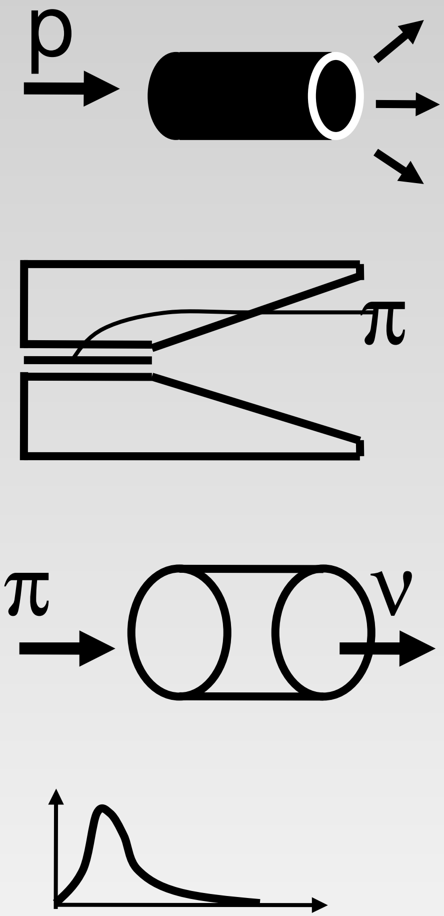
SPL-Fréjus: status and updates



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EUROnu annual meeting, WP2
CERN, March 23th, 2009

Outline

- Summary of simulation done so far + results
  - based on Campagne, Cazes : Eur Phys J C45:643-657,2006
- New software
  - Transition to FLUKA2008 and GEANT4
- New investigations on target:
  - impact of choosing a graphite target ?
    - Target energy deposition -> Pion yields -> Neutrino fluxes
- Conclusions and Outlook

Foreword and acknowledgments

Since I joined EUROnu quite recently (~1 month), a big part part of the results I will show is based on the work of A. Cazes, E. Campagne and others which pursued this work before me.

- 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

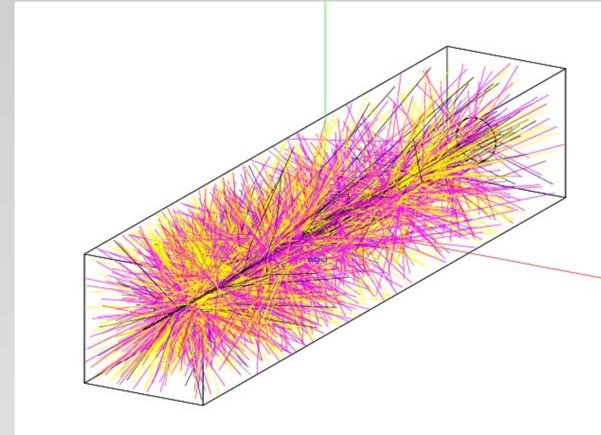
Increasing E:

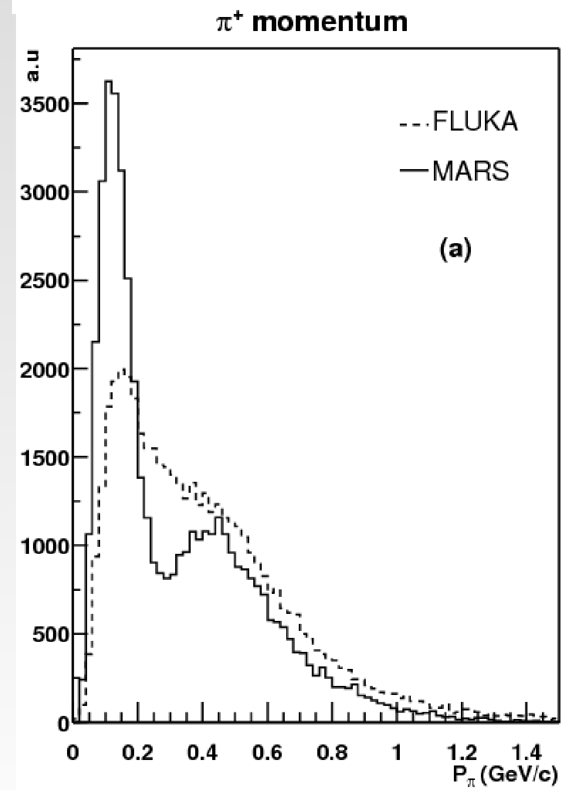
:) more pions

:) more boosted (will reach detector!)

: (more kaons (nu_e contamination)

: (lower pots available (fixed power: 4 MW)





Horn design and simulation

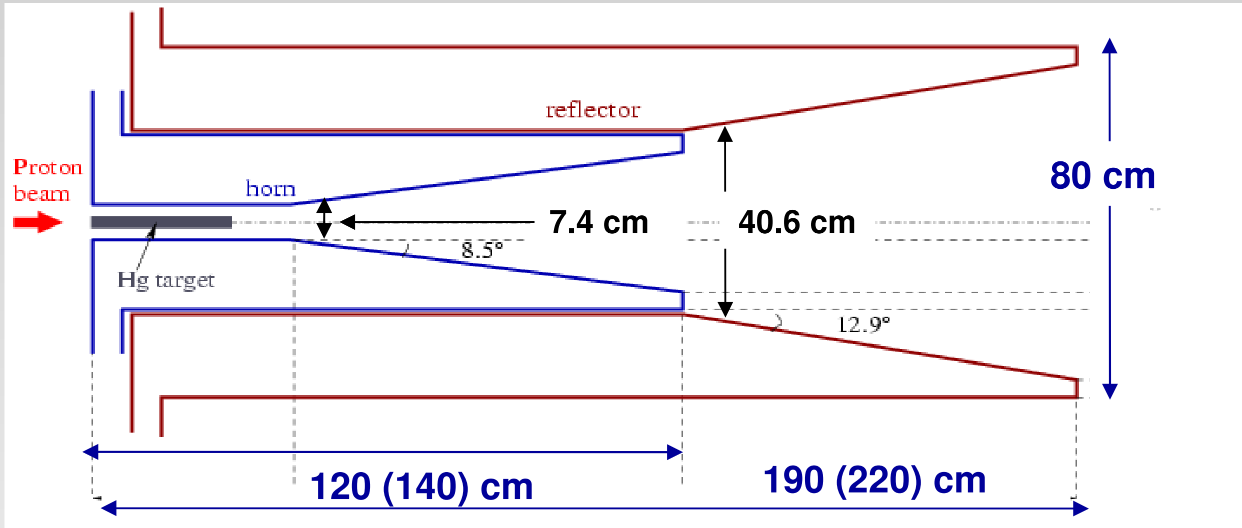
- Due to the low energy proton beam pions are mildly forward boosted ($<\theta_\pi> = 55°$)
  - -> Target inside the horn to recover collection efficiency

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

CERN-Fréjus = 130km

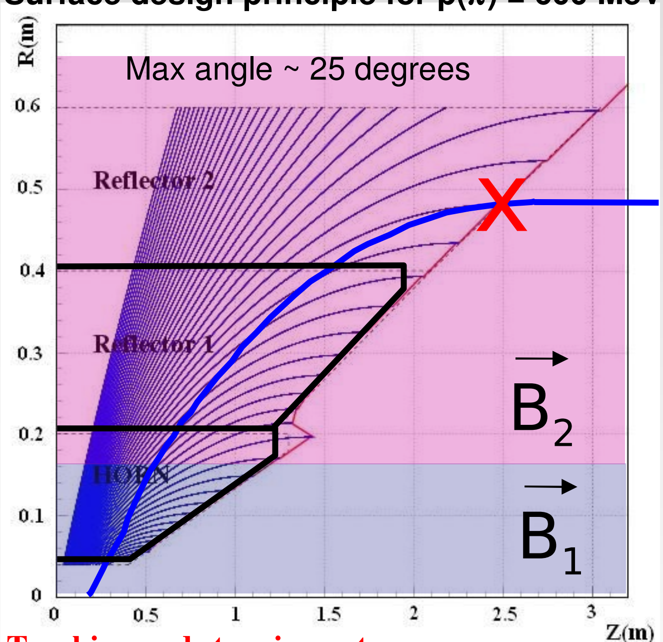
$\Rightarrow E_\nu \approx$ 260 MeV

$\Rightarrow p_\pi \approx$ 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



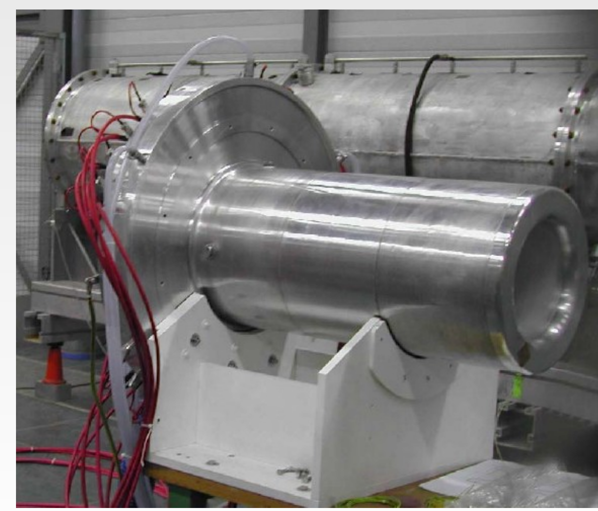
Tracking and stepping cuts:

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 $\rightarrow$ 40 m
    - ν_{μ} , antiν_{μ} + 50% to 70%
    - ν_{e}, antiν_{e} + 50% to 100%
  - 40 $\rightarrow$ 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 $\rightarrow$ 2 m (L = 40)
    - ν_{μ} , antiν_{μ} + 50%
    - ν_{e}, antiν_{e} + 70% to 100%
  - 2 m seems better

c , p = 0.6 GeV

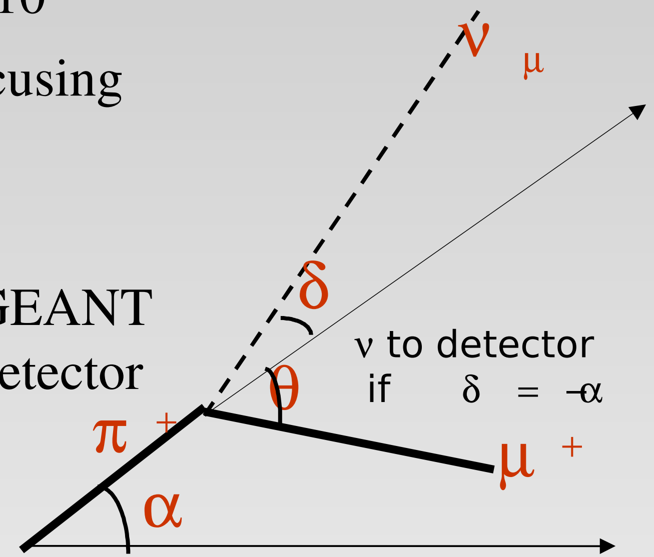
π	33.7 m
μ	3766 m
$K^{+/-}$	4.5 m
K^0_S	3.2 m
K^0_L	18.5 m

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

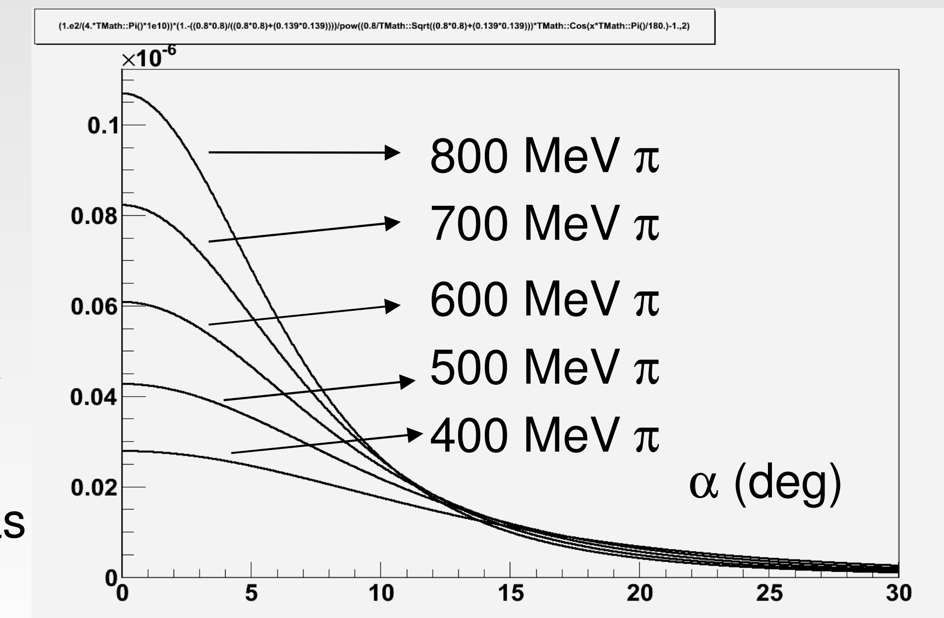
$\pi^+ \to \mu^+ \nu_\mu$

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

L : distance to detector
A : detector surface

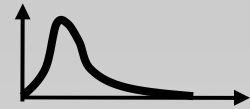
Angle of π w.r.t. beam axis in the lab frame: α

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



"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

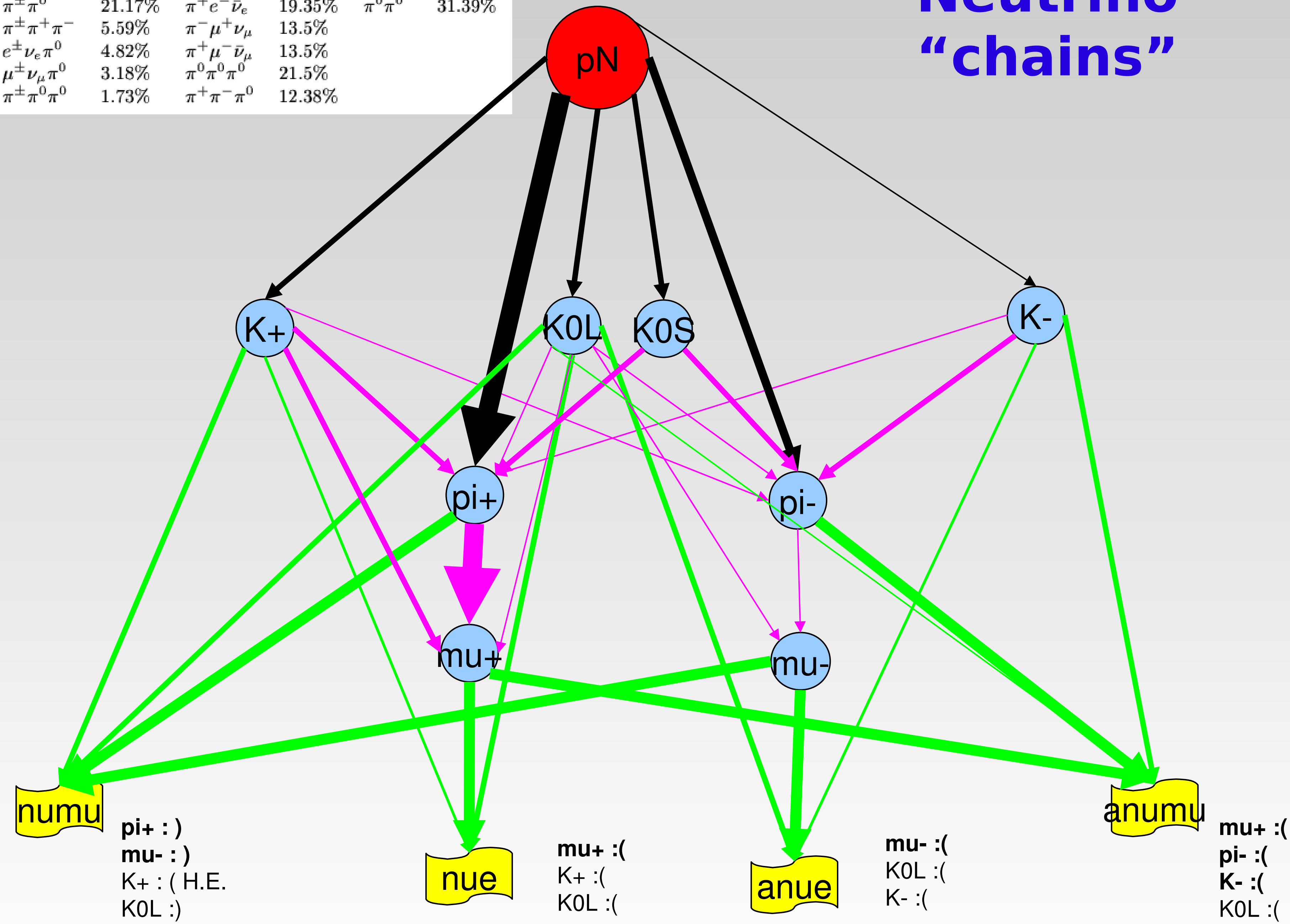
$$\frac{d\mathcal{P}_K}{dE_\nu} = \frac{1}{4\pi}\frac{A}{L^2}\frac{1}{m_K-m_\pi-m_l} \times \frac{1}{\gamma_K(1+\beta_K\cos\theta^*)}\frac{1-\beta_K^2}{(\beta_K\cos\delta-1)^2}$$

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)

$K^{\pm}$		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 "chains"

