Production of Hypernuclei at FAIR

T. Gaitanos, A.B. Larionov, U. Mosel

- Introduction
- The hybrid GiBUU+SMM approach

Giessen-BUU (GiBUU), SMM, combined GiBUU+SMM

- **HypHI** project: Li(C)+C@2AGeV

  Reaction dynamics, spectator fragmentation, results on single-Λ hypernuclei
- **PANDA** subproject: pbar+X@(3-5)GeV

  Reaction dynamics & strangeness yields, decay of residual source, predictions on single-Λ and double-Λ hypernuclei
- Final remarks

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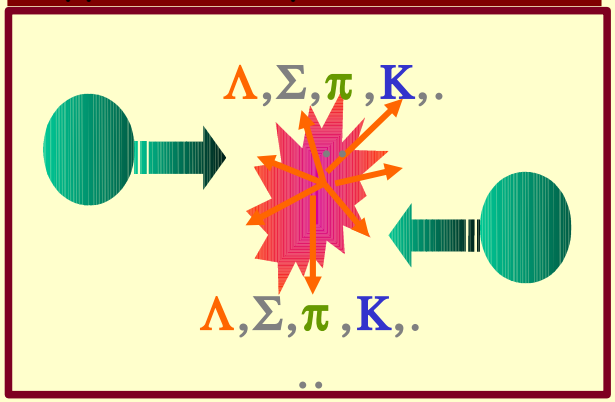
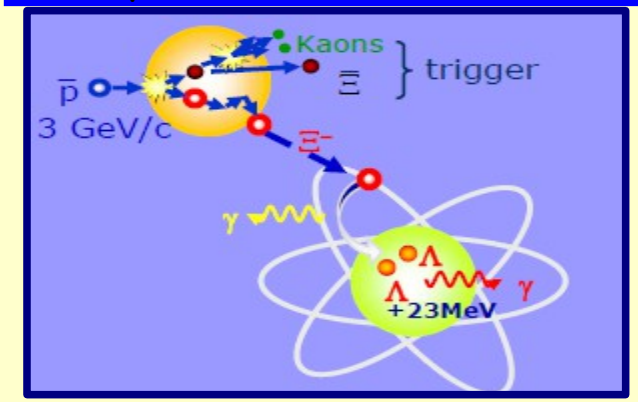
Introduction...

HypHI: Heavy-Ion collisions



antiproton-nucleus reactions



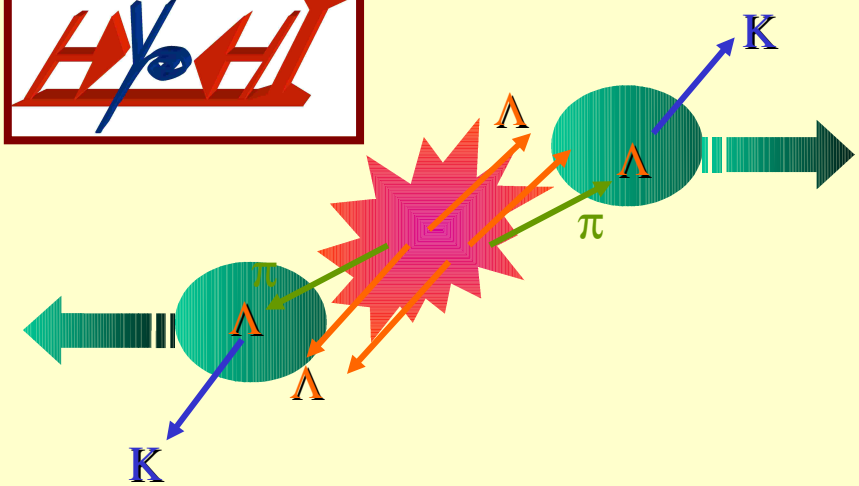
explore

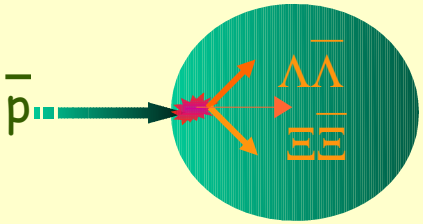
hyperon-baryon

hyperon-hyperon

- crucial to understand the strangeness sector of the hadronic EoS
- direct implications for nuclear astrophysics (max. mass of neutron stars)

Relativistic hypernuclei...





- **Production of hypernuclei in relativistic HIC / $\bar{p}$+X**

  hyperon production: pp->pΛK / $\bar{p}$p->$\Lambda\bar{\Lambda}$,$\Xi\bar{\Xi}$, (+) π,ρ,ω,... (σ_{abs} ~ 20mb)

  + Secondary rescattering (A.B. Larionov's talk for details)

  Multiple coalescence of hyperons with fragments

- **Theoretical framework**

  Phase-Space evolution Transport approaches (INC,BUU,RBUU,CBUU,(Ur)QMD,HSD,...)

  Description of fragment formation Statistical picture (SMM, Botvina & Mishustin)

  Description of hypernuclei formation?

  Phase-Space coalescence in coordinate and in momentum space

Giessen BUU...

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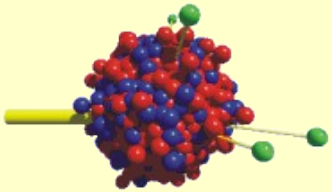
GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

Initial non-equilibrium stage



$$\left(p^*_\mu \partial^\mu_x + \left(p^*_\nu F^{\mu\nu} + m^*(\partial^\mu_x m^*)\right)\partial^{p^*}_\mu\right) f(x,p^*) = \mathcal{I}_{coll}[f(x,p^*),\sigma_{NN}]$$

$$F^{\mu\nu} = \frac{g_v^2}{m_v^2}\left(\partial^\mu j^\nu - \partial^\nu j^\mu\right) \quad \text{(repulsive "Lorentz"-contribution)}$$

$$m^* = M - g_\sigma \sigma \quad \text{(attractive part)}$$

(http://gibuu.physik.uni-giessen.de/GiBUU)

Relativistic mean-field

- Non-linear Walecka model (soft EoS) → Lalazissis parametrization
- Antibaryon-meson couplings: $g_\omega = -\xi g_\omega$, $g_\sigma = \xi g_\sigma$
- Isovector g_ρ (anti)baryon-meson interaction (no m* isospin splitting), coulomb

Collision term: as usual ... +

- primary: $\bar{p}p$->mesons
- Primary: $\bar{p}p$-> $\bar{\Lambda}\Lambda$, $\bar{\Xi}\Xi$ (data)
- Secondary: $\Lambda\Lambda(\Sigma)$<->Ξ B (data+Nijmegen-calc.), $\bar{K}B$->ΞK (data), ΛB<->ΣB (data)

Numerical realization (Test-Particle Ansatz):

- Initialization ➔ Propagation (Vlasov, collisions)

  Initialization: „test particles" initialized according to empirical density distributions

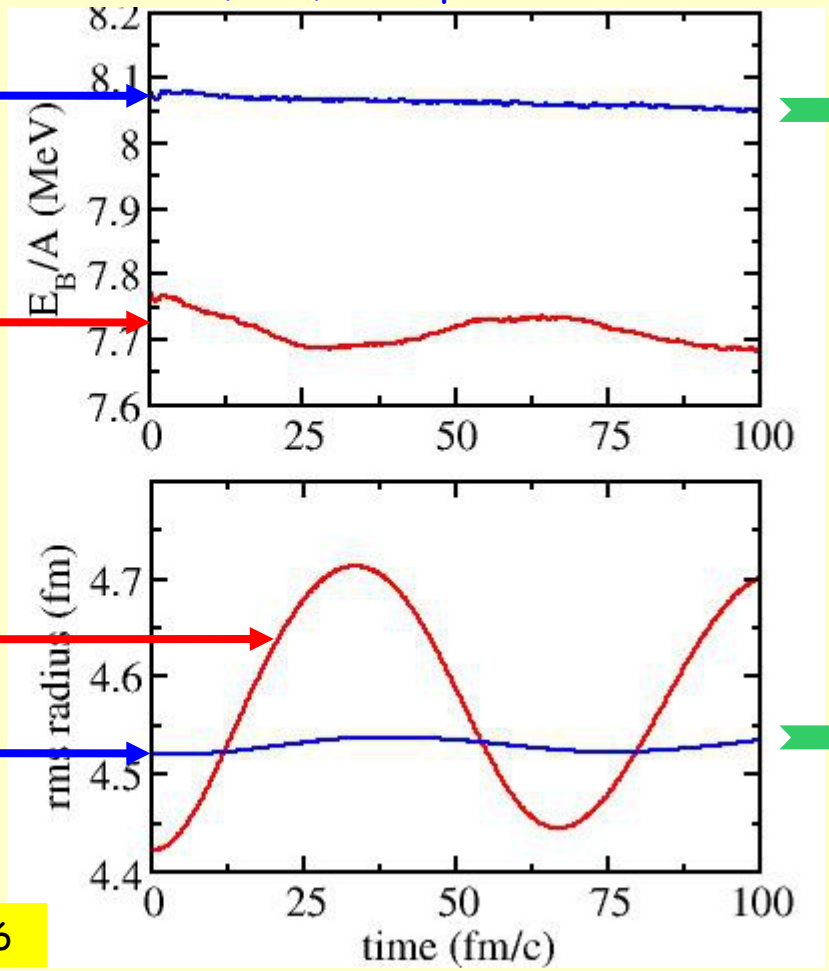
  Problem: density profiles not consistent with mean-field used in propagation

- Solution: Use the same energy density functional $\varepsilon[\rho_p,\rho_n]$ for initialization & propagation

  → Relativistic Thomas Fermi (RTF) for spherical nuclei

New initialization

Old initialization



Important in calculating E_{exc}

Old initialization

New initialization

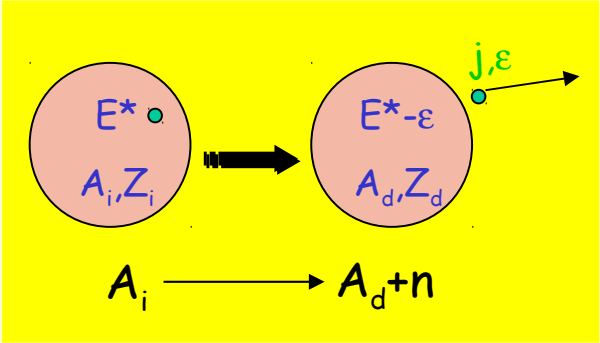
Important in calculating A,Z

PR **C81**, (2010), 054316

GiBUU+SMM...

