Study of possible opportunities for leptonic CP violation and ν mass hierarchy at LNGS

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INFN: LNF, PD, BO, MI-B

Outline

- Goals and working hypotheses
- Leptonic CP and mass hierarchy with a 730 km baseline
- Neutrino beam simulation
- Method: CP violation coverage vs exposure (Mton MW)
- Results and comparison with other baselines
- Conclusions

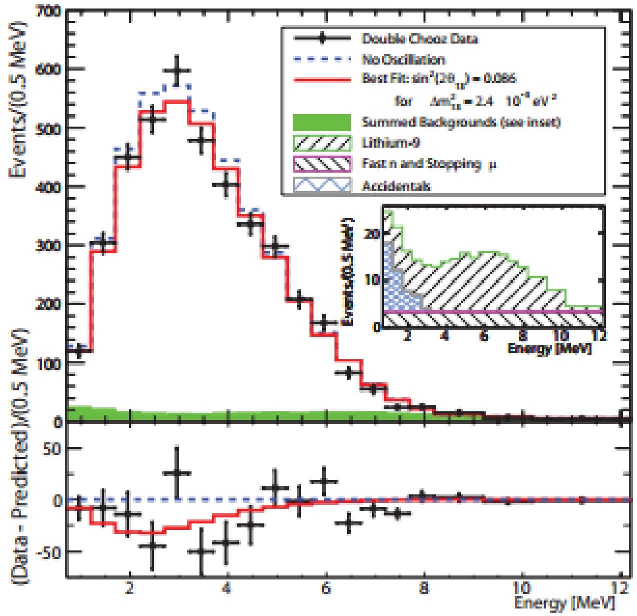
Goals

- Under the light of recent measurements of a large θ_{13}
- Which are the requirements for facilities based on the CERN-GranSasso baseline in order to have a given chance to measure CP violation (CPV)
  - i.e. at 3σ for > 40% of the cases (δ values) ?
- Impact of prior knowledge of the mass hierarchy (MH) ?

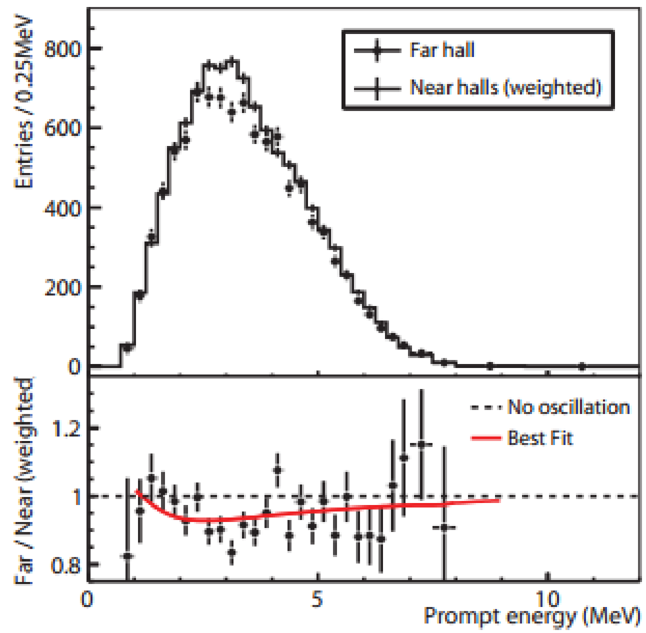
Assumptions

- LAr TPC technology
- Investigate (within reasonable contraints):
  mass of detector / number of pots (continuous sampling)
  proton energy / off-axis angle (a few trials)

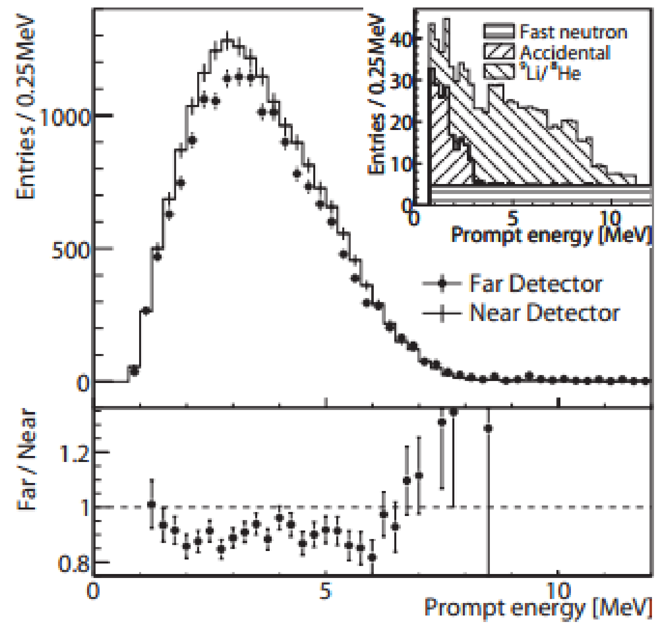
Double Chooz

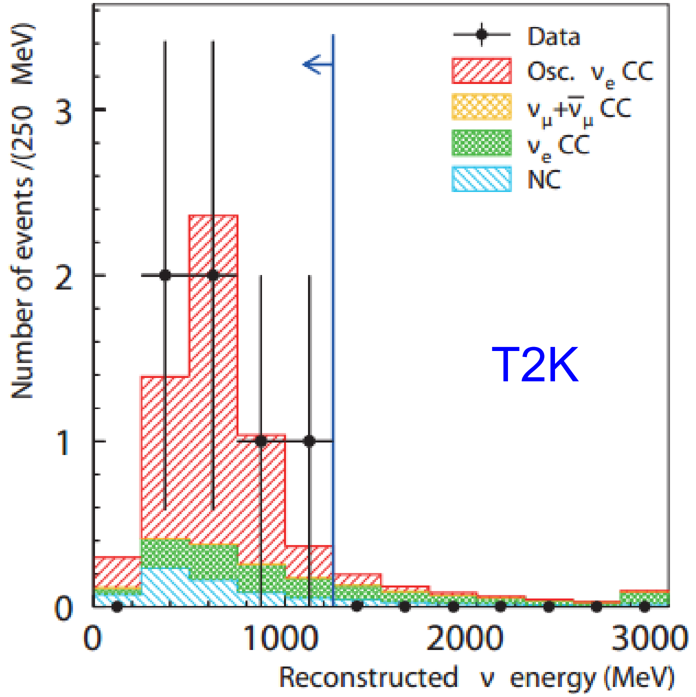


Daya Bay

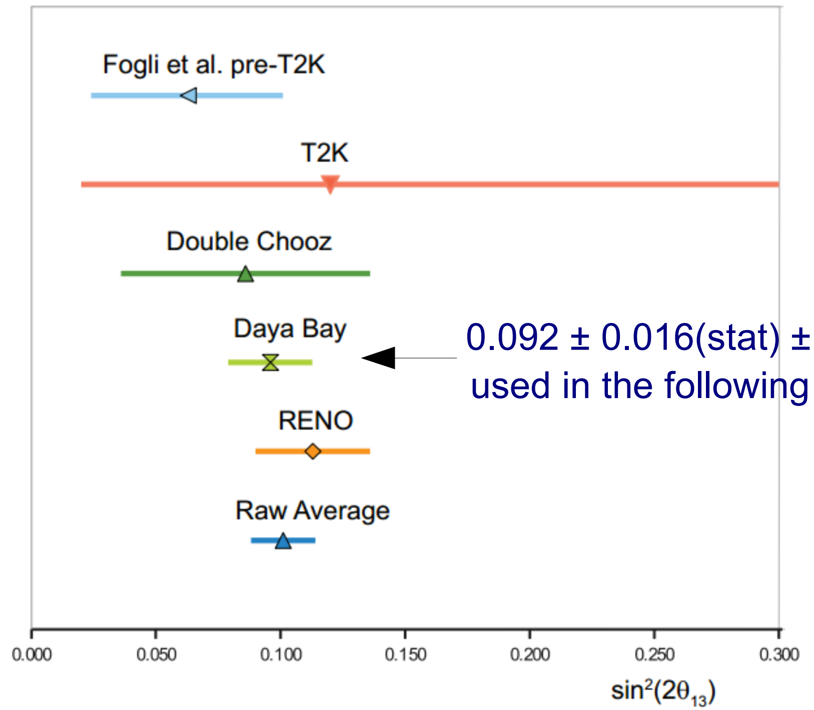


RENO





θ_{13}



0.092 ± 0.016(stat) ± 0.005(syst) used in the following

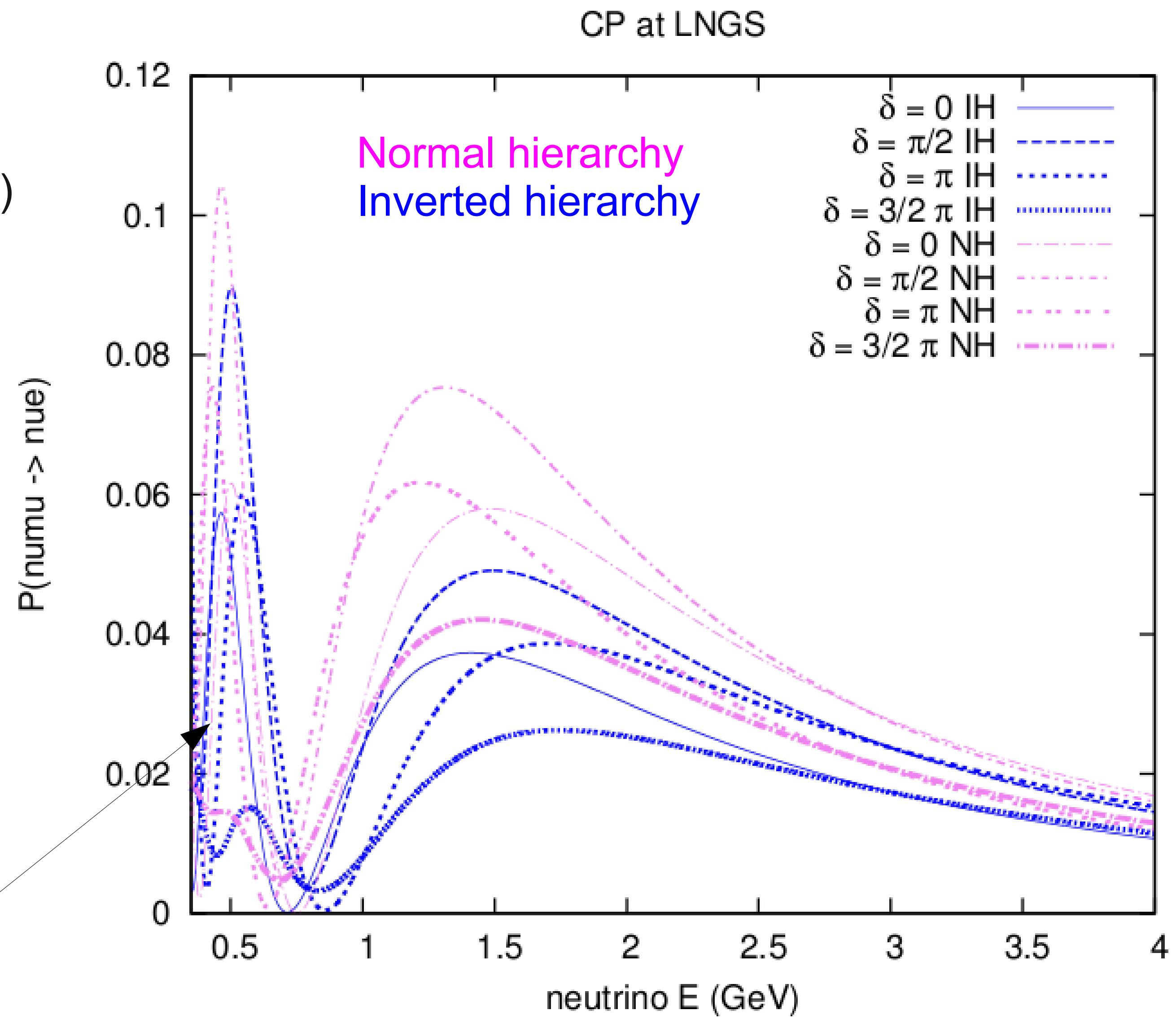
$\nu_\mu \to \nu_e$ probability at 730 km

Effects ruled by mass hierarchy (~matter effects) of comparable size w.r.t. CP phase effects

At first order a change in normalization → control of systematic errors is crucial

Hierarchy is "easier" than CPV even at 730 km

2nd maximum at a quite low energy (~500 MeV)



not easy to 'populate' using a high-E proton beam and due to cross section suppression

