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

CERN-SPSC-2012-021
SPSC-EOI-007

André Rubbia (ETH Zurich)

on behalf of the LBNO proto-collaboration

106th Meeting of the SPSC
June 26th, 2012

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

v2

~230 authors, 51 institutions

A. Stahl,[1] C. Wiebusch,[1] A. M. Guler,[2] M. Kamiscioglu,[2] R. Sever,[2] A.U. Yilmazer,[3] C. Gunes,[3] D. Yilmaz,[3] P. Del Amo Sanchez,[4] D. Duchesneau,[4] H. Pessard,[4] E. Marcoulaki,[5] I. A. Papazoglou,[5] V. Berardi,[6] F. Cafagna,[6] M.G. Catanesi,[6] L. Magaletti,[6] A. Mercadante,[6] M. Quinto,[6] E. Radicioni,[6] A. Ereditato,[7] I. Kreslo,[7] C. Pistillo,[7] M. Weber,[7] A. Ariga,[7] T. Ariga,[7] T. Strauss,[7] M. Hierholzer,[7] J. Kawada,[7] C. Hsu,[7] S. Haug,[7] A. Jipa,[8] I. Lazanu,[8] A. Cardini,[9] A. Lai,[9] R. Oldeman,[10] M. Thomson,[11] A. Blake,[11] M. Prest,[12] A. Auld,[13] J. Elliot,[13] J. Lumbard,[13] C. Thompson,[13] Y.A. Gornushkin,[14] S. Pascoli,[15] R. Collins,[16] M. Haworth,[16] J. Thompson,[16] G. Bencivenni,[17] D. Domenici,[17] A. Longhin,[17] A. Blondel,[18] A. Bravar,[18] F. Dufour,[18] Y. Karadzhov,[18] A. Korzenev,[18] E. Noah,[18] M. Ravonel,[18] M. Rayner,[18] R. Asfandiyarov,[18] A. Haesler,[18] C. Martin,[18] E. Scantamburlo,[18] F. Cadoux,[18] R. Bayes,[19] F.J.P. Soler,[19] L. Aalto-Setälä,[20] K. Enqvist,[20] K. Huitu,[20] K. Rummukainen,[20] G. Nuijten,[21] K.J. Eskola,[22] K. Kainulainen,[22] T. Kalliokoski,[22] J. Kumpulainen,[22] K. Loo,[22] J. Maalampi,[22] M. Manninen,[22] I. Moore,[22] J. Suhonen,[22] W.H. Trzaska,[22] K. Tuominen,[22] A. Virtanen,[22] I. Bertram,[23] A. Finch,[23] N. Grant,[23] L.L. Kormos,[23] P. Ratoff,[23] G. Christodoulou,[24] J. Coleman,[24] C. Touramanis,[24] K. Mavrokoridis,[24] M. Murdoch,[24] N. McCauley,[24] D. Payne,[24] P. Jonsson,[25] A. Kaboth,[25] K. Long,[25] M. Malek,[25] M. Scott,[25] Y. Uchida,[25] M.O. Wascko,[25] F. Di Lodovico,[26] J.R. Wilson,[26] B. Still,[26] R. Sacco,[26] R. Terri,[26] M. Campanelli,[27] R. Nichol,[27] J. Thomas,[27] A. Izmaylov,[28] M. Khabibullin,[28] A. Khotjantsev,[28] Y. Kudenko,[28] V. Matveev,[28] O. Mineev,[28] N. Yershov,[28] V. Palladino,[29] J. Evans,[30] S. Söldner-Rembold,[30] U.K. Yang,[30] M. Bonesini,[31] T. Pihlajaniemi,[32] M. Weckström,[32] K. Mursula,[32] T. Enqvist,[32] P. Kuusiniemi,[32] T. Räihä,[32] J. Sarkamo,[32] M. Slupecki,[32] J. Hissa,[32] E. Kokko,[32] M. Aittola,[32] G. Barr,[33] M.D. Haigh,[33] J. de Jong,[33] H. O'Keeffe,[33] A. Vacheret,[33] A. Weber,[33,34] G. Galvanin,[35] M. Temussi,[35] O. Caretta,[34] T. Davenne,[34] C. Densham,[34] J. Ilic,[34] P. Loveridge,[34] J. Odell,[34] D. Wark,[34] A. Robert,[36] B. Andrieu,[36] B. Popov,[36,14] C. Giganti,[36] J.-M. Levy,[36] J. Dumarchez,[36] M. Buizza-Avanzini,[37] A. Cabrera,[37] J. Dawson,[37] D. Franco,[37] D. Kryn,[37] M. Obolensky,[37] T. Patzak,[37] A. Tonazzo,[37] F. Vanucci,[37] D. Orestano,[38] B. Di Micco,[38] L. Tortora,[39] O. Bésida,[40] A. Delbart,[40] S. Emery,[40] V. Galymov,[40] E. Mazzucato,[40] G. Vasseur,[40] M. Zito,[40] V.A. Kudryavtsev,[41] L.F. Thompson,[41] R. Tsenov,[42] D. Kolev,[42] I. Rusinov,[42] M. Bogomilov,[42] G. Vankova,[42] R. Matev,[42] A. Vorobyev,[43] Yu. Novikov,[43] S. Kosyanenko,[43] V. Suvorov,[43] G. Gavrilov,[43] E. Baussan,[44] M. Dracos,[44] C. Jollet,[44] A. Meregaglia,[44] E. Vallazza,[45] S.K. Agarwalla,[46] T. Li,[46] D. Autiero,[47] L. Chaussard,[47] Y. Déclais,[47] J. Marteau,[47] E. Pennacchio,[47] E. Rondio,[48] J. Lagoda,[48] J. Zalipska,[48] P. Przewlocki,[48] K. Grzelak,[49] G. J. Barker,[50] S. Boyd,[50] P.F. Harrison,[50] R.P. Litchfield,[50] Y. Ramachers,[50] A. Badertscher,[51] A. Curioni,[51] U. Degunda,[51] L. Epprecht,[51] A. Gendotti,[51] L. Knecht,[51] S. DiLuise,[51] S. Horikawa,[51] D. Lussi,[51] S. Murphy,[51] G. Natterer,[51] F. Petrolo,[51] L. Periale,[51] A. Rubbia,[51,*] F. Sergiampietri,[51] and T. Viant[51]

1. III. Physikalisches Institut, RWTH Aachen, Aachen, Germany
2. Middle East Technical University (METU), Ankara, Turkey
3. Ankara University, Ankara, Turkey
4. LAPP, Université de Savoie, CNRS/IN2P3, F-74941 Annecy-le-Vieux, France
5. Institute of Nuclear Technology-Radiation Protection, National Centre for Scientific Research "Demokritos", Athens, Greece
6. INFN and Dipartimento interateneo di Fisica di Bari, Bari, Italy
7. University of Bern, Albert Einstein Center for Fundamental Physics, Laboratory for High Energy Physics (LHEP), Bern, Switzerland
8. Faculty of Physics, University of Bucharest, Bucharest, Romania
9. INFN Sezione di Cagliari, Cagliari, Italy
10. INFN Sezione di Cagliari and Università di Cagliari, Cagliari, Italy
11. University of Cambridge, Cambridge, United Kingdom
12. Universita' dell'Insubria, sede di Como/ INFN Milano Bicocca, Como, Italy
13. Alan Auld Engineering, Doncaster, United Kingdom
14. Joint Institute for Nuclear Research, Dubna, Moscow Region, Russia
15. Institute for Particle Physics Phenomenology, Durham University, United Kingdom
16. Technodyne International Limited, Eastleigh, Hampshire, United Kingdom
17. INFN Laboratori Nazionali di Frascati, Frascati, Italy
18. University of Geneva, Section de Physique, DPNC, Geneva, Switzerland
19. University of Glasgow, Glasgow, United Kingdom
20. University of Helsinki, Helsinki, Finland
21. Rockplan Ltd., Helsinki, Finland
22. Department of Physics, University of Jyväskylä, Finland
23. Physics Department, Lancaster University, Lancaster, United Kingdom
24. University of Liverpool, Department of Physics, Liverpool, United Kingdom
25. Imperial College, London, United Kingdom
26. Queen Mary University of London, School of Physics, London, United Kingdom
27. Dept. of Physics and Astronomy, University College London, London, United Kingdom
28. Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia
29. INFN Sezione di Napoli and Università di Napoli, Dipartimento di Fisica, Napoli, Italy
30. University of Manchester, Manchester, United Kingdom
31. INFN Milano Bicocca, Milano, Italy
32. University of Oulu, Oulu, Finland
33. Oxford University, Department of Physics, Oxford, United Kingdom
34. STFC, Rutherford Appleton Laboratory, Harwell Oxford, United Kingdom
35. AGT Ingegneria S.r.l., Perugia, Italy
36. UPMC, Université Paris Diderot, CNRS/IN2P3, Laboratoire de Physique Nucléaire et de Hautes Energies (LPNHE), Paris, France
37. APC, AstroParticule et Cosmologie, Université Paris Diderot, CNRS/IN2P3, CEA/Irfu, Observatoire de Paris, Sorbonne Paris Cité Paris, France
38. Università and INFN Roma Tre, Roma, Italy
39. INFN Roma Tre, Roma, Italy
40. IRFU, CEA Saclay, Gif-sur-Yvette, France
41. University of Sheffield, Department of Physics and Astronomy, Sheffield, United Kingdom
42. Department of Atomic Physics, Faculty of Physics, St.Kliment Ohridski University of Sofia, BG-1164, Sofia, Bulgaria
43. Petersburg Nuclear Physics Institute (PNPI), St-Petersburg, Russia
44. IPHC, Université de Strasbourg, CNRS/IN2P3, Strasbourg, France
45. INFN Trieste, Trieste, Italy
46. IFIC (CSIC & University of Valencia), Valencia, Spain
47. Université de Lyon, Université Claude Bernard Lyon 1, IPN Lyon (IN2P3), Villeurbanne, France
48. National Centre for Nuclear Research (NCBJ), Warsaw, Poland
49. Institute of Experimental Physics, Warsaw University (IFD UW), Warsaw, Poland
50. University of Warwick, Department of Physics, Coventry, United Kingdom
51. ETH Zurich, Institute for Particle Physics, Zurich, Switzerland

Neutrinos at the frontier

- A wealth of new results over the last years are clarifying the landscape in Particle Physics at the various frontiers and confirm the "invincible" Standard Model (SM). The discovery of a Higgs boson at ATLAS/CMS will crown the successful SM and will call for a verification of the Higgs boson couplings to the gauge bosons and to the fermions.
- In this rapidly emerging picture, neutrino masses and oscillations are today the only experimentally established evidence of physics **Beyond the Standard Model (BSM).**
- Very likely new BSM physics at a yet-unknown high-energy scale is a key ingredient to resolve these questions that the SM cannot answer:
  - What is the origin of the gauge structure of strong and electroweak interactions ?
  - Does a bigger gauge symmetry exist in Nature?
  - Is there a unique theory of family and flavor?
- **Being the only elementary fermions whose basic properties are still largely unknown, neutrinos must naturally be one of the main priorities in the quest to complete our knowledge of the SM.**
  - Their understanding has progressed considerably, but deeper studies are still needed to answer these profound questions.
  - The mixings among leptons have different values and are larger than those among quarks. And the smallness of the neutrino rest masses compared to those of other elementary fermions points to the preferred scenario of Majorana neutrinos and the see-saw mechanism.
  - The above observations are yet to be clarified within a unique and appropriate theoretical framework, and addressing such questions has therefore significant potential to offer new insights into the BSM physics at the very high-energy scale.
  - Is, as Bruno Pontecorvo said, the neutrino "the prototype of all other fermions" ?

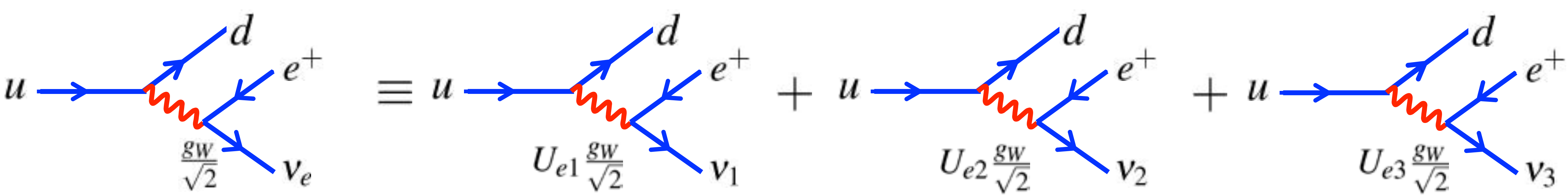
CP violation in leptonic sector

- CP-violation is an essential aspect of our understanding of the Universe and is related to the question of the matter dominance.
- A natural question is whether the SM can provide the necessary CP-violation to explain the baryon asymmetry (≈10^{-9}).
- Today we are certain that there are two places where CP-violation can enter: the CKM matrix and the newly found PMNS matrix !
- To date CP violation has **only** been observed in the quark sector

Mixing between weak and mass eigenstates:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Pontecorvo-Maki-Nakagawa-Sakata



T	$\nu_e \rightarrow \nu_\mu \quad \xrightarrow{\hat{T}} \quad \nu_\mu \rightarrow \nu_e$
CP	$\nu_e \rightarrow \nu_\mu \quad \xrightarrow{\hat{C}\hat{P}} \quad \overline{\nu}_e \rightarrow \overline{\nu}_\mu$
CPT	$\nu_e \rightarrow \nu_\mu \quad \xrightarrow{\hat{C}\hat{P}\hat{T}} \quad \overline{\nu}_\mu \rightarrow \overline{\nu}_e$

Since CKM is known to be a source of CP-violation in Nature, it is natural to expect a similar situation in the lepton sector.

The June 2011 revolution

- The T2K result which indicated electron-neutrino appearance triggered a revolution. The effect was confirmed by MINOS soon after.
- The observation of near/far ratios smaller than unity at long baseline reactor experiments were also interpreted as evidence for the disappearance of electron neutrinos and confirmed the non-zero value of θ_{13} with high statistical significance, as initially reported by Double-CHOOZ and culminating in the later announcement of a 5.2σ result by Daya Bay and 4.9σ by RENO
- With the present level of knowledge, neutrino oscillations are entering the precision era:
  - $\Delta m^2_{21}(3\%), \Delta m^2_{31}(4\%), \sin^2\theta_{12}(5\%), \sin^2\theta_{13}(15\%), and \sin^2 2\theta_{23}(15\%)$
  - MH unknown, $0<\delta_{CP}<2\pi$ full range at 2σ C.L.
- These exciting results close more than a decade of exploration of oscillations, and clearly define the way forward:
  - All three mixing angles of the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) leptonic mixing matrix are non-vanishing and large. This has ascertained the 3 × 3 unitary character of the PMNS matrix, opening the possibility to observe its non-trivial complex nature.
  - This raises the intriguing possibility that neutrinos (or their heavy neutrino partners) might have played an important role in the early age of the Universe contributing to the creation of the baryon asymmetry which is responsible today for the matter dominance.

➡ **These arguments strongly advocate a further exploration of neutrinos, and indeed in a more urgent and prominent way, but yet also more accessible given the large mixing angles.**

➡ **To observe evidence of CP violation in the leptonic sector has become one among the most important topics in Particle Physics today.**

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 CKM & PMNS angles are very different, what is the size of the CP effect in leptons??*

Beyond T2K&NOvA: LBNO ?

- LBNO is a next generation long baseline experiment which aims at a significantly better sensitivity than what is achievable with the combined T2K, NOvA and reactors experiments.
- **LBNO will explicitly observe MH induced matter effects and CP-violation, which is different from simply extracting the hierarchy or δ_{CP} value from global fits of all available data**:
  - ★ Large detectors and intense beam for a significant increase in statistics
  - ★ Measure all active-active transitions (e / mu / tau CC) and active-sterile (NC) at long baseline
  - ★ A precise investigation of the oscillation probabilities as a function of energy (L/E) and a direct comparison of neutrino and antineutrino behaviors to verify the expectations from 3-generations neutrino mixing.
  - ★ A very long baseline to have an excellent separation of the asymmetry due to the matter effects (i.e. the mass hierarchy measurement) and the CP asymmetry due to the δ_{CP} complex phase, and thus to break the parameter degeneracies, and to "see" the 1st and 2nd maxima !
  - ★ To directly observe the different MH induced matter- and CP-phase induced effects in oscillation probabilities for neutrinos and antineutrinos !
- Extend nucleon decay searches, a unique probe for BSM up to the Grand Unification Scale
- Perform very compelling and complementary atmospheric and astrophysical neutrino detection programs, which become accessible when the detector is deep underground.

⇨ **A new massive deep underground neutrino observatory for long baseline neutrino studies, capable of proton decay searches, atmospheric and astrophysical neutrino detection**

Pyhäsalmi far site location

2100 km from RAL, 1500 km from DESY, and 1160 km from Protvino.

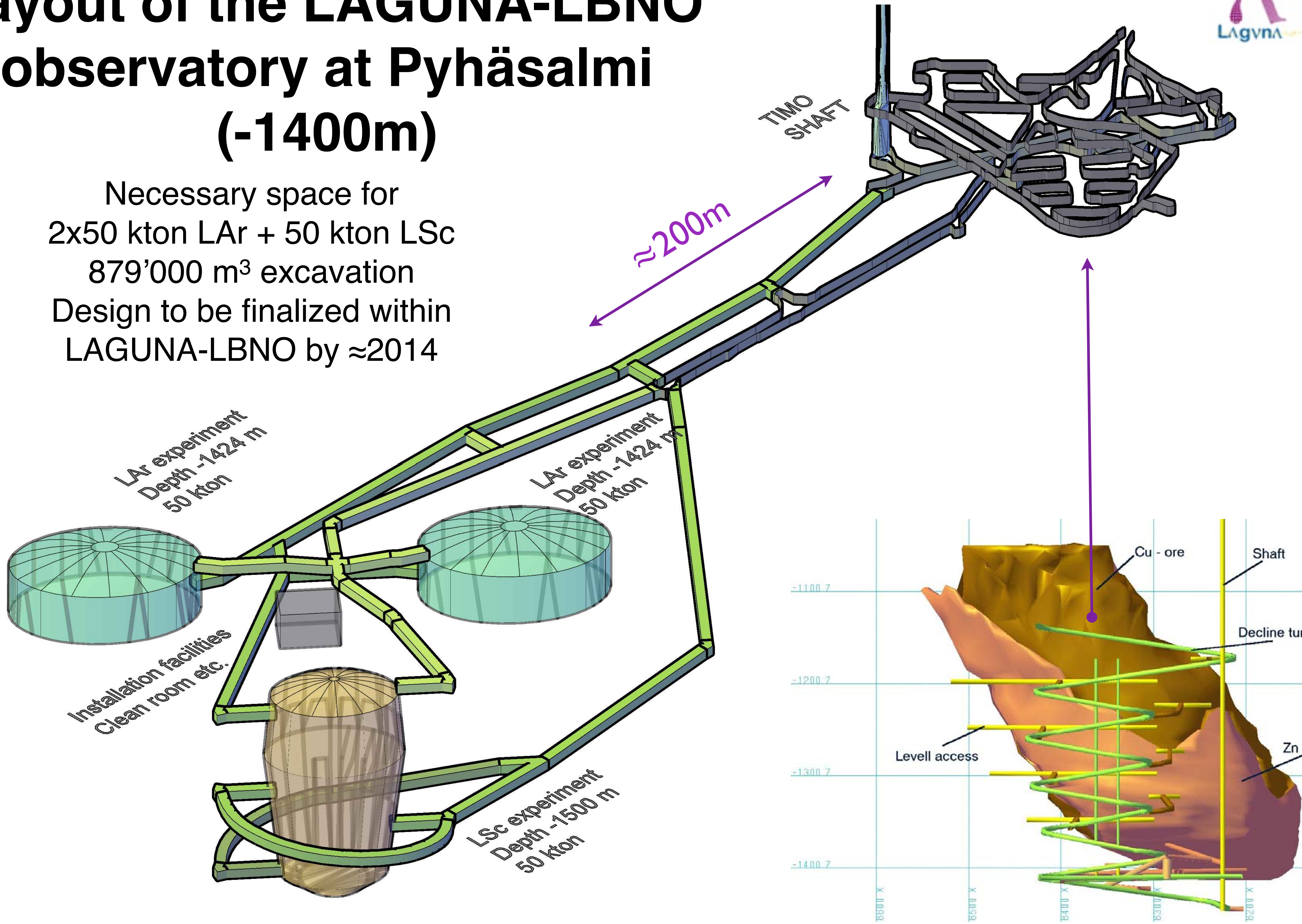
- CUPP : Centre for Underground Physics in Pyhäsalmi (www.cupp.fi)
- Location: 63° 39' 31"N – 26° 02' 48"E
- Distances (by roads)
  - Oulu – 165 km
  - Jyväskylä – 180 km
  - Helsinki – 450 km
- Distance to CERN 2300 km
- Good traffic connections
  - the main highway: Helsinki – Jyväskylä – Oulu – ...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

Being extensively investigated in LAGUNA DS since 2008

2300 km baseline is suitable for Neutrino Factory

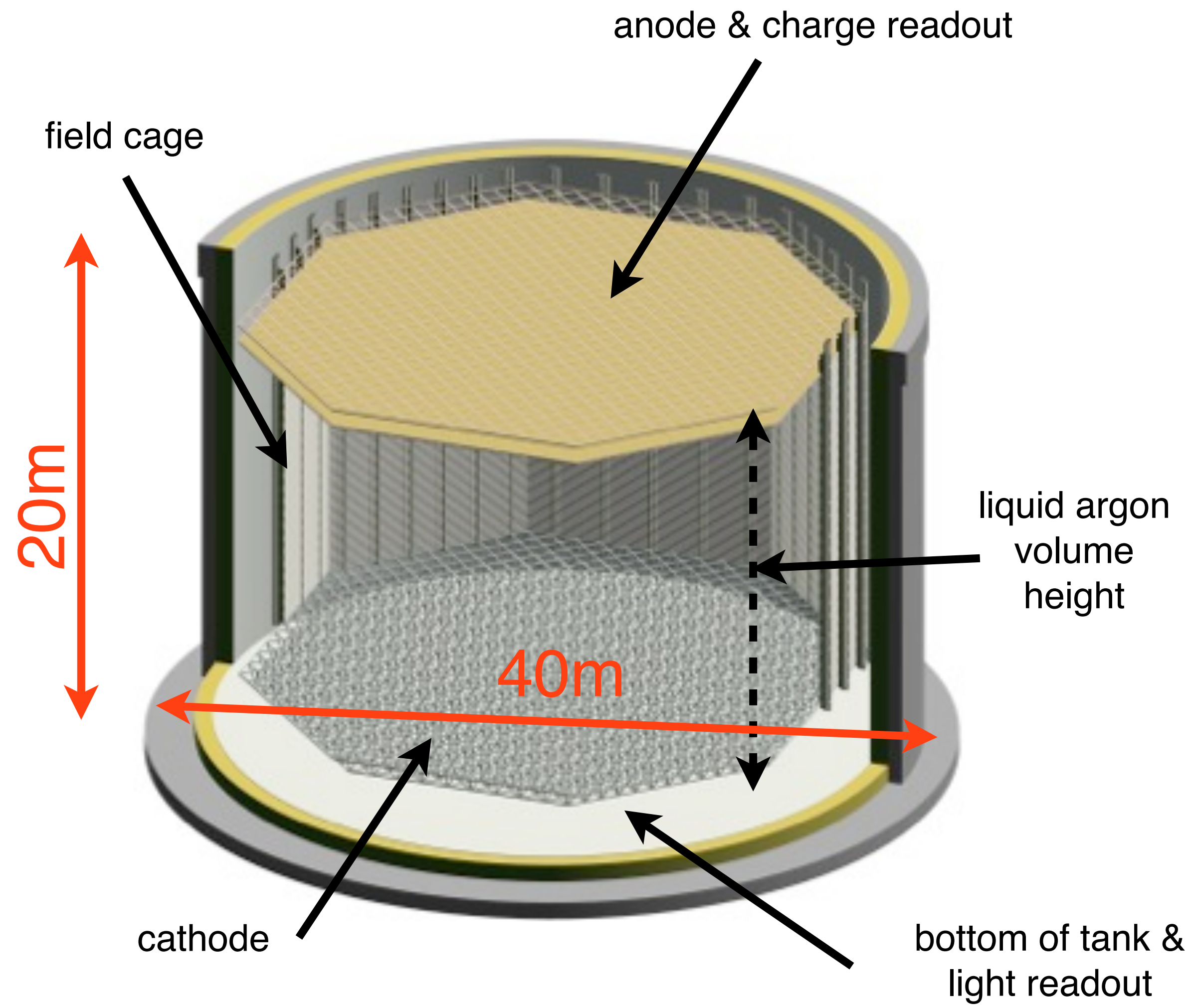
Layout of the LAGUNA-LBNO observatory at Pyhäsalmi (-1400m)

Necessary space for
2x50 kton LAr + 50 kton LSc
879’000 m³ excavation
Design to be finalized within
LAGUNA-LBNO by ≈2014

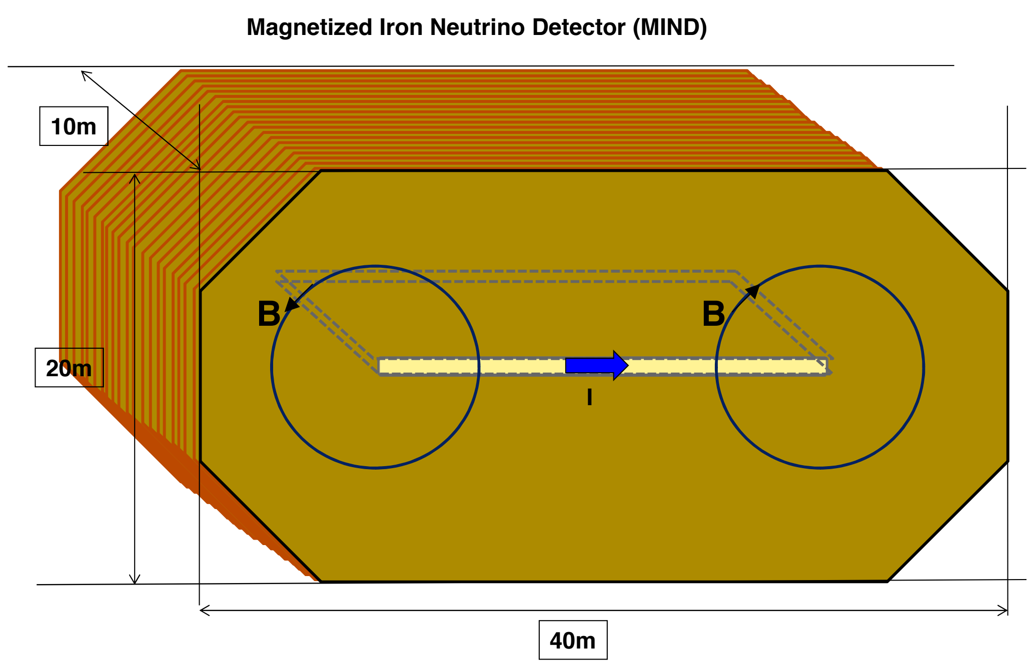


Far underground detectors

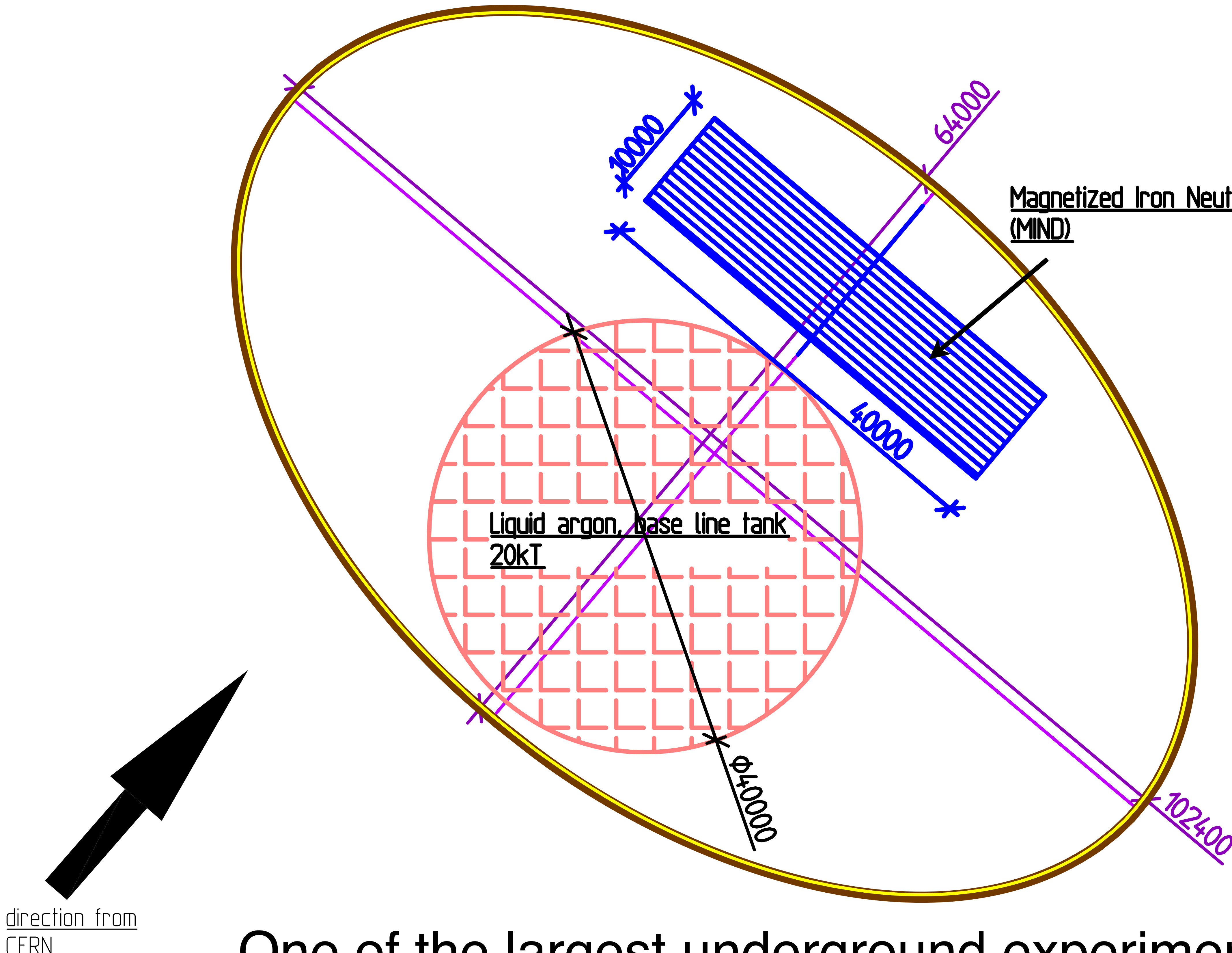
- **20 kton double phase LAr LEM TPC (GLACIER): best detector for electron appearance measurements with excellent energy resolution and small systematic errors**
  - Exclusive final states, low energy threshold on all particles
  - Excellent ν energy resolution and reconstruction ability from sub GeV 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



- **35 kton magnetized Muon Detector (MIND): conventional and well-proven detector for muon CC, and NC**
  - muon momentum & charge determination, inclusive total neutrino energy
  - rsμ/wsμ with Neutrino Factory
  - 3cm Fe plates, 1cm scintillator bars, B=1.5-2.5 T



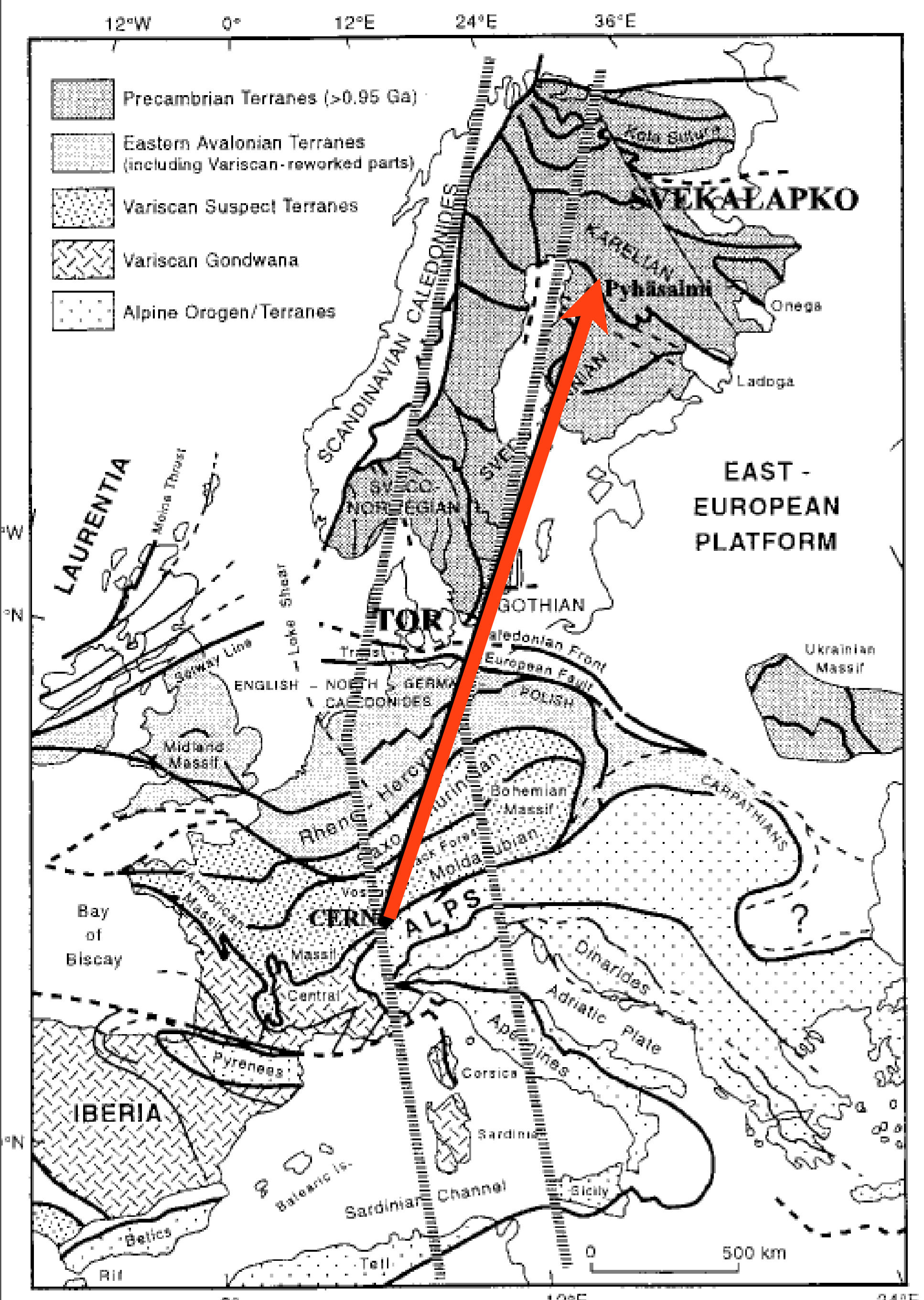
Top view of far detector cavern

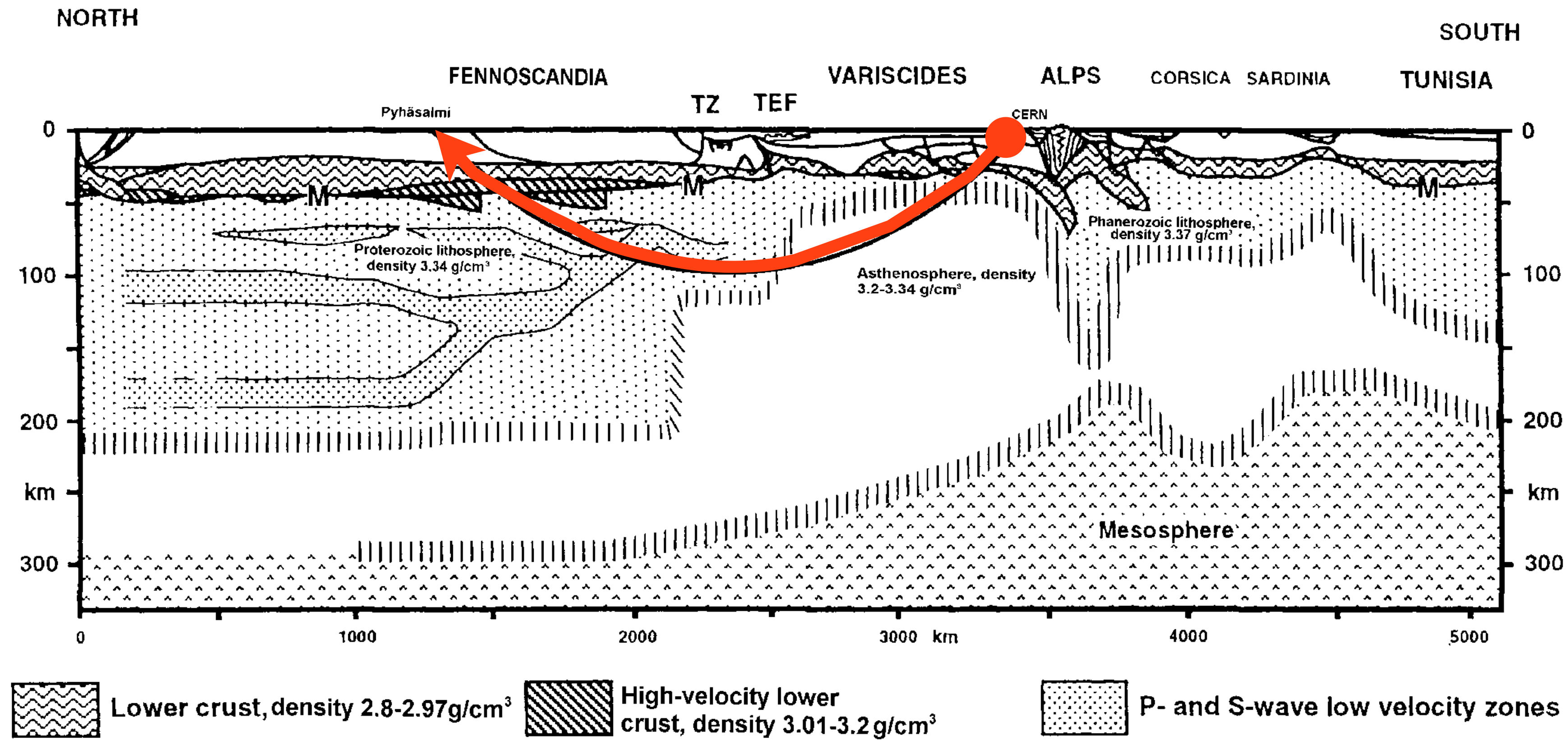


One of the largest underground experimental halls !

