Updates on the SPL-Fréjus Super Beam simulation

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EUROnu WP2 EVO meeting

- **Short reminder of previous studies**

- **New studies (not shown in previous WP2 meet.s)**
  - **Effect of dropping the reflector (+ increasing horn i)**
  - **Systematics on primary π production**
    - **characterization of interesting π phase space**
    - **another model : GIBUU**
  - **Future SB in Europe: SPL<-> PS2 ? early comparison**
  - **A deeper look into GLOBES parametrisations for SPL**
    - **E-resolution**
    - **cross-sections**
    - **event rates**
    - **oscillation probabilities (w/wo matter effects)**

Short summary of previous results

GRAPHITE target studies (w.r.t. Mercury)

- **reduced energy deposition in the target (FLUKA08+GEANT4)**
- **reduced neutron flux (~x15 FLUKA08)**
- **pion yields more asymmetric in charge but comparable**

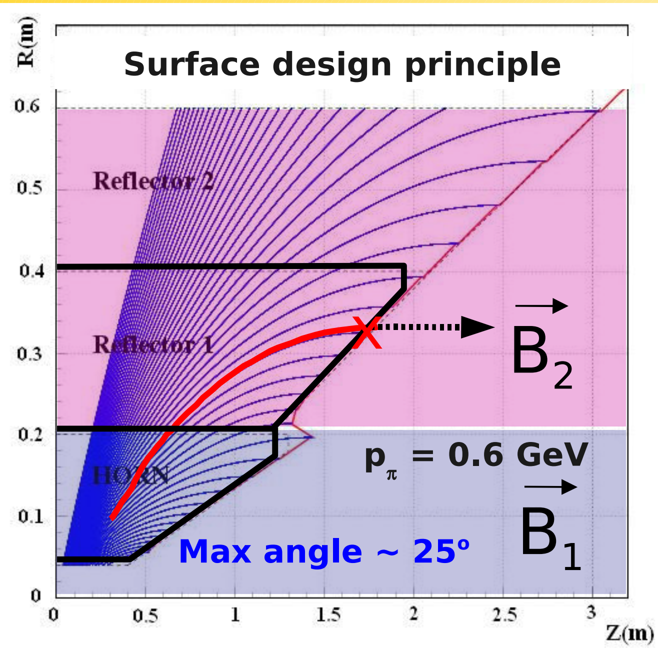
- **Using standard horn but new target (original Geant3 sim)**
  - **neutrino fluxes similar, less E dependent (larger high-E tail)**
  - **higher anti-nu contamination**
  - **Limits on $\sin^2 2\theta_{13}$ are competitive but more δ-dependent (worse in the anti-neutrino running region)**
    - **due to higher wrong charge contamination**

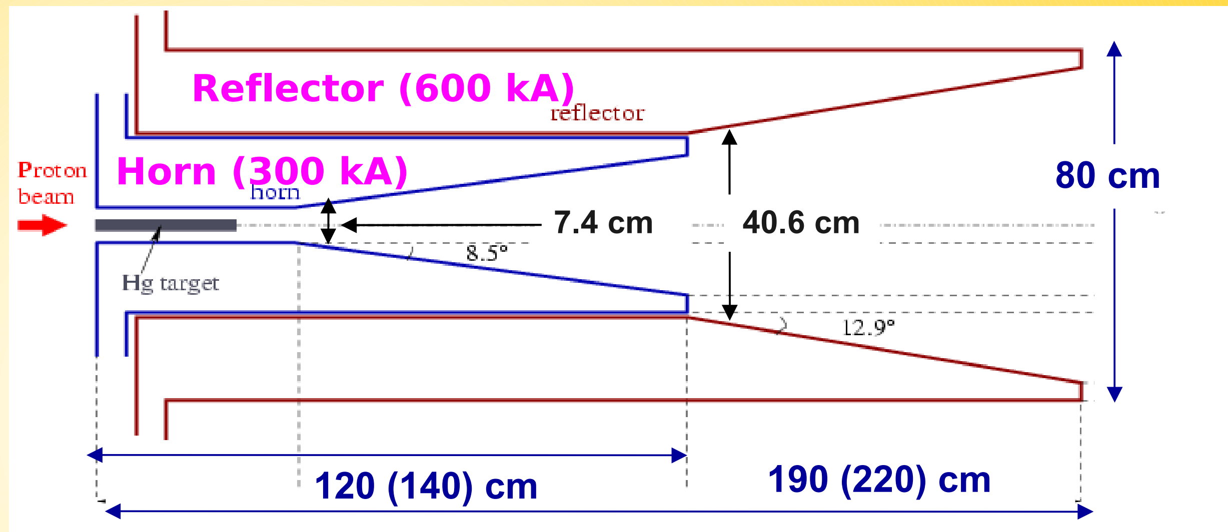
Documentation:

- **www.euronu,org: Documents -> WP2-> *Study of the performance of the SPL-Frèjus Super Beam using a graphite target (EUROnu note)***
- **proceedings for NUFACT09 (5pp)**
- **proceedings for the CERN workshop. Oct. 2009 (3pp).**

The standard focusing system

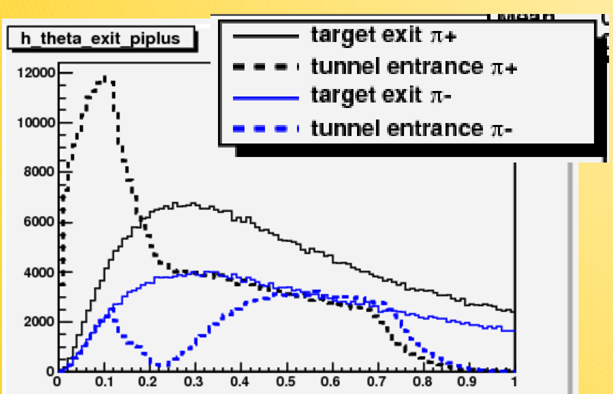
- Due to the low energy proton beam pions are mildly forward boosted ($<\theta_\pi> \sim 55°$)
  - -> **Target inside the horn** to recover collection efficiency





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)

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

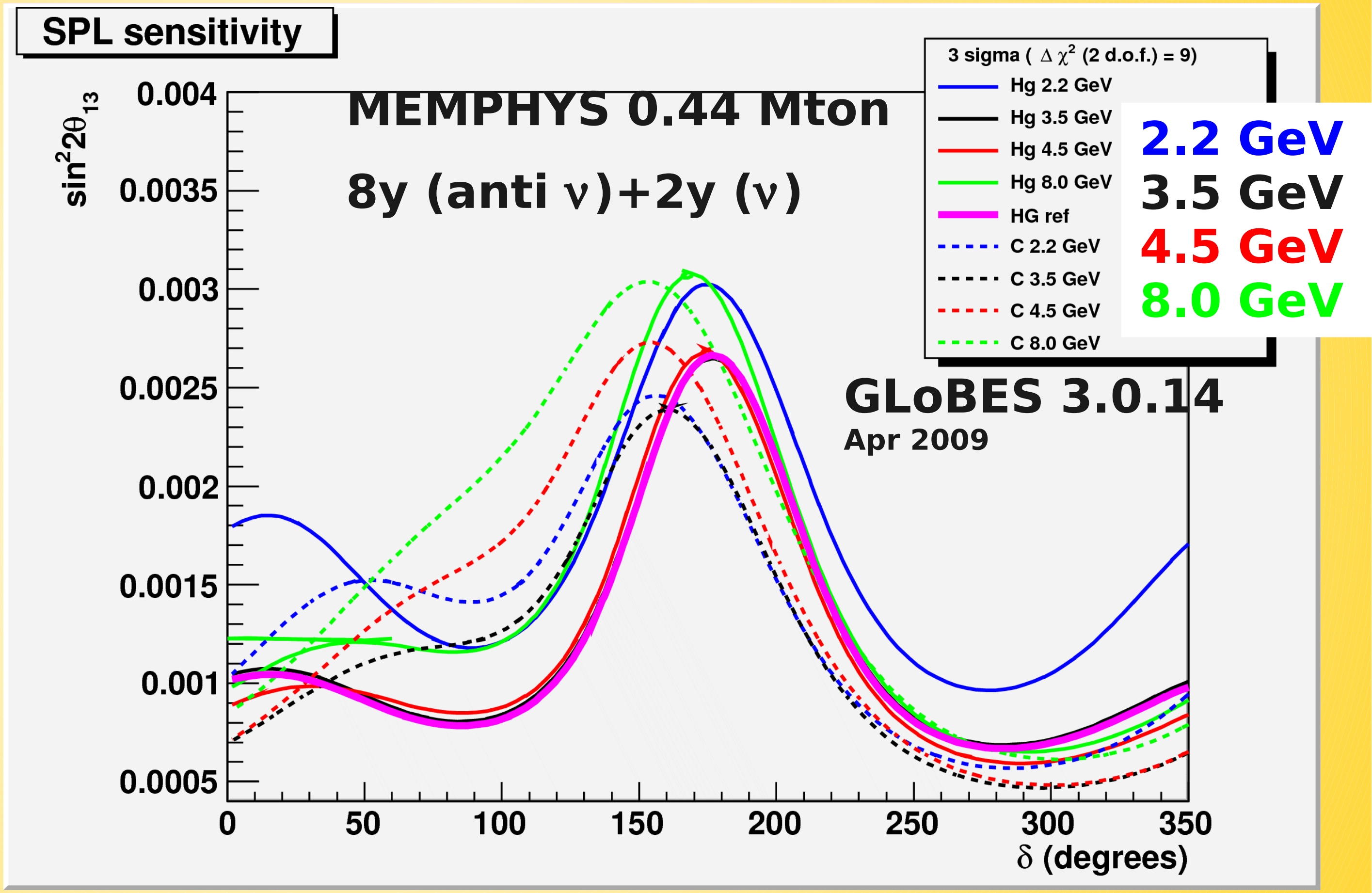
Carbon (- - - - - - -) Mercury (———)

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 $\pi^+ \rightarrow \mu^+$. Effect important in anti-ν running due to $\pi^+ > \pi^-$ & σ(ν)>σ(anti-ν)
- → let's minimize wrong charge pions !

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

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



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

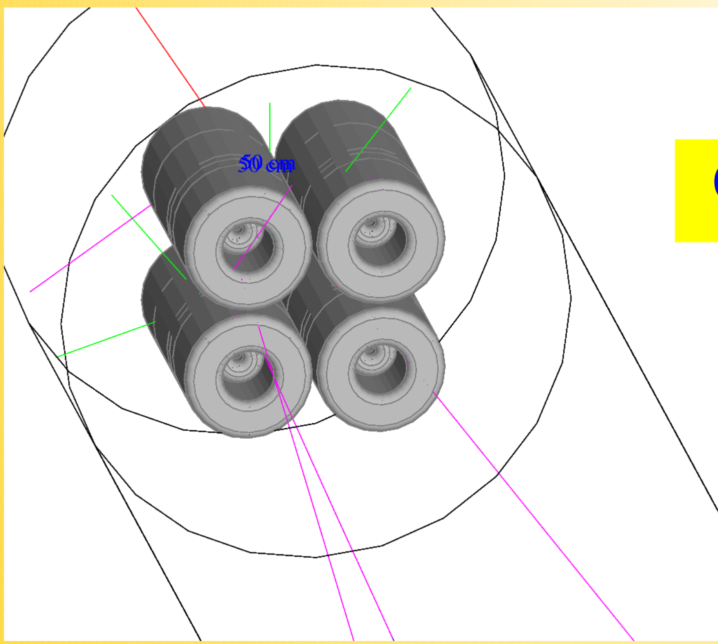
→ **Horn optimization for a long target**

The 4-horns scenario

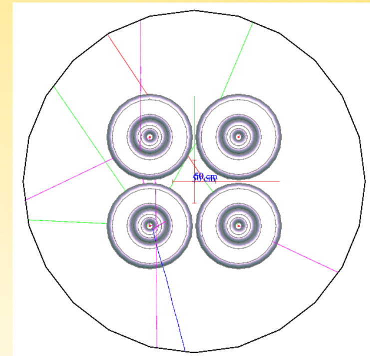
Reduced stress on target via
- **lower frequency (12.5 Hz) or**
- **lower p-flux (1 MW)**

depending on injection strategy

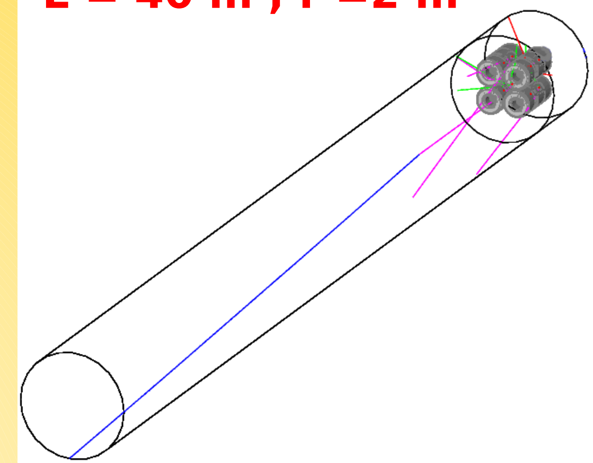
Profits of horn compactness (r~0.5m)



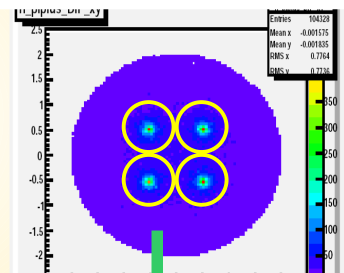
GEANT4



L = 40 m , r =2 m

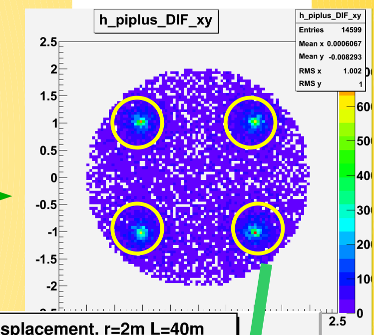


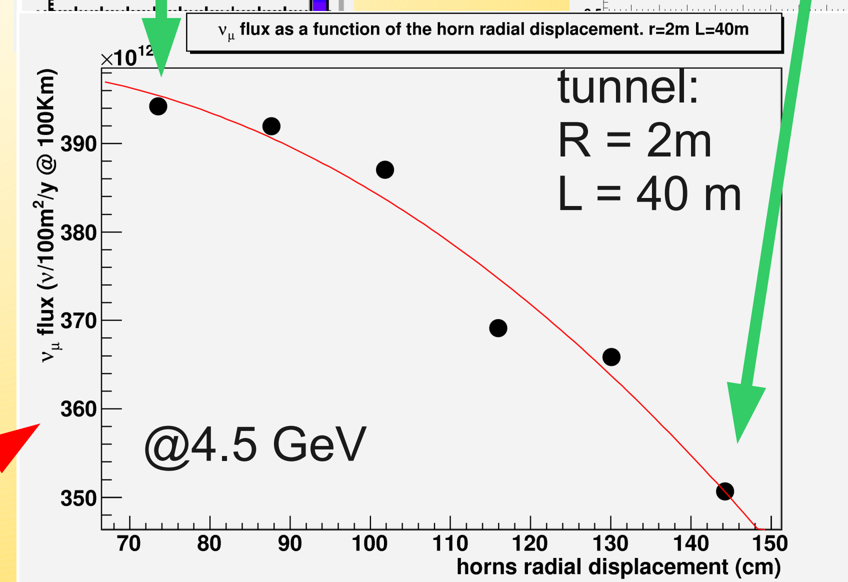
Baseline configuration with horns as "central" as possible



ν_μ **-13%**

Worst case



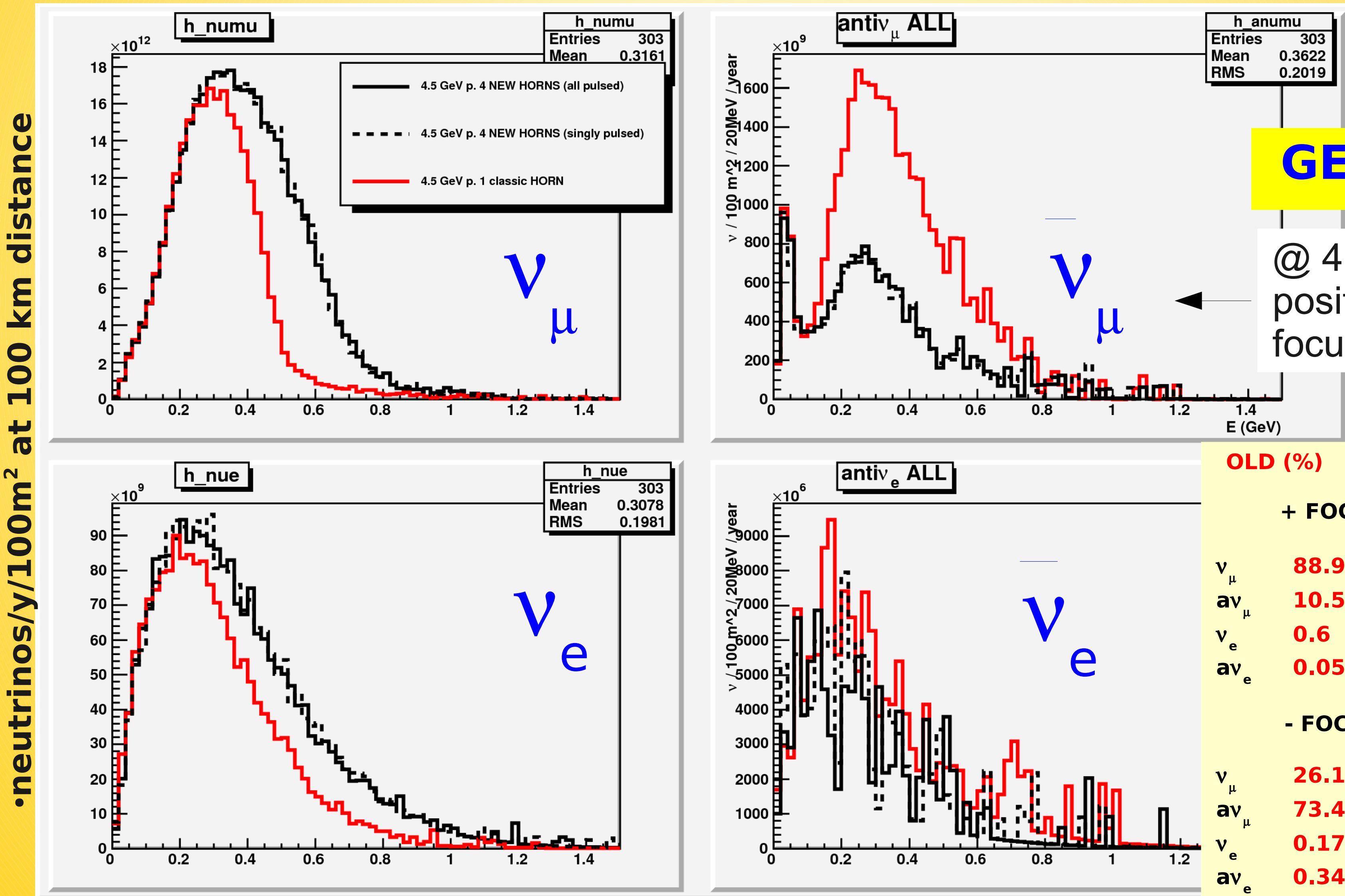


Small flux loss even up to big lateral displacements.

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

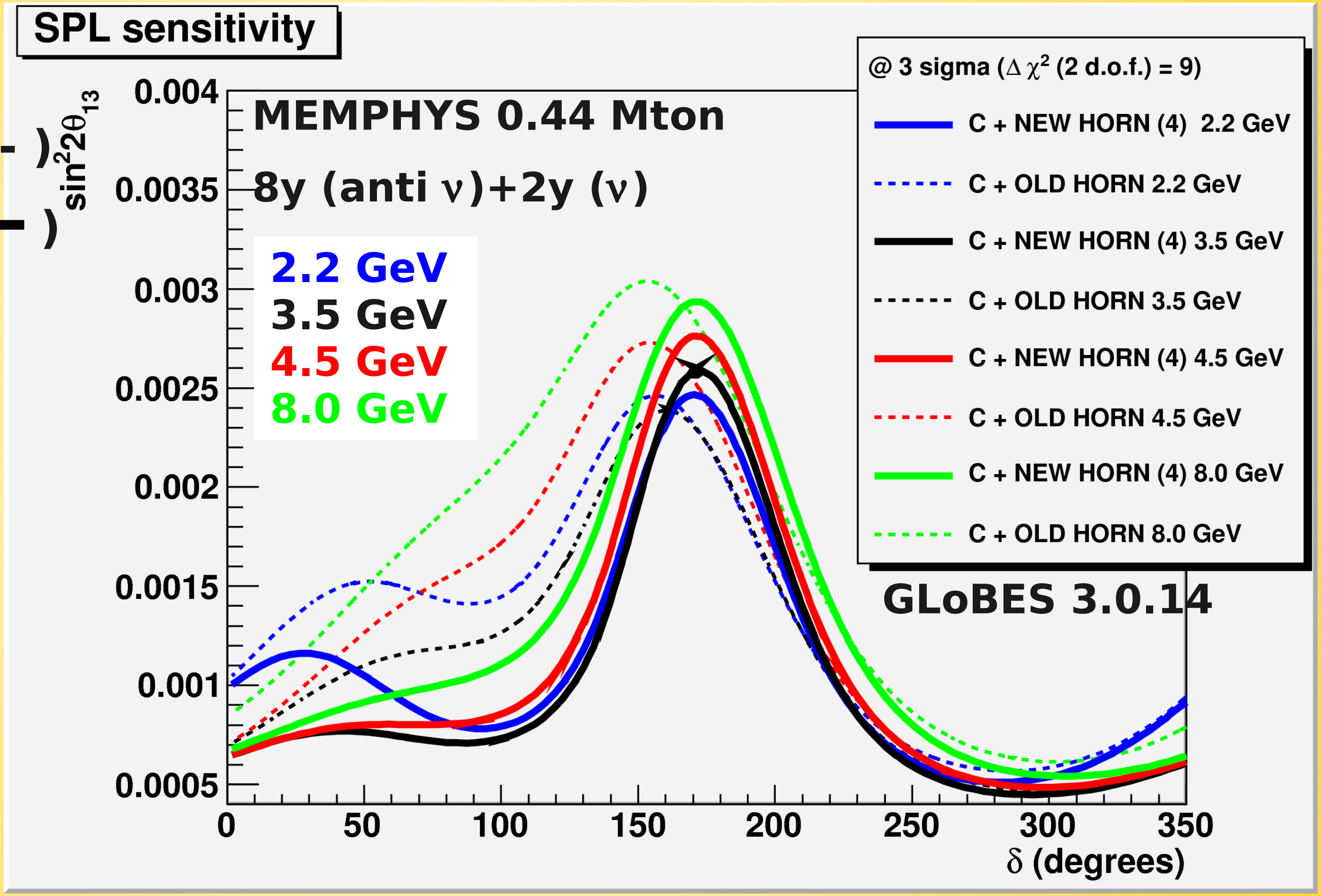
3σ sensitivity on θ_{13} with the new horn

Color codes: proton energies

Carbon target

old horn (- - - - - -)

new horn (———)



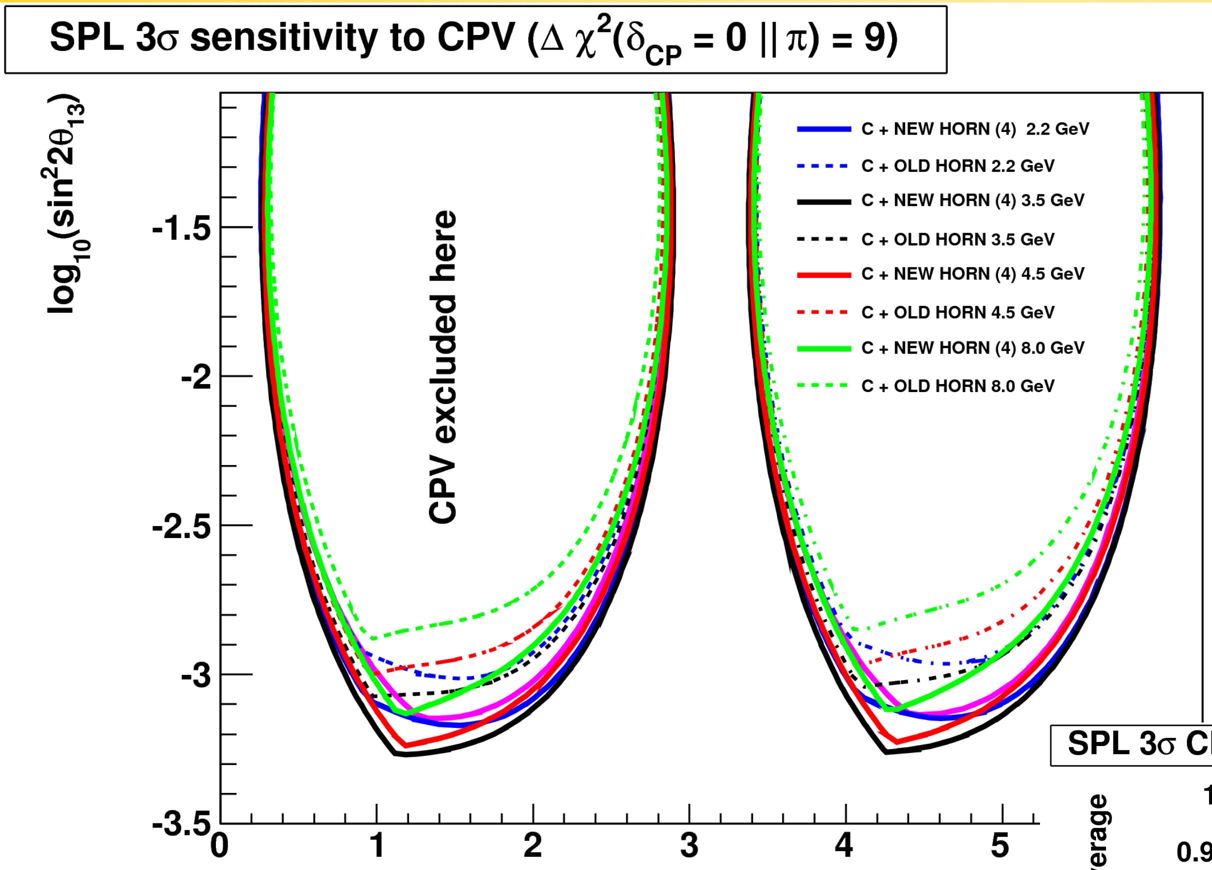
Significant improvement achieved by the new horn design mainly in the anti-ν region as needed.

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 (- - - - - -)

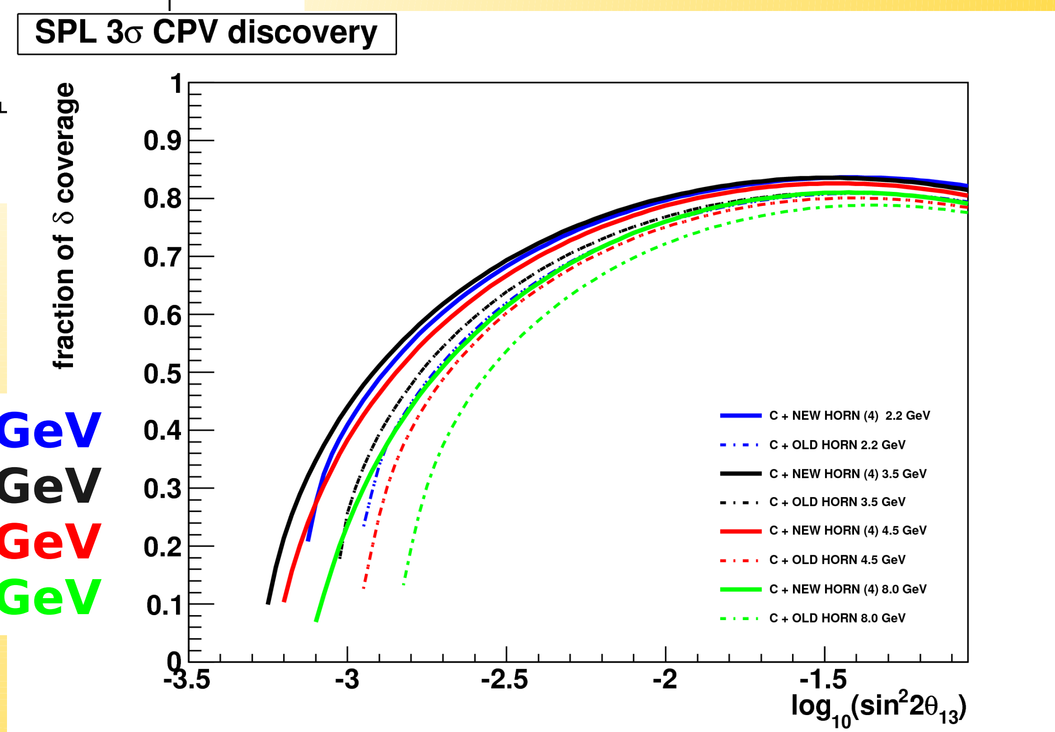
new horn (————)

Significant improvement achieved by the new horn design.

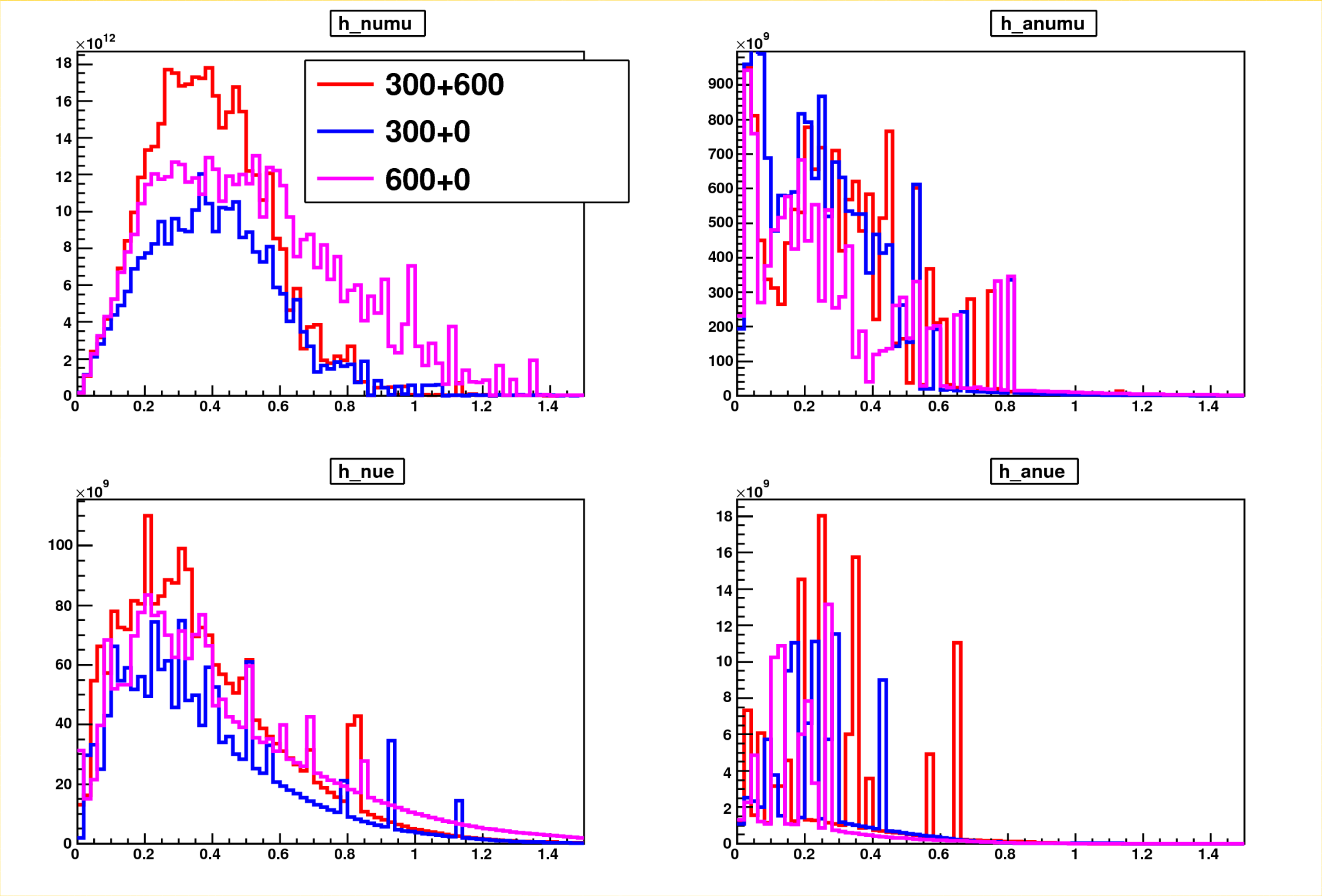
The change in the focusing does not alter the “ranking” of proton energies

3.5 and 4.5 GeV are preferred (in this order)

2.2 GeV
3.5 GeV
4.5 GeV
8.0 GeV



Dropping the reflector ?

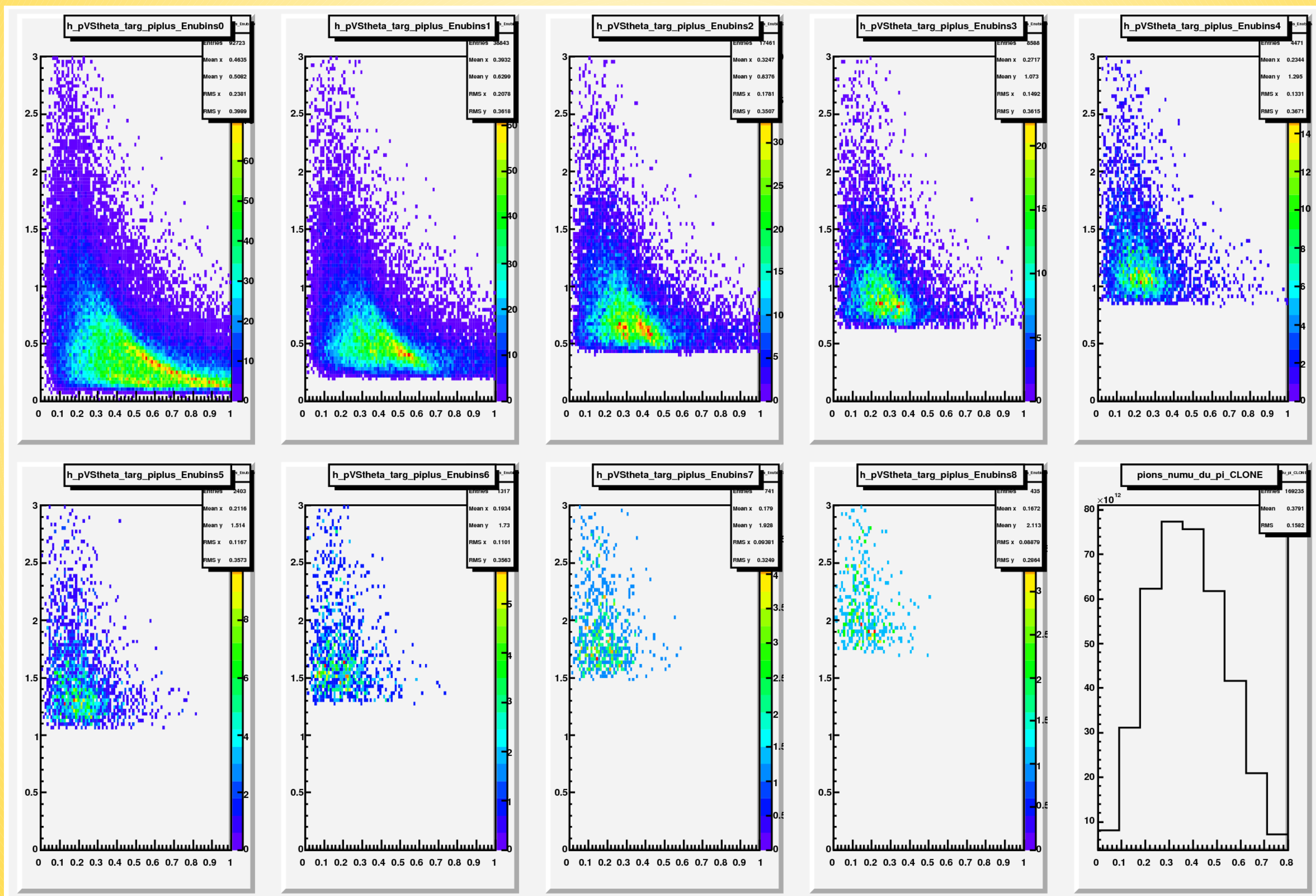


* Significant loss
* some recovery increasing i_horn to 600 kA (especially at high E) but
* technical challenges in sending 600 kA through a 4 cm radius cylinder ?
* we could try a no-reflector ad-hoc optimisation

Which are the “important” pions in our case ?*

***with the new horn+refl setup**

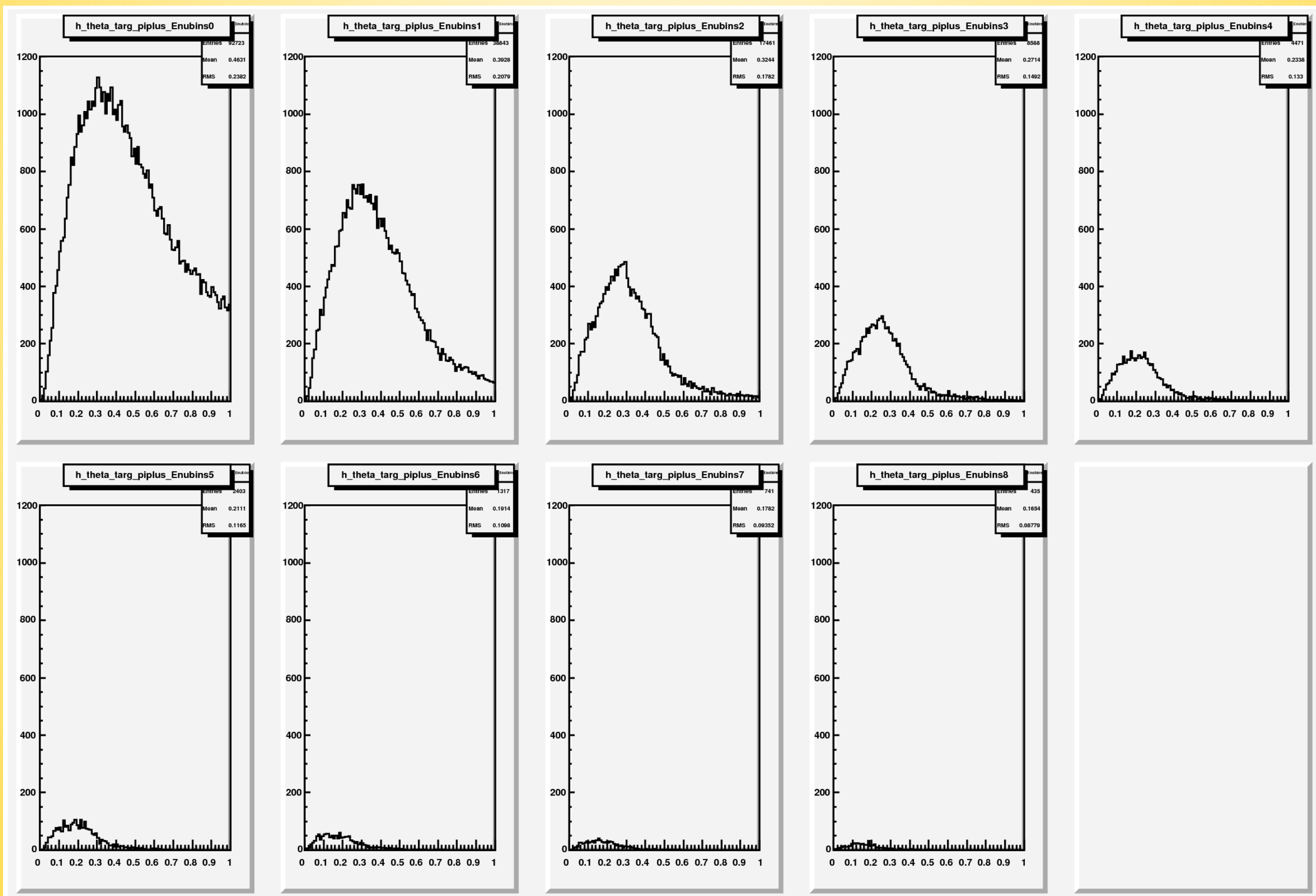
* Plot p VS theta of parent pions (at target exit) in 9 bins of E(nu) in [0-0.8] GeV



High energy neutrinos produced by low angle, high p pions

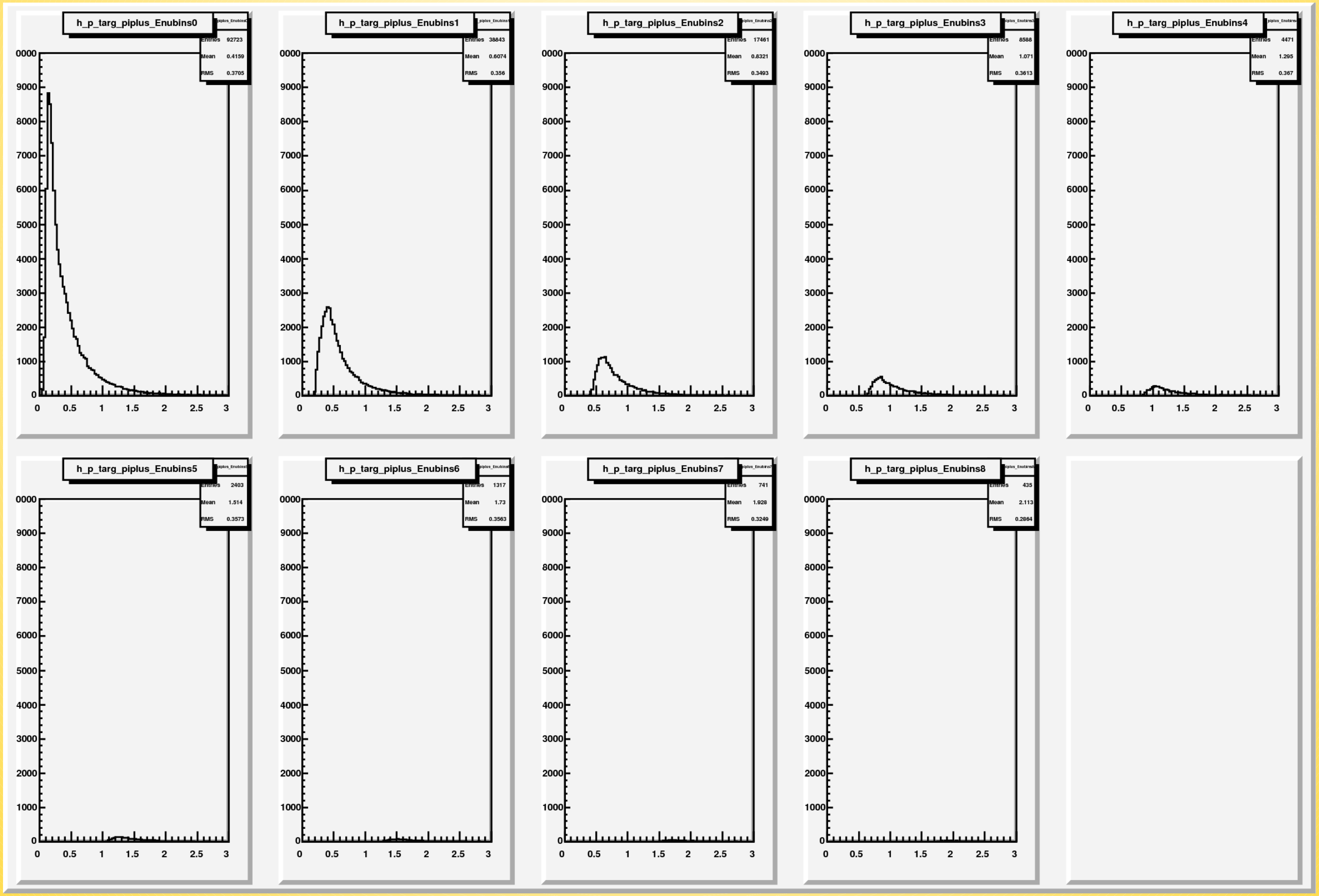
Which are the “important” pions in our case ?

