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

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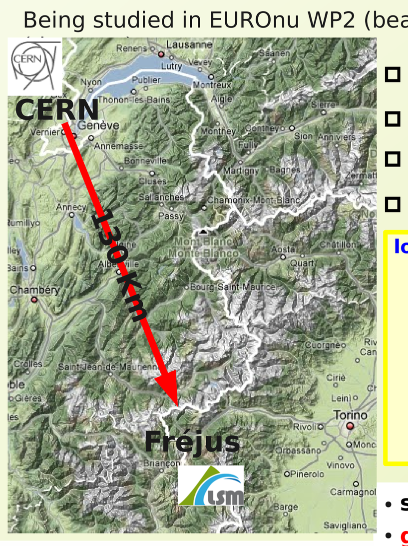
Abstract. An **optimization of the CERN SPL neutrino beam** line has been performed guided by the idea of employing a **graphite target**. The interactions of protons of kinetic energies of 2.2-3.5-4.5 and 8 GeV/c² on a cylindrical 1.5 cm diameter carbon target have been simulated with **FLUKA2008**. **Energy deposition and particle yields** with mercury and carbon have been **compared**. **Power deposition** and **neutron fluxes are suppressed** to a large extent **with carbon**. The transportation and decay of secondary mesons was done with **GEANT3** in order to calculate the **neutrino fluxes**. Sensitivities were calculated with **GLoBES** assuming a beam power of **4 MW (HP-SPL) and a 440 ktons water Cherenkov detector (MEMPHYS) located at 130 km** from the target in a new foreseen **Fréjus laboratory**. The obtained **sensitivities with the carbon target are comparable to the ones achieved with the mercury target**. The full simulation has been recently rewritten using **GEANT4** which allows a higher degree of flexibility for arranging the horn geometries. A detailed comparison of the algorithms has been done and a **good agreement** is found for the final neutrino fluxes. A preliminary comparison of the sensitivities to $\sin^2 2\theta_{13}$ as a function of δ with a **optimized horn shape** will also be presented.

The SPL-Fréjus Super Beam

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

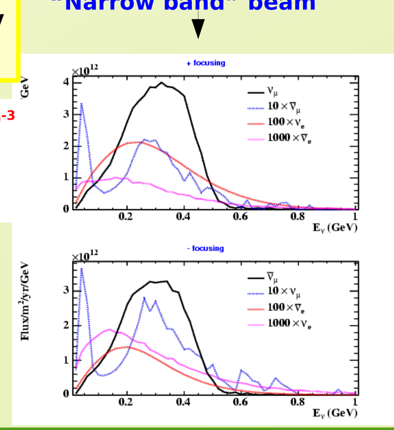


- SPL p driver @ **4MW** (H- linac E_k ~ **5 GeV**)
- **L** = **130 Km**
- Far Detector: **0.44 Mton Water Cherenkov**
- 1st oscillation maximum E_ν ~ **260 MeV**

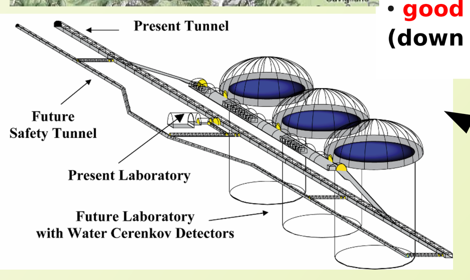
low E
- :) very few ν_e from K
- :) compact horn and tunnel
- :) good reconstruction in W.Ch.
  - ~ all elastic
  - σ_E: 43 MeV : [0.2-0.3] GeV
  - easy π^0 rejection

small L
- :) High flux
- :) No matter effects : (

"Narrow band" beam



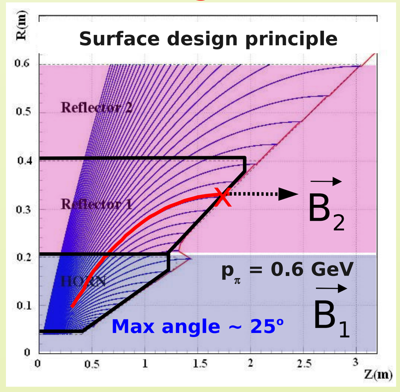
- $\sin^2 2\theta_{13}$ sensitivity limit @ ~ 10^{-3}
- good sensitivity to δ
(down to $\sin^2 2\theta_{13}$ ~ 10^{-2})

