DPhN
(Nuclear Science Department)

Production of strange particles and hypernuclei in nuclear reactions at a few GeV. New capabilities in INCL.

Jean-Christophe David

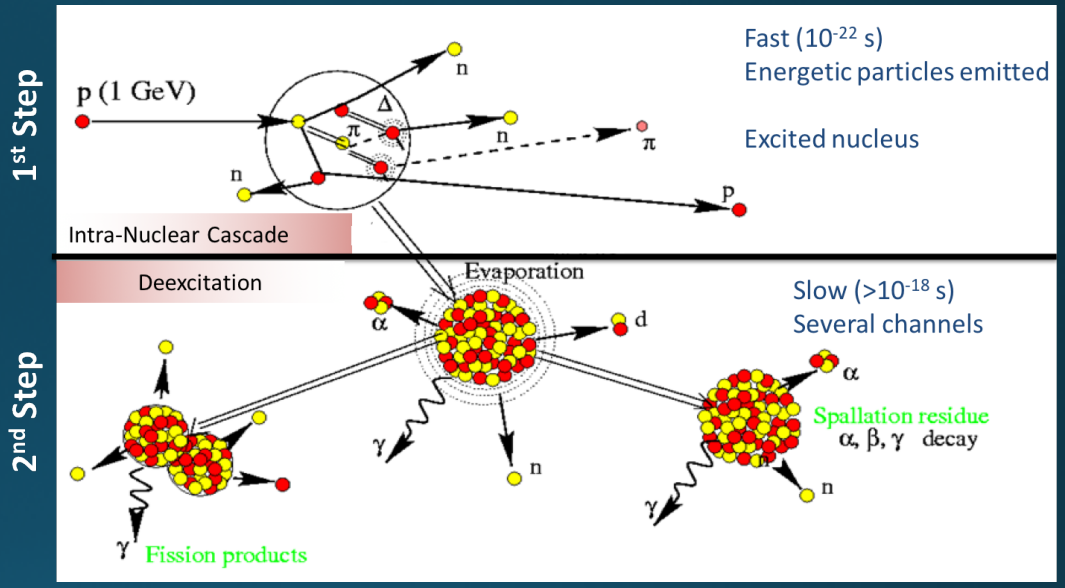
Our Model

INCL (Liège IntraNuclear Cascade)

- Projectiles (n, p, π, A < 19)
- Targets (all nuclei)
- From tens MeV to a few GeV

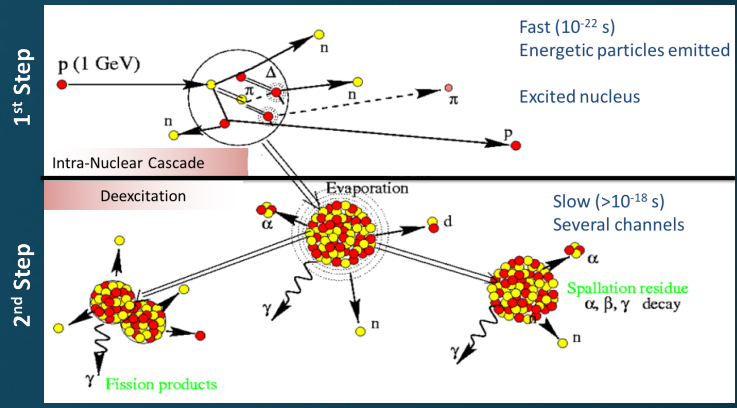
Abla (de-excitation) --- GSI

- Evaporation
- Fission
- Multifragmentation



Production of strange particles and hypernuclei in nuclear reactions at a few GeV. New capabilities in INCL.

Why this work?



- Spallation Benchmark IAEA 2010:
  INCL (combined to Abla)
  → good results in N + Nucleus (up to 2-3 GeV)

- INCL upgraded to ~15 GeV (multiple pion emission --- no resonances, but their decay products)

- … But other particles are produced (η, ω, K, Y, …)
  Minor role, but interesting in themselves

- Renewal of interest in studying Hypernucleus (HypHI/PANDA @ GSI/FAIR; J-PARC; JLab; …)

- Can INCL compete with other codes?
  (INCL is also implemented in transport codes)

Production of strange particles and hypernuclei in nuclear reactions at a few GeV. New capabilities in INCL.

