Study of the performance of the SPL-Fréjus Super Beam using a graphite target

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GDR neutrino, Strasbourg, 29 Oct 2009

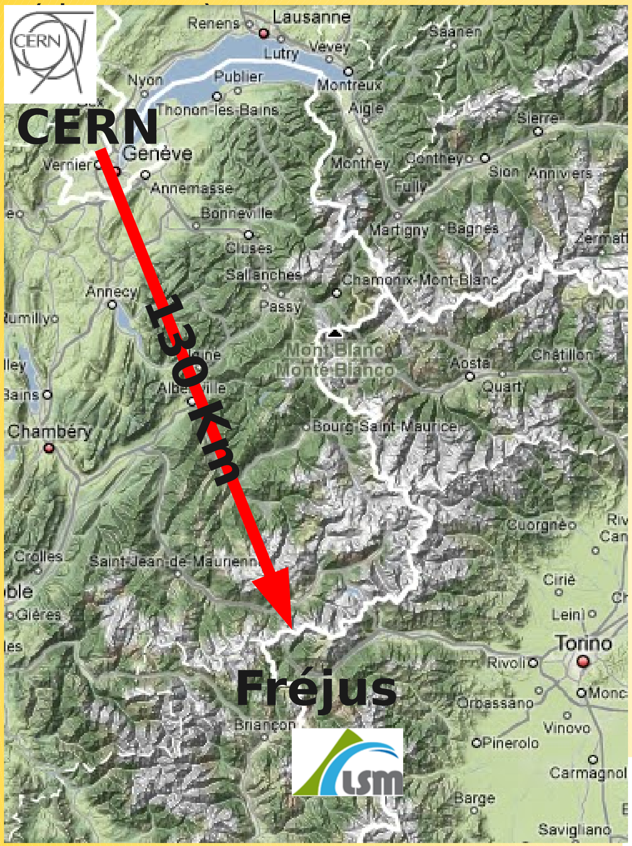
EURONU Working Package 2 (Super Beam)

- **The SPL-Fréjus Super Beam: general overview**
- **The graphite target option**
  - **energy deposition**
  - **mesons yields**
- **Fluxes and sensitivities**
- **Transition to GEANT4 and Horn optimization for a long target**
- **Updated fluxes and sensitivities**

Thanks to :
A. Cazes, M.Zito, J.E. Campagne, M. Mezzetto,

The SPL-Fréjus Super Beam

Being studied in EUROnu WP2 (beam), LAGUNA (far site) and MEMPHYS



- SPL p driver @ **4MW** (H- linac **E_k~ 4 GeV**)
- **L = 130 Km**
- Far Detector: **0.44 Mton Water Cherenkov**
- 1st oscillation maximum **E_ν ~ 260 MeV**

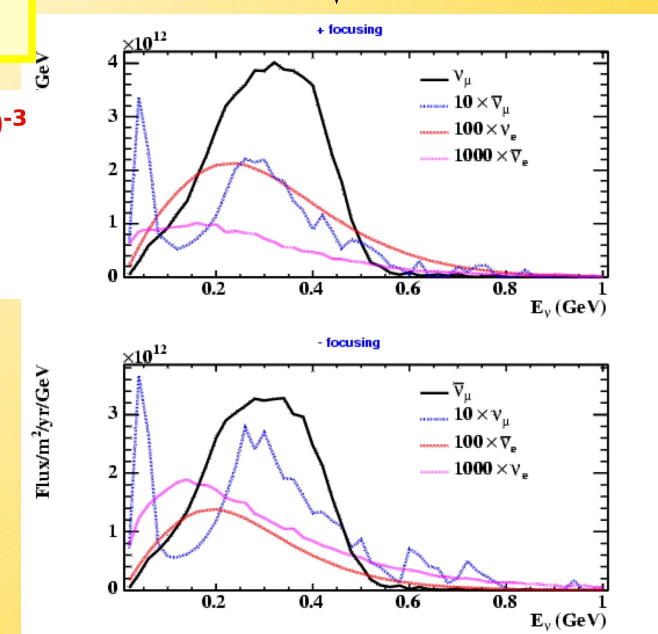
low E

- :) very few ν_e from K
- :) compact horn and tunnel
- :) good reconstruction in W.Ch.
  - ~ all elastic
  - σ_E: 43 MeV : [0.2-0.3] GeV
  - easy π^0 rejection

small L

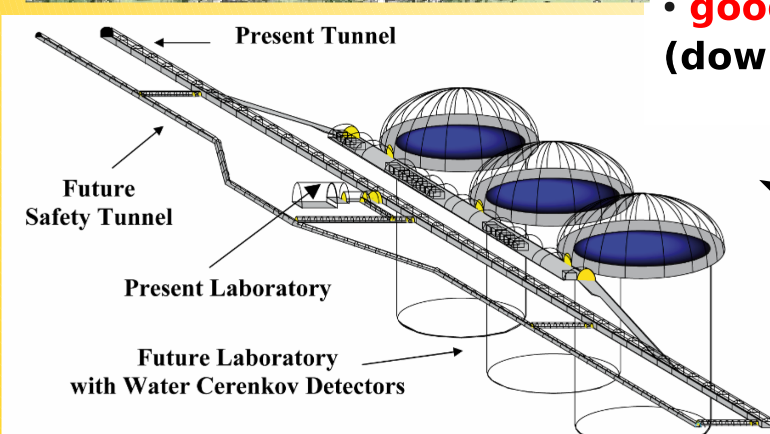
- :) High flux
- :) No matter effects : (
- : (mass hierarchy

"Narrow band" beam



- **$\sin^2 2\theta_{13}$ sensitivity limit @ ~ 10^{-3}**
- **good sensitivity to δ**

(down to $\sin^2 2\theta_{13}$ ~ 10^{-2})



MEMPHYS

multi purpose

p decay, atm-ν, SN-ν, ...

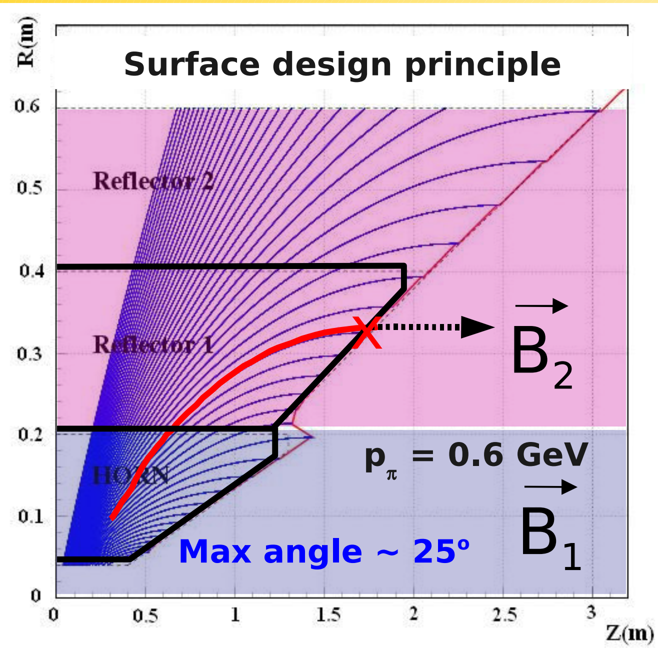
References to previous articles and more recent work

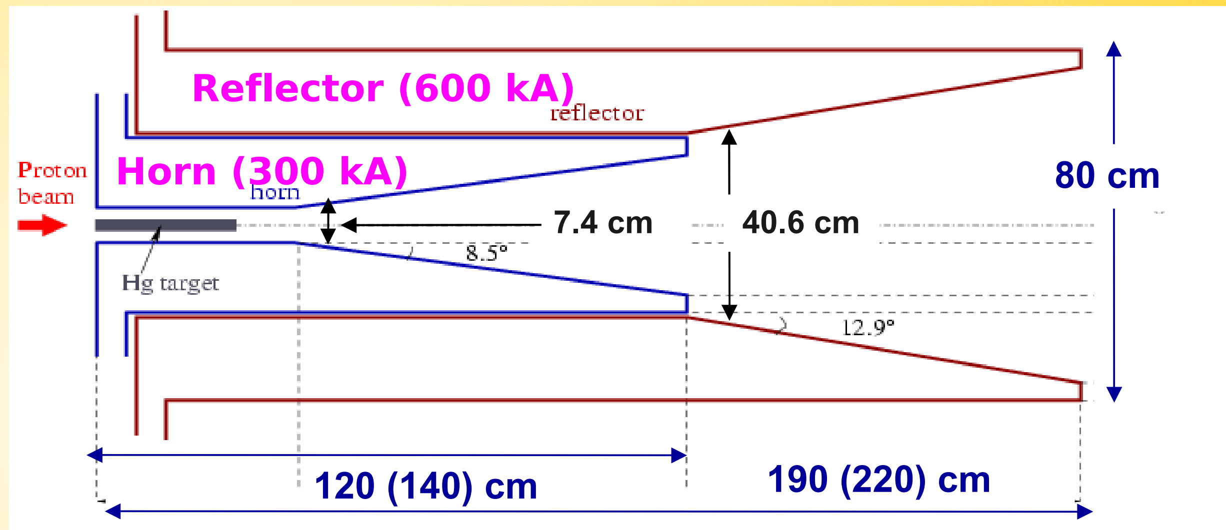
- M. Mezzetto *Physics potential of the SPL SuperBeam* J. Phys. G29 (2003),1781-1784, hep-ex/0302005.
- J.E. Campagne, A. Cazes. *The θ_{13} and CP sensitivities of the SPL-Fréjus project revisited*
- Eur. Phys. J. C45 (2006), LAL 04-102 October 2004. hep-ex/0411062v1
- J.E. Campagne, M. Maltoni, M. Mezzetto, T.Schwetz, *Physics potential of the CERN-MEMPHYS neutrino oscillation project* (2006), hep-ph/0603172

- NUFACT09 talk: http://nufact09.iit.edu/wg3/wg3_longhin-euronusuperbeam.pdf
- Poster @ CERN workshop “European Strategy for future neutrino physics” 1-3/10/09
- EUROnu WP2 indico page: http://indico.in2p3.fr/categoryDisplay.py?categId=203
- *Study of the performance of the SPL-Fréjus Super Beam using a graphite target* A. Longhin. www.euronu.org WP2-note

Focusing system

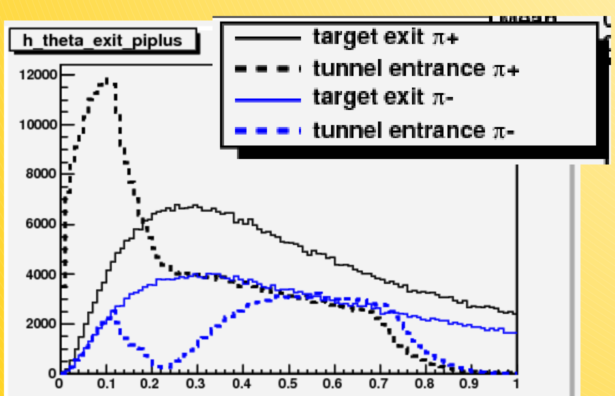
- Due to the low energy proton beam pions are mildly forward boosted ($<\theta_\pi> \sim 55°$)
  - -> **Target inside the horn** to recover collection efficiency





The outer conductor is placed where the slope becomes // to the beam (dr/dz =0)

all π of a certain p from a point-like source focused

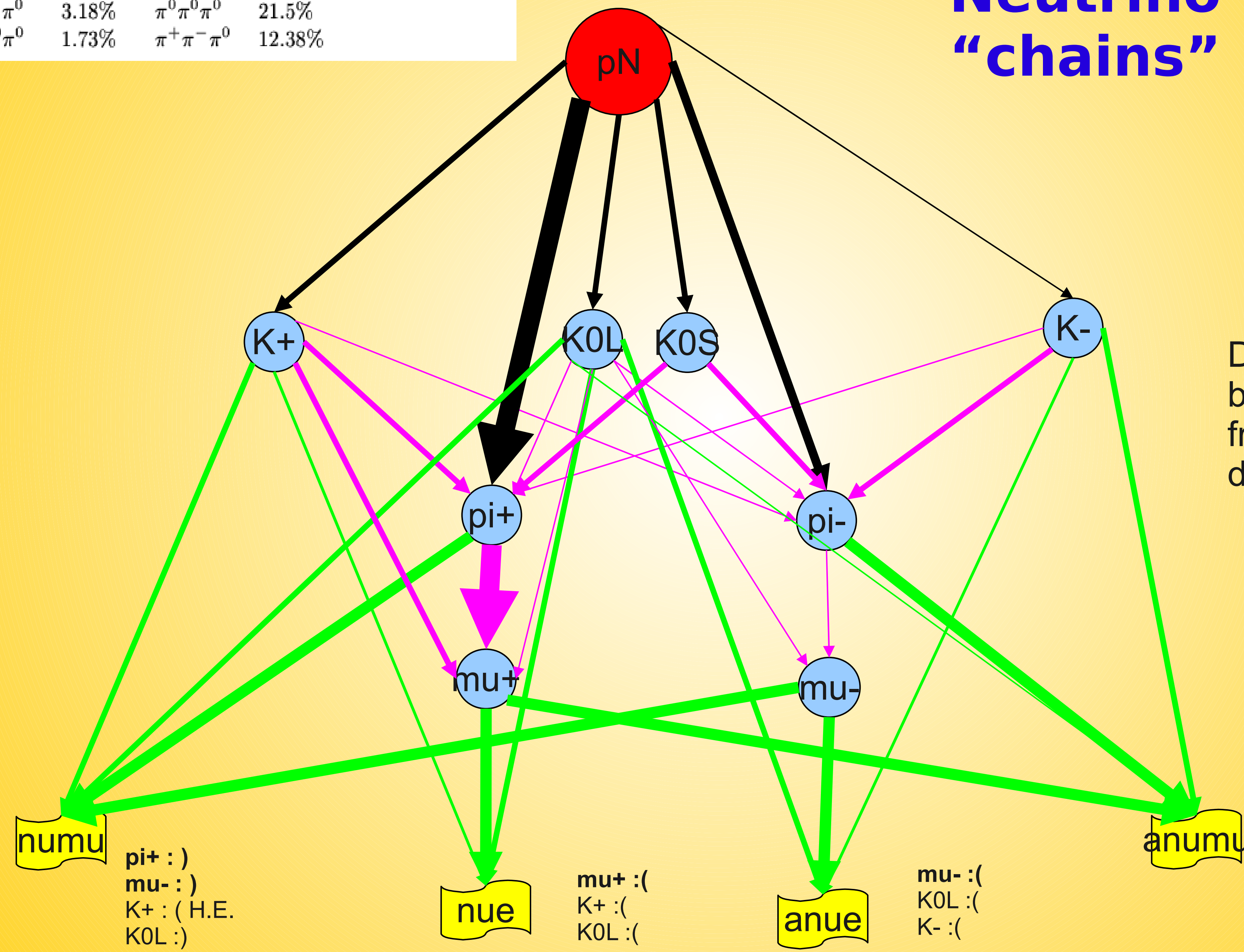


- i(h/r) = 300/600 kA
- pulsed @ 50 Hz
- Toroidal |B| ~ i / r
- B_1^{MAX} =1.5 T, B_2^{MAX}= 0.6 T
- 3 mm thick Al

Horn prototype at CERN (detailed geometry implemented in the Geant simulation)

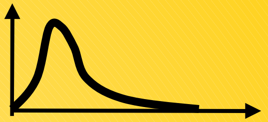
$K^{\pm}$		K_L^0		K_S^0	
$\mu^{\pm}\nu_{\mu}$	63.51%	$\pi^- e^+ \nu_e$	19.35%	$\pi^+\pi^-$	68.61%
$\pi^{\pm}\pi^0$	21.17%	$\pi^+ e^- \bar{\nu}_e$	19.35%	$\pi^0\pi^0$	31.39%
$\pi^{\pm}\pi^+\pi^-$	5.59%	$\pi^-\mu^+\nu_{\mu}$	13.5%		
$e^{\pm}\nu_e\pi^0$	4.82%	$\pi^+\mu^-\bar{\nu}_{\mu}$	13.5%		
$\mu^{\pm}\nu_{\mu}\pi^0$	3.18%	$\pi^0\pi^0\pi^0$	21.5%		
$\pi^{\pm}\pi^0\pi^0$	1.73%	$\pi^+\pi^-\pi^0$	12.38%		

Neutrino "chains"

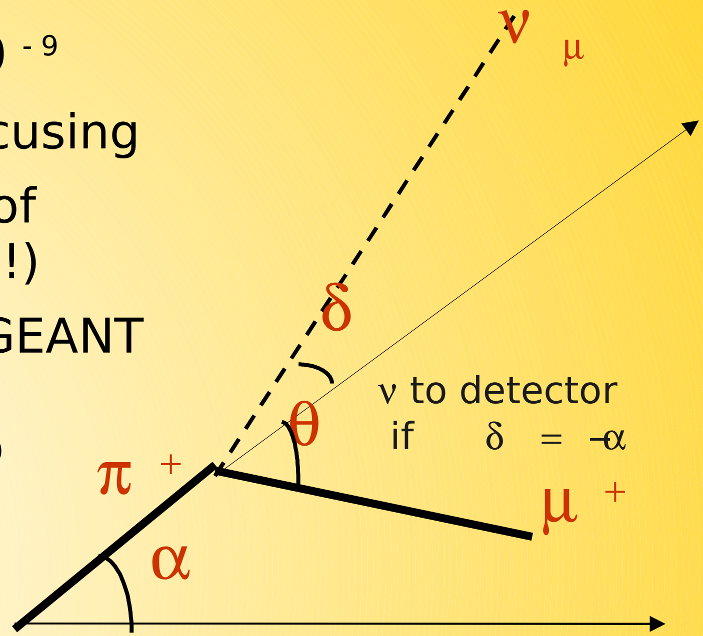


Dominant nue background from muon decays

Flux computation method



- Solid angle of detector seen from source: $A/4\pi L^2 \sim 10^{-9}$
- + small recovery: low energy -> small boost ->low focusing
- p.o.t. to be processed to have a reasonable statistics of neutrino reaching the far detector unfeasible ($\sim 10^{15}$!!!)
- -> Each time a pion, a muon or a kaon is decayed by GEANT calculate the probability for the neutrino to reach the detector and use as a weight when filling the neutrino energy distribution



