Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Expression of Interest for a very long baseline neutrino oscillation experiment (LBNO)

André Rubbia (ETH Zurich)

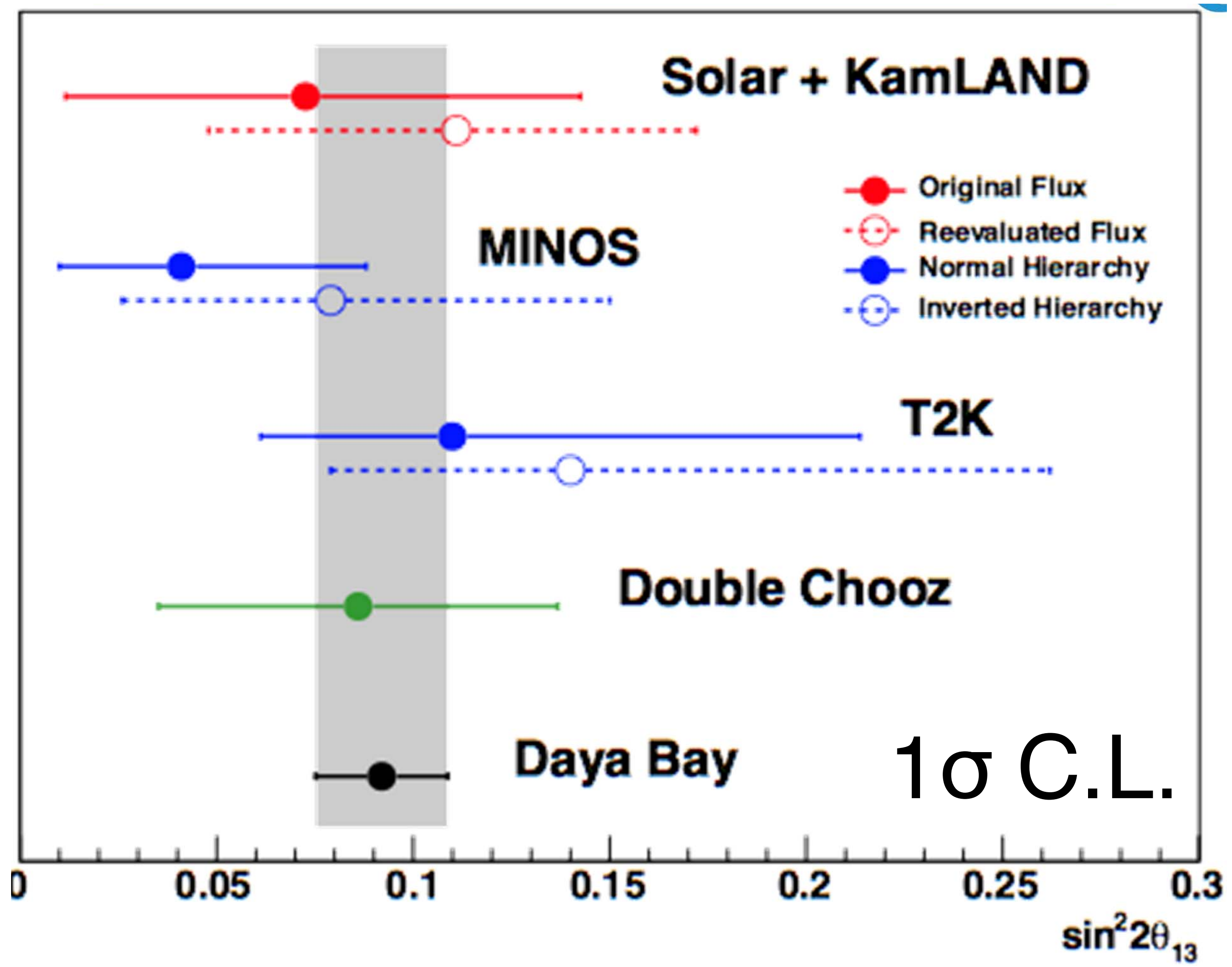
nuTURN2012 - Neutrino at the Turning Point

May 10th, 2012

A decade after CHOOZ: the θ_{13} revolution

See talk by GL Fogli

- T2K (Jun 2011):
  $\sin^2 2\theta_{13} = 0.03 - 0.34$ (90% CL).
  T2K Collaboration, Phys.Rev.Lett. 107 (2011) 041801
- MINOS (July 2011):
  $\sin^2 2\theta_{13} \neq 0$ at 89% CL.
  MINOS Collaboration, Phys.Rev.Lett. 107 (2011) 181802
- Double CHOOZ (Dec 2011):
  $\sin^2 2\theta_{13} = 0.017 - 0.16$ (90% CL).
  Double CHOOZ Collaboration, arXiv: 1112.6353 [hep-ex].
- Daya Bay (Mar 2012):
  $\sin^2 2\theta_{13} \neq 0$ at 5.2σ (!),
  best-fit = 0.092.
  Daya Bay Collaboration, arXiv: 1203.1669 [hep-ex].
- Reno (April 2012):
  exclude no oscillations at 4.9σ
  Reno Collab, arXiv:1204.0626v2



$$\sin^2(2\theta_{13}) = 0.092 \pm 0.016(stat) \pm 0.005(syst)$$

$$\sin^2 2\theta_{13} = 0.113 \pm 0.013(stat) \pm 0.019(syst)$$

The knowns and unknowns...

$$\sin^2\theta_{12} = 0.312^{+0.017}_{-0.015}$$

$$\Delta m^2_{12} = (7.59^{+0.20}_{-0.18}) \times 10^{-5}\,\mathrm{eV}^2$$

Solar parameters

SK,SNO, Kamland

$$\sin^2\theta_{23} = \begin{array}{c} 0.51 \pm 0.06 \\ 0.52 \pm 0.06 \end{array}$$

$$\Delta m^2_{31} = \begin{array}{c} 2.45 \pm 0.09 \\ -(2.34^{+0.10}_{-0.09}) \end{array} \times 10^{-3}\mathrm{eV}^2$$

Atmospheric parameters

SK,K2K, MINOS,T2K

→ *Mass ordering is hierarchical or inverted ?*

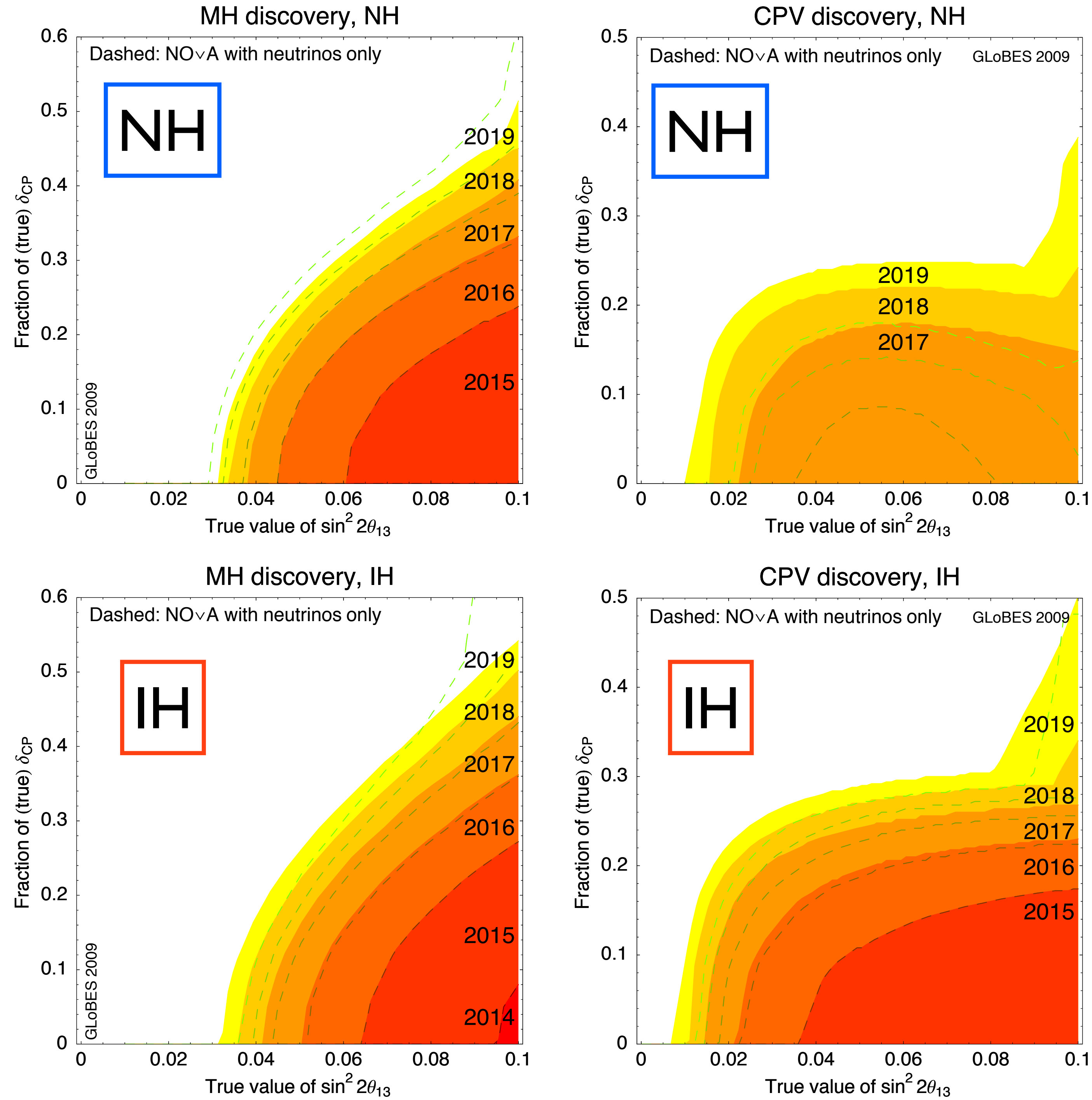
$$\sin^2(2\theta_{13}) \simeq 0.09 \pm 0.02$$

$\delta_{CP} = [0, 2\pi]$ → *Complex phase is unknown. Because of similarities with CKM matrix, it is natural to expect a CP violation in the lepton sector. But what is the size of the effect ??*

T2K and NOvA: in the future

- Preliminary estimation of sensitivity of T2K and NOvA *See talk by Schwetz*
- Nominal beam power scenarios (750kW). Need to check beam power assumptions.
- For $\sin^2 2\theta_{13}=0.1$, approximately (at 90%C.L.):
  - MH: ≈50% coverage
  - CPV: ≈30-40% coverage (robustness vs MH ?)
- Is 90% C.L. enough ? at 3σ C.L. sensitivity is highly reduced even with largely increased statistics.
- Atmospherics to the rescue ?
- Official curves to be produced by experiments with revised projections.

MH 90%C.L. sensitivity CPV



Huber et al., JHEP 0911:044,2009

not official

Ultimate physics goal - the next decade

- We cannot be satisfied with just setting limits.
- Neutrino oscillations data now indicate that significant CP-violation could occur in the leptonic sector.
- Need to address the **unsolved puzzle of the matter-antimatter asymmetry of the Universe** in a satisfactory way, by finding new sources of CPV and possibly baryon number violation
  - ★ **We must determine the neutrino mass hierarchy, measure δ_{CP} and determine the existence of CPV**
  - ★ **We must search for proton decay to test GUT**

⇨ **A new massive neutrino observatory for long baseline neutrino studies, expandable to cover full CPV parameter space, and located deep underground, capable of proton decay searches**

Oscillation phenomenology

Approximate formula (M. Freund)

quadratic dep. on θ_{13}

matter effect ~E

~7500 km magic bln

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(\hat{A}-1)^2}\sin^2((\hat{A}-1)\Delta)$$

$$+\alpha\frac{8J_{CP}}{\hat{A}(1-\hat{A})}\sin(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$

$$+\alpha\frac{8I_{CP}}{\hat{A}(1-\hat{A})}\cos(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$

$$+\alpha^2\frac{\cos^2\theta_{23}\sin^2 2\theta_{12}}{\hat{A}^2}\sin^2(\hat{A}\Delta)$$

CPV term approximate dependence ~L/E

~2540 km magic bln

solar term

linear dep. on θ_{13}

$$J_{CP} = 1/8\sin\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

$$I_{CP} = 1/8\cos\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

$$\alpha = \Delta m^2_{21}/\Delta m^2_{31},\ \Delta = \Delta m^2_{31}L/4E$$

$$\hat{A} = 2VE/\Delta m^2_{31} \approx (E_\nu/GeV)/11 \text{ For Earth's crust.}$$

CP asymmetry grows as θ_{13} becomes smaller !

Correlations !

CP and Matter Asymmetries

★ CP-asymmetry in vacuum:

$$\mathcal{A}_{CP}^{vac}(\delta_{CP}) \equiv abs\left(\frac{P^{vac}(\nu) - P^{vac}(\bar{\nu})}{P^{vac}(\nu) + P^{vac}(\bar{\nu})}\right)$$

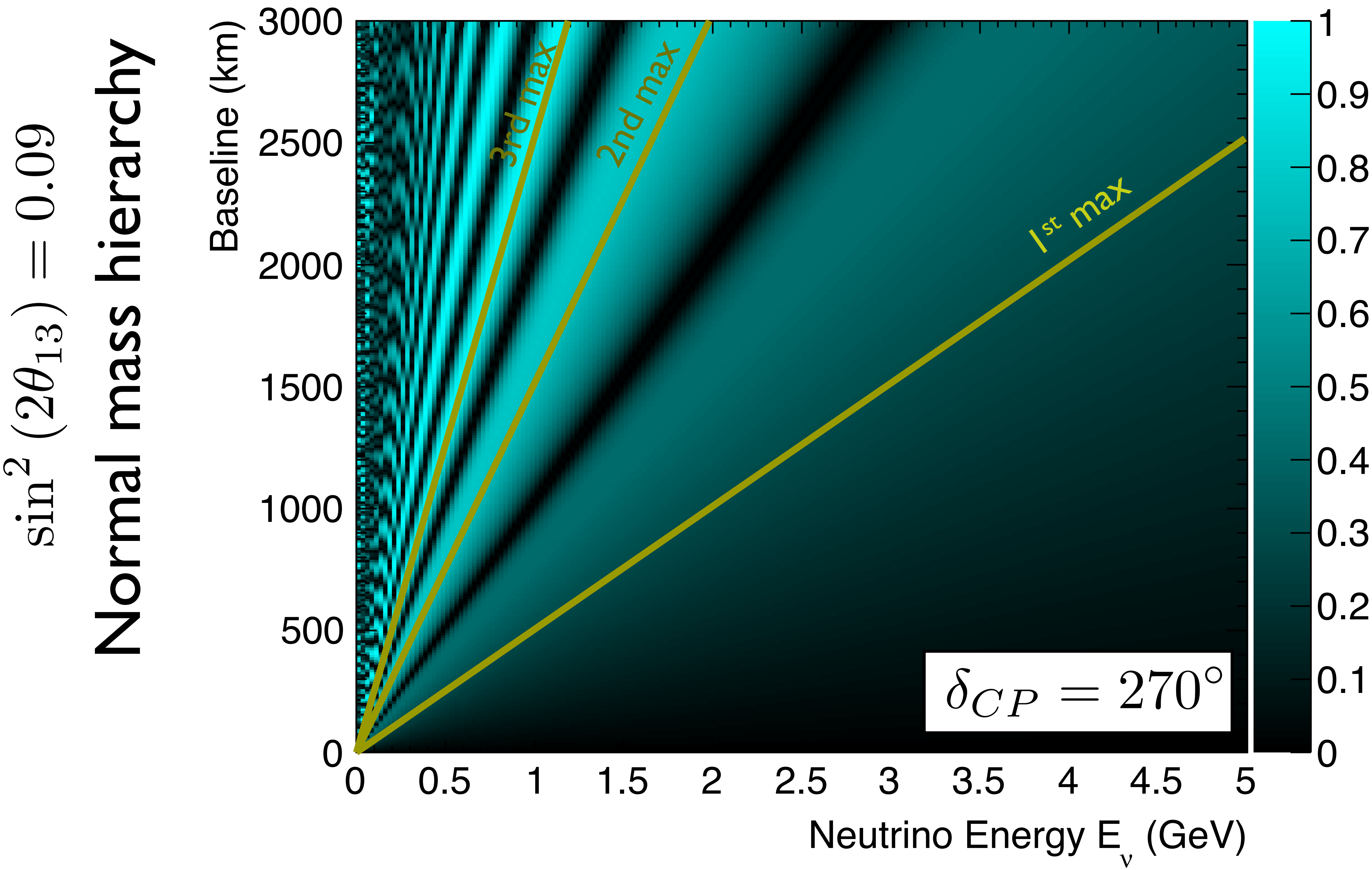
★ Asymmetry due to matter effects:

$$\mathcal{A}_{CP}(\rho) \equiv abs\left(\frac{P^{mat}(\nu) - P^{mat}(\bar{\nu})}{P^{mat}(\nu) + P^{mat}(\bar{\nu})}\right)$$

- CP asymmetries are largest at the 2nd, 3rd, ... maxima.
- Matter asymmetry dominates around the 1st maximum.
- Long(er) baselines, wide-band beams to cover several maxima are needed to resolve degeneracies.
- Experimentally: $E_\nu^{2nd\,max} \gtrsim 0.5\,\mathrm{GeV} \Longrightarrow \mathrm{L} \gtrsim 1000\ \mathrm{km}$

CP-violation determination (CPV)

$$\mathcal{A}^{vac}_{CP}(\delta_{CP}) \equiv abs\left(\frac{P^{vac}(\nu) - P^{vac}(\bar{\nu})}{P^{vac}(\nu) + P^{vac}(\bar{\nu})}\right)$$