Ingredients

INCL

- $\sigma_{reaction}$ production/scattering/absorption

$NN \rightarrow NYK\ (+1\pi;\ +2\pi)$
$NNK\bar{K}$
$K + X$

$\pi N \rightarrow YK\ (+1\pi;\ +2\pi)$
$NK\bar{K}$
$K + X$

$\bar{K}N \rightarrow \bar{K}N\ (+1\pi;\ +2\pi)$
$Y\pi\ (+1\pi)$

$KN \rightarrow KN\ (+1\pi;\ +2\pi)$

$NY \rightarrow NY'$

$\Delta N \rightarrow NYK$
ΔYK
$NNK\bar{K}$

Production of strange particles and hypernuclei in nuclear reactions at a few GeV.
New capabilities in INCL.

Ingredients

INCL

- $\sigma_{reaction}$ production/scattering/absorption
- (E, Θ) output particles — From exp. data, or isotropy, or phase-space
- Nuclear Potential — Λ:-28 / Σ:16 / K^+:25 / K^-:-60 / K^0:15 / $\bar{K}^0$:-50 MeV
- Decay — Not in the nucleus, except Σ^0

Production of strange particles and hypernuclei in nuclear reactions at a few GeV. New capabilities in INCL.

Ingredients

INCL

- $\sigma_{reaction}$ production/scattering/absorption
- (E, Θ) output particles — From exp. data, or isotropy, or phase-space
- Nuclear Potential — Λ:-28 / Σ:16 / K^+:25 / K^-:-60 / K^0:15 / $\bar{K}^0$:-50 MeV
- Decay — Not in the nucleus, except Σ^0

ABLA

- De-excitation of Hyper-remnants
  - Λ evaporation
    - Separation energy (Samanta – J. Phys. G: Nucl. Part. Phys. 32, 323 (2006))
    - $\sigma_{capture}$ (Λ) = $\sigma_{capture}$ (n)
    - Level density parameter (as for « normal » nucleus)
  - Fission
    - Barrier: LDM + Hyper-energy (Botvina – PRC 94, 054615 (2016))
    - Λ attachement (to FF) probability increases with A (Nifenecker – NPA 531, 539 (1991))

Ingredients

INCL

Jason Hirtz (PhD)

- $\sigma_{reaction}$ production/scattering/absorption
- (E, Θ) output particles — From exp. data, or isotropy, or phase-space
- Nuclear Potential — Λ:-28 / Σ:16 / K^+:25 / K^-:-60 / K^0:15 / $\bar{K}^0$:-50 MeV
- Decay — Not in the nucleus, except Σ^0

ABLA

Jose Luis Rodriguez-Sanchez (Post-Doc)

- De-excitation of Hyper-remnants
  - Λ evaporation
    - Separation energy (WHO?)
    - $\sigma_{capture}$ (Λ) = $\sigma_{capture}$ (n)
    - Level density parameter (as for « normal » nucleus)
  - Fission
    - Barrier: LDM + Hyper-energy (Botvina – PRC 94, 054615 (2016))
    - Λ attachement (to FF) probability increases with A (Nifenecker – NPA 531, 539 (1991))

Main difficulty

Lack of exp. data

$NN \rightarrow NYK$ **$(+1\pi; +2\pi)$** $\underline{\bar{K}}$ **$NN\bar{K}K$**

$\bar{K}N \rightarrow \bar{K}N\ (+1\pi; +2\pi)$
$Y\pi\ (+1\pi)$

$KN \rightarrow KN\ (+1\pi; +2\pi)$

$\pi N \rightarrow YK\ (+1\pi; +2\pi)$
$NK\bar{K}$

$NY \rightarrow NY'$

	From experimental data	→	17%
+	isospin symmetry at initial/final state	→	35%
+	isospin symmetry at Feynman diagram level	→	72%

