The FLUKA code

A (very) short introduction to FLUKA:
a Multipurpose Particle Interaction and Transport MC code

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FLUKA short description:

- FLUKA is a general purpose tool for calculations of particle transport and interactions with matter
- All Hadrons (p, n, π, K,pbar, nbar, (anti)hyperons…) [0-10000 TeV]
- Nucleus-nucleus [0-10000 TeV/n]

  (the two ranges above are bracketed together: $\sqrt{s_{NN}}$~20 TeV)
- Electromagnetic (γ, $e^{+/-}$) and μ and ν [1 keV – 10000 TeV]
- Low energy neutrons (0-20 MeV, multigroup, ENDF…)
- Transport in magnetic field
- Combinatorial (boolean) and Voxel geometries
- Double capability to run either fully analogue and/or biased calculations
- On-line evolution of induced radioactivity and dose
- Radiation damage predictions (NIEL, DPA)
- User-friendly GUI interface thanks to the Flair interface

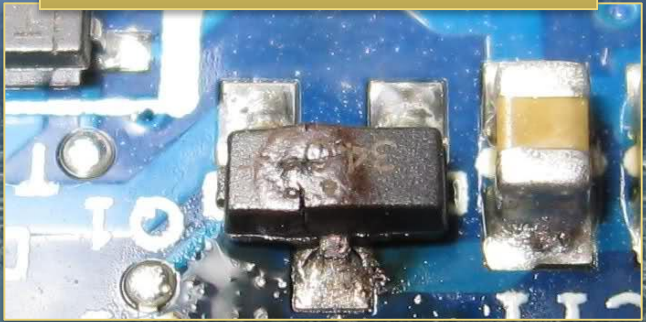
http://www.fluka.org ~11000 registered users worldwide

What can be done with FLUKA?

Some examples

Cern & Fluka (~1[...] worldwide, http://www.fluka.org)

Radiation damage (electronics, insulations)



Shielding, residual dose rates

LH[...] 2.5+2.5 TeV/n

LHCb

ATLAS

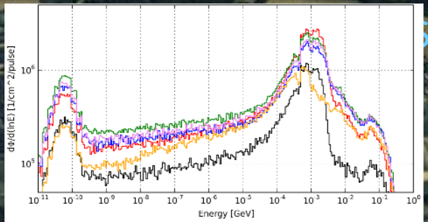
Activation, Waste disposal

SUISSE

FRANCE

Spallation sources (n_ToF), secondary beams (ν!!)

SPS 7 km

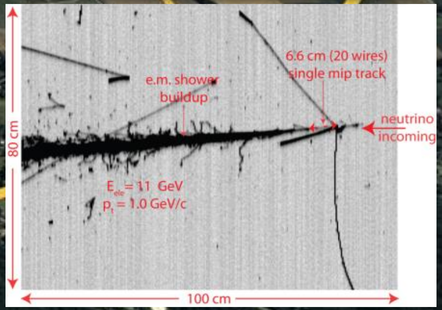


SPS: 450 GeV p

ALICE

Energy deposition (quenching, damage)

(ν) Experiments



LHC 27 km

FLUKA applications in Astroparticle physics

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

The FLUKA atmospheric neutrino flux calculation

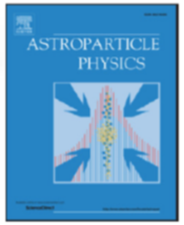
ELSEVIER
Astroparticle Physics 20 (2003) 221–234
www.elsevier.com/locate/astropart

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

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

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

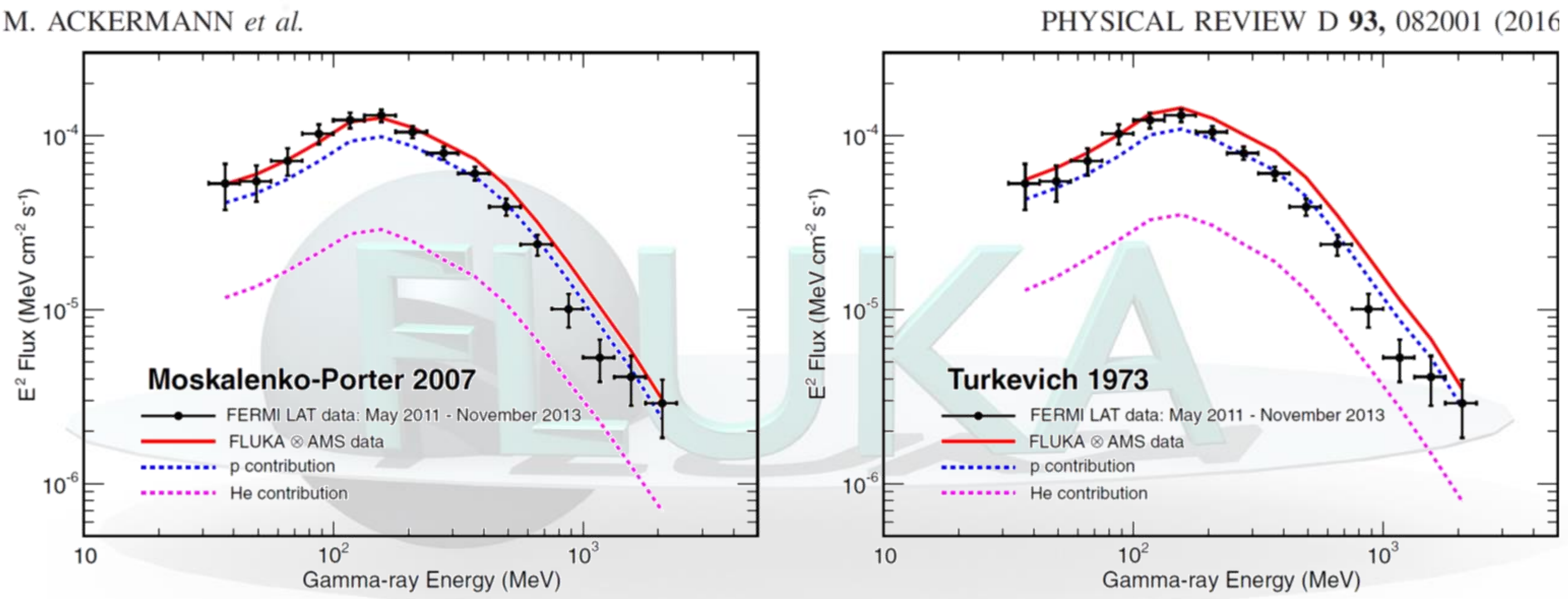
Astroparticle Physics 81 (2016) 21–38
Contents lists available at ScienceDirect
Astroparticle Physics
ELSEVIER
journal homepage: www.elsevier.com/locate/astropartphys



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

CrossMark

Gamma rays from GCR interactions with the moon:

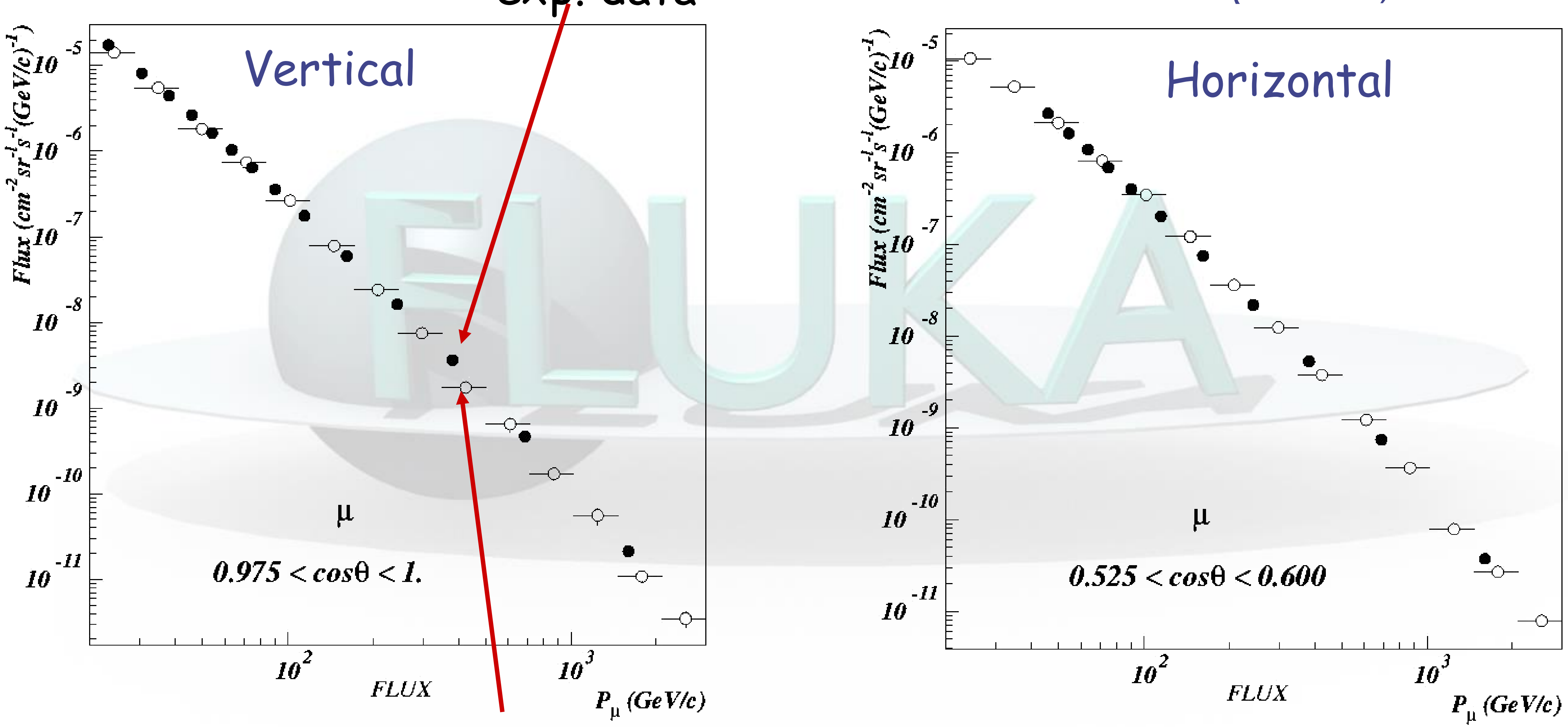


Gamma-ray flux from the Moon in the period May 2011 –November 2013, measured (**FERMI-LAT**) and computed (**FLUKA**) for two different Lunar surface composition models. Primary CR spectra from AMS-02

"Cosmic" muons at ground level: L3 Muons

● exp. data

(S.Muraro, PhD thesis Milano)



° FLUKA simulation (absolute comparison)

Fluka hA/AA models:

PEANUT
$2{\cdot}10^4 > E > \sim 0.01$ GeV

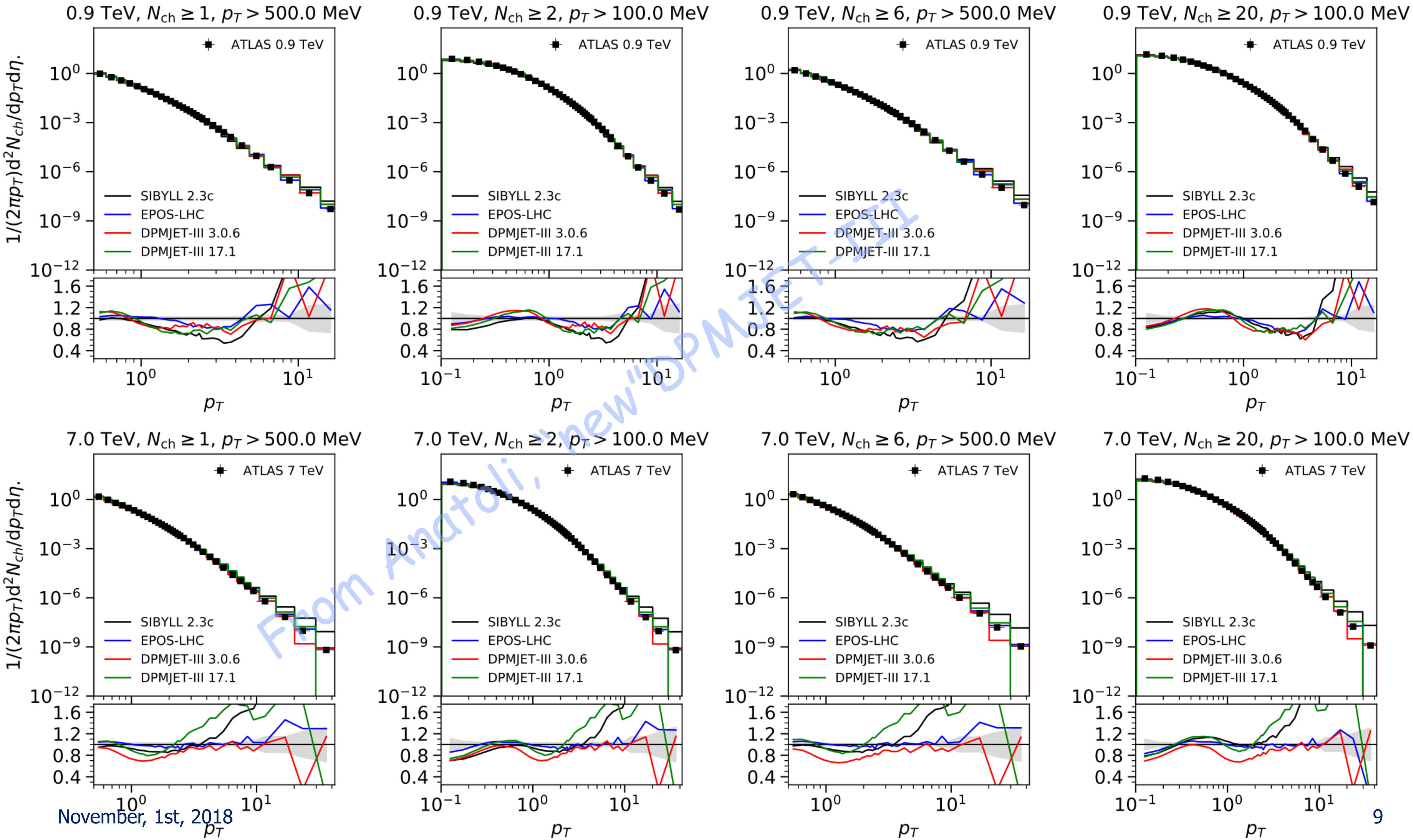
Photonuclear interactions
ElectroMagneticDissociation
Leptonuclear interactions

DPMJET-3
$10^8 > E > 2{\cdot}10^4$ GeV
$10^8 > E/n > 5\text{-}10$ GeV

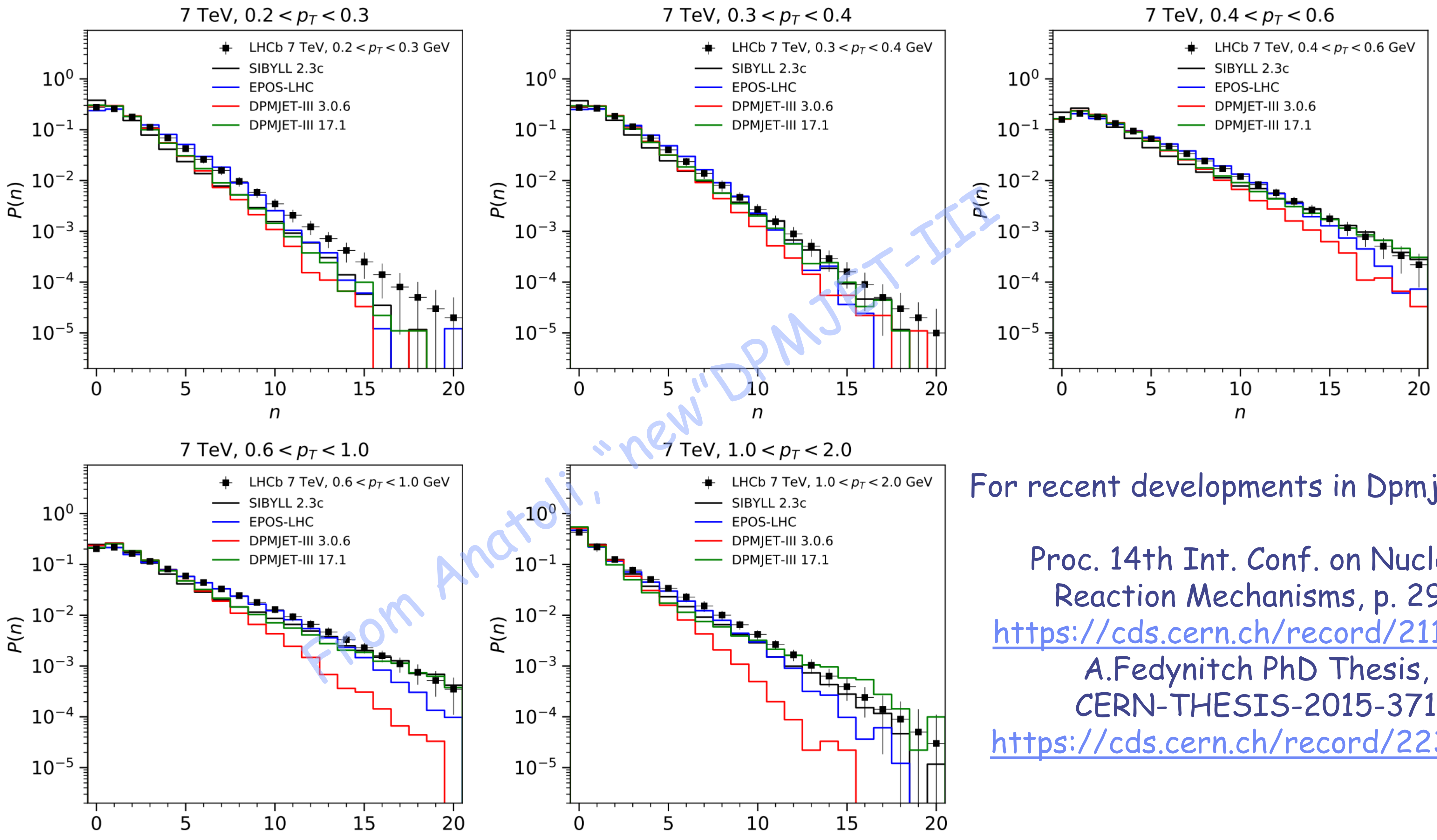
Extended rQMD
5-10 > E/n > 0.1-0.15 GeV

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

DPMJET-III, pp



DPMJET-III, pp



LHCb. EPJ C74,2888 (2014)