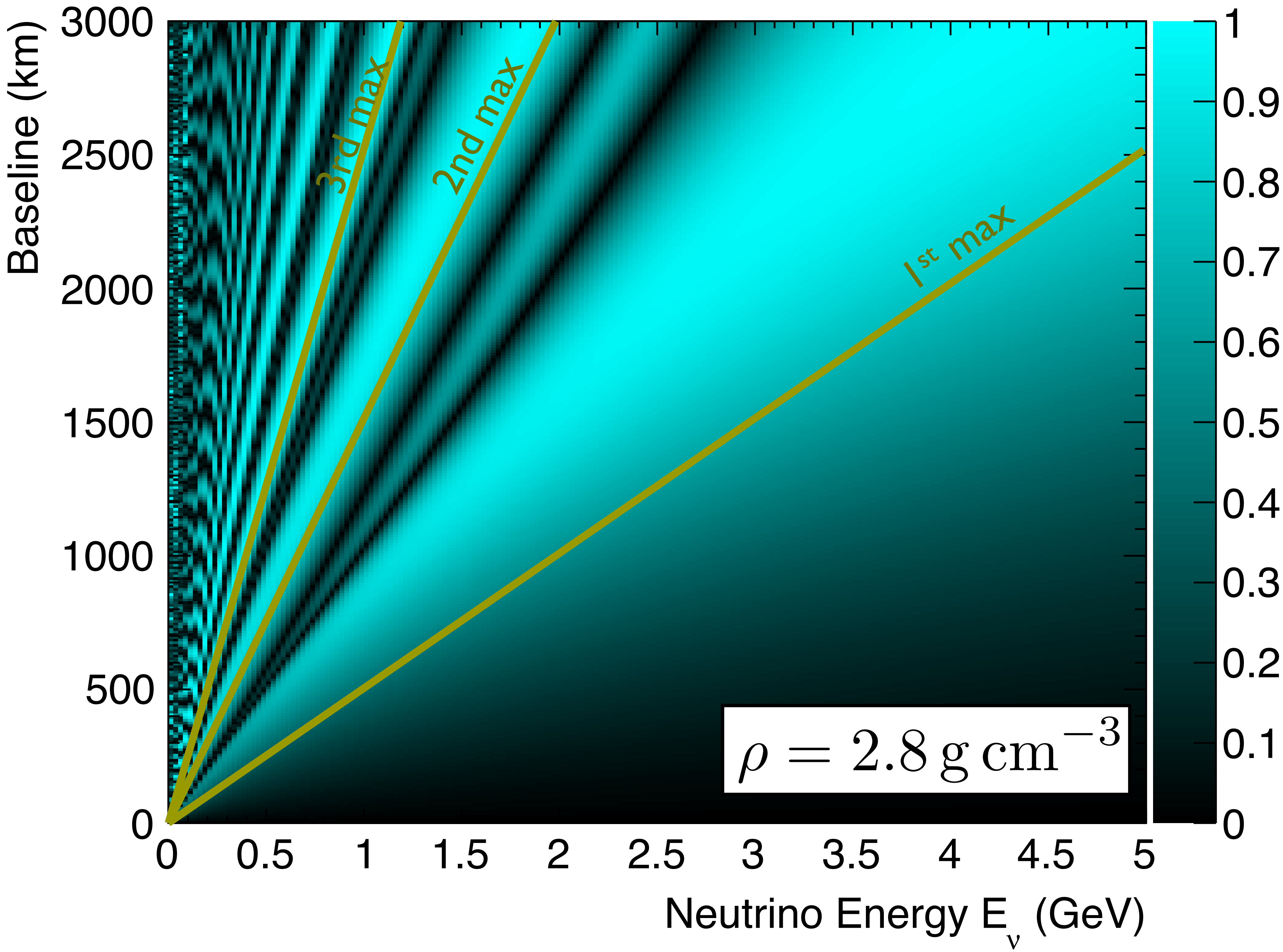


Mass hierarchy determination (MH)

$$\mathcal{A}_{CP}(\rho) \equiv abs\left(\frac{P^{mat}(\nu) - P^{mat}(\bar{\nu})}{P^{mat}(\nu) + P^{mat}(\bar{\nu})}\right)$$

$\sin^2(2\theta_{13}) = 0.09$

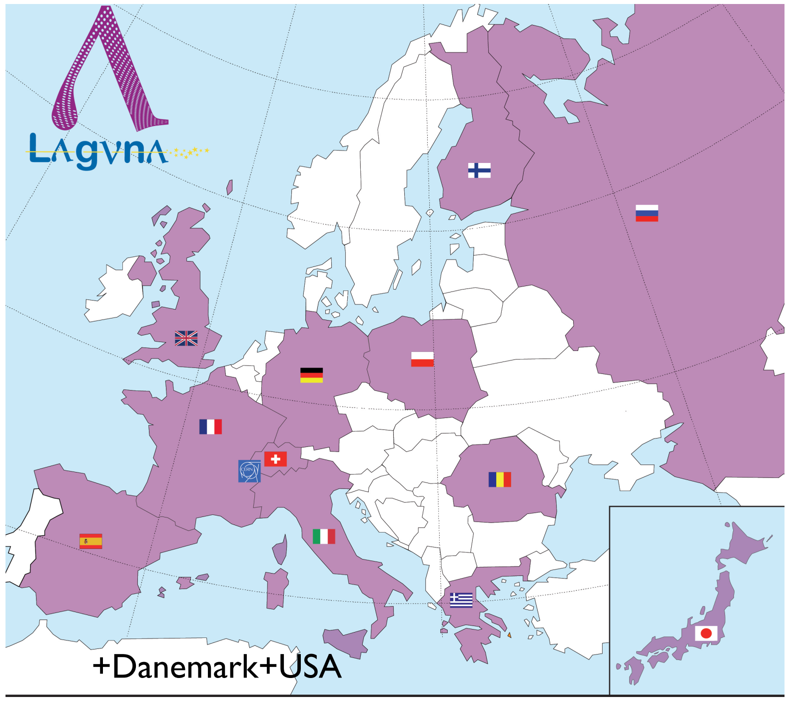
Normal mass hierarchy



Large
Apparatus for
Grand
Unification and
Neutrino
Astrophysics
-
Long
Baseline
Neutrino
Oscillations

- Deep Underground Science Facilities for ν Physics & Proton decay
- Feasibility of a next generation ν observatory with very large volume detectors
- Prospects for next generation long baseline flavor oscillations with neutrino beams from CERN
- Options in Europe
- Funded by the EC FP7 framework programme since 2008 (present grant until 2014)

LAGUNA-LBNO consortium



14 countries, 47 institutions, ~300 members (growing)

Switzerland
University Bern
University Geneva
ETH Zürich (*coordinator*)
Lombardi Engineering*

Finland
University Jyväskylä
University Helsinki
University Oulu
Rockplan Oy Ltd*

CERN

France
CEA
CNRS-IN2P3
Sofregaz*

Germany
TU Munich
University Hamburg
Max-Planck-Gesellschaft
Aachen
University Tübingen

Poland
IFJ PAN
IPJ
University Silesia
Wroklaw UT
KGHM CUPRUM*

Greece
Demokritos

Spain
LSC
UA Madrid
CSIC/IFIC
ACCIONA*

United Kingdom
Imperial College London
Durham
Oxford
QMUL
Liverpool
Sheffield
Sussex
RAL
Warwick
Technodyne Ltd*
Alan Auld Ltd*
Ryhal Engineering*

Romania
IFIN-HH
University Bucharest

Denmark
Aahrus

Italy
AGT*

Russia
INR
PNPI

Japan
KEK

USA
Virginia Tech

(=industrial partners)*

European sites: LAGUNA-LBNO

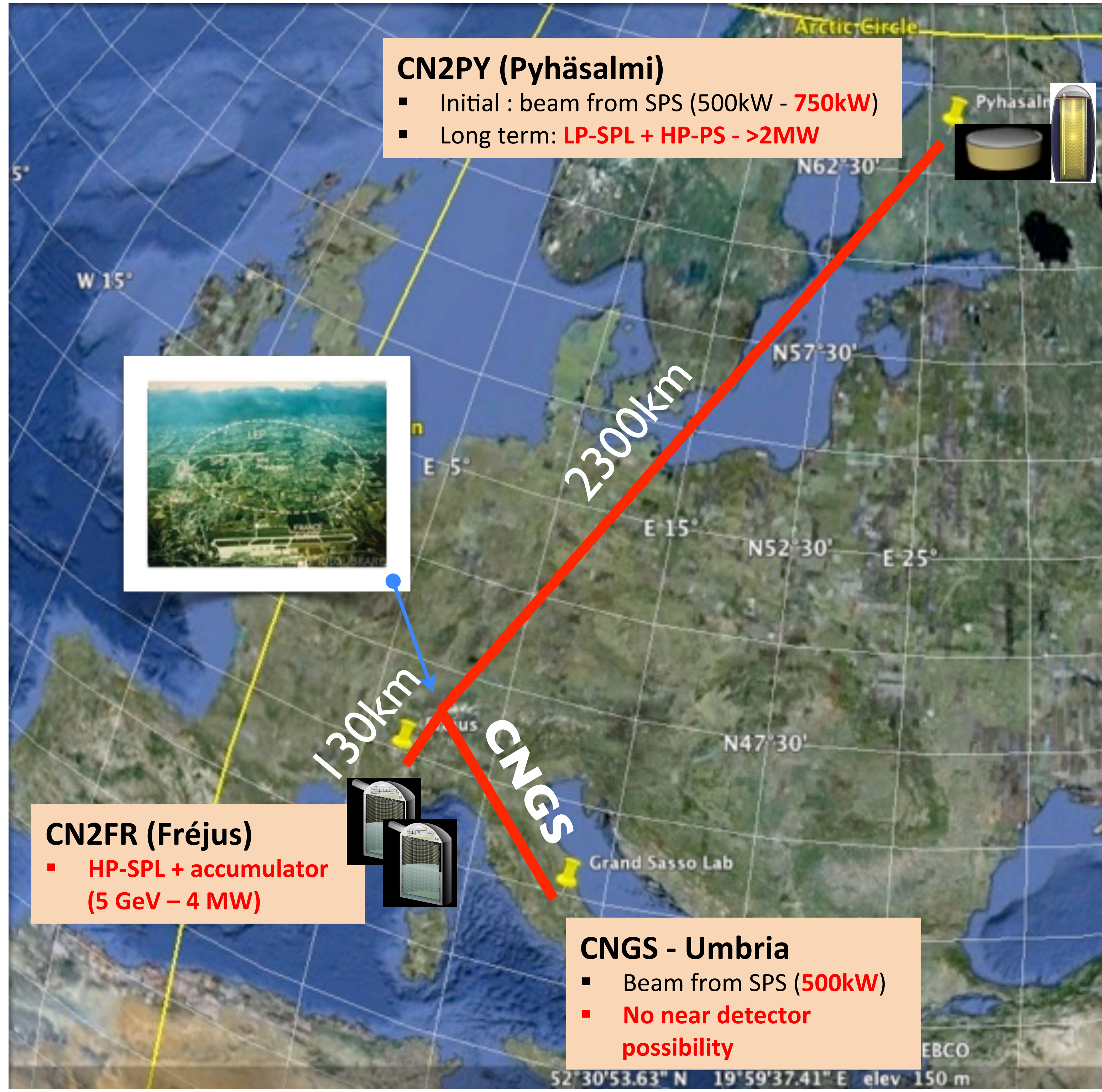
arXiv:1003.1921 [hep-ph]

Three far sites considered in details

- Large Water Cerenkov Detector. CERN-Fréjus is a short baseline. It offers good synergy for enhanced physics reach with β-beam at γ=100

- Liquid Argon TPC & magnetized iron + Liquid Scintillator detectors CERN-Pyhäsalmi is the longest baseline. It offers good synergy for enhanced physics reach with a NF

- [CNGS is an existing beam but is considered at lower priority (missing near detector, limited power upgrade scenarios)]



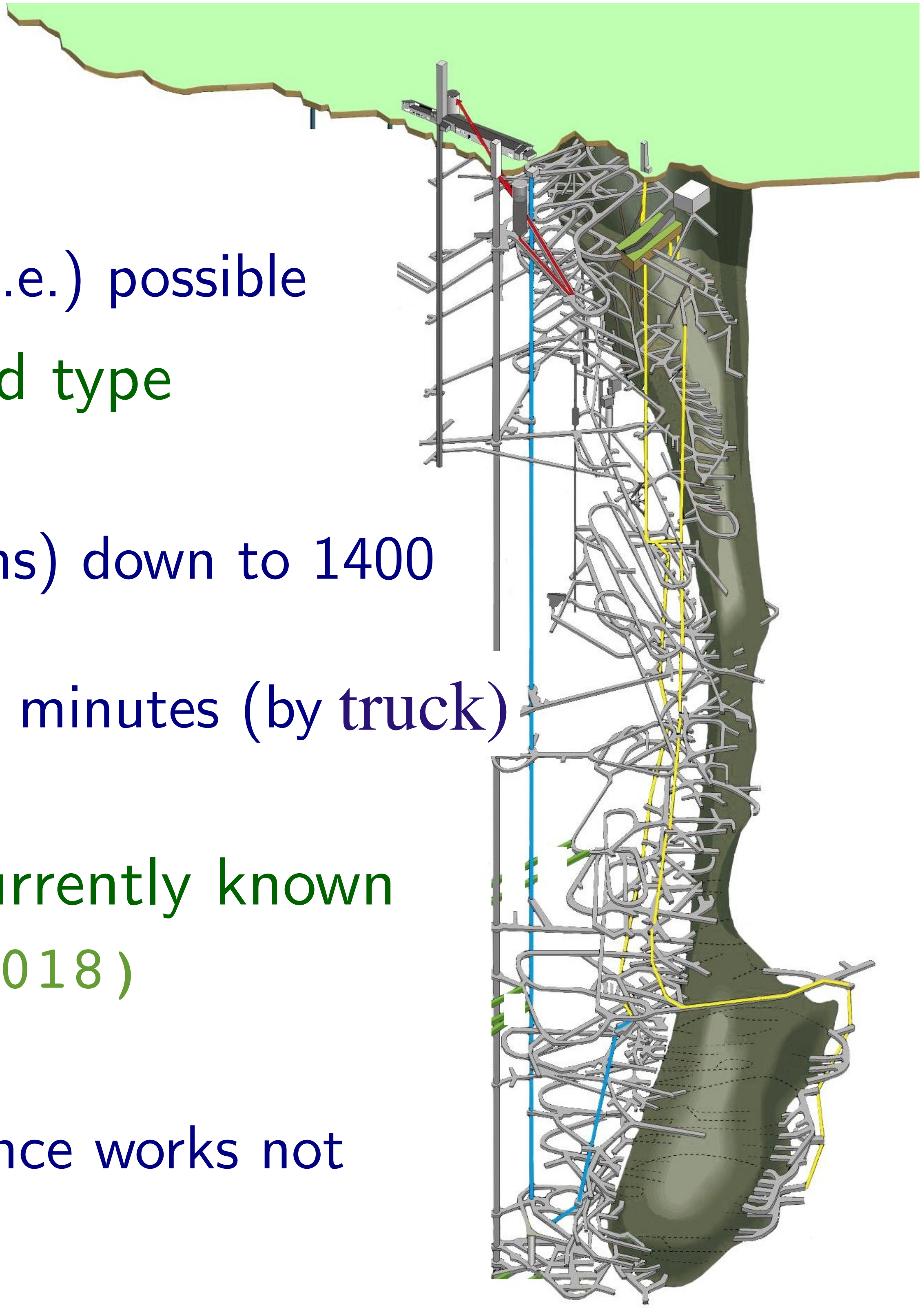
Pyhäsalmi site location

See talk by T Enqvist

- CUPP : Centre for Underground Physics in Pyhäsalmi (www.cupp.fi)
- Location: 63° 39' 31"N – 26° 02' 48"E
- Distances (by roads)
  - Oulu – 165 km
  - Jyväskylä – 180 km
  - Helsinki – 450 km
- Distance to CERN 2300 km
- Good traffic connections
  - the main highway: Helsinki – Jyväskylä – Oulu – ...
  - the second busiest airport in Oulu
  - rail yard at the mine
- Inhabitants: ∼6000

Present state of mine

Present: The Pyhäsalmi mine (Inmet Mining Ltd., Canada)



- Produces Cu, Zn, and FeS_2
- The deepest mine in Europe
  - Depths down to 1400 m (4000 m.w.e.) possible
- The most efficient mine of its size and type
- Very modern infrastructure
  - lift (of 21.5 tons of ore or 20 persons) down to 1400 metres takes ∼3 minutes
  - via 11-km long decline it takes ∼40 minutes (by truck)
  - good communication systems
- Operation time still 7–8 years with currently known ore reserves (presumably until 2018)
- Compact mine, small 'foot print'
  - water pumping and other maintenance works not major issues

Some unique features of Pyhäsalmi

- **Many optimal conditions satisfied simultaneously**:
  - Infrastructure in **perfect state** because of current exploitation of the mine
  - **Unique assets available** (shafts, decline, services, sufficient ventilation, water pumping station, pipes for liquids, underground repair shop...)
  - **Very little environmental water**
  - Could be **dedicated to science activities** after the mine exploitation ends (around 2018)
- One of the deepest location in Europe (4000 m.w.e.)
- The distance from CERN (2300 km) offers unique long baseline opportunities.
- The site has the lowest reactor neutrino background in Europe, important for the observation of very low energy MeV neutrinos.

Cosmic Ray experiment EMMA at shallow depth

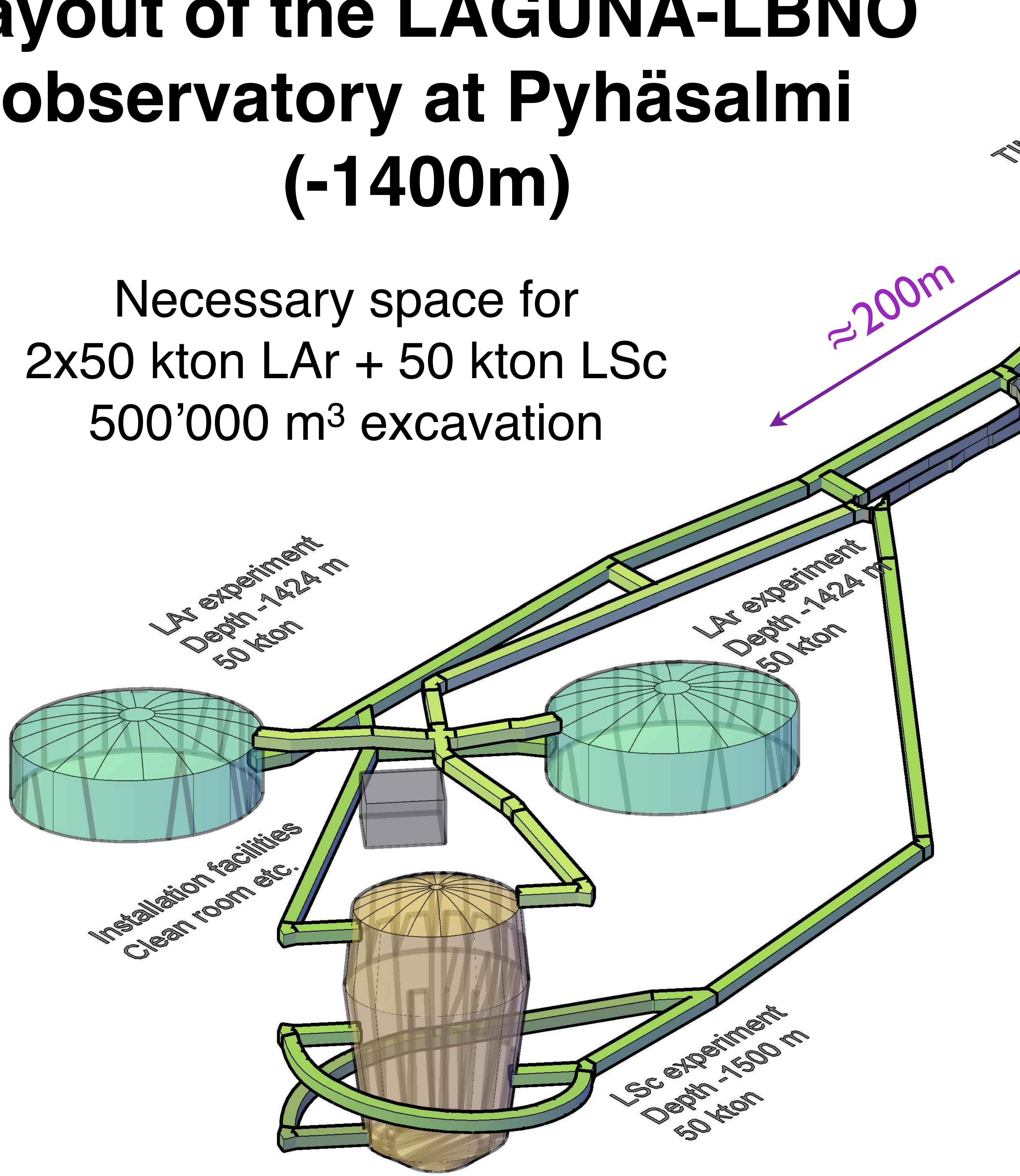
250 m long tunnel and a cavern at 1400m excavated for LAGUNA R&D