POLAR ANGLE [0,1] rad of parent pion in E_nu bins



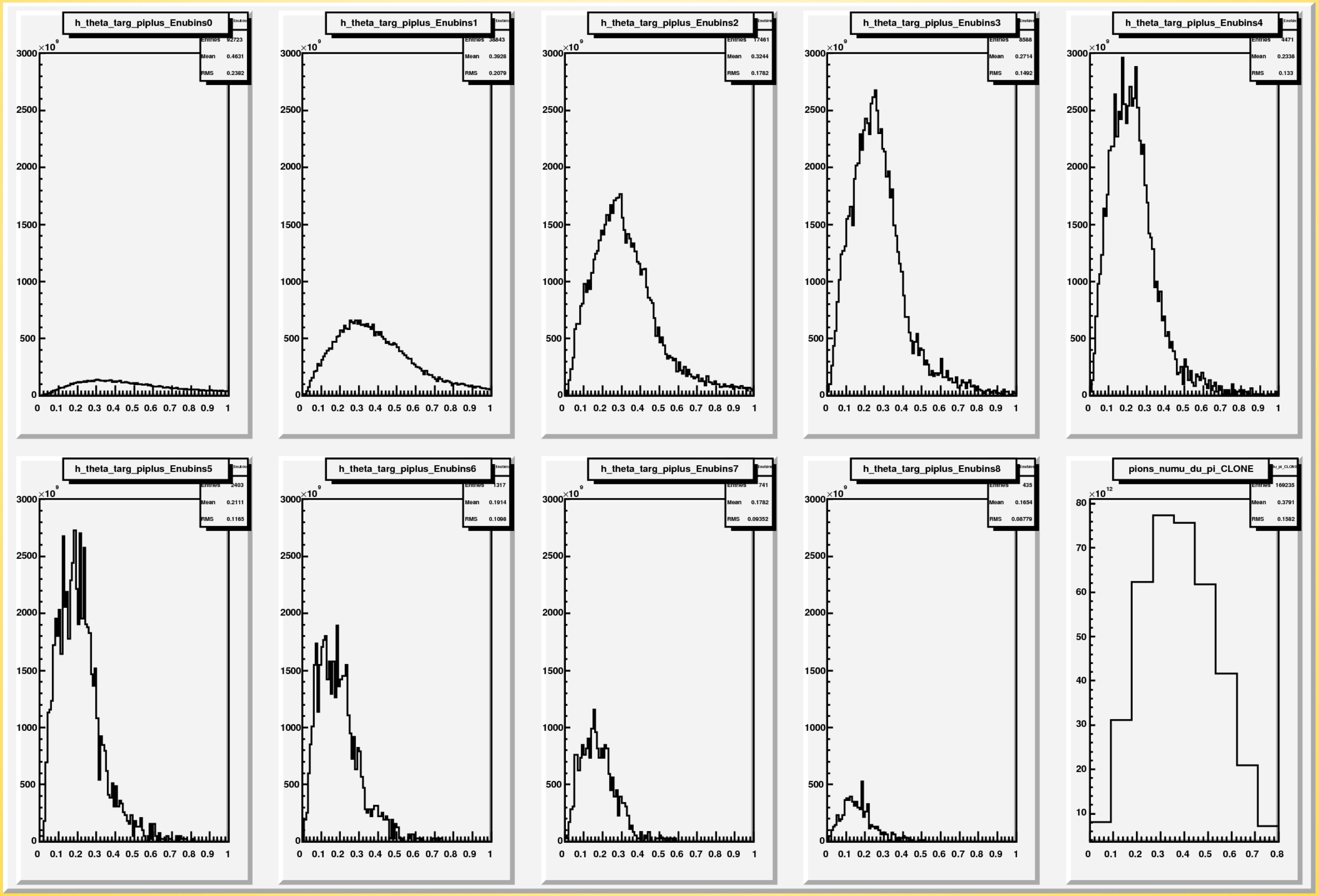
Which are the "important" pions in our case ?

MOMENTUM of parent pion [0-3 GeV] in E_nu bins



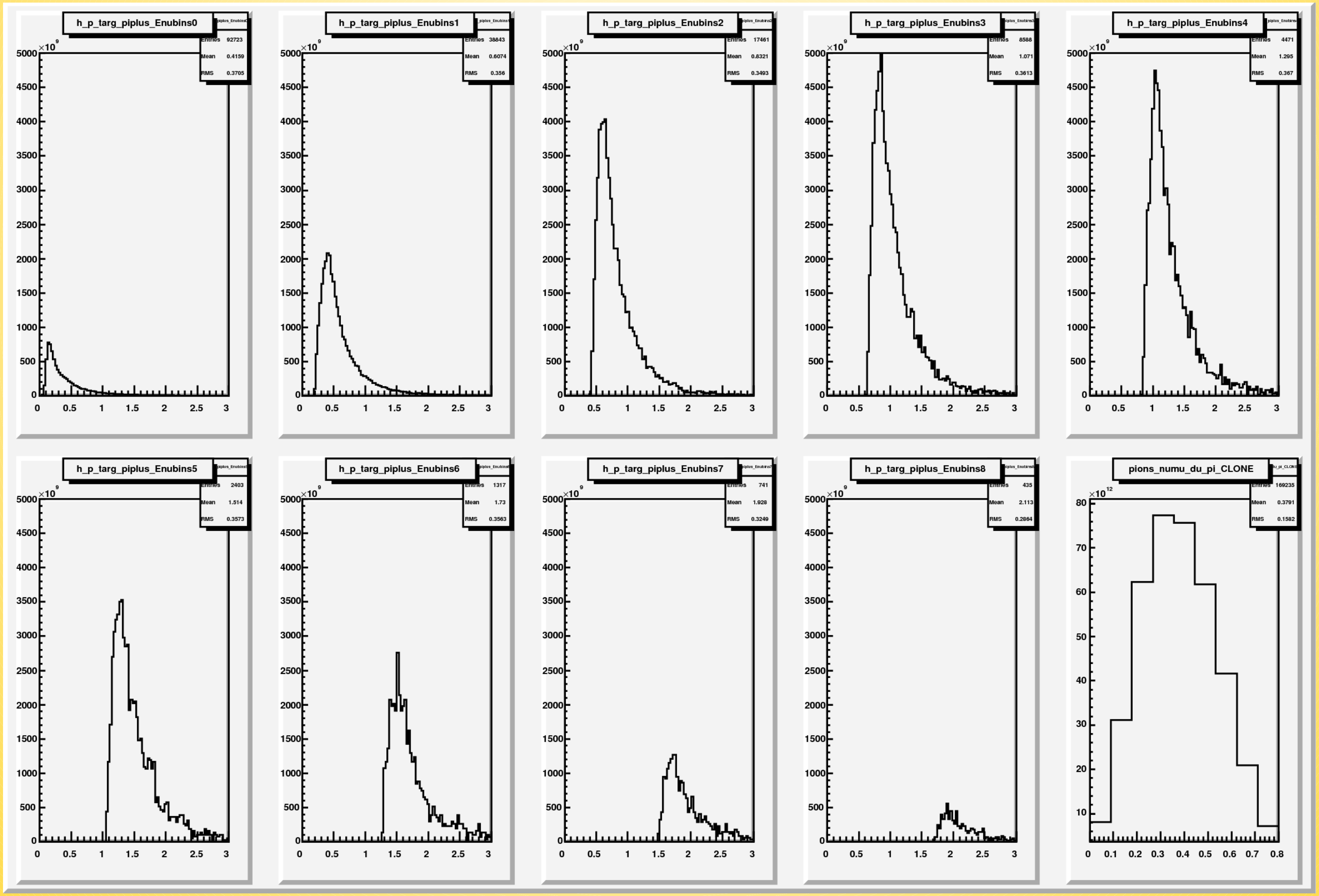
Which are the "important" pions in our case ?

* Normalize each sample to a factor proportional to the height of that neutrino energy bin
POLAR ANGLE



Which are the "important" pions in our case ?

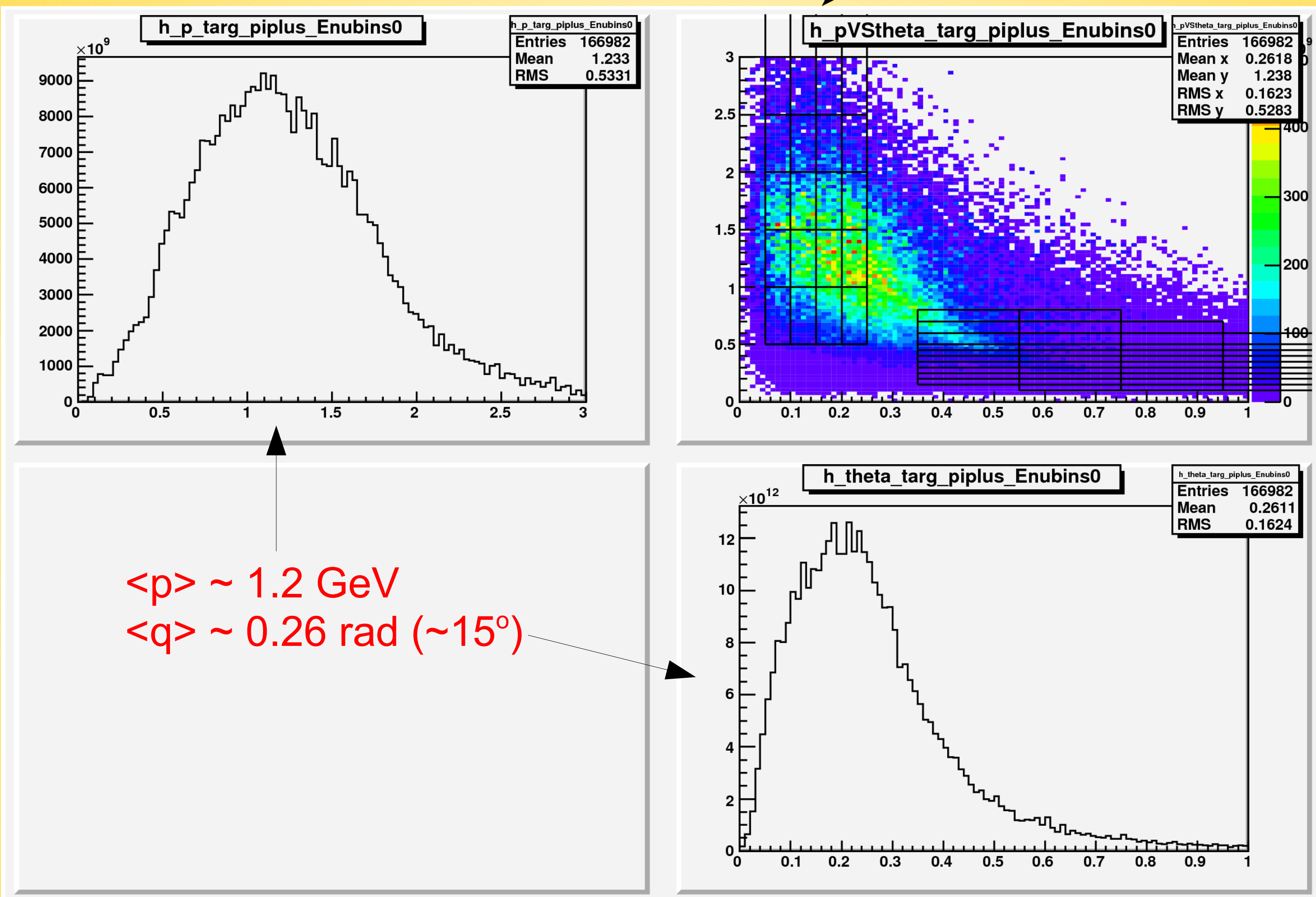
* Normalize each sample to a factor proportional to the height of that neutrino energy bin
MOMENTUM



Which are the “important” pions in our case ?

* Add these weighted contributions

Small angle

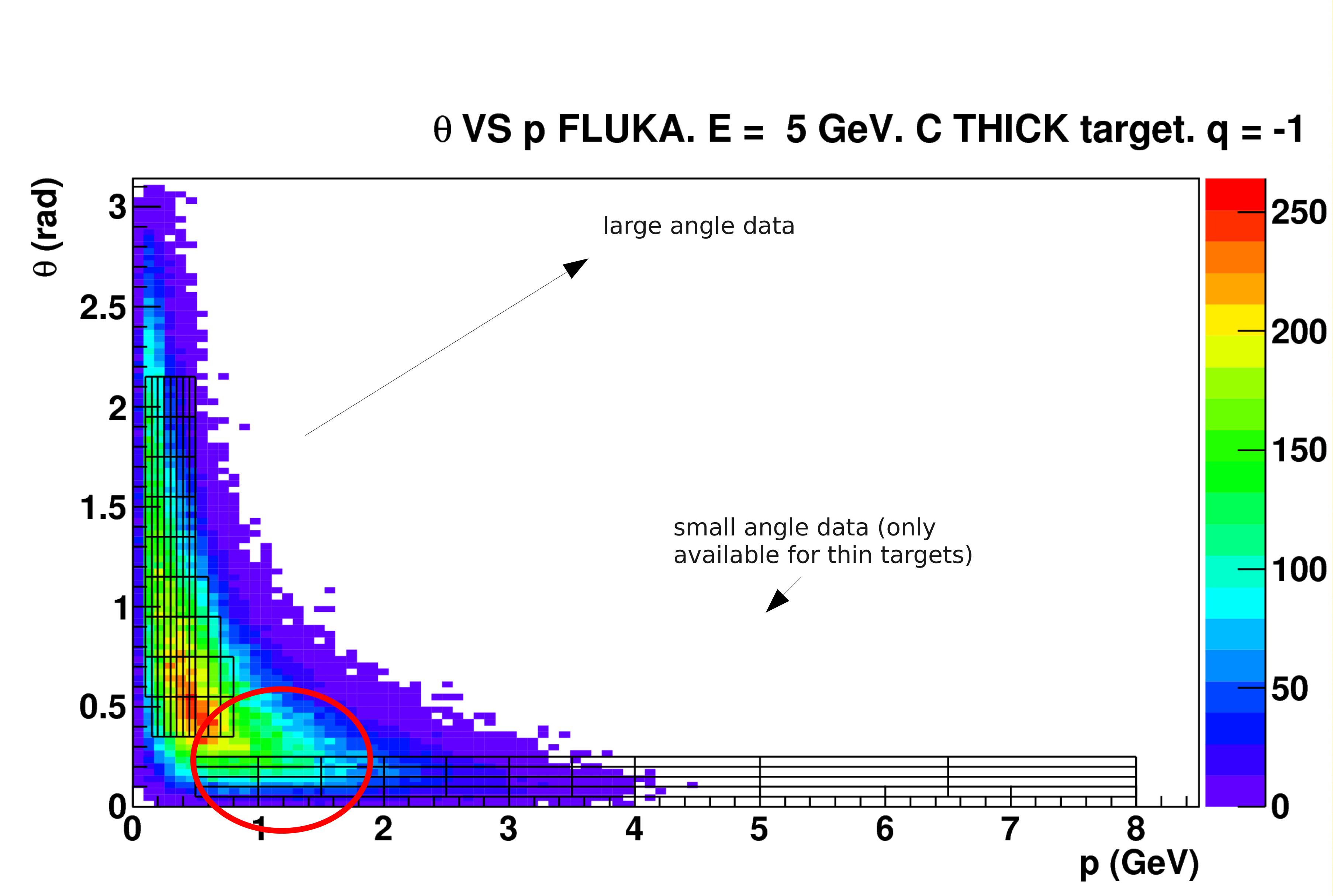


HARP bins indicated with lines

Large angle

“flux weighted” pions are more represented by the HARP
* “small angle” bins [0.5,2] GeV
* “large angle” bins [0.35,0.55] GeV
* quite some of these are in “the gap”

Which are the "important" pions in our case ?



Systematics on primary pion production II

Comparison of GEANT4 pion yields and HARP differential cross sections

Chosen configuration among the available HARP (the closest to our foreseen setup):

A (gmol^{-1})	ρ (gcm^{-3})	t (cm)	$A/(N_A \rho t)$ (barn)	r (cm)
12	1.85	39	0.276	1.5
180	16.69	11.14	1.616	1.5

- E(p) = 5 GeV
- materials: C and Tantalum (similar to Mercury)
- “thick target” ($1\lambda_I$) (“thin target” also, 5% λ_I)
- small and large angles data-sets

- L = 39 (1.95) cm, R = 1.5 cm C
- L = 11 (0.775) cm, R = 1.5 cm (Ta)

The published cross sections have been reproduced using the HARP procedure but taking the “true-level” pion tracks from the generator as input

- N_{ij} becomes the # of pions generated in the i-th p bin and j-th θ bin by N_{pot} protons on target
- **M** =1 (by definition efficiency =1, no migrations. HARP data instead are corrected for all this!)

$$\frac{\mathrm{d}^2\sigma}{\mathrm{dp_i d}\theta_\mathrm{j}} = \frac{1}{N_{pot}} \frac{A}{N_A \rho t} \sum_{i',j'} M^{-1}_{iji'j'} \cdot N_{i',j'}$$

- t = target length

Then a re-weighting table has been built in (p,theta) space taking ratios btw the genarator cross sections and the measured ones.

Correction applied to MC -> neutrino flux comparison after re-weighting.

GIBUU

Thanks to B. Popov for suggesting it and providing files

GIBUU model added for comparison (for Carbon for the time being)

Institut für Theoretische Physik, JLU Giessen

GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

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GiBUU model

The BUU equation, which can be derived from the so-called Kadanoff-Baym-equations, describes the time evolution of the Wigner transform of the real-time Green's function. This Wigner transform represents a generalization of the classical phase-space density. We get for each particle species one such equation. All are coupled through the gain and loss terms which represent scattering processes and the mean fields being included in the Hamiltonians.

The GiBUU model includes 61 baryonic and 31 mesonic states. The necessary parameters (e.g. pole masses, life times in vacuum, branching ratios) are based on the Manley analysis and the PDG compilation. The BUU equation is solved applying a test-particle ansatz in a full ensemble scheme which guarantees locality in the scattering processes of the test-particles. Resonances are explicitly propagated, in particular off-shell. Hence an off-shell potential according to Effenberger et al. is introduced which influences the time-development of the spectral functions. The loss and gain terms include besides particle decays also two and three-body reaction channels. The low-energy two-body reaction rates are to a large extent given by resonance excitations. Whereas at higher center-of-mass energies (above 2 GeV for meson-baryon and above 2.6 GeV baryon-baryon scattering) an enhanced version of Pythia is implemented to describe the reaction processes. The Hamiltonian of the nucleon and baryonic resonances includes a momentum-dependent Skyrme-like potential. For the pion, we consider a low-energy potential based on the Delta-hole model and on pionic atom phenomenology. Also Coulomb distortions are taken into account. The nuclear ground state is treated within a local Thomas-Fermi approximation. For this the nuclear density profiles are parametrized according to elastic electron-scattering data and

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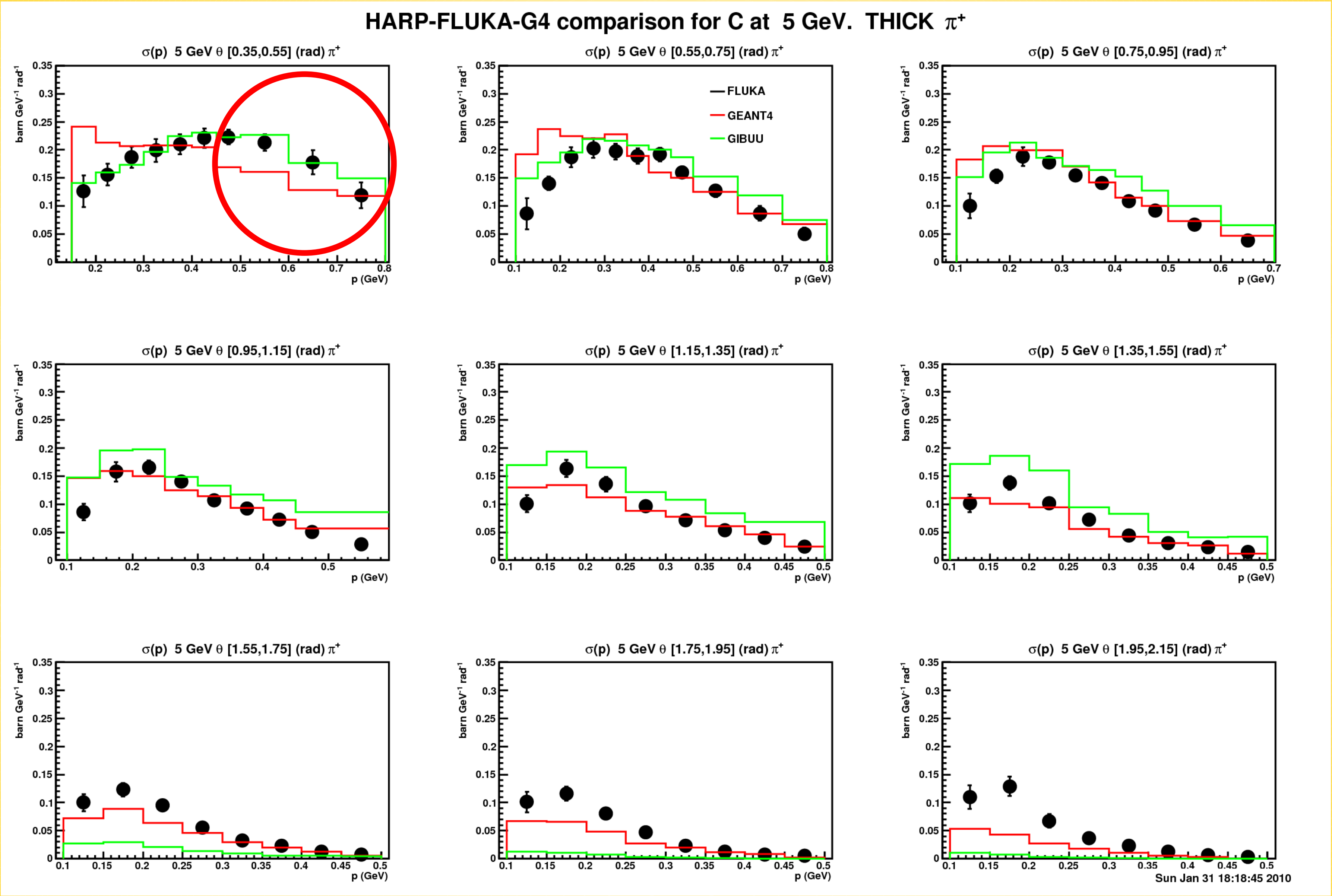
Only primary interaction, no propagation through matter
-> GEANT4 was used to track particles at the target exit
(the comparison with HARP is done at this level)

Comparison done for Carbon-large angle-thick target configuration

HARP-GEANT4-GIBUU. Large angle. THICK target. C. 5 GeV. pi+

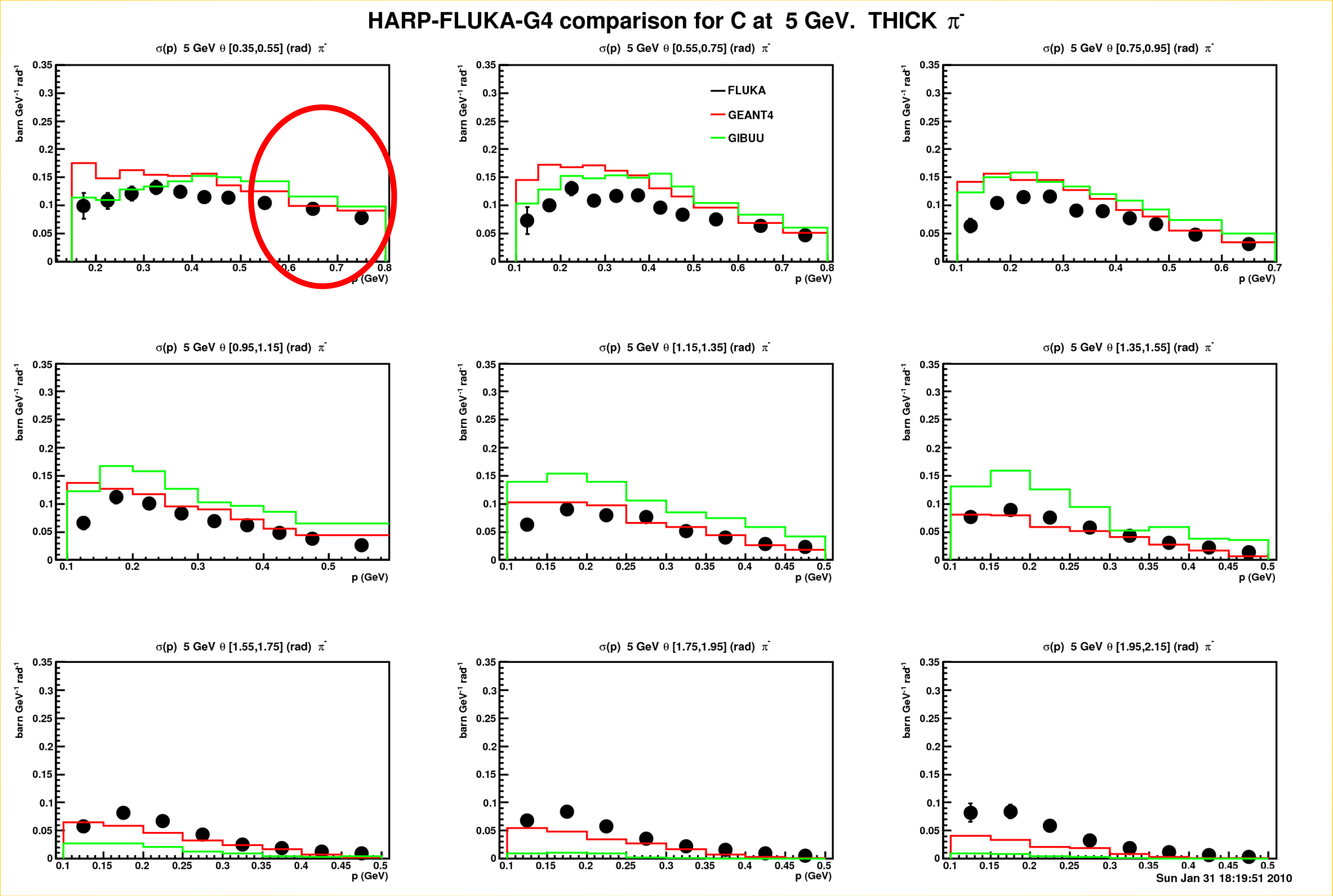
σ(p) in θ bins



tends to underestimate production at large angles
GIBUU rather good in the interesting region (high-p, small θ)

HARP-GEANT4-GIBUU. Large angle. THICK target. C. 5 GeV. pi-

σ(p) in θ bins



tends to underestimate production at large angles

Global χ^2/N

	No sys	Sys 10 %	Sys 20%
C+ THICK G4 LA	9.9	3.9	1.7
C+ THICK GIBUU LA	45.1	15.6	10.5
C- THICK G4 LA	19.4	4.8	1.8
C- THICK GIBUU LA	76.2	18.5	11.3
TA+ THICK G4 LA	20.8	15.3	10.8
TA- THICK G4 LA	25.1	17.9	13.1
C+ THIN G4 LA	11.7	5.4	2.6
C- THIN G4 LA	18.0	5.3	2.2
TA+ THIN G4 LA	92.6	23.7	13.4
TA- THIN G4 LA	149.3	32.9	21.3
C+ THIN G4 SA	30.7	12.3	4.9
C- THIN G4 SA	39.1	18.5	7.5
TA+ THIN G4 SA	25.0	8.2	3.5
TA- THIN G4 SA	27.0	9.2	3.7

N=80 (SA)
N=75 (LA)

Only HARP errors — HARP errors + model sys errors

GIBUU bad χ^2 due to large angle bins (too low) - G4 also but less
Probably more interesting for us to restrict to the relevant phase space region

Plans

Complete comparison with GIBUU (small angle+thin target, Ta(?)).

Add other models and test performance (can be easily achieved using those already available in GEANT4, QGSP used up to now)

Concentrate in particular on the interesting region for the SPL

Documentation/publication ongoing (in collaboration with Christoph)

Futures SB in Europe: SPL<->PS2 early comparison

It would be interesting to make a comparison on the same ground with the same tools!

CERN-SPL

- ~5 GeV
- 440 kton Water Cherenkov
- L=130 Km (Frejus,It-Fr) OA 0 °
- No big matter effects (clean CP)
- Narrow band, well matched to WC

CERN PS2 (CNXX Cern neutrinos to XX)

- 50 GeV
- 100 kton Liquid Argon
- Far site (“XX”)
  - 950 Km OA 0.50 ° (Sieroszowice, Poland)
  - 1544 Km OA 0.25 ° (Slanic, Romania)
  - 2300 Km OA 0.25 ° (Phyhäsalmi, Finland)
- Partially covers also 2^{nd} osc max
- More sensitivity to matter effects
- studied within LAGUNA (A.Rubbia, A.Meregaglia)

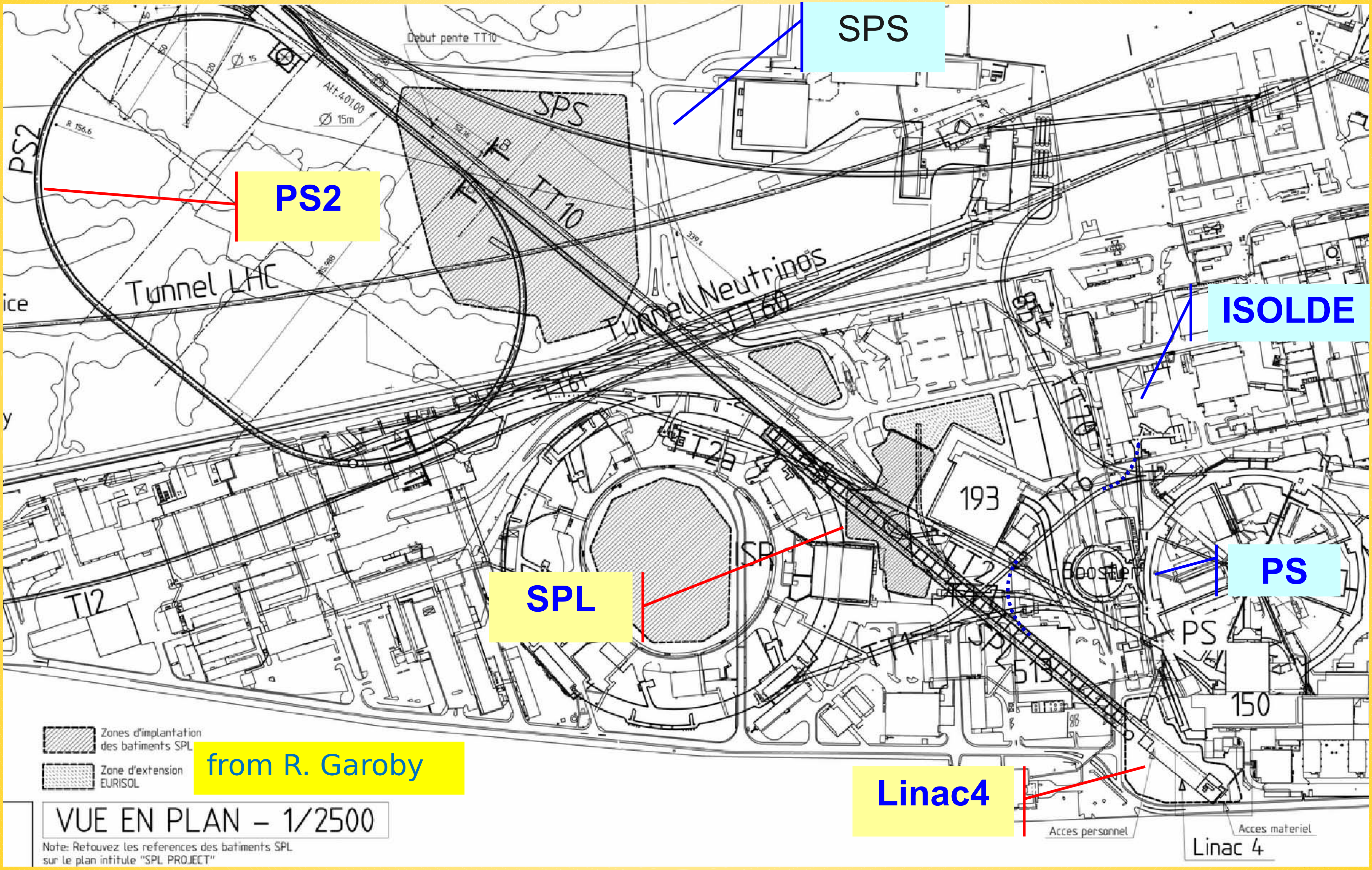
Some numbers (for PS2 from WIN09 talk by A. Rubbia)

	PS2	PS2++	SPL
E(p) (GeV)	50	50	5
ppp	1.20E+014	2.50E+014	1.00E+014
Tc(s)	2.4	1.2	0.02
efficiency	1	1	1
day/year	200	200	116
Average power (MW) / 200d	0.40	1.67	
Average power (MW) / 1e7s			4.00
pot/year	8.64E+020	3.60E+021	5.00E+022

Tc(s) 0.02 → 50 Hz

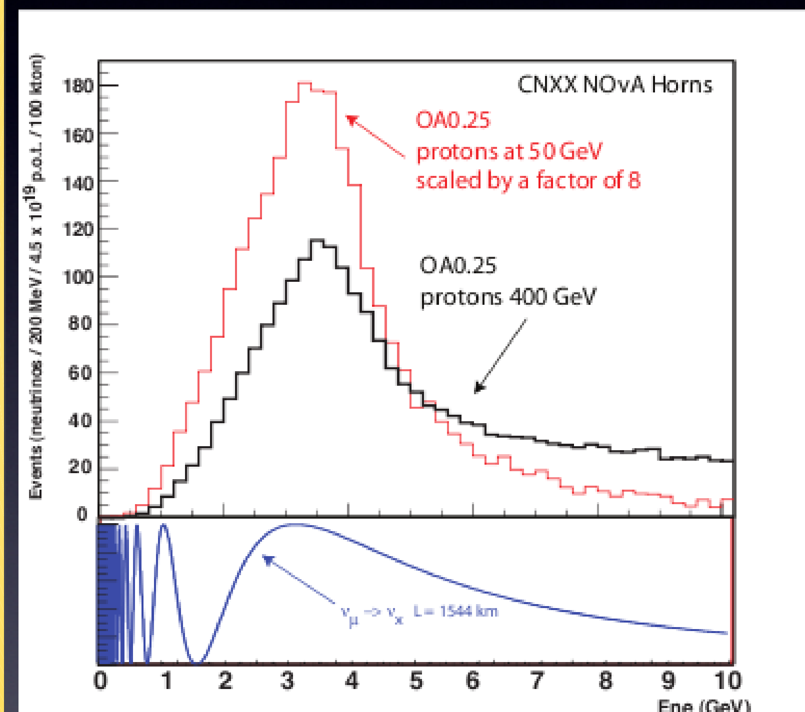
day/year 116 → 1e7 s (Snowmass year)

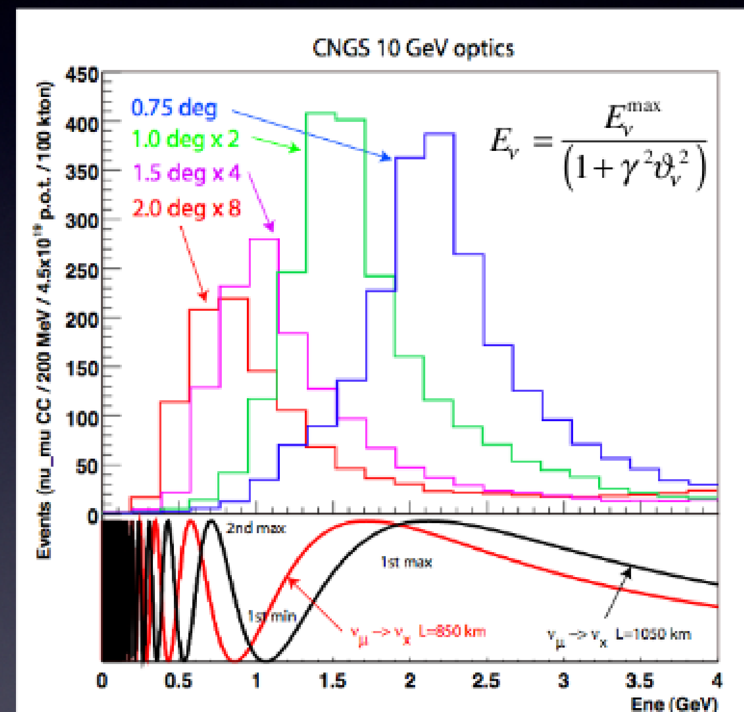
PLANS FOR FUTURE INJECTORS: Layout



Considering a new neutrino line

- We can consider two options:
  - 400 GeV protons from SpS with PS2 as new injector
  - 50 GeV protons from an intensity upgraded PS2 (PS2++)
- Neutrino flux scaling: (pot @ 50 GeV) ≈ 8x (pot @ 400 GeV)





New ν line ➠ must be designed to sustain several MW beam power

A. Rubbia 22nd International Workshop on Weak Interactions and Neutrinos 30

Wednesday, September 16, 2009 30

A. Rubbia WIN09

PS2 comparison: advances/problems

Original results based on the BMPT fast parametrization (full neutrino beam-line simulation for CNGS but with some flexibility). Focusing: NOvA horns and “CNGS 10GeV” optics.

