Multi-Strangeness Production in Hadron Induced Reactions

T. Gaitanos, Ch. Moustakidis, G.A. Lalazissis

ΤΜΗΜΑ ΦΥΣΙΚΗΣ
ΑΡΙΣΤΟΤΕΛΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΟΝΙΚΗΣ

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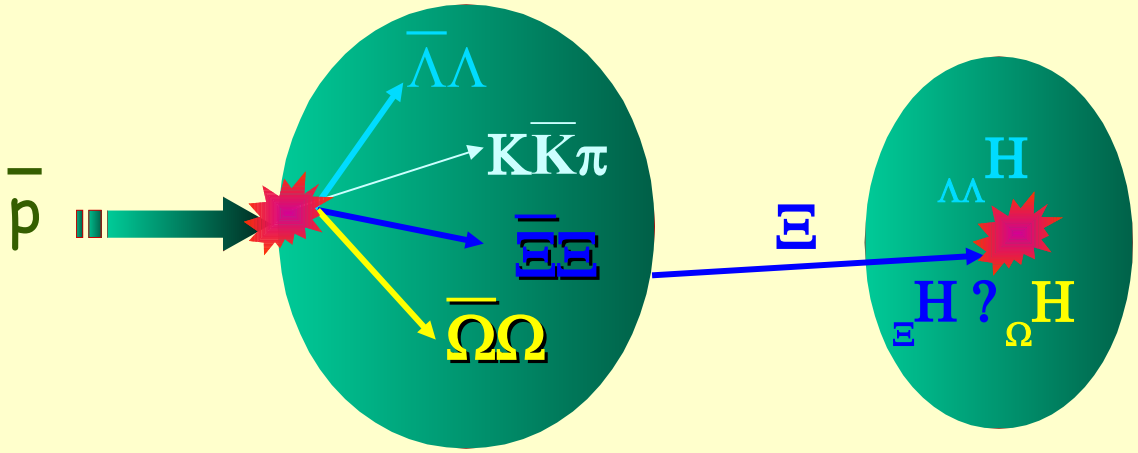
T. Gaitanos, Ch. Moustakidis, G.A. Lalazissis, H. Lenske, arXiv:1602.08905, Nucl.Phys. (2016), in press

Athens, 08.04.16

Outline…



- Introduction
- Theoretical aspects

  GiBUU+SMM hybrid transport model,

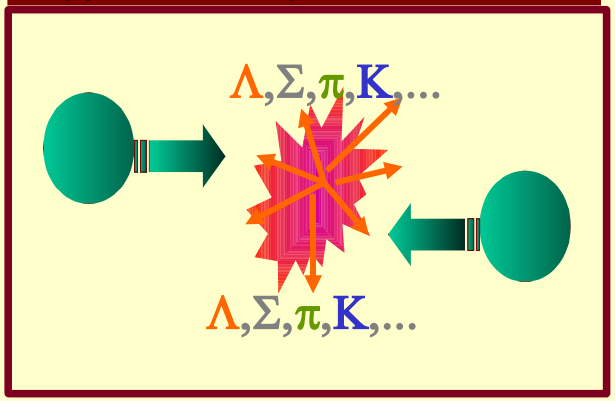
  Mean-field, YN interaction models & parametrizations
- GiBUU+SMM in $\bar{p}$-induced & Ξ-induced reactions ($\bar{P}$ANDA)

  double-strangeness ($\Lambda\Lambda$, Ξ) hypernuclei & the YN-interaction

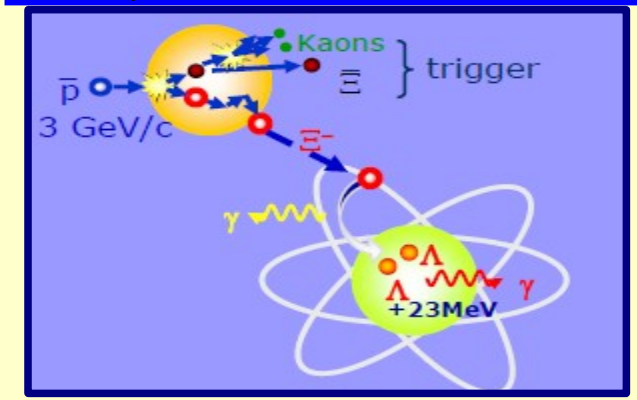
  remarks on multi-strangeness (Ω) hypernuclei
- Final remarks

Introduction...

HypHI: Heavy-Ion collisions



antiproton-nucleus reactions



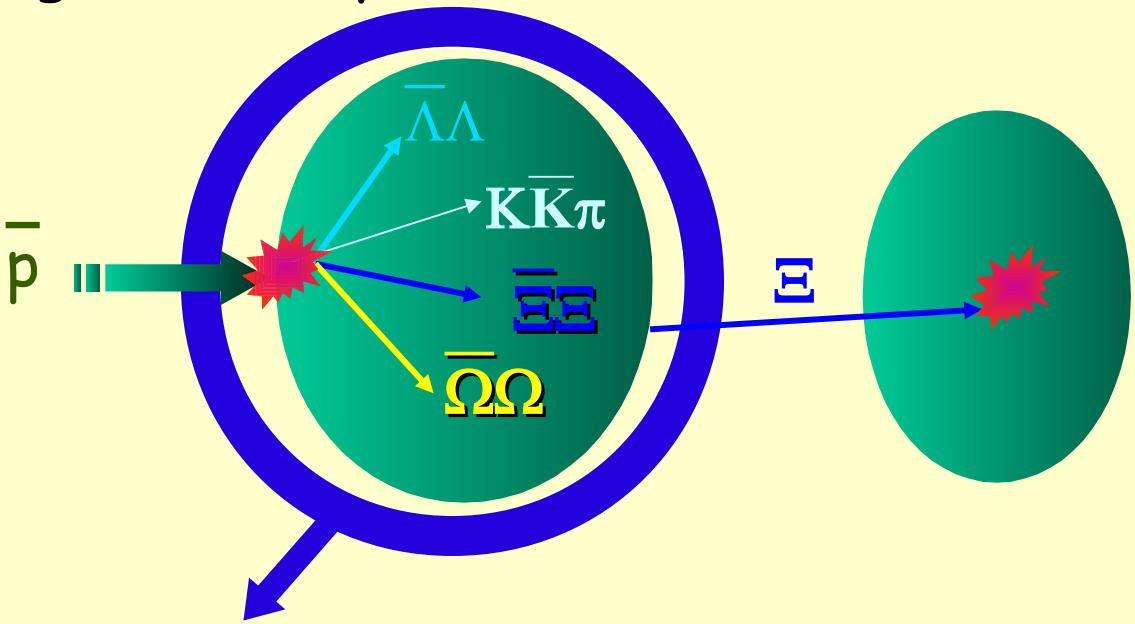
explore

hyperon-baryon

hyperon-hyperon

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

Multi-strange bound systems at PANDA

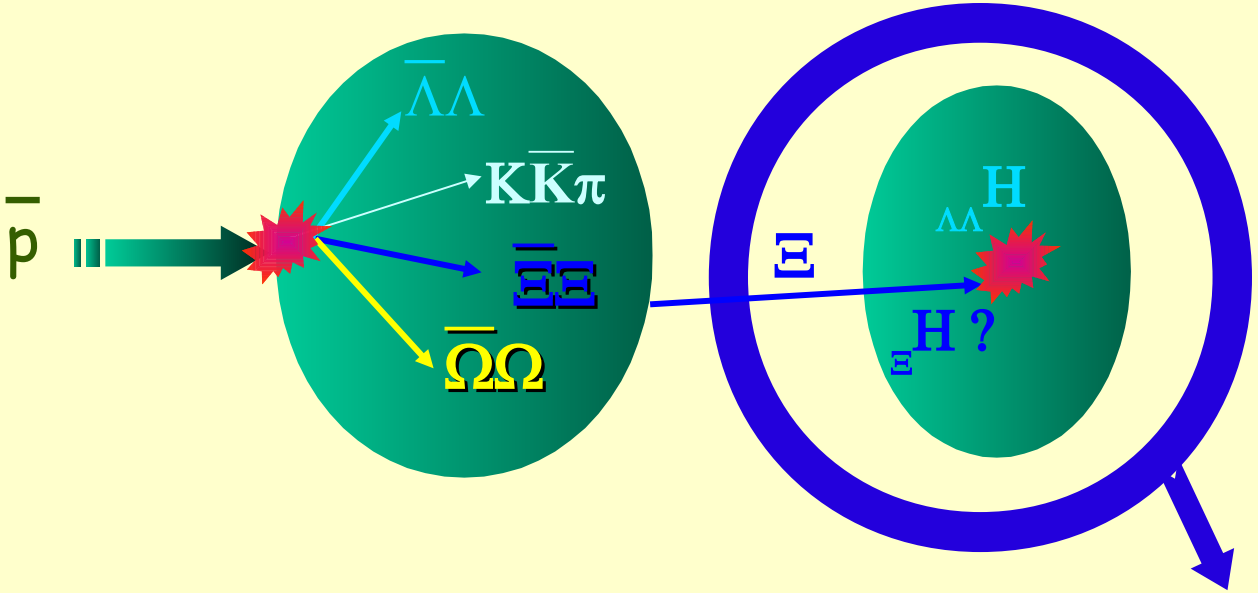


1. target: pp->$\bar{\Lambda}\Lambda$, $\bar{\Xi}\Xi$,$\bar{\Omega}\Omega$, $K\bar{K}\pi$ (annih.)
   πB->ΛK, B$K\bar{K}$ (s=0)
   $\bar{K}$B-> KΞ (s=-1)

X-Sections mostly known for S=-1

Unknown for higher sectors (S=-2,-3)

Multi-strange bound systems at PANDA



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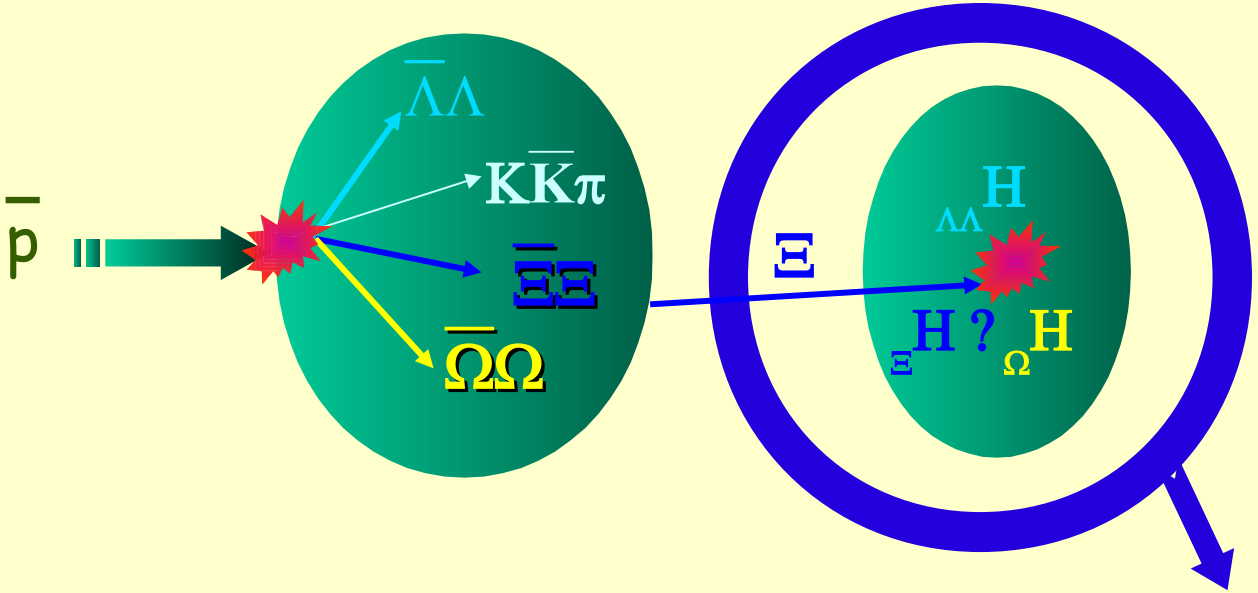
low-energy Ξ-beams

2. target: ΞB->ΞB, $\Lambda\Lambda$ (s=-2)

X-Sections mostly known for S=-1

Less known for higher sectors (S=-2,-3)

Multi-strange bound systems at PANDA



1. target: $pp \to \bar{\Lambda}\Lambda$, $\bar{\Xi}\Xi$, $\bar{\Omega}\Omega$, $K\bar{K}\pi$ (annih.)
   $\pi B \to \Lambda K$, $B K\bar{K}$ ($s=0$)
   $\bar{K}B \to K\Xi$ ($s=-1$)

X-Sections mostly known for S=-1

Less known for higher sectors (S=-2,-3)

low-energy Ξ-beams

2. target: $\Xi B \to \Xi B$, $\Lambda\Lambda$ ($s=-2$)

high-energy Ξ-beams

2. target: $\Xi B \to \Omega B K$ ($s=-3$)

Theoretical framework...

