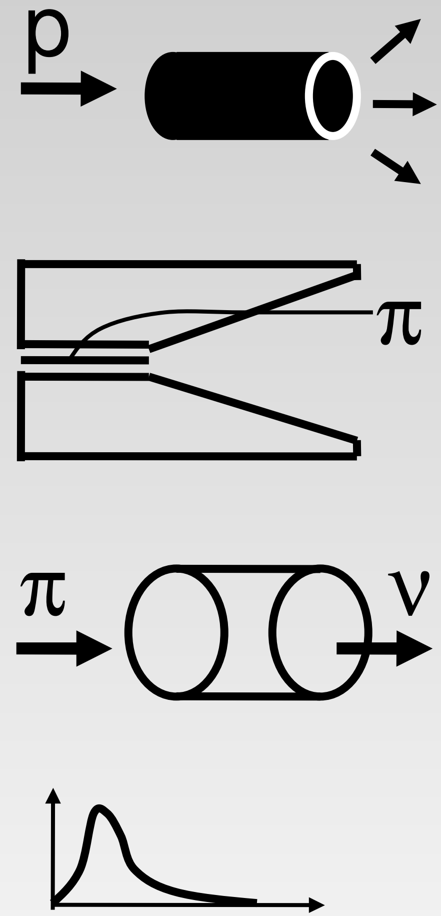
SPL-Fréjus using a carbon target



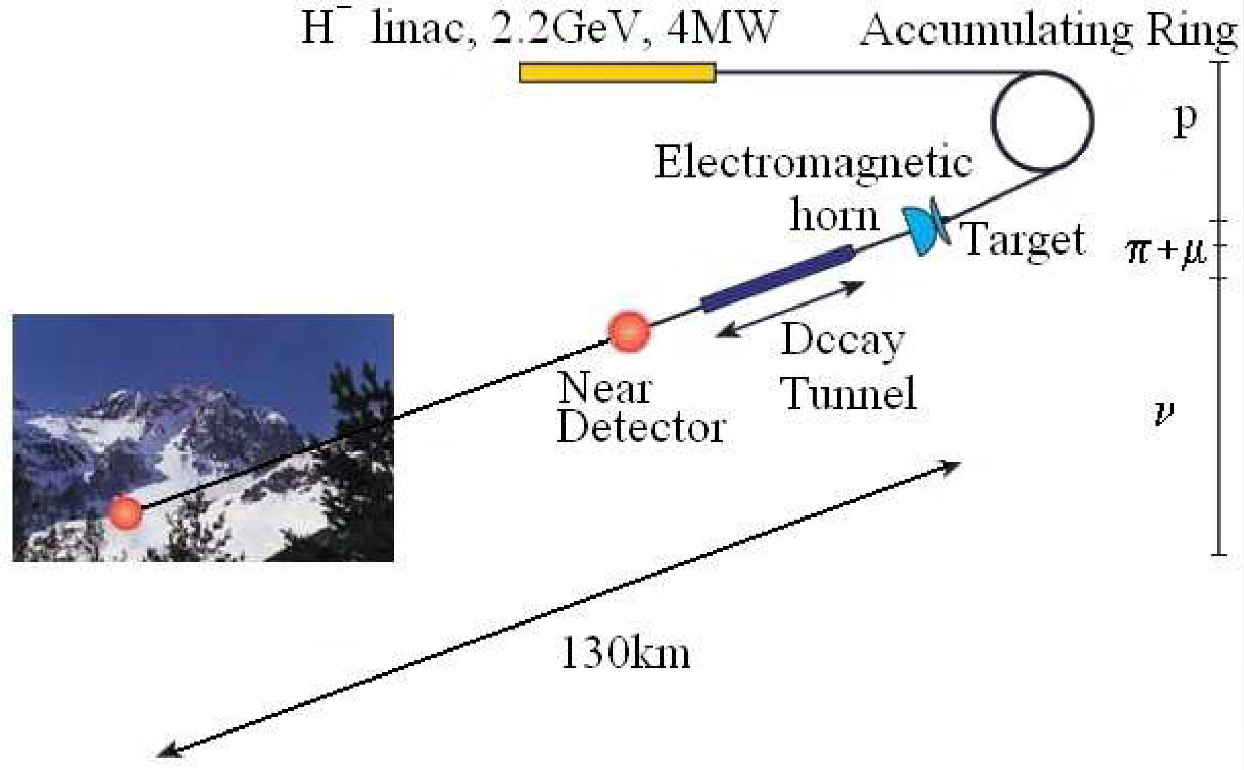
Andrea Longhin
CEA Saclay

Reunion Memphys-Lena-Glacier
APC, Paris, 6 Mai 2009

Outline

- Summary of simulation done so far + results
  - based on **Campagne, Cazes : Eur Phys J C45:643-657,2006**
- Software updates
- New investigations:
  - impact of choosing a graphite target ?
    - Simulation tools
    - Target energy deposition
    - Pion/kaon yields
    - Neutrino fluxes
    - Sensitivity curves
- Conclusions and Perspectives

- Summary of simulation done so far + results
  - based on **Campagne, Cazes : Eur Phys J C45:643-657,2006**

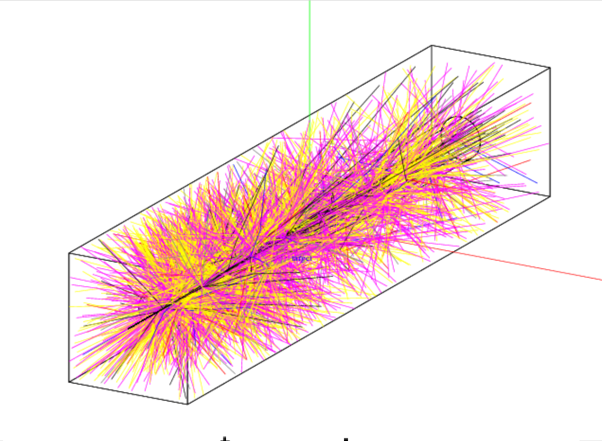


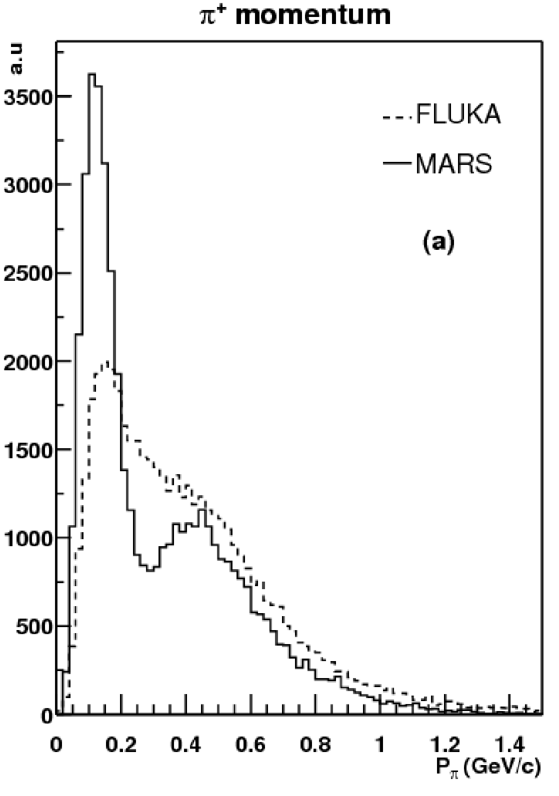
Target simulation

- Production: FLUKA 2002.4 and MARS
- Proton beam
  - Pencil like (will soon change to finite spread)
  - $E_k(p) = 2.2 – 3.5 – 4.5 – 6.5 – 8$ GeV
- Cylindrical target (~ 2 λ_I long)
  - Liquid mercury: L = 30 cm, r = 7.5 mm
- Normalization to fixed 4 MW power:
  - 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
- A sample of 10^6 protons has been simulated

Increasing E:

:) more pions
:) more boosted (will reach detector!)
: (more kaons (nu_e contamination)
: (lower pots available (fixed power: 4 MW)





Horn design and simulation

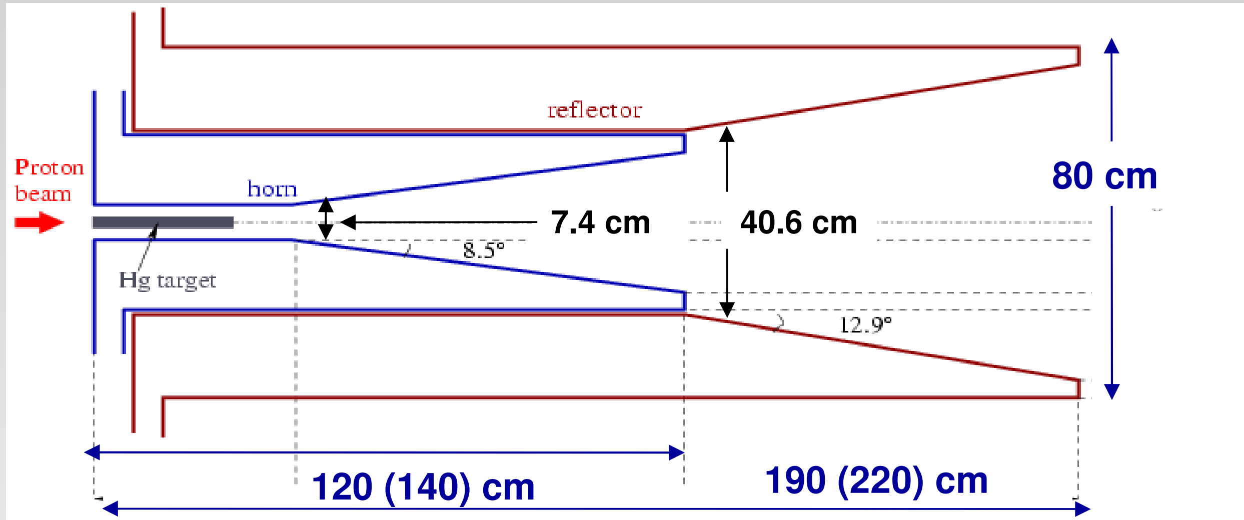
- Due to the low energy proton beam pions are mildly forward boosted ($<\theta_\pi> = 55°$)
  - -> Target inside the horn to recover collection efficiency

$\Delta m^2 \approx 2.5\ 10^{-3}\ eV^2$

CERN-Fréjus = 130km

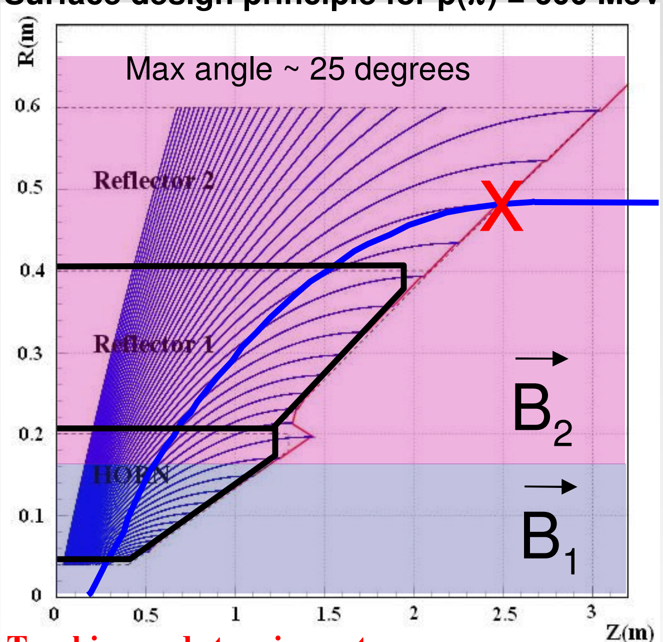
$\Rightarrow E_\nu \approx 260$ MeV

$\Rightarrow p_\pi \approx 600$ MeV/c



Higher length (in parenthesis) refer to a horn optimized for a higher E_ν ~ 300 MeV

Surface design principle for p(π) = 600 MeV



Tracking and stepping cuts:

100 KeV (μ, hadr.) 10 KeV (e+e- gamma)

10 mrad if B, 100 μm and lose <1% E_k in conductors

- i(h/r) = 300/600 kA
- pulsed @ 50 Hz
- Toroidal |B| ~ i / r
- B_1^{MAX} =1.5 T, B_2^{MAX}= 0.3T
- Al 3mm thick

Horn prototype at CERN (geometry implemented in the Geant 3 simulation)

Decay tunnel optimization

- Length
  - modify purity
  - L=10-20-40-60 m tested
  - 10 → 40 m
    - ν_μ, antiν_μ + 50% to 70%
    - ν_e, antiν_e + 50% to 100%
  - 40 → 60 m
    - ν_μ, antiν_μ + 5%
    - ν_e, antiν_e + 20%
  - 40 m seems better

- Radius
  - modify acceptance
  - R = 1-1.5-2 m tested
  - 1 → 2 m (L = 40)
    - ν_μ, antiν_μ + 50%
    - ν_e, antiν_e + 70% to 100%
  - 2 m seems better

$\beta\gamma c\tau$, p = 0.6 GeV

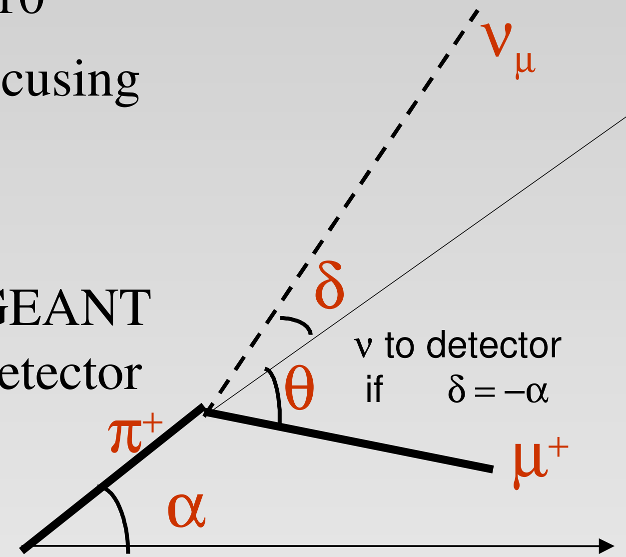
π	33.7 m
μ	3766 m
$K^{+/-}$	4.5 m
K^0_S	3.2 m
K^0_L	18.5 m

These indications have been confirmed also at the level of sensitivity to θ_{13} anδ_{CP}

-> see later

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

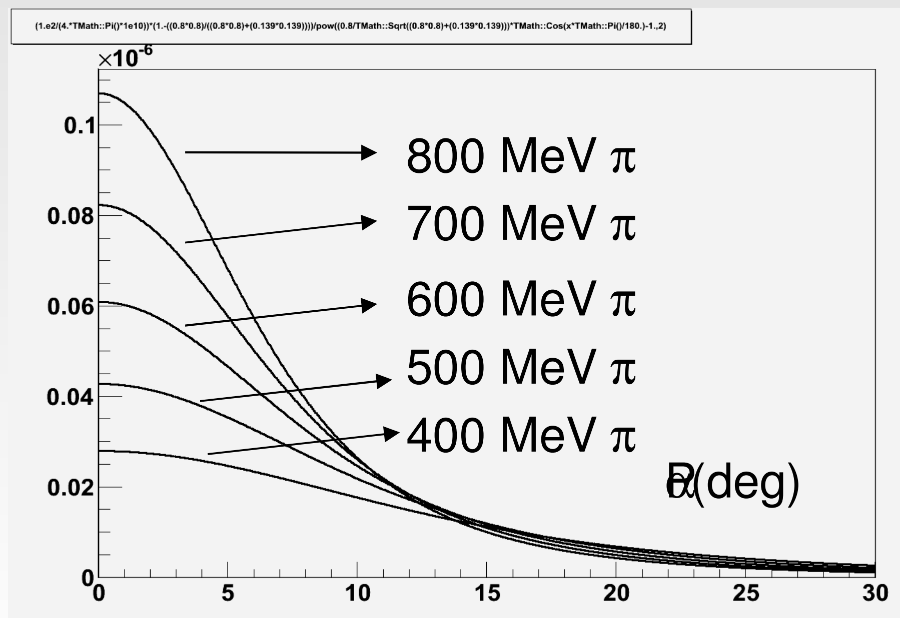
$\pi^+ \rightarrow \mu^+ \nu_\mu$

$K^+ \rightarrow \mu^+ \nu_\mu$

L : distance to detector
A : detector surface

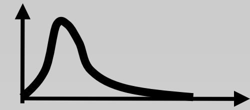
Angle of π w.r.t. beam axis in the lab frame: α

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



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

Probability for the ν to reach the detector: case of muon and kaon 3 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

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

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

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

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

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

Π is the muon polarisation

K → 3 body

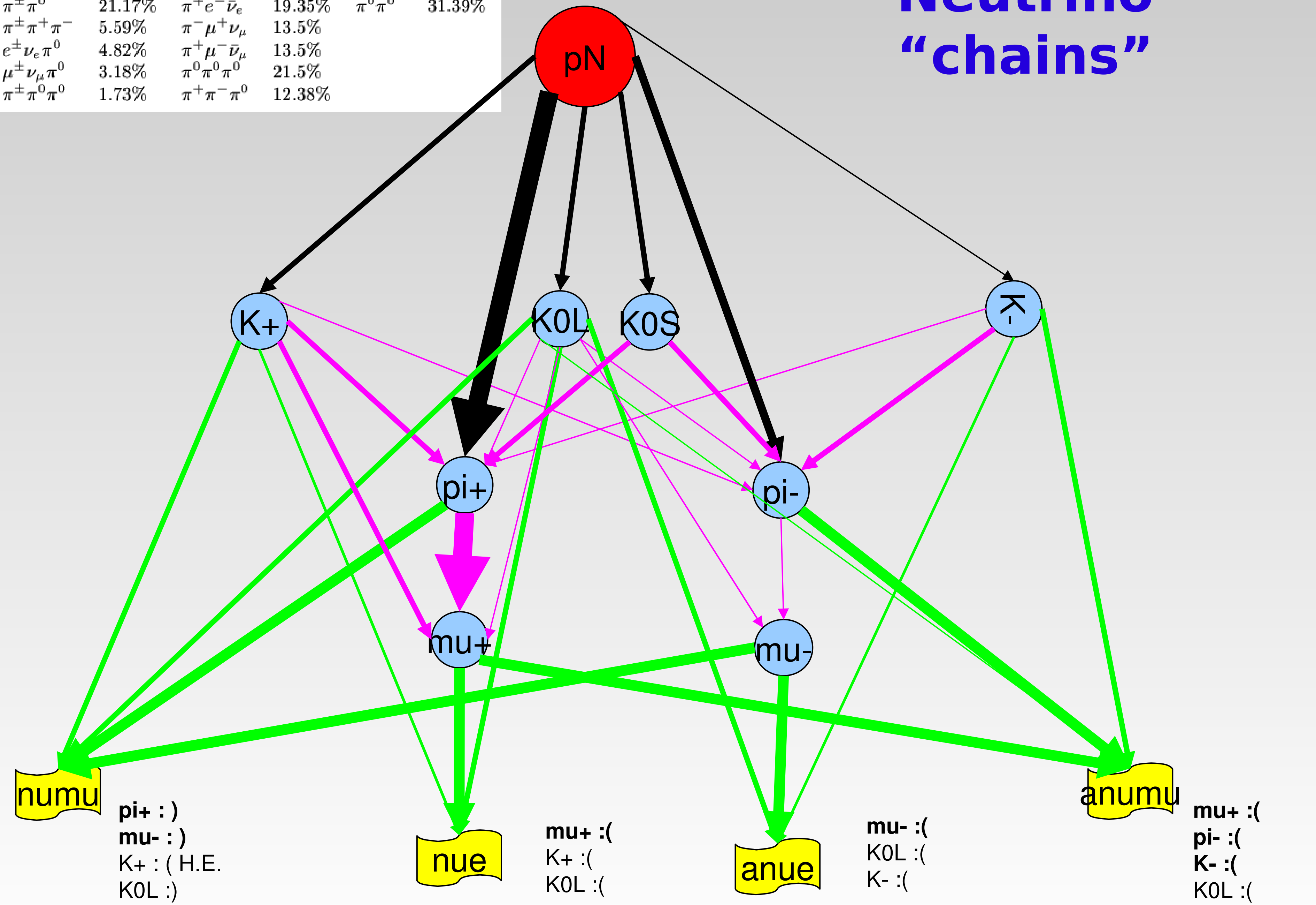
$$\frac{d\mathcal{P}_K}{dE_\nu} = \frac{1}{4\pi}\frac{A}{L^2}\frac{1}{m_K-m_\pi-m_l} \times \frac{1}{\gamma_K(1+\beta_K\cos\theta^*)}\frac{1-\beta_K^2}{(\beta_K\cos\delta-1)^2}$$

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)

Neutrino "chains"

$K^{\pm}$		K^0_L		K^0_S	
$\mu^{\pm}\nu_{\mu}$	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%		

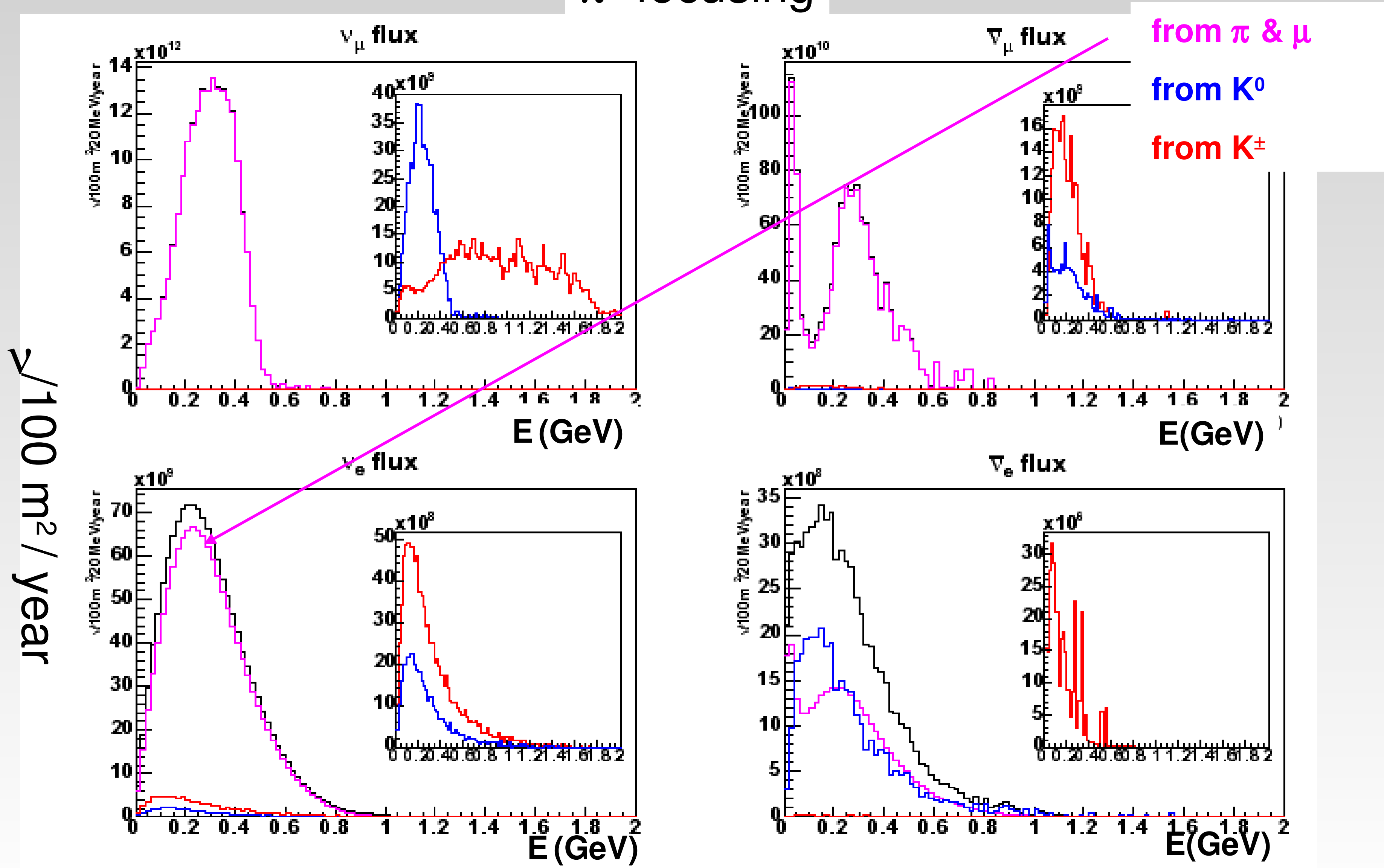


Neutrino fluxes at 100 km

$E_k = 3.5$ GeV
$E_\nu \sim 350$ MeV
L = 40 m, R = 2 m

1 year := 10^7 s

π^+ focusing



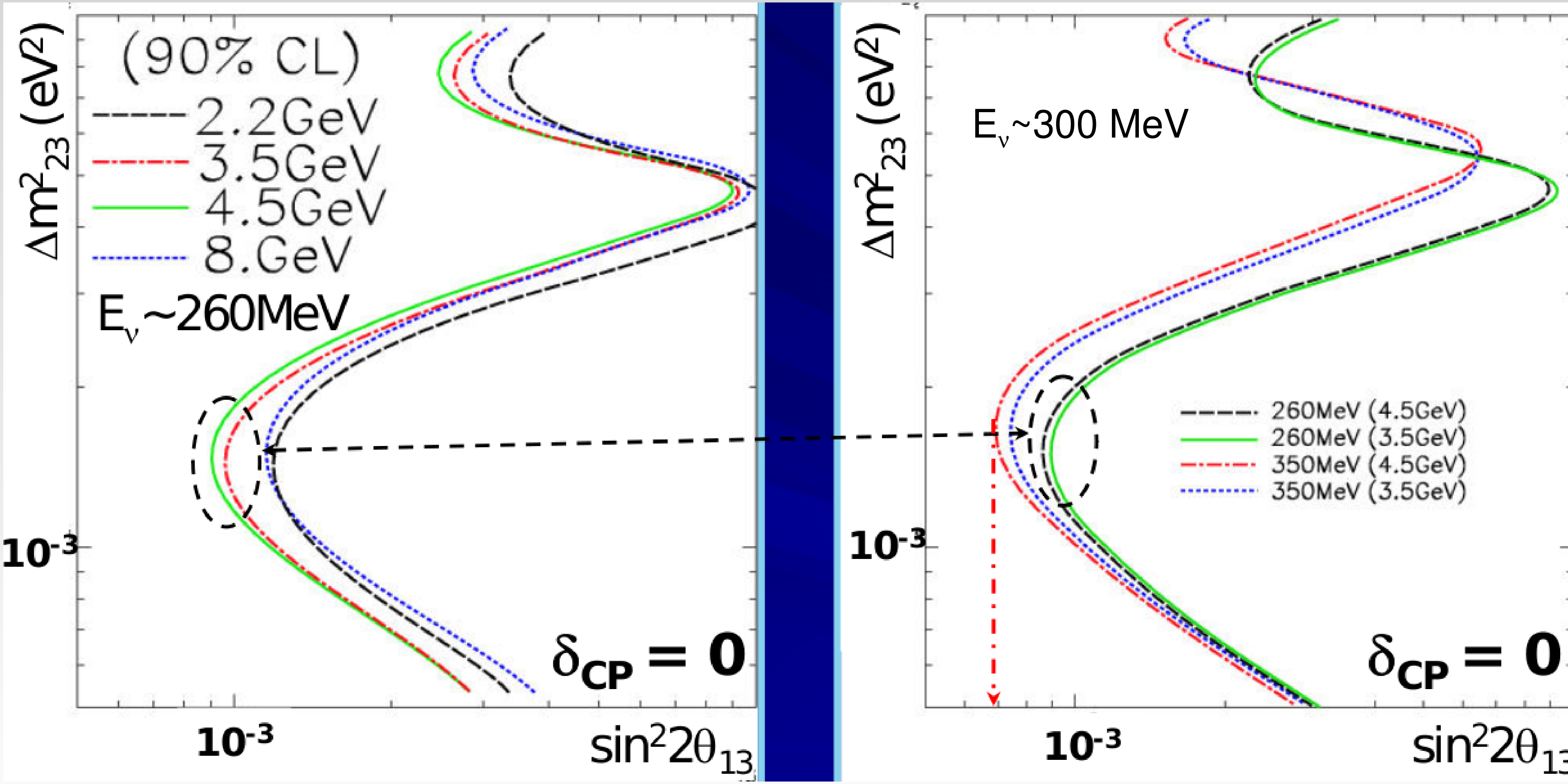
Sensitivity

w-Cerenkov 440 kTon
2% err sys ν_e

For Ek(p) = 3.5-4.5 GeV +

For different proton kin. Energies
tunnel: 20/1 m

- Longer horn: E_ν~350 MeV
- Larger tunnel 40/2 m

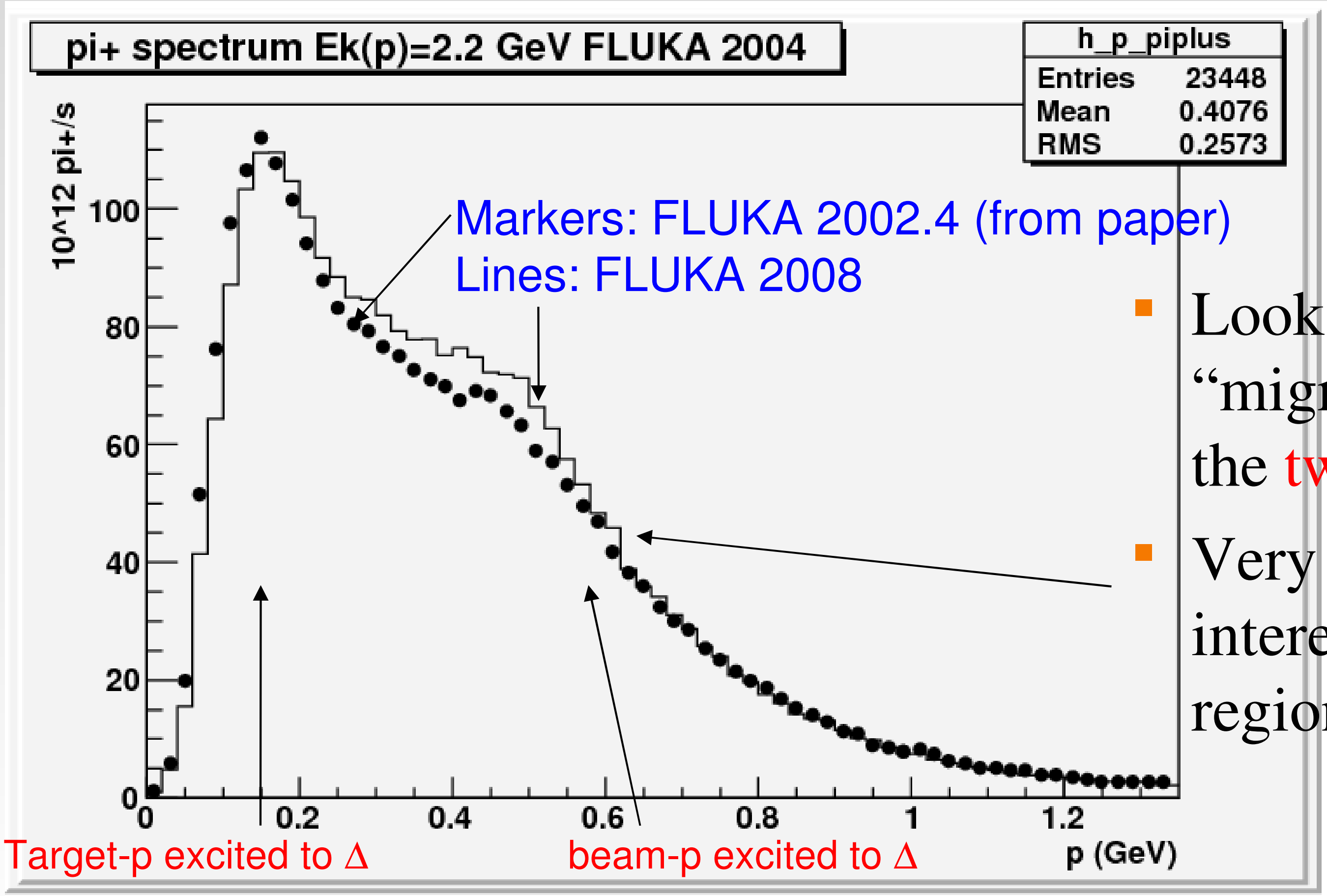


$\sin^2 2\theta_{13} < 7.1 \ 10^{-4}$ 90% C.L.

