Nuclear reaction codes development for the particles and nuclei production in meteoroids and planetary atmospheres

Jason Hirtz

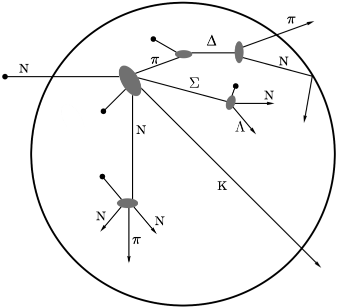
CEA Saclay - 22 November 2019

Outline

Introduction

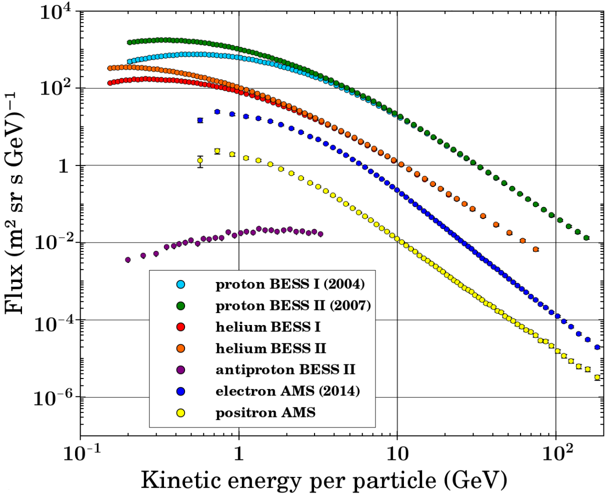
Main concepts

- Cosmic rays
- Nuclear spallation
- Cosmogenic nuclides



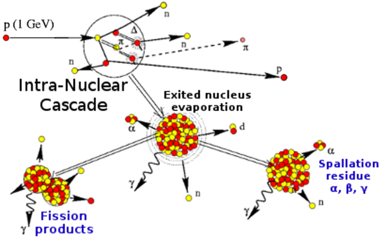
Cosmic rays

- Protons ($\sim$ 90%)
- Alphas ($\sim$ 10%)
- Others ($\sim$ 1%)



Nuclear spallation

Spallation reaction

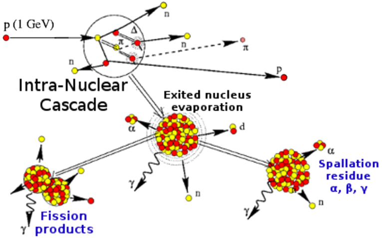


Spallation with numbers

- Light projectile (p, π, α,...)
- Kinetic energy around the GeV
- Heavy target (^{12}C, ^{208}Pb,...)
- Time scale: $\sim 10^{-22} - 10^{-20}$ s

Nuclear spallation

Spallation reaction
or
How to transmute lead into gold
(Did you say cosmochemistry? No! Alchemy!)



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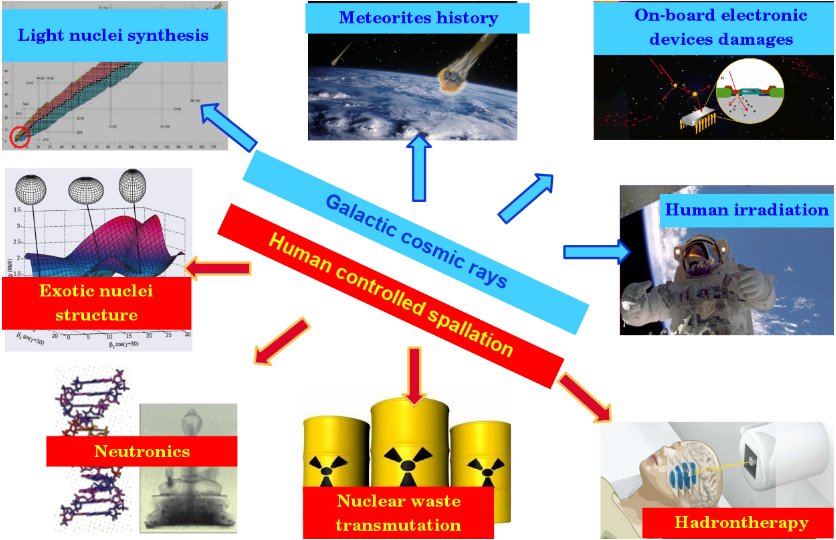
Spallation applications



Cosmogenic nuclides

Dating techniques

- ^{14}C

Cosmogenic nuclides

Dating techniques

- $^{14}C/C$ $\tau \sim 10^3 years$
- $^{10}Be/^{14}C$ $\tau \sim 10^4 years$
- $^{26}Al/^{21}Ne$ $\tau \sim 10^6 years$
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Isotope conditions

- Natural abundance low → resolve production vs natural occurrence

⇒ Order of magnitude of production: 10^4 $atom\ g^{-1}\ year^{-1}$ vs $\mathcal{N}_a$

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- Measurable

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- Stable or half-life comparable to the event of interest
- Measurable
- Theoretical understanding of production processes

Theoretical understanding of cosmogenic nuclide production processes

Need of improved spallation reaction description

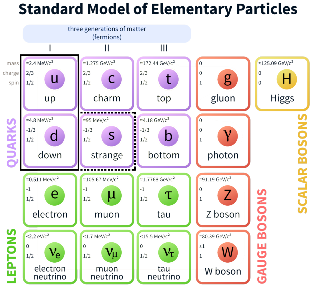
Interest in spallation reaction applications

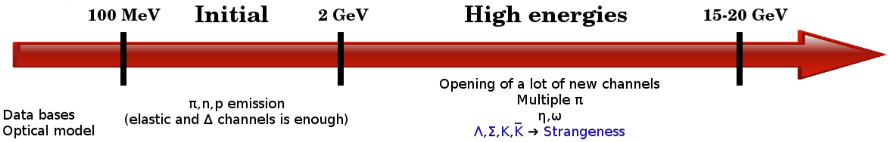
Need of improved cosmic ray irradiation simulation

Interest in cosmic ray behaviour

INCL improvement

Improvement of the intra-nuclear cascade simulation code at high energy through a new degree of freedom: **Strangeness**





Ingredients

Old particles

- Nucleons (protons and neutrons)
- Pions (π^-,π^0, and π^+)
- Deltas (Δ^-,Δ^0, Δ^+, and Δ^{++})

New particles

- Kaons (K^0 and K^+)
- Antikaons ($\overline{K}^0$ and K^-)
- Sigmas (Σ^-,Σ^0, and Σ^+)
- Lambda (Λ)

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Particle properties

- Mass
- Half life
- Decay channel
- Nuclear potential

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Cross sections

- Production
- Interaction
- Absorption

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Particle properties

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Cross sections

- Production
- Interaction
- Absorption

Angular distributions

- Energy
- Direction

Cross sections to parametrise

NN	$\rightarrow$	$N\Lambda K$	πN	$\rightarrow$	ΛK	NK	$\rightarrow$	NK	$N\overline{K}$	$\rightarrow$	$N\overline{K}$
	$\rightarrow$	$N\Sigma K$		$\rightarrow$	ΣK		$\rightarrow$	$NK\pi$		$\rightarrow$	$\Lambda\pi$
	$\rightarrow$	$N\Lambda K\pi$		$\rightarrow$	$\Lambda K\pi$		$\rightarrow$	$NK\pi\pi$		$\rightarrow$	$\Sigma\pi$
	$\rightarrow$	$N\Sigma K\pi$		$\rightarrow$	$\Sigma K\pi$	$N\Lambda$	$\rightarrow$	$N\Lambda$		$\rightarrow$	$N\overline{K}\pi$
	$\rightarrow$	$N\Lambda K\pi\pi$		$\rightarrow$	$\Lambda K\pi\pi$		$\rightarrow$	$N\Sigma$		$\rightarrow$	$\Lambda\pi\pi$
	$\rightarrow$	$N\Sigma K\pi\pi$		$\rightarrow$	$\Sigma K\pi\pi$	$N\Sigma$	$\rightarrow$	$N\Lambda$		$\rightarrow$	$\Sigma\pi\pi$
	$\rightarrow$	$NNK\overline{K}$		$\rightarrow$	$NK\overline{K}$		$\rightarrow$	$N\Sigma$		$\rightarrow$	$N\overline{K}\pi\pi$

