Fluxes, horn optimization, sensitivities

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EUROnu annual meeting WP2 session

New GEANT4 simulation

SPL-Fréjus
- **parametric MiniBoone-like focusing**
  - **optimization for a long (solid target)**
- **putting 4 horns in parallel**
- **other solutions without reflector**
  - **comparison of sensitivities**
- **characterization of interesting π phase space**
- **HARP data reweighting**

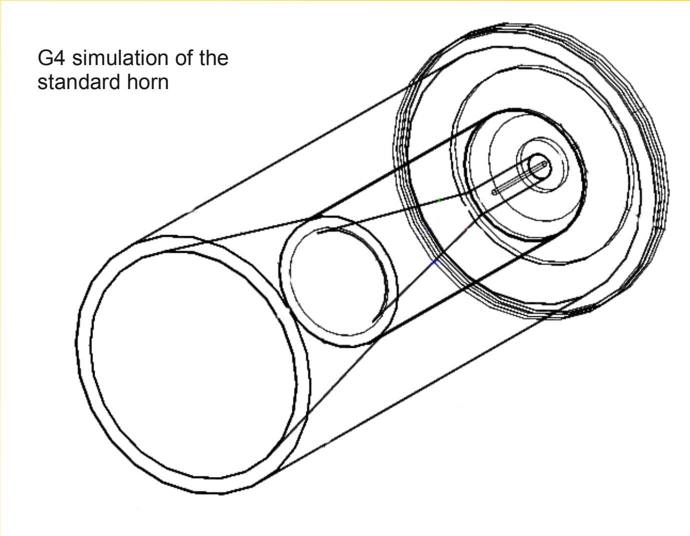
Studies using different baselines/energies (LAGUNA)

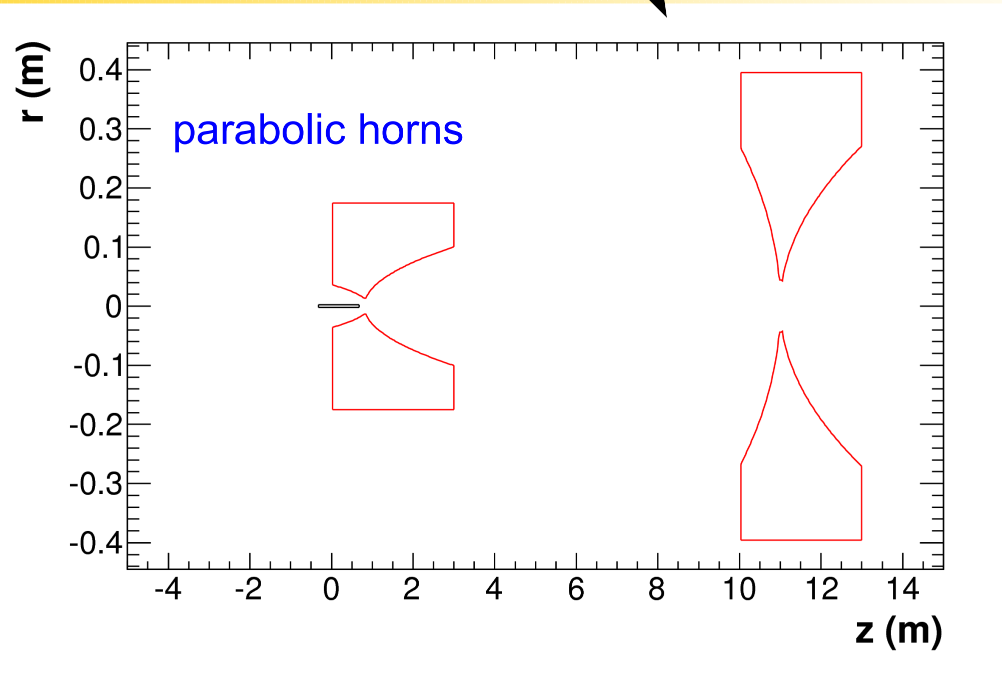
New GEANT4 beamline simulation

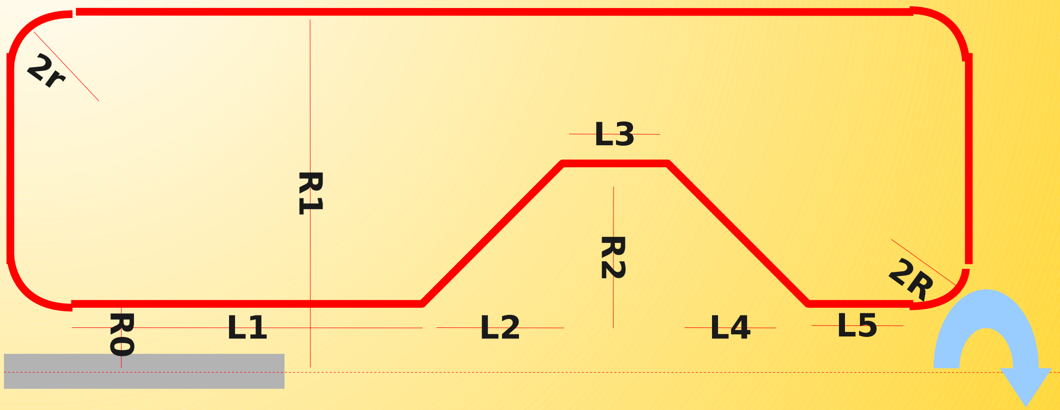
The full simulation has been migrated GEANT3 (A. Cazes, J-E. campagne) to GEANT4

Geometry implementations:

- 1) the standard horn reproducing the existing CERN prototype
- 2) a new parametric model implemented (MINIBOONE inspired)
- 3) a generic horn shape whose coordinates are define through an external ASCII file





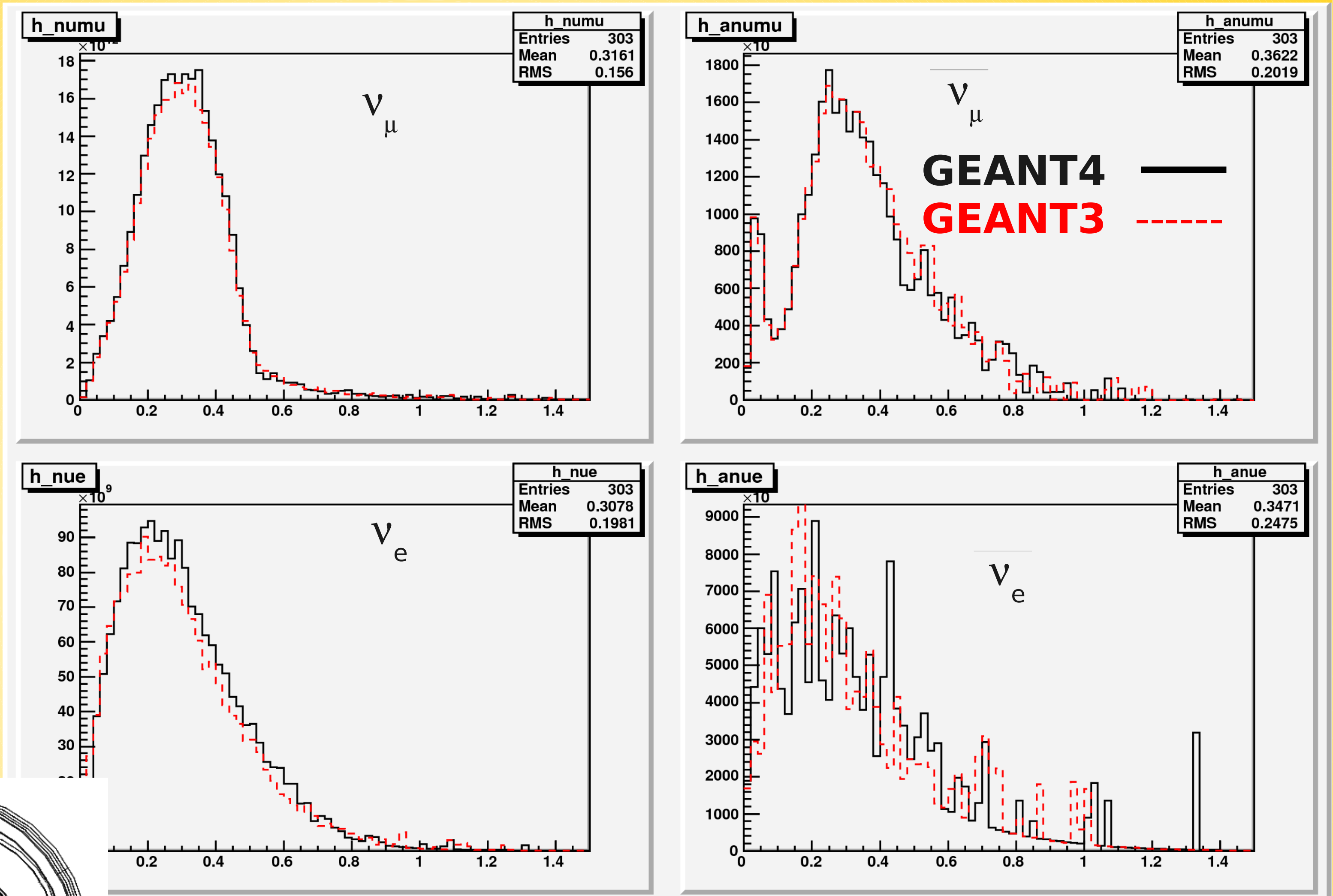


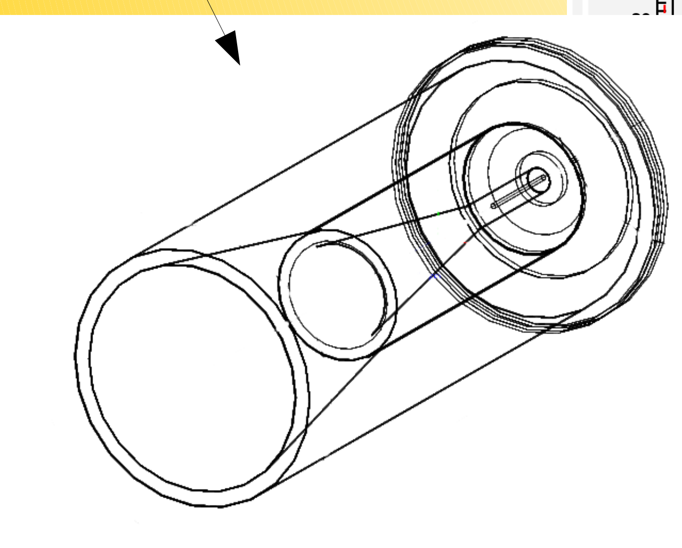
GEANT3-4 comparison with SPL standard horn

The original GEANT3 software (A. Cazes) rewritten in GEANT4

Fluxes comparison with the original horn geometry

standard horn geometry (GEANT4)





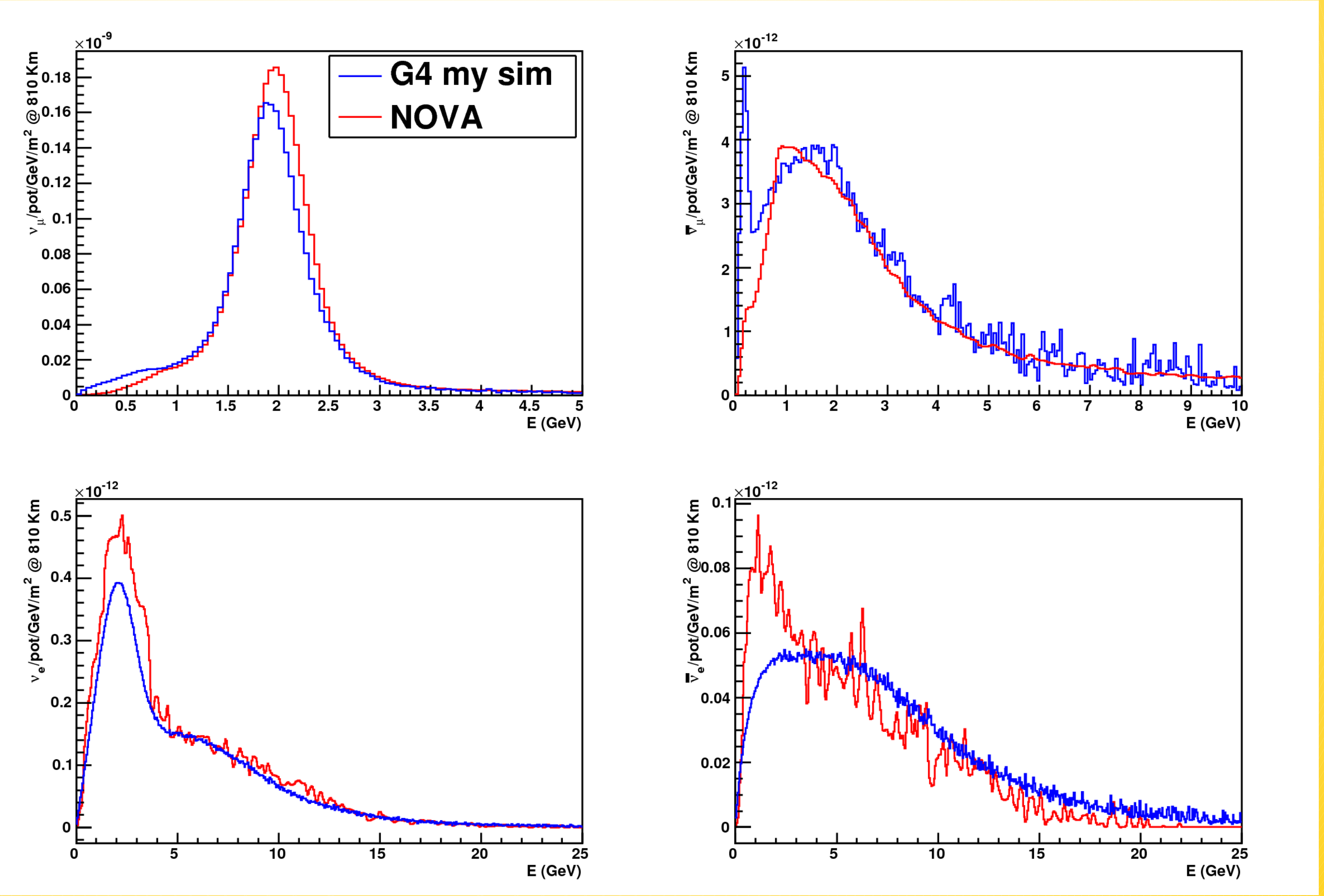
Good agreement found between the two simulation programs

GEANT4: benchmarking with NOvA fluxes

NOVA setup reproduced in the new GEANT4 framework
E= 120 GeV, L=810 Km, 10.8 Km OFF-AXIS
GEANT4 used also for the primary proton interactions (in place of FLUKA)

Reference fluxes from NoVA public web pages
http://enrico1.physics.indiana.edu/messier/off-axis/spectra/

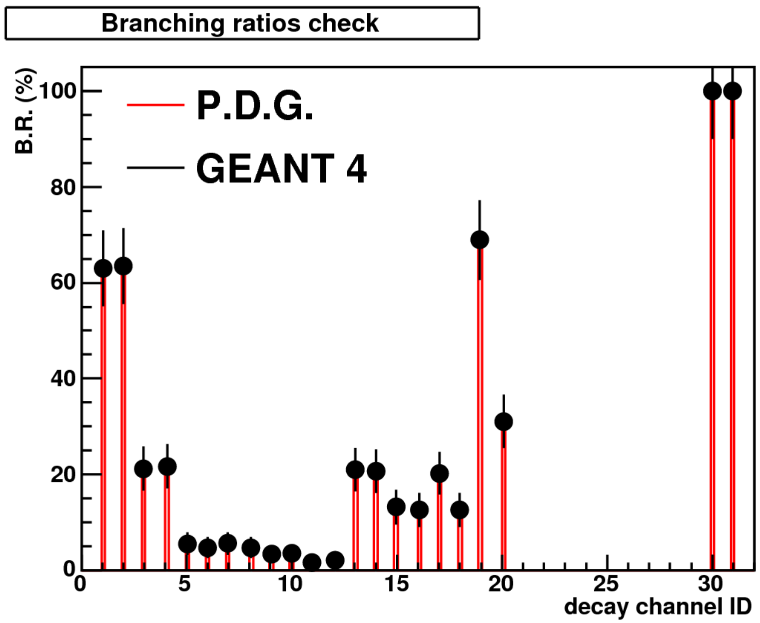
Comparison in normalization and shape

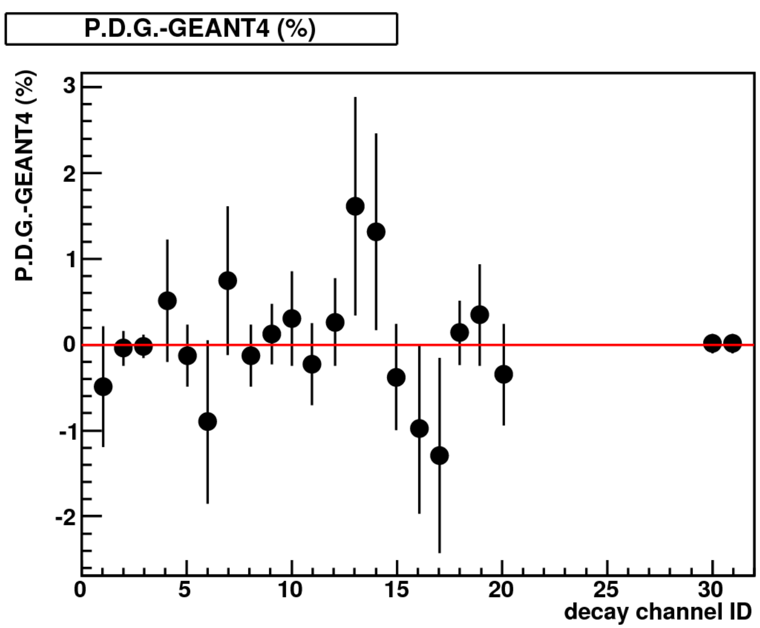


Reasonable agreement - also considering that geometry is reproduced with approximations.

Simulations are completely independent

GEANT4 branching ratios cross check





1) $K^+ \to \mu^+\nu_\mu$
2) $K^- \to \mu^-\bar{\nu}_\mu$
3) $K^+ \to \pi^+\pi^0$
4) $K^- \to \pi^-\pi^0$
5) $K^+ \to \pi^+\pi^+\pi^-$
6) $K^- \to \pi^-\pi^-\pi^+$
7) $K^+ \to e^+\nu_e\pi^0$
8) $K^- \to e^-\bar{\nu}_e\pi^0$
9) $K^+ \to \mu^+\nu_\mu\pi^0$
10) $K^- \to \mu^-\bar{\nu}_\mu\pi^0$
11) $K^+ \to \pi^+\pi^0\pi^0$
12) $K^- \to \pi^-\pi^0\pi^0$

Implementation is correct

13) $K^0_L \to e^+\nu_e\pi^-$
14) $K^0_L \to$ #$e^-\bar{\nu}_e\pi^+$
15) $K^0_L \to \mu^+\nu_\mu\pi^-$
16) $K^0_L \to \mu^-\bar{\nu}_\mu\pi^+$
17) $K^0_L \to \pi^0\pi^0\pi^0$
18) $K^0_L \to \pi^+\pi^-\pi^0$
19) $K^0_S \to \pi^+\pi^-$
20) $K^0_S \to \pi^-\pi^0$
30) $\pi^+ \to \mu^+\nu_\mu$
31) $\pi^- \to \mu^-\bar{\nu}_\mu$

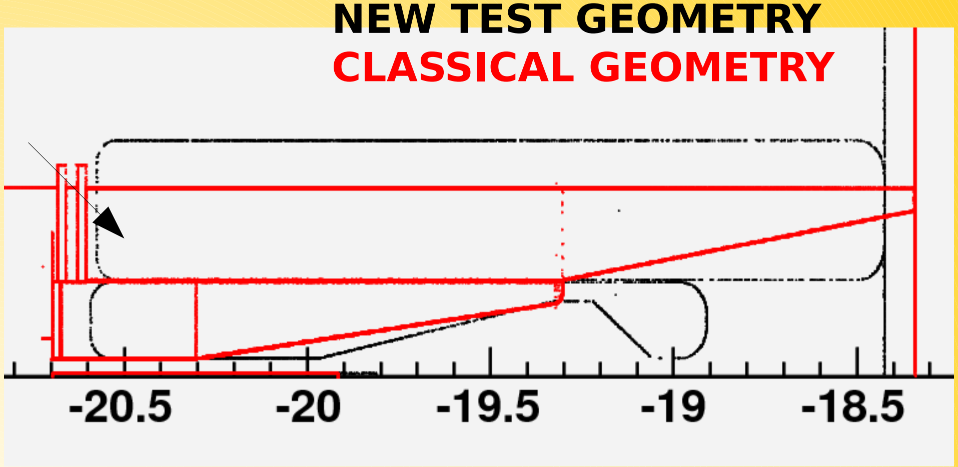
MiniBoone like horn

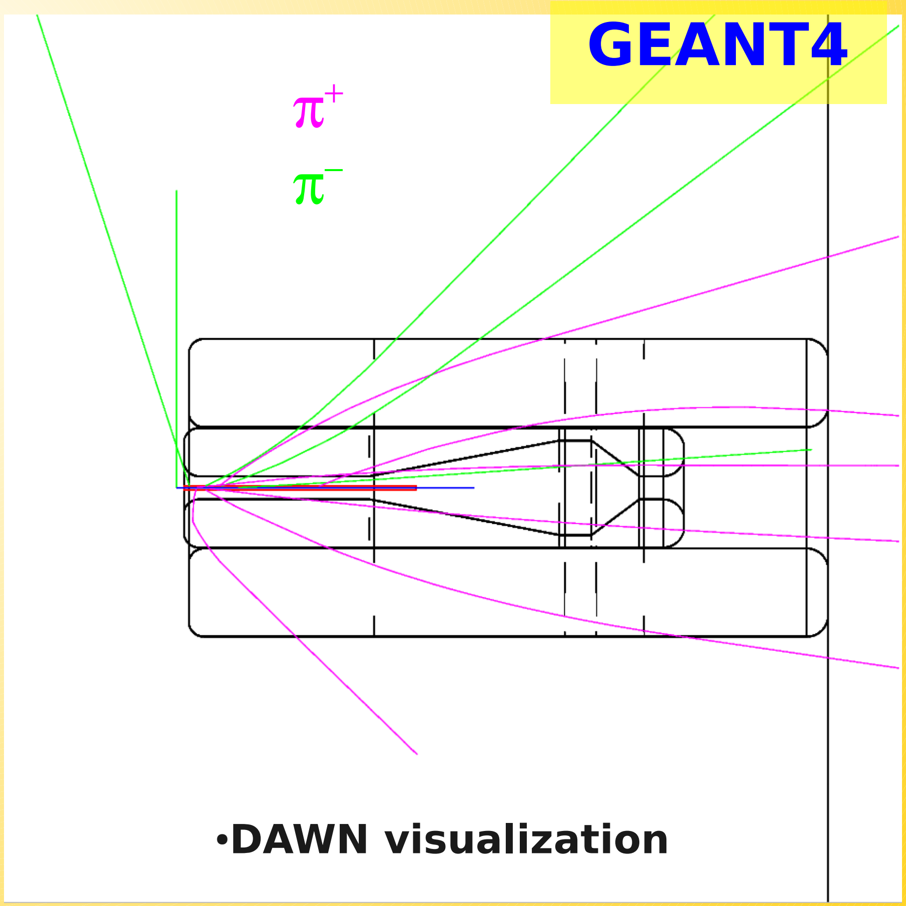
- The standard conic horn (designed for a 30 cm L mercury target) allows too many pions to escape in the forward direction without being defocused. Problem in particular for the anti-ν running (- focusing) due to ν_e from:
  - $\pi^+ \rightarrow \mu^+ \rightarrow e^+ \nu_e$ anti-ν_μ
  - N.B. $\pi^+ > \pi^-$ and $\sigma(\nu_e) > \sigma$(anti-ν_e)
- more "forward closed"
- better wrong charge pion rejection
- Forward "end-cap" "sweeps away" wrong charged forward going pions
- higher mean neutrino energy

Optimised design:

- Thicker reflector (+10cm)
- 50 cm total radius, ~2 m length
- Currents (300kA for horn +600 kA reflector)
  - as in the original design

Hit maps (r,z) plane

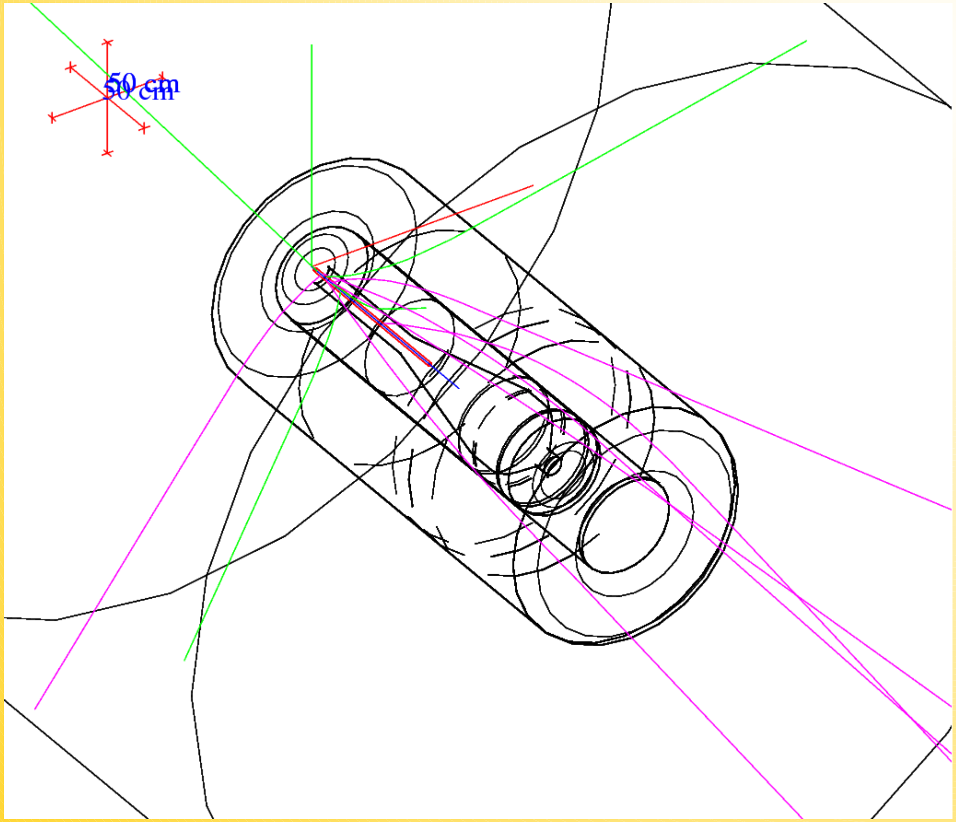


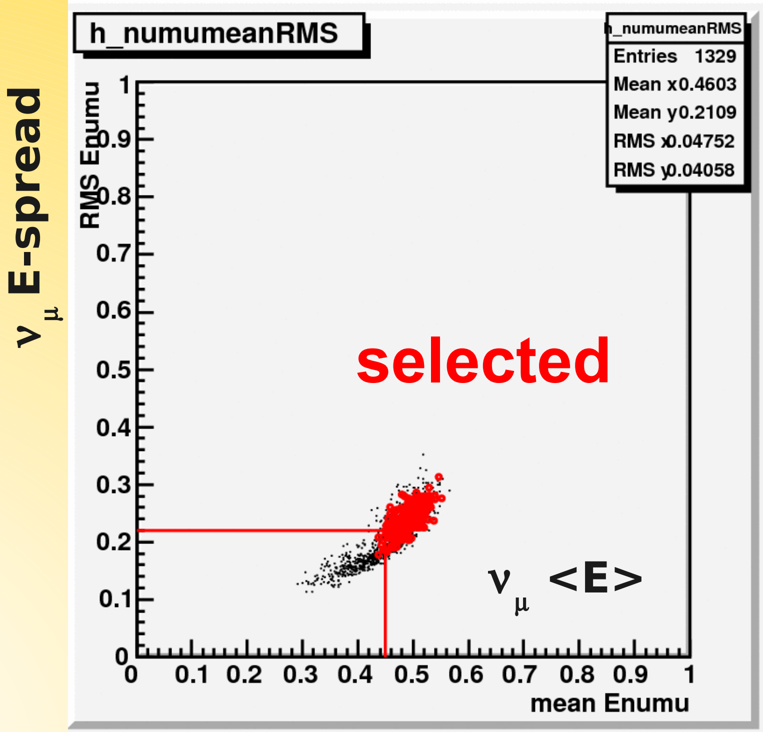


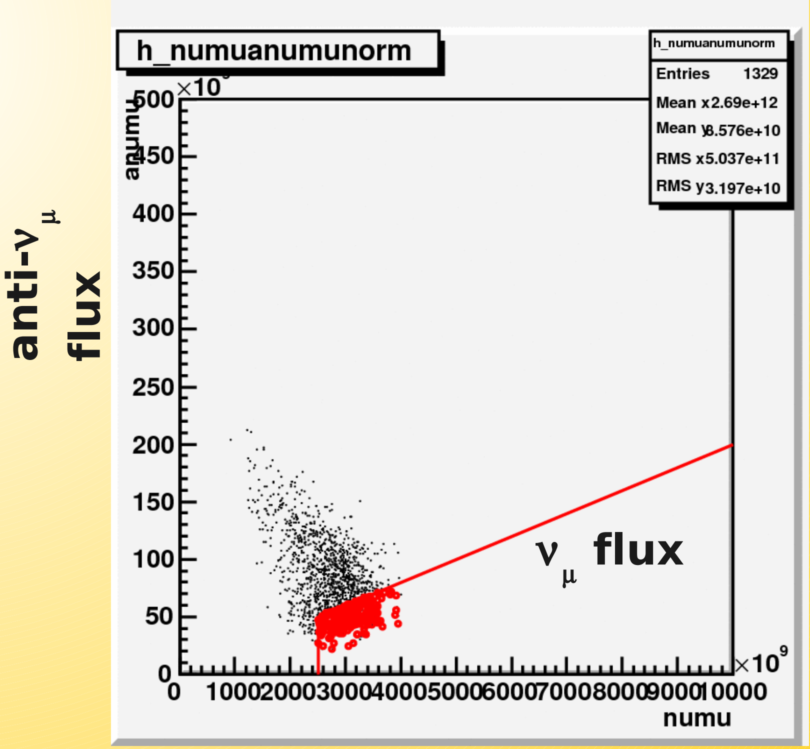
•DAWN visualization

MiniBoone like horn: design procedure and selection criteria

- random sampling of parameters
- selection criteria on ν-fluxes
  - small anti-ν_μ component
  - low $<E_\nu>$, narrow beam
- mildly tuned
- no optimisation for the tunnel
  L = 40 m r = 2 m