- New software
  - Transition to FLUKA2008
    - π^+ spectrum
    - K/π multiplicities vs E_p
  - Transition to GEANT4
    - geometry

FLUKA 2008 vs FLUKA 2002.4

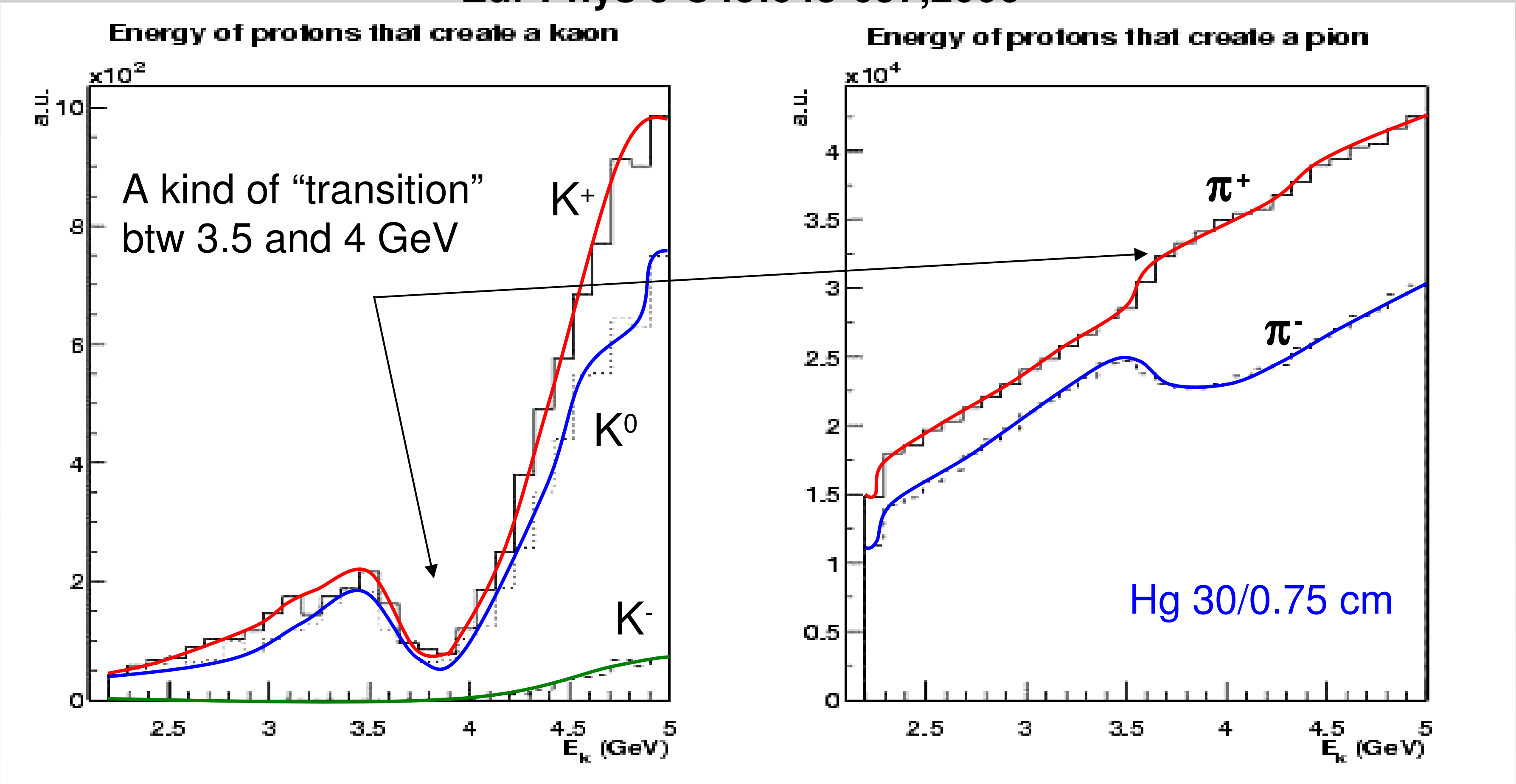
- Momentum spectrum of π^+ exiting the target
  - $E_k(p)$ = 2.2 GeV, Hg cylinder L = 30cm, r = 0.75 cm
  - Normalization + shape comparison



- 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

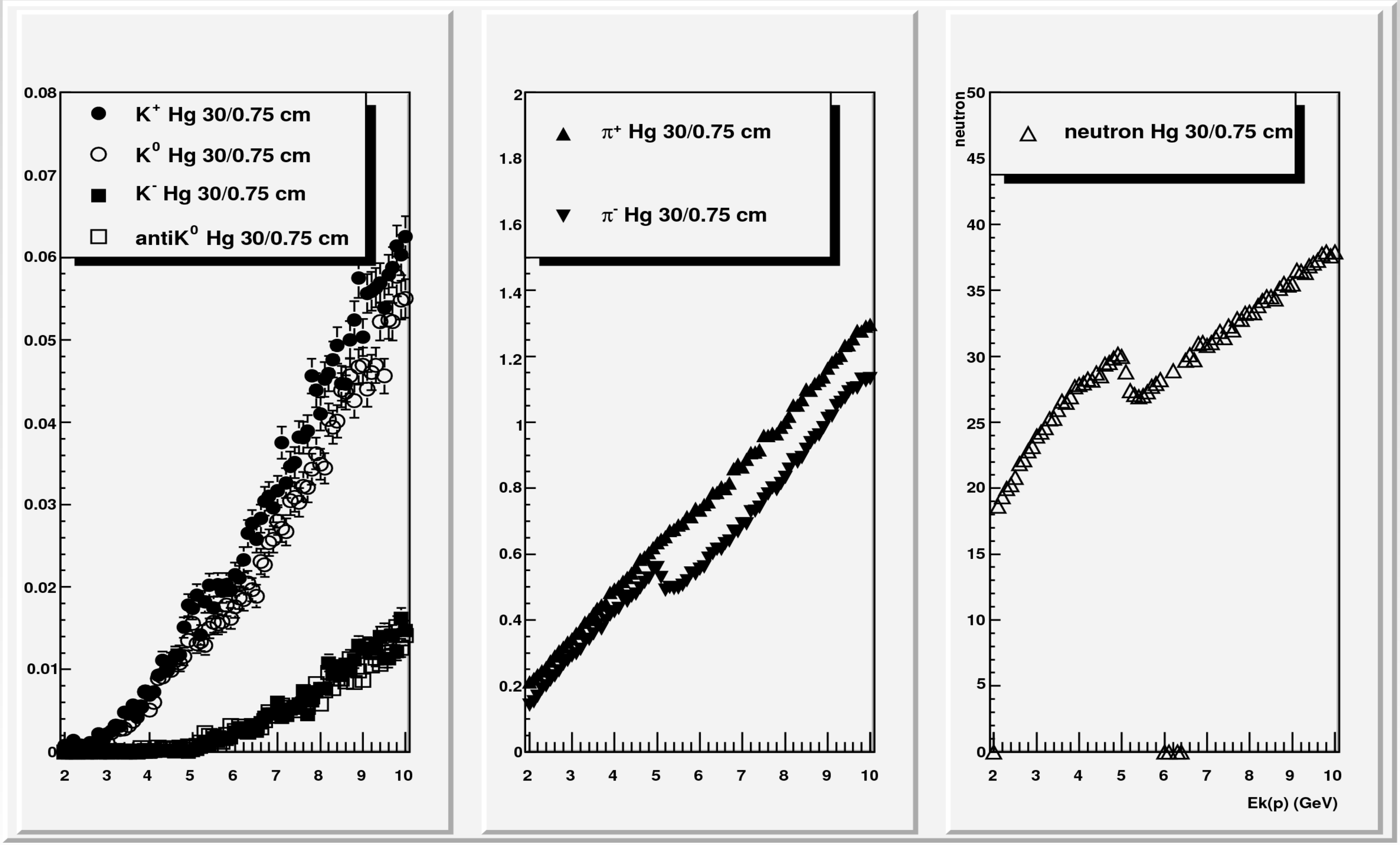
Eur Phys J C45:643-657,2006



- 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

Particle multiplicities: FLUKA 2008

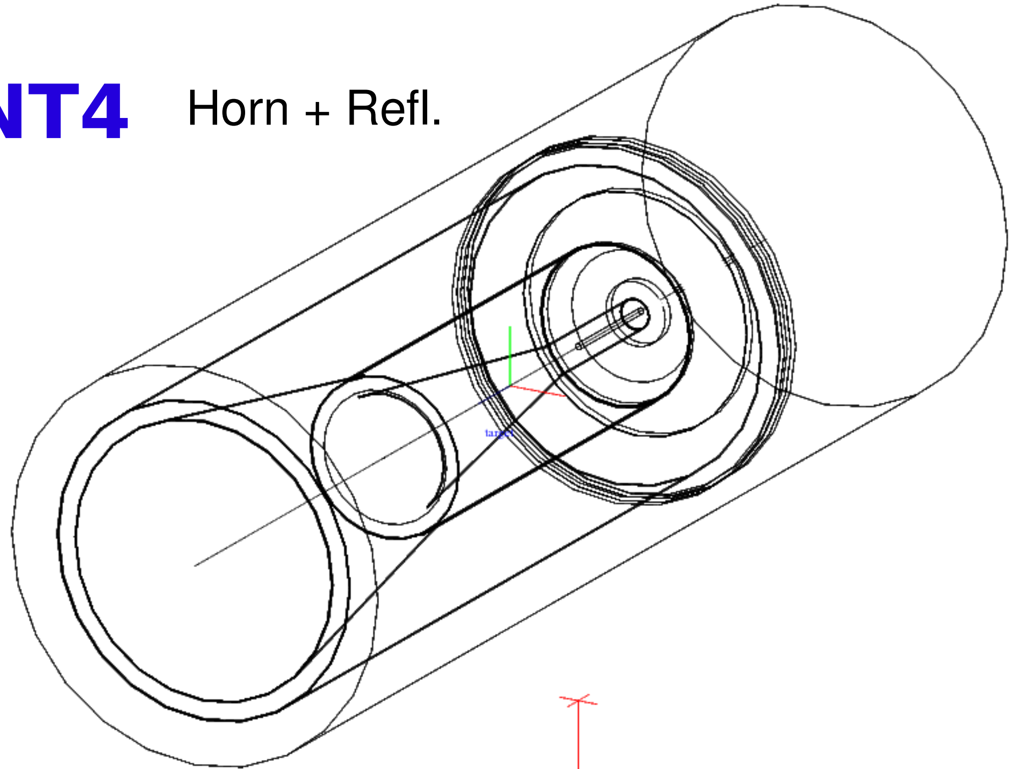
- structure at ~5 GeV for pi- and neutrons

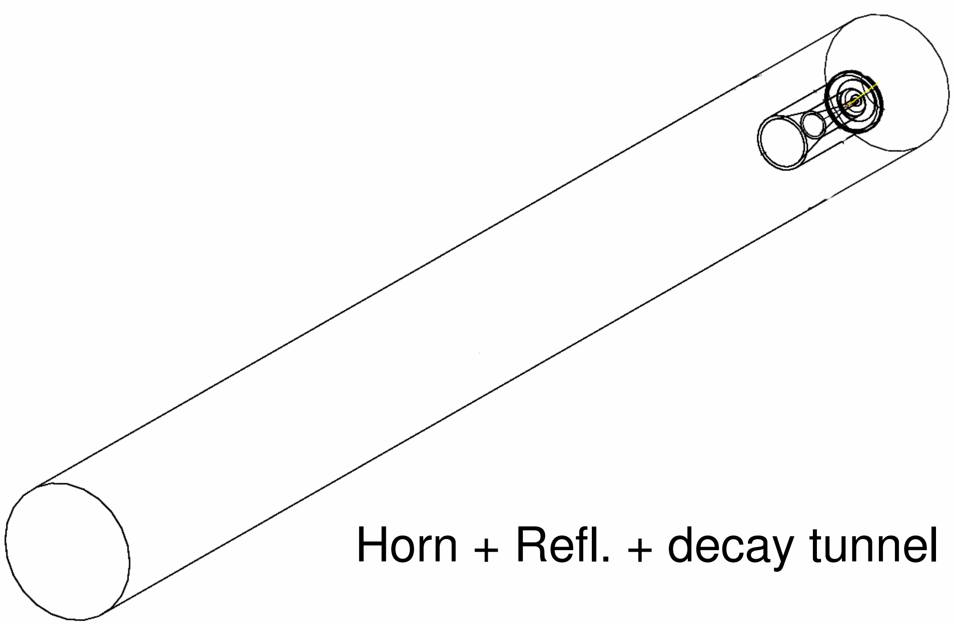


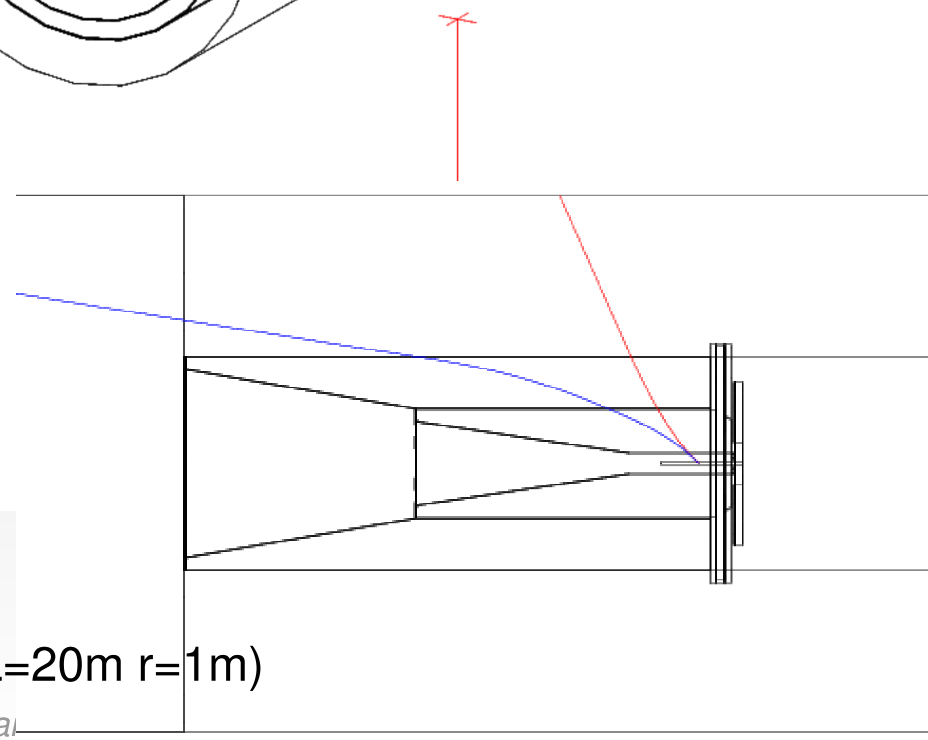
GEANT3.2.1 to GEANT4

- Geometry implemented in GEANT4
- Full migration + comparisons in progress

Horn + Refl.







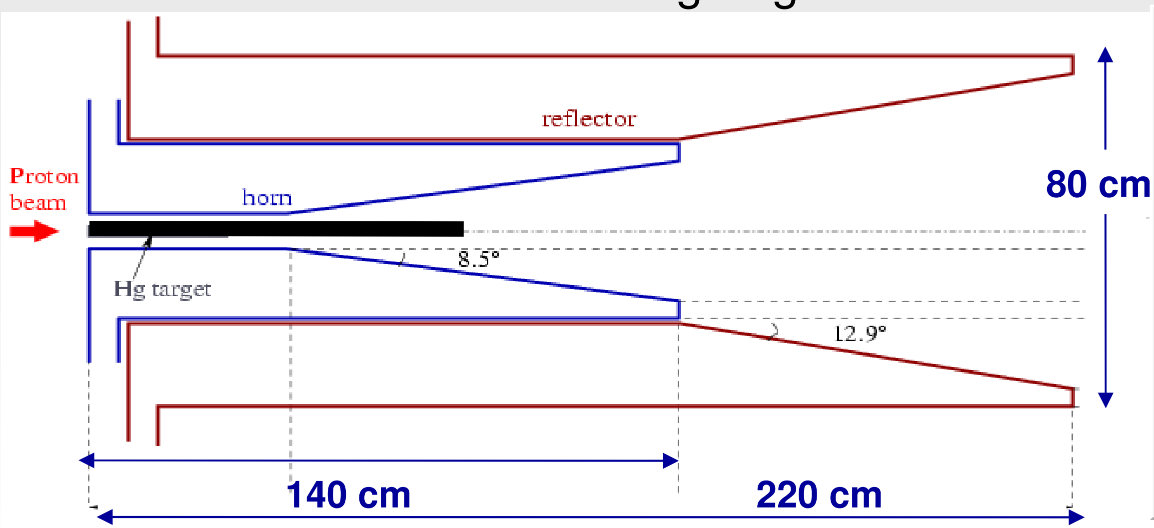
Horn + Refl. + decay tunnel (L=20m r=1m)

- New investigations on the target
  - impact of choosing a graphite target ?
    - Target energy deposition -> Pion yields -> Neutrino fluxes -> sensitivity

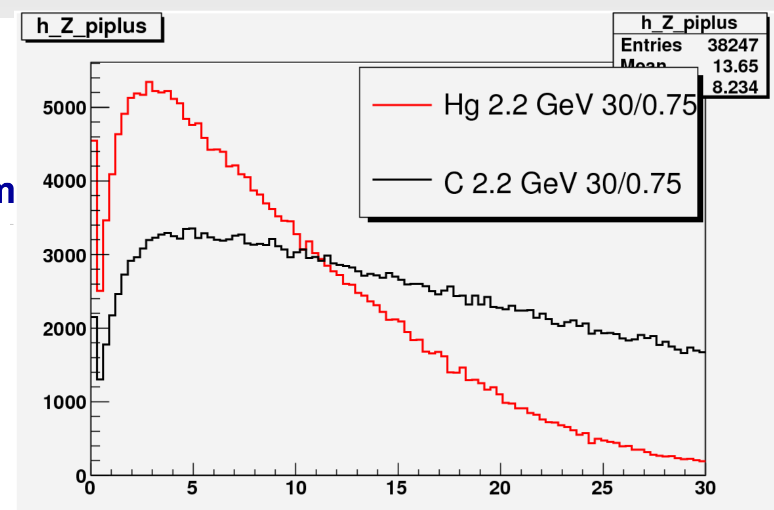
using a graphite target ?

- Important technical aspects of integration of the Hg jet within the horn have not been fully addressed in the present simulation.
- As an exercise, I tried to replace liquid Hg with C **keeping the present setup**..
- ... except for L_{target} : 30 -> 78 cm (i.e. sticking to a ~ $2\lambda_I$ target)
- graphite density : 1.85 g/cm3 (as in the T2K target – IG43 by ToyoTanso)
- Covered items:
  - Power dissipation / pion yield / kaon yield / pi+ collection + ν fluxes

Horn + Refl. + 78 cm long target



Z of pi+ exiting the target



Simulation tools & settings

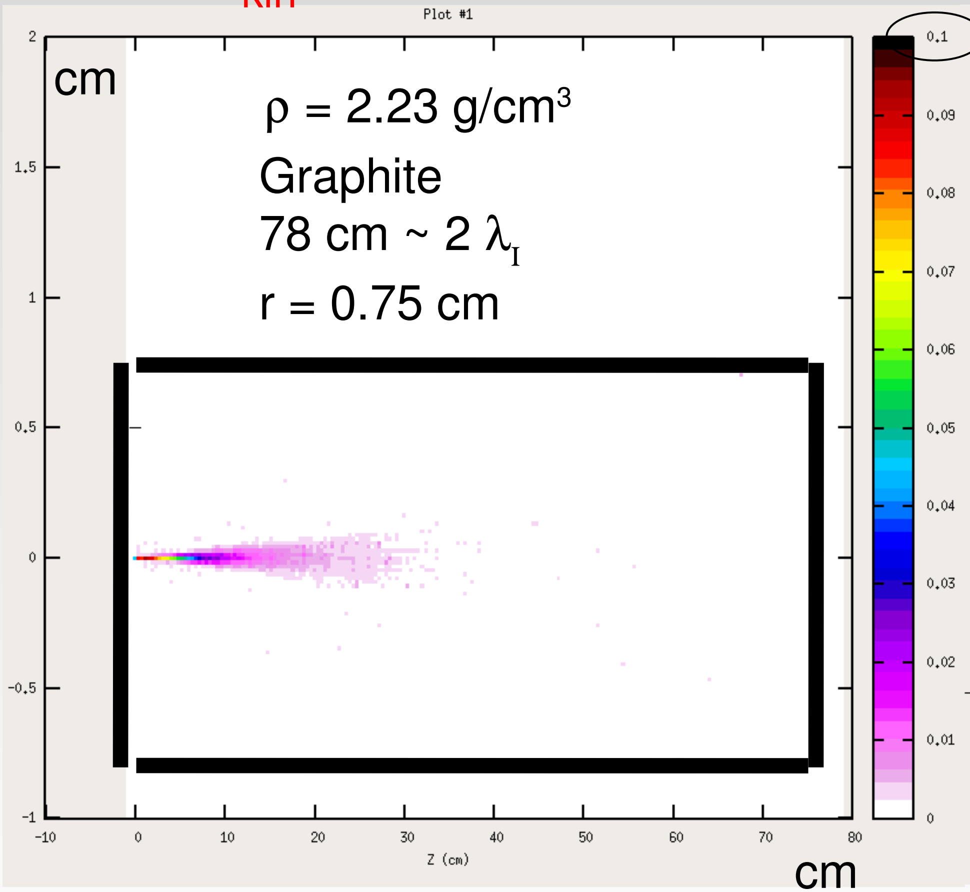
- Primary event: FLUKA 2008.3 (latest)
- Energy deposit in the target: GEANT4 and FLUKA 2008.3
- Pion focusing + decay+ neutrino fluxes: GEANT3. Same setup used in the studies performed by Antoine Cazes but input is now given through FLUKA2008 ascii-files (2002.4 for the previous simulation)
- Sensitivities: GloBes-3.0.13 (latest)
- Used configuration: “350 MeV”-horn (longer one) with $L_{tun} = 40$ m $r_{tun} = 2$ m

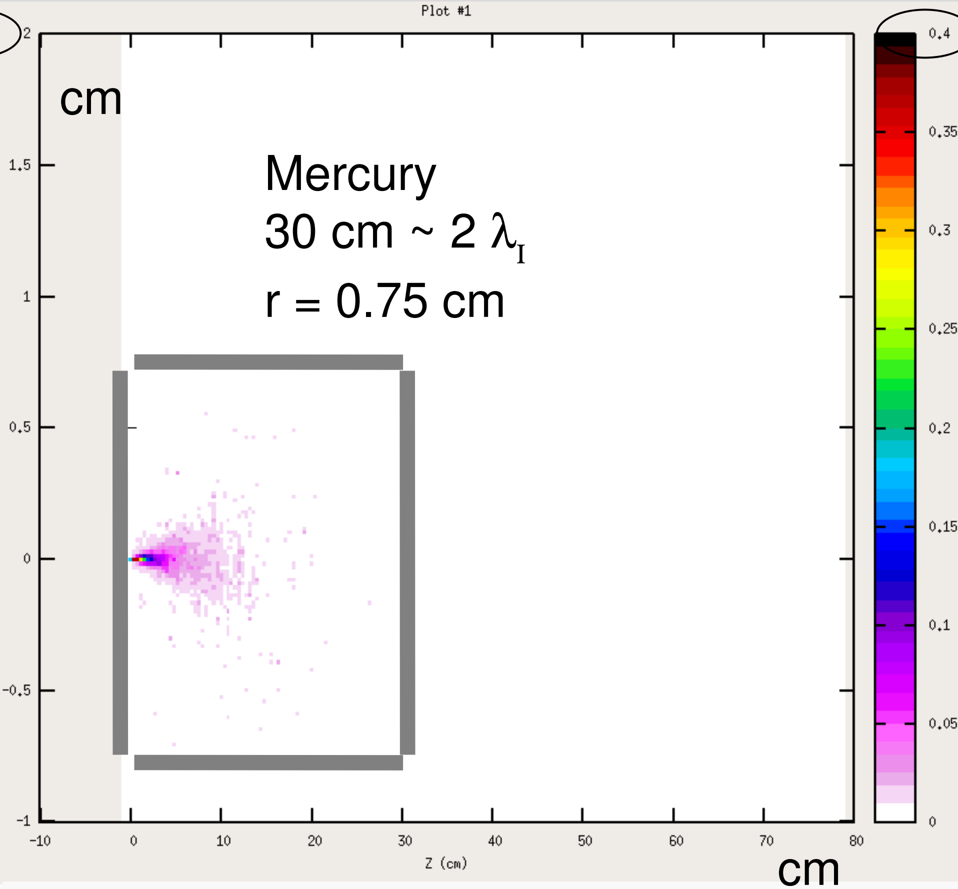
Graphite-Mercury energy deposition: FLUKA08

- (GeV/cm^3/proton)