2 body case

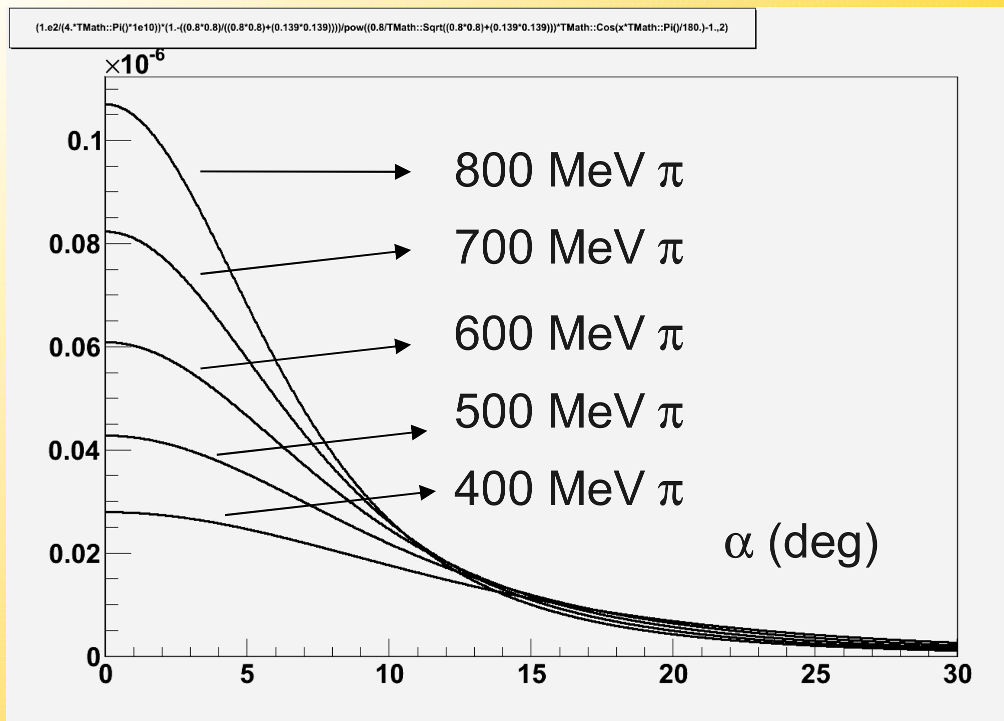
L : distance to detector
A : detector surface

$\pi^+ \to \mu^+ \nu_\mu$

$K^+ \to \mu^+ \nu_\mu$

Angle of π w.r.t. beam axis in the lab frame: α

$$\mathcal{P}_\pi = \frac{1}{4\pi}\frac{A}{L^2}\frac{1-\beta^2}{(\beta\cos\alpha - 1)^2}$$



"Narrower" around detector direction (α=0) as the boost (beta) increases

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μ and K3 body decays

Additional suppression of statistics with full simulation due to mu decay length (~ 2Km) wrt >> tunnel length (20-40 m)

L : distance to detector
A : detector surface

$$\mu^+ \to e^+ \nu_\mu \nu_e$$

Recipe: weight each μ with the probability of decay within the tunnel. Available energy for the ν in the lab. frame is divided into 20 MeV bins and a ν with energy in each bin is simulated and weighted with the probability to reach the detector (see formula).

$$\frac{d\mathcal{P}_\mu}{dE_\nu} = \frac{1}{4\pi}\frac{A}{L^2}\frac{2}{m_\mu}\frac{1}{\gamma_\mu(1+\beta_\mu\cos\theta^*)} \times \frac{1-\beta_\mu^2}{(\beta_\mu\cos\rho - 1)^2}\left[f_0(x) \mp \Pi_\mu^L f_1(x)\cos\theta^*\right]$$

Angle w.r.t. beam axis
of ν in μ rest frame: θ^*
of μ in the lab frame: ρ

$$x = 2E_\nu^*/m_\mu$$

	$f_0(x)$	$f_1(x)$
ν_μ	$2x^2(3-2x)$	$2x^2(1-2x)$
ν_e	$12x^2(1-x)$	$12x^2(1-x)$

$$\Pi_\mu^T = \frac{\gamma_\pi\beta_\pi}{\gamma_\mu\beta_\mu}\sin\theta^* \text{ and } \Pi_\mu^L = \sqrt{1-\Pi_\mu^{T2}}$$

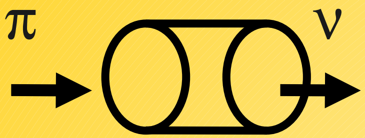
Π is the muon polarisation

K $\to$ 3 body

$$\frac{d\mathcal{P}_K}{dE_\nu} = \frac{1}{4\pi}\frac{A}{L^2}\frac{1}{m_K - m_\pi - m_l} \times \frac{1}{\gamma_K(1+\beta_K\cos\theta^*)}\frac{1-\beta_K^2}{(\beta_K\cos\delta - 1)^2}$$

Angle of K w.r.t. beam axis
in the lab frame: δ

Due to limited K statistics, K tracks emerging from the target are replicated many times (~100) and each event is weighted 1/N(replication). On top weighting for the probability to reach the detector is applied (differently depending on 2 or 3 body decay)

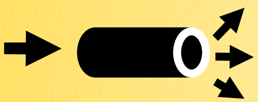


Decay tunnel

- Cylindrical filled with low -pressure air.
- Tested geometries: L=10-20-40-60 m / r =1-1.5-2 m
  - **L = 40 m , r =2 m** chosen as central value
  - Based on sensitivities. L>40 m gives ν_ε contaminations from μ decay which spoil gain given by increase of ν_μ statistics

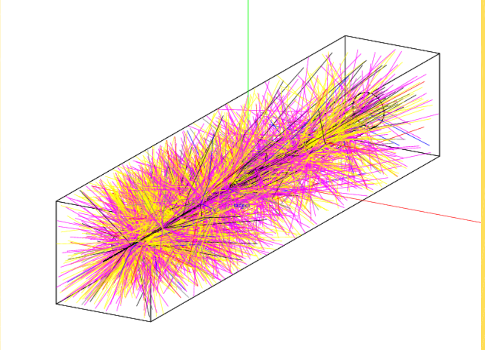
Decay lengths (m) @ 600 MeV

π	33.7
μ	3766
$K^{+/-}$	4.5
K^0_S	3.2
K^0_L	18.5



Target

- Cylindrical (~ 2 λ_I long)
  - **r = 0.75 cm**
  - **Liq. mercury (Hg)**: **L = 30 cm**



Simulation tools

new

Power dissipation / **mesons yield** / **π collection** / **ν fluxes** / **sensitivities**

Power dissipation	mesons yield	π collection	ν fluxes	sensitivities
FLUKA 2008.3 + GEANT4	FLUKA 2008.3*	GEANT3 GEANT4	GEANT3 GEANT4	GLoBES 3.0.14

new

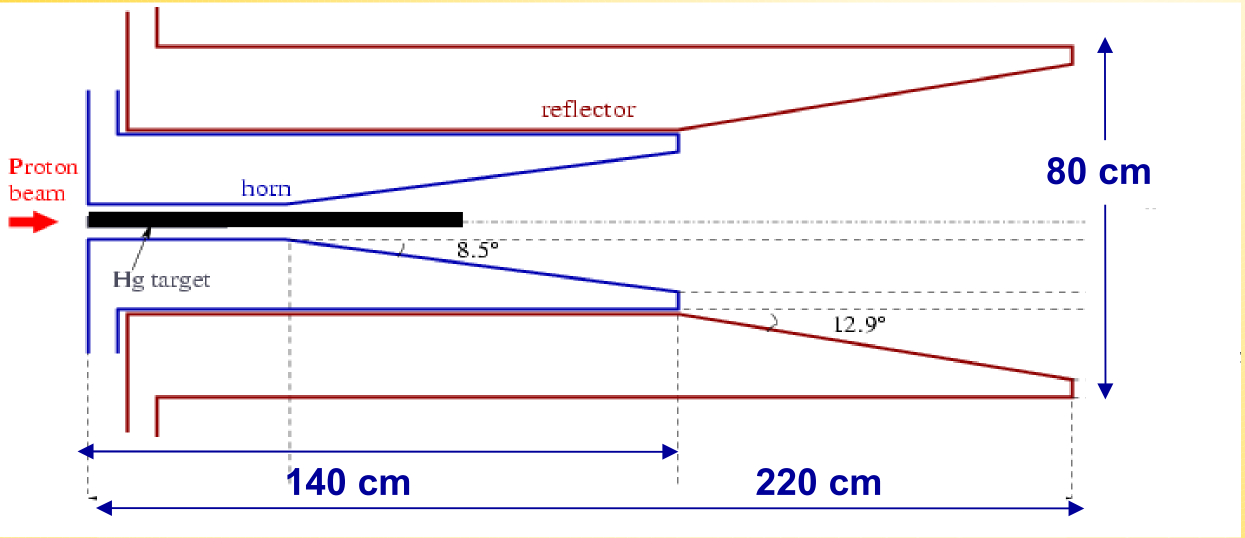
ν fluxes: probabilistic approach. Each decay is weighted with the probability of the ν to reach the far detector. Event duplication + weighting for μ and K decays.

A graphite target: motivations

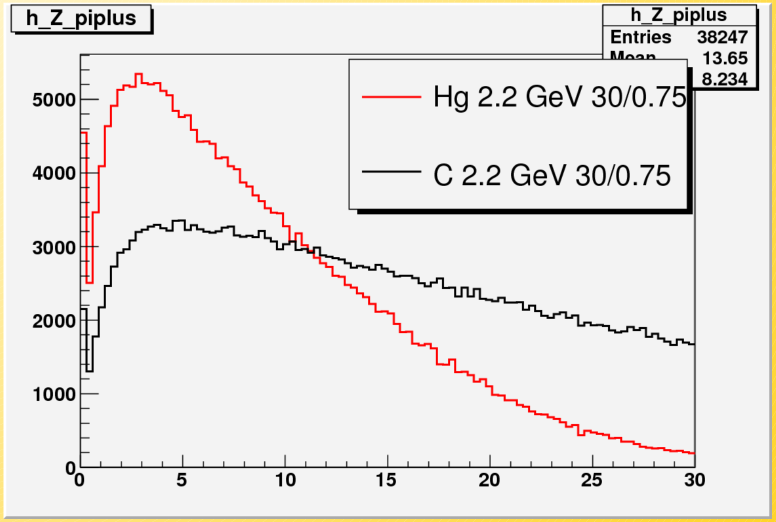
- Integration of the Hg jet within the horn not addressed
- Hg-Al chemical incompatibility
- No magnetic field for a standard magnetic horn to mitigate the explosion of the mercury jet (MERIT) as in the case of superconducting solenoids used for the neutrino factory design (no charge discrimination, not for a SB)
- Already used (i.e. T2K, He cooled, 750 kW)

  - First approach: replace the target keeping focusing + tunnel
  - L_{target} : 30 -> 78 cm (i.e. sticking to a ~ 2 λ_I target, same R)

Horn + Refl. + 78 cm long target

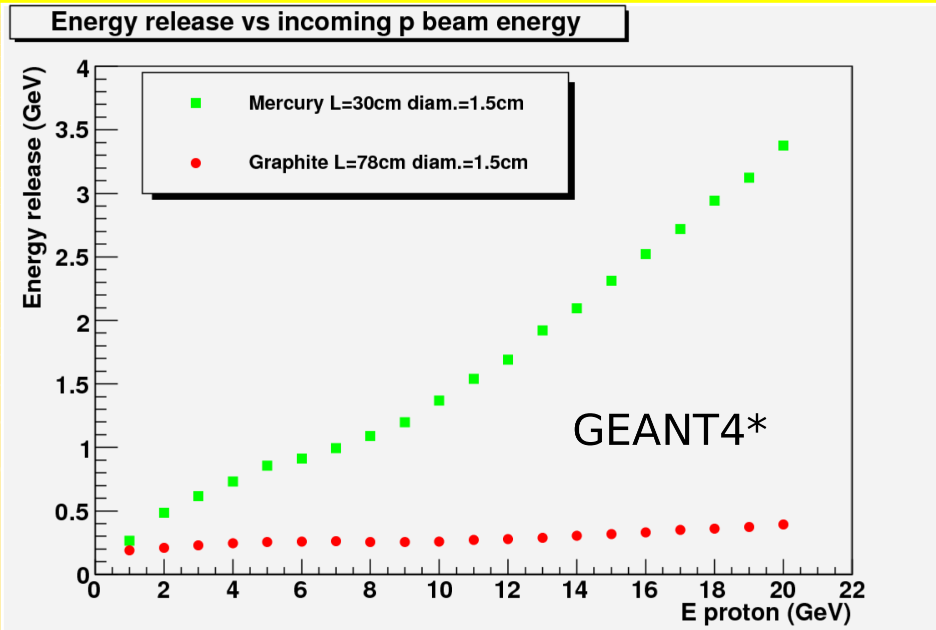


Z of pi+ exiting the target

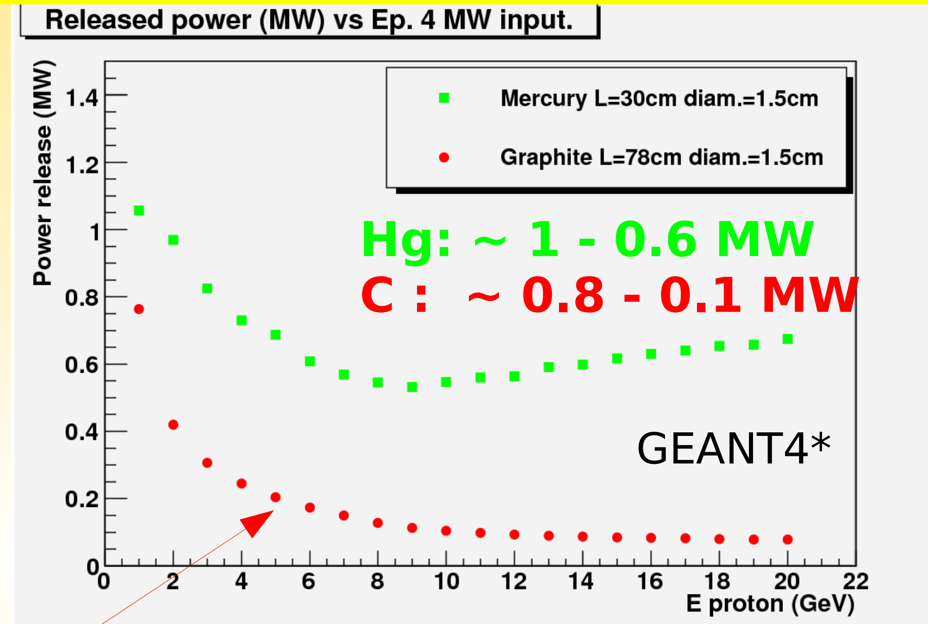


C vs Hg: energy deposition in the target

Mean energy deposition vs Ek(p)



Power release: 4 MW * $<E_{dep}>/E_k(p)$

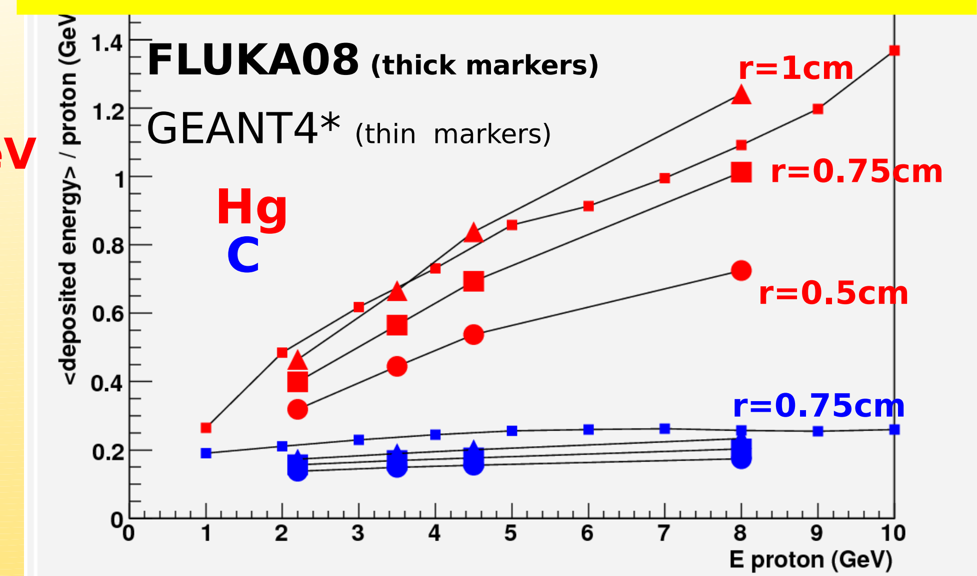


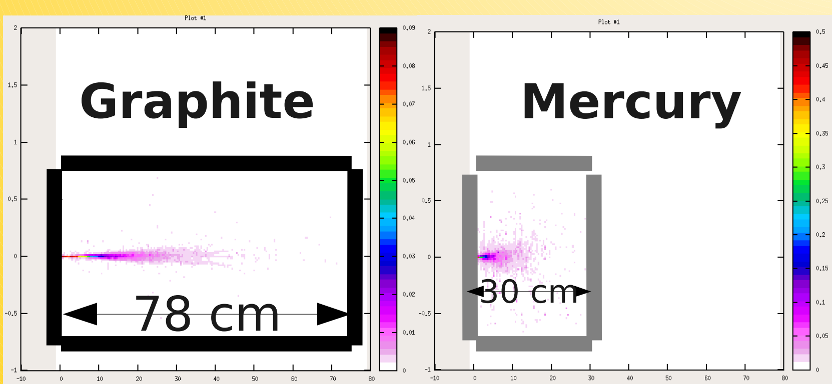
*with (hadronic “QGSP physics list”)

- G4 larger than FLUKA. ~ +10% for Hg
- General trend is confirmed

considerably lower for C! ~ 200 kW @ 5GeV

Mean energy deposition vs Ek(p)