Initial set: $\sim$400 channels

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	$\rightarrow$	$N\Sigma K\pi$		$\rightarrow$	$\Sigma K\pi$	$N\Lambda$	$\rightarrow$	$N\Lambda$		$\rightarrow$	$N\overline{K}\pi$
	$\rightarrow$	$N\Lambda K\pi\pi$		$\rightarrow$	$\Lambda K\pi\pi$		$\rightarrow$	$N\Sigma$		$\rightarrow$	$\Lambda\pi\pi$
	$\rightarrow$	$N\Sigma K\pi\pi$		$\rightarrow$	$\Sigma K\pi\pi$	$N\Sigma$	$\rightarrow$	$N\Lambda$		$\rightarrow$	$\Sigma\pi\pi$
	$\rightarrow$	$NNK\overline{K}$		$\rightarrow$	$NK\overline{K}$		$\rightarrow$	$N\Sigma$		$\rightarrow$	$N\overline{K}\pi\pi$

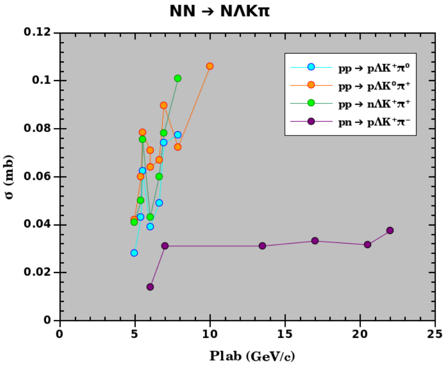
Initial set: $\sim$400 channels

ΔN	$\rightarrow$	$N\Lambda K$	NN	$\rightarrow$	$K+X$
	$\rightarrow$	$N\Sigma K$			
	$\rightarrow$	$\Delta\Lambda K$	πN	$\rightarrow$	$K+X$
	$\rightarrow$	$\Delta\Sigma K$			
	$\rightarrow$	$NNK\overline{K}$			

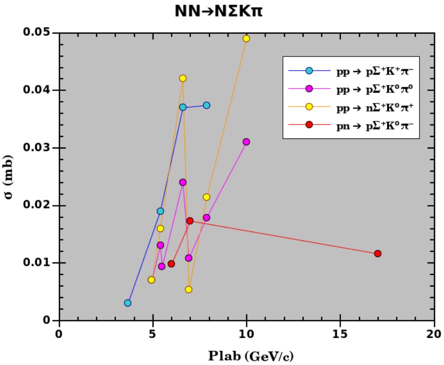
Second set: No data but needed. $\rightarrow$ Thousands of new channels.

Sparse data

10 channels, 29 data points



26 channels, 43 data points



Data for 17% of the channels of the first set, including the above channels.
(0% for the second set)

Data completion

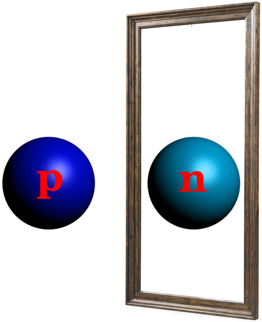
First set

- **Experimental data** **17%**

Data completion

First set

- **Experimental data** **17%**
- **Bystricky procedure** **18%** **total: 35%**

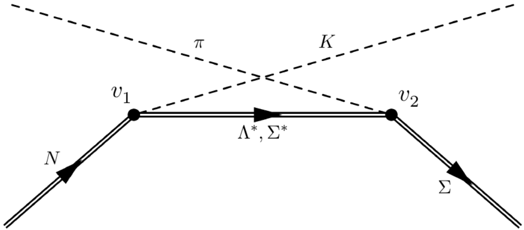


Symmetries between the channels

Data completion

First set

- **Experimental data** **17%**
- **Bystricky procedure** **18%** **total: 35%**
- **Hadron exchange model** **37%** **total: 72%**



Symmetries between the Feynman diagrams

Data completion

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• **Experimental data**	**17%**	
• **Bystricky procedure**	**18%**	**total: 35%**
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• **Models-hypotheses-approximations**	**28%**	**total: 100%**

Data completion

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Second set: Models-hypotheses-approximations 100%

J. Hirtz, J.C. David, et al., Eur. Phys. J. Plus 133:436 (2018)

Angular distributions

Angular distributions:
the direction and the energy of the particles in the final state

Angular distributions

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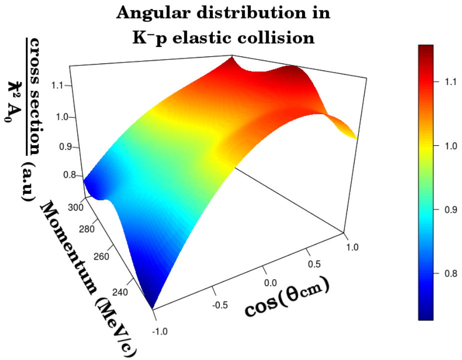
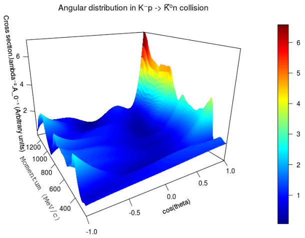
the direction and the energy of the particles in the final state

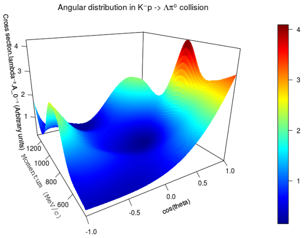
Use of phase space generators when no experimental data

A refine model when possible

Angular distribution







J. Hirtz, J.C. David, et al., Eur. Phys. J. Plus 133:436 (2018)

Variance reduction scheme

Strangeness production represents 0.014% (0.15%) of the total cross section in p-p collision at kinetic energies of 2(3) GeV.

Computational time problem

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Scheme: Increase the production of strangeness, register "how much I cheat", and correct the results accordingly
(plus a lot of mathematics)

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How to use the scheme?

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Computational time problem

My solution: I cheat! (and I correct the results a posteriori)

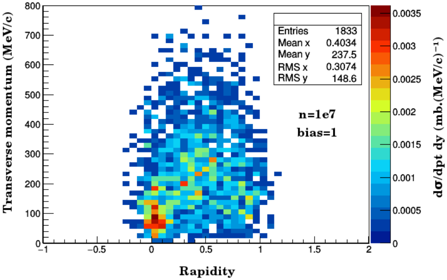
Scheme: Increase the production of strangeness, register "how much I cheat", and correct the results accordingly
(plus a lot of mathematics)

How to use the scheme?
The user requires an increase of the statistics by a factor 10 and the scheme increases the statistics by a factor 10 and tells you how to weight the results

