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

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INFN: LNF, PD, BO, MI-B

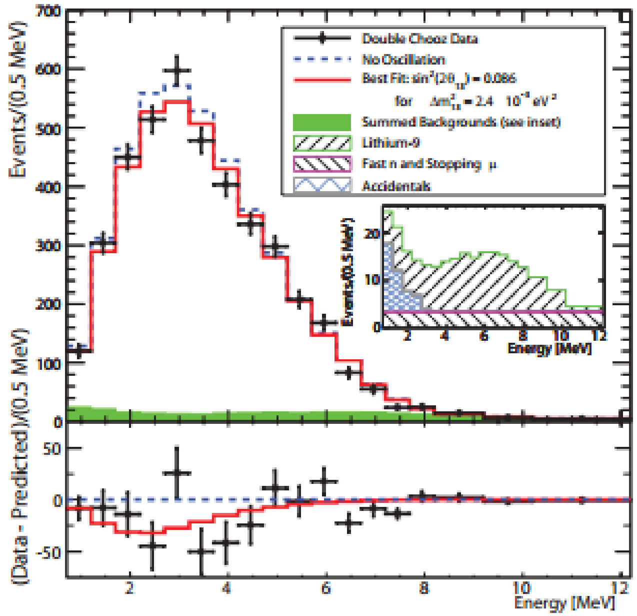
Outline

- Goals and working hypotheses
- Leptonic CP and mass hierarchy with a 730 km baseline
- ν beam simulation/optimization
- Parametrization of LAr TPC performances
- Results and comparison with other baselines

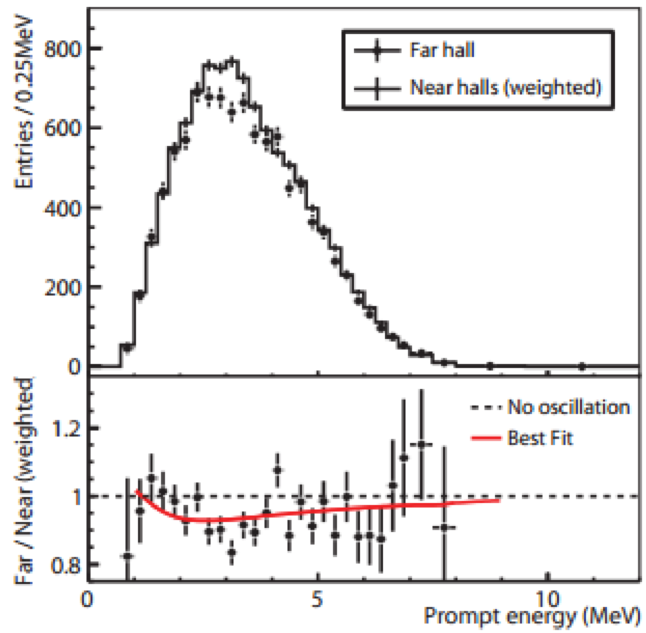
Goals

- 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) ?
- Assumption: use the LAr TPC technology
- Investigate (within reasonable/realistic contraints):
  - mass of detector / number of pots
  - proton energy / off-axis angle

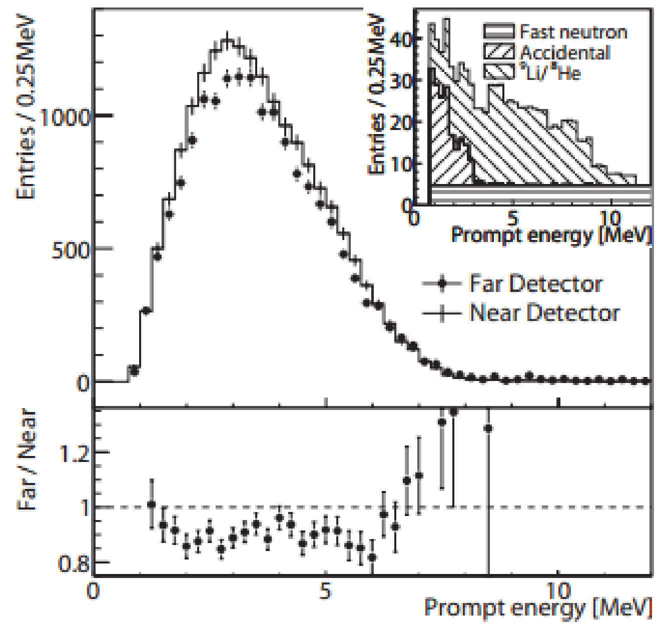
Double Chooz

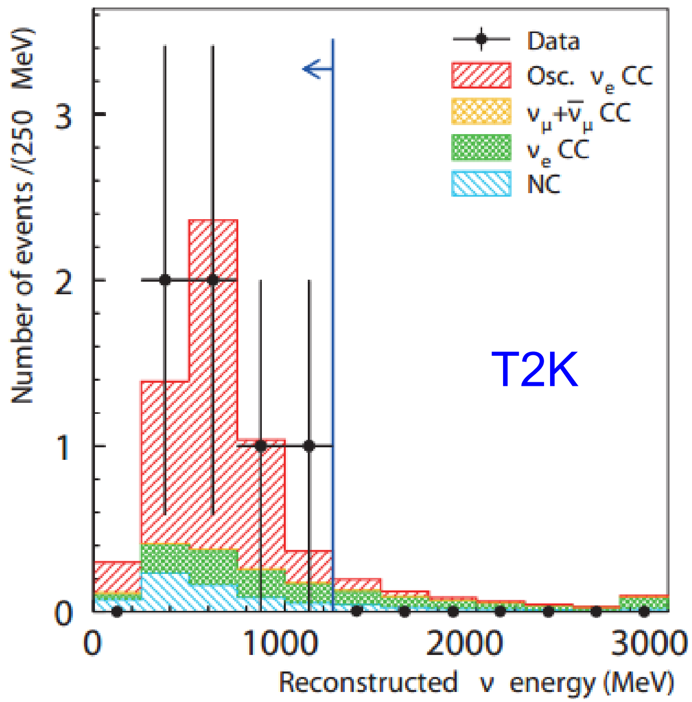


Daya Bay

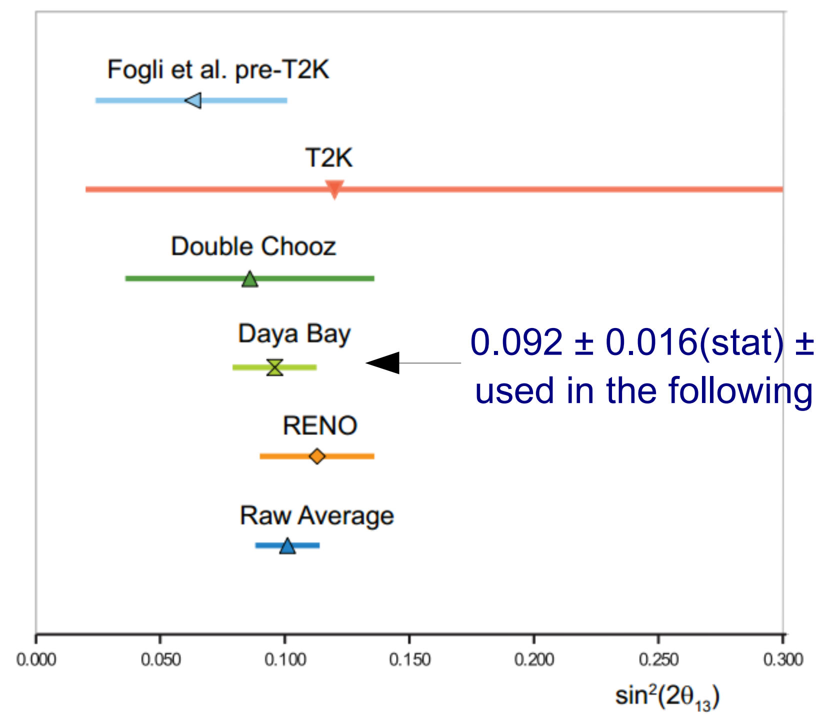


RENO





θ_{13}



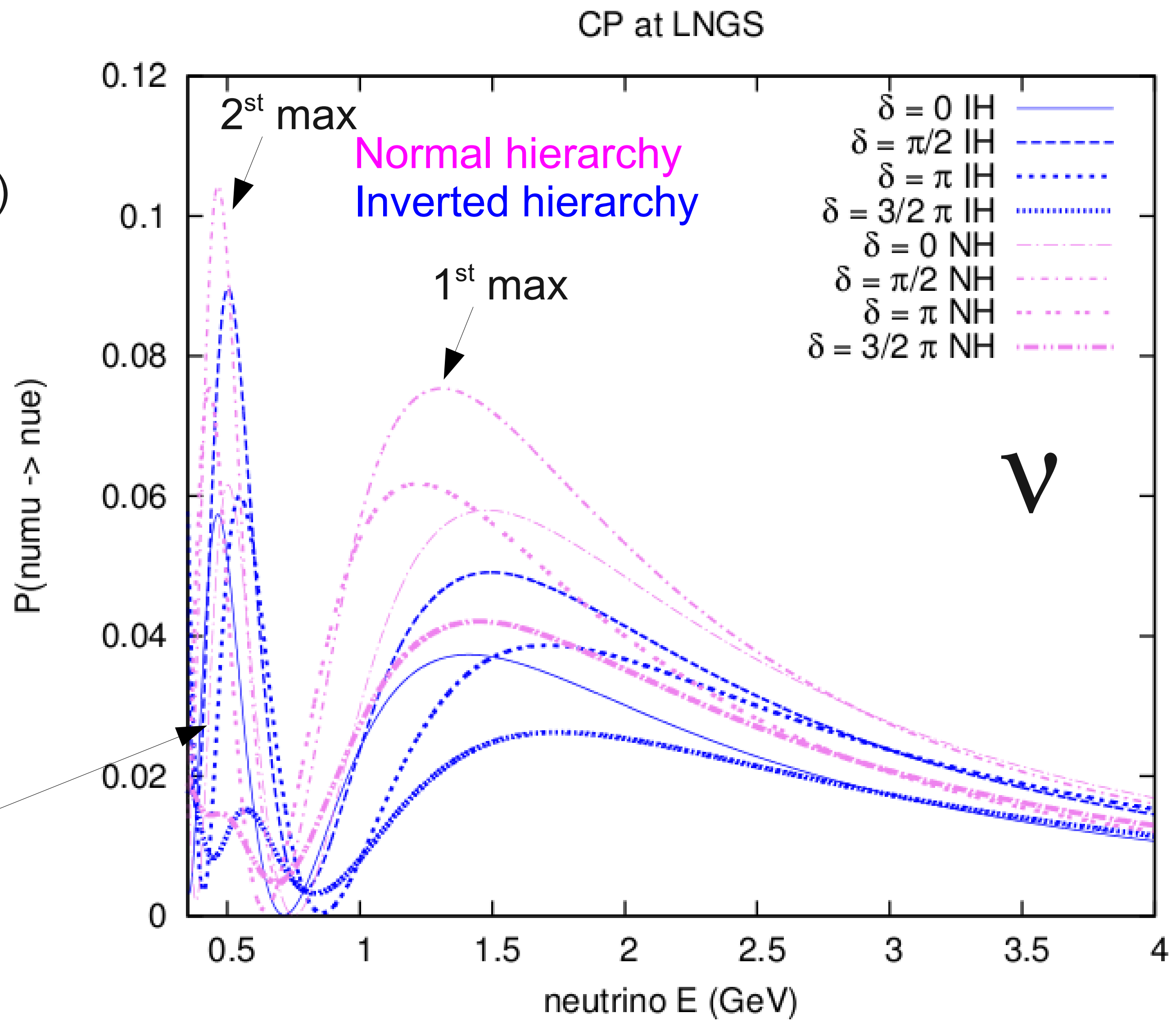
0.092 ± 0.016(stat) ± 0.005(syst)
used in the following

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

Effects ruled by the mass hierarchy (~matter effects) and the CP phase effects are of comparable size

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

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



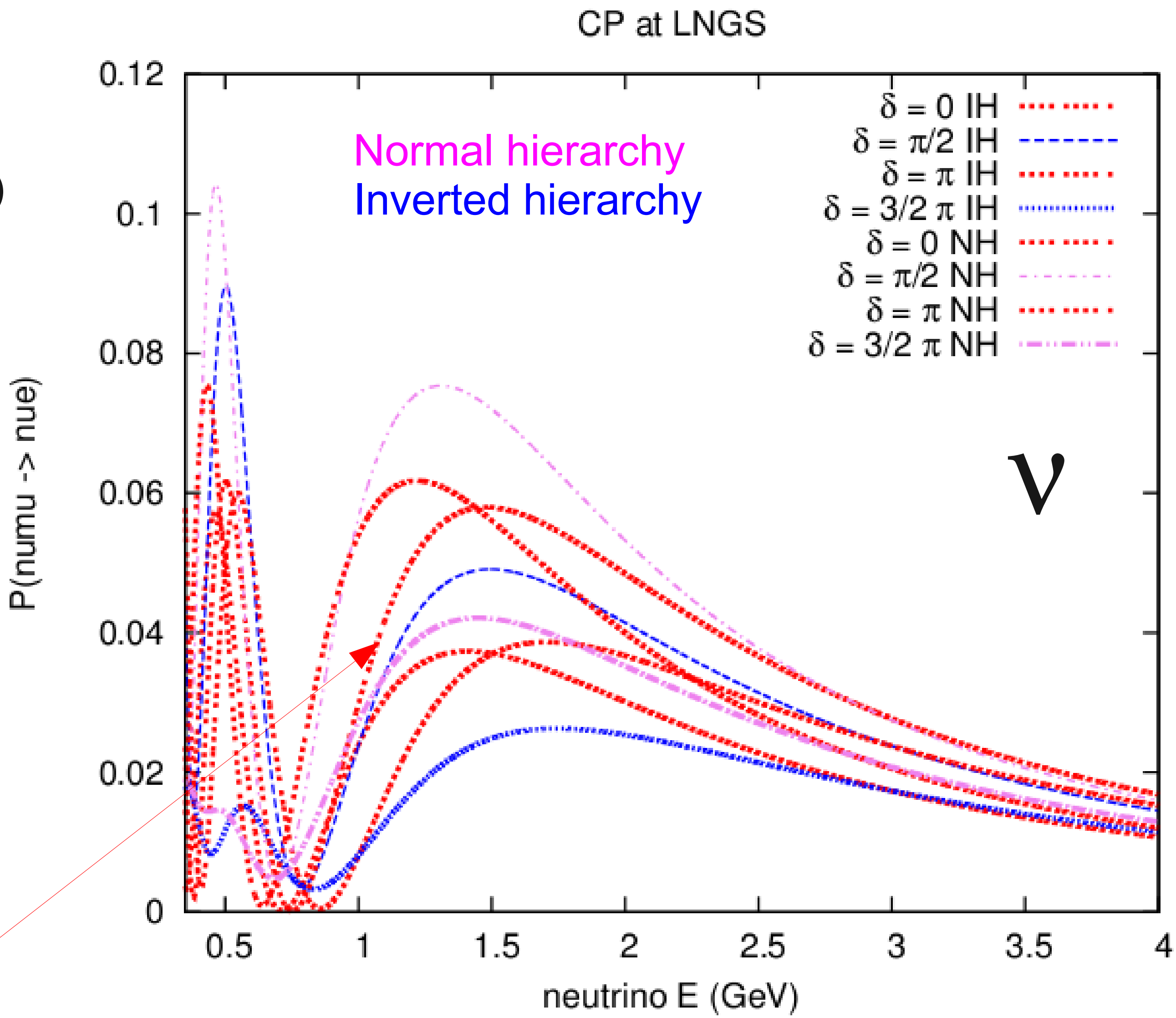
$\nu_\mu \rightarrow \nu_e$ probability at 730 km

Effects ruled by the mass hierarchy (~matter effects) and the CP phase effects are of comparable size

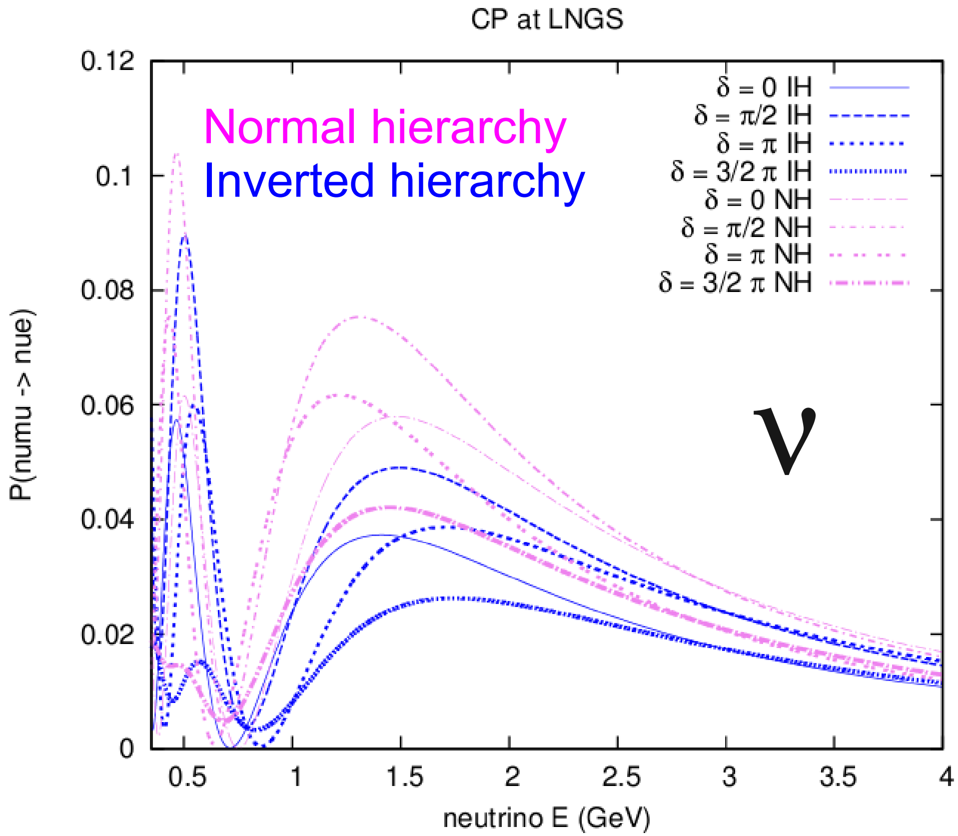
At first order a change in normalization → control of systematic errors is crucial

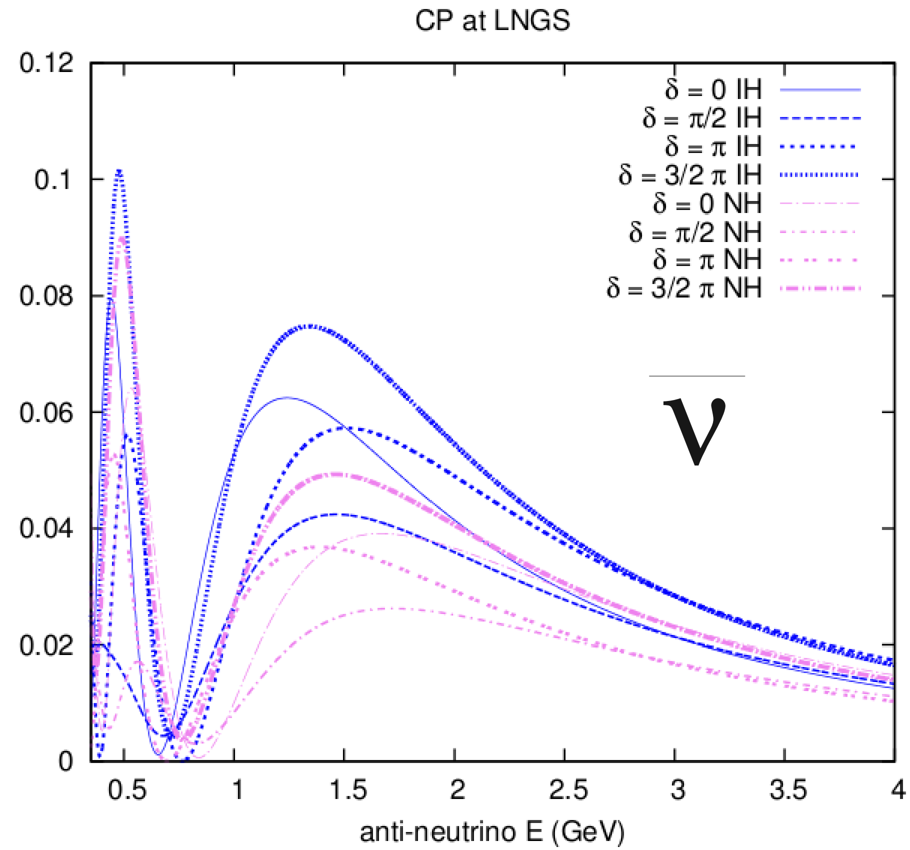
2nd maximum at a quite low energy (~ 500 MeV)

Discover CP violation = exclude δ = 0 or π (CP conserving).