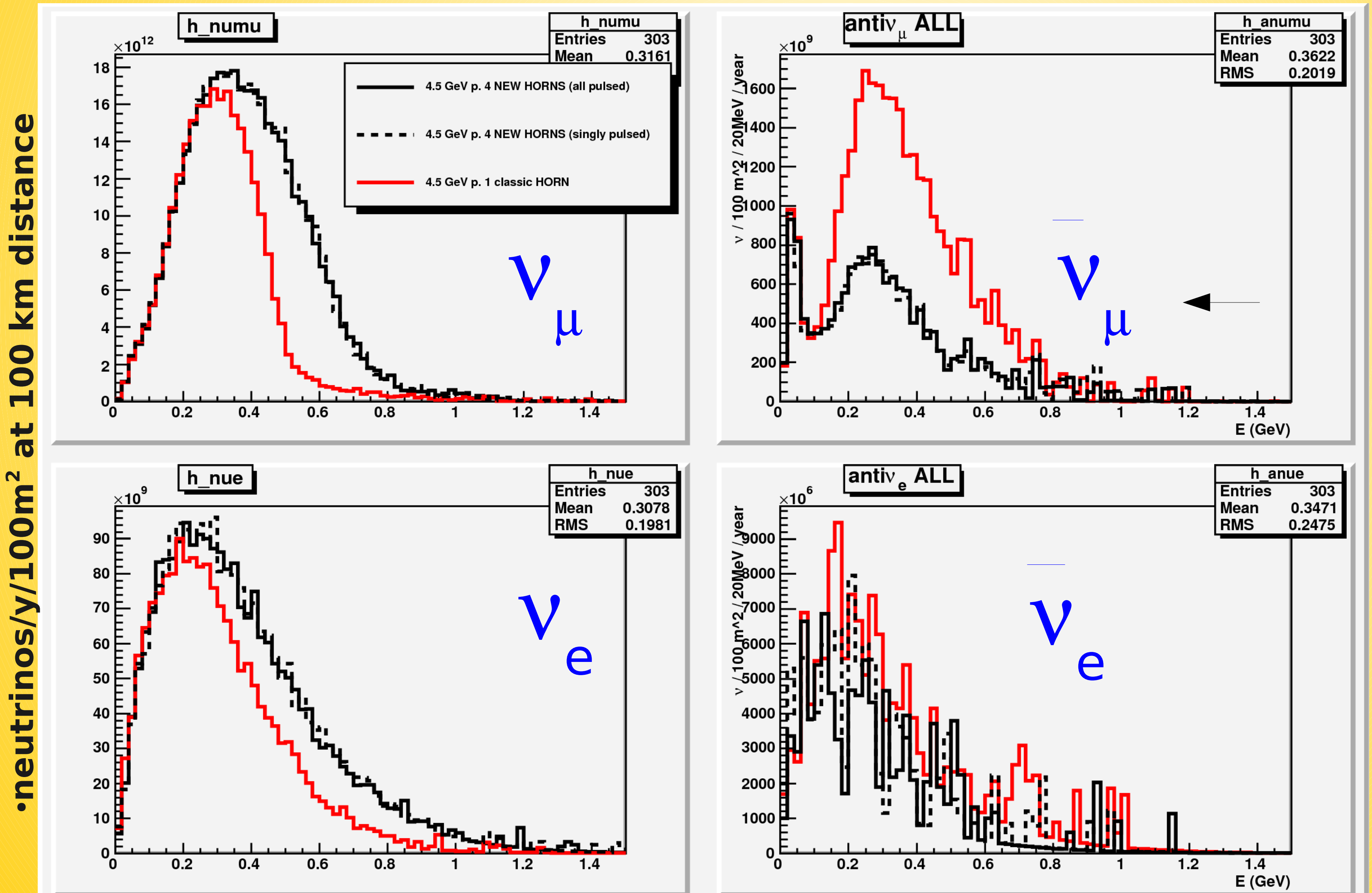




Fluxes: new VS old horn

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

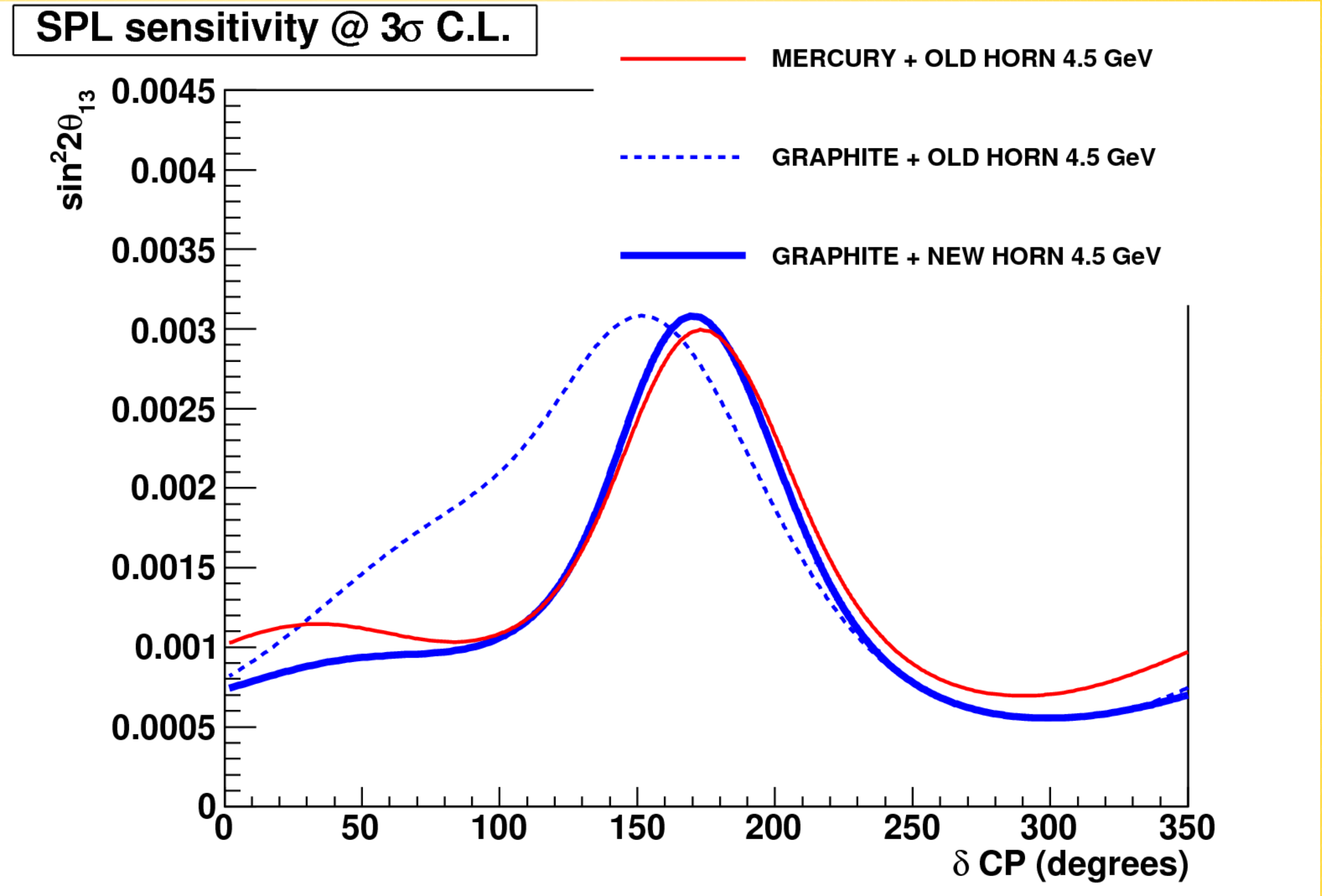
@ 4.5 GeV positive focusing

	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

MiniBoone-like horn sensitivity

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



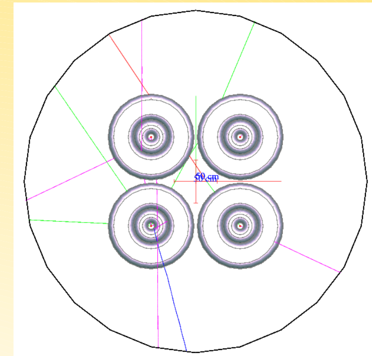
The 4-horns scenario

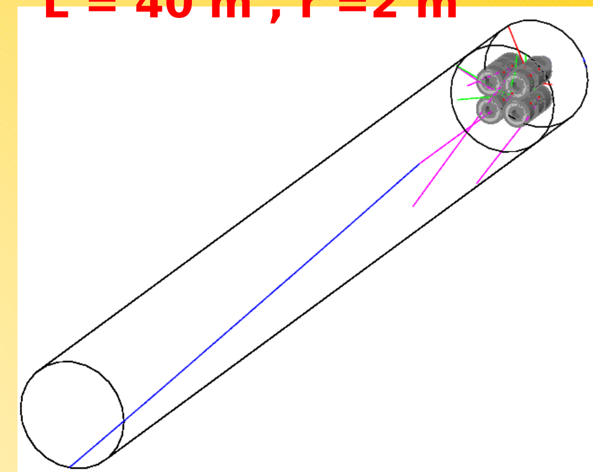
Reduced stress on target via
- **lower frequency (12.5 Hz) or**
- **lower p-flux (1 MW)**

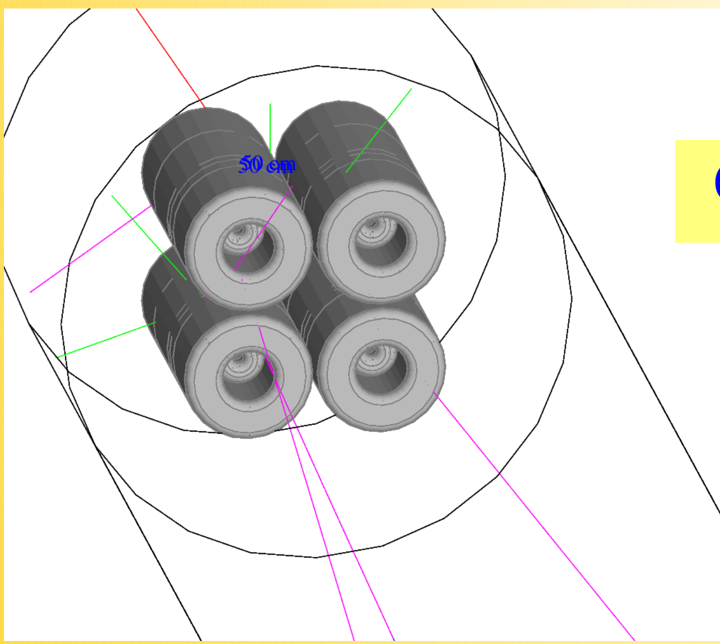
depending on injection strategy

Profits of horn compactness (r~0.5m)

L = 40 m , r =2 m

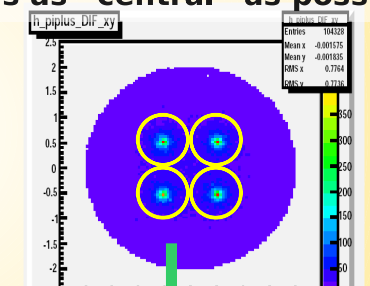






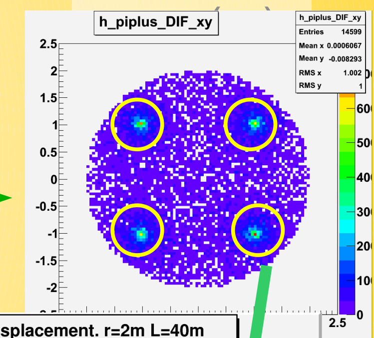
GEANT4

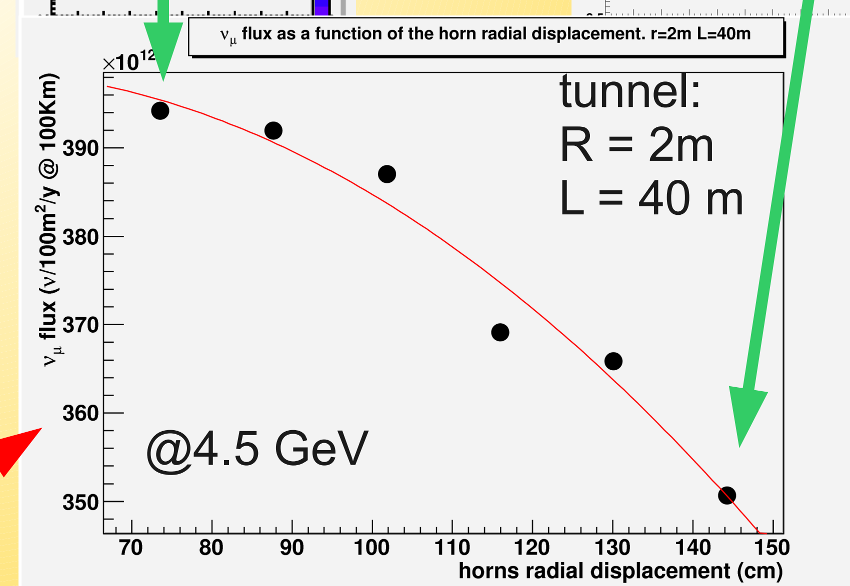
Baseline configuration with horns as "central" as possible



ν_μ **-13%**

Worst case

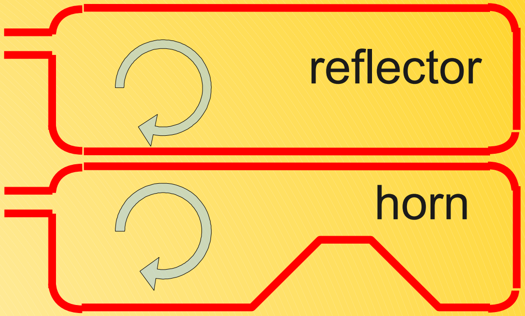


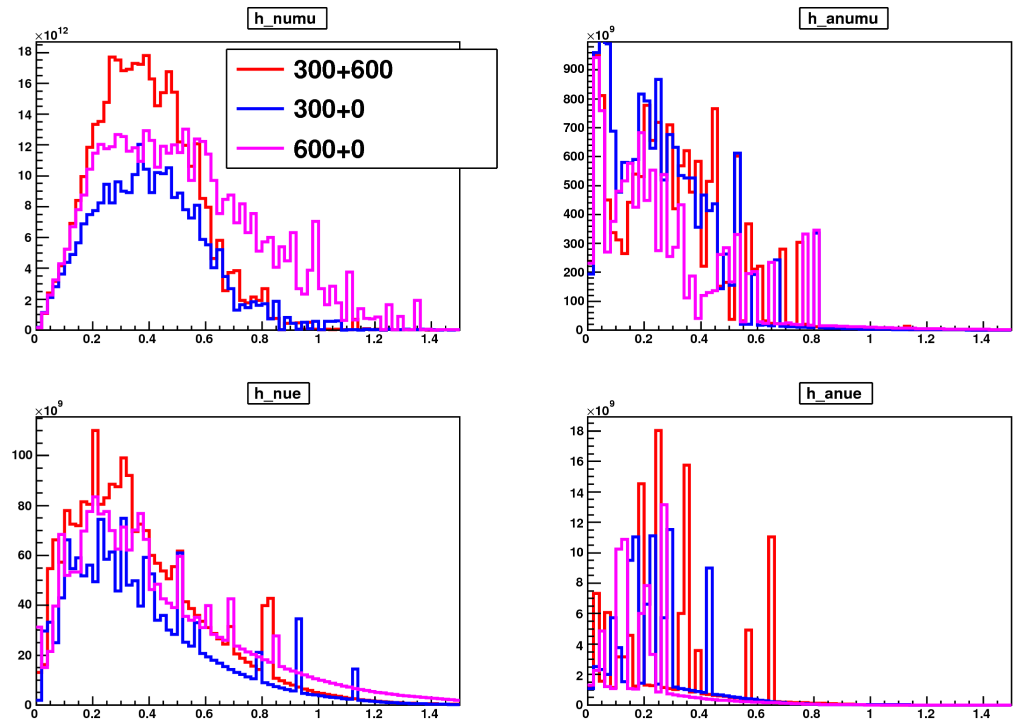


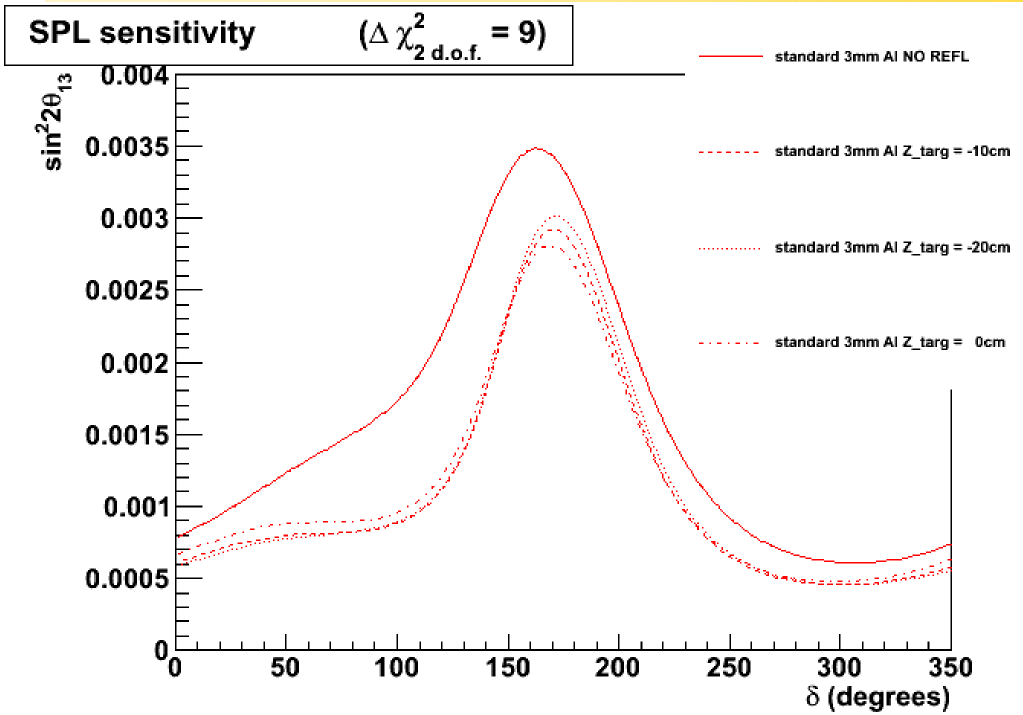
Small flux loss even up to big lateral displacements.

Possible solutions without reflector ?

- Motivations:
- 600 kA @ 50 Hz not easy
- refl. current in opposite sense (and close) to the horn current (300kA).
- Mechanical stresses ?
- Complications for horn cooling design ?







- Just dropping the reflector implies significant loss both in term of fluxes and sensitivity
- Try a no-reflector ad-hoc optimization ==>

MiniBoone-like horn: optimization without reflector

Recover performance

2 approaches followed up to now

1) fix horn i at 300 kA and allow for smaller inner radius

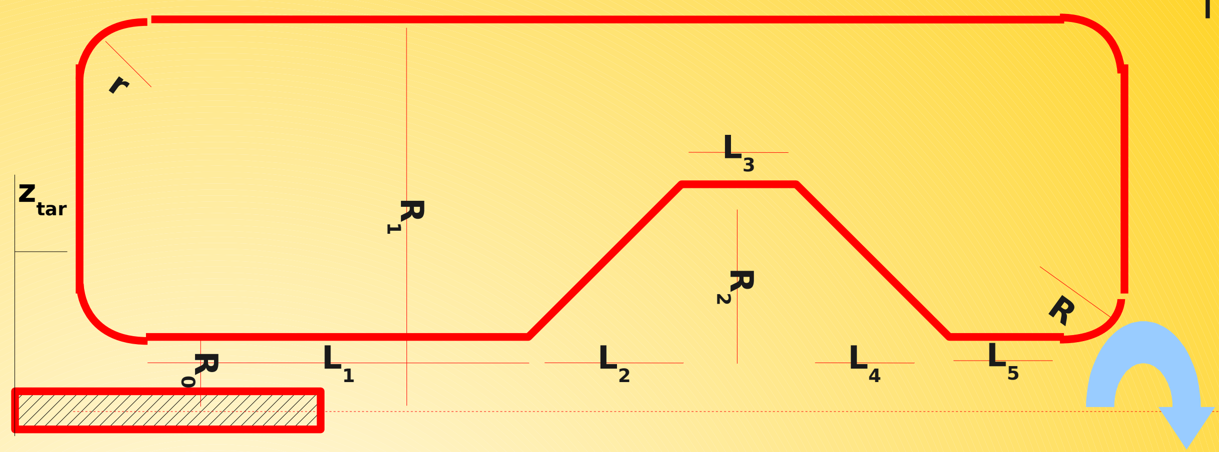
- down to 1.2 cm ~ integrated target-horn: “hornet” -

2) impose minimal inner radius of 4 cm and allow for higher i up to 400 kA

Will describe 1) in more detail (recent work)

Approach 1) also followed by Christoph (see next talk) sticking to a conical shaped horn as in the original design

Horn optimization with the parametric model



Flat distributions

Parameter	Interval
L_1	[50,250]
L_2	[1,250]
L_3	[1,250]
L_4	[1,250]
L_5	[1,15]
L_{max}	[250]
R	[1.2,80]
r	[5.08]
R_0	[1.2,4]
R_1	[1.2,80]
R_2	[1.2,80]
i	300 kA
z_{tar}	[-30,0]
L_{tun}	[35,45] m
r_{tun}	[1.8,2.2] m
L_{tar}	0.78 m
r_{tar}	1.5 cm
s	3 mm

fixed

Aluminum uniform thickness

$$r + L_1 + L_2 + L_3 + L_4 + L_5 + R < L_{max}$$

$$R_1 < r_{max}$$

$$R_0 > r_{min}$$

size constraints

L_{max} = 250 cm

r_{max} = 80 cm

r_{min} = 1.2 cm

$$R_2 < R_1$$

$$R < \frac{1}{2}(R_1 - R_0)$$

$$r < \frac{1}{2}(R_1 - R_0)$$

geometry

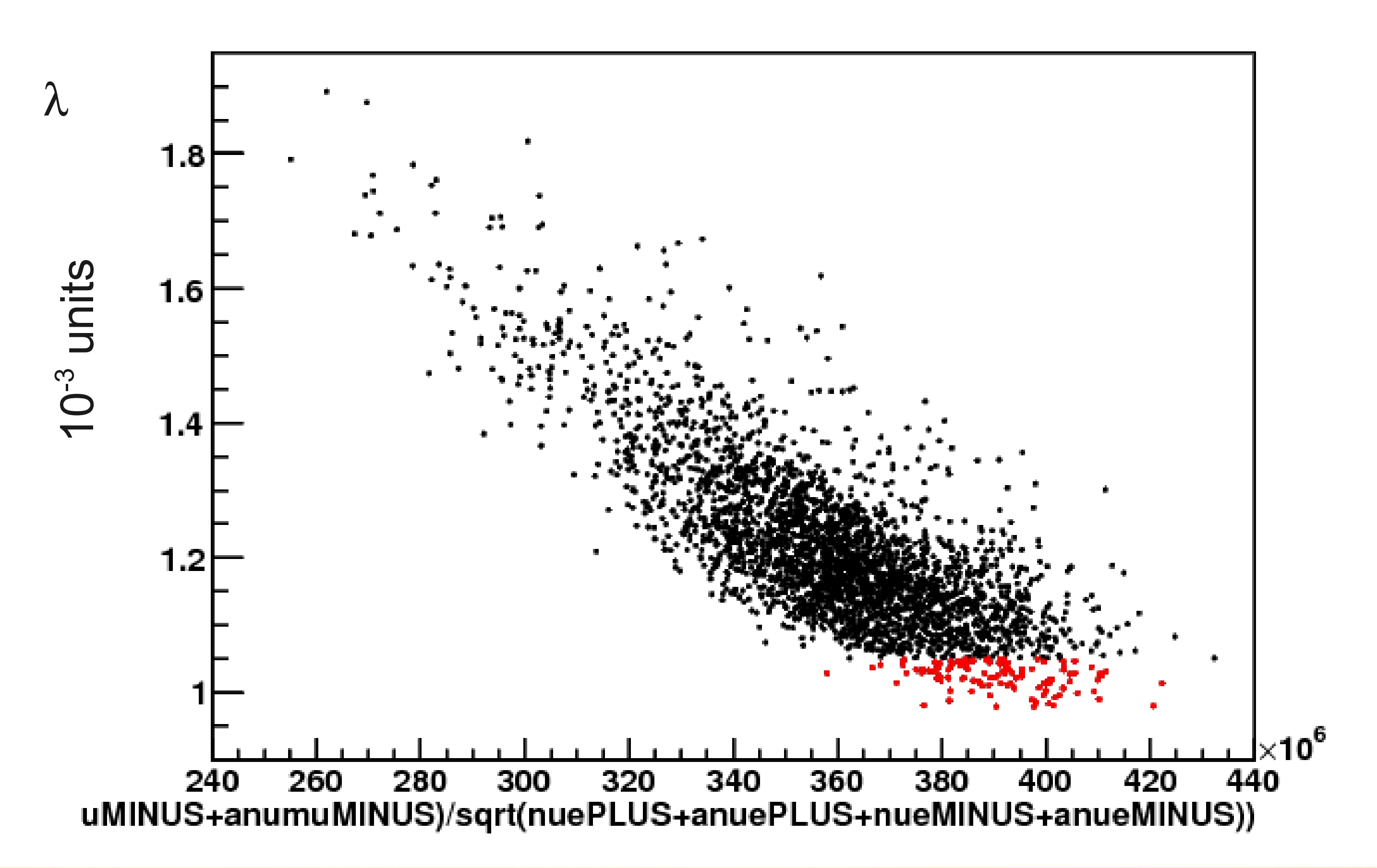
Sampling of parameters: limits

3000 configurations
10^5 pot each

Figure of merit:
99 % C.L. limit on
$\sin^2 2\theta_{13}$ averaged on
$:= \lambda$

8ν+2ν-bar running
440 kton W.Ch.

correlation btw limit (λ) and significance S/√B



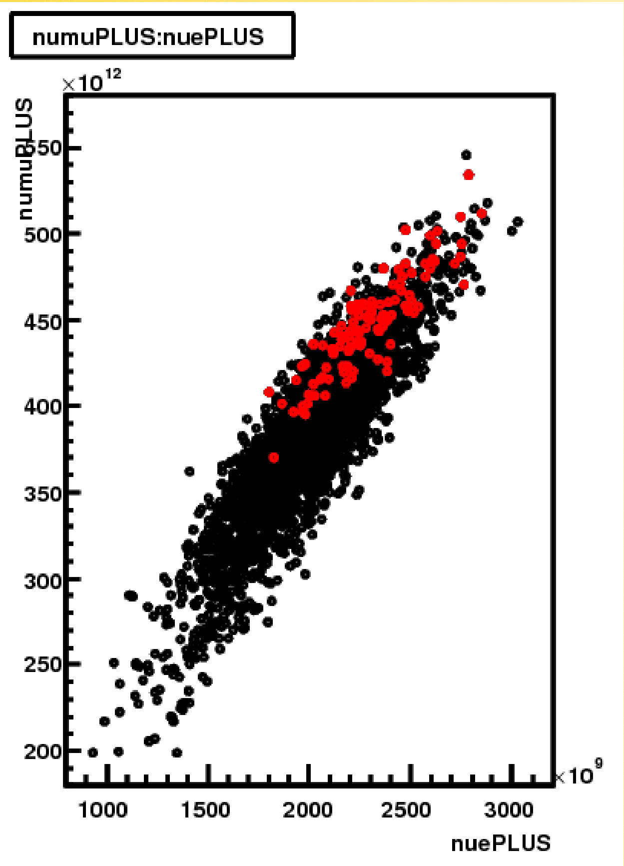
S/√B approximated as

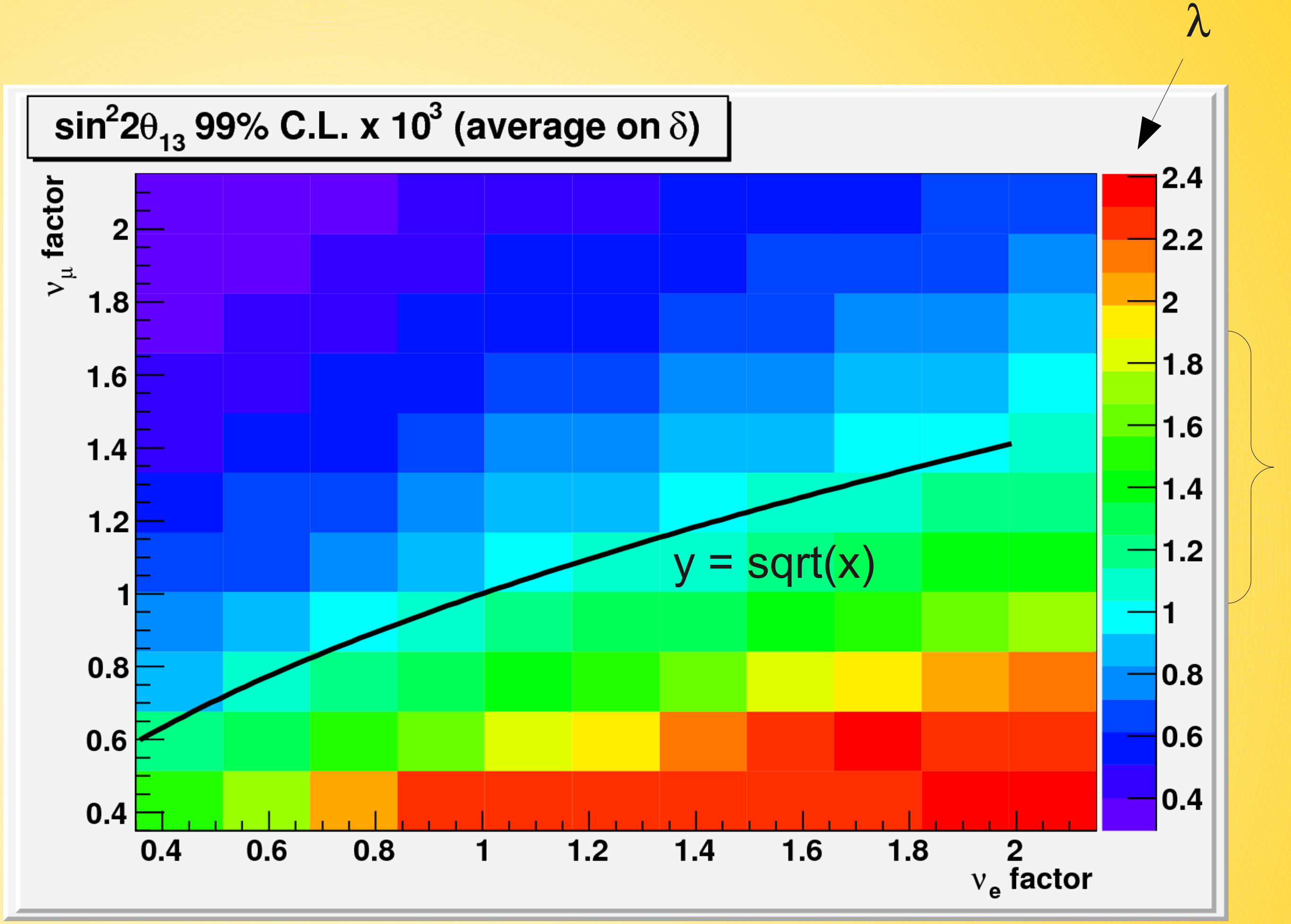
$$\frac{(\nu_\mu + \text{bar-}\nu_\mu)_+ + (\nu_\mu + \text{bar-}\nu_\mu)_-}{\sqrt{[(\nu_e + \text{bar-}\nu_e)_+ + (\nu_e + \text{bar-}\nu_e)_-]}}$$