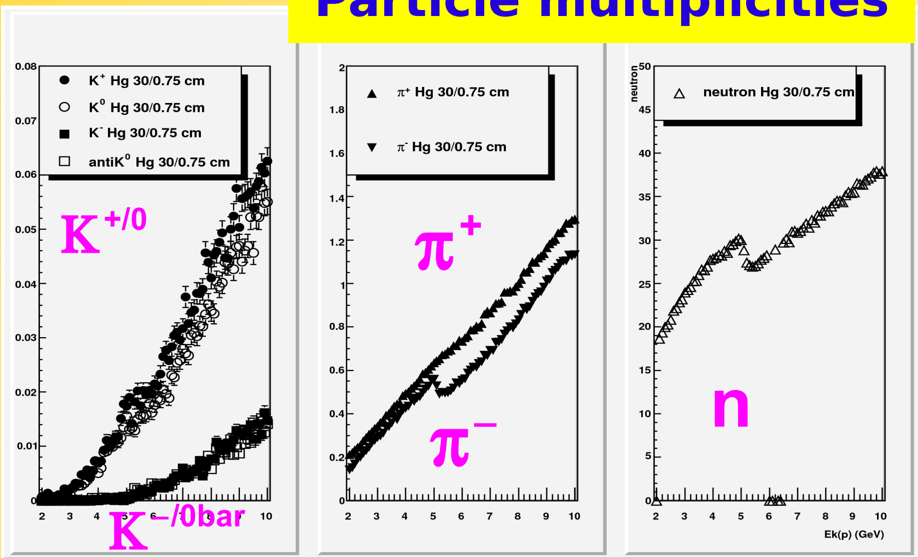


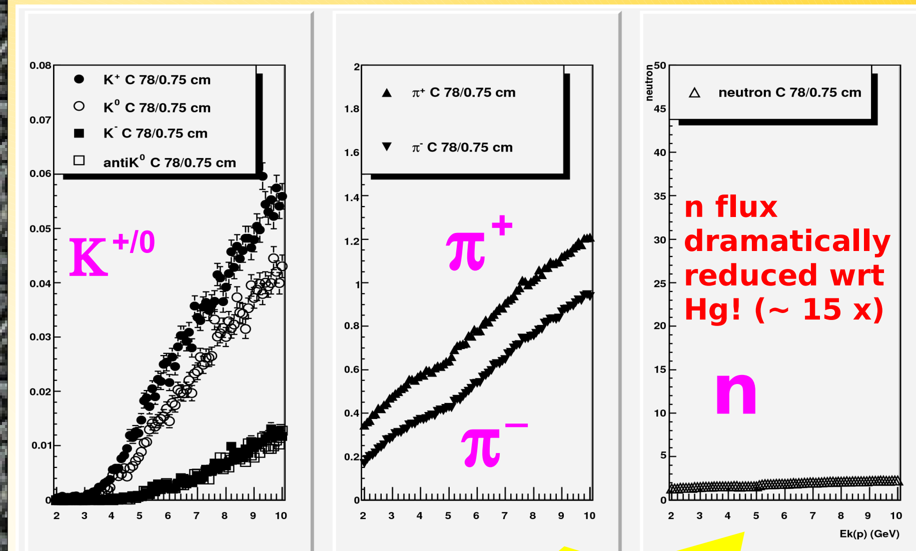
C vs Hg: meson production (FLUKA2008)

vs proton kinetic energy [2-10] GeV

4MW
- 1.13×10^{16} pot/s at 2.2 GeV
- 0.71×10^{16} pot/s at 3.5 GeV
- 0.55×10^{16} pot/s at 4.5 GeV
- 0.31×10^{16} pot/s at 8.0 GeV

Particle multiplicities





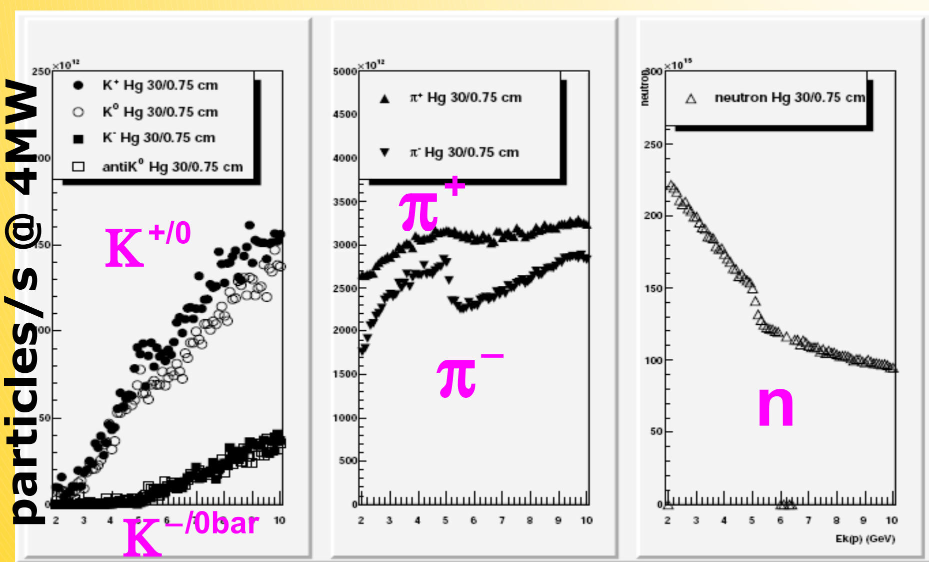
Mercury

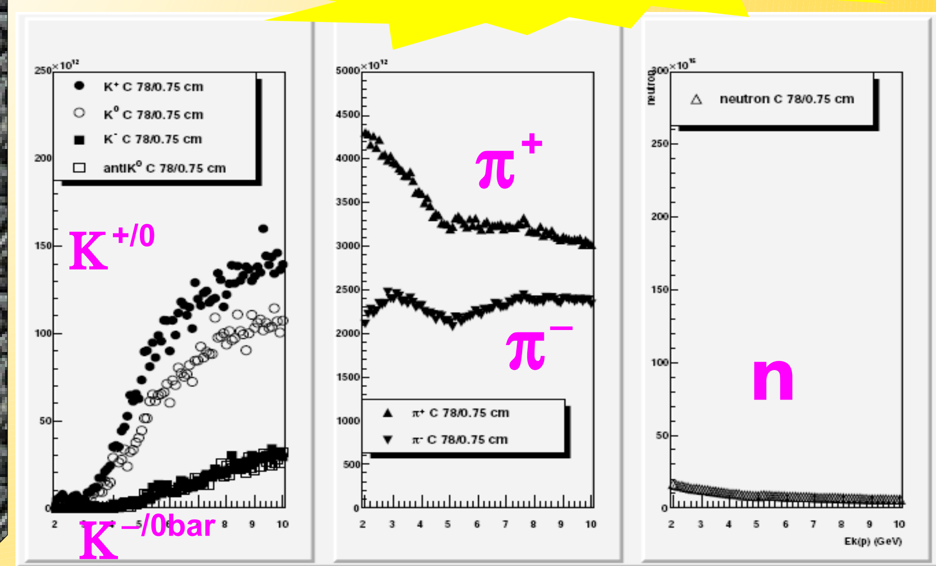
Particle yields

Graphite

Same vert. scale

particles/s @ 4MW





Pion yields comparable, neutron flux reduced by ~ x15 with C !!

C vs Hg: ν fluxes

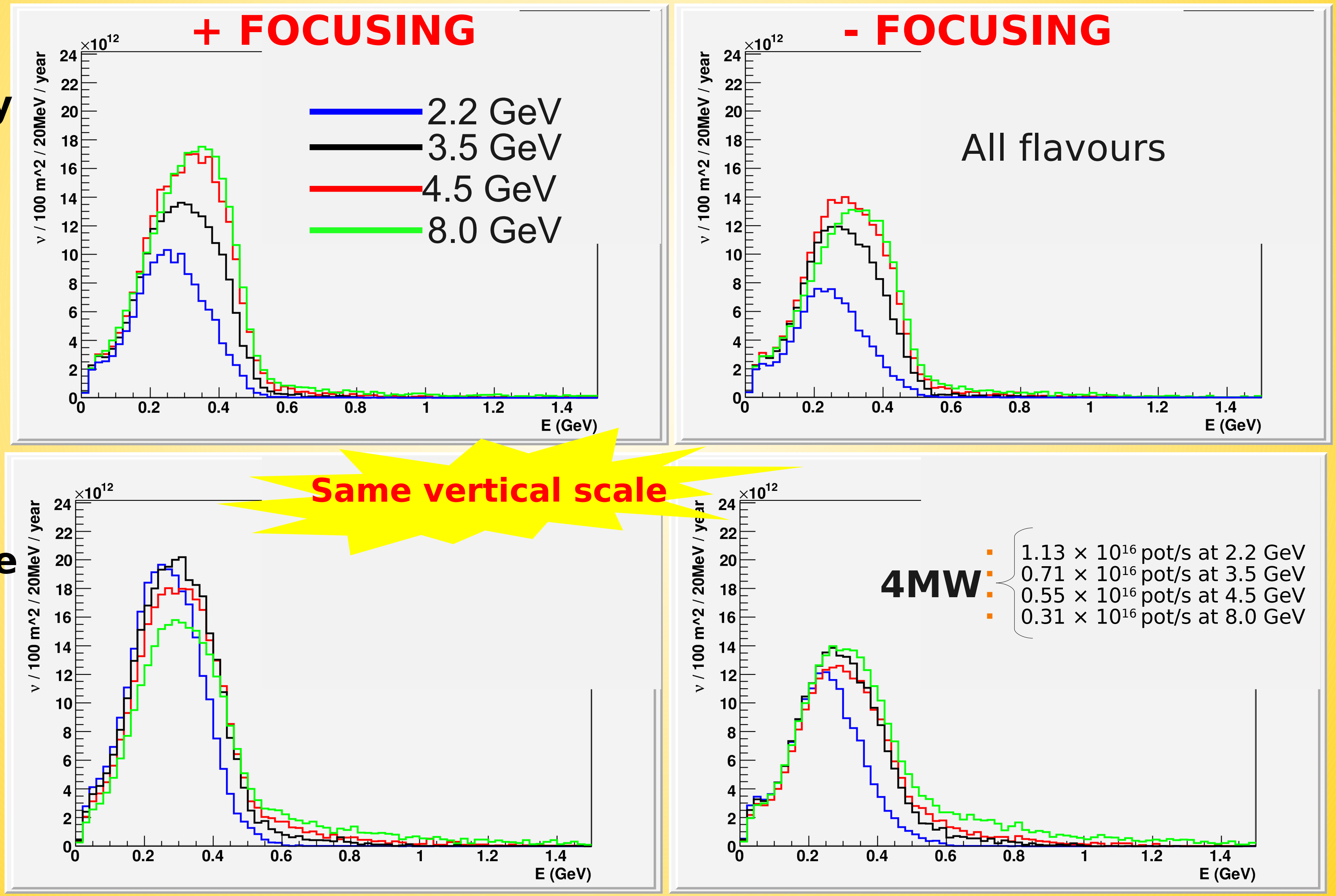
Minimal change approach

- Standard Horn
- Geant3 simulation
- 30 cm Hg->78 cm C (FLUKA)

- pion yield trends are reflected in fluxes despite non optimized focusing for long C target
- Fluxes from C and Hg are comparable
- higher high energy tail for C due to not optimized focusing

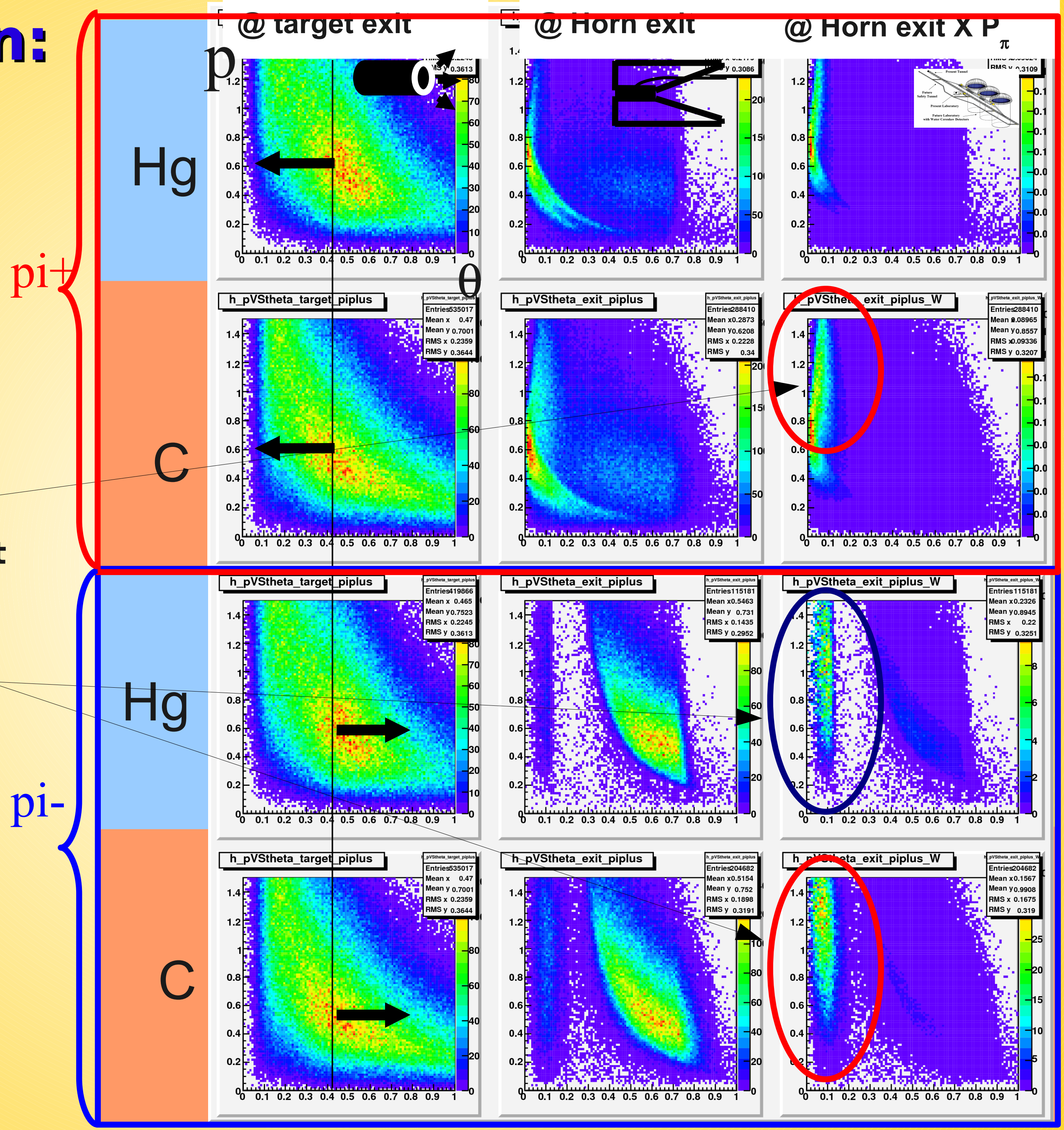
Mercury

Graphite



Pion collection: Hg-C

- p vs θ plots
- Positive focusing (negative defocusing)
- Carbon:
  - focused pi+ less “monochromatic” (tail at high momentum)
  - larger fraction of not defocused pi-
- 4.5 GeV



probability to reach the far detector

$$\mathcal{P}_\pi = \frac{1}{4\pi}\frac{A}{L^2}\frac{1-\beta^2}{(\beta\cos\alpha - 1)^2}$$

C vs Hg: 3σ sensitivity on θ_{13} vs δ

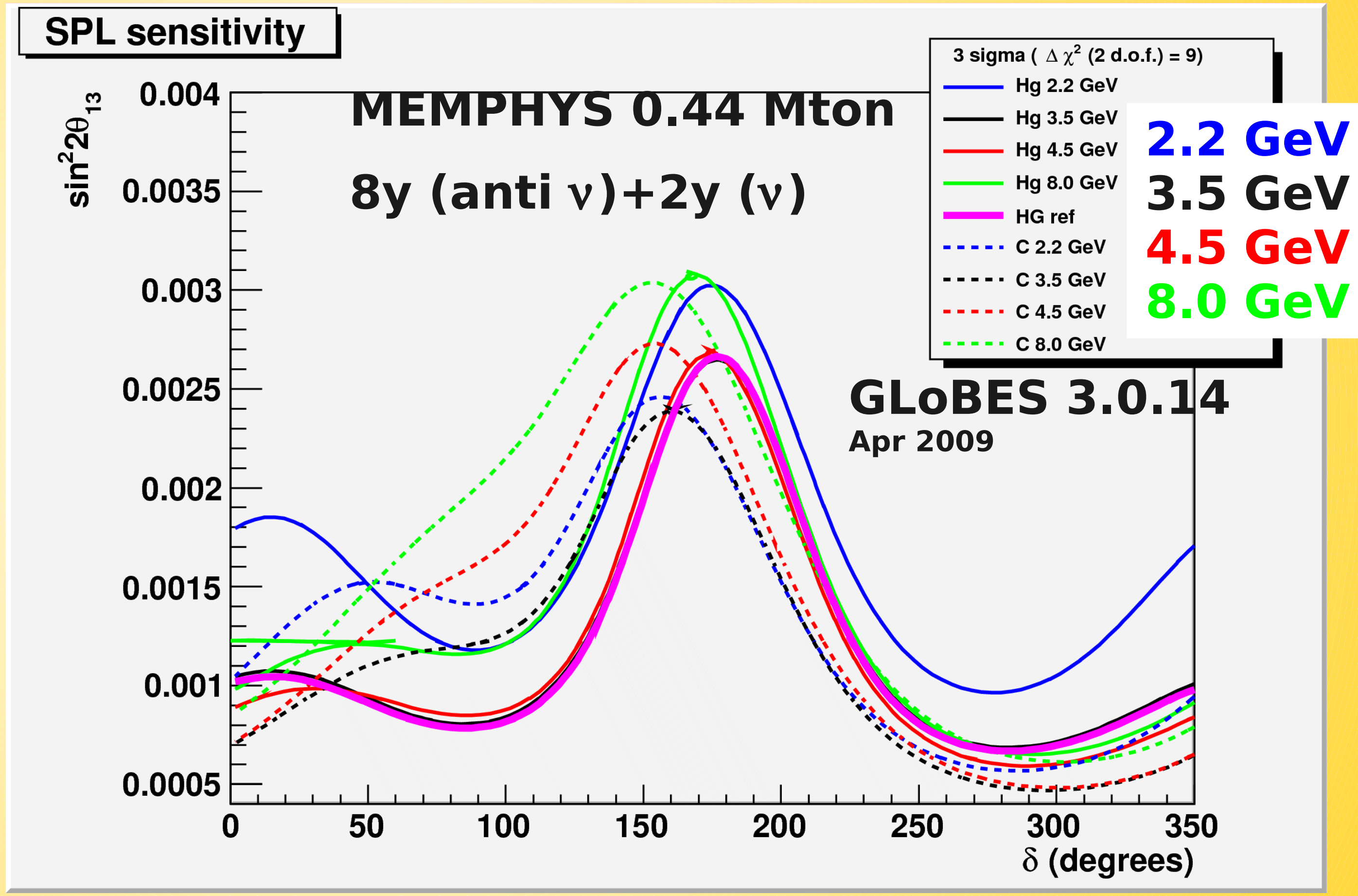
Carbon (- - - - - - -) Mercury (———)

