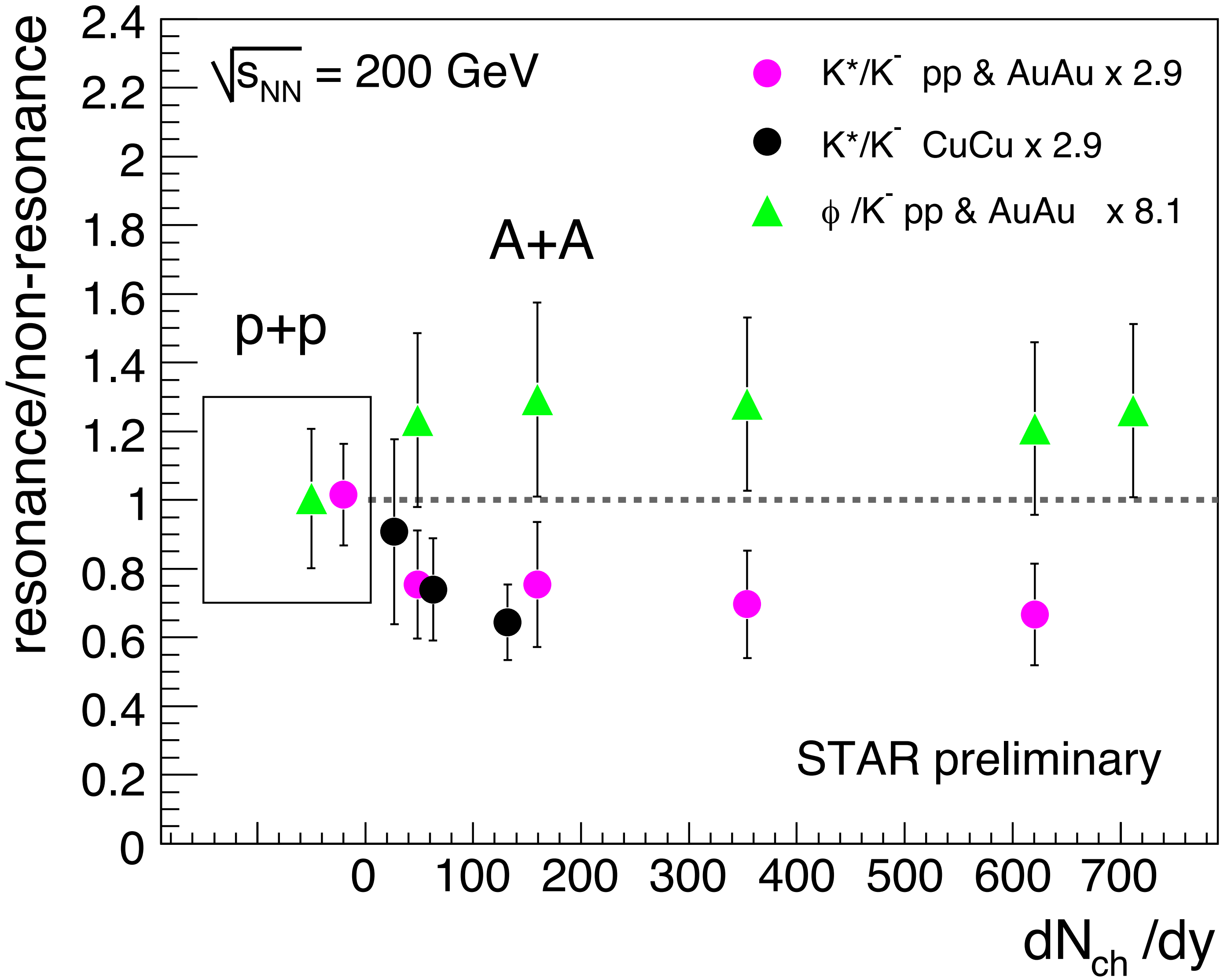


Torrieri, Rafelski, Phys.Lett.B509:239-245

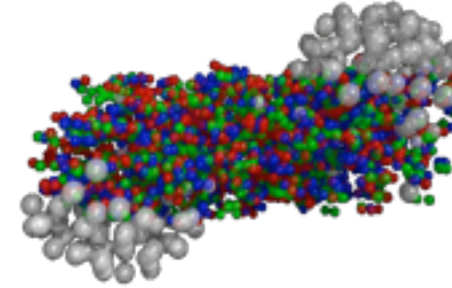


Rescattering

- well known effect, studied in
  ➡ experiment

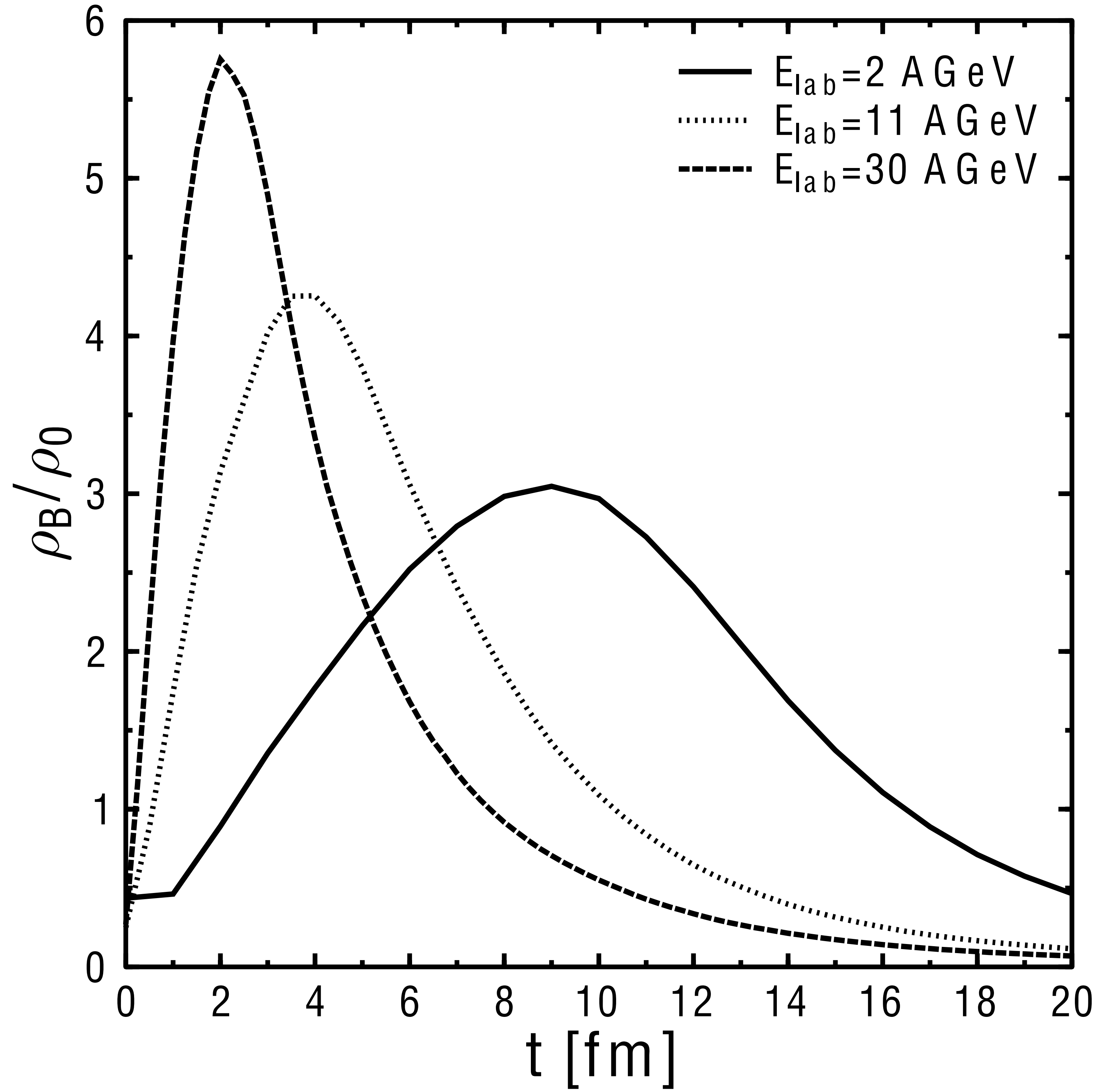


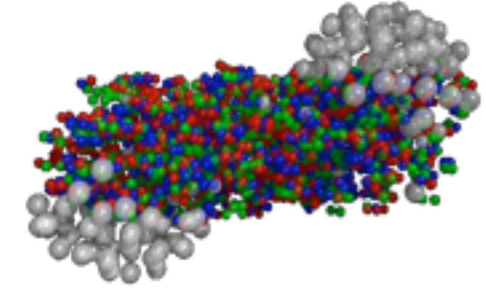
Markert et al. [STAR], J.Phys.G35:044029,2008



Time evolution of ρ_B

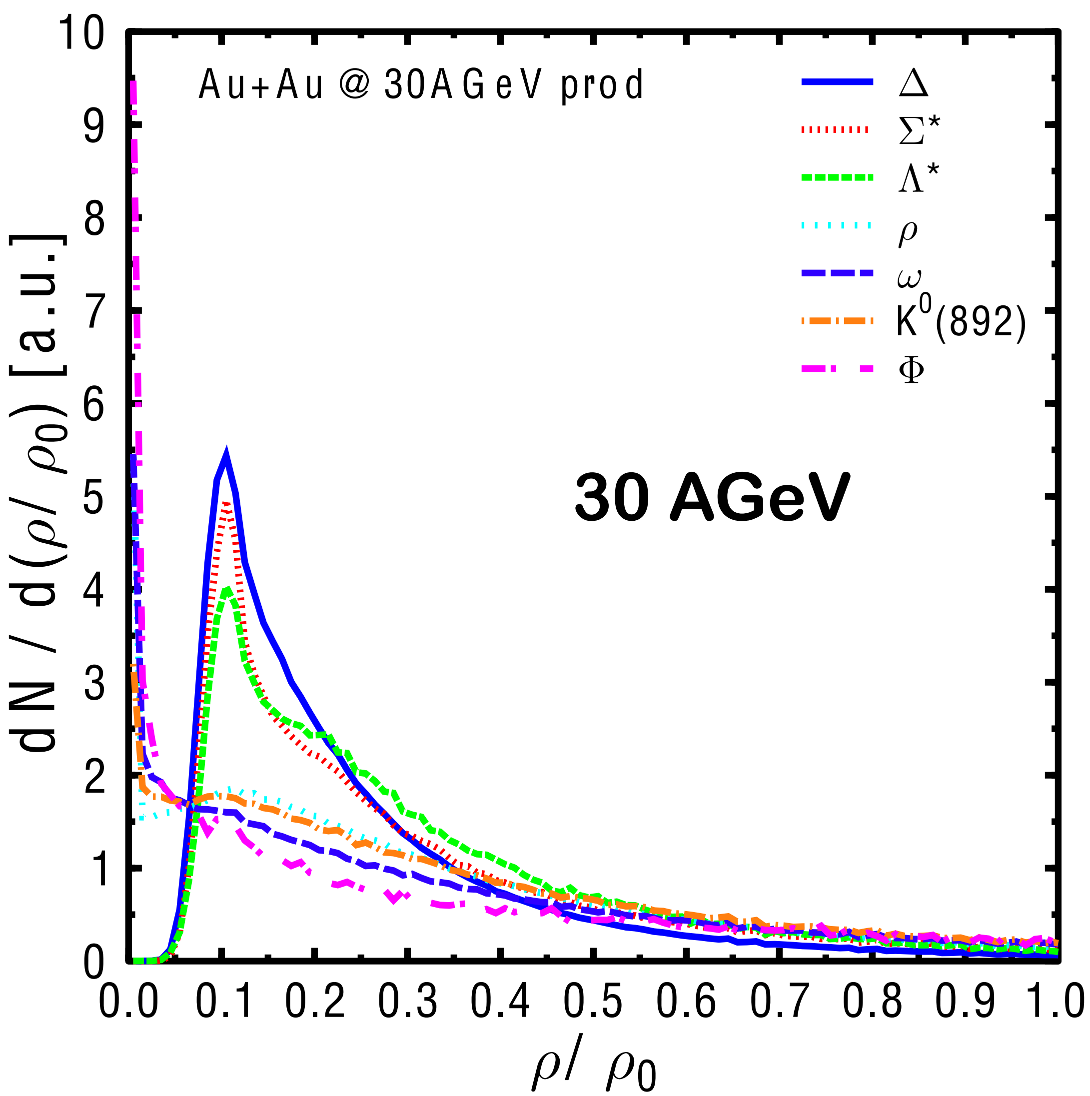
- **Central Pb+Pb (Au+Au) collisions**
- **Averaged over all hadron positions**

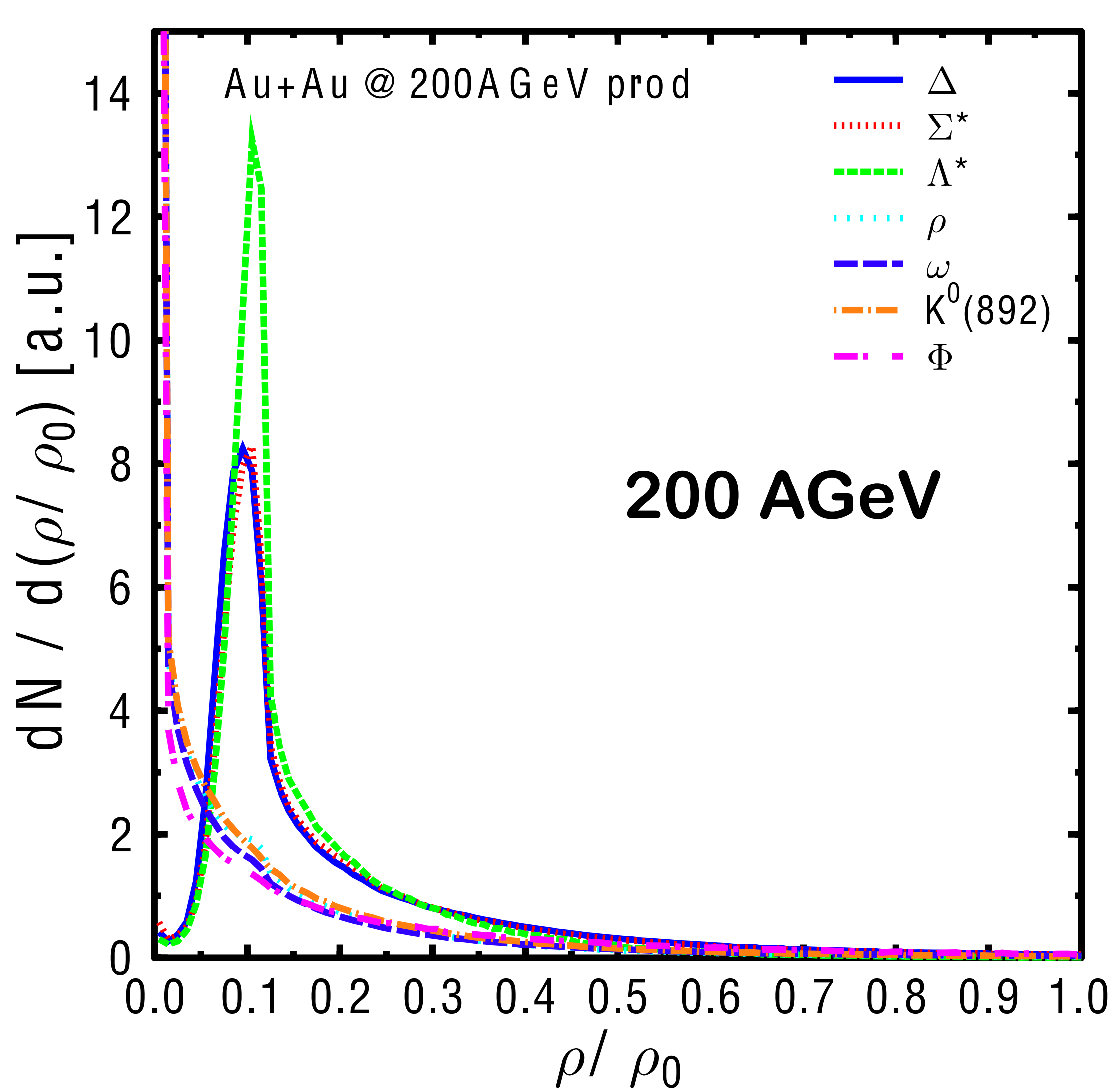


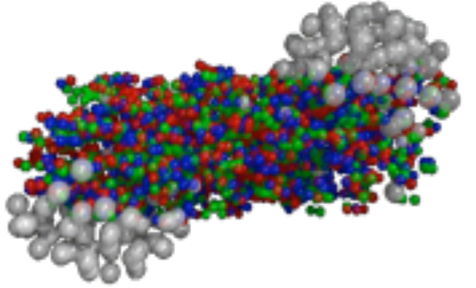


Reach in density

- **Normalized density spectrum**
- **Most resonances originate from very low density**



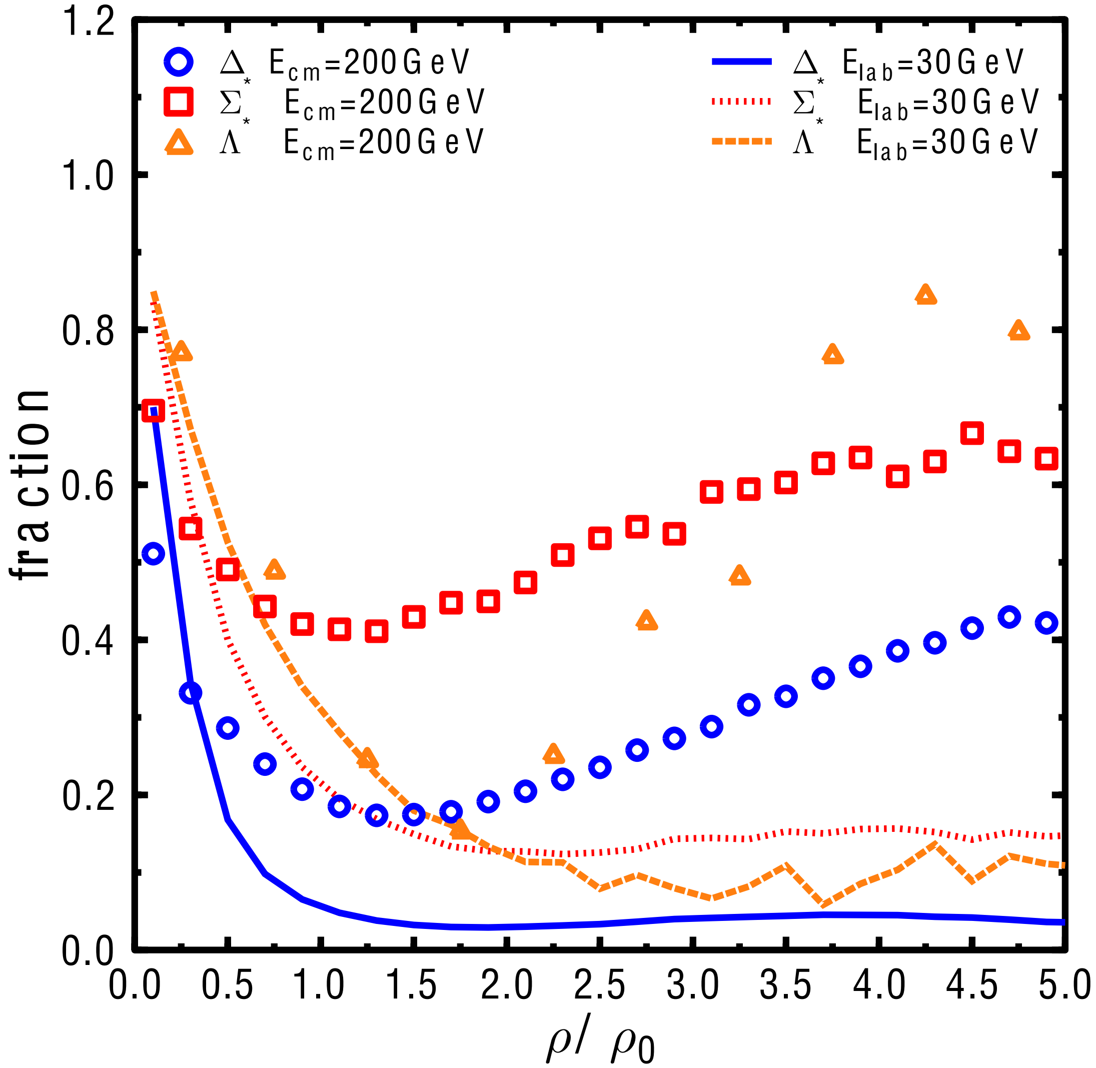




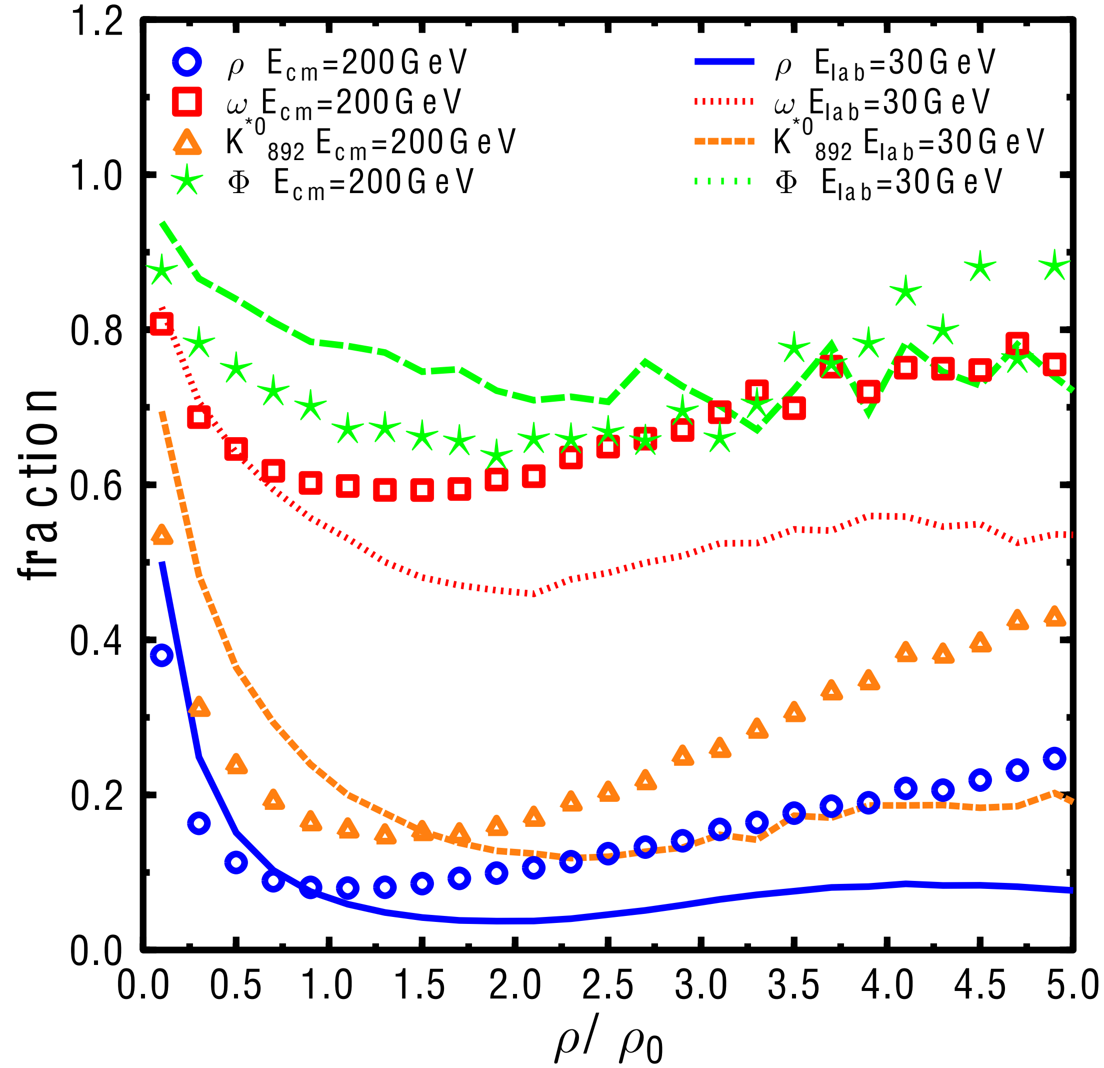
Reconstruction probability

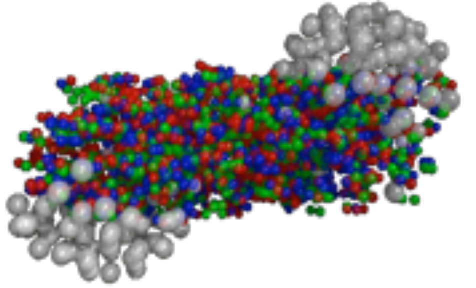
- **Probability to reconstruct resonances from a certain density**

