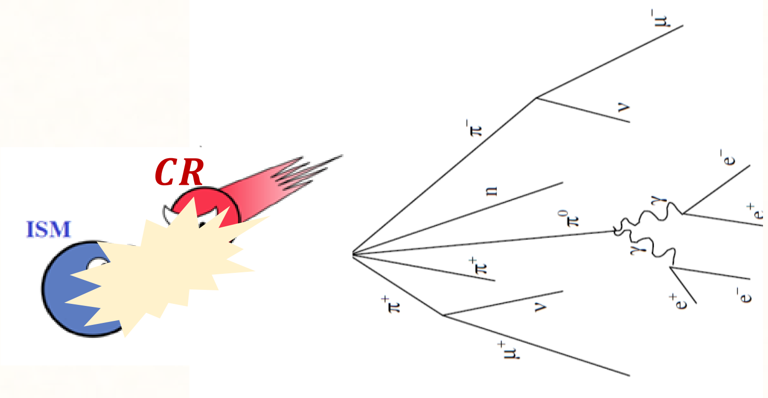
The FLUKA cross sections for secondary cosmic rays: Latest results

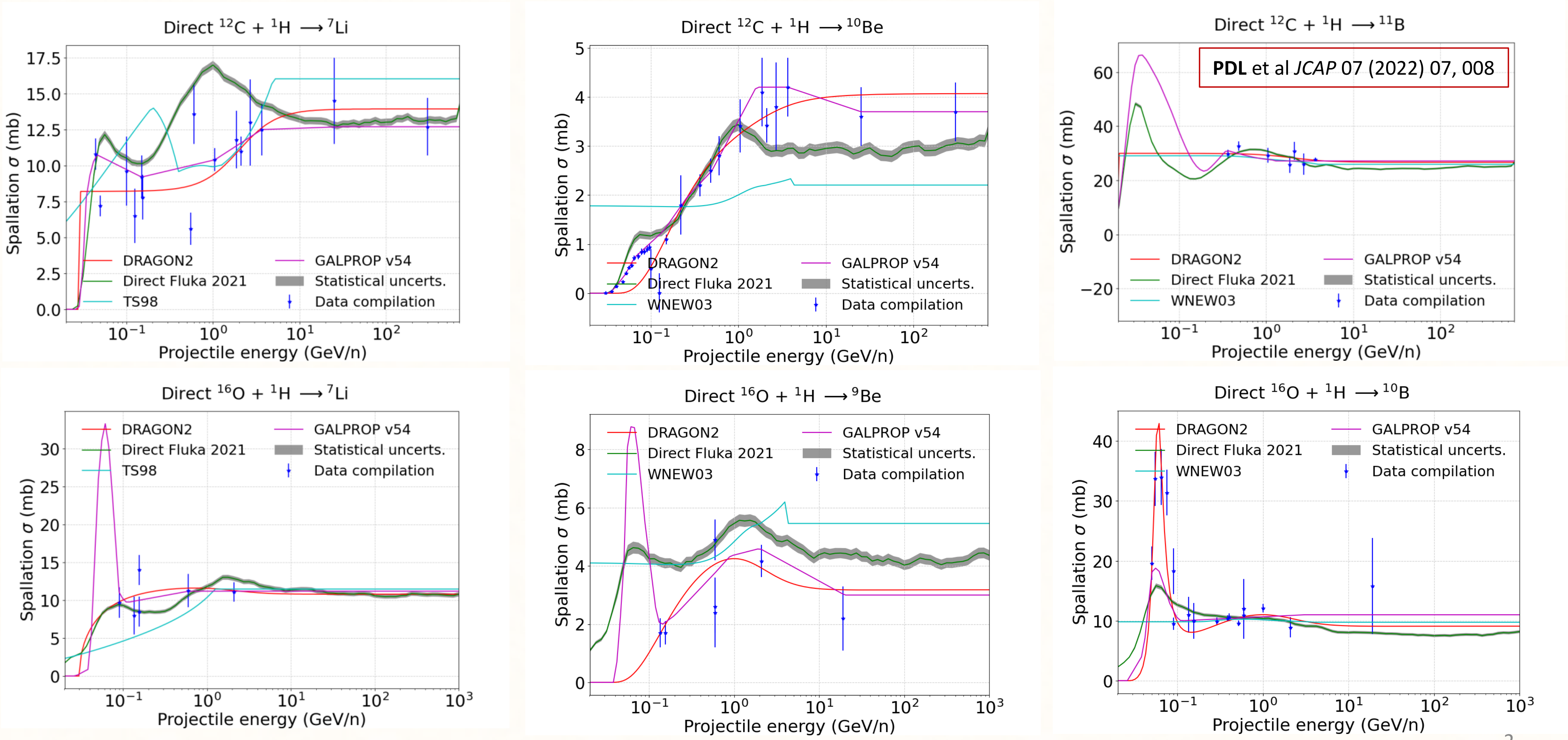
Along with Nicola Mazziotta



Pedro de la Torre Luque --- pedro.delatorre@uam.es
Juan de la Cierva fellowship (IFT/UAM - Madrid)

XSCRC@CERN
18/10/2024

FLUKA (direct) inclusive cross sections

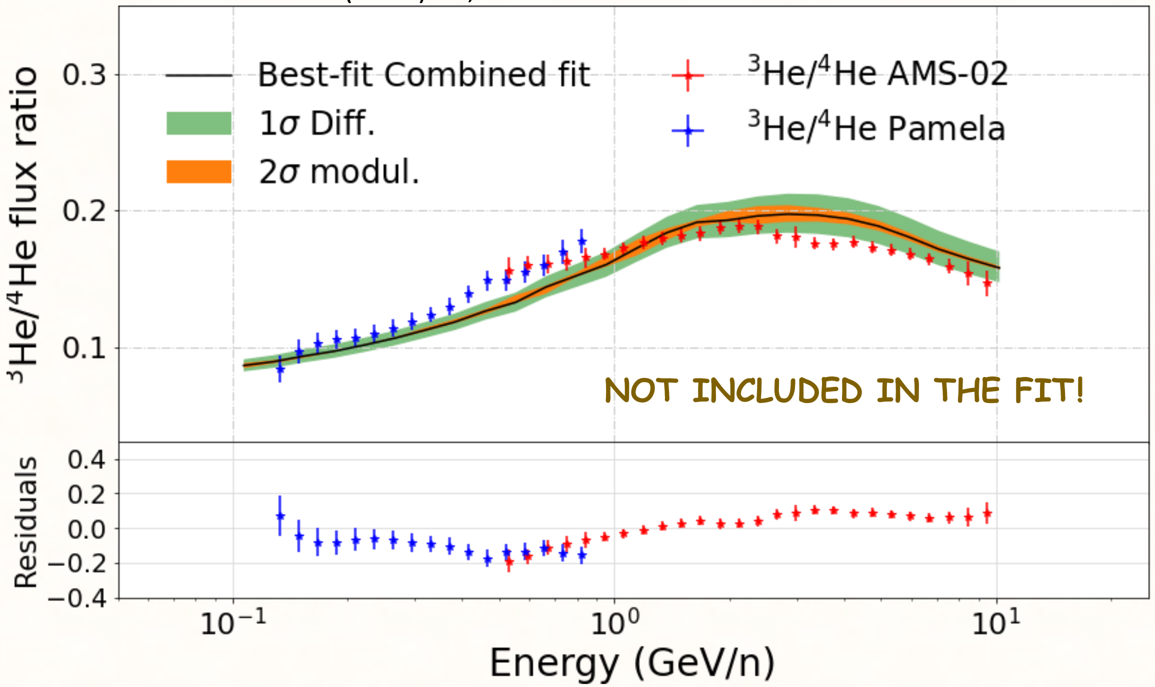


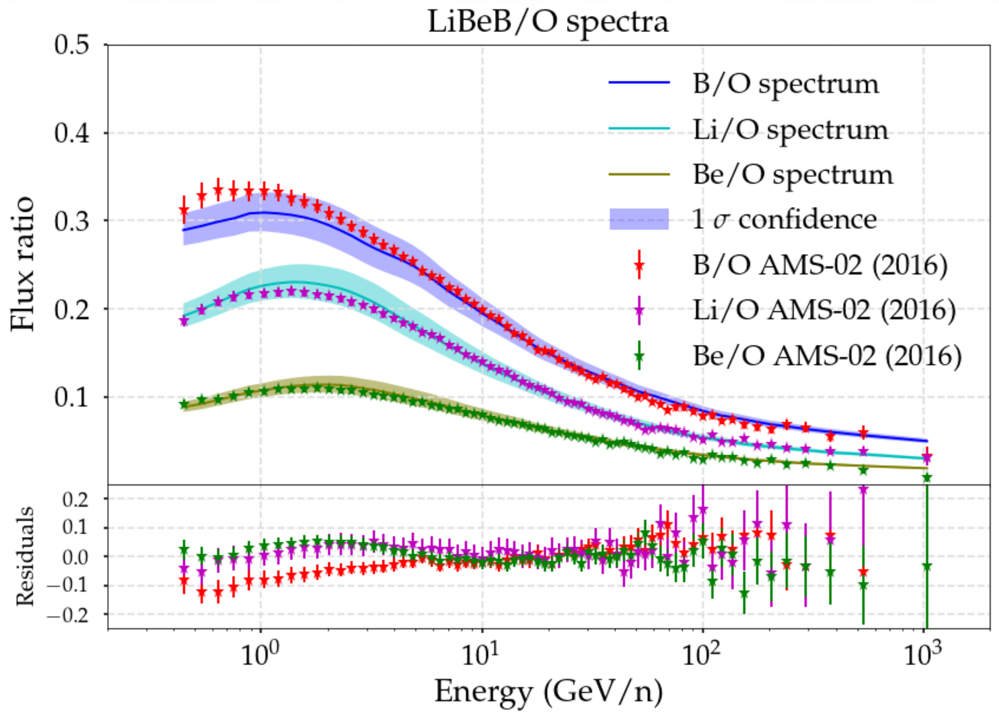
Combined fit of light secondary CRs

MC Monte Carlo analysis: Combination of the ratios of secondary CRs (**P.D.L.** et al *JCAP*07, 2021, 010) including nuisance parameters (<u>Scale factors</u>) for renormalizing FLUKA cross sections.

We can simultaneously reproduce all light secondary CRs with small scaling factors (~10%) !!

PDL et al *JCAP* 07 (2022) 07, 008



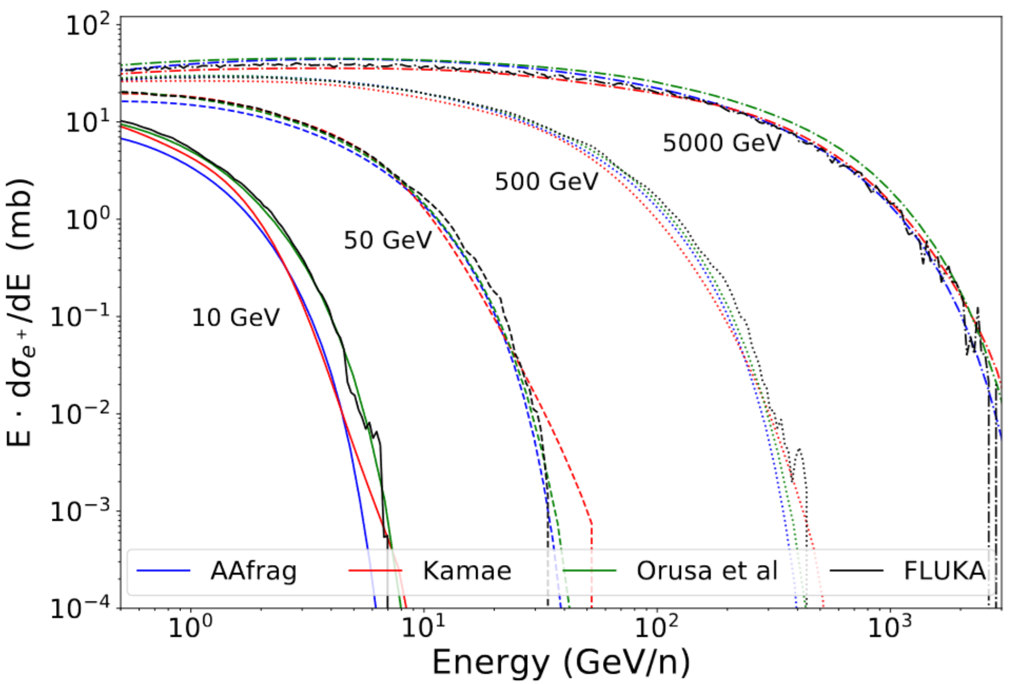


Fluka cross sections: e^+ uncertainties

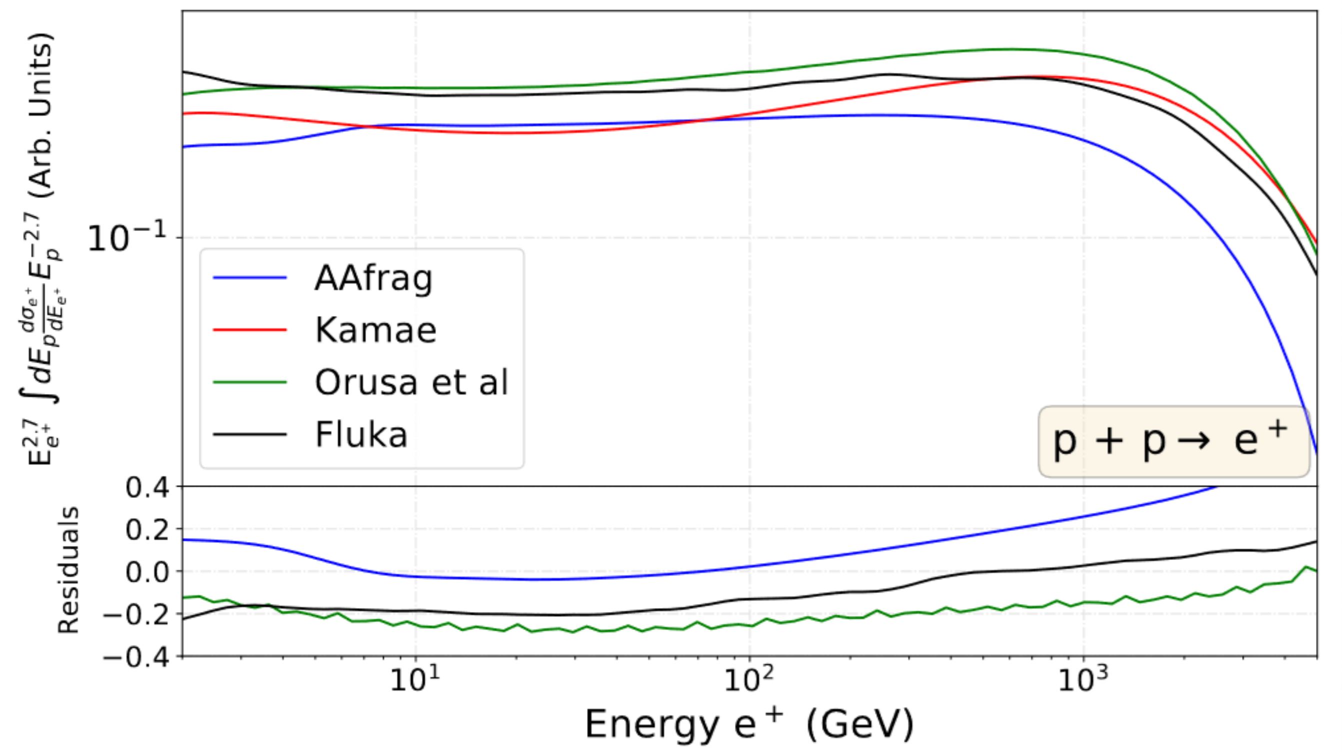
Different cross sections differ by up to 25%-30% below 30 GeV in the p+p channel. The different XS show very similar trends in this energy range.

Other main cross sections data-sets available:

- Kamae 2006 APJ 647:692–708 (2006)
- AAfrag 2021 PRD 104, 123027 (2021)
- Orusa 2022 PRD 105 (2022) 12, 123021



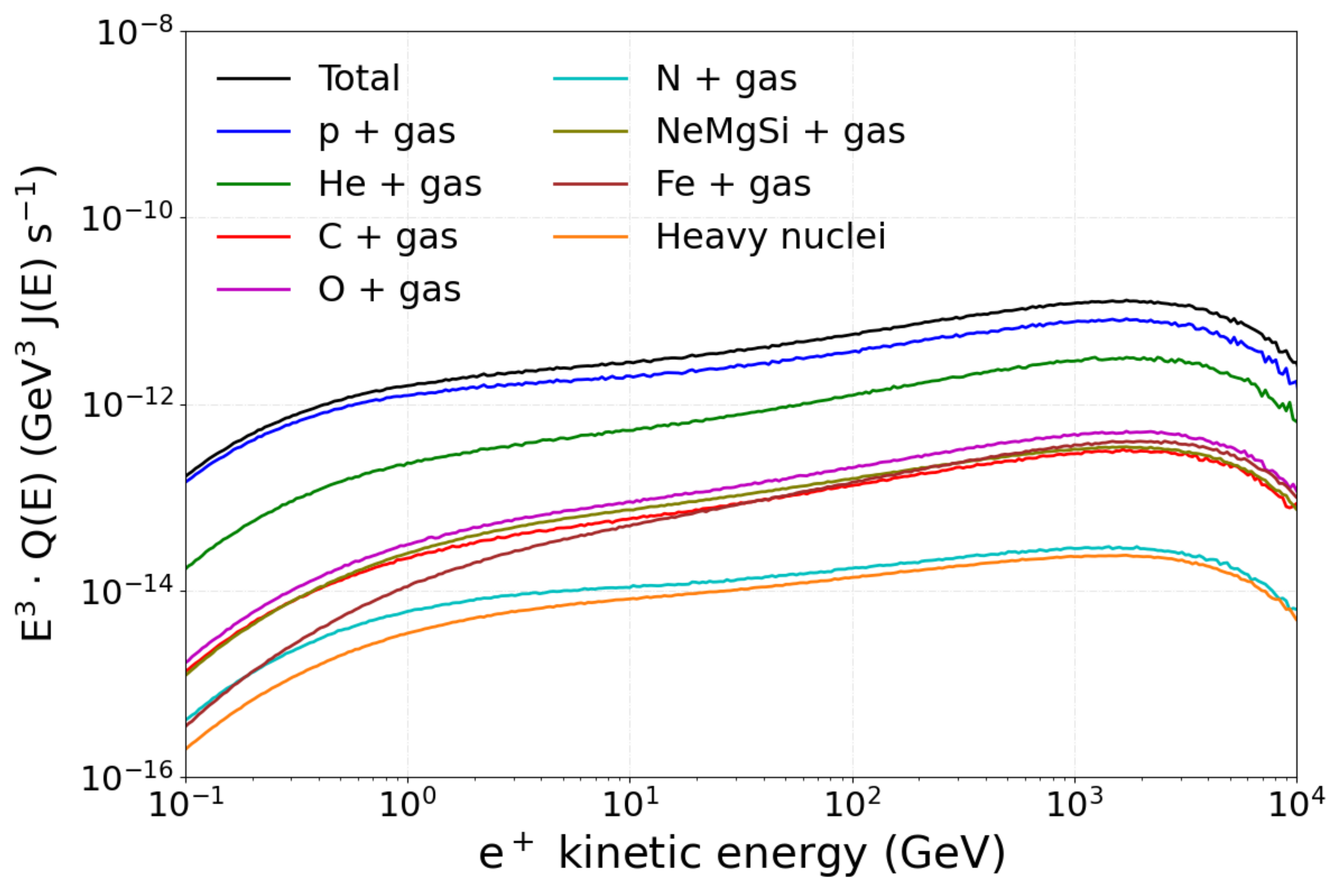
Residuals w.r.t. Kamae (Kamae - σ /Kamae)