For recent developments in Dpmjet-III:

Proc. 14th Int. Conf. on Nuclear Reaction Mechanisms, p. 291
https://cds.cern.ch/record/2114737
A.Fedynitch PhD Thesis, CERN-THESIS-2015-371
https://cds.cern.ch/record/2231593

Hadron Nucleon interactions in FLUKA (threshold-<10 TeV lab)

(assumptions already explained by R.Engel Monday, his "low" and "intermediate" energy parts)

Nonelastic hN interactions: (very) short summary

Up to a few GeV's:

Dominance of the Δ resonance and of the N^*, ρ... resonances

$\rightarrow$ isobar model

$\rightarrow$ 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: $\approx$ 60 resonances, and $\approx$ 100 channels

At energies above a few GeV's:

- Interacting strings (quarks held together by the gluon-gluon interaction into the form of a string)
- Interactions treated in the Reggeon-Pomeron framework (**Dual Parton Model, DPM**)
- Each of the two hadrons splits into **2 colored partons** $\rightarrow$ combination into **2 colourless chains** $\rightarrow$ **2 back-to-back jets**
- each jet is then **hadronized** into physical hadrons
- Fluka contains its own hadronization model

For further details on nonelastic hN interactions in FLUKA, please look at the R.Engel slides, and/or the "extra" slides, or the FLUKA documentation

Pion production in p-p collisions:

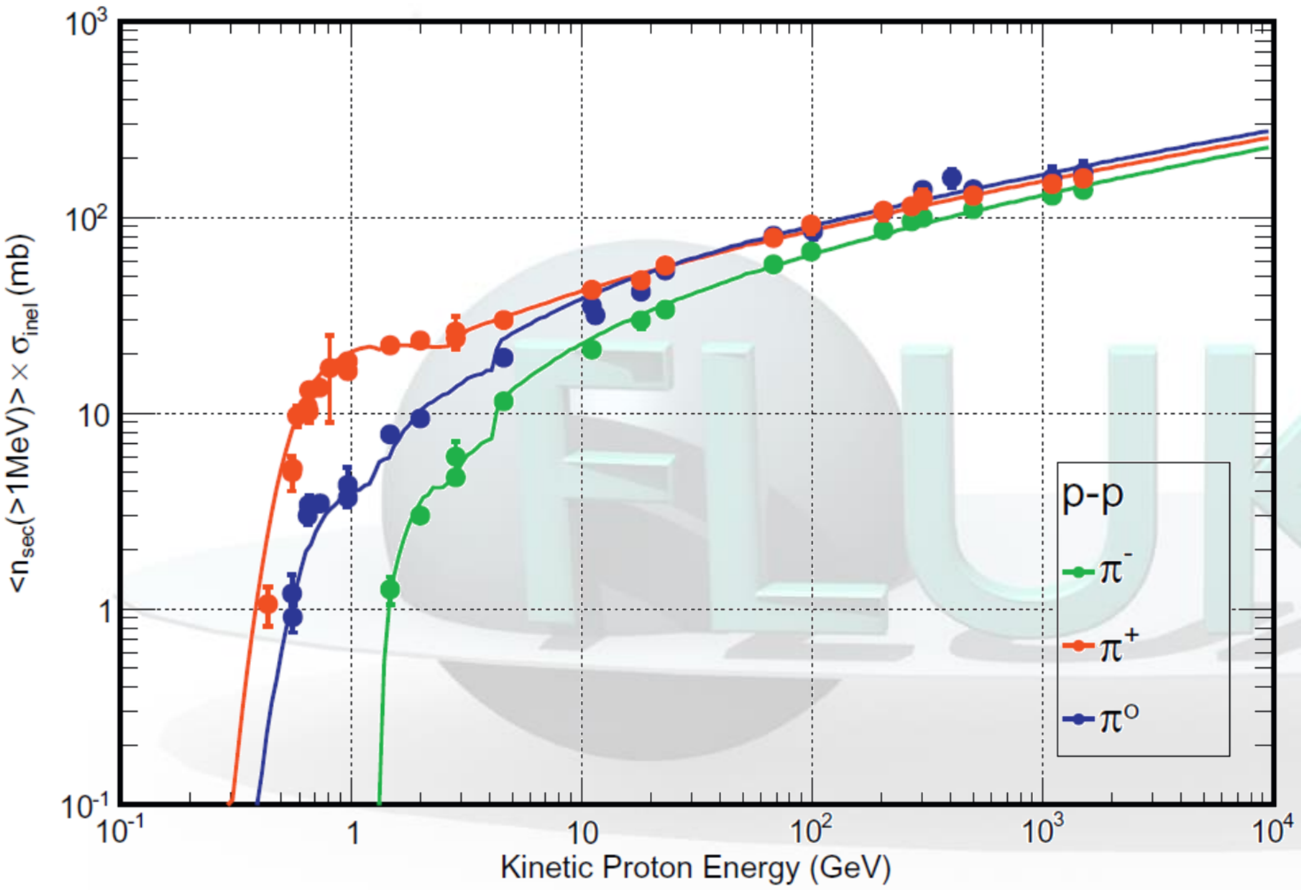
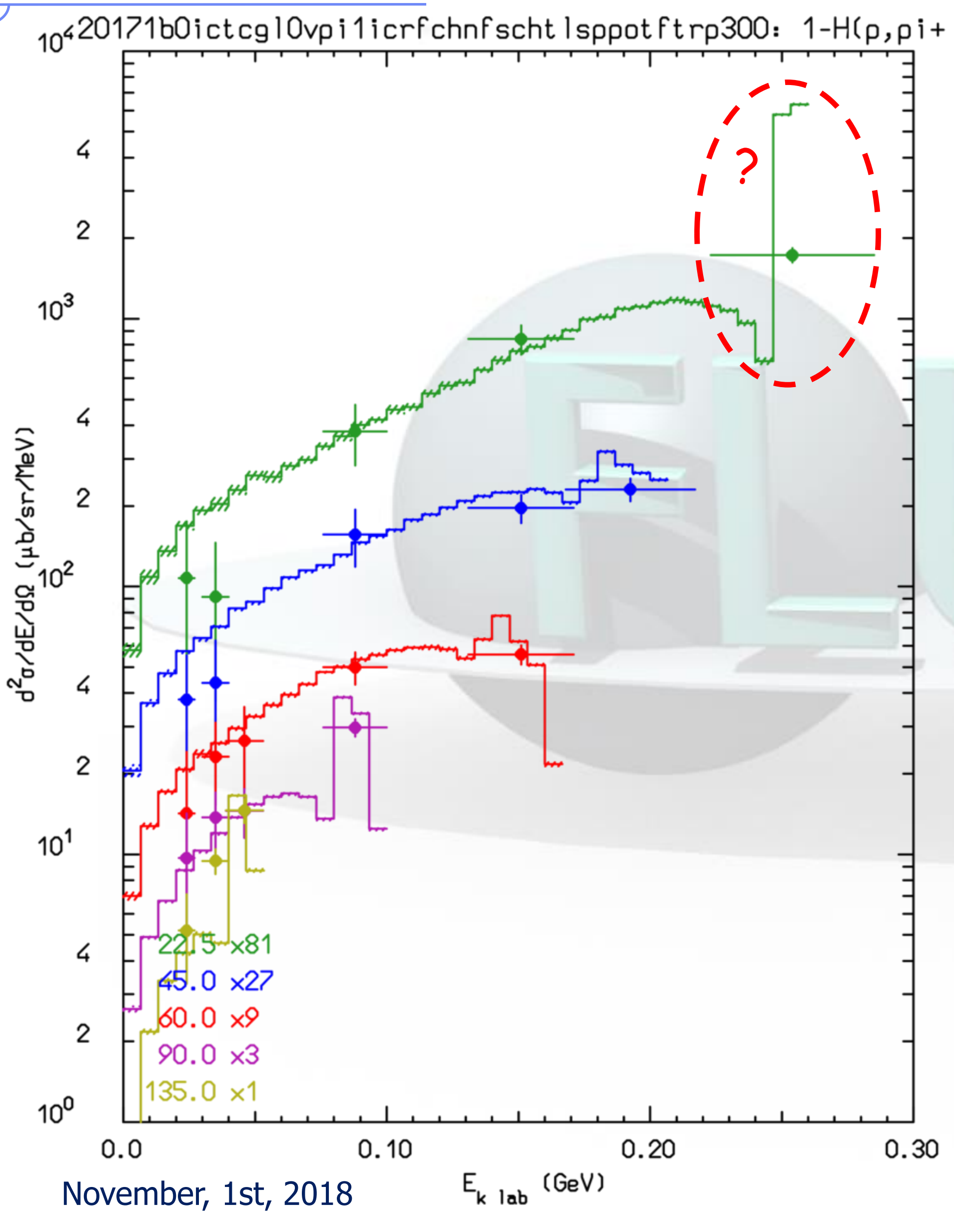


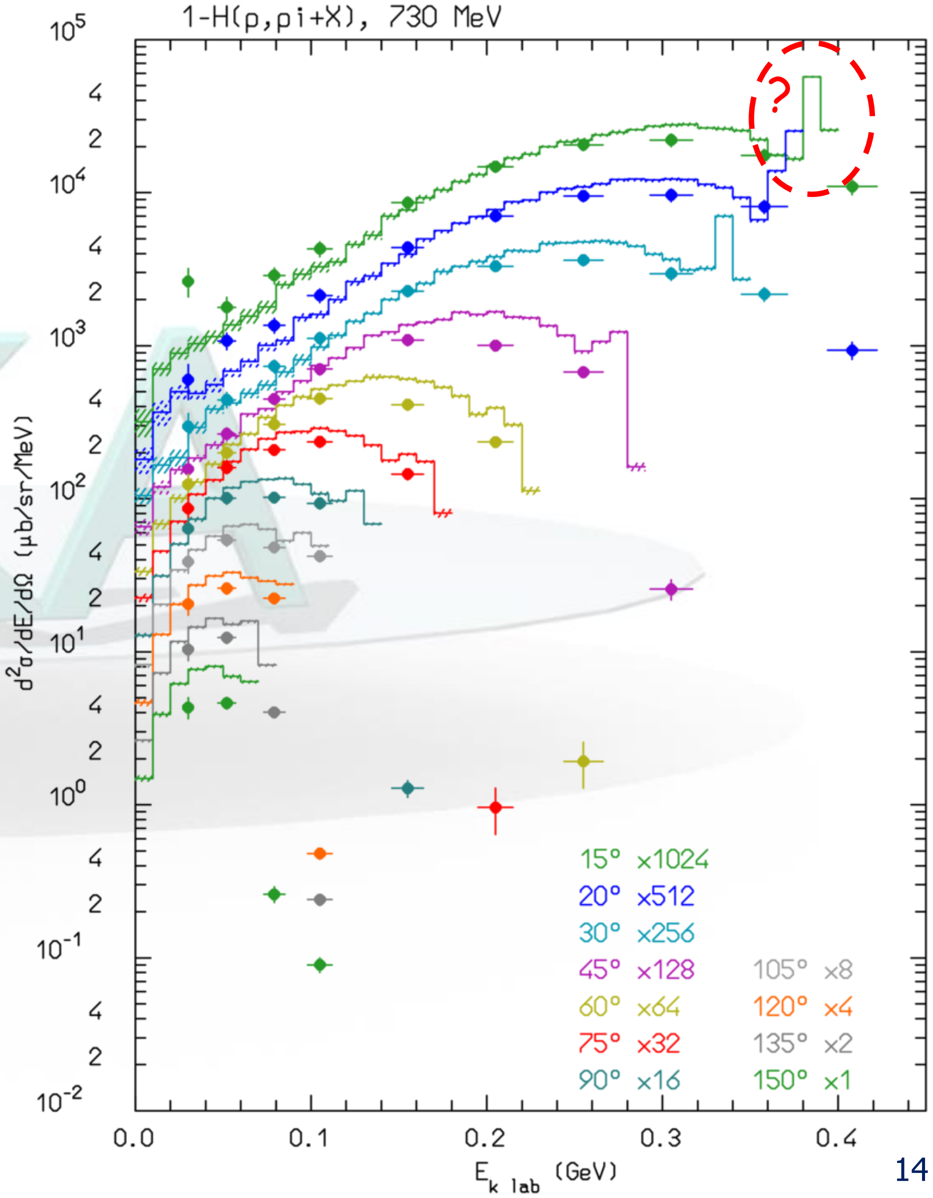
Fig. 2. Inclusive cross sections for the production of π^0 (blue), π^+ (red) and π^- (green) in p–p collision as function of the incoming proton kinetic energy. Lines: FLUKA simulation; points: data from Ref. [28]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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))

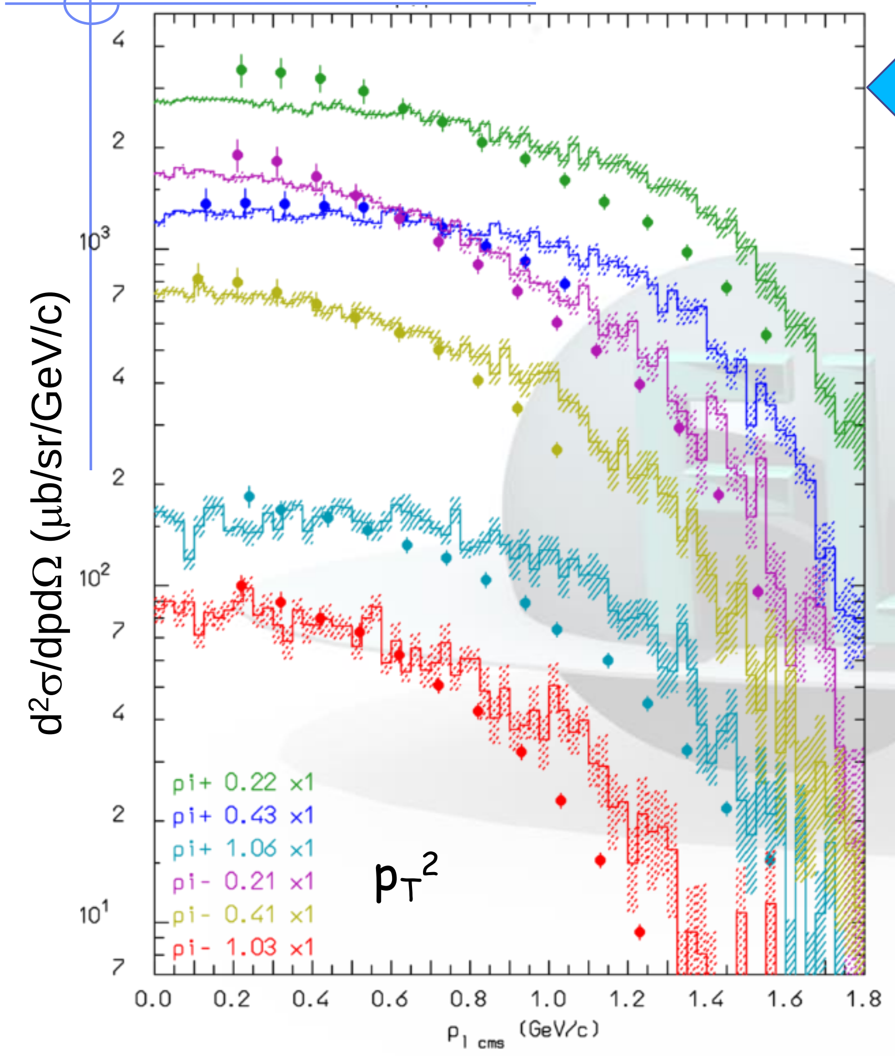
$pH \rightarrow \pi^+ X$ @ 585 MeV and 730 MeV:



π^+ production from proton interactions on hydrogen at 585 MeV (left) and 730 MeV (right) at different angles.
Symbols: data, histograms: Fluka



Effect of low $\sqrt{s}_{chain}$ “phase-space” like explosion

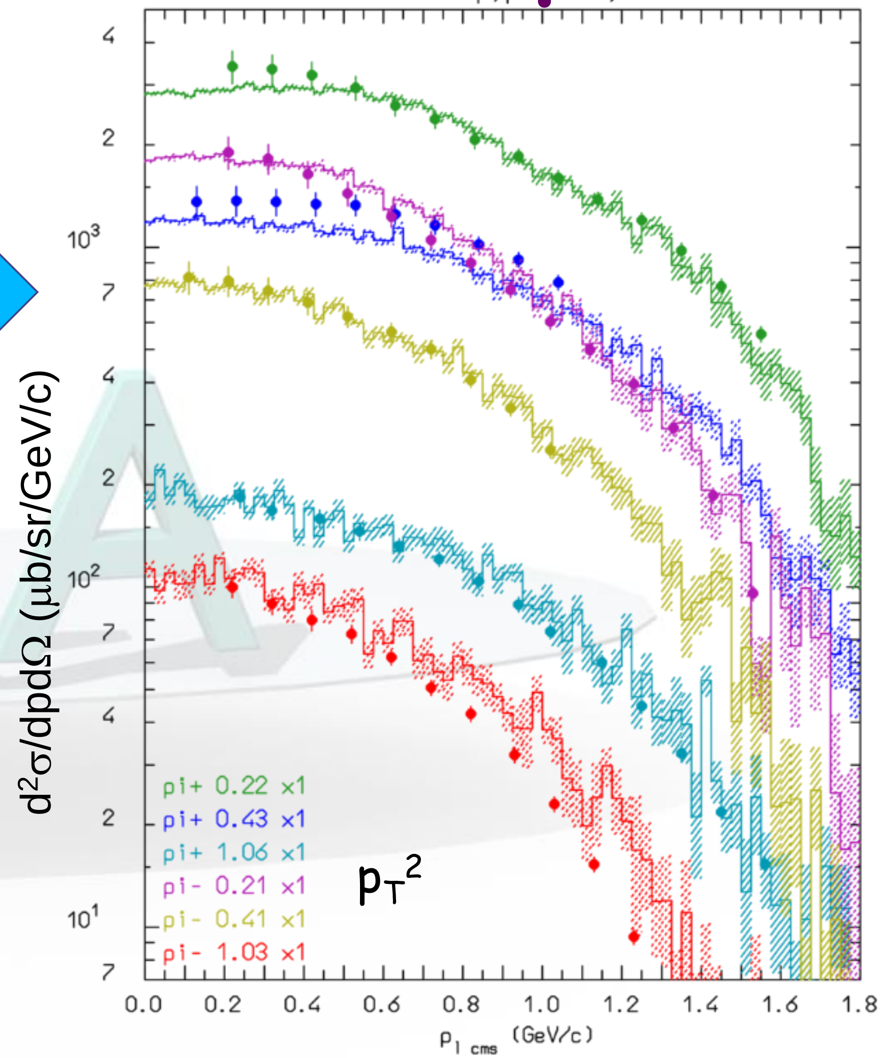


“standard” FLUKA hadronization

With low-mass chain “phase-space” like explosion

With low-mass chain explosion: much better agreement for forward emission!!