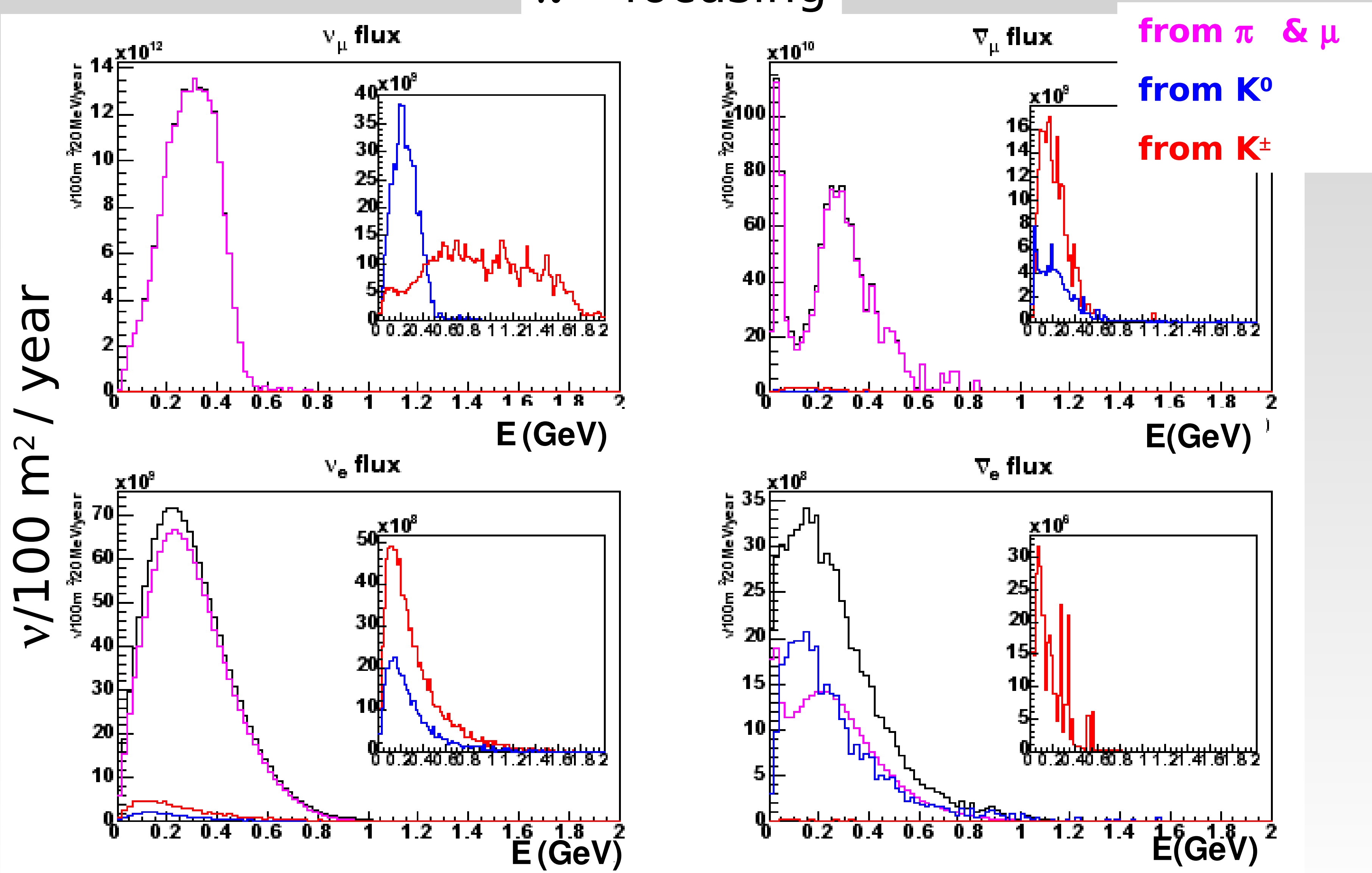


Neutrino fluxes at 100 km

$E_k = 3.5$ GeV
$E_\nu \sim 300$ MeV
L = 40 m, R = 2 m

1 year := 10^7 s

π^+ focusing



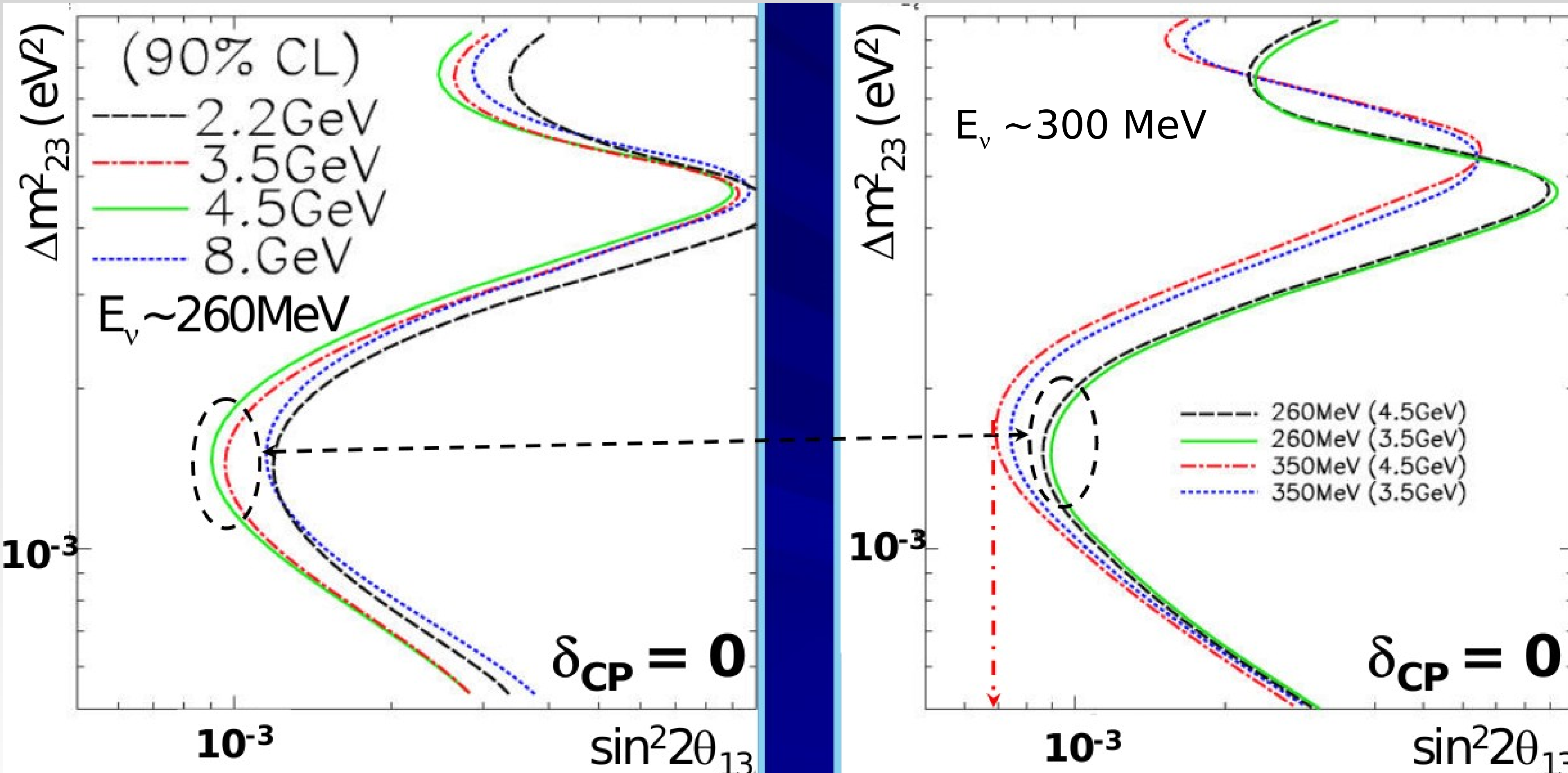
Sensitivity

UNO-like 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 ~300 MeV
- Larger tunnel 40/2 m

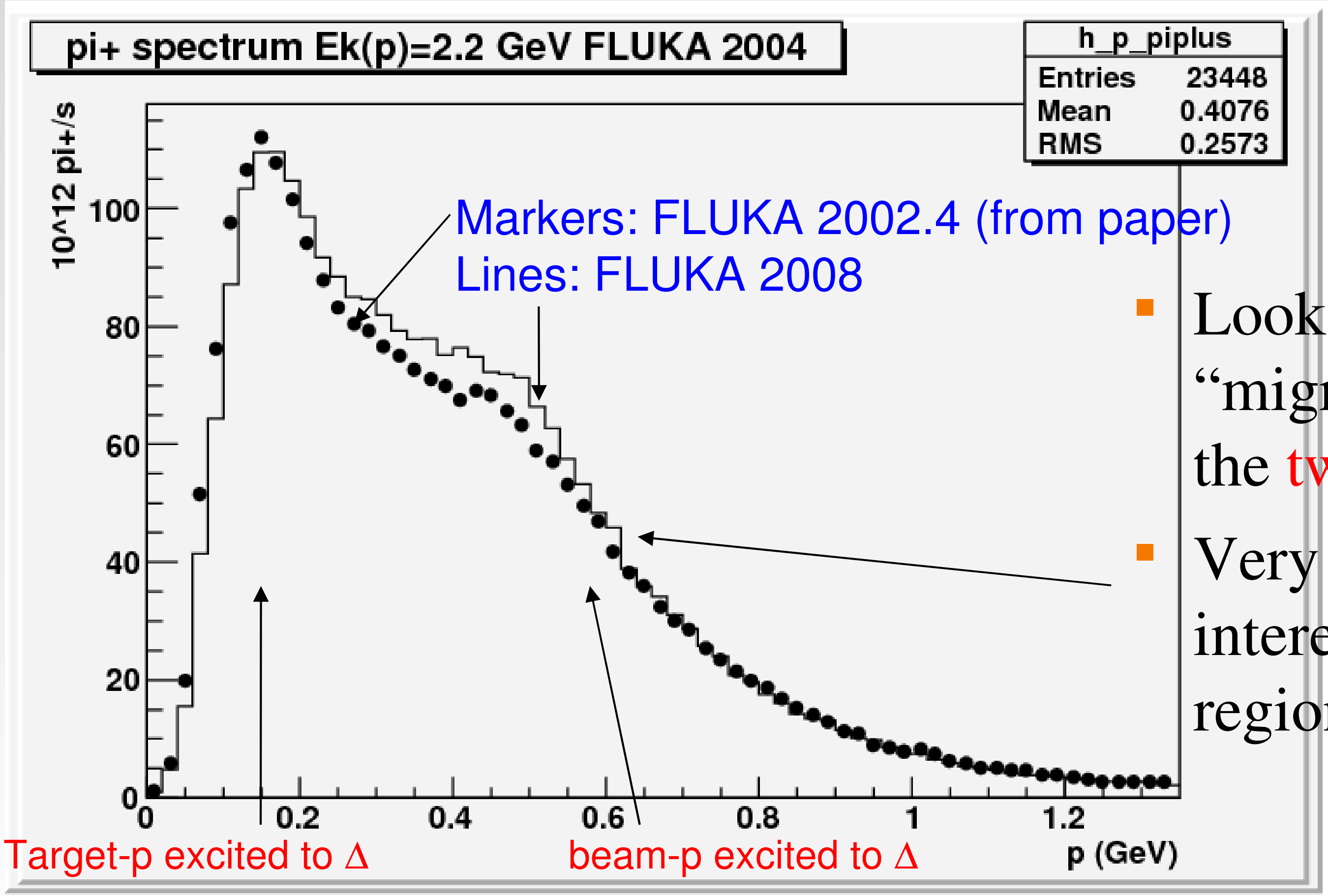


$\sin^2 2\theta_{13} < 7.1\ \ 10^{-4}$ 90% C.L.

- 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

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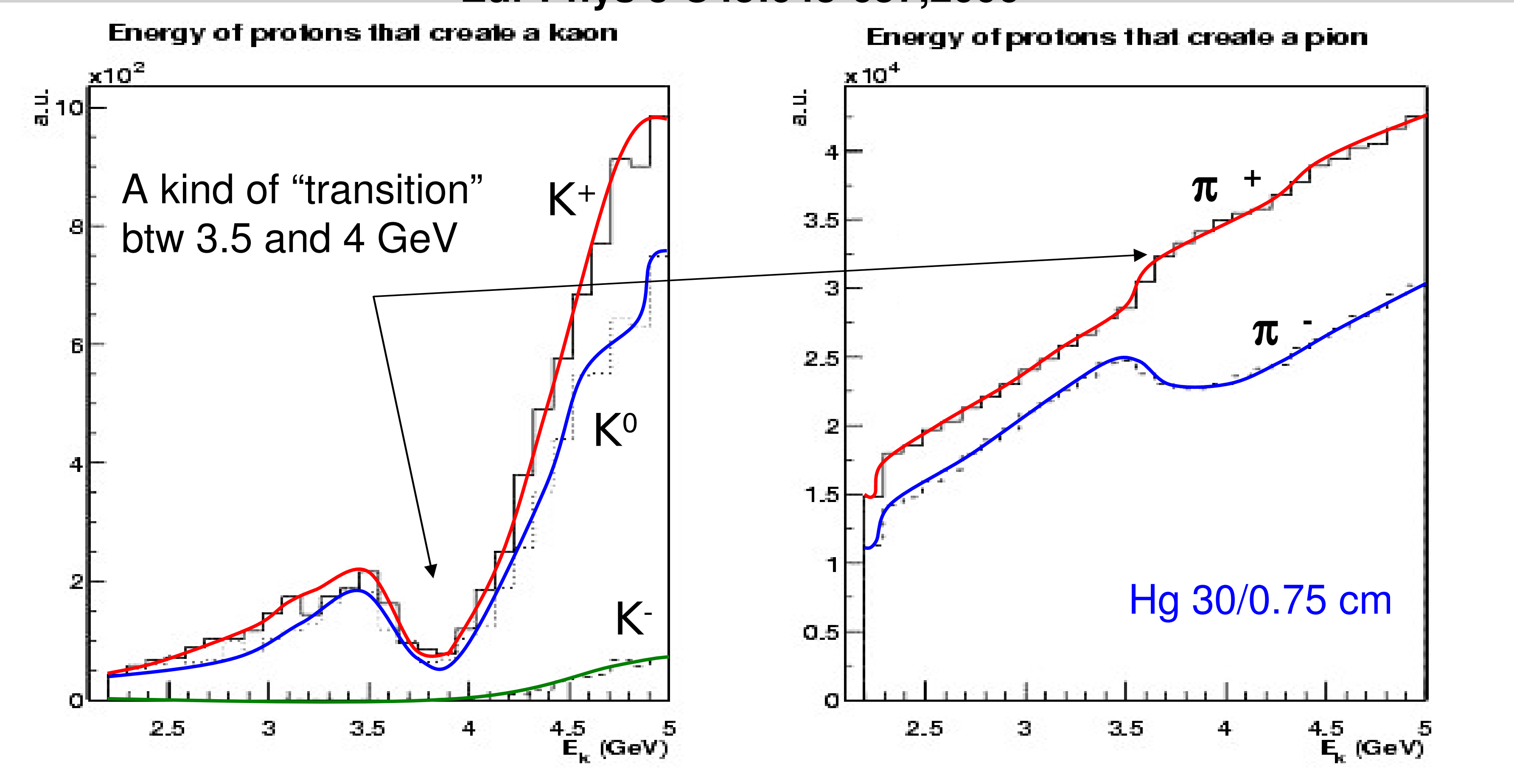
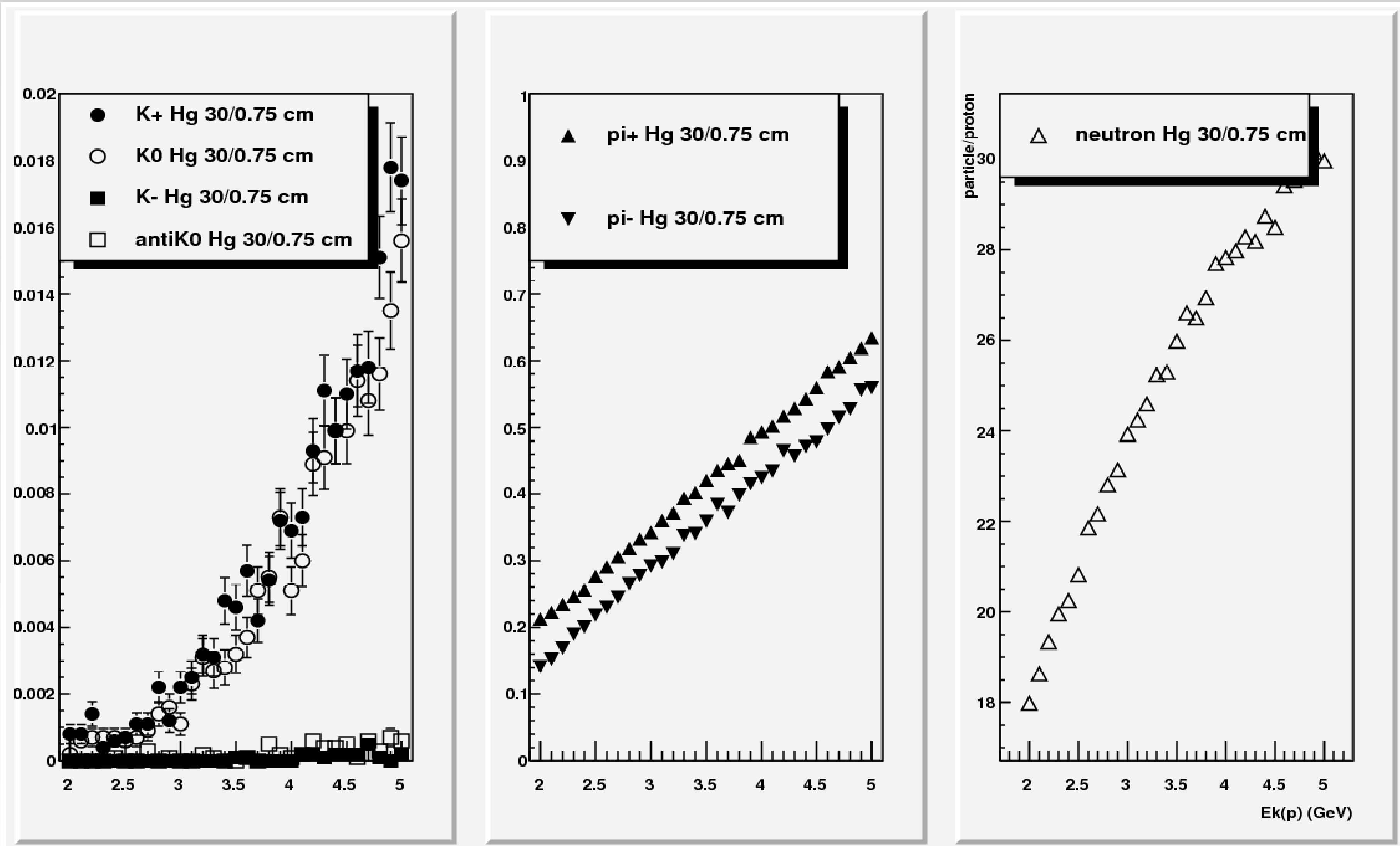


- at 2.2GeV :
  - 0.26 π^+/s
  - 0.8 10^{-3} K^+/s
- at 3.5GeV :
  - 0.29 π^+/s
  - 2.8 10^{-3} K^+/s
- at 4.5GeV :
  - 0.32 π^+/s
  - 5.2 10^{-3} K^+/s