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





Hierarchy scheme affect the $\nu_\mu \rightarrow \nu_e$ appearance rates

Normal hierarchy : appearance (ν-bar) < appearance (ν)

Inverted hierarchy : appearance (ν-bar) > appearance (ν)

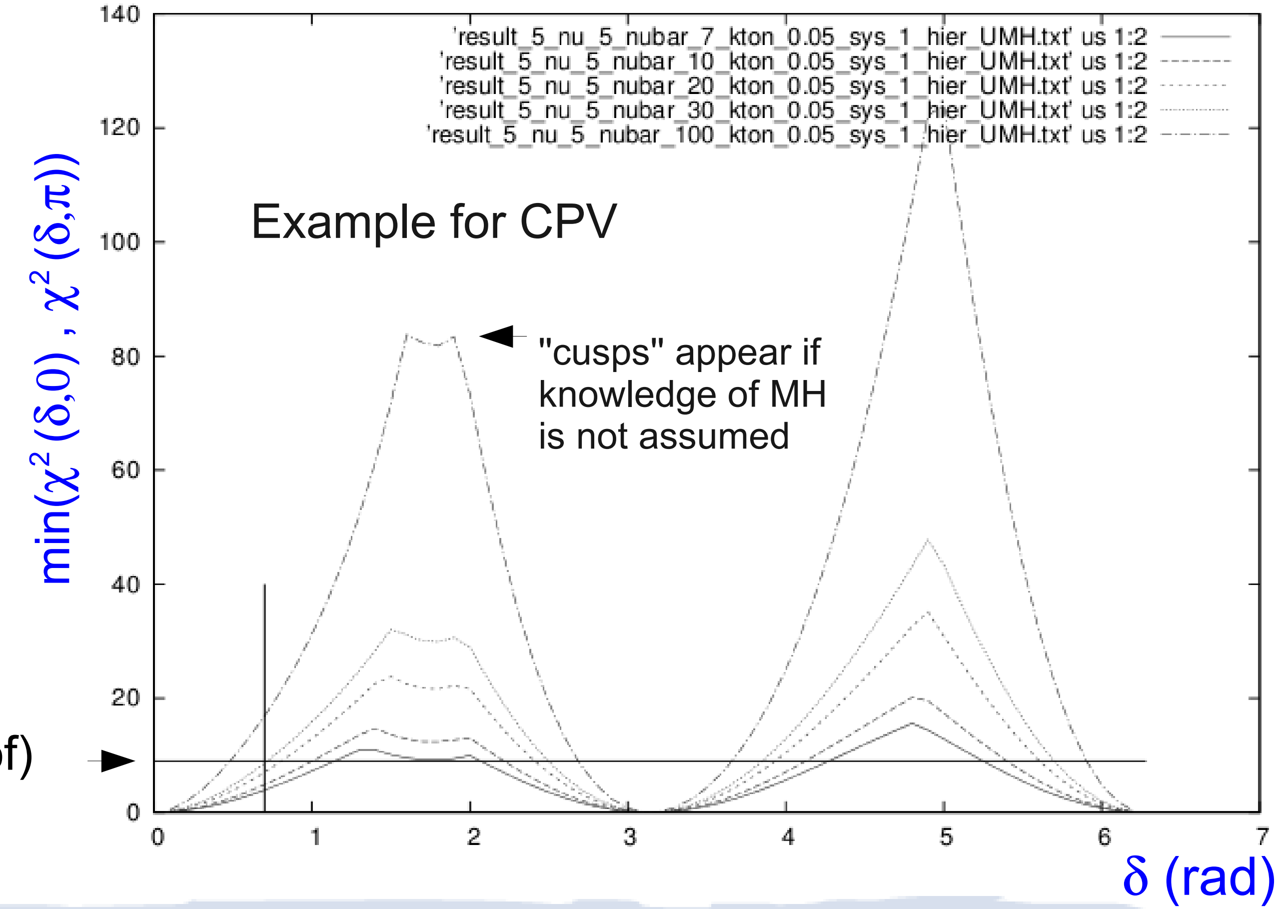
CPV discovery and MH determination

• **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

"coverage": fraction of the values of δ for which CPV / MH is possible

9 (3σ, 1 dof)



Far detector at LNGS

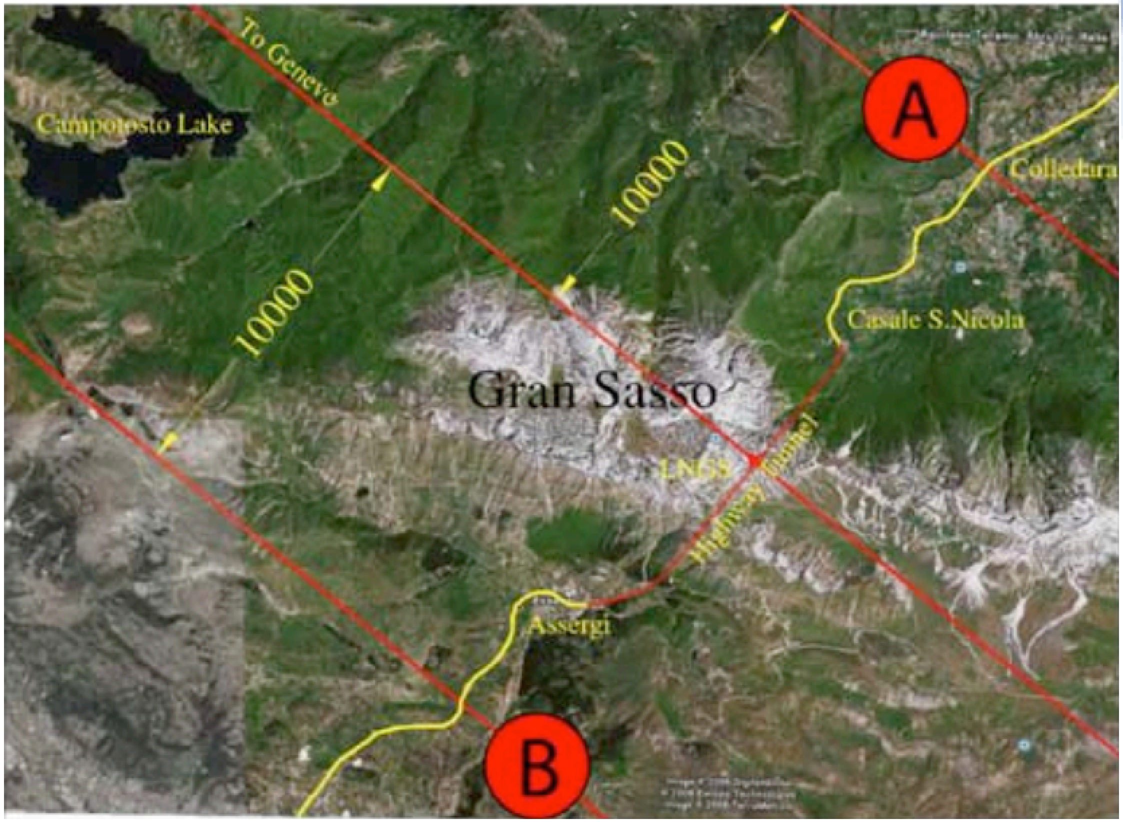
- Three sites investigated for the LAr TPC
  - on-axis inside the existing underground lab (with a mass up to 10 kt)
  - off-axis new shallow depth sites (up to 100 kt)
    - 7 km off-axis
    - 10 km off-axis

- We have considered these options separately for the time being (no double detector on-axis and off-axis)

Off-axis configurations (MODULAr)

hep-ph/0704.1422

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



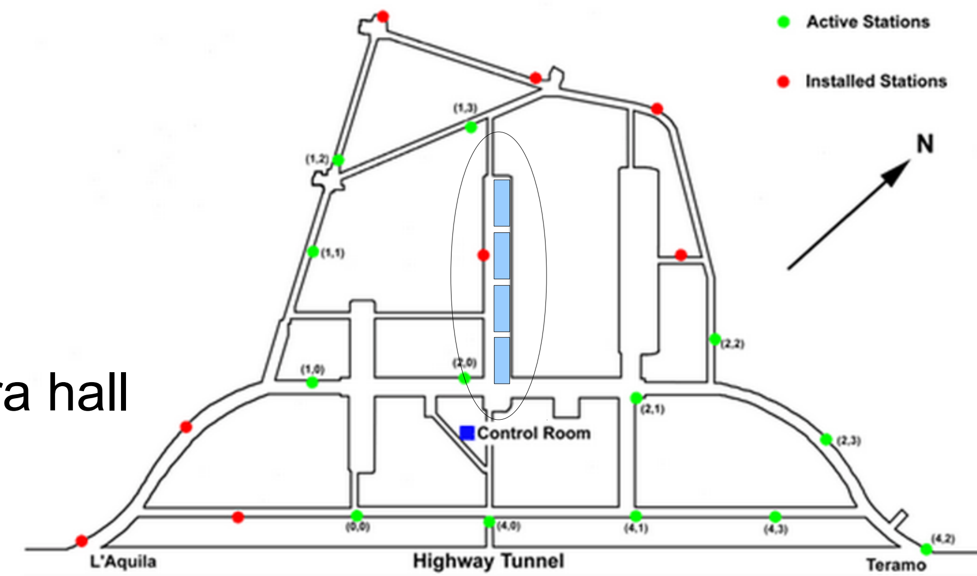
From hep-ph/0704.1422

Contraints on mass underground

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

CERN/SPSC 2002-027

- 4 x T1200 modules → ~ 4 kt fiducial
- ad-hoc design: could go up to ~ 7.5 kt
- ~ 10 kt allowing for extra space in extra hall



Considered beams from CERN

- off-axis configurations: the SPS at 400 GeV
- on-axis configurations: a 50 GeV machine

Why? Using a 400 GeV p-driver it is difficult to efficiently populate the low energy region (see for example hep-ph/0609106v1)

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.

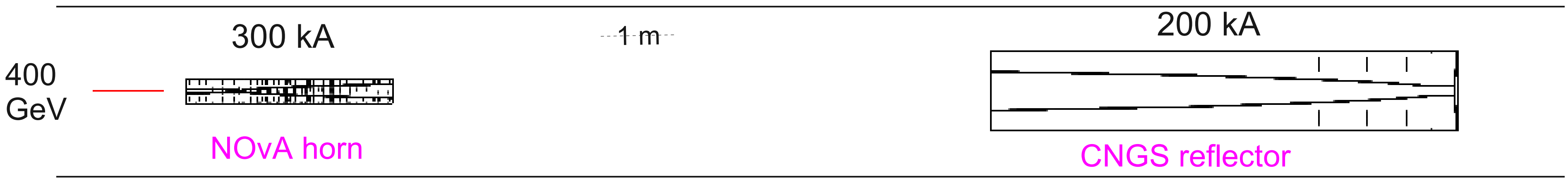
Anyway we set some reasonable benchmarks to allow an easier "reading" of the plots :

- SPS at 400 GeV
  - 1.2×10^{20} pot/year = 2.7 nominal CNGS ~ 770 kW + variable mass
  - Same pot/year as in the MODULAr study
- 50 GeV machine (as assumed in the context of LAGUNA):
  - 0.77 → 2.4 MW + 10 kt mass (could fit in existing LNGS)

We use a run sharing of: 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: fast simulation BMPT code (E.P.J.C20:13-27,2001)
Final fluxes obtained with a GEANT4 based simulation (E.P.J.C71:1745, 2011)

Systematic variation of:

- currents,
- horn-reflector distance
- target position

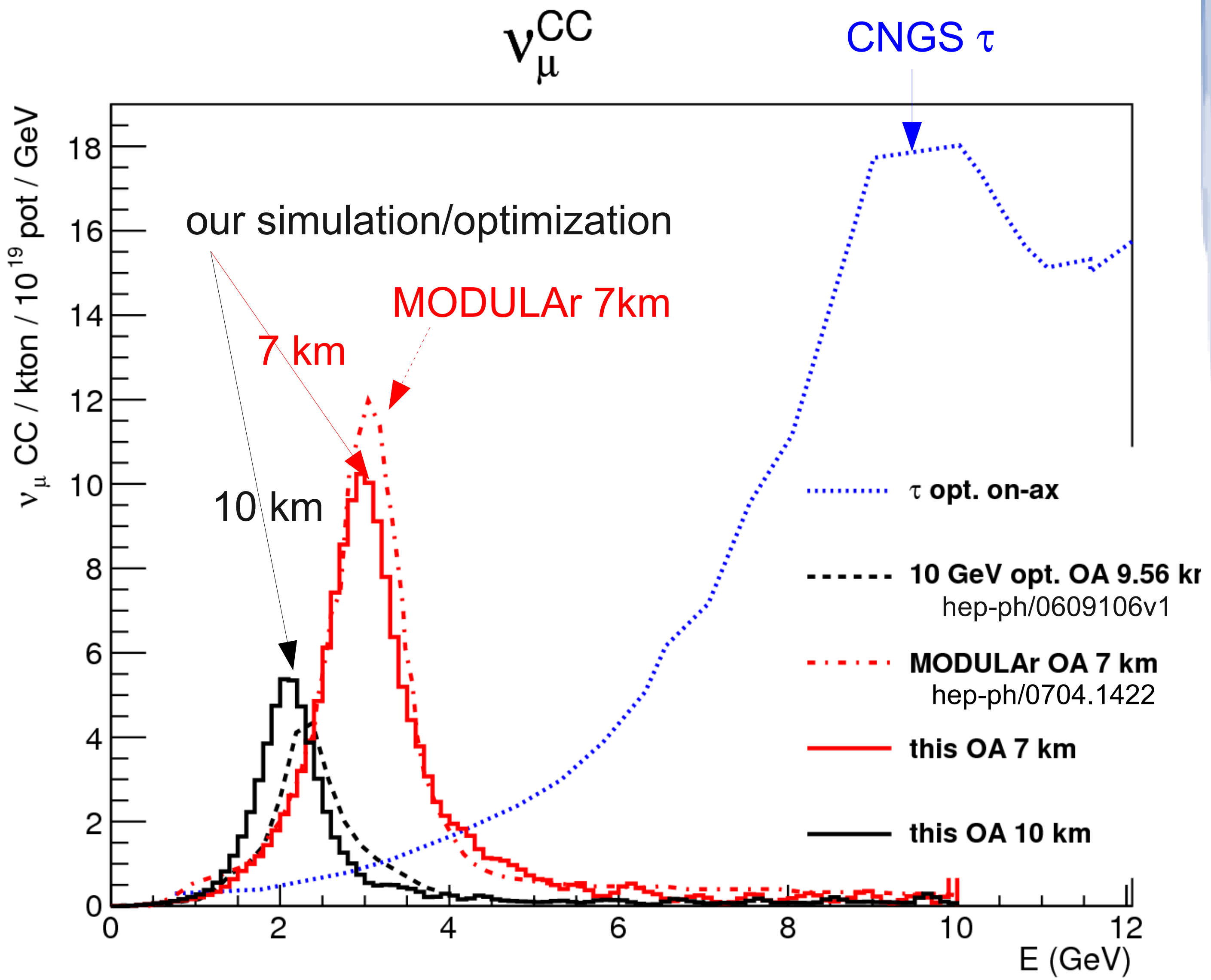
keeping the shapes of horn (NOvA) and reflector (CNGS one) fixed.

