(Hadronic) FLUKA and the Corsika interface

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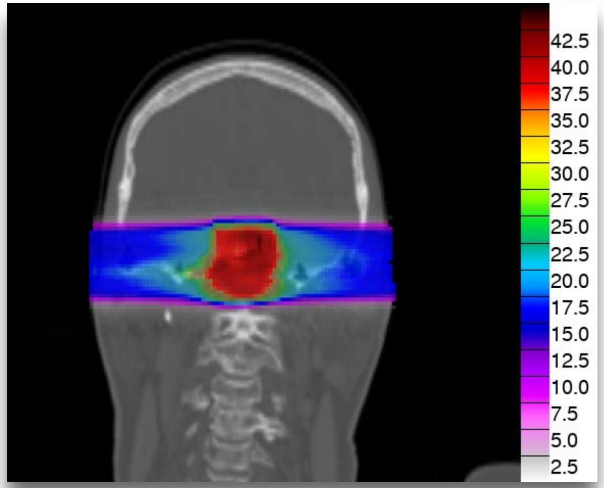
for the FLUKA Collaboration

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

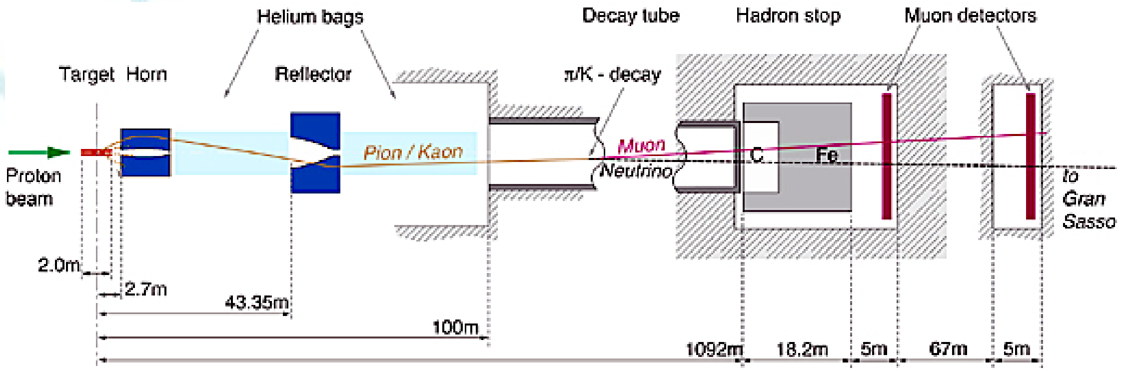
FLUKA is a general purpose tool for calculations of particle transport and interactions with matter

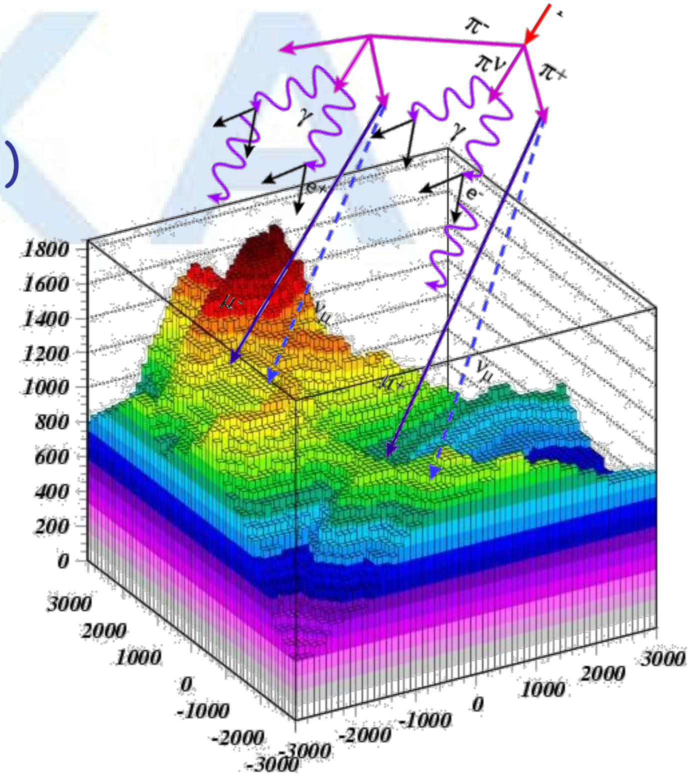


FLUKA Applications:

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





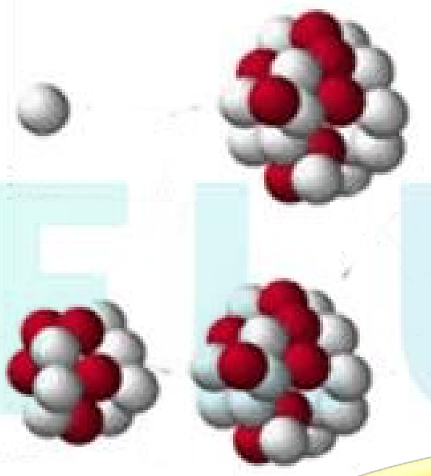
http://www.fluka.org ~14000 registered users worldwide

Fluka hA/AA models:

PEANUT
$10^4 > E > \sim 0.01$ 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
$10^{11} > E/n > 10\text{-}15$ GeV

BME
$100\text{-}150 > E/n > \sim 5$ MeV

Extended rQMD
$10\text{-}15 > E/n > 0.1\text{-}0.15$ GeV

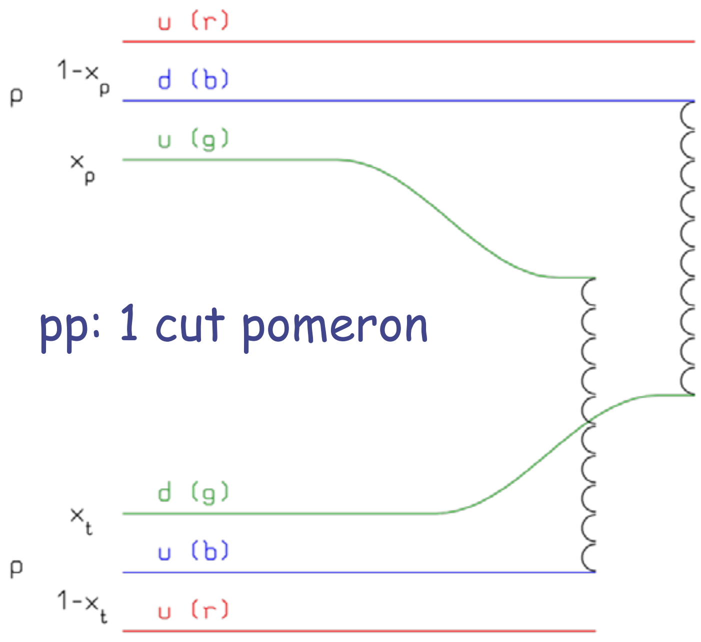
Nonelastic hN interactions: (very) short summary

Up to a few GeV's:
Dominance of the Δ and of the N^*, ρ... resonances
→ isobar model
→ all reactions proceed through an intermediate state containing at least one resonance

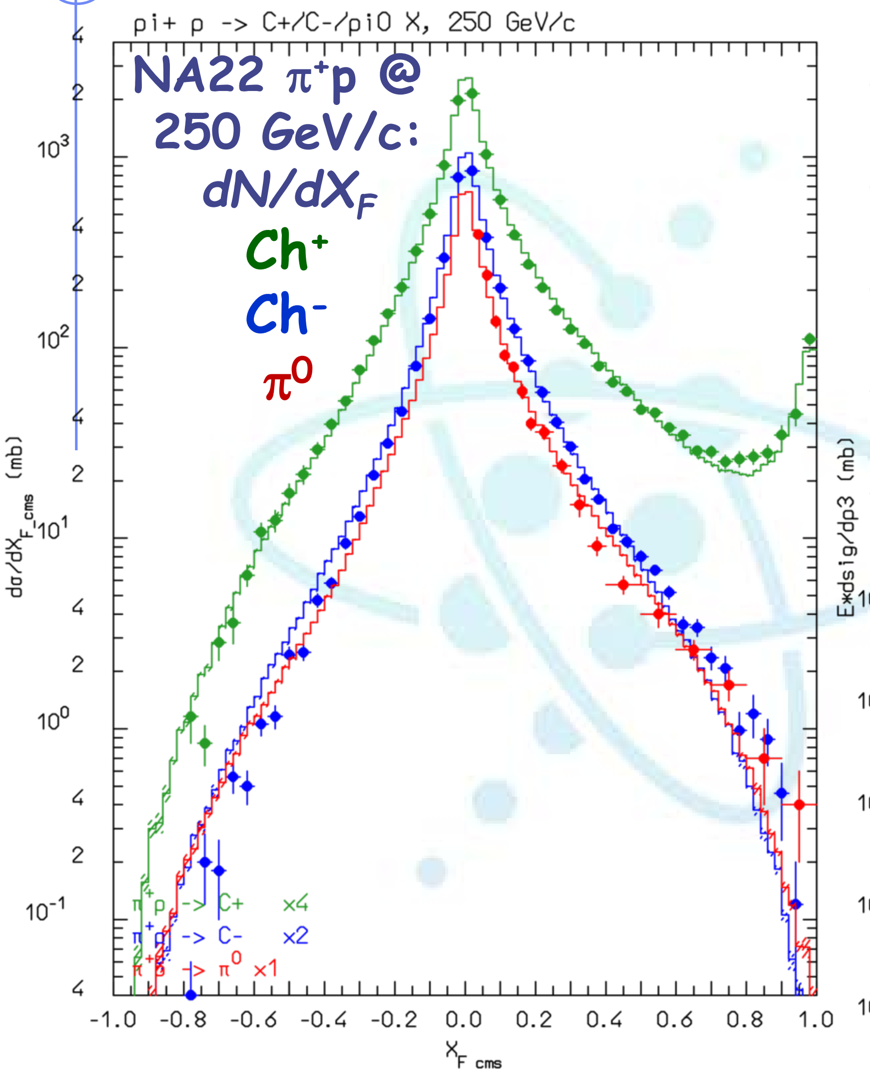
$N_1 + N_2 \rightarrow N''_1 + \Delta(1232) \rightarrow N_1' + N_2' + \pi$
$\pi + N \rightarrow \Delta(1600) \rightarrow \pi' + \Delta(1232) \rightarrow \pi' + \pi'' + N'$
$N_1 + N_2 \rightarrow \Delta_1(1232) + \Delta_2(1232) \rightarrow N_1' + \pi_1 + N'_2 + \pi_2$

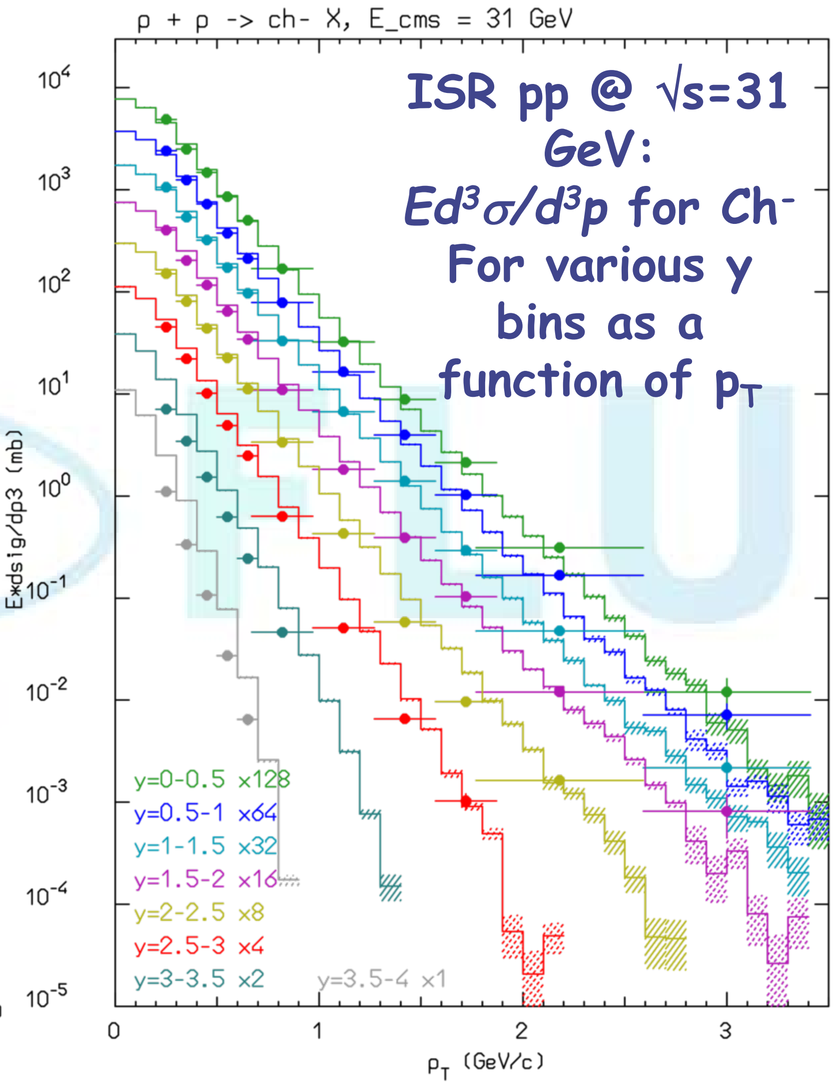
FLUKA: ≈ 60 resonances, and ≈ 100 channels

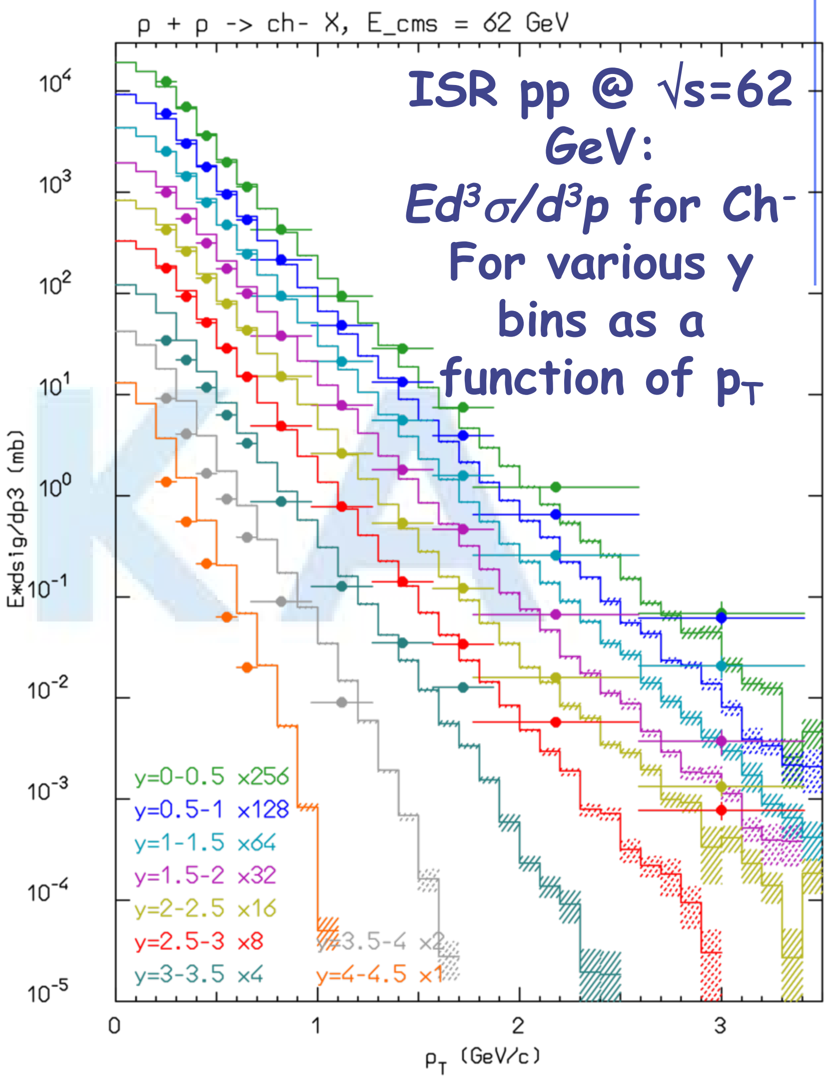
At energies above a few GeV's:
- Interacting strings (quarks held together by gluons into the form of a string)
- Interactions treated in the Reggeon-Pomeron framework (**Dual Parton Model, DPM**)
- Each hadron splits into **2 colored partons**
  → combination into **2 colourless chains**
  → **2 back-to-back jets**
- each jet is then **hadronized** into physical hadrons
- Fluka contains **its own hadronization** model



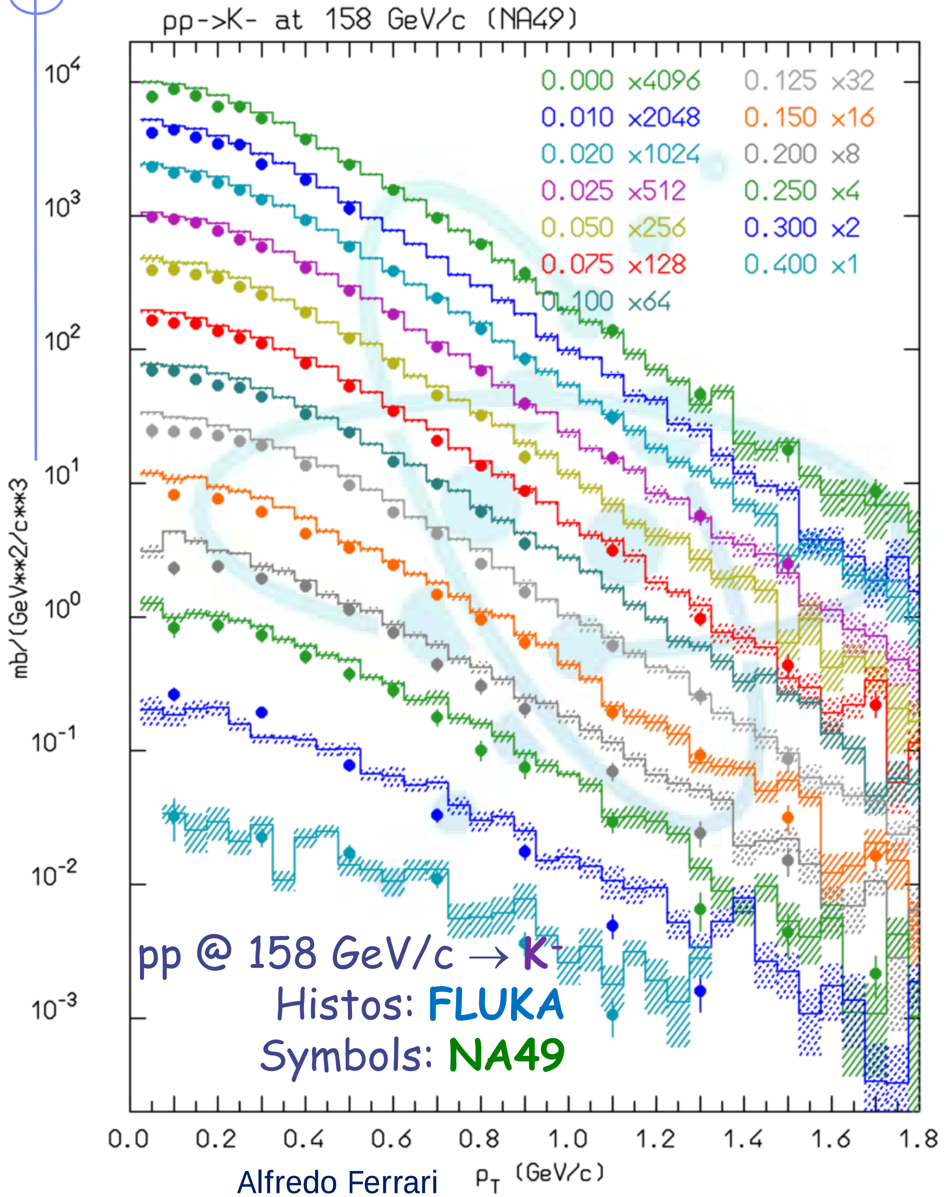
πp and pp interactions (histos Fluka symbols exp.):



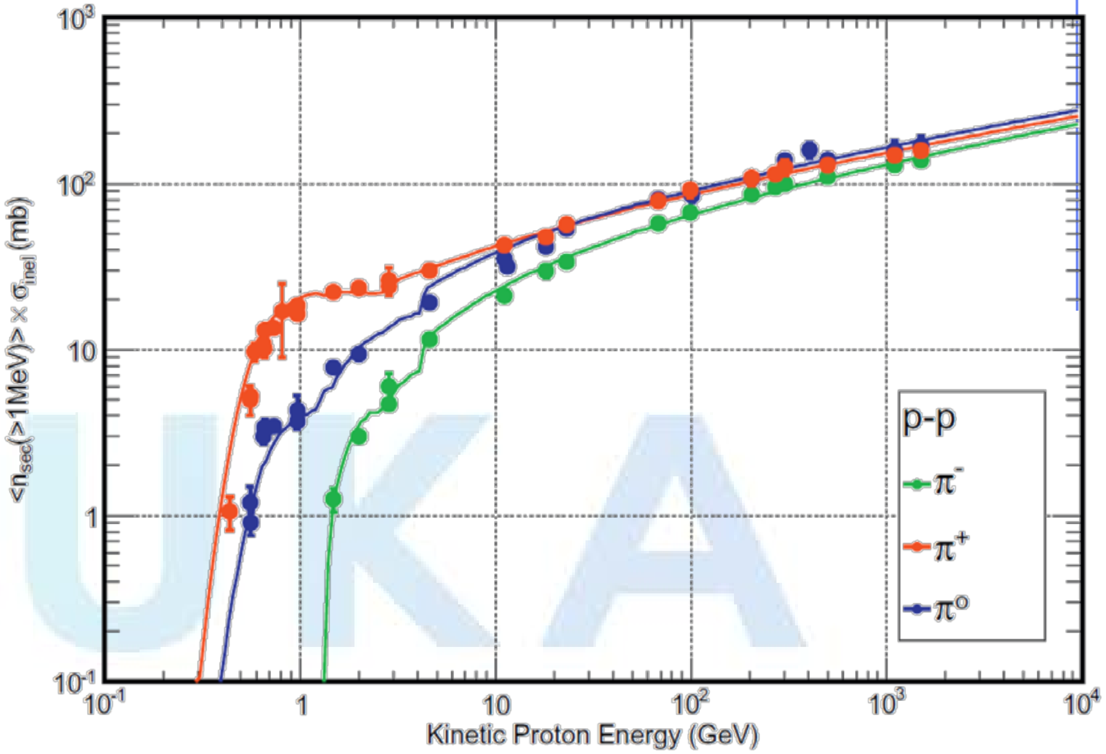




Pion/Kaon production in p-p collisions:

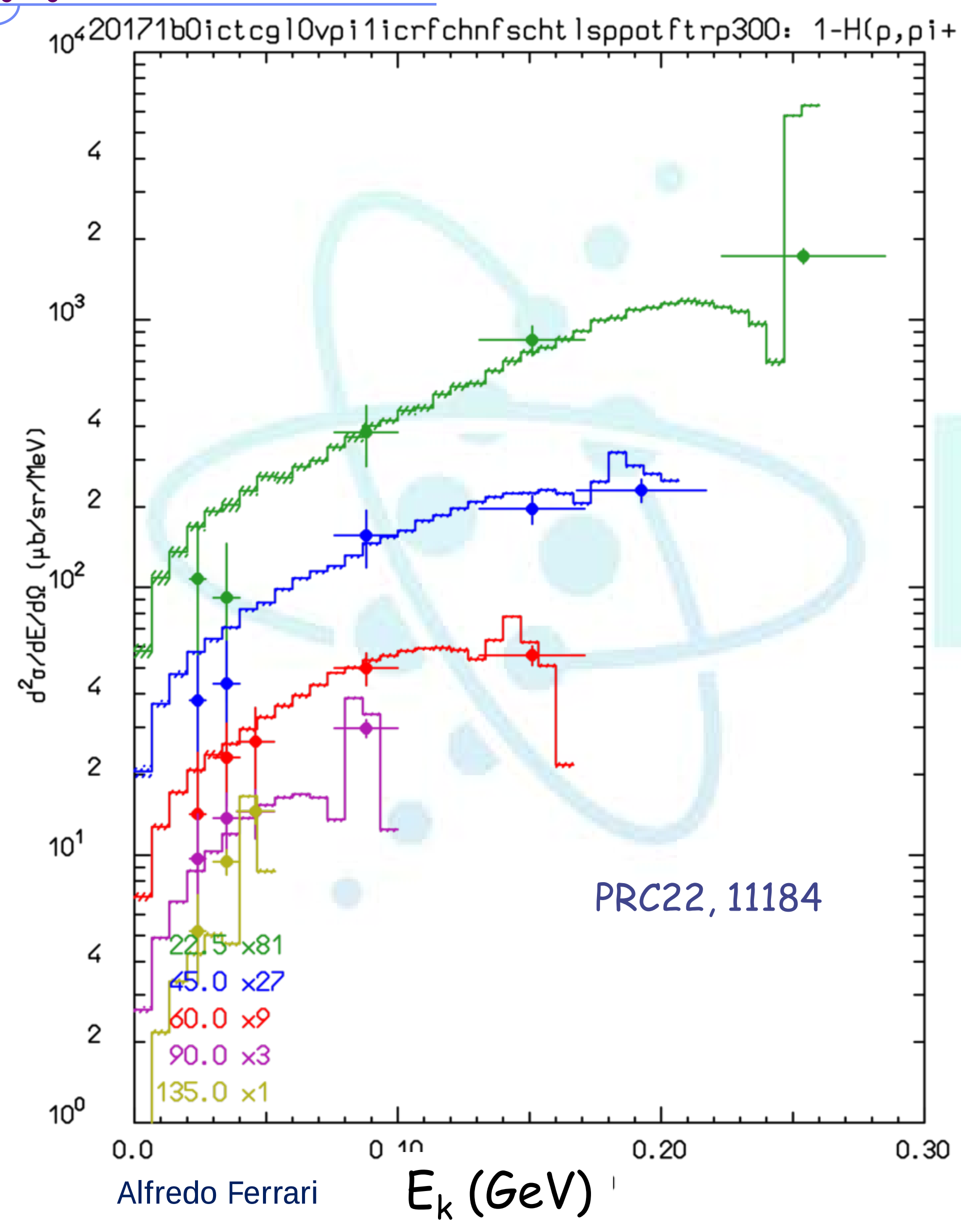


K^- yield as a function of p_T for different X_F bins, for 158 GeV/c protons on hydrogen



Inclusive cross section for the production of π^0 **(blue)**, π+ **(red)**, and π^- **(green)** in p-p collisions as a function of the proton kinetic energy. Lines: simulations, symbols exp. Data. (figure from AstrPhys81, 21 (2016))

$pp \rightarrow \pi^+X$ @ 585 MeV and $\pi^+p \rightarrow \pi^+X$ @ 6 and 22 GeV/c

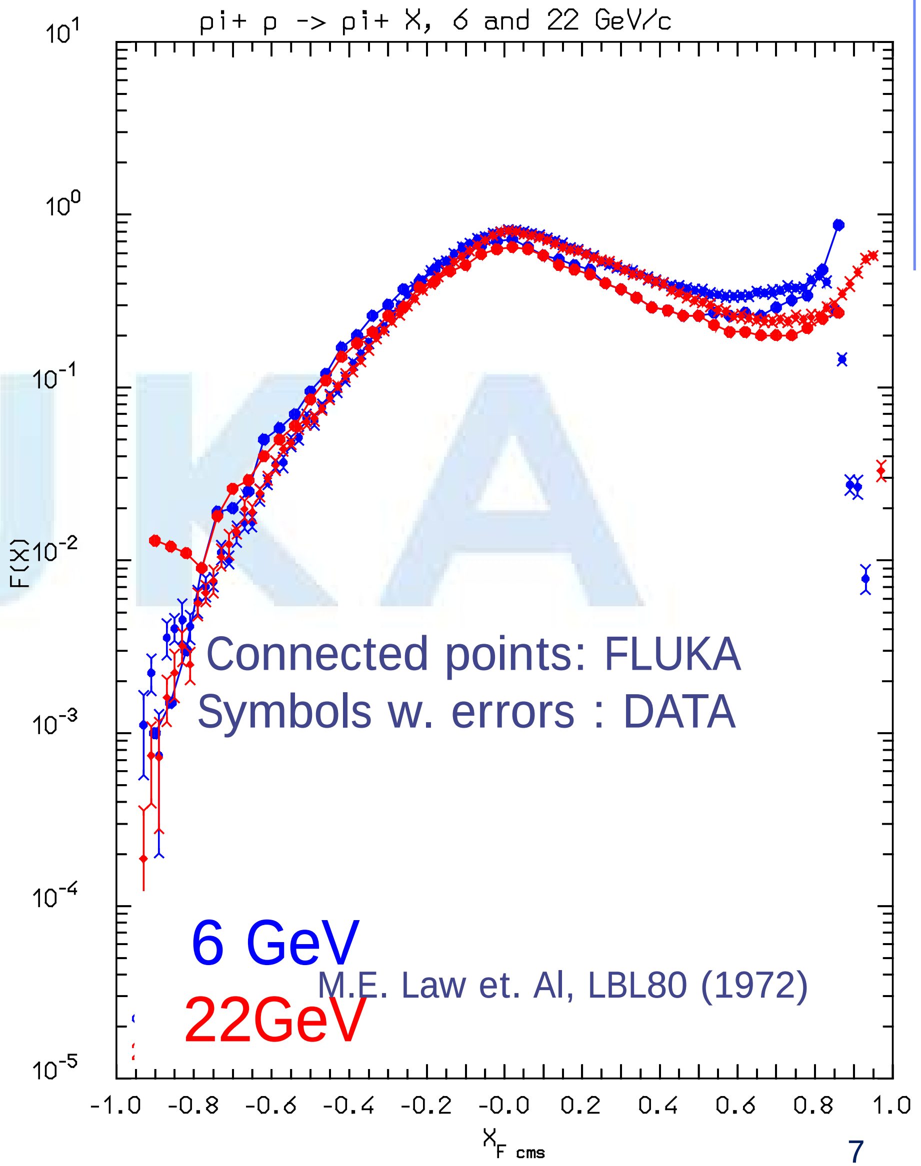


LEFT: π^+ $d^2\sigma/dE/d\Omega$ from proton – proton interactions at 585 MeV at different angles.

RIGHT: π^+ X_F distribution for 6 and 22 GeV/c π^+ on hydrogen

Symbols: data, histograms: Fluka

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



FLUKA (PEANUT) modeling of nuclear interactions

Target nucleus description (density, Fermi motion, etc)

⇓

Glauber-Gribov cascade with formation zone

⇓

(Generalized) IntraNuclear cascade

⇓

Preequilibrium stage with current exciton configuration and excitation energy
(all non-nucleons emitted/decayed + all nucleons below 30-100 MeV)

⇓

Evaporation/Fragmentation/Fission model

⇓

γ deexcitation

t (s)

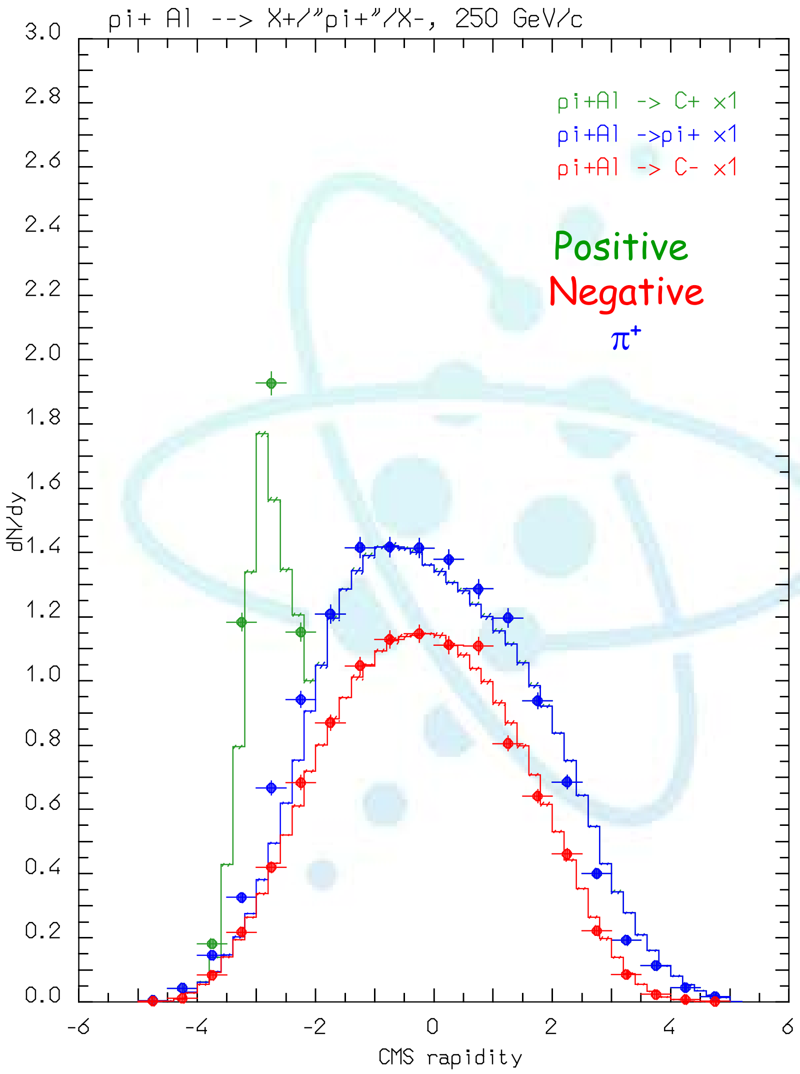
10^{-23}

10^{-22}

10^{-20}

10^{-16}

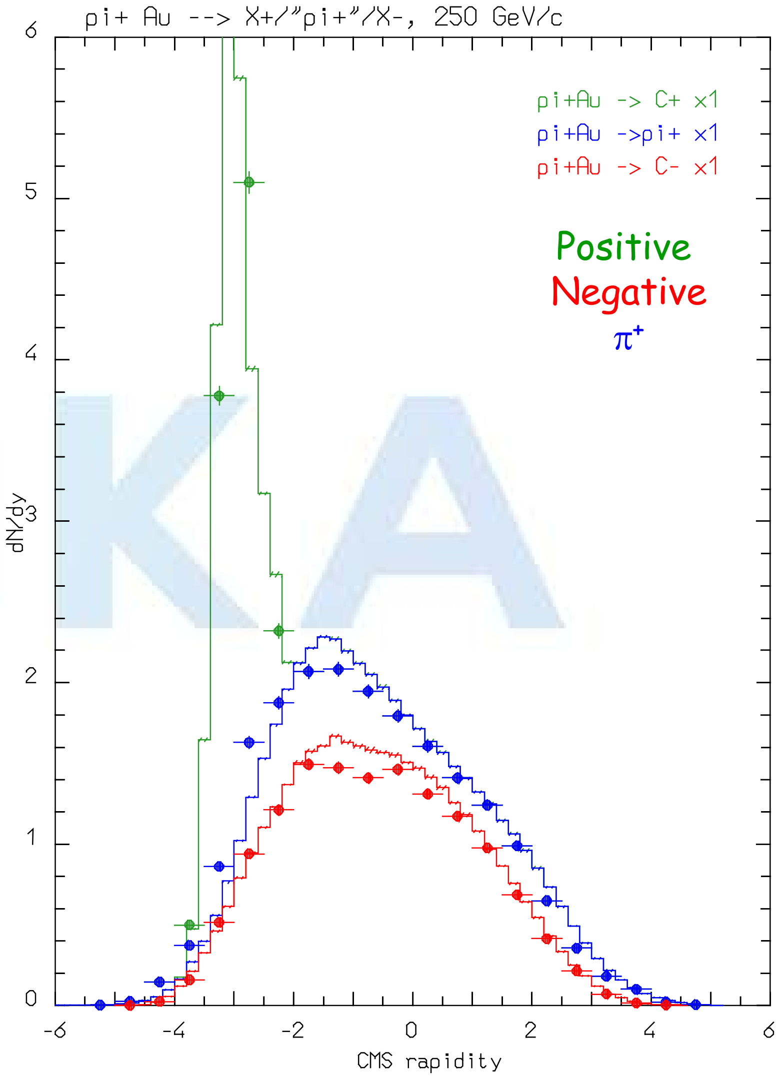
Setting the formation zone:



(Pseudo)rapidity y (η) distribution of charged particles produced in 250 GeV π^+ collisions on ← Aluminum (left) and Gold (right) →
Points: exp. data (ZPC50, 361 (1991))

Fluka hadronic models still work ***well up to a few TeV***! With the added benefit of a sophisticated nuclear environment for evaporation/fragments etc

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



Glauber with cross section fluctuations!

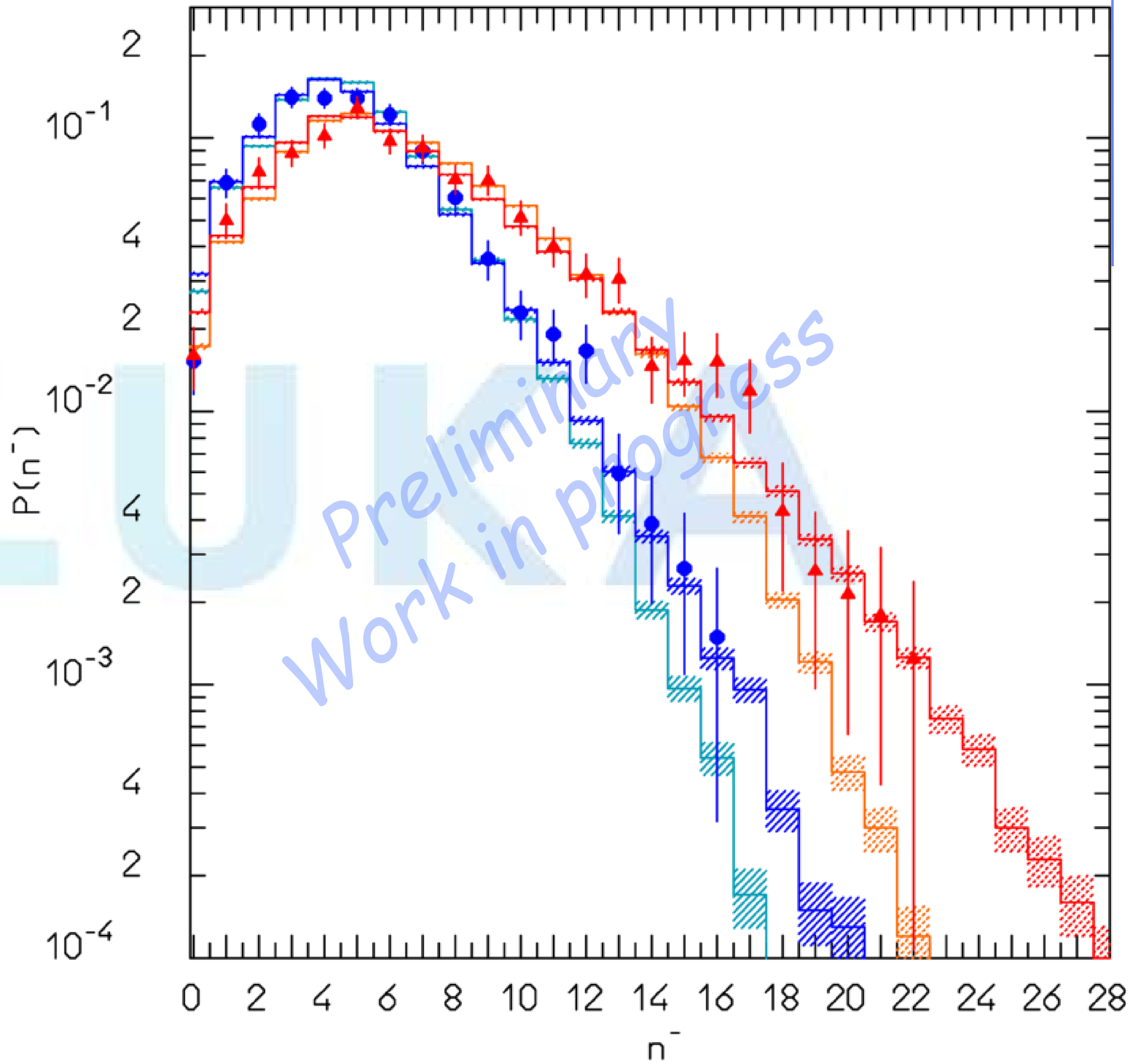
- The ***observed*** σ_{hN} is just the ***average*** of the σ's corresponding to all possible proj/targ (quark) configurations
- Considering the ***hadron as a color dipole*** a **fluctuating** σ can be used **inside the Glauber formalism**, providing among others ***inelastic screening for "free"***

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

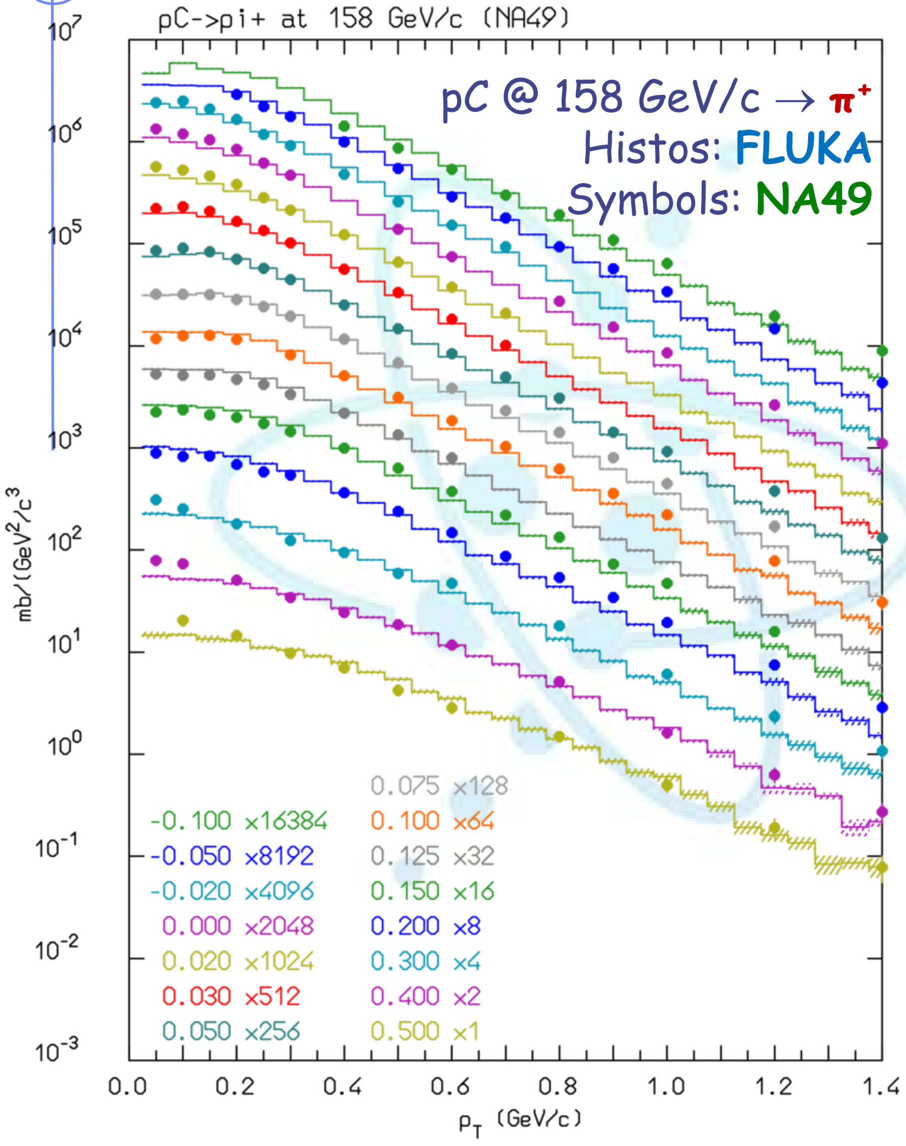
K⁺ Al K⁺ Au :