Main difficulty

Lack of exp. data

$NN \rightarrow NYK$ **(+1π; +2π)**
NNKK

$\bar{K}N \rightarrow \bar{K}N$ (+1π; +2π)
Yπ (+1π)

$KN \rightarrow KN$ (+1π; +2π)

$\pi N \rightarrow YK$ (+1π; +2π)
$N\bar{K}K$

$NY \rightarrow NY'$

	From experimental data	→	17%
+	isospin symmetry at initial/final state	→	35%
+	isospin symmetry at Feynman diagram level	→	72%
+	**Models** and/or **hypotheses**	→	100% !

Main difficulty

Lack of exp. data

NN → NYK (+1π; +2π)
NNKK̄
K + X

πN → YK (+1π; +2π)
NKK̄
K + X

K̄N → K̄N (+1π; +2π)
Yπ (+1π)

KN → KN (+1π; +2π)

NY → NY'

ΔN → NYK
ΔYK
NNKK̄

	From experimental data	→	17%
+	isospin symmetry at initial/final state	→	35%
+	isospin symmetry at Feynman diagram level	→	72%
+	**Models** and/or **hypotheses**	→	100% !

Models

Results

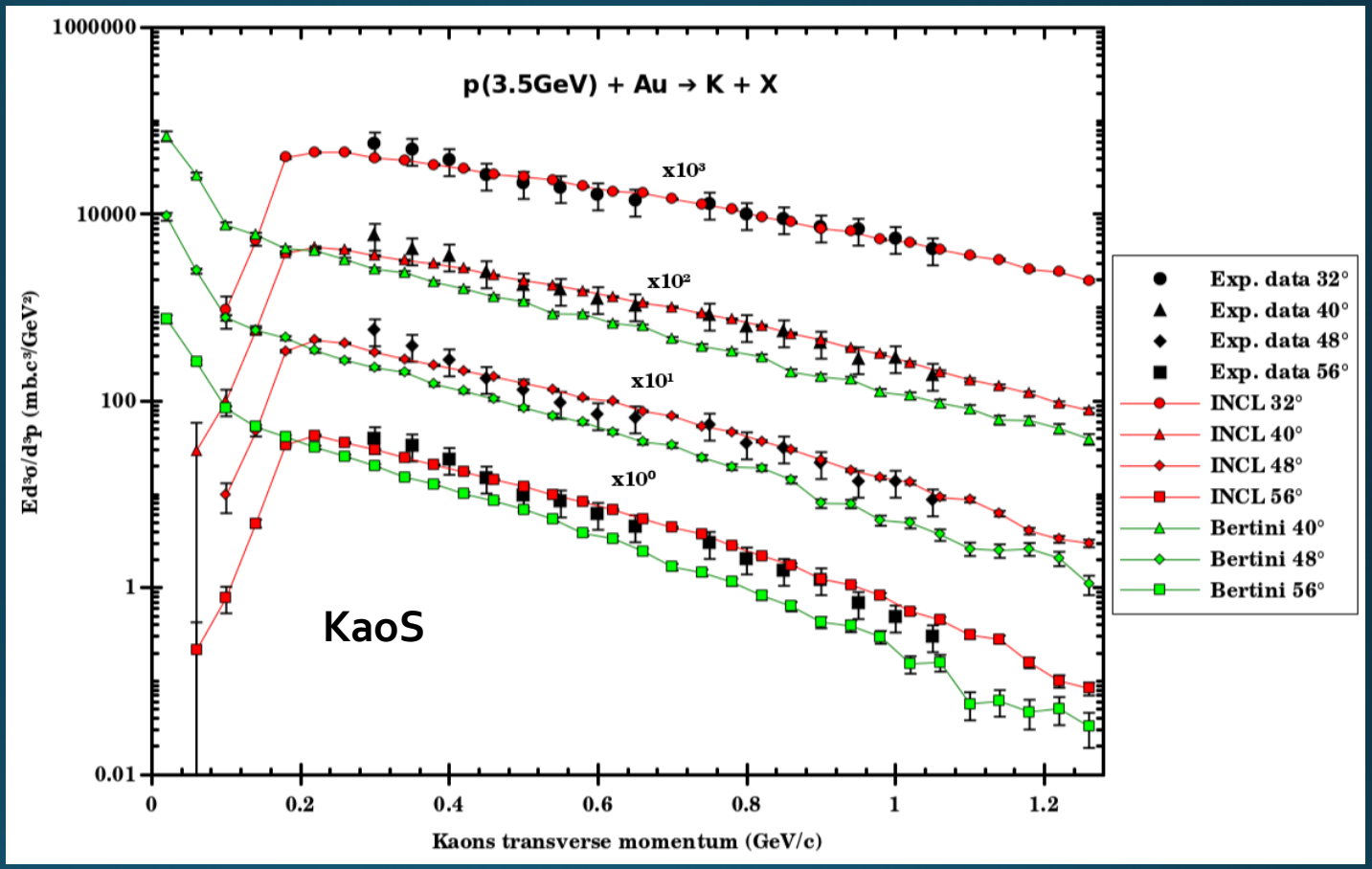
- K emission
- Λ emission
- Hypernucleus yields