Figure of merit: ν_μ^{CC} rate in the peak region for the 7 km off-axis

Off-axis 400 GeV event rates

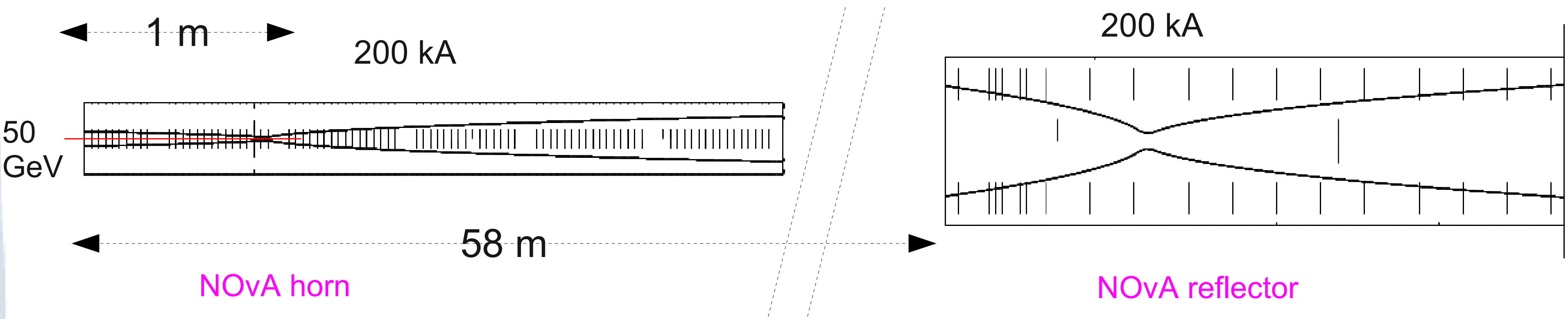
Comparison with previous simulations/studies

Optimal configuration yields similar event rates w.r.t. to configurations optimised by the MODULAr group



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: based on performances on θ_{13} discovery (LAGUNA, 2010).
GEANT4 based simulation + GLOBeS
Variation of the relative positions of horn-reflector-target

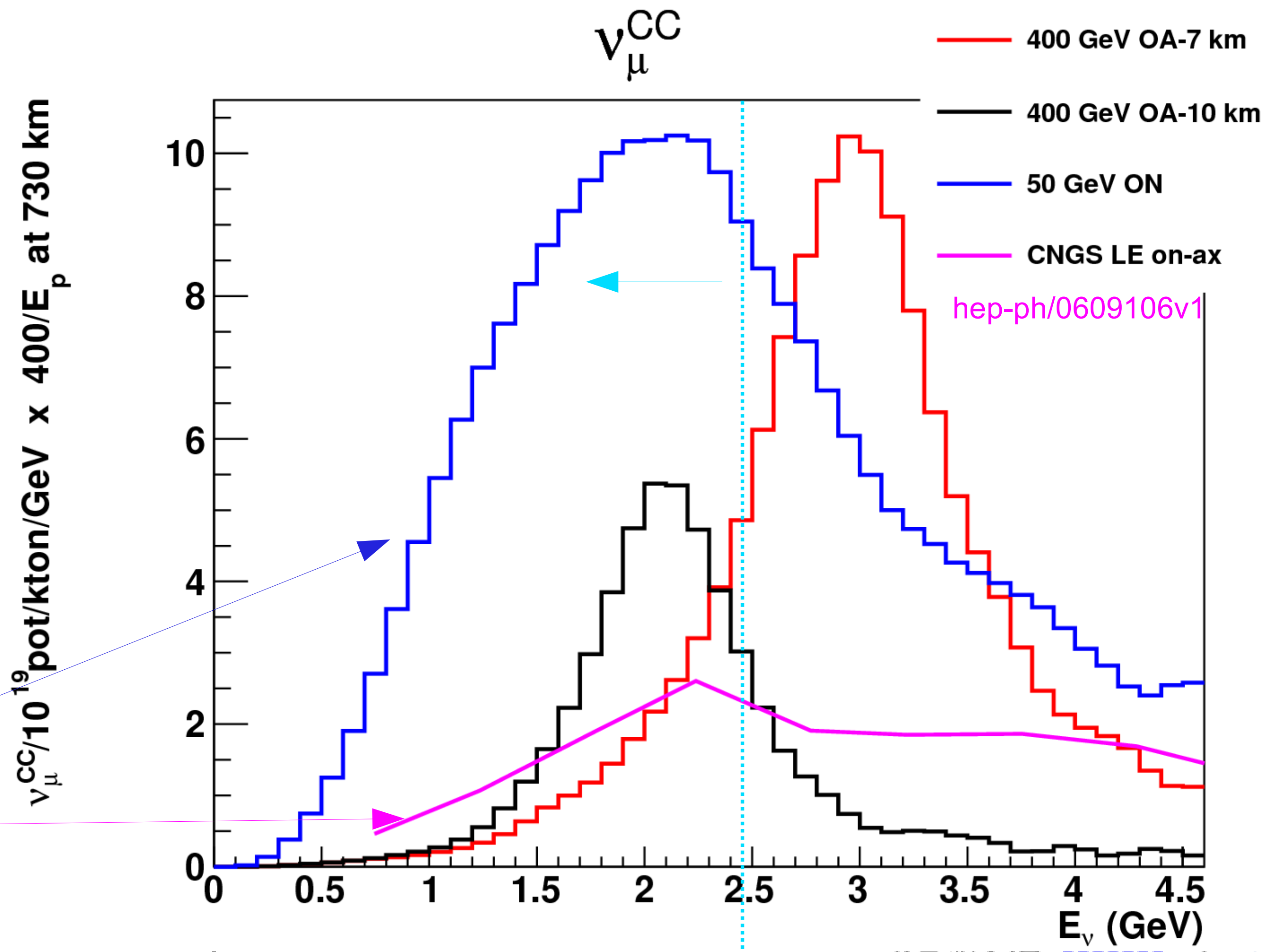
http://pos.sissa.it/archive/conferences/120/325/ICHEP%202010_325.pdf

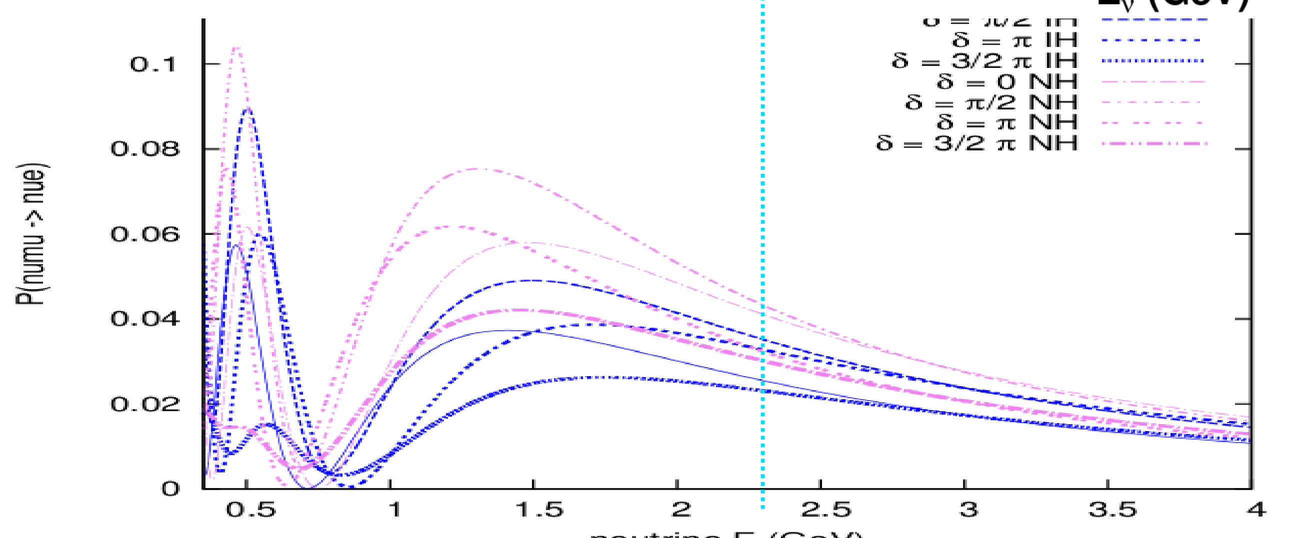
Power normalized ν_μ^{CC} spectra

"Region of interest" lies rougly below 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 – A. Rubbia, A. Meregaglia).

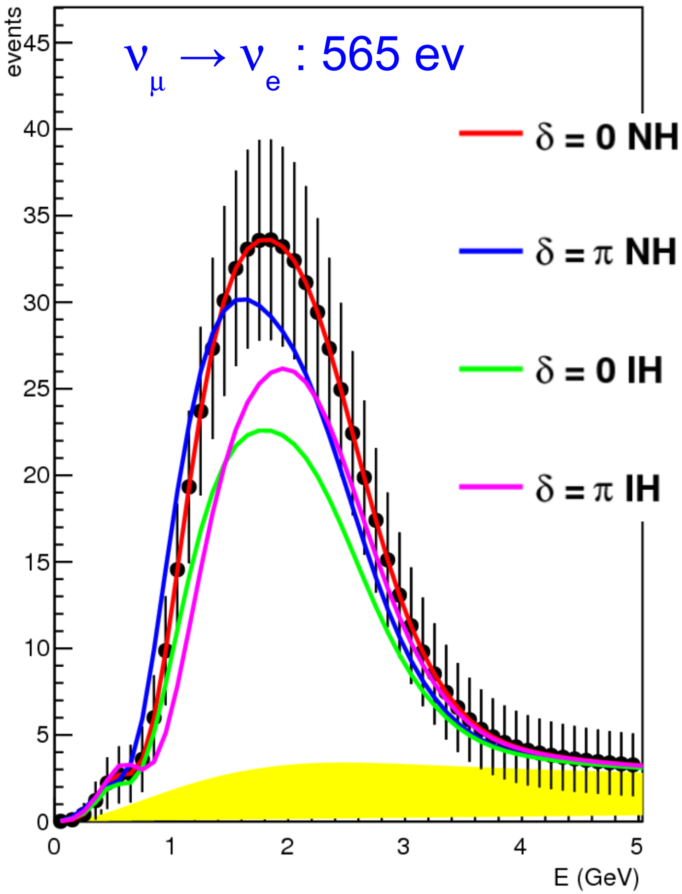




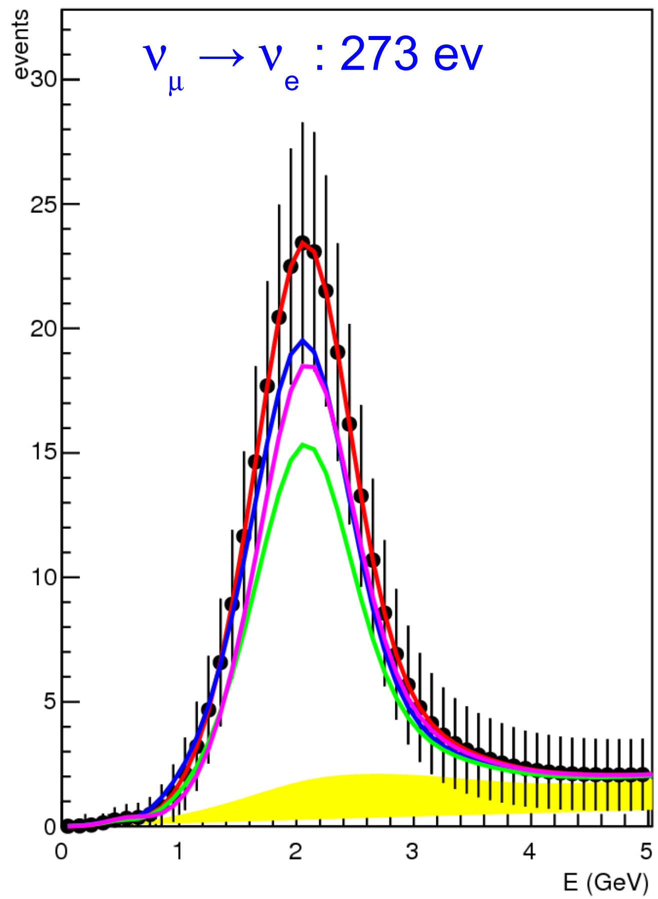
ν_e^{CC} appearance spectra

5 years of ν run

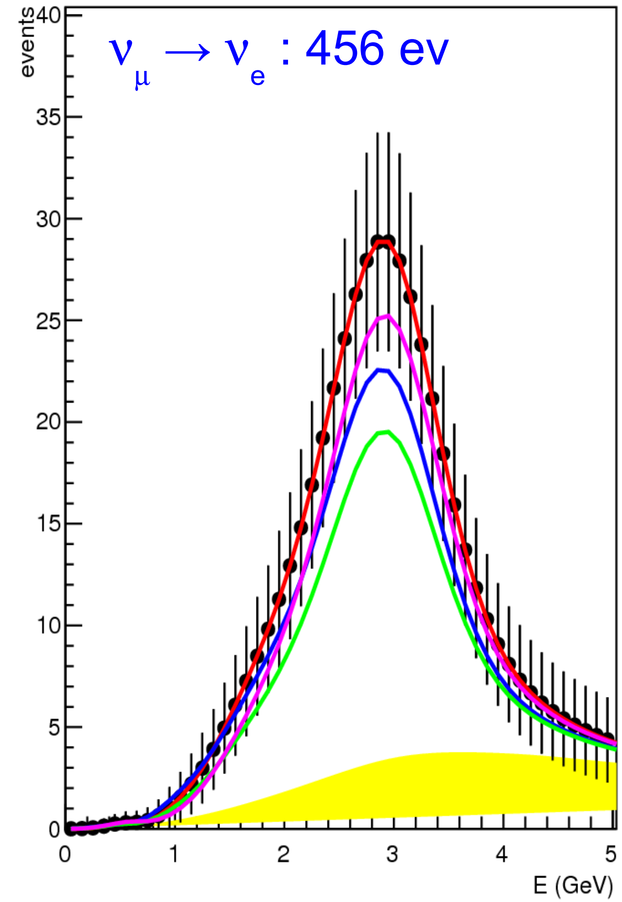
On-axis 50 GeV
10 kt 3 ·10[21] pot/y (2.4 MW)



Off-axis 10km 400 GeV
20 kt 1.2·10[20] pot/y (0.77 MW)



Off-axis 7km 400 GeV
20 kt 1.2·10[20] pot/y (0.77 MW)



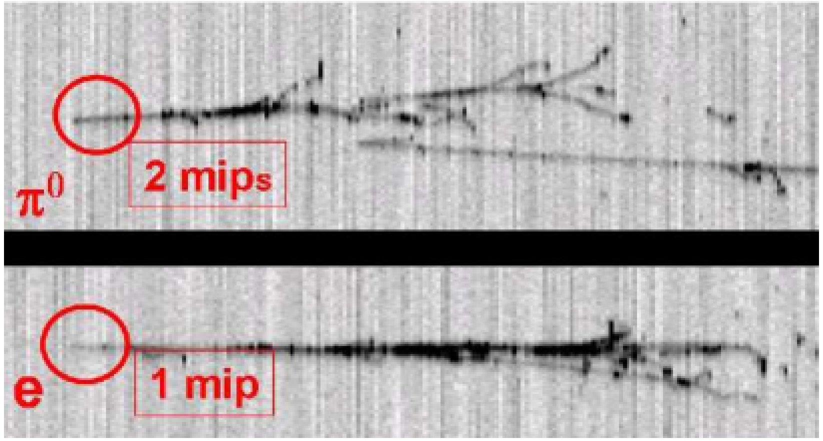
Moving away from the oscillation maximum causes a loss in spectral information (shape) and discrimination power for the MH

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}

ICARUS events



From studies in 0704.1422 (MODULAr)

- Default 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)

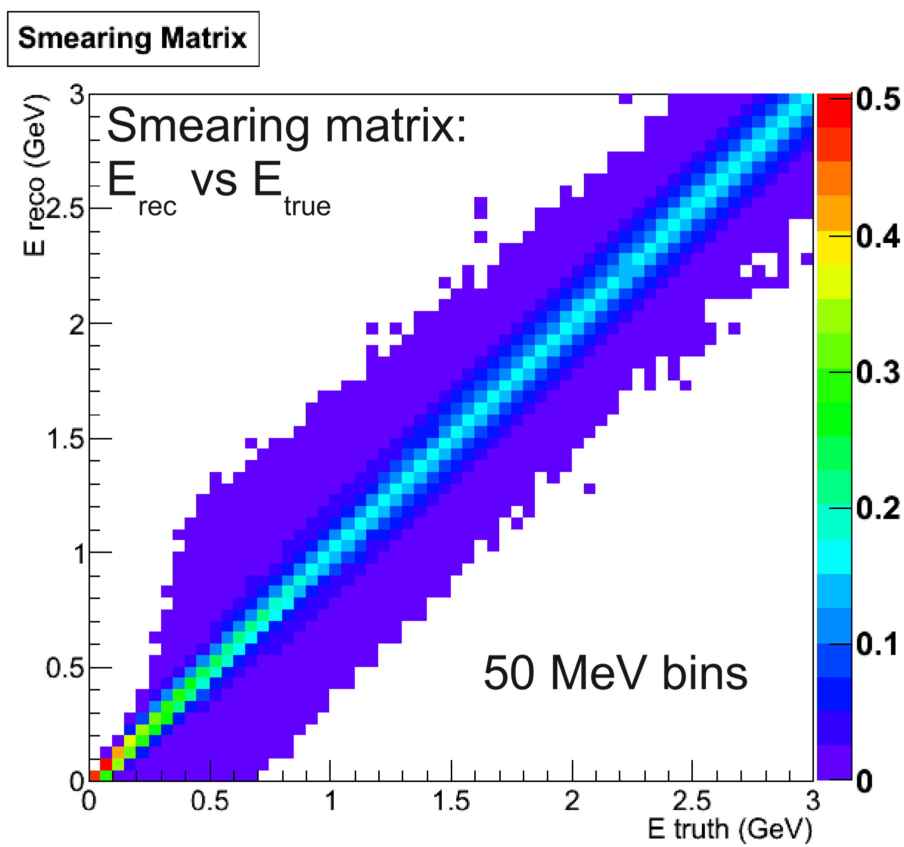
Quasi elastic (QE)

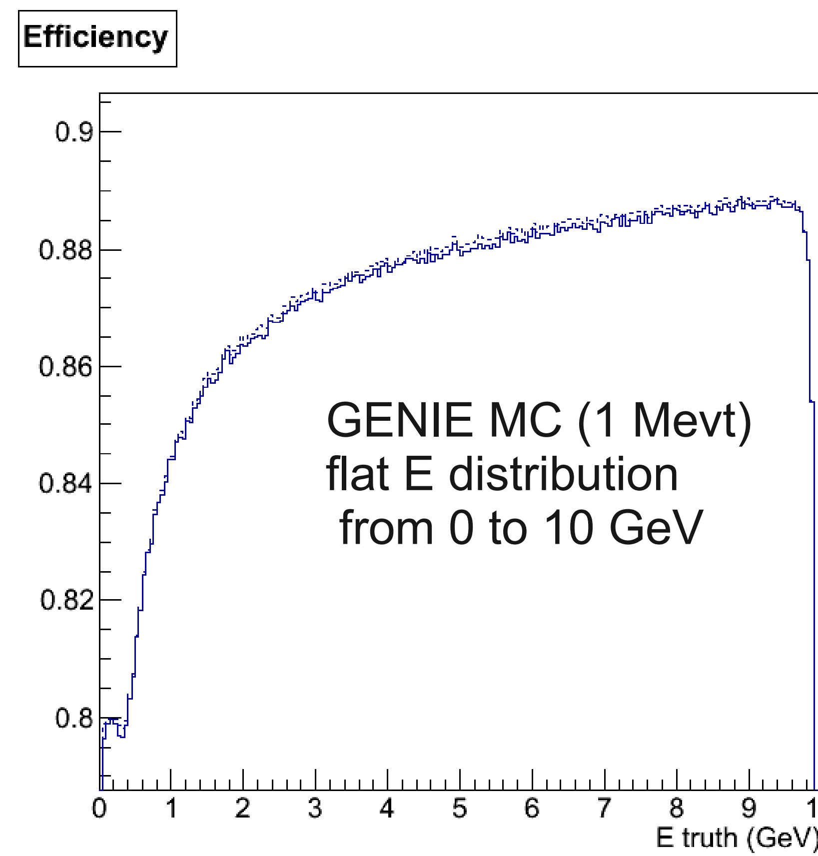
- 80% efficiency
- smearing of true-level e-momentum
- 2-body formula for E_{rec}
- yields $\sigma(E_\nu)/E_\nu \sim 0.05/\sqrt{E_\nu}$

Non-QE

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

Matrices calculated for ν_e and anti-ν_e separately.