Non-Equilibrium dynamics: relativistic transport equation

$$\left[p^{*\mu}\partial_\mu^x + \left(p_\nu^* F^{\mu\nu} + m^* \partial_x^\mu m^*\right)\partial_\mu^{p^*}\right] f(x,p^*) = \mathcal{I}_{coll}$$

GiBUU: O. Buss, T. Gaitanos, et al., Phys. Reports 512 (2012) 1-124

→ **single-particle phase-space: p,n,mesons (π,K,...), hyperons (Λ,Σ,Ξ,Ω)**

Asymptotic equilibrated stage

Statistical Multifragmentation Model (SMM)

Botvina & Mishustin, Bondorf Nucl. Phys. A475 (1987) 663; Phys. Rept. 257 (1995) 133

→ Fragments from evaporation/fission/multifragm./de-excitation

Hypernuclei

Momentum-coalescence: bound hyperons (inside residual target) & SMM-fragments

(SMM+H: Botvina & Pochodzalla, PR **C76** ('07) 024909, PL **B697** ('11) 222)

Physics input…

Equation of State (EoS): Relativistic Mean-Field (RMF)

- Non-linear Walecka model (soft EoS) → Lalazissis, *et al.*, PL B**671** ('09) 36.
- Antibaryon-meson couplings: $g_\omega=-\xi g_\omega$, $g_\sigma=\xi g_\sigma$ (ξ~0.2-0.3) Larionov, PR **C80** ('09) 021601(R)
- → better description of $\bar{p}$-**nucleus** (but not for **p-nucleus** opt. Potential)

Momentum-Dependent (MD) Relativistic Mean-Field model:

Non-Linear Derivative (NLD) approach → MD-regulators in RMF-interactions

NLD describes **simultaneously** p-nucleus & $\bar{p}$-nucleus U_{opt} using *G*-parity only!

T.G. & M. Kaskulov, Nucl. Phys. A899 (2013) 133-169

T.G. & M. Kaskulov, Nucl.Phys. A940 (2015) 181-193

Collision term: all standard channels, NN → NR, NN→ NYK, mN→ YK, etc, …

- primary: $B\bar{B}$ → **mesons** Golubeva, Pshenichnov, NP **A537** ('92) 393 →$\Lambda\bar{\Lambda}$, $\Xi\bar{\Xi}$, $\Omega\bar{\Omega}$ (data,models)
- Secondary: $\bar{K}B\to\Xi K$ (data), $\Lambda B\leftrightarrow\Sigma B$ (data,Nijmegen)

$\Xi B\to\Xi B,\Lambda\Lambda$ (Nijmegen,Fujiwara)

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T.G. & M. Kaskulov, Nucl. Phys. A899 (2013) 133-169

T.G. & M. Kaskulov, Nucl.Phys. A940 (2015) 181-193

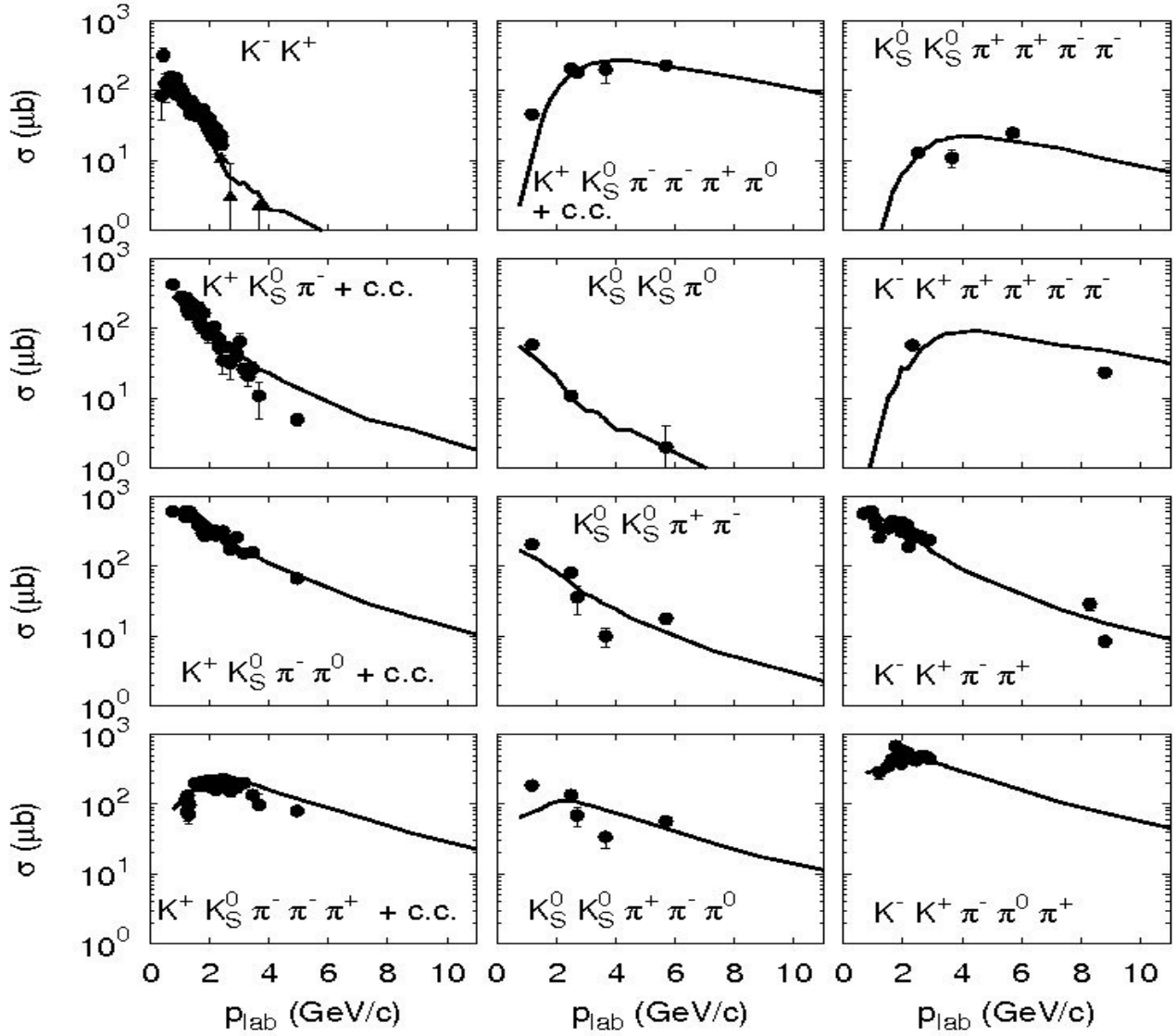
Collision term: all standard channels (elastic, inelastic, resonance production, etc.)

- primary: $B\bar{B}$ → **mesons** $B\bar{B}\to\Lambda\bar{\Lambda}$, $\Xi\bar{\Xi}$, $\Omega\bar{\Omega}$ (data,models)
- Secondary: $\bar{\mathbf{K}}\mathbf{B}\to\Xi\mathbf{K}$ (data), $\Lambda\mathbf{B}\leftrightarrow\Sigma\mathbf{B}$ (data,Nijmegen)

$\Xi\mathbf{B}\to\Xi\mathbf{B},\Lambda\Lambda$ **(Nijmegen,Fujiwara)** $\mathbf{mB},\mathbf{B\bar{B}}\to\Omega\bar{\Omega}$, Ω**+X (PYTHIA)**

Elementary primary channels: $\bar{p}p$-> X…

Statistical annihilation model ($p\bar{p}$-> mesons) up to 6-particles final states ($\pi,\eta,\omega,\rho,K,\bar{K},K^*,\bar{K}^*$)



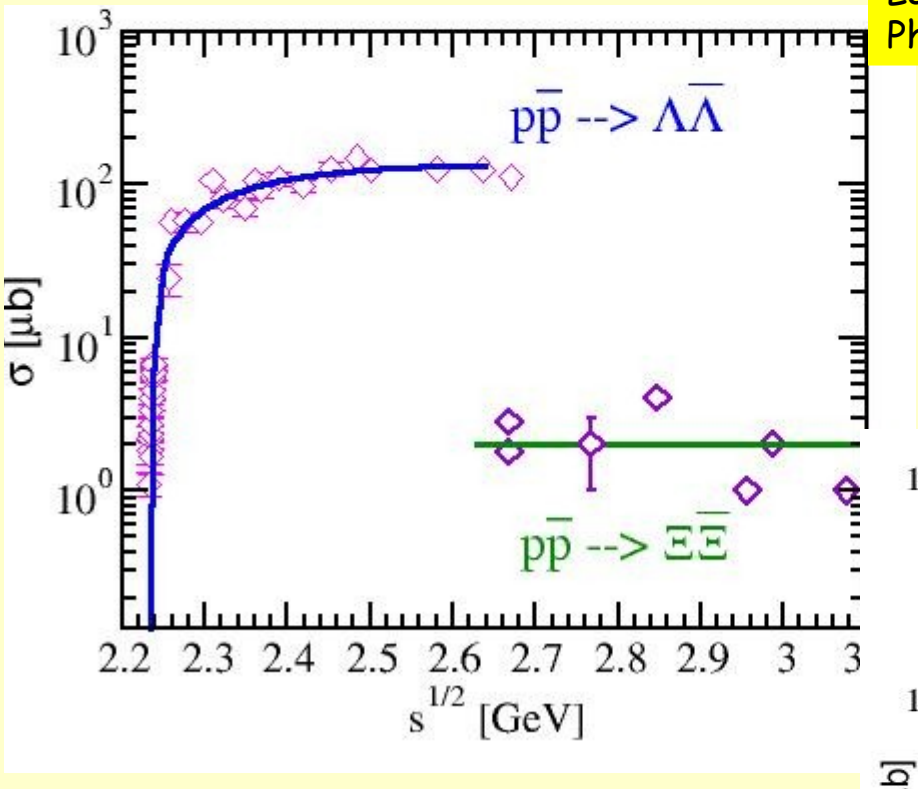
Golubeva, Pshenichnov, *et al.*, Nucl. Phys. ***A537*** ('92) 393

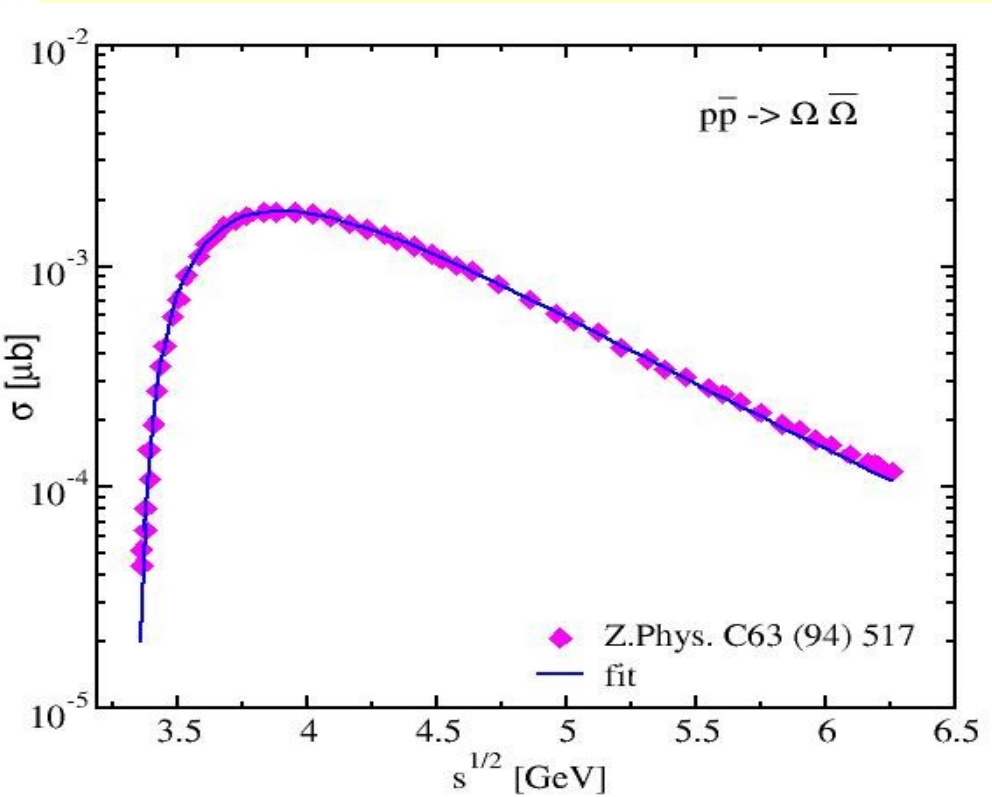
Larionov, *et al.*, Phys. Rev. ***C78*** ('08) 014604

Elementary primary channels: $\bar{p}p$-> X...

