FLUKA and the Corsika7/8 interface

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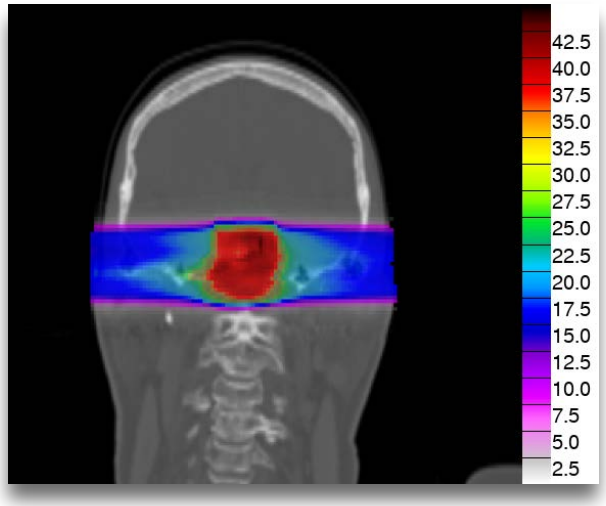
FLUKA (A.Fasso`, A.Ferrari, J.Ranft, P.R.Sala):

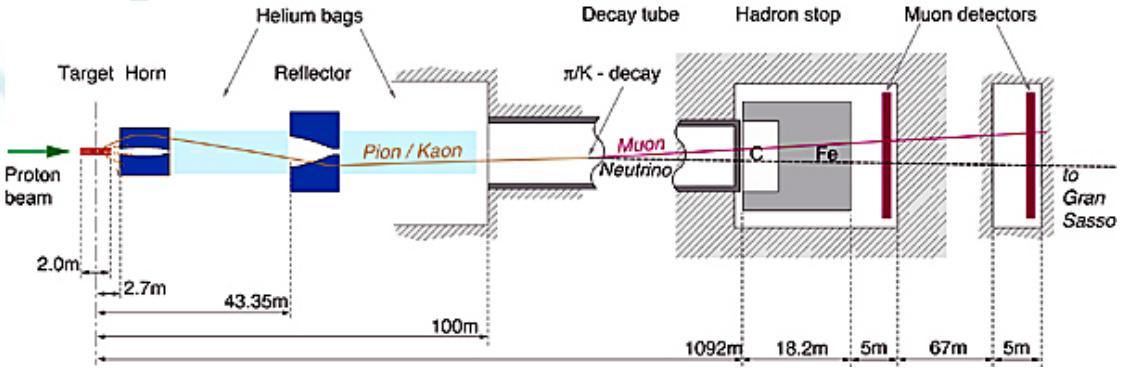
FLUKA is a general purpose tool for calculations of particle transport and interactions with matter

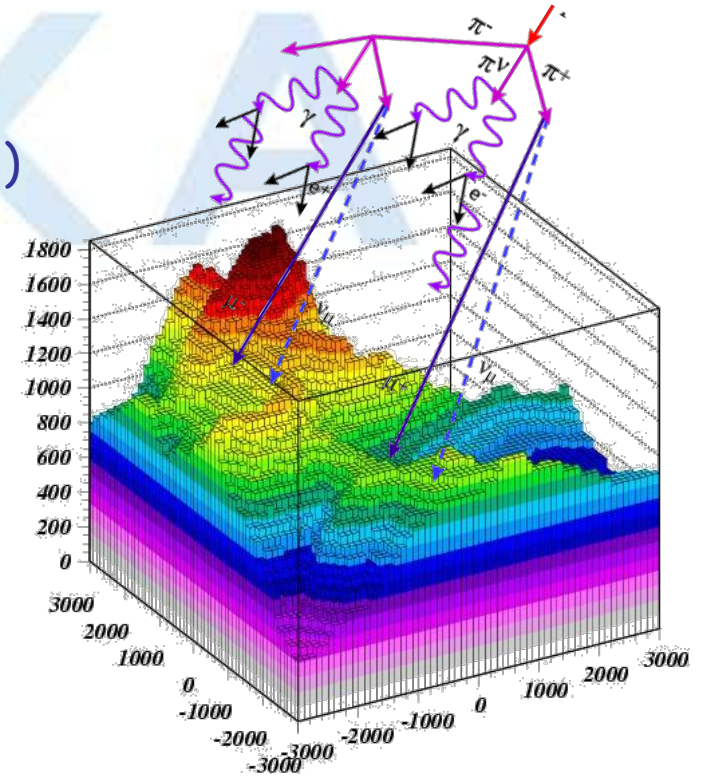


FLUKA Applications:

Tested up 10 EeV (10^{19} eV)

- Cosmic ray physics
- Neutrino physics
- Accelerator design (→ n_ToF, CNGS, LHC systems, μCollider)
- Particle physics: calorimetry, tracking and detector simulation etc. (→ ALICE, ICARUS, …)
- ADS systems, waste transmutation, (→"Energy amplifier", FEAT, TARC,…)
- Shielding design
- Dosimetry and radioprotection
- Radiation damage
- Space radiation
- Hadron therapy
- Neutronics





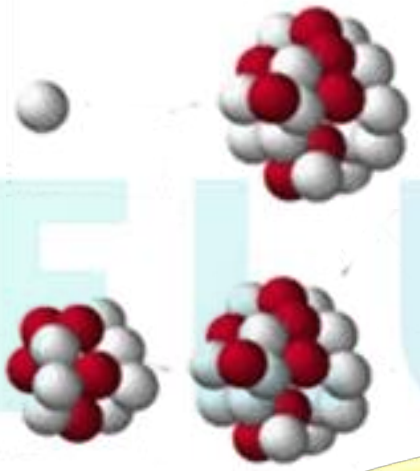
http://www.fluka.org ~14000 registered users worldwide

Fluka hA/AA models:

PEANUT
10^4 > E > ~0.01 GeV

Photonuclear interactions
ElectroMagneticDissociation
Leptonuclear interactions

10^{-5}eV< Neut <20 MeV
ENDF + EAF
Grxs and pwxs
(Fluka2021)



DPMJET-3
10^{11} > E > 10^4 GeV
10^{11} > E/n > 10-15 GeV

BME
100-150 > E/n > ~5 MeV

Extended rQMD
10-15 > E/n > 0.1-0.15 GeV

New interface with Corsika7/8:

- The interface with Corsika7 had been reworked, made more general and easy to maintain, and already "Corsika8 ready" with no change;
- The interface is already distributed in the latest Fluka respins, and it is already in use by Corsika7 users;
  - It includes since several months a big reduction of the FLUKA memory imprinting
- It is made up of 4 modules:
  - Stpxyz: cross sections and material initialization (only once), it support whichever material/compound
  - Sgmxyz: run time cross sections for the requested processes
  - Evtxyz: run-time event generator(s) call
  - Peafll: interaction initial and final state loading on the standard HEP common
- Processes implemented (selectable at run-time):
  - Hadron non-elastic and quasi-elastic nuclear interactions (including photonuclear, ***new***)
  - Hadron (coherent) elastic nuclear interactions (***new***)
  - ElectroMagnetic dissociation of projectile/target ions (***new***)
- … and in principle nucleus-nucleus interactions as well with Dpmjet3/rQMD-2.4

New interface with Corsika7/8: cont.

- … in production with Corsika7 (hadron nuclear quasi-elastic and non-elastic only, as in the past);
- … tested also with coherent elastic by Max/Tanguy…
- … and also tested within Corsika8 (Max) with surprisingly no major problem!
- What is still to be tested:
  - ElectroMagnetic Dissociation (if Fluka standalone tests will show it is important)
  - Nucleus-nucleus interactions with Dpmjet3
  - Compatibility with the next Fluka (2023) release, more in the following
- The cross-section/interaction threshold can be as low as the Coulomb barrier for charged hadrons, and down to 20 MeV for neutrons;
- (Coherent) nuclear elastic scattering is important if one wishes to compute neutrons down to 20 MeV

Fluka2023.x vs Corsika7/8:

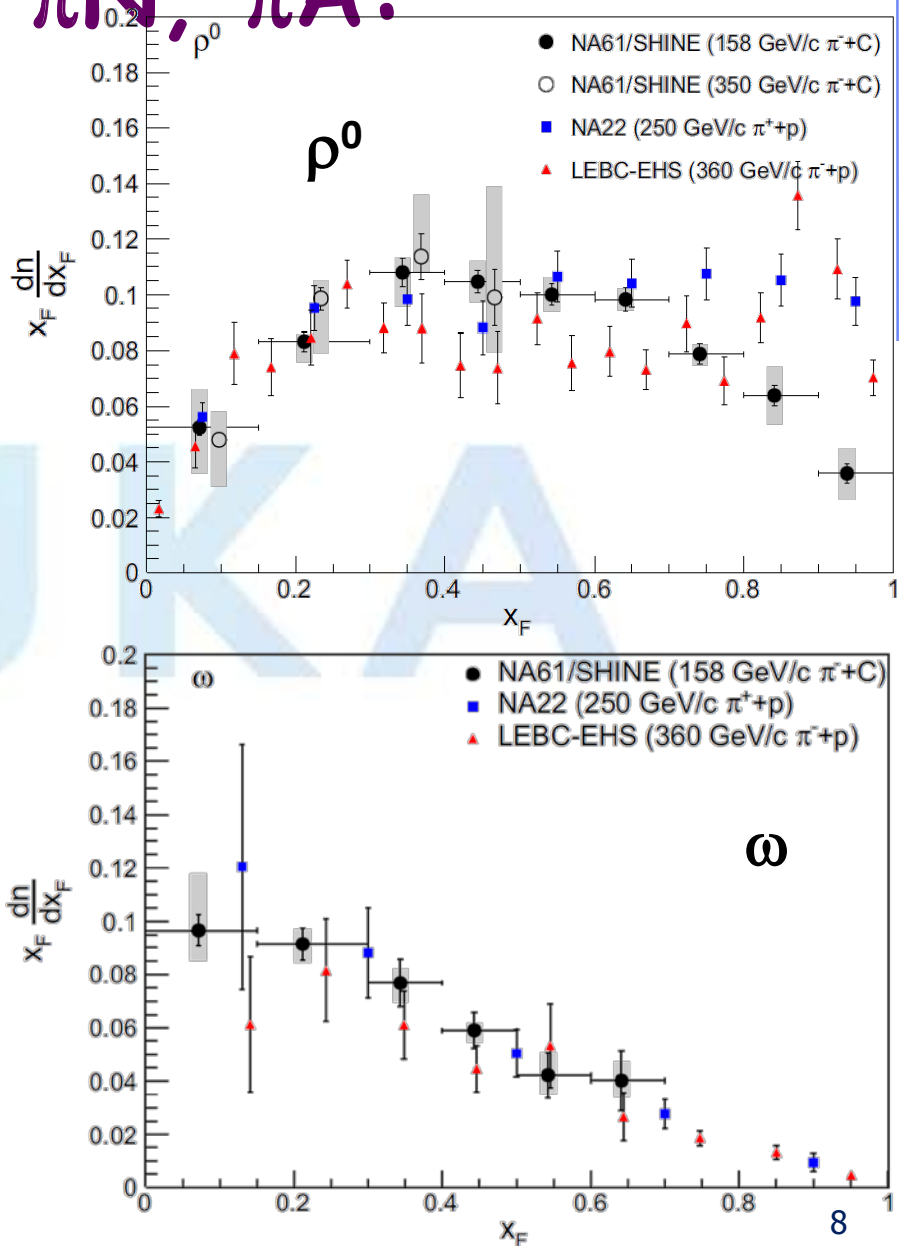
- Many **important improvements/additions** wrt Fluka2021.2;
- A devel version, **Fluka2023.2, will be soon made available**;
- The goal is to test it thoroughly in June/July and **make a public release end of July**;
- In the following the **major changes/additions**, physics-wise, which could be of interest for Corsika **will be presented**;
- Many more changes occurred in the code organization, which has been deeply reworked, eliminating parts which are now obsolete, streamlining other ones, and adding several new routines.