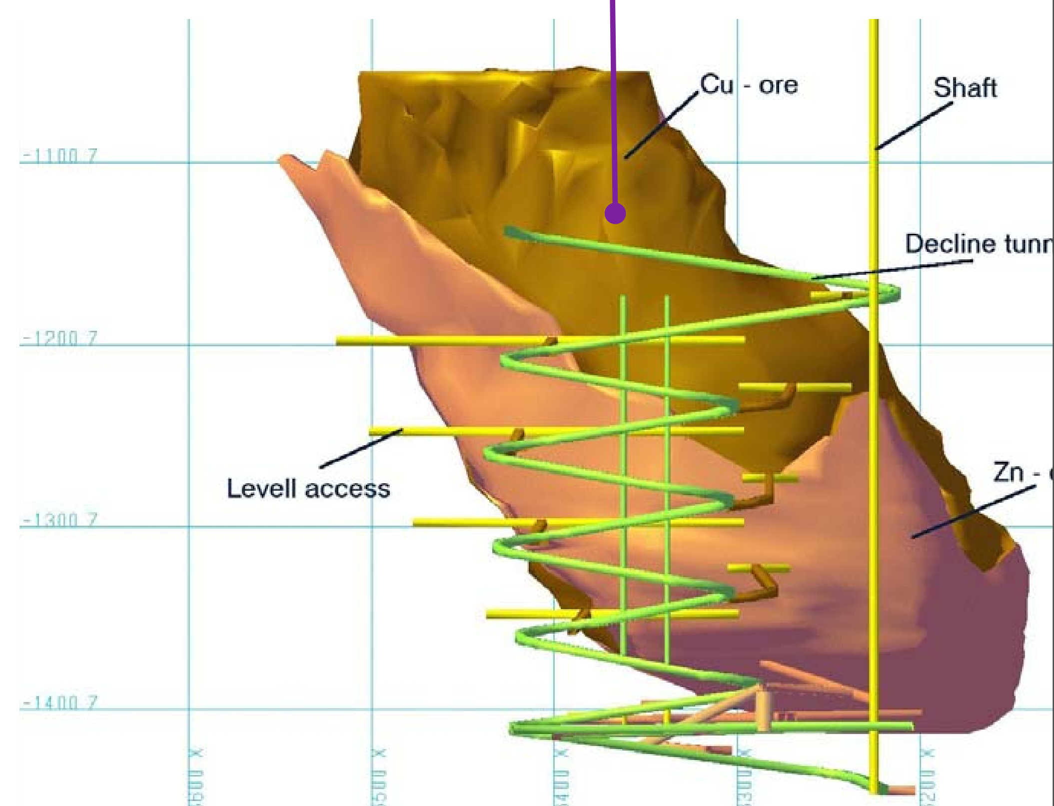
Cafeteria, meeting room and sauna at 1400 m below ground

Mobile phones work and internet available also at 1400 m

Layout of the LAGUNA-LBNO observatory at Pyhäsalmi (-1400m)

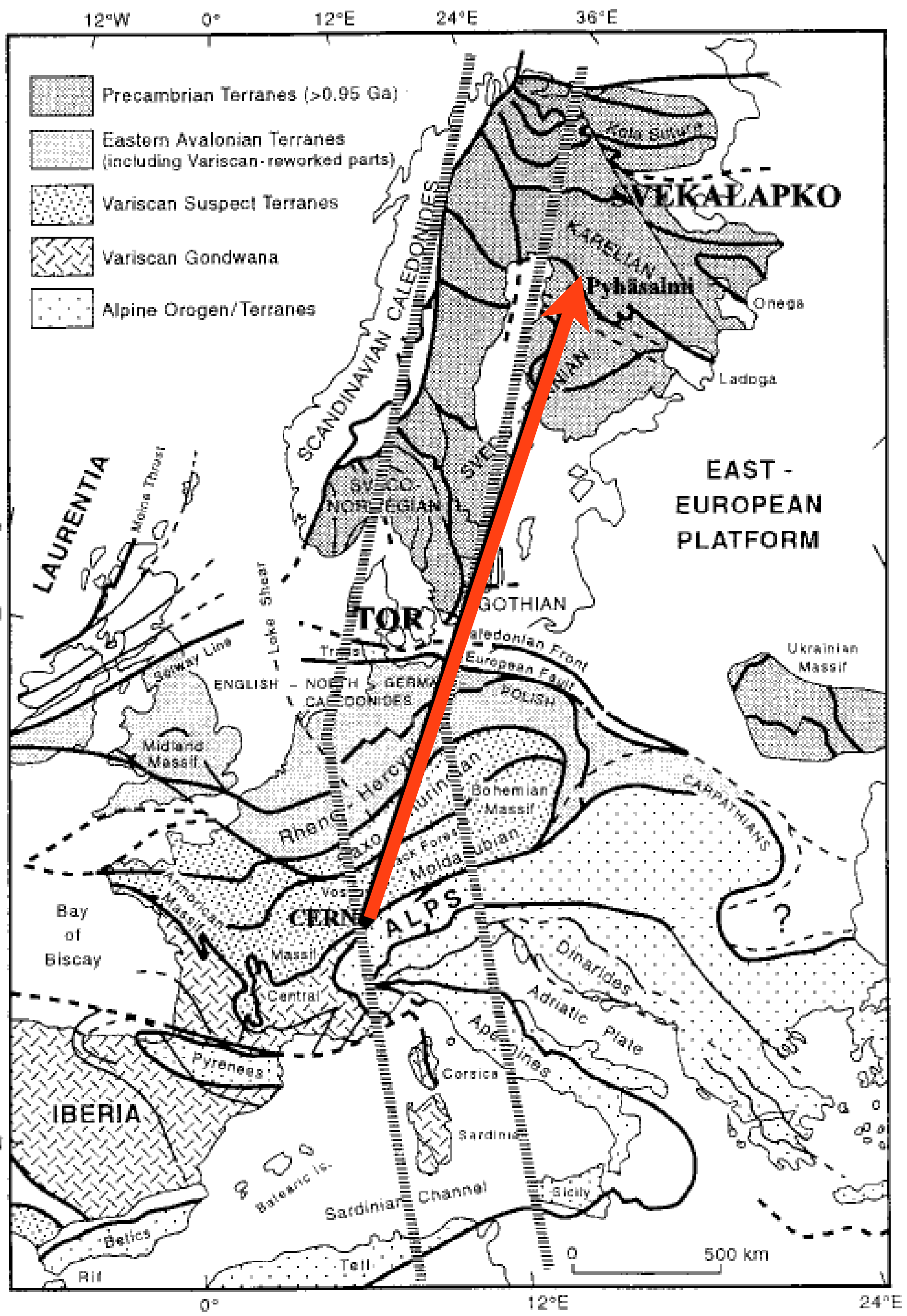
Necessary space for
2x50 kton LAr + 50 kton LSc
500’000 m^3 excavation

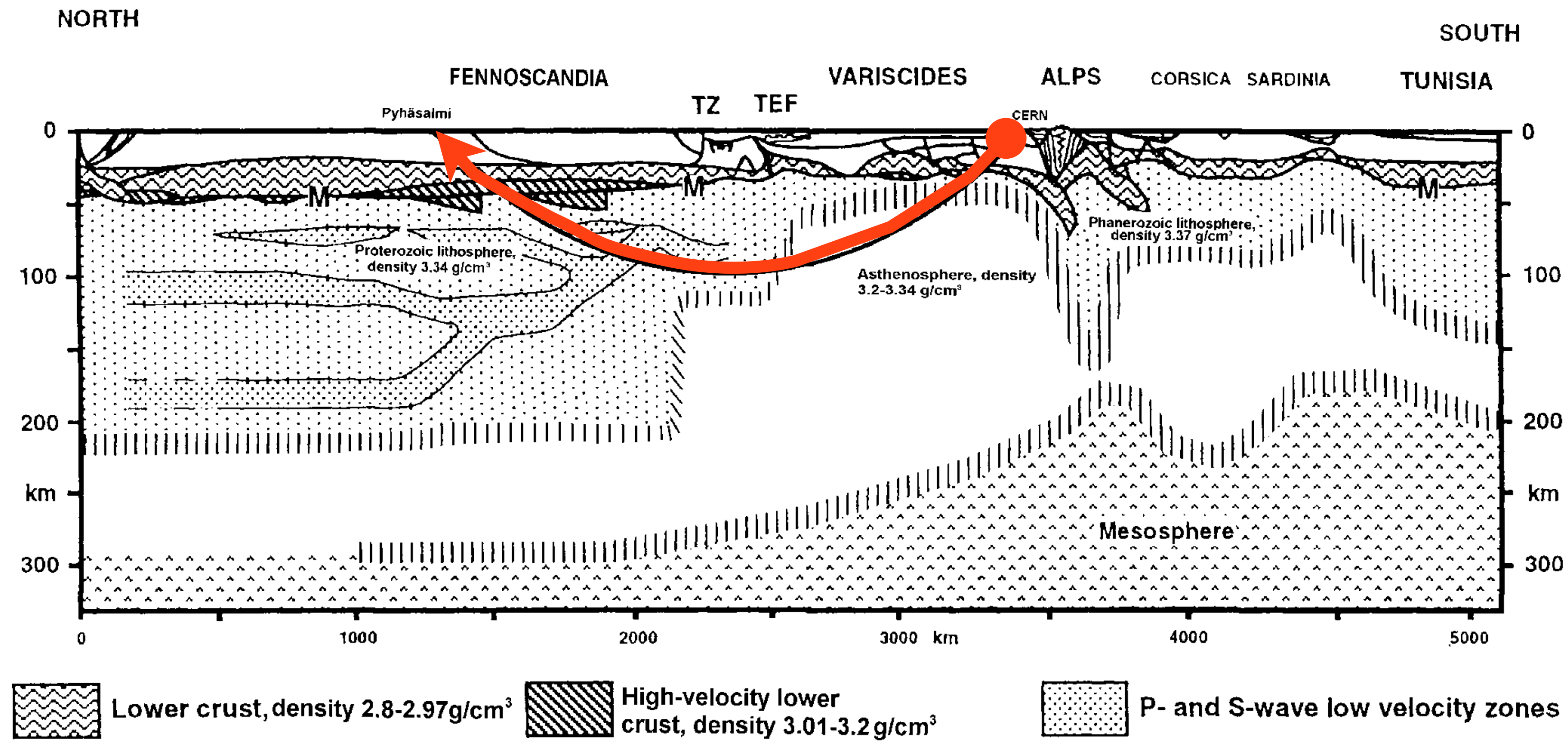




Neutrinos from CERN to Pyhäsalmi

arXiv:hep-ph/0305042v1



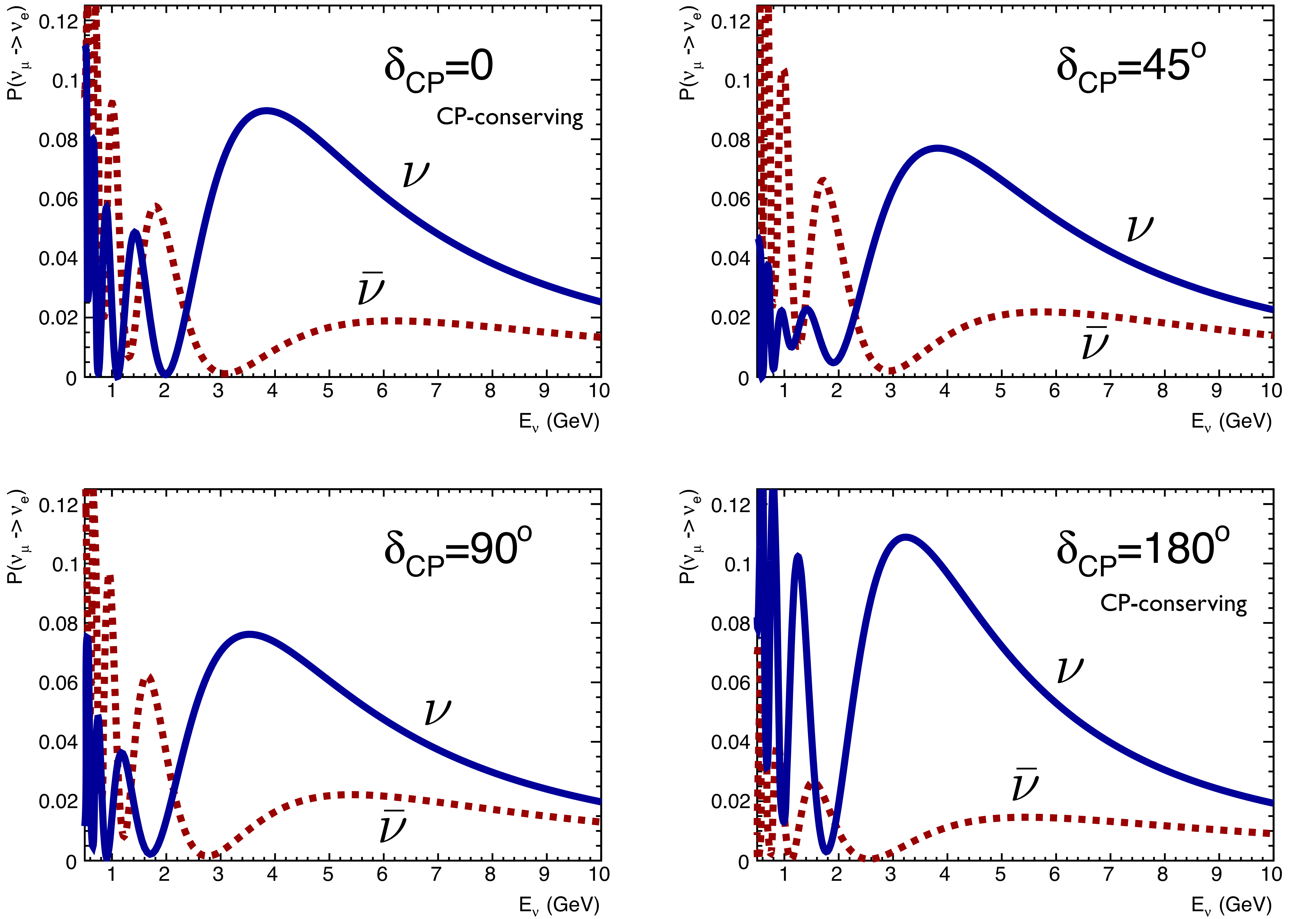


- Distance CERN-Pyhäsalmi = 2288 km
- Deepest point = 103.8 km
- Abundant geophysical data about crust and upper mantle available
- Densities = 2.4÷3.4 g/cm^3
- Remaining uncertainty has small effect on neutrino oscillations

CERN-Pyhäsalmi: oscillations

★Normal mass hierarchy L=2300 km

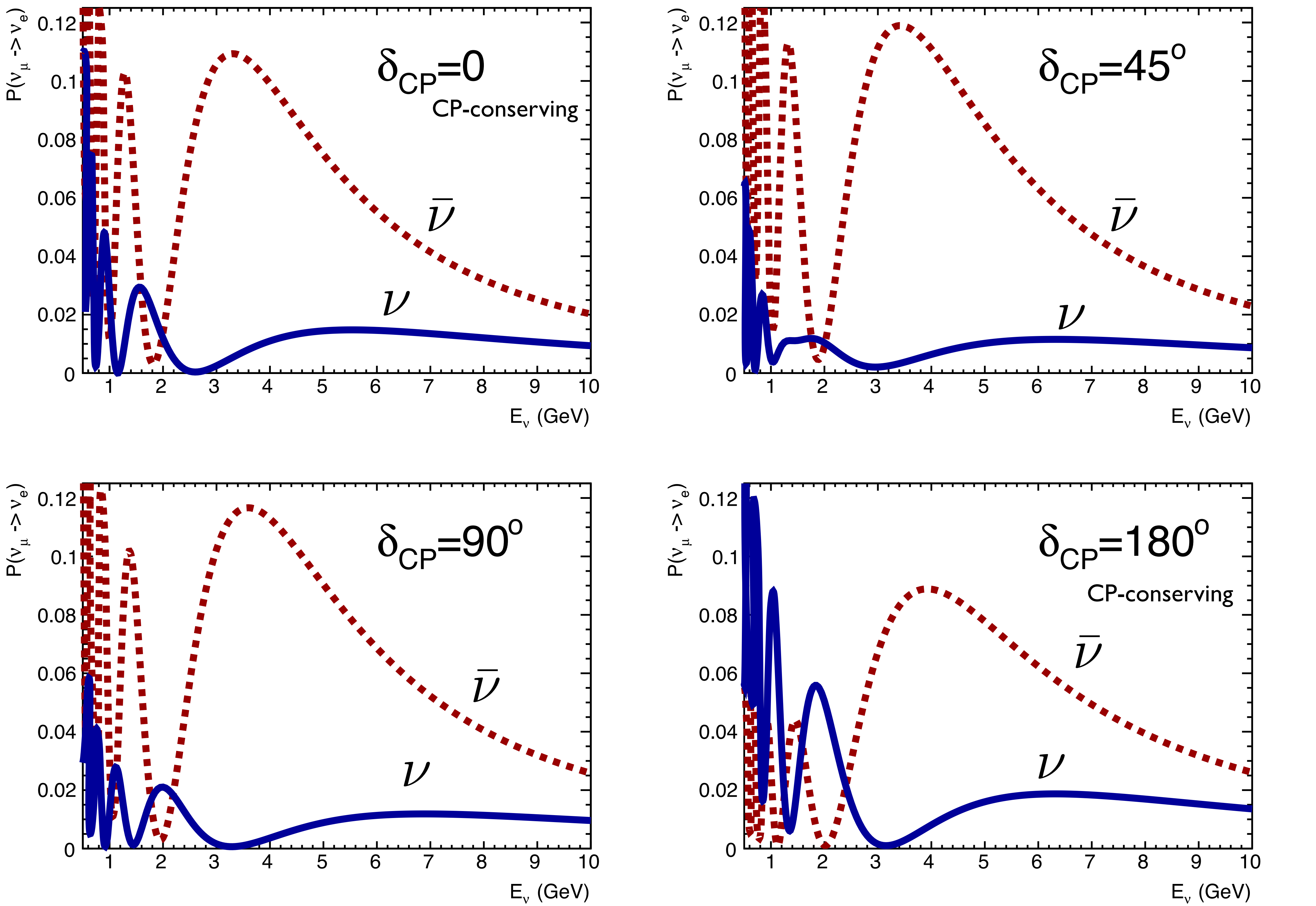
$\sin^2(2\theta_{13}) = 0.09$



CERN-Pyhäsalmi: oscillations

★Inverted mass hierarchy L=2300 km

$\sin^2(2\theta_{13}) = 0.09$



LBNO EoI: the priors

- A significantly better sensitivity than the (combined) T2K and NOvA, with an improved method to conclusively determine mass ordering and to explore CP-violation ➠ **exploit L/E dependence with WBB at long baseline** ➠ **spectral information provides unambiguous oscillation parameters sensitivity.**
- A detector with better signal efficiency and better background rejection than T2K & NOvA but with a mass of the same order as T2K/SuperK & NOvA → **>20 kton very fine sampling tracking detector**
- There are compelling ν-astrophysics measurements and nucleon decay searches to be performed → **deep underground location**
- A conventional wide band beam at an energy above 500 MeV is technically achievable and affordable, and enables at long baseline to study L/E dependence of oscillation probability with 1st & 2nd maxima → **new conventional beam aimed at a baseline >1000 km**
- Large sensitivity to mass hierarchy with 100% coverage at >5σ and the presently available beam power requires a very long baseline → **baseline >1500 km**
- At a distance suitable for the NF for long term → **baseline >2000 km.**