Hyperon production

Larionov, Gaitanos, Mosel,
Phys.Rev. **C85** (2012) 024614

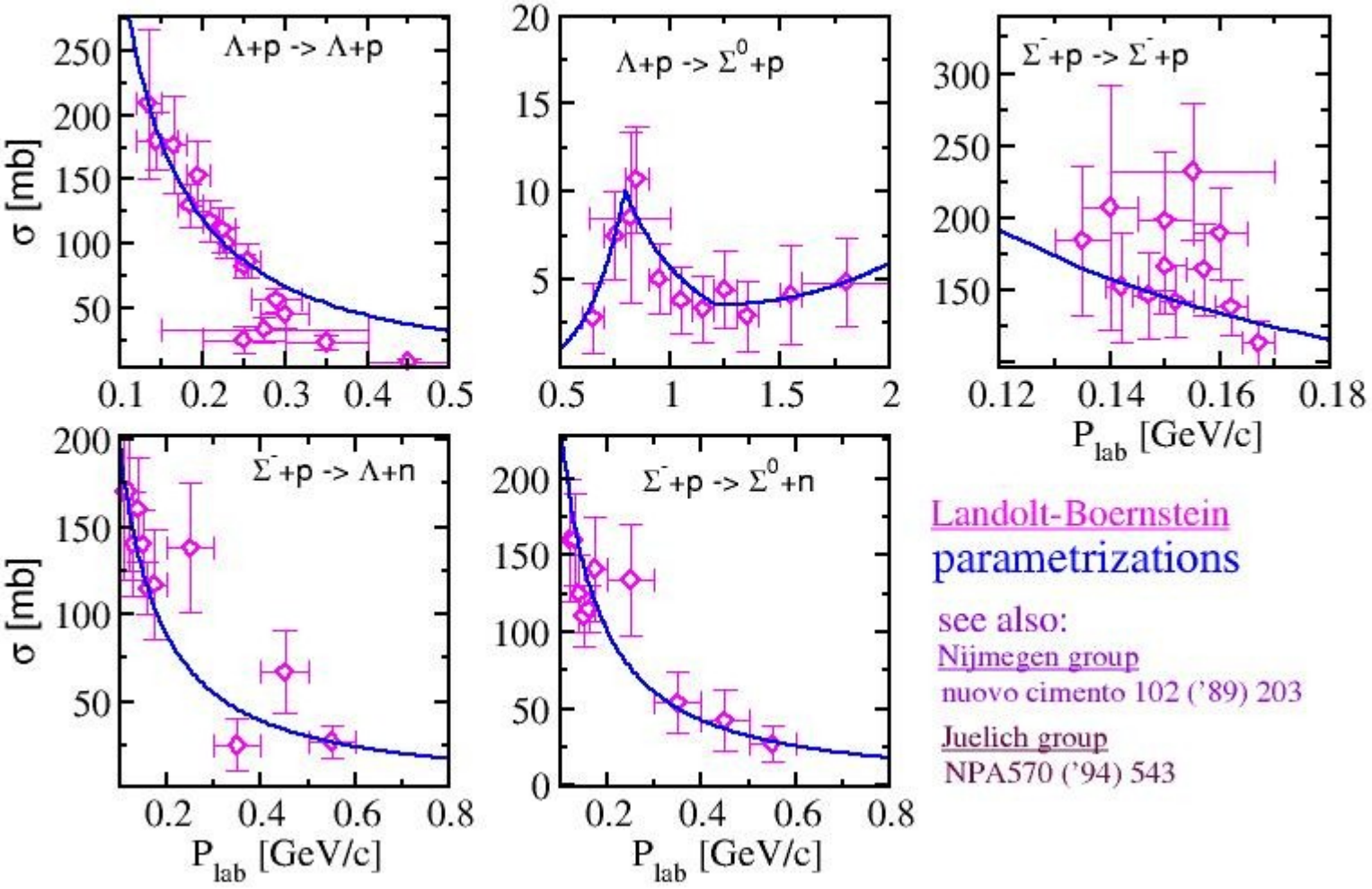




Gaitanos,Moustakidis,Lalazissis,Lenske,
arXiv:1602.08905, Nucl. Phys. A (2016) in press

Elementary secondary channels (S=-1)

Hyperon-Nucleon rescattering ($\Sigma N \longleftrightarrow \Lambda N$)



Landolt-Boernstein
parametrizations

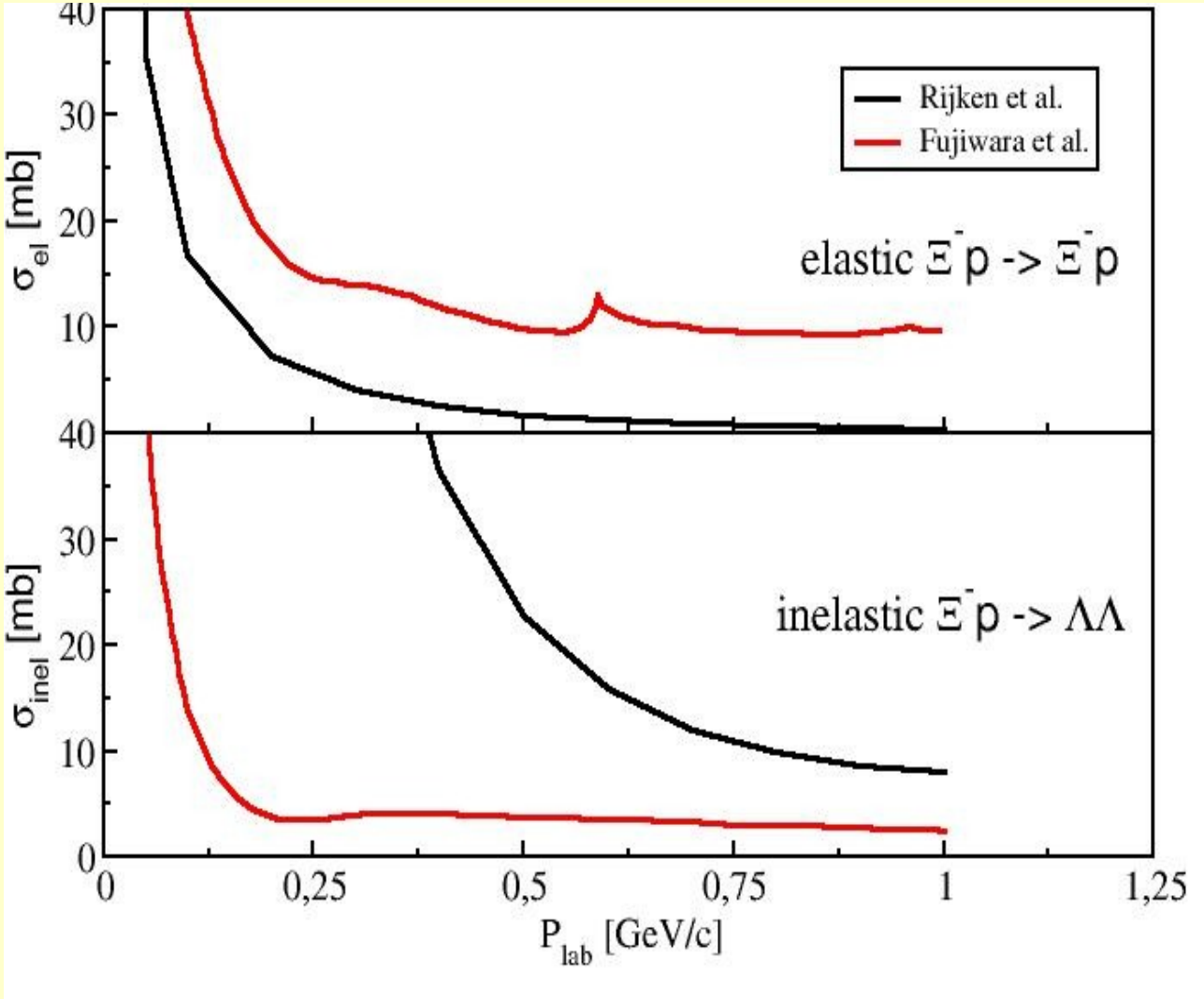
see also:
Nijmegen group
nuovo cimento 102 ('89) 203
Juelich group
NPA570 ('94) 543

Antikaon-Nucleon rescattering ($\bar{K}N \rightarrow \Xi K$) similar situation

Gaitanos, Larionov, Lenske, Mosel, Nucl.Phys. ***A914*** ('13) 405

Elementary secondary channels (S=-2)

Hyperon-Nucleon rescattering (ΞN <—> ΞN,ΛΛ)



No exp. Data!

Rijken, Yamamoto, et al:
OBE (NN) + SU(3) (YN)
nucl-th/0608074
Nucl. Phys. A804 ('08) 139

Fujiwara et al.:
Quark-Cluster-models
Phys. Rev. C64 ('01) 054001

→ big model diffs at low P_{lab}

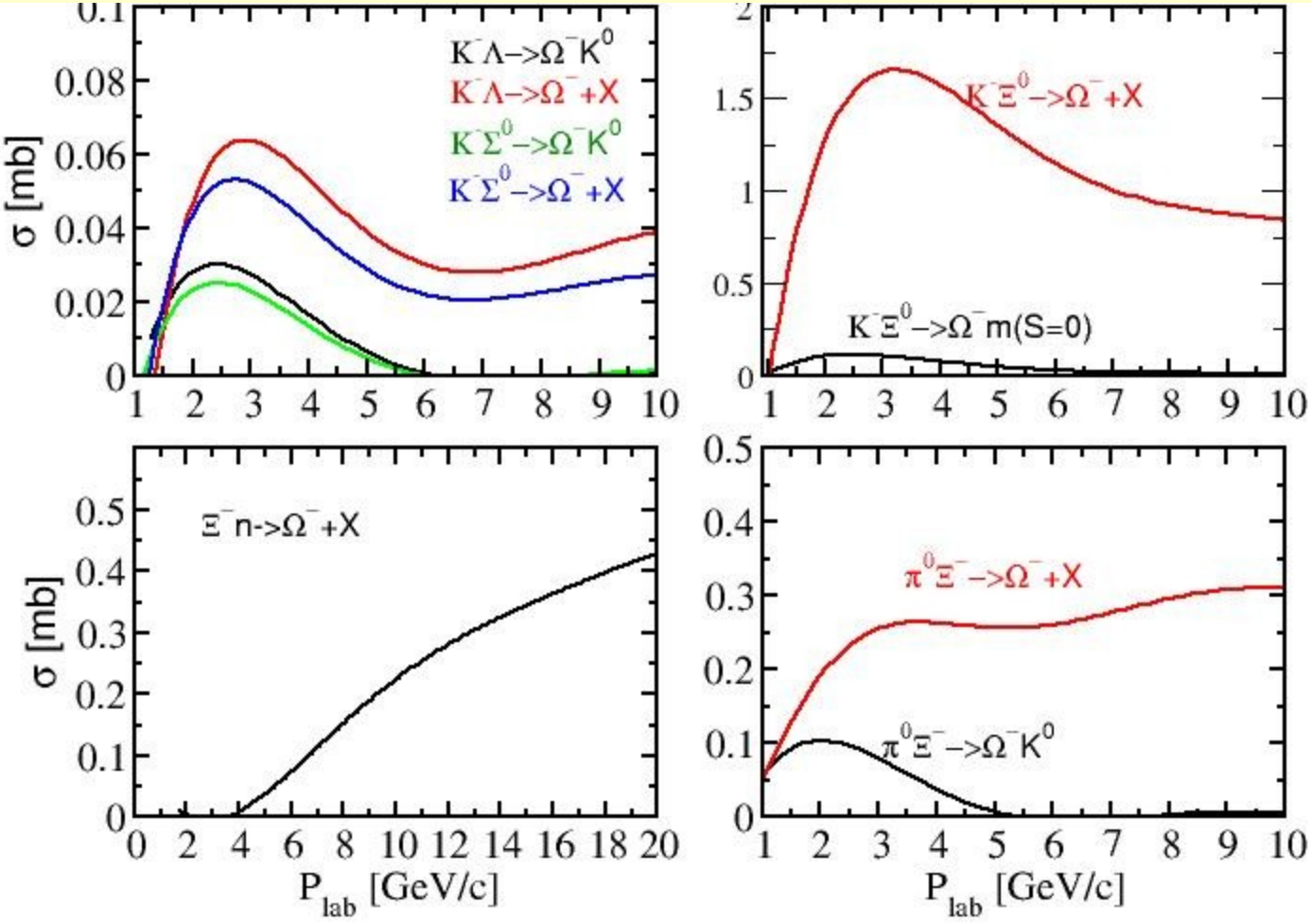
Rijken:
strong Ξ-absorption

Fujiwara:
more Ξ-dynamics (rescatt.)
Ξ-bound matter at $\bar{P}$ANDA?

Gaitanos, H. Lenske, Phys. Lett. B737 (2014) 256

Elementary secondary channels (S=-3)

Hyperon-Nucleon rescattering (Ω-production)

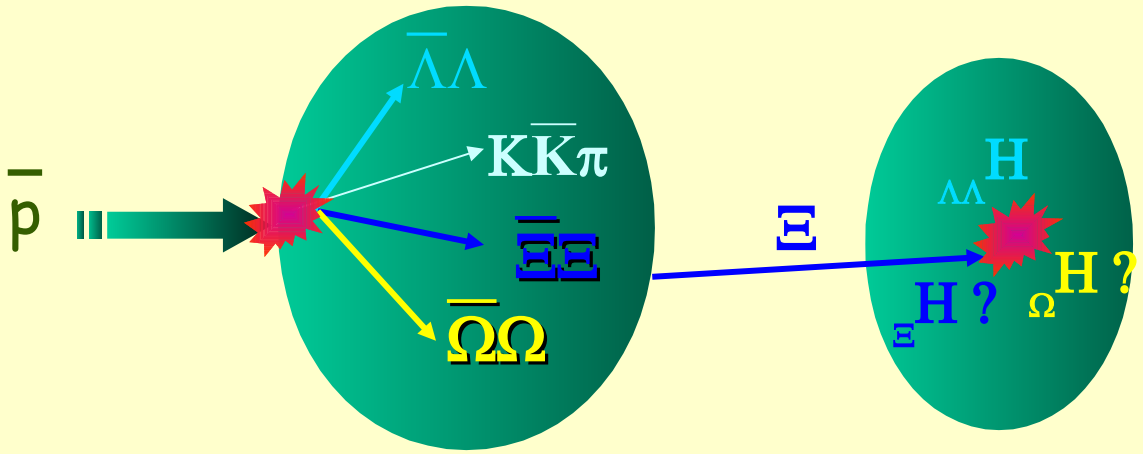


No exp. Data!