PDL et al JCAP 10 (2023) 011 ArXiv:2305.02958

Fluka cross sections: e^+ uncertainties

Contribution of each channel to the total positron spectrum



The contribution of elements with high mass number is as important as that from C or O above ~10 GeV

Contribution of heavy nuclei (above He and up to ^{56}Fe) constitutes between 7.5% and 10% of the total e^+flux at 10 GeV → Overestimation due to the lack of data on sub-Fe elements

***PDL** et al JCAP* 10 (2023) 011 ArXiv:2305.02958

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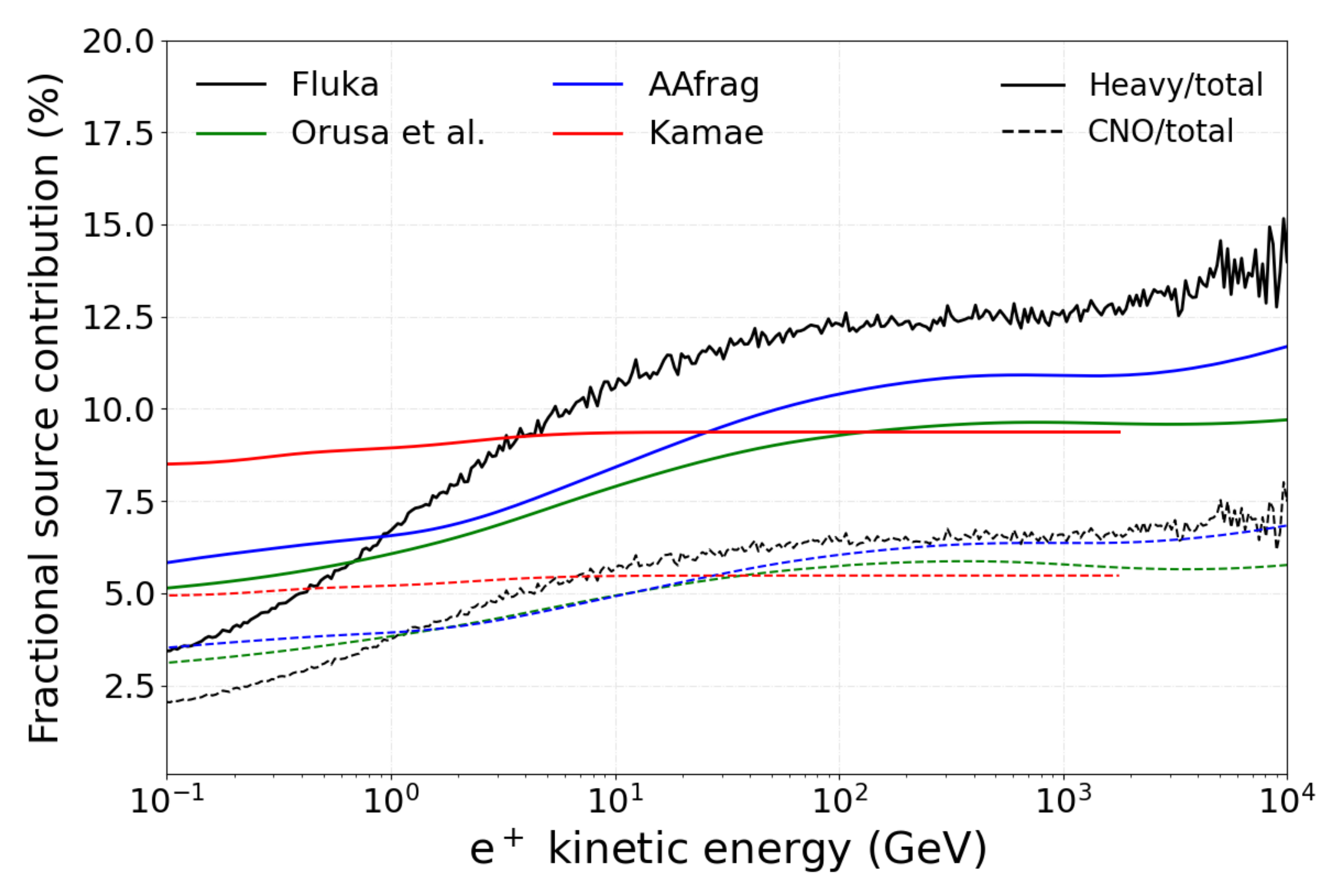

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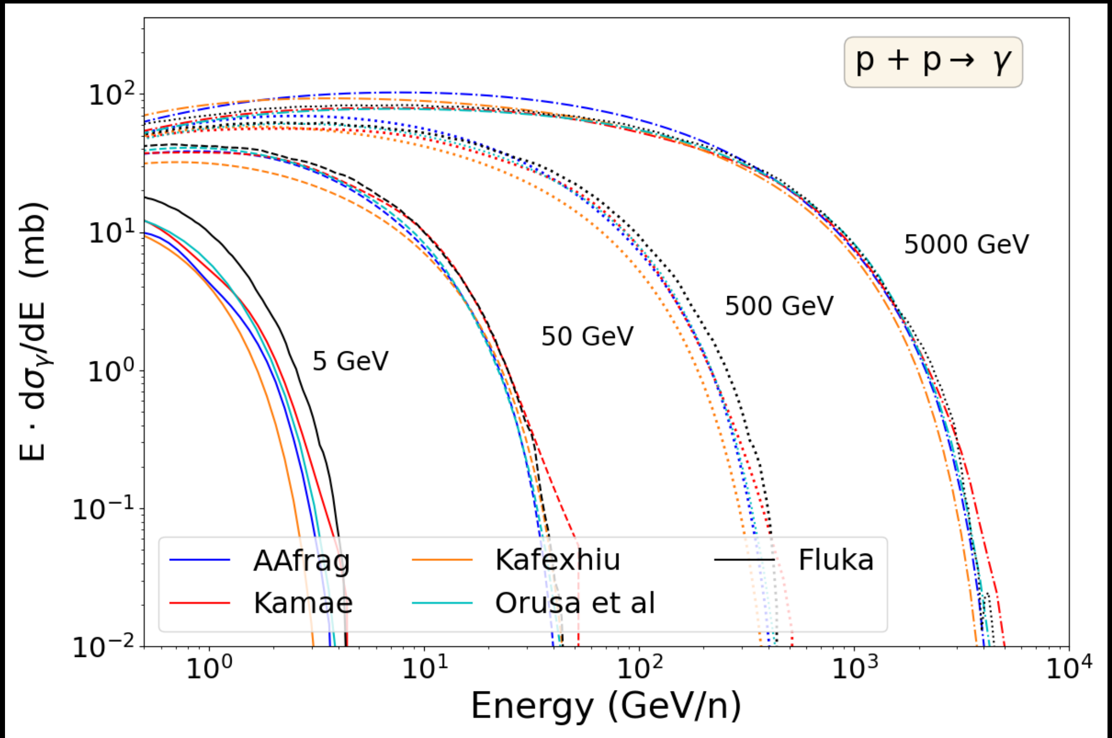
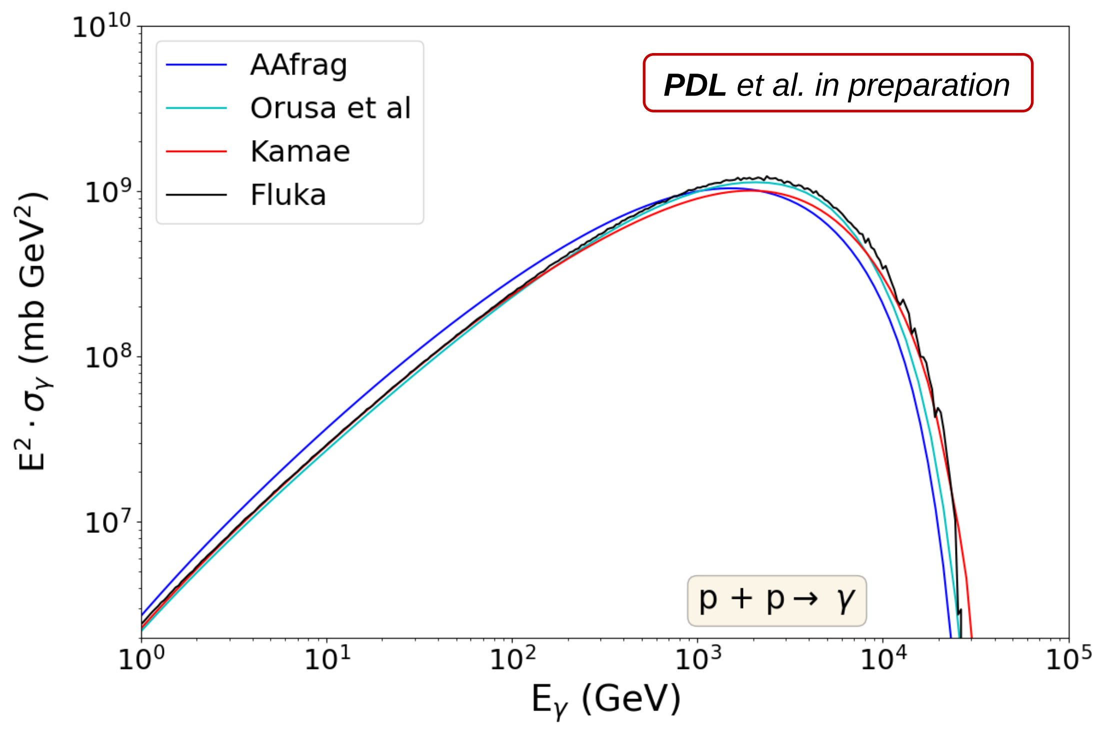
***PDL** et al JCAP* 10 (2023) 011 ArXiv:2305.02958

New measurements require better predictions of the γ-ray and ν flux at high energies

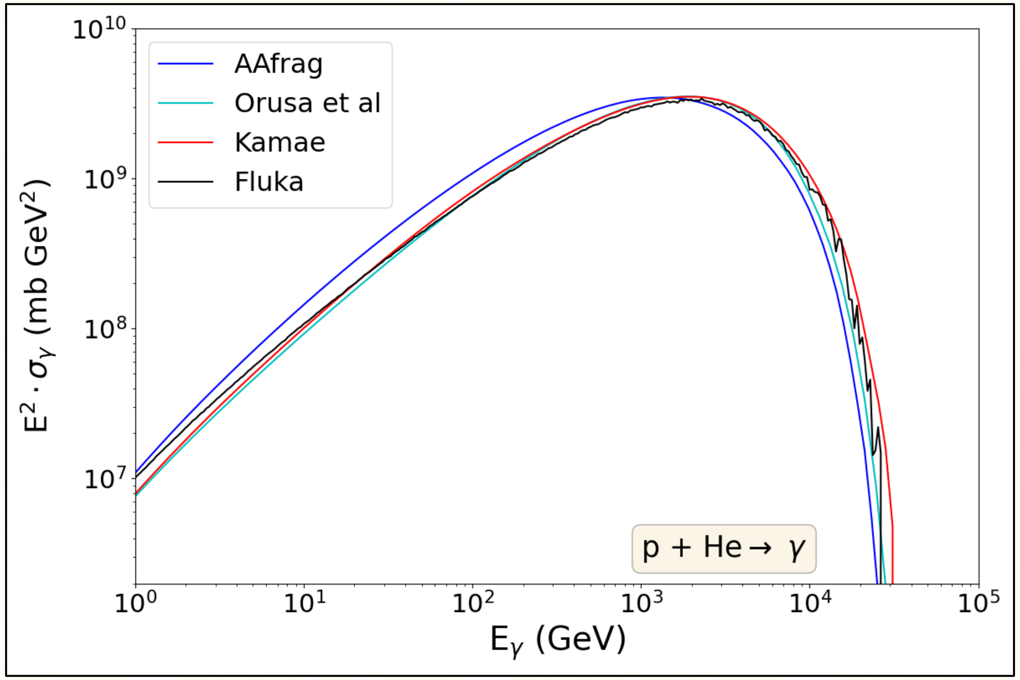
Fast evolution of γ-ray experiments covering the sky from the MeV to the PeV allow us to improve our knowledge of the Galactic and extragalactic environment. However, cross sections uncertainties are a problem in the whole energy range…

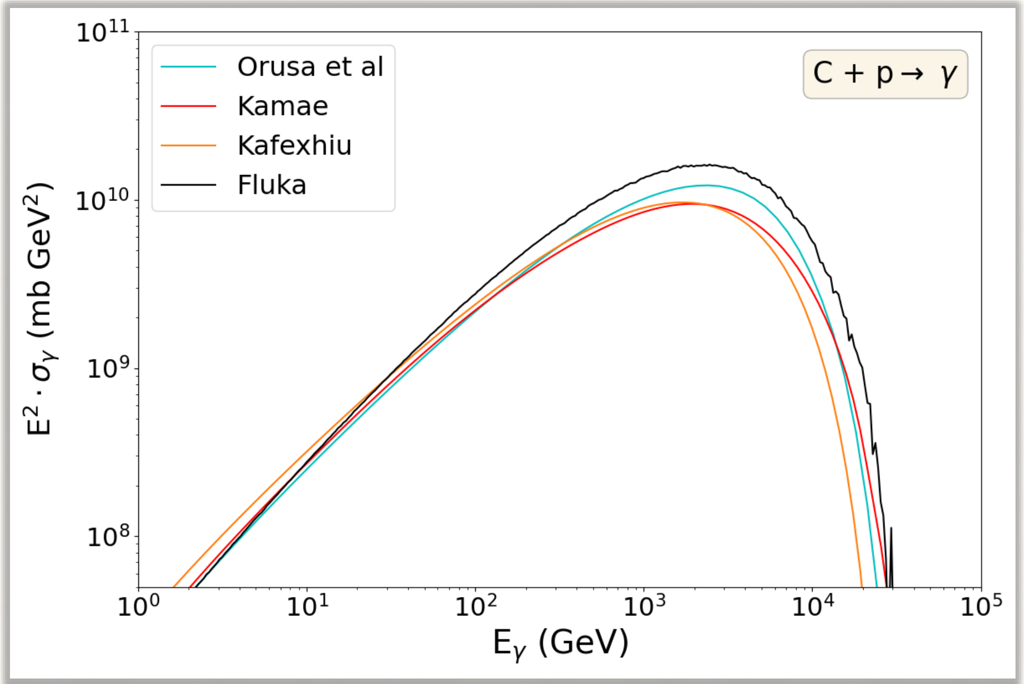


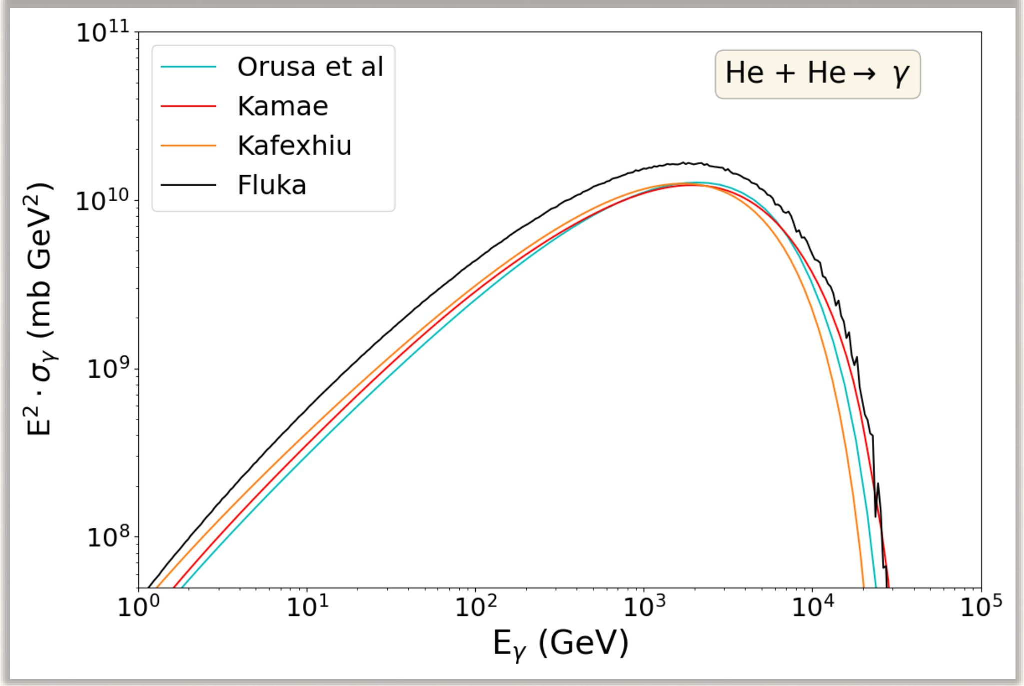


γ-ray production XS

While for p-p and p-He interactions the agreement is quite good with Orusa et al. and Kamae cross sections, for interactions of heavier nuclei the deviations are significant