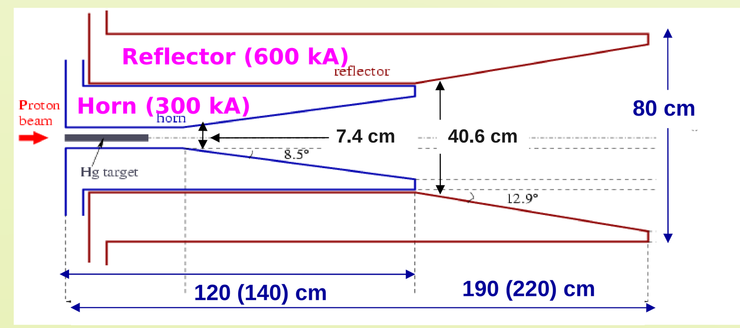


MEMPHYS
multi purpose
p decay, atm-ν, SN-ν, …

Focusing system

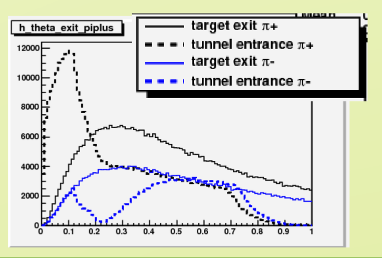
- Due to the low energy proton beam pions are mildly forward boosted (<θπ> ~ 55°)
  - **-> Target inside the horn** to recover collection efficiency





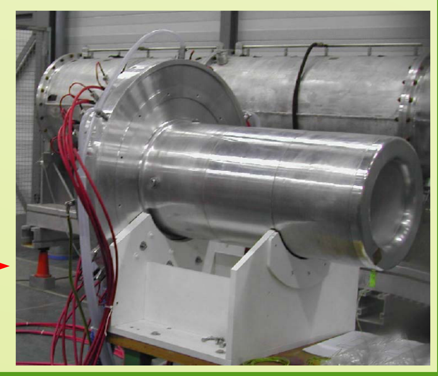
The outer conductor is placed where the slope becomes // to the beam (dr/dz =0)

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)



Decay tunnel

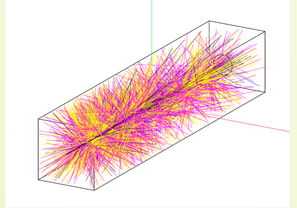
- Cylindrical filled with low -pressure air.
- Tested geometries: L=10-20-40-60 m / r =1-1.5-2 m
  - **L = 40 m , r =2 m** chosen as central value
  - Based on sensitivities. L>40 m gives ν_e contaminations from μ decay which spoil gain given by increase of ν_μ statistics

Decay lengths (m) @ 600 MeV

π	33.7
μ	3766
K+/-	4.5
K0S	3.2
K0L	18.5

Target

- Cylindrical (~ 2 λ_I long)
  - **r = 0.75 cm**
  - **Liq. mercury (Hg): L = 30 cm**
  - **Carbon (C) : L = 78 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

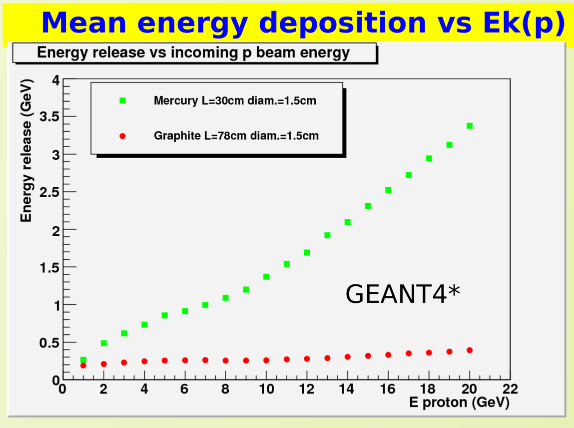
new

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.