Rely on PYTHIA...

Gaitanos, H. Lenske, Phys. Lett. B737 (2014) 256

Gaitanos,Moustakidis,Lalazissis,Lenske, arXiv:1602.08905, Nucl. Phys. A (2016) in press

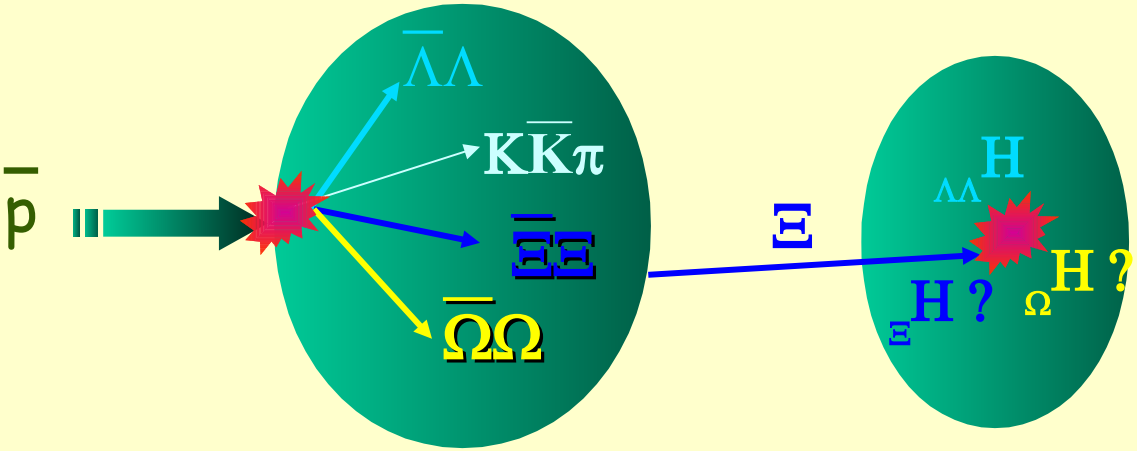


Results for $\bar{\text{p}}$anda

1) fragmentation dynamics

2) strangeness dynamics

→ multi-strangeness hypernuclei



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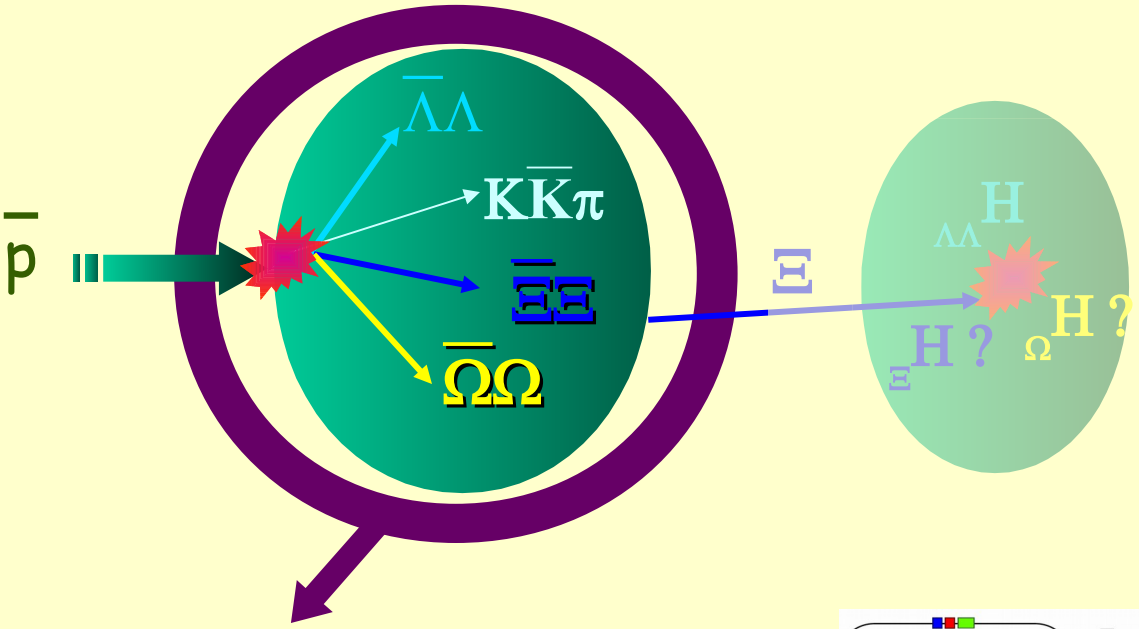


Strangeness dynamics at $\bar{p}$anda

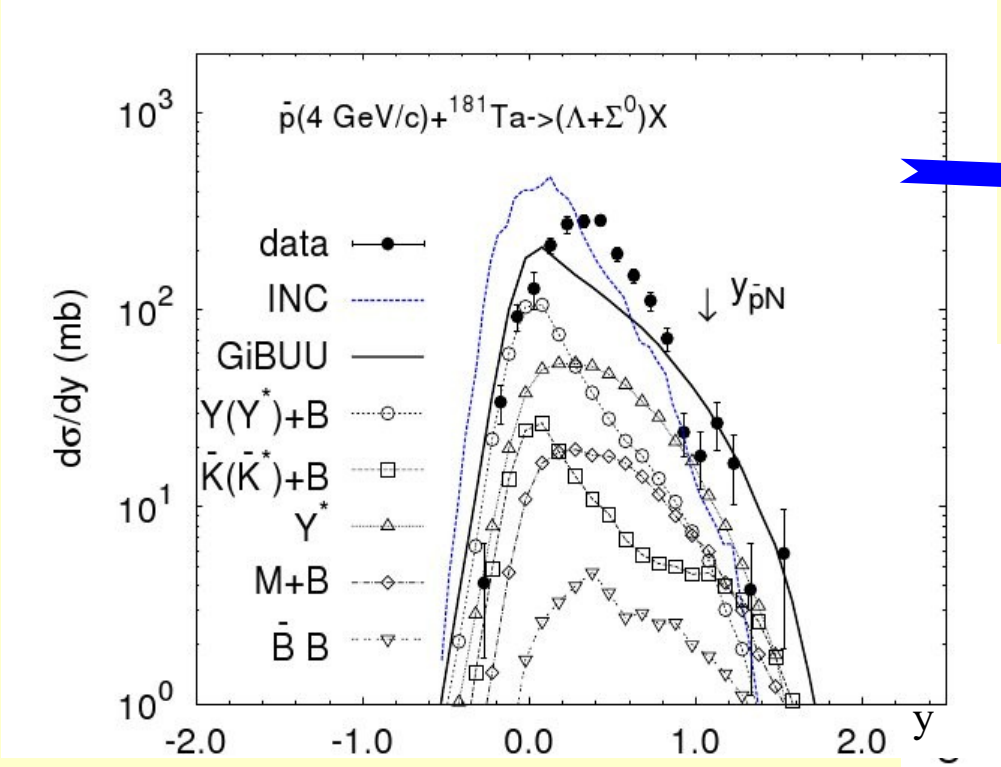
Larionov, Gaitanos, Mosel, Phys. Rev. **C85** (2012) 024614

Gaitanos, Larionov, Lenske, Mosel, Nucl. Phys. **A881** (2012) 240

Larionov, Gaitanos, Lenske, Mosel, EPJ Web Conf. **37** (2012) 06007

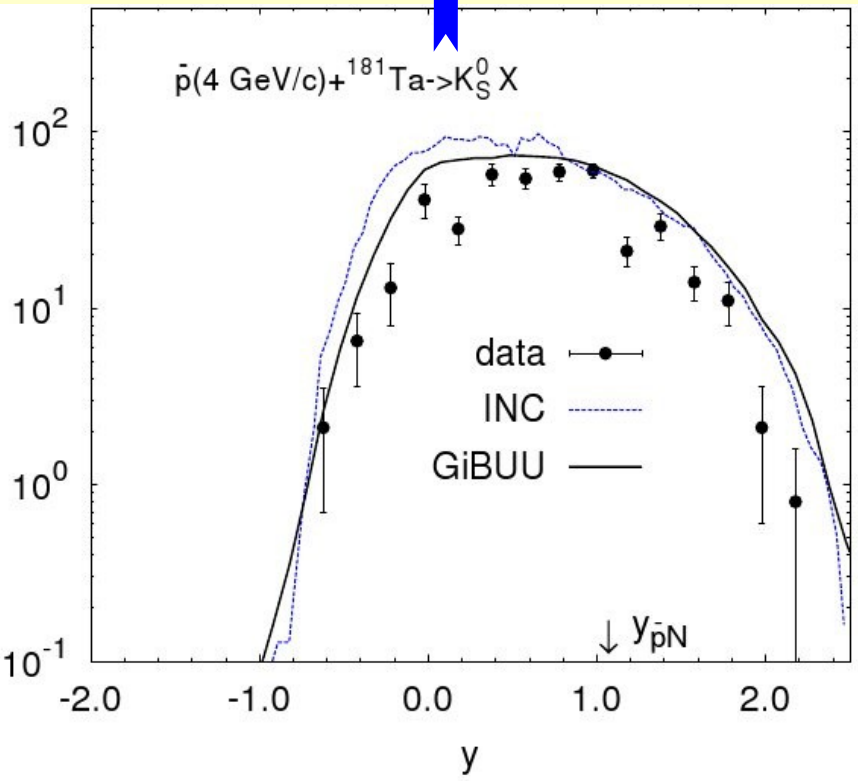
Larionov, Gaitanos, Mosel, Hyperfine Interactions **213** (2012) 81

Strangeness dynamics: S=-1 hyperons & mesons (K)



Good description of strangeness data

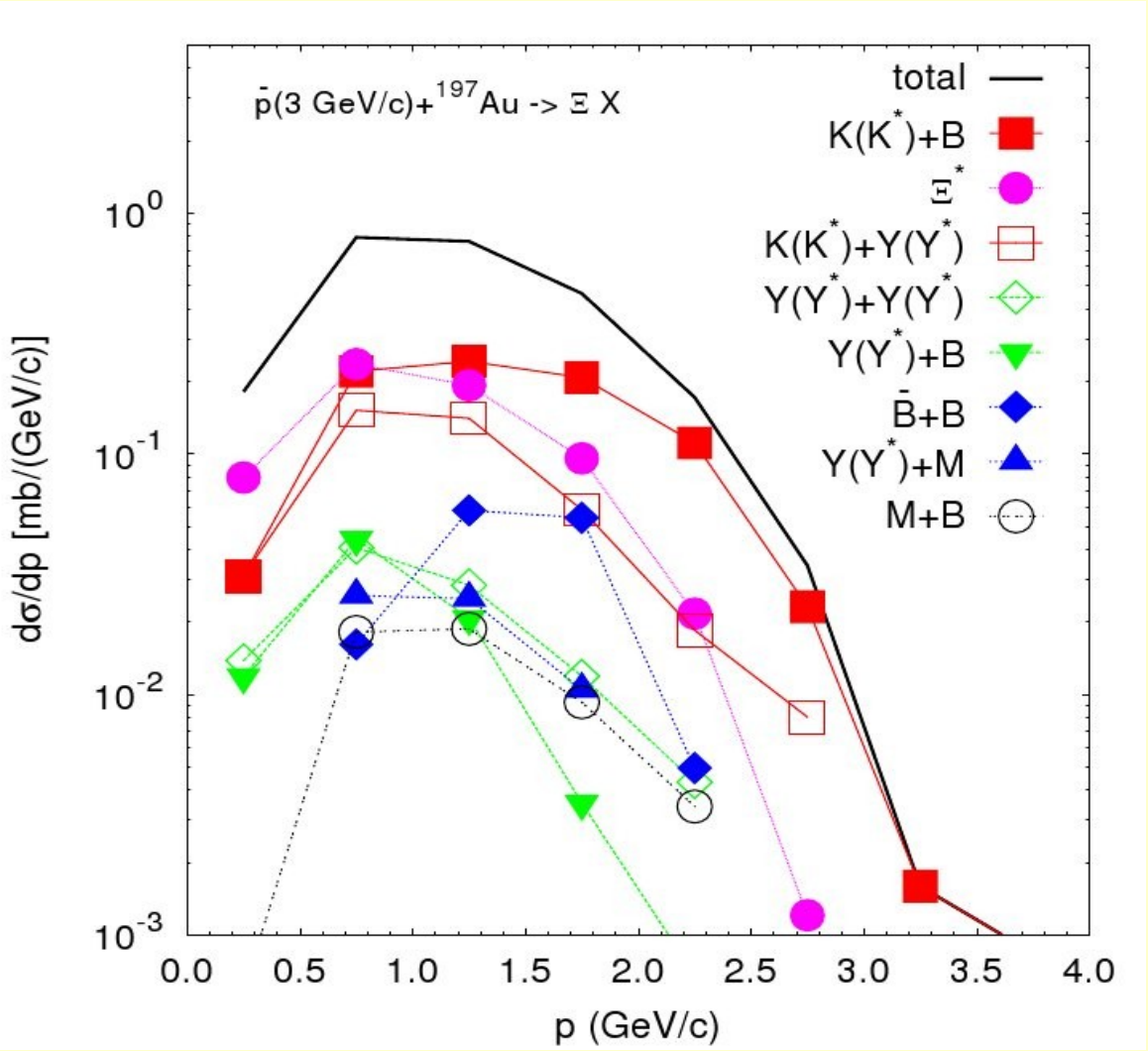
Secondary channels important!