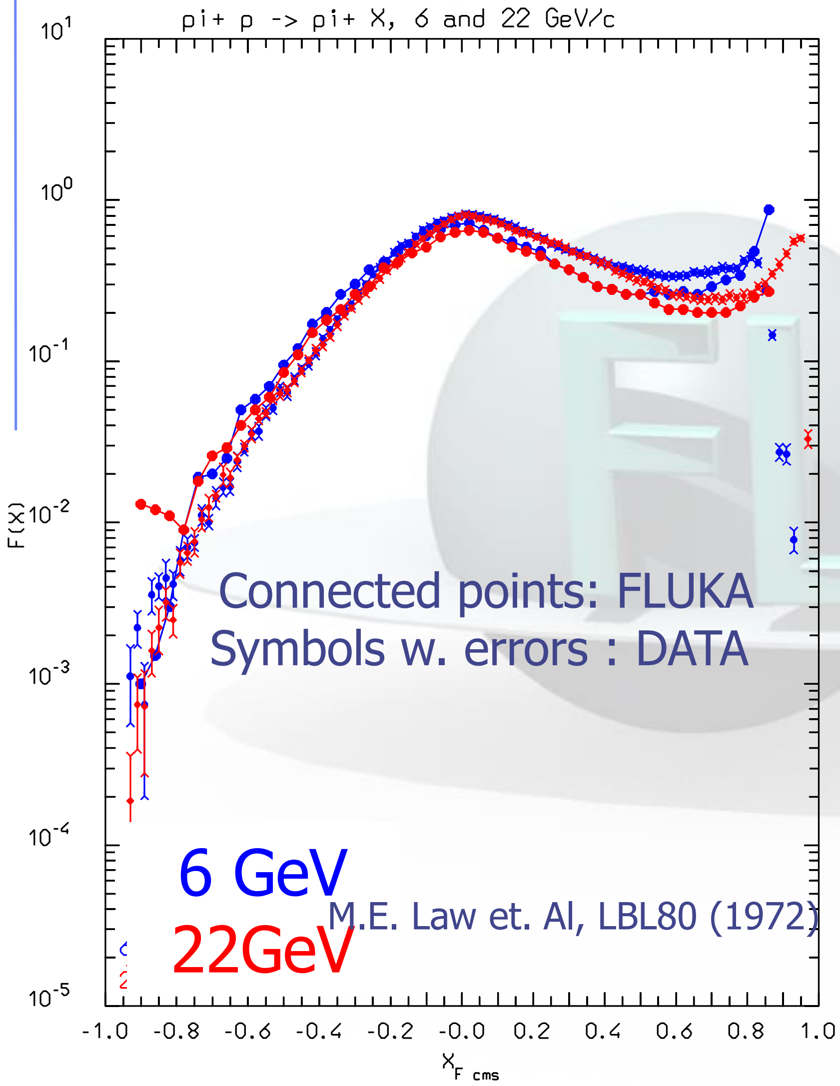
Fluka: histos
Data: symbols



Pion+ and Pion- emission from proton-proton interactions at 12.2 GeV/c. Longitudinal momentum distributions at different transverse momenta^2

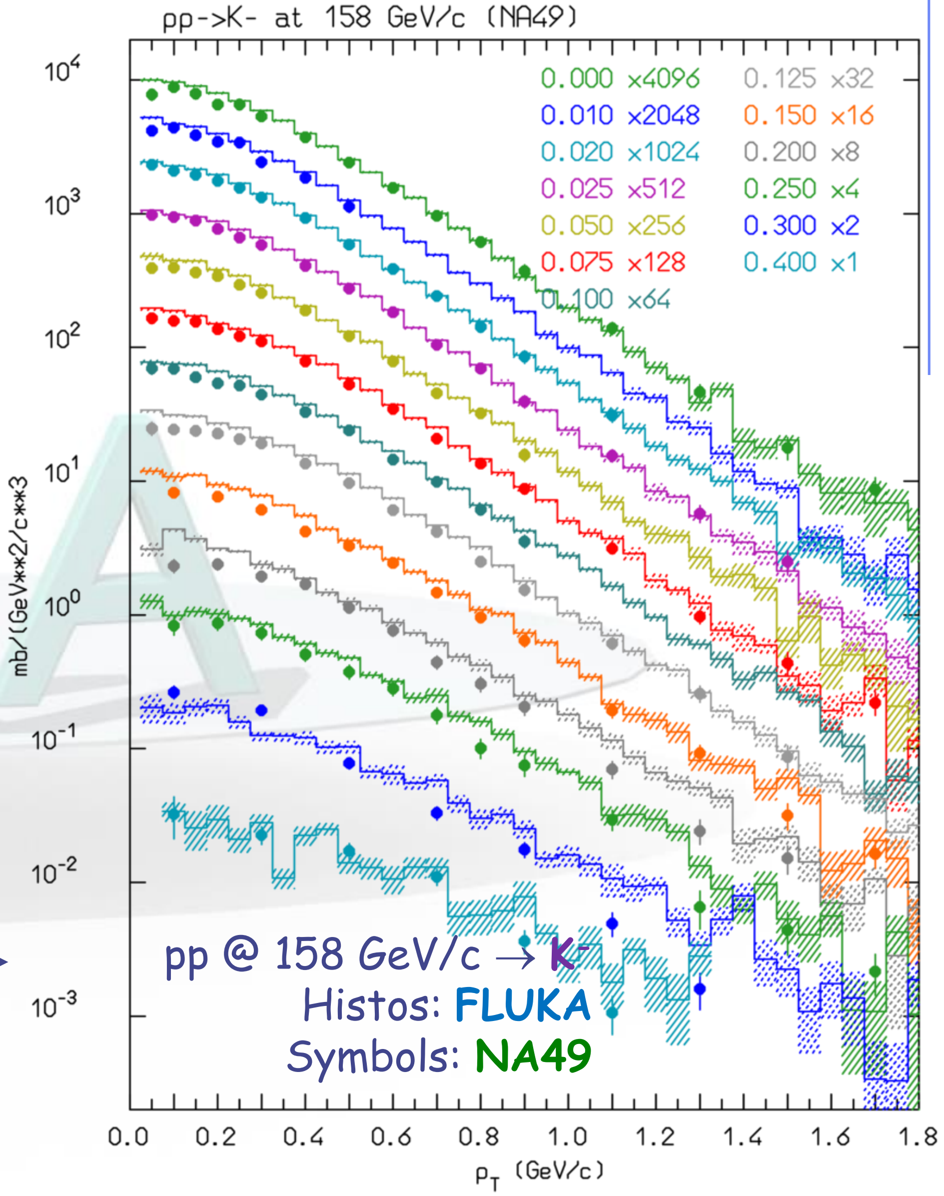
Hadronization in hadron-nucleon: examples

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



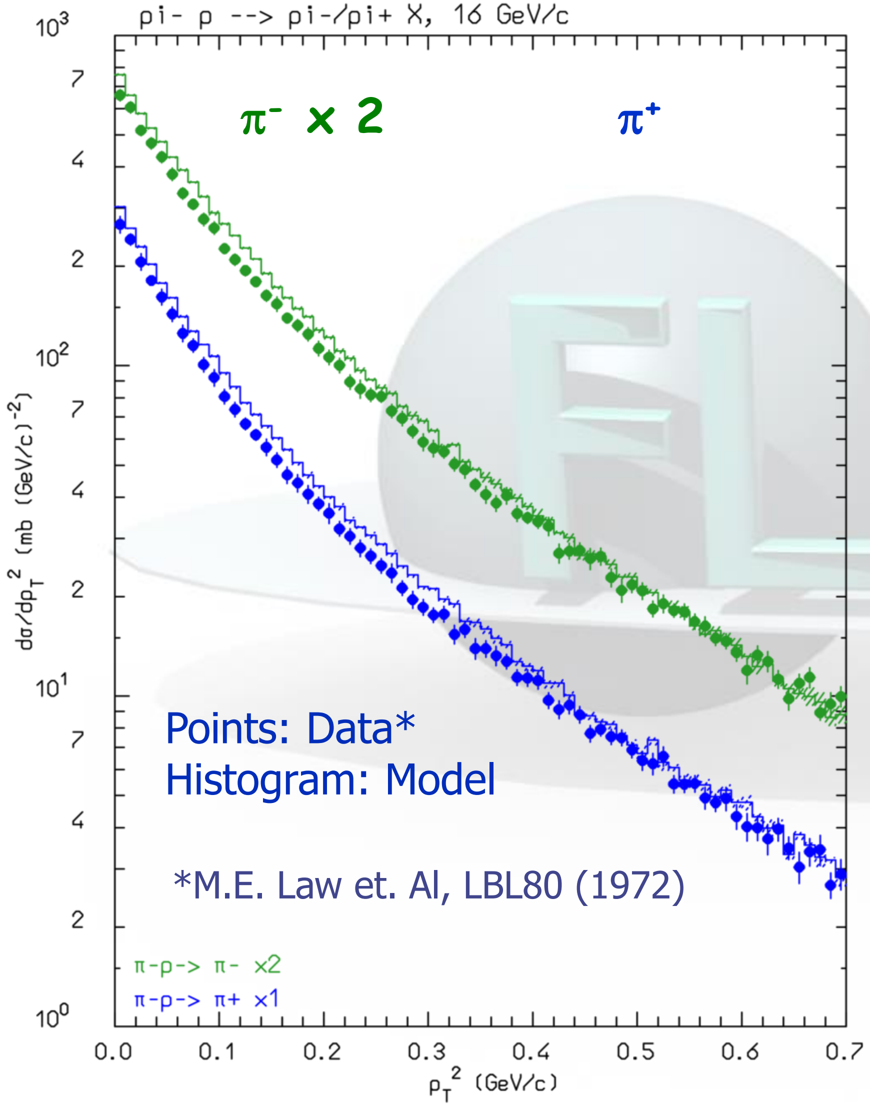
Positive pion X_F distribution for 6 and 22 GeV/c π^+ on hydrogen

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



Transverse momentum:

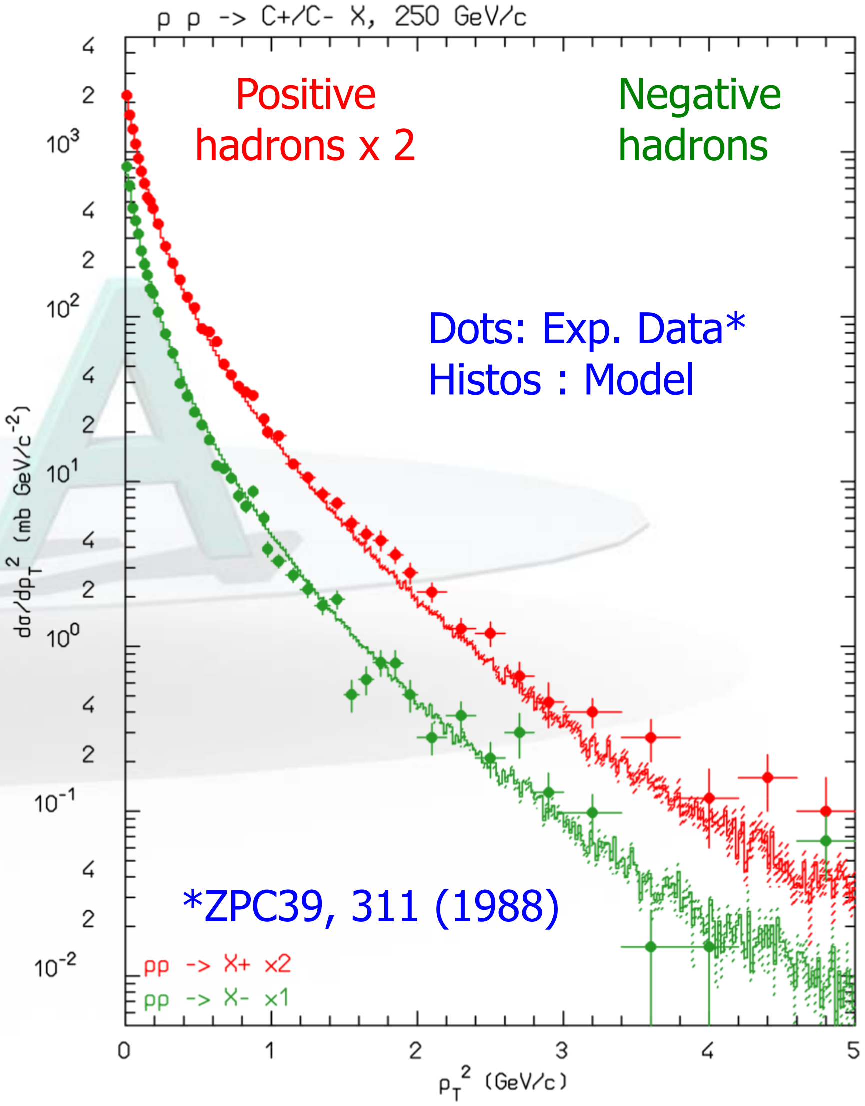
$\pi^- + p \rightarrow \pi^+/\pi^- + X$ (16 GeV/c)



Don't be cheated by the different p_T^2 horizontal scales!

