LAgvnA

LAGUNA/LBNO

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on behalf of LAGUNA-LBNO

16th LOMONOSOV CONFERENCE ON ELEMENTARY PARTICLE PHYSICS

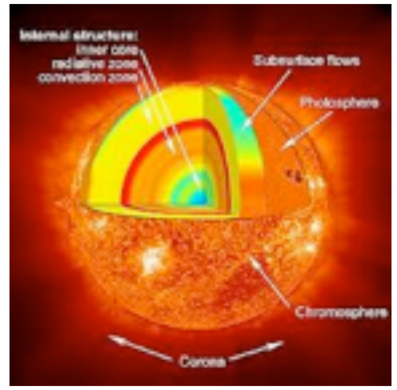
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

State University, Moscow, August 22-28th, 2013

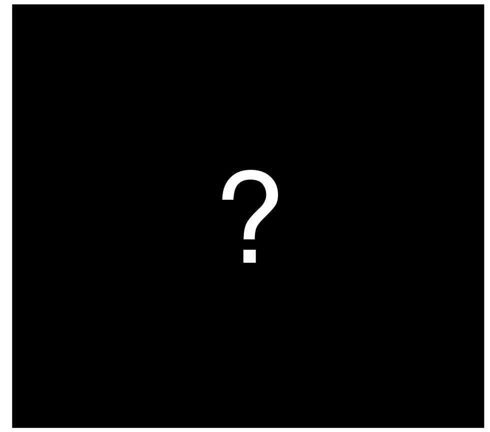
v1

Goal: neutrino underground observatory

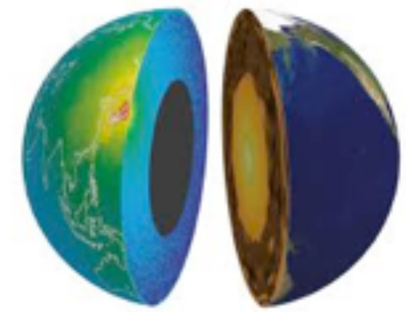
Supernova



Sun

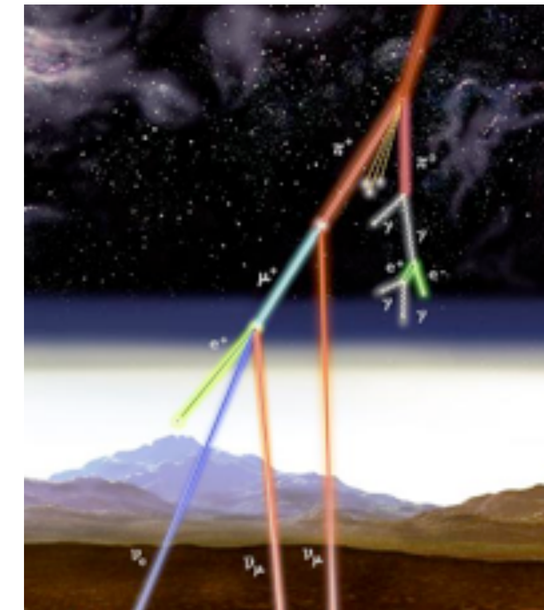


Unknown ?



Earth

Atmosphere



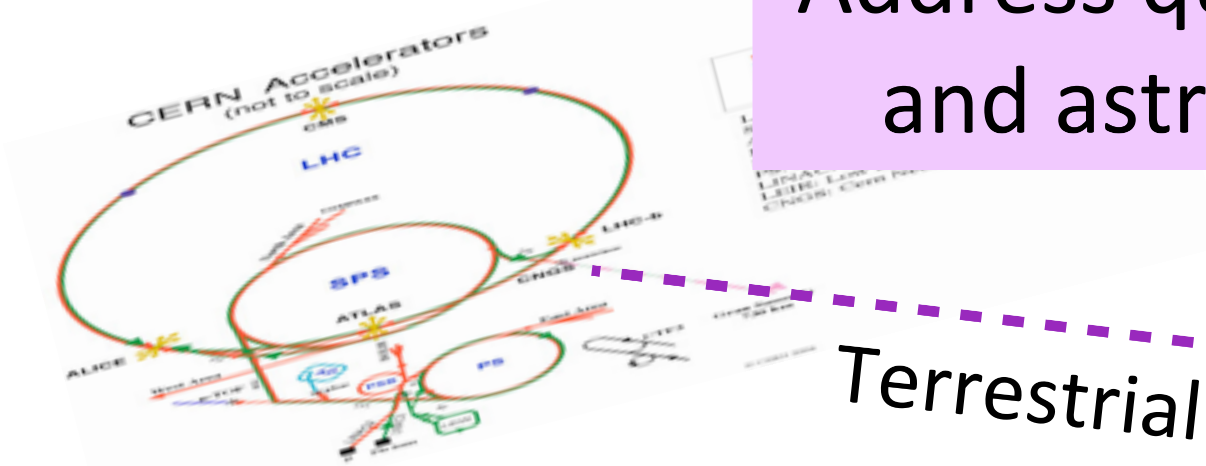
Neutrinos from MeV to 10’s GeV

Neutrino oscillations → MH, CPV, precision

Proton lifetime

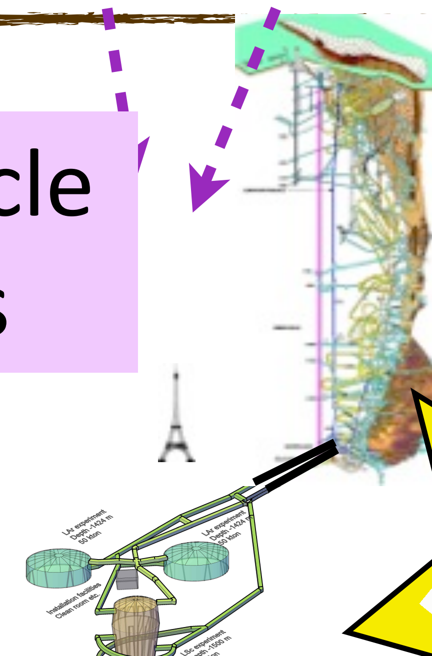
Reactors

Address questions of particle and astroparticle physics



Accelerators

Terrestrial baseline



Deep underground

Proton decays

The LAGUNA history

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

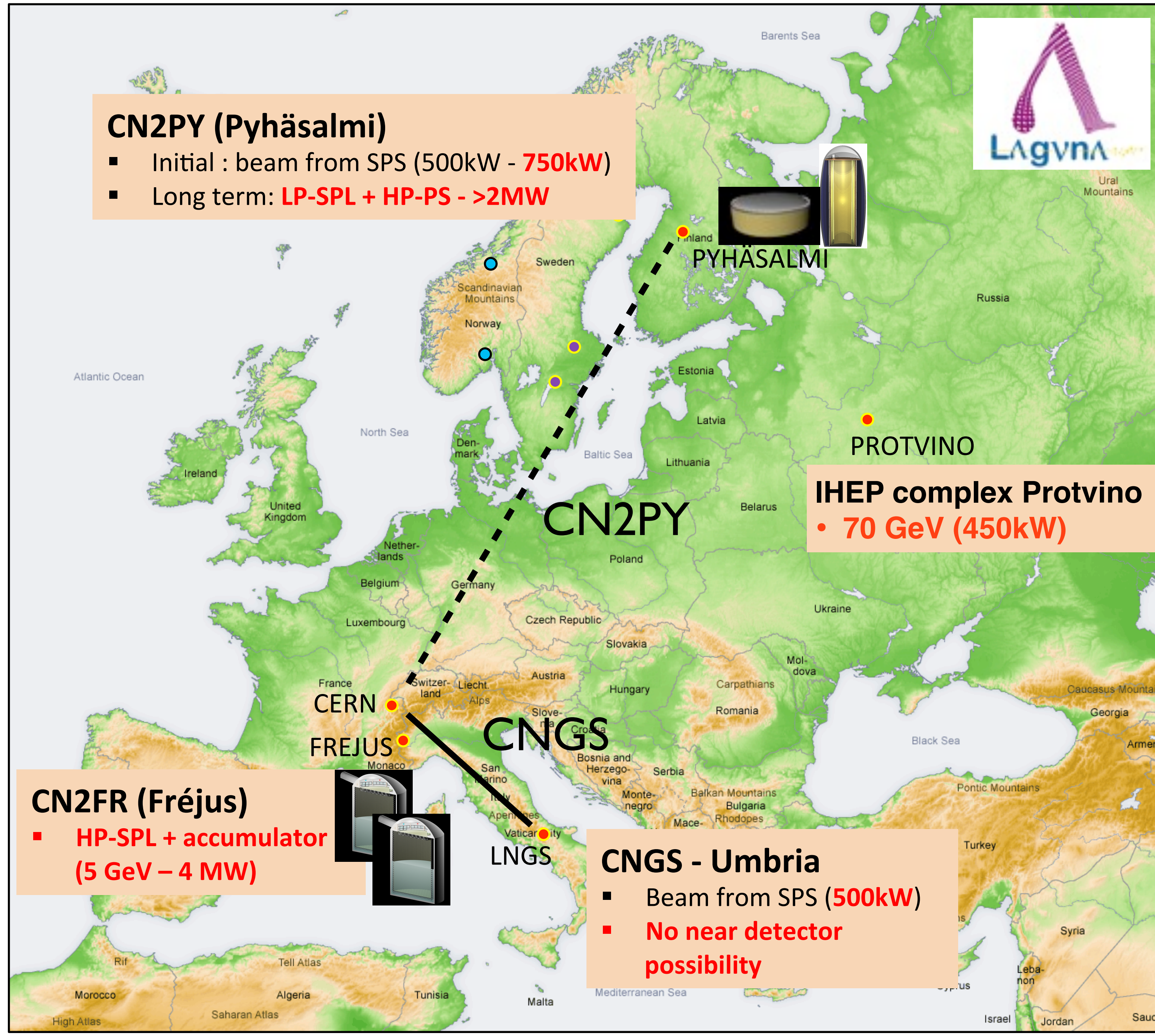
- **LAGUNA DS** (FP7 Design Study 2008-2011)
  - ~100 members; 10 countries
  - 3 detector technologies ⊗ 7 sites, different baselines (130 → 2300km)
- **LAGUNA-LBNO DS** (FP7 DS Long Baseline Neutrino Oscillations, 2011-2014)
  - ~300 members; 14 countries + CERN
  - Down selection of sites & detectors
- **LENA** (Low Energy Neutrino Astrophysics "Whitepaper", March 2012)
  - Focused at low energy (MeV) region, with GeV range physics complementary to LBNO
  - ~80 authors; 36 institutions
- **LBNO** (CERN SPSC EoI for a very long baseline neutrino oscillation experiment, June 2012)
  - Consensus towards full long baseline physics + full astroparticle as mandatory physics drivers
  - An incremental approach with clear phase 1 physics capabilities
  - ~230 authors; 51 institutions
  - CERN-SPSC-2012-021 ; SPSC-EOI-007, under review

LAGUNA-LBNO: sites overview

Three far sites considered in details

arXiv:1003.1921 [hep-ph]

- **Option 1: Pyhäsalmi mine** (privately owned), 4000 m.w.e overburden, excellent infrastructure for deep underground access
- **Option 2: Fréjus**, nearby road tunnel, 4800 m.w.e. overburden, horizontal access
- **Option 3: Umbria** (LNGS extension), green site with horizontal access, 2000 m.w.e., CNGS off-axis beam
- **Protons and beams:**
  - Design of new CERN conventional neutrino beam to Finland (CN2PY) Baseline = 2300 km
  - Upgrades of CERN SPS to 700kW
  - New CERN HP-PS (2MW@50 GeV)
  - **Recently**: assessment of a new conventional beam coupled to accelerator upgrade at Protvino, Russia (OMEGA project) – Baseline = 1160 km



- **Detector options:** 20, 50, 100 kton LAr; 50 kton LSc and 540 kton WCD

LBNO (CERN SPSC-EOI-007)

http://cdsweb.cern.ch/record/1457543

- **In June 2012, an enlarged LAGUNA-LBNO Consortium has put forward an Expression of Interested to CERN, focused on neutrino Mass Hierarchy determination and CPV discovery coupled to a full astrophysics programme at the Pyhäsalmi (Finland) site**
  - Based on the findings of several design studies – LAGUNA/LAGUNA-LBNO and EUROν.
  - Supported by rock, civil, detector engineering designs and many years of detector R&D
- **An incremental long-baseline program with a competitive 1st stage guaranteeing high level physics performance from the beginning.**
  - LBNO Stage 1 is based on a 20 kt fid. LAr detector (double phase) and a conventional beam from the CERN SPS of 700 kW at 2300 km.
  - If the findings from Stage 1 require, the detector and the beam will be upgraded to 70 kton mass and 2 MW proton power.
  - The costs, possible implementation schemes and physics potentials will be further studied until the end of 2014.
- **Initial positive feedback from SPSC (108^{th} minutes, January 2013)**
  - **The SPSC supports the physics case and recognises its timely relevance in the rapidly evolving neutrino physics landscape.**
  - **SPSC notes that the Finnish Government could not commit to host LAGUNA-LBNO in the proposed Pyhäsalmi site**
  - **SPSC supports double phase LAr TPC as promising technique for future LBL**
  - **SPSC encourages LBNO to proceed with necessary R&D for validation of double phase LAr TPC on large scale**