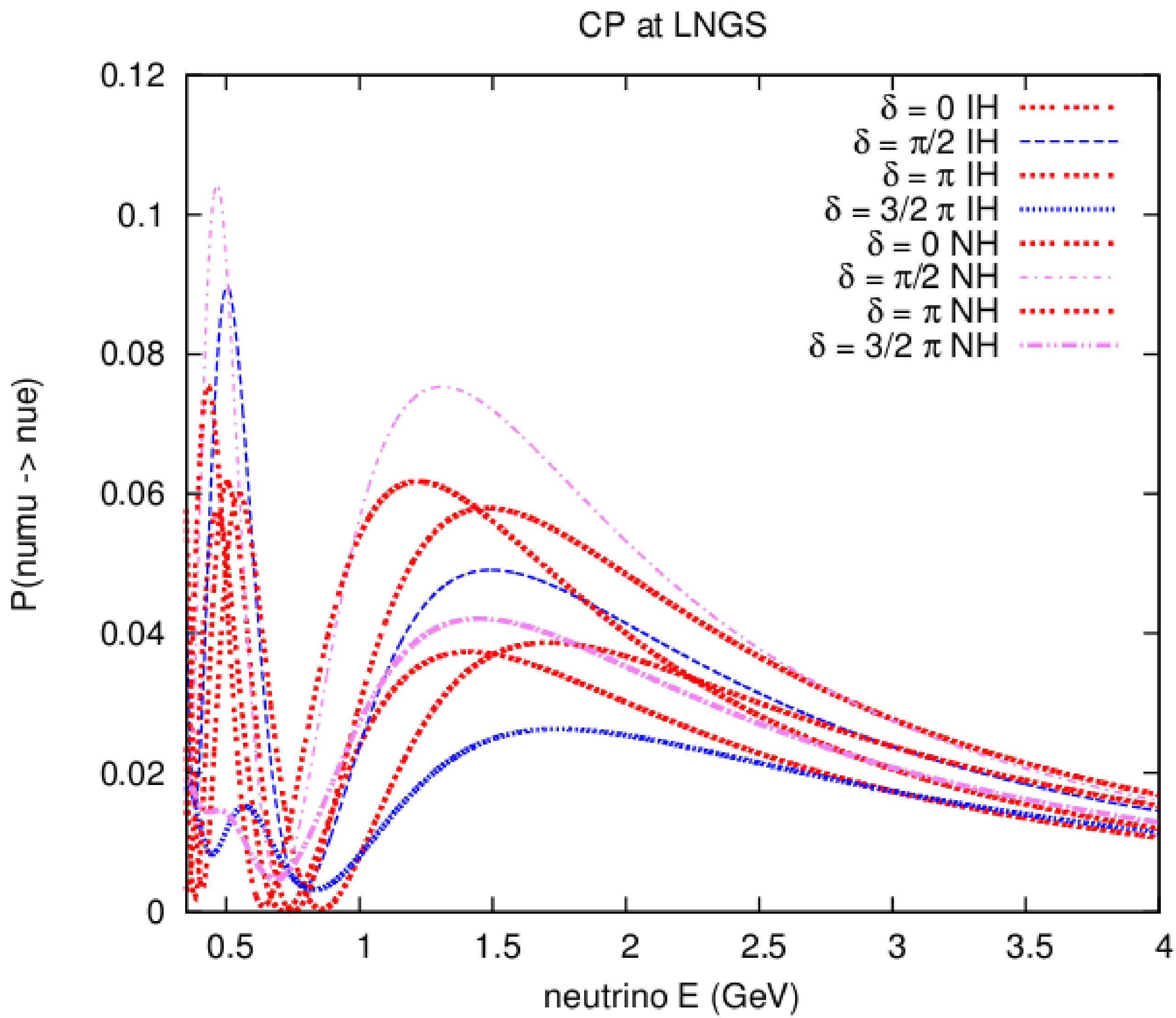
$\nu_\mu \to \nu_e$ probability at 730 km

CP conserving values $(0,\pi)$ lie "in the middle".

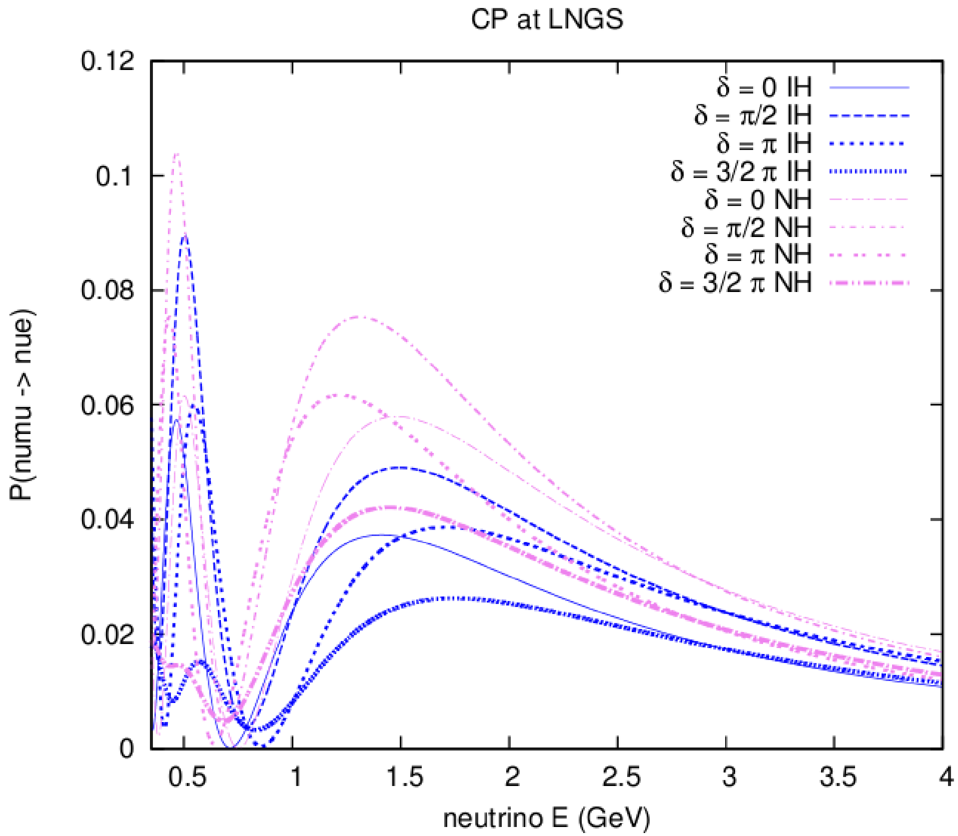
To exclude CPV we have to be able to "exclude the red lines"

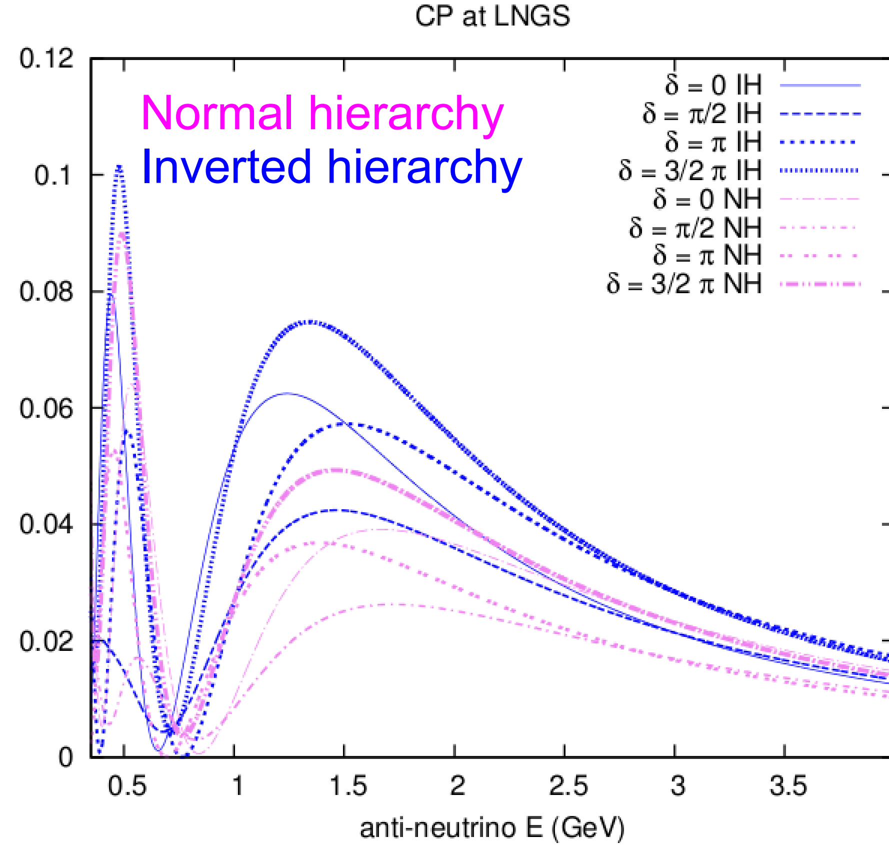
$\delta \sim \pi/2$ appearance ↑ for ν.
$\delta \sim 3/2\pi$ appearance ↓ for ν.

CP violation := CPV
Mass hierarchy:= MH
Normal hierarchy: NH
Inverted hierarchy: IH



$\nu_\mu \rightarrow \nu_e$ probability at 730 km





Normal hierachy : appearance (ν-bar) > appearance (ν)

Inverted hierachy : appearance (ν-bar) < appearance (ν)

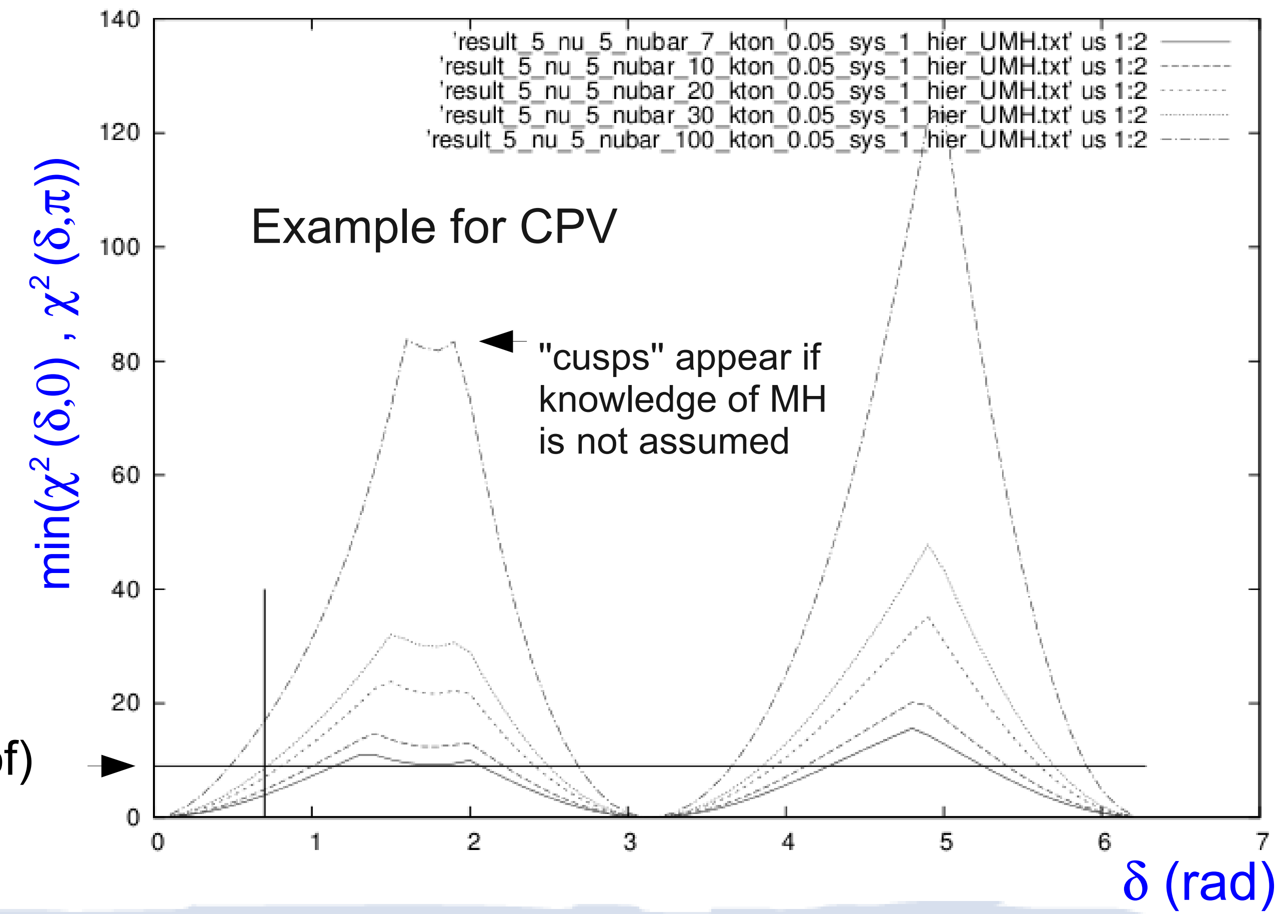
CPV discovery and MH determination

- **CPV**: for each δ value claim 3 σ discovery if the CP conserving cases $(\delta = 0, \pi)$ can be excluded (for both hypotheses on MH, unless it is assumed known)

- **MH** : make a MH assumption ”A”. For each δ value claim MH determination if MH B can be excluded for any δ value

The "coverage" is the fraction of the values of δ for which CPV / MH is reachable

9 (3σ, 1 dof)



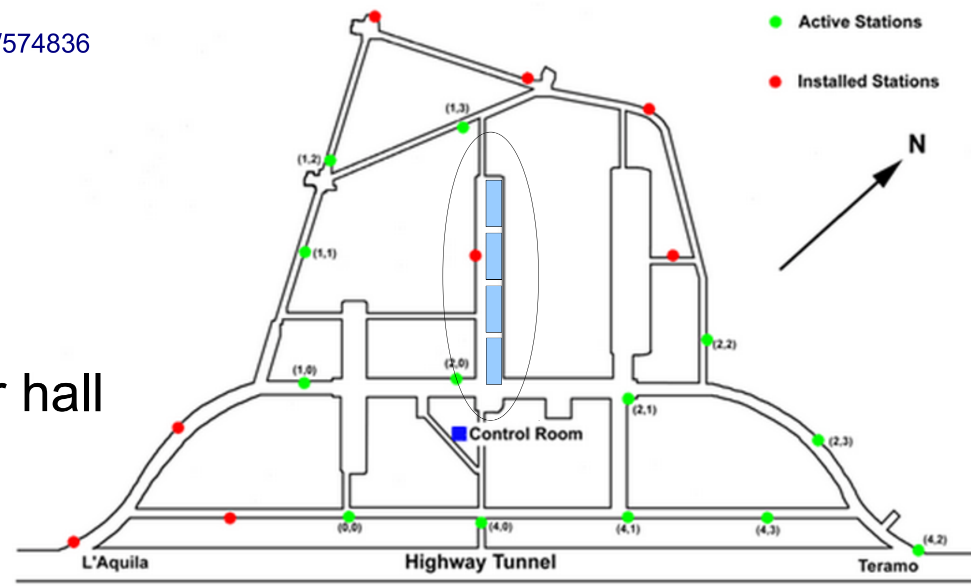
Far detector at LNGS

- LNGS
  - On-axis underground LAr TPC (up to 10 kt)
  - Off-axis shallow depth LAr TPC (up to 100 kt)
- We have considered these options separately for the time being (no double detector on-axis and off-axis)