$E_{kin} = 2.2$ GeV

NB. “pencil-like” beam



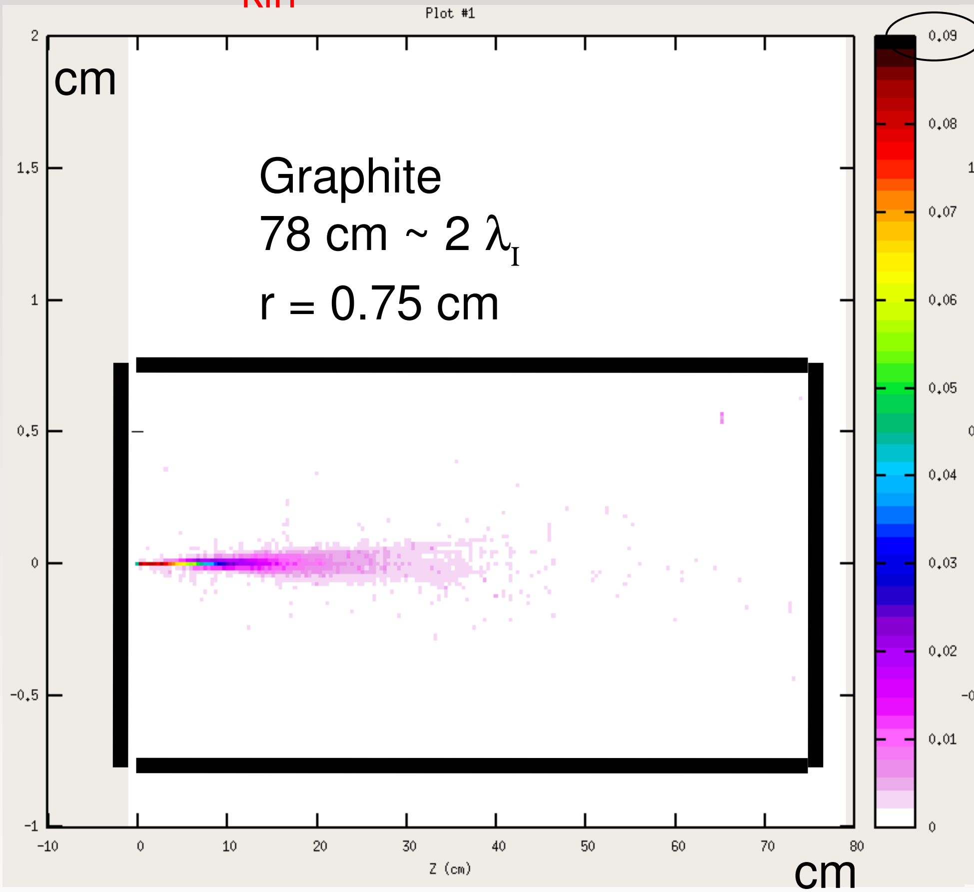


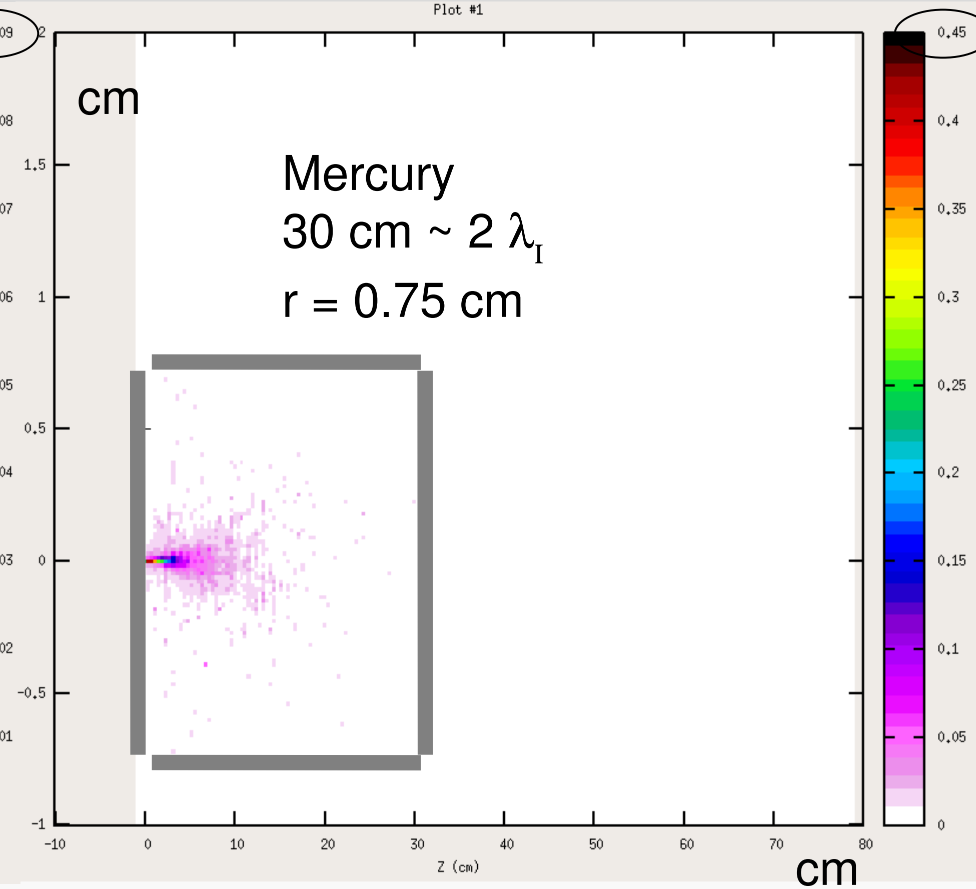
Graphite-Mercury energy deposition: FLUKA08

- (GeV/cm³/proton)

E_{kin} = 3.5 GeV

NB. “pencil-like” beam



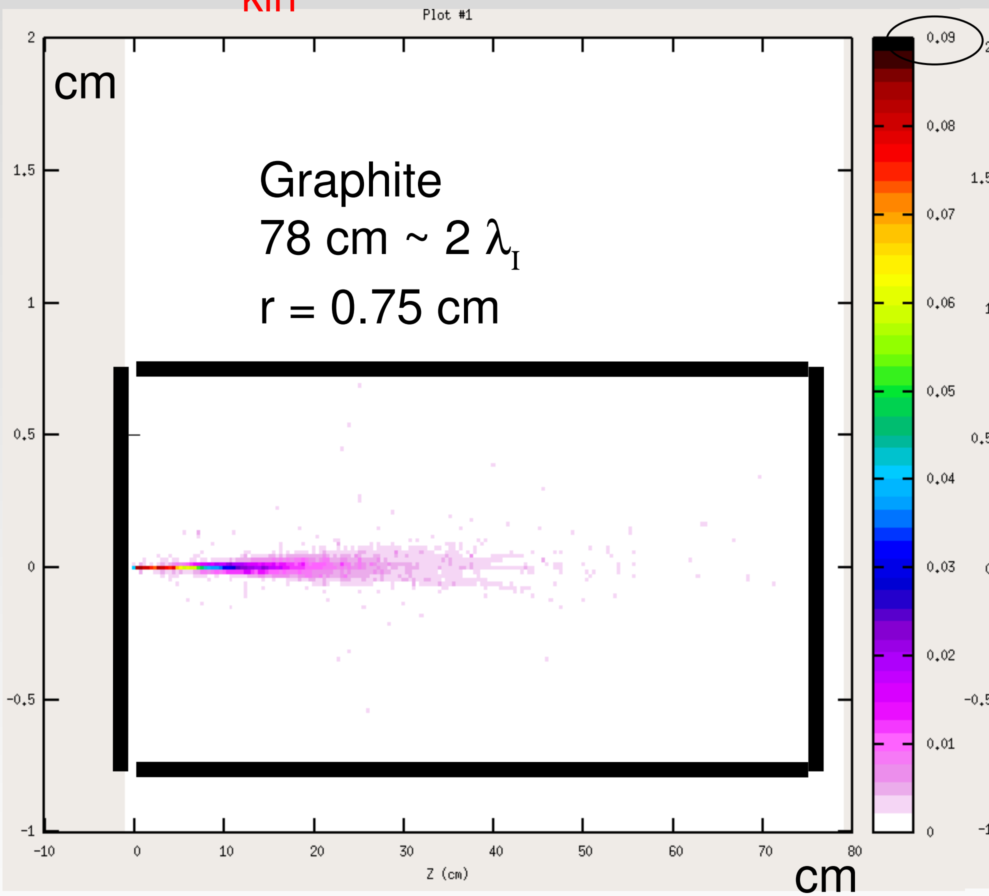


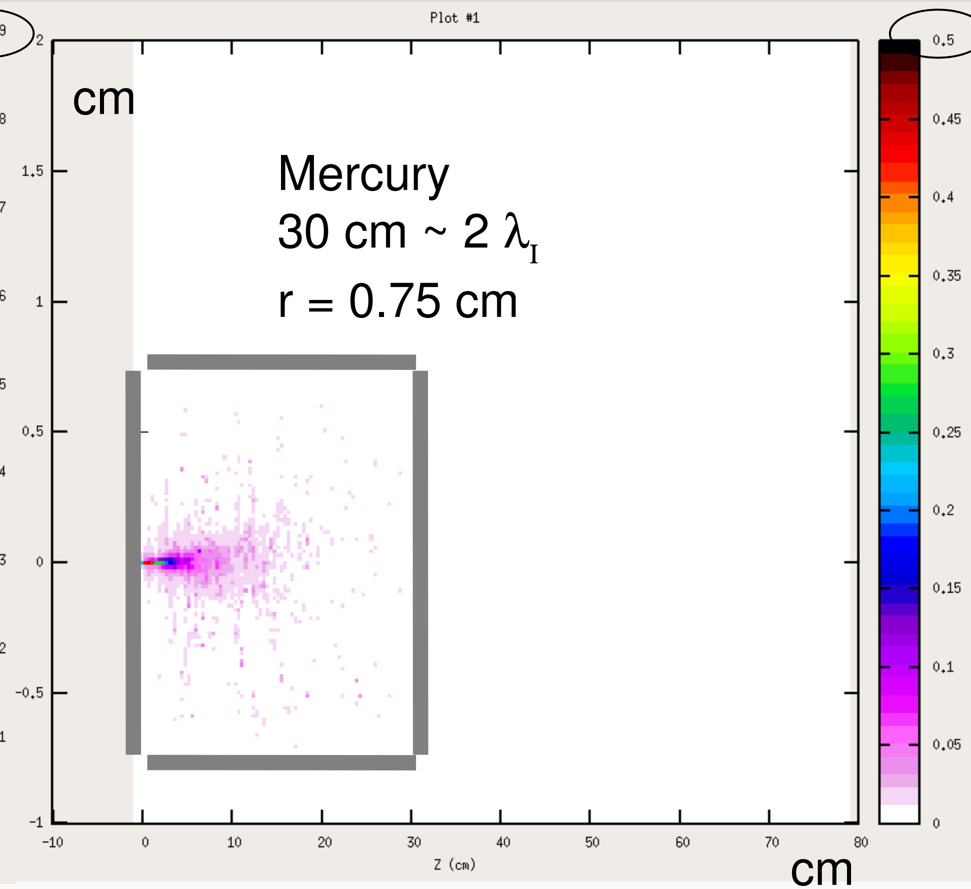
Graphite-Mercury energy deposition: FLUKA08

- (GeV/cm³/proton)

E_{kin} = 4.5 GeV

NB. "pencil-like" beam



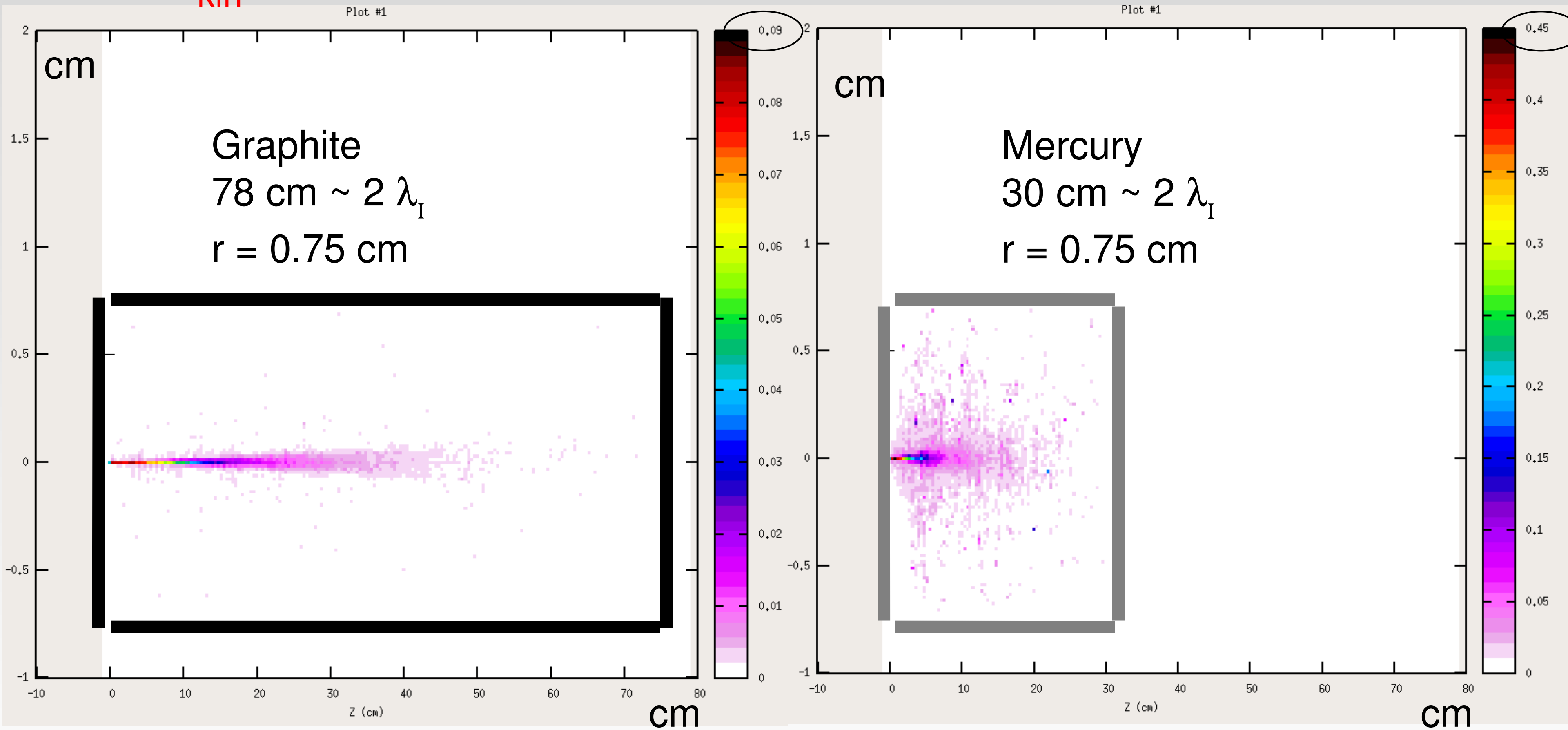


Graphite-Mercury energy deposition: FLUKA08

- (GeV/cm³/proton)

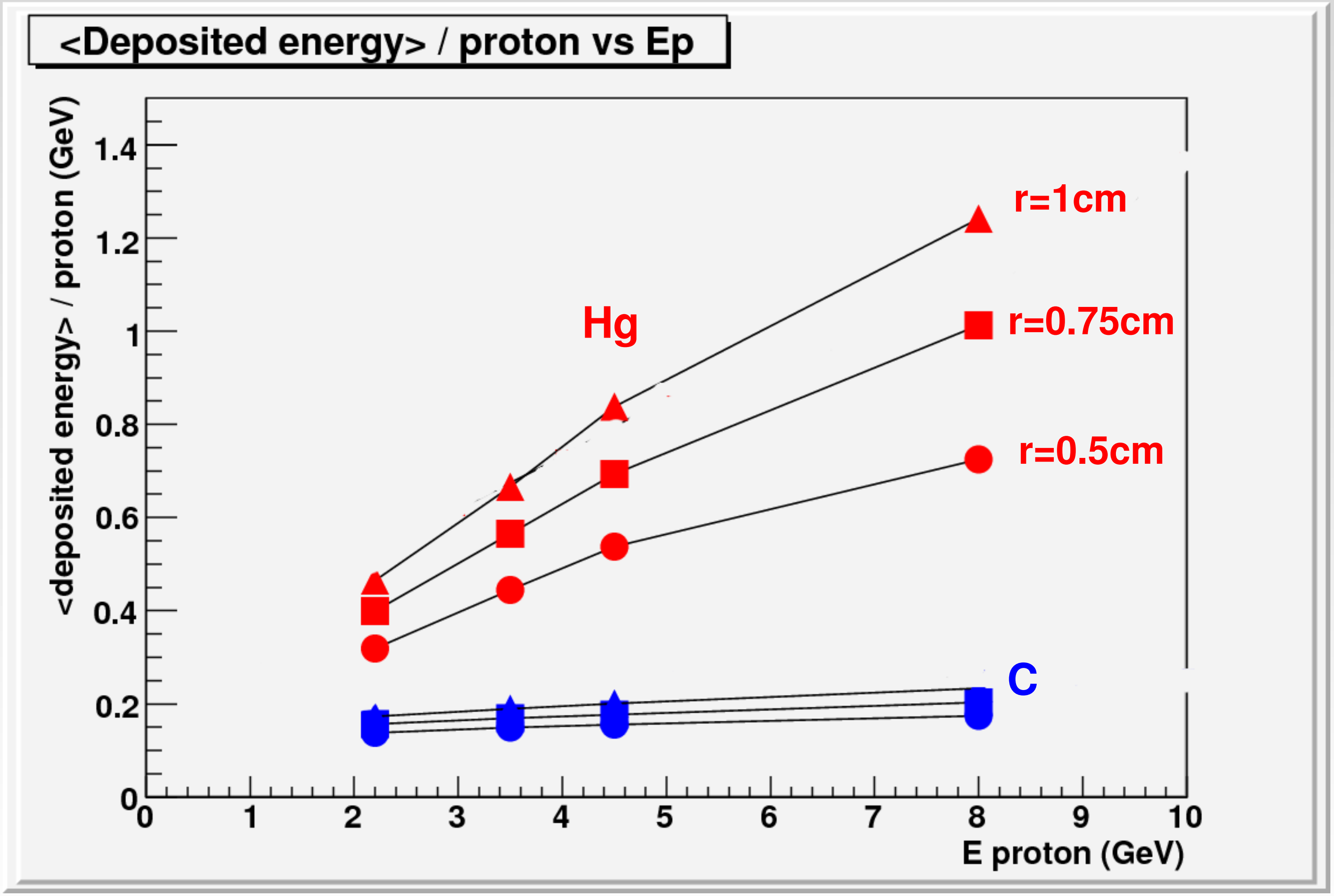
E_{kin} = 8.0 GeV

NB. “pencil-like” beam



Graphite-Mercury energy deposition: FLUKA08

- Target radius: 0.5-0.75-1.0 cm



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

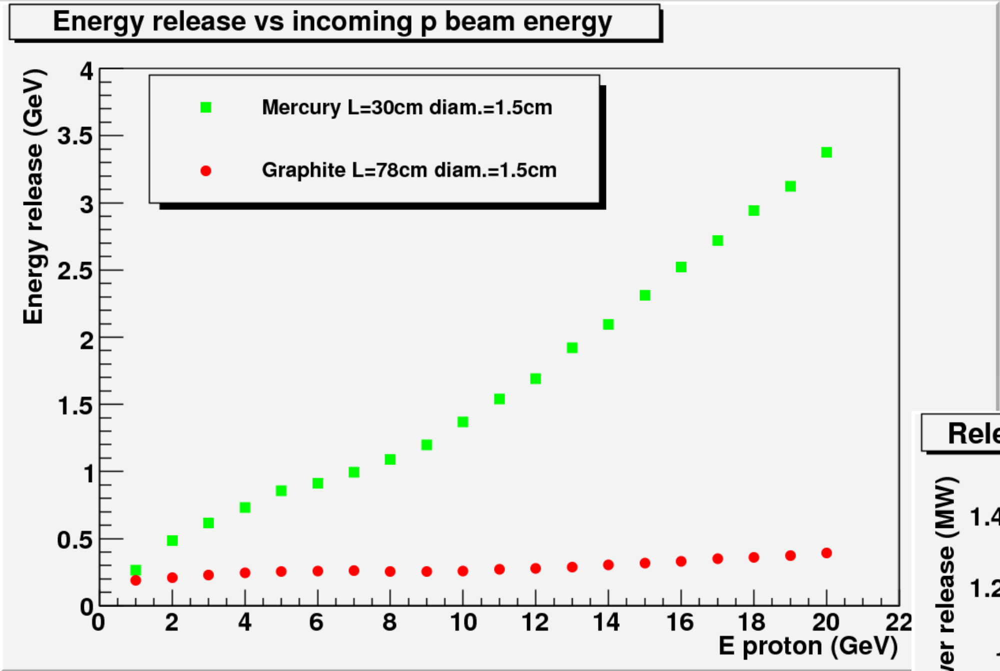
x-axis: 0-2 GeV

peak: ionization loss of elastic or not-interacting p

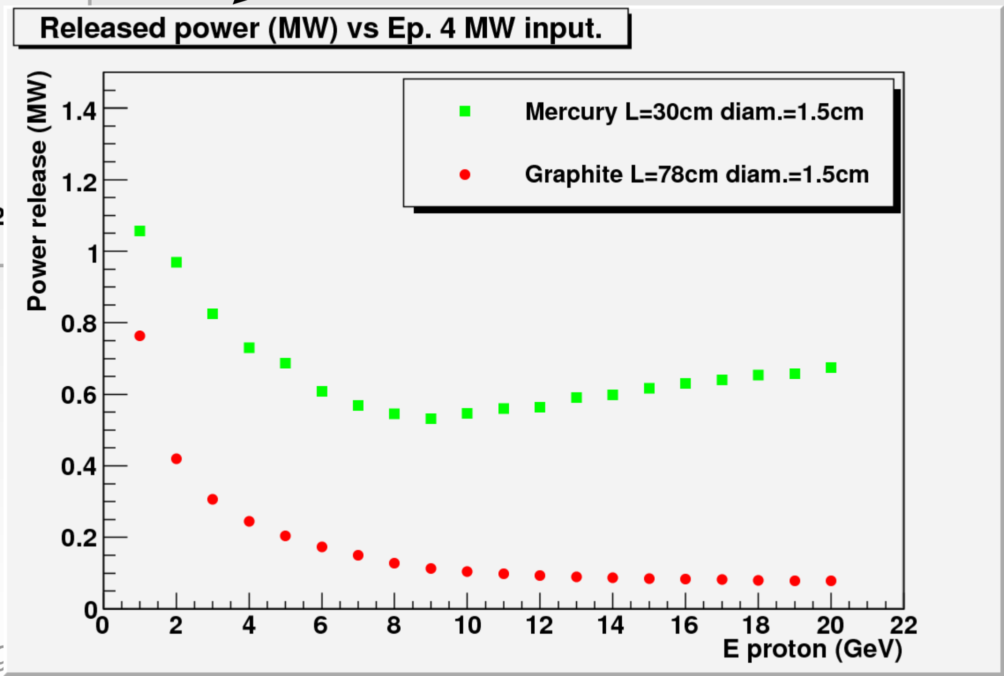
Graphite-Mercury energy deposition: GEANT4

GEANT4 (hadronic "QGSP physics list")

- Mean energy deposition vs Ek(p)



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



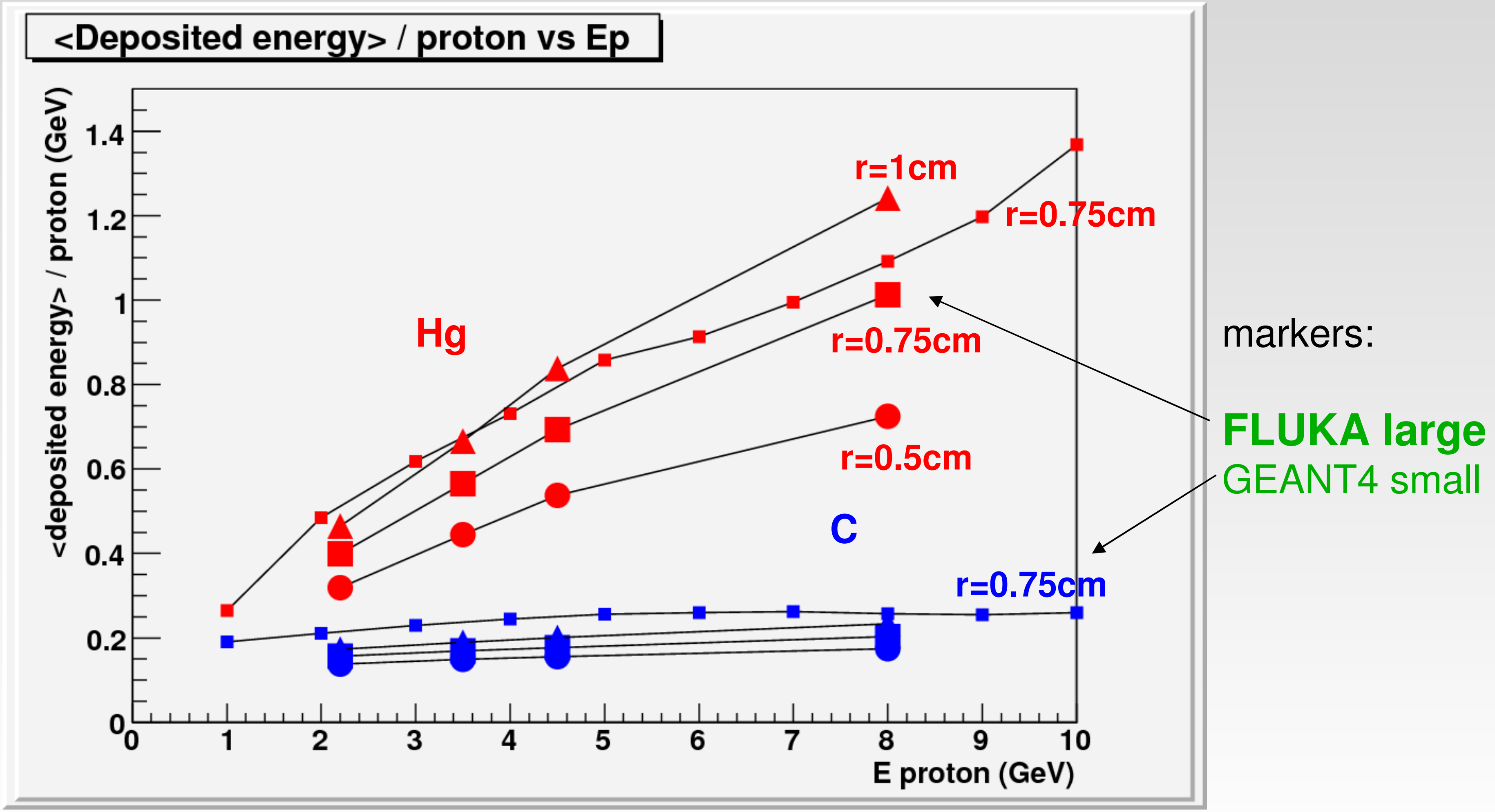
Power released in target:

Hg: ~ 1 - 0.6 MW for Hg
C : ~ 0.8 - 0.1 MW

considerably lower for Carbon

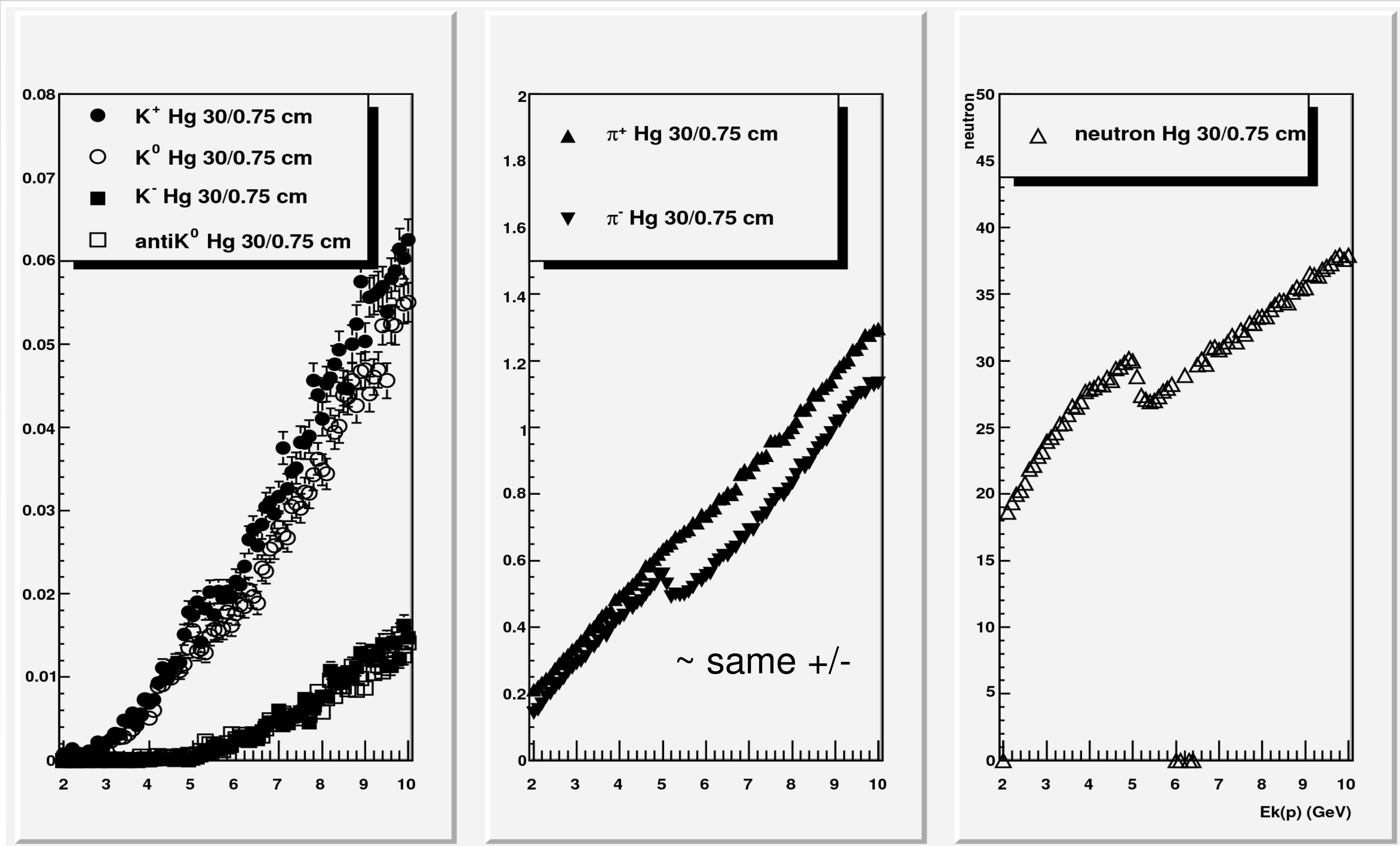
Graphite-Mercury energy deposition: G4/FLUKA08