The distributions left and right are ~ the same, with a characteristic p_T scale of ~ 300 MeV/c ≈ $\square/r_{hadron}$

$p + p \rightarrow Ch^+/Ch^- + X$ (250 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}

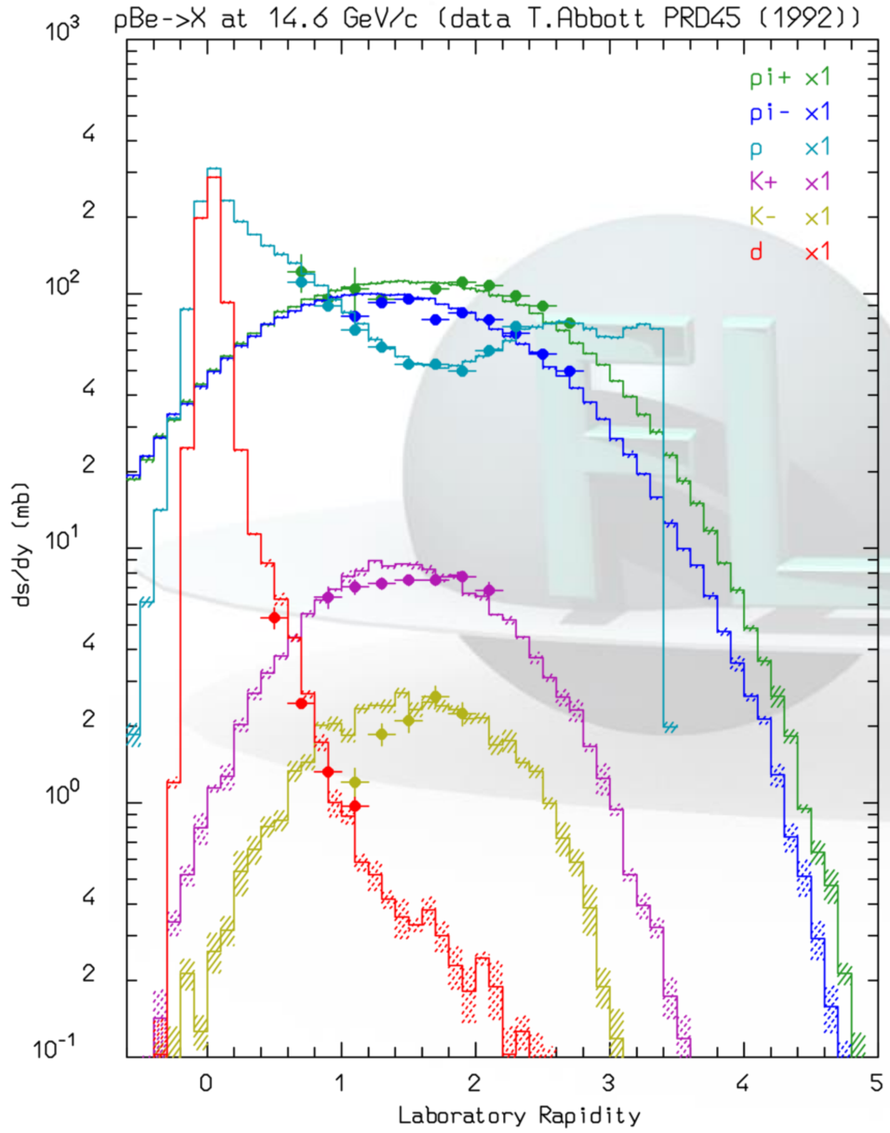
10^{-20}

10^{-16}

(Generalized) IntraNuclear Cascade in PEANUT

- Primary and secondary particles moving in the nuclear medium
- Target nucleons motion and nuclear well according to the Fermi gas model
- Interaction probability
  σ_{free} + Fermi motion × $\rho(r)$ + exceptions (ex. π)
- Glauber cascade at higher energies
- Classical trajectories (+) nuclear mean potential (resonant for π)
- Curvature from nuclear potential → refraction and reflection throughout the nucleus
- Interactions are incoherent and uncorrelated
- Interactions in projectile-target nucleon CMS → Lorentz boosts
- Multibody absorption for π, μ^-, K^-
- Quantum effects (Pauli, formation zone, coherence length, correlations…)
- Preequilibrium step
- Energetic light ion production by coalescence
- Exact conservation of energy, momenta and all additive quantum numbers, including nuclear recoil

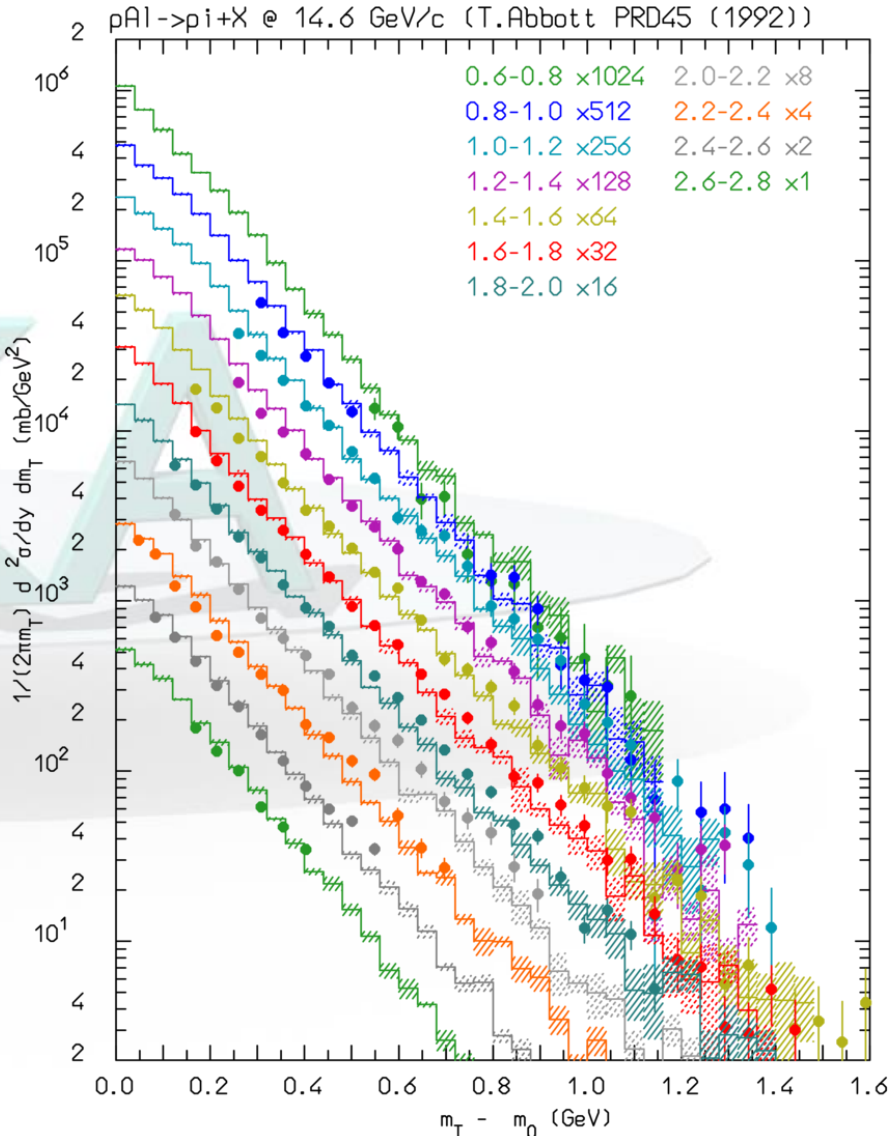
pBe, pAl @ 14.6 GeV/c



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

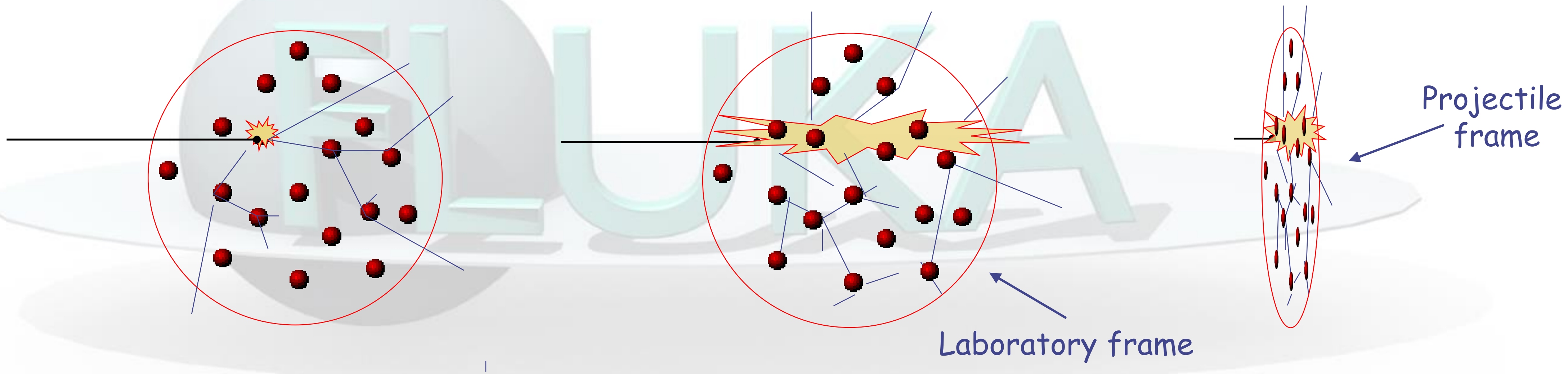
Symbols: exp. data
Histos: FLUKA



From one to many: Glauber cascade

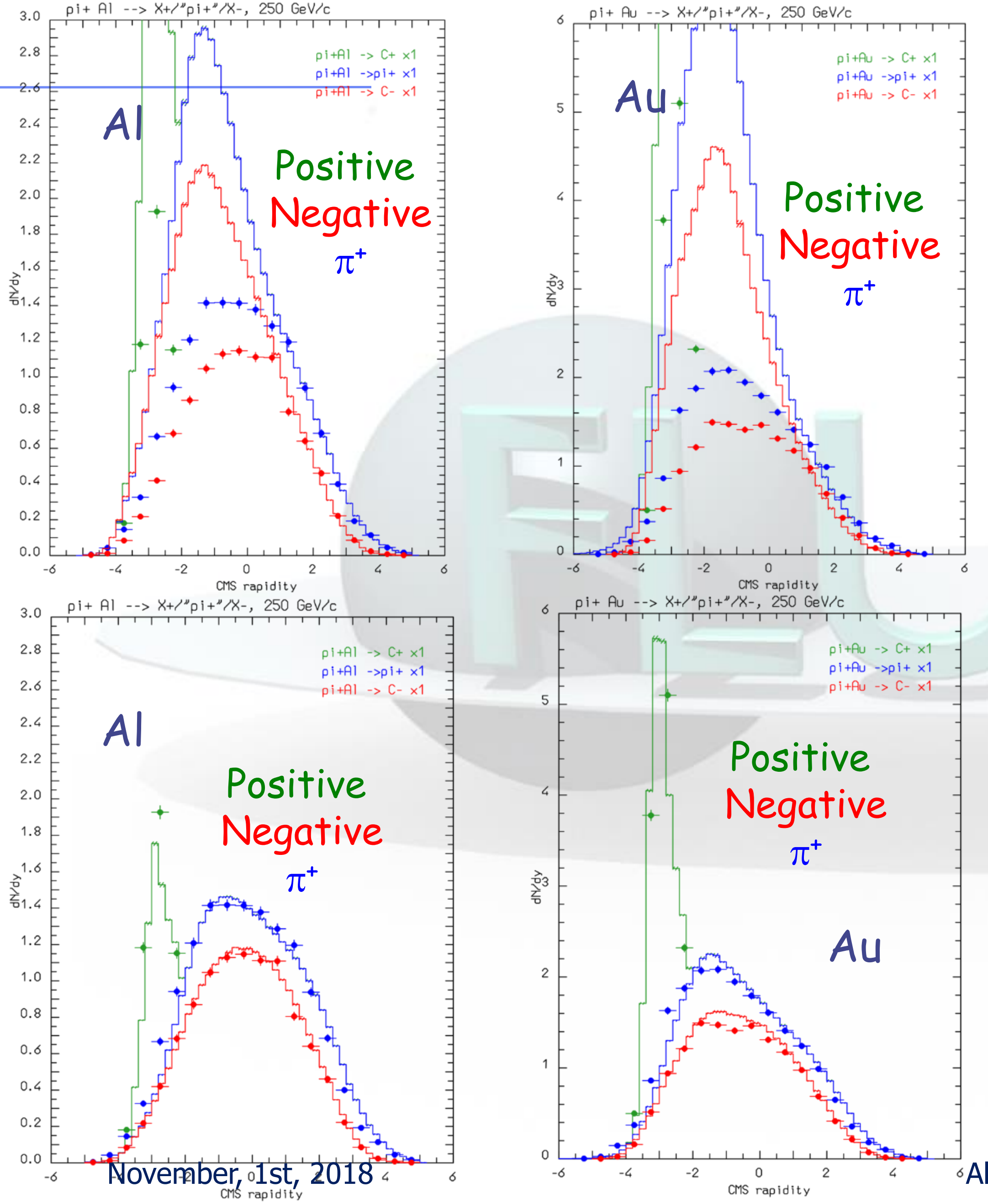
At energies below a few GeV hA interactions can be described by a single primary collision hN (elastic or non-elastic), followed by reinteraction of the secondary particles (INC).

At higher energies, the **Glauber** calculus predicts explicit multiple primary collisions



Due to the relativistic length contraction and the uncertainty principle, at high energy most of the newly produced particles escape the nucleus without further reinteraction

Formation zone: effect on hadron-induced reactions

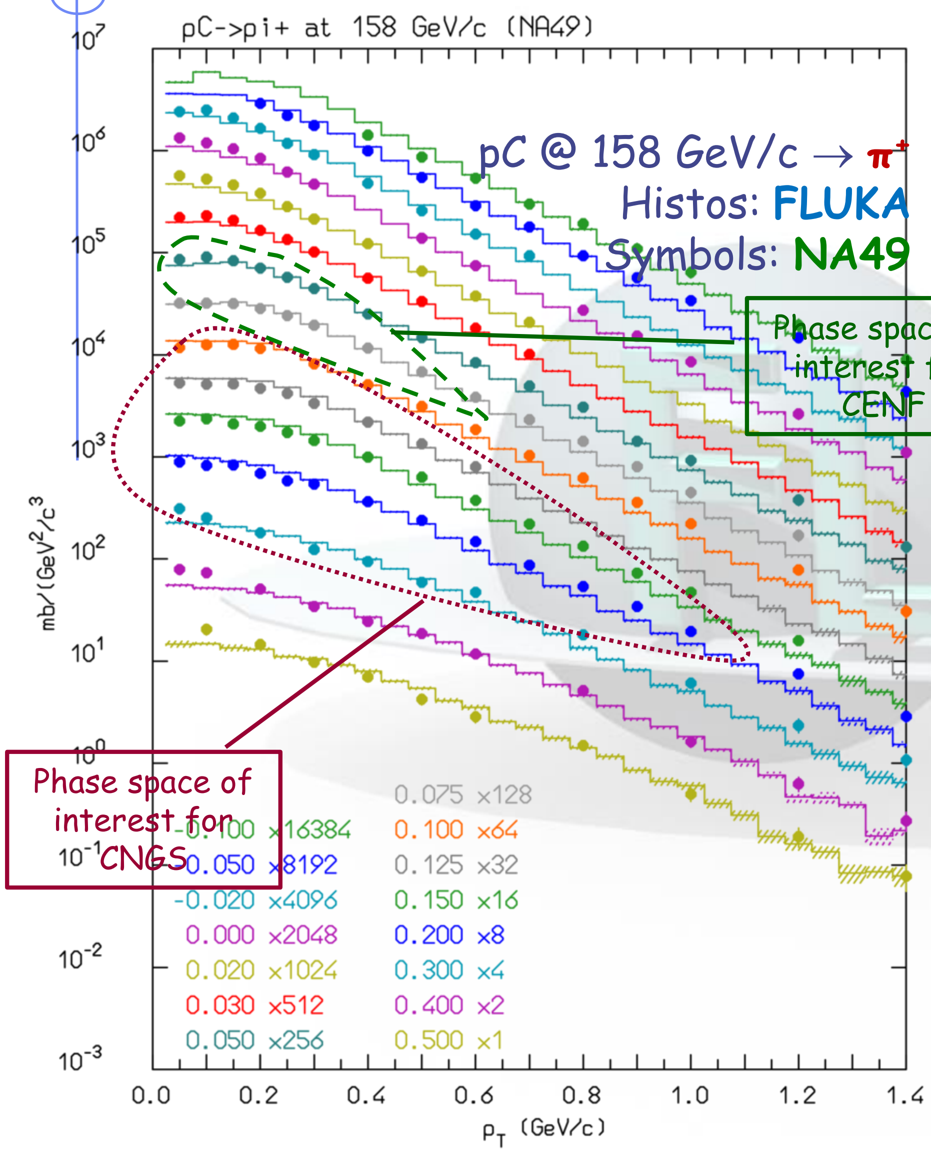


Rapidity distribution of charged particles produced in 250 GeV π^+ collisions on Aluminum (left) and Gold (right)
Histos: FLUKA
Points: exp. data (Agababyan et al., ZPC50, 361 (1991)).