Contraints on mass underground

- Hall B (110 m)
- ICARUS T600 module
  - 3.9 × 4.3 × 19.6 m^3
  - 0.735 kt (0.476 fiducial)
- ICARUS T1200 design
  - 10.3 × 10.3 × 21 m^3
  - 1.47 kt (0.952 fiducial)

CERN/SPSC 2002-027 p.122-130 http://cdsweb.cern.ch/record/574836
Tab. 6.1-3, Fig. 6.1 p.122



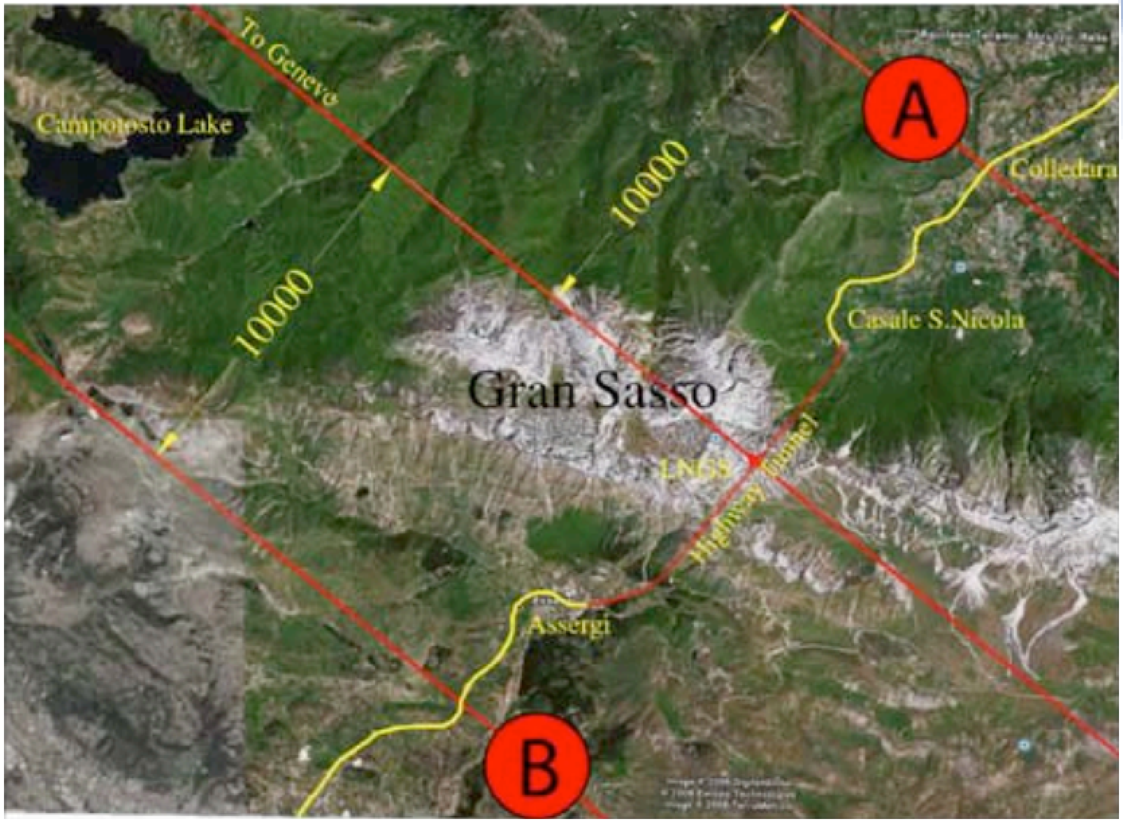
4 x T1200 modules → ~ 4 kt fiducial

ad-hoc design: could go up to ~ 7.5 kt

10 kt allowing for extra space in another hall

Off-axis configurations

- ~ 7 km optimal from studies on θ_{13} reach from MODULAr (hep-ph/0704.1422)
- Possible shallow depth sites identified at 10 km outside of natural park and with roads (hep-ph/0704.1422)
- 7 km tends to be quite far from maximum but with higher statistics with respect to 10 km



From hep-ph/0704.1422

- Both 7 and 10 km are considered in the following
- ~ 9.6 and 13 mrad

Beams from CERN

For the off-axis configurations we consider the SPS @ 400 GeV

For the on-axis configuration using 400 GeV tends to produce poor results since it is quite hard to populate the low energy region (see for example hep-ph/0609106v1).

For this reason a 50 GeV beam has been considered. This allows to populate the right energy region.

Further optimization considering other p energies could be pursued.

We will show results as a function (MW Mt 10^7s) thus allowing to "read" the combination of mass and beam needed to get a certain coverage.

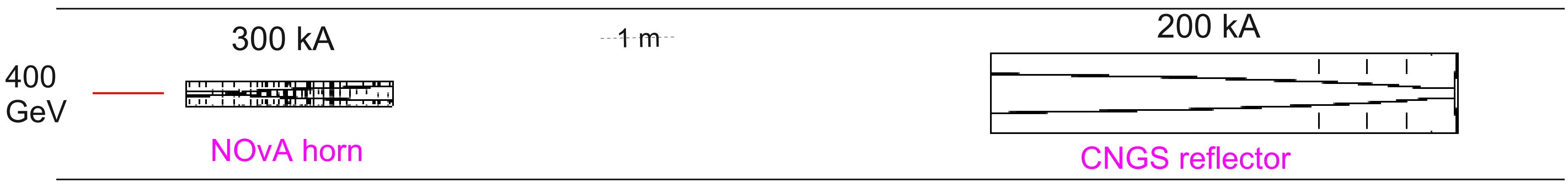
Anyway we set some benchmarks:

> SPS@400 GeV: 1.2 10^{20} pot/year = 2.7 nominal CNGS ~ 770 kW
> 50 GeV machine: 0.77 → 2.4 MW (PS2 LAGUNA)

Run sharing: 5 years of ν + 5 years of anti-ν

Focusing system: off-axis 400 GeV

Optimised configuration for off-axis beam (to scale)



Tunnel L = 1000 m r =1.225 m (CNGS)
1 m long graphite target

Optimization: done with the fast simulation BMPT code (E.P.J.C20:13-27,2001). Final fluxes obtained with a GEANT4 based simulation (E.P.J.C 71:1745, 2011)

Systematic variation of currents, horn-reflector distance and target position keeping the shapes of horn (NOvA) and reflector (the CNGS one) fixed.

The figure of merit was taken as the ν_μ^{CC} rate in the peak region for the 7 km configuration.

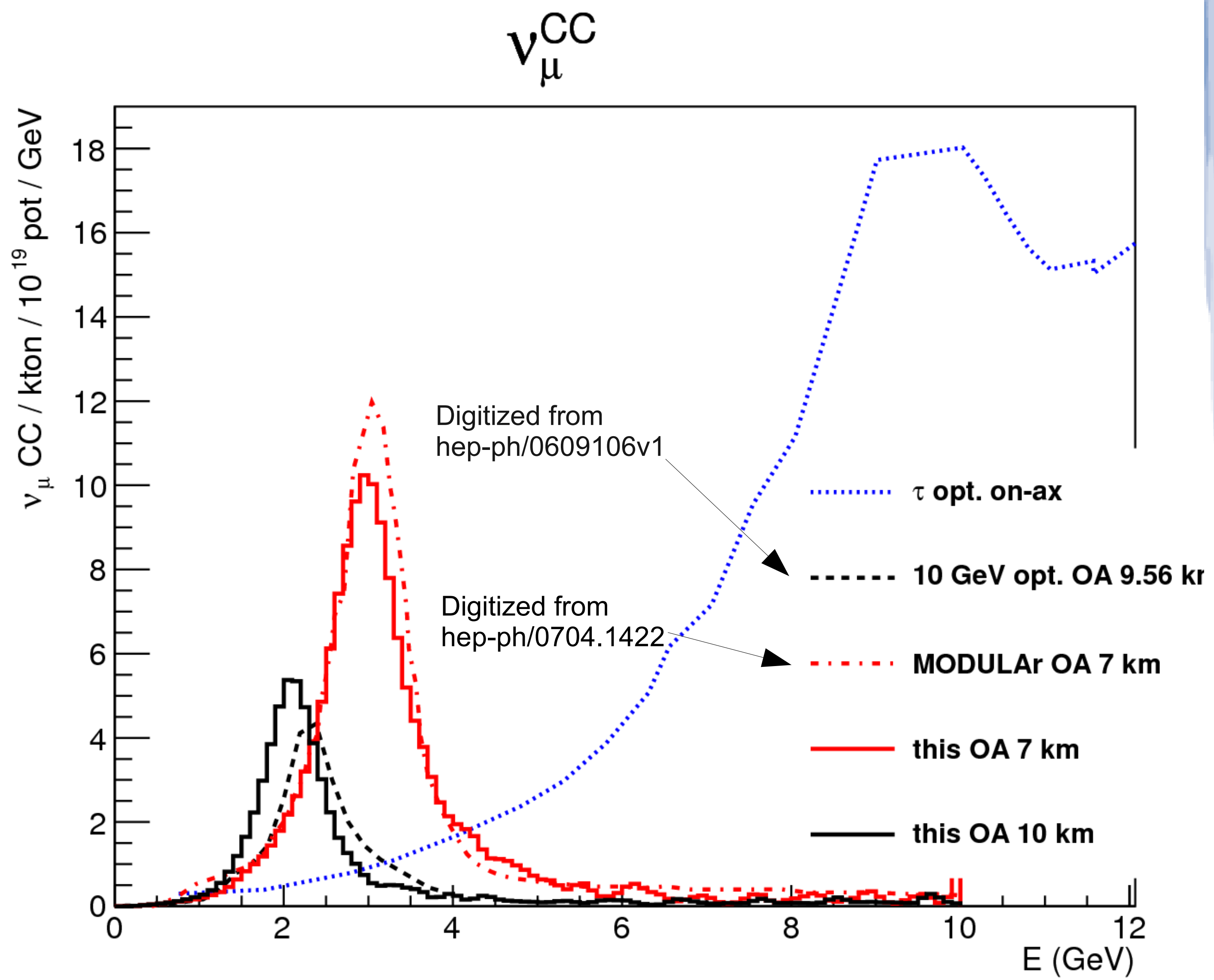
Optimal configuration yields similar event rates wrt to configurations optimised by the MODULAr group (see next →)

Off-axis 400 GeV event rates

Fair agreement with other simulations – optimizations.

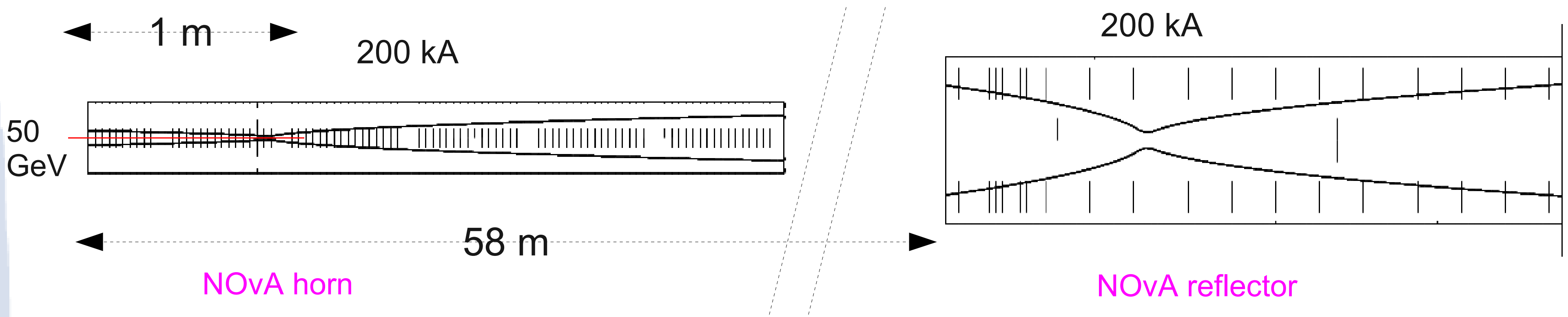
Our best fluxes are ~10% lower than best MODULAr one.

Our fluxes scaled up by 10% (considered as an improvement factor)



Focusing systems: on-axis 50 GeV

Optimised configuration for on-axis beam (to scale)



Tunnel L = 90 m r =2.2 m
1 m long graphite target

Optimization done in 2010 to get optimal performances on θ_{13} in the context of LAGUNA. GEANT4 based simulation + GLOBeS. Scanning of relative positions of the magnetic lenses and target position.