Asymptotic equilibrated stage

- Statistical Multifragmentation Model (SMM)
- Fission/spallation, evaporation, multifragmentation... (with increasing excitation)
- Statistical determination of partial decay widths → Monte-Carlo method



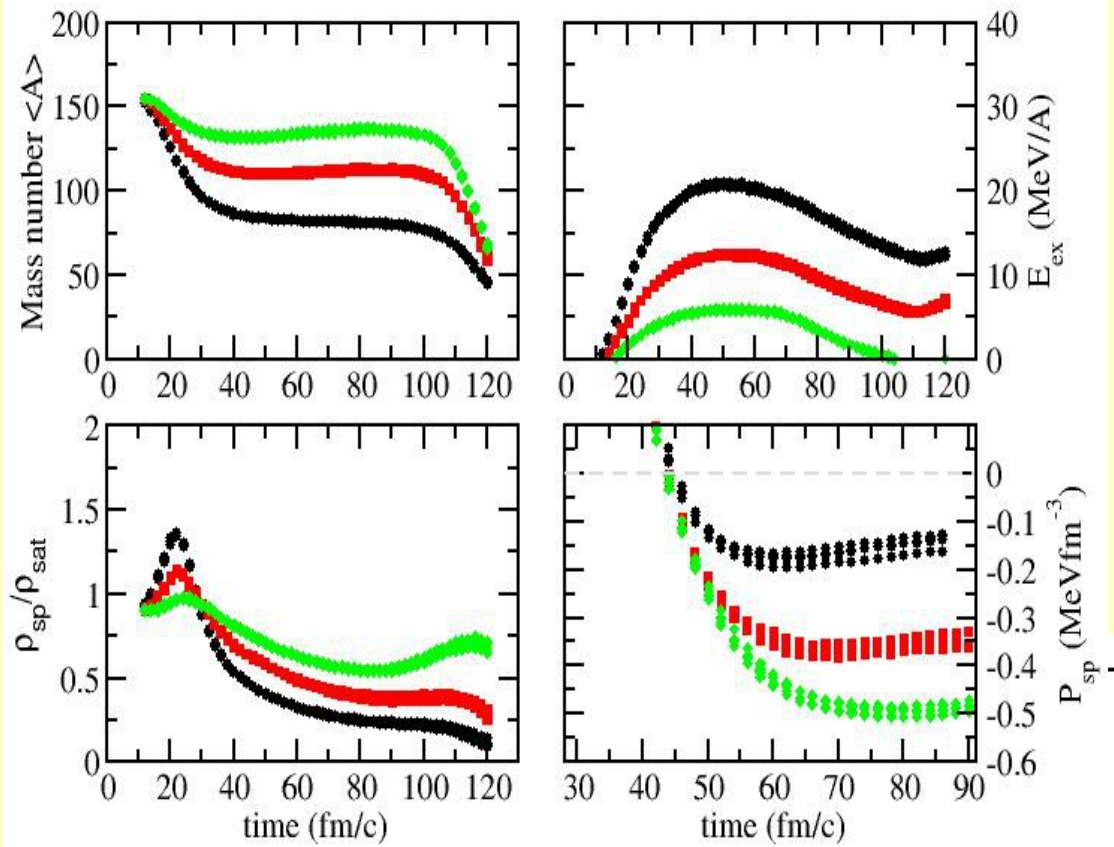
$$\Gamma_j = \int_V^{E^*} \mathcal{P}_j(\epsilon)\, d\epsilon$$

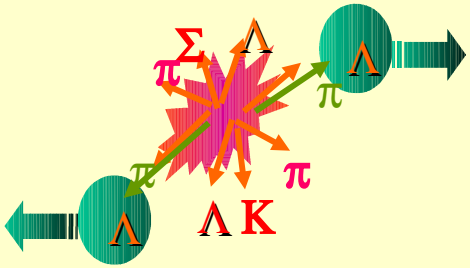
SMM code: Botvina & Mishustin, PR257('95) 133

Hybrid GiBUU+SMM...

* Non-Equilibrium dynamics within BUU until source(s) approaches stable configuration and local equilibration at $t=t_f$
* Determination of **mass (A)**, **charge (Z)** and **excitation energy E_{exc}** of a source at time $t=t_f$, then apply SMM

HypHI-project: C+C@2AGeV…





- Def. of Spectators

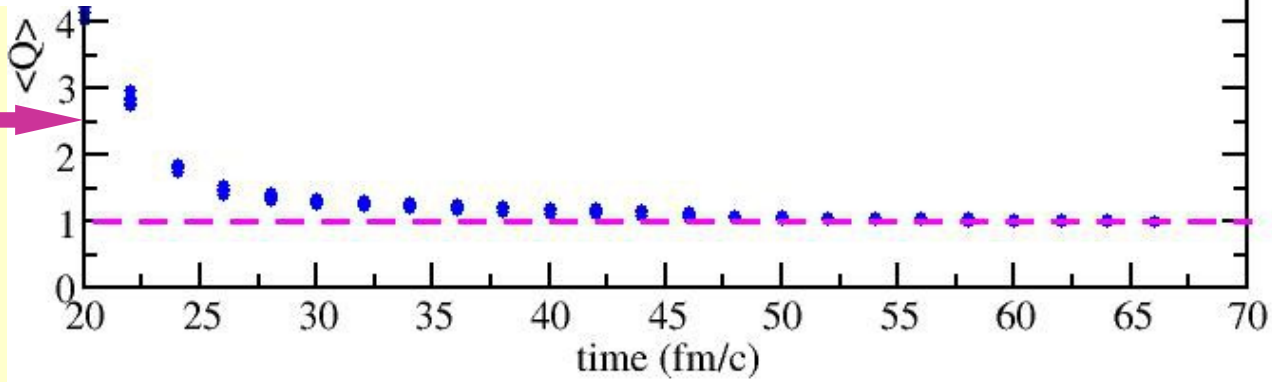
$Y^{(0)} > 0.75 + \rho > \rho_{sat}/100$

- Spectators

Well defined conditions after onset of instability…

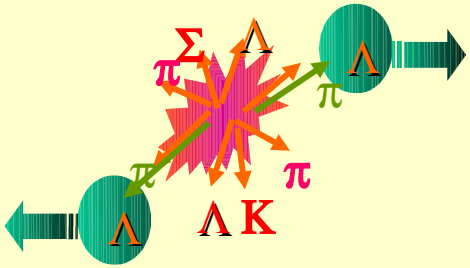
- Spectators

…and onset of equilibration



PL **B663**, 197 (08) & PL**B675** (09) 297

HypHI-project: Li+C@2AGeV...

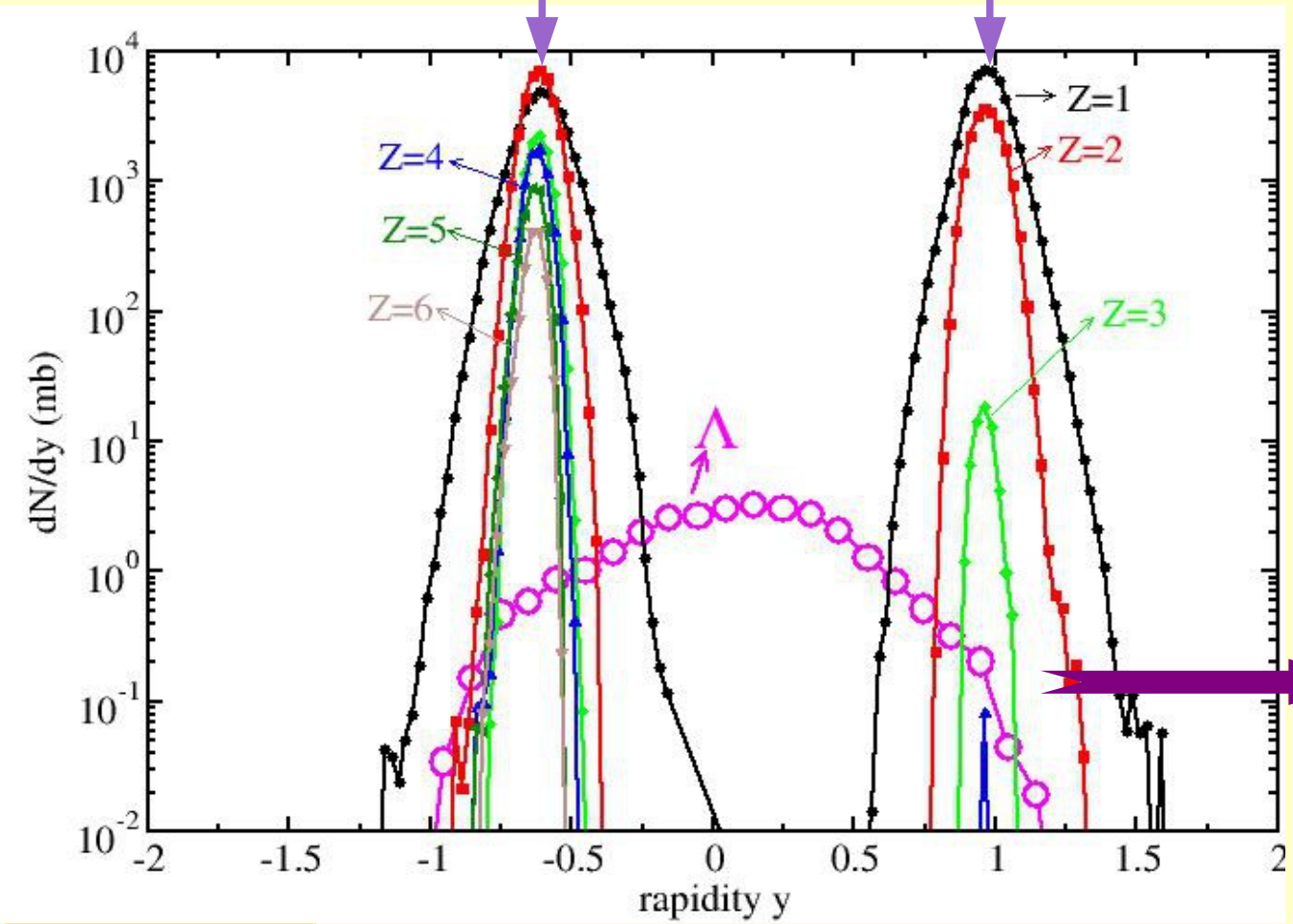


BUU: fragmenting sources & strangeness (consistent with FOPI/KaoS)

SMM: spectator fragmentation (consistent with ALADIN)

