NEUTRINO TOWN

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

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European Strategy for Neutrino Oscillation Physics - II

May 15th, 2012

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Eidgenössische Technische Hochschule Zürich
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LBNO physics goals

- We cannot be satisfied with just setting limits. *See e.g. talk by J. Thomas*
- 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 (MH), measure δ_{CP} and determine the existence of CP-violation in the lepton sector (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**

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:

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

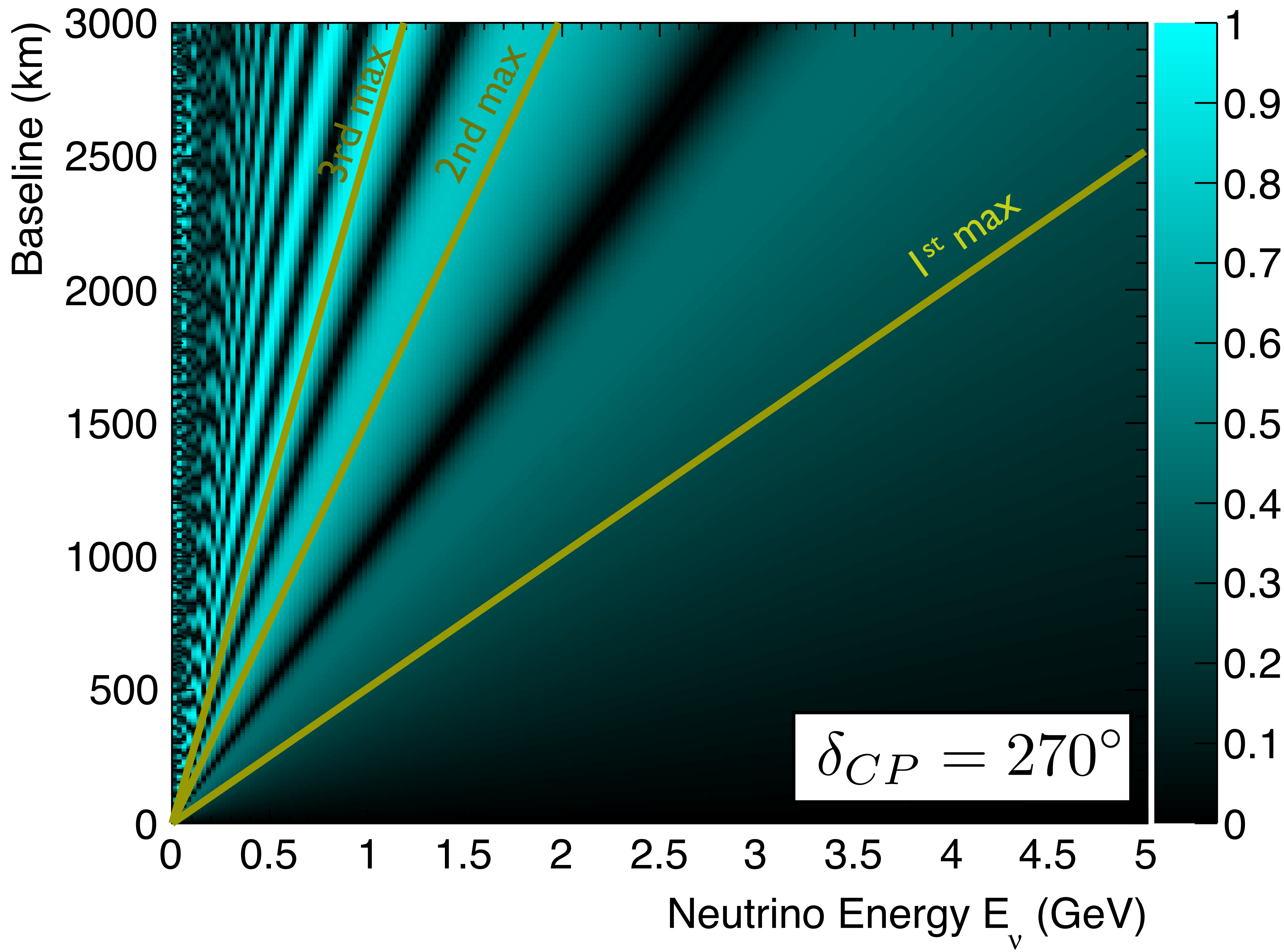
- CP asymmetries are largest at the 2nd, 3rd, ... maxima.
- Matter asymmetry dominates around the 1st maximum.
- Long(er) baselines, wide-band beams to cover several maxima are needed to resolve degeneracies.
- Experimentally: $E_\nu^{2nd\,max} \gtrsim 0.5\,\mathrm{GeV} \Longrightarrow \mathrm{L} \gtrsim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

CP-violation determination (CPV)

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

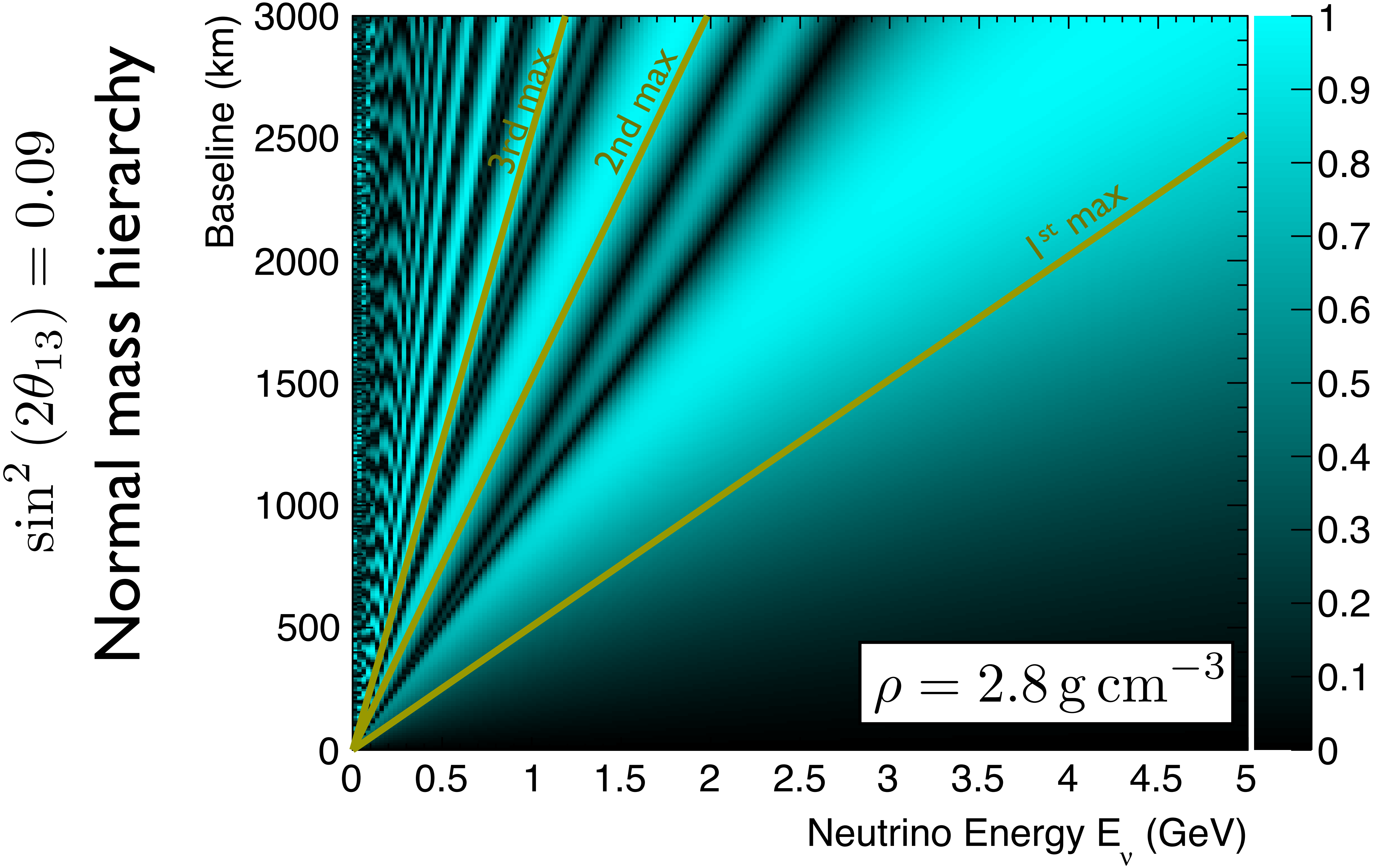
$\sin^2(2\theta_{13}) = 0.09$

Normal mass hierarchy



Mass hierarchy determination (MH)

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



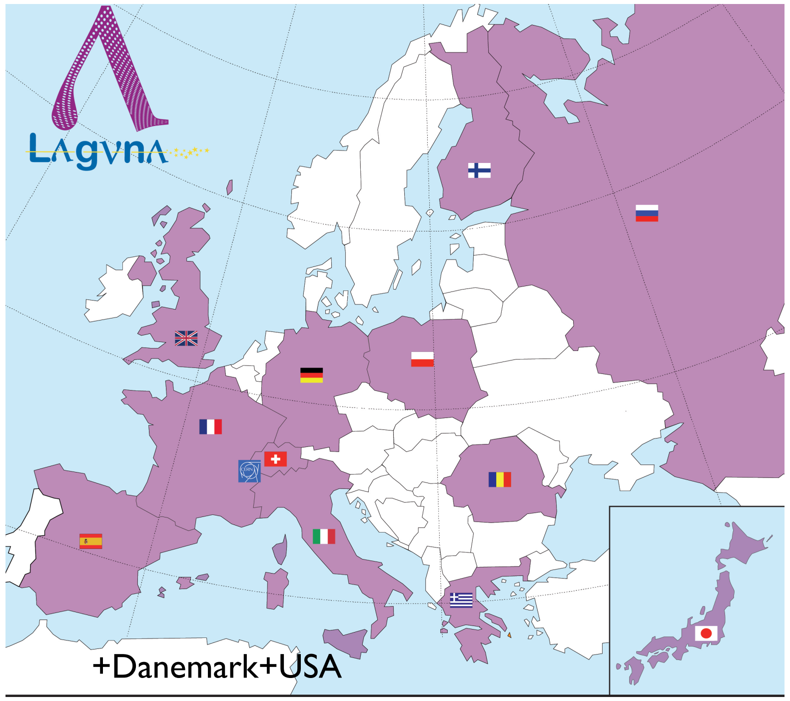
Large
Apparatus for
Grand
Unification and
Neutrino
Astrophysics
-
Long
Baseline
Neutrino
Oscillations

- 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
- Present prioritization of sites: (1) Pyhäsalmi (2) Fréjus (3) others
- Funded by the EC FP7 framework programme since 2008 (present grant until 2014)

See talk by W Trzaska

LAGUNA-LBNO consortium

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



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ETH Zürich (*coordinator*)
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Japan
KEK

USA
Virginia Tech

(=industrial partners)*

Pyhäsalmi site location

- CUPP : Centre for Underground Physics in Pyhäsalmi (www.cupp.fi)
- Location: 63^o 39’ 31’’N – 26^o 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

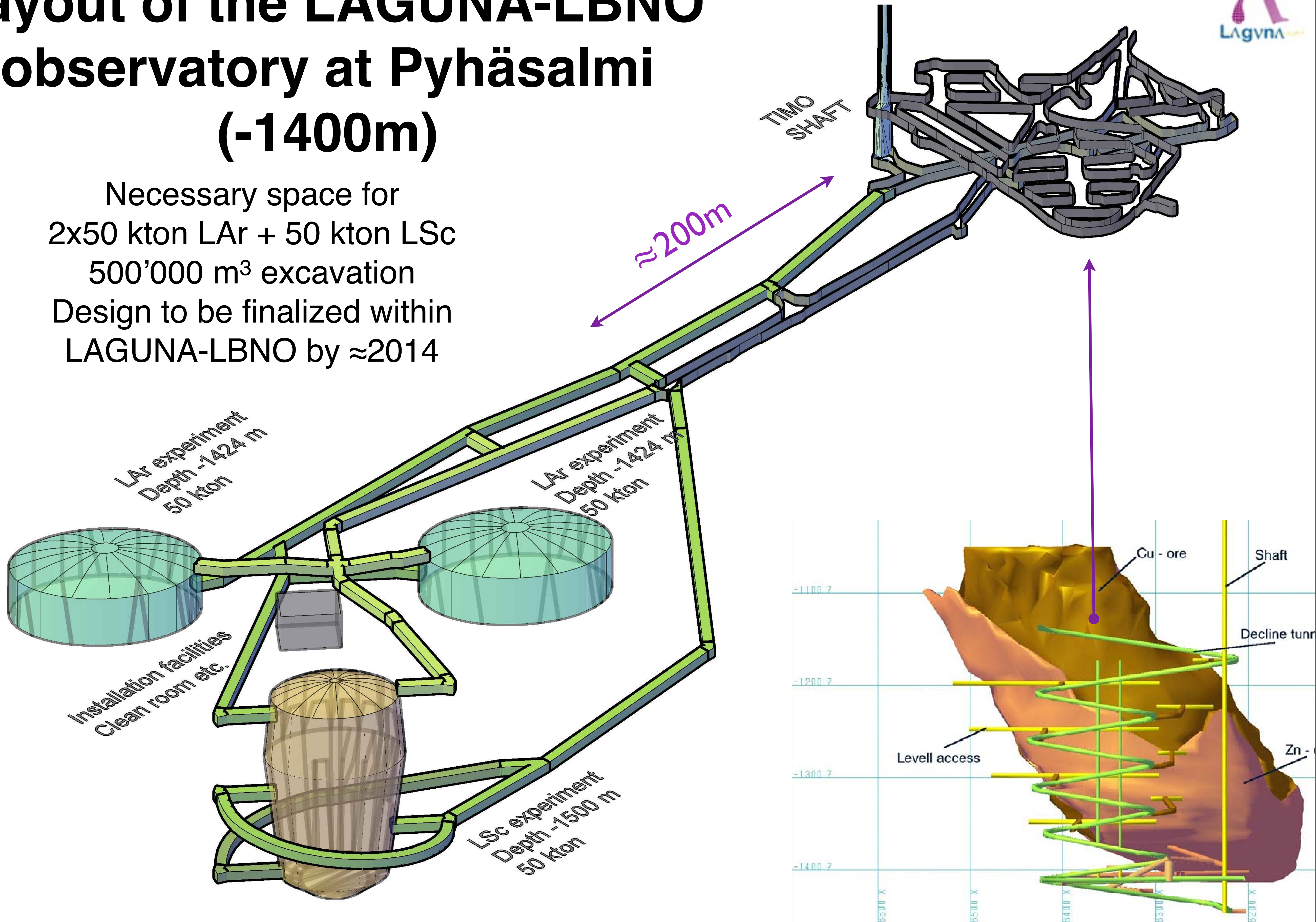
Being extensively investigated in LAGUNA DS since 2008

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.**
- **Extensive site investigation with rock drilling and detailed analysis planned during the period 2012-2014 (Finnish contribution).**