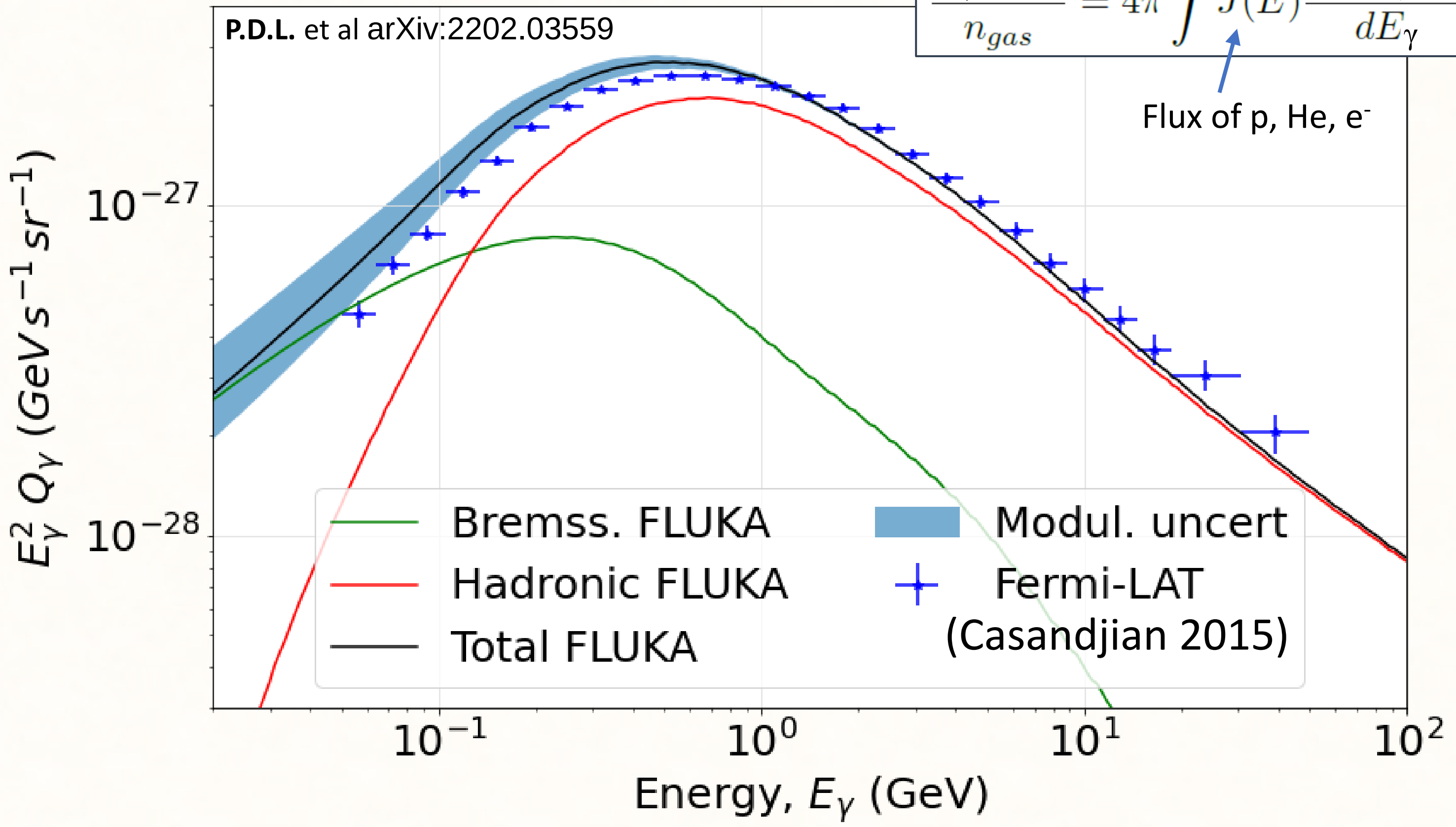


FLUKA cross sections for gamma-ray production

Study of the **local emissivity** (at latitudes 10° < |b| < 70°) ISM composition with relative abundance of H : He : C : N : O : Ne : Mg : Si = 1:0.096 : 4.65 10^{-4} : 8.3 10^{-5} : 8.3 10^{-4} : 1.3 10^{-4} : 3.9 10^{-5} : 3.69 10^{-5}.

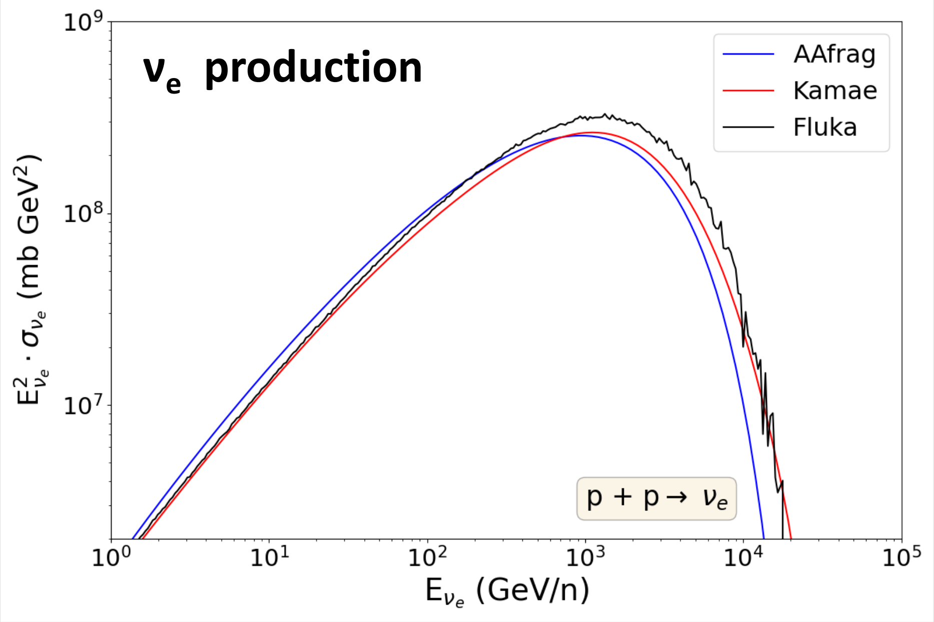
$$\frac{Q_\gamma(E_\gamma)}{n_{gas}} = 4\pi \int J(E) \frac{d\sigma(E_\gamma|E)}{dE_\gamma} dE$$

Flux of p, He, e^-

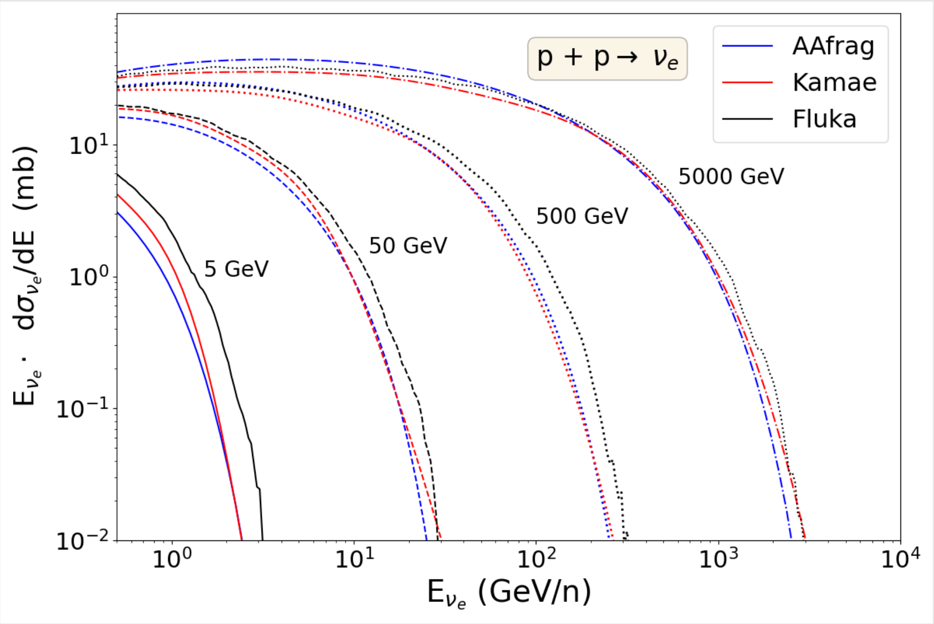


This quantity just depends on the cross sections of gamma-ray production and the spectrum of electrons, protons and He (**low-energy especially uncertain due to solar modulation uncertainties!**)

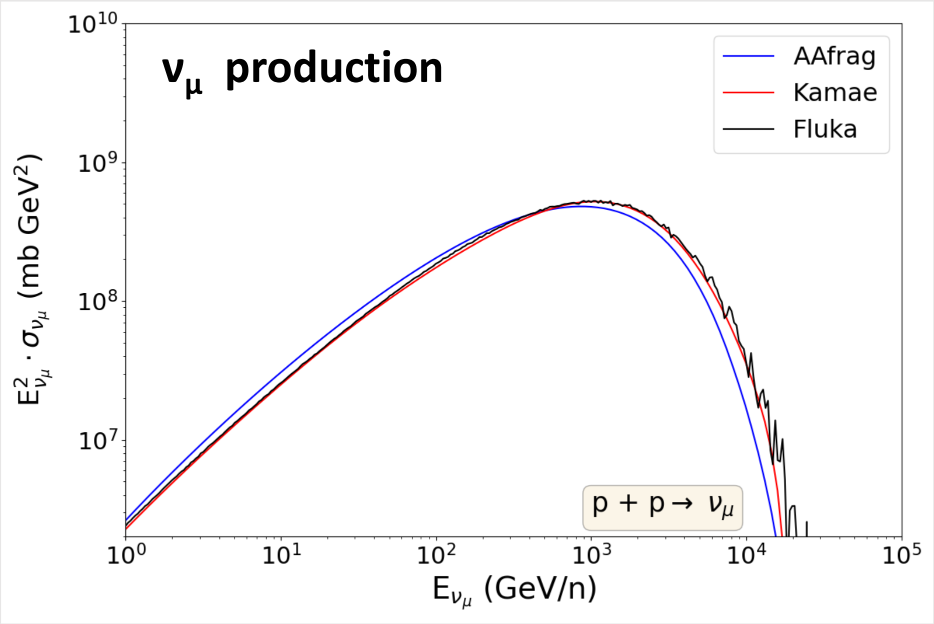
Cross sections implemented in the *GammaSky* code



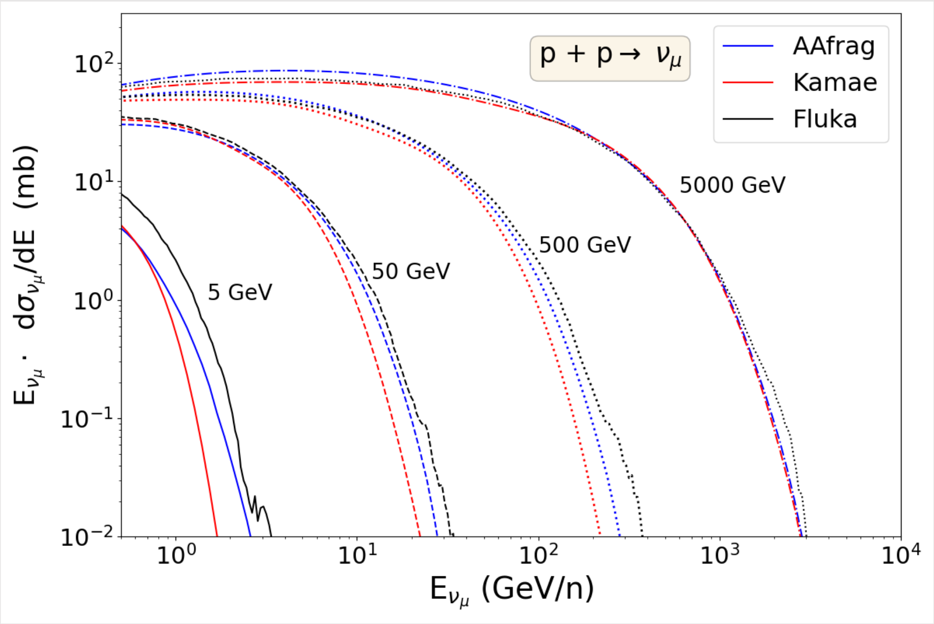
ν_e production
AAfrag
Kamae
Fluka
$p + p \rightarrow \nu_e$
$E^2_{\nu_e} \cdot \sigma_{\nu_e}$ (mb GeV^2)
E_{ν_e} (GeV/n)



$p + p \rightarrow \nu_e$
AAfrag
Kamae
Fluka
5 GeV
50 GeV
500 GeV
5000 GeV
$E_{\nu_e} \cdot d\sigma_{\nu_e}/dE$ (mb)
E_{ν_e} (GeV/n)



ν_μ production
AAfrag
Kamae
Fluka
$p + p \rightarrow \nu_\mu$
$E^2_{\nu_\mu} \cdot \sigma_{\nu_\mu}$ (mb GeV^2)
E_{ν_μ} (GeV/n)



$p + p \rightarrow \nu_\mu$
AAfrag
Kamae
Fluka
5 GeV
50 GeV
500 GeV
5000 GeV
$E_{\nu_\mu} \cdot d\sigma_{\nu_\mu}/dE$ (mb)
E_{ν_μ} (GeV/n)

Conclusions

- **FLUKA provides cross sections over a wide energy range and for every isotope and channel, not depending on the limited data**
- FLUKA demonstrates to be compatible with the current cross section data and allows us to **simultaneously reproduce B, Be and Li and ^{3}He.** However, there are caveats: Fluorine and antiprotons seem significantly deviated!
- Production cross sections of γ-rays seem to be compatible with other predictions for p-(p, He) interactions, but deviations seem more important for interactions of heavier nuclei
- In the next future, we want to consider coalescence and antinuclei with FLUKA

BACK UP SLIDES

Evaluation of cross sections for CR interactions with the FLUKA code

http://www.fluka.org/fluka.php

FLUKA has been used in other CR studies as in Mazziotta, **P.D.L**. et al PRD 101(8):083011 (2020), as well as for other astrophysical applications as atmospheric neutrino studies (Astropart. Phys., 23:526–534, 2005) or gamma-ray flares from the Sun (Solar Phys., 294(8):103, 2019).

We have computed inelastic and inclusive cross sections of interactions of all isotopes of the CR nuclei up to Z=26 (Iron) with protons and helium, including a careful analysis of those short-living particles produced (ghost nuclei) from 1 MeV/n to 35 TeV/n.

The result is a set a cross sections of secondary CRs that can be used in CR propagation codes. We have also computed cross sections for gamma-ray, secondary electrons and positrons, neutrinos and antiprotons.

The FLUKA toolkit and the evaluation of cross sections for CR interactions

http://www.fluka.org/fluka.php

- **Resonances** produced in hadron-nucleon inelastic collisions dominate from the MeV up to 3-5 GeV
- Above 3-5 GeV hadronizations through Dual Parton Model (**DPMJET-3**) takes over
- Extension to hadron-nucleus collisions is achieved through the **PEANUT** model (GINC) + relaxation
- Nucleus-Nucleus use **Boltzmann thermal equation** at E<0.1GeV/u, **rQDM** model up to 5 GeV/u and **DPMJET** above

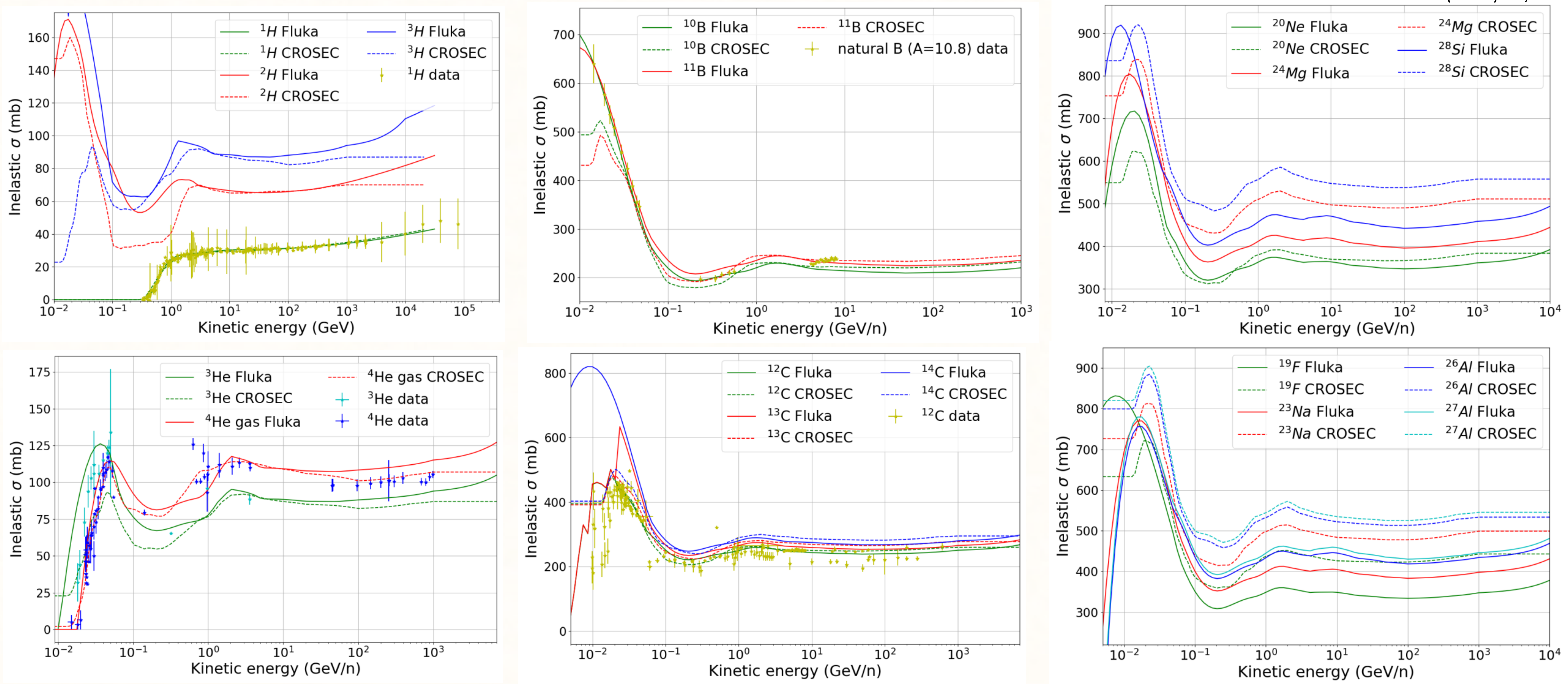
<table>
<tr><th colspan="6">Hadron-Hadron</th></tr>
<tr><td colspan="2">Elastic,exchange
Phase shifts
data, eikonal</td><td colspan="2">P<3-5GeV/c
Resonance prod
and decay</td><td>low E π,K
Special</td><td>High Energy
DPM
hadronization</td></tr>
<tr><td rowspan="2">Hadron-Nucleus

PEANUT
Sophisticated GINC
Gradual onset of Glauber-Gribov
multiple interactions
Preequilibrium
Coalescence</td><td colspan="5">Nucleus-Nucleus</td></tr>
<tr><td colspan="2">E< 0.1GeV/u
BME
Complete fusion+
peripheral</td><td colspan="2">0.1< E< 5 GeV/u
rQMD-2.4
modified
new QMD</td><td>E> 5 GeV/u
DPMJET
DPM+
Glauber+
GINC</td></tr>
<tr><td colspan="6">Evaporation/Fission/Fermi break-up
γ deexcitation</td></tr>
</table>