Top: without formation zone

Bottom: with formation zone

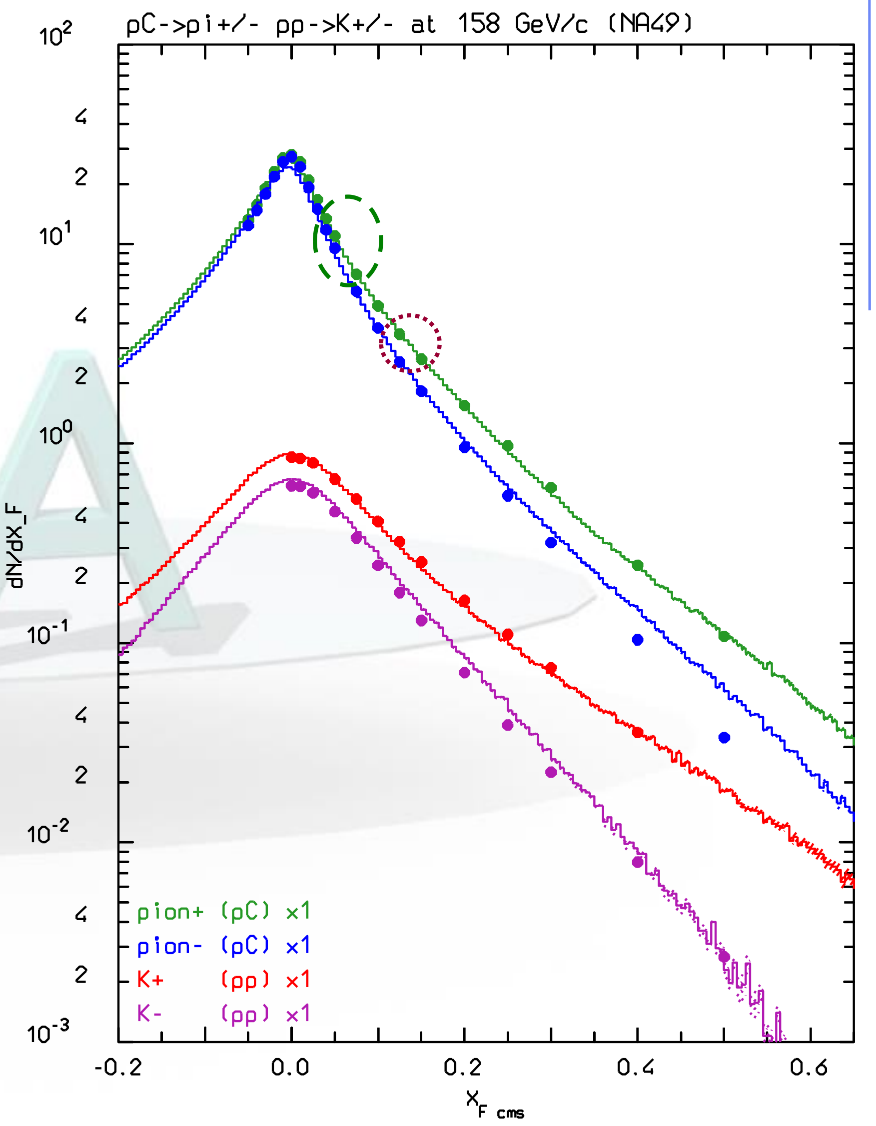
Pion and Kaon production data (ν beams…)



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

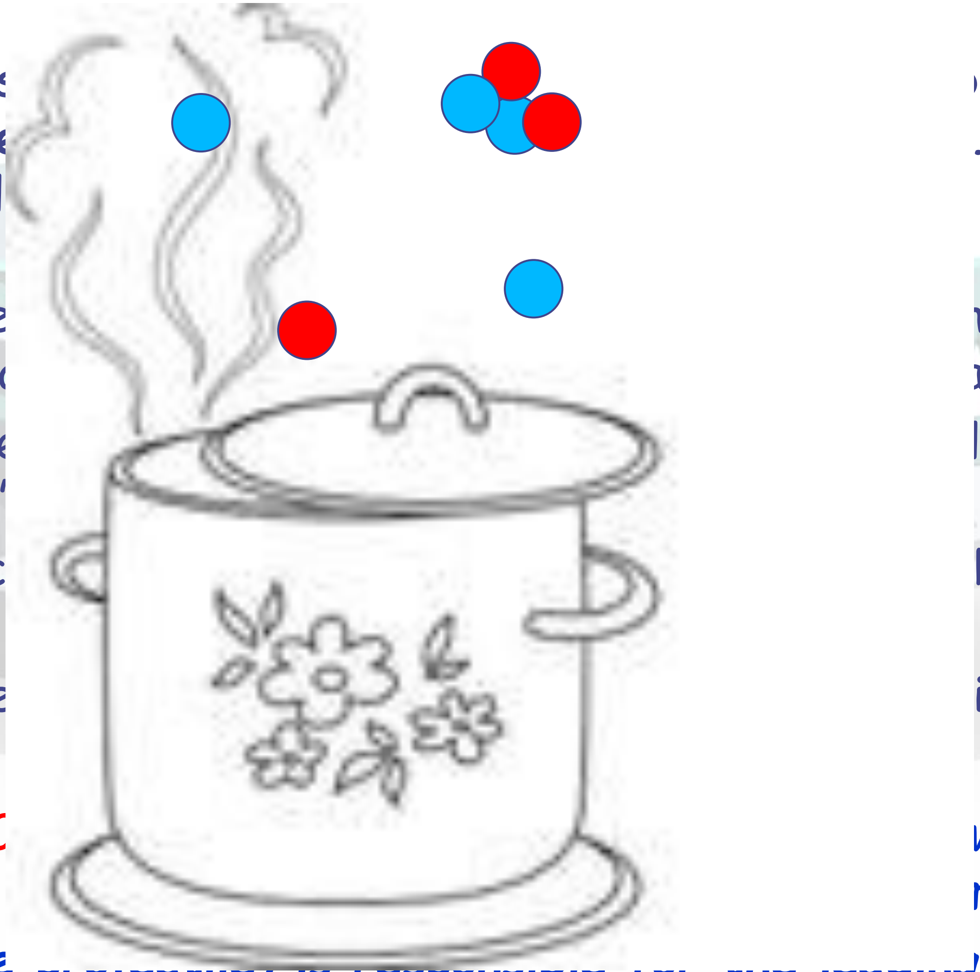
Angle integrated distributions are the most relevant for judging the reliability of ν predictions, at least for the bulk of the spectrum.

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), together with the "focused" zones for **CNGS** and **CENF**



Compound nucleus: evaporation

- After many collisions and possibly particle emissions, the residual nucleus is left in a highly excited "equilibrated" state
- De-excitation can be des ... le the **evaporation** of "droplets", actually **low e** ... .) from a "boiling"soup characterized by a "nucl



- Formation and decay are ... the same **A, Z, U** (exc. Energy), (and J^{π}) will decay the s ... ated them
- The process is terminate ... leftover nucleus, possibly radioactive, is now "cold" ...
- For heavy nuclei the exc ... breaking into two major chunks (**fission**).
- Since only neutrons have ... **is strongly favoured**.

In FLUKA: *~60(* ... *vith an extended (heavy)* ... *n*

In AA evaporation (of the ... ***particle(s) and for the resulting A, Z of the (projectile) remnant(s)***

Equilibrium particle emission (evaporation, fission and nuclear break-up)

From statistical considerations and the detailed balance principle, the probabilities for emitting a particle of mass m_j, spin $S_j \hbar$ and energy E, or of fissioning are given by*:
(i, f for initial/final state, Fiss for fission saddle point)

Probability per unit time of emitting a particle j with energy E

$$P_J = \frac{(2S_j+1)m_j c}{\pi^2 \hbar^3} \int_{V_j}^{U_i - Q_j - \Delta_f} \frac{\rho_f(U_f)}{\rho_i(U_i)} \sigma_{inv}(E) E dE$$

Probability per unit time of fissioning

$$P_{Fiss} = \frac{1}{2\pi\hbar} \int_0^{U_i - B_{Fiss}} \frac{\rho_{Fiss}(U_i - B_{Fiss} - E)}{\rho_i(U_i)} dE$$

- ρ's: nuclear level densities
- U's: excitation energies
- V_j's: possible Coulomb barrier for emitting a particle type j
- B_{Fiss}: fission barrier

- Q_j's: reaction Q for emitting a particle type j
- σ_{inv}: cross section for the inverse process
- Δ's: pairing energies

*Weisskopf-Ewing approach

Neutron emission is strongly favoured because of the lack of any barrier
Heavy nuclei generally reach higher excitations because of more intense cascading

Fermi Break-up in FLUKA:

Statistical (evaporation) models are known to work poorly for light nuclei. An alternative, better performing, description of light nuclei de-excitation can be obtained with the Fermi break-up mechanism. The probability of splitting a **nucleus A, Z**, with **excitation U** into **n** fragments of given masses, m_i, spins, s_i, … is given by:

$$P_n(E_{kin}) = S_n G_n \left(\frac{V}{(2\pi\hbar)^3} \right)^{n-1} \left(\frac{\prod_{i=1}^{n} m_i}{M_{A,Z} + U} \right)^{3/2} \frac{(2\pi)^{3/2(n-1)}}{\Gamma\left[3/2(n-1)\right]} \left(E_{kin} - E_{Coul} \right)^{3n/2-5/2}$$

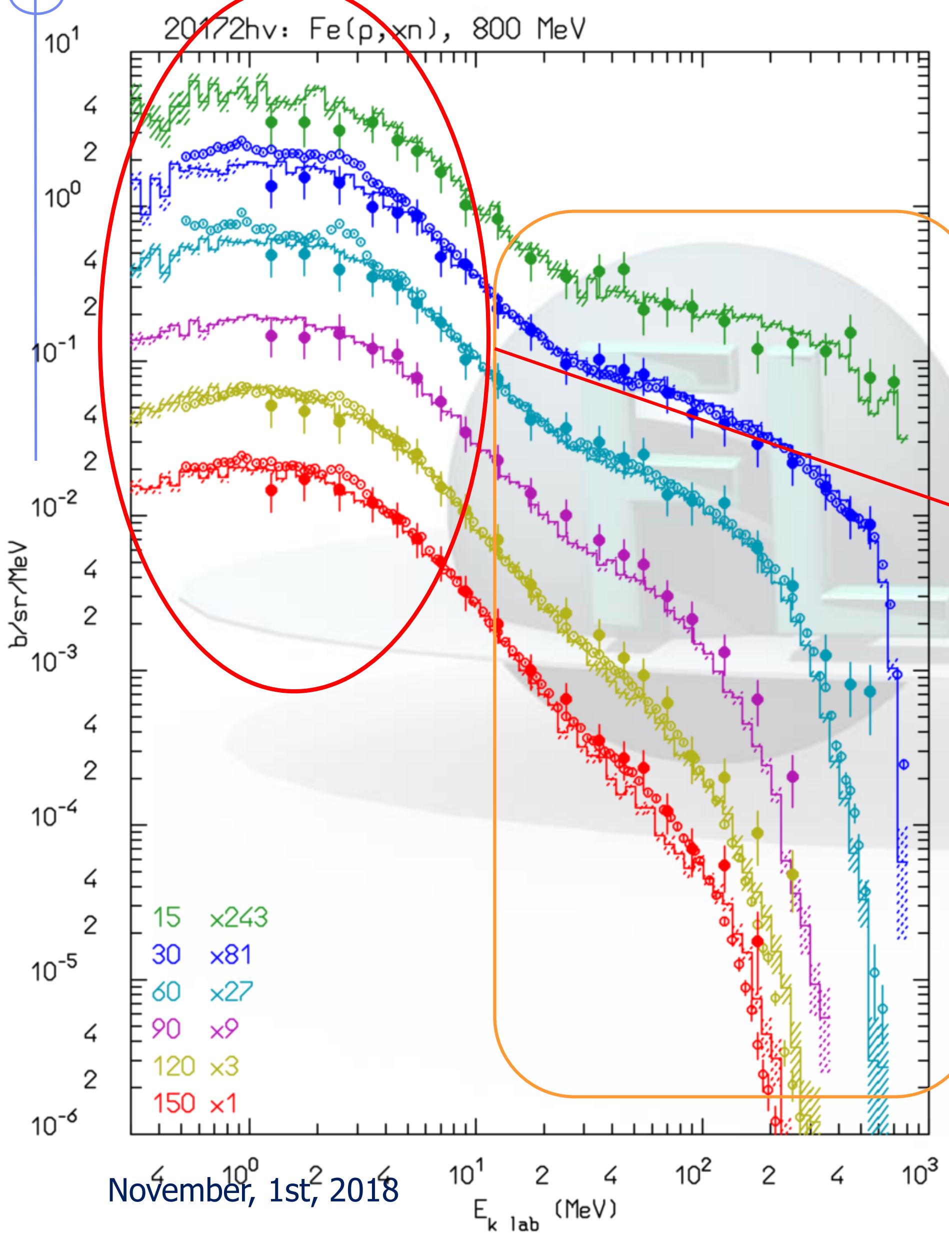
$$S_n = \prod_{i=1}^{n} (2s_i + 1) \qquad G_n = \prod_{k=1}^{l} \frac{1}{n_k!} \qquad \sum_{k=1}^{l} n_k = n$$

… however it implicitly assumes that the emission takes place in L=0.

Significant improvement can be obtained when the compound nucleus spin and parity, J^π, are known:

- The minimum orbital momentum, L_{min}, required to match J^π is computed
- S_n is restricted to the subset of spin combinations compatible with L_{min}
- If $L_{min} > 0$, then $E_{Coul} \rightarrow E_{Coul} + B_{centrifugal}$

Thin target examples II: neutrons



Double differential ← cross section $d^2\sigma/dEd\Omega$ for Fe(p,xn) @ 800 MeV, thin target

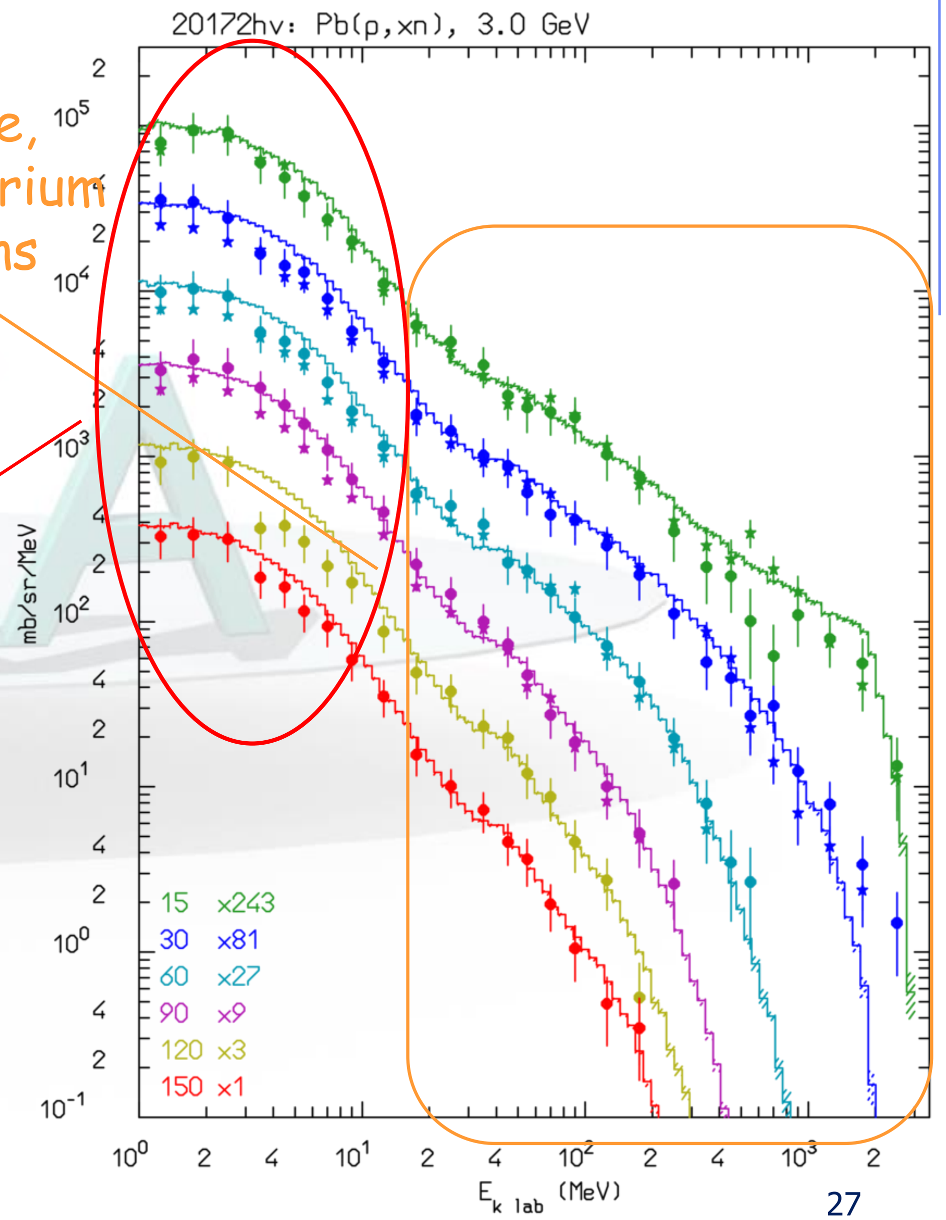
Data: NSE112, 78 (1992), NST34, 529 (1997)

