FLUKA for neutrino production

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for the FLUKA Collaboration

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Outline

- Fluka hadronic interaction model: short description and examples
- A few technical aspects
- Application to CNGS
- Studies for the CENF facility
- Neutrino interactions in FLUKA

FLUKA short description:

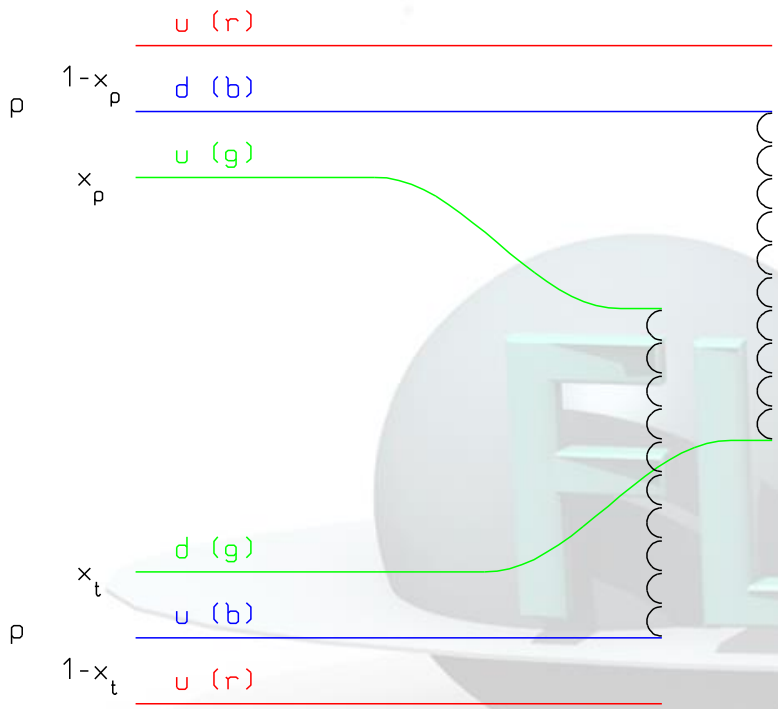
- FLUKA is a general purpose tool for calculations of particle transport and interactions with matter
- All Hadrons (p, n, π, K, pbar, nbar, (anti)hyperons…)
- Electromagnetic (γ, $e^{+/-}$) and μ and ν
- Nucleus-nucleus
- Low energy neutrons (0-20 MeV, multigroup, ENDF…)
- Full mixed field capability
- 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

1 keV-1000 TeV

More than 7000 users all over the world

http://www.fluka.org

Hadron-hadron collisions: DPM + hadronization



Leading two-chain diagram in DPM for p-p scattering. The color (red, blue, and green) and quark combination shown in the figure is just one of the allowed possibilities

Dual Parton Model (DPM) :

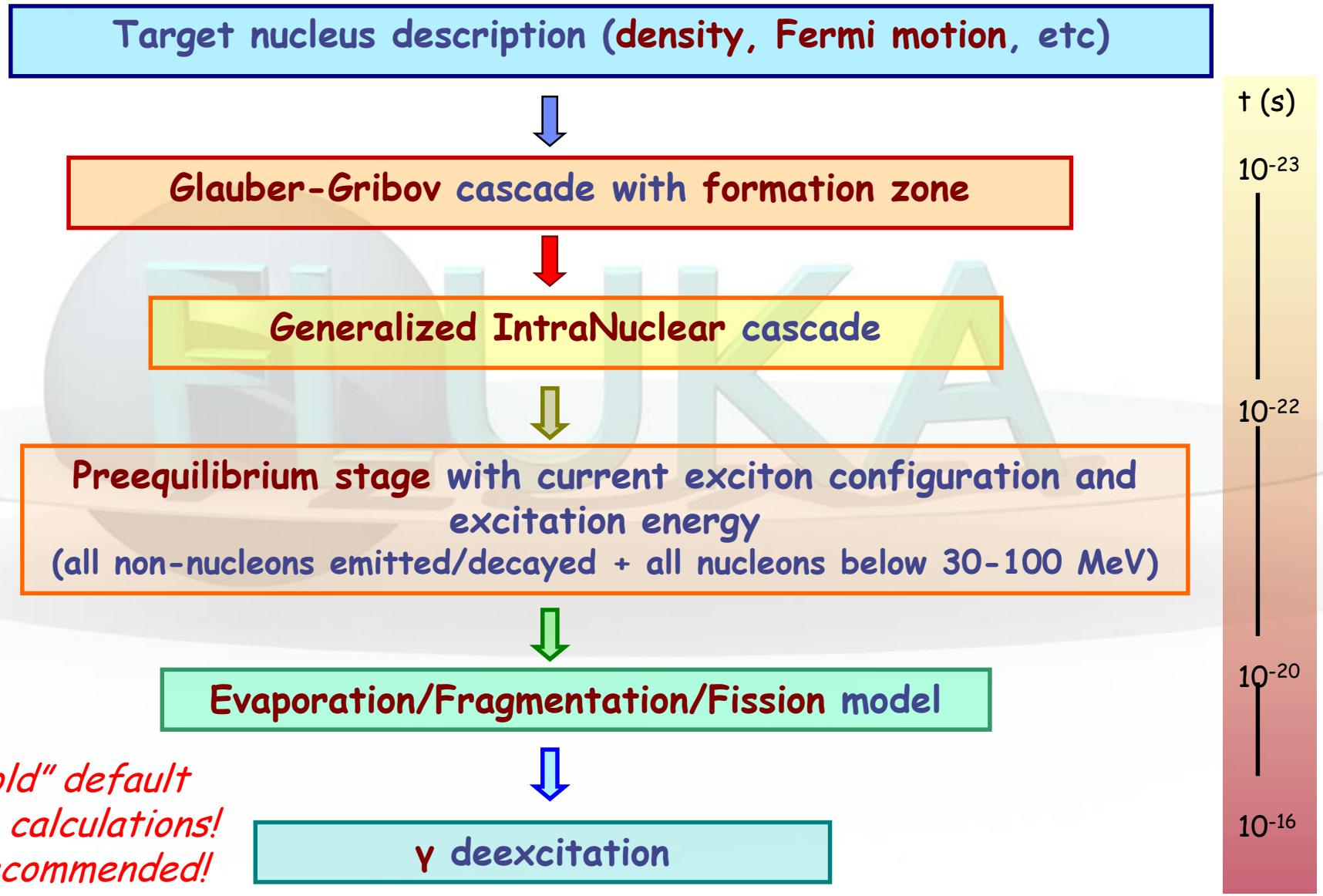
- Hadrons→ Interacting strings
- Interactions treated in the Reggeon-Pomeron framework
- Each of the two hadrons splits into 2 colored partons → combination into 2 colourless chains → 2 back-to-back jets
- each jet is then hadronized into physical hadrons

Chain hadronization (FLUKA specific)

- Assumes chain universality
- Fragmentation functions from hard processes and *e+e-* scattering
- Transverse momentum from uncertainty considerations
- Mass effects at low energies

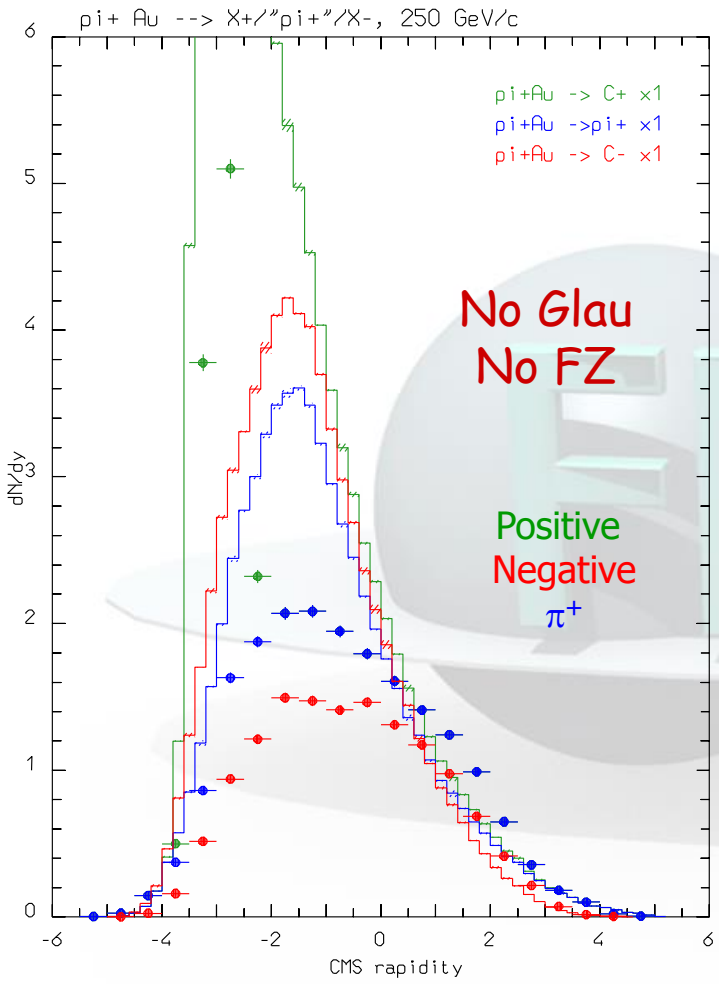
The same functions and (few) parameters for all reactions and energies

In the nucleus: the PEANUT generator*

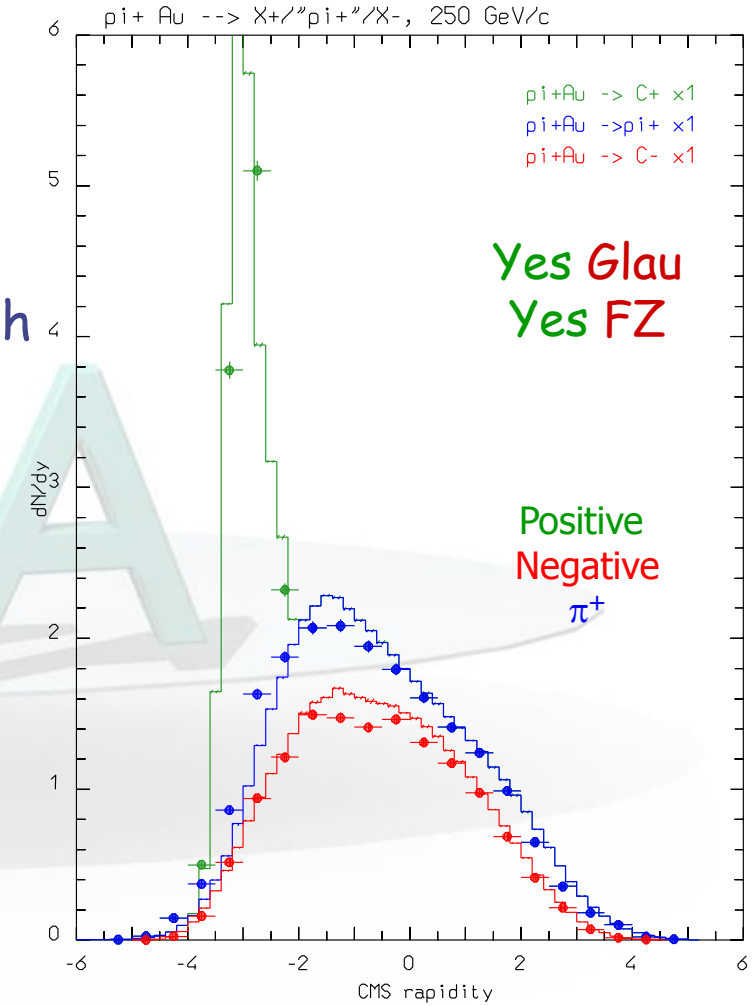


*Never use the "old" default model for precision calculations! Use PEANUT as recommended!

Glauber and formation zone

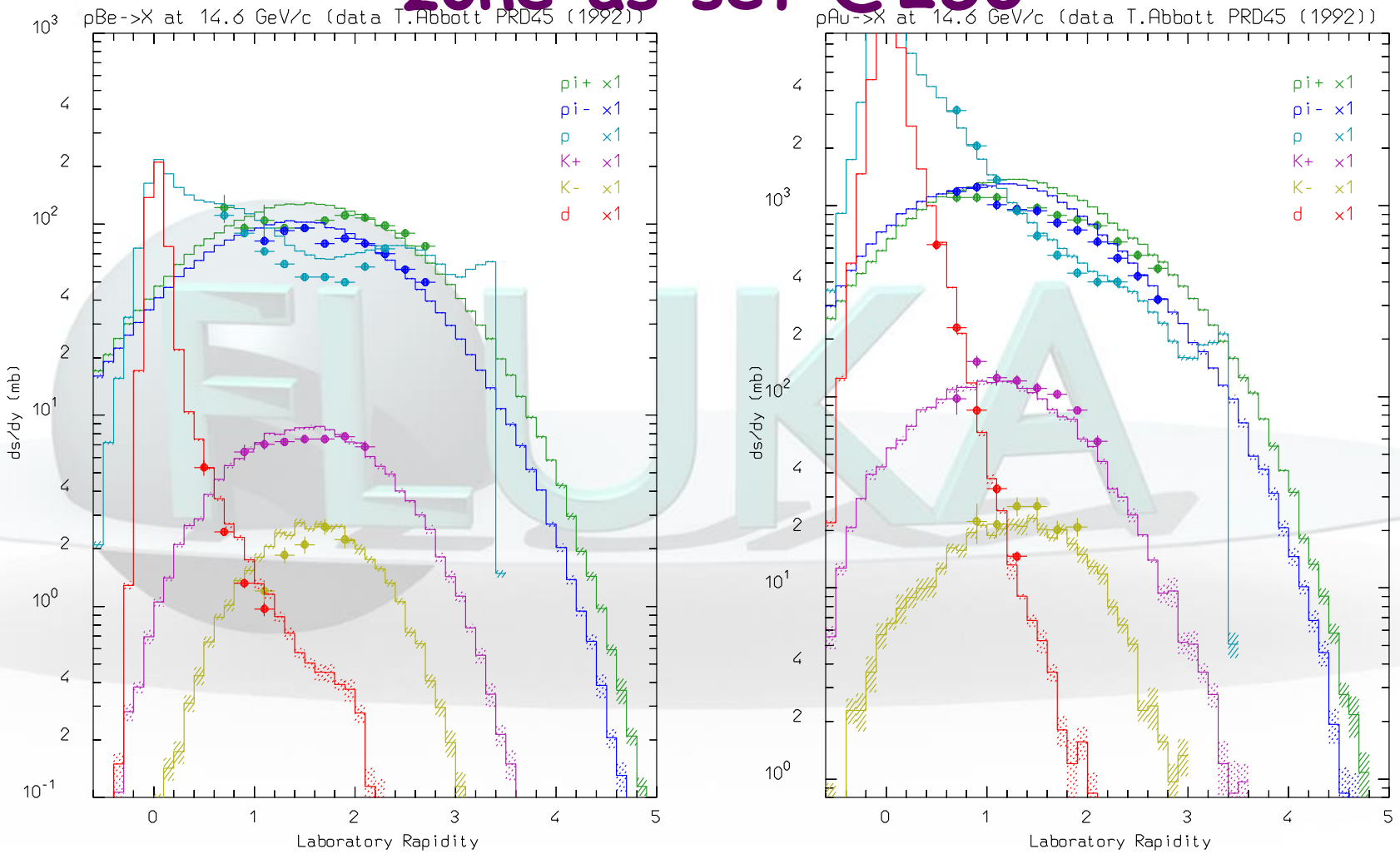


Example of the effects of Glauber cascade
(1st interaction == multiple collisions of the projectile with several target nucleons)
And Formation Zone
(time needed by an hadron to "materialize" --> free zone before reinteractions)