Results

K⁺ spectra

Good results!
-> Shape and values

For all angles



W. Scheinast et al., PRL 96, 072301 (2006)

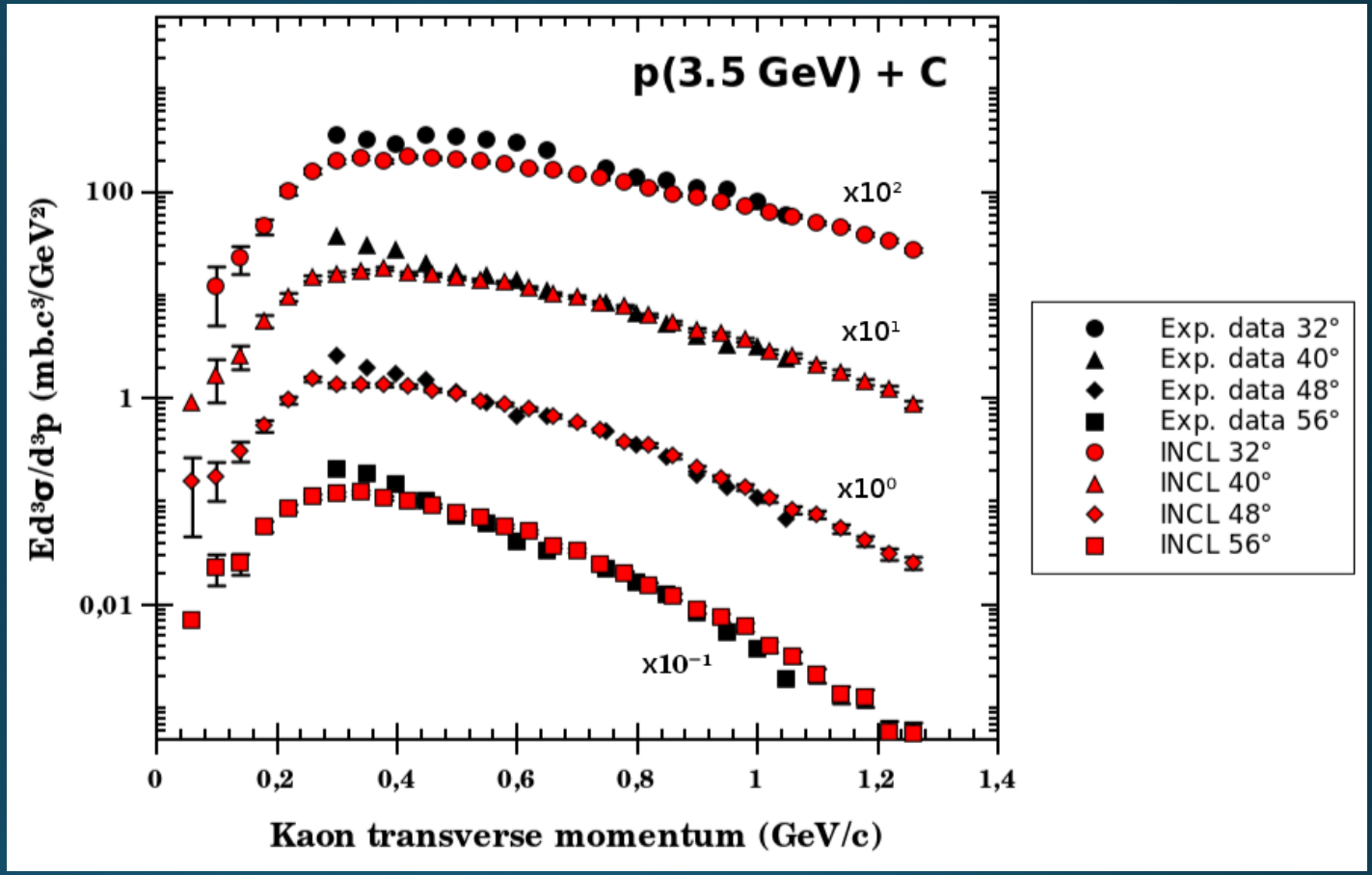
Results

K⁺ spectra

Good results also with a light target!