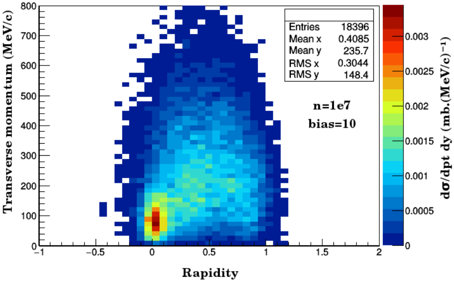
Efficiency

Λ production in $p(1.7\ GeV) + Ca$ collision

Before

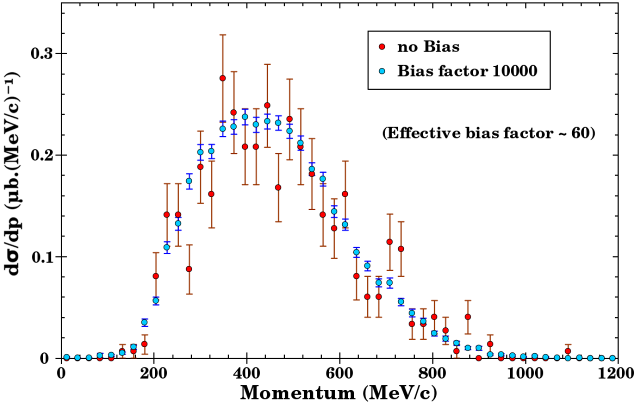


After



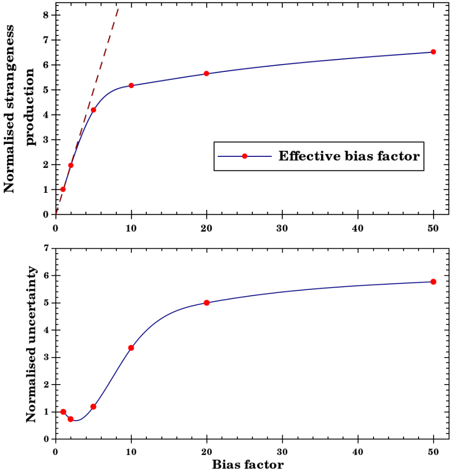
Physical limits

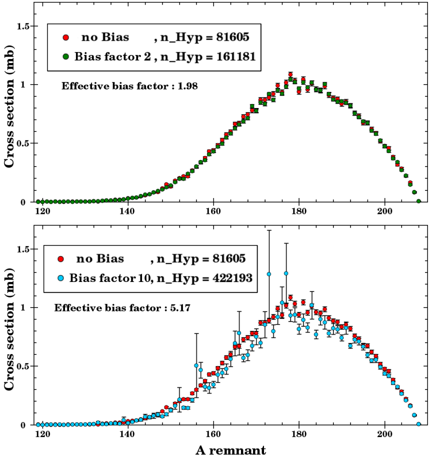
K^+ momentum in $p(1.6\ GeV) + ^{12}C$ with 10^7 events



Borderline cases

p(10 GeV) $+^{208}$ Pb (10^7 shots)



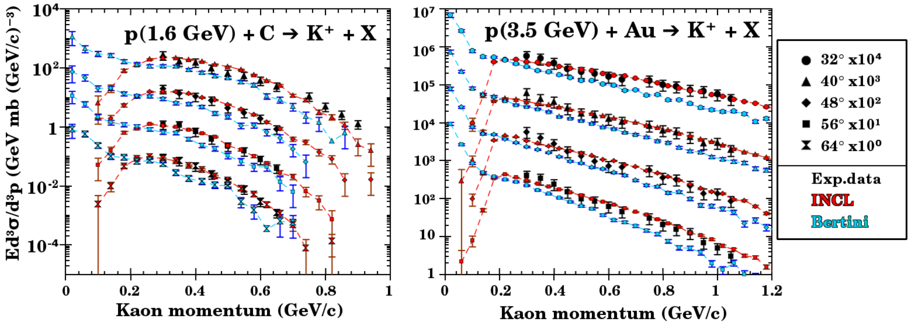


INCL++6 results

Time to control the results!

KaoS experiment

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



Good points

Excellent agreement with experimental data

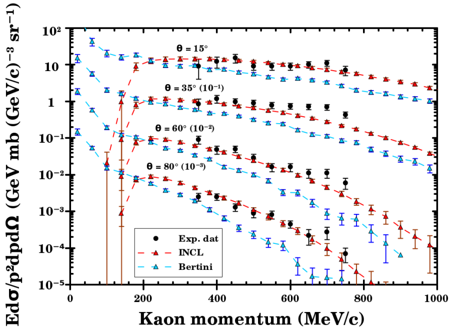
Observations

Threshold very different compared to the Bertini model because of repulsive K^+'s potential

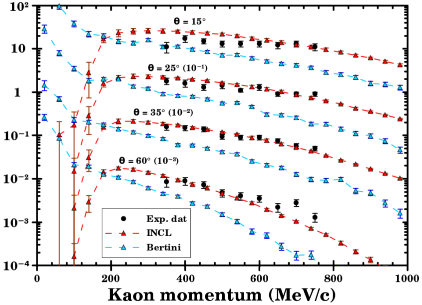
LBL experiment

S. Schnetzer et al., Phys. Rev. C 40, 640(1989)

$\mathbf{p(2.1\ GeV) + ^{208}Pb \rightarrow K^+ + X}$



$\mathbf{H^2(2.1\ GeV/A) + ^{208}Pb \rightarrow K^+ + X}$



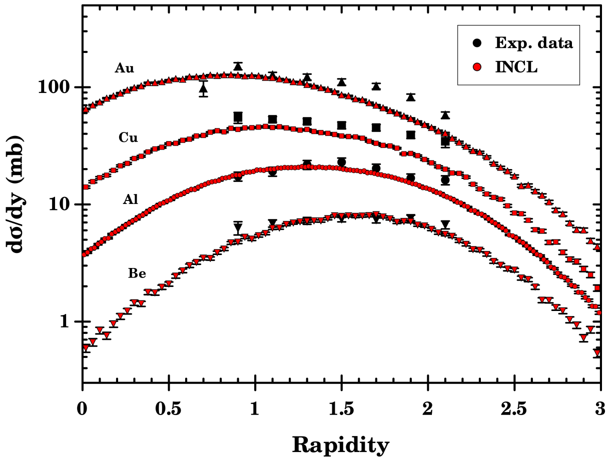
Observations

- Results globally fine for proton as well as for deuteron induced reaction

E-802 experiment

E-802 Collaboration Phys. Rev. D 45, 3906 (1992)

$$p(14.6\ GeV/c) + A \rightarrow K^{+} + X$$



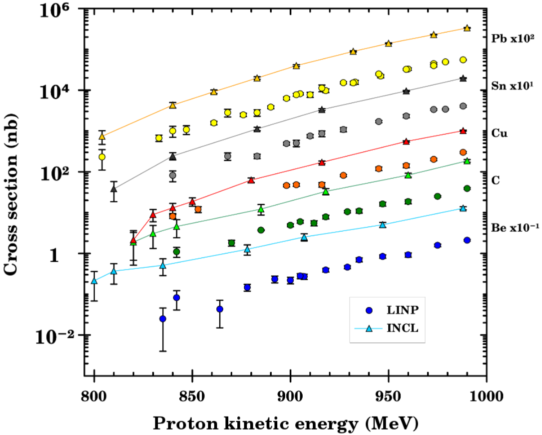
Observations

Relatively good results at high energy
Promising for cosmic ray applications

LINP experiment

V.P. Koptev et al., Zh. Eksp. Teor. Fiz. 94,1-14 (1988)

$$p + A \rightarrow K^+ + X$$



Remark

- Threshold $pp \rightarrow p\Lambda K^+$ 1580 MeV

Observations

- Factor 4 with experimental data
- Far sub-threshold
  - → Use of biasing (speed up by a factor 1 000)
  - → Other models cannot produce results in a reasonable time

CosmicTransmutation

Simulation of spallation reactions improved

New version implemented in the Geant4 toolkit (open source)

Time to simulate cosmic ray irradiation

Creation of a new program: CosmicTransmutation (Geant4 based)