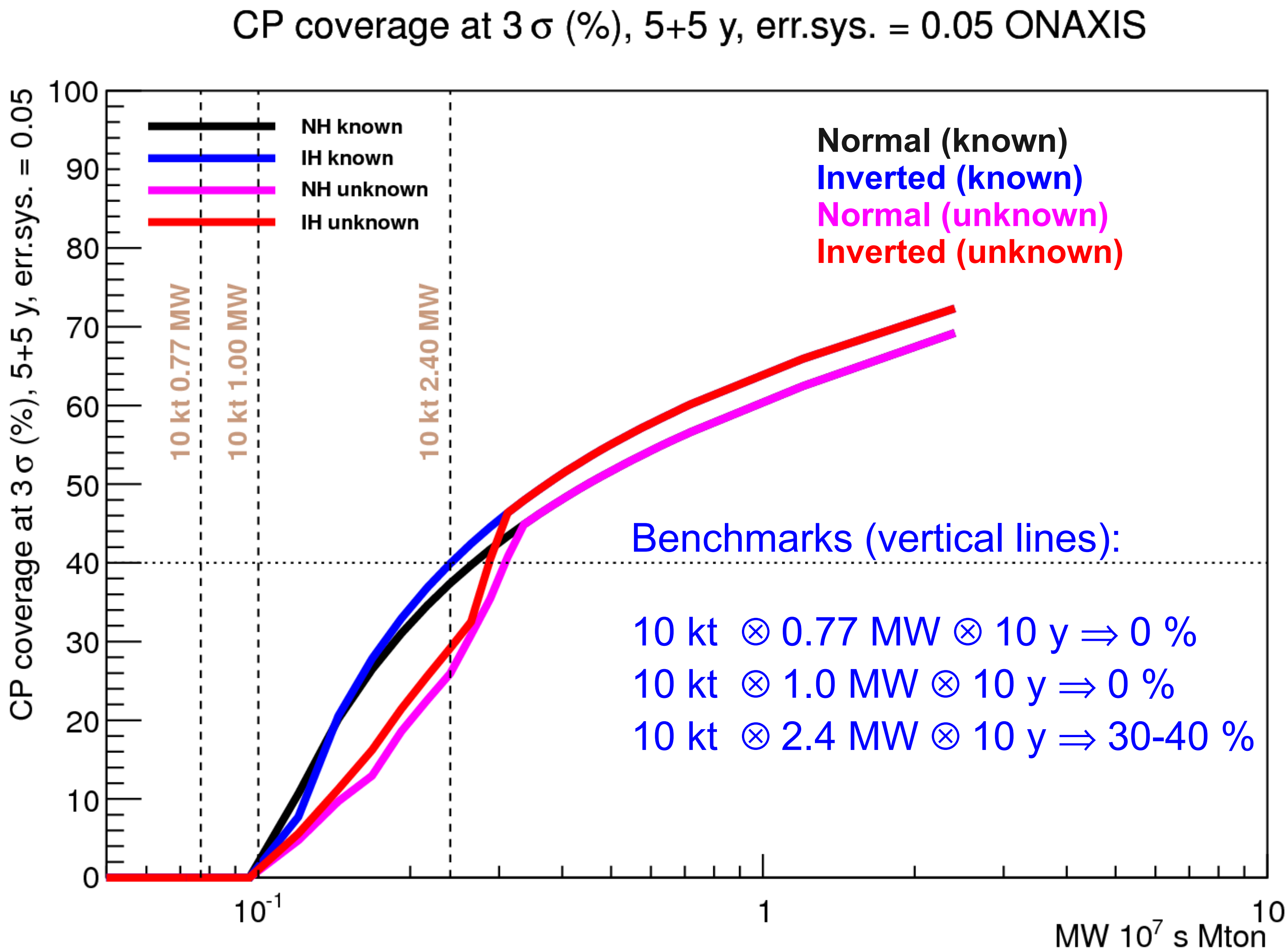


Results →

CPV coverage (on-axis 50 GeV)

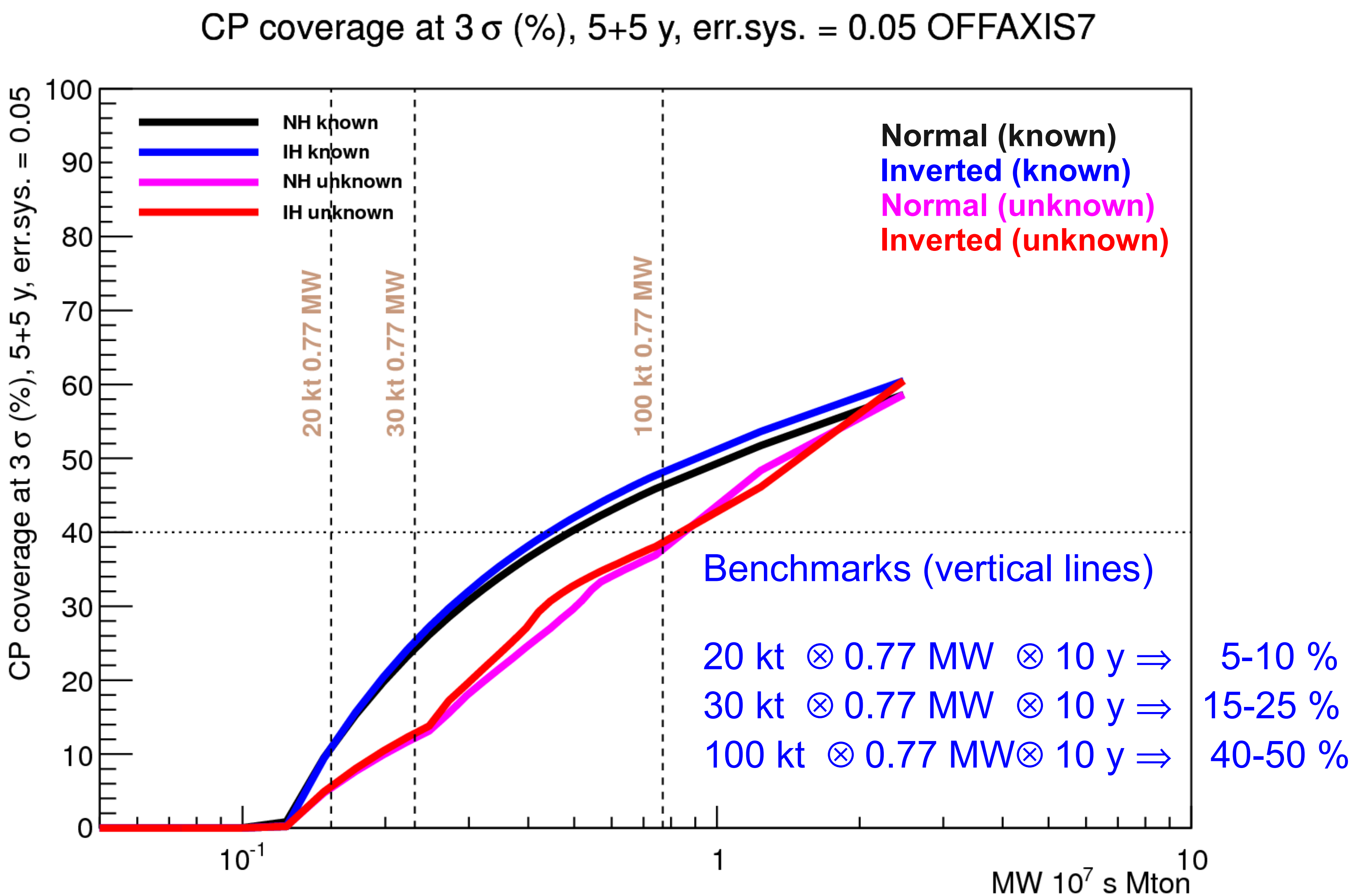
5% systematic error on flux normalization

5 ν + 5 νbar years



CPV coverage (off-axis 7 km 400 GeV)

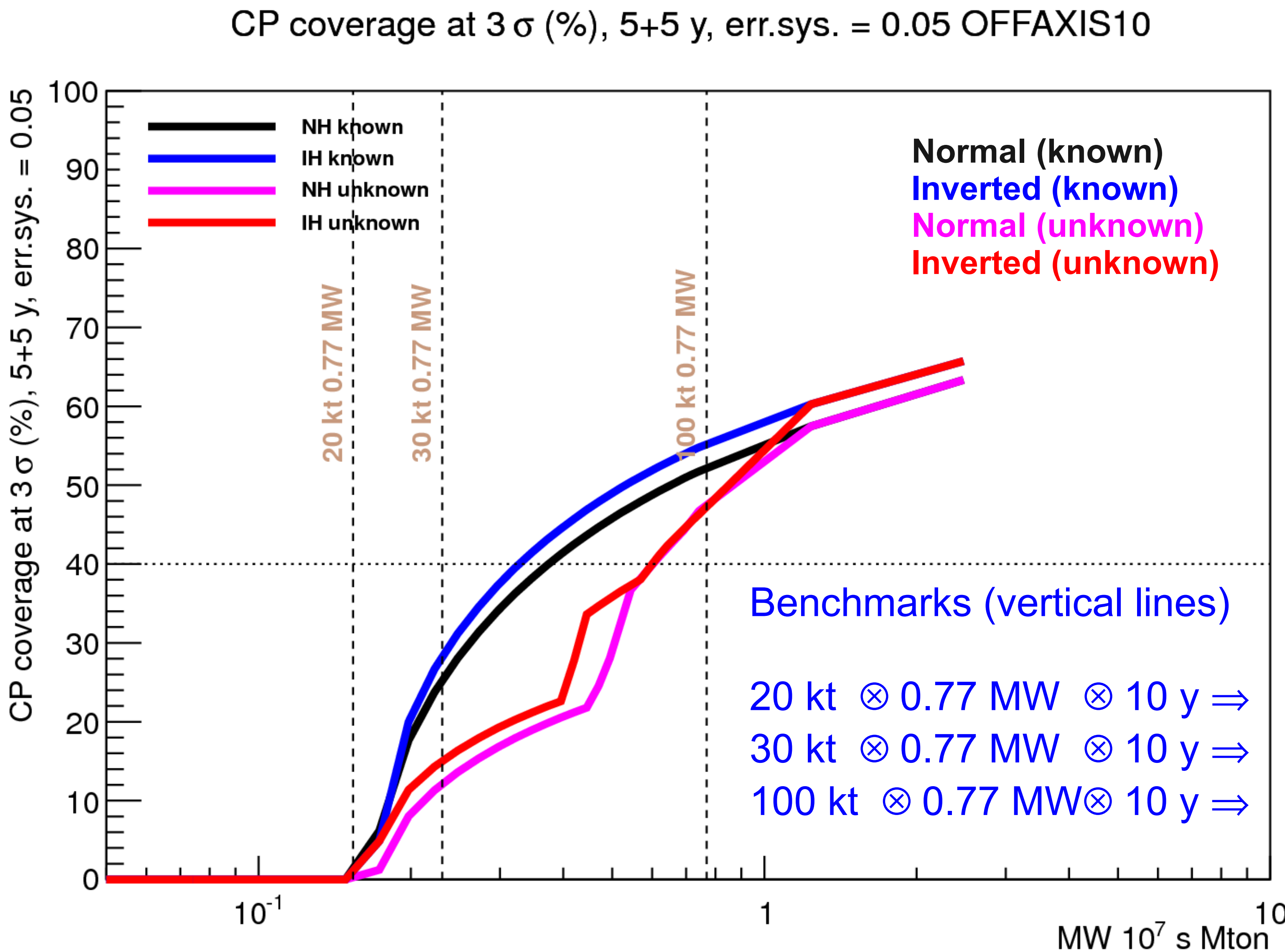
5% systematic error on flux normalization 5 ν + 5 νbar years



CPV coverage (off-axis 10 km 400 GeV)

5% systematic error on flux normalization

5 ν + 5 νbar years



Benchmarks (vertical lines)

20 kt ⊗ 0.77 MW ⊗ 10 y ⇒ 0 %

30 kt ⊗ 0.77 MW ⊗ 10 y ⇒ 15-25 %

100 kt ⊗ 0.77 MW⊗ 10 y ⇒ 45-55 %

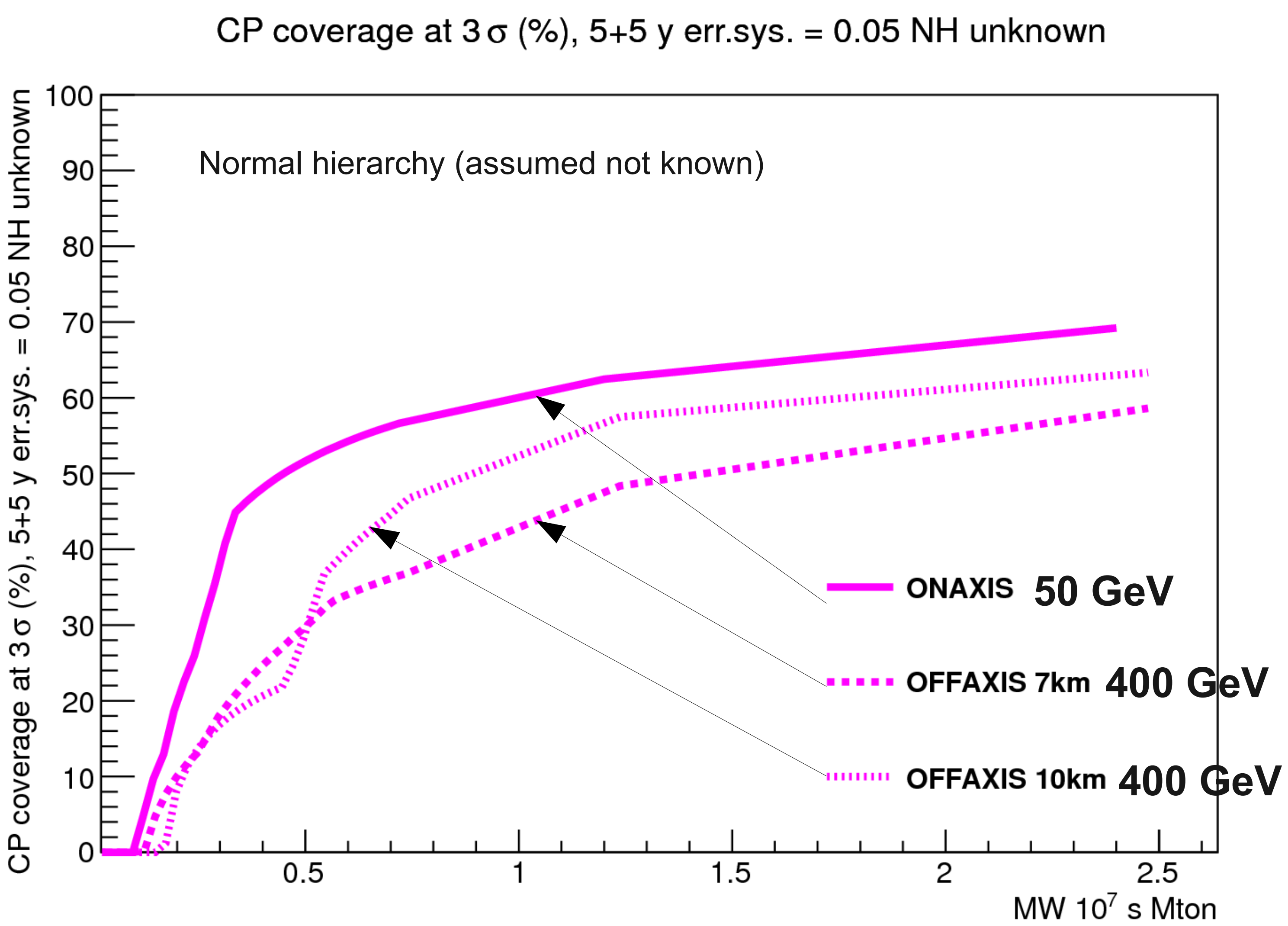
CPV coverage comparison for the 3 options

5% systematic error on flux normalization

5 ν + 5 νbar years

- On-axis 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) matters



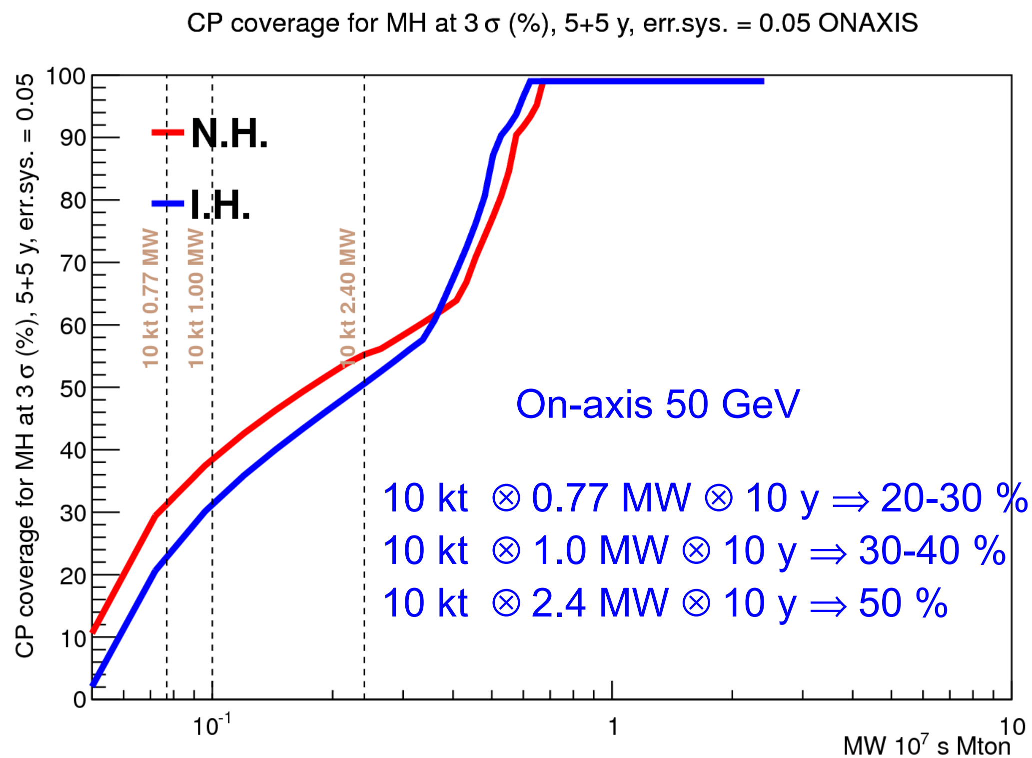
MH coverage

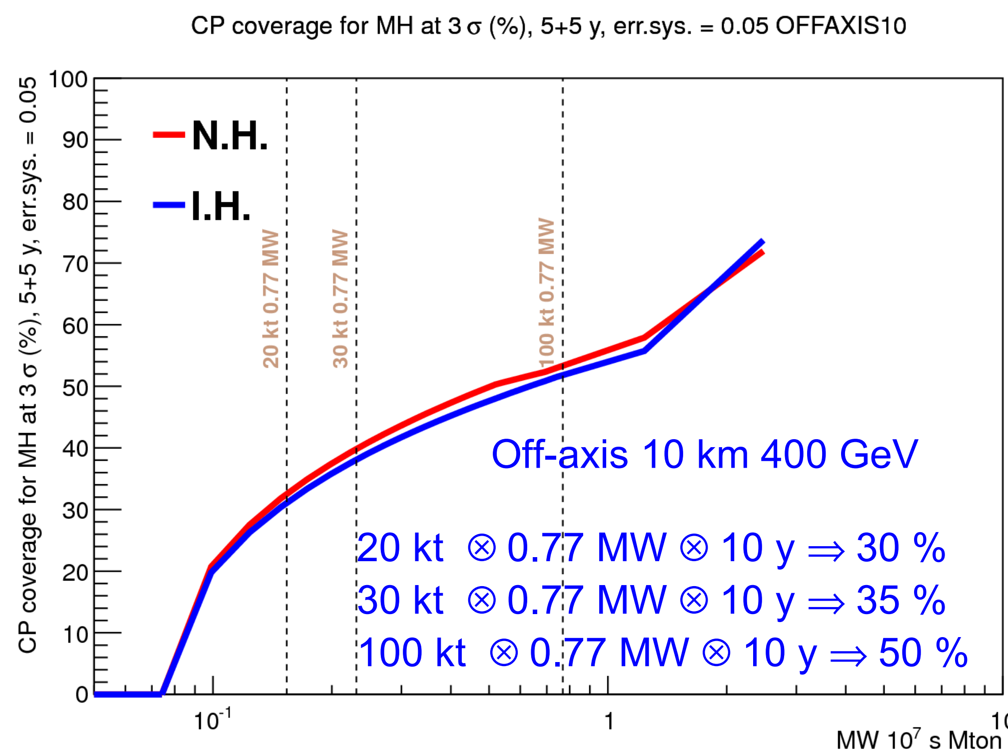
5 % systematic error
on flux normalization

5 ν + 5 νbar years

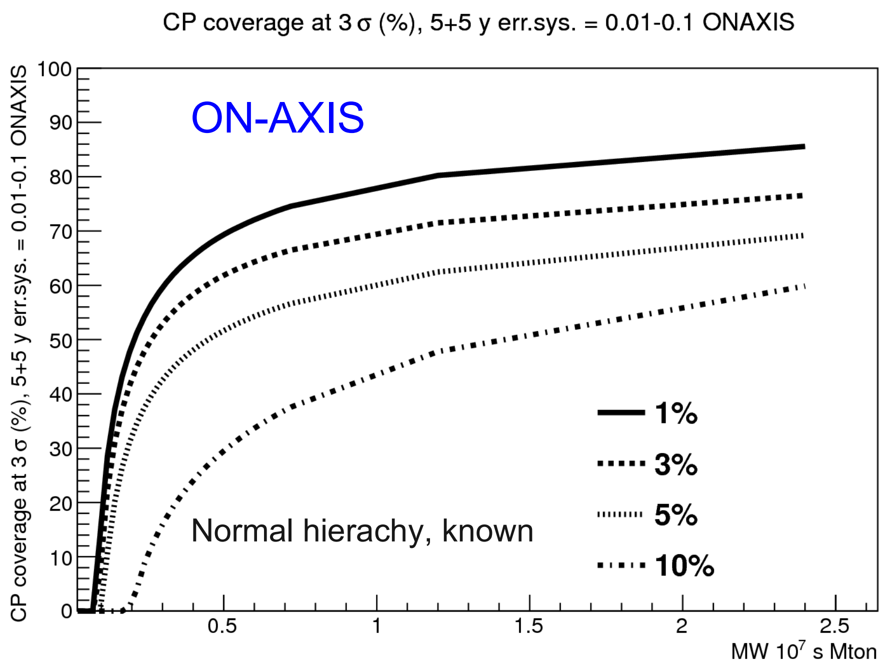
MH reach evolution is better for the on-axis configuration (evident from ν_e appearance spectra shown earlier).

