FLUKA

Cosmic ray physics

Hadron therapy

Space radiation

Accelerator design

Neutrino physics

Detector simulation

Shielding design

ADS systems, waste transmutation

Dosimetry and radioprotection

Radiation damage

Neutronics

http://www.fluka.org

Alfredo Ferrari
IAP & IBPT, KIT
for the FLUKA Collaboration

Fluka authors 1989-today:
A.Fassò, A.Ferrari, J.Ranft, P.R.Sala

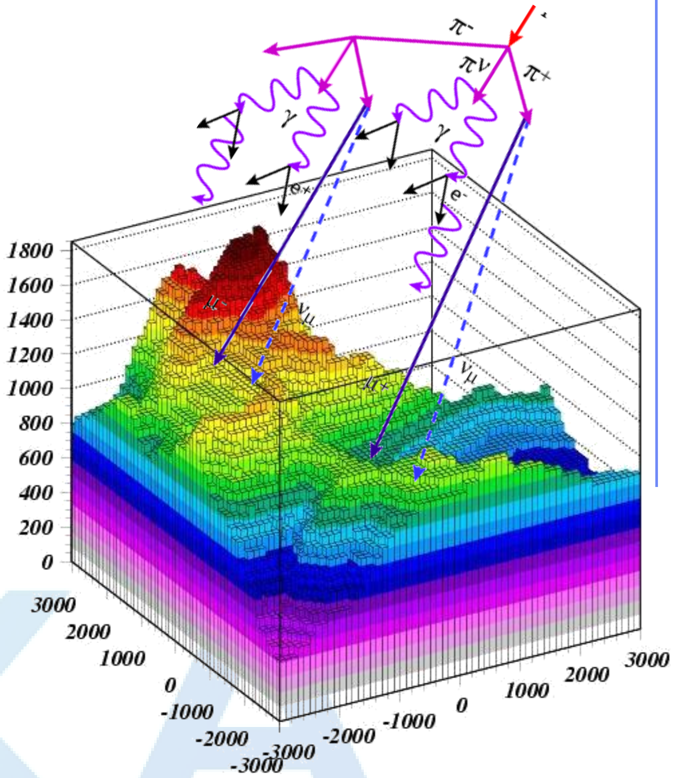
FLUKA is a general purpose tool for calculations of particle transport and interactions with matter

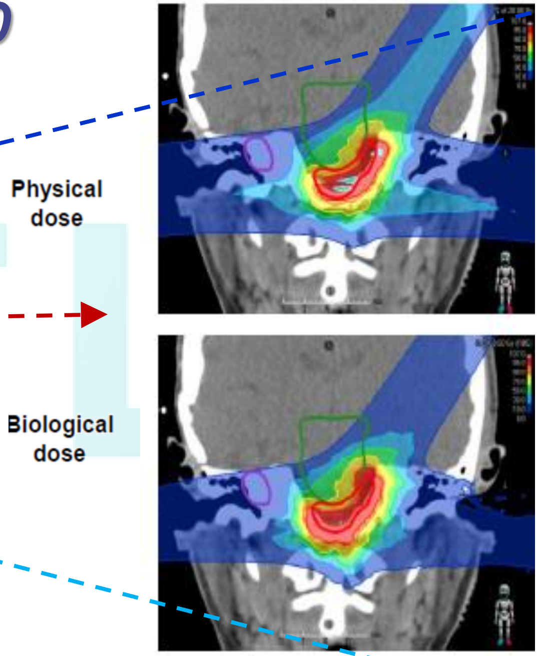
*Latest release: **FLUKA 2024.1.0***

http://www.fluka.org

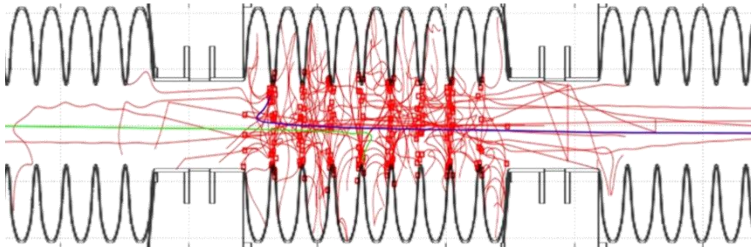
FLUKA Applications:

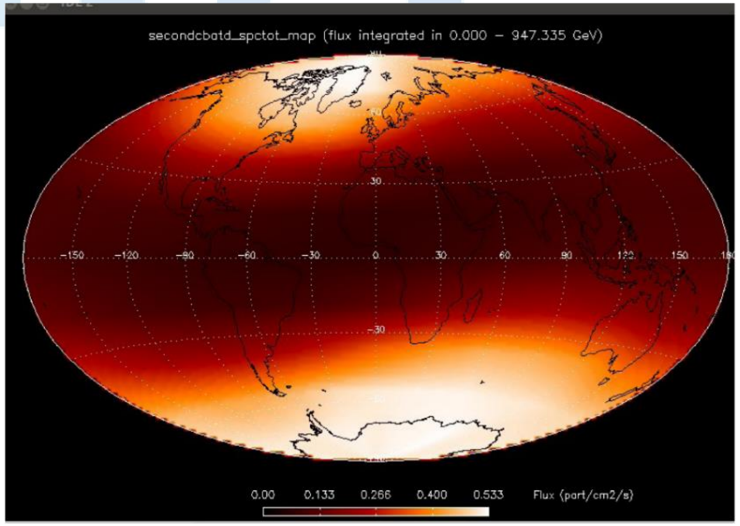
- **Cosmic ray physics** *Tested up 10 EeV*
- Hadron therapy
- Space radiation
- Accelerator design
- **Neutrino physics**
- Particle physics: calorimetry, tracking and detector simulation
- ADS systems, waste transmutation
- Shielding design
- Dosimetry and radioprotection
- Radiation damage
- **Neutronics**




Physical dose

Biological dose





Talk overview:

FLUKA hadronic models:
- Minimal introduction
- Recent developments
- What matters for neutrons

Real and virtual photon interactions:
- Cross sections
- Nuclear effects
- ElectroMagneticDissociation

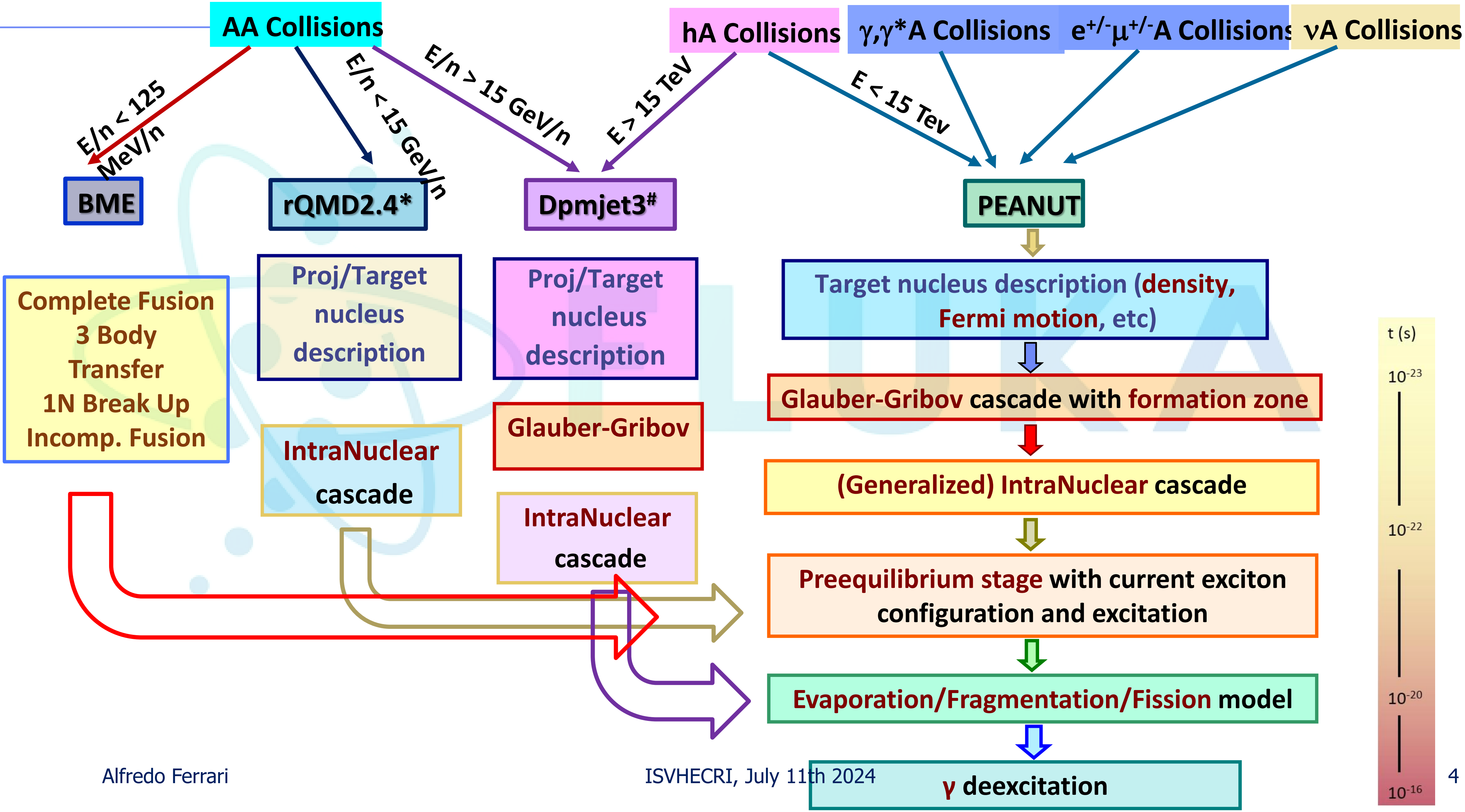
Muon propagation and interactions:
- Energy losses
- Photonuclear interactions

(Anti)neutrino interactions:
- Cross sections
- CNGS/Icarus/Lar

Relations with other codes:
- Interface with Corsika7/8
- Interface with Sibyll/EPOS

Only minimal details will be given for each topic, with some examples/benchmarking for each of them
Emphasis will be on what matters for reliable neutron predictions

FLUKA nuclear interaction models:



AA Collisions

E/n < 125 MeV/n

E/n < 15 GeV/n

E/n > 15 GeV/n

hA Collisions

E > 15 TeV

E < 15 Tev

γ,γ^*A Collisions

$e^{+/-}\mu^{+/-}$A Collisions

νA Collisions

BME

Complete Fusion
3 Body
Transfer
1N Break Up
Incomp. Fusion

rQMD2.4*

Proj/Target nucleus description

IntraNuclear cascade

Dpmjet3#

Proj/Target nucleus description

Glauber-Gribov

IntraNuclear cascade

PEANUT

Target nucleus description (density, Fermi motion, etc)

Glauber-Gribov cascade with formation zone

(Generalized) IntraNuclear cascade

Preequilibrium stage with current exciton configuration and excitation

Evaporation/Fragmentation/Fission model

γ deexcitation

t (s)

10^{-23}

10^{-22}

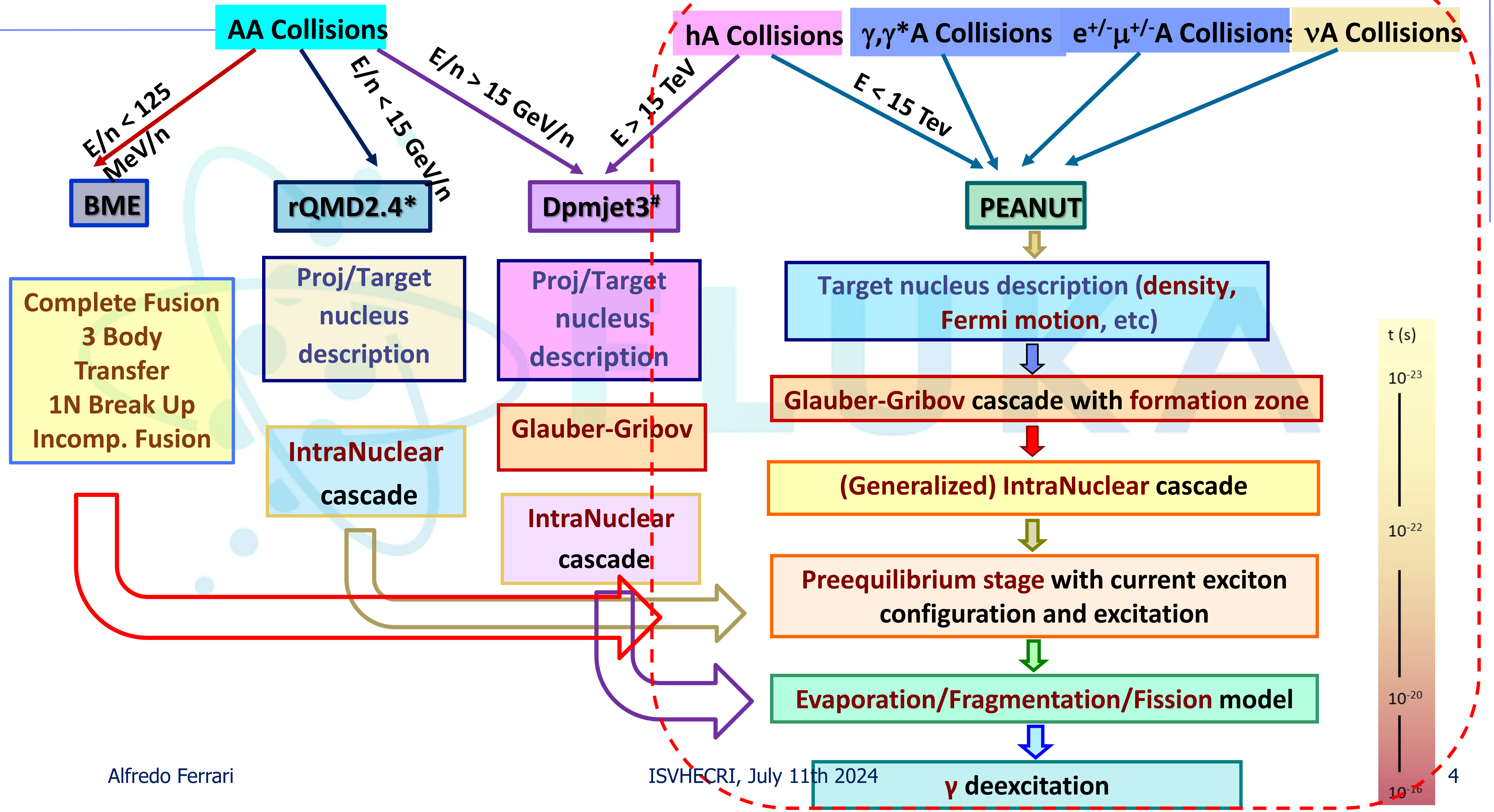
10^{-20}

10^{-16}

*AnnPhys192 266
ASR24 1302

#CERN-THESIS-2015-371
PRD54 4244

FLUKA nuclear interaction models:



AA Collisions

E/n < 125 MeV/n → **BME**

Complete Fusion
3 Body Transfer
1N Break Up
Incomp. Fusion

E/n < 15 GeV/n → **rQMD2.4***

Proj/Target nucleus description

IntraNuclear cascade

E/n > 15 GeV/n → **Dpmjet3#**

Proj/Target nucleus description

Glauber-Gribov

IntraNuclear cascade

hA Collisions | **γ,γ^*A Collisions** | **$e^{+/-}\mu^{+/-}$A Collisions** | **νA Collisions**

E > 15 TeV → **Dpmjet3#**

E < 15 Tev → **PEANUT**

Target nucleus description (density, Fermi motion, etc)