Color codes: proton energies

- **graphite limit worse in the low δ region (driven by anti-ν running)**
- **related to rising ν_e contamination in the anti-ν beam from not defocused $\pi^+ \to \mu^+$. Effect important in anti-ν running due to $\pi^+ > \pi^-$ & $\sigma(\nu) > \sigma(\text{anti-}\nu)$**
- **→ let's minimize wrong charge pions !**

$$\pi^- \to \mu^- \, \bar{\nu}_\mu$$
$$\searrow e^- \, \bar{\nu}_e \, \nu_\mu$$

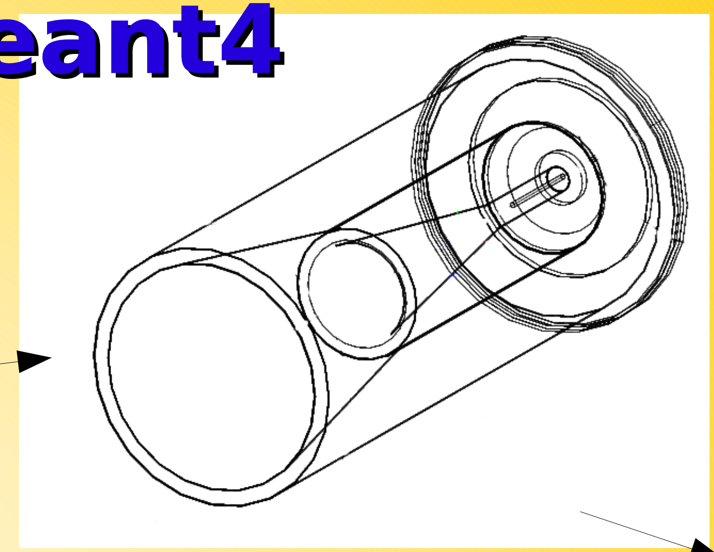
$$\pi^+ \to \mu^+ \, \nu_\mu$$
$$\searrow e^+ \, \nu_e \, \bar{\nu}_\mu$$



AEDL file SPL.glb in GloBES (with M=0.44Mton)
J. Phys. G29 (2003),1781-1784

→ Horn optimization for a long target

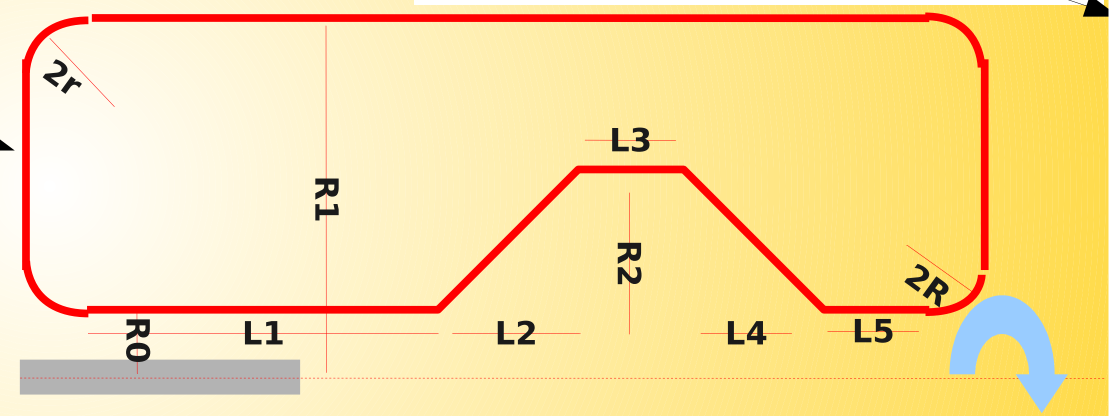
New simulation with Geant4



The full simulation has been recently migrated **from Geant3 to Geant4**

2 geometry implementations:

- 1) the **standard horn** reproducing the existing CERN prototype
- 2) a new **parametric model** implemented (MINIBOONE inspired)



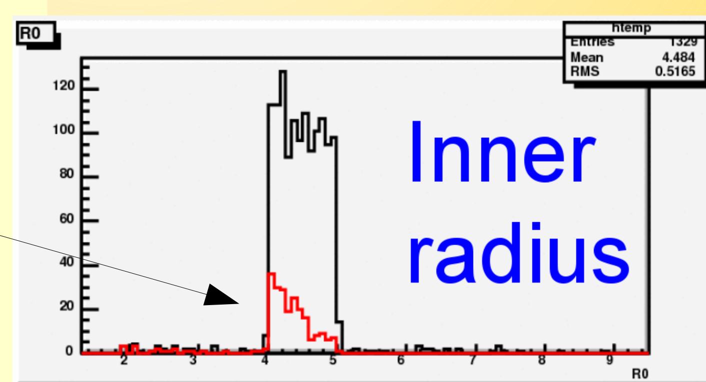
Better wrong charge pion rejection (more "forward closed") and **higher mean neutrino energy**

Flexible enough to reproduce also standard conical geometry

"Heuristic" approach to find favorable geometries based on the generation of **random configurations** using the horn parametric model

The resulting fluxes are **selected** according to quality parameters (ν_μ normalization, $\bar{\nu}_\mu$ contamination, mean energy, energy spread)

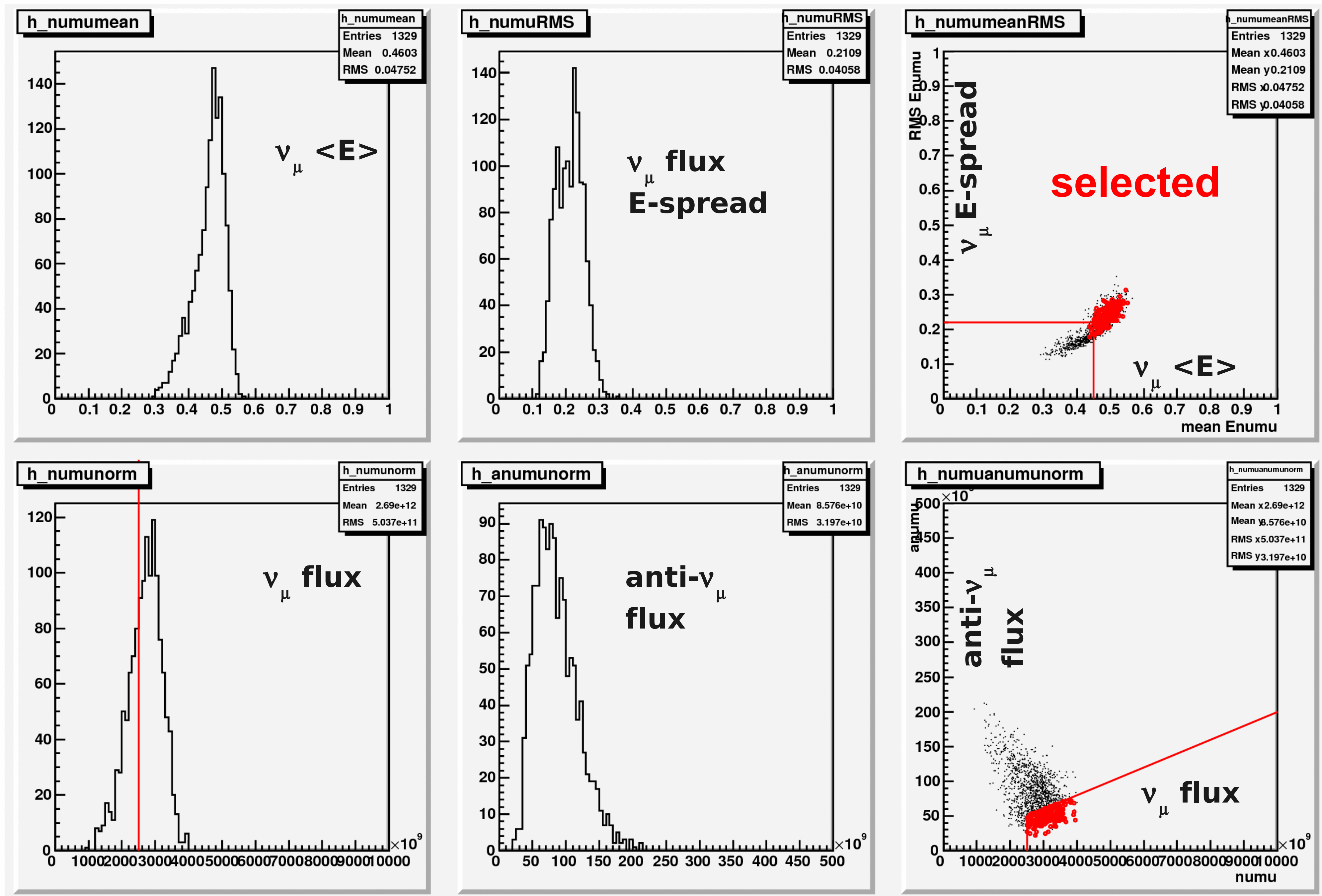
Randomly generated
Accepted after cuts on spectra



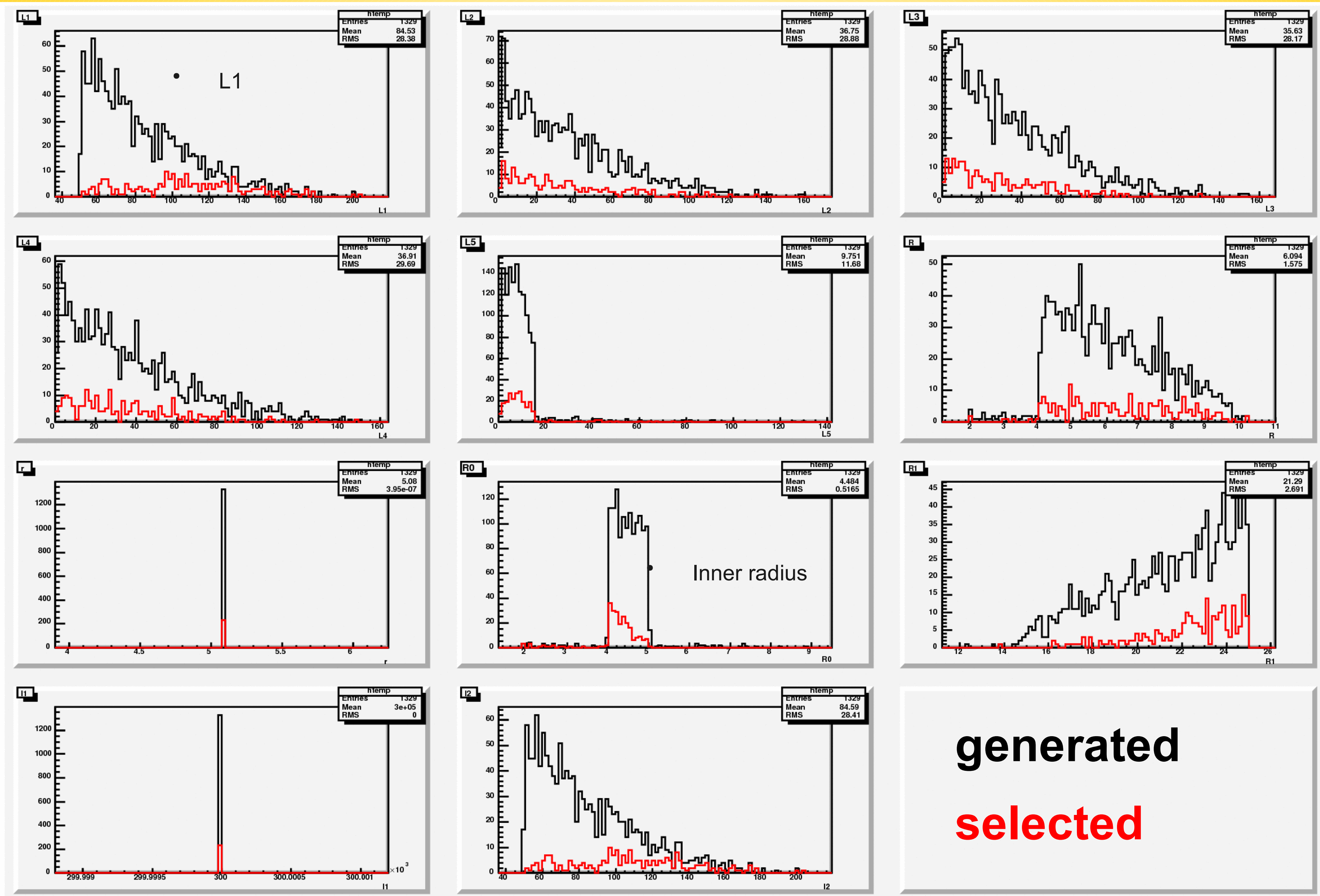
9 parameters fully accessible from external macro file

```
#
/SB/det/HornDesign 2
/SB/det/Horn_L1 57.3895 cm
/SB/det/Horn_L2 63.8771 cm
/SB/det/Horn_L3 10.797 cm
/SB/det/Horn_L4 16.0441 cm
/SB/det/Horn_L5 8 cm
/SB/det/Horn_R 7.16565 cm
/SB/det/Horn_r 5.08 cm
/SB/det/Horn_R0 4. cm
/SB/det/Horn_R1 20. cm
/SB/det/Horn_R2 16. cm
/SB/det/Horn_I1 300000 ampere
#
```

Horn configurations ranking (example)



Distributions of the horn geometrical parameters

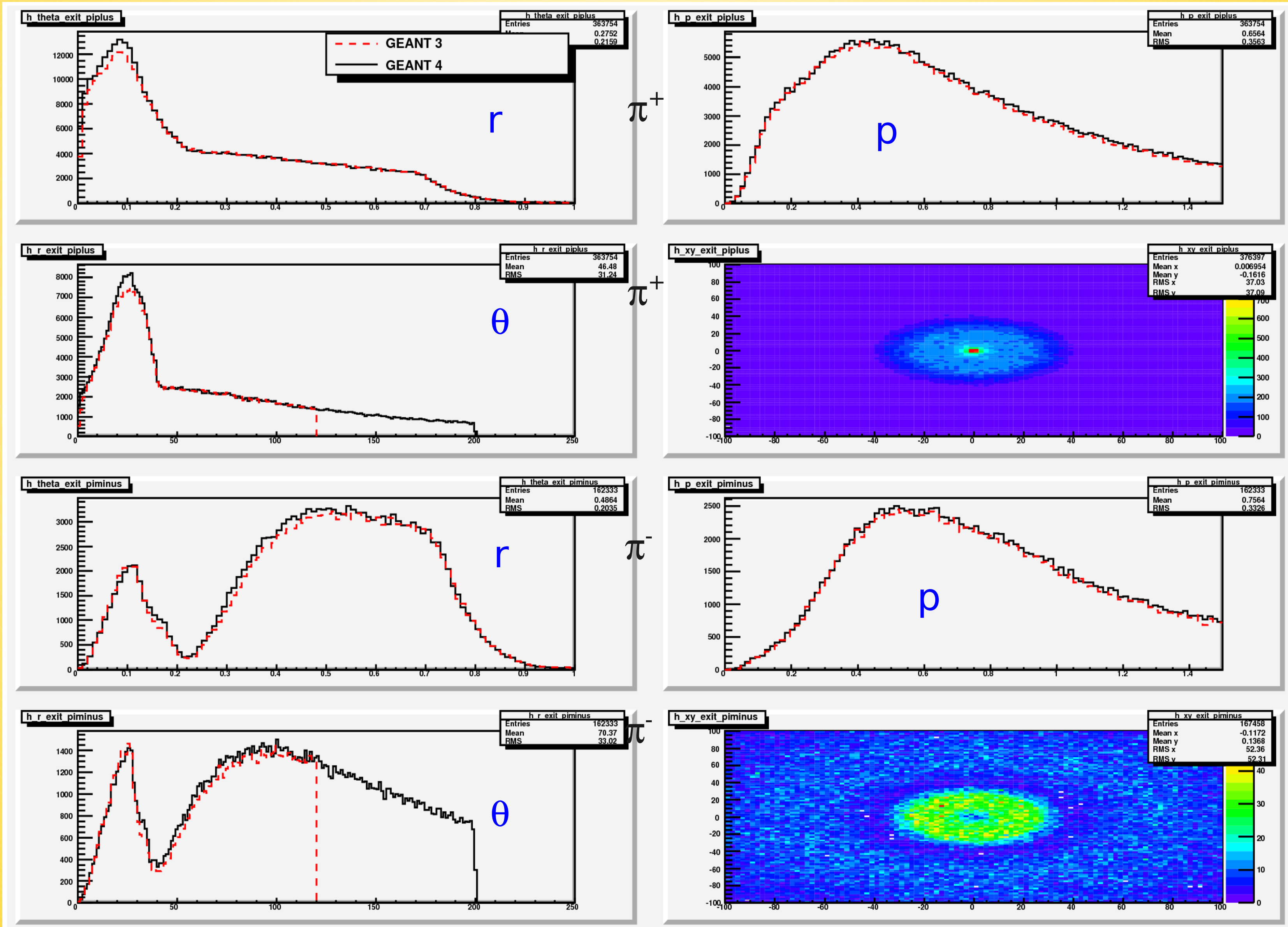


GEANT3-4 comparison with standard horn (I)