- **Blue (Al)/Red (Au) symbols** with error bars: exp. data (NA22 experiment)
- **Blue (Al)/Red (Au) histos**: Fluka simulation with cross section fluctuations
- **Cyan (Al)/Orange (Au) histos**: Fluka simulation without cross section fluctuations

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

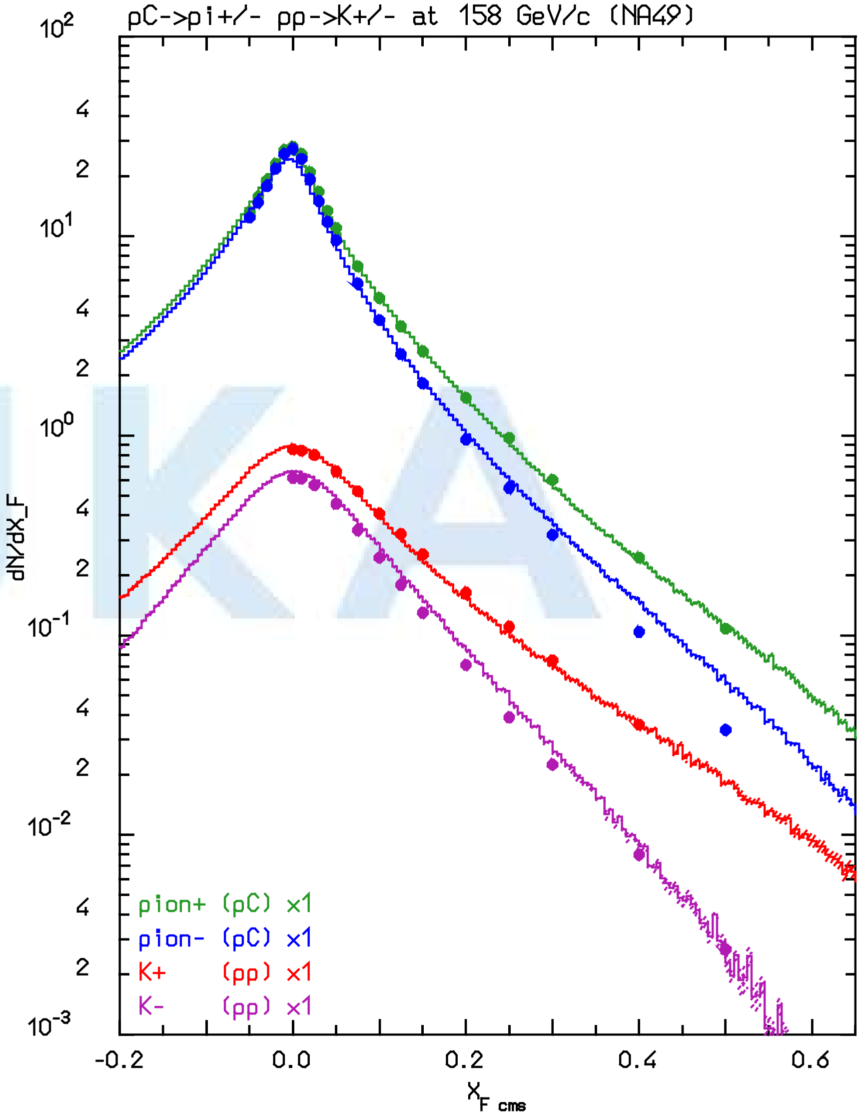


Pion (Kaon) hA (hp) production data

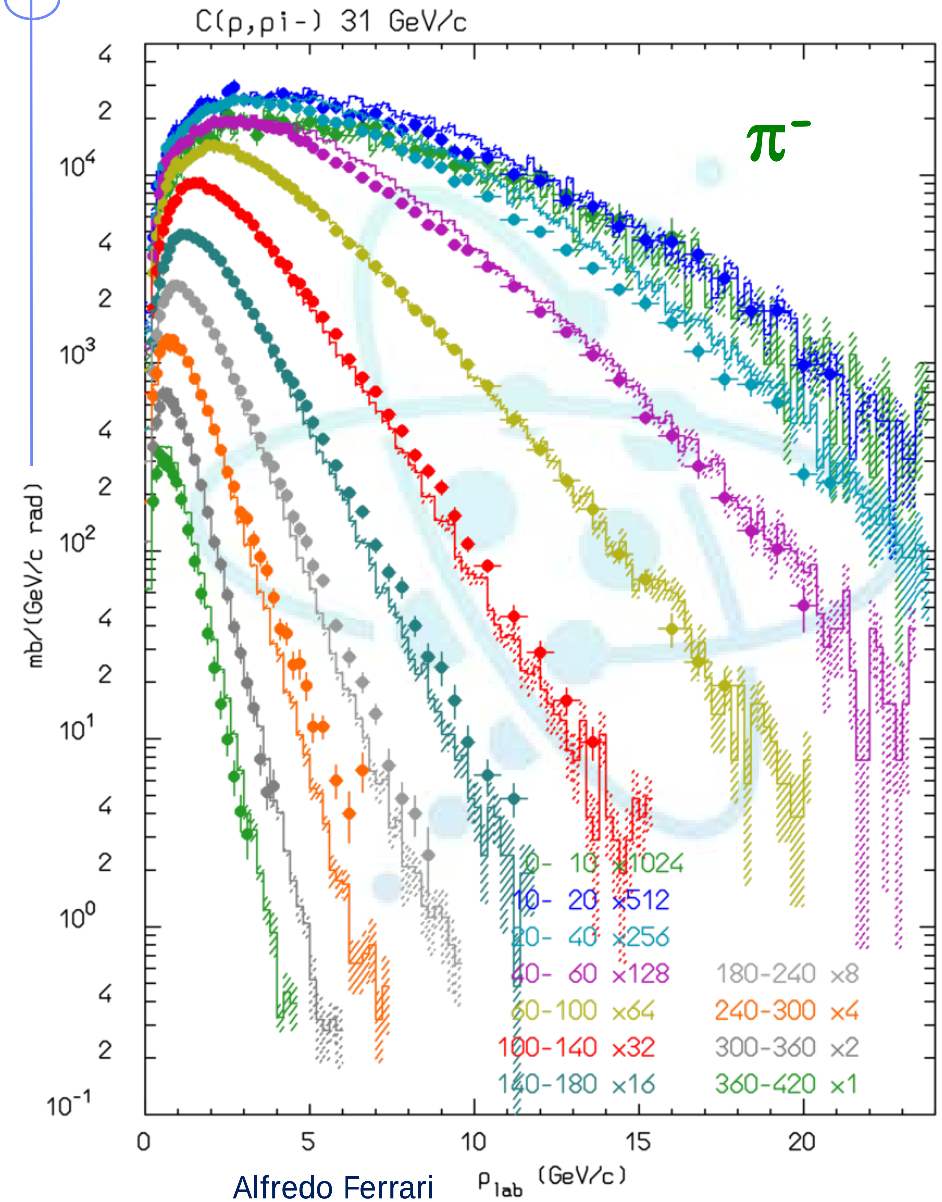


π^+ (left) yield as a function of p_T for different X_F bins for **158 GeV/c p on C**

The p_T integrated distributions for **pC**→π^+, π^- and **pp**→ K^+, K^- are shown in the right Figure as a function of Feynman X_F (dots exp. data, **NA49**, lines **FLUKA** predictions)

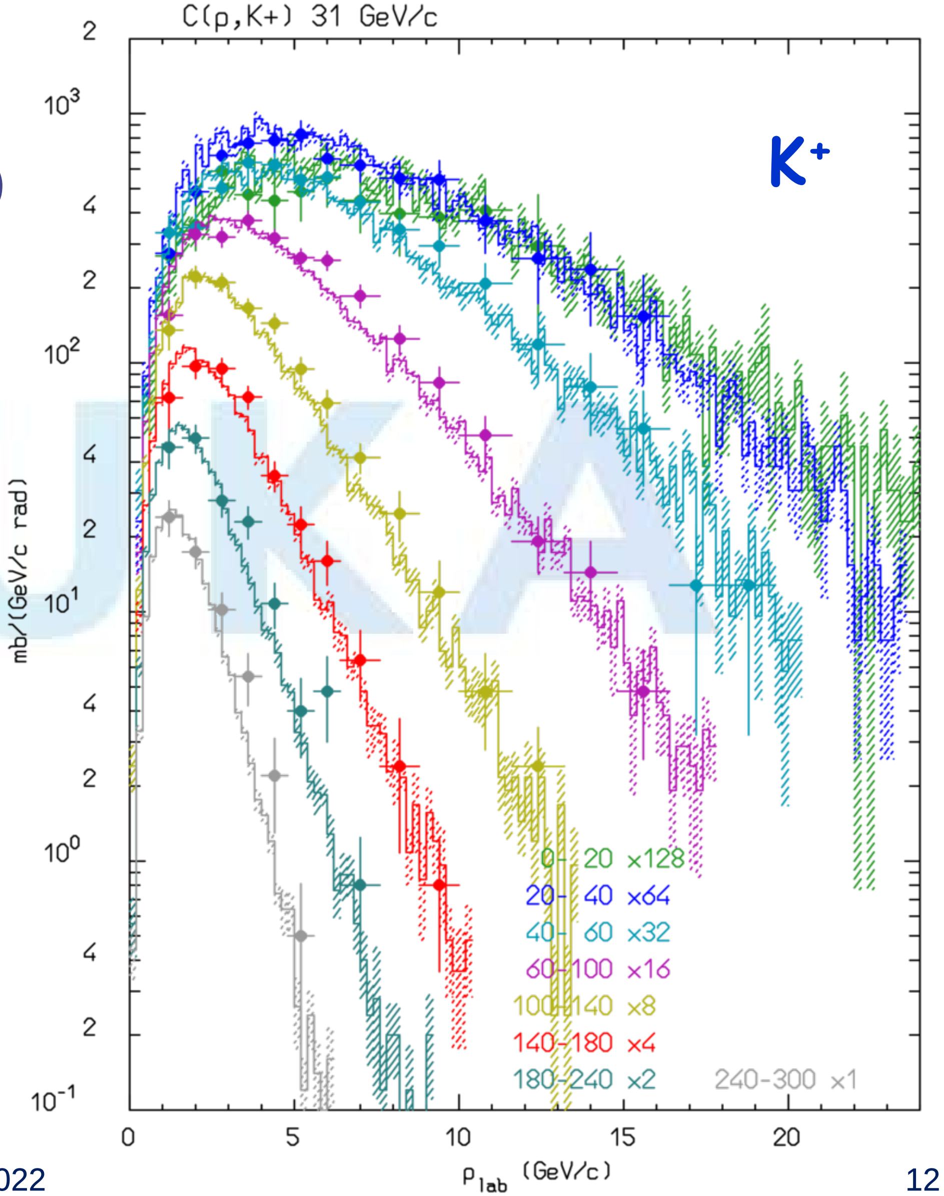


pC @ 31 GeV/c: π^- and K^+

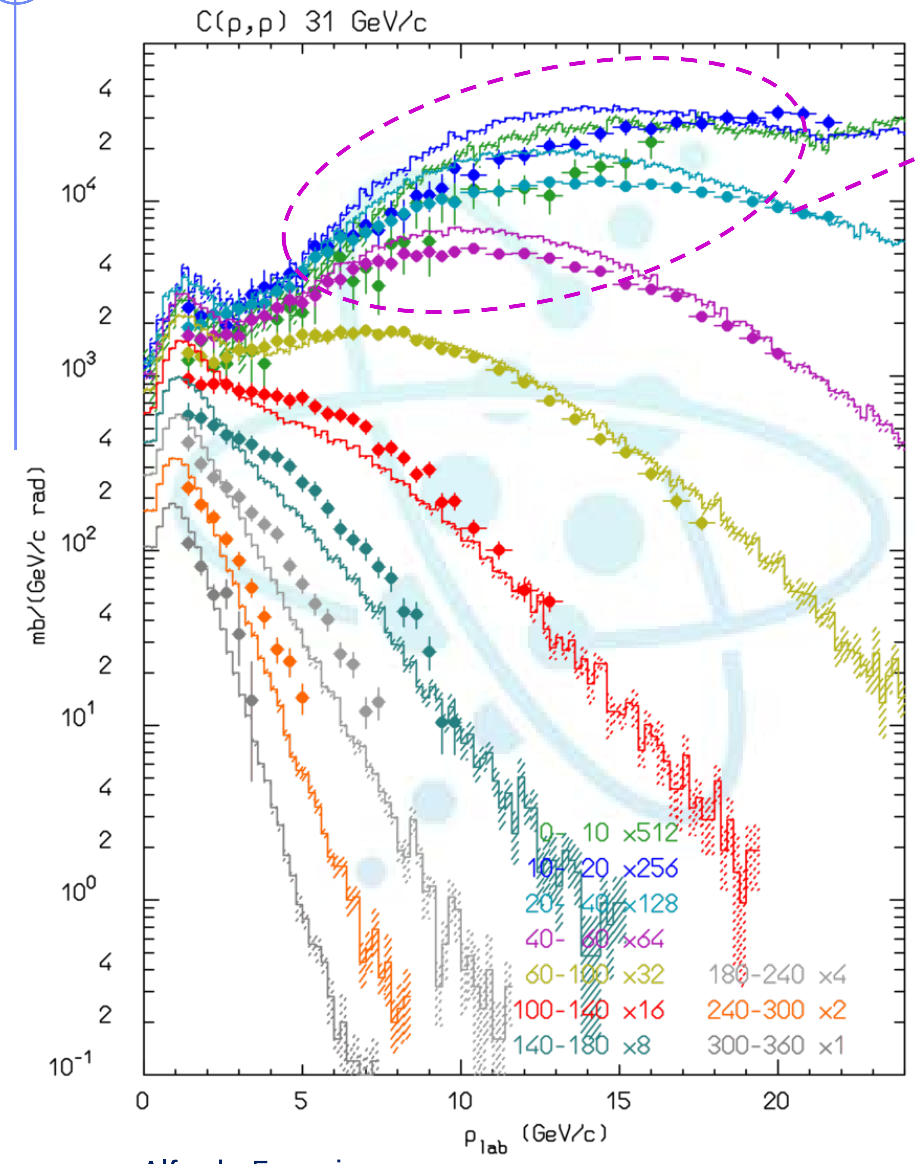


π^-(left) and **K^+**(right) momentum spectra for various angular bins (from 0-10 to 360-420 mrad for π^- and 0-20 to 240-300 for **K+**) for pC @ 31 GeV/c

Symbols: exp. Data (NA61 EPJC85, 84)
Histos: FLUKA



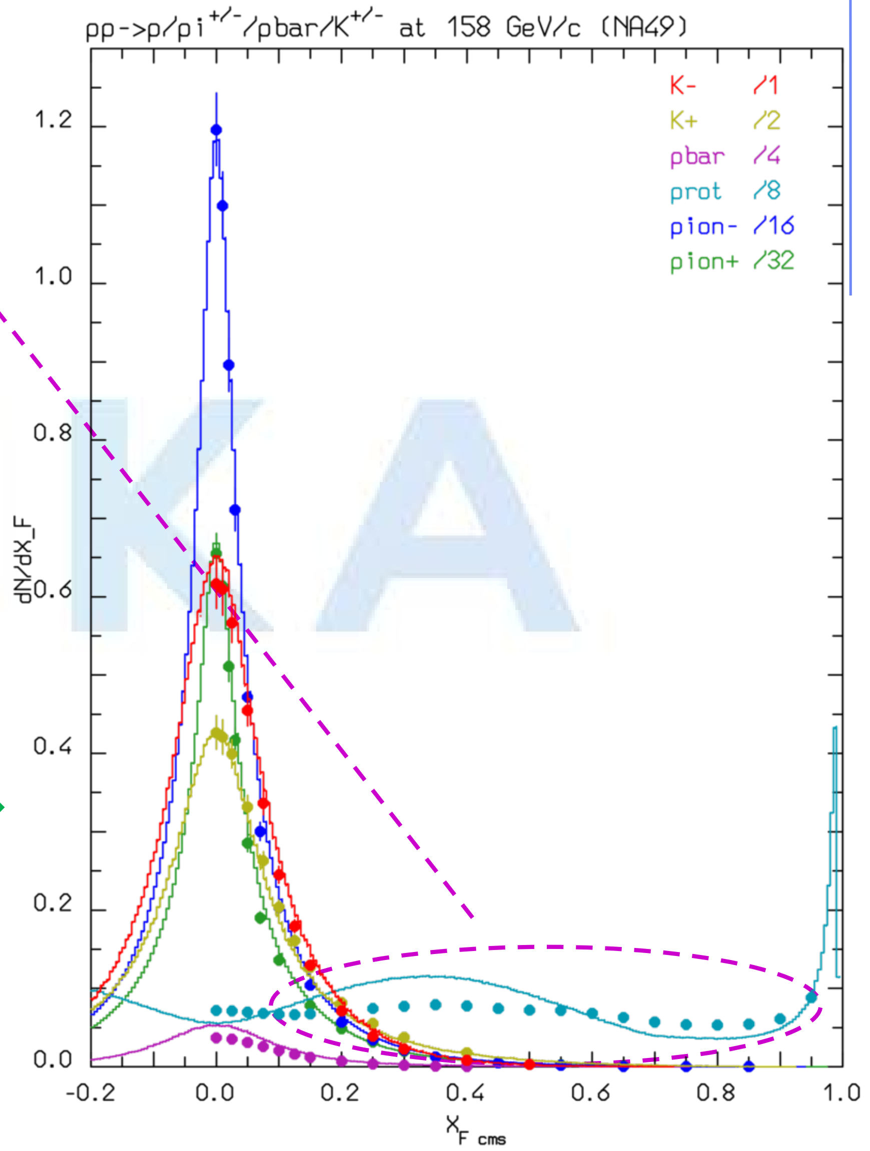
Baryon stopping: improvements required



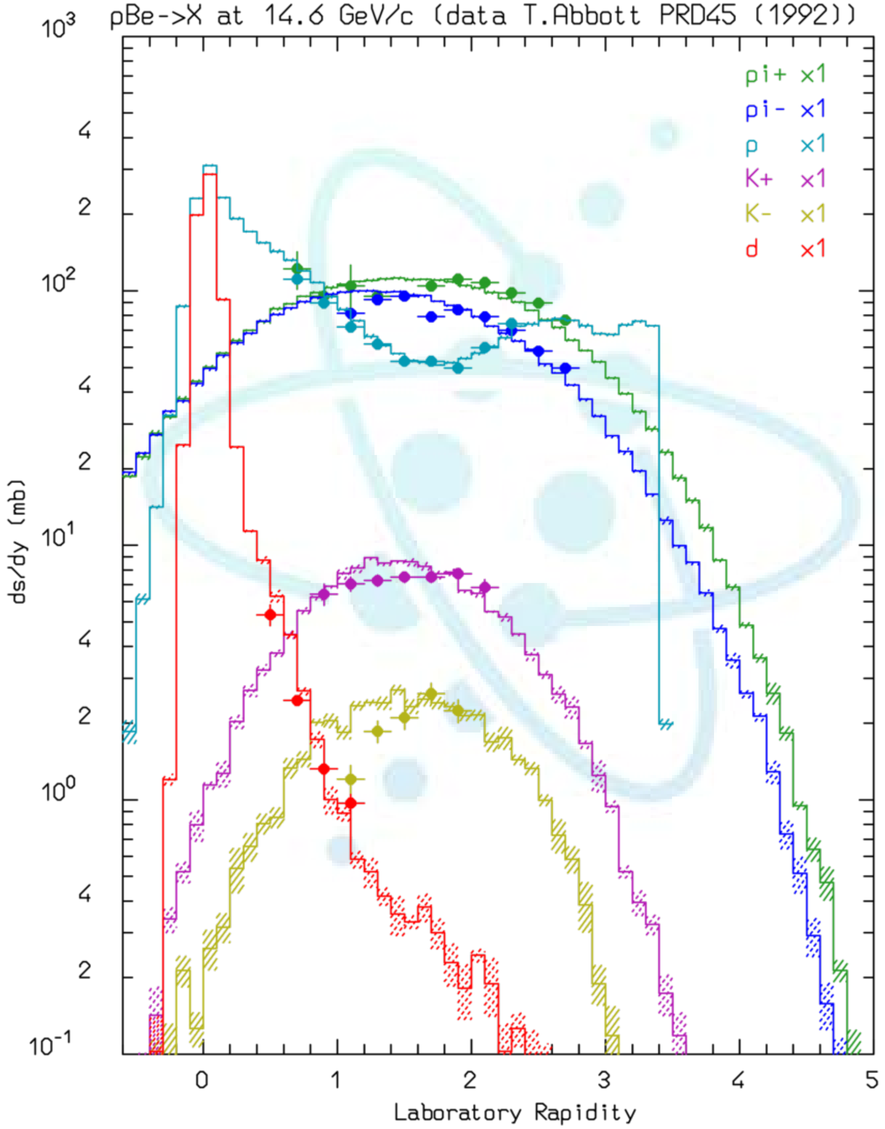
Areas where there is room for improvements together with resonance (ρ^0...) production

double differential proton spectra for different angular intervals for 31 GeV/c protons on Carbon (data NA61)