Baryons



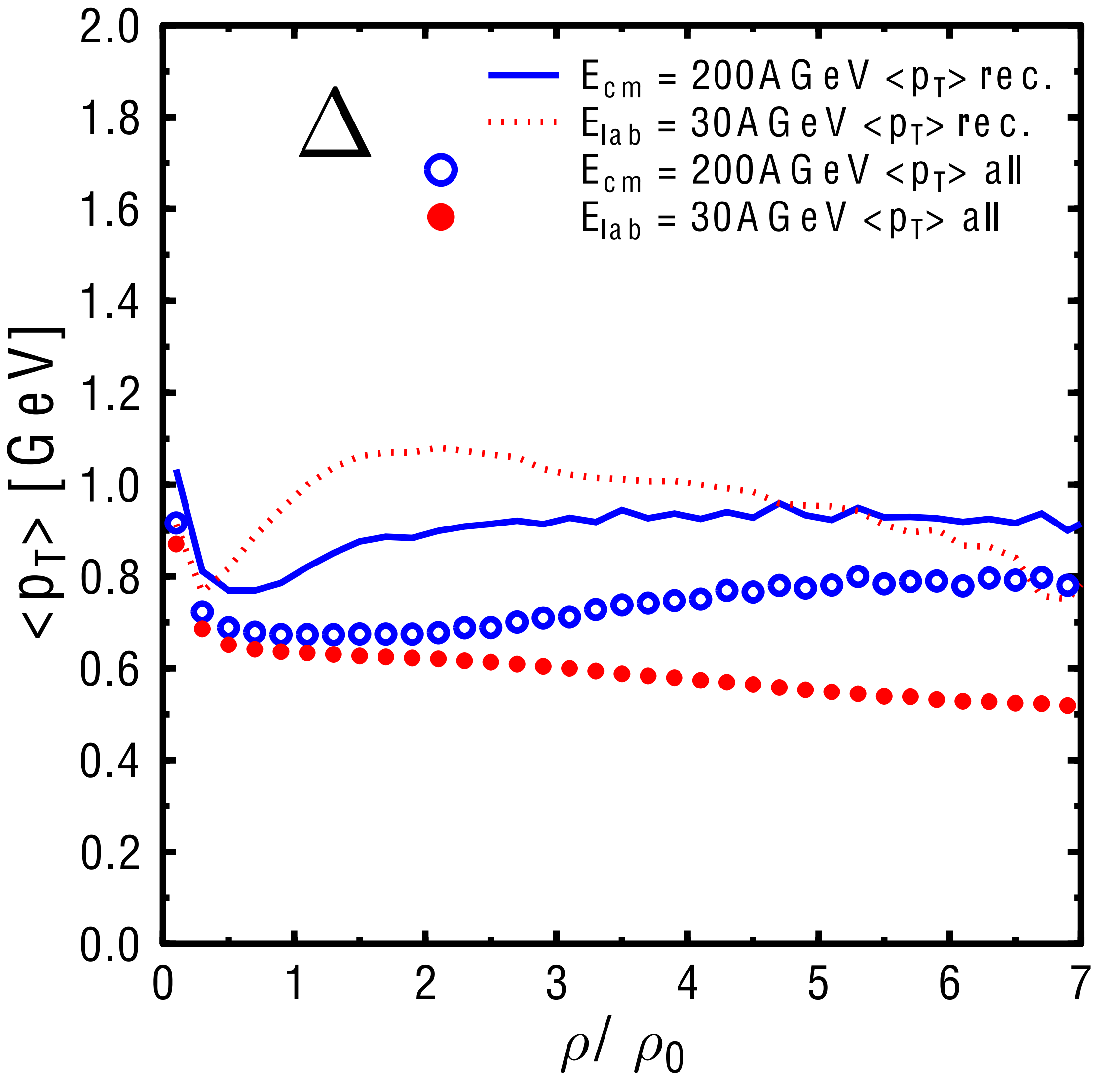
Mesons

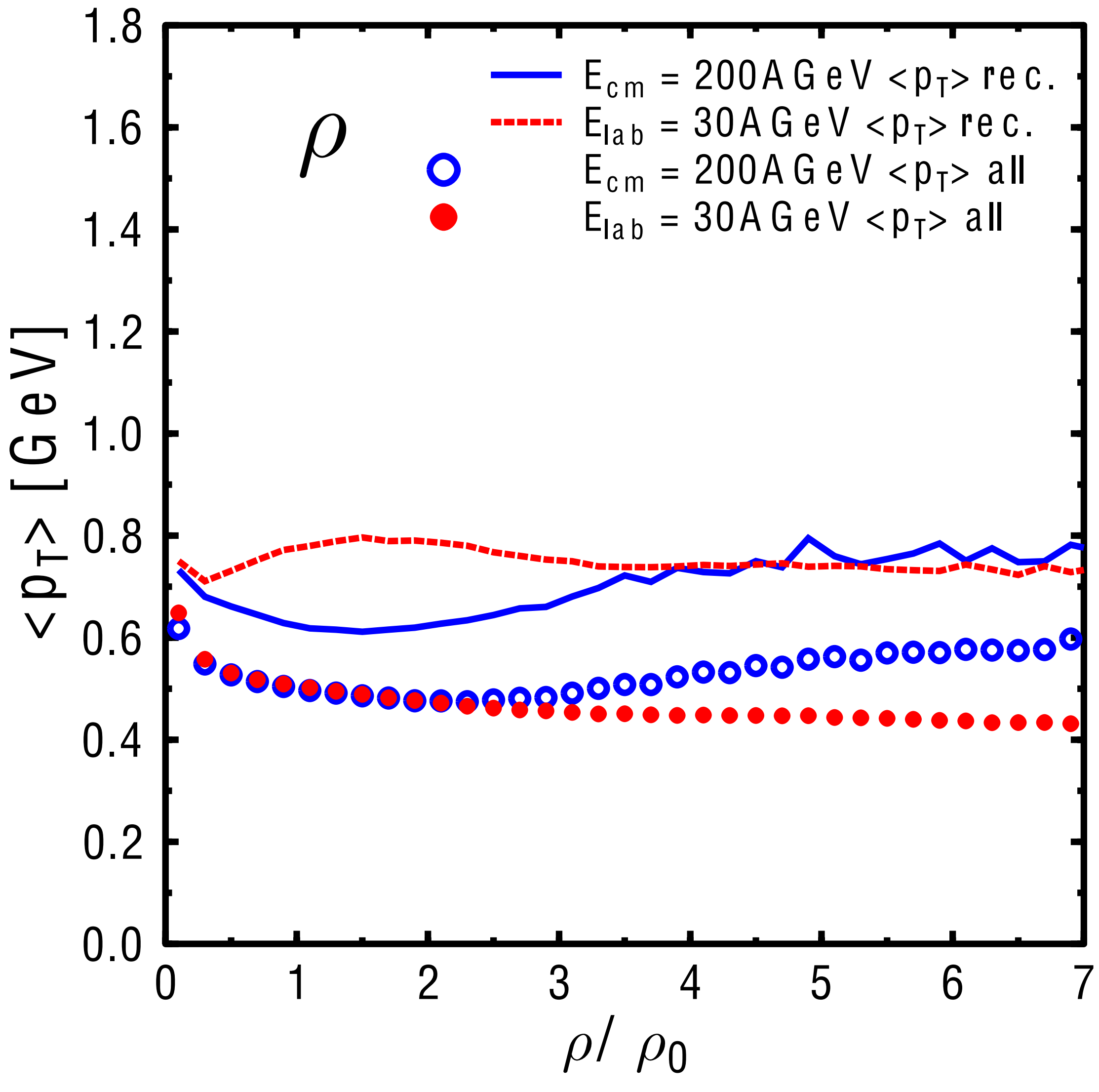


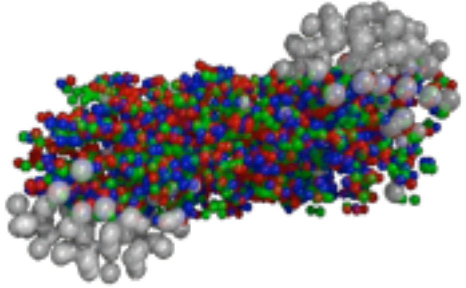


p_T dependence

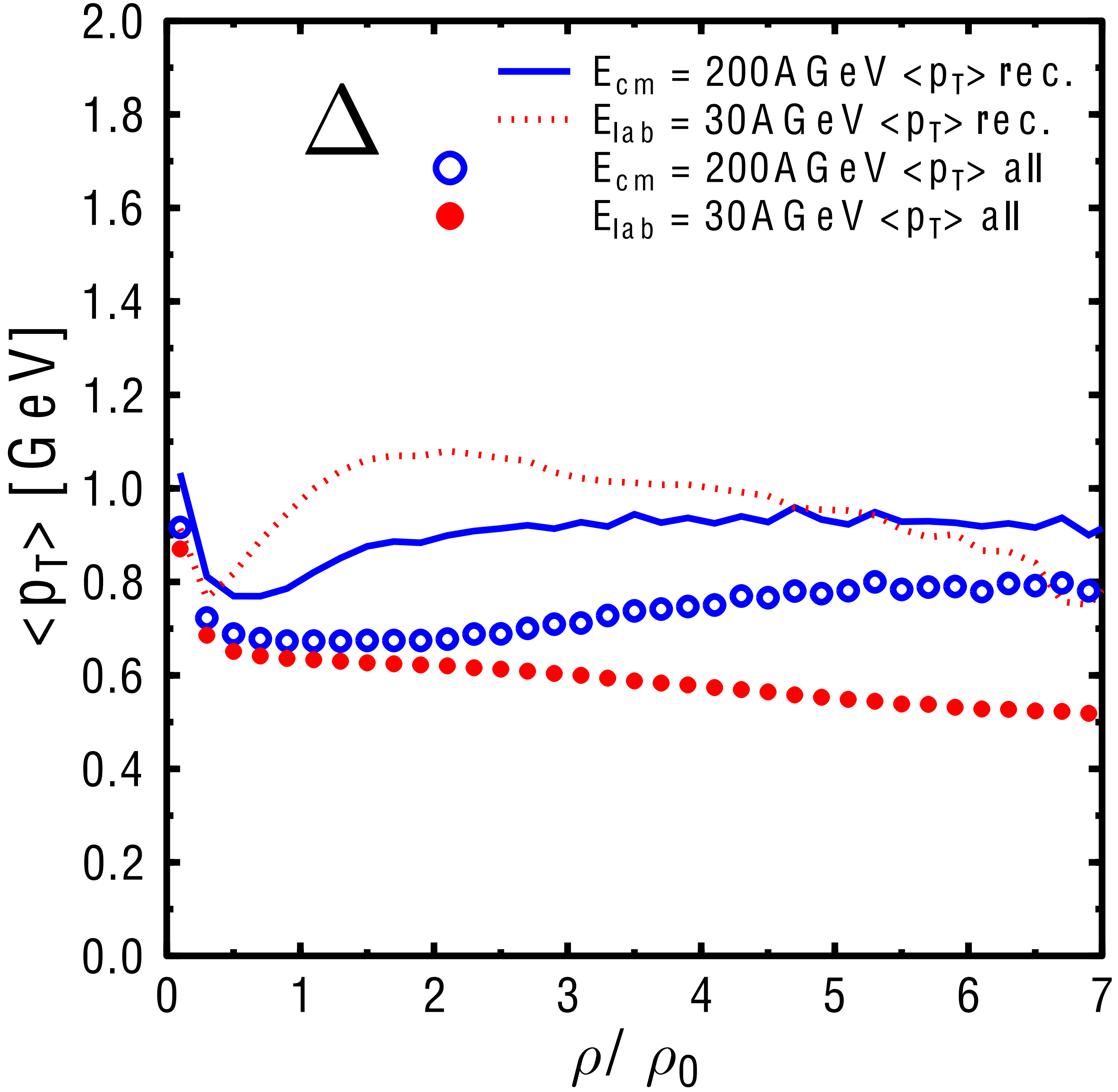
- **average transverse momentum depends on density**
- **reconstructable resonances have higher p_T**

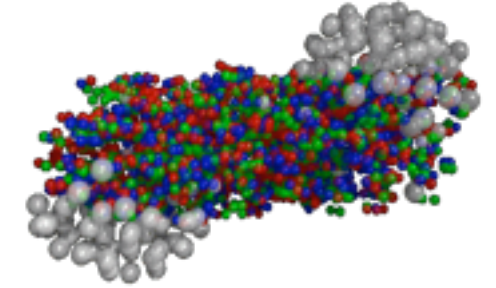






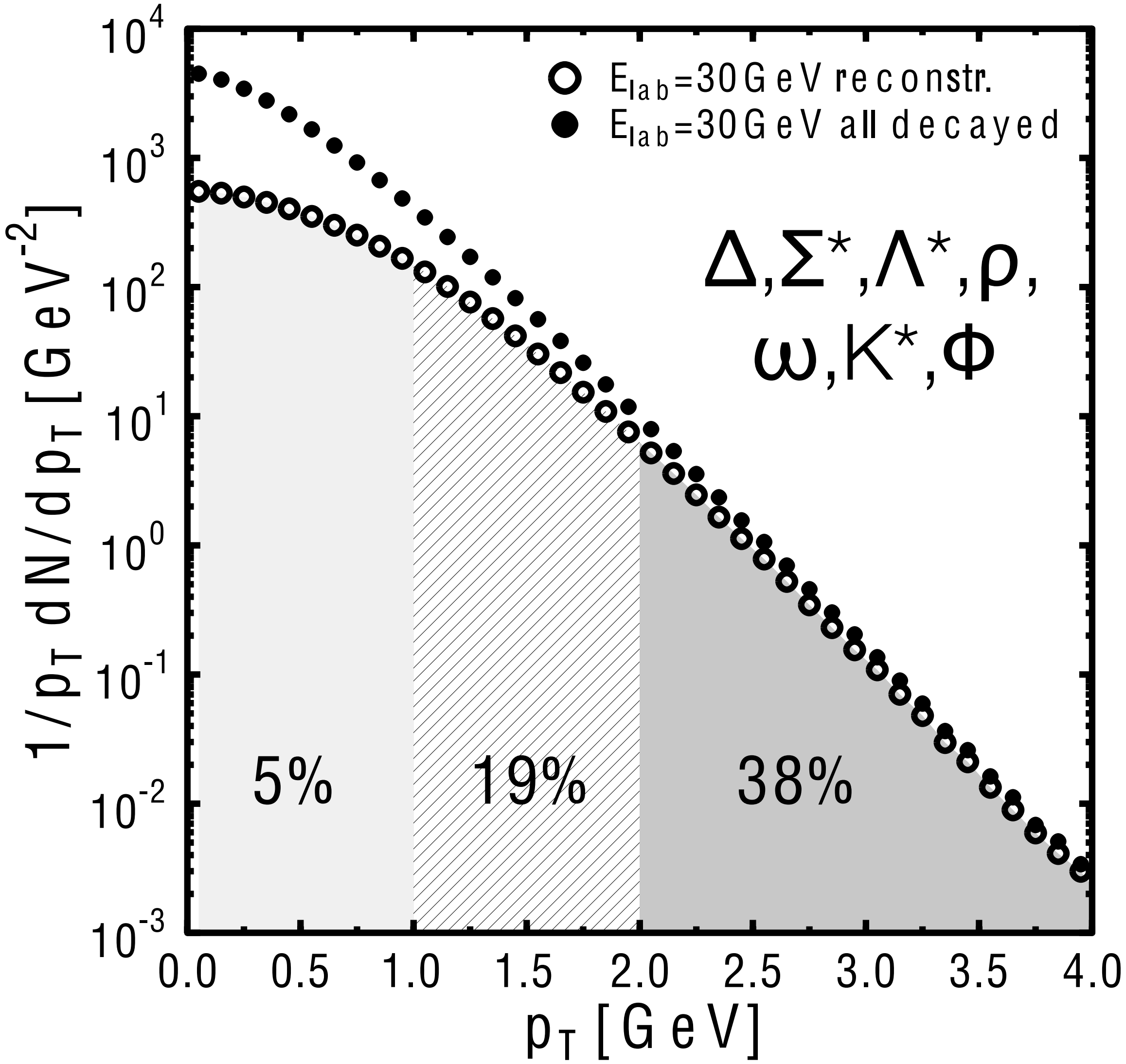
p_T dependence

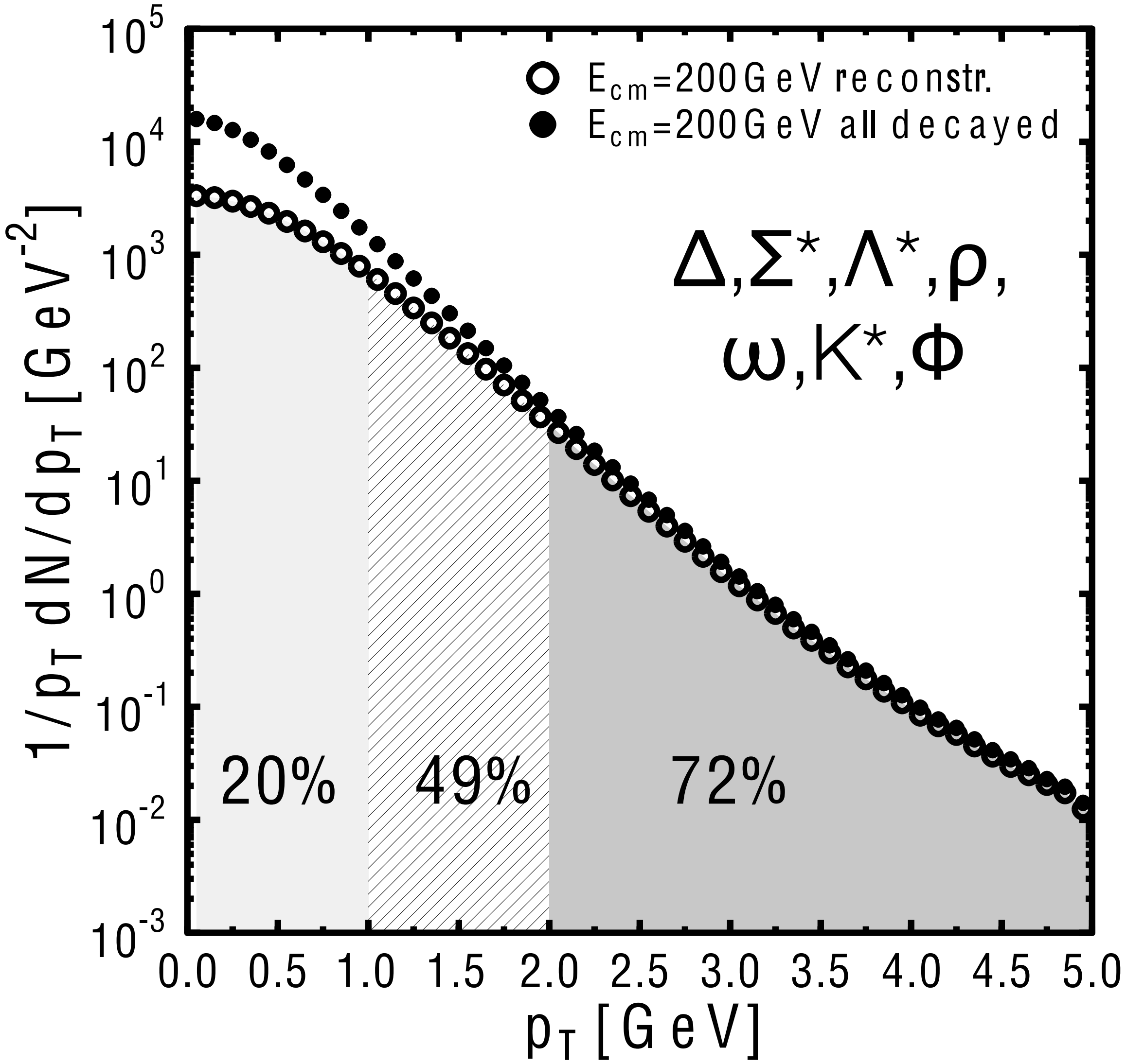


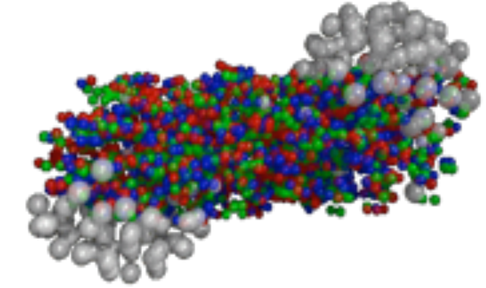


p_T dependence

- **difference in p_T spectrum between observable and all decayed**
- **percentage of reconstructable resonances produced at $\rho > 2\rho_0$ increases with p_T**