Up to now problem to reproduce the spectrum with BMPT and nominal parameters :(
(I get an energy peak shifted to lower energies)

BUT

a technical known problem related to 50 GeV running (x_R scaling variable gets out of bounds). **B**(MPT) author contacted.

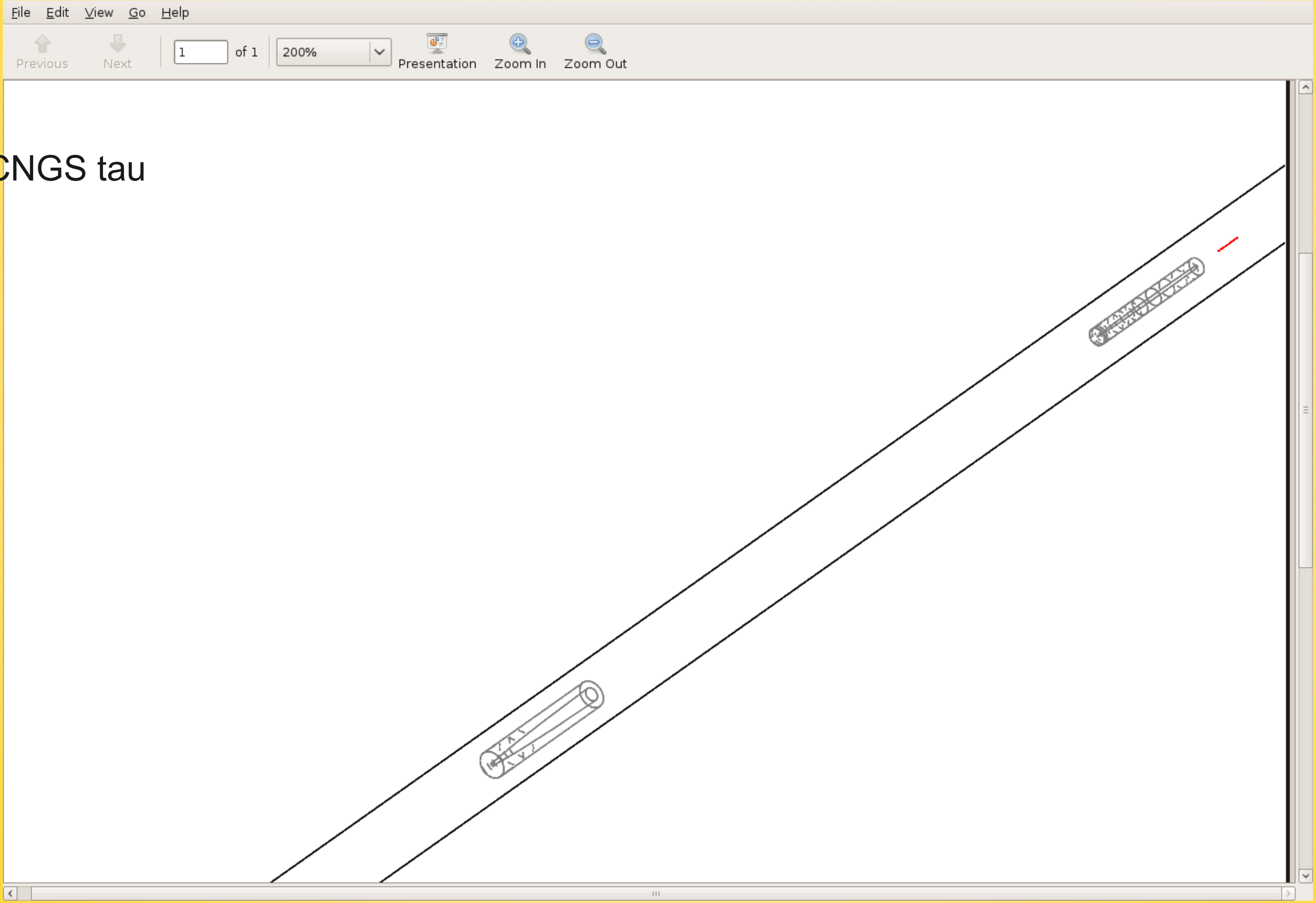
Reproduce the results with my GEANT4 simulation ? (that would be a fully independent cross check!). Steps done:

1) possibility to introduce arbitrarily shaped horns via an external file introduced
   CNGS 10 GeV optics + NovA horn shapes implemented
2) possibility to simulate off axis beams OK (needs some more testing)
3) used GEANT4 as primary generator for the time being

A test with CNGS tau beam (shape quite OK, normalization to be understood) => see
A test at 50 GeV (not so good at first attempt, need to fix my OA sim?)

WORK IN PROGRESS!

My G4 simulation in unbeaten territories...



CNGS tau

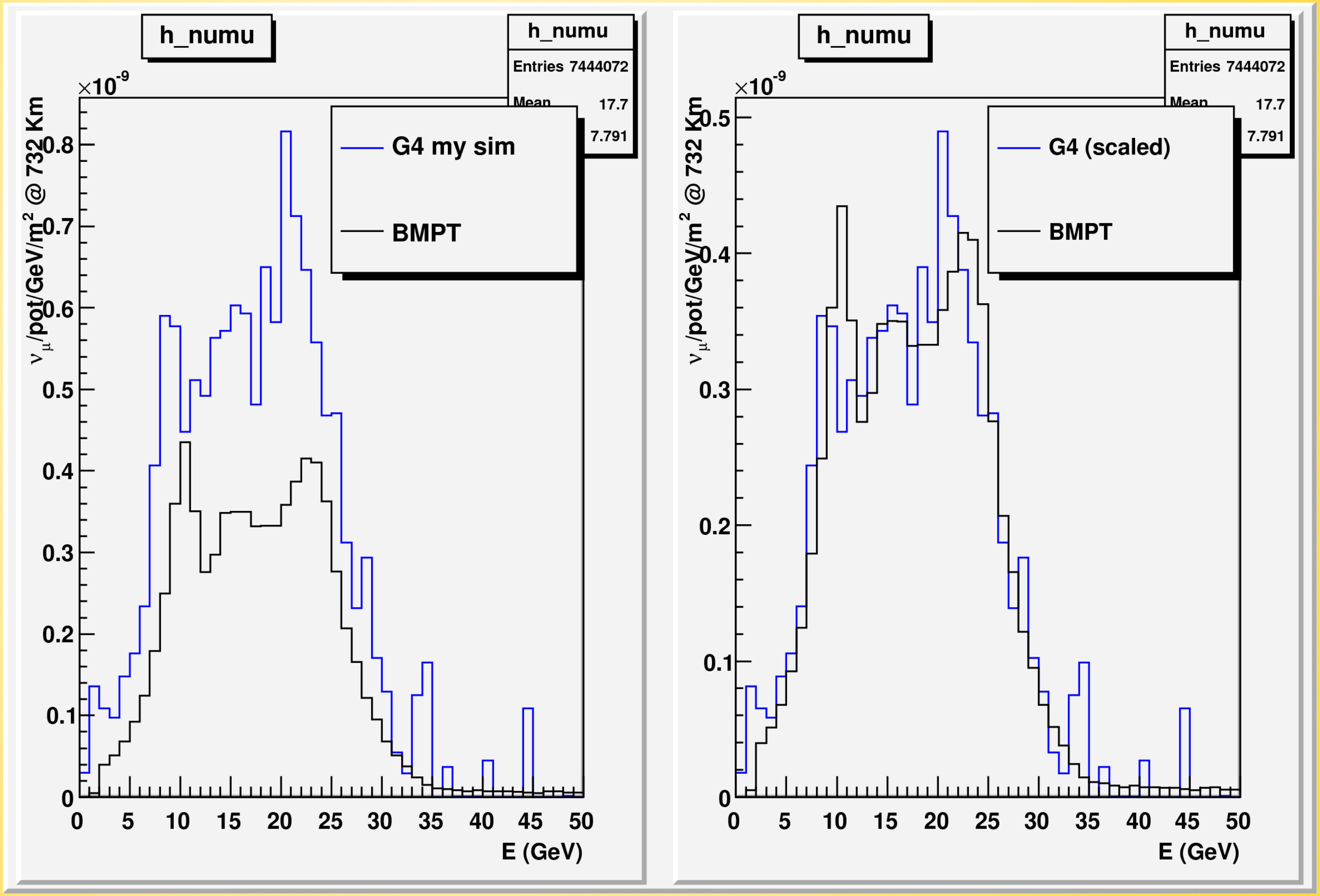
My G4 simulation in unbeaten territories...

Comparison with BMPT parametrization

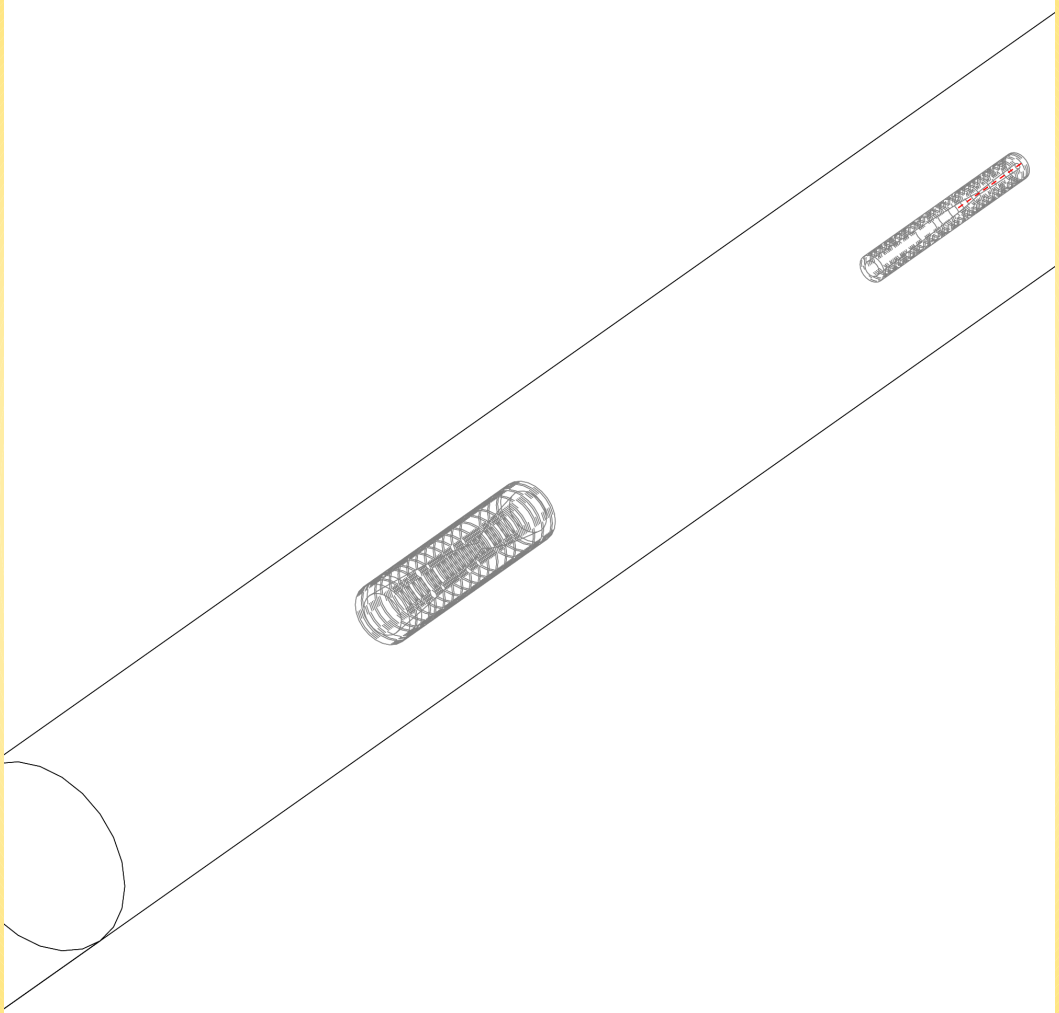
No realistic simulation of horns structure and collimators

more understanding/ tuning needed for normalization...

but shape look very good!



GEANT4 with NovA horns + CNGS like target



- **A deeper look into GLOBES description**
  - **E-resolution**
  - **cross-sections**
  - **event rates**
  - **oscillation probabilities (w/wo matter effects)**

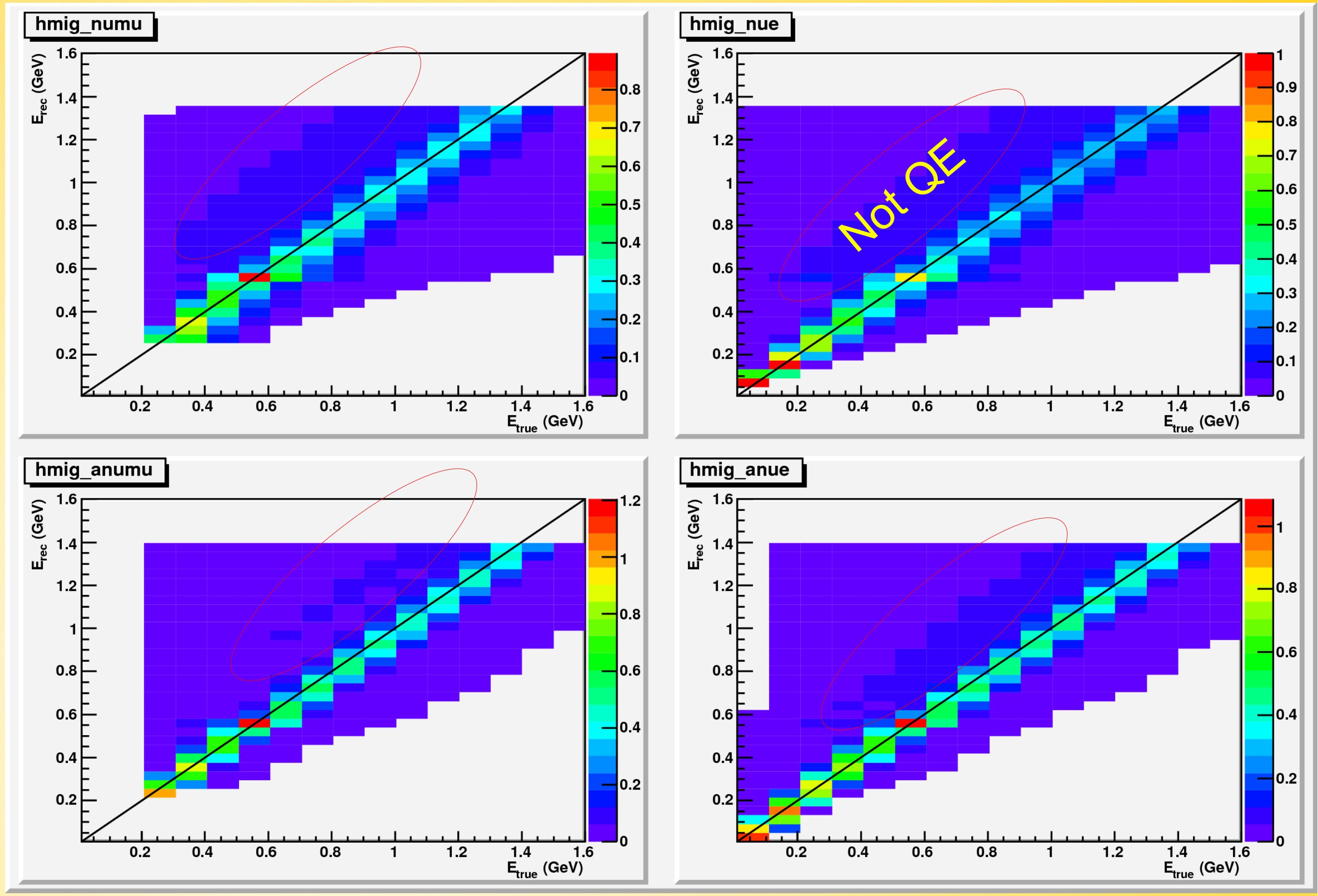
Data taken from the AEDL file SPL.glb (publicly available)

Reference:

Physics potential of the CERN-MEMPHYS neutrino oscillation project (hep-ph/0603173v3)

GLOBES: energy resolution

Migration matrices for ν_μ ν_e anti-ν_μ anti-ν_e



E_{true} vs E_{rec}

to properly handle Fermi motion smearing and non QE contamination

E_{rec} 100 MeV bins
E_{true} 40 MeV bins

smearing applied to both signal and background spectra

Event selection and PID:
SK algorithms results
(MEMPHYS w 81k PMTs/shaft ~> coverage 30%. SK 40% but final photo-statistics is the same)

Monte Carlo: NUANCE

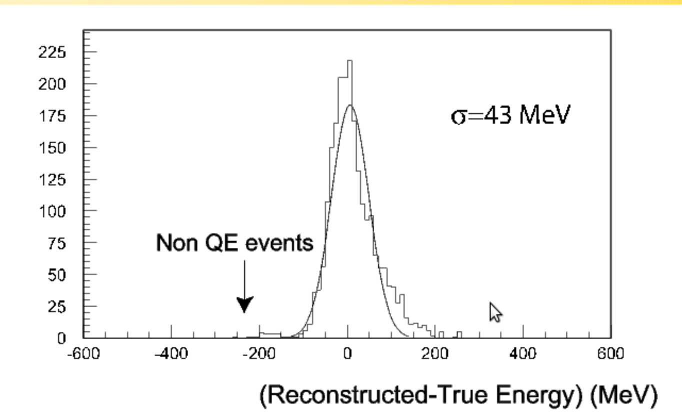
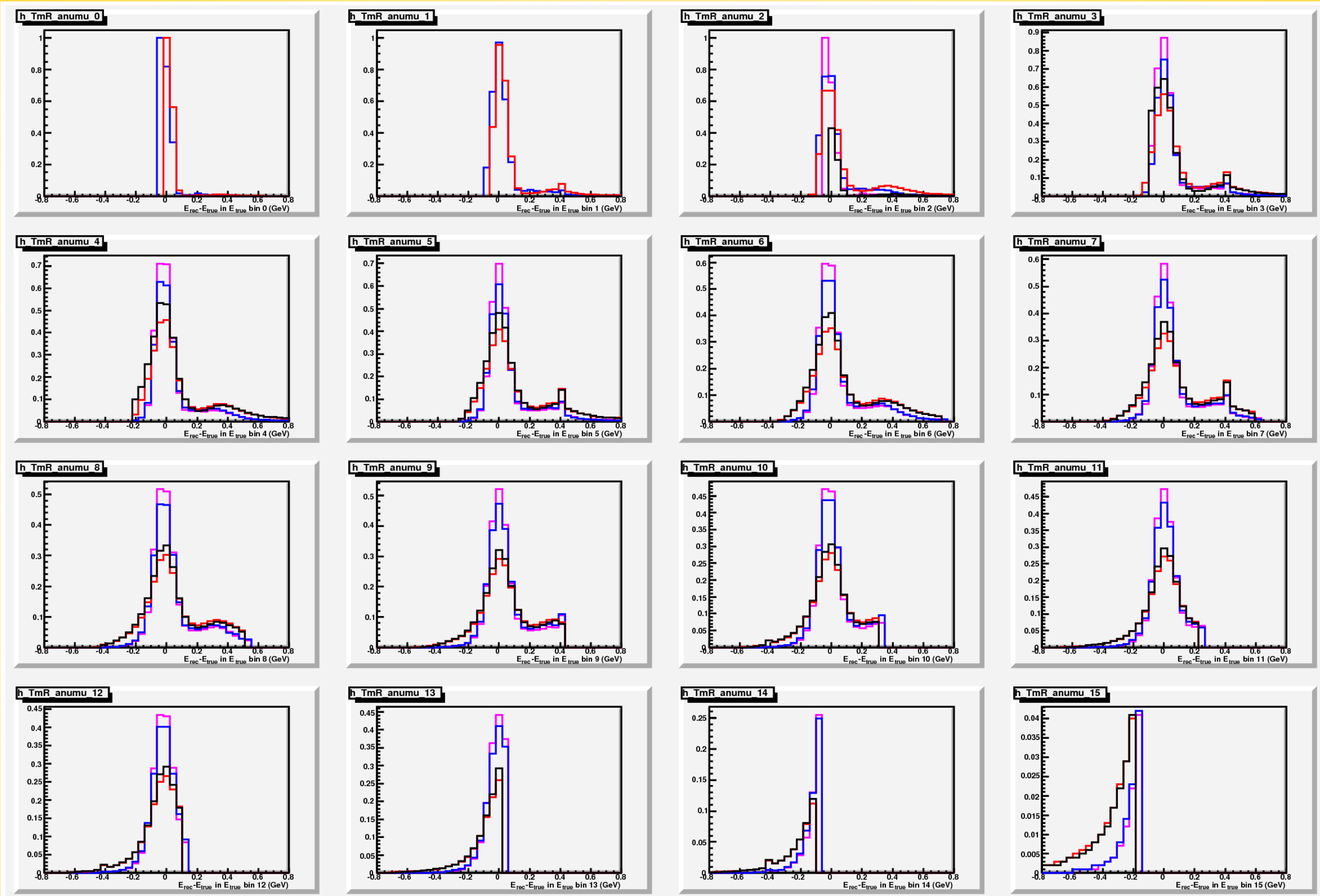


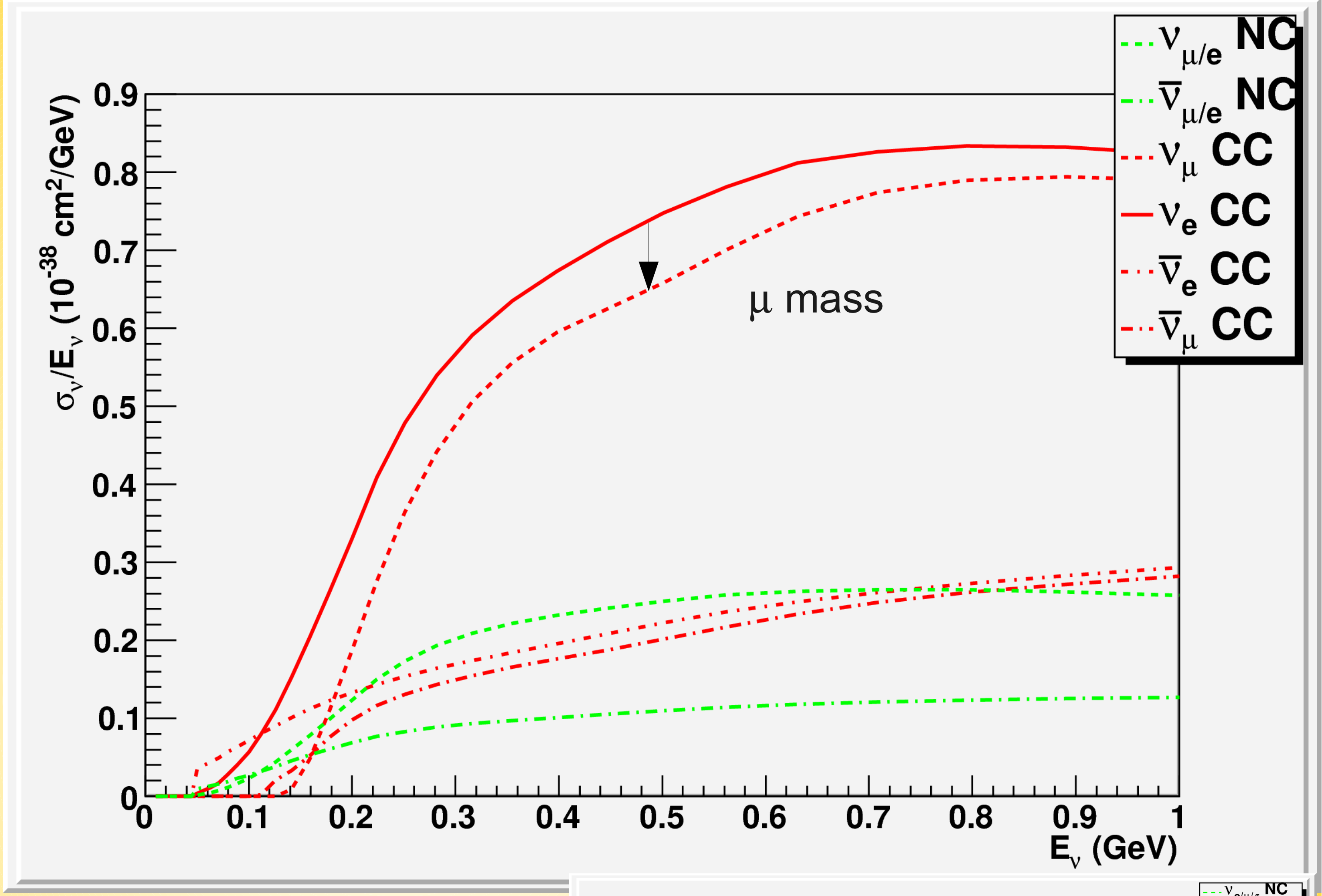
Figure 2: Energy resolution for ν_e interactions in the 200–300 MeV energy range. The quantity displayed is the difference between the reconstructed and the true neutrino energy.

A. Longhin

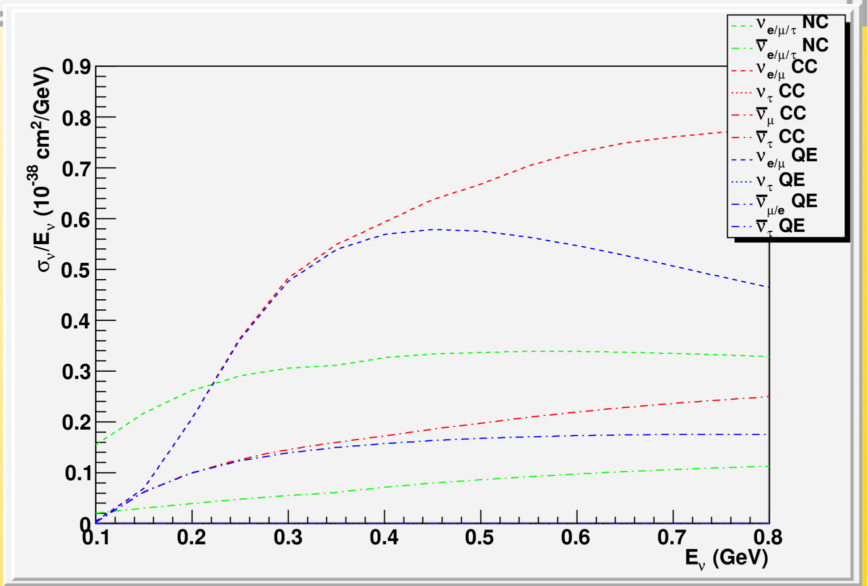
GLOBES resolution



GLOBES neutrino cross sections

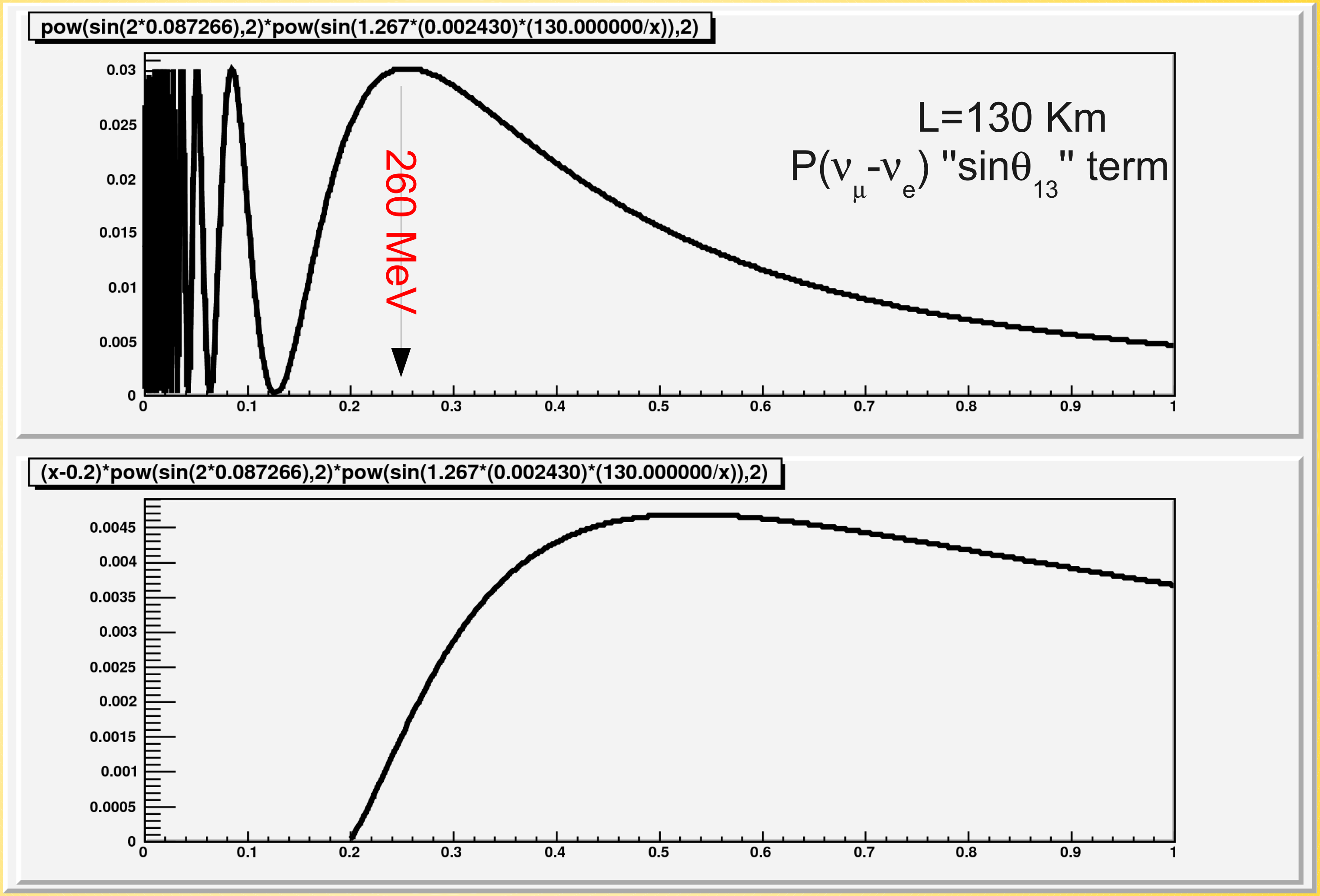


Purely Quasi elastic up to ~ 400 MeV



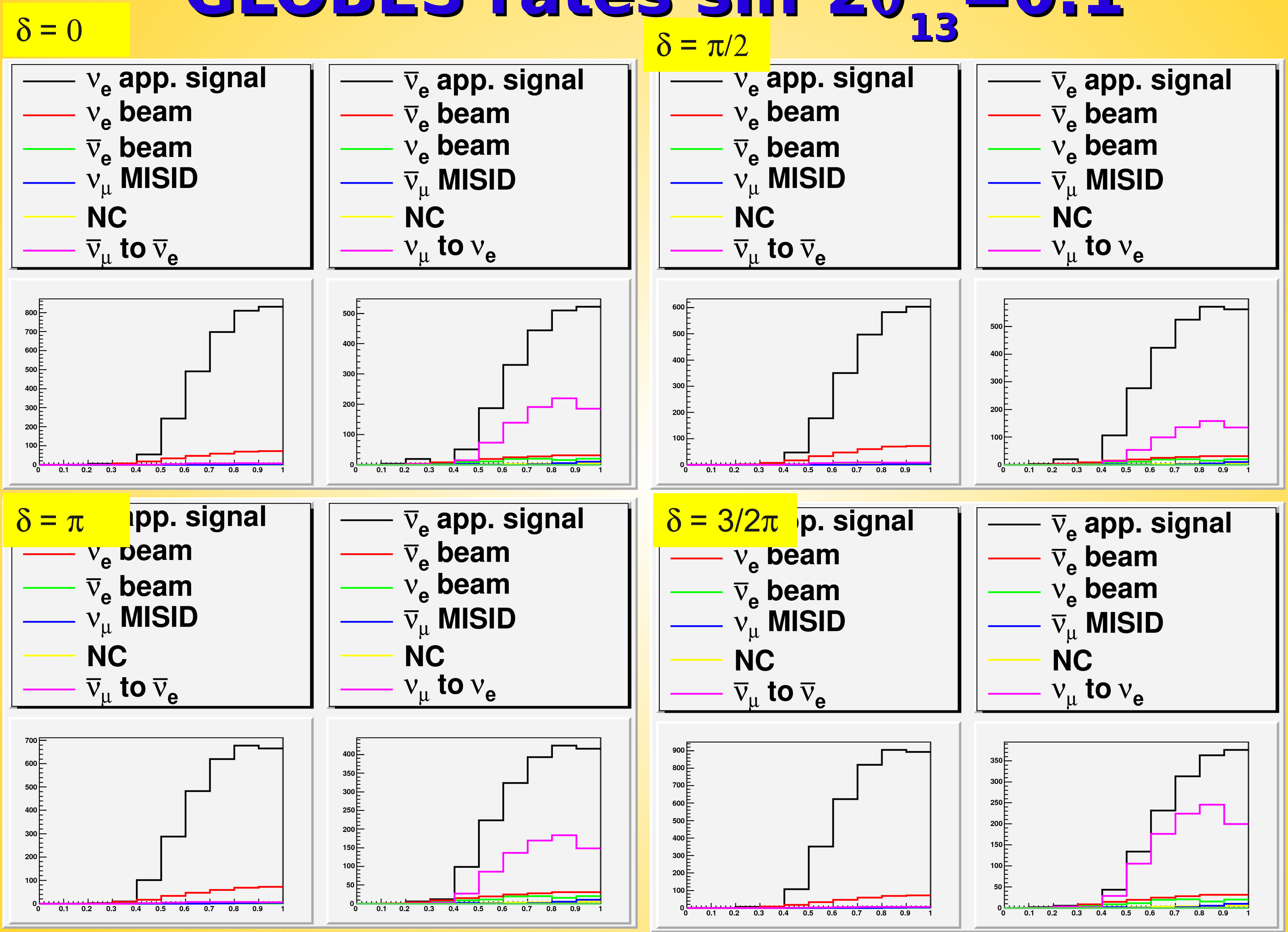
A. Longhin

On the spectra shape of evt rates

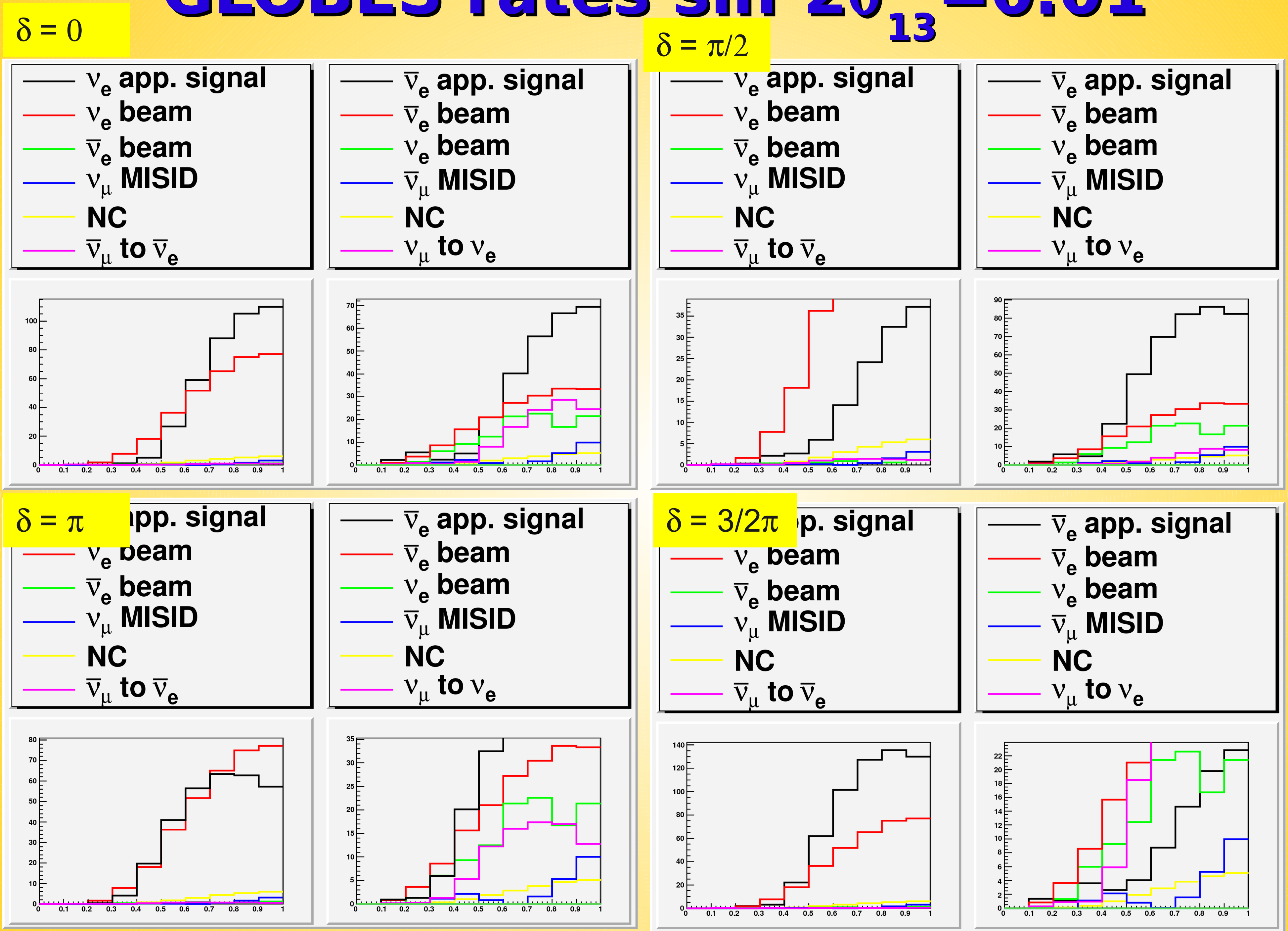


Most of the appearance signal appears at Energies above 260 MeV due to suppression related to cross sections (threshold effects).