LBNO EoI: the rationale

- The adequacy and choice of the far location are based on several years of extensive and detailed site studies performed within the LAGUNA and LAGUNA-LBNO design studies. The LAGUNA-Pyhäsalmi project is well advanced and on track.
- The choice of Pyhäsalmi/FI recognizes that the features of the infrastructure at the deepest mine in Europe allowing underground access to -1400 m, and a baseline of 2300 km from CERN, **fulfill all priors**, and **offer unique technical advantages and physics opportunities not found or easily replicated elsewhere**.
- The EoI considers as an initial step a **new conventional neutrino beam** from CERN aimed at an **20 kton double phase LAr LEM TPC** (GLACIER) and **a magnetized iron detector** (MIND).
  - LAr LEM TPC offers new look and increased physics reach in many physics channels with a mass comparable to SuperK and NOvA.
  - The magnetized detector with muon momentum and charge determination collects an independent neutrino sample, and serves as a tail catcher for events occurring in the LAr.
  - The Pyhäsalmi site allows virtually limitless excavation possibilities hence target mass expansion until the ultimate "megaton" scale envisioned by LAGUNA.
- **This project, called LBNO, is the first priority of the LAGUNA-LBNO consortium and is endorsed by the NF community.**

LBNO EoI: the physics reach

- Initial setup 20 kton LAr LEM TPC + MIND + CERN SPS 700kW upgrade
- **Ultimate** long baseline oscillations measurements:
  - LBNO can measure all transitions (e/μ/tau) and determine precisely oscillation parameters. It can achieve a **5σ C.L. determination of the neutrino mass hierarchy** in a few years. In a 10 years run, it explores a **significant part of the CPV parameter space, namely 60% CPV coverage at 90%C.L.**
  - Both the local situation and the distance make it such that it can evolve into larger detector(s) and a more powerful beams (e.g HP-PS and/or NF) and thus, **offers a long term vision**. For example, with a three-fold increase in exposure, **it reaches 75% CPV coverage at 3σ C.L.**. Competitive with T2HK (even more with JPARC MR at 700kW...) and LBNE.
- **Strongly** extended sensitivity to nucleon decay in several channels. E.g. some channels with sensitivity similar to HK:

$$Br(p \to \bar{\nu}K) > 2 \times 10^{34} y(90\%C.L.) \qquad Br(n \to e^- K^+) > 2 \times 10^{34} y(90\%C.L.)$$

- **Interesting** astrophysics: LBNO acts as an nu-observatory in the 10 MeV-100 GeV range.

5600 atmospheric events/yr **relic SN, WIMP annihilation, ...**

>10000's events @ SN explosion@10kpc

Far detectors for long baseline

- **Double phase LAr LEM TPC (GLACIER): best detector for electron appearance measurements with excellent energy resolution and small systematic errors**
  - Exclusive final states, low energy threshold on all particles
  - Excellent ν energy resolution and reconstruction ability from sub GeV to a few GeV, from single prong to high multiplicity
    - ➡ Suitable for spectrum measurement with needed wide energy coverage
  - Excellent π^0/electron discrimination
    - ➡ Wide band On-Axis beam is tolerable
- **Magnetized Muon Detector (MIND): conventional and well-proven detector for muon CC, and NC**
  - muon momentum & charge determination, inclusive total neutrino energy
  - compatible with NF

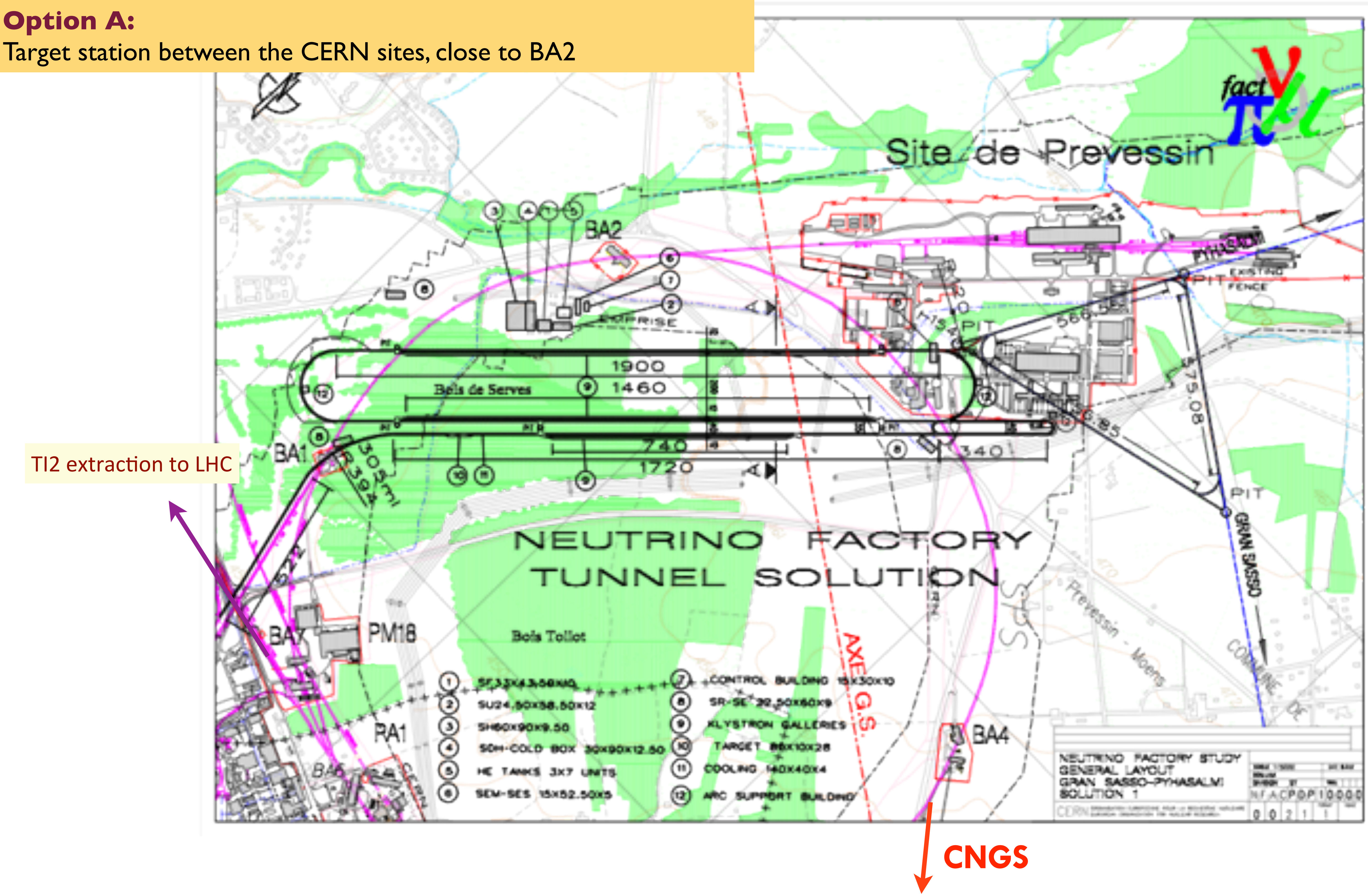
New LBNO neutrino beam

See talk by I Efthymiopoulos

- **CN2PY horn focused neutrino beam towards Pyhäsalmi/FI**
  - Starting point is SPS and CNGS operation (achieved 420kW)
  - Protons extraction, transfer & secondary beam lines
  - Target, horn focusing systems, beam monitors design
  - Decay tunnel ≈300m, 10deg dip angle
  - Low energy optimization; WBB covering 0.5→5 GeV
- **Benefit from improved performance of SPS+injectors; consider further options to upgrade power of SPS (LAGUNA-LBNO WP4)**
- **Upgrade path: HP-PS accelerator (50 GeV) with significant power improvement compared to SPS complex (→ "MW" beam). Exploit synergies with the NF R&D.**

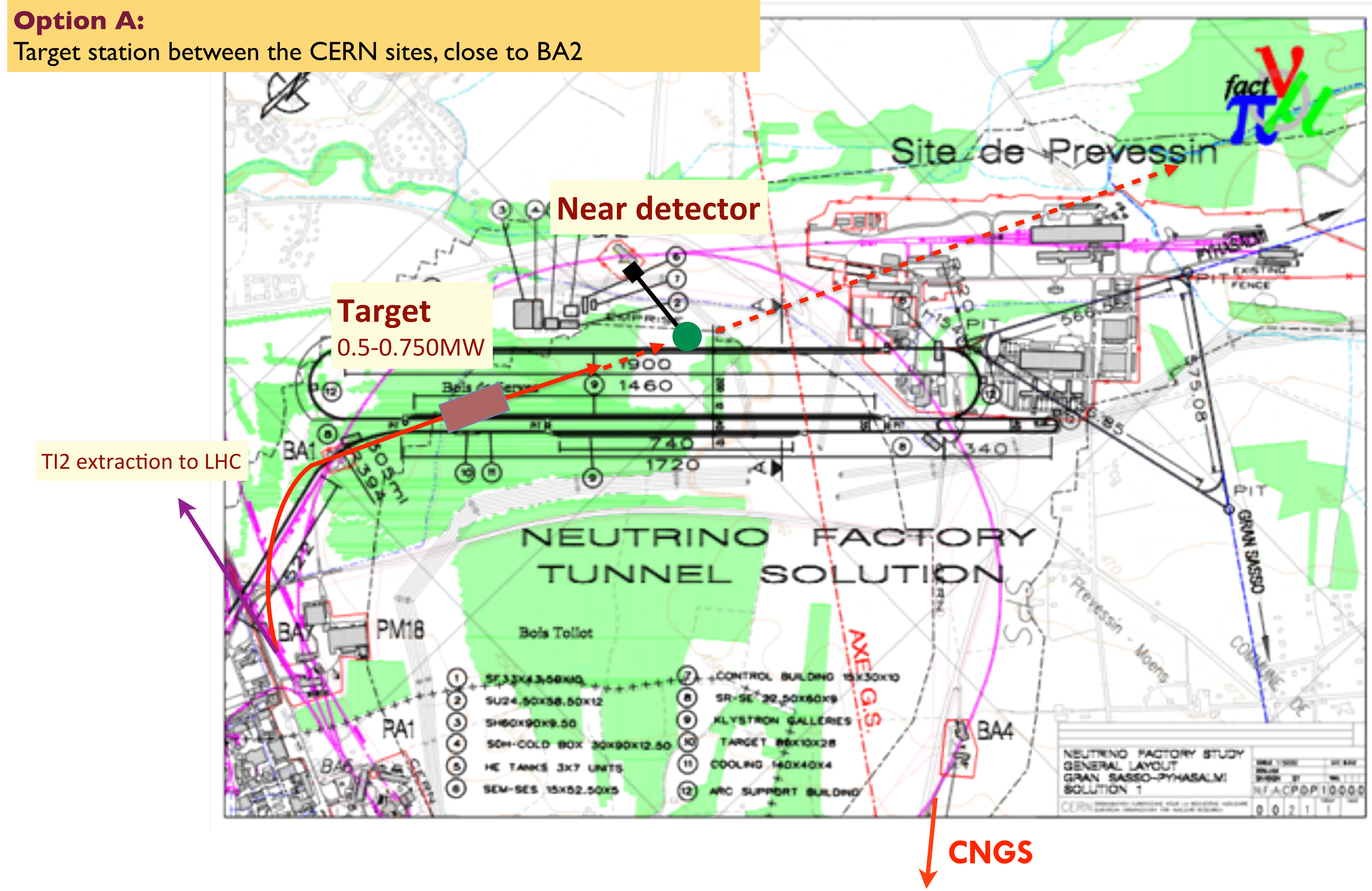
CN2PY layout (option A)

Option A:
Target station between the CERN sites, close to BA2



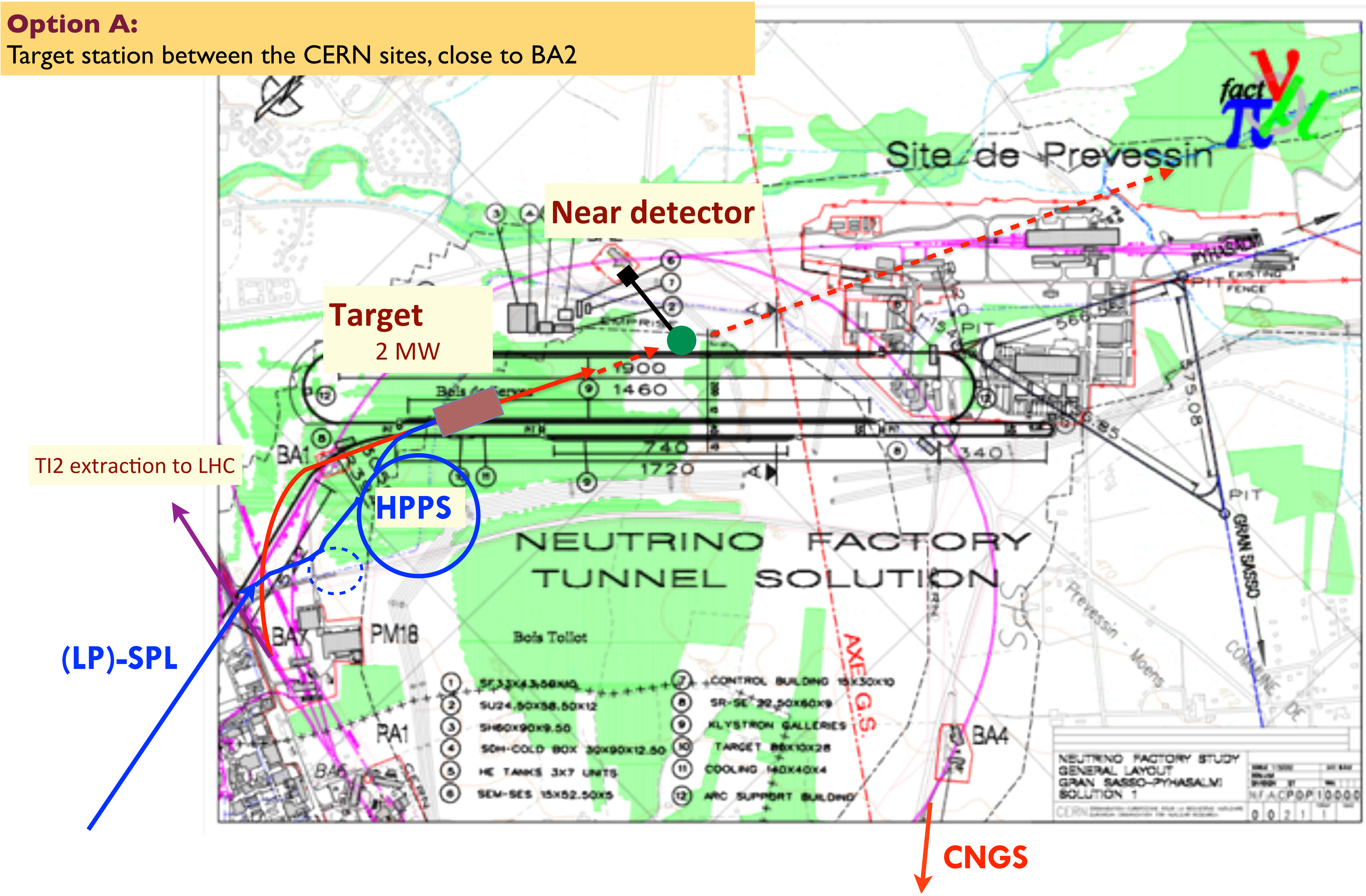
CN2PY layout (option A)