^{12}C-fragmentation

^{6}Li-fragmentation

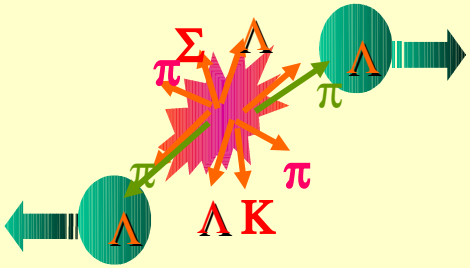


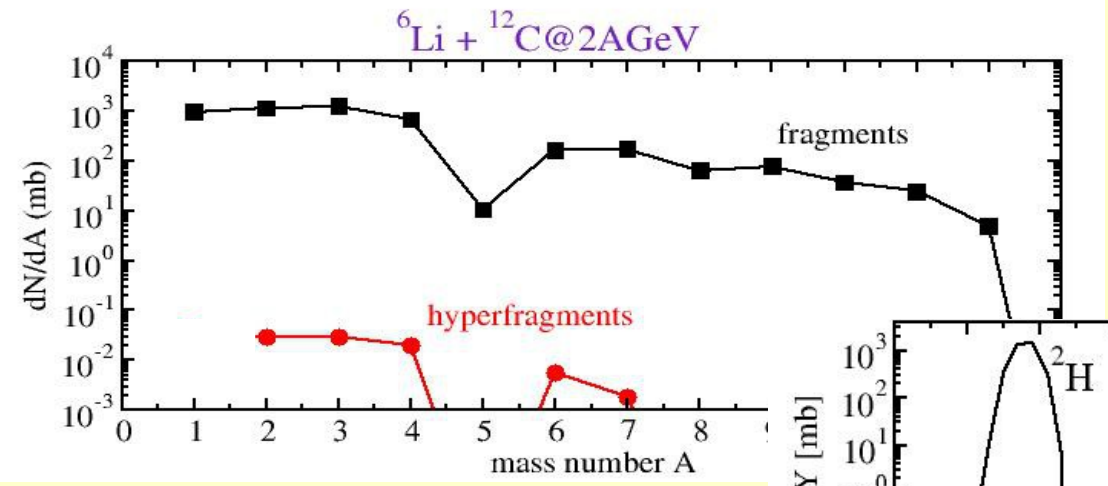
Λ & ^X coalescence possible

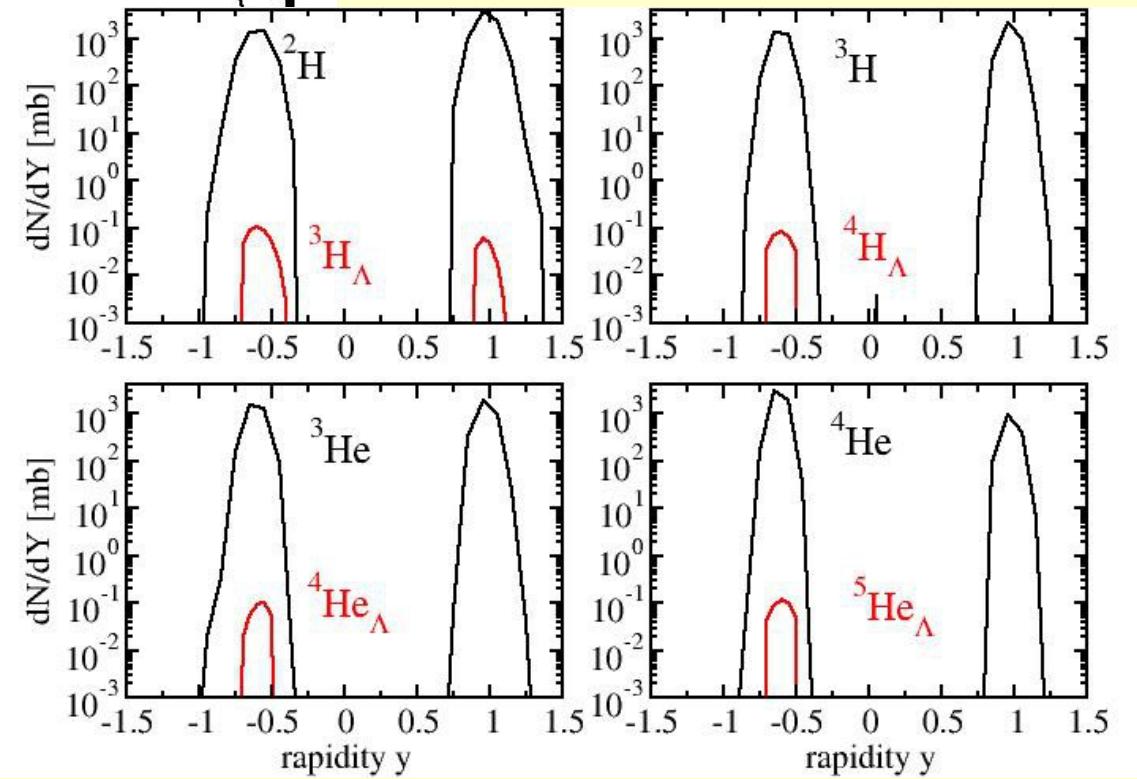
In preparation...

HypHI-project: Li+C@2AGeV...

Coal.: momentum coalescence for Λ close to spectators



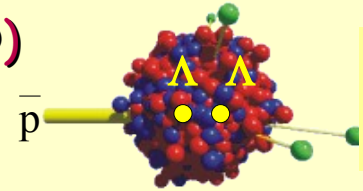


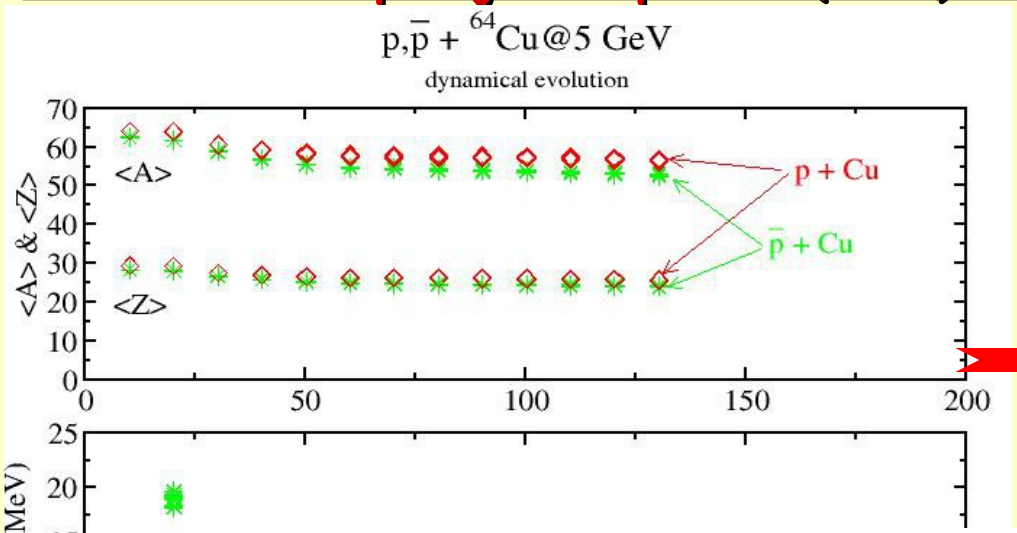


Predictions: projectile/target fragmentation: $\sigma(^3H_\Lambda, {}^{4,5}He_\Lambda) \sim (6\text{-}10)\mu b$

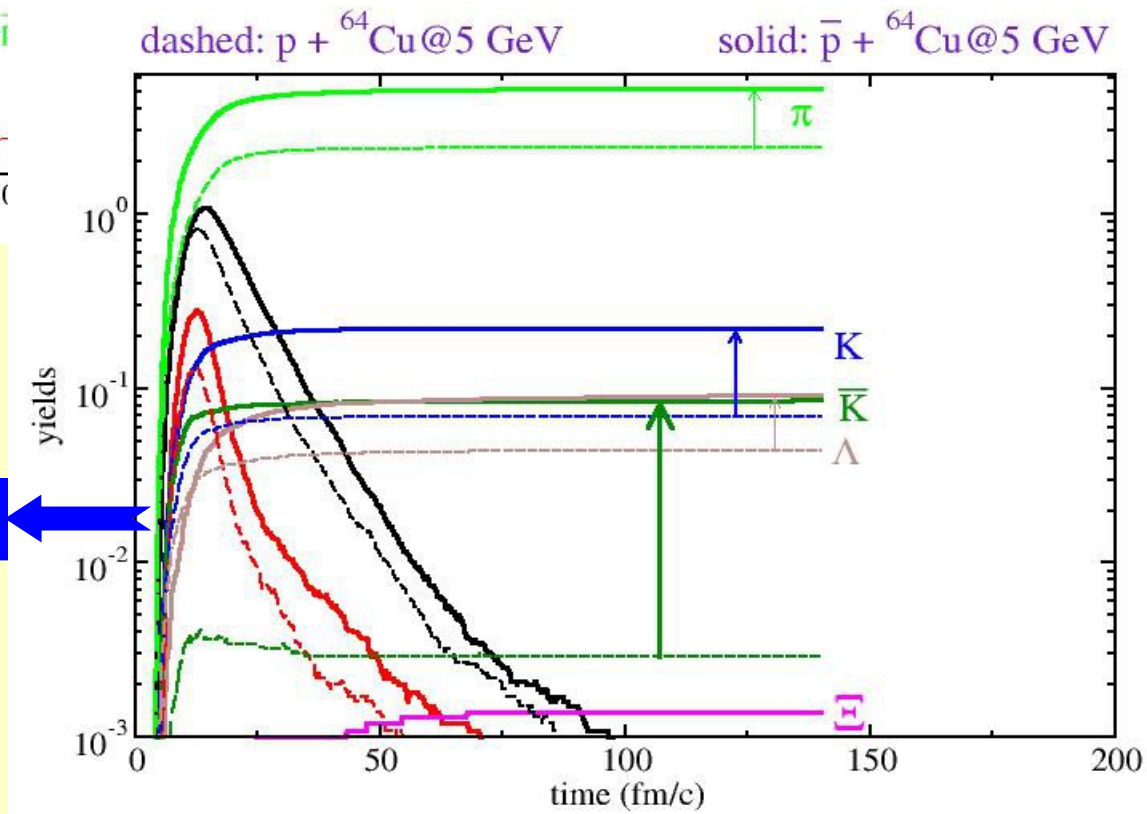
In preparation...

PANDA-subproject: $\bar{p}$+X@(3-5)GeV…(Why $\bar{p}$-nucleus ?)





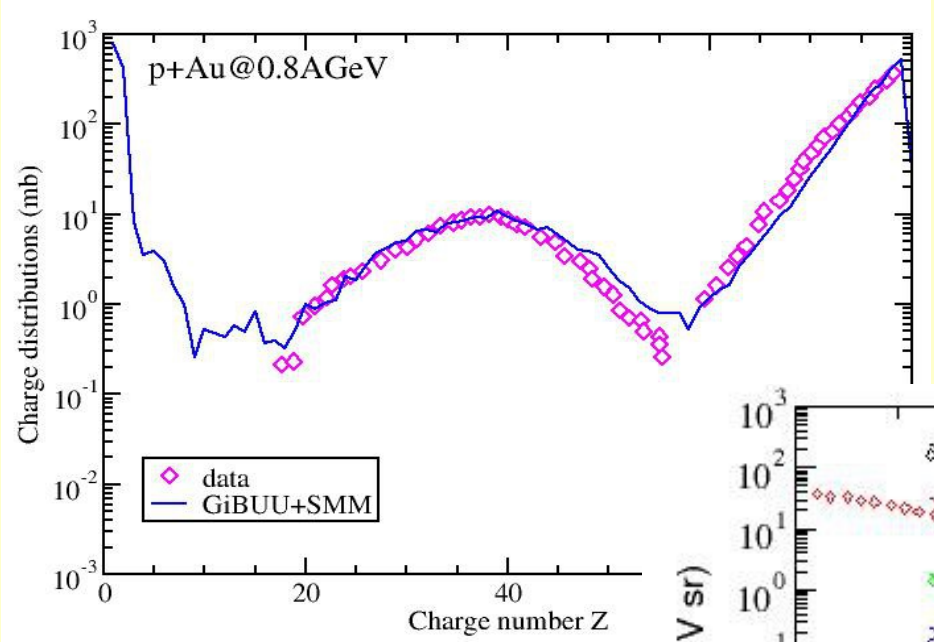
Residual source: minor differences



Particle yields: huge differences

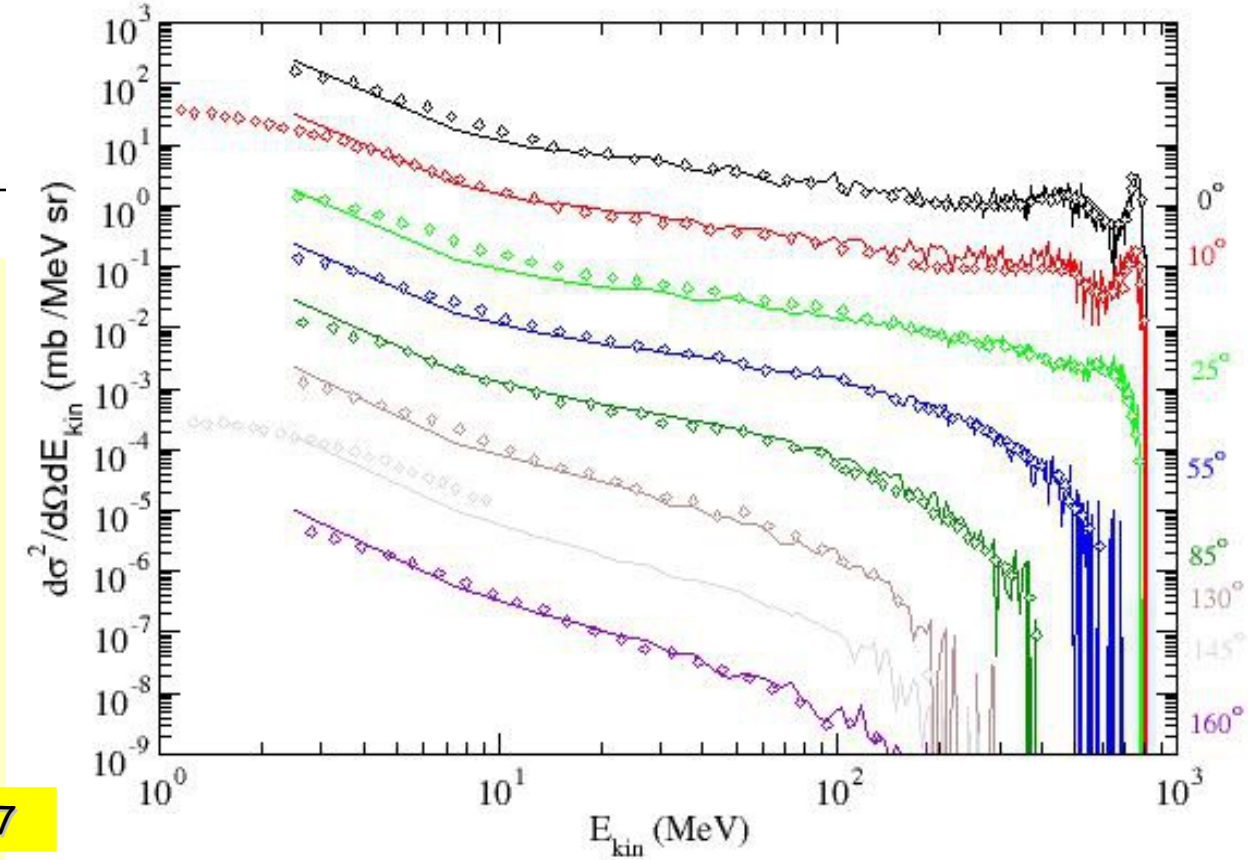
In preparation…

fragmentation in p+X...(reminder)