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

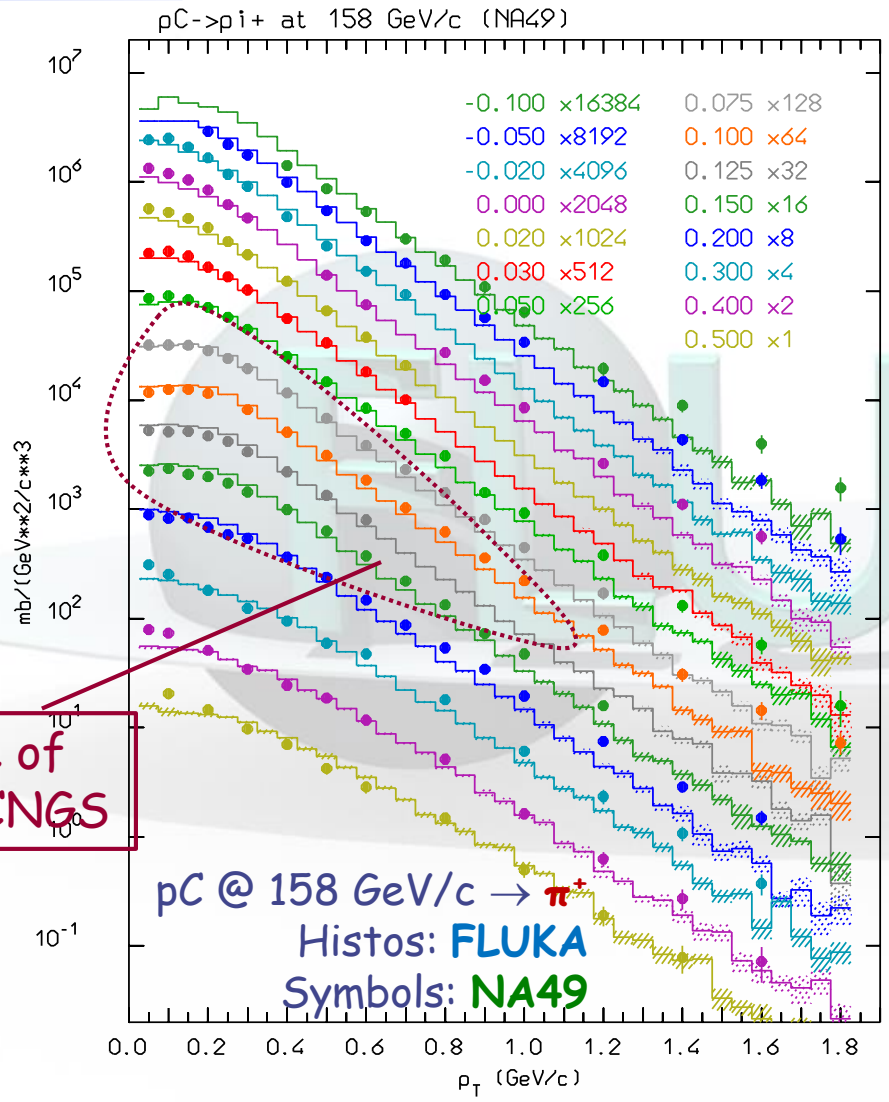
Going to lower energies: yes Glauber, yes formation zone as set @250



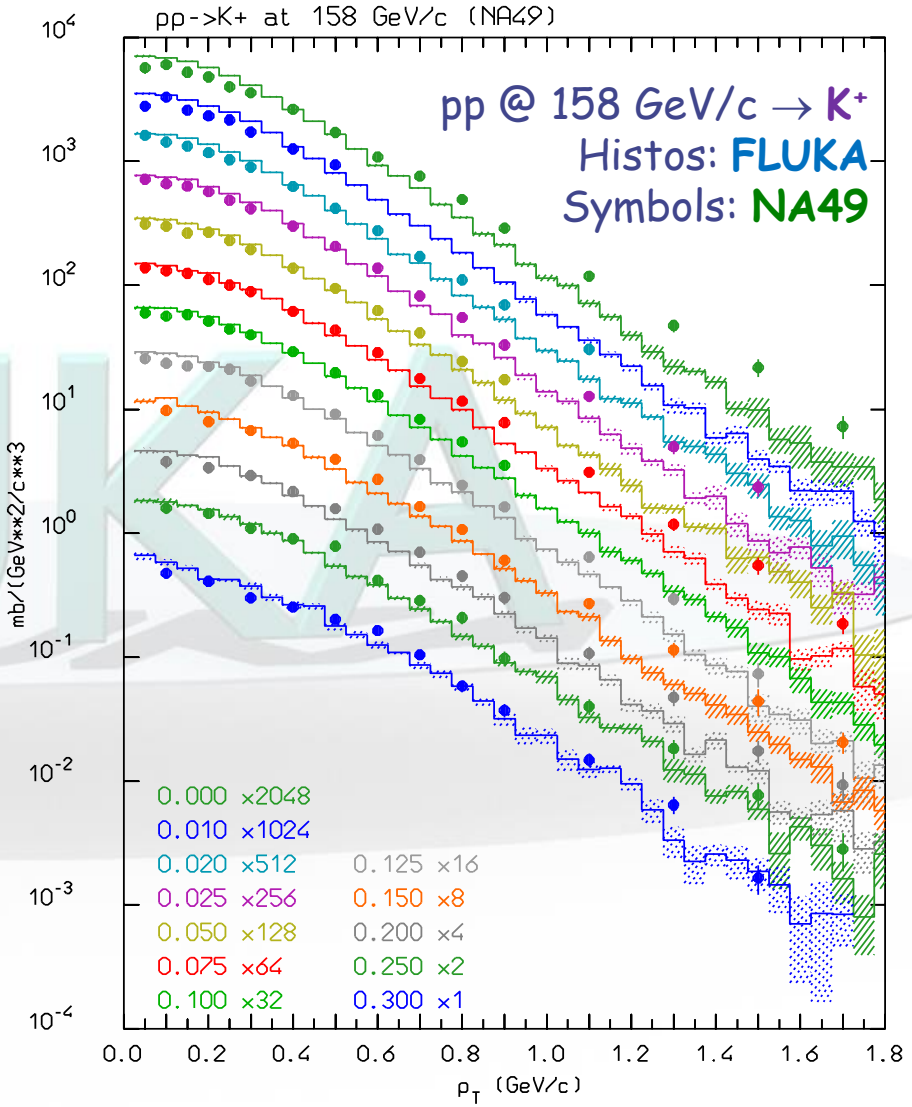
Rapidity distribution of protons, deuterons, positive pions, negative pions, positive kaons and negative kaons produced in 14.6 GeV/c p collisions on Beryllium (left) and Gold (right)
Points: exp. data (Abbott et al., PRD45, 3906 (1992)). P. Sala, A. Ferrari

Pion and Kaon production data (NA49)

p C -> π +



Phase space of interest for CNGS

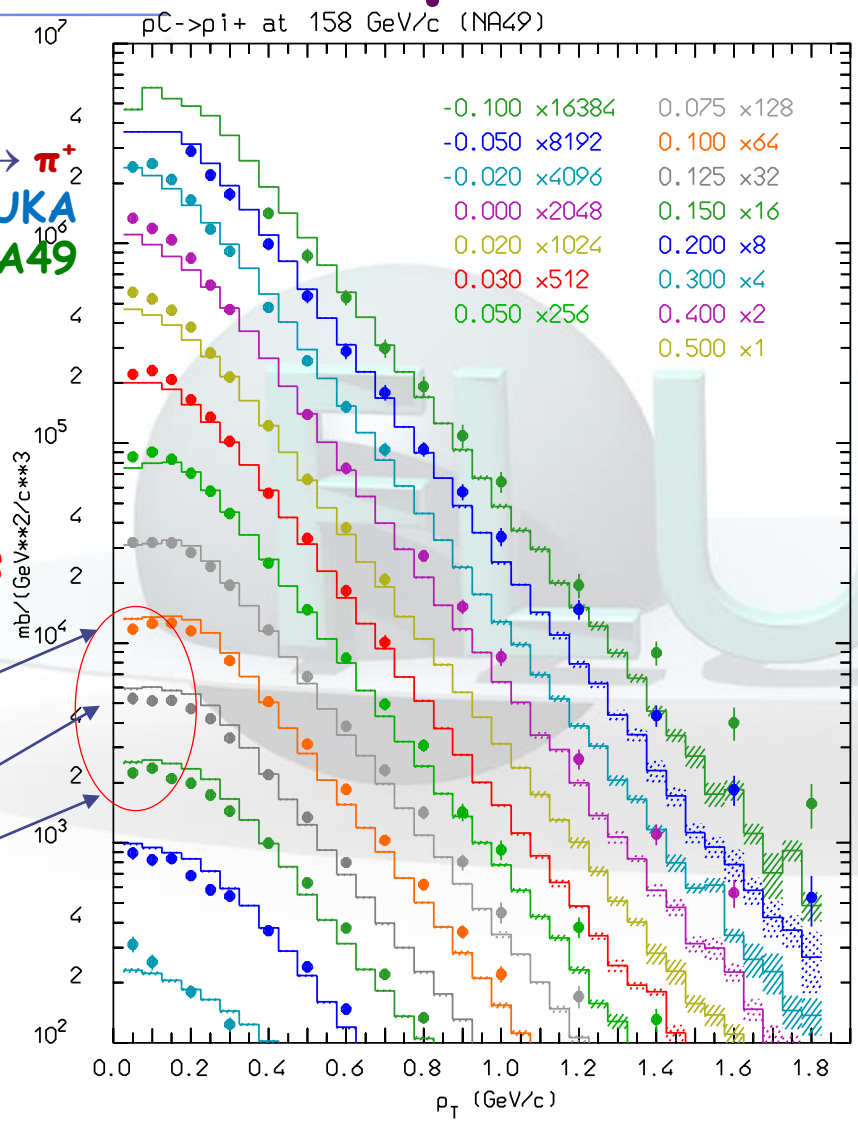


p p -> K+

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

Pion and Kaon production data

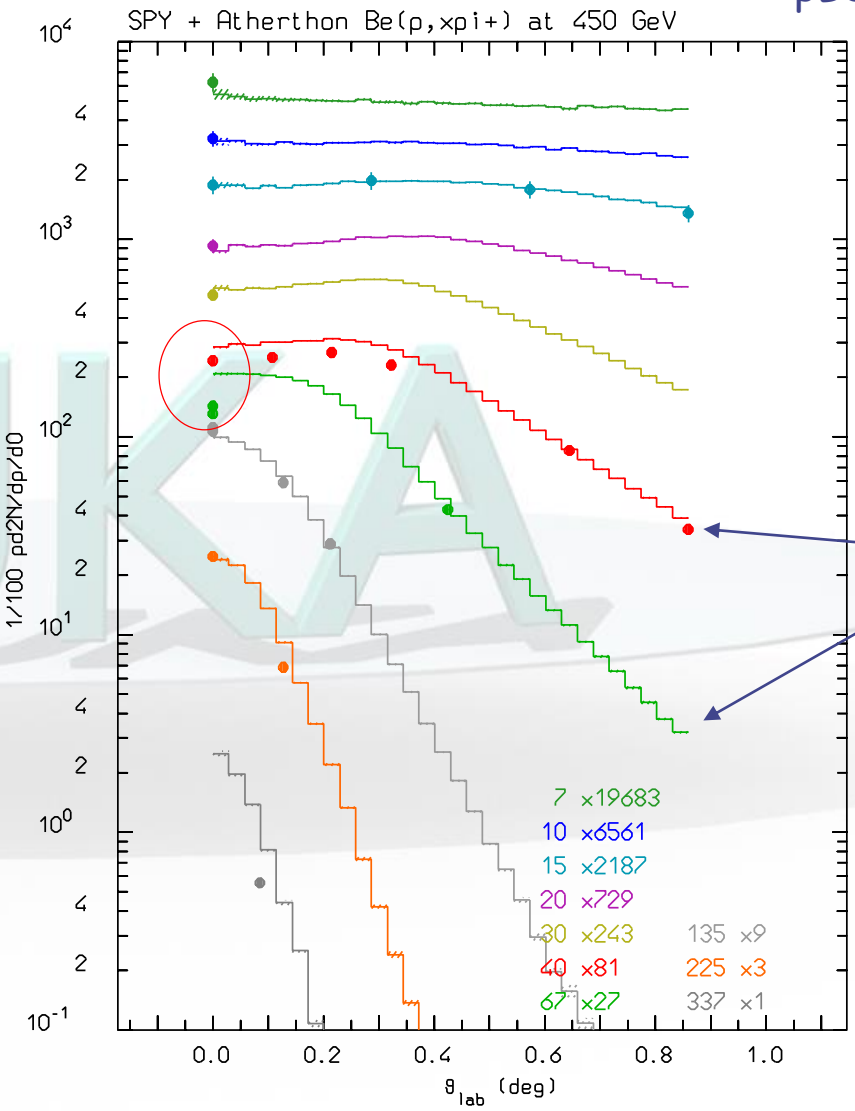
pC @ 158 GeV/c → π^+
Histos: FLUKA
Symbols: NA49



p_T spectra
In X_F intervals

X_F =0.100
X_F =0.125
X_F =0.150

pBe @ 450 GeV/c → π^+
Histos: FLUKA
Symbols: SPY

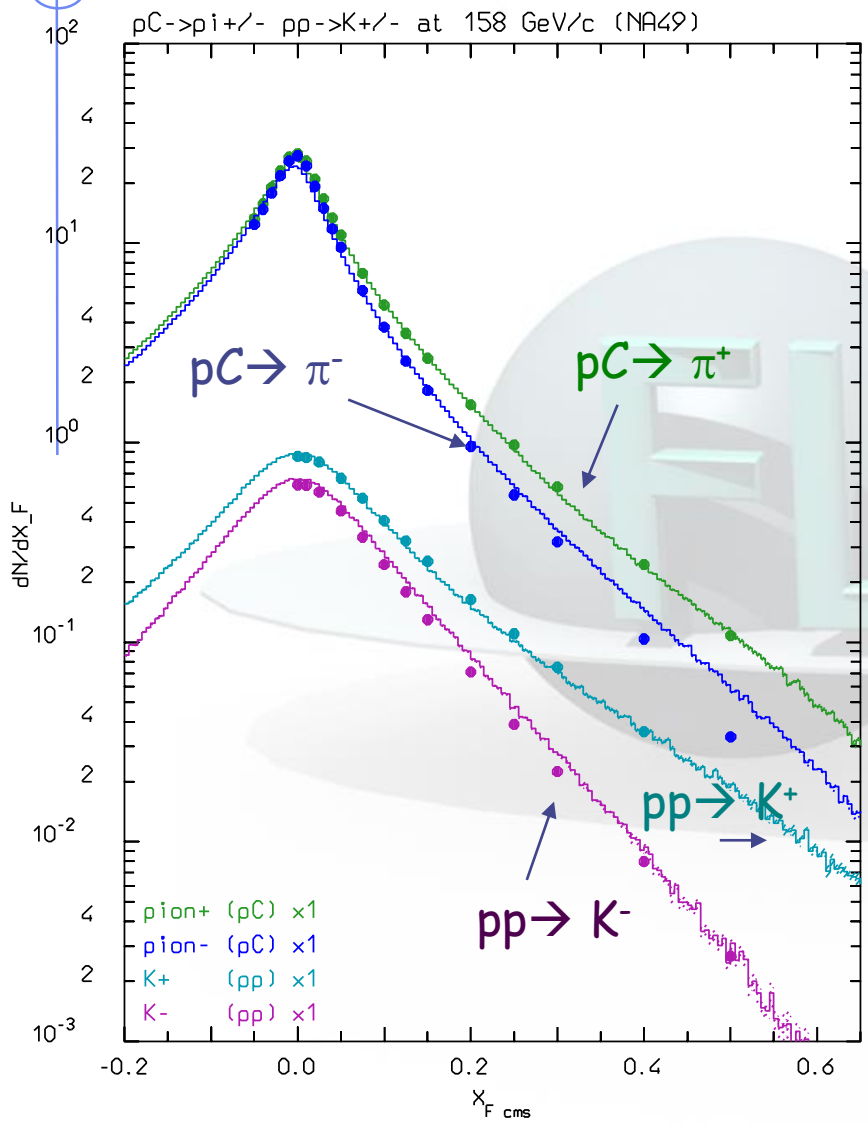


θ_{lab} spectra
In p intervals

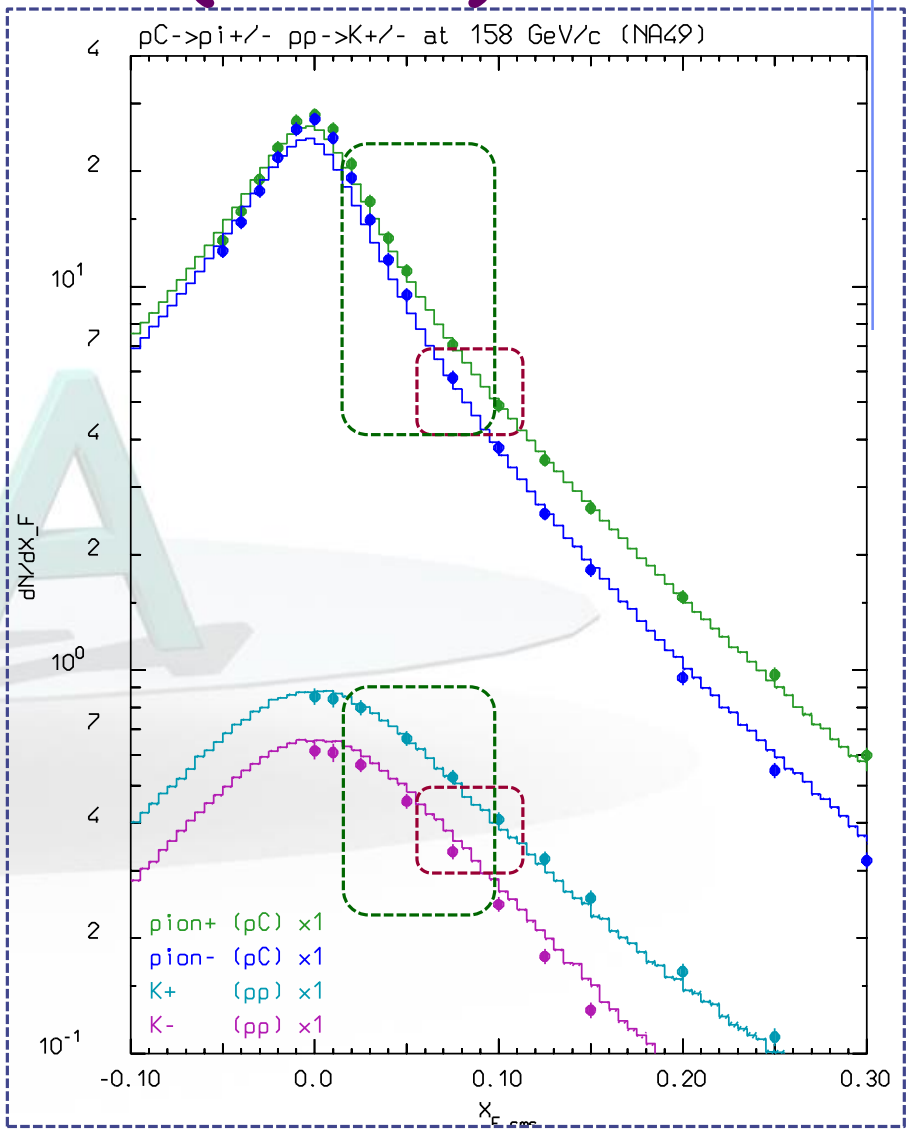
P=40 -> X_F =0.09
P=67 -> X_F =0.150

"large": discrepancy wrt SPY data at 67 GeV/c not seen wrt NA49 data

Pion and Kaon production data (NA49)