Option A:
Target station between the CERN sites, close to BA2

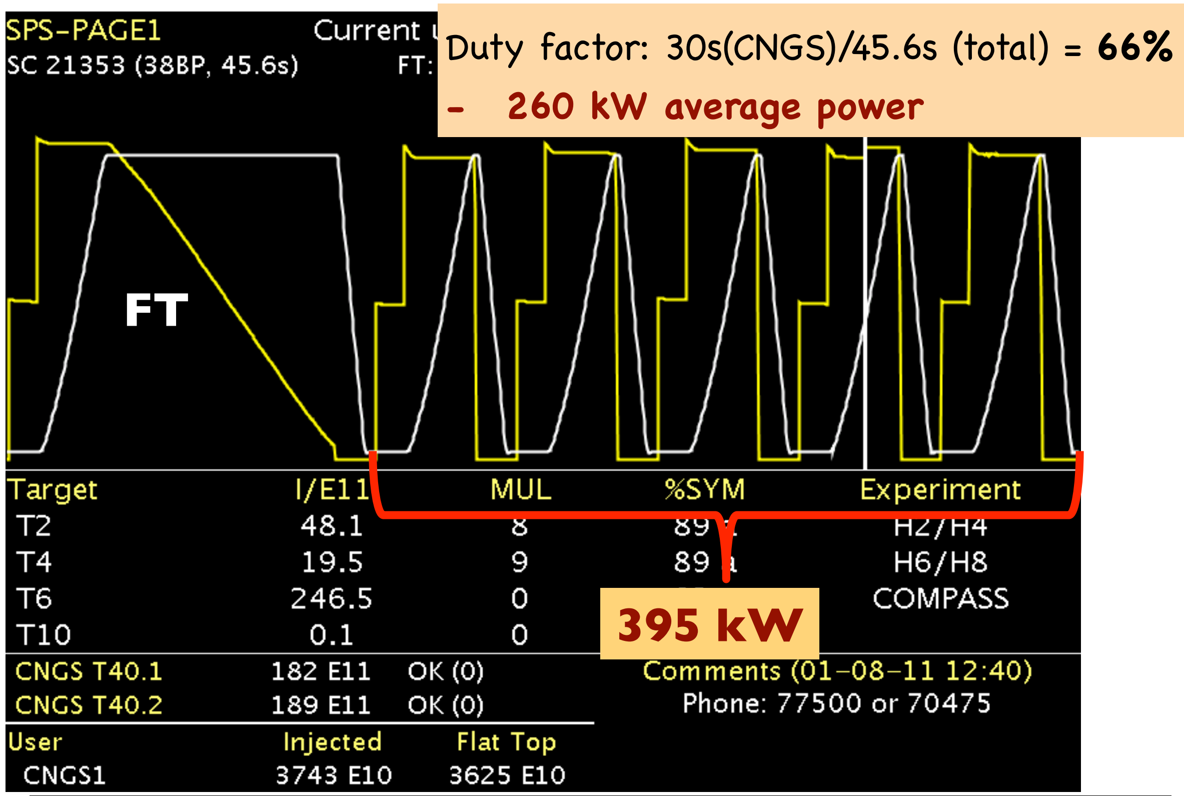


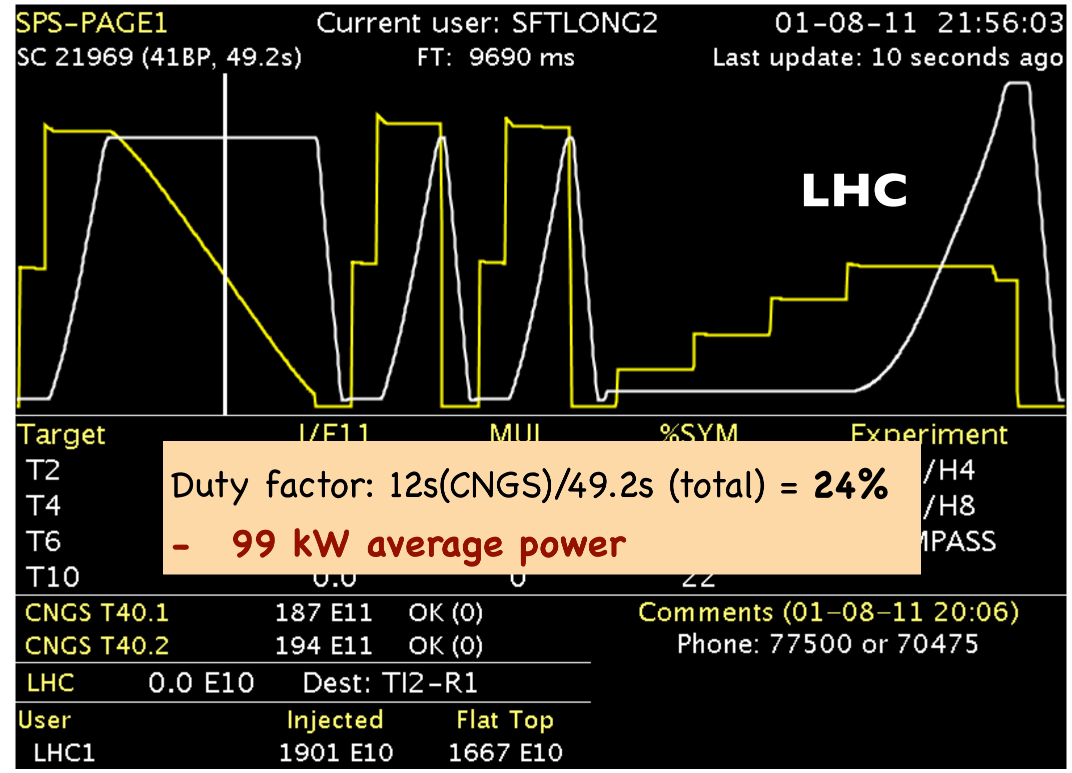
CN2PY layout (option A)

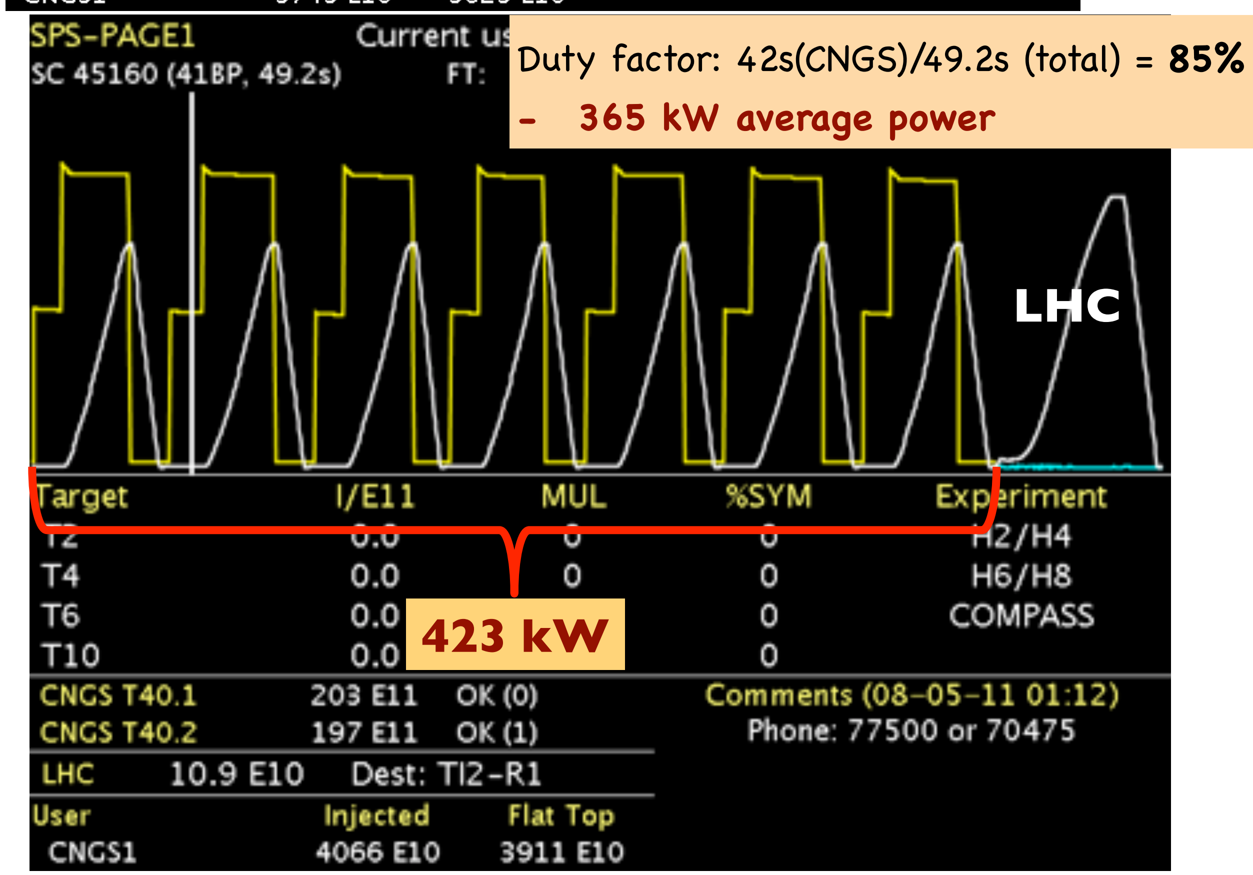
Option A:
Target station between the CERN sites, close to BA2

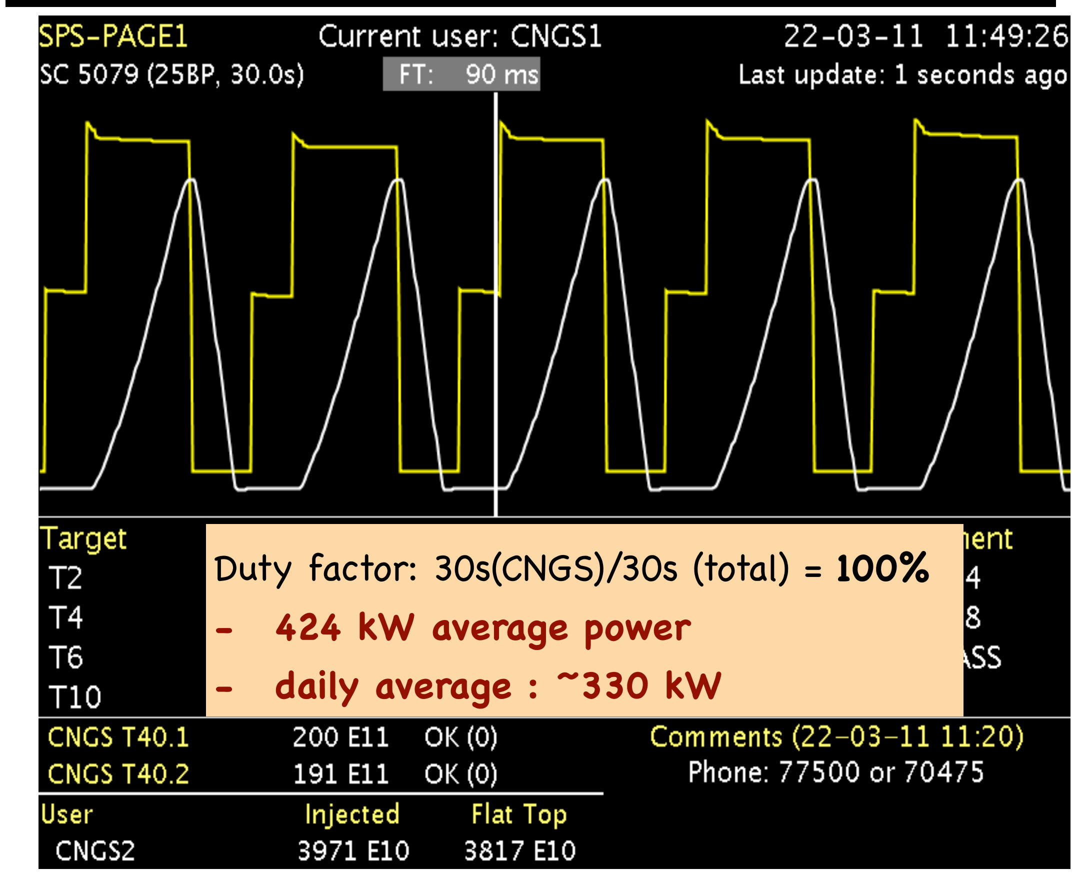


SPS/FT : Operation experience





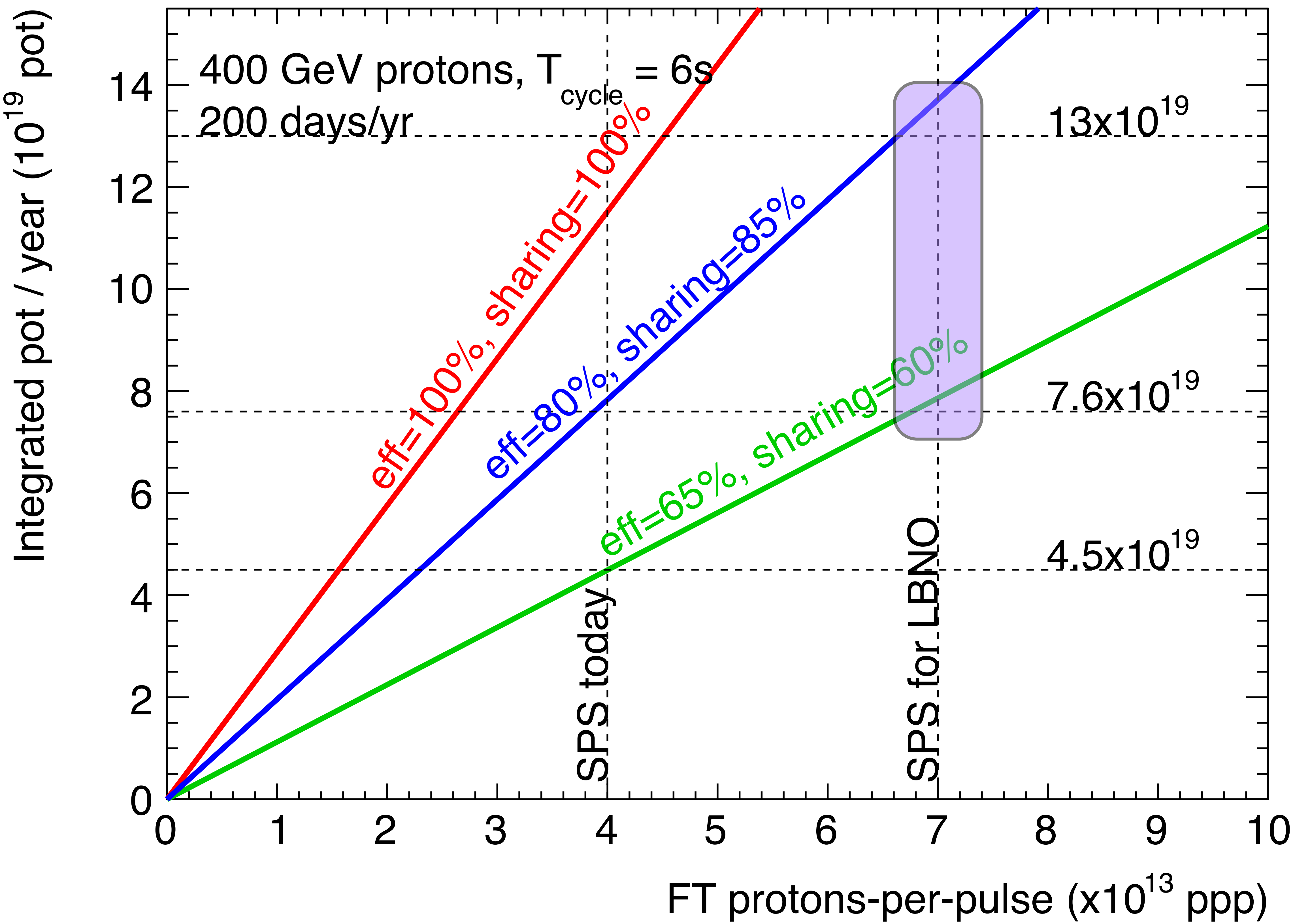




Realistic SPS proton intensity for LBNO

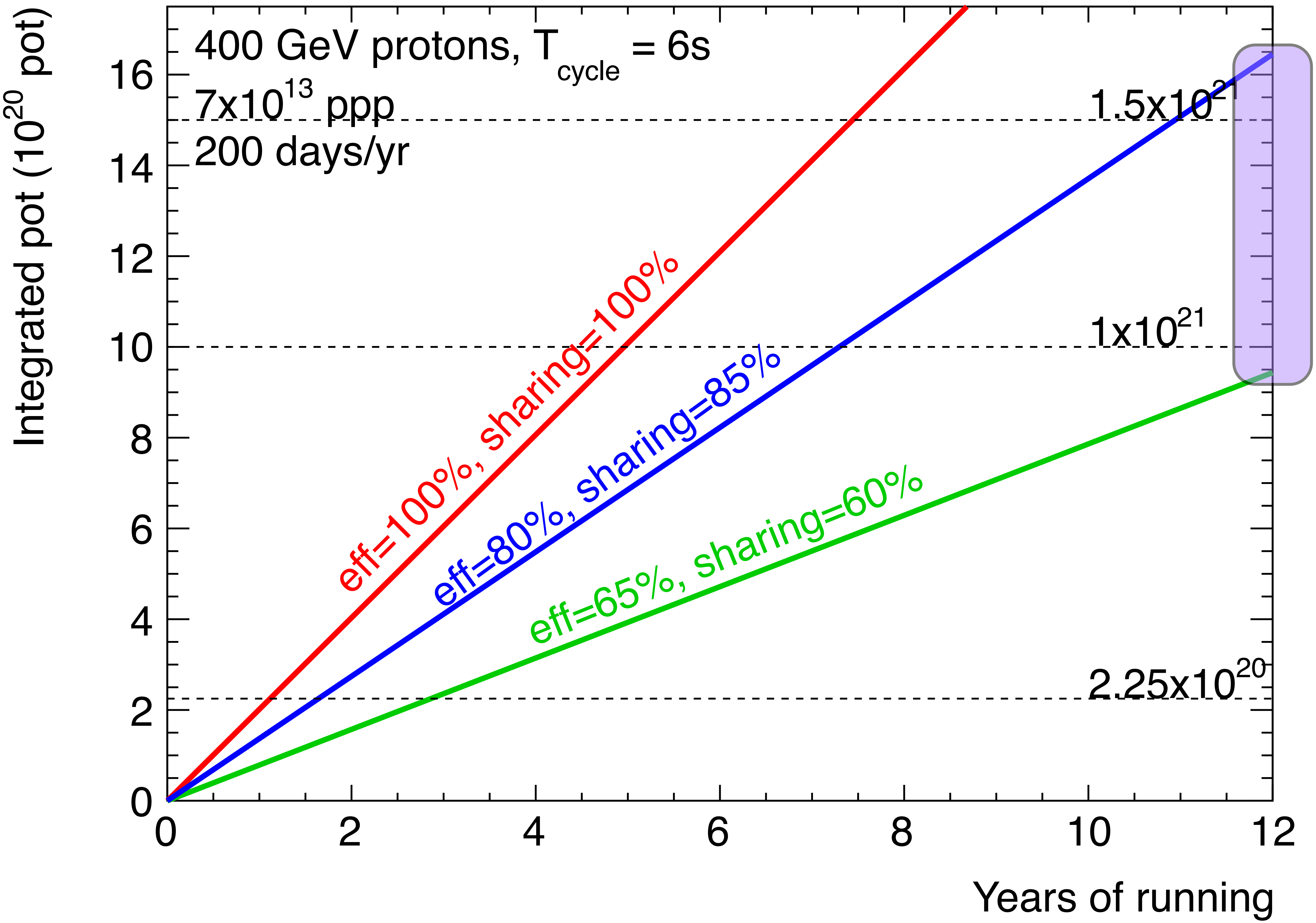
- We consider the CERN SPS 400 GeV as the only realistic accelerator for the initial LBNO phase. Then, we assume:
  - ★ 85% SPS “sharing” by taking 2 hours/day out for LHC filling
  - ★ 80% efficiency for the accelerators
- Today: SPS intensity is 4e13 ppp and factor 61% from SPS sharing (situation of today, likely can change within the timescale of LBNO when NA62 or COMPASS physics is completed).
- **In the context of LBNO (>2018):** the SPS intensity is upgraded (also thanks to LIU project) to 7e13 ppp at 400 GeV with cycle time = 6 seconds.
  - ★ yearly integrated pot = **(0.8–1.3)x 1e20 pot / yr**
  - ★ total integrated (12 years) = **(1–1.5)x 1e21 pot**
  - ★ range corresponds to sharing 60–85%
  - ★ studies ongoing within CERN accelerator team in LAGUNA-LBNO WP4