Particle multiplicities: FLUKA 2008

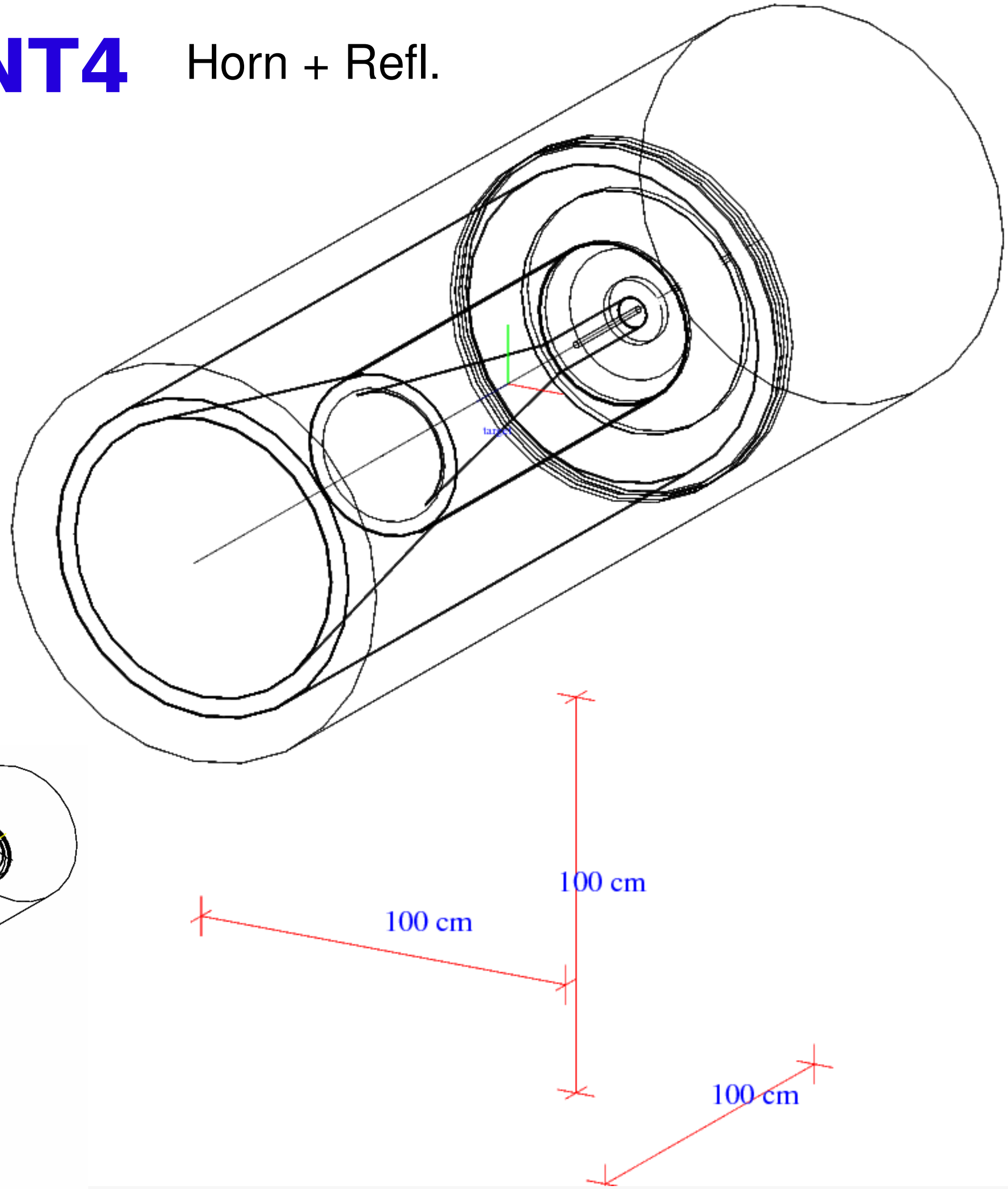
- Energy trend is "smoother" (same E range)

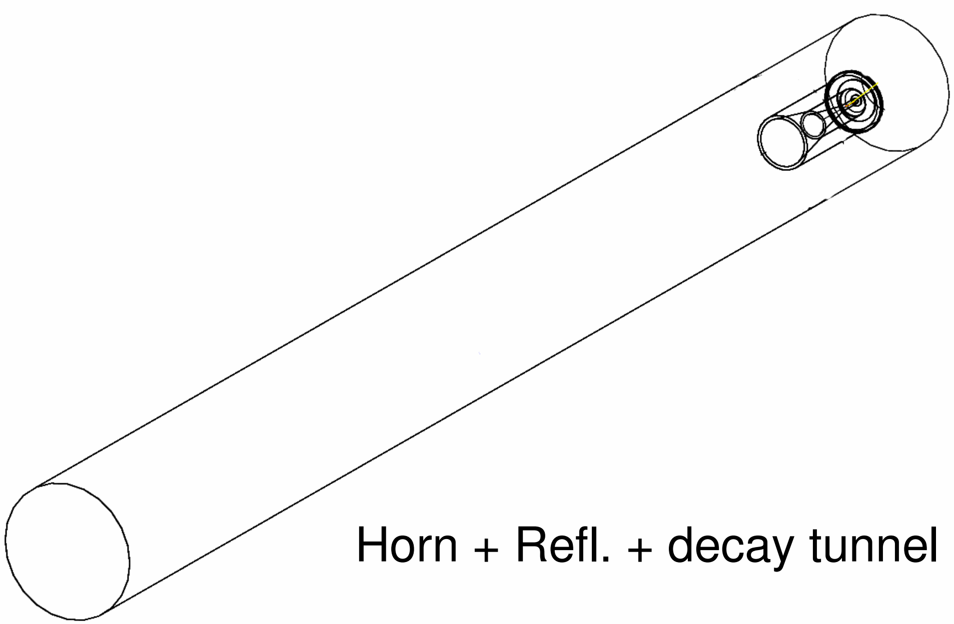


GEANT3.2.1 to GEANT4

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

Horn + Refl.





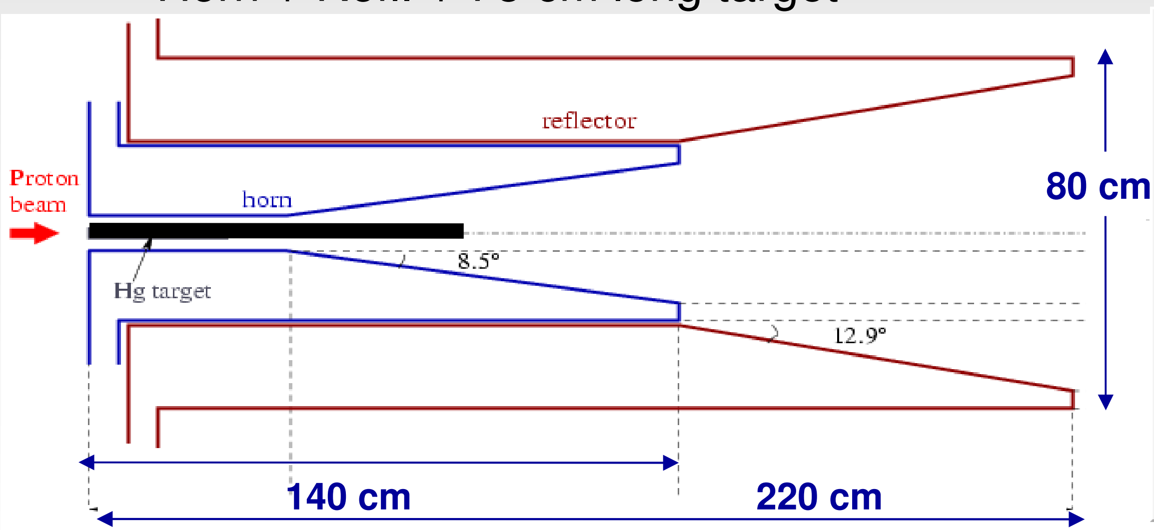
Horn + Refl. + decay tunnel (L=20m r=1m)

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

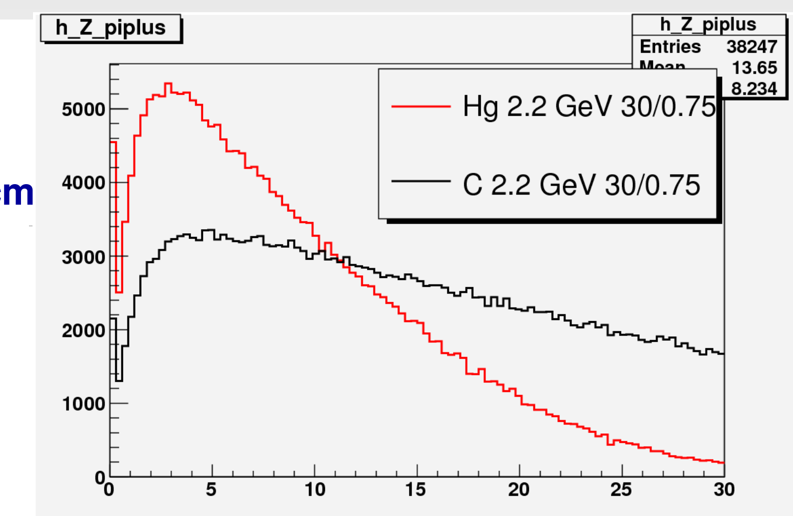
What using a graphite target ?

- 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)
- Covered items:
  - Power dissipation / pion yield / kaon yield / pi+ collection + ν fluxes

Horn + Refl. + 78 cm long target



Z of pi+ exiting the target

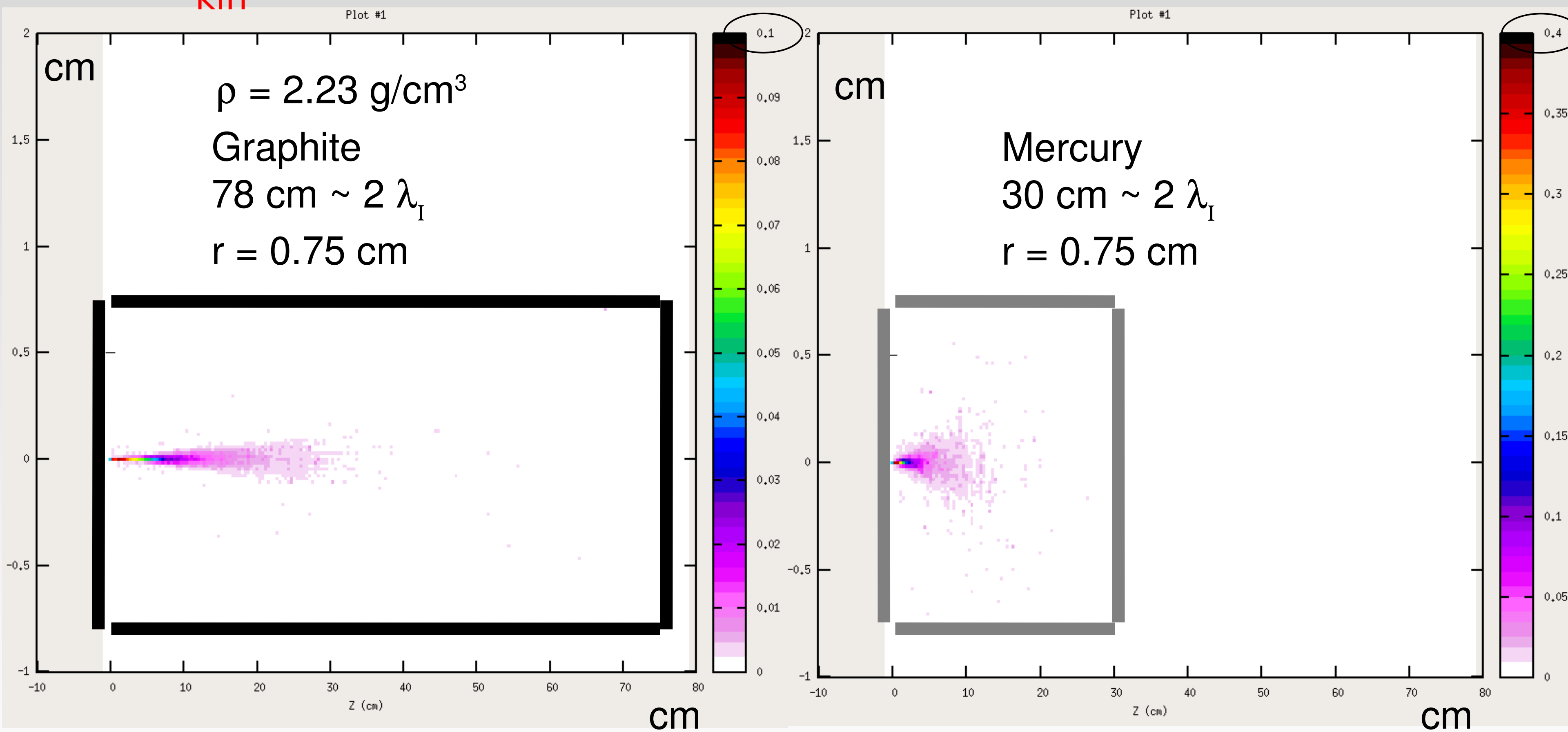


Graphite-Mercury energy deposition: FLUKA08

- (GeV/cm³/proton)

$E_{kin} = 2.2$ GeV

NB. “pencil-like” beam

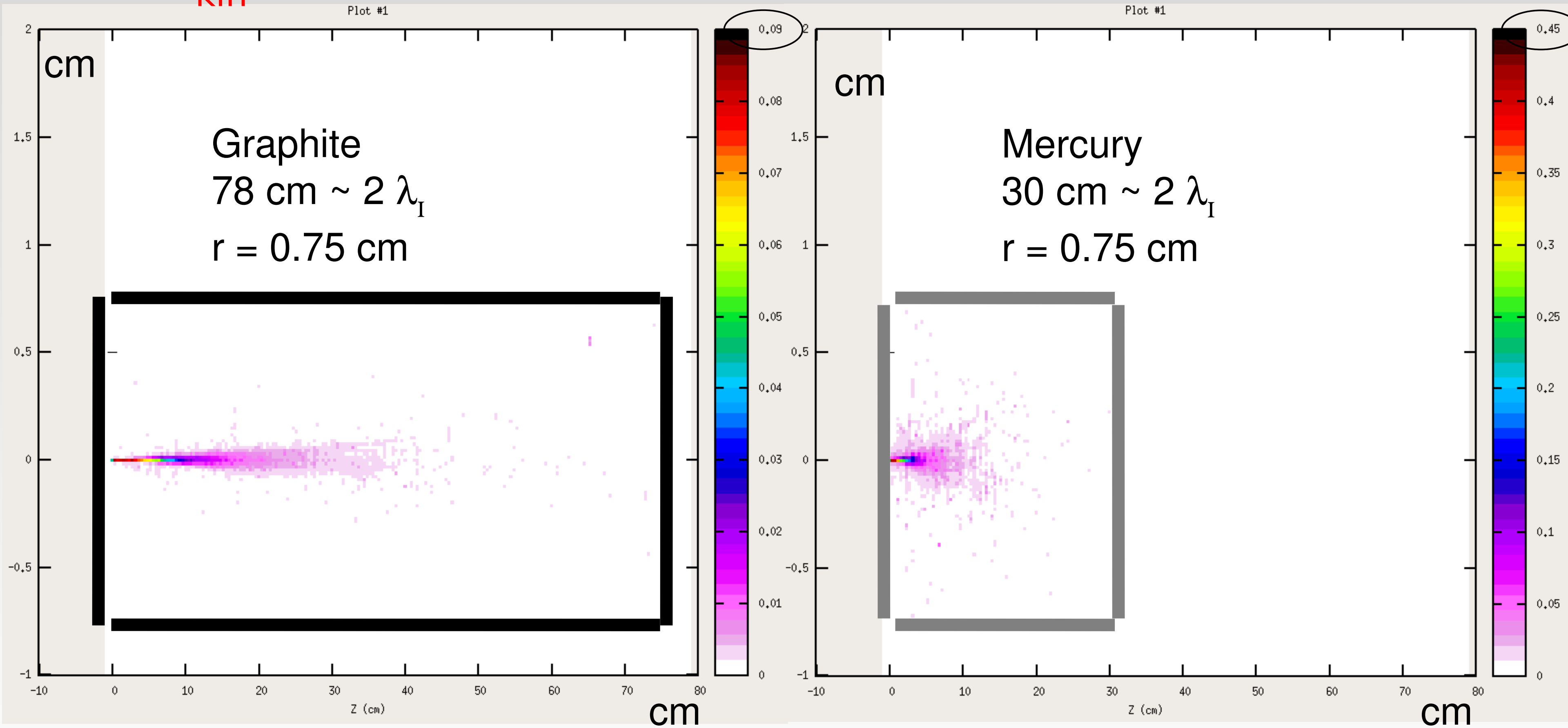


Graphite-Mercury energy deposition: FLUKA08

- (GeV/cm³/proton)