Glauber-Gribov cascade with formation zone

(Generalized) IntraNuclear cascade

Preequilibrium stage with current exciton configuration and excitation

Evaporation/Fragmentation/Fission model

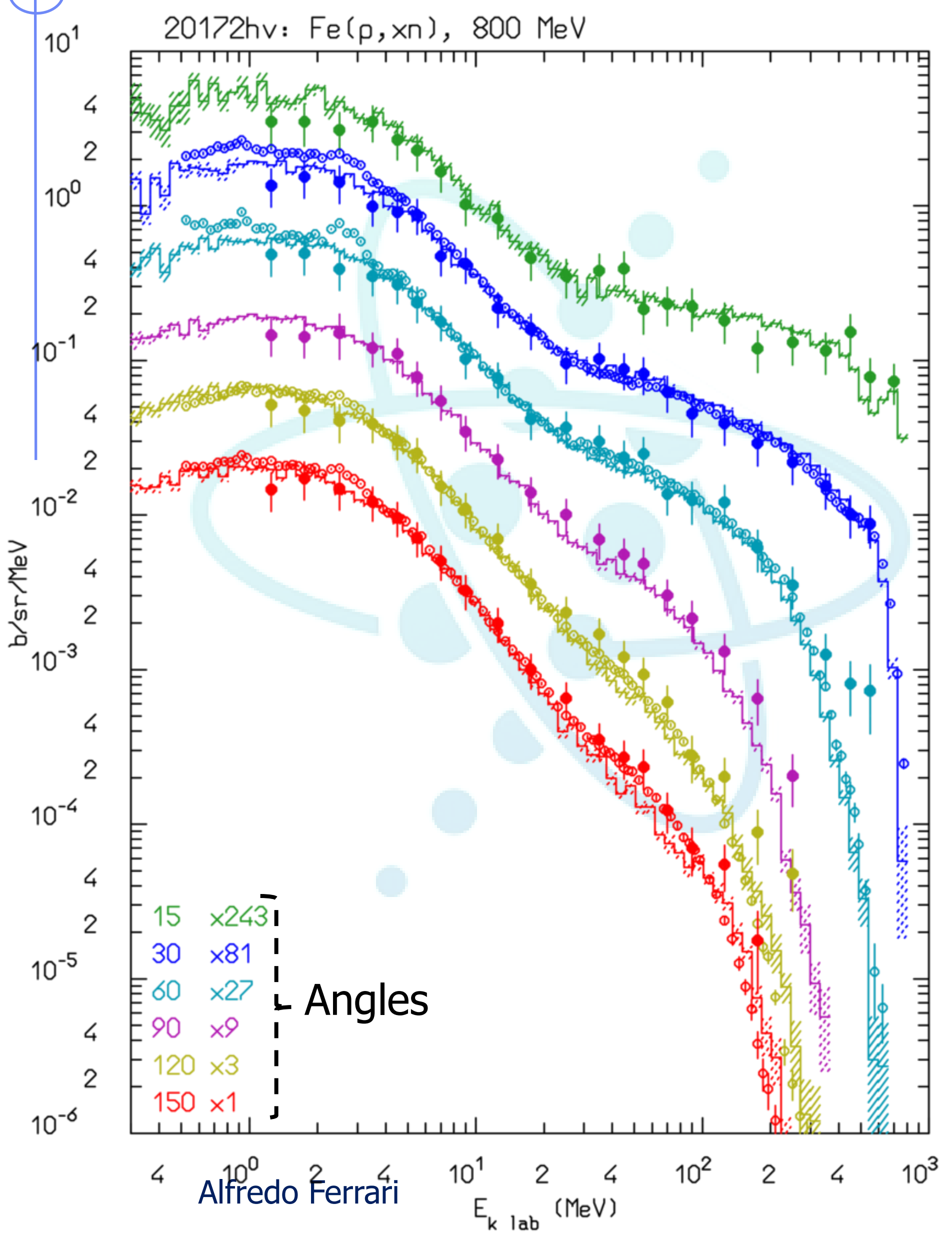
γ deexcitation

*AnnPhys192 266
ASR24 1302

#CERN-THESIS-2015-371
PRD54 4244

$(\gamma,\mu,\nu,e^{+/-})$ and hadron Nucleus interactions in PEANUT

Thin target examples: neutrons double differential production

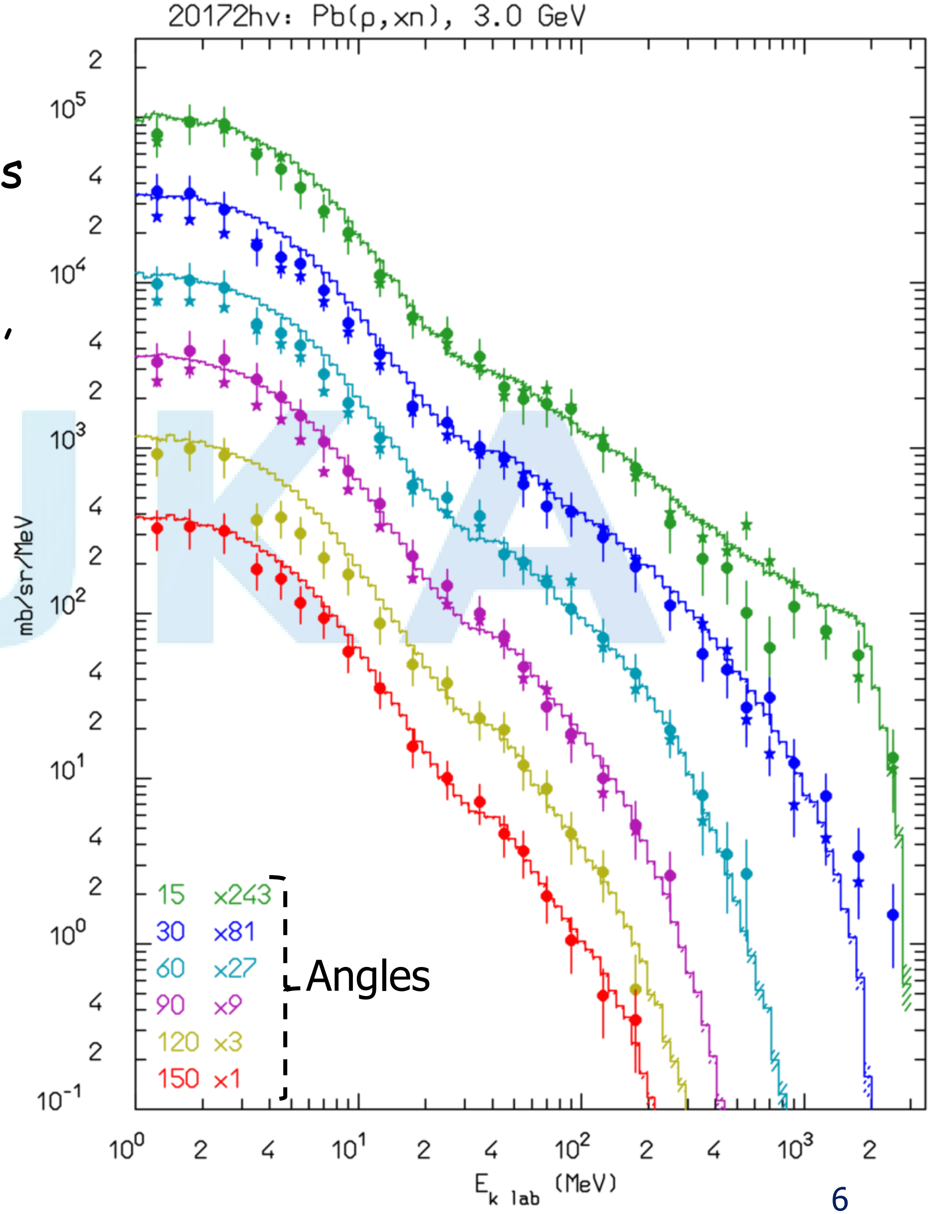


Symbols: exp data
Histos: FLUKA

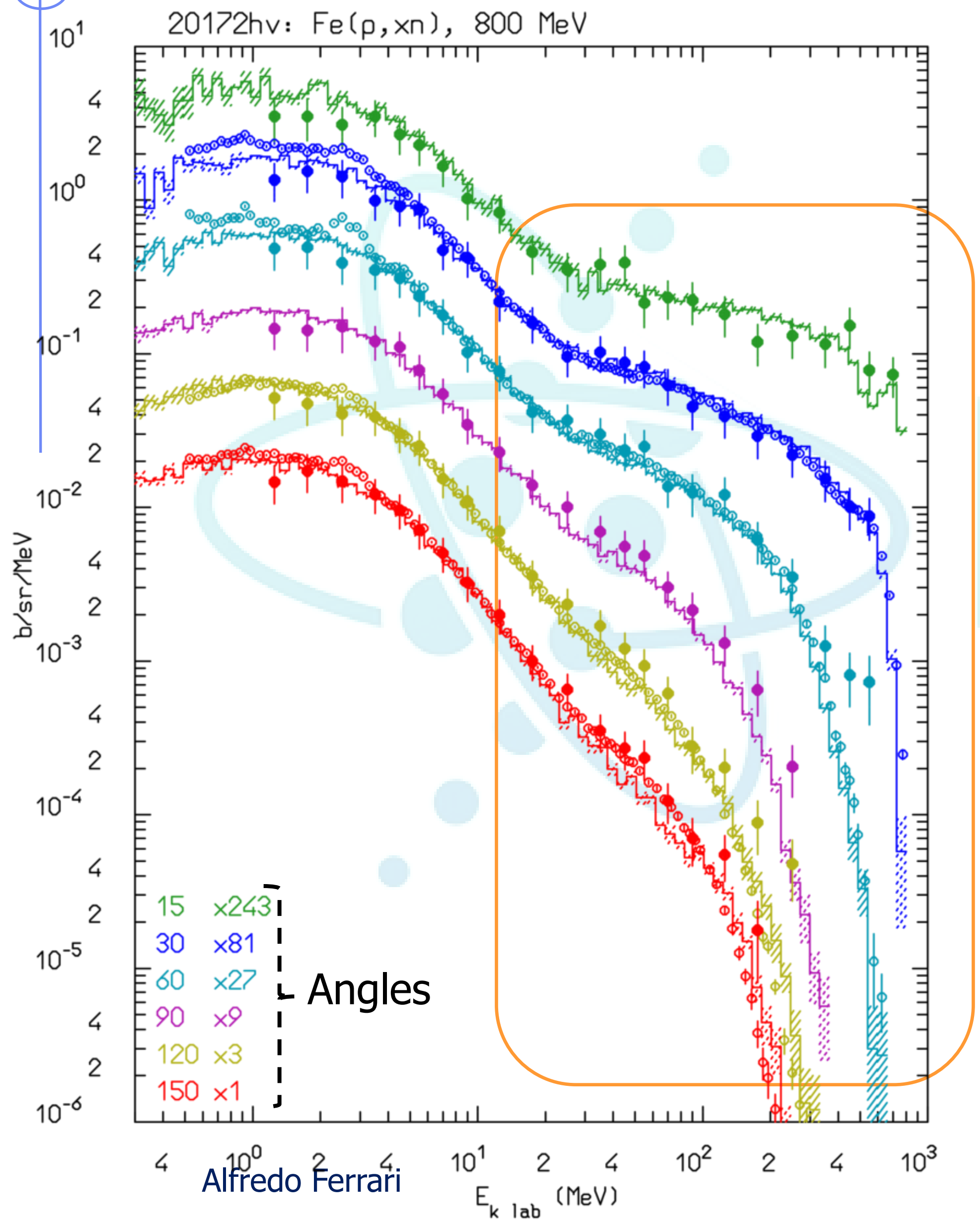
Double differential cross sections $d^2\sigma/dEd\Omega$ for:

← Fe(p,xn) @ 800 MeV,
Data: NSE112, 78,
NST34, 529

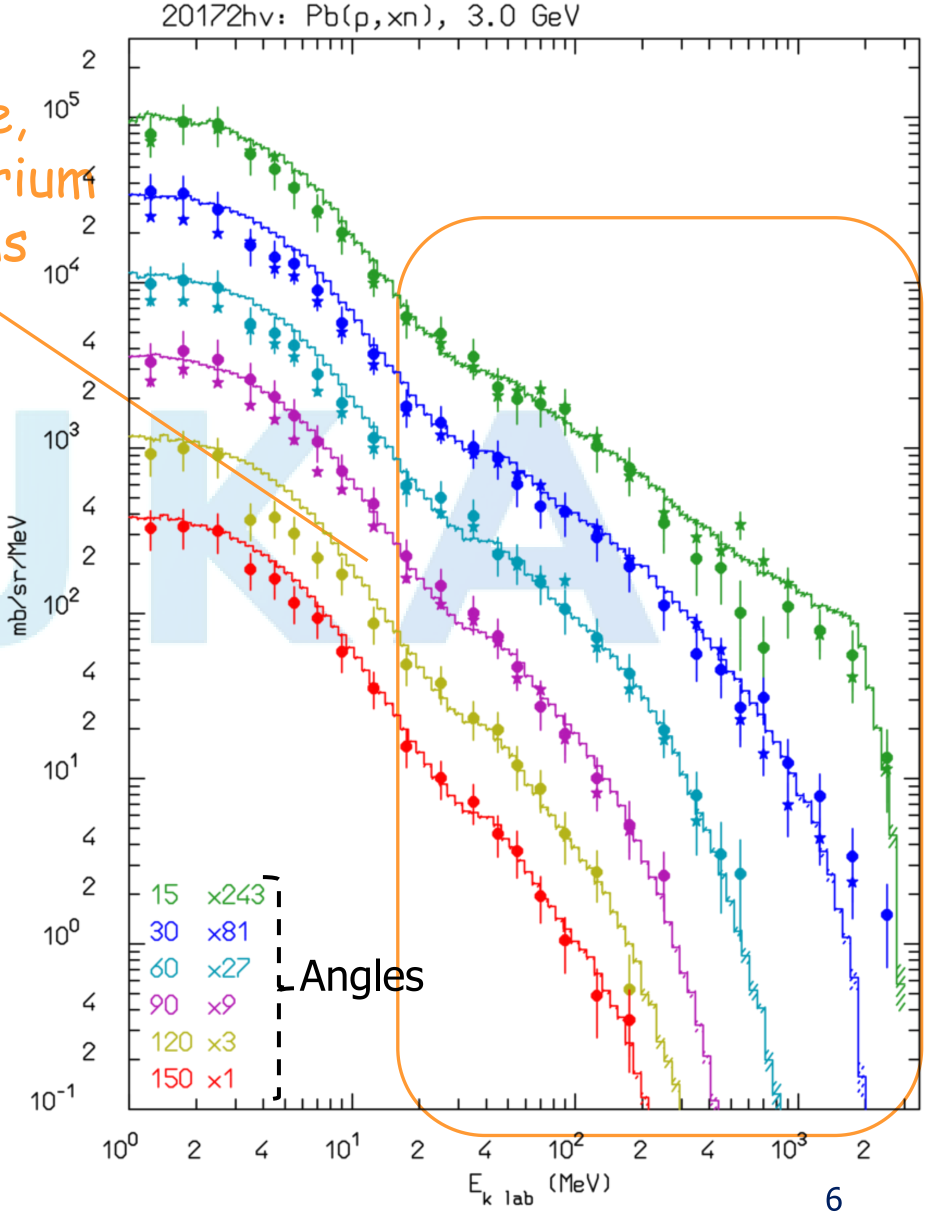
Pb(p,xn) @ 3 GeV →
Data: NST32, 827



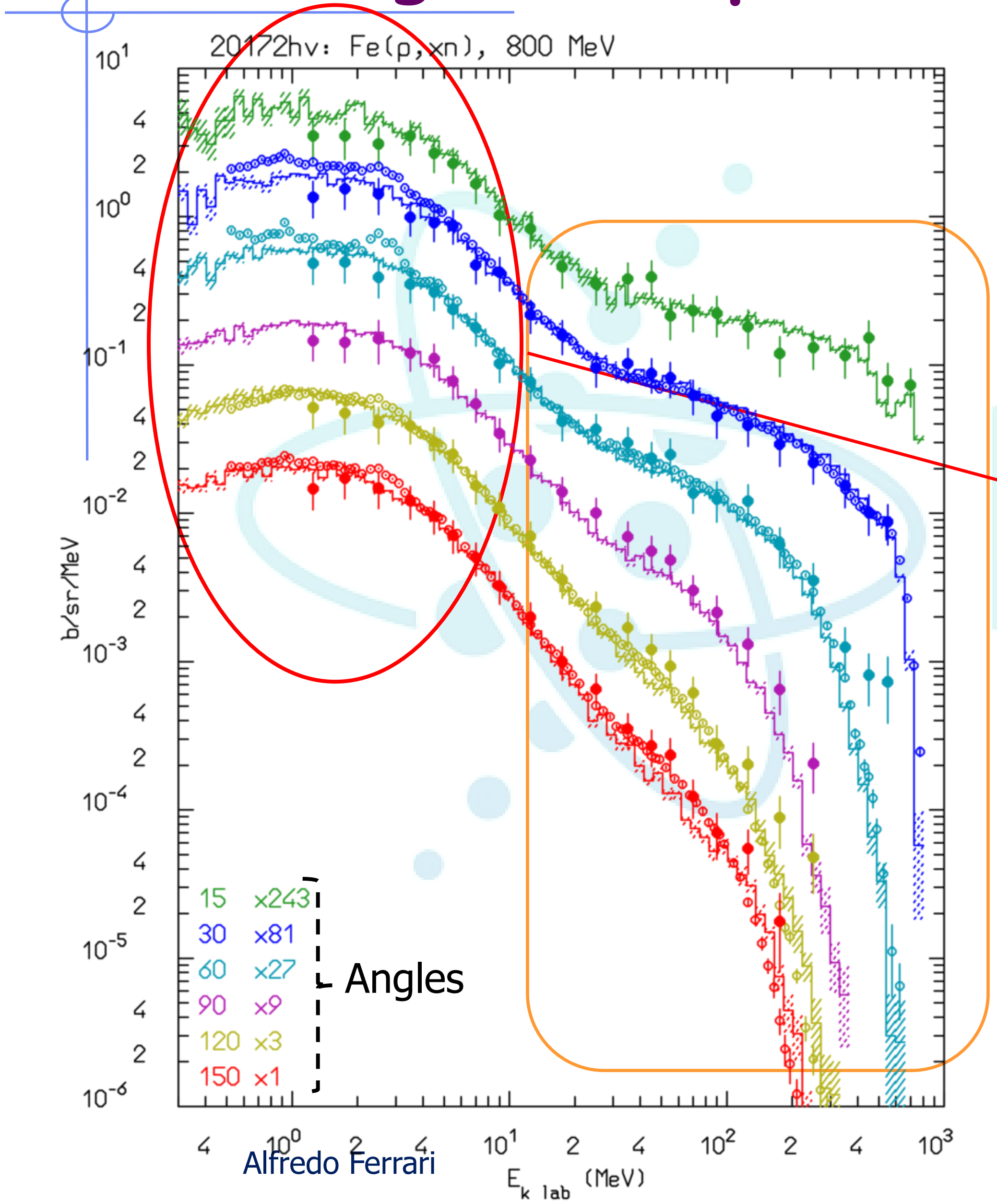
Thin target examples: neutrons double differential production