- G4 larger than FLUKA. ~ +10% for Mercury
- General trend is confirmed
- r = 0.5 / 0.75 / 1.0 cm



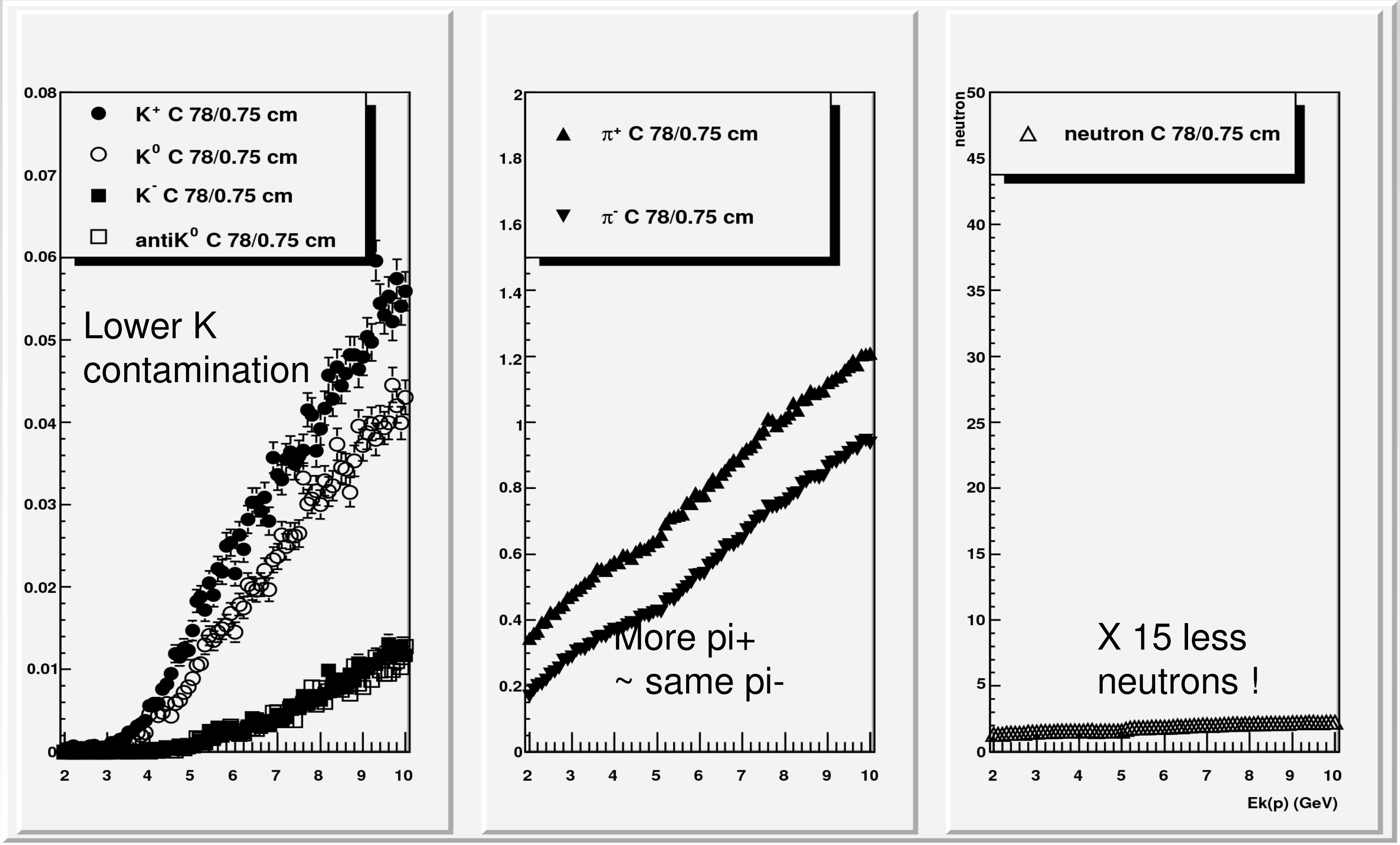
Particle multiplicities: FLUKA 2008

- Mercury



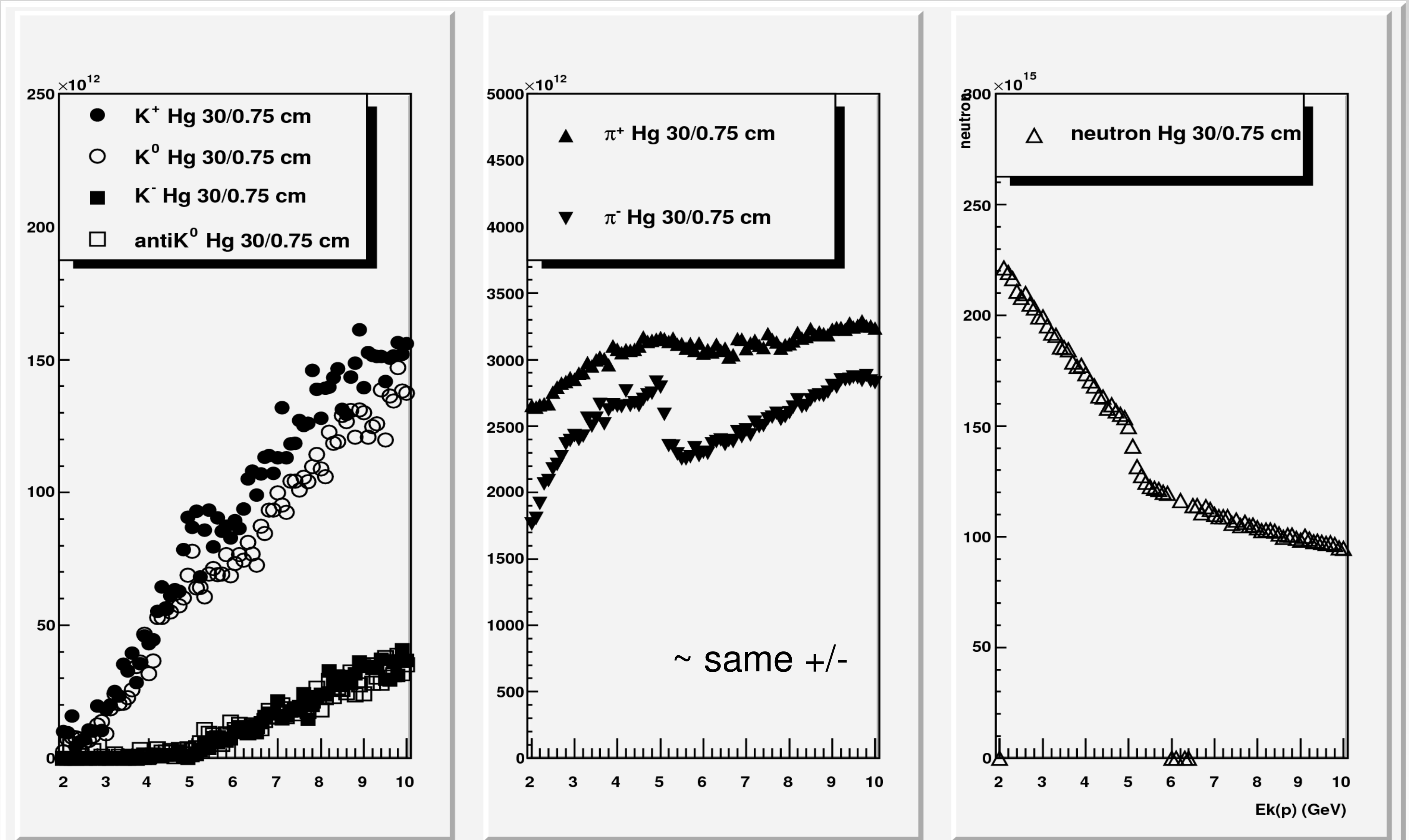
Particle multiplicities: FLUKA 2008

- Carbon



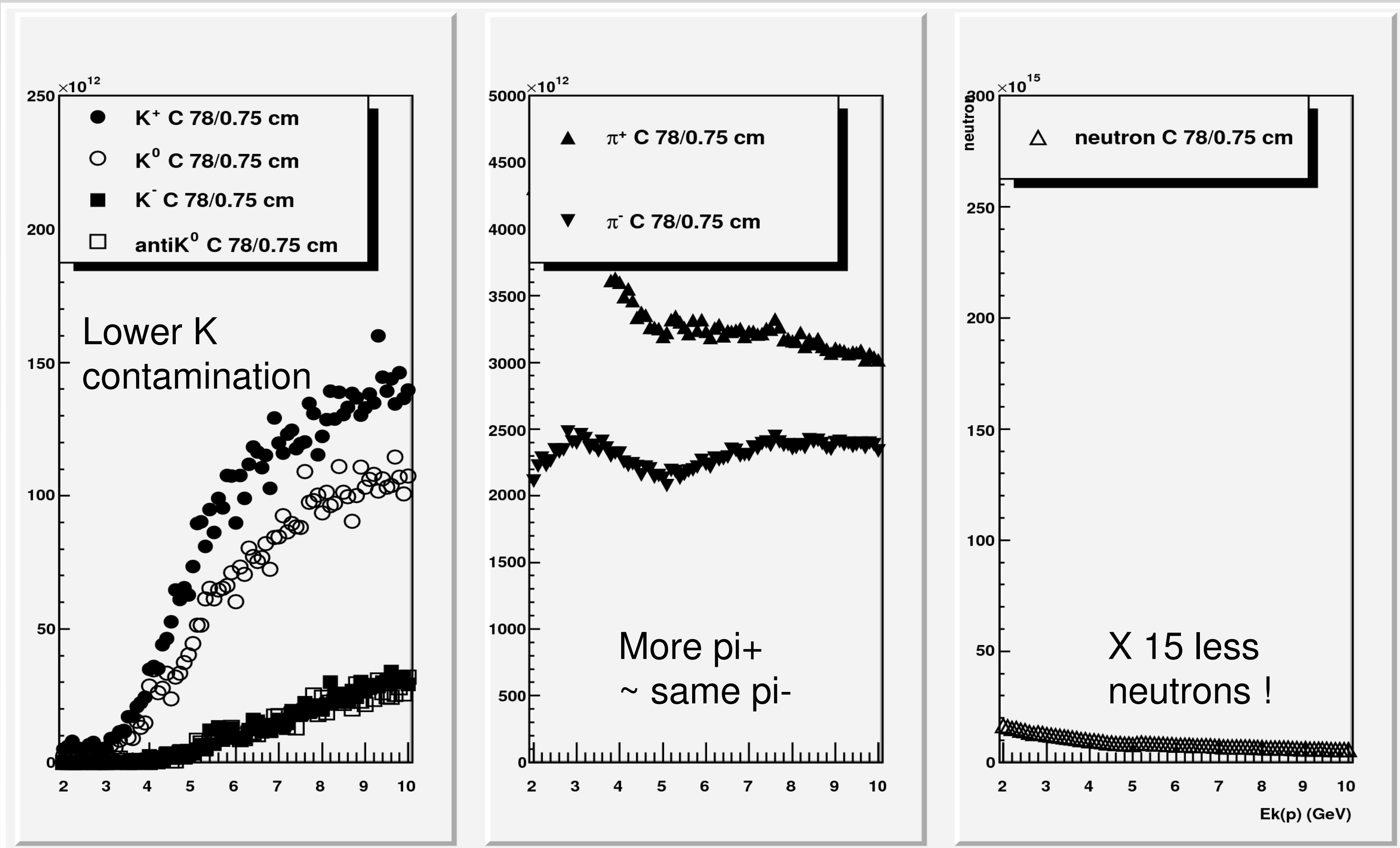
Particle yields: FLUKA 2008

- Mercury



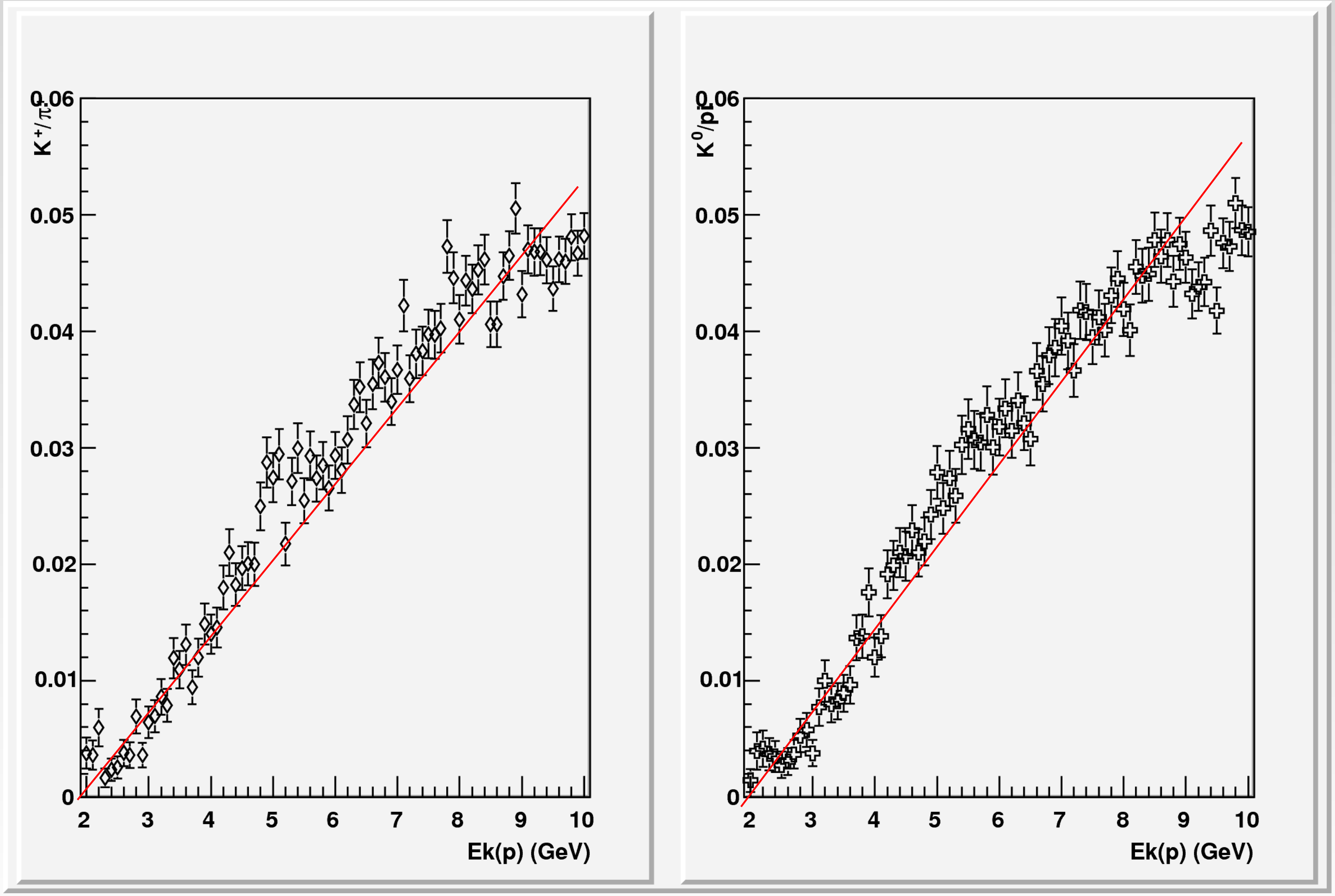
Particle yields: FLUKA 2008

- Carbon



K/pi ratios vs E (FLUKA 2008)

- Mercury
  - K+/pi+ and K0/pi-



K/pi ratios vs E (FLUKA 2008)

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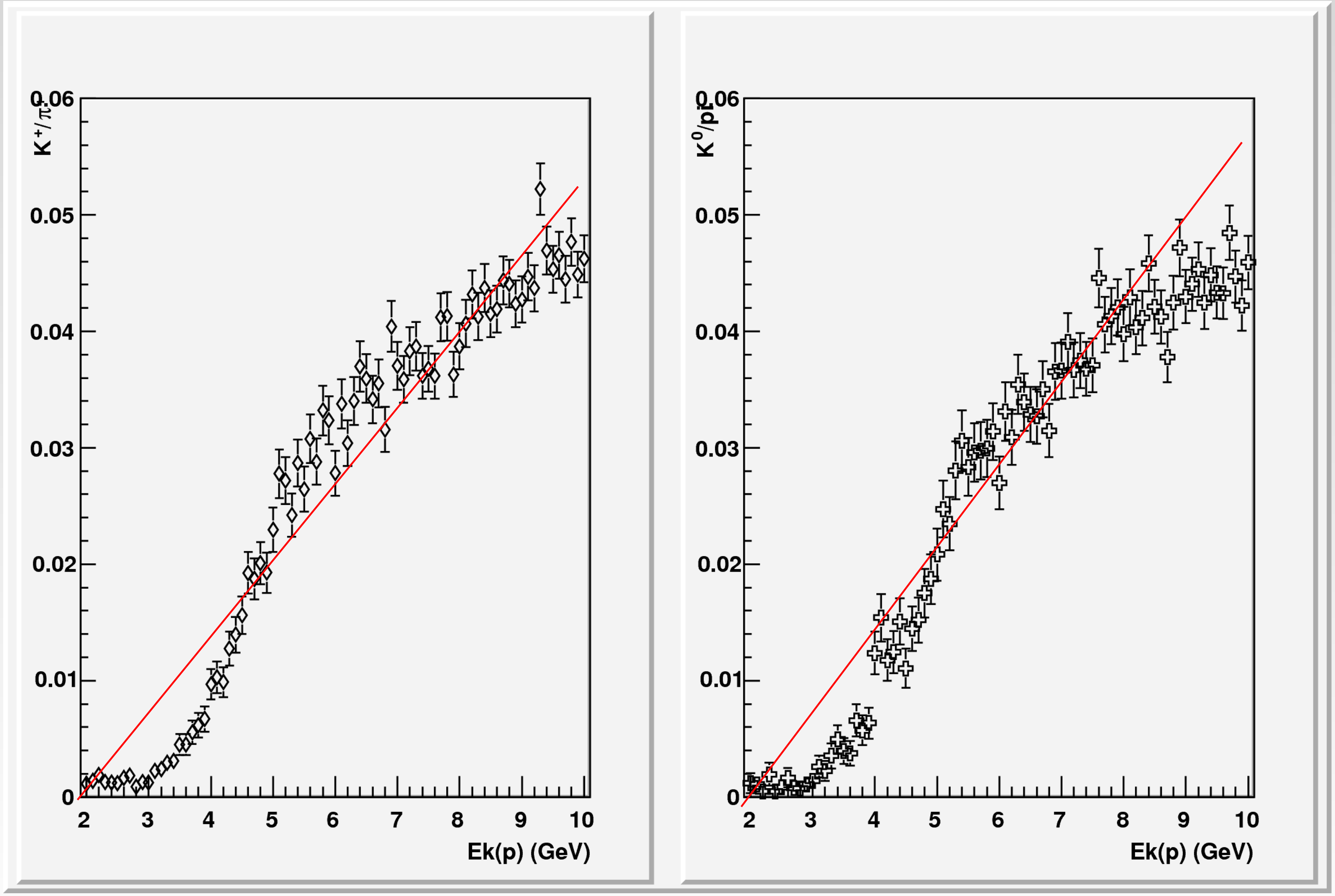
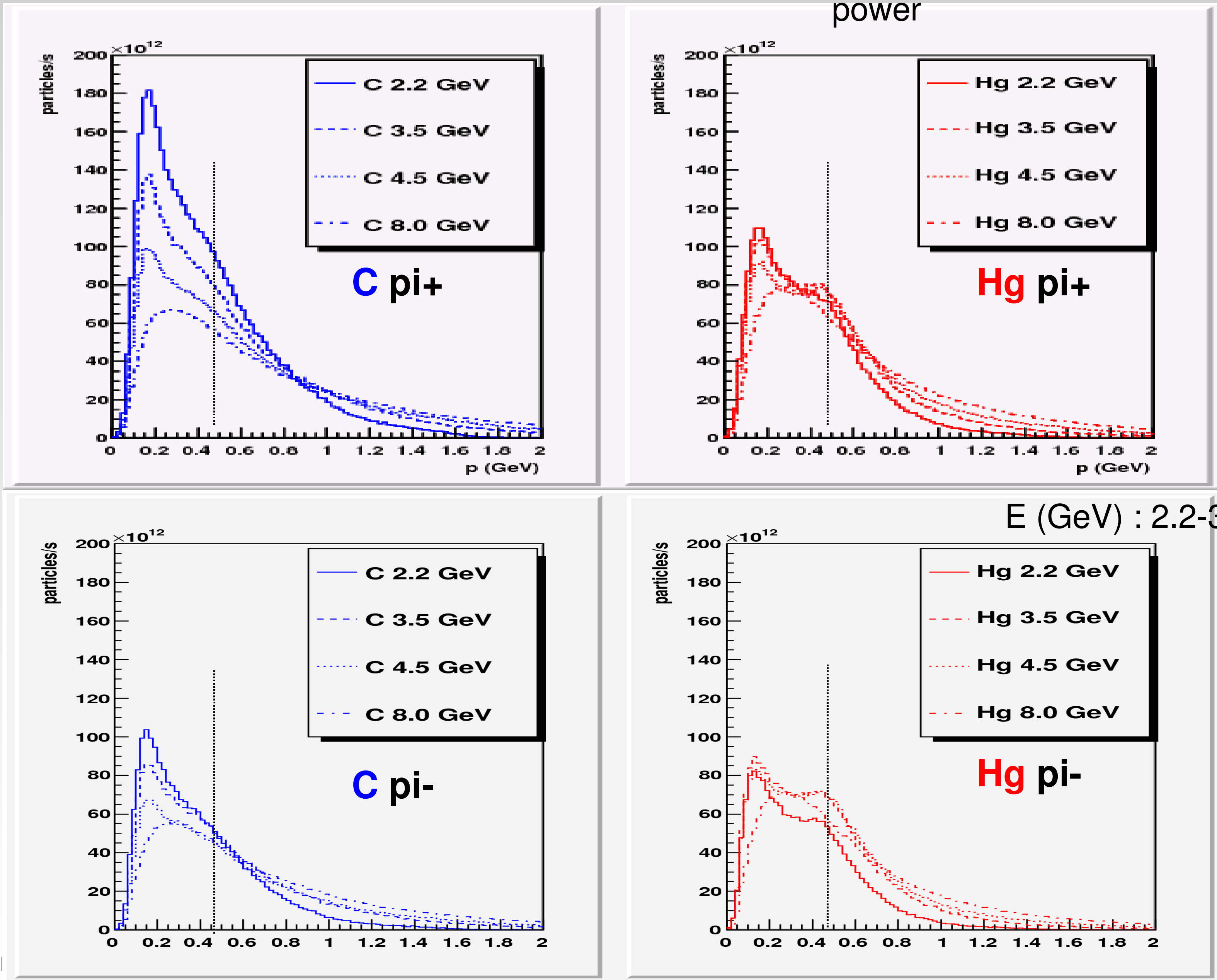


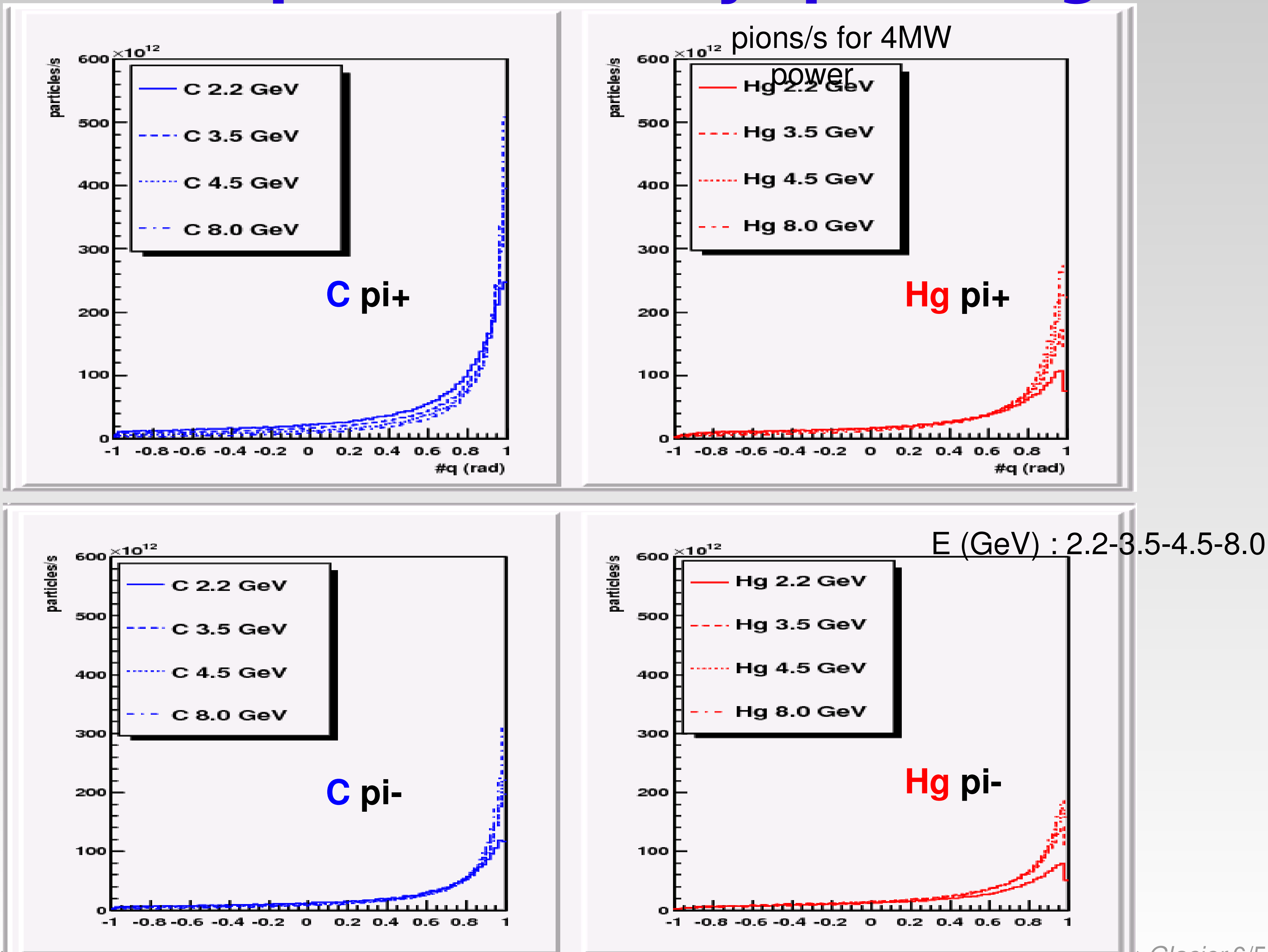
Graphite-Mercury: pion spectra

pions/s for 4MW power



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

Graphite-Mercury: pion angles



Pion multiplicities vs Energy:

C and Hg

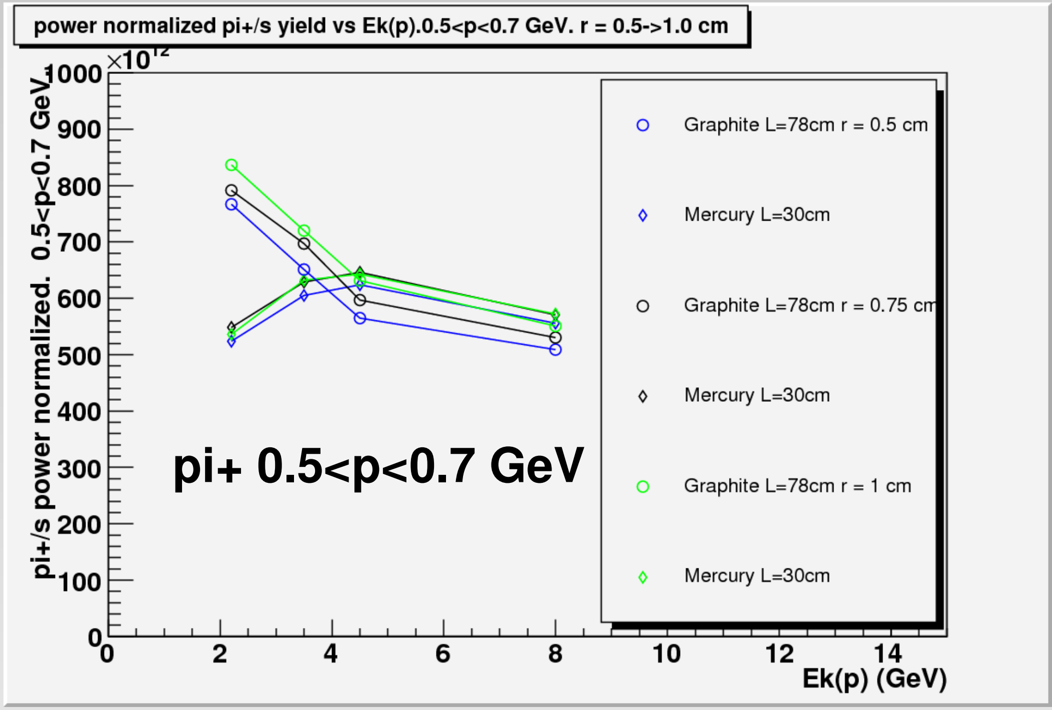
restrict to pions producing neutrino around the oscillation maximum