Excercise: limit improvement and fluxes

λ as a function of a multiplicative factor for μ and e fluxes put by hand

fluxes from an average configuration taken as central value



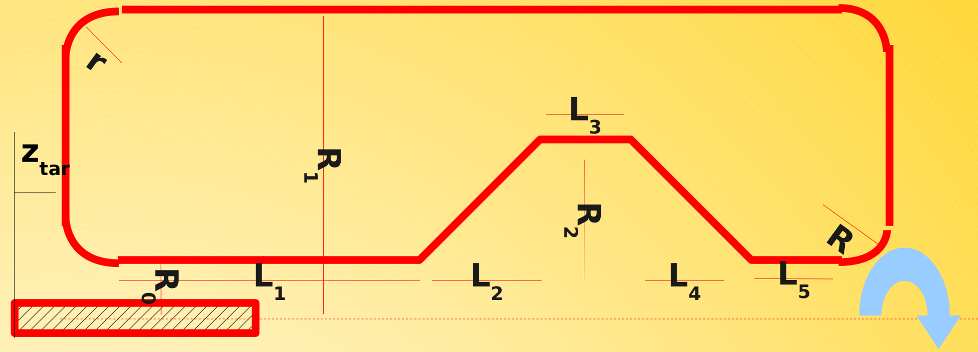


ν_μ x 2 and ν_e x 0.5 => $\lambda \sim 1 \rightarrow \lambda \sim 0.4$

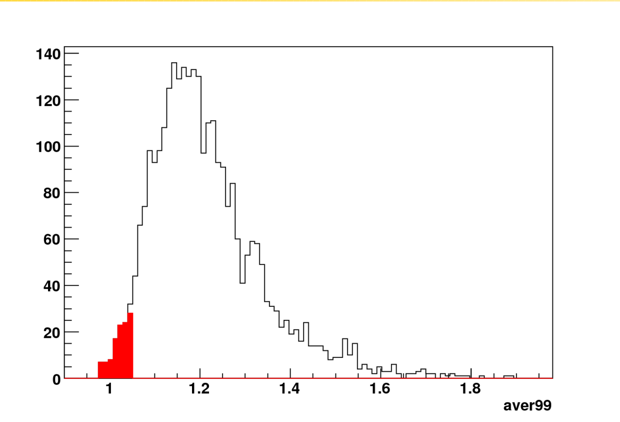
sampling of configurations: fluxes variations up to factors 2-3

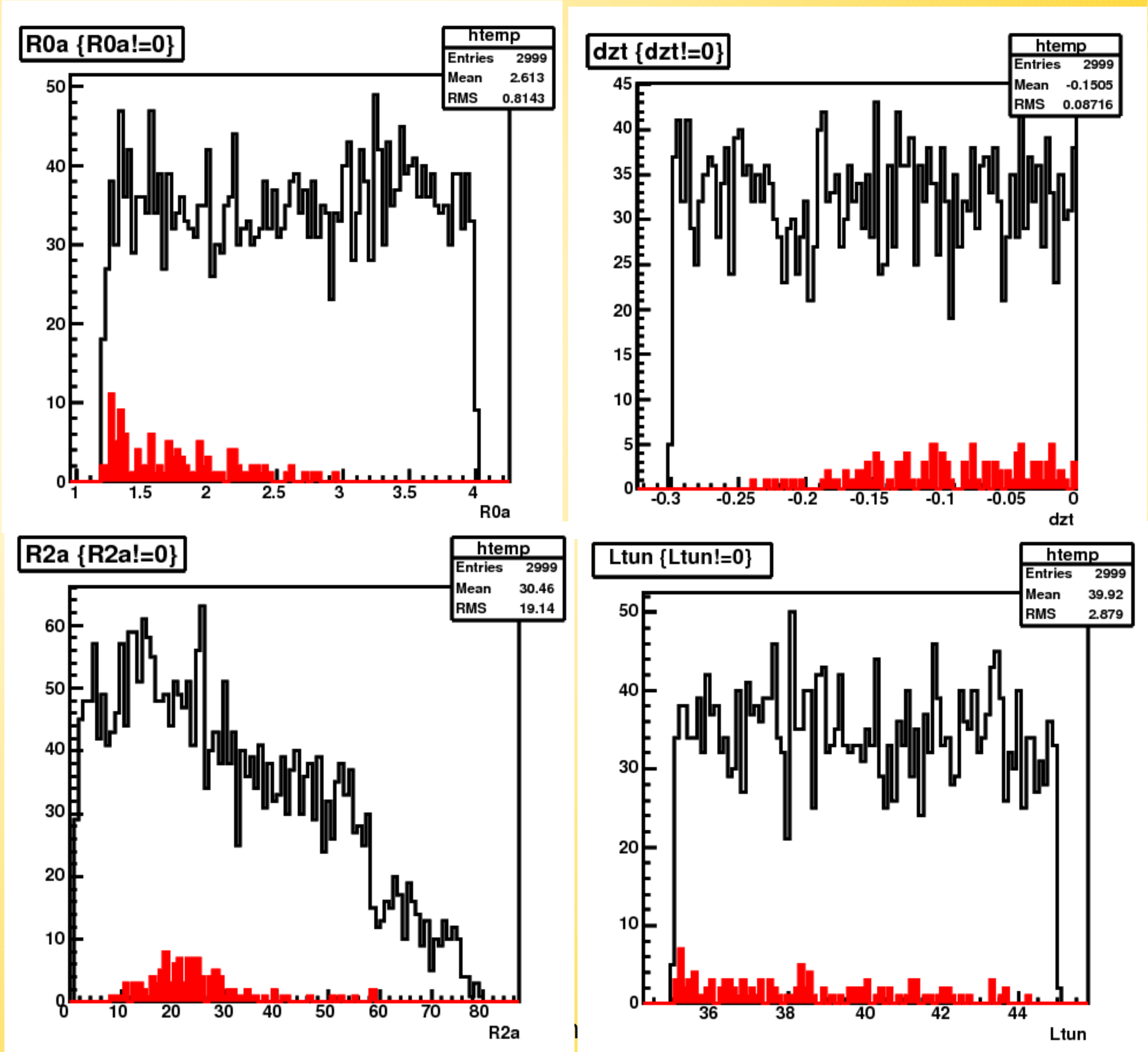
but with strong correlation btw ν_e and ν_μ (bulk of the ν_e from μ decays)

Effective parameters



Configurations with $\lambda < 1.05$





New interval for parameters

R_0 = 1.2 cm

R_2 = [20-22] cm

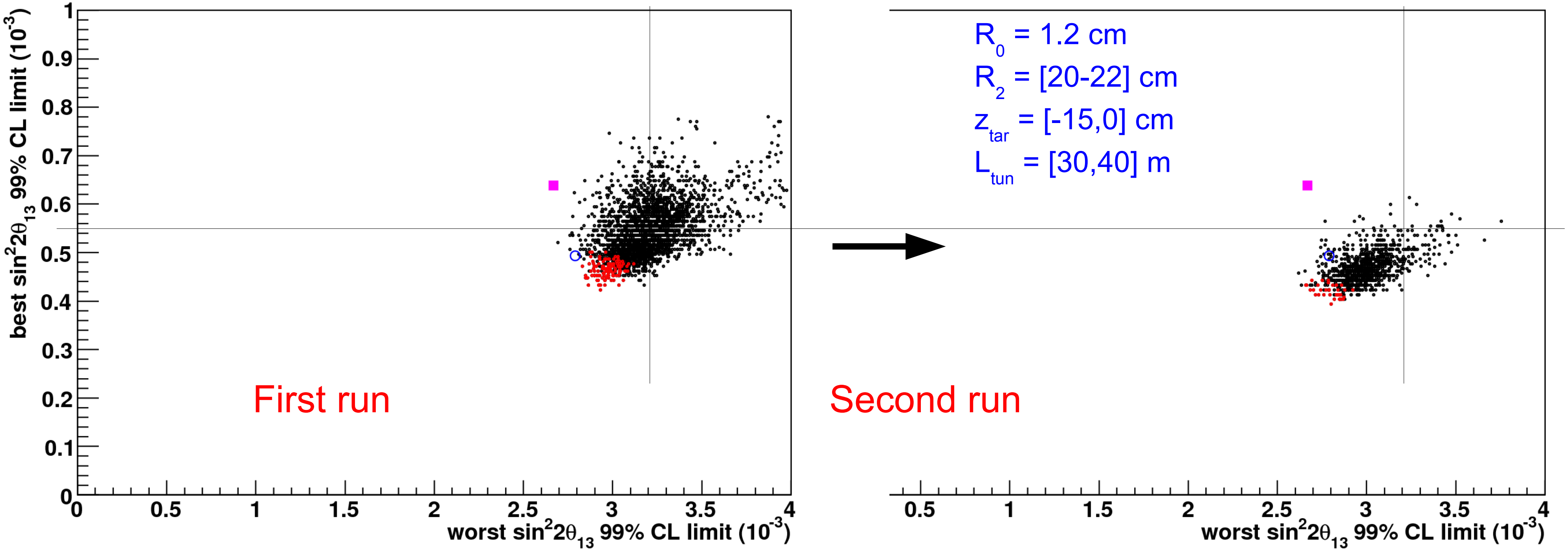
z_{tar} = [-15,0] cm

L_{tun} = [30,40] m

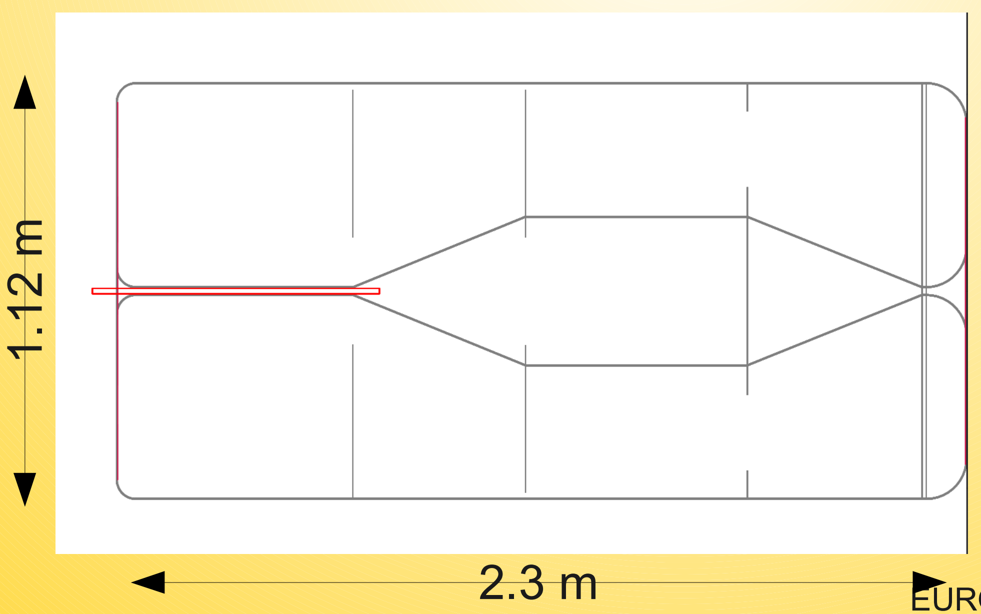
A. Longhin

Configuration with minimum λ

New interval for parameters



Best configuration



Z_{tar} = -6.8 cm

L_1 = 58.9 cm
L_2 = 46.8 cm
L_3 = 60.3 cm
L_4 = 47.5 cm
L_5 = 1.08 cm
R = 10.8 cm
r = 5.08 cm

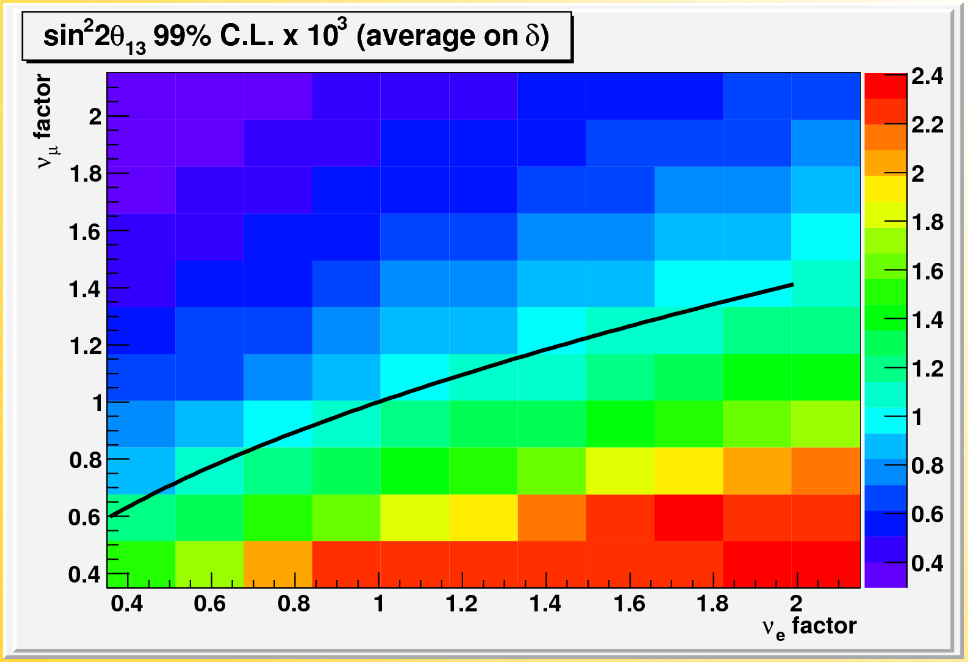
R_0 =1.2 cm
R_1 = 56.2 cm
R_2 = 20.3 cm
I_1 = 300 kA
L_{tun} = 32.4 m
r_{tun} = 2.06 m

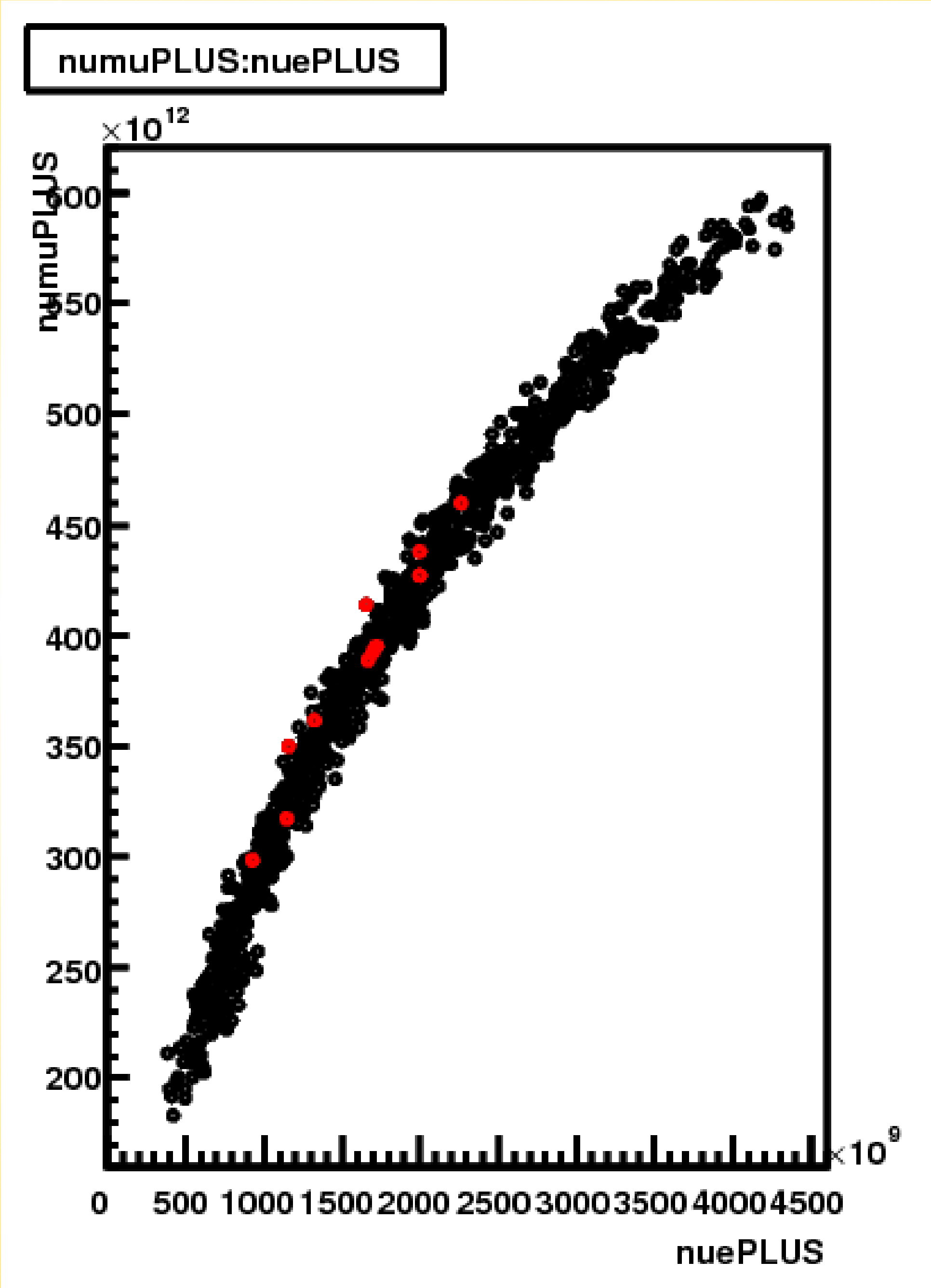
Fix horn shape and tune the tunnel size

variations:

L : 10 - 60 m
r : 0.5- 2.5 m

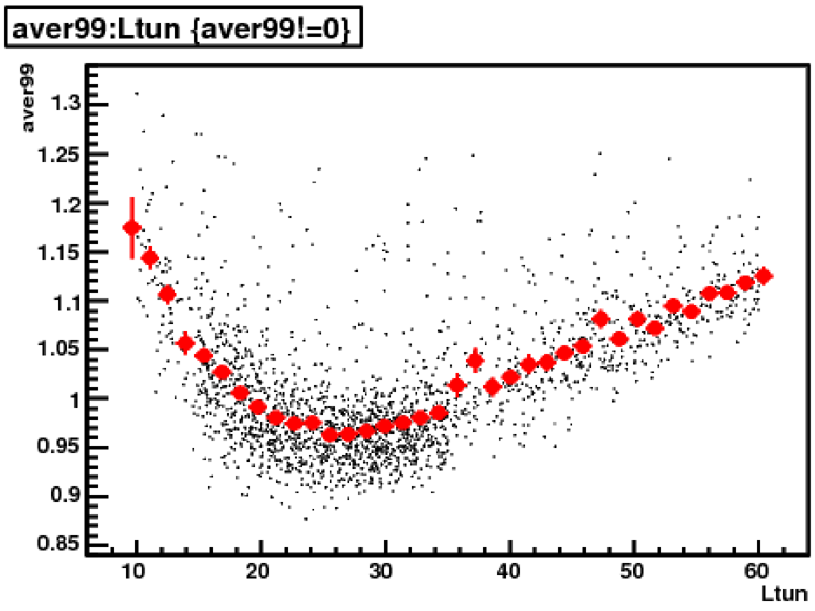
The natural correlation between ν_μ and ν_e fluxes is such that one variations tend to be ~ "at constant sensitivity" at first order

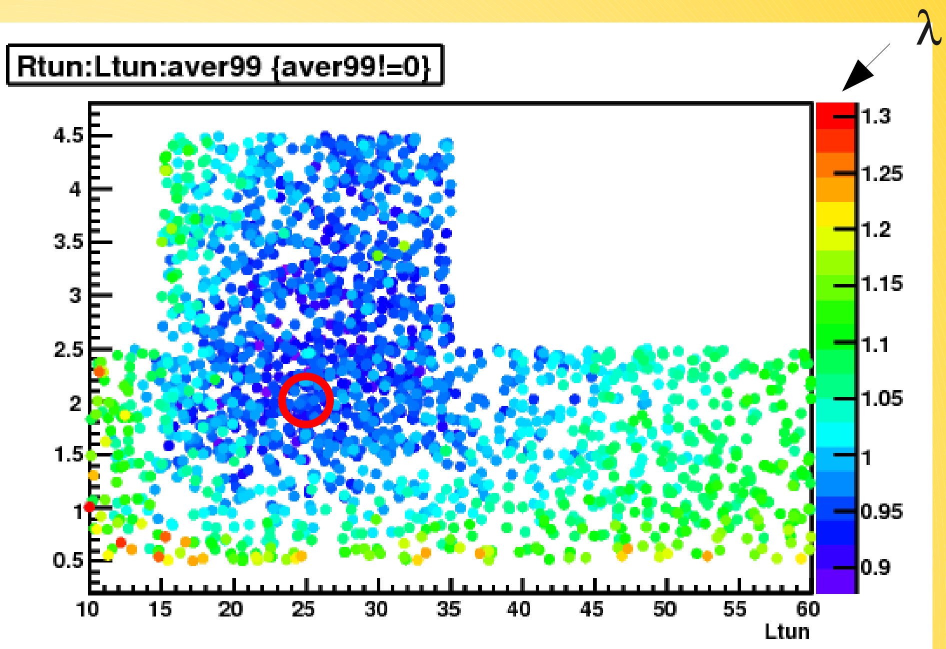


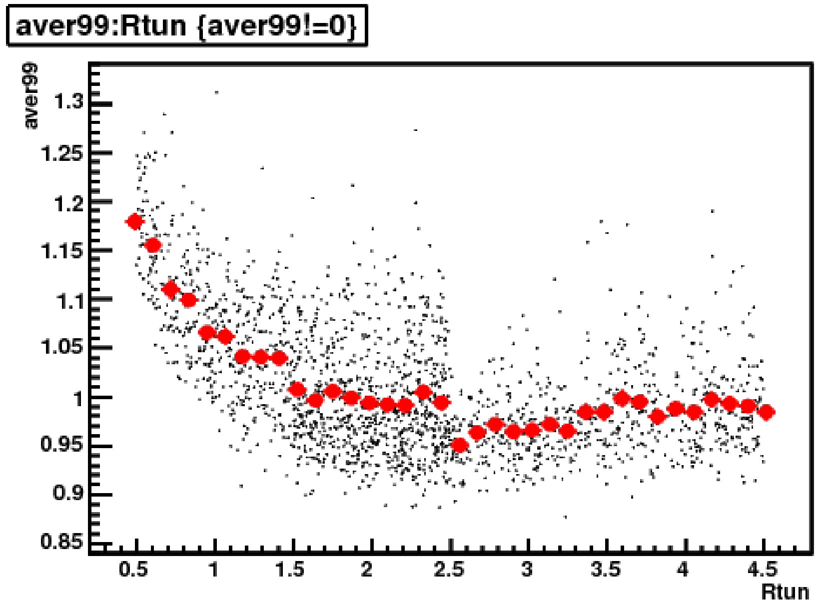


use non-cylindric tunnels ?

Fix horn shape and tune the tunnel size







Optimal tunnel for this horn for L ~ 25 m and r > 2 m

broad minimum

choose 25,2 as central choice

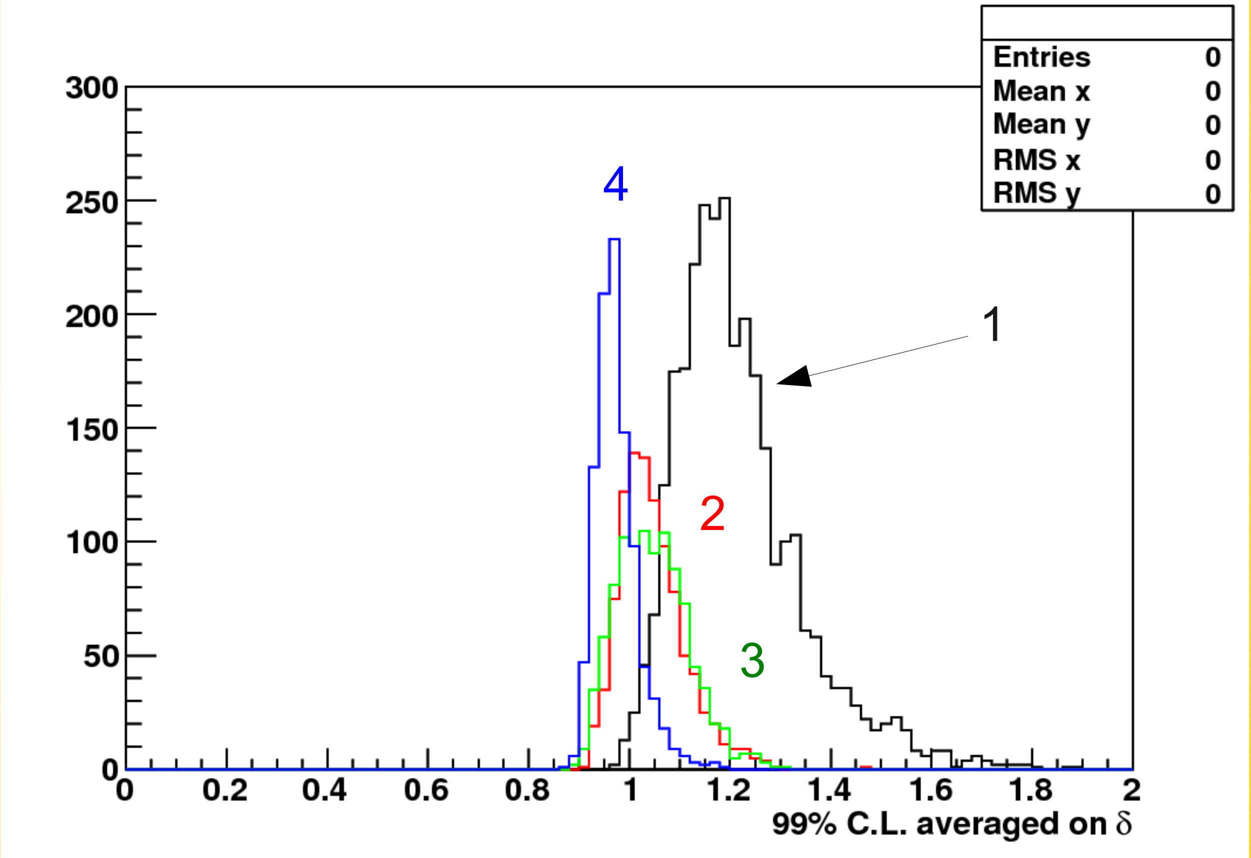
larger tunnels may turn to be expensive/unpractical

Summary of the optimisation steps

- step 1 general search (3000 confs)
  study distribution of parameters for ($\lambda < 1.05$) wrt to input distributions
  restrict parameters to proper intervals
- step 2 restricted intervals for effective parameters
  choose horn with lowest λ
- step 3 vary tunnel parameters in L [10-60] m r [0.5-2.5] m
- step 4 L [15-35] m r [1.5-4.5] m