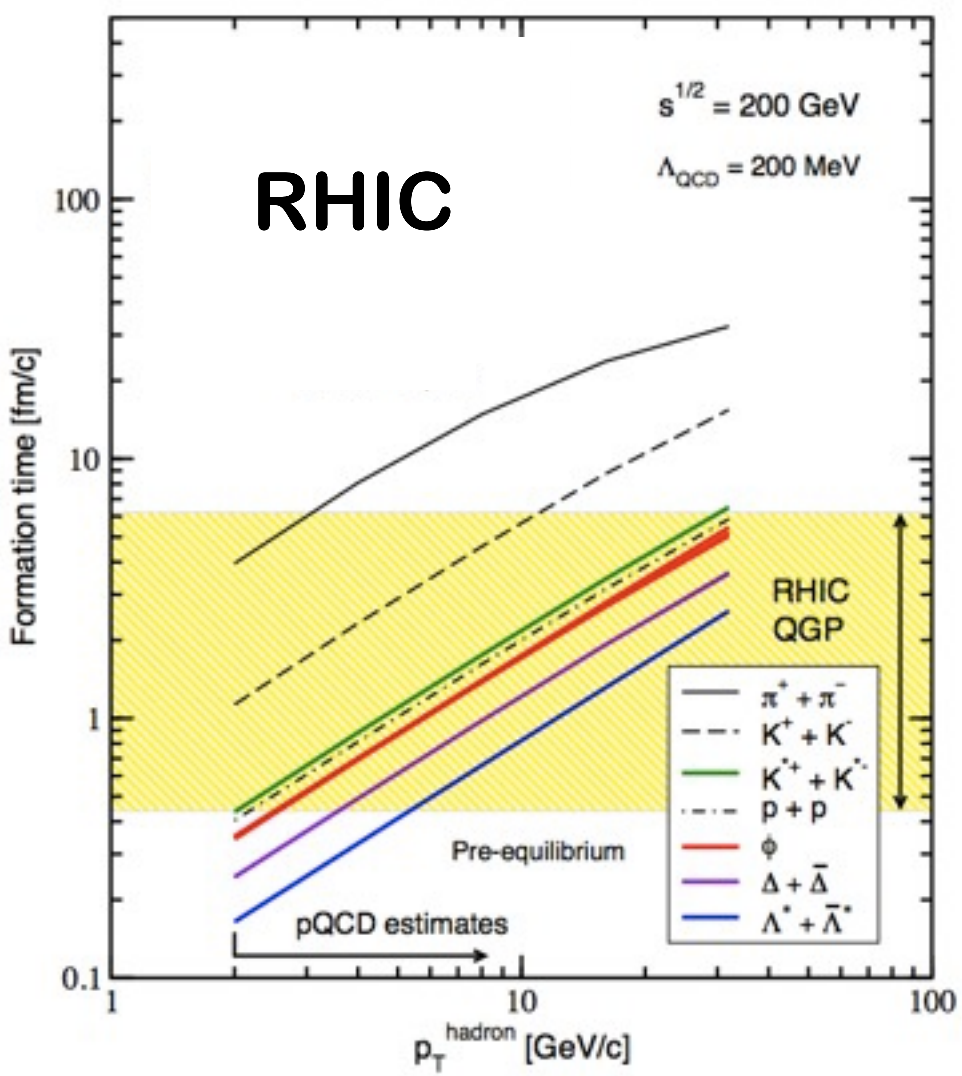


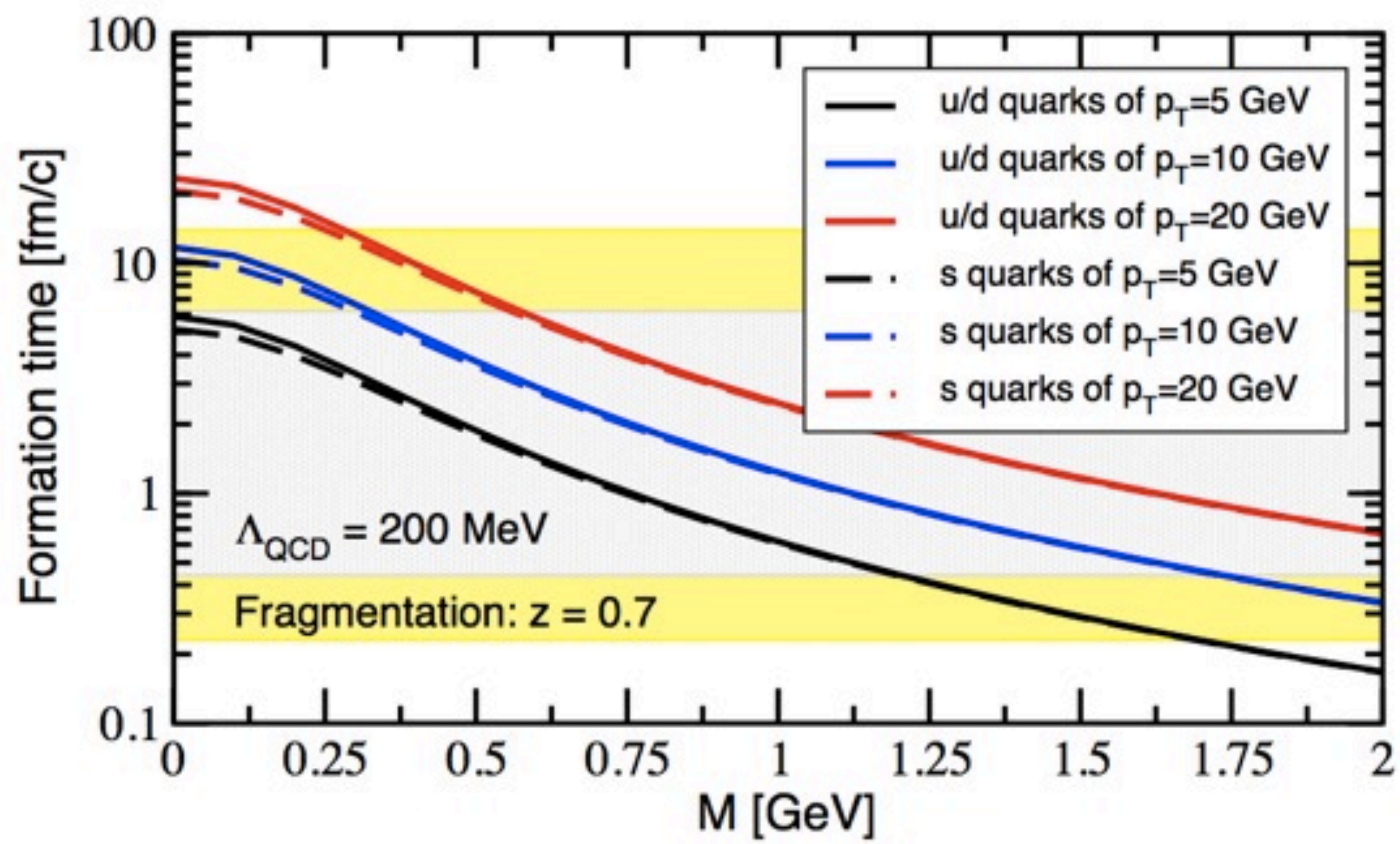




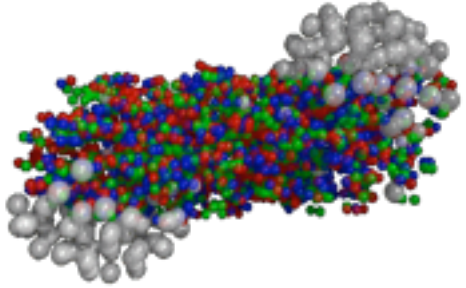
Formation time

- formation time is mass and p_T dependent
- shaded areas indicate the estimated lifetime of the partonic phase





Markert, Bellwied, Vitev,
Phys.Lett.B669:92-97,2008



First conclusion

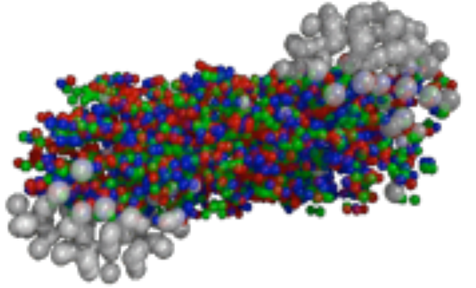
High p_T resonances might shed some light on the dense phase of heavy ion collisions!

(but are they really what we want to measure?)

Dileptons

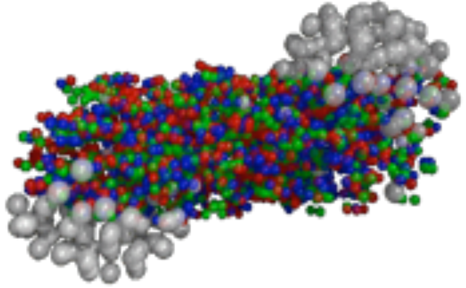
Using dileptons… how far can we look into the dense phase?

(can we at all?)

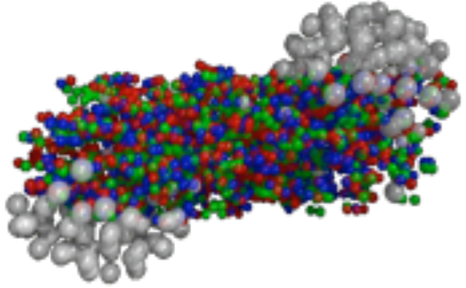


Gain/Loss terms

- Resonances can stem from two processes
  - Collisions (e.g. $\pi\pi \rightarrow \rho$)
  - Decays of heavier resonances (e.g. $N^*_{1520} \rightarrow N + \rho$)
- Resonances can be destroyed by two processes
  - Decays (e.g. $\rho \rightarrow e^+e^-$)
  - Absorption (e.g. $N + \rho \rightarrow N^*_{1520}$)



Density distribution



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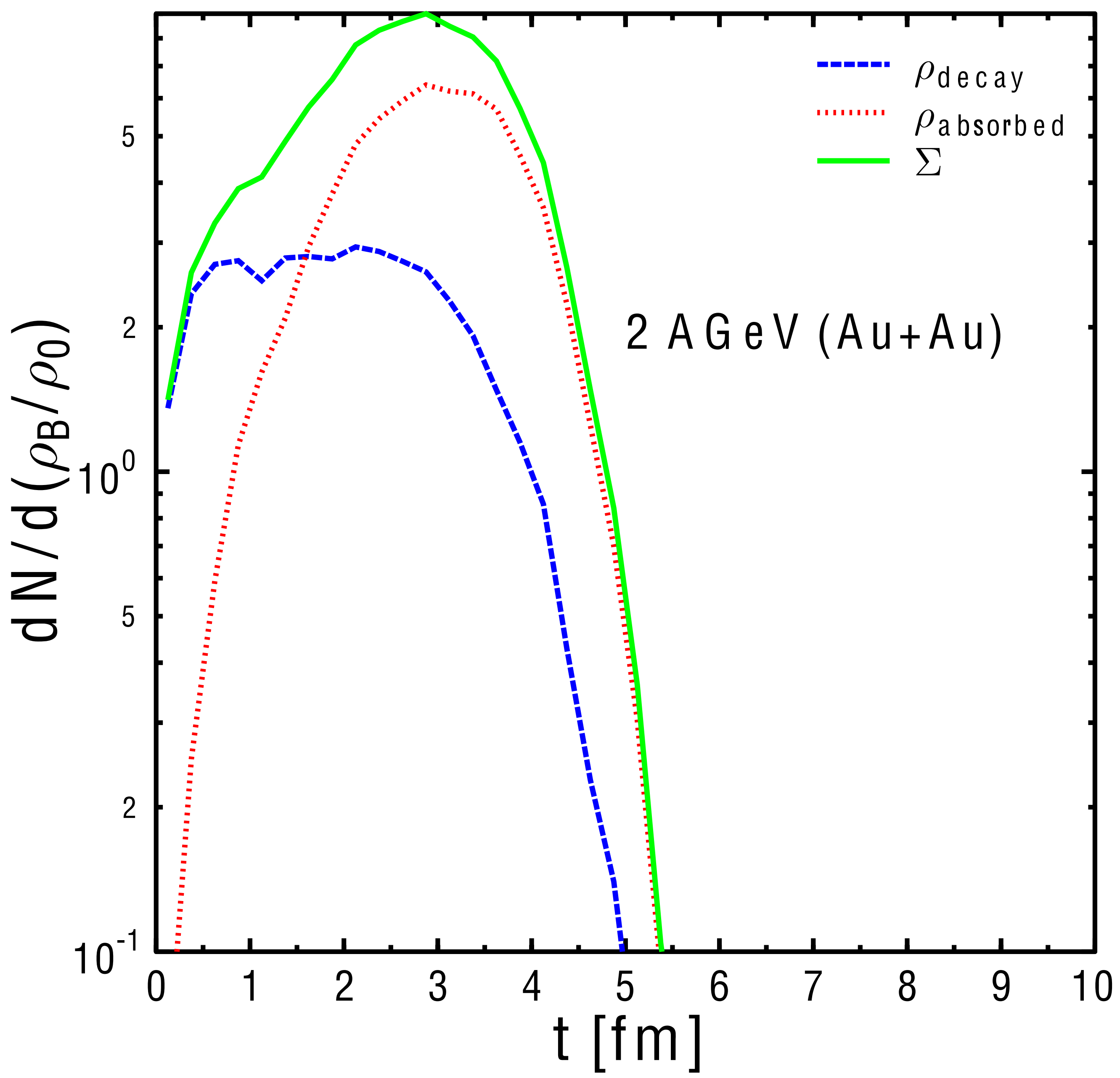

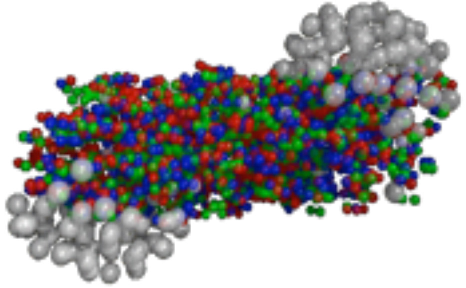

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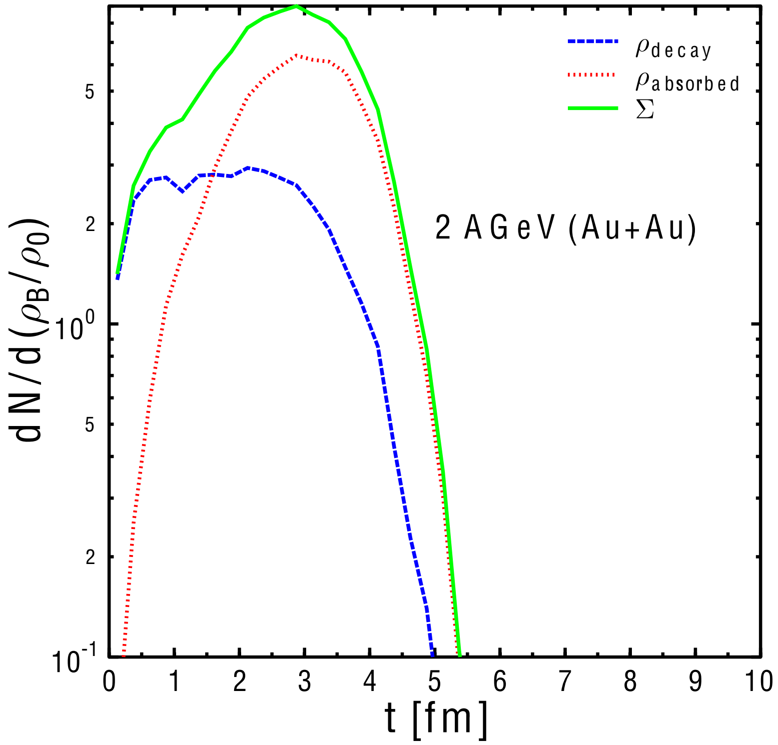

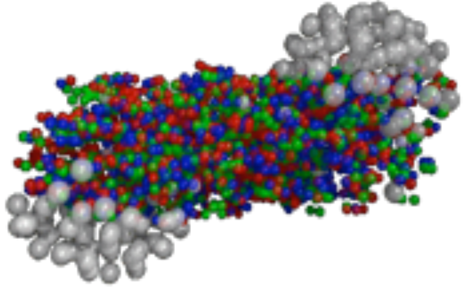

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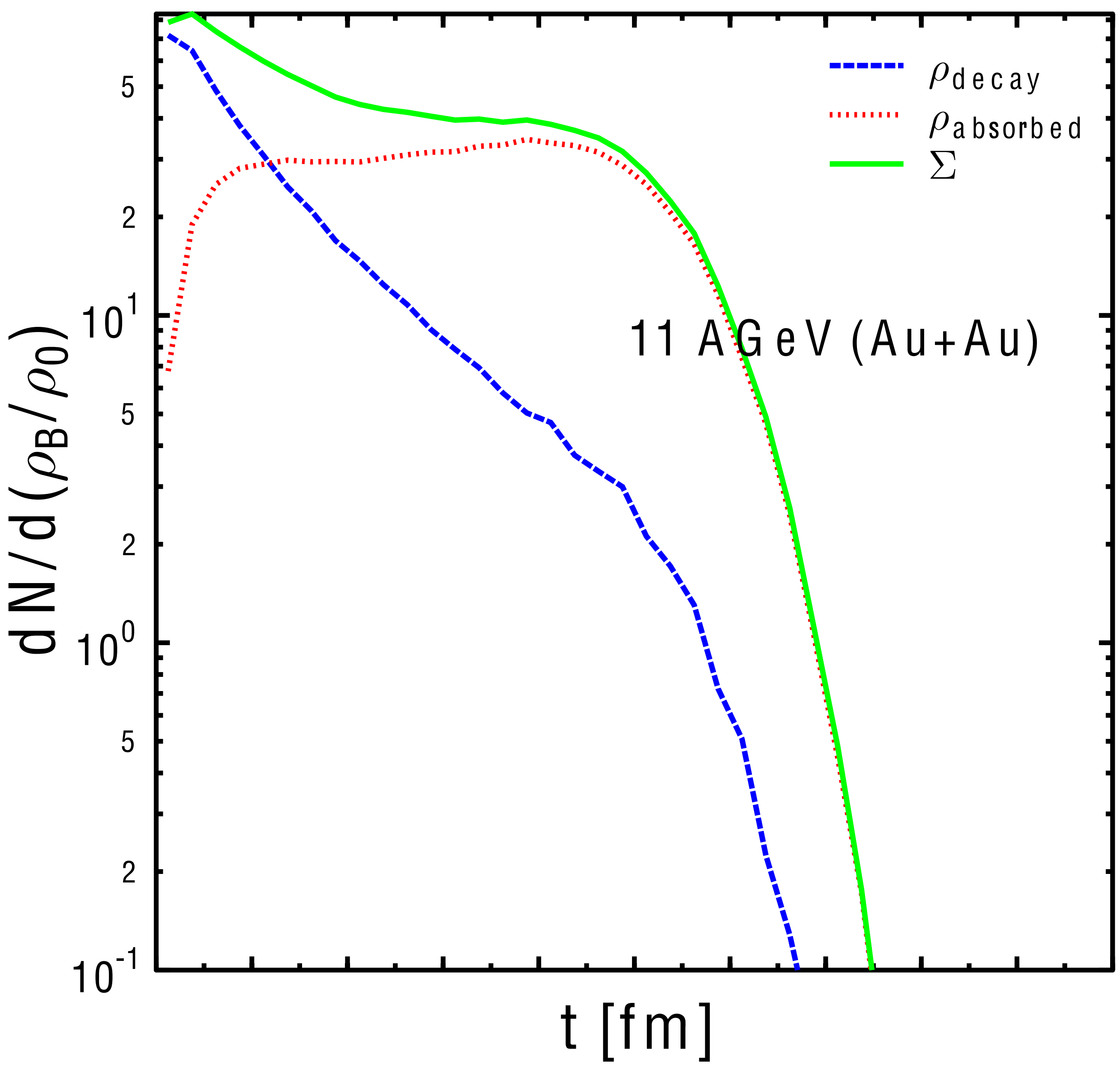
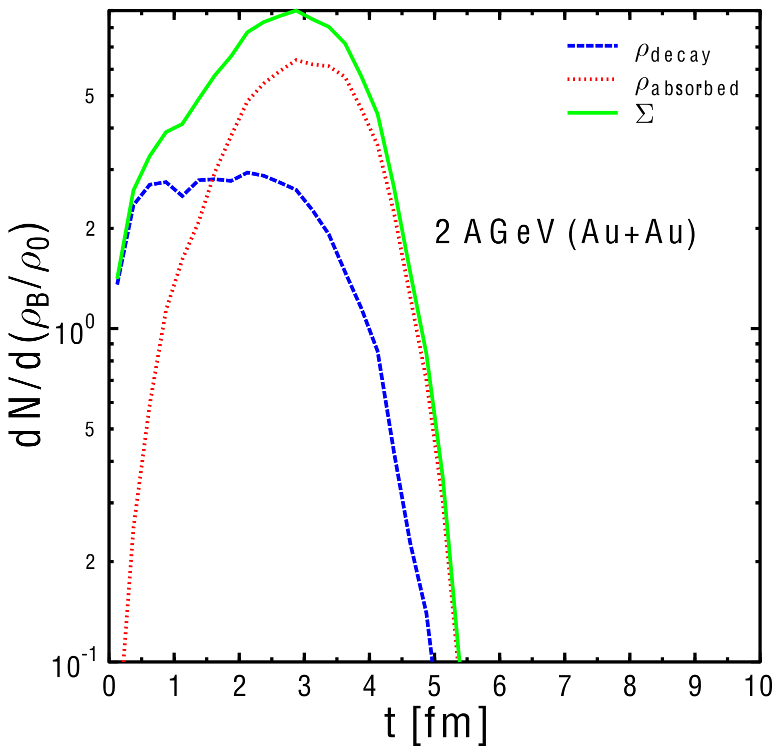
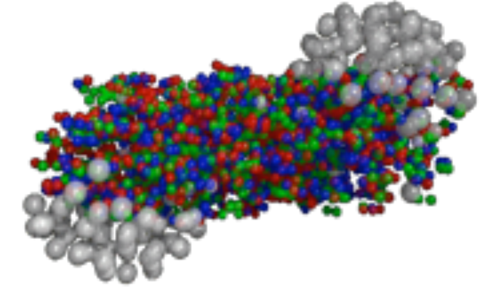
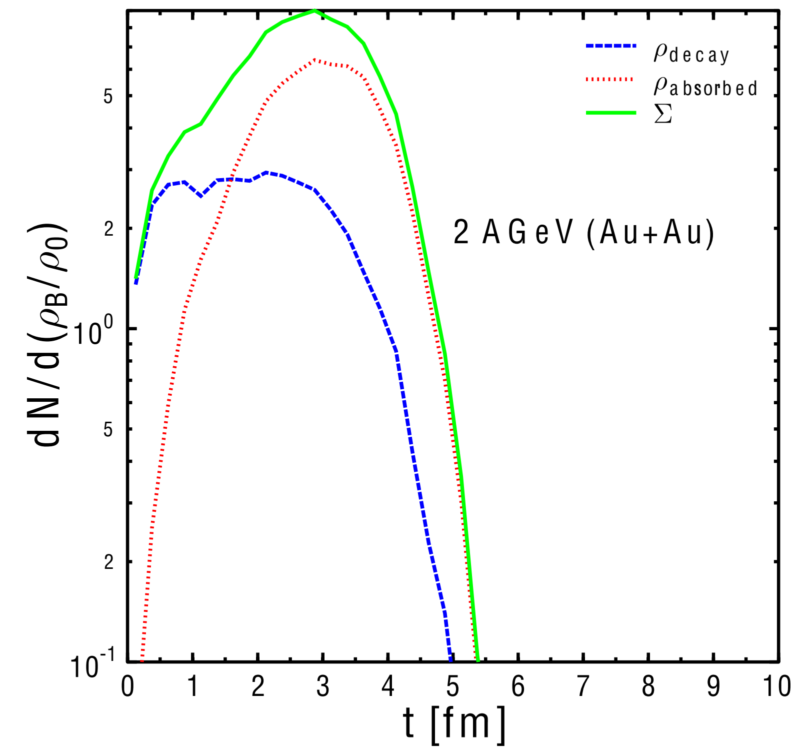
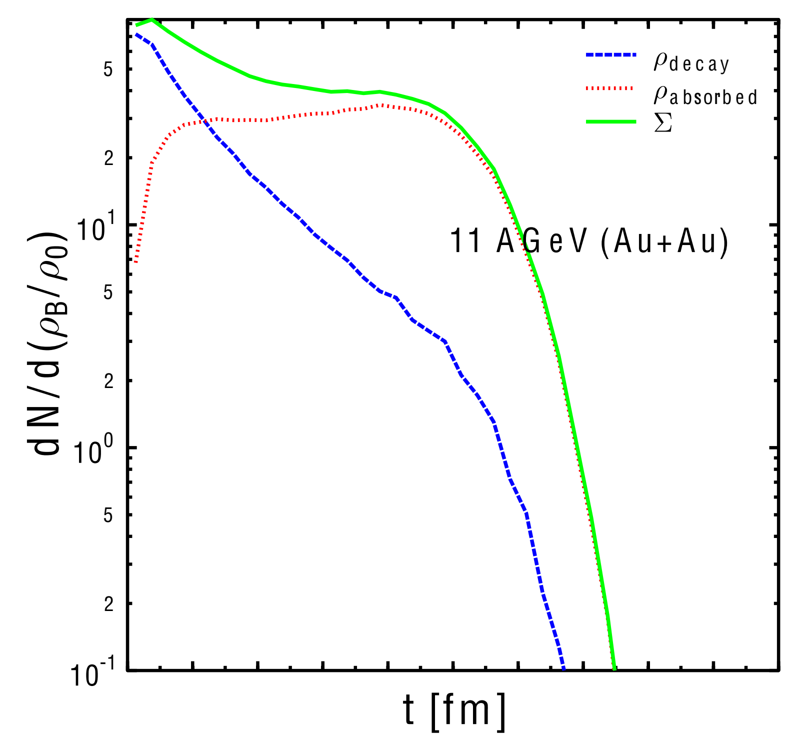