Objectives

Observables

- Cosmogenic nuclide production rates
- Light particle fluxes (p, n, α)

Meteoroids (asteroids, moons)

- Shape
- Composition
- Size

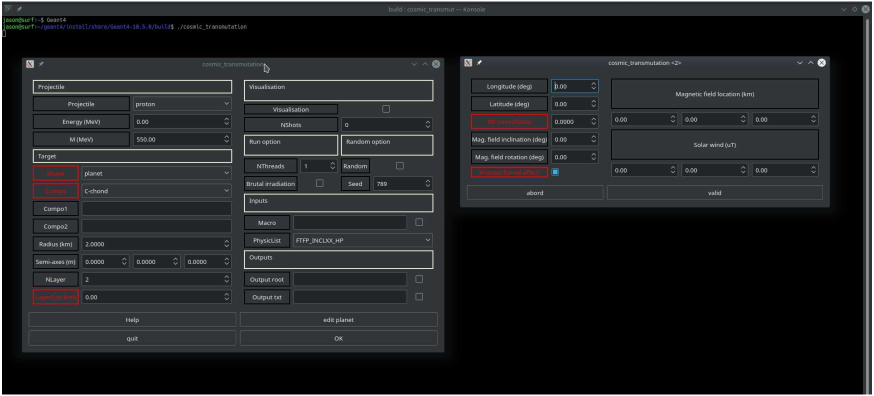
Planets

- Planet size
- Atmosphere size, composition, density profile
- **Magnetic field**

Requirements

- User-friendly
- Simple input and output
- Code documentation for analyses

User-friendly interface



Interface

- A few steps to run the program
- Simple definition of input parameters
- Able to tell the user if something is wrong or if an input file is missing

Simple output

Different type of output as a function of the needs

Data file

- Small output file
- Automatically normalised results
- Only the fluxes of light particles

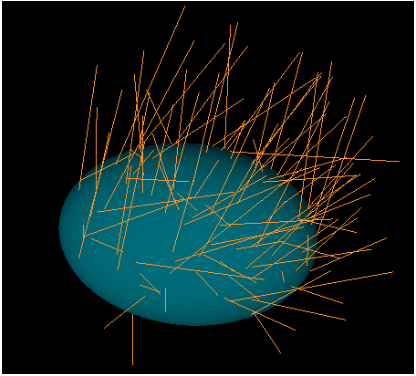
ROOT file

- All the information
- Possibility to cross observables
- More complex to manipulate

Development

Algorithms - interface

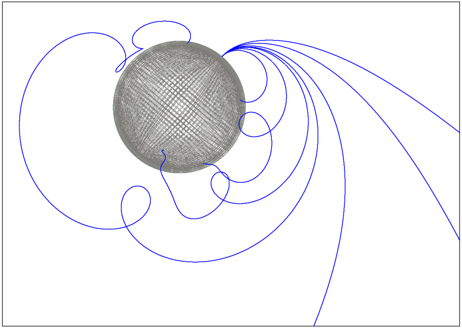
- Uniform irradiation (symmetries)
- User defined compositions
- etc...

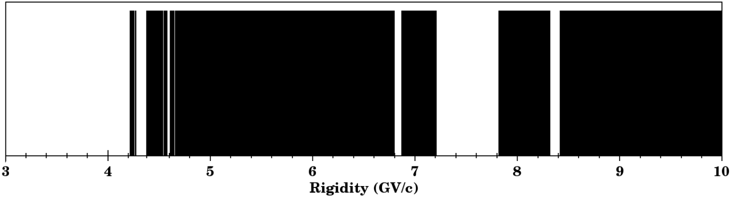


Planets and magnetospheres

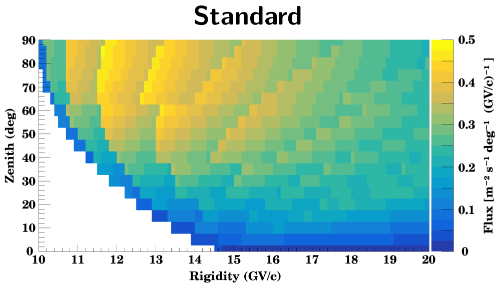
Algorithms

- 2 phases
- Reverse kinematic calculations
- Map of allowed trajectories (Longitude, Latitude, Zenith, Azimuth, Rigidity)





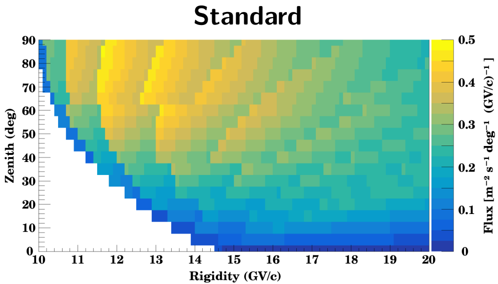
Cut-off maps



New considerations

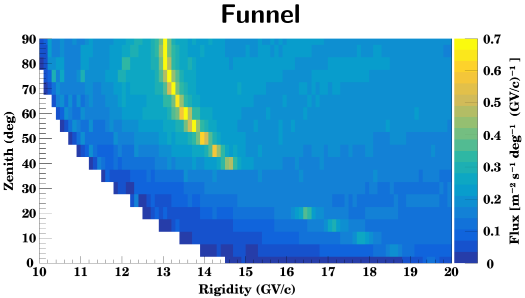
- Structure of the penumbra

Cut-off maps



New considerations

- Structure of the penumbra
- Consideration of focusing and dispersion **Funnel effect**



CosmicTransmutation results

Time to control the results! (Again)

Meteoroids

What to compare with?

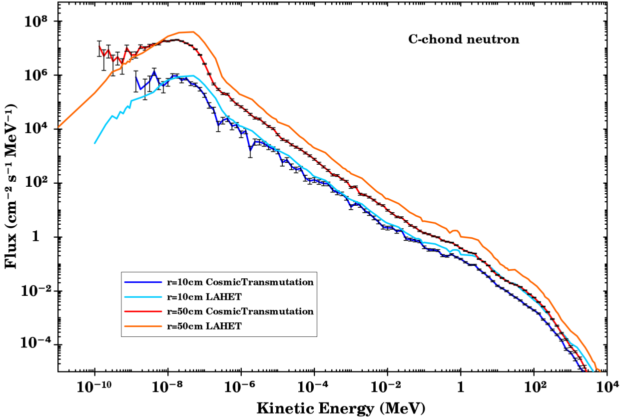
Cosmogenic nuclide production rate

- What we try to understand
- Models use fluxes to calculate cosmogenic nuclide production

Particle fluxes

- No experimental data
- Other models

Neutron flux - Surface



Observations

- Factor 2 below LAHET

→ Likely an error of normalisation

- Shapes similar

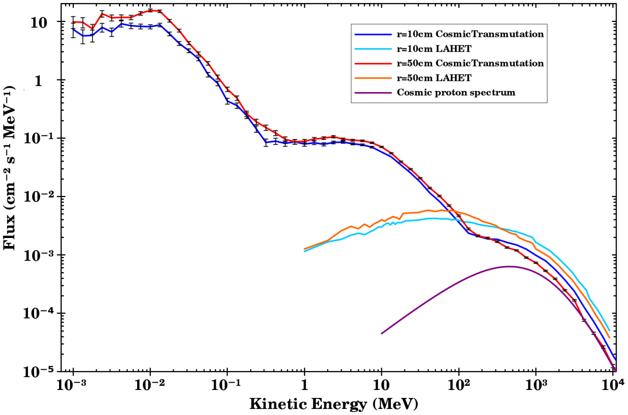
Proton flux - Surface

Observations

- Factor 2 below LAHET

→ Confirmation error of normalisation

- High energy flux corresponds to the cosmic ray spectrum
- High energies (INC): similar shapes
- Low and intermediate energies: very different



Planetary atmospheres

What to compare with?