New hadronization

Eur. Phys. J. C (2017) 77:626

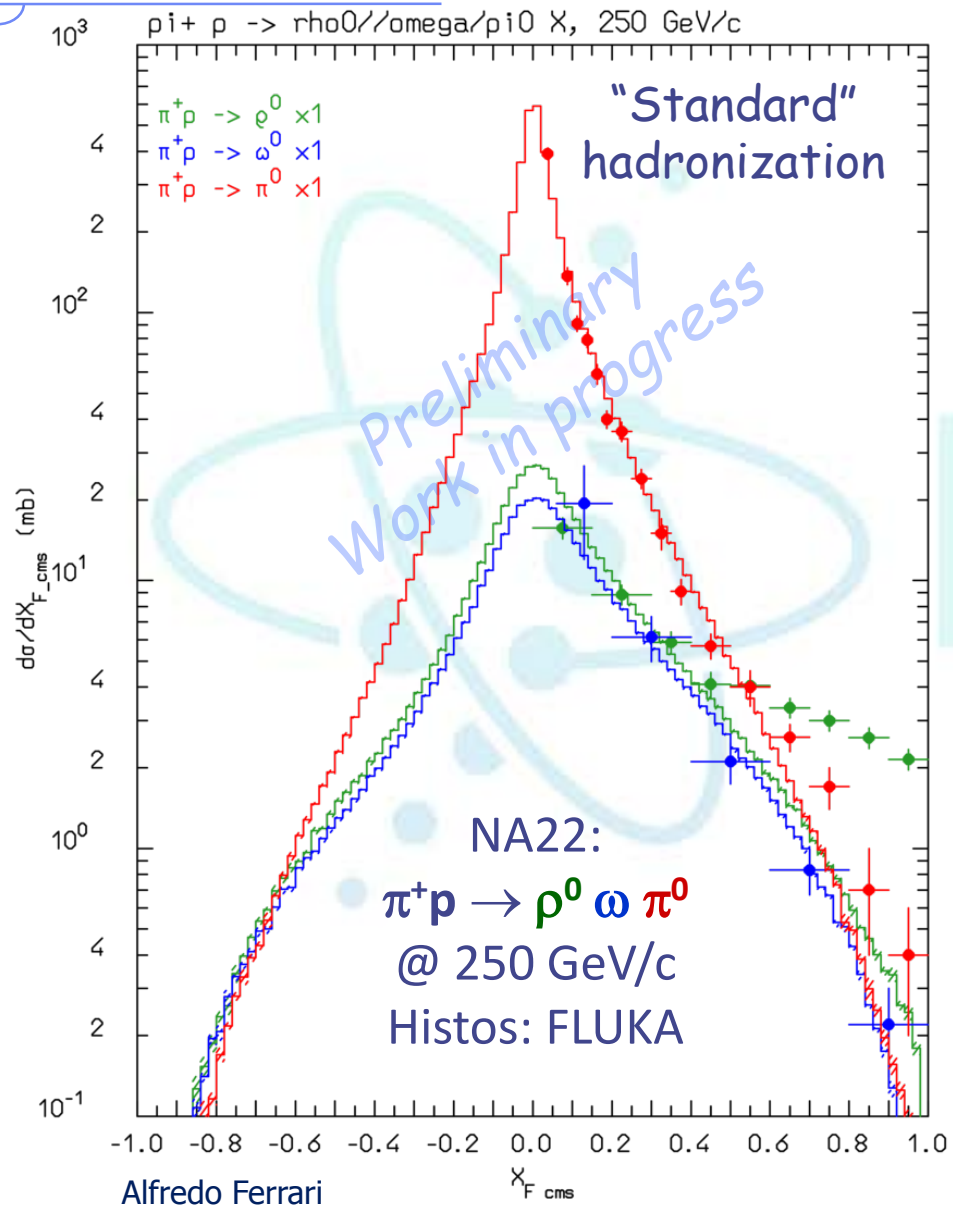
Hadronization: vector mesons in πN, πA:

- Surprisingly **large yield of ρ^0's** measured in **πN** and **πA** experiments in the forward region
- Ratio $\rho^0/\pi^0/\omega$ ***strongly*** rapidity/x_F dependent !!
- It **contradicts** one **critical assumption** of all **hadronization** models used in all codes up to now !
- Important for **very high energy cosmic rays** → it could slow down the increase of the EM fraction in air showers → increase the muon content
- Important for **calorimeters**, it can impact the e/h ratio



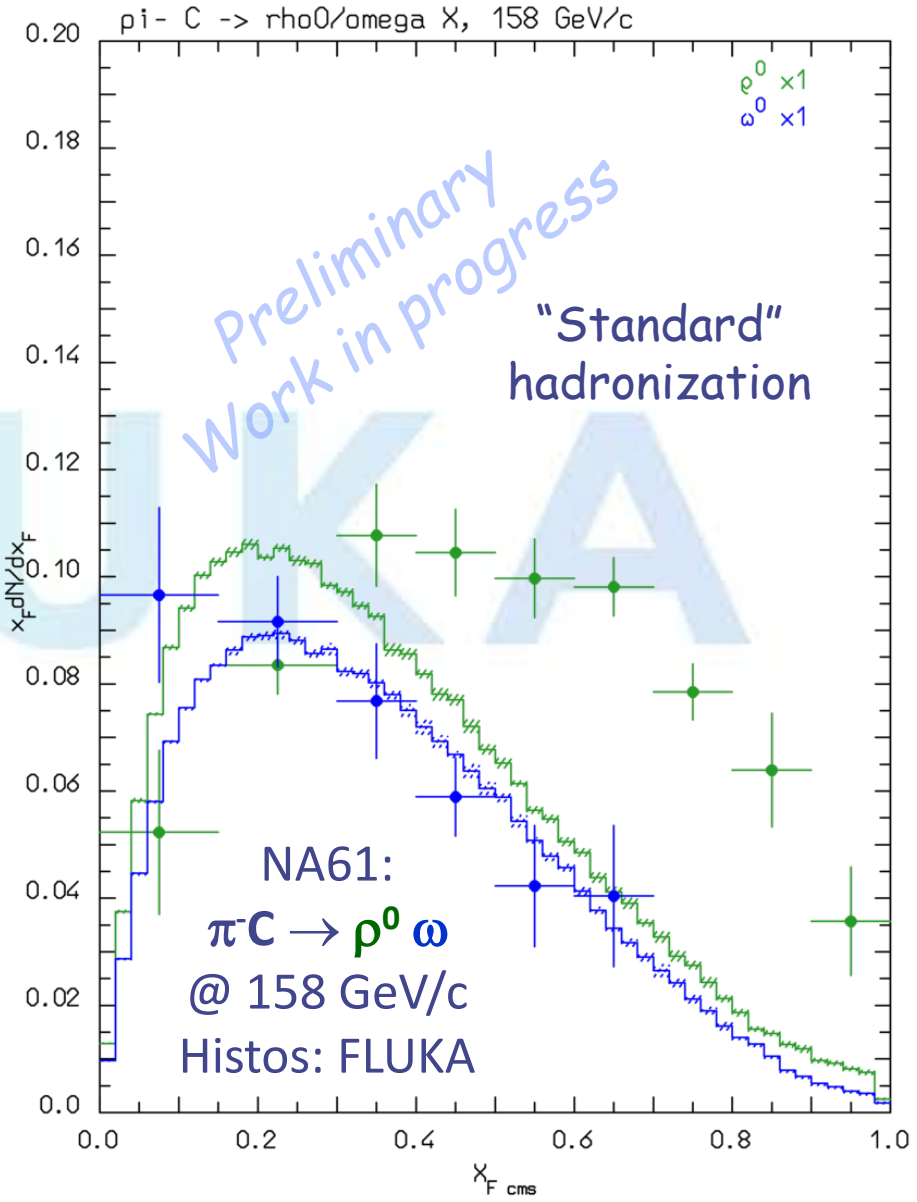
- Fluka hadronization completely revised;
- The only extra assumption is that valence (di)quarks fragment differently from sea-quarks…;
- … while still fulfilling all isospin/spin etc symmetries and conservations;

"New", completely revised, hadronization:

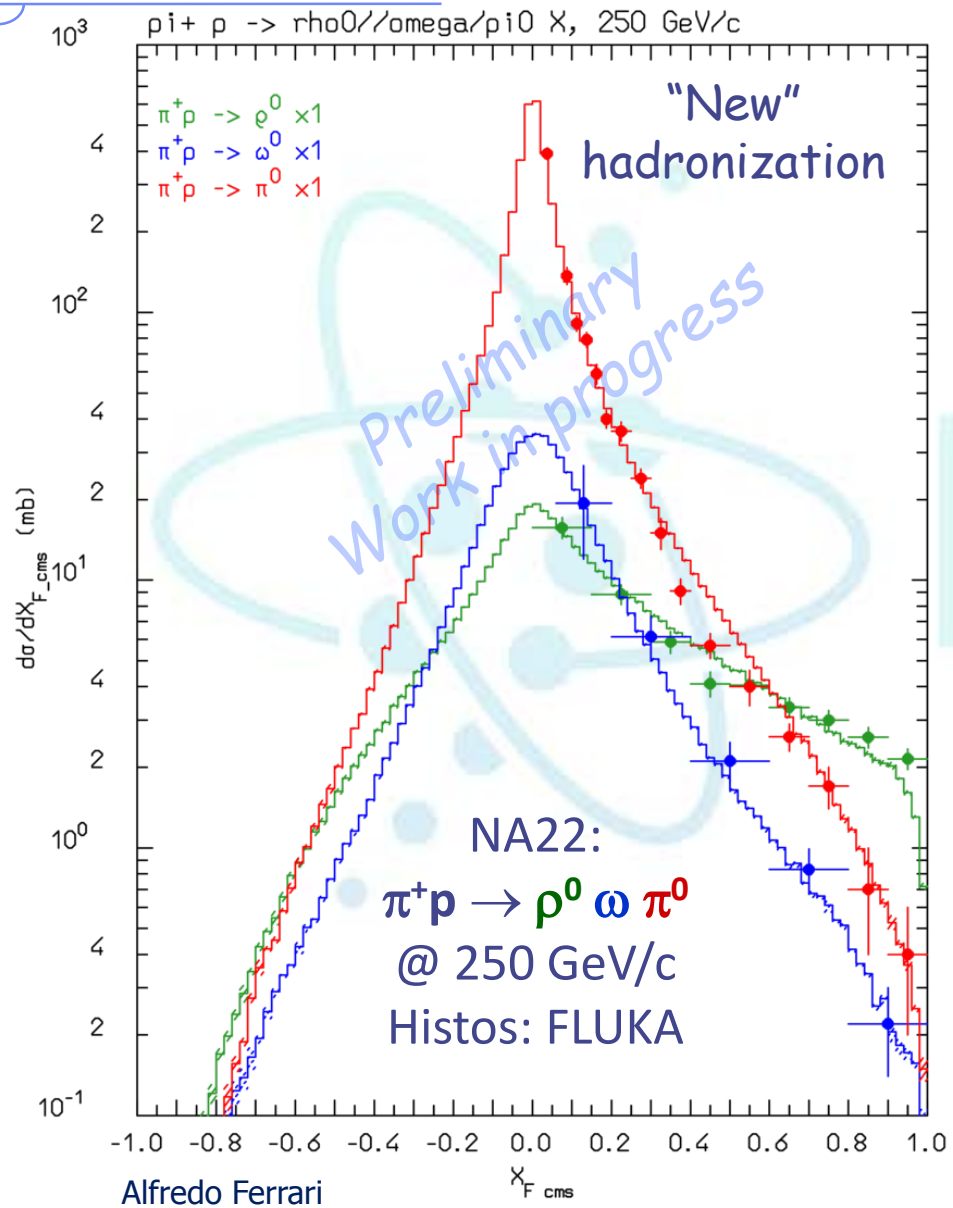


← $d\sigma/dx_F$

$x_F dN/dx_F$ →



"New", completely revised, hadronization:



← $d\sigma/dx_F$

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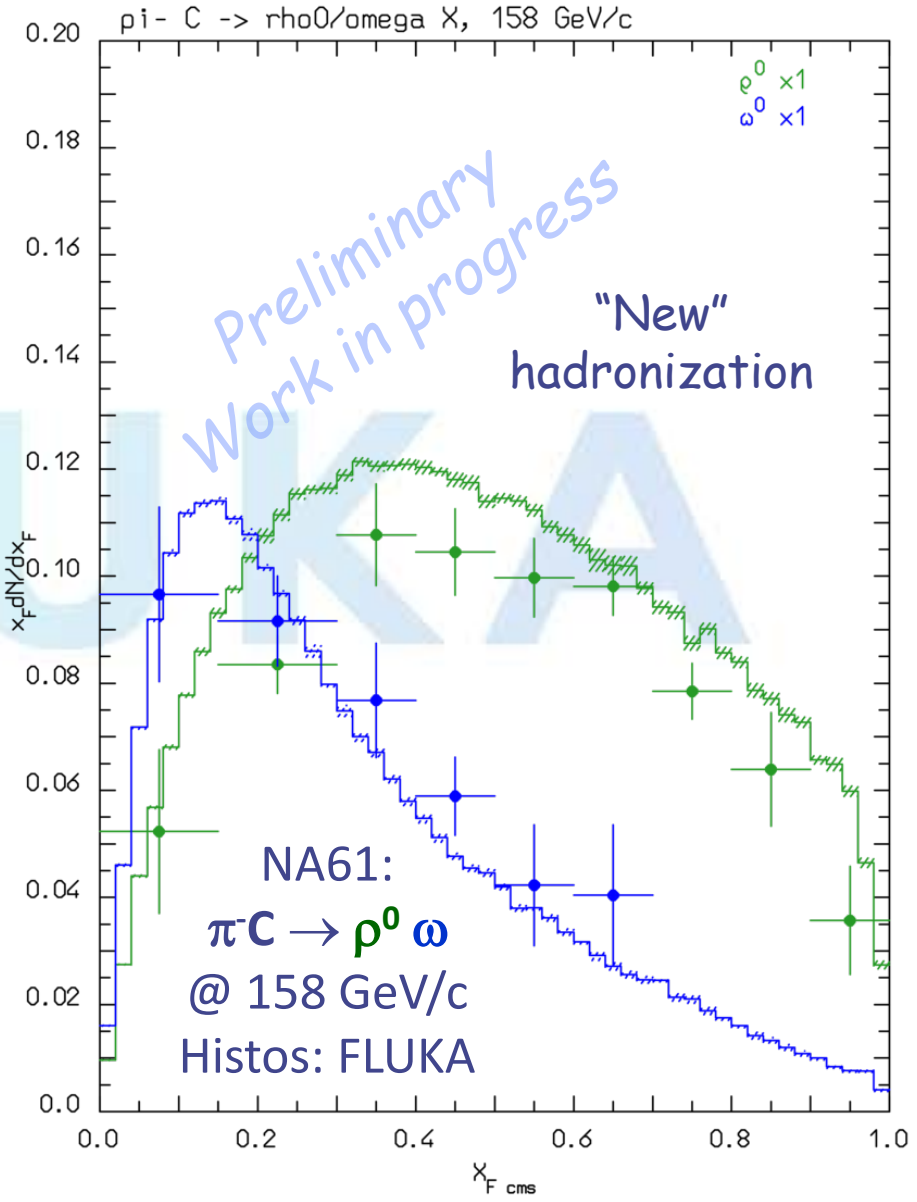
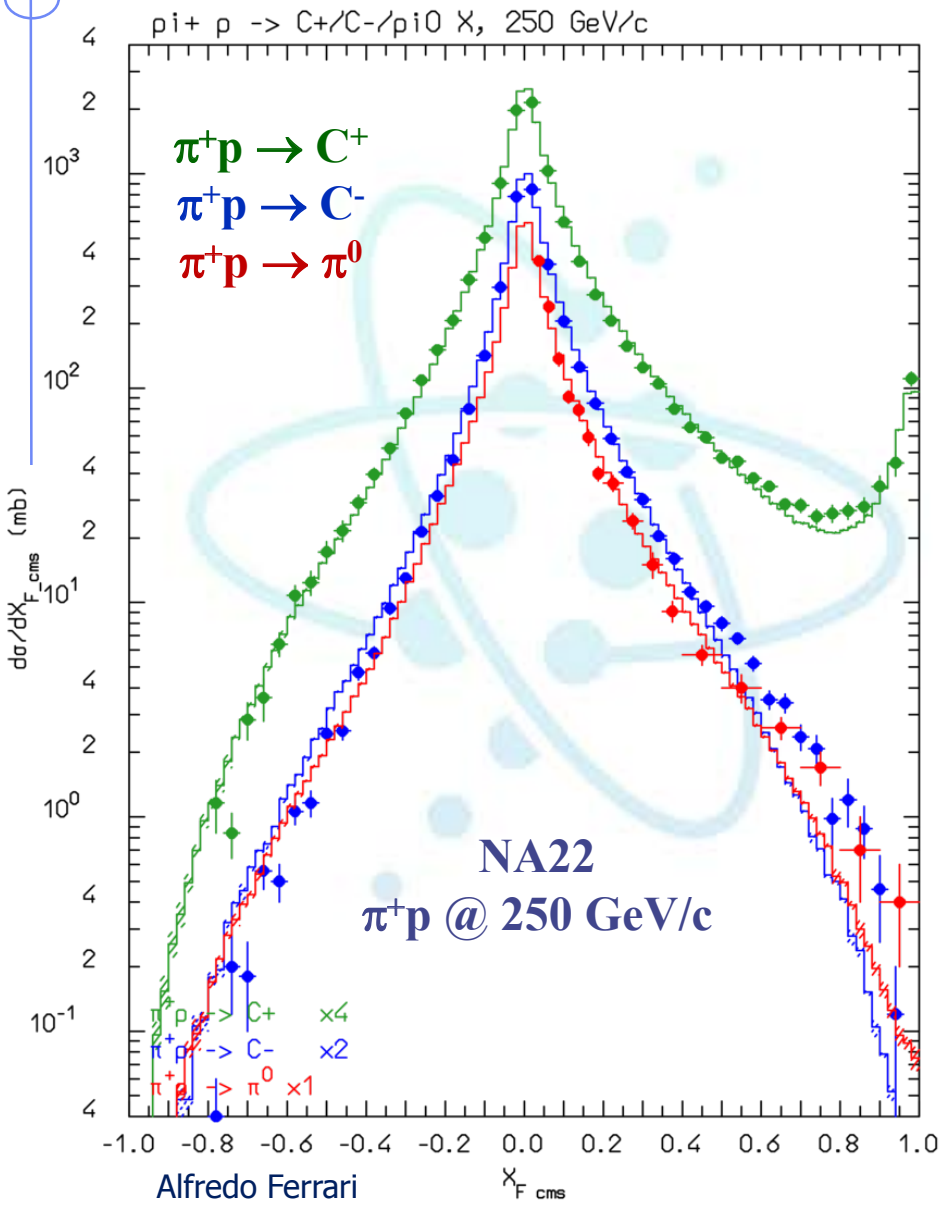


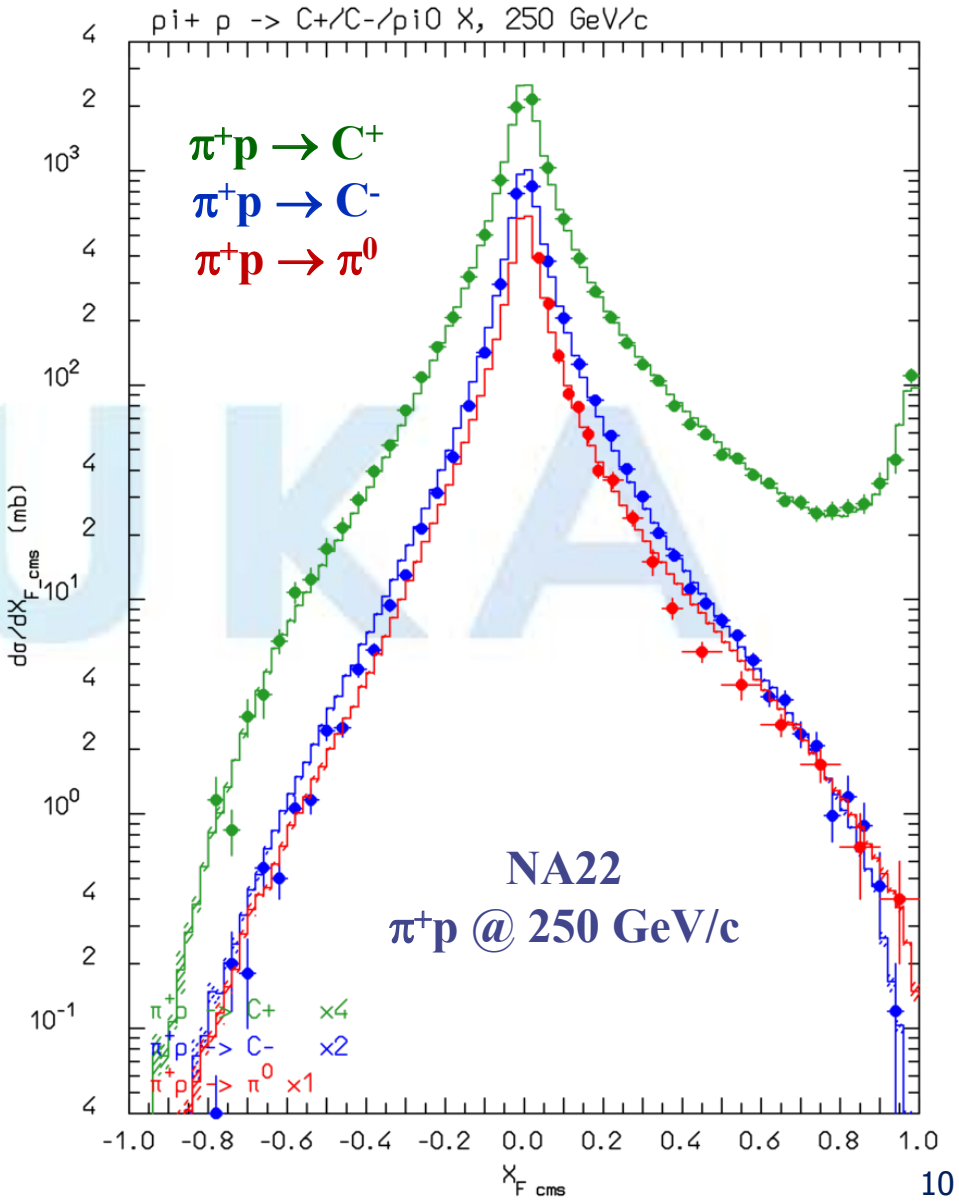
New hadronization: inclusive distributions