Pions, kaons, protons and antiproton Feynman X distributions for 158 GeV/c protons on protons (data NA49)



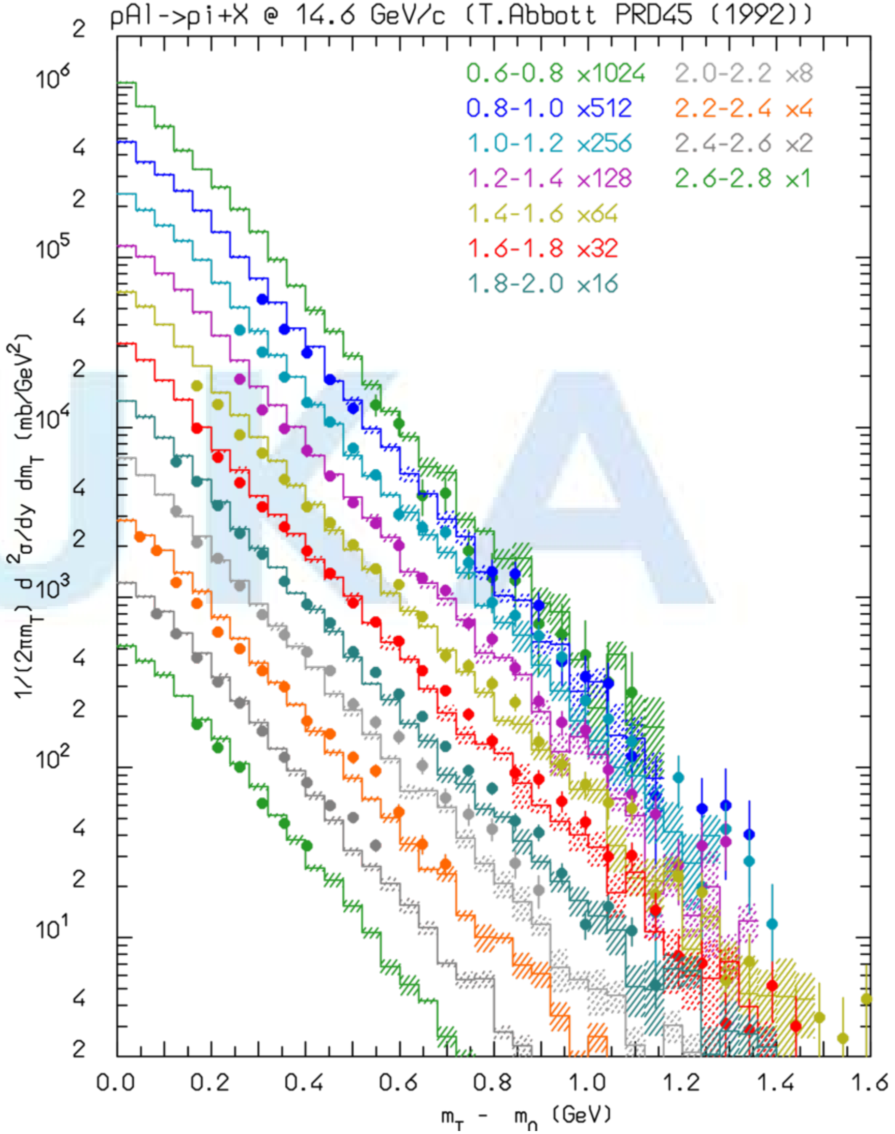
pBe, pAl @ 14.6 GeV/c



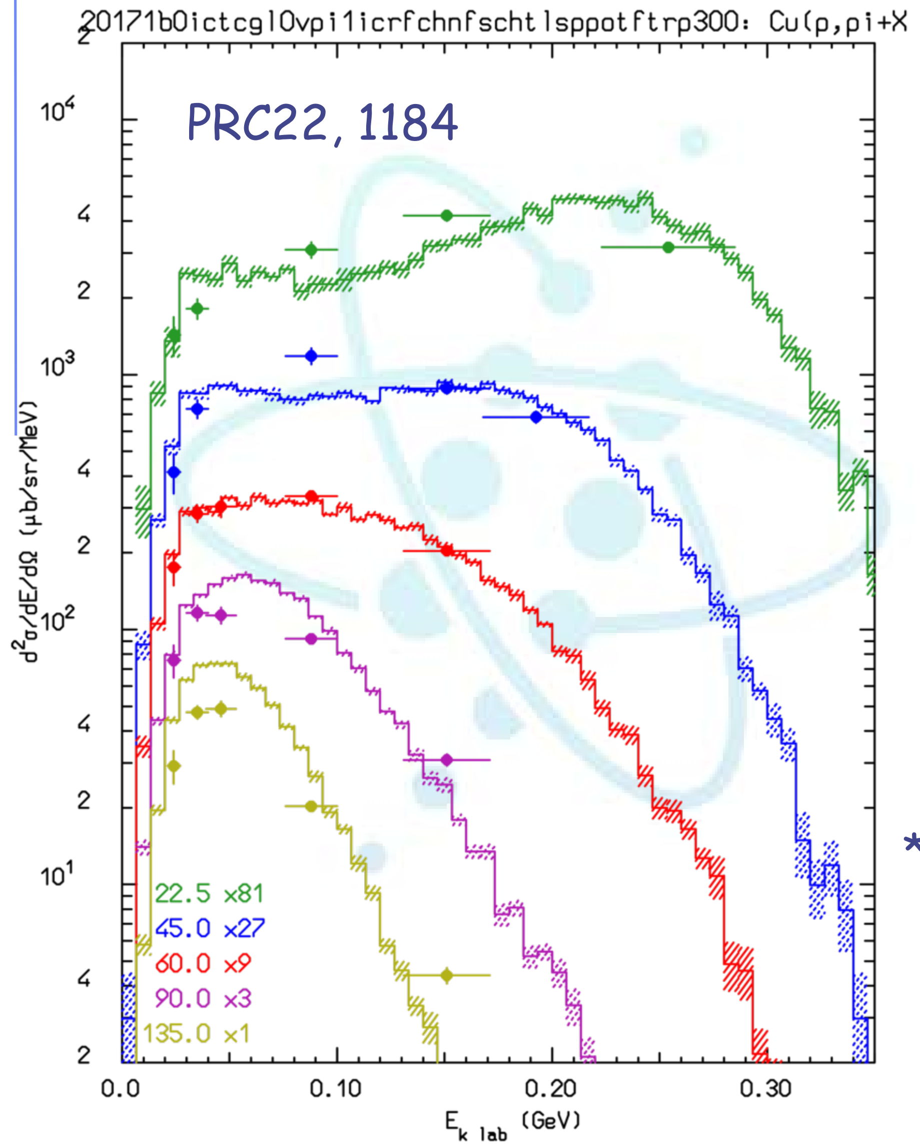
π^+, π^-, K^+, K^-, p, d, ← rapidity distributions for pBe @ 14.6 GeV/c (left)

π^+ production → double differential cross section for pAl @ 14.6 GeV/c as a function of the transverse mass, for different rapidity intervals

Symbols: exp. data
Histos: FLUKA



Pion production in pA at lower energies, examples:

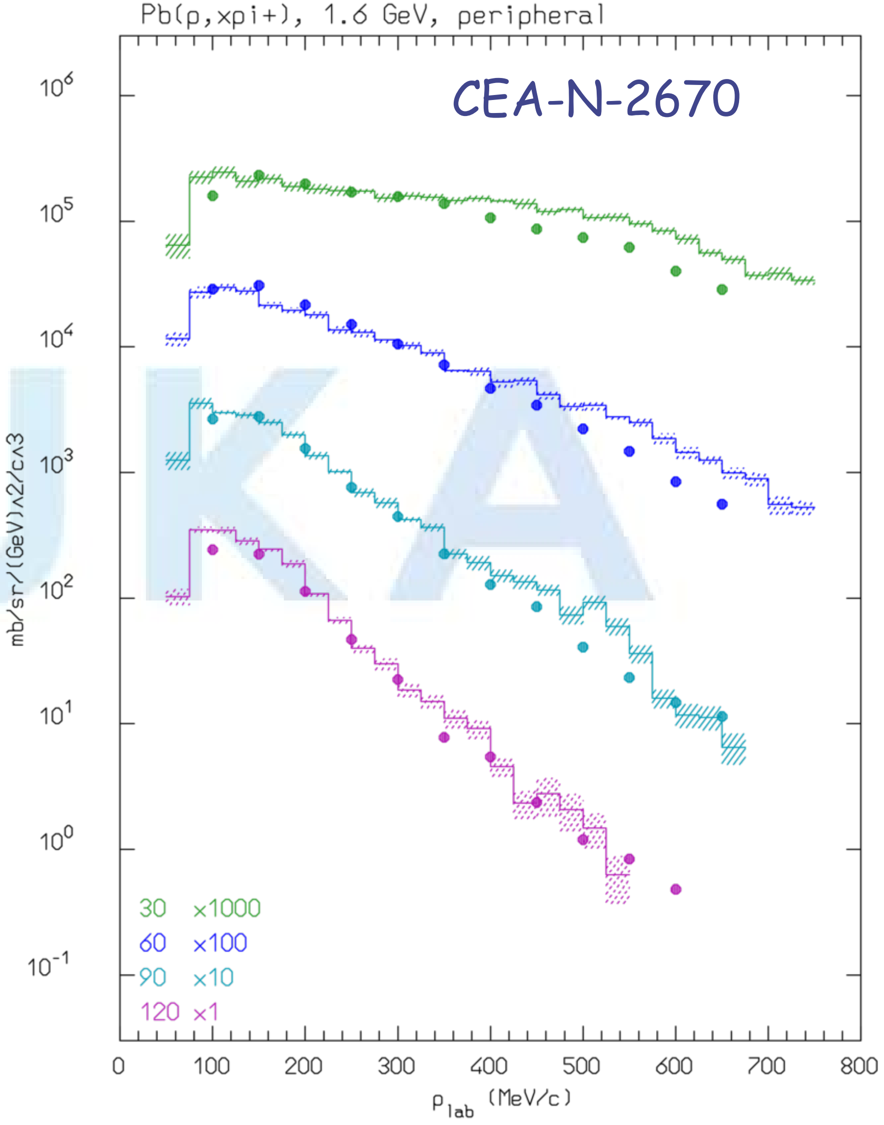


Double differential pion production cross sections $d^2\sigma/dEd\Omega$ for **585 MeV p on Cu** (left), and for **1.6 GeV p on Pb** (right), at various angles

Symbols: exp. data*
Histograms: Fluka

*CEA-N-2670
PRC22, 11184

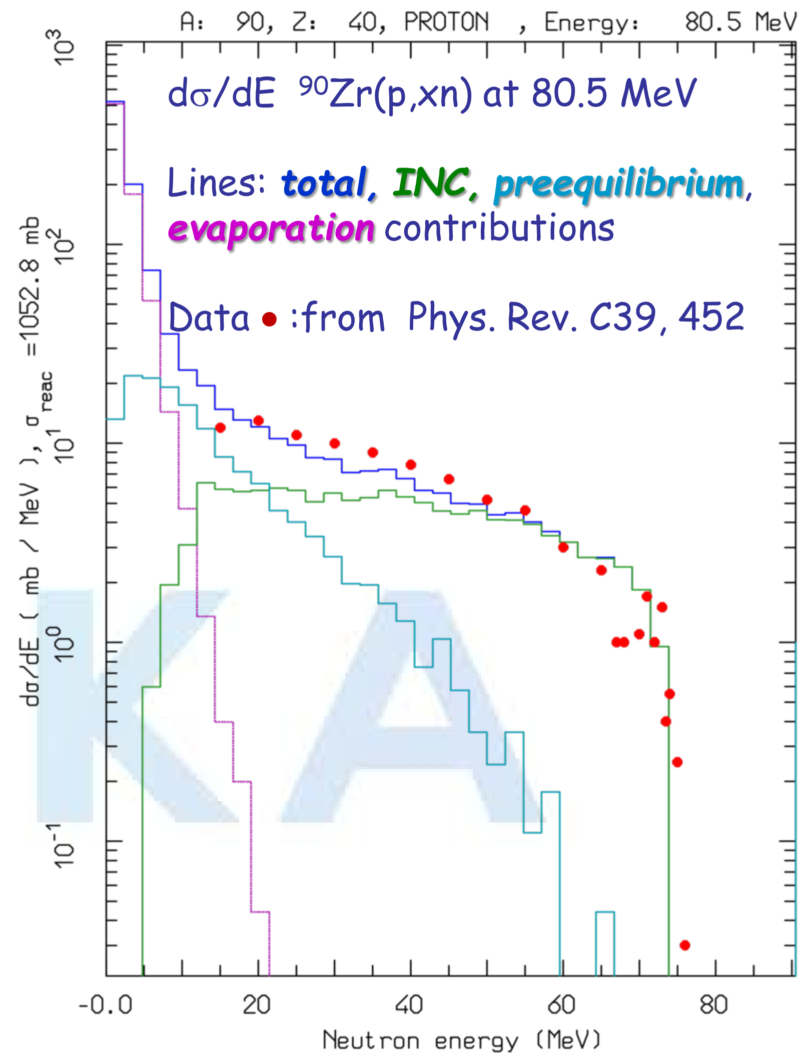
$p+Pb \rightarrow \pi^{+}+X$ (1.6 GeV), peripheral



Preequilibrium/Evaporation/γ de-exc.:

The processes below are critical for particle production from projectile fragments (Z. Phys C 71, 75) !

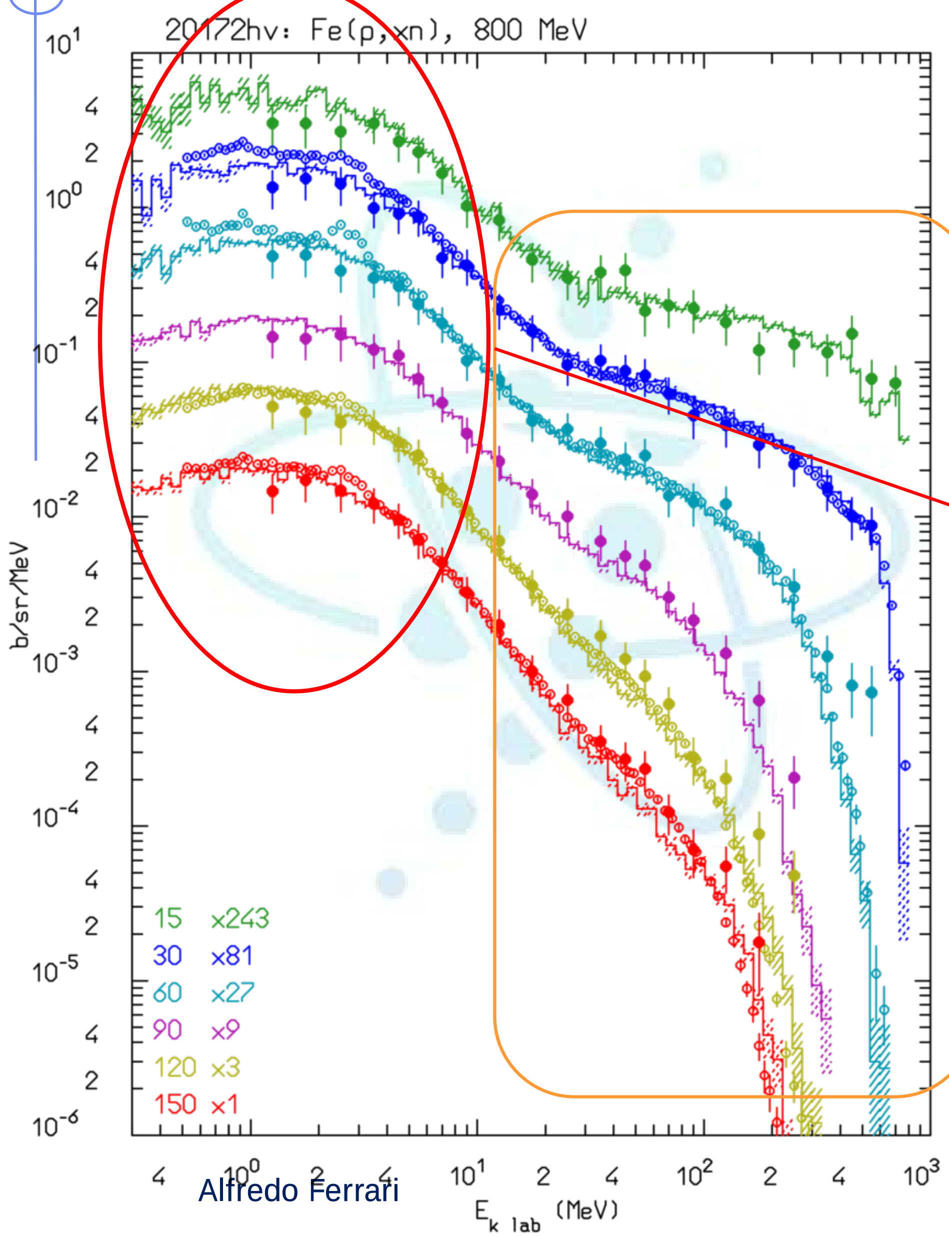
For E > π prod. threshold → only (G)INC models. At lower energies INC inapplicable → ***preequilibrium models*** == share the excitation energy among many nucleons/holes. **FLUKA:** directly for p/n induced reactions below **30-100 MeV**, or all remaining nucleons/clusters below **30-100 MeV/n.**



When the system is fully equilibrated, particle emission through evaporation, fission and nuclear break-up. ***In FLUKA:*** ***~600 possible emitted particles/states (A<25) with an extended evaporation/ fission/ fragmentation formalism.*** ***For light nuclei (A<17): enhanced Fermi break up***

When particle emission is no longer possible → γ **de-excitation**. In Fluka: **at high excitation:** statistical emission. **At low excitation:** discrete levels, either **tabulated exp. levels** (RIPL-3b library from IAEA) and branchings, or **rotational approximation**

Thin target examples: neutron production

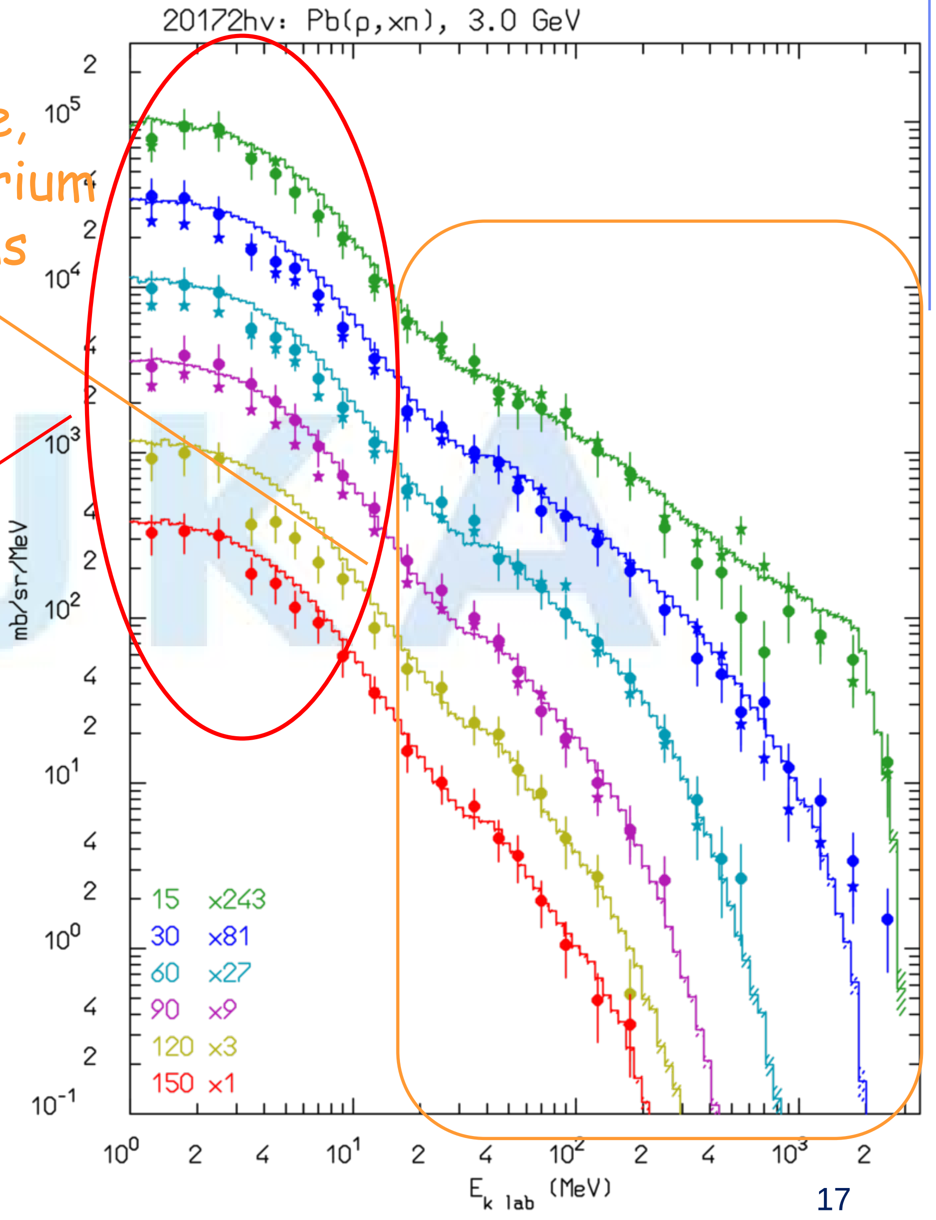


Double differential
← cross section
$d^2\sigma/dEd\Omega$ for
Fe(p,xn) @ 800 MeV,
thin target
Data: NSE112, 78 (1992), NST34, 529 (1997)