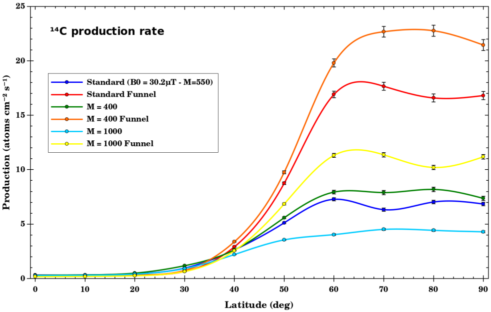
Particle fluxes

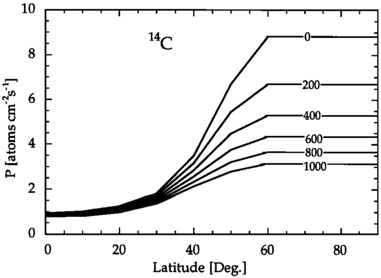
- Experimental data: Input data or unmeasured
- Models: No data found + funnel effect

Cosmogenic nuclide production rate

- Experimental data: hard to measure, atmosphere aerodynamics
- Models: funnel effect should not be considered to be comparable

Solar modulation parameter



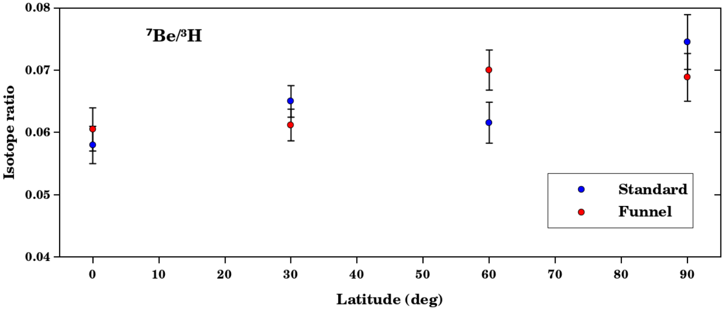


Without funnel vs Masarik and Beer

- Similar shapes
- 40% above

→ alpha particles ($\sim$ 10% of the cosmic ray spectrum; made of 4 nucleons)

Cosmogenic nuclide ratios



Observations

- Isotope ratio can change with a modification of the irradiation spectrum
- No observation of isotope ratio modification due to the funnel effect

Conclusion

Successful implementation of strangeness in INCL

- Improved simulation at high energy
- New fields of simulation opened
- Very good results for most of the observables studied
- Bonus: Variance reduction scheme

Creation of CosmicTransmutation

- State-of-the-art simulation models used
- New features: alpha particles, ellipsoidal meteorite, penumbra structure, funnel effect, ...

Future and perspective

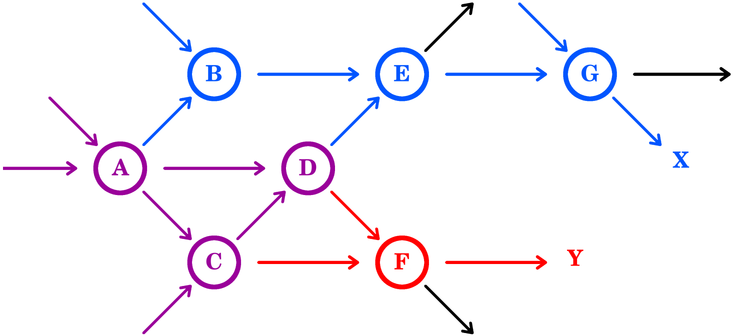
- Study of the impact of funnel effect (cosmic ray flux, cosmogenic nuclides)
- Date things!

Conclusion

The End

Backup

Graph theory



Isospin symmetry - Bystricky procedure

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s^2}\frac{P_f}{P_i}|\mathcal{M}_{fi}|^2 \qquad \rightarrow \qquad \sigma \propto |\mathcal{M}_{fi}|^2$$

$$\mathcal{M}(NN \rightarrow NN\ x\pi) = (\langle NN| \otimes \langle x\pi|)\, M\, |NN\rangle$$

Superposition of state

$$\Rightarrow \langle I^{(1)} I_3^{(1)}\ \ I^{(2)} I_3^{(2)}|\, M\, |I^i I_3^i\rangle = CG\ \ M_{I^{(1)} I^{(2)} I^i}$$

Equations of the type $\sigma_1 = ax + by,\ \sigma_2 = cx + dy,\ \ldots$

$$\begin{aligned}
&\mathcal{M}\left(Initial\ state \rightarrow x_N N\ x_\pi \pi\ x_Y Y\ x_K K\ x_{\overline{K}}\overline{K}\right)\\
&= \left(\langle x_N N| \otimes \langle x_\pi \pi| \otimes \langle x_Y| \otimes \langle x_K K| \otimes \langle x_{\overline{K}}\overline{K}|\right) M\, |Initial\ state\rangle\\
&= (\langle system1| \otimes \langle system2|)\, M\, |Initial\ state\rangle
\end{aligned}$$

Isospin symmetry - Bystricky results

$$\sigma(pp \to p\Sigma^+ K^0) = \sigma(nn \to n\Sigma^- K^+)$$

$$\sigma(pn \to p\Sigma^- K^+) + \sigma(pp \to n\Sigma^+ K^+) + \sigma(pp \to p\Sigma^+ K^0)$$
$$= 2\sigma(pn \to p\Sigma^0 K^0) + 2\sigma(pp \to p\Sigma^0 K^+)$$

Data for 17% $\to$ 35% of the channels.

Isospin projection

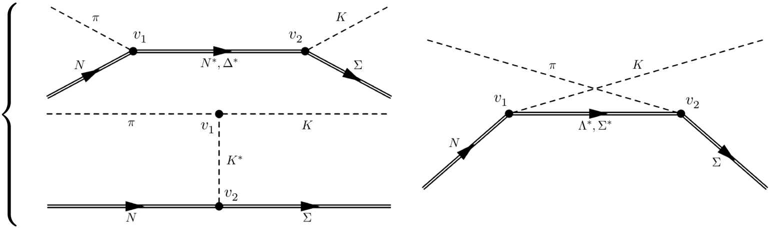
$$|pp\rangle = |1\ 1\rangle$$
$$|pn\rangle = \frac{\sqrt{2}}{2}|1\ 0\rangle + \frac{\sqrt{2}}{2}|0\ 0\rangle$$
$$|np\rangle = \frac{\sqrt{2}}{2}|1\ 0\rangle - \frac{\sqrt{2}}{2}|0\ 0\rangle$$
$$|nn\rangle = |1\ -1\rangle$$

$$|p\Sigma^+\rangle = |3/2\ 3/2\rangle$$
$$|p\Sigma^0\rangle = \sqrt{\frac{2}{3}}|3/2\ 1/2\rangle - \sqrt{\frac{1}{3}}|1/2\ 1/2\rangle$$
$$|p\Sigma^-\rangle = \sqrt{\frac{1}{3}}|3/2\ -1/2\rangle - \sqrt{\frac{2}{3}}|1/2\ -1/2\rangle$$
$$|n\Sigma^+\rangle = \sqrt{\frac{1}{3}}|3/2\ 1/2\rangle + \sqrt{\frac{2}{3}}|1/2\ 1/2\rangle$$
$$|n\Sigma^0\rangle = \sqrt{\frac{2}{3}}|3/2\ -1/2\rangle + \sqrt{\frac{1}{3}}|1/2\ -1/2\rangle$$
$$|n\Sigma^-\rangle = |3/2\ -3/2\rangle$$