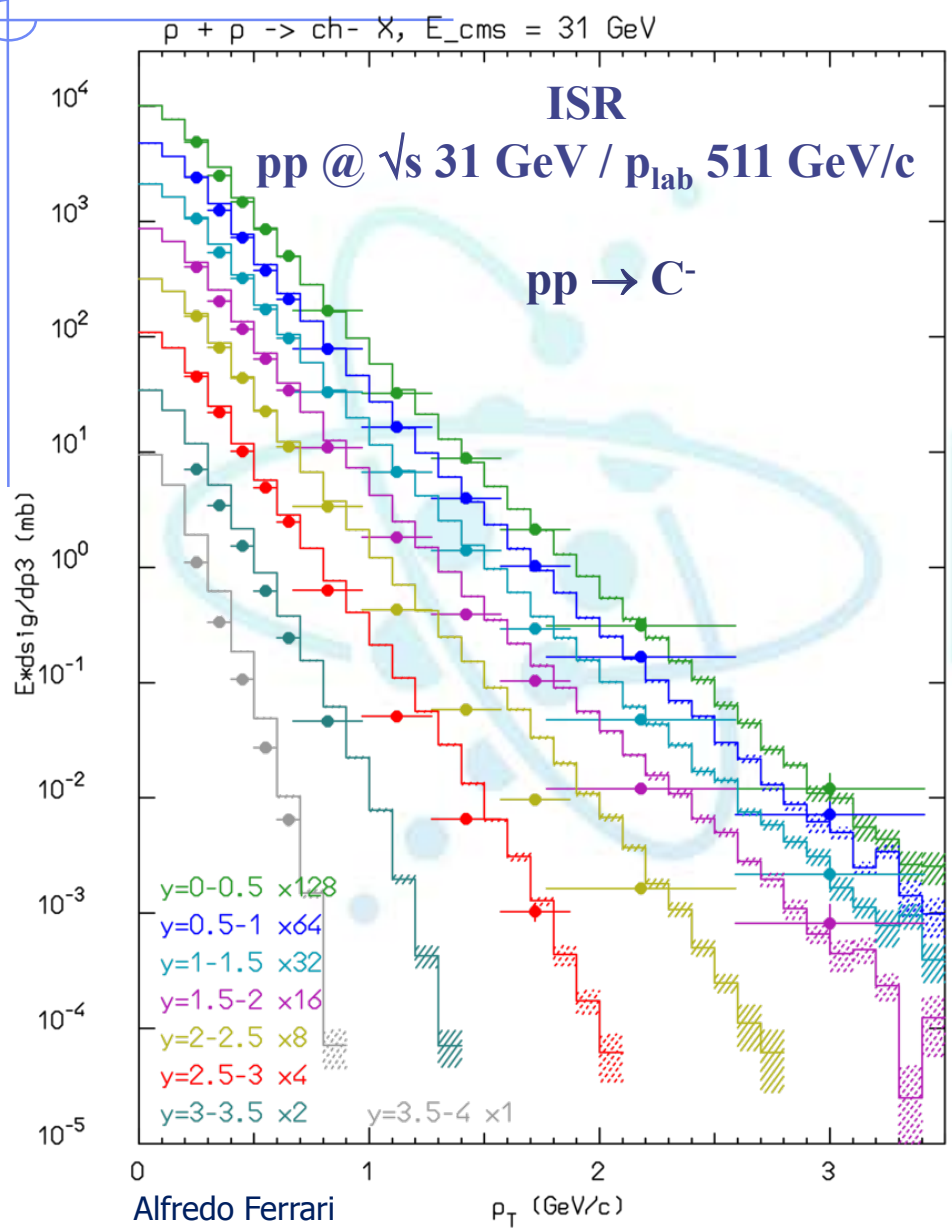
← dσ/dx$_F$ →

NEW

OLD



Inclusive distributions at higher (ISR) energies

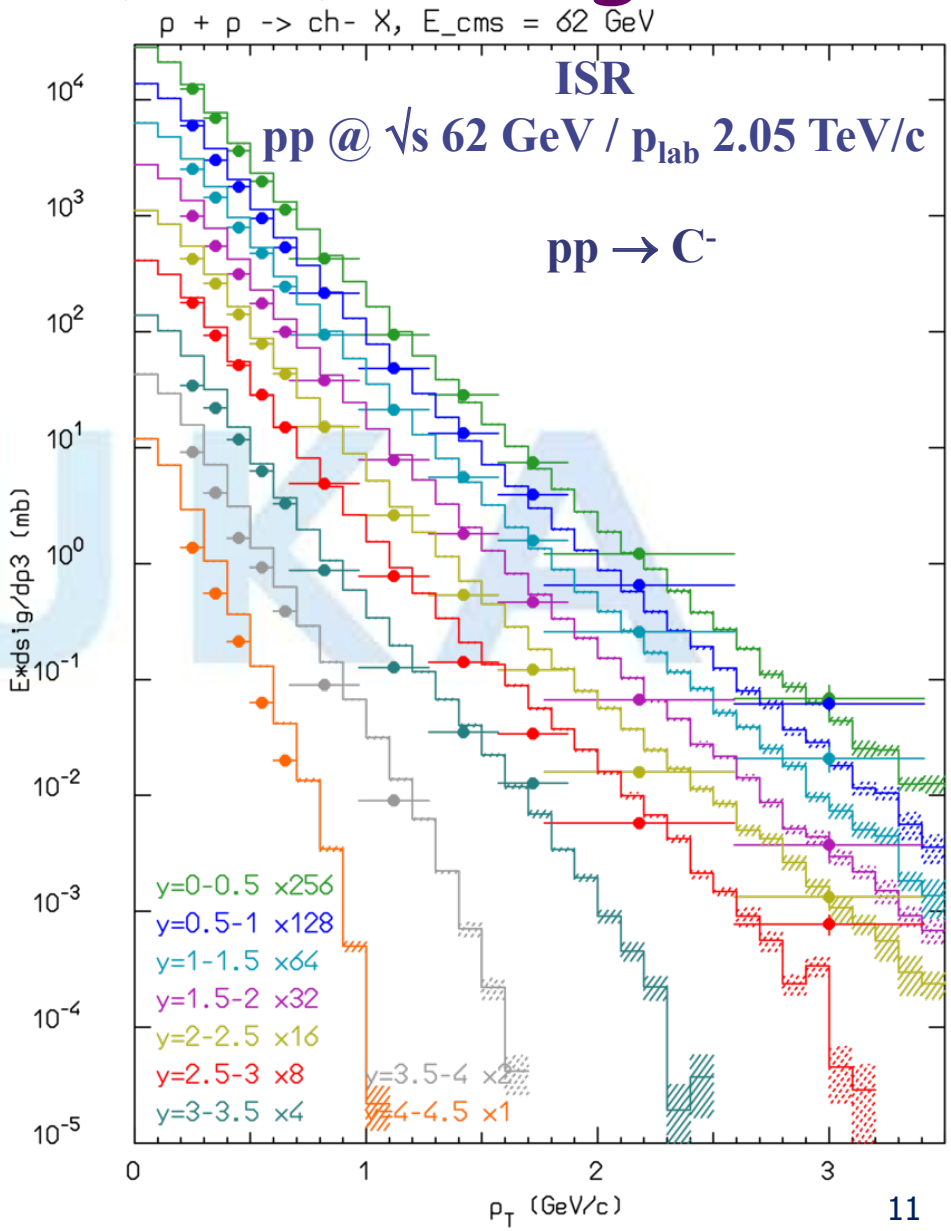


←Ed³σ/dp³ →

√s 62 GeV

√s 31 GeV

FLUKA (Peanut) can be reliably used up to much higher energies than those used in Corsika7/8



Peanut based cross sections

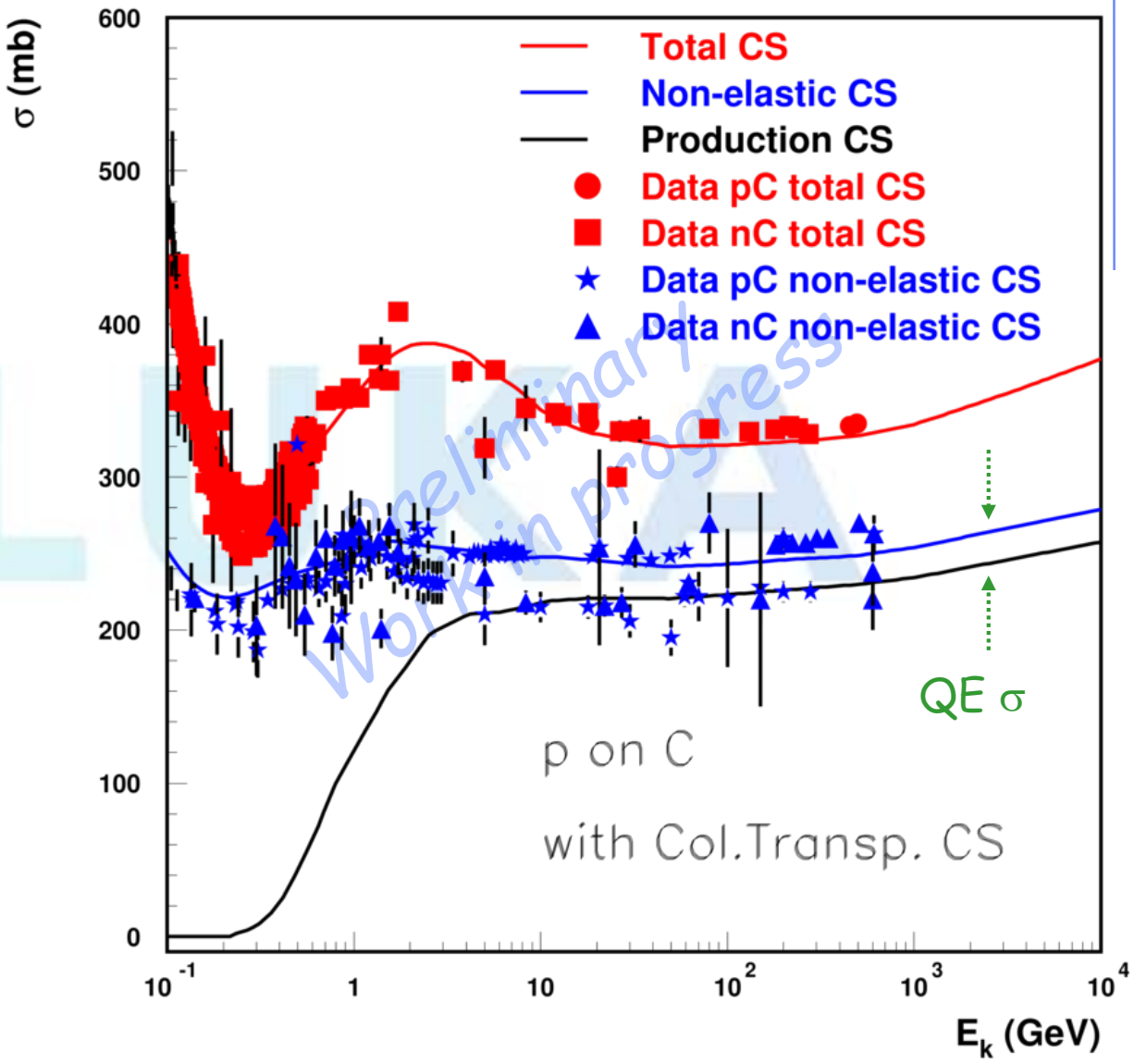
Glauber in Peanut: extended to highest energies for σ's

- Thanks to the inclusion of σ **fluctuations**, the **Fluka (Peanut) Glauber model** is now able to compute absorption and quasi-elastic **cross sections for all hadrons/targets up to UHECR energies**

Example: **proton Carbon** cross sections as computed with Peanut: **symbols**: exp. data, **lines** Fluka

- **Red: total**
- **Blue: non-elastic**
- **Black: absorption** aka particle production
- **Difference blue/black lines: quasi-elastic**