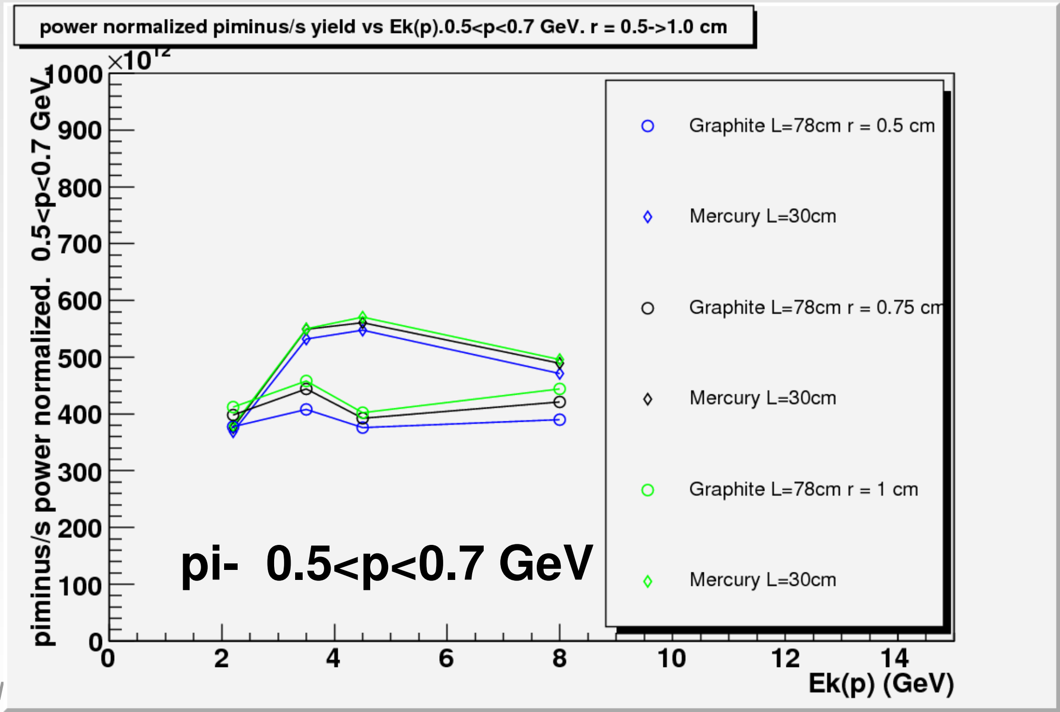
500 < p < 700 MeV

normalized to 4 MW fixed power

More pi+ from carbon at low energy, gets ~ equal at about 4 GeV

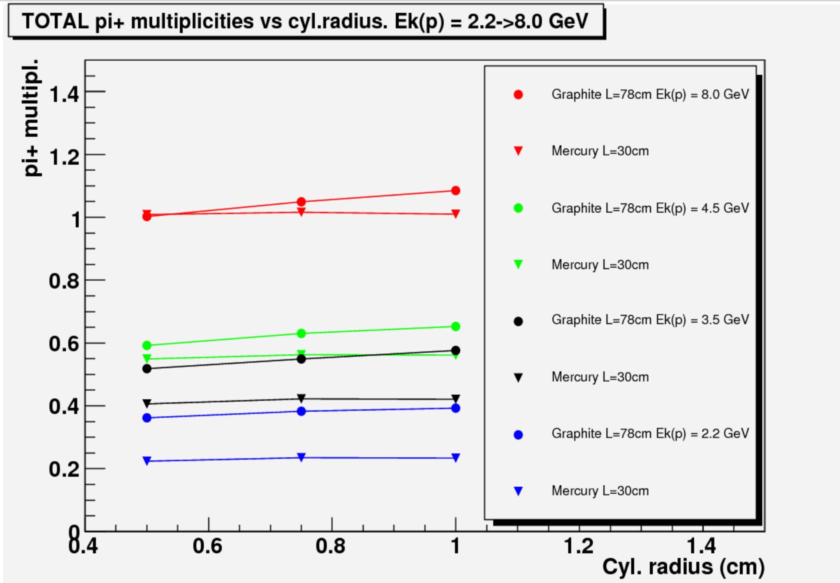
pi- yield similar at low energy (better with Hg at higher energies)

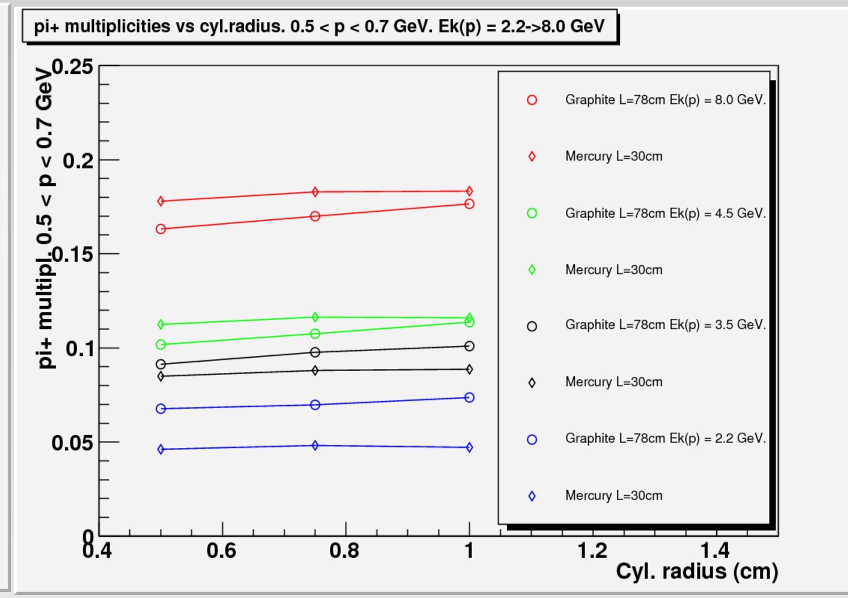


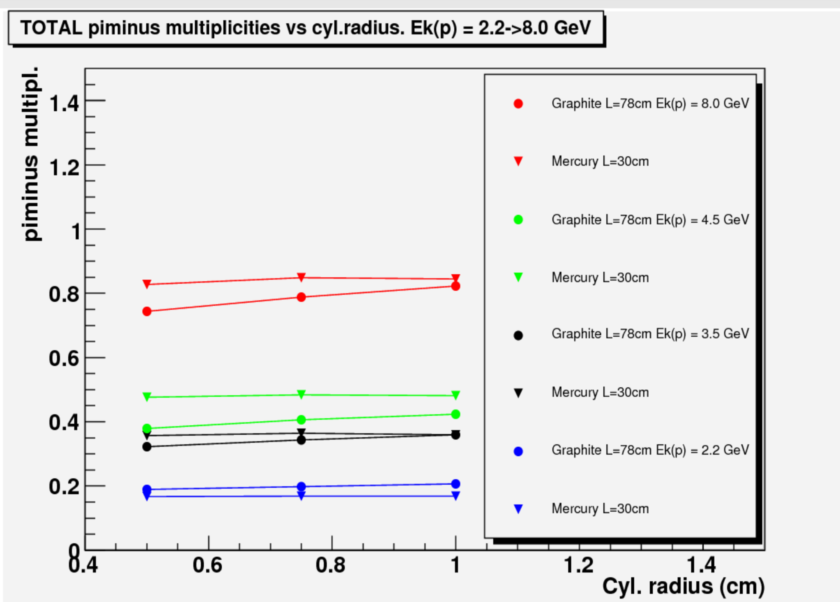


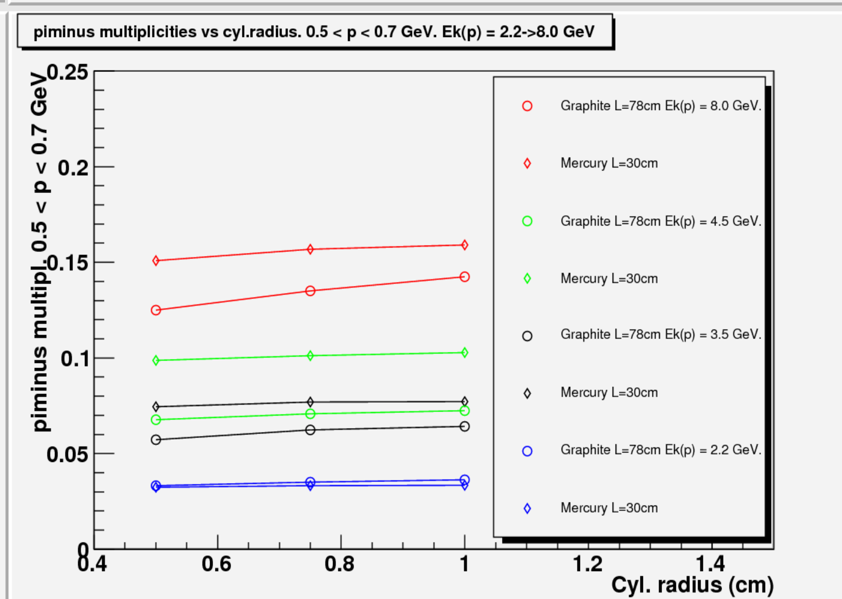
Effect of radius on pion multiplicities

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



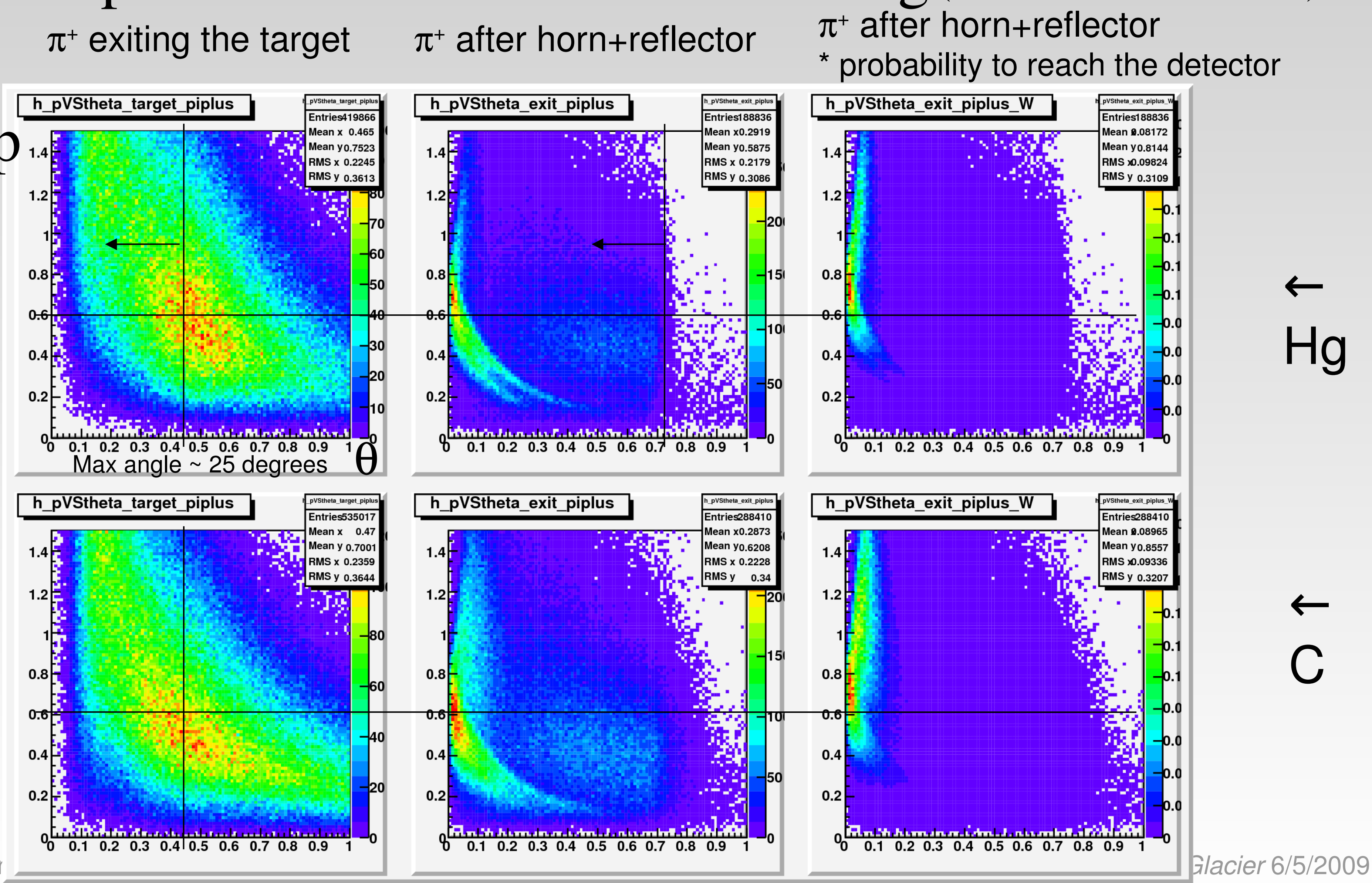






Pi+ collection: Mercury-Graphite

- p vs θ : before and after focusing (4.5 GeV L=30/78 r=0.75)



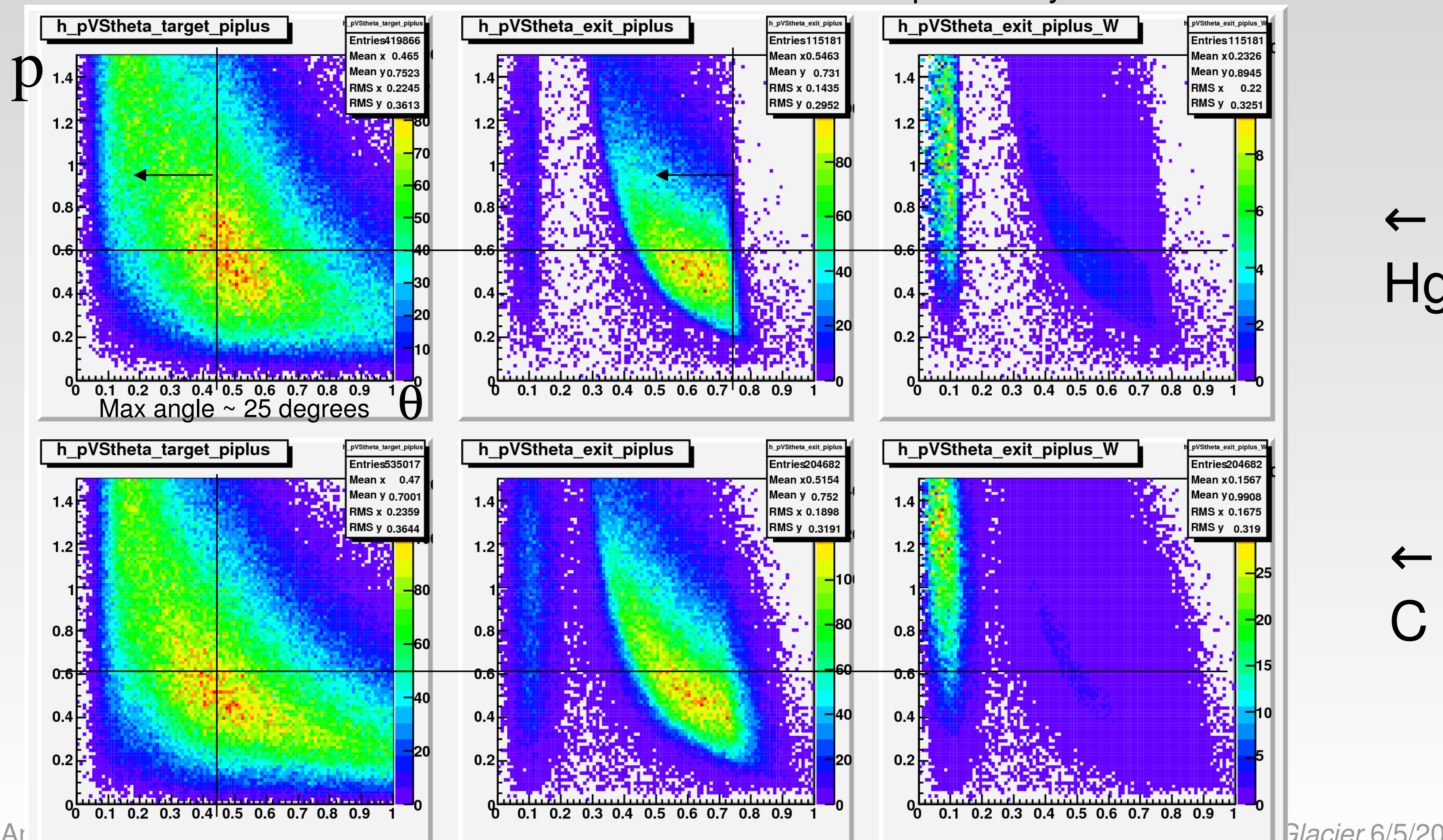
Pi- collection: Mercury-Graphite

- p vs θ : before and after focusing (2.2 GeV L=30 r=0.75)

π^- exiting the target

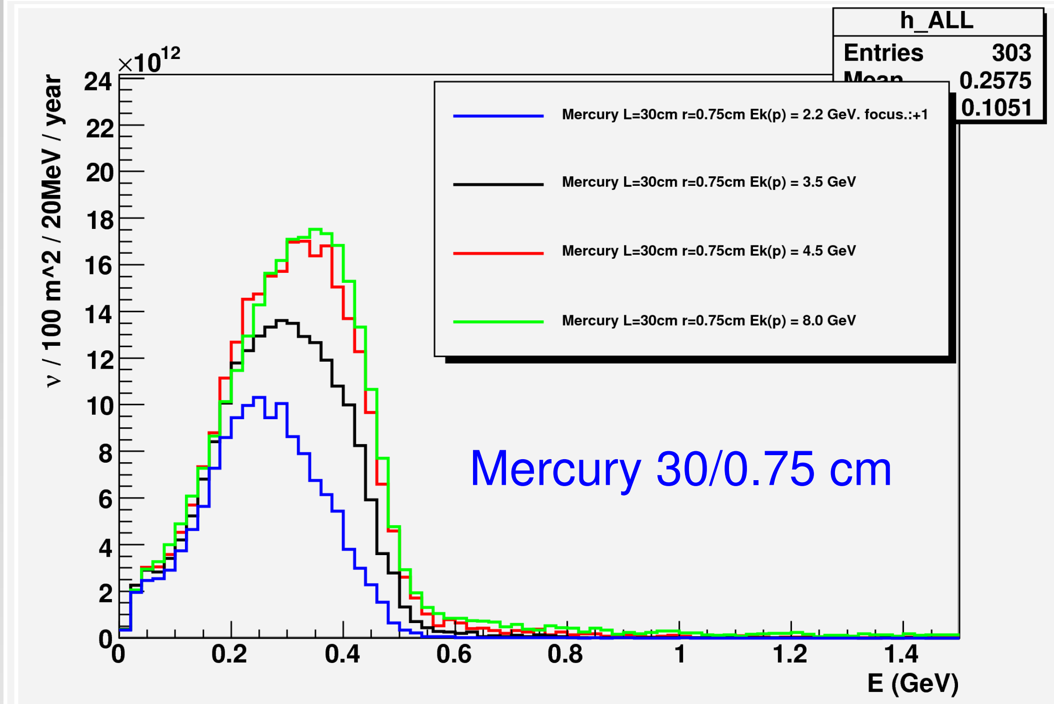
π^- after horn+reflector

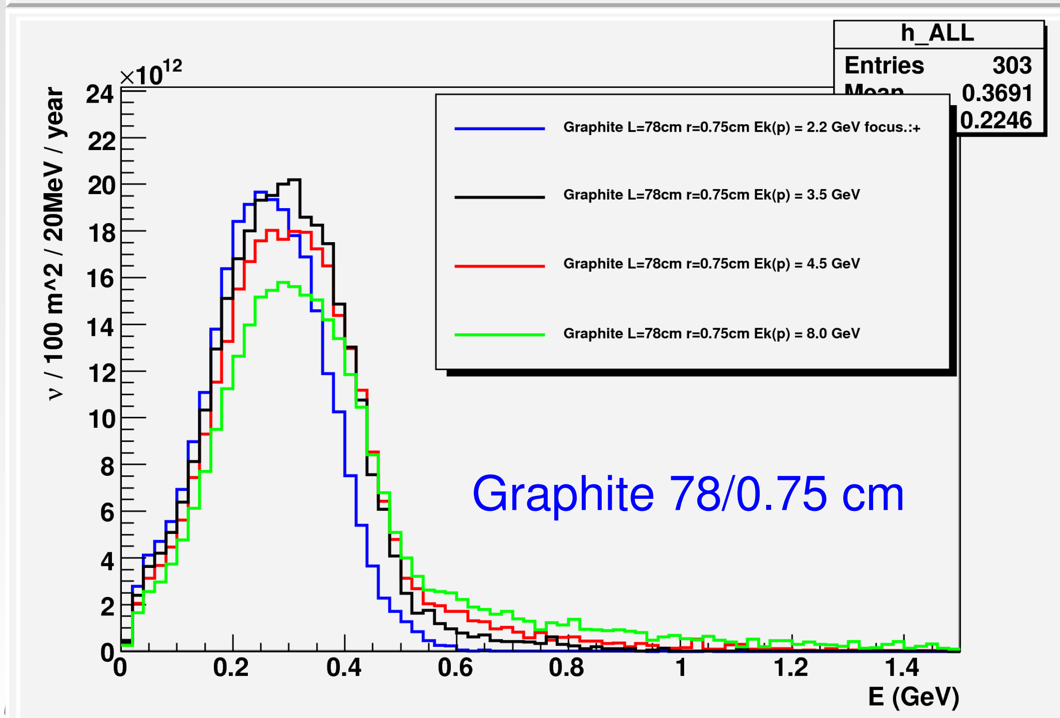
π^- after horn+reflector
* probability to reach the detector



ν_{ALL} fluxes: Mercury-Graphite (+FOCUSING)

- pion yield trends are reflected in fluxes despite non optimized focusing for long Graphite target
- Fluxes intensities are similar
- Slightly higher high energy tail for Graphite (most likely cured with optimized focusing)

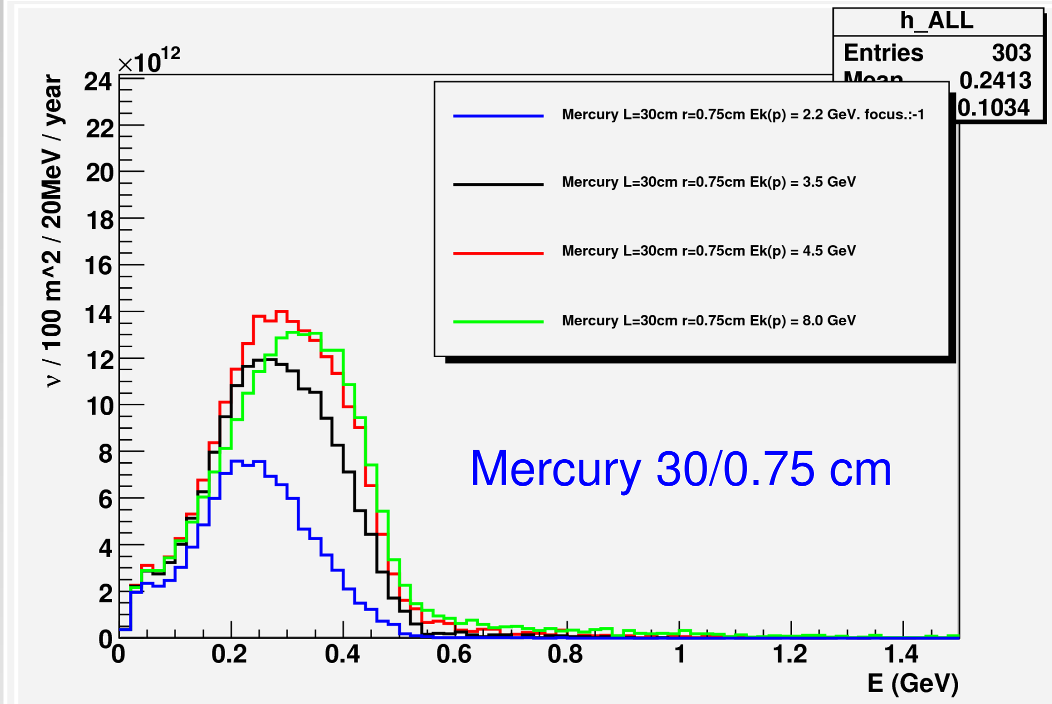


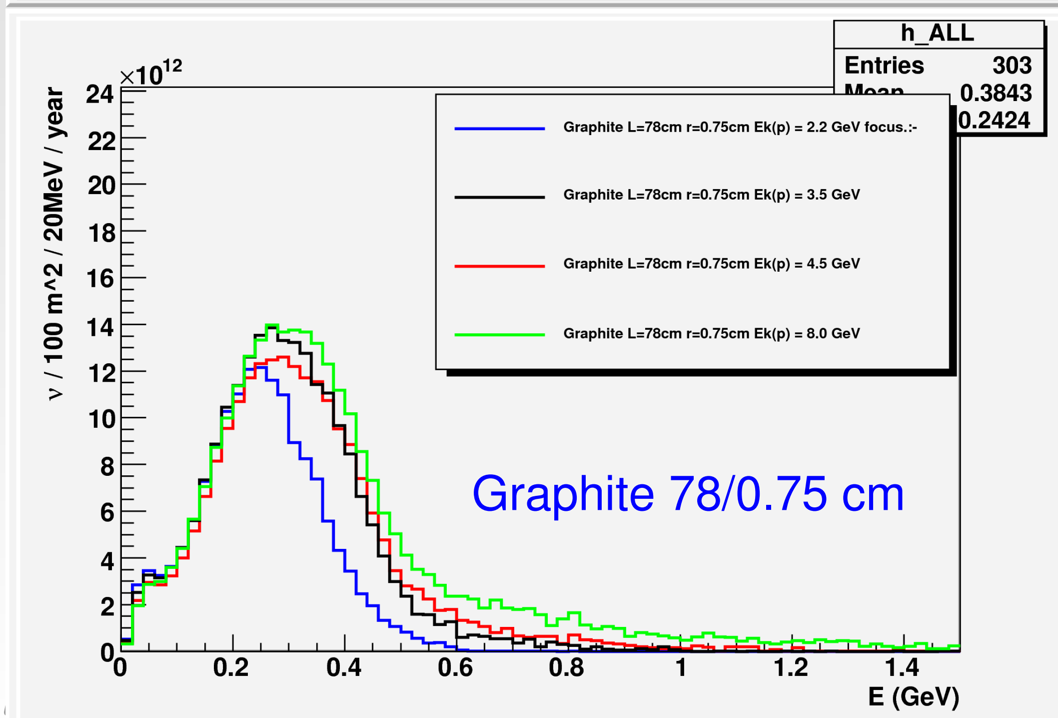


- Positive focusing

ν_{ALL} fluxes: Mercury-Graphite (- FOCUSING)

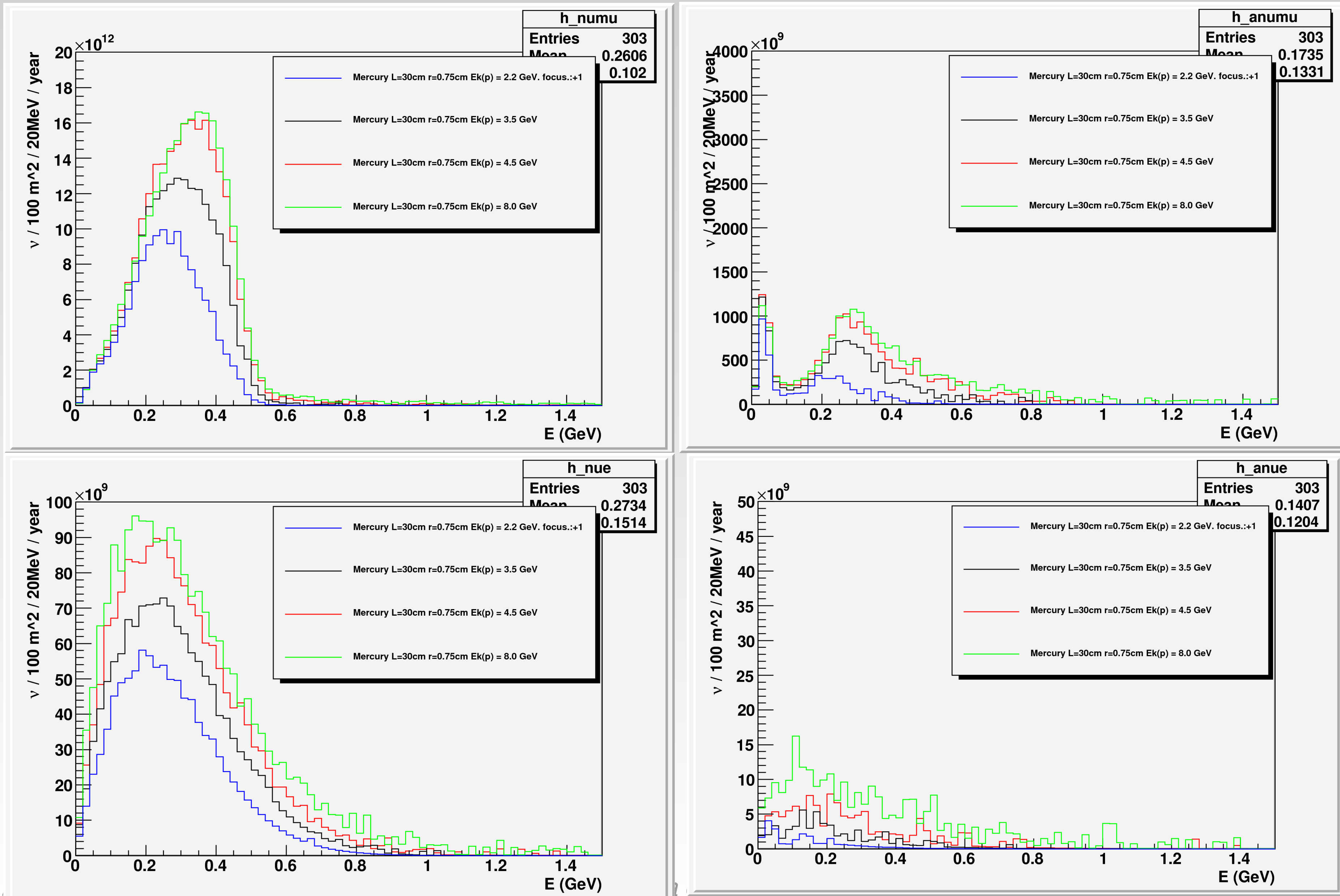
- pion yield trends are reflected in fluxes despite non optimized focusing for long Graphite target
- Fluxes intensities are similar
- Slightly higher high energy tail for Graphite (most likely cured with optimized focusing)