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

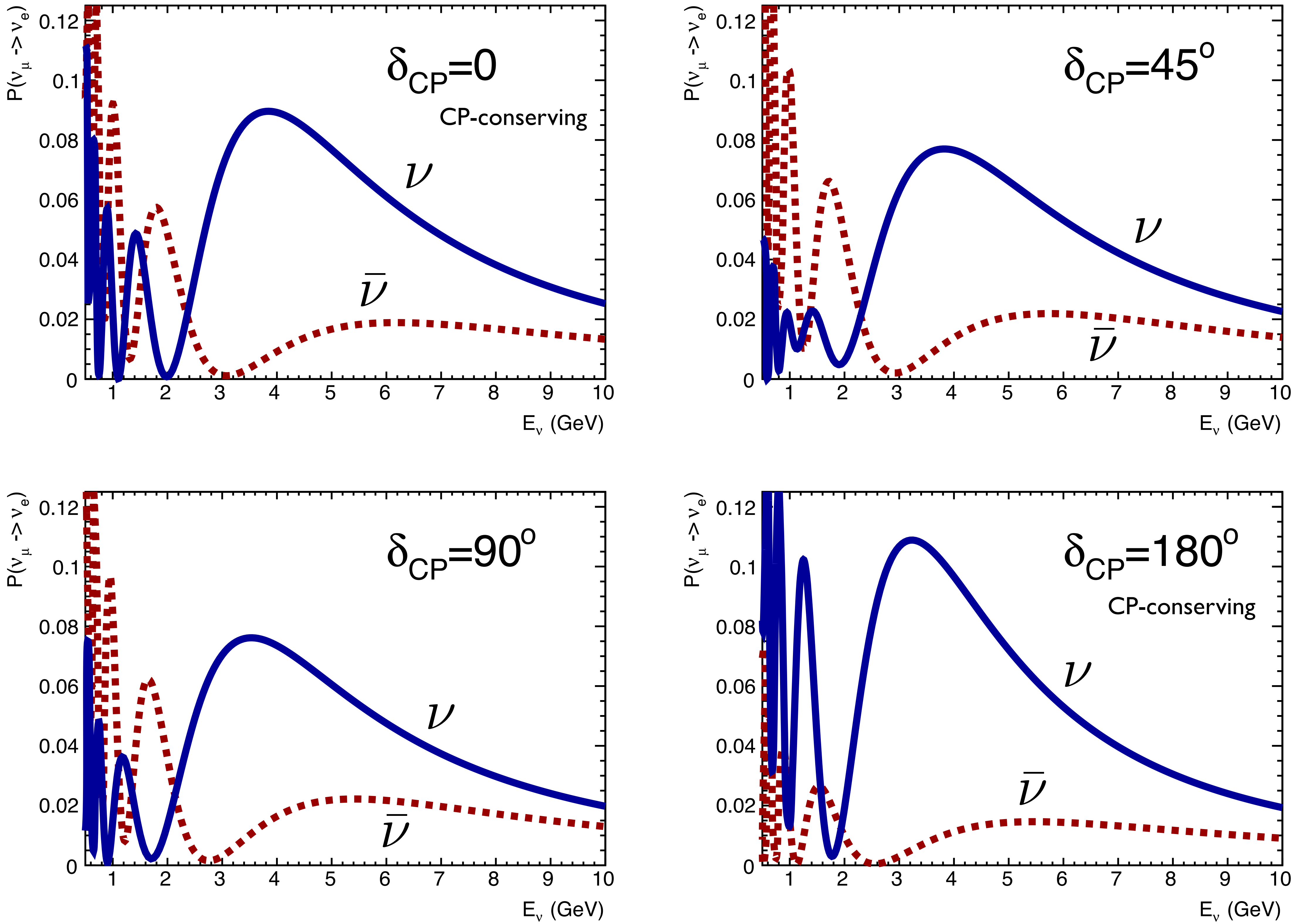
Necessary space for
2x50 kton LAr + 50 kton LSc
500'000 m^3 excavation
Design to be finalized within
LAGUNA-LBNO by ≈2014



CERN-Pyhäsalmi: spectral information $\nu_\mu \rightarrow \nu_e$

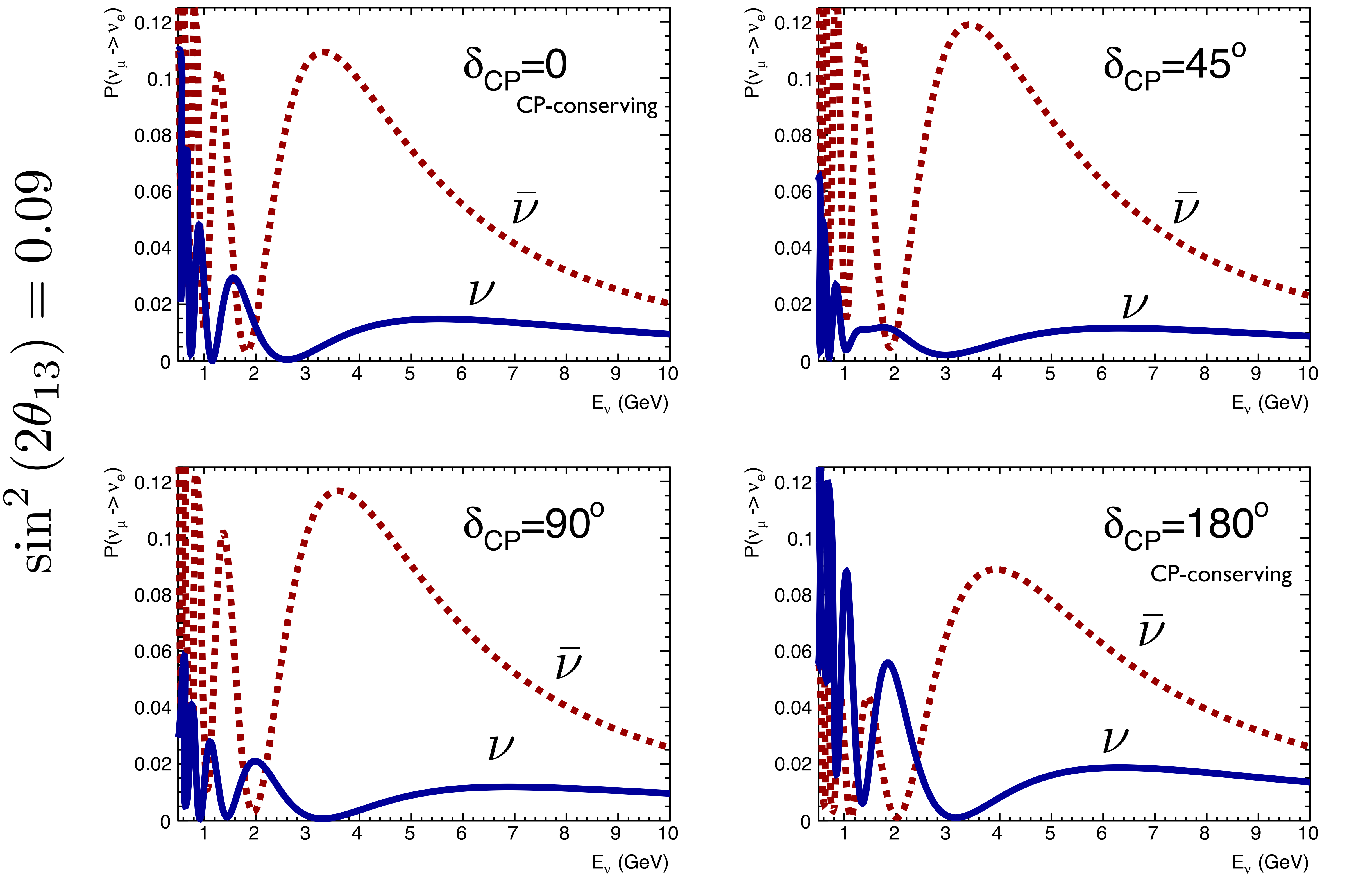
★Normal mass hierarchy L=2300 km

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



CERN-Pyhäsalmi: spectral information $\nu_\mu \rightarrow \nu_e$

★Inverted mass hierarchy L=2300 km



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. The site allows synergies and shared access with a large LSc detector, complementary and optimized for MeV-scale measurements.

LSc → see talk by C. Hagner

- **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.
- **Significantly** 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.

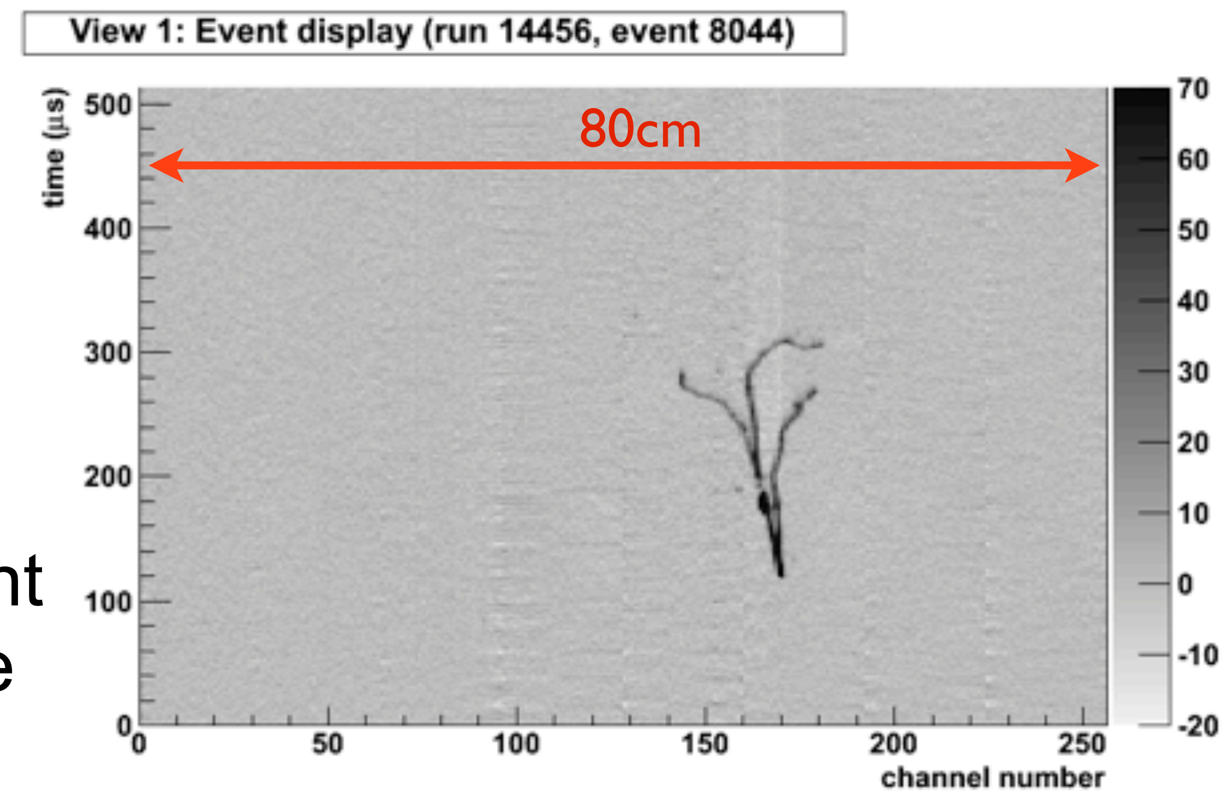
5600 atmospheric events/yr **relic SN, WIMP annihilation, ...**

>10000's events @ SN explosion@10kpc

Far detectors for long baseline

LAGUNA-LBNO WP2+WP3

- **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



Cosmic Data from 40x80cm2 LAr LEM TPC@CERN

- **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 LAGUNA-LBNO neutrino beam

LAGUNA-LBNO WP4 *See talks by I Efthymiopoulos and R Garoby*

- **CN2PY horn focused neutrino beam towards Pyhäsalmi/FI**
  - Starting point is SPS and CNGS operation (achieved 420kW)
  - Consider protons extraction, transfer & secondary beam lines
  - Design optimized target and horn focusing systems.
  - Afford relatively short decay tunnel ≈300m, but 10deg dip angle
  - Necessity of a near detector station to achieve target systematic errors
  - Consider dedicated set of hadron-production measurements *→See B. Popov's talk*

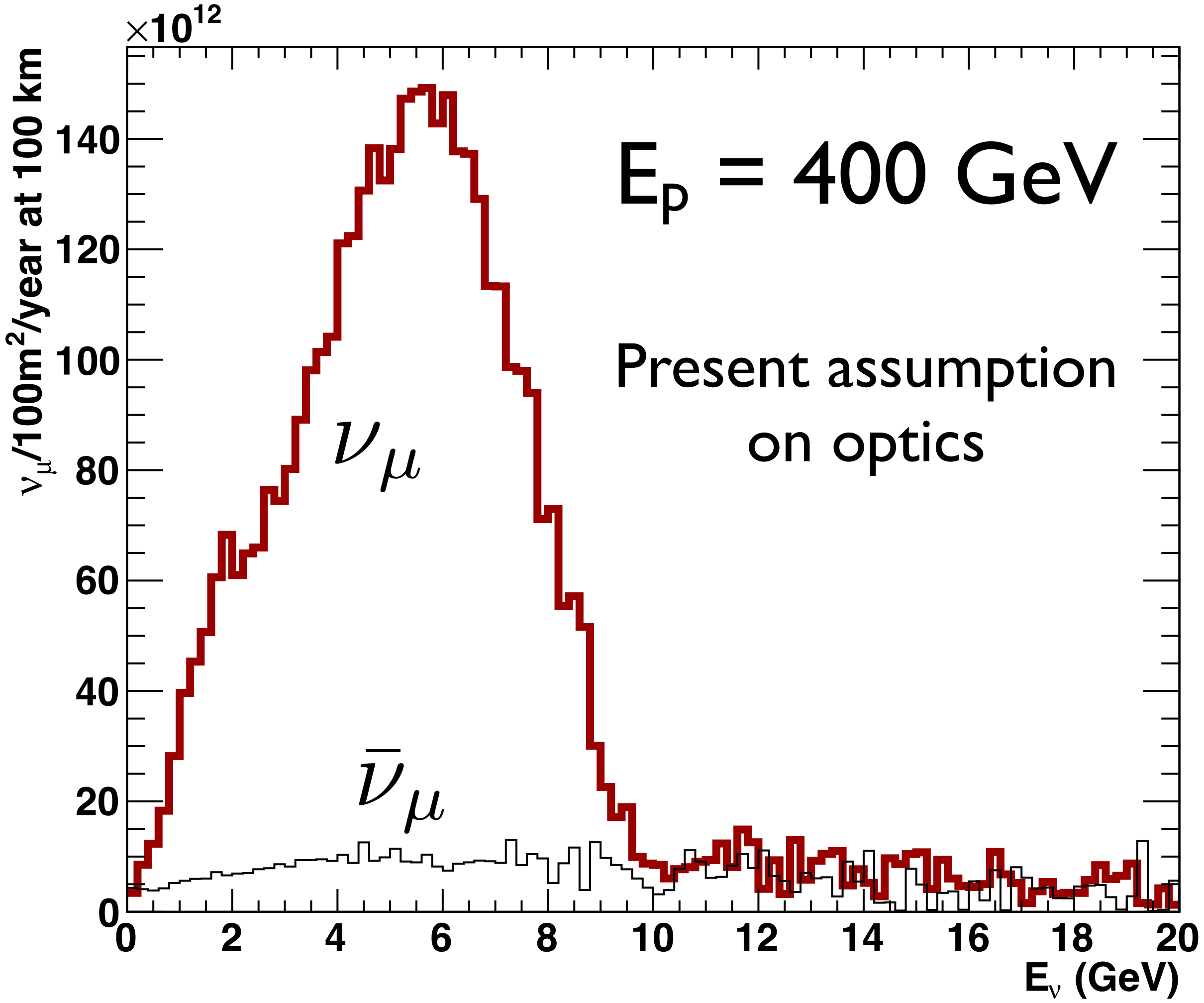
- **Benefit from improved performance of SPS+injectors; consider further options to upgrade power of SPS:**
  - SPS intensity is upgraded to 7e13 ppp at 400 GeV with cycle time = 6 seconds.
  - Yearly integrated pot = **(0.8–1.3)x 1e20 pot / yr**
  - Total integrated (12 years) = **(1–1.5)x 1e21 pot**
  - Range corresponds to sharing 60–85%
  - Studies ongoing within CERN accelerator team in LAGUNA-LBNO WP4

- **Upgrade path: HP-PS accelerator (50 GeV) with significant power improvement compared to SPS complex (→ "MW" beam). Exploit synergies with the NF R&D.**

Beam spectrum optimization

LAGUNA-LBNO WP4

- Low-energy neutrino beam (0-10 GeV) optimization done within LAGUNA DS for various baselines to maximize θ_{13} sensitivity, assuming 50 GeV protons from HP-PS.
- Present activities:
  - Optimization for 200, 300 and 400 GeV SPS protons vs 50 GeV HP-PS;
  - Focusing optimization maximizing MH&CPV physics reach (1^{st} & 2^{nd} maxima);
  - Target optimization.