Larionov, Gaitanos, Mosel,
Phys.Rev. **C85** (2012) 024614

Larionov, Gaitanos, Mosel,
Hyperfine Interactions **213** (2012) 81
arXiv:1202.0748 [nucl-th]

Strangeness dynamics: S=-2 hyperons (Ξ)

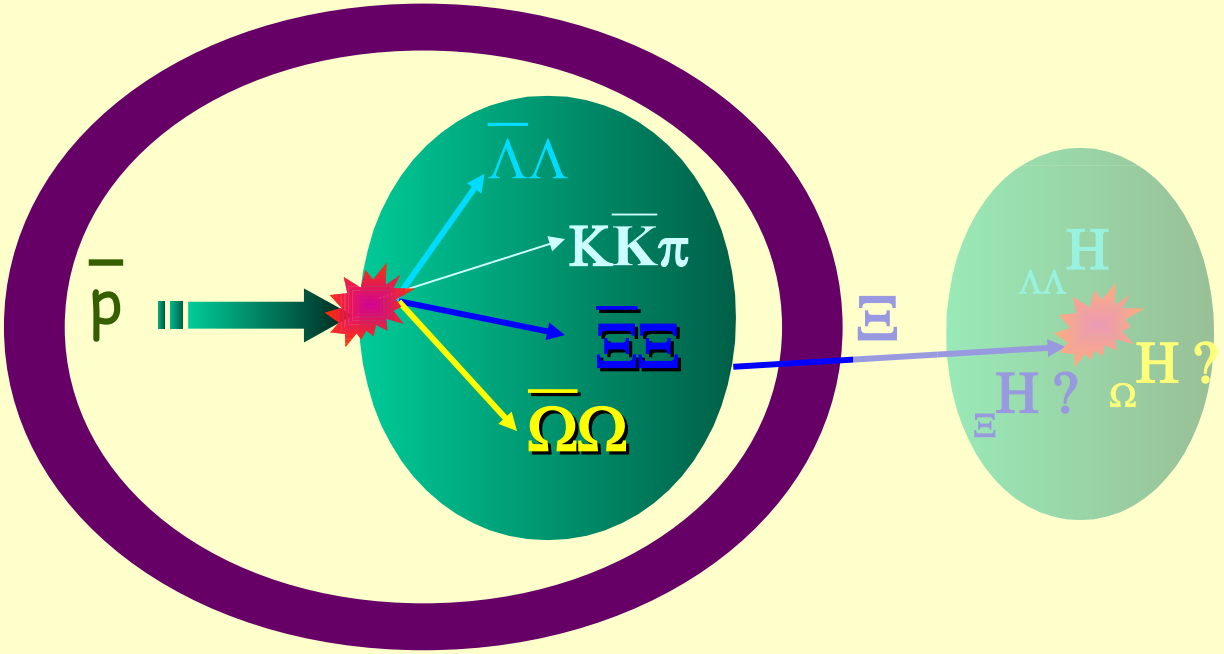


No data exist at all !!!

Low energy Ξ production due to secondary channels!

P_{Ξ} ~ 1 GeV/c ==> E_{kin} ~ 0.3 GeV

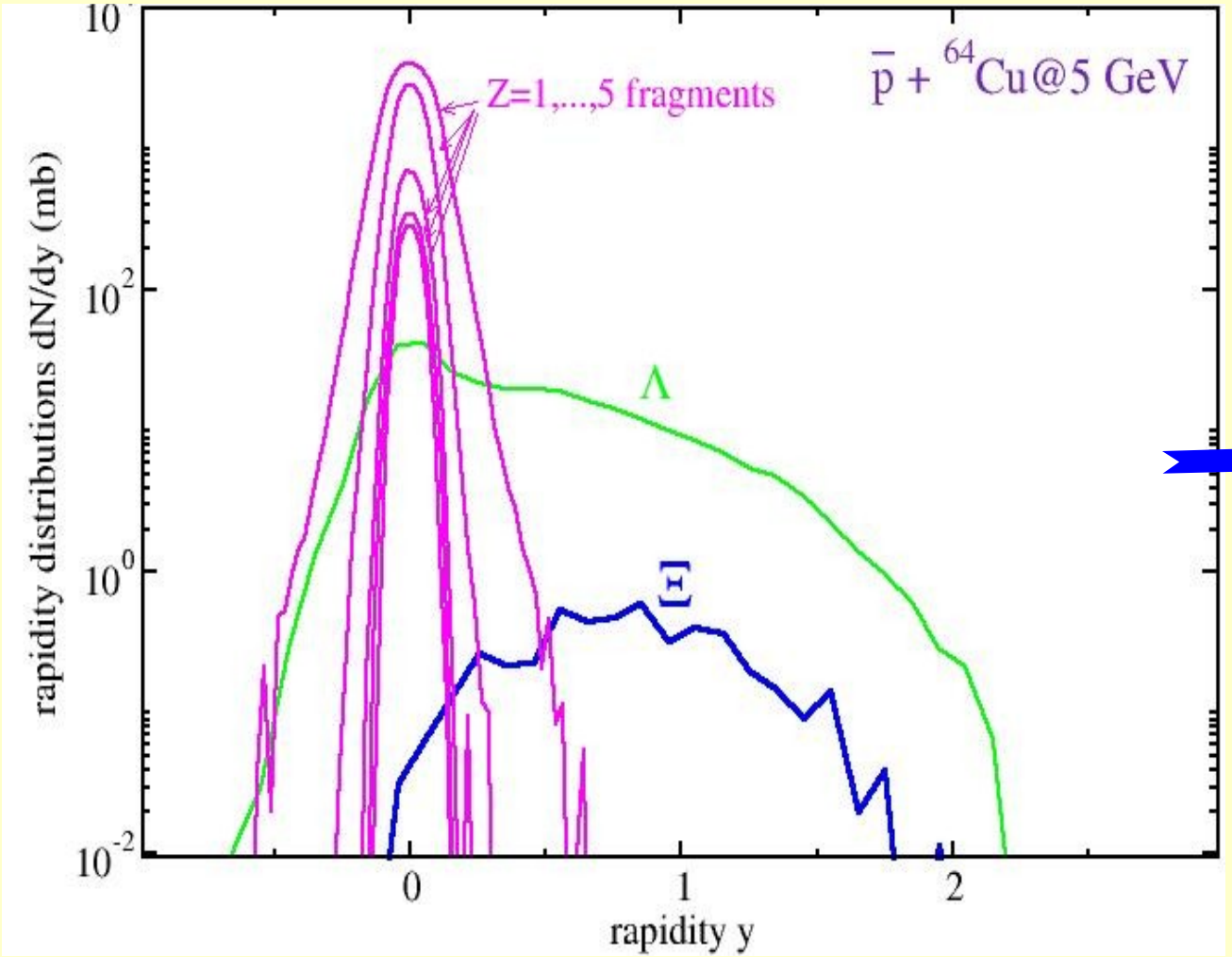
Larionov, Gaitanos, Mosel, Phys.Rev. **C85** (2012) 024614

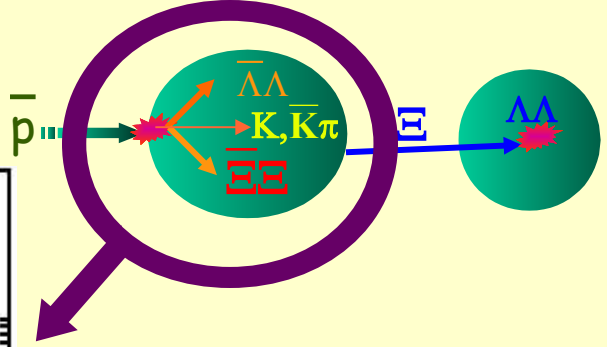


Multi-strangeness hypernuclei at $\bar{p}$anda

primary $\bar{p}$-beam on 1. target

Dynamics in 1. target...





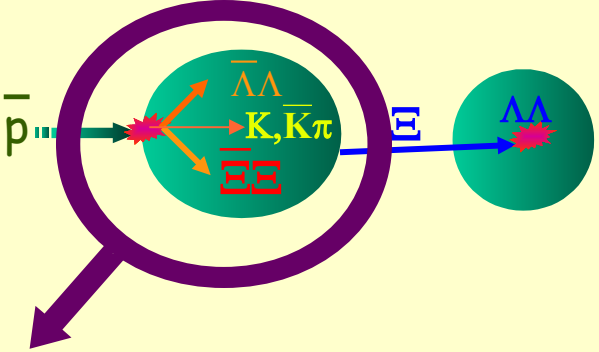
Coalescence with stopped Λ's possible

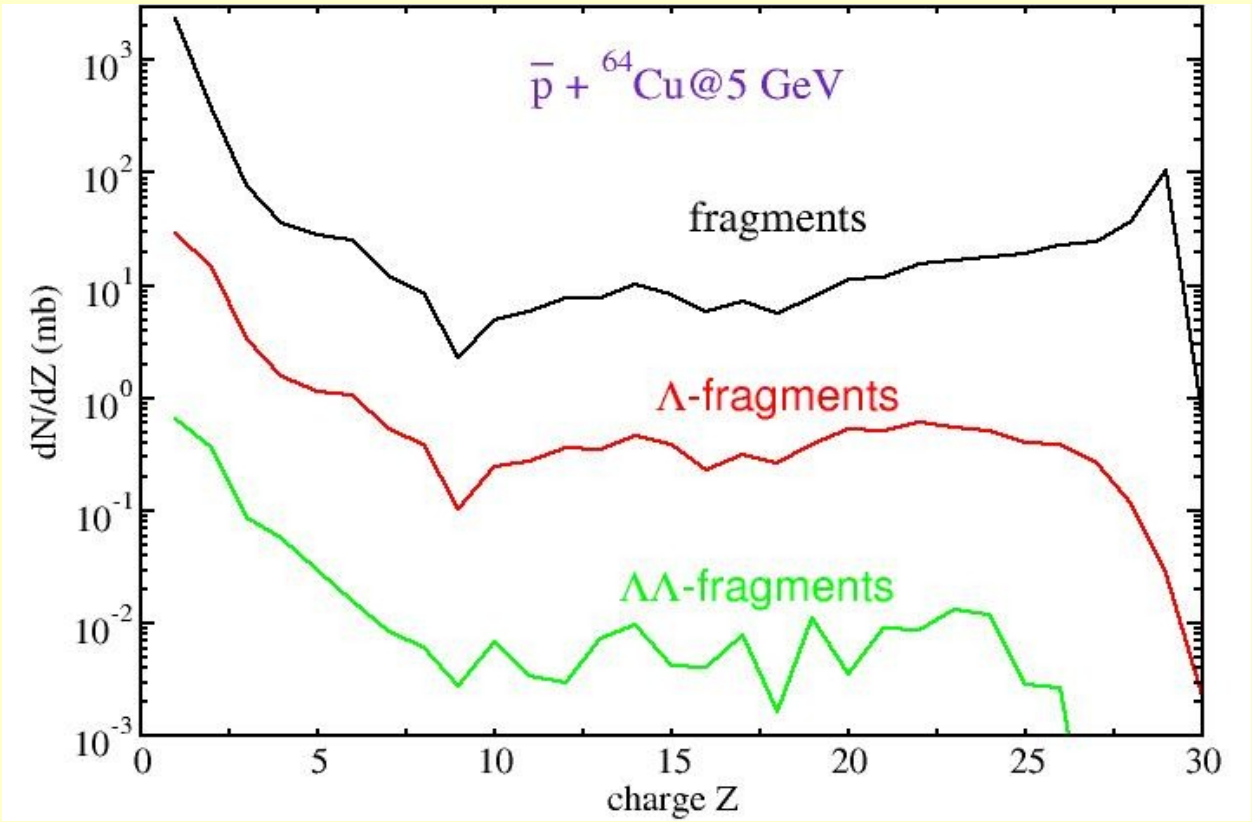
No coalescence with Ξ's (in 2nd target)

Gaitanos, Larionov, Lenske, Mosel, Nucl.Phys. **A881** (2012) 240

Multi-strangeness Hyp. in 1. target...