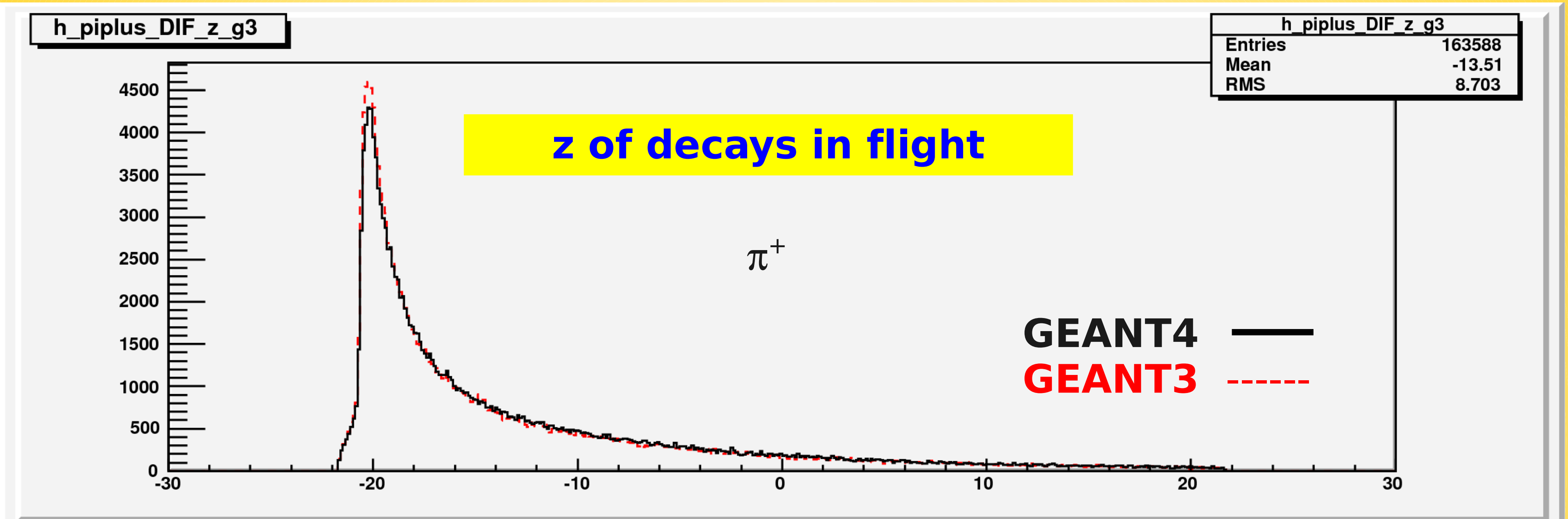
GEANT4 ——

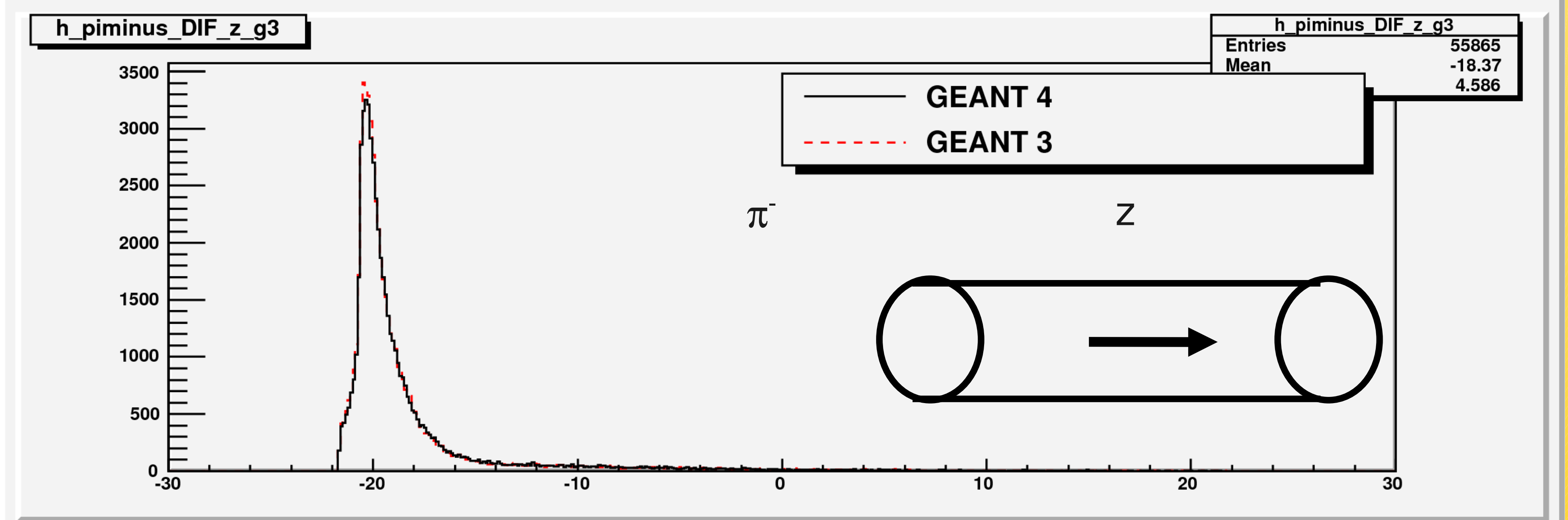
GEANT3 - - - - - -

Parameters of pions at tunnel entrance

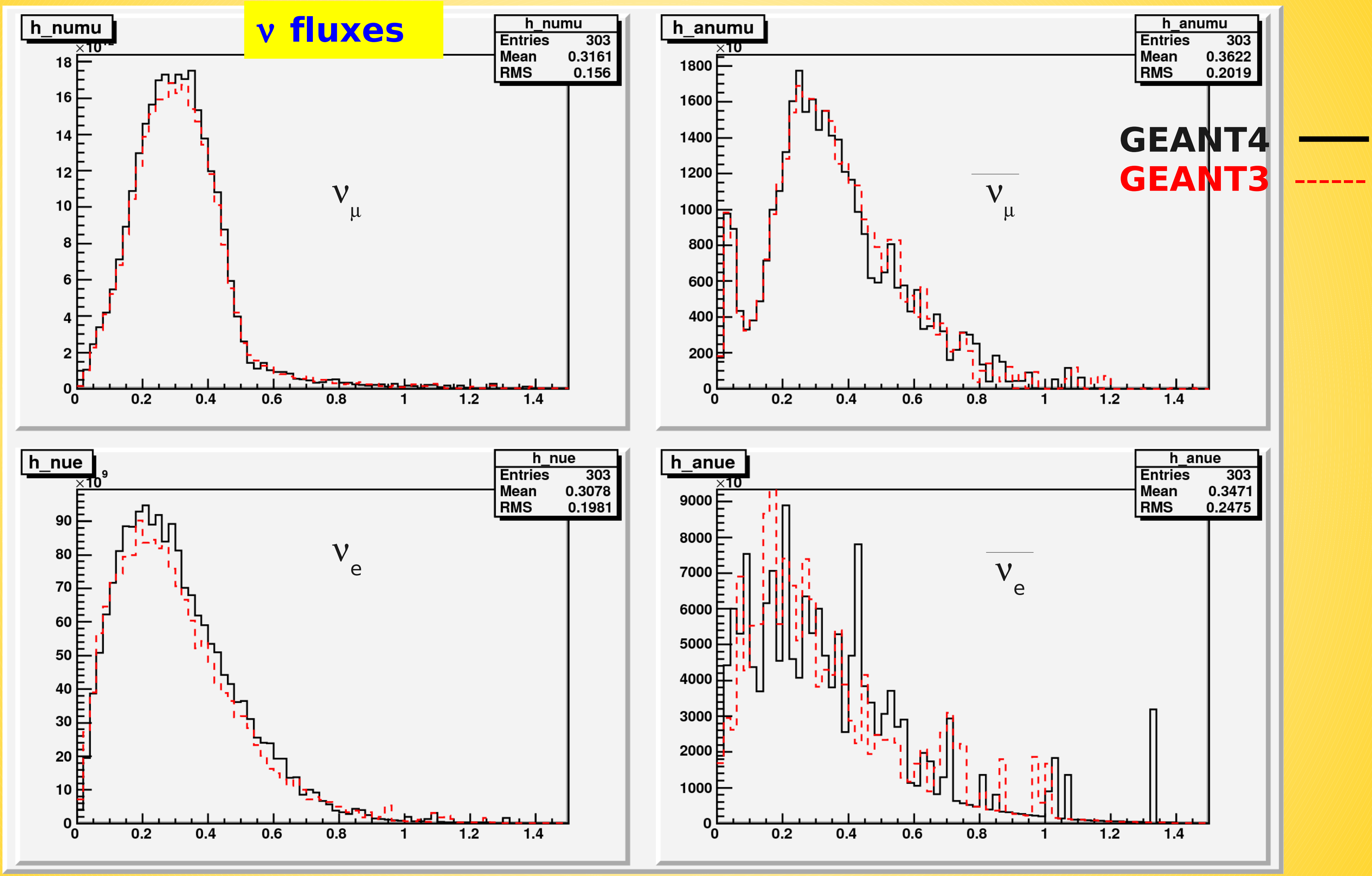


GEANT3-4 comparison with standard horn (II)





GEANT3-4 comparison with standard horn (III)

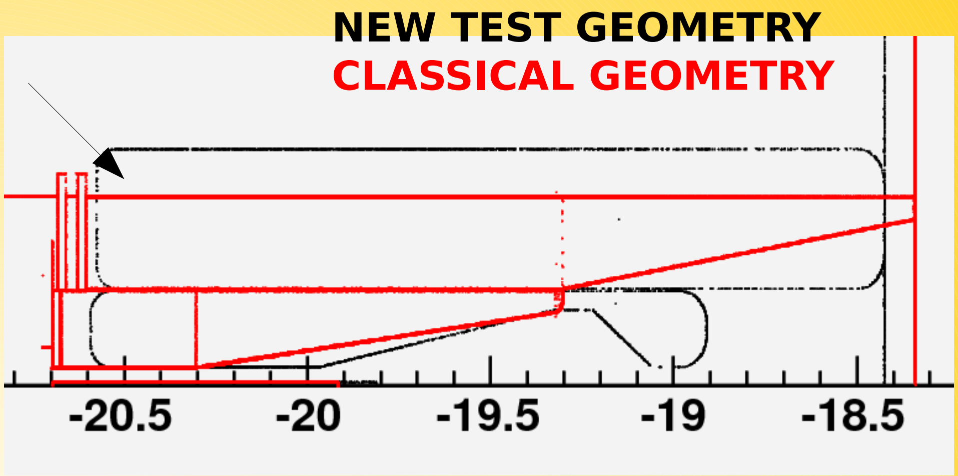


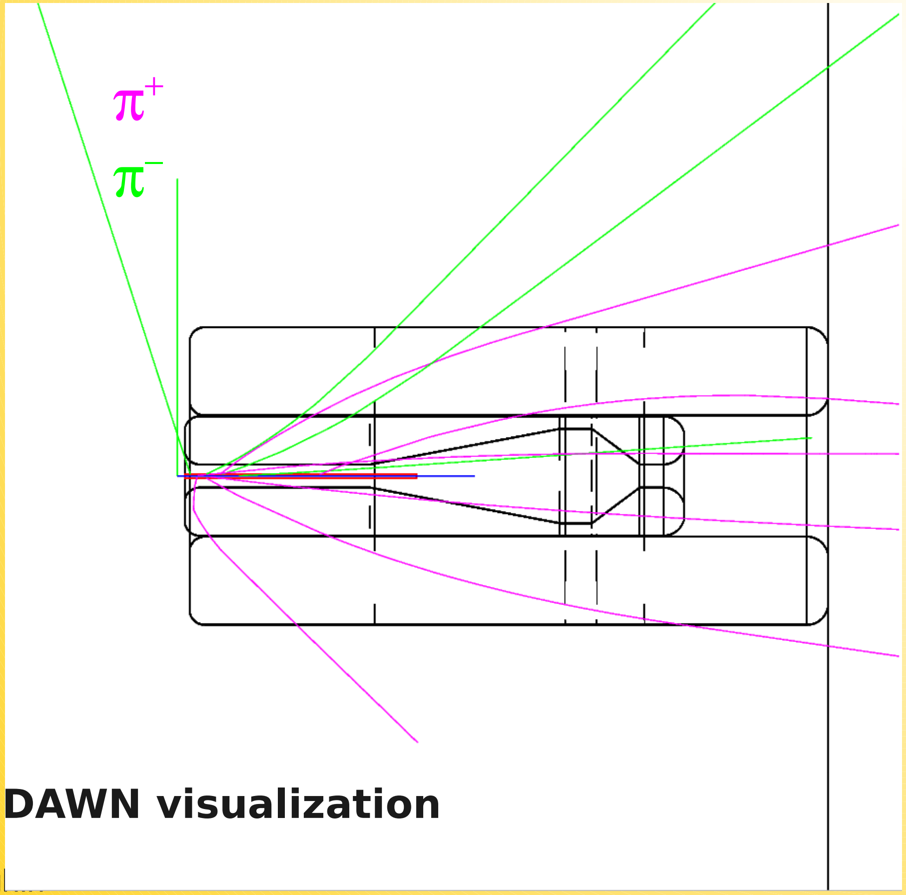
Good agreement between the two simulation programs

A new test horn

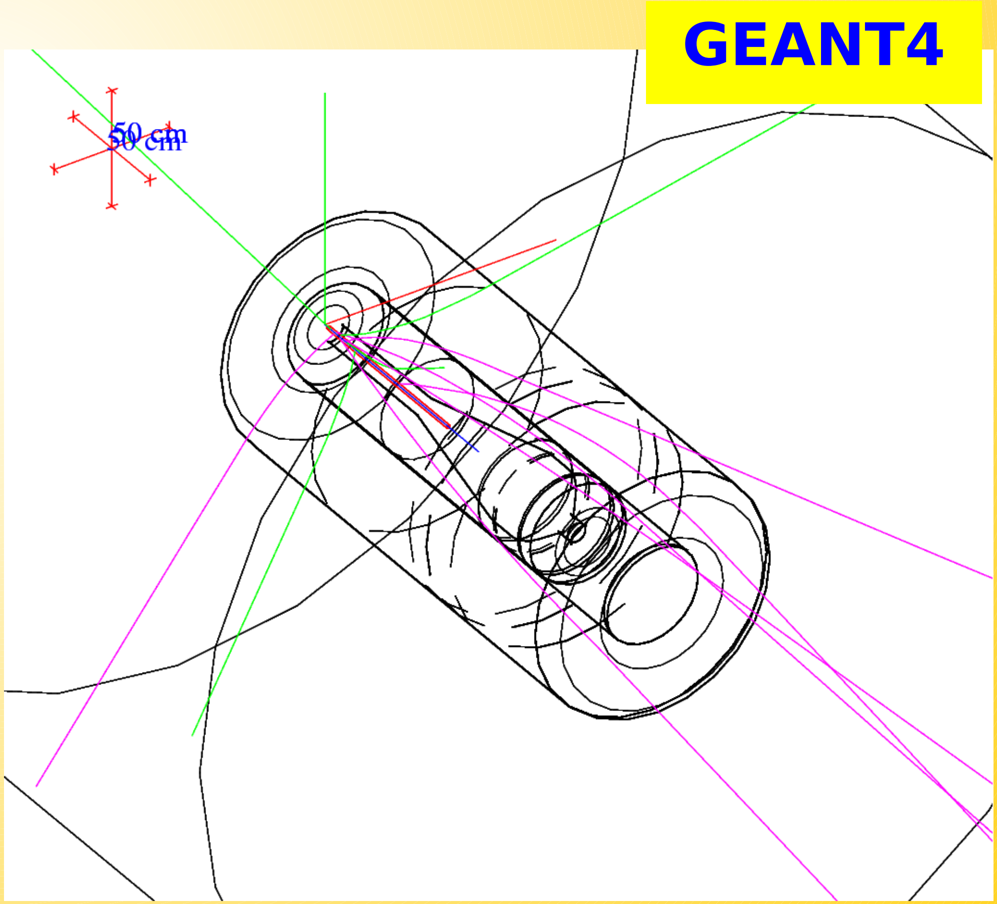
- Only **mildly "tuned".**
  - "found" by "random search" with limited samplings and preliminary selection criteria on ν-fluxes.
- **Thicker reflector** (+10cm)
- **Forward "end-cap"** to "sweep away" wrong charged forward going pions
- Usual currents (300+600 kA)

Hit maps (r,z) plane





•DAWN visualization

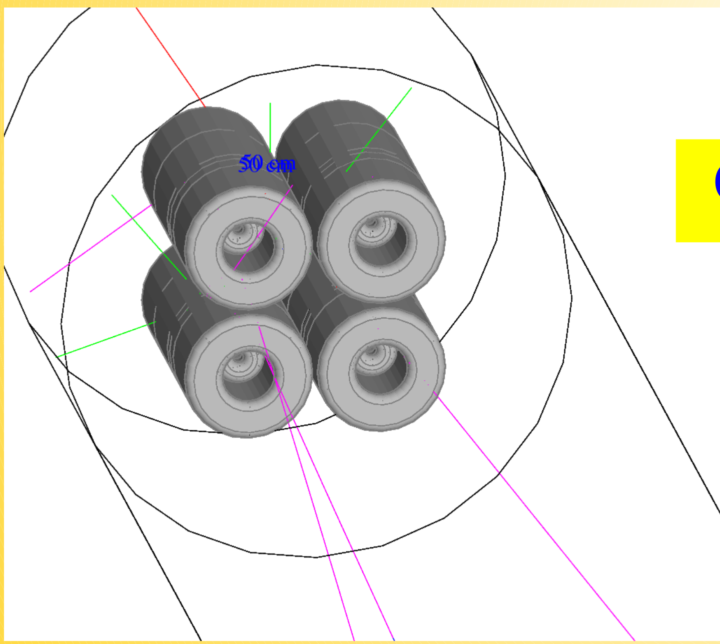


The 4-horns scenario

Reduced **stress** on target via
- **lower frequency** (12.5 Hz) **or**
- **lower p-flux** (1 MW)

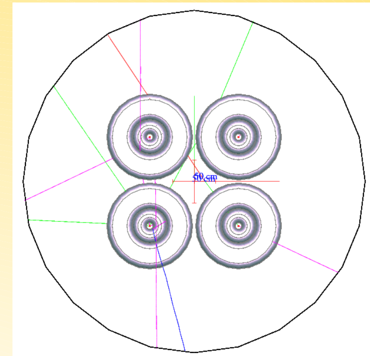
depending on injection strategy

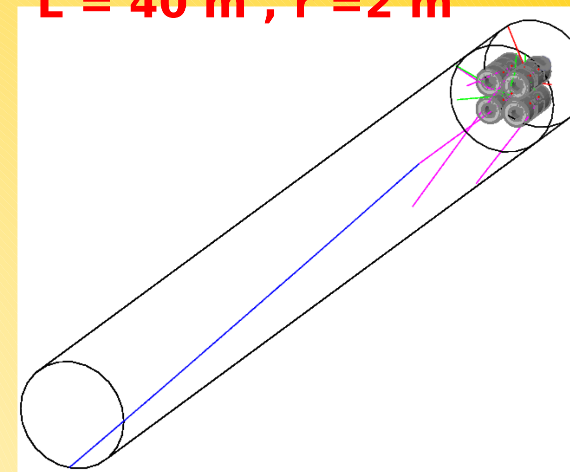
Profits of **horn compactness** (r~0.5m)