Isospin symmetry - Hadron Exchange Model

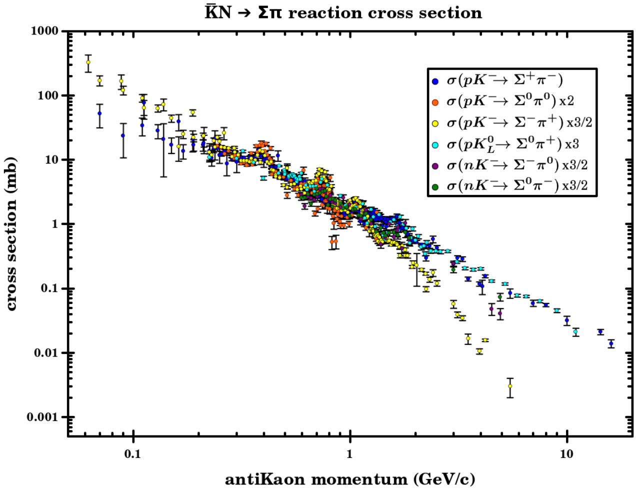
Zoom from reactions level to Feynman diagrams level.
More powerful but need more hypotheses.

$\pi N \to \Sigma K \Rightarrow$



$$\sigma(\pi N \to \Sigma K) = a_K^2 \int |\mathfrak{M}_K|^2 d\Omega + a_\Lambda^2 \int |\mathfrak{M}_\Lambda|^2 d\Omega + a_\Sigma^2 \int |\mathfrak{M}_\Sigma|^2 d\Omega + a_N^2 \int |\mathfrak{M}_N|^2 d\Omega + a_\Delta^2 \int |\mathfrak{M}_\Delta|^2 d\Omega.$$

Isospin symmetry - HEM results



Data for 35% → 72% of the channels.

Model, Hypotheses, and approximations

Still 28% of the channels without possible parametrisation. All important!

$$\sigma_{NN\to N\Lambda K\pi}(\sqrt{s}) = 3\ \sigma_{NN\to N\Lambda K}(\sqrt{s}) \times \frac{\sigma_{NN\to NN\pi\pi}(\sqrt{s}-540)}{\sigma_{NN\to NN\pi}(\sqrt{s}-540)}$$

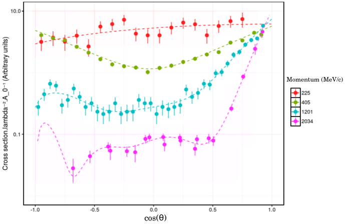
$$\sigma_{NN\to N\Sigma K\pi}(\sqrt{s}) = 3\ \sigma_{NN\to N\Sigma K}(\sqrt{s}) \times \frac{\sigma_{NN\to NN\pi\pi}(\sqrt{s}-620)}{\sigma_{NN\to NN\pi}(\sqrt{s}-620)}$$

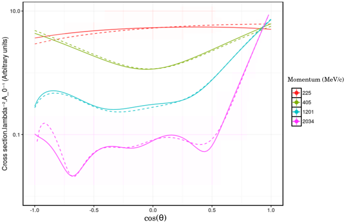
$$\sigma_{NN\to N\Lambda K\pi\pi}(\sqrt{s}) = \sigma_{NN\to N\Lambda K\pi}(\sqrt{s}) \times \frac{\sigma_{NN\to NN\pi\pi}(\sqrt{s}-675)}{\sigma_{NN\to NN\pi}(\sqrt{s}-675)}$$

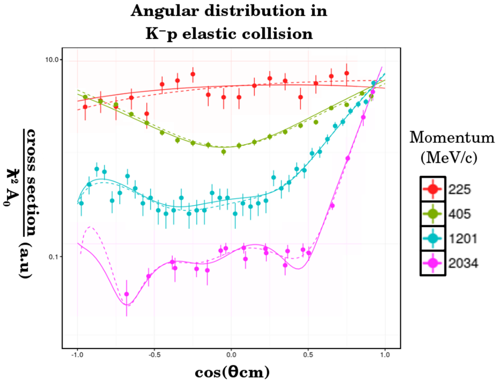
$$\sigma_{NN\to N\Sigma K\pi\pi}(\sqrt{s}) = \sigma_{NN\to N\Sigma K\pi}(\sqrt{s}) \times \frac{\sigma_{NN\to NN\pi\pi}(\sqrt{s}-755)}{\sigma_{NN\to NN\pi}(\sqrt{s}-755)}$$

Data for 100% of the channels! This is what I fought...