momentum coalescence between SMM-clusters & **captured** Λ

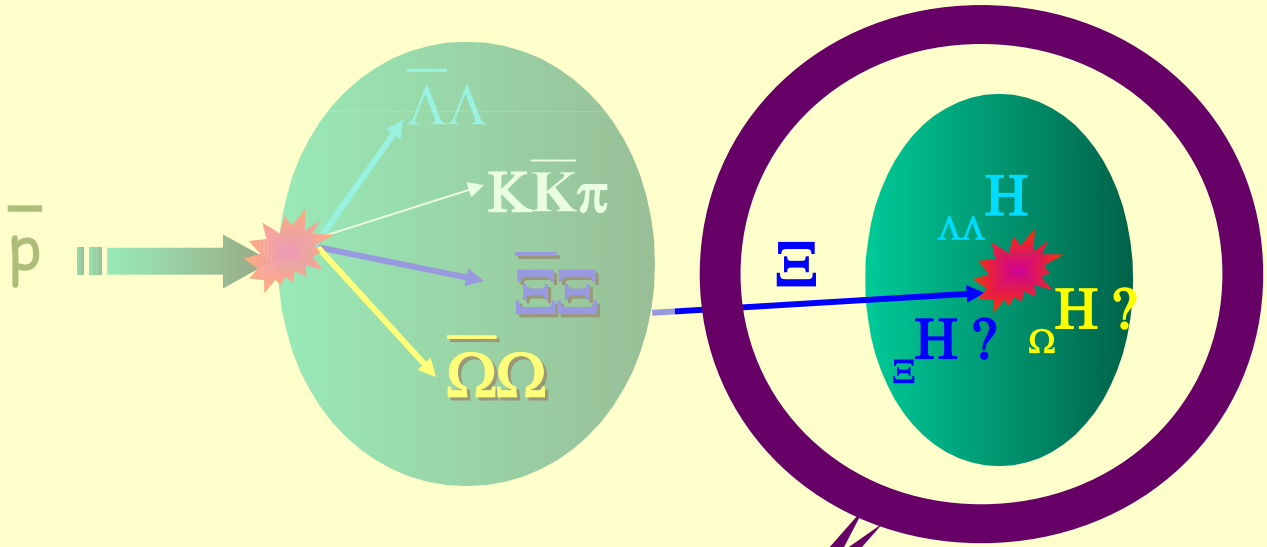




...charge distributions

Production of single-Λ hypernuclei possible

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

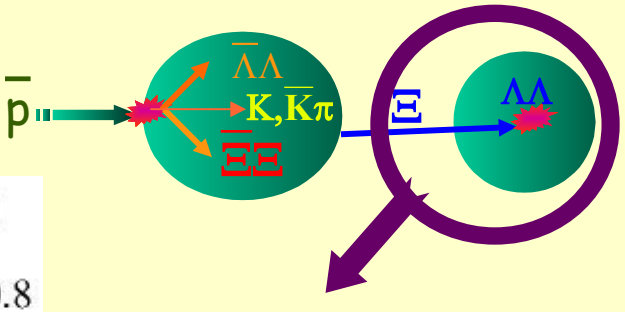


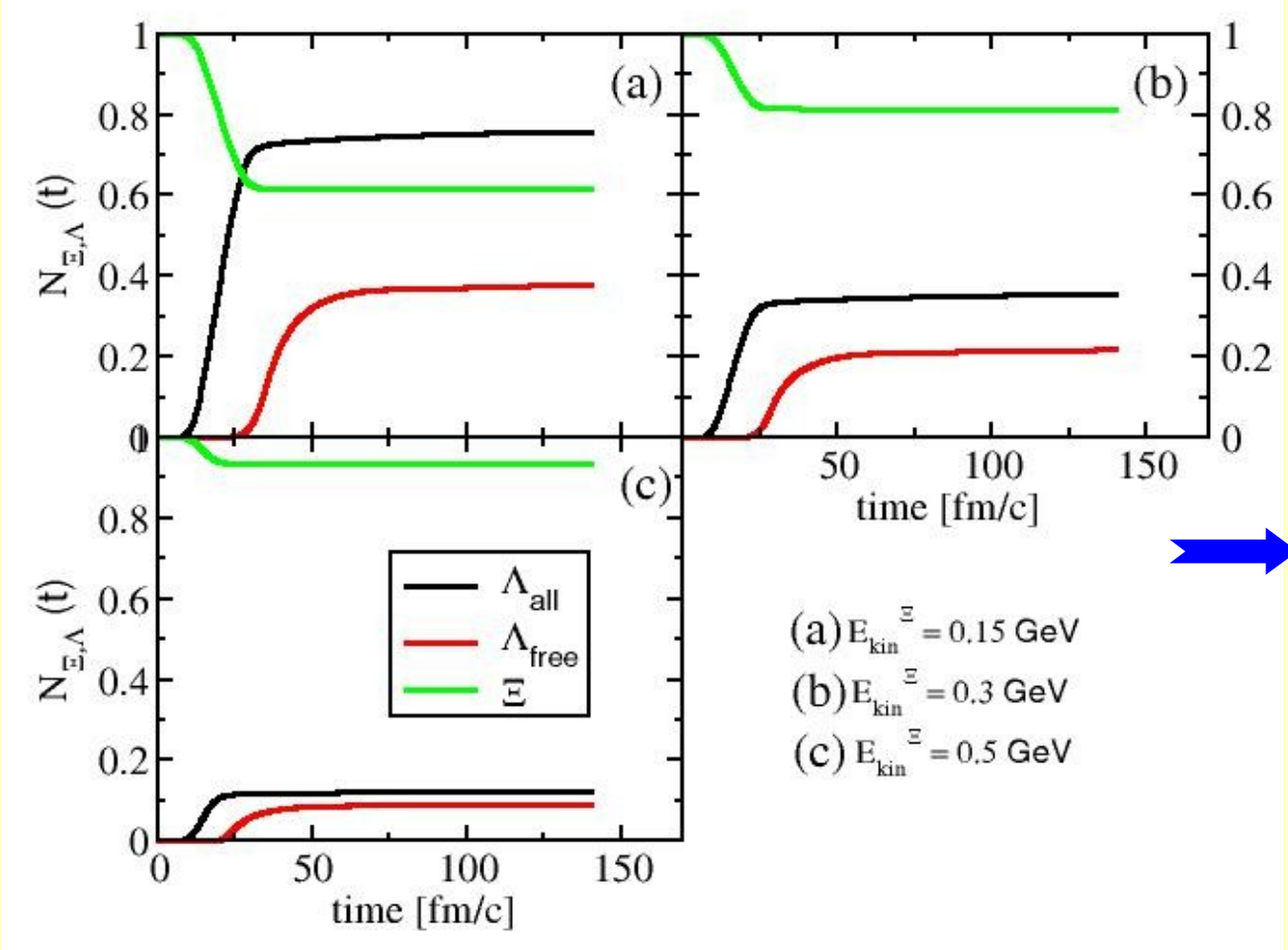
Multi-strangeness hypernuclei at $\bar{p}$anda

primary $\bar{p}$-beam on 1. target

+ secondary Ξ-beam on 2. target

Dynamics in 2. target...





Ξ-capture in 2nd target

and production of ΛΛ possible

Process strongly energy dependent:

→ Repulsive RMF fields

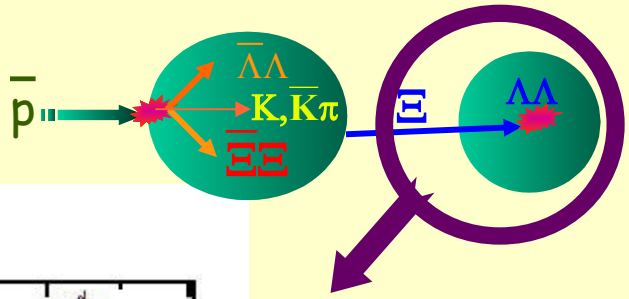
→ fall of ΞN →ΛΛ at high energies

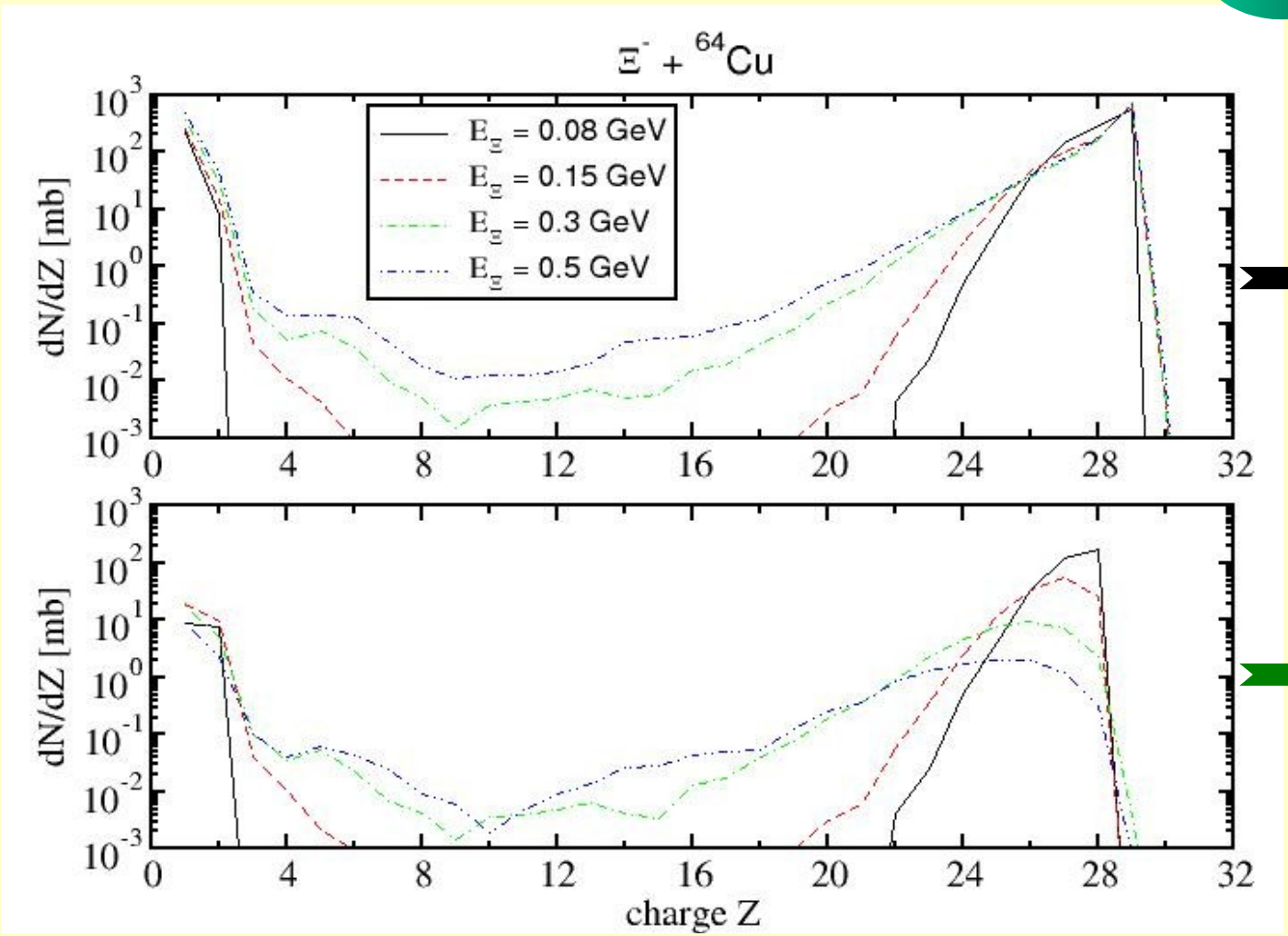
Gaitanos, Larionov, Lenske, Mosel, Nucl.Phys. ***A914*** ('13) 405

Gaitanos, H. Lenske, Phys. Lett. **B737** (2014) 256

Multi-strangeness Hyp. in 2. target...