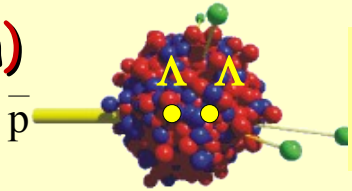
data

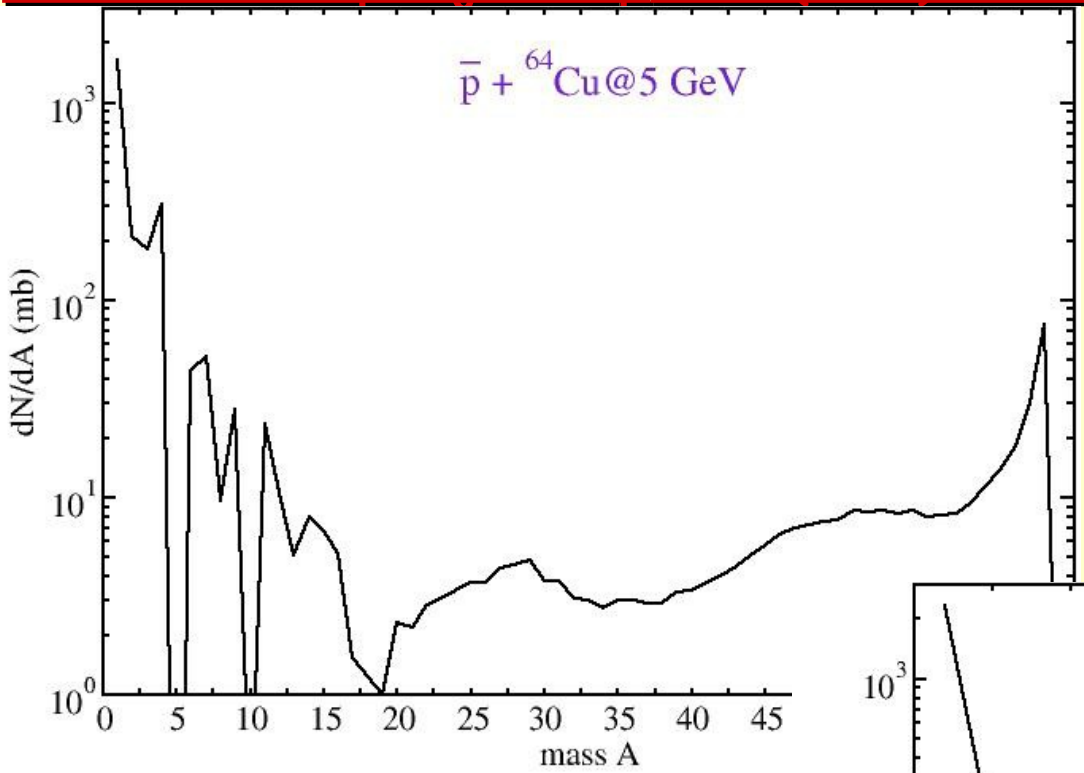
J. Benlliure et al., Nucl. Phys. A683 (2001) 513.
F. Rejmund et al., Nucl. Phys. A683 (2001) 540
(Saclay) S. Leray et al., PRC65,044621



PL **B663**, 197 (08) & PL**B675** (09) 297

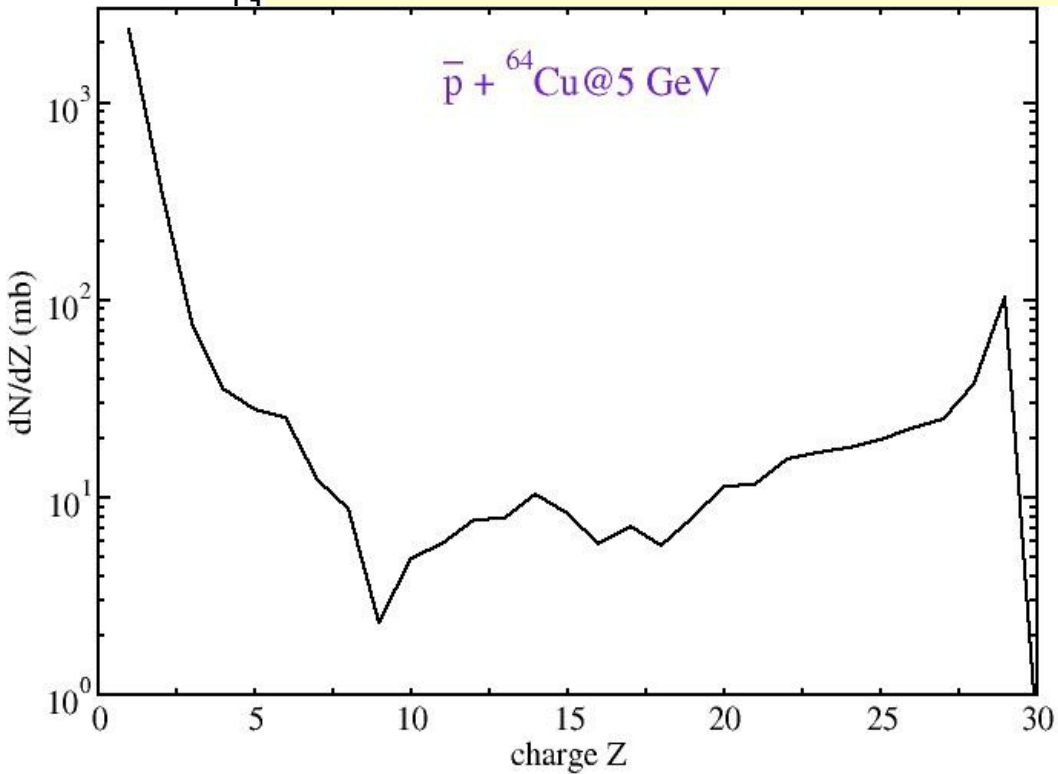
PANDA-subproject: $\bar{p}$+X@(3-5)GeV… (fragmentation)





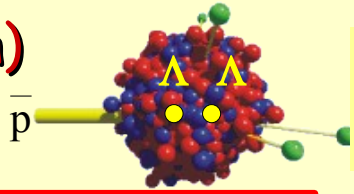
Mass distribution…

…Charge distribution



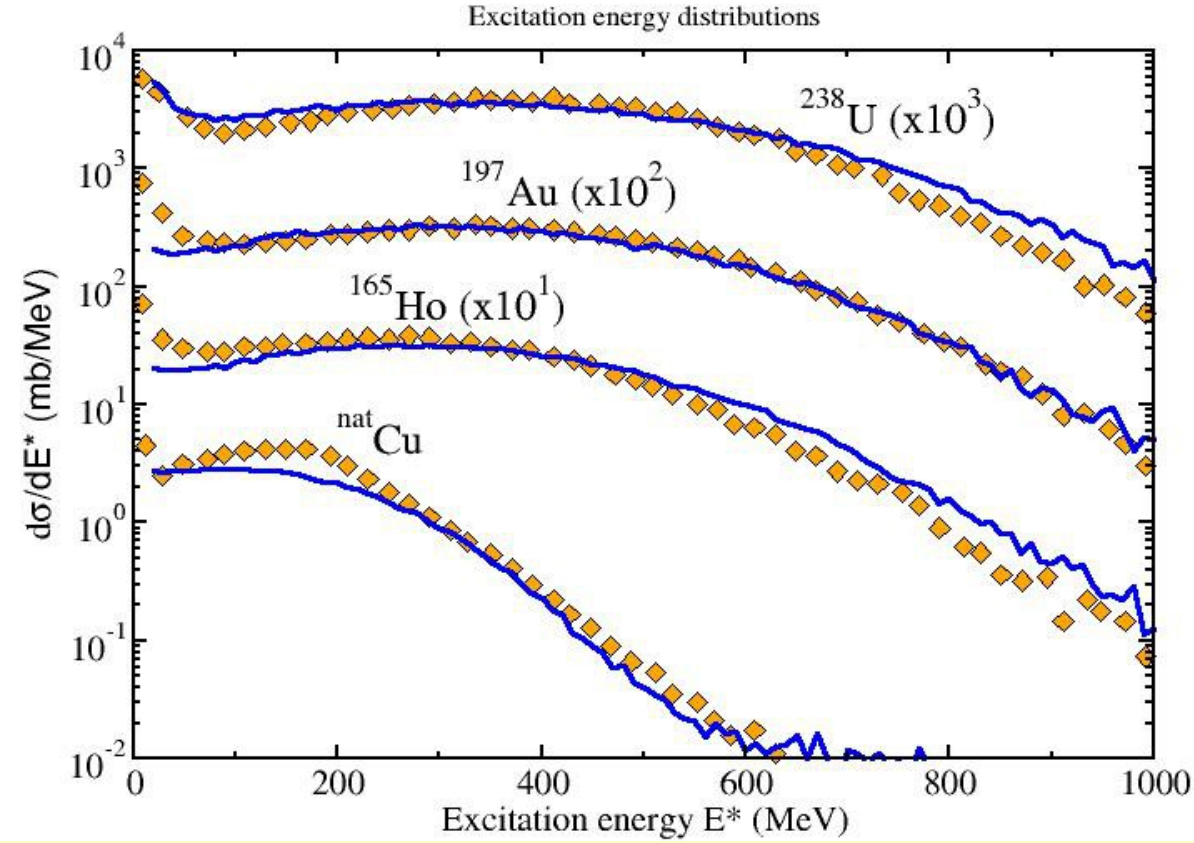
In preparation…

PANDA-subproject: $\bar{p}$+X@(3-5)GeV… (fragmentation)



$E^* = E_{\bar{p}} + (M_{targ} - B_{targ})A_{targ} - (M_{res} - B_{res})A_{res} - E_{em} - E_{rec}$ (energy balance event-by-event)

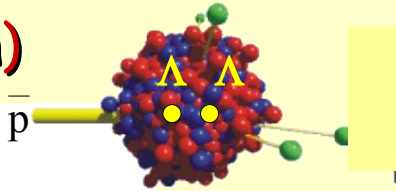
data: PRC63, 034616 $\bar{p}$+A@1.22 GeV