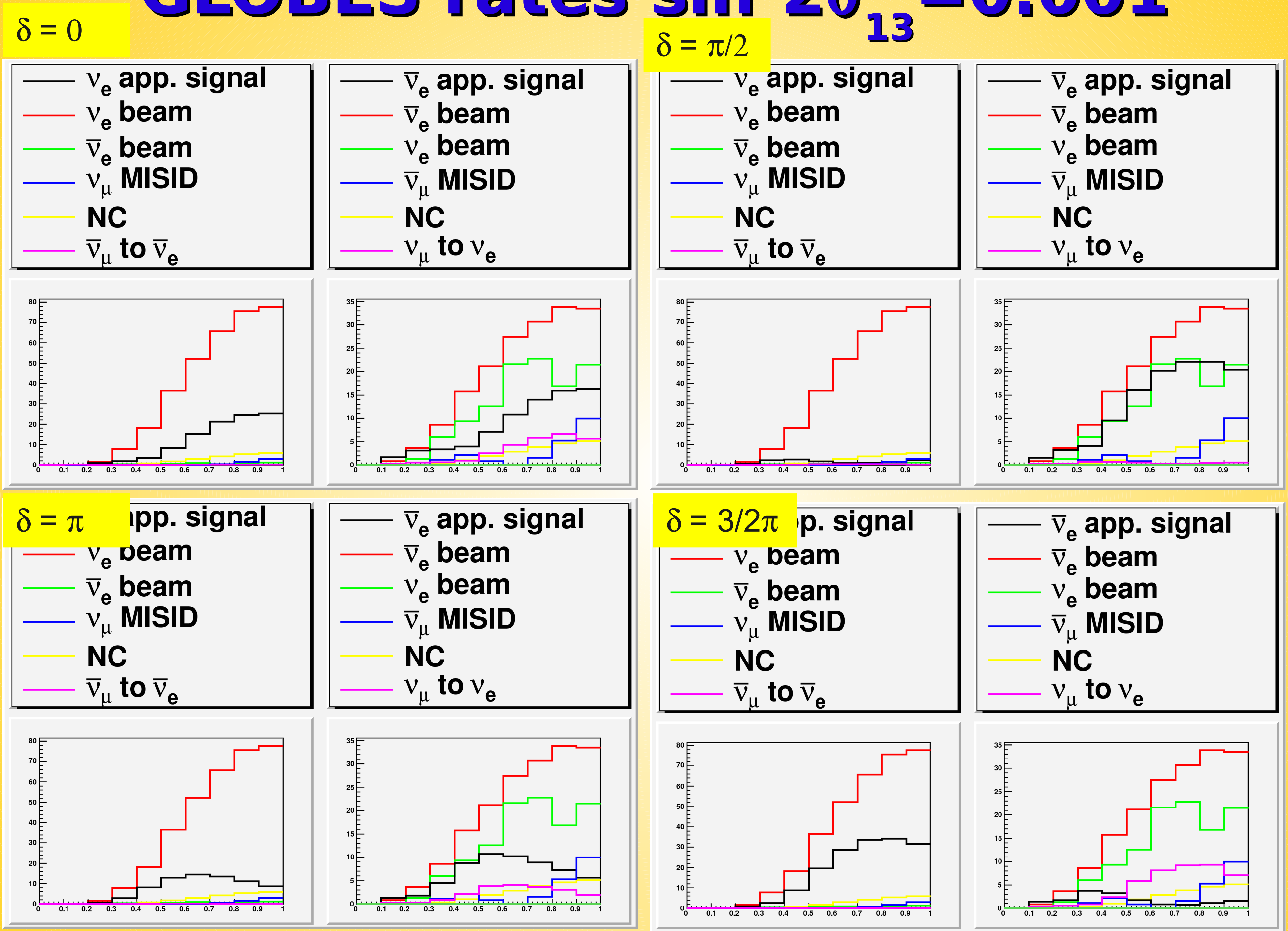
GLOBES rates $\sin^2 2\theta_{13} = 0.1$



GLOBES rates $\sin^2 2\theta_{13} = 0.01$

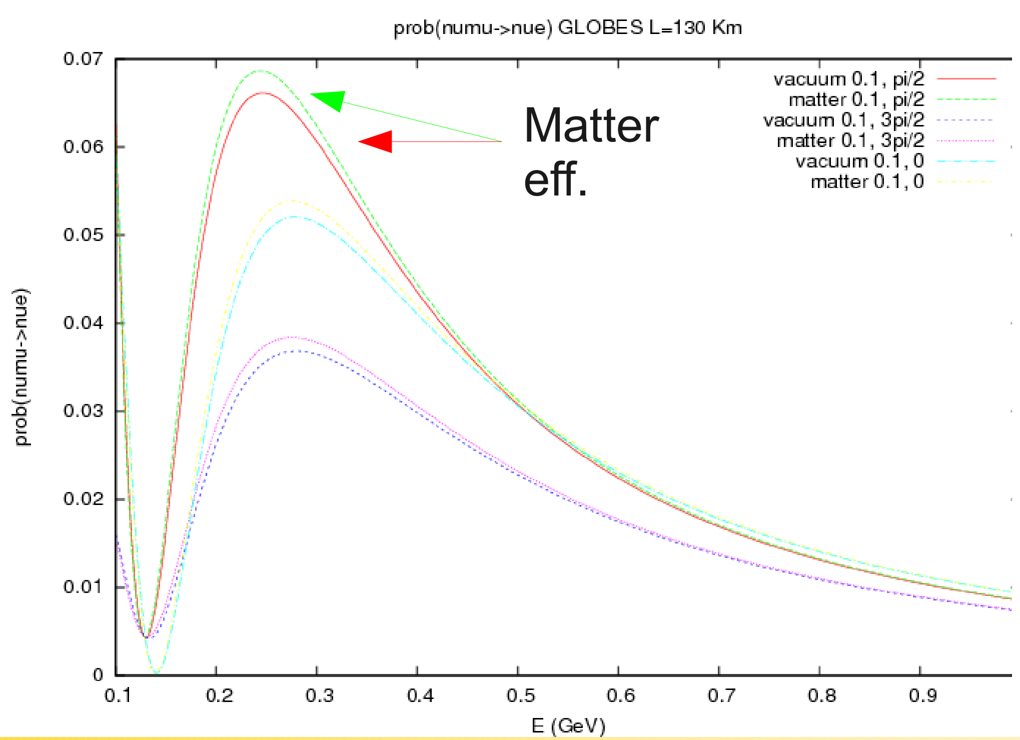


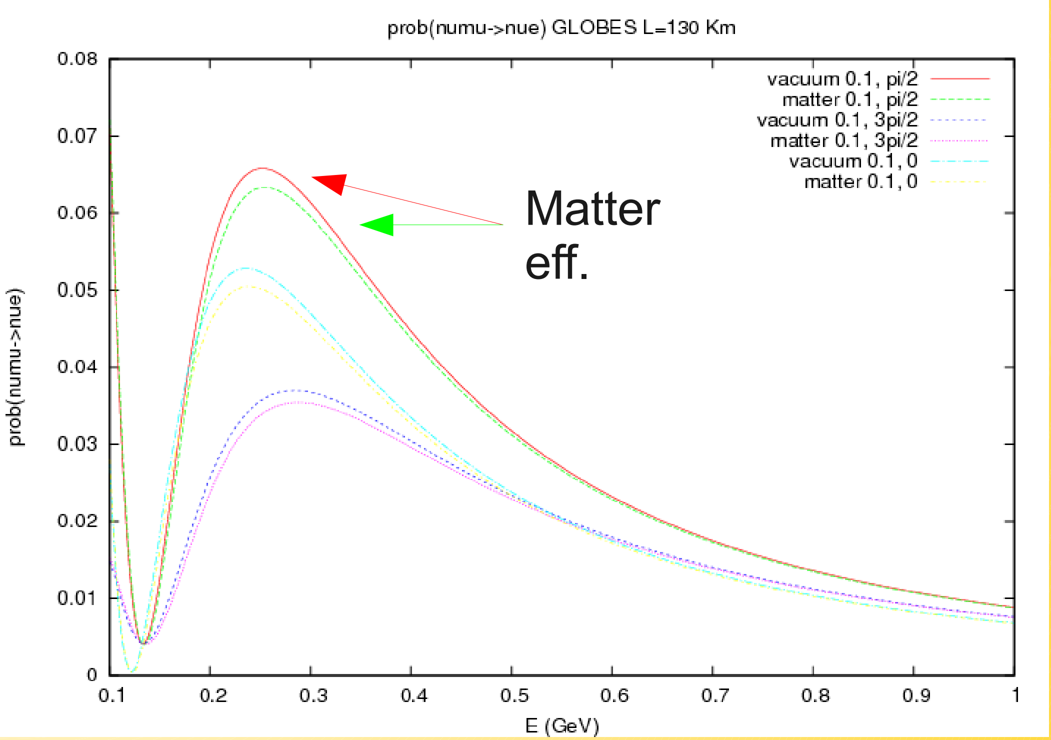
GLOBES rates $\sin^2 2\theta_{13} = 0.001$



GLOBES oscillation probs

$\sin^2 2\theta_{13}=0.1$





Normal hierarchy

Inverted hierarchy

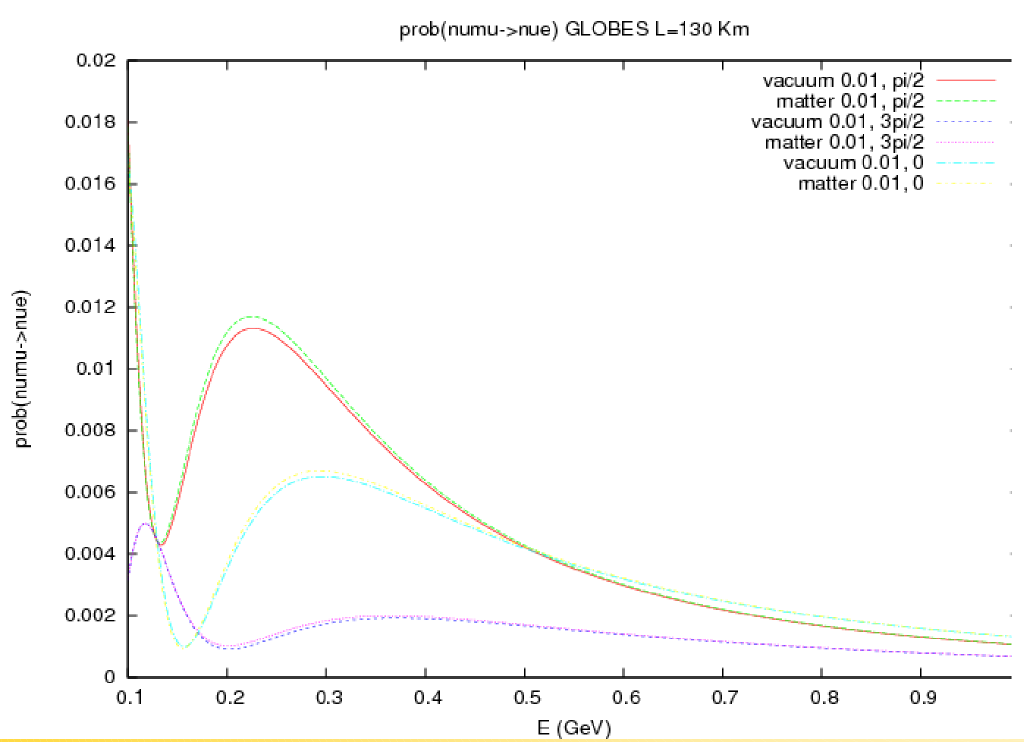
Hierarchy sensitivity through M.E. Exemplified

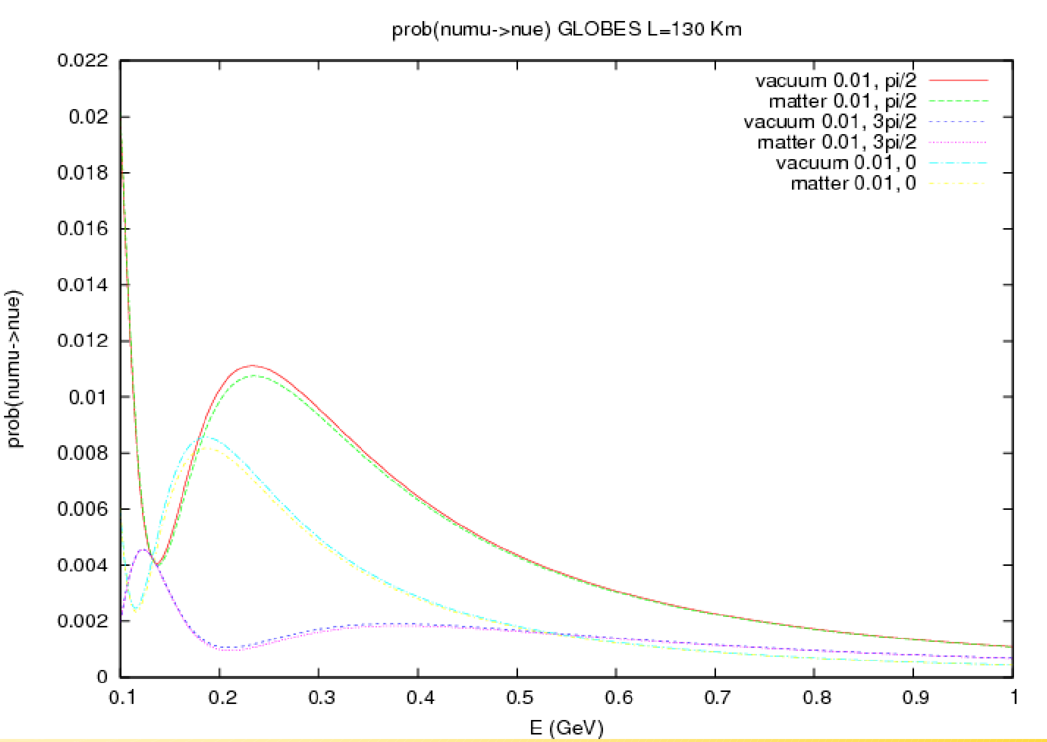
M.E. small. Does not lead to ambiguities wrt value of δ (as it happens at larger L)

Hierarchy sensitivity from spectral shape for δ=0 ? To be checked

GLOBES oscillation probs

$\sin^2 2\theta_{13}=0.01$





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GLOBES oscillation probs

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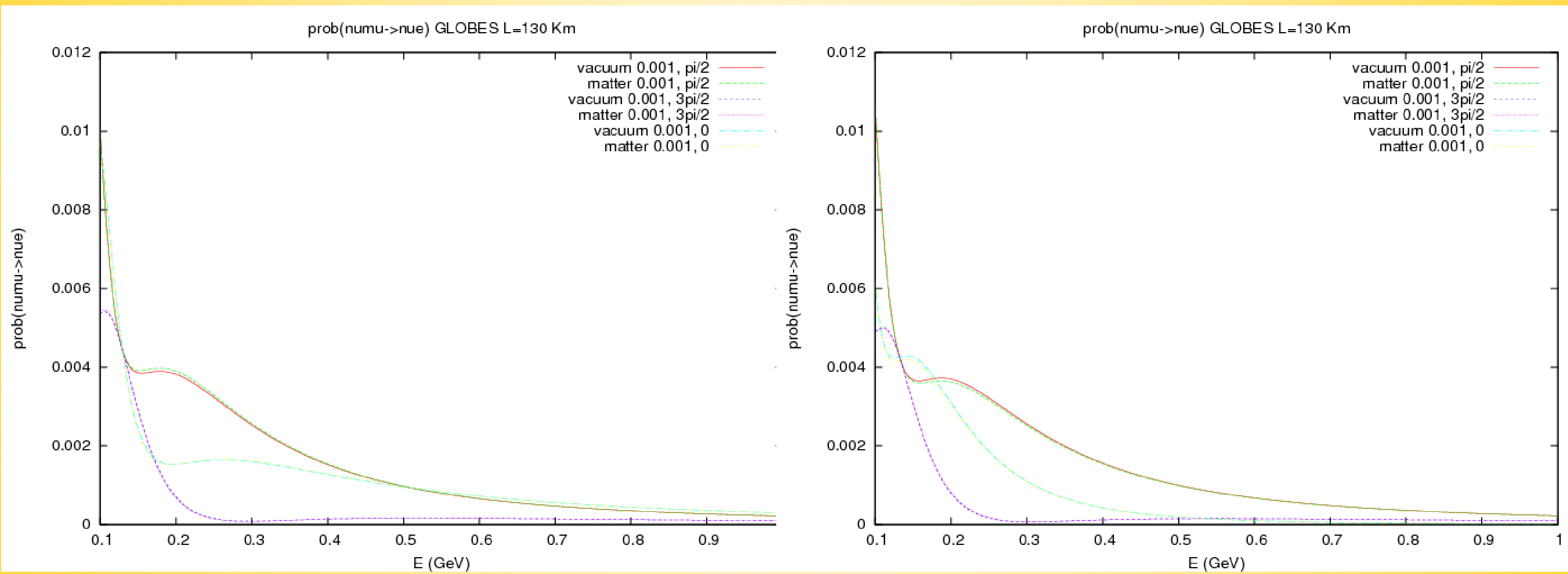

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M.E. small. Does not lead to ambiguities wrt value of δ (as it happens at larger L)

Hierarchy sensitivity from spectral shape for δ=0 ? To be checked

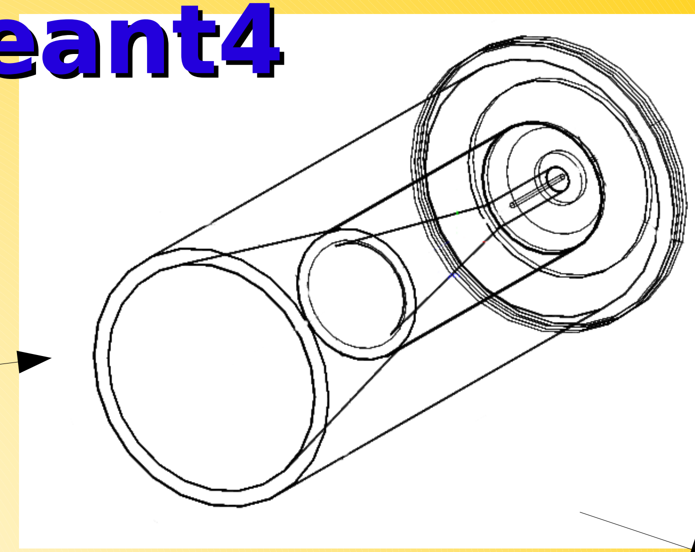
Conclusions

- Effect of dropping the reflector (+ increasing horn I)
  - Significant, ad hoc optimization would be needed
- Systematics on primary π production
  - characterization of interesting π phase space (PhS)

    <p> ~ 1.2 GeV. <θ> ~ 0.26 rad (~15º)
  - another model : GIBUU
    - Not so bad in the relevant PhS!
- Future SB in Europe: SPL<-> PS2 ?
  - Progress towards a comparison, some key issues to be solved
- A deeper look into GLOBES parametrisations for SPL
  - E-resolution
  - Cross-sections
  - event rates
  - oscillation probabilities (w/wo matter effects)

- **Horn optimization with GEANT4**

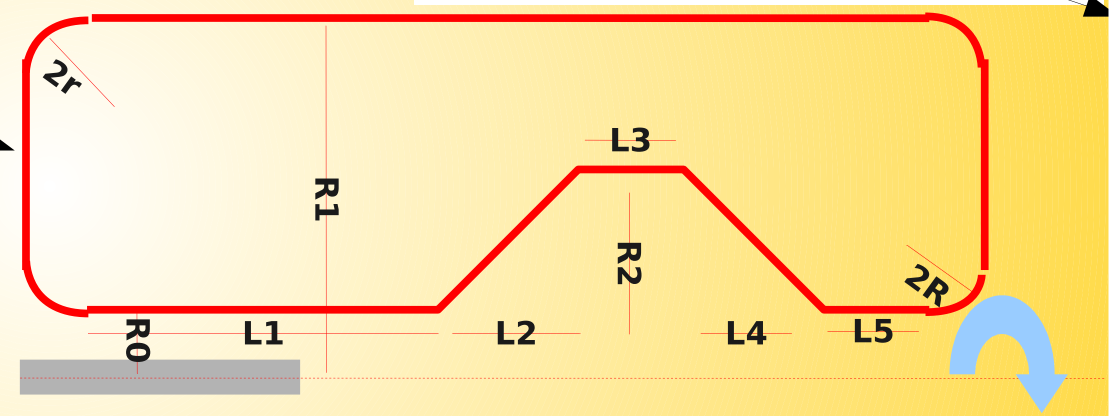
New simulation with Geant4



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

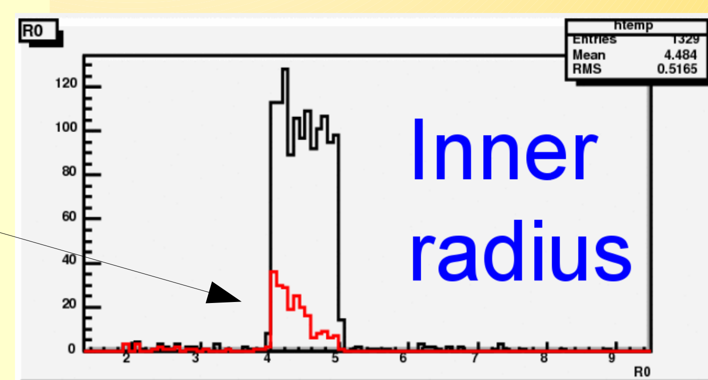
Flexible enough to reproduce also standard conical geometry