Cascade, preequilibrium neutrons

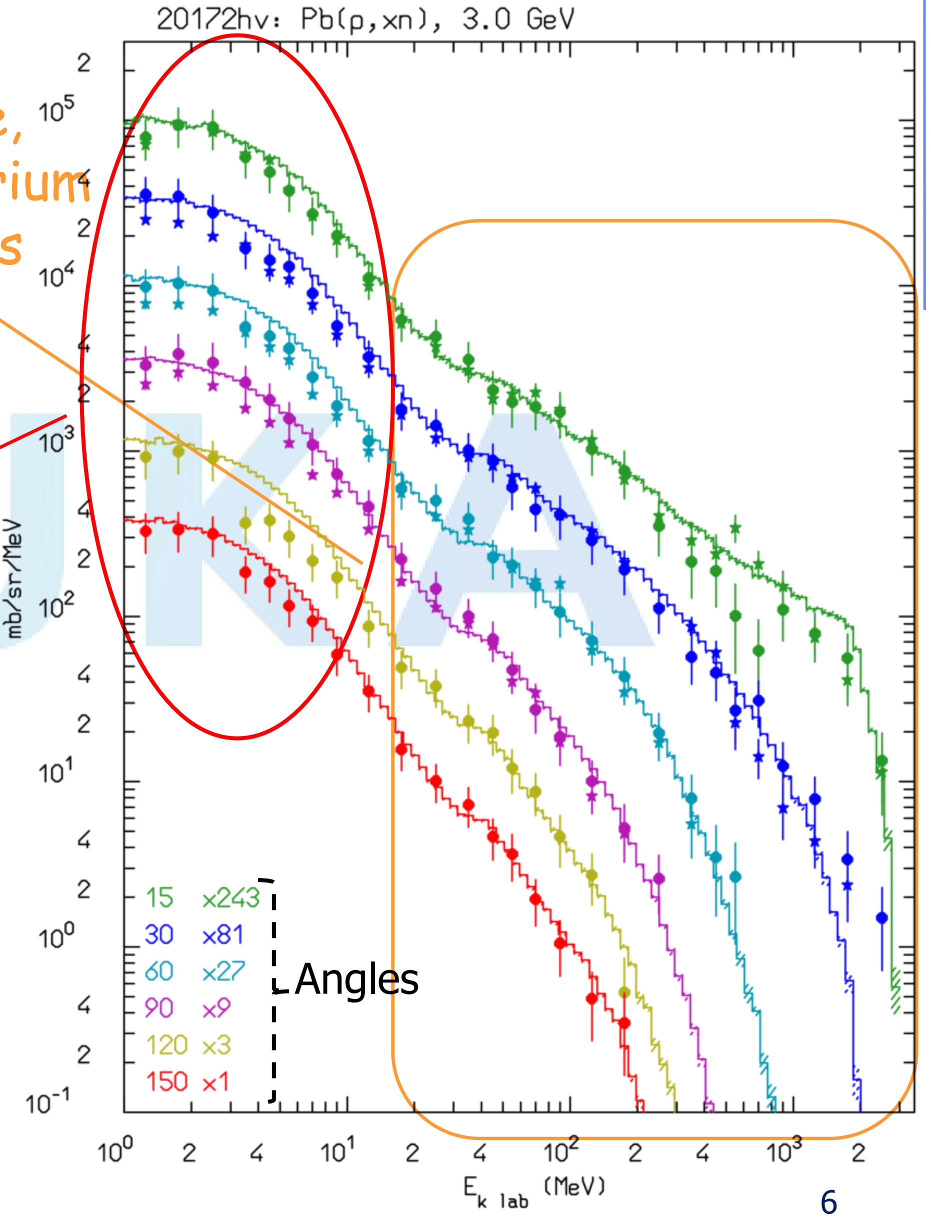


Thin target examples: neutrons double differential production

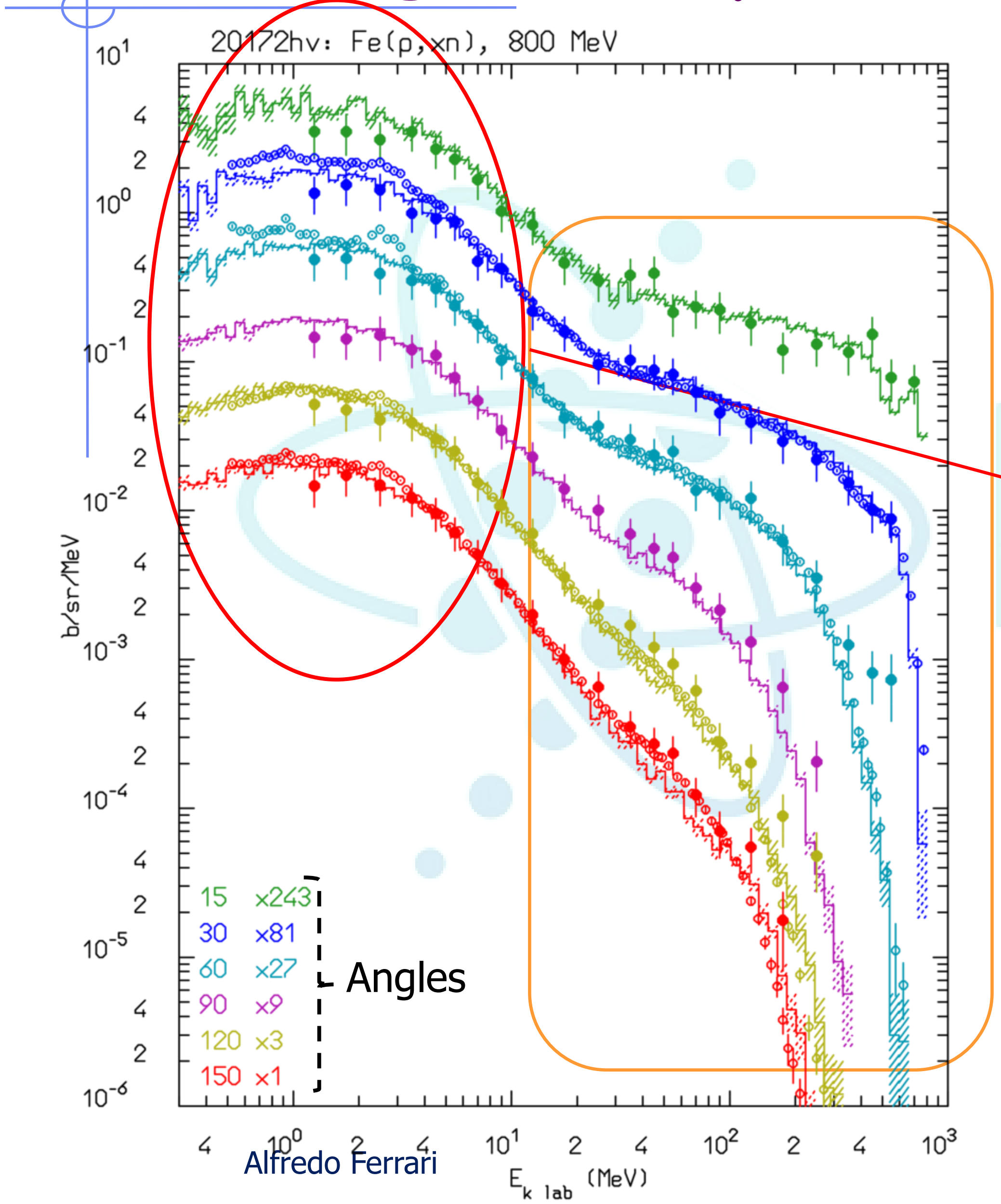


Cascade, preequilibrium neutrons

Evaporation neutrons



Thin target examples: neutrons double differential production

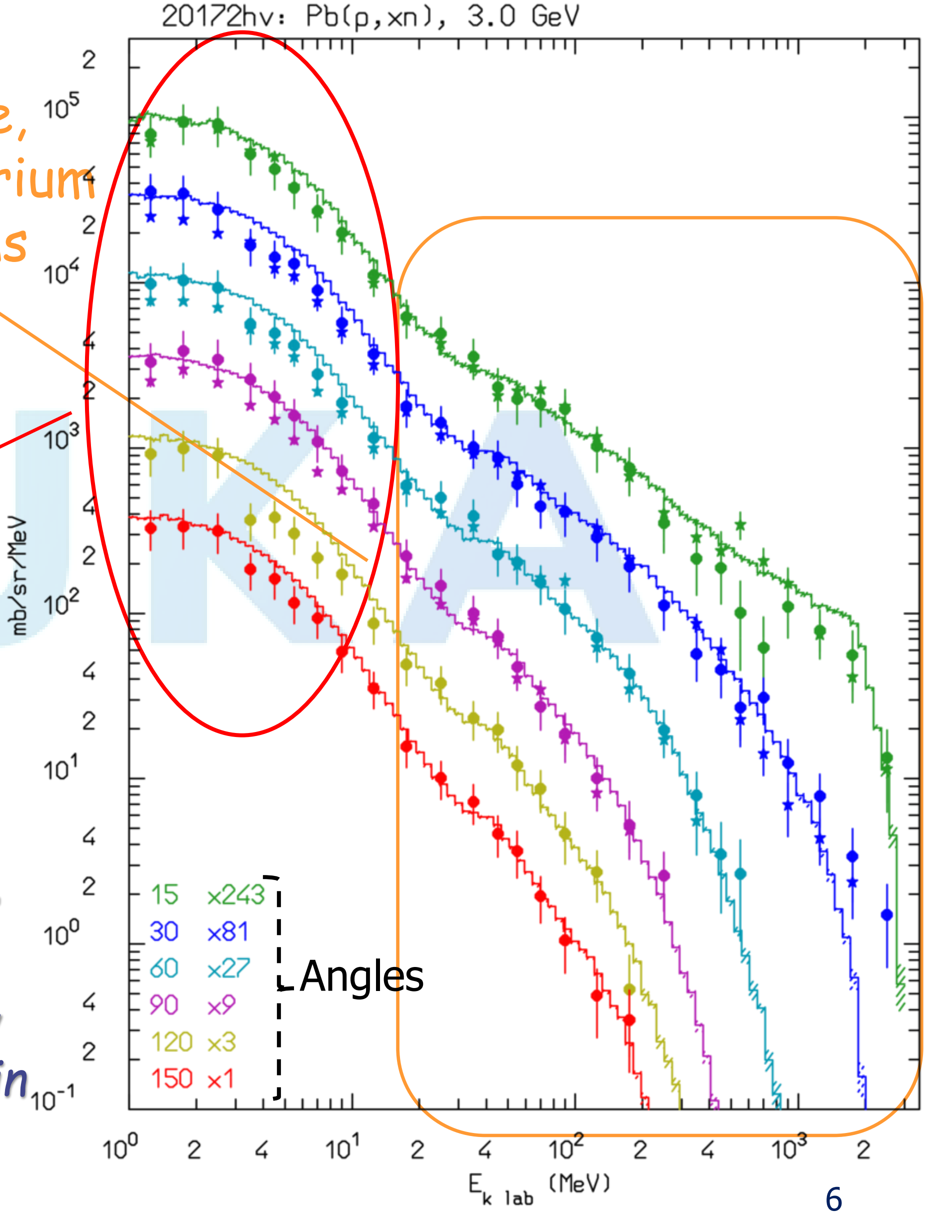


Cascade, preequilibrium neutrons

Evaporation neutrons

Most neutrons are produced by nuclear evaporation/ fragmentation

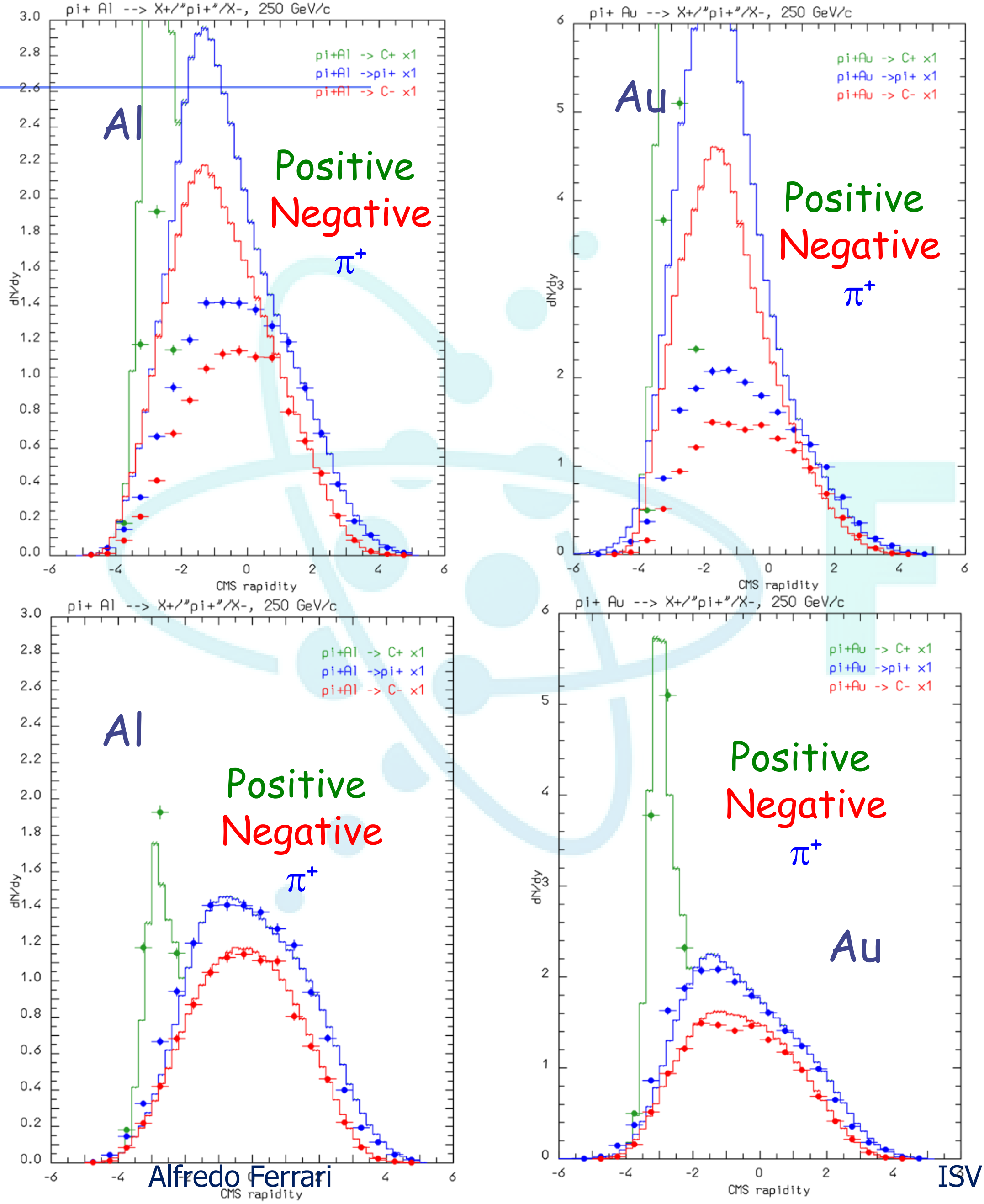
Energetic ones comes mostly from INC and pre-eq., only very few are directly produced in chain hadronization



Formation zone:

Naively "materialization" time: due to the relativistic length contraction and the uncertainty principle, at high energy most of the newly produced particles escape the nucleus without further re-interaction

$$\Delta x_{for} \approx k_{for} \frac{\hbar p_{lab}}{p_T^2 + M^2} \qquad k_{for} \sim 1$$



Top: without formation zone

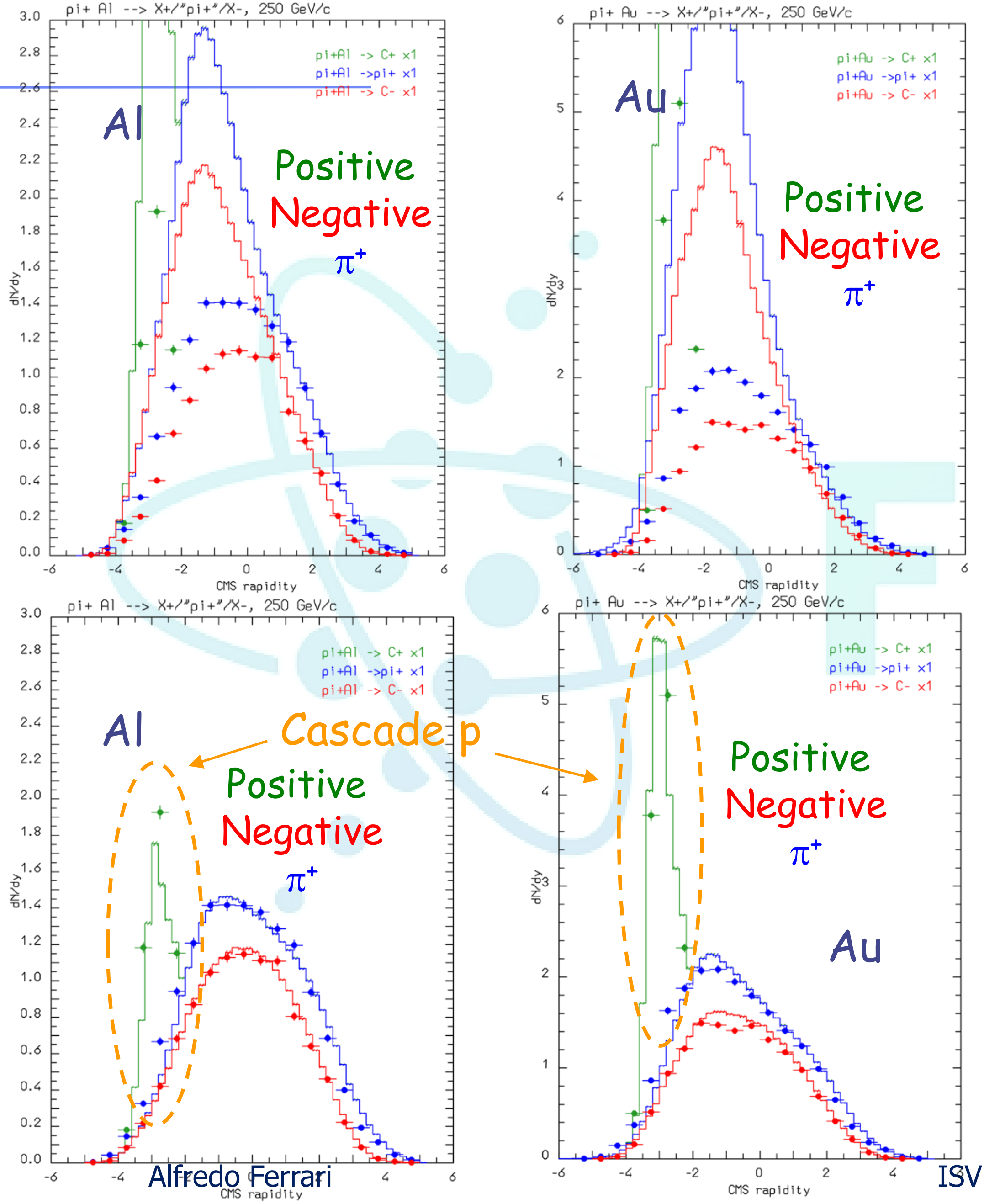
Bottom: with formation zone

Rapidity distribution of charged particles produced in 250 GeV π^+ collisions on Aluminum (left) and Gold (right)
Histos: FLUKA
Points: Agababyan et al., ZPC50, 361

Formation zone:

Naively "materialization" time: due to the relativistic length contraction and the uncertainty principle, at high energy most of the newly produced particles escape the nucleus without further re-interaction

$$\Delta x_{for} \approx k_{for} \frac{\hbar p_{lab}}{p_T^2 + M^2} \qquad k_{for} \sim 1$$



Note the essential role of INC/preeq in producing the intermediate energy nucleon peak

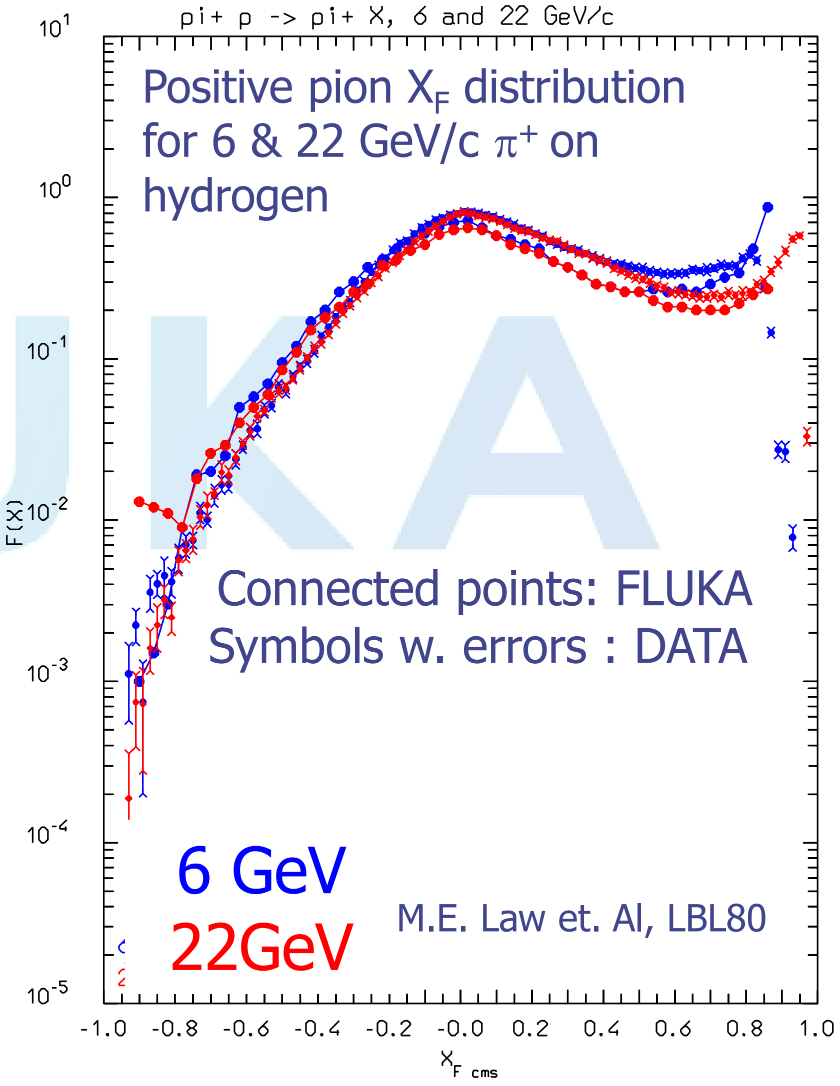
Hadronization: vector mesons in πN, πA:

- ❑ Fluka h-h interaction model: DPM for strings production;
- ❑ Fluka has its own chain hadronization model;
- ❑ For low string invariant masses it smoothly morphs into a Fermi break-up like phase space explosion (example on the right for $\pi^+ p \rightarrow \pi + X$ @6 & 22 GeV/c);
- ❑ At even lower energies 1 or2 resonance creation and decay;

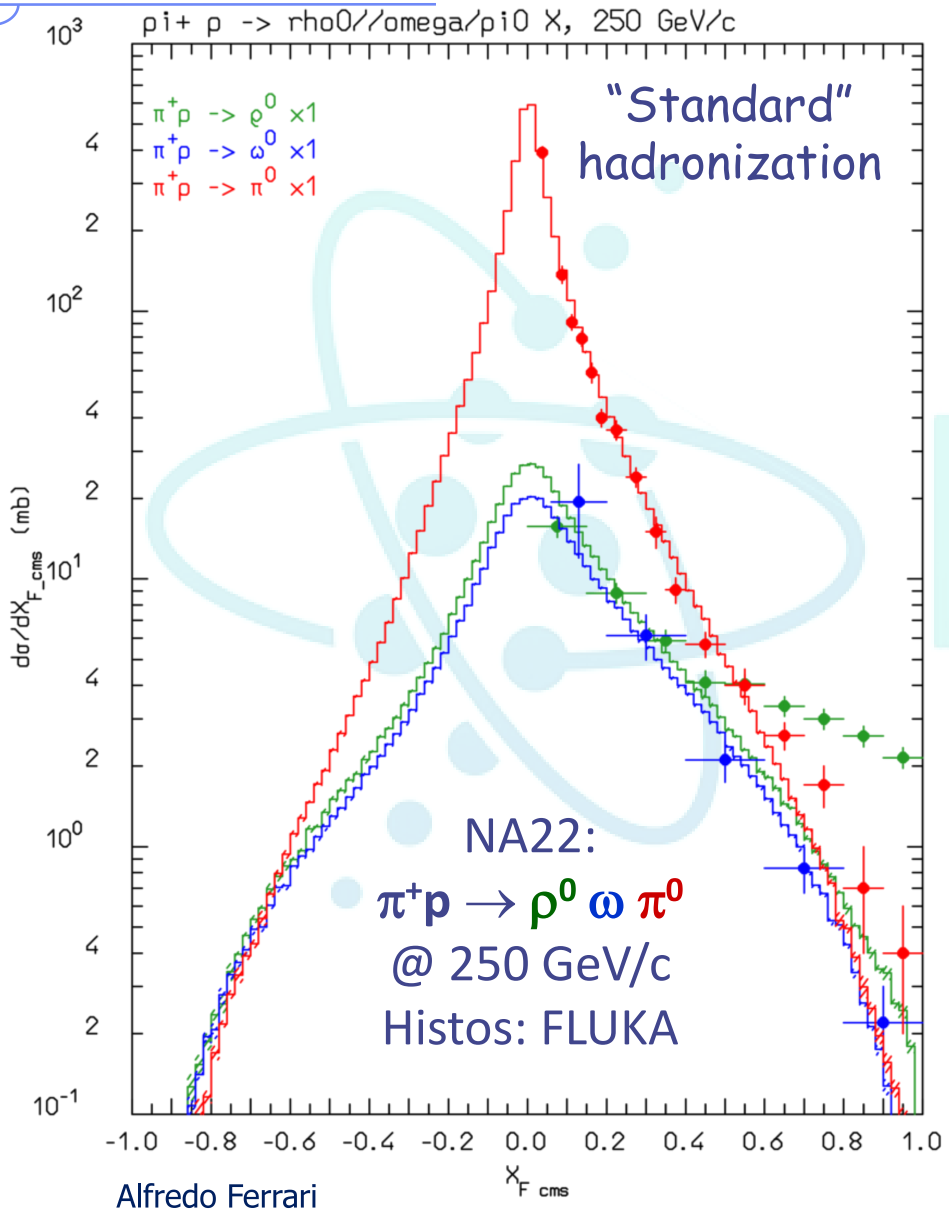
After the following observation:

- ➢ Surprisingly **large yield of ρ'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
- ➢ Hadronization deeply revised differentiating between valence and sea (anti)quarks

$\pi^+ + p \rightarrow \pi^+ + X$ (6 & 22 GeV/c)



"New", completely revised, hadronization:

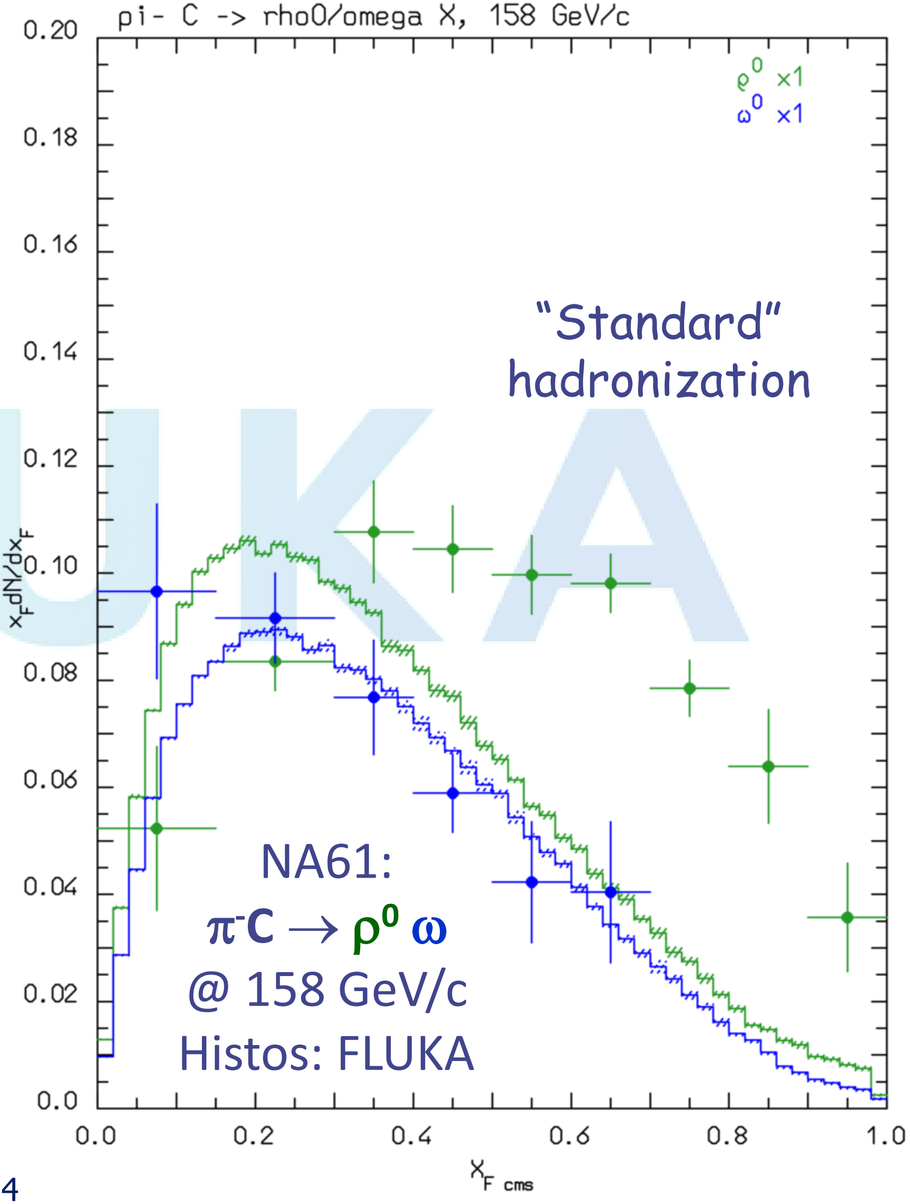


"Standard" hadronization

NA22:
$\pi^+p \to \rho^0\ \omega\ \pi^0$
@ 250 GeV/c
Histos: FLUKA

← $d\sigma/dx_F$

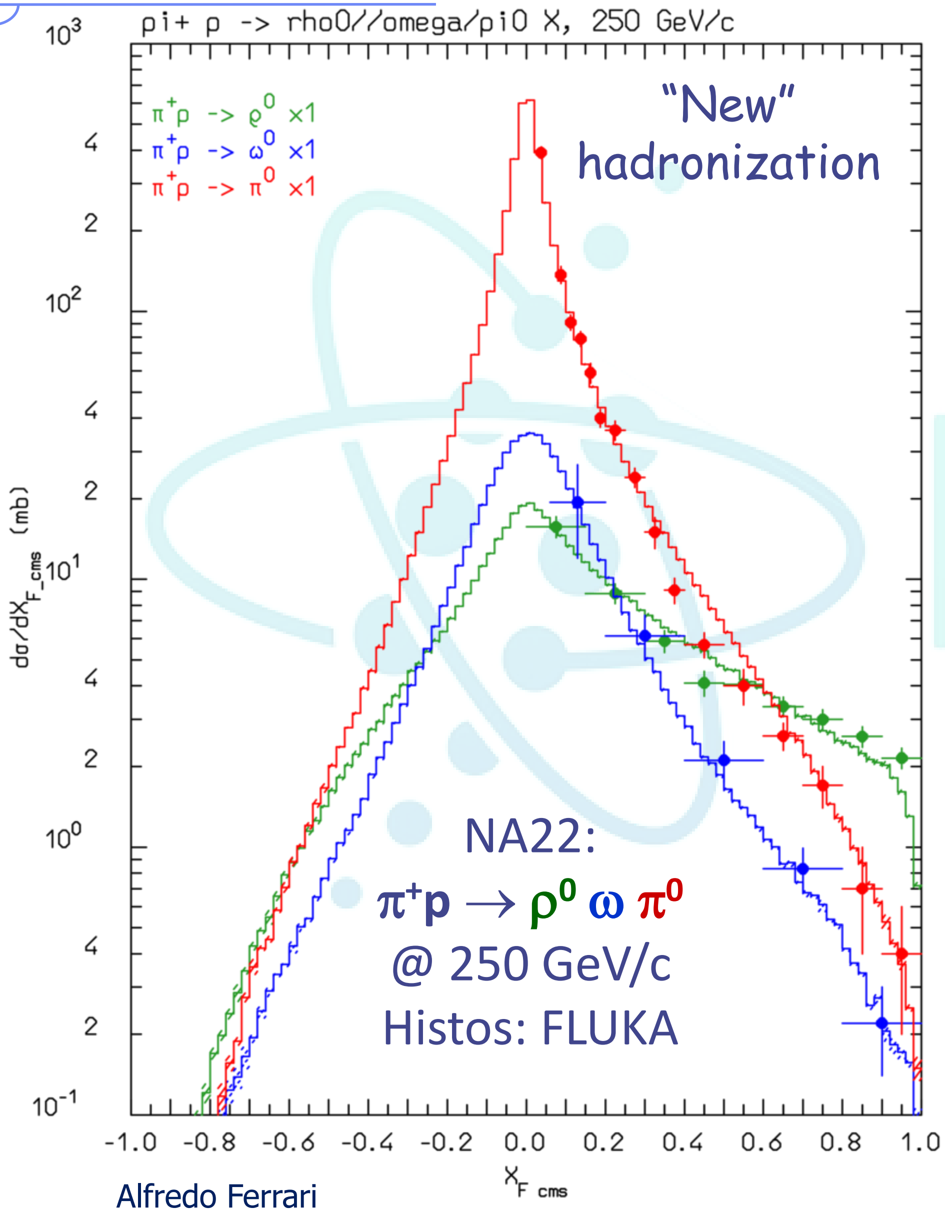
$x_F dN/dx_F$ →



"Standard" hadronization

NA61:
$\pi^-C \to \rho^0\ \omega$
@ 158 GeV/c
Histos: FLUKA

“New”, completely revised, hadronization:

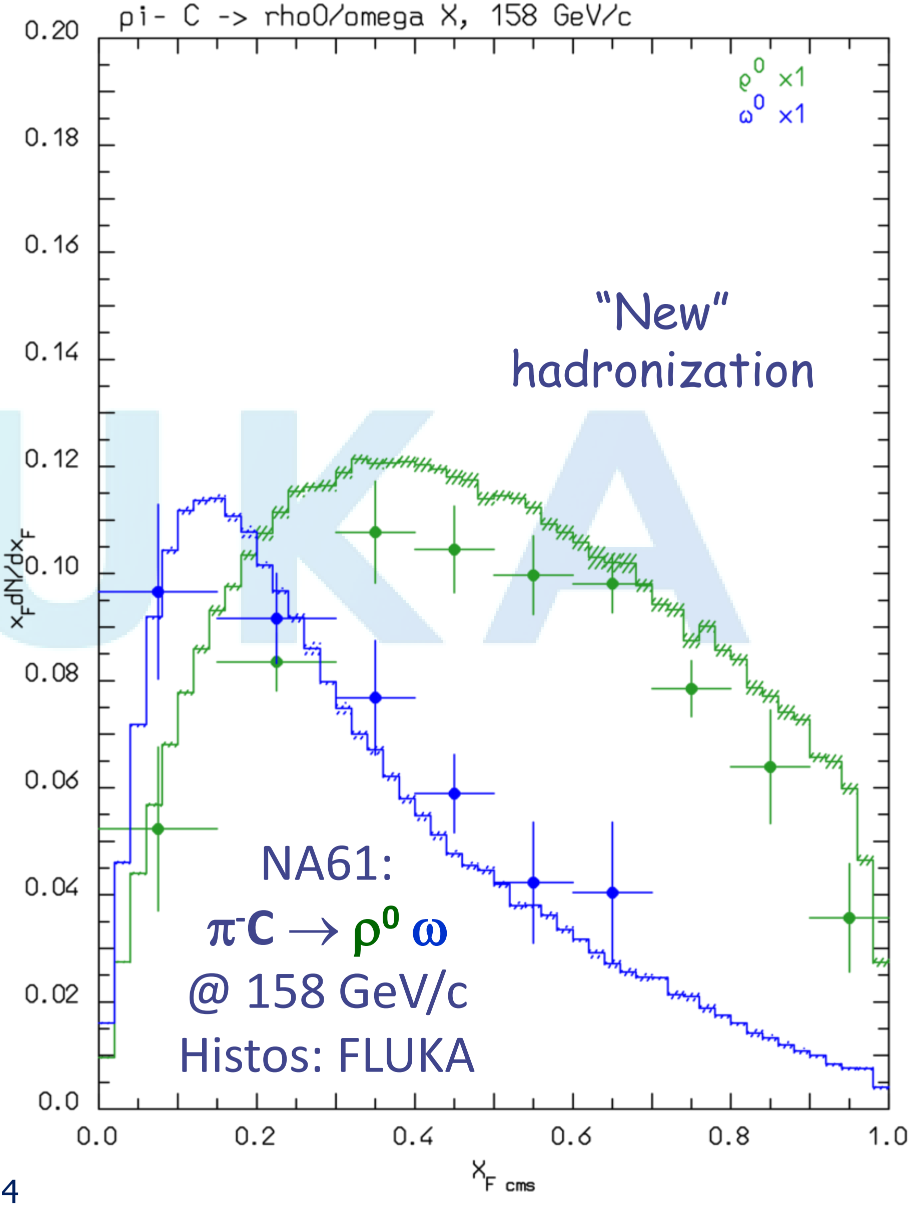


“New” hadronization

NA22:
$\pi^+p \to \rho^0\ \omega\ \pi^0$
@ 250 GeV/c
Histos: FLUKA

← $d\sigma/dx_F$

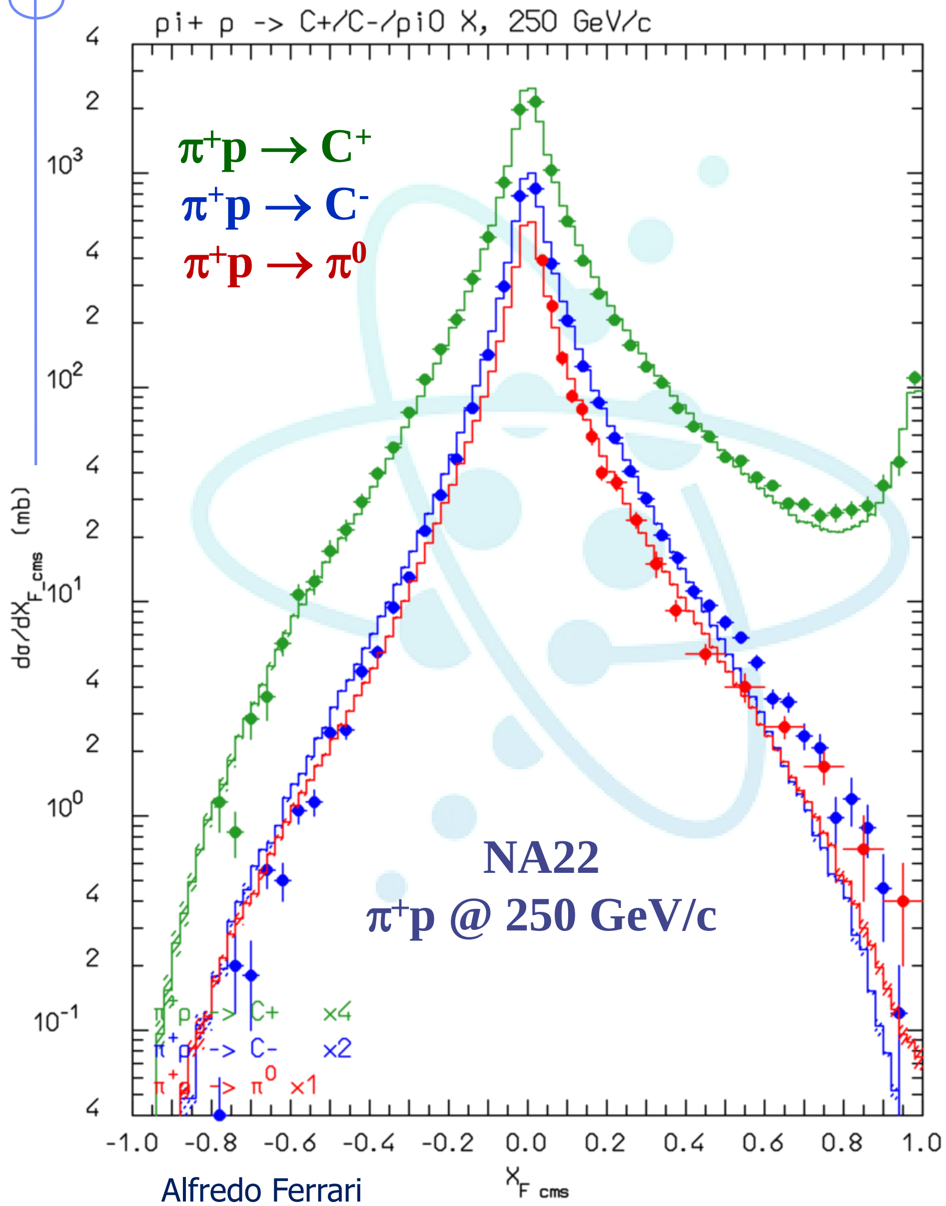
$x_F dN/dx_F$ →



“New” hadronization

NA61:
$\pi^-C \to \rho^0\ \omega$
@ 158 GeV/c
Histos: FLUKA

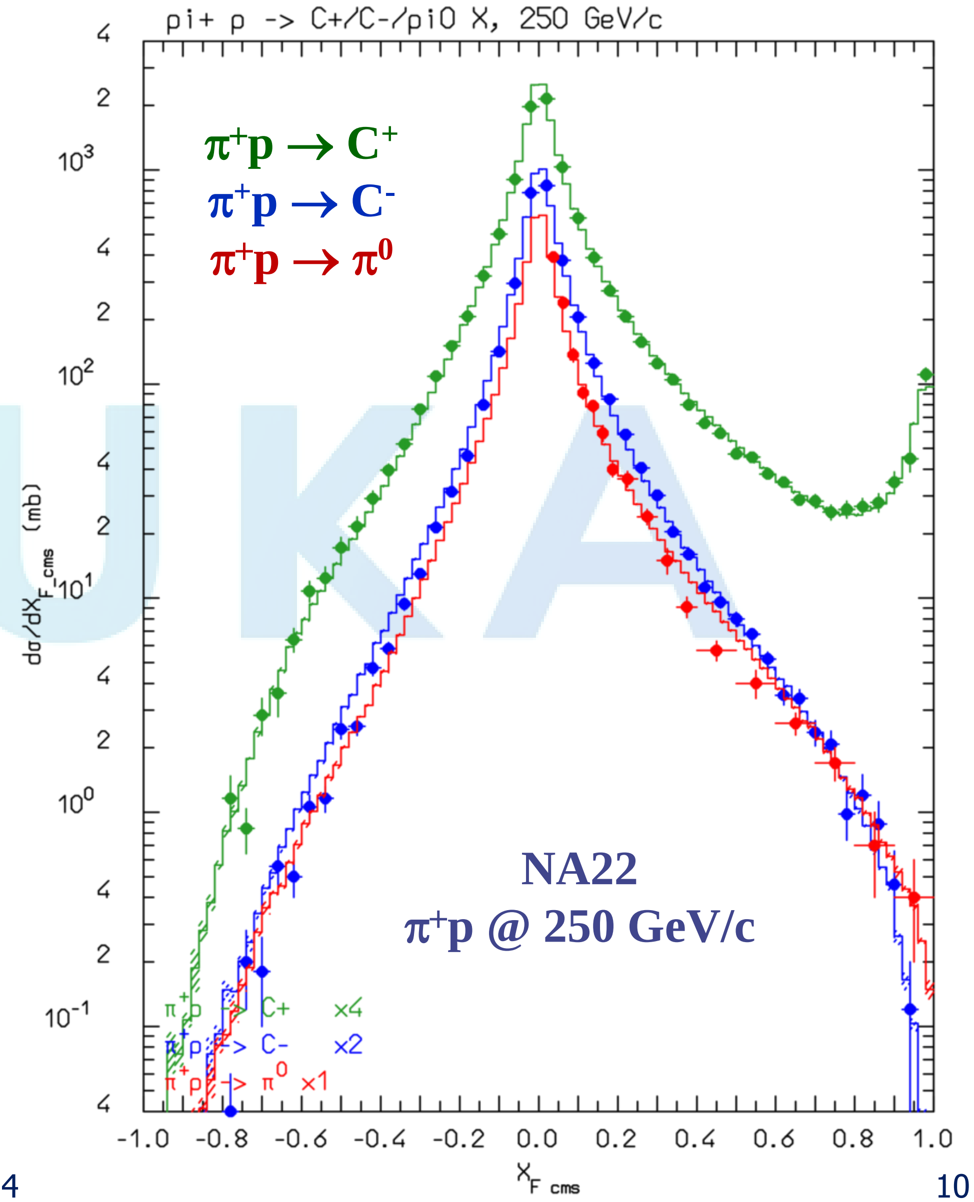
New hadronization: inclusive distributions