Coal.: momentum coalescence with captured Ξ & ΞN →ΛΛ





fragments

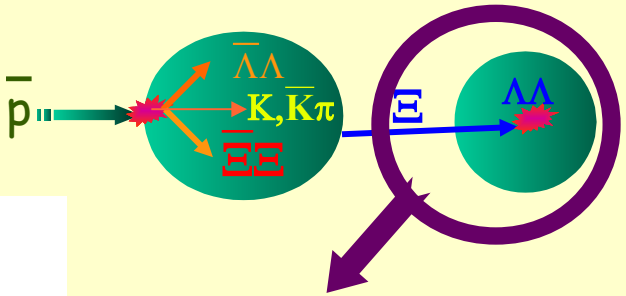
ΛΛ-fragments

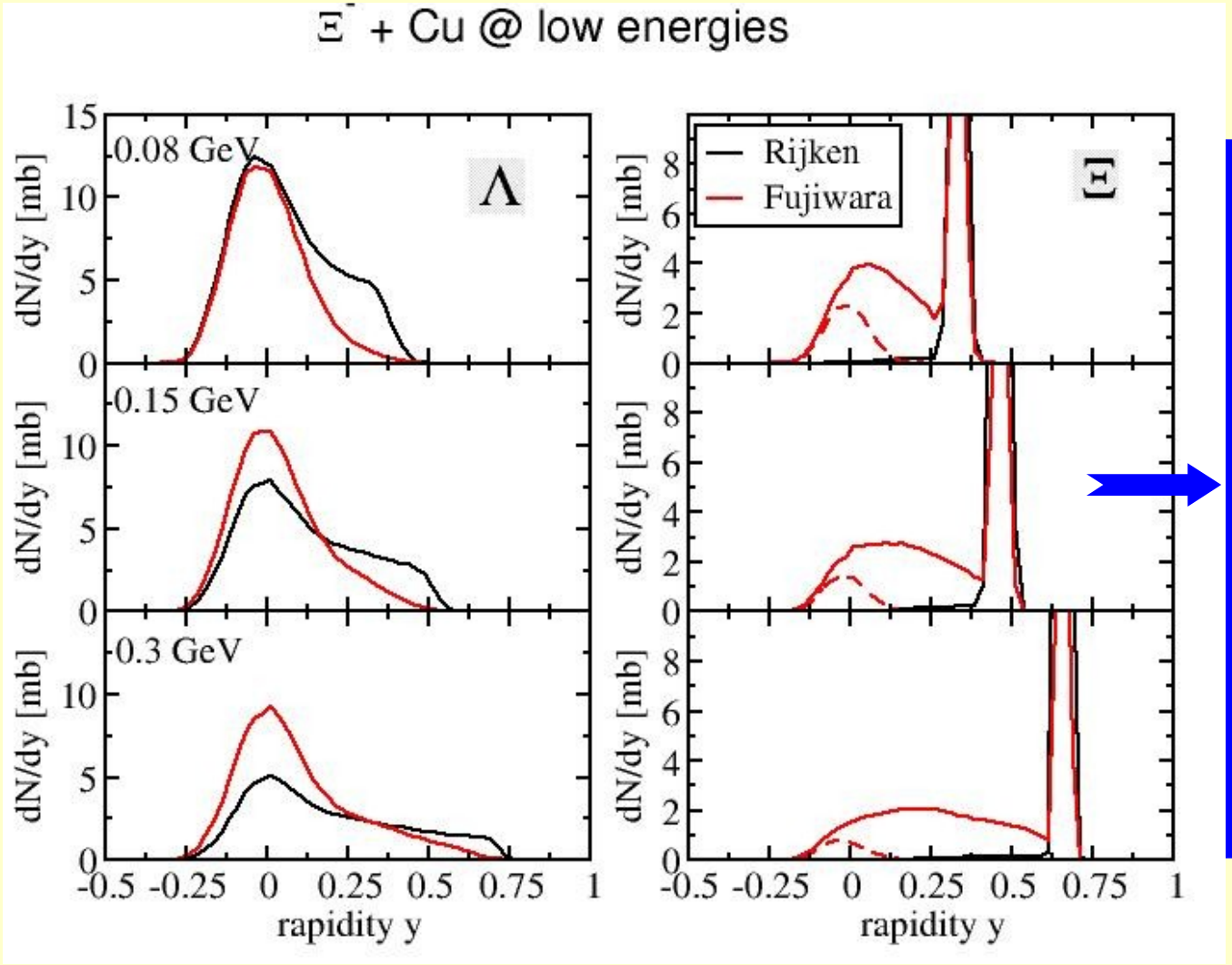
Copious production of ΛΛ–hypernuclei via Ξ-capture in 2nd target...

Process strongly dependent on Ξ-energy (ΞN →ΛΛ)

T.G., Larionov, Lenske, Mosel, Nucl.Phys. **A914** ('13) 405

Role of ΞN-interaction?...





→ Dynamics strongly model dependent

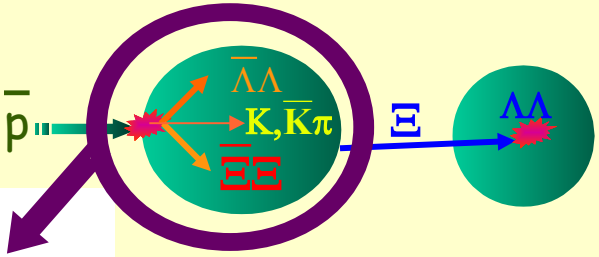
→ Ξ-bound systems possible, again strongly model dependent

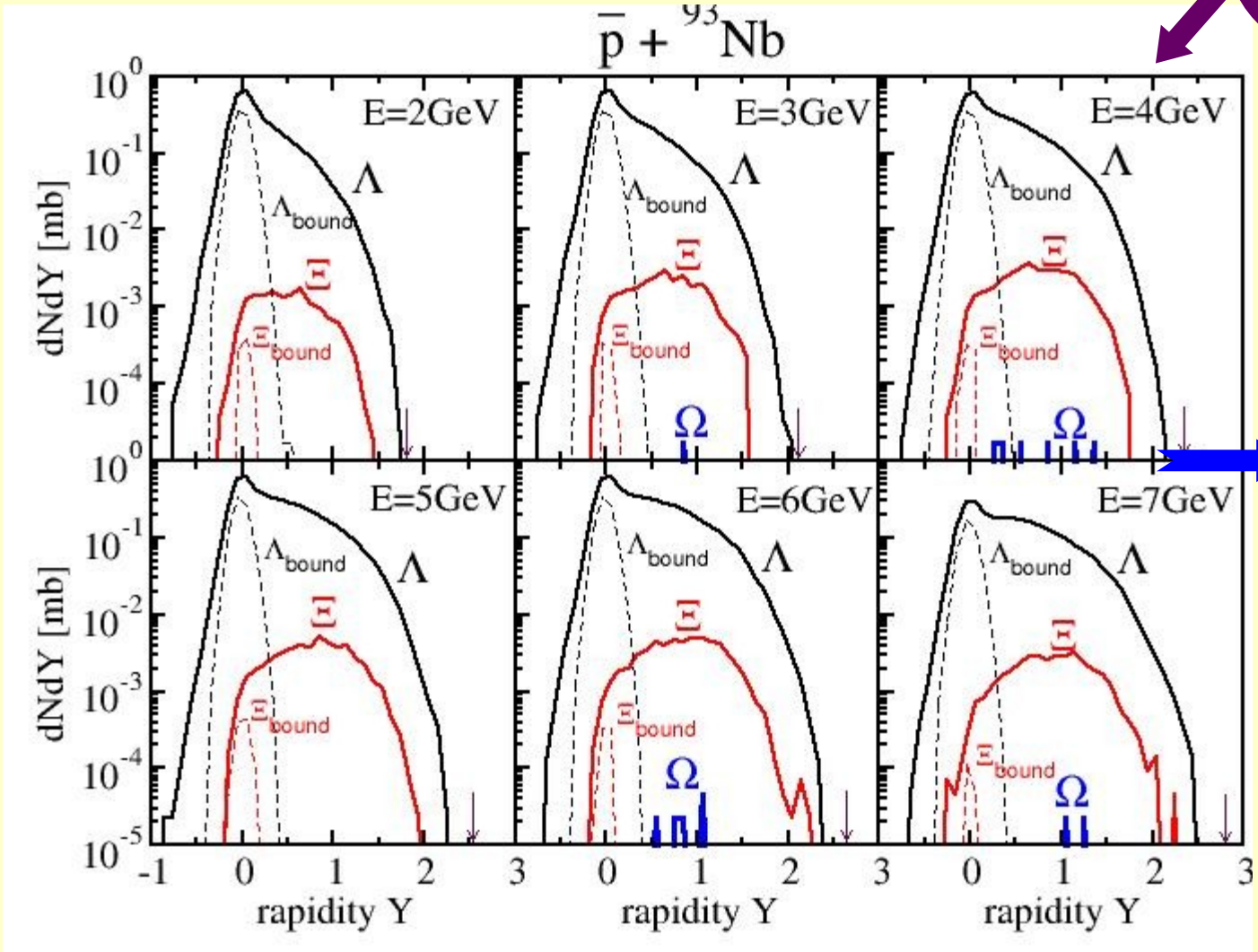
→ **ΛΛ- and Ξ-hypernuclear yields important observables to better constraint the still unknown ΞN-interaction**

Gaitanos, H. Lenske, Phys. Lett. B737 (2014) 256

$\bar{P}$ANDA: $\bar{p}$+X@(3-5)GeV...

Ω-production?





$\bar{p}$+nucleus

Extremely rare events

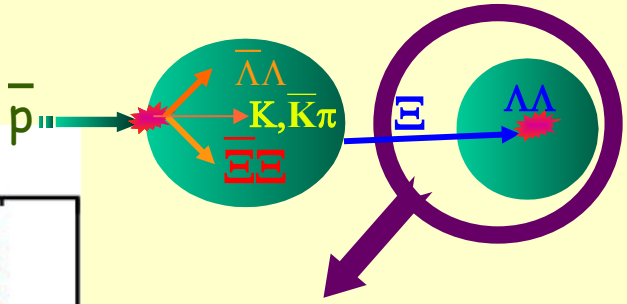
Primary production nb-region!

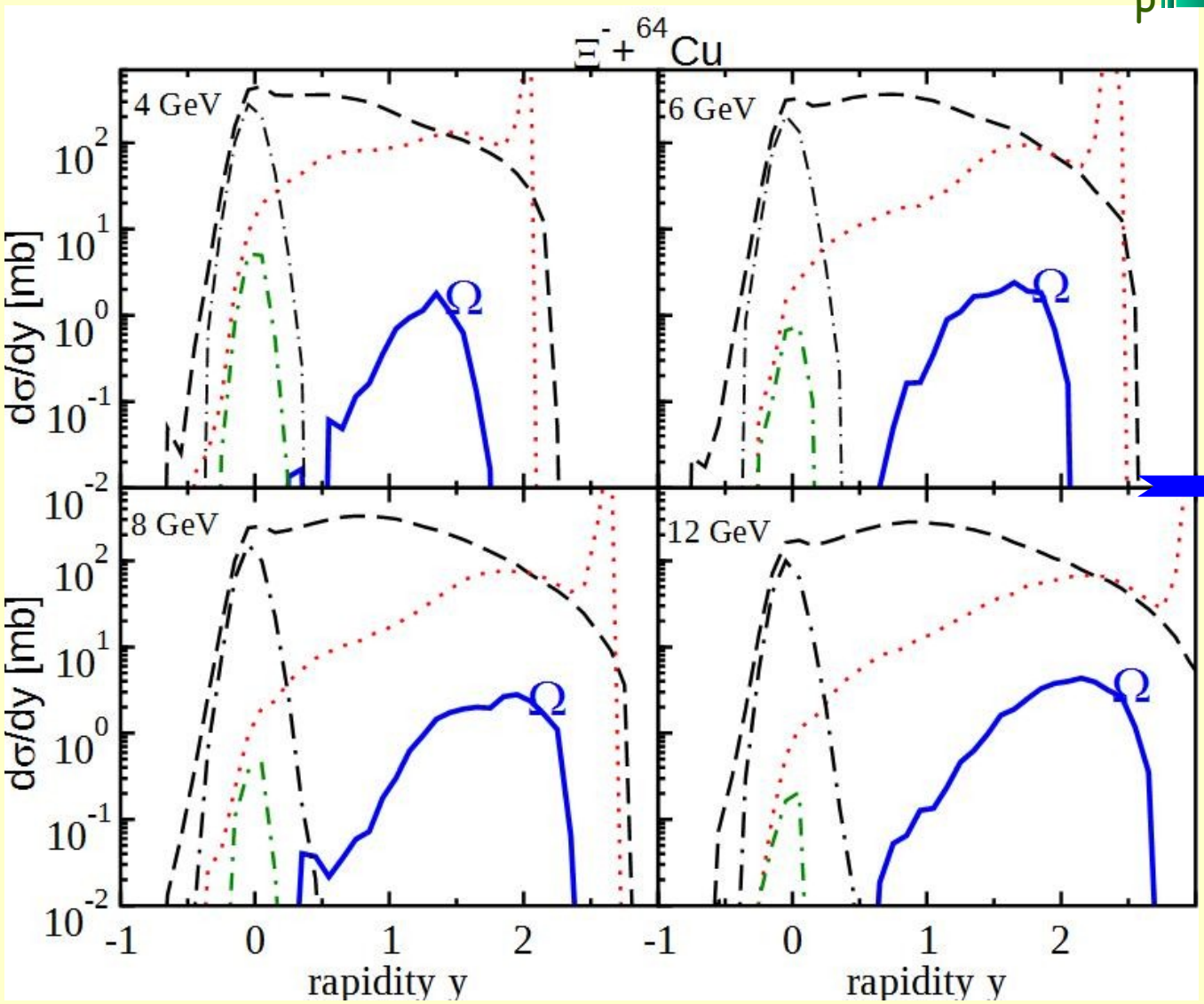
secondary channels with $\bar{K}$ not helpful!

However: Ω-production from secondary Ξ-beam enhanced!

Gaitanos,Moustakidis,Lalazissis,Lenske, arXiv:1602.08905, Nucl. Phys. A (2016) in press

$\bar{P}$ANDA: Ξ+X@(3-5)GeV...





Ξ+nucleus

Ambudant Ω-production (mb!)

secondary Ξ-channels important

Gaitanos,Moustakidis,Lalazissis,Lenske, arXiv:1602.08905, Nucl. Phys. A (2016) in press

Final remarks...

- **"FAIR"-Physics @ Thessaloniki & Giessen**
  - → GiBUU+SMM: NE-dynamics + statistical model of fragmentation
  - → suitable tool for $\bar{P}$ANDA-reactions

- **Predictions on double-Λ & $-\Xi$ hypernuclei**
  - → formation of multi-strange hypermatter at PANDA possible
  - → strong dependence on underlying YN-models!
  - → good observables to constraint more the still unknown S=-2 YN-sector

- **First predictions on S=-3 Ω-production**
  - → production of Ω-particles only in secondary beams abundantly
  - → high $\Xi-$beam momenta are necessary

To do/in progress....