"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

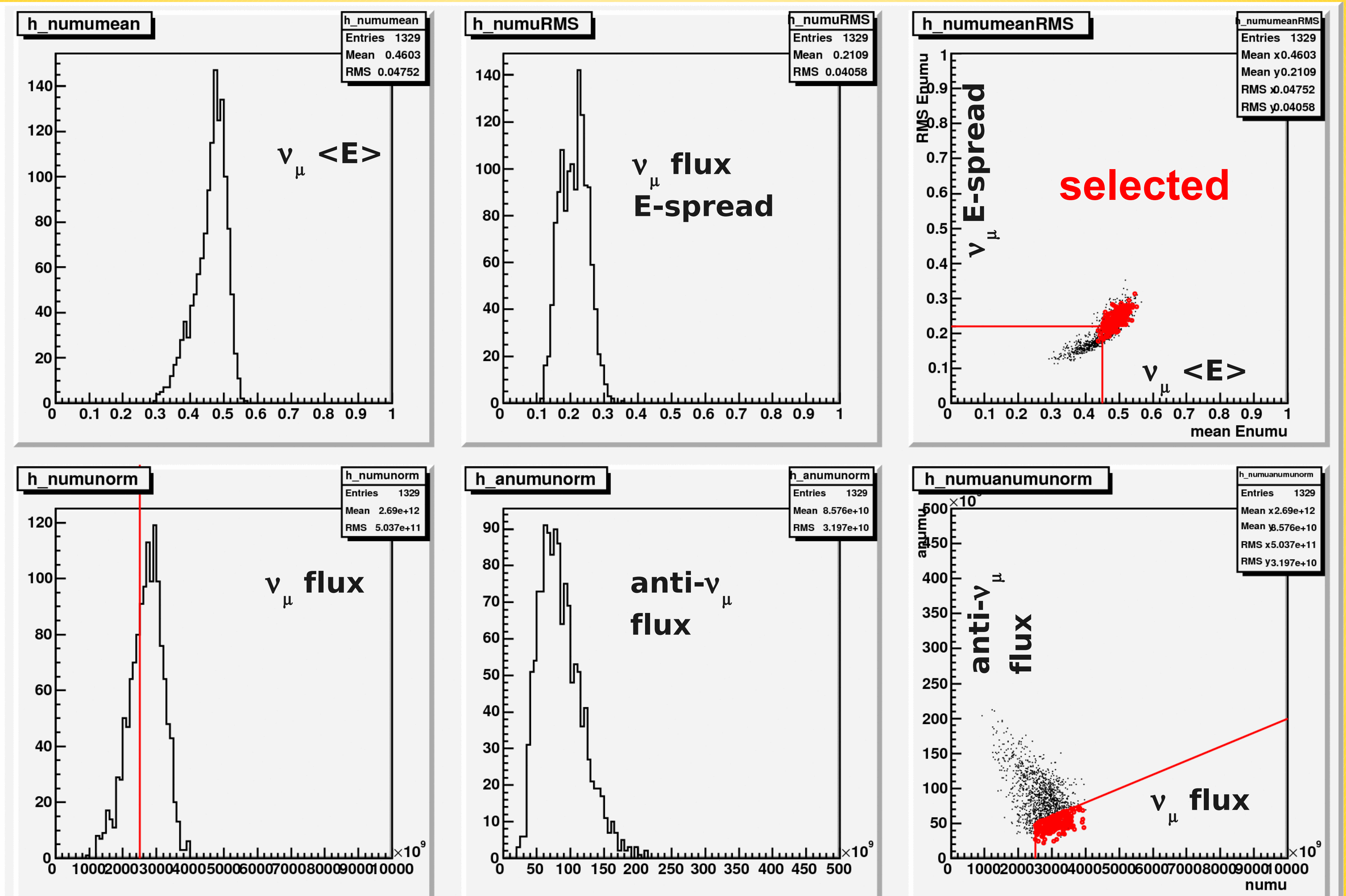
Accepted after cuts on spectra



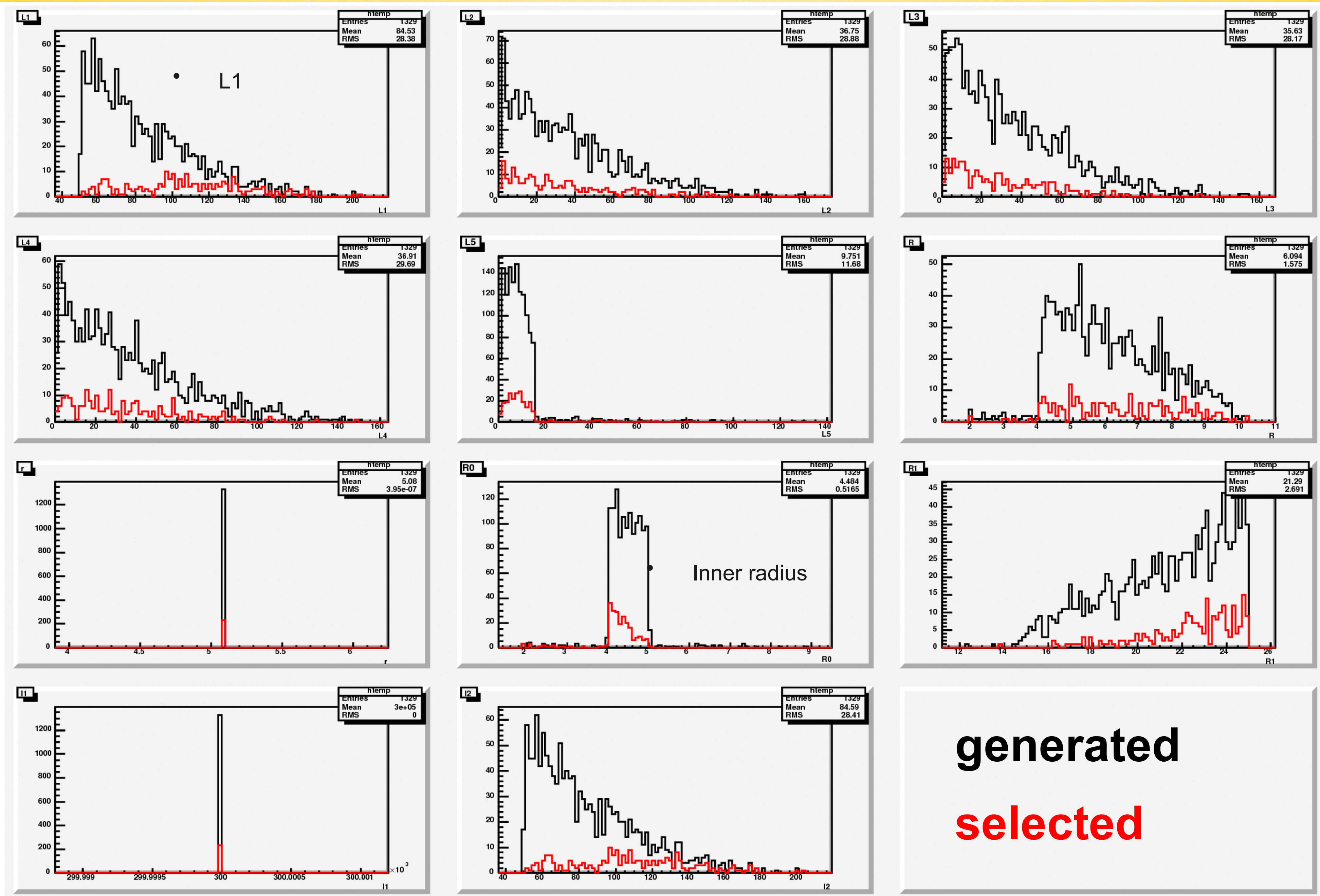
9 parameters fully accessible from external macro file

```
#
/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

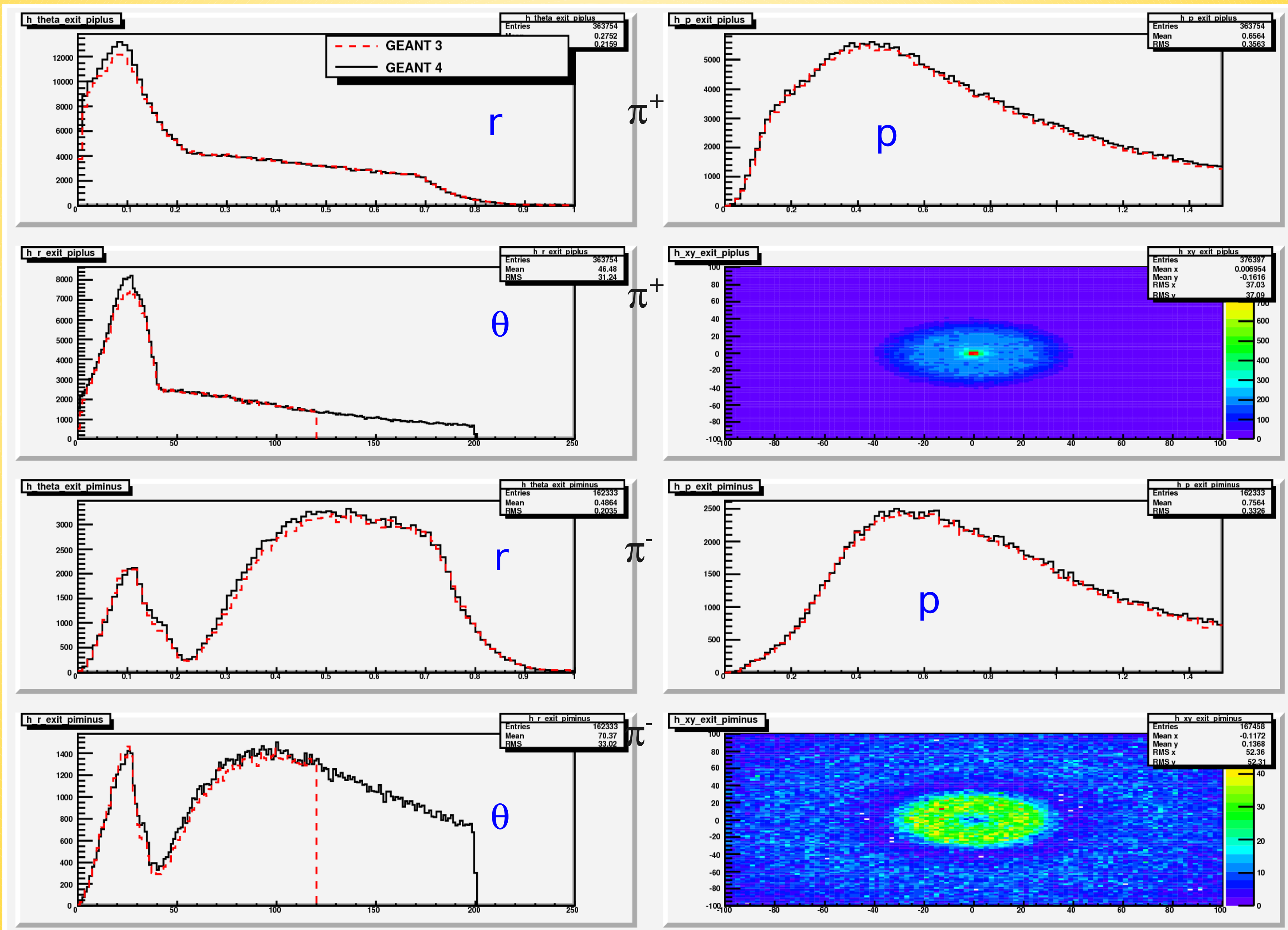


GEANT3-4 comparison with standard horn (I)

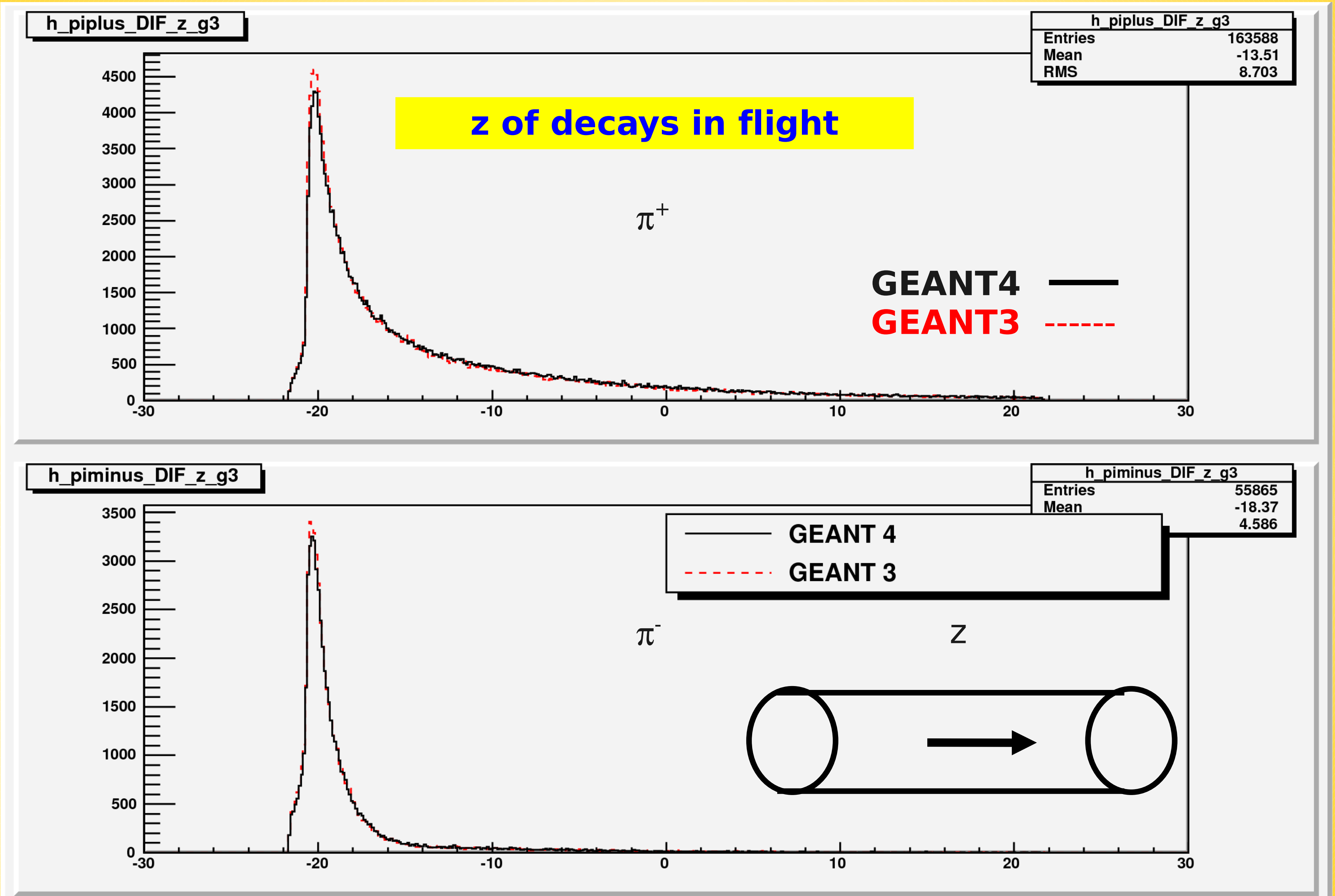
Parameters of pions at tunnel entrance

GEANT4 ——

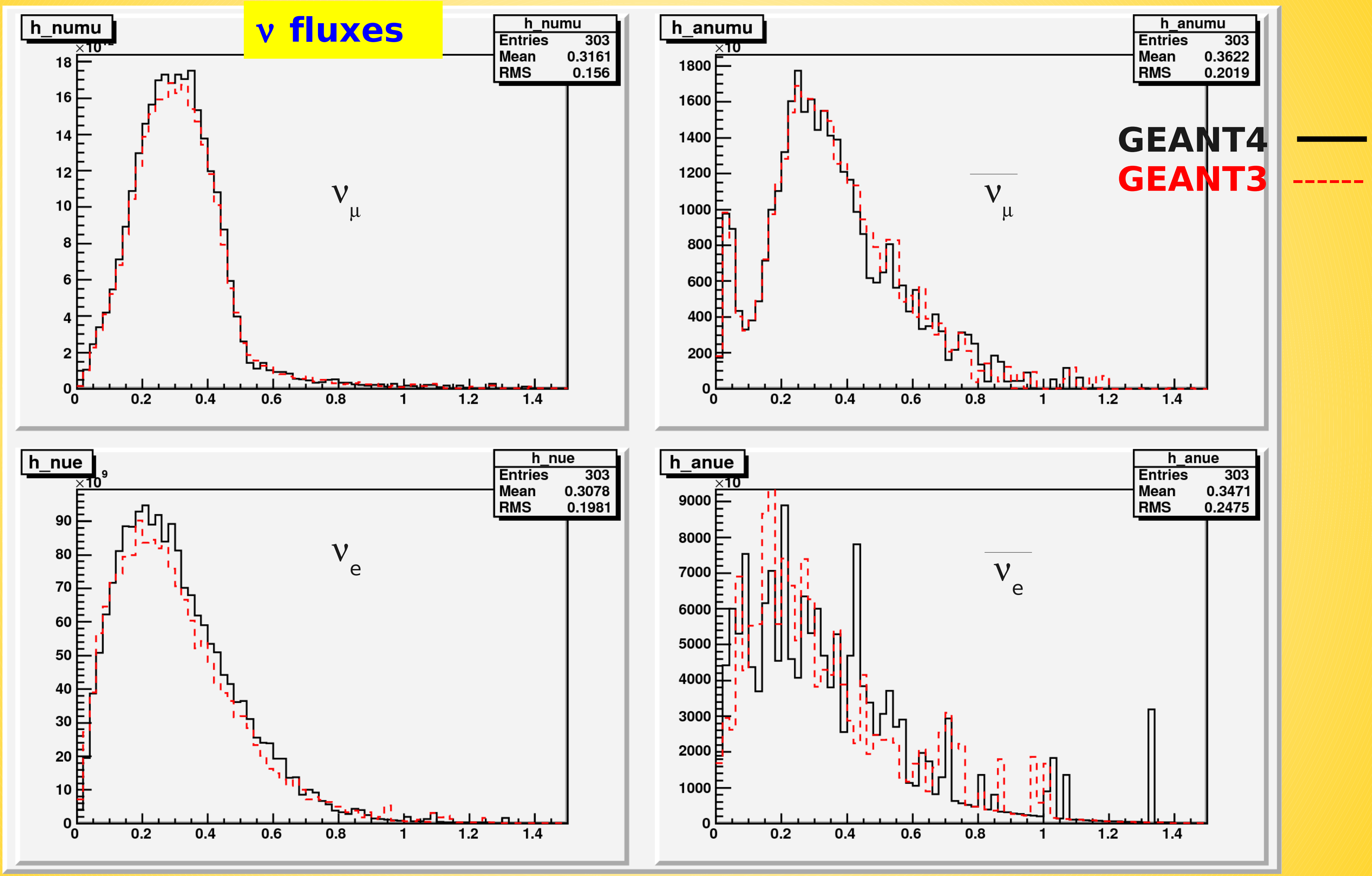
GEANT3 ------



GEANT3-4 comparison with standard horn (II)



GEANT3-4 comparison with standard horn (III)

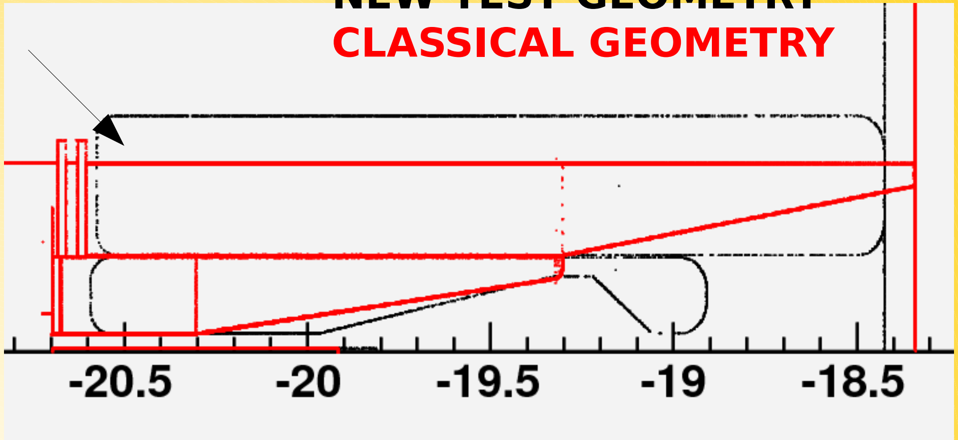


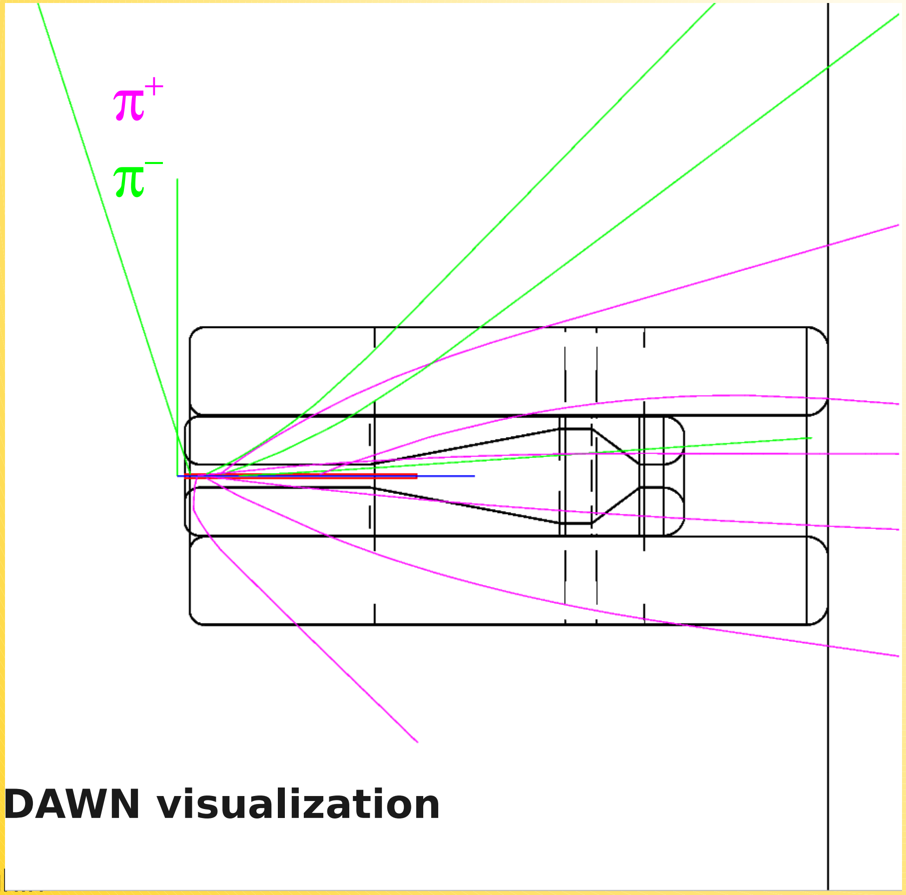
Good agreement between the two simulation programs

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)

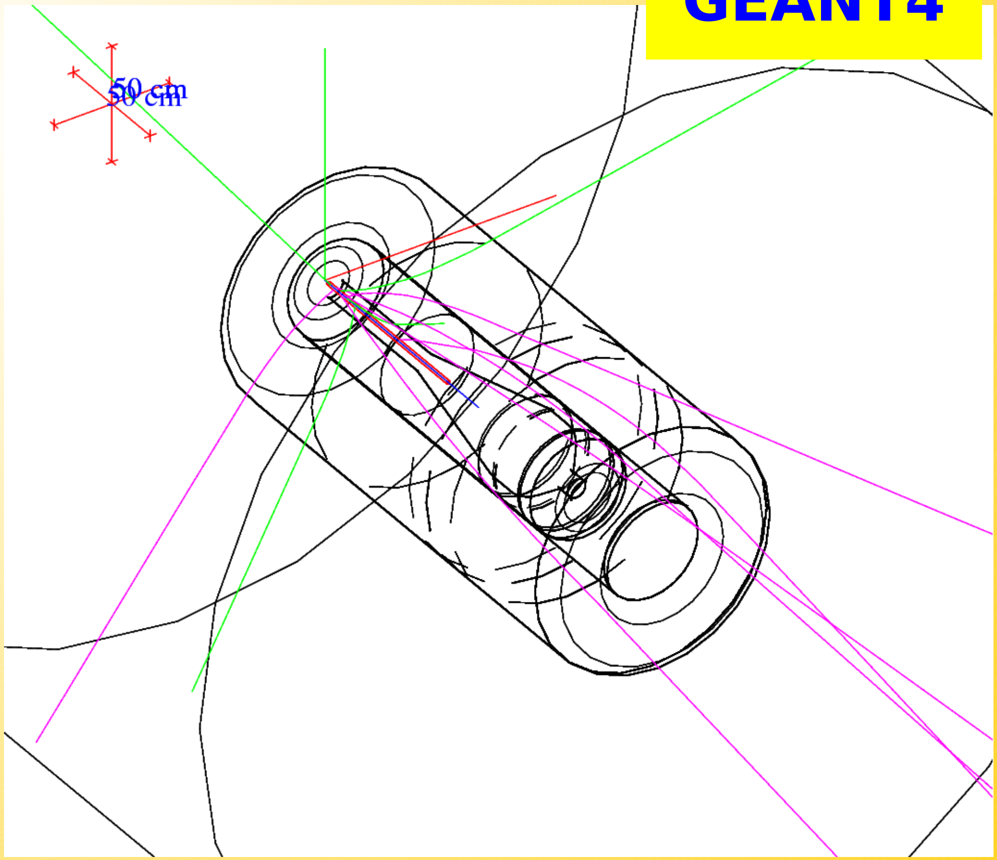
Hit maps (r,z) plane





•DAWN visualization

GEANT4



- **Horn optimization with GEANT4**
- **4 horns in parallel**

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- **performance of the new horn design**

- **Horn optimization with GEANT4**
- **4 horns in parallel**
- **performance of th new horn design**
- **π^0 background**

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)

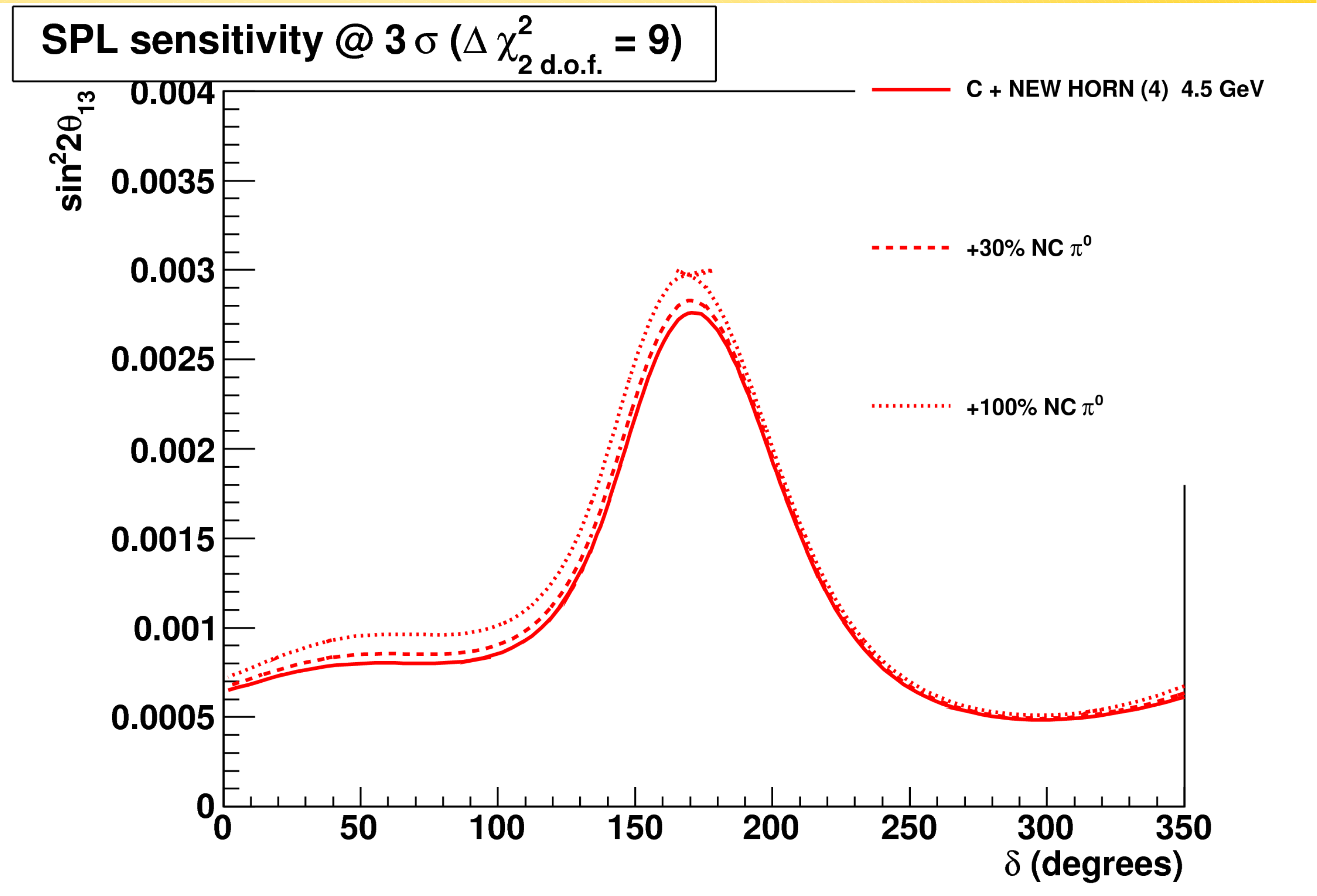
rough (conservative) variation applied to estimate the effect

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



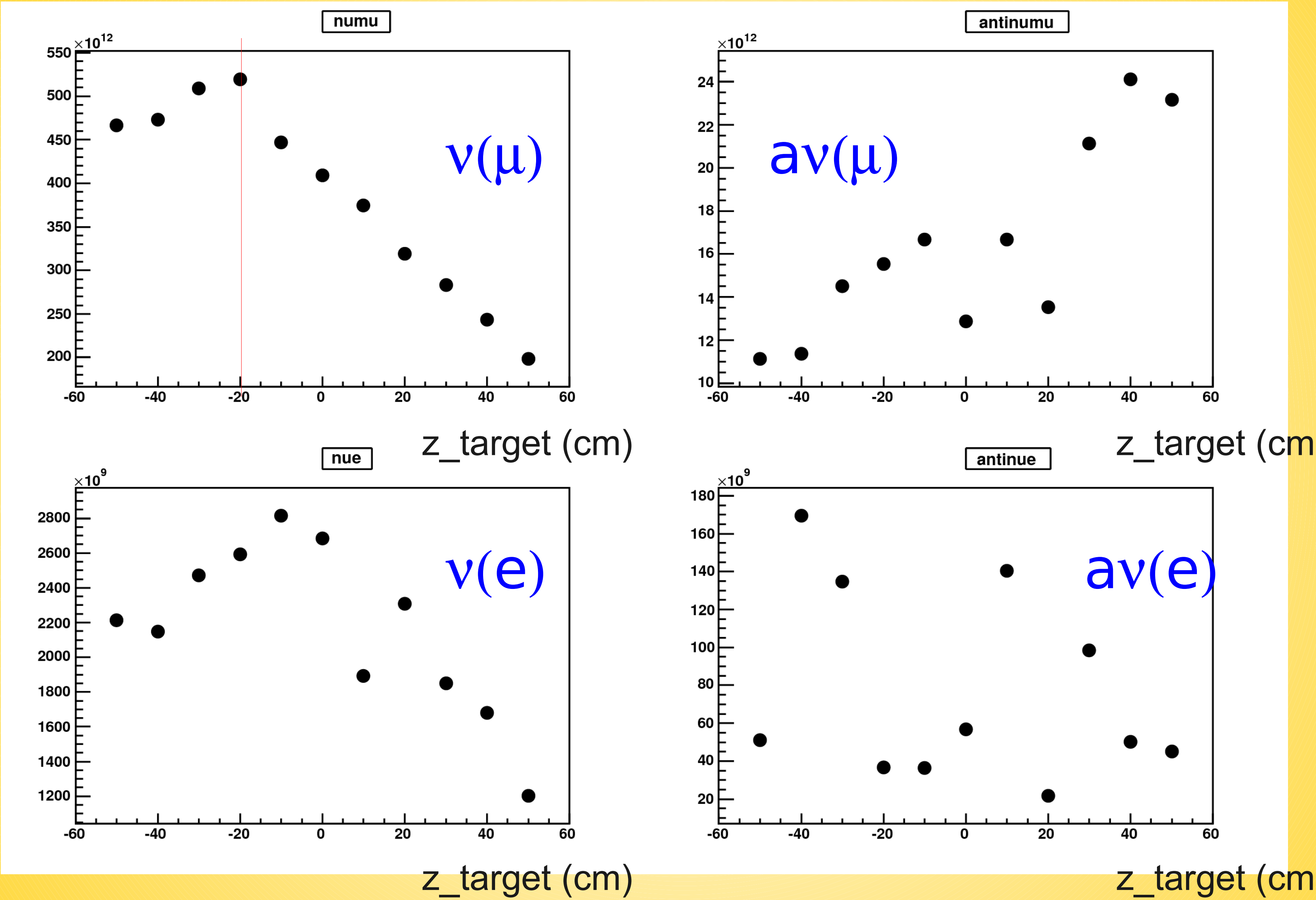
Backgrounds to ν_e appearance @ 3.5 GeV (standard conf.)

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%

- **Horn optimization with GEANT4**
- **4 horns in parallel**
- **performance of the new horn design**
- **π^0 background**
- **Target z optimization**

Fluxes vs Z of target (w.r.t. horn)

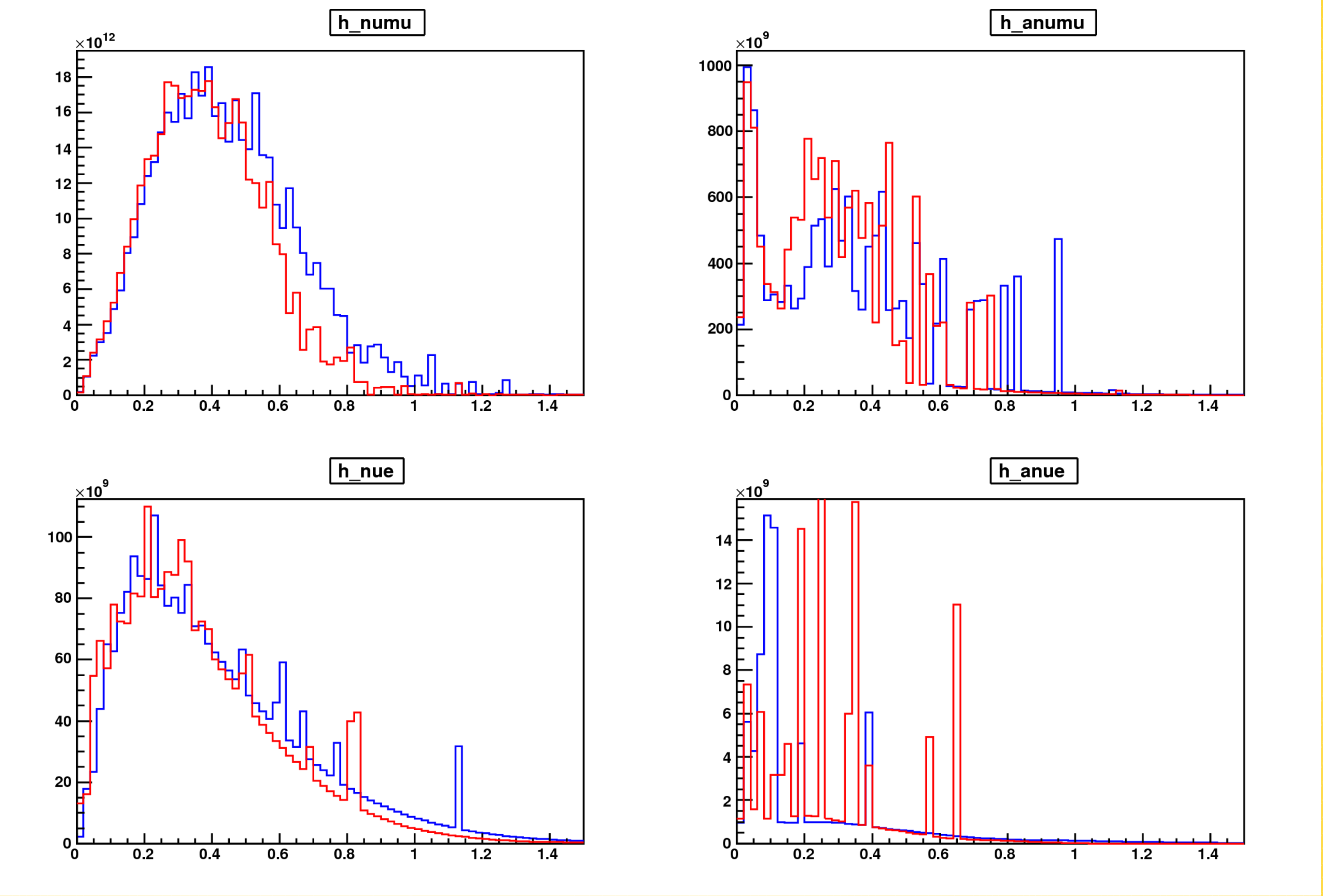


Moving the target upstream by 20 cm seems to be better ~>

Fluxes with a target shifted upstream by 20 cm

Target:

z=0
z=-20cm



- some gain in numu at high energies
- some reduction in antinumu component
- nue-antinue ~same
- Not yet studied at the level of sensitivity curves

- Horn optimization with GEANT4
- 4 horns in parallel
- performance of a new horn design
- π^0 background
- Target z optimization
- **Systematics on primary pion production**
  - **1) pC: FLUKA ~> GEANT4**

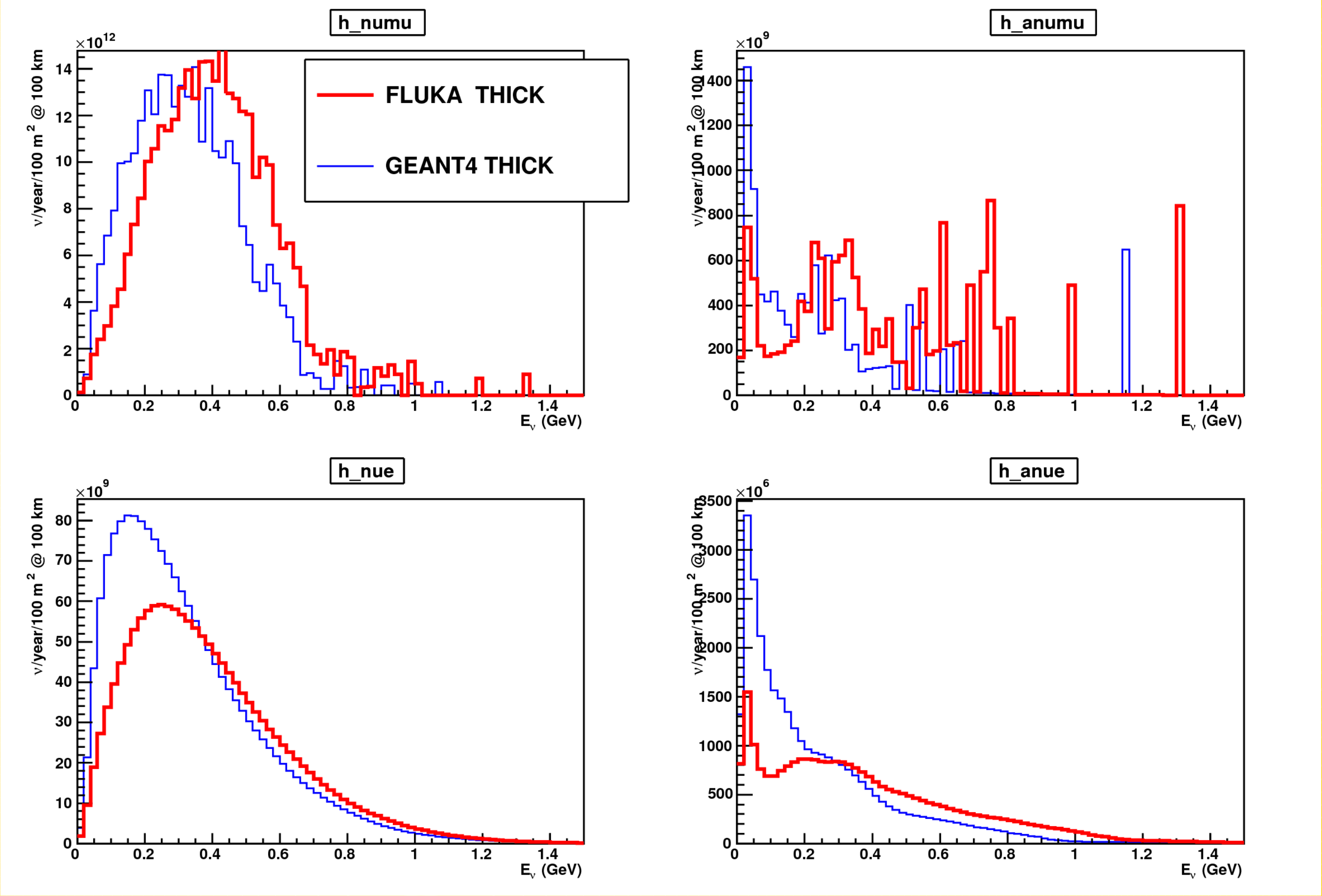
Systematics on primary pion production I

Difference in the fluxes obtained using GEANT4 or FLUKA for the primary p-C interactions

NB. Here the target is a 39 cm long carbon cylinder with 3 cm diameter in order to reproduce the geometry tested by HARP (see later)

while our standard target is 78cm long.

Difference with the 78cm long target not tried yet (presumably quite similar)



~ same normalization, lower energy with GEANT4, ~more antinue (more "slow" muons) sizable effect, to be addressed at the level of sensitivities

- Horn optimization with GEANT4
- 4 horns in parallel
- performance of a new horn design
- π^0 background
- Target z optimization
- **Systematics on primary pion production**
  - 1) pC: FLUKA ~> GEANT4
  - **2) reweight GEANT4 with HARP data**

Systematics on primary pion production II

Comparison of GEANT4 pion yields and HARP differential cross sections

Chosen configuration among the available HARP (the closest to our foreseen setup):

A (gmol^{-1})	ρ (gcm^{-3})	t (cm)	$A/(N_A \rho t)$ (barn)	r (cm)
12	1.85	39	0.276	1.5
180	16.69	11.14	1.616	1.5

- E(p) = 5 GeV
- materials: C and Tantalum (similar to Mercury)
- "thick target" ($1\lambda_I$) ("thin target" also, 5% λ_I)
- small and large angles data-sets

- L = 39 (1.95) cm, R = 1.5 cm C
- L = 11 (0.775) cm, R = 1.5 cm (Ta)

The published cross sections have been reproduced using the HARP procedure but taking the "true-level" pion tracks from the generator as input

- N_{ij} becomes the # of pions generated in the i-th p bin and j-th θ bin by N_{pot} protons on target