For all angles

Maybe a slight underestimate at low K momenta



W. Scheinast et al., PRL 96, 072301 (2006)

Results

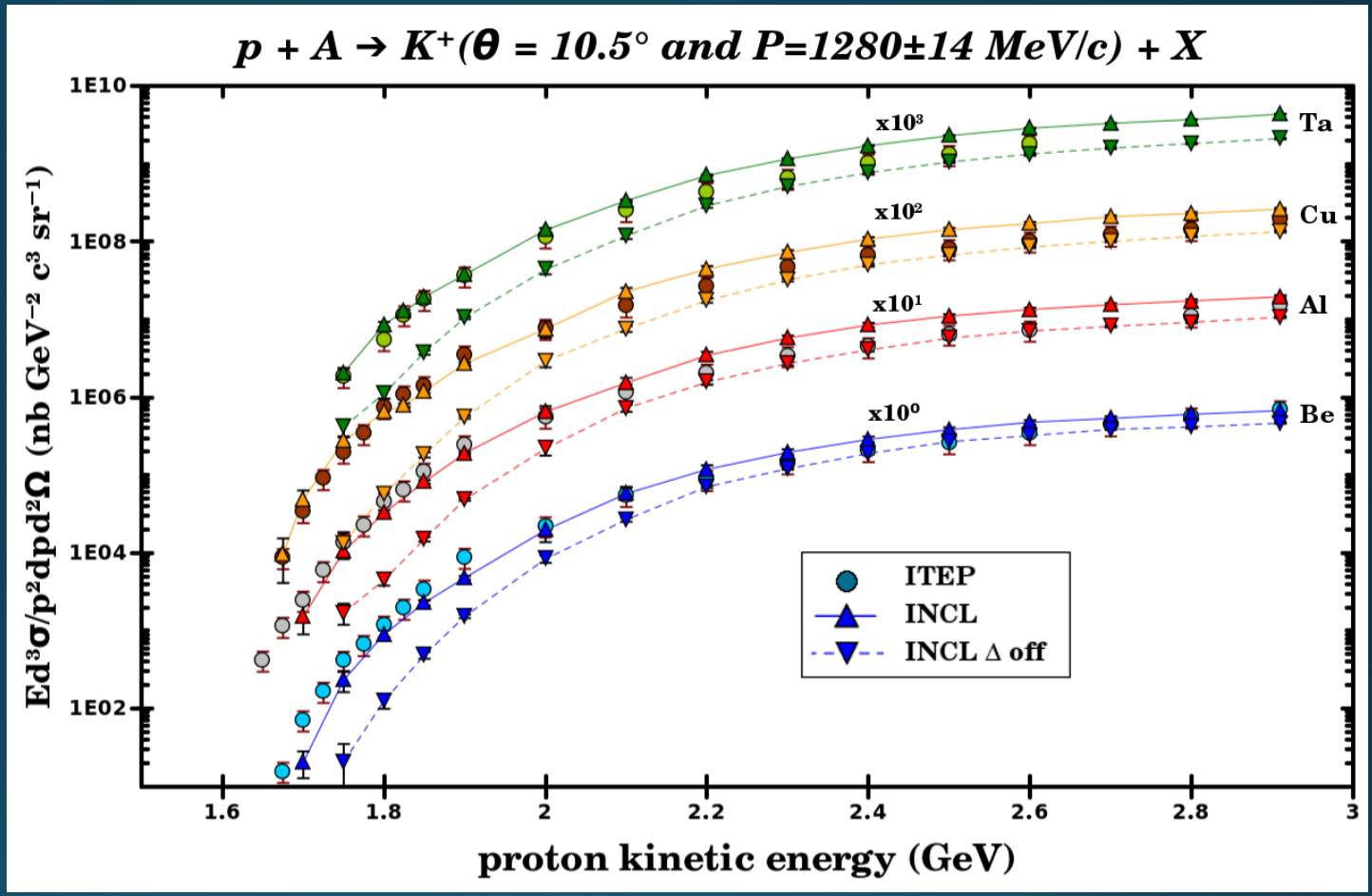
K⁺ excitation function

Good results!