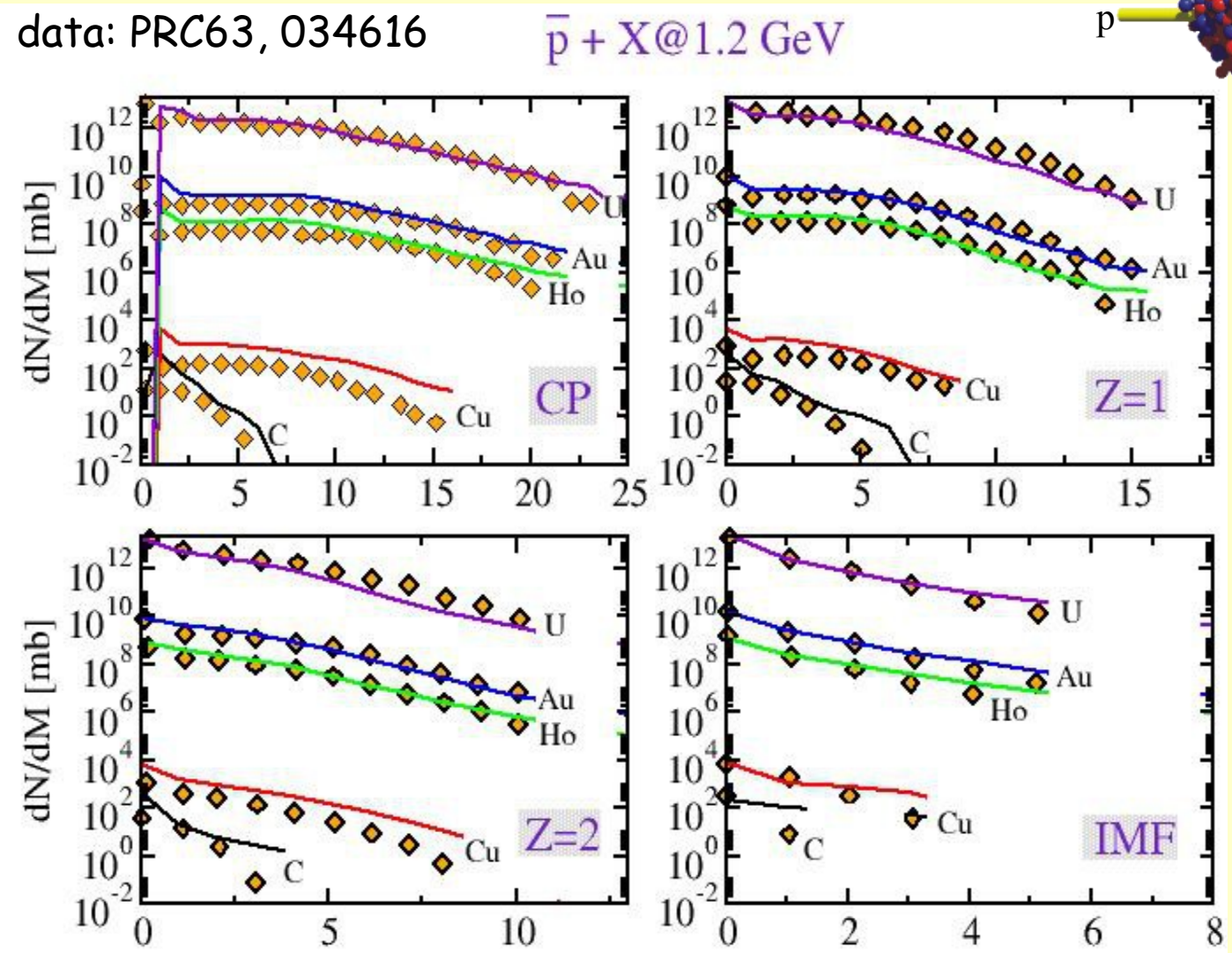
Good description of excitation spectrum

In preparation…

PANDA-subproject: $\bar{p}$+X@(3-5)GeV... (fragmentation)



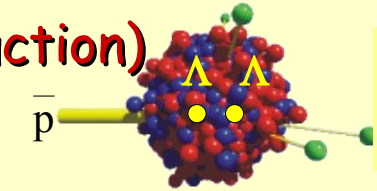
data: PRC63, 034616

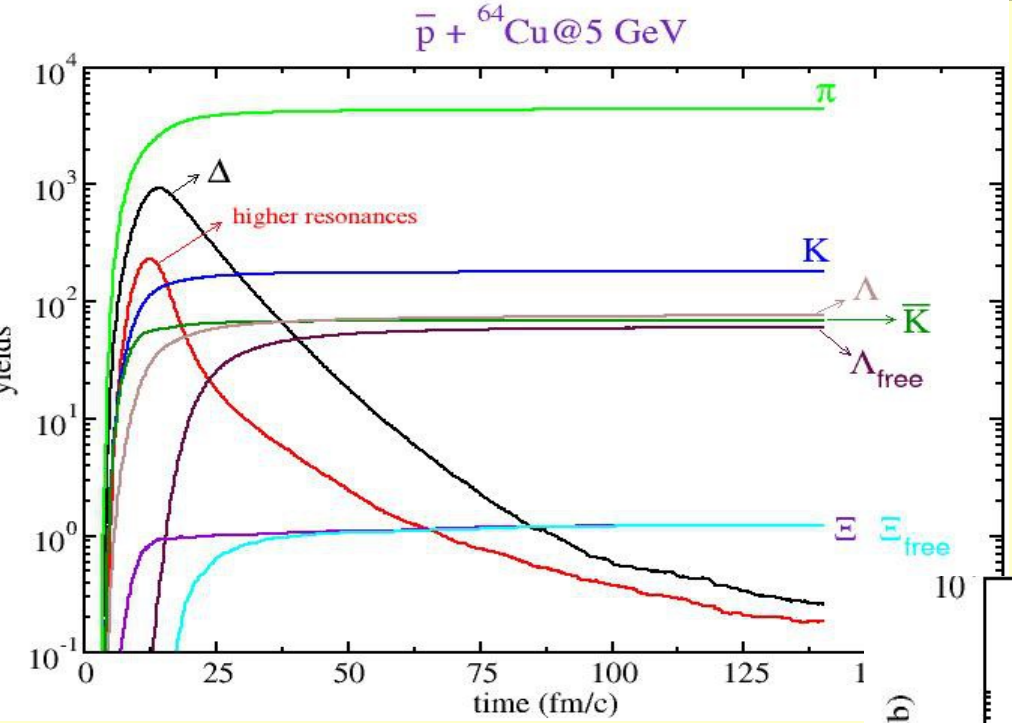


→ Overal good description of different fragment multiplicities

In preparation...

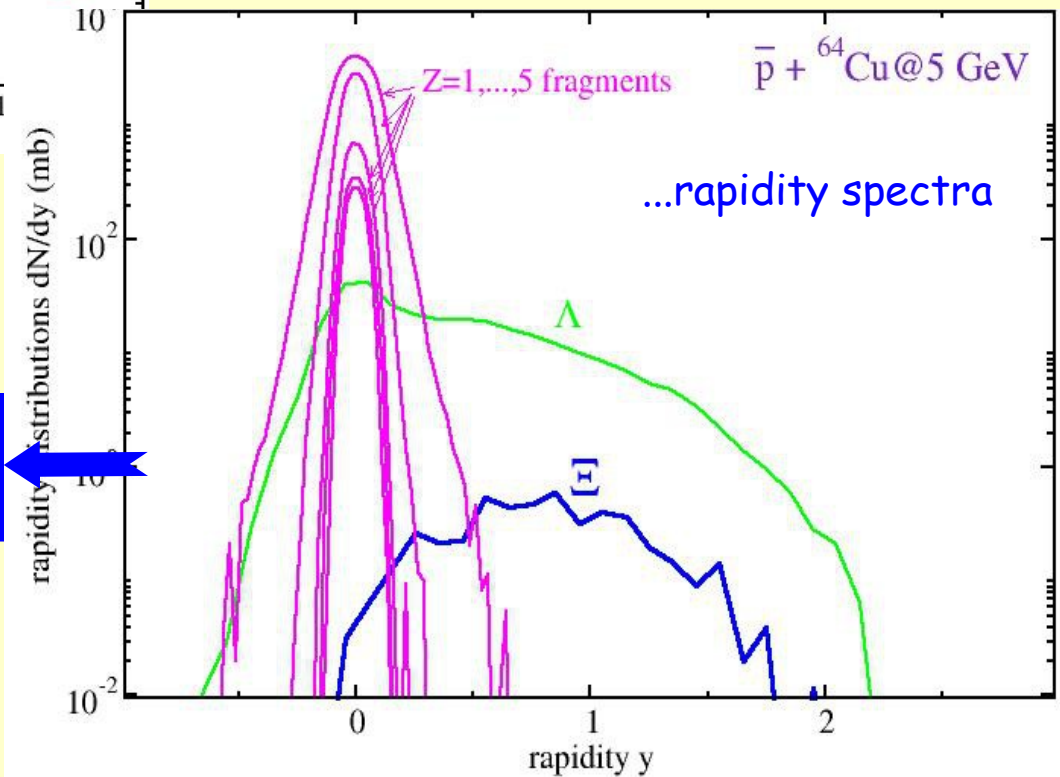
PANDA-subproject: $\bar{p}$+X@(3-5)GeV...(particle production)





Strangeness production...

(consistent with data-> Larionov's talk)

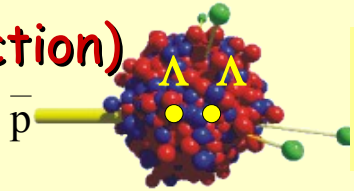


Coalescence with stopped Λ's possible

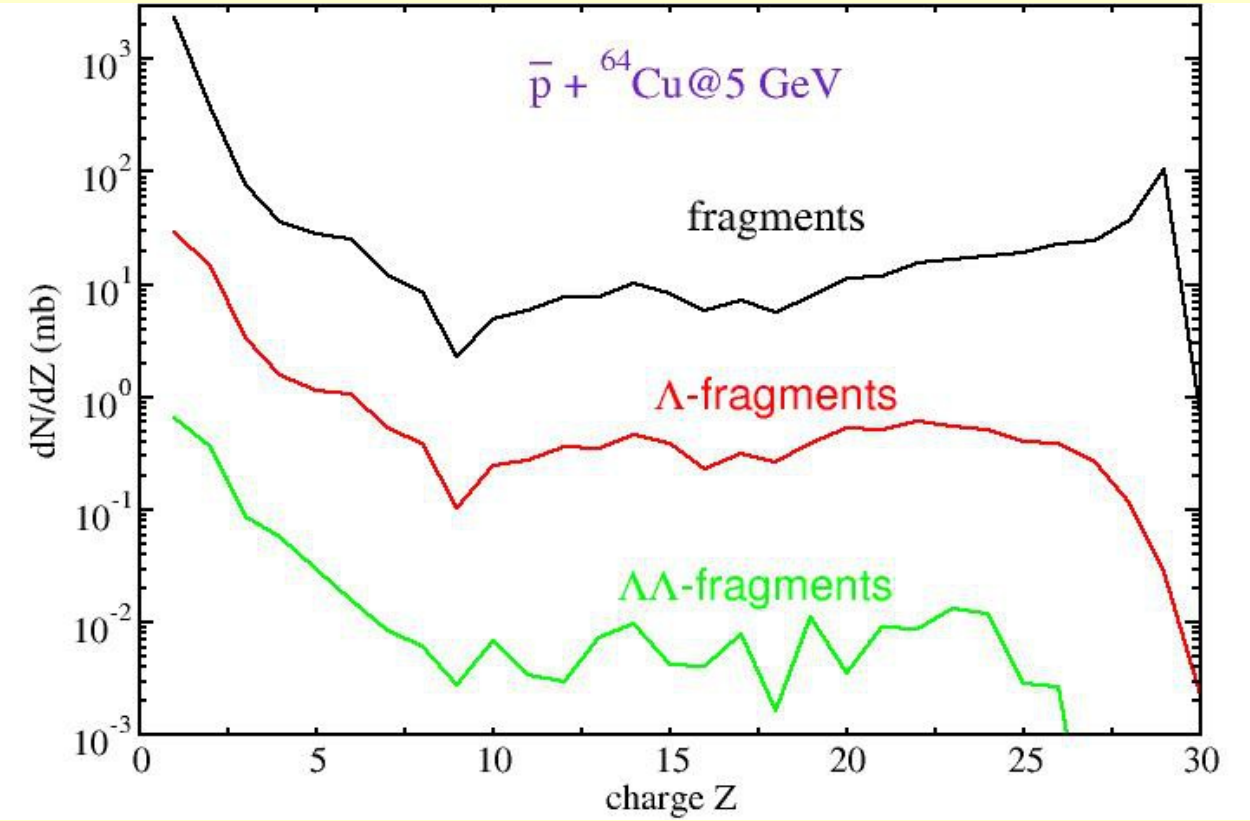
No coalescence with Ξ's (in 2th target)

In preparation...