GEANT4

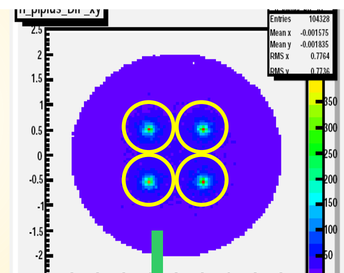
L = 40 m , r =2 m

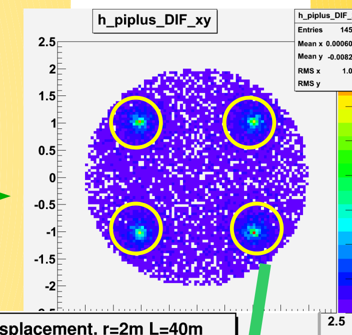




Baseline configuration with horns as "central" as possible

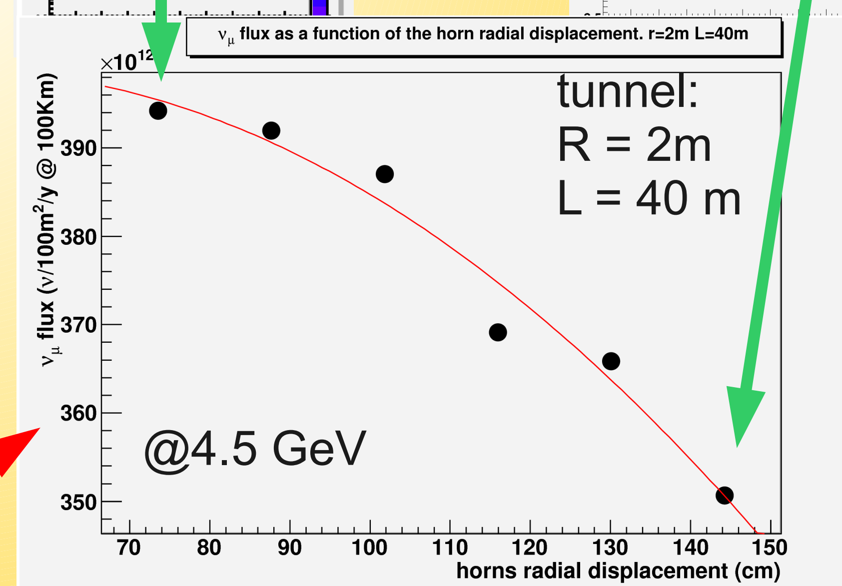
Worst case





ν_μ

-13%

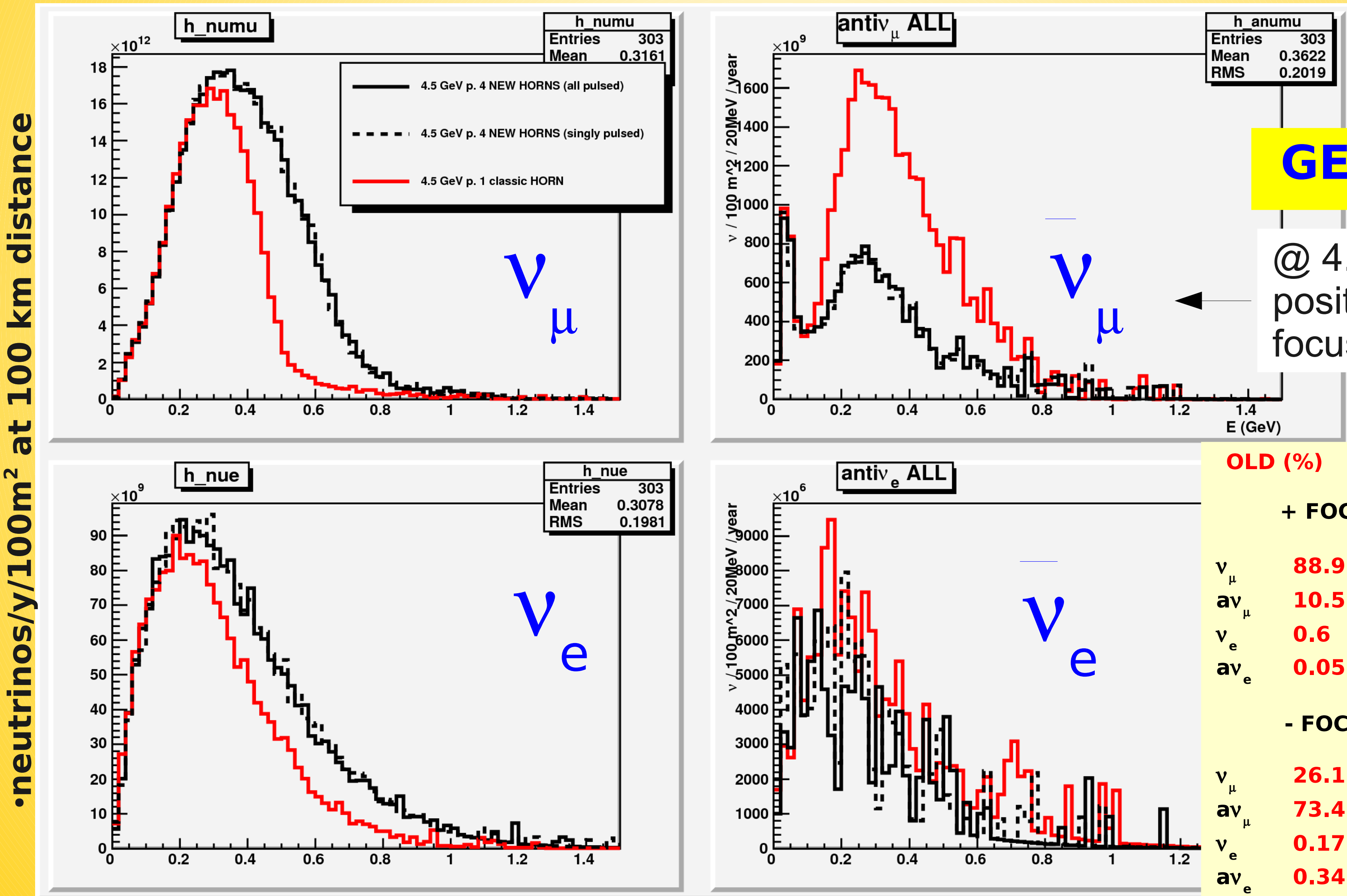


Small flux loss even up to big lateral displacements.

Fluxes: new VS old horn

Carbon target
new horns / old horn

- **gain ν_μ at higher energies**
- **Effectively suppressed contributions from wrong charge pions (more than a factor 2 less anti-ν_μ, lower anti-ν_e +c.c.)**



GEANT4

@ 4.5 GeV positive focusing

	OLD (%)	NEW (%)
+ FOCUSING		
ν_μ	88.9	-> 95.55
aν_μ	10.5	-> 3.9
ν_e	0.6	-> 0.56
aν_e	0.052	-> 0.025
- FOCUSING		
ν_μ	26.1	-> 11.2
aν_μ	73.4	-> 88.4
ν_e	0.17	-> 0.09
aν_e	0.34	-> 0.35

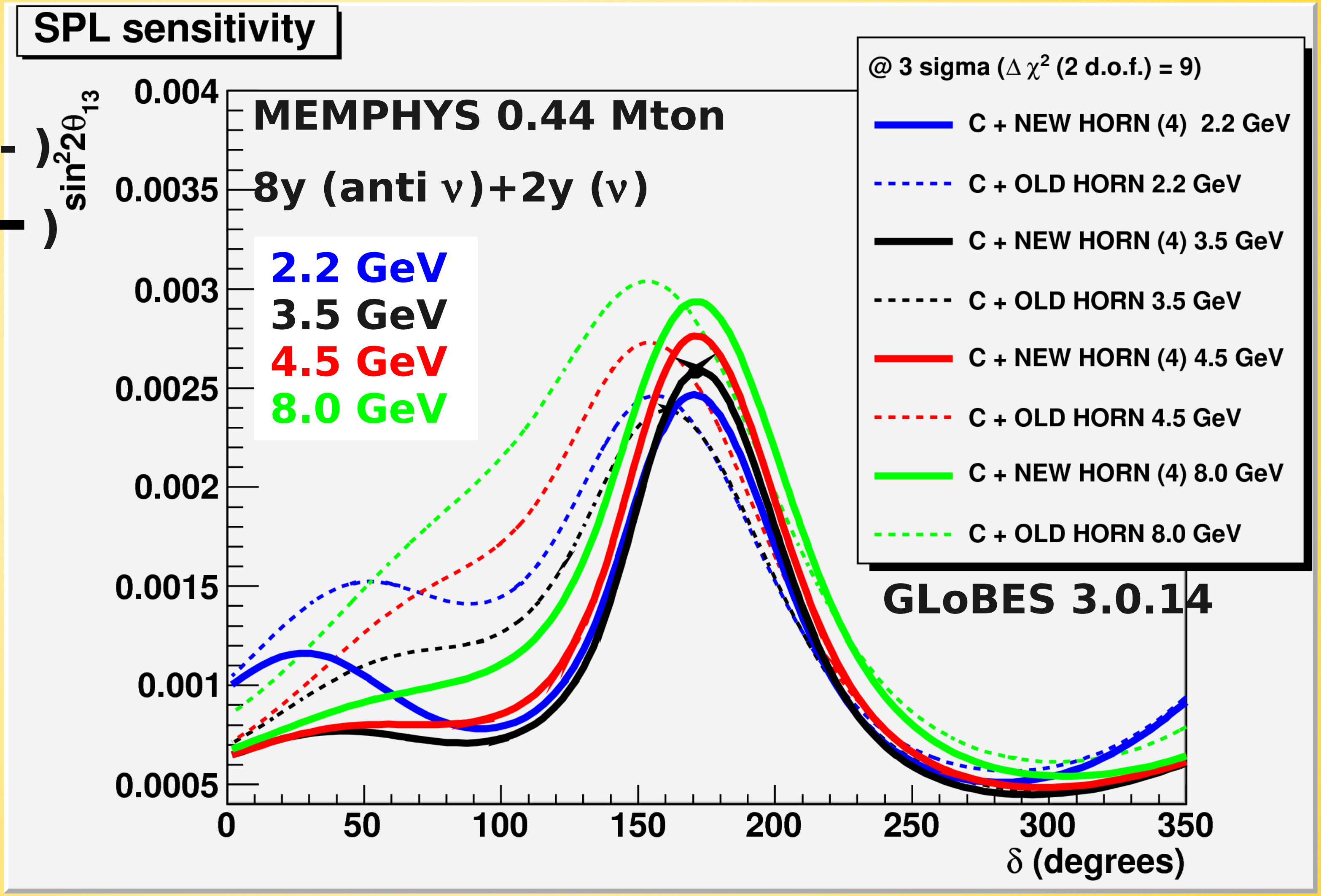
3σ sensitivity on θ_{13} with the new horn

Color codes: proton energies

Carbon target

old horn (- - - - - -)

new horn (———)



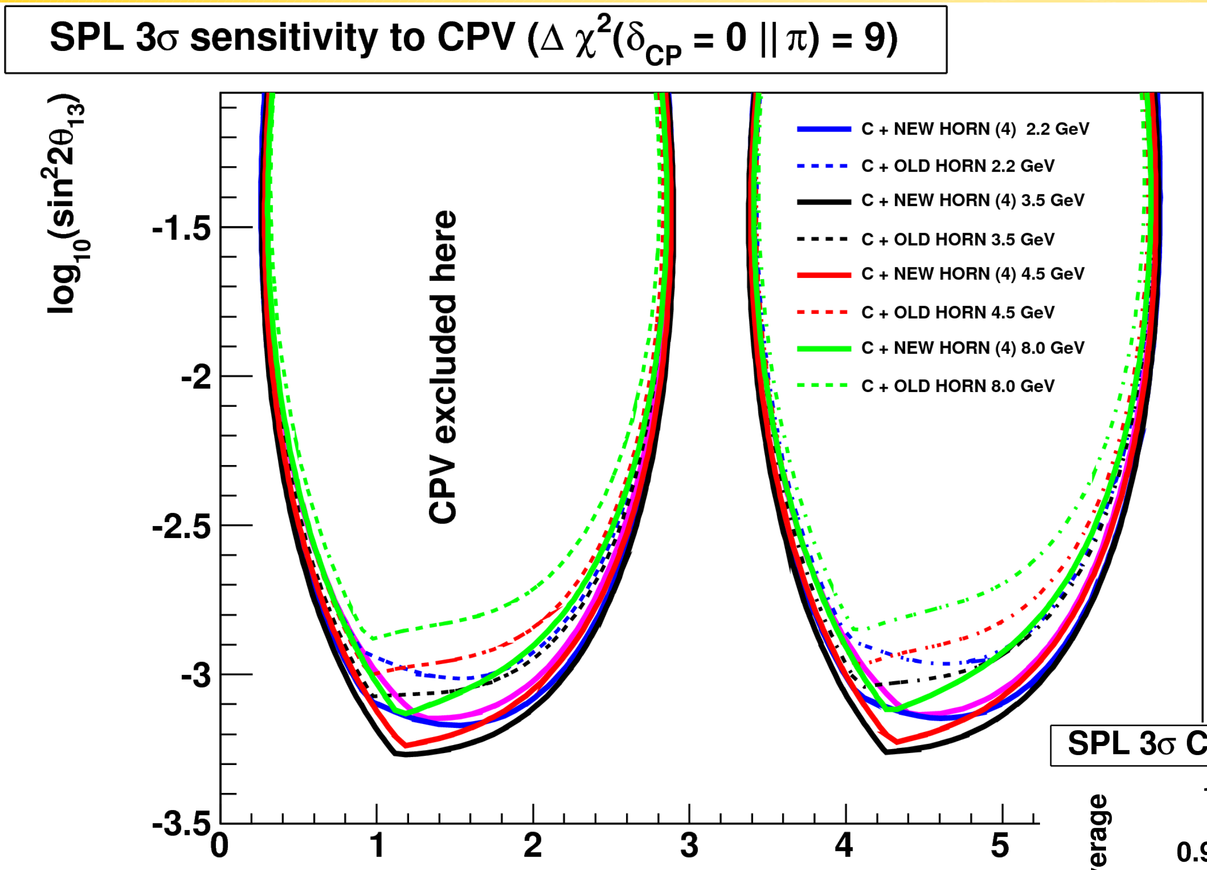
Significant improvement achieved by the new horn design mainly in the anti-ν region as needed.

Limits gets even better than mercury ones with standard horn

GEANT4

AEDL file SPL.glb in GloBES (with M=0.44Mton)
J. Phys. G29 (2003),1781-1784

3σ CP violation discovery coverage



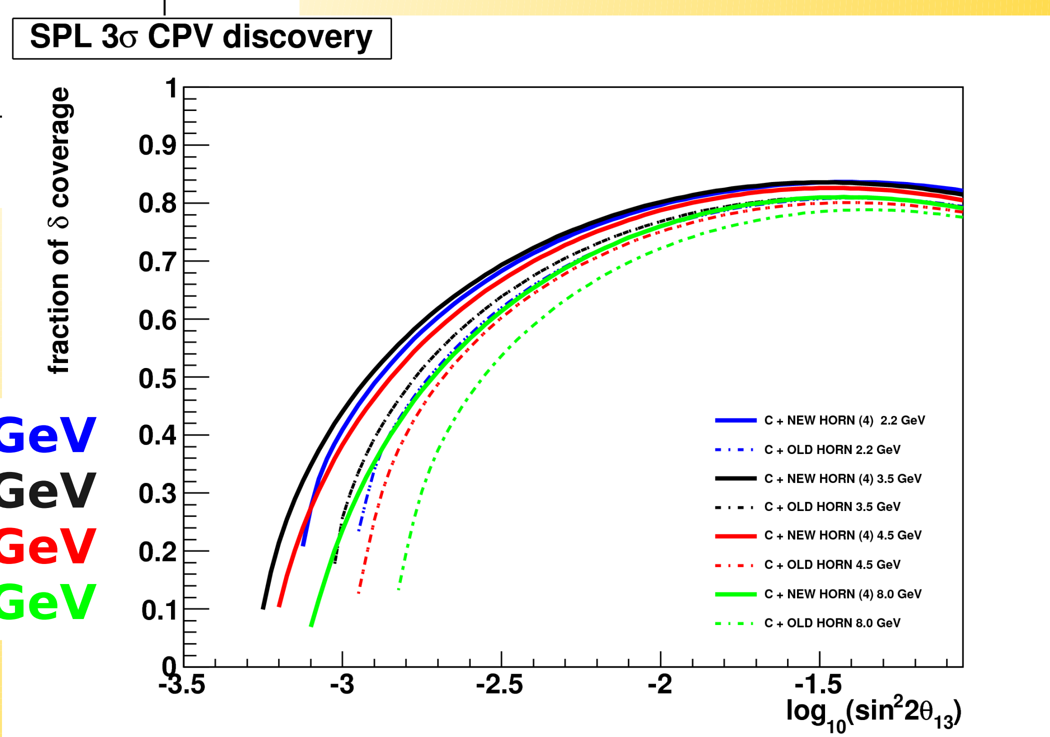
Color codes: p energies

Carbon target

old horn (- - - - - - -)

new horn (———)

Significant improvement achieved by the new horn design.