LBNO Expression of Interest

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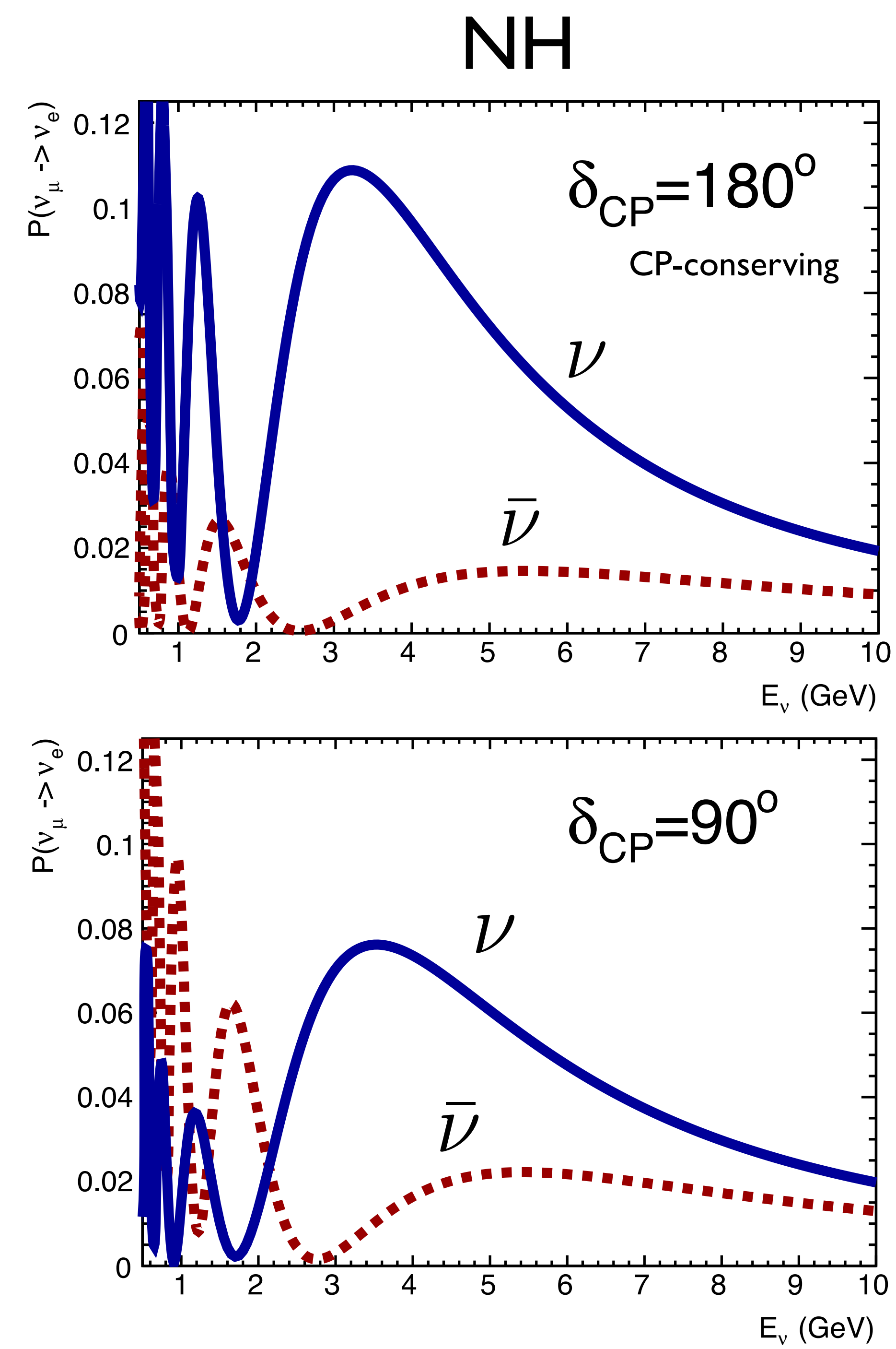
LBNO main physics goals

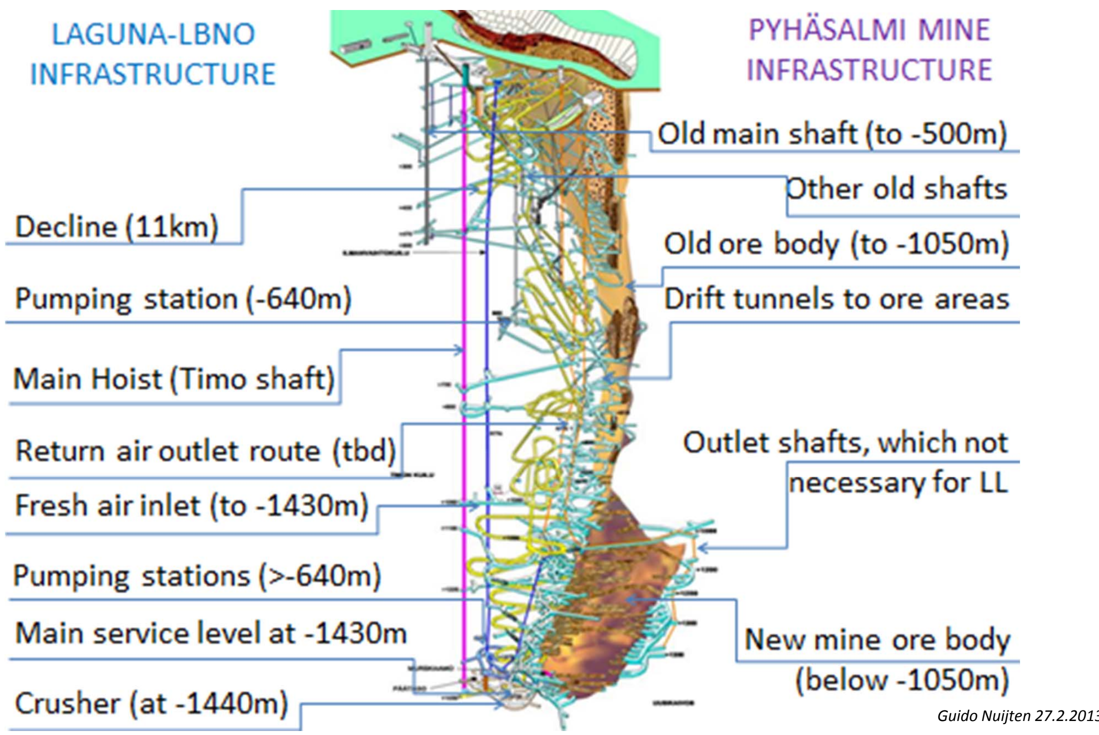
- **Long baseline neutrino oscillations**
  - $\nu\mu \rightarrow \nu e$ & $\nu\mu \rightarrow \nu\tau$ & $\nu\mu \rightarrow \nu\mu$ & νNC
  - Direct measurement of the energy dependence (L/E behaviour) induced by matter effects and CP-phase terms, independently for ν and anti-ν, by direct measurement of event spectrum, in particular covering 1st and 2nd oscillation maxima
  - Mass hierarchy determination at >5σ C.L. in first two years of running
  - CP-phase measurement and CPV “discovery” (⇒ 5σ C.L.)
  - Test of three generation mixing paradigm

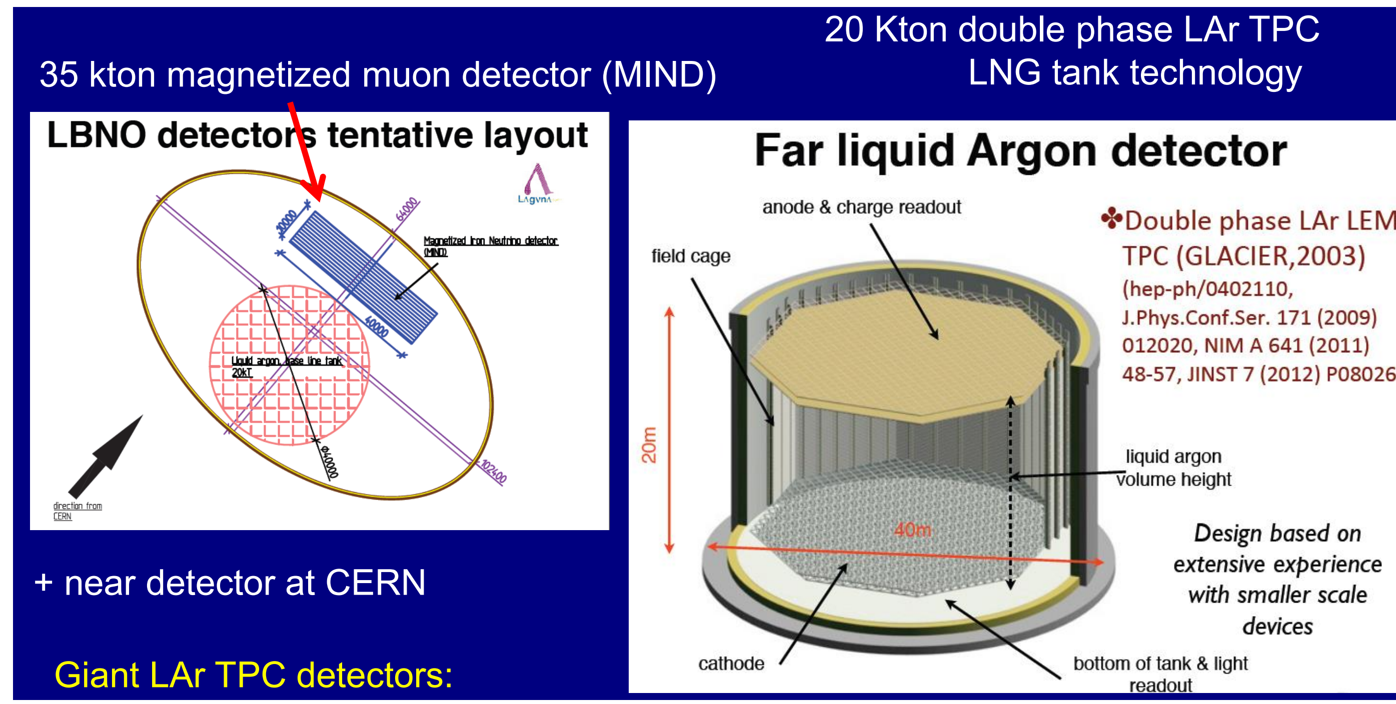


- **A full astrophysics programme**
- Nucleon decays (direct GUT evidence)
- Atmospheric neutrino detection with complementary oscillation measurements and Earth spectroscopy
- Astrophysical neutrino detection and searches for new sources of neutrinos

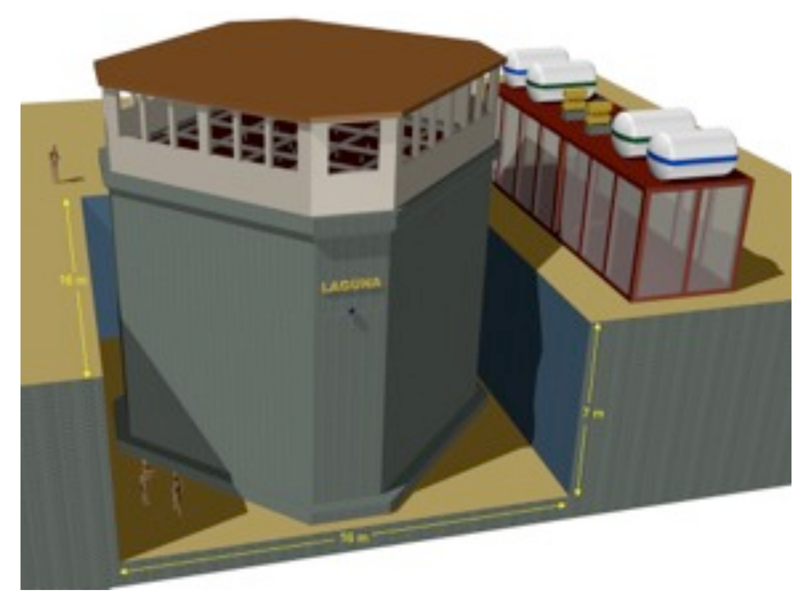
LBNO far site and detectors

- The LAGUNA LBNO collaboration is in the most advanced state for what concerns all technical implementation and site studies, costing and prototyping.
- The Pyhäsalmi site is extremely convenient (baseline, infrastructures, depth, excavation aspects). An extended site investigation is progressing well (750 m drilled) ➞Discussions will continue with Finland in order to define its real contribution, after some initial misunderstanding. Alternative sites in Scandinavia are been looked into.



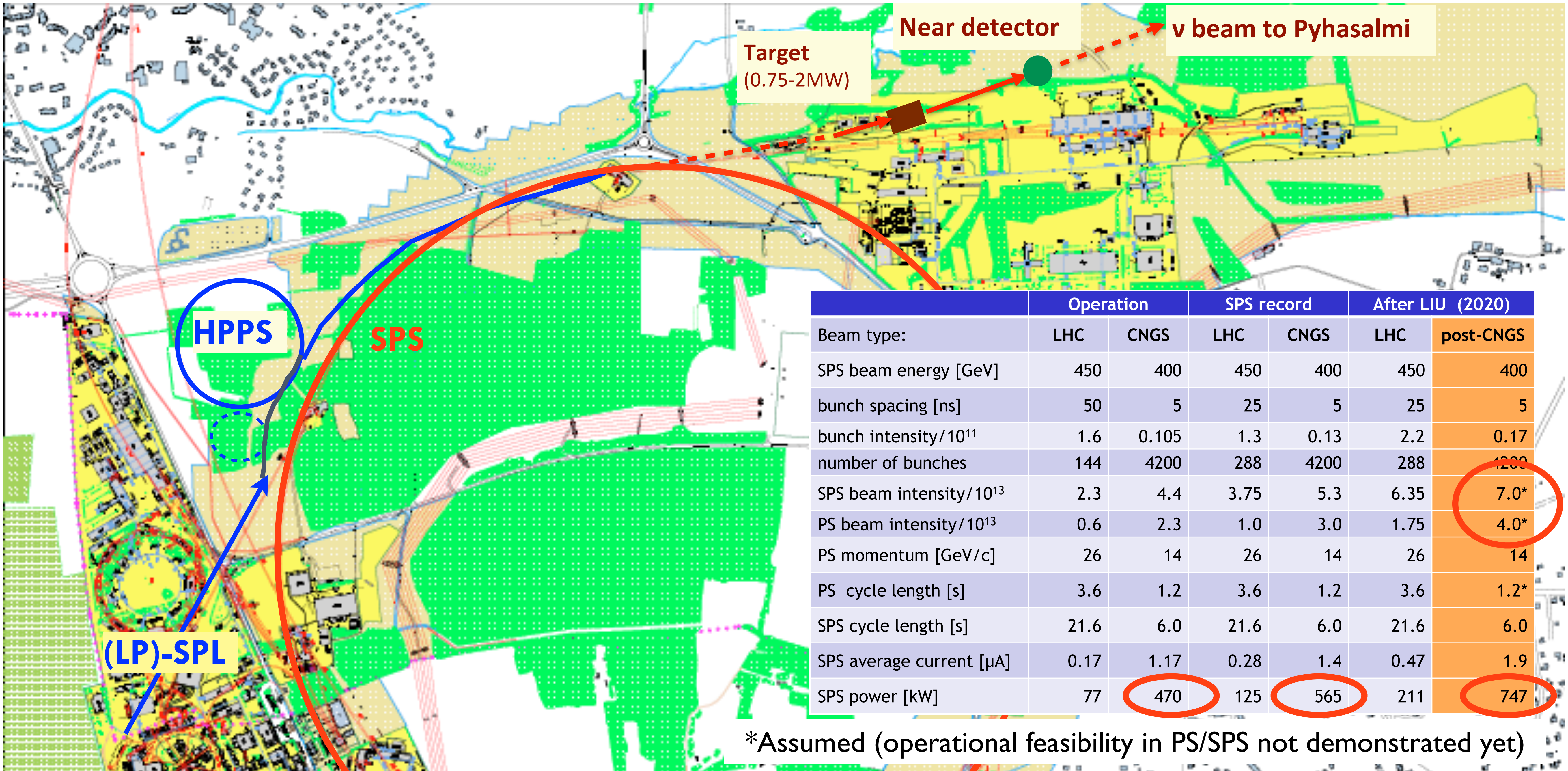


- **Next milestone: Large-scale LBNO detectors prototyping at CERN, with priority emphasis on a large double-phase LAr demonstrator, using charged-particle test beams (2014-2017).**