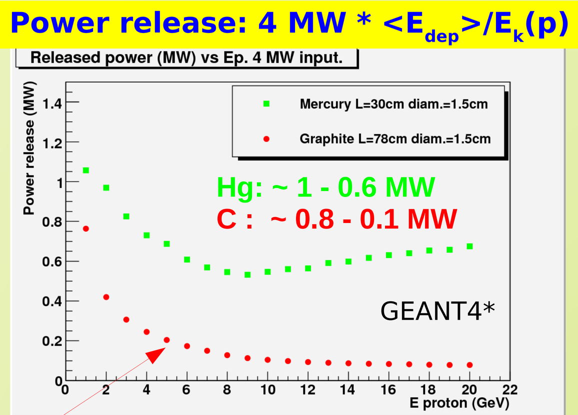
*FLUKA 2002.4 and MARS in previous study

C vs Hg: energy deposition in the target

Mean energy deposition vs Ek(p)



Power release: 4 MW * <Edep>/Ek(p)

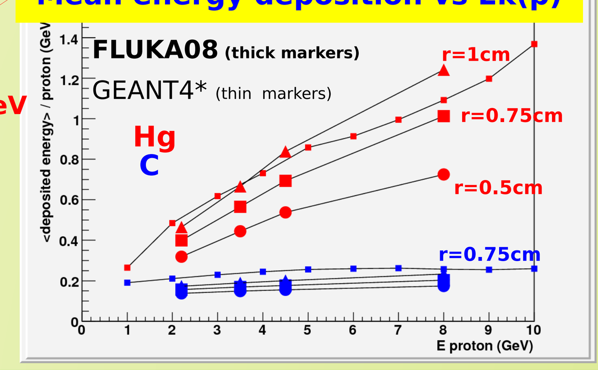


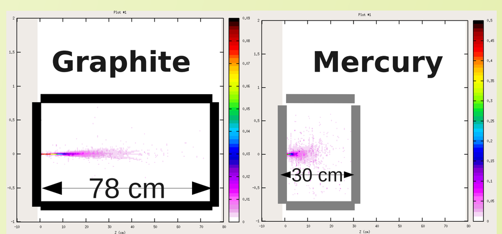
*with (hadronic "QGSP physics list")

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

considerably lower for C! ~ 200 kW @ 5GeV

Mean energy deposition vs Ek(p)