SPS 400 GeV p.o.t / year



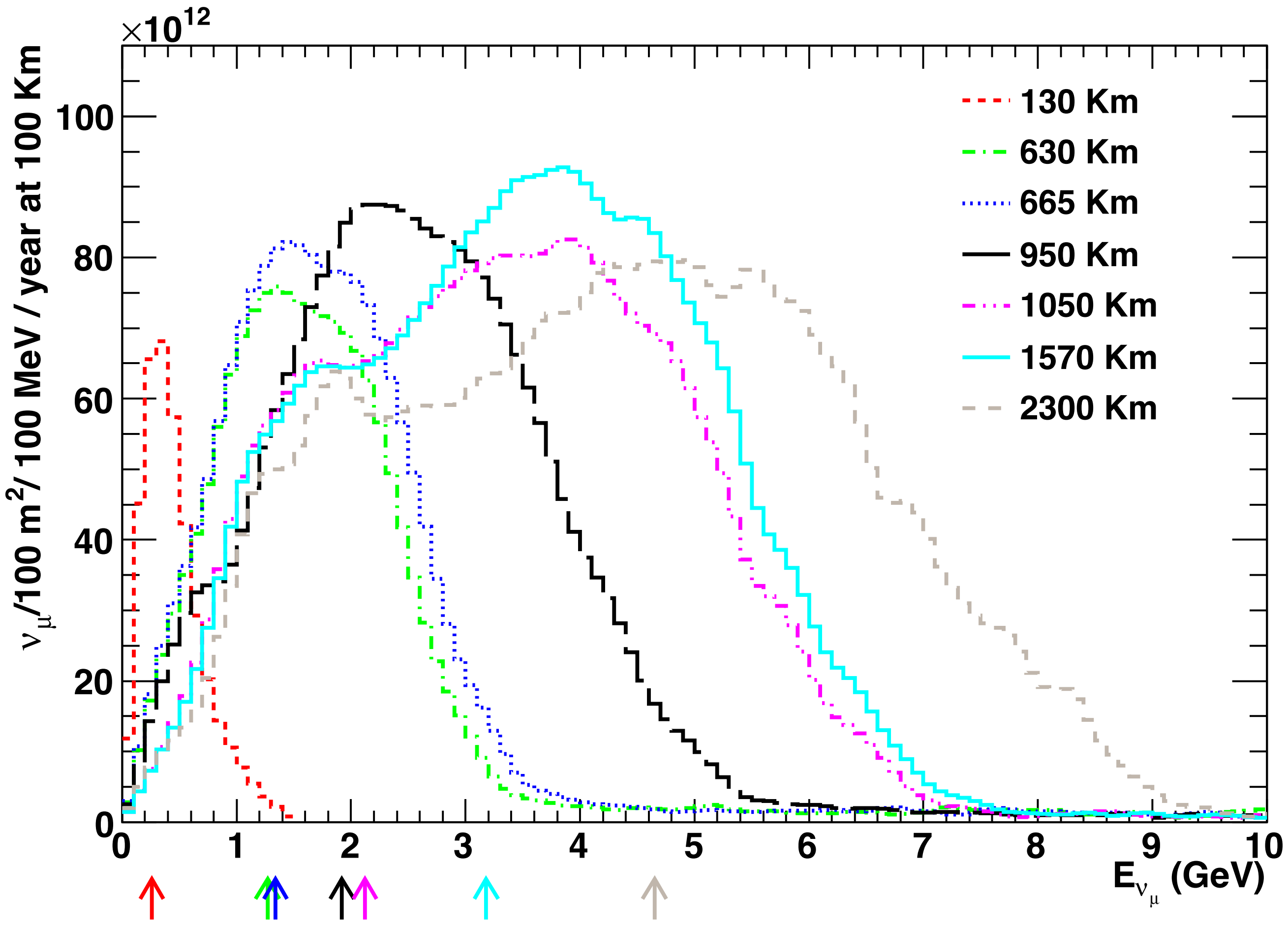
≈300kW

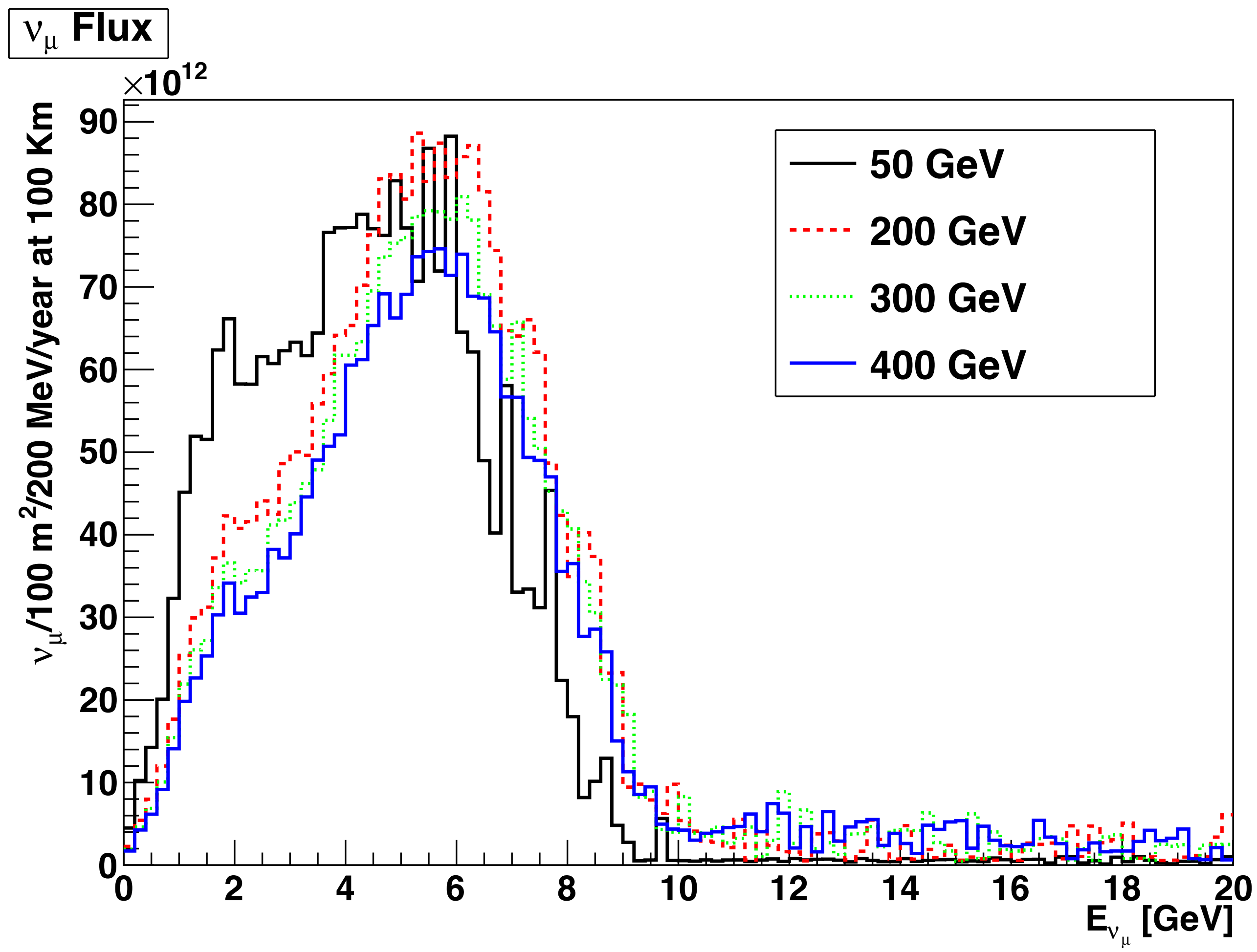
Total integrated p.o.t.



Target, optics optimization

- Preliminary optimization done within LAGUNA DS for various baselines to maximize θ_{13} sensitivity, and assuming 50 GeV protons from HP-PS
- Present activities within LAGUNA-LBNO WP4:
  - Optimization for 50 HP-PS vs 200, 300 and 400 GeV SPS protons
  - Focusing optimization to maximize MH&CPV physics reach.
  - Target optimization.





Expected sensitivity

- We estimate the significance C.L. with a chi2sq method, with which we can

  1)exclude the opposite mass hierarchy and

  2)exclude $\delta_{CP} = 0$ or π (CPV)

- We minimize chi2sq w.r.t to the known 3-flavor oscillations and the nuisance parameters using Gaussian constraints:

$$\begin{cases} \Delta m^{2,0}_{32} = (2.40 \pm 0.09) \times 10^{-3}\,\mathrm{eV}^2 \\ \sin^2 2\theta^0_{23} = 0.51 \pm 0.06 \\ \sin^2 2\theta^0_{13} = 0.10 \pm 0.02 \end{cases}$$

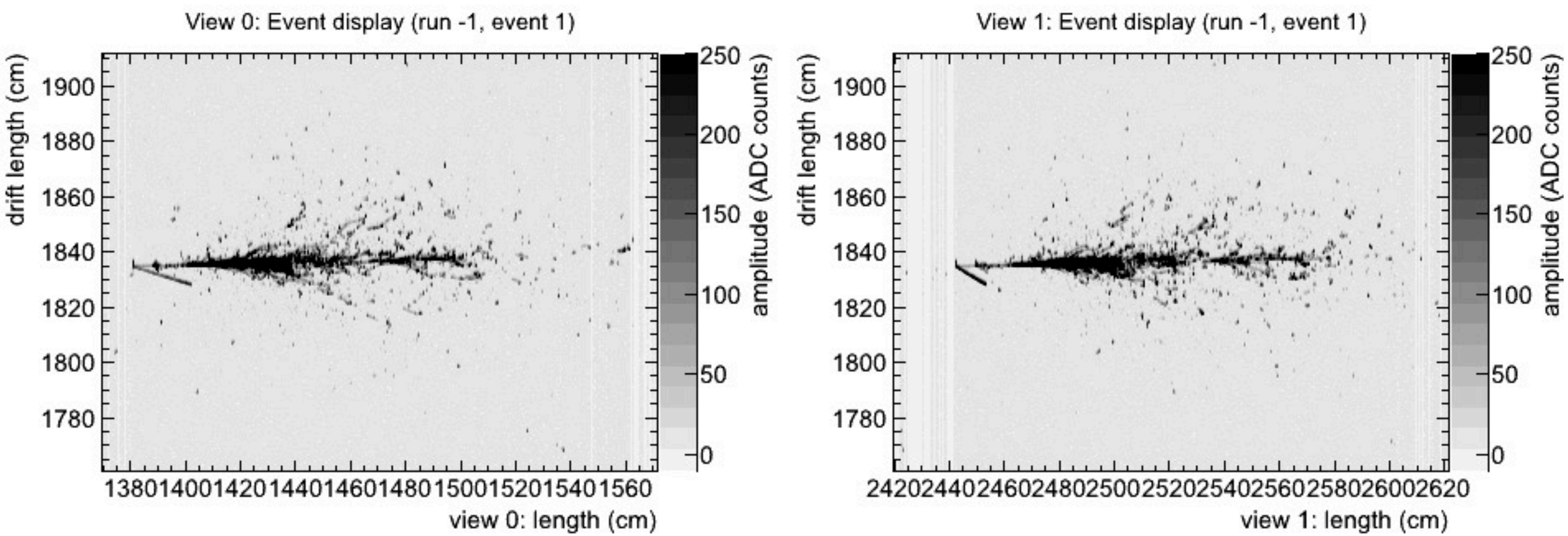
±1σ present errors

✦ solar terms fixed
✦ include systematic errors (see later)

LAr detector performance

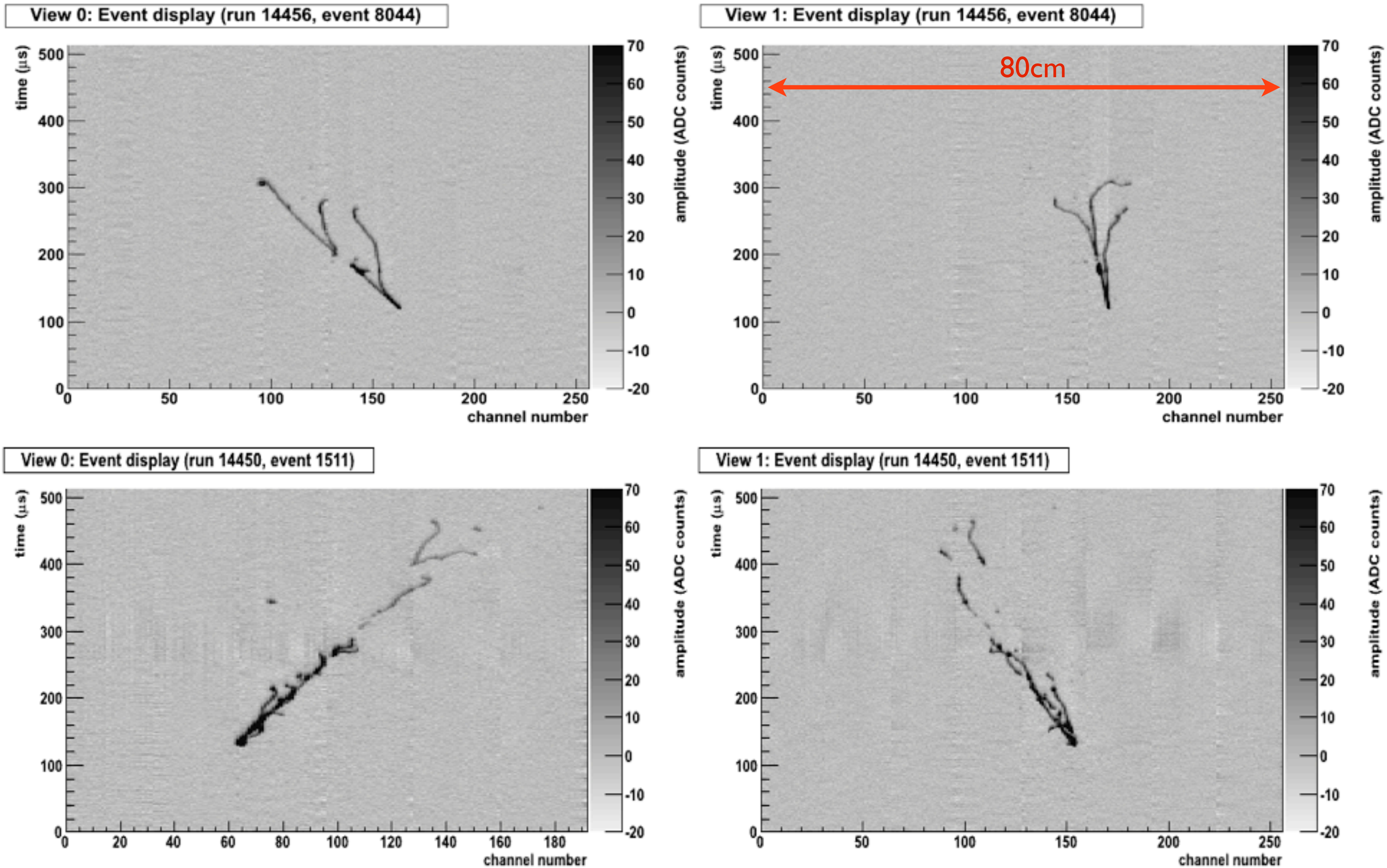
- Based on simulated exclusive final state events (*Qscan* revival part of LAGUNA-LBNO WP5 task).
- Fast simulation through detector geometry.
- Do not simply rely on “Gaussian” parametrizations

Realistic digitization (based on measured LAr LEM TPC performance):



Real cosmic rays in LAr LEM-TPC

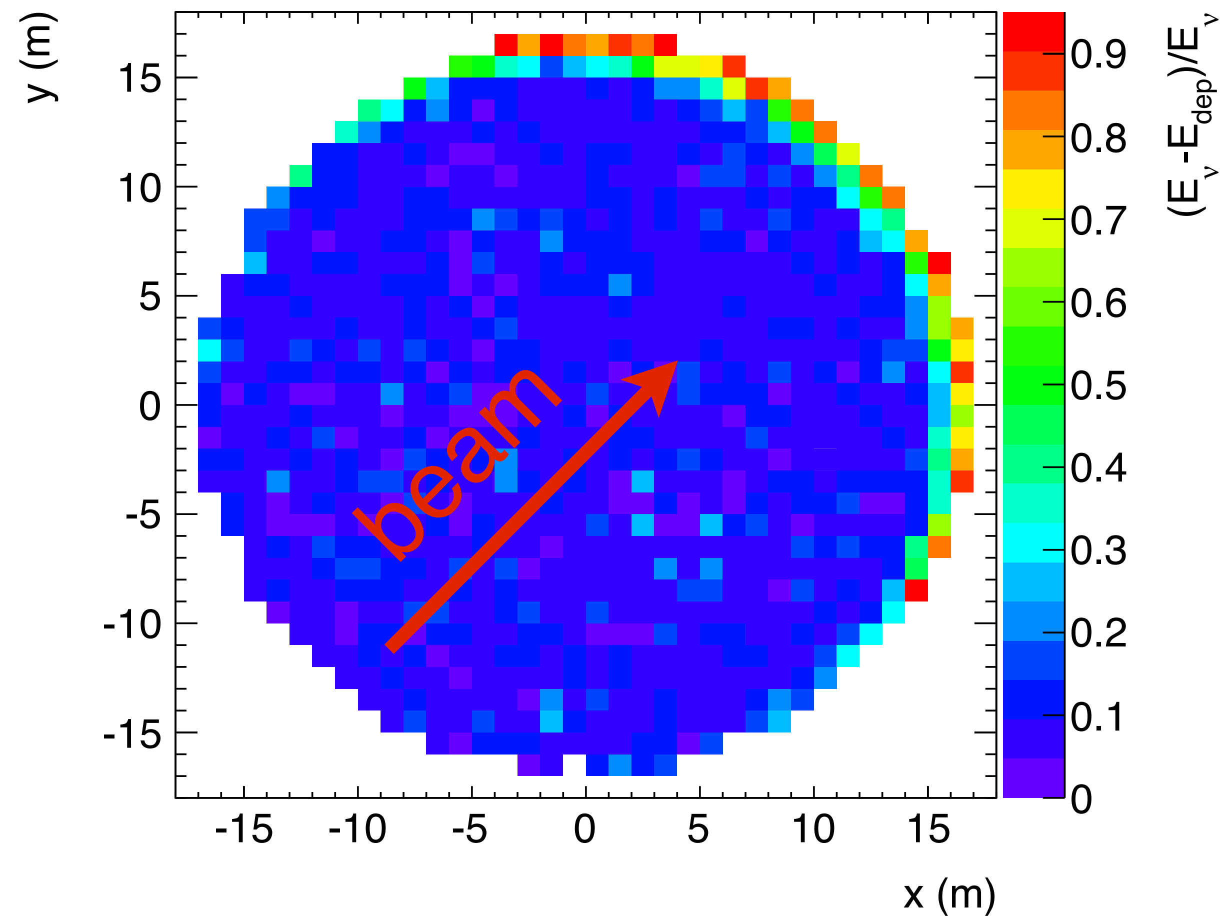
Cosmic track in double phase 80x40cm2 LAr-LEM TPC with adjustable gain : S/N > 100 for m.i.p !!