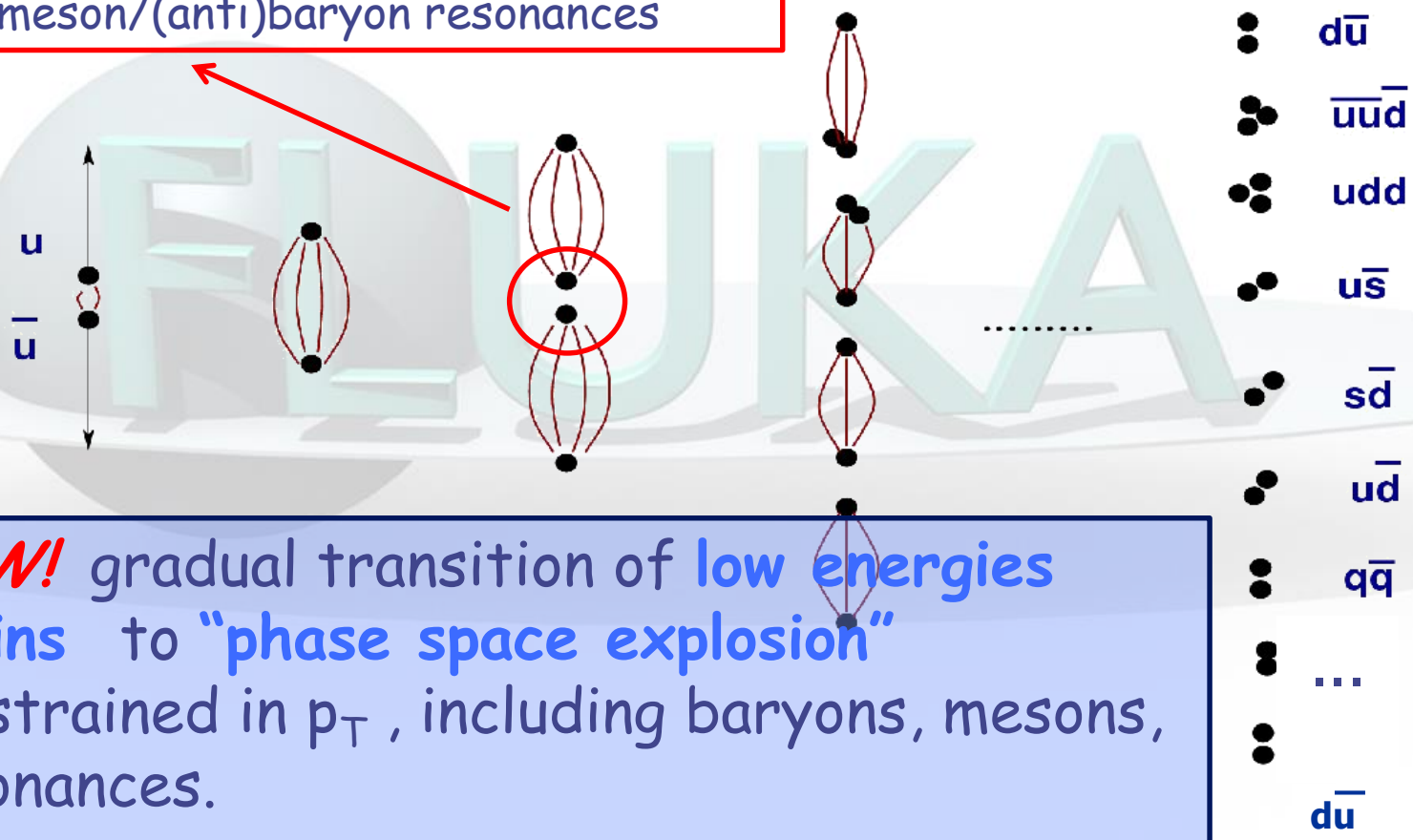
Angle integrated distributions are the most relevant for judging the reliability of ν predictions, at least for the bulk of the spectrum.
p_T integrated distributions for $pC \rightarrow \pi^+, \pi^-$ and $pp \rightarrow K^+, K^-$ are shown as a function of Feynman X_F (dots exp. data, **NA49**, lines **FLUKA** predictions), together with the "focused" zones for **CNGS** and **CENF**



DPM at low energies

An example:

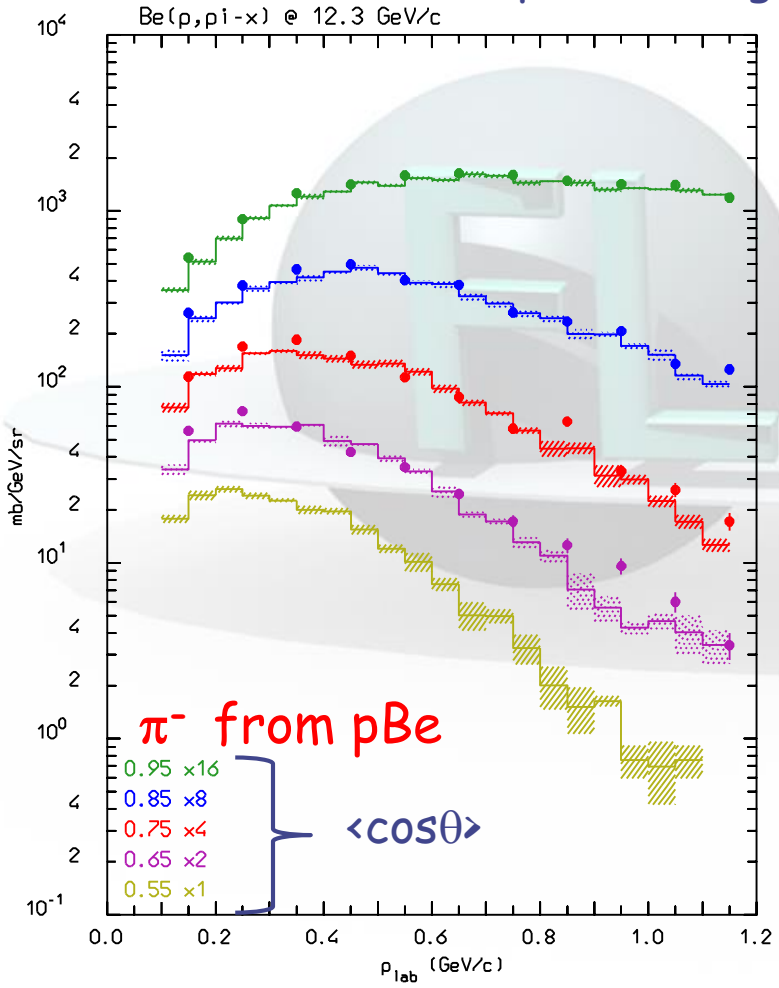
Low mass chain: just 2-3 meson/(anti)baryon resonances

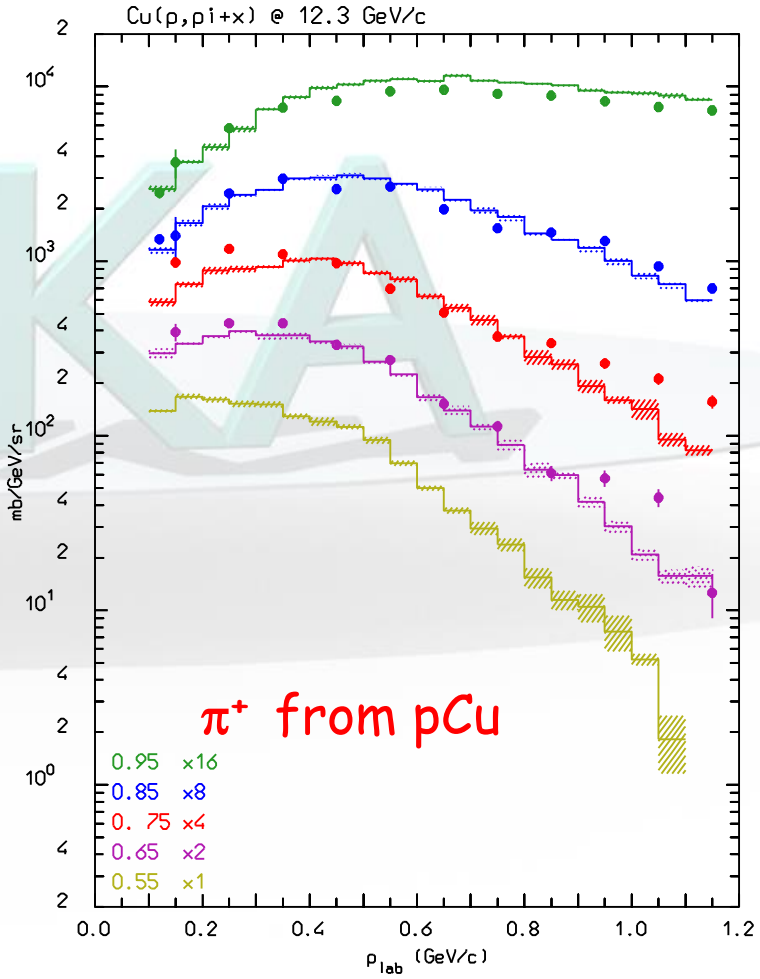


NEW! gradual transition of **low energies chains** to **"phase space explosion"** constrained in p_T , including baryons, mesons, resonances.

Pion production close to DPM thr.

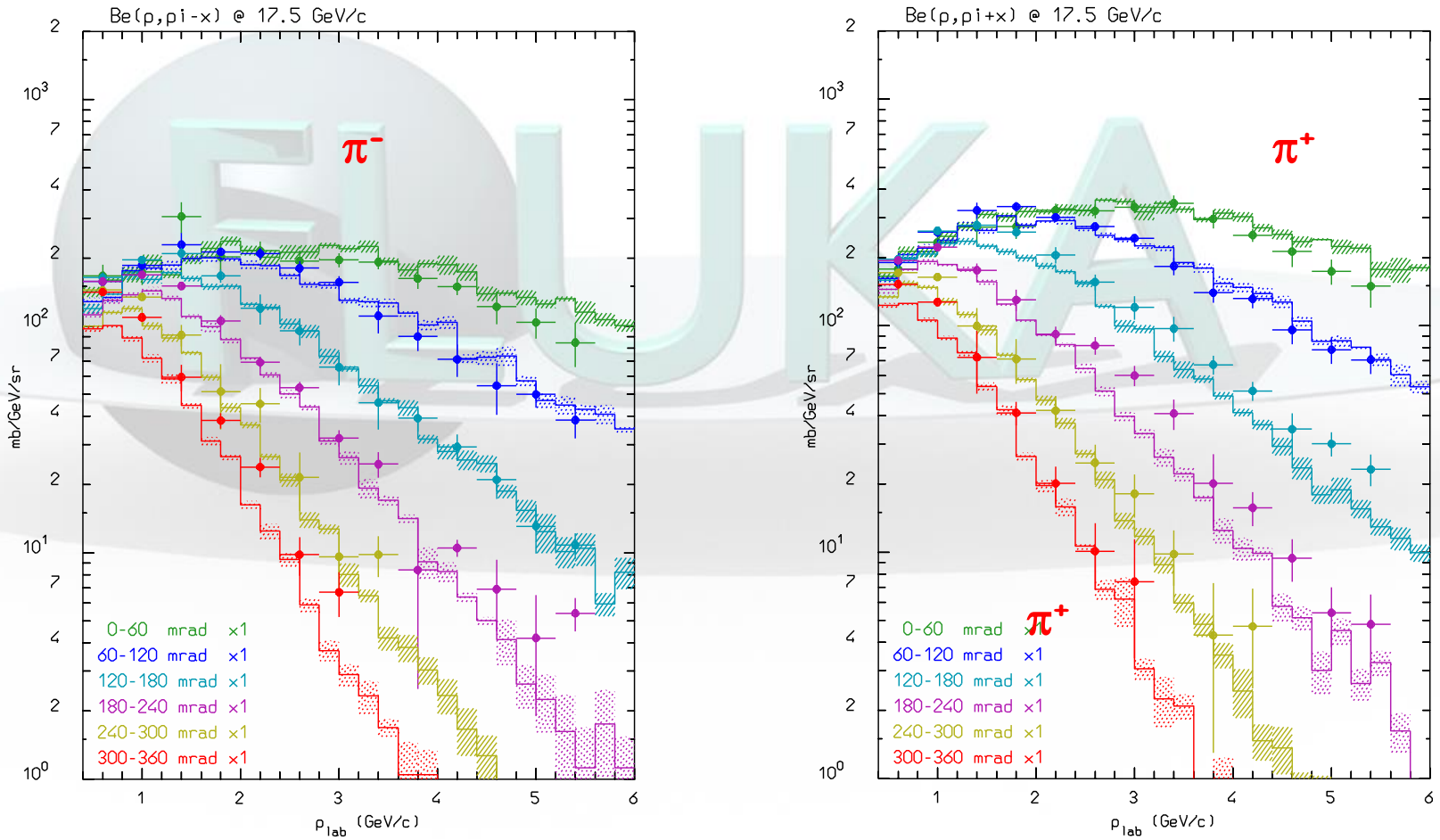
Double differential pion production from proton interactions on Be and Cu at 12.3 GeV
Emitted pion spectra at different angles in the range cosθ=1-0.5
Dots: data (BNL910 expt.), histograms : Fluka





Pion production close to DPM thr.