- → YN & YY: full in-medium (selfenergies), S=-2 – sector ($\bar{K}\Lambda$->ΞB, ΞB->$\Lambda\Lambda$)

Combined GiBUU+SMM model…

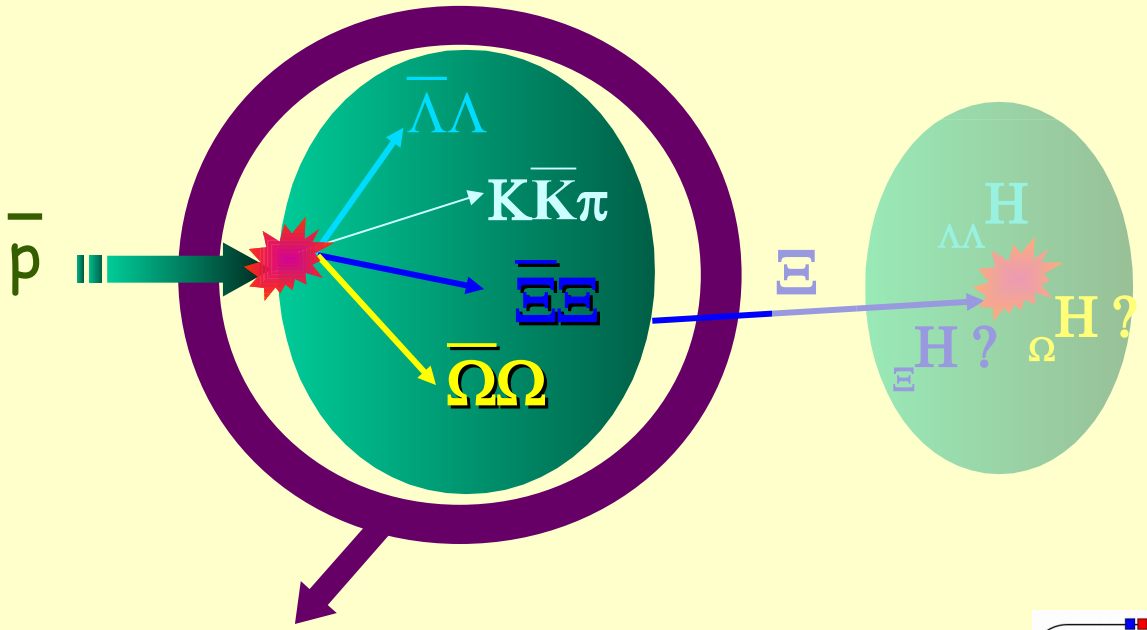
* Non-Equilibrium dynamics within GiBUU; determine source(s)

  (Source: residual nuclei in hadron-induced reactions)

* GiBUU: Determine A, Z, excitation energy E_{exc} and local pressure p of the source versus time

* Temporal GiBUU evolution until source approaches stable configuration, e.g., local equilibrium, at freeze-out time $t=t_f$

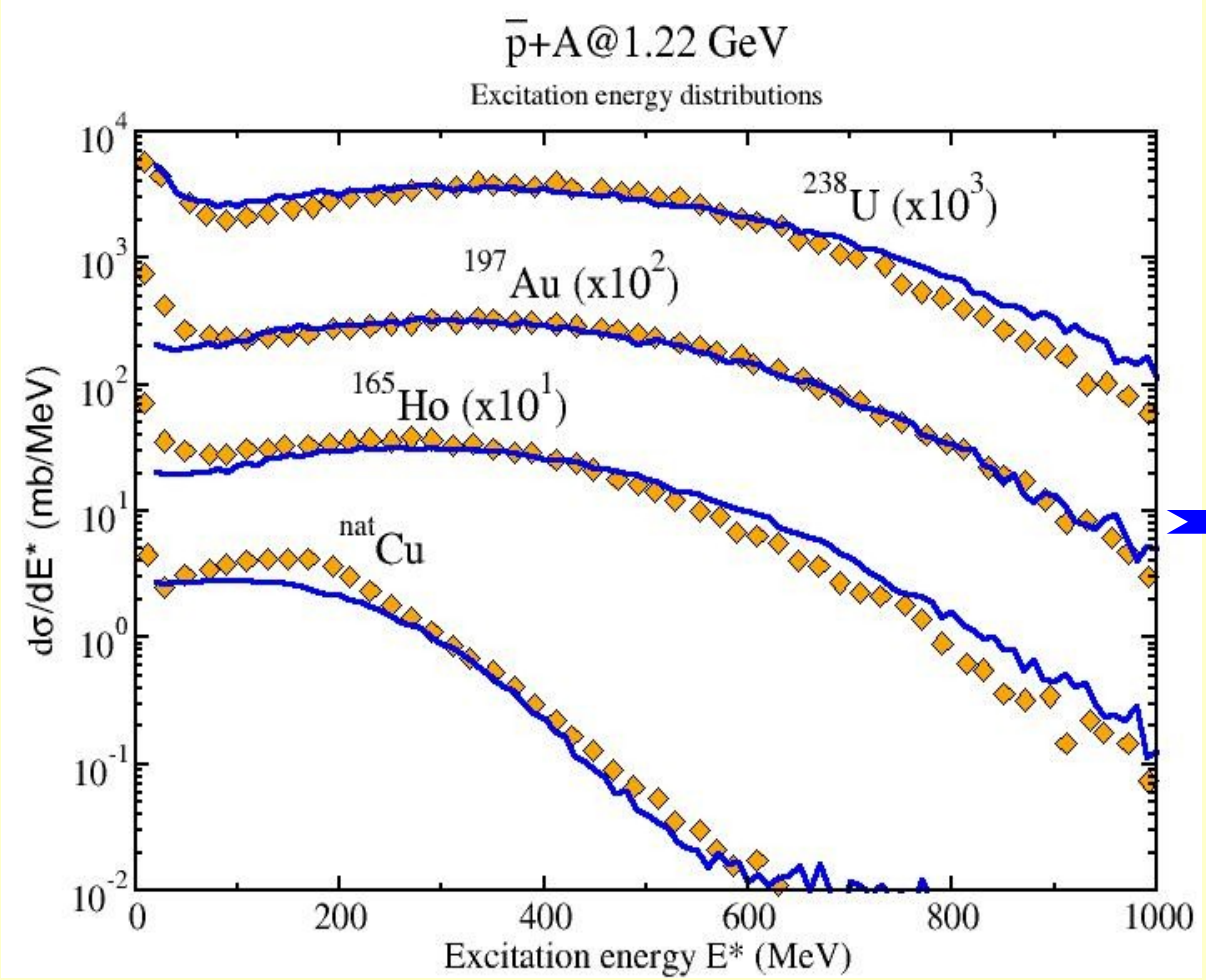
* Apply for each GiBUU event the SMM code with A,Z and E_{exc} as input from GiBUU



1) Fragmentation of residual nuclei at p̄anda

Fragmentation of residual nuclei...

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



data: PRC63, 034616

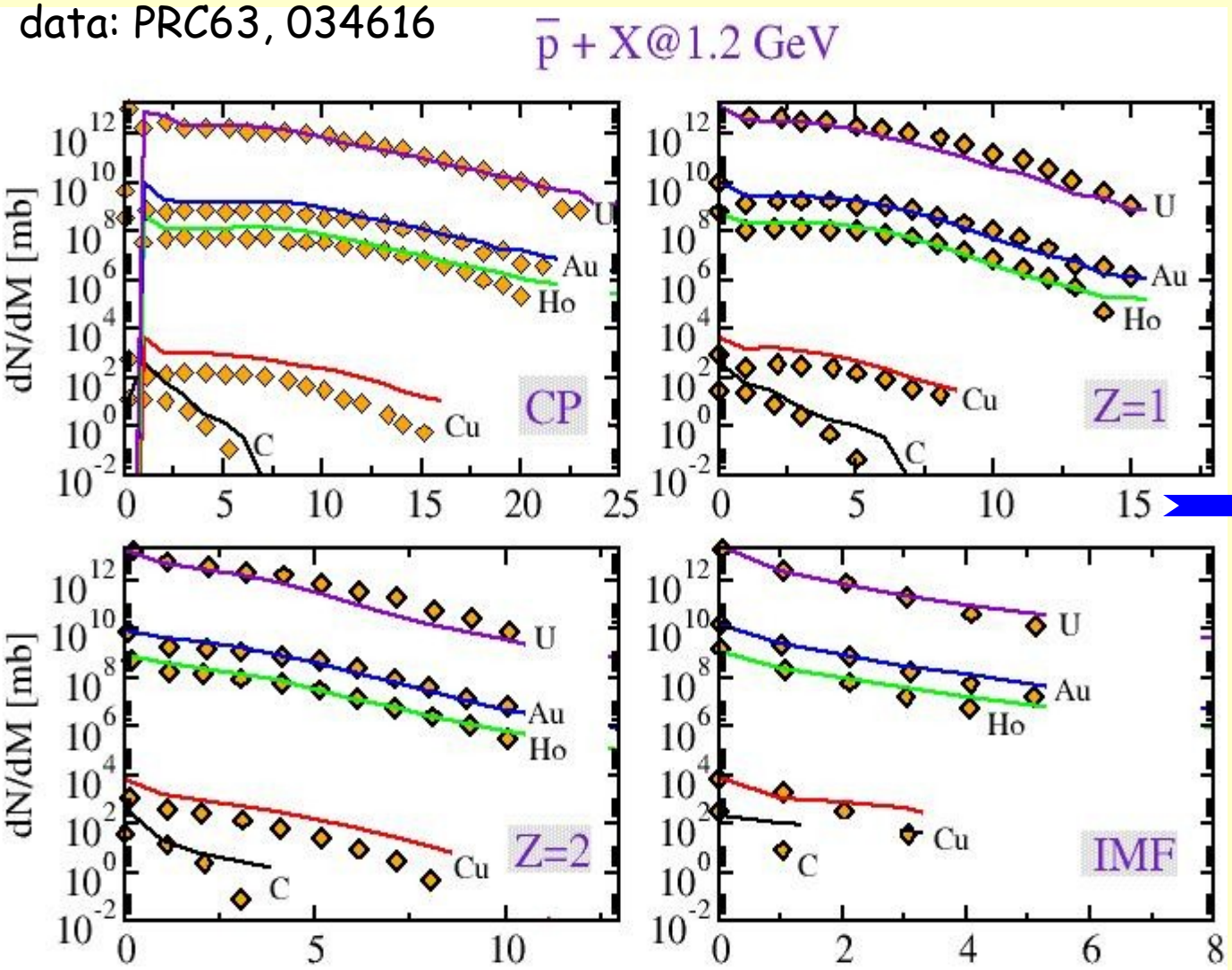
Overall good description of excitation energy spectrum

Important issue before applying SMM

T.G., et al,Nucl.Phys. **A881** ('12) 240

Fragmentation of residual nuclei...

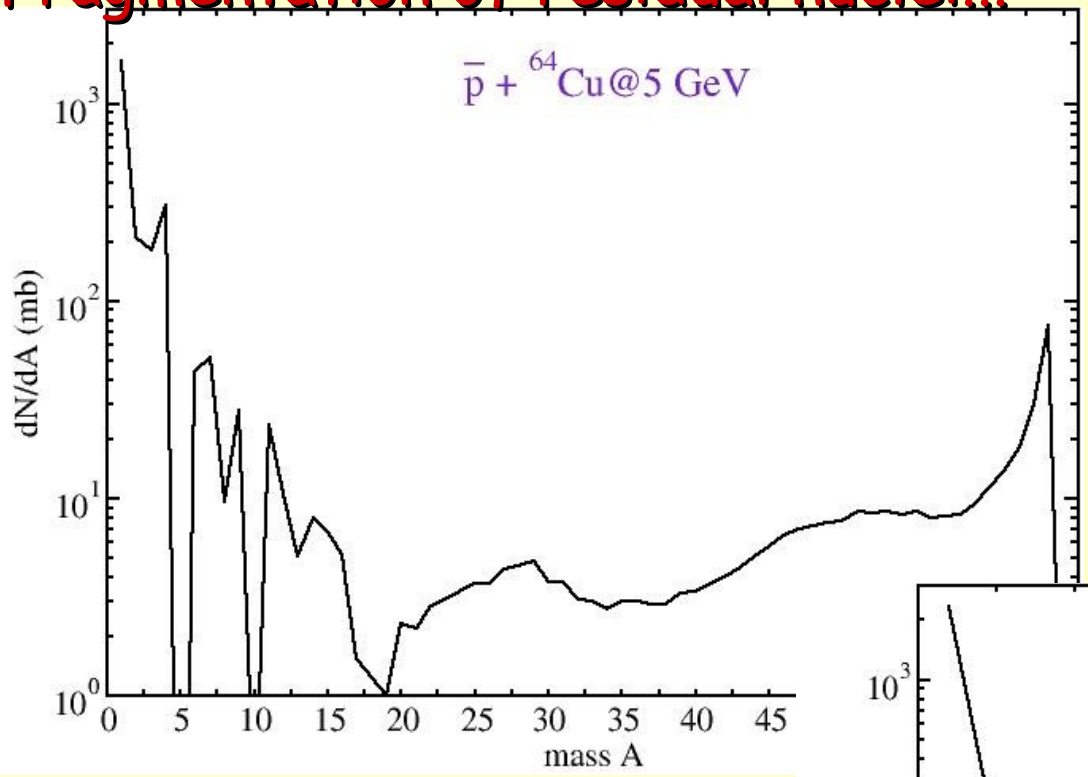
data: PRC63, 034616



Overall good description of different fragment multiplicities

T.G., Larionov, Lenske, Mosel, Nucl.Phys. **A881** ('12) 240

Fragmentation of residual nuclei...



Mass distribution...

...Charge distribution