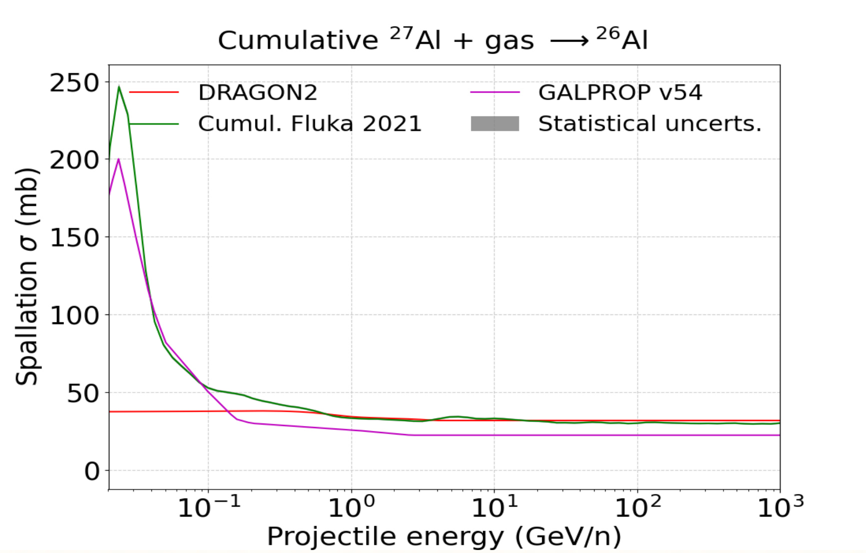
Credit: Paola sala

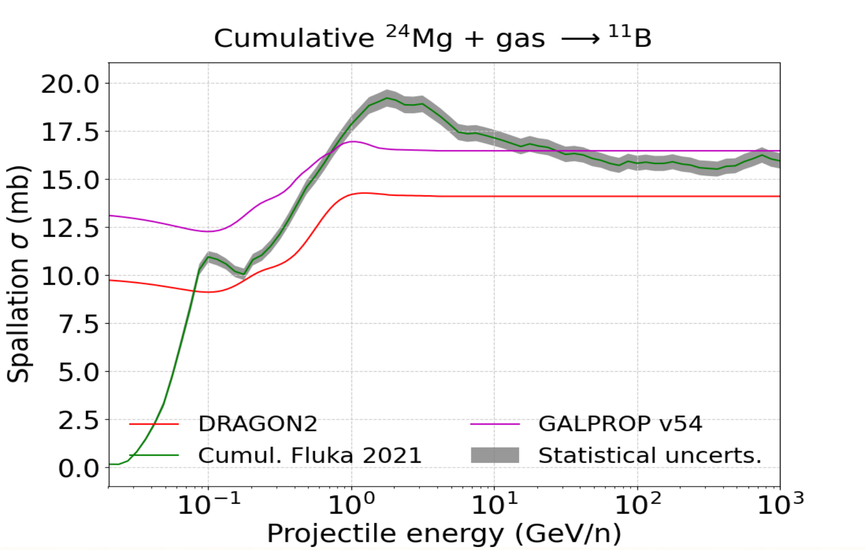
FLUKA inelastic cross sections

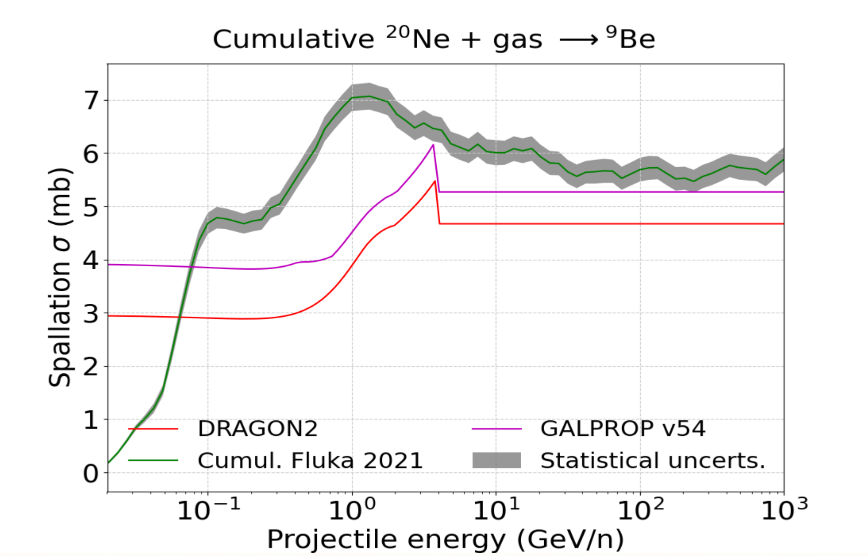
PDL et al *JCAP* 07 (2022) 07, 008

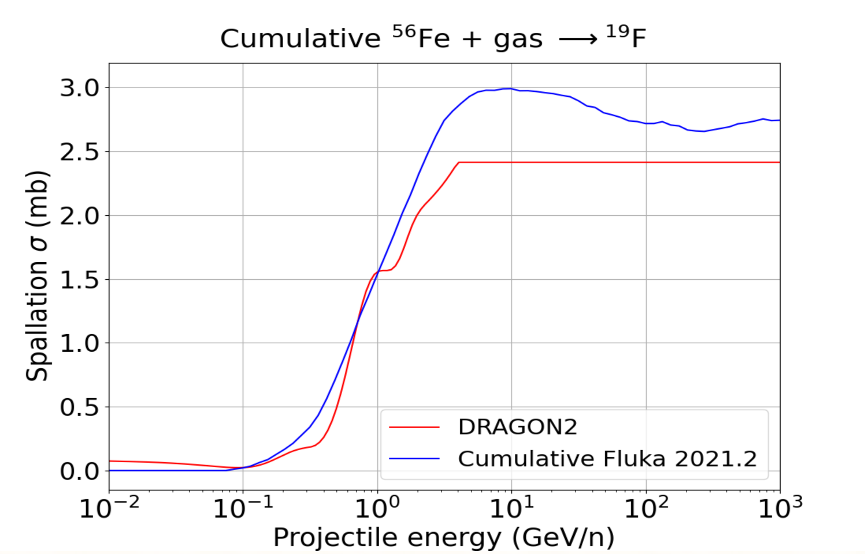


FLUKA inclusive cross sections for rare channels



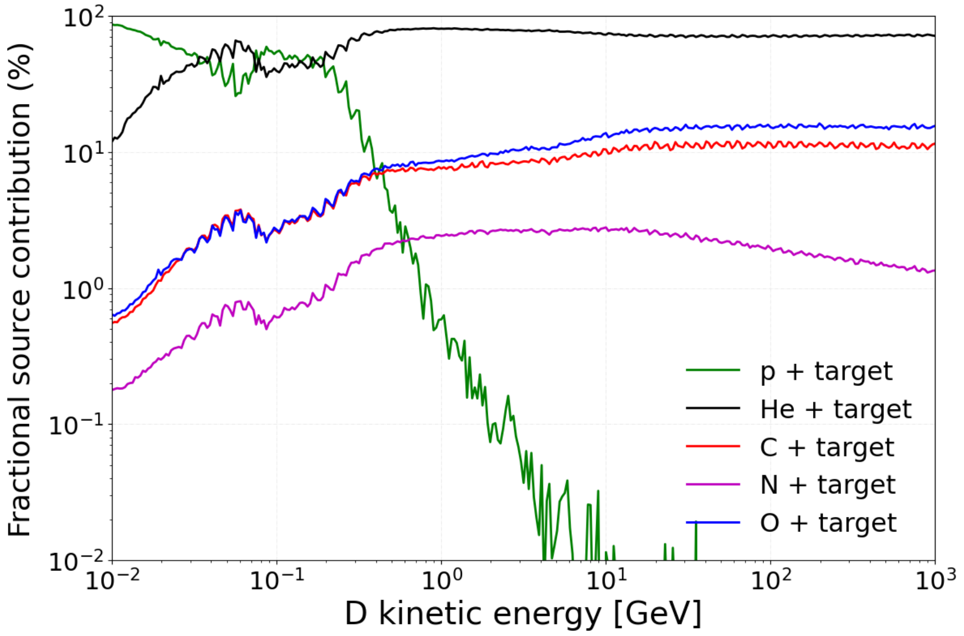


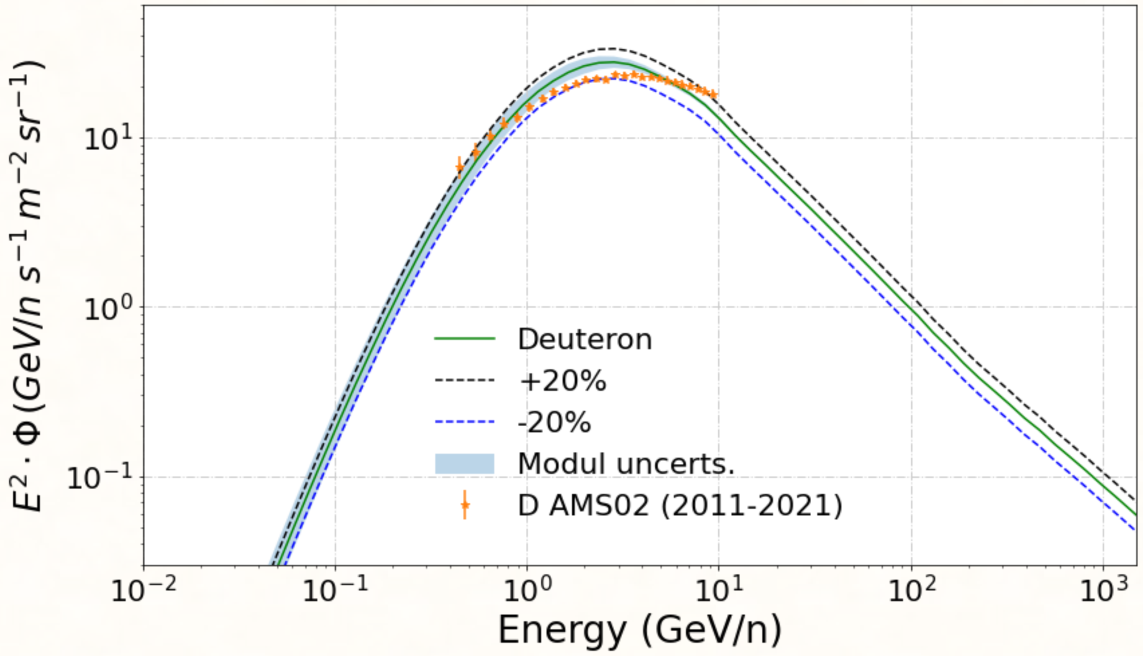


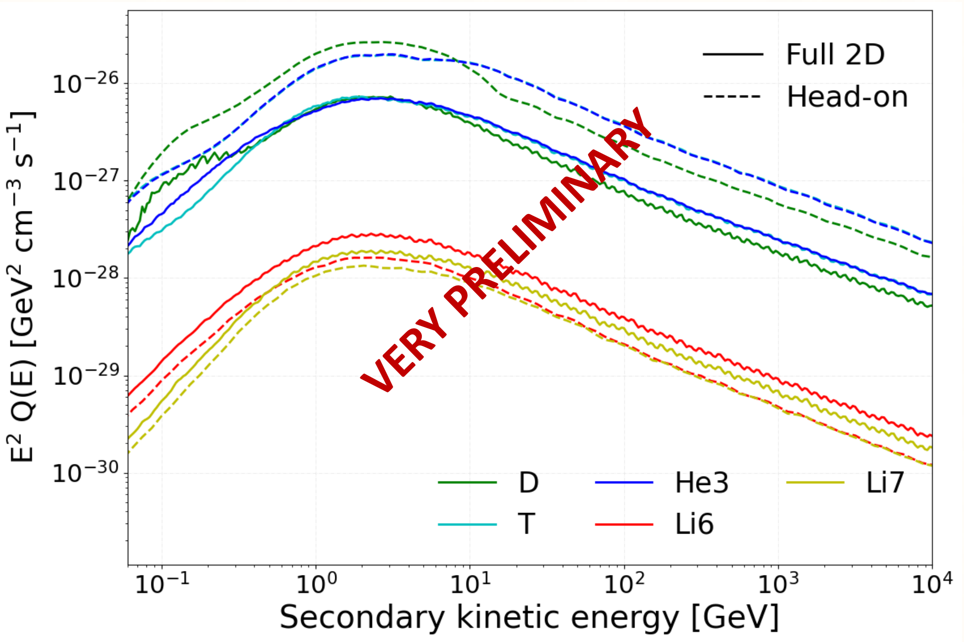


Deuteron seems incompatible with our expectations

Fluka provides a similar prediction as when using other cross sections params., all being too steep compared to the data above a few GeV/n. The head-on approximation does not seem to be the problem… Correlated errors? Other contributions?

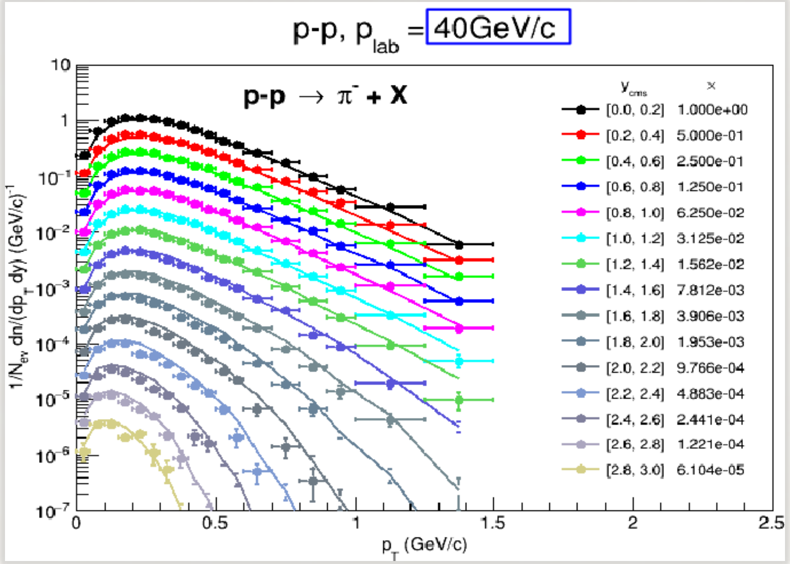


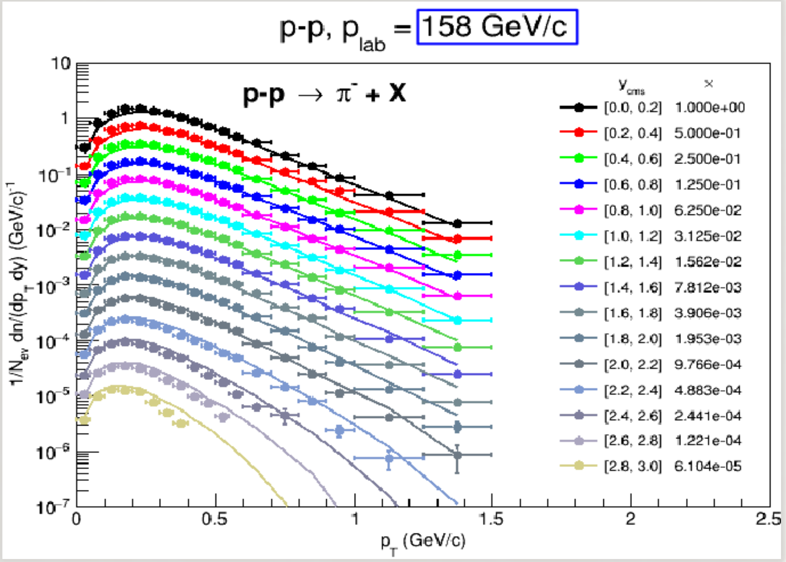


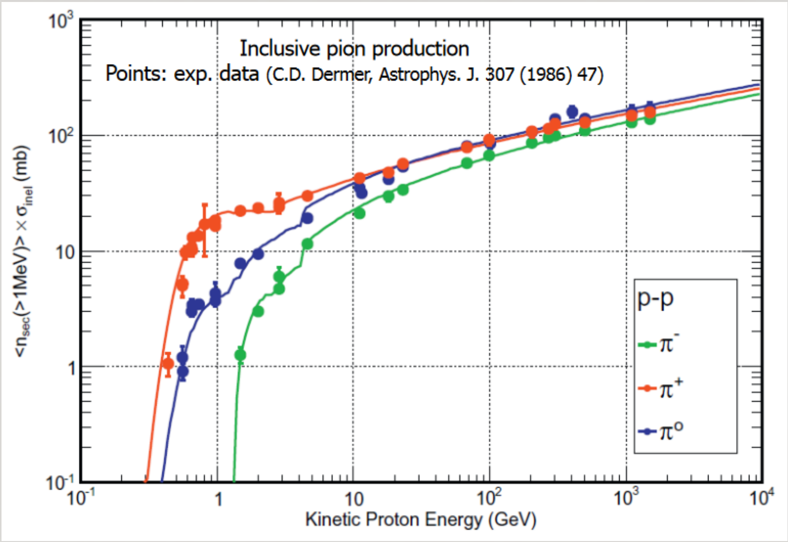


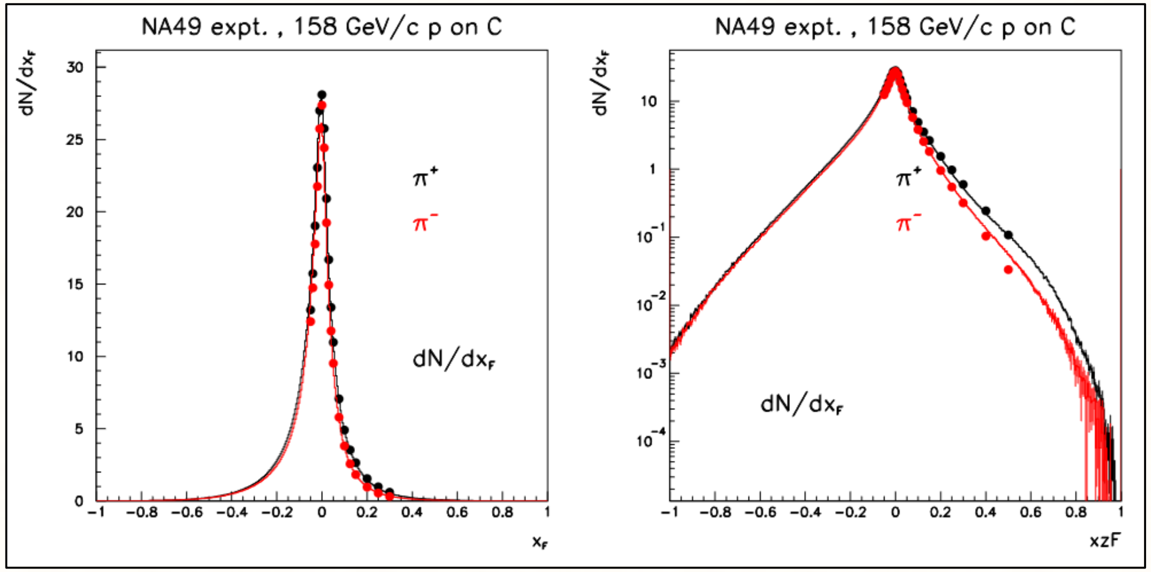
Fluka cross sections

http://www.fluka.org/fluka.php









A few Refs:

G. Battistoni et al, Annals of Nuclear Energy, Vol. 82 (2015)

T. Böhlen Nuclear data sheets, Vol. 120 (2014)

F. Cerutti, “FLUKA: theoretical grounds and wished new data”, Talk at XSCR (2017)

Fluka cross sections

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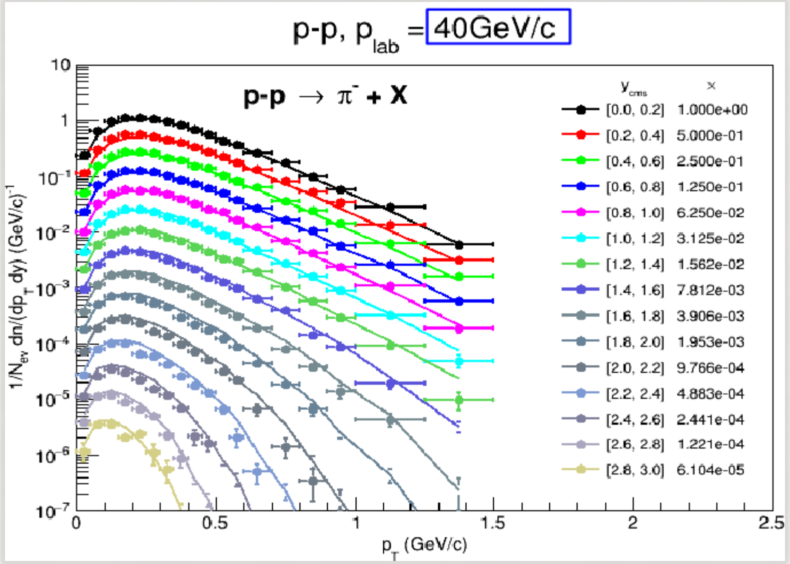
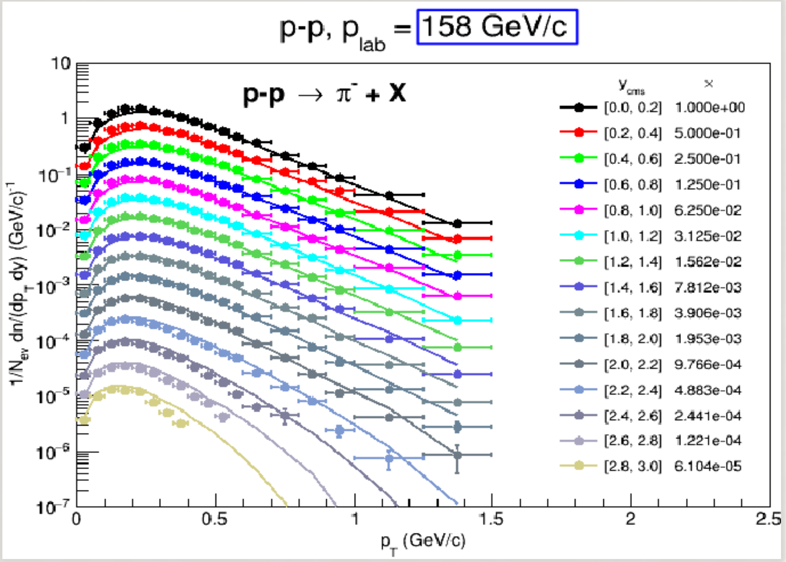
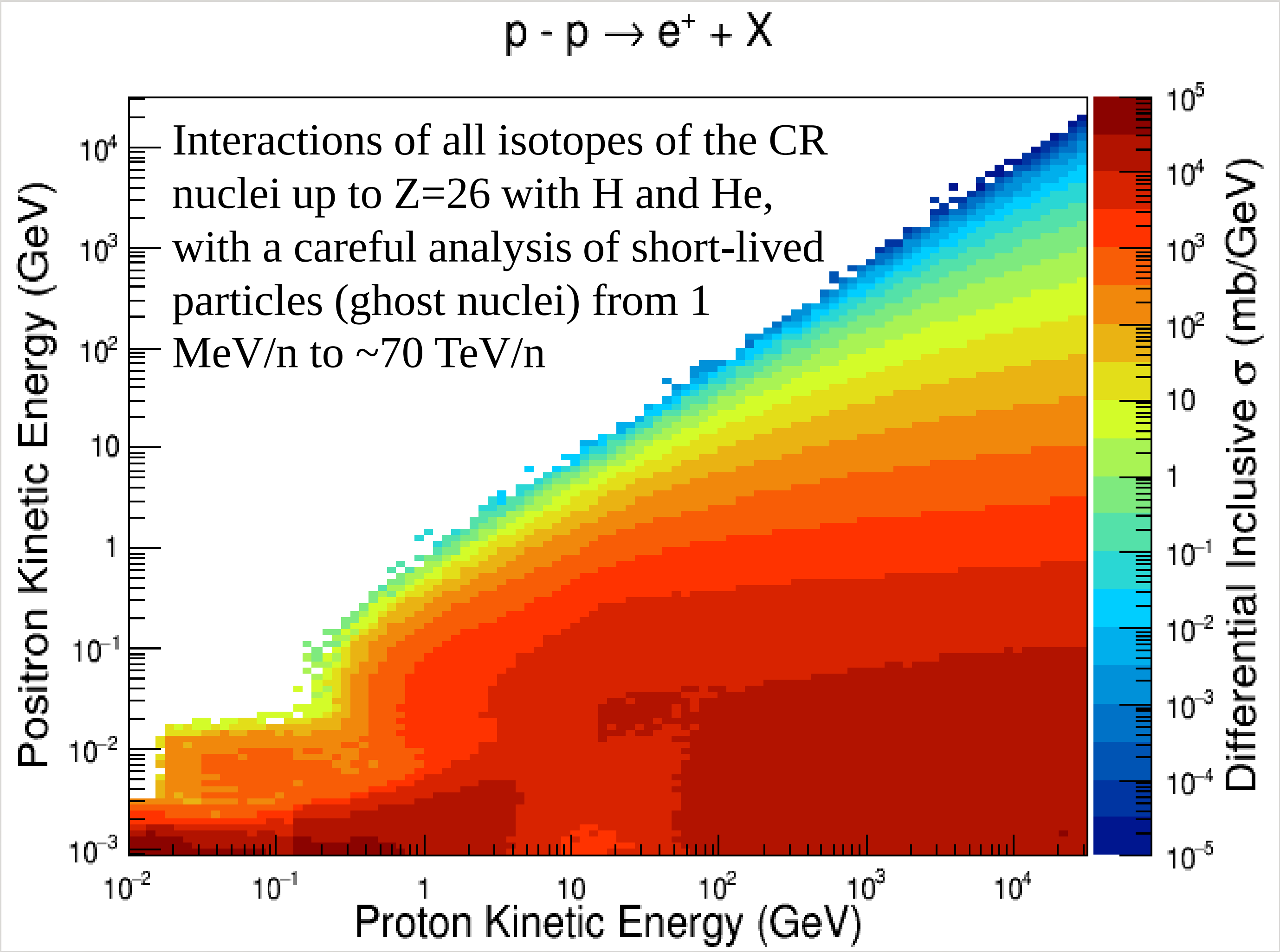
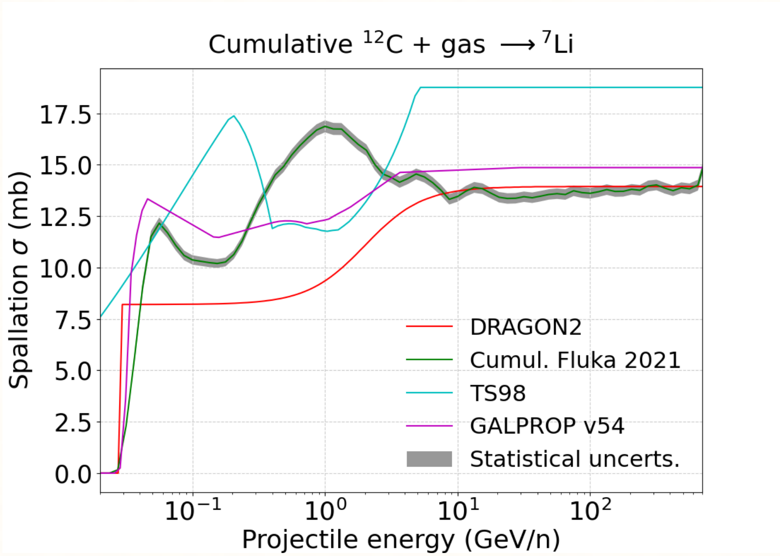
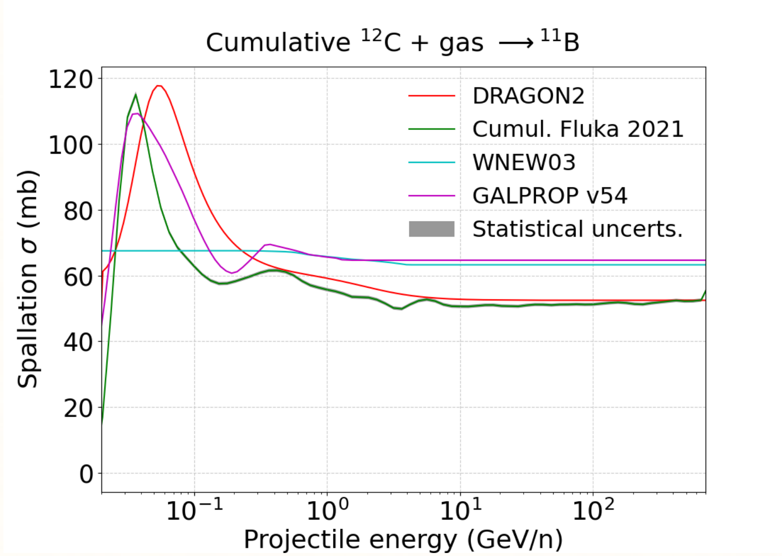


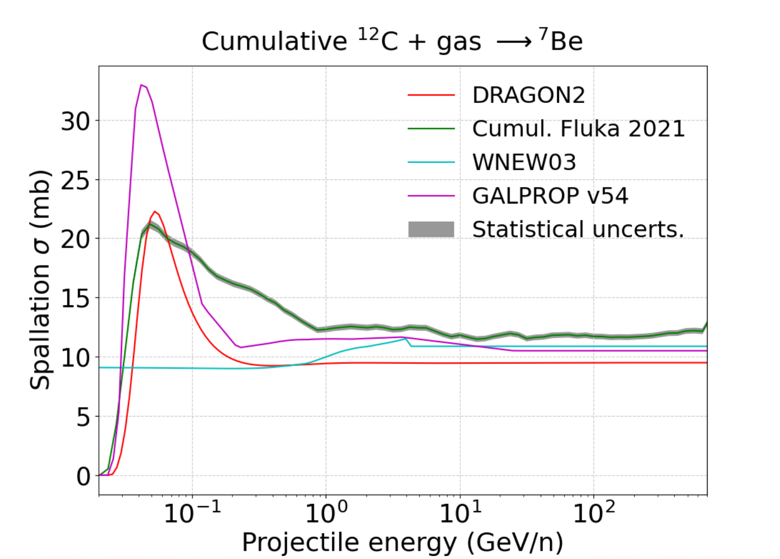


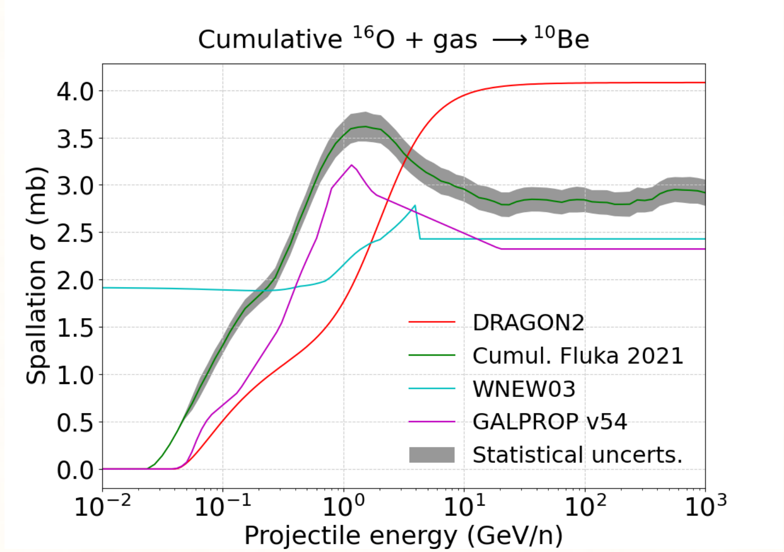


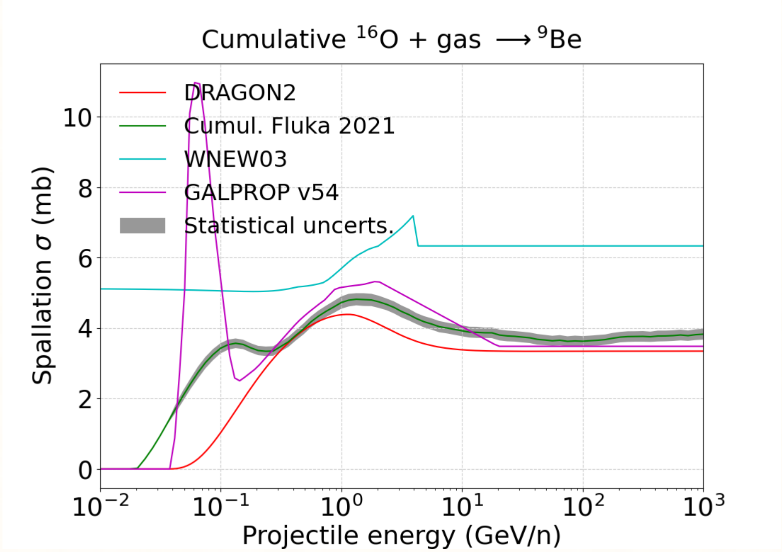
FLUKA (cumulative) inclusive cross sections