Cascade, preequilibrium neutrons

Evaporation neutrons

Double differential
cross section
$d^2\sigma/dEd\Omega$ for
Pb(p,xn) @ 3 GeV →
thin target
Data: NST32, 827 (1995)



Coherent and quasi-elastic hA nuclear scattering

- The latest Fluka has novel models for ***hA nuclear coherent elastic***, and for ***high energy hA quasi-elastic*** *(incoherent elastic, from elastic on individual nucleons)* scatterings (see next slides)
- The relevant qe cross sections are tabulated out of the Fluka Glauber model *(warning: qe cross sections computed out of "naïve" Glauber which does not account for Pauli blocking are increasingly overestimated at very high energies)*

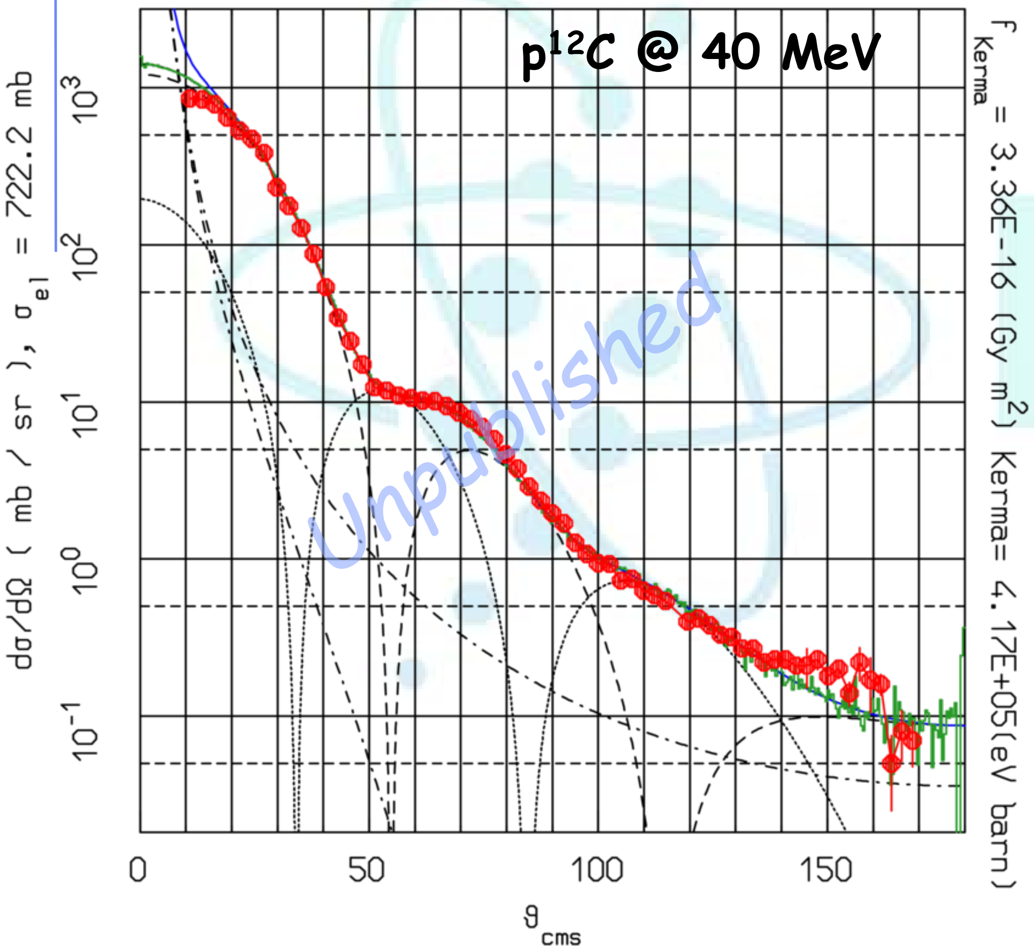
Relevance for Corsika8?

- **Typical quasi-elastic p_T*: ~300 MeV/c**, and **cross sections** (hAir) **~10%** of the absorption one
- Quasi-elastic interactions (**energy transfer* ~50 MeV**) will most of the time produce some (low energy) particles → important for neutrons, and sometimes even mesons *($p^{14}N$ @ 1 TeV, on average 0.8 p, 0.6 n, 0.14 π, 0.15 d, 0.9 α "extra"!)*
- **Typical coherent elastic p_T on** ^{14}N at high energies: **~80 MeV/c**, and **cross sections** of the **same order** of the **non-elastic** ones
- *Likely important for **ice**!! There you have hp and Ap interactions!!*

** Assuming a hp slope of ~10 $(GeV/c)^{-2}$*

Hadron (coherent) elastic scattering: new model

"Ferrari-Sala" model: effective simple model for nuclear elastic scattering, applicable from low to very high energies

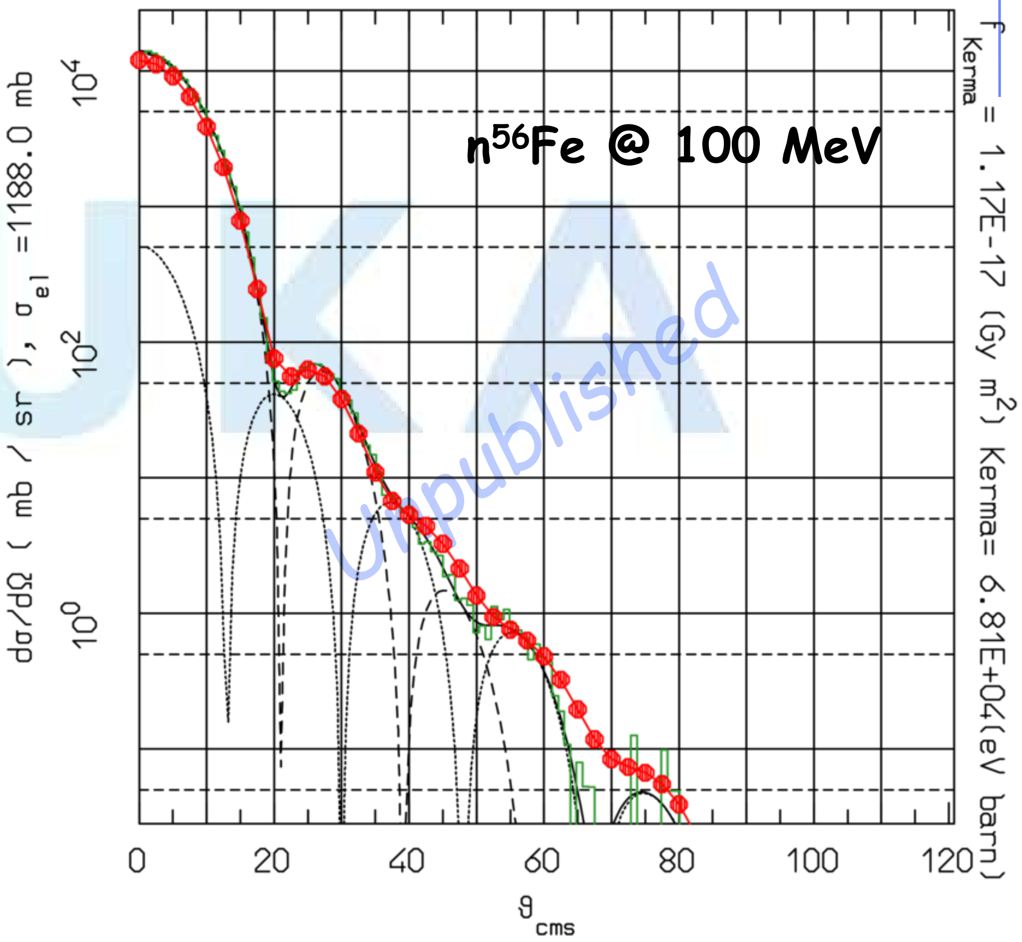


Low energies: parameters fitted out of optical potential calculation for p and n up to 200 MeV (Jendl-4 and Endf/b-8r0). Examples:

Green Fluka

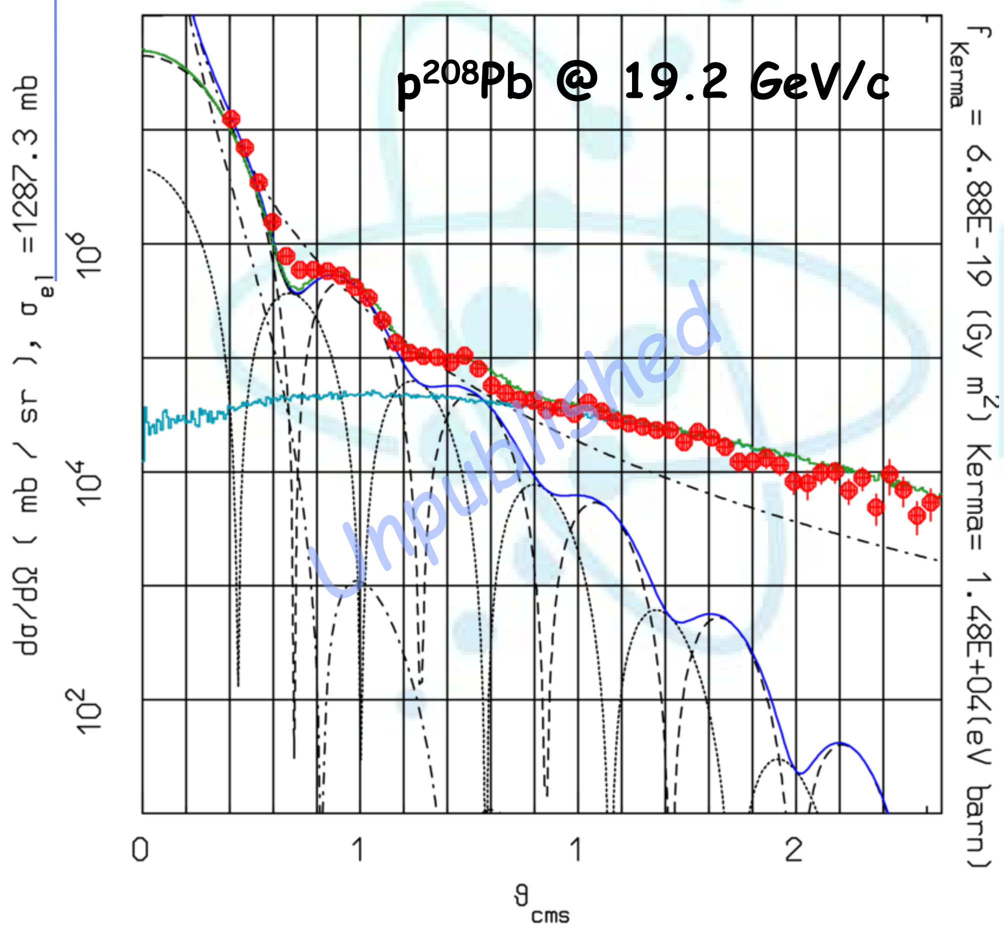
(Blue with Coul.)

Red: exp. data (p), DWBA calculations (n)



Hadron coh. and qe scattering: high energy scaling

The model parameters, being physics driven, naturally scale with energy.
Almost identical parameters obtained from 1 GeV to 175 GeV/c!



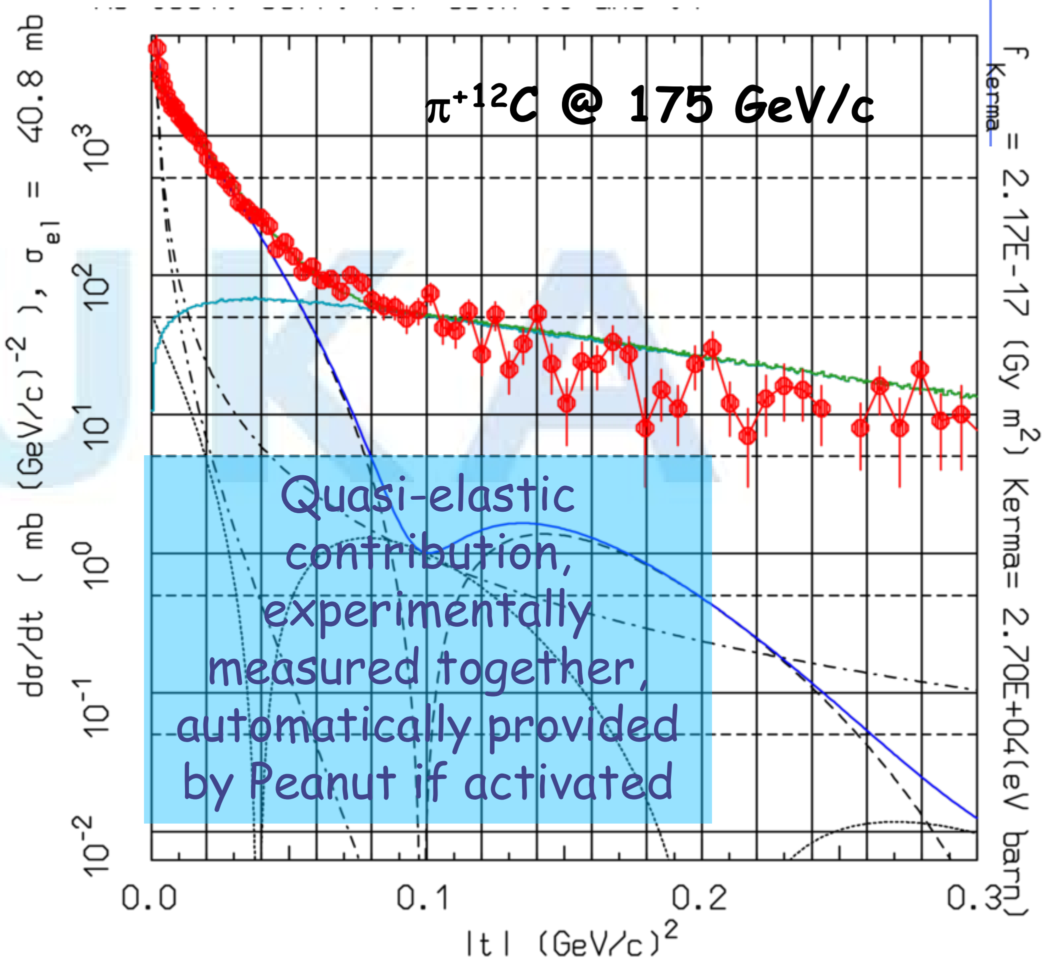
Green Fluka

Red: exp. Data

Light Blue Fluka qe

Blue Coh. only

the model works for coherent scattering at high energy, while Peanut does the quasi-elastic component

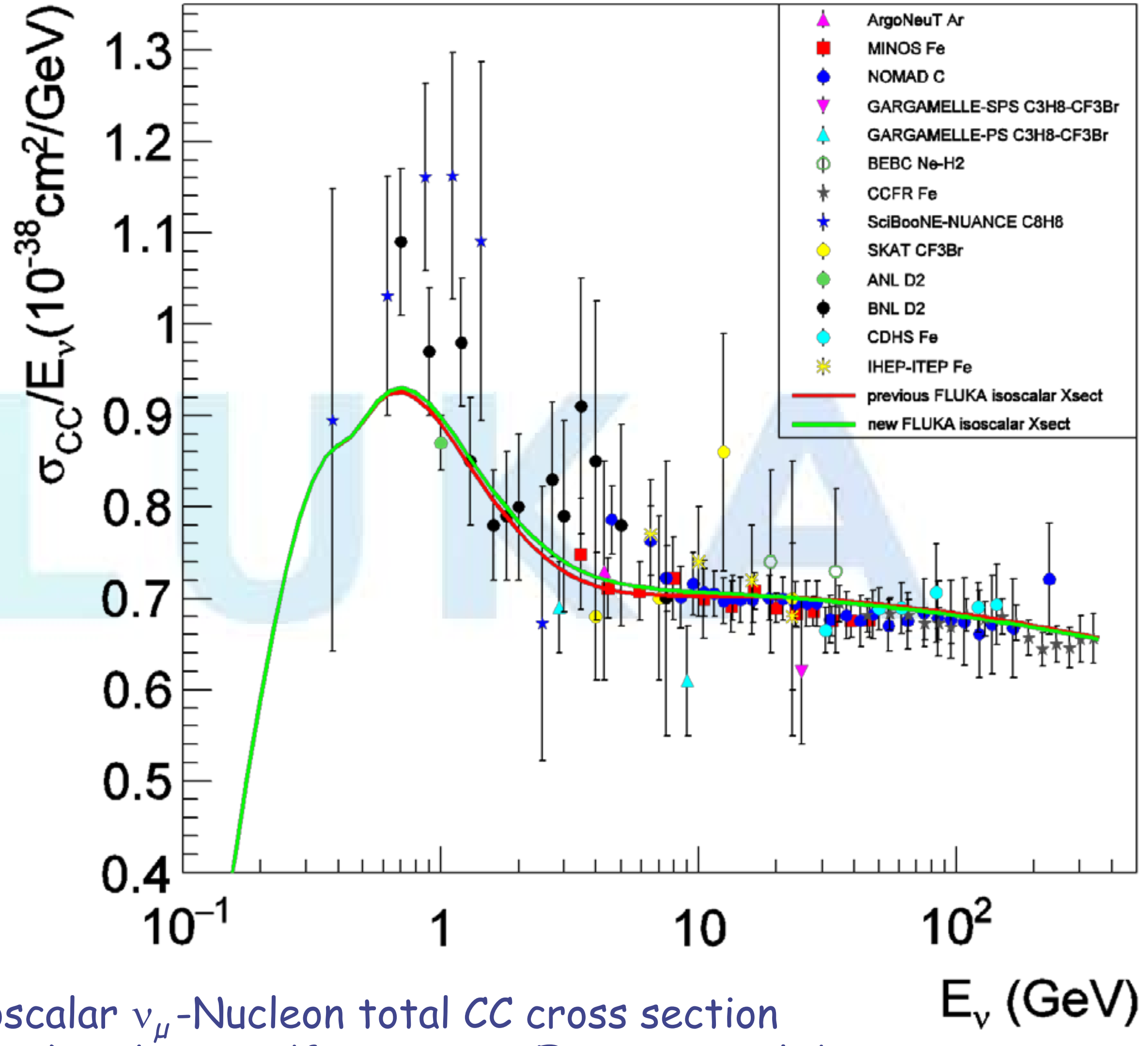


(Anti)Neutrinos in FLUKA:

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

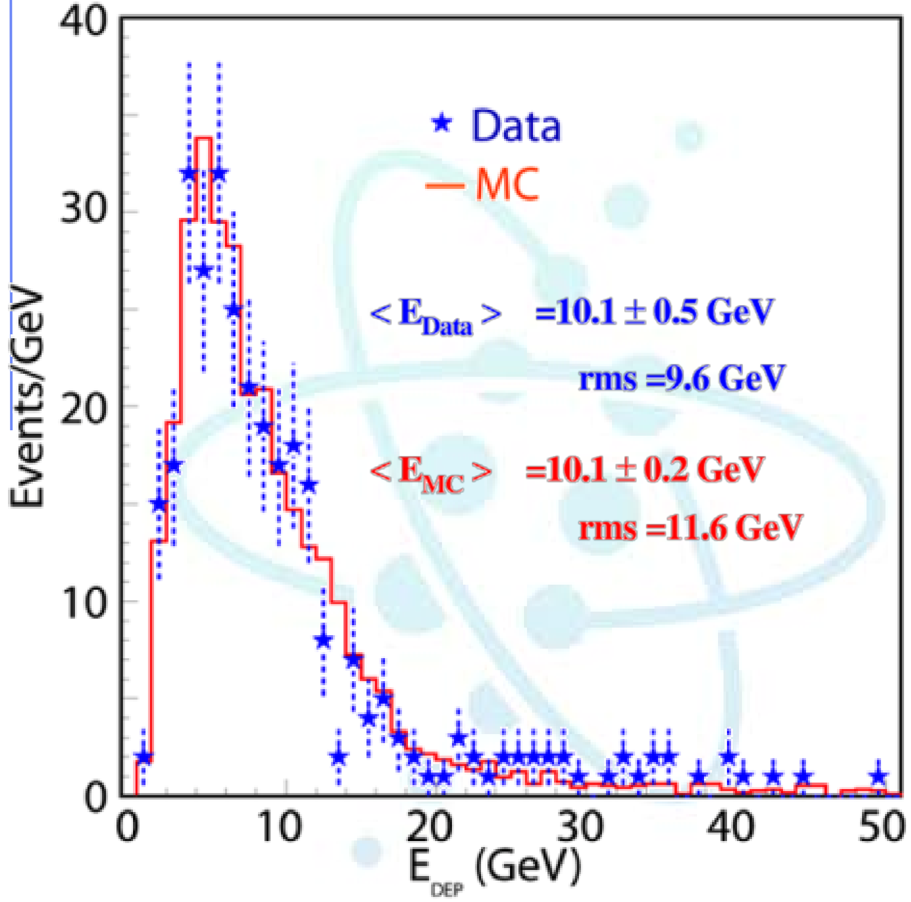
- **νN QuasiElastic (from ~0.1 GeV upward):**
- **νN Resonance production**
- **νN Deep Inelastic Scattering**
- **νN interactions** embedded in PEANUT for **νA** (Initial State and Final State effects)
- **Fermi/GT absorption** of few-MeV (solar) neutrinos on ^{40}**Ar**
- Used for all **ICARUS** simulations/publications