$E_{kin} = 3.5$ GeV

NB. “pencil-like” beam

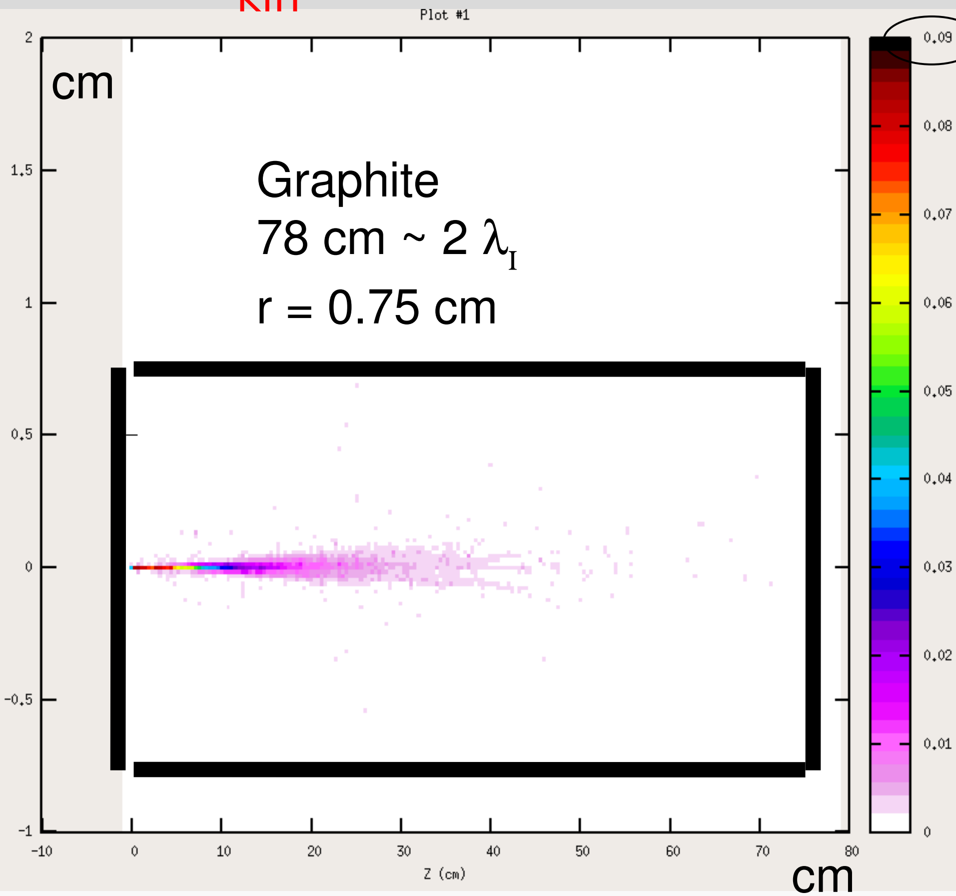


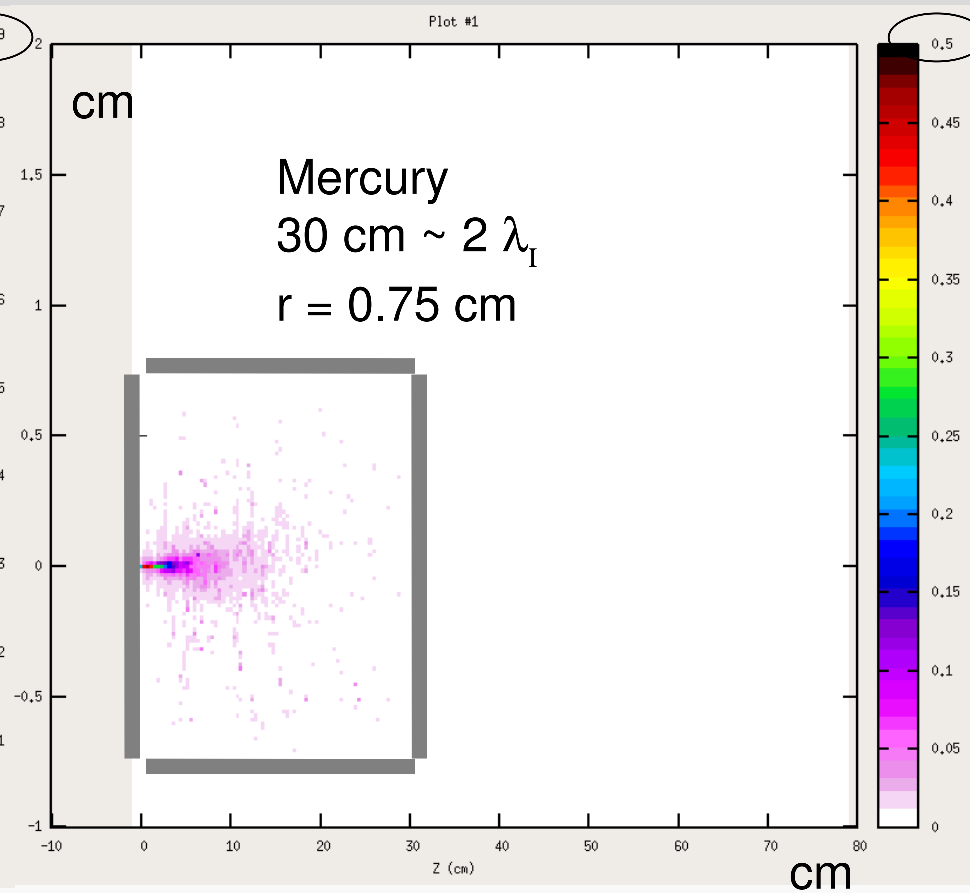
Graphite-Mercury energy deposition: FLUKA08

- (GeV/cm³/proton)

$E_{kin} = 4.5$ GeV

NB. “pencil-like” beam



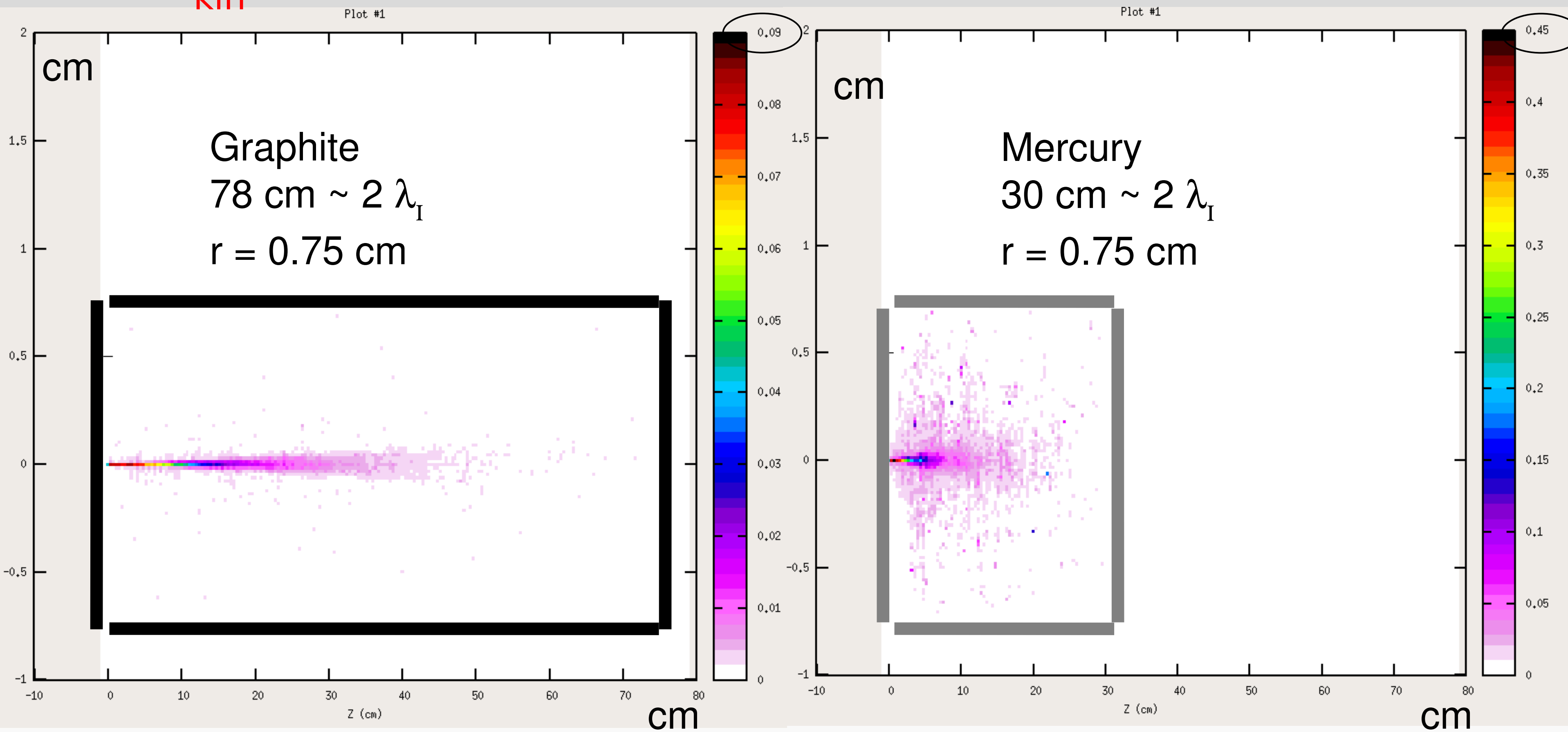


Graphite-Mercury energy deposition: FLUKA08

- (GeV/cm³/proton)

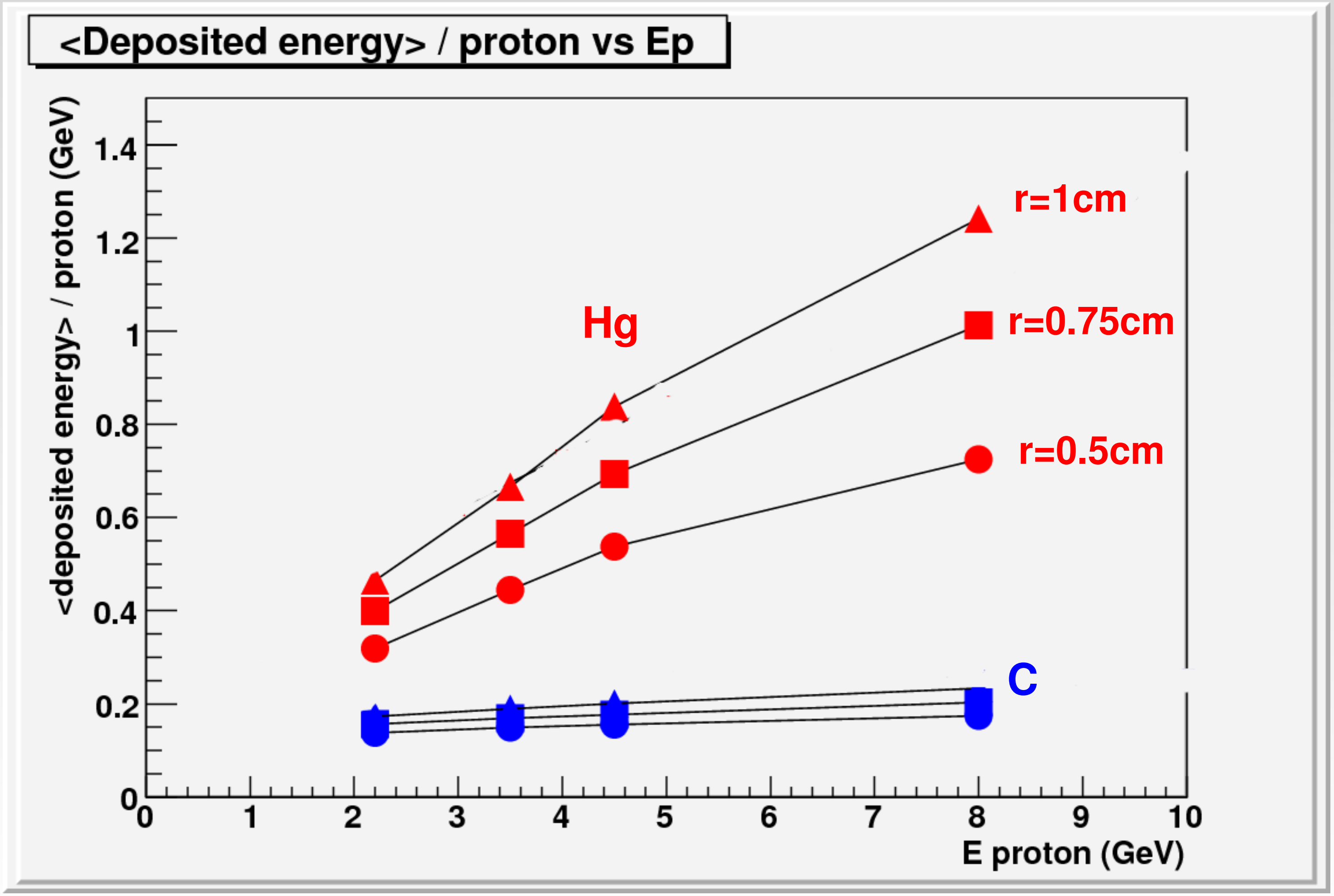
E_{kin} = 8.0 GeV

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

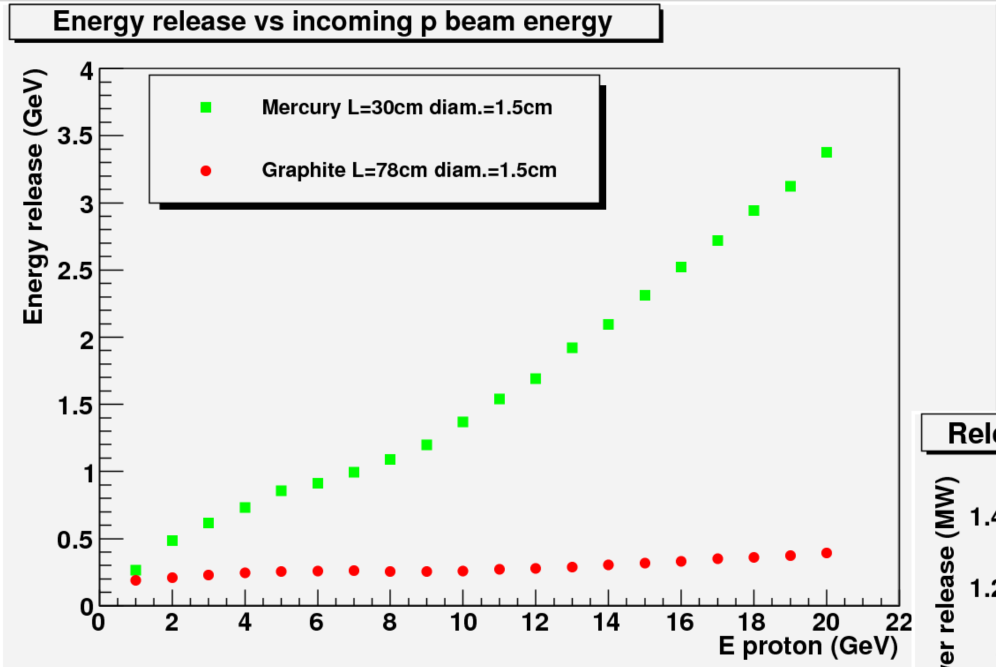
x-axis: 0-2 GeV

peak: ionization loss of elastic or not-interacting p

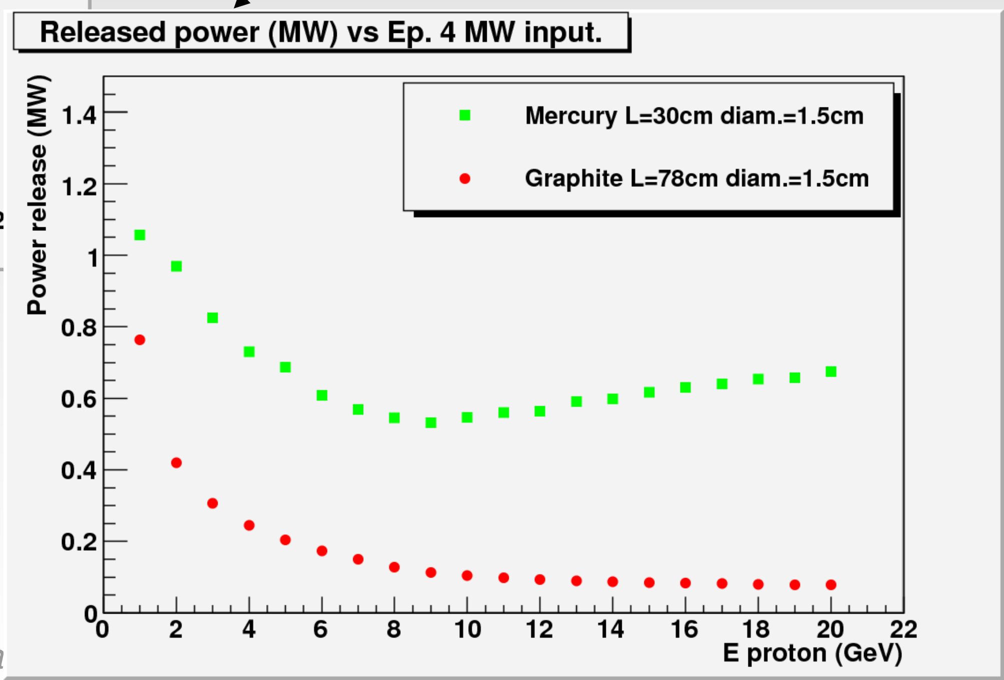
Graphite-Mercury energy deposition: GEANT4

GEANT4 (hadronic "QGSP physics list")

- Mean energy deposition vs Ek(p)



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



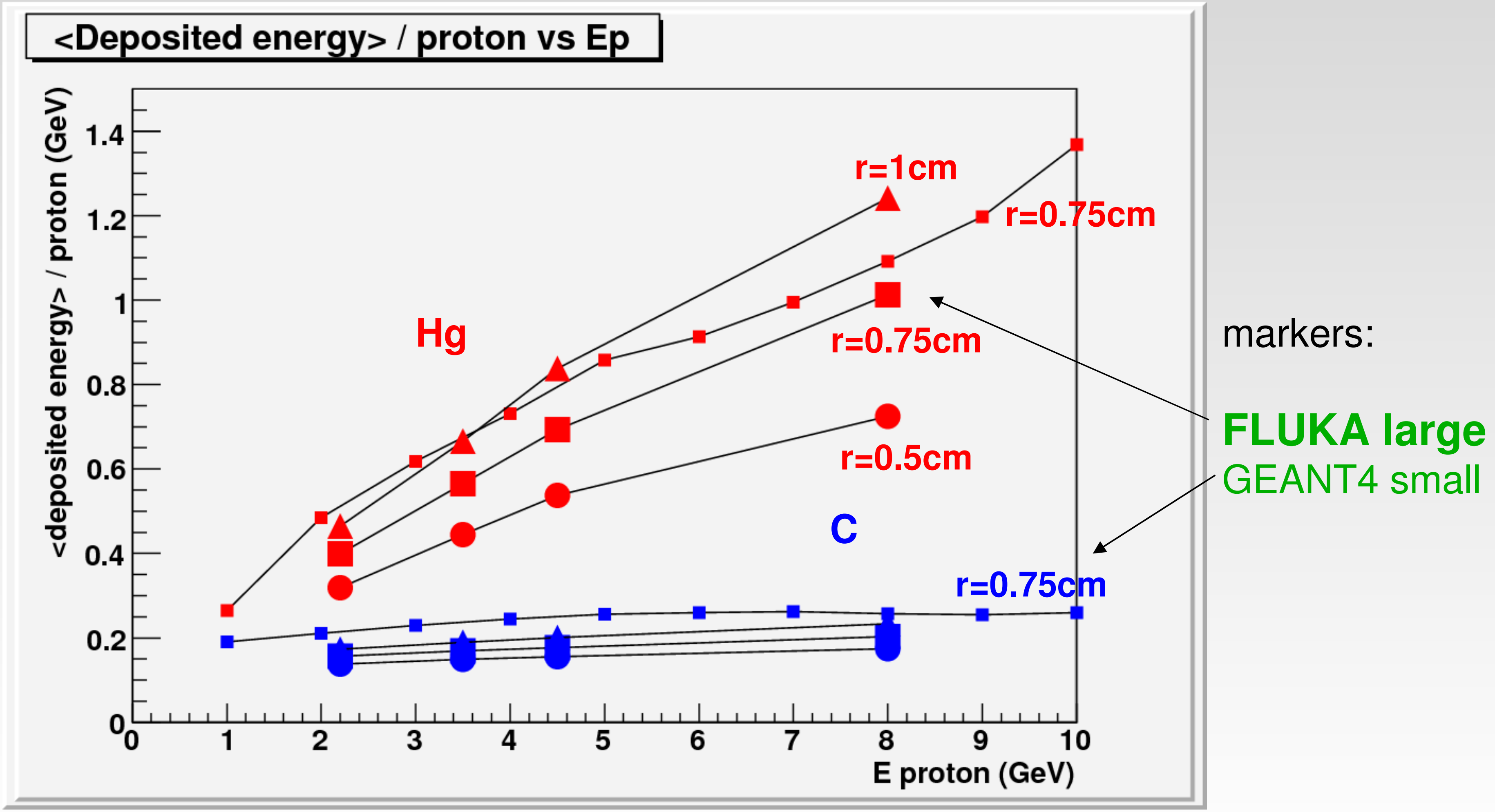
Power released in target:

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

considerably lower for Carbon

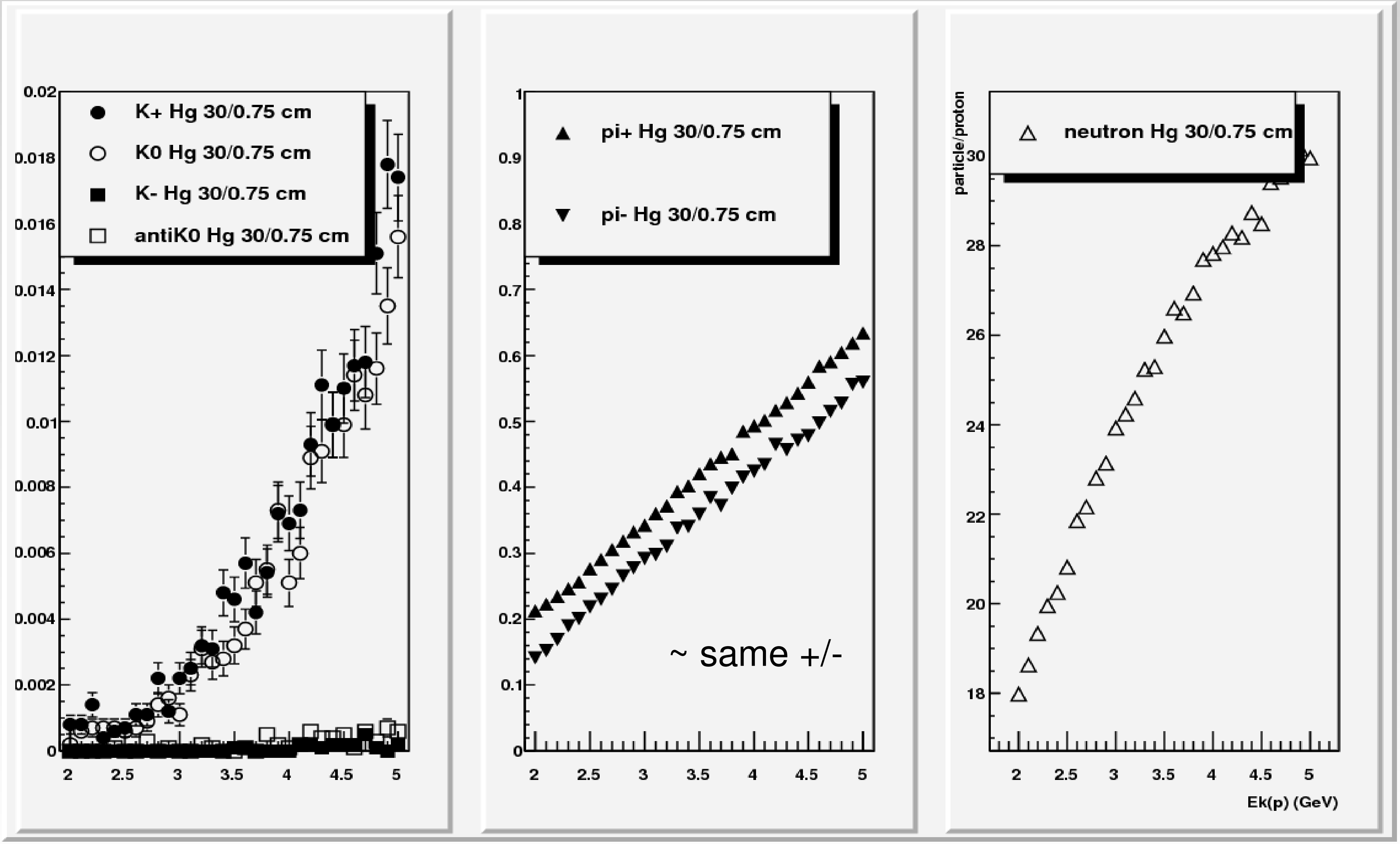
Graphite-Mercury energy deposition: G4/FLUKA08

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



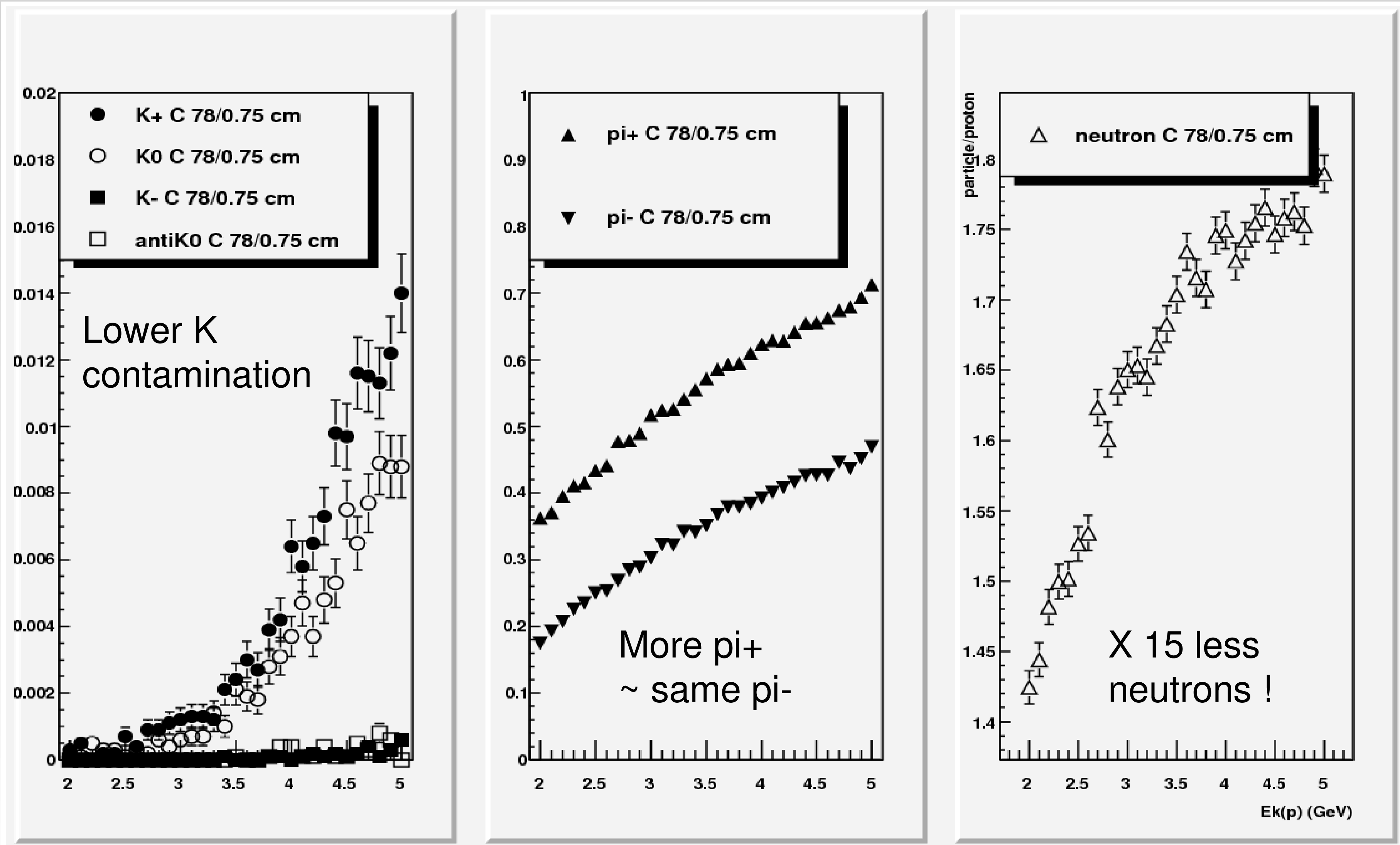
Particle multiplicities: FLUKA 2008

- Mercury



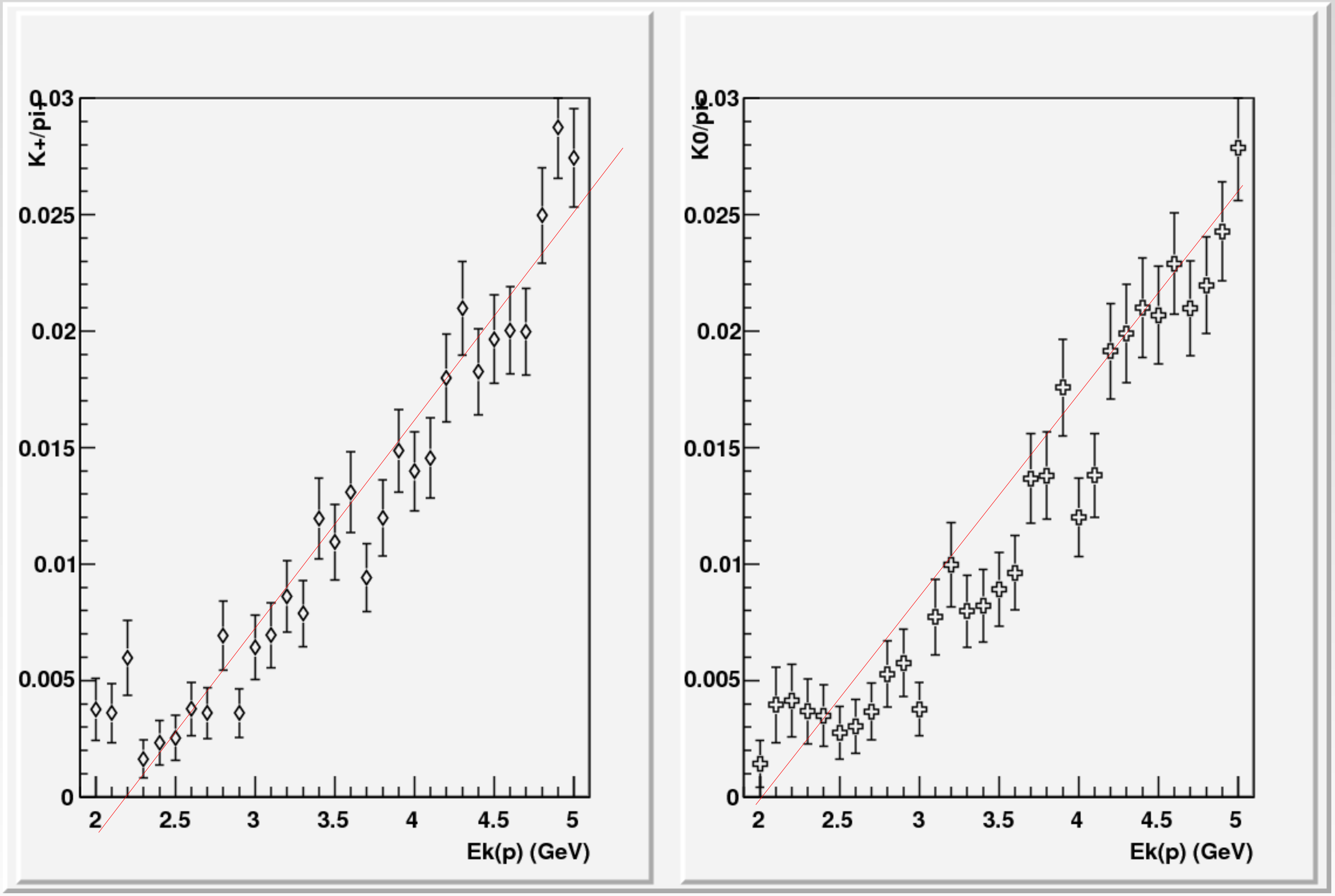
Particle multiplicities: FLUKA 2008

- Carbon



K/pi ratios vs E (FLUKA 2008)

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



K/pi ratios vs E (FLUKA 2008)

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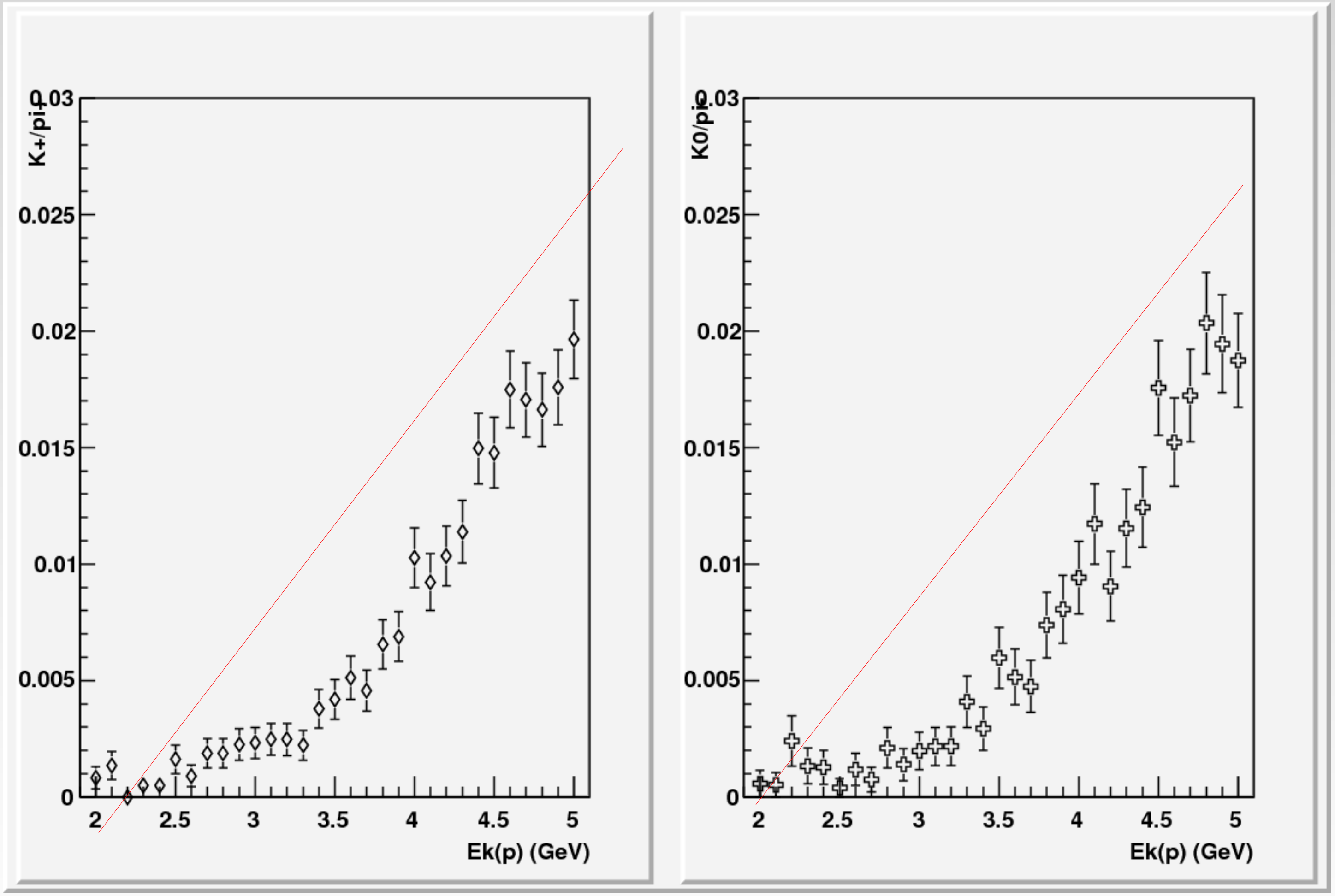
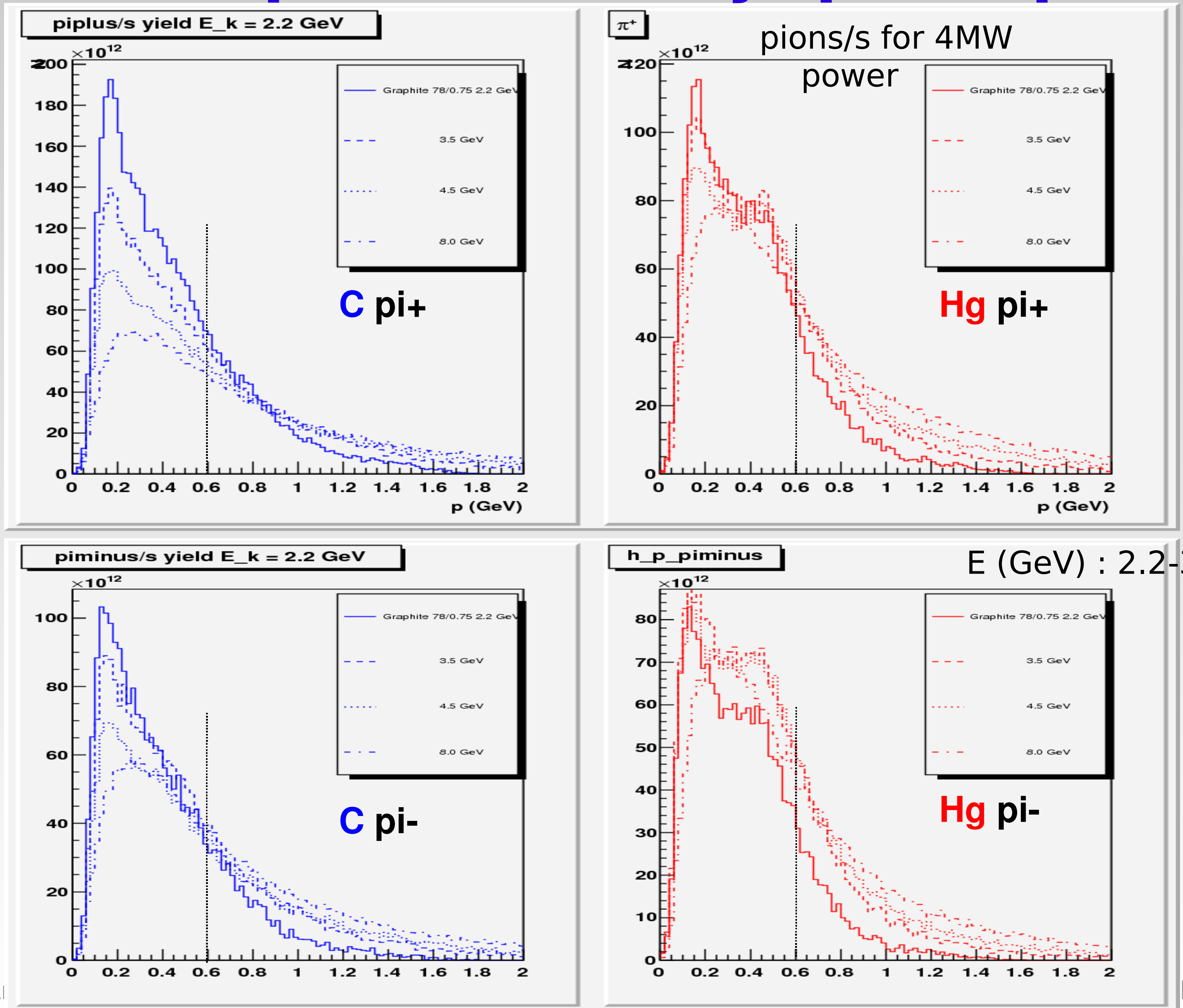
  - K+/pi+ and K0/pi-