On-going optimization

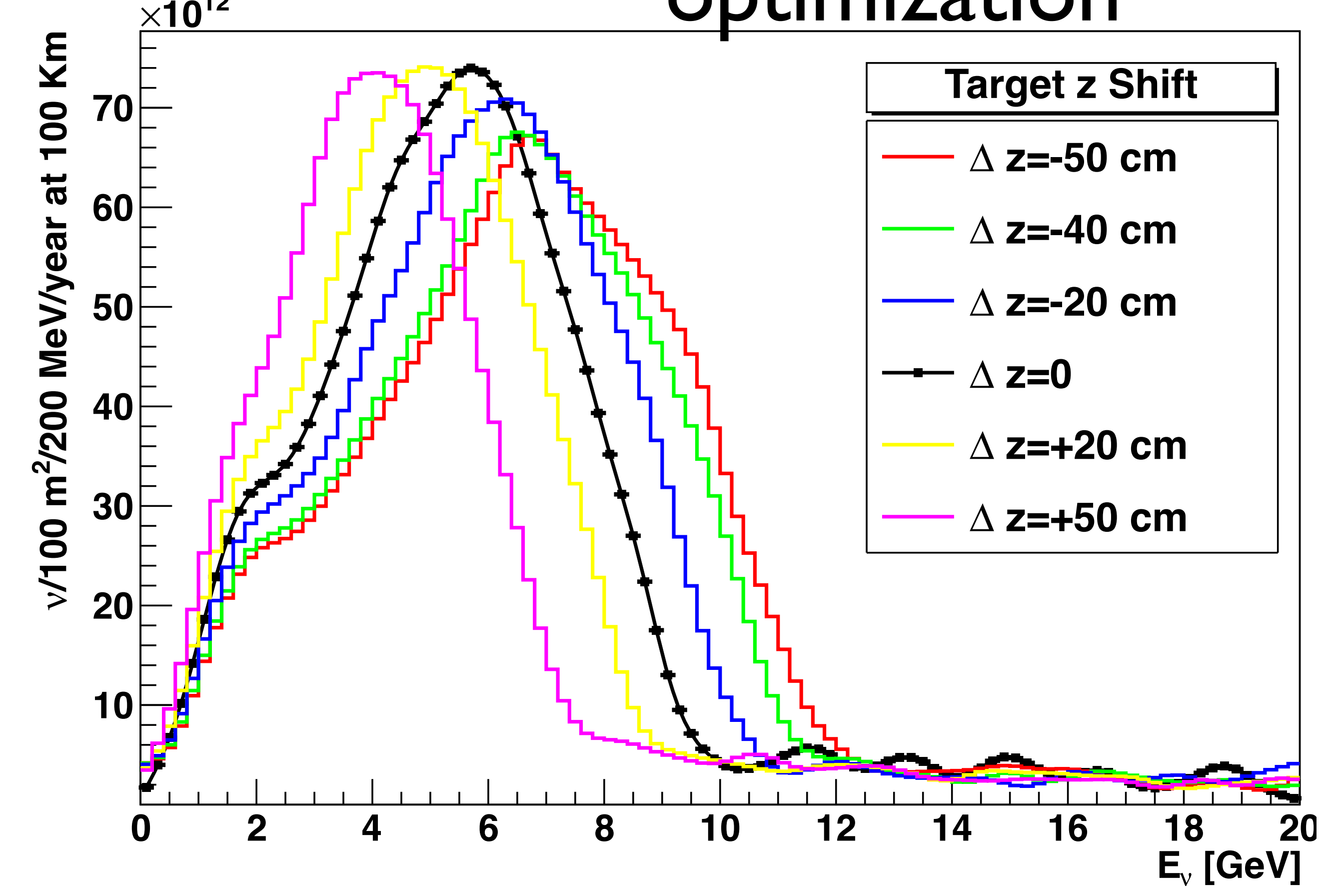


Illustration of MH&CPV sensitivity

- 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:

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

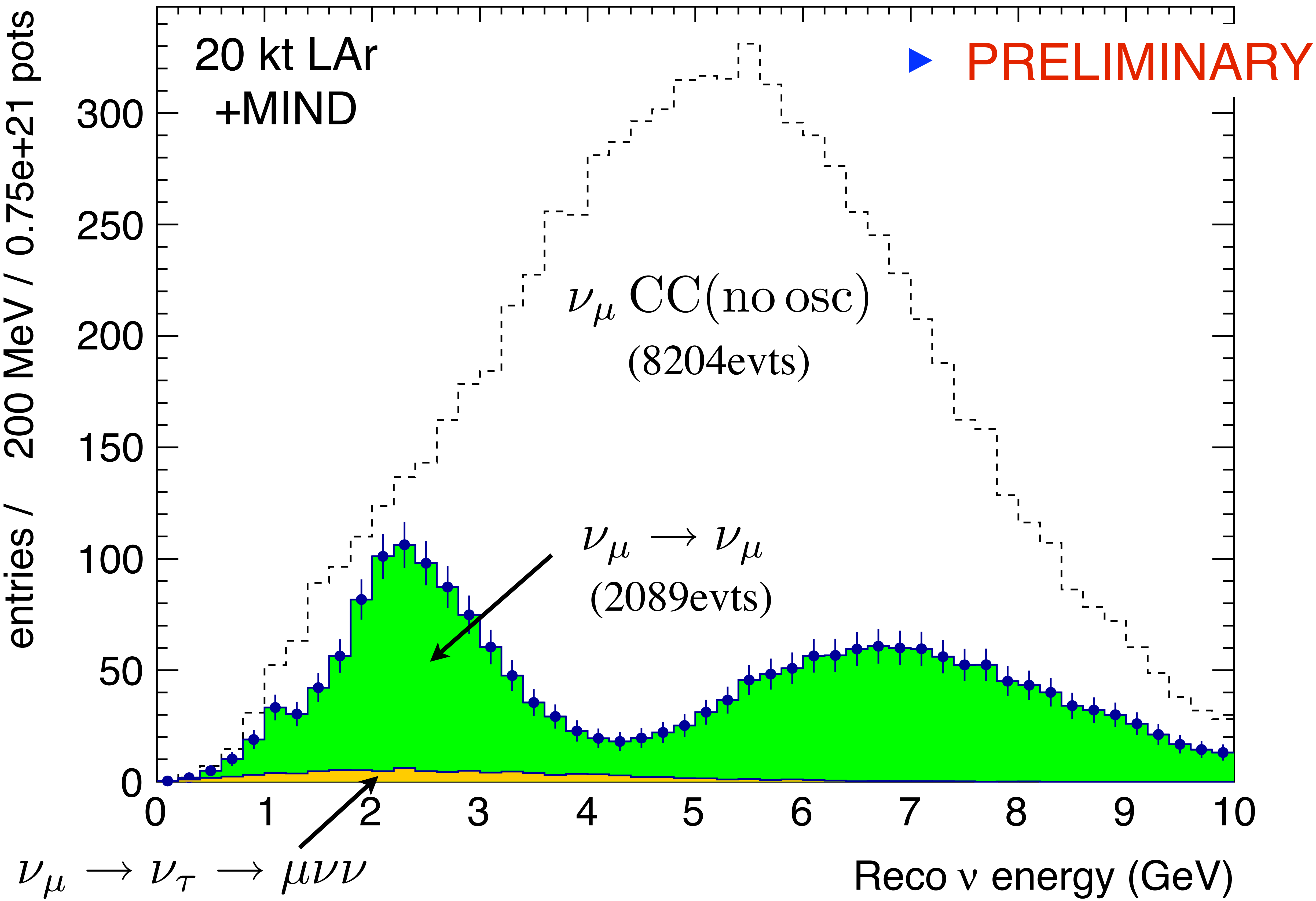
$\pm 1\sigma$ present errors

  ✦ solar terms fixed

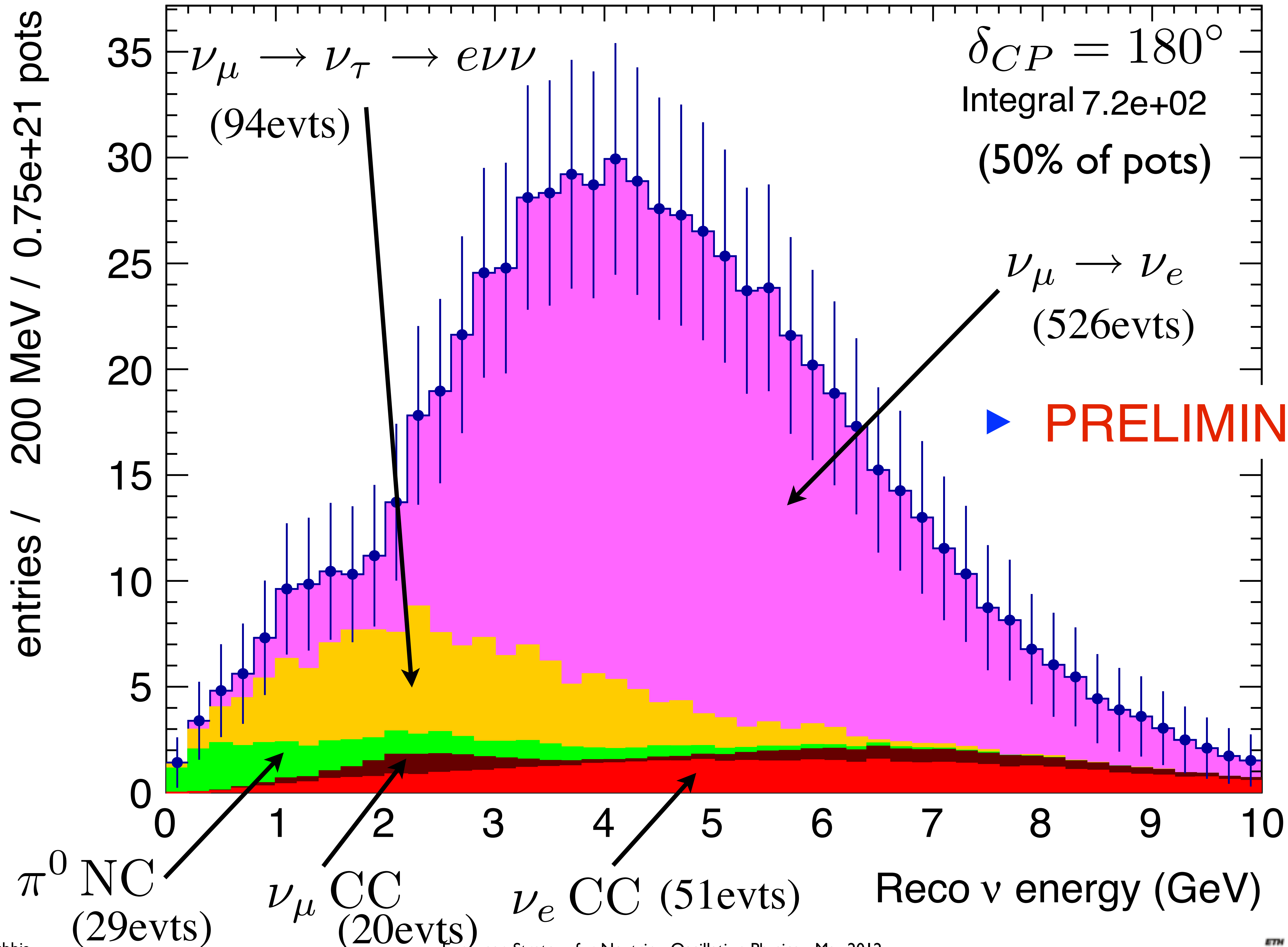
  ✦ matter density free (±2% error)

  ✦ other systematic errors (see later)

μ-like CC sample (+)



e-like CC sample (+)



▸ PRELIMINARY

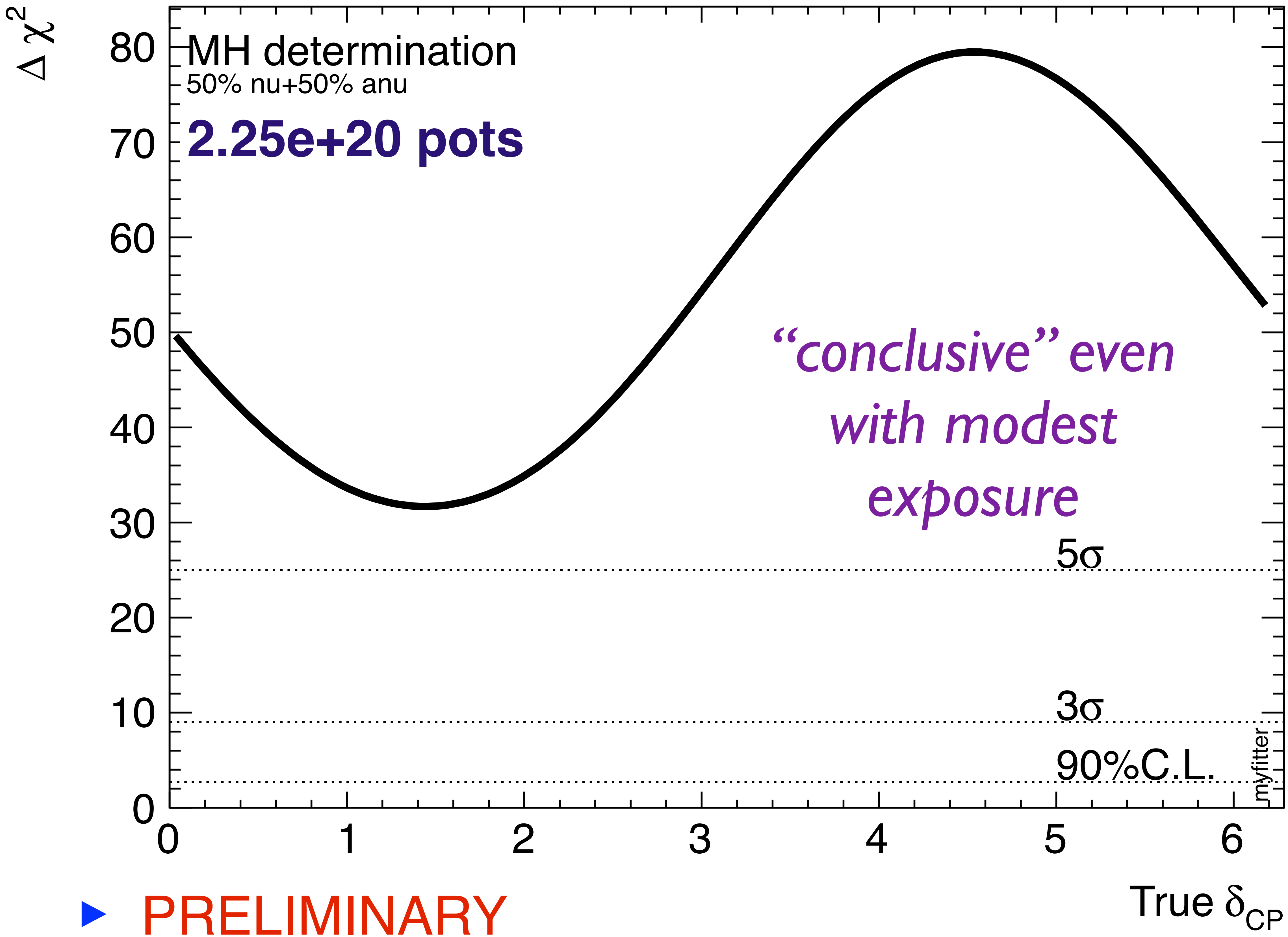
Analysis method (=myfitter)

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

$$\chi^2 = \sum_{+,-}\sum_i \left[N^i - \left\{1 \pm \frac{1}{2} f_{\nu/\overline{\nu}}\right\} \cdot \Big((1+f_{\rm sig}) \cdot n^i_{\rm sig} + (1+f_{NC}) \cdot n^i_{NC} + (1+f_{\nu_e CC}) \cdot n^i_{\nu_e CC} + (1+f_{\nu_\tau CC}) \cdot n^i_{\nu_\tau CC} \Big) \right]^2 / N^i + \frac{f^2_{\rm sig}}{\sigma^2_{\rm sig}} + \frac{f^2_{NC}}{\sigma^2_{NC}} + \frac{f^2_{\nu_e CC}}{\sigma^2_{\nu_e CC}} + \frac{f^2_{\nu_\tau CC}}{\sigma^2_{\nu_\tau CC}} + \frac{f^2_{+/-}}{\sigma^2_{+/-}},$$