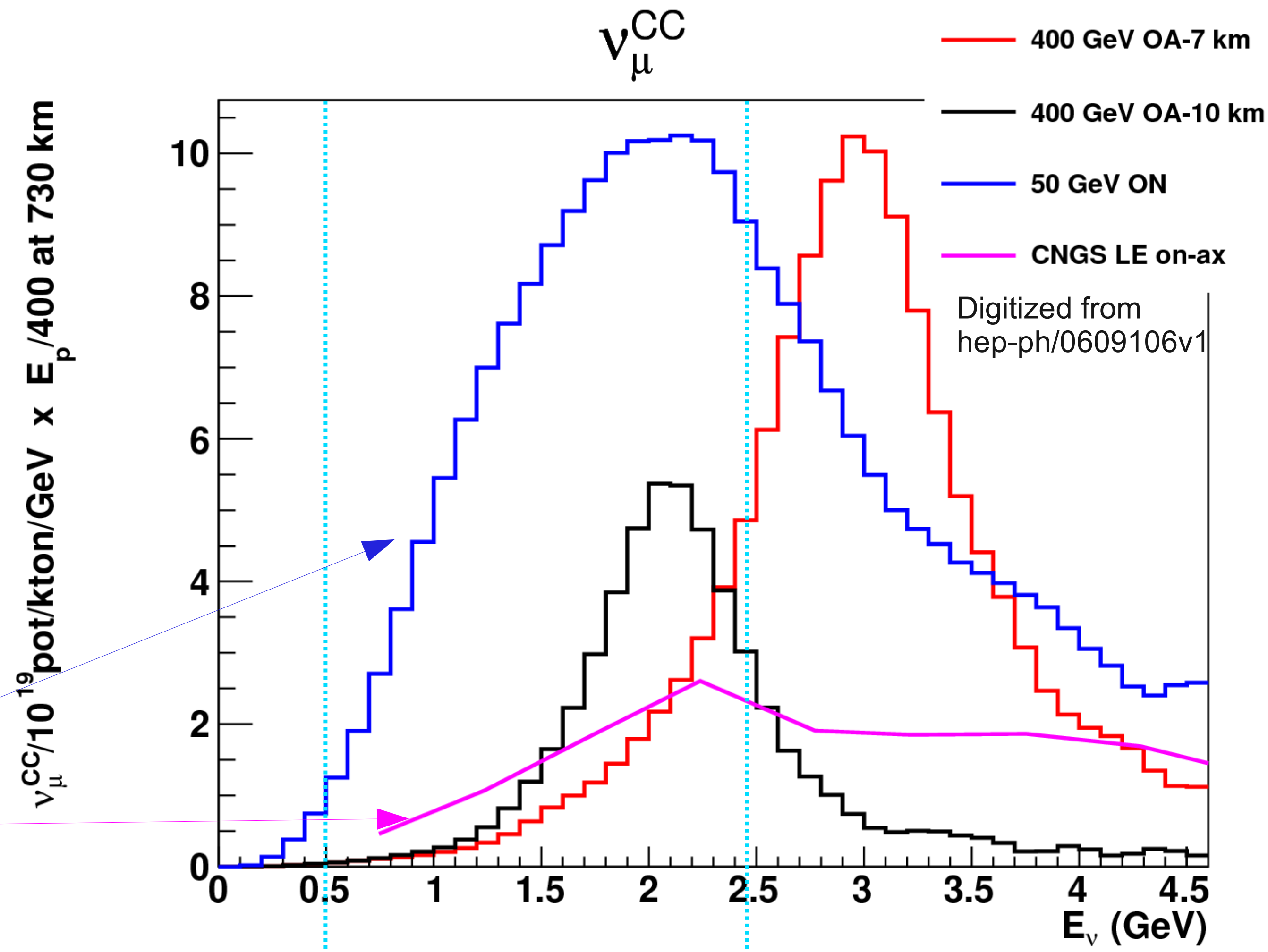
http://pos.sissa.it/archive/conferences/120/325/ICHEP%202010_325.pdf

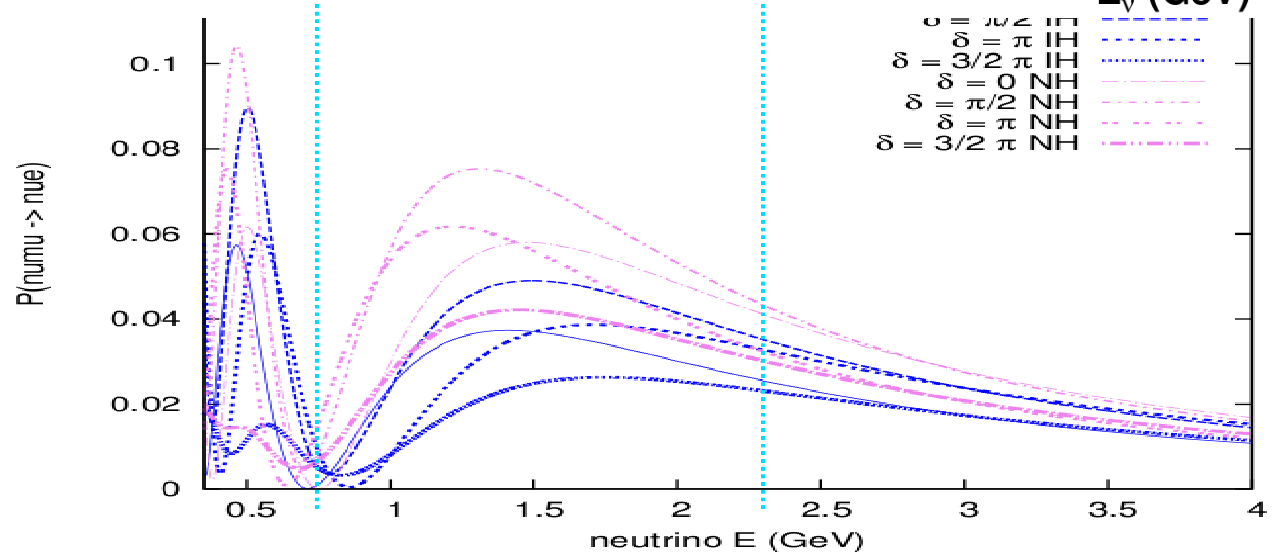
ν_μ^{CC} spectra (power normalized)

"Region of interest" ~ < 2.5 GeV

Second maximum highly suppressed by flux and cross section.

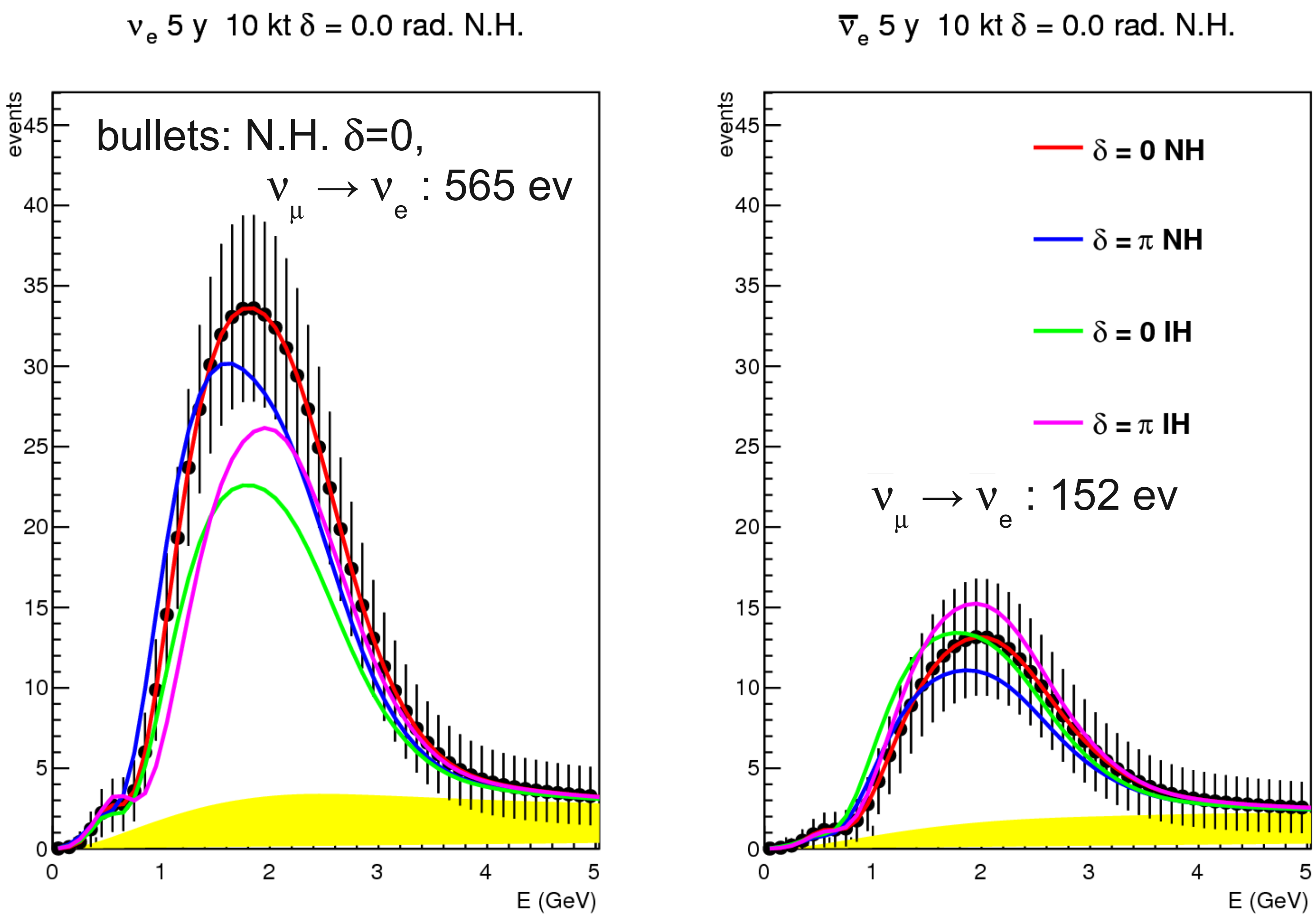
Power normalized 50 GeV on axis beam outperforms 400 GeV on axis beam (CNGS-LE optimization of hep-ph/0609106v1 taken as reference).





ν_e^{CC} spectra, 10 kt on-axis

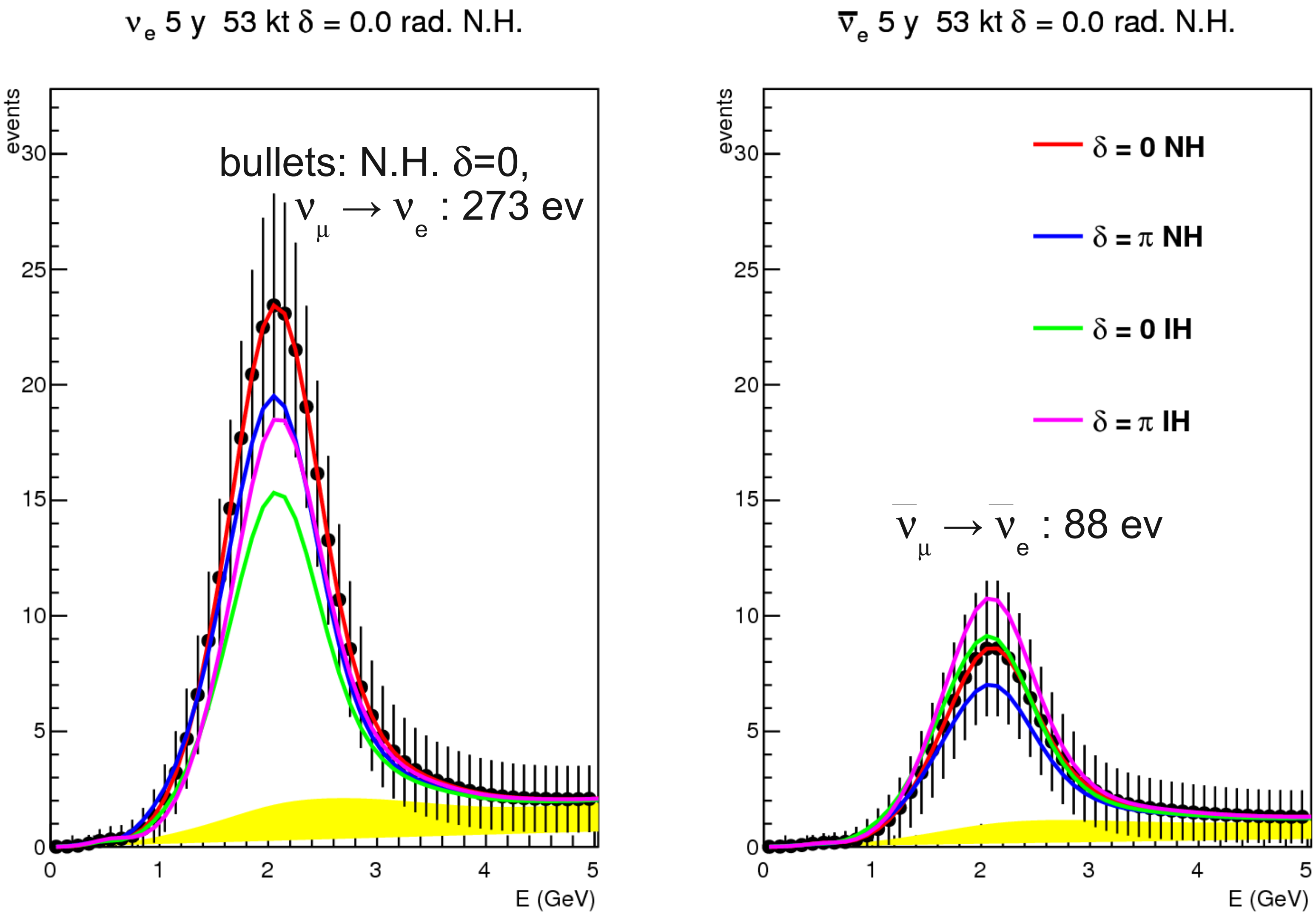
E_p = 50 GeV, 3 ·10^{21} pot/year (2.4 MW), 5 ν + 5 bar-ν years



Fair separation of mass hierarchy. Some sensitivity from the shape of spectrum.