The CN2PY beam

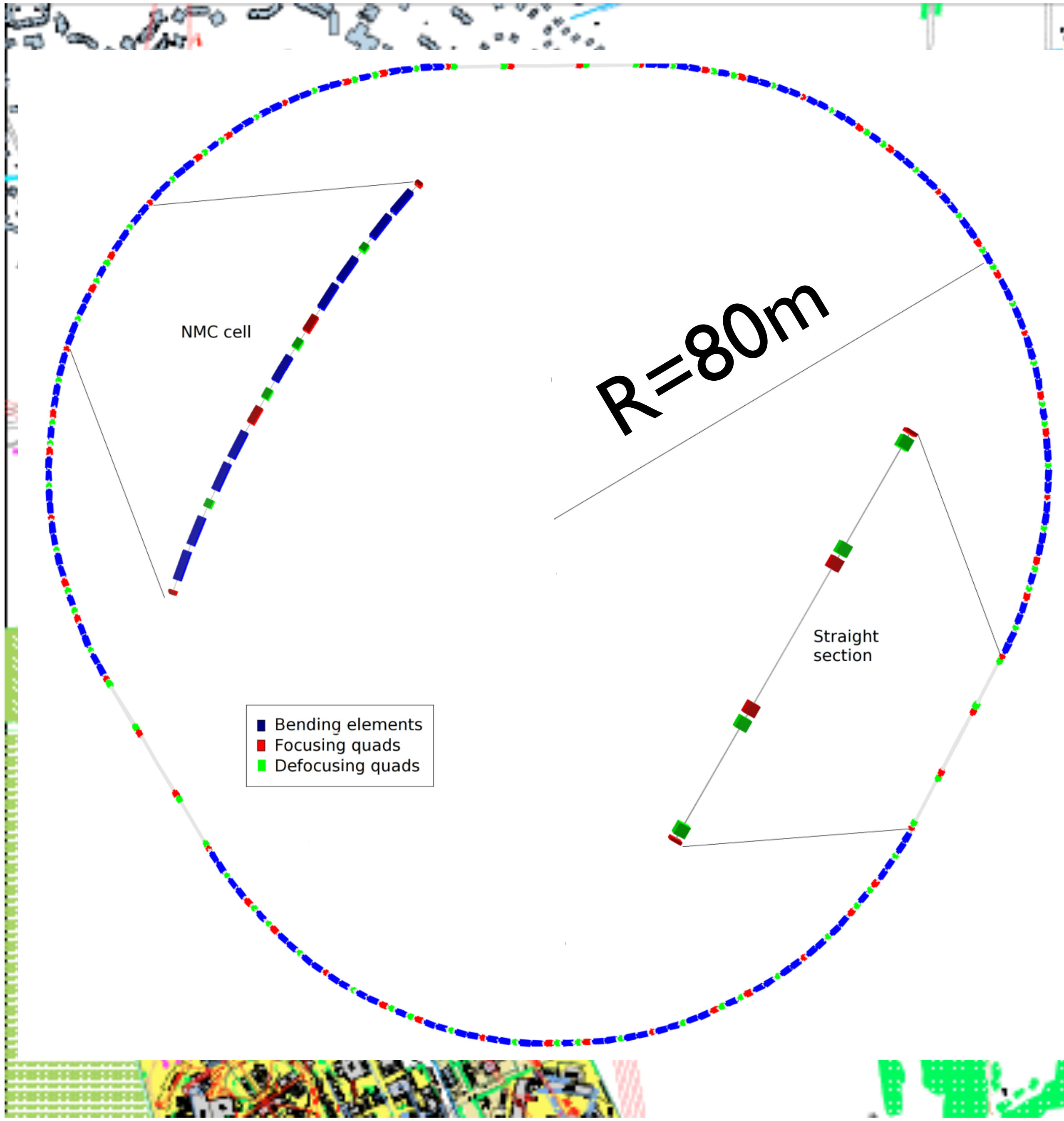
- **Phase 1** : use the proton beam extracted beam from SPS
  - **400 GeV**, max 7.0 10^{13} protons every 6 sec, **750 kW** nominal beam power, 10 µs pulse
  - Yearly integrated pot = (8–13)e19 pot / yr depending on “sharing” with other fixed target programmes.
- **Phase 2** : use the proton beam from the new HP-PS
  - **50**(70) GeV, 1 Hz, 2.5e14 ppp, **2 MW** nominal beam power, 4 µs pulse

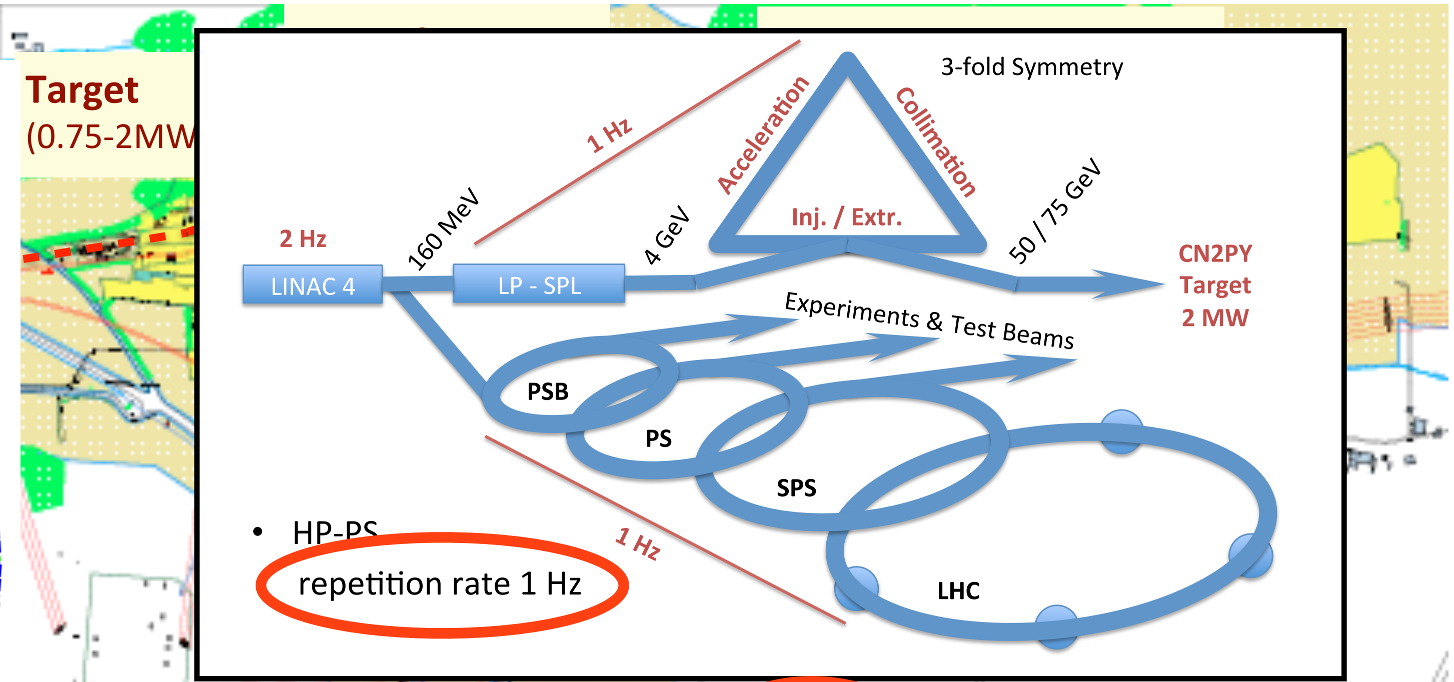


	Operation		SPS record		After LIU (2020)	
Beam type:	LHC	CNGS	LHC	CNGS	LHC	post-CNGS
SPS beam energy [GeV]	450	400	450	400	450	400
bunch spacing [ns]	50	5	25	5	25	5
bunch intensity/10^{11}	1.6	0.105	1.3	0.13	2.2	0.17
number of bunches	144	4200	288	4200	288	4200
SPS beam intensity/10^{13}	2.3	4.4	3.75	5.3	6.35	7.0*
PS beam intensity/10^{13}	0.6	2.3	1.0	3.0	1.75	4.0*
PS momentum [GeV/c]	26	14	26	14	26	14
PS cycle length [s]	3.6	1.2	3.6	1.2	3.6	1.2*
SPS cycle length [s]	21.6	6.0	21.6	6.0	21.6	6.0
SPS average current [µA]	0.17	1.17	0.28	1.4	0.47	1.9
SPS power [kW]	77	470	125	565	211	747

*Assumed (operational feasibility in PS/SPS not demonstrated yet)

High power HP-PS study



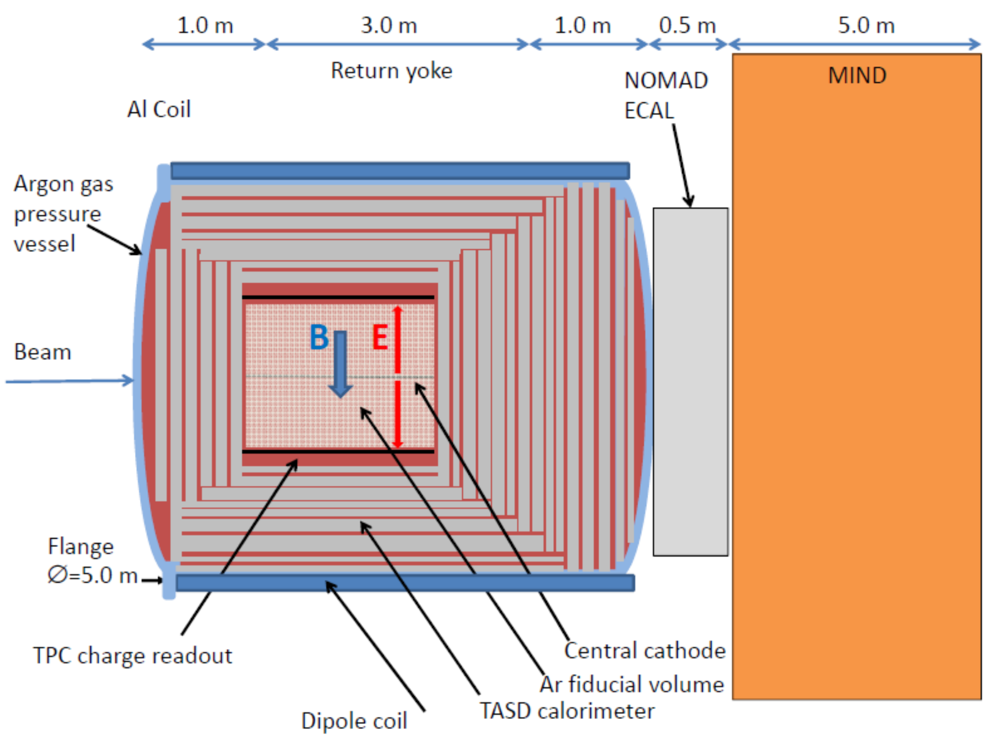


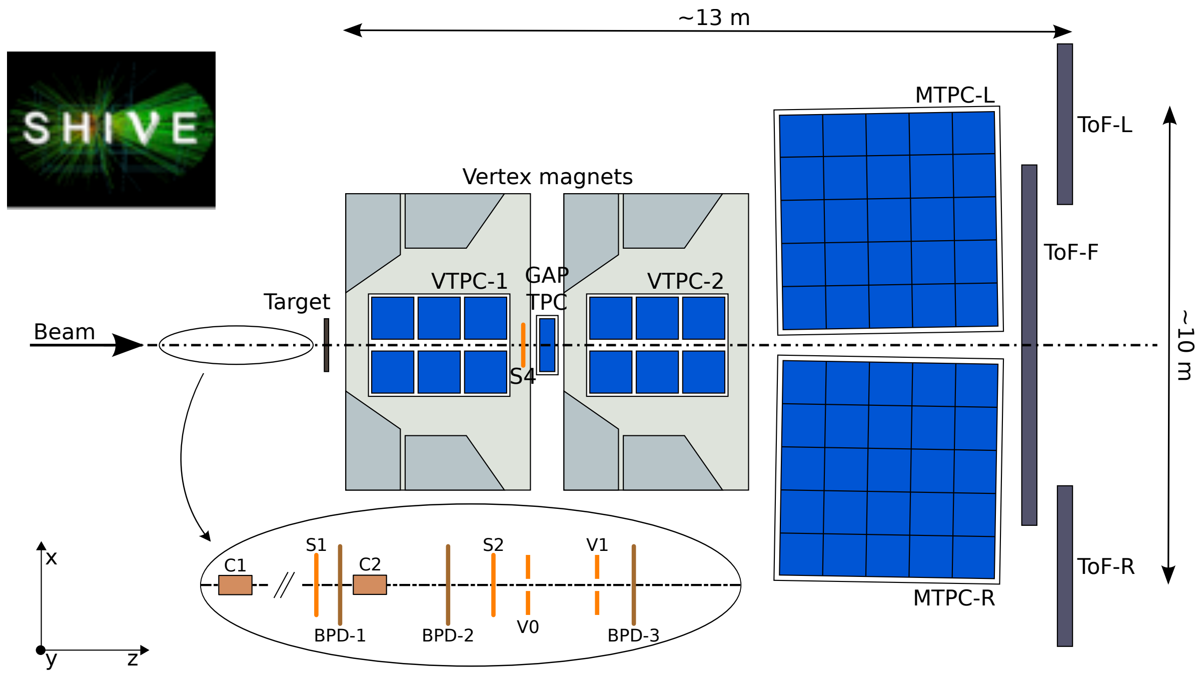
Parameter	50 GeV	75 GeV	Units
Inj. / Extr. Kinetic Energy	4 / 50	4 / 75	[GeV]
Beam power	2		[MW]
Repetition rate	1		[Hz]
f_{rev} / f_{RF} @ inj.	0.248 / 38.97		[MHz]
RF harmonic	157		-
f_{rev} / f_{RF} @ extr.	0.255 / 40.08	0.255 / 40.09	[MHz]
Bunch spacing @ extr.	25		[ns]
Total beam intensity	2.5×10^{14}	1.7×10^{14}	-
Number of bunches	147		-
Intensity per bunch	1.7×10^{12}	1.25×10^{12}	-
Main dipole field inj. / extr.	0.17 / 2.1	0.17 / 3.13	[T]
Ramp time	500	500	[ms]
Dipole field rate dB/dt (acc. ramp)	3.9	5.9	[T/s]

- Basic design well underway and main parameters available
- Optics design well advanced
- Injection and extraction concepts are available
- Basic ideas about accelerating RF system
- Basic ideas about collimation
- Consolidate optics and establish set of requirements for different magnet families.
- Design of magnet foreseen.