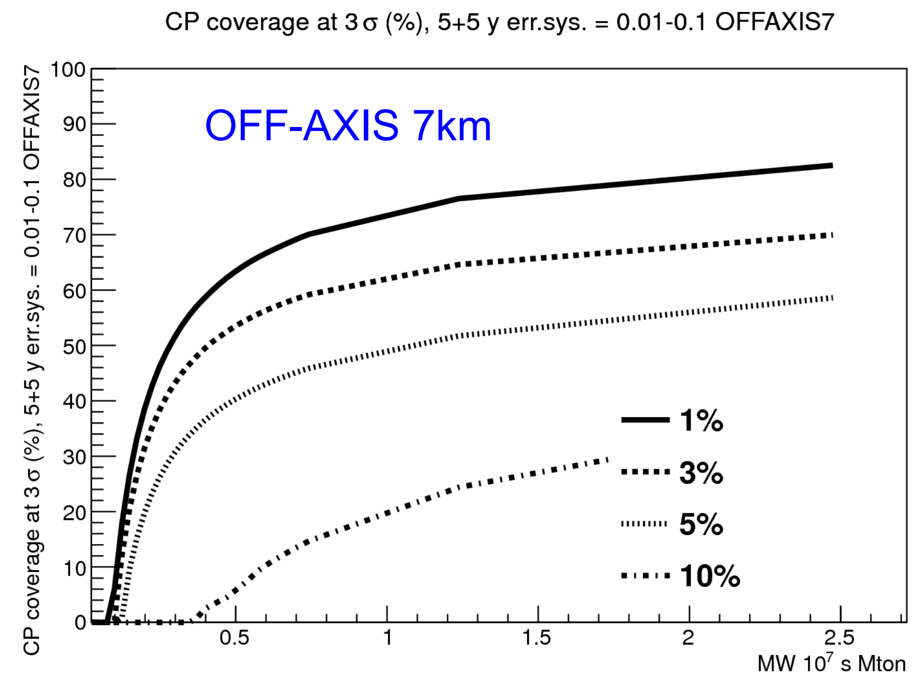
The 10 km off-axis is better than 7 km for the same reason (only 10 km shown)





Systematics on absolute flux normalization





Very relevant effect

expected: δ induces mostly a change in normalization at L=730 km

5 % : widely used but the T2K super-beam nowadays is still above the 10% level

Crucial for the design of future experiments

- LAr TPC already goes in this direction
- Ancillary detectors: near, on-axis far + off-axis far

Improving the systematic error pays more than brute force (boosting mass/beam)

Comparison with other baselines

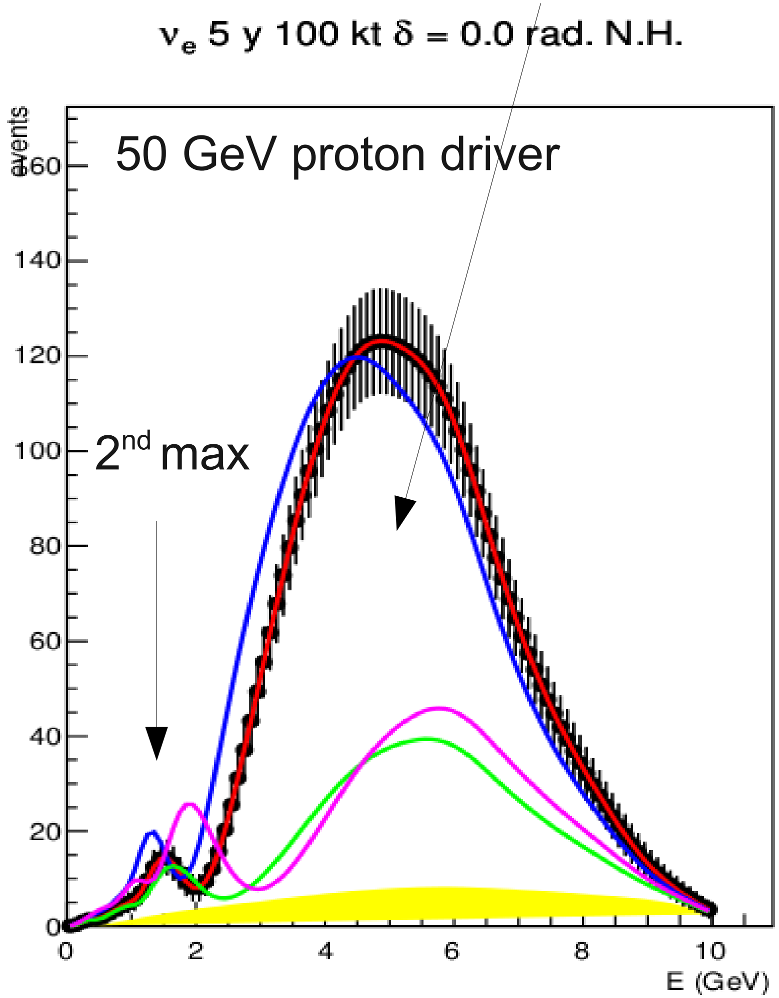
Being either very long (~2300 km) or very short (~100 km).

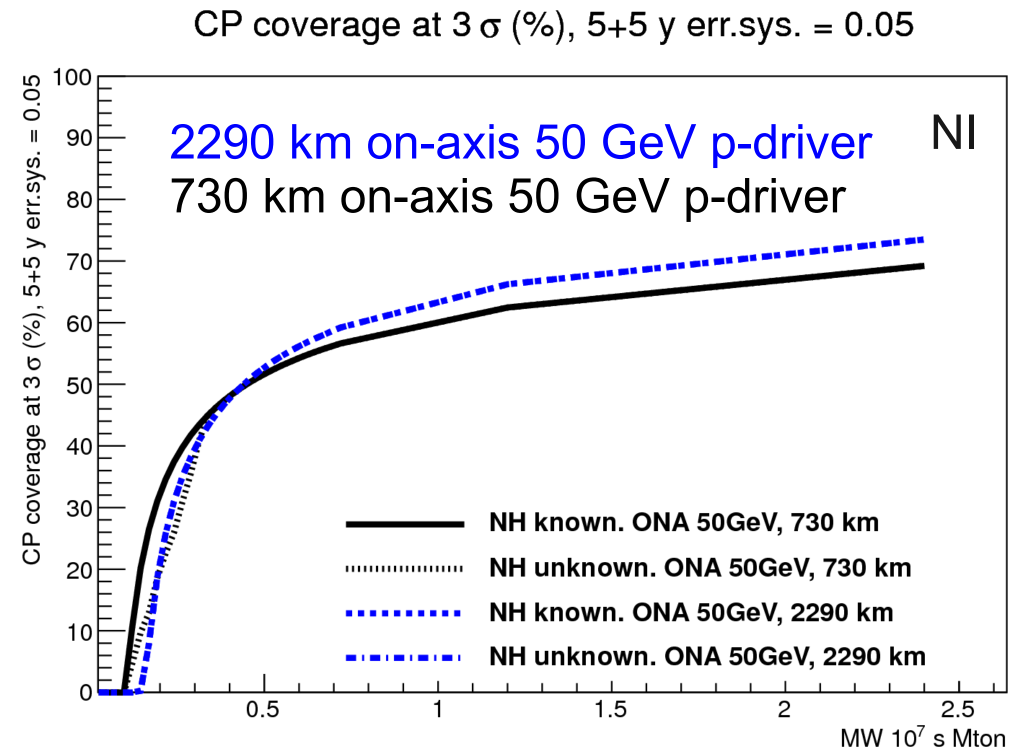
Performed under the same assumptions on LAr detector performances, systematics errors and with the same analysis program.

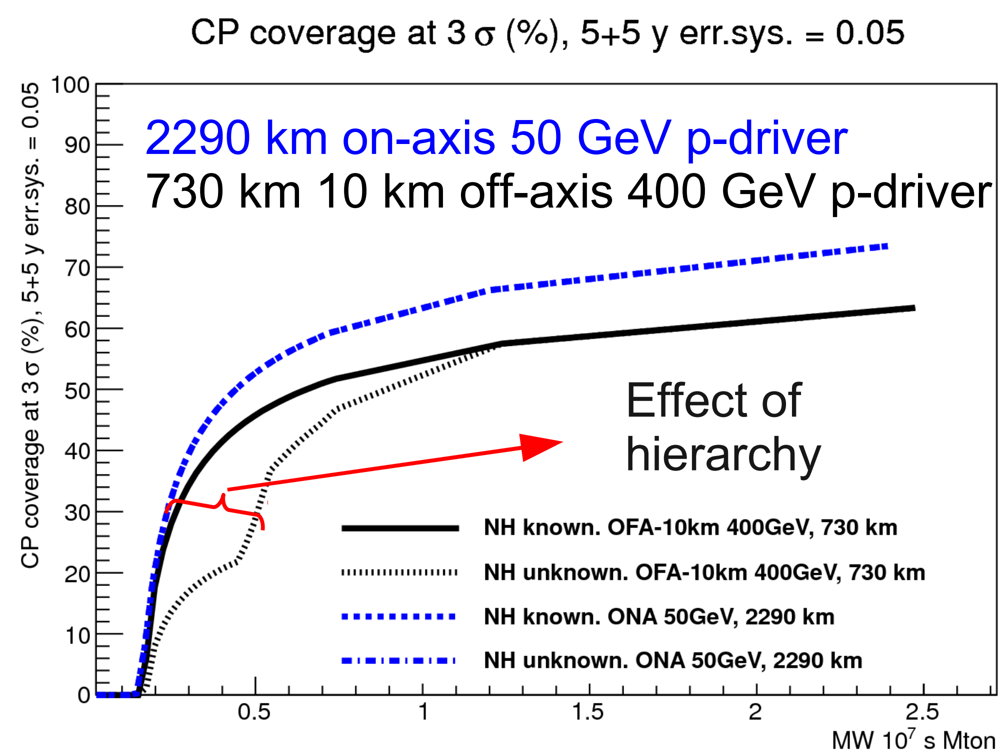
→

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 2nd max starts to play a role)

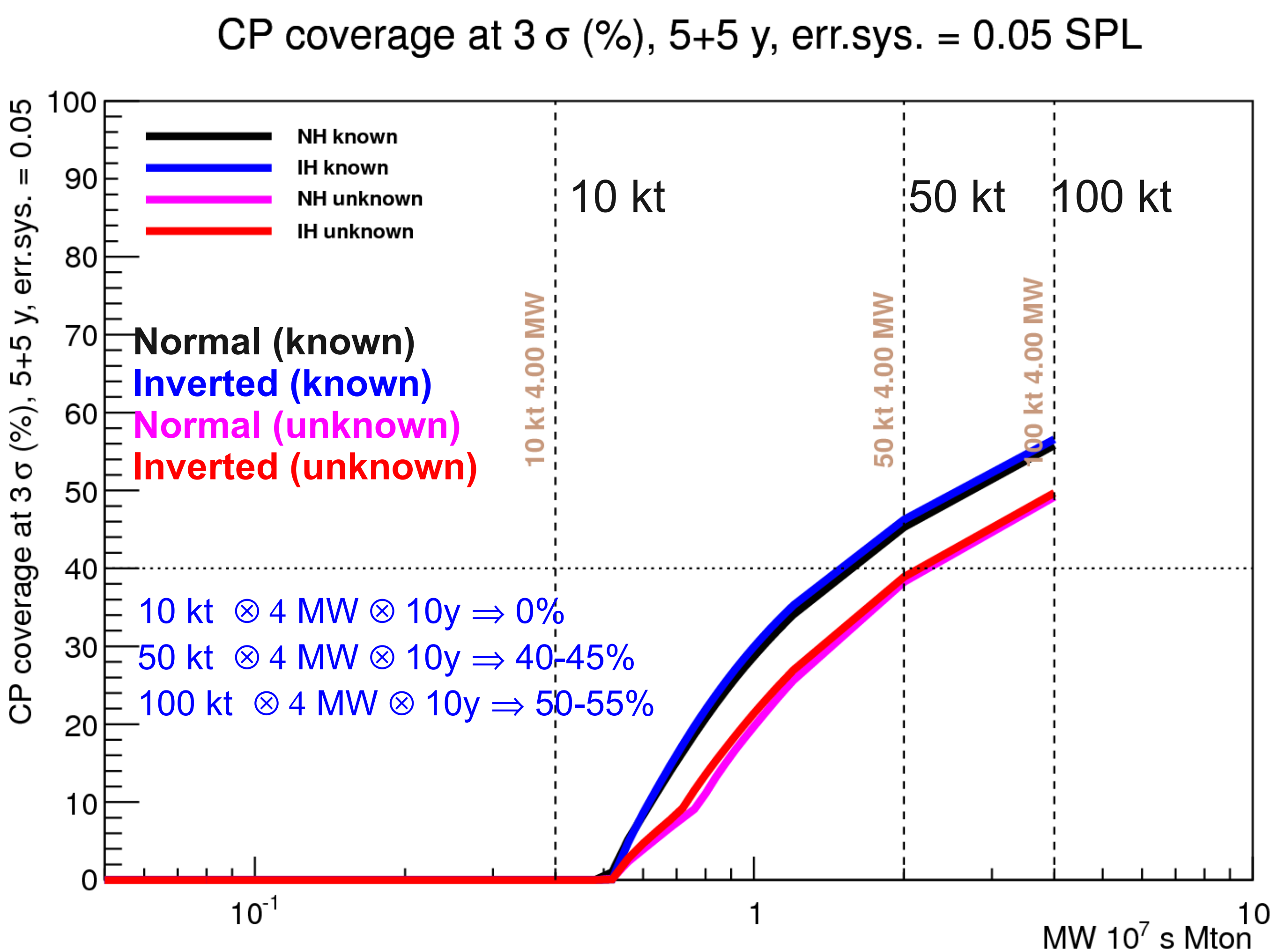
Exercise: low-E + short baseline (~100 km) ?

New J.Phys. 4 (2002) 8
JHEP 0704 (2007) 003
E.P.J.C 71:1745, 2011

Philosophy of SPL-Fréjus (L=130 km) E_p = 4.5 GeV, 4 MW SPL

Despite better performances of LAr quite large masses are still required to get a reasonable coverage even with a 4 MW driver.

NB. original design is 440 kt of water



Not suited for existing underground. Would need an external site (and p-driver).

5 % Sys. Err. LAr TPC	**CP (%)**	**MH (%)**
On axis 50 GeV L=730 km		
10 kt ⊗ 0.77 MW ⊗ 10 y	-	20-30 %
10 kt ⊗ 1.0 MW ⊗ 10 y	-	30-40 %
10 kt ⊗ 2.4 MW ⊗ 10 y	30-40 %	50 %
Off-axis 400 GeV (7 km) L=730 km		
20 kt ⊗ 0.77 MW ⊗ 10 y	5-10 %	25%
30 kt ⊗ 0.77 MW ⊗ 10 y	15-25 %	35%
100 kt ⊗ 0.77 MW ⊗ 10 y	40-50 %	50%
Off-axis 400 GeV (10 km) L=730 km		
20 kt ⊗ 0.77 MW ⊗ 10 y	-	30 %
30 kt ⊗ 0.77 MW ⊗ 10 y	15-25 %	35 %
100 kt ⊗ 0.77 MW ⊗ 10 y	45-55 %	50 %
On-axis 4.5 GeV L = 100 km		
10 kt ⊗ 4 MW ⊗ 10 y	0 %	-
50 kt ⊗ 4 MW ⊗ 10 y	40-45 %	-
100 kt ⊗ 4 MW ⊗ 10 y	50-55 %	-

Preliminary conclusions

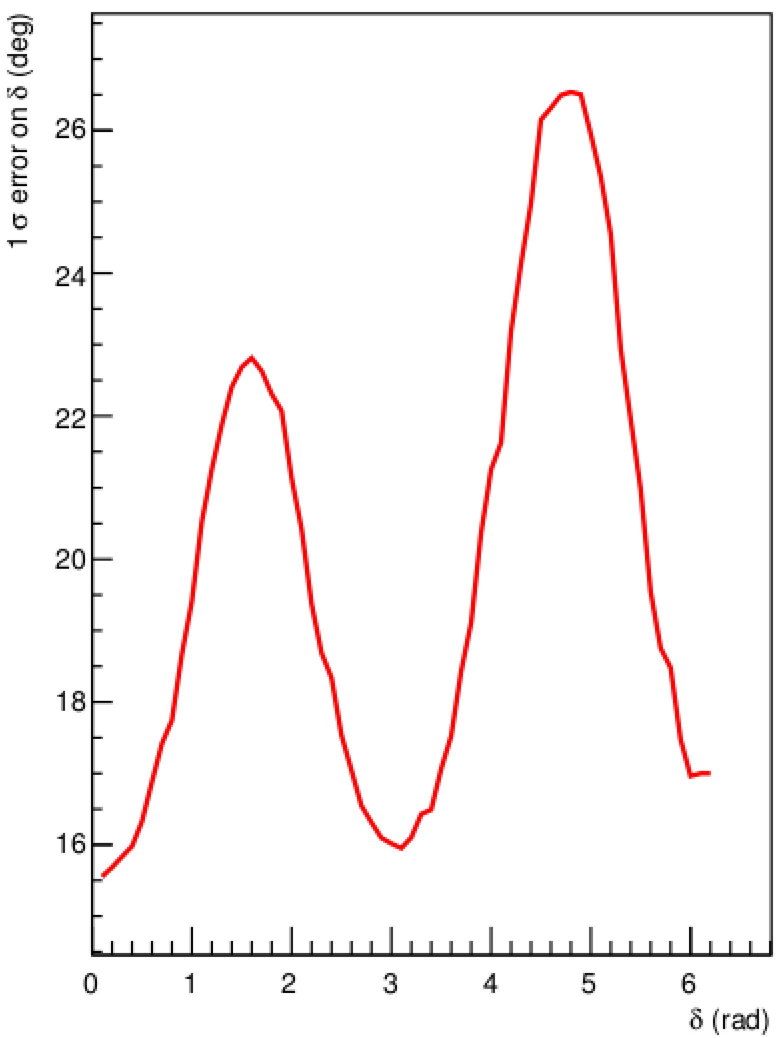
- On-axis using a 50 GeV p-driver: performs better than off-axis in terms of coverage vs exposure. Limitation at 10 kt (inside LNGS) would forces to use a multi-MW driver.
- Off-axis with a reasonably upgraded SPS@400 GeV (< x 3): suffers more from mass hierarchy degeneracies w.r.t. on-axis at 50 GeV. 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}). 2290 km is unbeatable for MH. 2^{nd} oscillation maximum is usable and "pays" at high exposures (2290 km becomes better).
- short-baseline+high power linac: despite high achievable power, still large masses are needed (not compatible with existing underground lab constraints).
- Systematic errors control is crucial. Near (ancillary) detector(s) mandatory.
- Outlook: investigate other SPS energies, on-axis + off-axis detector.