ν_e^{CC} spectra: 20 kt, 10 km off-axis

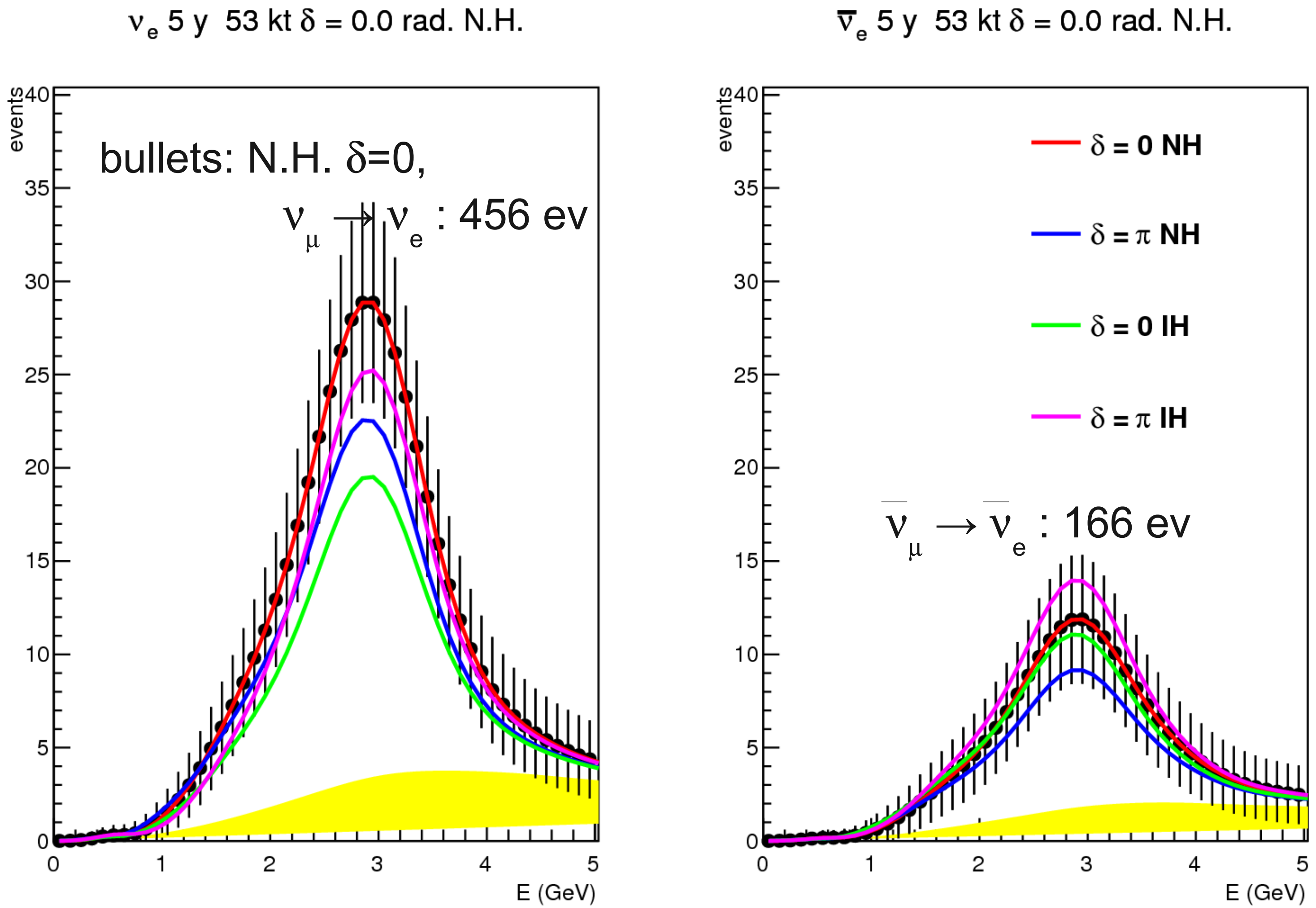
E_p = 400 GeV, 1.2 · 10^{20} pot/year (770 kW), 5 ν + 5 bar-ν years



Reduced separation of mass hierarchy. Reduced sensitivity from the shape of spectrum.

ν_e^{CC} spectra: 20 kt, 7 km off-axis

E_p = 400 GeV, 1.2 · 10^{20} pot/year (770 kW), 5 ν + 5 bar-ν years

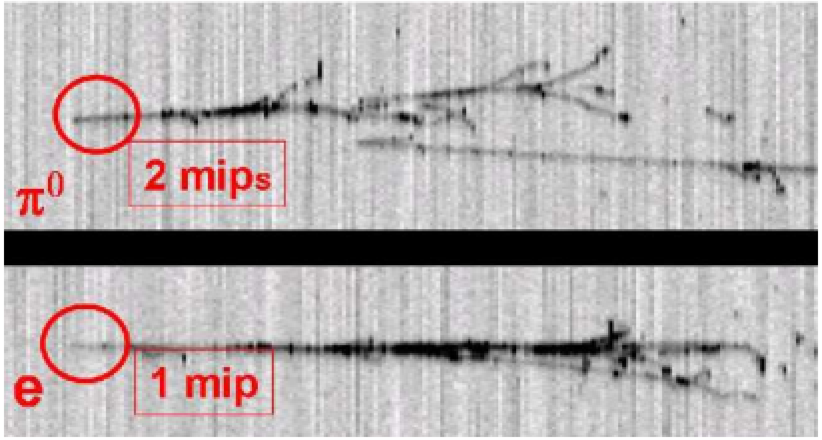


More statistics wrt to 10 km off-axis but lower sensitivity to mass hierarchy and less information from the shape of spectrum.

Parametrization of the LAr TPC (I)

- In the framework of the GLOBeS program (v3.1.11)

- NC background contamination (conservative) 0.1% of ν_μ^{CC}



From studies in 0704.1422 (MODULAr)

- Error on signal and background normalization 5 %

- Energy resolution and efficiency for ν_e and bar-ν_e implemented through smearing matrices obtained from GENIE Monte Carlo generator →

Parametrization of the LAr TPC (II)

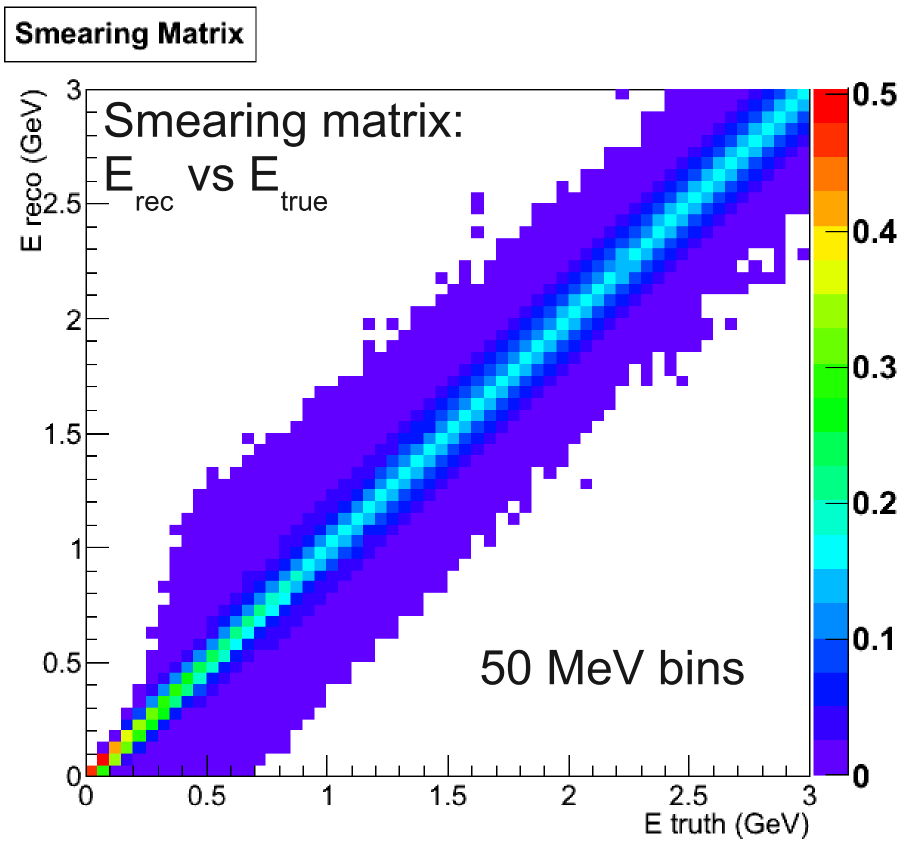
Quasi elastic (QE)

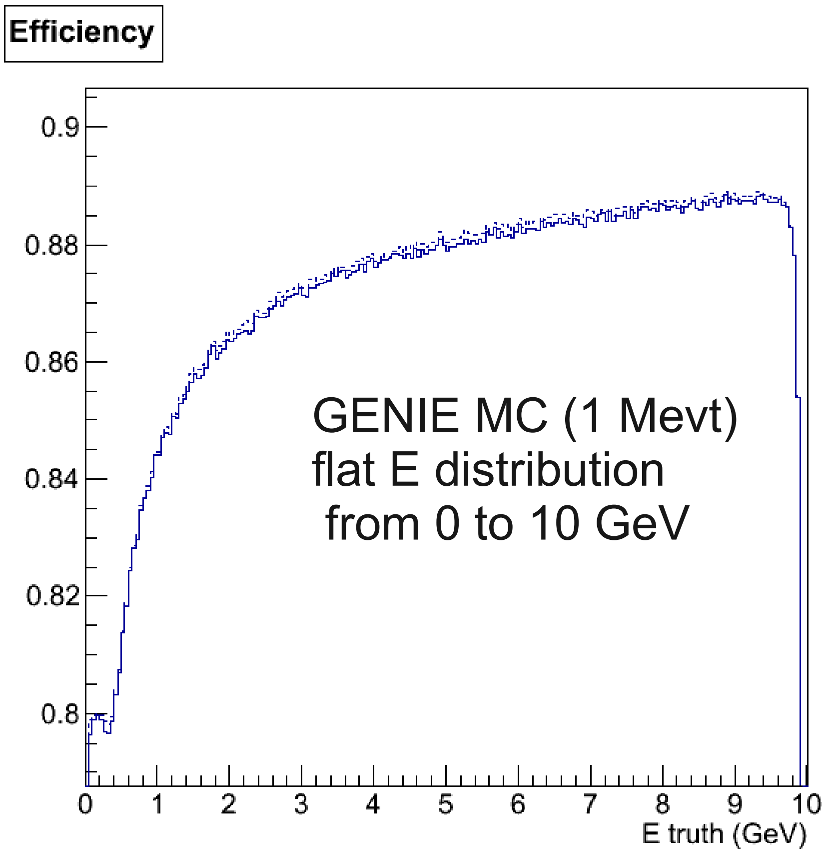
- 80% efficiency
- smearing of true-level e-momentum
- 2-body formula for E_{rec}
- yields $\sigma(E_\nu)/E_\nu \sim 0.05/\sqrt{E_\nu}$

Non-QE

- 90 % efficiency
- $\sigma(E_{had})/E_{had} = 20\%/\sqrt{E_{had}}$

Matrices calculated for ν_e and anti-ν_e separately.



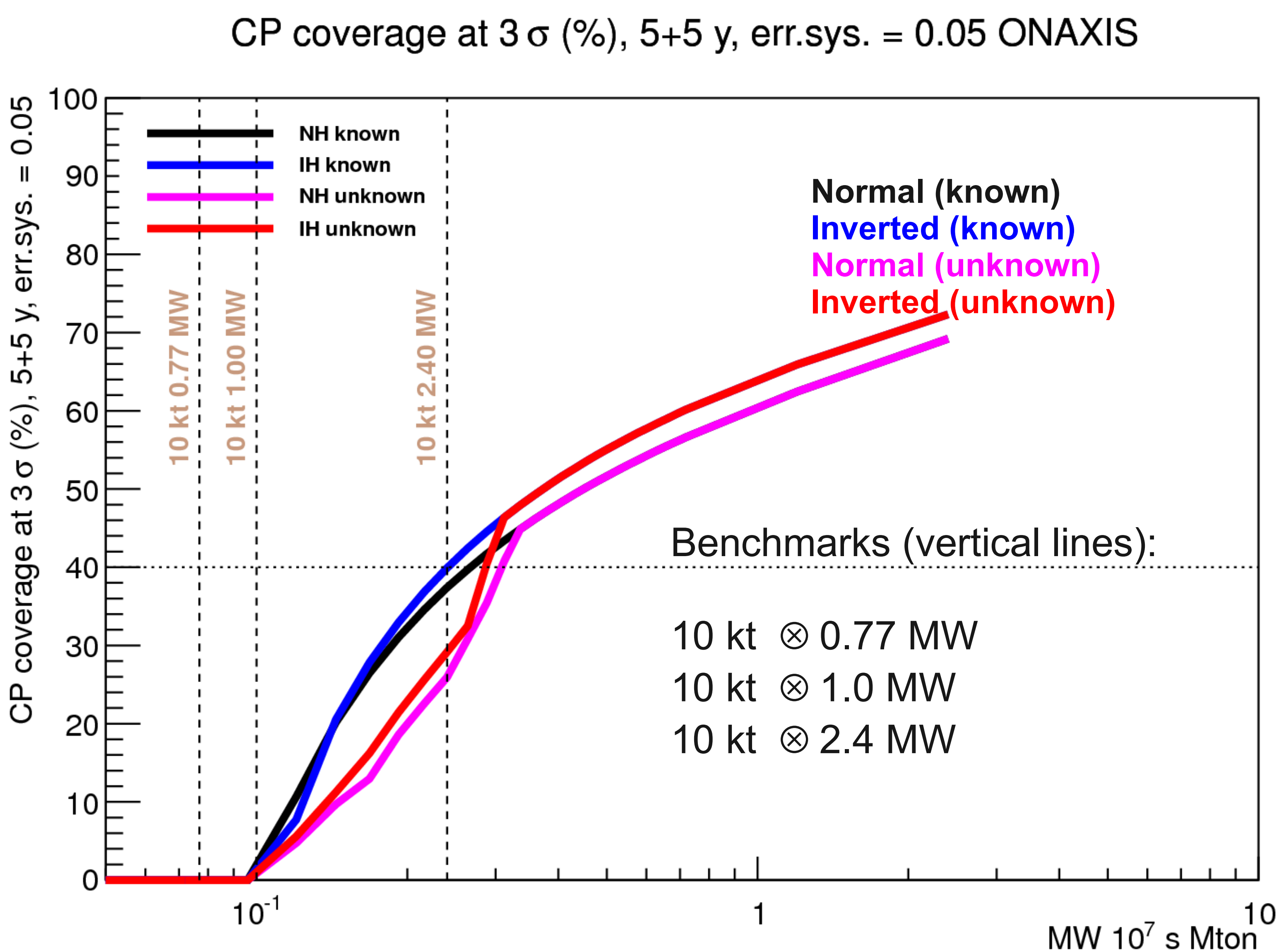


Results ! $\rightarrow$

CPV coverage (on-axis 50 GeV)