FLUKA can currently manage (anti)ν-A interations from ~0.1 GeV up to 1000 TeV



Isoscalar ν_μ-Nucleon total CC cross section
Fluka (lines) with two pdf options vs Experimental data

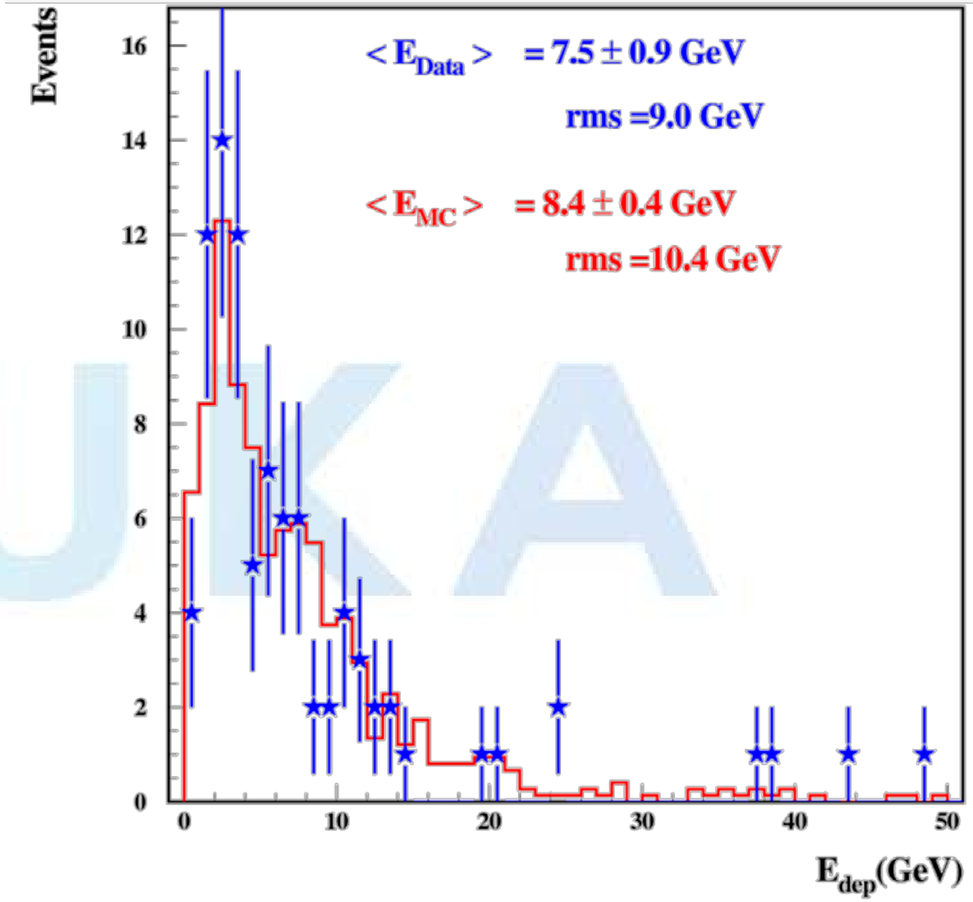
Reaction products: CNGS/ICARUS data (≈20 GeV $\langle E_\nu \rangle$)



Distribution of total deposited energy in the T600 detector

← Left:
ν_μ CC events

Right:→
ν NC events



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

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

Real and Virtual Photonuclear Interactions

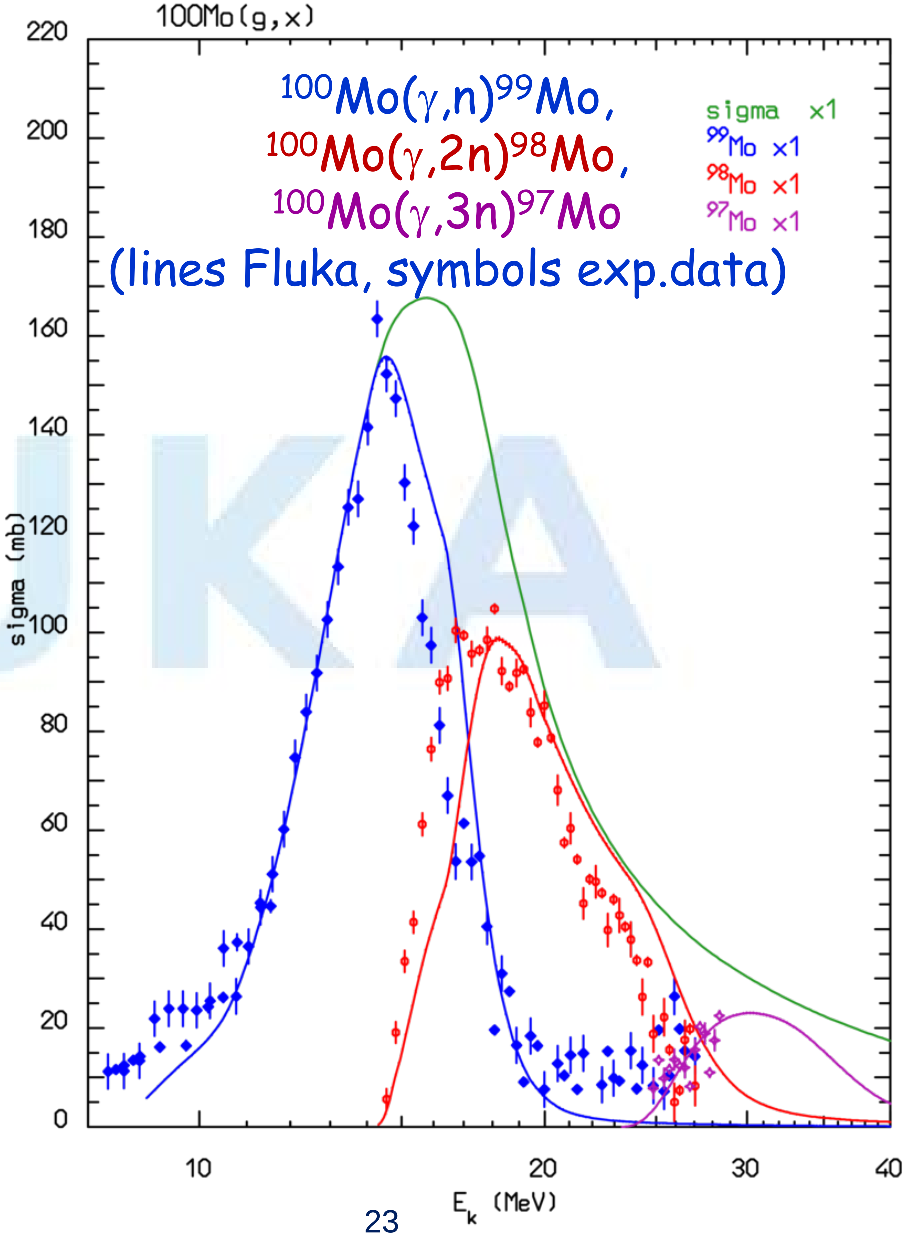
Photonuclear reactions

- 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

Virtual photon reactions

- Muon photonuclear interactions
- Electronuclear interactions
- Electromagnetic dissociation

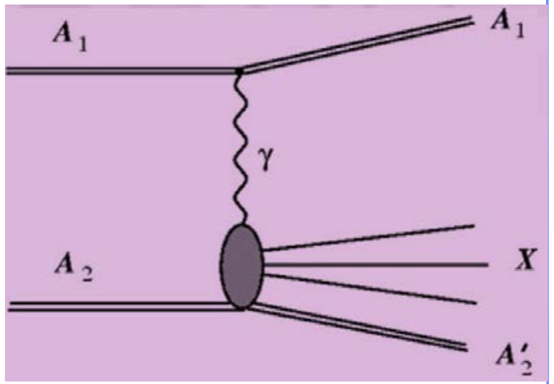
With help from ***P.Degtiarenko and G.Kharashvili***

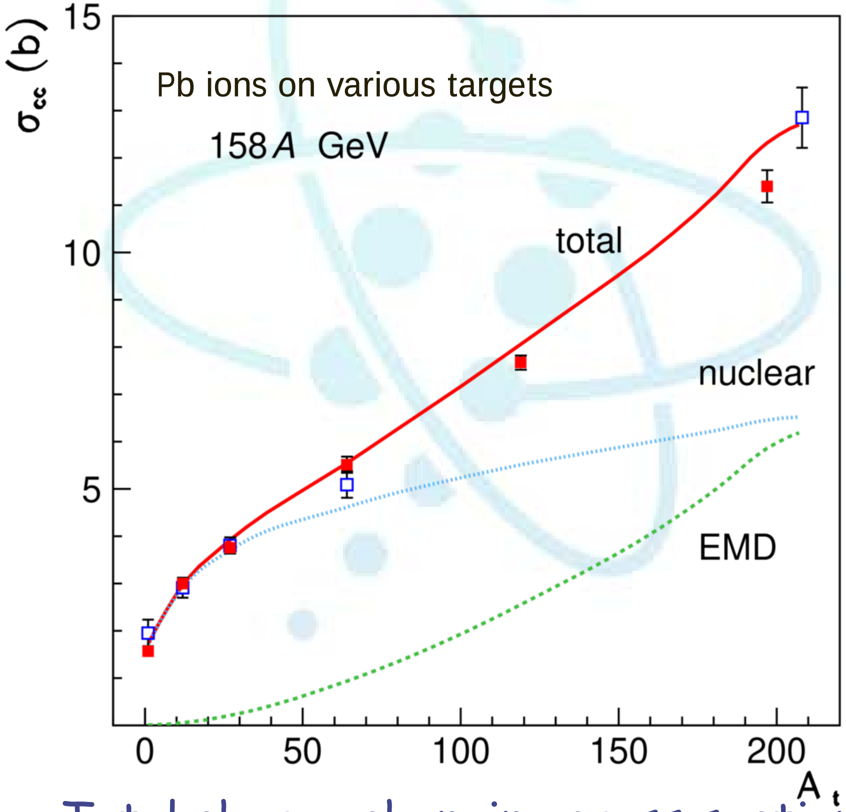


ElectroMagnetic Dissociation

… nuclear and, mostly, **ElectroMagneticDissociation** collisions on LHC machine elements or at IP's produce a **variety** of (excited), possibly radioactive, **fragments** ***in flight***

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



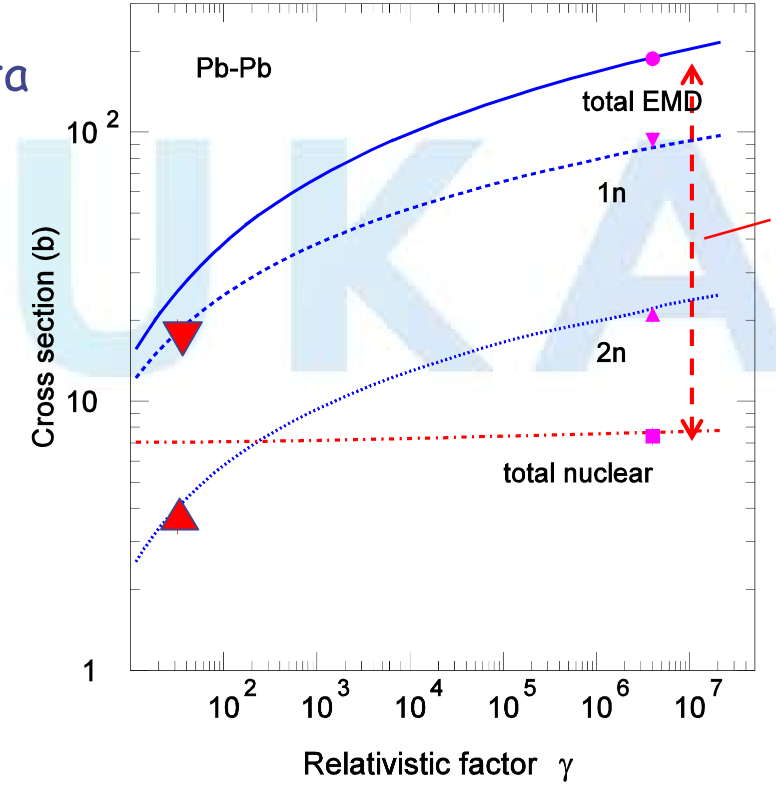


Total charge changing cross section as a function of target atomic mass

Symbols: exp. data
PRC71 02495
PRC70 014902
NPA707 513
NPA662 207

Lines: Fluka

Ref. for FLUKA model
PRSTAB17 021006



Alice:
$\sqrt{s_{nn}}$=2.8 TeV
PRL109 252302 (2012)

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

Current Corsika interface: hA non-elastic interactions

- Worked out more than 20 years ago by Dieter and myself;
  - At the beginning:
    - Loads some essential block data;
    - Initializes a few arrays (many useless for Corsika by the way);
    - Reads in the Fluka nuclear data files (nuclear.bin, sigmapi.bin, …);
    - Initializes the nuclear properties of Air nuclei;
  - Run time:
    - Calls the routines providing the non-elastic cross section;
    - Calls the Fluka interaction model (Peanut) at non-elastic interactions;
- … essentially unchanged since then, apart minor issues;
- … recently slightly modified in order to minimize the memory imprinting of FLUKA within Corsika;
- Limitations:
  - Target composition hardwired (Air);
  - No distinction absorption/quasi-elastic, actually it does quasi-elastic as well;
  - No other process possible

Is EMD important for UHE (atmospheric) showers?

	E (eV/n)	Proj diss. (mb)	1n (mb)	2n (mb)	Mesons	Target diss. (mb)	<Eloss> (TeV)
56Fe on 14N							
	1.e+17	384	119	19	44.6%	1256	~ 8
	1.e+18	464	133	22	48.6%	1527	~ 77
	1.e+19	553	151	26	51.4%	1832	~ 670
	1.e+20	647	163	30	54.4%	2170	~6000
56Fe on 16O							
	1.e+17	502	155	25	44.3%	1446	~ 8
	1.e+18	605	175	30	48.3%	1769	~ 79
	1.e+19	718	192	34	51.5%	2118	~ 670
	1.e+20	846	218	38	54.2%	2501	~5400
56Fe on 40Ar							
	1.e+17	2513	770	127	44.5%	3681	~ 7
	1.e+18	3034	881	149	47.8%	4451	~ 59
	1.e+19	3603	982	177	51.0%	5325	~ 530
	1.e+20	4234	1080	193	54.2%	6255	~4800
14N on 14N							
	4.e+17	105	1.9	0	56.5%	105	~ 46
	4.e+18	126	2.1	0	59.7%	126	~ 380
	4.e+19	150	2.4	0	62.4%	150	~3400
	4.e+20	176	2.6	0	65.0%	176	~29000
4He on 14N							
	14.e+17	34	1.9	0	62.0%	9.6	~ 190
	14.e+18	41	8.5	0	64.8%	11.5	~1600
	14.e+19	48	10	0	67.3%	13.6	~14000

Hard to say… on the left the computed EMD cross sections for various energy/ target/ projectile combinations (statistical errors ~2-3%)

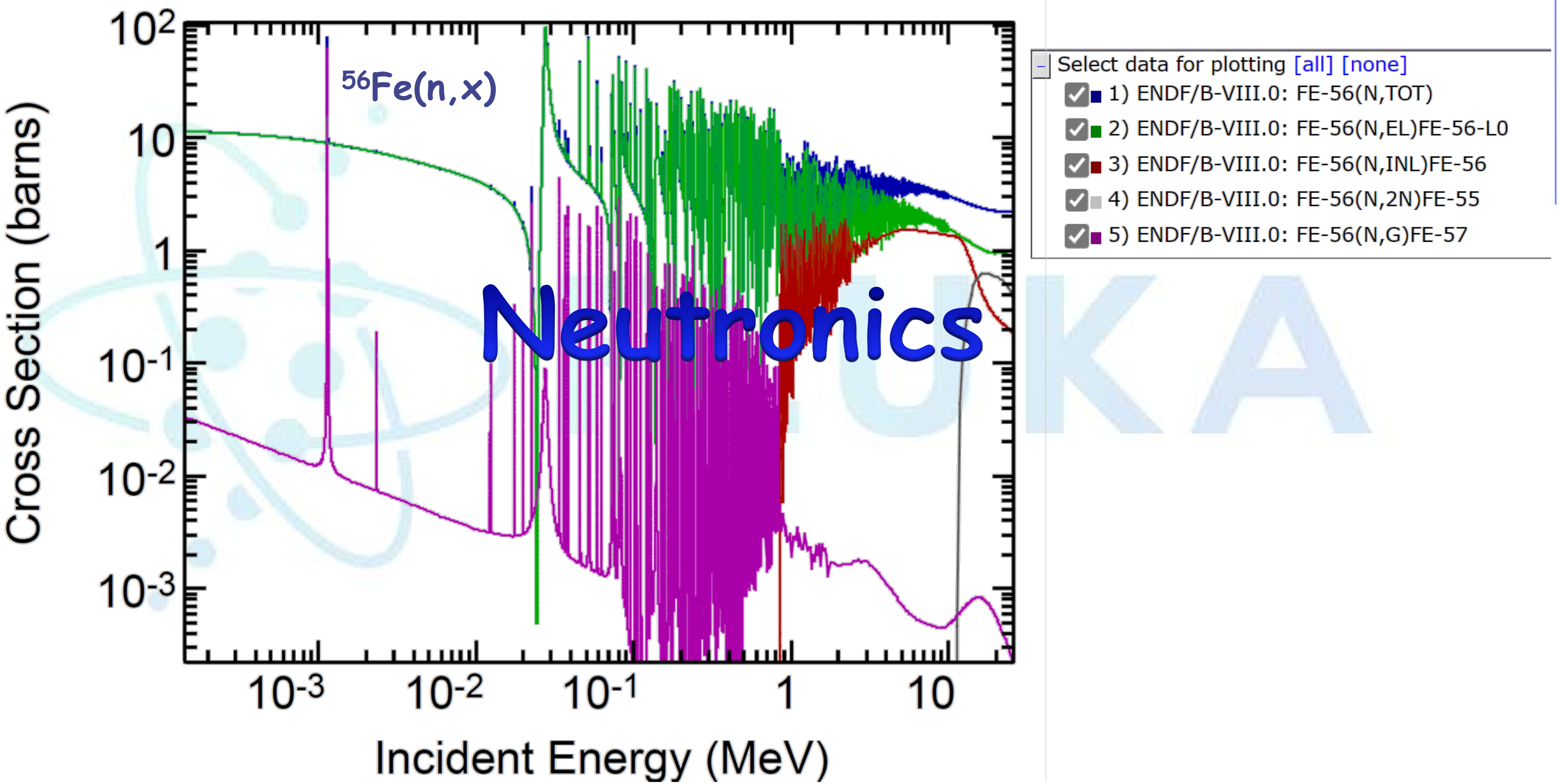
Cross sections are not negligible wrt absorption ones…
Energy losses are significant

- "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)

A "flexible" interface for hA (γ*A?) in the future?

- Generic interface accepting ***projectile***, ***energy*** (momentum), ***target A and Z*** …
- … and a ***flag*** indicating which interactions are supposed to be simulated (***absorption, quasi-elastic (!?!), coherent elastic, EMD***) …
- … the interface could ***select the interaction by itself*** or be ***forced to perform a specific one***;
- (Relatively) easily adaptable from something which already exists in Fluka;
- Products will always be put on the same stack, with the same id's etc, so collecting them would work as it works now;
- Of course an interface to ***all relevant FLUKA cross section routines*** should be implemented, not only the to the non-elastic ones (*tabulations at initialization?*);
- … ***EMD*** for products of previous interactions makes sense if and only if the ***A*** and ***Z*** of those products are ***meaningful*** (exc. energies, evaporation, charge conservation etc).