The change in the focusing does not alter the "ranking" of proton energies

3.5 and 4.5 GeV are preferred (in this order)

2.2 GeV
3.5 GeV
4.5 GeV
8.0 GeV

A. Longhin

NC π^0 background correction

Currently estimated as a fixed fraction of the NC events w/o energy dependence in the GloBES parametrization

needs to be corrected for the new spectrum (higher-E)

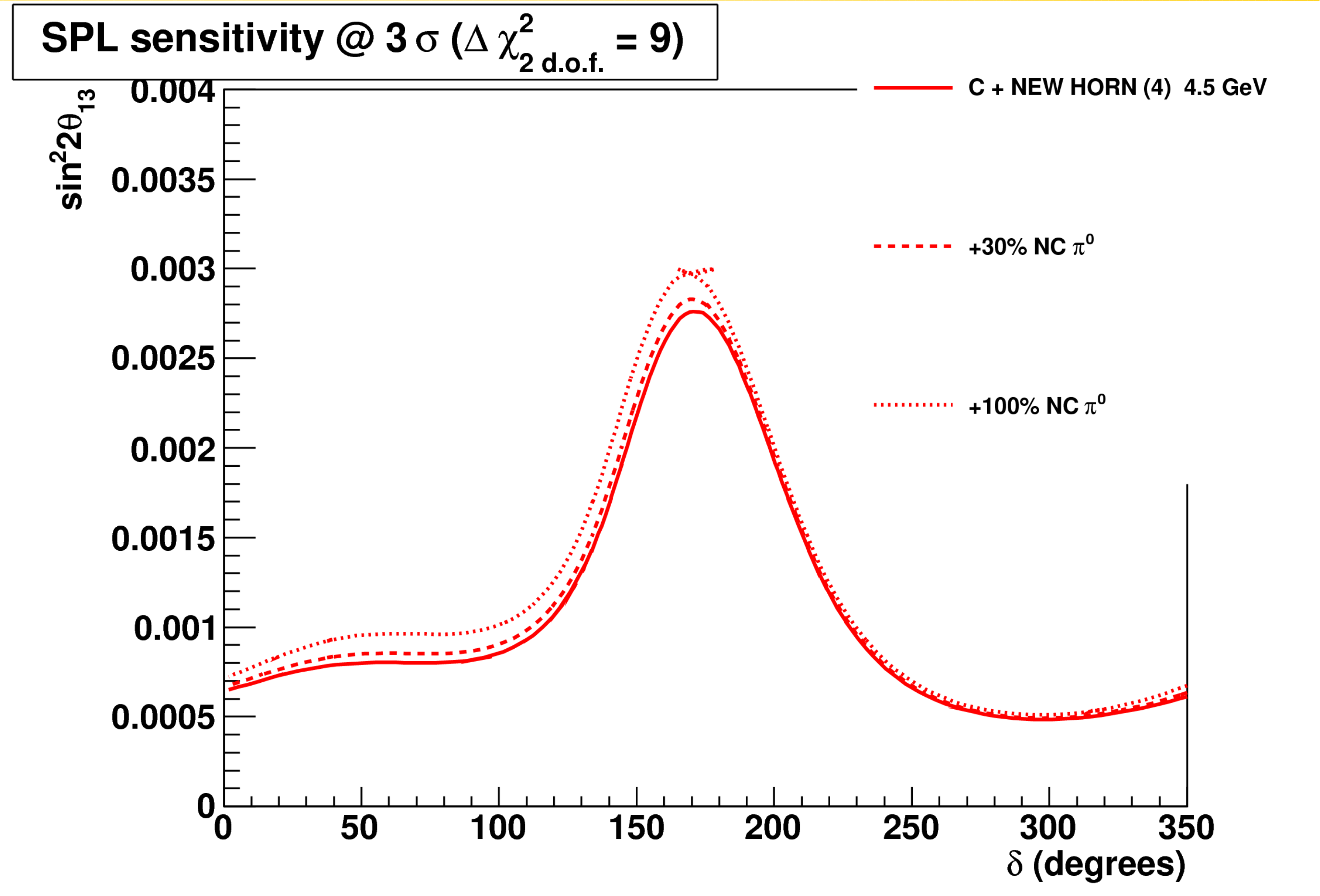
rough (conservative) variation applied to estimate the effect

small effect (~10^{-4}) even with a X 2 increase (in anti-ν region)

main background from intrinsic ν_e (correctly accounted for with new spectra).

more refined algorithms developed within SK since the initial study

implementation foreseen

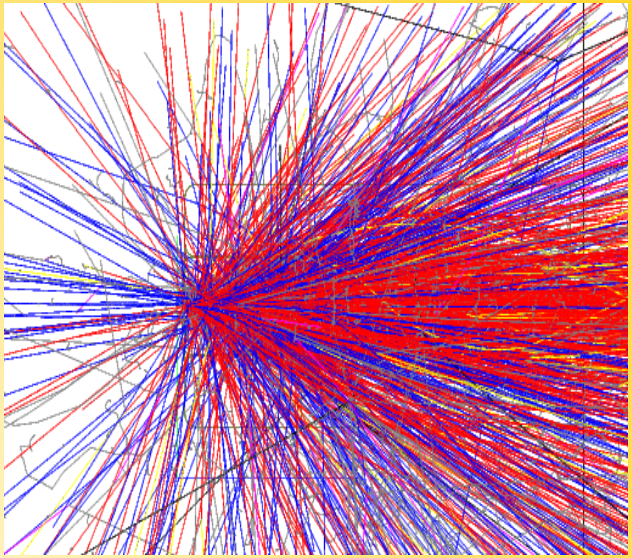


Backgrounds to ν_e appearance @ 3.5 GeV (standard conf.)

ν run:	90% ν_e , 06% NCπ^0, 3% ν_μ MIS-ID, 01% anti-ν_e
anti-ν run:	45% ν_e , 18% NCπ^0, 2% ν_μ MIS-ID, 35% anti-ν_e

Signal eff. 70%

Conclusions



Activity on the SPL-Fréjus project revived within EUROnu. Simulation tools working and being updated (GEANT4-FLUKA2008.3-GLoBES 3.0.14).

Solid target: simulation indicate much reduced energy deposition and neutron fluxes (-X 15), comparable neutrino fluxes and competitive/better performances at the level of θ_{13} sensitivity.

Simulation rewritten in Geant4. Good agreement with previous Geant3 simulation

New optimized horn design suited for a long target worked out.

4 horn concept viable under the point of view of fluxes (only mildly reduced)

Solid target option in association with multiple horns looks appealing for the SPL-Fréjus Super Beam

Outlook

Study systematic effect by using HARP "thick target" data to reweight FLUKA (or other models) spectra. First steps already done.

Improve estimation of π^0 background

Backup slides

EUROnu

A High Intensity Neutrino Oscillation Facility in Europe

EUROnu is a Framework Programme 7 Design Study which started on 1st September 2008 and will run for 4 years. The primary aims are to study three possible future neutrino oscillation faciltiies for Europe and do a cost and performance comparison.

The three facilities being studied are:

- **CERN to Frejus superbeam ← our interest**
- **Neutrino Factory**
- **Beta Beam with higher Q isotopes**

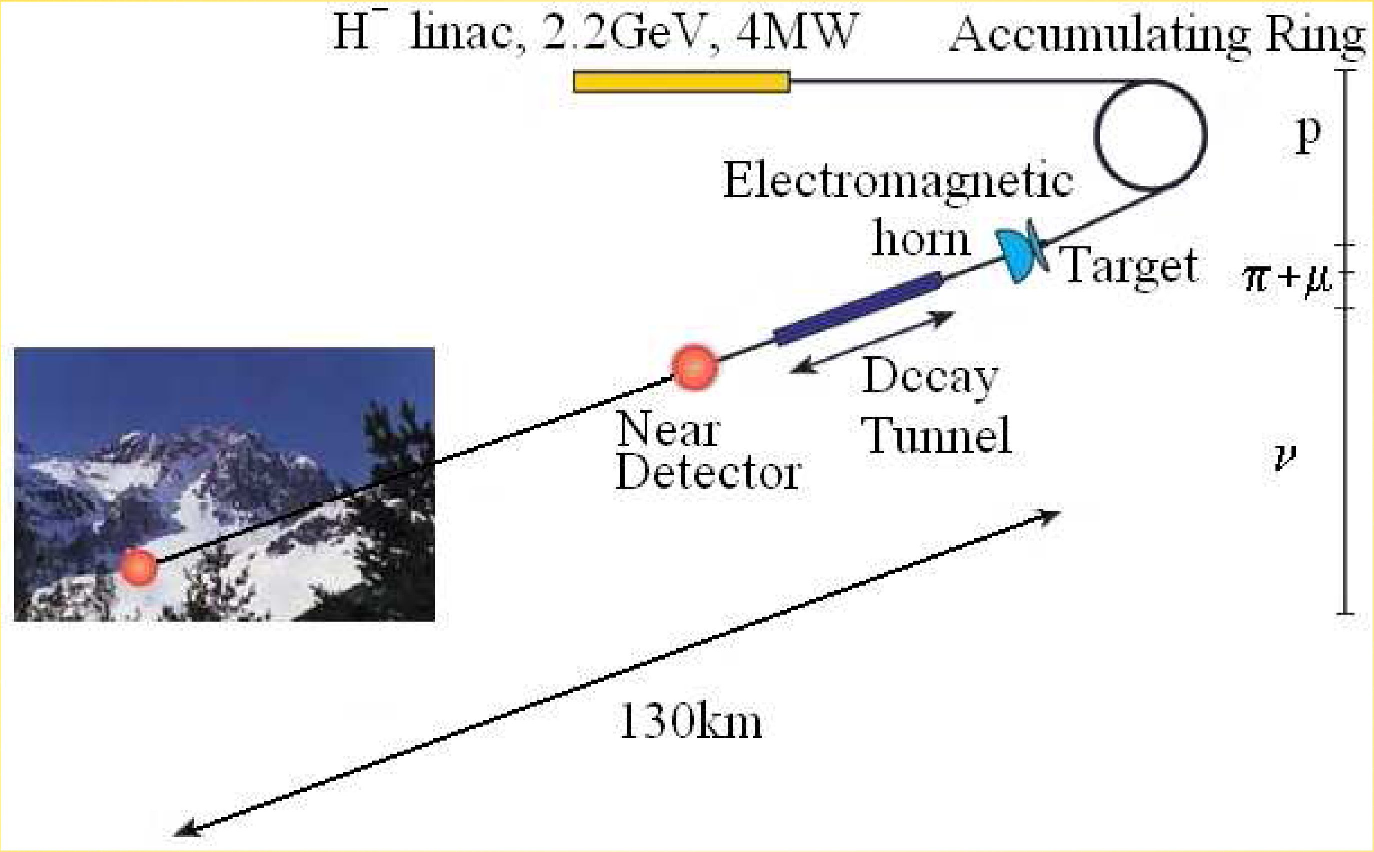
In addition, EUROnu will look at the performance of the baseline detectors for each facility and determine the physics reach of each. Although a European project, EUROnu will collaborate closely with related international activities, in particular the International Design Study for a Neutrino Factory, IDS-NF.

Work Packages

WP1: Management and Knowledge Dissemination
WP2: Super-Beam
WP3: Neutrino Factory
WP4: Beta-Beam
WP5: Detector Performance
WP6: Physics

More info at: www.euronu.org and in particular in the slides of the annual meeting held in CERN in march 2009:
http://indico.cern.ch/conferenceDisplay.py?confId=42846

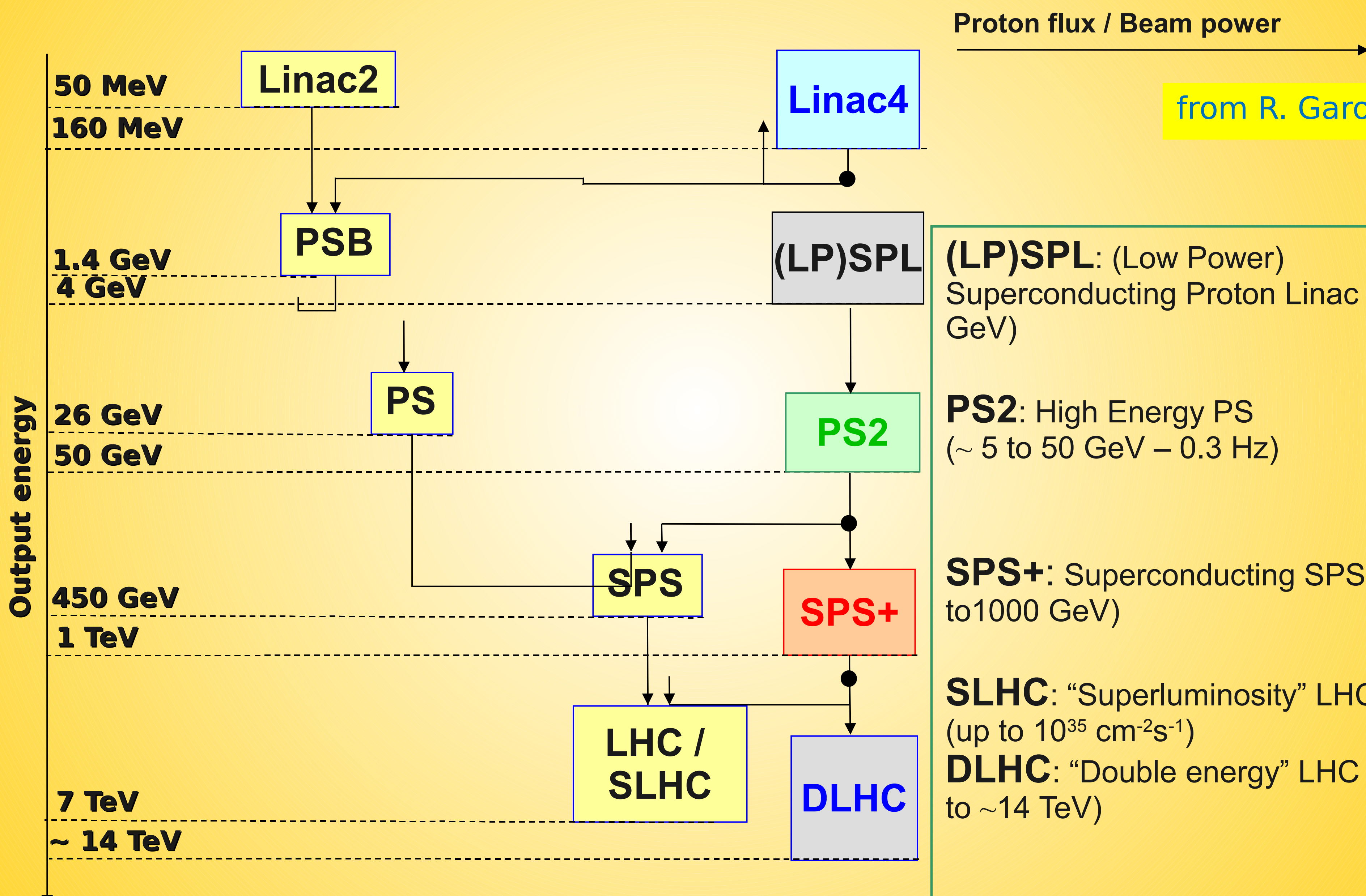
SPL- Frejus layout



SPL (Superconducting Proton Linac) is already funded as part of the new injection chain for the LHC.

Far detector: a 440kton Cerenkov detector (MEMPHYS)

PLANS FOR FUTURE INJECTORS: Description



from R. Garoby

(LP)SPL: (Low Power) Superconducting Proton Linac (4-5 GeV)

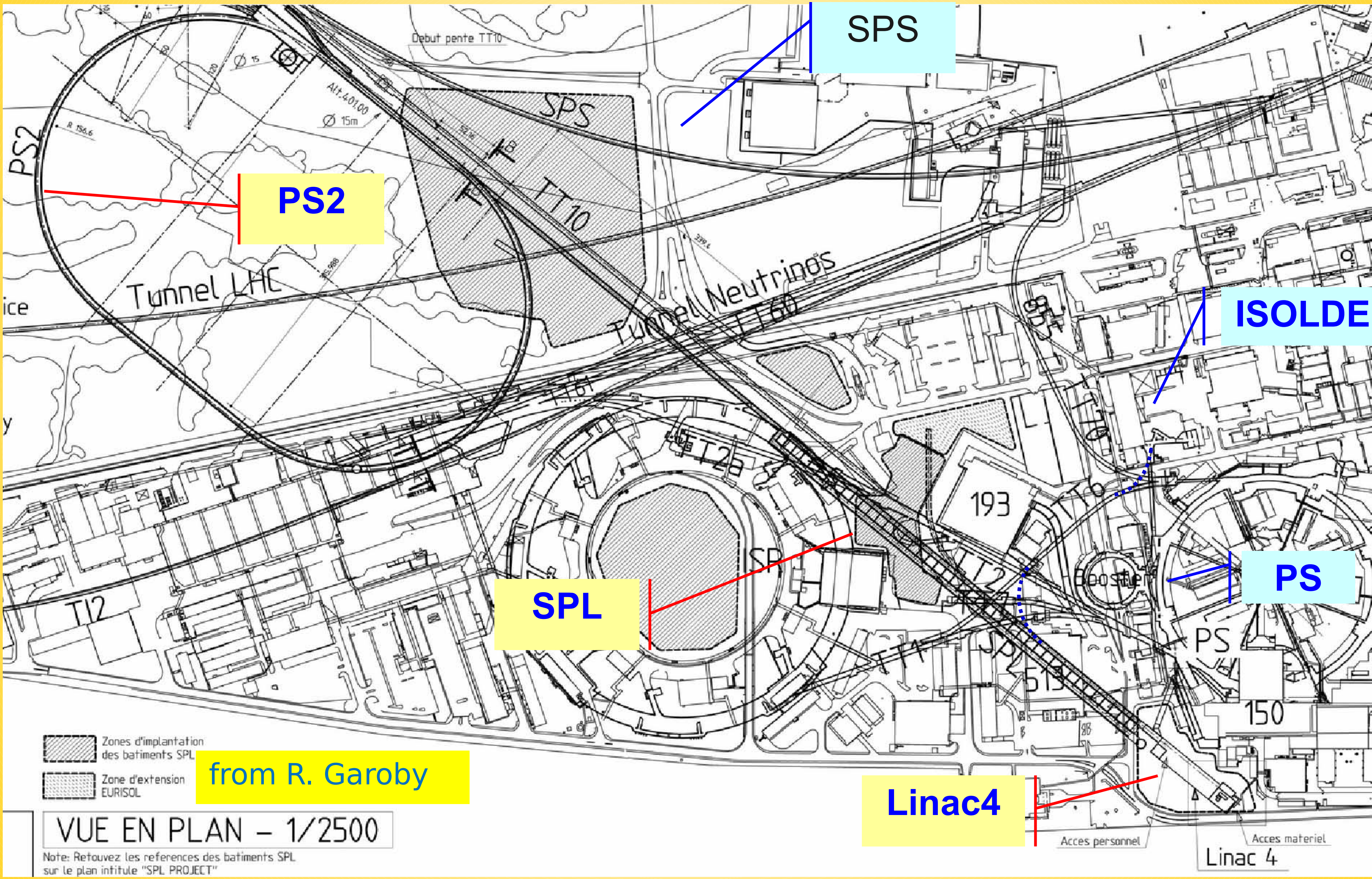
PS2: High Energy PS (~ 5 to 50 GeV – 0.3 Hz)

SPS+: Superconducting SPS (50 to1000 GeV)

SLHC: "Superluminosity" LHC (up to 10^{35} $cm^{-2}s^{-1}$)

DLHC: "Double energy" LHC (1 to ~14 TeV)