Back-up slides

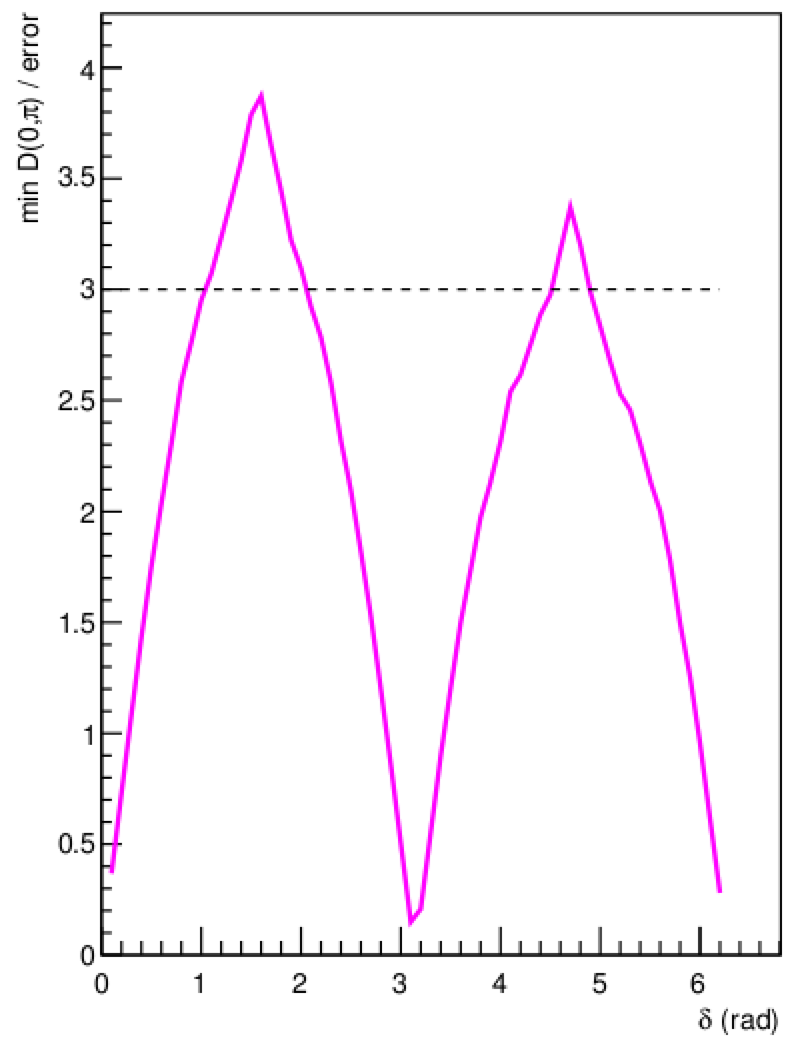
Error on δ

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

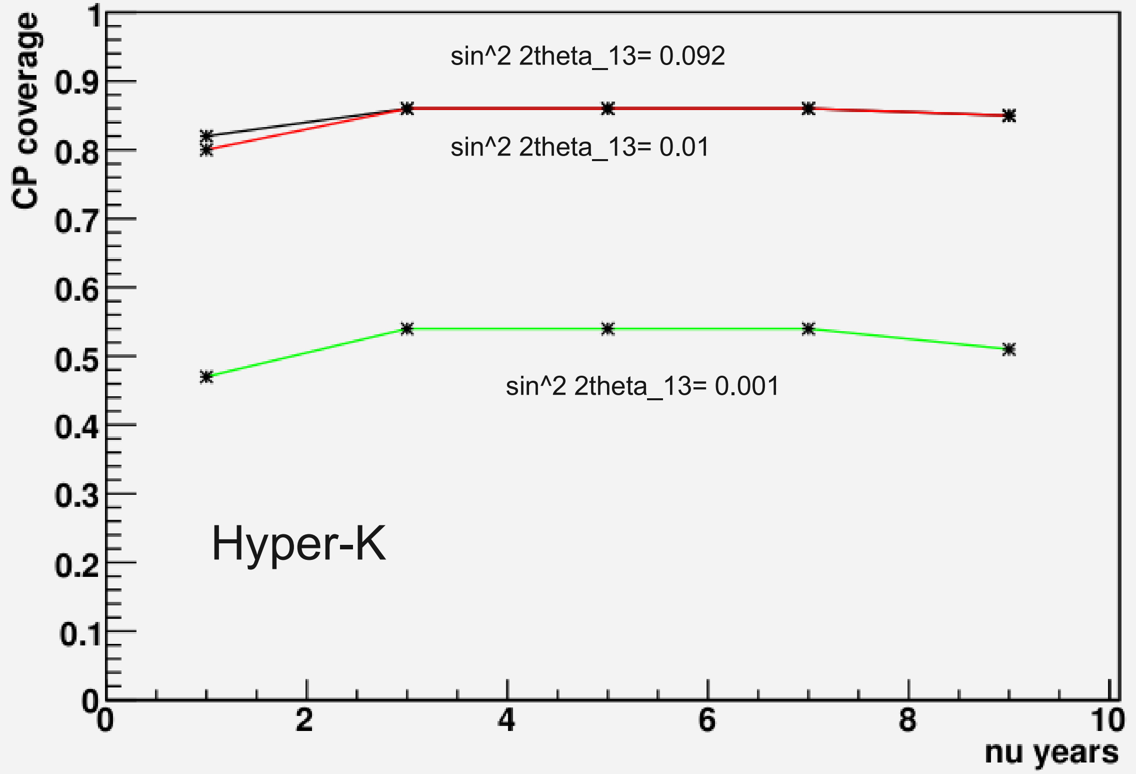
1σ error on δ VS δ



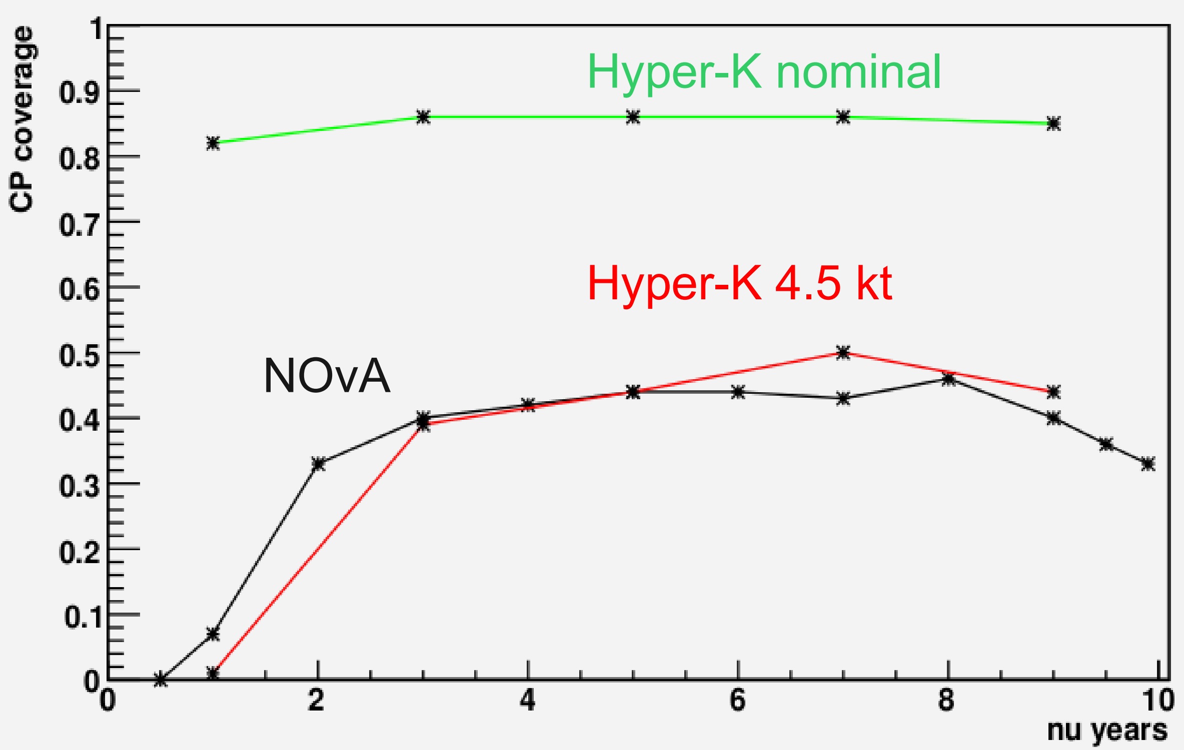
min D(0,π) / error VS δ



Run sharing

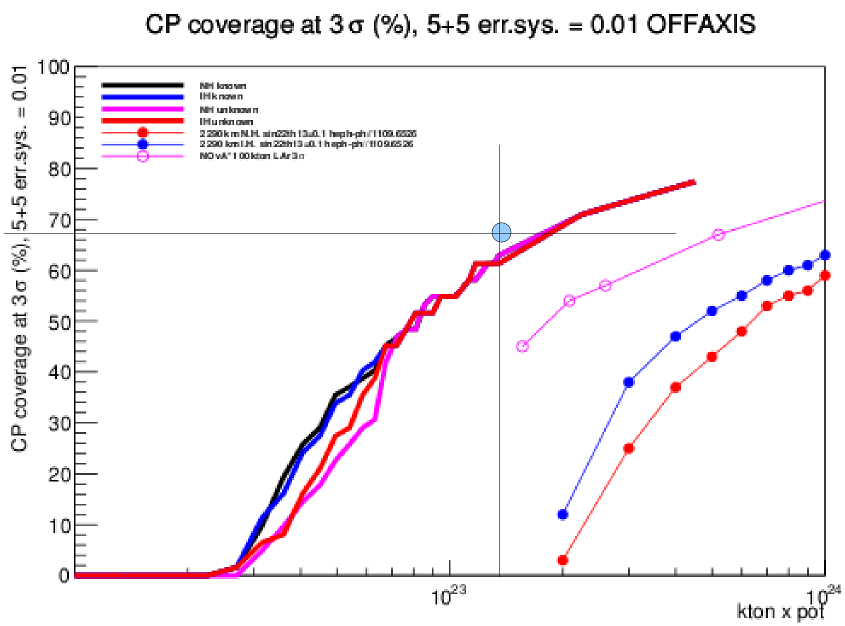


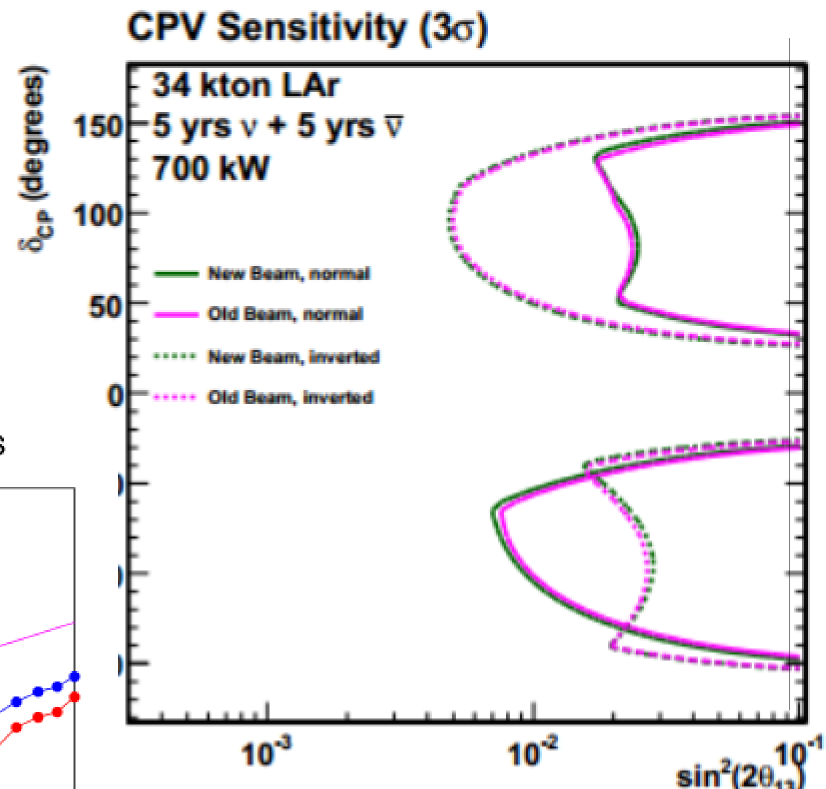
90 %CL



Comparison with LBNE for CPV

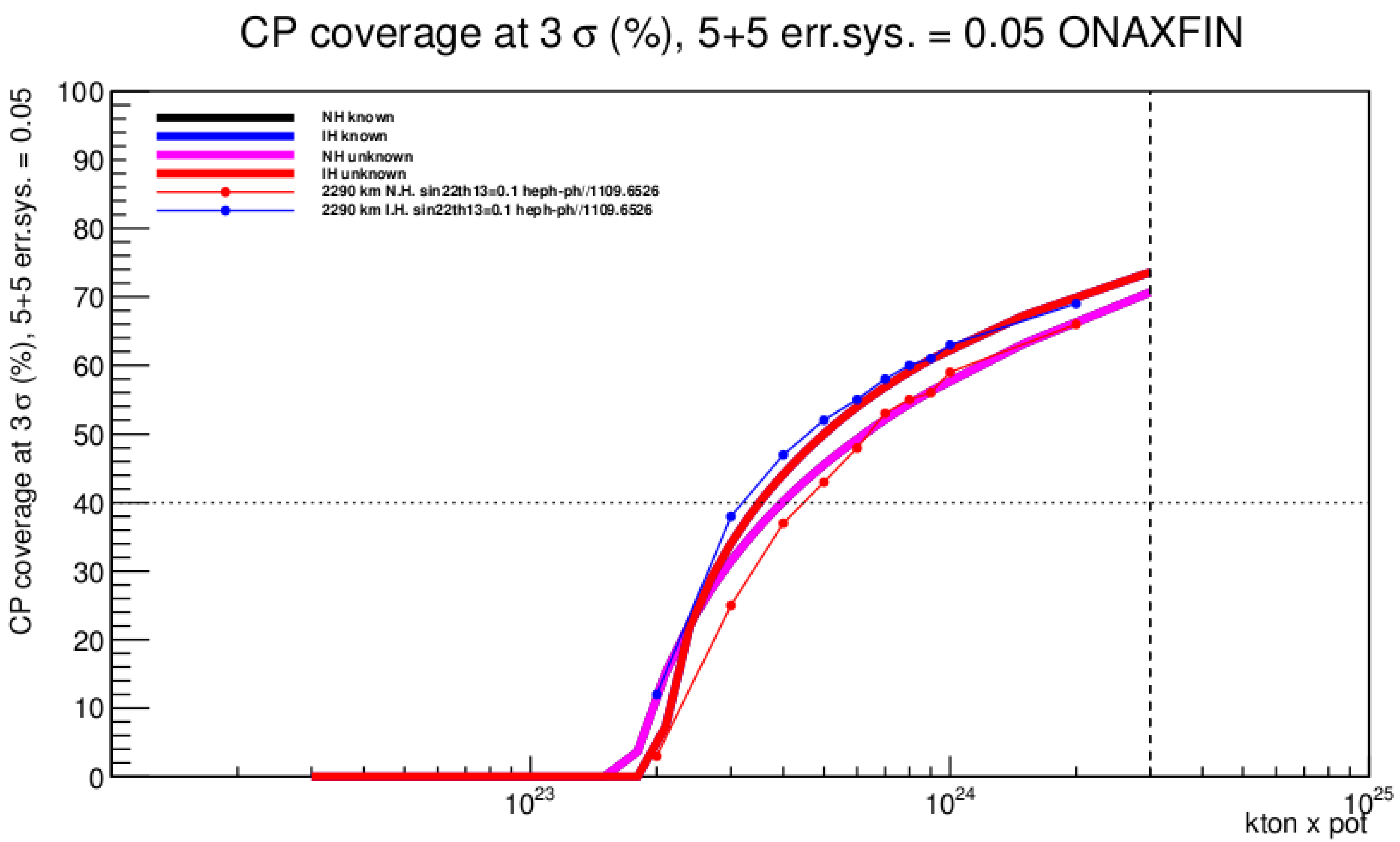
700 kW 120 GeV
34 kton 5+5
1% norm err on signal
Coverage ~ 67 %



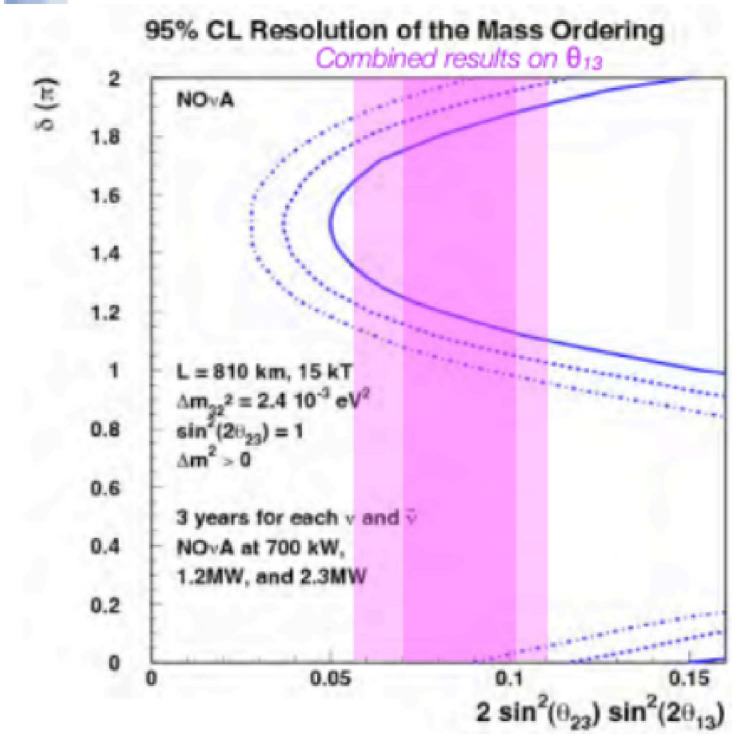


LAGUNA vs LAGUNA

Comparison with literature



Comparison with NOvA for MH



MW at 120 GeV 15 kton	pot	pot kton y
0.7	3.64e20	3.28e22
1.2	6.24e20	5.62e22
2.3	11.96e20	1.08e23