Cascade, preequilibrium neutrons

Evaporation neutrons

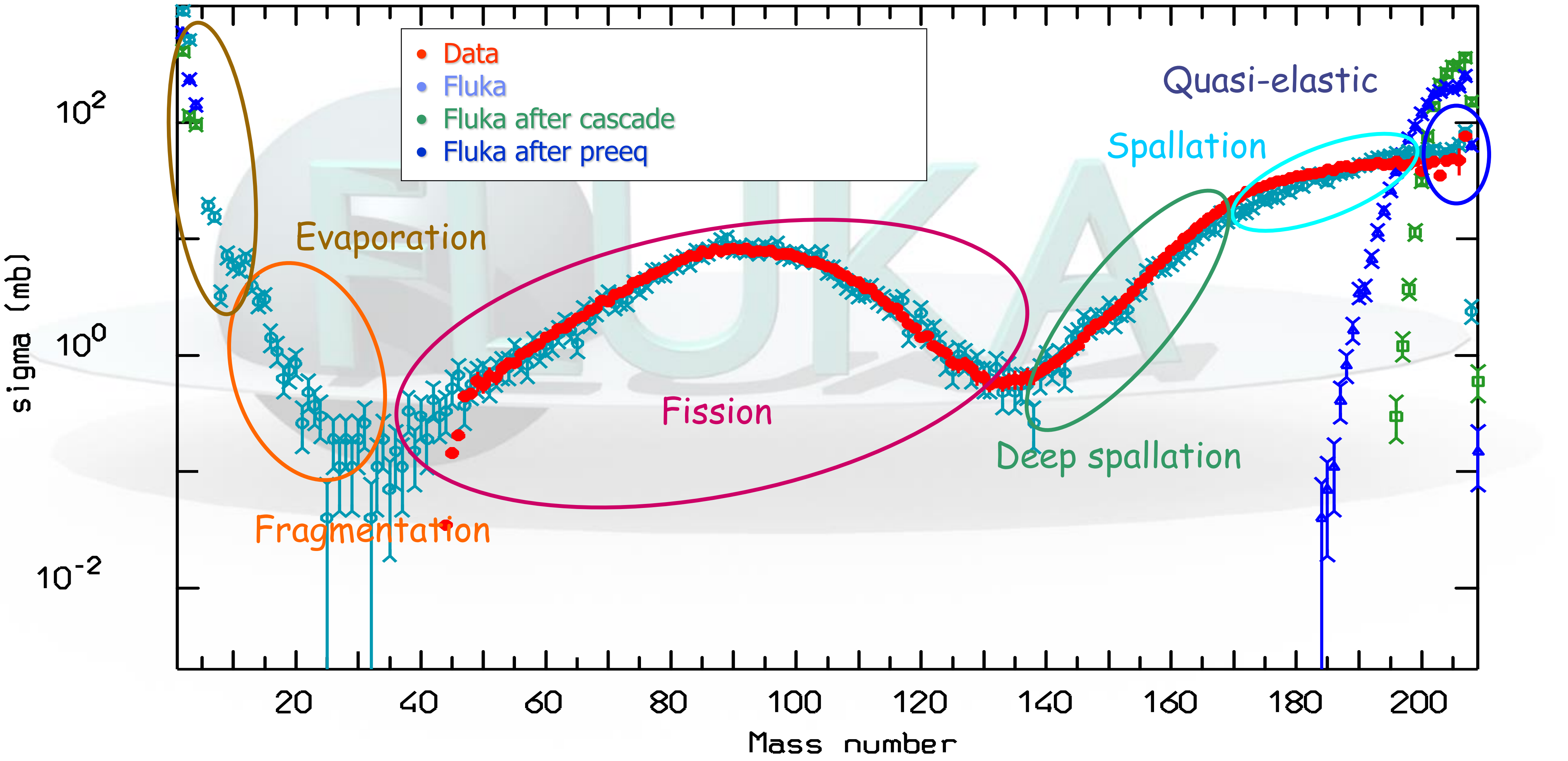
Double differential cross section $d^2\sigma/dEd\Omega$ for Pb(p,xn) @ 3 GeV → thin target

Data: NST32, 827 (1995)



Example of fission/evaporation

1 A GeV ^{208}Pb + p reactions Nucl. Phys. A 686 (2001) 481-524



Heavy ion interaction models in FLUKA

10^{10}

5

0.1

E (GeV/A)

Electromagnetic dissociation

DPMJET-III

DPMJET (R. Engel, A.Fedynitch, J. Ranft , S. Roesler[1]): Nucleus-Nucleus interaction model. Used in many Cosmic Ray shower codes. Based on the Dual Parton Model and formation zone Glauber cascade, like the high-energy FLUKA h-A event generator

Modified and extended version[3] of rQMD-2.4

rQMD-2.4 (H. Sorge et al.[2]) Cascade-Relativistic QMD model
Successfully applied to relativistic A-A particle production

BME (BoltzmannMasterEquation)

FLUKA implementation of BME from E.Gadioli et al (Milan)

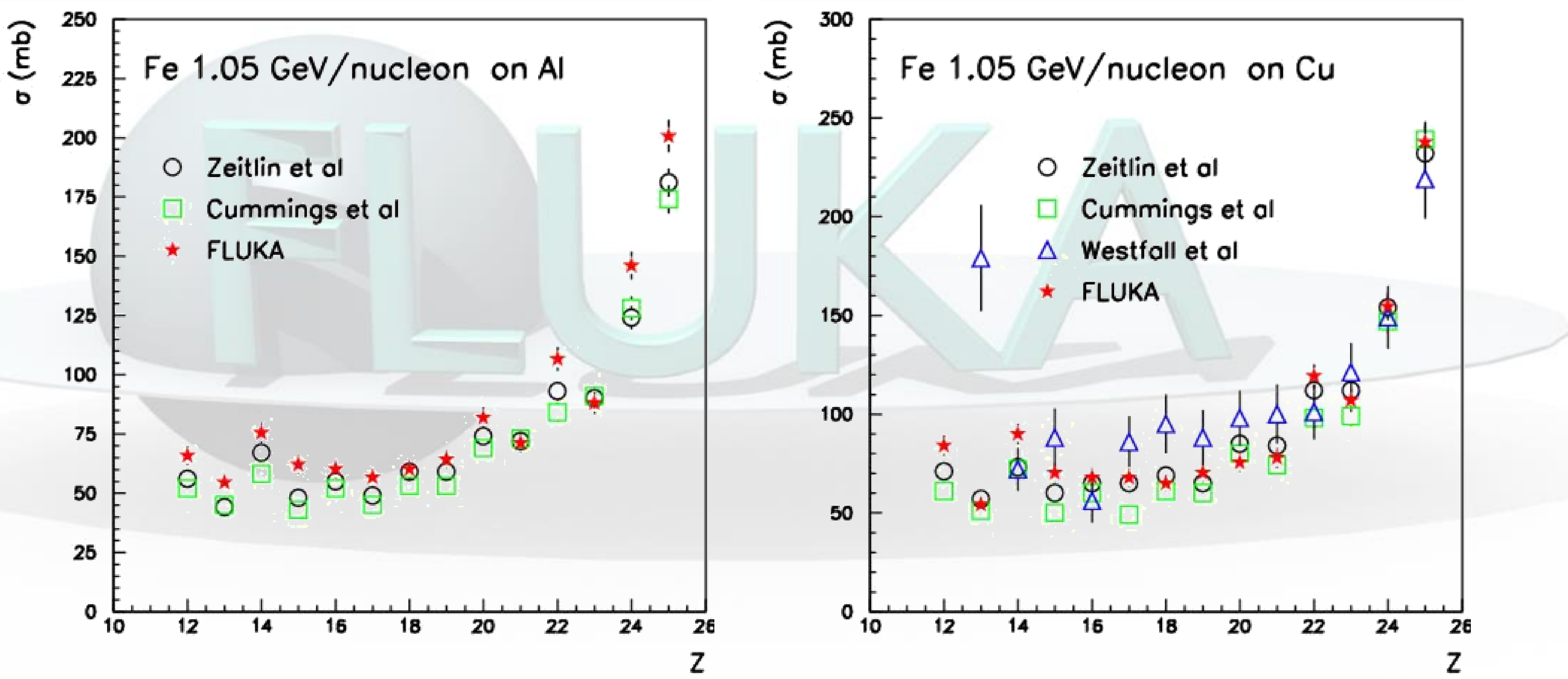
FLUKA Evaporation-fission-fragmentation module handles fragment deexcitation **Tested and benchmarked** in h-A reactions

(Projectile-like evaporation is responsible for the most energetic fragments)

[1]proc. MC2000 , p 1033 (2001), A.Fedynitch PhD Thesis, CERN-THESIS-2015-371
[2]NPA 498, 567c (1989), Ann.Phys. 192,266 (1989), PRC 52, 3291 (1995)
[3]ASR 34, 1302 (2004)

FLUKA with heavy ion generators:

(Projectile) fragmentation is critical for heavy ion interactions!!!



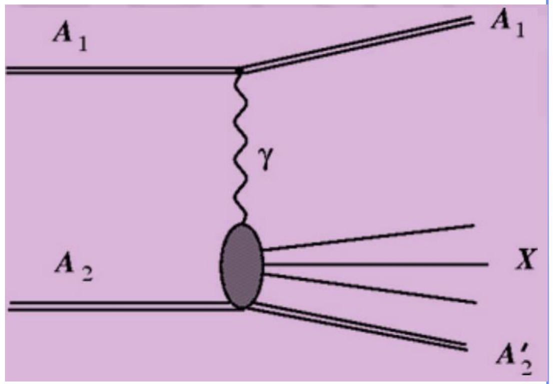
Fragment charge cross section for 1.05 GeV/n Fe ions on Al (left) and Cu (right).

★: FLUKA, ○ : PRC 56, 388 (1997), □ : PRC42, 5208 (1990), Δ: PRC 19, 1309 (1979)

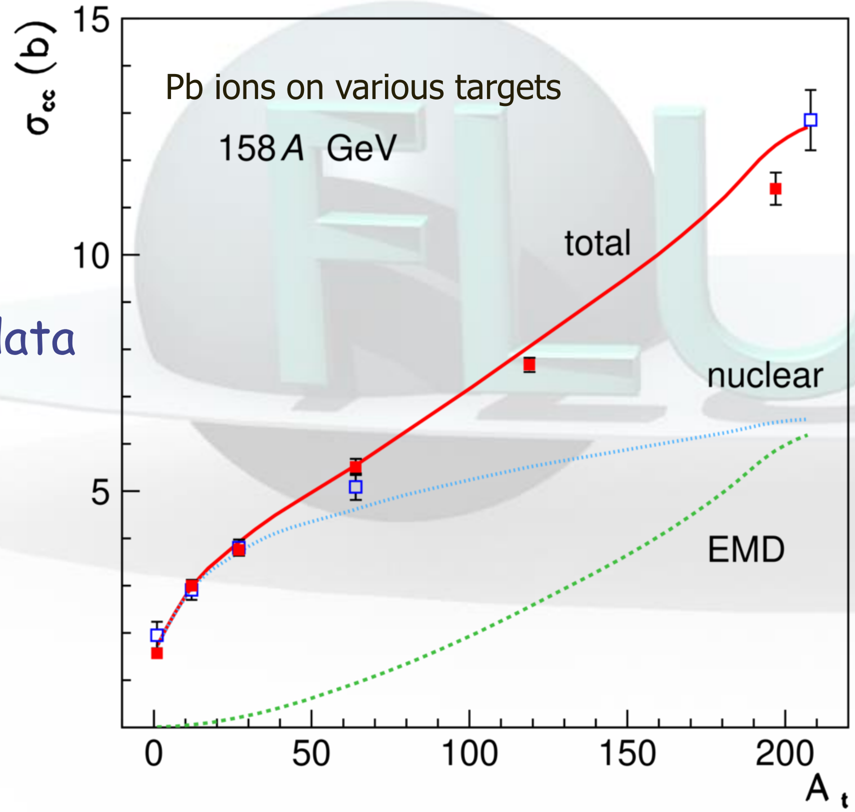
Electromagnetic dissociation

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

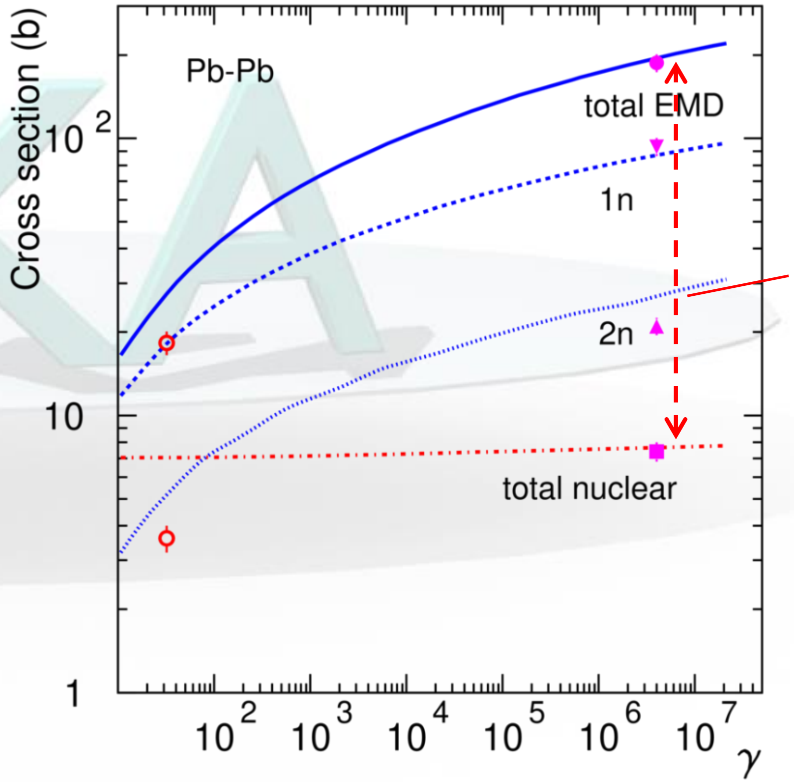
- Very peripheral collisions
- Break-up of one of the colliding nuclei in the electromagnetic field of the other nucleus



Symbols: exp. data
Lines: Fluka

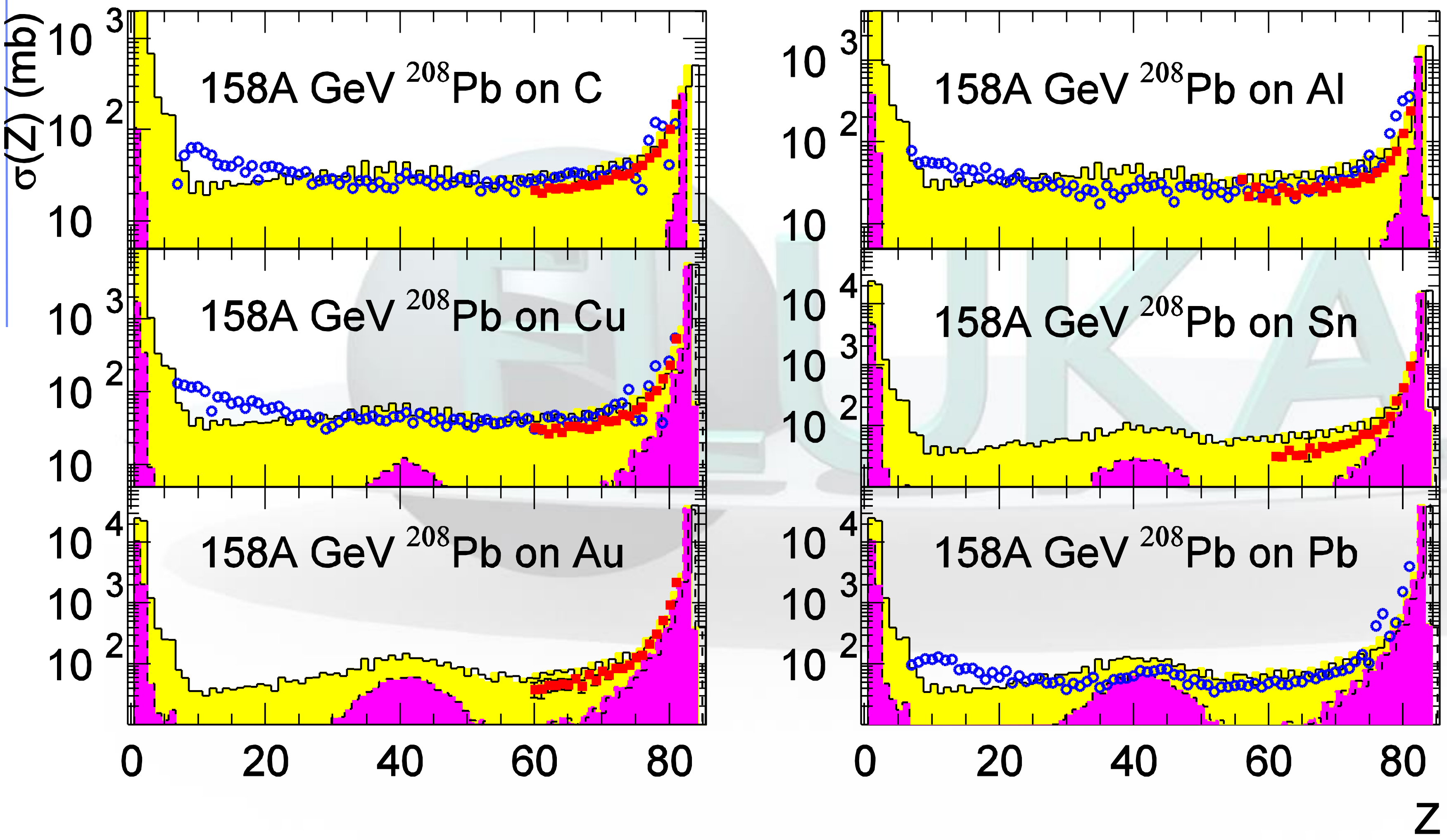


Total charge changing cross section as a function of atomic mass



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

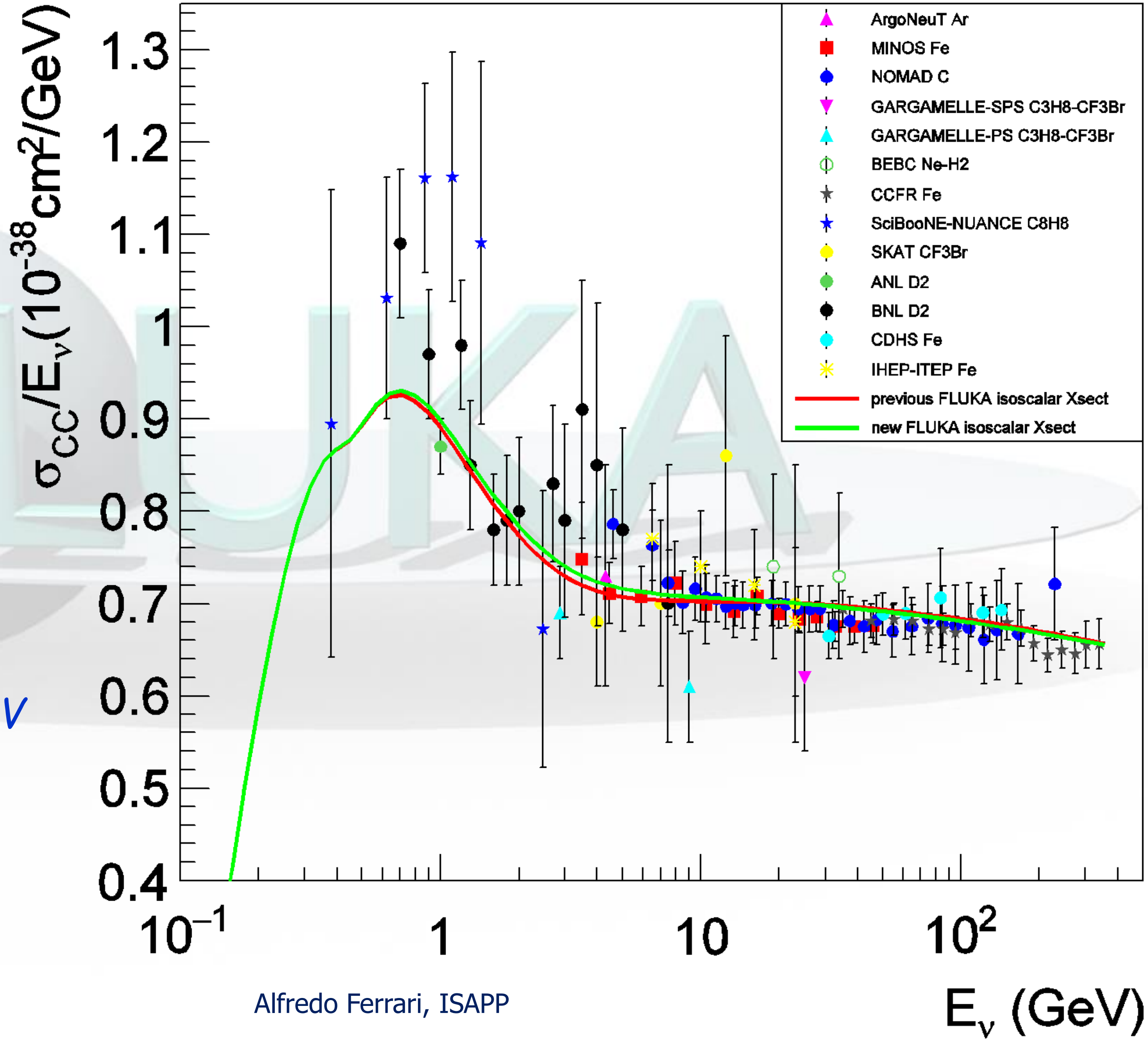
(Anti)Neutrinos in FLUKA:

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
  - M_A = 1.03, M_V = 0.84
  - Lepton masses accounted for
- **νN Resonance production**
  - From Rein-Sehgal formulation
  - Keep only Δ production
  - Non-resonant background term assumed to come from DIS
- **νN Deep Inelastic Scattering**
  - NunDIS model (developed ad hoc for FLUKA)
- **νN interactions** embedded in PEANUT for **νA** (Initial State and Final State effects)
- Only for Argon: **Fermi/GT absorption** of few-MeV (solar) neutrinos on ^{40}**Ar**
- Products of the neutrino interactions can be directly transported in the detector (or other) materials
- Used for all **ICARUS** simulations/publications

Comparison with data on total cross section

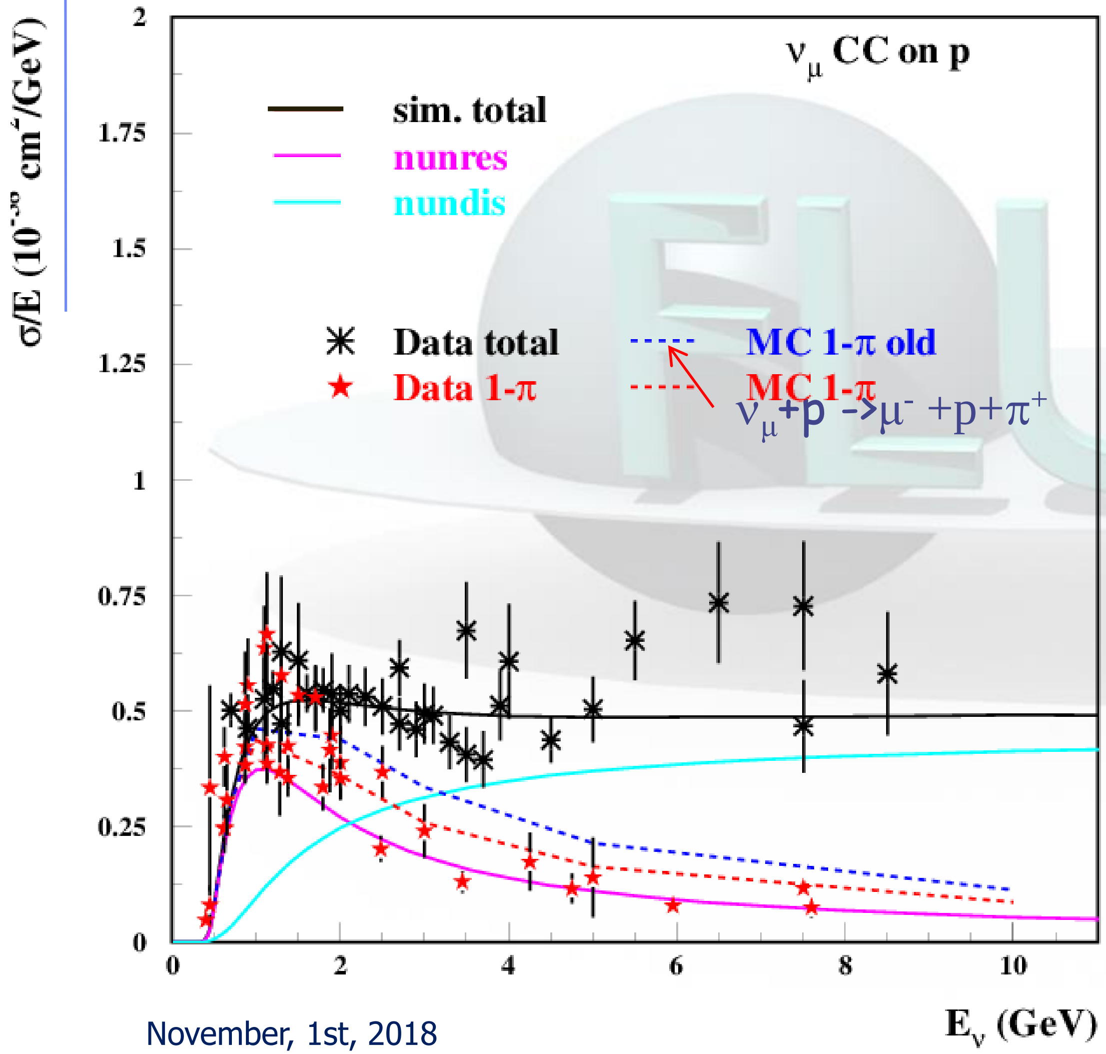
Isoscalar ν_μ - Nucleon total CC cross section Fluka (lines) with two pdf options vs Experimental data



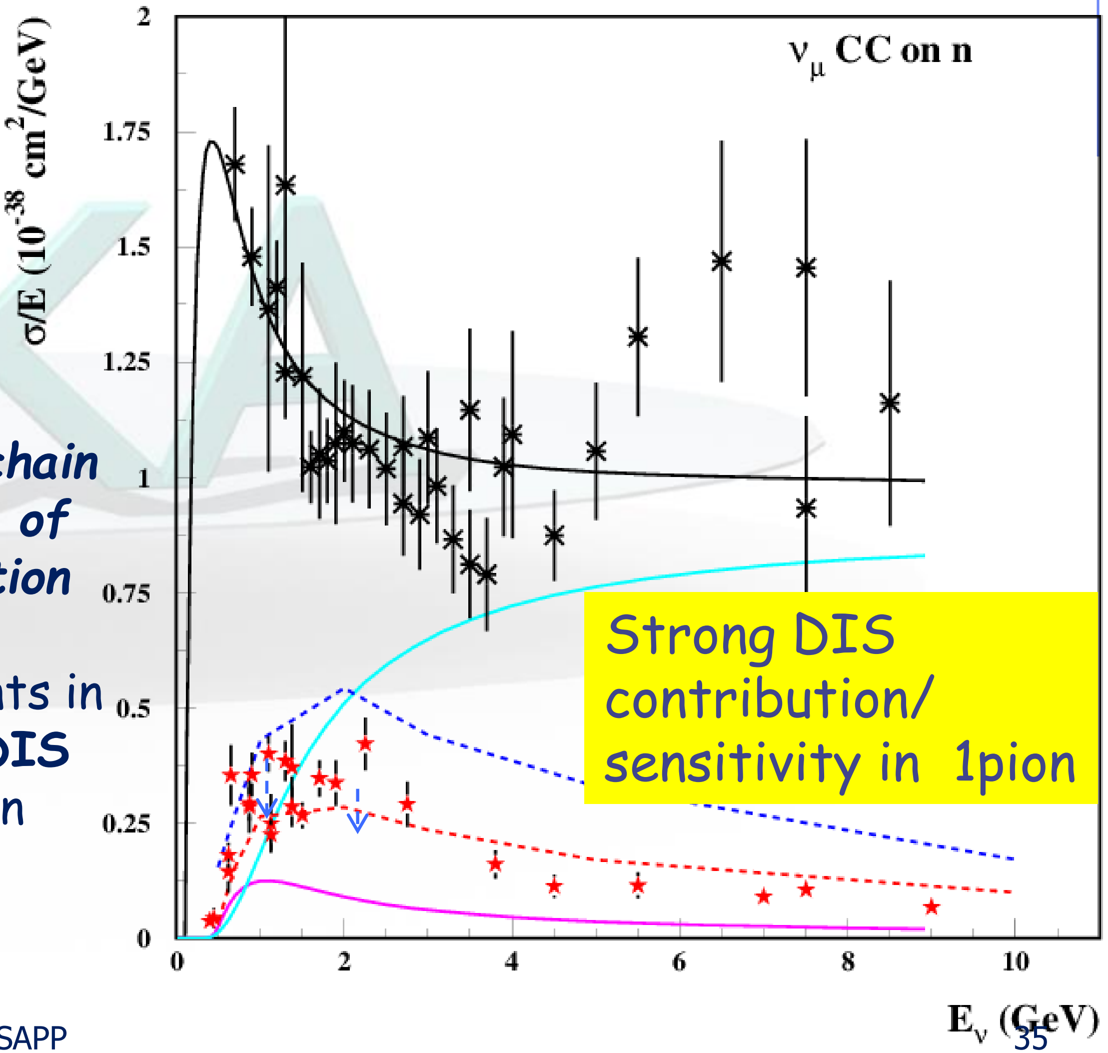
FLUKA can currently manage (anti)ν-A interations from ~0.1 GeV up to 1000 TeV

Single pion production in νN CC interactions:

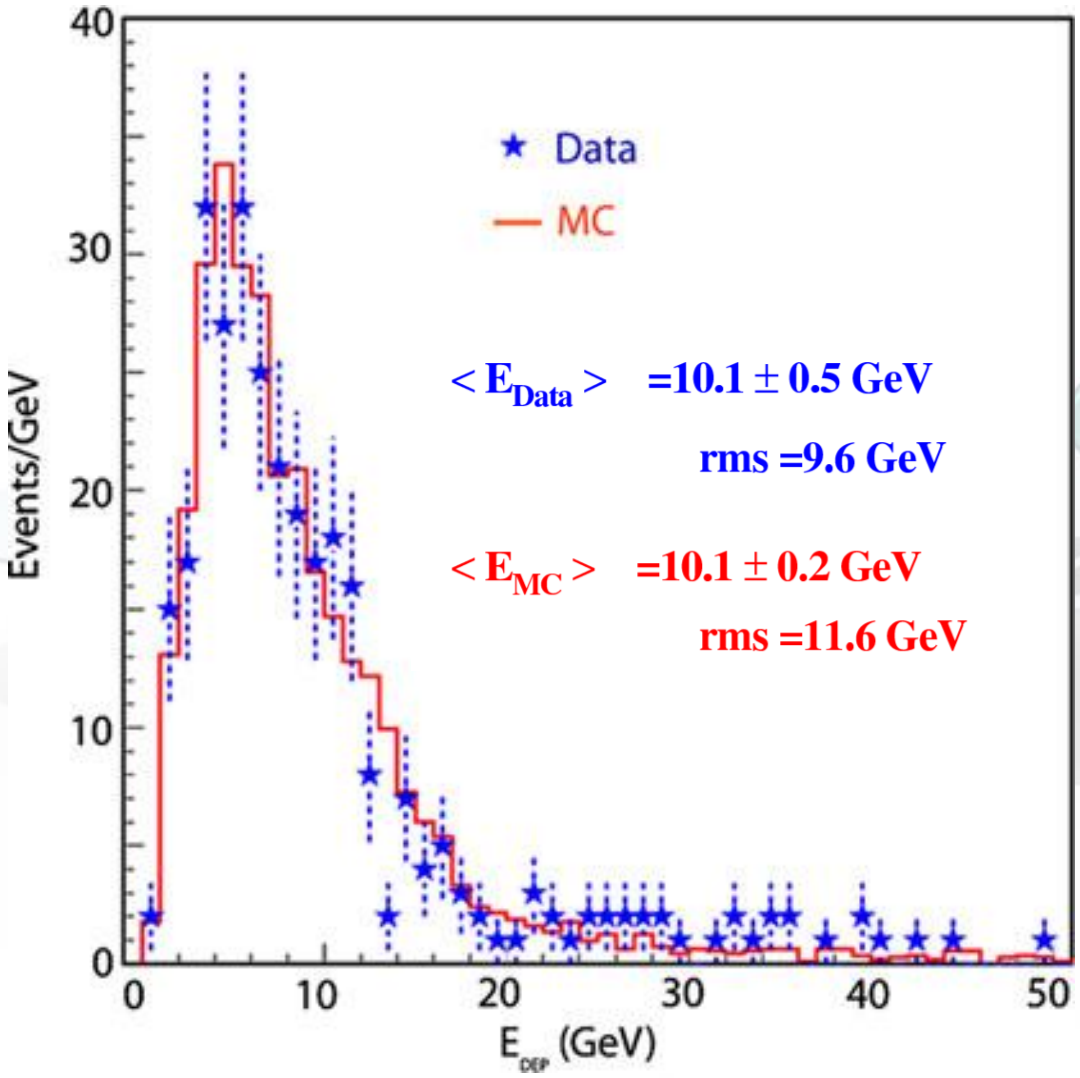
Chains from ν DIS : One ***quark-diquark*** chain if interaction on ***valence*** quark
One ***quark-diquark*** plus one ***q-qbar*** chain if int. on ***sea*** quark



Low-mass chain treatment of hadronization
↓
improvements in the **RES-DIS** transition



ICARUS: CNGS data



Distribution of total deposited energy in the ICARUS T600 detector

- CNGS numuCC events (~20 GeV E_ν peak)
- Same reconstruction in MC (FLUKA) and Data
- Neutrino fluxes from FLUKA CNGS simulations
- Absolute agreement on neutrino rate within 6%

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

One further example *(if there is time)*

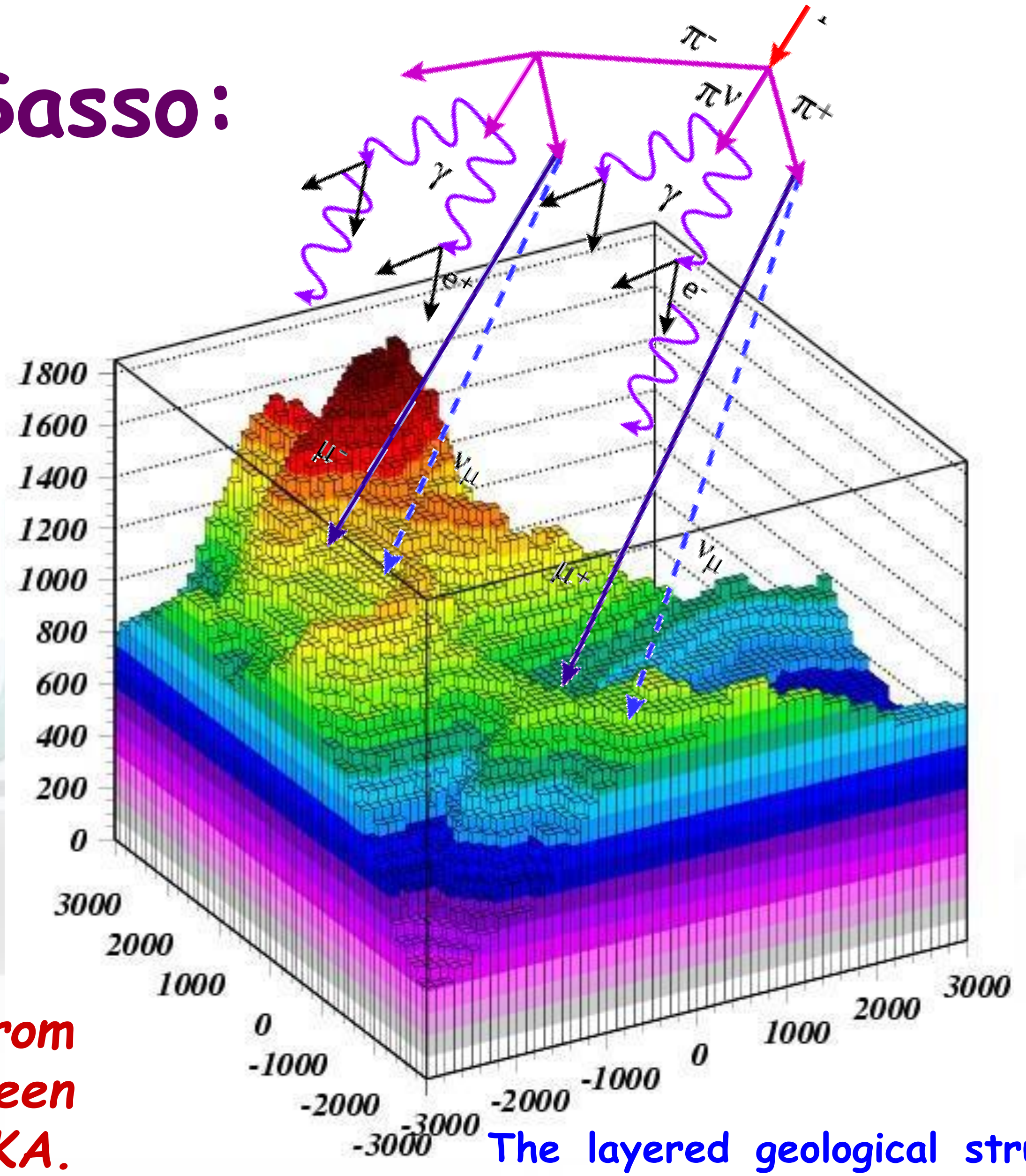
Cosmic muons at Gran Sasso:

Cosmic rays in the atmosphere:

cosmic rays induced showers in the earth atmosphere can produce $\mu^{\pm}$ through the decay of mesons

Experiment underground:

the most energetic muons can reach the underground lab at the depth of underground GS lab corresponding to ~3800 mwe



The geometry of the mountain (as taken from the map used in MACRO experiment) has been described using the "voxel" system of FLUKA. Our choice: 1 voxel = 100x100x50 m³

The layered geological structure has been reproduced (5 different materials)

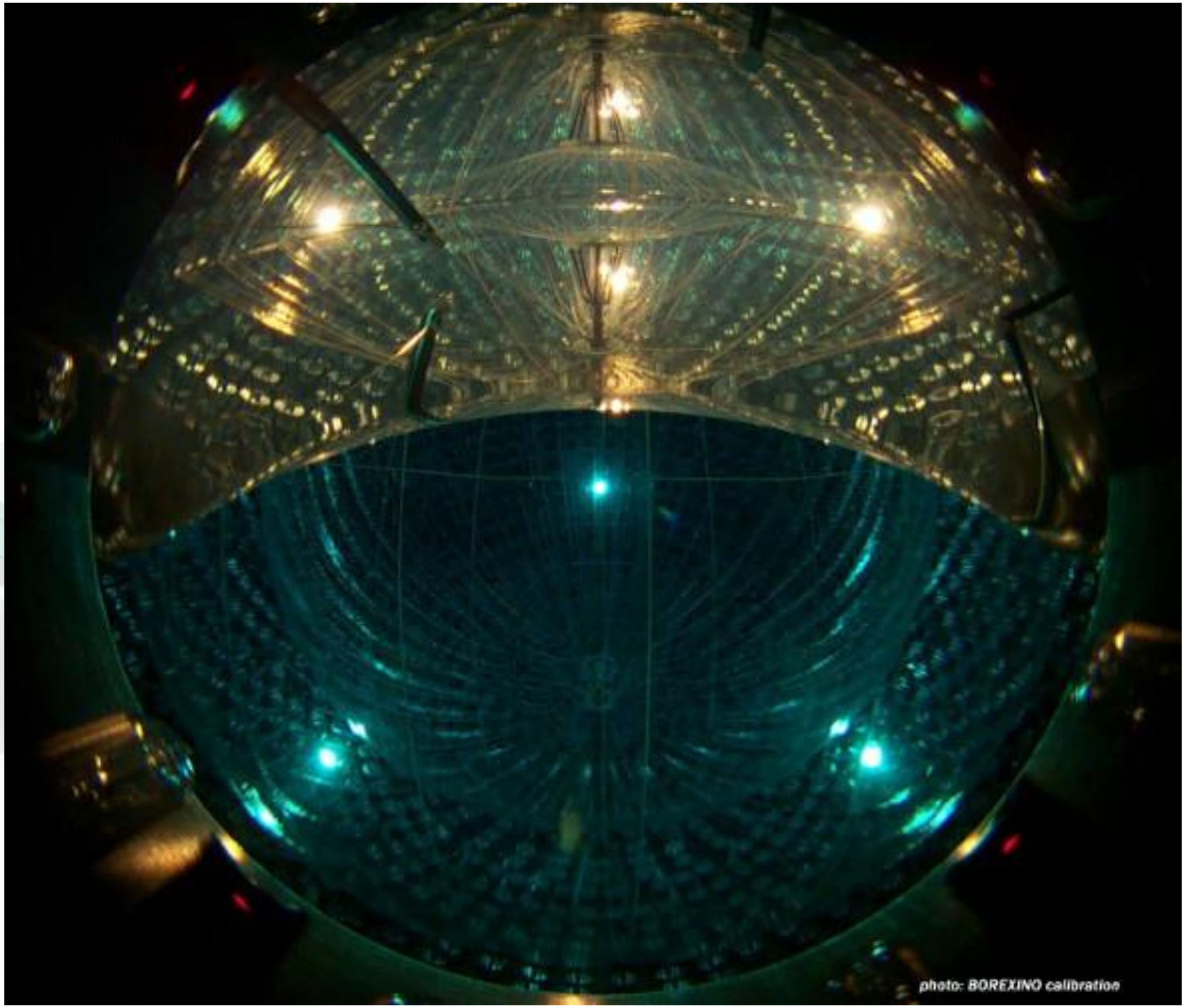
Cosmogenic backgrounds at Gran Sasso

Borexino detector:

- ~300 tons of liquid scintillator surrounded by 1000 + 2400 tons of Sci/H_2O shielding
- Primary physics goal: solar ν's
- Possibility of measuring ***neutrons*** and ***radioactive decays*** related to ***passing cosmic muons*** (average energy of μ's at Gran Sasso depth ~283 GeV)

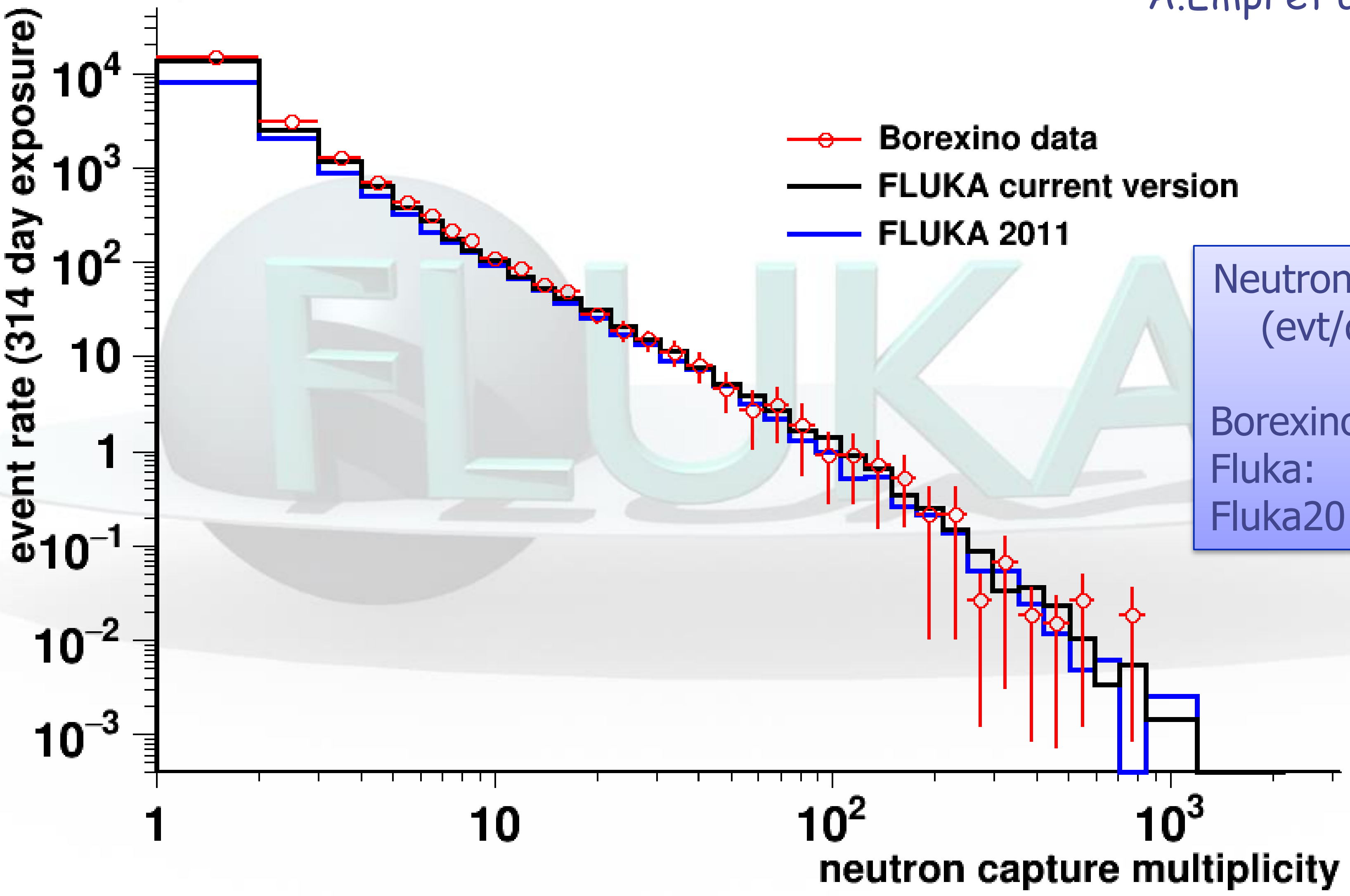
↓

Critical test of (μ and γ) photonuclear interactions, as well as of μ atomic physics (dE/dx, $e^{\pm}$ pair prod., bremss.)



μ Induced neutron multiplicity events @ Borexino*

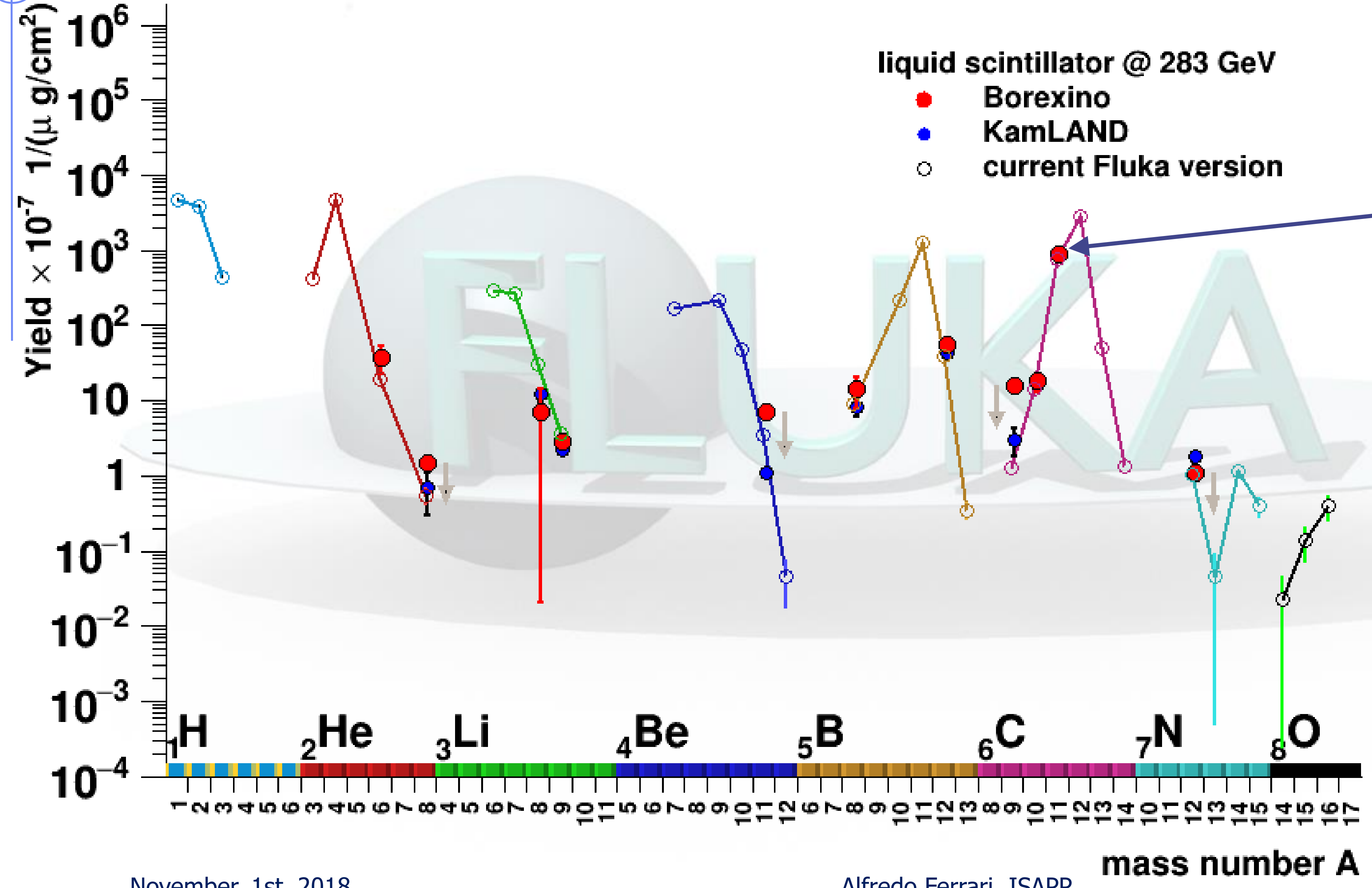
*A.Empl et al, APCPC,1672,090001



Neutron producing μ event rate
(evt/day @ inner detector)

Borexino: 67±1
Fluka: 62±1
Fluka2011: 42±1

μ Produced radioisotopes @ Borexino*

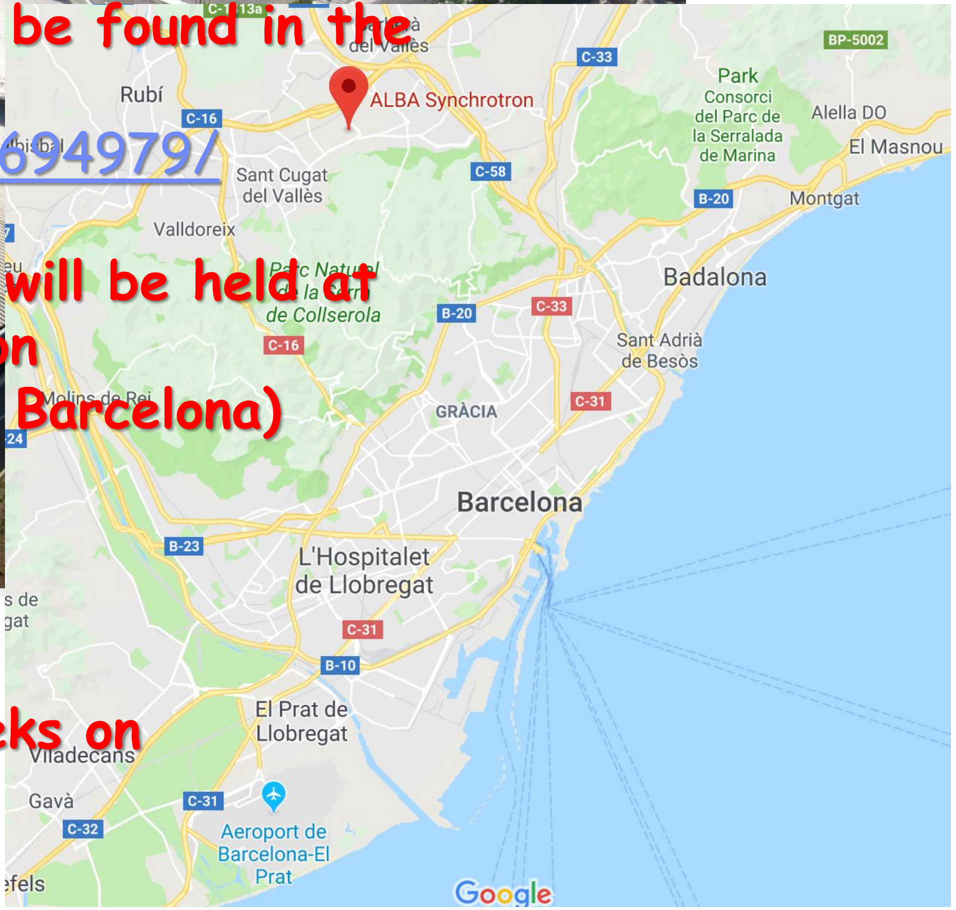


^{11}C prod yield: $(10^{-7}/(\mu\ g/cm^2))$

Borexino: 866±115
Fluka: 767± 19

*A.Empl private comm. & APCPC,1672,090001

Next FLUKA course!



- More informations about Fluka can be found in the material of the last course: https://indico.cern.ch/event/694979/

…the next beginner FLUKA course will be held at
The ALBA Synchrotron
(roughly 15 km from downtown Barcelona)
Cataluna, Spain

April 2019

- Registrations will open in a few weeks on www.fluka.org