Neutrinos from CERN to Pyhäsalmi

arXiv:hep-ph/0305042v1





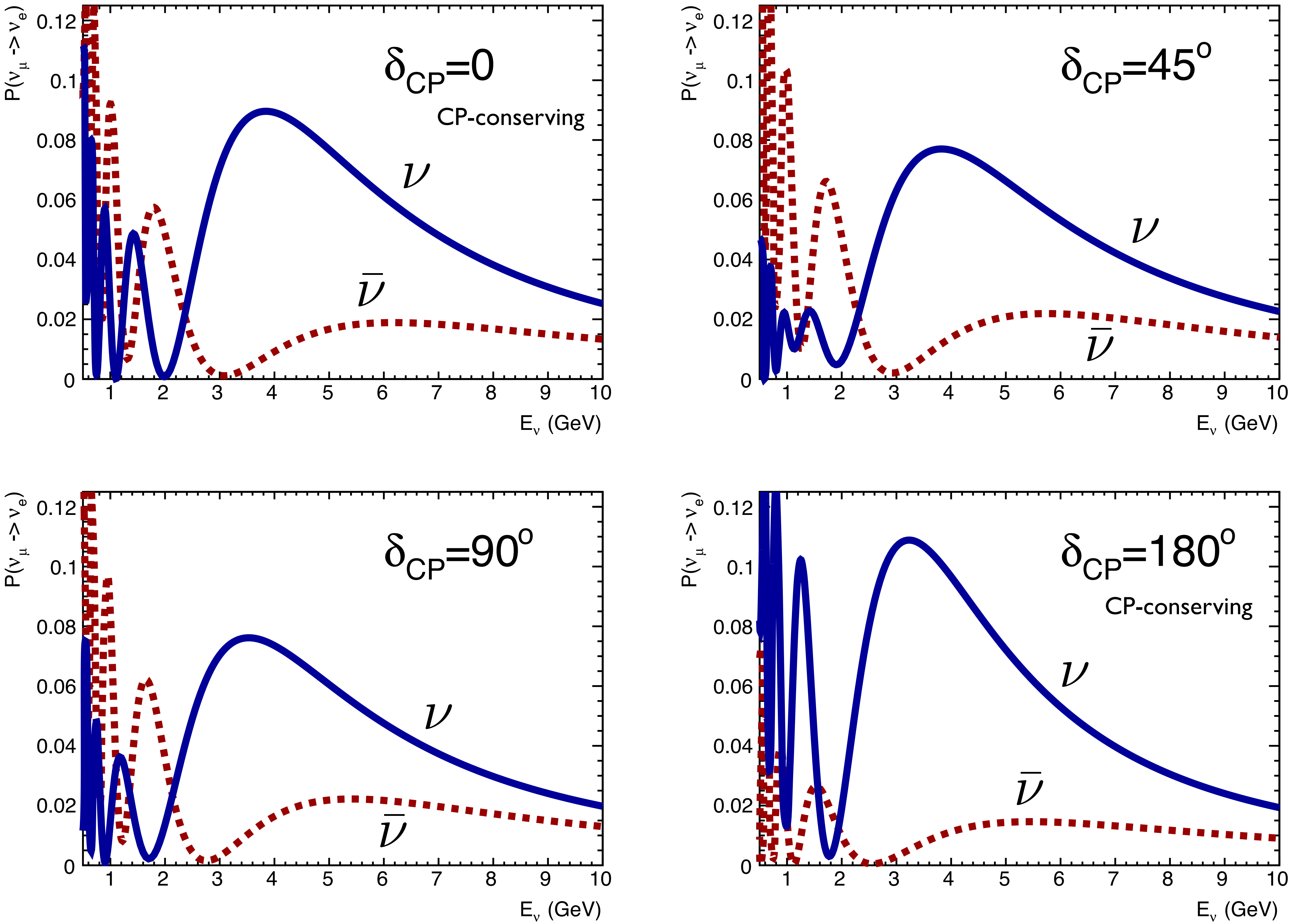
- Distance CERN-Pyhäsalmi = 2288 km
- Deepest point = 103.8 km
- Abundant geophysical data about crust and upper mantle available
- Densities = 2.4÷3.4 g/cm^3
- Remaining uncertainty has small effect on neutrino oscillations (assumed equivalent to ±4% global change in matter density)

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

★Normal mass hierarchy

L=2300 km

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

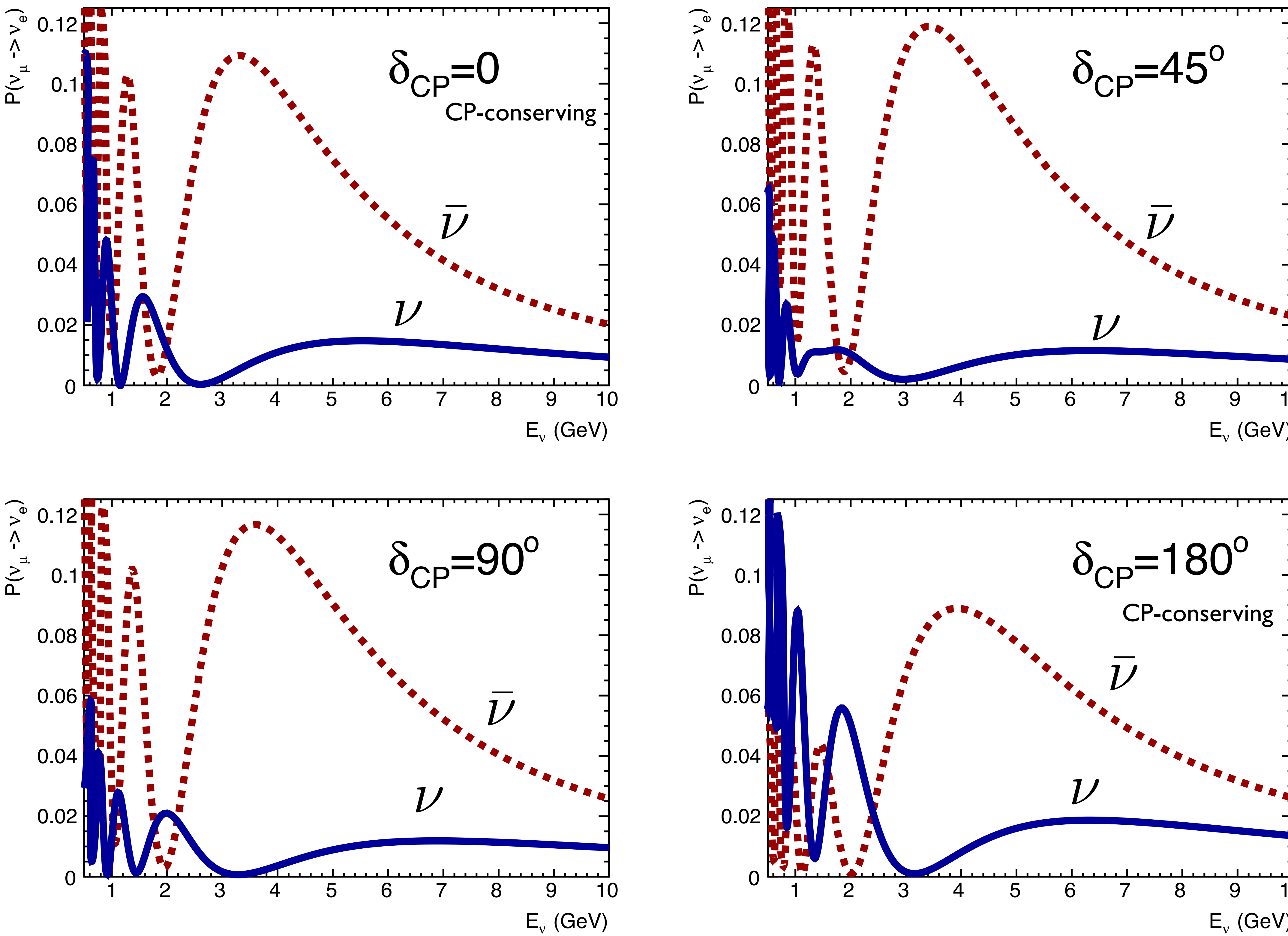


CERN-Pyhäsalmi: spectral information $\nu_\mu \rightarrow \nu_e$

★Inverted mass hierarchy

L=2300 km

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



New LAGUNA-LBNO neutrino beam

LAGUNA-LBNO WP4

- **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

- **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 (three options):**
  - **SPS upgrades (e.g. SUPER-SPS/SPS+ @ 800-1200 GeV) → 2 MW**
  - **New HP-PS accelerator (50 GeV) → 2 MW**
  - **NF storage ring (staged program with initially 1% of the NF baseline).**

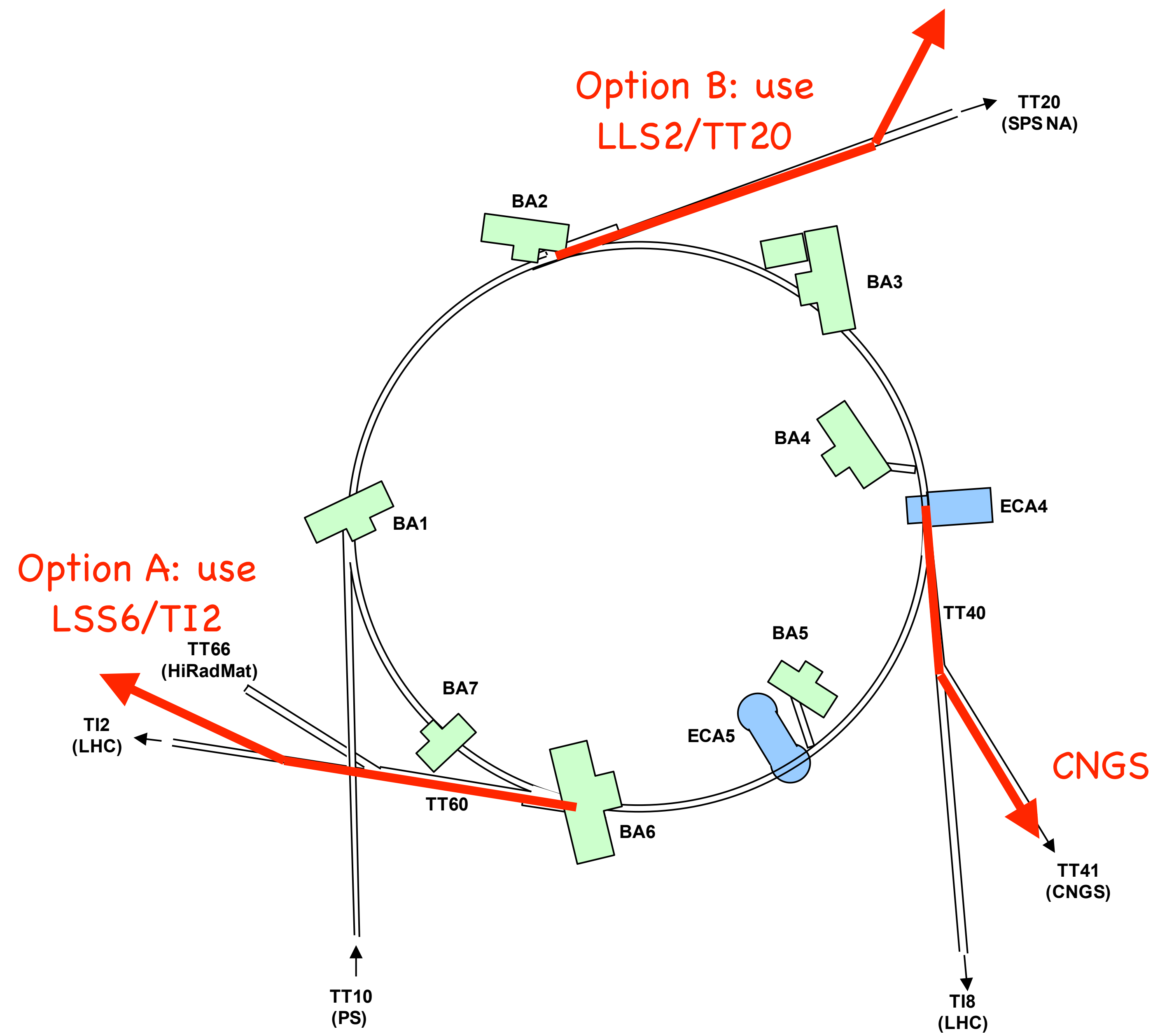
Two presently considered layouts

- Phase 1 layout using the 400 GeV beam from SPS

Possibilities:

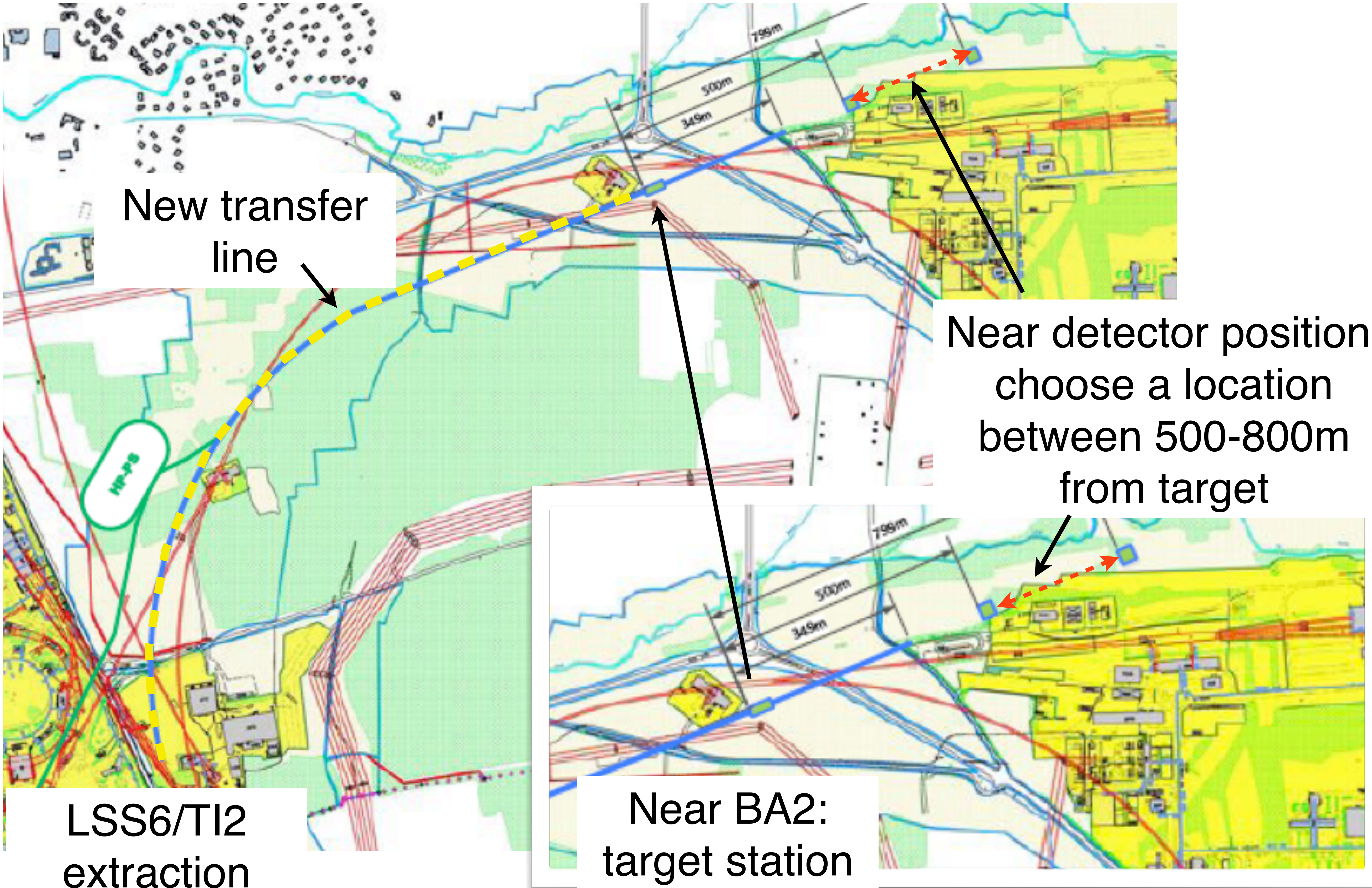
- **Option A**: LSS6 extraction, target near BA2
  - LSS6 fast extraction and TT60 beam line exists
  - New switch to direct the proton beam towards North
  - Long (~1.6km) proton tunnel to bring the beam towards BA2

- **Option B** : LSS2 extraction, target near TCC2
  - new fast extraction system in LSS2
  - TT20 beam line exists
  - Target area near existing TCC2



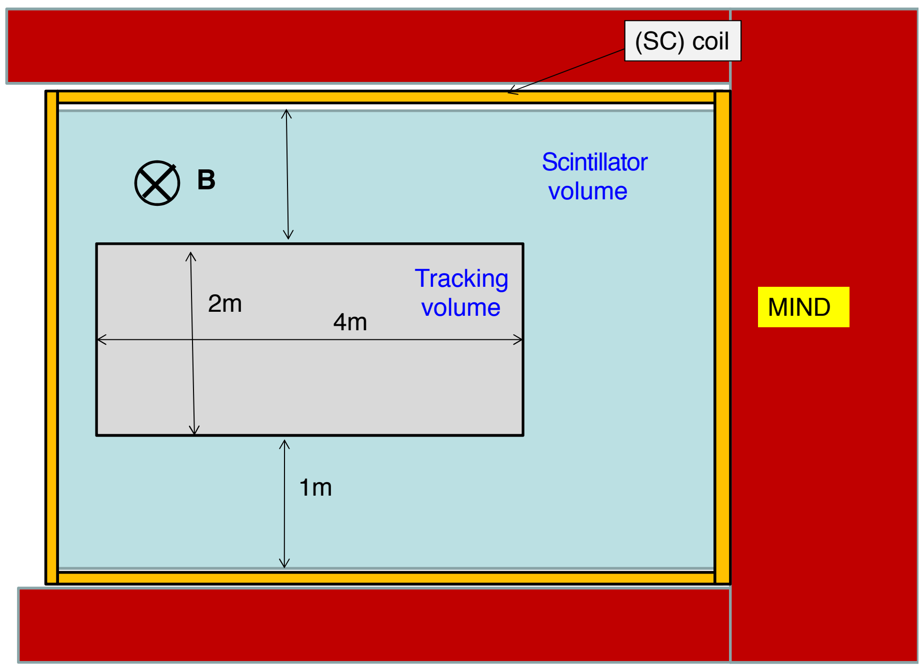
Courtesy : B. Goddard - LLBNO

Detailed view of CN2PY layout : Option A

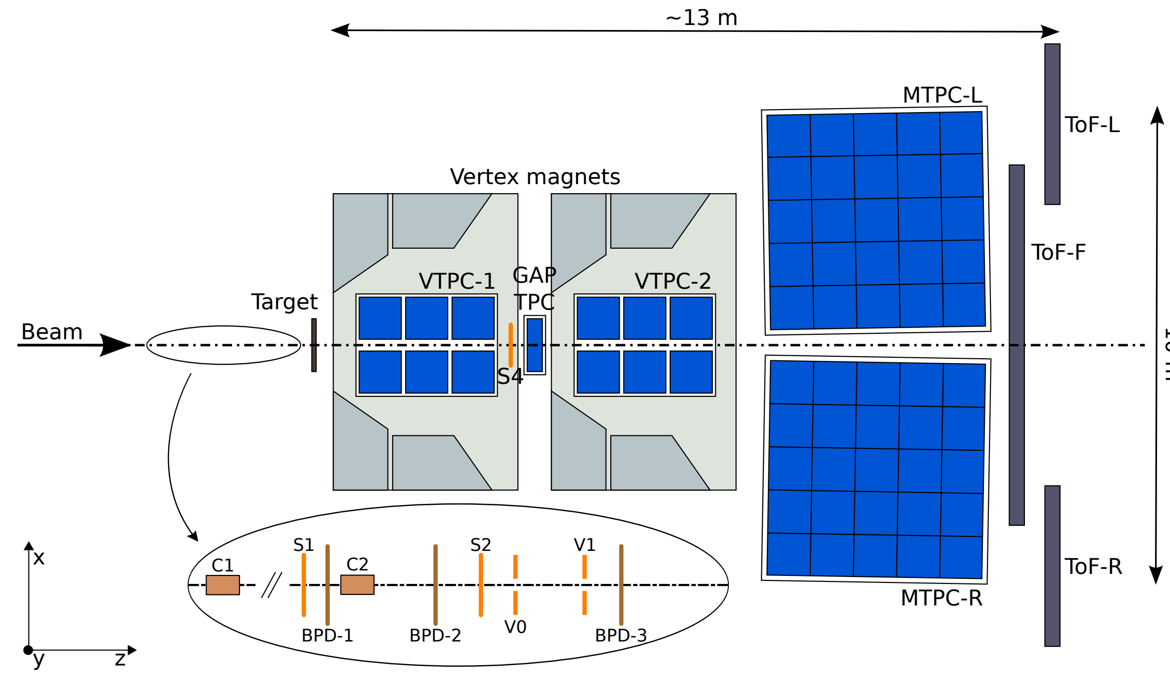


Near detector and hadro-production

- 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: 10 bar gas argon-mixture TPC surrounded by scintillator bar tracker embedded in an instrumented magnet with field 0.5T
- 270 kg argon mass, of which ≈100 kg fiducial
- 0.2 event/spill @ 700 kW
- O(100’000) events/year



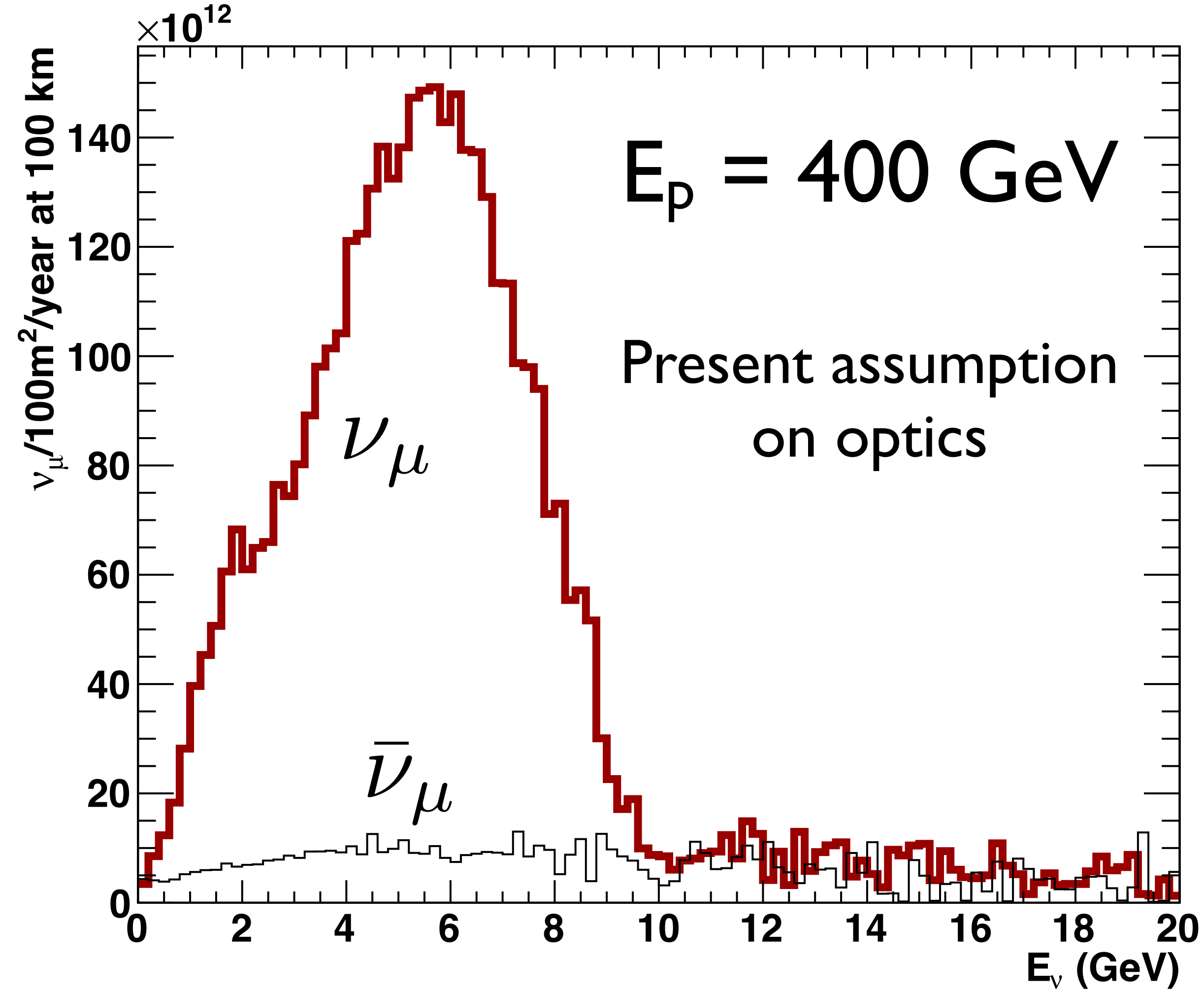
- It is widely recognized that hadro-production measurements with thin or replica target are really crucial for precision neutrino experiments (eg. K2K, T2K, MINOS).
- CERN NA61 acceptance study for 400 GeV incident protons

- Precision neutrino cross-section measurements: e.g. MINERVA, T2K-ND, also nuSTORM (FNAL LoI)

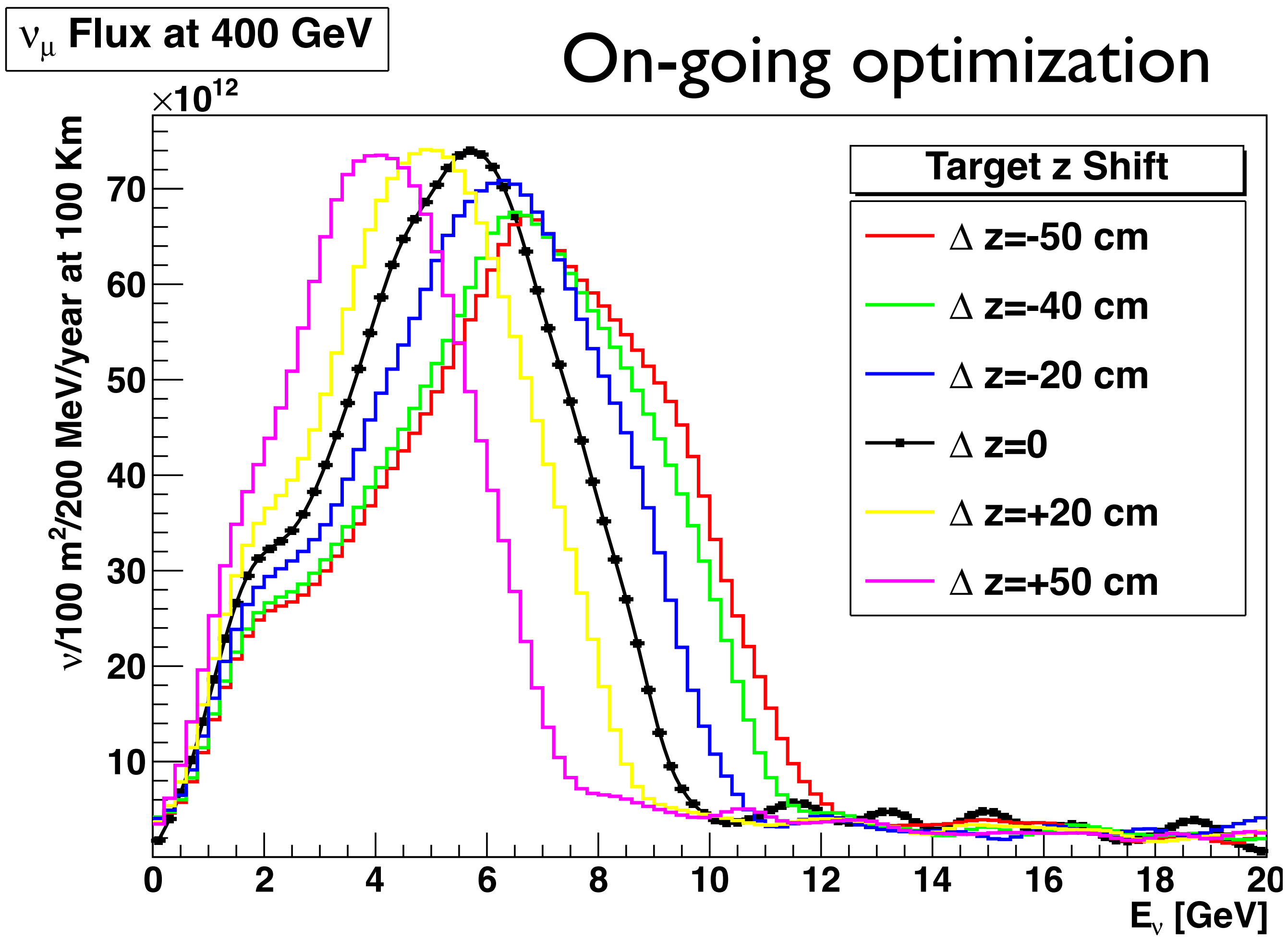
Beam spectrum optimization

LAGUNA-LBNO WP4

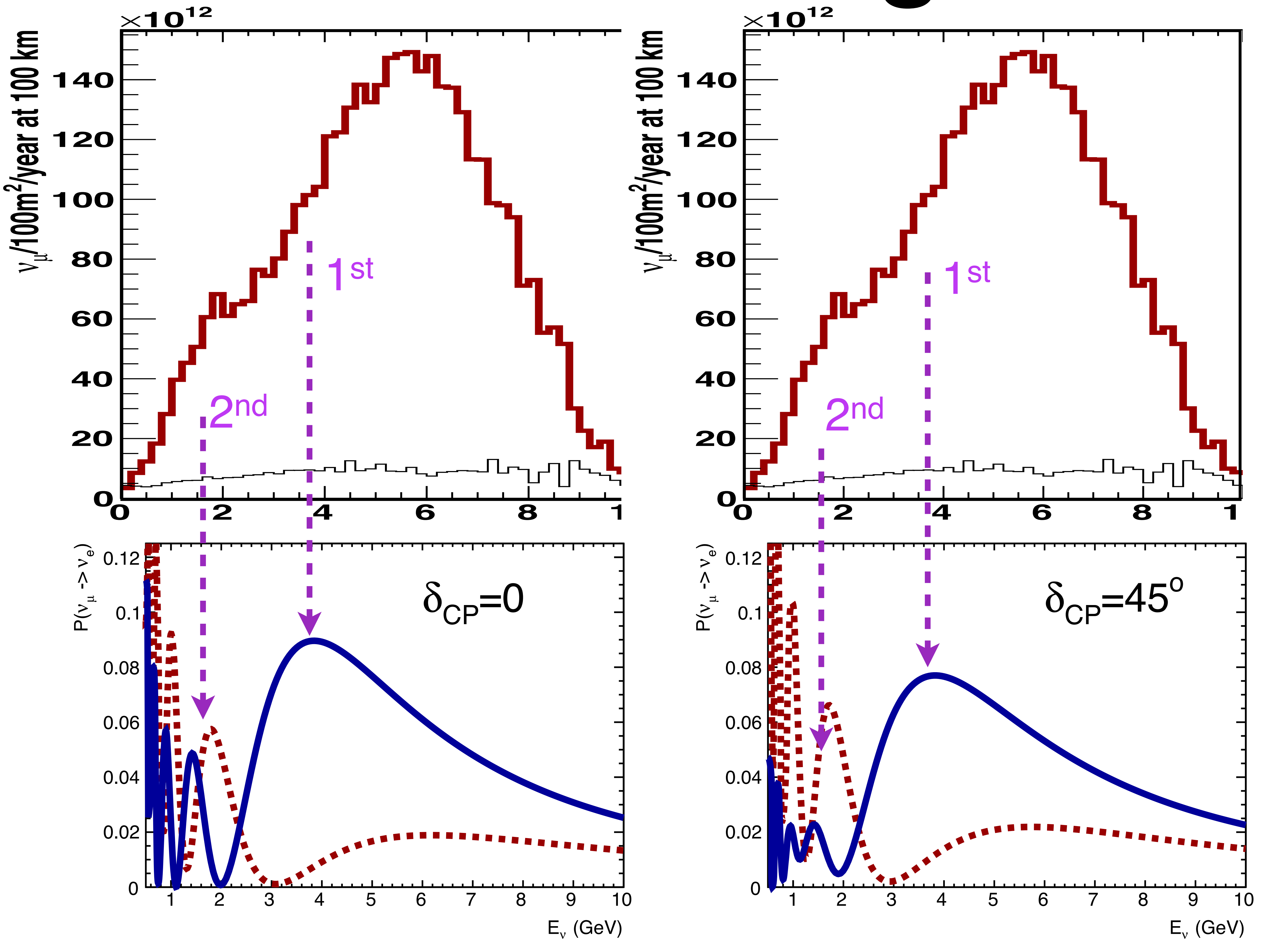
- Low-energy neutrino beam (0-10 GeV) optimization done within LAGUNA DS for various baselines to maximize θ_{13} sensitivity, assuming 50 GeV protons from HP-PS.
- Present activities:
  - Optimization for 200, 300 and 400 GeV SPS protons vs 50 GeV HP-PS;
  - Focusing optimization maximizing MH&CPV physics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



On-going optimization

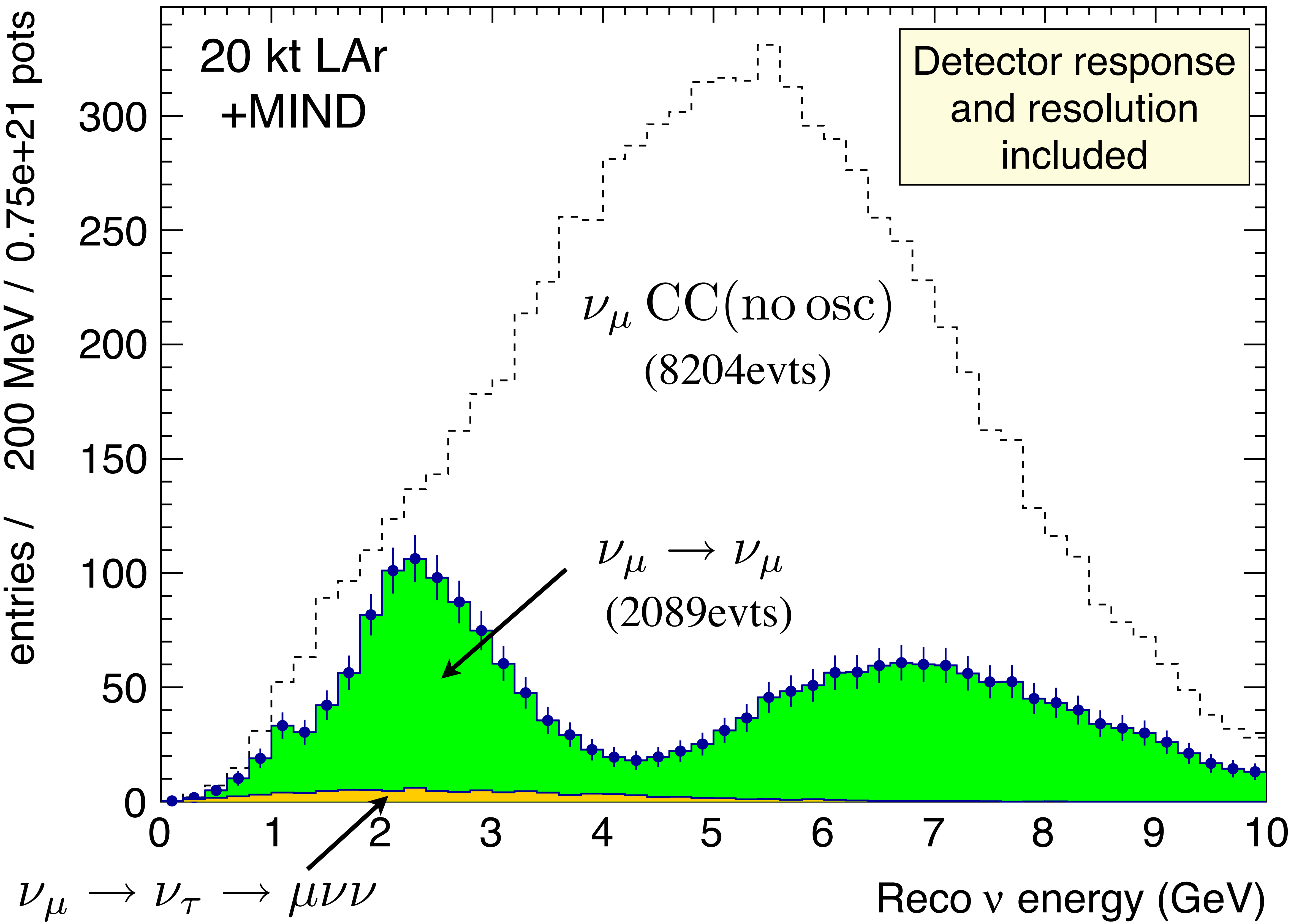


Flux tuning

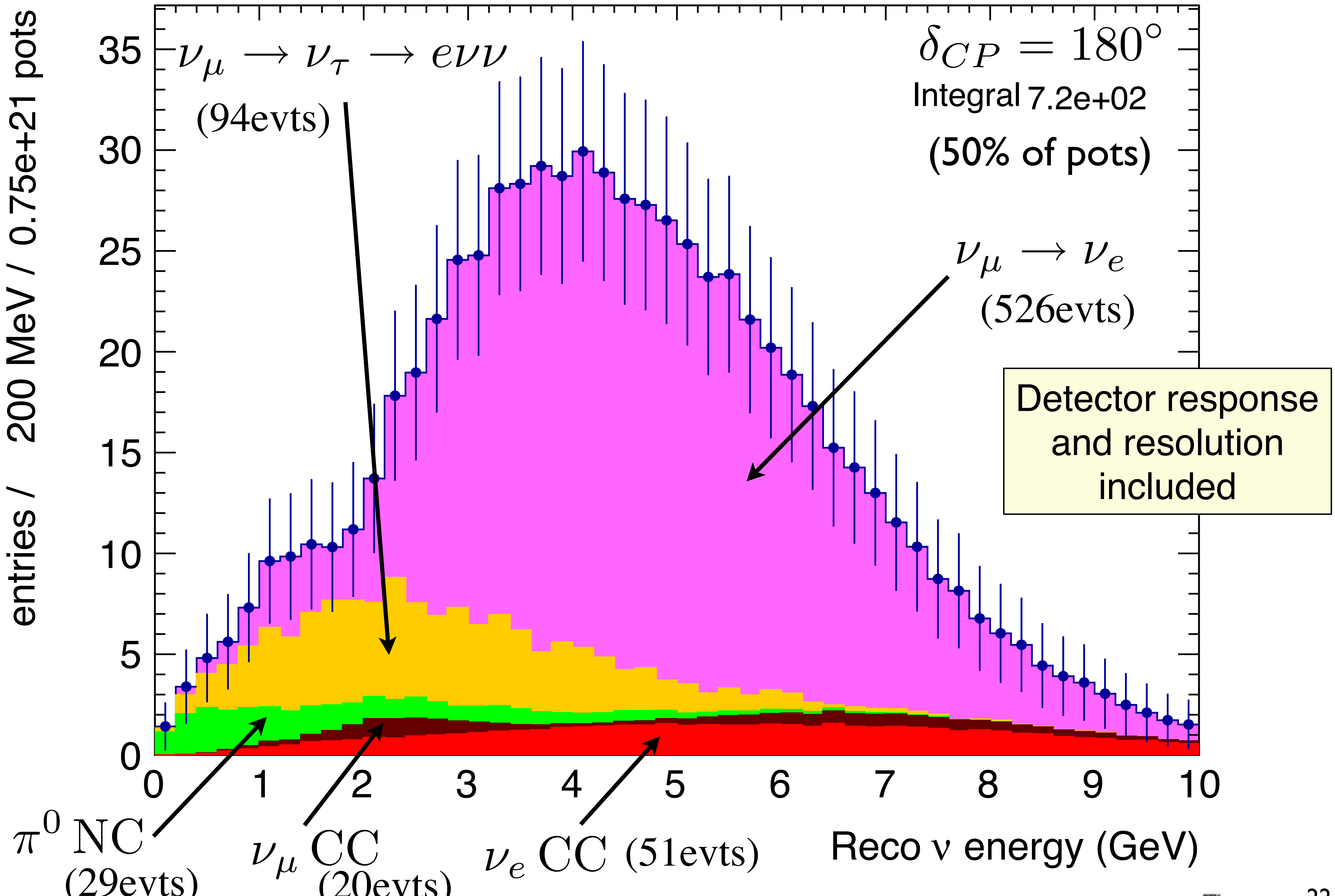


×10¹²
ν_μ/100m²/year at 100 km
140
120
100
80
60
40
20
0
0
2
4
6
8
1
1st
2nd
×10¹²
ν_μ/100m²/year at 100 km
1st
2nd
P(ν_μ -> ν_e)
0.12
0.1
0.08
0.06
0.04
0.02
0
1
2
3
4
5
6
7
8
9
10
δ_{CP}=0
δ_{CP}=45°
E_ν (GeV)

μ-like CC sample (+)

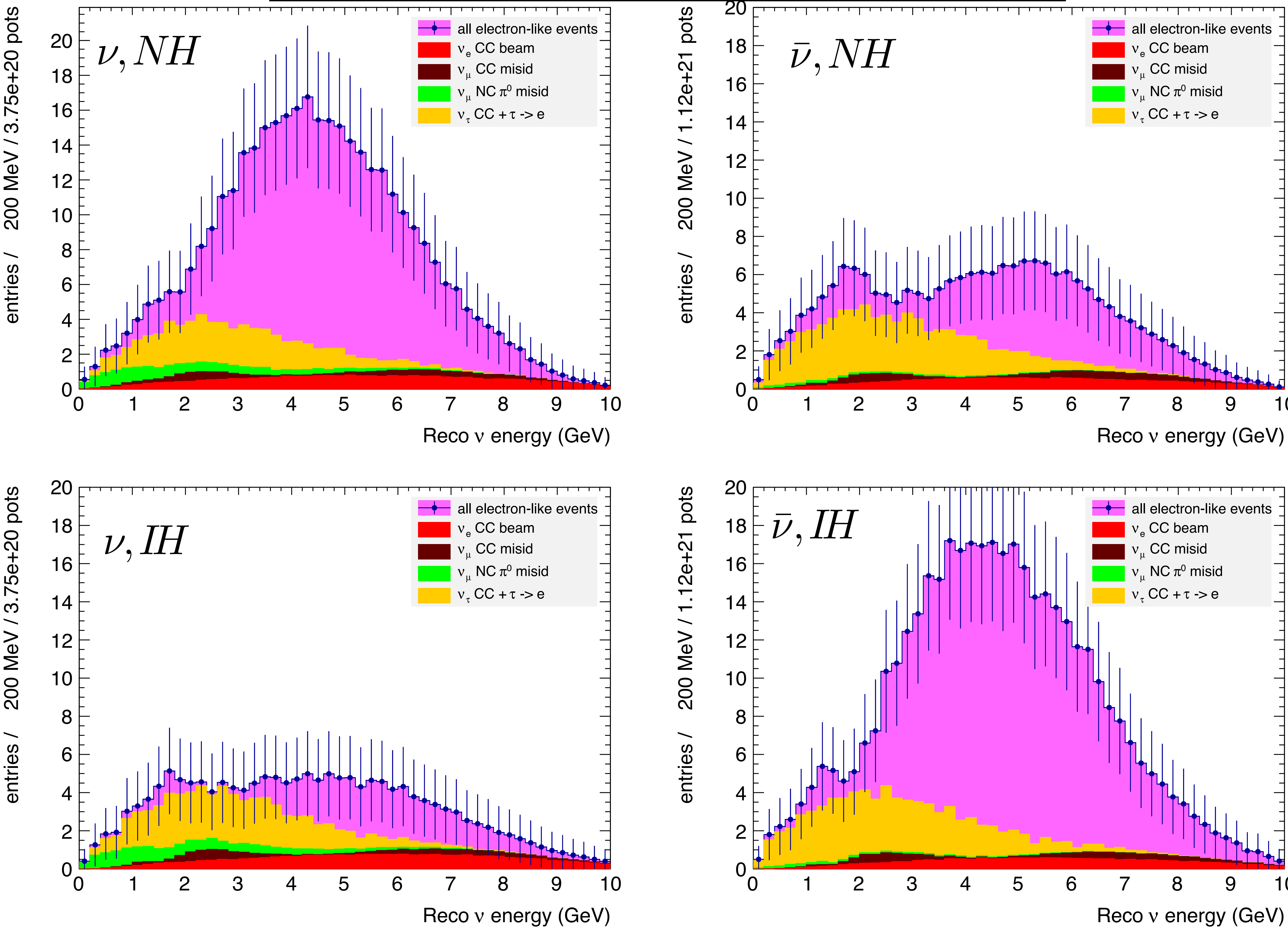


e-like CC sample (+)



Neutrino/antineutrinos and MH

Detector response and resolution included



LBNO sensitivity for MH&CPV

- 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

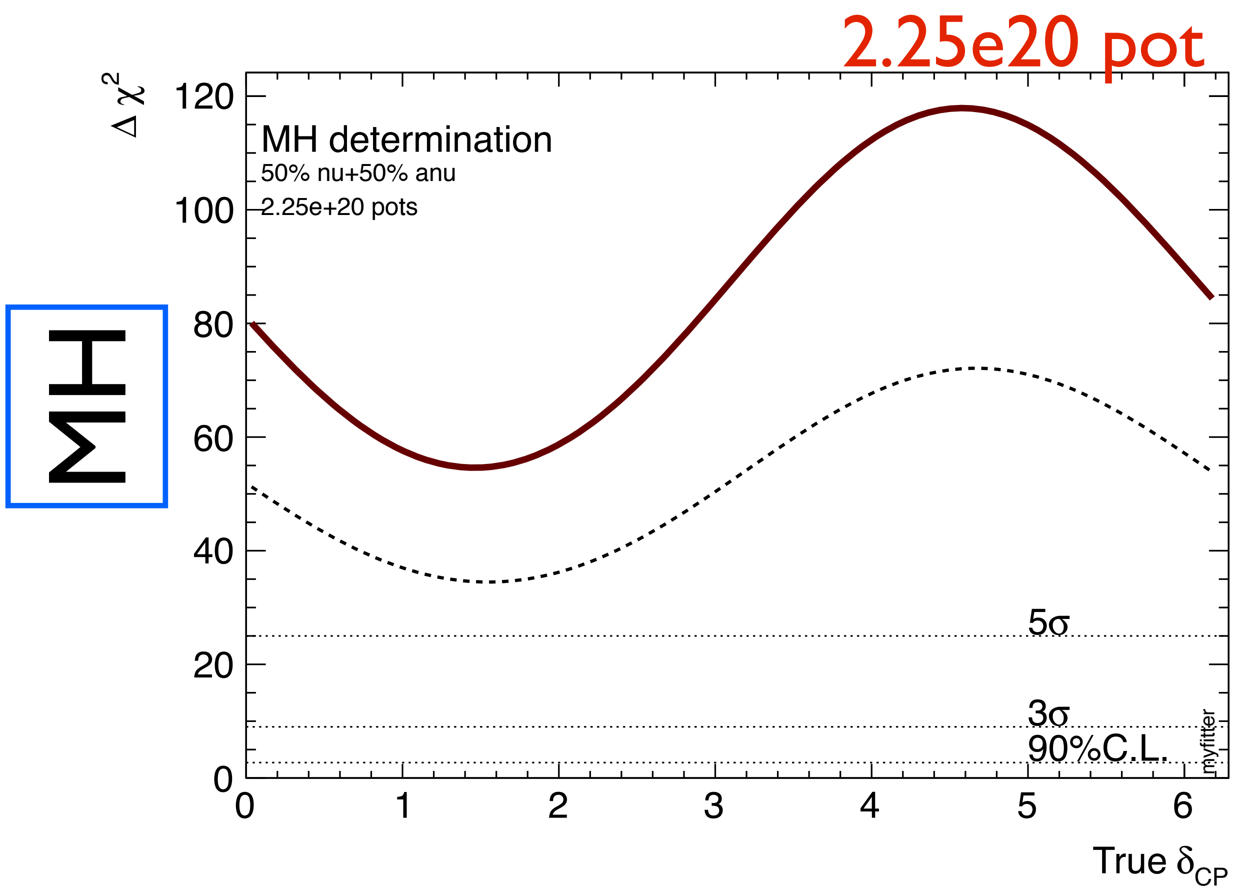
Name	Value	Error (1σ)
L	2300 km	exact
Δm^2_{21}	7.6×10^{-5} eV^2	exact
$\lvert\Delta m^2_{32}\rvert$ $\times10^{-3}$ eV^2	2.40	±0.09
$\sin^2\theta_{12}$	0.31	exact
$\sin^2 2\theta_{13}$	0.10	±0.02
$\sin^2\theta_{23}$	0.50	±0.06
Average density of traversed matter (ρ)	3.2 g/cm^3	$\pm4\%$