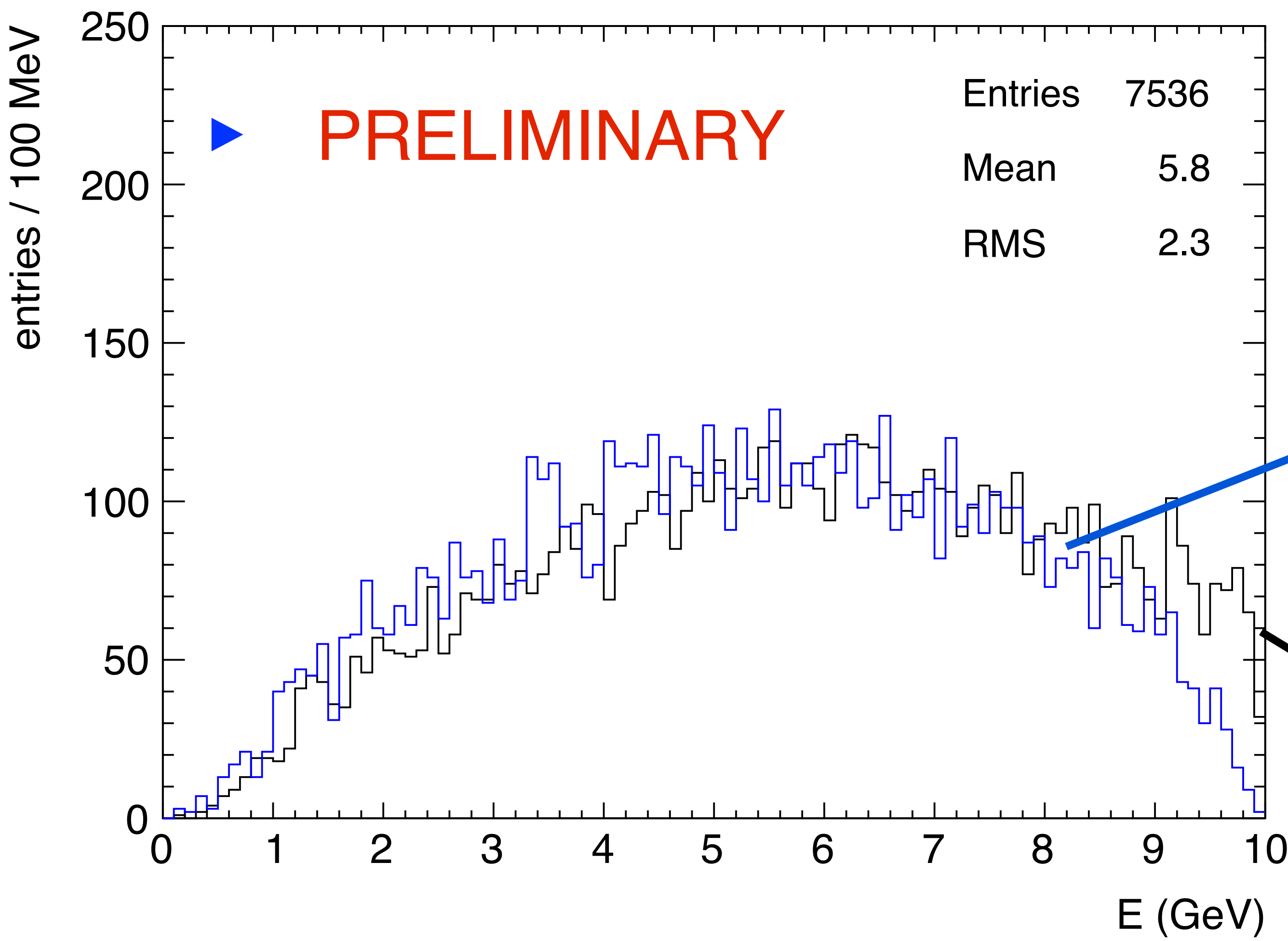


Neutrino energy reconstruction

- nue CC events generated with GENIE and CN2PY fluxes
- GEANT4
- CCNuE resolution: **8.7% RMS** for vertex in center of detector
- Preliminary result**:** **(Edep-Ereco)/Edep = 0.7%**

top view of detector



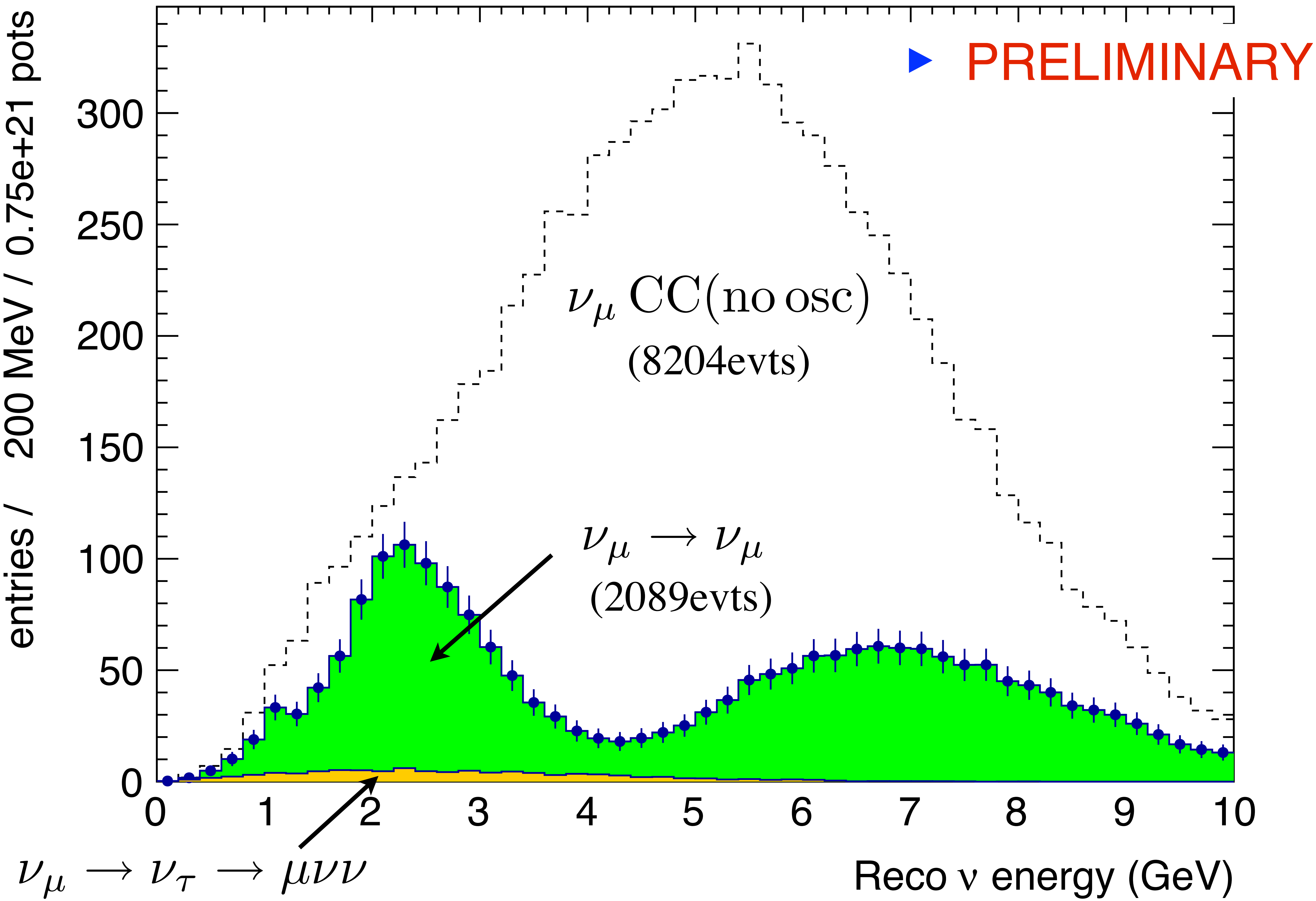


deposited energy in fiducial volume

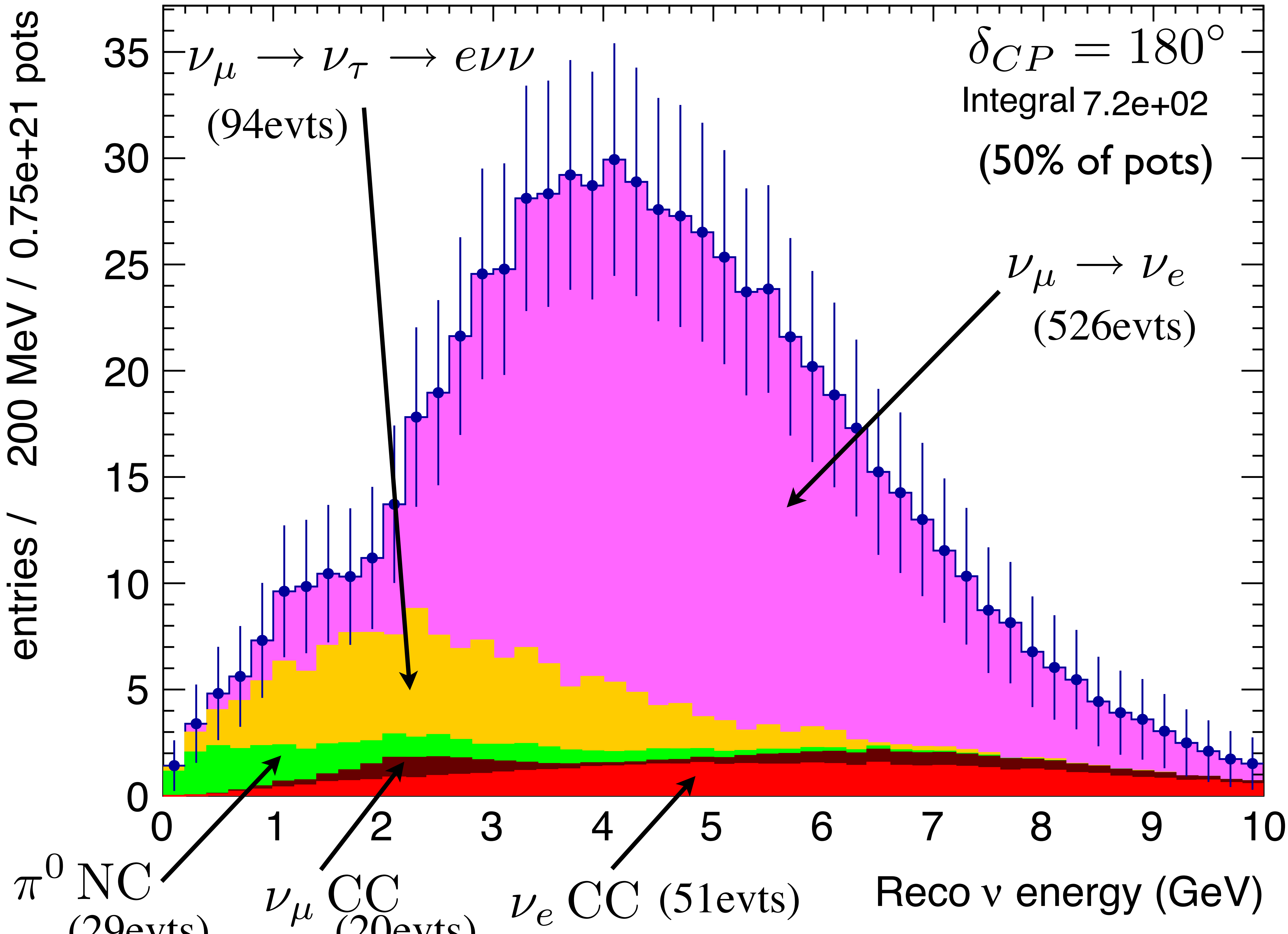
neutrino energy

2012

μ-like sample



e-like sample



Analysis method (=myfitter)

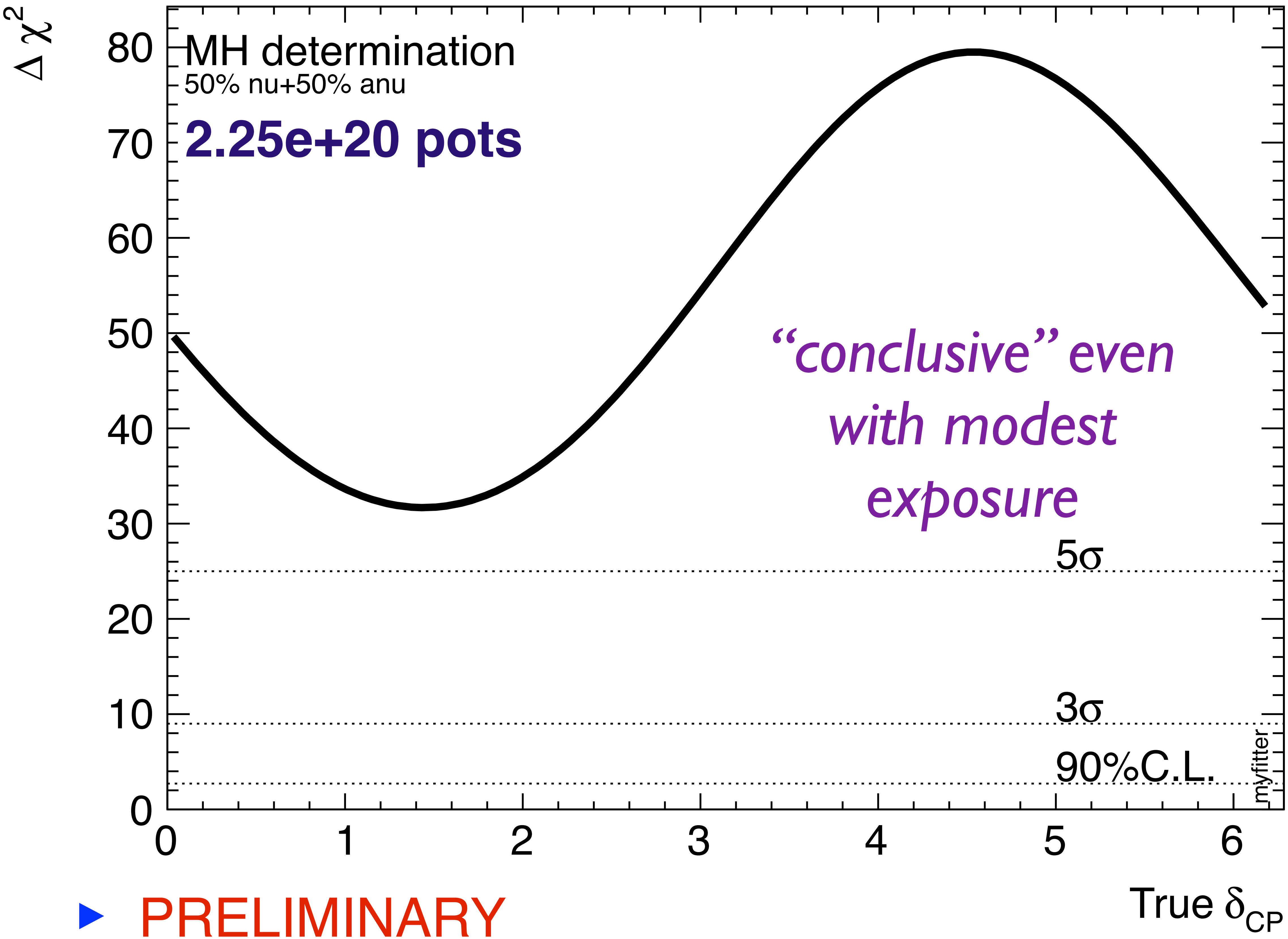
- Based on simulated exclusive final state events. Fast simulation through detector geometry.
- Binned chi2sq method:

$$\chi^2 = \sum_{+,-}\sum_i \Big[N^i - \Big\{1 \pm \frac{1}{2} f_{\nu/\bar{\nu}}\Big\} \cdot \Big((1+f_{\rm sig})\cdot n^i_{\rm sig} + (1+f_{NC})\cdot n^i_{NC} + (1+f_{\nu_e CC})\cdot n^i_{\nu_e CC}$$

$$+(1+f_{\nu_\tau CC})\cdot n^i_{\nu_\tau CC}\Big)\Big]^2 / N^i + \frac{f^2_{\rm sig}}{\sigma^2_{\rm sig}} + \frac{f^2_{NC}}{\sigma^2_{NC}} + \frac{f^2_{\nu_e CC}}{\sigma^2_{\nu_e CC}} + \frac{f^2_{\nu_\tau CC}}{\sigma^2_{\nu_\tau CC}} + \frac{f^2_{+/-}}{\sigma^2_{+/-}},$$

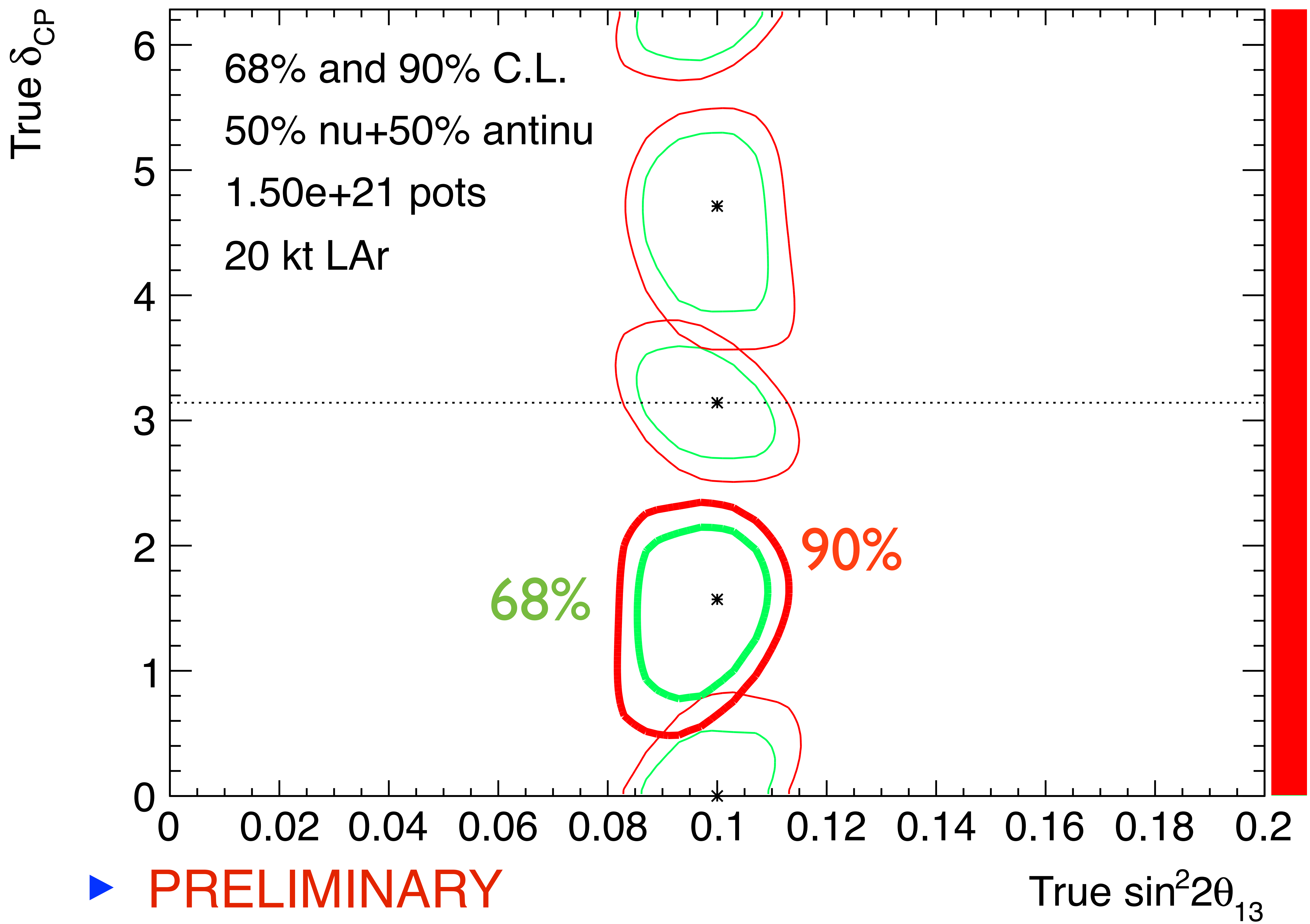
- +, – = beam (horn) polarity → at present assume 50%-50% sharing between + and – runs
- Ni = simulated number of expected events in energy bin i
- n_{xi} = number of expected events from source "x" in energy bin i
- f_x = systematic error for "x" → at present assume 5% systematic errors for each source