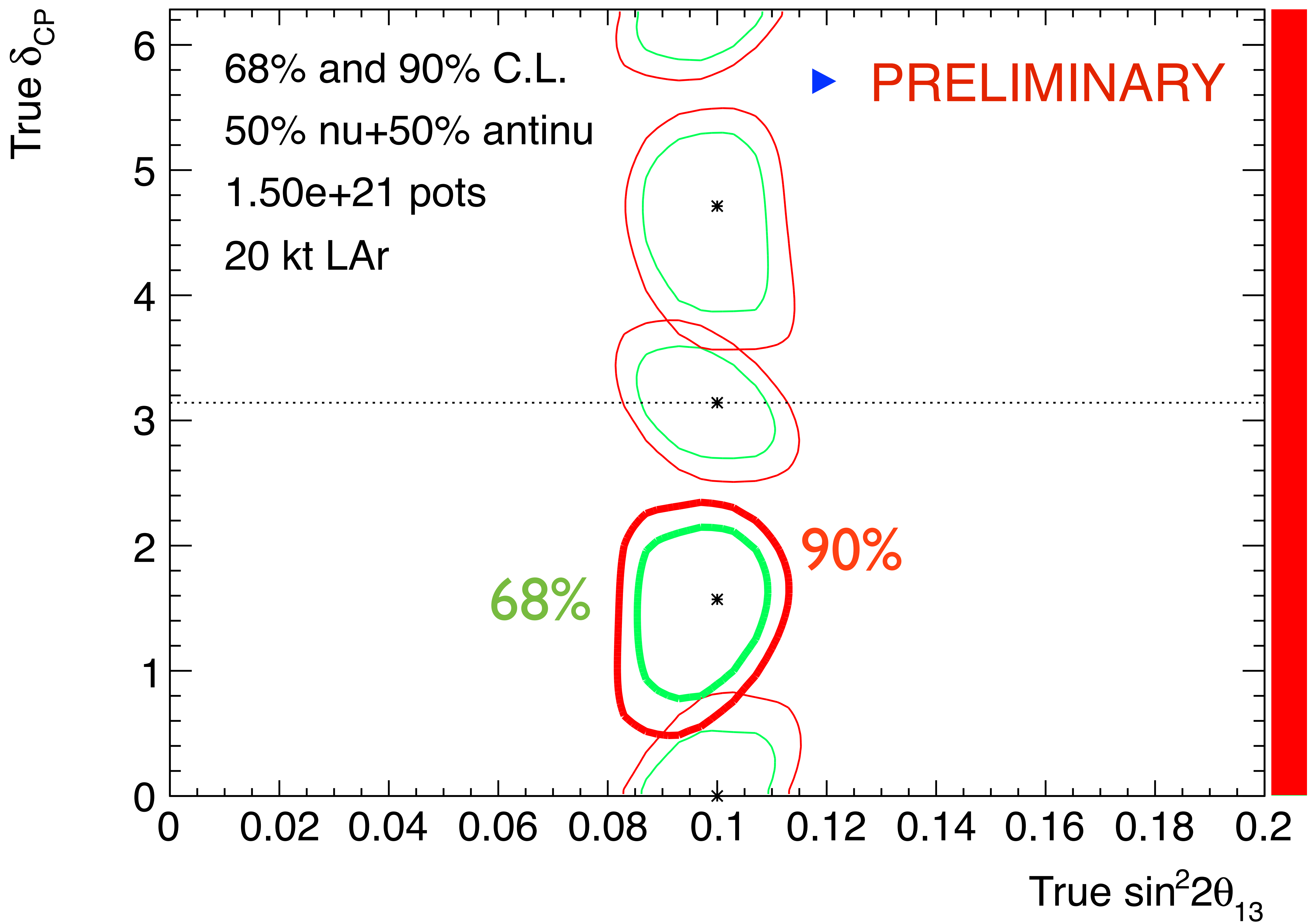
- +, – = beam (horn) polarity → at present assume 50%-50% sharing between + and – runs
- Ni = simulated number of expected events in energy bin i
- n_{xi} = number of expected events from source "x" in energy bin i
- f_x = systematic error for "x" → at present assume 5% systematic errors for each source

MH determination

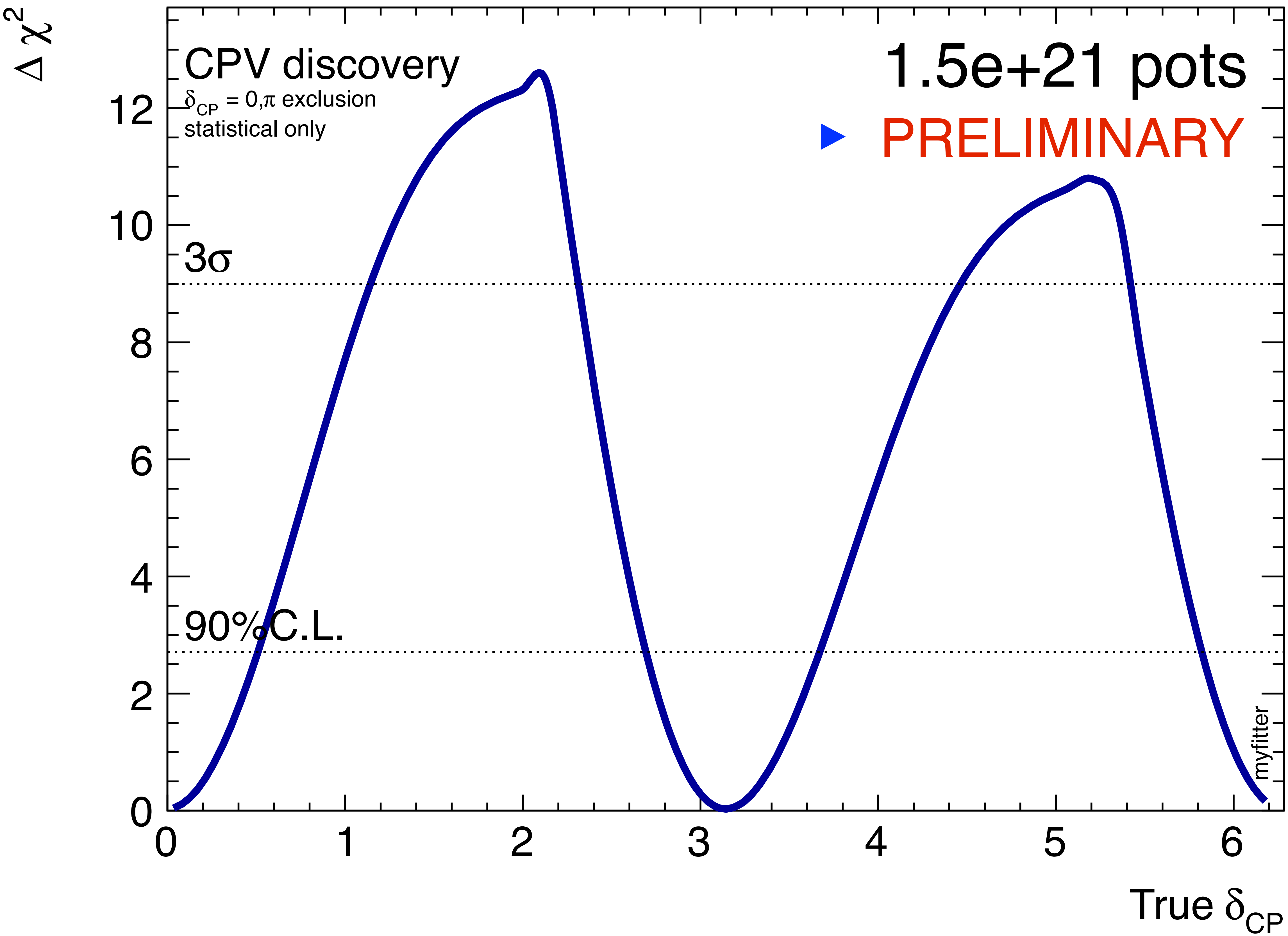


▸ PRELIMINARY

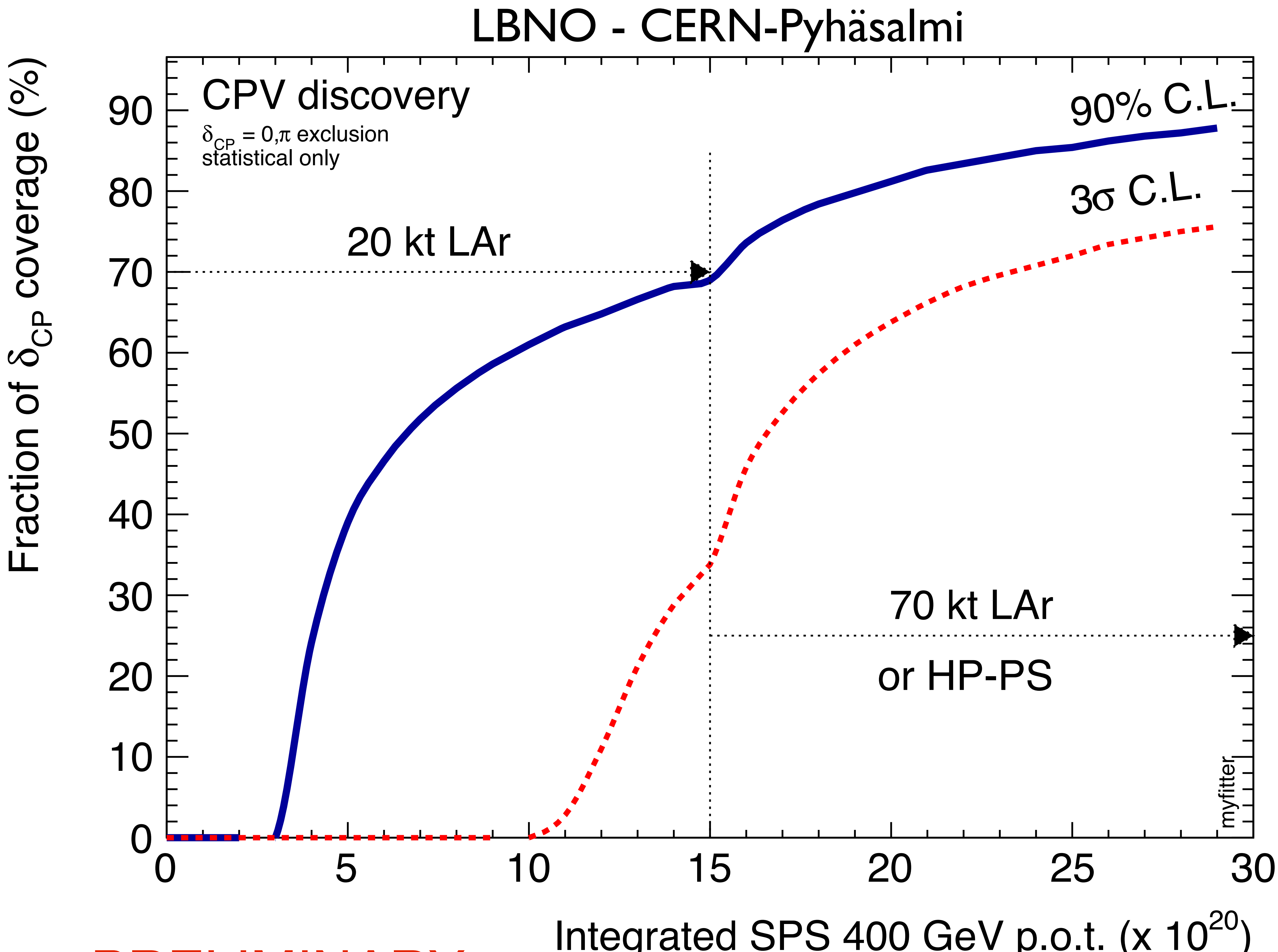
CP-phase determination



CPV discovery



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**
Start of LAGUNA-LBNO	**2011**
Submission of LBNO EoI to CERN	**2012**
End of LAGUNA-LBNO DS: technical designs, layouts, liquids handling&storage, safety, ...	**2014**
Critical decision	**2015 ?**
Excavation-construction (incremental):	**2016-2021 ?**
Phase 1 LBL physics start:	**2023 ?**
Phase 2 incremental step implementation:	**>2025 ?**

Conclusions

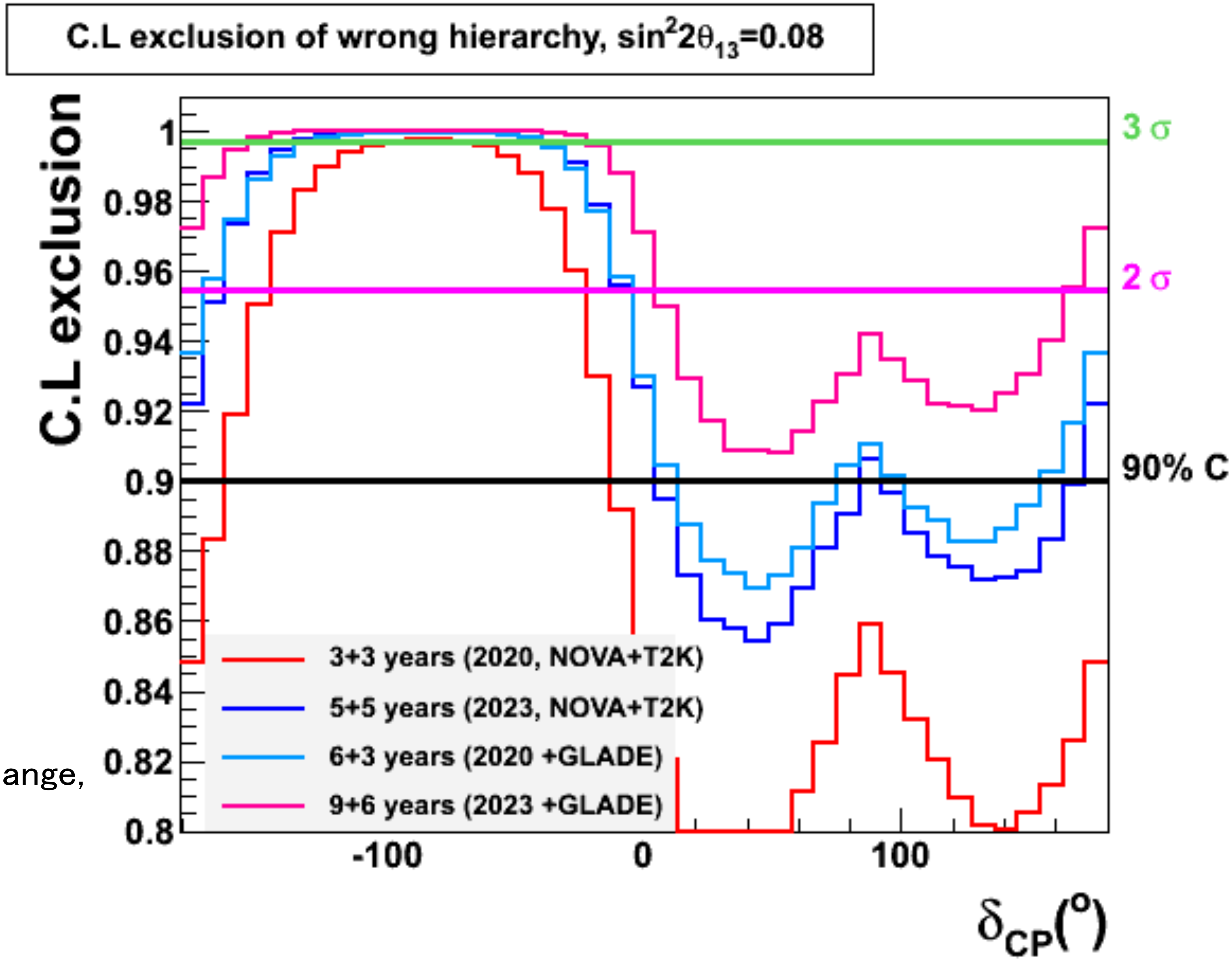
- **LBNO, to be located underground at Pyhäsalmi 2300km away from CERN, has truly unique scientific opportunities**:
  - ➡ all transitions (e/μ/tau) measurable in neutrino/antineutrino in a single experiment
  - ➡ a fully conclusive mass hierarchy determination, in a cleaner and more significant way than any other methods/proposals
  - ➡ a 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, competitive to HK LoI.
  - ➡ detection of several astrophysical sources (SN,...) and fresh new look at atmospheric neutrinos with high granularity and resolution (atm tau app., atm MH, ...).
- **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 LoI 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

Situation in 2023 ?