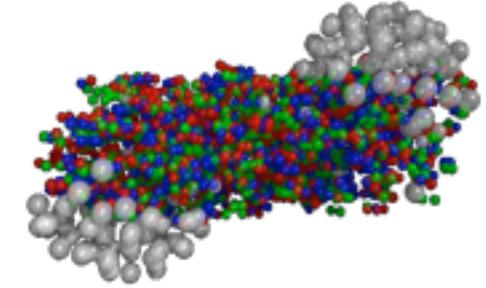




Density distribution







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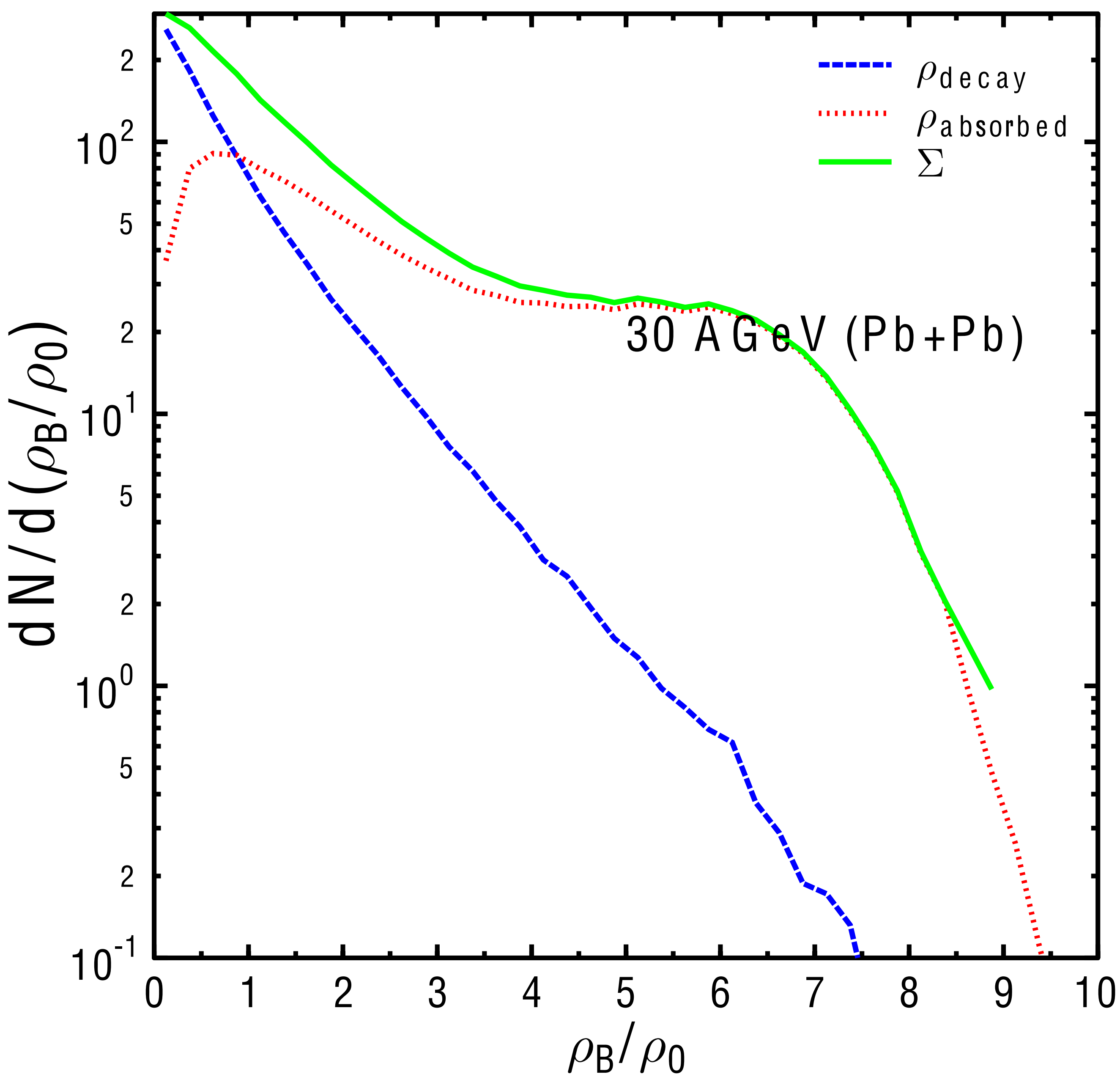

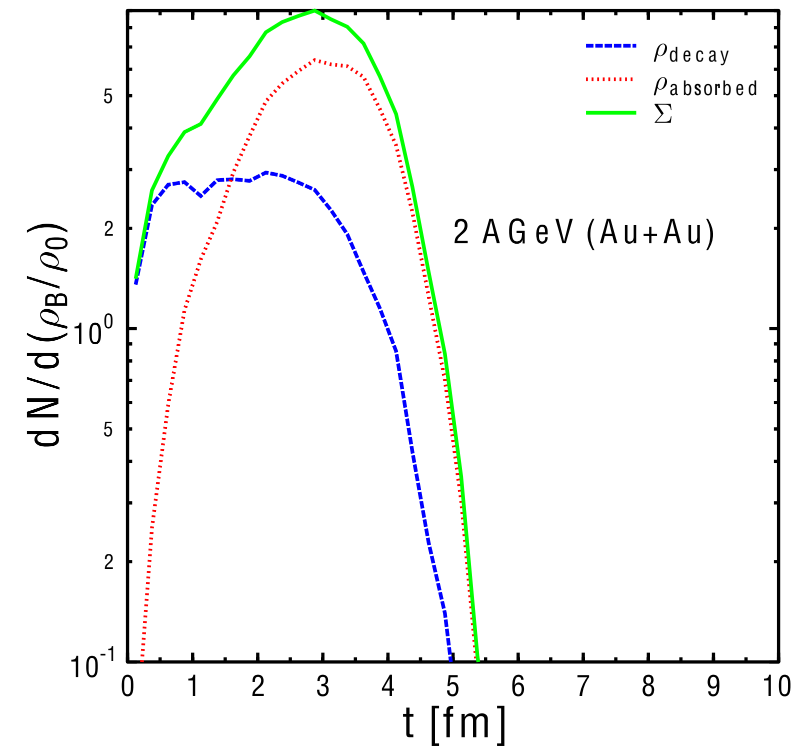

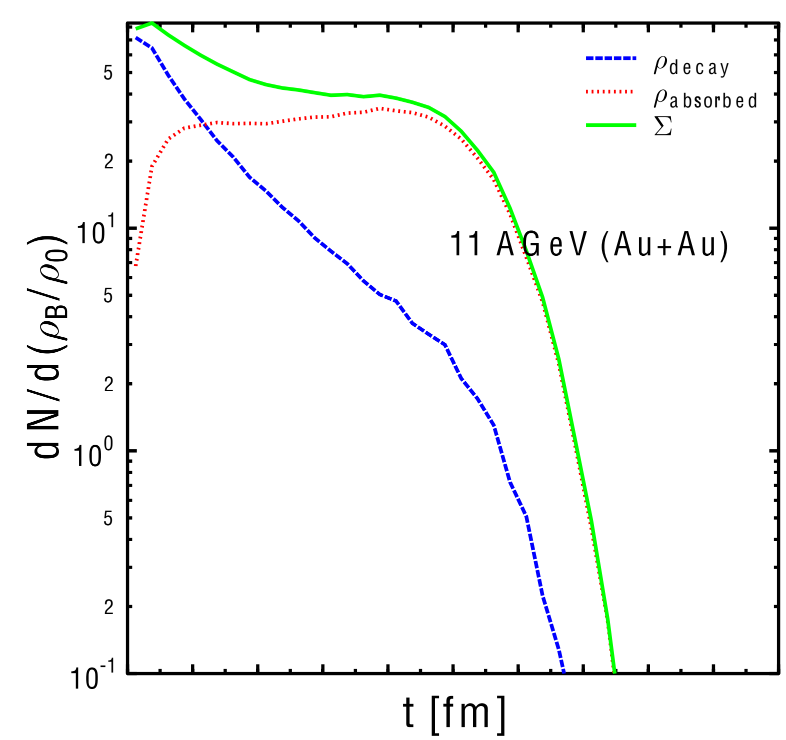

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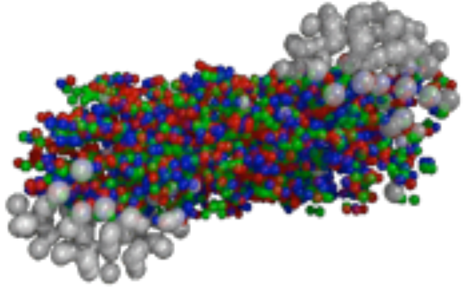
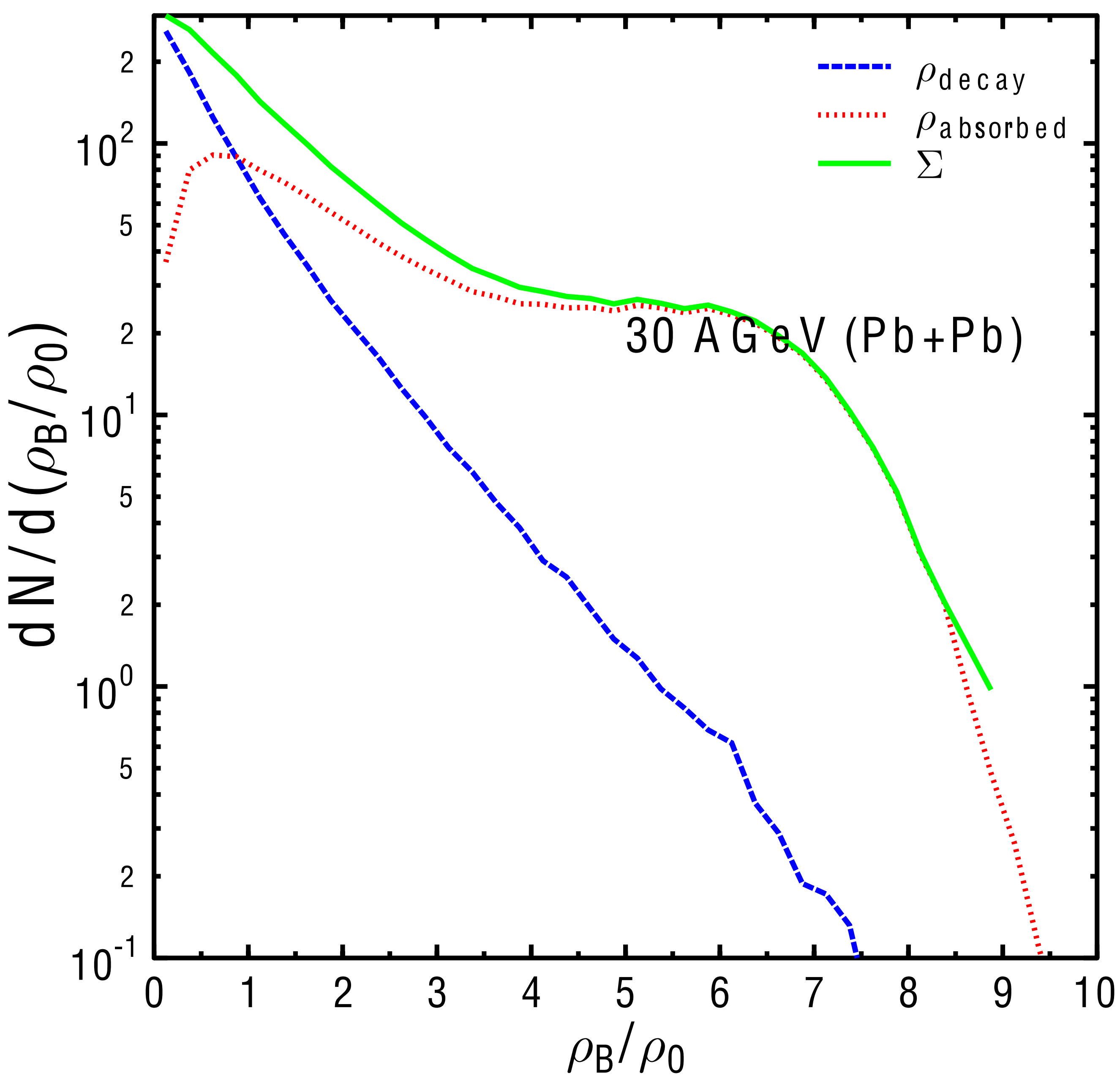
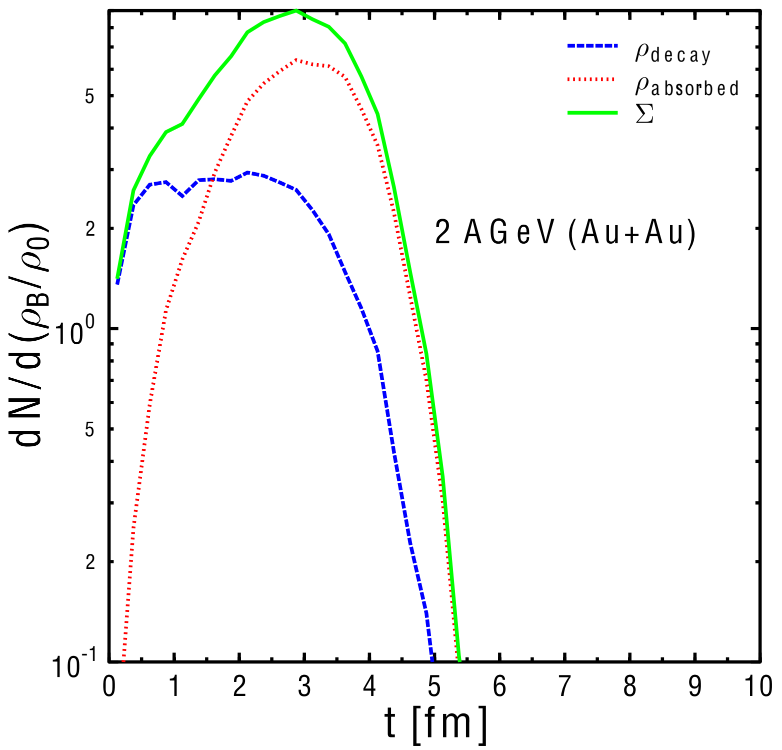
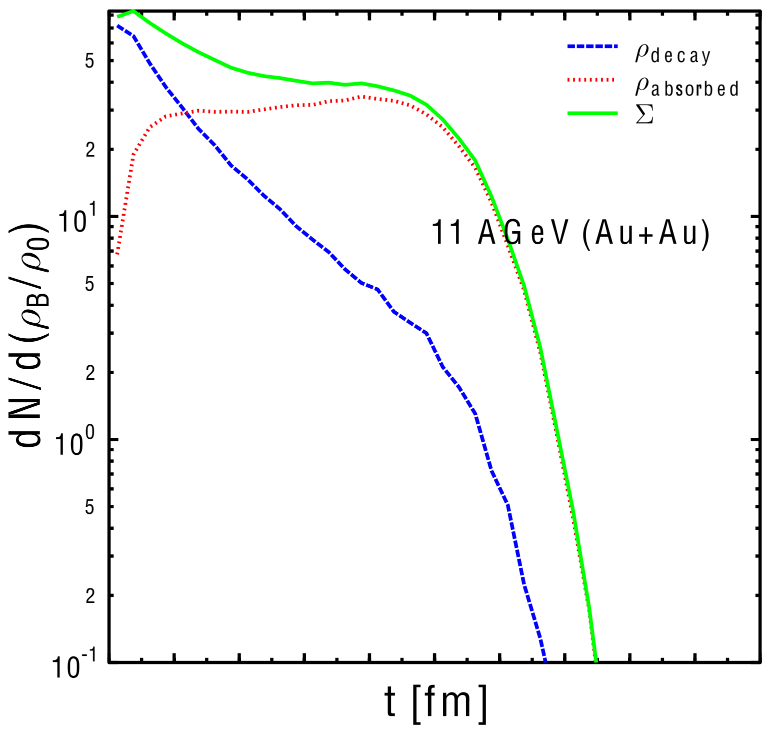


- ρ decays do not reach out to high density
- most resonances at such densities are re-absorbed

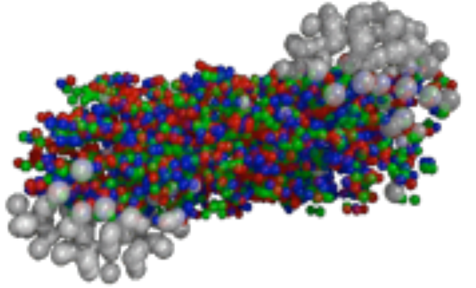






Gain/Loss rates of ρ mesons

SiS energies: Most gain from decay
AGS and FAIR energies: More gain from collisions
In the early stage - loss by absorption dominant
Decays set in in the late stage



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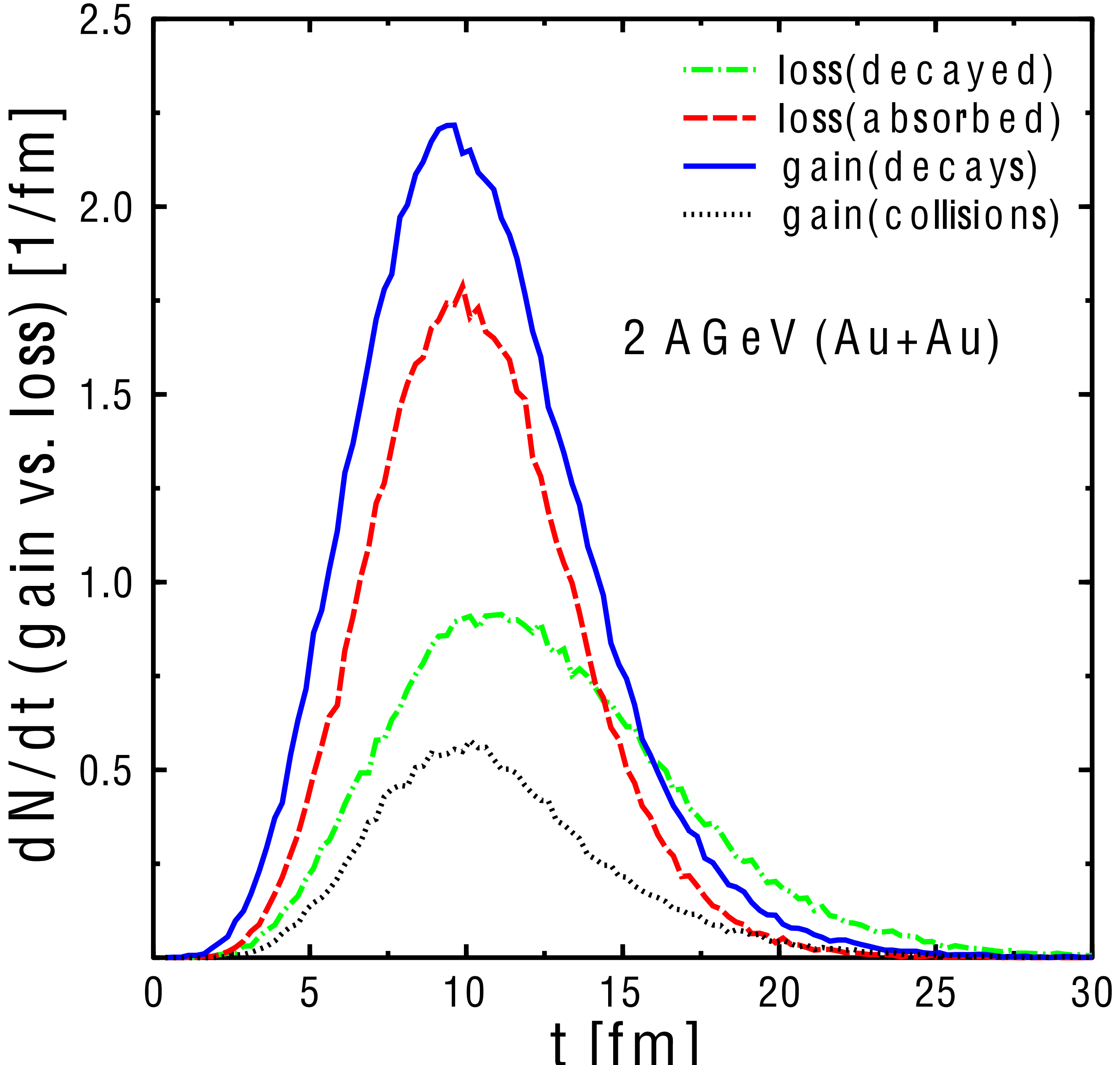

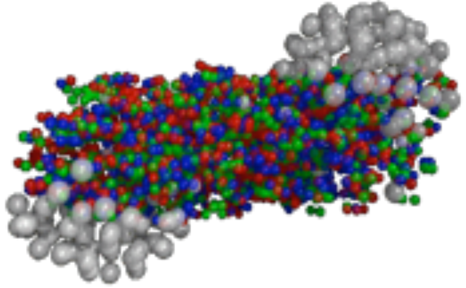

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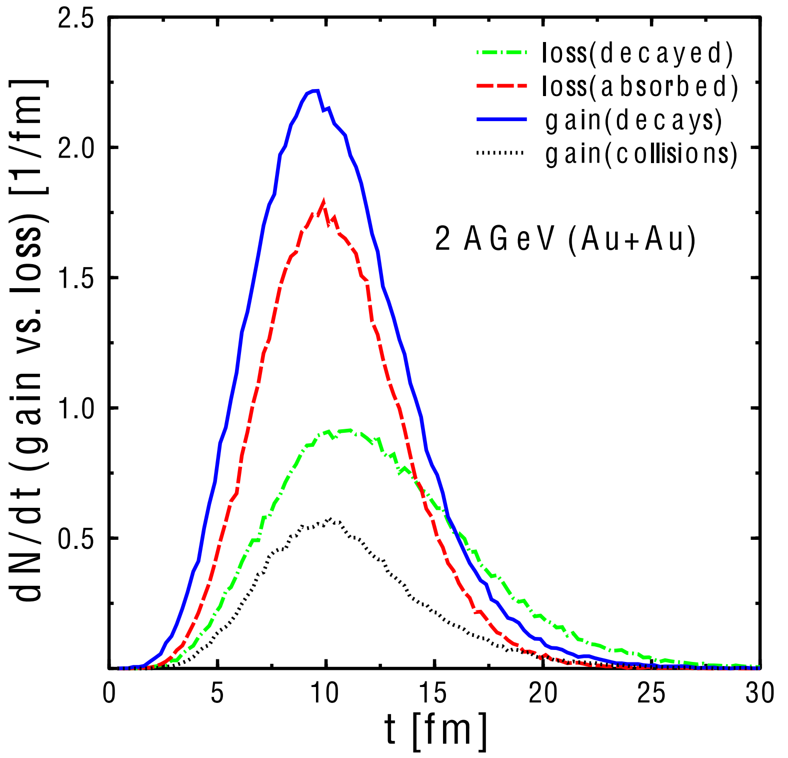