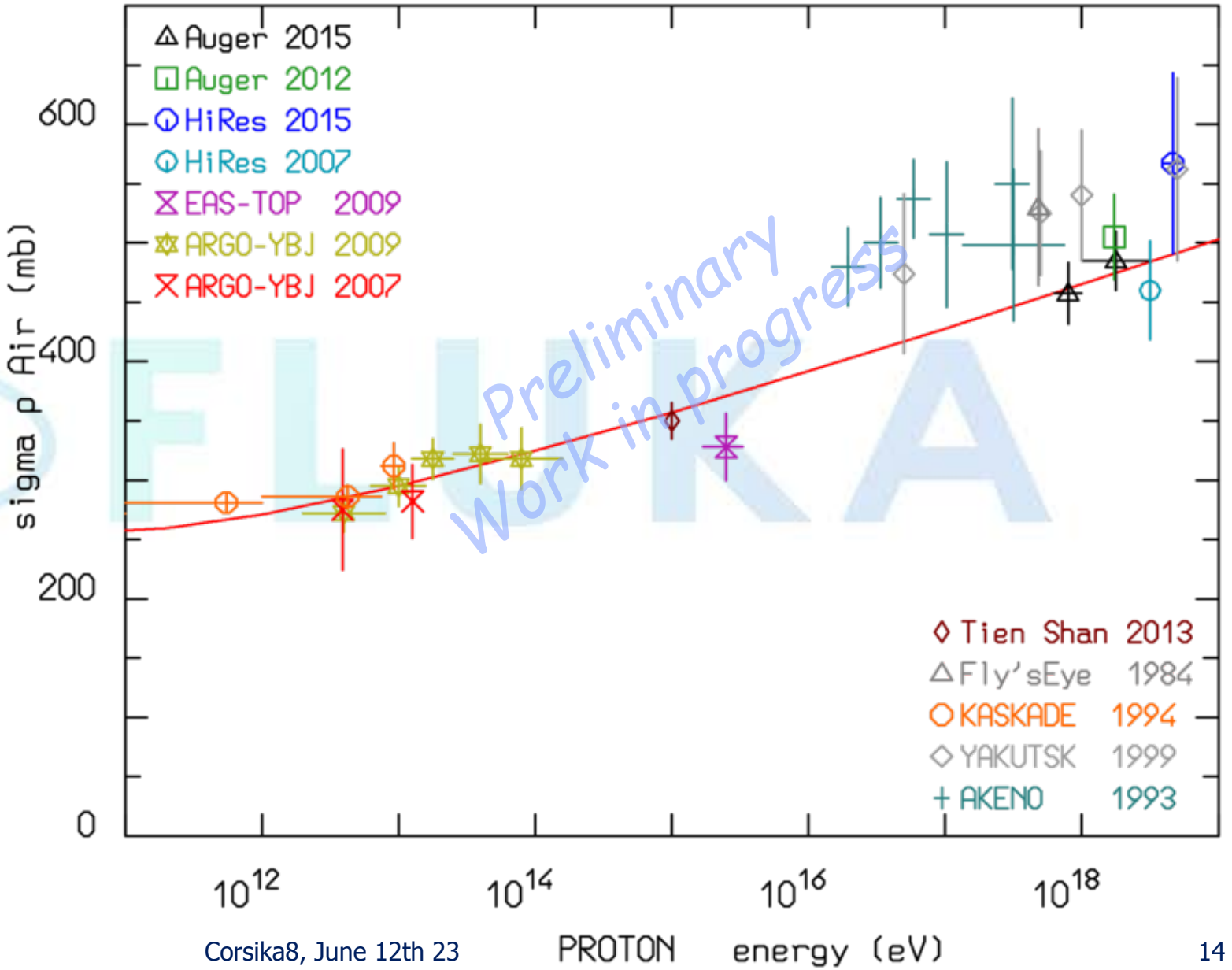
The **blue** experimental points are a mix of non-elastic and absorption measurements (often not specified in the exp. papers), depending whether quasi-elastic is included in the measurements or not



It works up to UHE !

On the right the FLUKA (Peanut) computed **cross sections** for the **proton Air** "particle production" cross section are compared with (indirect) experimental data from CR experiments up to 10^{19} eV. The agreement is particularly good with the most recent measurements.

*In Fluka2023.x Peanut computed **QE** and **particle production cross sections** for all hA combinations are the **default***



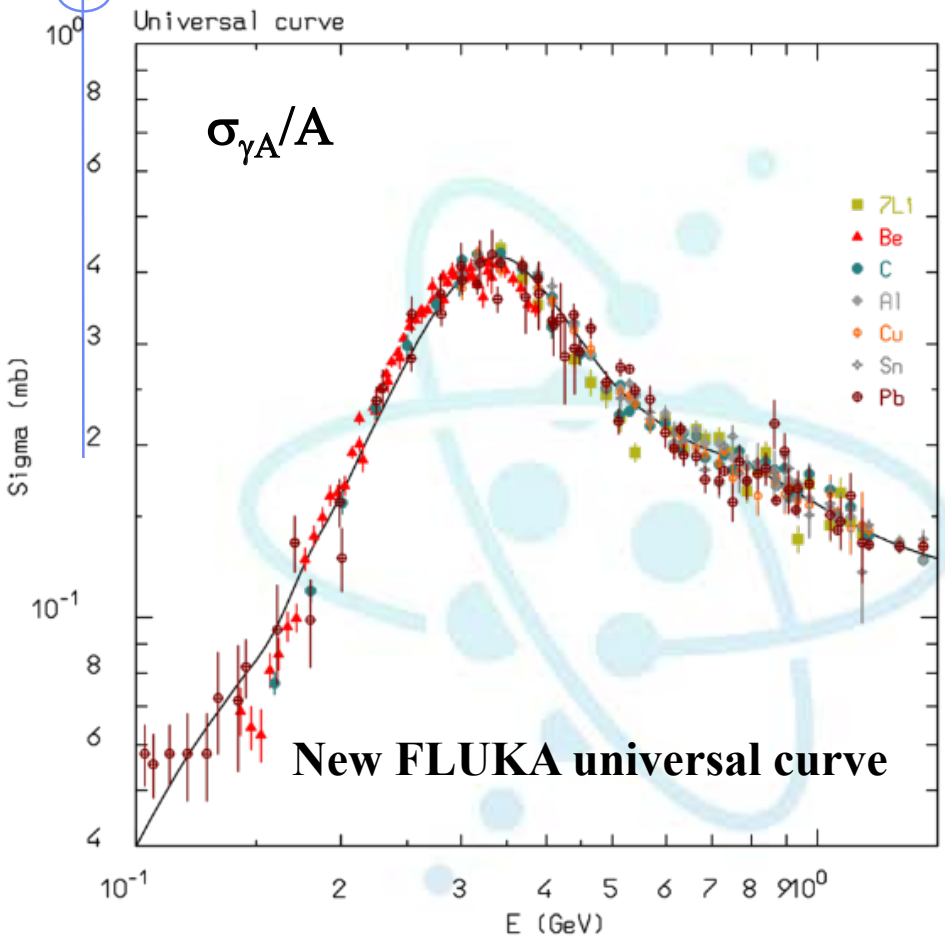
Photonuclear reactions

Photonuclear reactions: deeply improved!

Up to Fluka2021.x:

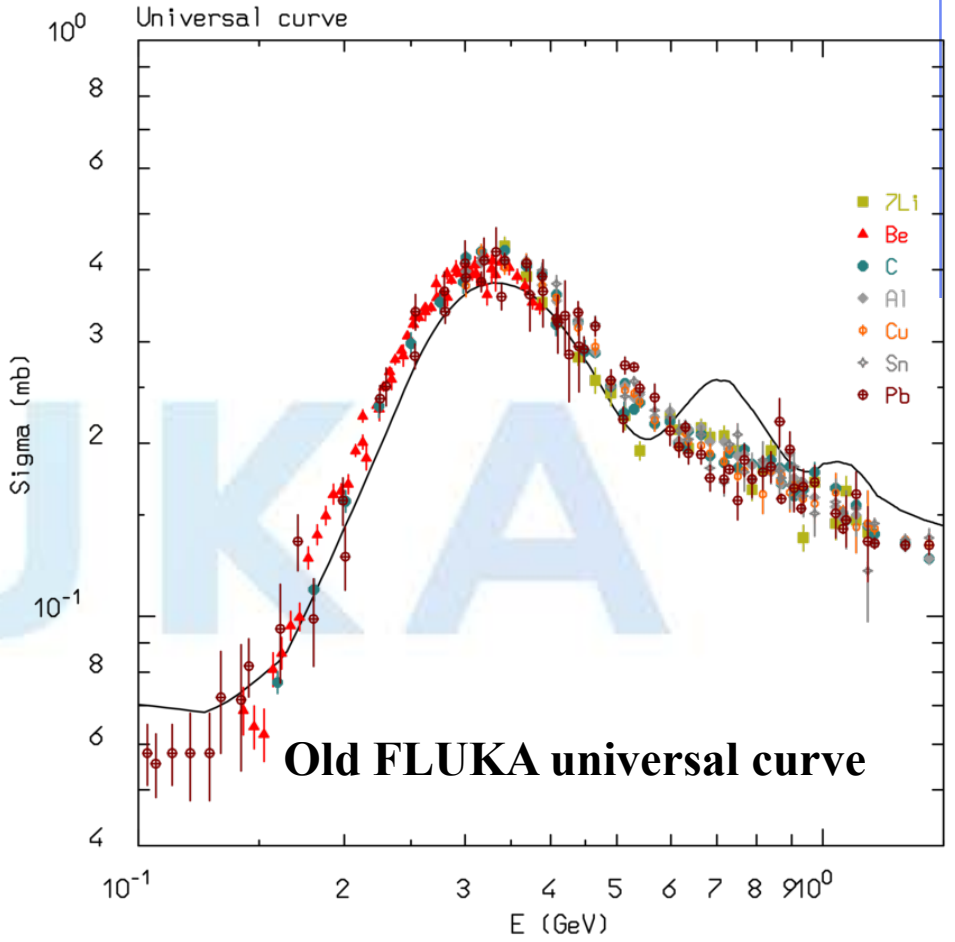
- Real and virtual photonuclear reactions in the Δ region and up to ~ 3 GeV were performed flipping a $\gamma \rightarrow \pi^0$ (still conserving energy and momentum) and using Peanut:
  - … however photons behave somewhat differently, and in particular their couplings to Δ's are not subject to isospin rules, contrary to pions;
  - … also the in-medium nuclear effects for $\gamma\, N \rightarrow \Delta$ (including 2 and 3 nucleon absorption) are not the same as for pions;
  - … last but not least, photons at these energies mostly probe the nucleus volume, rather than the nucleus surface like pions.
- γN and γA in the Δ region and above were based on old parameterizations, while most accurate data are now available
- Above ~ 2-3 GeV, reactions assume $\gamma \rightarrow \rho^0\, \omega\, \Phi$, (virtual vector mesons, according to VMD), and up to now the interactions were performed using the old high energy model, which lacks all sophisticated nuclear physics of Peanut;

Fluka2023.x: γA, Δ region and just above



Above the pion threshold, and up to ~2 GeV for nuclei with $A > 4$, $\sigma_{\gamma A}$ scales with A (see plot on ← the left). The new "universal" curve is shown in black.

On the right → the same experimental data are shown with the "old" curve used up to Fluka2022 included.