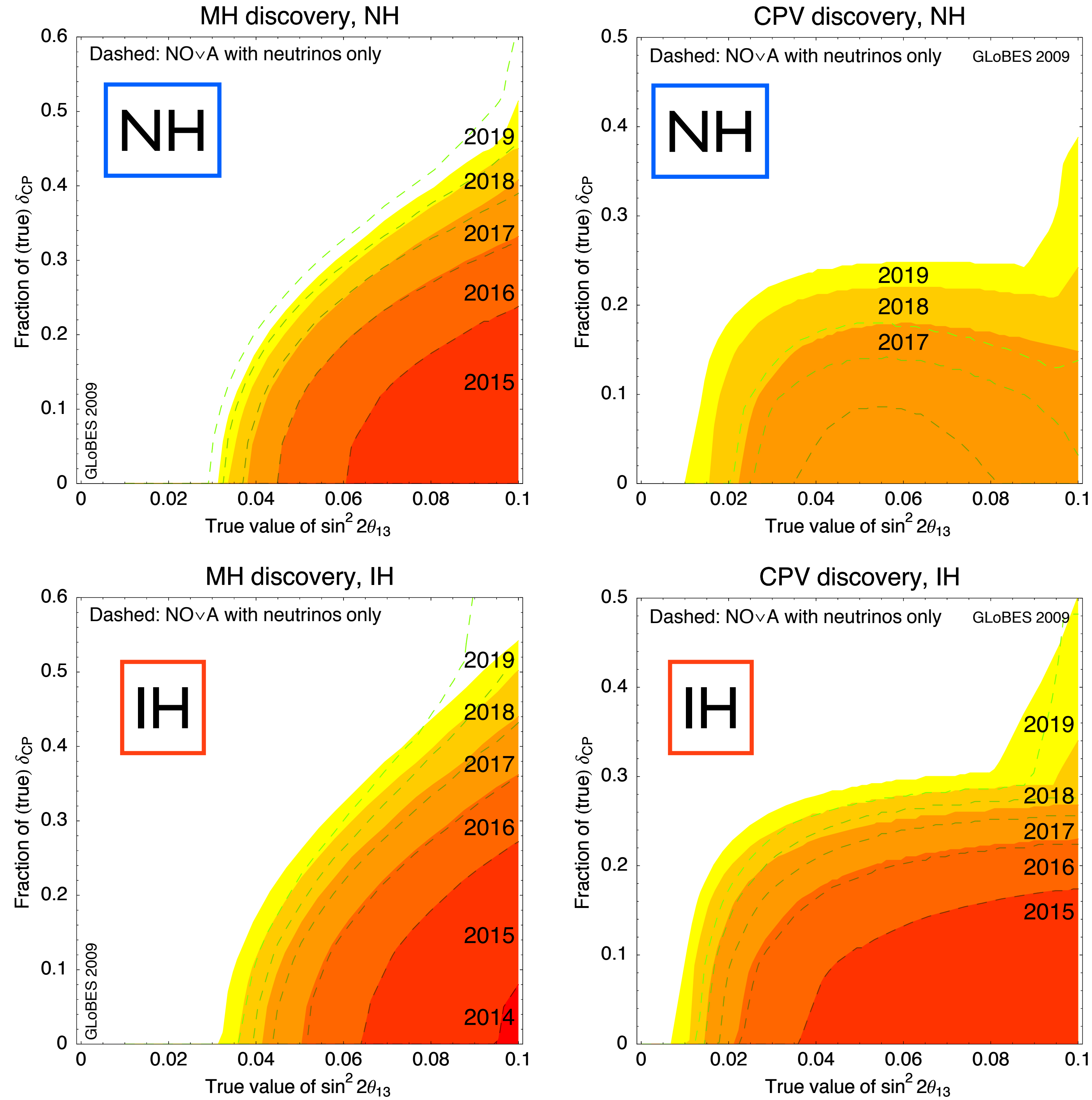
ıange,

Most likely we will reach a ≈2σ MH determination

T2K and NOvA: in the future

- Preliminary estimation of sensitivity of T2K and NOvA
- 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

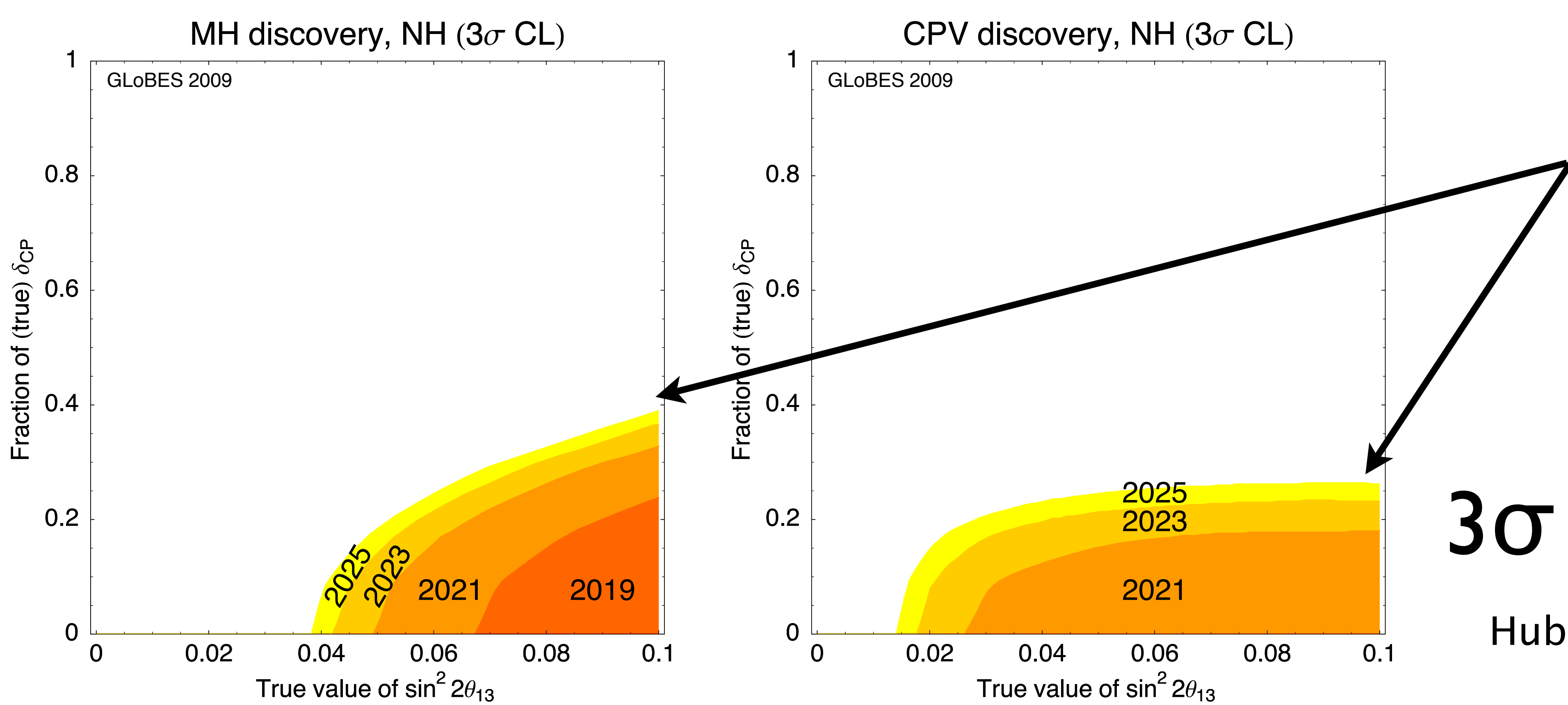


Huber et al., JHEP 0911:044,2009

not official

Benefit of beam power upgrades

- Assume power upgrades for NOvA to ProjectX (0.7MW → 2.3MW) and for T2K to JPARC MR (intensity,cycle) (0.75MW → 1.66MW)
  ➠ 6 years running after 2019 ➠ improved sensitivity (but systematics limited).
- For $\sin^2 2\theta_{13}$=0.1, approximately (at 3σ C.L.):
  - MH: <40% coverage
  - CPV: <30% coverage
- Official curves will be produced by experiments soon.



assume MW power running after 2019

not official

3σ C.L. sensitivity

Huber et al., JHEP 0911:044,2009

MH & CPV phenomenology

Approximate formula (M. Freund)

quadratic dep. on θ_{13}

matter effect ~E

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

~7500 km magic bln

CPV term approximate dependence ~L/E

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

~2540 km magic bln

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

solar term

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

linear dep. on θ_{13}

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

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

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

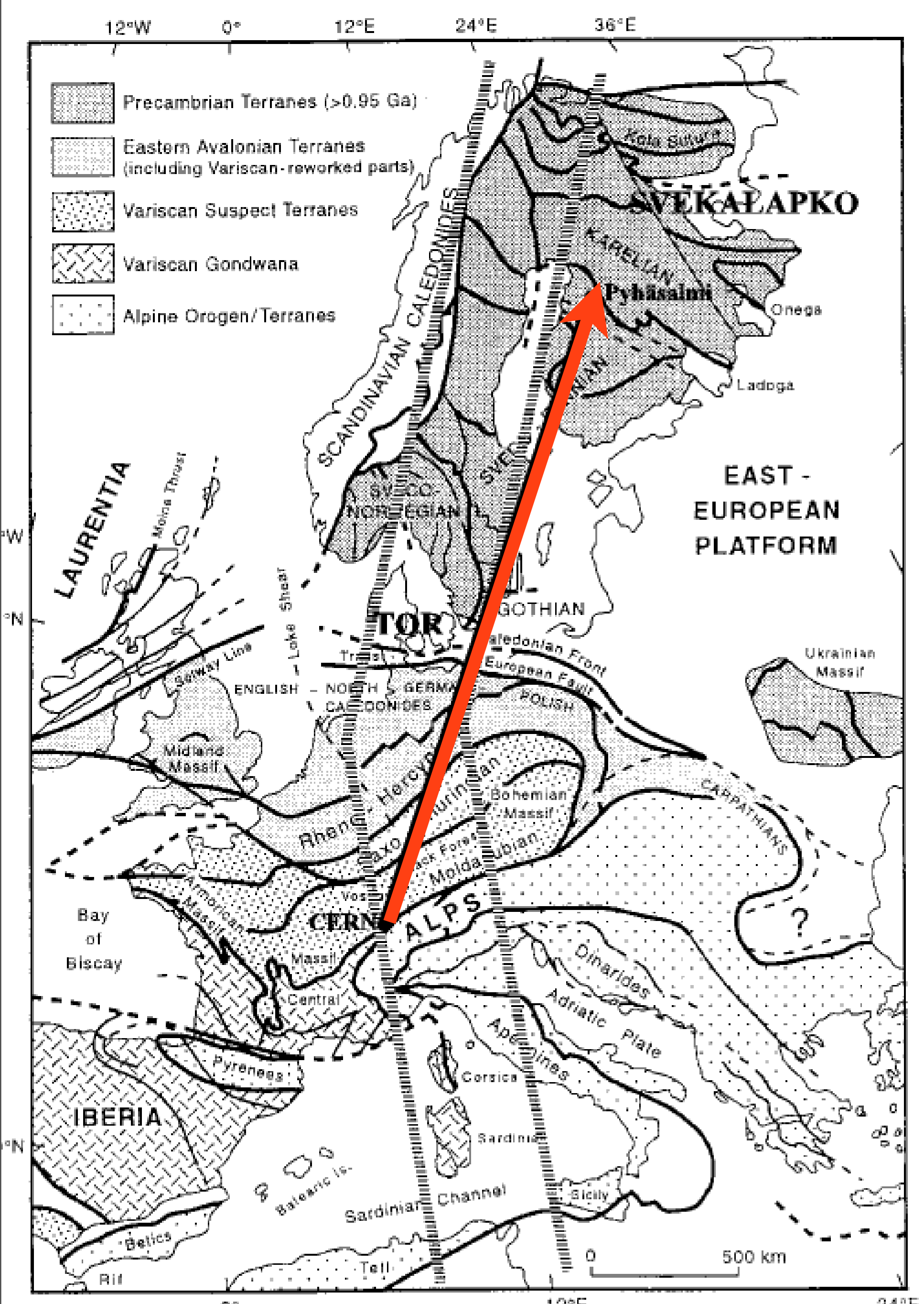
$$\hat{A} = 2VE/\Delta m^2_{31} \approx (E_\nu/GeV)/11 \text{ For Earth's crust.}$$

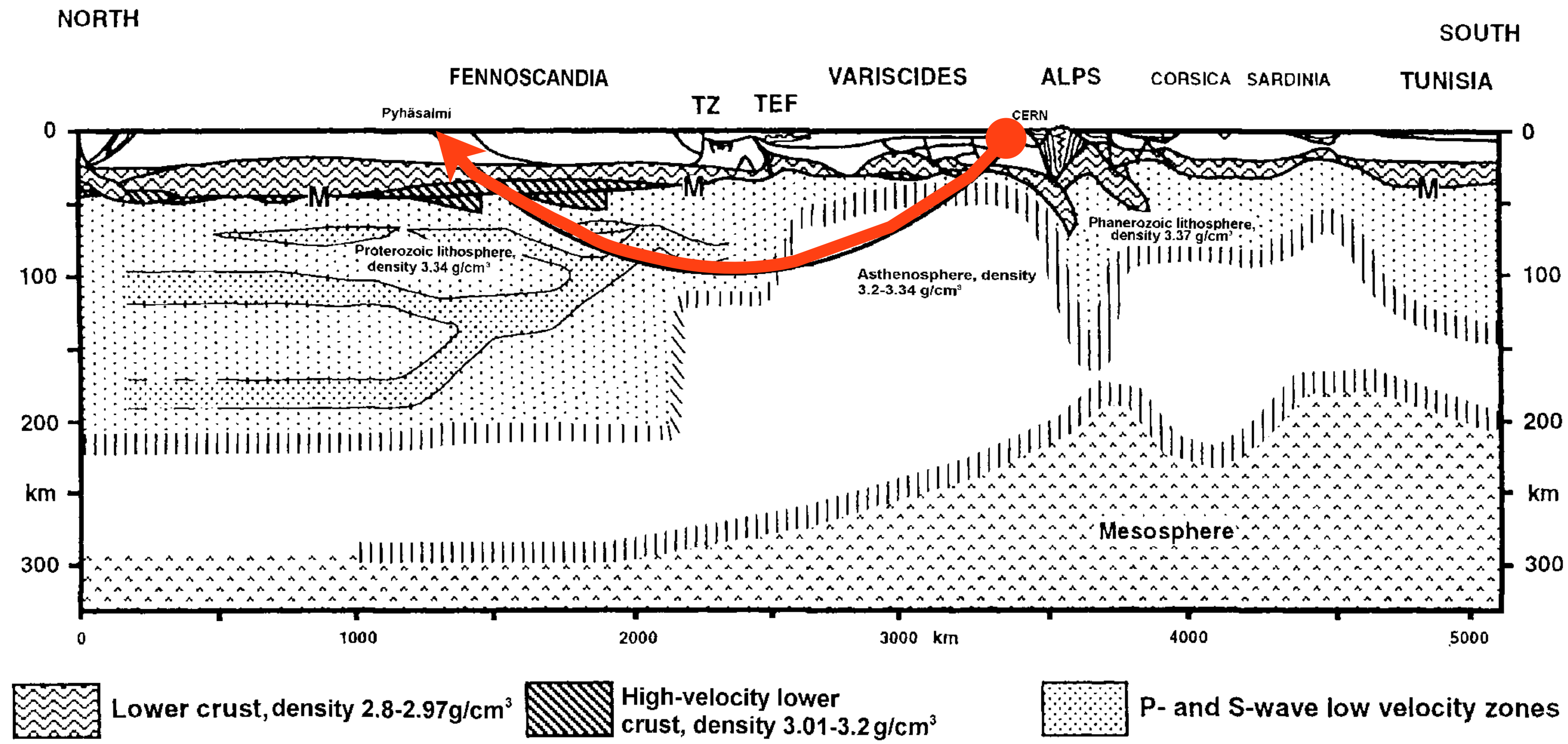
CP asymmetry grows as θ_{13} becomes smaller !

Correlations !