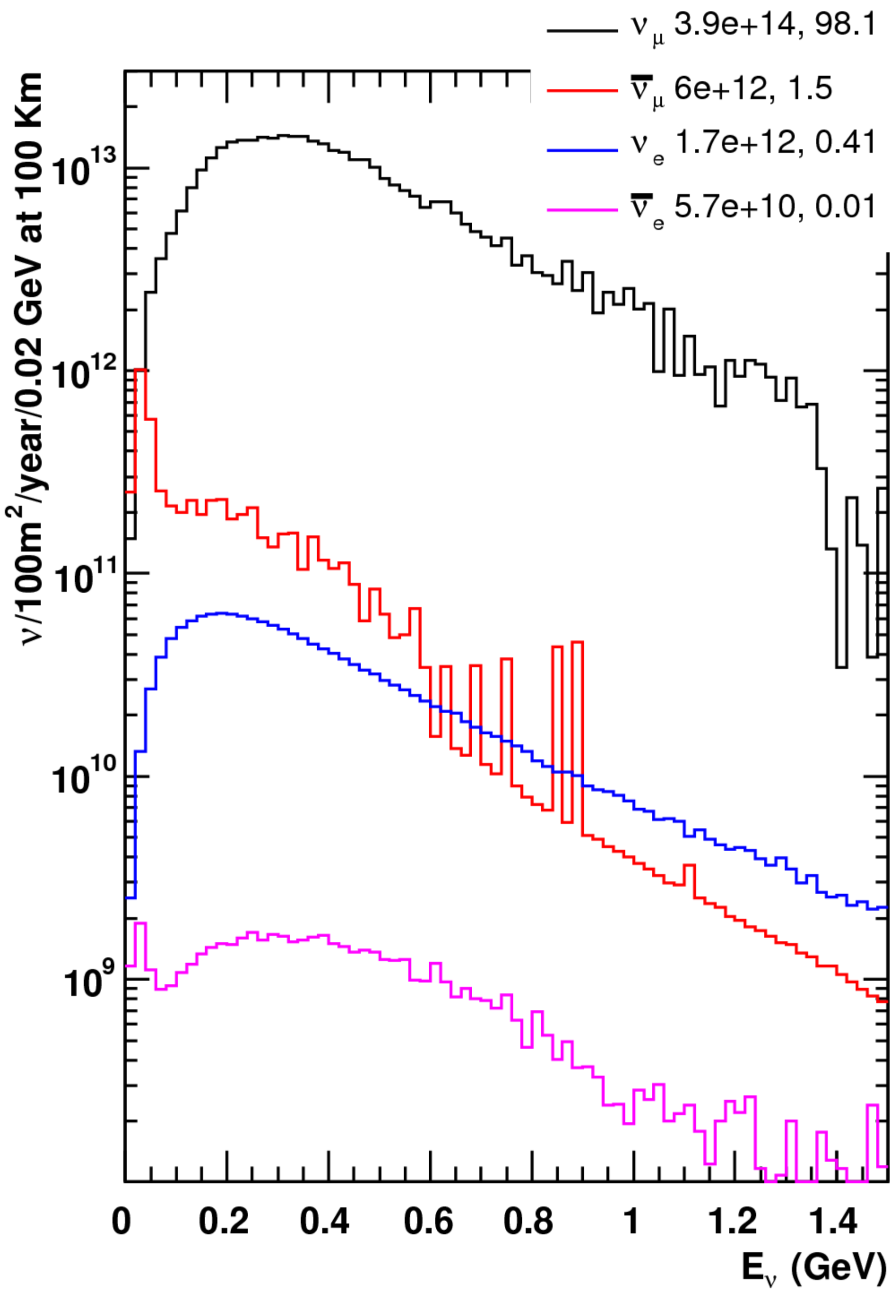
Better configuration yields
$\lambda \sim 0.87$

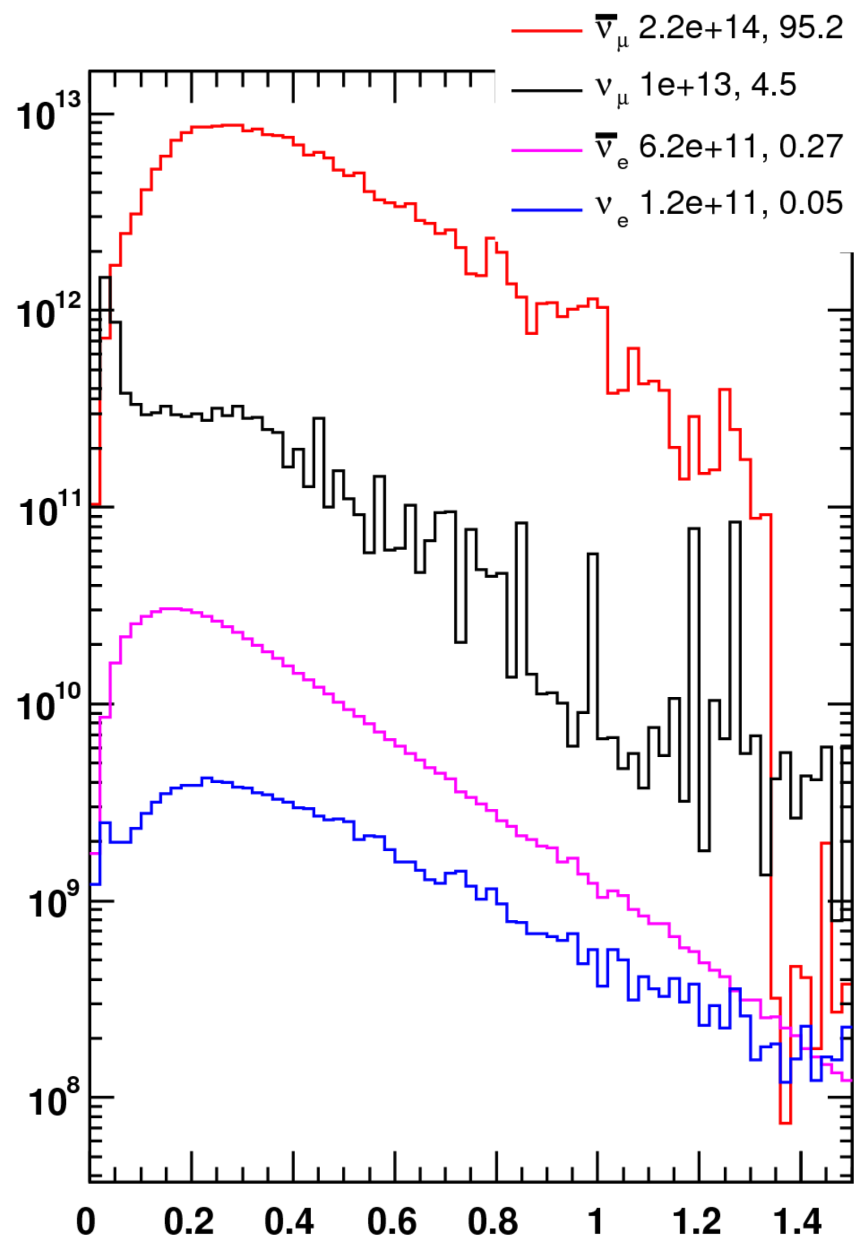
~ 30 % improvement w.r.t. to a generic initial configuration



1: 3k configurations
2-4: 1k configurations

Optimized setup: fluxes

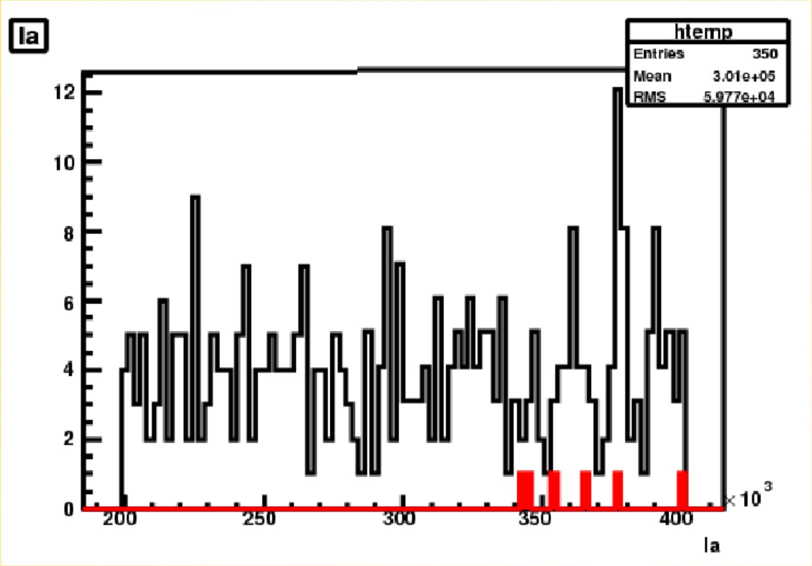


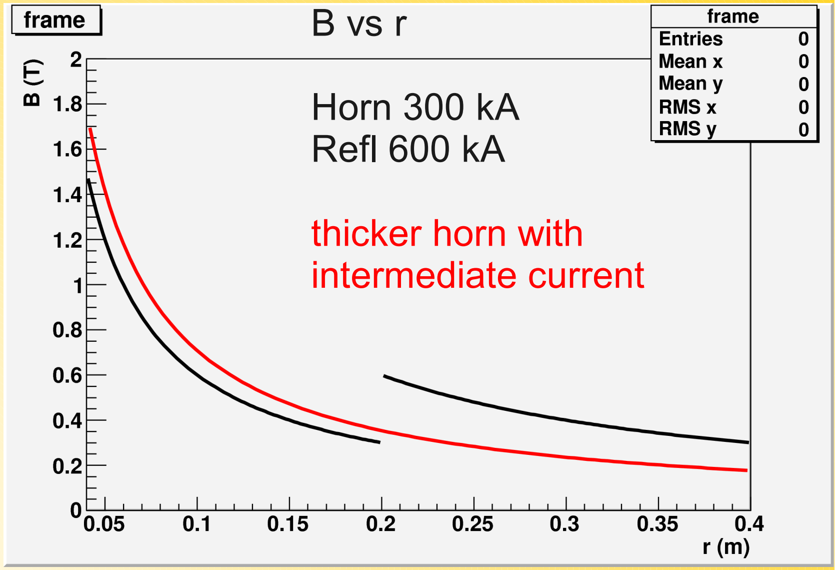


Search with R_0>4 cm I < 400 kA

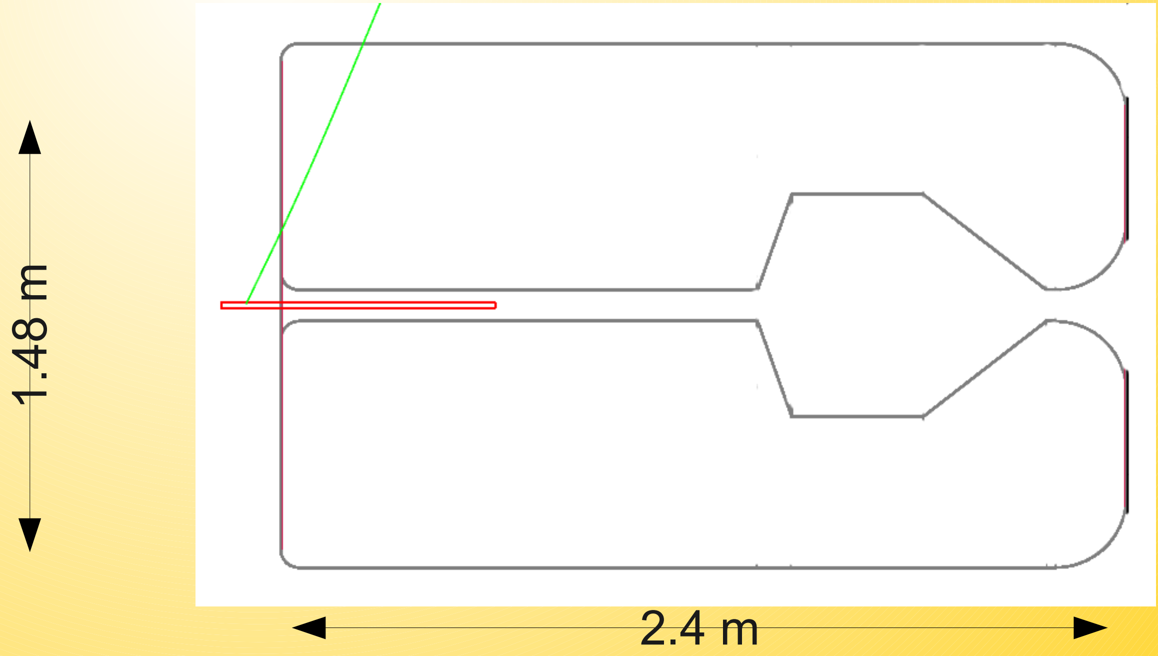
Similar procedure but with less statistics/iterations

Higher currents are preferred by sensitivity-based ranking



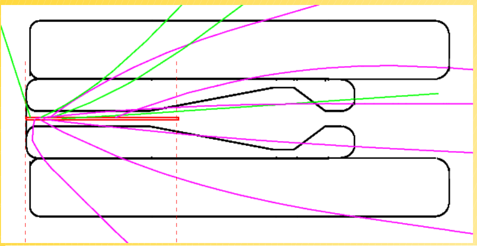


L_{tun} = 28 m
r_{tun} = 1.8 m
z_{tar} = -0.171 m
L_1 = 130.269 cm
L_2 = 9.69801 cm
L_3 = 37.6085 cm
L_4 = 35.0146 cm
L_5 = 2.50632 cm
R = 20.0991 cm
r = 5.08 cm
R_0 = 4.58477 cm
R_2 = 31.6614 cm
R_1 = 74.2263 cm
I = 389952 A

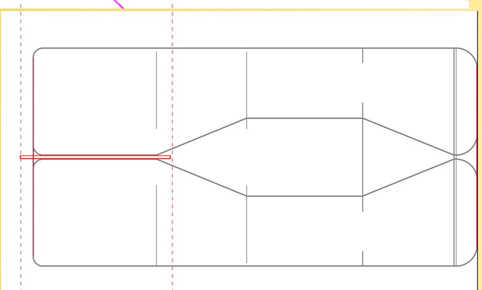


Sensitivity curves for tuned configurations

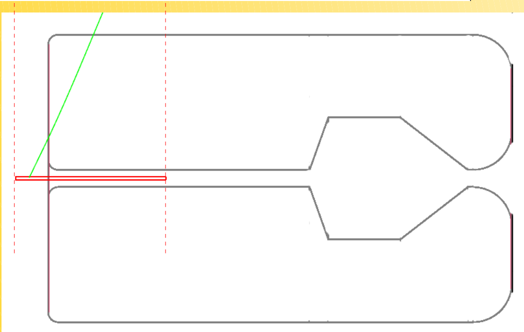
Conical horns (see next presentation by Christoph)
MiniBoone 300+600 kA 4 cm inner r
MiniBoone 300 kA 1.2 cm inner r
MiniBoone 400 kA 4 cm inner r



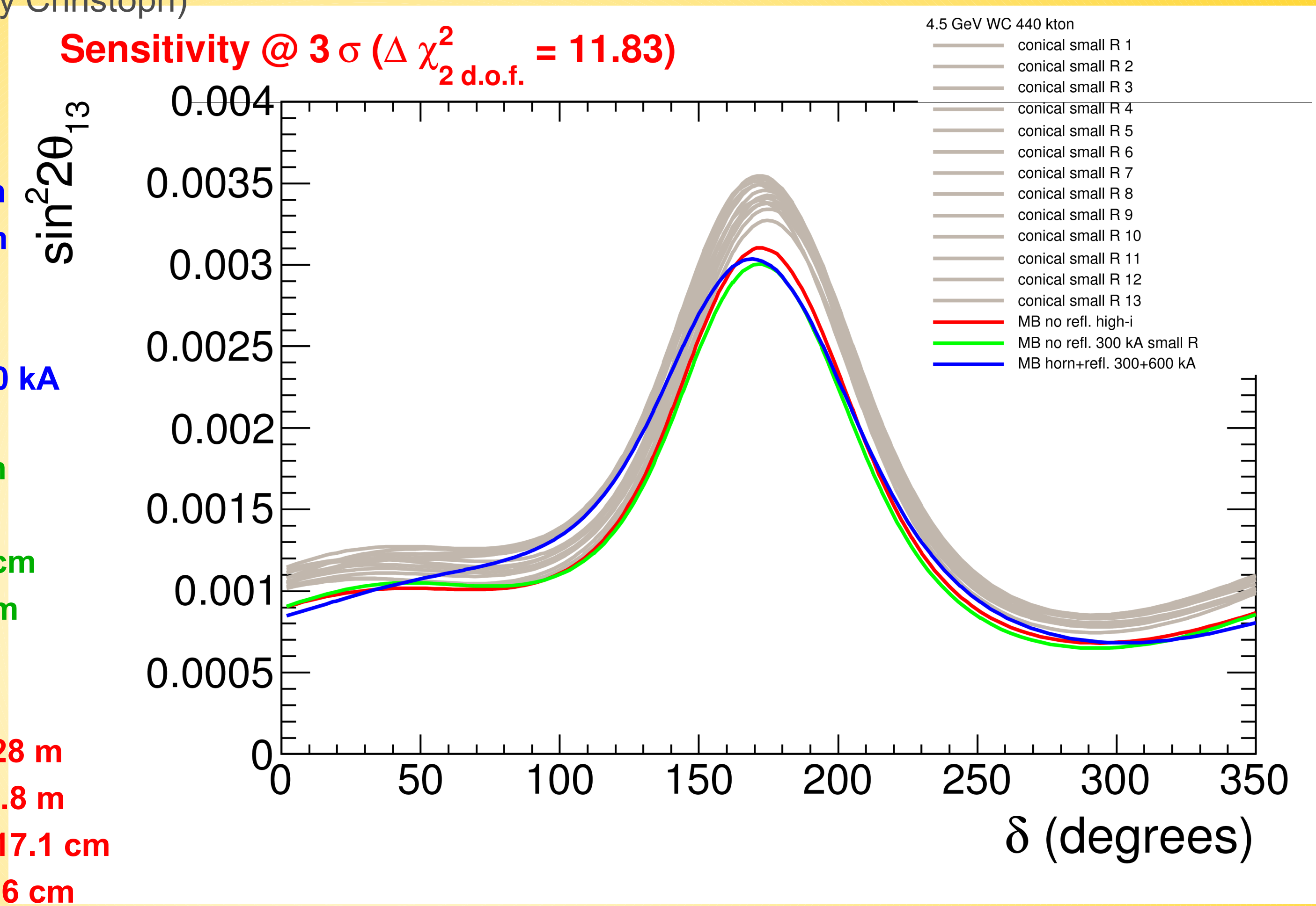
L_{tun} = 28 m
r_{tun} = 1.8 m
z_{tar} = 0 cm
R_0 = 4 cm
I = 300/600 kA



L_{tun} = 25 m
r_{tun} = 2 m
z_{tar} = -6.8 cm
R_0 = 1.2 cm
I = 300 kA

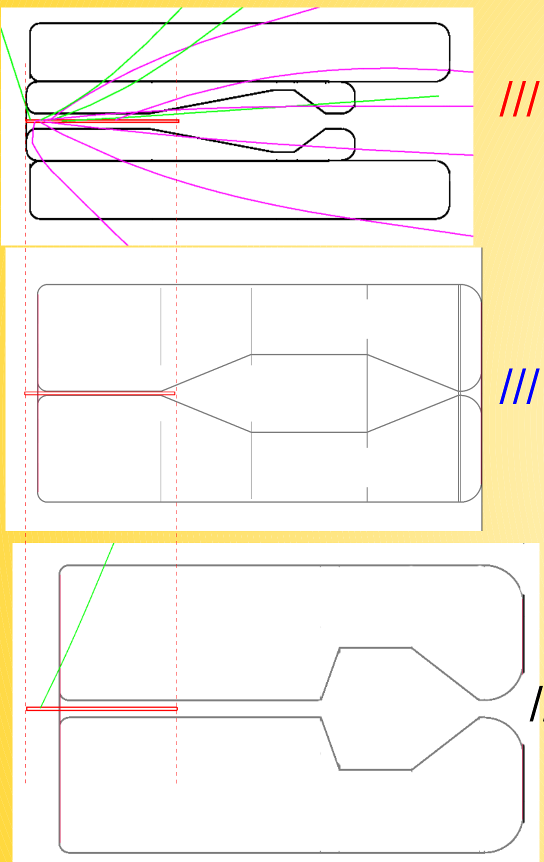


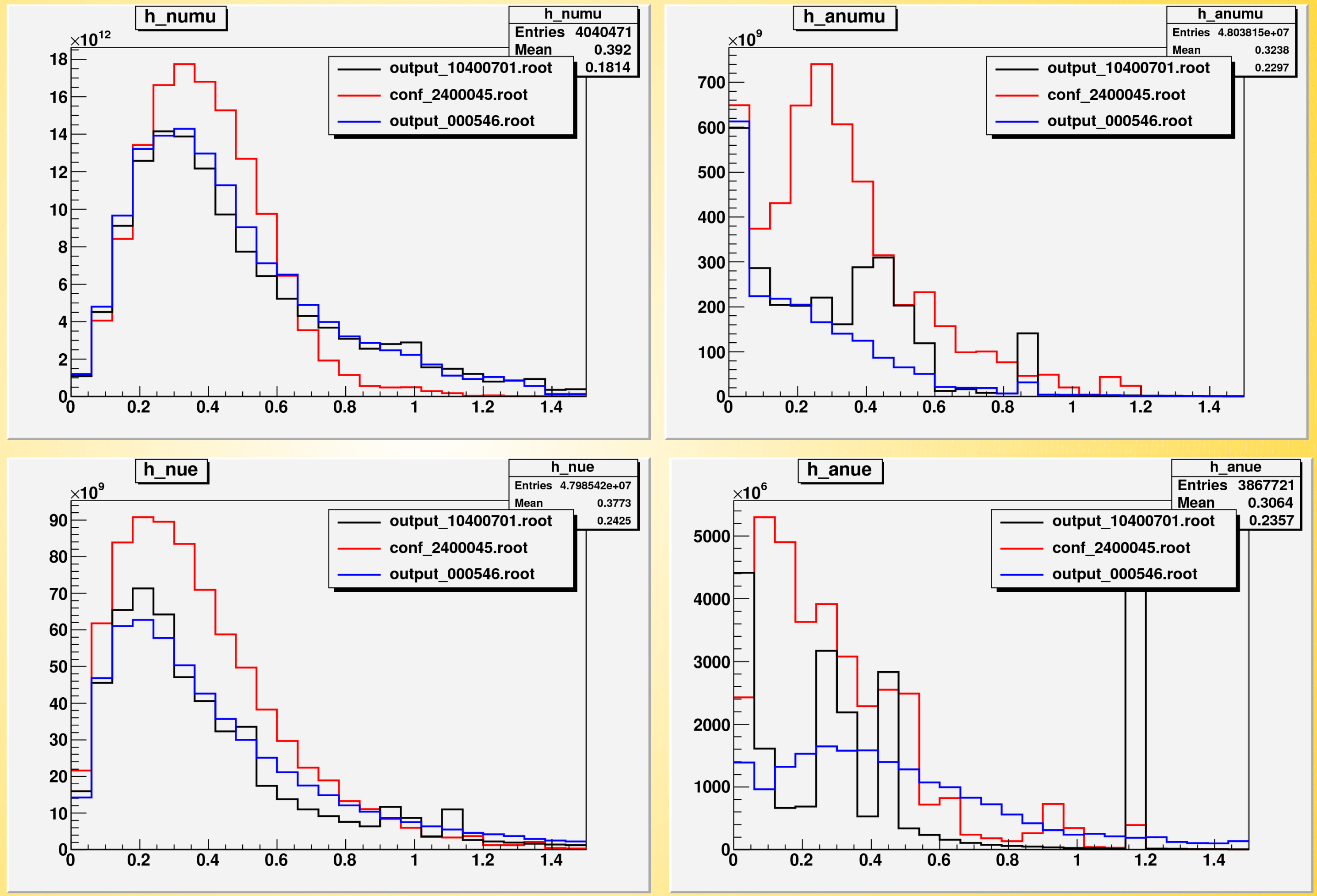
L_{tun} = 28 m
r_{tun} = 1.8 m
z_{tar} = -17.1 cm
R_0 = 4.6 cm
I = 390 kA



- similar/better exclusion obtainable even without reflector
  - using high current (400 kA and large outer radius) or
  - using 300 kA current and allowing for a small inner radius 1.2 cm
- conical shapes worse on average p
  - perform an optimization with similar tools

Fluxes for tuned configurations

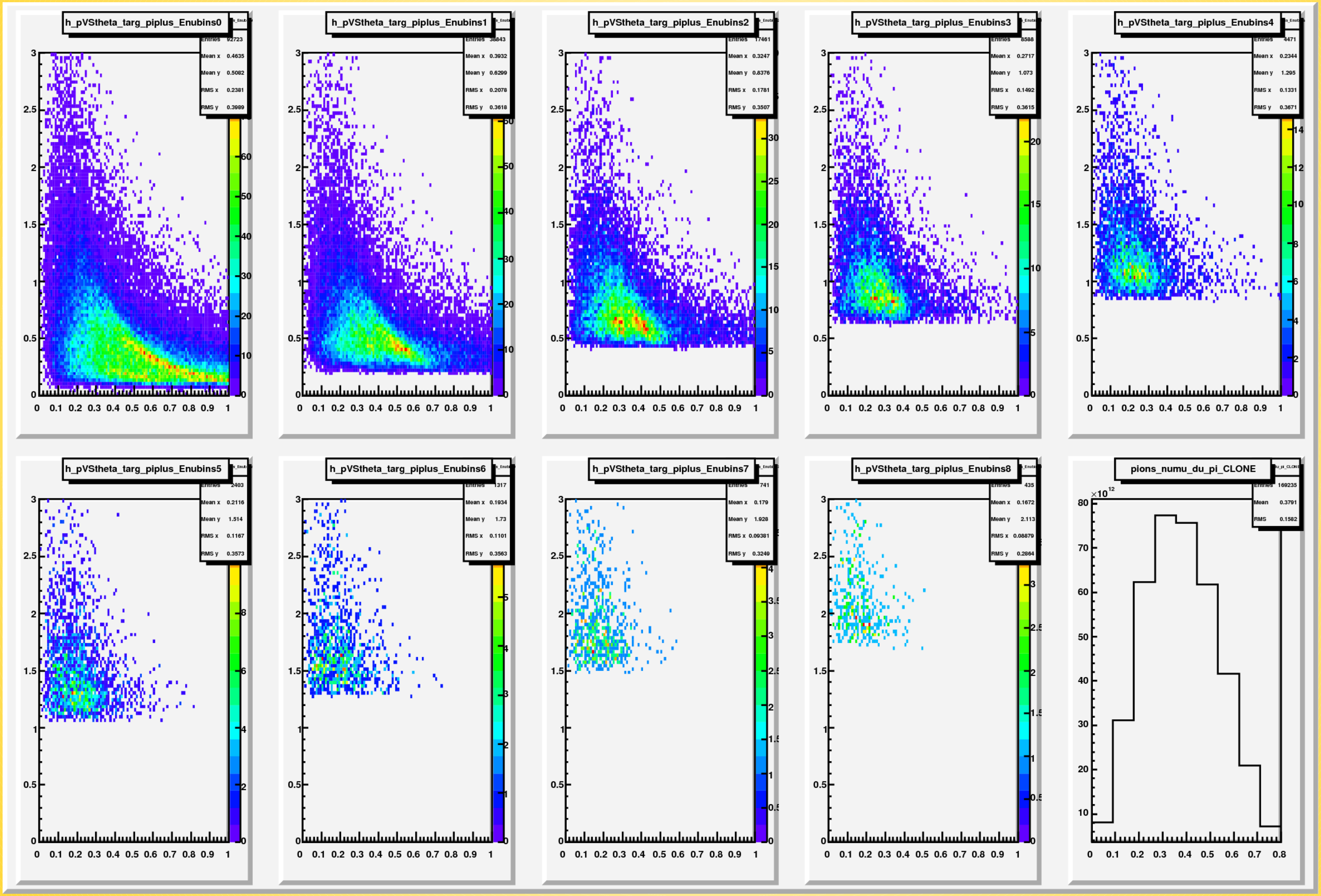




Which are the "relevant" pions ?*

***with the horn+refl setup (300+600 kA)**

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

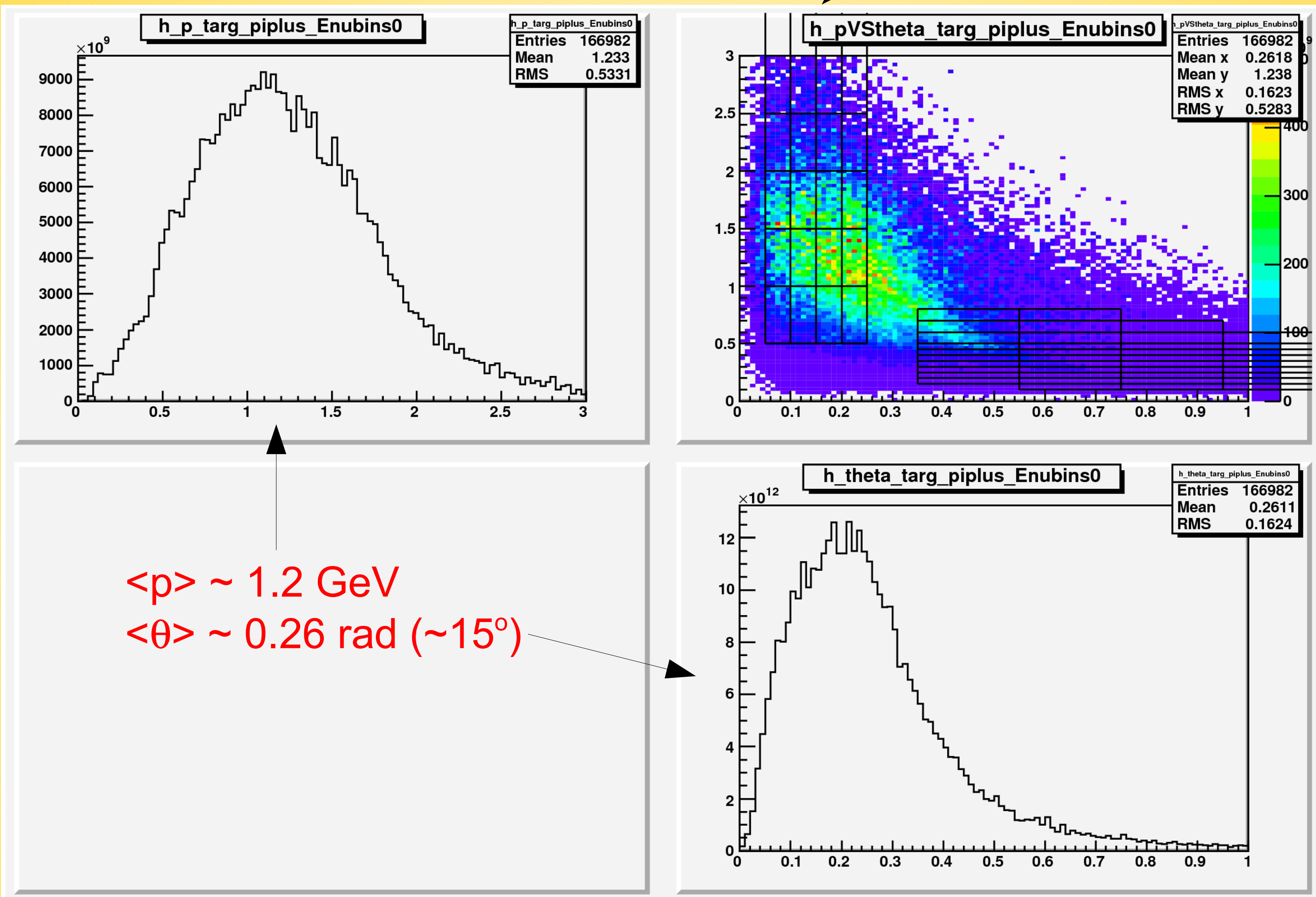


High energy neutrinos are produced by low angle, high momentum pions

Which are the “relevant” pions ?