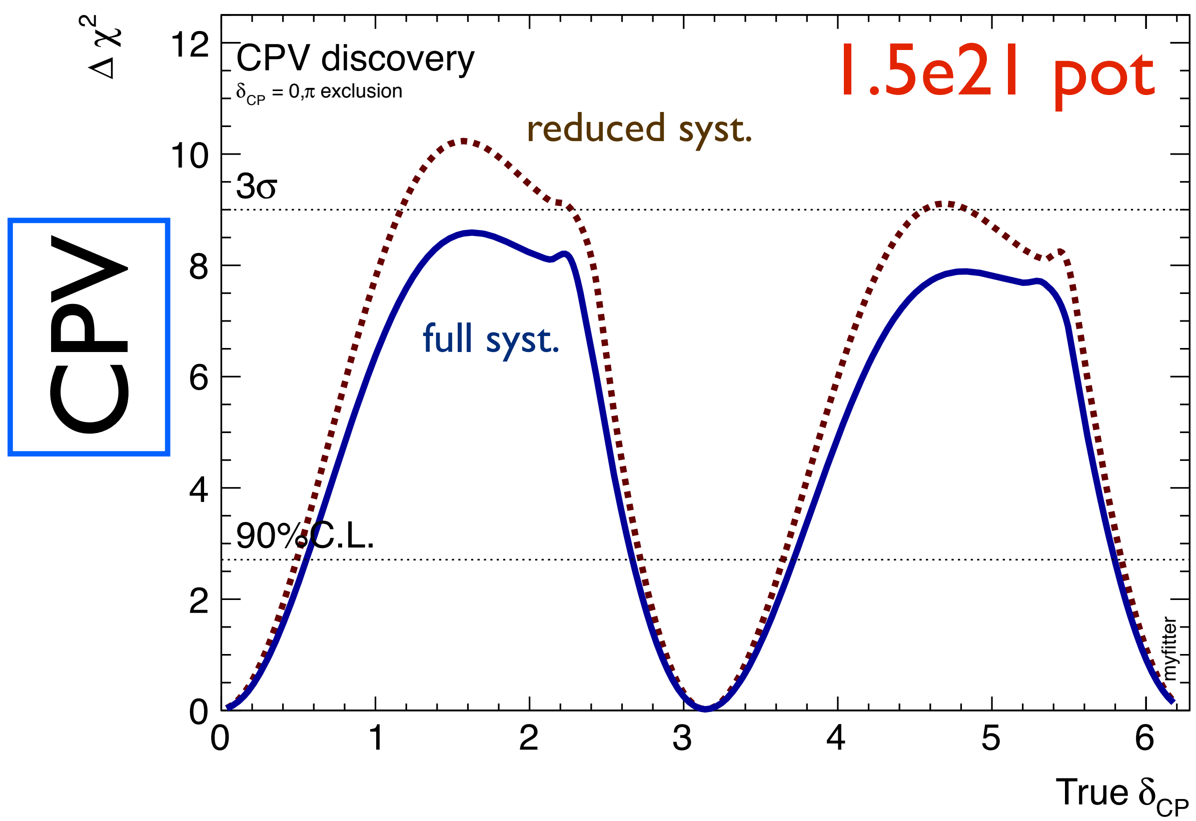
Name	MH determination	CP determination
	Error (1σ)	Error (1σ)
Bin-to-bin correlated:		
Signal normalization (f_{sig})	$\pm5\%$	$\pm5\%$
Beam electron contamination normalization ($f_{\nu_e CC}$)	$\pm5\%$	$\pm5\%$
Tau normalization ($f_{\nu_\tau CC}$)	$\pm50\%$	$\pm20\%$
ν NC and ν_μ CC background ($f_{\nu_{NC}}$)	$\pm10\%$	$\pm10\%$
Relative norm. of "+" and "-" horn polarity ($f_{+/-}$)	$\pm5\%$	$\pm5\%$
Bin-to-bin uncorrelated	$\pm5\%$	$\pm5\%$

Control of systematic errors will be fundamental

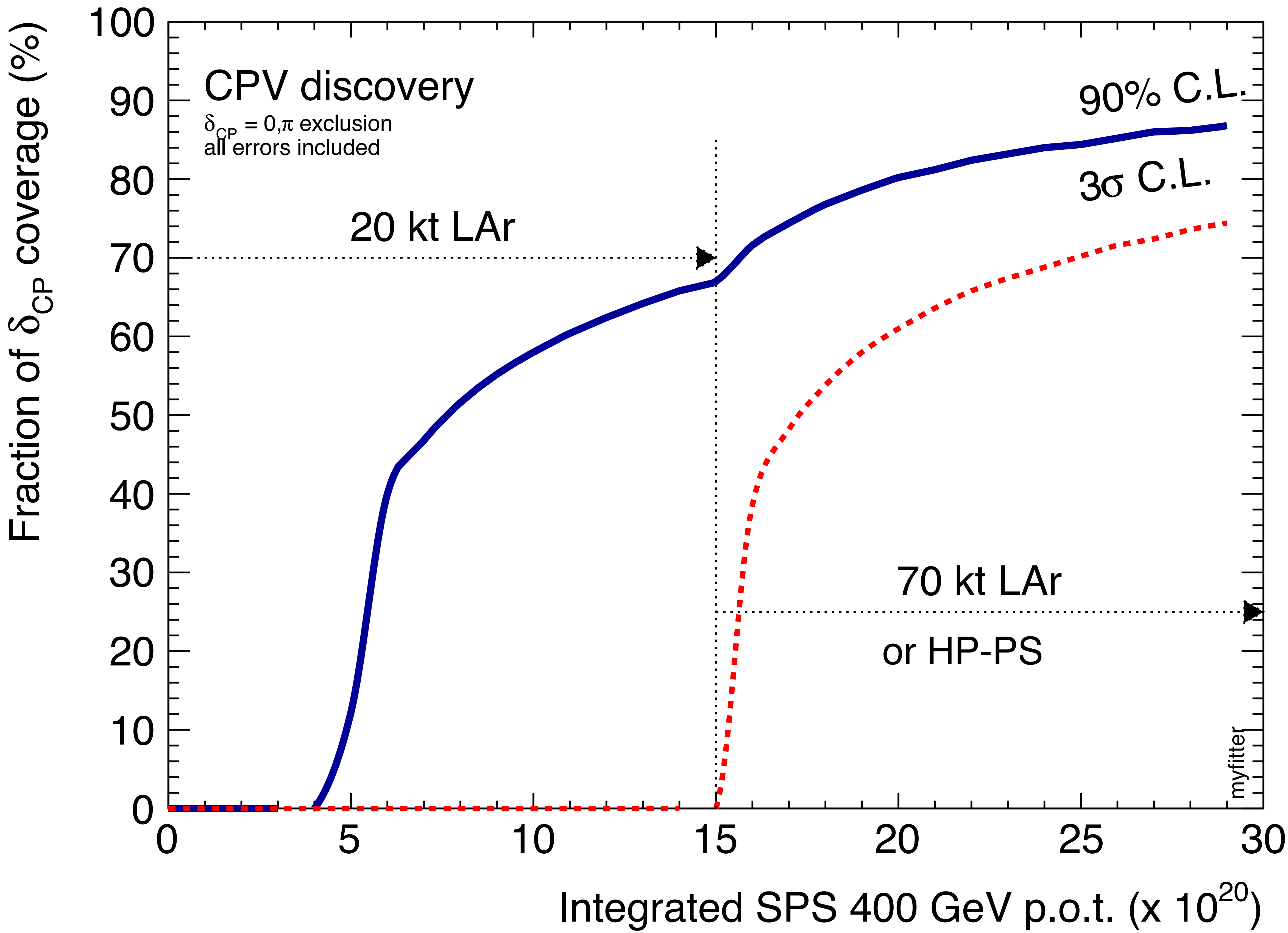
MH & CPV sensitivities

- Estimation using all systematic errors mentioned previously.
- Nominal beam power scenarios (700kW).
- For $\sin^2 2\theta_{13}$=0.1, approximately (at 90%C.L.):
  - MH: 100% coverage at >5σ in a few years of running
  - CPV: ≈60% coverage and evidence for maximal CP (π/2, 3π/2) at 2.9σ in 10 years
- CPV coverage already sensitive to systematic errors.
- With more details studies and a better definition of the near detector, hadron production measurements, and other auxiliary measurements, they might be reduced.
- In case of negative result, the CPV sensitivity can be improved with longer running periods and/or an increase in beam power and far detector mass. For instance, CPV becomes accessible at > 3σ's C.L. for 75% of the δ_{CP} parameter space with a three-fold increase in exposure, provided that systematic errors can be controlled well below the 5% level.





Incremental approach with conventional beams



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 ≈60% CPV coverage at 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. LBNO is a possible first step towards the Neutrino Factory.
- **We are calling on CERN to engage in a collaborative effort with the LBNO Collaboration to prepare a full engineering design of the CN2PY beam and to promptly support the necessary R&D and test beams needed to develop a Proposal by the end of 2014.**

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)

- We are grateful to the CERN Management for supporting the LAGUNA-LBNO design study.

- We thank the CERN staff participating in LAGUNA-LBNO, in particular M.Benedikt, M.Calviani, I.Efthymiopoulos, A.Ferrari, R.Garoby, F.Gerigk, B.Goddard, A.Kosmicki, J.Osborne, Y.Papaphilippou, R.Principe, L.Rossi, E.Shaposhnikova and R.Steerenberg.

- The contributions of Anselmo Cervera are also recognized.

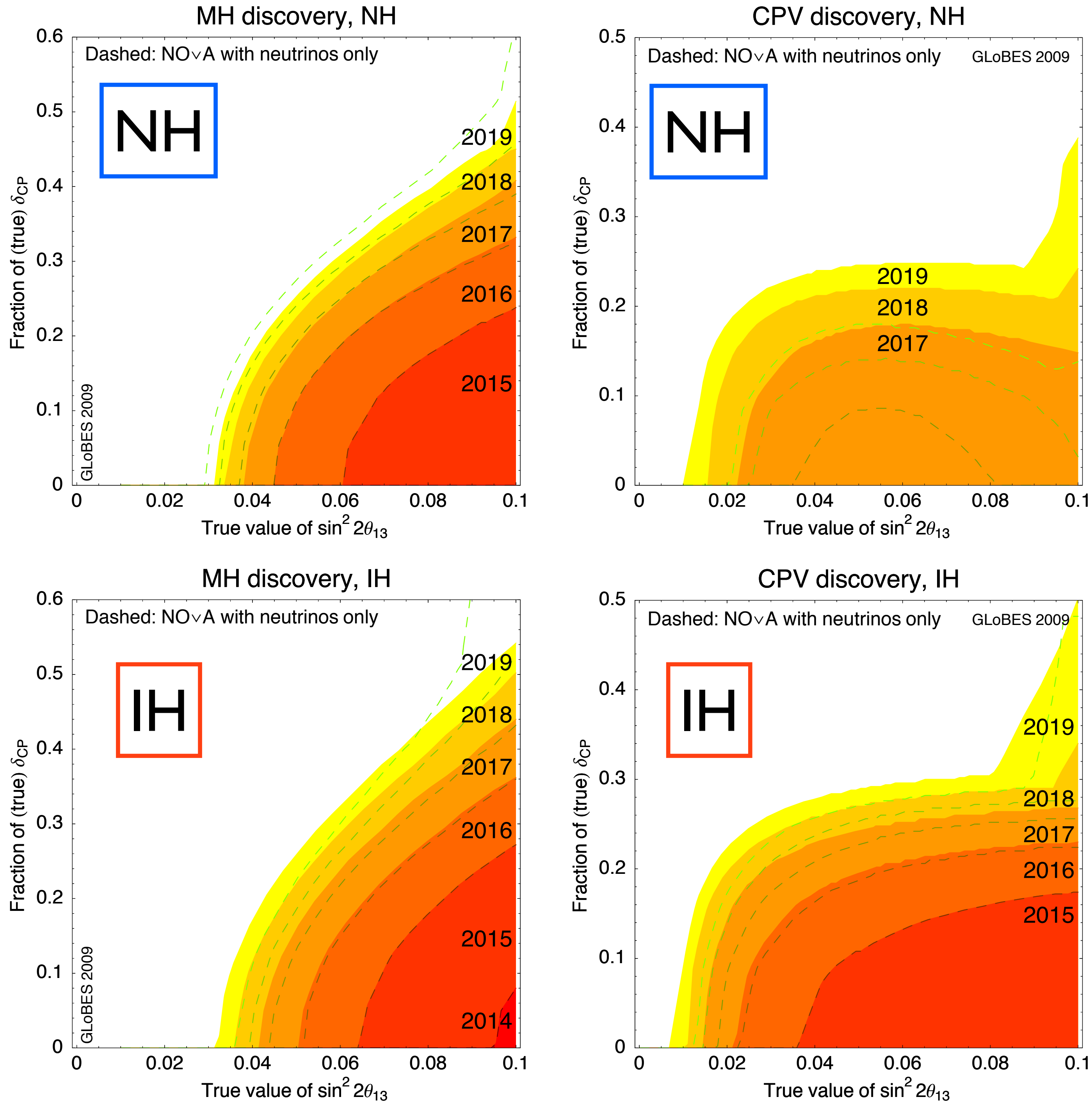
Backup slides

Courtesy PvZ

T2K and NOvA: in the future

- Preliminary and not official estimates of the combined T2K, NOvA and reactors sensitivity
- 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 ?)
- Are these curves too optimistic ?
- Atmospherics to the rescue ?
- Official predictions to be produced by experiments with revised projections.
- **CPV and MH are "extracted" from a global fit. Not a direct proof of CP nor direct measurement of MH induced matter effect !!**

MH 90%C.L. sensitivity CPV



Huber et al., JHEP 0911:044,2009

not official

LBNO EoI: the physics reach

- Initial setup 20 kton LAr LEM TPC + MIND + CERN SPS 700kW
- **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.

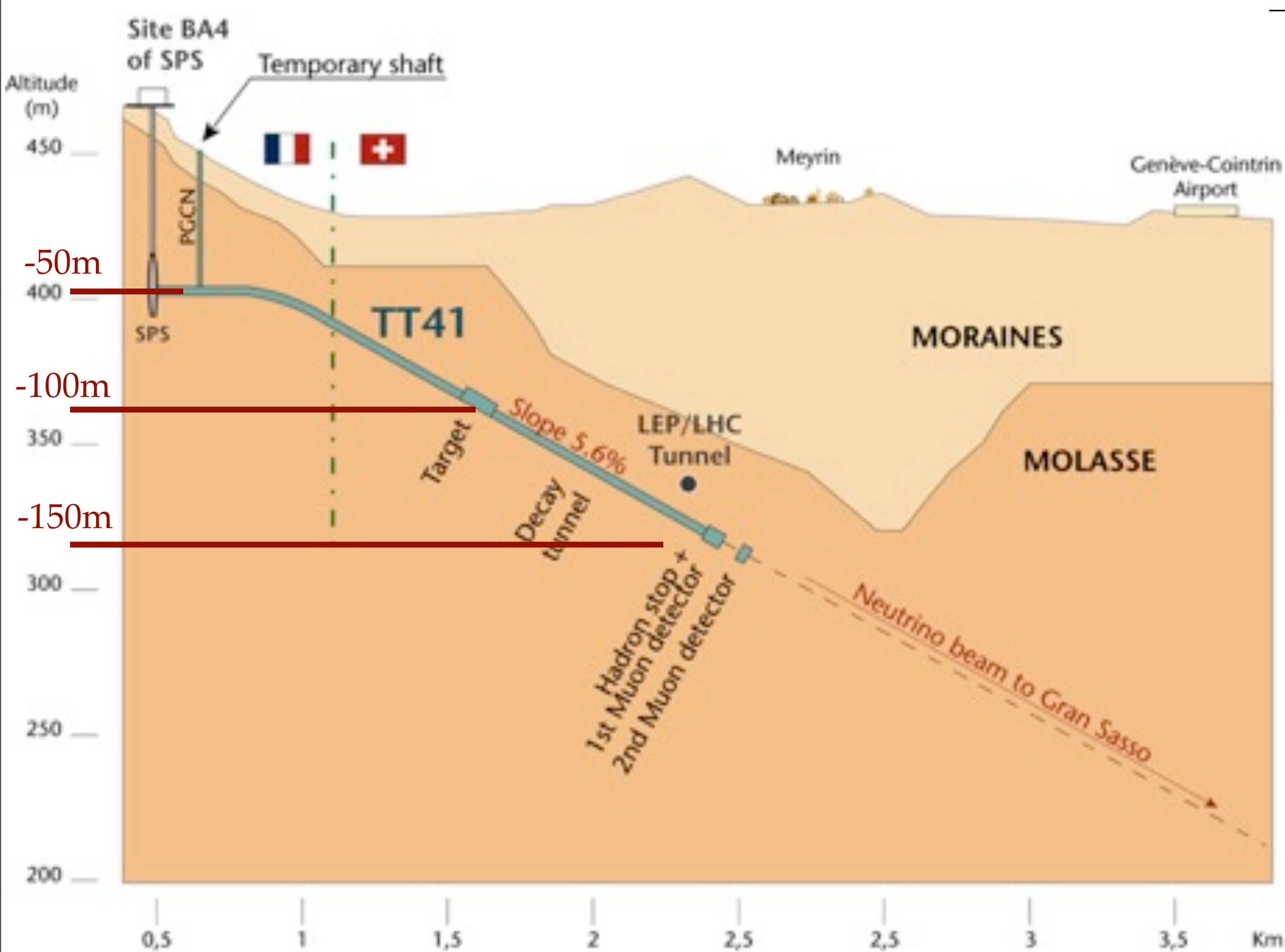
5600 atmospheric events/yr **relic SN, WIMP annihilation, ...**

>10000's events @ SN explosion@10kpc

Depth considerations for CN2PY

	Distance [m]	Depth [m]
target	-	0
hadron stop	300	-54.3
muon station	330	-59.9
1st position for near detector	500	-90.57
2nd position for near detector	800	-145.21

- The depth for the installations is the major concern
  - 18% slope compared to 5.6% for CNGS



Starting the beam from the SPS level adds **~100m** to the depthof the installations

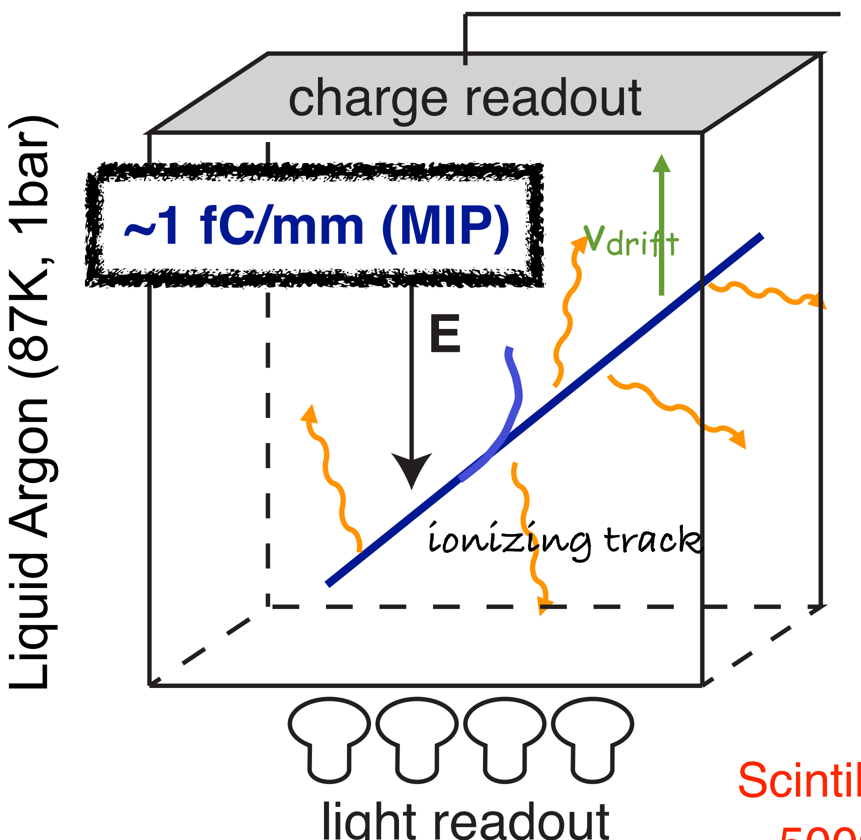
- Staying in the **molasse layer** has quite some advantages for the civil engineering and radiation to environment (underground water activation) issues

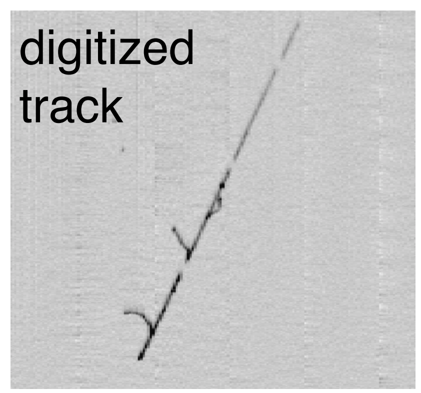
Physical parameters and challenges

Liquid Argon:
+ High density, cheap medium
+ Quasi free electrons from ionizing tracks are drifted in LAr (87K, 1bar) by E_{drift}.
+ Electron drift velocity ≈ 2mm/μs @ 1 kV/cm
+ Electron cloud diffusion is small
  ($\sigma \approx \sqrt{2Dx/v_{drift}}$ ≈ mm after several meters of drift)
+ High scintillation yield (@ 128 nm) can be used for T_0, trigger, ...

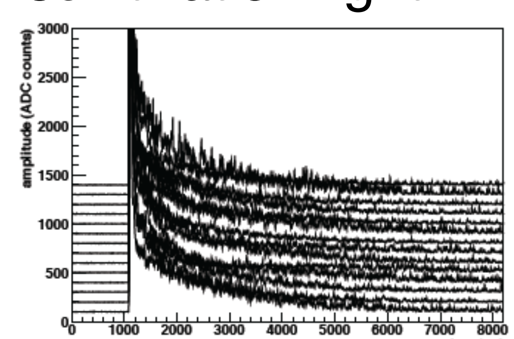
Technical challenges:
– Long drift requires ultra high purity
  * free of electro-negative molecules (O_2, H_2O, ...)
    Goal << 100 ppt O_2 equivalent !!
  * Drift field implies high voltage on the cathode
– Large wire chambers at cryogenic T
– No charge amplification in liquid: fC-level charge sensitive preamplifiers (can be partially solved by LAr LEM TPC – see later)
– Large #readout channels
– Large cryogenic systems

Charge yield after e-ion recombination (mip) ~ 1 fC/mm (~ 6000 electrons/mm) before finite e-lifetime correction

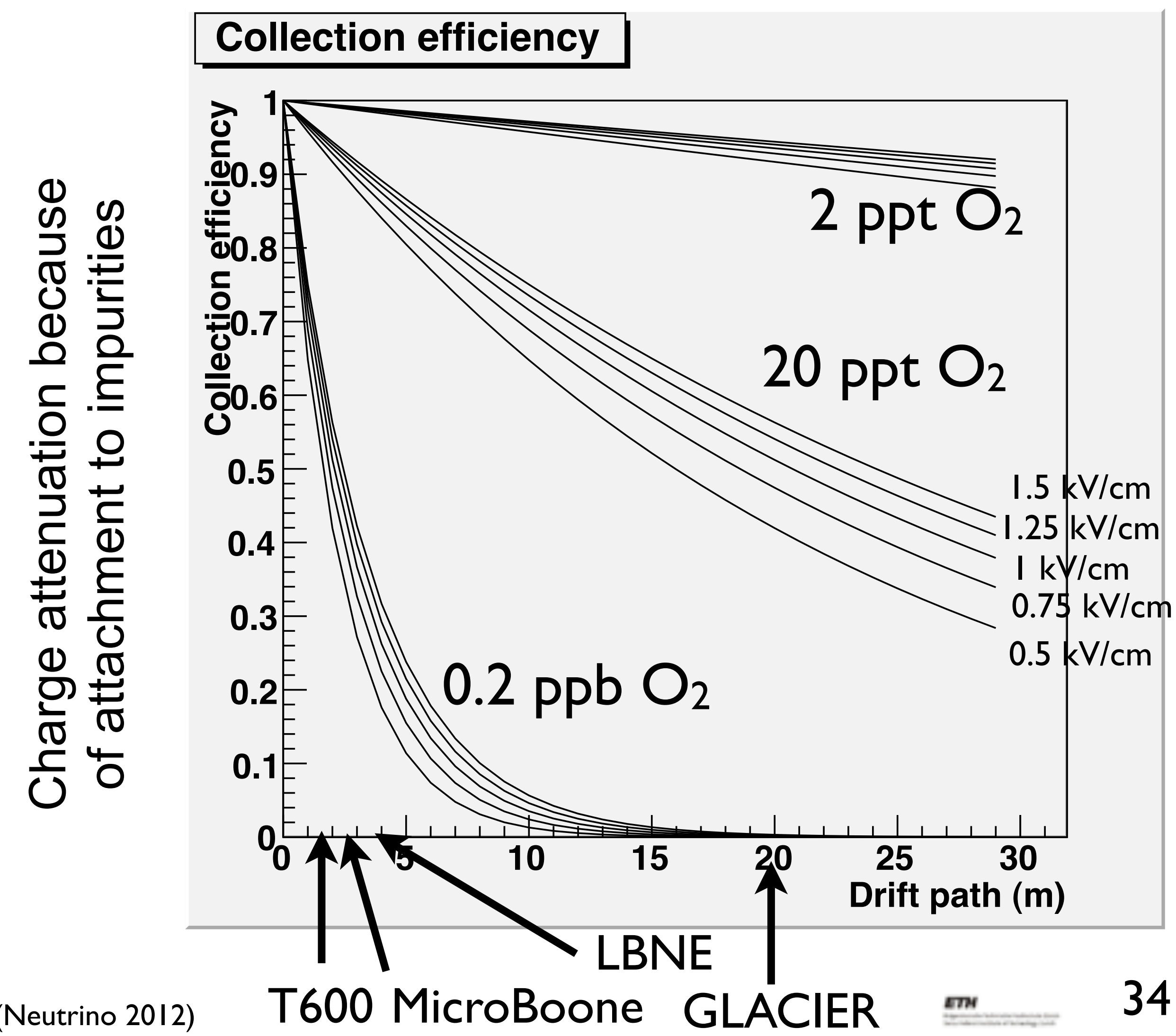




scintillation light



Scintillation yield (mip)
~ 5000/mm @ 128nm



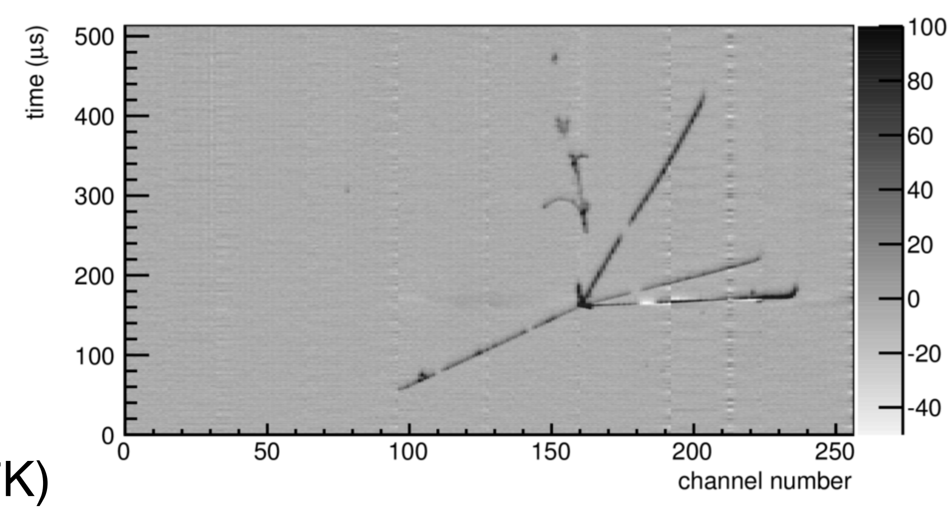
The LAr TPC features

★ The LAr TPC is the very successful marriage between the "gaseous TPC" and "the liquid argon calorimeter" to obtain a dense and very fine grained three dimensional tracking device with local dE/dx information and a homogenous full sampling calorimeter

★ Detector performance:

- 3D tracking, mm-scale spatial resolution with local dE/dx
- fully sensitive, ≈2%X_0 sampling rate and excellent energy resolution
- excellent particle identification (range vs dE/dx), e/π0 separation with ε=90% for rejection factor >100.
- continuously sensitive ("trigger-less" mode)

Cosmic interaction in double phase 40x80cm^2 LAr-LEM TPC with adjustable gain @ CERN-ETHZ



★ Technology achievement:

- large ultra high vacuum (<1e-9 mbar lt/s) and cryogenic systems (T=87K)
- ultra high purity liquid argon (<30 ppt O_2 equiv ➠ >10 ms lifetime)
- large cryogenic wire chambers (up to 9m long wires)
- very high drift voltage (up to 150 kV)
- low noise fC charge sensitive readout electronics (S/N > 10 for m.i.p with C_{det} ≈ 400pF)

★ Physics performance:

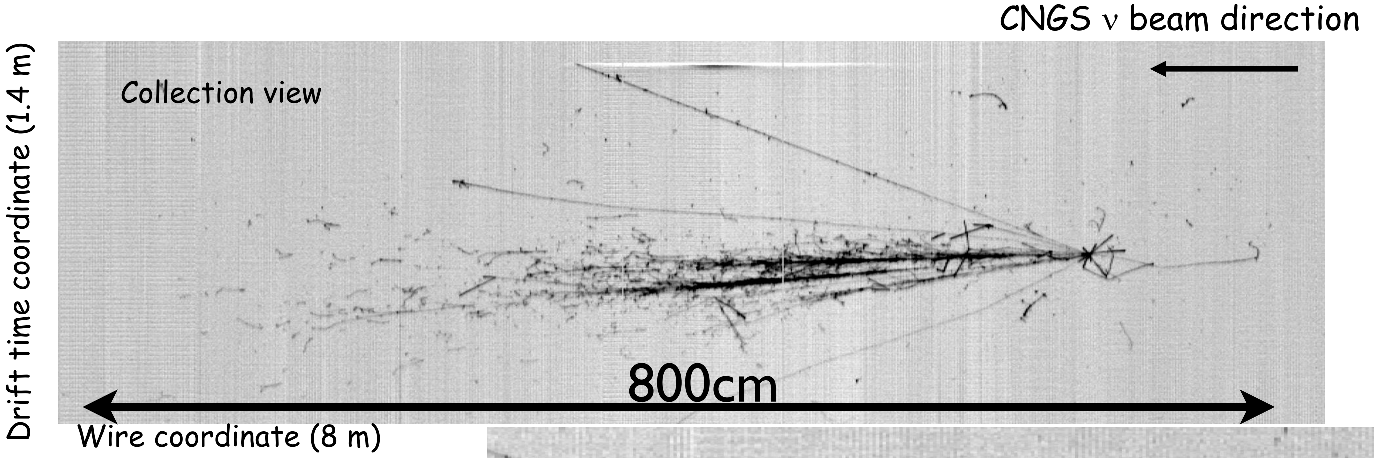
- Kinematical reconstruction of QE events (ICARUS 50L@CERN WANF) — **PRD 74, 112001 (2006)**
- Inclusive cross-section measurement on Argon (ArgoNEUT) — **PRL 108 (2012) 161802**
- Many published studies on:
  - Proton decay
  - Atmospheric neutrinos: e.g. detection of ντ
  - Supernova core collapse neutrinos
  - Diffuse supernova neutrino background
  - Indirect DM detection
  - Long baseline neutrino oscillation for CPV & MH

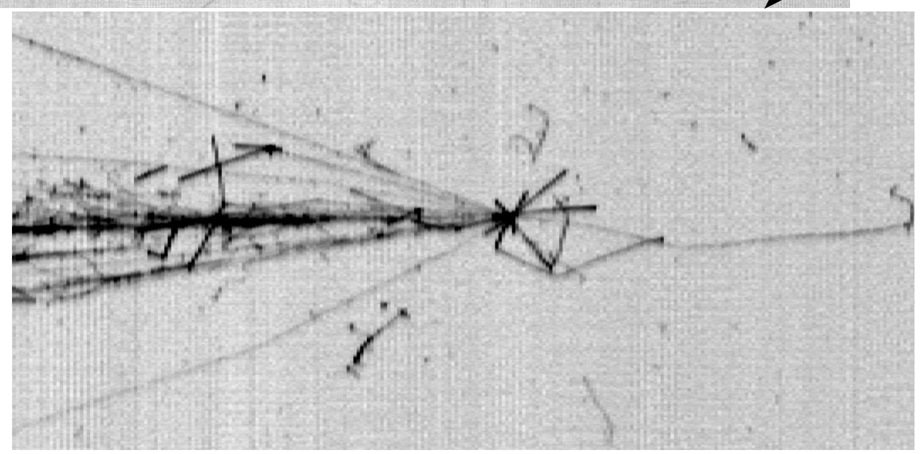
For example:

JHEP 0704 (2007) 041
JCAP 0408 (2004) 001
JCAP 0412 (2004) 002
arXiv:1105.4077 [hep-ph]
Nucl. Phys. B 589 (2000) 577

PRD82, 093012 (2010)
Nucl. Phys. B. Proc. Suppl. 91, 223 (2001)
arXiv:1003.1921 [hep-ph]
arXiv:0804.2111 [hep-ph]
arXiv:0801.4035 [hep-ph]
JHEP 0611 (2006) 032
+ etc...

The "electronic bubble chamber"

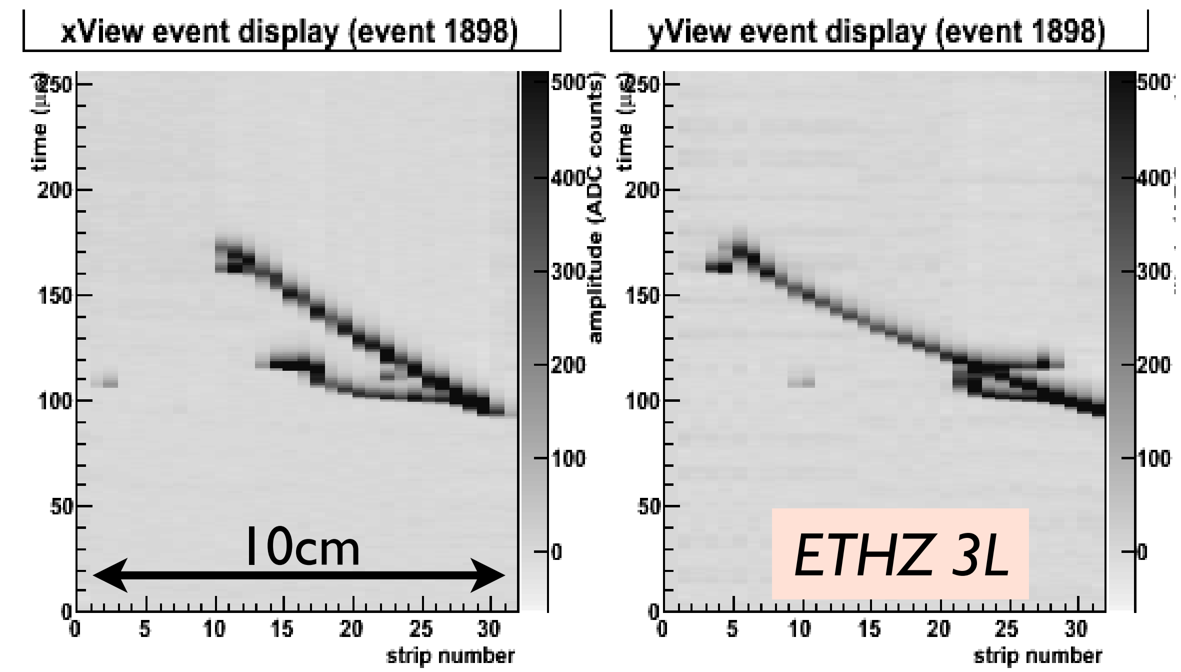




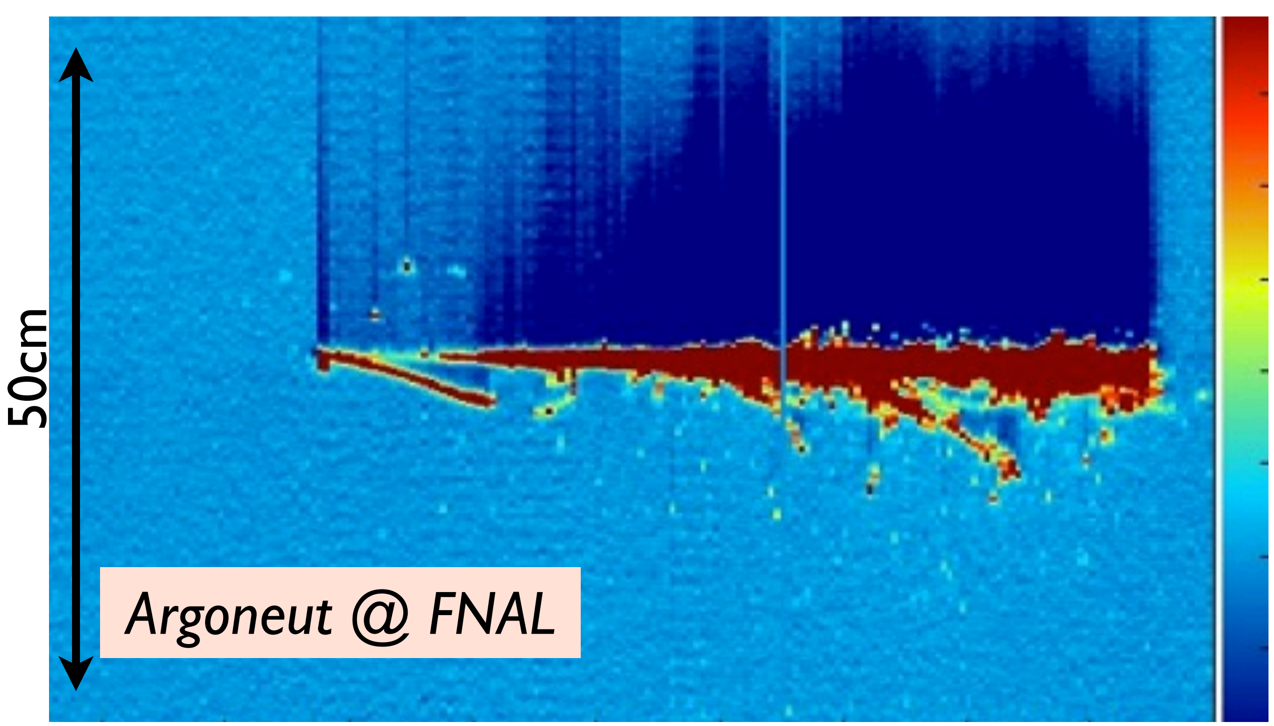
ICARUS T600 @ LNGS

Courtesy A. Guglielmi

Cosmic track in double phase 3L LAr-LEM TPC with adjustable gain @ CERN-ETHZ

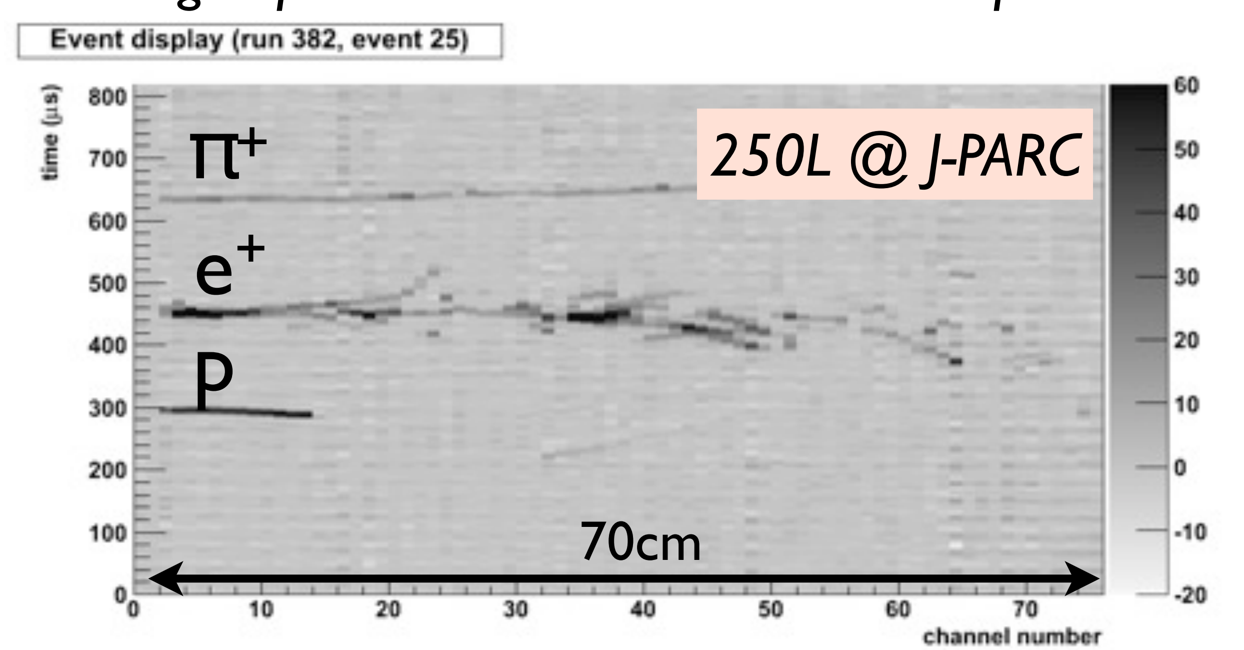


Much improved S/N (>100) compared to single-phase LAr operation (≈15)