For all targets

Note:
overestimate when E_p ↗

-> Role of the ΔN production?
OK at low energies
Too high at high energies



A. V. Akindinov et al., JETP Letters, Vol. 72, No. 3, 2000, pp. 100-105

Results

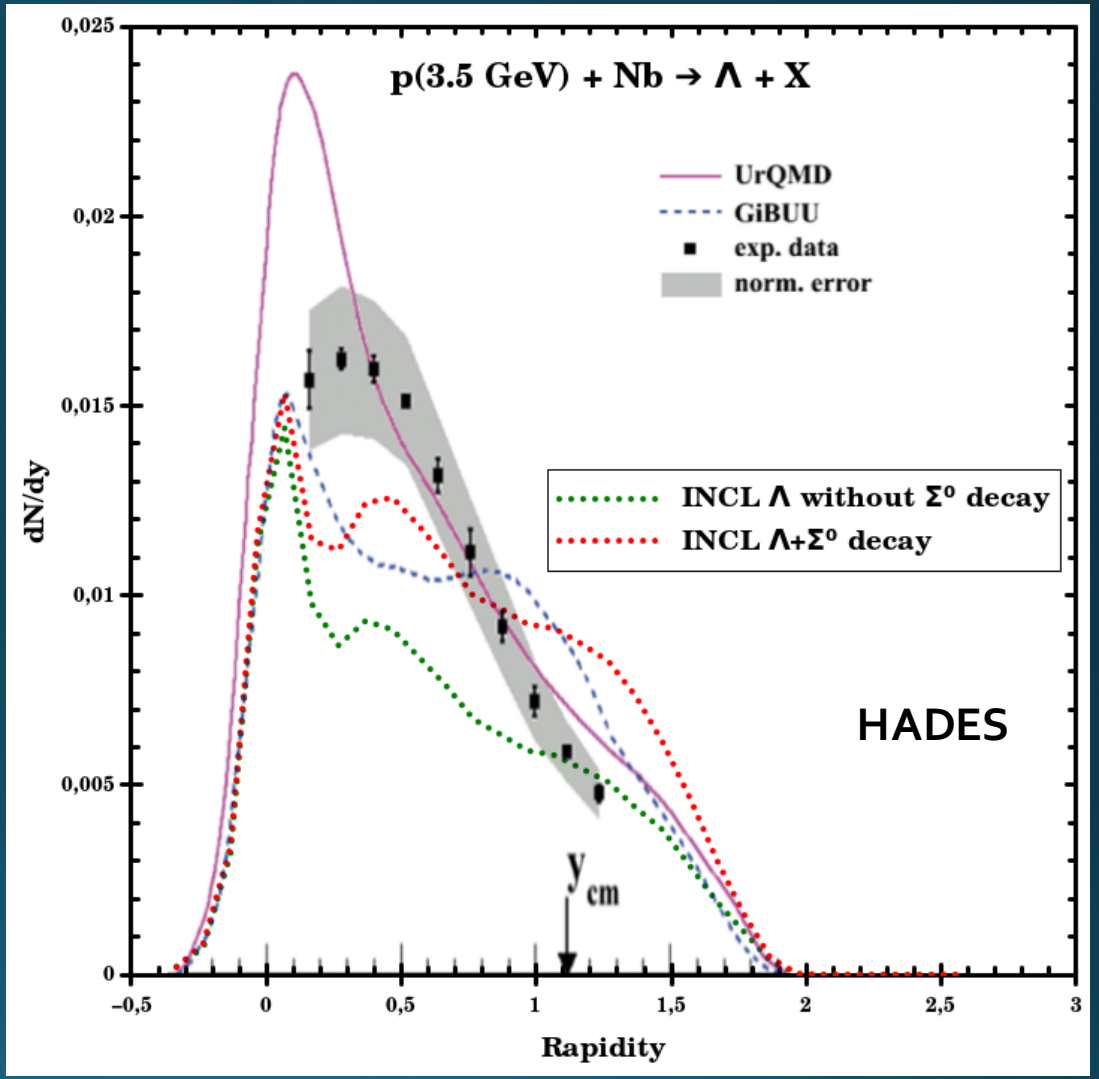
Λ rapidity

Not too bad results indeed….

when compared to other models.

To much in the forward direction and strange behaviors (bumps)…

Investigation needed!