* Add these weighted contributions

Small angle

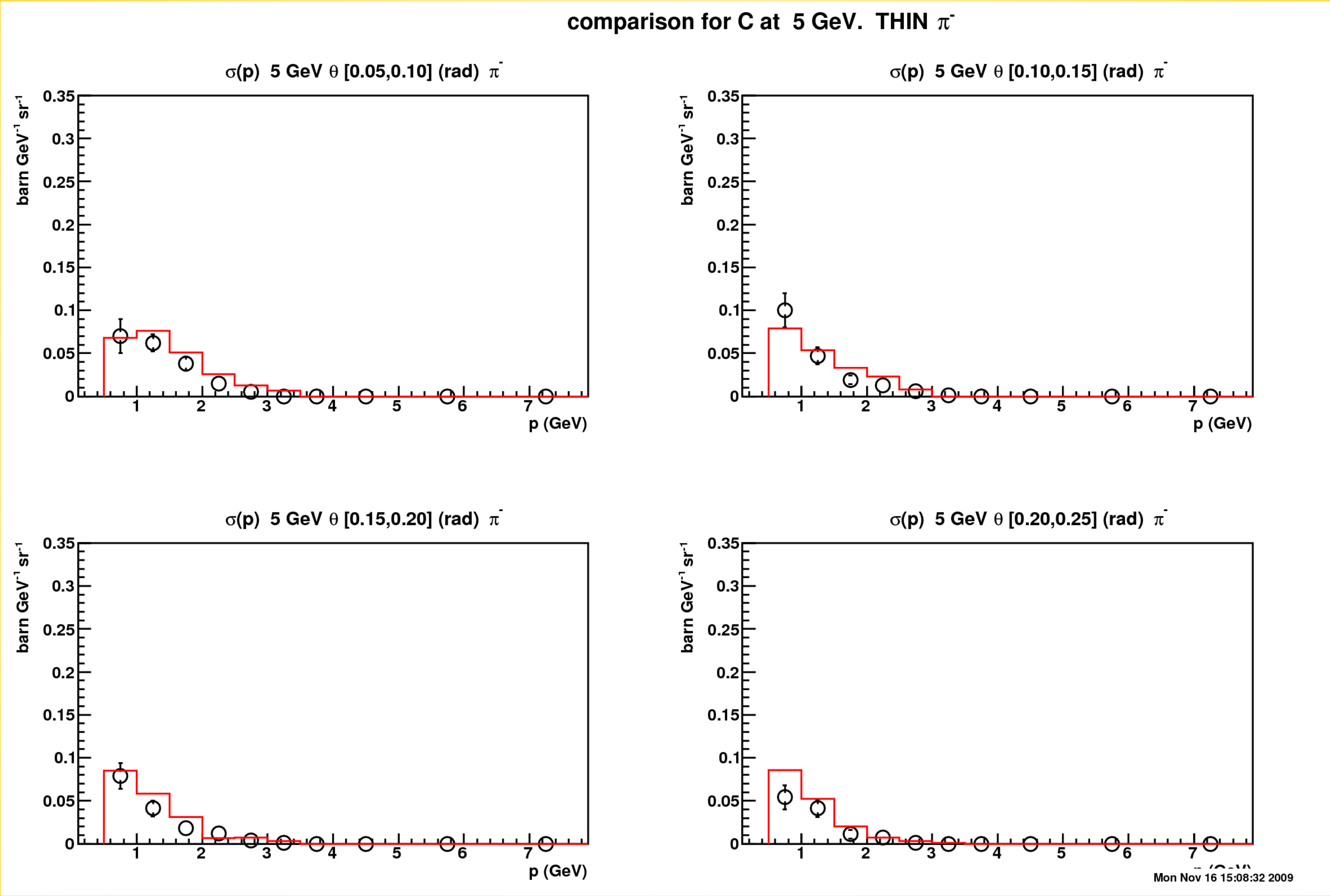


HARP bins indicated with lines

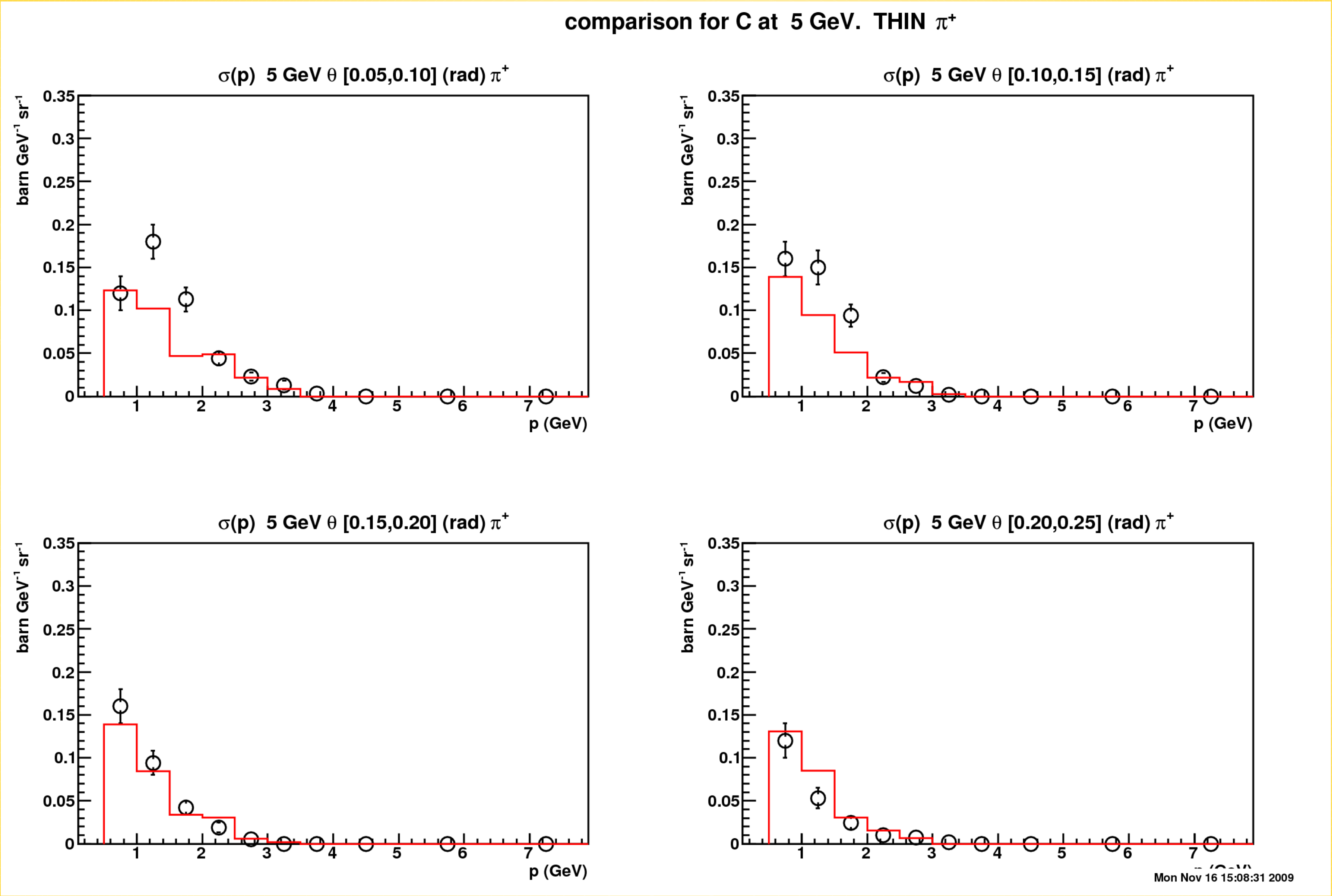
Large angle

“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”

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

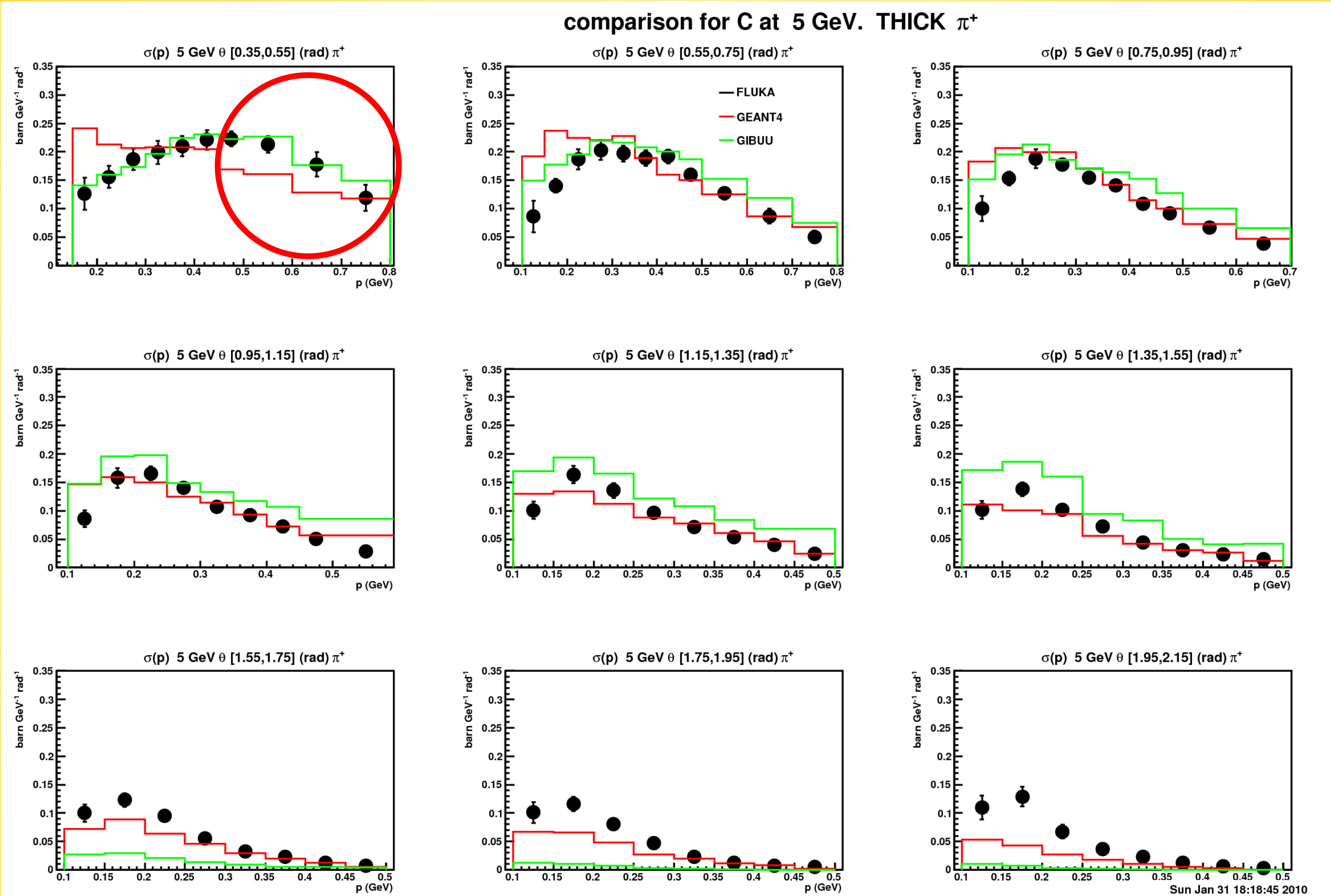


HARP-GEANT4. Small angle. THIN target. C. 5 GeV. pi+



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

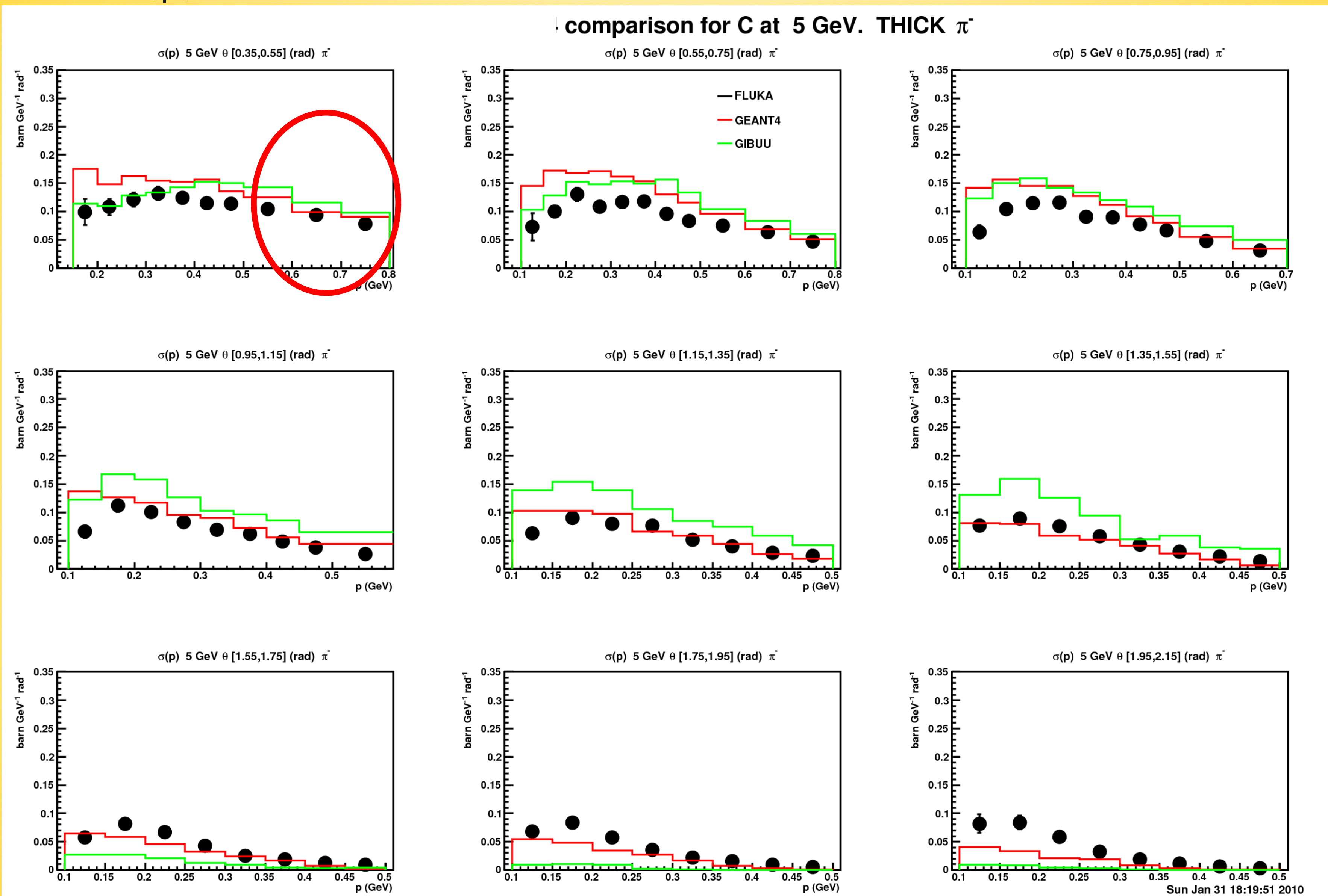
σ(p) in θ bins



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

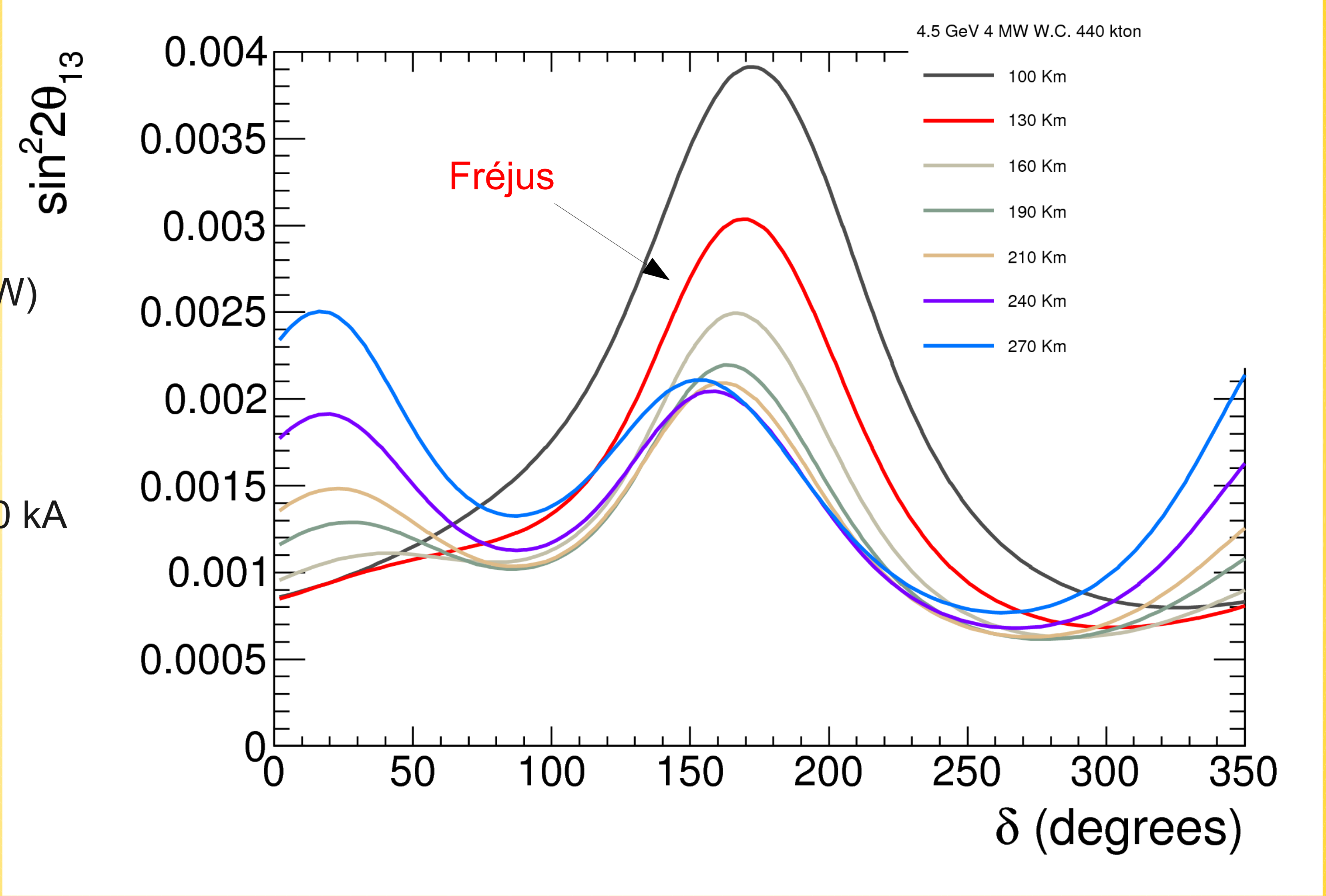
HARP-GEANT4-GIBUU. Large angle. THICK target. C. 5 GeV. pi-

σ(p) in θ bins



tends to underestimate production at large angles

An exercise: SPL→W.Ch. at L≠130 km ?



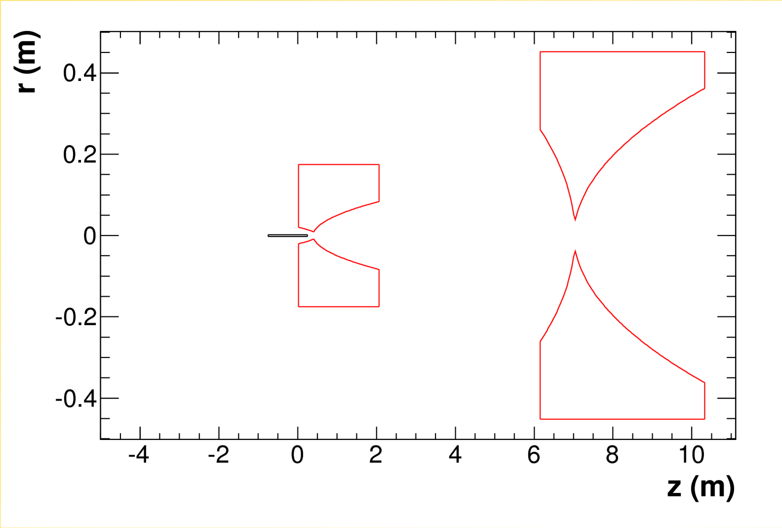
* HP-SPL 4.5 GeV
* $5.6 \cdot 10^{22}$ pot/y (4MW)
* 2 % sys err.
* 440 kton W.Ch.
* 8+2 years
* 3σ C.L.
* horn+refl. 300+600 kA

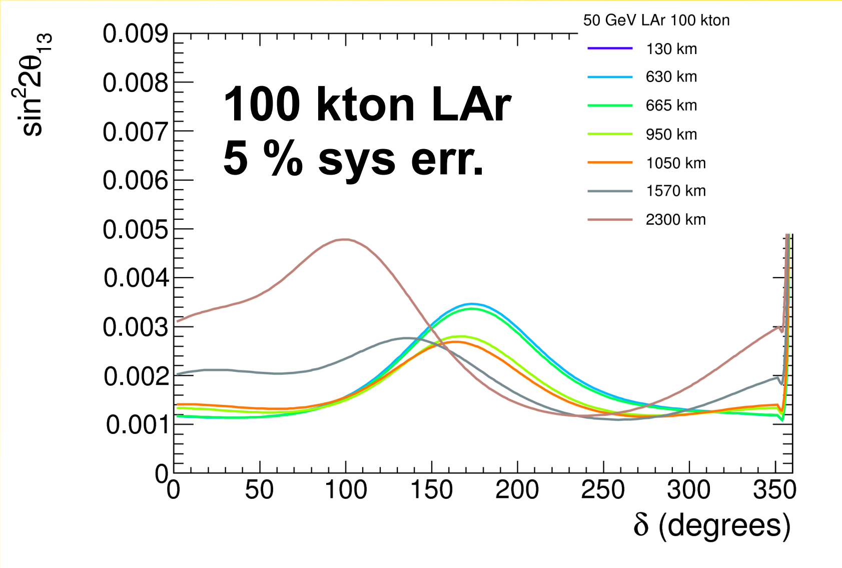
The new focusing produces spectra with higher mean energy so that longer baselines ~ 160-200 Km become favored

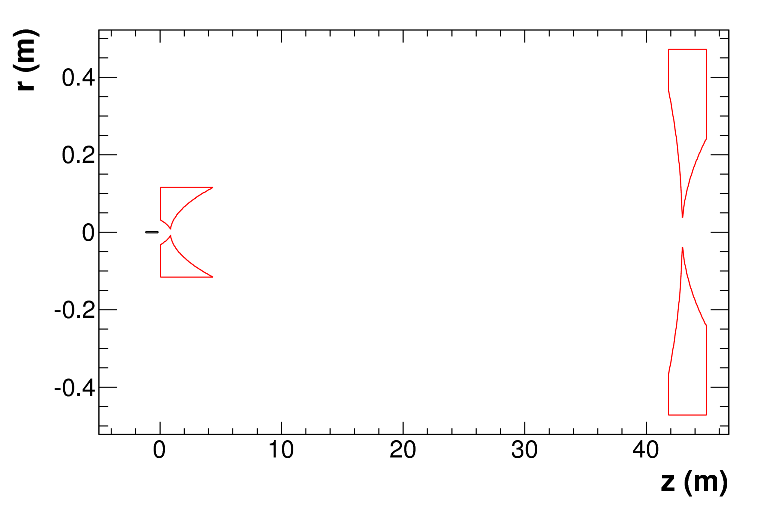
Other Super Beam options (@ higher E, L)

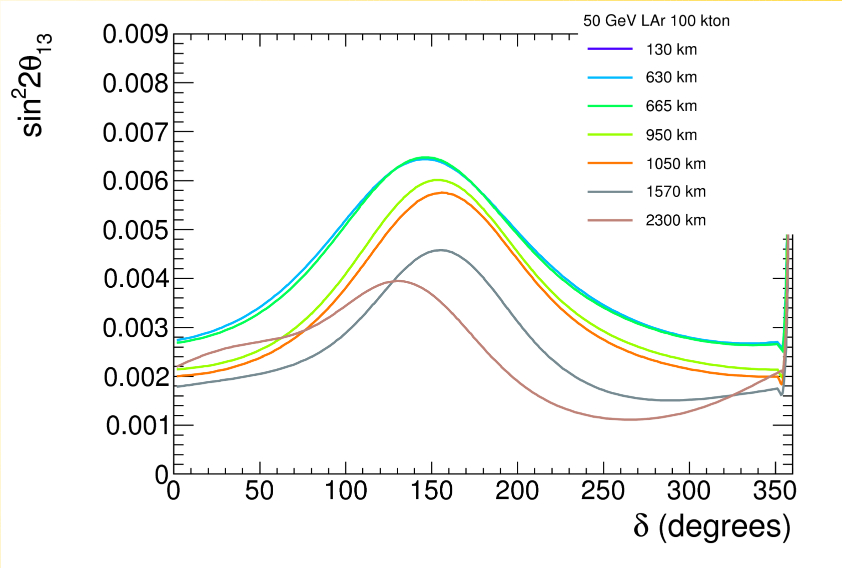
The GEANT4 simulation and optimization tools are being used to study Super Beams from a 50 GeV proton driver ("HP-PS2") to LAGUNA sites equipped with a 100 kton LAr detector

study ongoing within the LAGUNA-WP2 (physics)

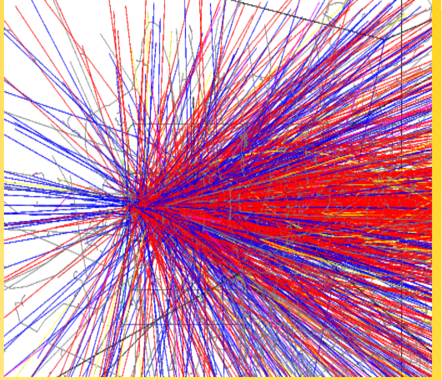








Conclusions



Reliable GEANT4 simulation

Horn optimization tool based on sensitivities developed and working

3 optimized focusing designs studied and proposed.

- horn+reflector (300-600 kA)
- horn w/ small inner radius – integrated target 300 kA
- horn w/ larger inner radius and higher current (~400 kA)

Similar sensitivities. Different technical aspects involved. To be discussed.

4 horn concept viable under the point of view of fluxes/sensitivity. Current baseline for the solid target option

Systematic effects on primary pion production. HARP data to re-weight the simulated spectra. To be finalized

Other baselines-energy-detector being looked upon in the context of LAGUNA

Systematics on primary pion production

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!)

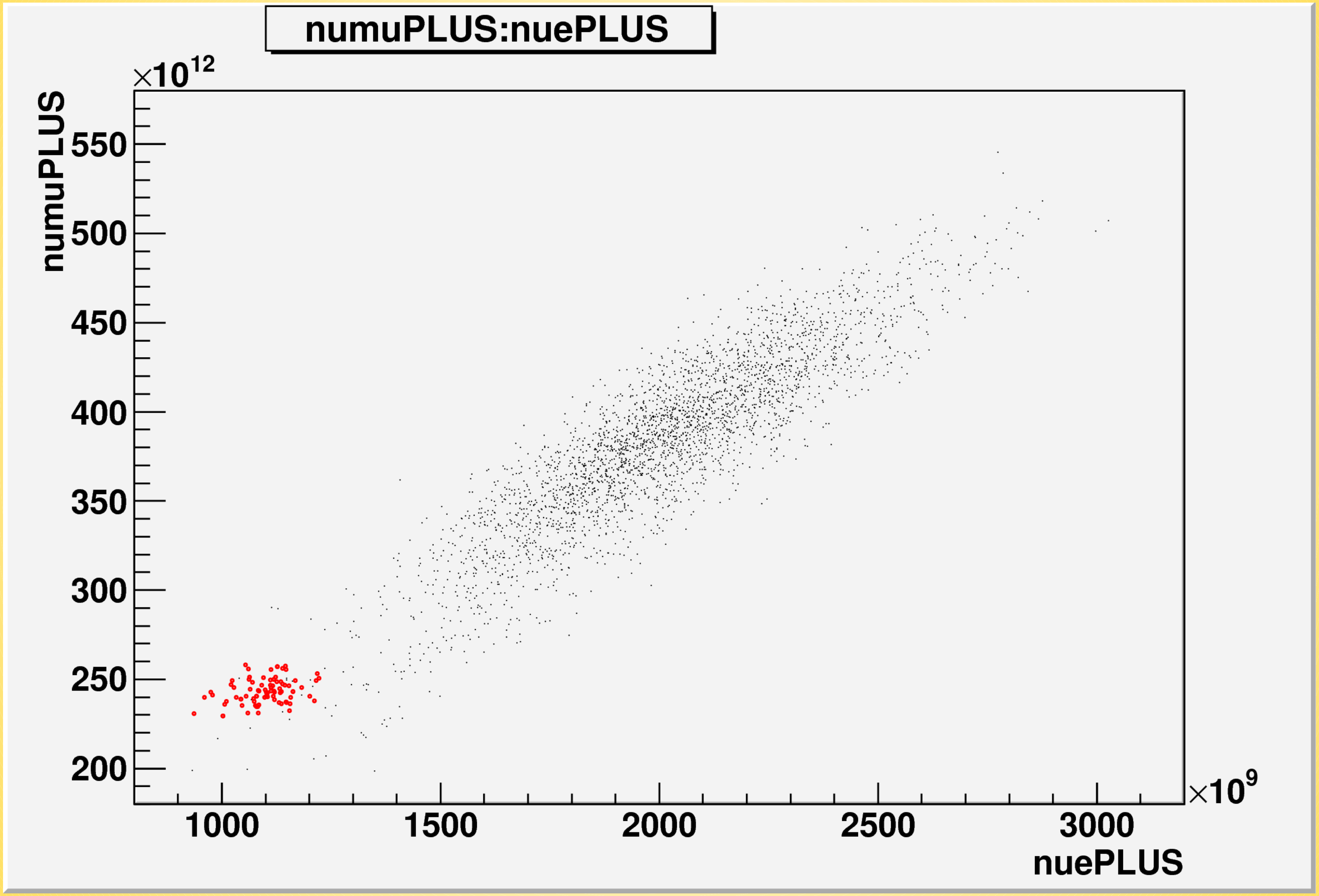
$$\frac{\mathrm{d}^2\sigma}{\mathrm{dp_i d}\theta_\mathrm{j}} = \frac{1}{N_{pot}} \frac{A}{N_A \rho t} \sum_{i',j'} M^{-1}_{iji'j'} \cdot N_{i',j'}$$

- 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.