Courtesy B. Fleming

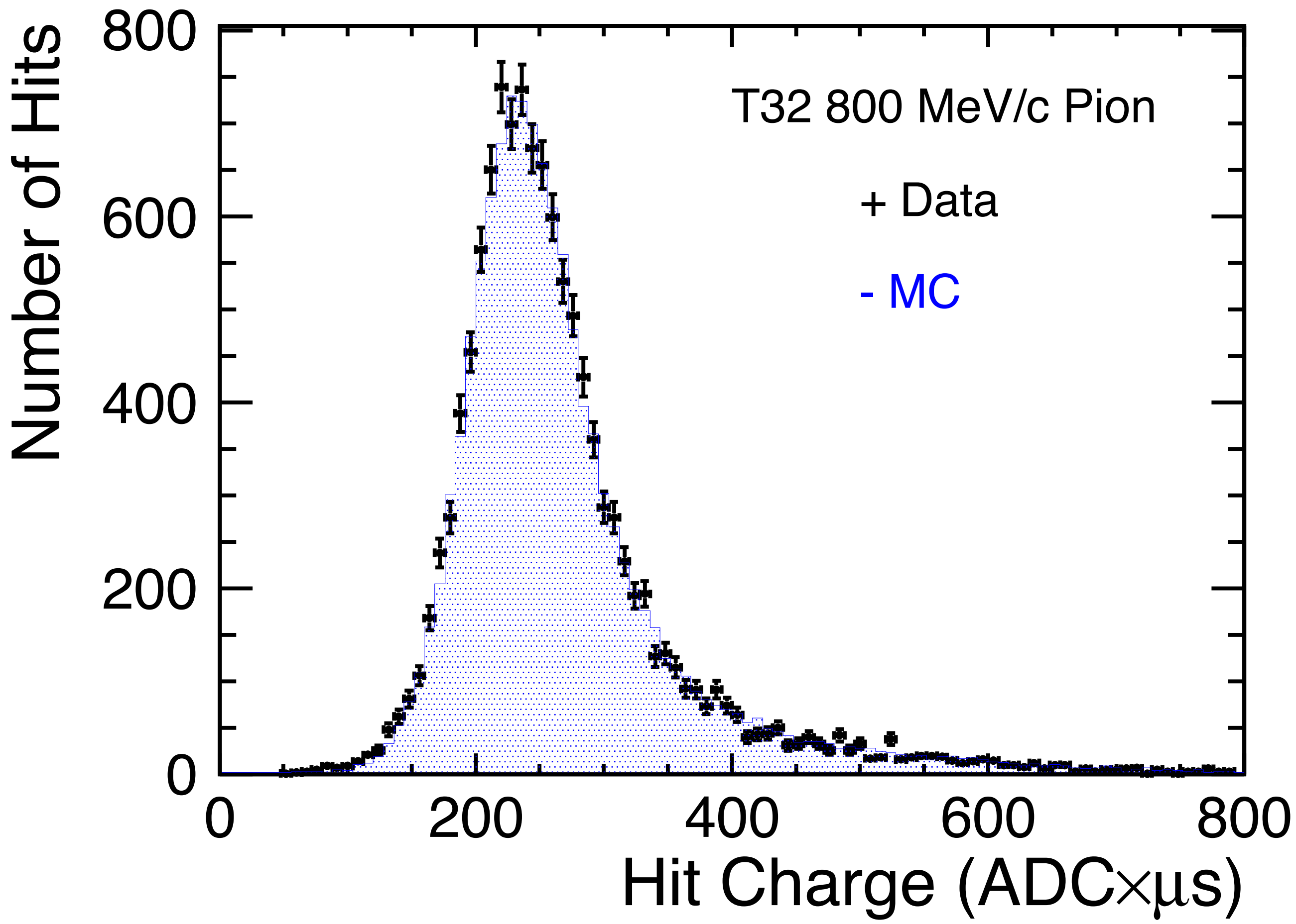
Charged particle beam ≈800 MeV/c exposure



Tracking performance

JPARC T32 exposed to K1.1BR tagged beam

J.Phys.Conf.Ser. 308 (2011) 012008



Data well described by:

Birks Law

$$Q = A \frac{Q_0}{1+(k/\varepsilon)\times(dE/dx)\times(1/\rho)}$$

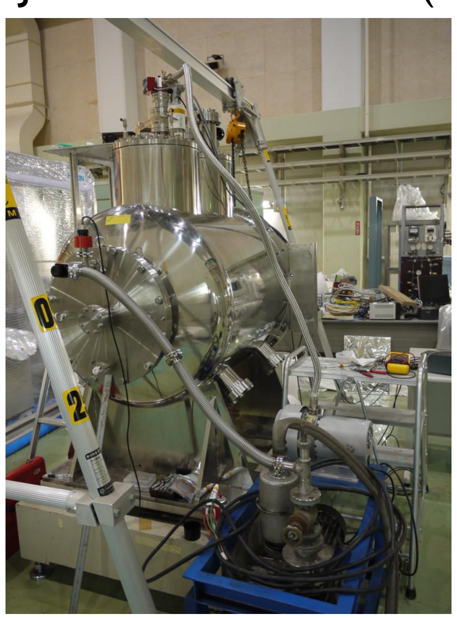
Q: Observable charge; Q_0: Raw charge

$$A = 0.8$$

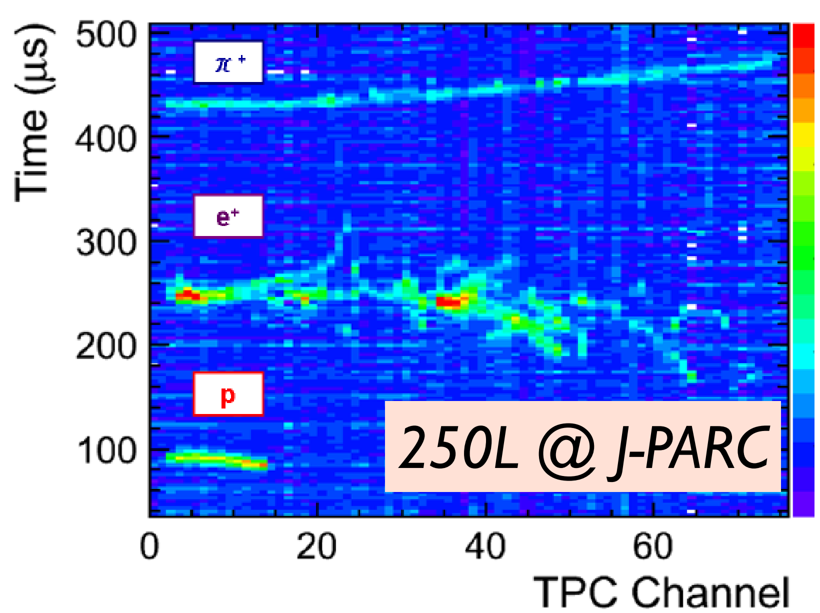
$$k = 0.0486\ \mathrm{kV/cm}\,\frac{\mathrm{g/cm^2}}{\mathrm{MeV}}$$

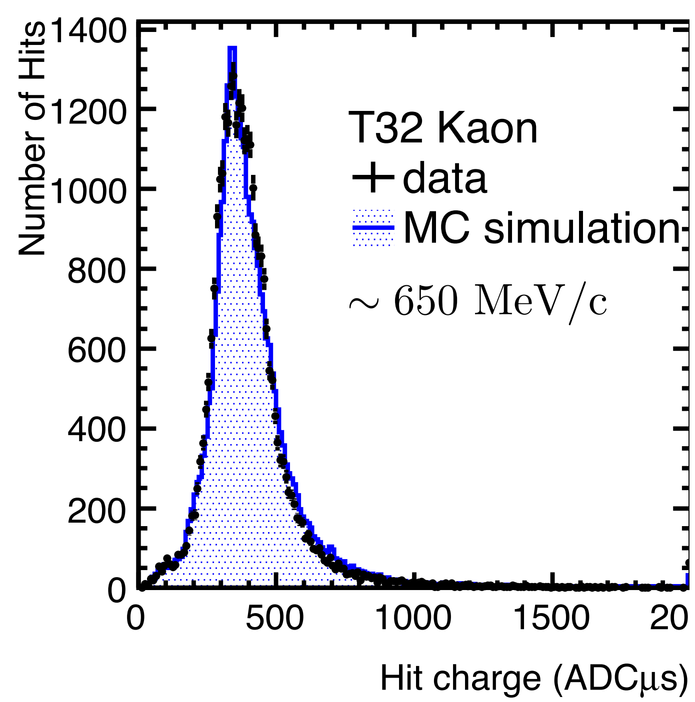
NIM A 523, 275 (2004)

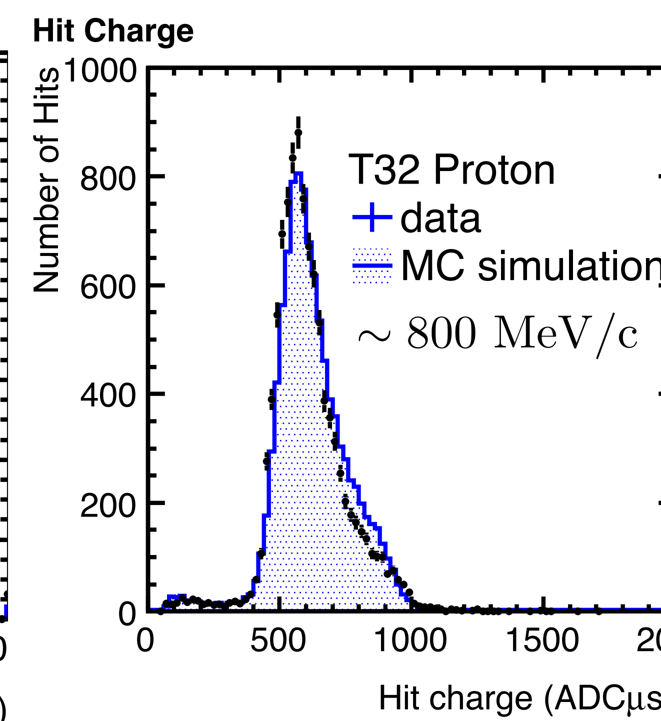
J-PARC T32 chamber (ETHZ-KEK-Iwate-Waseda)



Courtesy T. Maruyama





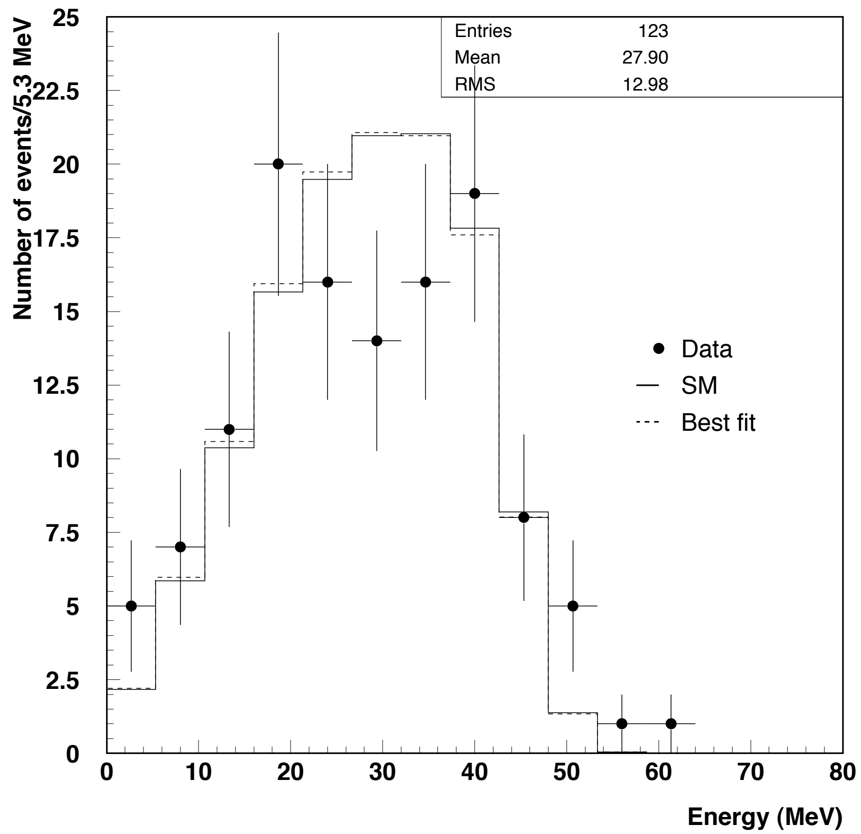


Good understand of tracking

Calorimetric performance

Michel electrons form stopping muon decay sample

$$\frac{\sigma_e}{E} \simeq \frac{11\%}{\sqrt{E(\mathrm{MeV})}} \oplus 4\%$$



Eur. Phys. J. C33, 233 (2004)

MC simulations at higher energies:

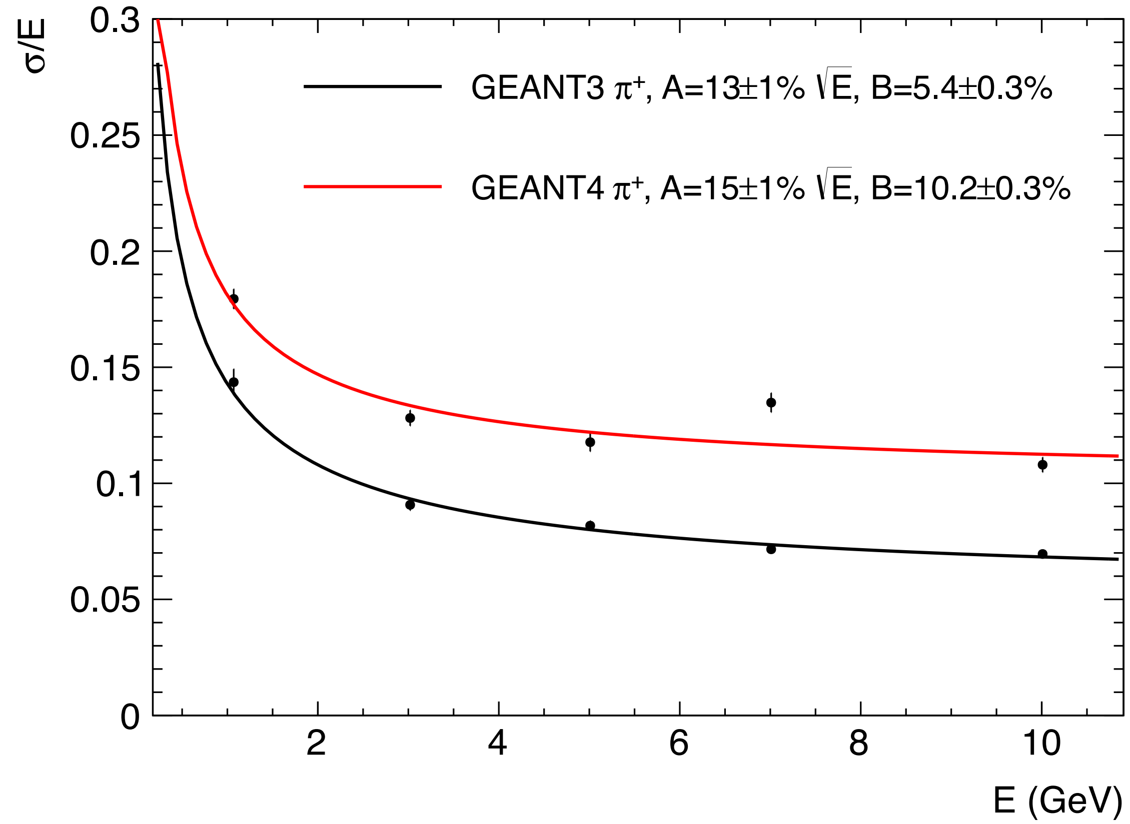
$$\frac{\sigma^{MC}_{em}}{E} \simeq \frac{3\%}{\sqrt{E}} \oplus 1\%$$

$$\frac{\sigma^{MC}_{had}}{E} \simeq \frac{15\%}{\sqrt{E}} \oplus 10\%$$

↑

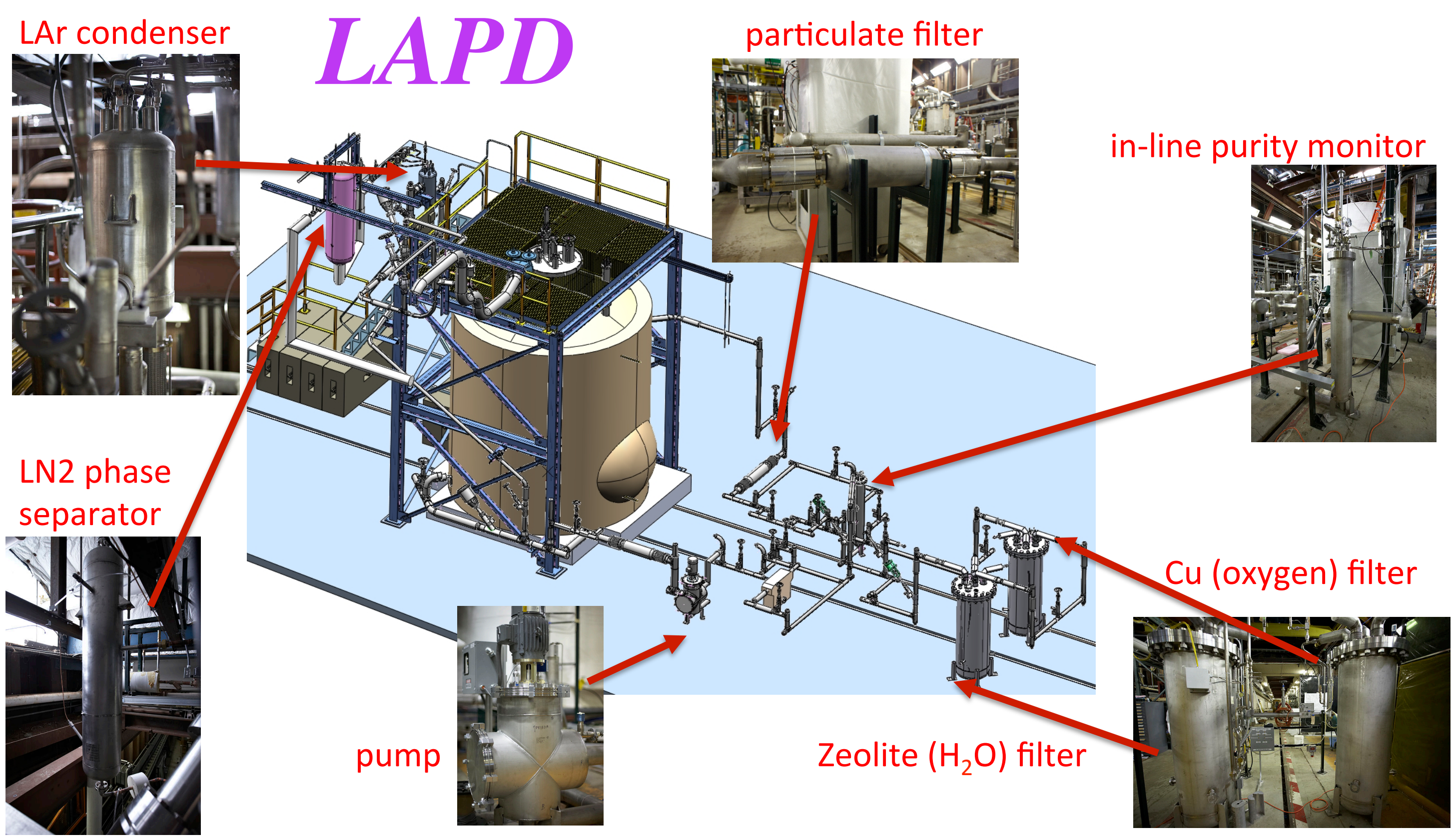
needs to be confirmed by experimental data

G3 and G4 comparison

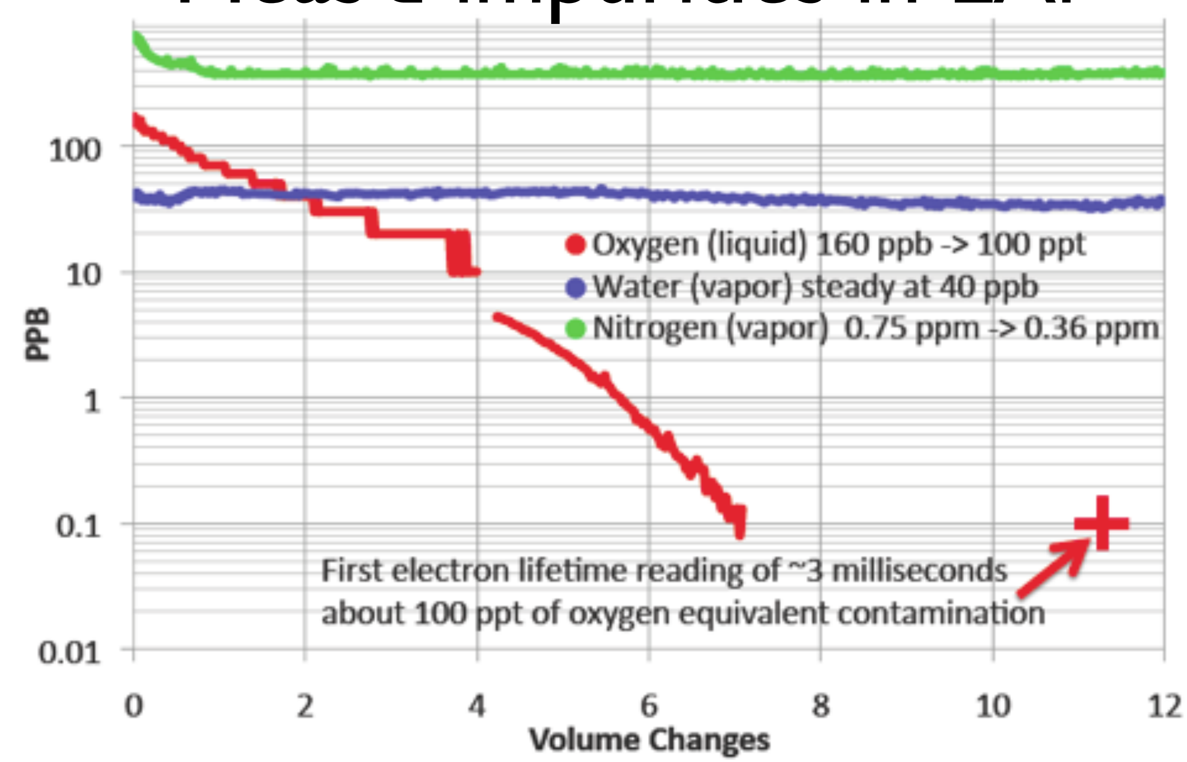


Purity and vessel evacuation

- ★ Several independent groups performed numerical simulations and concluded that the vacuum evacuation phase could be avoided for larger detectors:
  - more favorable surface / volume ratio for large volume (also larger volumes are less sensitive to micro leaks !!)
  - initial purity of argon when delivered is typ. O(1) ppmv O_2 → purification from ppm to << 1 ppb anyhow needed
  - outgassing of material from hot components, impurities “frozen” at low temperature
- ★ GAr flushing and purging are effective ways to remove air and impurities.
- ★ Purging on 6m3 volume (ETHZ-KEK-Liverpool @ CERN)
  - Piston effect seen in gas and reached 3ppm O_2 after several volumes exchange (J.Phys.Conf.Ser. 308 (2011) 012024)
- ★ LAPD @ FNAL – Liquid Argon Purity Demonstrator – First test in Liquid Phase !
  - Tank size: 30 ton LAr (25,000 liters)
  - Milestone successfully reached!! it is possible to obtain a **better than 3 ms electron lifetime** in a large non-evacuated vessel !



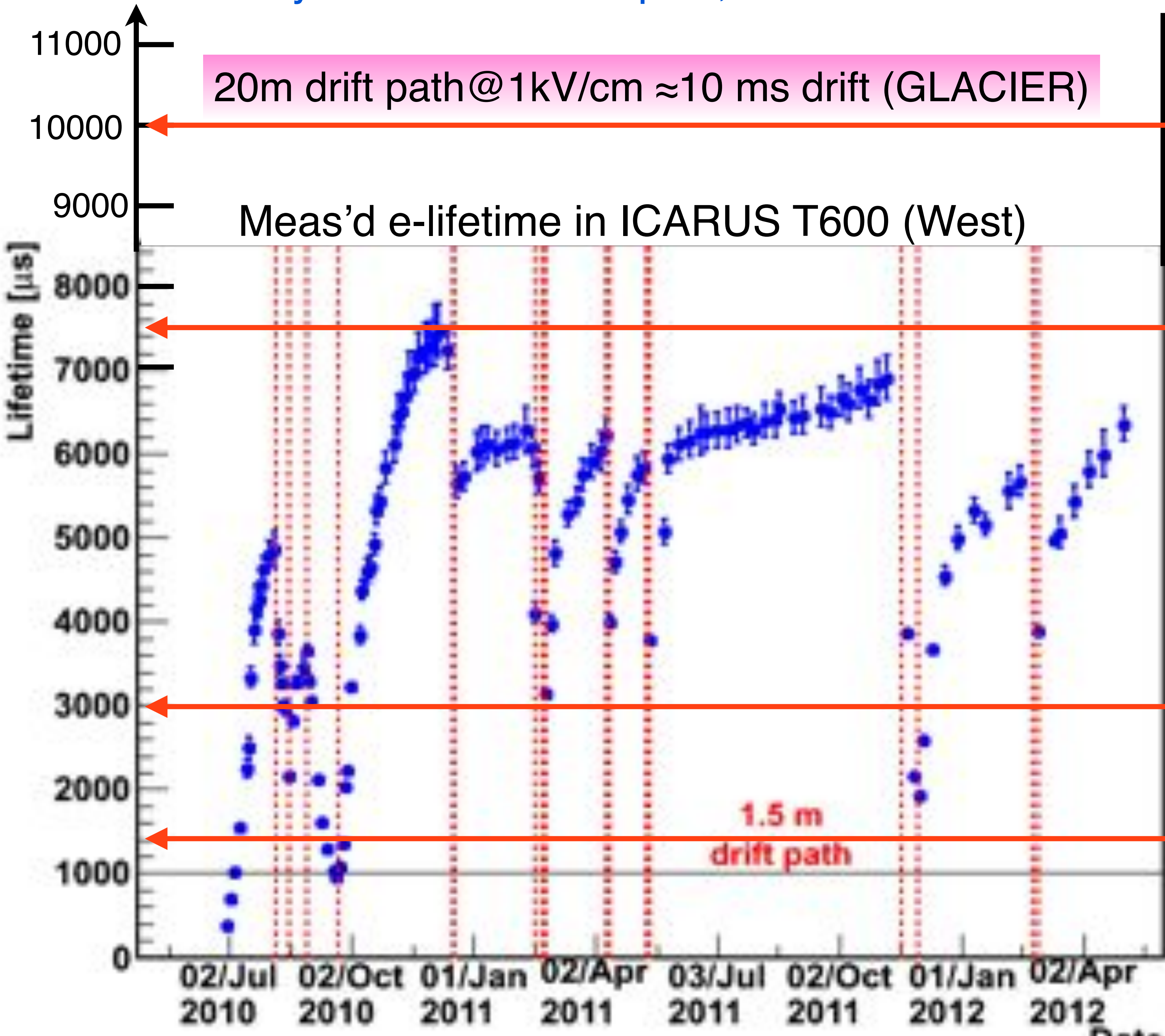
Meas’d impurities in LAr



Courtesy B. Baller & B. Rebel

Purity and evacuation

★ Excellent purity has been reproducibly achieved in various setups always relying on commercially available techniques, of various sizes and capacities.



Courtesy F. Pietropaolo

Record purity in ICARUS 50L @ CERN >10 ms (volume evacuated)
Phys.Rev. D74 (2006) 112001

Record purity in ICARUS T600 ≈7.5 ms (volume evacuated)

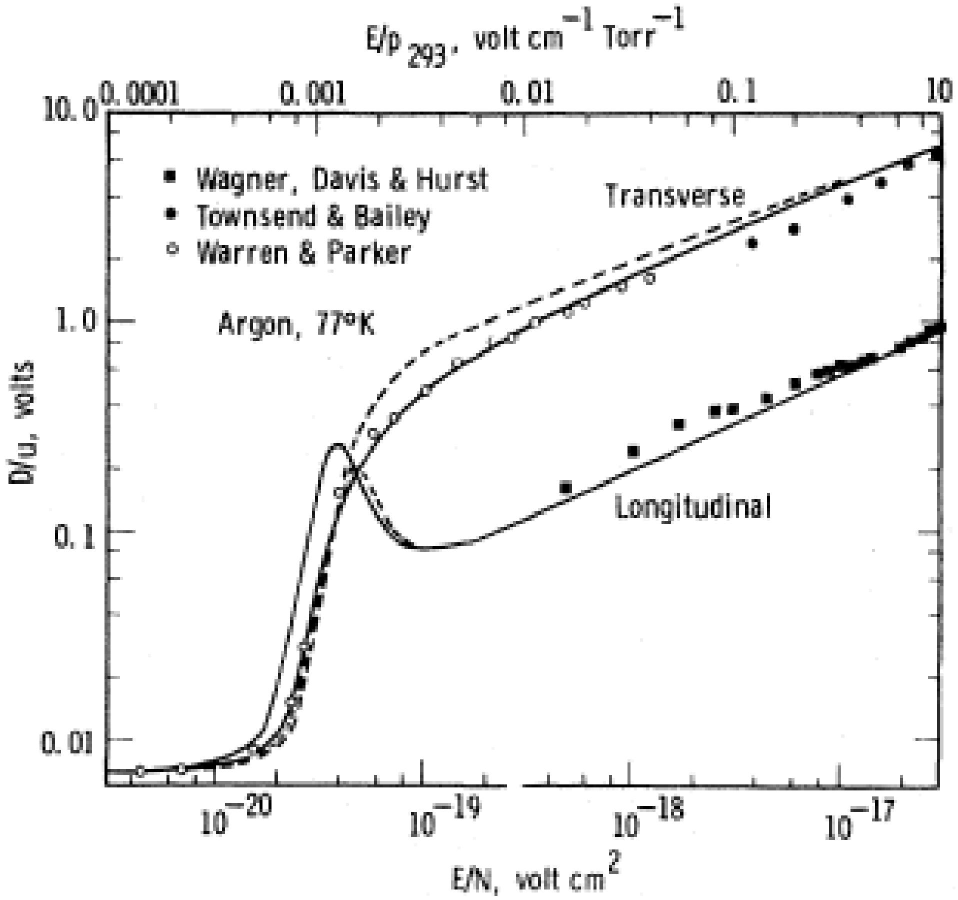
Lower bound in LAPD ≈3 ms (volume non-evacuated !)

LBNE requirement ≈1.4 ms for $S/N_{mip} > 9$

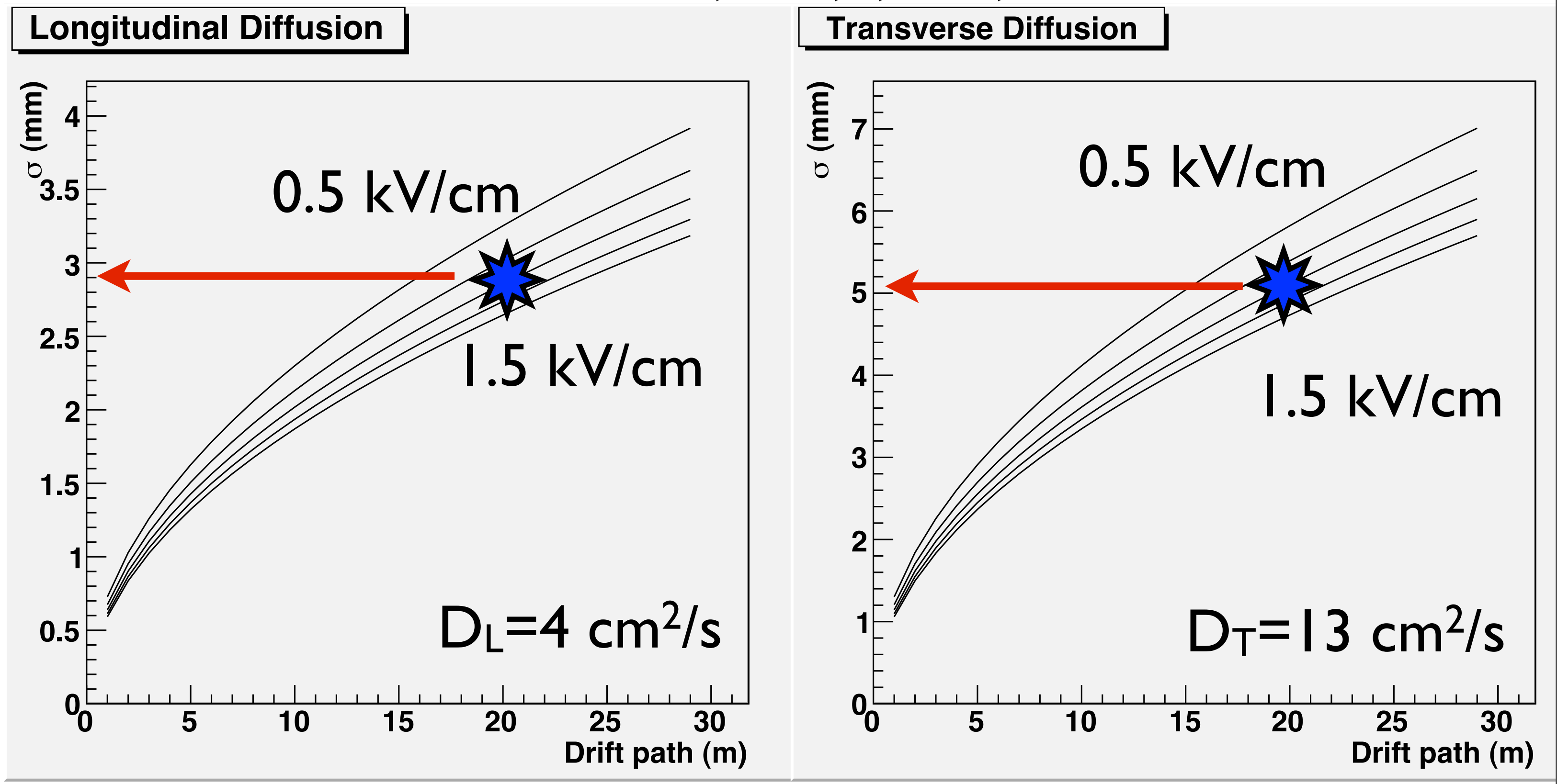
NB: "Outgassing" sources should become negligible after long periods of purification (e.g. 1 year)

Electron cloud diffusion

★ The physical limit to long drifts is determined by diffusion ➠ likely 20m !



Drift fields E=0.5,0.75,1,1.25,1.5 kV/cm

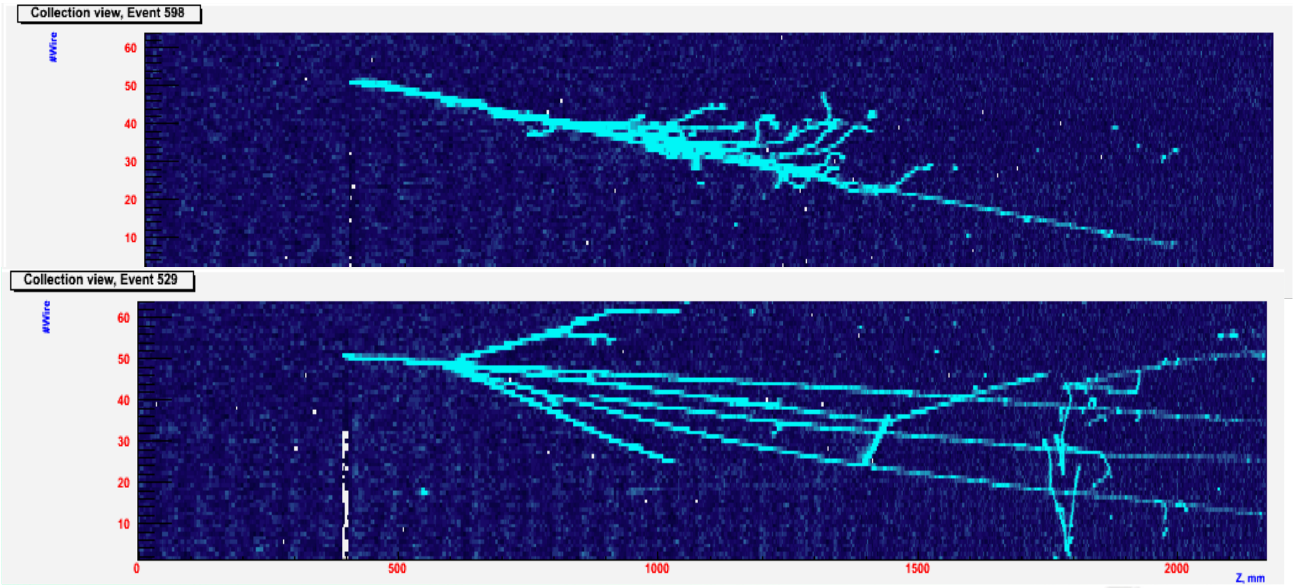


★ Diffusion coefficients not well known (in particular for transverse diff.):

- after 20 m drift: transverse diffusion ≈ **5mm**, longitudinal diffusion ≈ **3mm**

★ New measurements:

- •ArgonTube (Bern University)
  - -tracks >4 m length observed !
  - -lifetime ≈ 2ms after 24hrs
- •5m drift (UCLA)



Courtesy I. Kreslo

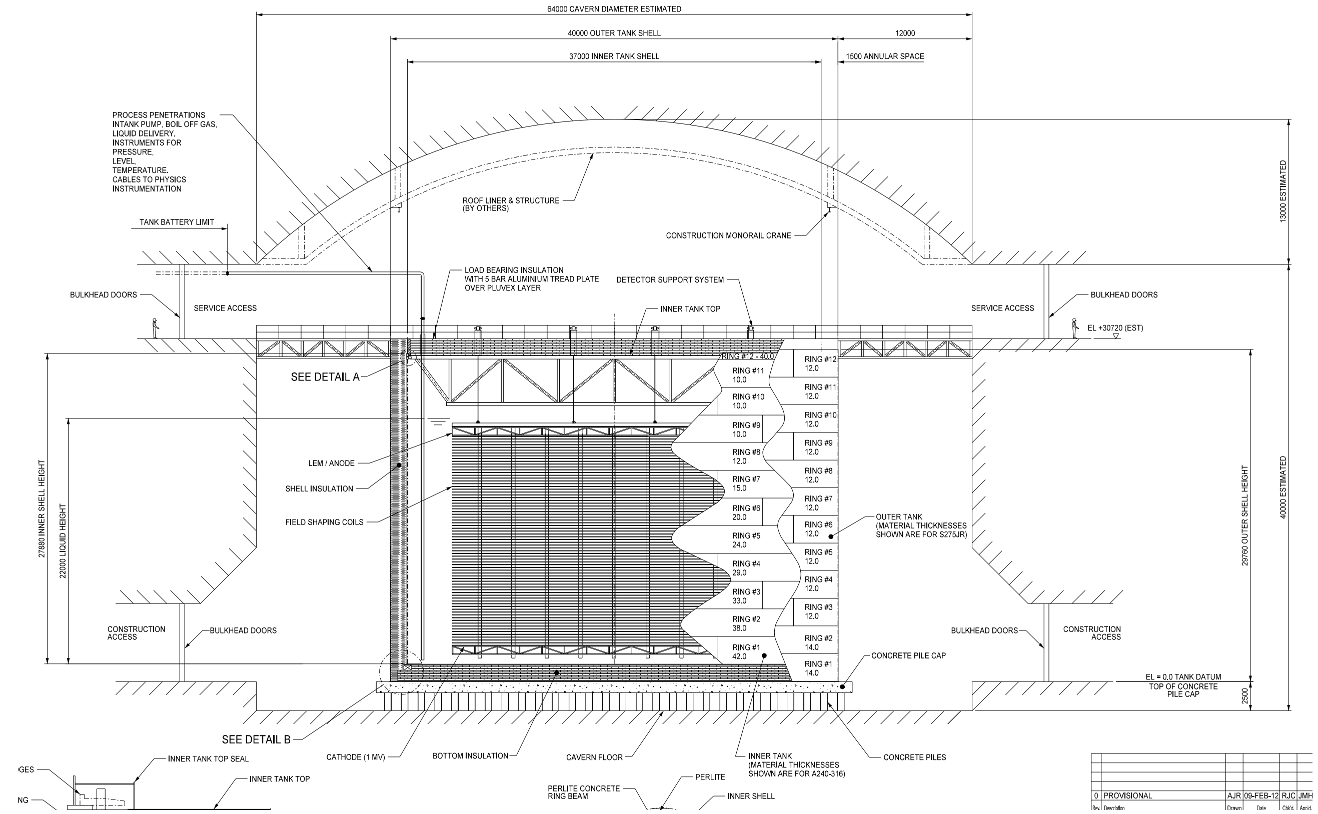
Future LAr TPC detectors

Project	LAr mass (tons)	Goal	Baseline (km)	Where	Status
MicroBOONE	170 (70 fid.)	short baseline	0.47	FNAL BNB	Under construction
LAr1	≈1'000	2nd detector for short baseline	≈0.7	FNAL BNB	Proposal submitted
ICARUS-NESSIE	150 + 478	two-detectors short baseline	0.3 + 1.6	CERN + new SBL beam	Proposal submitted
MODULAr	5'000 unit	shallow depth far detector	730	Italy, new lab nearby LNGS	plan
GLADE	5000	surface	810	NUMI off-axis	Letter of Intent
LBNE LAr (*)	2x17'000(*)	underground(*) far detector	1300(*)	Homestake(*) + new FNAL beam(*)	CD-0
GLACIER LAGUNA-LBNO	initially 20'000 (incremental)	underground far detector	2300	Finland + new CERN LBL beam	Expression of interest in preparation
GLACIER Okinoshima	up to 100'000	underground far detector	665	Japan + JPARC neutrino beam	R&D proposal at JPARC

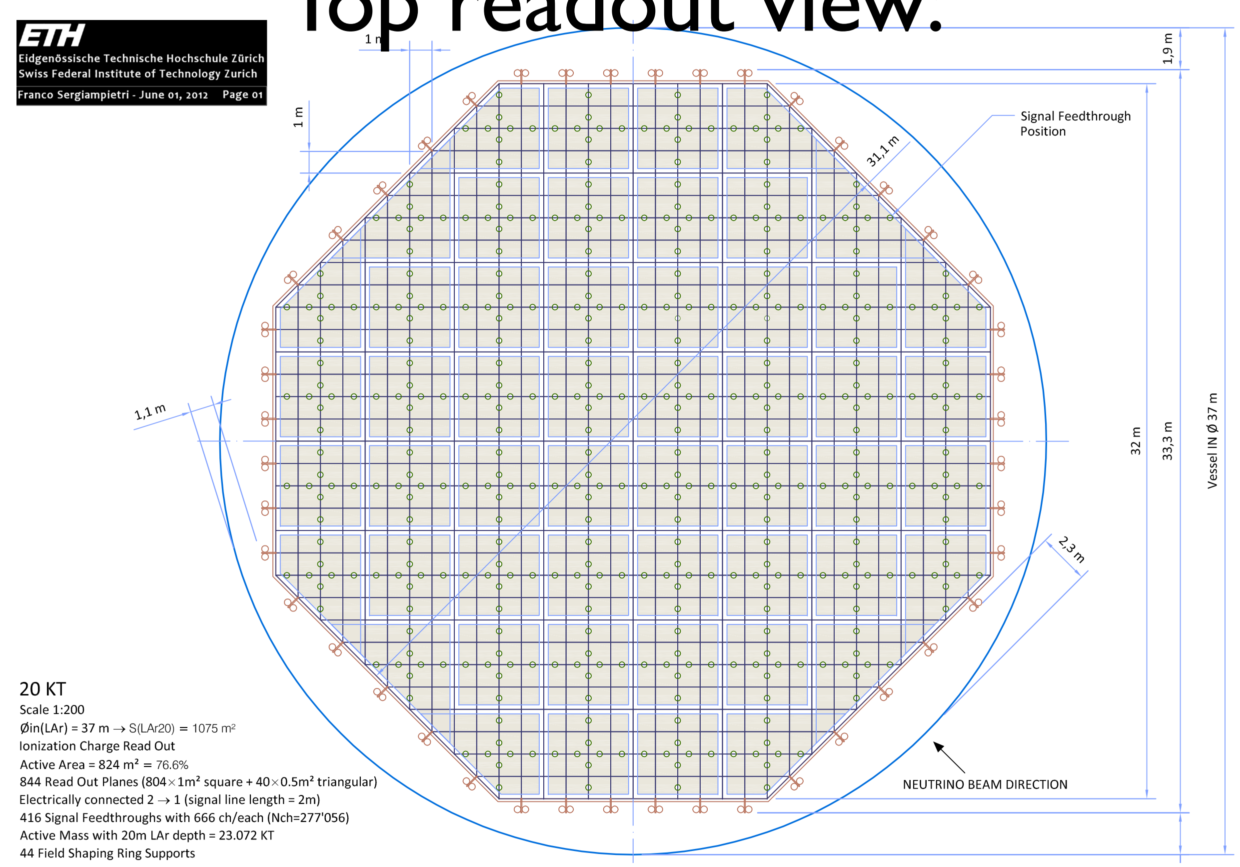
(*) LBNE reconfiguration for cost reduction / staging in progress (cf. Svoboda's talk)

GLACIER detector design

- ★ Concept unchanged since 2003: Simple, scalable detector design, from one up to 100 kton (hep-ph/0402110)
- ★ Single module non-evacuable cryo-tank based on industrial LNG technology
  - industrial conceptual design (Technodyne, AAE, Ryhal engineering, TGE, GTT)
  - two tank options: 9% Ni-steel or membrane (detailed comparison up to costing of assembly in underground cavern)
  - three volumes: 20, 50 and 100 kton
- ★ Liquid filling, purification, and boiloff recondensation
  - industrial conceptual design for liquid argon process (Sofregaz), 70kW total cooling power @ 87 K
  - purity < 10 ppt O_2 equivalent
- ★ Charge readout (e.g. 20 kton fid.)
  - 23'072 kton active, 824 m^2 active area
  - 844 readout planes, 277'056 channels total
  - 20 m drift
- ★ Light readout (trigger)
  - 804 8" PMT (e.g. Hamamatsu R5912-02MOD) WLS coated placed below cathode
- ★ The concept and the designs are reaching the required level of maturity for submission to SPSC.