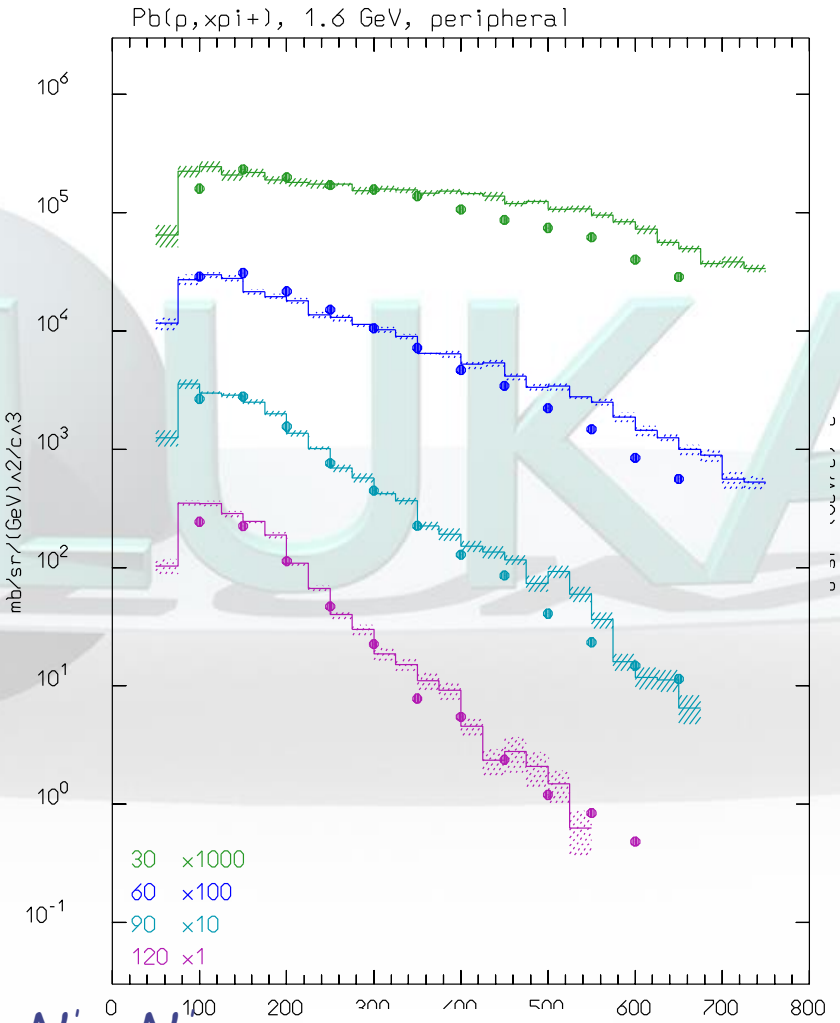
Pion production from proton interactions on Be at 17.5 GeV
Emitted pion spectra at different angles in the range 0^0 - 20^0
Dots: data (BNL910 expt.), histograms : Fluka



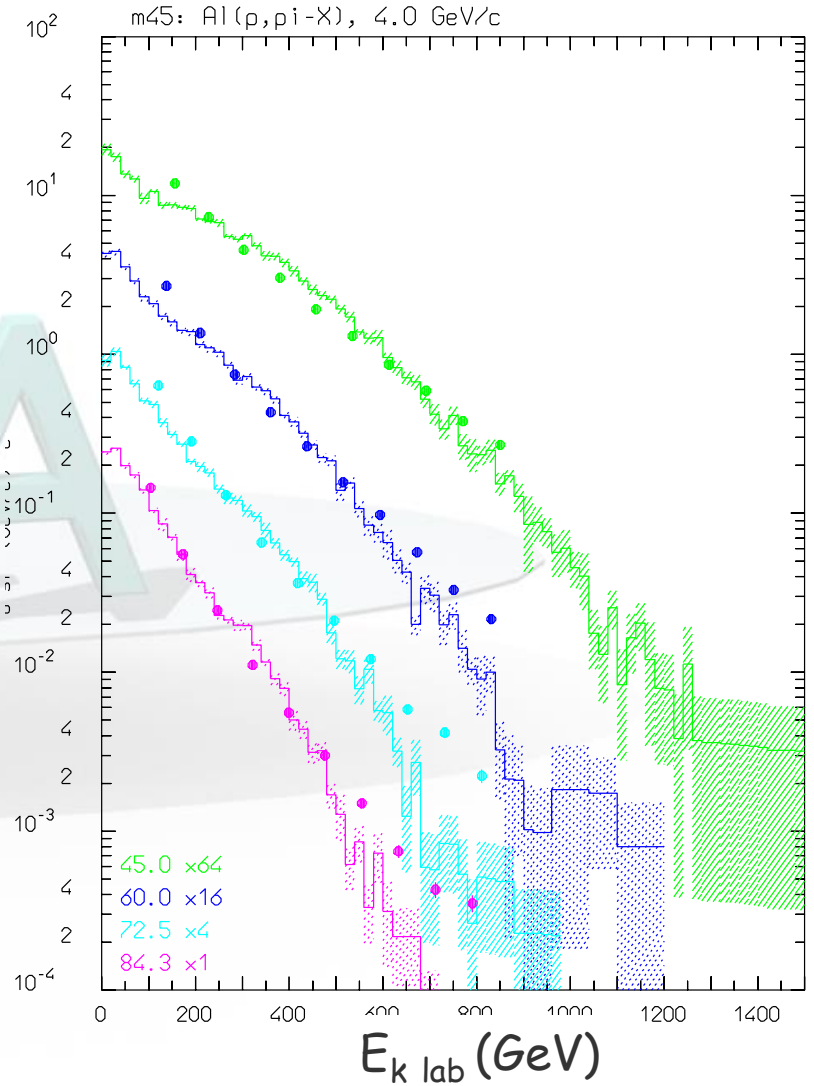
Below few GeV : resonance production and decay

Hadron-hadron interaction via production of one or more resonances
Nuclear environment: PEANUT as for DPM

p+Pb → π⁺+X (1.6 GeV)



p+Al → π⁻+X (4 GeV/c)



Examples:

$N_1 + N_2 \rightarrow N''_1 + \Delta(1232) \rightarrow N'_1 + N_2 + \pi$

$\pi + N \rightarrow \Delta(1600) \rightarrow \pi' + \Delta(1232) \rightarrow \pi' + \pi'' + N'$

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

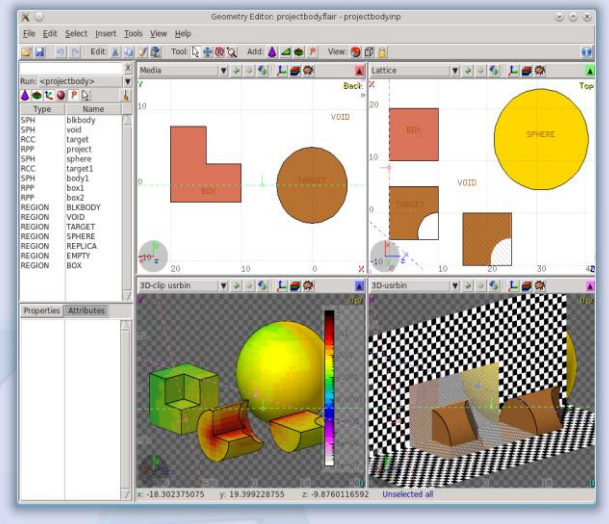
Fluka is easy

...

- Everything can be managed with a few clicks from Flair, powerful graphical interface!
  - Geometry input, debugging, visualization (2D/3D)
  - Material, physics, scoring input
  - Run submission and management
  - Analysis and plots of the results

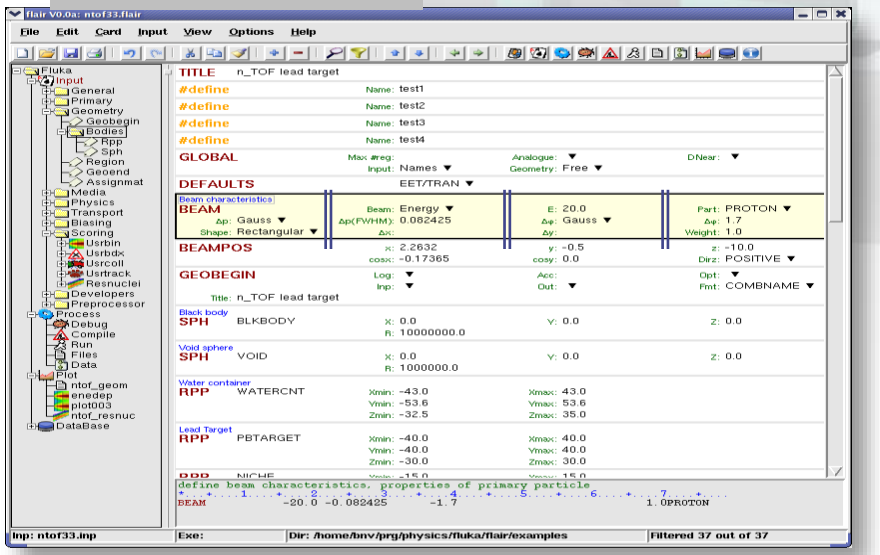
... with no programming skill or file editing!

Graphical Geometry Editor/Debugger



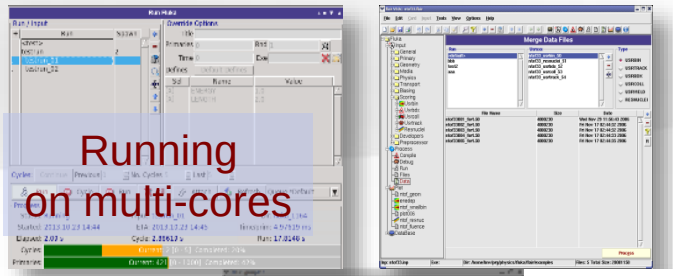
Videos available: www.youtube.com/user/Flair4Fluka

Input creation

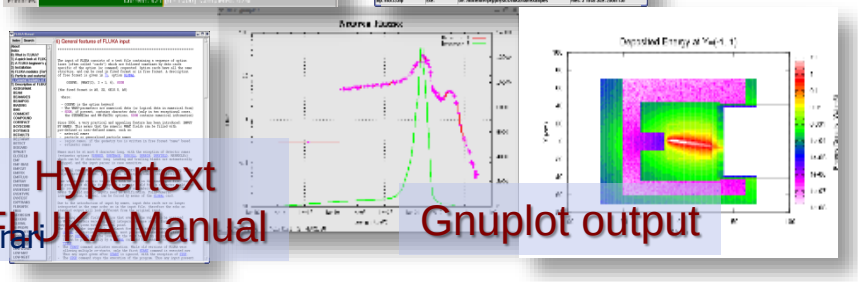


FLAIR main application window

Running / Processing / Analyzing



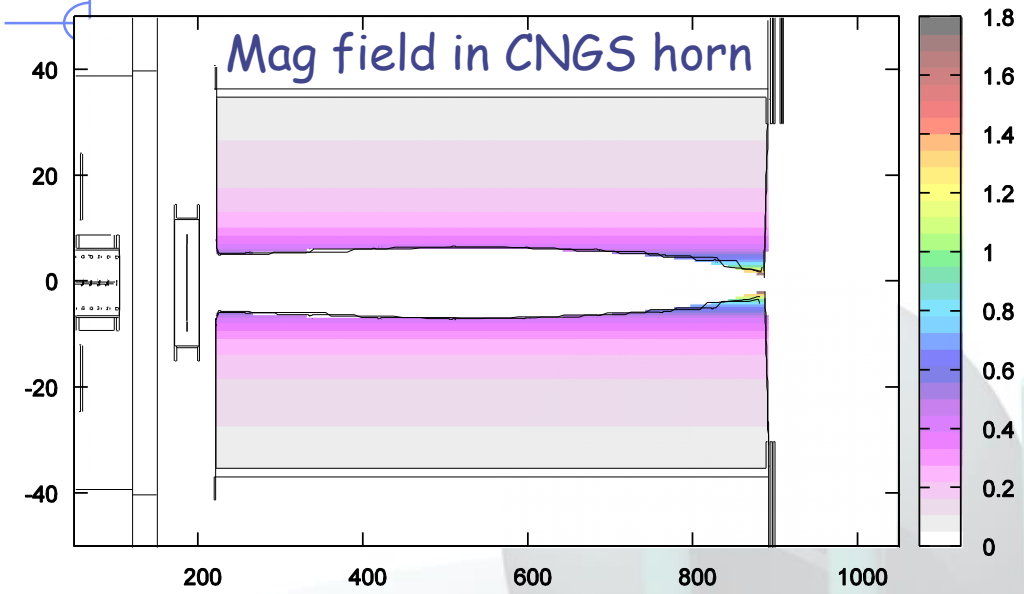
Running on multi-cores



Hypertext FLUKA Manual

Gnuplot output

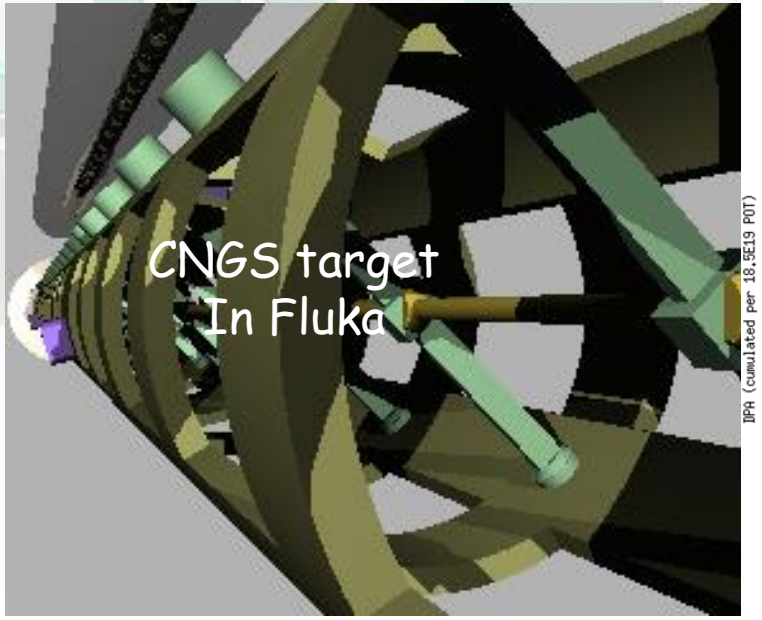
A few bonuses for neutrino beams

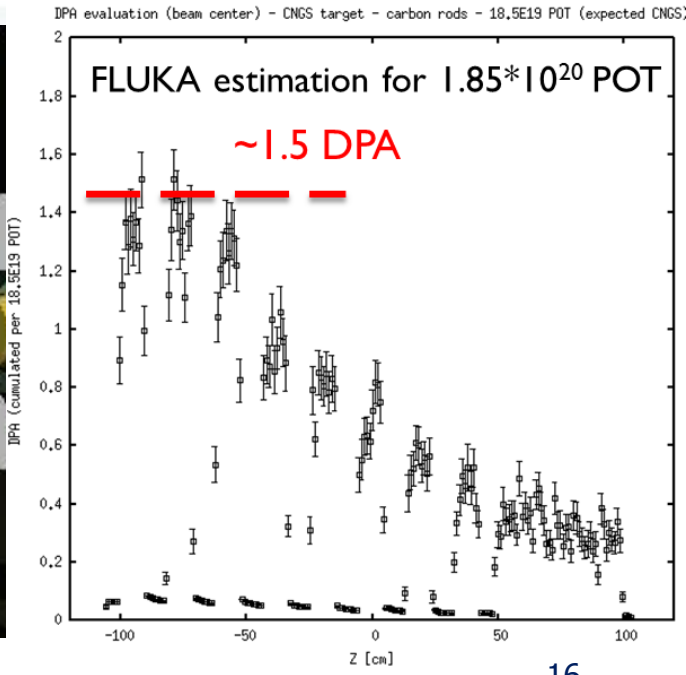


- Magnetic field : easily input through external routine
- Particle decay: accounts for polarization and matrix elements
- Biased decay length implemented
- Biased decay direction implemented

Engineering:

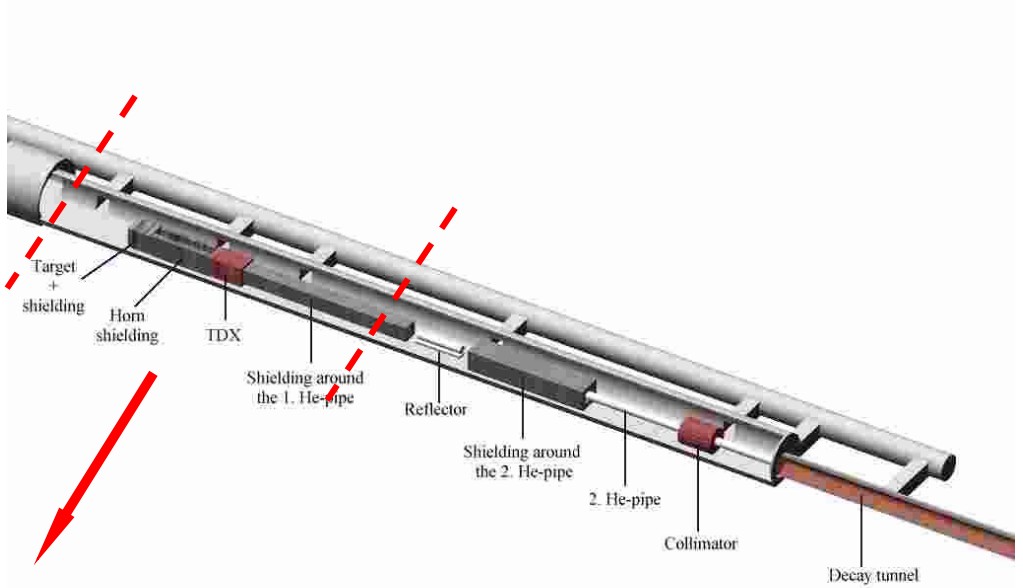
- Accurate calculation of energy deposition in the beamline elements
- Prompt and delayed radiation fields, inventory of residual nuclei, residual dose rate vs cooling time calculated online
- Radiation damage to structural elements and electronics