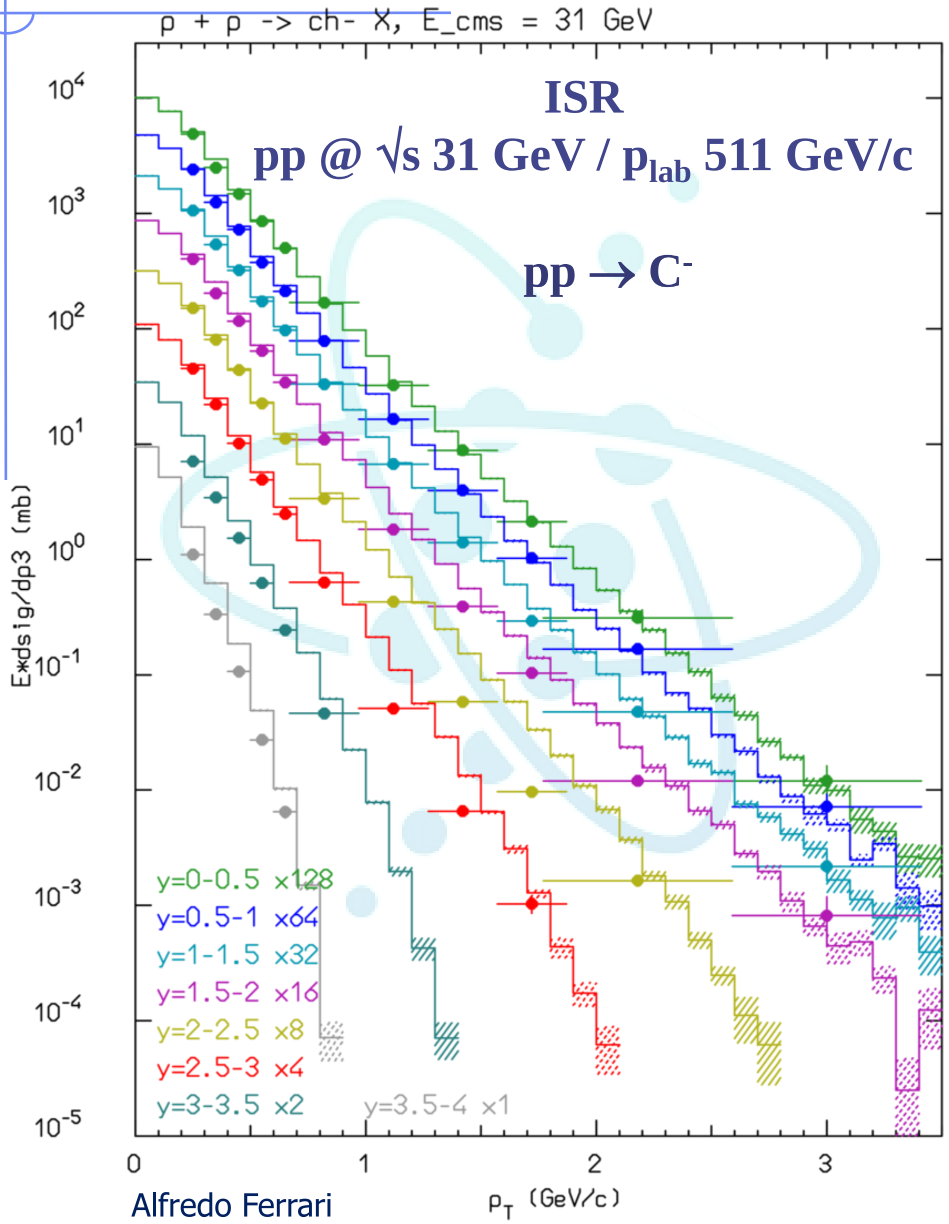
← $d\sigma/dx_F$ →

NEW

OLD



Inclusive distributions at higher (ISR) energies

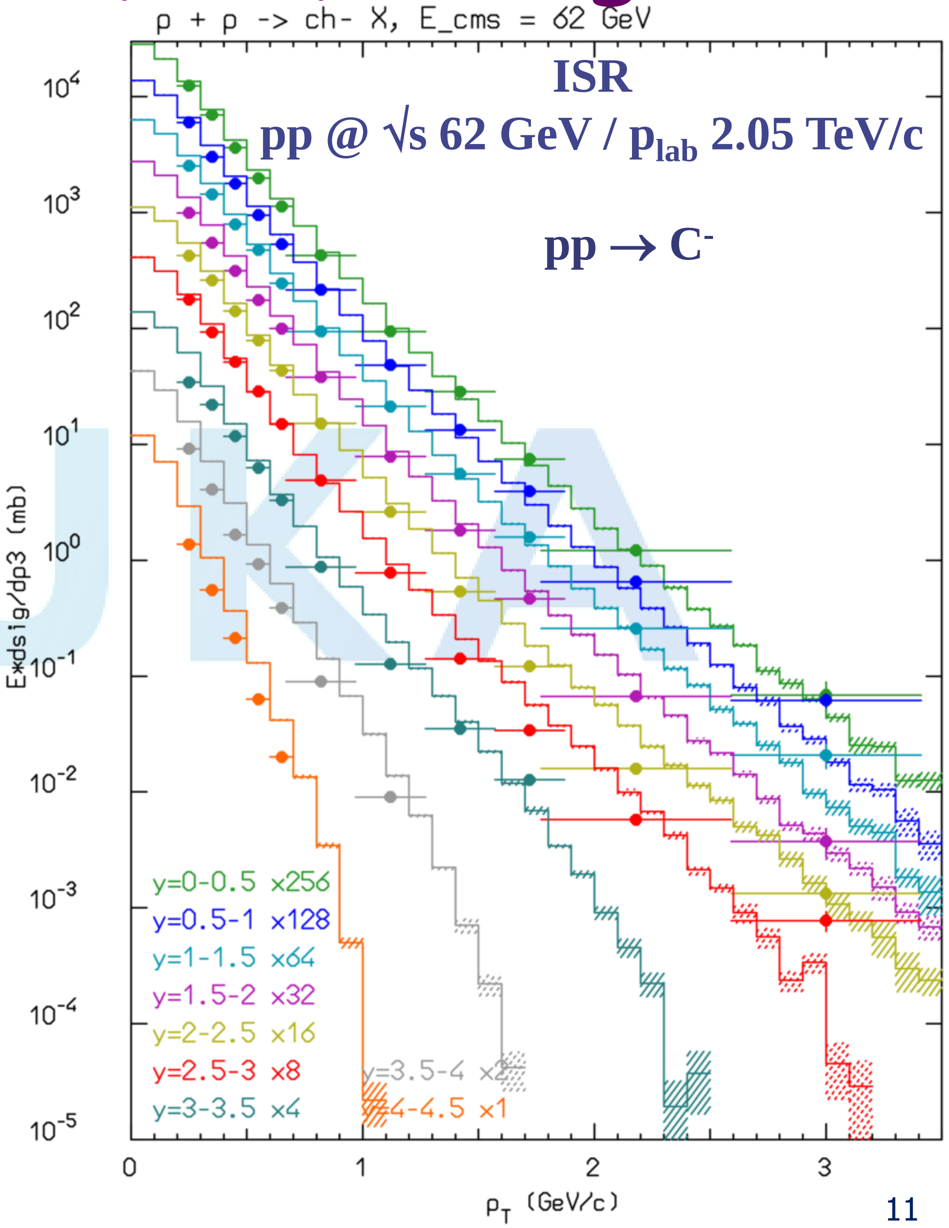


←$Ed^3\sigma/dp^3$ →

√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

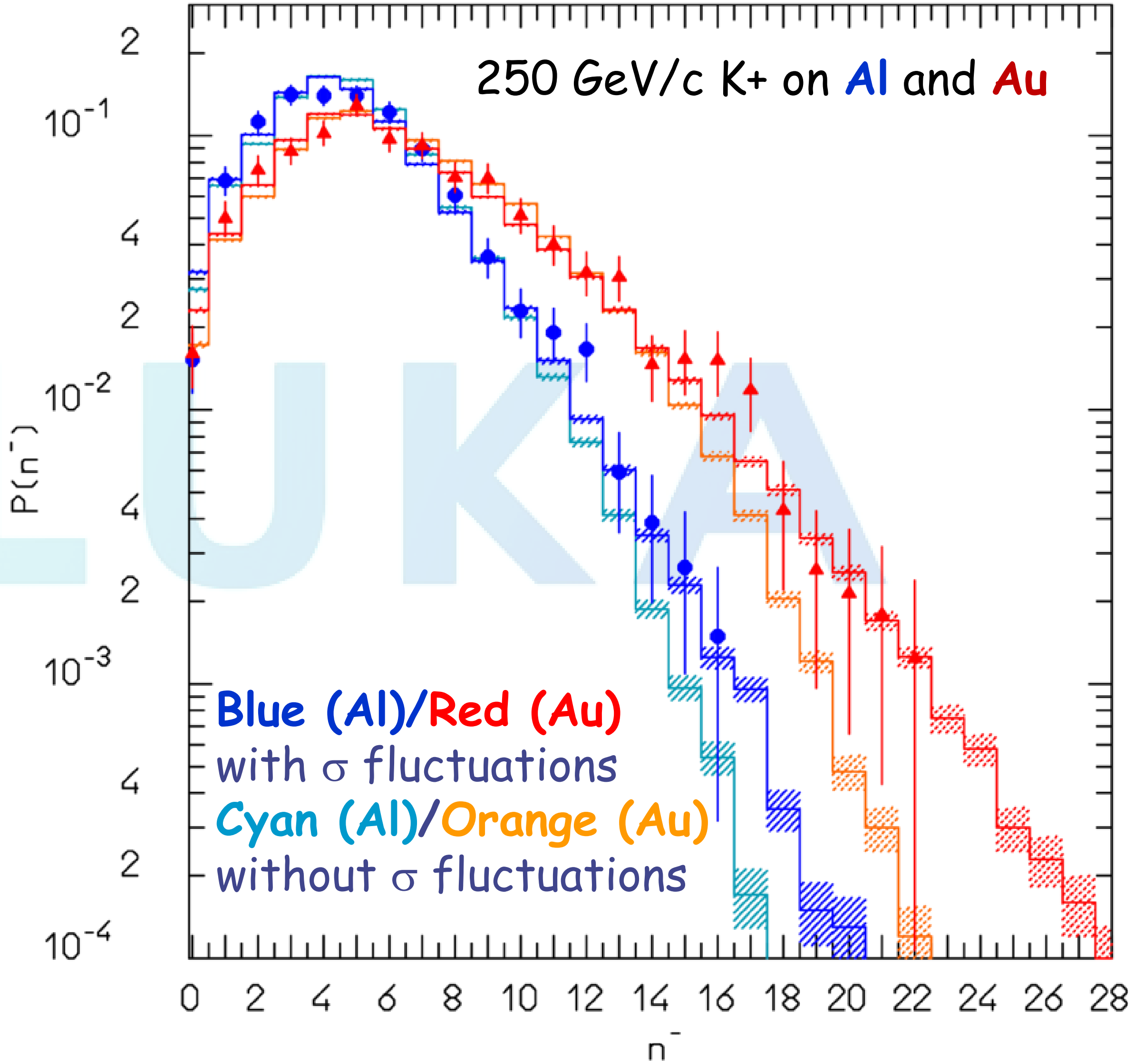
Glauber with cross section fluctuations *(color transparency)!*

- The ***observed*** σ_{hN} is just the ***average*** of the σ's corresponding to all possible proj/targ (quark) configurations
- Considering the ***hadron as a color dipole*** a **fluctuating** σ can be used **inside the Glauber formalism**, providing among others ***inelastic screening for "free"***

Example: multiplicity distributions of negative particles for **250 GeV/c K$^+$** on **Al** and **Au**:

- **symbols** with error bars: exp. data (NA22)
- **histos**: Fluka simulation with/without cross section fluctuations

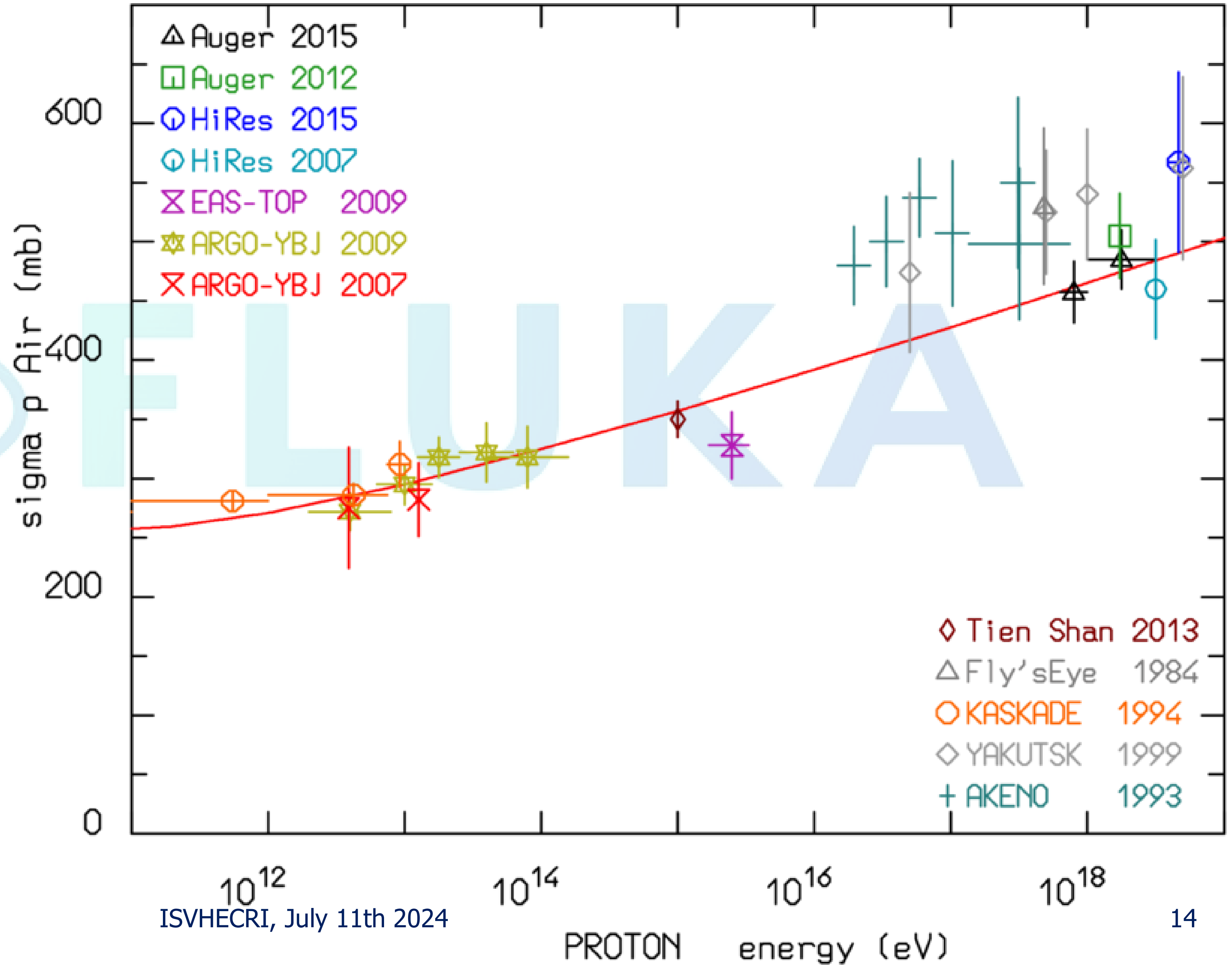
*Please note that the **average** multiplicities are ~equal with and without cross section fluctuations*



It works up to UHE !

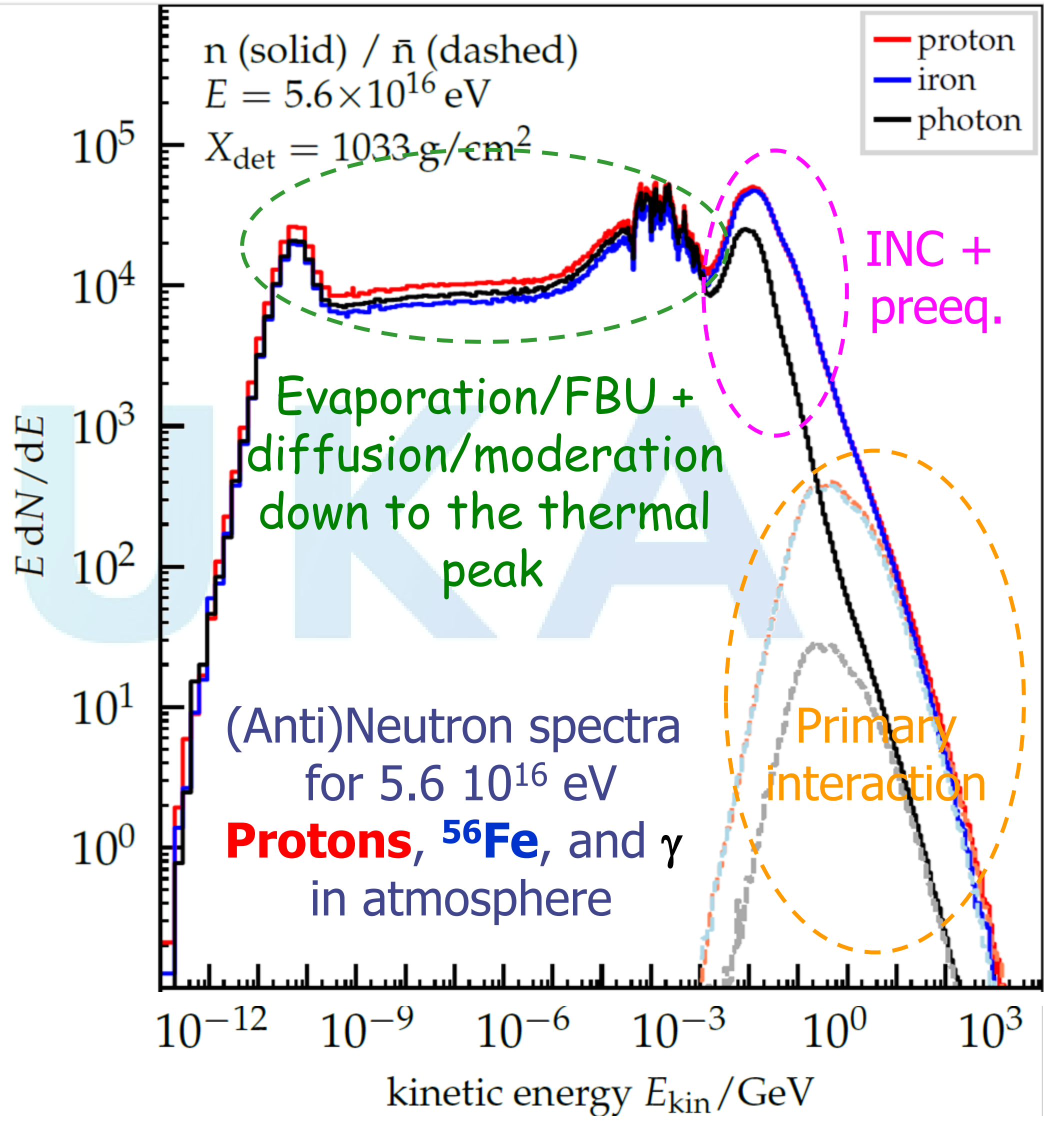
- Thanks to the inclusion of σ **fluctuations**, the **Fluka (Peanut) Glauber model** is now able to compute absorption and *quasi-elastic* **cross sections for all hadrons/targets up to UHECR energies**

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.



Neutron production: critical "ingredients"

- Fermi motion and actual isotope-by-isotope binding energies: residual excitation energies fully determined by the "hole" depths in the Fermi sea and by the actual binding energies for p/n/d/t/h/α emission;
- IntraNuclearCascade: "energetic" reinteractions contribute to excitation energies and produce the quasi-elastic peak as well the rapidity "peak" (nucleons in the ten-few hundreds MeV energy range, old "grey" particles);
- Pre-equilibrium: same as INC, limited to E < 100 MeV;
- Evaporation/fragmentation/Fermi Break-Up (FBU): source of the ~totality of slow (below 10 MeV, old "black" particles) neutrons, protons etc;



Evaporation/FBU + diffusion/moderation down to the thermal peak

INC + preeq.

Primary interaction

(Anti)Neutron spectra for 5.6 10^{16} eV **Protons**, **^{56}Fe**, and γ in atmosphere

See http://arxiv.org/abs/2406.11702 and R.Engel talk on Tuesday afternoon

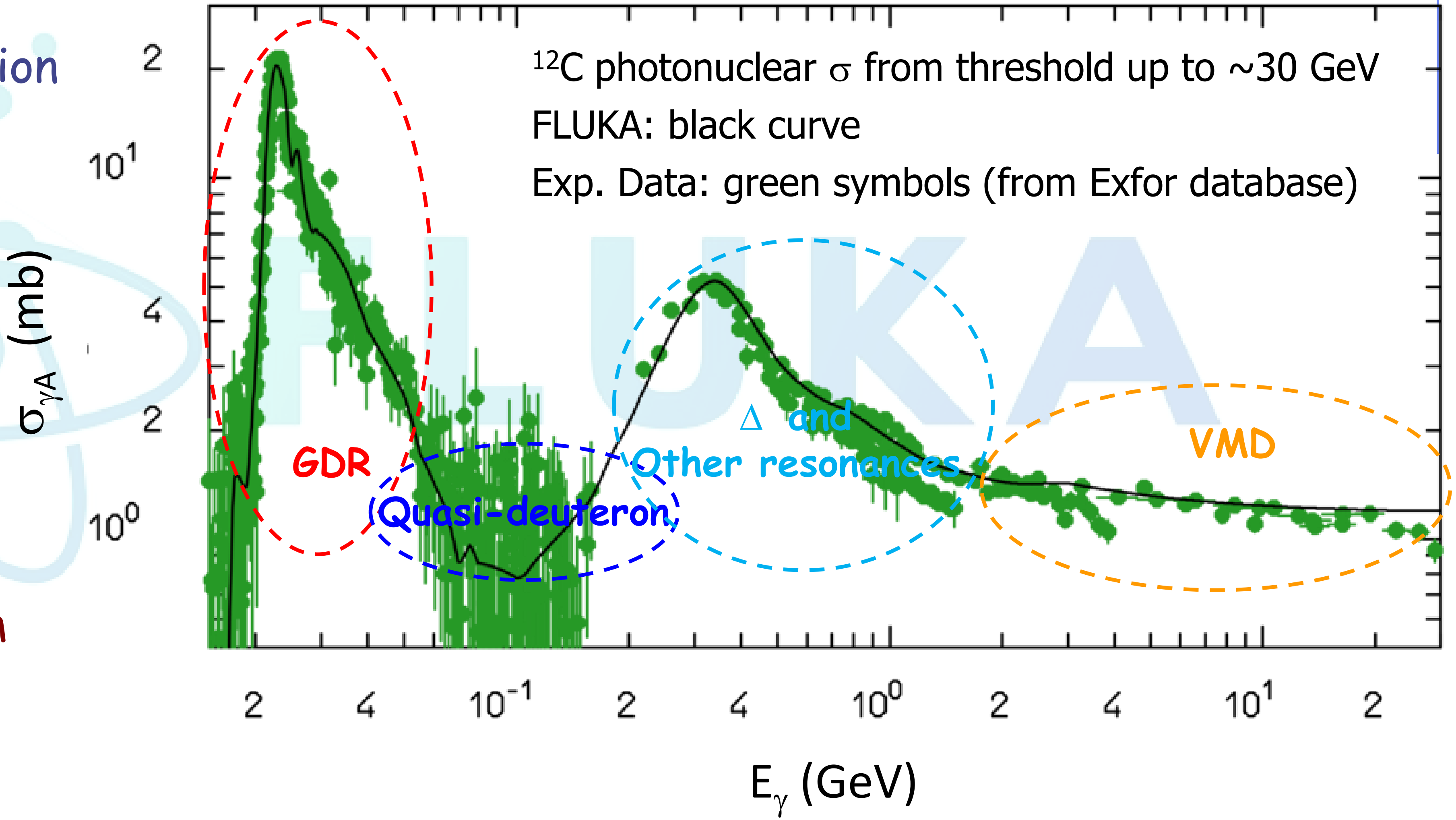
Real and virtual photons

Photonuclear interactions in FLUKA*:

**Deeply revised and improved in Fluka2023.3*

Photonuclear reactions

- ☐ Giant Dipole Resonance interaction (special database)
- ☐ Quasi-Deuteron effect
- ☐ Delta Resonance energy region
- ☐ Vector Meson Dominance at high energies
- ☐ INC, preequilibrium and evaporation via the PEANUT model

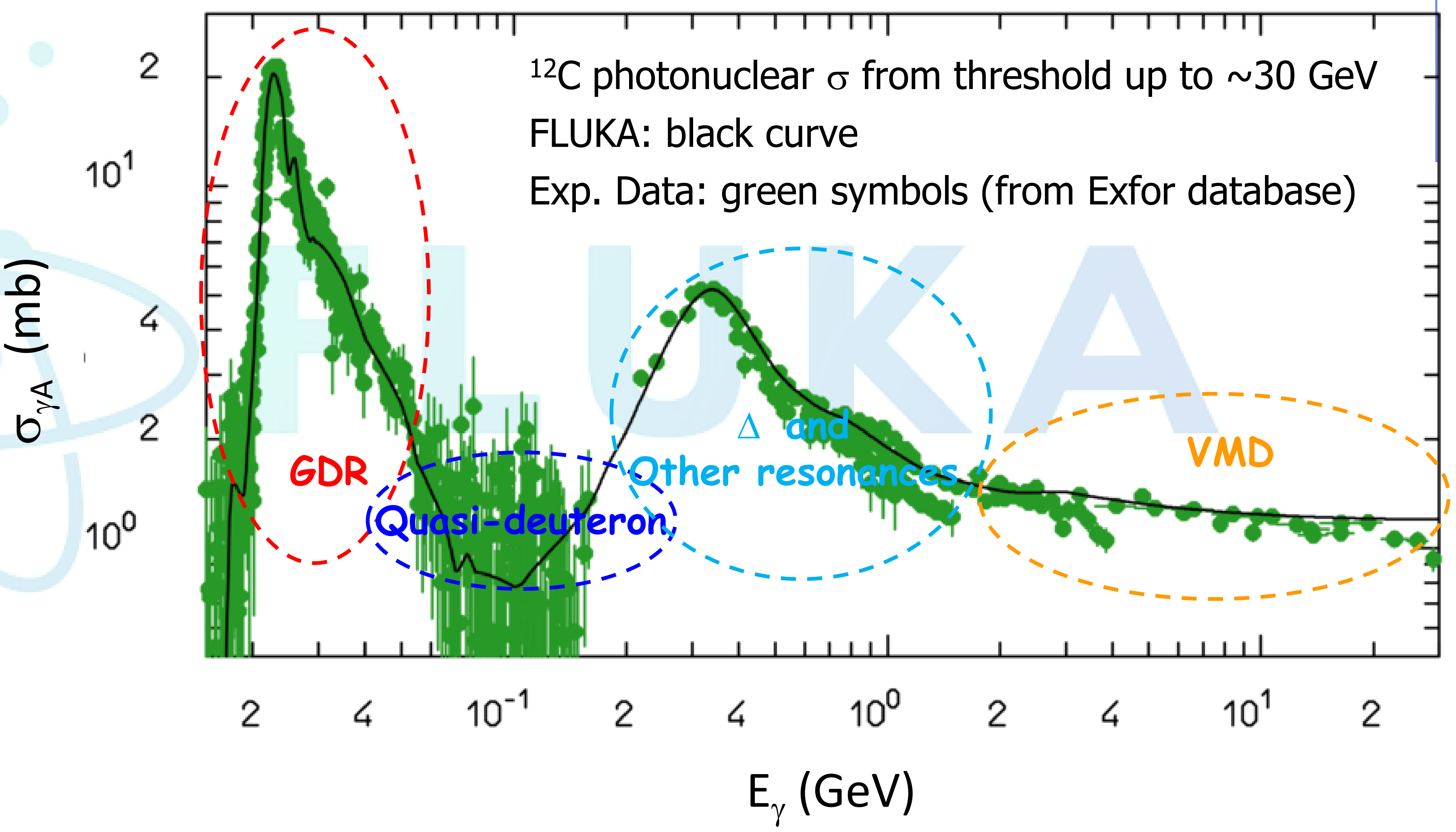


Photonuclear interactions in FLUKA*:

**Deeply revised and improved in Fluka2023.3*

Virtual photon reactions

- Muon photonuclear interactions
- Electronuclear interactions
- Electromagnetic dissociation



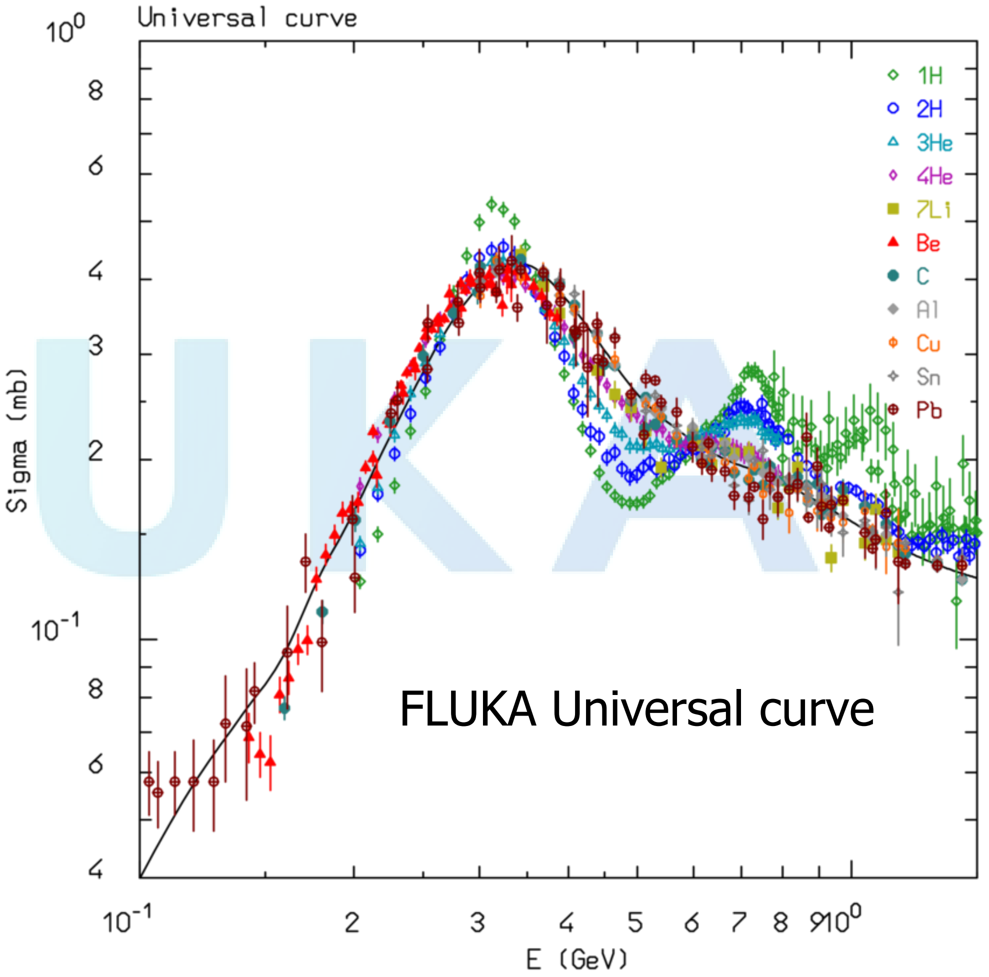
^{12}C photonuclear σ from threshold up to ~30 GeV

FLUKA: black curve

Exp. Data: green symbols (from Exfor database)

Relevance of photonuclear interactions for CR

- 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:
  - ~ **16-20%** of the **muons** come from real or virtual photonuclear interactions;
  - … and ~1/4 of these muons (~**4-5 %** of the total) originate from ***muon photonuclear*** interactions;
  - ~ **70%** of the **neutrons** come from real or virtual photonuclear interactions (GDR range very important);
  - … and 1/7 of these neutrons (**~10%** of the total) originate from ***muon photonuclear*** interactions.