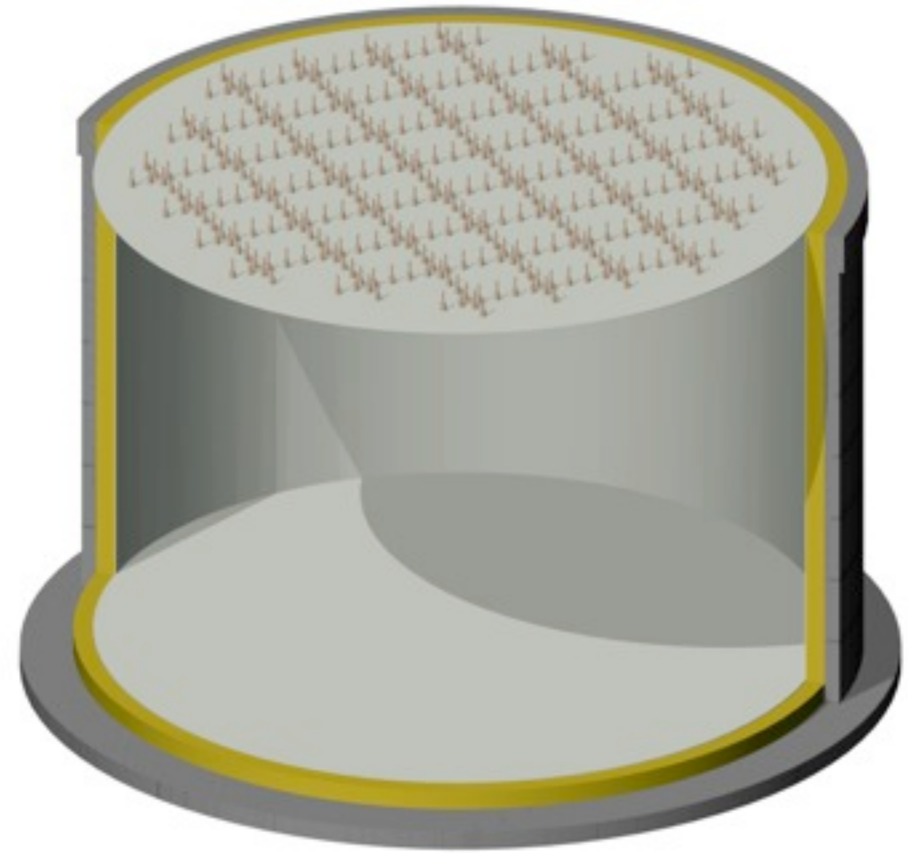


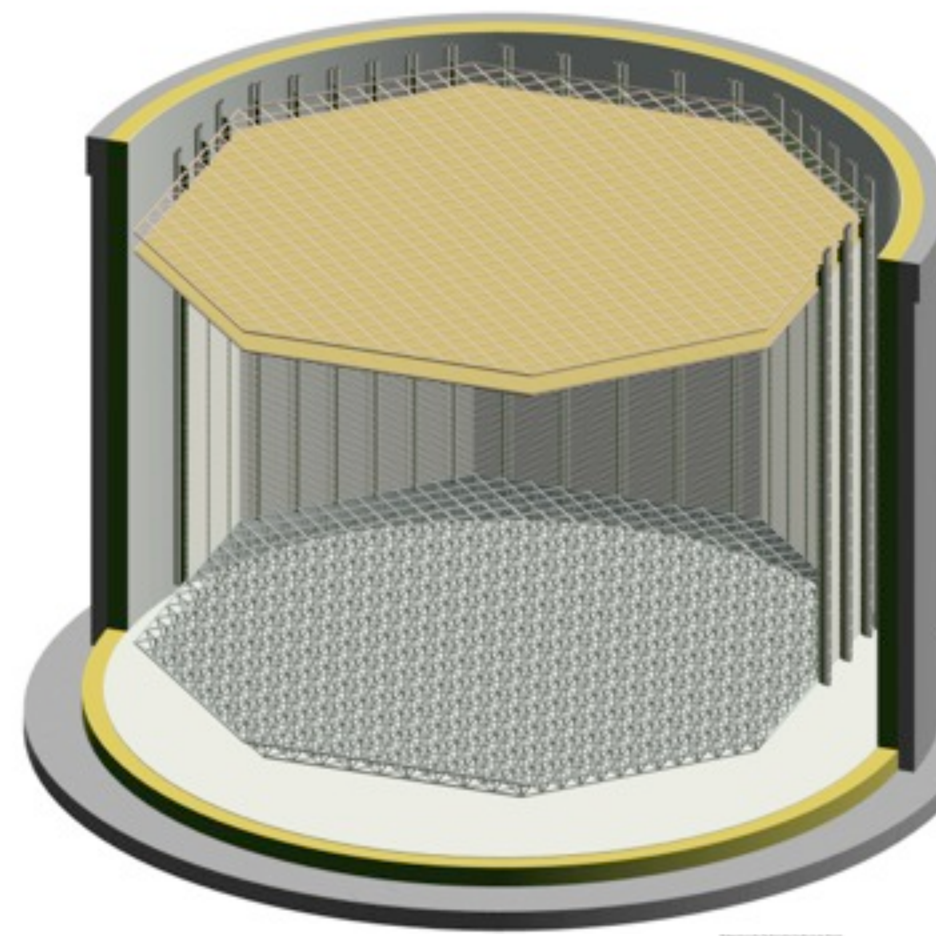
Top readout view:



GLACIER detector parameters

		20 KT	50 KT	100 KT
Liquid argon density at 1.2 bar	[T/m^3]	1.38346		
Liquid argon volume height	[m]	22		
Active liquid argon height	[m]	20		
Pressure on the bottom due to LAr	[T/m^2]	30.4 (≡ 0.3 MPa ≡ 3 bar)		
Inner vessel diameter	[m]	37	55	76
Inner vessel base surface	[m^2]	1075.2	2375.8	4536.5
Liquid argon volume	[m^3]	23654.6	52268.2	99802.1
Total liquid argon mass	[T]	32525.6	71869.8	137229.9
Active LAr area (percentage)	[m^2]	824 (76.6%)	1854 (78%)	3634 (80.1%)
Active (instrumented) mass	[KT]	22.799	51.299	100.550
Charge readout square panels (1m×1m)		804	1824	3596
Charge readout triangular panels (1m×1m)		40	60	72
Number of signal feedthroughs (666 channels/FT)		416	1028	1872
Number of readout channels		277056	660672	1246752
Number of PMT (area for 1 PMT)		804 (1m×1m)	1288 (1.2m×1.2m)	909 (2m×2m)
Number of field shaping electrode supports (with suspension SS ropes linked to the outer deck)		44	64	92





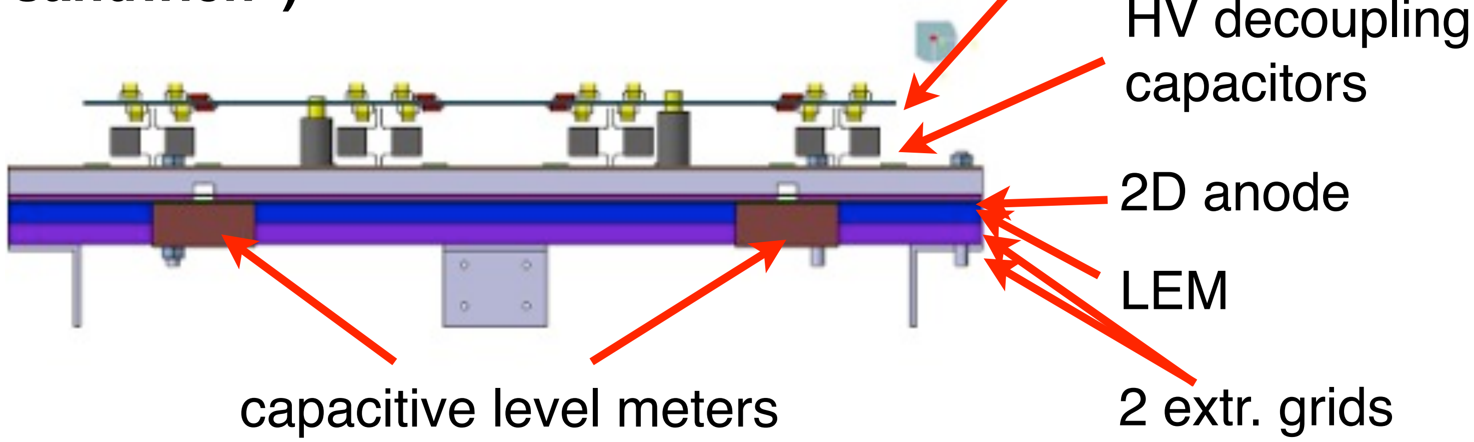
GLACIER charge readout

- A. Badertscher, et al., NIM A 641 (2011) 48-57
- See also arXiv:1204.3530 [physics.ins-det]

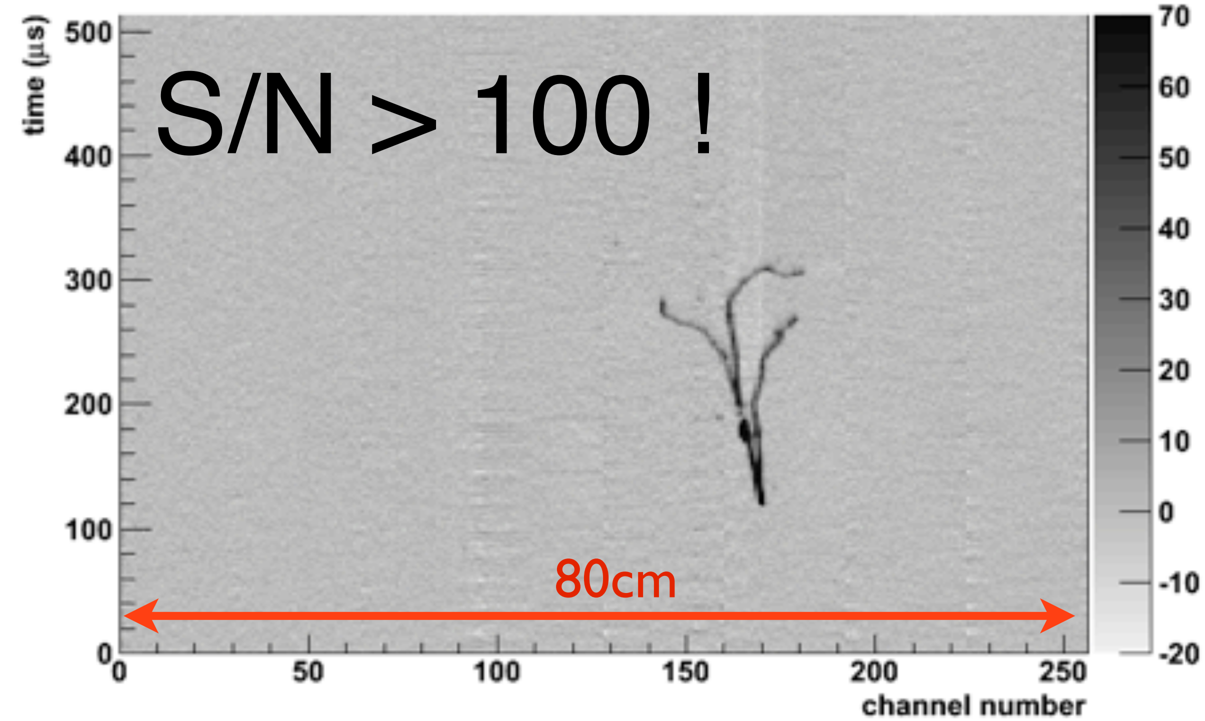
★ Novel double phase LAr LEM-TPC readout:

- ionization electrons are drifted to the liquid-gas interface
- if the E-field is high enough (≈ 3 kV/cm) they can efficiently be extracted to the gas phase
- in the holes of the LEM the E-field is high enough to trigger an electron avalanche
- the multiplied charge is collected on a 2D readout
- gain allows **sharing charge in collection mode for both views!!**

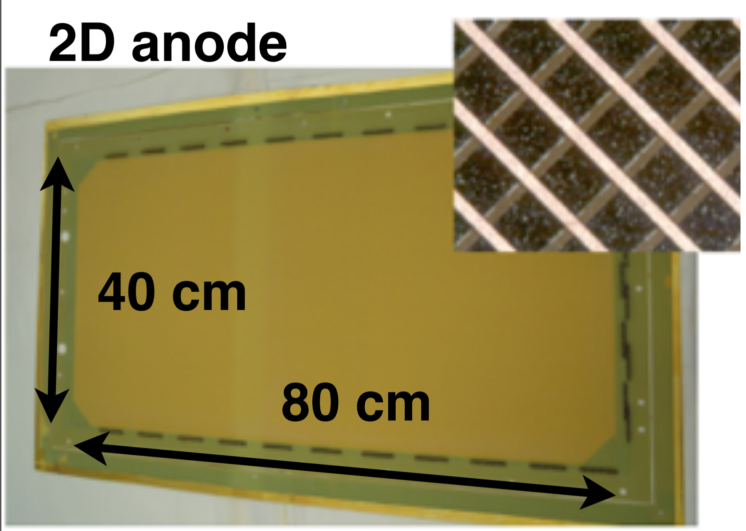
Design of a compact, robust and scalable readout cassette ("sandwich")



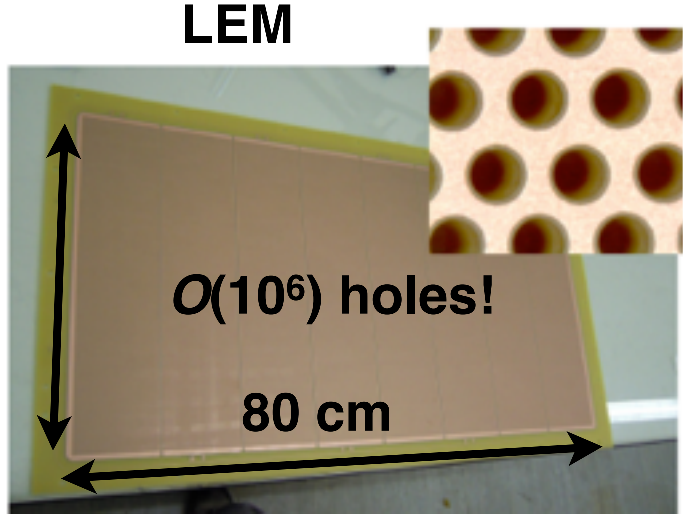
Cosmic Data from 40x80cm^2 LAr LEM TPC@CERN-ETHZ



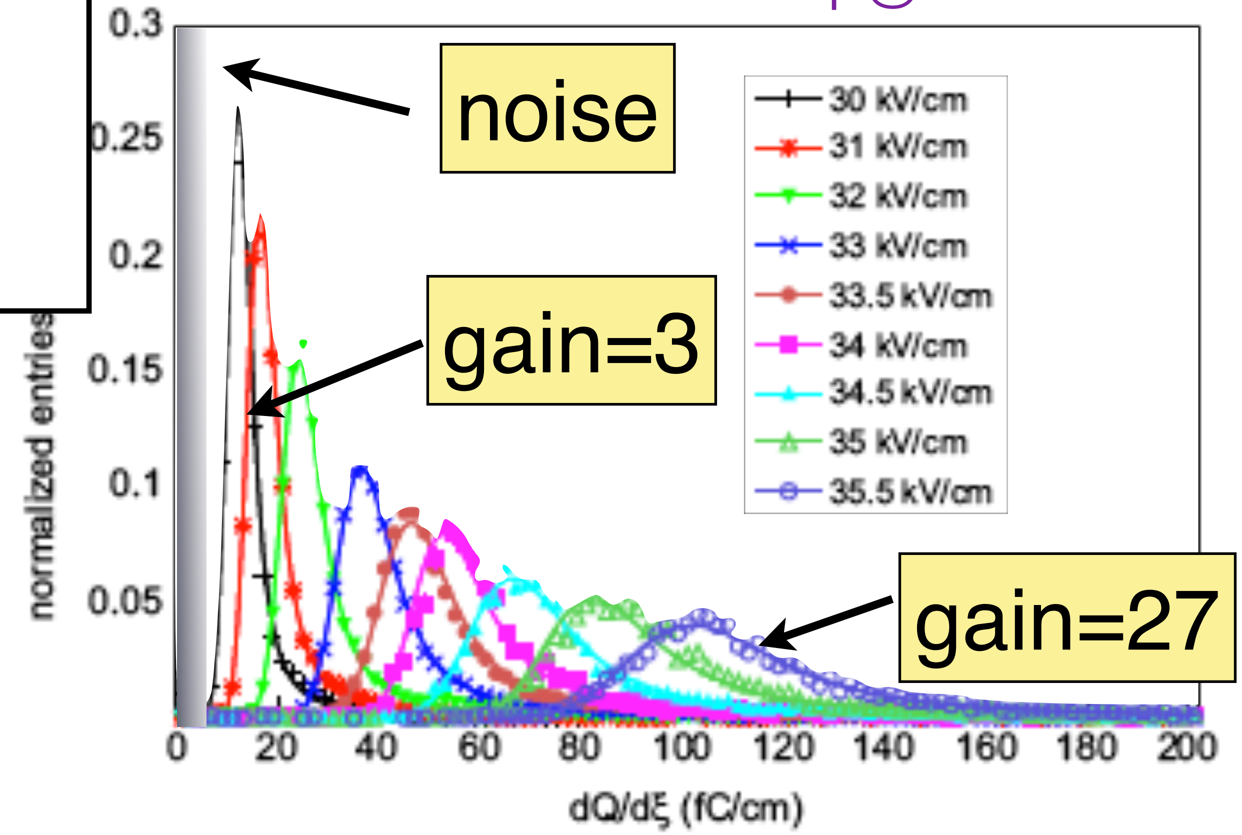
2D anode



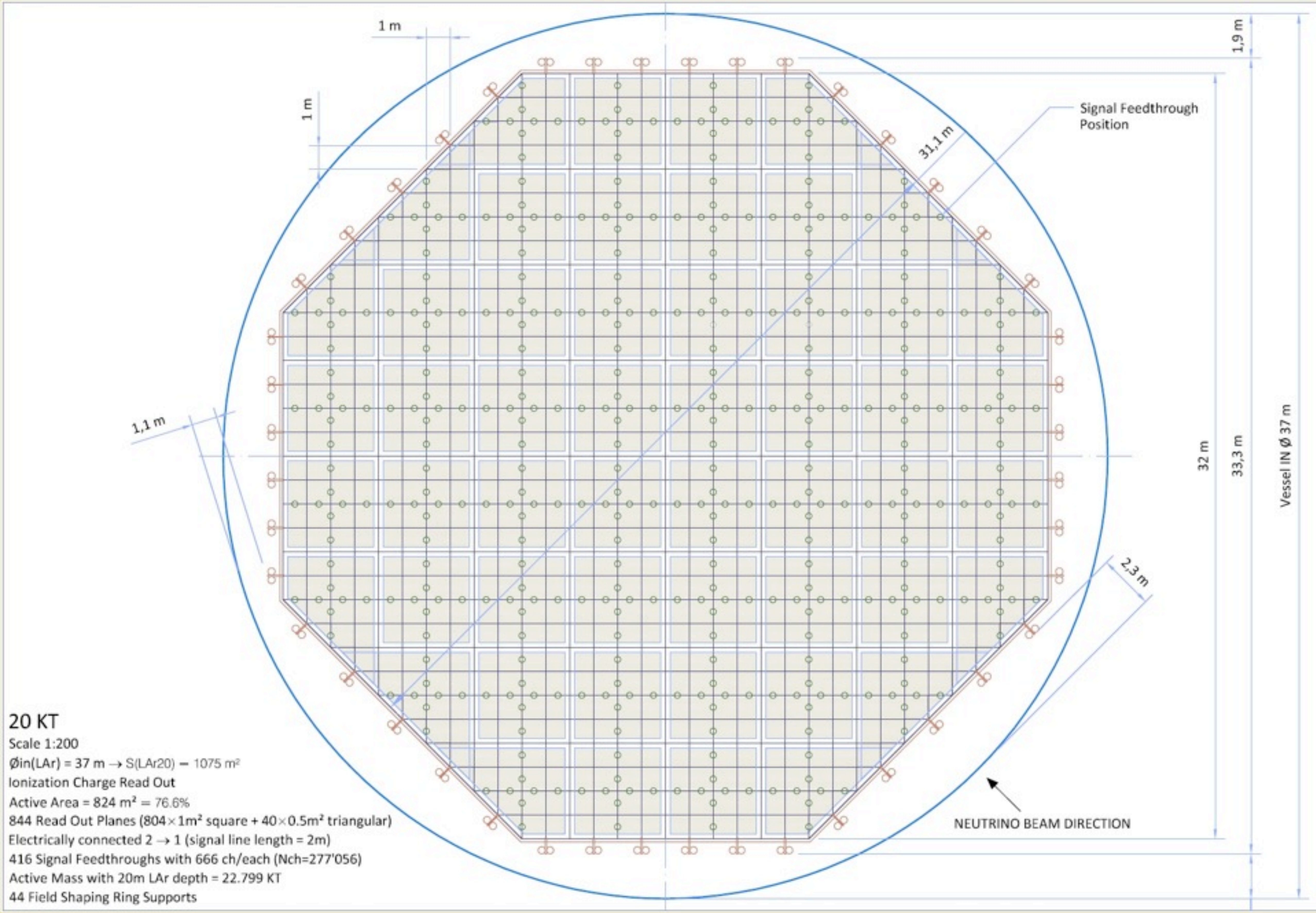
LEM



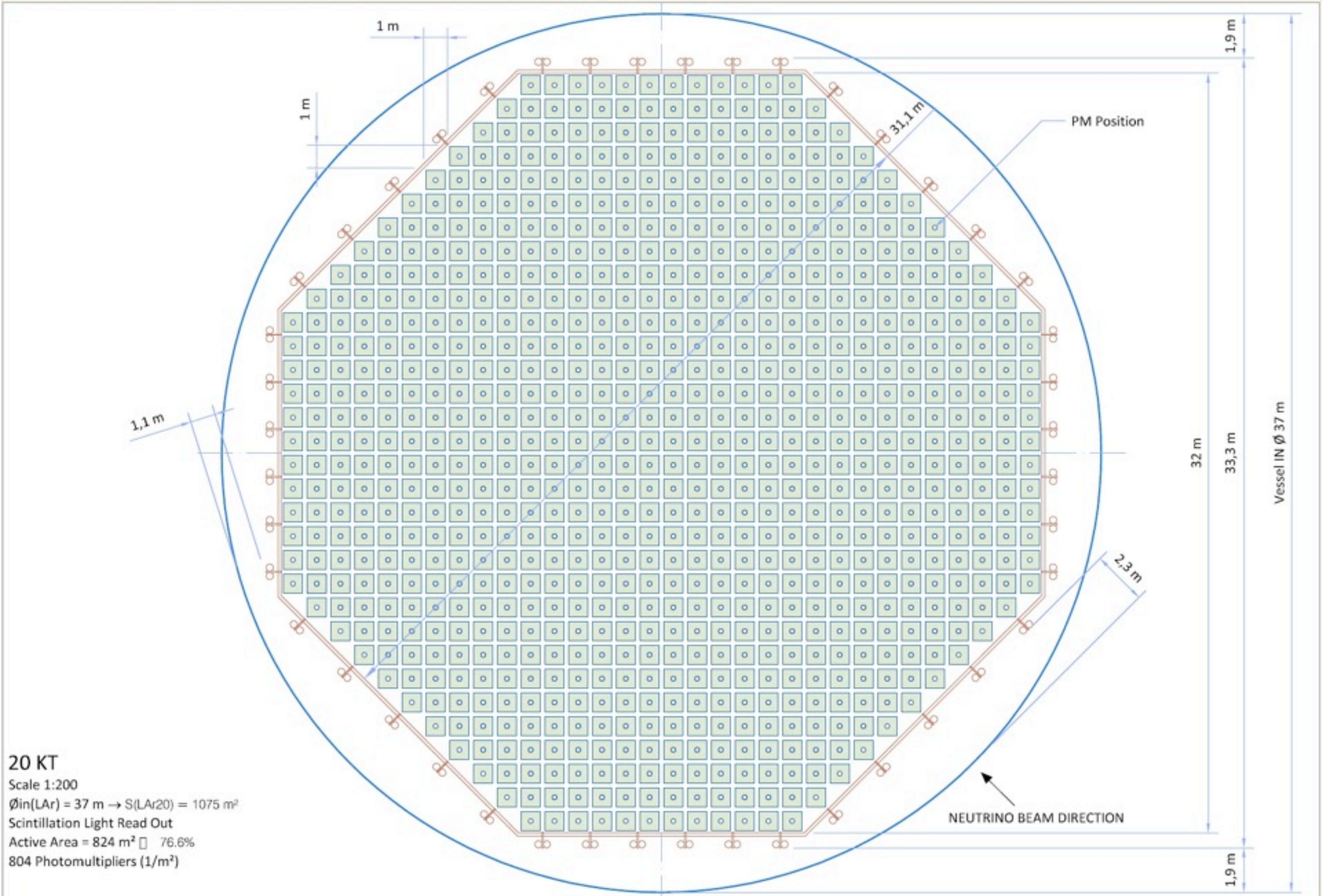
Landau distribution fitted to dE/dx distributions of muons on 3L LAr LEM-TPC setup @ CERN-ETHZ



GLACIER charge readout layout

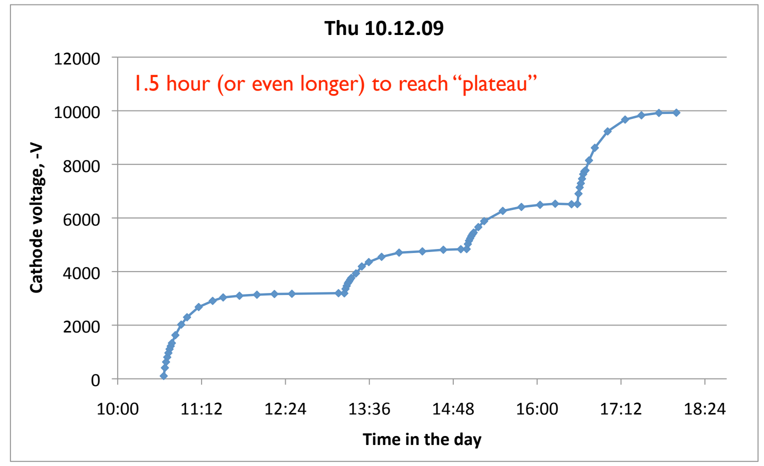


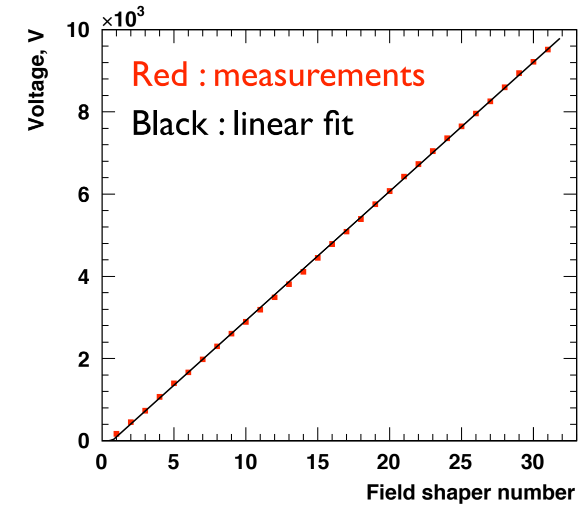
GLACIER light readout layout



Drift high voltage multiplier

J.Phys.Conf.Ser. 308 (2011) 012027
arXiv:1204.3530 [physics.ins-det]





Extrapolation to long drift

Extrapolation of the ArDM design

Changing Cs for fixed Cp = 2.35 pF and Vpp-in = 2E = 2.5 kV

		ArDM				
Drift length	m	1.24	5	10		20
Total output voltage for 1 kV/cm	V	124k	500k	1M		2M
Input voltage Vpp-in = 2E	V	820	2.5k	2.5k	$\times\sqrt{2}$	3.5k
Shunt capacitance, Cp	F	2.35p	2.35p	2.35p	$\times1/2$	1.18p
Capacitor	F	328/164n	475n	1.90µ		1.90µ
Number of stages, N	–	210	319	638		903
N per 10 cm	–	16.9	6.38	6.38		4.51
Total capacitance	F	125µ	303µ	2.43m		3.43m
Capacitance per 10 cm	F	10.4µ	5.99µ	24.3µ		17.2µ
Total stored energy	J	21.7	948	7.58k		21.5k

Actual ArDM parameters are given just for comparison.

For extrapolation, 2γN = 1.42 is always assumed.

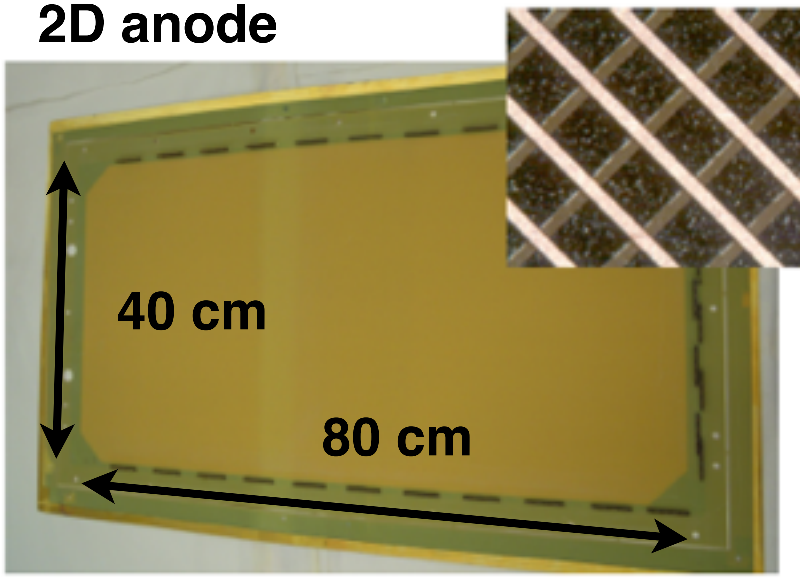
LAr vaporization heat 160 kJ/kg

$$V_{\max} = \frac{E}{\gamma},\ \gamma \approx \sqrt{\frac{C_{\mathrm{p}}}{C_{\mathrm{s}}}}$$

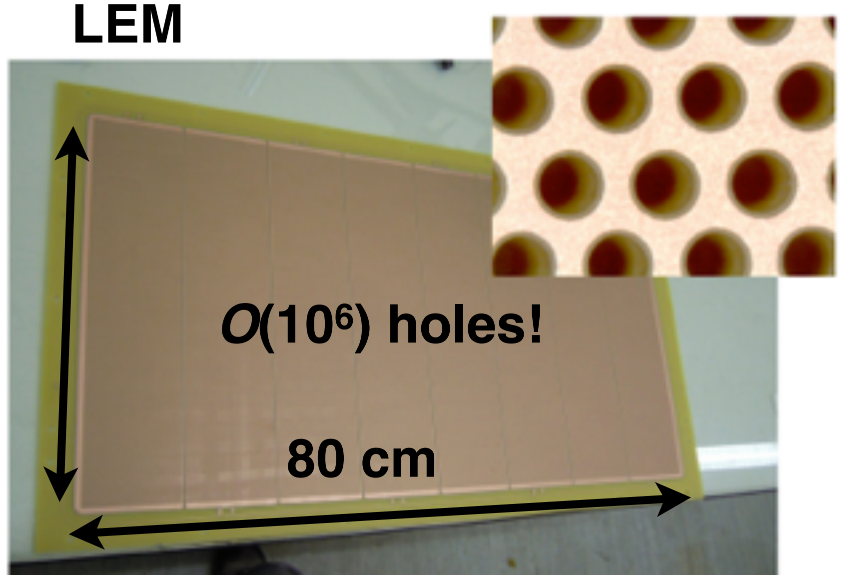
LAr-LEM TPC@CERN: Production of a 40x80 cm² charge readout sandwich

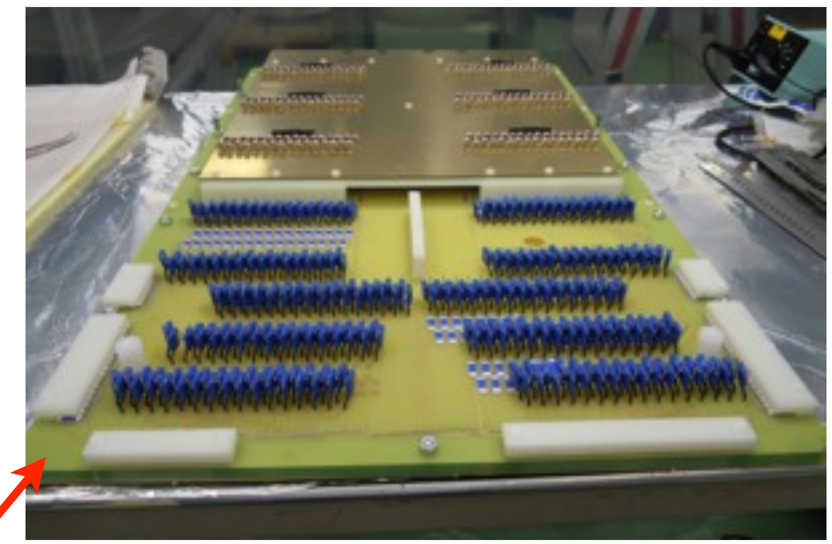
- After successful test of LEM and 2D anode in the 3L setup we designed and produced a 40x80 cm² charge readout for a new 250L LAr LEM-TPC (production and assembling finished by summer 2011)
- The ArDM cryostat @CERN was used for a first test of the new charge readout system

2D anode



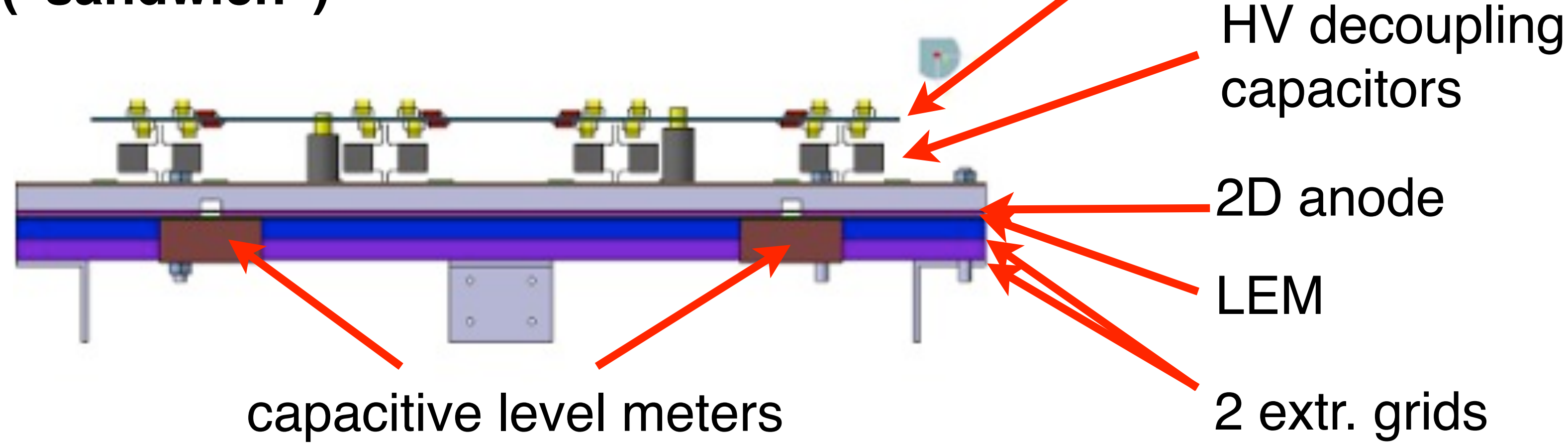
LEM

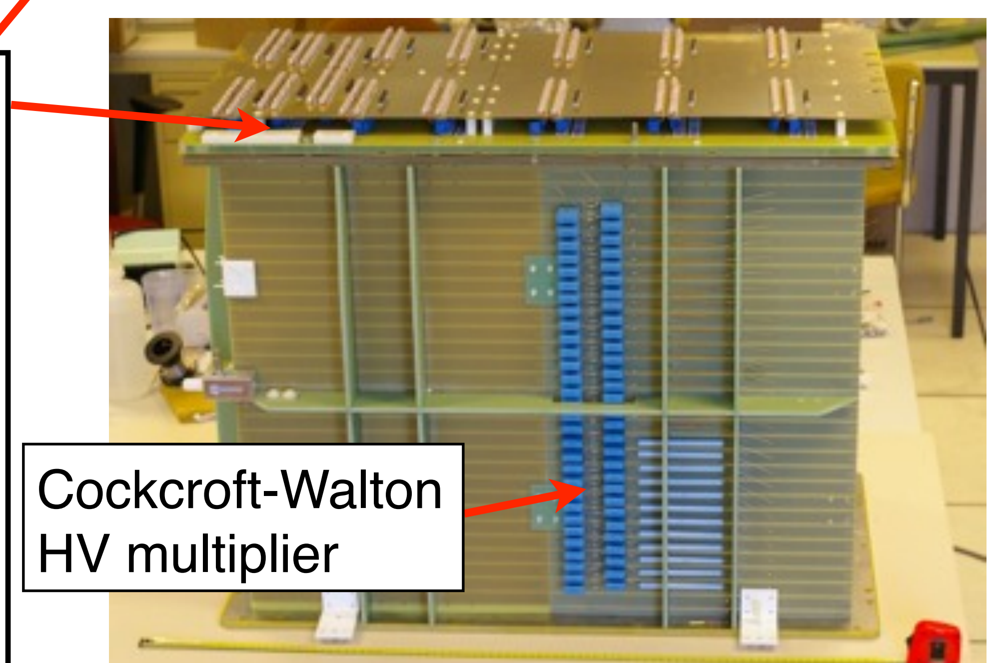




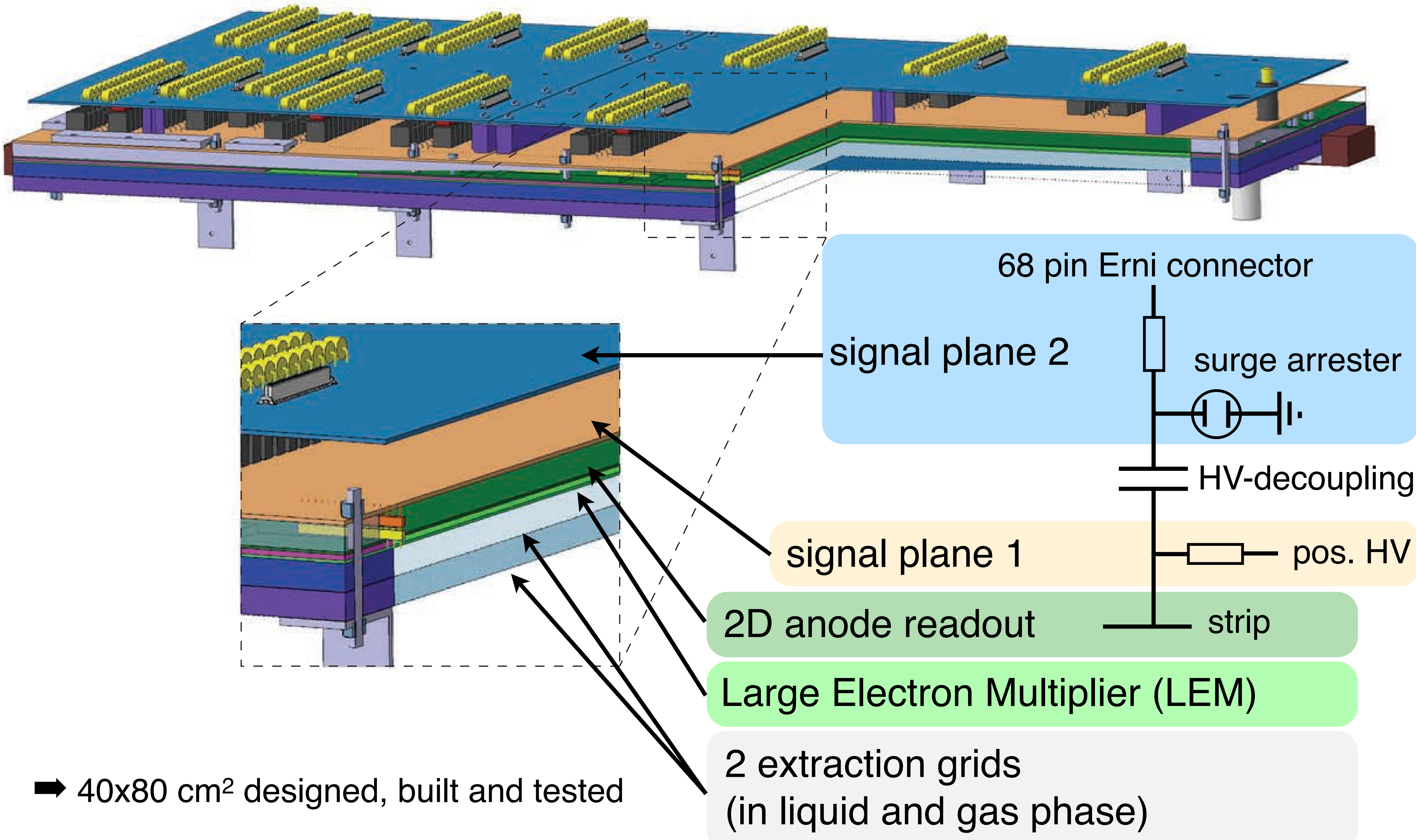
- Manufacturer: CERN TS/DEM group and ELTOS company (Italy)
- Largest LEM/THGEM and 2D readout ever produced!!!