LNGS

Mass (kton)	Kton pot
20	0.24e23
30	0.36e23
100	1.2e23

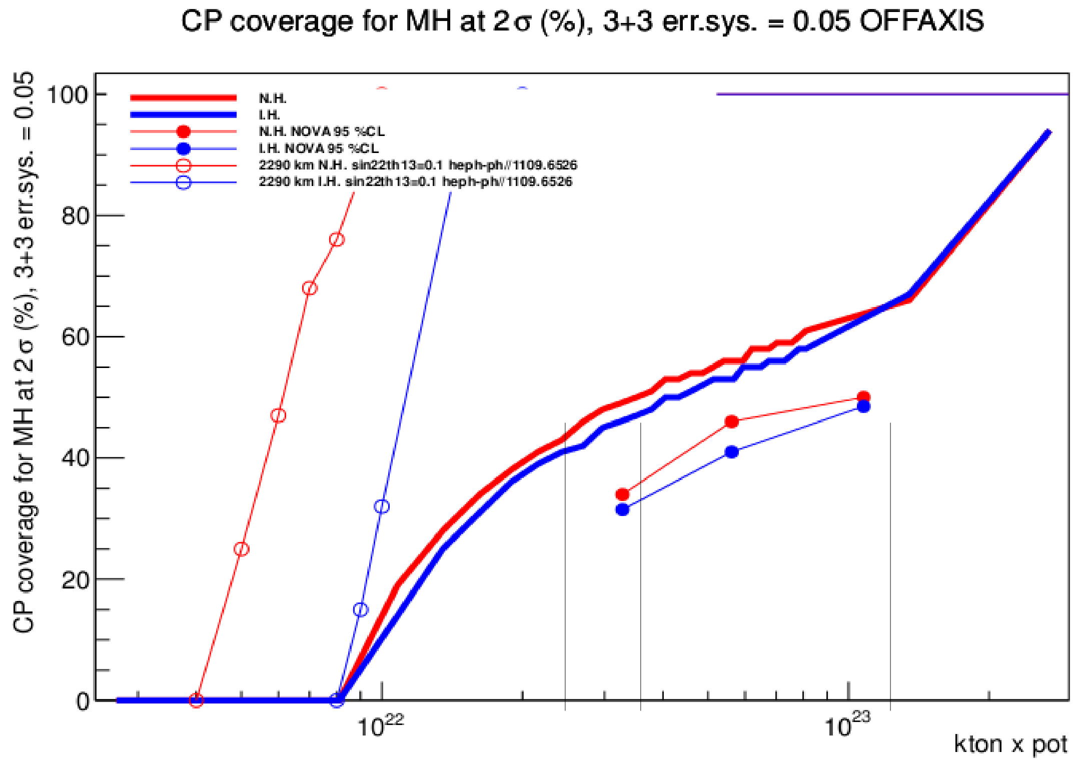
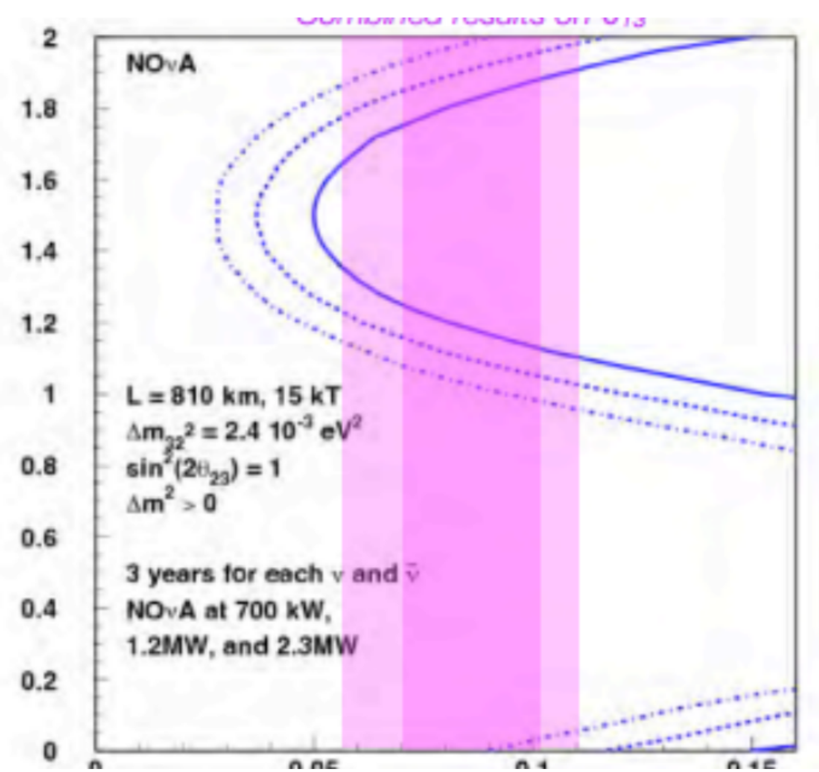
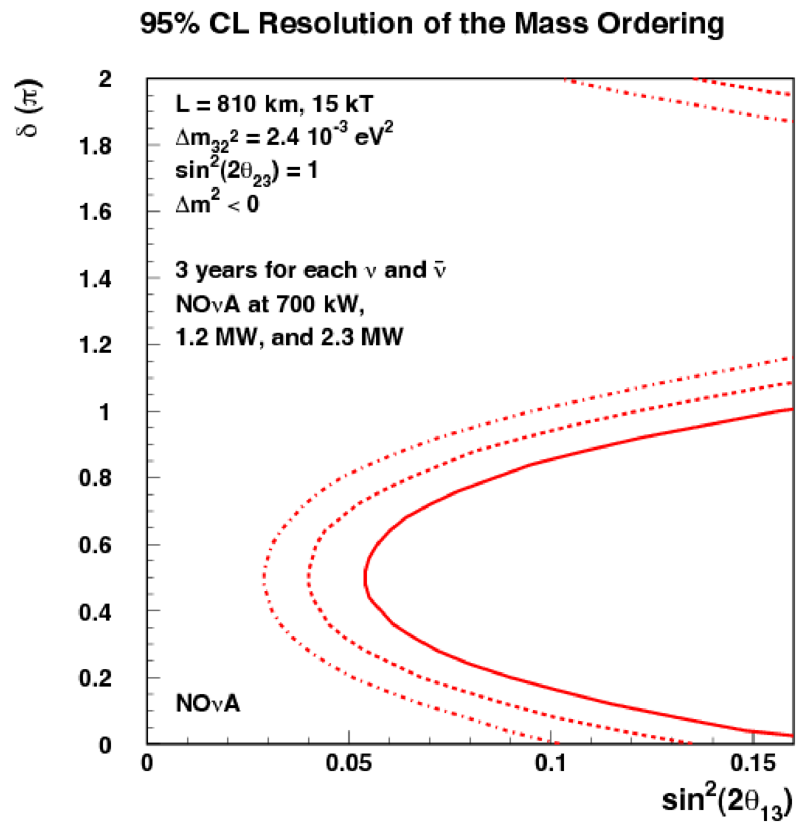


Figure 34: Mass hierarchy discovery at 95% C.L., systematic error on flux: 5%. 3+3 years. Off axis. Results are compared to NOvA.

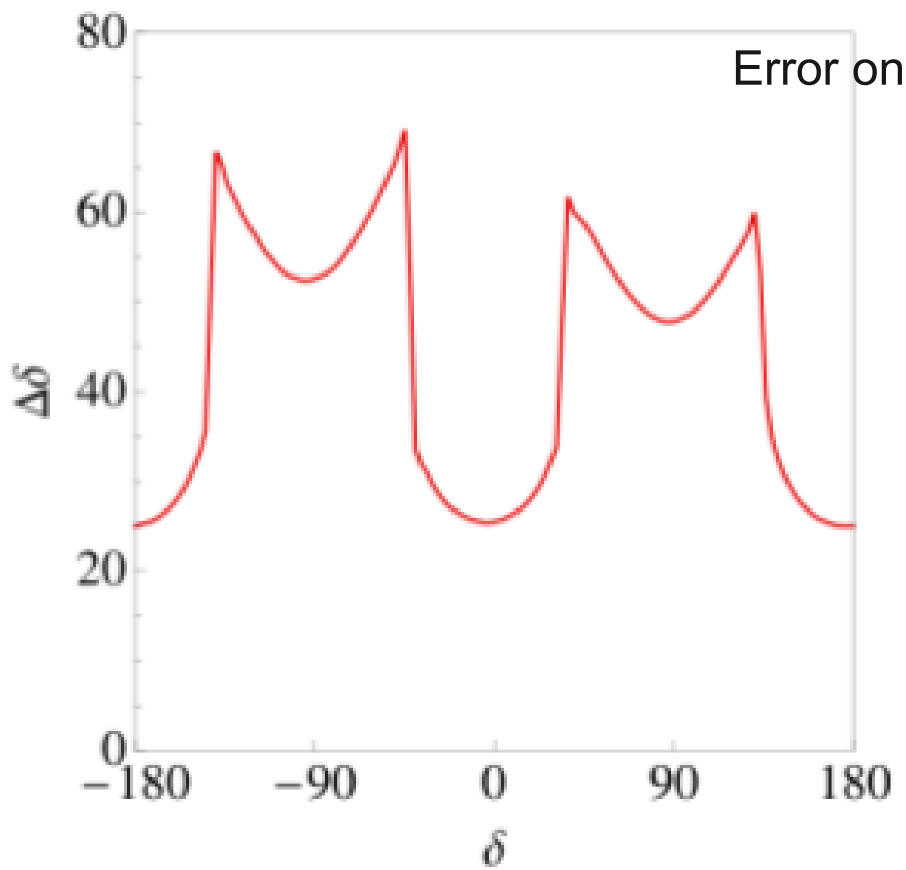
Mass hierarchy NOvA





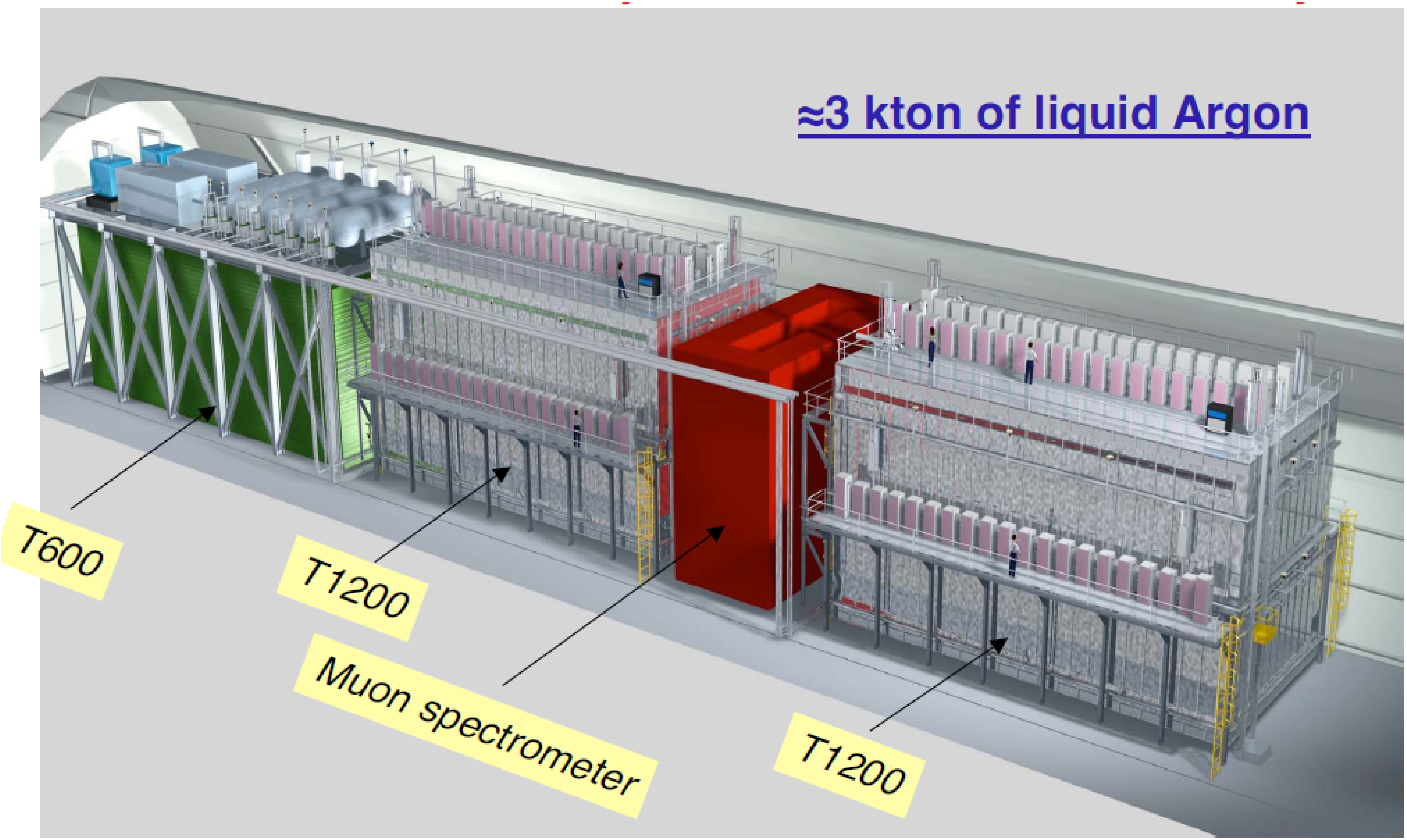
Curve discovery CPV per NOvA ?

δ_{CP} NOvA +T2K



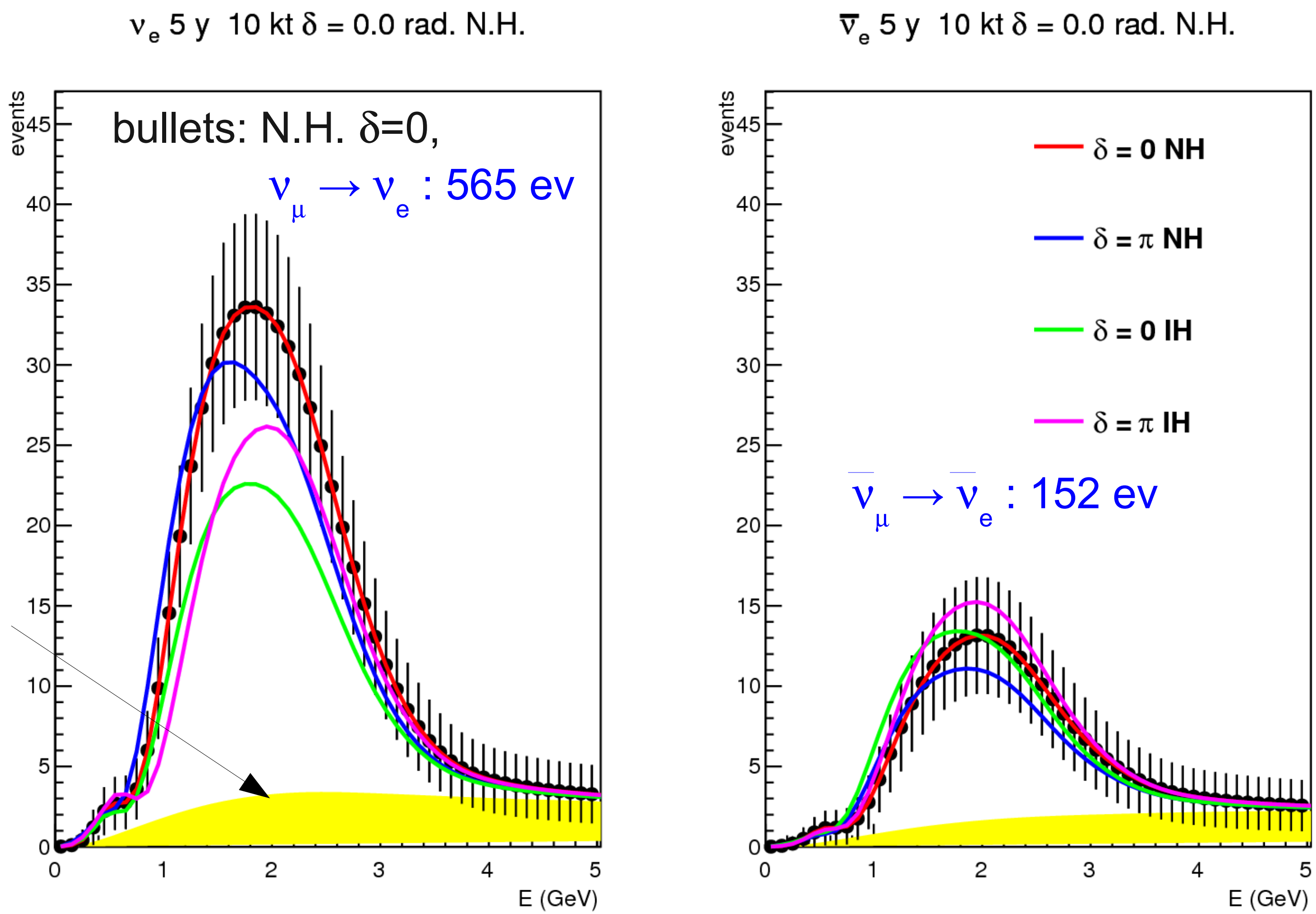
Error on δ at 1σ level

http://ltp.web.psi.ch/forummeeting/Rubbia.pdf



ν_e^{CC} spectra, 10 kt on-axis

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

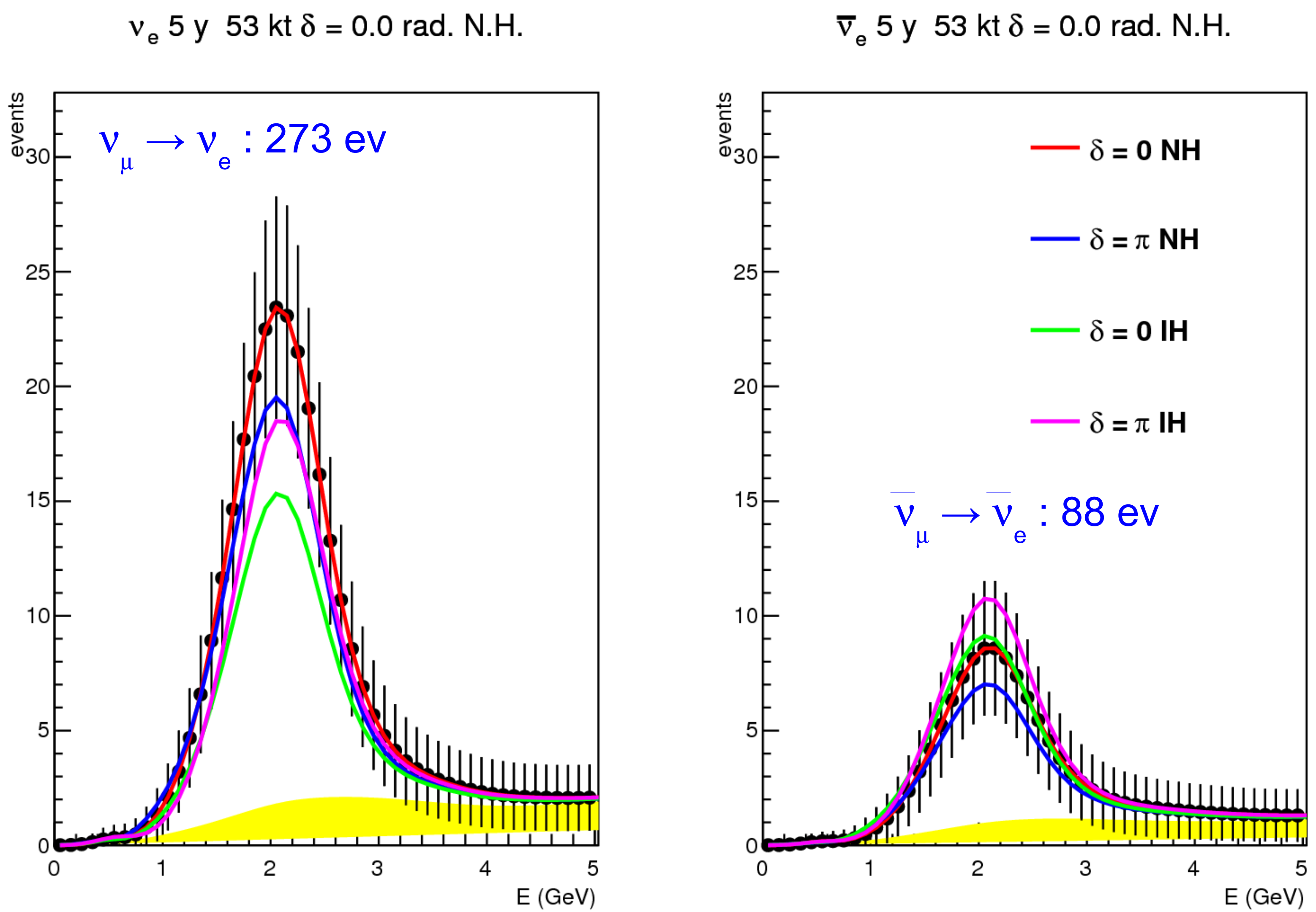


Background
(mainly intrinsic ν_e)

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.