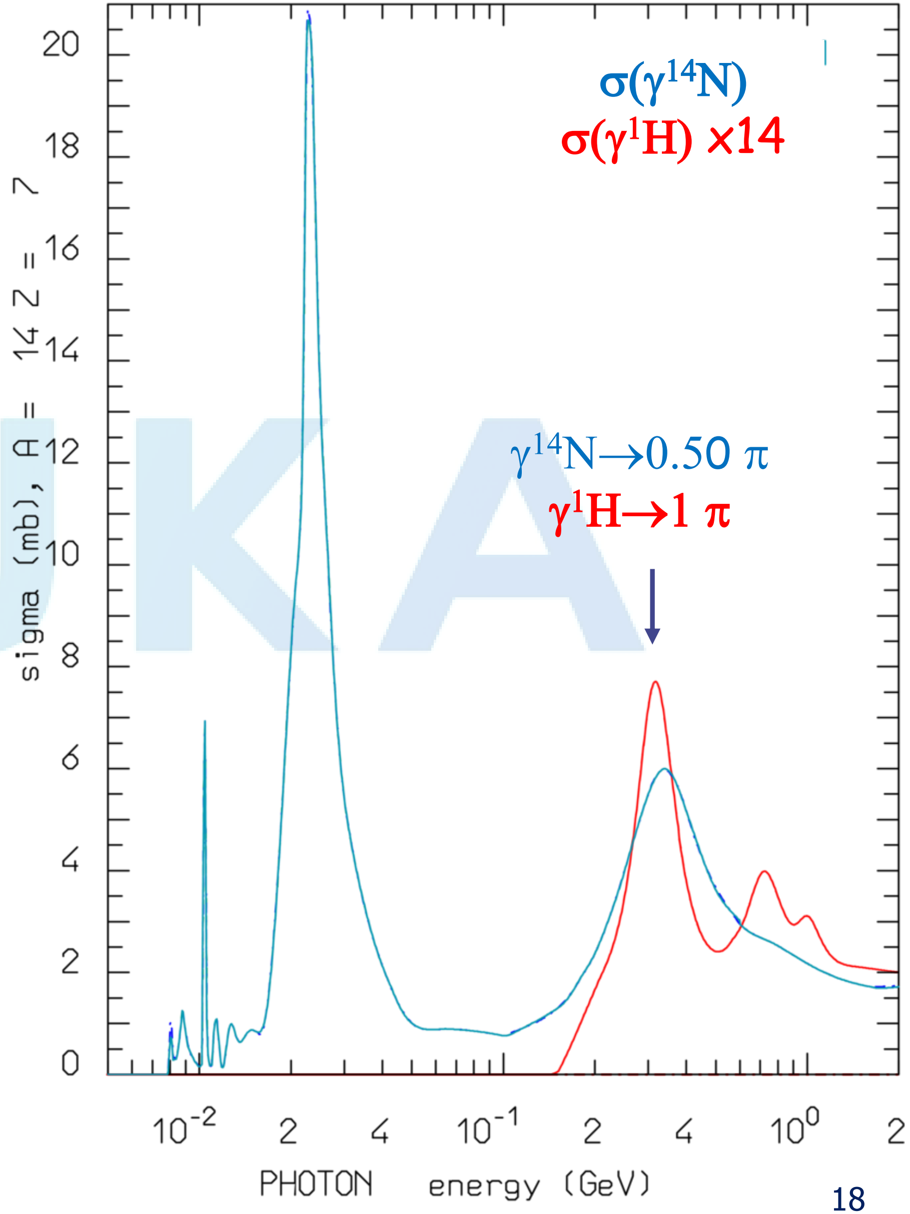


FLUKA Universal curve

Relevance of photonuclear interactions for CR

For $E_\gamma < 1$ GeV, σ for pion production in γA is much smaller than A x γp because of the dominance of:

- *(initial state) $\gamma NN \rightarrow NN$, $\gamma NNN \rightarrow NNN$*
- *(final state) $\pi NN \rightarrow NN$, $\pi NNN \rightarrow NNN$*



… at higher (multi GeV) energies

FLUKA includes:

a) $\gamma A \to \rho^0(\Phi,\omega)A \to \rho^0 A$ coherent, from the optical theorem suitably adapted to γ hadronic fluctuations;

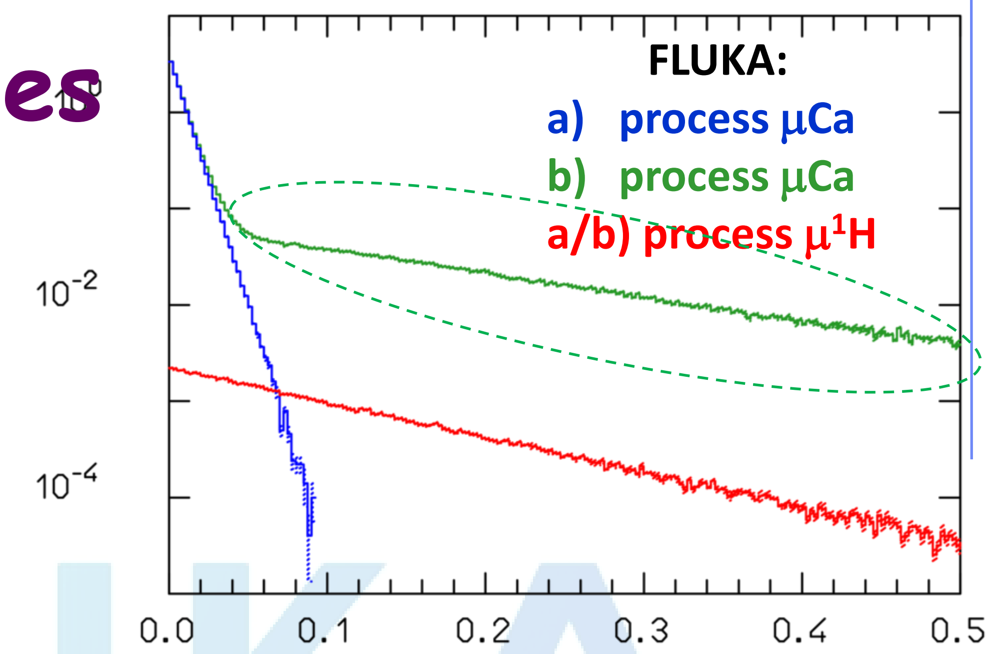
b) $\gamma A \to \rho^0(\Phi,\omega)A \to \rho^0 A^*$ from incoherent quasi-elastic scattering;

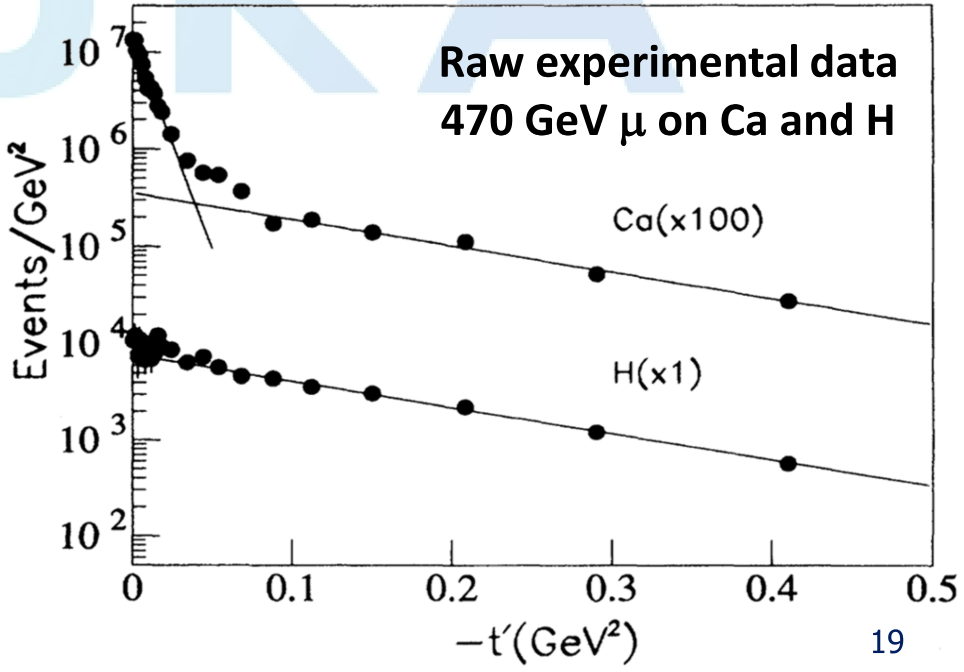
c) $\gamma A \to \rho^0(\Phi,\omega)A \to X$ from VMD mediated Glauber-Gribov interactions

a), b) are often overlooked

The plots on the right show the ρ^0 **distribution** as a function of 4-momentum transfer for **470 GeV muons** on **Ca** and **H** (PRL74 1525).

The plots are in arbitrary units, no attempt has been made to apply the complex experimental acceptances

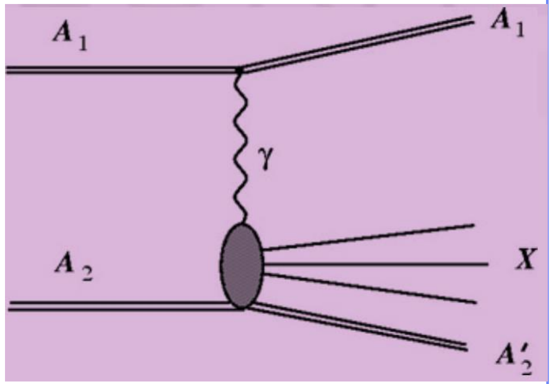




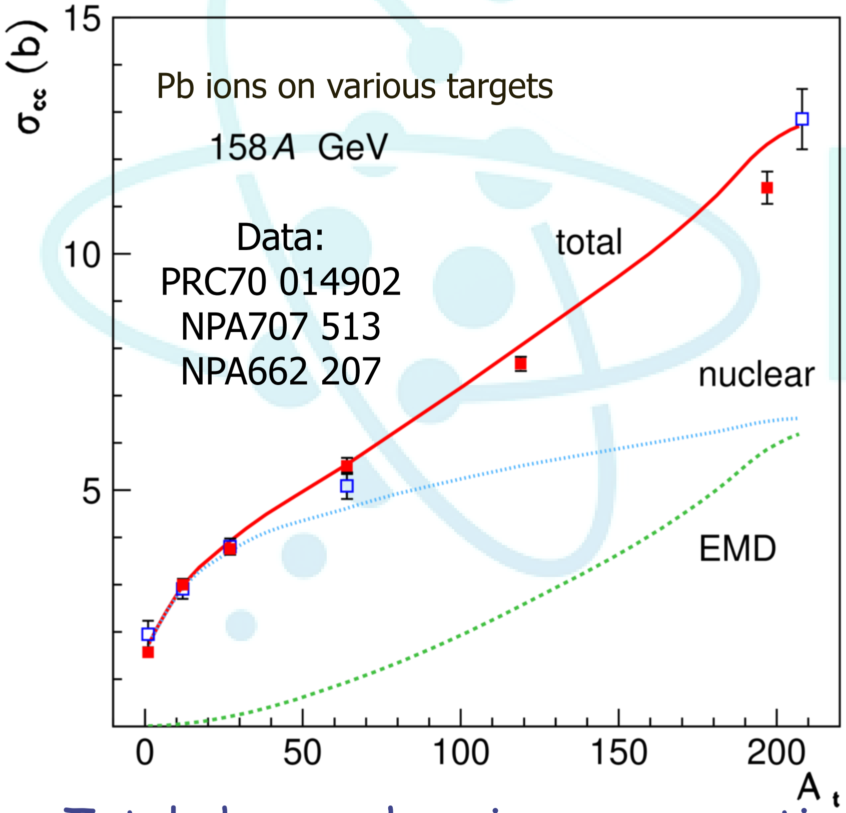
ElectroMagnetic Dissociation

… nuclear and, mostly, **ElectroMagneticDissociation** collisions produce a **variety** of (excited), possibly radioactive, **fragments**

- Very peripheral collisions
- Break-up of one of the colliding nuclei in the electromagnetic field of the other nucleus



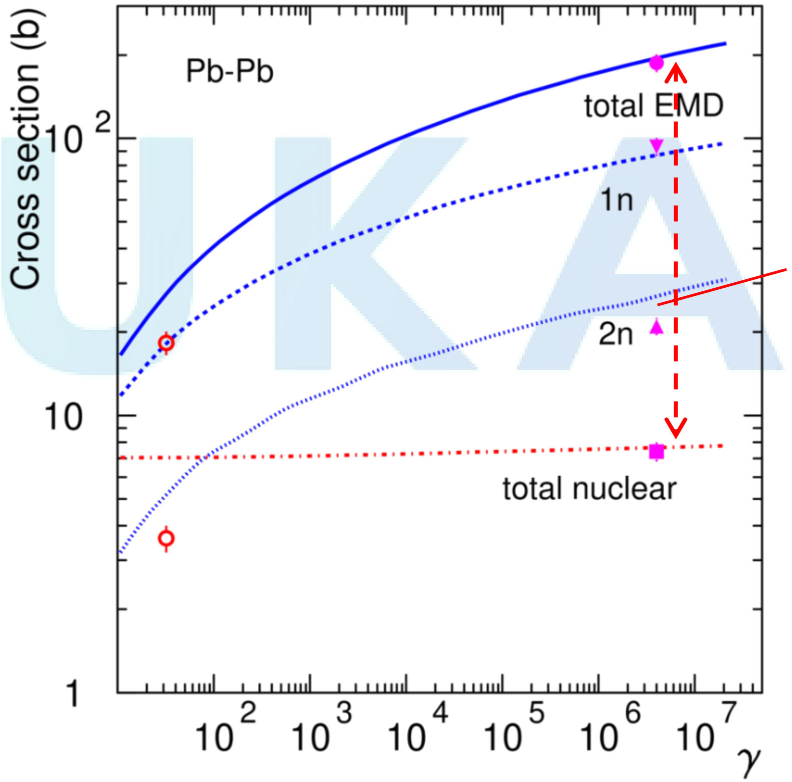
Example with SPS (left) and LHC (right)



Total charge changing cross section as a function of target atomic mass

Symbols: exp. data
Lines: Fluka

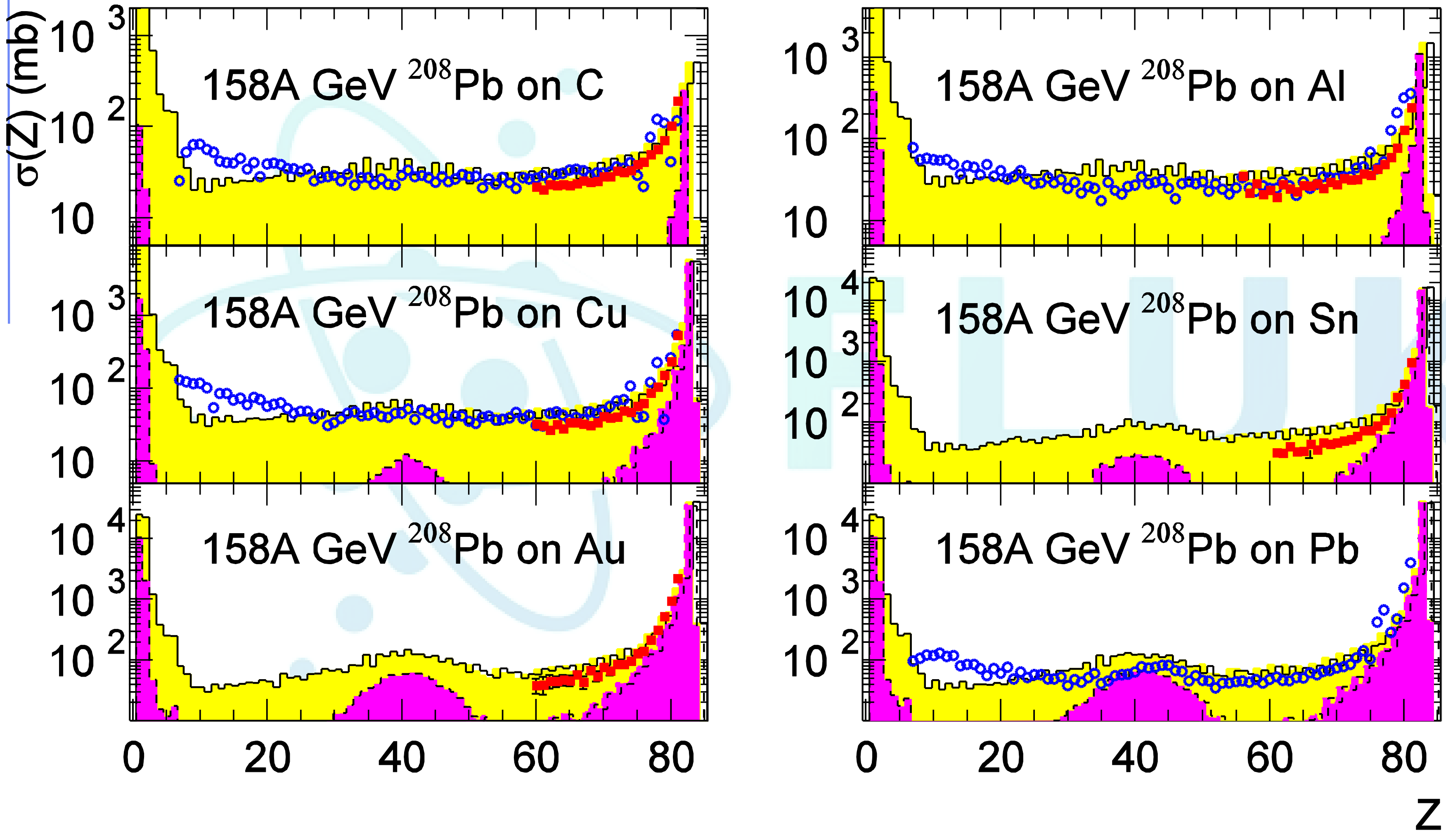
PRSTAB17 021006



Purple sym.
Alice:
$\sqrt{s_{nn}}$=2.8 TeV
PRL109 252302

Total EMD, 1 n, 2 n, and nuclear cross sections as a function of the effective γ factor

158 GeV/n Pb ion fragmentation: EMD and nuclear



Fragment charge cross section for 158 AGeV Pb ions on various targets.

Data (symbols) from NPA662, 207 (2000), NPA707, 513 (2002) (blue circles)

and from

C.Scheidenberger et al. PRC70, 014902 (2004), (red squares),

yellow histos are FLUKA (with DPMJET-III) predictions: *purple* histos are the EMD

Is EMD important for UHE (atmospheric) showers?