LBNO near detector and hadroproduction

- **Aim: systematic errors for signal and backgrounds in the far detectors below ±5%, possibly at the level of ±2% ⇒ control of fluxes, cross-sections, efficiencies,...**



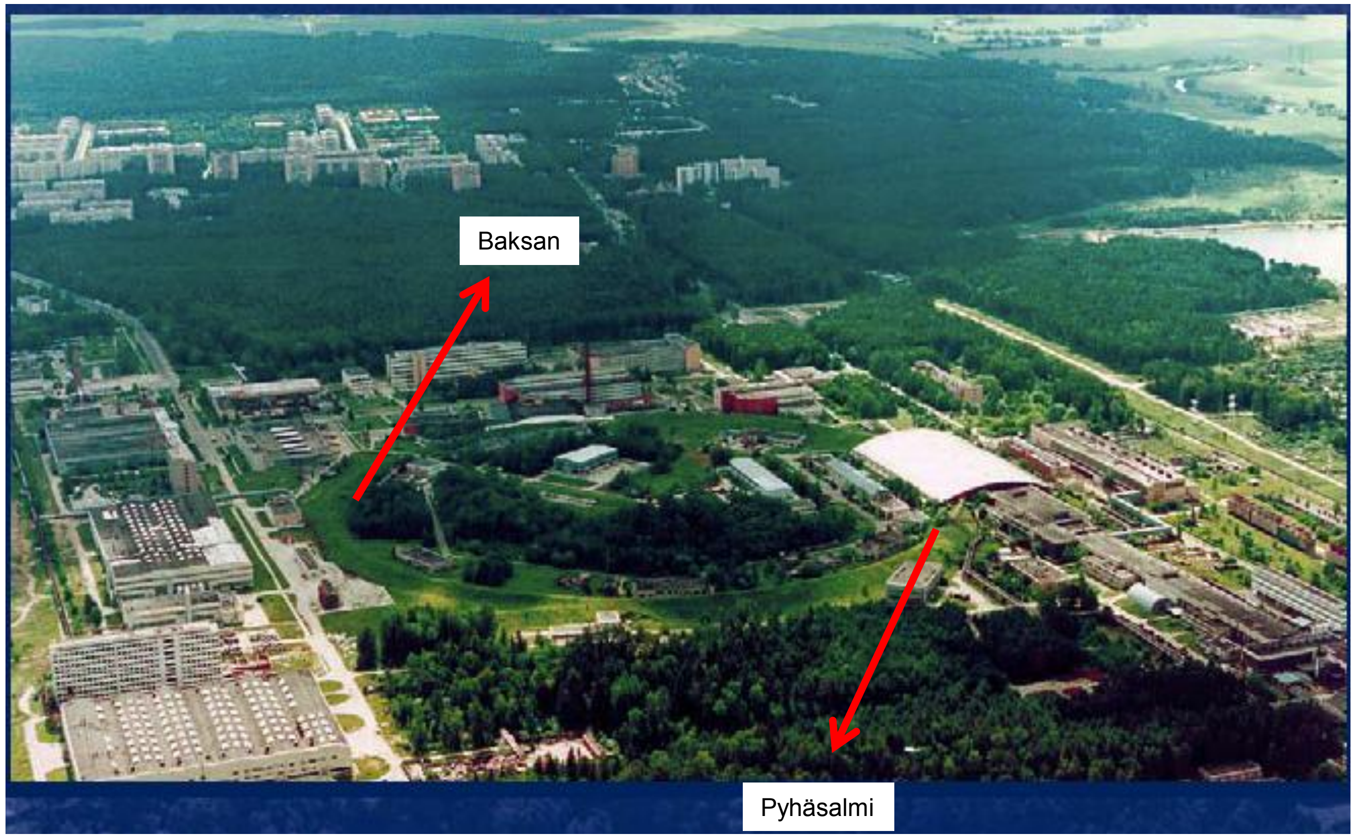


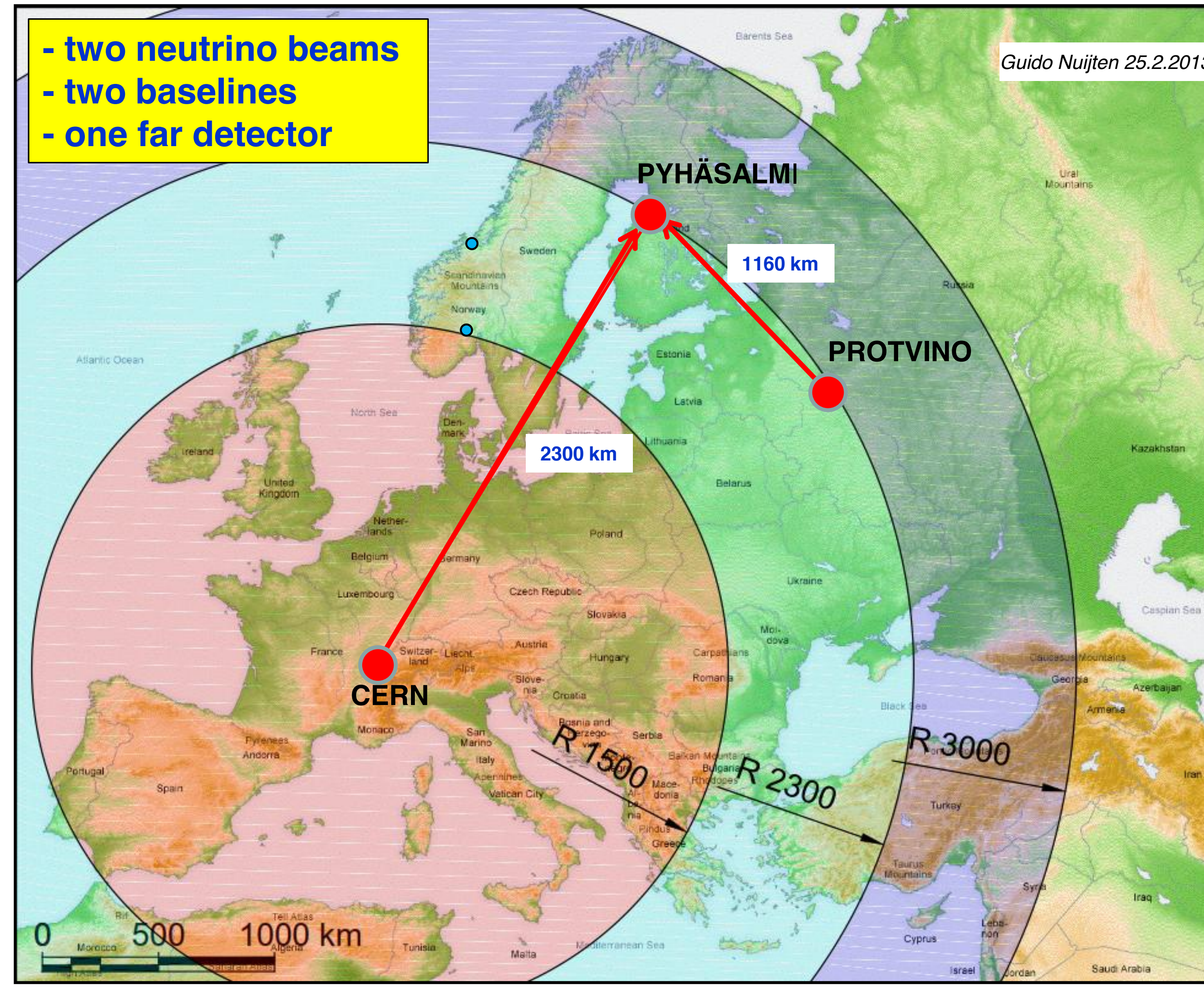
- Concept: 20 bar gas argon-mixture TPC (2.4 m × 2.4 m × 3 m) surrounded by scintillator bar tracker embedded in an instrumented magnet with field 0.5T
- 600 kg argon mass in TPC
- 0.2 event/spill @ 7e13 ppp 400 GeV
- O(100'000) events/year

- It is widely recognized that hadro-production measurements with thin or replica target are really crucial for precision neutrino experiments (eg. K2K, T2K, MINOS).
- CERN NA61 upgrade needed for 400 GeV incident protons

- Precision neutrino cross-section measurements: e.g. MINERVA, T2K-ND280, also nuSTORM

Possibility of neutrinos from Protvino

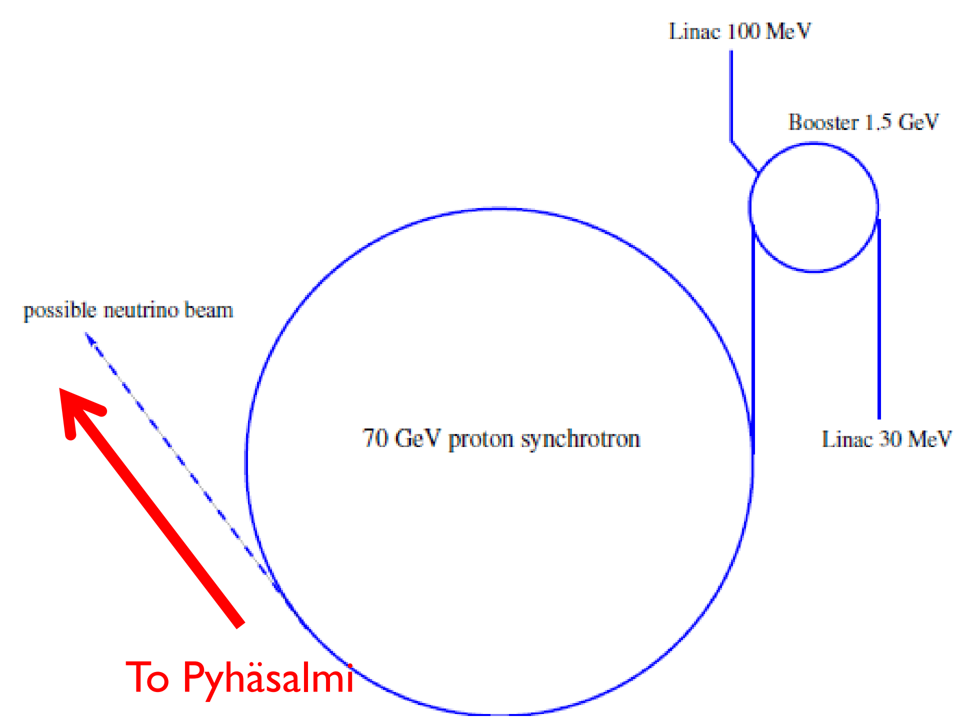




Assumed parameters for neutrino beam:

Proton energy	70 GeV
Repetition rate	0.2 Hz
Intensity	2.2×10^{14} ppp
Power	450 kW
Neutrino channel	200-300 m
Angle to Pyhäsalmi	5.2 deg
Distance to ND	500 - 750 m
ND depth (at 500m)	46 m

≈1800 $\nu\mu$ CC / 20 kton / year (no osc.)



Rich MH & CP phenomenology

- **First order approximation in expansion (Sato et al.):**

$$P(\nu_\mu \to \nu_e; L) \simeq 4c_{13}^2 s_{13}^2 s_{23}^2 \left\{1 + \frac{a}{\delta m_{31}^2}\cdot 2(1-2s_{13}^2)\right\} \sin^2\frac{\delta m_{31}^2 L}{4E}$$

$$+ c_{13}^2 s_{13} s_{23} \left\{-\frac{aL}{E} s_{13}s_{23}(1-2s_{13}^2) + \frac{\delta m_{21}^2 L}{E} s_{12}(-s_{13}s_{23}s_{12} + c_\delta c_{23} c_{12})\right\} \sin\frac{\delta m_{31}^2 L}{2E}$$

$$-4\frac{\delta m_{21}^2 L}{2E} s_\delta c_{13}^2 s_{13} c_{23} s_{23} c_{12} s_{12} \sin^2\frac{\delta m_{31}^2 L}{4E}$$

Matter terms∼a

CP-even

L/E dependence

CP-odd∼sinδ

$$a \equiv 2\sqrt{2} G_F n_e E = 7.56\times 10^{-5}\mathrm{eV}^2 \frac{\rho}{\mathrm{g\,cm}^{-3}} \frac{E}{\mathrm{GeV}}$$

- **Difference between neutrinos and antineutrinos:**

$$\mathcal{A} \equiv P(\nu_\mu \to \nu_e) - P(\bar\nu_\mu \to \bar\nu_e) =$$

$$16\frac{a}{\delta m_{31}^2}\sin^2\frac{\delta m_{31}^2 L}{4E} c_{13}^2 s_{13}^2 s_{23}^2 (1-2s_{13}^2)$$

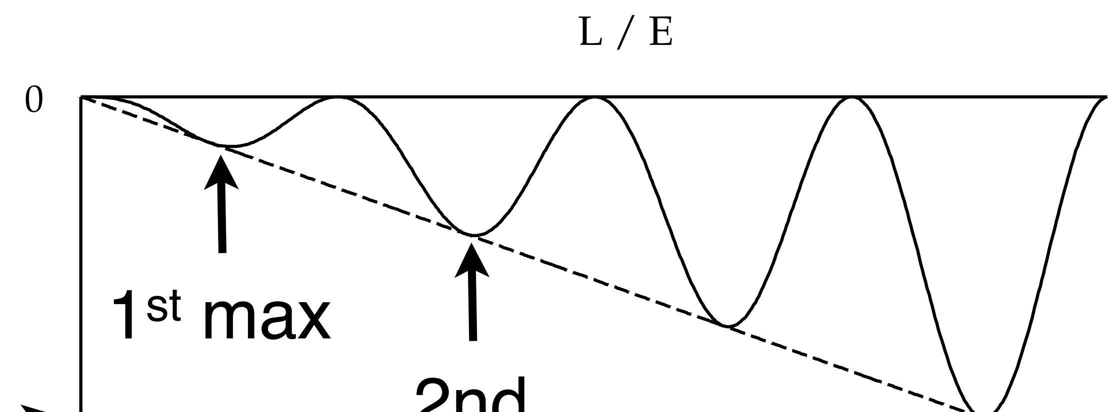
$$-4\frac{aL}{2E}\sin\frac{\delta m_{31}^2 L}{2E} c_{13}^2 s_{13}^2 s_{23}^2 (1-2s_{13}^2)$$

$$-8\frac{\delta m_{21}^2 L}{2E}\sin^2\frac{\delta m_{31}^2 L}{4E} s_\delta c_{13}^2 s_{13} c_{23} s_{23} c_{12} s_{12}$$