Design of a compact, robust and scalable readout cassette ("sandwich")





Charge readout sandwich

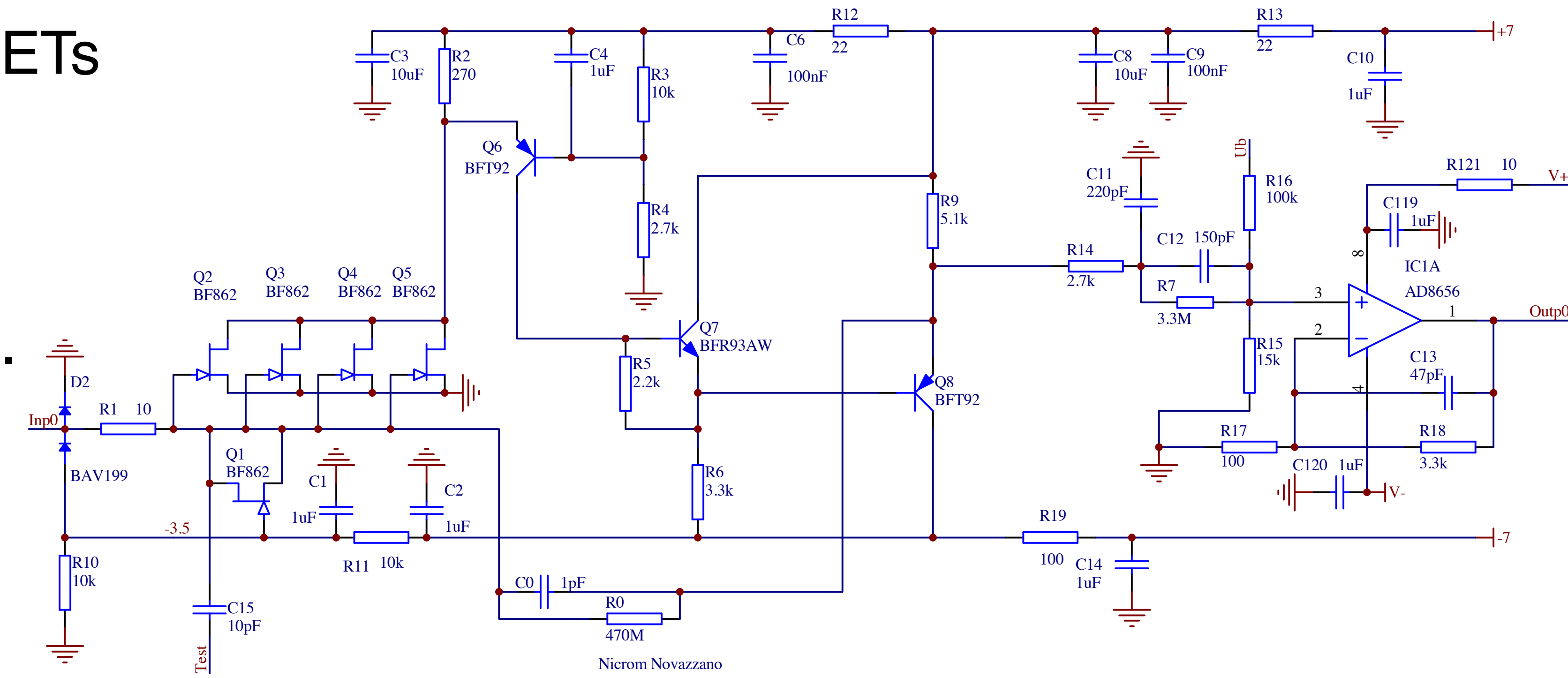


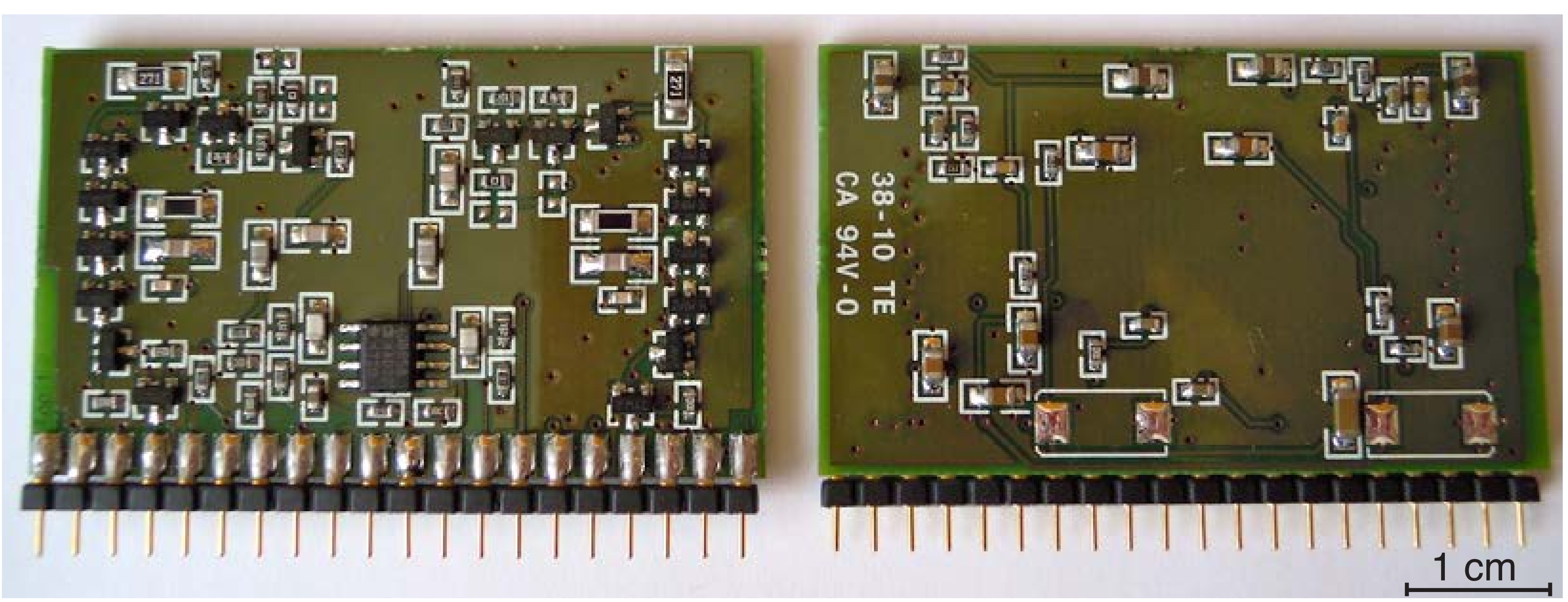
➡ 40x80 cm^2 designed, built and tested

The ETHZ preamplifier

electric layout

- Cascode design with 4 parallel JFETs at the input (C. Boiano et al. IEEE Trans. Nucl. Sci. 52 (2004) 1931)
- RC=470 μs feedback (C=1pF)
- RC-CR shaper with zero-pole sub. mechanism (no undershoot)
- over-voltage protection at input



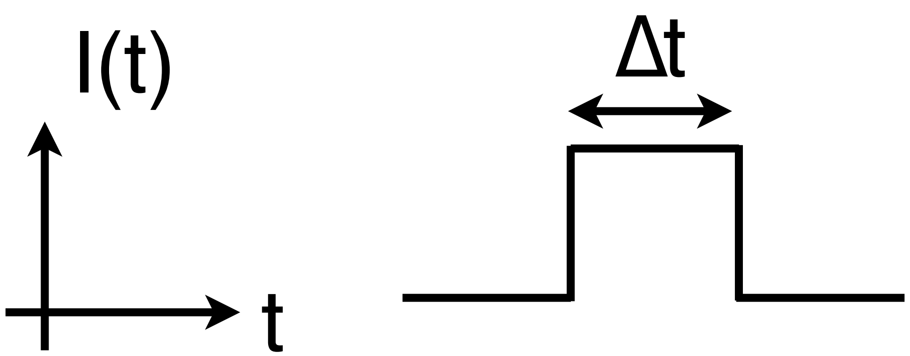


realization

- preamplifier is realized with discrete components
- two preamplifier circuits are implemented on a single 4-layer PCB

Performance of the ETHZ preamplifier

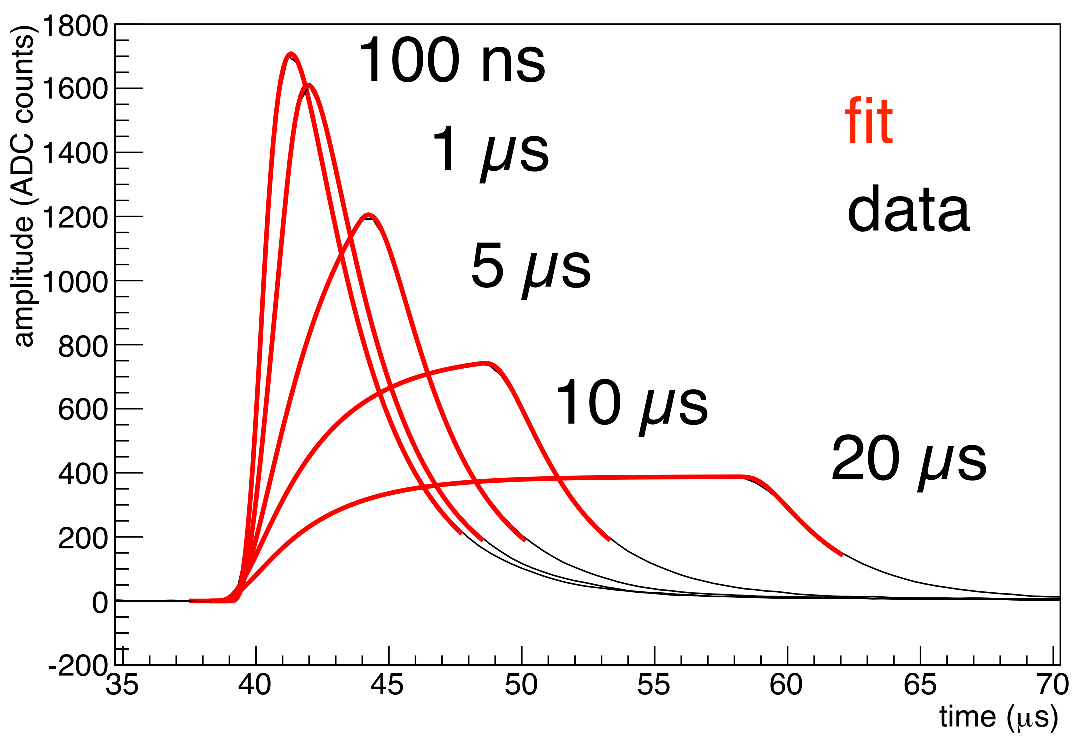
32 preamplifiers have been characterized with a well defined charge input:



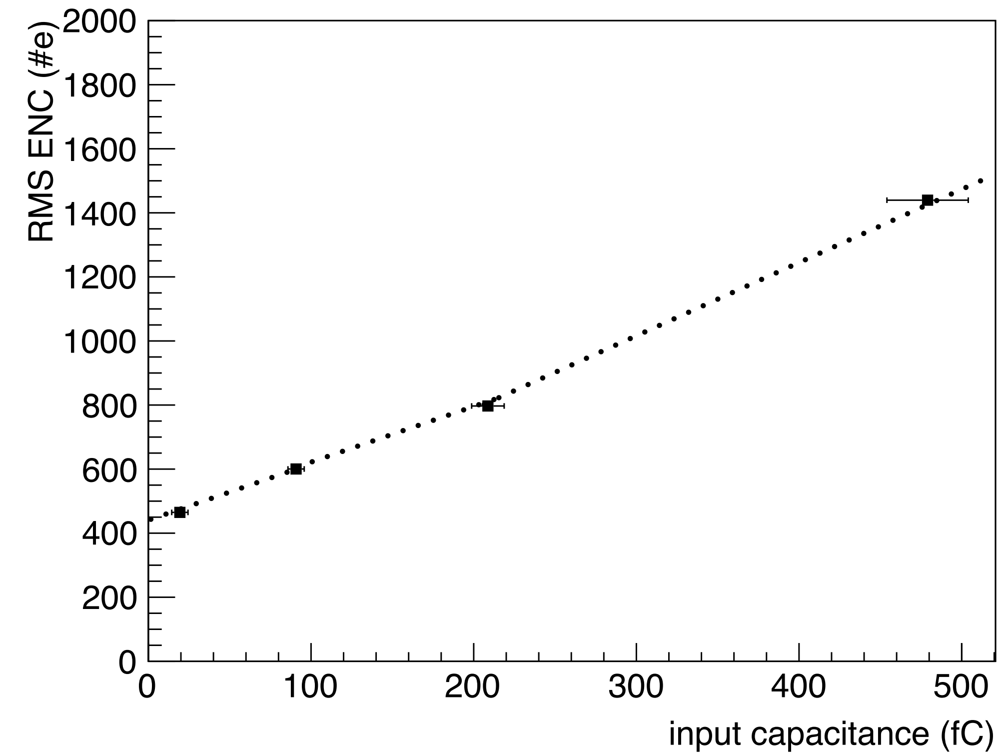
Summary

shaping time τ_D	$2.8 \pm 0.1\ \mu s$
shaping time τ_I	$0.45 \pm 0.02\ \mu s$
sensitivity	13.8 ± 0.4 mV/fC
open loop gain	$\approx 10^4$
linearity (0-180 fC)	$\pm 1\%$
ENC (RMS, $C \approx 200$ pF)	770 ± 30 electrons
S/N (1 fC, $C \approx 200$ pF)	8.1 ± 0.3

pulse shaping (varying Δt)



RMS ENC vs. input capacitance



The CAEN A2792 acquisition board

TT-link clock and trigger propagation

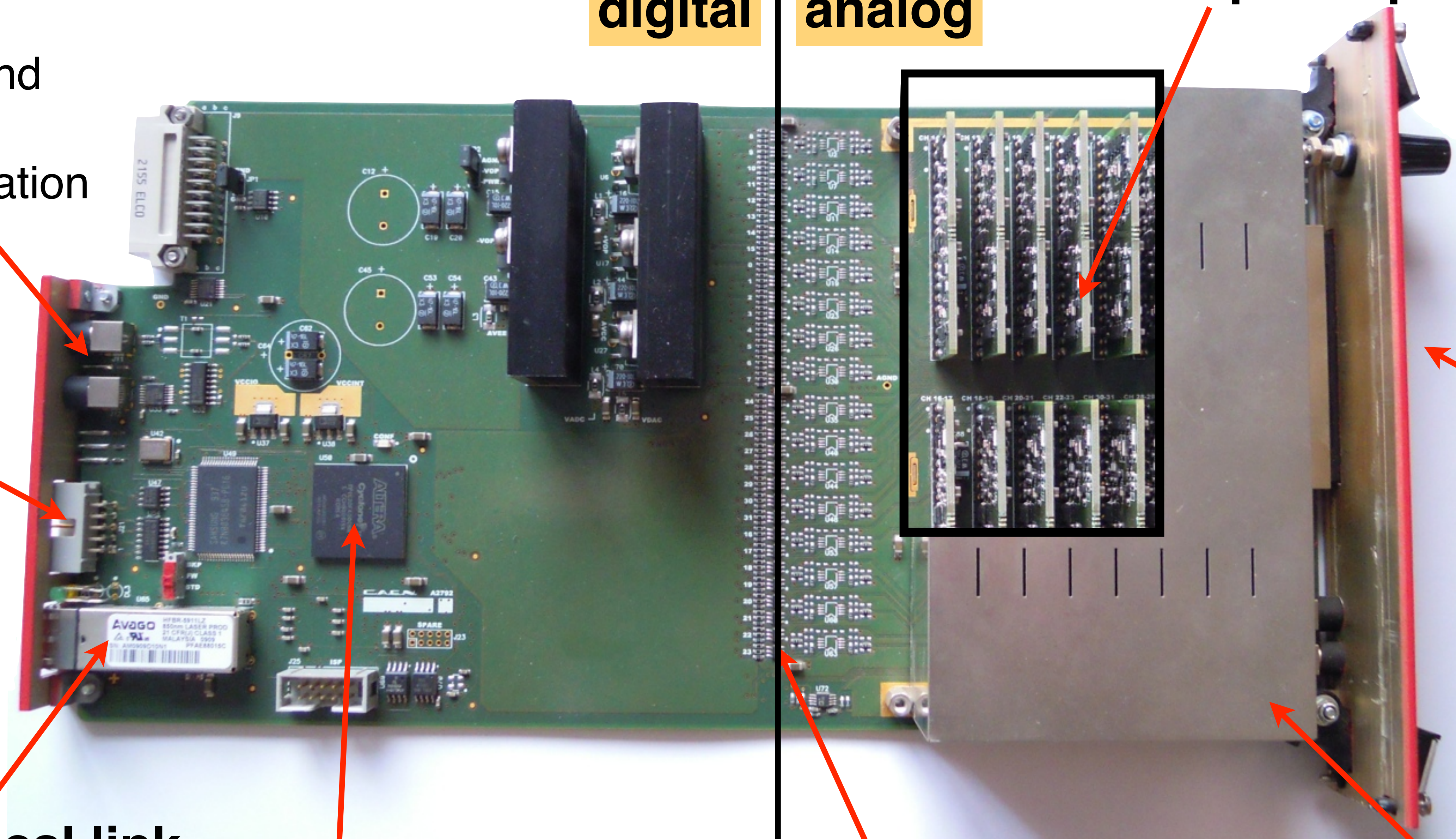
I/O

optical link

programmable FPGA

digital | **analog**

16 preamplifier prints



input connector (32 ch.)

screening box

32 ADCs: 2.5 MHz 12 bit ADCs with serial interface (no multiplexing)

Signal feed-through technology

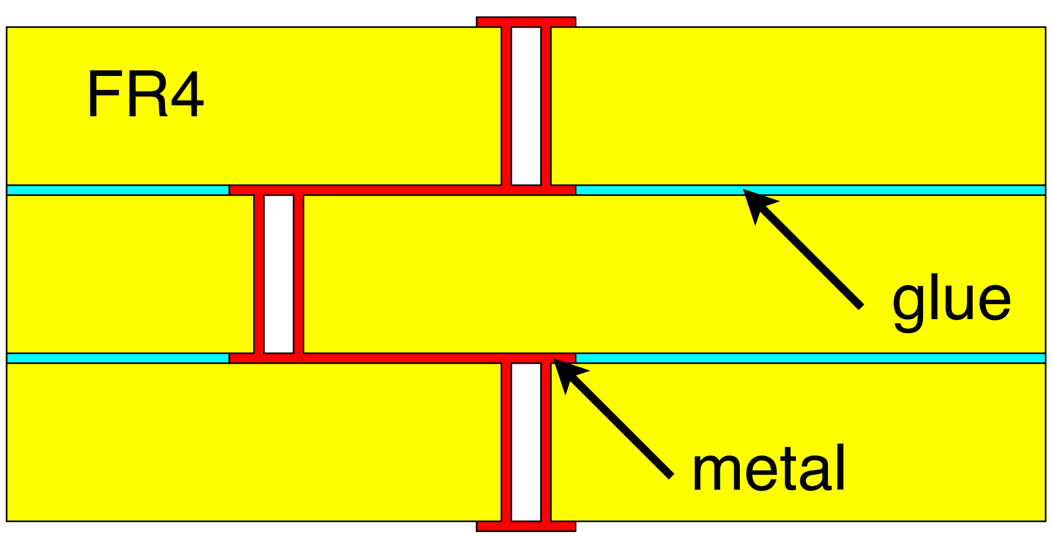
➡vacuum tightness

- Four layer printed circuit board (PCB) with displaced vias (through-hole paths) guarantees tightness
- The PCB is attached to a metal flange
  - CF-standard for cryogenic temperatures
  - sealed with glue or gasket

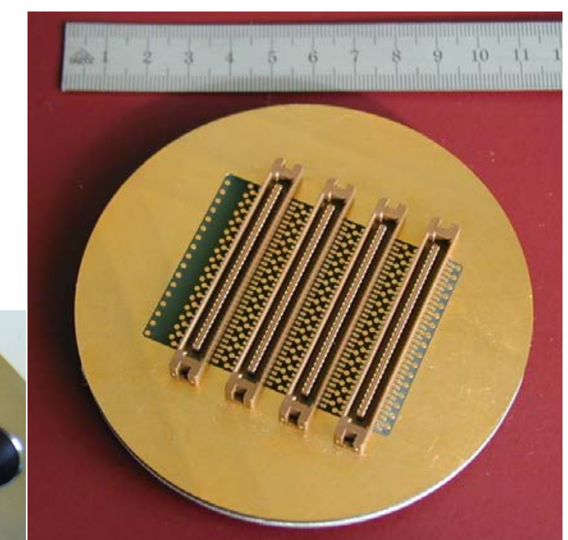
➡High channel density

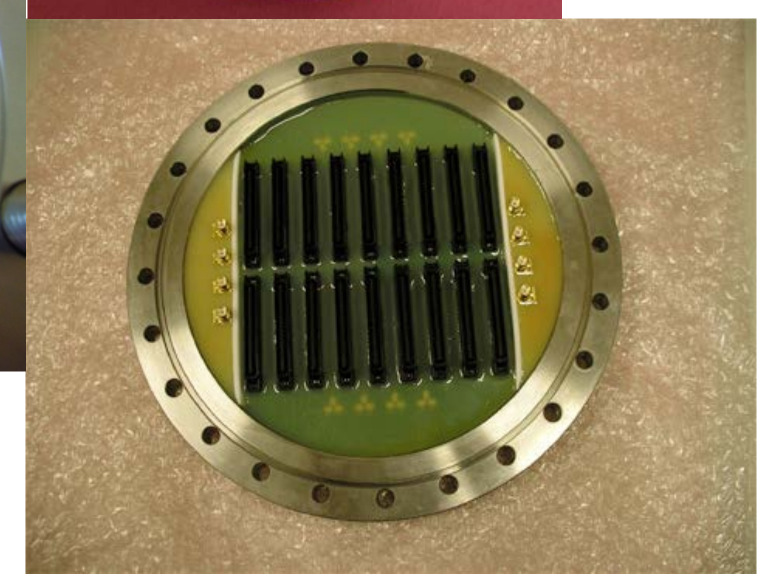
PCB technique allows to place 18 68-pin plugs on a single CF-250 lange

design

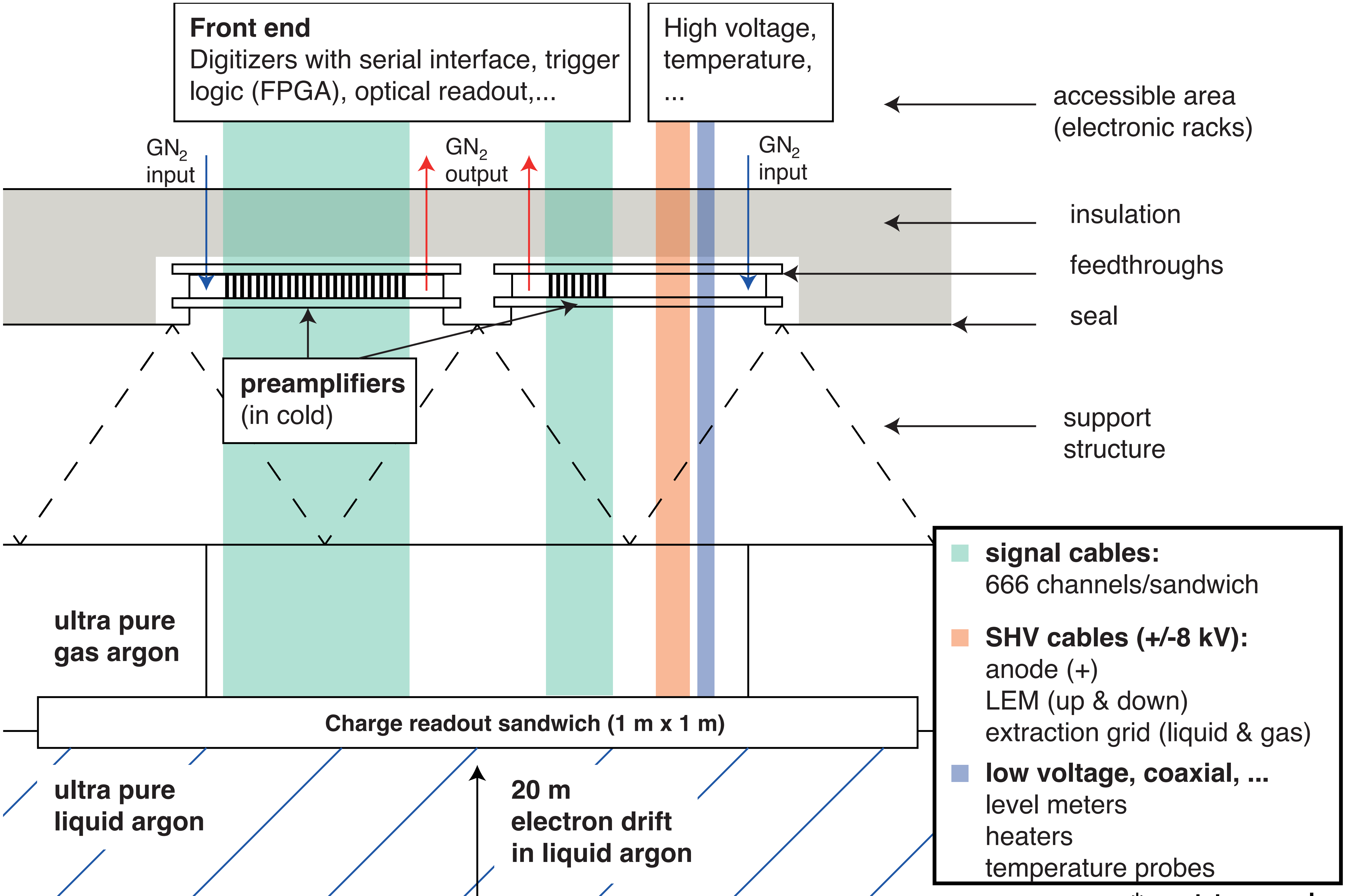


Examples from different experiments





Charge readout unit



* not to scale

Development of a front end ASIC CMOS preamplifier

working group

E.Bechetoille, S.Gardien, C.Girerd, H.Mathez (electronics), Bruno Carlus (software), Dario Autiero, Yves Déclais, Jacques Marteau
CNRS / IN2P3 / UCBL - Institut de Physique Nucléaire de Lyon

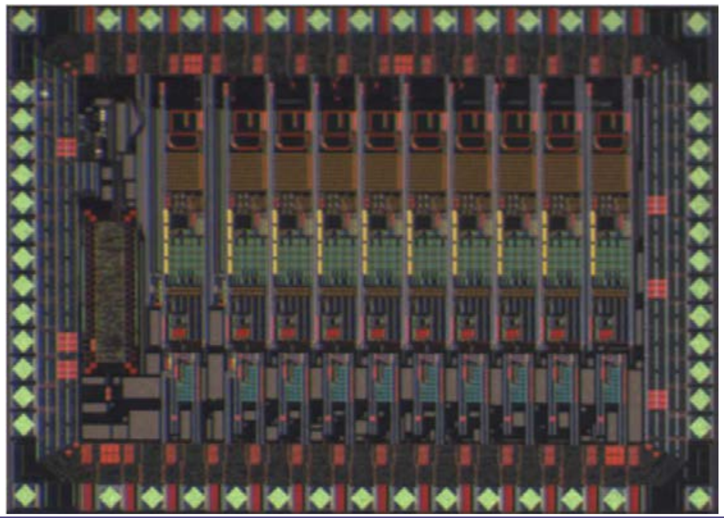
Advantages of ASIC cold electronics

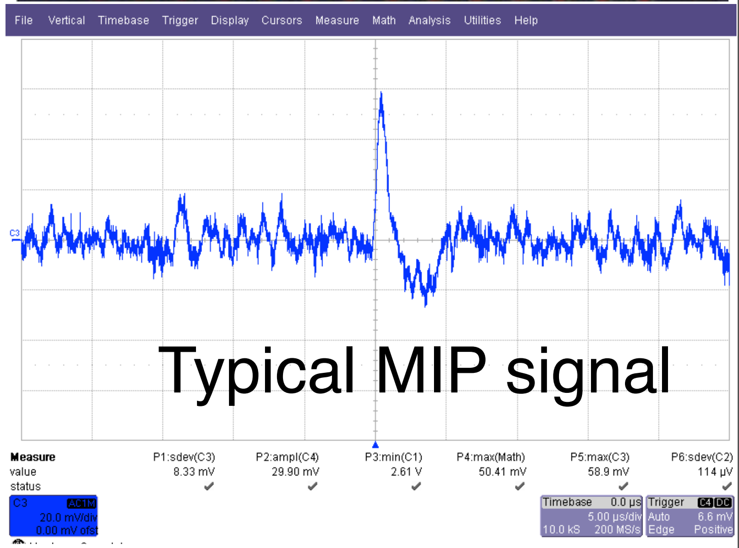
- Exploit intrinsic noise reduction at low T (minimum around 110K)
- Large scale integration and costs reduction (1~1.5 eur/ch)

Summary

- Activity started in 2007
- R&D on a analog ASIC preamplifier working at cryogenic temperature for the charge readout of the LAr TPC
- Performance of the 4th generation:
  - 18 mV/fC sensitivity
  - 1500 ENC at the end of the full chain with 250 pF input capacitance @ 110K (-20%)
- R&D on the Gigabit Ethernet readout chain + network time distribution system PTP (IEEE1588)