Residual dose rate: example at CNGS

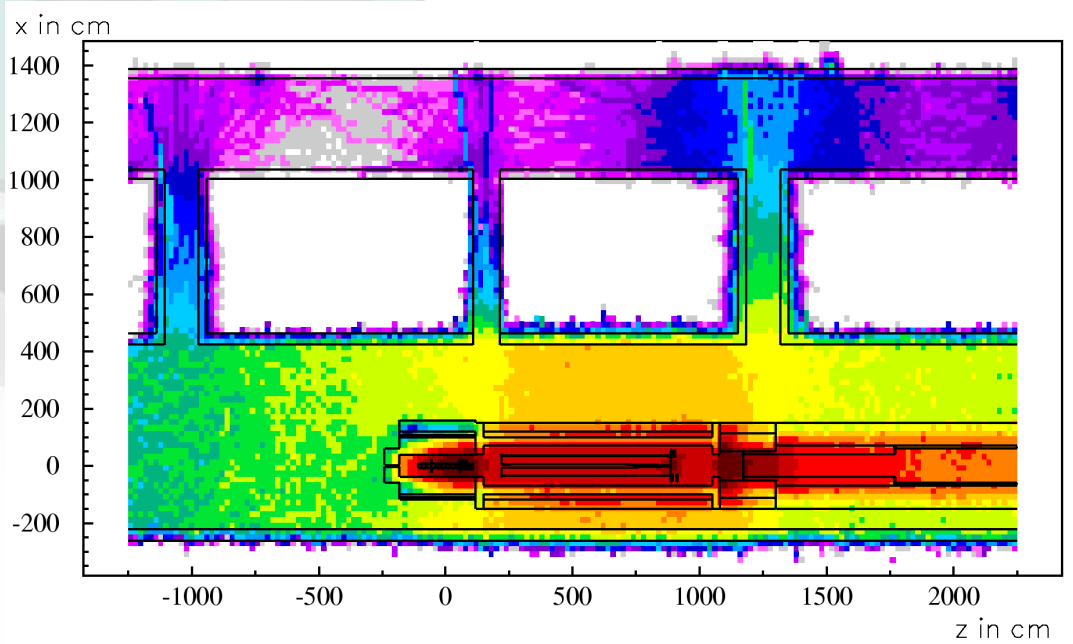
Target and horn region

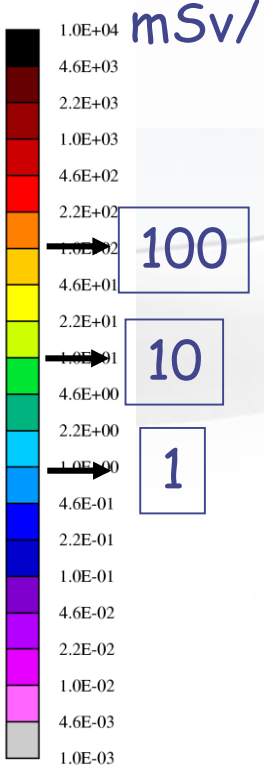


Fluka calculates dose and time evolution of activation online

Example:

t_{cool} = 1 day



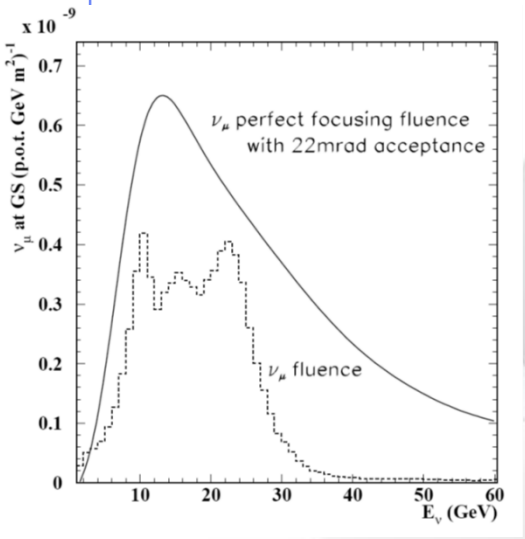


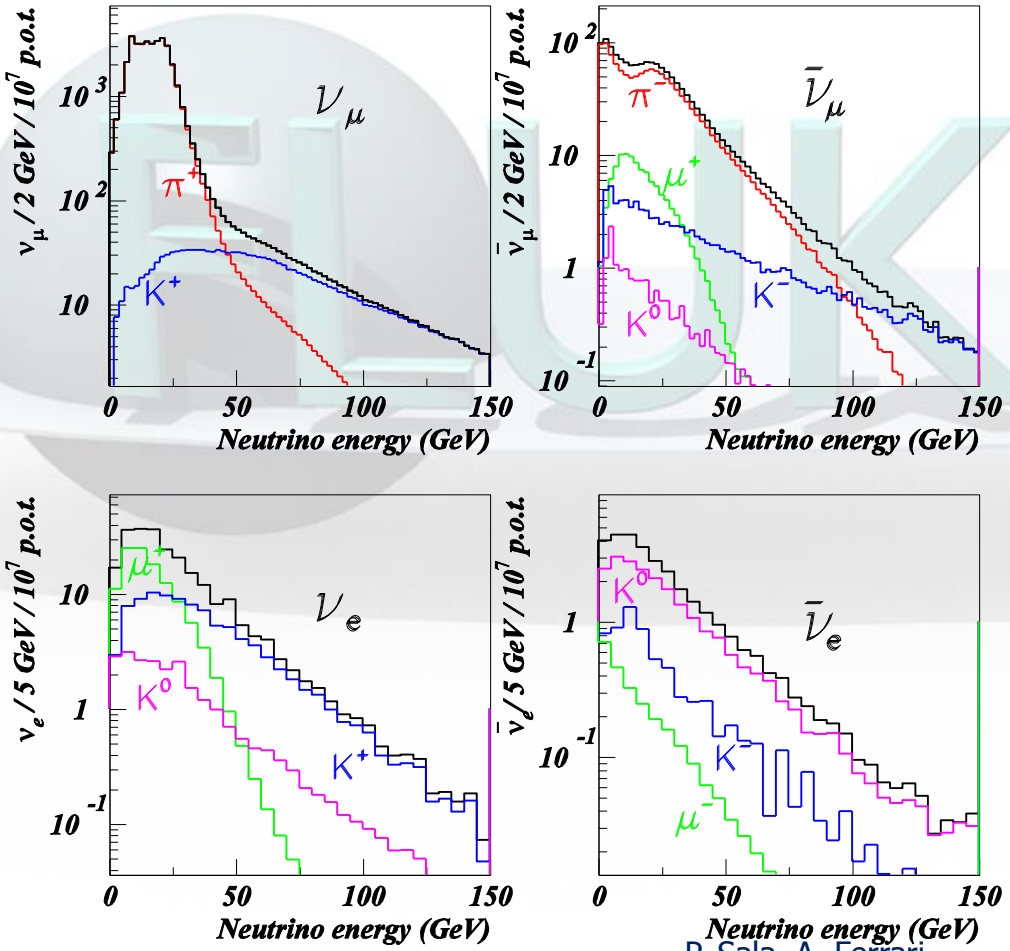
Residual Dose Equivalent Rate (mSv/h)
200 days irradiation, 1 day cooling
8×10^{12} protons/s

Cern Neutrino to Gran Sasso

400 GeV p on C target
Horn + reflector optimized for ν_τ appearance
All simulations with FLUKA

Simulated neutrino fluxes at GranSasso : see
http://www.mi.infn.it/~psala/Icarus/cngs.html
(also linked from www.cern.ch/cngs)





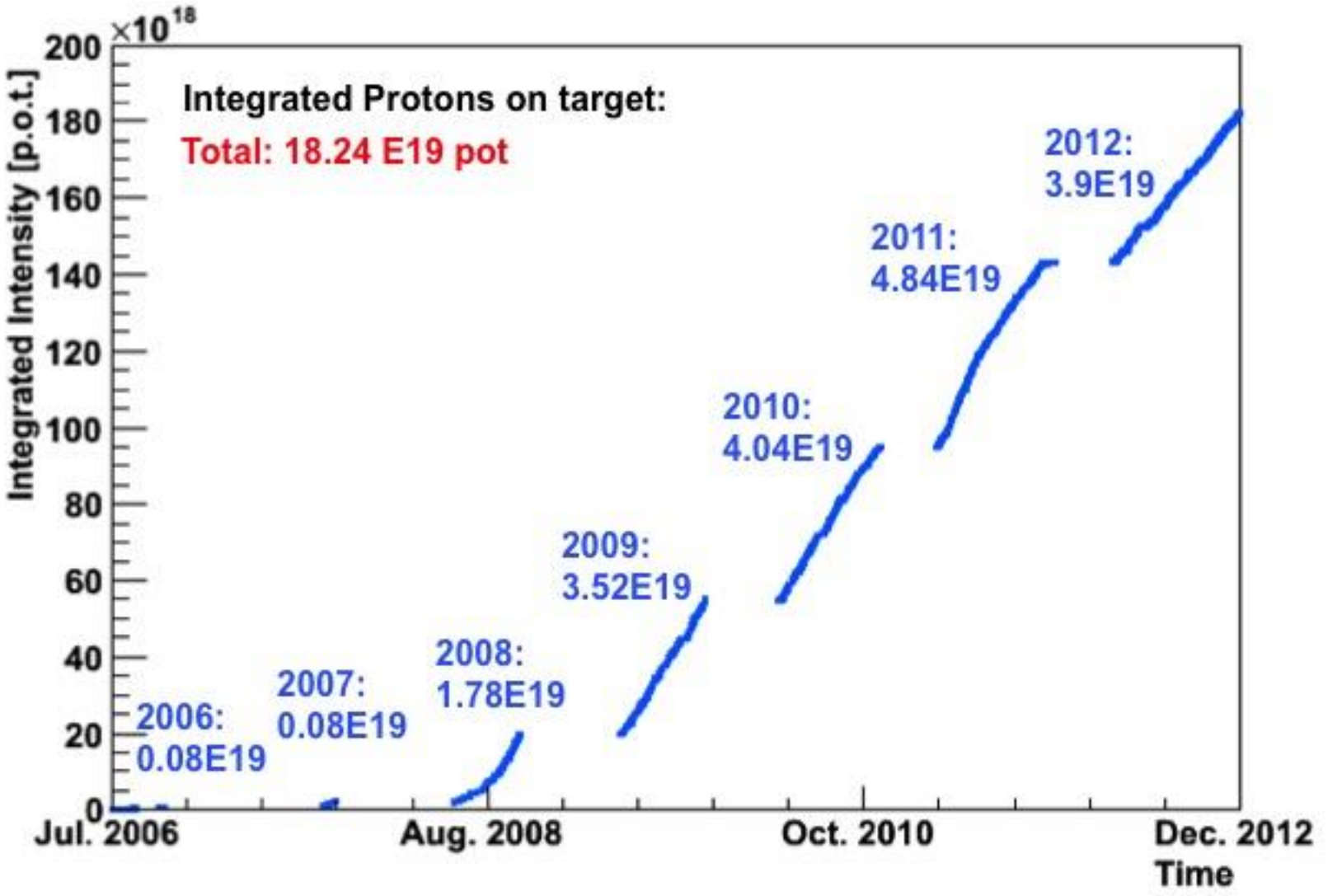
	Flux	$< E_\nu >$	ν_i/ν_μ	ν_i/ν_μ-CC
	$(\nu/\text{cm}^2/10^{19}\text{pot})$	$[GeV]$	(%)	(%)
ν_μ	$7.4 \cdot 10^6$	17.9		
$\bar{\nu}_\mu$	$2.9 \cdot 10^5$	21.8	3.9	2.40
ν_e	$4.7 \cdot 10^4$	24.5	0.65	0.89
$\bar{\nu}_e$	$6.0 \cdot 10^3$	24.4	0.08	0.06

CC event rate
600 ν_μ CC/kt/ 10^{19}pot
5.5 ν_e CC/kt/ 10^{19}pot

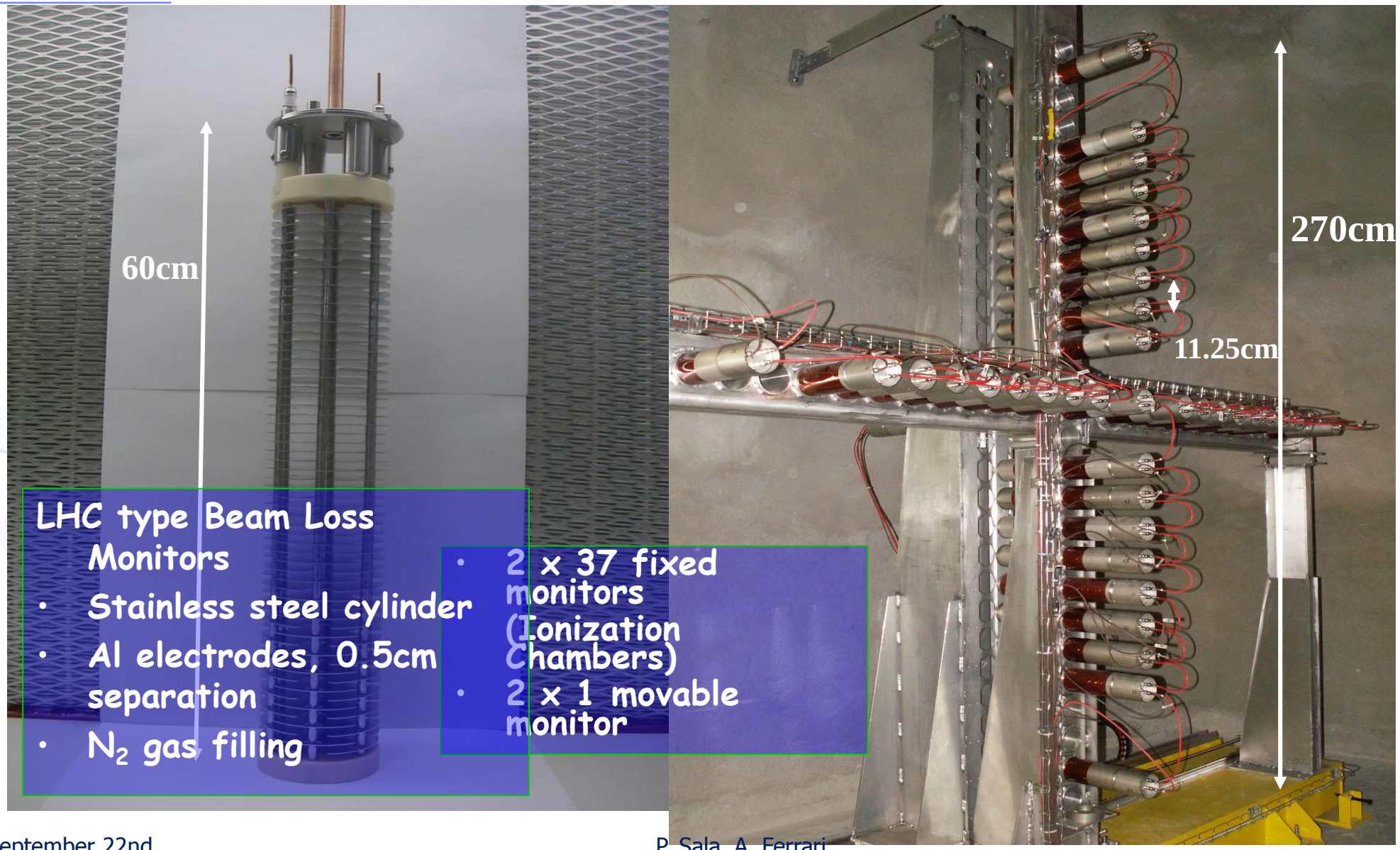
Nominal intensity : 4.5 10^{19} pot/y

CNGS 2006 - 2012

Total Integrated Protons on Target: 18.24 E19 pot



Beam monitoring : 2 "muon pits"