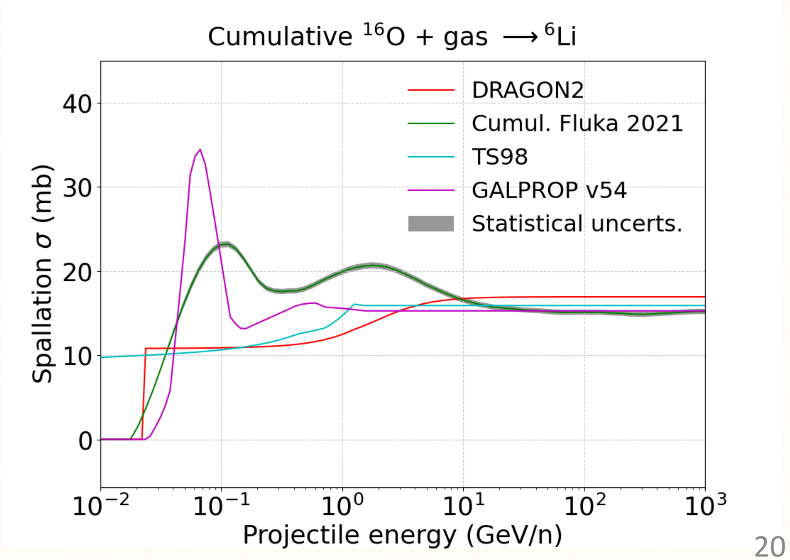






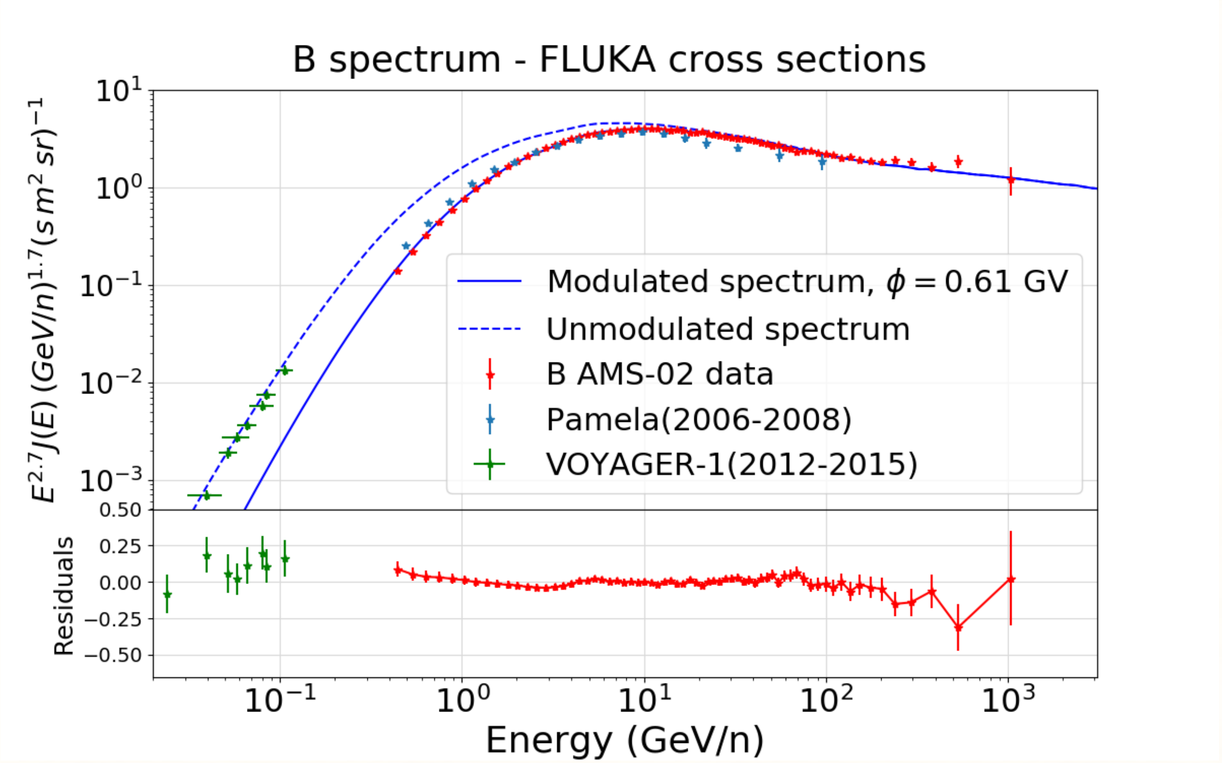


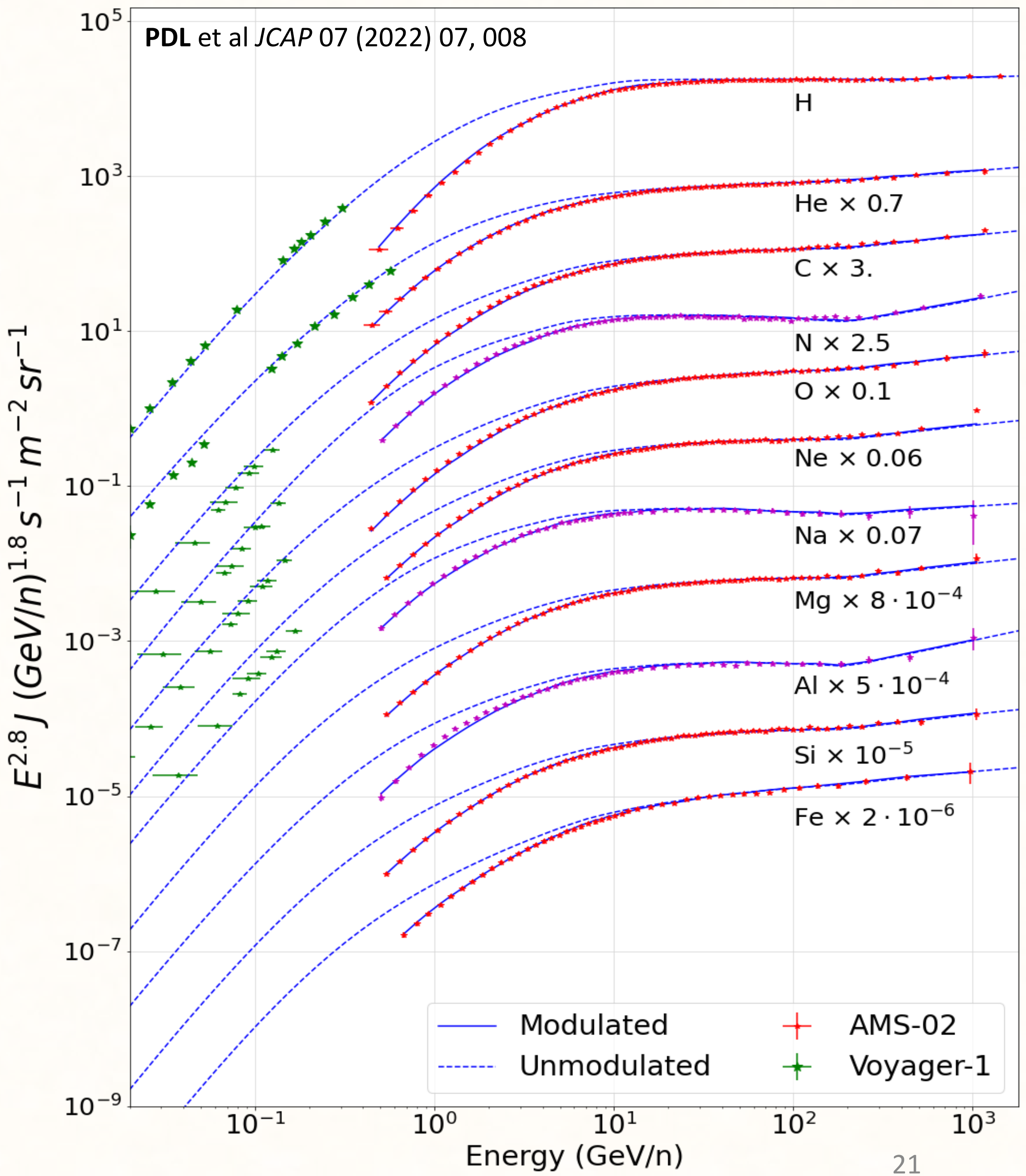




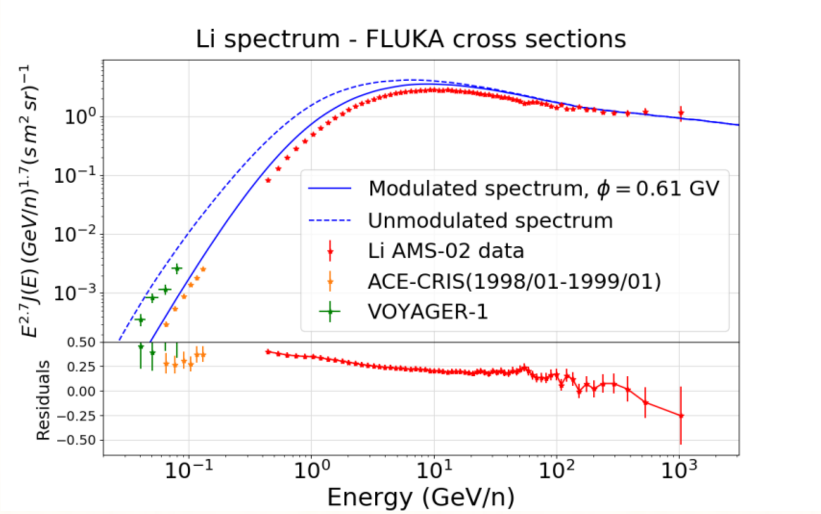
These cross sections are implemented in the DRAGON2 code with the aim of studying the production of the secondary CRs B, Be and Li

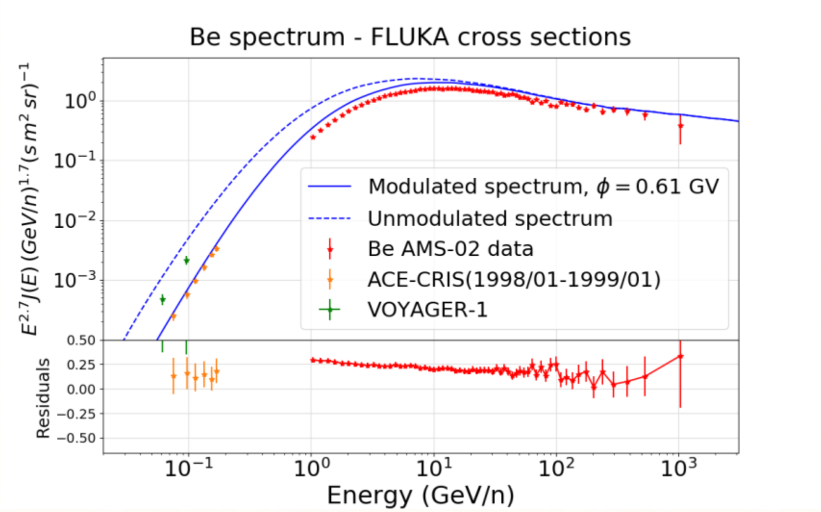
The propagation params. inferred from the B/C ratio are very compatible with those derived from other updated parametrizations





FLUKA cross sections: B, Be and Li ratios





$$\frac{J_k}{J_j}(E) \propto \frac{\sum^{\alpha\to k} J_\alpha(E)\sigma_{\alpha\to k}(E)}{\sum^{\alpha\to j} J_\alpha(E)\sigma_{\alpha\to j}(E)} \xrightarrow{\text{high energies}} \sim \frac{\sum^{\alpha\to k} C_\alpha E^{-\gamma_\alpha}\sigma_{\alpha\to k}(E)}{\sum^{\alpha\to j} C_\alpha E^{-\gamma_\alpha}\sigma_{\alpha\to j}(E)}$$

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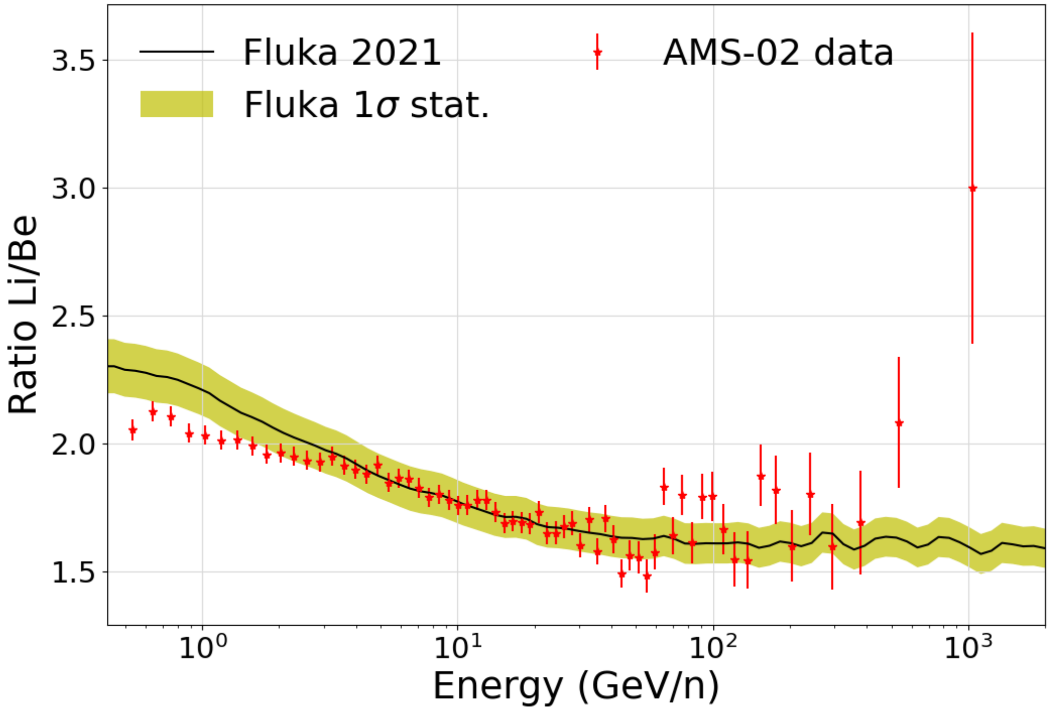

FLUKA cross sections: B, Be and Li ratios

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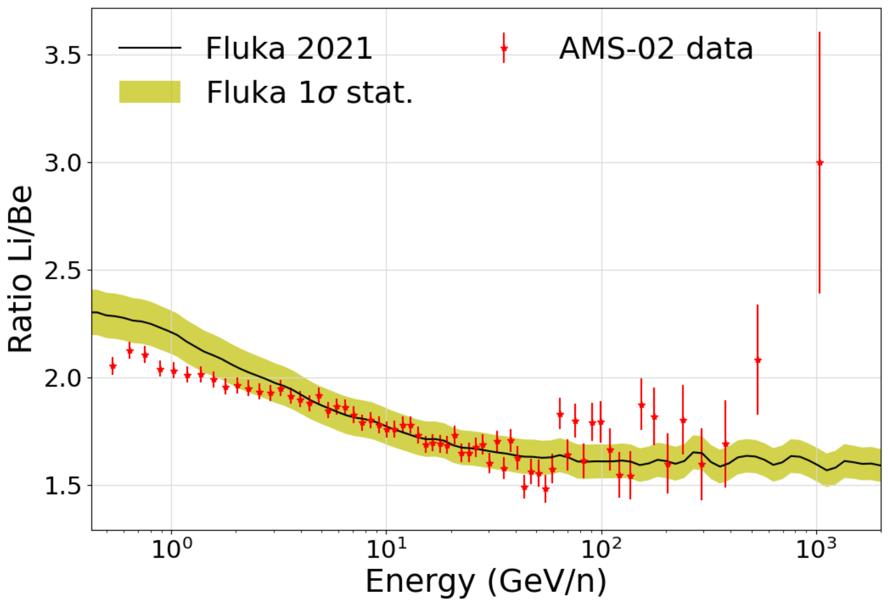
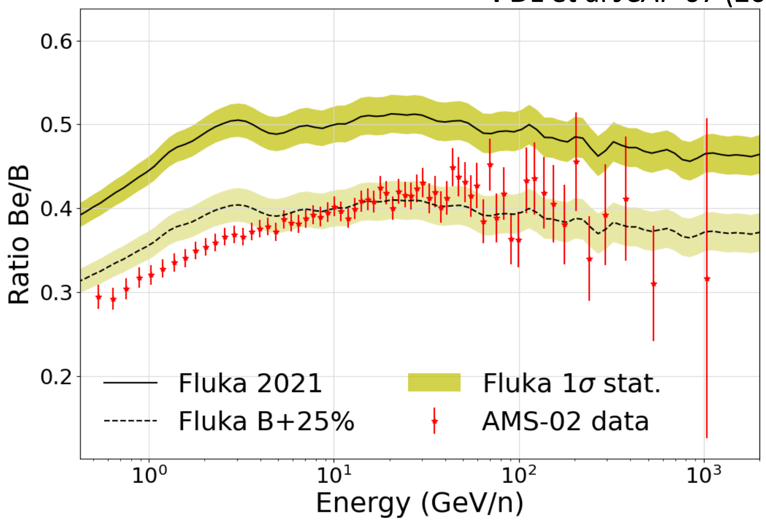
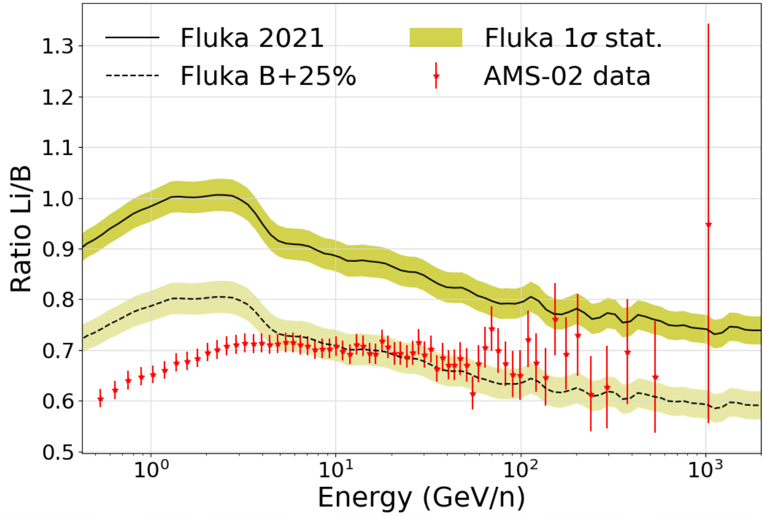
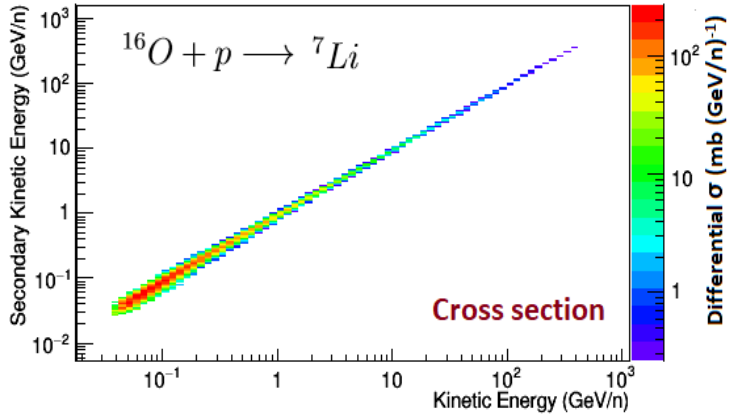
Energy dependence is greatly reproduced above a few GeV per nucleon
These ratios match AMS-02 data considering a ~10-25% scaling of the cross sections

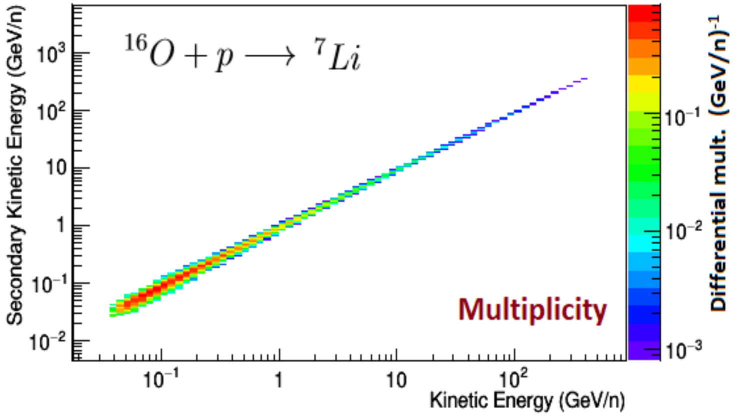


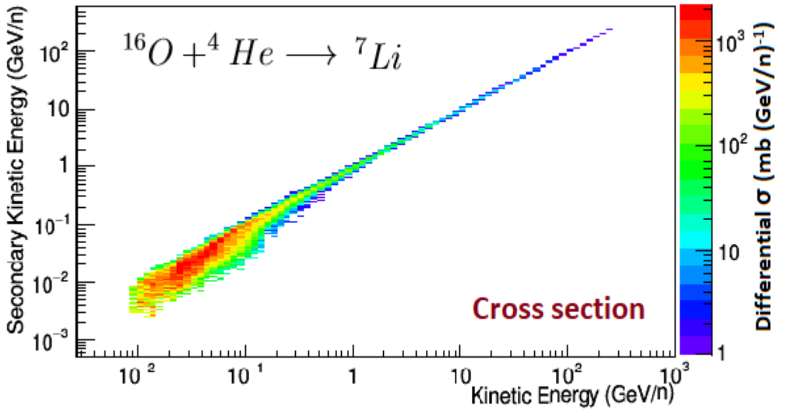


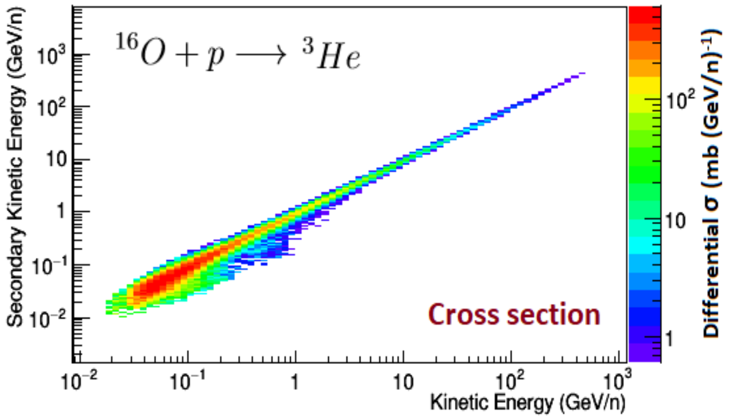


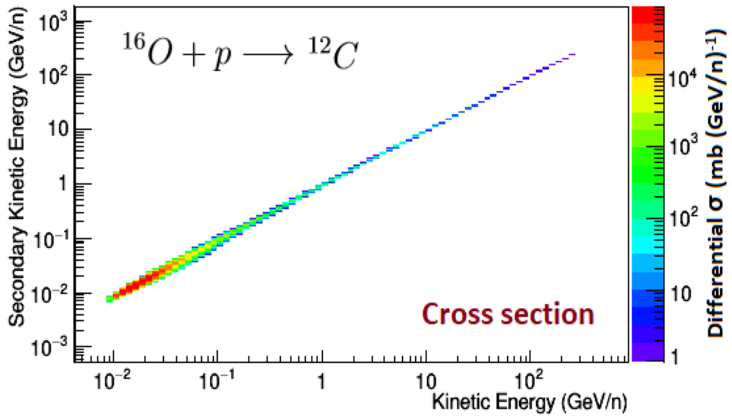
How valid is the head-on approximation below Li?