Matter terms

Pure CP-term

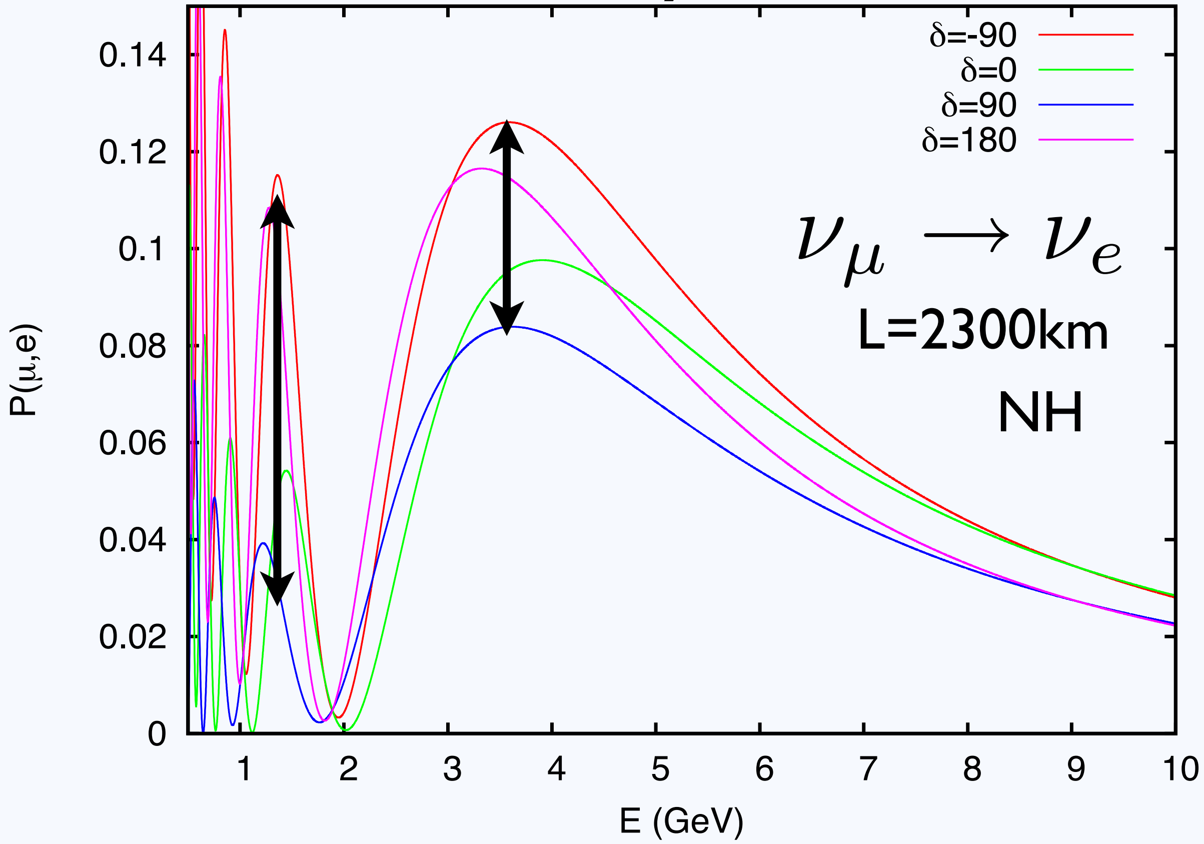
$$\left.\frac{P(\nu)-P(\bar\nu)}{P(\nu)+P(\bar\nu)}\right|_{a=0} \approx -\frac{2 s_\delta c_{12} s_{12}}{s_{13}} \cot\theta_{23} \frac{\delta m_{21}^2 L}{2E}$$