5 % systematic error on flux normalization

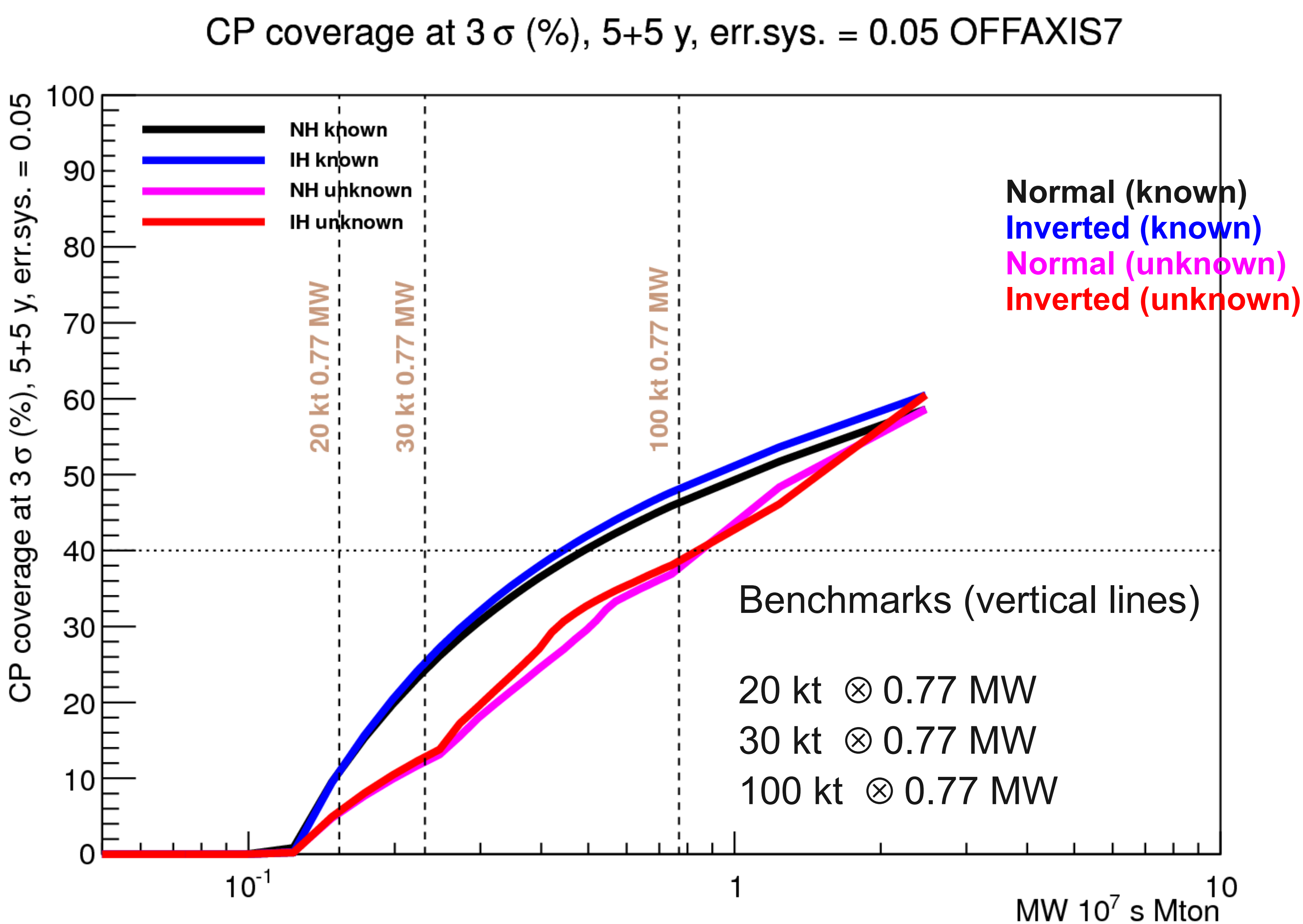
5 ν + 5 νbar years



CPV coverage (off-axis 7 km 400 GeV)

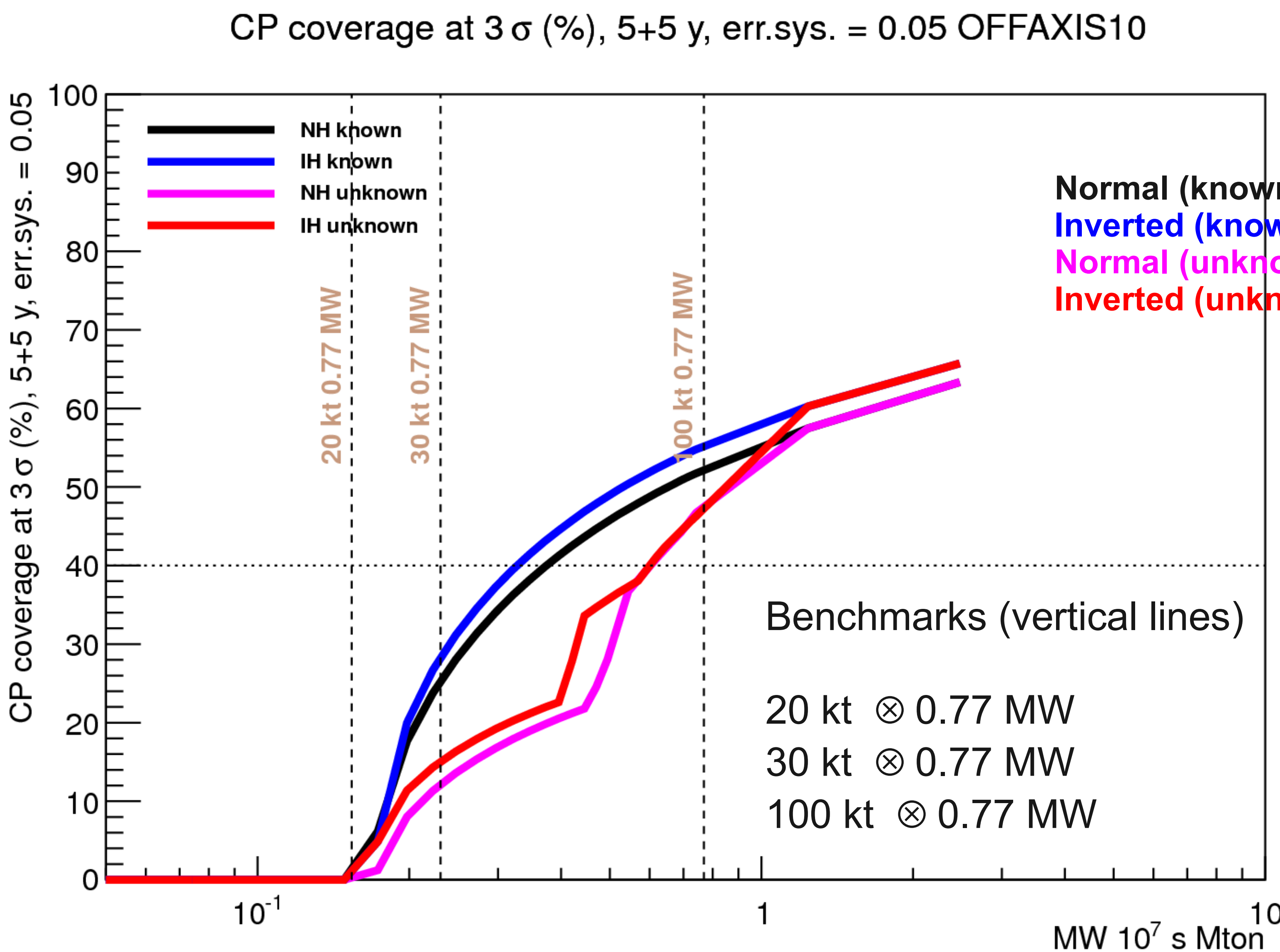
5 % systematic error on flux normalization

5 ν + 5 νbar years



CPV coverage (off-axis 10 km 400 GeV)

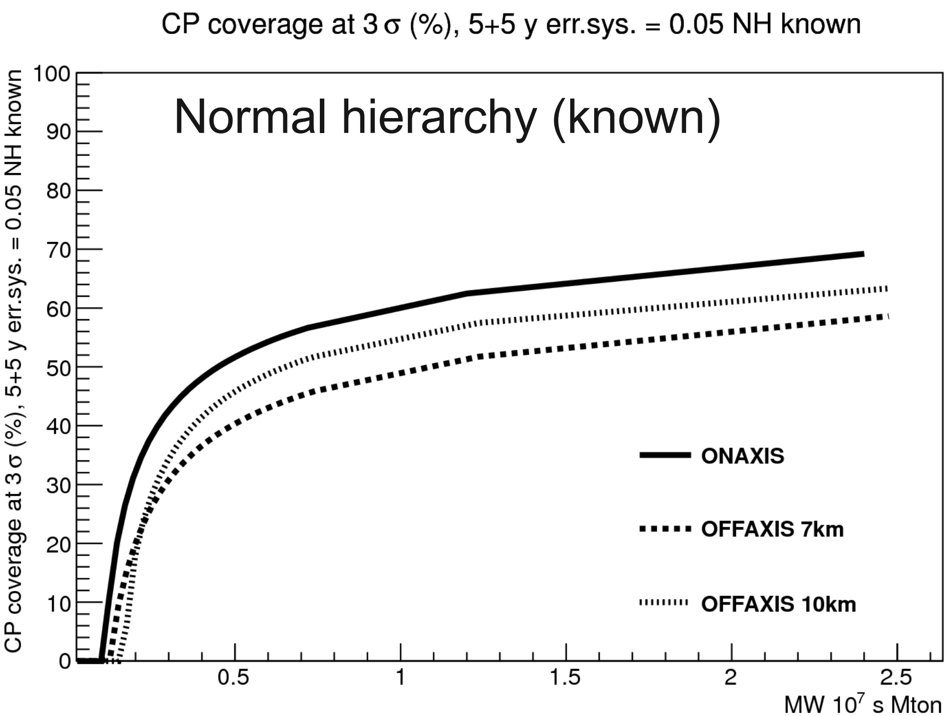
5 % systematic error on flux normalization 5 ν + 5 νbar years

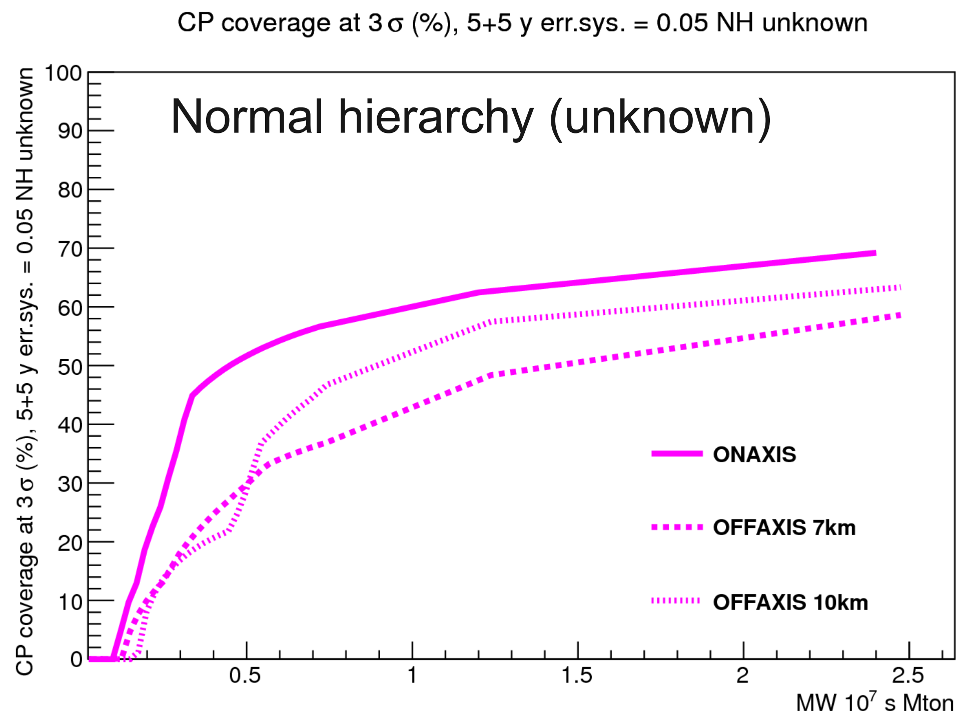


CPV coverage comparison

ON-AXIS 50GeV
OFF-AXIS 400 GeV at 7 km
OFF-AXIS 400 GeV at 10 km

as a function of exposure (MW Mton 10^7 s)





- ONAXIS in general works better due to better coverage of the 1st oscillation maximum
- For the same reason 10 km performs better that 7 km except for very low exposures where lack of statistics (at 10 km) counts