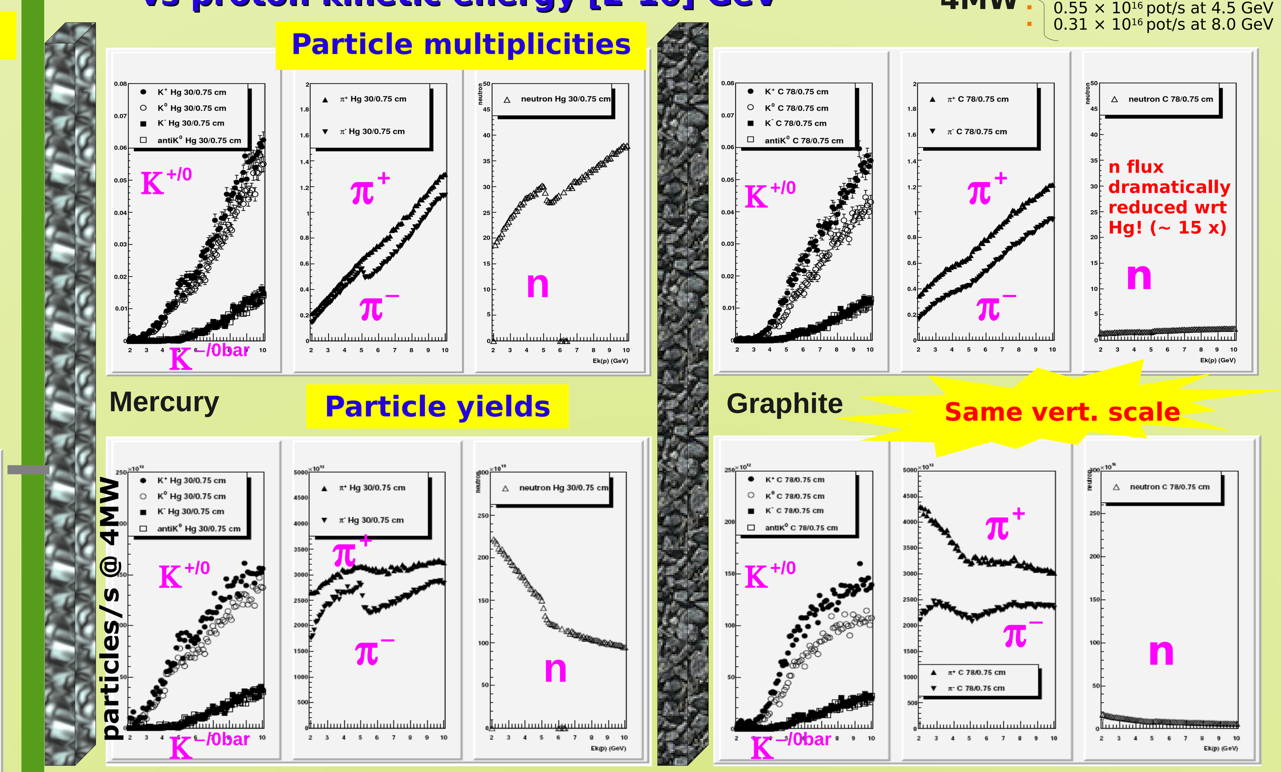




C vs Hg: meson production (FLUKA2008) vs proton kinetic energy [2-10] GeV

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

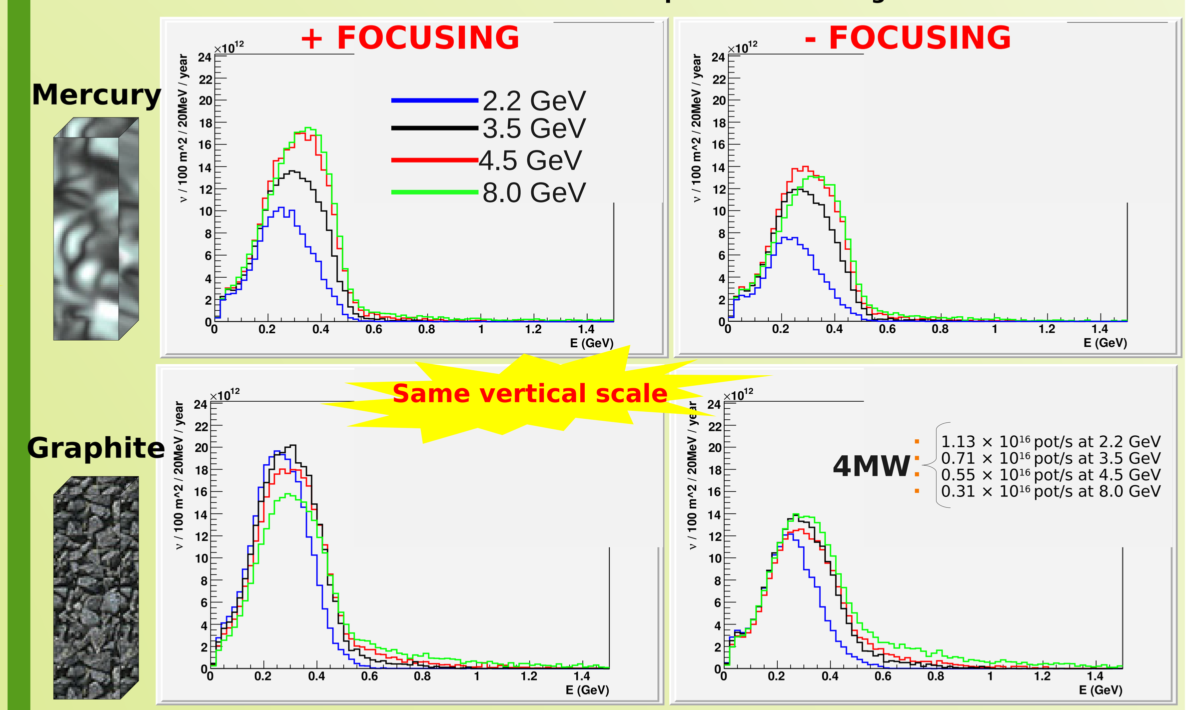


Pion yields comparable, neutron flux reduced by ~ x15 with C !!