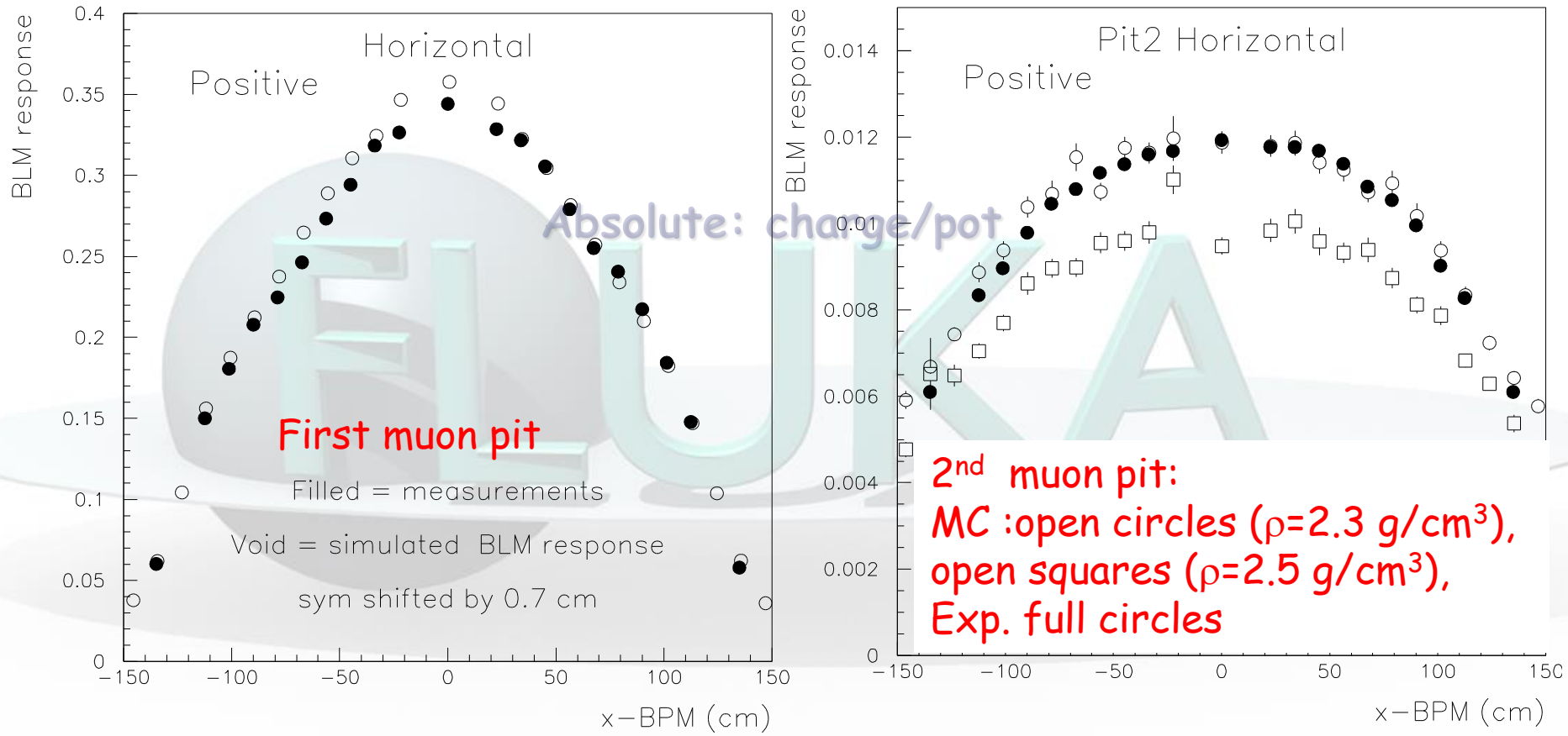


LHC type Beam Loss Monitors

- Stainless steel cylinder
- Al electrodes, 0.5cm separation
- N_2 gas filling

- 2 x 37 fixed monitors (Ionization Chambers)
- 2 x 1 movable monitor

Results at CNGS Muon pits: data vs MC



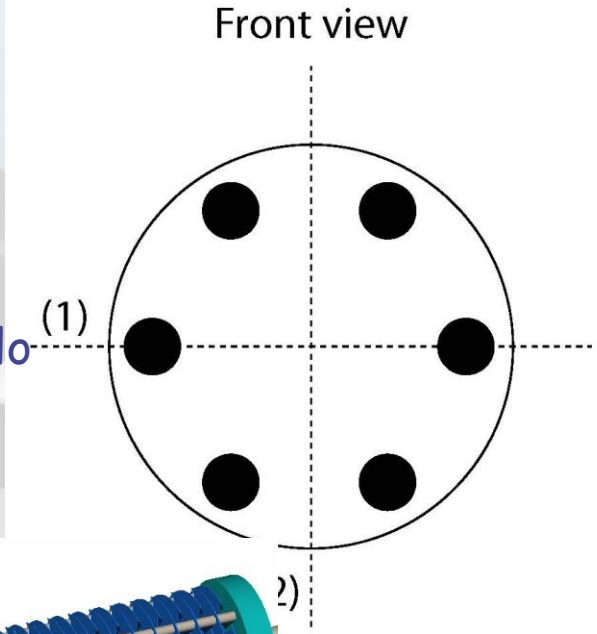
Included in MC: effect of **earth magnetic field** (in the 1 km long decay tunnel)
Experimental uncertainties: detector calibration and sensitive volume, density of the rock in between the two pits (67 m, drilling in similar areas show large variations)

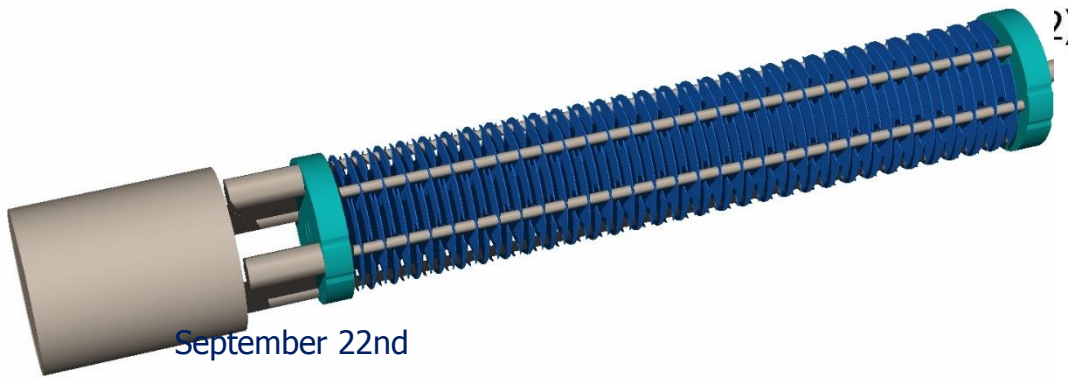
Muon Detectors: electric field maps

Ongoing : run-time corrections according to charge collection probability vs position in nominally active and inactive gas regions

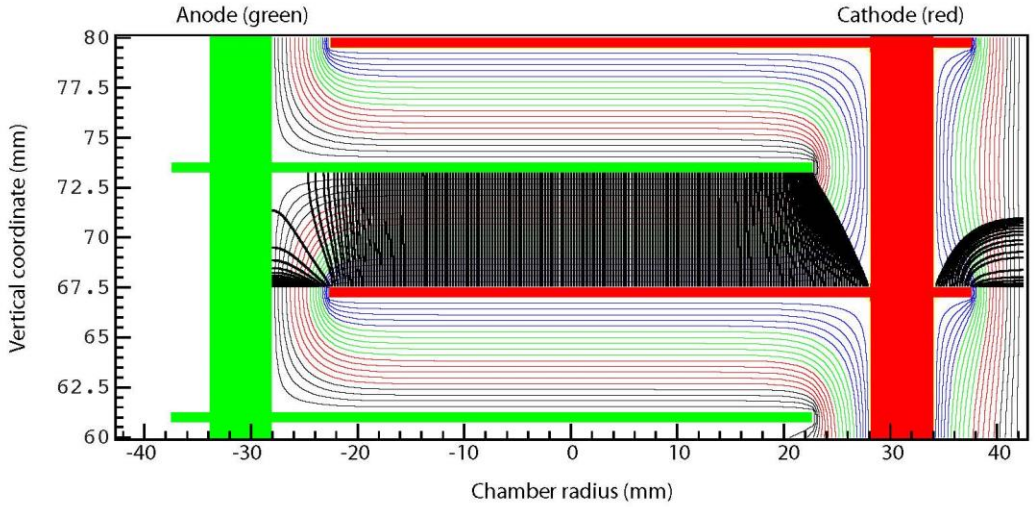
Field calculations by F.Pietropaolo (ICARUS, INFN-Pd), implementation into FLUKA A.Lechner (CERN)

Electric field in BLM chamber

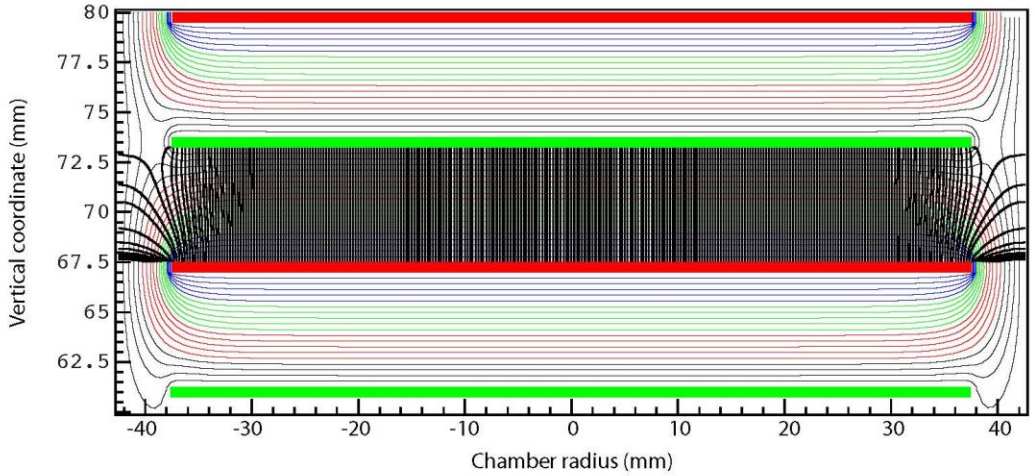




Cross section through columns (1)

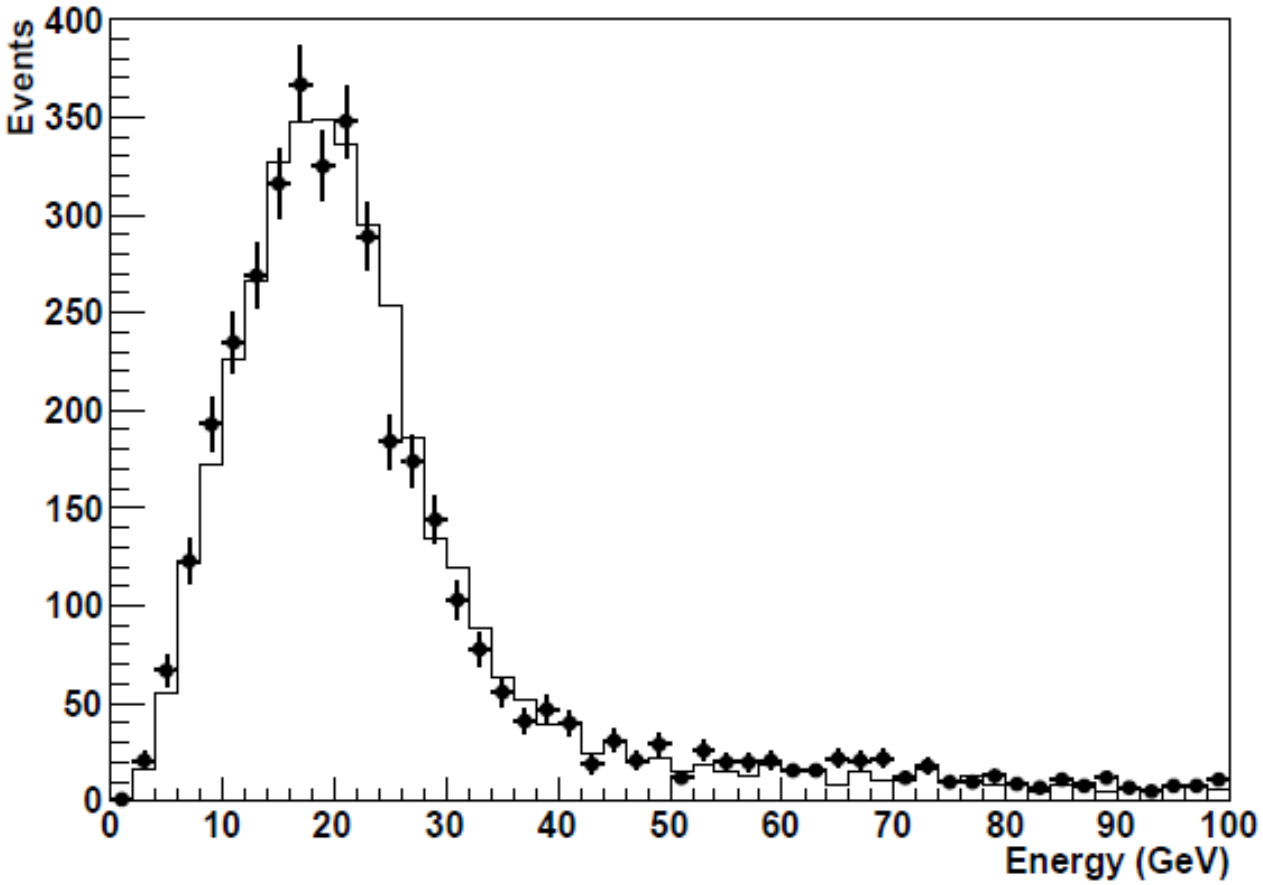


Cross section in-between columns (2)



OPERA reconstruction of the CNGS spectrum

- **New J.Phys. 13 (2011) 053051** «Study of neutrino interactions with the electronic detectors of the OPERA experiment"
- Fluxes from **FLUKA**
- Interactions and reconstruction from **OPERA**



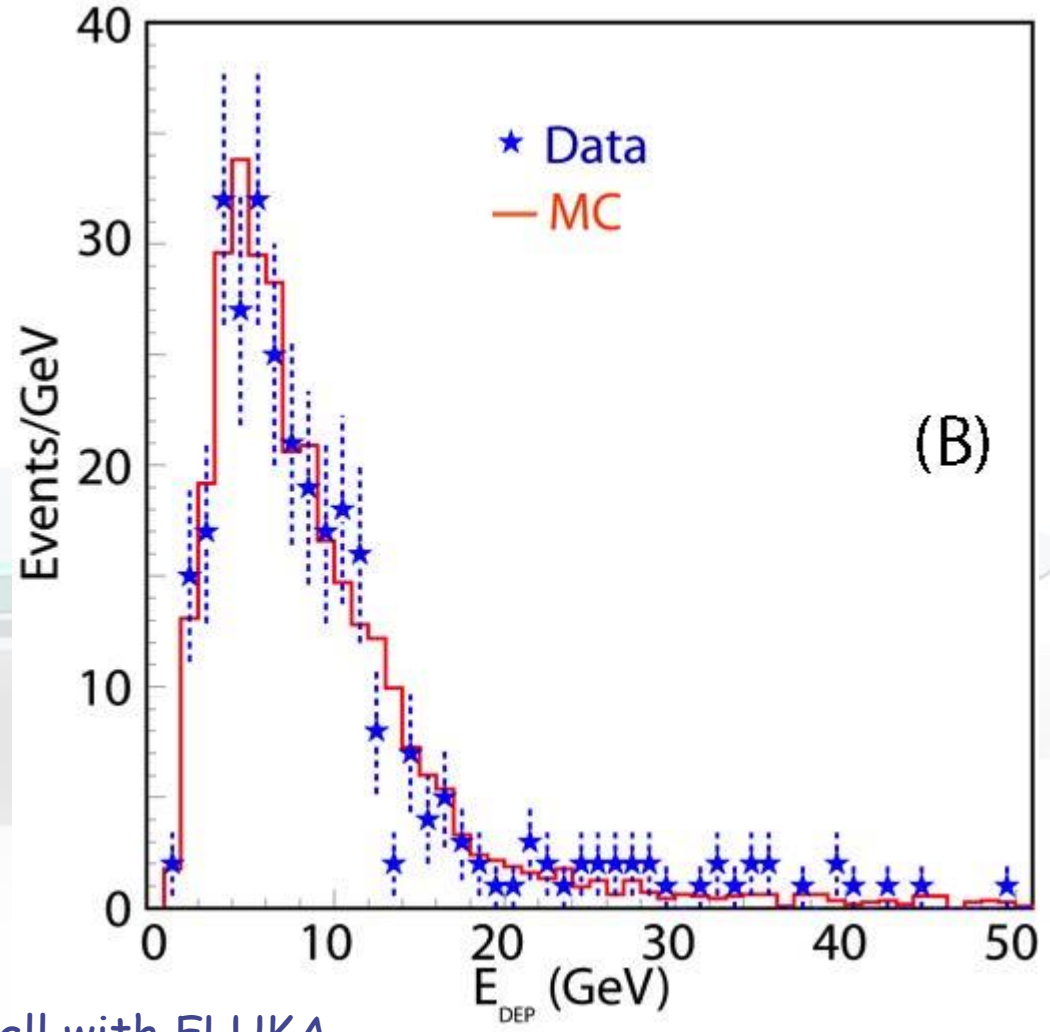
Total reconstructed energy for events with at least one identified muon for data (dots with error bars) and MC (solid line). The MC distribution is normalised to data.