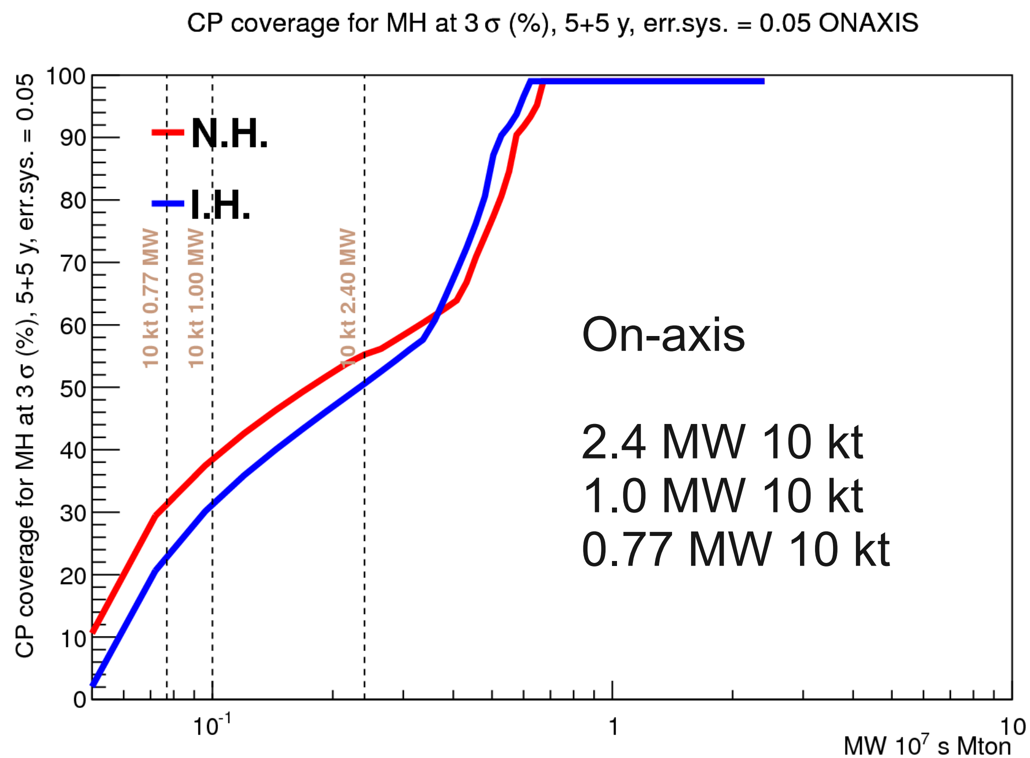
MH coverage

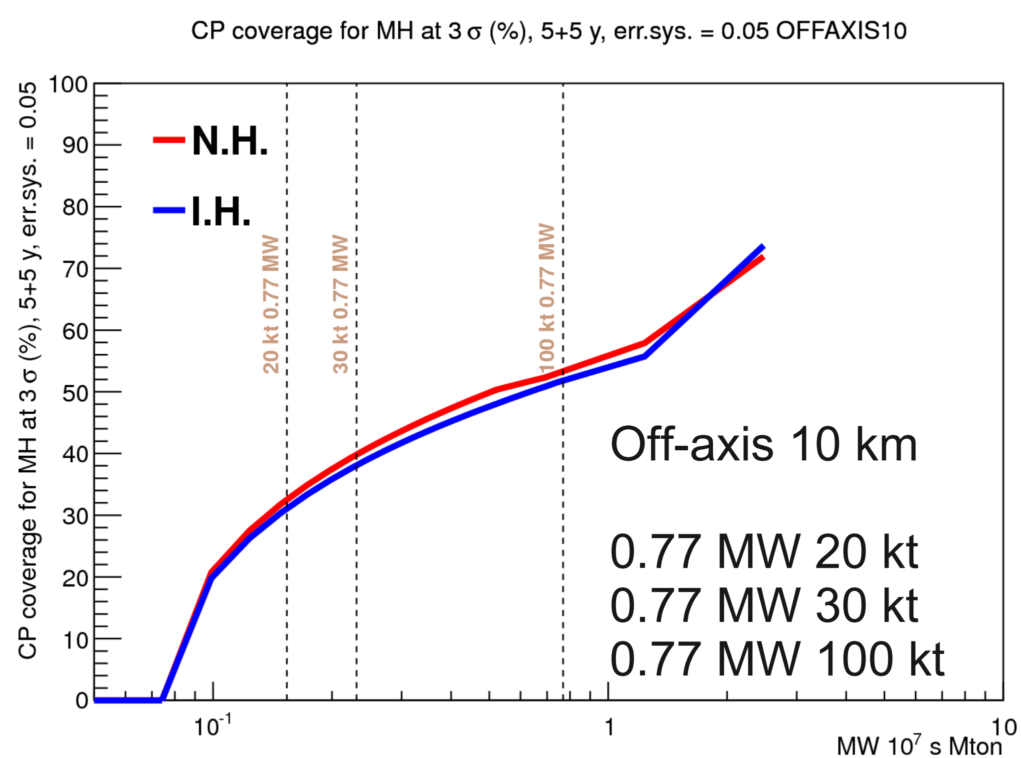
5 % systematic error
on flux normalization

5 ν + 5 νbar years

Mass hierarchy reach is better for the on-axis configuration (evident from ν_e appearance spectra shown earlier).

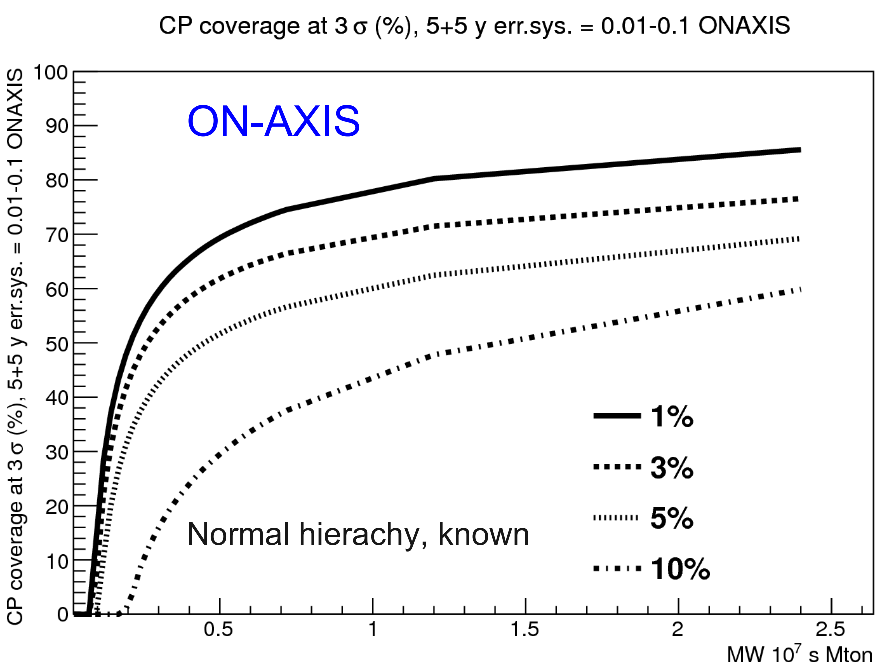
The 10 km off-axis is better than 7 km for the same reason (only 10 km shown)

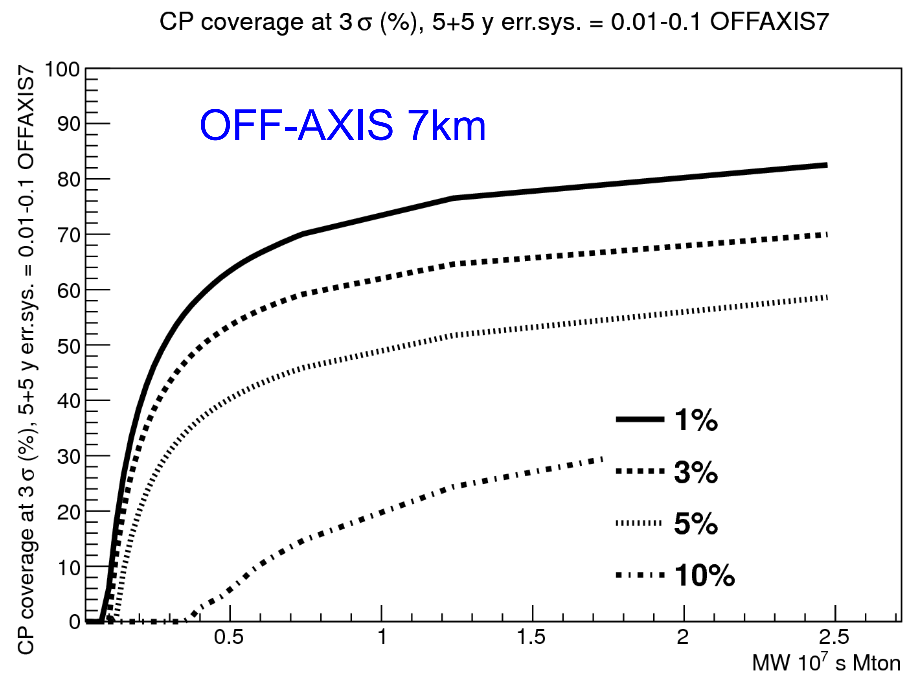




Systematics on absolute flux normalization

Considered values 1-3-5-10 %





The effect is very relevant as expected (δ variations induce mostly a change in normalization at this baseline)

5 % is a widely used in many calculations, T2K super-beam nowadays is still above the 10% level

Design of future experiments must address this point (LAr TPC already goes in this direction). Improving the systematic error pays more tha brute force (boosting mass)

Comparison with other baselines

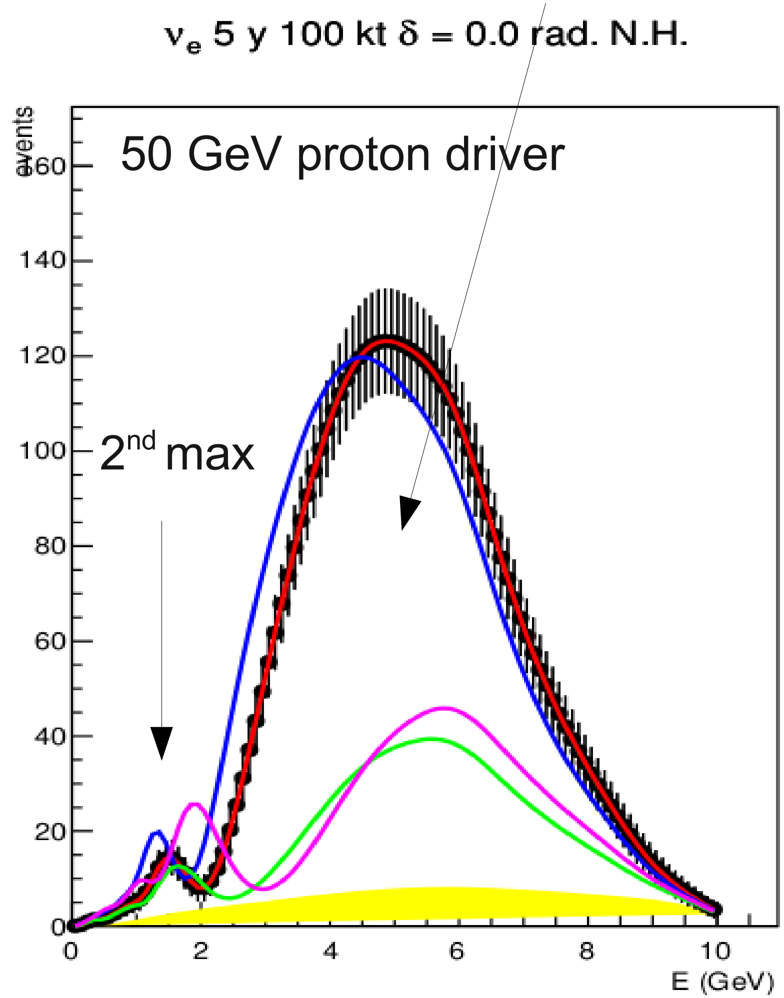
Being either very long (~2300 km) or very short (~100 km).

Performed under the same assumptions on LAr detector performances, systematics errors and with the same analysis program.