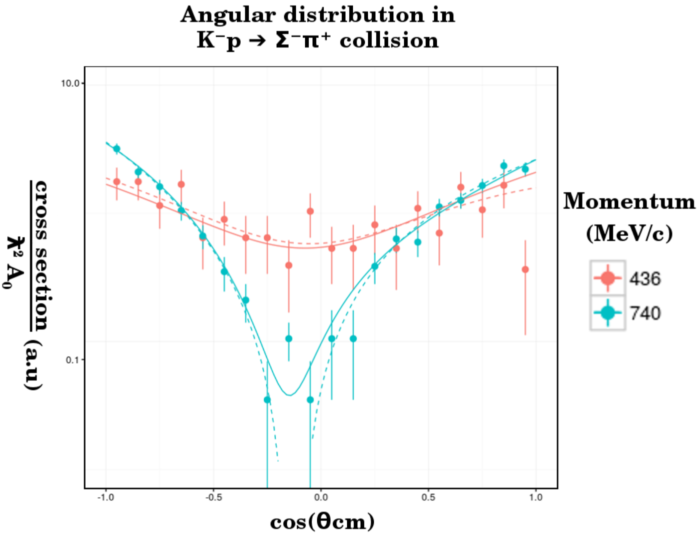
Angular distributions



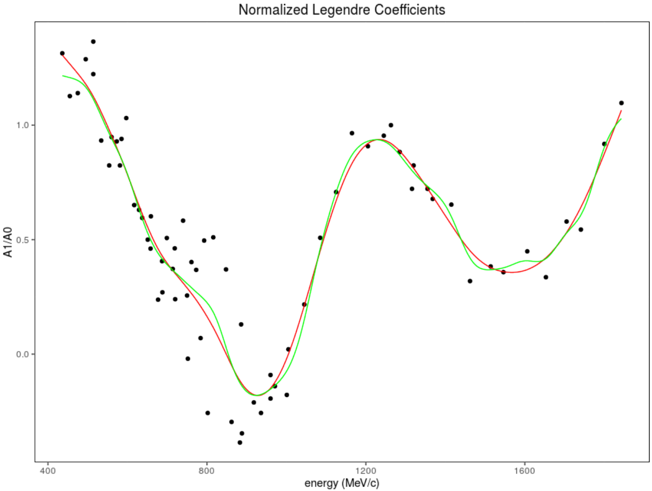




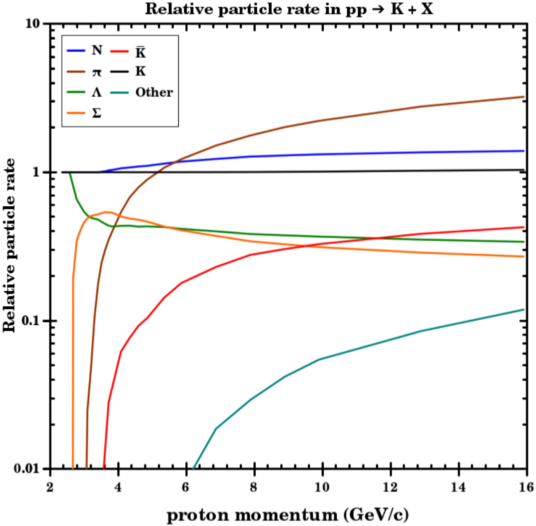
Negative density of probability



Smoothing splines vs Nadaraya-Watson kernel regression

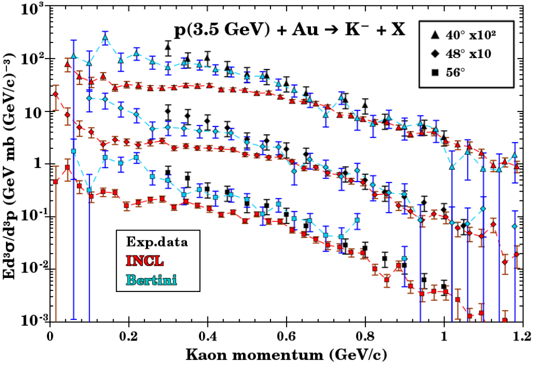


Fritiof rates



KaoS Experiment

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



A word about K^- production

Relatively bad results, notably at low energy

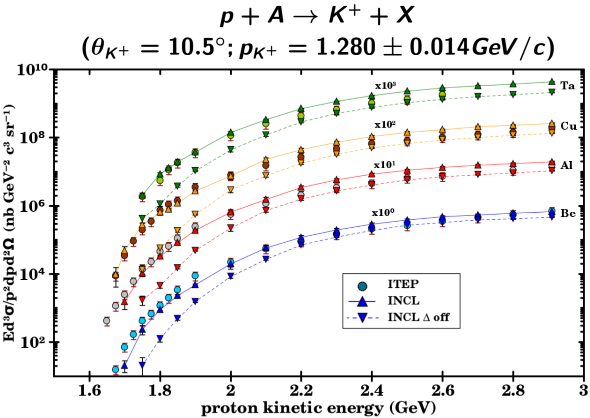
→ Possible explanation: missing channels. $\overline{K}$ production in strangeness exchange reaction not taken into account (e.g. $\Lambda N \to NN\overline{K}$)

ITEP experiment

A test for unmeasured cross sections

Observations

- Results correct in the threshold region
- Huge impact of Δ-induced reactions

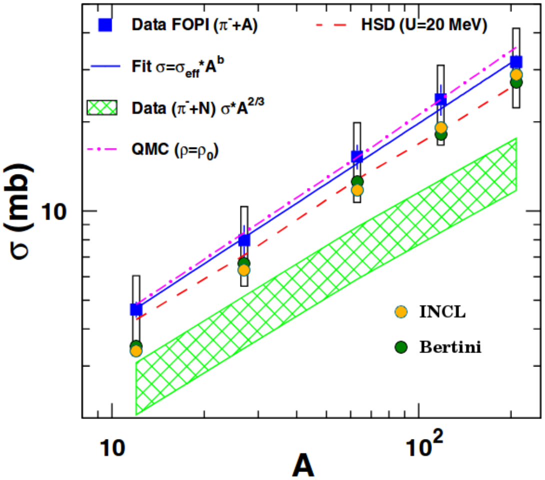


A. V. Akindinov et al., JETP Letters, Vol. 72, No. 3, 2000, pp. 100-105

FOPI experiment

M. L. Benabderrahmane et al., Phys. Rev. Lett. 102, 182501

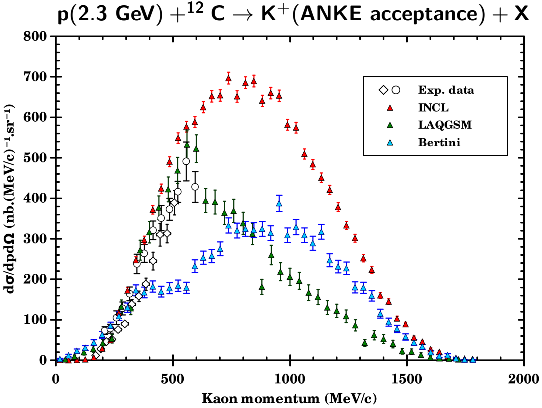
$$\pi^-(1150 MeV/c) + A \rightarrow K^0 + X$$



Observations

- Within the systematic errors
- INCL slope $\propto A^{3/4}$
  FOPI slope $\propto A^{2/3}$

ANKE experiment



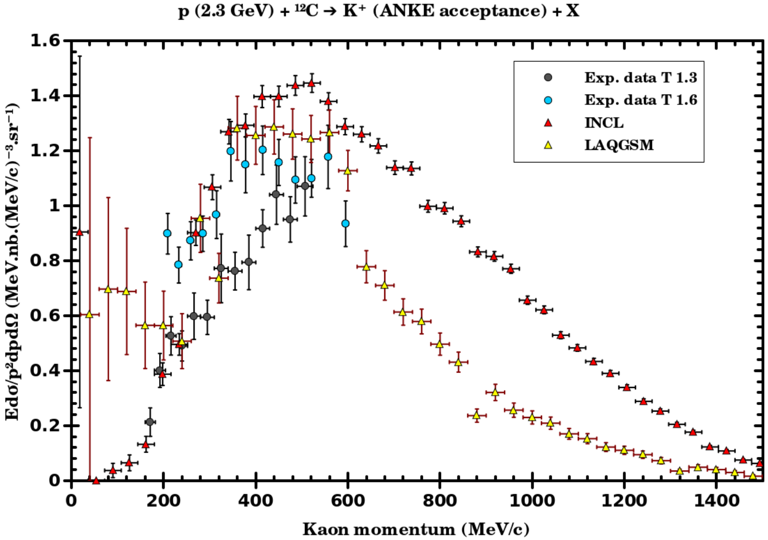
Observations

- Good threshold simulation
- Prediction very different of LAQGSM at energies higher than 600 MeV/c

M. Büscher et al., Eur.Phys. J. A 22, 301-317(2004)

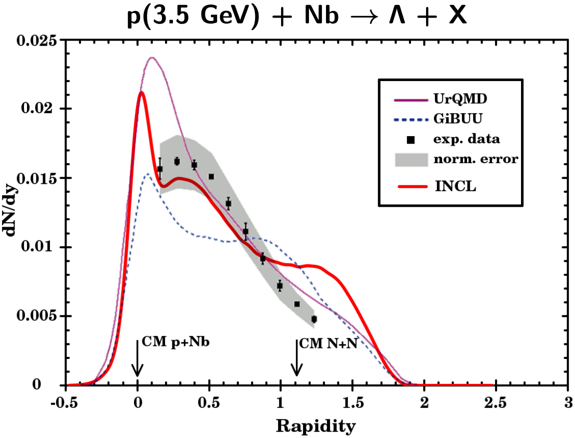
Thanks Nikolai Mokhov for LAQGSM data

ANKE invariant cross section



HADES - The Λ

HADES Collaboration, Eur. Phys. J. A (2014) 50:81



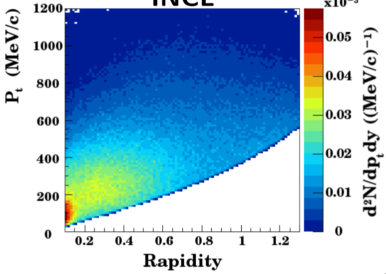
Observations

- Good reproduction in the region [0.15-0.9] (Amplitude, shape)
- Bump around *CM N+N*

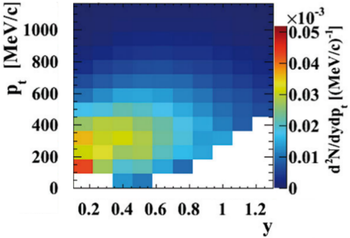
HADES - The Λ

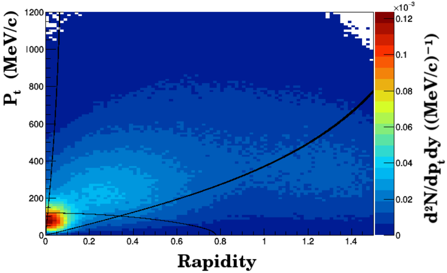
HADES Collaboration, Eur. Phys. J. A (2014) 50:81