Thanks to Tanguy, an interface of FLUKA with Sibyll and EPOS is more or less established. Work is in progress with Tanguy and Max in setting up simple test cases with Fluka vs Corsika with the same event generators/conditions in order to assess the relevance of those processes not (yet) implemented/interfaced



Neutronics
^{56}Fe(n,x)
Cross Section (barns)
Incident Energy (MeV)
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-3}
10^{-2}
10^{-1}
1
10
Select data for plotting [all] [none]
1) ENDF/B-VIII.0: FE-56(N,TOT)
2) ENDF/B-VIII.0: FE-56(N,EL)FE-56-L0
3) ENDF/B-VIII.0: FE-56(N,INL)FE-56
4) ENDF/B-VIII.0: FE-56(N,2N)FE-55
5) ENDF/B-VIII.0: FE-56(N,G)FE-57

Low E n in Fluka: Point-wise and Group-wise cross sections

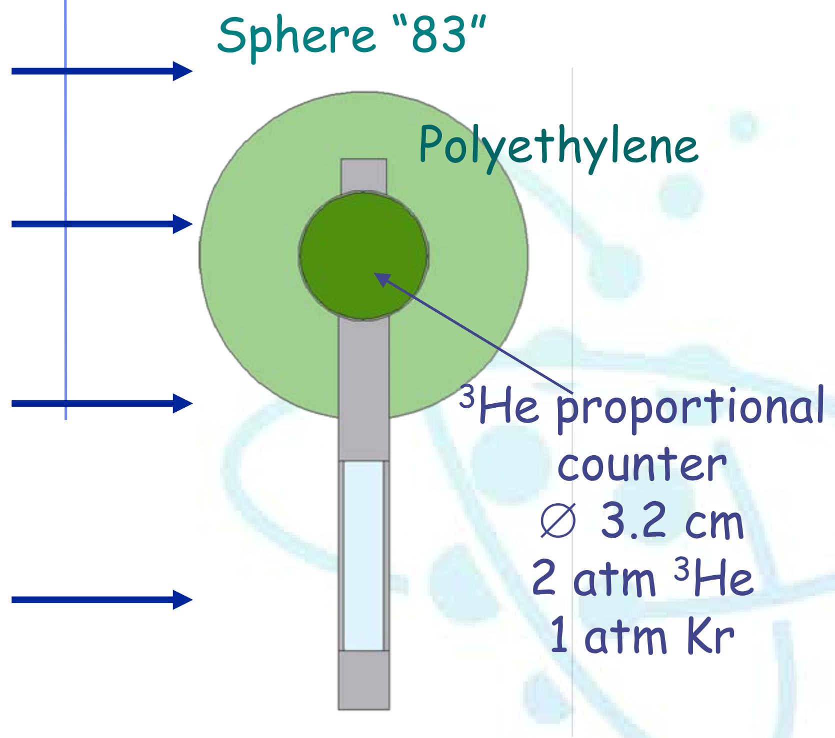
Neutrons below 20 MeV "*low energy neutrons*" cannot be treated with models due to the complexity of cross section structures (resonances etc)

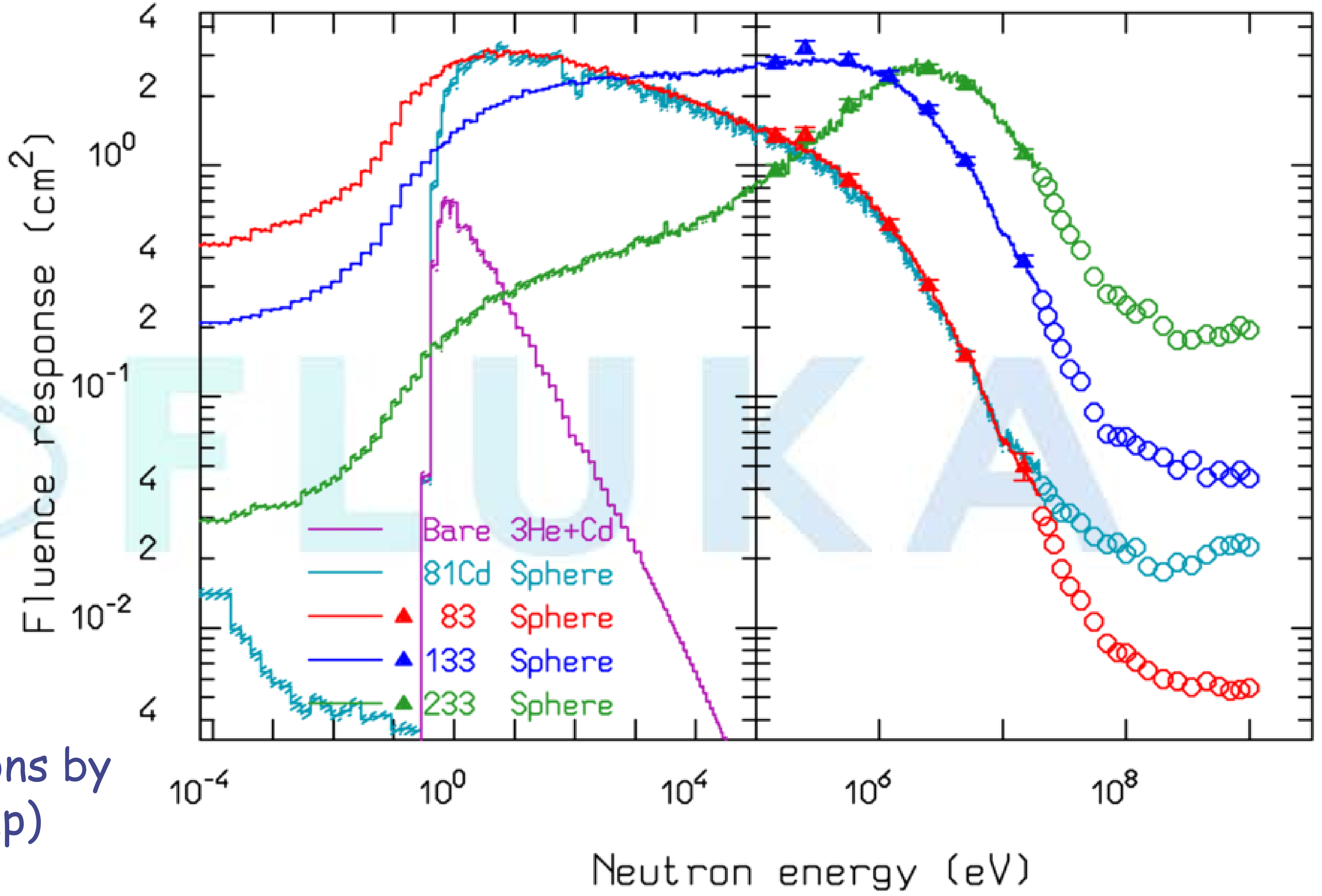
- Evaluated nuclear data files (ENDF/B, JEFF, JENDL...) provide neutron σ (cross sections) and ***inclusive*** distributions of products for E_n<20 MeV for all channels
- In neutron transport codes in general two approaches are used: ***point-wise*** ("continuous energy" cross sections) and ***group-wise*** ("energy group" averaged σ's) transport
- ***Point-wise*** follows cross sections precisely but it can be time and memory consuming
- ***Group approach*** is widely used in neutron transport codes because it is fast and gives good results for most applications → no charged secondary, hopelessly inclusive
- For both, ***inclusive, uncorrelated, distributions*** → no event-by-event studies ***(unless...)***

*Complex programs (NJOY, PREPRO...) convert ENDF files to **point-wise or group-wise cross sections**, including Doppler broadening, URR's etc.*

Until 2021 FLUKA used group-wise cross sections with some exceptions. Recently, fully correlated, pointwise σ's have been implemented, allowing event-by-event studies

Example of n Response functions: Bonner Spheres



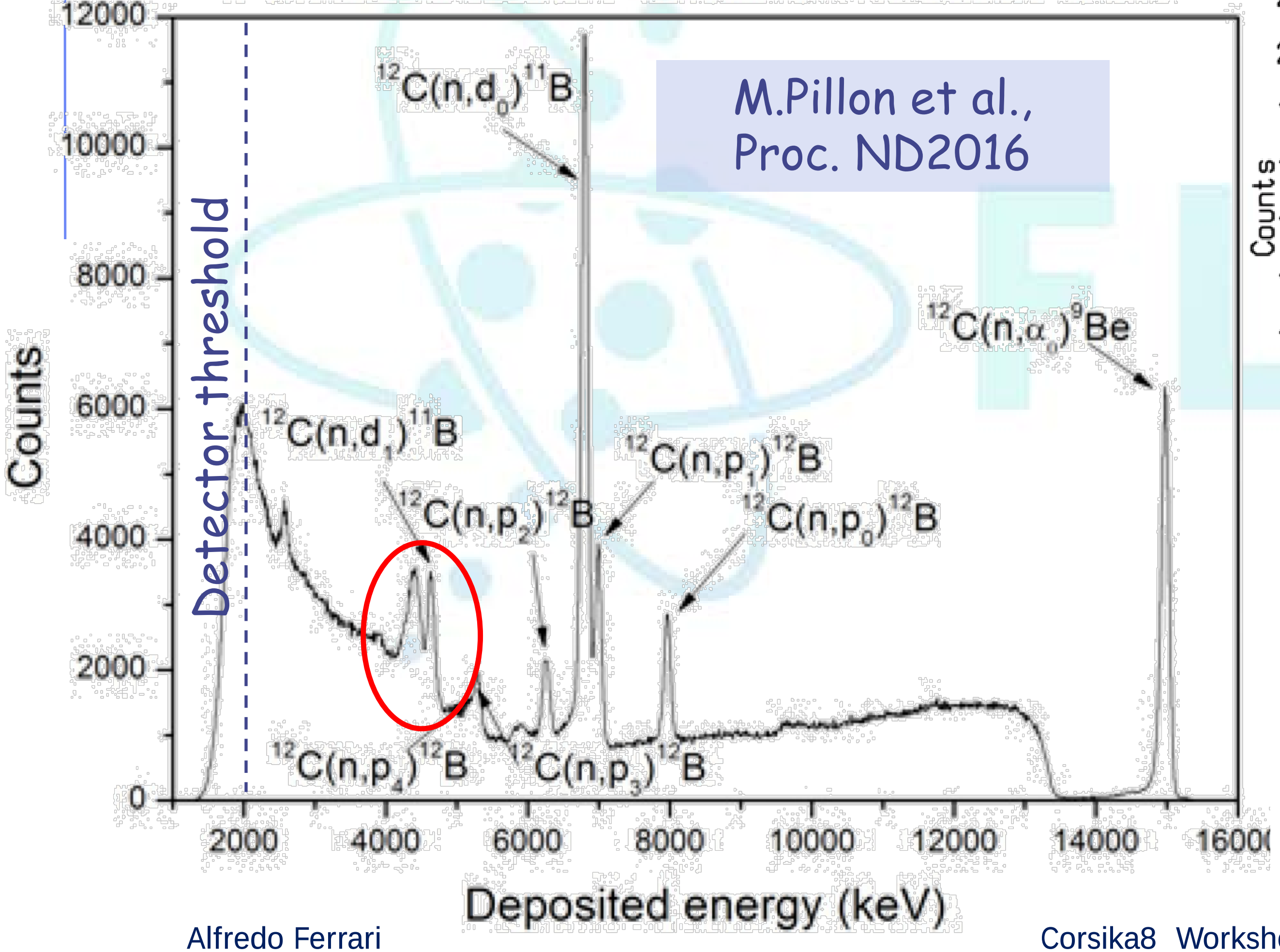


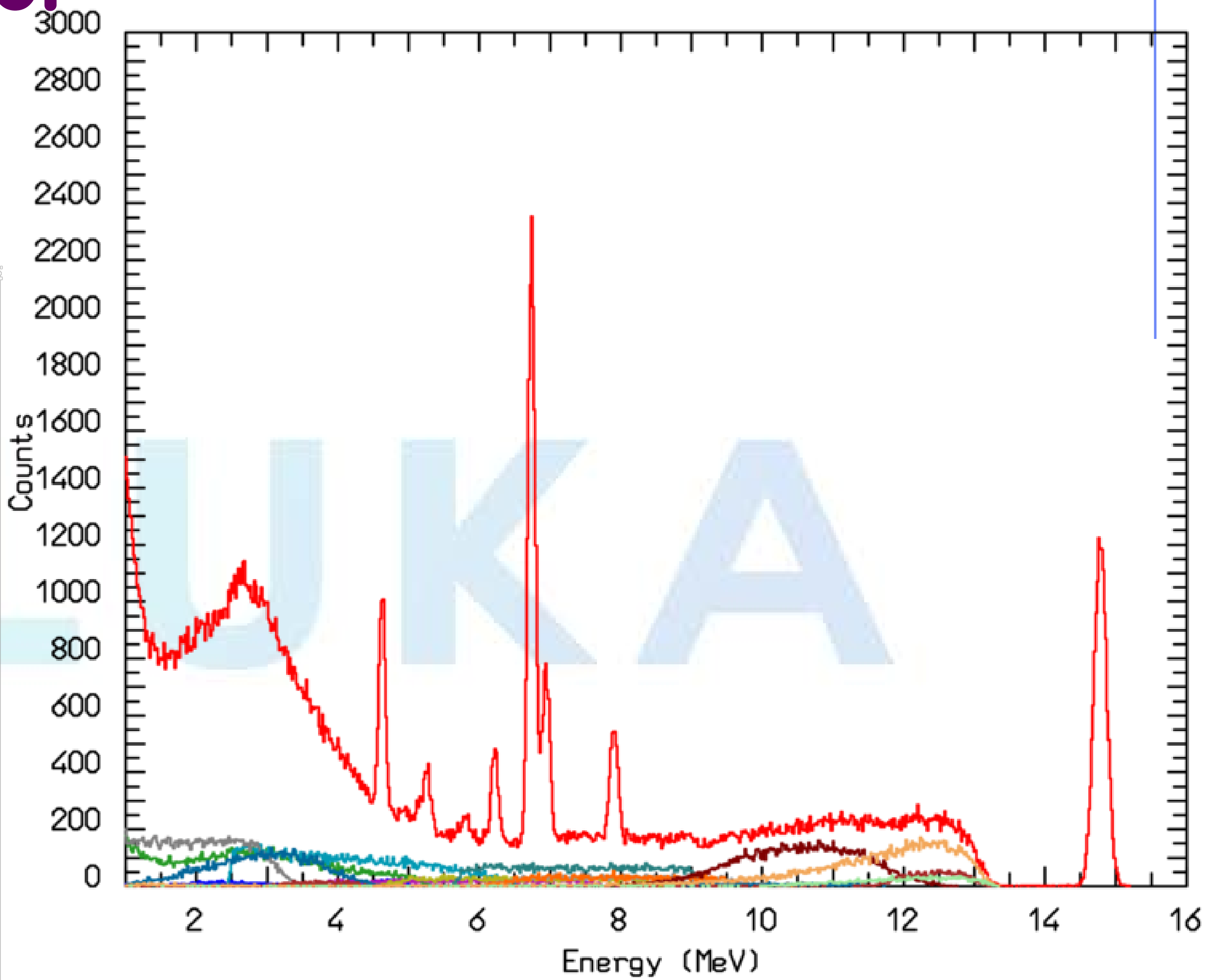
Histos: Computed response functions by folding n-spectra with σ for ^{3}He(n,p)

Symbols: exp. data with mono-energetic neutron beams at PTB

Example: Diamond detector

- **500 μm thick diamond** semiconductor device which acts as target and detector at the same time for **20.49 MeV** neutrons





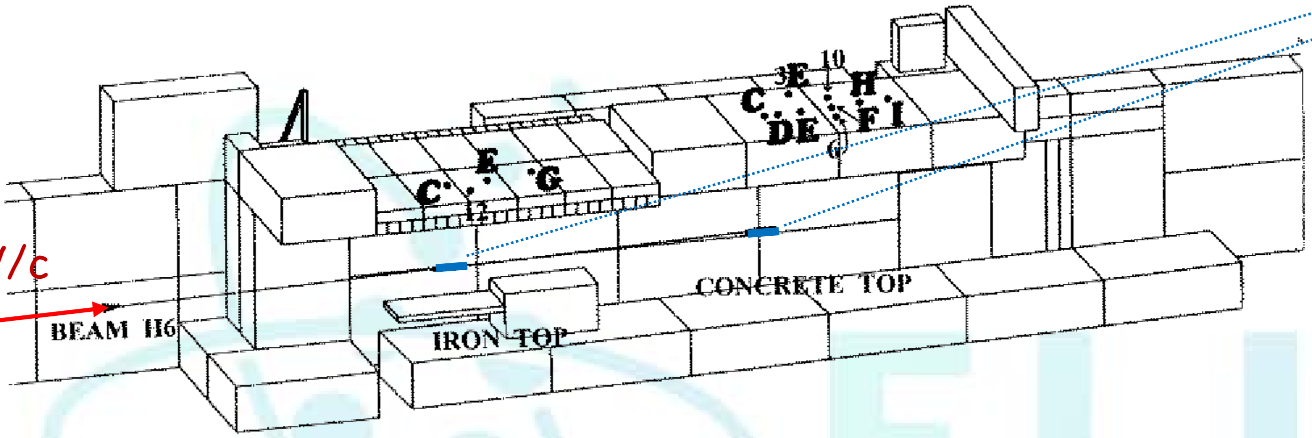
Deposited energy: total (red), the other coloured curves are the various channels contributions to $^{12}C(n,n\alpha)$
(the applied exp. resolution is arbitrary)

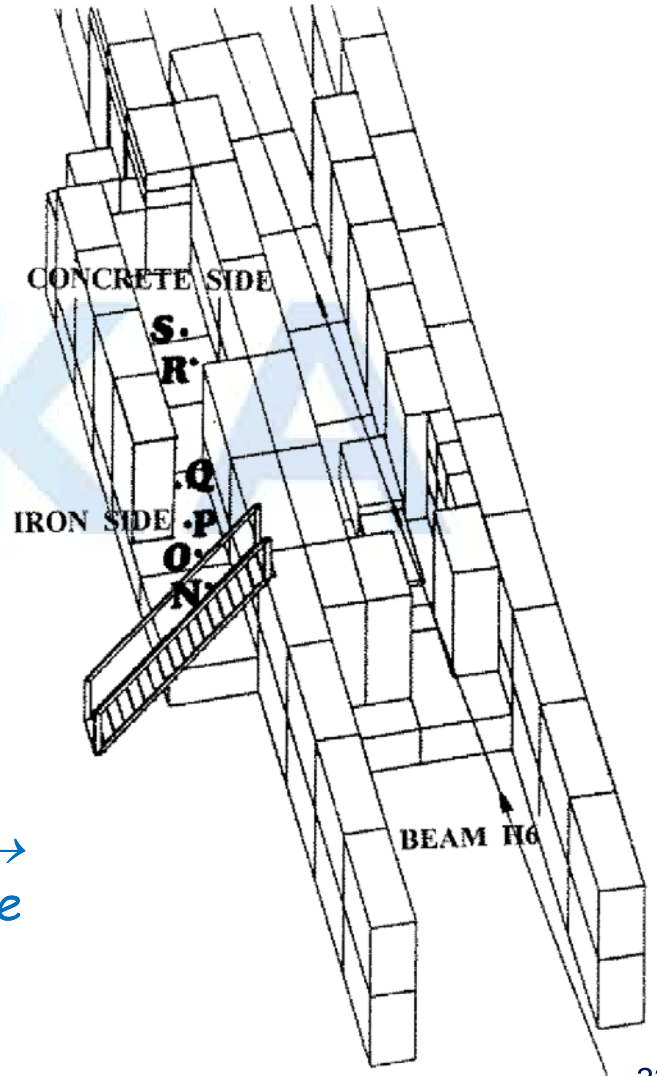
CERN-EU High-Energy Reference Field (CERF) facility:

Target (Cu L=50 cm, ∅ = 7 cm)

Iron and concrete positions

120 GeV/c





Top (left, one side removed) and side (right, roof removed) views of the CERF facility with the measuring positions

120 GeV secondary SPS mixed hadron beam

Measurement taken with several Bonner spheres (various diameters ↔ different neutron energy ranges), and a couple of "REM counters", one containing Pb to make it sensitive to high energy neutrons

CERF: neutron detector count rates

	experimental		FLUKA		experimental		FLUKA	
	cts/PIC	%	cts/PIC	%	cts/PIC	%	cts/PIC	%
	CONCRETE TOP "E"				IRON TOP "C"			
LINUS rem counter*	0.364	0.36	0.409	2.2	1.78	0.30	1.68	2.1
SNOOPY rem counter*	0.200	0.59	0.207	3.3	1.83	0.75	1.71	2.0
233 sphere	0.788	0.33	0.899	3.7	9.28	0.28	9.23	2.0
178 sphere	0.989	0.36	1.01	3.4	16.1	0.24	16.9	1.9
133 sphere	1.02	0.30	0.981	3.2	19.2	0.19	21.2	1.9
108 sphere	0.942	0.35	0.883	3.1	17.7	0.20	19.2	1.9
83 sphere	0.704	0.30	0.717	3.1	11.2	0.26	12.1	1.9

Bonner spheres of various diameters (mm)

Absolute comparison between the FLUKA predictions and the experimental response of the various detectors in stray radiation fields at CERN. The percent statistical (%) uncertainty is indicated

* C.Birattari et al, Rad.Prot.Dos., 76 135

Are neutrons of interest for Corsika8?

- If "reasonable" neutron production and transport down to ~ 20 MeV is a goal:
  - (in)coherent nuclear elastic scattering is a must;
  - Presence/absence of hydrogen is important (detailed composition);
  - Proj/targ accurate excitation/evaporation is a must;
  - … technically, apart elastic scattering and low energy γA, no major interface change required;
- Otherwise if full neutron transport including the 20 MeV $\rightarrow$ thermal (meV) energy range is wished for, than it is a completely different world/technical challenge:
  - *If the, inclusive uncorrelated, group-wise approach is sufficient:*
    - The relevant neutron libraries for target ***elements*** must be loaded (~300 Mb for all elements/T's);
    - New interface to the group-wise routines, vastly different from the one for non-elastic interactions;
    - Corsika8 must deal with neutron energy "groups", not continuous energies, and material temperatures;
  - *Vice versa, if the exclusive, fully correlated, point-wise transport is required:*
    - The relevant neutron data sets for target ***isotopes*** must be loaded (~3 Gb for all isotopes/T's);
    - Very complex new interface to a variety of required routines;
    - Very memory/CPU intensive;
    - Corsika8 must deal with material temperatures,

Thanks for your attention!