G. Agakishiev et al, Eur. Phys. J. A (2014) 50: 81

Results

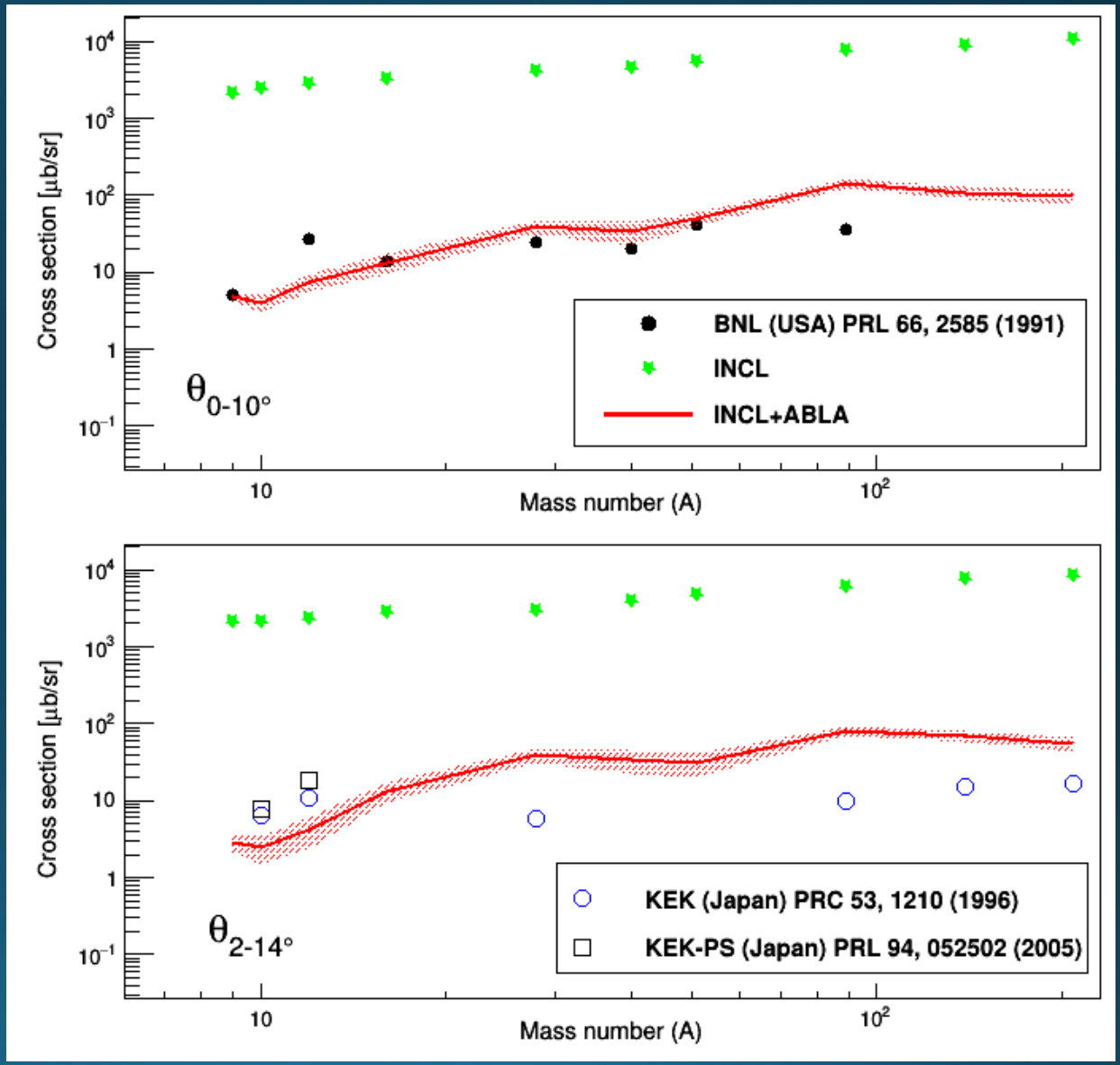
Hypernucleus yields from

$(\pi^+,K^+)_\Lambda X$

Beams: 1.06 and 1.048 GeV/c

- $\pi N \rightarrow KY$ seems well parametrized
- De-excitation important and well done

Very encouraging!



Conclusions

- K, Λ and hypernuclei are rather well taken into account
- However there is room for improvement
    - Production from ΔN
    - Direction of the emitted particles
- The main difficulty is the source of information (too few exp. data)
- INCL with strangeness is in Geant4 (10.4)
    - but no hypernucleus is produced (Λ forced to decay at the end of the cascade)
- ABLA07 also ! (translated in C++ by Jose Luis Rodriguez-Sanchez)
    - 10.4 : without Λ evaporation and « strange » fission
- Next:
    - It's time to investigate the deficiencies more carefully
    - Addition of Ξ? (FAIR; JPARC)
    - new projectiles ($\bar{p}$?, e^-?) (FAIR; MAMI; JLab)

TEAM

A. Boudard, J. Cugnon, J. Hirtz, S. Leray, D. Mancusi, Jose-Luis Rodriguez-Sanchez and G. Schnabel

Thank you!

BACKUP

Main difficulty

Lack of exp. data

$NN \rightarrow NYK\,(+1\pi;\,+2\pi)$ $NNK\bar{K}$ $K + X$	$\bar{K}N \rightarrow \bar{K}N\,(+1\pi;\,+2\pi)$ $Y\pi\,(+1\pi)$
$\pi N \rightarrow YK\,(+1\pi;\,+2\pi)$ $NK\bar{K}$ $K + X$	$KN \rightarrow KN\,(+1\pi;\,+2\pi)$ $NY \rightarrow NY'$
	$\Delta N \rightarrow NYK$ ΔYK $NNK\bar{K}$

Models

- K + X : missing XS parametrized and channels drawn from fritiof calculation results
- ΔN : parametrization from
  K. Tsushima, A. Sibirtsev, A. W. Thomas, and G. Q. Li, Phys. Rev. C 59, 369

Role of the Λ evaporation