Neutrinos from CERN to Pyhäsalmi

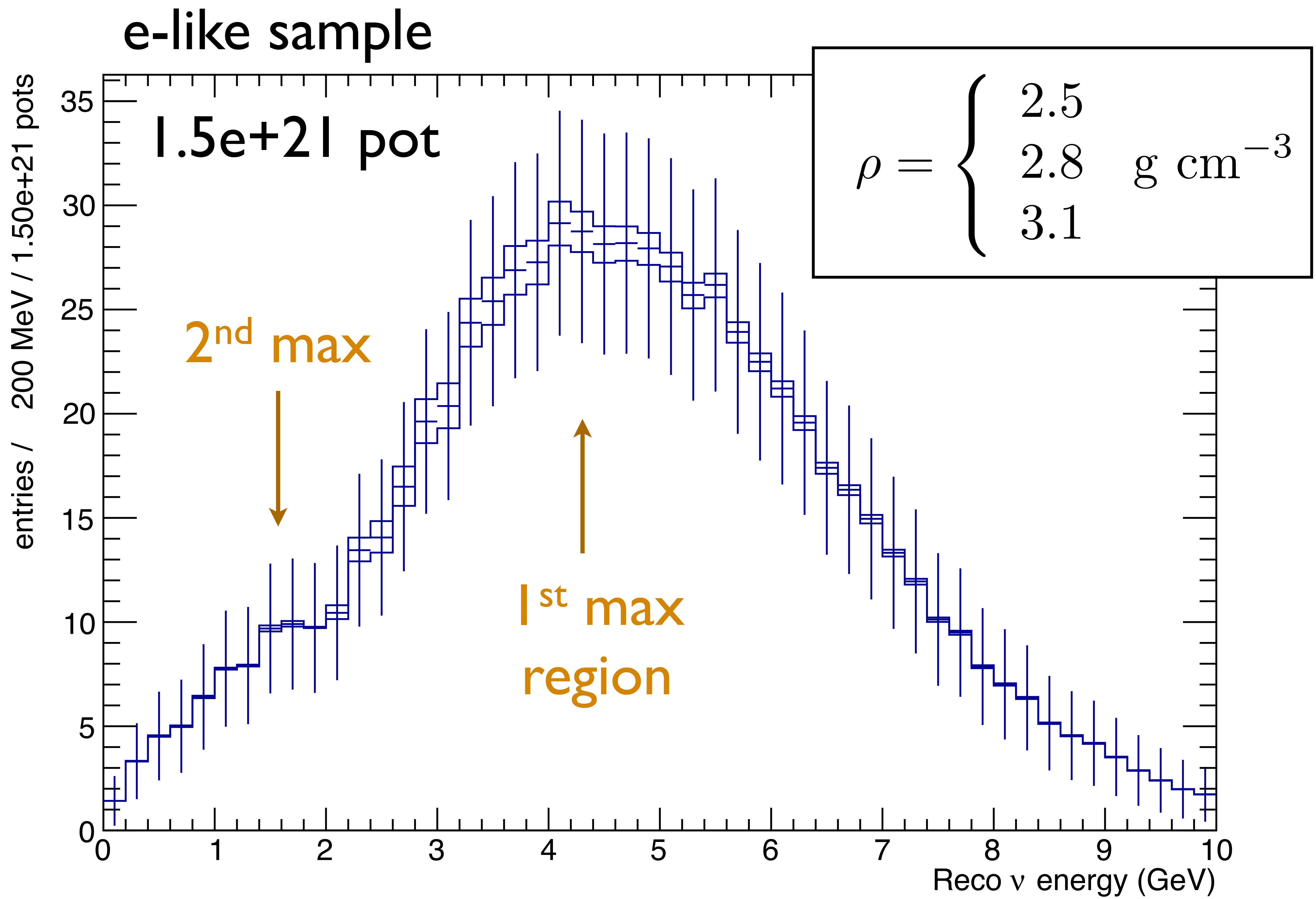
arXiv:hep-ph/0305042v1





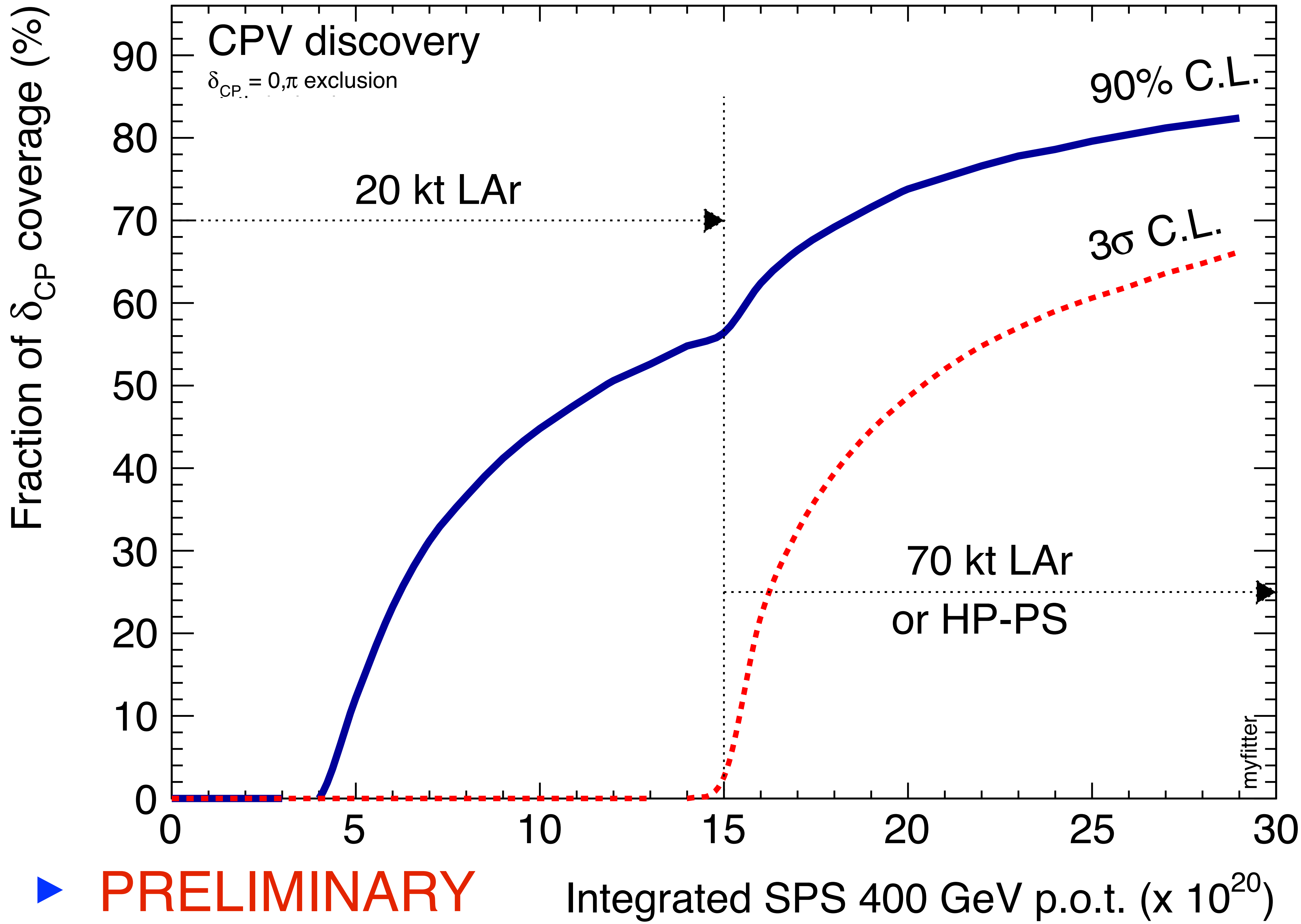
- Distance CERN-Pyhäsalmi = 2288 km
- Deepest point = 103.8 km
- Abundant geophysical data about crust and upper mantle available
- Densities = 2.4÷3.4 g/cm^3
- Remaining uncertainty has small effect on neutrino oscillations (equivalent to 2% change in matter density)

Matter density effects



Effect of matter uncertainty

★ INFLATED ERROR ON MATTER DENSITY ±10%

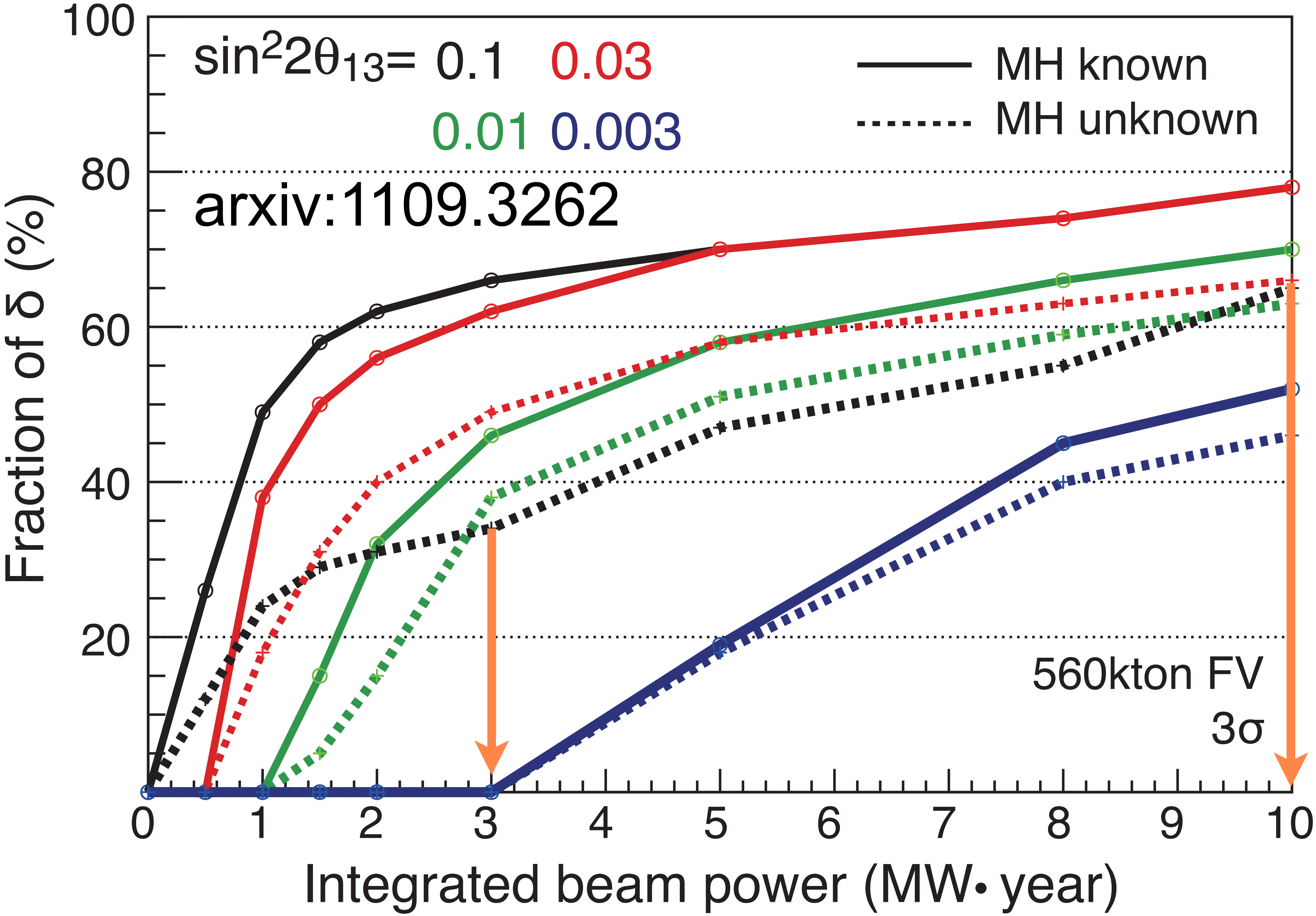


▶ PRELIMINARY

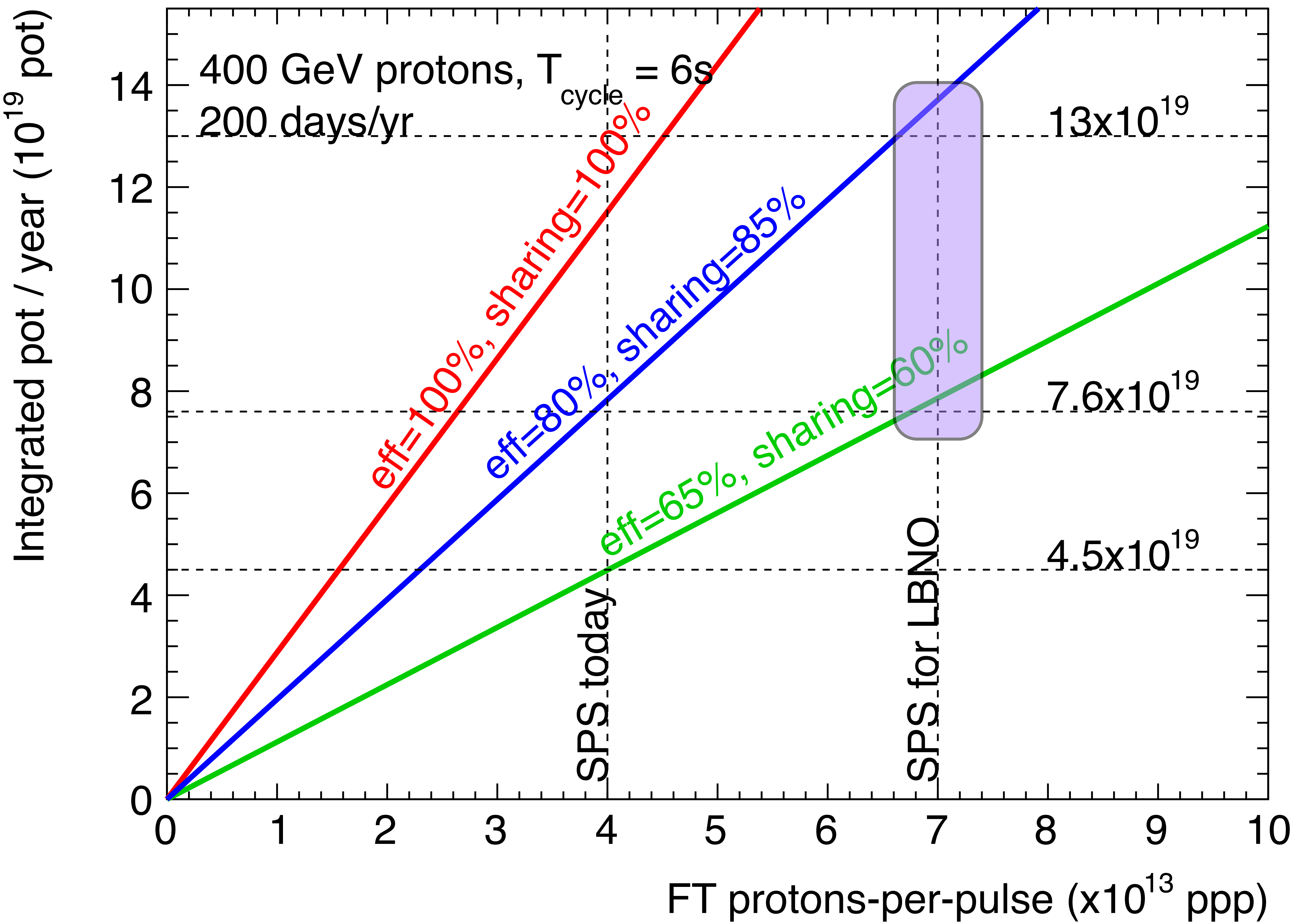
Why the neutrino mass hierarchy ?