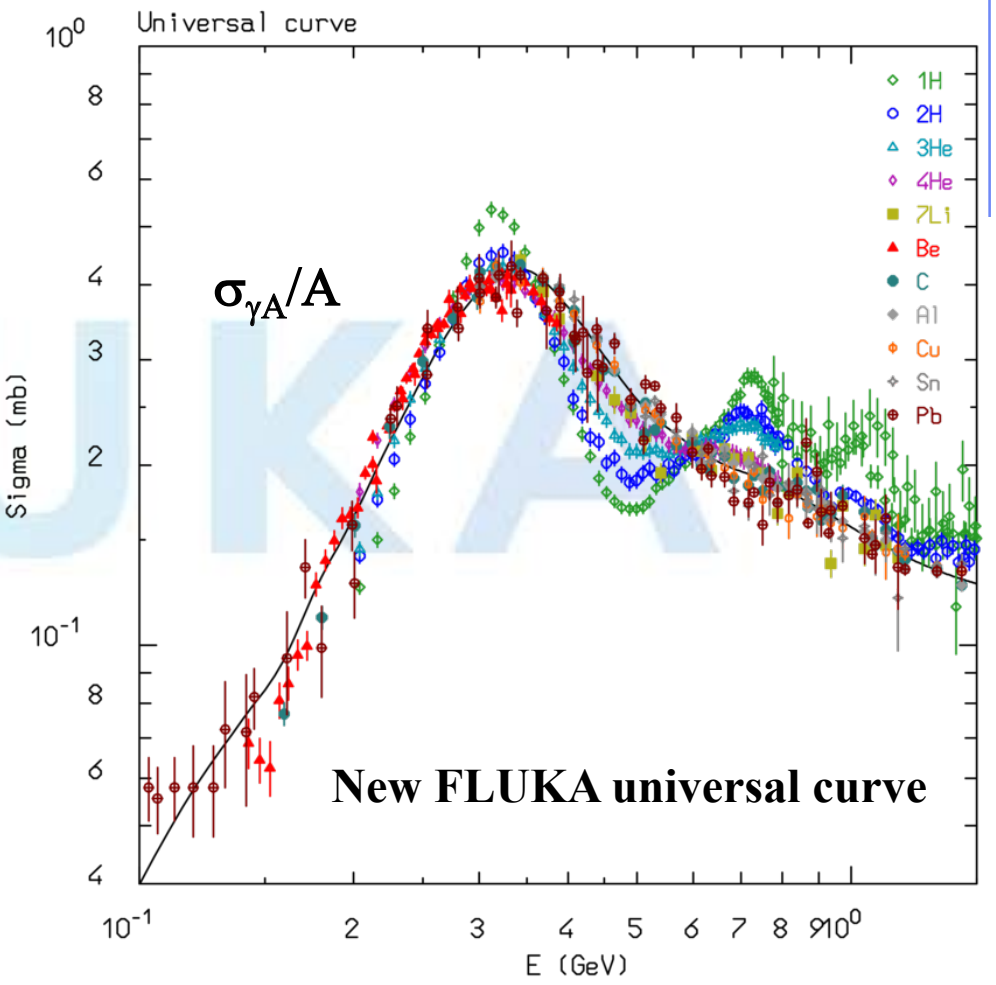


Fluka2023.x: γA, Δ region and just above

Now, γA interactions for A>4, and in this energy range are simulated with Peanut as such (no longer as pseudo-π^0), by:

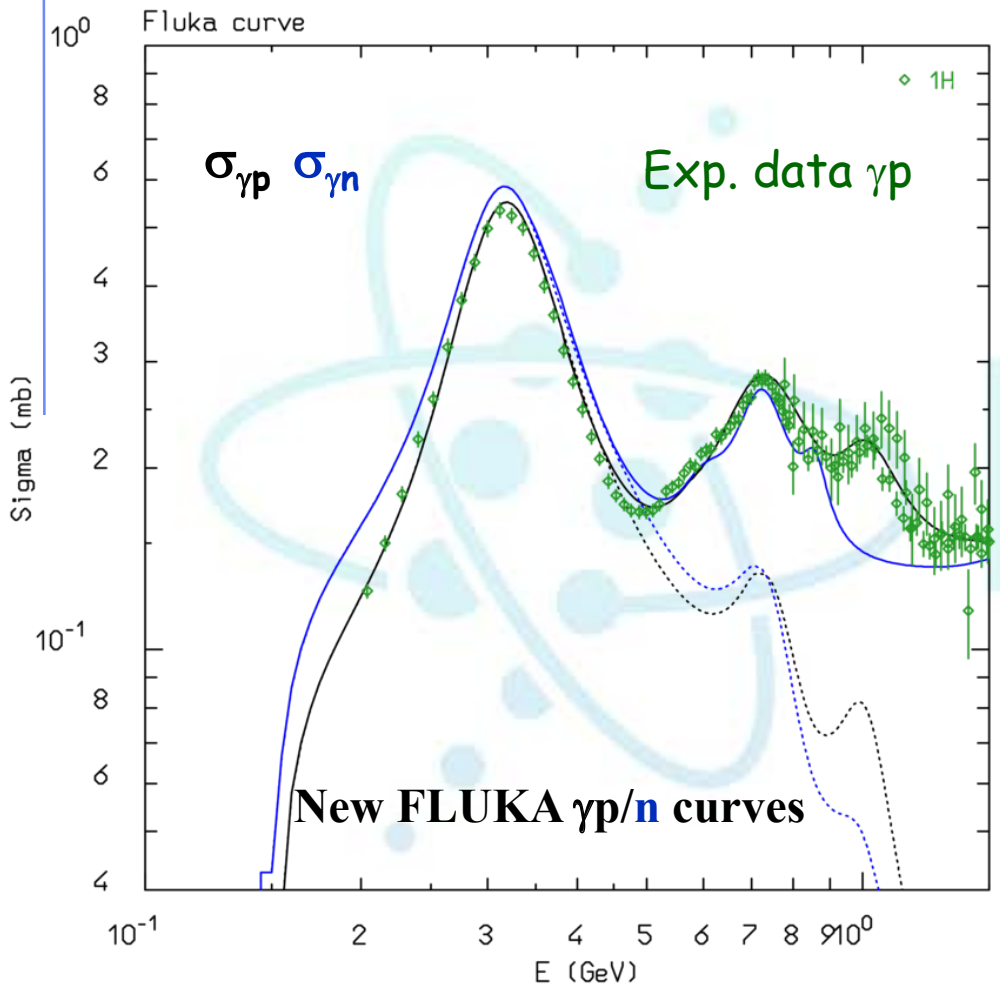
- properly choosing the initial target nucleon from the nuclear volume;
- using new parametrizations for the γN cross sections (see next slides);
- accounting for the in-medium broadening of the intermediate Δ and the resulting 2 and 3-nucleon absorption according to the Oset formalism;
- using MAID07* data for the single pion cross section and angular distributions (available up to Eγ ~1.25 GeV);
- Using resonant and non resonant channels to model multi-pion and strangeness production up to ~2-3 GeV

The universal curve does not apply to very light nuclei, as can be seen by the ^{1}H, ^{2}H, ^{3}He, and ^{4}He exp. points on the right plot → ^{1}H comes from free from the work above, for the others ad-hoc σ's are going to be implemented *(already done for ^{2}H, work in progress)*



* https://maid.kph.uni-mainz.de/maid2007

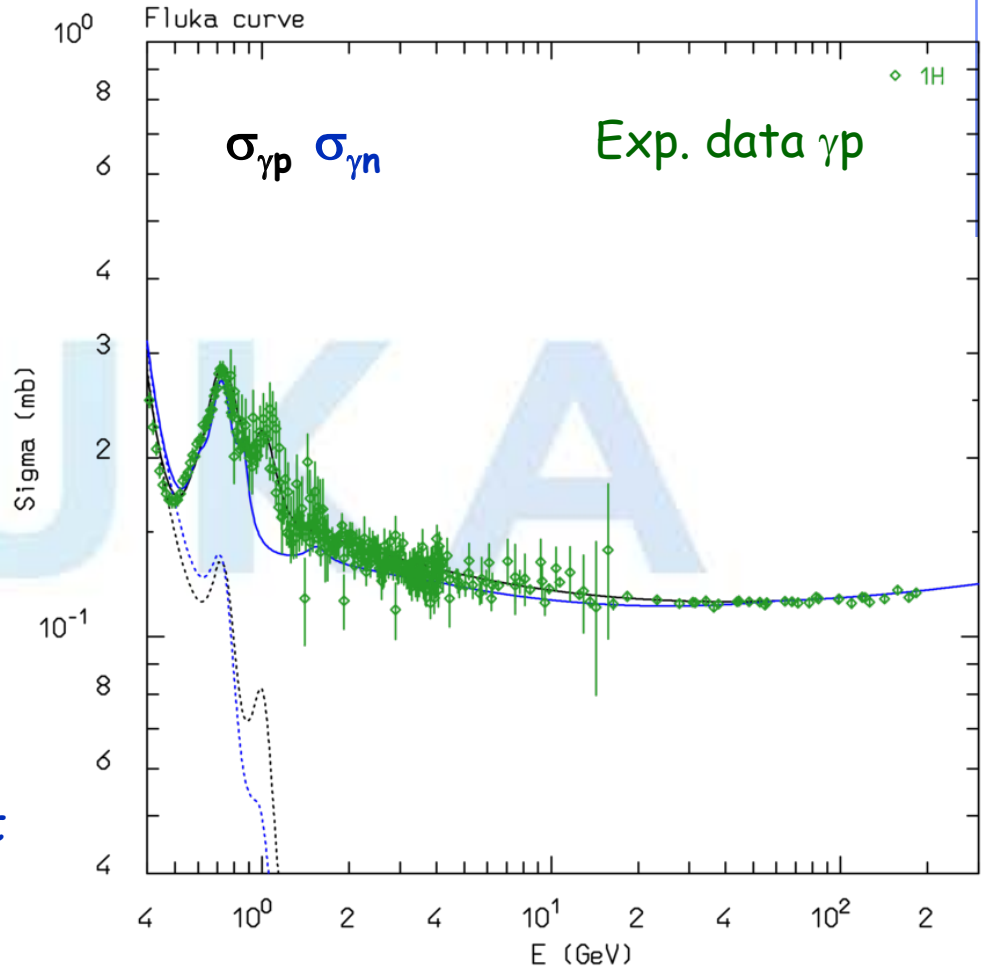
Fluka2023.x: γ p/n, Δ region and above



New γp/n cross sections:

- continuous lines, in **black** $\sigma_{\gamma p}$, in **blue** $\sigma_{\gamma n}$
- dotted lines, 1 pion cross section as obtained from MAID07
- **green** symbols, $\sigma_{\gamma p}$ exp. data

Note the different γ coupling with p/n and resonances



Fluka2023.x: γN above Δ, until a few GeV

- The γN cross section is known to be partially due to resonant intermediate states (γN → Δ*(x) or N*(x) → decay products) and to a non resonant background which rapidly becomes dominant above the Δ region
- The resonances included (following PRC54, 1688) are: Δ(1232), N*(1440), N*(1520), N*(1535), N*(1680), Δ(1950);
- For the non resonant part, the following channels are included with educated guesses based on available exp. data: γN→ηN, γN→ρN, γN→ωN, γN→ΦN, γN→KΛ, γN→K $\bar{K}$N
- The previous channels don't exhaust the non resonant cross section. The rest is split among the following channels, with weights set ad hoc to reproduce multipion production data: γN→πN*(1440), γN→σΔ(1232), γN→ρΔ(1232), γN→σN*(1440), γN→ρN*(1440)