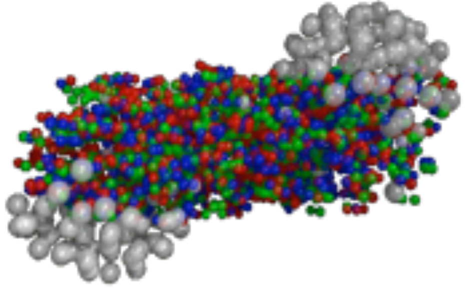

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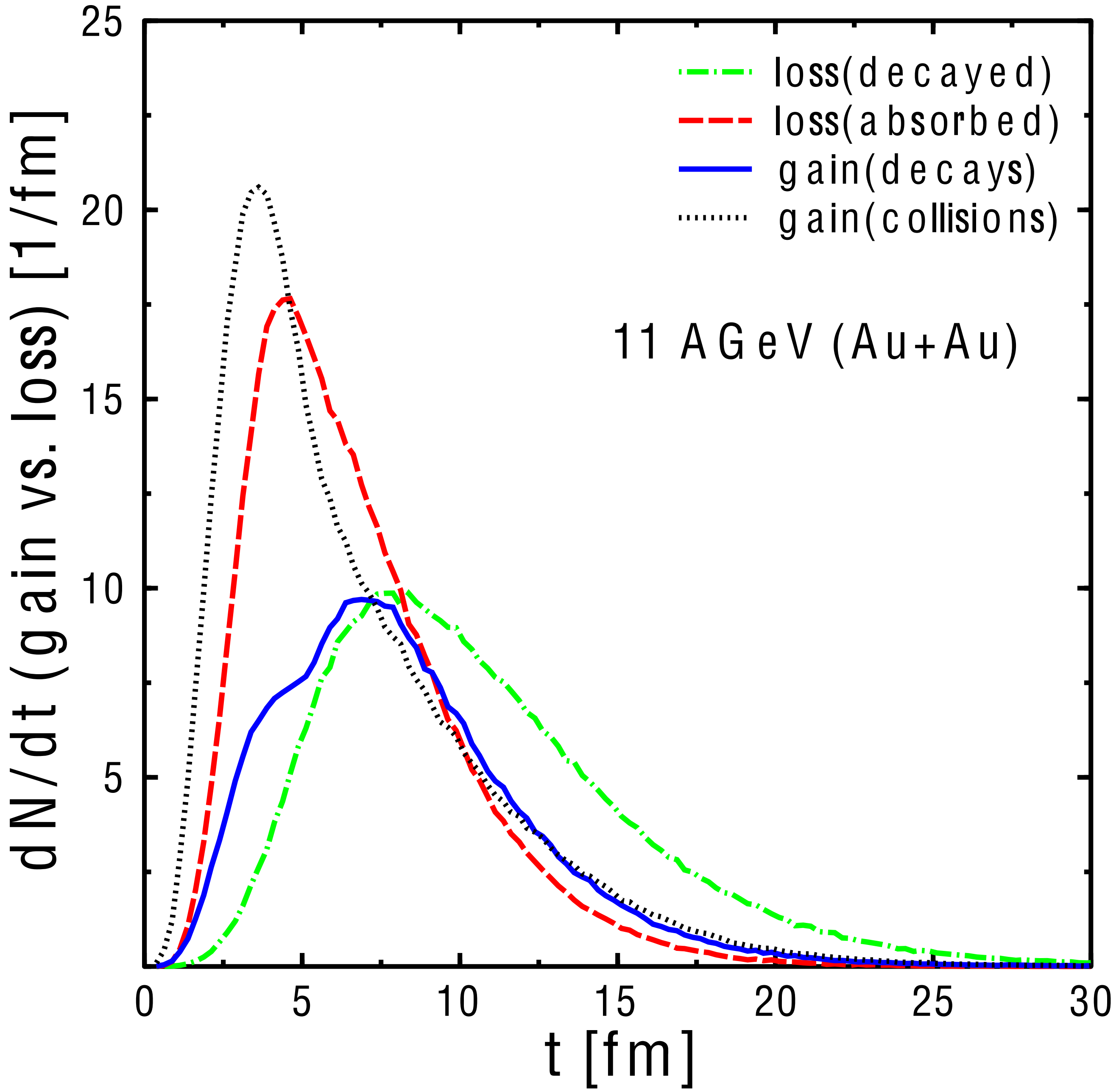

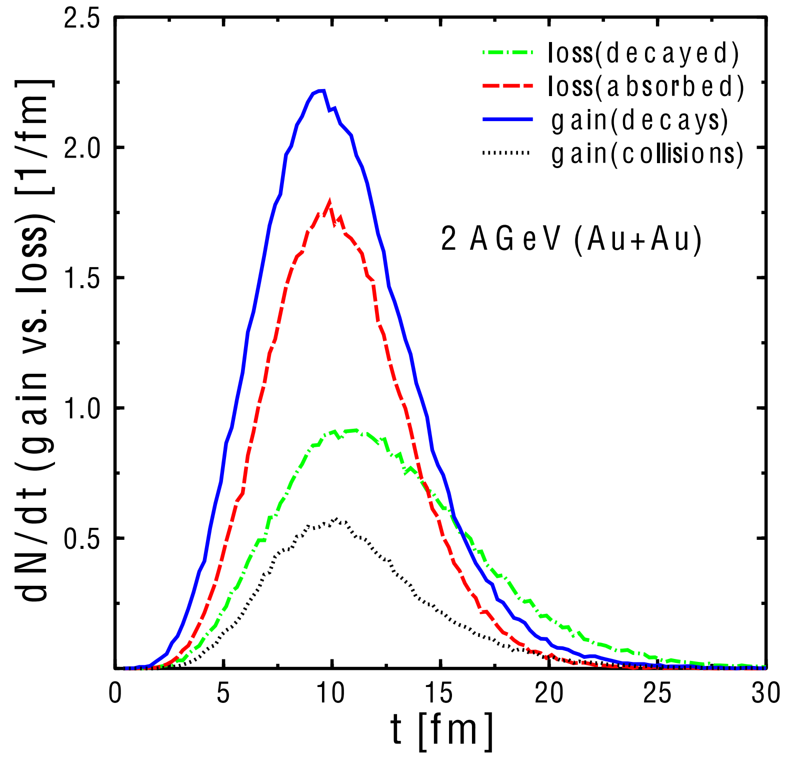

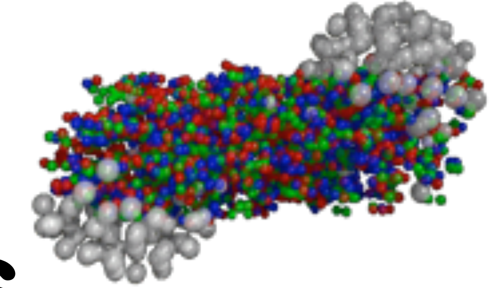

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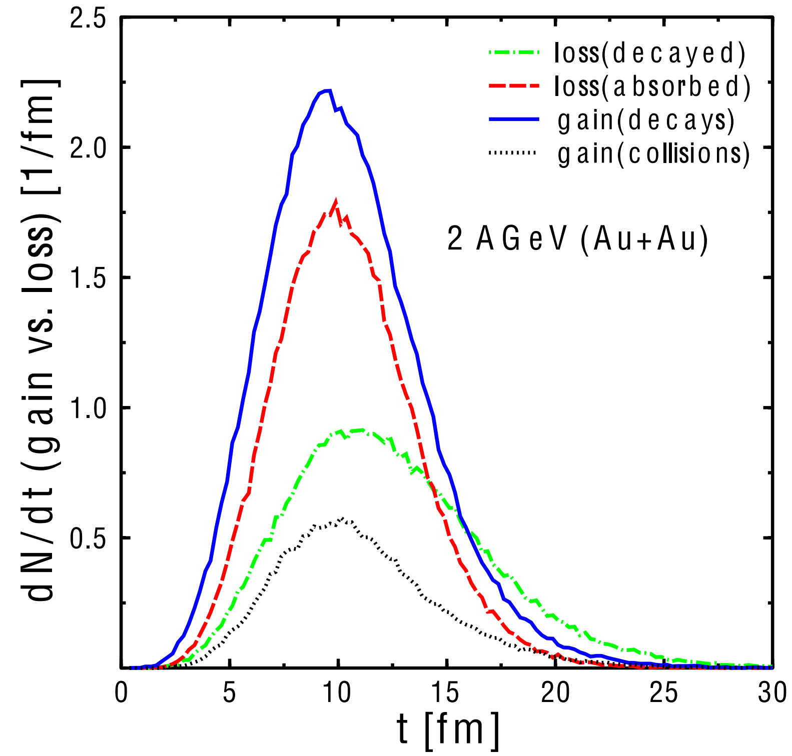

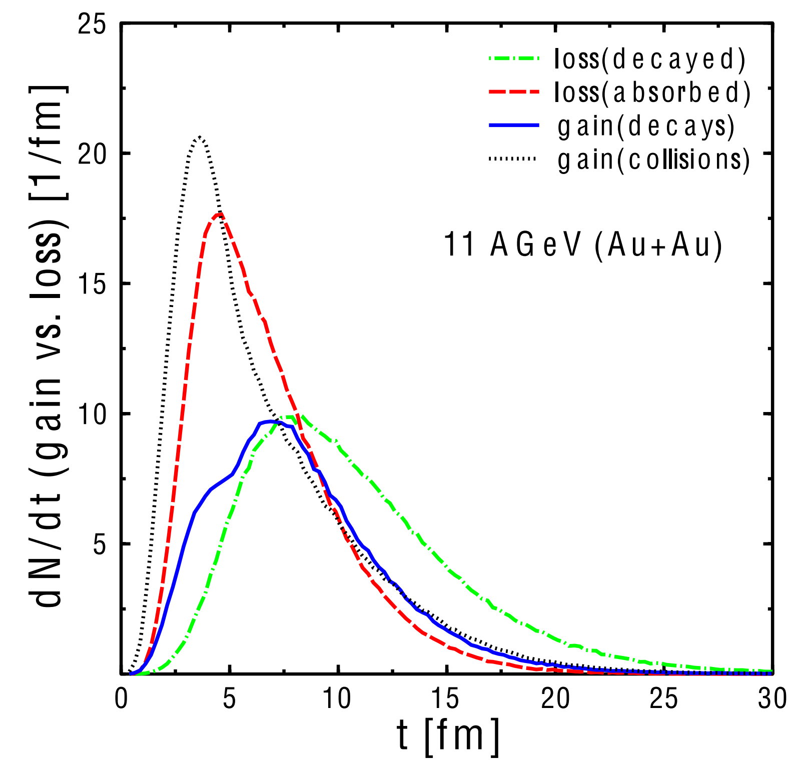

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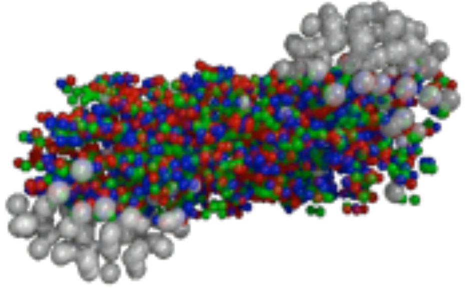

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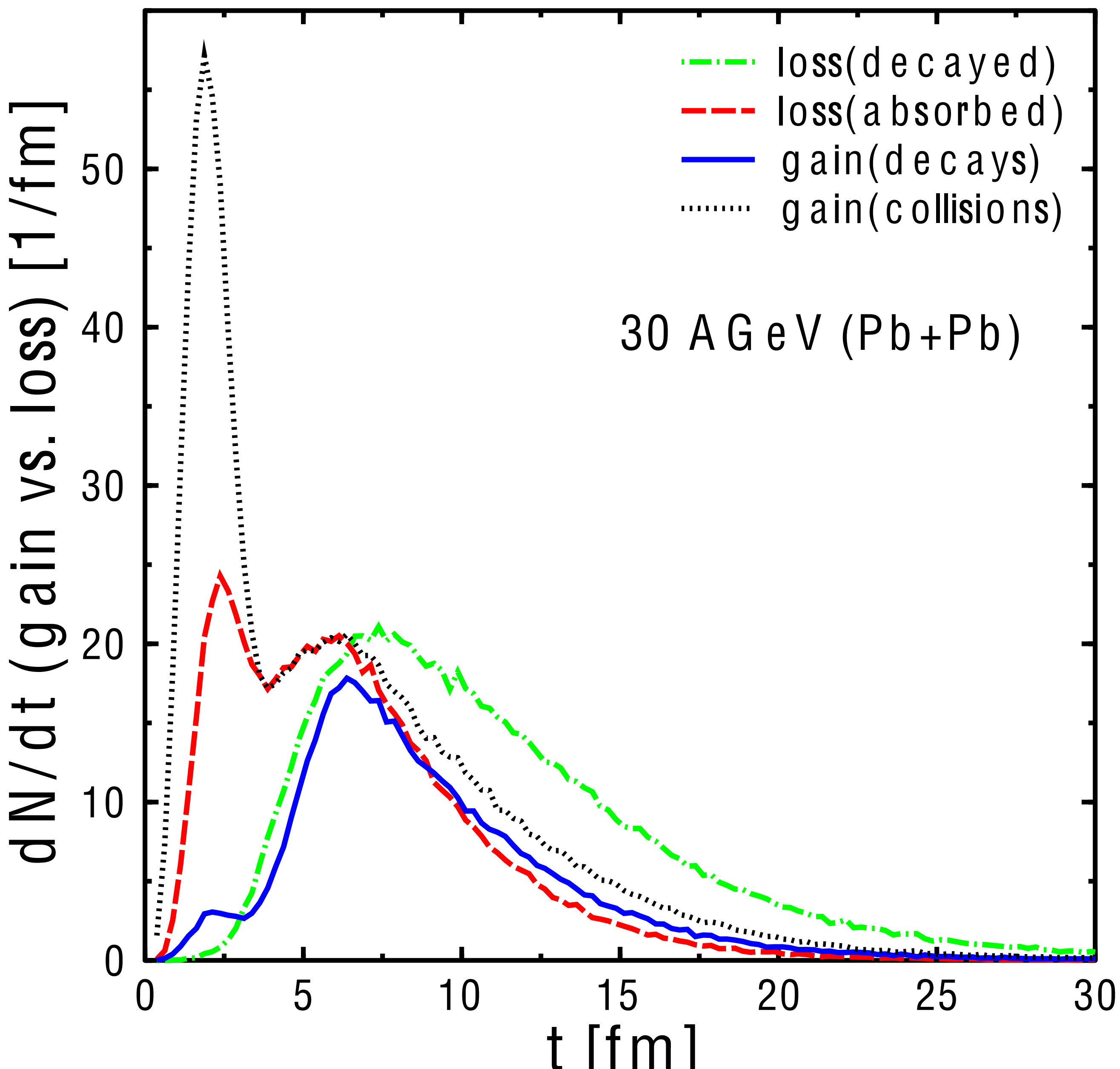
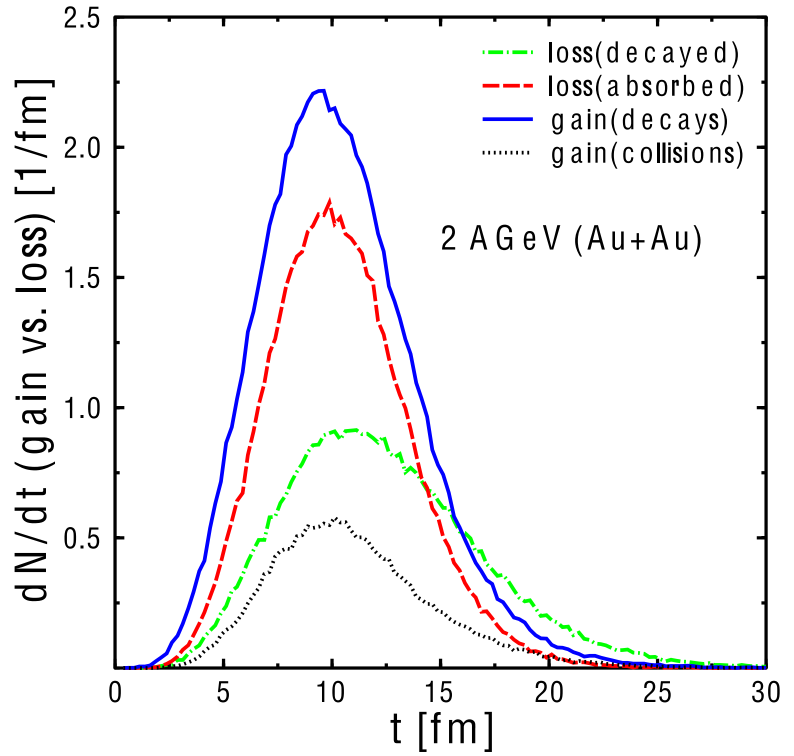
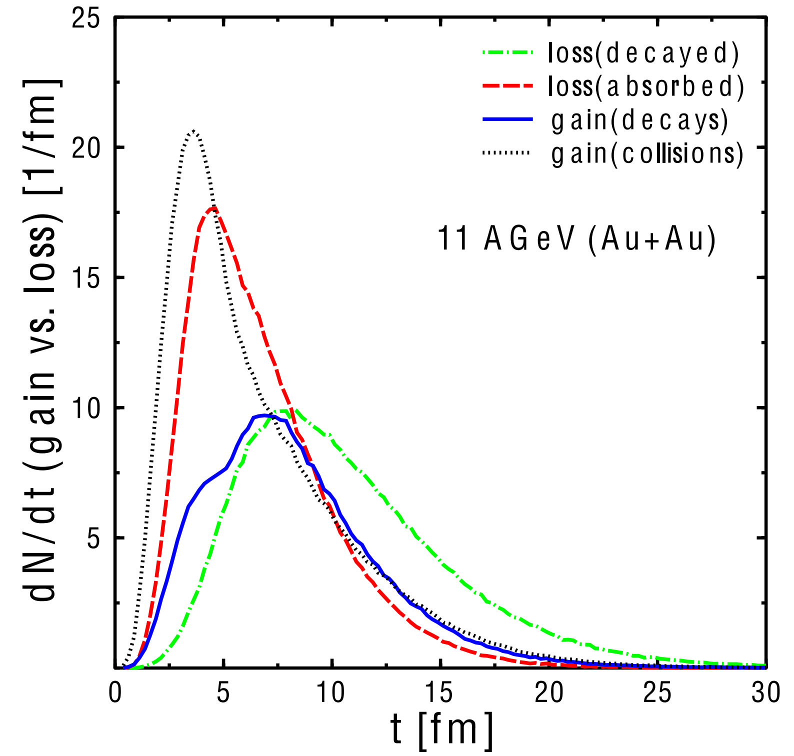
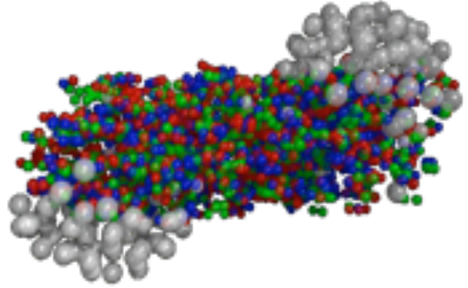