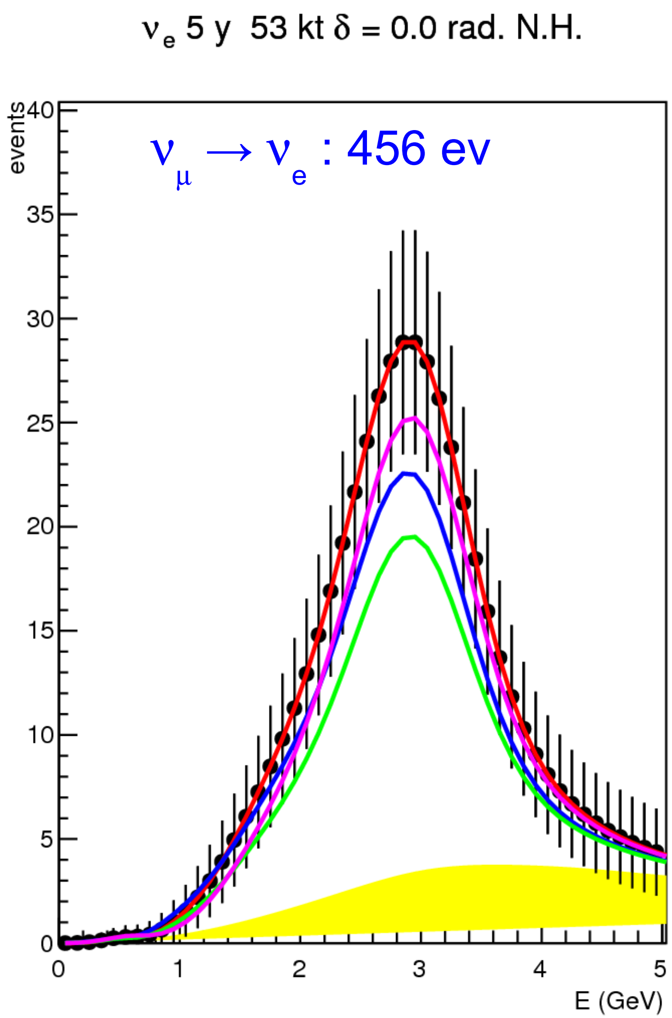
ν_e^{CC} spectra: 20 kt, 7 km off-axis

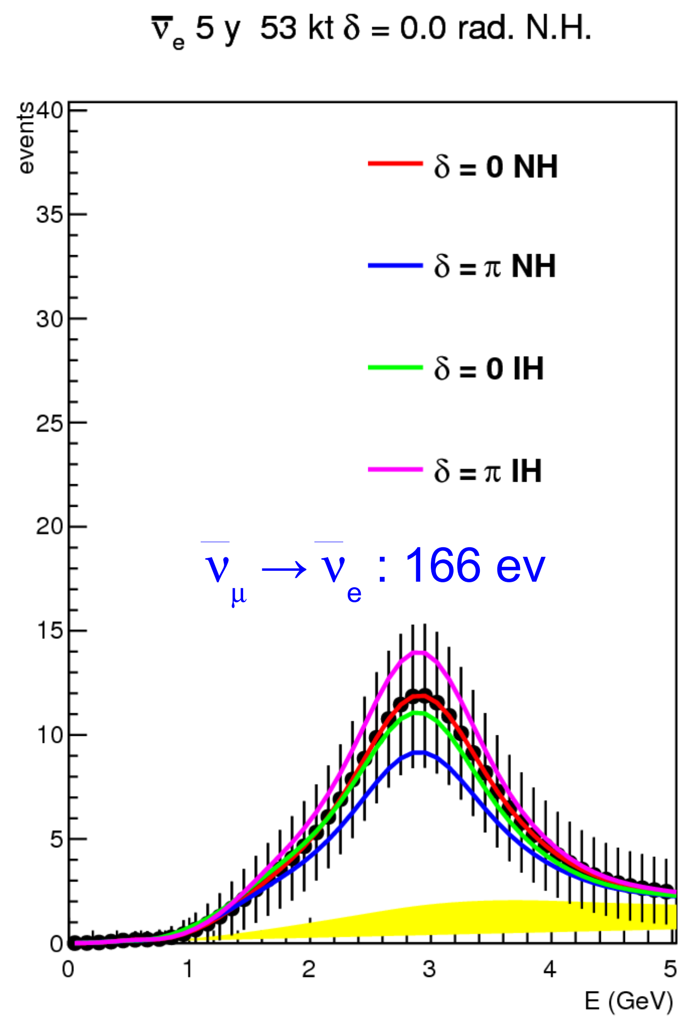
E_p = 400 GeV, 1.2 · 10^{20} pot/year (770 kW), 5 ν + 5 bar-ν years

More statistics w.r.t. to 10 km off-axis but

lower sensitivity to MH

less information from the shape of spectrum.

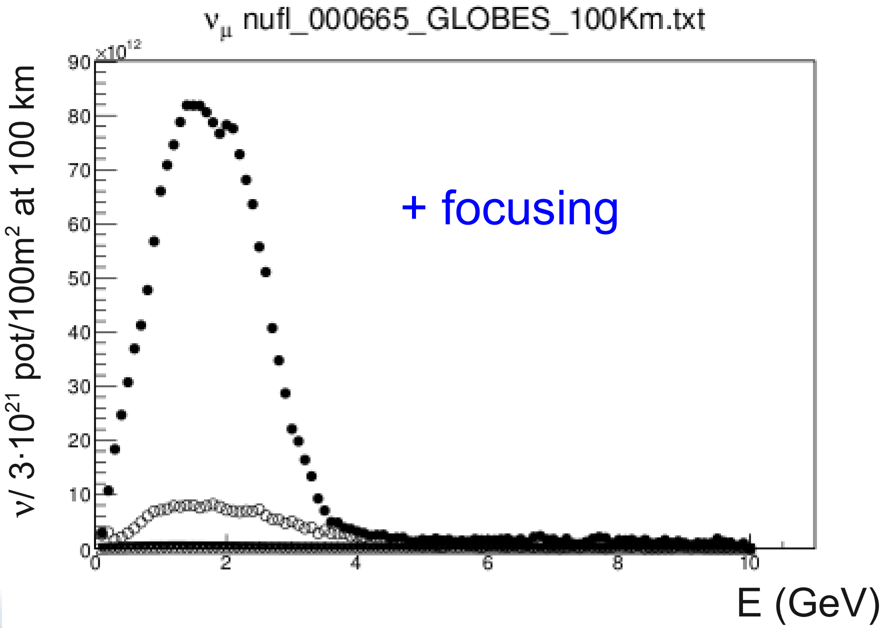


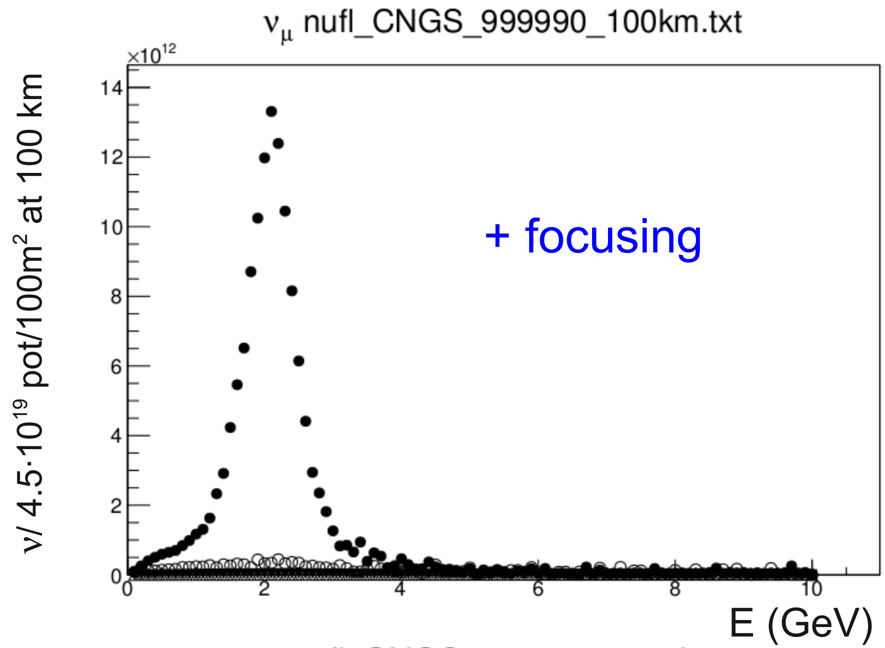


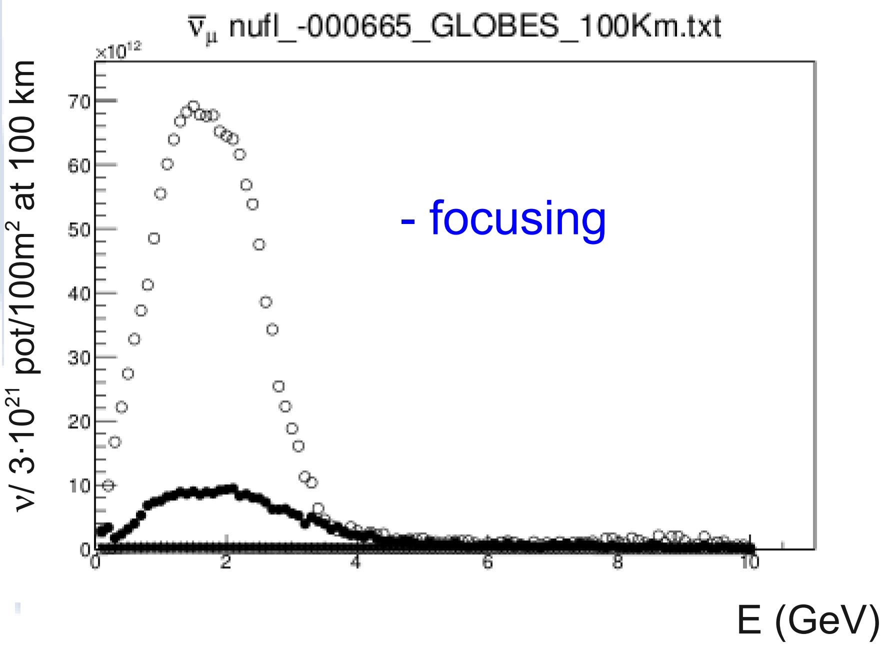
ν fluxes

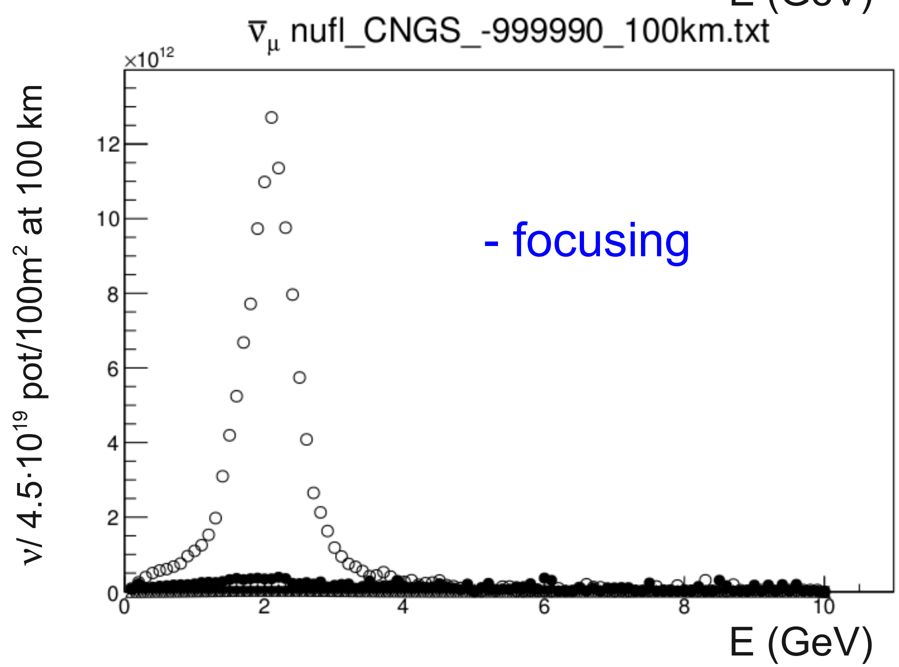
On-axis

Off-axis 10 km





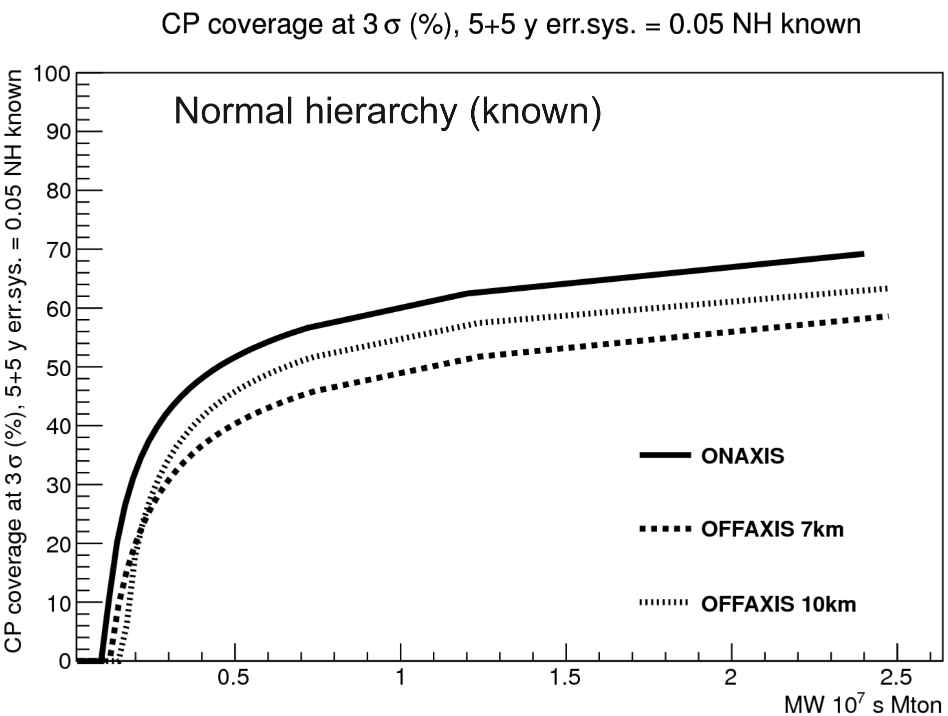


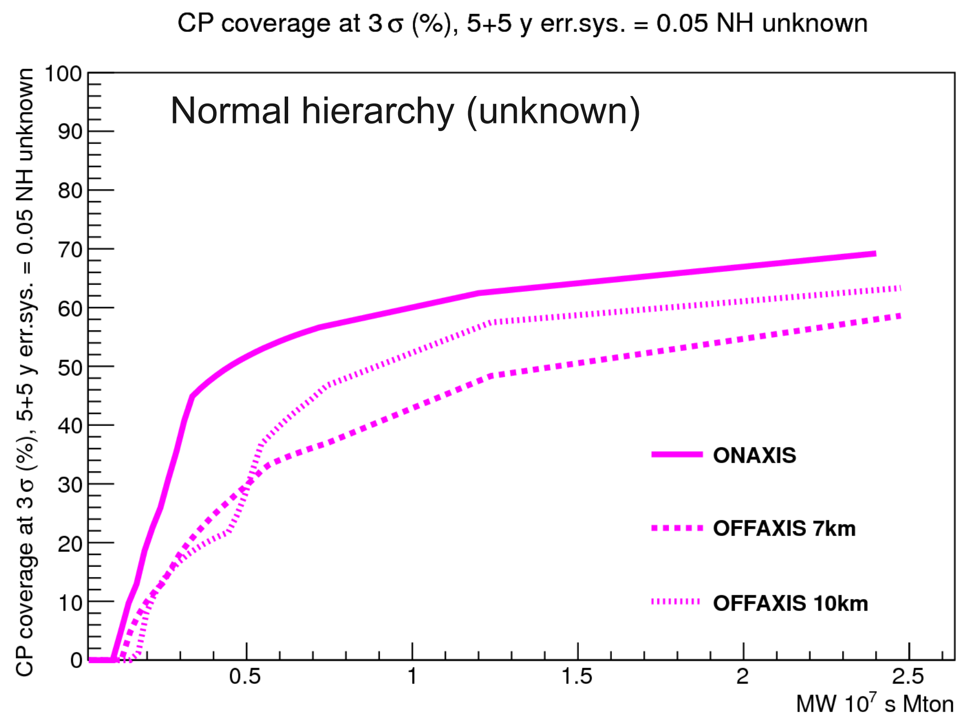


CPV coverage comparison

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)





- ON-AXIS 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