ICARUS data

Eur.Phys.J. C73 (2013) 2345

Number of observed neutrino events, in good agreement, within 6%, with the Monte Carlo expectation

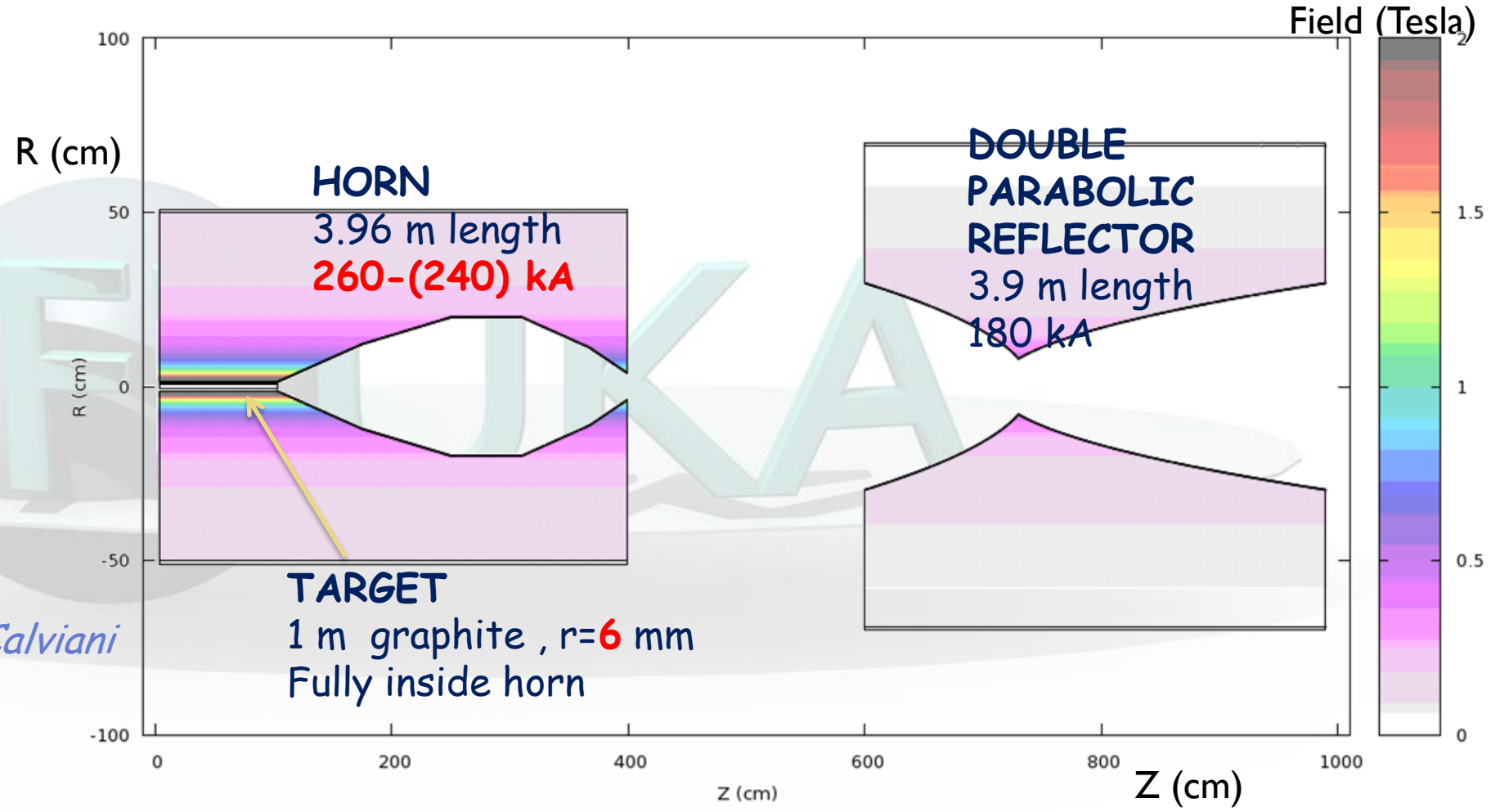
Experimental raw energy distribution Edep for muon neutrinos and antineutrinos CC interaction in the ICARUS T600 detector (blue symbols) compared with the Monte Carlo expectations (red solid histogram), normalised to the same number of entries.



Fluxes, neutrino interactions, detector sim, all with FLUKA

Studies for the CENF facility*

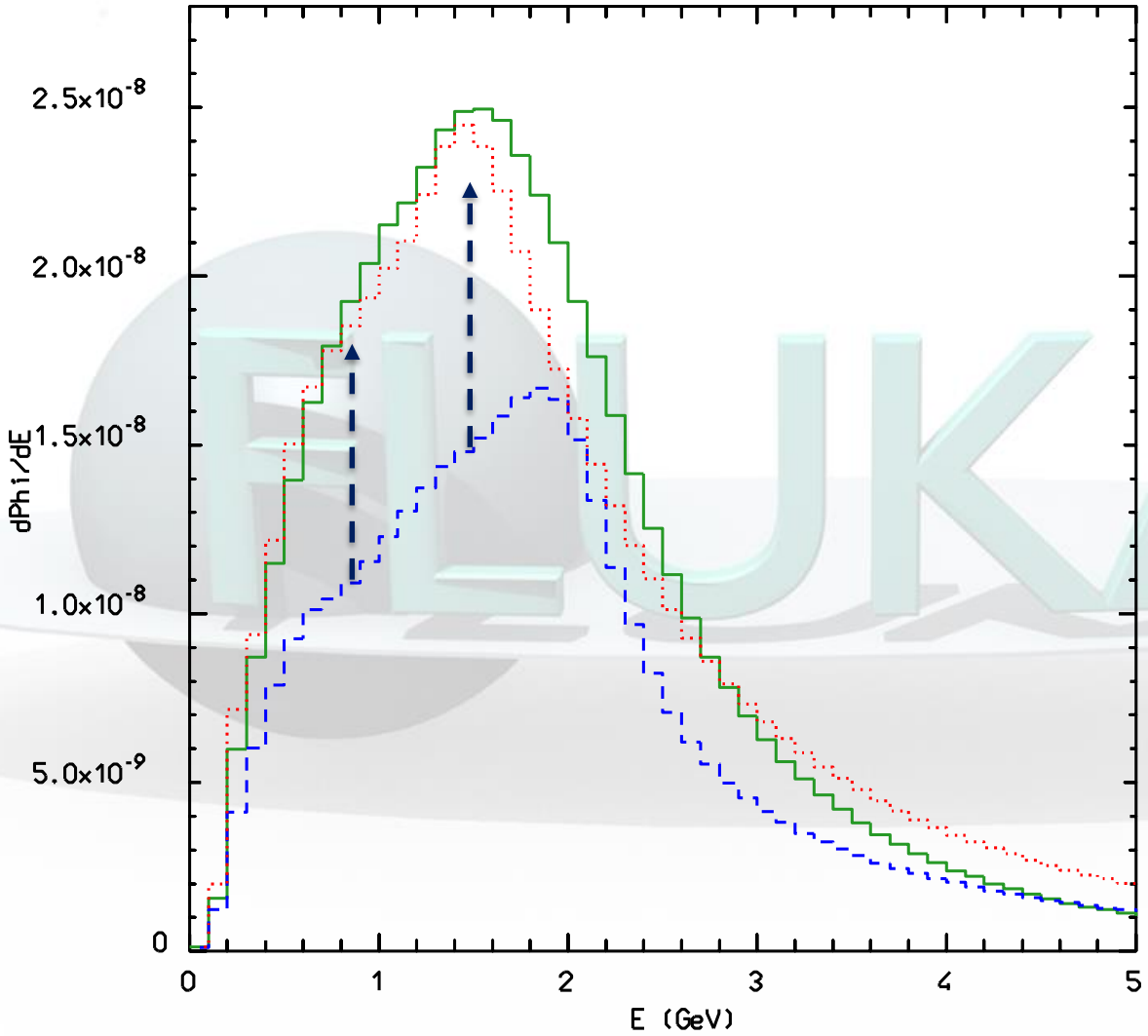
CErnNeutrinoFacility
(..virtual..)
100 GeV protons
Optimized for Short Base Line neutrino experiments



Many more details in M.Calviani talk @ NBI

CENF optimization by the CERN EN/STI section (M. Calviani, A. Ferrari, W.Kozlowska, + P.Sala)

CENF: ν_μ flux optimization



ν_μ fluence @ Near Detector

Blue: LoI

Red: Old-new

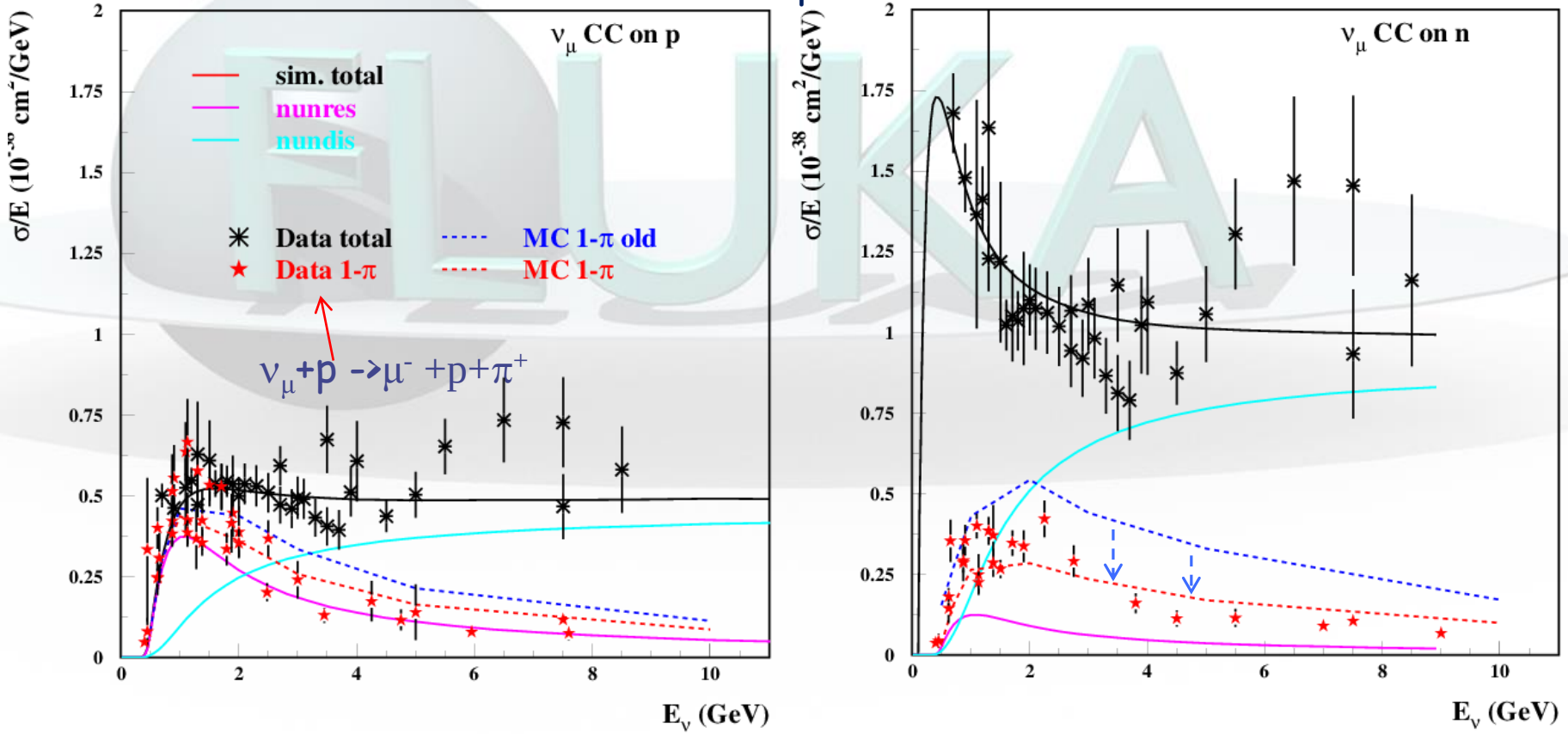
Green: New-new ("best")

Major increase (x ~1.5! in rate) over the LoI flux which was already highly optimized

CENF optimization by the CERN EN/STI section (M. Calviani, A. Ferrari, V.Kozlowska + P.Sala)

Neutrino interactions

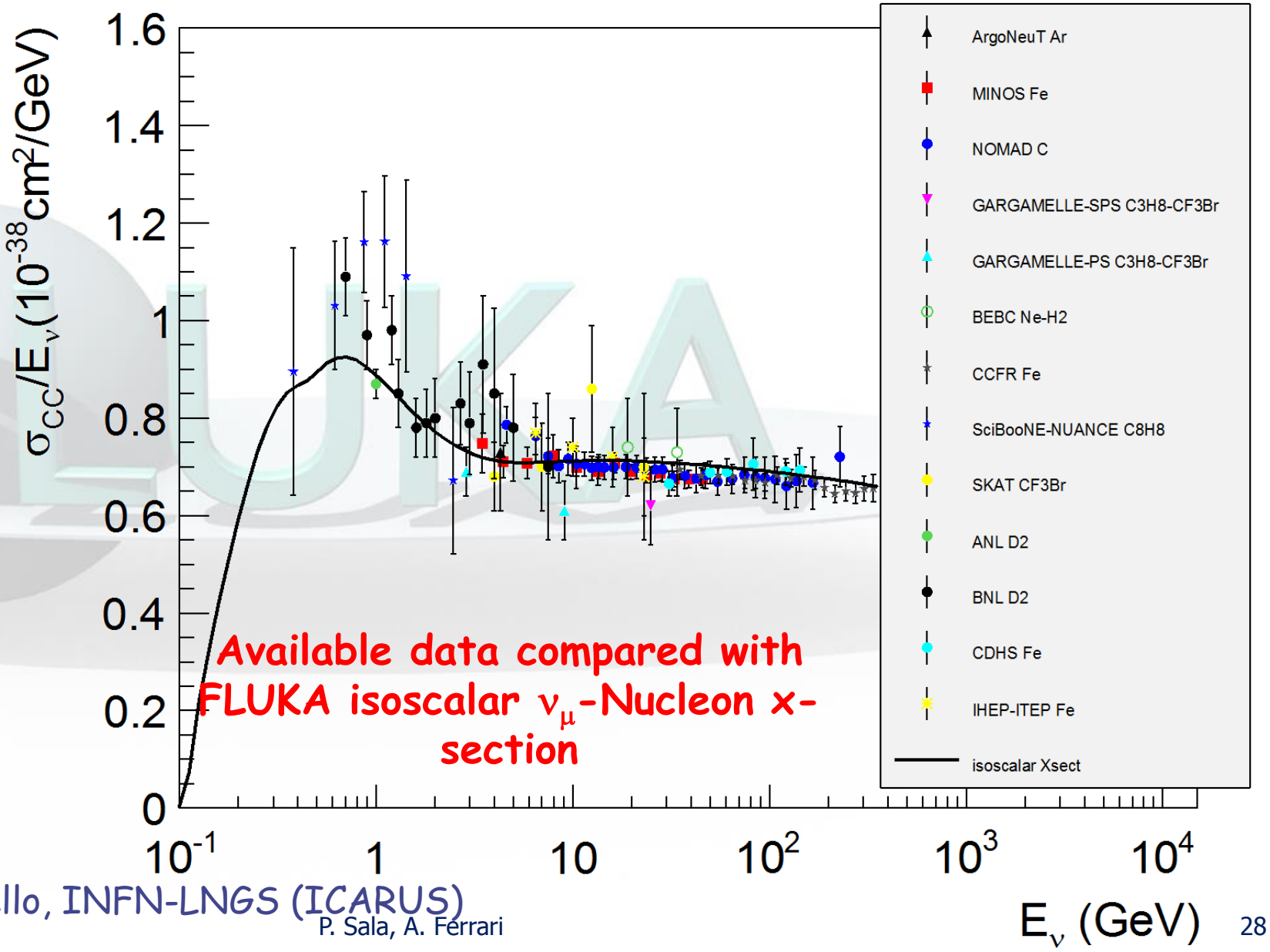
FLUKA has its own neutrino interaction generator, including ***QuasiElastic, RESonance, DeepInelasticScattering***
DIS uses the same chain ***hadronization*** as DPM
Embedded in the **FLUKA** nuclear environment (**PEANUT**)
New ***low-mass chain treatment***-> improvements in the **RES-DIS** transition