- **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.
- **0νββ 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

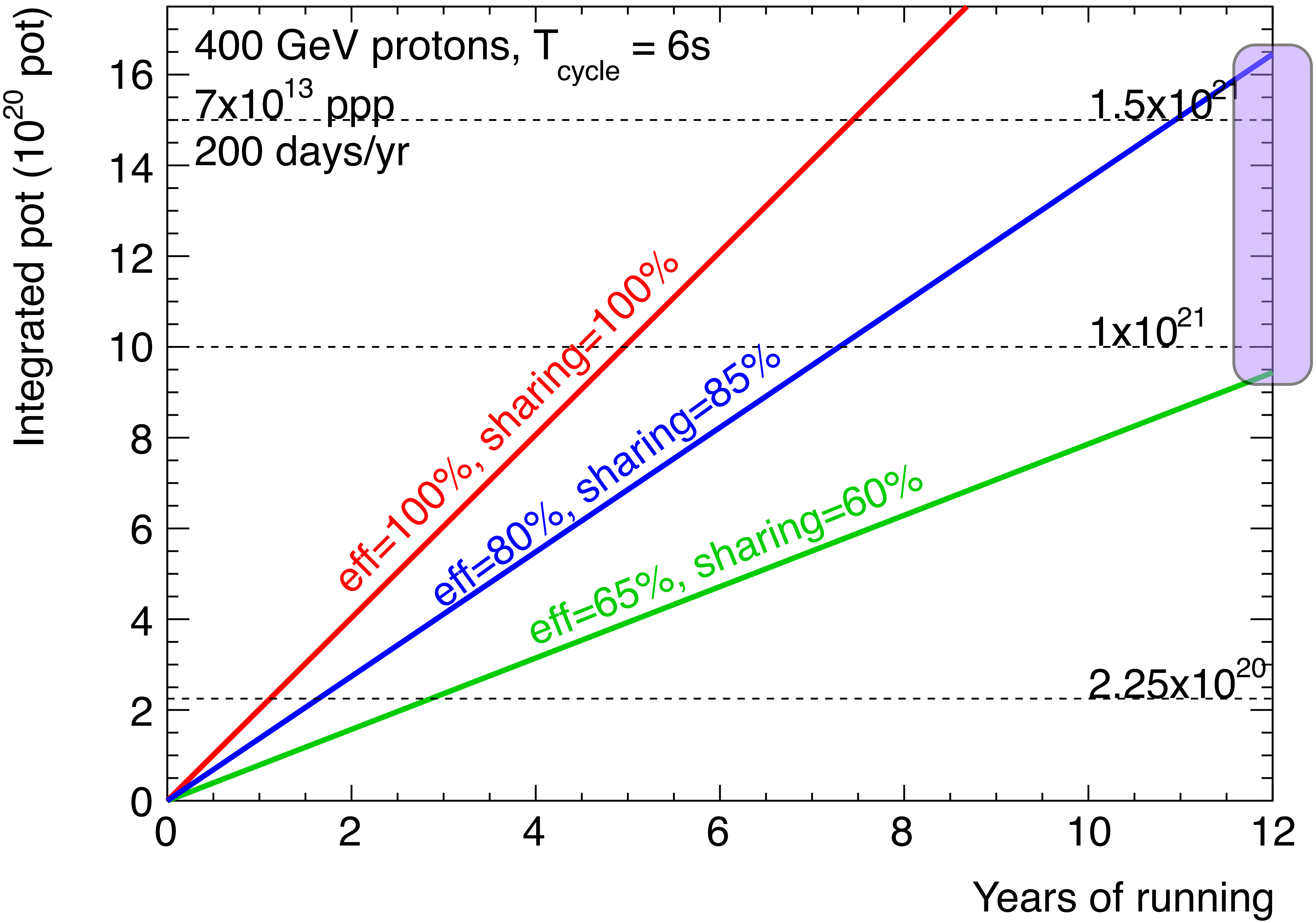


SPS 400 GeV p.o.t / year



≈300kW

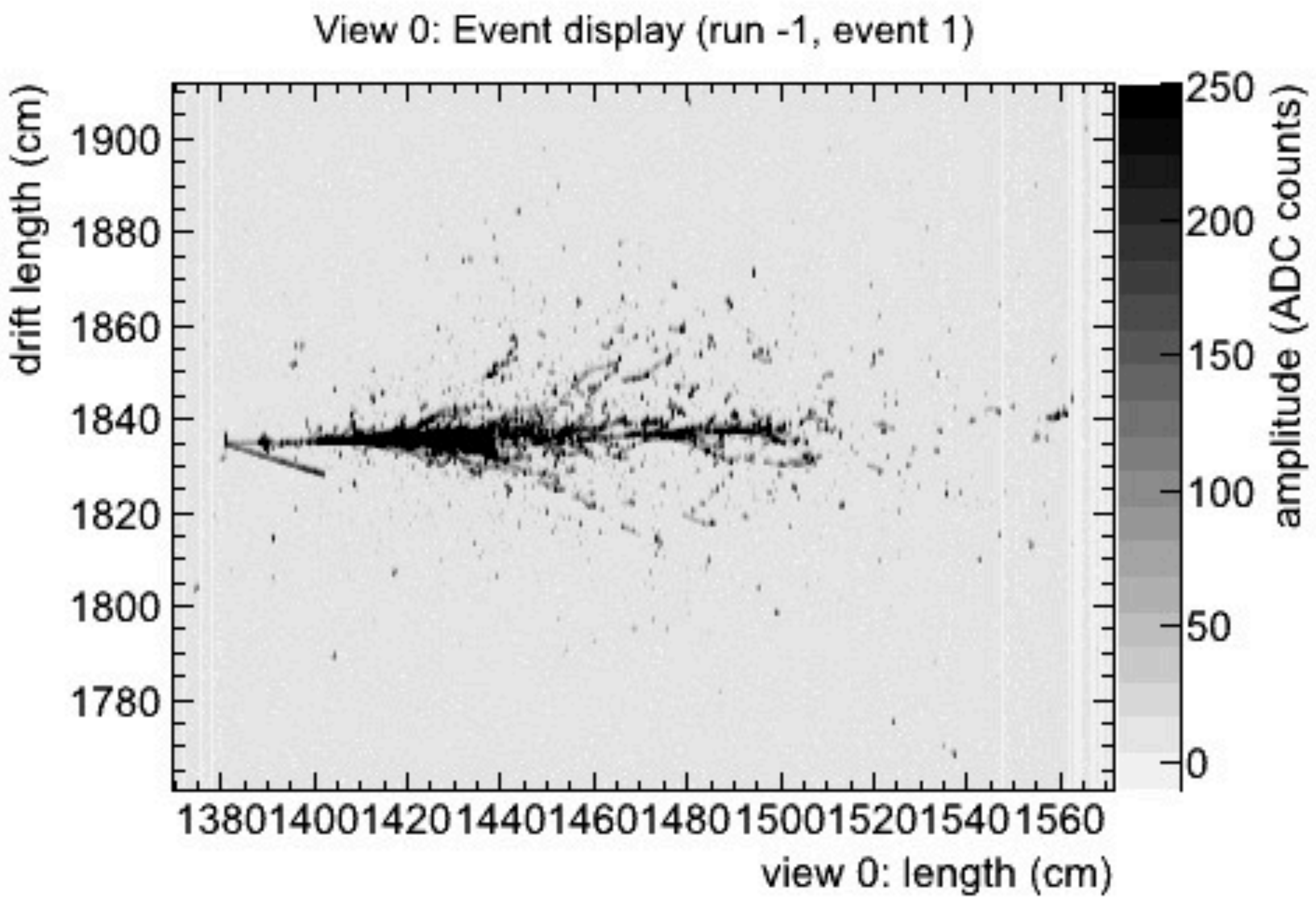
Total integrated p.o.t.

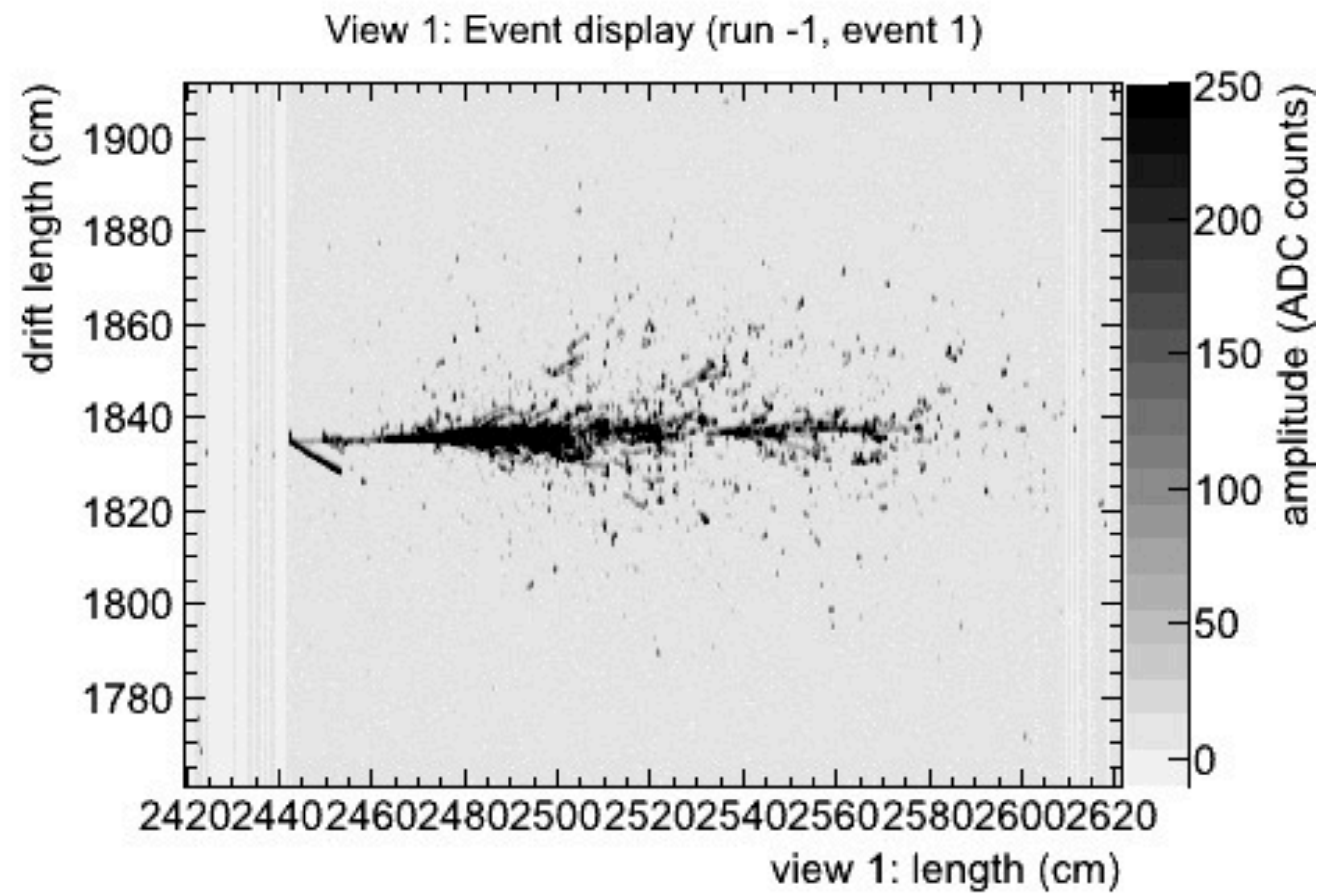


LAr detector performance

- 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

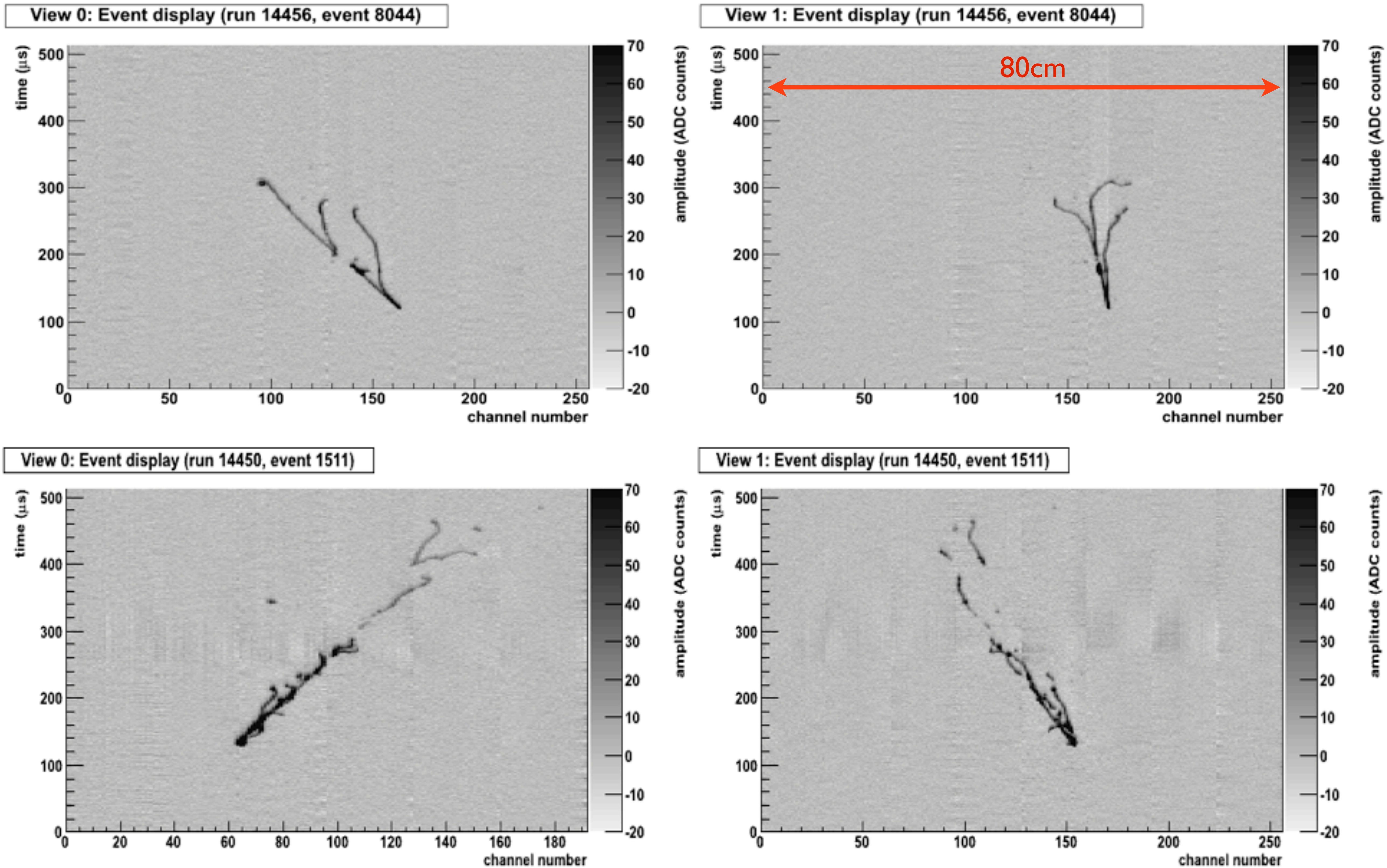
Realistic digitization
(based on measured LAr LEM TPC performance):





Real cosmic rays in LAr LEM-TPC

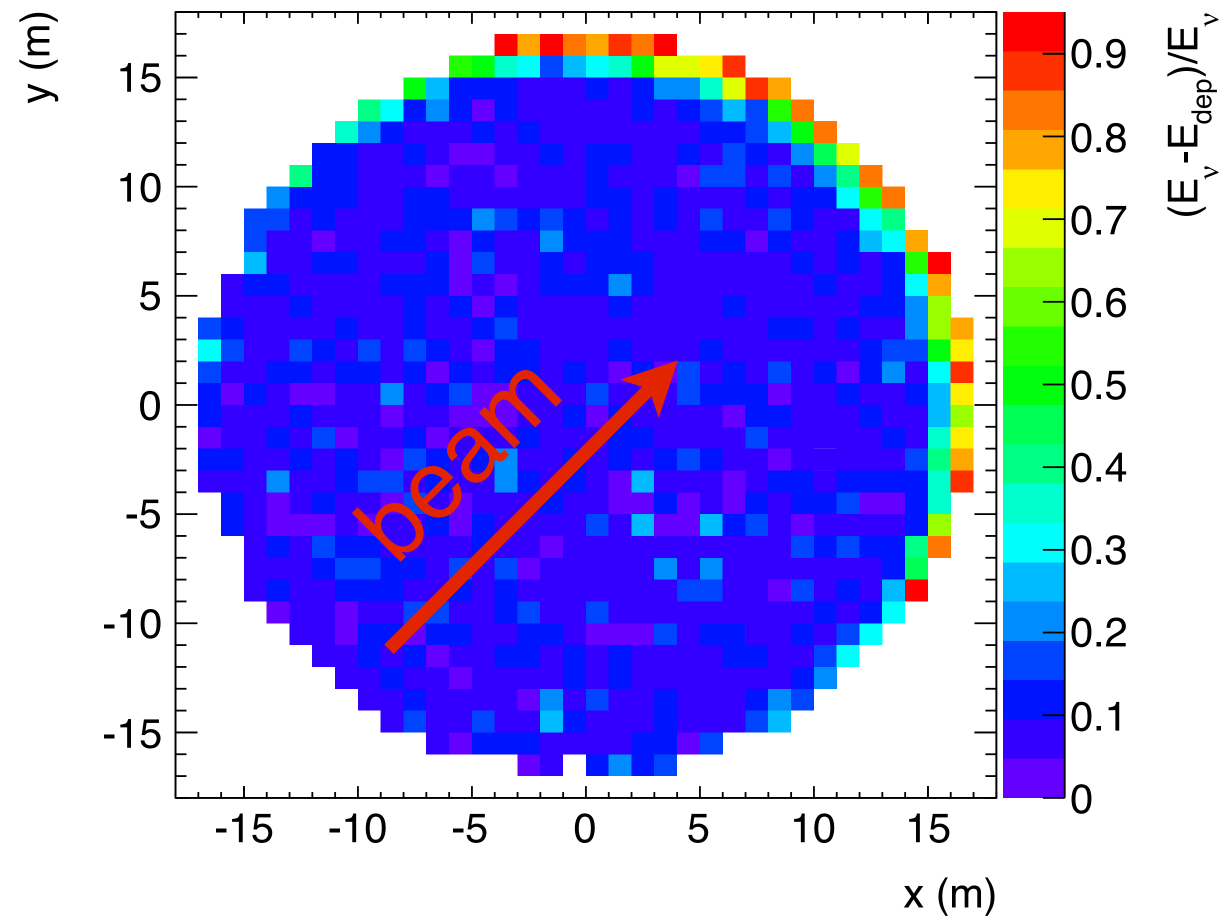
Cosmic track in double phase 80x40cm2 LAr-LEM TPC with adjustable gain : S/N > 100 for m.i.p !!