ASIC V4

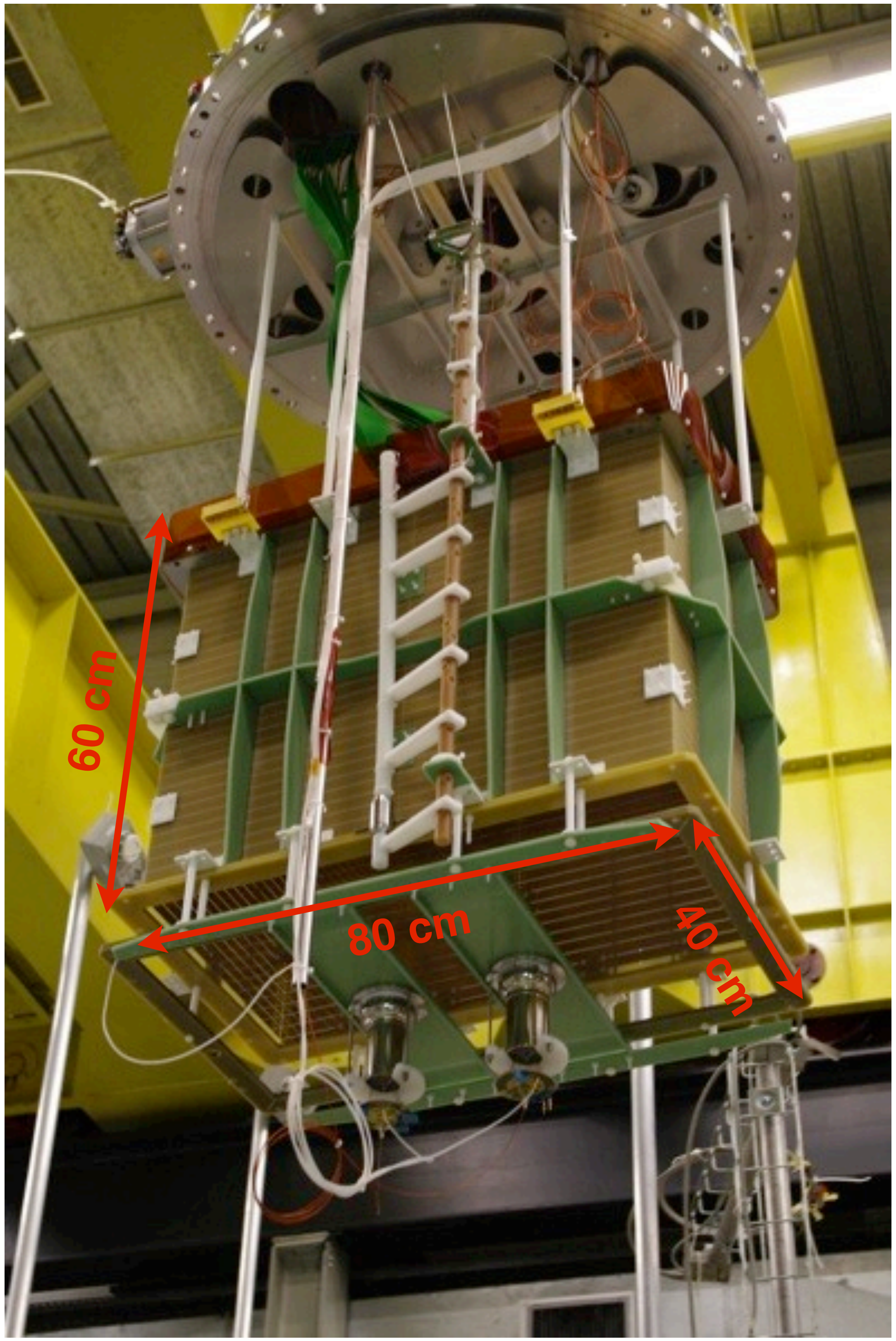




Typical MIP signal

LAr-LEM TPC@CERN:The largest LEM-TPC ever

Detector fully assembled

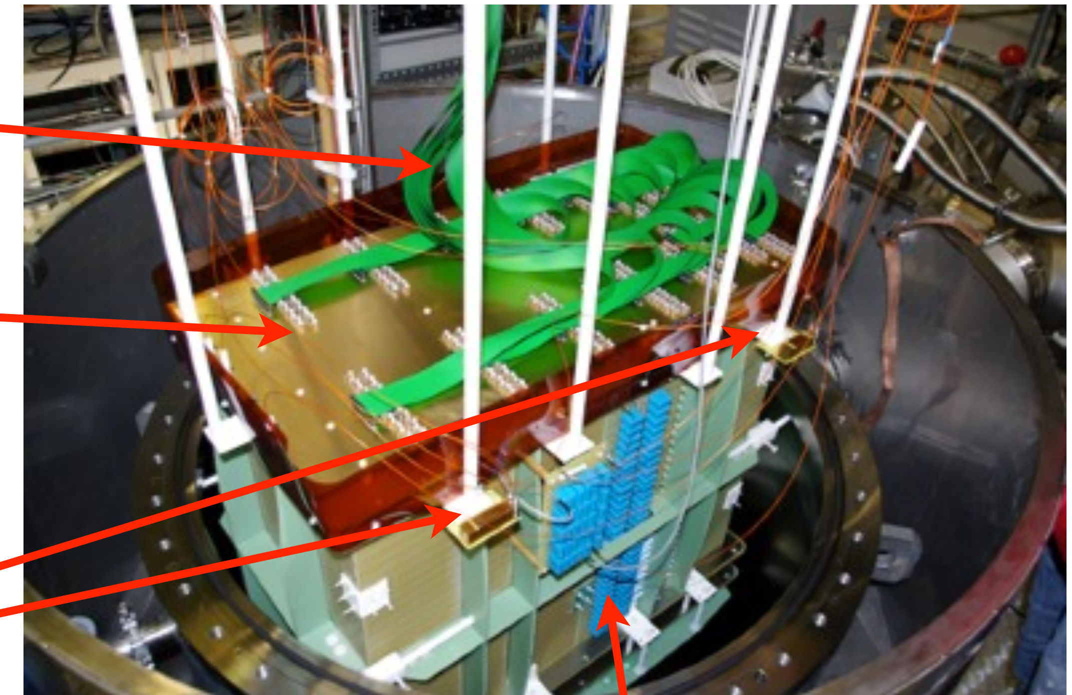


Chamber going into the ArDM cryostat

16 signal cables

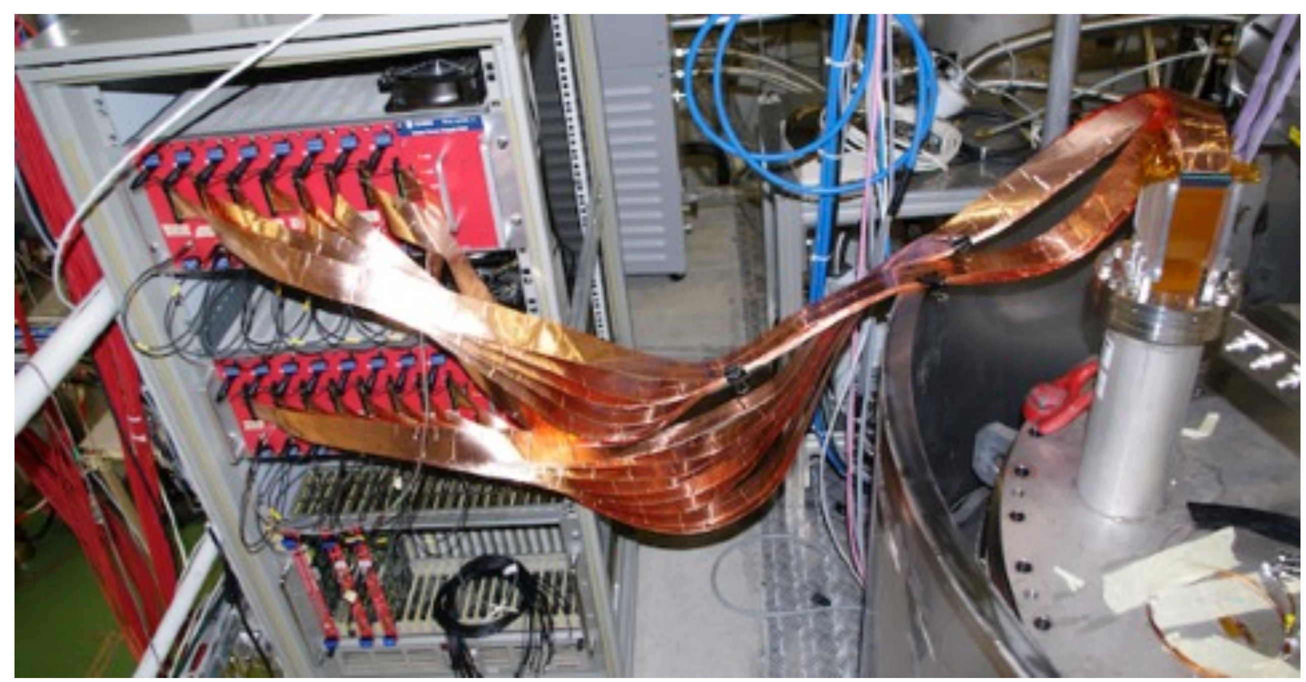
charge readout sandwich

4 capacitive level meters



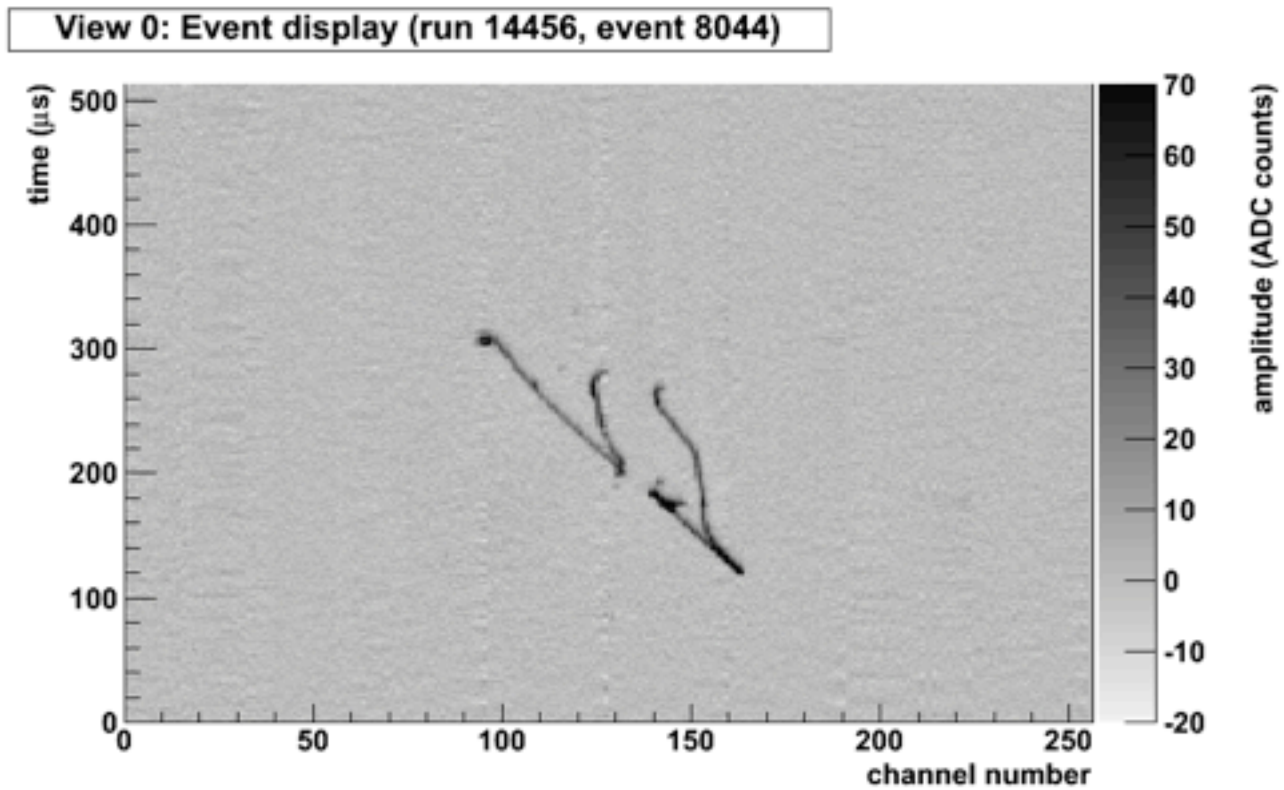
Cockcroft-Walton HV system

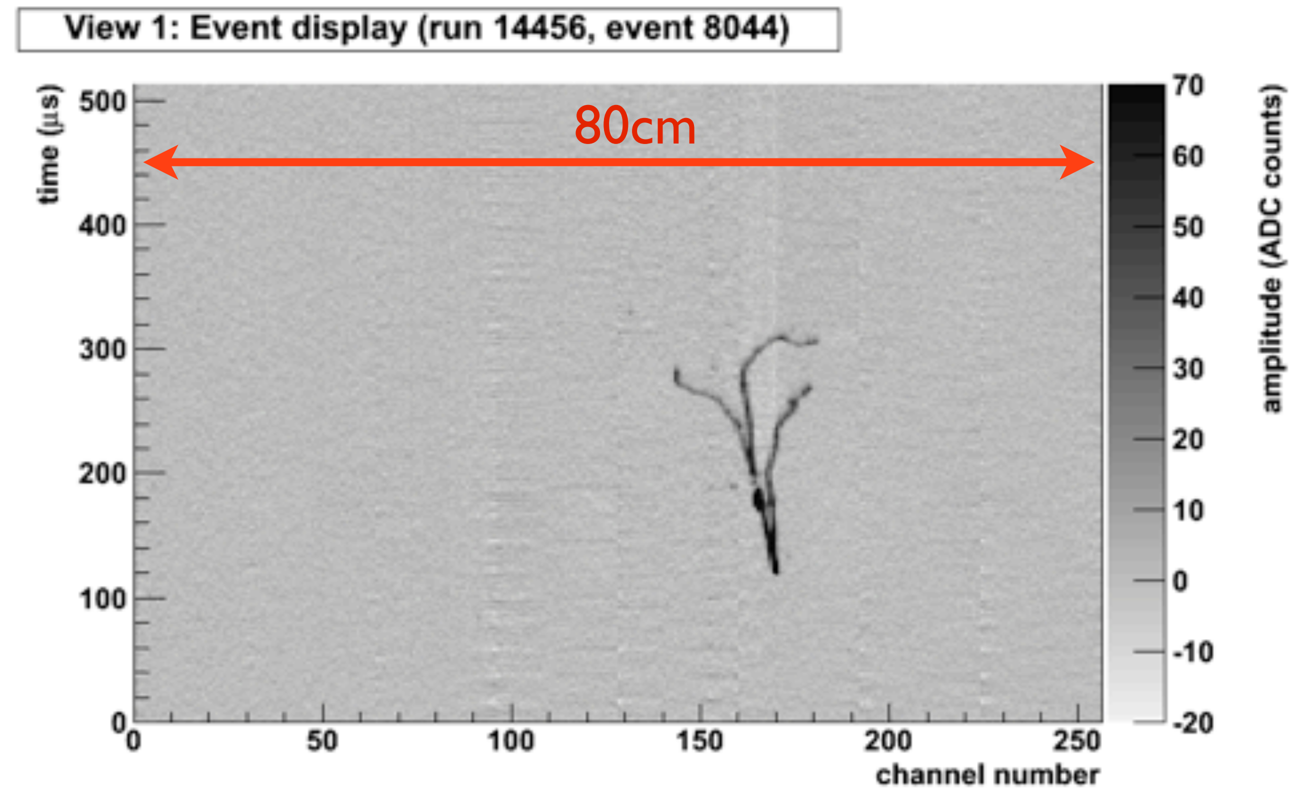
Final connection to the DAQ system

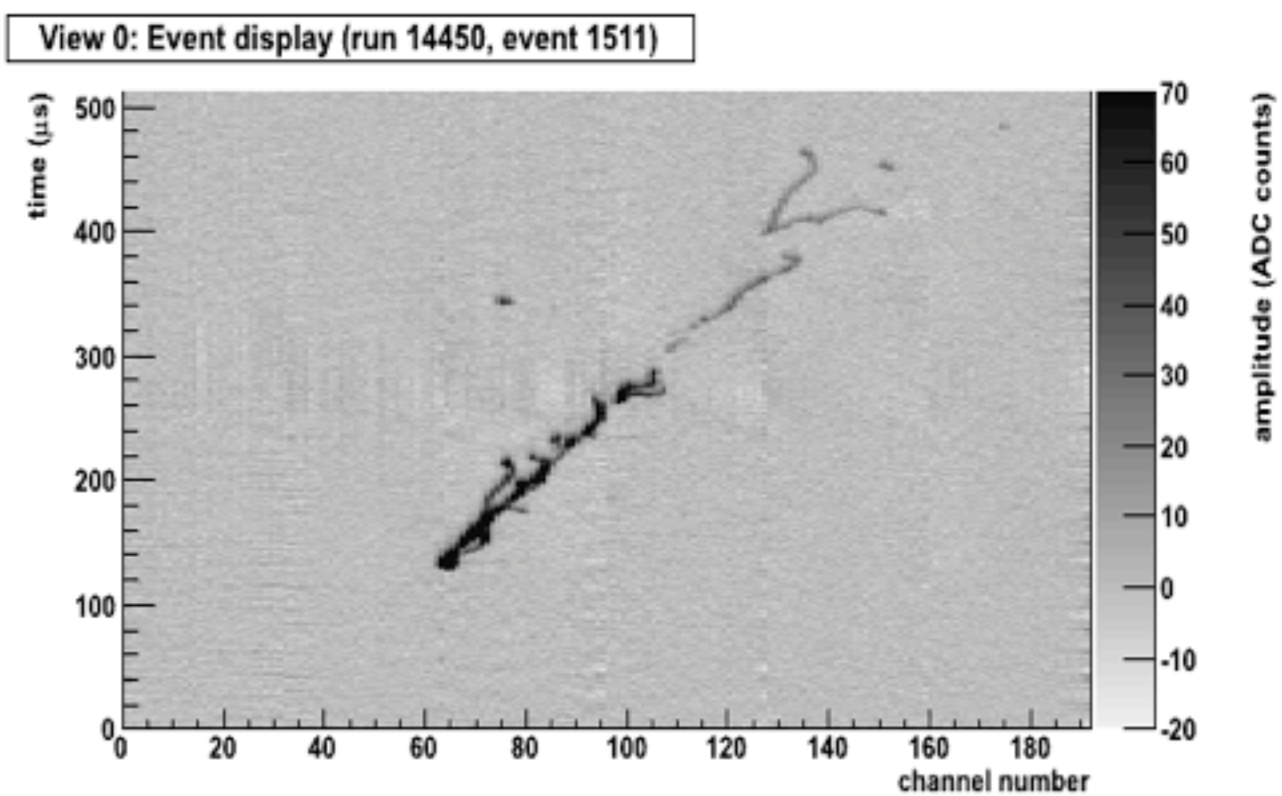


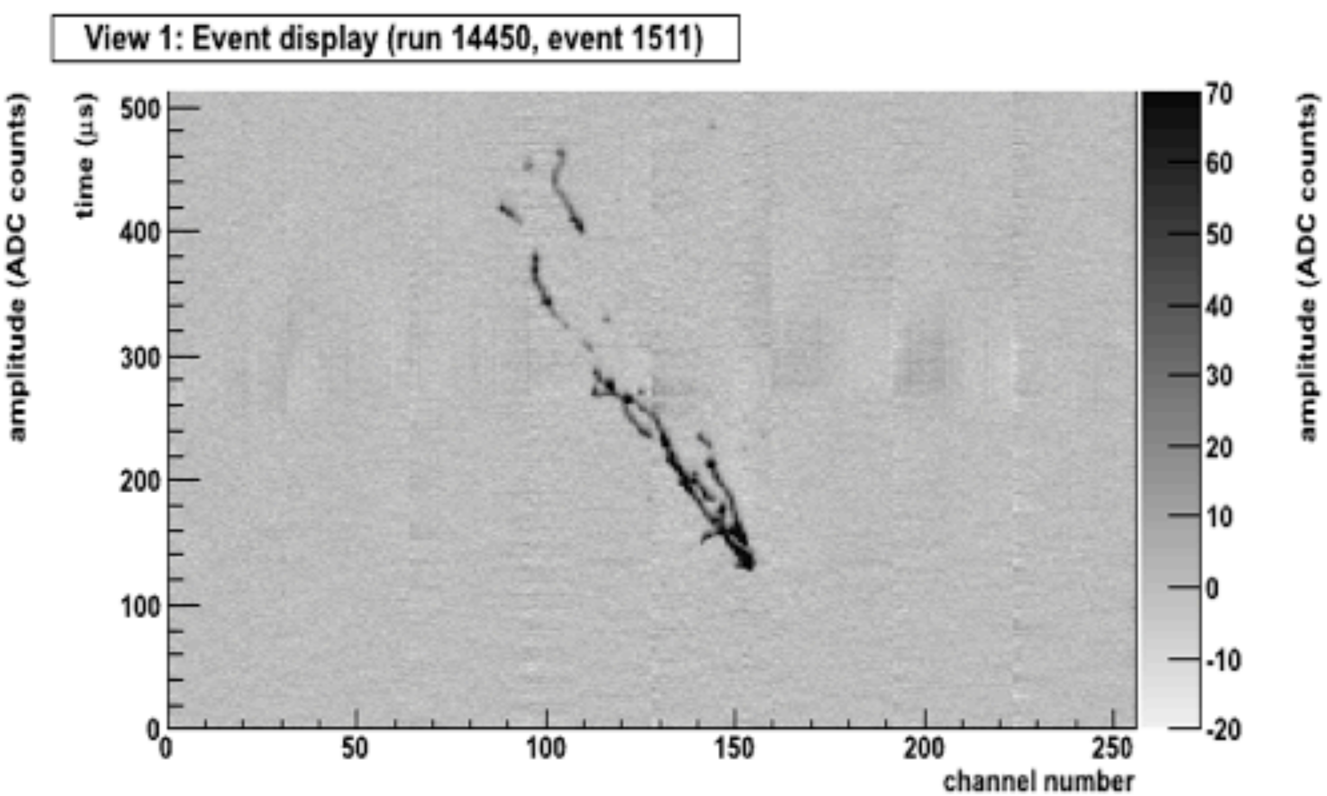
Real cosmic rays in LAr LEM-TPC

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

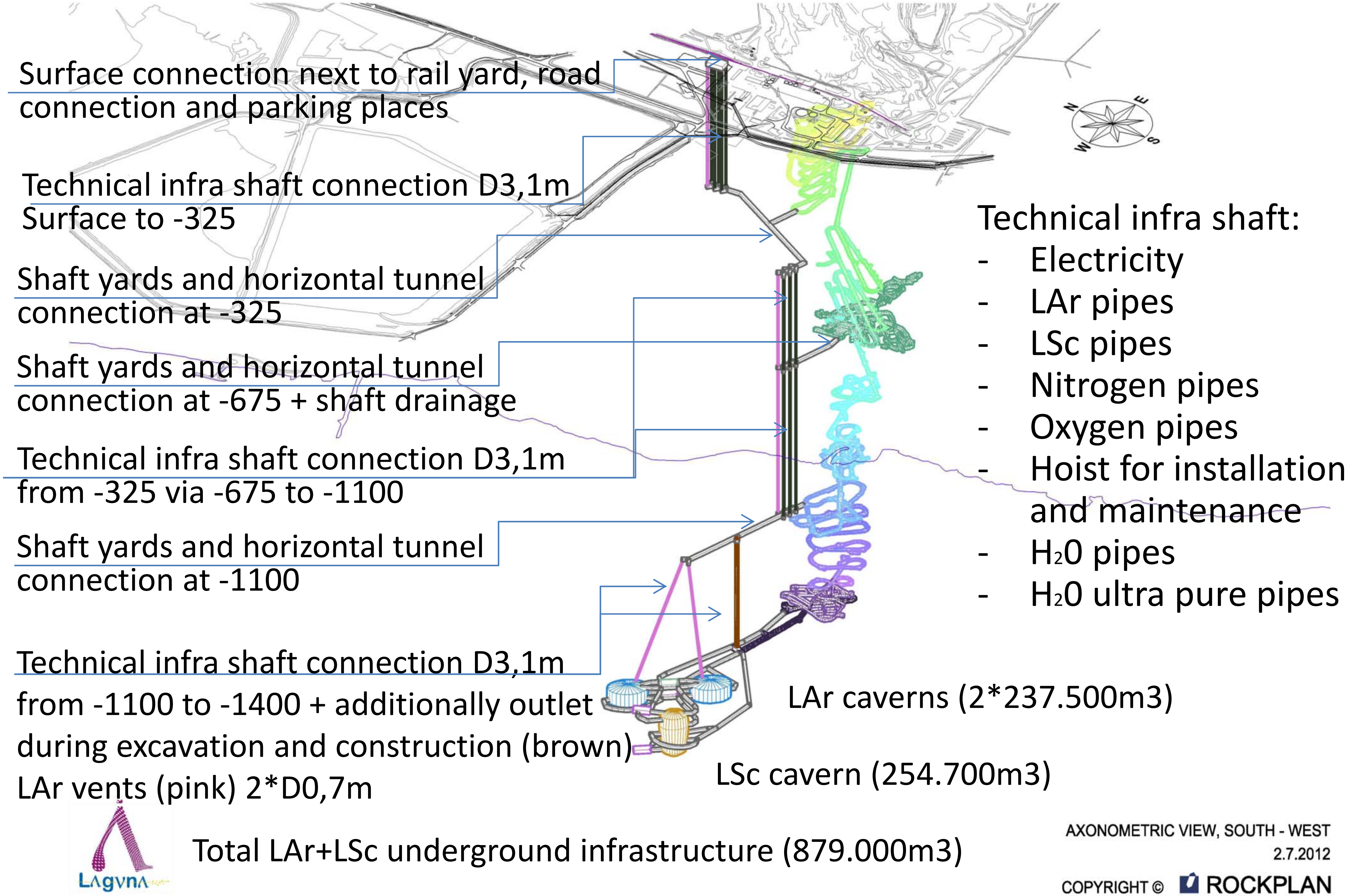








Mine infrastructure extension



LAgvnA

Total LAr+LSc underground infrastructure (879.000m3)

CP-phase sensitivity

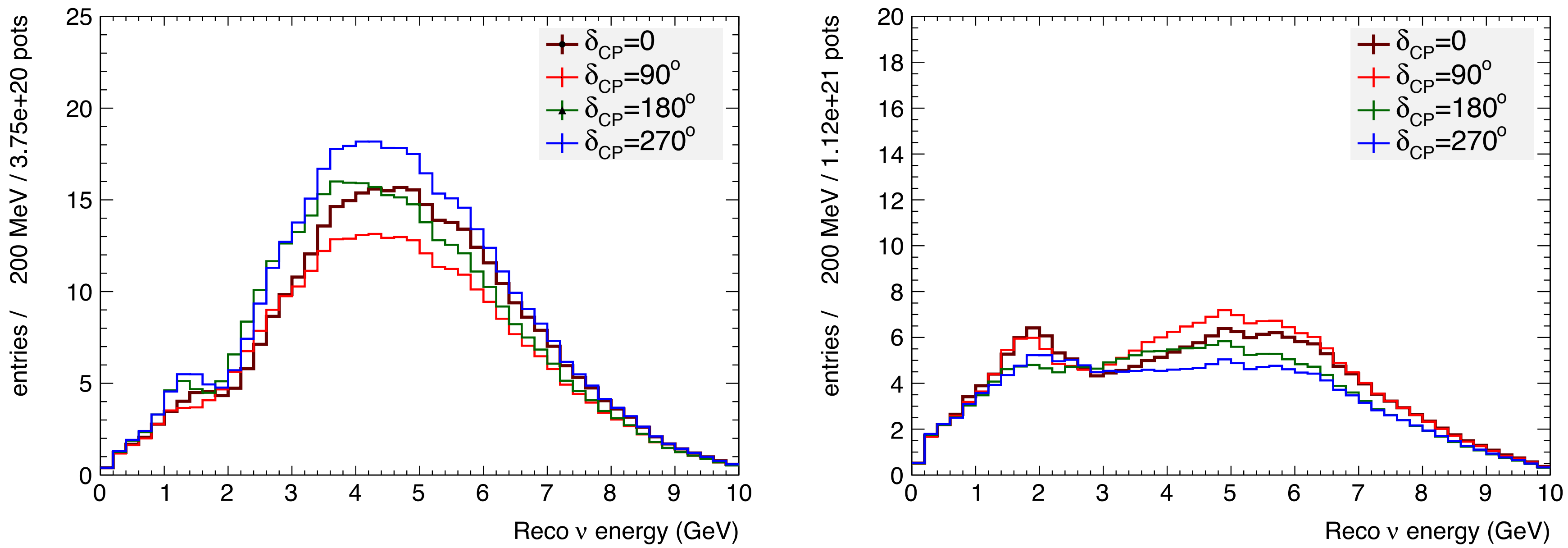


FIG. 73: Reconstructed event energy for (left) neutrino horn polarity running and (right) antineutrino ho polarity running, for different values of true δ_{CP} and for normal mass hierarchy (NH). A 25%-75% shar between neutrino and antineutrino running mode and a total of 1.5×10^{21} pot have been chosen.

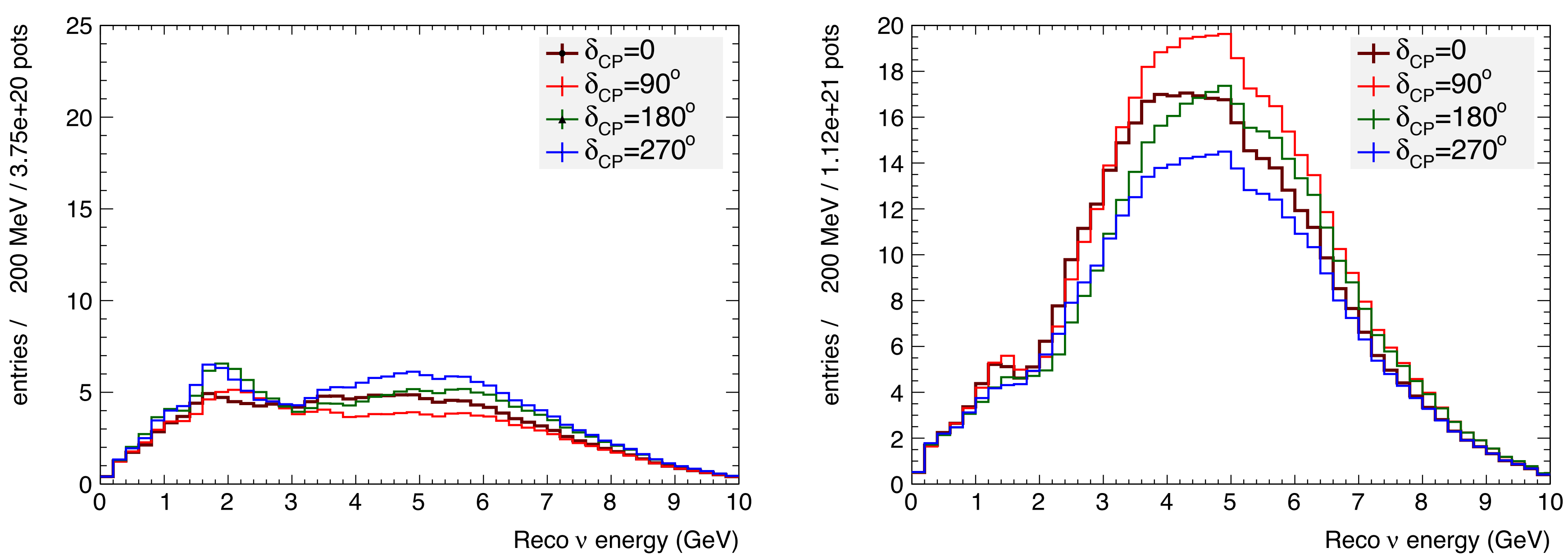
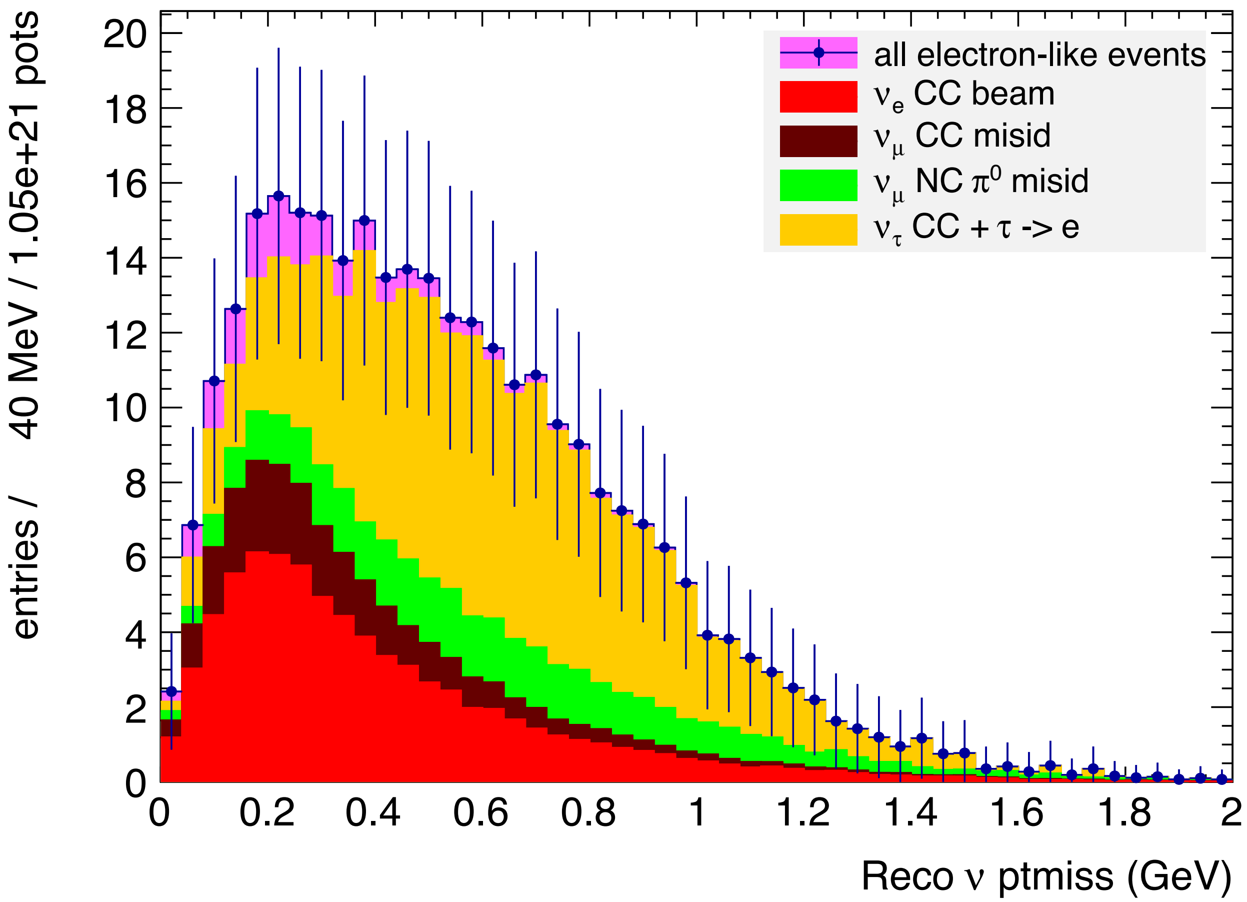
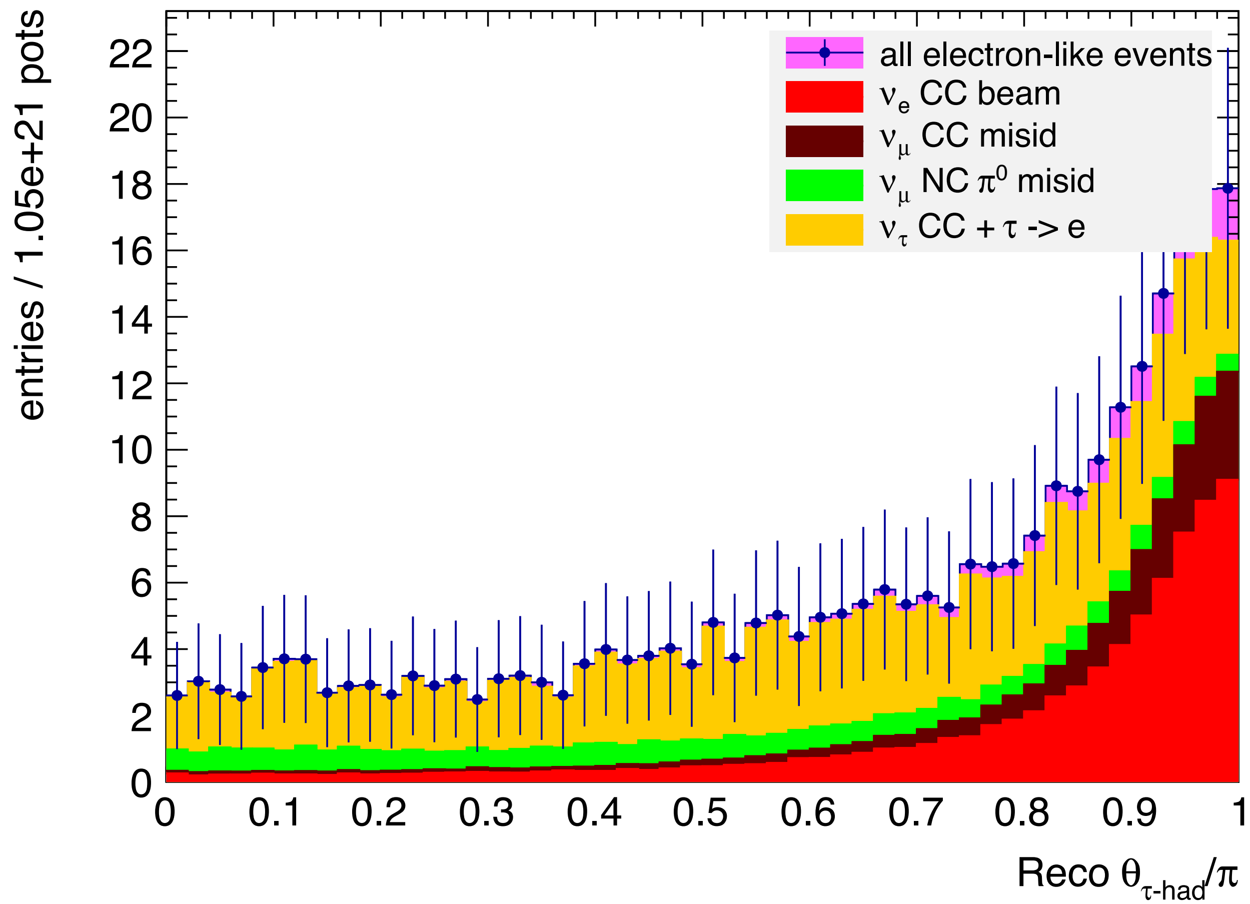


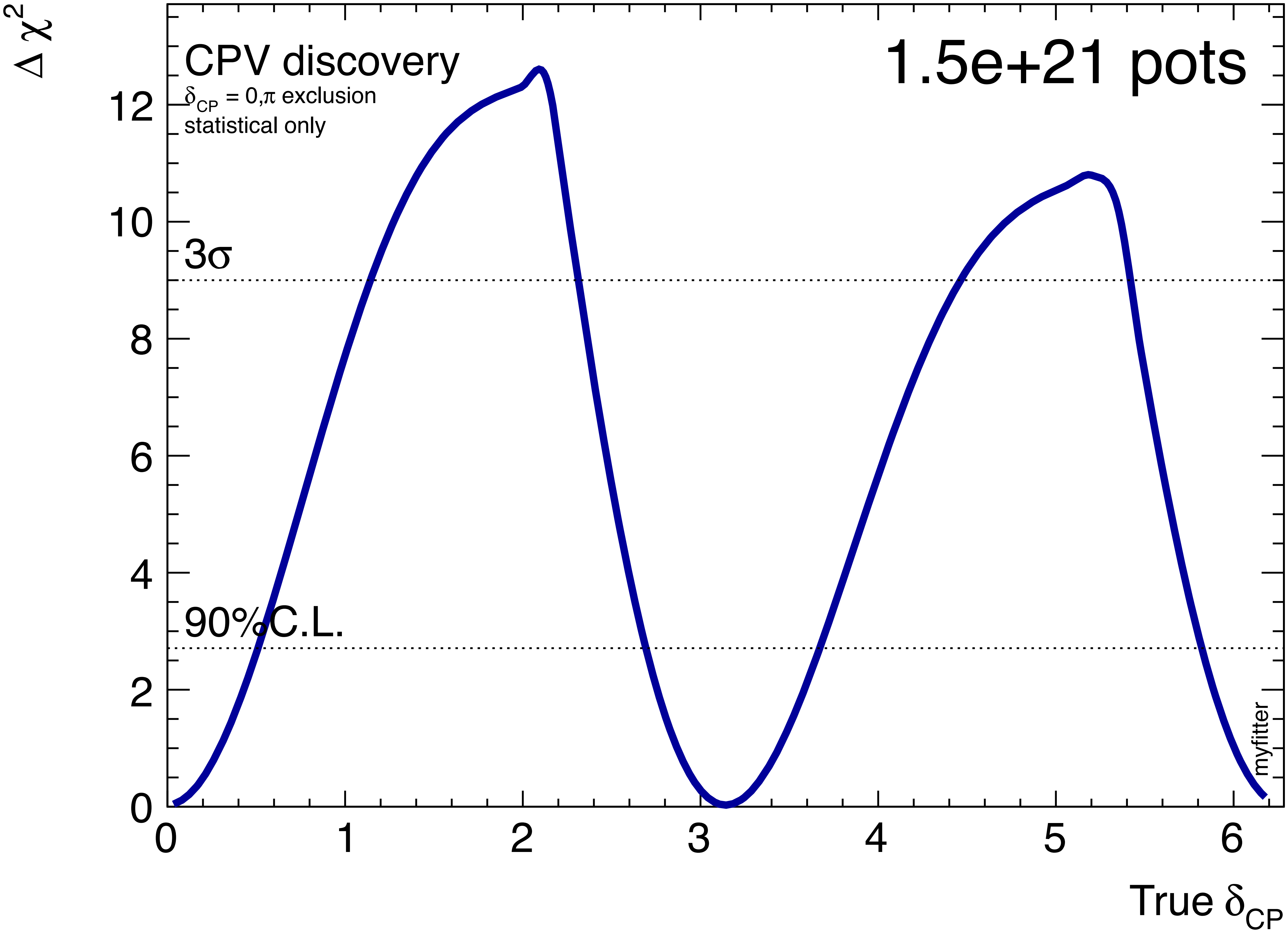
FIG. 74: Same as Figure 73 but for inverted mass hierarchy (IH).