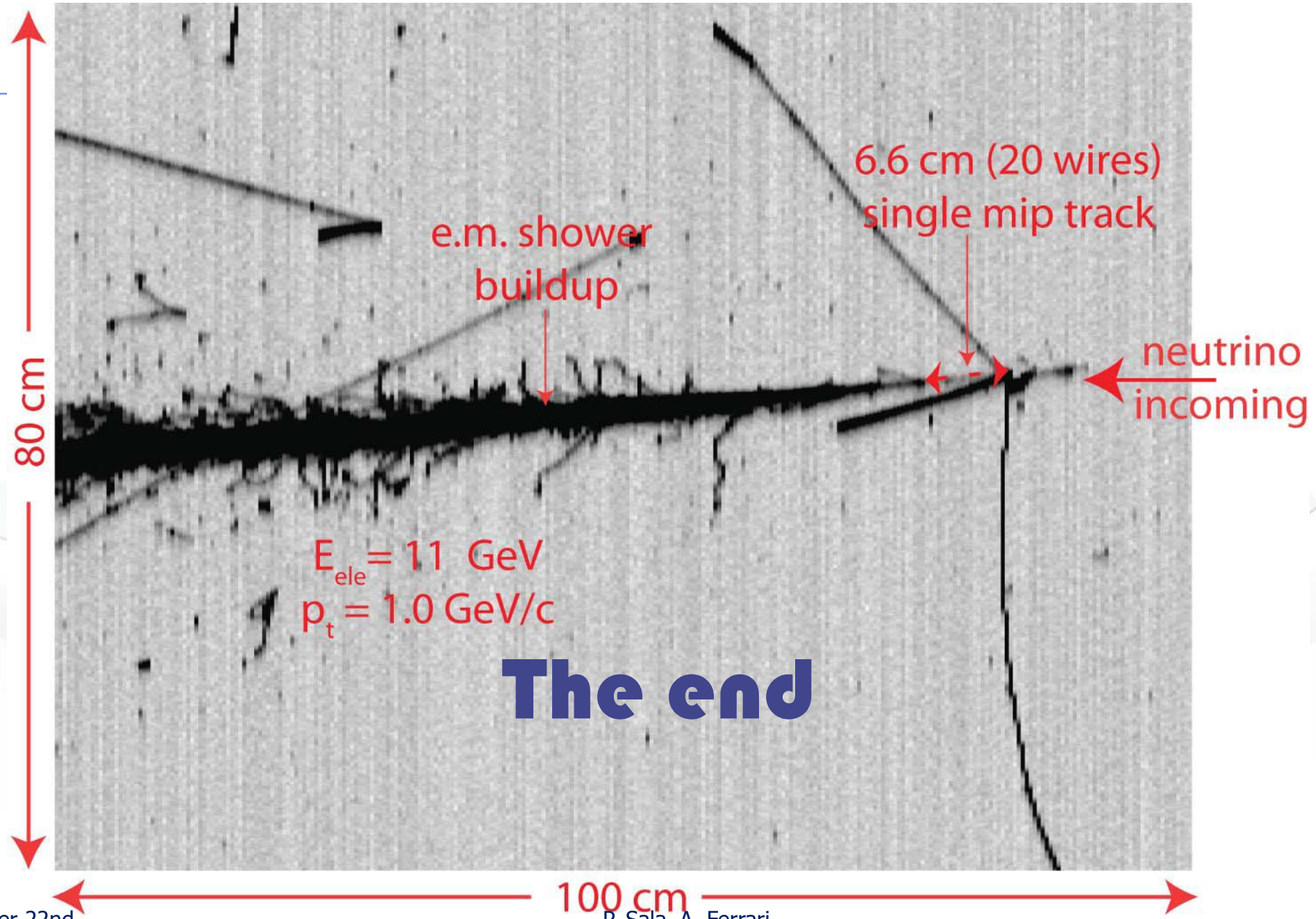
Neutrino cross sections:

Work in progress:

- Radiative corrections (G.Smirnov CERN)
- Re-evaluation of experimental systematic error (correlation among experiments due to common normalisation)



Plot : courtesy of M. Antonello, INFN-LNGS (ICARUS)


6.6 cm (20 wires)
single mip track
e.m. shower
buildup
neutrino
incoming
80 cm
$E_{ele} = 11$ GeV
$p_t = 1.0$ GeV/c
The end
100 cm

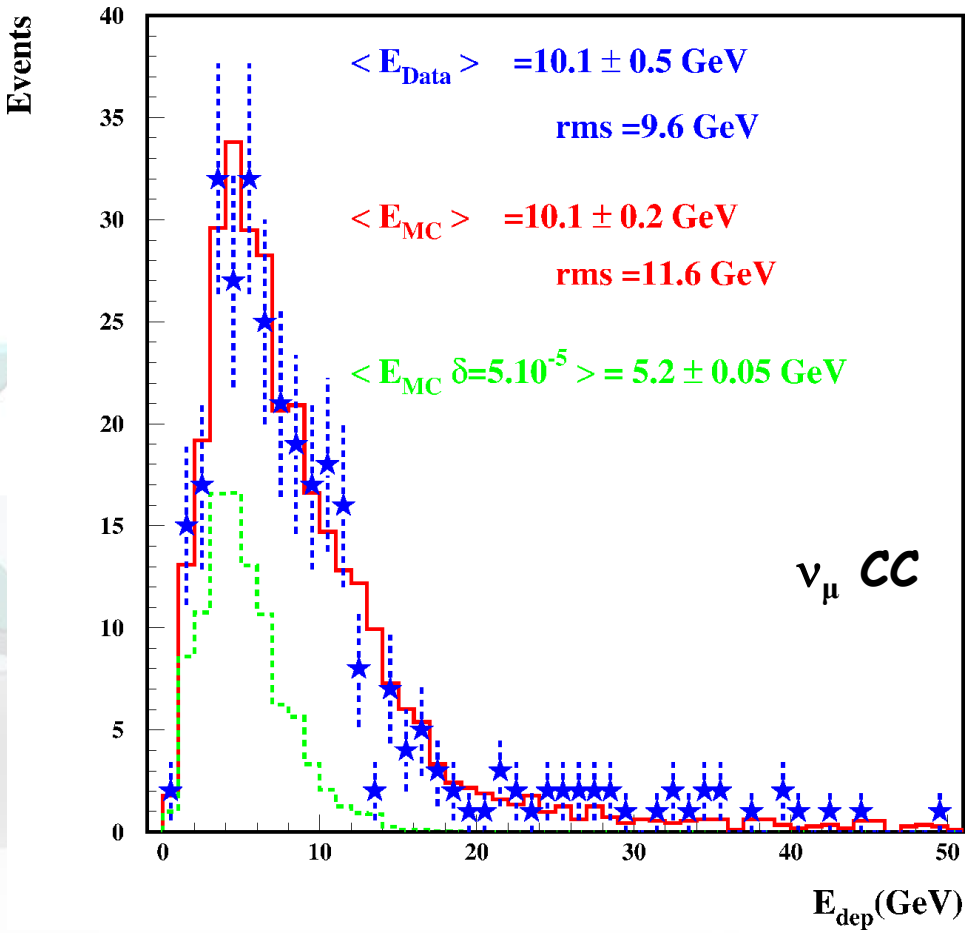
Search for superluminal ν's radiative processes in ICARUS

- Following the OPERA claim for superluminal neutrinos, Cohen and Glashow argued that superluminal ν should loose energy mainly via e^+e^- bremsstrahlung, on average $0.78 \cdot E_\nu$ energy loss/emission
- Full FLUKA simulation of the process kinematics, folded in the CNGS beam, studied as a function of $\delta = (v_\nu^2 - c^2)/c^2$

  For $\delta = 5\ 10^{-5}$ (OPERA first claim):
  - full ν event suppression for E > 30 GeV
  - ~10^7 e^+e^- pairs /10^{19} pot/kt
- Effects searched in ICARUS exposure to CNGS
  - No spectrum suppression found in both NC , CC data
- The lack of pair in ICARUS 2010/2011 data sets the limit*:
  - No e^+e^- pair bremsstrahlung event candidate found

$$\delta = (v_\nu^2 - c^2)/c^2 < 2.5\ 10^{-8}\ 90\%\ CL$$

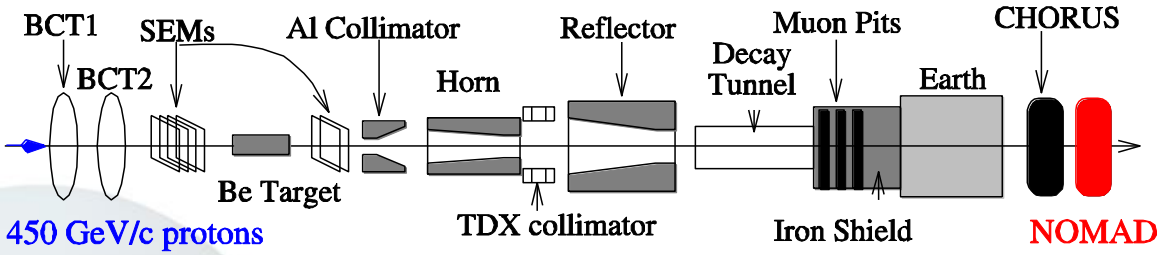
- comparable to the SuperK limit $\delta < 1.4\ 10^{-8}$, somewhat larger than the lower energy velocity constraint $\delta < 4\ 10^{-9}$ from SN1987A.

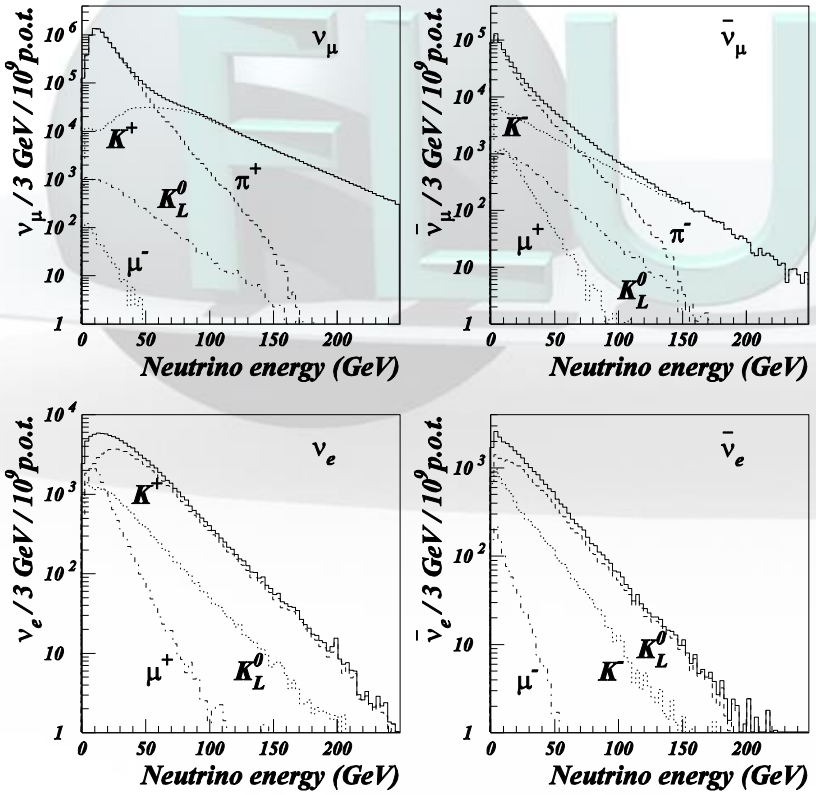


Comparison of the predicted (full MC) and detected deposited energy spectrum from CC events **Green: expectation for $\delta = 5 \times 10^{-5}$**

*PLB711, 270 (2012)

Comparison with the WANF data (NOMAD)





- ν_μ: $< E_{\nu_\mu} > \sim 24.3$ GeV
- $\bar{\nu}_\mu$: 7 %, $< E_{\bar{\nu}_\mu} > \sim 17.2$ GeV
- ν_e: 1 %, $< E_{\nu_e} > \sim 36.4$ GeV
- $\bar{\nu}_e$: 0.3 %, $< E_{\bar{\nu}_e} > \sim 27.6$ GeV

Correct reconstruction of:

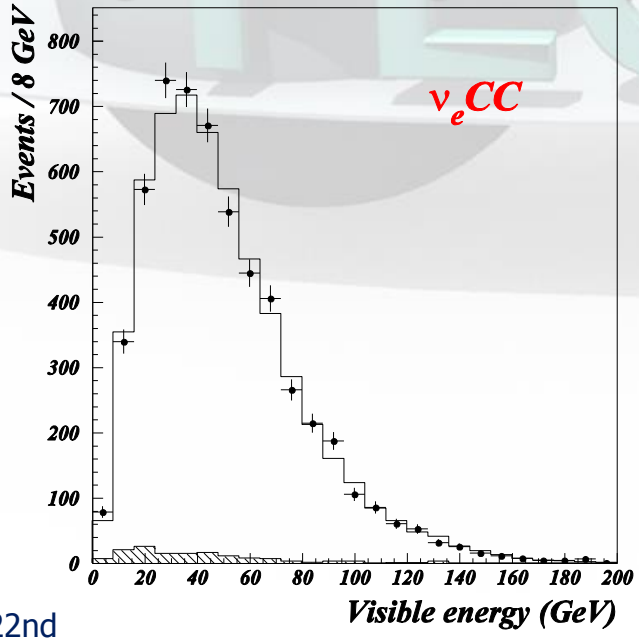
- ν_μ from π^+, K^+ + … decays
- $\bar{\nu}_\mu$ from π^-, K^-. K^0 + … decays
- ν_e from K^0, K^- + … decays

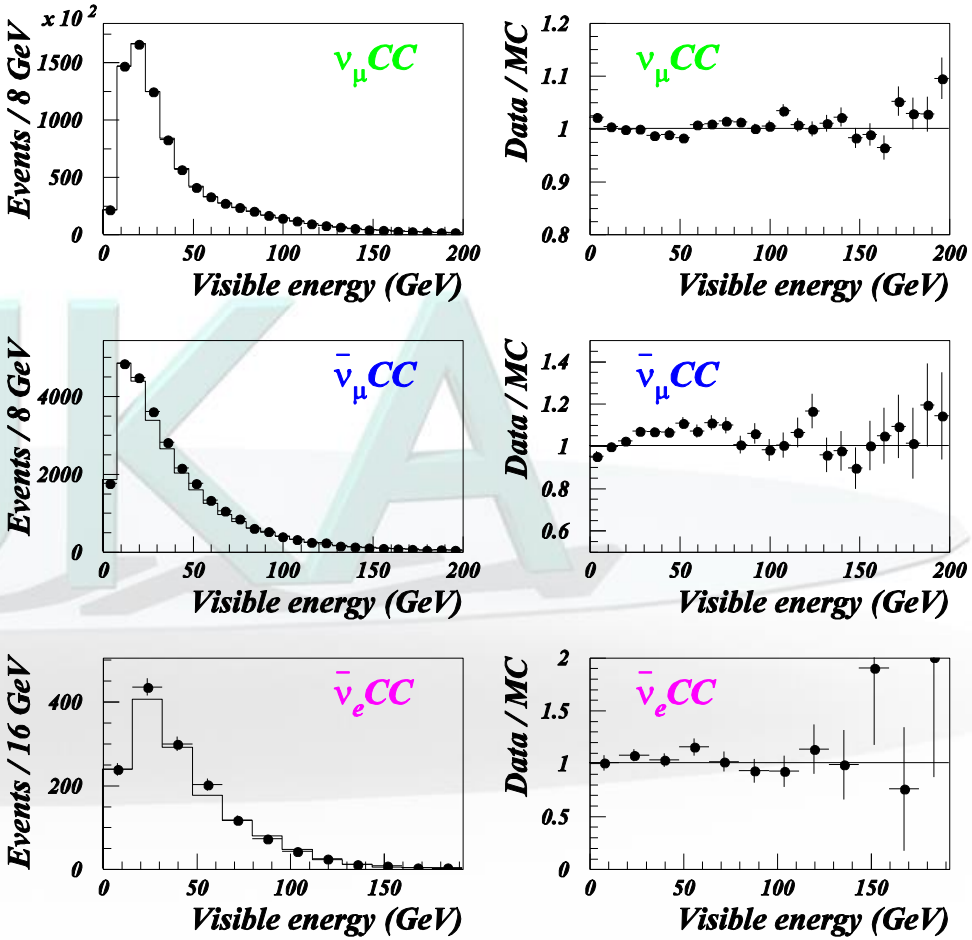
Accurate prediction of ν_e (K^+, K^0 and μ^+) which was the main background for the $\nu_\mu \rightarrow \nu_e$ search in NOMAD

Comparison with NOMAD Data

- prompt isolated μ in the final state
- prompt isolated e in the final state
- charge/momentum measurements
  - B = 0.4 T, $\Delta p/p \approx 4$ % at 1 GeV/c
- visible energy (hadrons + leptons)
  - $\Delta E/E_{e.m} \approx 3.5\%\sqrt{E(GeV)}$
- syst. errors on ν flux:
  - 7 % on ν_μ and ν_e
  - ν_e/ν_μ 4.2 % normaliz., 5 % E-dep.

nice agreement→ good K prod.





Control samples: ν_μ anti ν_μ .
CC ν_μ normalized to data