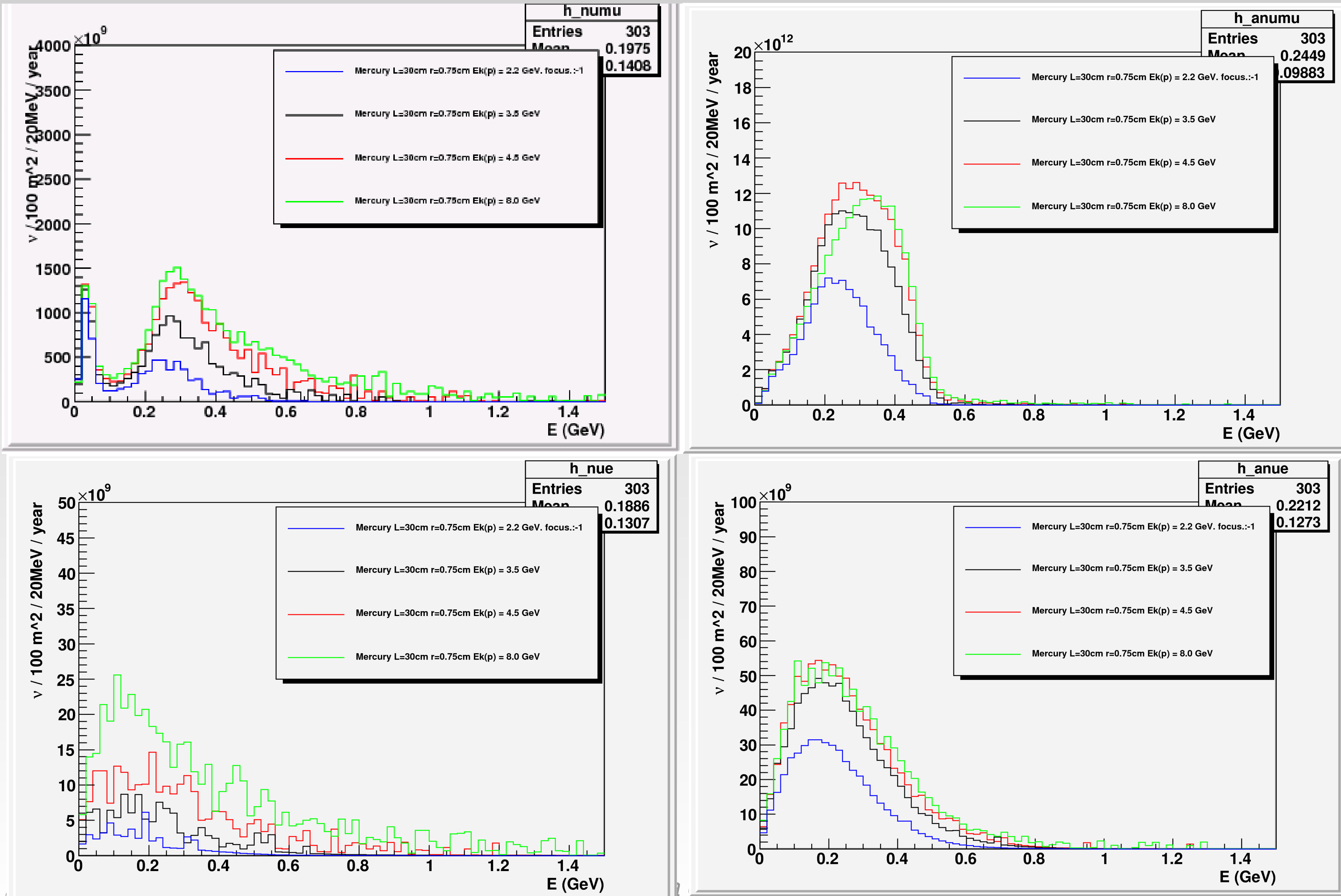


- Negative focusing

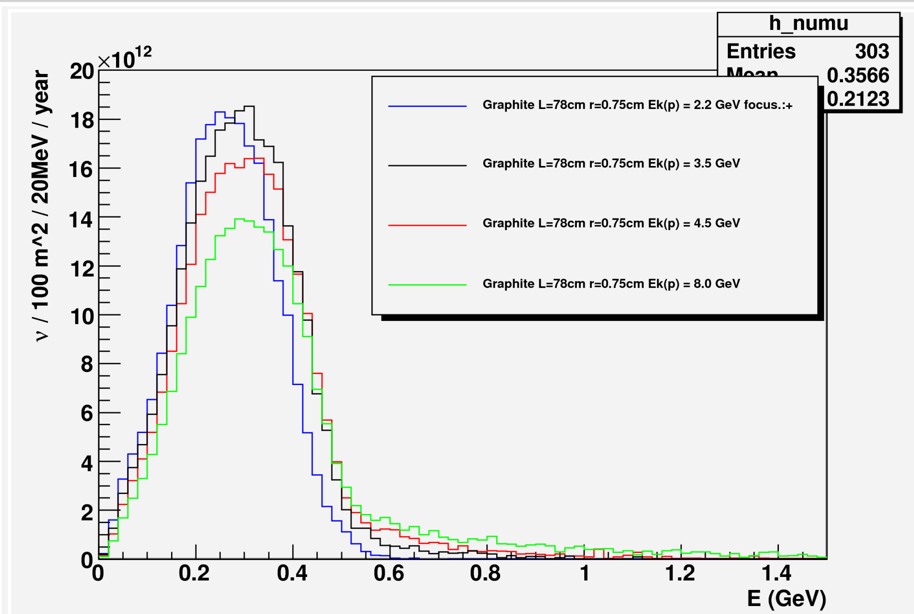
ν fluxes: Mercury (+ FOCUSING)

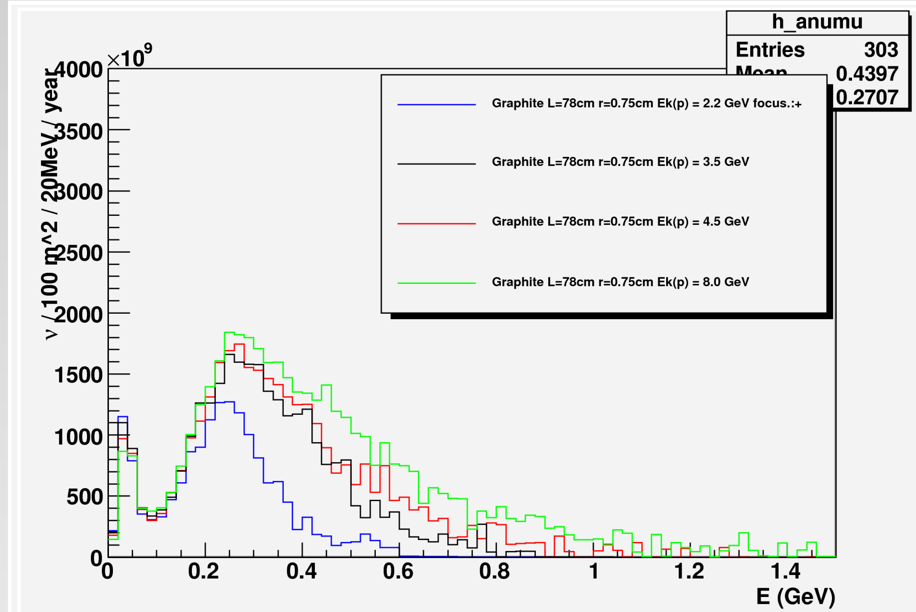


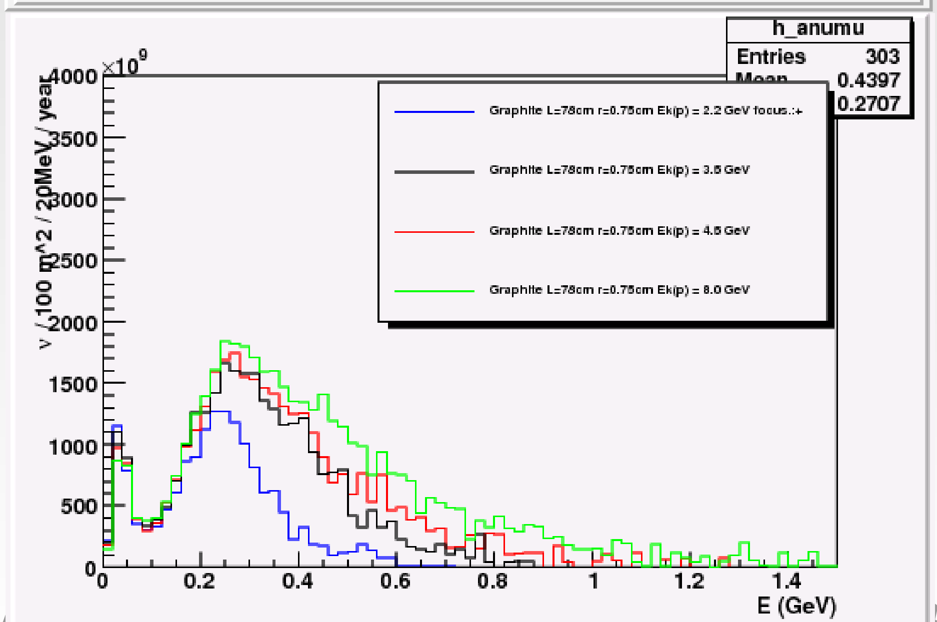
ν fluxes: Mercury (- FOCUSING)

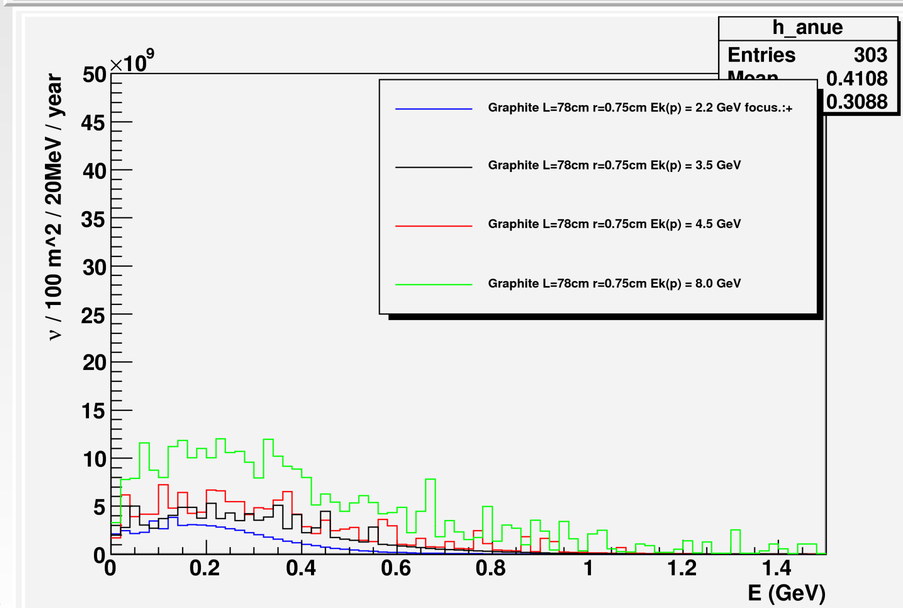


ν fluxes: Graphite (+ FOCUSING)

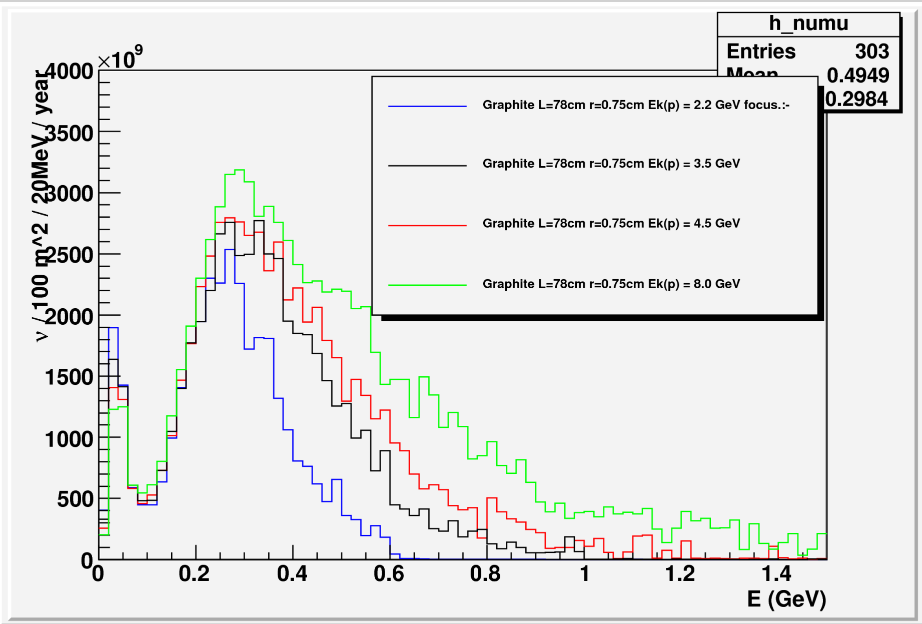


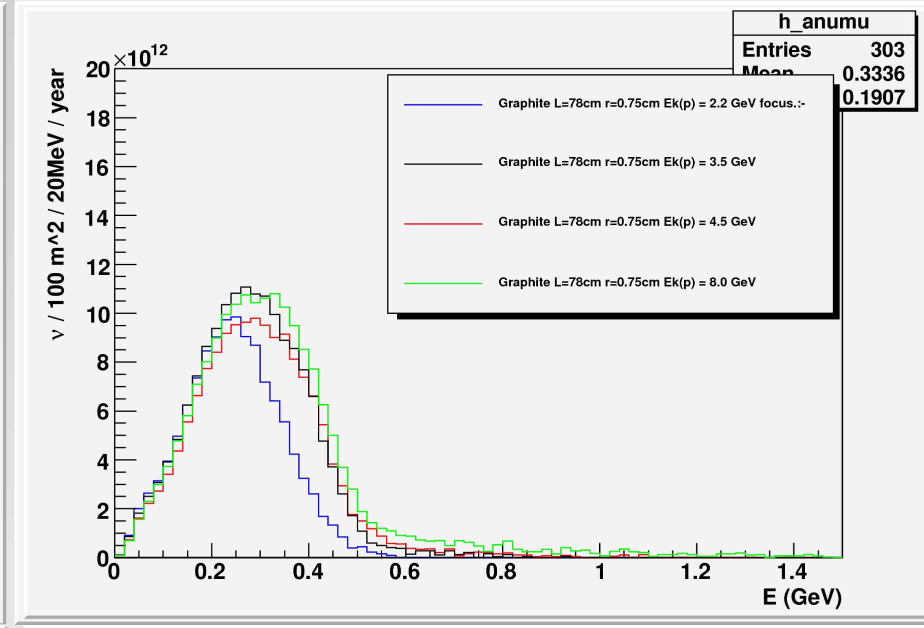


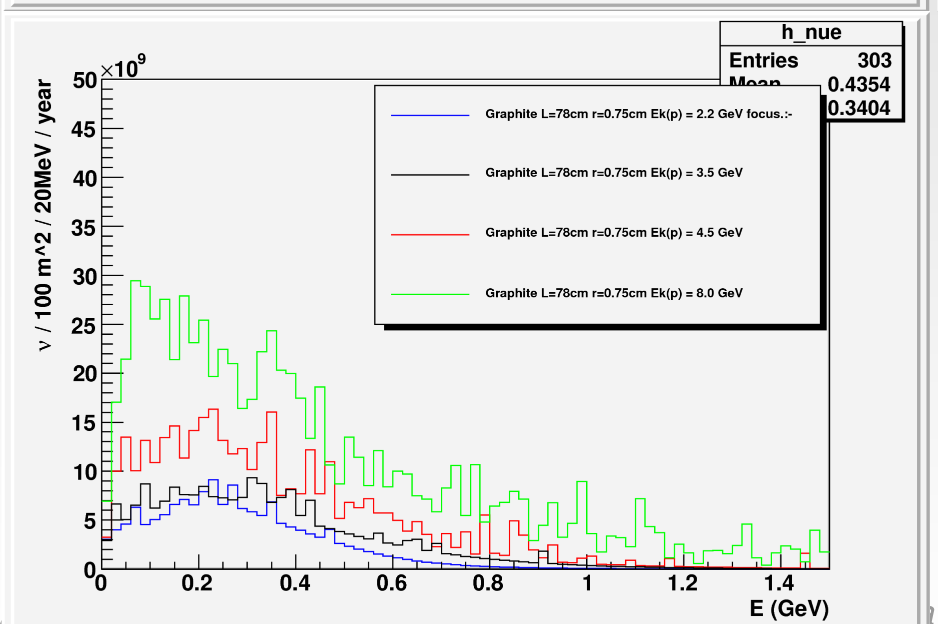


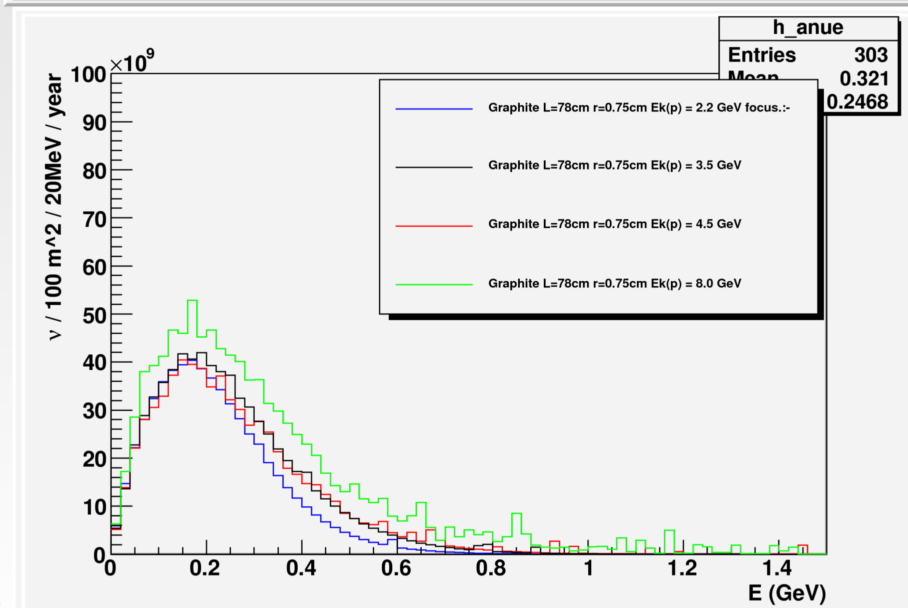


ν fluxes: Graphite (- FOCUSING)





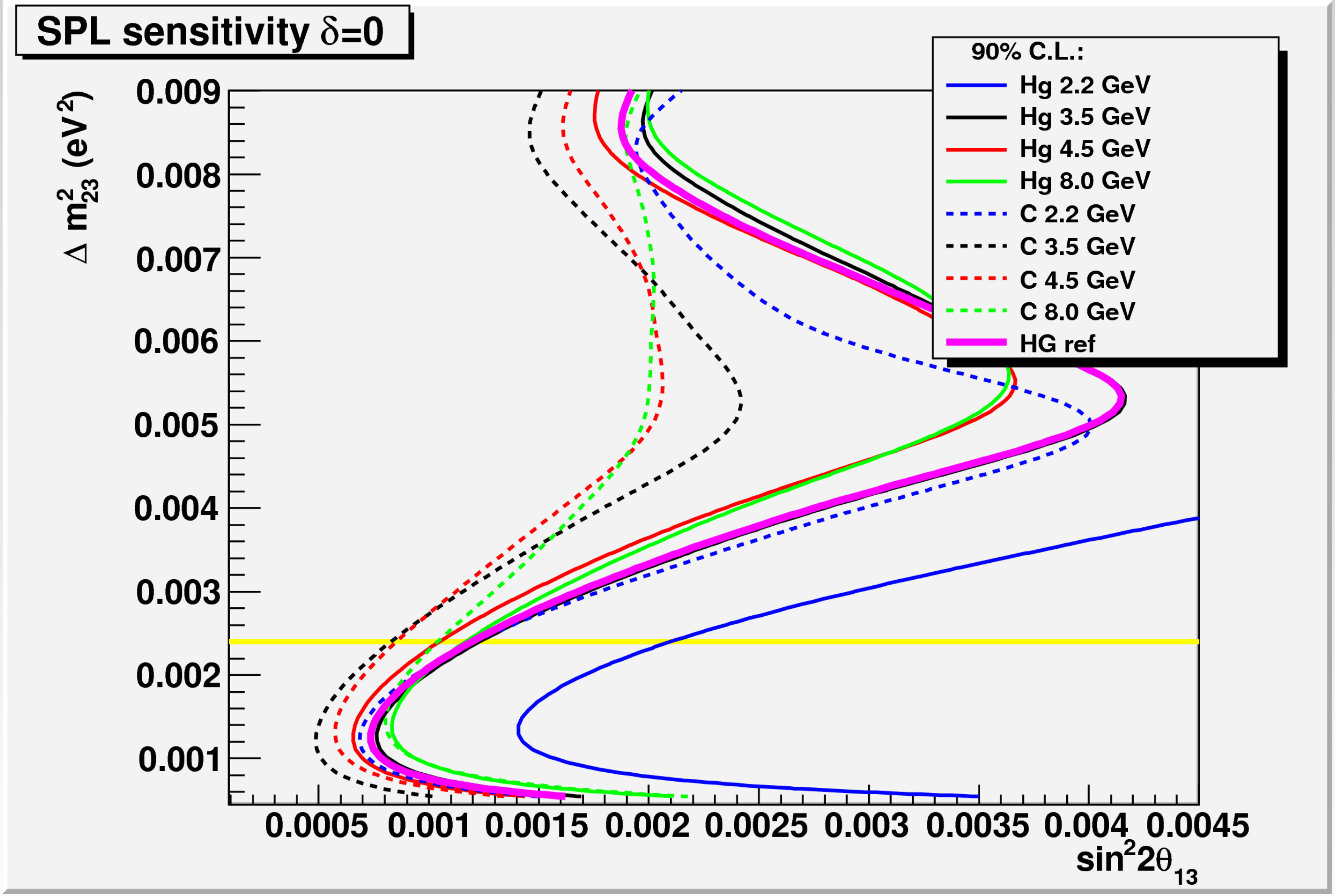




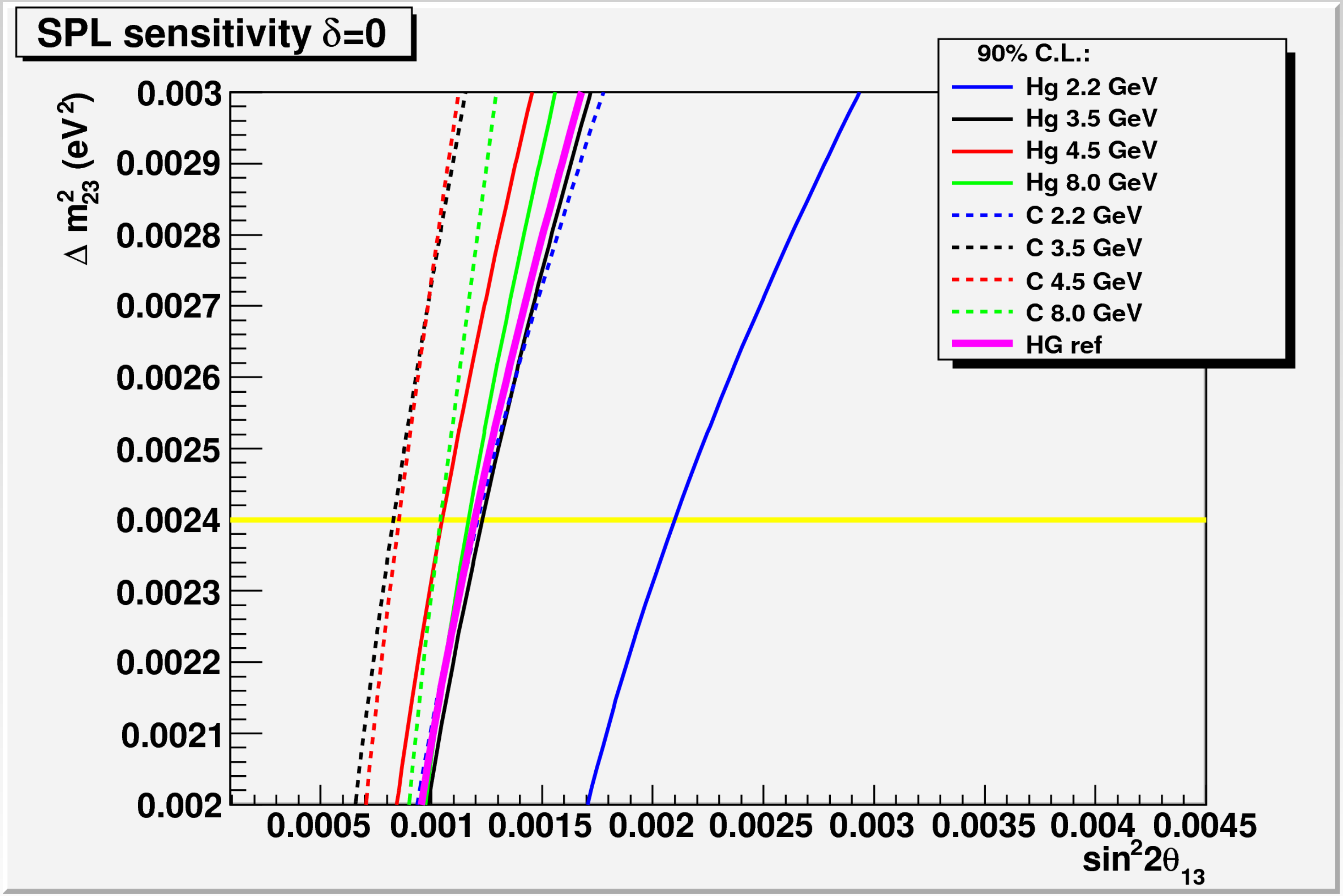
Sensitivities

- Calculated for 8y(antinu)+2y(nu) running scenario as in previous publication
- used the MEMPHYS description implemented in AEDL file SPL.glb coming with the standard GloBES package and developed by M.Mezzetto with m = 0.44 Mton
- Paper curve with Mercury reproduced with current simulation ("Hg ref.")