MH determination



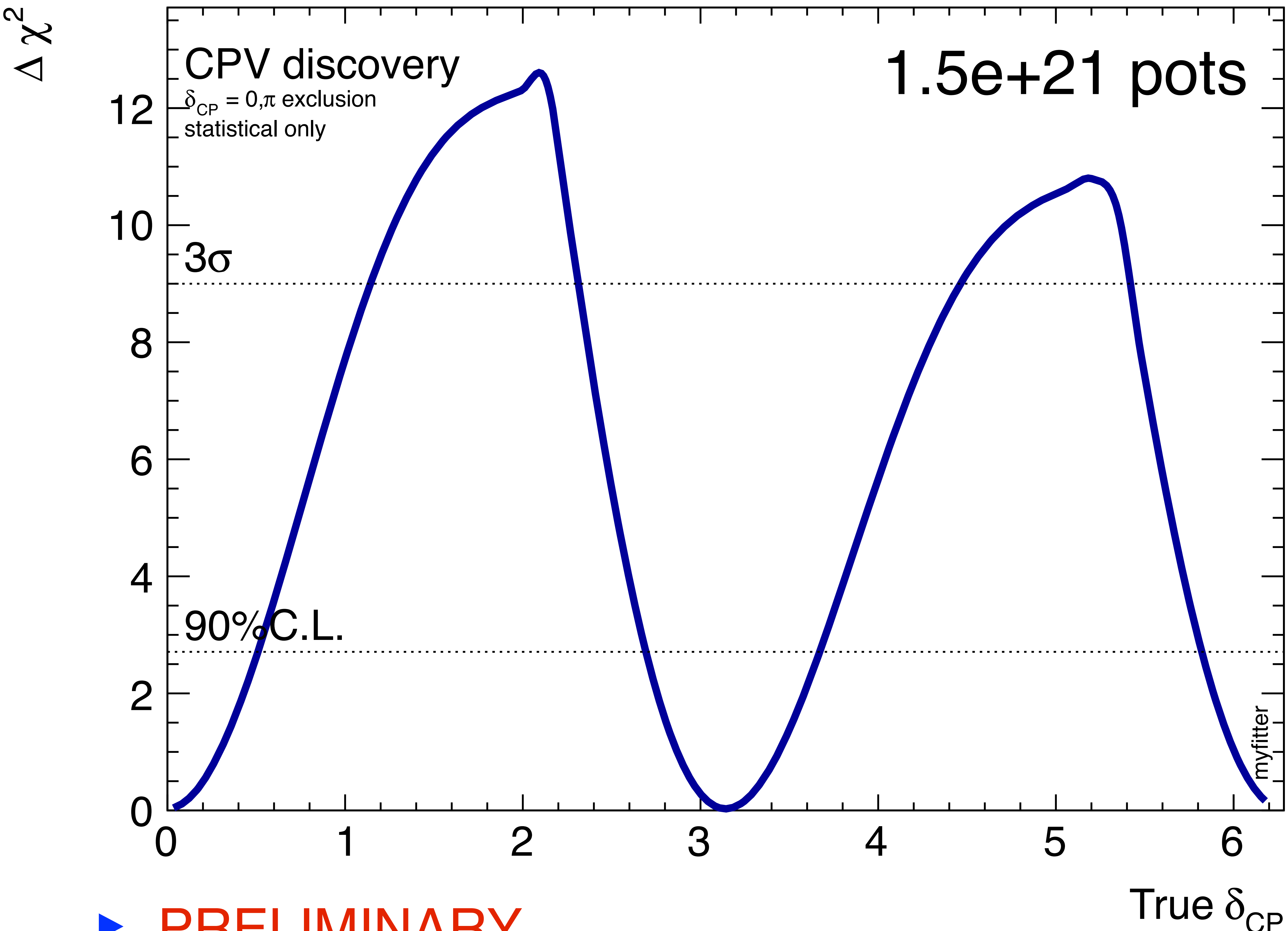
- PRELIMINARY

CP-phase determination



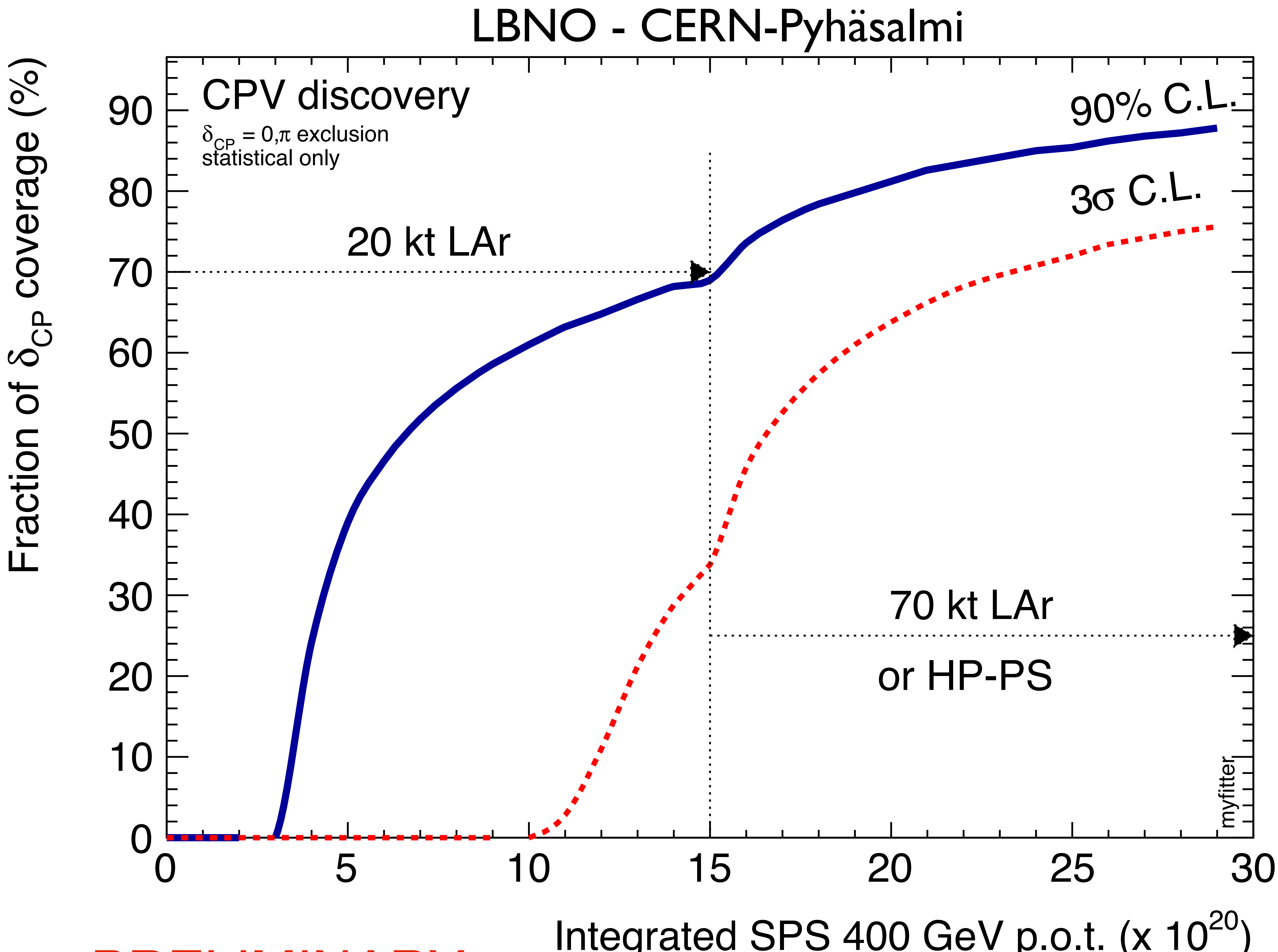
- PRELIMINARY

CPV discovery



- PRELIMINARY

CPV discovery as function of p.o.t.



- PRELIMINARY

Milestones - Timescale

LAGUNA Design Study funded for site studies:	**2008-2011**
Categorize the sites and down-select:	**Sept. 2010**
LAGUNA-LBNO: detector design, costing and LBL beam options	**2011-2014**
Submission of LBNO EoI to CERN	**2012**
Critical decision	**2015 ?**
Excavation-construction (incremental):	**2016-2021 ?**
Phase 1 LBL physics start:	**2023 ?**
Phase 2 incremental step implementation:	**>2025 ?**

Conclusions

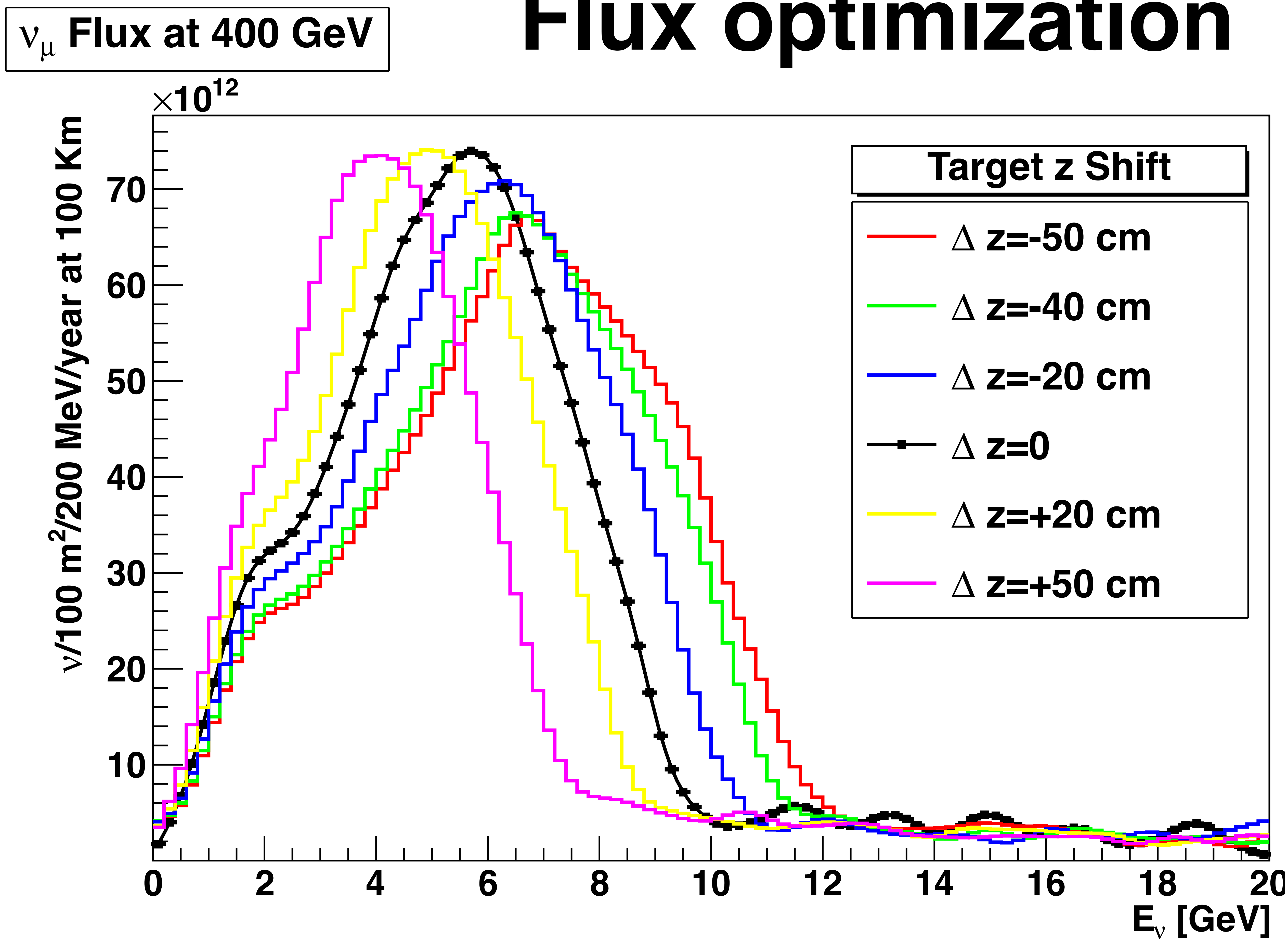
- **LBNO, to be located underground at Pyhäsalmi 2300km away from CERN, has truly unique scientific opportunities**:
  - ➡ conclusive mass hierarchy determination, in a cleaner and more significant way than any other methods/proposals
  - ➡ very good chance to find CPV with the spectral information providing unambiguous oscillation parameters sensitivity. With 10 years at 700kW SPS and 20 kton LAr +MIND (=initial phase), the reach is 30%(70%) CPV coverage at 3σ(90%) C.L. This step will inform future investigations (e.g. systematics).
  - ➡ >x10 better sensitivity in several nucleon decay channels
  - ➡ detection of several astrophysical sources and fresh new look at atmospheric neutrinos with high granularity and resolution.
- **LBNO defines a clear upgrade path** (long term vision / incremental approach) to fully explore CPV. E.g., a three-fold exposure yields 75% CPV coverage at 3σ C.L. !! Comparable to T2HK and better than "other" proposals with conventional beams. Baseline adopted by NF community and LBNO has magnetized detector in initial phase.
- We are submitting an expression of interest to CERN SPSC. The proposal offers an attractive and effective approach to move neutrino physics forward (in Europe and in a global context) and has a long term vision. **EoI already largely endorsed by the community and open to anyone willing to contribute !**

Acknowledgements

- FP7 Research Infrastructure “Design Studies” LAGUNA (Grant Agreement No. 212343 FP7-INFRA-2007-1) and LAGUNA-LBNO (Grant Agreement No. 284518 FP7-INFRA-2011-1)

Backup slides

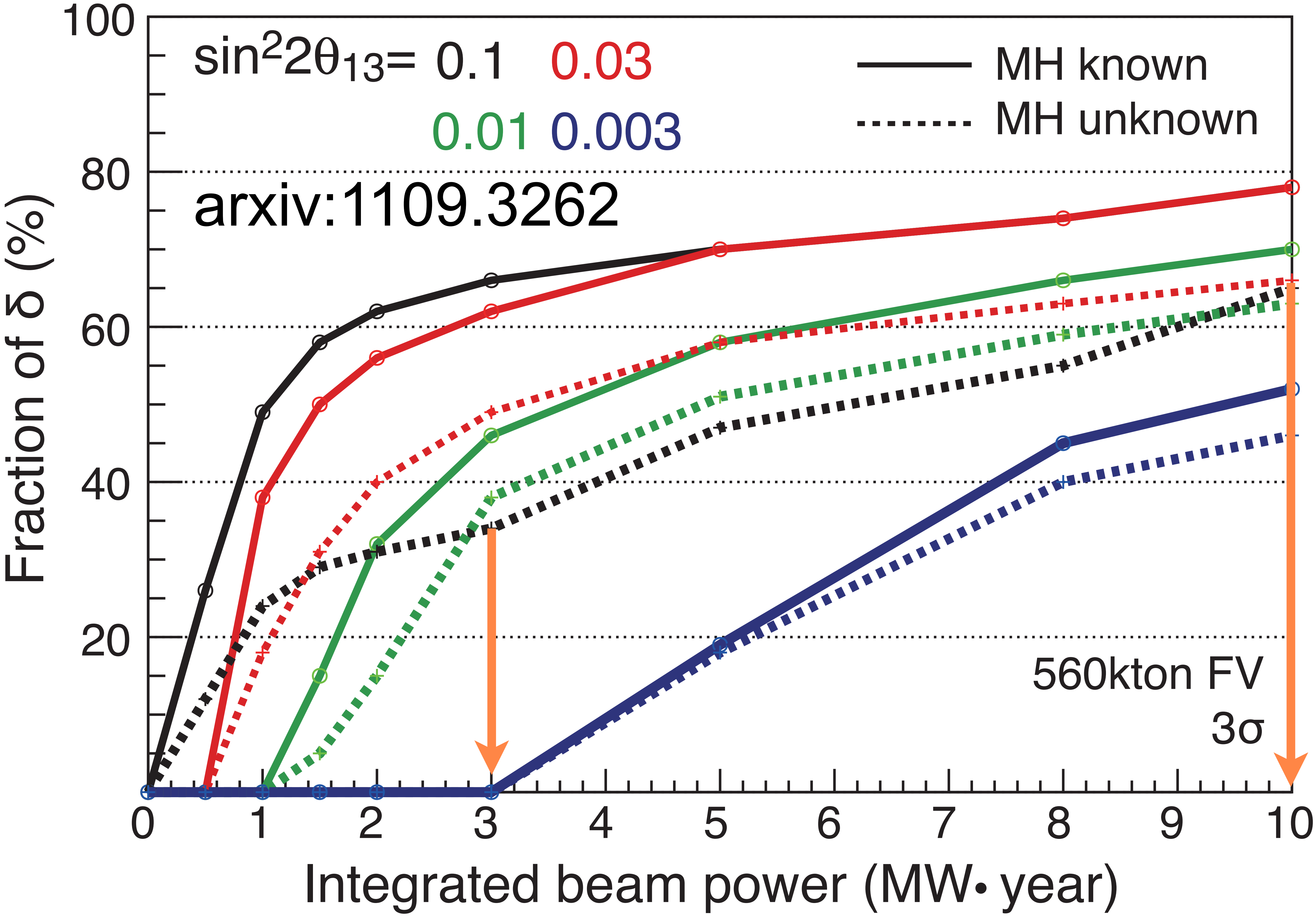
Flux optimization



Why the neutrino mass hierarchy ?

- **CP-violation:** necessary input to solve CPV problem. For example, for the HyperK LOI arxiv:1109.3262 (which considers a 540kton FV and hence has the highest statistical power):
  - 3 MW×years (note: >10 years at present JPARC MR power) MH known: 65% coverage → MH unknown: 35% coverage
  - 10 MW×years needed to reach 65% coverage if MH unknown! rather unlikely within present JPARC projections.
- **$0\nu\beta\beta$ searches:** necessary input to interpret both negative and positive isotope lifetime results, in terms of neutrinos (as opposed to some other source of lepton number violation).
- **BSM/GUT theories:** important ingredient for model building. An inverted hierarchy would have interesting implications.
- **We need a definitive & conclusive determination of the MH !**

HyperKamiokande CPV



Matter effects density effect