C vs Hg: ν fluxes

- 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

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



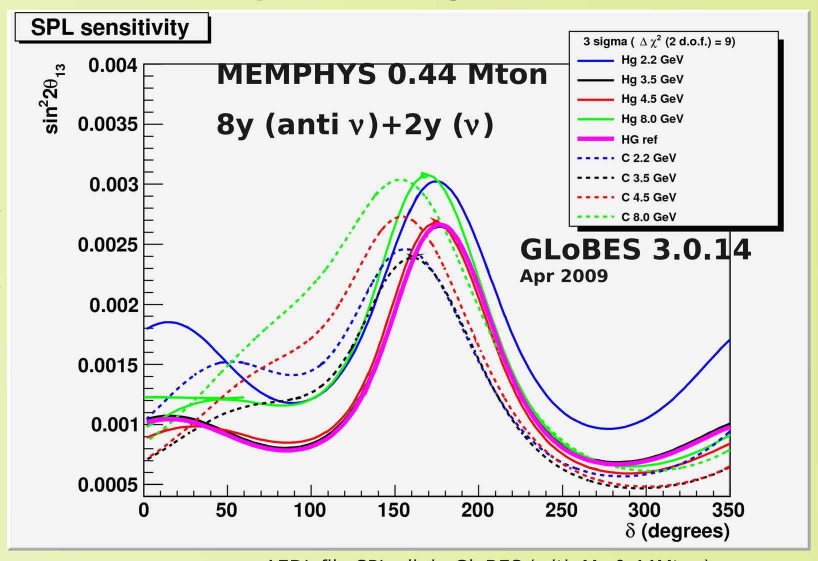
C vs Hg: 3σ sensitivity on θ_{13} vs δ

Carbon (- - - - - -) Mercury (———)
Color codes: proton energies

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

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

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



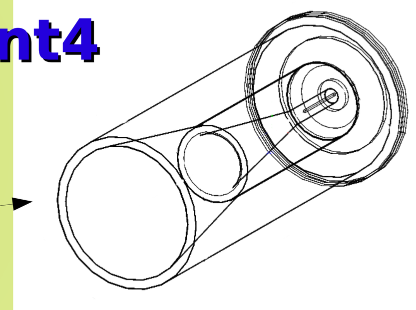
AEDL file SPL.glb in GloBES (with M=0.44Mton)
J. Phys. G29 (2003),1781-1784

Horn optimization for a long target

New simulation with Geant4

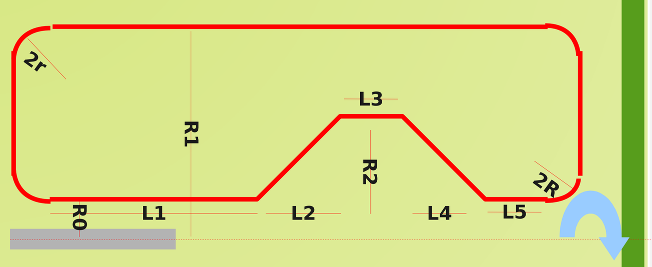
The full simulation has been recently migrated **from Geant3 to Geant4**

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



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

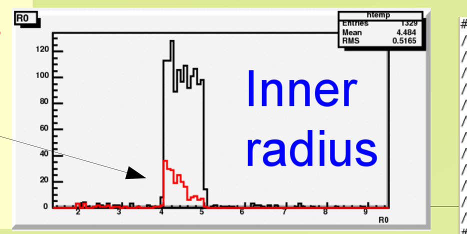
Flexible enough to reproduce also standard conical geometry



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

The resulting fluxes are **selected** according to quality parameters (ν_μ normalization, ν_e contamination, mean energy, energy spread)