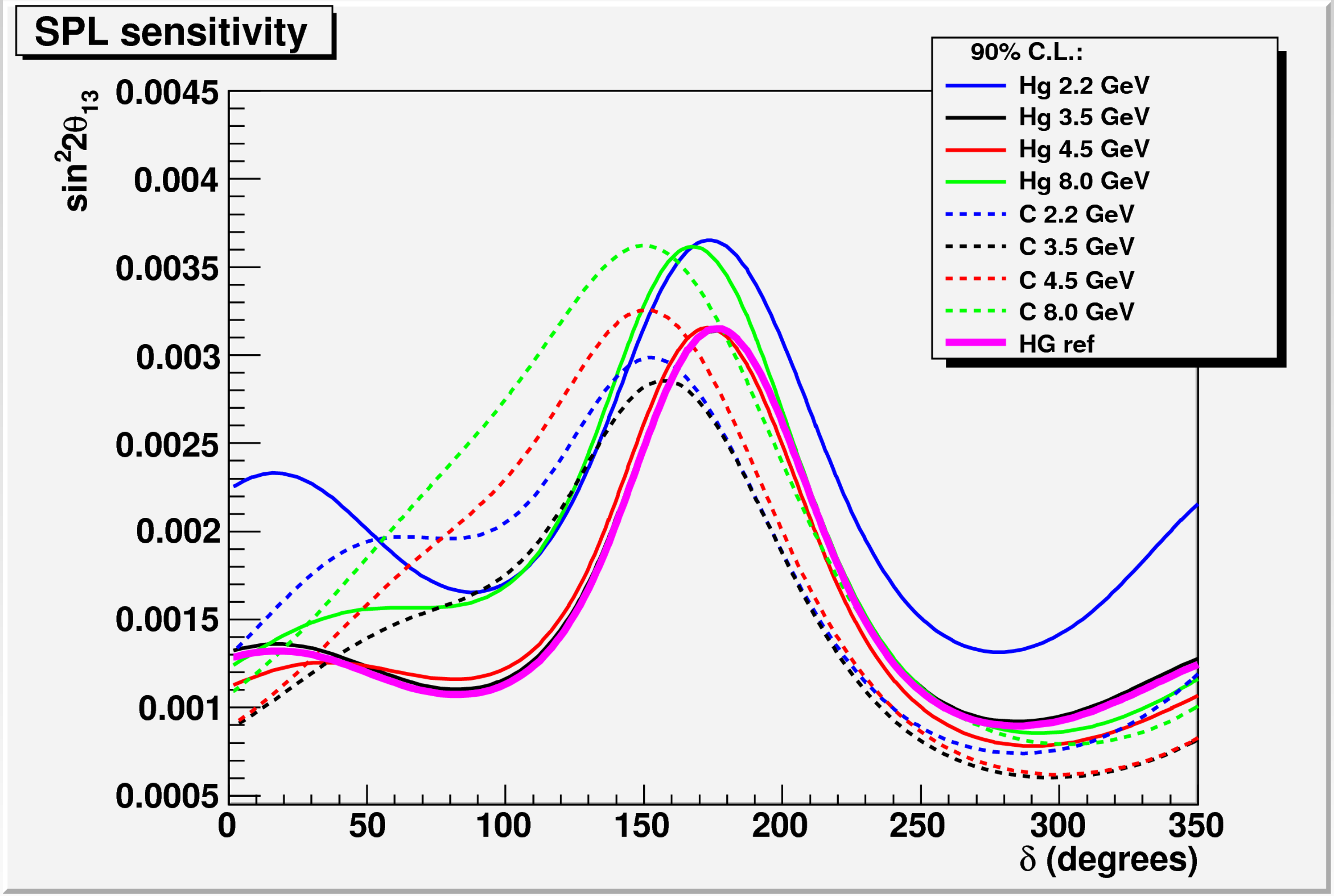
Sensitivity



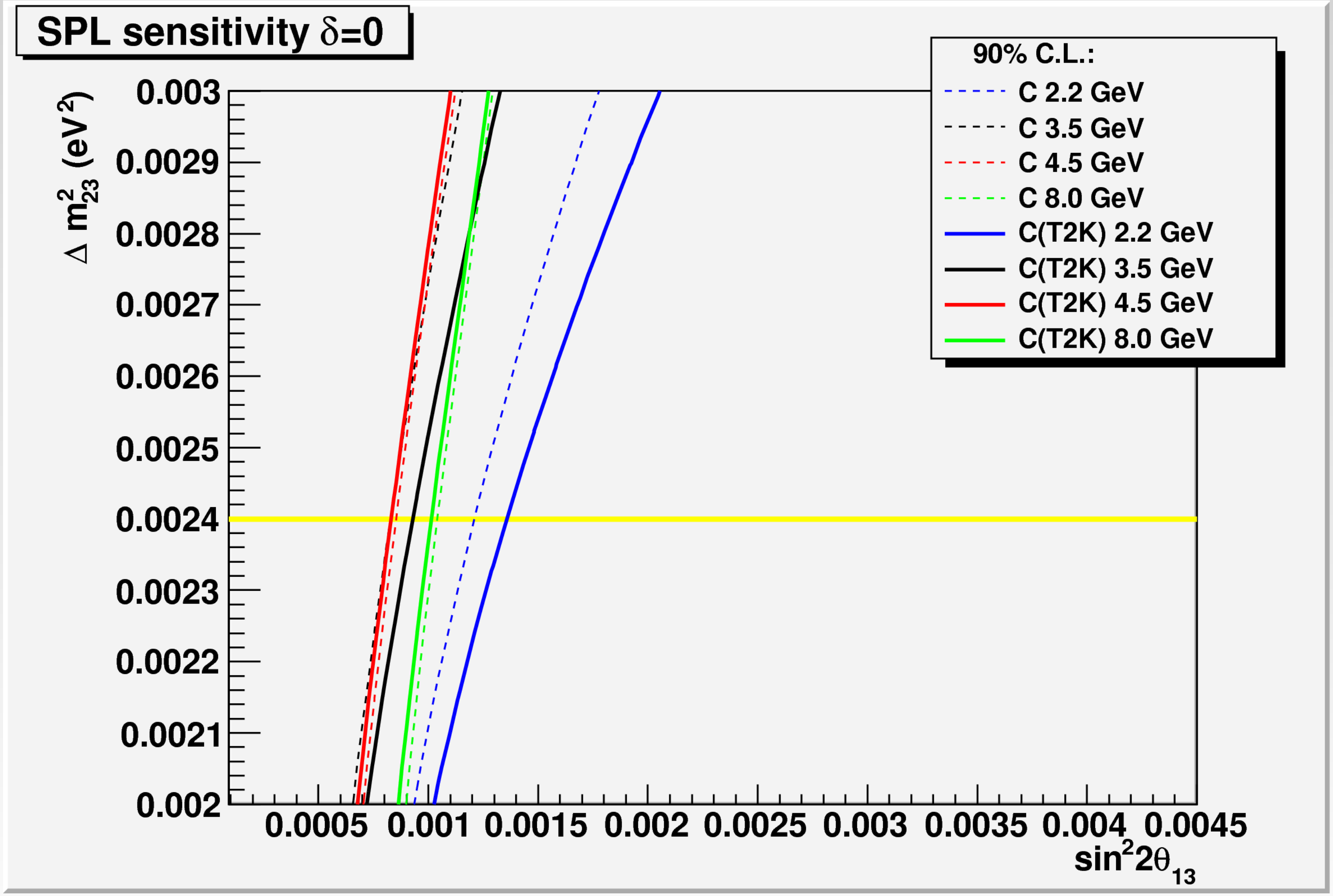
Sensitivity



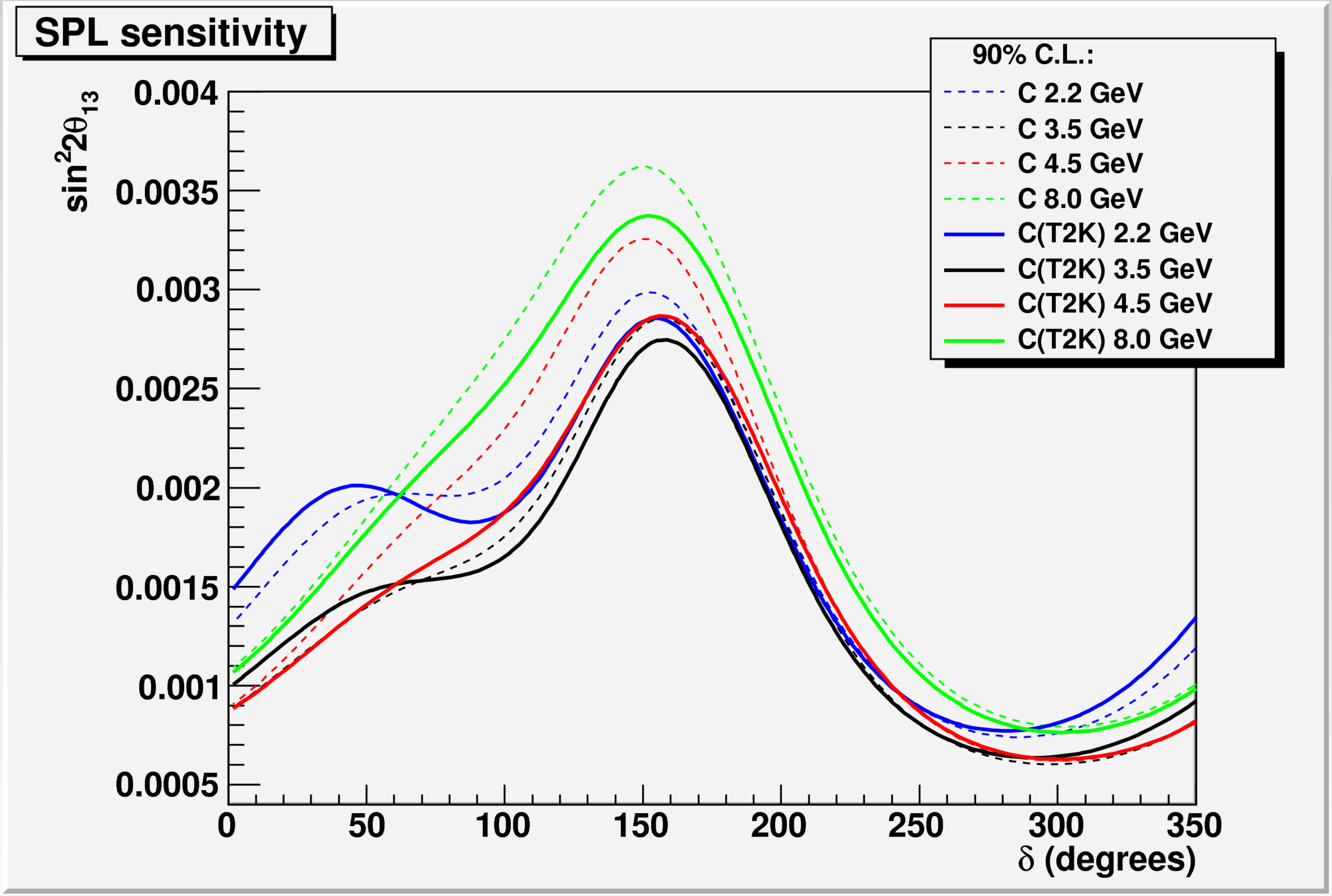
Sensitivity



Sensitivity



Sensitivity



Documentation

- A note on the subject is almost completed. Will be submitted soon to the EUROnu web site. http://www.euronu.org

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

A. Longhin

CEA Saclay - IRFU - SPP

Internal note EURONU-WP2-09-04

22nd April 2009

VERSION 0.0

Abstract

The viability of using a graphite target for the SPL-Fréjus Super Beam in place of the previously foreseen liquid mercury target has been studied using the full neutrino beam simulation. This new option has been characterized in terms of the energy deposition in the target up to the final sensitivity to the oscillation parameters δ and θ_{13}. The results are encouraging on both levels. The energy deposition is such that if one assumes a 4-target scenario, the 4 MW incoming power could be sustained already with current technologies (a He cooled graphite target in T2K is foreseen to work at 0.75 MW). The neutron flux is also dramatically reduced ($\times$ 15). The sensitivity to the physical parameters using a graphite target is better than using a mercury target for some choices of the CP phase δ and worse for other. This is due to a larger contamination of $\bar{\nu}$ in the ν beam (and viceversa). Further studies are envisaged to optimize the pion collection system in view of using a longer target.

Conclusions

- Getting experience with the SPL-Fréjus neutrino fluxes and physics reach. Software tools are ready / working and being updated.
- Migration to GEANT4 in progress
- Migration to FLUKA 2008 done:
  - some slight modification in the pi+ spectra observed. General results from study performed with older version not significantly modified. Still some bizarre features in particle production yields vs energy (now @ ~5 GeV... damn!)

Conclusions (II)

- Graphite target option simulated. Looks appealing. W.r.t. Hg:
  - much lower energy deposition (but dissipation more difficult...)
  - similar K contamination
  - much lower neutron flux (~ -15 X)
  - higher or equal pion yield (depending on E)
  - comparable neutrino fluxes despite collection system was not yet optimized for longer target
  - technically less challenging (see T2K He cooled target)
  - Sensitivity on theta13 is better for graphite for delta=0
  - The theta13 sensitivity for graphite shows a stronger dependance on theta13 (becomes less competitive than mercury in some regions and viceversa)
  - This is probably related to a higher occurrence on antinu in the nu beam and viceversa in the case of graphite
  - Ad hoc focusing optics optimization for the graphite target could improve (contaminantion come from inefficiently defocused wrong charge pions!)

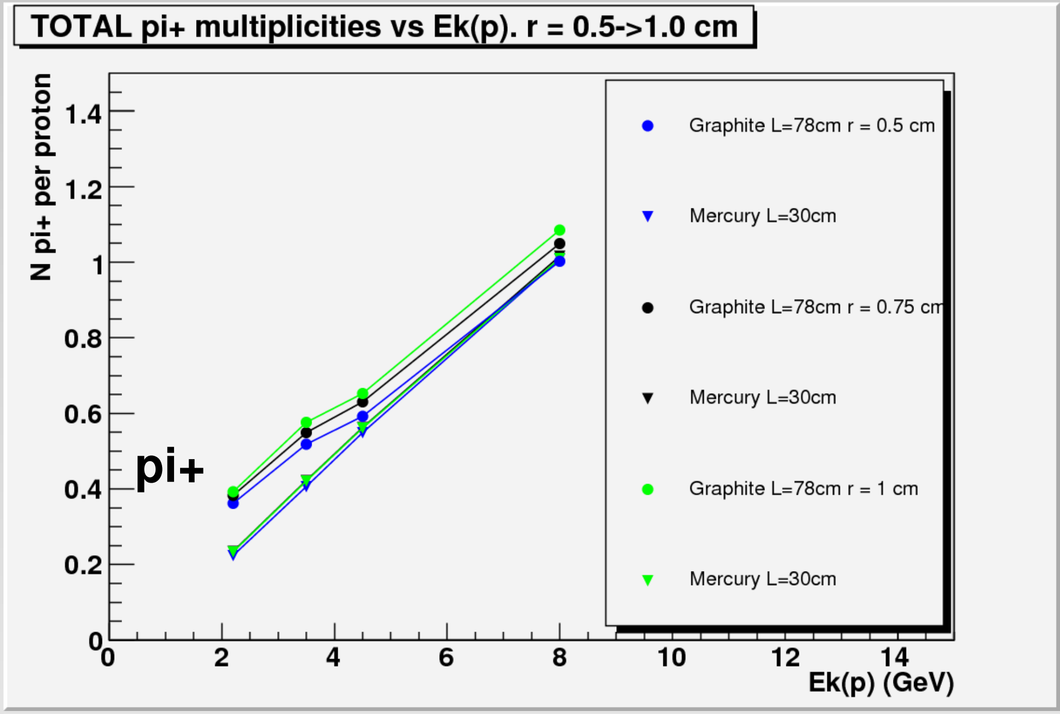
(near) future plans

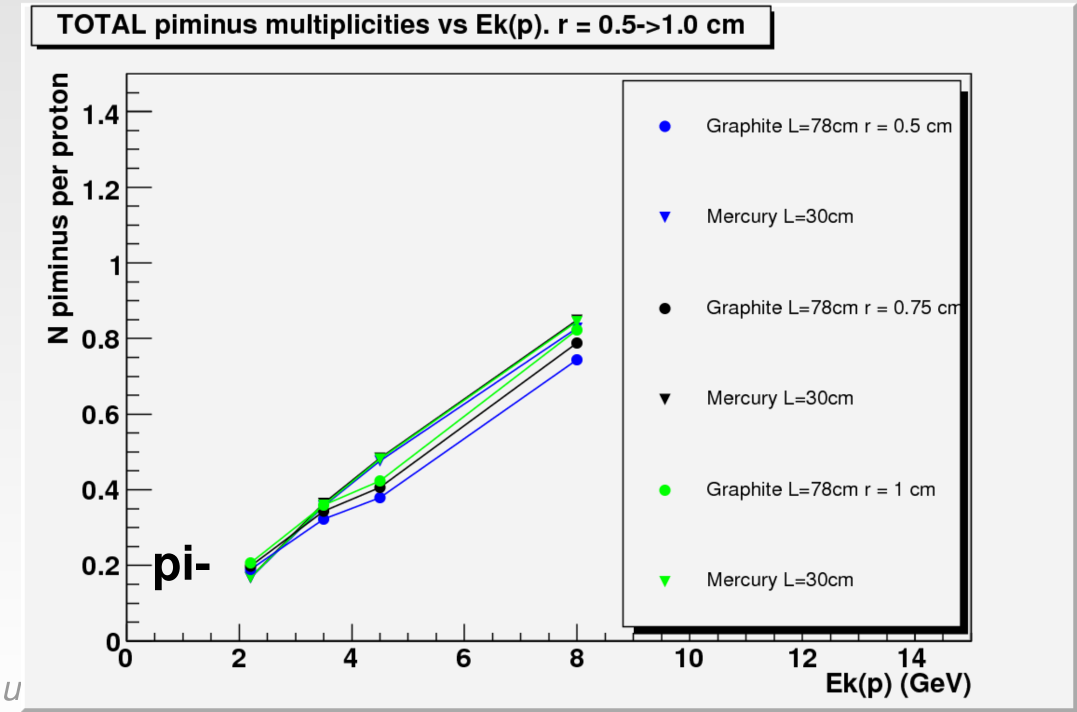
- Benefit of hadro-production data (HARP) to improve reliability of target simulation and verify Carbon-Mercury description of FLUKA
- Compare with MARS
- Finalize transition to GEANT4 (horn oprimization probably easier after transition)
- horn re-optimization

Backup slides

Pion multiplicities vs Energy:

C and Hg





NOT normalized to 4 MW

Pion multiplicities vs Energy:

C and Hg

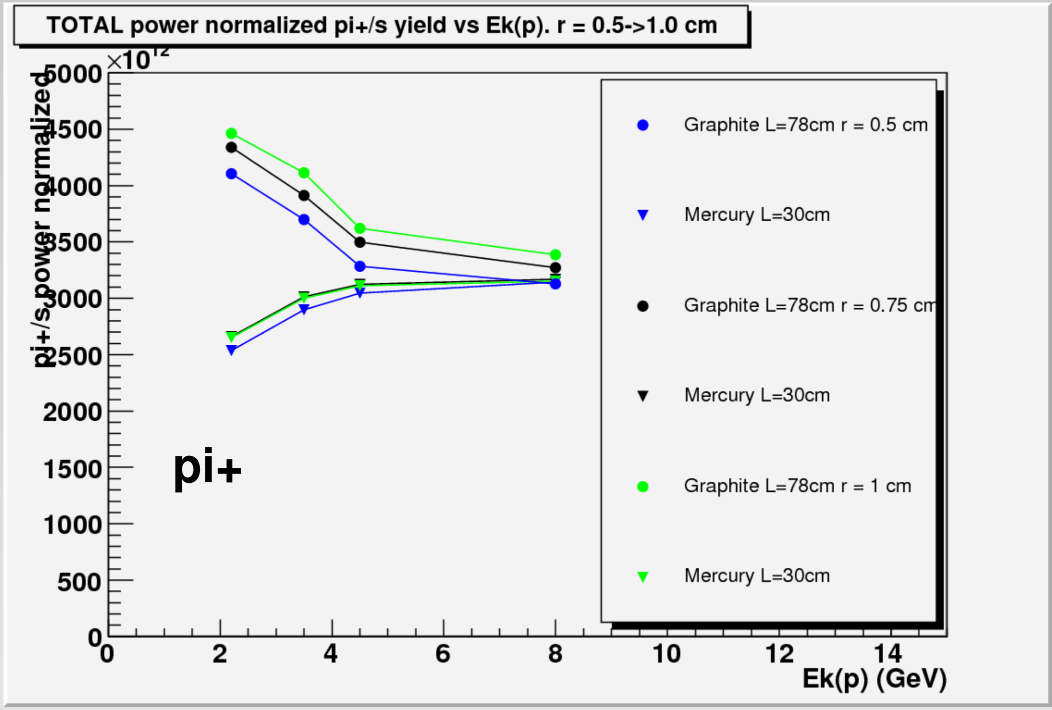
normalized to 4 MW fixed power

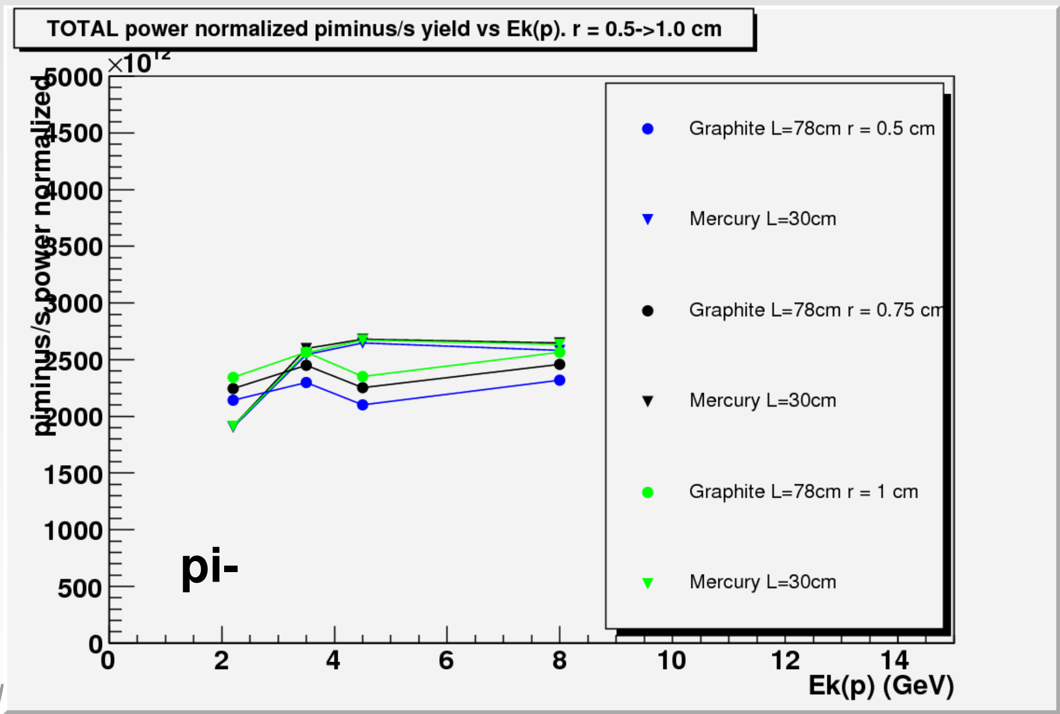
- 1.13×10^{16} pot/s at 2.2 GeV
- 0.71×10^{16} pot/s at 3.5 GeV
- 0.55×10^{16} pot/s at 4.5 GeV
- 0.31×10^{16} pot/s at 8.0 GeV

More pi+ from carbon at low energy, gets ~ equal at about 8 GeV

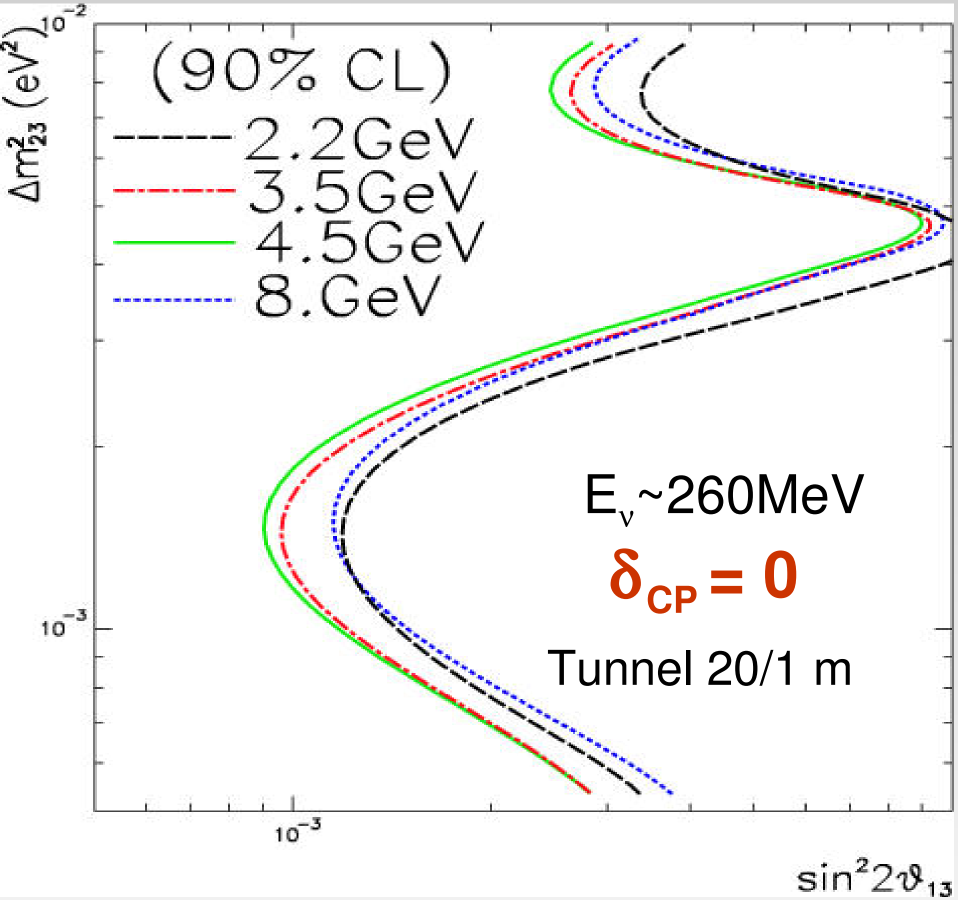
pi- yield similar (a bit better with Hg)

for carbon r=1 looks preferable

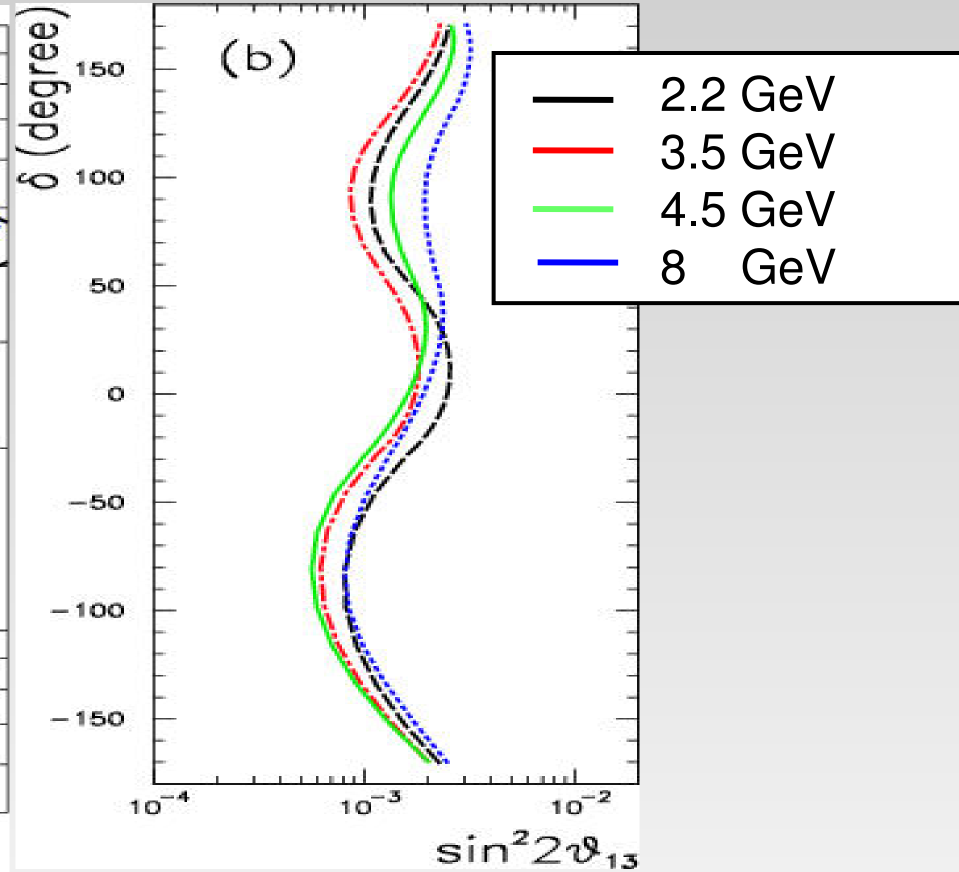




Sensitivity vs beam energy



5 year positive focusing



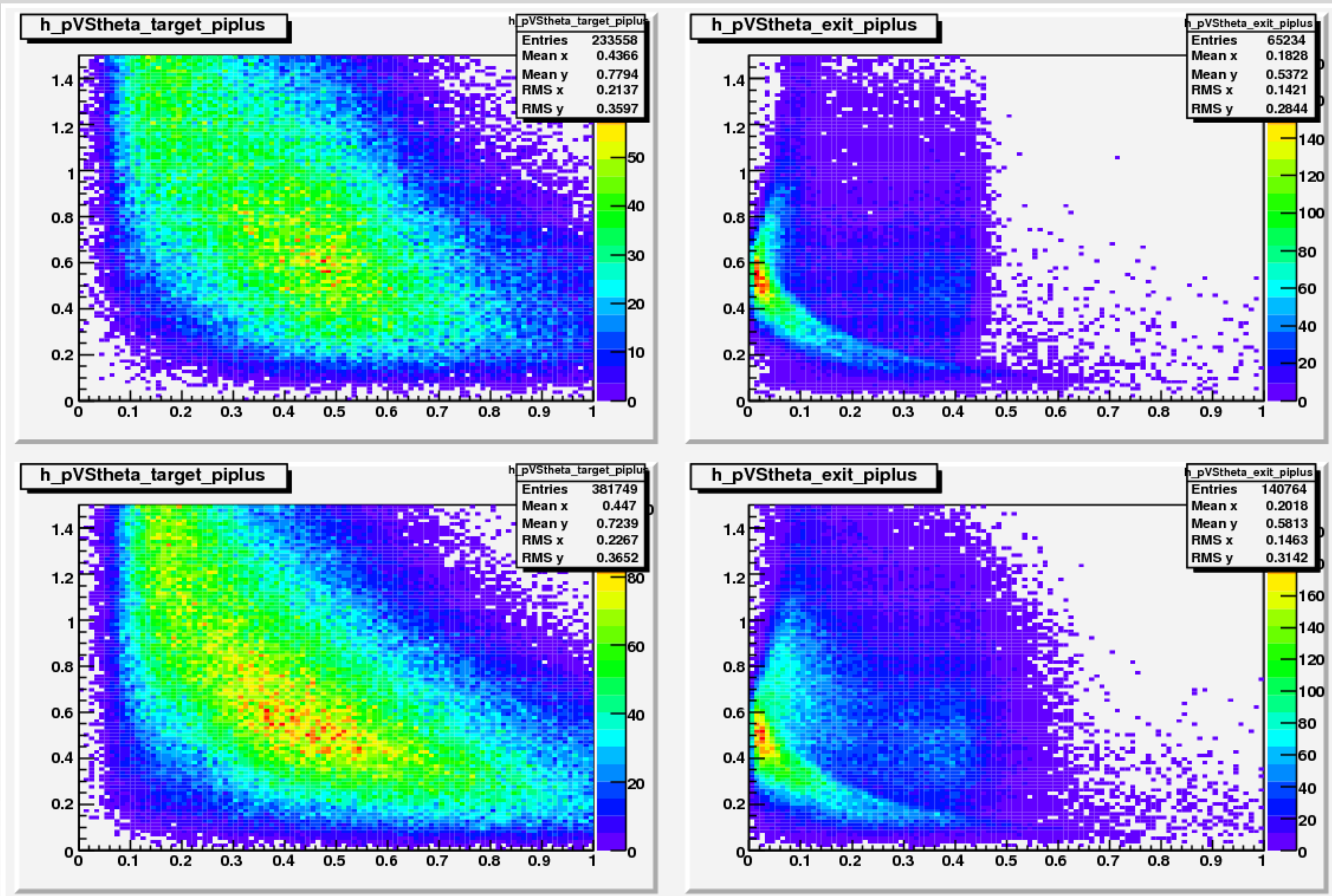
10 years mixed focusing (8y + and 2y -)