- **M** =1 (by definition efficiency =1, no migrations. HARP data instead are corrected for all this!)

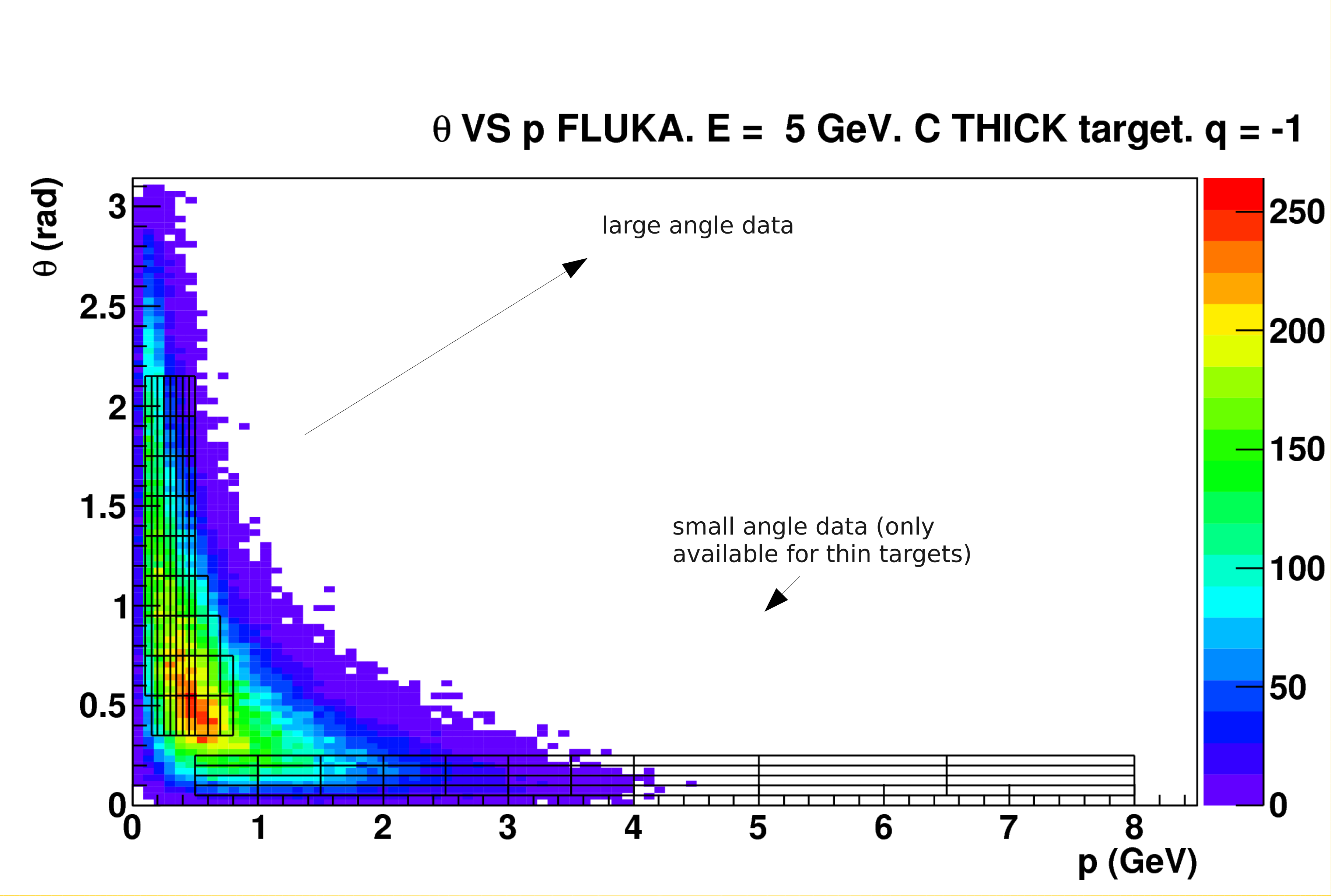
$$\frac{d^2\sigma}{dp_i d\theta_j} = \frac{1}{N_{pot}} \frac{A}{N_A \rho t} \sum_{i',j'} M^{-1}_{iji'j'} \cdot N_{i',j'}$$

- t = target length

Then a re-weighting table has been built in (p,theta) space taking ratios btw the genarator cross sections and the measured ones.

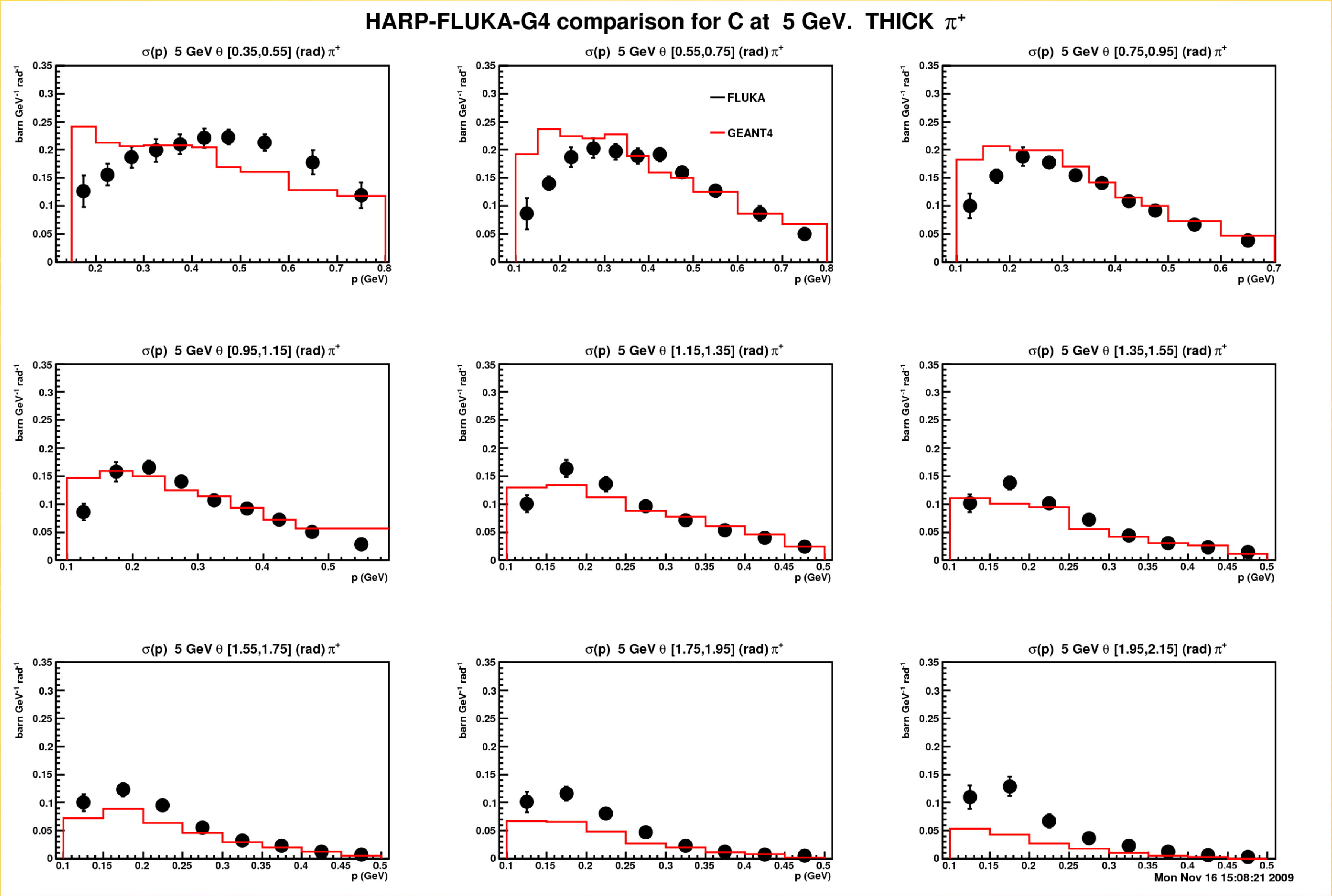
Correction applied to MC -> neutrino flux comparison after re-weighting.

HARP binning



GEANT4. Large angle. THICK target. C. 5 GeV. pi+

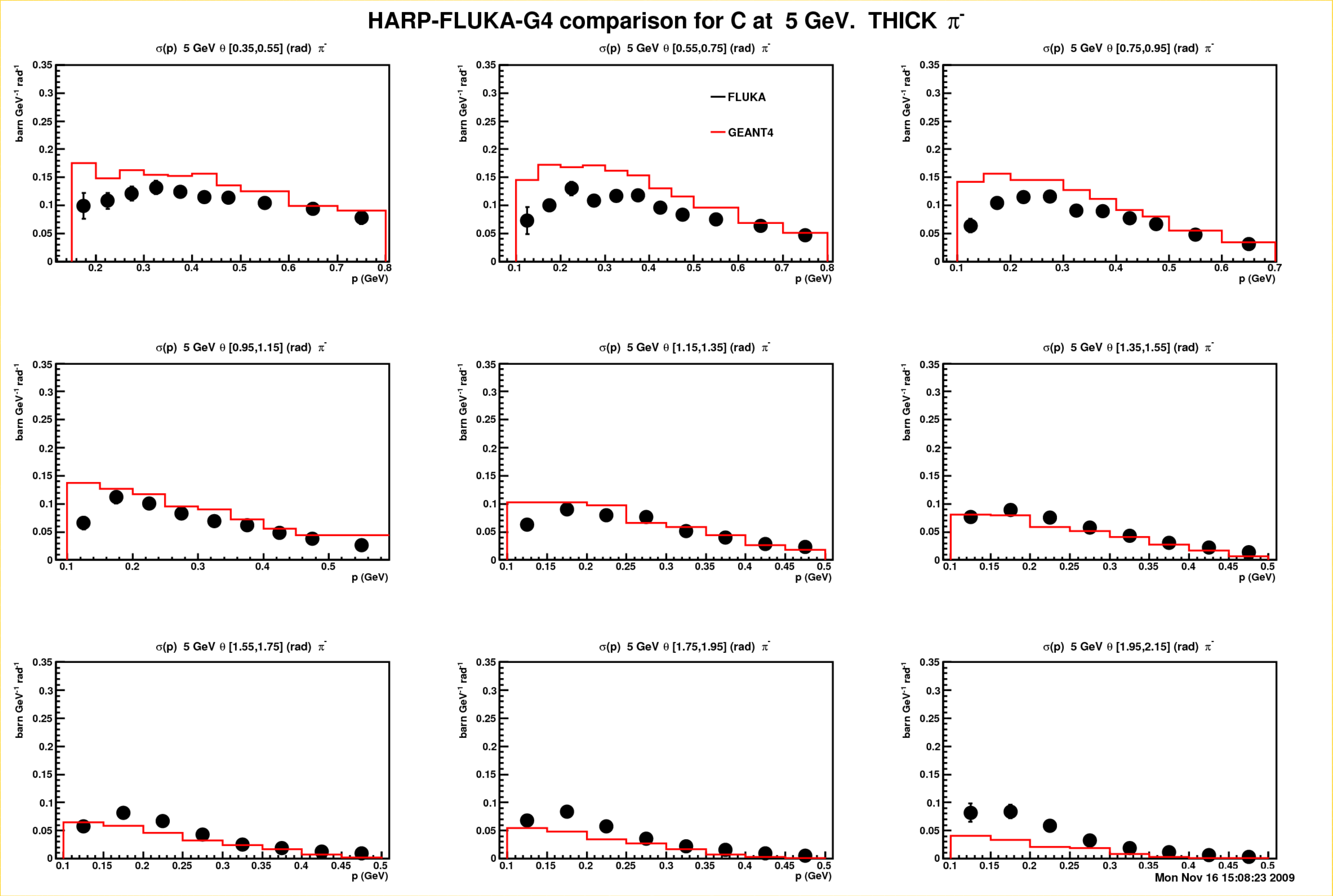
$\sigma(p)$ in θ bins



tends to underestimate production at large angles

HARP-GEANT4. Large angle. THICK target. C. 5 GeV. pi-

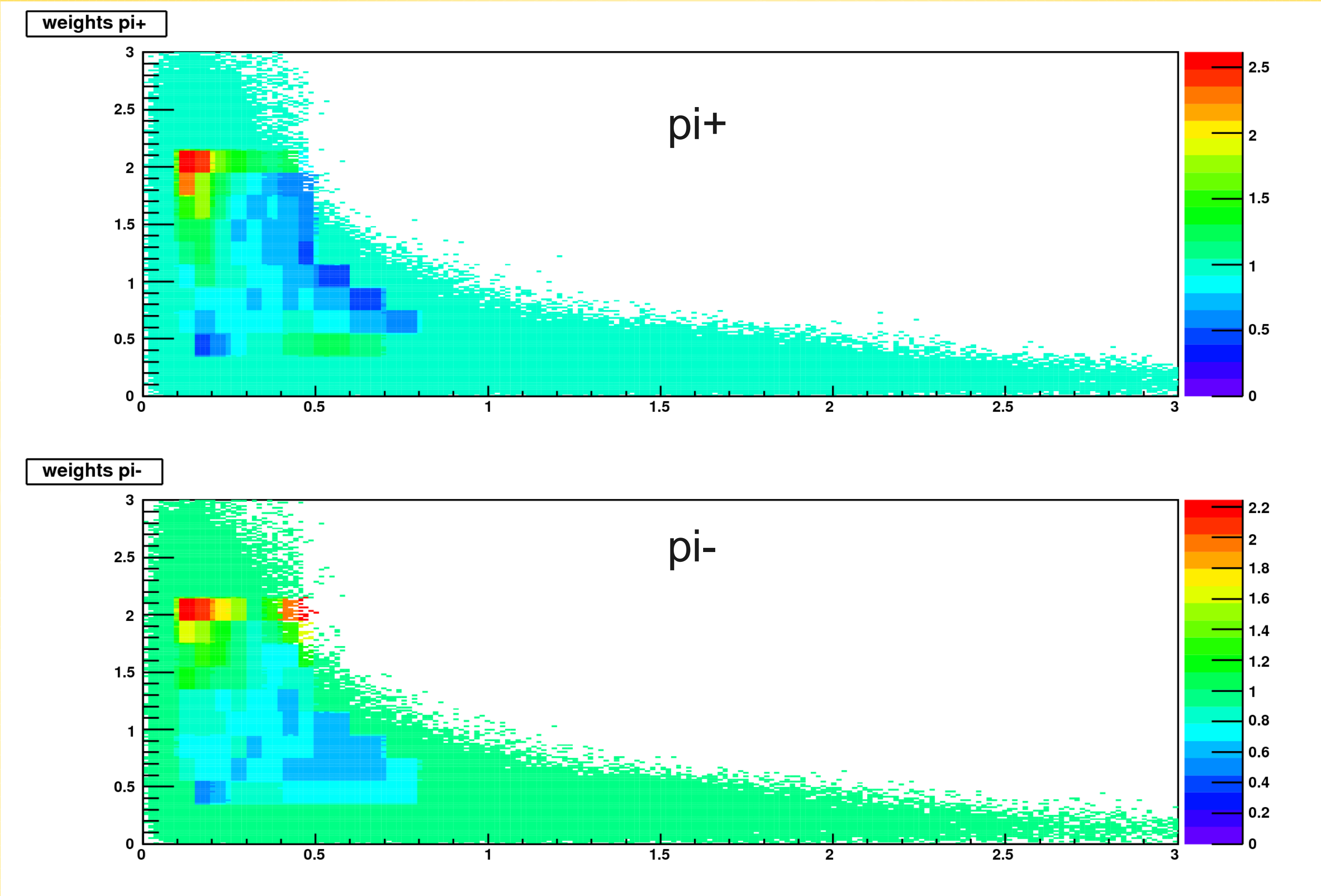
σ(p) in θ bins



tends to underestimate production at large angles

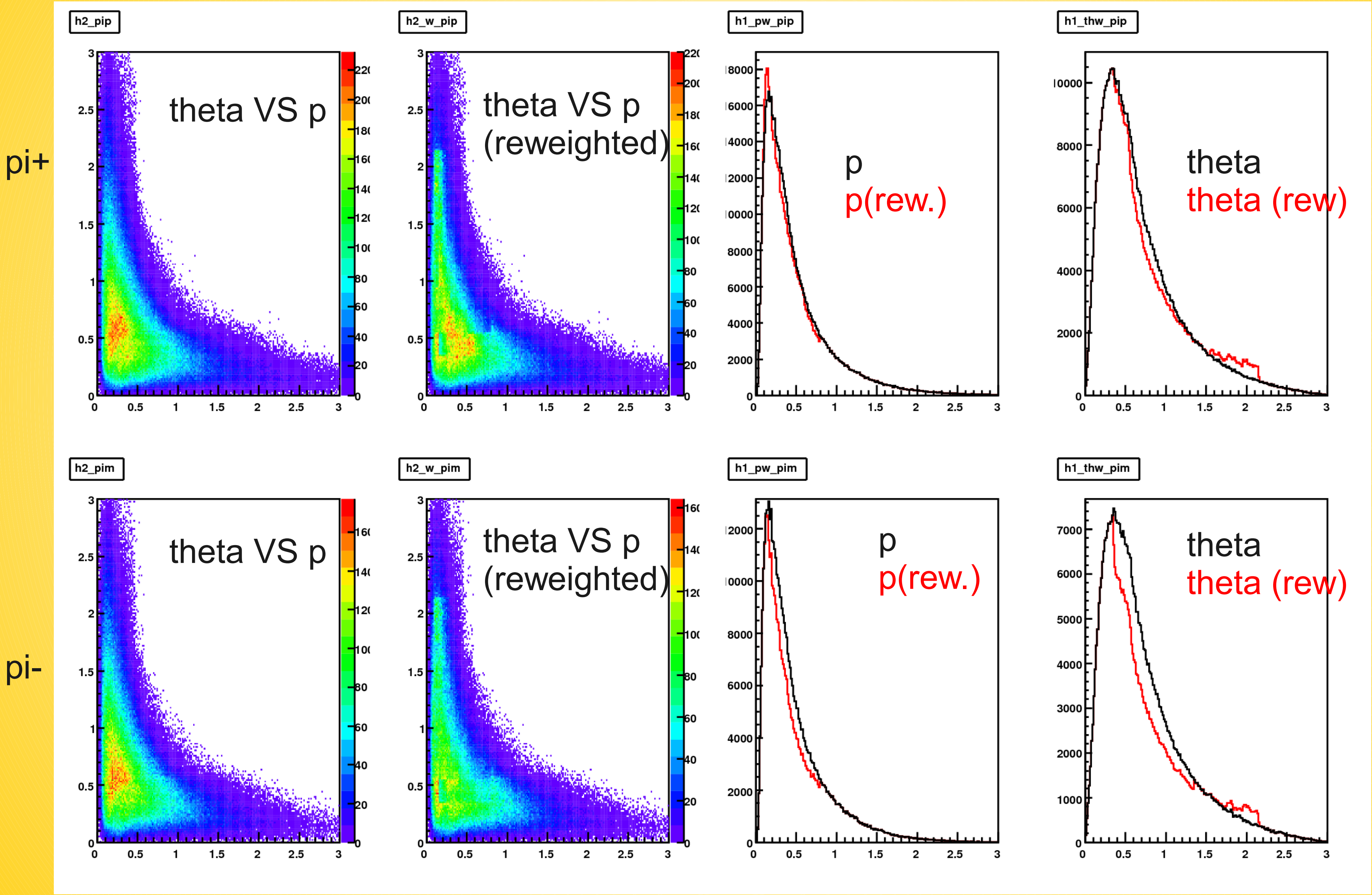
Weights (THICK target, C 5 GeV, HARP/G4)

theta VS p



- No correction in the phase space not covered by meas.. Use Sanford -Wang outside ?
- Not straightforward “shape” for correction factor (~saddle).
- method: track with weight “w” is duplicated “w-times” on average (using random variable with uniform distribution).

GEANT4 re-weighting (THICK target, C 5 GeV)

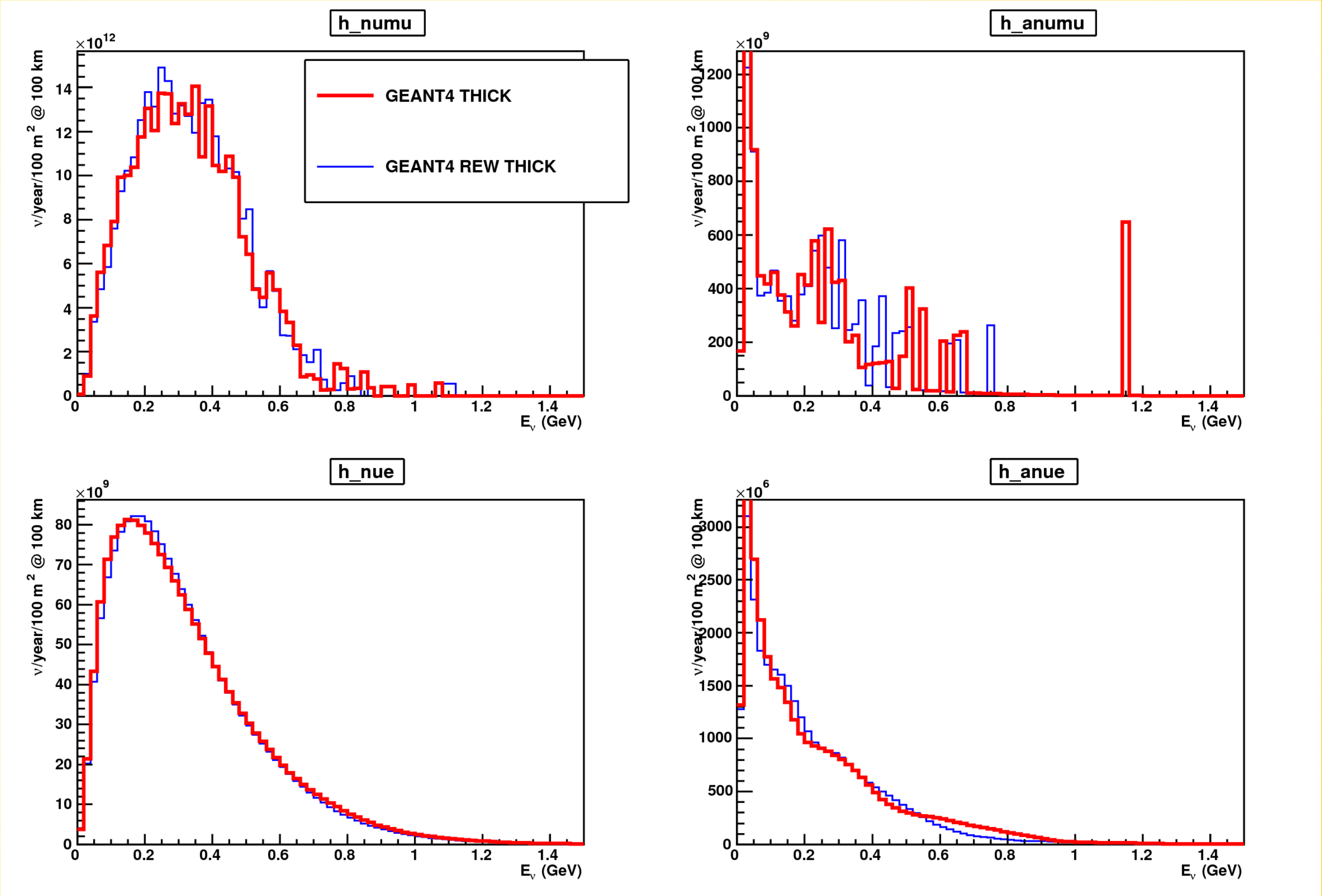


Re-weighting impact on fluxes (GEANT4)

NB. Here the target is a 39 cm long carbon cylinder with 3 cm diameter in order to reproduce the geometry tested by HARP (see later)

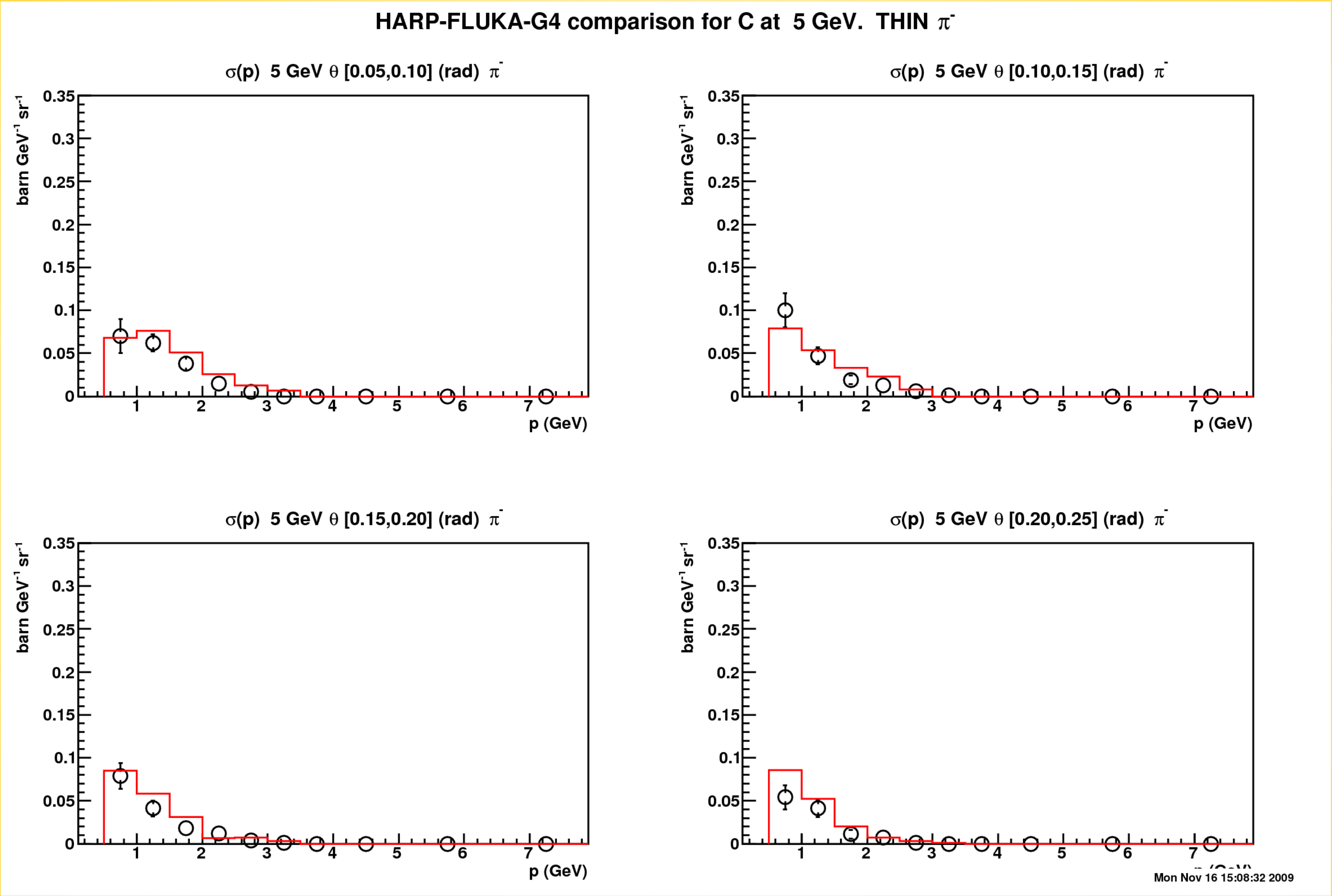
while our standard target is 78cm long.

Difference with the 78cm long target not tried yet (presumably very similar)

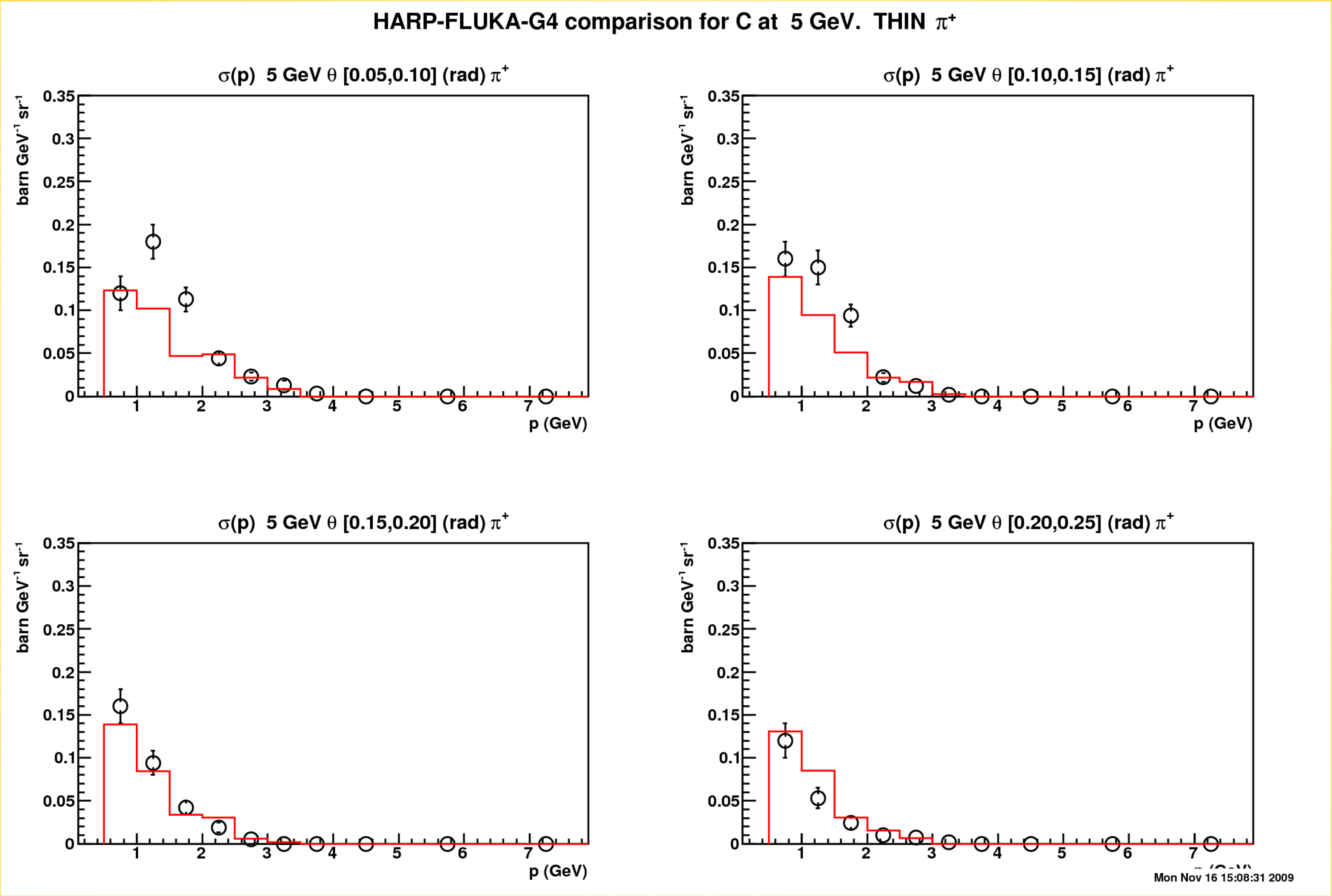


THICK TARGET data re-weighting
new focusing scheme

HARP-GEANT4. Small angle. THIN target. C. 5 GeV. pi-

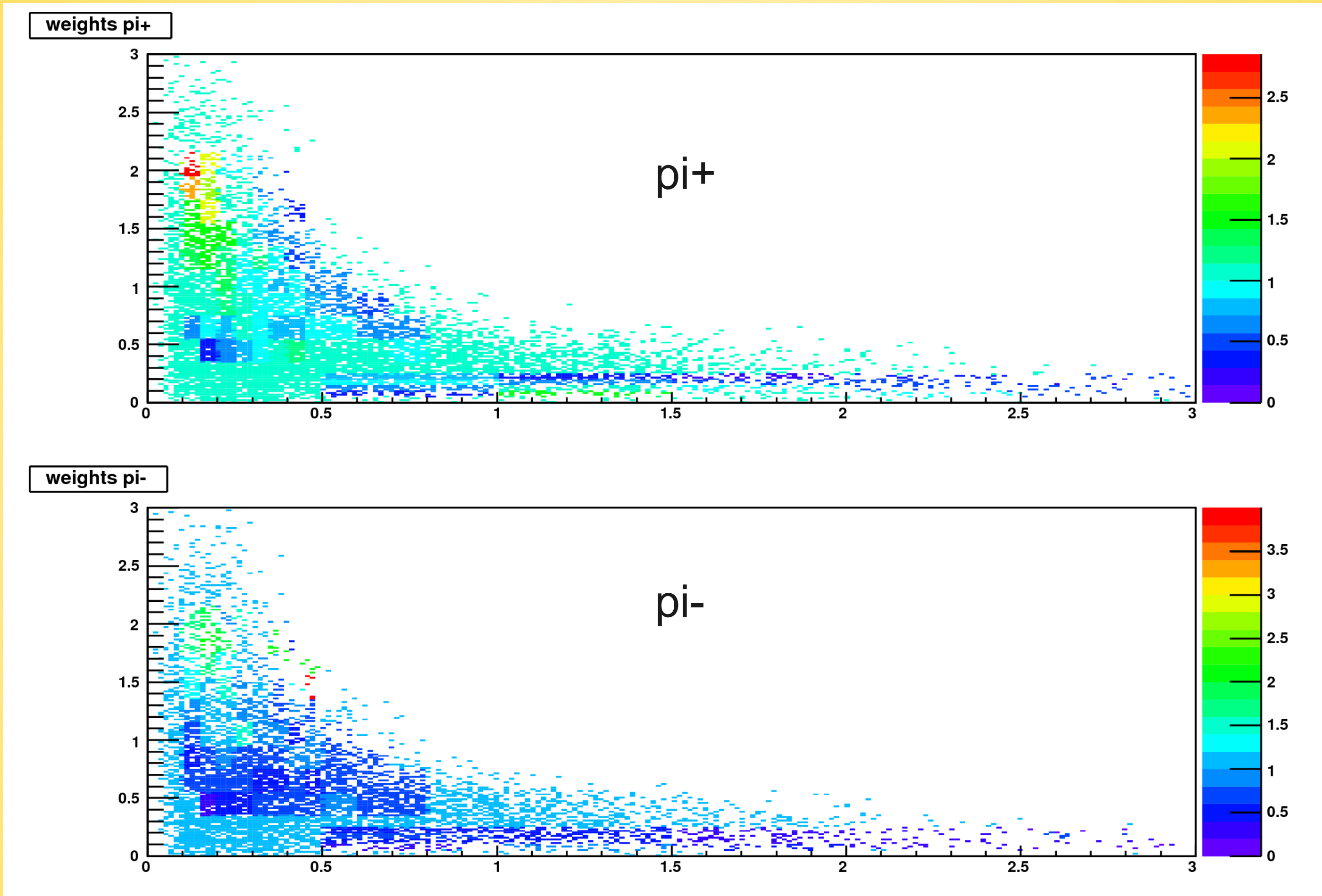


HARP-GEANT4. Small angle. THIN target. C. 5 GeV. pi+



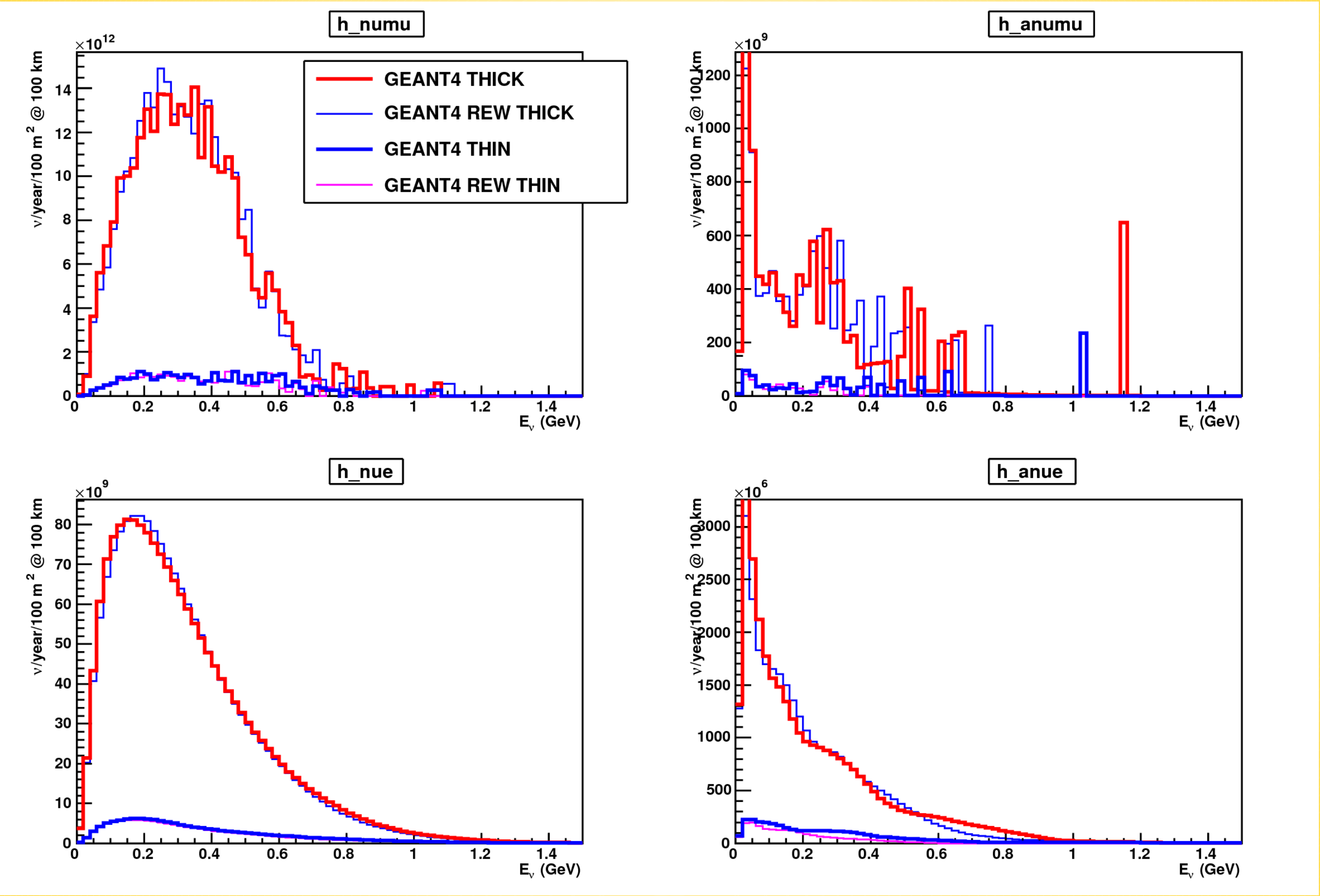
Weights (THICK target, C 5 GeV, HARP/G4)

theta VS p

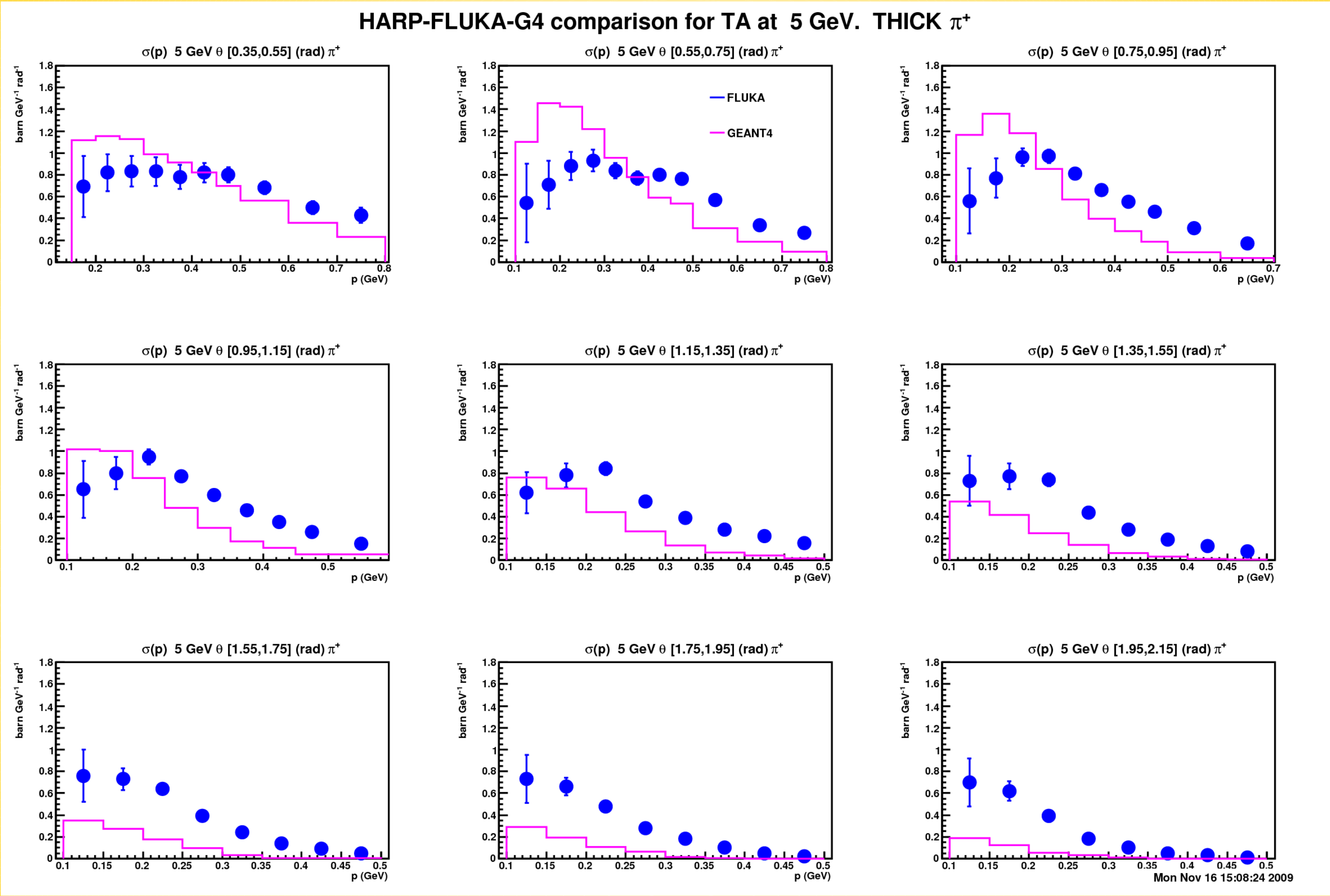


The correction factors pattern for large angle bins is similar to that found with the thick target dataset.

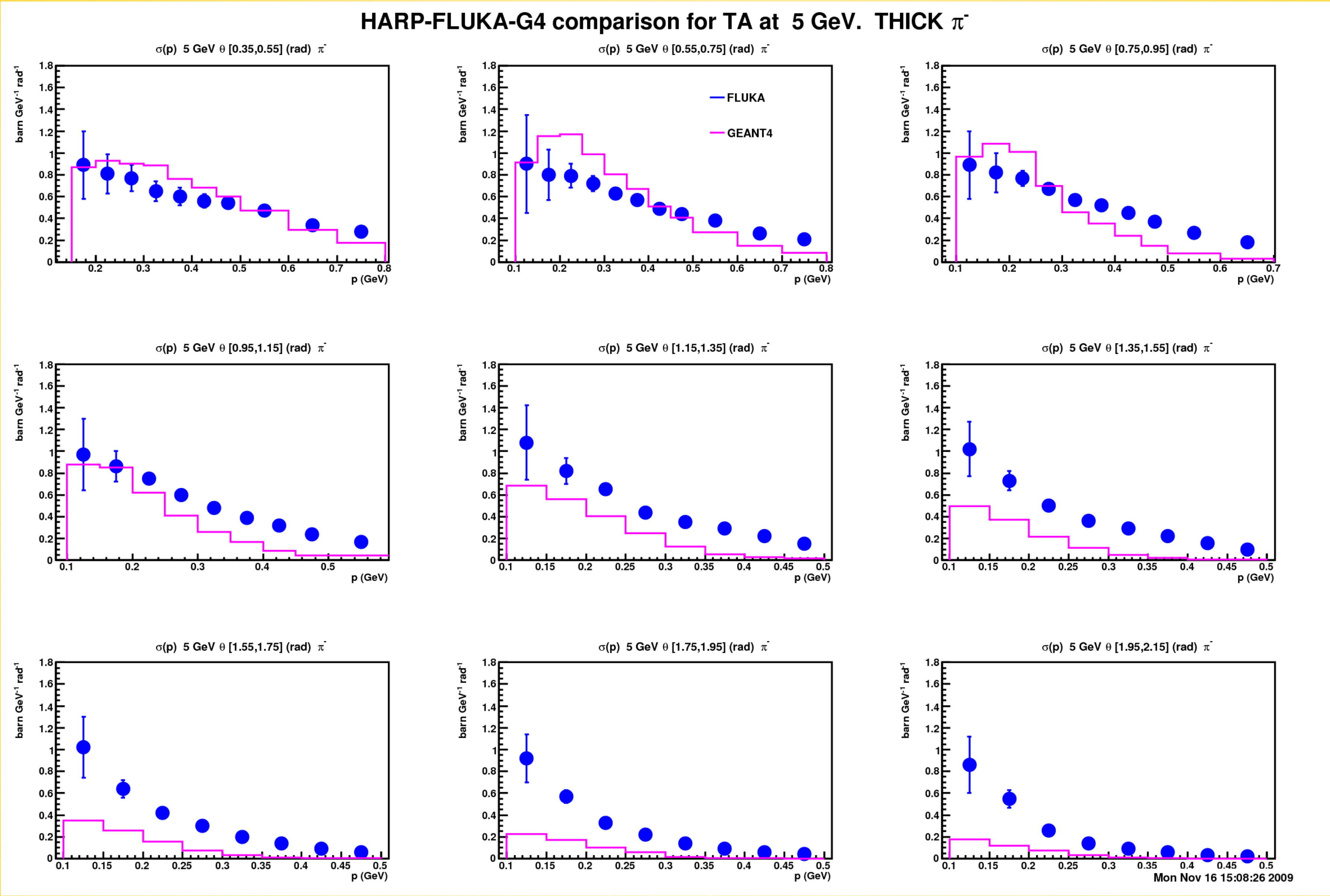
Re-weighting impact on fluxes (GEANT4)
THICK target + THIN target



HARP-GEANT4. Small angle. THICK target. Ta. 5 GeV. pi+



HARP-GEANT4. Large angle. THICK target. Ta. 5 GeV. pi-



Syst. on primary pion production: summary

- NB. “fresh”, preliminary results

- GEANT4 predicts similar fluxes but shifted to lower energies w.r.t. to FLUKA

- GEANT4 not too bad in reproducing the HARP data for Carbon and Tantalum

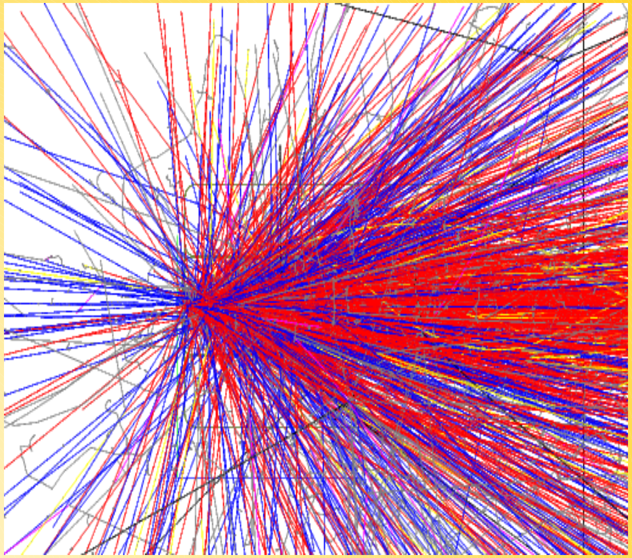
- pions distribution re-weighting does not alter the neutrino fluxes significantly

- FLUKA comparison available (also independent analysis by Christoph)

- need to stick to FLUKA policy for comparison with data before presenting (not present even in HARP articles)

- First impression is that GEANT4 looks better

Conclusions



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)

NC π^0 with new spectrum not a major issue, better treatment planned

Some room for improvement moving the target upstream. To be studied further. More systematic search for horn configurations also possible.

Use of HARP data to constrain uncertainty on fluxes on its way

Outlook

More HARP related studies

a few remarks received at GDR neutrino (french meeting) in the pipeline:

- **Take into account $\pi^+ \sim> e^+ \nu_e$ + c.c.. A relevant contribution ?**
- **Split flux from pions from the target or from the infra-structure**
- **use "Virtual Monte Carlo" ? (common interface to FLUKA, GEANT4, GEANT3)**

Event rates

File Edit View Go Help
Previous Next 4 of 32 175% Presentation Zoom In Zoom Out

	βB		SPL		T2HK	
	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$
appearance ν						
background	143		622		898	
$\sin^2 2\theta_{13} = 0$	28		51		83	
$\sin^2 2\theta_{13} = 10^{-3}$	76	88	105	14	178	17