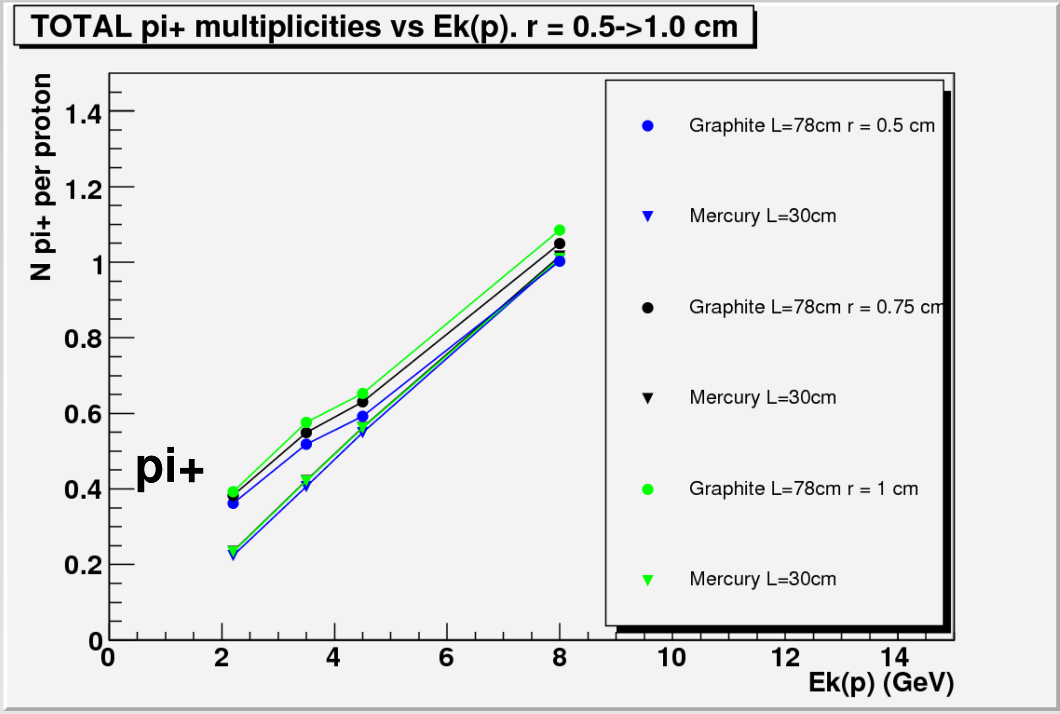
Graphite-Mercury: pion spectra

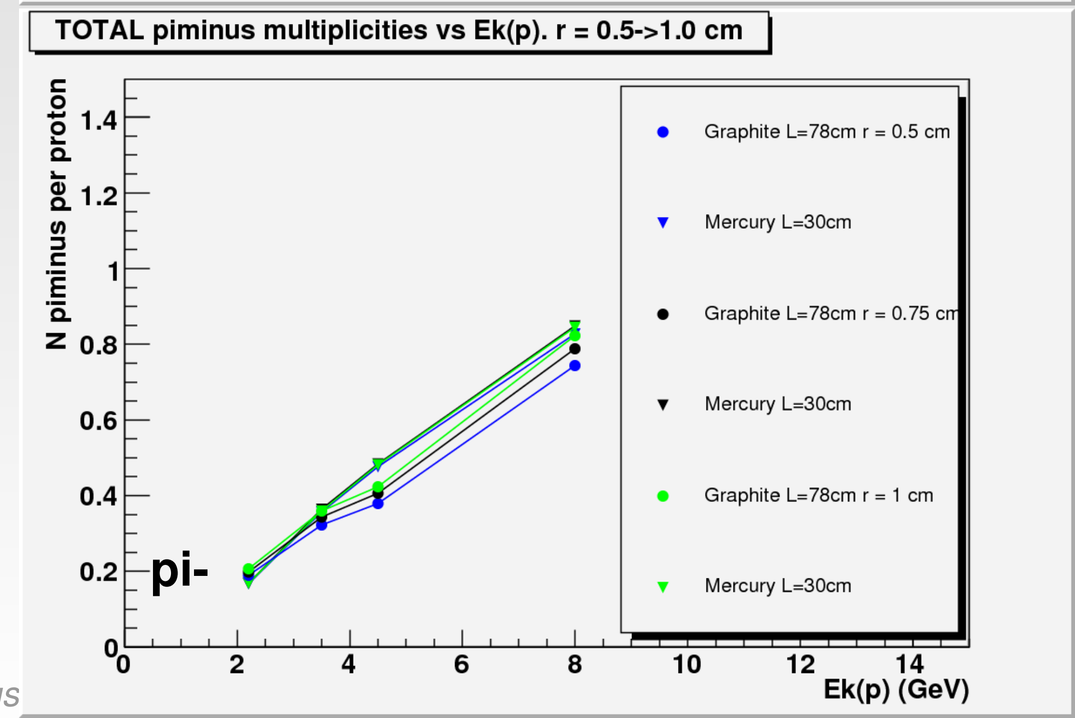


Pion multiplicities vs Energy:

C and Hg

NOT normalized to 4 MW





Pion multiplicities vs Energy:

C and Hg

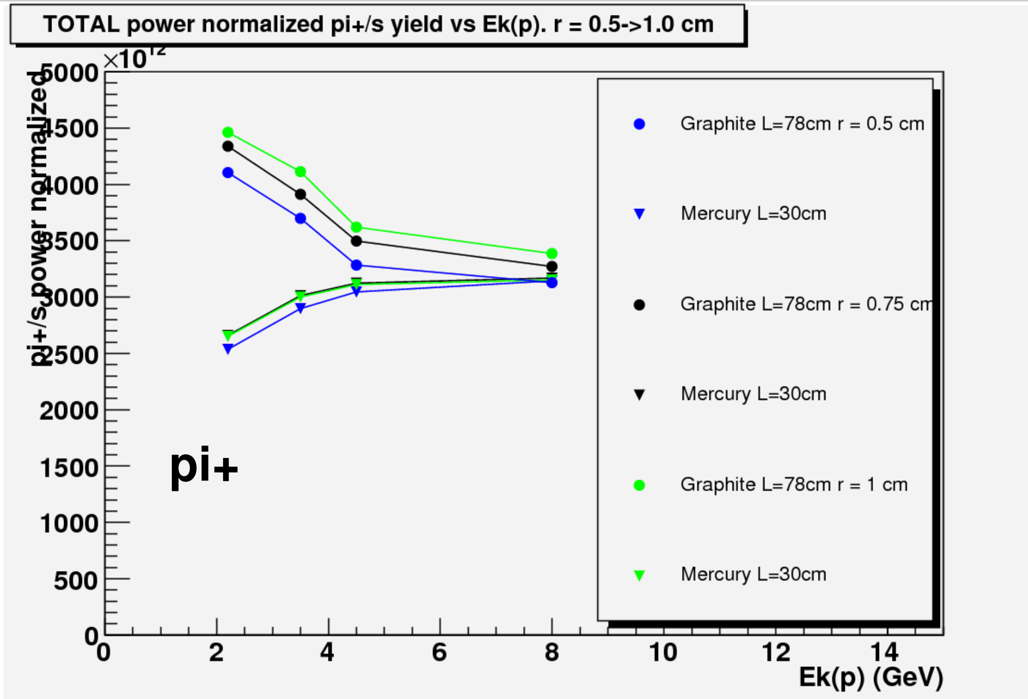
normalized to 4 MW fixed power

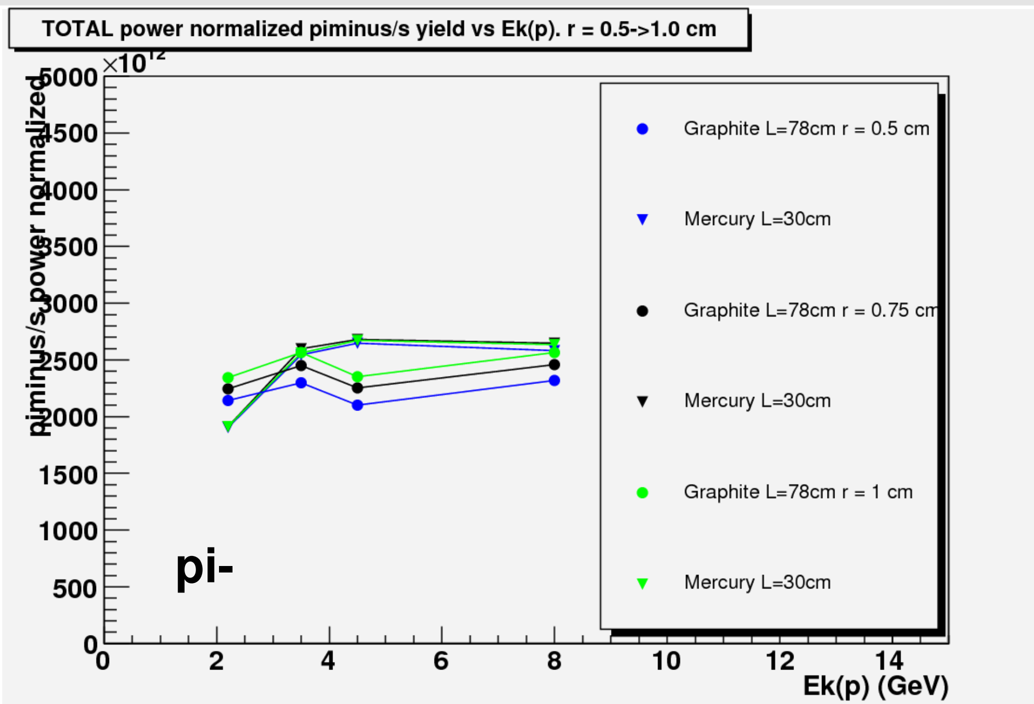
- 1.13×10^{16} pot/s at 2.2 GeV
- 0.71×10^{16} pot/s at 3.5 GeV
- 0.55×10^{16} pot/s at 4.5 GeV
- 0.31×10^{16} pot/s at 8.0 GeV

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





Pion multiplicities vs Energy:

C and Hg

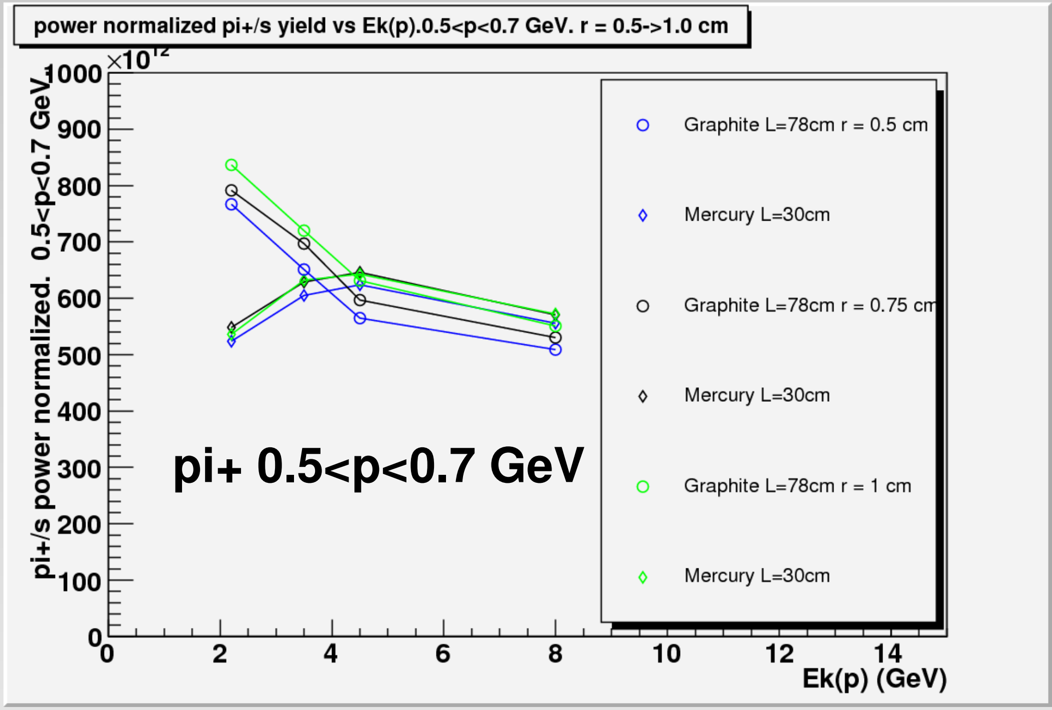
restrict to pions producing neutrino around the oscillation maximum

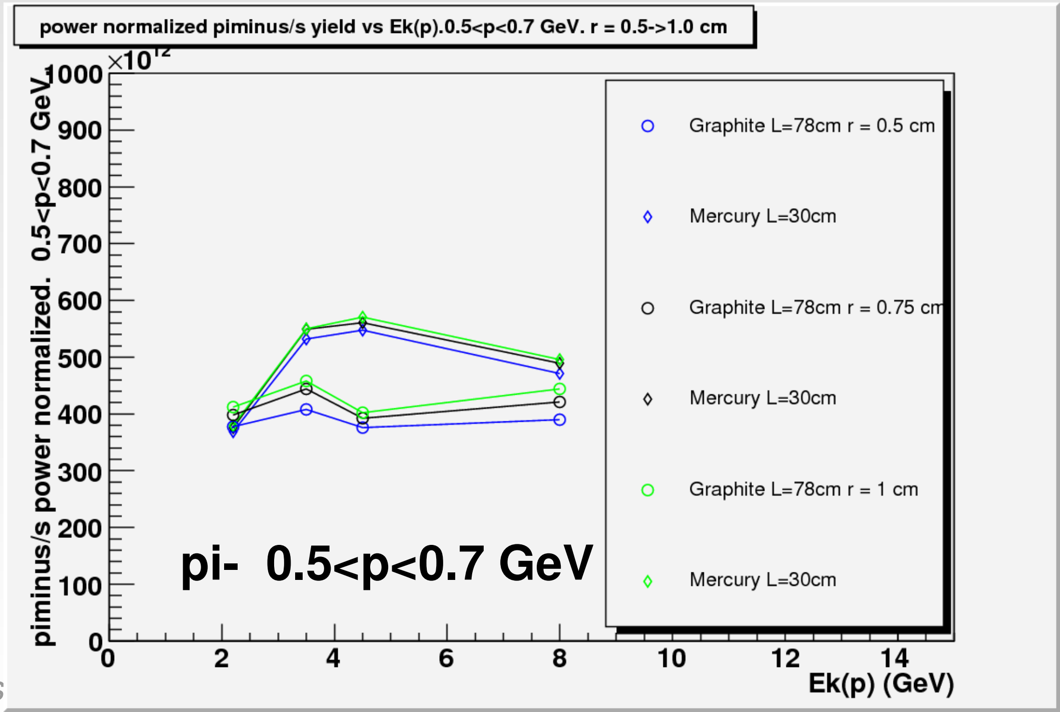
500 < p < 700 MeV

normalized to 4 MW fixed power

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

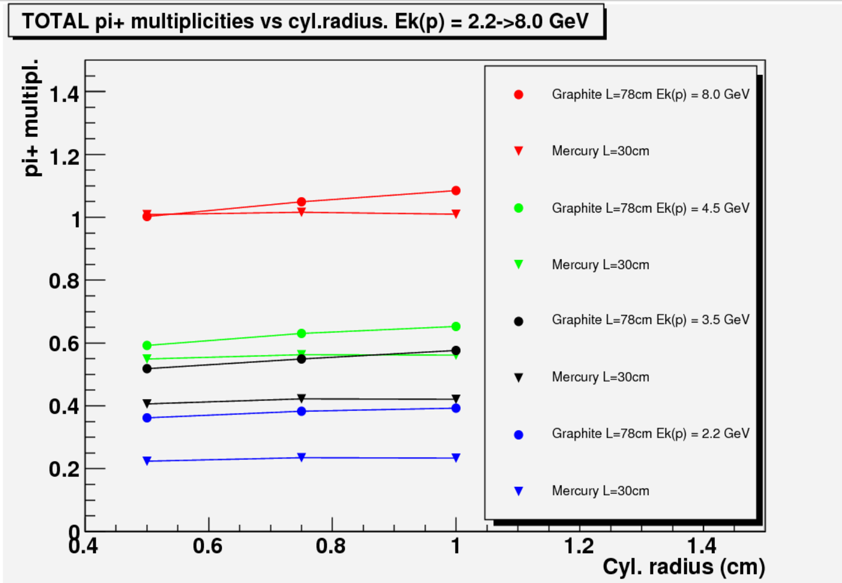
pi- yield similar at low energy (better with Hg at higher energies)