Computed EMD cross sections for various energy/ target/ projectile combinations (statistical errors ~2-3%)

	E (eV/n)	Proj diss. (mb)	1n (mb)	2n (mb)	Mesons	Targ diss. (mb)	σ_{abs} (mb)	<Eloss> (TeV)
56Fe on 14N								
	1.e+18	464	133	22	48.6%	1527	2335	~ 77
	1.e+20	647	163	30	54.4%	2170	2477	~6000
56Fe on 16O								
	1.e+18	605	175	30	48.3%	1769	2476	~ 79
	1.e+20	846	218	38	54.2%	2501	2623	~5400
56Fe on 40Ar								
	1.e+18	3034	881	149	47.8%	4451	3310	~ 59
	1.e+20	4234	1080	193	54.2%	6255	3478	~4800
14N on 14N								
	4.e+18	126	2.1	0	59.7%	126	1352	~ 380
	4.e+20	176	2.6	0	65.0%	176	1457	~29000

Cross sections are not negligible wrt absorption ones…
Energy losses are significant

- "xn" column: σ for emission of x neutrons only (proj. diss.);
- "mesons" column: fraction of EMD interactions (proj+targ) resulting in meson emissions;
- $\langle E_{loss} \rangle$ column: indication (rough, it converges slowly) of the average energy spent in each interaction (proj+targ)

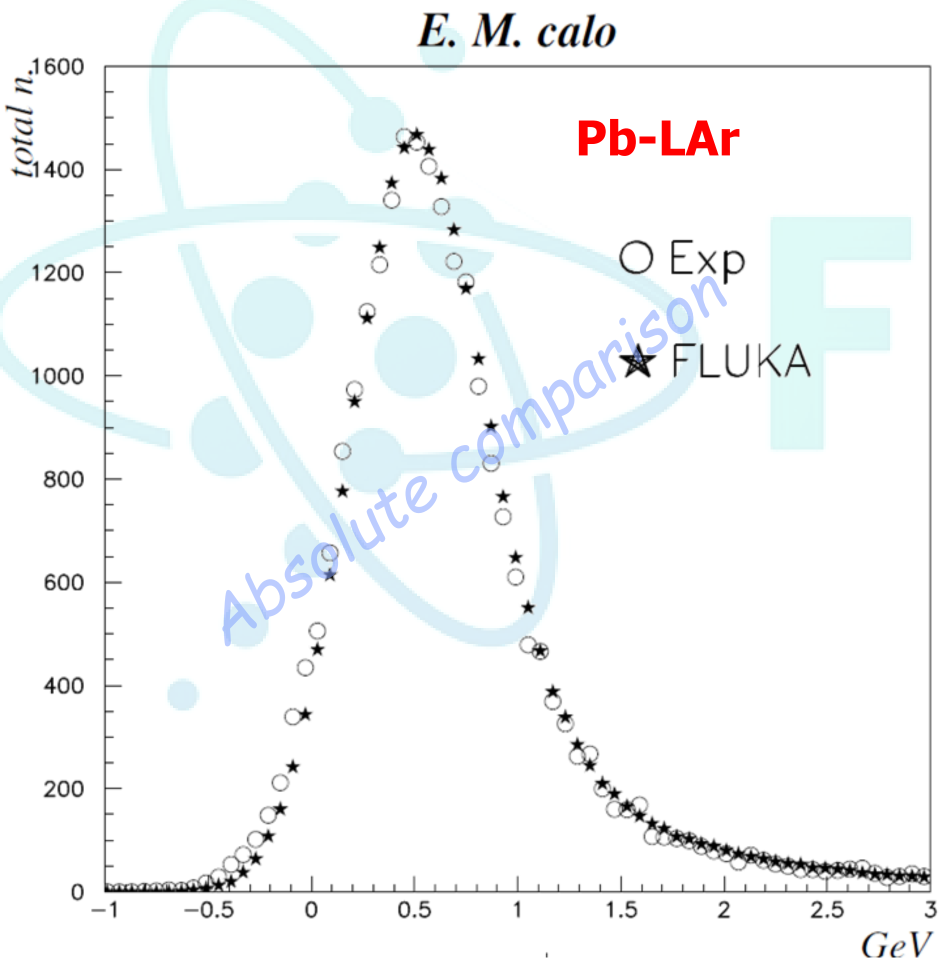
Do they matter? Hard to say… in terms of average muon and neutron production apparently not much, the jury is still out for other observables

Muon and (anti)neutrino physics in FLUKA

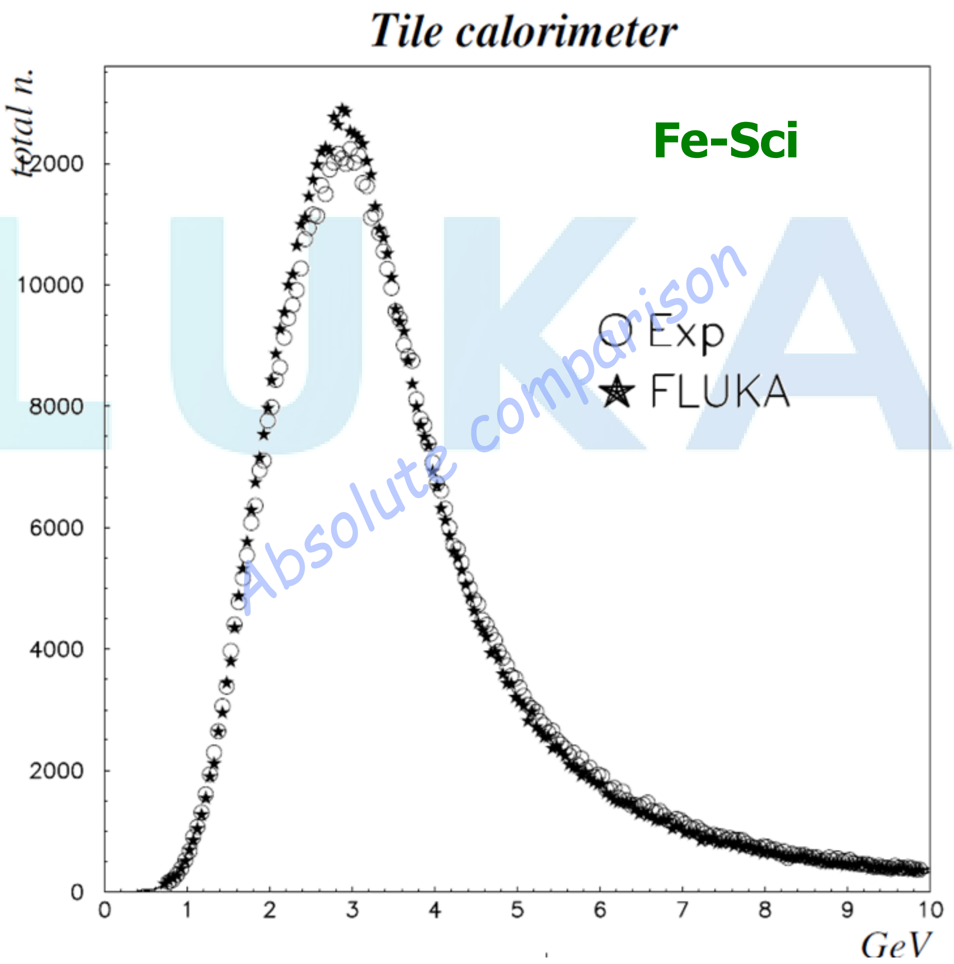
300 GeV muons: *ATLAS combined calorimeter test(s) (mid '90's):*

MIP signal in the calorimeters

E.M. Calorimeter



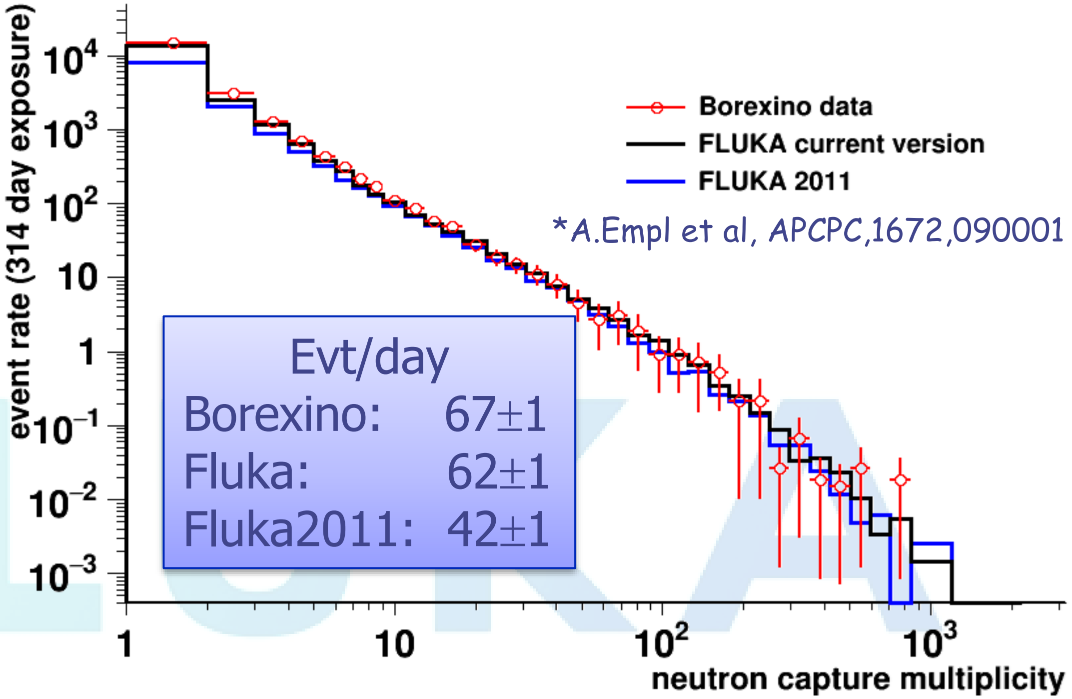
Tile Calorimeter



Muons in FLUKA

- Ionization energy losses
- Multiple Coulomb scattering
- Decay, accounting for polarization
- (Virtual) Photonuclear interactions
- Pair Production
- Bremsstrahlung

μ Induced neutron multiplicity @ Borexino, $\langle E_\mu \rangle$ = 283 GeV



*A.Empl et al, APCPC,1672,090001

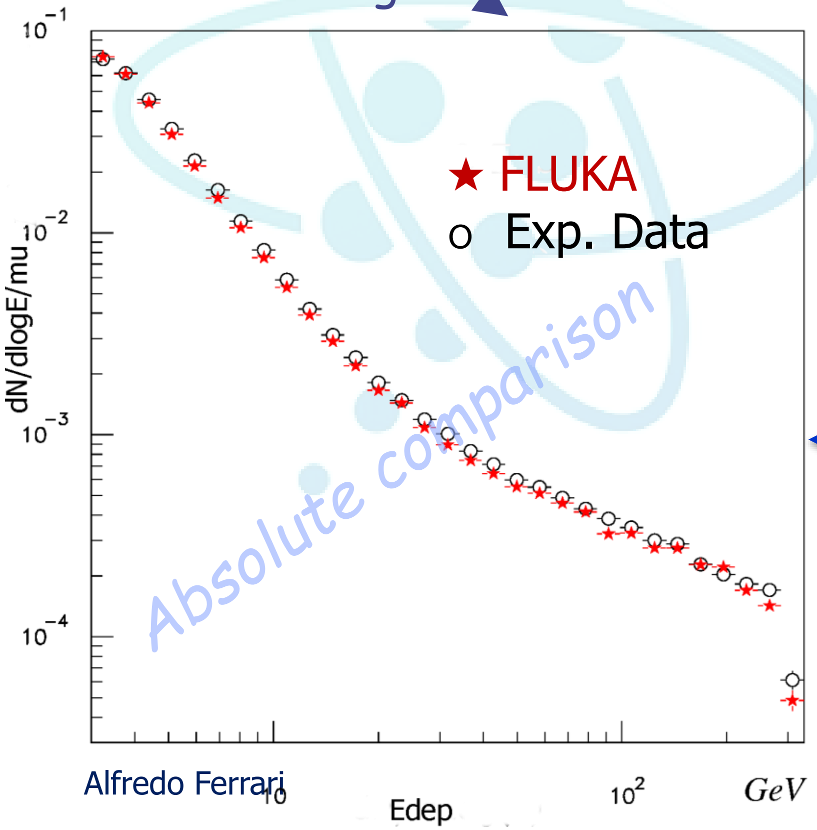
Evt/day

Borexino: 67±1

Fluka: 62±1

Fluka2011: 42±1

Energy loss spectrum, from 300 GeV muons in the ATLAS Tile calorimeter prototype (Fe+Sci), for E_{loss} >3GeV

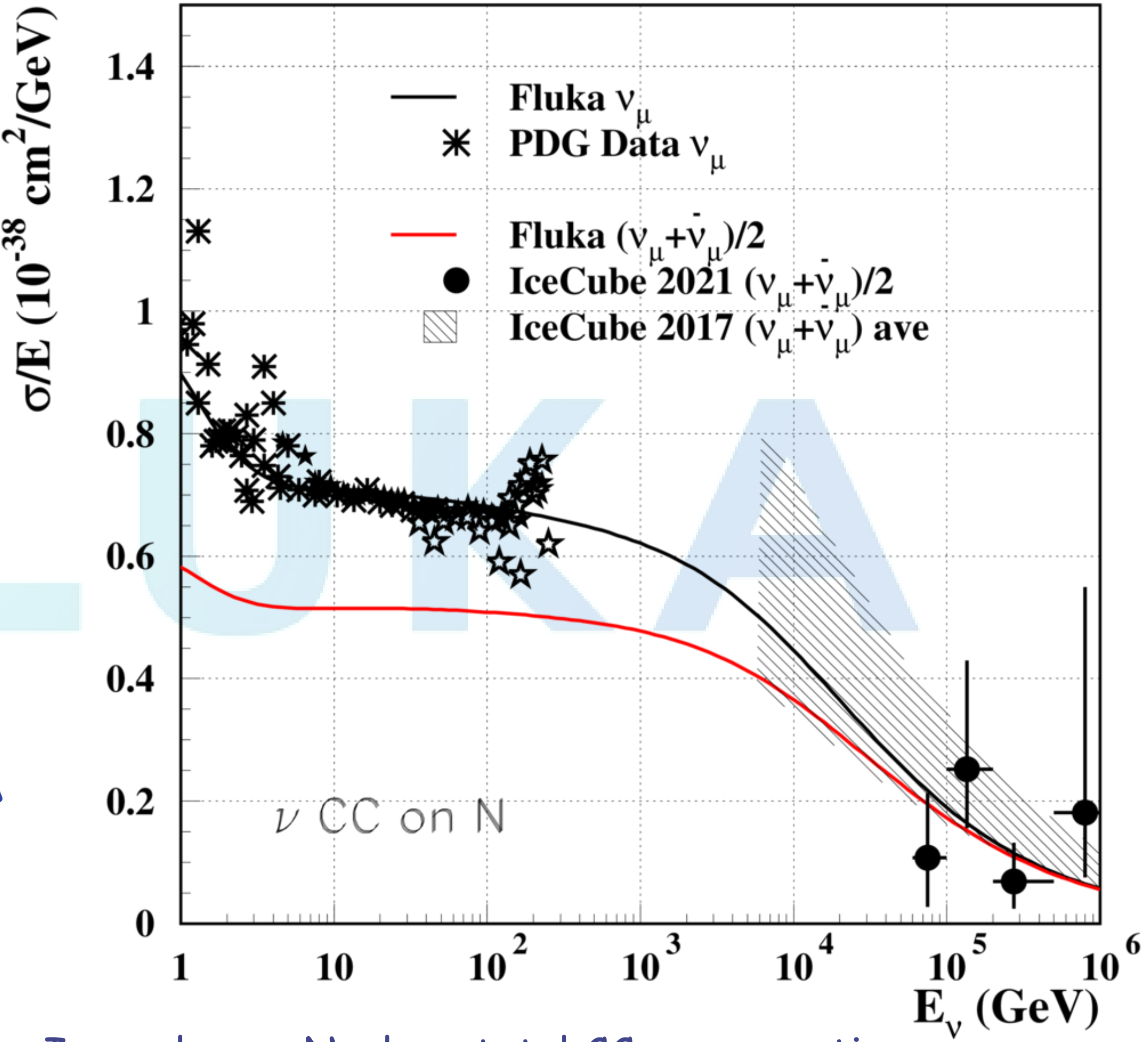


Absolute comparison

(Anti)Neutrinos in FLUKA:

Acta Phys.Polon. B40 (2009) 2491-2505
CERN-Proceedings-2010-001 pp.387-394.

- **νN QuasiElastic (from ~0.1 GeV upward):**
  - Following Llewellyn Smith formulation
  - Lepton masses accounted for
- **νN Resonance production**
  - From Rein-Sehgal formulation
  - Keep only Δ production
  - Non-resonant background term from DIS
- **νN Deep Inelastic Scattering**
  - NunDIS model (developed ad hoc for FLUKA)
  - Chains from νN DIS: → FLUKA hadronization
- **νN interactions** embedded in PEANUT for **νA** (Initial State and Final State effects)
- **Fermi/GT absorption** of few-MeV (solar) neutrinos on ^{40}**Ar**

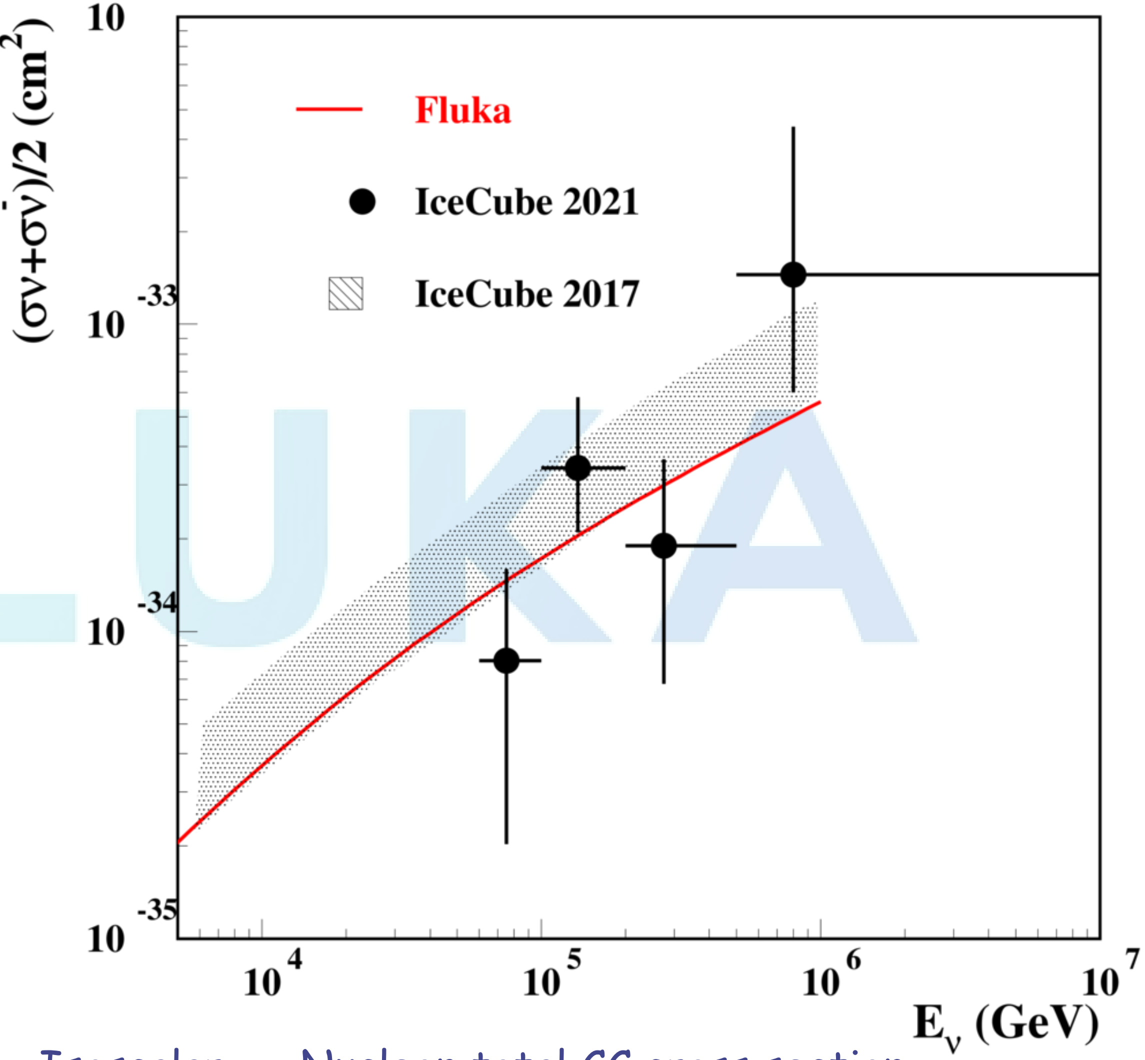


Isoscalar ν_μ-Nucleon total CC cross section
Fluka (lines) vs experimental data

(Anti)Neutrinos in FLUKA:

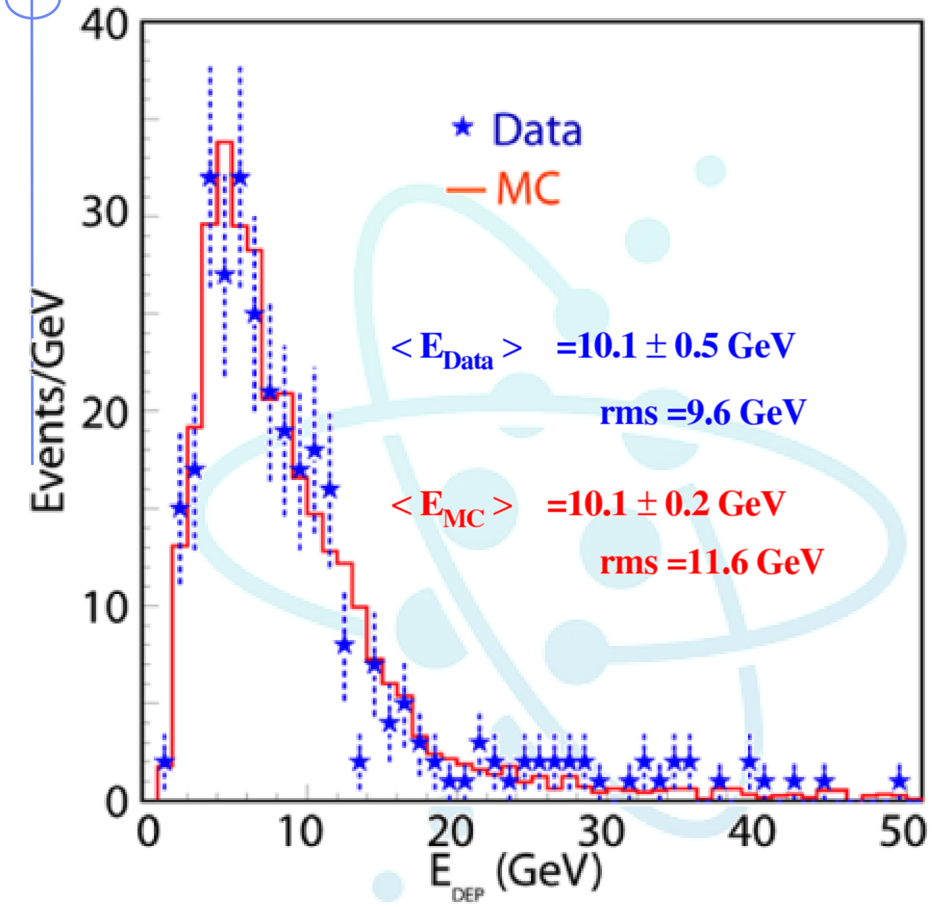
Acta Phys.Polon. B40 (2009) 2491-2505
CERN-Proceedings-2010-001 pp.387-394.