Tau like sample

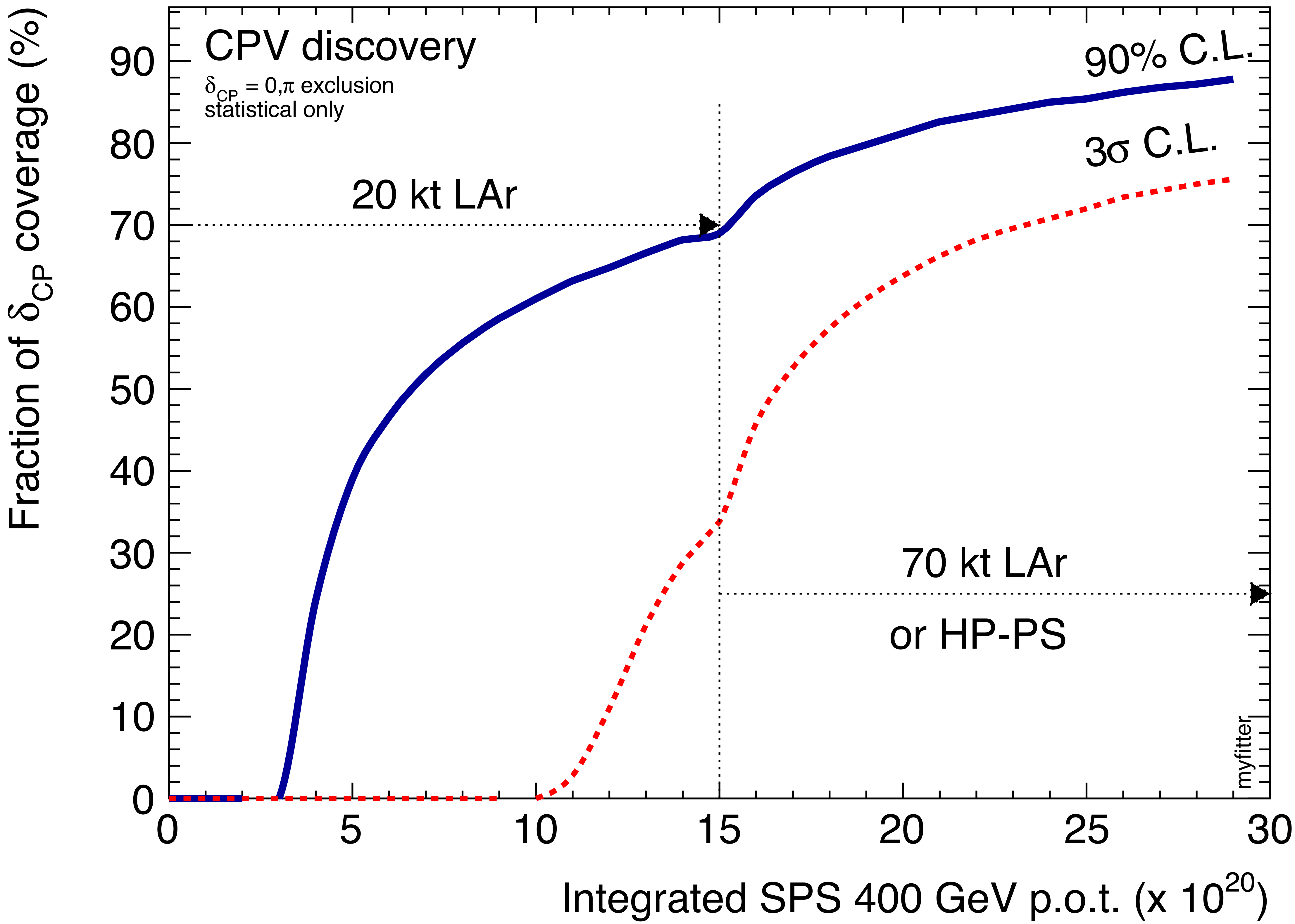




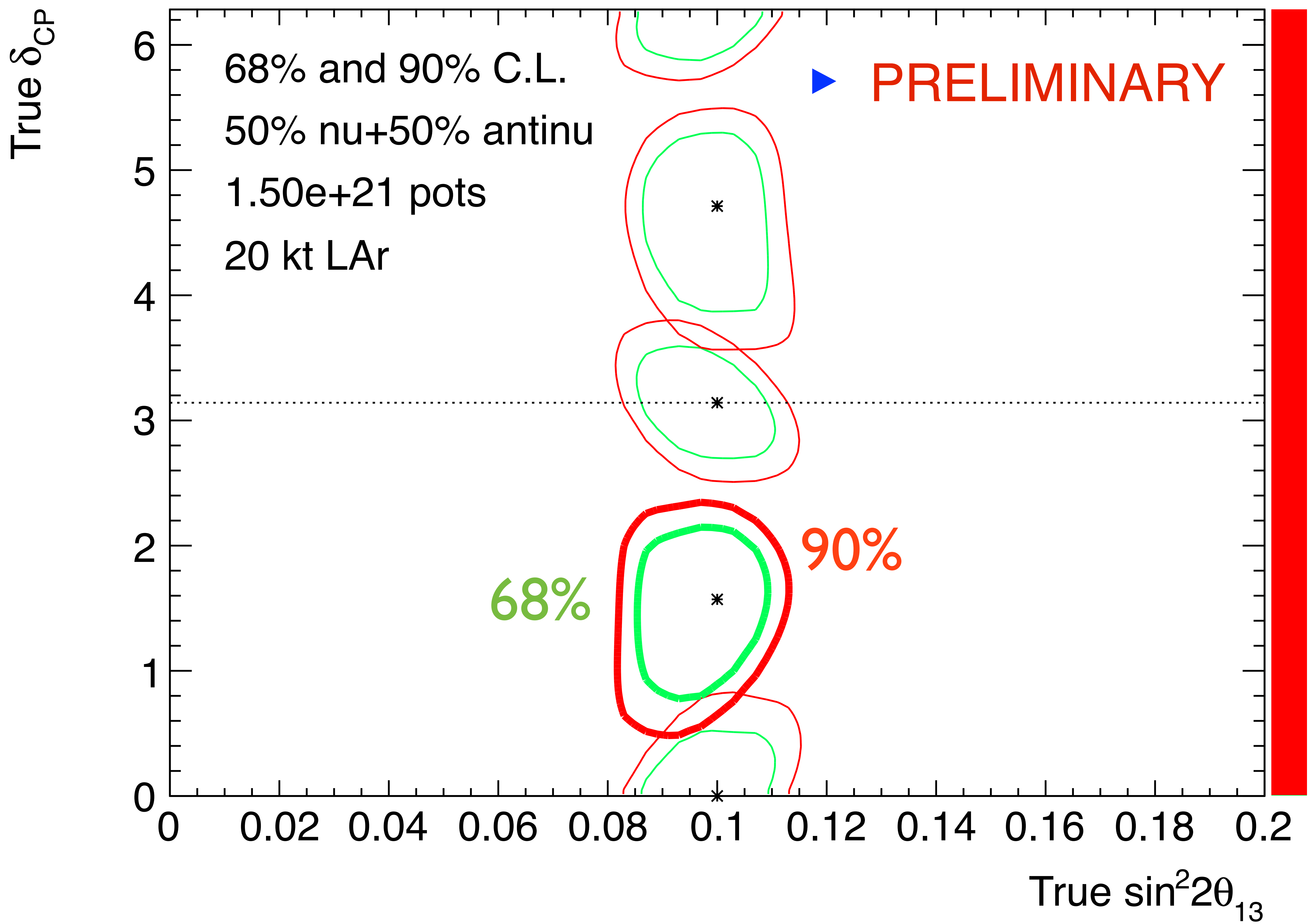
CPV discovery - statistical only



CPV discovery - statistical only

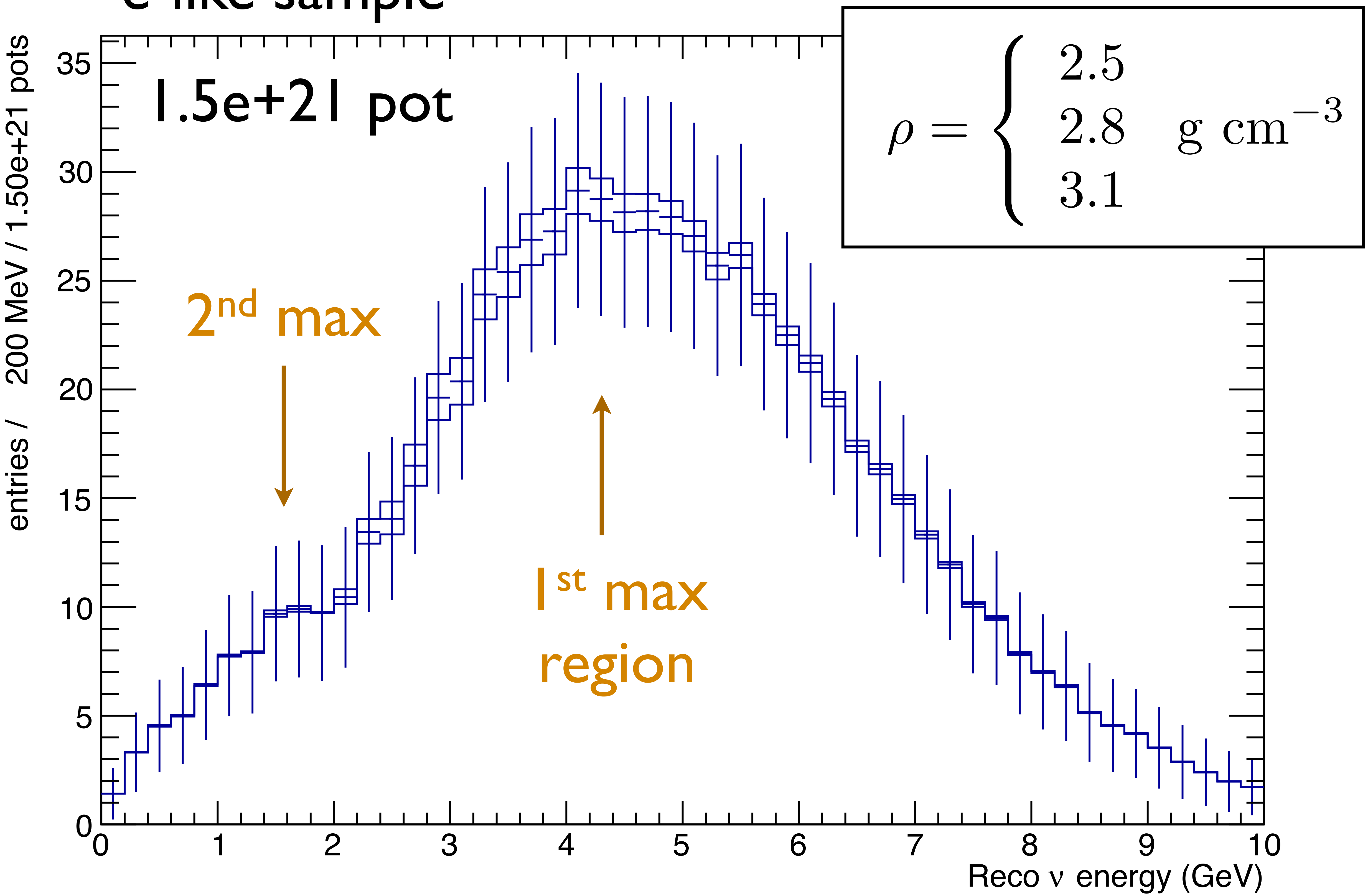


CP-phase determination



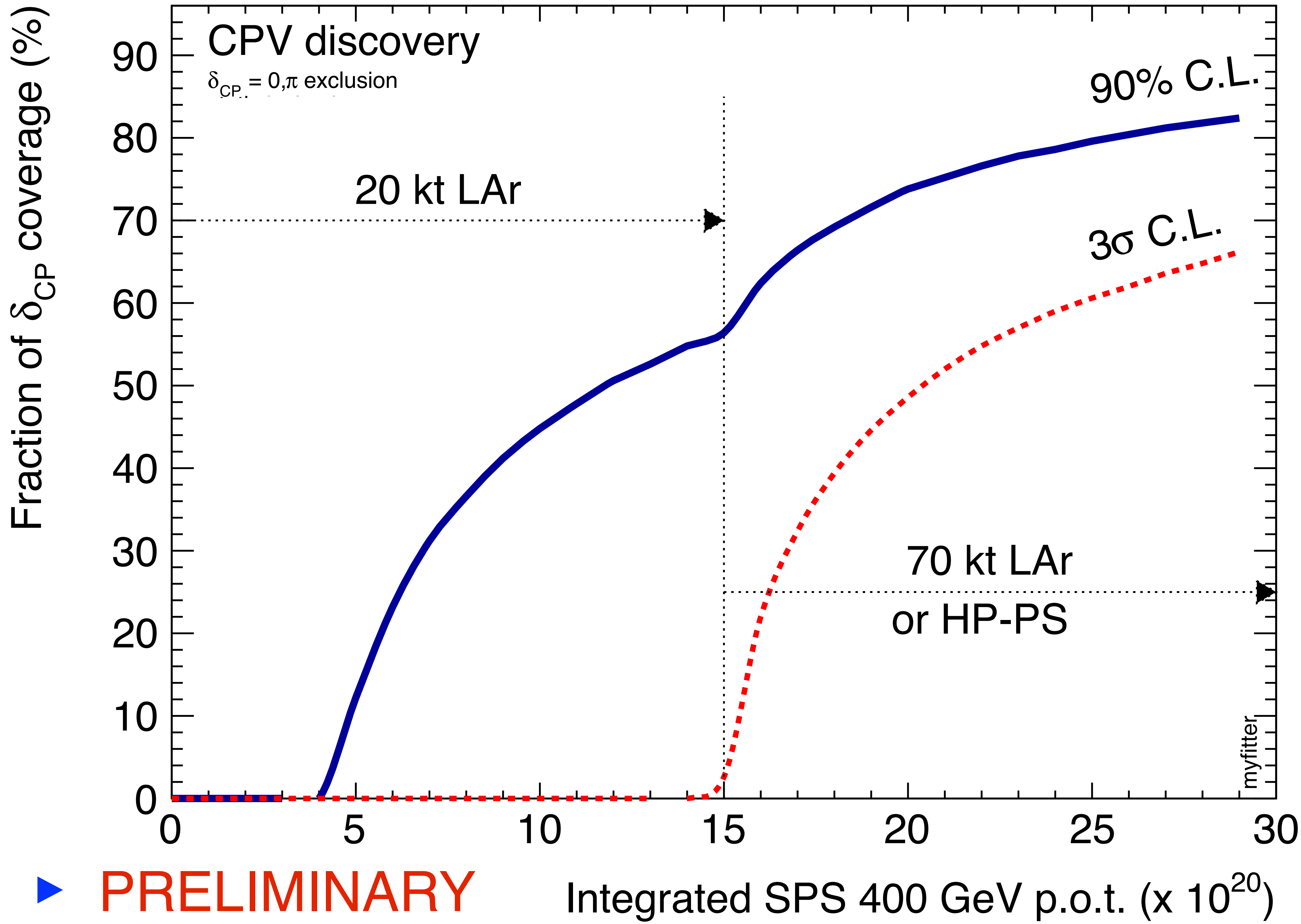
Matter density effects

e-like sample



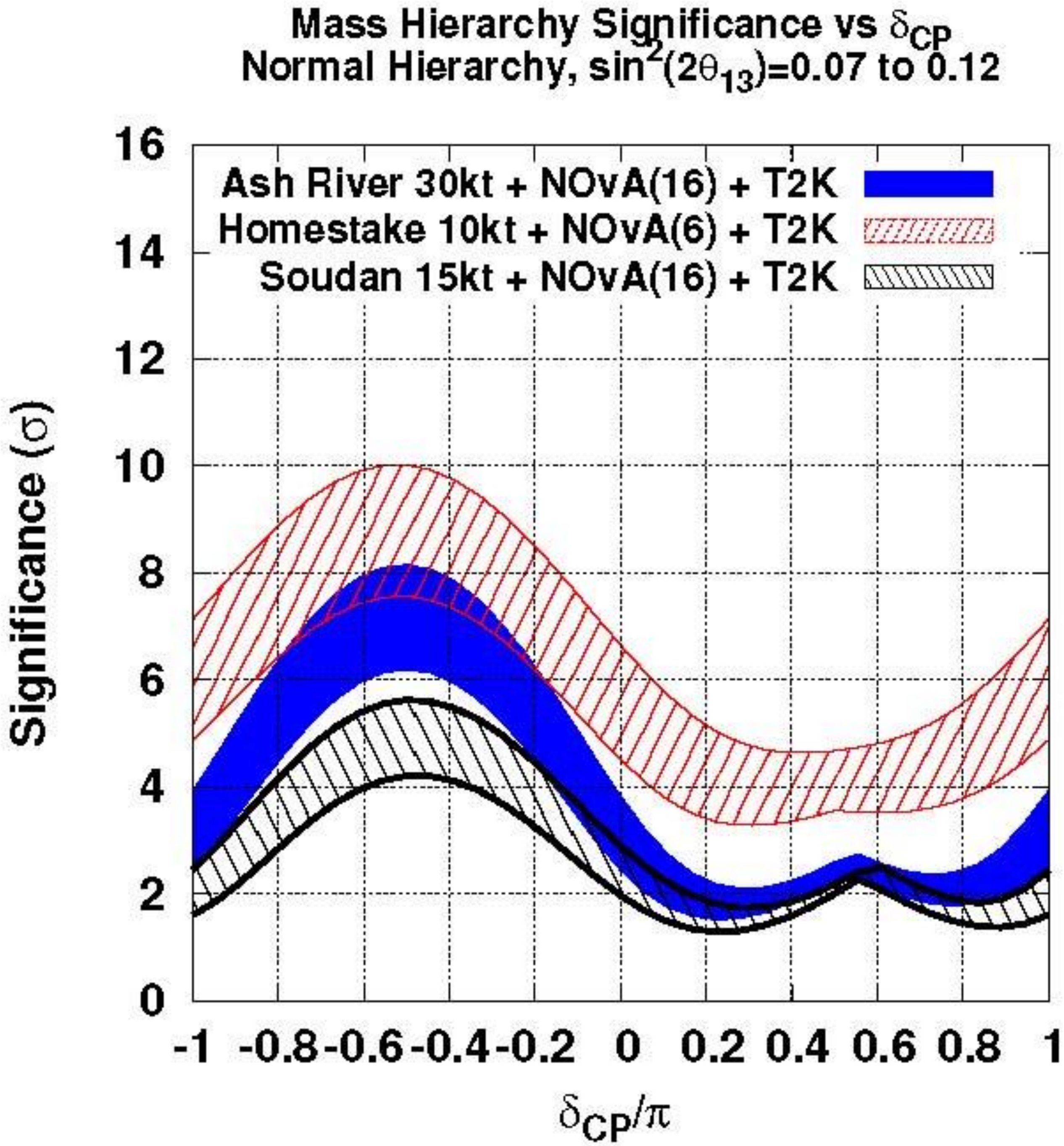
Effect of matter uncertainty

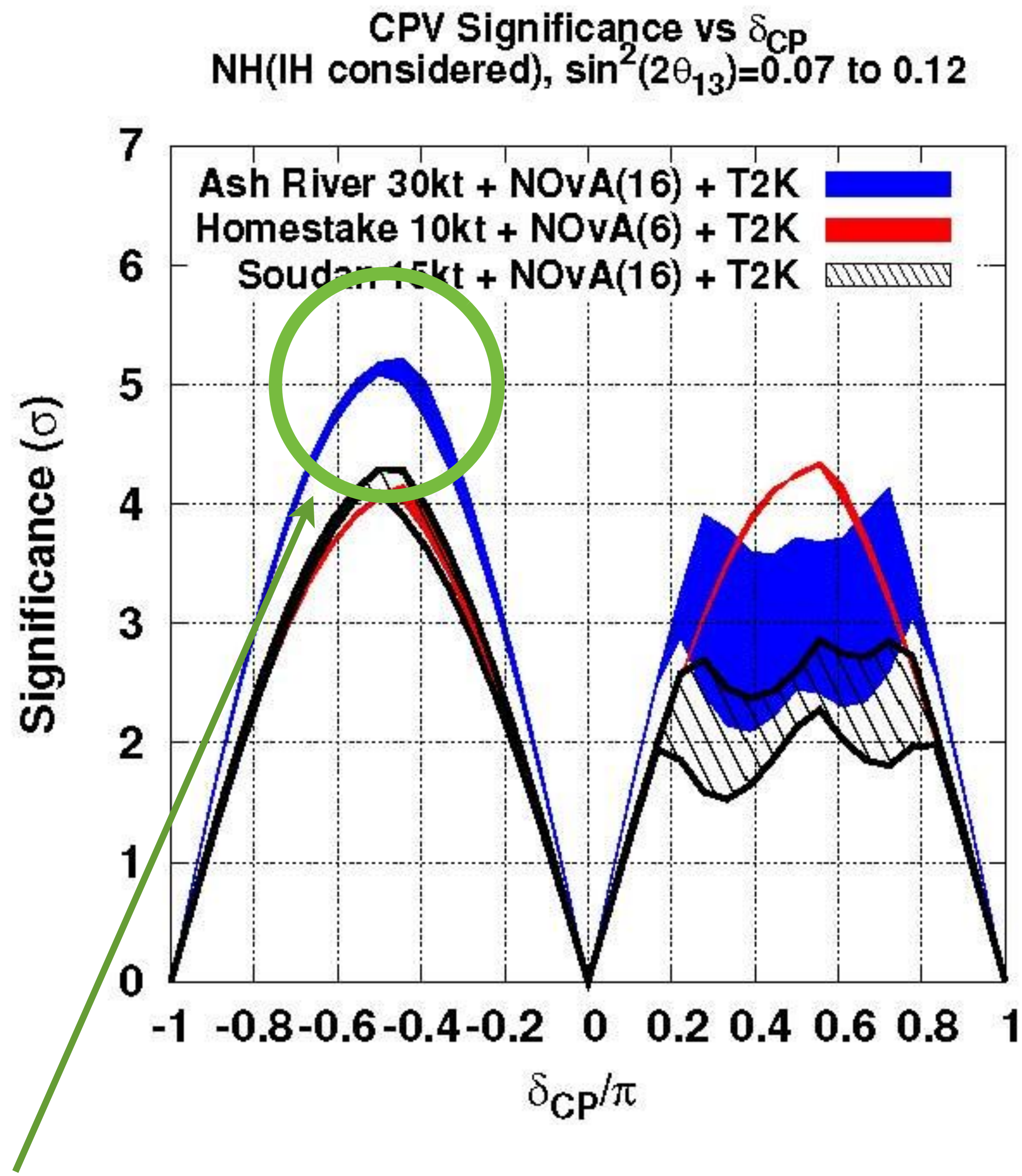
★ INFLATED ERROR ON MATTER DENSITY ±10%



▸ PRELIMINARY

LBNE: 10 years @ 700kW

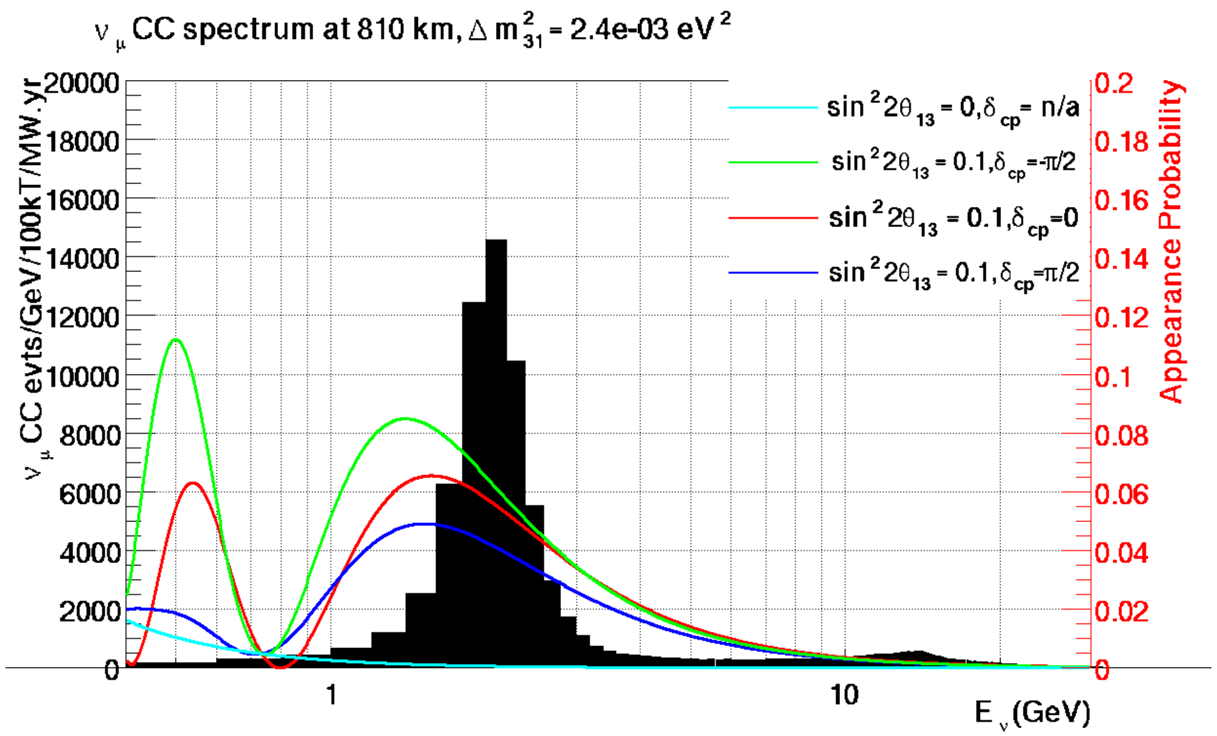


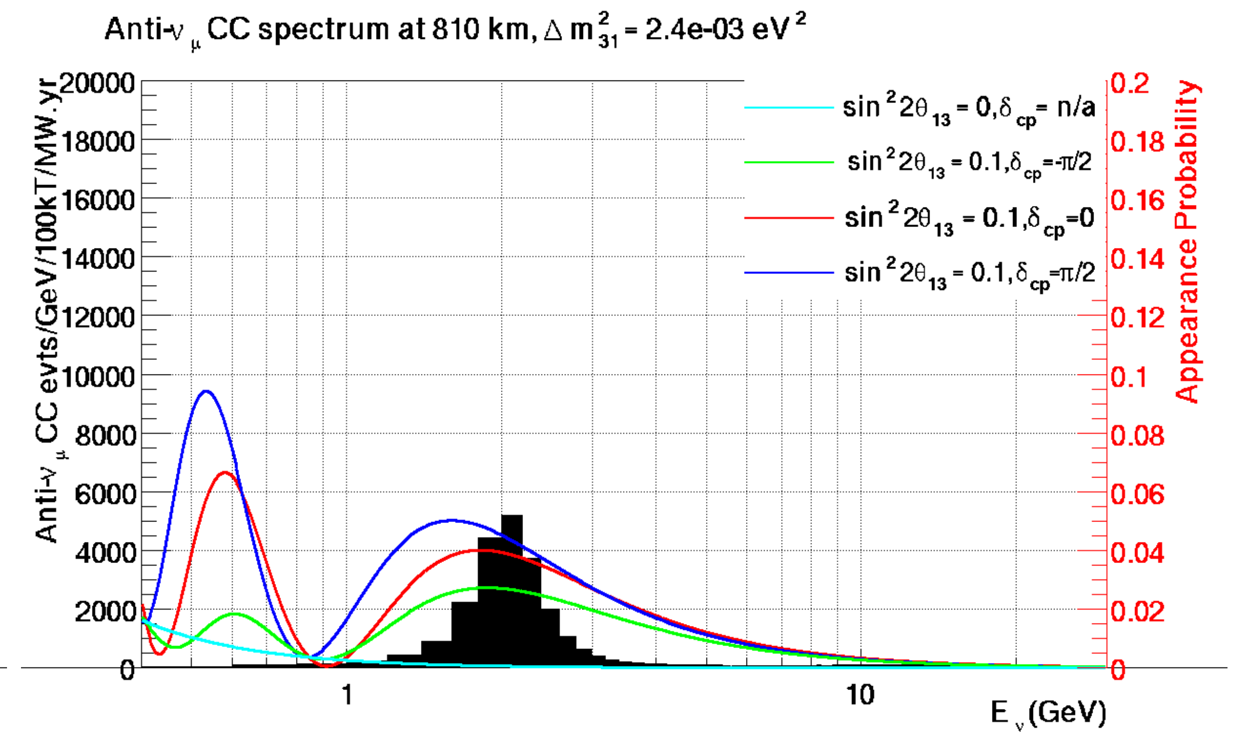


Be aware: Ash River has the best CPV sensitivity when MH is determined ! the displayed sensitivities come mostly from parameter fitting around 1st maximum

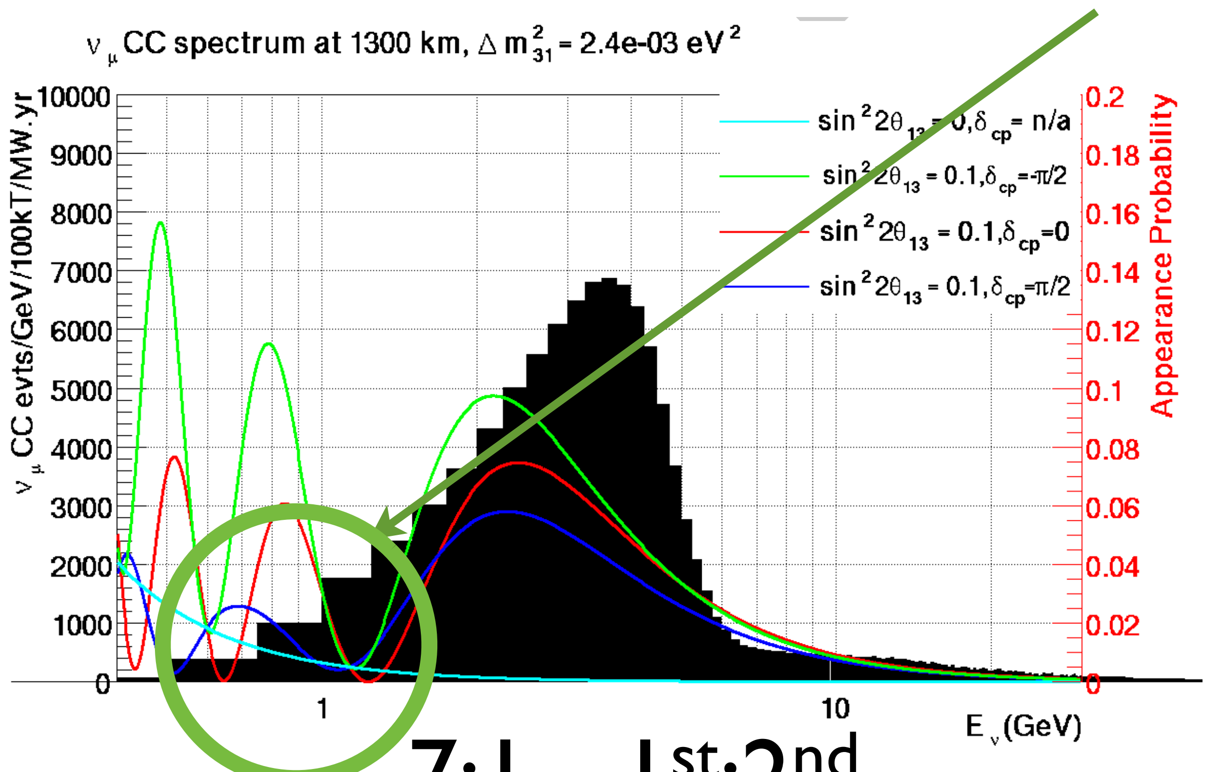
LBNE: Ash River & Homestake

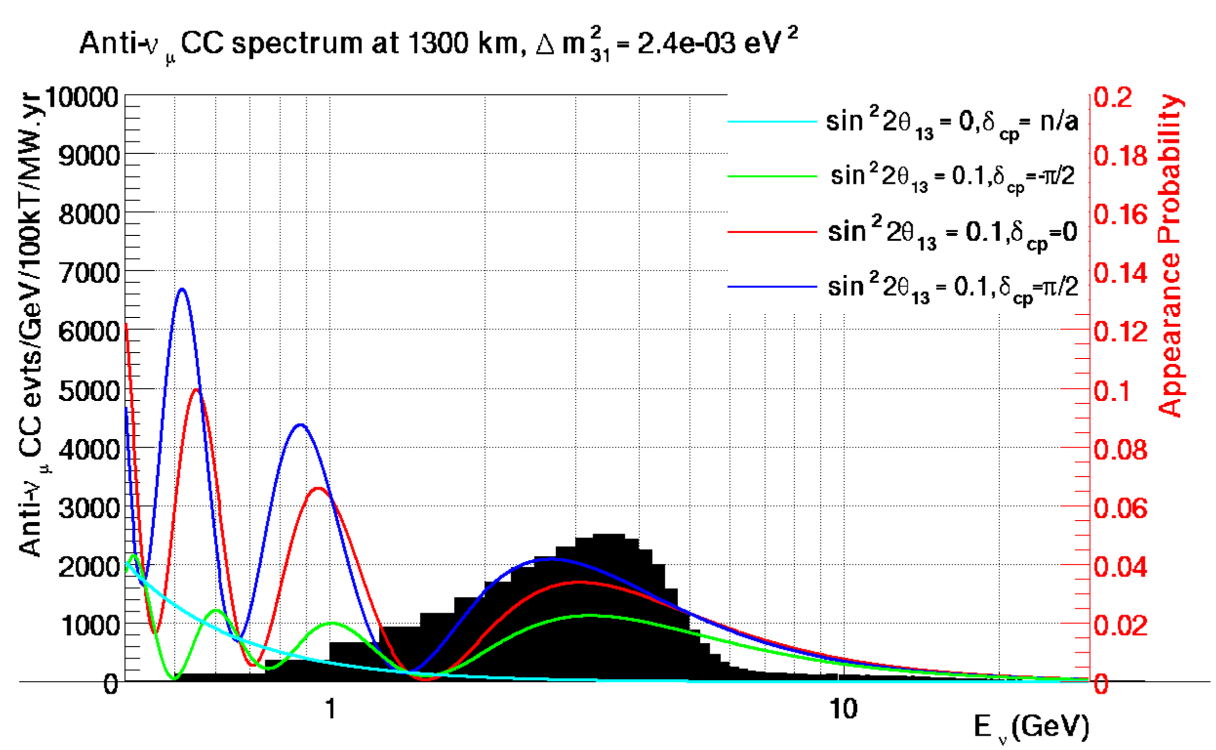
810 km off-axis is totally discounted (no E-dependence !)





Even at 1300 km the second maximum is hard to observe !





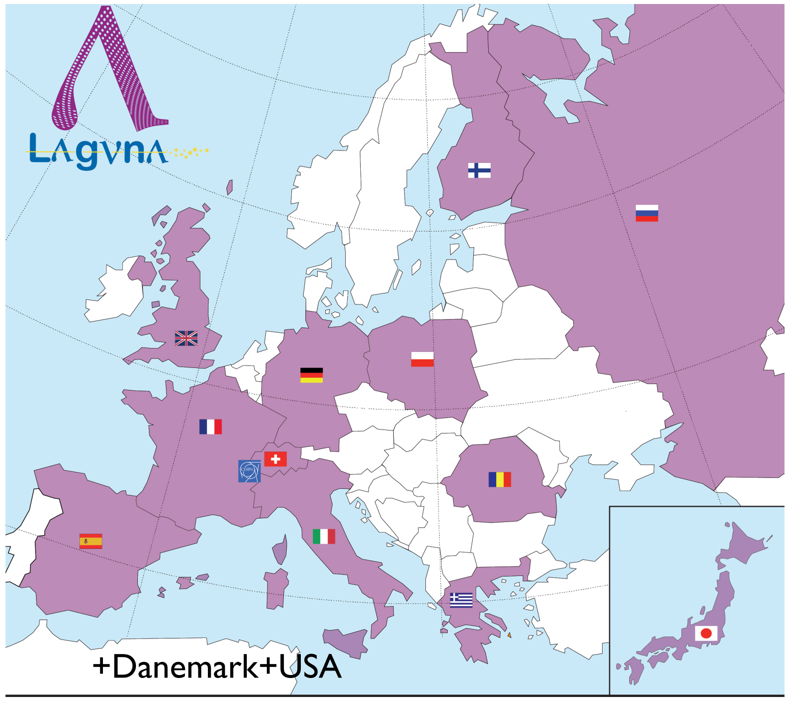
7:1 - $1^{st}:2^{nd}$

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)

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*

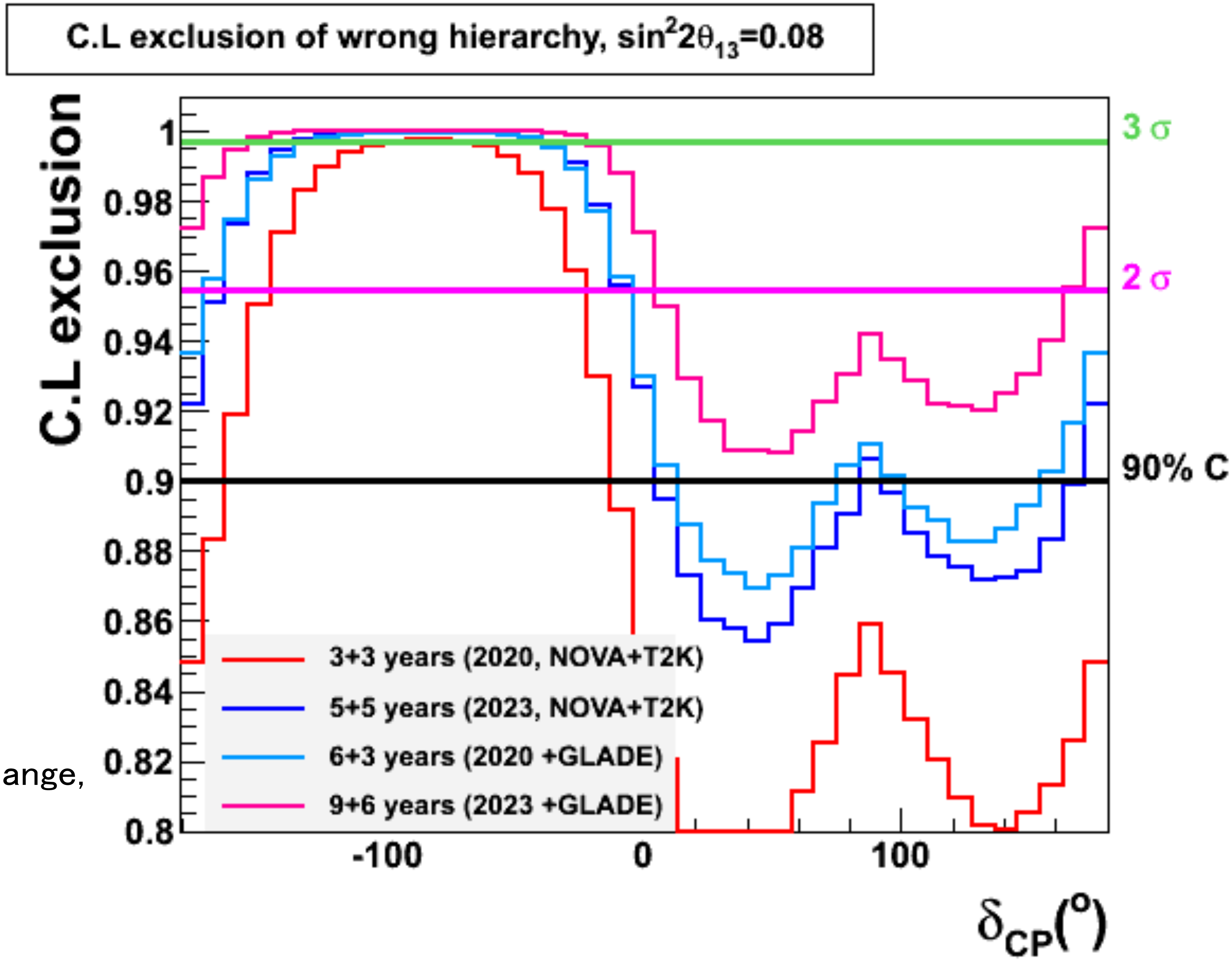
Russia
INR
PNPI

Japan
KEK

USA
Virginia Tech

(=industrial partners)*

Situation in 2023 ?



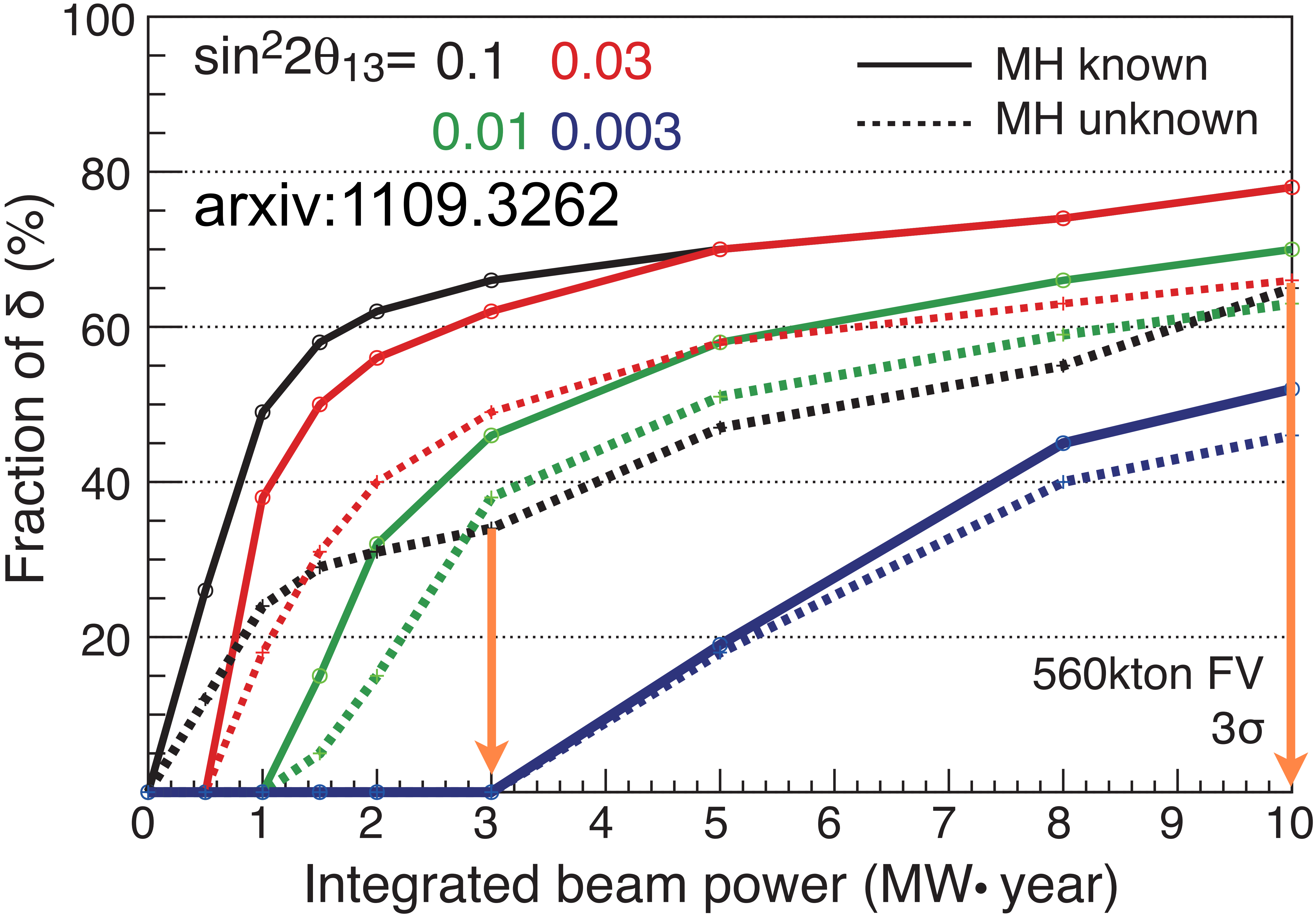
ıange,

Most likely we will reach a ≈2σ MH determination

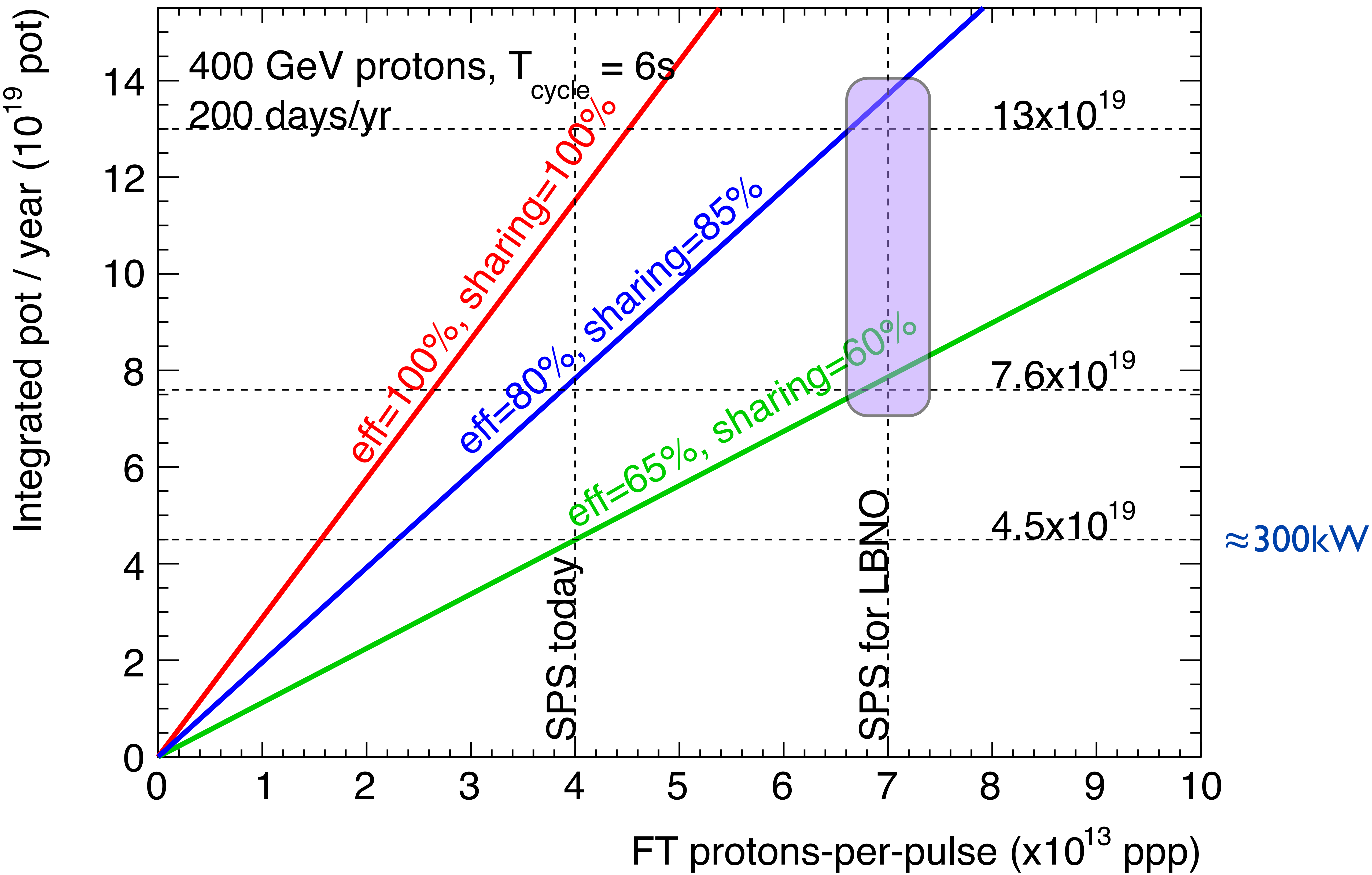
Why the neutrino mass hierarchy ?

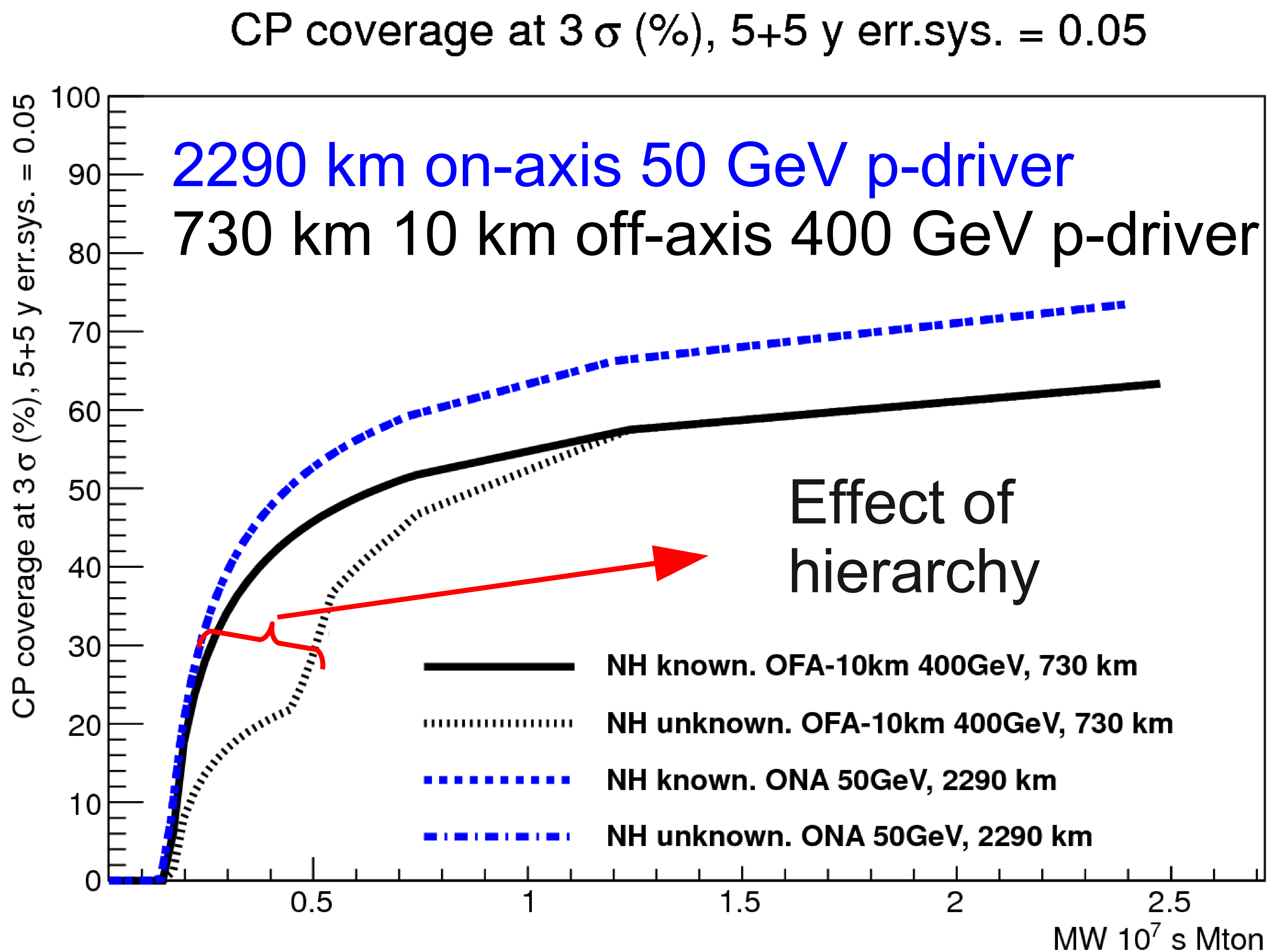
- **CP-violation:** necessary input to solve CPV problem. For example, for the HyperK LOI arxiv:1109.3262 (which considers a 540kton FV and hence has the highest statistical power):
  - ➡ 3 MW×years (note: >10 years at present JPARC MR power) MH known: 65% coverage → MH unknown: 35% coverage
  - ➡ 10 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





A. Longhin et al., NUTurn12

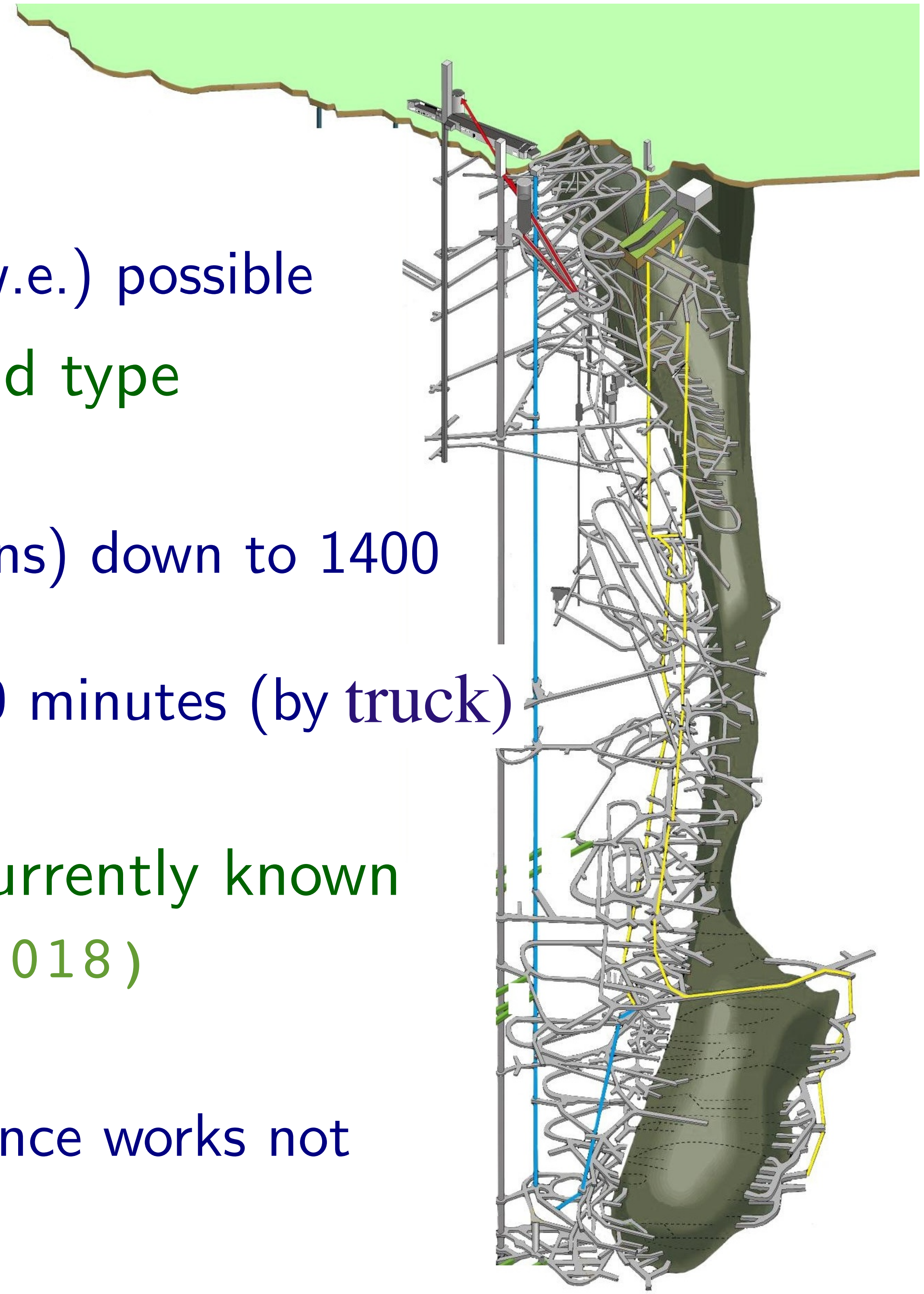
Some unique features of Pyhäsalmi

- **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).**

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



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

CP and Matter Asymmetries

★ CP-asymmetry in vacuum:

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

★ Asymmetry due to matter effects:

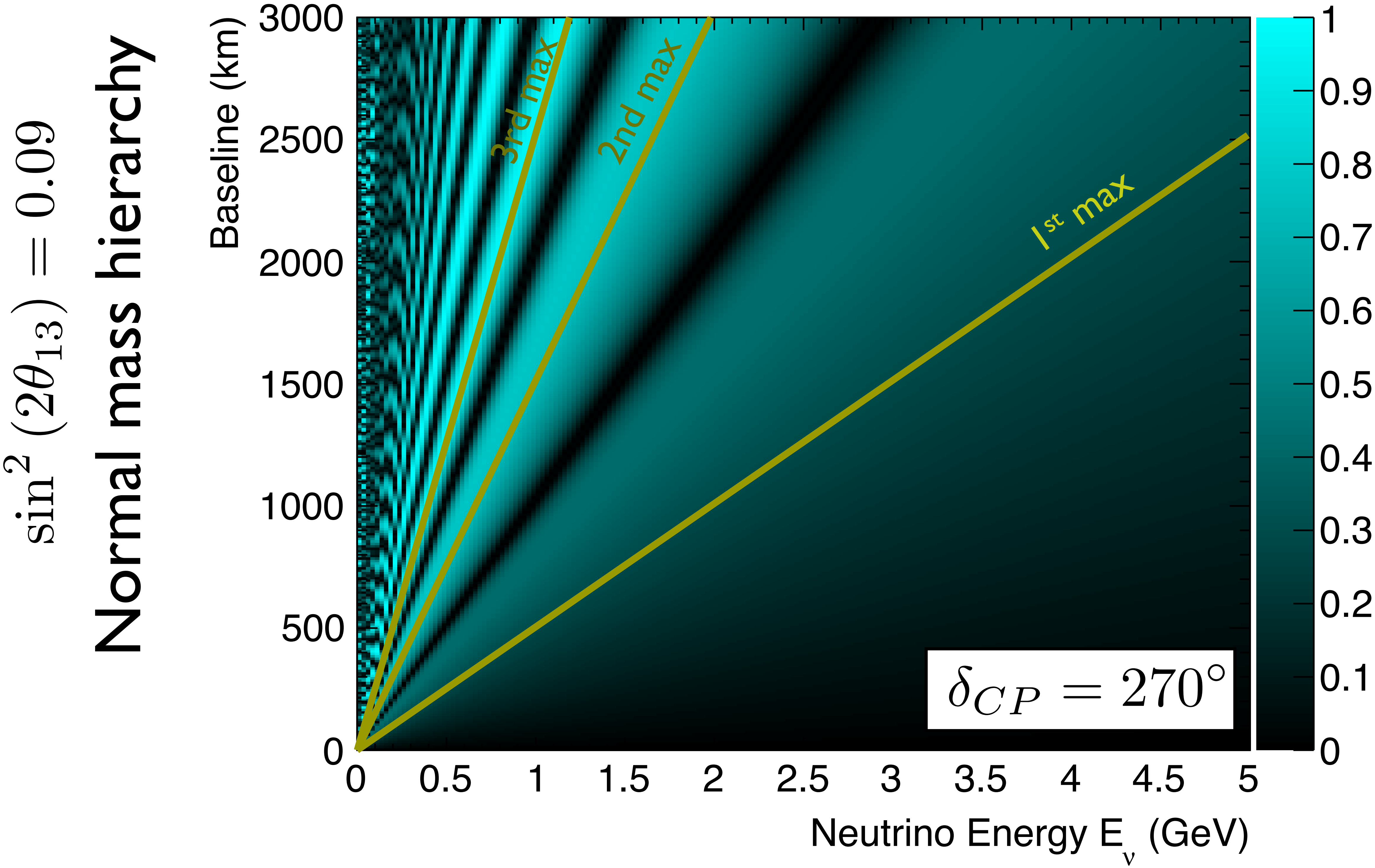
$$\mathcal{A}_{CP}(\rho) \equiv abs\left(\frac{P^{mat}(\nu) - P^{mat}(\bar{\nu})}{P^{mat}(\nu) + P^{mat}(\bar{\nu})}\right)$$

- 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: $E^{2nd\,max}_{\nu} \gtrsim 0.5\,\mathrm{GeV} \Longrightarrow \mathrm{L} \gtrsim 1000\ \mathrm{km}$

  (fluxes, cross-sections, ...)

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