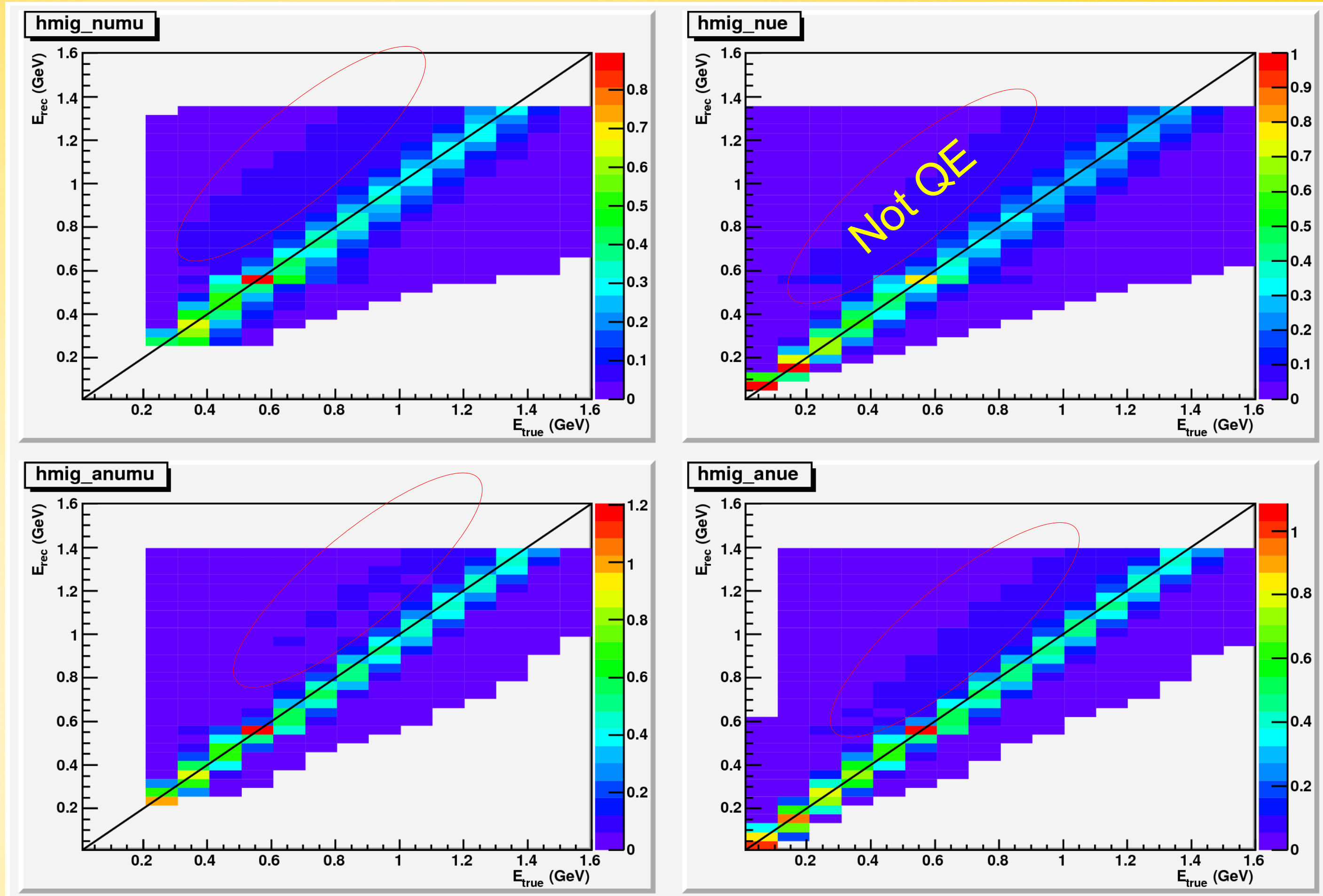
Effect of limited statistics



100.000 pots sample

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

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

Reference:

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

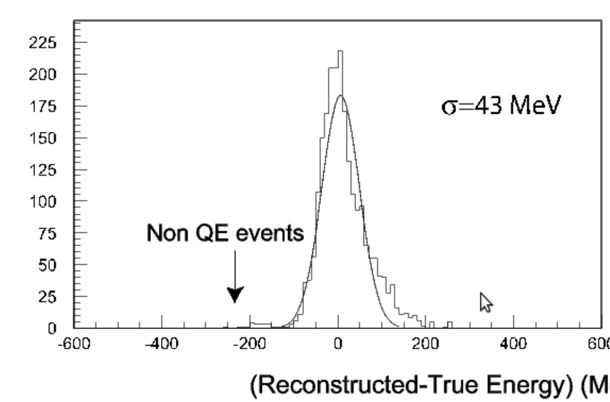
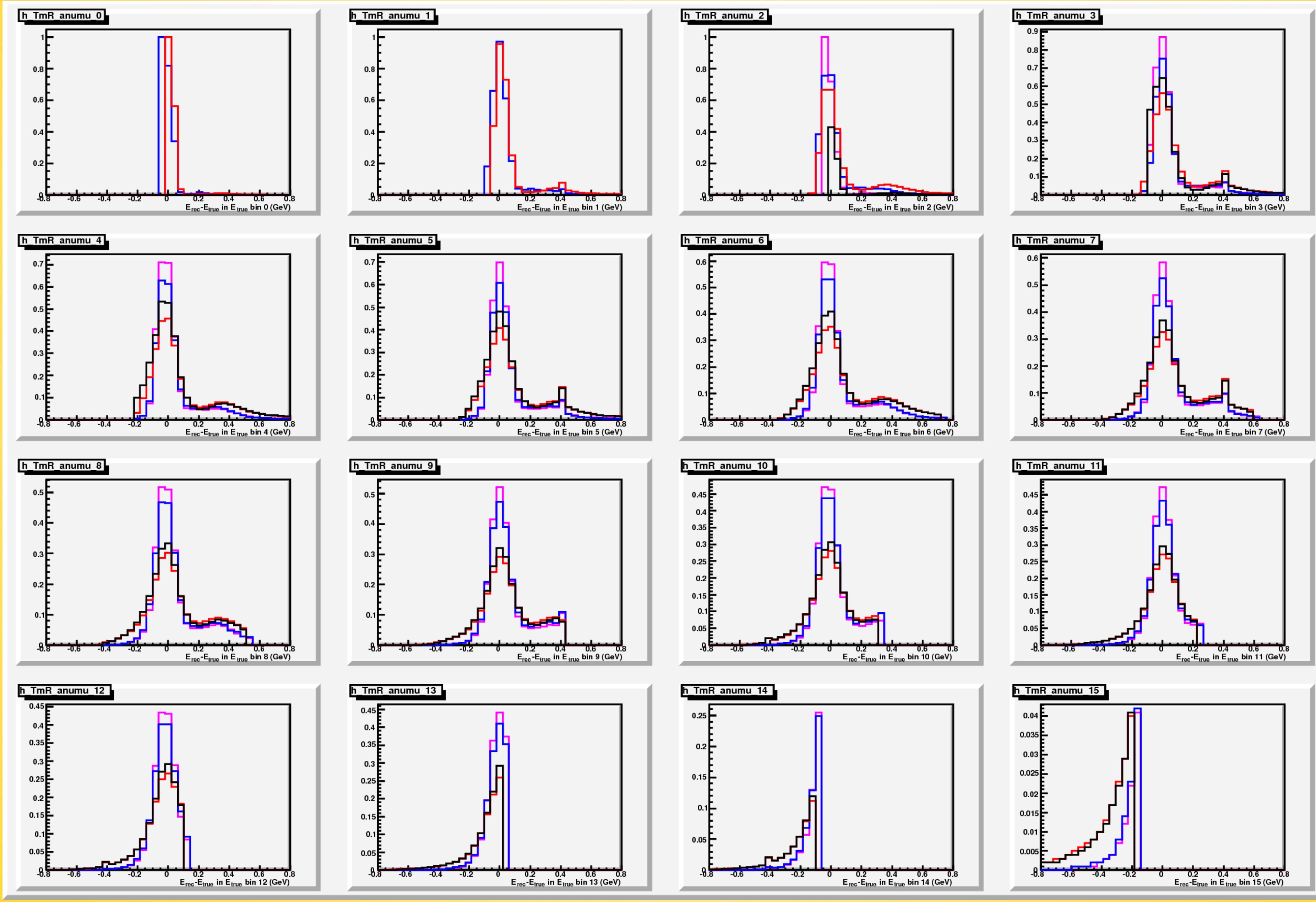


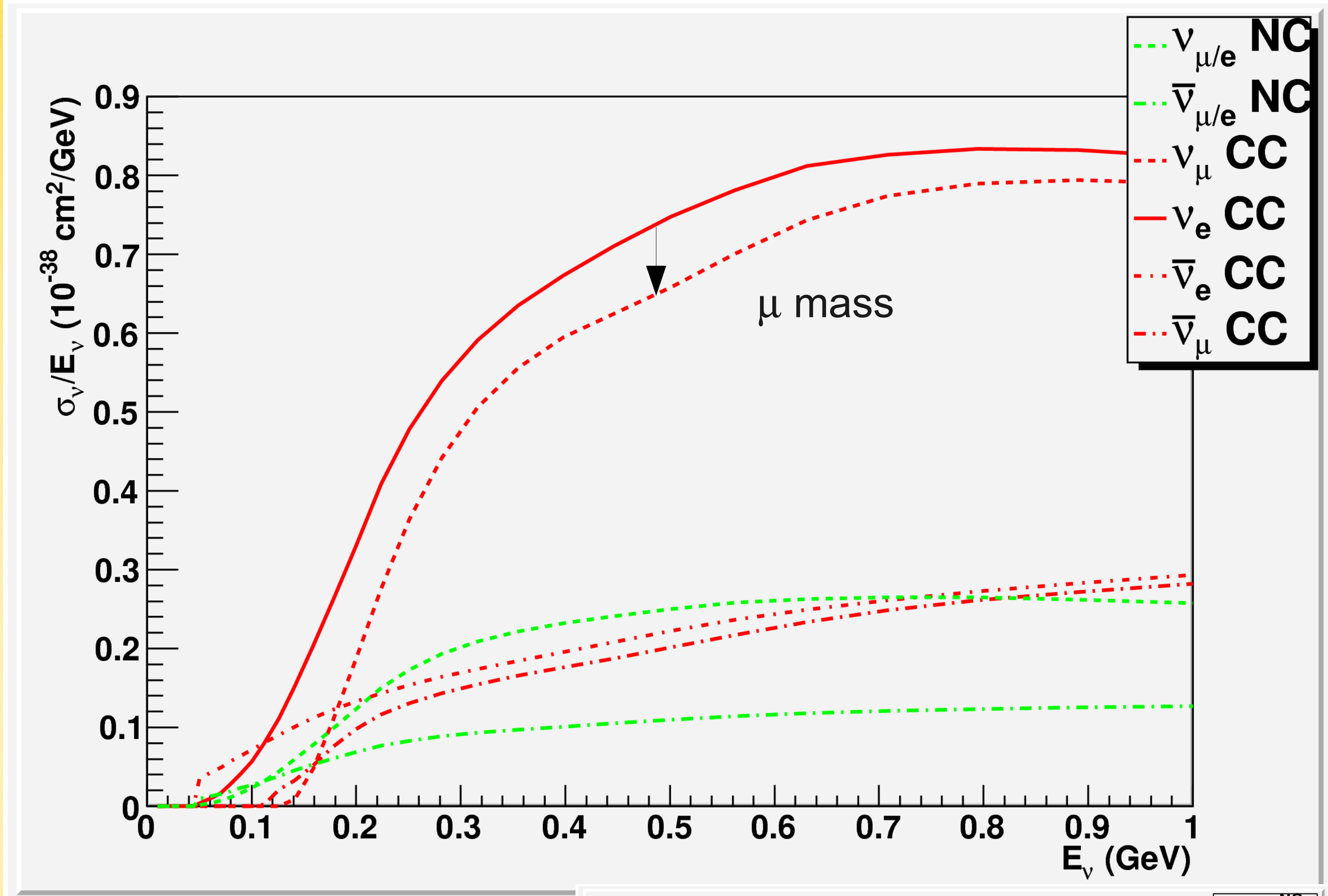
Figure 2: Energy resolution for ν_e interactions in the 200–300 MeV energy range. The quantity displayed is the difference between the reconstructed and the true neutrino energy.

A. Longhin

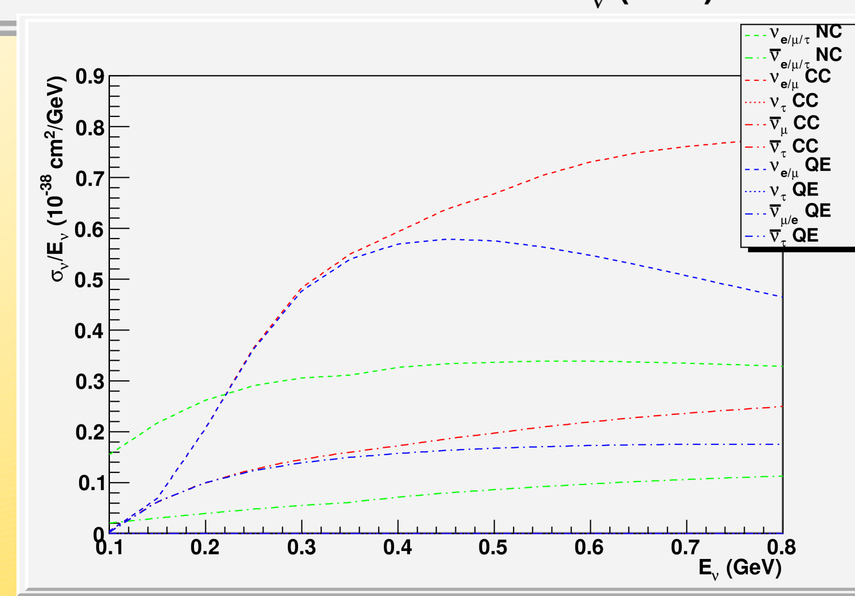
GLOBES resolution

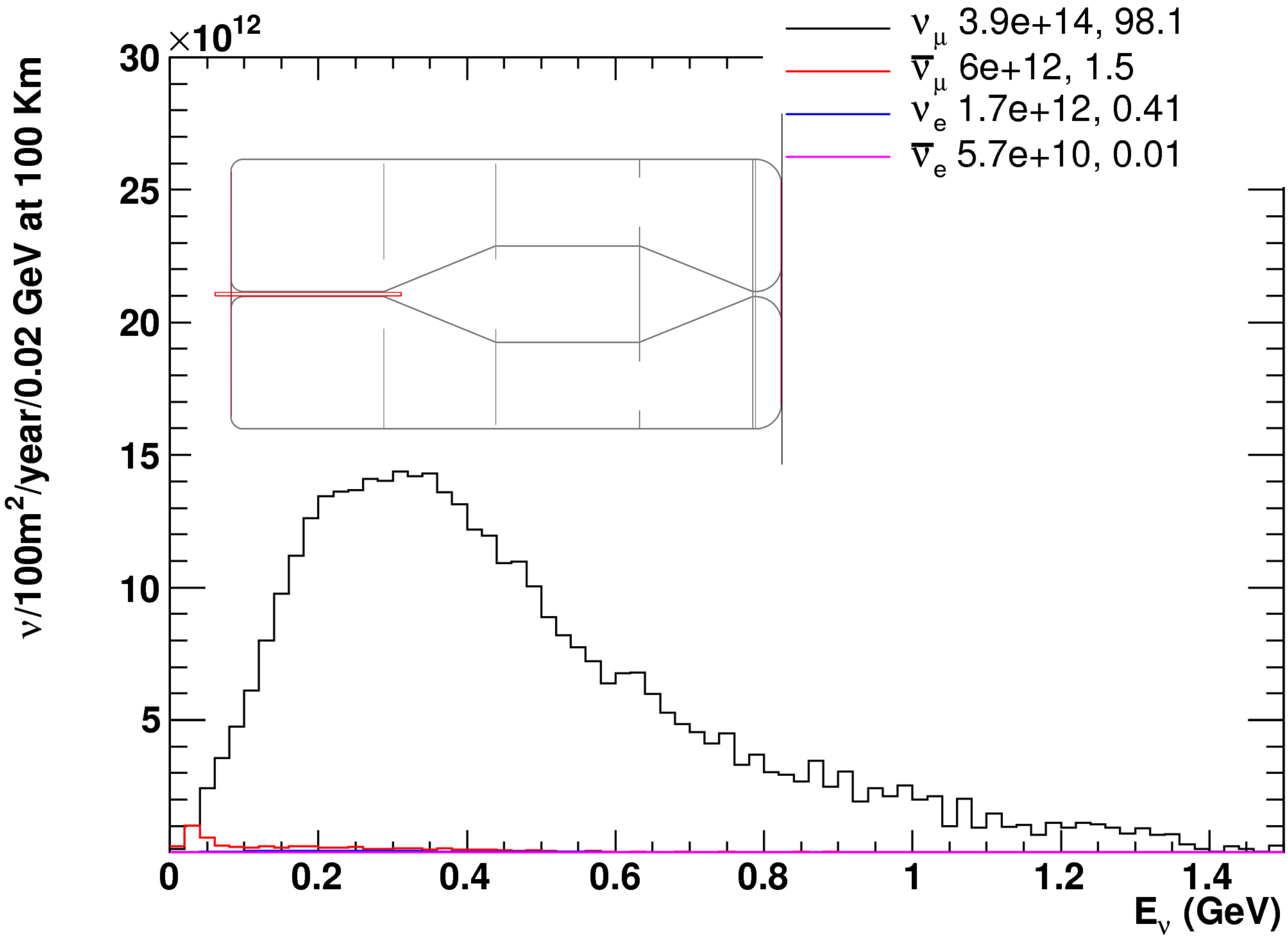


GLOBES neutrino cross sections



Purely Quasi elastic up to ~ 400 MeV





ν_μ 3.9e+14, 98.1
$\bar{\nu}_\mu$ 6e+12, 1.5
ν_e 1.7e+12, 0.41
$\bar{\nu}_e$ 5.7e+10, 0.01
$\times 10^{12}$
30
25
20
15
10
5
0
0.2
0.4
0.6
0.8
1
1.2
1.4
$\nu/100m^2$/year/0.02 GeV at 100 Km
E_ν (GeV)

Cross-check: ν counting

To validate: 1) probability approach 2) off-axis treatment

Select neutrinos generated by GEANT4 decays in narrow cones around the forward direction and off axis direction

Easier with high energy beam. Done for the NOvA configuration.

$\Omega = 1 / (4\pi L^2)$ (1 m^2 at 810 Km) ~ 1.5 prad

considered 8 cones of semi-aperture:

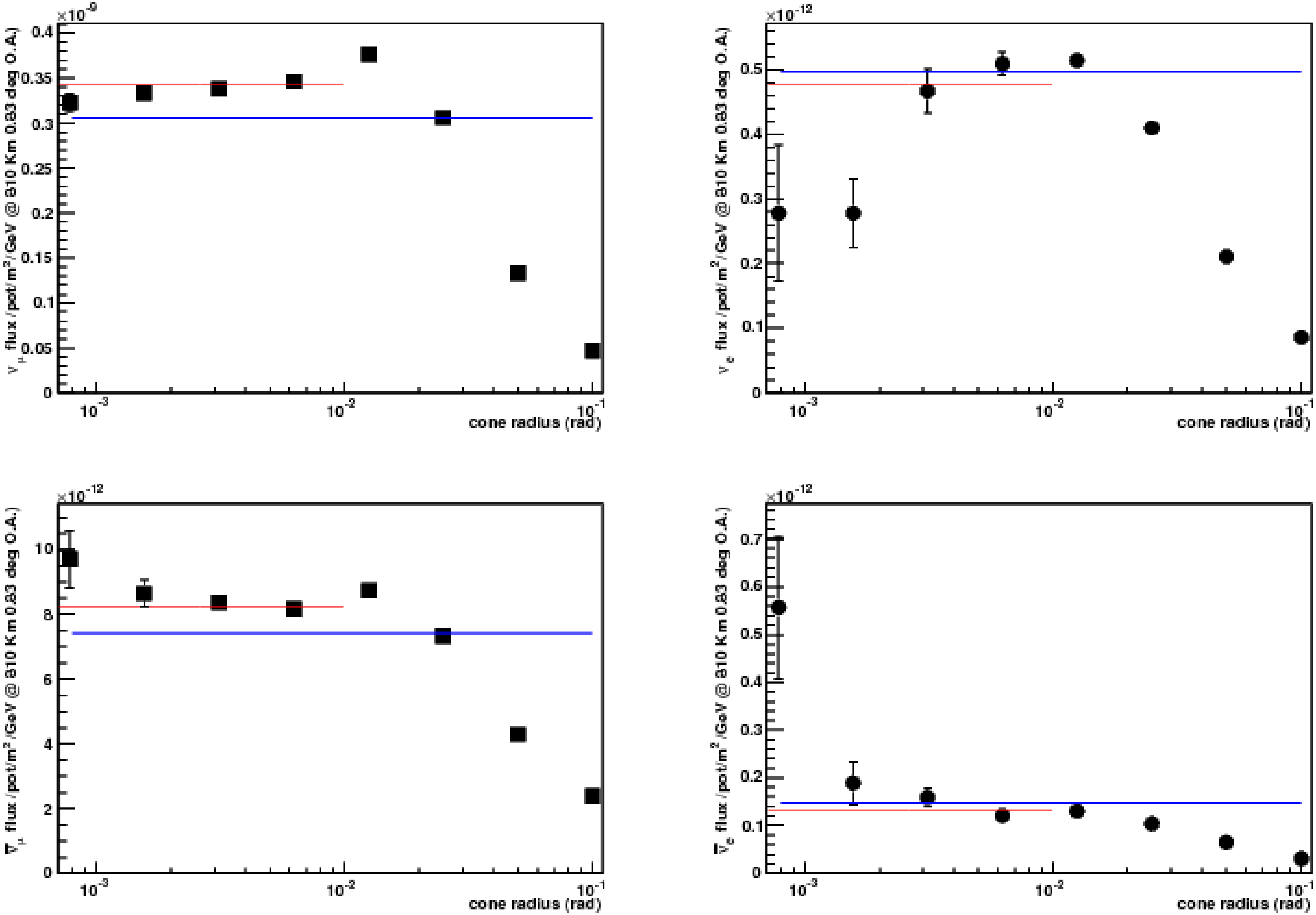
α =0.1-0.05-0.025-0.0125-0.00625-0.003125-0.0015625-0.00078125

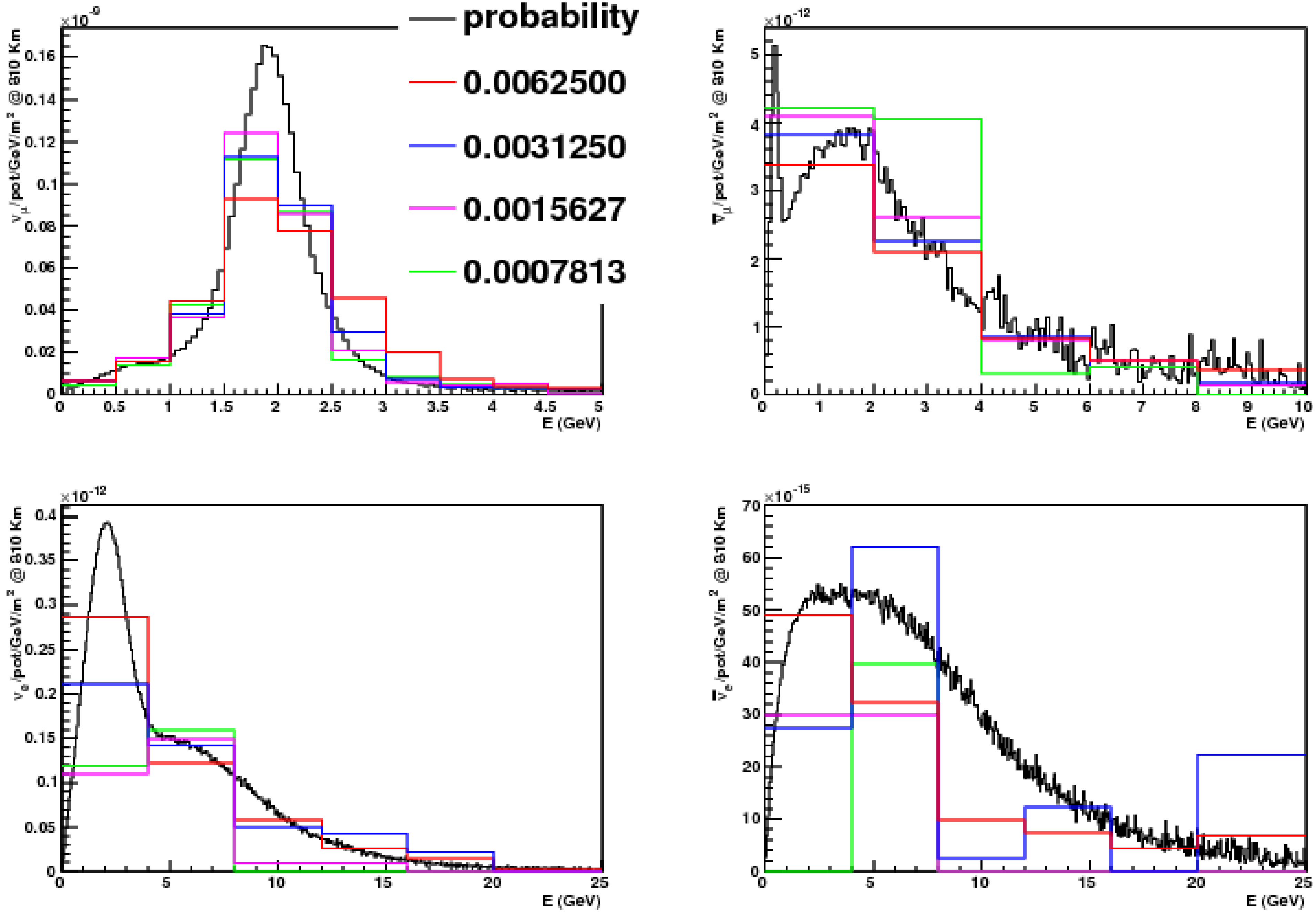
solid angles Ω' (prad):

$\Omega' = 2\pi (1 - \cos\alpha)$ = 3.1e10/7.8e9/2.0e9/4.9e8/1.2e8/3.1e7/7.7e6/1.9e6

last cone ~ a detector ~ 630 m x 630 m

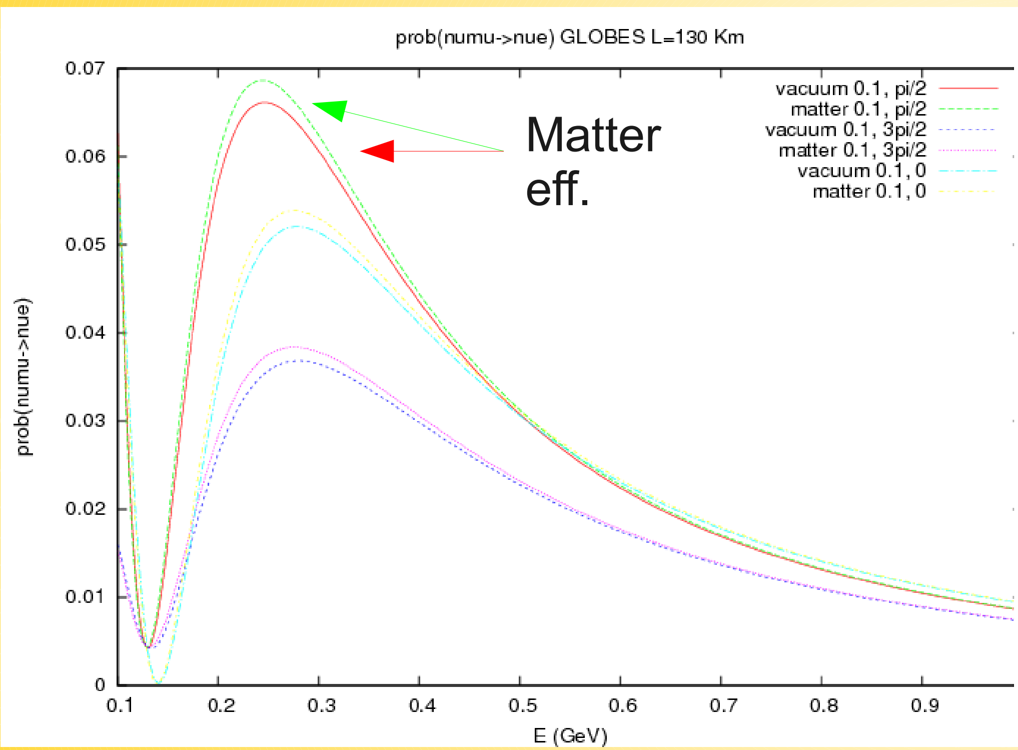
scale fluxes obtained with counting neutrinos in the cone by Ω/Ω'