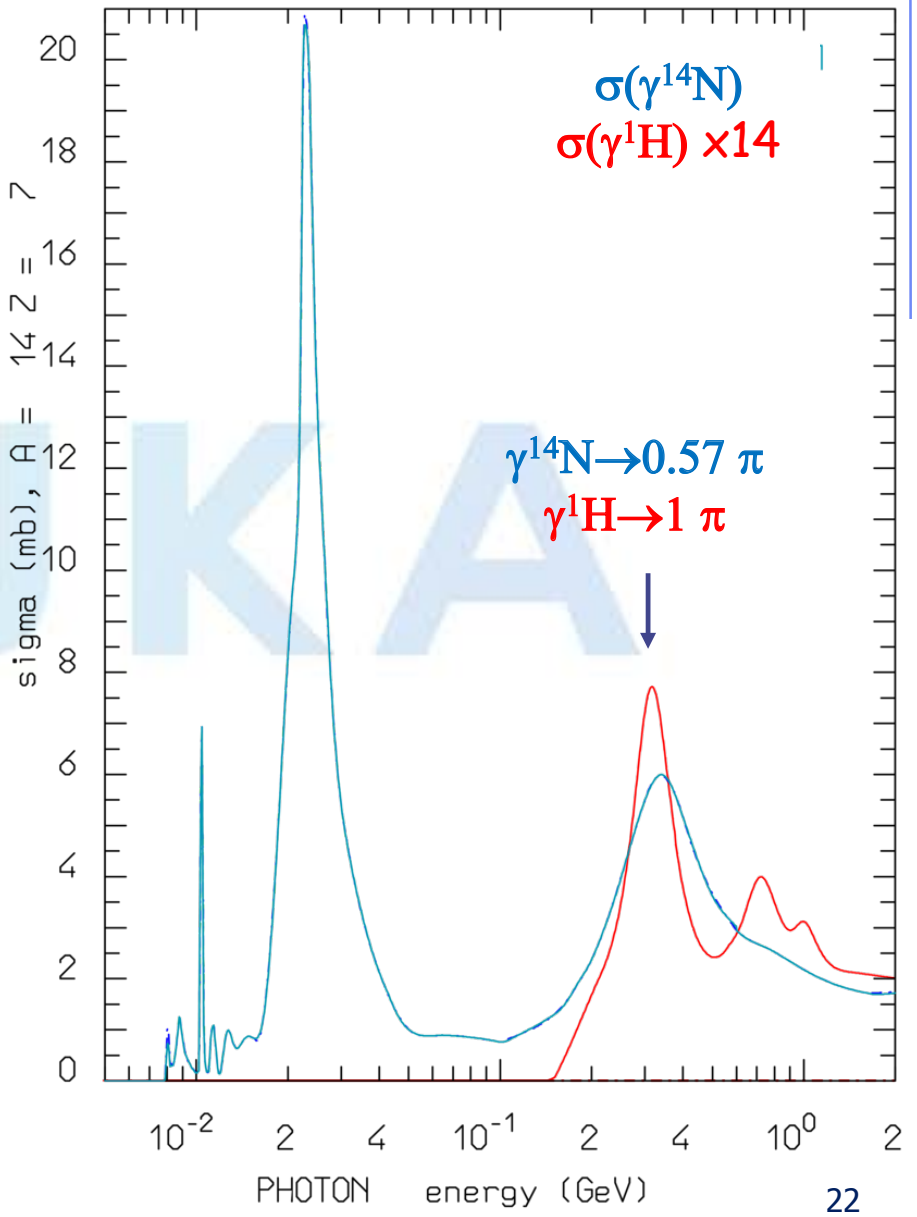
Fluka2023.x: γN,A, above 2-3 GeV

Now, γN,A interactions at higher energies are described with Peanut and no longer with the old interaction model which will be deleted in the next official release.
The procedure is the following:

- The photon is supposed to **fluctuate into a vector meson**, ρ^0, ω, Φ, with probability according to the experimental relative coupling (same as in the past);
- … then the selection is made between a **(~point-like) photon interaction** (a volume one **with no shadowing**), and a **vector-meson nucleus like** one with shadowing.
- … if the interaction is not a point-like one, it is selected whether the interaction proceeds through a **diffractive-like coherent pseudo-elastic scattering** $\gamma \rightarrow \rho^0 \rightarrow \rho^0 + A \rightarrow \rho^0 A$, or through a **non elastic vector meson nucleus one** (the latter including the **pseudo-quasielastic** $\gamma \rightarrow \rho^0 \rightarrow \rho^0 + A \rightarrow \rho^0 A^*$**)**
- … if the interaction is a point-like one, or a VMD non-elastic one, the **vector meson** is used as **projectile in Peanut**, in the former case with a volume selection of the target nucleon, in the latter with a hadron like (Glauber) interaction;
- Peanut can now deal with vector meson projectiles and their (re)interaction and decay inside the nucleus;
- All this machinery is applied to real as well as virtual photon interactions.

Relevance of photonuclear interactions for Corsika

- Real and virtual (electro-/muon-photonuclear and EMD) photonuclear interactions represent a major source of "interesting" particles in CR showers
- For example, for **5.6 10^{18} eV protons**, vertical incidence, at 878 g/cm^2 depth:
  - ~ **20%** of the **muons** come from real or virtual photonuclear interactions;
  - … and ~1/4 of these muons (~ **5 %** of the total) originate from ***muon photonuclear*** interactions;
  - ~ **70%** of the **neutrons** come from real or virtual photonuclear interactions;
  - … and 1/7 of these neutrons (**~ 10%** of the total) originate from ***muon photonuclear*** interactions.



Interface with UHECR generators

New (FLUKA) interface to high energy generators

- Completely new interface for calling very high energy generators within FLUKA

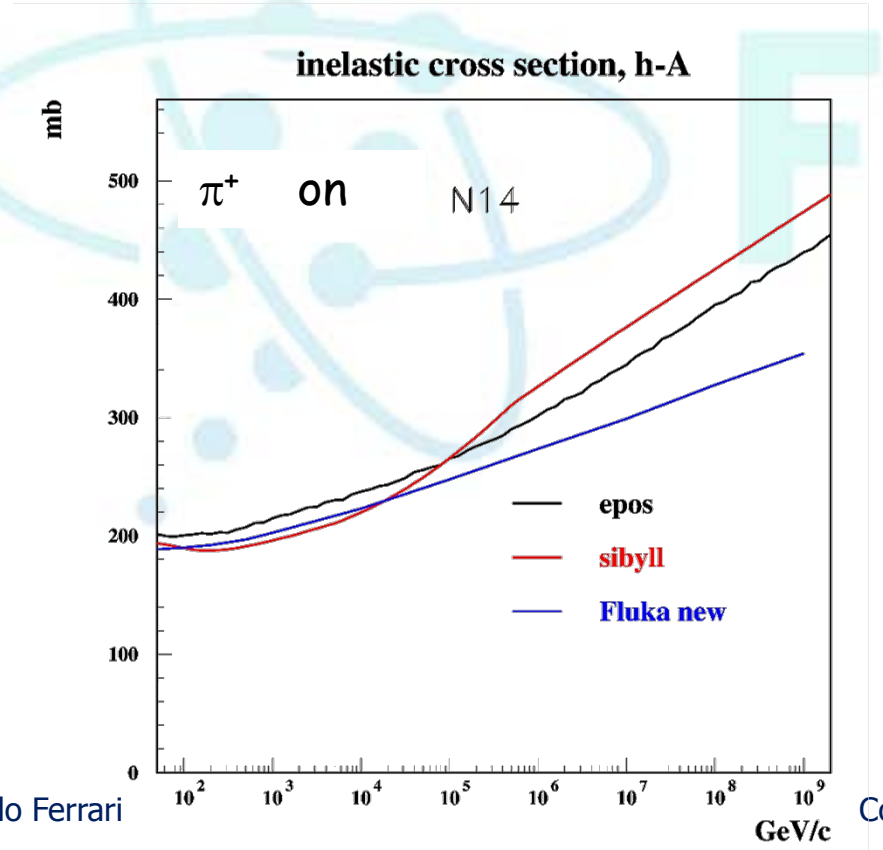
- EPOS (T.Pierog, K.Werner, Nucl.Phys.Proc.Suppl. 196:102-105, 2009)
- SIBYLL (E-J Ahn et al, Phys.Rev.D80:094003,2009)
- QGSJET (S.Ostapchenko, Phys.Rev. D83 (2011) 014018)
- **Exploiting the existing CRMC environment** (CRMC: R. Ulrich, T.Pierog, C. Baus. (2021) https://doi.org/10.5281/zenodo.4558705)
- (DPMJET-3 is natively interfaced with FLUKA)

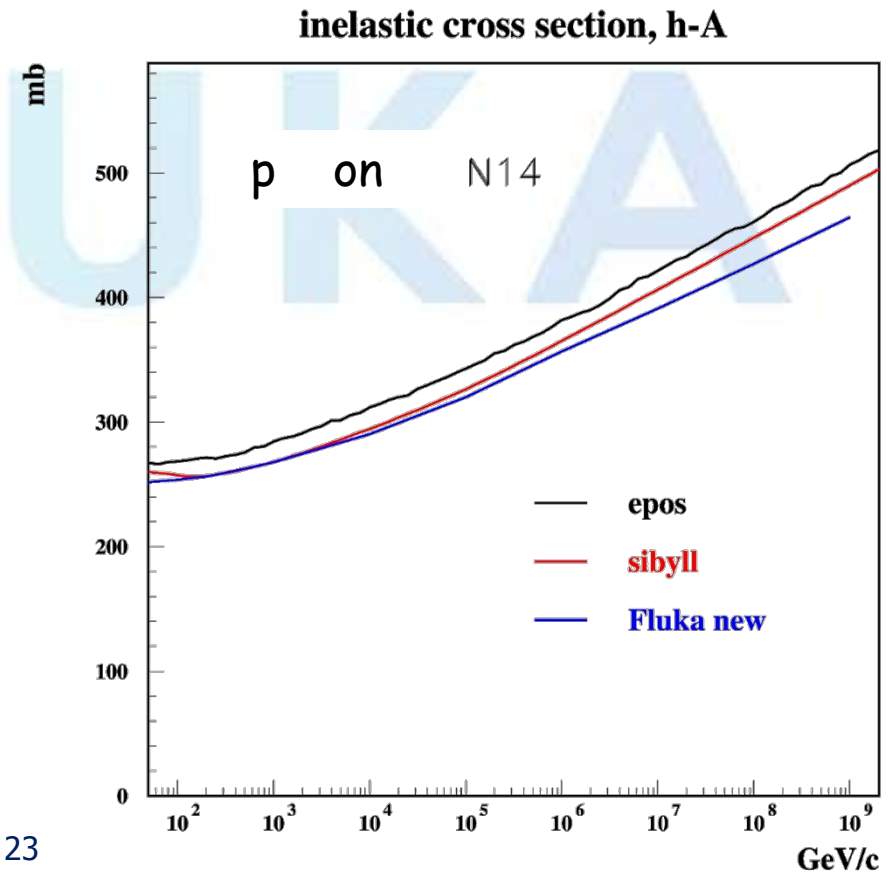
- Clear advantage for FLUKA: expand the energy range
- Goal for the CORSIKA interface: explore the effects of FLUKA physics processes on the development of atmospheric showers within the FLUKA environment in view of deciding whether to include them or not in the CORSIKA interface

Status of the UHE generators coupling:

Work in progress:

- Call to event generator, lab/cms transformations, partial recovery of energy non conservation
- Possibility to run with FLUKA native cross sections or with EPOS/SIBYLL cross-sections
- Debugging and simple exercises ongoing