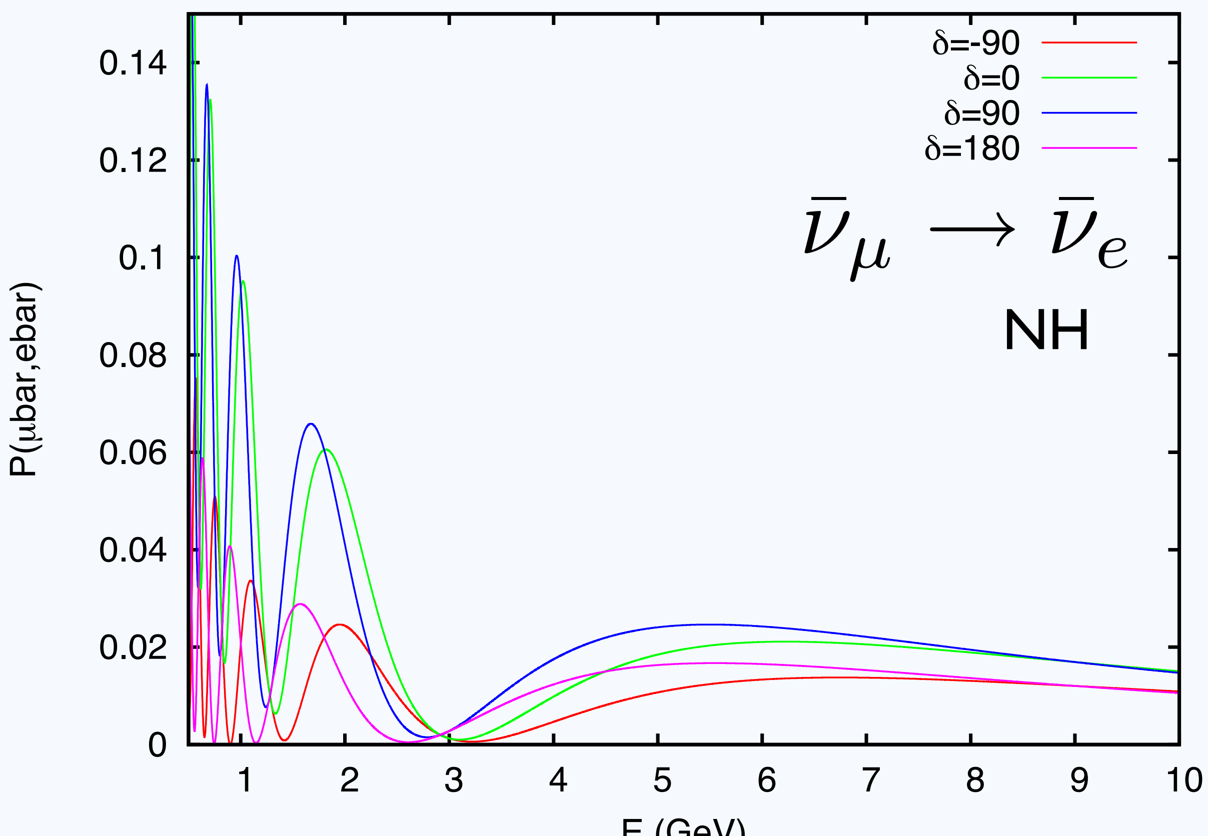


The enveloppe increases linearly with L/E

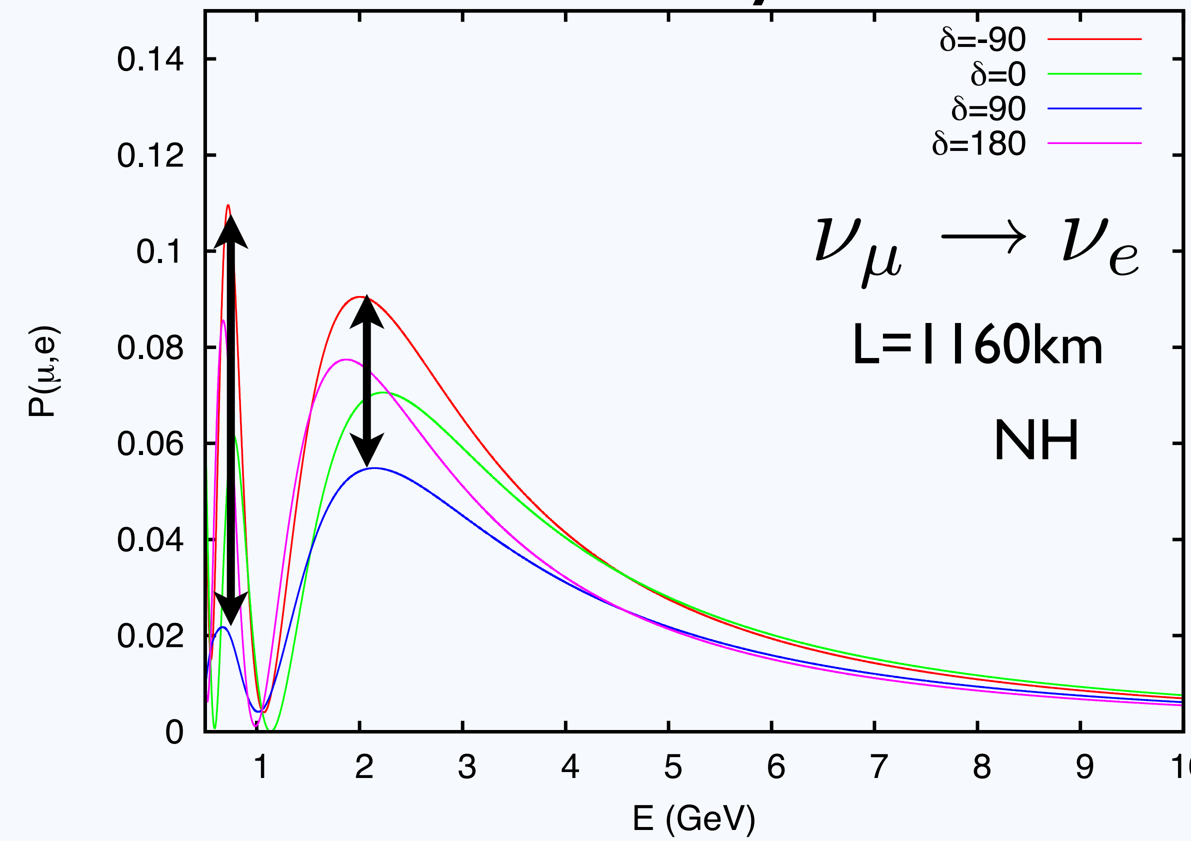
Expected oscillation probability

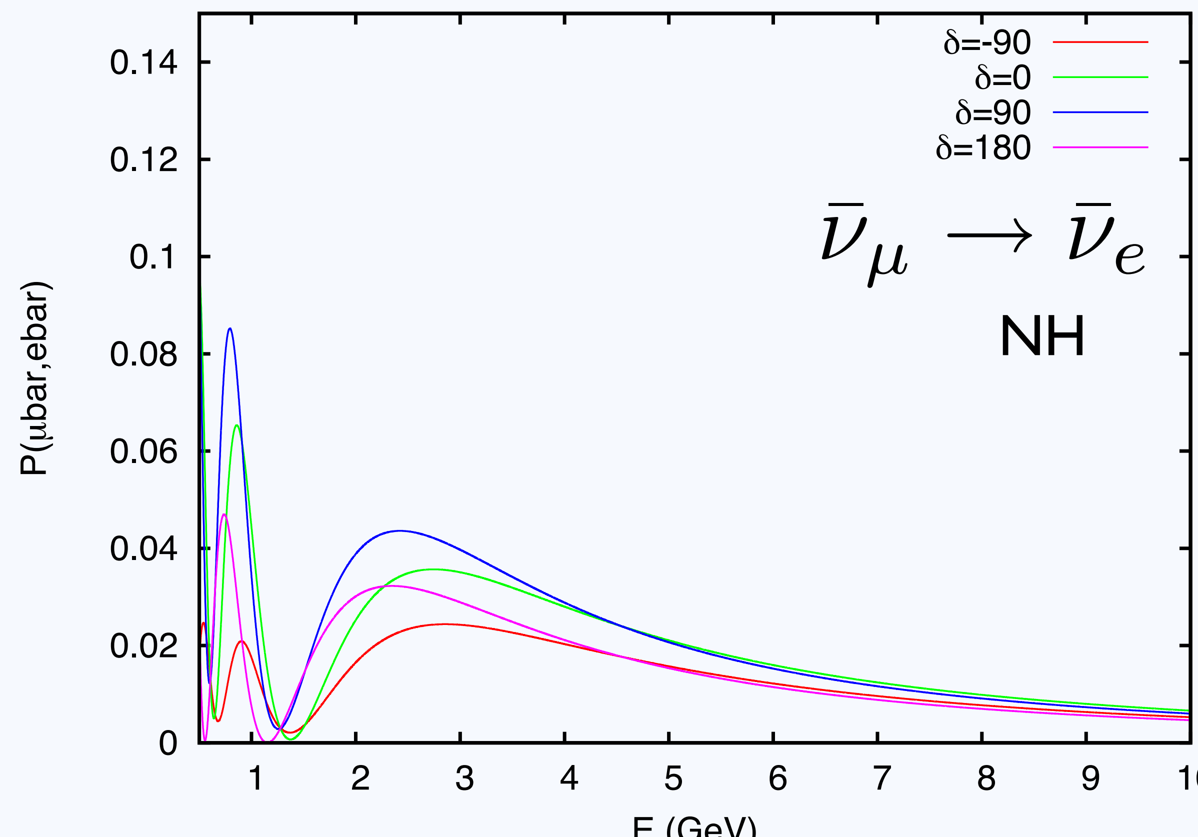
CERN-Pyhäsalmi





Protvino-Pyhäsalmi



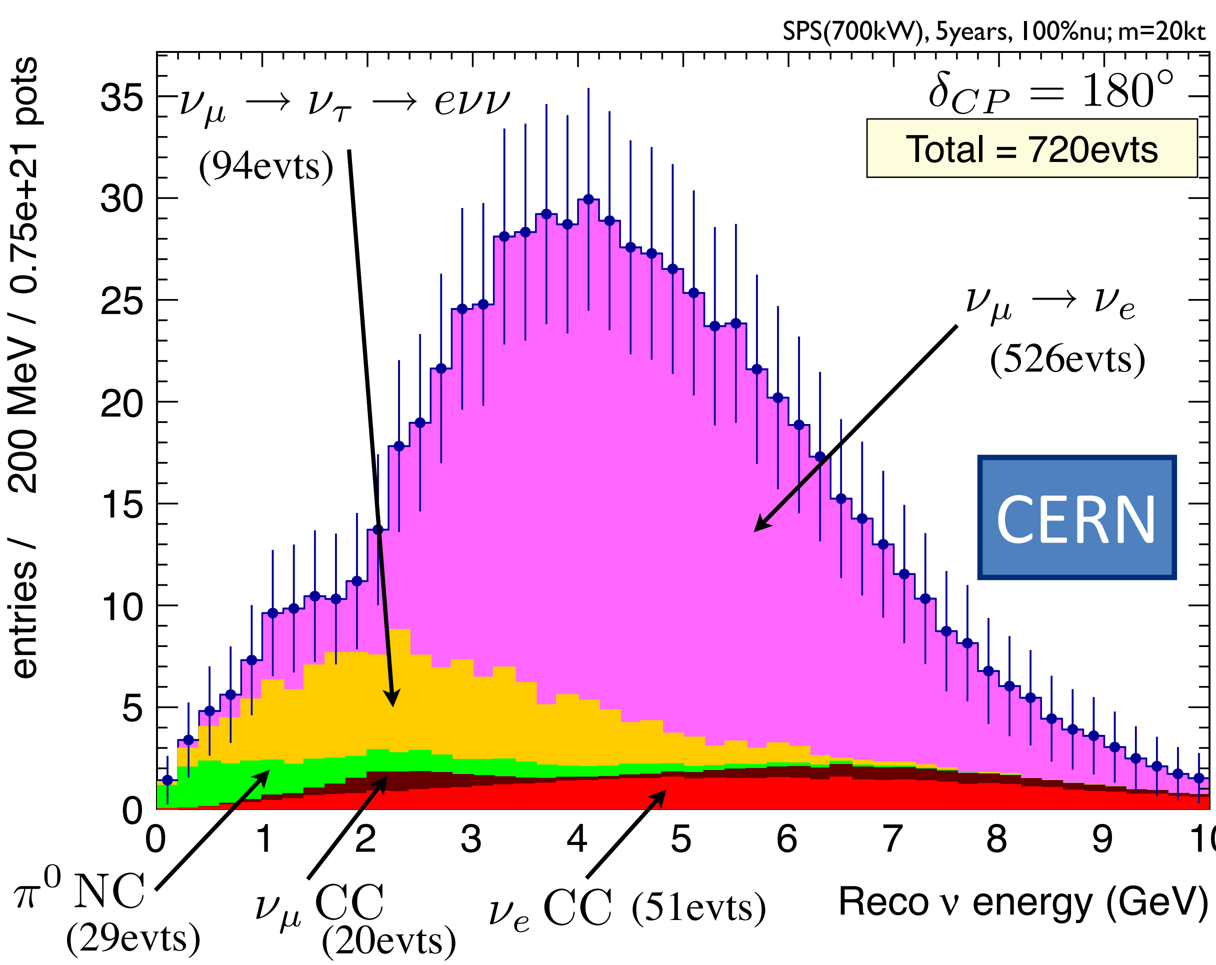


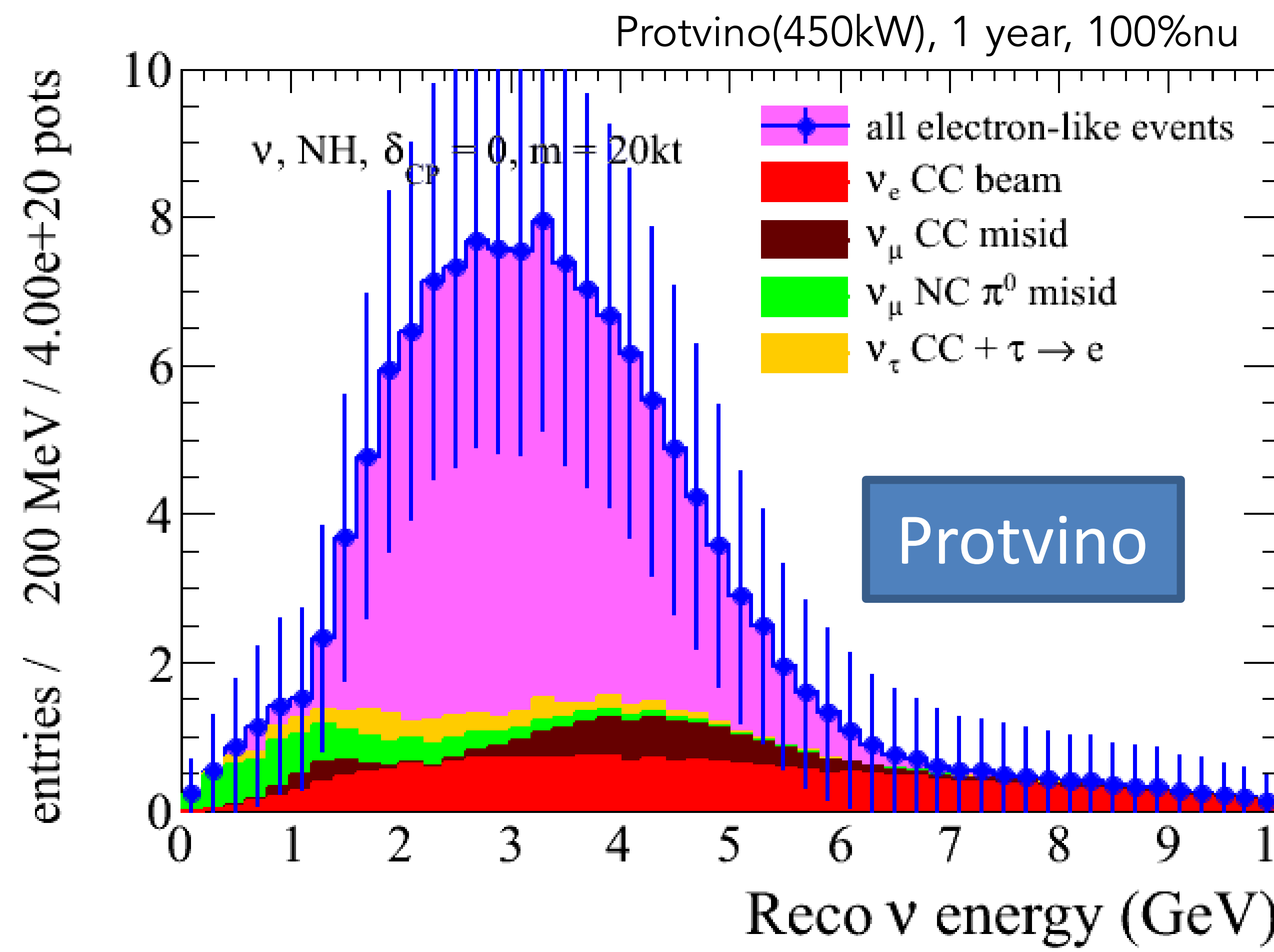
Event rates/year for 20 kton

POT normalisation
(corresponds events/1 year):

Protvino: 4e20 pot @ 70 GeV
CERN: SPS 1.5e20 pot @ 400GeV and HP-PS 3.5e21 pot @ 50 GeV

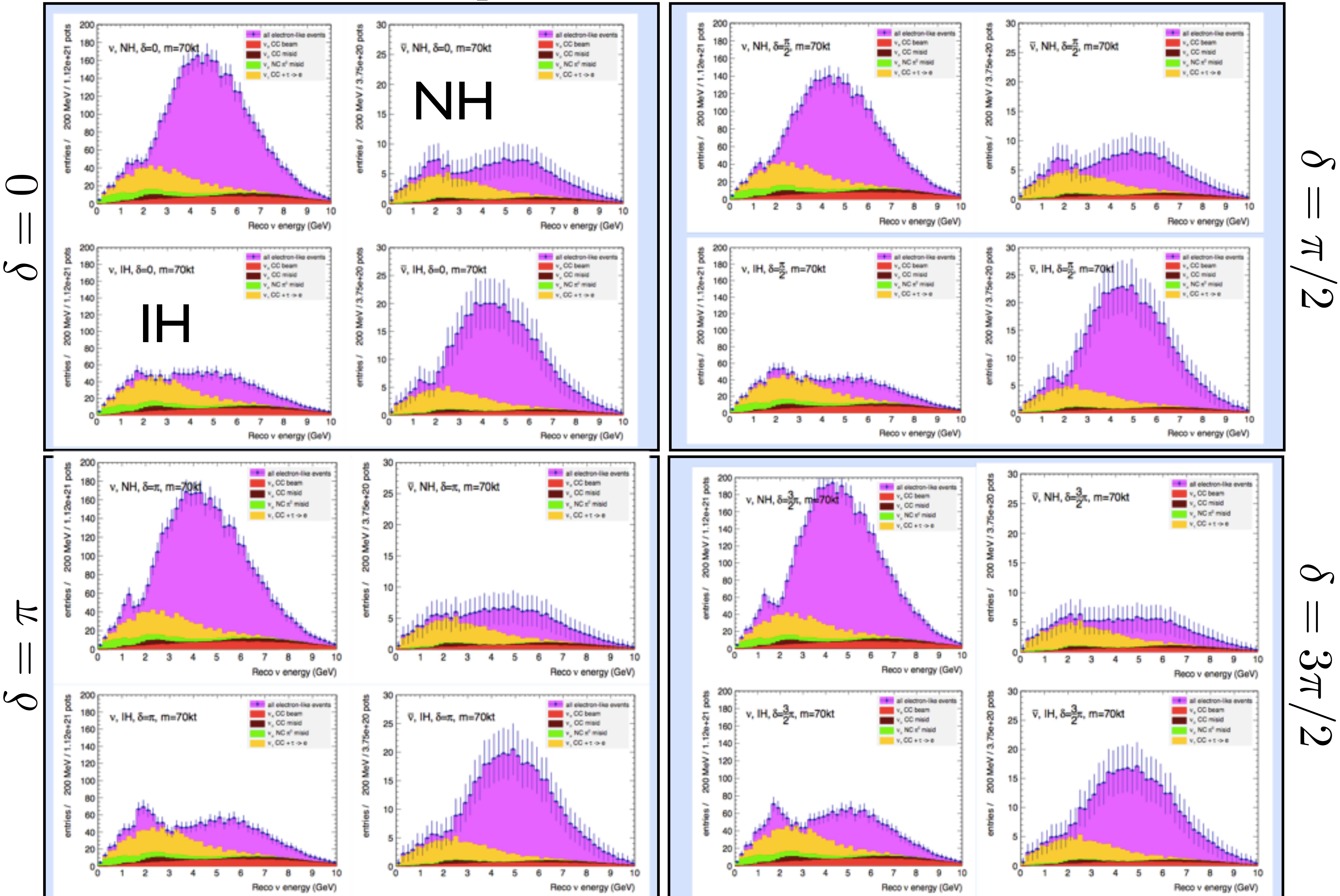
Nu beam	CERN SPS 700kW		CERN HP-PS 2MW		Protvino 450kW	
	ν_μ CC	$\nu_e+\bar{\nu}_e$ CC	ν_μ CC	$\nu_e+\bar{\nu}_e$ CC	ν_μ CC	$\nu_e+\bar{\nu}_e$ CC
NEUT					2056	21
GENIE	**1428**	10	**4007**	26	**1805**	18
GLOBES	1426	10	3975	26	1756	18