PANDA-subproject: $\bar{p}$+X@(3-5)GeV...(particle production)



Coal.: momentum coalescence with captured Λ



...charge distributions

Production of single-Λ & double-Λ hypernuclei possible

Production of double-Λ hypernuclei via Ξ-capture in 2th target...

In preparation...

Final remarks...

- **Theoretical studies: "FAIR" @ Giessen**
  → GiBUU+SMM: NE-dynamics + statistical process of fragmentation
  → suitable tool for HypHI- & PANDA-reactions

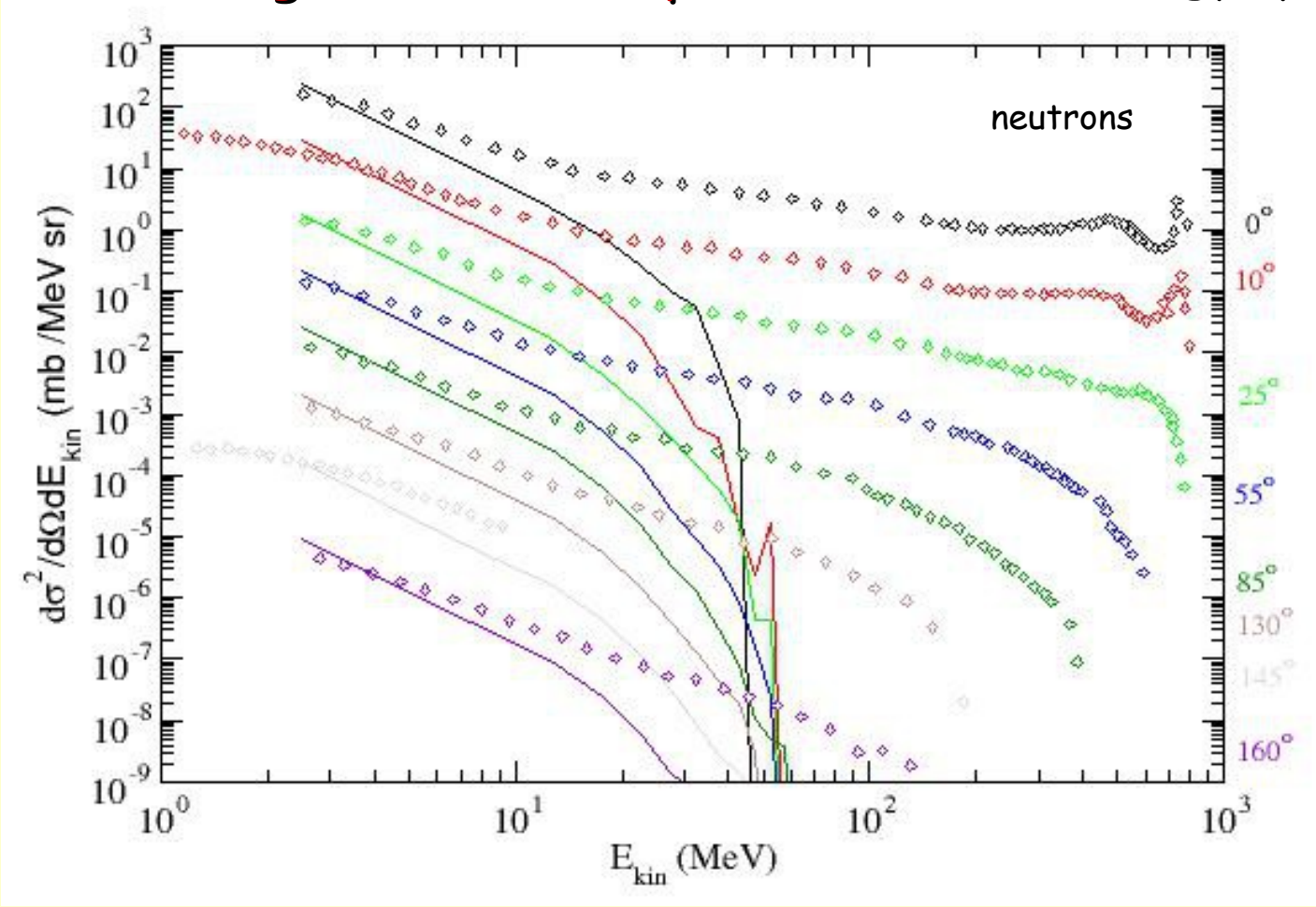
- **Benchmark tests (low energy)**
  → proper description of fragmentation process in p- & $\bar{p}$-reactions and in heavy-ion collisions

- **First predictions on single-Λ hypernuclei (HypHI)**
  → $\sigma \sim \mu b$ for ${}_{\Lambda}H$ & ${}_{\Lambda}He$ in spectator/target fragmentation in HIC
  → consistency with HypHI-experiment... (on work together with T. Saito)

- **First predictions on double-Λ hypernuclei (PANDA)**
  → multiply coalescence of captured Λ's already in first target
  → Ξ's escape, might need 2th target...(on work)

Backup slides

Application-I: Fragmentation in p+X@0.8 GeV (energy spectra…)

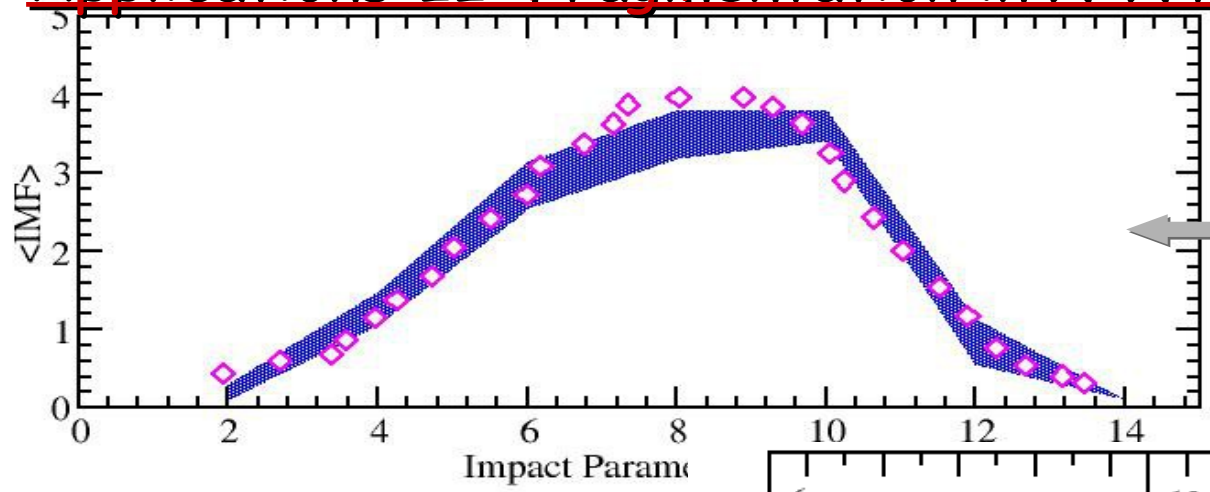


- Final Result: Hybrid GiBUU+SMM
- Asymptotic final state (SMM): Statistical decay of excited source
- Pre-Equilibrium (GiBUU): high-energy n-emission, QE-peak

data: S. Leray et al., PRC65,044621

Prog. Part. Nucl. Phys. (2009), in press (arXiv:0811.3506)

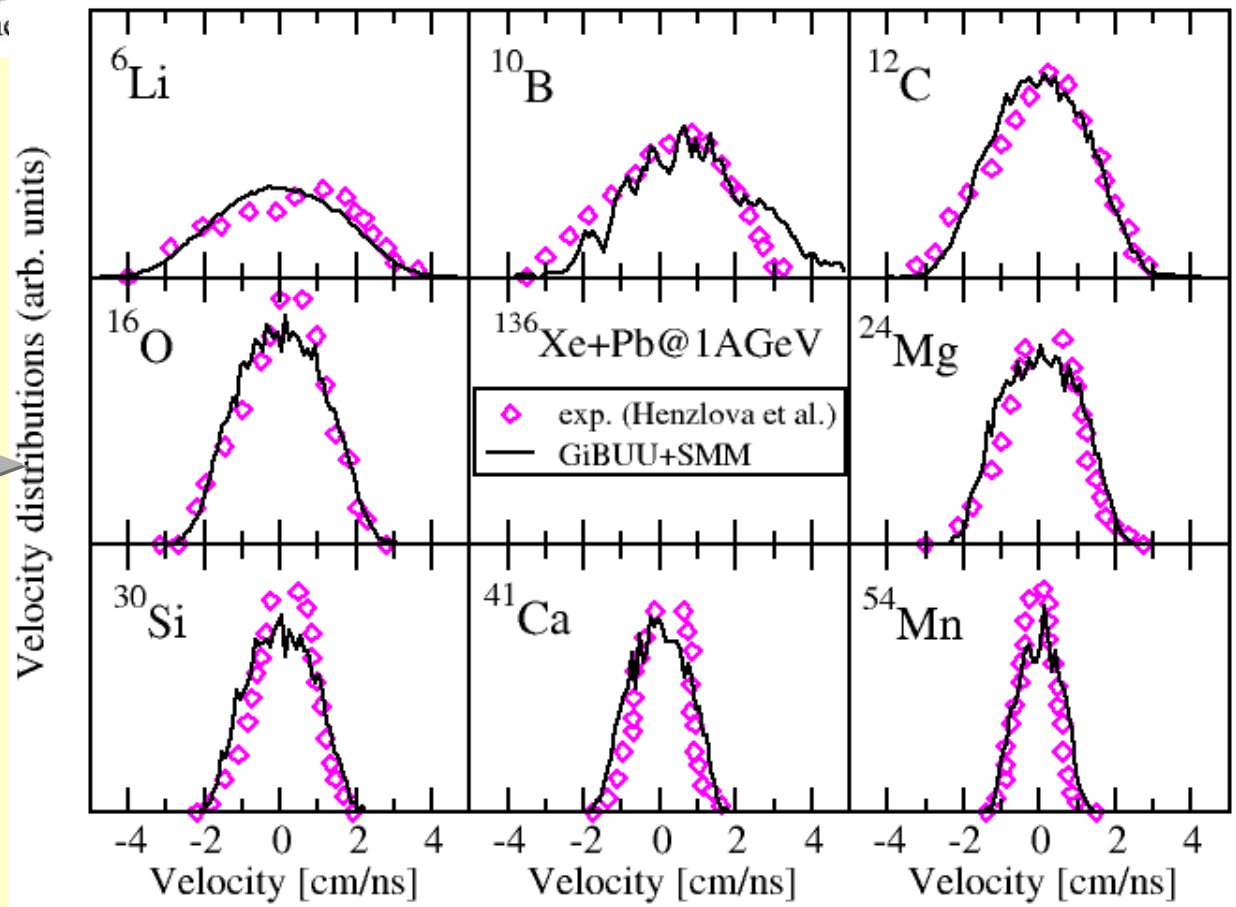
Applications-II: Fragmentation in X+X reactions