×10⁻⁹
ν μ flux / pot/ m²/ GeV @ 810 Km 0.83 deg O.A.)
cone radius (rad)
×10⁻¹²
ν e flux / pot/ m²/ GeV @ 810 Km 0.83 deg O.A.)
cone radius (rad)
×10⁻¹²
ν̄ μ flux / pot/ m²/ GeV @ 810 Km 0.83 deg O.A.)
cone radius (rad)
×10⁻¹²
ν̄ e flux / pot/ m²/ GeV @ 810 Km 0.83 deg O.A.)
cone radius (rad)

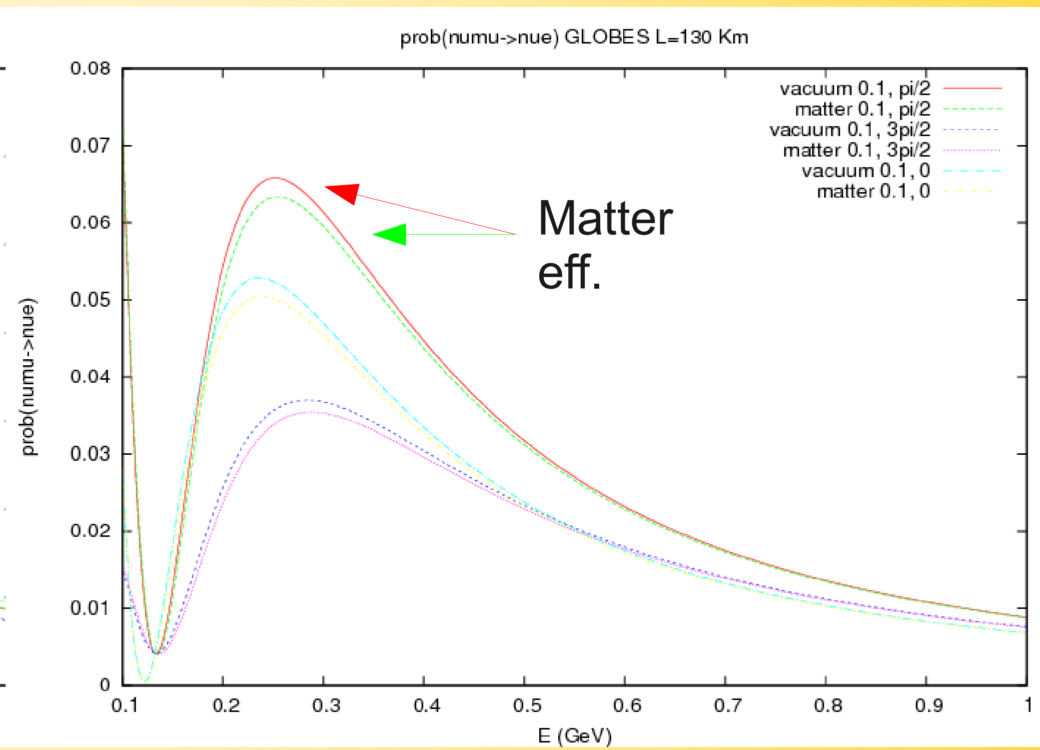

probability
0.0062500
0.0031250
0.0015627
0.0007813
E (GeV)

GLOBES oscillation probs

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



Normal hierarchy



Inverted hierarchy

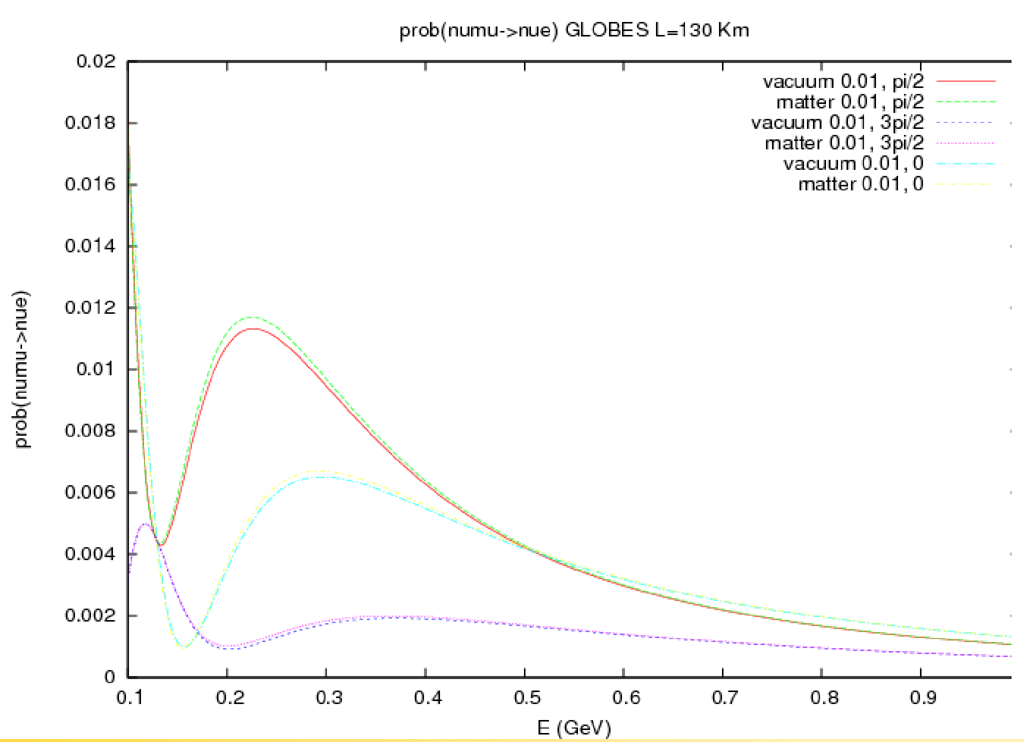
Hierarchy sensitivity through M.E. Exemplified

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

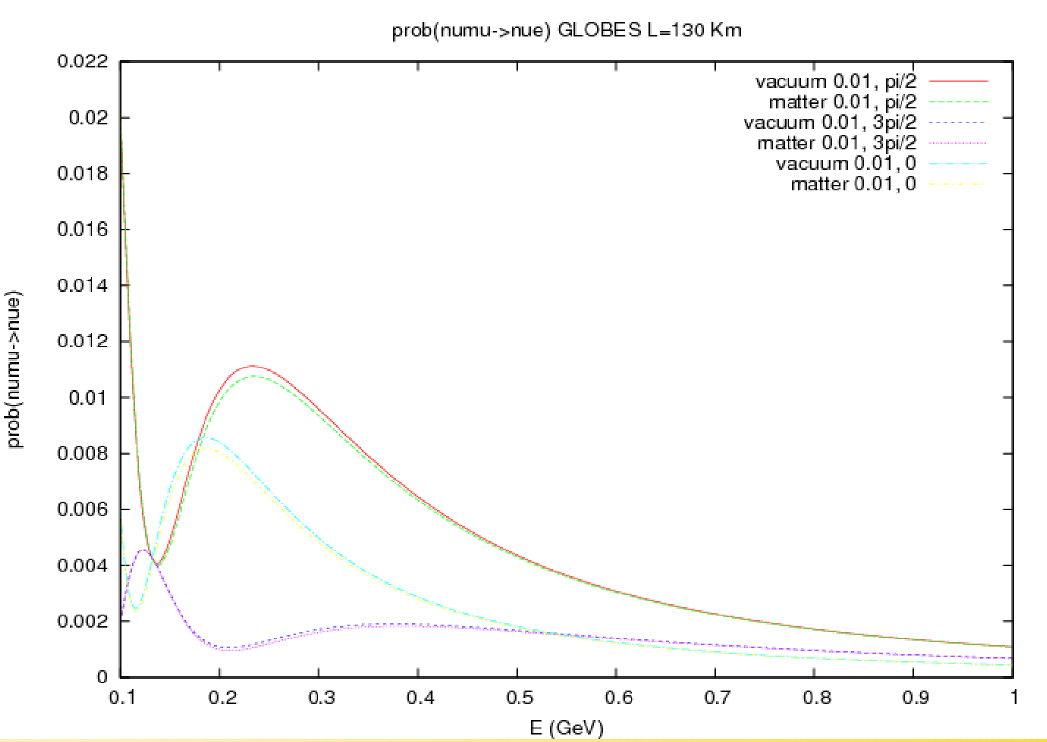
Hierarchy sensitivity from spectral shape for δ=0 ? To be checked

GLOBES oscillation probs

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



Normal hierarchy



Inverted hierarchy

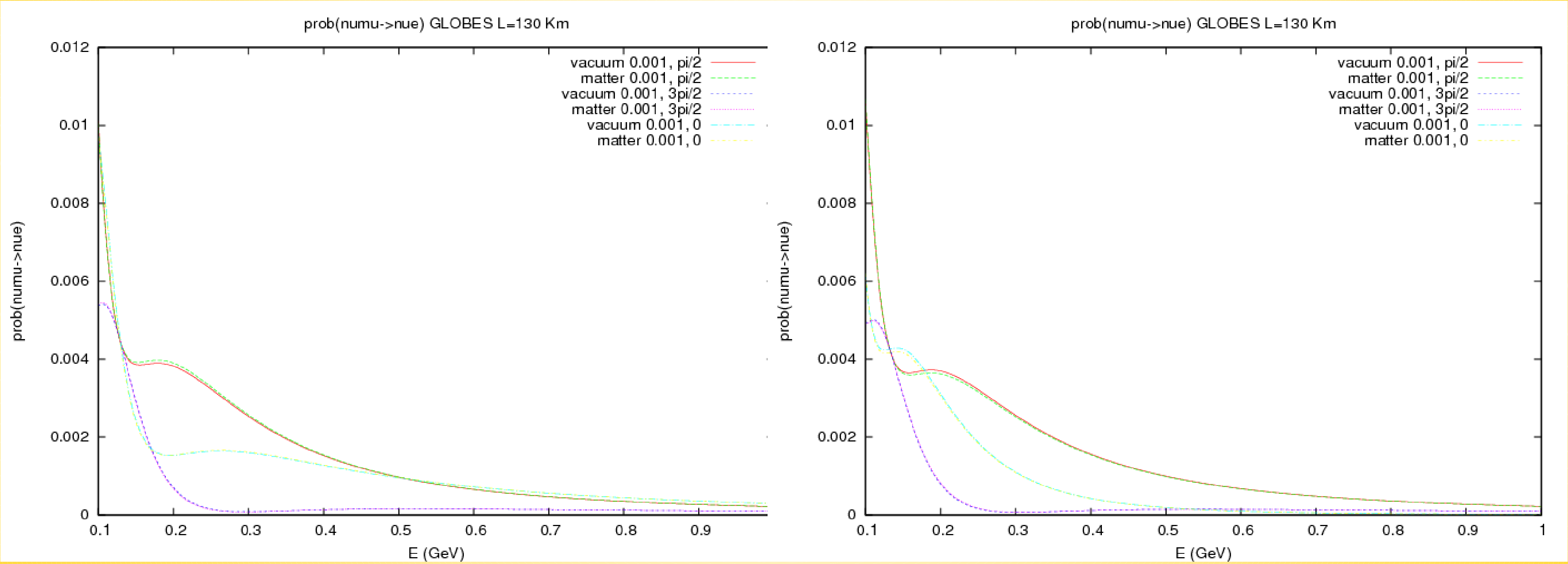
Hierarchy sensitivity through M.E. Exemplified

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

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



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

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)

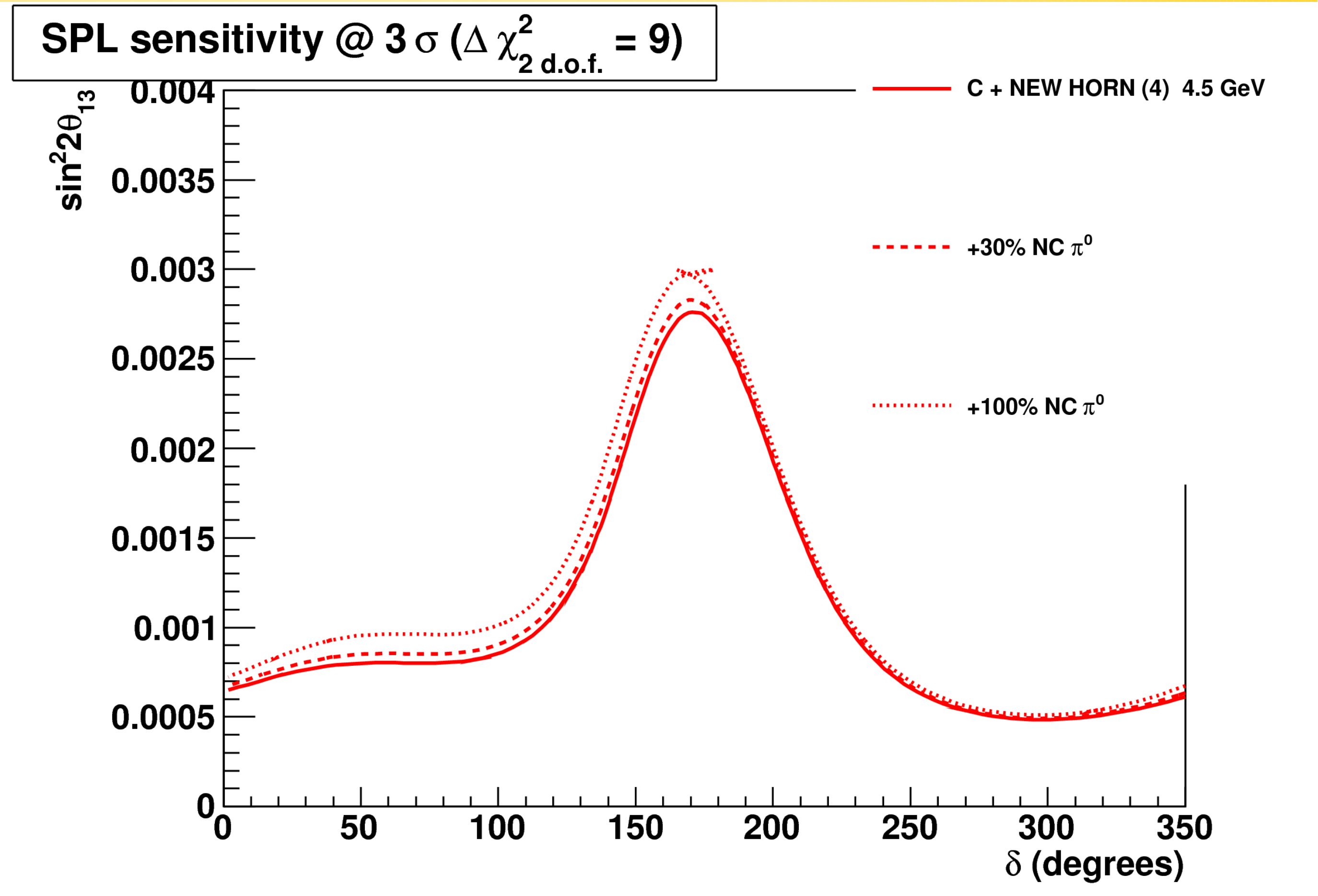
rough (conservative) variation applied to estimate the effect

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.)

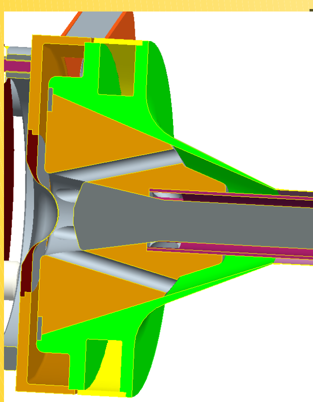
ν run: 90% ν_e , 06% NCπ^0, 3% ν_μ MIS-ID, 01% anti-ν_e

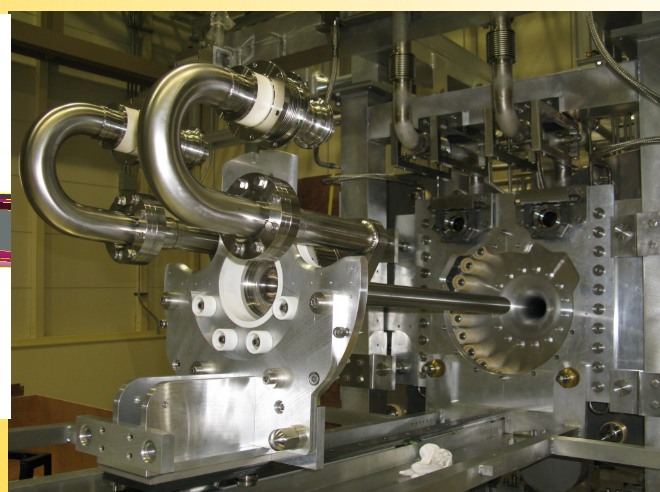
anti-ν run: 45% ν_e , 18% NCπ^0, 2% ν_μ MIS-ID, 35% anti-ν_e

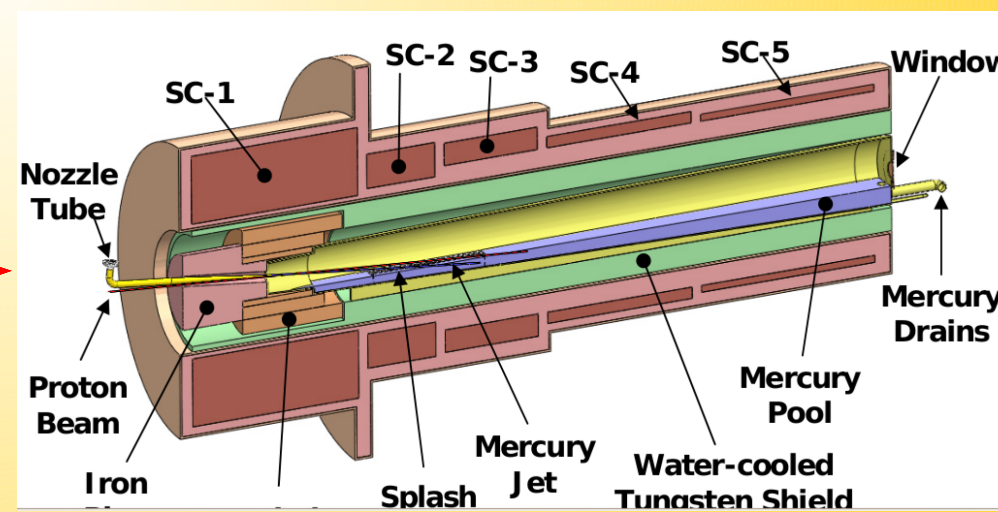
Signal eff. 70%

A graphite target: motivations

- **Integration of the Hg jet within the horn challenging**
- **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)**
- **Close collaboration within EUROnu with the team at RAL responsible for the He cooled T2K target 750 kW**

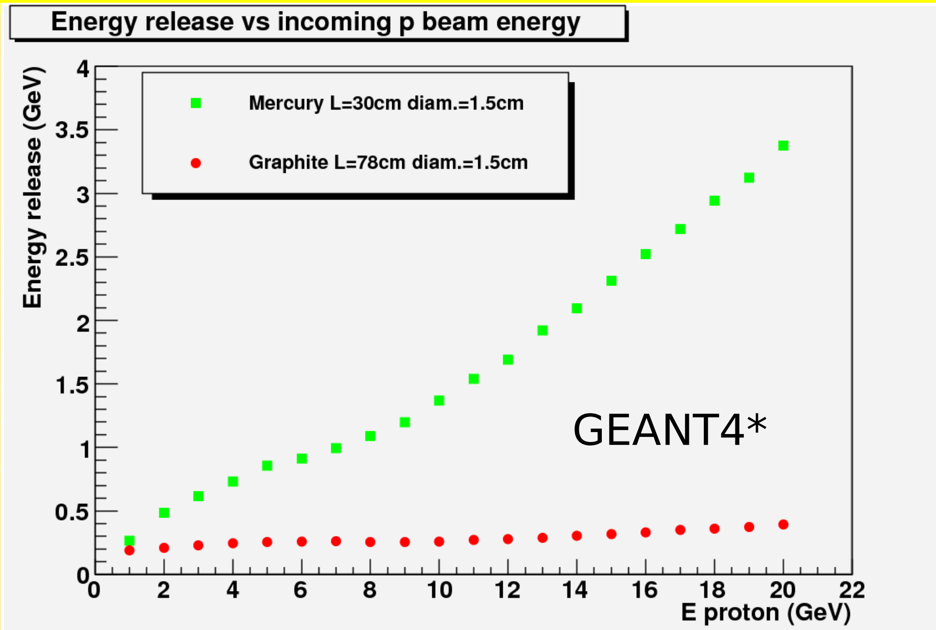




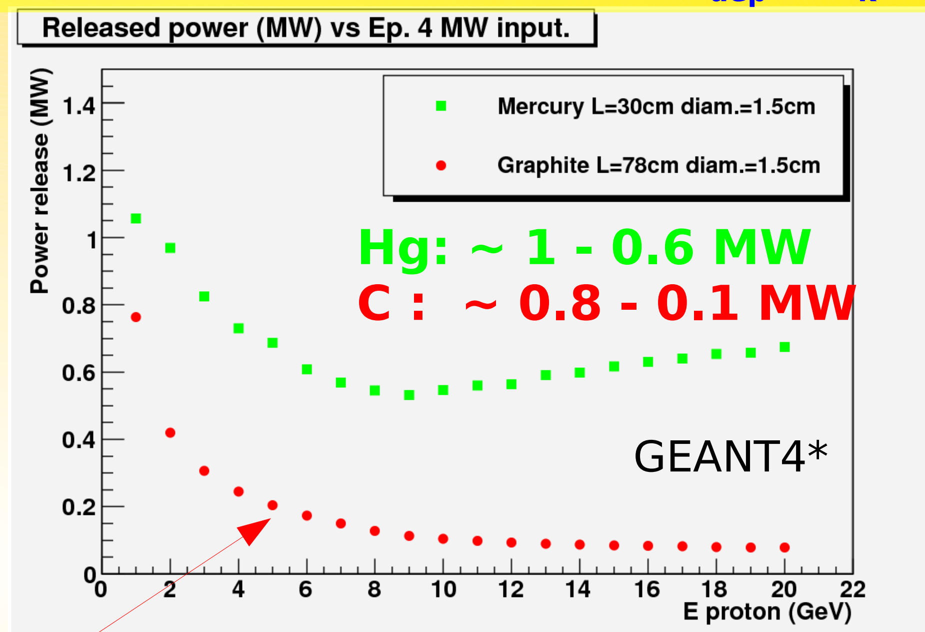


C vs Hg: energy deposition in the target

Mean energy deposition vs Ek(p)



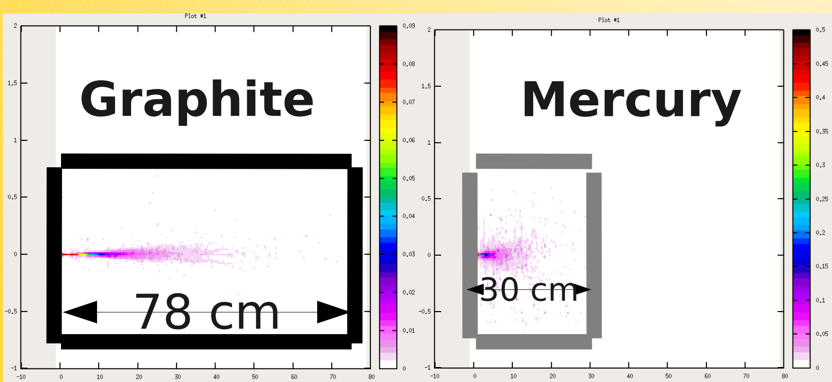
Power release: 4 MW * $<E_{dep}>/E_k(p)$



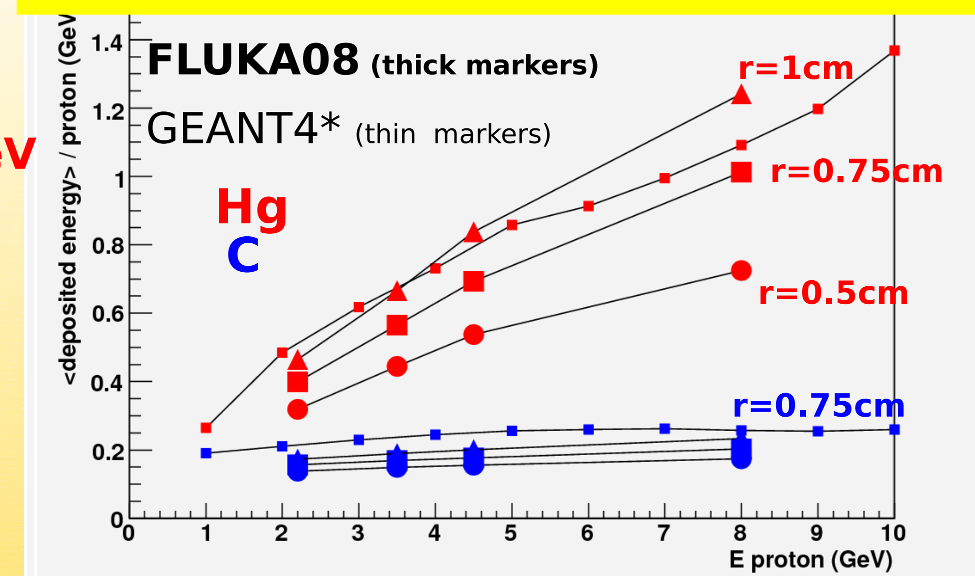
*with (hadronic “QGSP physics list”)

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

considerably lower for C! ~ 200 kW @ 5GeV



Mean energy deposition vs Ek(p)

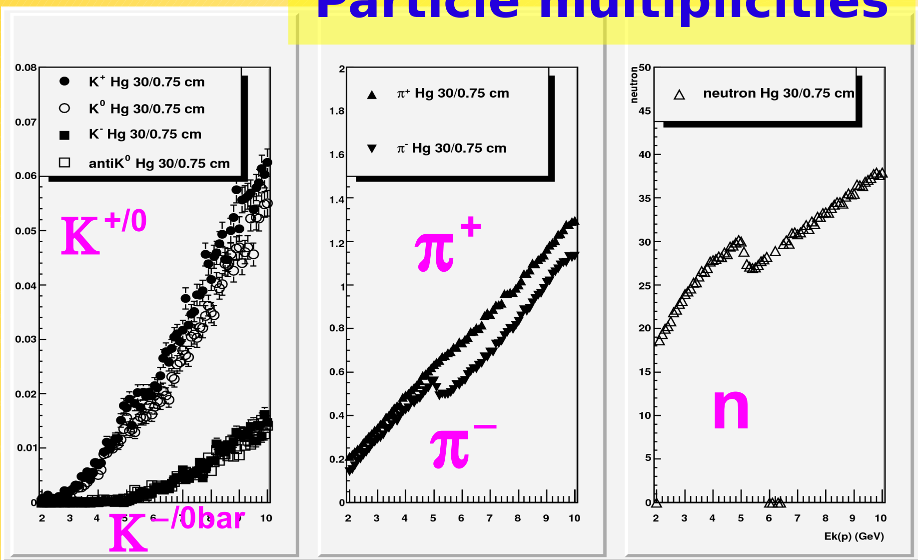


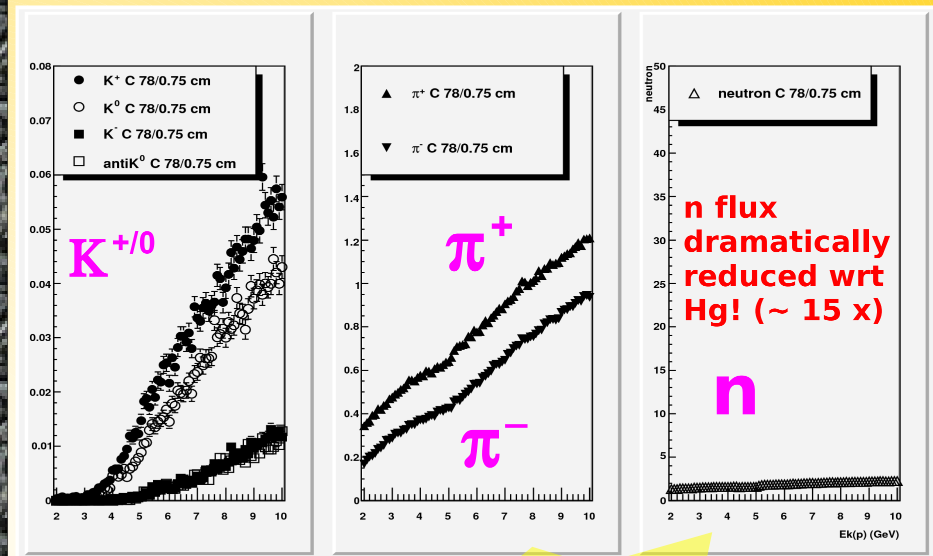
C vs Hg: meson production (FLUKA2008)