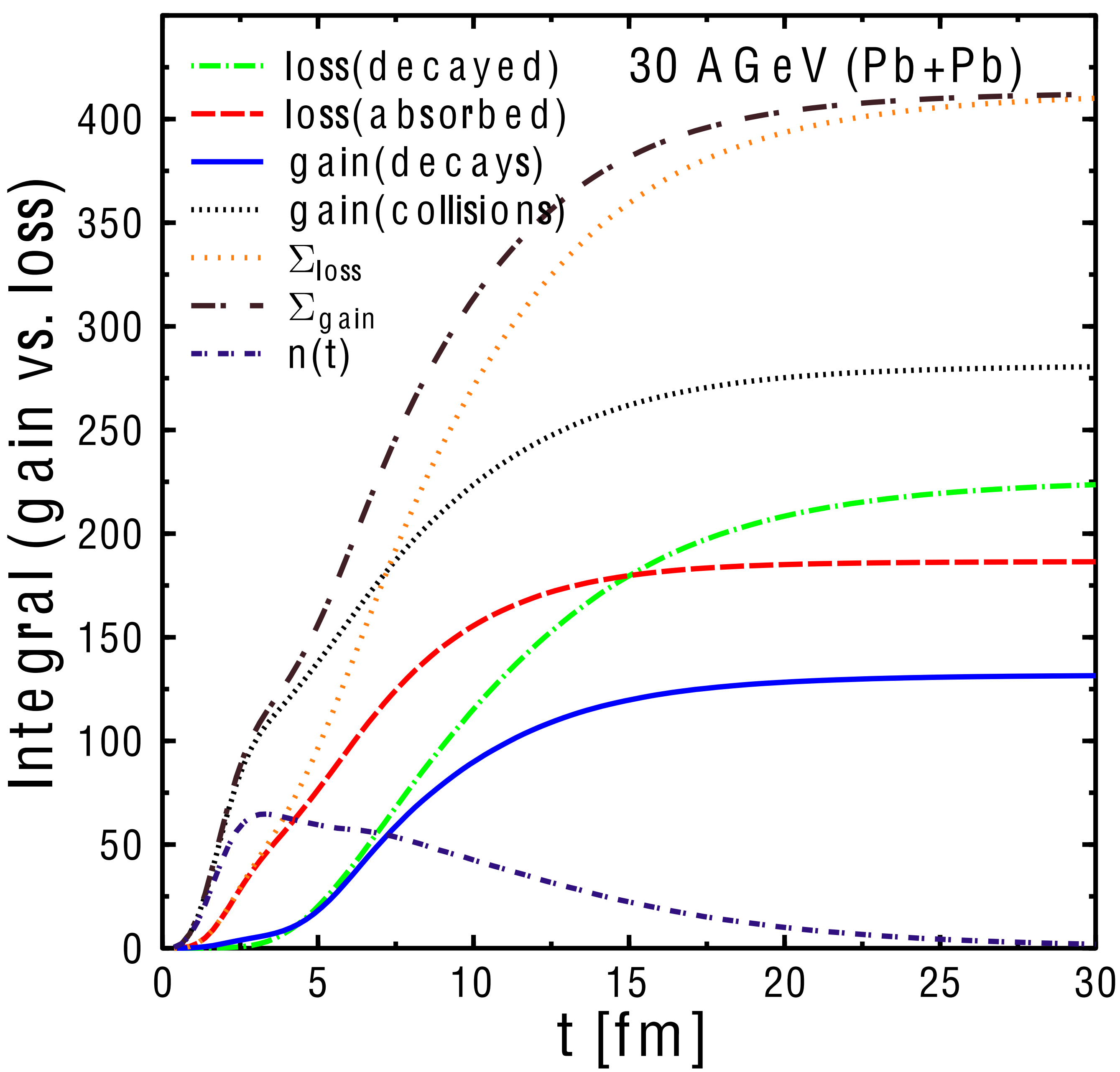


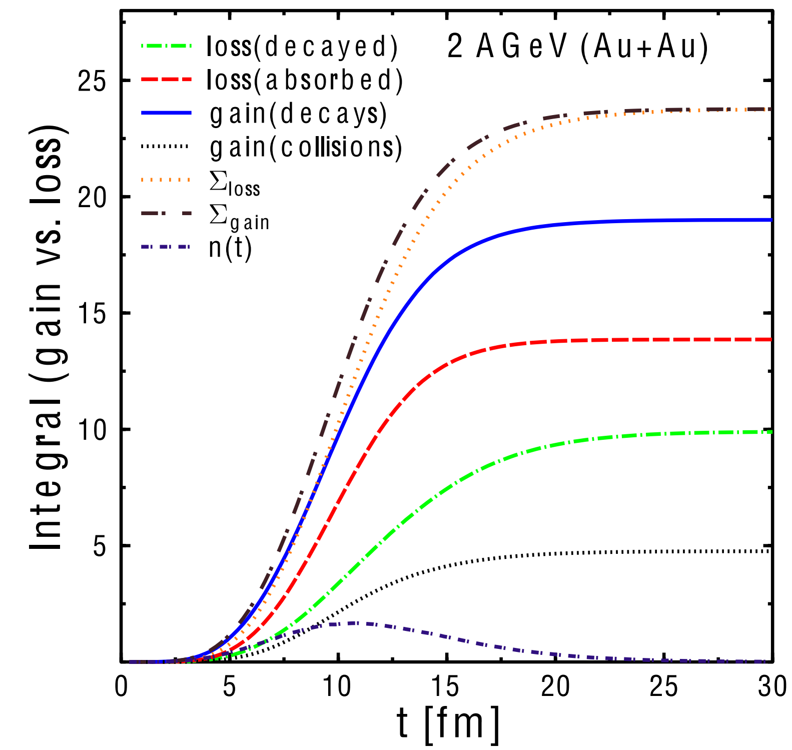


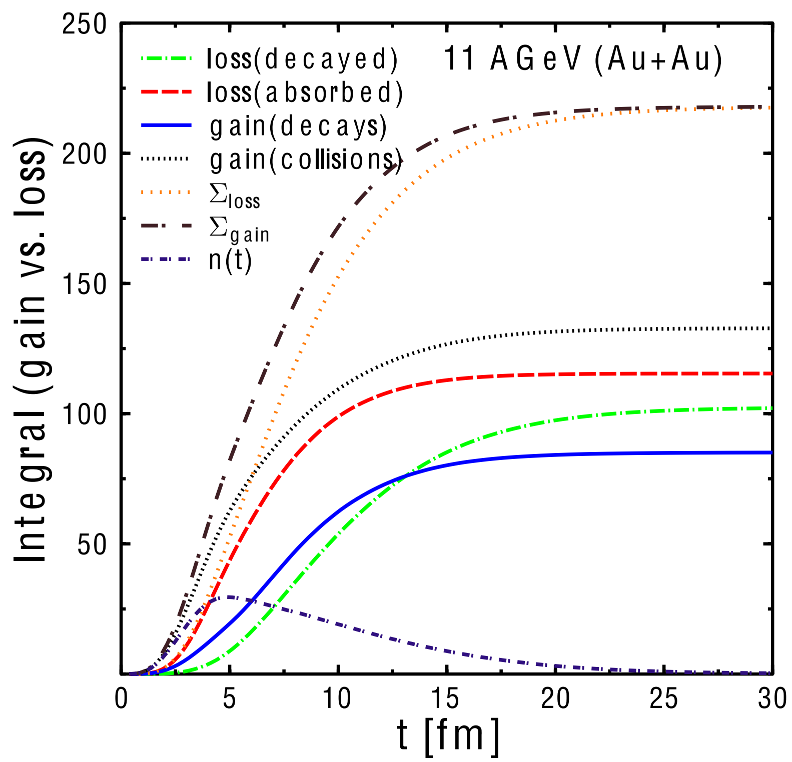


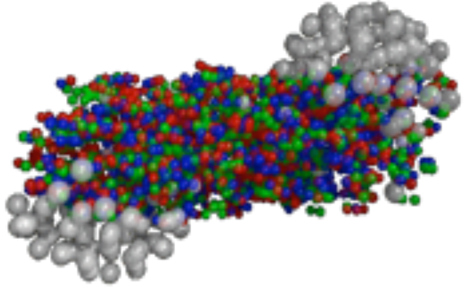
Integral values

- Consistency check: Sum of gain and collision agree
- Difference gives the number of resonances in the system









Dilepton approaches

1) Shining

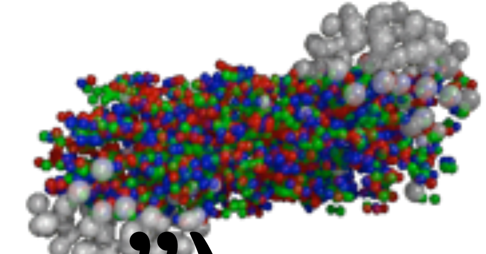
- Evaluate lifetime of the resonance, weight accordingly

2) Full weight only when resonance decays - ignore absorbed resonances

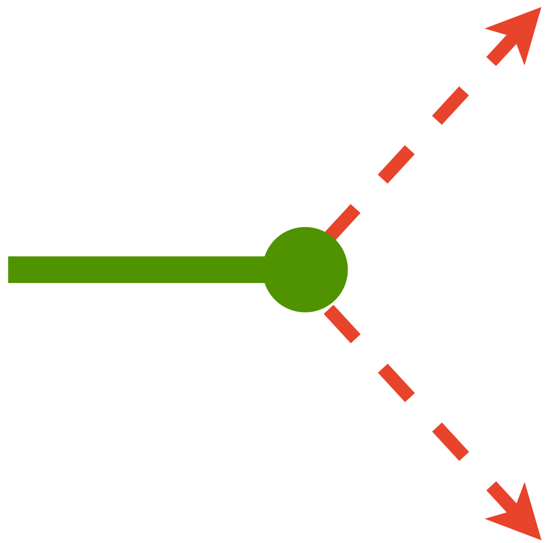
- Weight decayed resonance with vacuum width / BR

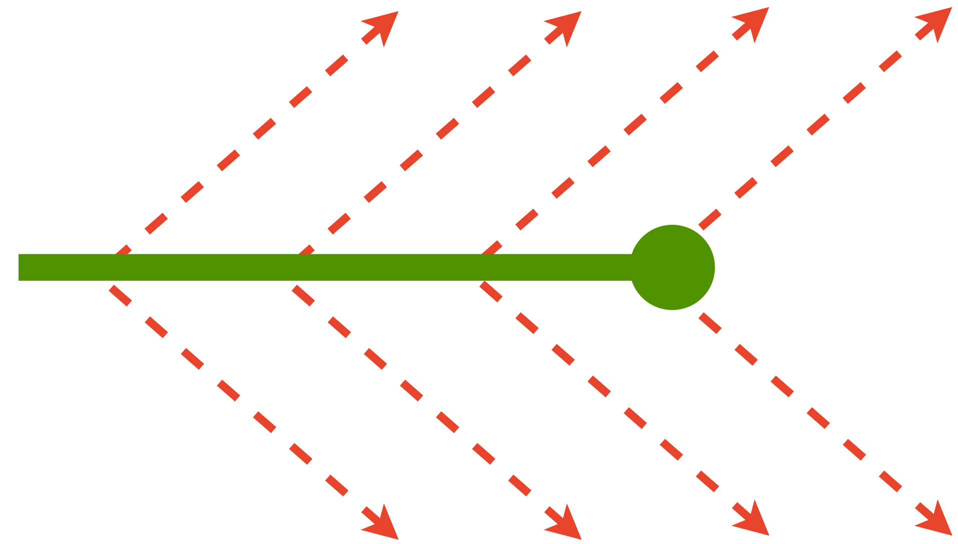
3) Full weight when absorbed/decayed

- Weight all decayed/absorbed resonances with vacuum width / BR (most optimistic approach)



Time integration method ("shining")





decay method

one pair

$$BR = \frac{\Gamma_i}{\Gamma_{tot}}$$

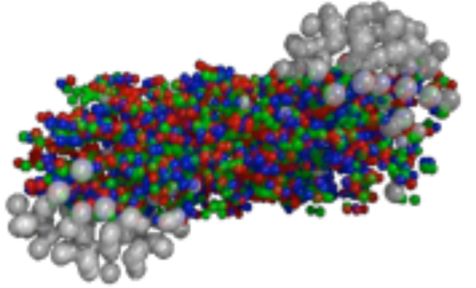
shining

continuous emission

$$\frac{dN_{e^+e^-}}{dM} = \frac{\Delta N_{e^+e^-}}{\Delta M} = \sum_{j=1}^{N_{\Delta M}} \int_{t_i^j}^{t_f^j} \frac{dt}{\gamma} \frac{\Gamma_{e^+e^-}(M)}{\Delta M}$$

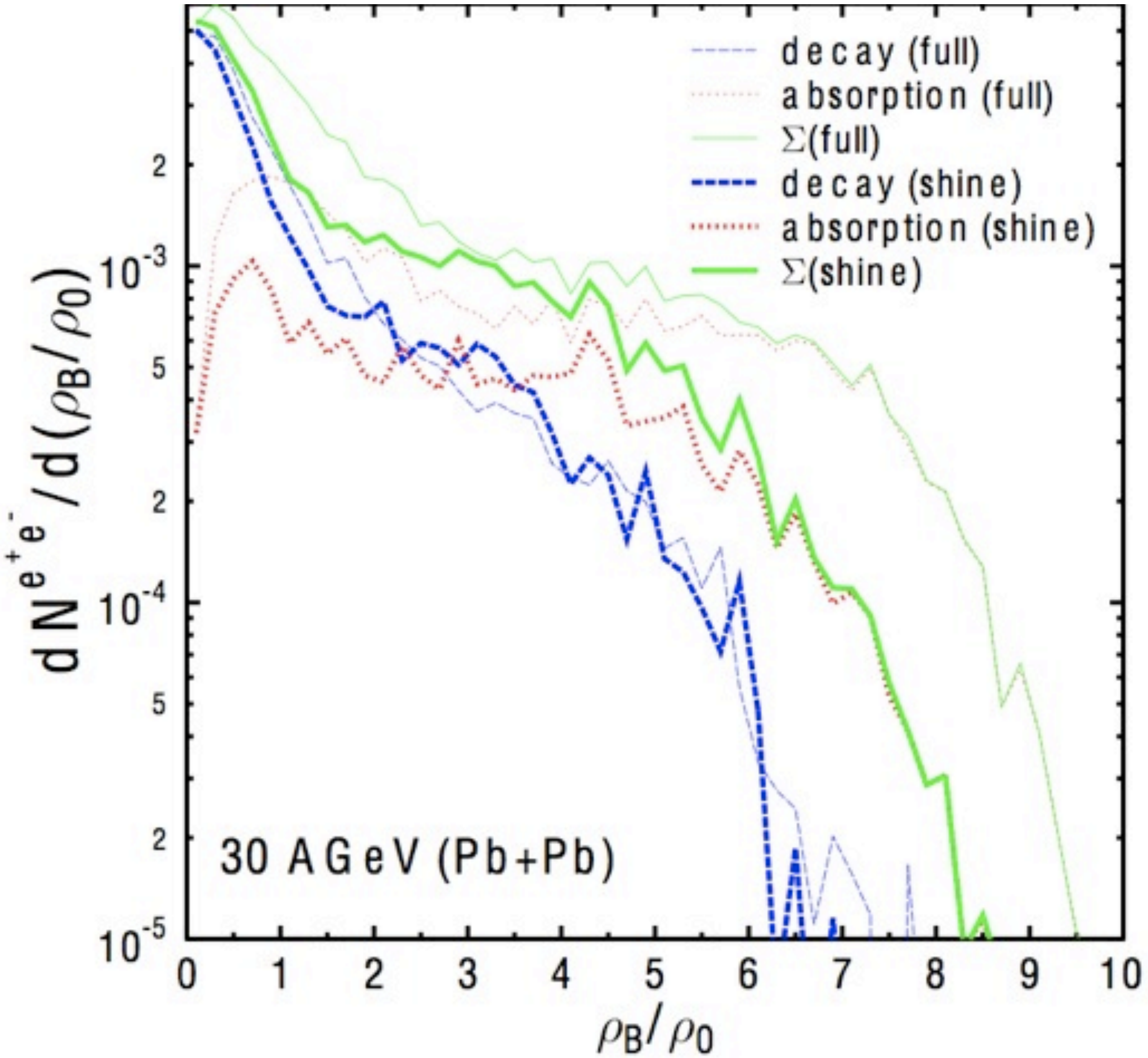
Heinz and Lee, Nucl.Phys.A544:503-508,1992

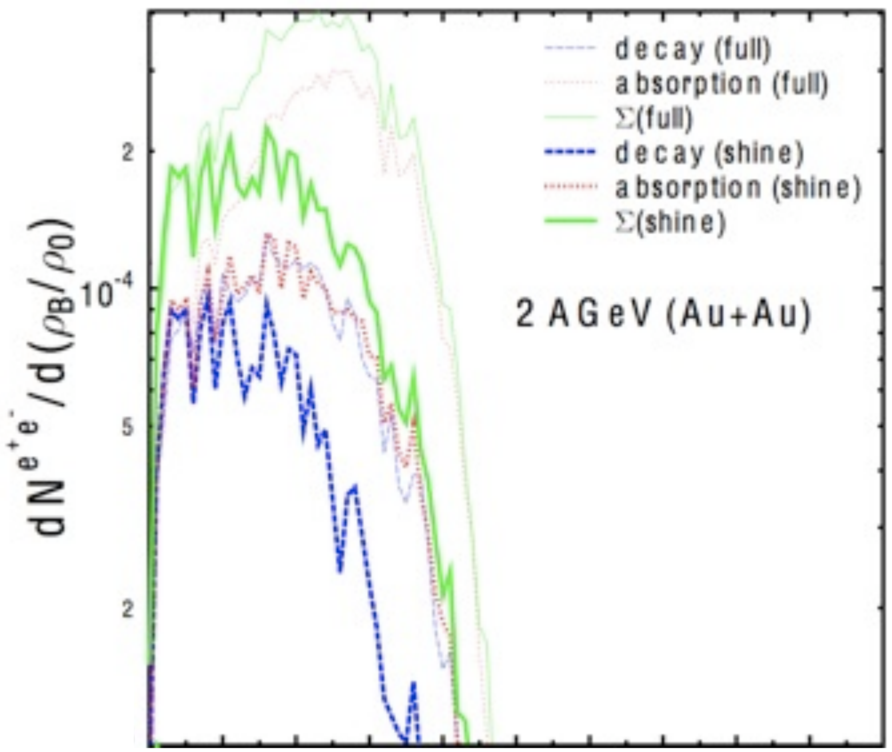
Ko and Li, Nucl.Phys.A582:731-748,1995

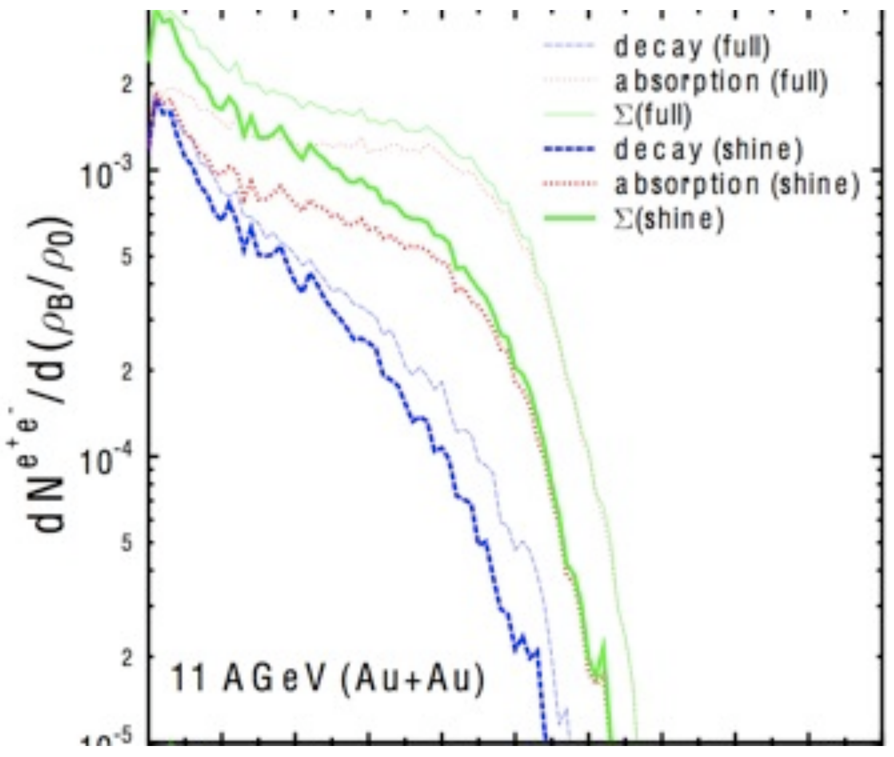


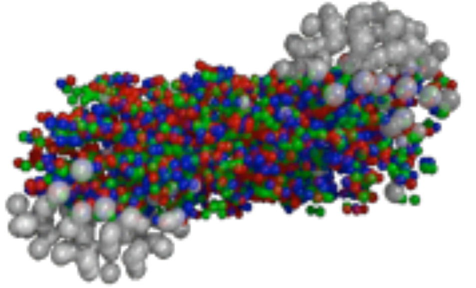
Dileptons

Even in the most optimistic approach dileptons only reach out to 2-3 ρ_0
Shining approach only reaches out to 1-2 ρ_0



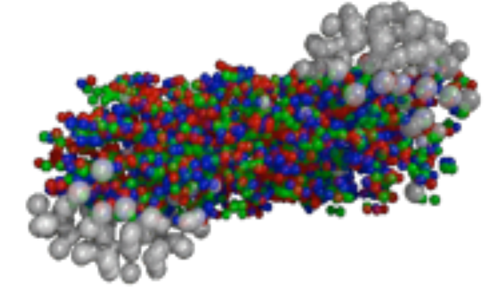






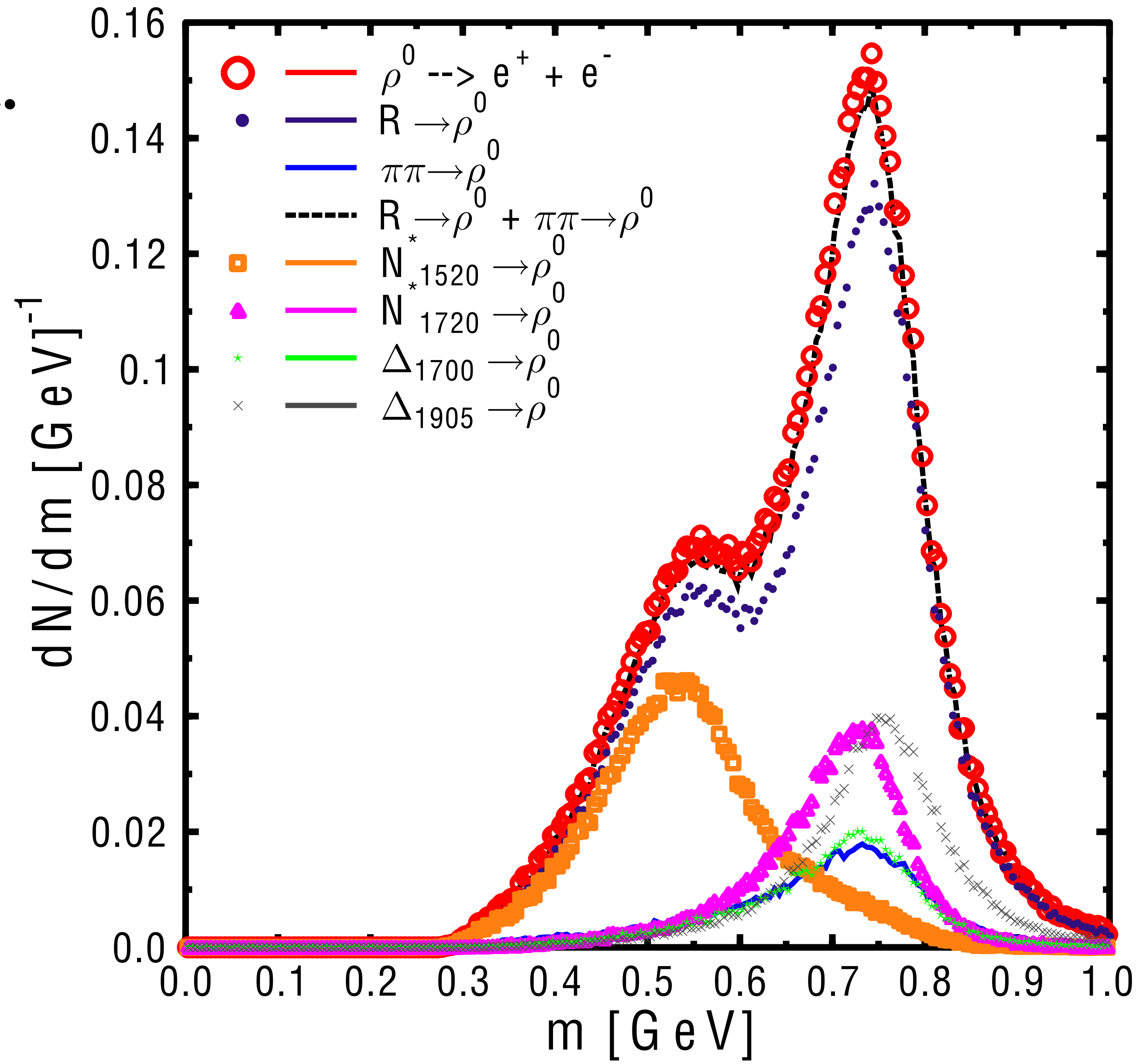
Baryons

What is the deal about them at low energies?



ρ meson in C+C @ 2AGeV

At low energies (~2 AGeV) contributions from baryon resonance decays are dominant.



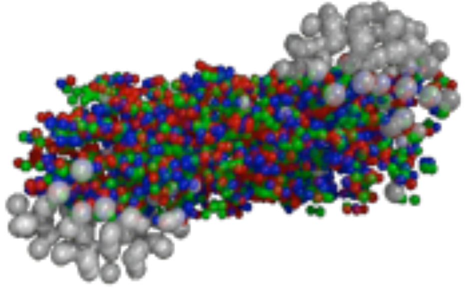
N^*_{1520} contributes via the decay chain

$N^*_{1520} \to N + \rho$

$\rho \to \pi^+\pi^-$ or $\rho \to e^+e^-$

to the low mass part of the ρ meson mass spectrum.