absolute yields from spectator fragmentation in Au+Au@0.6AGeV

(ALADIN-data)

fragment velocity spectra in Xe+Pb@1.0AGeV

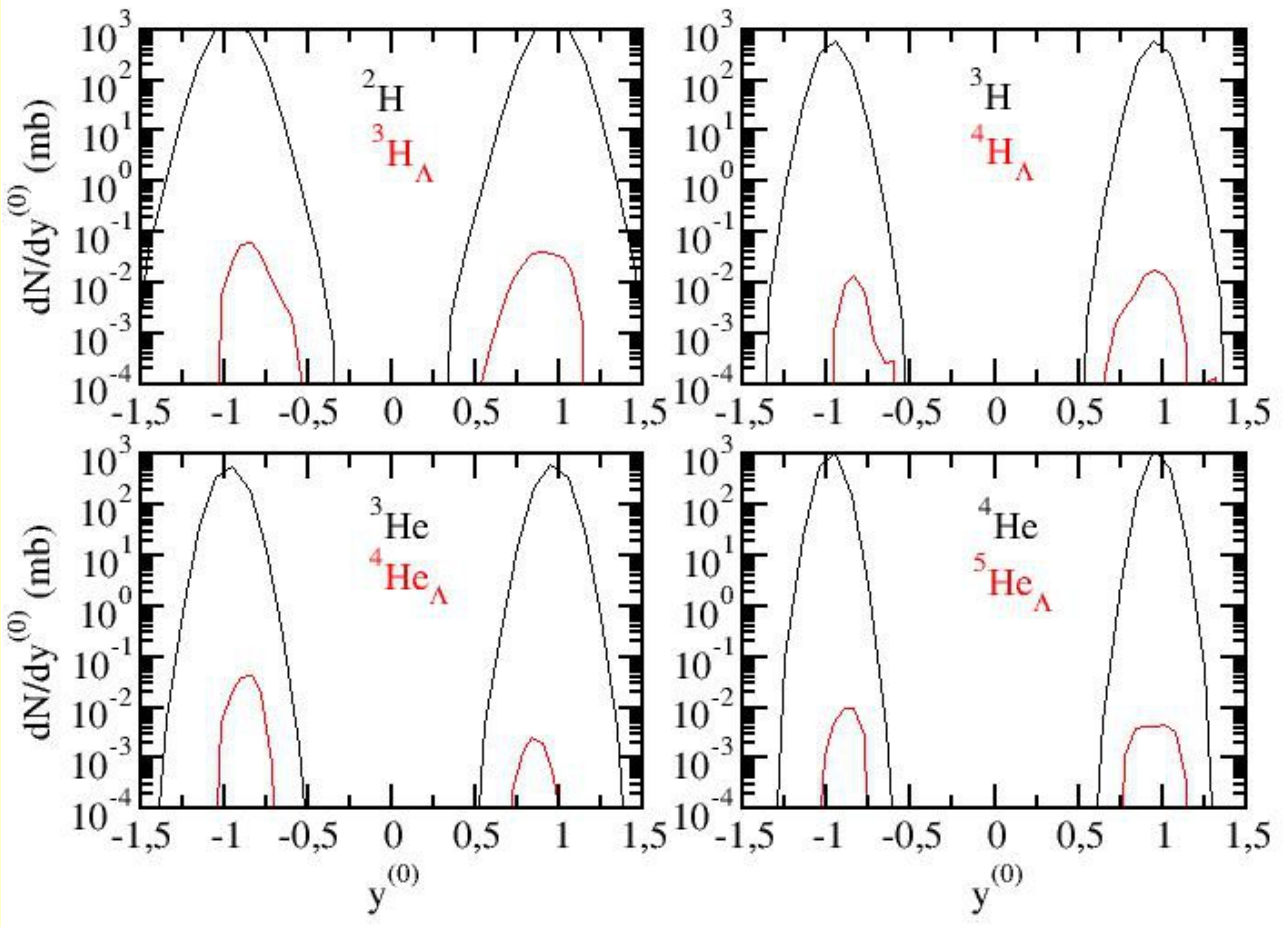


data:

Henzlova, PRC78, 044616

Applications-II: Hypernuclei in spectator fragmentation…

(HypHI, $^{12}C+^{12}C$@2AGeV)



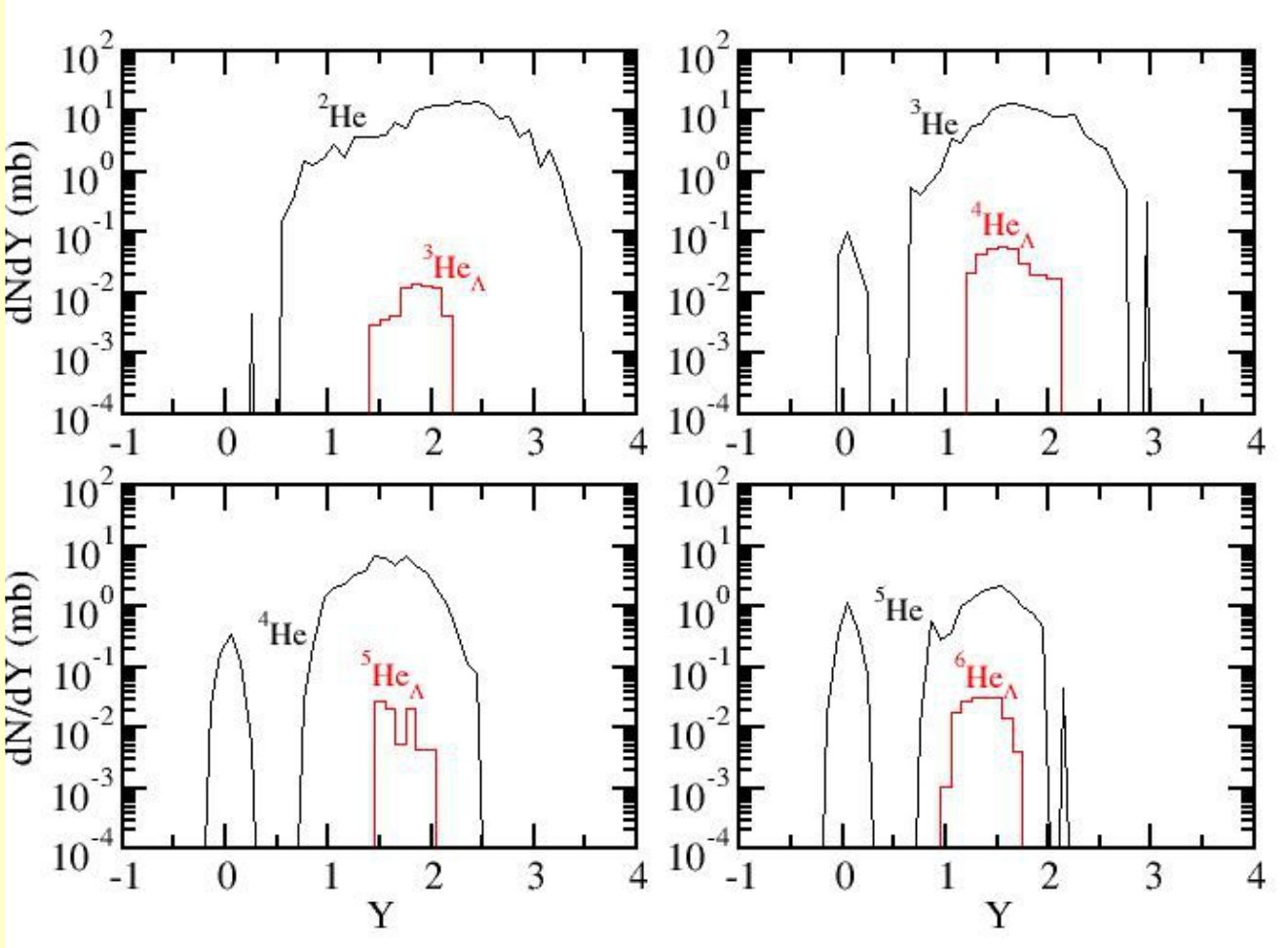
- First transport theoretical predictions: total yields ~μb
- Consistent with previous studies: M.Wakai, NPA547(92)89c

Prog. Part. Nucl. Phys. (2009), in press
(arXiv:0811.3506)

Phys. Lett. B (2008), submitted

Applications-II: Hypernuclei from high energy proton-induced reactions…

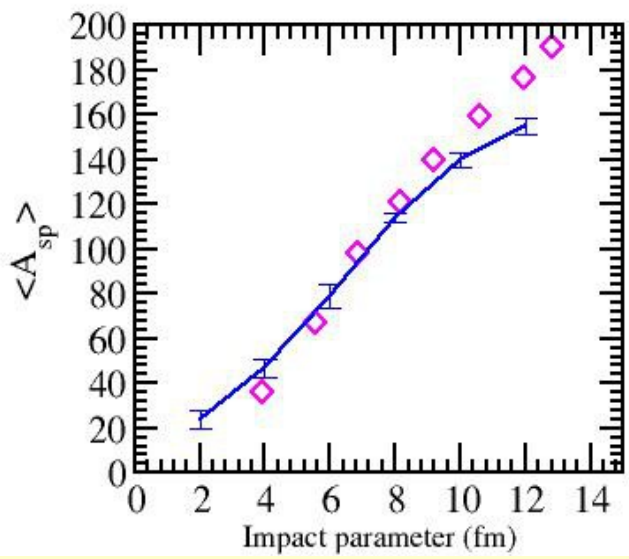
(PANDA/J-PARC, p+^{12}C@50GeV)

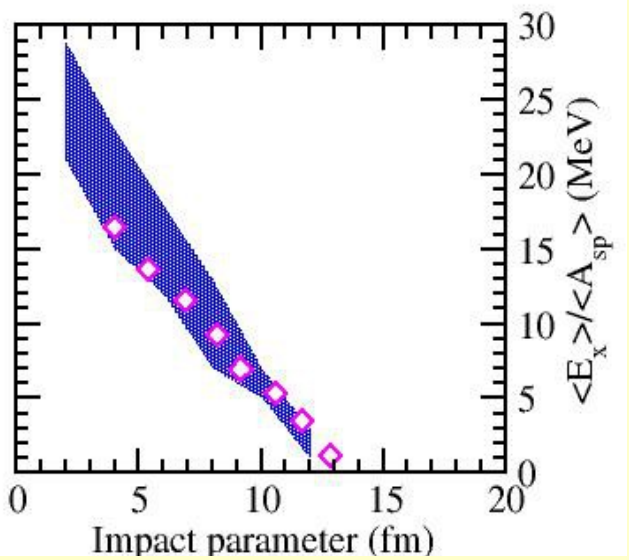


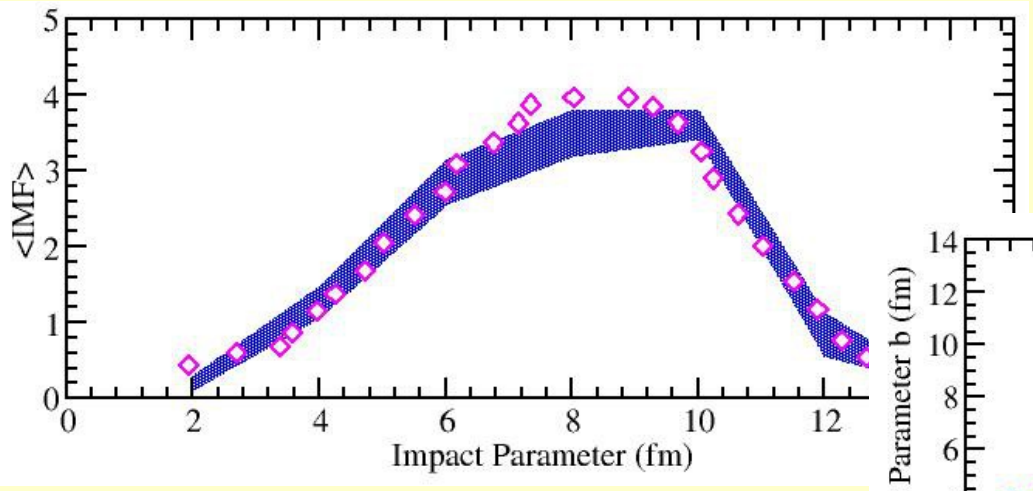
- Two sources (residual target+moving source)
- Most of hyperons created & rescatter inside moving source