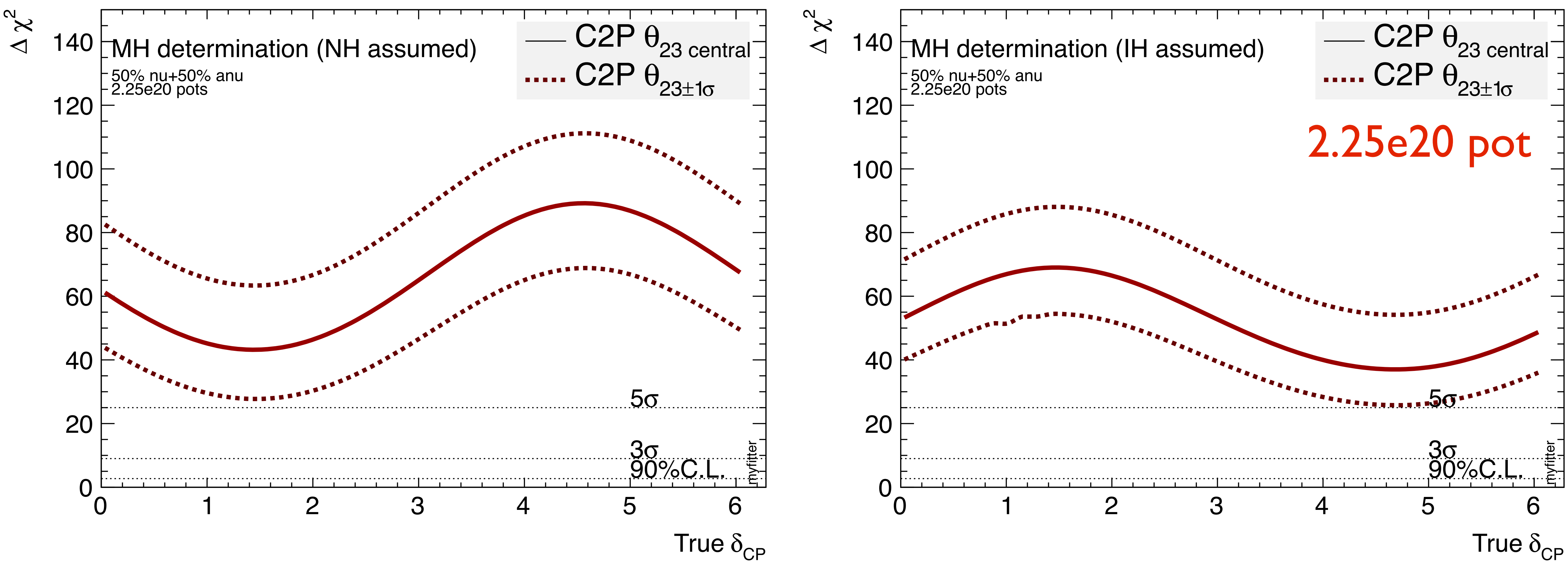
δ_{CP} & MH dependence

SPS(700kW), 10y, 75%nu-25%antinu; m=70kt



Sensitivity to mass hierarchy

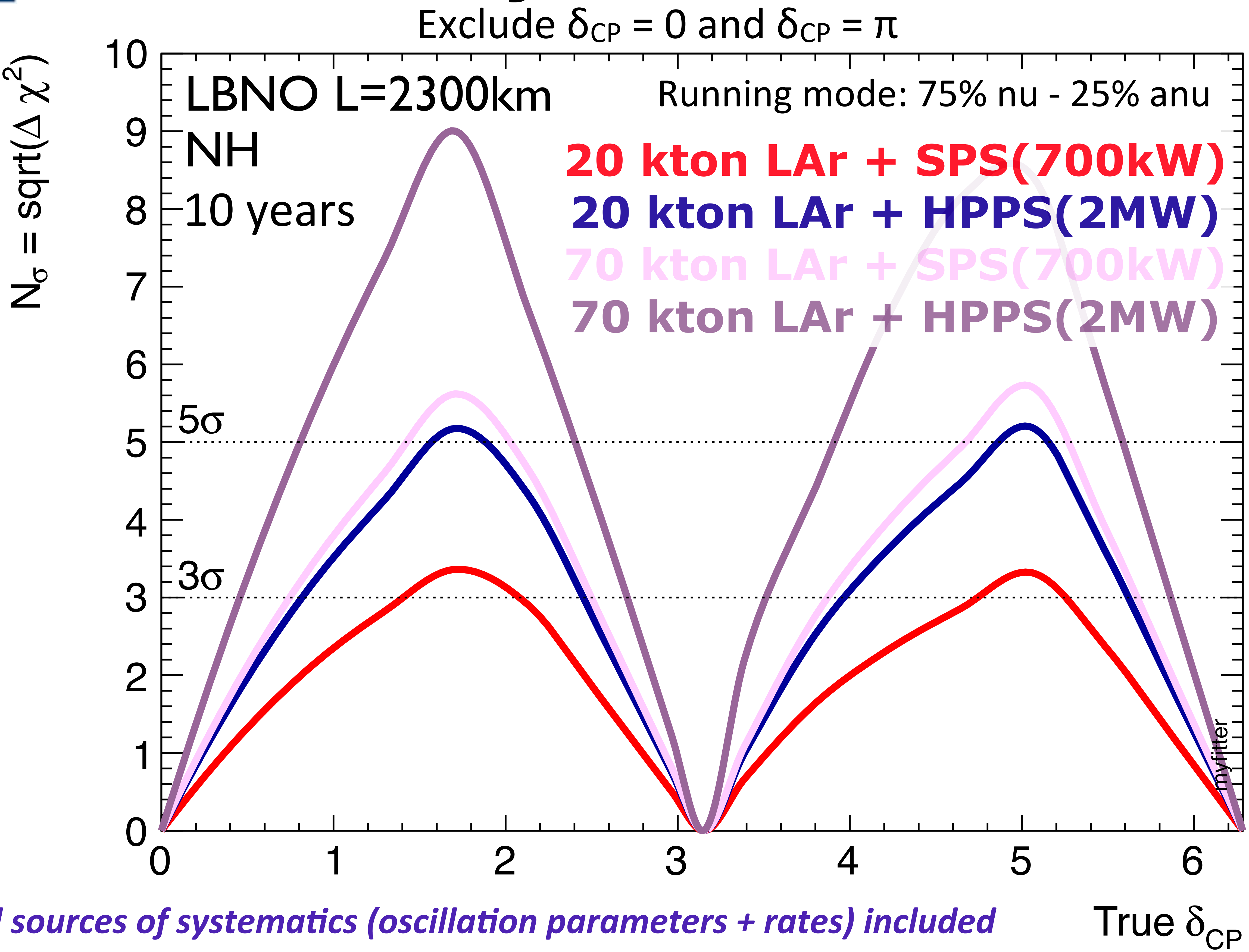
Extracting MH from global fits can not replace a direct 5σ measurement from a direct measurement !



Provide a >5σ direct determination of MH independent of the values of θ_{23} & δ_{CP} in ≈2 years of running

Other methods proposed (atmospheric neutrinos, reactors) do not provide such a level of sensitivity and could be prone to irreducible systematic errors

Sensitivity to CP violation

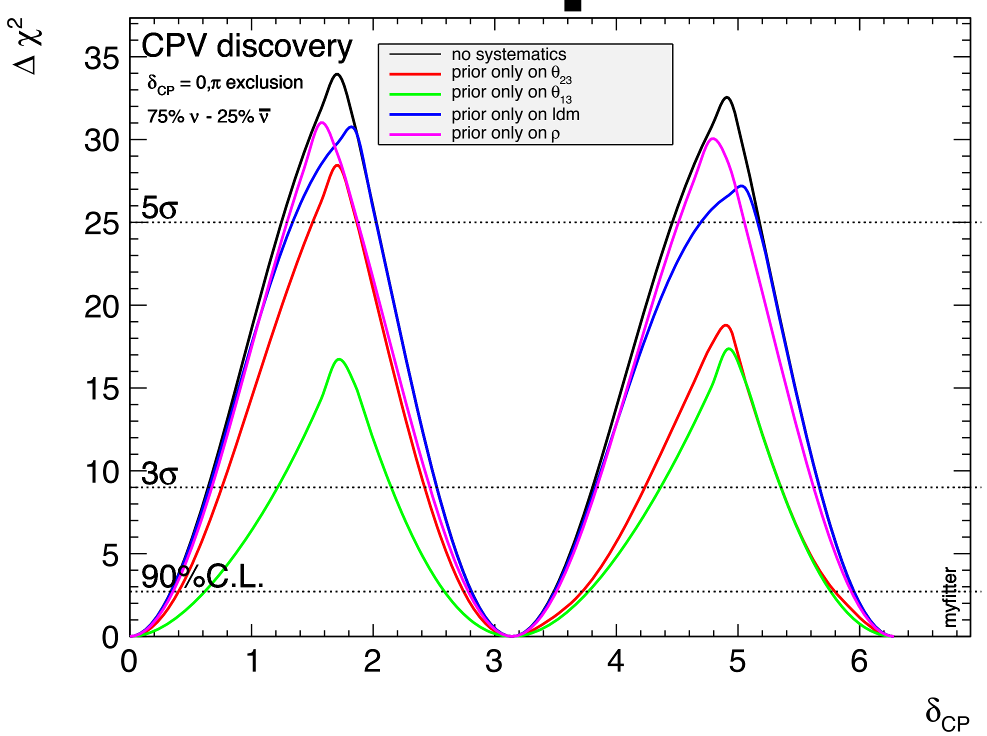


All sources of systematics (oscillation parameters + rates) included

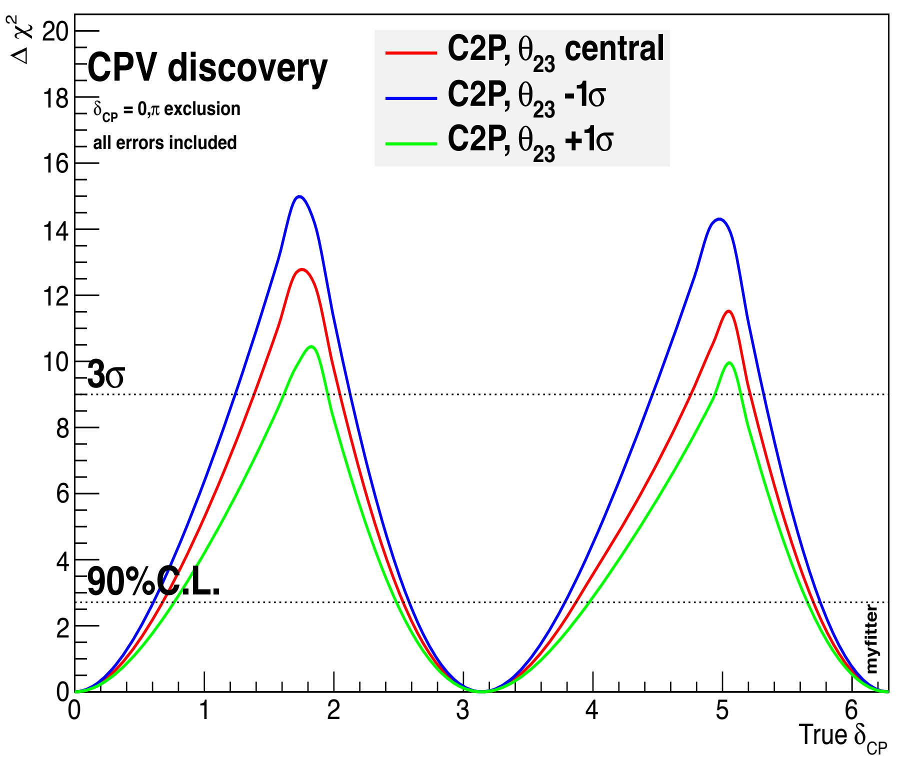
Effect of systematic errors

LBNO L=2300km, 20 kton, 10 years

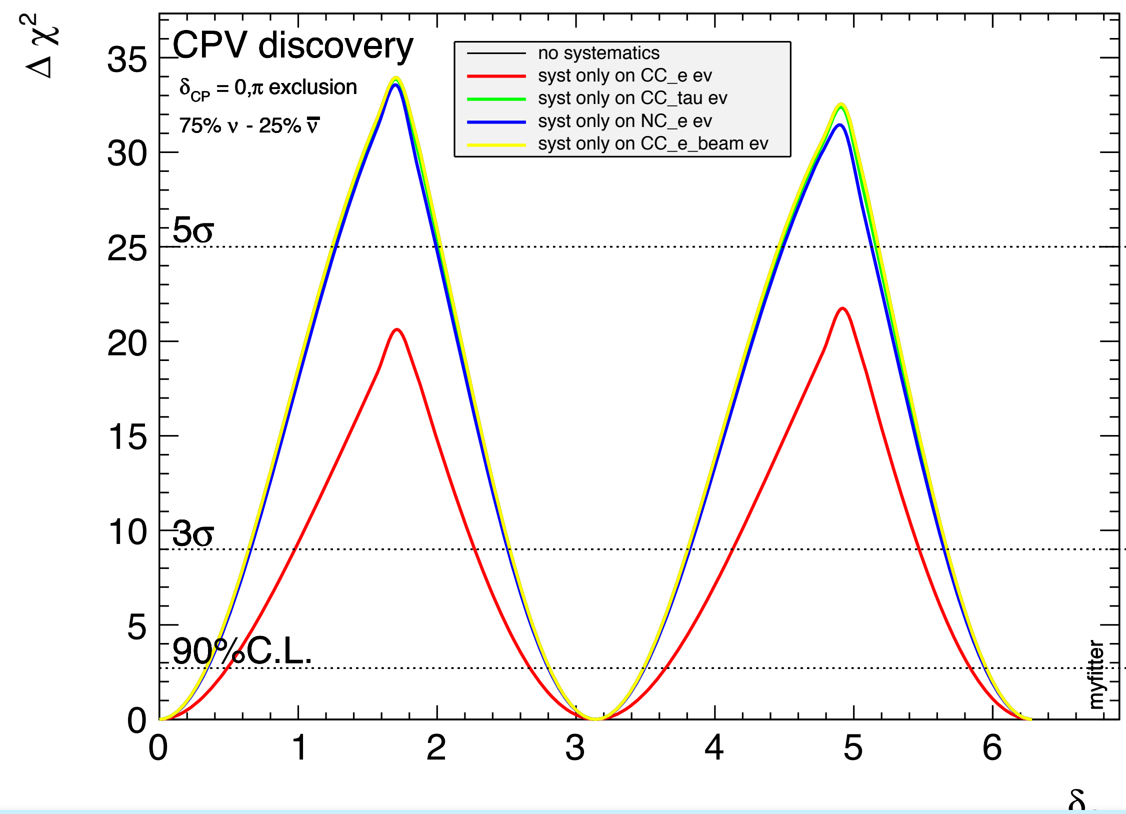
Oscillation parameters



Effect of θ_{23}



Detector related

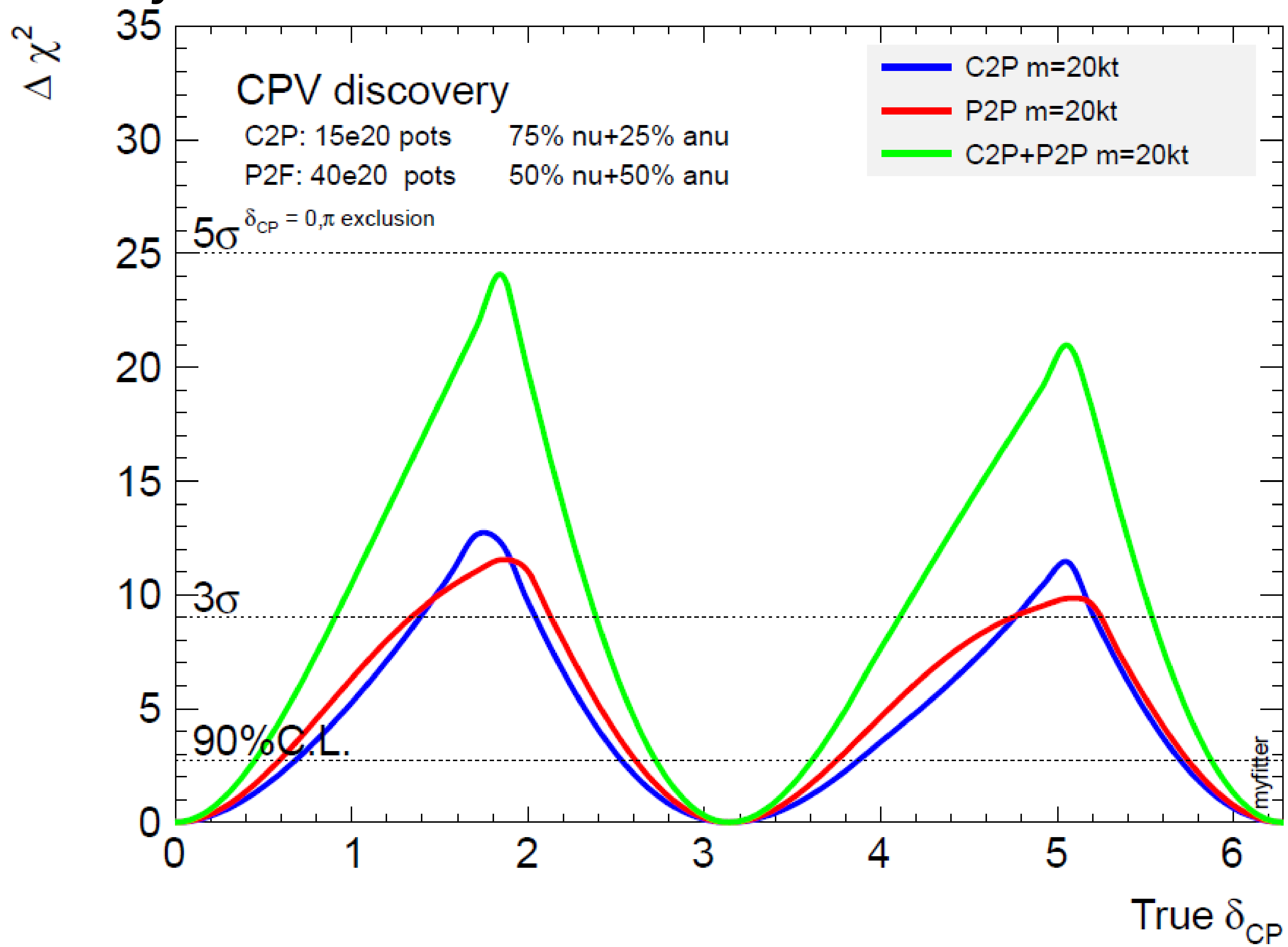


Without systematic errors, the 20 kton can reach 5sigma CPV in 10 years ! The most important oscillation parameters are θ_{23} and θ_{13} and the most important systematics is the knowledge of the absolute rate of ν_e CC events.