Randomly generated
Accepted after cuts on spectra



9 parameters fully accessible from external macro file

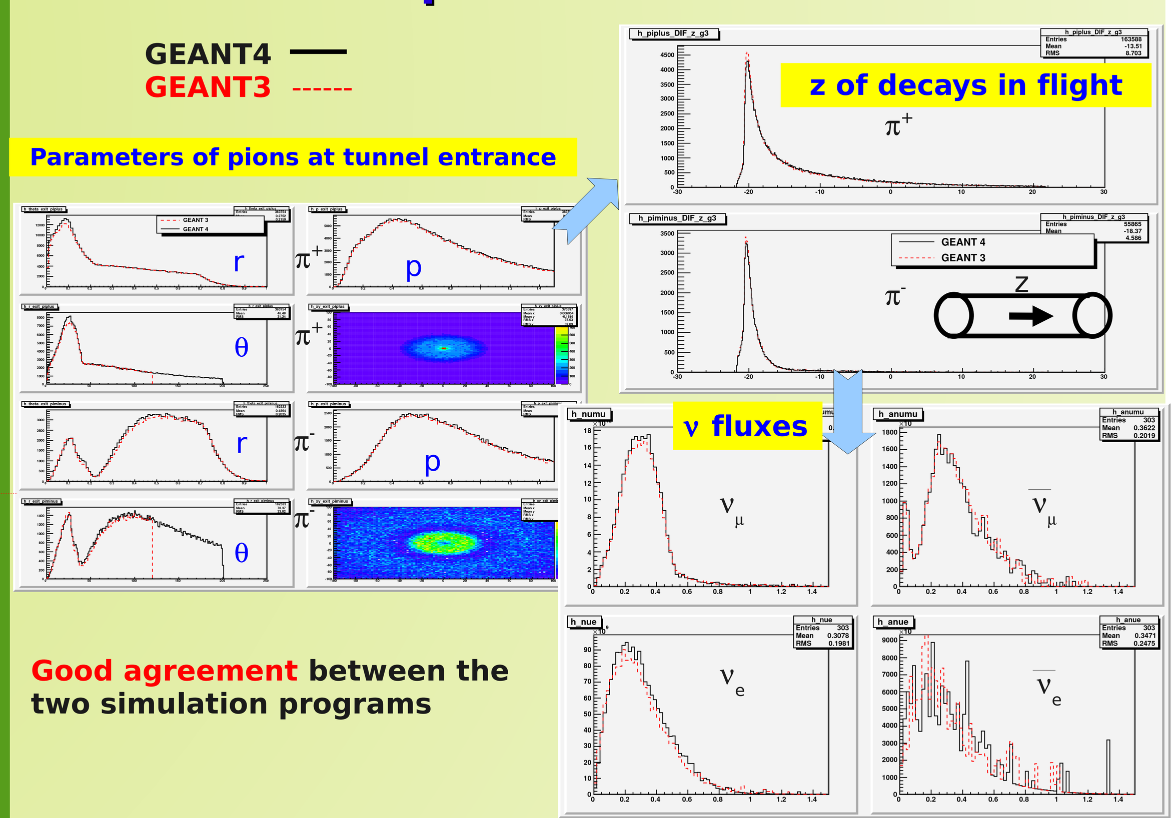
GEANT3-4 comparison with standard horn

GEANT4 ——
GEANT3 - - - -

Parameters of pions at tunnel entrance

z of decays in flight

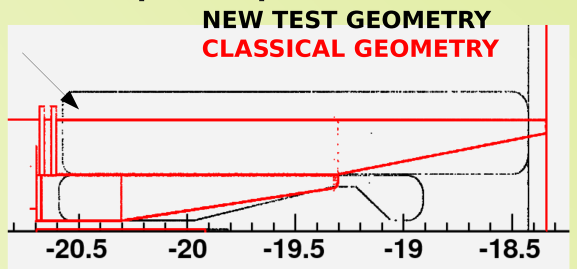
ν fluxes



Good agreement between the two simulation programs

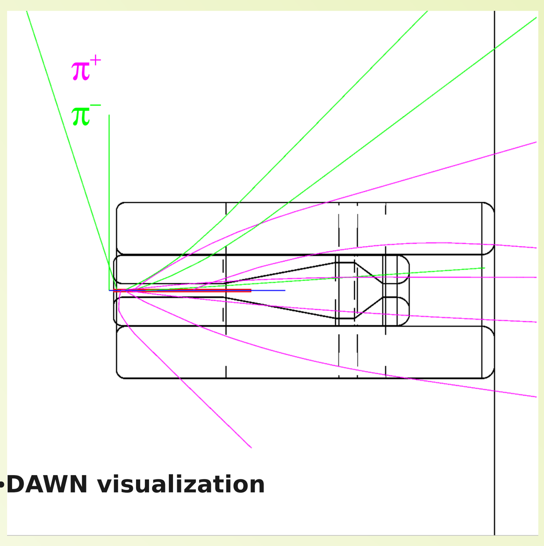
A new test horn

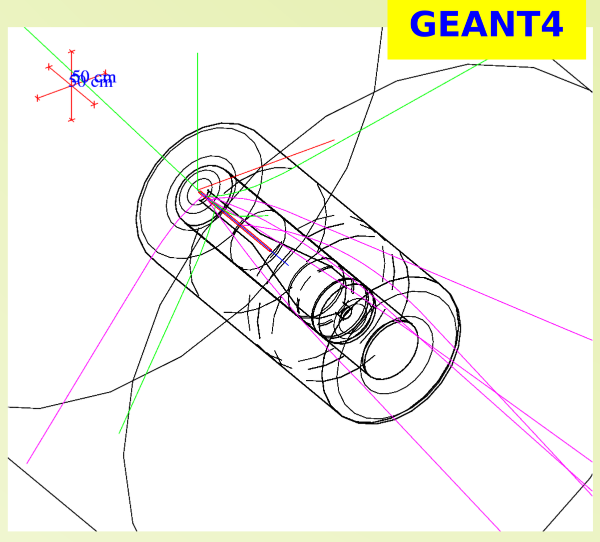
Hit maps (r,z) plane
NEW TEST GEOMETRY
CLASSICAL GEOMETRY