- **νN QuasiElastic (from ~0.1 GeV upward):**
  - Following Llewellyn Smith formulation
  - Lepton masses accounted for
- **νN Resonance production**
  - From Rein-Sehgal formulation
  - Keep only Δ production
  - Non-resonant background term from DIS
- **νN Deep Inelastic Scattering**
  - NunDIS model (developed ad hoc for FLUKA)
  - Chains from νN DIS: → FLUKA hadronization
- **νN interactions** embedded in PEANUT for **νA** (Initial State and Final State effects)
- **Fermi/GT absorption** of few-MeV (solar) neutrinos on ^{40}**Ar**



Isoscalar ν_μ-Nucleon total CC cross section
Fluka (lines) vs experimental data

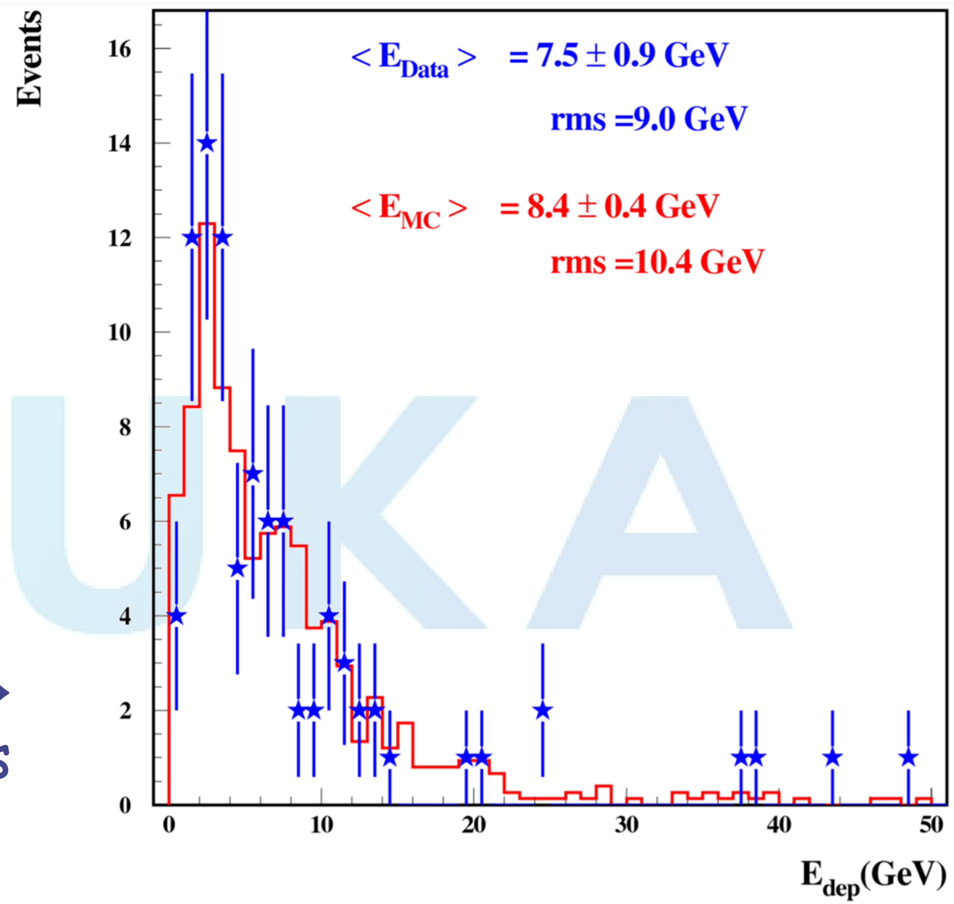
Reaction products: CNGS data (≈20 GeV $\langle E_\nu \rangle$)



Distribution of total deposited energy in the ICARUS T600 detector*

← Left: ν_μ CC events

Right:→ ν NC events



*Eur. Phys. J. C (2013) 73:2345
Phys. Lett. B (2014)

Same reconstruction in MC and Data. Neutrino fluxes from FLUKA CNGS simulations
Absolute agreement on neutrino rates within 6%

For an example at lower energies see Phys. Rev. D **99**, 012002

Interface with UHECR generators (and with Corsika7/8)

New interfaces to, and from, Corsika/HE generators

- "Standard" code for high energy atmospheric showers simulations: CORSIKA (D. Heck et al., Forschungszentrum Karlsruhe Report **FZKA 6019 (1998)**)
- Since long, CORSIKA is using the FLUKA hadronic models for interactions below some user defined threshold (D. Heck et al., Proc. 28th ICRC p.279 (2003))

Two development lines:*

**With the essential help of T.Pierog*

Revised interface for performing FLUKA interactions within CORSIKA (*completed!*)

- More flexible
- All materials/compounds (was only air)
- *(New)* Elastic and qe scattering events
- *(New)* EMD
- *(New)* Electro- and photonuclear interactions

Adapted also for CORSIKA 8

Completely new interface for calling very high energy generators within FLUKA

EPOS-LHC (T.Pierog, K.Werner, Nucl.Phys.Proc.Suppl. 196:102-105, and this conference)
SIBYLL-2.3d(*) (F.Riehn this conference, Phys.Rev.D102, 063002)
In the future also:
QGSJET (S.Ostapchenko, Phys.Rev. D83 014018)

Exploiting the existing CRMC environment

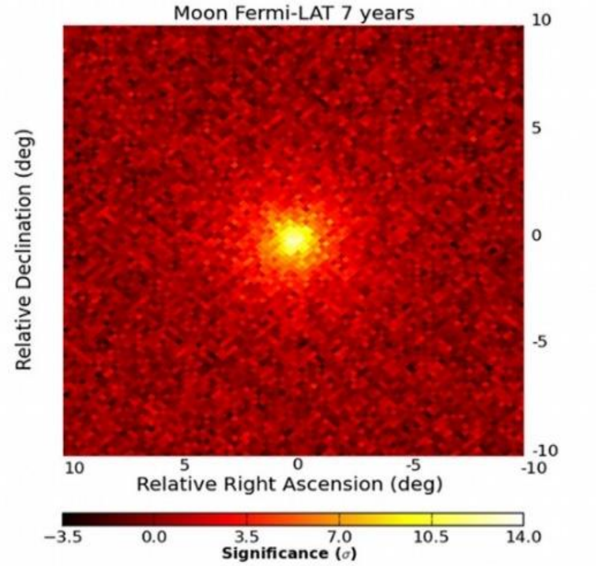
(CRMC: R. Ulrich, T.Pierog, C. Baus. (2021) https://doi.org/10.5281/zenodo.4558705)

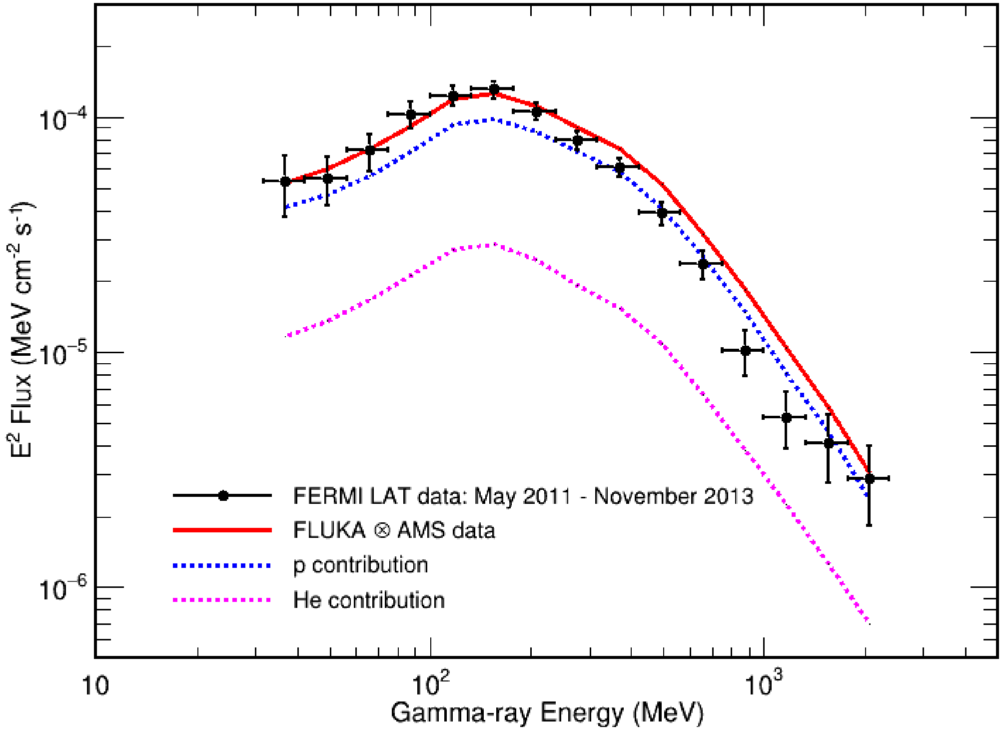
Some recent FLUKA CR applications

The Moon in gamma-rays

https://doi.org/10.1103/PhysRevD.93.082001

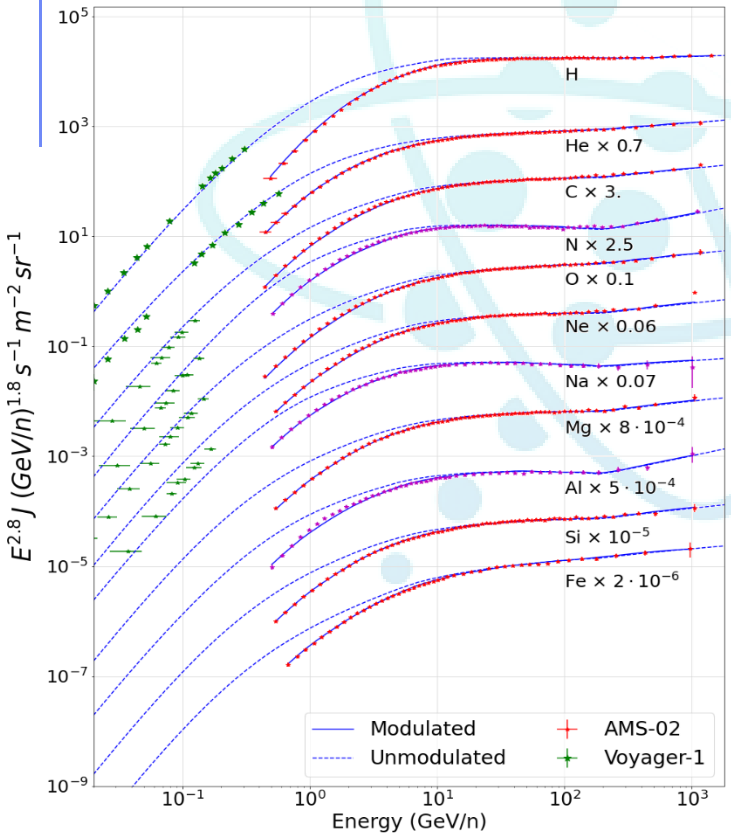
- Gamma rays are produced in the interactions of primary CRs with the lunar surface
- The lunar gamma-ray flux is sensitive to:
  - Primary CR composition and spectra
  - Lunar surface composition
  - Interaction process of primary CRs with the lunar regolith
- The gamma-ray flux from the Moon is correlated with Solar activity
- The gamma-rays yield has been calculated with Fluka using the Moon as a target…
- … and compared with FERMI-LAT measurements



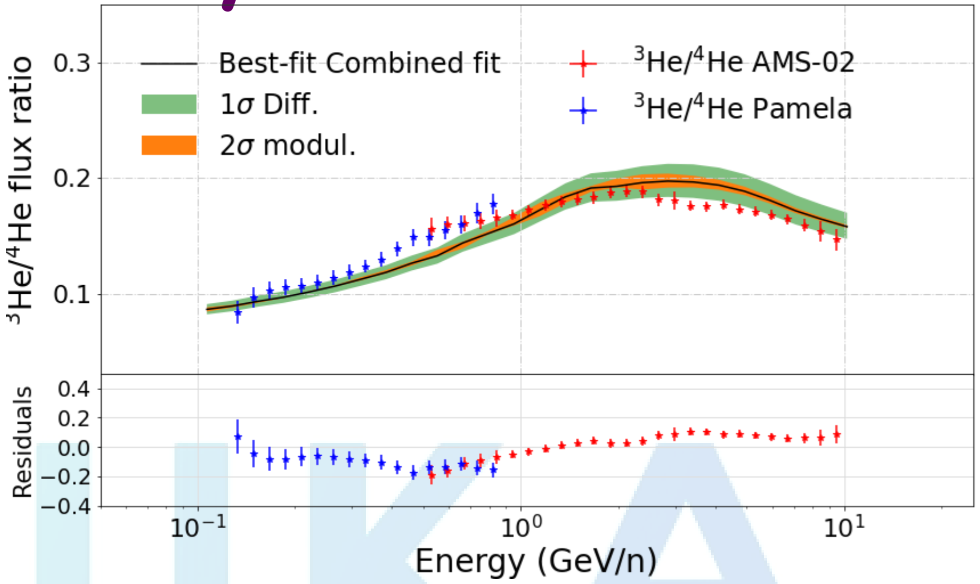


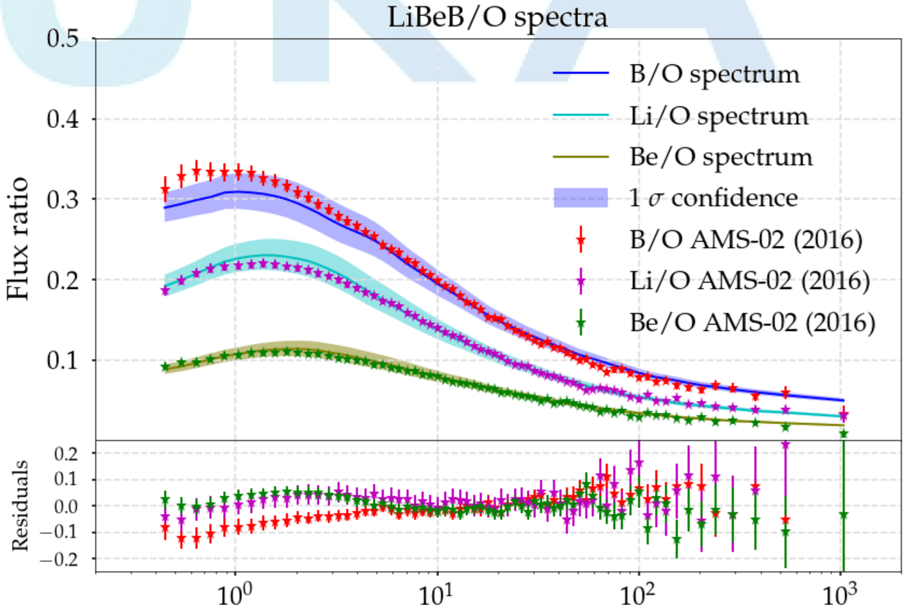
FLUKA Cross sections for cosmic-ray interactions

Inelastic and inclusive **cross sections for interactions of all CR isotopes of CR** nuclei up to Iron were calculated using Fluka.They have been **implemented in the DRAGON2 code to study Galactic CR propagation**



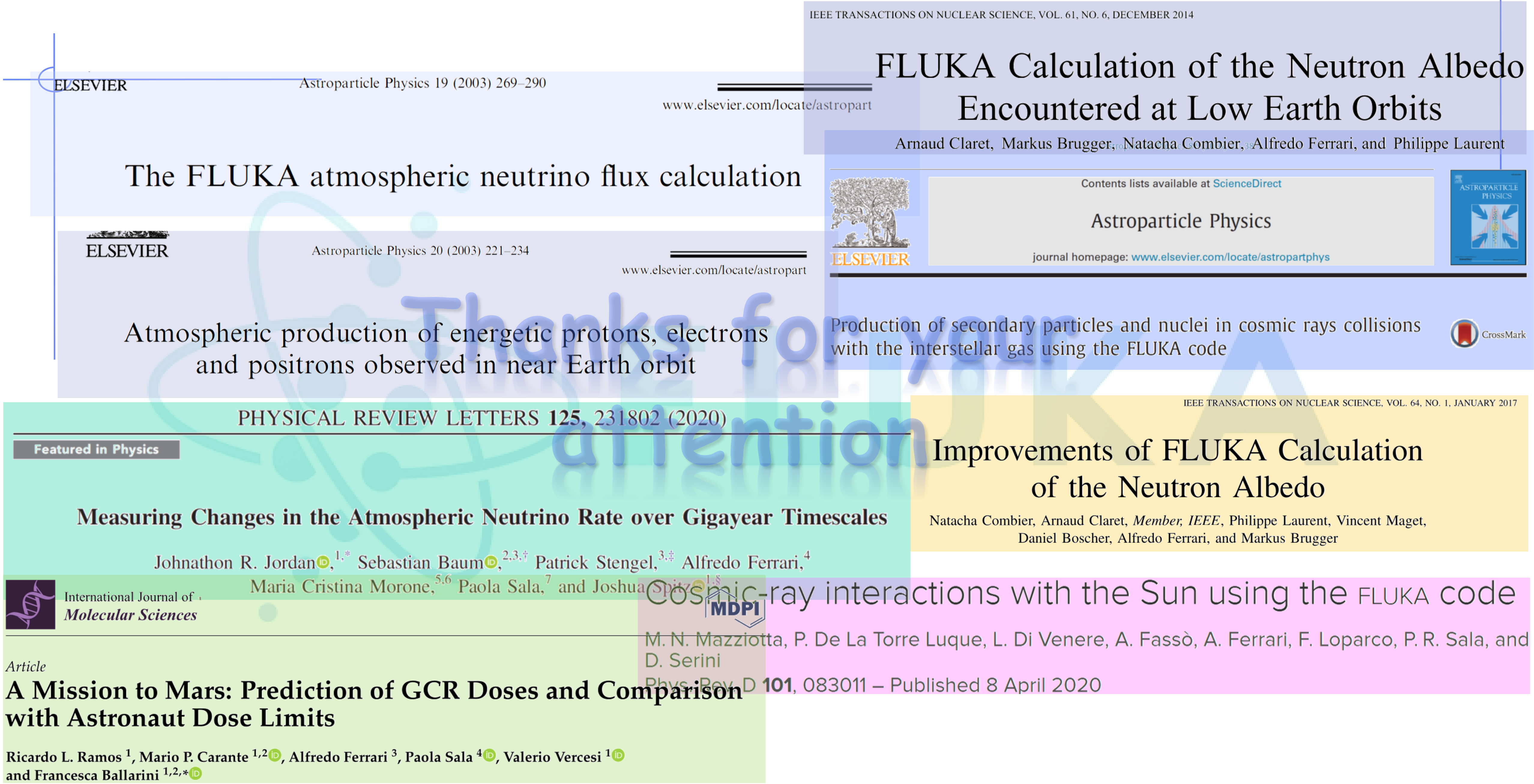
The Fluka cross sections allow us to reproduce all light secondary CRs simultaneously





P. De La Torre Luque *et al*

JCAP07(2022)008



ELSEVIER

Astroparticle Physics 19 (2003) 269–290

www.elsevier.com/locate/astropart

The FLUKA atmospheric neutrino flux calculation

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 61, NO. 6, DECEMBER 2014

FLUKA Calculation of the Neutron Albedo Encountered at Low Earth Orbits

Arnaud Claret, Markus Brugger, Natacha Combier, Alfredo Ferrari, and Philippe Laurent

---

ELSEVIER

Astroparticle Physics 20 (2003) 221–234

www.elsevier.com/locate/astropart

Atmospheric production of energetic protons, electrons and positrons observed in near Earth orbit

---

Contents lists available at ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropartphys

ELSEVIER

ASTROPARTICLE PHYSICS

Production of secondary particles and nuclei in cosmic rays collisions with the interstellar gas using the FLUKA code

CrossMark

Thanks for your attention

PHYSICAL REVIEW LETTERS **125**, 231802 (2020)

Featured in Physics

Measuring Changes in the Atmospheric Neutrino Rate over Gigayear Timescales

Johnathon R. Jordan[1,*] Sebastian Baum[2,3,†] Patrick Stengel,[3,‡] Alfredo Ferrari,[4]
Maria Cristina Morone,[5,6] Paola Sala,[7] and Joshua Spitz[1,§]

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 64, NO. 1, JANUARY 2017

Improvements of FLUKA Calculation of the Neutron Albedo

Natacha Combier, Arnaud Claret, *Member, IEEE*, Philippe Laurent, Vincent Maget,
Daniel Boscher, Alfredo Ferrari, and Markus Brugger

International Journal of
Molecular Sciences

MDPI

Article

A Mission to Mars: Prediction of GCR Doses and Comparison with Astronaut Dose Limits

**Ricardo L. Ramos [1], Mario P. Carante [1,2], Alfredo Ferrari [3], Paola Sala [4], Valerio Vercesi [1]
and Francesca Ballarini [1,2,*]**

Cosmic-ray interactions with the Sun using the FLUKA code

M. N. Mazziotta, P. De La Torre Luque, L. Di Venere, A. Fassò, A. Ferrari, F. Loparco, P. R. Sala, and D. Serini

Phys. Rev. D **101**, 083011 – Published 8 April 2020