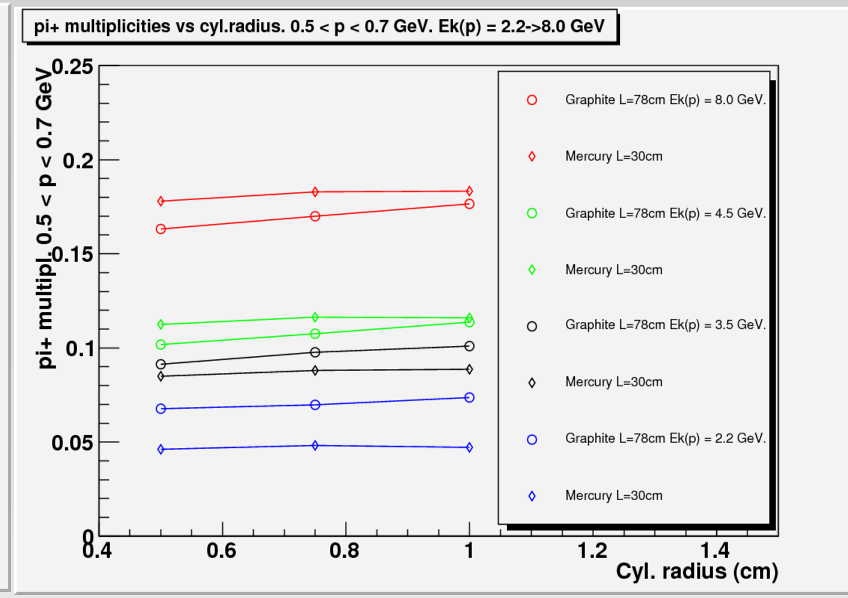


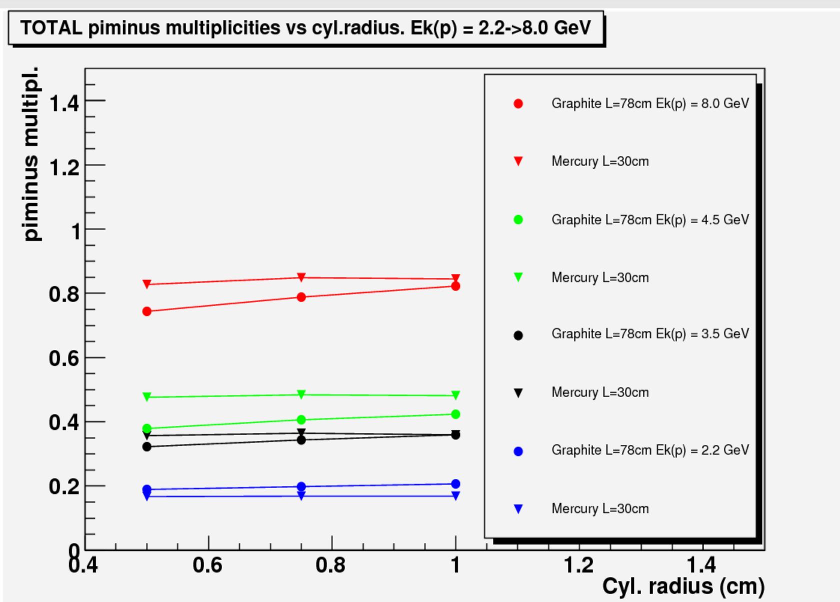


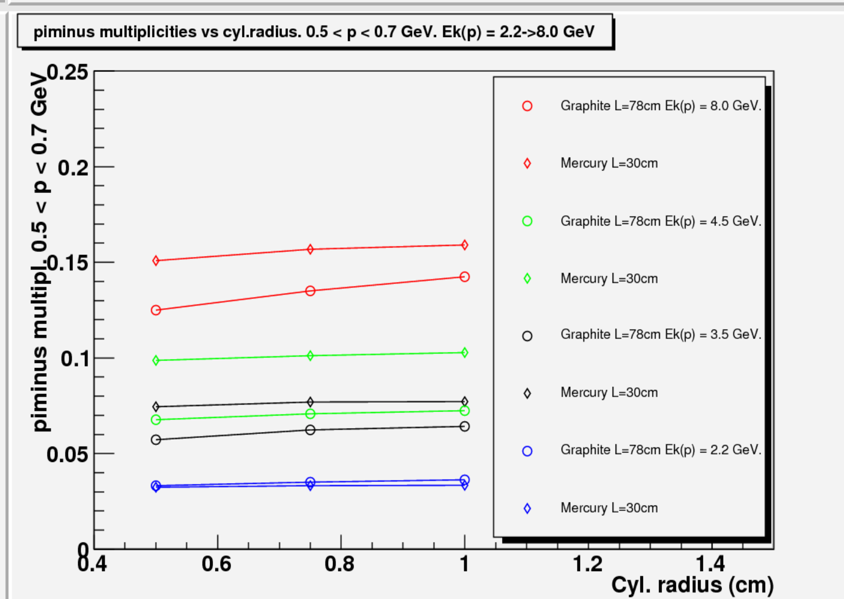
Effect of radius on pion multiplicities

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



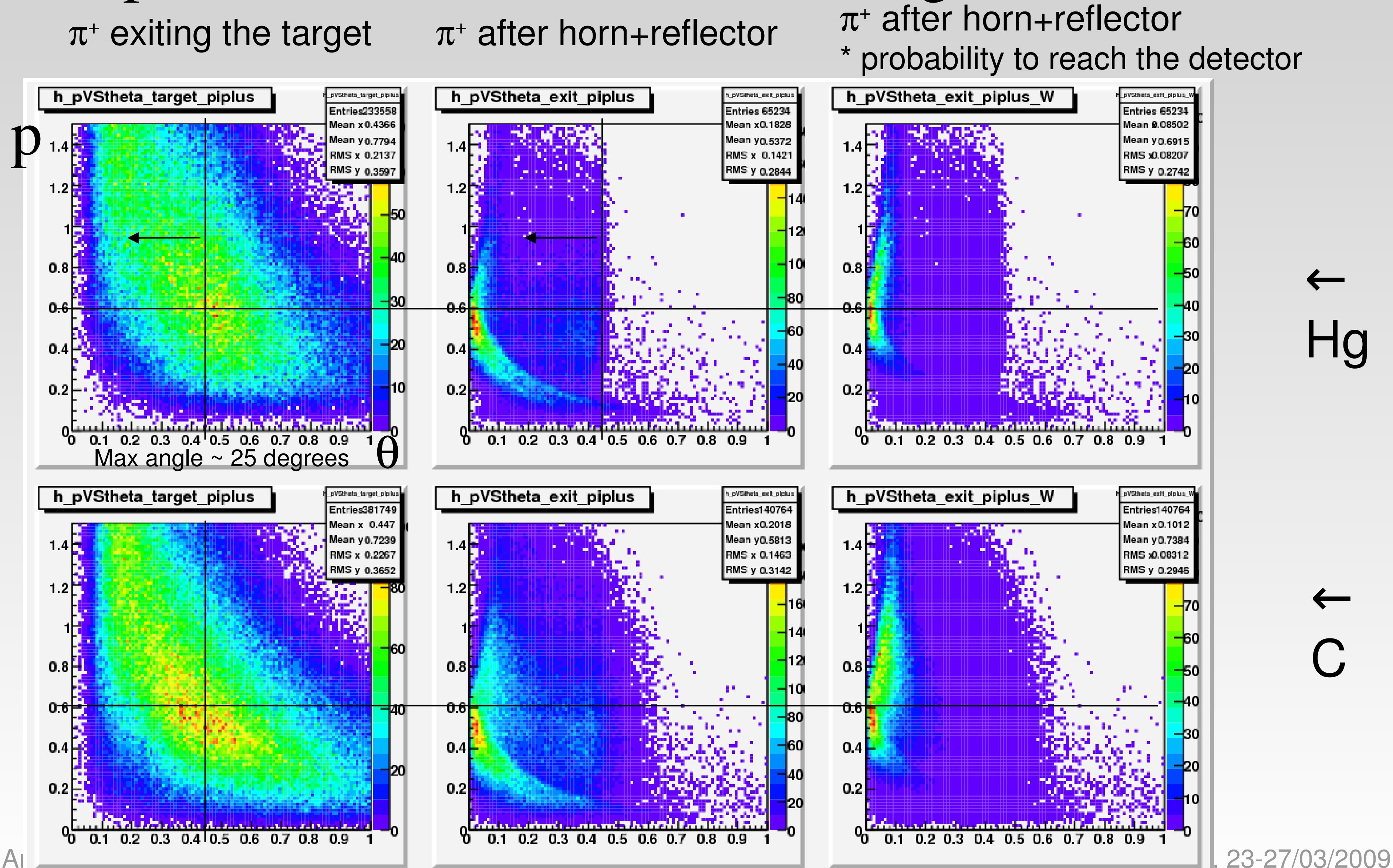






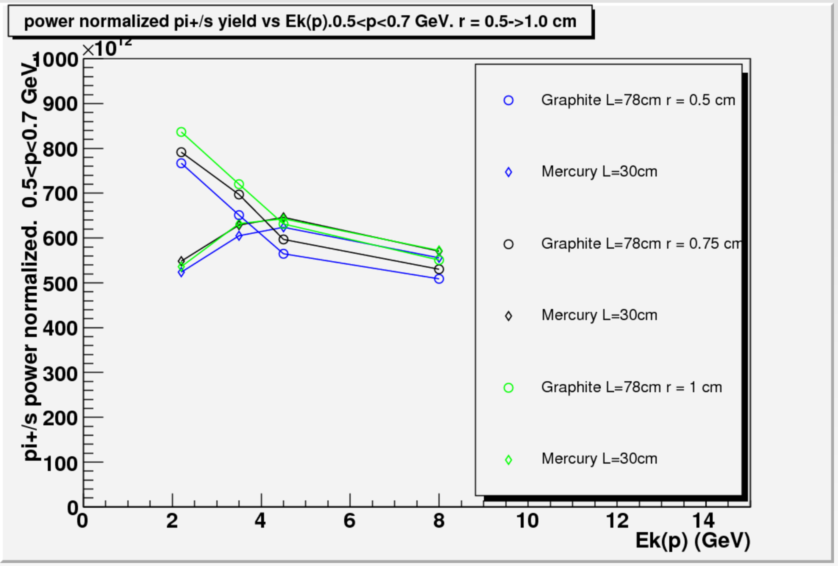
Pion collection: Mercury-Graphite

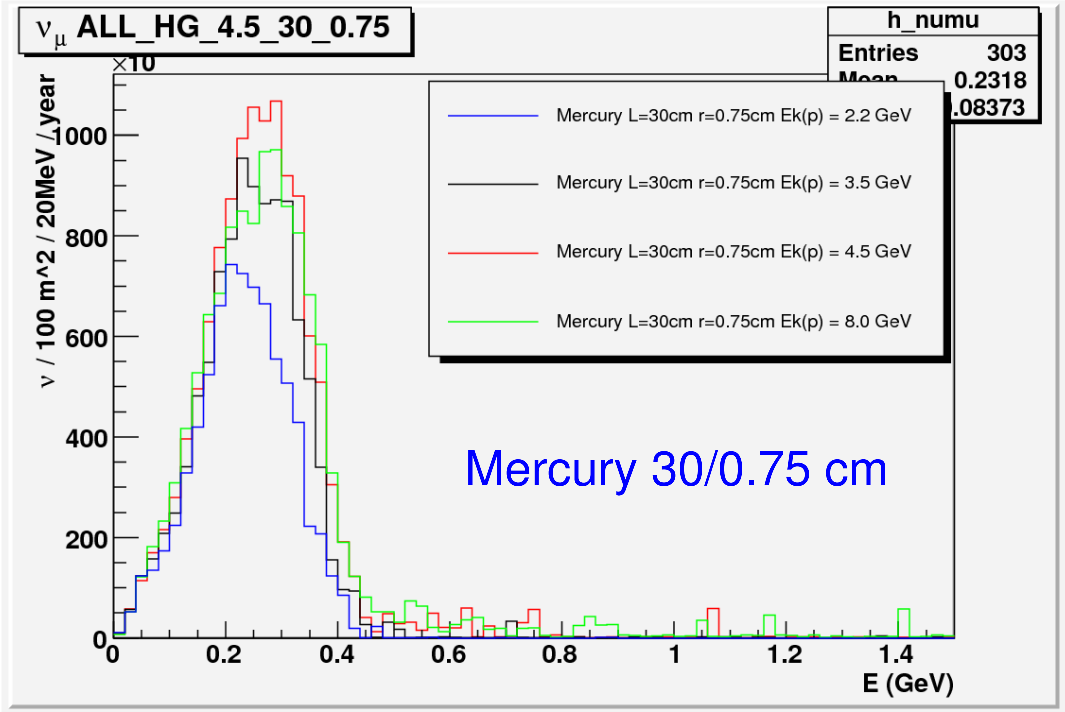
- p vs θ : before and after focusing (2.2 GeV L=30 r=0.75)

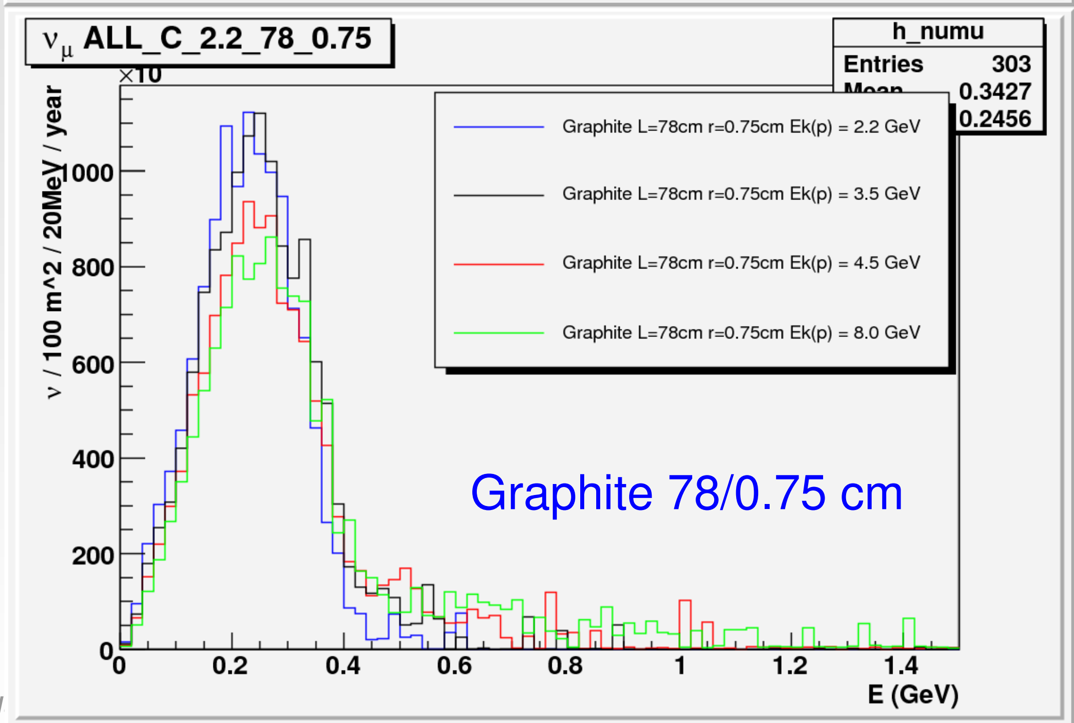


ν_μ fluxes: Mercury-Graphite

- 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

Conclusions

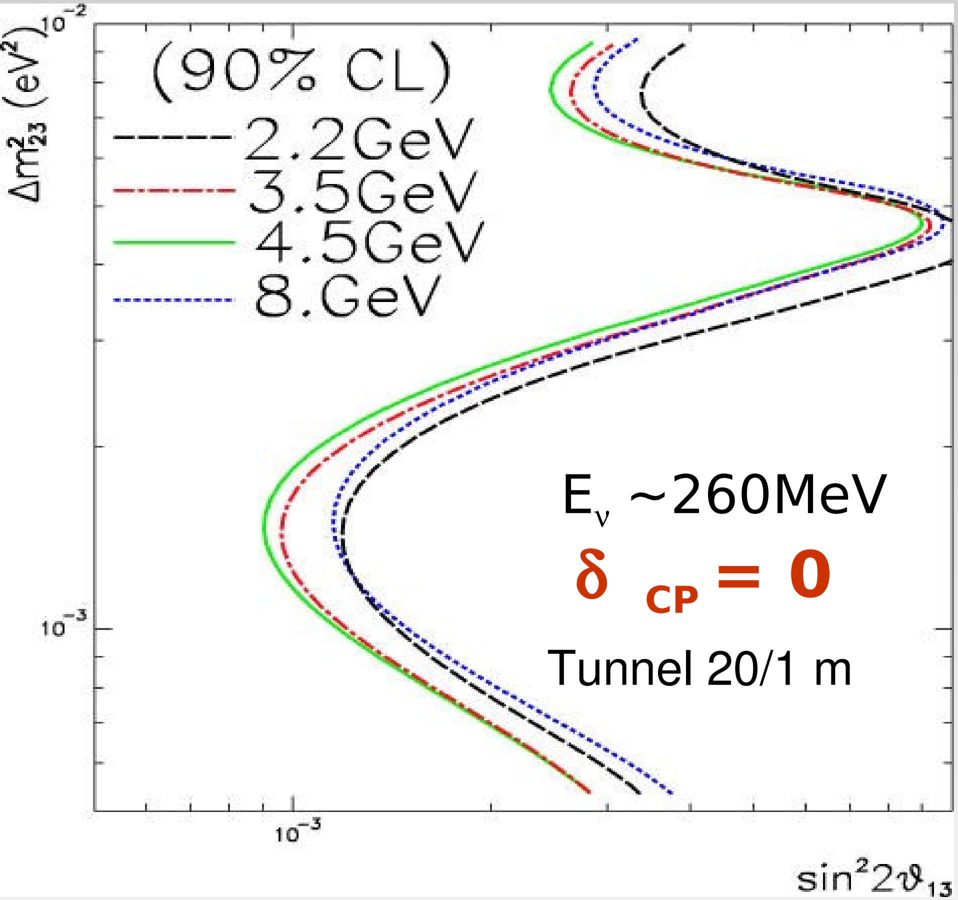
- Getting experience with the SPL-Fréjus neutrino fluxes and physics reach. Software tools are ready / working and being updated.
- Migration to GEANT4 in progress
- Migration to FLUKA 2008 done:
  - "looks" better in terms of K production in the target (smoother dependence with E), some slight modification in the pi+ spectra observed. General results from study performed with older version not significantly modified.
- Graphite target option simulated. Looks appealing. W.r.t. Hg:
  - much lower energy deposition (but dissipation more difficult...)
  - lower K contamination (~-30/40% for E = 2-5 GeV)
  - 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)