Examples of FLUKA Cosmic Rays and Space Applications (likely no time)

FLUKA applications in Astroparticle physics: examples

ELSEVIER Astroparticle Physics 19 (2003) 269–290
www.elsevier.com/locate/astropart

The FLUKA atmospheric neutrino flux calculation

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

Astroparticle Physics 81 (2016) 21–38
Contents lists available at ScienceDirect
Astroparticle Physics
journal homepage: www.elsevier.com/locate/astropartphys

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

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,§]

PHYSICAL REVIEW D **93**, 082001 (2016)

Measurement of the high-energy gamma-ray emission from the Moon with the Fermi Large Area Telescope

ONLINE ICRC 2021

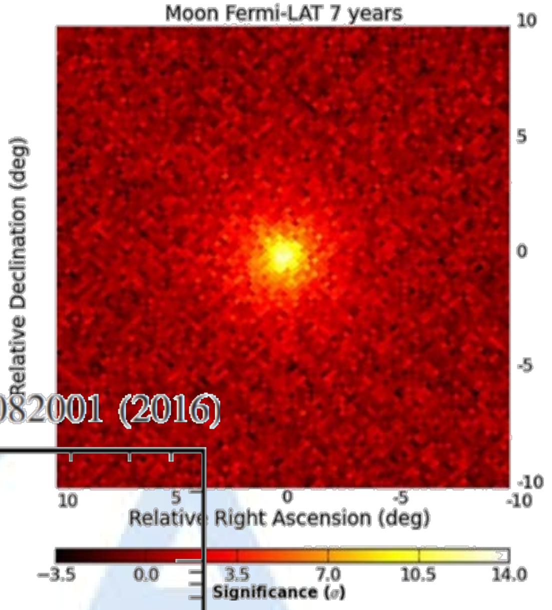
Neutron Production in Extensive Air Showers

*Investigation of the **neutron component** in **Very High Energy Air showers** (run up to ~10^{19} eV)*

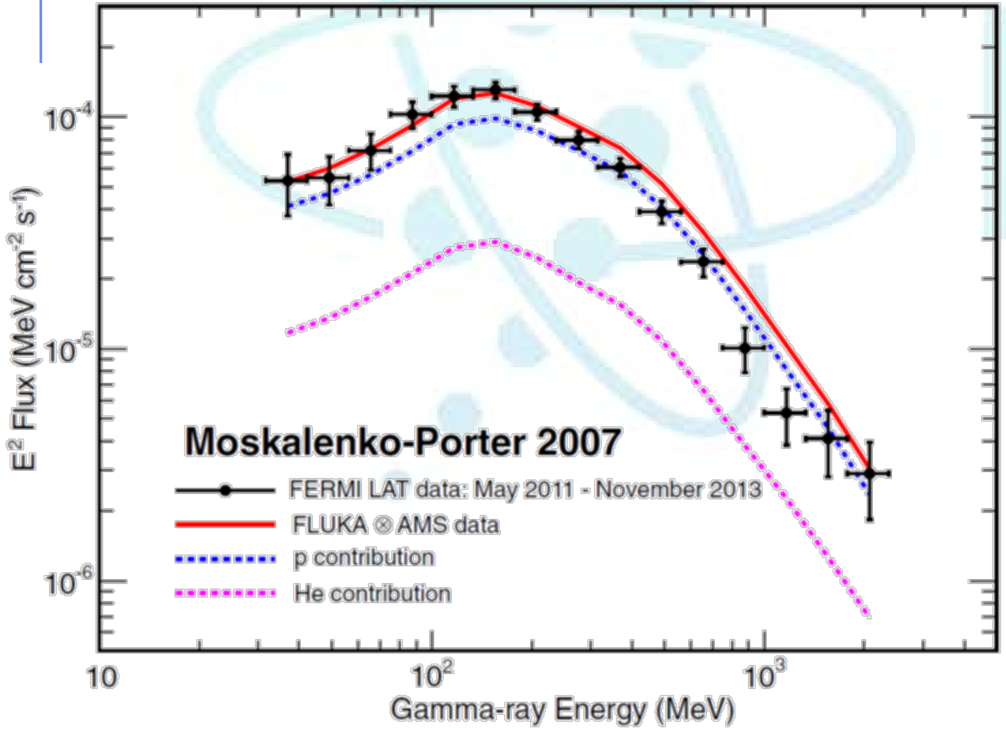
Ralph Engel,[a,b,*] Alfredo Ferrari,[a,c] Markus Roth,[a] Martin Schimassek,[b] David Schmidt[b] and Darko Veberič[a]

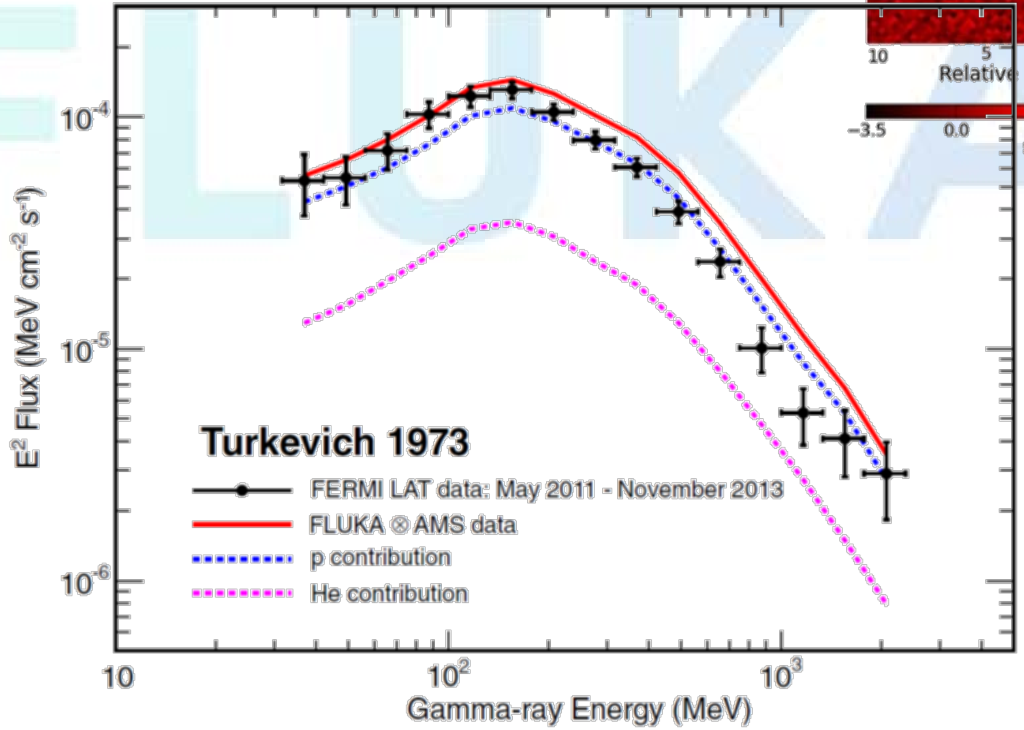
Gamma rays from GCR interactions with the moon:

Gamma-ray flux from the Moon in the period May 2011 –November 2013, measured (**FERMI-LAT**) and computed (**FLUKA**) for two different Lunar surface composition models (courtesy of M.Mazziotta, INFN Bari). Primary CR spectra from AMS-02

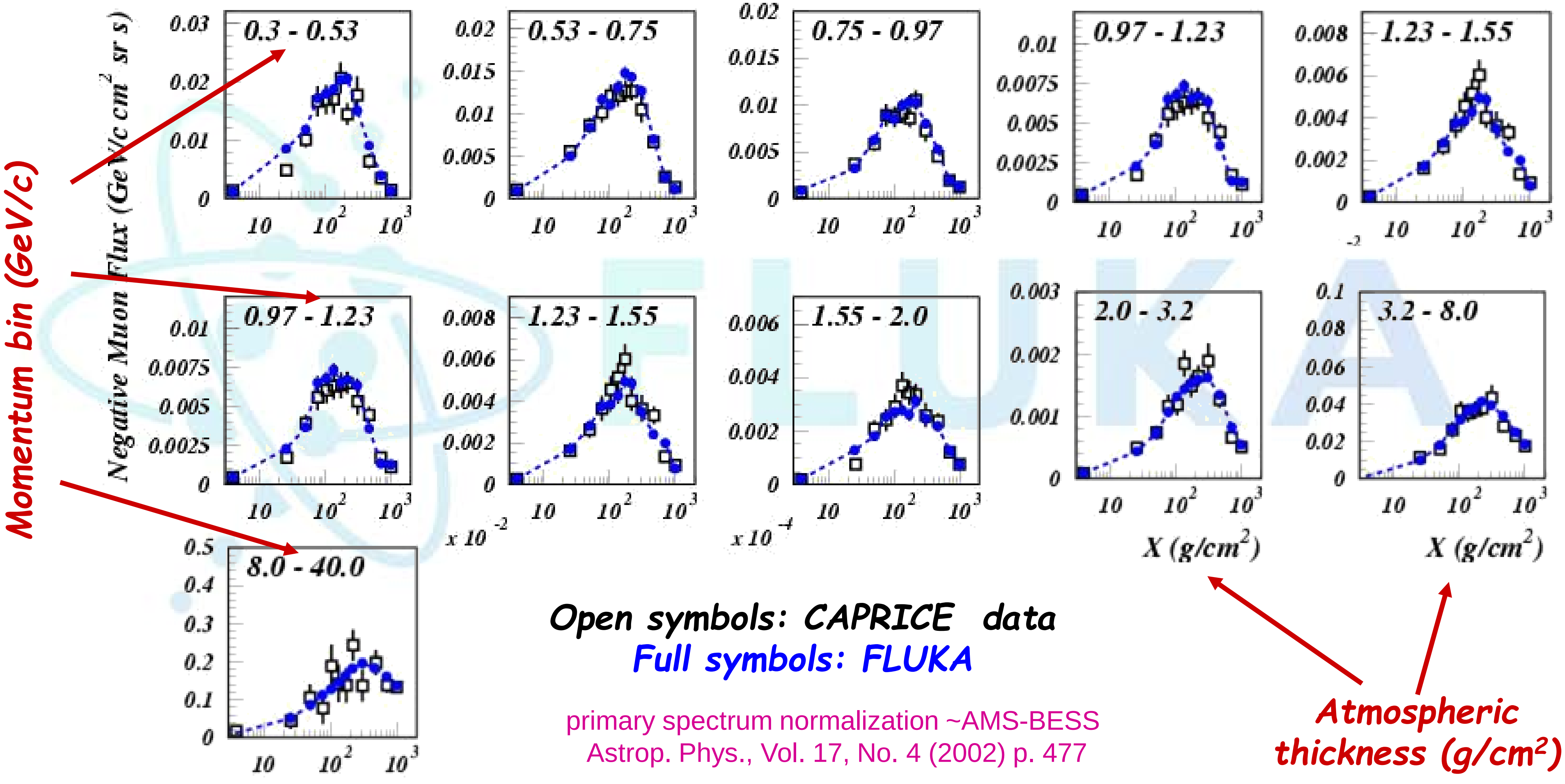


M. ACKERMANN *et al.* PHYSICAL REVIEW D 93, 082001 (2016)





Negative muons at floating altitudes: CAPRICE94



Open symbols: CAPRICE data

Full symbols: FLUKA

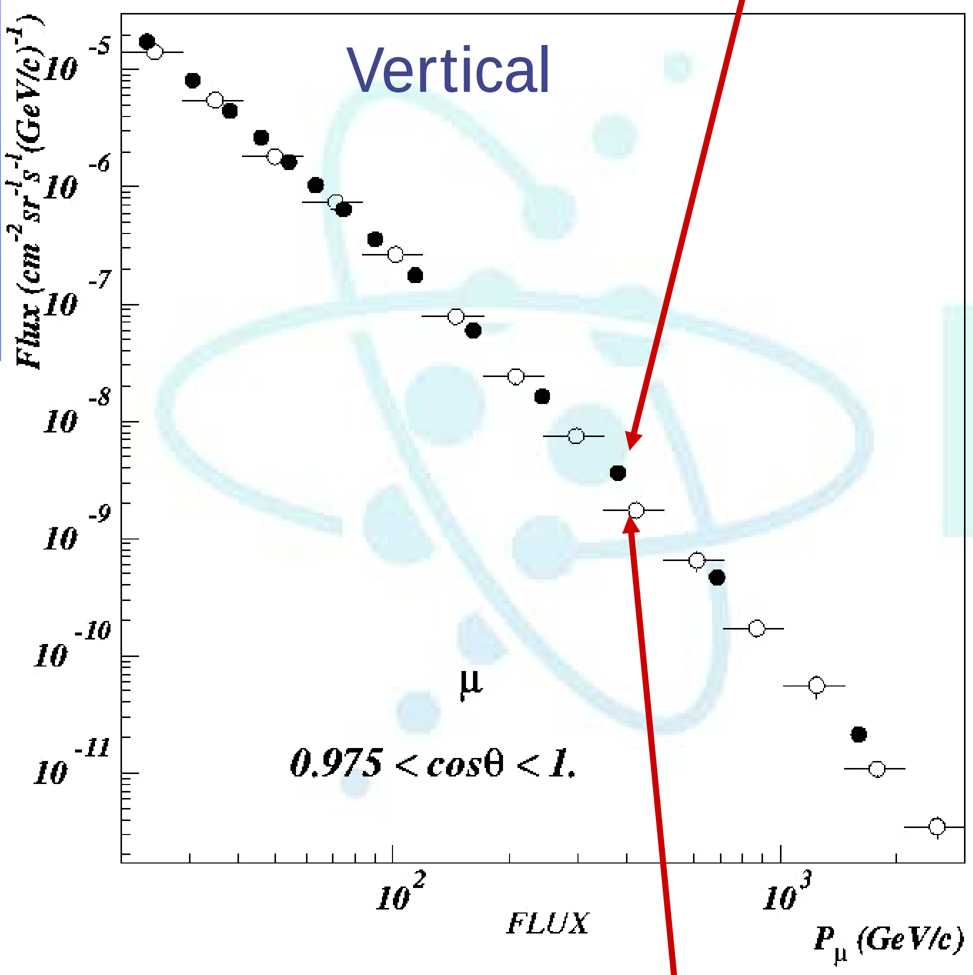
primary spectrum normalization ~AMS-BESS
Astrop. Phys., Vol. 17, No. 4 (2002) p. 477

Atmospheric thickness (g/cm^2)

"Cosmic" muons at ground level: L3 Muons

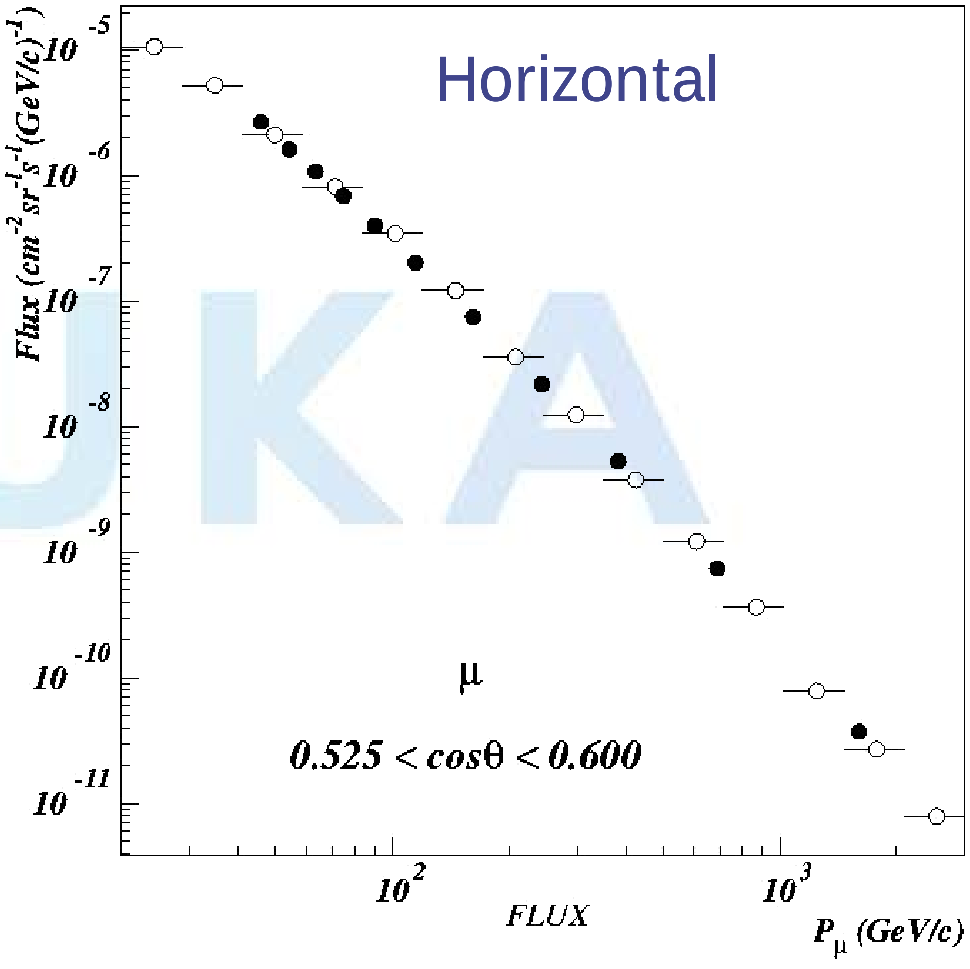
exp. data

*(S.Muraro, PhD thesis Milano, NPB Proc.Suppl.**168**, 169)*



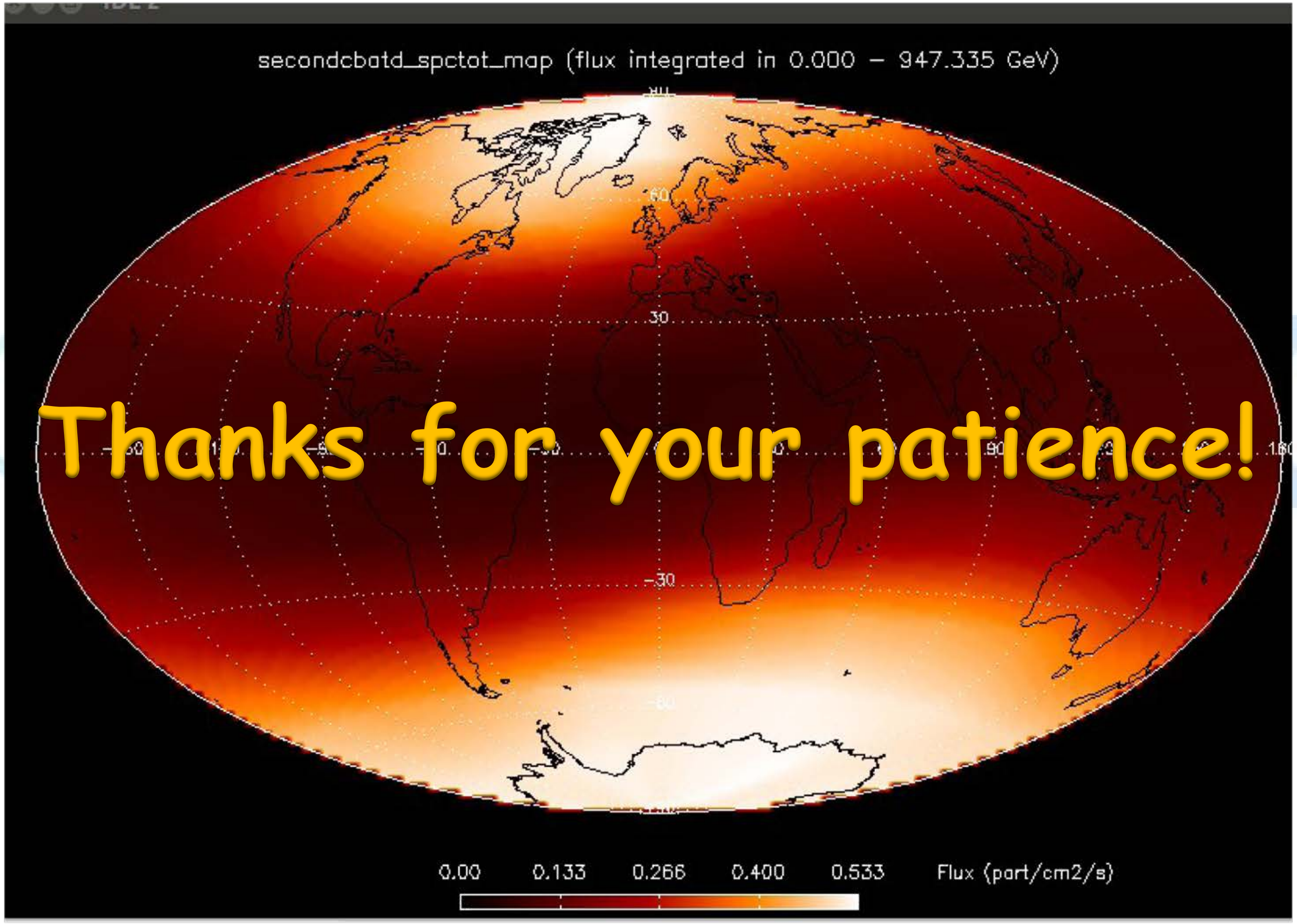
FLUKA simulation

Please note that muons of a given energy originate from GCR primaries of 10-100 times that energy → from energies where the majority of phase space is unmeasured



The neutron albedo from GCR's at 400 km altitude*

*Courtesy of the late N.Combier, CEA-Saclay



Thanks for your patience!

Computed with a full 3D FLUKA simulation of the whole Earth, the atmosphere, and of the geomagnetic field

Important for satellites