LBNO++: two beam experiment!

CERN-Protvino-Pyhäsalmi – 1160&2300 km baselines

study in progress

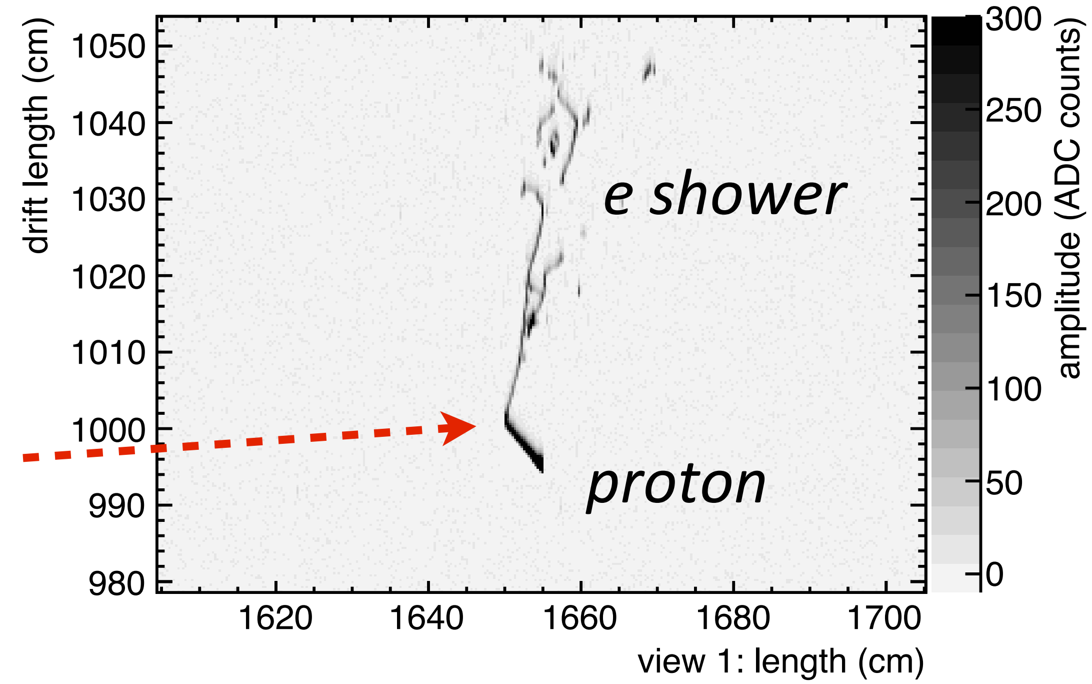


Sensitivity can be significantly enhanced and systematic errors cross-checked with CERN+Protvino beams with different baselines in the single far LBNO experiment → Unique setup!

Atmospheric neutrinos

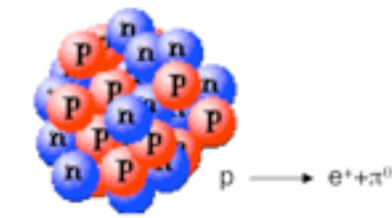
Mode	Events/20kt/yr
ν_eCC	1440
$\bar{\nu}_e$CC	310
ν_μCC	2440(w/o osc)
$\bar{\nu}_\mu$CC	680(w/o osc)
νNC	640

MC: ν_eCC



- **Neutrino oscillation physics complementary to long baseline beam**
- Clean ν_e & ν_μ CC over all range of energies (GeV,MultiGeV)
- Good neutrino energy and angular reconstruction
- Recoil hadronic system on an event-by-event basis
- Statistical separation of ν and anti-ν by exclusive final states
- $\nu_\mu \rightarrow \nu_\tau$ appearance significance >3σ after 3 years exposure (≈12 ν_τ CC / year)

Proton decay sensitivity



For a 20kton exposure of 10 years (200 kton×year)

JHEP 0704 (2007) 041

Mode	Lifetime (90%C.L.)
$p \to \nu K^+$	**$>3\times10^{34}$ yrs**
$p \to e^+\gamma$, $p \to \mu^+\gamma$	**$>3\times10^{34}$ yrs**
$p \to \mu^-\pi^+K^+$	**$>3\times10^{34}$ yrs**
$n \to e^-K^+$	**$>3\times10^{34}$ yrs**
$p \to \mu^+K^0$, $p \to e^+K^0$	$>1\times10^{34}$ yrs
$p \to e^+\pi^0$	$>1\times10^{34}$ yrs
$p \to \mu^+\pi^0$	$>0.8\times10^{34}$ yrs
$n \to e^+\pi^-$	$>0.8\times10^{34}$ yrs

Expect ≈linear sensitivity improvement with exposure until 1000 kton×year

Supernova detection channels

For 20 kton and a SN explosion at the distance of 5 kpc:

JCAP 0310 (2003) 009
JCAP 0408 (2004) 001

$$\langle E_{\nu_e}\rangle = 11MeV, \langle E_{\bar{\nu}_e}\rangle = 16MeV, \langle E_{\nu_x}\rangle = \langle E_{\bar{\nu}_x}\rangle = 25MeV$$

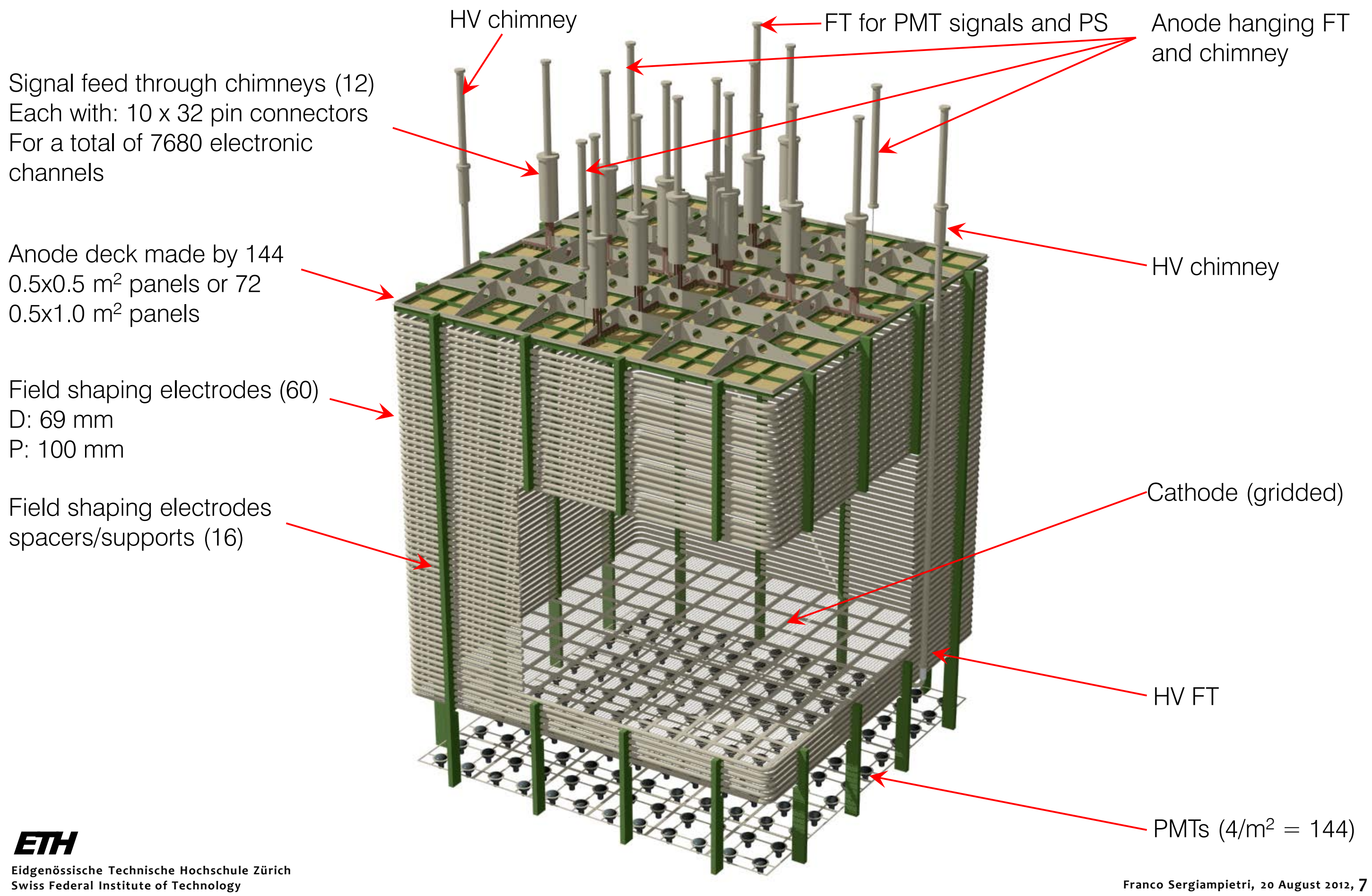
Reaction	Threshold	Events:
$\nu_e\ {}^{40}Ar \rightarrow e^-\ {}^{40}K^*$	(E_ν > 1.5 MeV)	≈23820
$\bar{\nu}_e\ {}^{40}Ar \rightarrow e^+\ {}^{40}Cl^*$	(E_ν > 7.48 MeV)	≈2420
$\nu_x\ {}^{40}Ar \rightarrow \nu_x + {}^{40}Ar^*$		≈30440
$\nu_x\ e^- \rightarrow \nu_x\ e^-$		≈1330

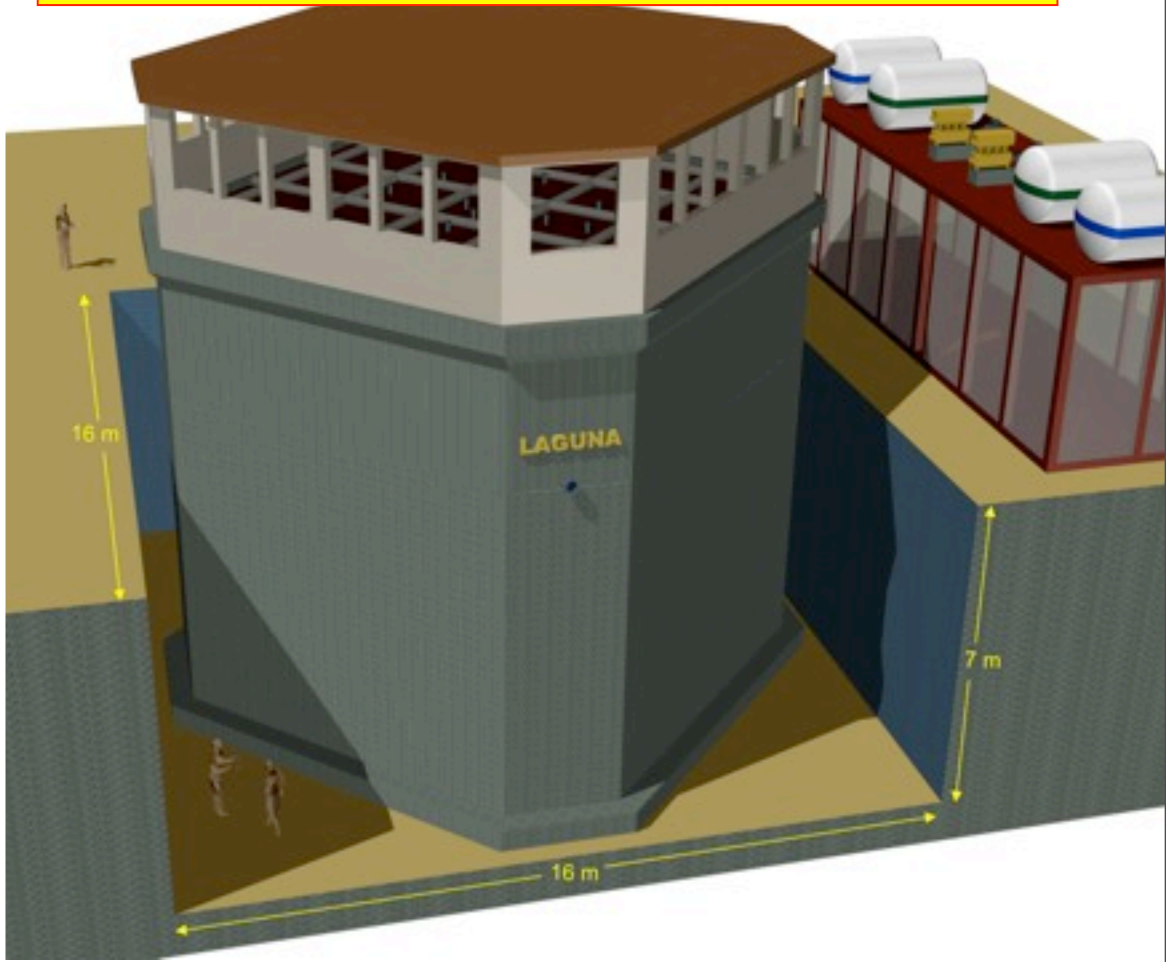
- Unique sensitivity to electron neutrino flavour (most other SN-detectors detect inverse beta decays)
- Combined analysis of all reaction modes
- Neutrino mass via TOF

Double phase LBNO LAr demonstrator

- We are proposing a **6x6x6 = 216 m³ active volume double phase LAr detector** to be constructed and operated at CERN
- Charged test beams to collect the large controlled data set allowing **electromagnetic** and **hadronic calorimetry** and general **detector performance** (PID, ...) to be measured, **simulation and reconstruction** to be improved and validated.
- Proposal to SPSC ready for submission

CERN committed to provide support for these Important developments. FNAL interest.





Conclusion

- EU FP7 LAGUNA/LBNO design study has made significant progress at designing and optimising a next generation deep underground neutrino observatory.
- LBNO (SPSC-EOI-007) has been put forward to CERN with unique physics potentials, including astro-particle physics and proton decay search.
- It is conceived as an incremental approach starting with an underground LAr detector, a clear stage 1 physics goal and well-defined upgrade plan, in order to reach a CPV discovery.
- Protvino could complement LBNO, greatly enhancing its physics potential. A Protvino near-detector complex can provide important neutrino physics.
- We are now proposing to CERN an LBNO demonstrator for the double phase LAr technology at a relevant scale (216m^3).
- The LAGUNA/LBNO consortium plans to finalise its findings and submit its reports by the end of 2014.

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