- 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)

GEANT4





•DAWN visualization

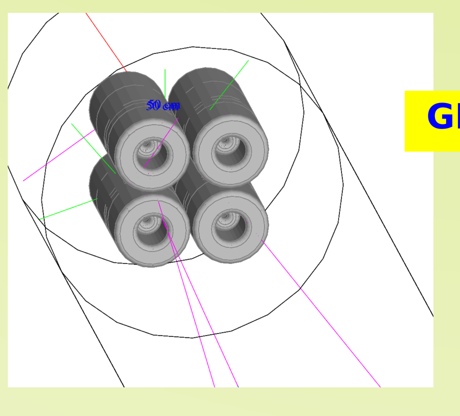
The 4-horns scenario

L = 40 m , r =2 m

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

depending on injection strategy

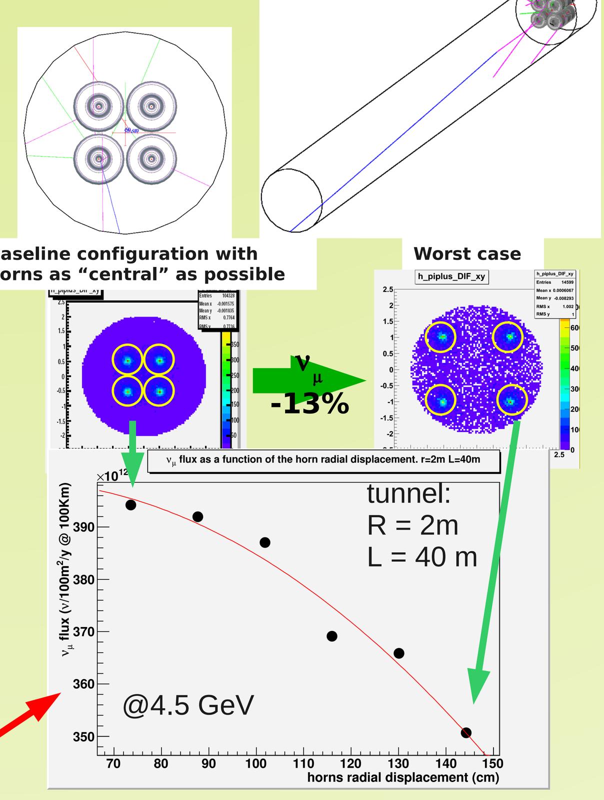
Profits of **horn compactness** (r~0.5m)



GEANT4

Baseline configuration with horns as "central" as possible

Worst case



Small flux loss even up to big lateral displacements.