PLANS FOR FUTURE INJECTORS: Layout

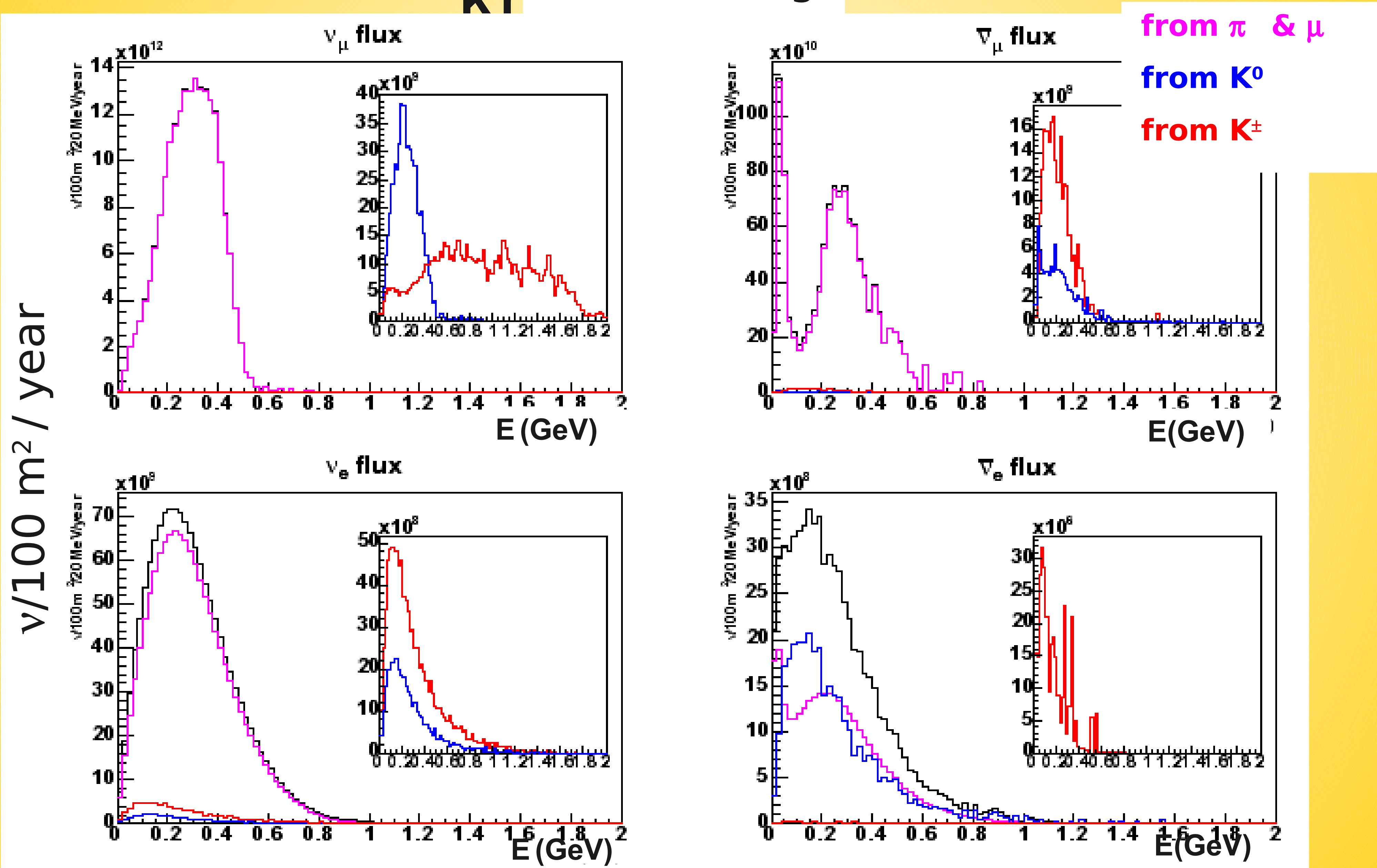


Neutrino fluxes at 100 kr

1 year := 10^7 s

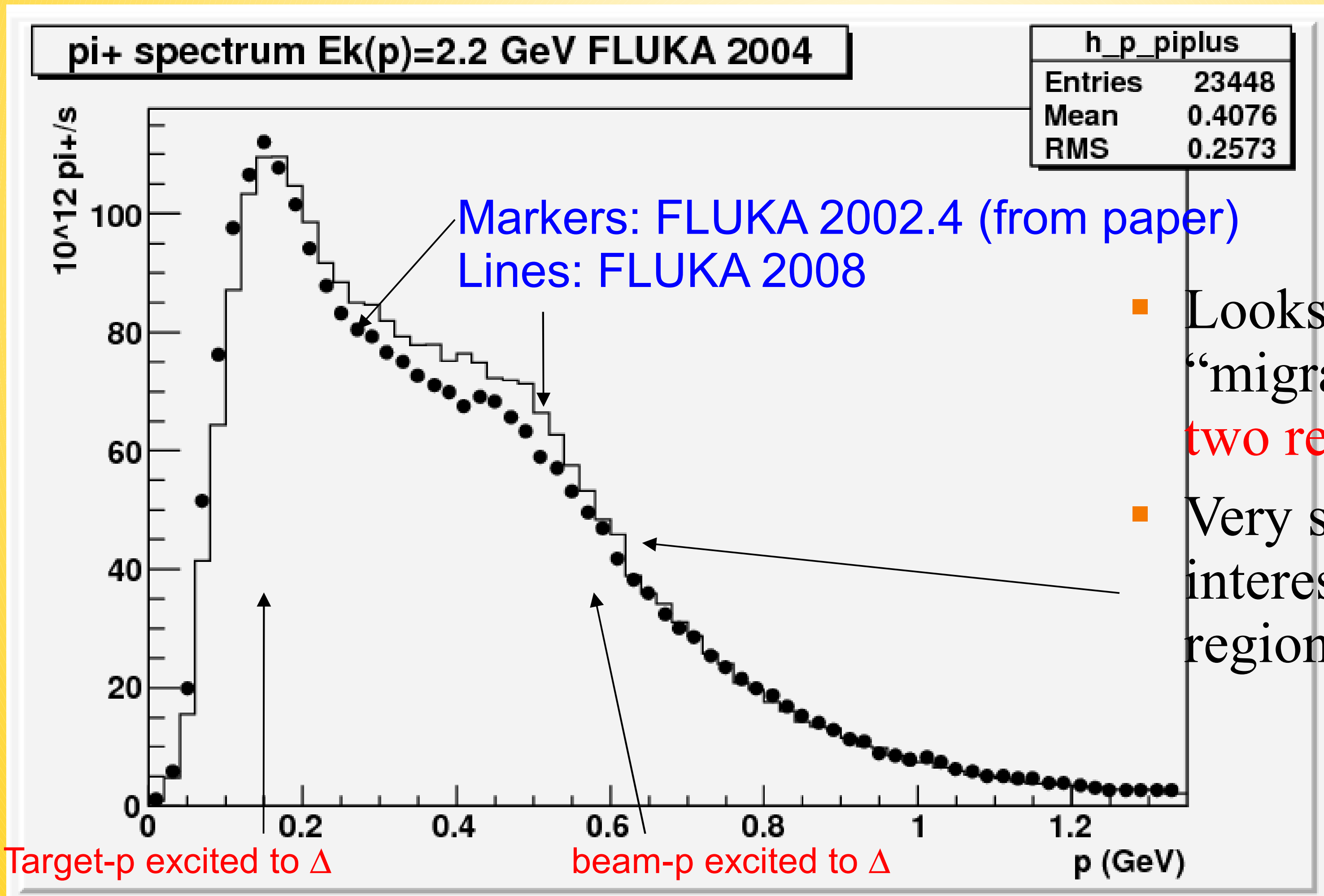
E_k = 3.5 GeV
E_ν ~ 300 MeV
L = 40 m, R = 2 m

π^+ focusing



FLUKA 2008 vs FLUKA 2002.4

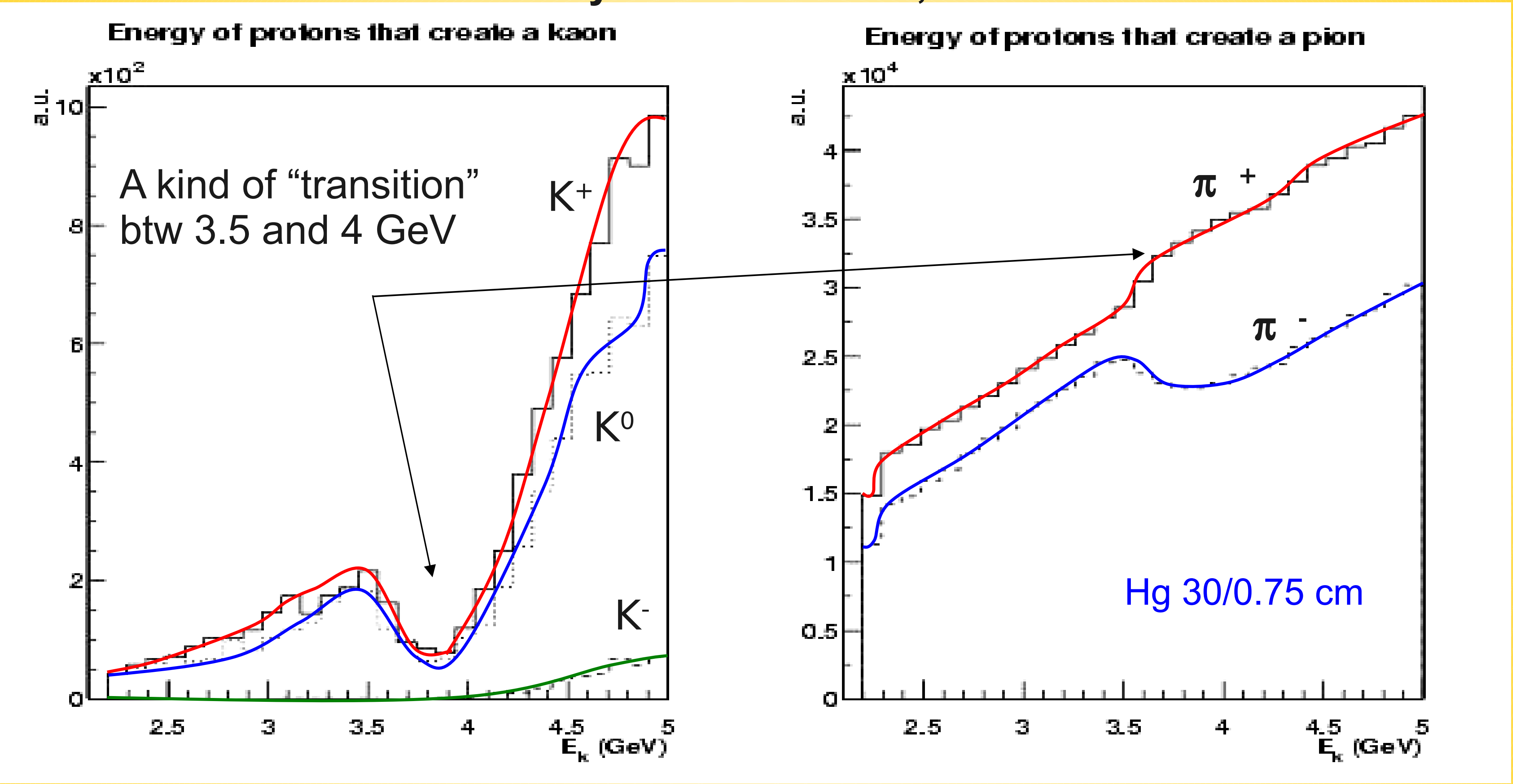
- Momentum spectrum of π^+ exiting the target
  - $E_k(p)$ = 2.2 GeV, Hg cylinder L = 30cm, r = 0.75 cm
  - Normalization + shape comparison



- Looks like a kind of "migration" between the two regions
- Very similar in the interesting momentum region at ~ 600 MeV

Particle multiplicities: FLUKA 2002.4

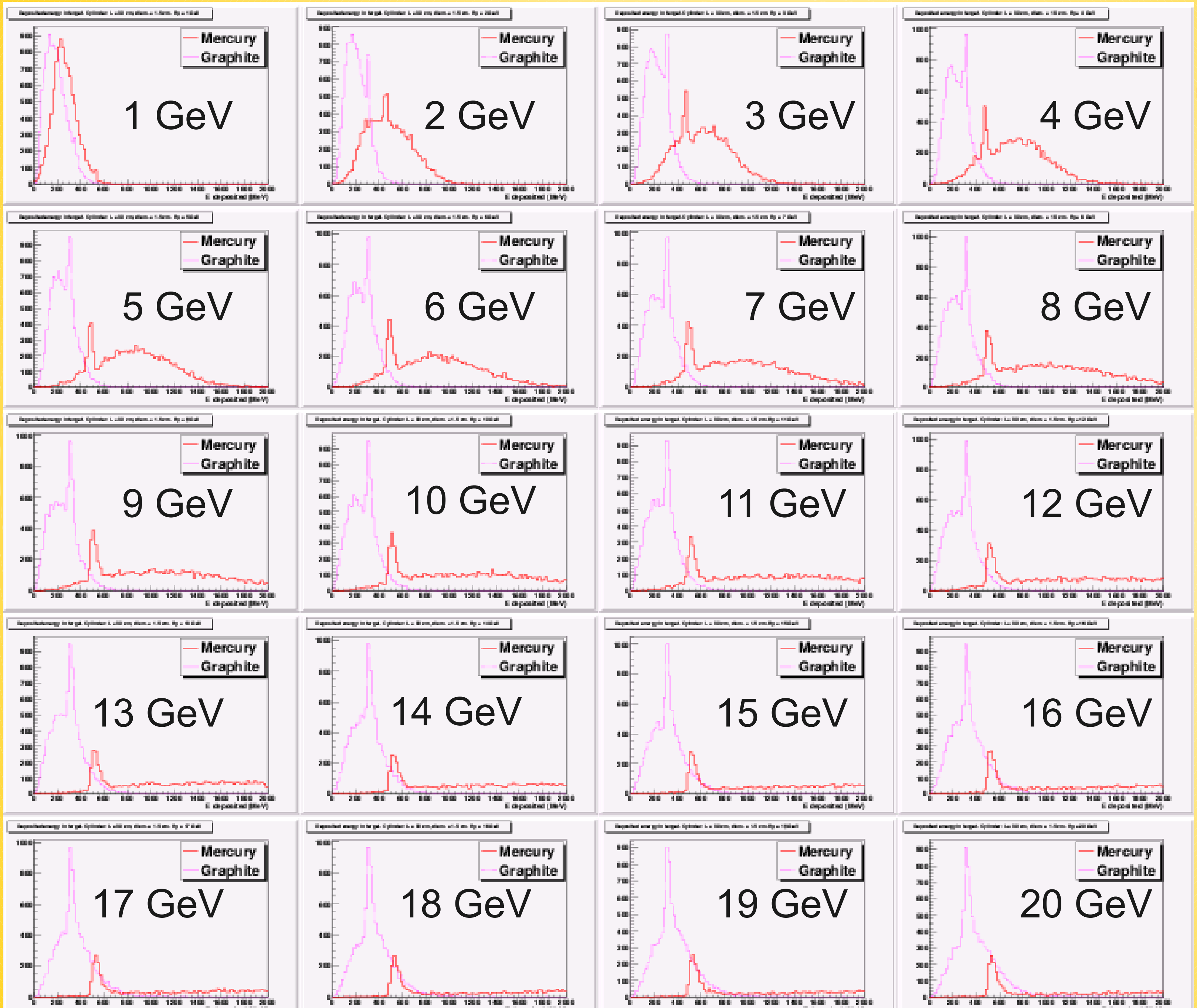
Eur Phys J C45:643-657,2006



- at 2.2GeV :
  - 0.26 π^+/s
  - 0.8 10^{-3} K^+/s
- at 3.5GeV :
  - 0.29 π^+/s
  - 2.8 10^{-3} K^+/s
- at 4.5GeV :
  - 0.32 π^+/s
  - 5.2 10^{-3} K^+/s

Graphite-Mercury energy deposition: GEANT4

- Distribution of deposited energy in bins of $E_k(p)$ [1-20] GeV



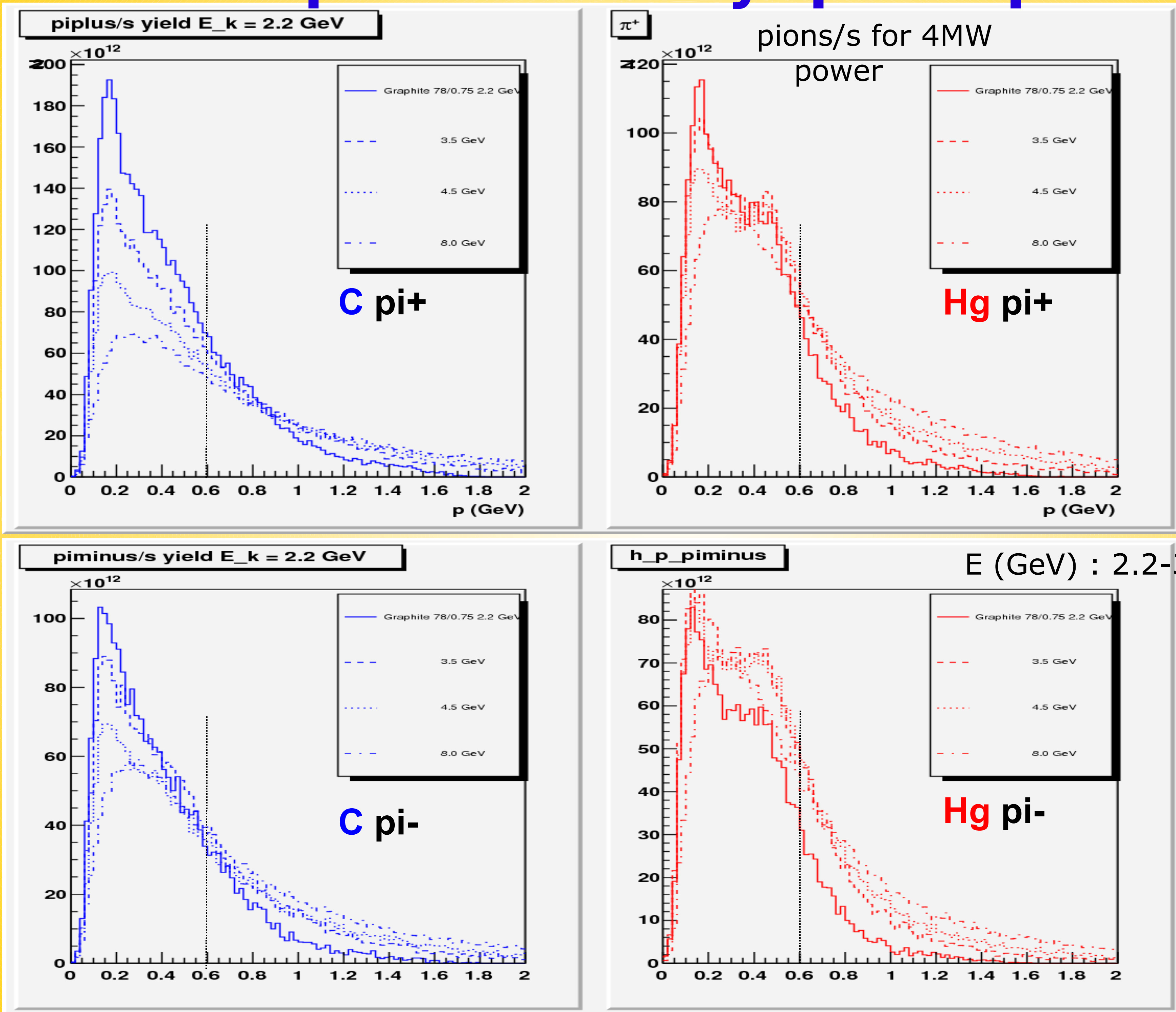
- GEANT4 (hadronic “QGSP physics list”)

Hg
C

x-axis: 0-2 GeV

peak: ionization loss of elastic or not-interacting p

Graphite-Mercury: pion spectra



E (GeV) : 2.2-3.5-4.5-8.0

Effect of radius on pion multiplicities

- Not a major effect but pion yield from graphite would benefit of a larger target radius