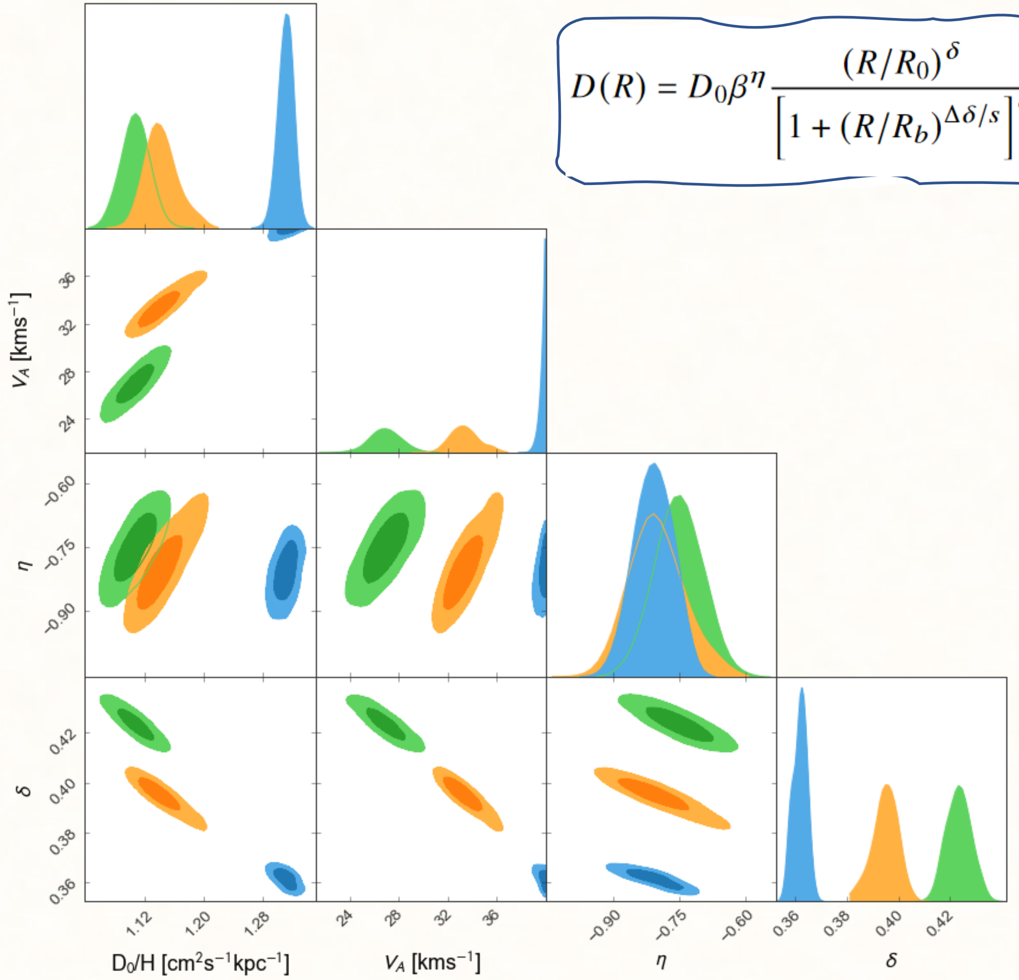




Combined fit of light secondary CRs

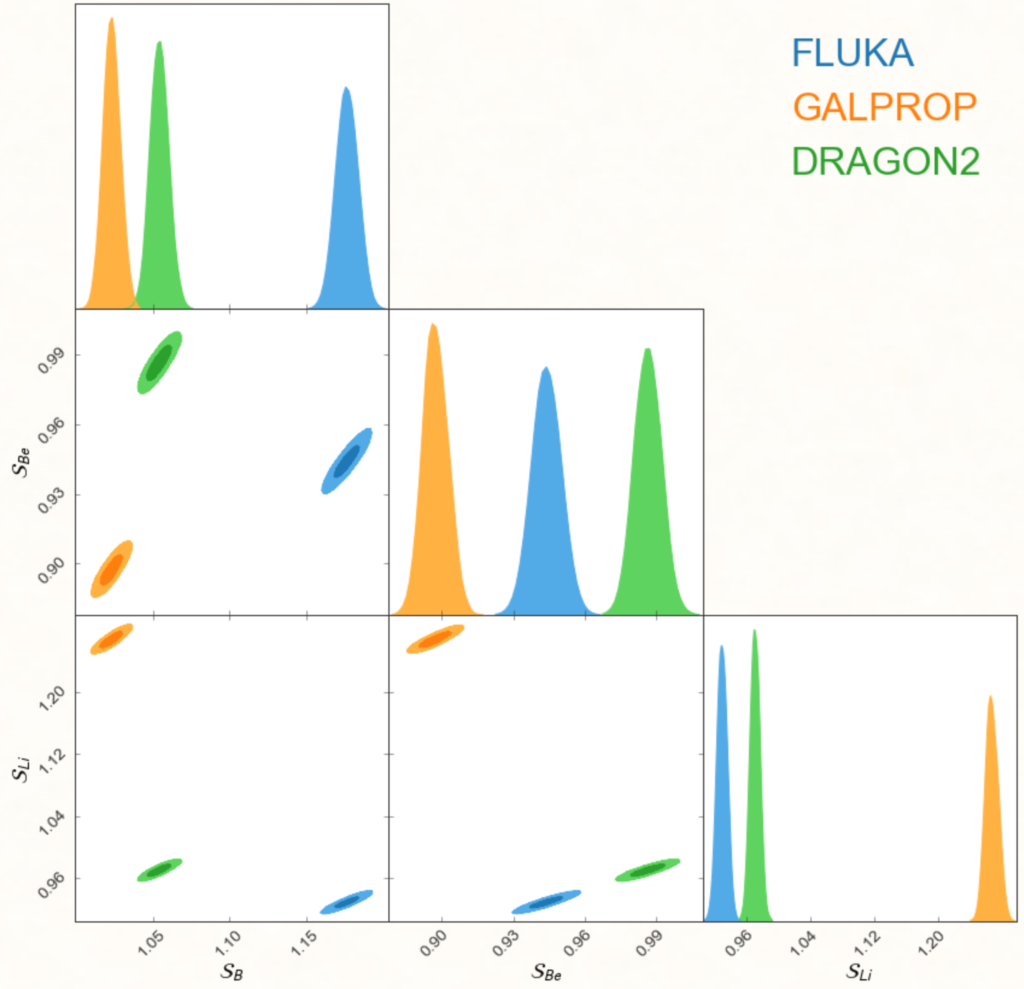
Main propagation parameters

$$D(R) = D_0 \beta^{\eta} \frac{(R/R_0)^{\delta}}{\left[1 + (R/R_b)^{\Delta\delta/s}\right]^{s}}$$

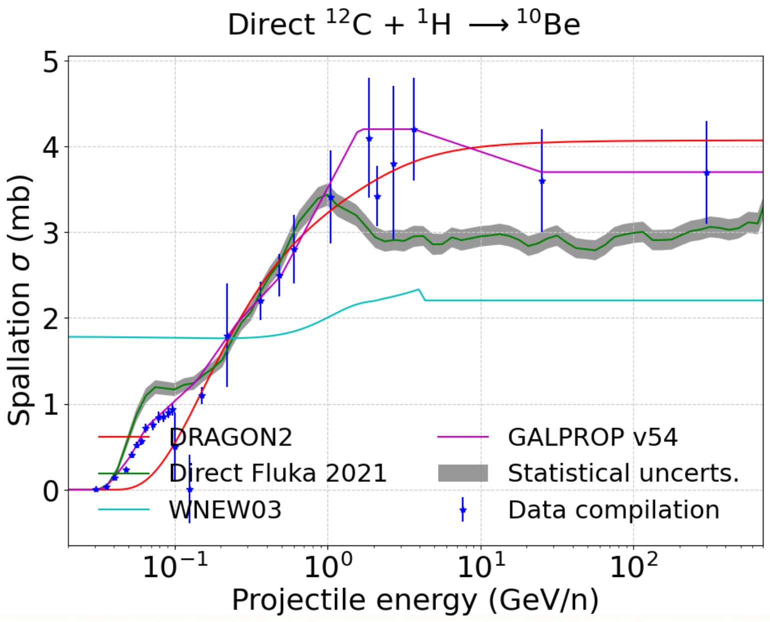


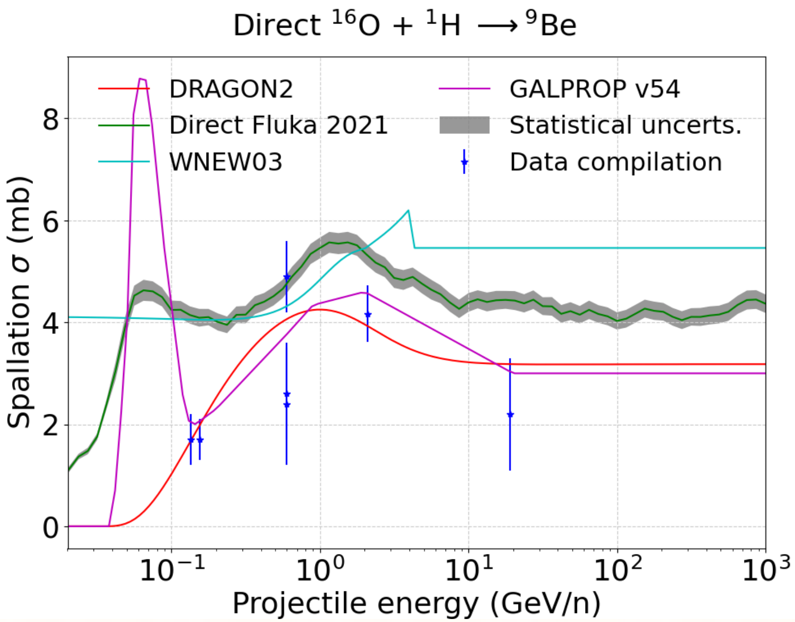
Scale factors

FLUKA
GALPROP
DRAGON2

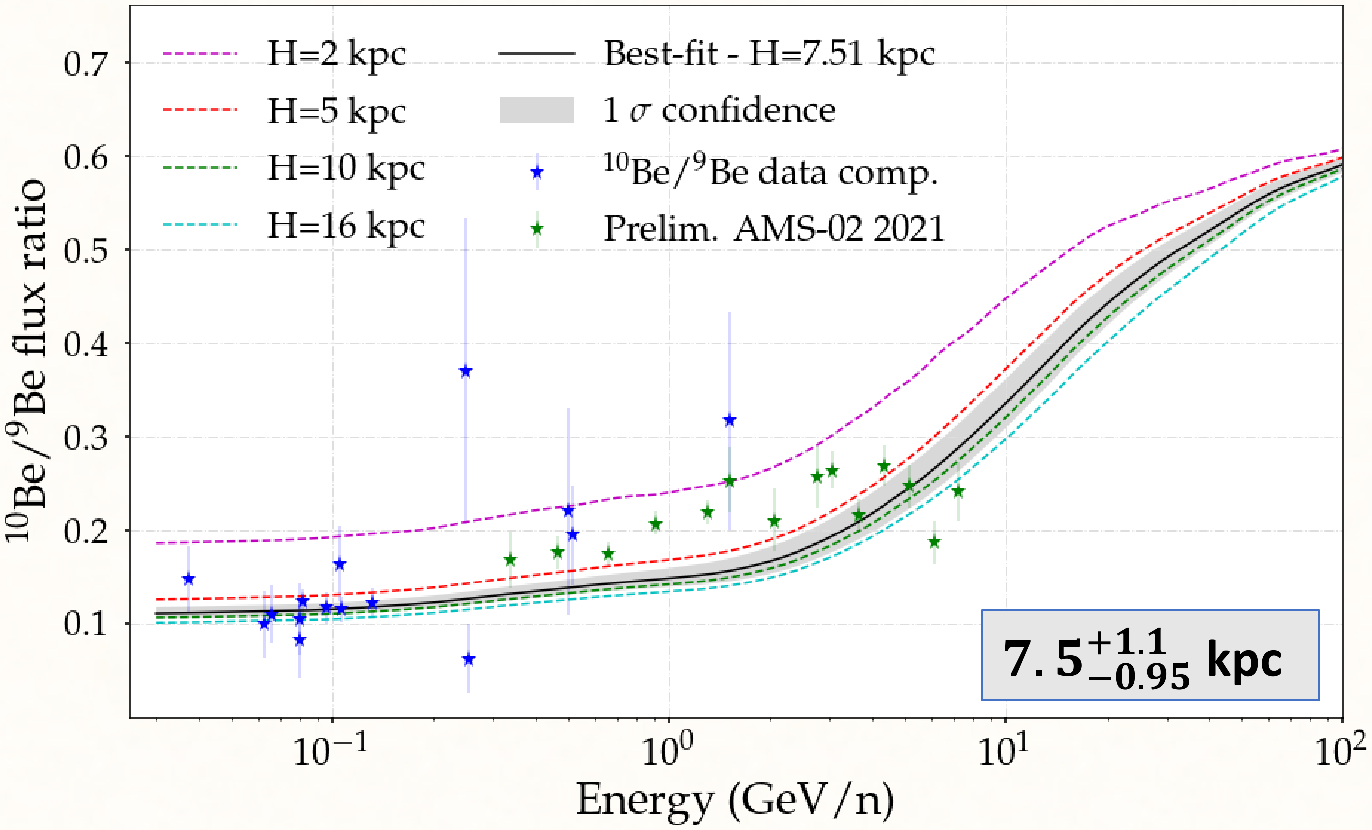


FLUKA cross sections: The halo size





P.D.L. et al arXiv:2202.03559

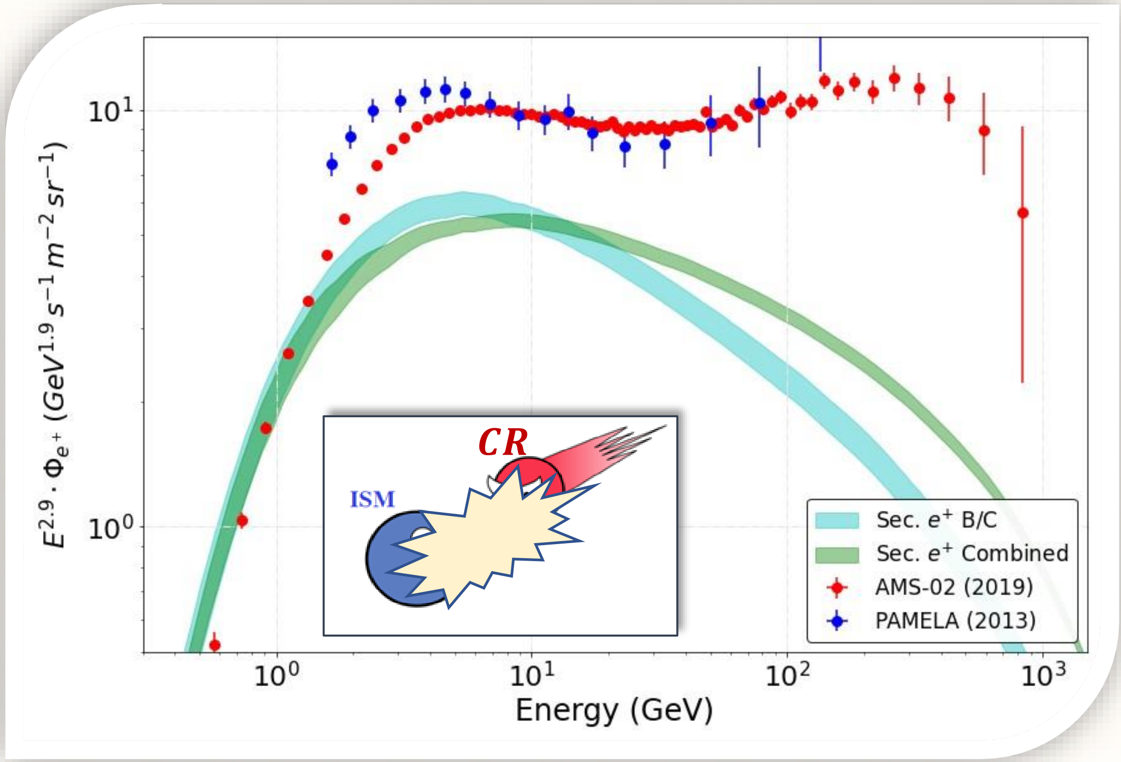


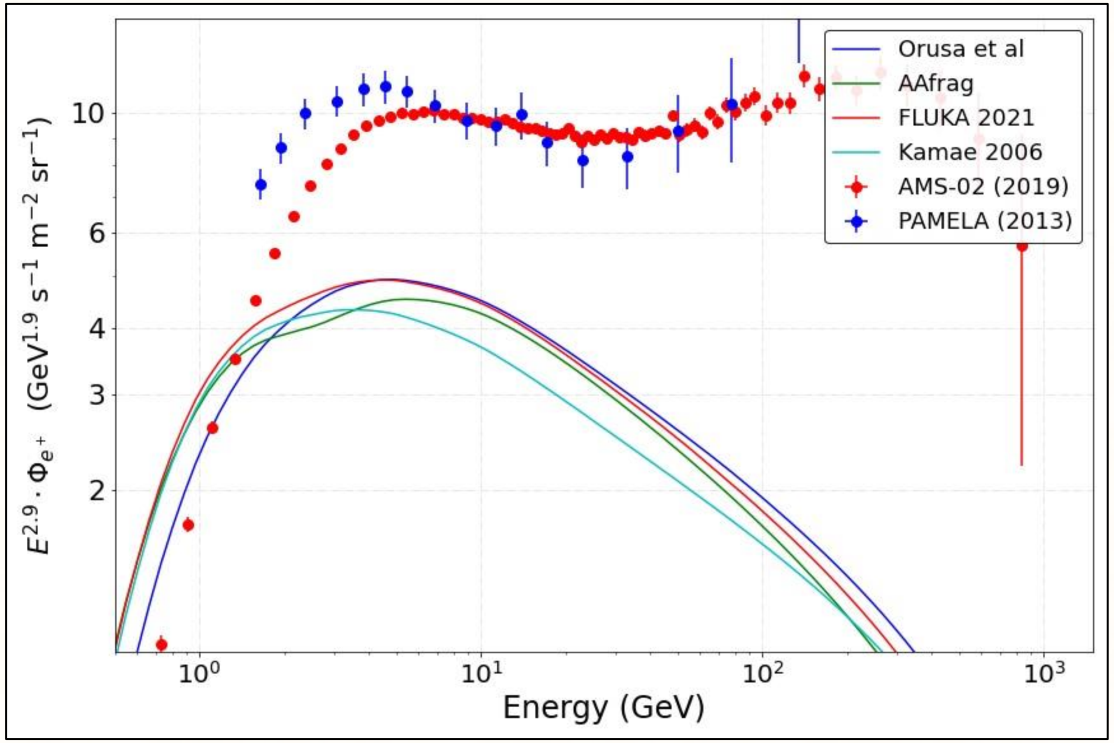
Cross sections e^+ uncertainties

$$D(R) = D_0 \beta^{\eta} \frac{(R/R_0)^{\delta}}{\left[1 + (R/R_b)^{\Delta\delta/s}\right]^{s}}$$