Outlook

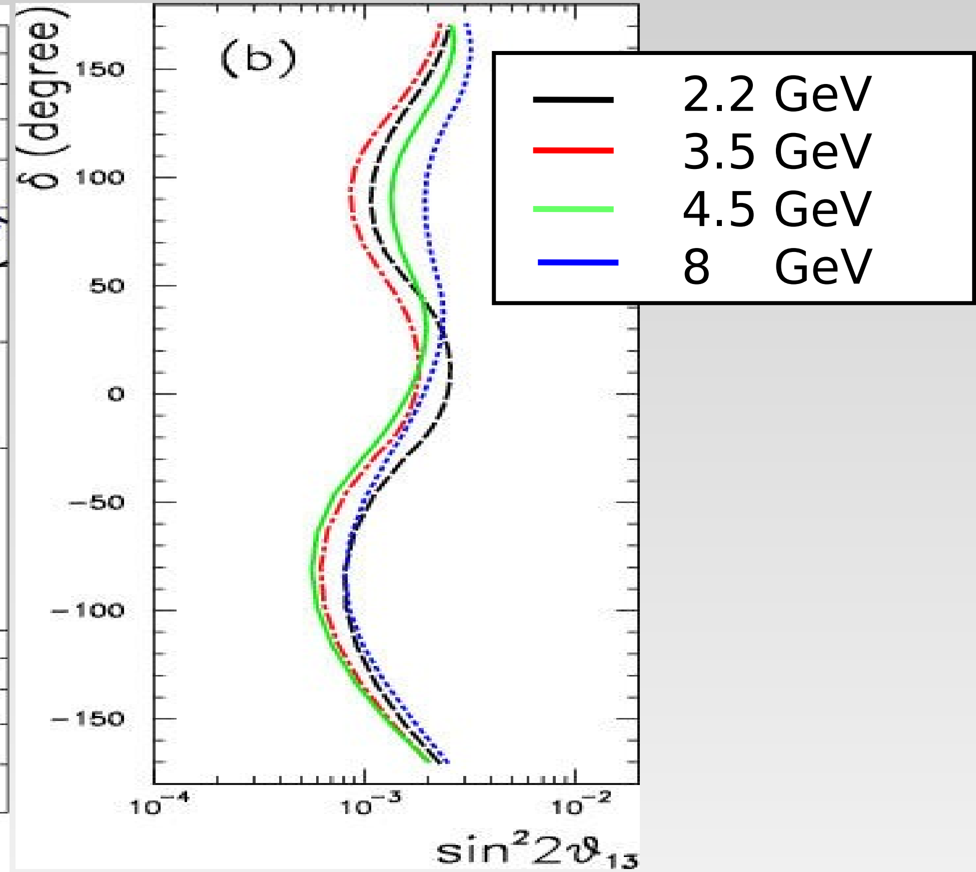
- Benefit of hadro-production data (HARP) to improve reliability of target simulation.
- Perform comparison also with more recent version of MARS.
- Use beam with finite profile in simulation.
- Finalize transition to GEANT4.
- Reevaluate sensitivities with new setup and use other programs (GLOBES).
- Finalize study on Graphite target by studying room for improvement coming from horn re-optimization (consider also shifting the target back-forth). Evaluate difference at the level of θ_{13} sensitivity.

Backup slides

Sensitivity vs beam energy



5 year positive focusing



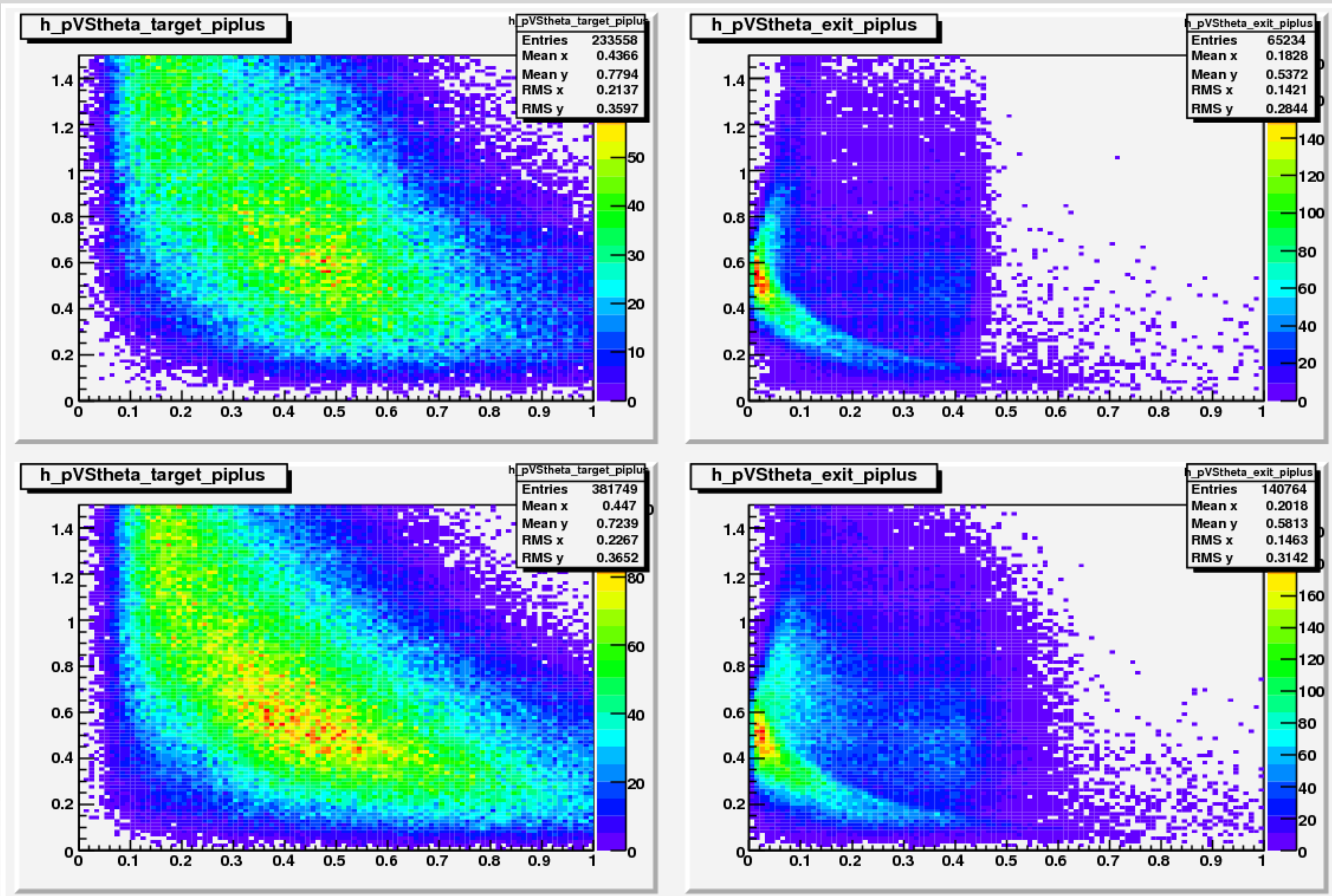
10 years mixed focusing (8y + and 2y -)

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

Pion collection: Mercury-Graphite

- P vs θ : before and after focusing

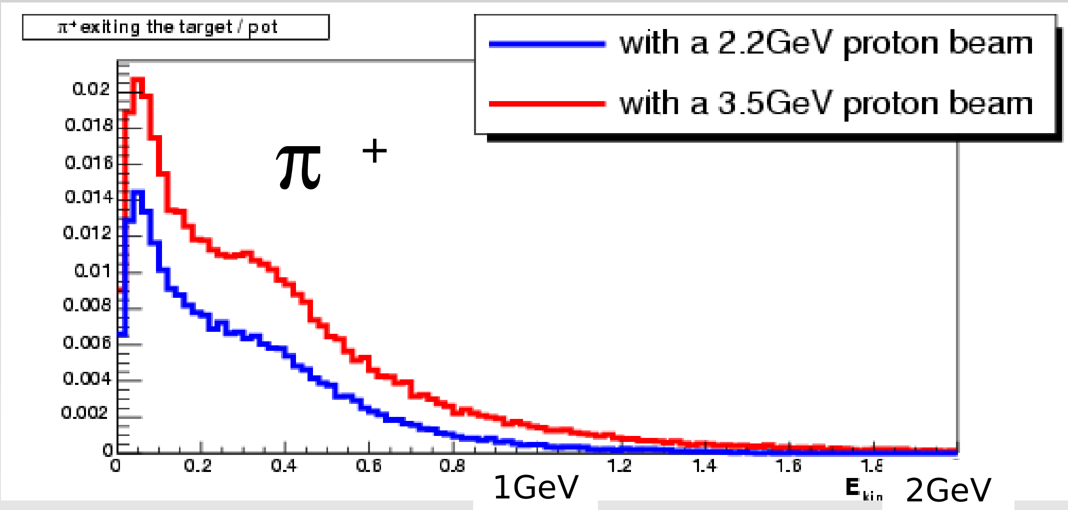
π^+ exiting the target π^+ after horn+reflector

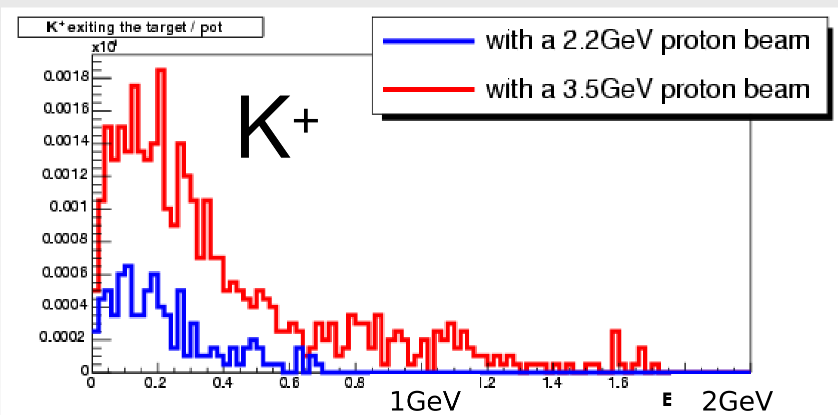


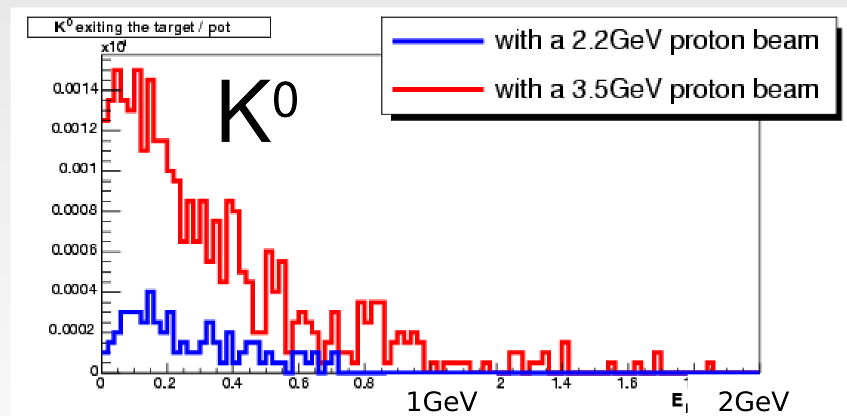
← Hg

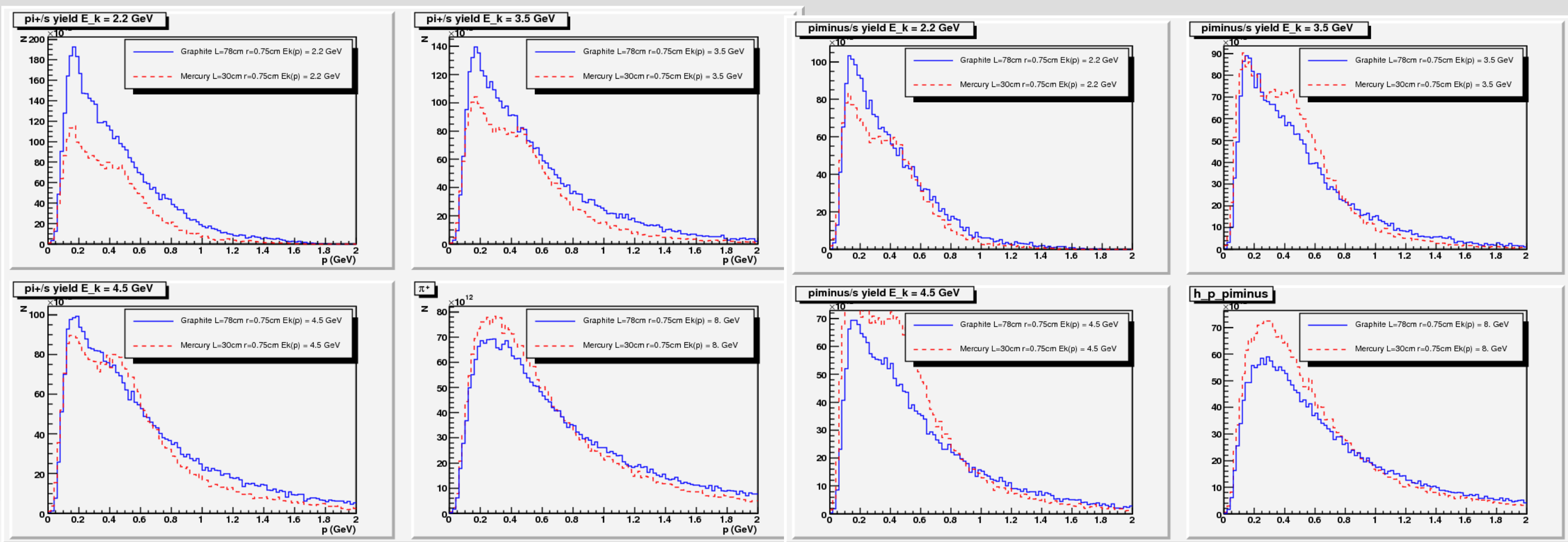
← C

Kinetic energy (GeV) of pions and kaons

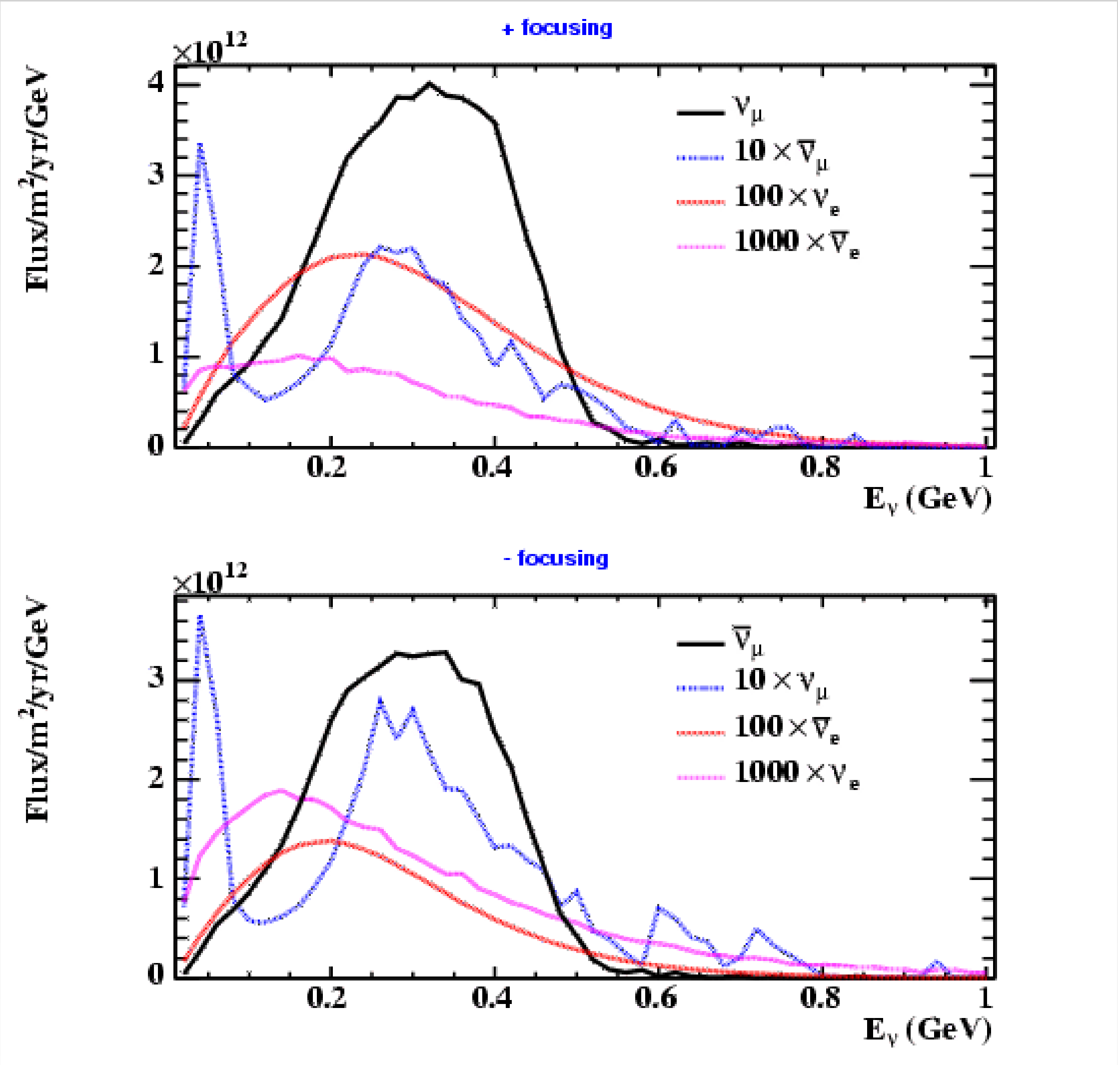







pi+/s yield E_k = 2.2 GeV
pi+/s yield E_k = 3.5 GeV
piminus/s yield E_k = 2.2 GeV
piminus/s yield E_k = 3.5 GeV
pi+/s yield E_k = 4.5 GeV
π+
piminus/s yield E_k = 4.5 GeV
h_p_piminus
Graphite L=78cm r=0.75cm Ek(p) = 2.2 GeV
Mercury L=30cm r=0.75cm Ek(p) = 2.2 GeV
Graphite L=78cm r=0.75cm Ek(p) = 3.5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

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.