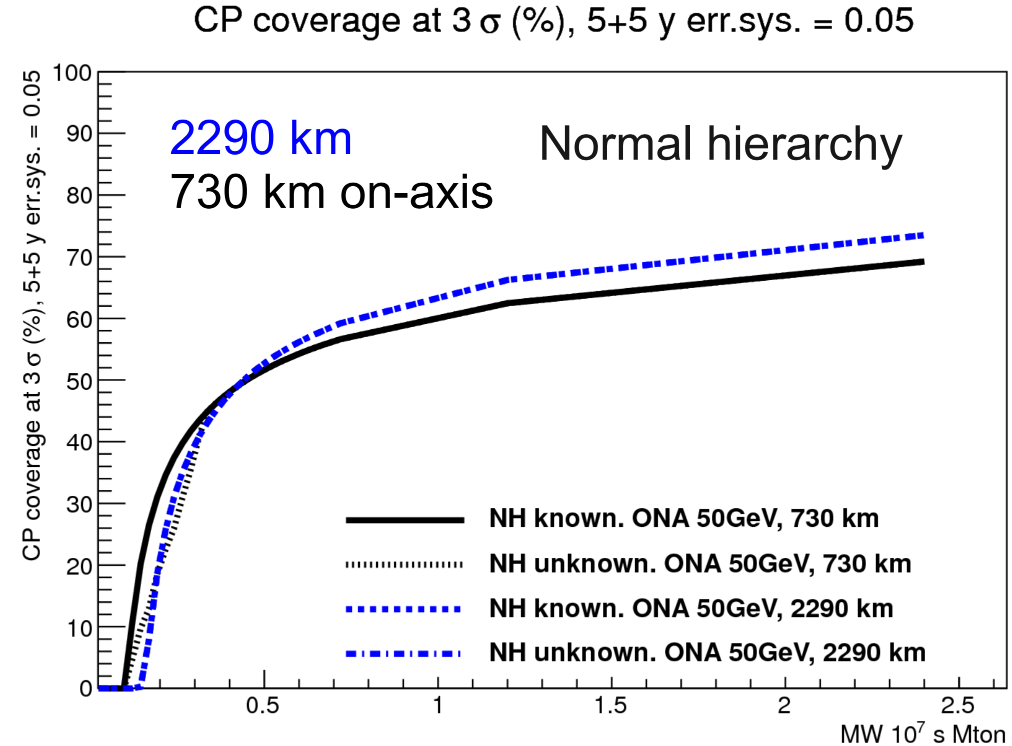
→

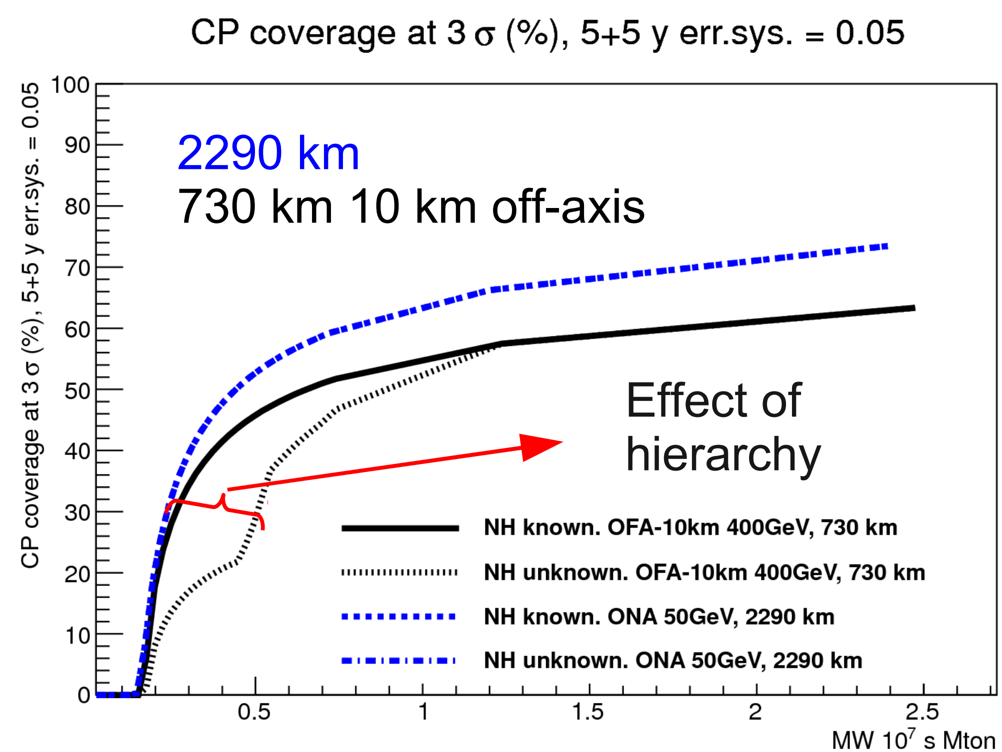
2290 ↔ 730 km

- MH: 2290 km is superior (large matter effects), no ambiguities from MH knowledge



- CP violation: not a huge difference
- Higher coverage at 2290 at high exposures (where 2^{nd} max starts to play a role)





Exercise: low-E + short baseline (102 km) ?

E.P.J.C 71:1745, 2011

Philosophy of SPL-Fréjus:
L=130 km, E^{1st} = 260 MeV. E_p = 4.5 GeV, 4MW SPL + 440 kton Water Cherenkov

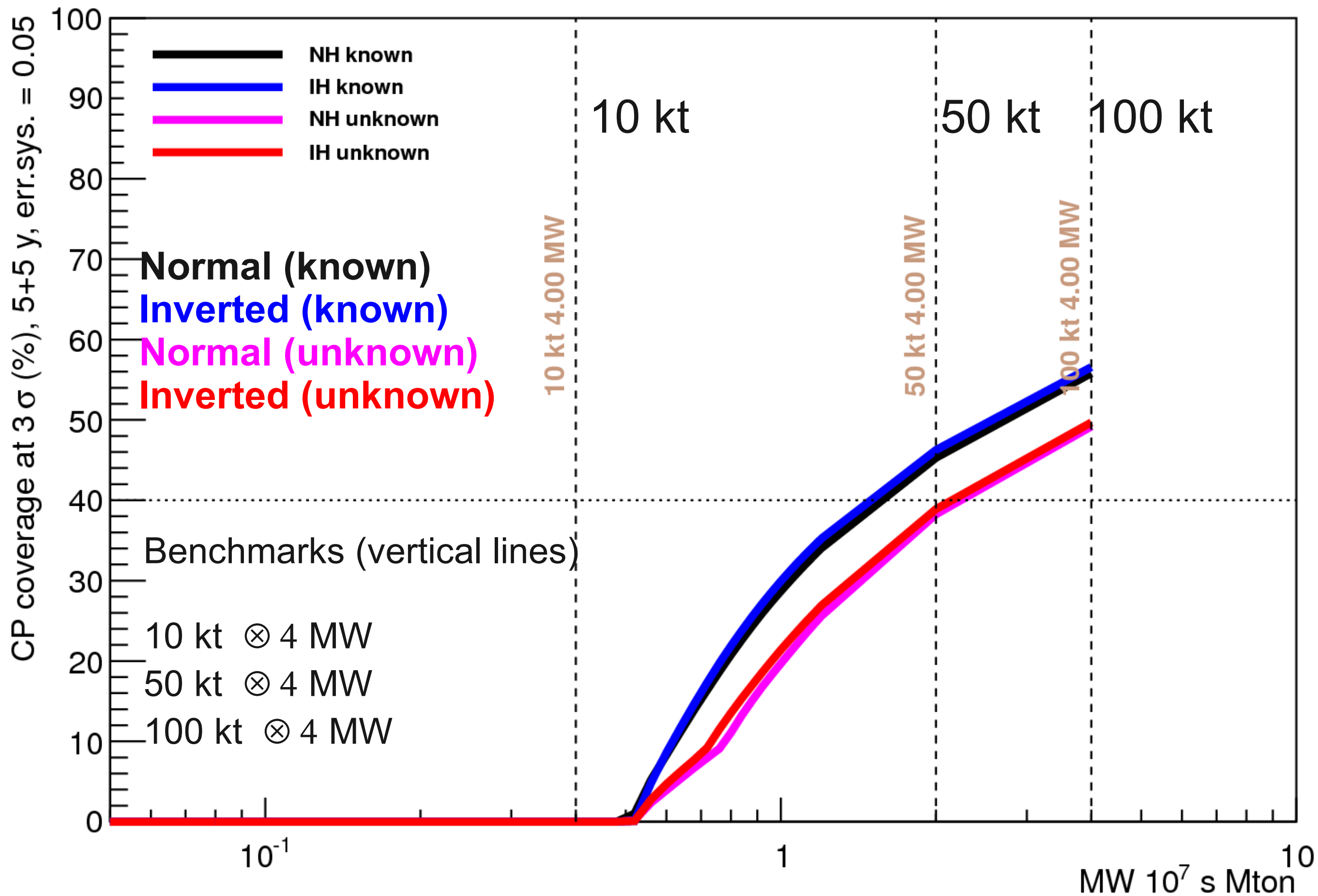
Tor Vergata (Rome) – LNGS. L = 102 km

Clean CP. Knowledge of MH plays no role.

Despite better performances of LAr quite large masses are still required to get a reasonable coverage.

NB. original design is 440 kt of water

CP coverage at 3 σ (%), 5+5 y, err.sys. = 0.05 SPL



Not suited for underground. Would need a new site (and p driver)

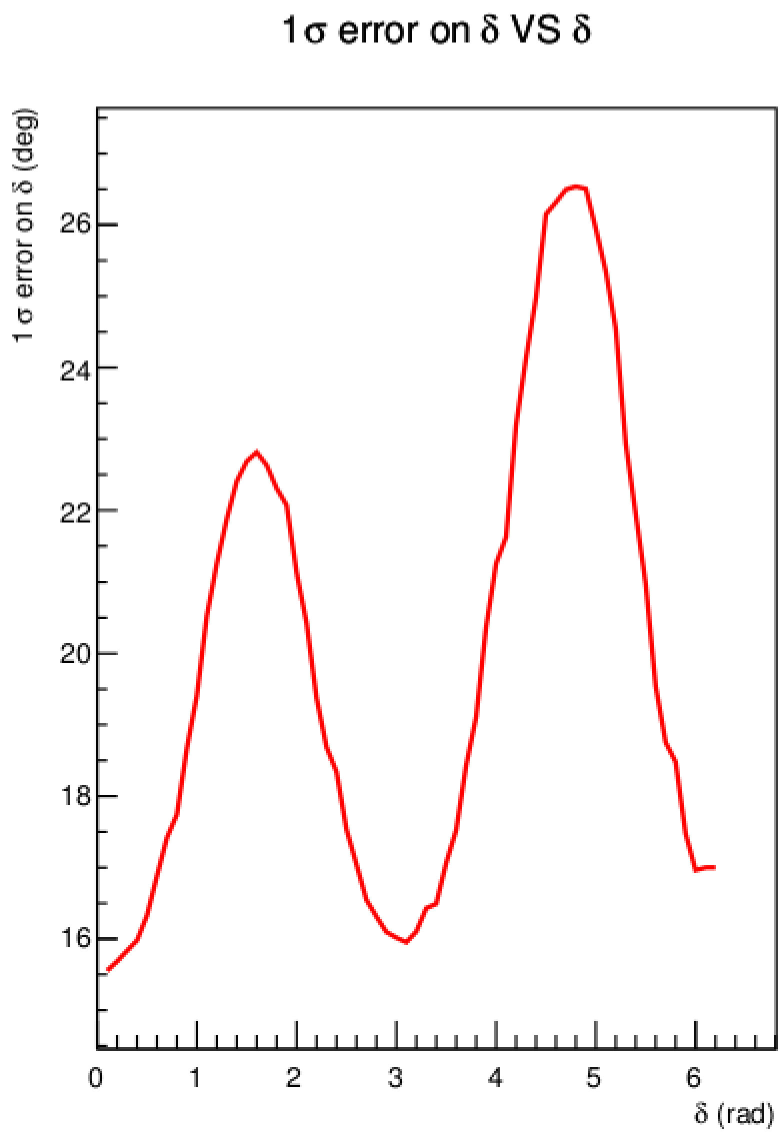
Preliminary conclusions

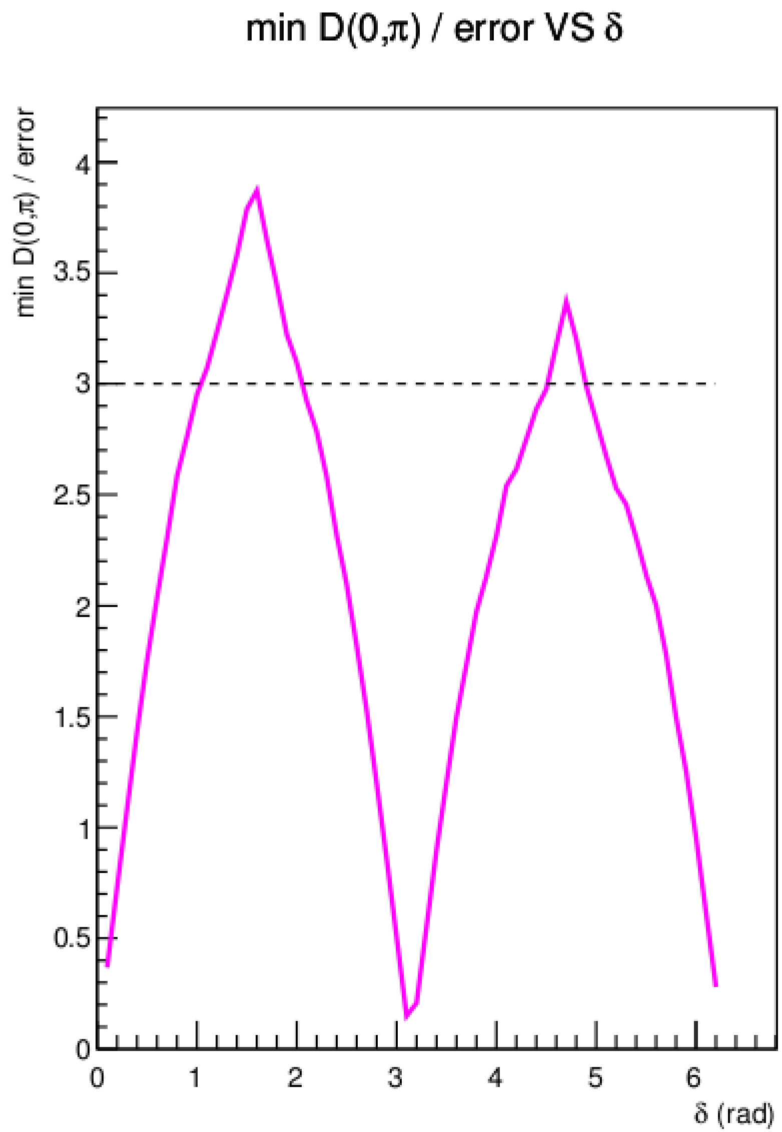
- On-axis configuration using a 50 GeV p-driver performs better than off-axis in terms of coverage vs exposure. Limitation at 10 kt (inside LNGS) would forces to use a multi-MW driver.
- Off-axis configuration with SPS@400 GeV. A reasonable upgrade (< x 3) considered. More sensitive to degeneracy with mass hierarchy w.r.t. on-axis at 50 GeV. 10 km better even though at small exposure 7 km "wins".
- Comparison with 2290 km baseline: CP performance is not much different w.r.t. 730 km (there is a sort of "baseline invariance" at large θ_{13}). Unbeatable for MH. 2^{nd} oscillation maximum is usable and "pays" at high exposures.
- Low baseline+high power Linac. Despite high power, still large masses are needed (not compatible with existing underground lab constraints).
- Systematic errors control is crucial. Near (ancillary) detector(s) mandatory. Allows sparing brute force ('kt').
- Outlook: other SPS energies could be investigated, association of on-axis and off-axis detector ? Further focusing optics optimization.

Back-up slides

Error on δ

On axis 7 kton
3e21 pot/y
5+5 years 0.05 sys
Known hierarchy





Comparison with LBNE for CPV

700 kW 120 GeV
34 kton 5+5
1% norm err on signal
Coverage ~ 67 %