$\sin^2 2\theta_{13} = 10^{-2}$	326	365	423	137	746	238
appearance $\bar{\nu}$						
background	157		640		1510	
$\sin^2 2\theta_{13} = 0$	31		57		93	
$\sin^2 2\theta_{13} = 10^{-3}$	83	12	102	146	192	269
$\sin^2 2\theta_{13} = 10^{-2}$	351	126	376	516	762	1007
disapp. ν	100315		21653		24949	
background	6		1		444	
disapp. $\bar{\nu}$	84125		18321		34650	
background	5		1		725	

Table 2: Number of events for appearance and disappearance signals and backgrounds for the βB, SPL, and T2HK experiments as defined in Tab. 1. For the appearance signals the event numbers are given for several values of $\sin^2 2\theta_{13}$ and $\delta_{CP} = 0$ and $\pi/2$. The background as well as the disappearance event numbers correspond to $\theta_{13} = 0$. For the other oscillation parameters the values of Eq. (1) are used.

New vs old focusing: fluxes + tot. event rates

2y ν + 8y anti-ν
MEMPHYS 440 kton

	+ focusing	- focusing
ν_μ (%)	88.9 $\rightarrow$ **95.6**	26.1 $\rightarrow$ **11.2**
$\bar{\nu}_\mu$ (%)	10.5 $\rightarrow$ **3.9**	73.4 $\rightarrow$ **88.4**
ν_e (%)	0.60 $\rightarrow$ **0.56**	0.17 $\rightarrow$ **0.09**
$\bar{\nu}_e$ (%)	0.052 $\rightarrow$ **0.025**	0.340 $\rightarrow$ **0.352**

Table 1. Standard horn $\rightarrow$ **test horn.**

	standard focusing	
	$\delta_{CP}=0$	$\delta_{CP}=\pi/2$
ν_e appearance		
background	623	
$\sin^2 2\theta_{13}=0$	54	
$\sin^2 2\theta_{13}=10^{-3}$	106	14
$\sin^2 2\theta_{13}=10^{-2}$	431	140
ν_e disappearance		
background	643	
$\sin^2 2\theta_{13}=0$	60	
$\sin^2 2\theta_{13}=10^{-3}$	104	153
$\sin^2 2\theta_{13}=10^{-2}$	381	536

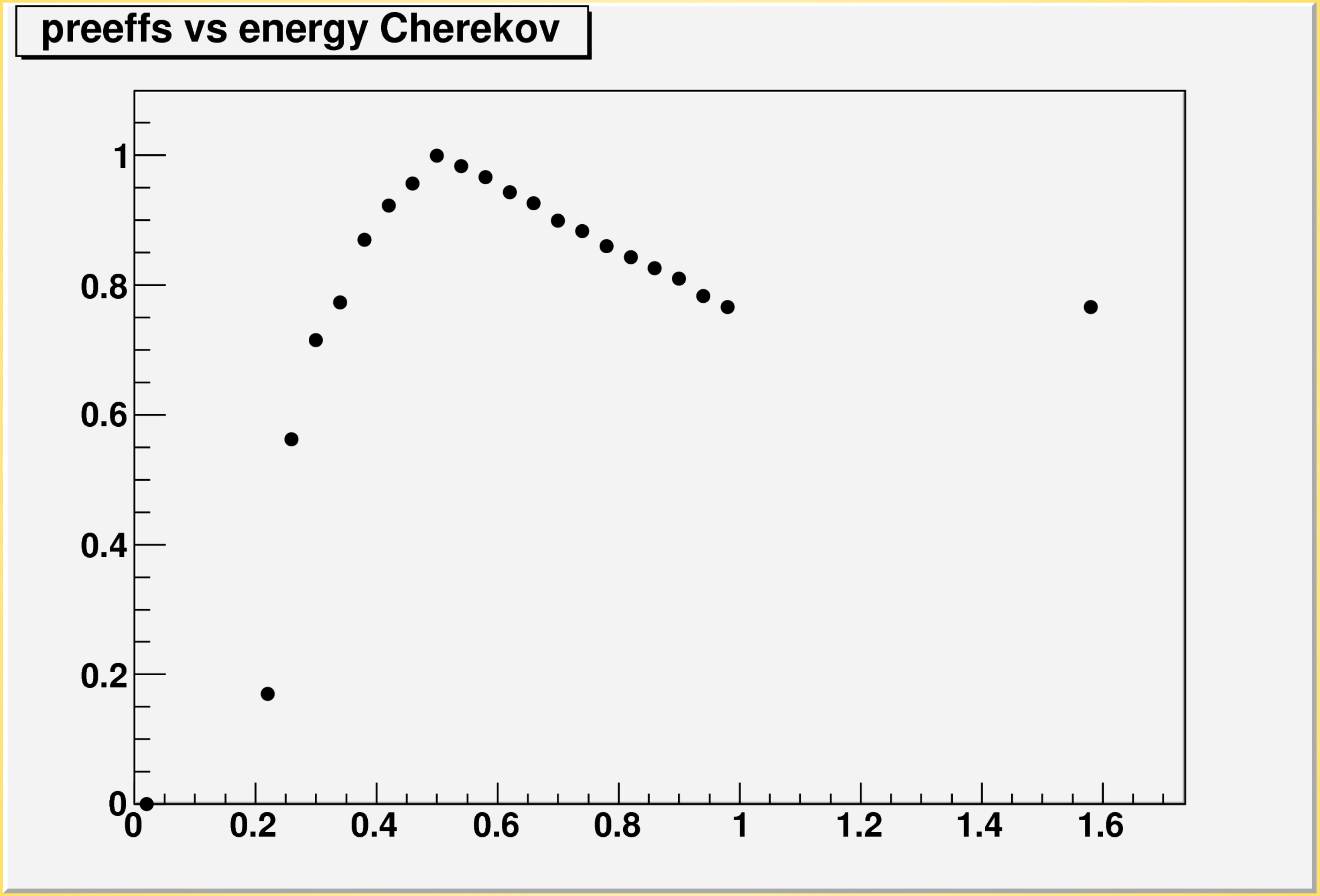
	new focusing	
	$\delta_{CP}=0$	$\delta_{CP}=\pi/2$
ν_e appearance		
background	1674	
$\sin^2 2\theta_{13}=0$	118	
$\sin^2 2\theta_{13}=10^{-3}$	286	46
$\sin^2 2\theta_{13}=10^{-2}$	1200	444
ν_e disappearance		
background	1753	
$\sin^2 2\theta_{13}=0$	88	
$\sin^2 2\theta_{13}=10^{-3}$	191	241
$\sin^2 2\theta_{13}=10^{-2}$	758	916

In good agreement with values in hep-ph 0603172

Both B and S increase (main background (nue from mu decays) ~ 100% correlated with numu)

gain at the level of S/sqrt(B)

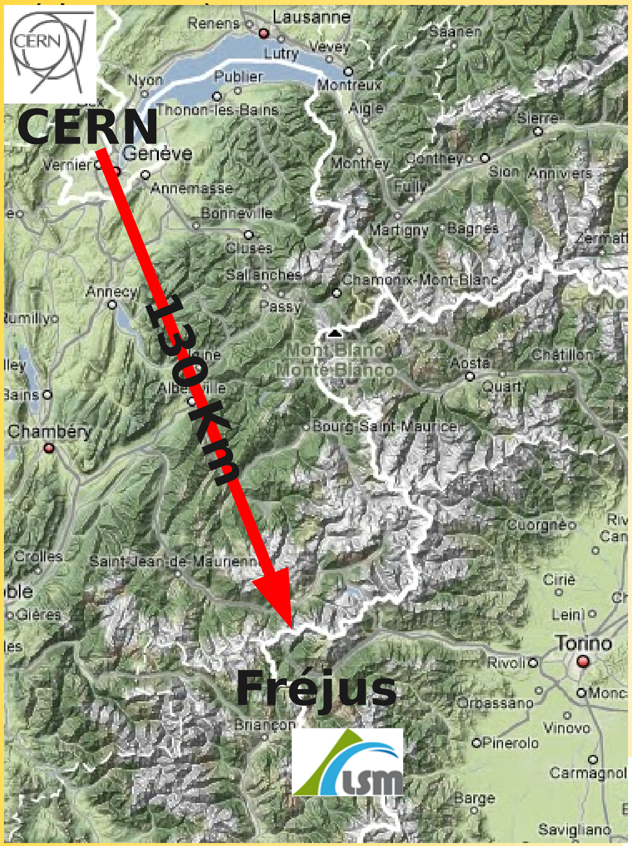
GLOBES efficiencies



Backup slides

The SPL-Fréjus Super Beam

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



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

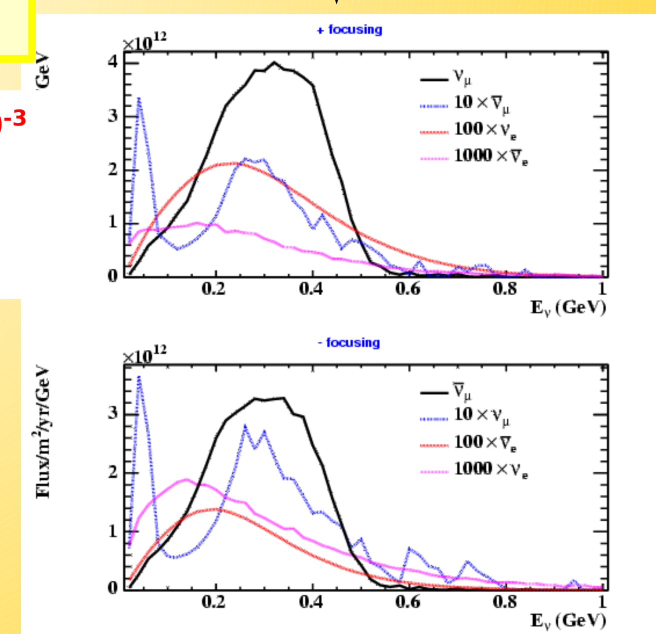
low E

- **:) 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

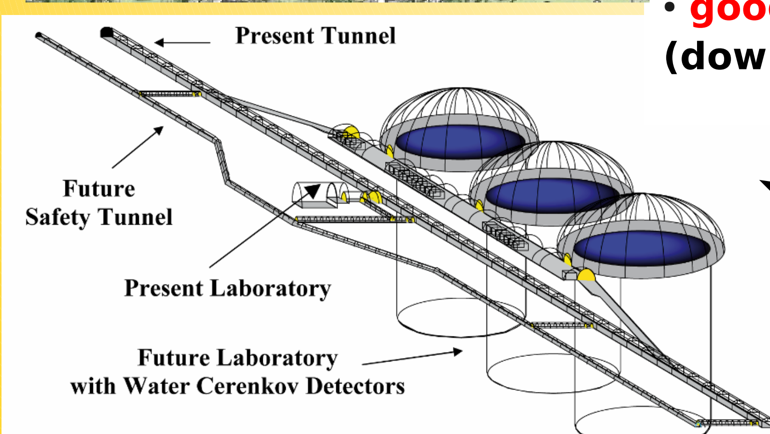
- **:) High flux**
- **:) No matter effects : (**
- **: (mass hierarchy**

"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})



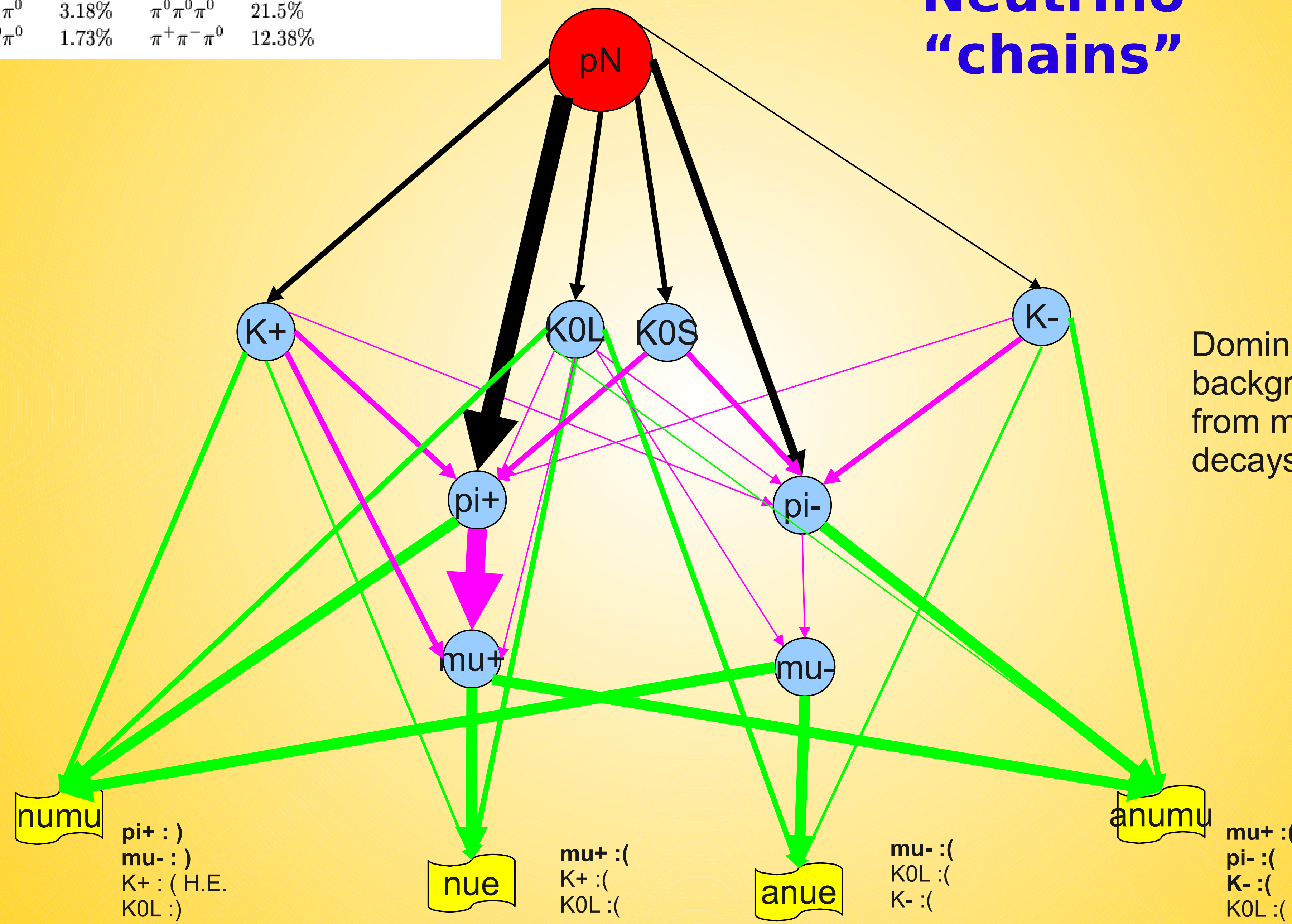
MEMPHYS

multi purpose

p decay, atm-ν, SN-ν, ...

$K^{\pm}$		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%		

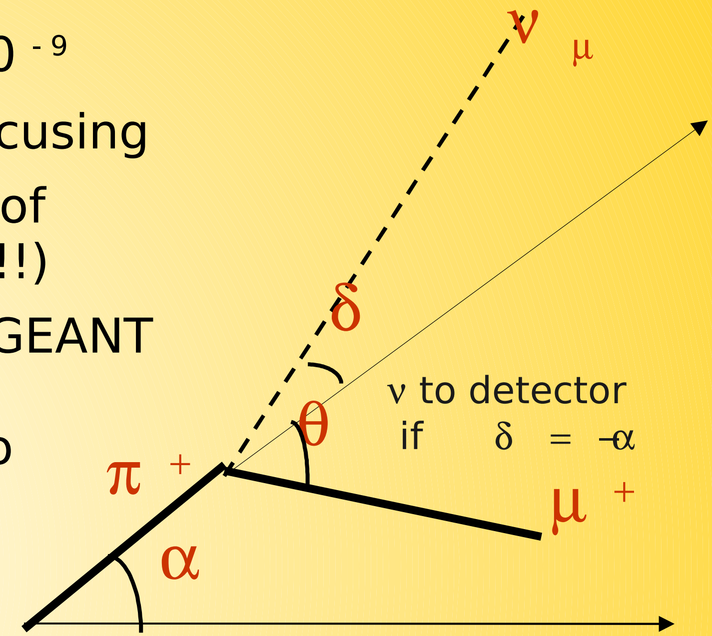
Neutrino “chains”



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

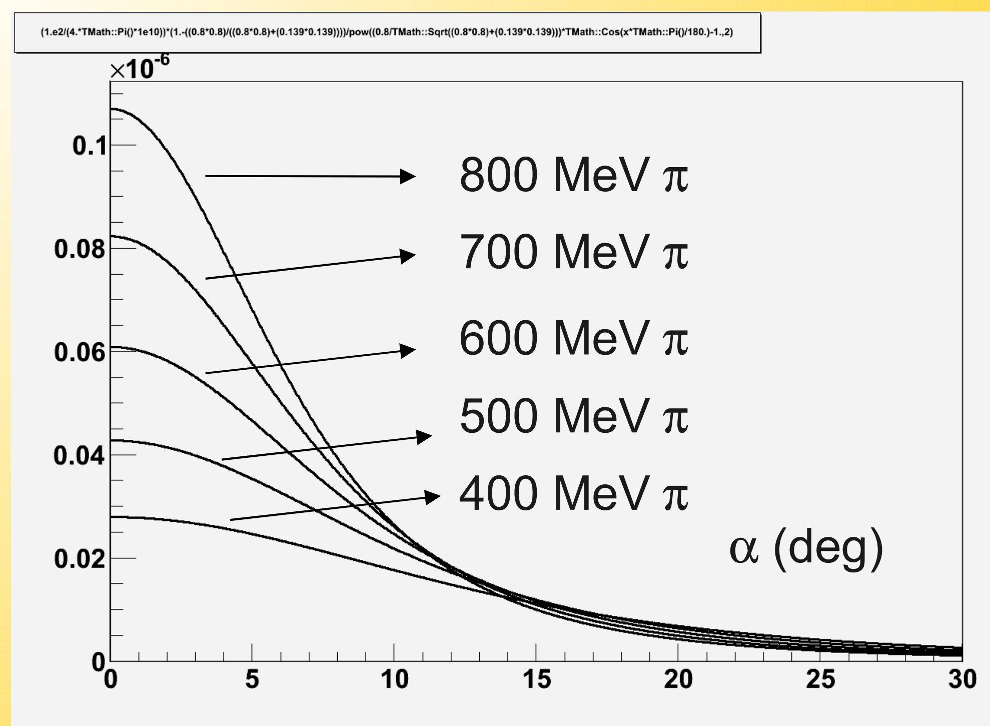
$\pi^+ \rightarrow \mu^+ \nu_\mu$

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

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

A. Longhin

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

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

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	$12x^2(1-x)$	$12x^2(1-x)$

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

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

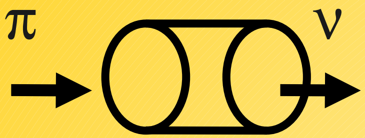
Π is the muon polarisation

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)

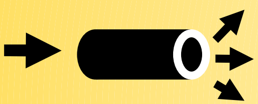


Decay tunnel

- 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

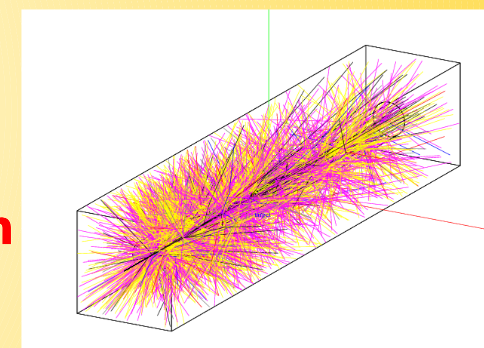
Decay lengths (m) @ 600 MeV

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

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

new

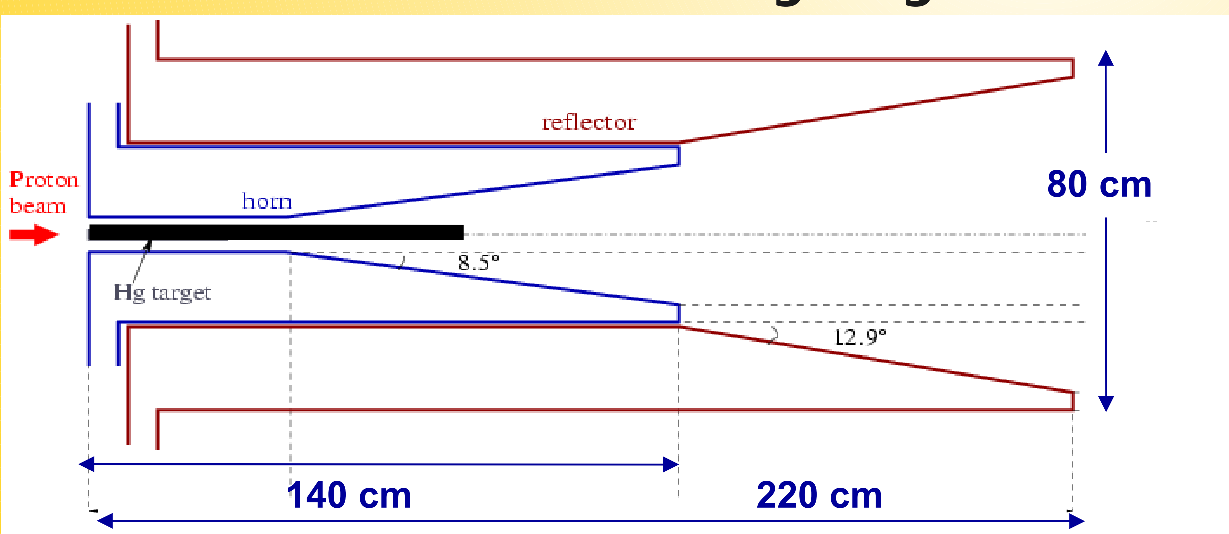