vs proton kinetic energy [2-10] GeV

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

Particle multiplicities





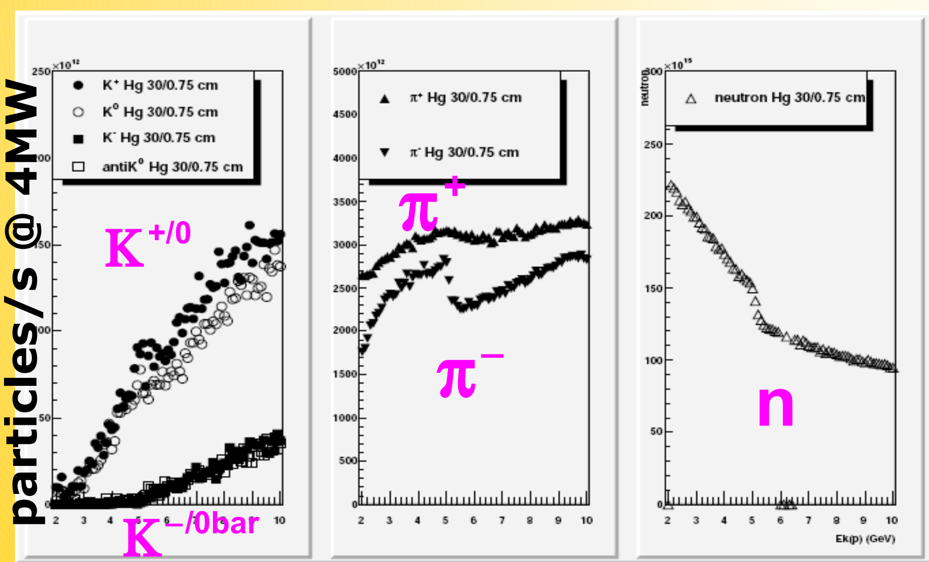
Mercury

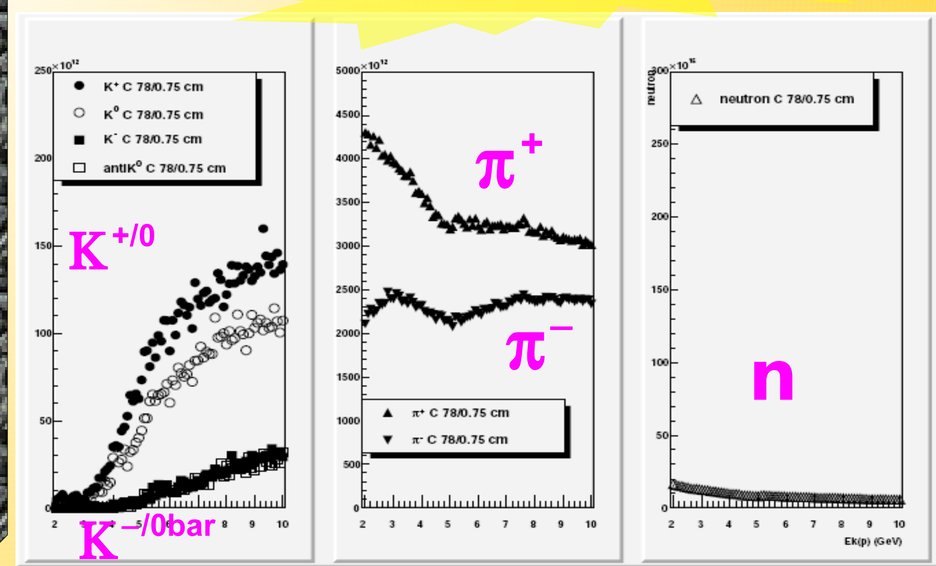
Particle yields

Graphite

Same vert. scale

particles/s @ 4MW

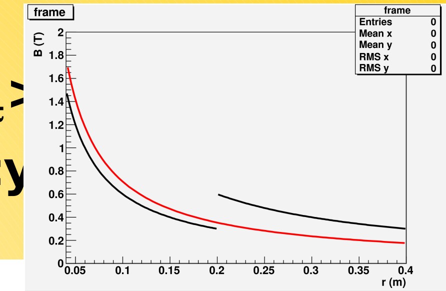


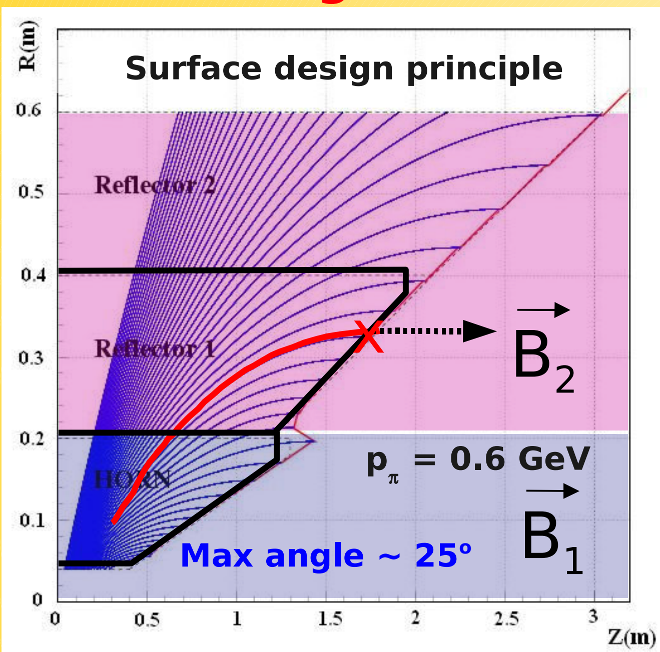


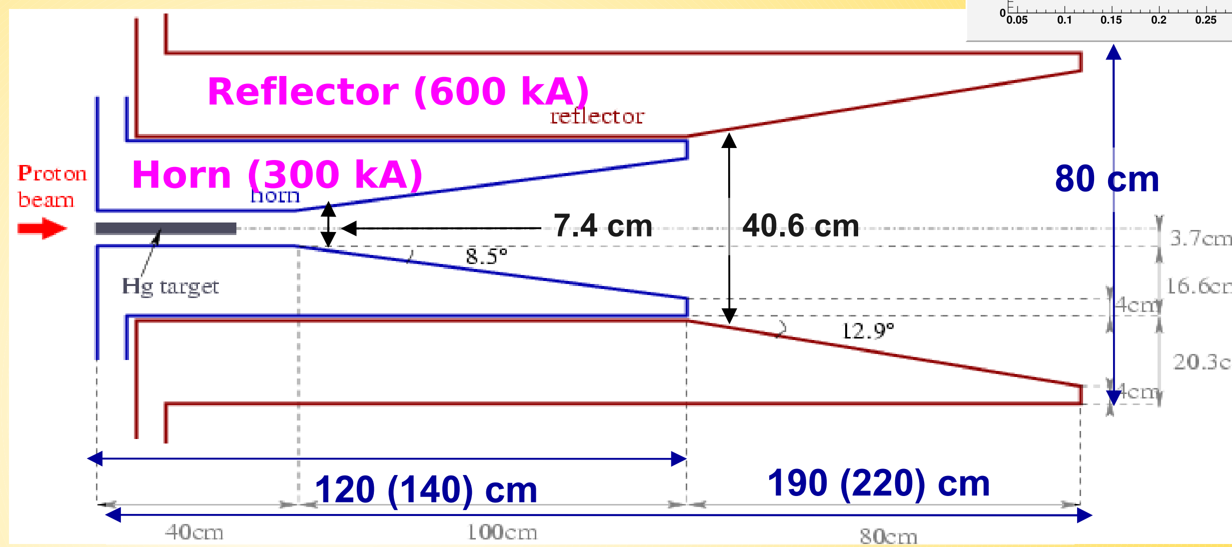
Pion yields comparable, neutron flux reduced by ~ x15 with C !!

The standard focusing system

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

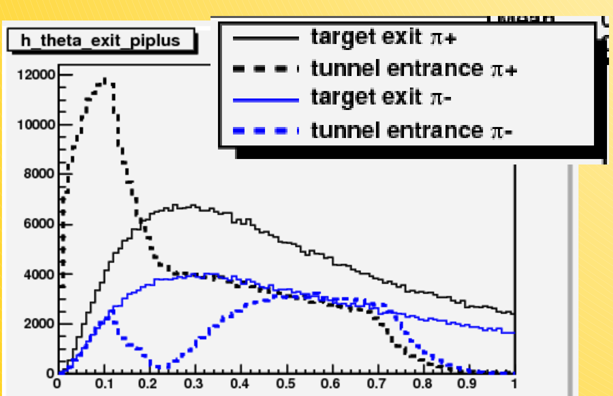






The outer conductor is placed where the slope becomes // to the beam (dr/dz =0)

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



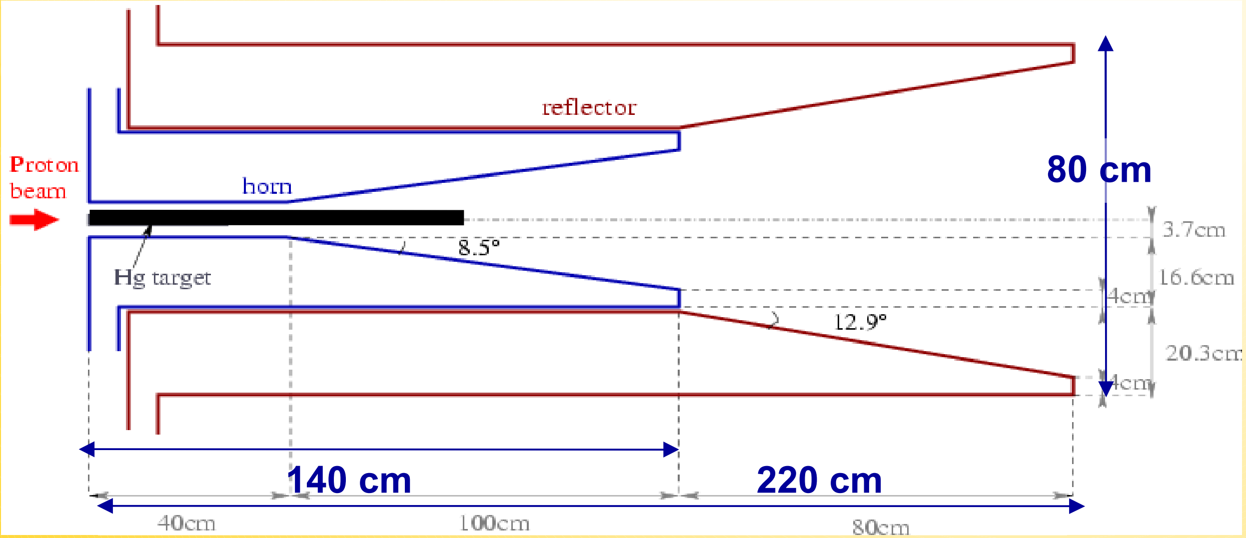
- i(h/r) = 300/600 kA
- pulsed @ 50 Hz
- Toroidal |B| ~ i / r
- B_1^{MAX} =1.5 T, B_2^{MAX}= 0.6 T
- 3 mm thick Al

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

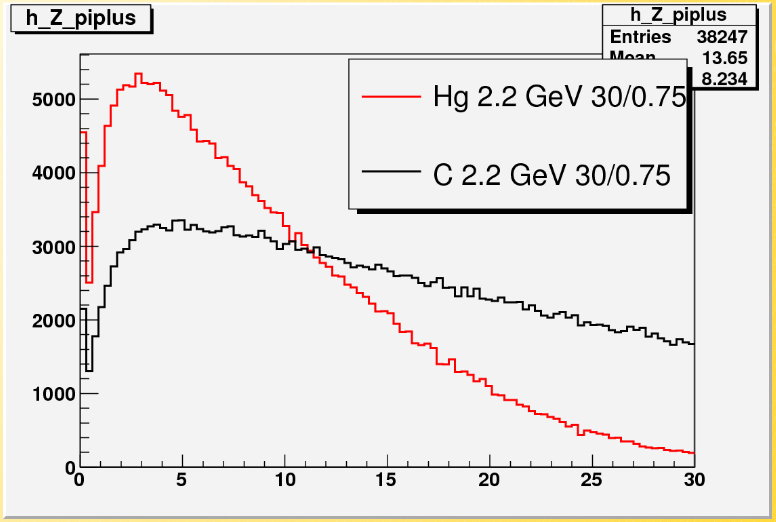
Standard focusing with a longer graphite target

- 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

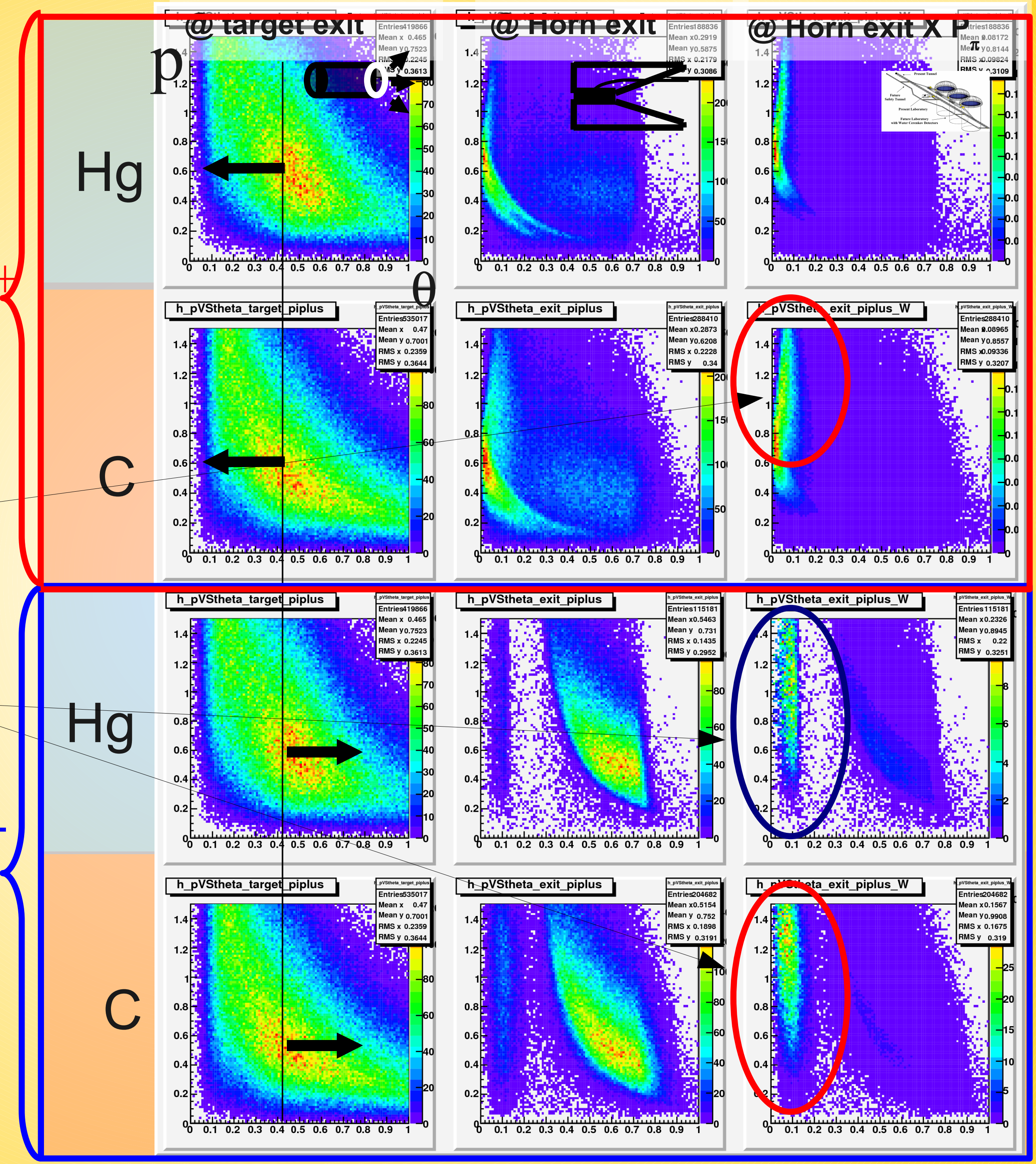


Z of pi+ exiting the target



Pion collection: Hg-C

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



probability to reach the far detector

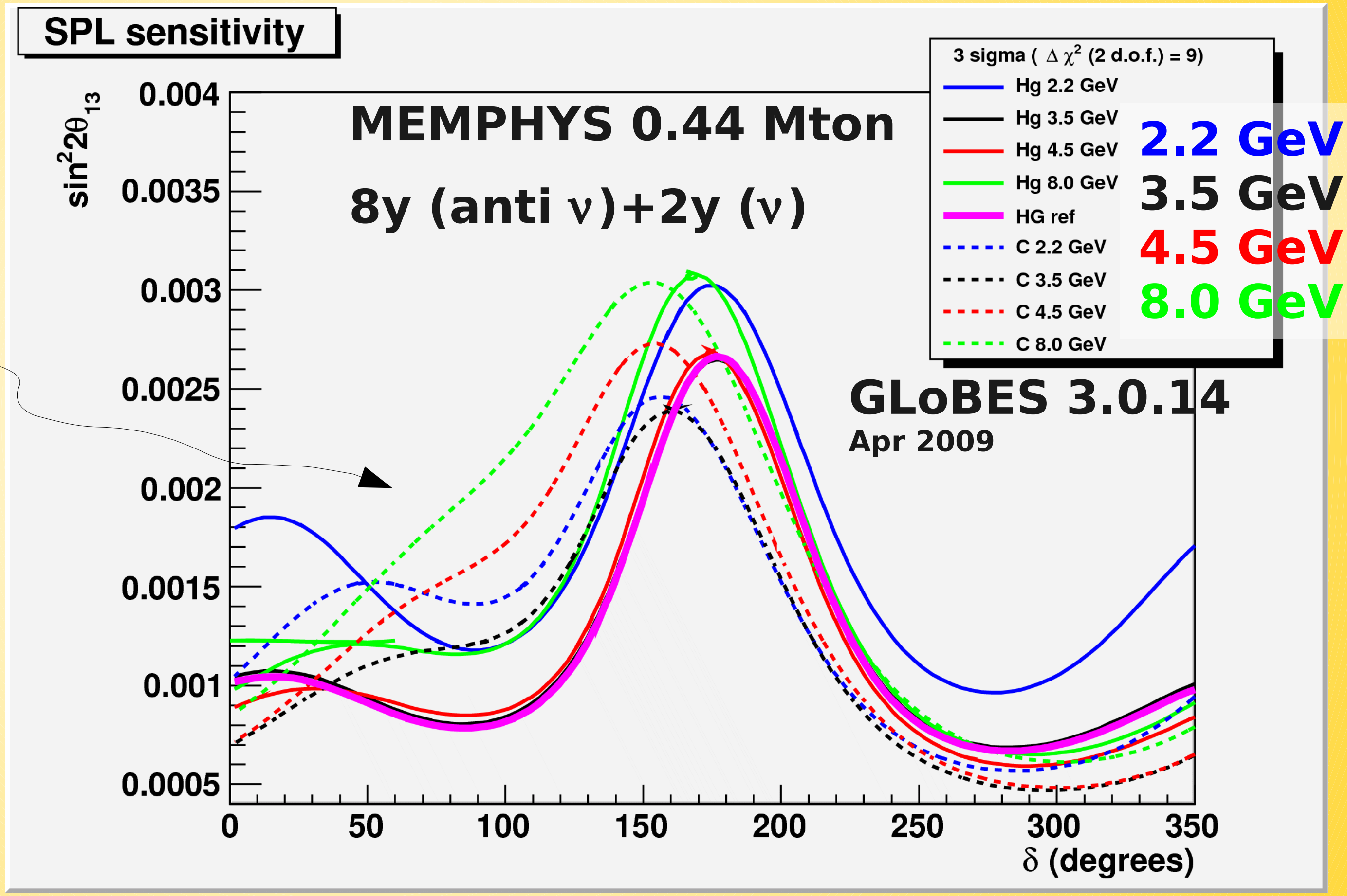
$$\mathcal{P}_\pi = \frac{1}{4\pi}\frac{A}{L^2}\frac{1-\beta^2}{(\beta\cos\alpha - 1)^2}$$

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

Carbon (- - - - - -)   Mercury (———)

Color codes: proton energies

- **graphite limit worse in the δ [0-π] region**
- **This region is driven by the 8-year anti-ν running**

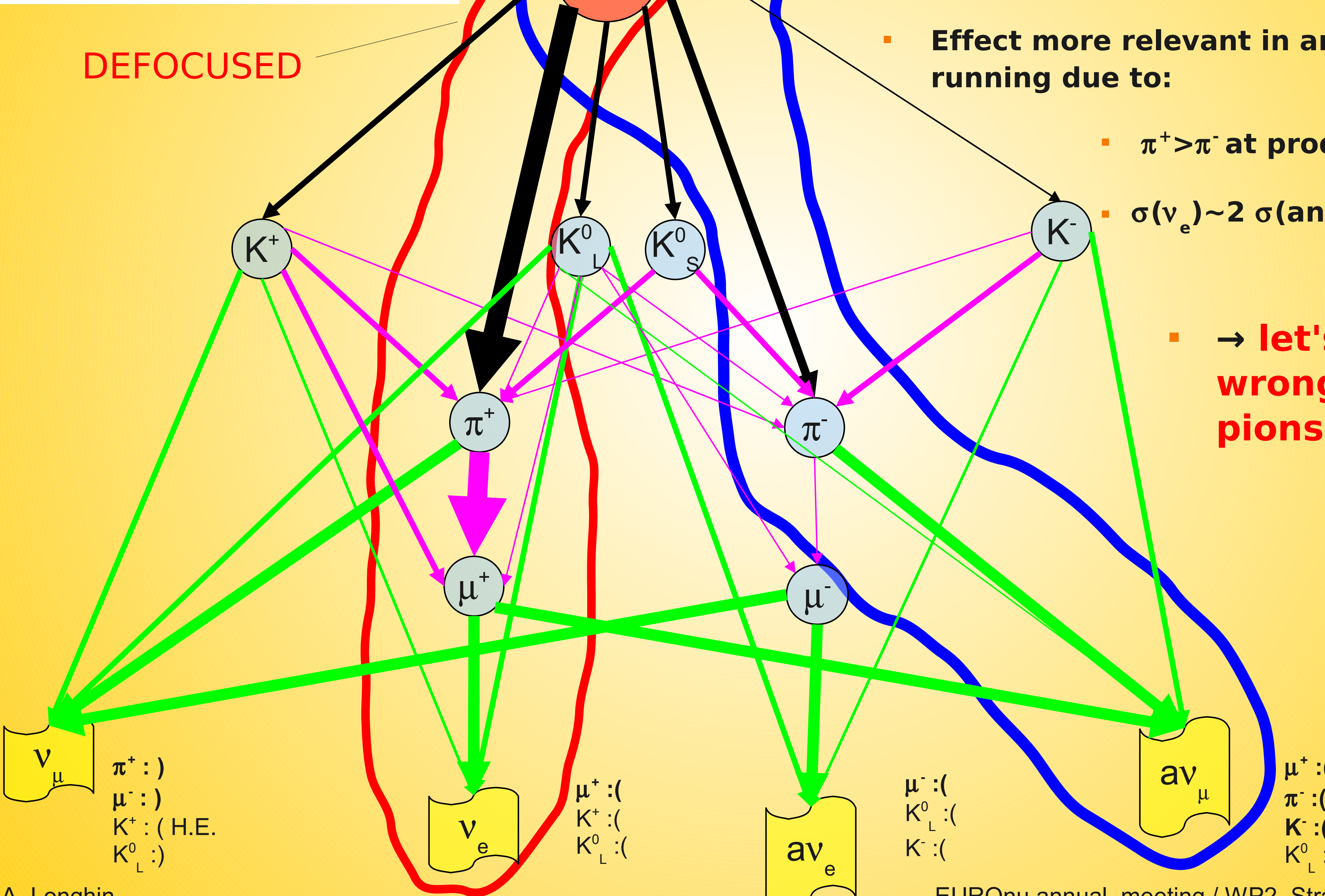


AEDL file SPL.glb in GloBES (with M=0.44Mton)
J. Phys. G29 (2003),1781-1784

Horn optimization for a long target

Deterioration of the limit for the anti-ν run (- focusing)

$K^{\pm}$		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%		



- **related to rising ν_e contamination in the anti-ν_μ beam from not defocused $\pi^+ \rightarrow \mu^+ \rightarrow \nu_e$**
- **Effect more relevant in anti-ν running due to:**
  - **$\pi^+ > \pi^-$ at production**
  - **$\sigma(\nu_e) \sim 2\,\sigma(\text{anti-}\nu_e)$**
- **→ let's minimize wrong charge pions !**

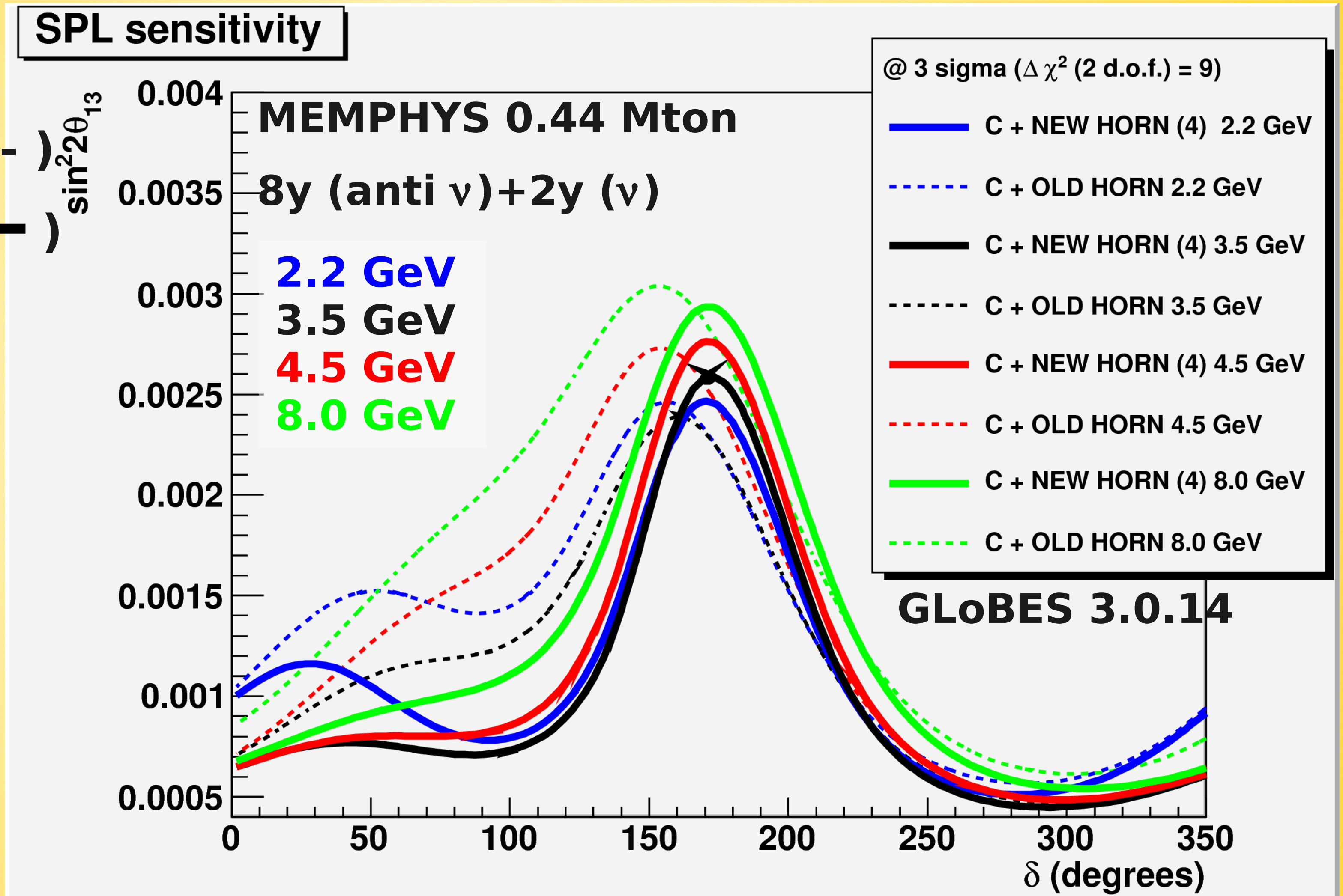
3σ sensitivity on θ_{13} with the new horn

Color codes: proton energies

Carbon target

old horn (- - - - - -)

new horn (———)



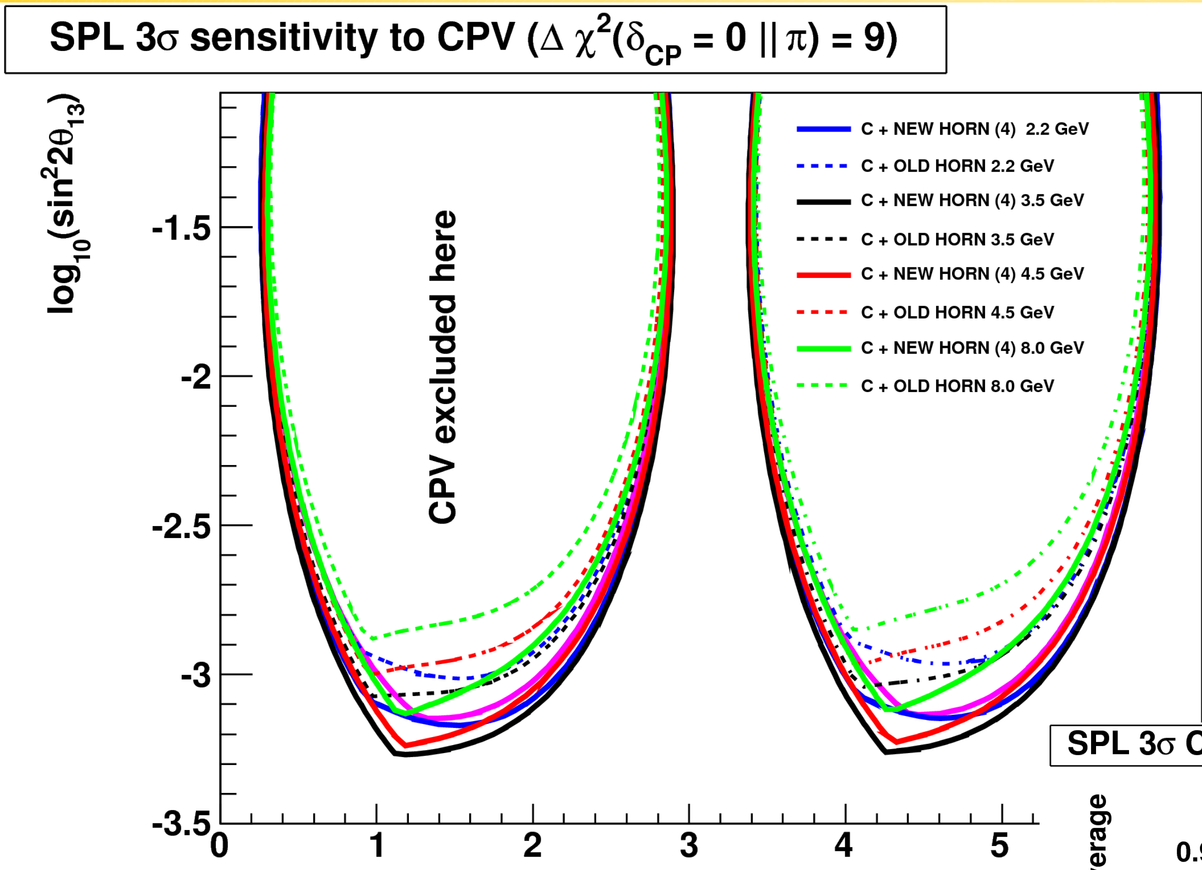
Significant improvement achieved by the new horn design mainly in the anti-ν region as needed.

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