INCL



HADES



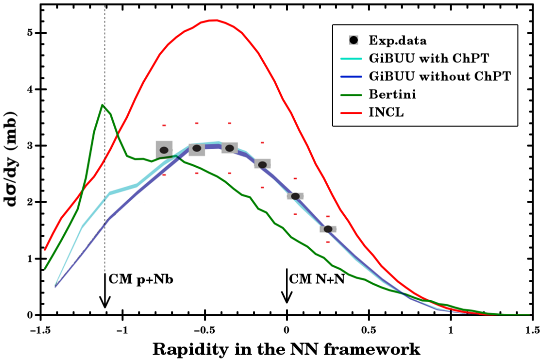


Observations

- Consistent with experimental data
- Tension with the extrapolation

HADES experiment - The K^0_S

$p(3.5GeV) + Nb \rightarrow K^0_S + X$



HADES Collaboration, T.Gaitanos and J. Weil, Phys. Rev. C 90, 054906 (2014)

Observations

- Same experiment as the previous one but results very different
- Reaction cross section:
  HADES - 848 ± 127 *mb*,
  INCL - 1047.87 *mb*,
  Bertini - 1164 *mb*

Remark

GiBUU has been rescaled
Impossible to make proper comparisons

GiBUU versions

HADES Collaboration, T.Gaitanos and J. Weil,
Phys. Rev. C 90, 054906 (2014)

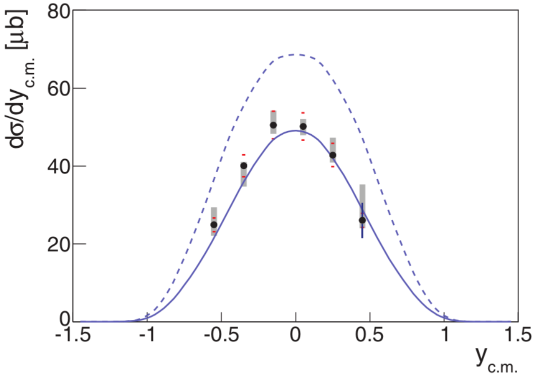


FIG. 4. (Color online) K_S^0 rapidity distribution in $p + p$ collisions (black circles) and GiBUU transport model simulations (dashed curve–original resonance model [30], solid curve–modified resonance model; see text).

Simple input - Irradiation flux

Only one input parameter to fully define proton and alpha spectra: The solar modulation parameter M

proton

$$\mathbf{J_p(T,M) = c_p \times \frac{T\ (T + 2m_pc^2)\ (T + 780 \times e^{-2.5\ 10^{-4} \times T} + M)^{-2.65}}{(T + M)\ (T + 2m_pc^2 + M)}}$$

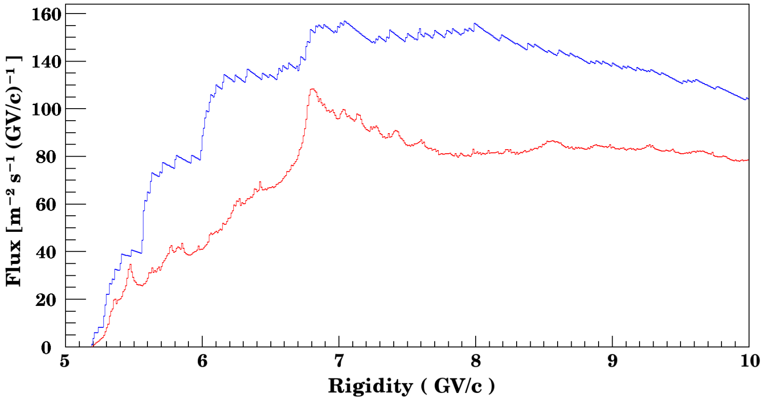
---

alpha (new)

$$\mathbf{J_\alpha(T,K) = \frac{c_\alpha \times T^K \times (T + 2m_\alpha c^2)}{(T + 700)(T + 2m_\alpha c^2 + 700)(T + 312500\ T^{-2.5} + 700)^{1.65+K}}}$$

$$\mathbf{K = (1.786\ 10^{-3} \times M) - 0.1323}$$

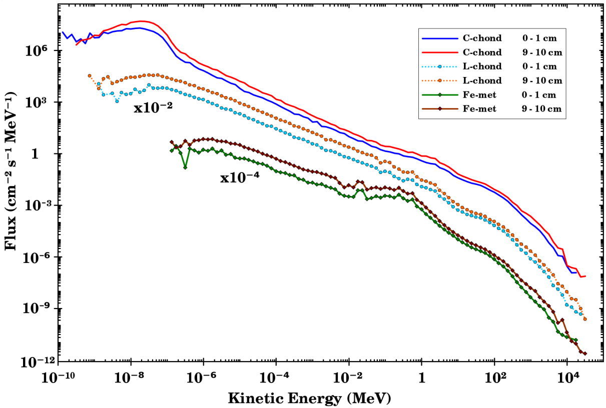
Cut-off effects



New effects

- Modified irradiation flux
- Modified ratio p/α particles

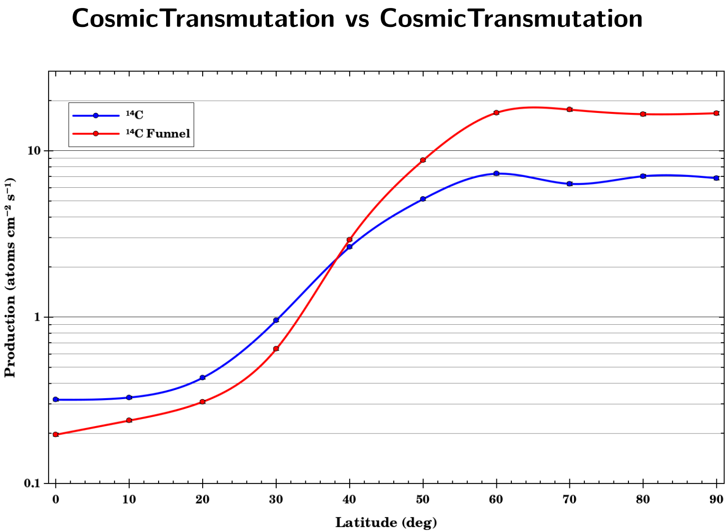
Meteoroid types



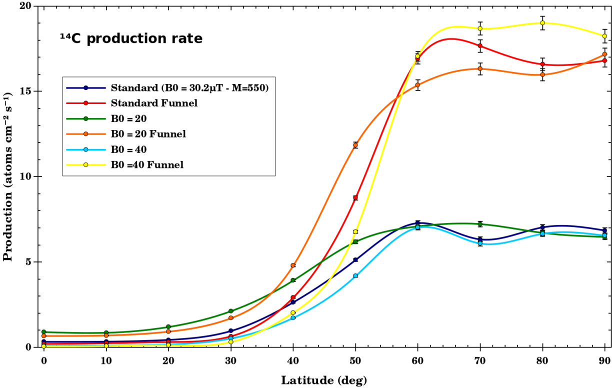
Observations

- Increased flux at 10 cm
- Higher neutron flux with heavier elements
- Composition influence the spectrum shape

Funnel effect



Magnetic field intensity



Observations

- Higher magnetic field increases the particle flux at the poles (higher focusing)

Test Funnel algorithm