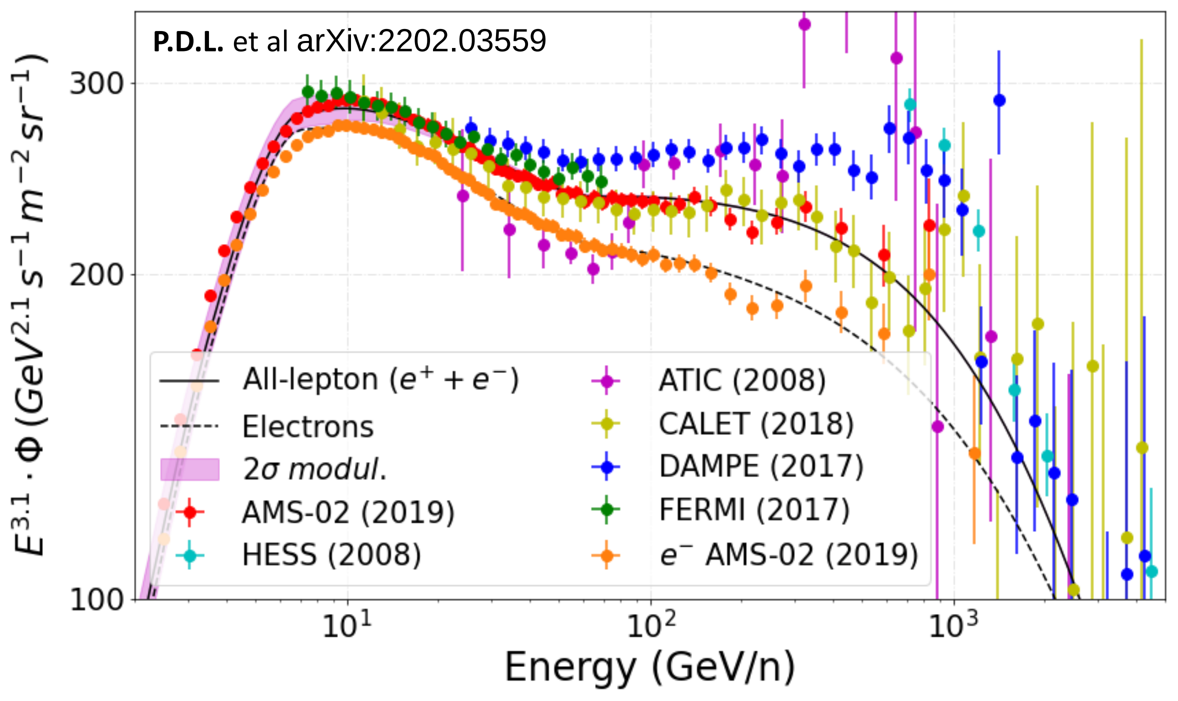
Conventional set-up: Cylindrical symmetry of gas density (dependence on **r** and **z**), source distribution, magnetic field. Prop. adjusted from secondary CRs (ArXiv:2202.03559)

Predicted secondary e+ from different analysis of secondary CRs with Fluka cross sections



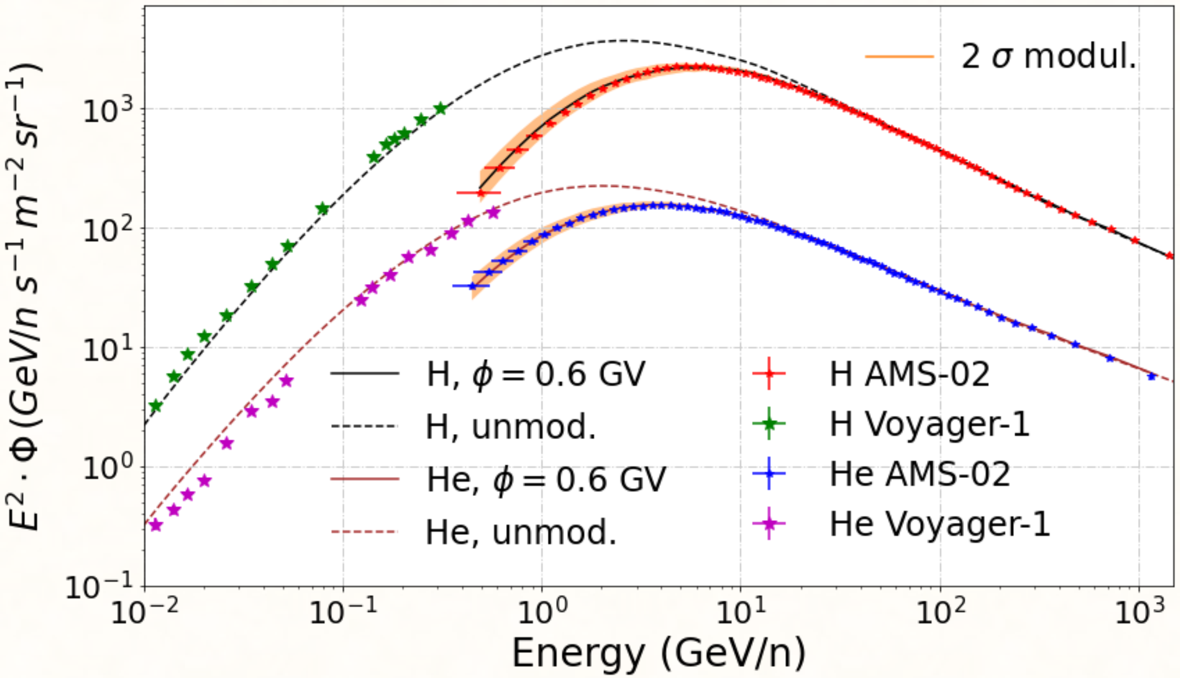


FLUKA cross sections for gamma-ray production



γ-ray production from different gas nuclei

Protons, He and electrons are treated with the *Force field* approximation and need a break at around 8 GeV/n to fit well experimental data



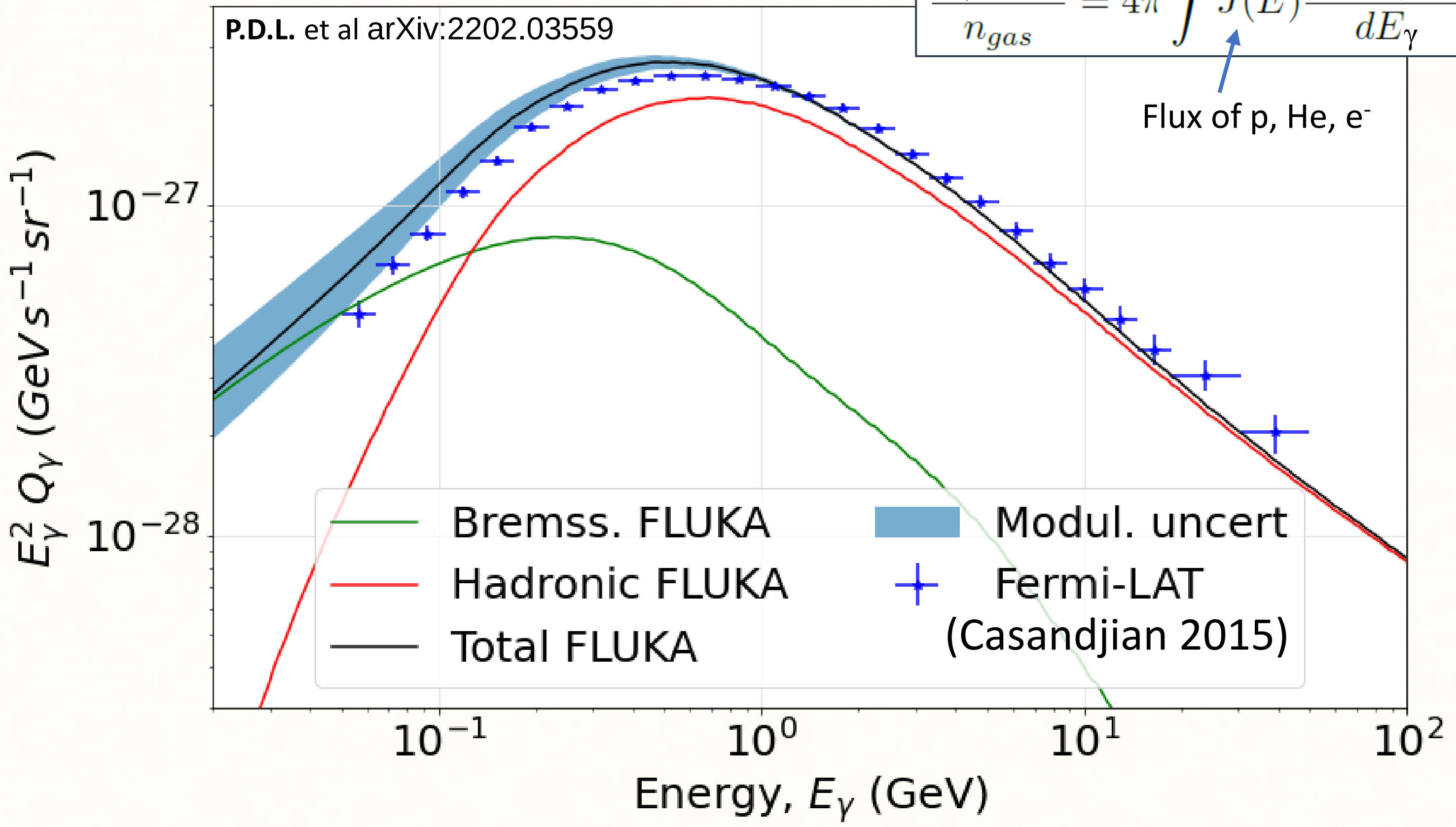
Electrons require a doubly broken power-law in order to reproduce at the same time local CR measurements and **local γ-ray emissivity** at low energies

FLUKA cross sections for gamma-ray production

Study of the **local emissivity** (at latitudes 10° < |b| < 70°) ISM composition with relative abundance of H : He : C : N : O : Ne : Mg : Si = 1:0.096 : 4.65 10^{-4} : 8.3 10^{-5} : 8.3 10^{-4} : 1.3 10^{-4} : 3.9 10^{-5} : 3.69 10^{-5}.

$$\frac{Q_\gamma(E_\gamma)}{n_{gas}} = 4\pi \int J(E) \frac{d\sigma(E_\gamma|E)}{dE_\gamma} dE$$

Flux of p, He, e^-

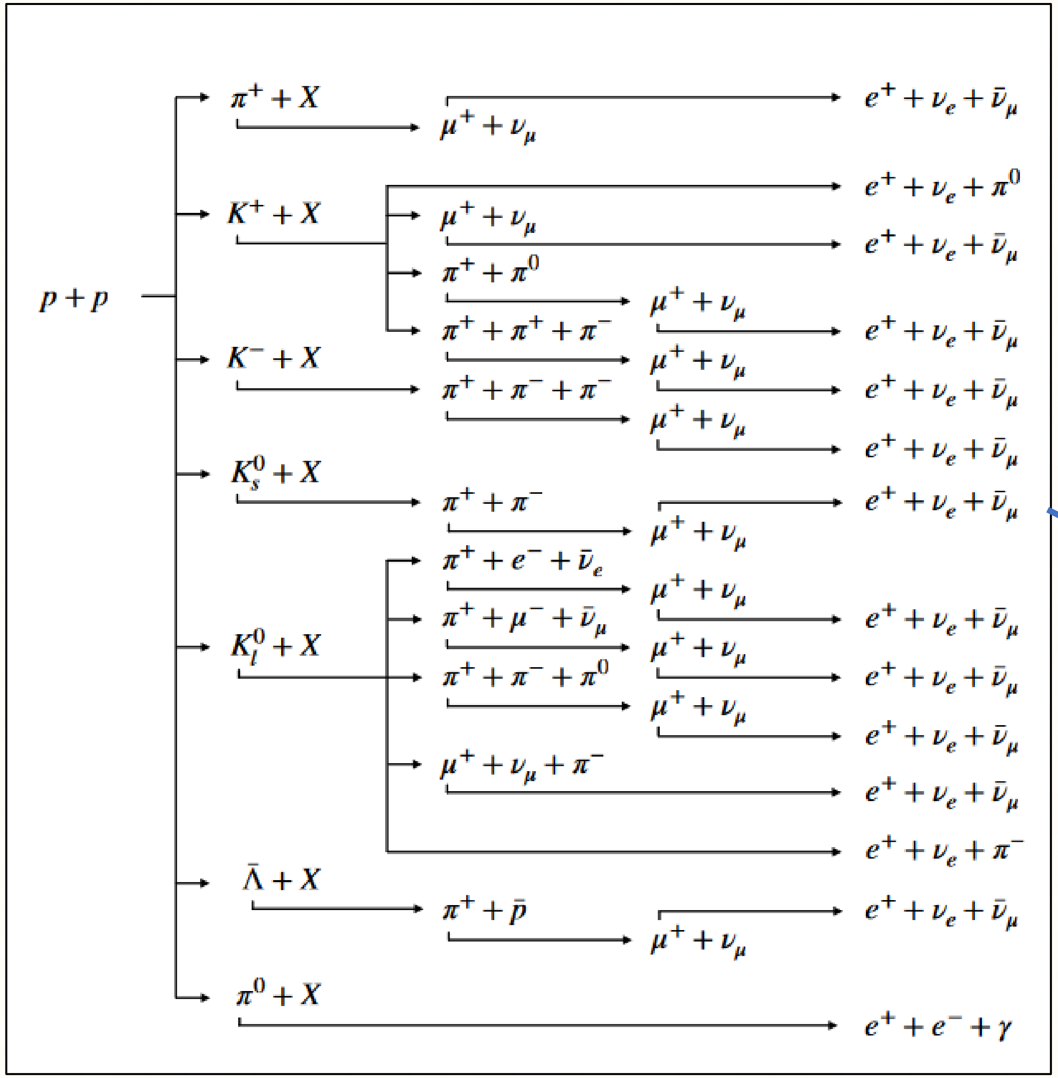


This quantity just depends on the cross sections of gamma-ray production and the spectrum of electrons, protons and He (**low-energy specially uncertain due to solar modulation uncertainties!**)

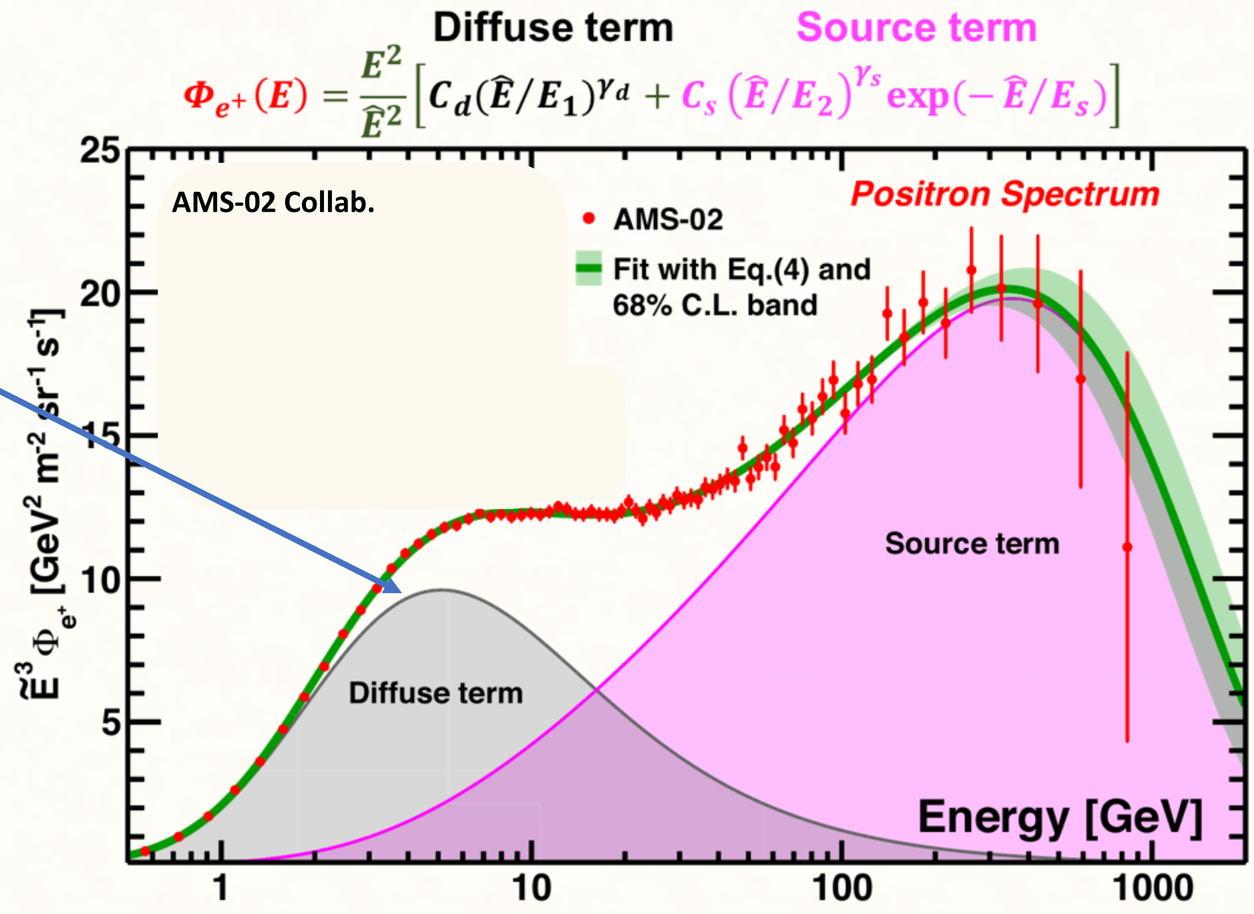
Cross sections implemented in the *GammaSky* code

The cross section problem

Orusa et al PRD 105 (2022) 12



Positrons mainly produced from p+p interactions, but also He and heavier CRs are involved and produce positrons!



Fluka cross sections: e^+ uncertainties

Scaling –> $\frac{\sigma_{A+p}}{\sigma_{p+p}} \sim A^s$

s found to be 0.9-1.1