ν fluxes: probabilistic approach. Each decay is weighted with the probability of the ν to reach the far detector. Event duplication + weighting for μ and K decays.

A graphite target: motivations

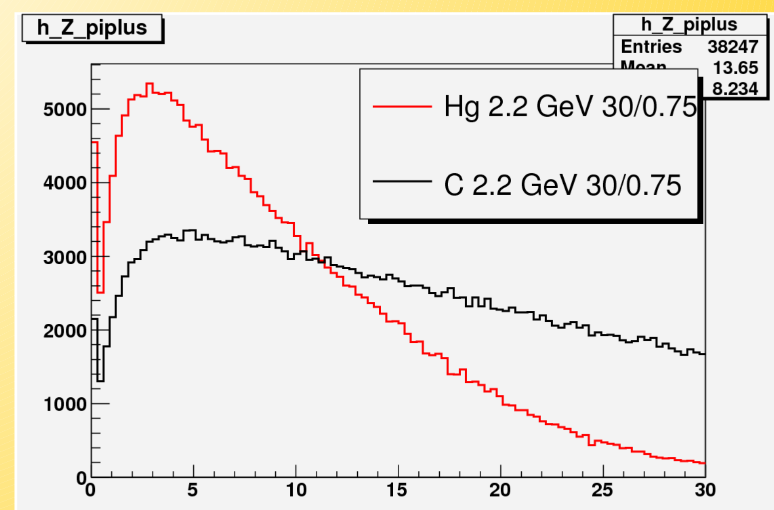
- **Integration of the Hg jet within the horn not addressed**
- **Hg-Al chemical incompatibility**
- **No magnetic field for a standard magnetic horn to mitigate the explosion of the mercury jet (MERIT) as in the case of superconducting solenoids used for the neutrino factory design (no charge discrimination, 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

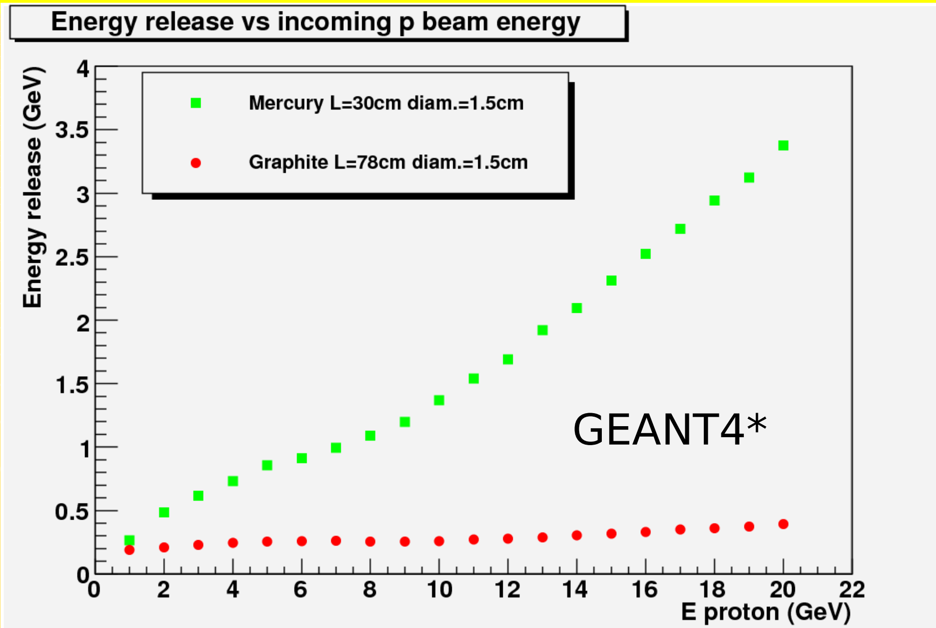


Z of pi+ exiting the target

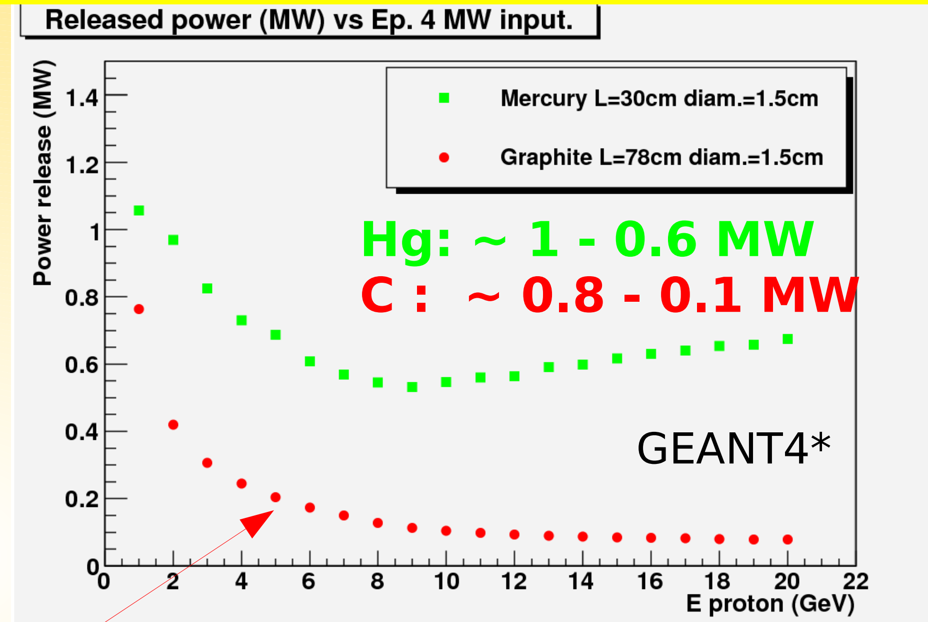


C vs Hg: energy deposition in the target

Mean energy deposition vs Ek(p)



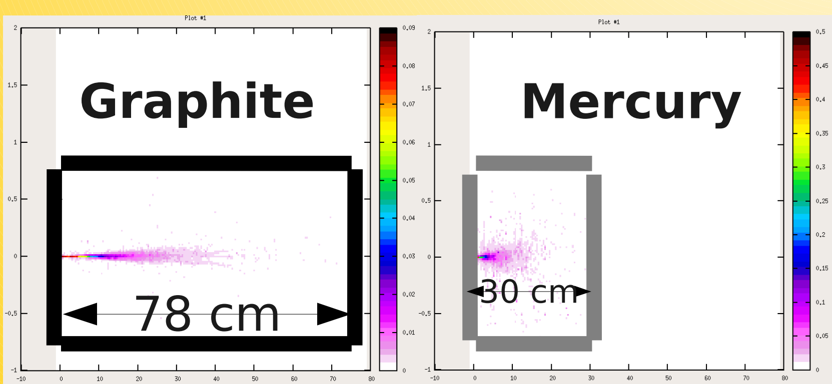
Power release: 4 MW * $<E_{dep}>/E_k(p)$



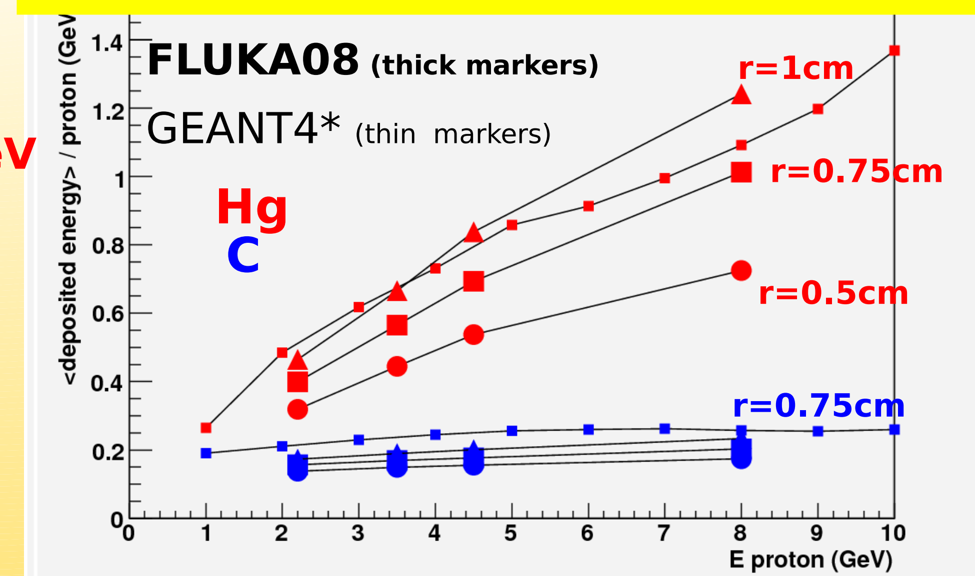
*with (hadronic “QGSP physics list”)

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

considerably lower for C! ~ 200 kW @ 5GeV



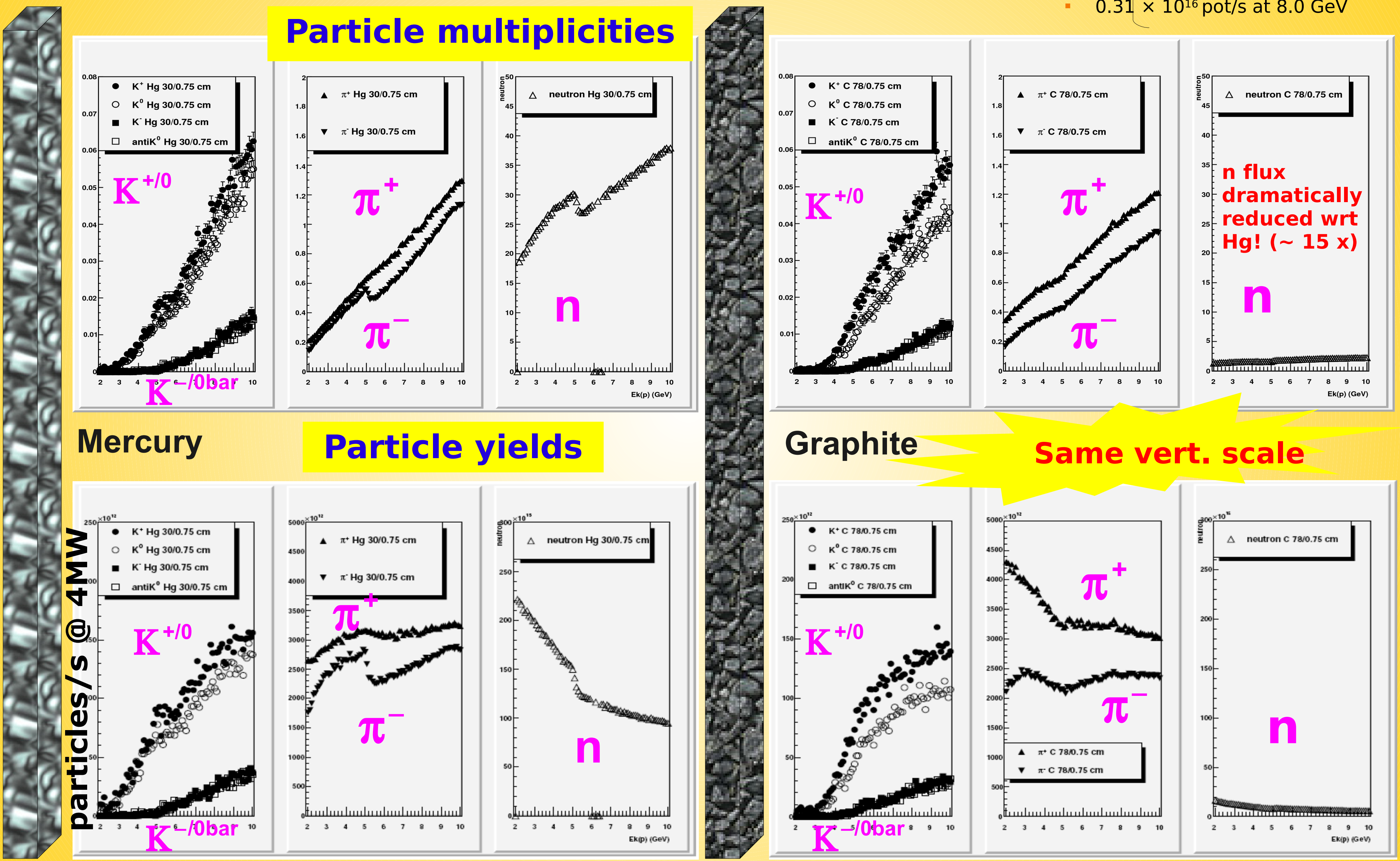
Mean energy deposition vs Ek(p)



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



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

C vs Hg: ν fluxes

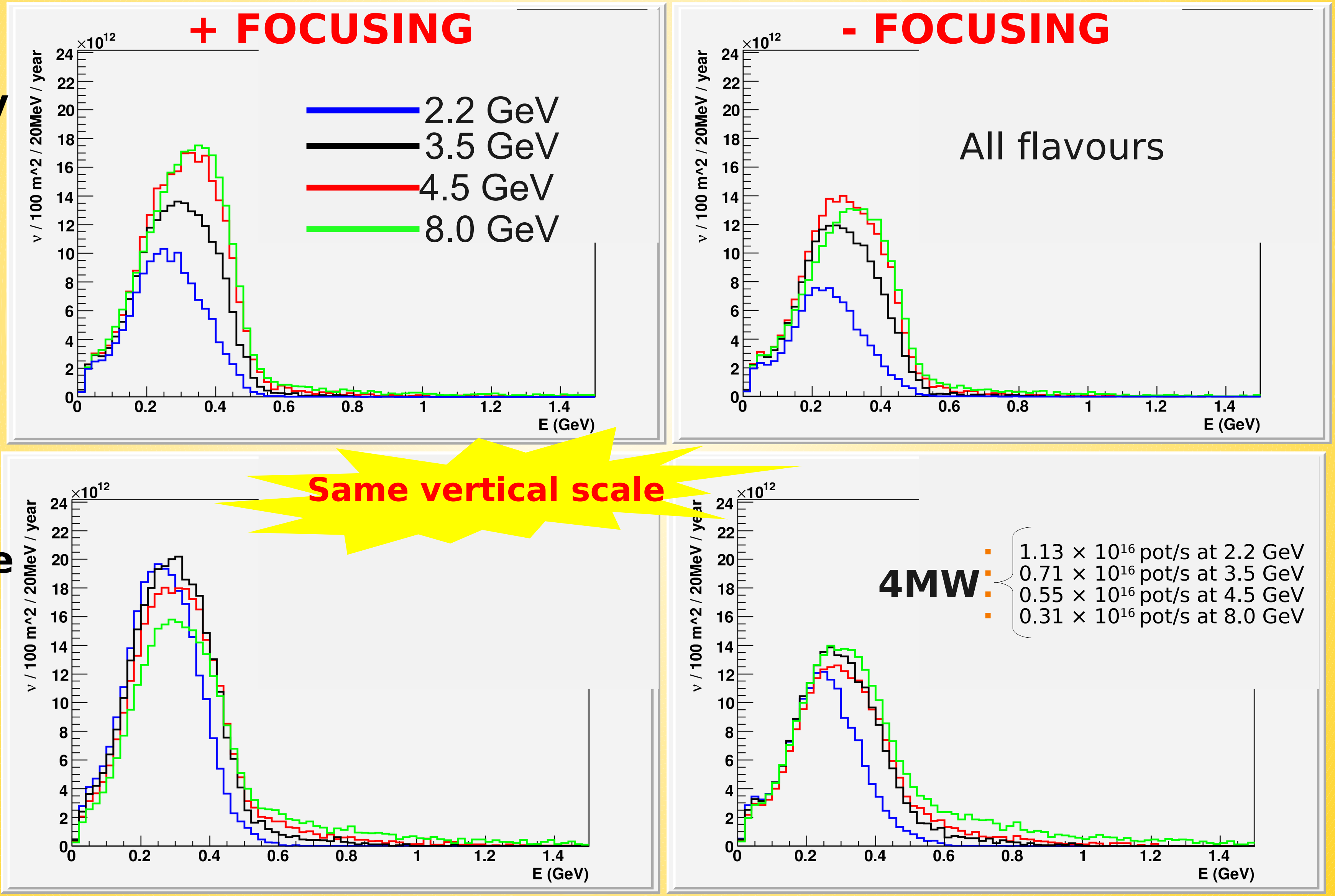
Minimal change approach

- 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

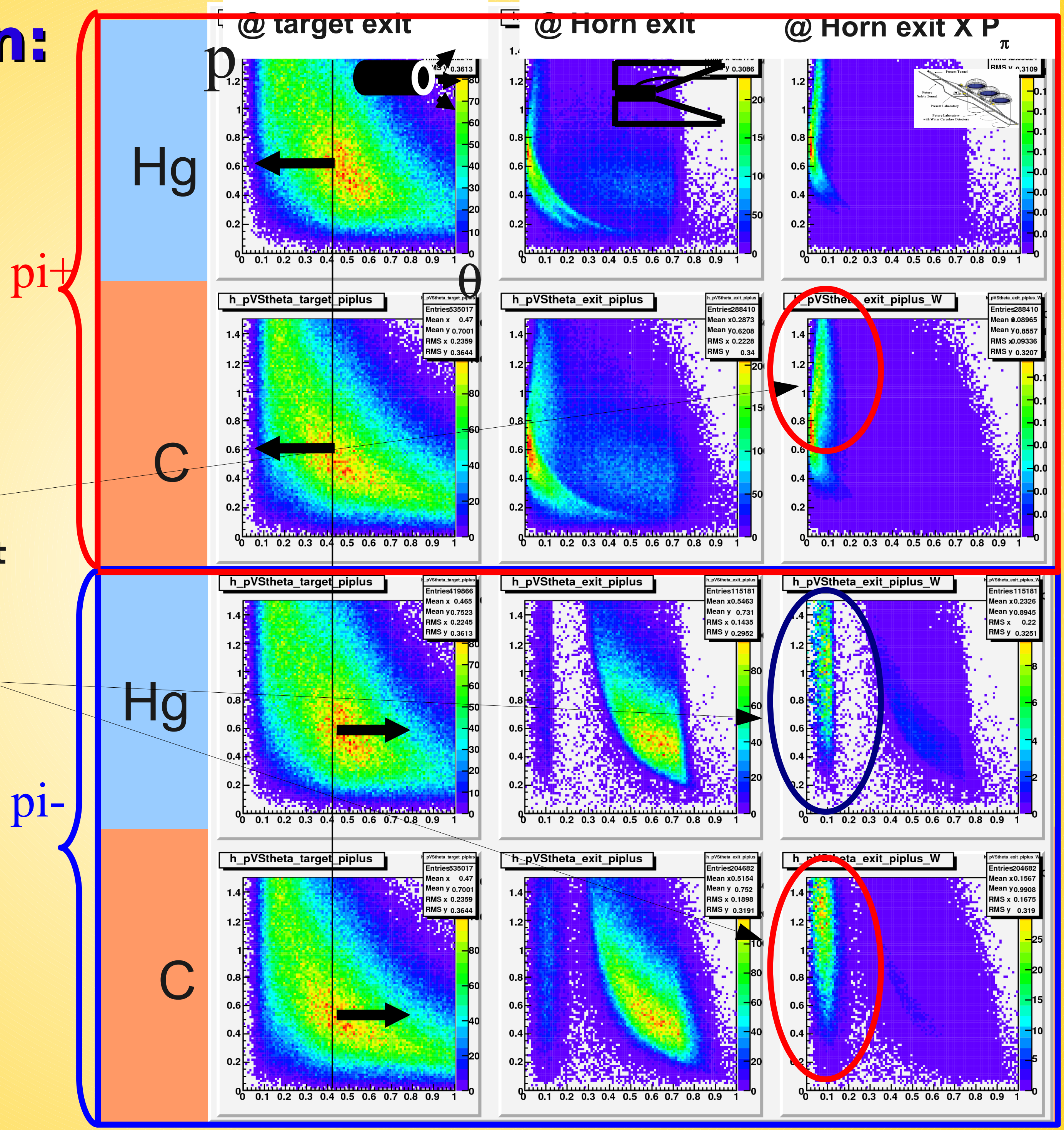
Mercury

Graphite



Pion collection: Hg-C

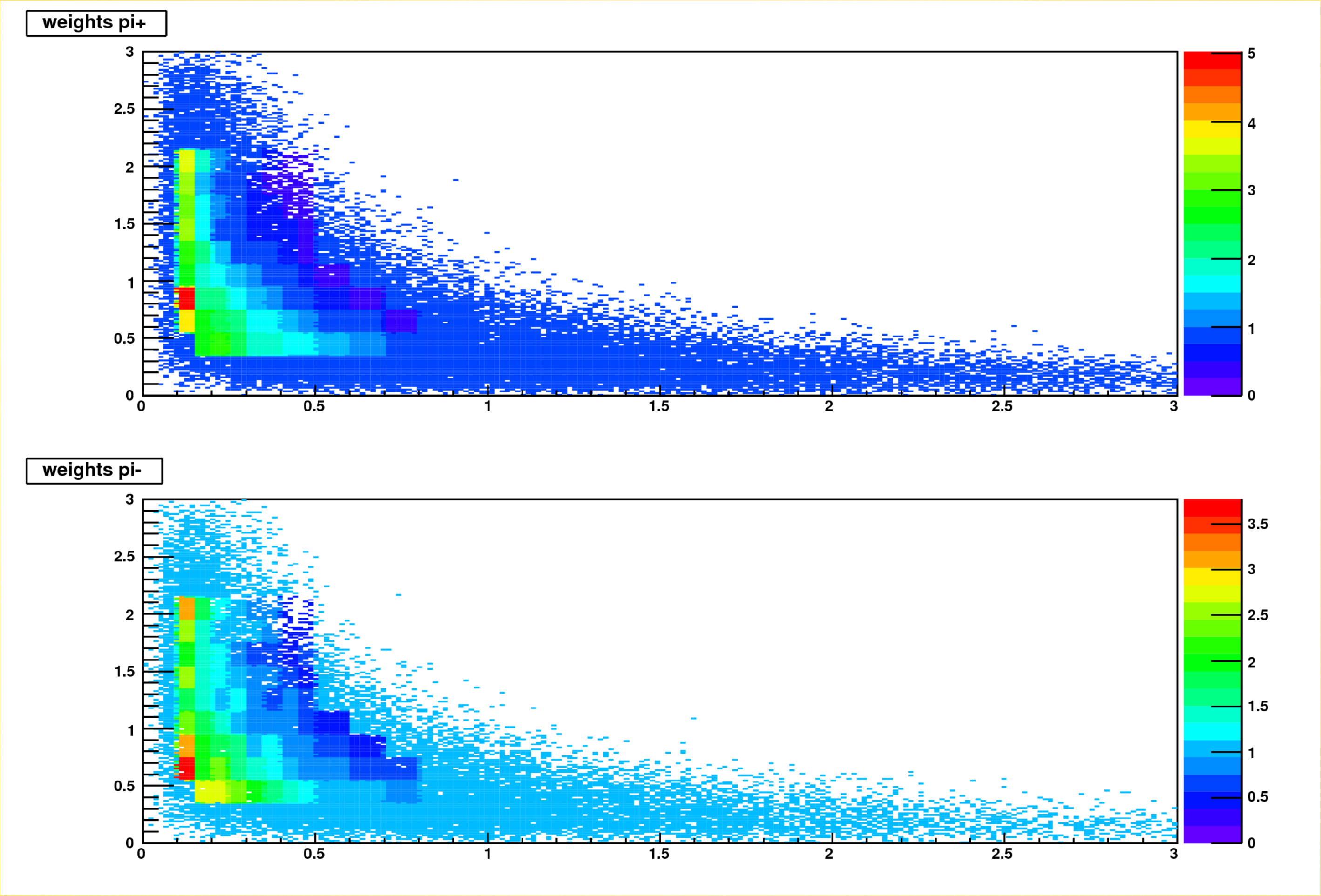
- p vs θ plots
- Positive focusing (negative defocusing)
- Carbon:
  - focused pi+ less “monochromatic” (tail at high momentum)
  - larger fraction of not defocused pi-
- 4.5 GeV



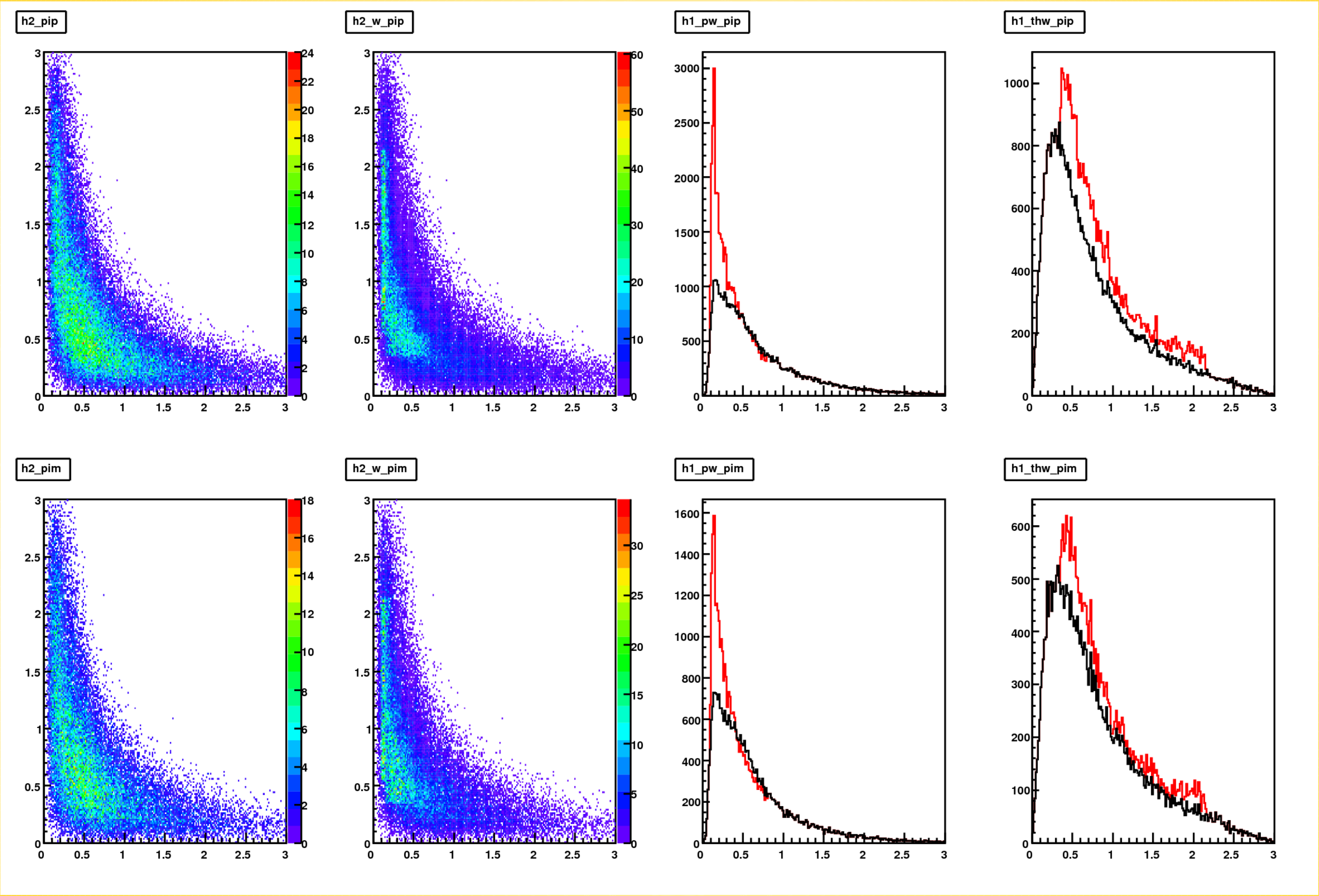
probability to reach the far detector

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

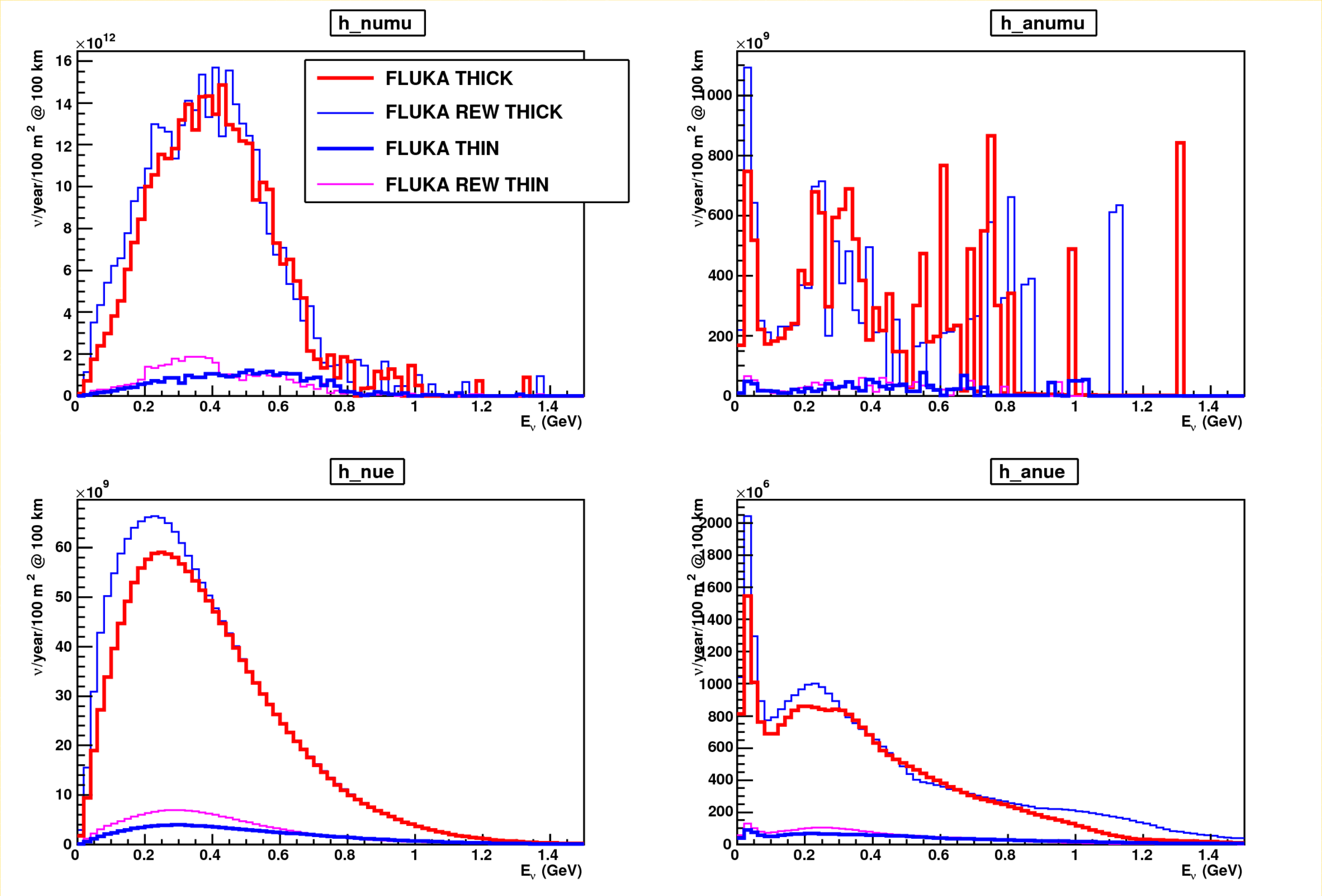
Weights (THICK target, C 5 GeV, HARP/FLUKA)



Reweighting (THICK target, C 5 GeV, HARP/FLUKA)

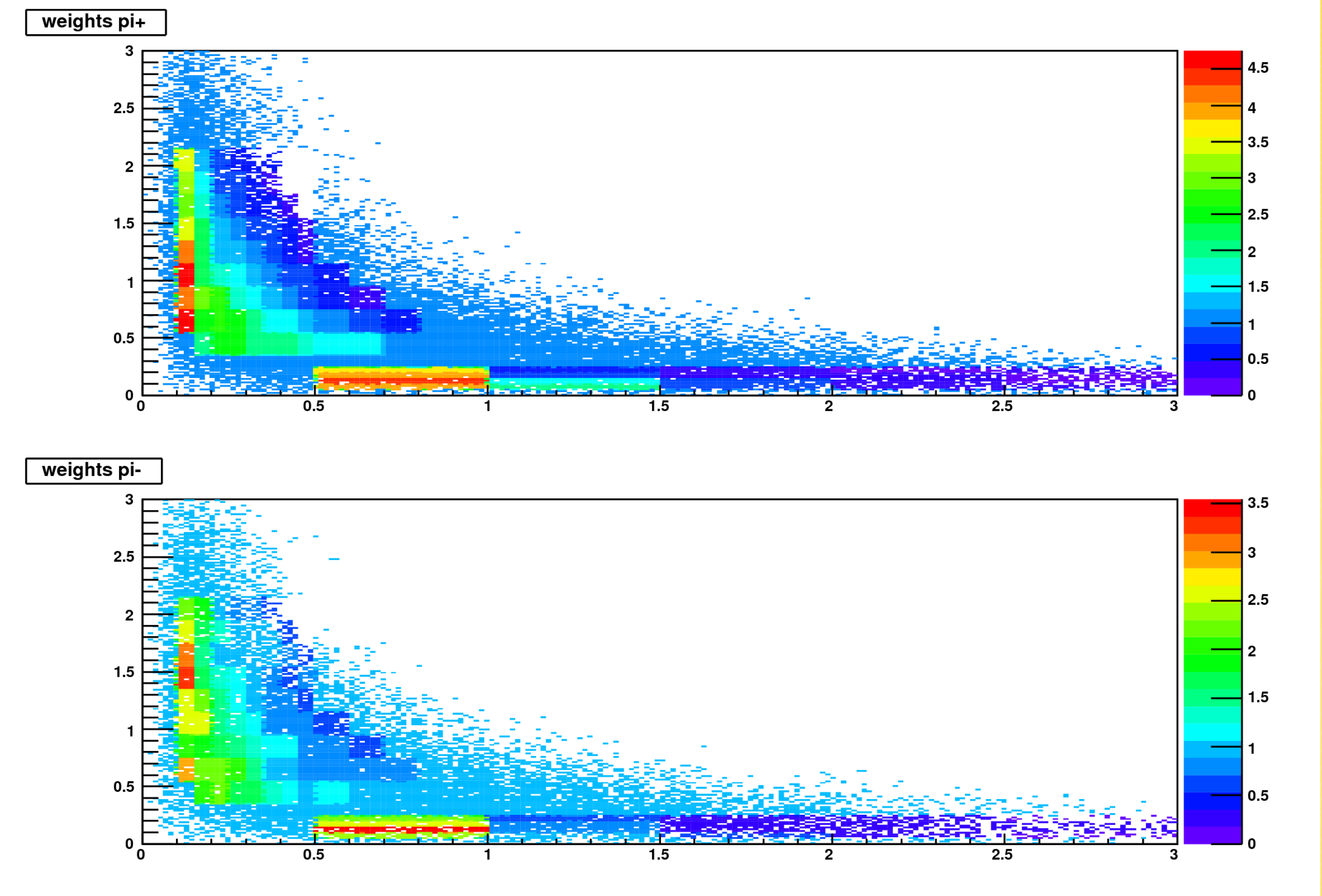


Re-weighting impact on fluxes (FLUKA)

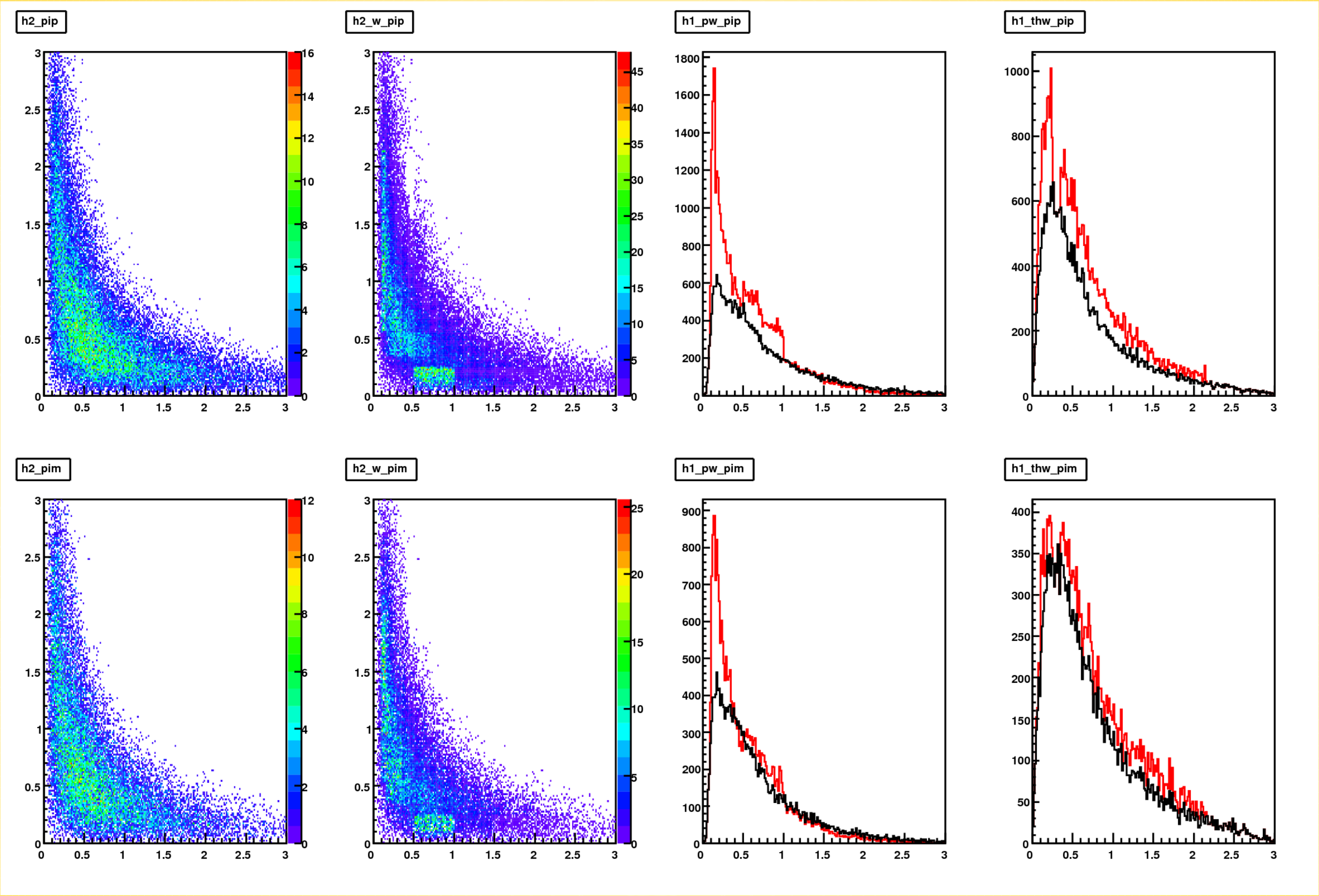


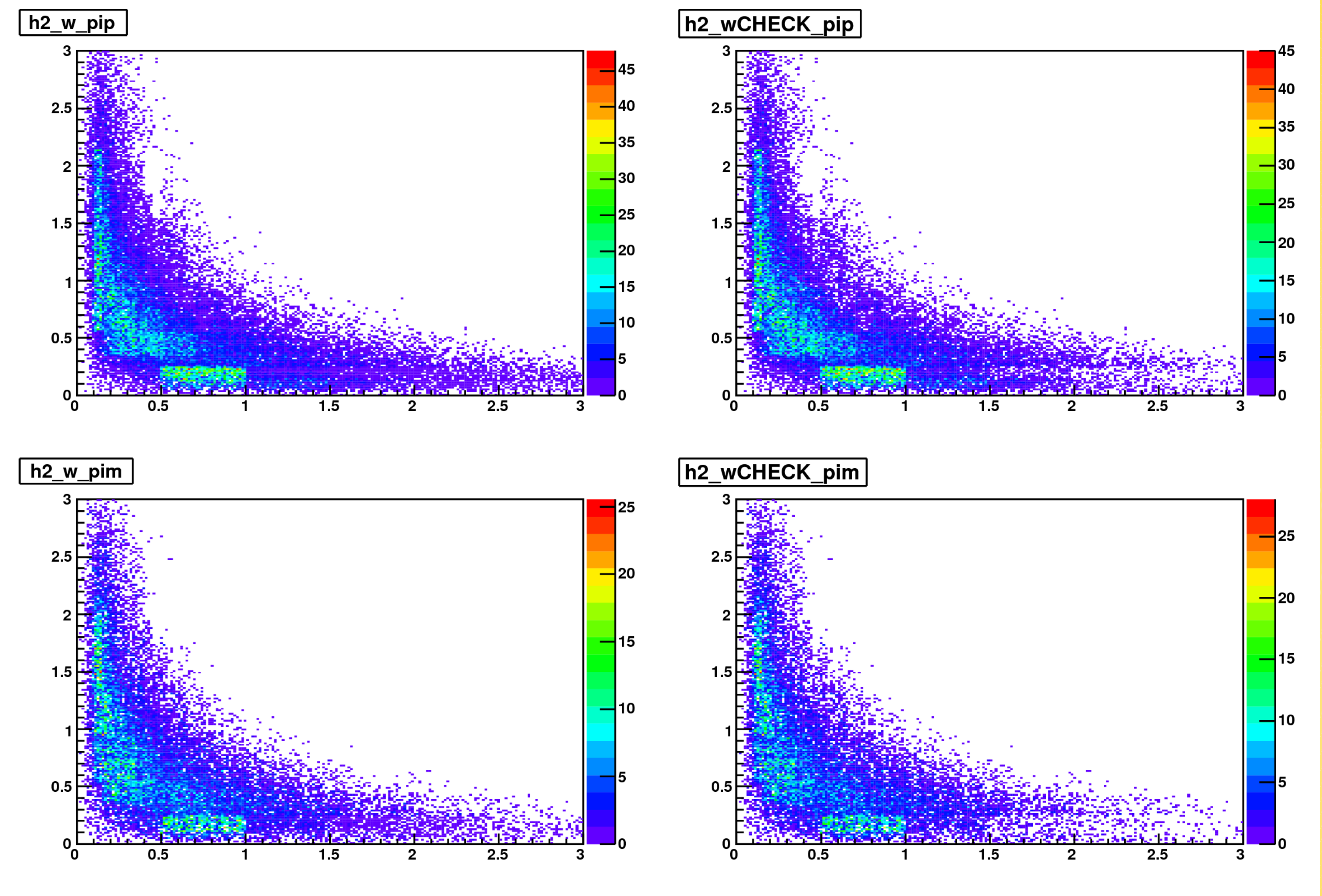
HARP-like C thick target simulated with FLUKA
THICK TARGET data reweighting
new focusing scheme

Weights (THIN target, C 5 GeV, HARP/FLUKA)



Systematics on primary pions




h2_w_pip
h2_wCHECK_pip
h2_w_pim
h2_wCHECK_pim

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**

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**

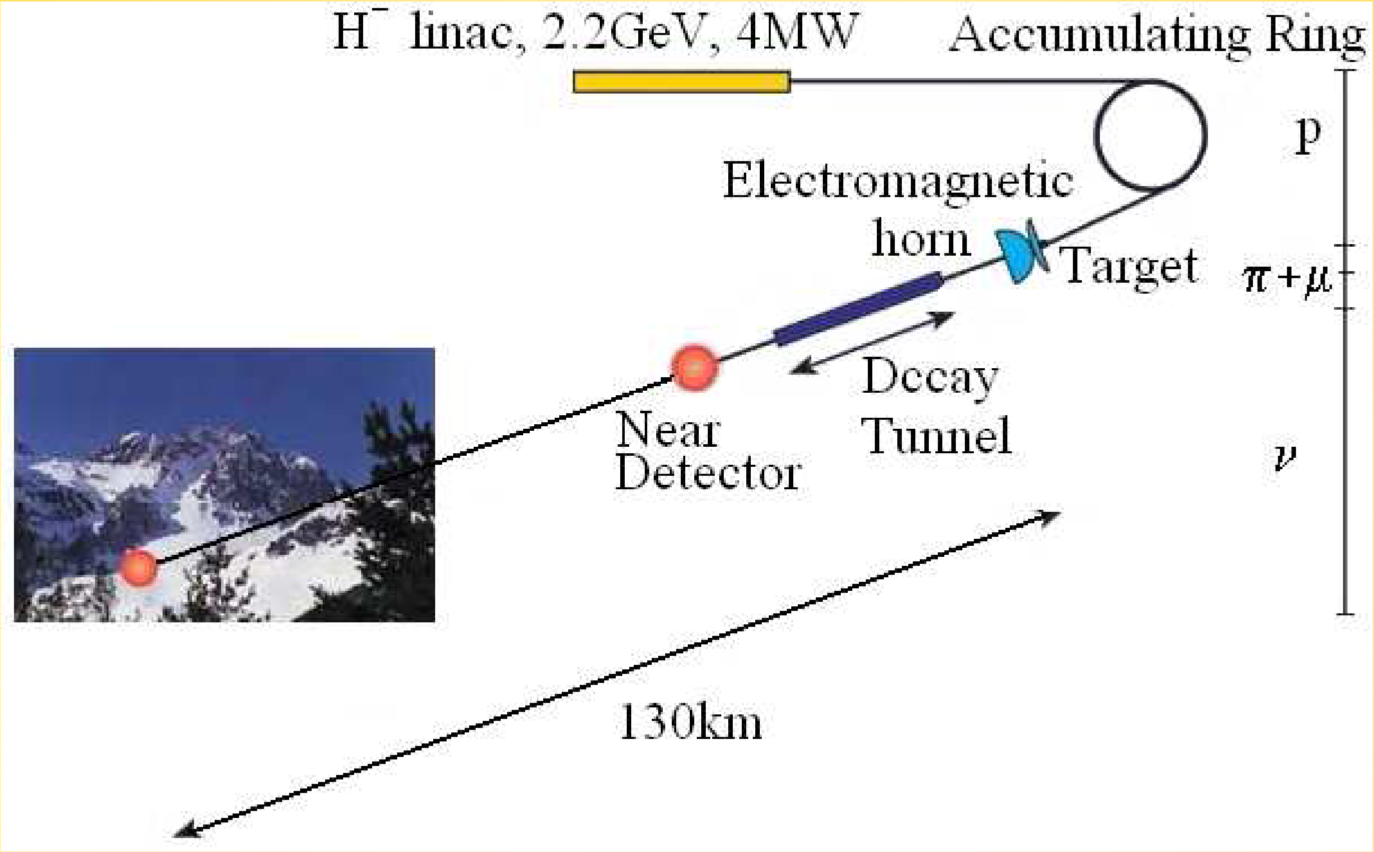
In addition, EUROnu will look at the performance of the baseline detectors for each facility and determine the physics reach of each. Although a European project, EUROnu will collaborate closely with related international activities, in particular the International Design Study for a Neutrino Factory,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



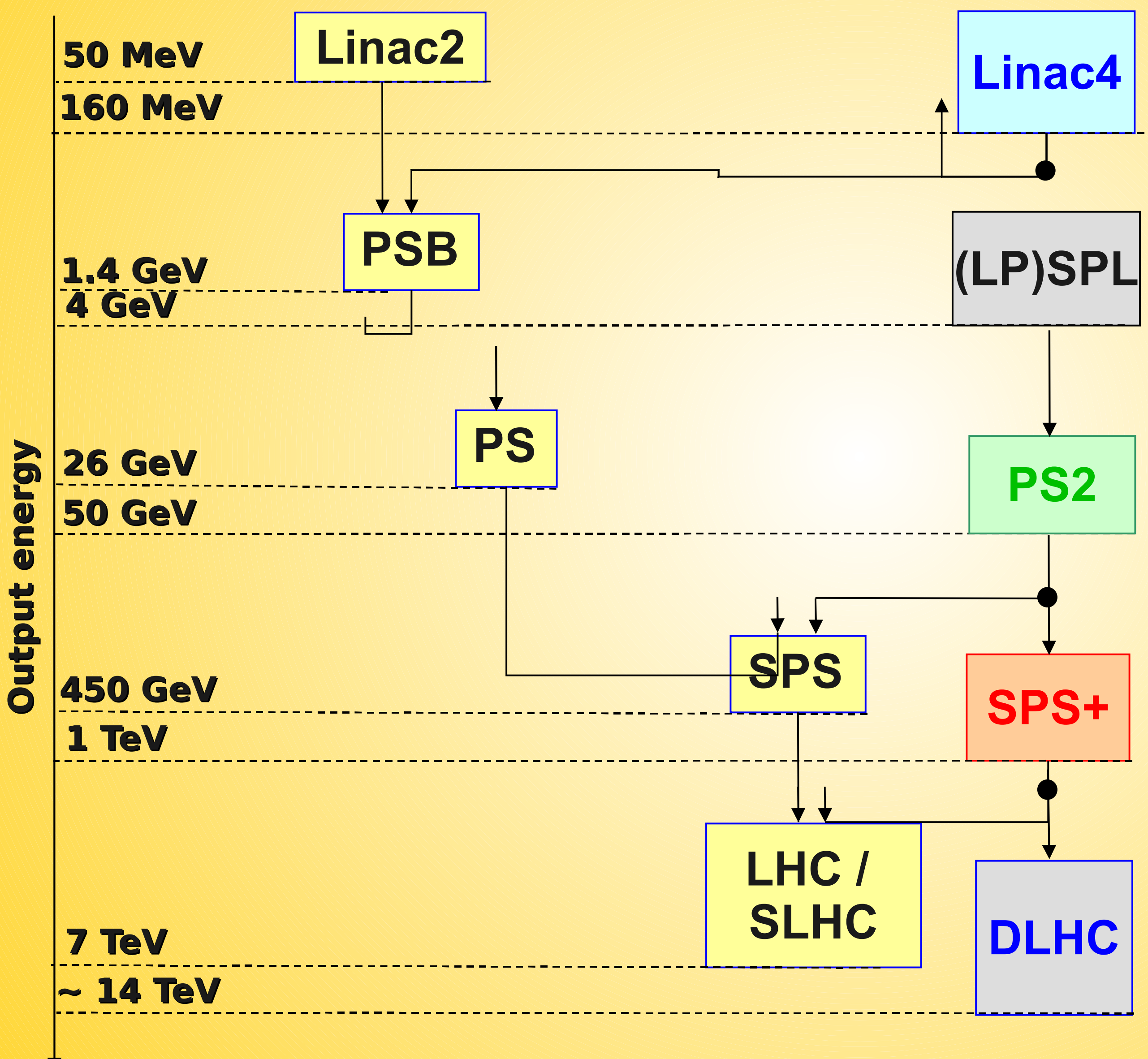
SPL (Superconducting Proton Linac) is already funded as part of the new injection chain for the LHC.

Far detector: a 440kton Cerenkov detector (MEMPHYS)

PLANS FOR FUTURE INJECTORS: Description

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} $cm^{-2}s^{-1}$)

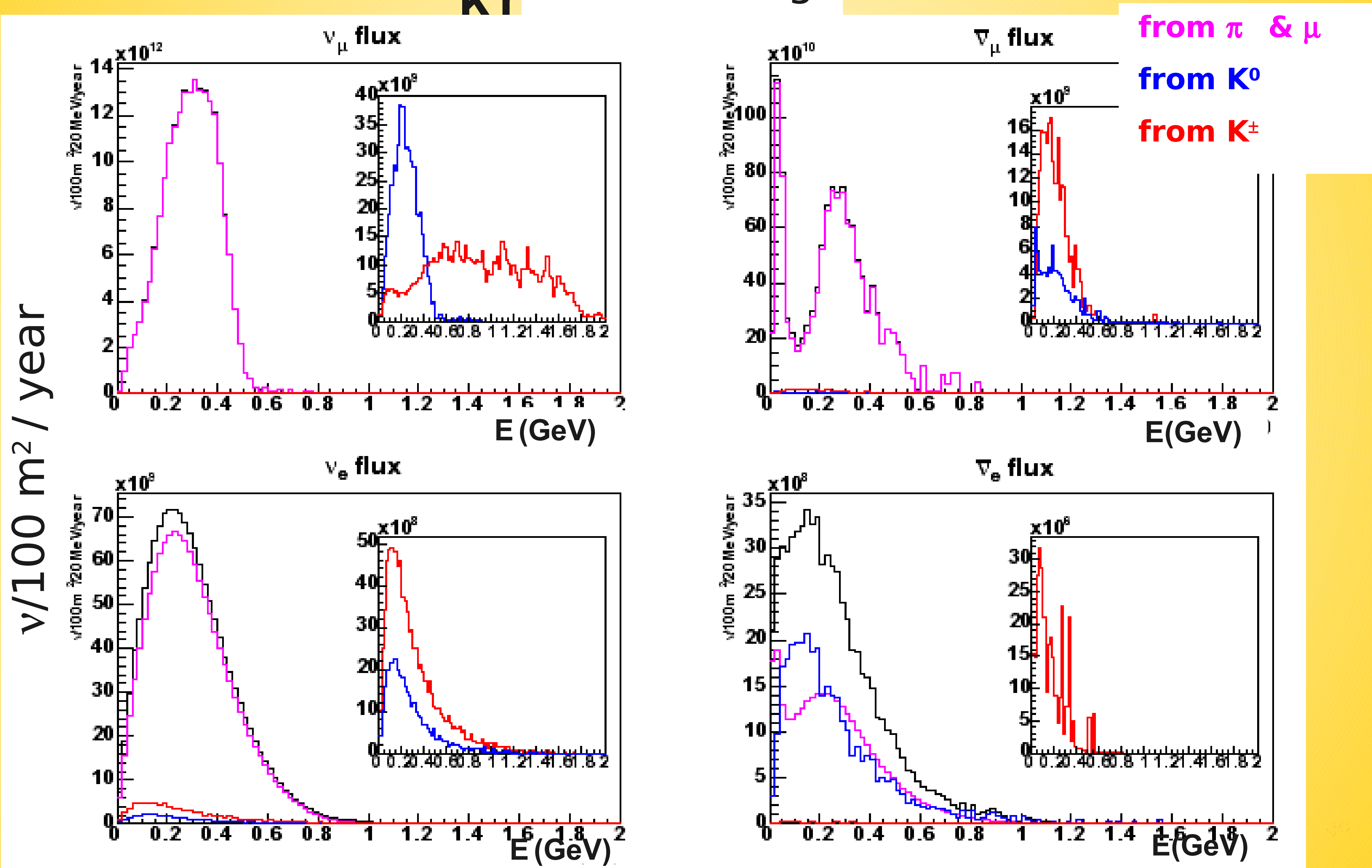
DLHC: "Double energy" LHC (1 to ~14 TeV)

Neutrino fluxes at 100 km

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

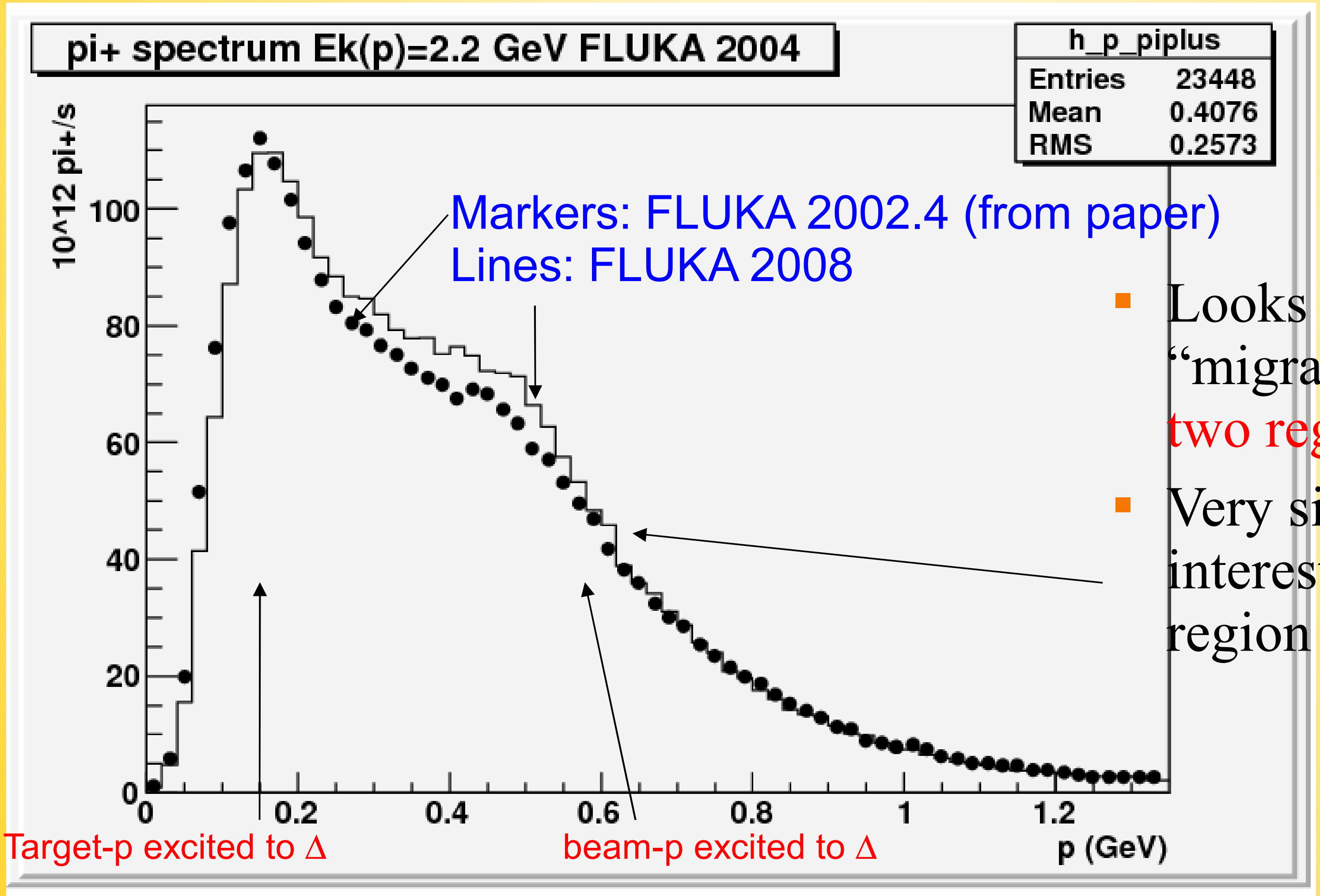
1 year := 10^7 s

π^+ focusing



FLUKA 2008 vs FLUKA 2002.4

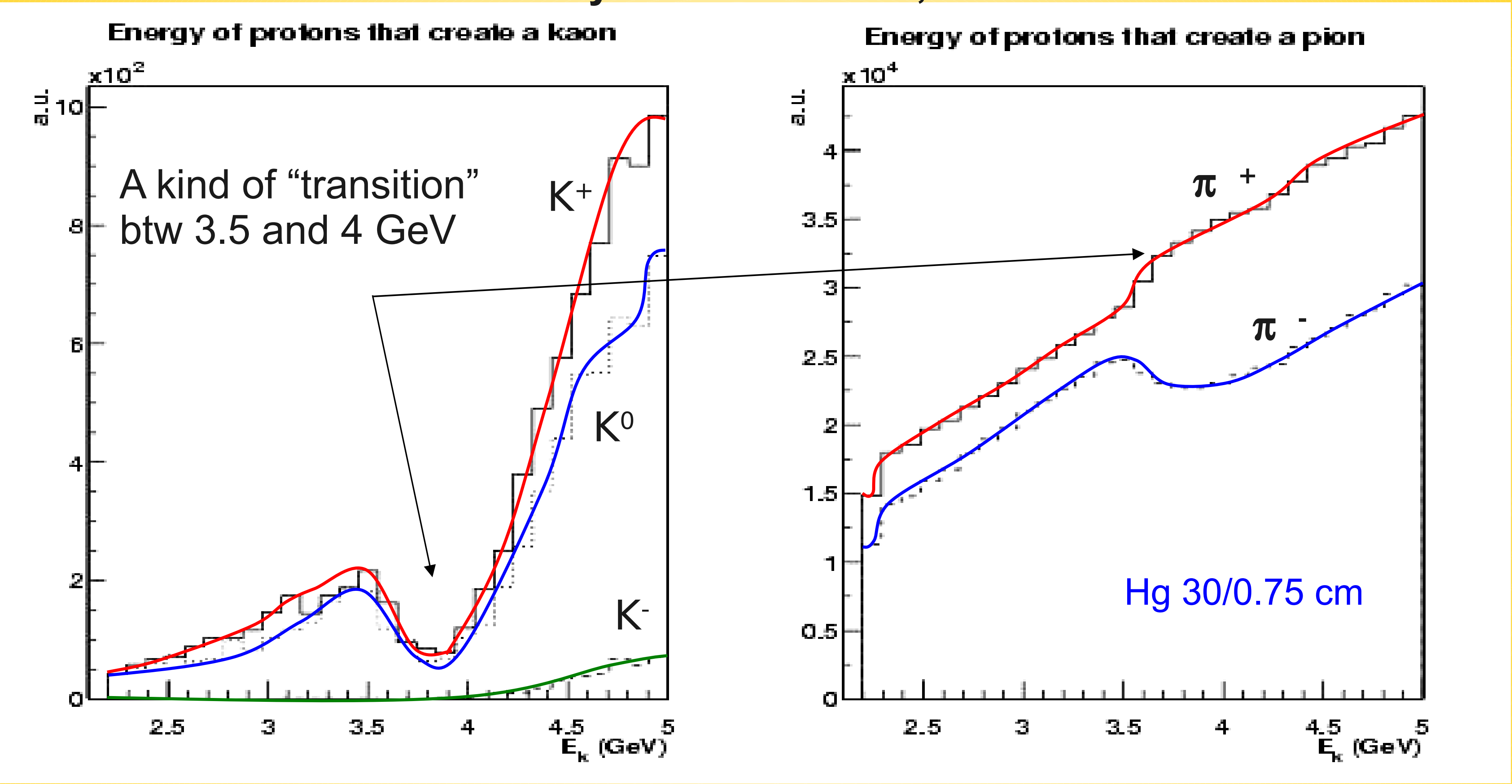
- Momentum spectrum of π^+ exiting the target
  - $E_k(p)$ = 2.2 GeV, Hg cylinder L = 30cm, r = 0.75 cm
  - Normalization + shape comparison



- 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

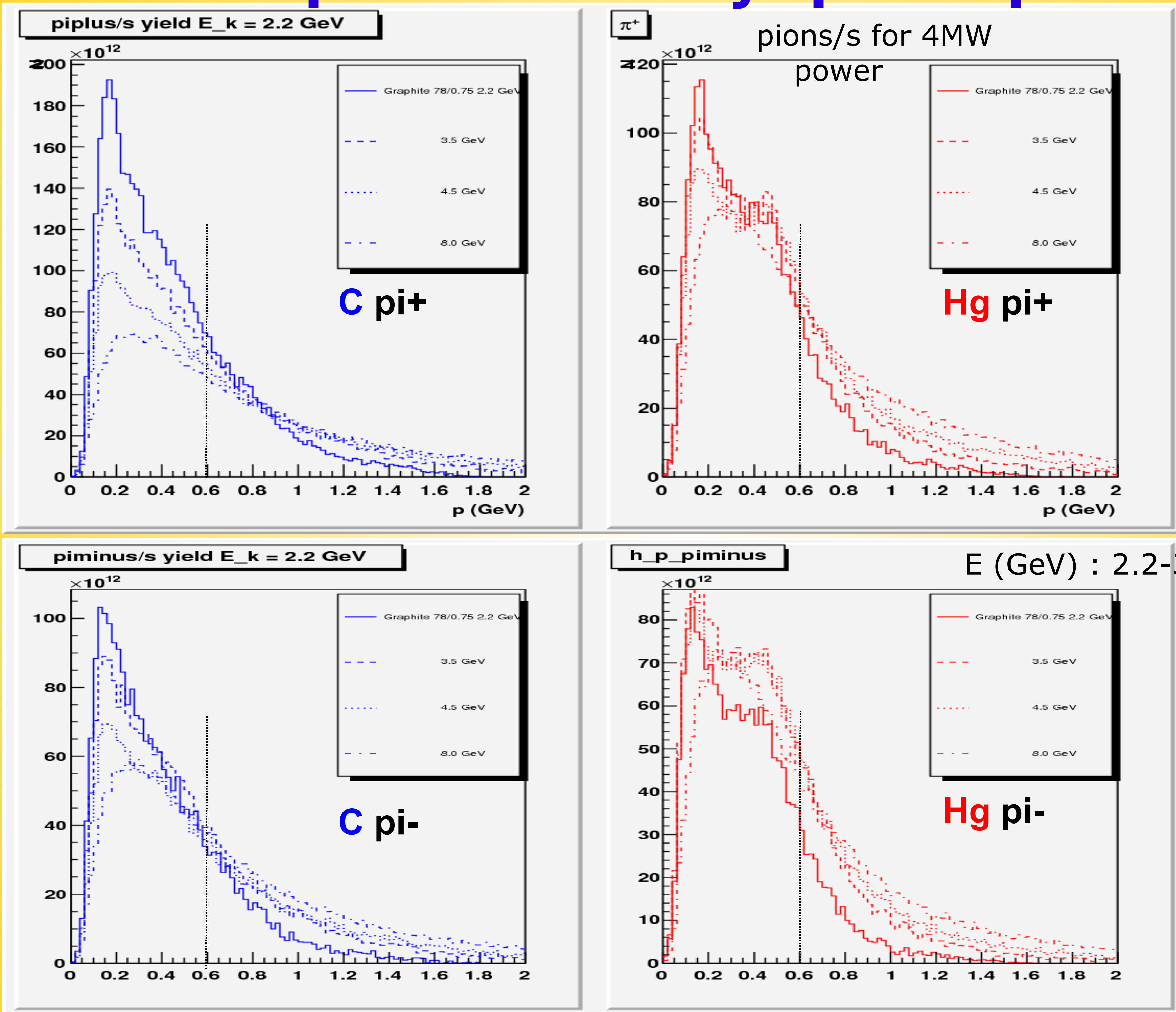
- GEANT4 (hadronic "QGSP physics list")

Hg
C

x-axis: 0-2 GeV

peak: ionization loss of elastic or not-interacting p

Graphite-Mercury: pion spectra



Effect of radius on pion multiplicities

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