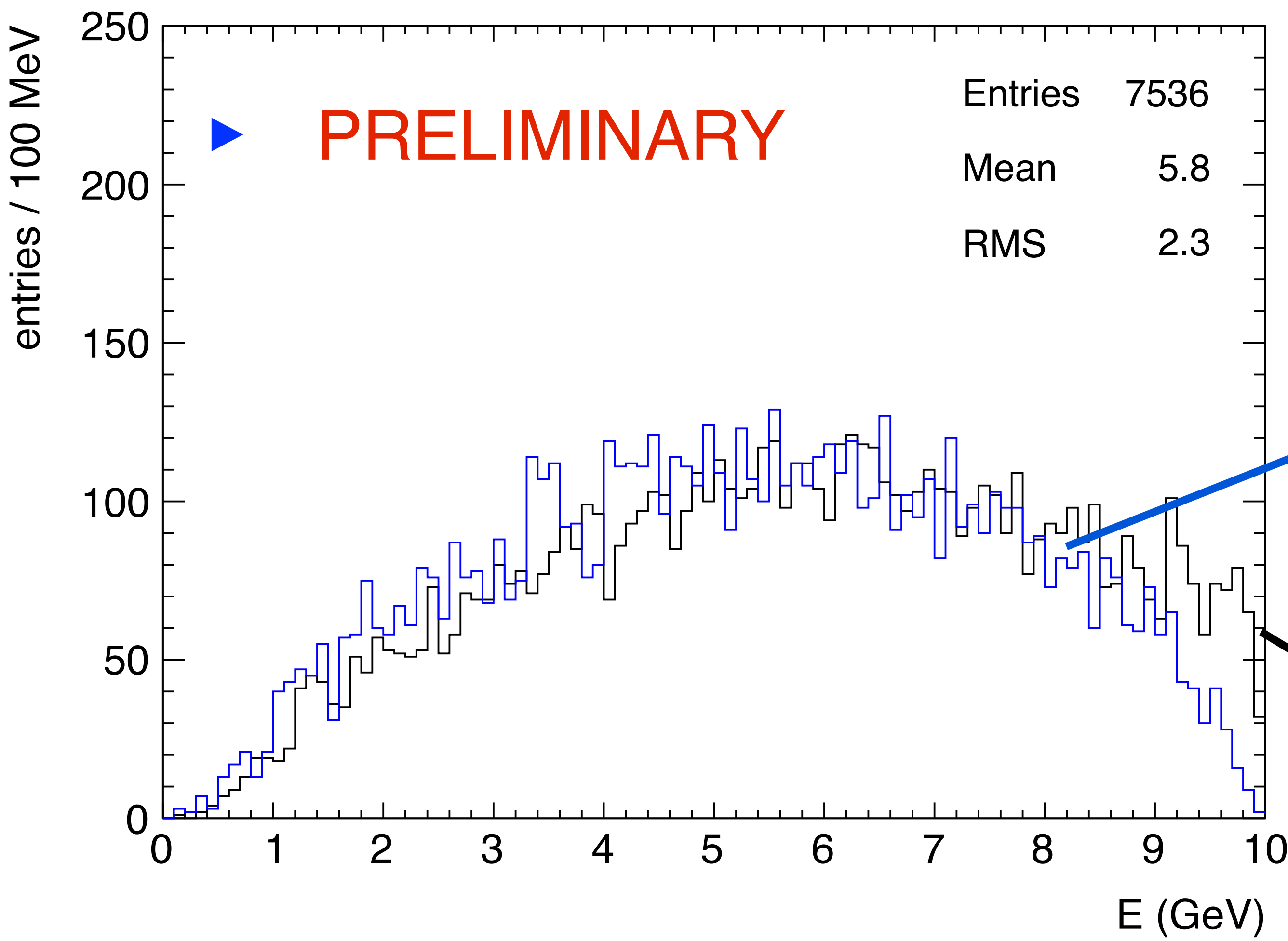


Neutrino energy reconstruction

- 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% RMS**

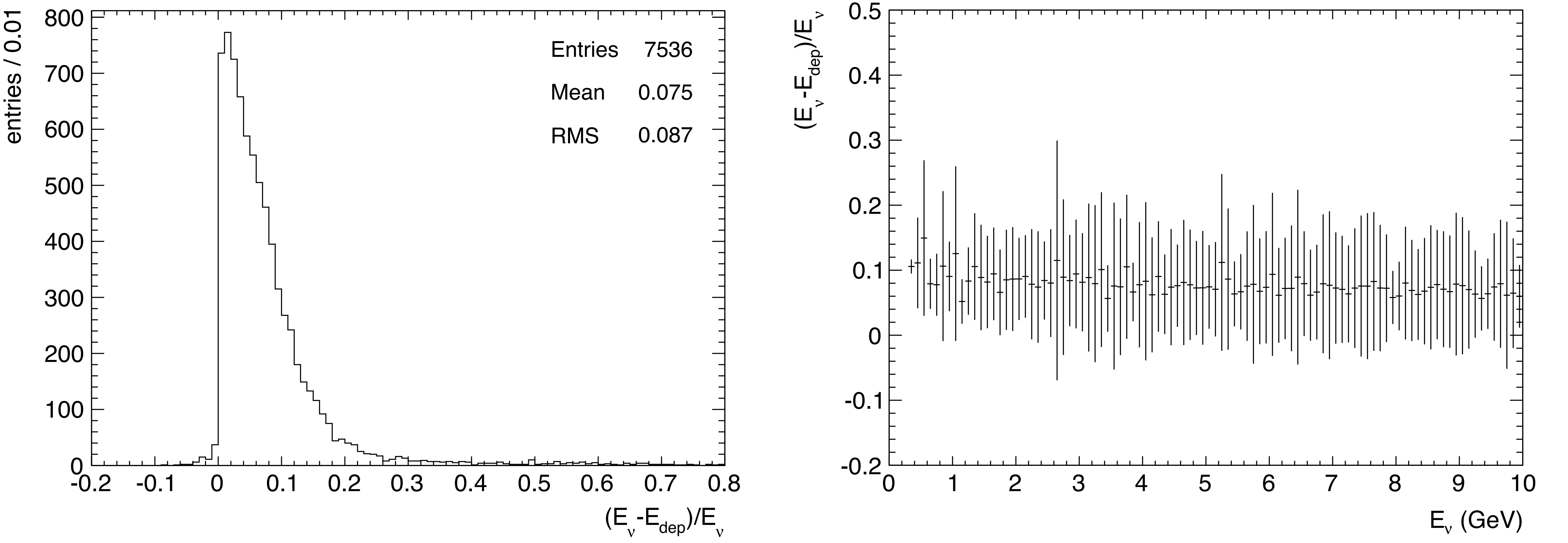
top view of detector





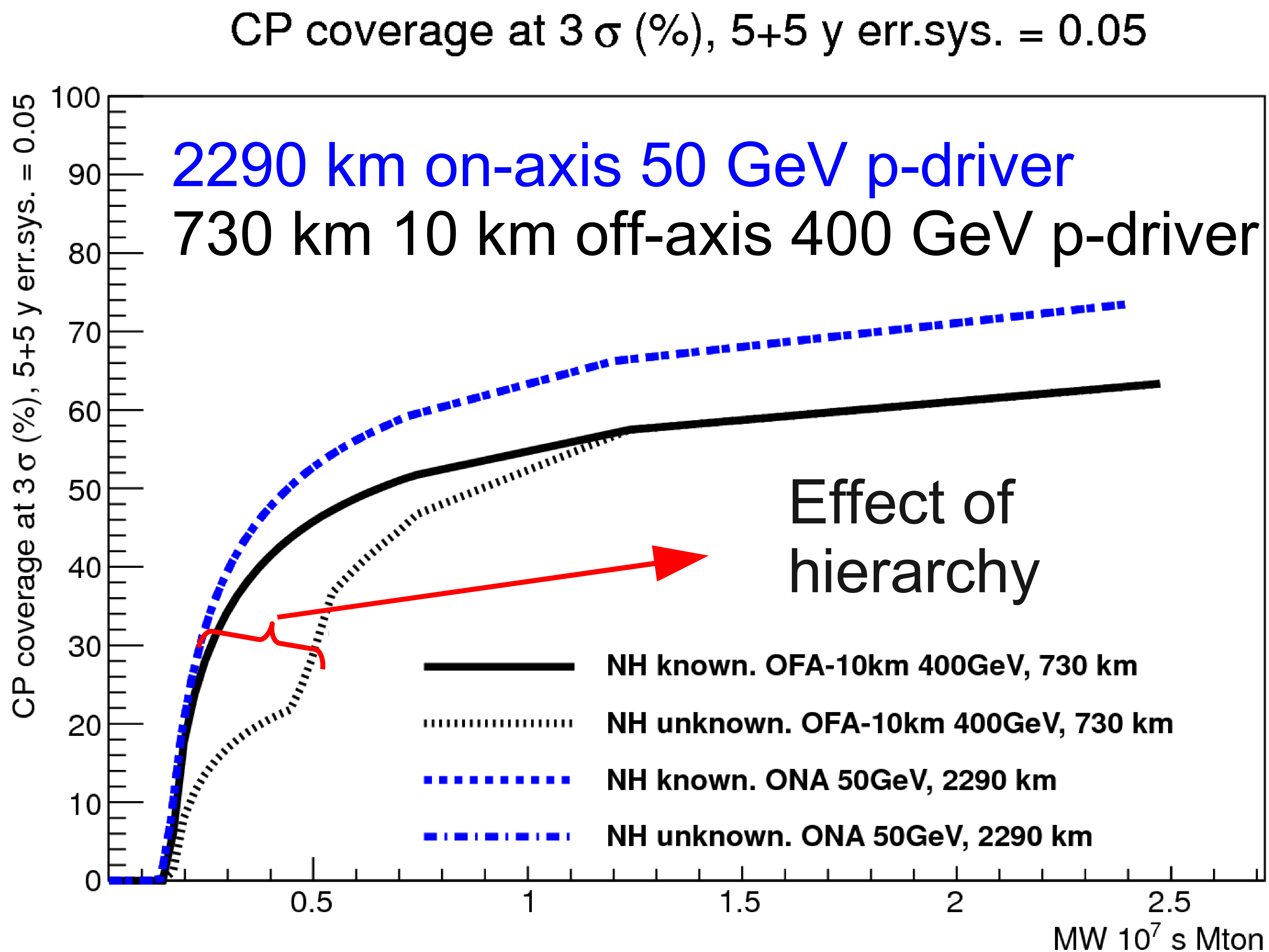
deposited energy in fiducial volume

neutrino energy



CCNuE resolution
(vertex in center of detector): 8.7% RMS

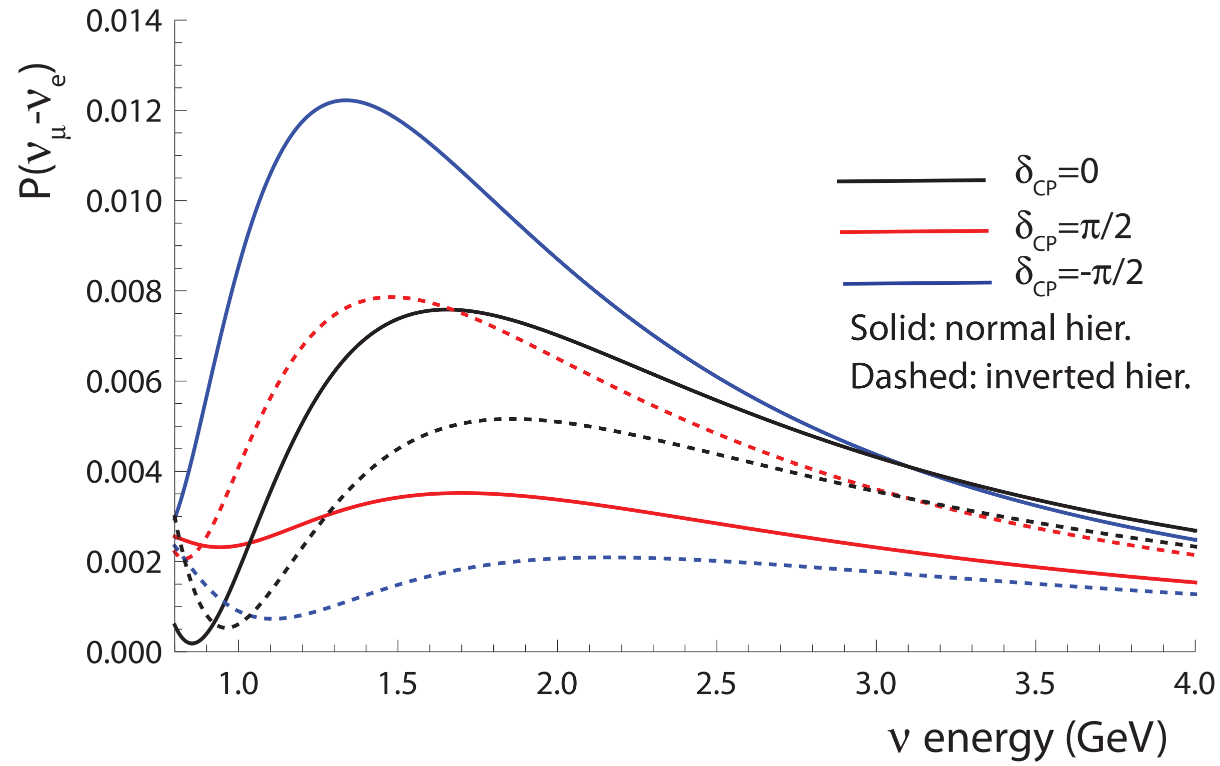
Comparison with Okinoshima beam study:
without π-mass corr.: 8.5% RMS



A. Longhin et al., NUTurn12

CPV vs. mass hierarchy

At 730 km matter effects are sizable. Probabilities differ.
Note however as the normal hierarchy $\delta_{\rm CP} = 0$ probability is very similar to inverse hierarchy $\delta_{\rm CP} = \pi/2$, $\Rightarrow$ very difficult to experimentally disentangle the two.



Let's move at 2500 km where the matter effects are bigger. Note how the two probabilities are more different and note how their behavior is very much different at the second oscillation maximum.