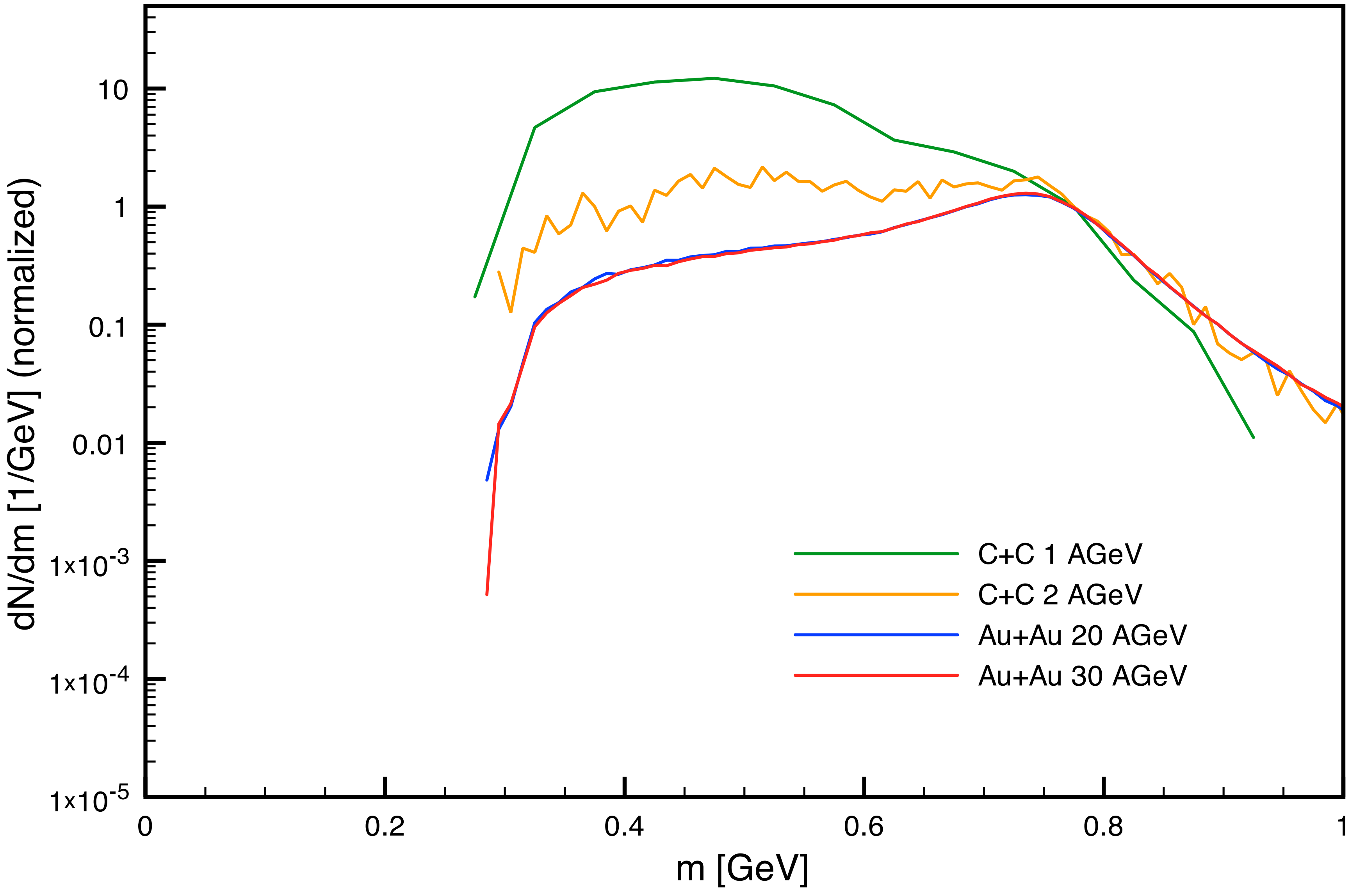
SV, M. Bleicher, Phys.Rev.C74:014902,2006

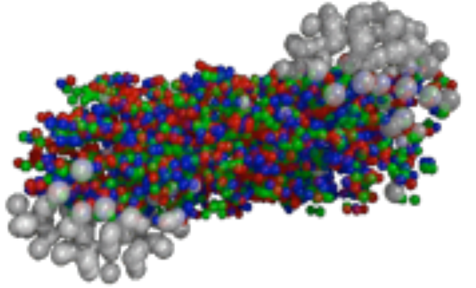


ρ meson at higher energies

At higher energies the contribution from baryonic resonance decays become less important.

Note: All curves normalized to the 770 MeV point.

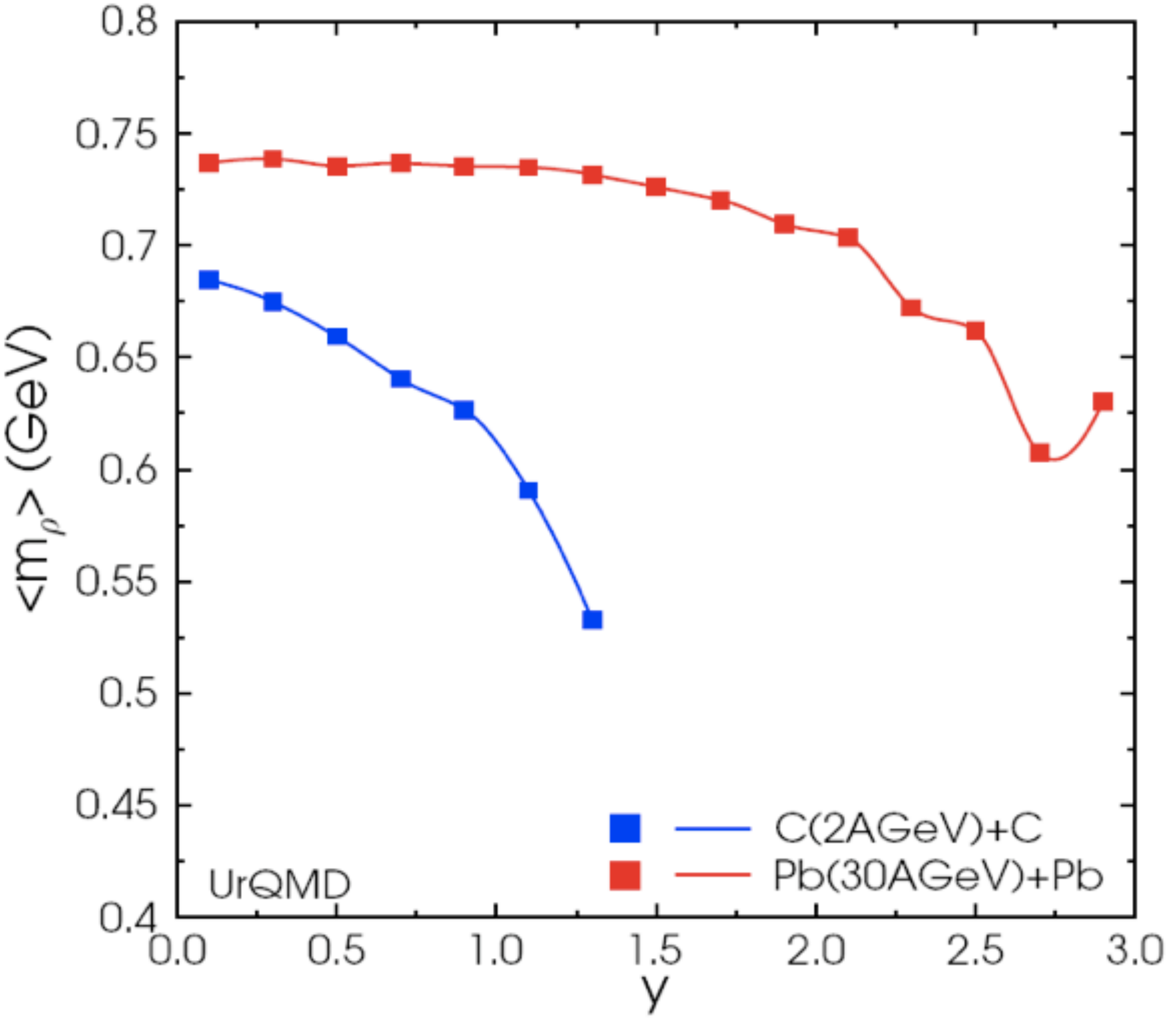


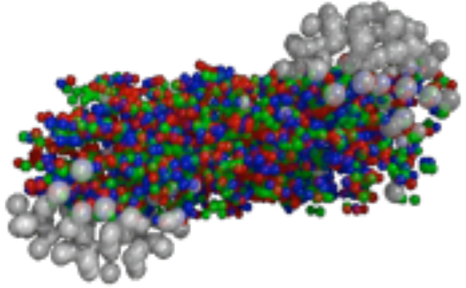


ρ meson at higher energies

Due to the dependence on the baryon density the mass of the ρ meson is rapidity dependent.

The ρ meson mass drops towards higher rapidity.

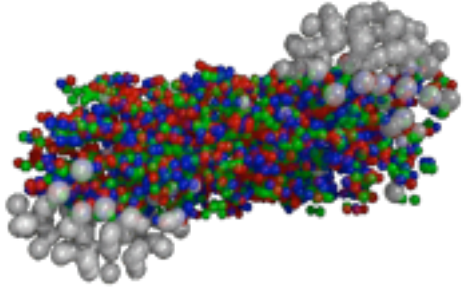




Second conclusion

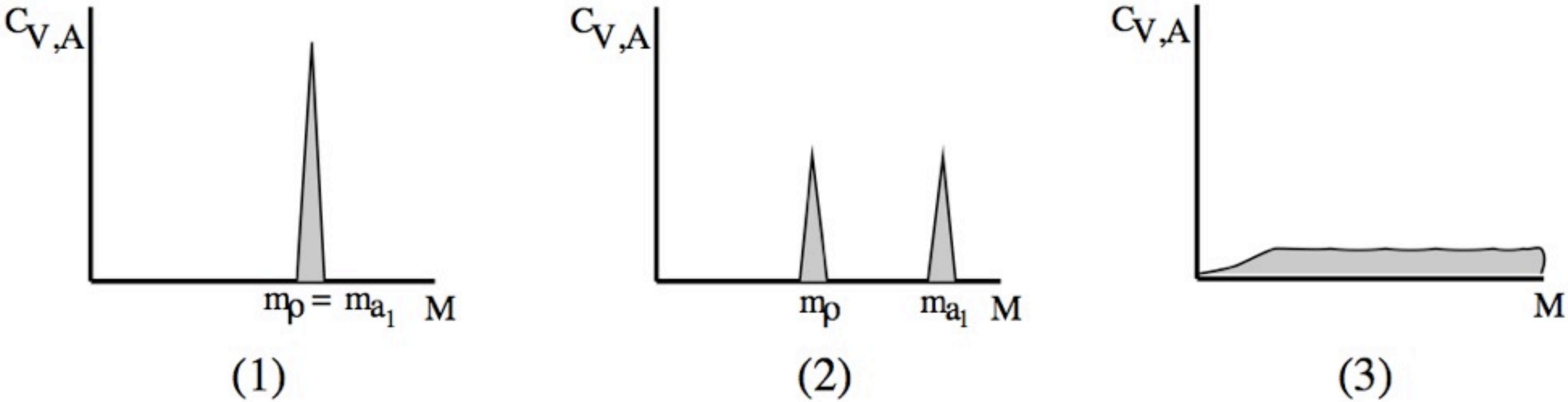
Controlling baryon kinematics is important

(otherwise some spectra seem more interesting than they are)

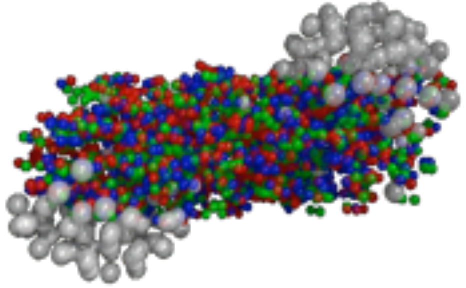


Measuring Chiral Symmetry

- Can we observe a chirally restored phase? (and how?)
- What happens to the ρ meson in the medium? What happens to the a_1 meson?
- What can we learn from reasonable hadronic dynamics (without a chirally restored phase)?



V. Koch, Int.J.Mod.Phys.E6:203-250,1997



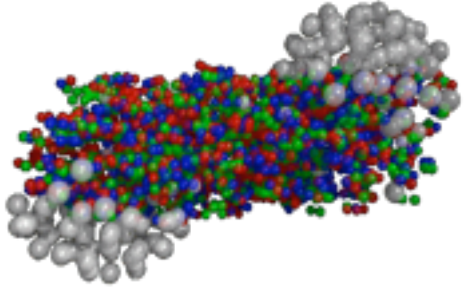
a_1 meson

The a_1 meson mass is expected to be equal to the mass of the ρ meson, in case of chiral symmetry restoration.

Problem:
It is hard to measure.

$a_1(1260)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi^+\pi^-\pi^0$	
Γ_2	$\pi^0\pi^0\pi^0$	
Γ_3	$(\rho\pi)_{S-\text{wave}}$	seen
Γ_4	$(\rho\pi)_{D-\text{wave}}$	seen
Γ_5	$(\rho(1450)\pi)_{S-\text{wave}}$	seen
Γ_6	$(\rho(1450)\pi)_{D-\text{wave}}$	seen
Γ_7	$\sigma\pi$	seen
Γ_8	$f_0(980)\pi$	not seen
Γ_9	$f_0(1370)\pi$	seen
Γ_{10}	$f_2(1270)\pi$	seen
Γ_{11}	$K\overline{K}^*(892)+$ c.c.	seen
Γ_{12}	$\pi\gamma$	seen



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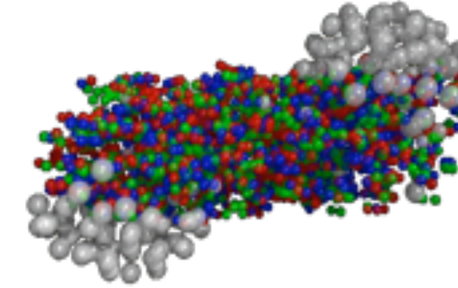
Γ_6	$(\rho(1450)\pi)_{D-\text{wave}}$	seen
Γ_7	$\sigma\pi$	seen
Γ_8	$f_0(980)\pi$	not seen
Γ_9	$f_0(1370)\pi$	seen
Γ_{10}	$f_2(1270)\pi$	seen
Γ_{11}	$K\overline{K}^*(892) + c.c.$	seen
Γ_{12}	$\pi\gamma$	seen



a_1 meson

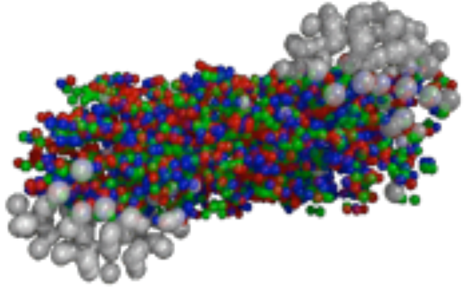
What about the other channels?

Experimentally not feasible:

Higher mass resonances are either not known or the decay channel analyses contradict each other (further exp. studies certainly useful!).

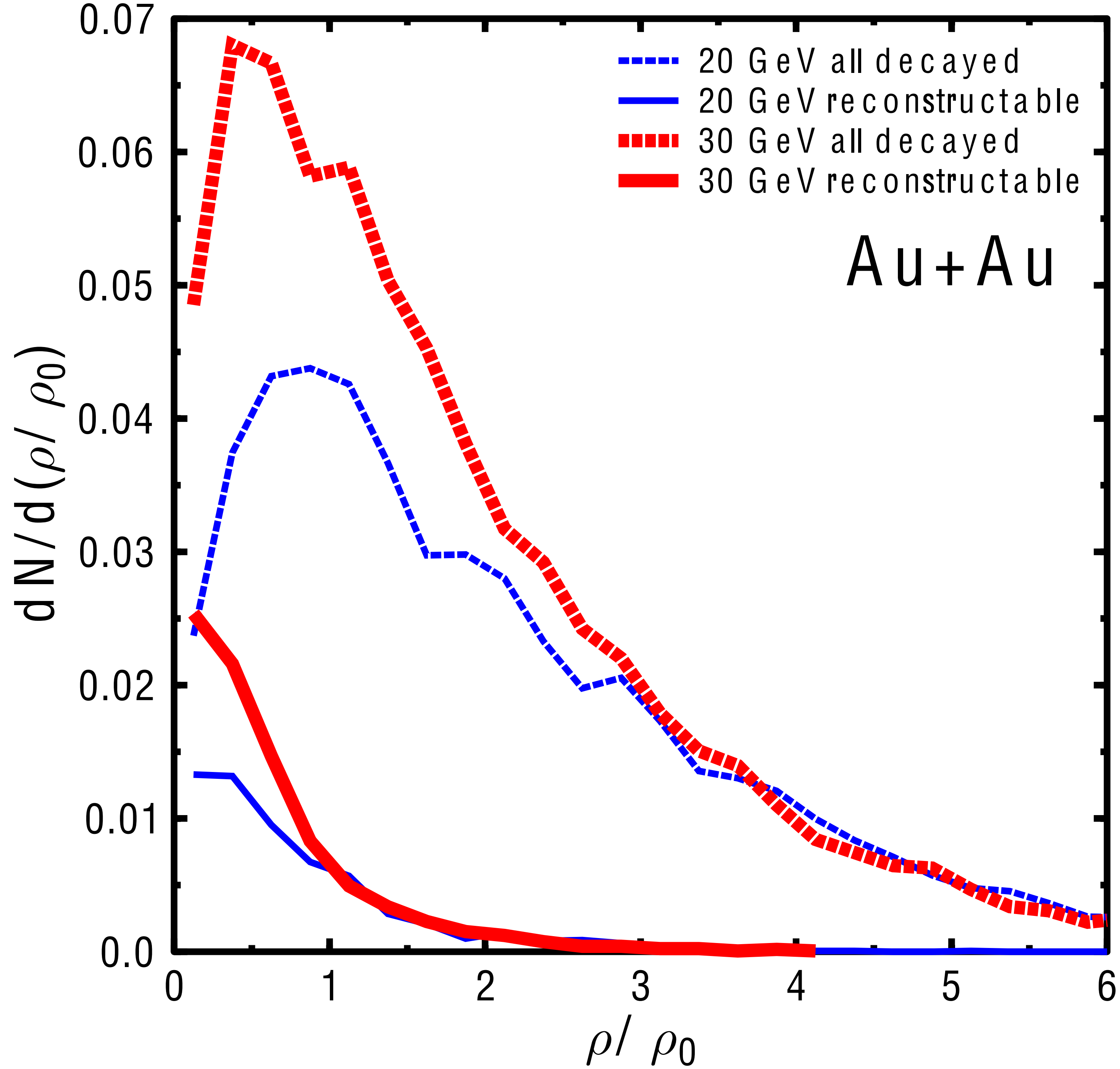
$a_1(1260)$ DECAY MODES

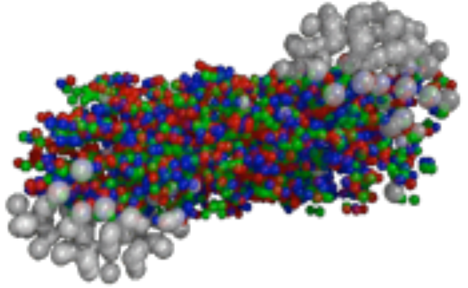
	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi^+\pi^-\pi^0$	
Γ_2	$\pi^0\pi^0\pi^0$	
Γ_3	$(\rho\pi)_{S-\text{wave}}$	seen
Γ_4	$(\rho\pi)_{D-\text{wave}}$	seen
Γ_5	$(\rho(1450)\pi)_{S-\text{wave}}$	seen
Γ_6	$(\rho(1450)\pi)_{D-\text{wave}}$	seen
Γ_7	$\sigma\pi$	seen
Γ_8	$f_0(980)\pi$	not seen
Γ_9	$f_0(1370)\pi$	seen
Γ_{10}	$f_2(1270)\pi$	seen
Γ_{11}	$K\overline{K}^*(892)+$ c.c.	seen
Γ_{12}	$\pi\gamma$	seen



a_1 meson - density

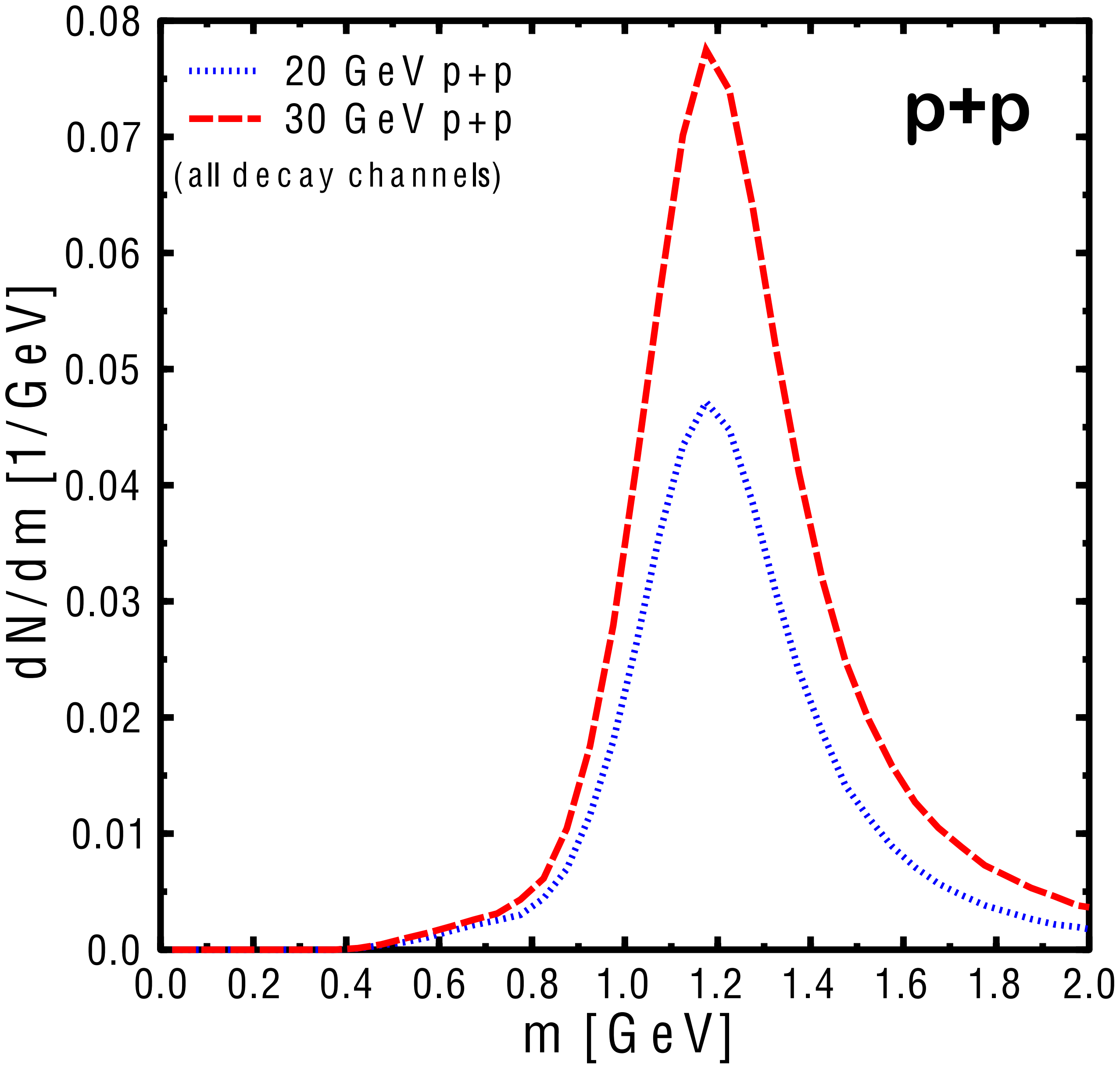
Density at the point of decay of the a_1 meson