Campagne, Cazes : Eur Phys J C45:643-657,2006

Pion collection: Mercury-Graphite

- P vs θ : before and after focusing

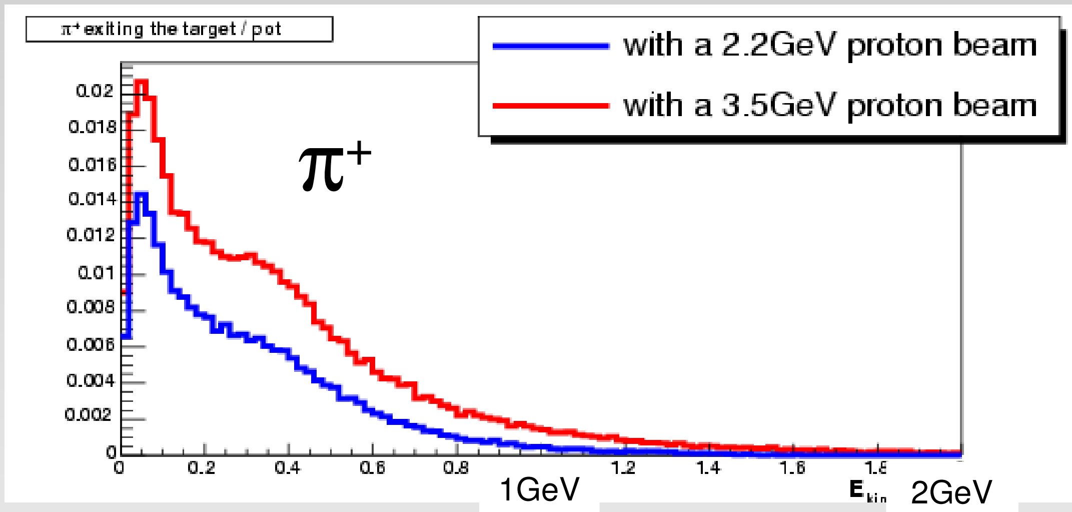
π^+ exiting the target π^+ after horn+reflector

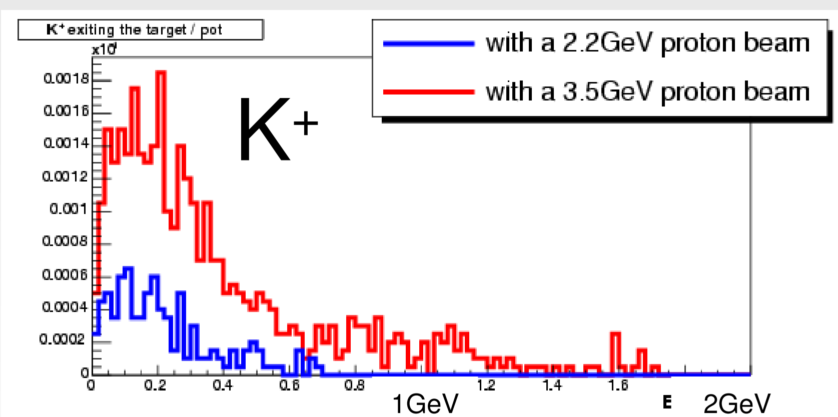


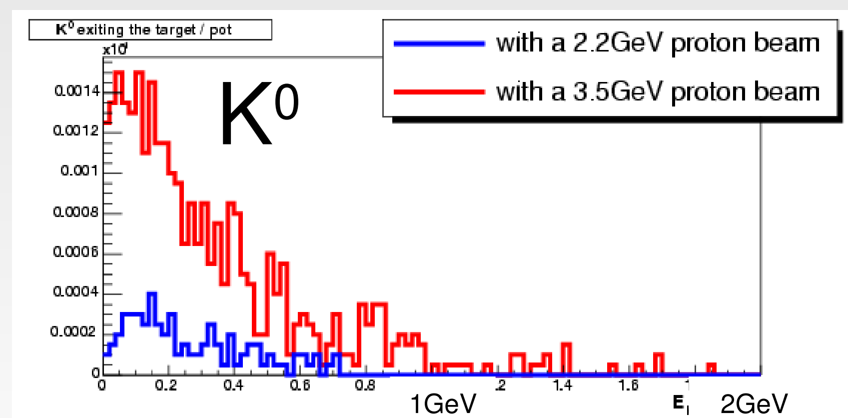
← Hg

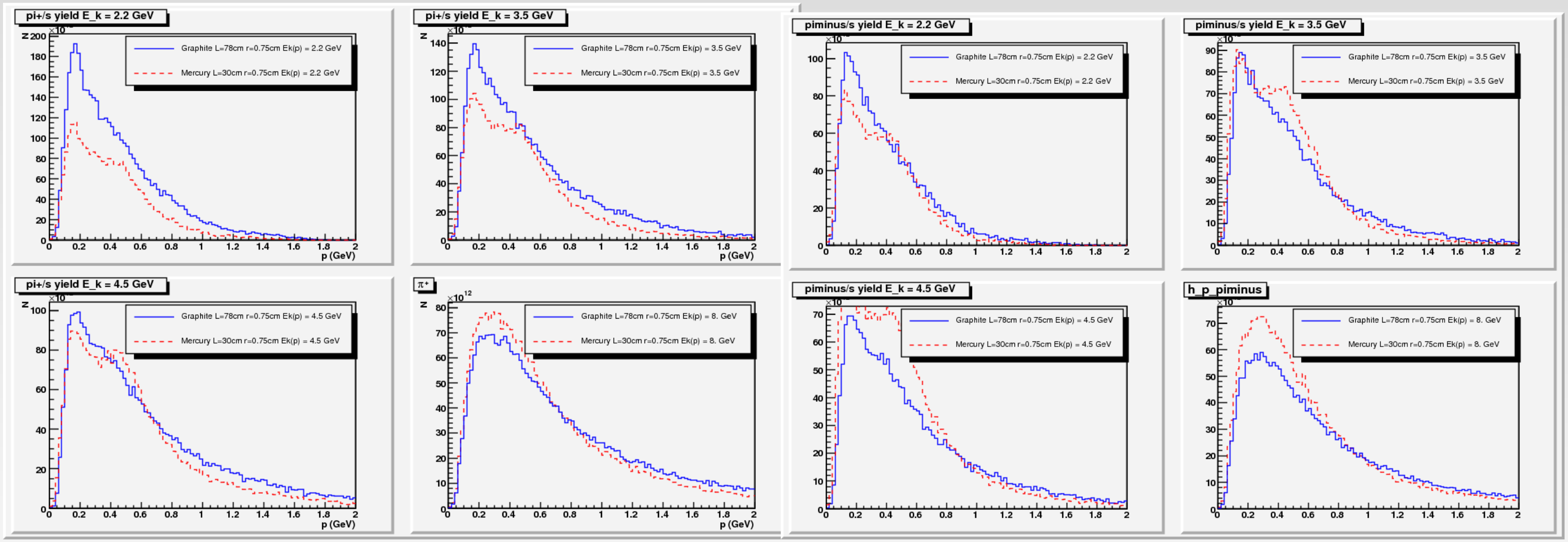
← C

Kinetic energy (GeV) of pions and kaons

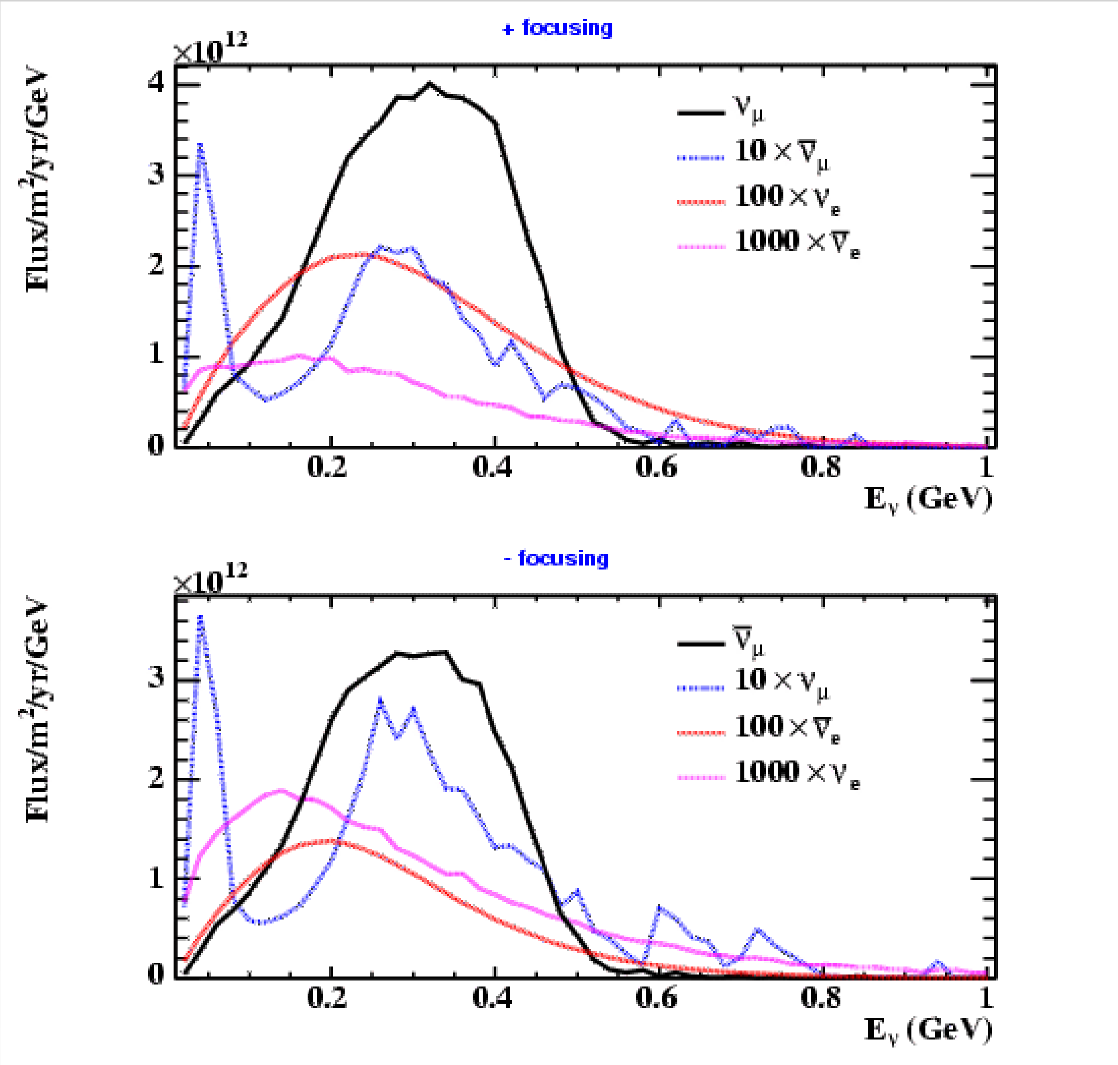







pi+/s yield E_k = 2.2 GeV
pi+/s yield E_k = 3.5 GeV
piminus/s yield E_k = 2.2 GeV
piminus/s yield E_k = 3.5 GeV
pi+/s yield E_k = 4.5 GeV
π+
piminus/s yield E_k = 4.5 GeV
h_p_piminus
Graphite L=78cm r=0.75cm Ek(p) = 2.2 GeV
Mercury L=30cm r=0.75cm Ek(p) = 2.2 GeV
Graphite L=78cm r=0.75cm Ek(p) = 3.5 GeV
Mercury L=30cm r=0.75cm Ek(p) = 3.5 GeV
Graphite L=78cm r=0.75cm Ek(p) = 4.5 GeV
Mercury L=30cm r=0.75cm Ek(p) = 4.5 GeV
Graphite L=78cm r=0.75cm Ek(p) = 8. GeV
Mercury L=30cm r=0.75cm Ek(p) = 8. GeV
p (GeV)
N

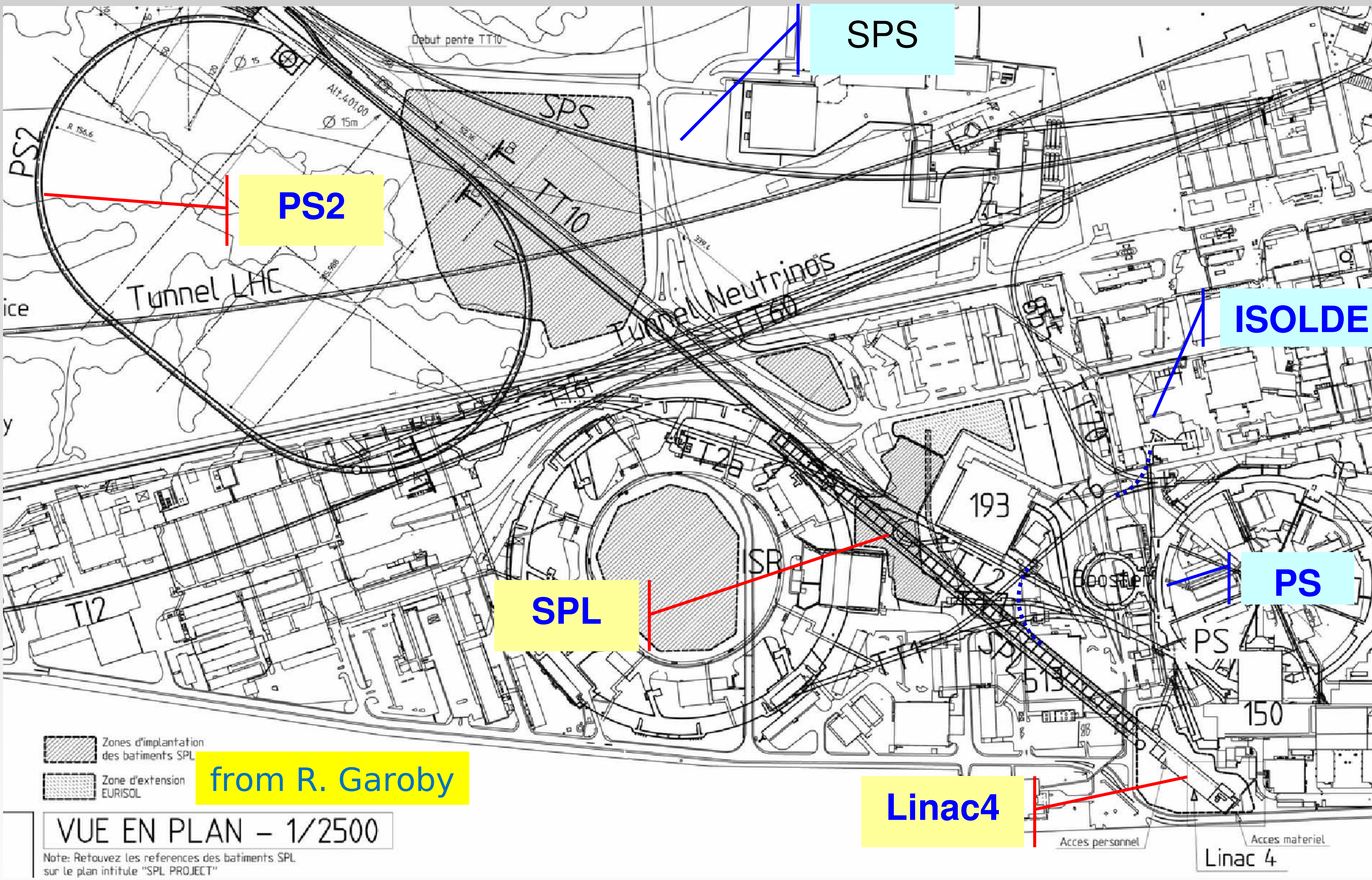
Neutrino flux @ 130km



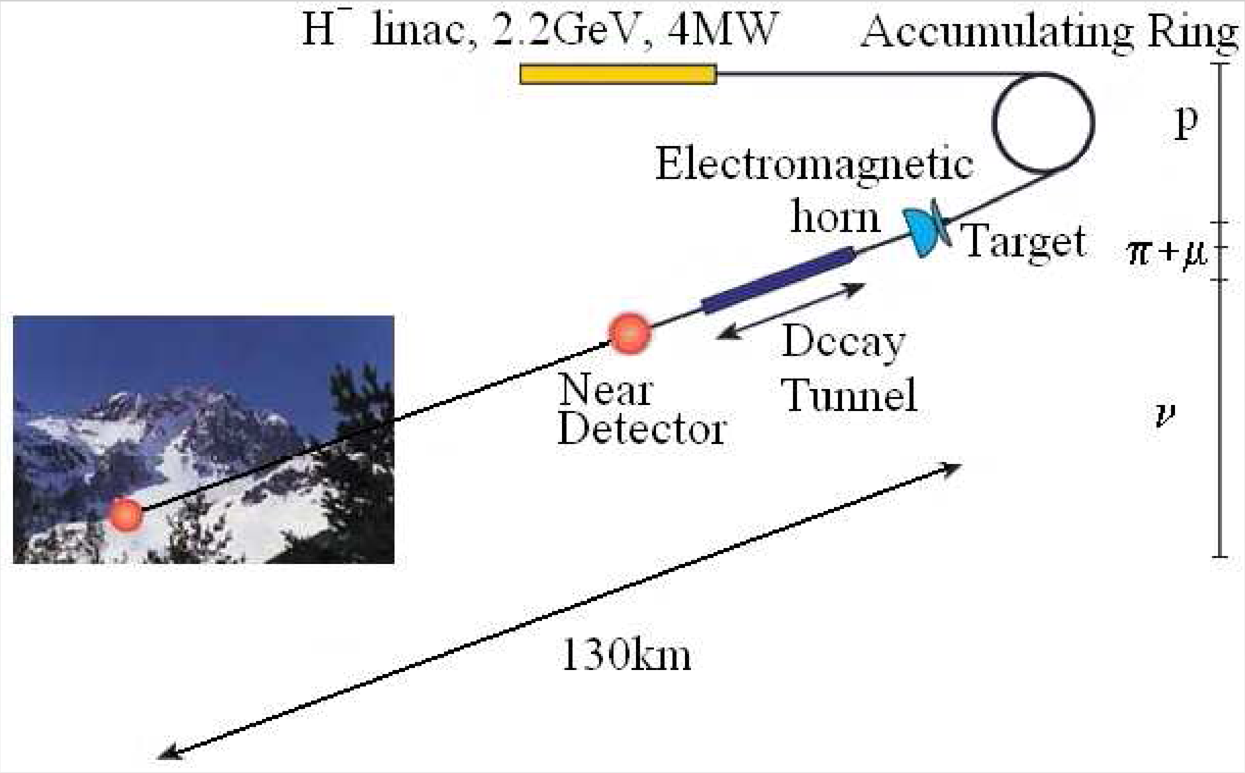
- 3.5GeV Kinetic proton beam
- ~800MeV π focusing
- ~300MeV neutrinos
- 40m decay tunnel length
- 2m decay tunnel radius

- Flux available for E_k=2.2GeV, 3.5GeV, 4.5GeV, 6.5GeV and 8GeV and two type of focalization system.

PLANS FOR FUTURE INJECTORS: Layout



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)

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

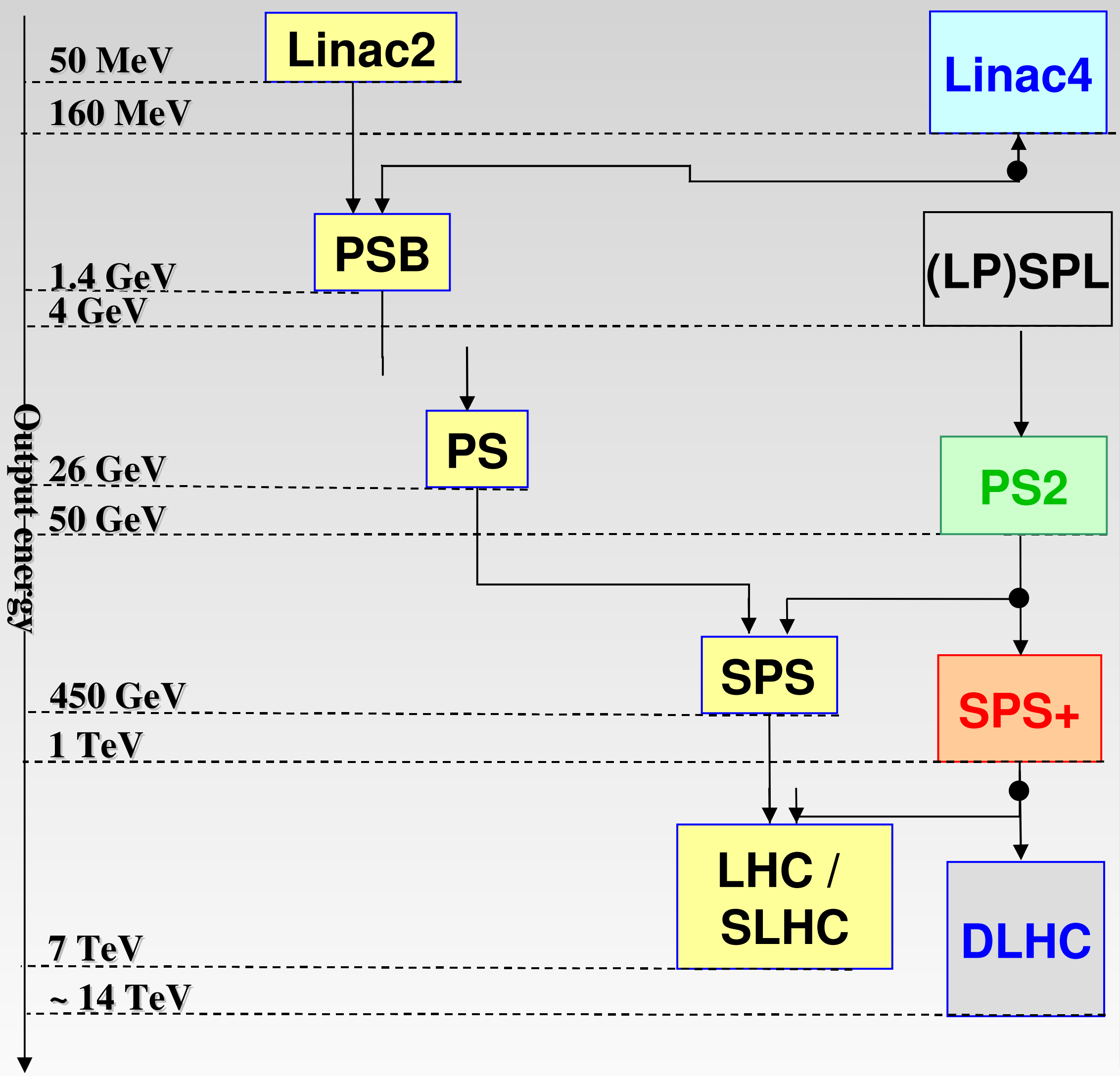
WP1: Management and Knowledge Dissemination
WP2: Super-Beam
WP3: Neutrino Factory
WP4: Beta-Beam
WP5: Detector Performance
WP6: Physics

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

PLANS FOR FUTURE INJECTORS: Description

Proton flux / Beam power

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)

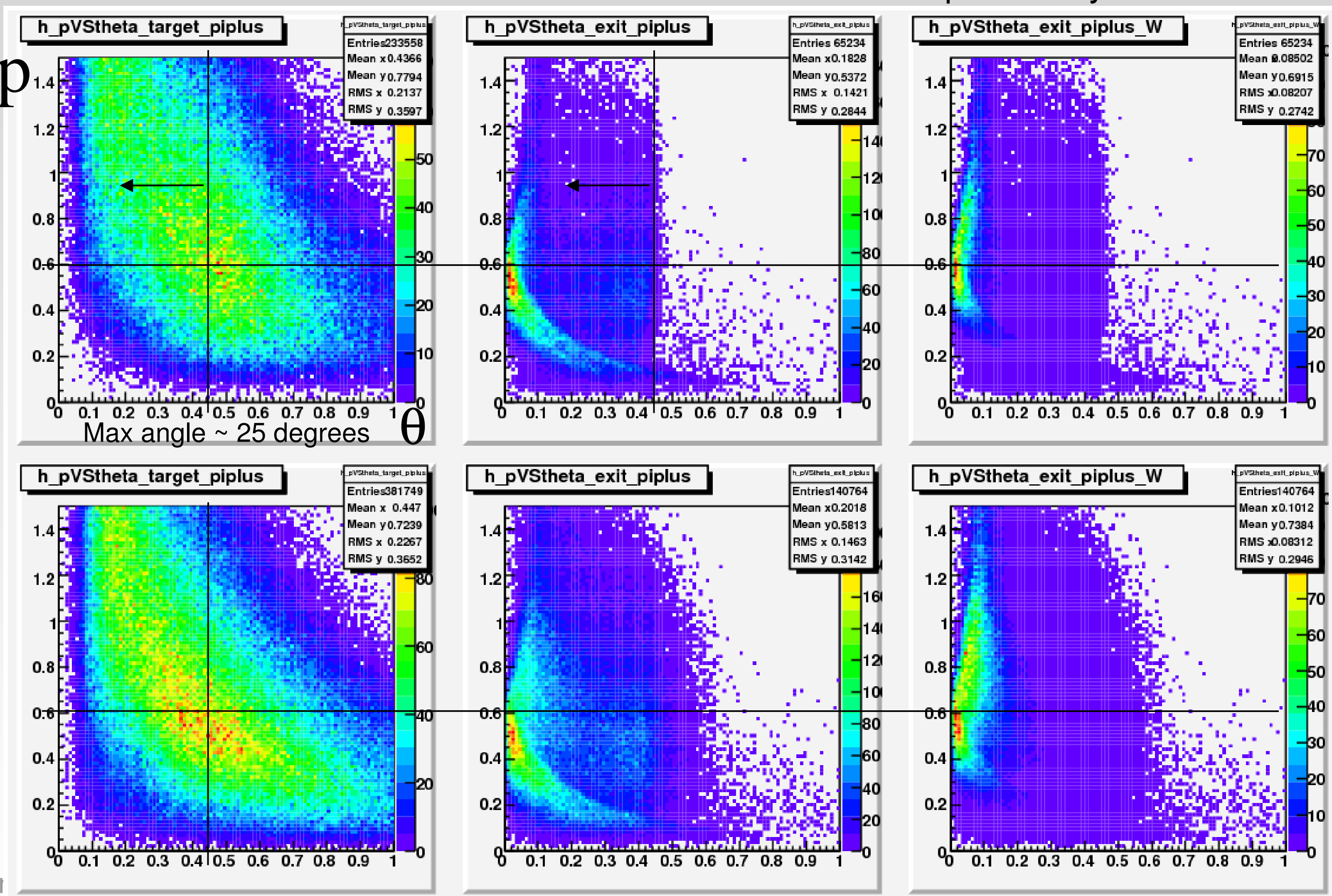
EPAC'08
June 23 -27, 2008

R.G.

Pion collection: Mercury-Graphite

- p vs θ : before and after focusing (2.2 GeV L=30 r=0.75)

π^+ exiting the target | π^+ after horn+reflector | π^+ after horn+reflector * probability to reach the detector



← Hg

← C