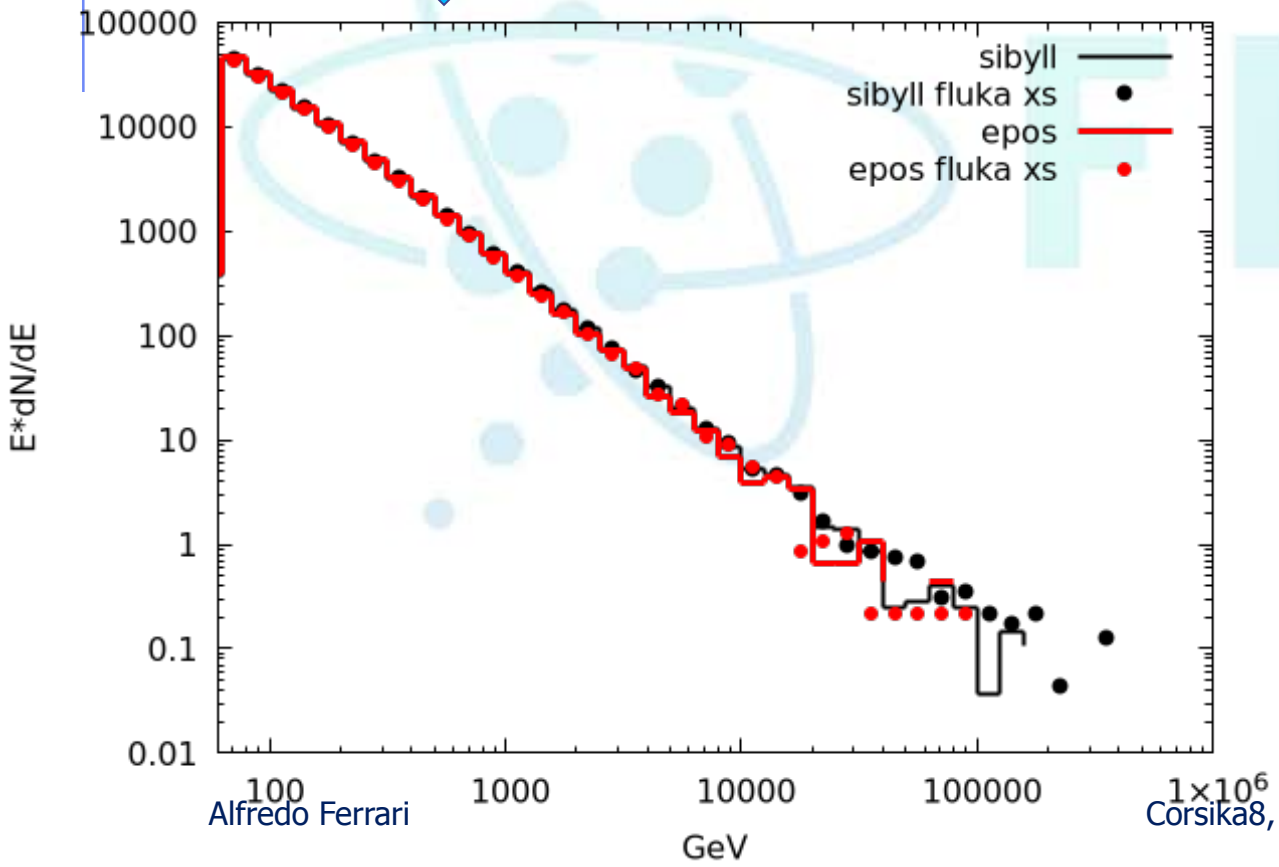




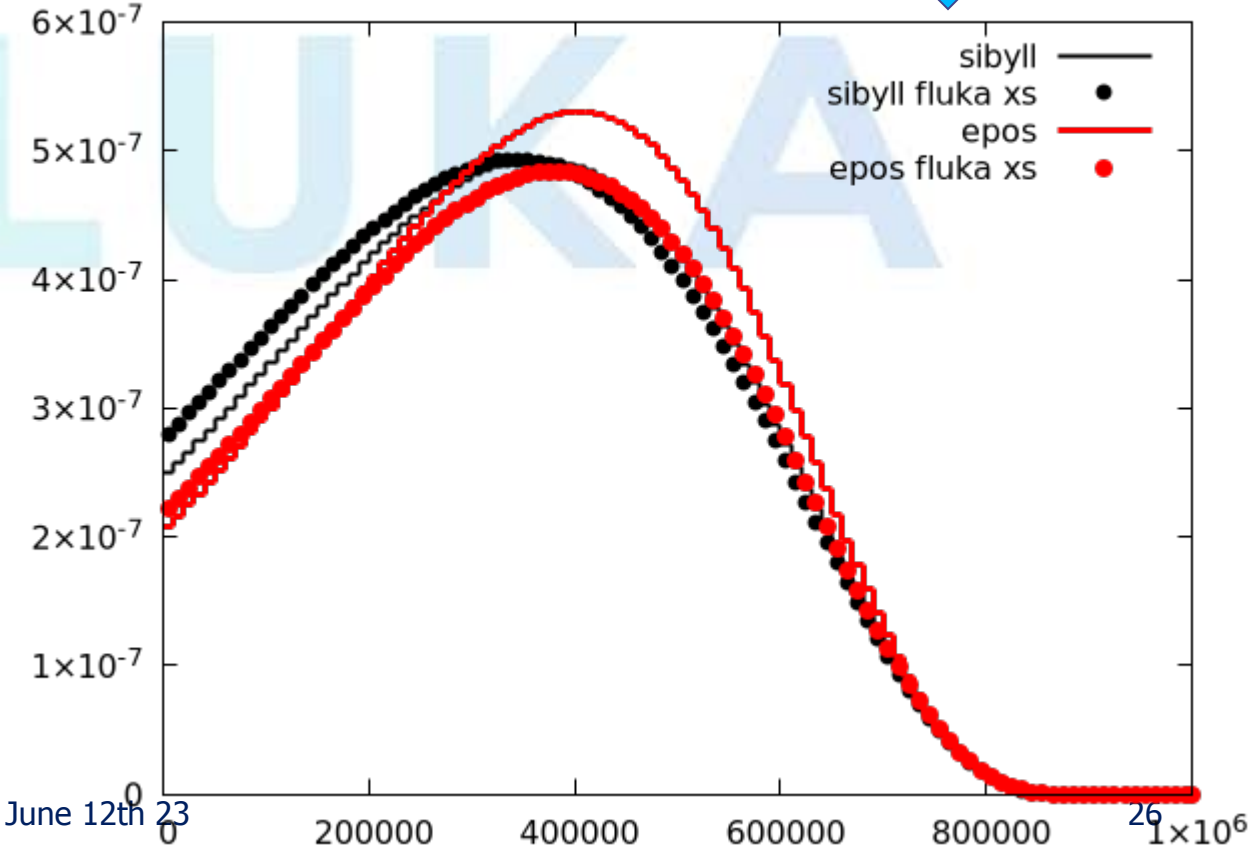
1st test

- Flat uniform atmosphere
  - 8.7 km
  - Density $1.x10^{-3}$
- Protons at 10^9 GeV vertical
- Injected at top of atmosphere
- Particles killed below 63 GeV

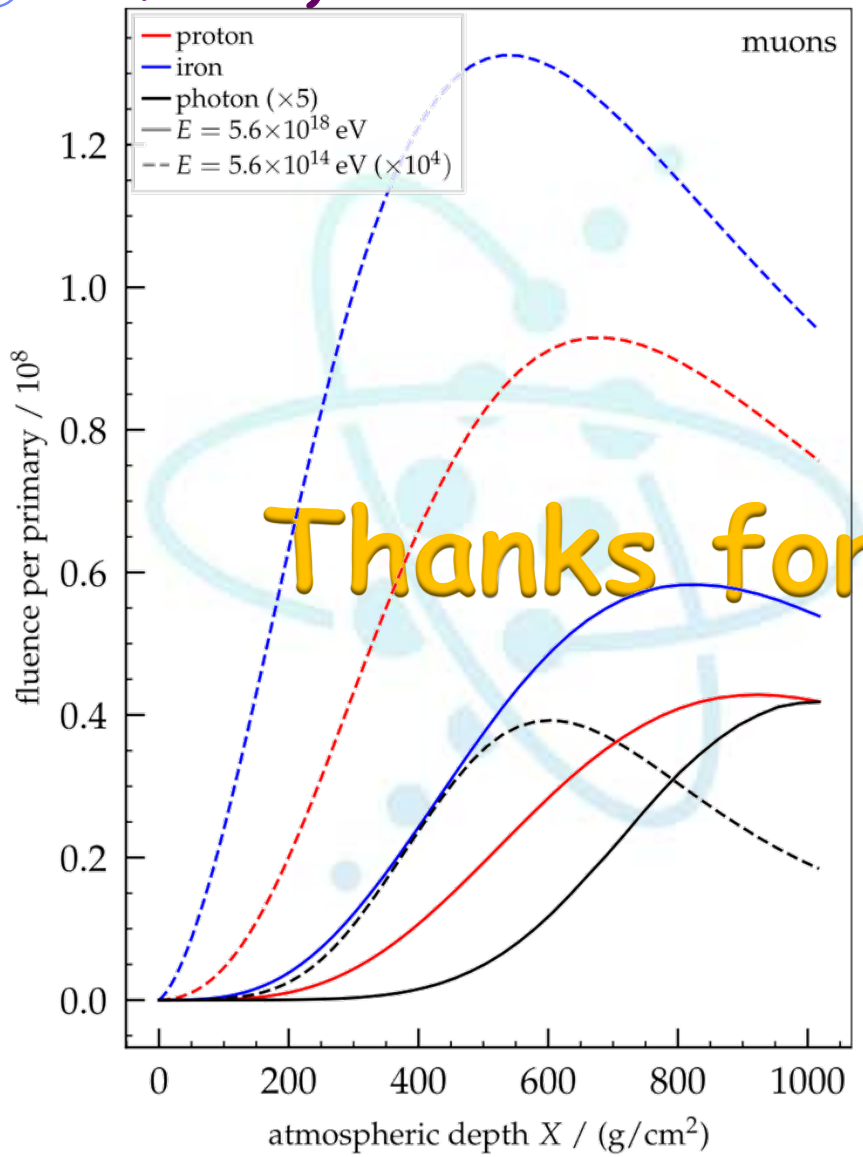
Positive muon spectra at ground, within 20km from axis

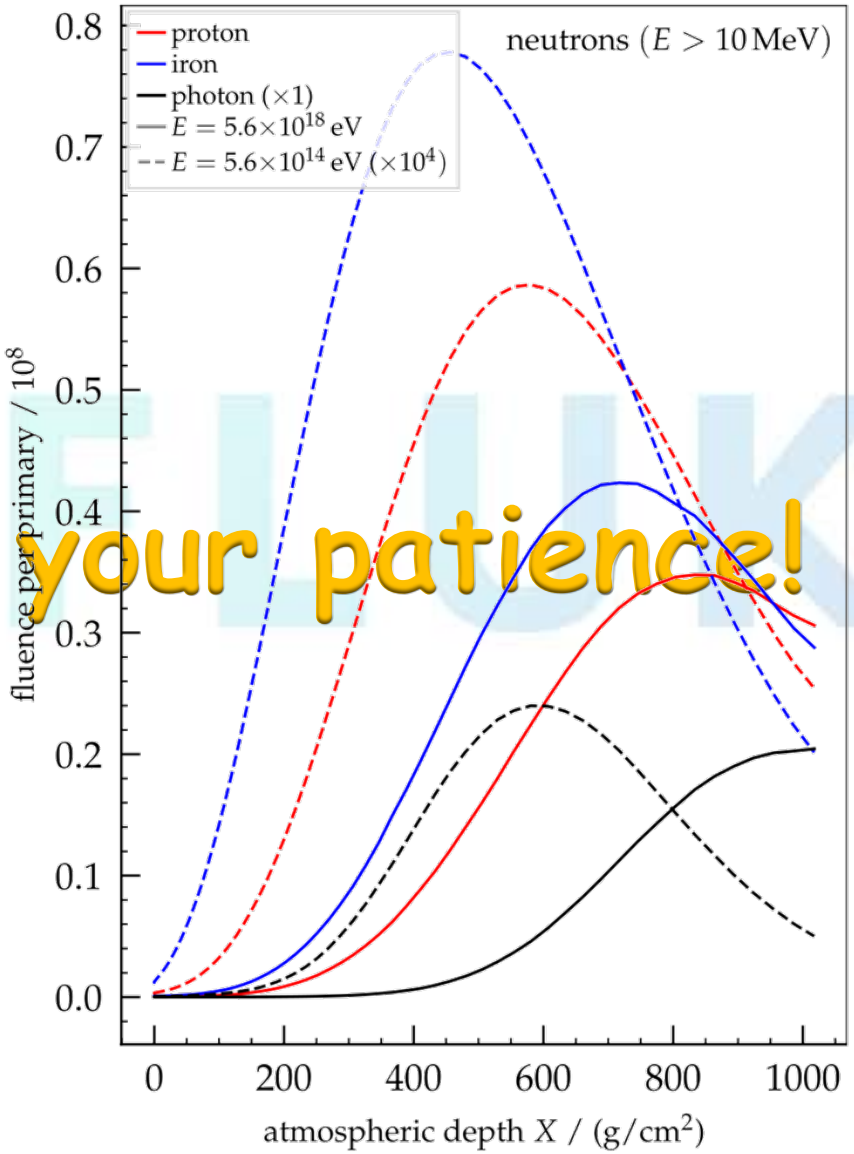


π^+ flux within 2km from shower axis as a function of height (cm, 0=ground)



The neutron component of UHECR (to be published, also ICRC by M. Schimassek)





Thanks for your patience!

Muon (left) and neutron (right) depth profiles for $5.6\cdot10^{14}$ (dashed) and $5.6\cdot10^{18}$ eV (solid) **p**, **^{56}Fe**, and γ showers