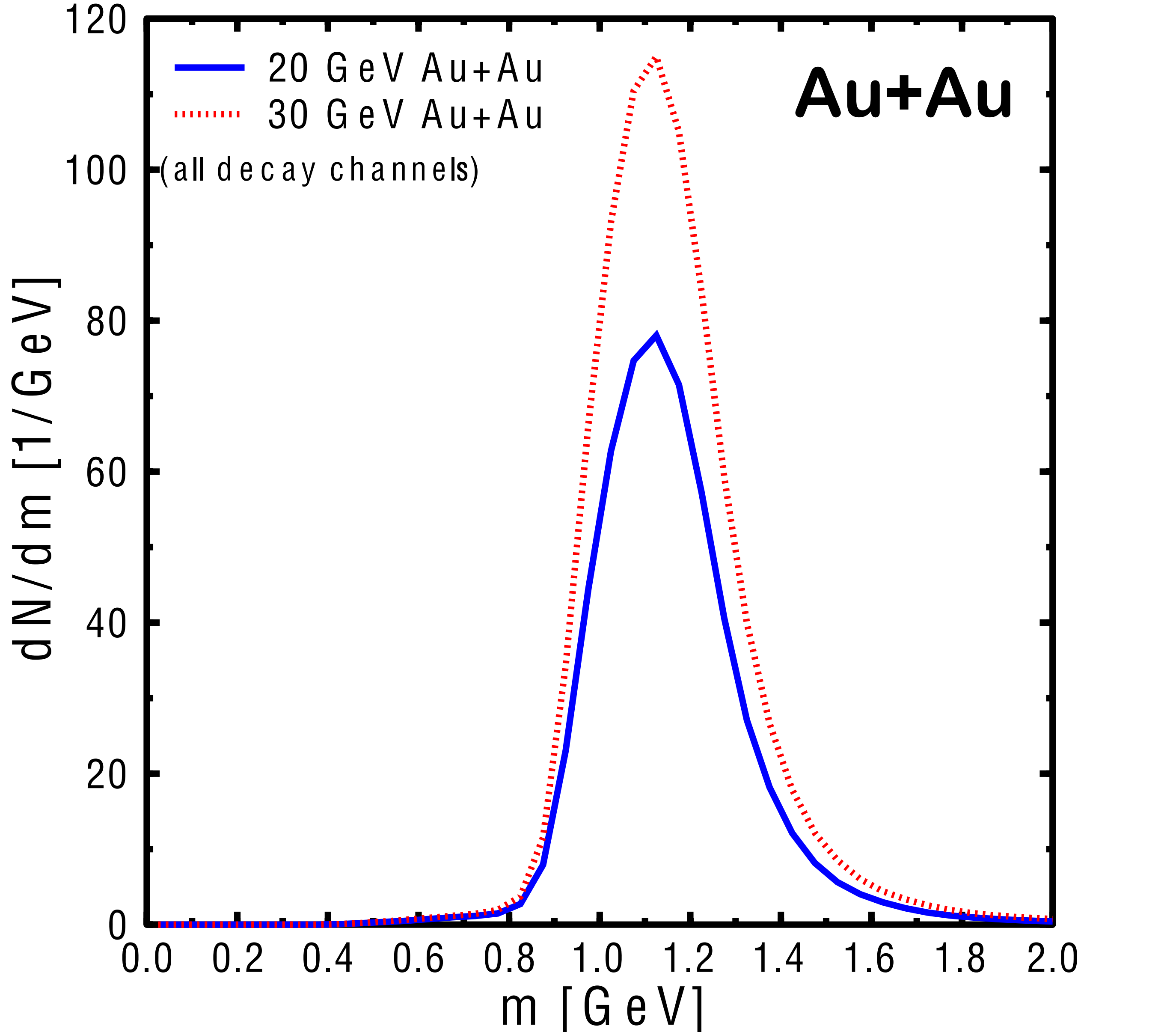


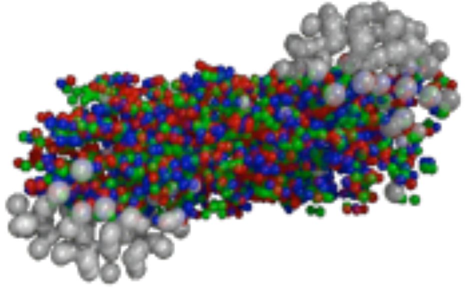


a_1 meson

Idea: Check the mass distribution from the transport code.

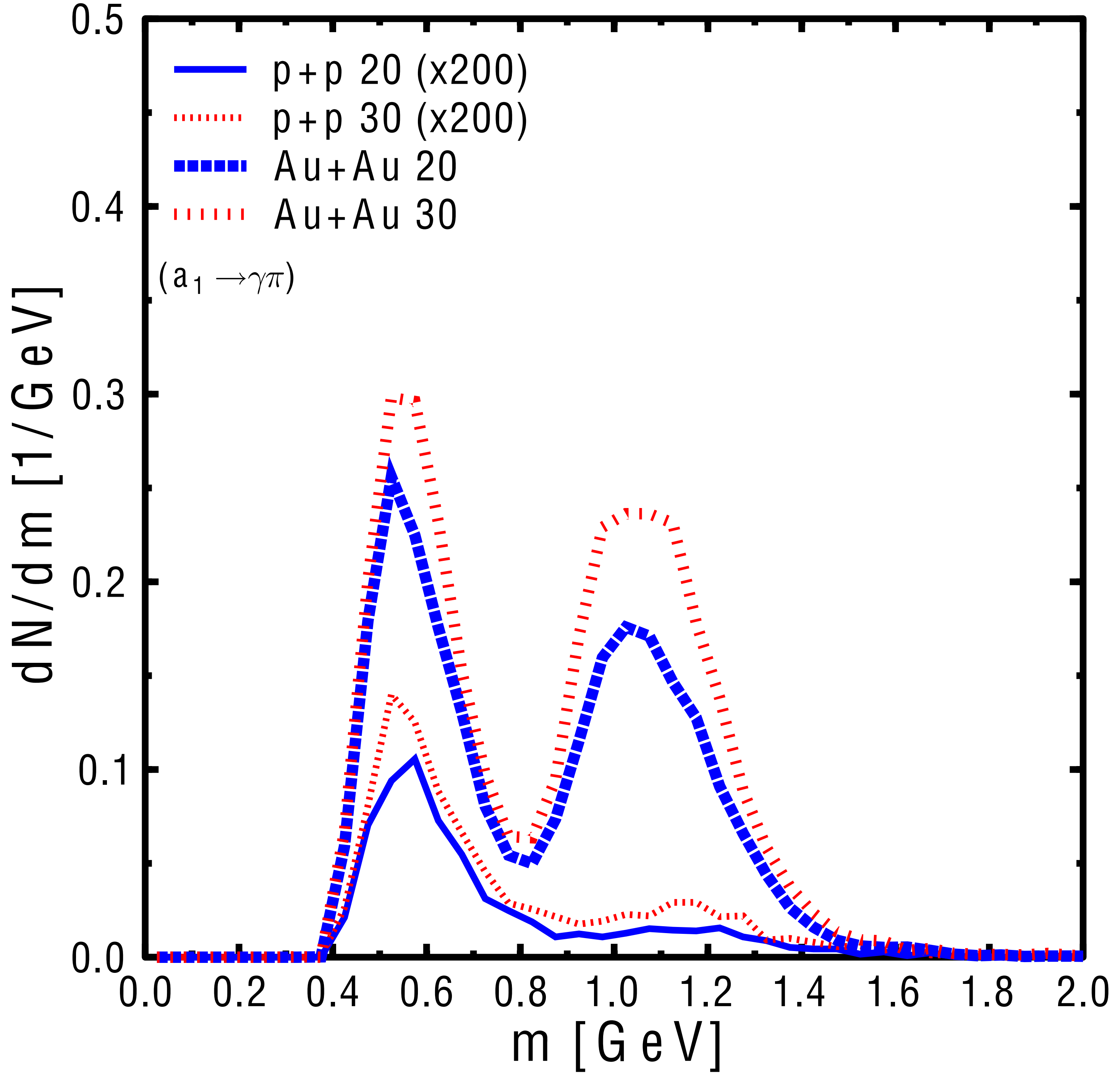


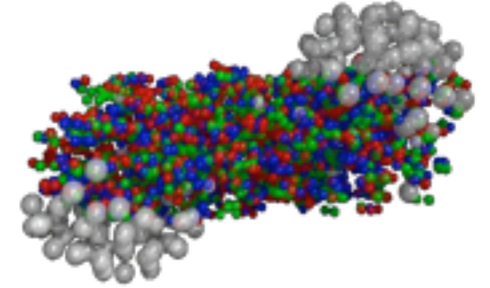




a_1 meson

Next: trigger on the decay channel $a_1 \rightarrow \gamma\pi$ (assumed width = 640keV)





a_1 meson

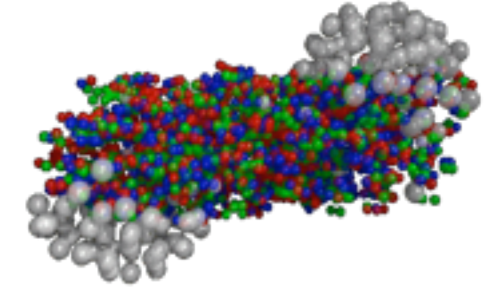
→ **Mass dependent branching ratios**

$$\Gamma_{i,j}(M) = \Gamma_R^{i,j} \frac{M_R}{M} \left(\frac{\langle p_{i,j}(M) \rangle}{\langle p_{i,j}(M_R) \rangle} \right)^{2l+1} \frac{1.2}{1 + 0.2 \left(\frac{\langle p_{i,j}(M) \rangle}{\langle p_{i,j}(M_R) \rangle} \right)^{2l}}$$

Low mass a_1 favors $\gamma\pi$ decay, not $\rho\pi$

Trigger on $a_1 \rightarrow \gamma\pi$ = trigger on low mass a_1 mesons

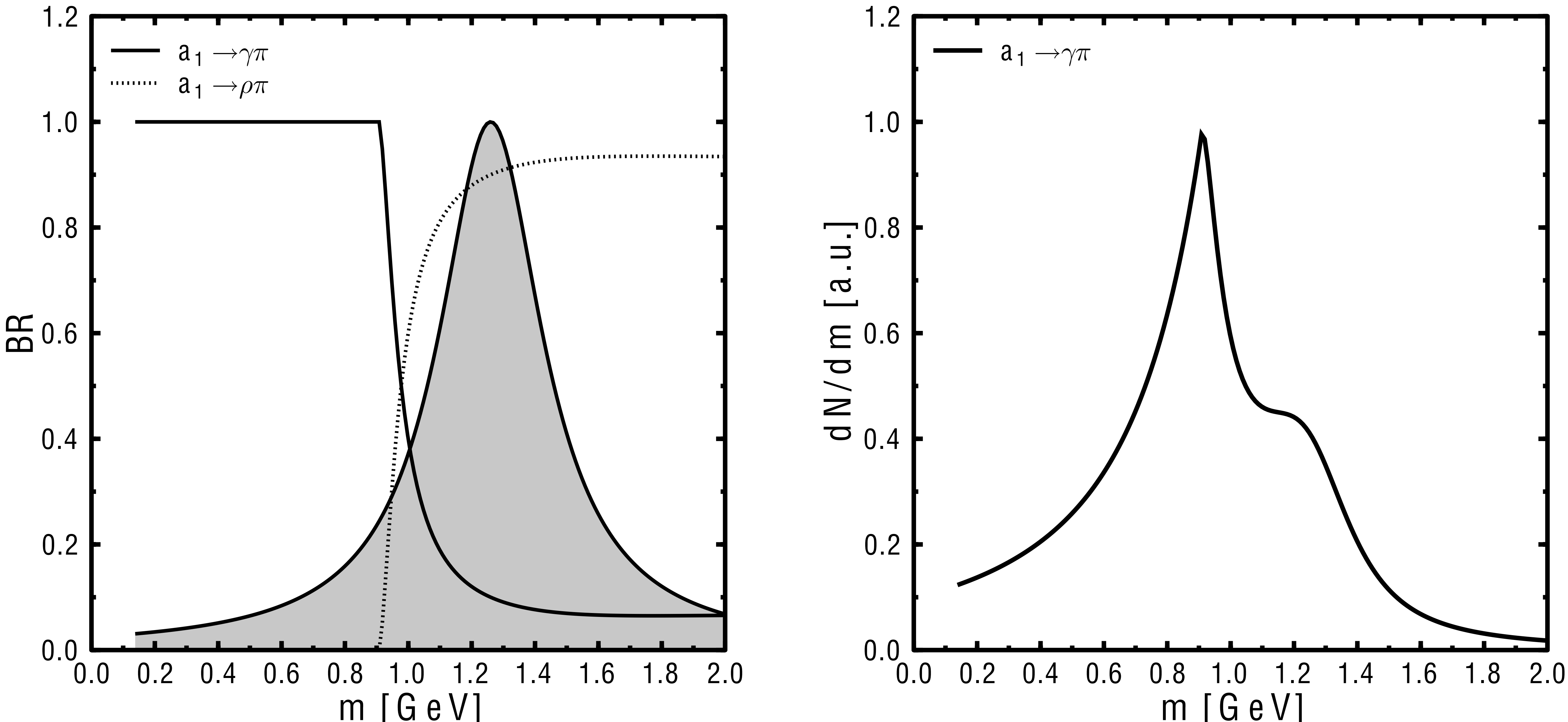
H. Sorge, Phys.Rev.C52:3291,1995

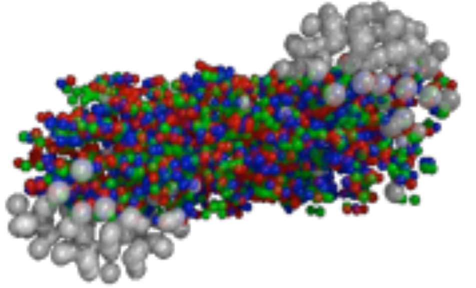


a_1 meson

Below 900 MeV γπ decay is dominant, ρπ is kinematically suppressed.

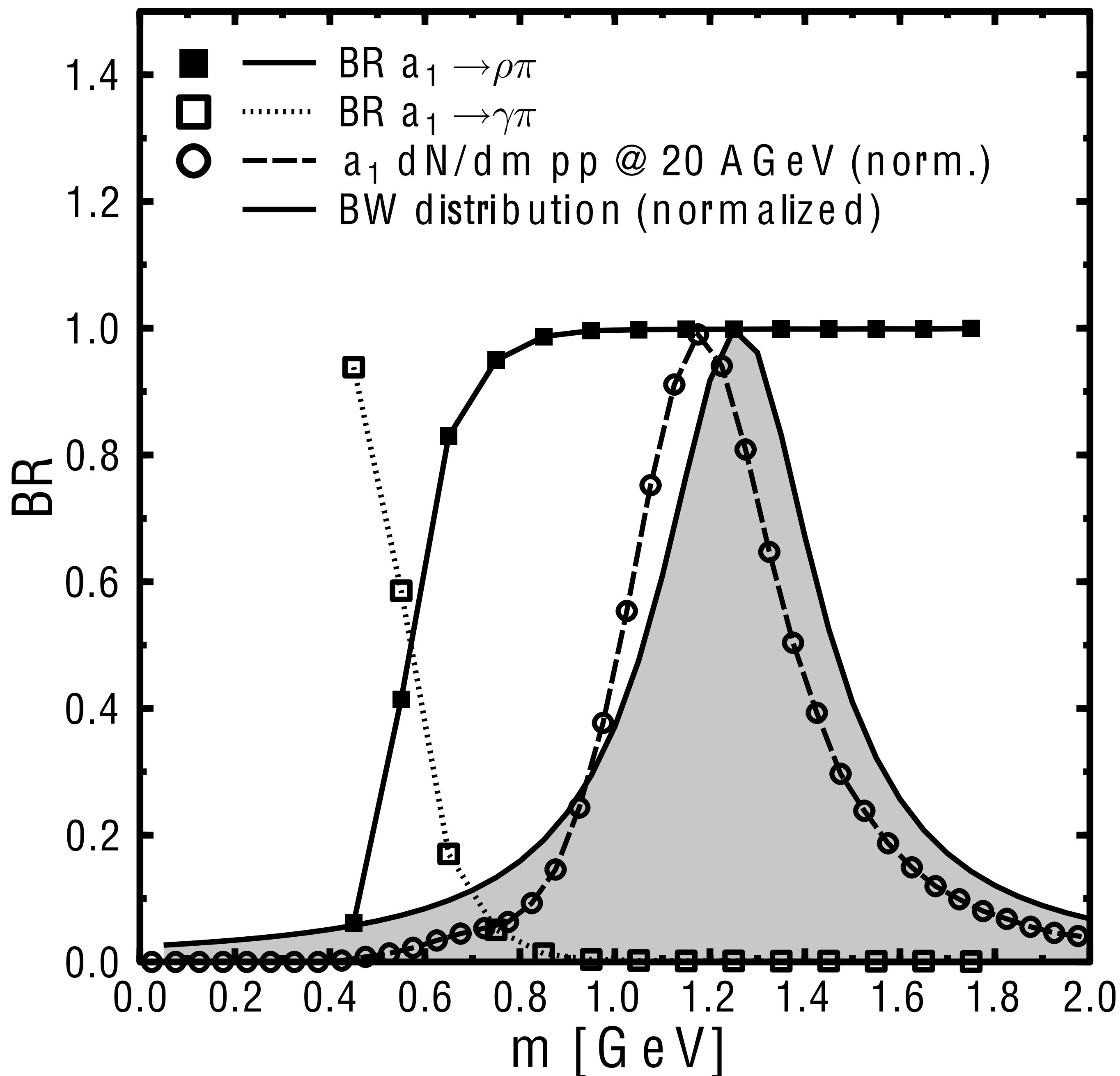
Branching ratio folded with BW distribution



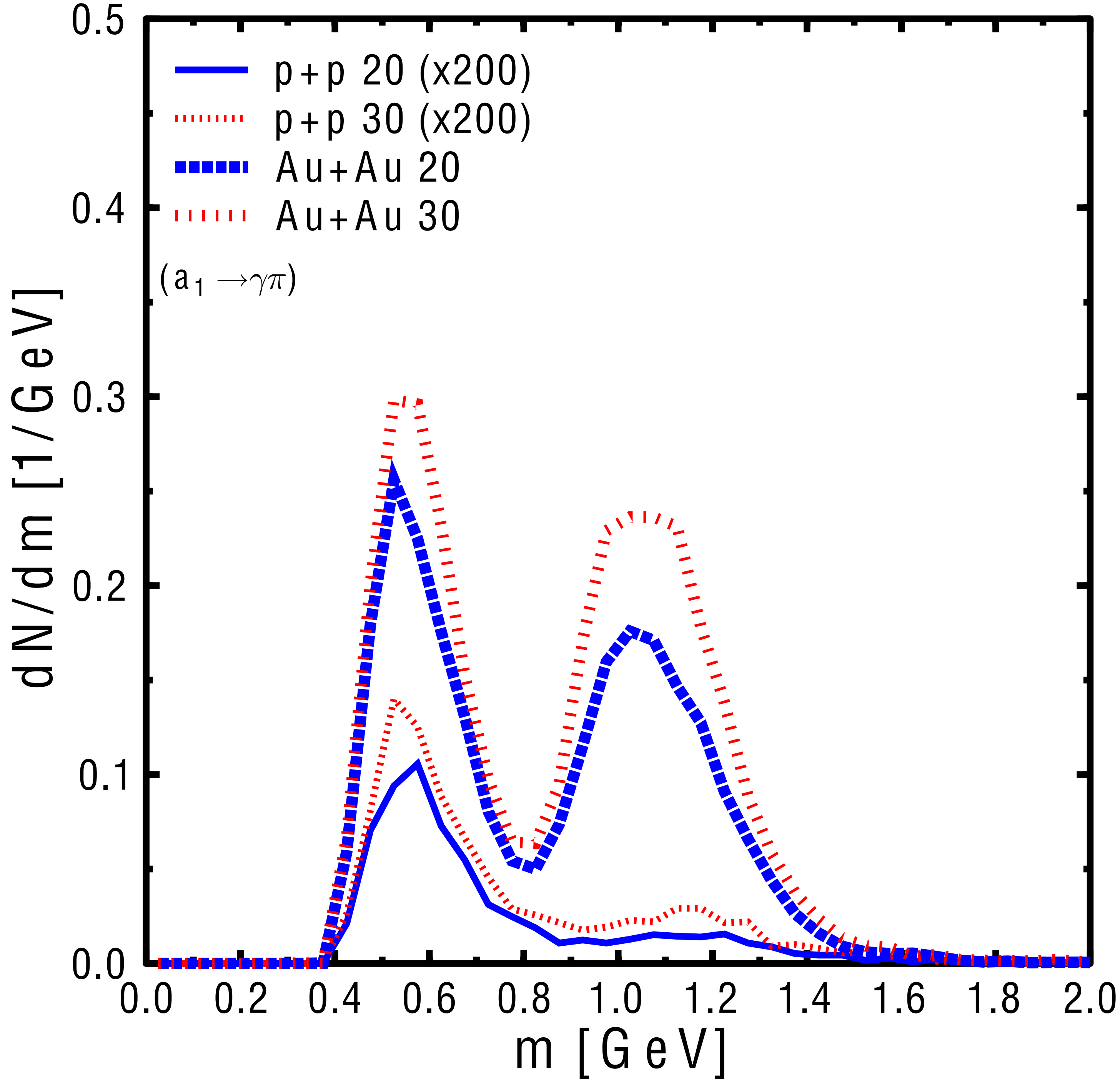


a_1 meson

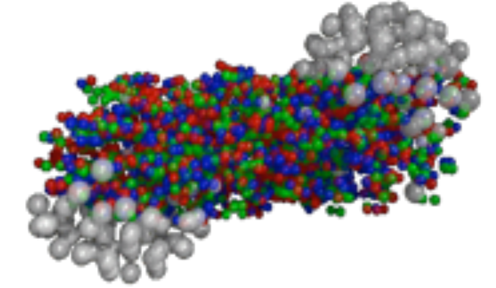
Full model calculation



a_1 meson

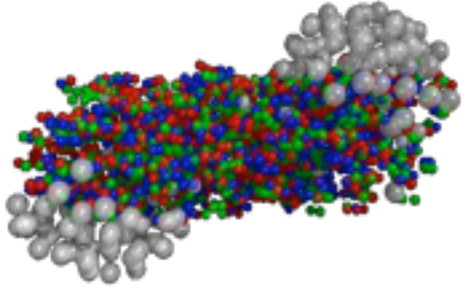


p+p 20 (x200)
p+p 30 (x200)
Au+Au 20
Au+Au 30
(a1 →γπ)
dN/dm [1/GeV]
0.0
0.1
0.2
0.3
0.4
0.5
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
m [GeV]



Take home messages

- Experimentally reconstructable resonances are not sensitive to the high density region unless measured at high p_T
- Beware of baryons kinematics
- $a_1 \rightarrow \gamma\pi$ might not be the golden channel



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Thanks!