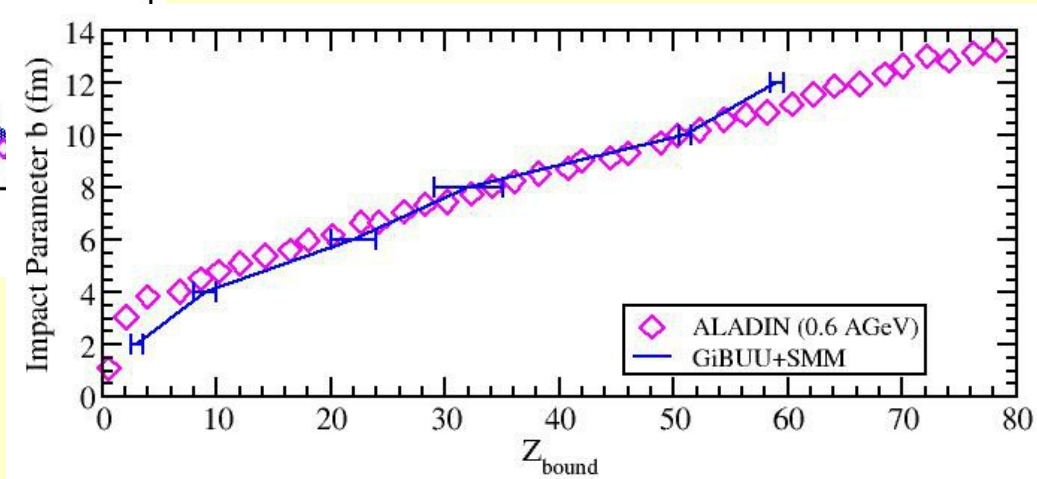
Prog. Part. Nucl. Phys. (2009), in press (arXiv:0811.3506), Phys. Lett. B (2008), submitted

Getting started: Spectator fragmentation at Au+Au@0.6 GeV





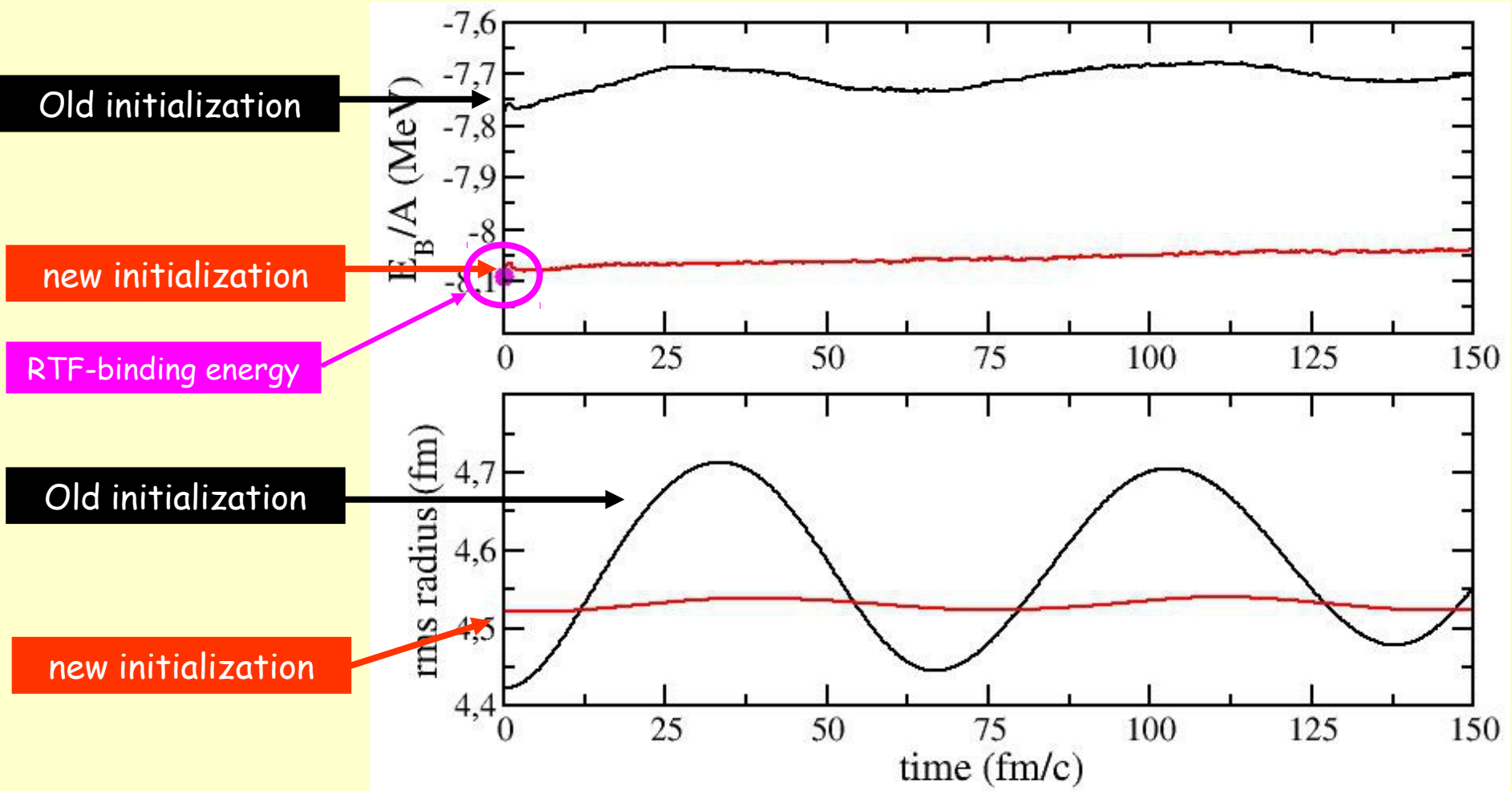




Prog. Part. Nucl. Phys. (2009), in press

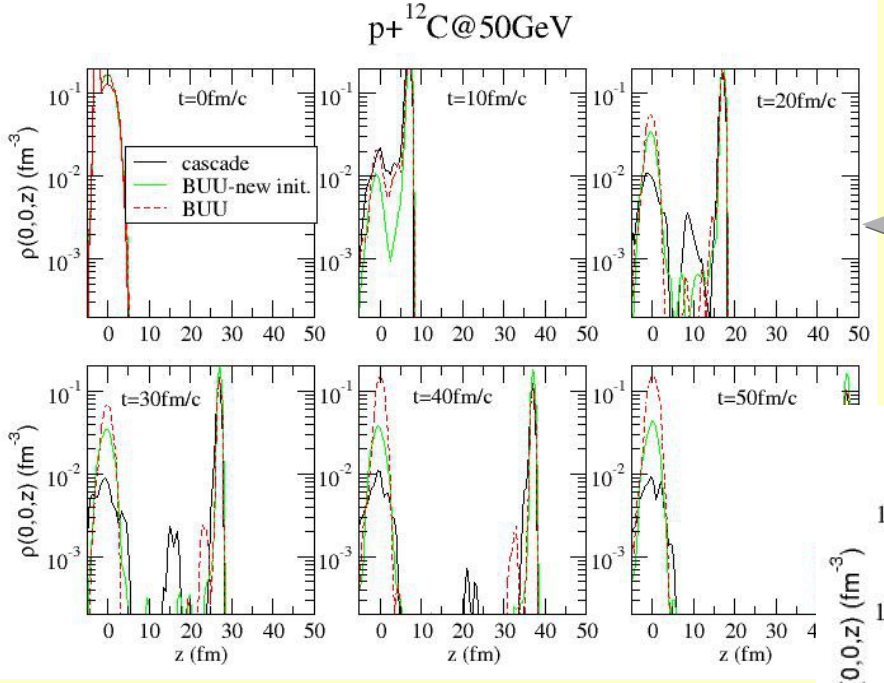
Phys. Lett. B (2008), submitted

New initialization: Binding energy & rms-radius in BUU…



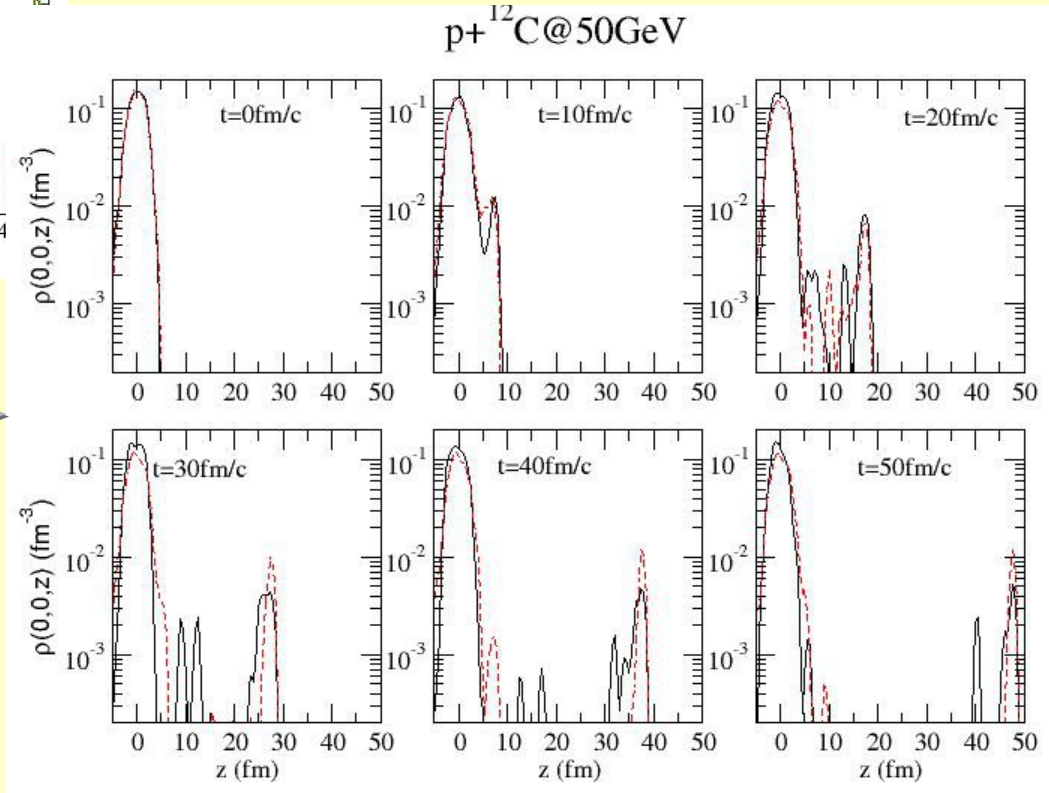
Mean-field vs cascade – the role of the mean-field…

(PANDA/J-PARC, p+^{12}C@50GeV)



central

peripheral



Ground state in BUU-II: Results (application to proton-induced reactions)