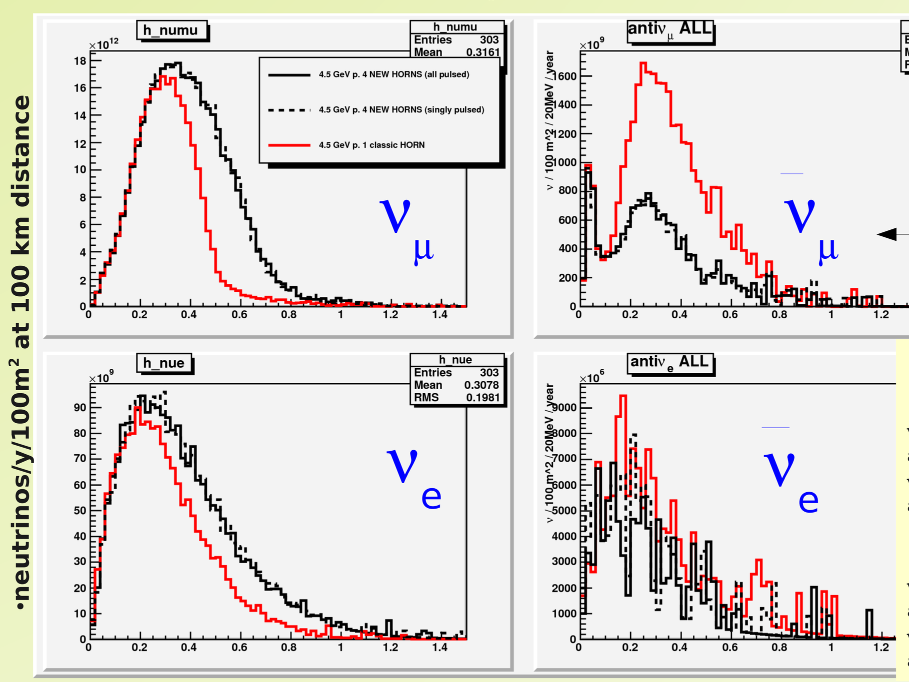
Fluxes: new VS old horn

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



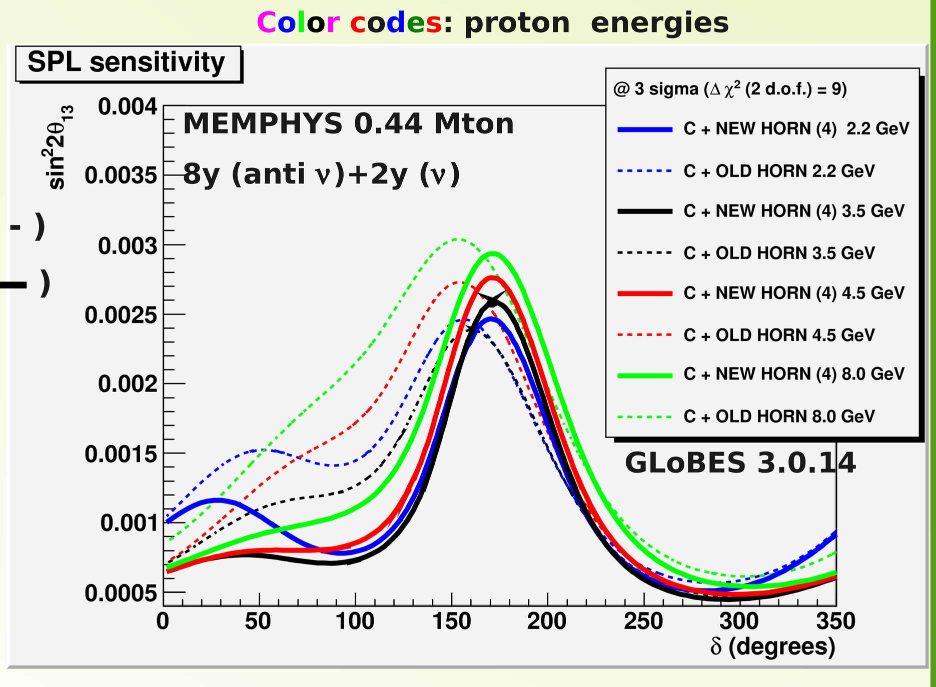
OLD (%)	NEW (%)
+ FOCUSING	
88.9	-> 95.55
10.5	-> 3.9
0.6	-> 0.56
0.052	-> 0.025
- FOCUSING	
26.1	-> 11.2
73.4	-> 88.4
0.17	-> 0.09
0.34	-> 0.35

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.**



GEANT4

AEDL file SPL.glb in GloBES (with M=0.44Mton)
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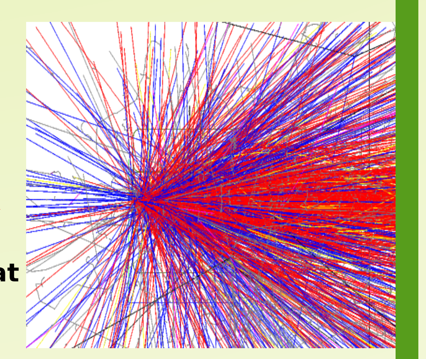
Conclusions



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

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

Simulation rewritten in **Geant4**. Good agreement with previous Geant3 simulation

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

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

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

Outlook

Verify FLUKA description of carbon target with **HARP** "thick target" data (synergy with EURONU-WP3) and other models

References

- 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
- 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

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A. Cazes, M.Zito, J.E. Campagne, M. Mezzetto,

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