Exotic physics with OPERA data

OPERA general meeting

May 30th 2018

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Oscillation probability parametrization with 3+1

$$
\begin{aligned}
P(E) \;=\; & C^2 sin^2(1.27\Delta m^2_{31} L/E) \;+\; sin^2(2\theta_{\mu\tau}) sin^2(1.27\Delta m^2_{41} L/E) \\
& + \; 0.5 C sin(2\theta_{\mu\tau}) cos(\phi_{\mu\tau}) sin(2.54\Delta m^2_{31} L/E) sin(2.54\Delta m^2_{41} L/E) \\
& - \; C sin(2\theta_{\mu\tau}) sin(\phi_{\mu\tau}) sin^2(1.27\Delta m^2_{31} L/E) sin(2.54\Delta m^2_{41} L/E) \\
& + \; 2C sin(2\theta_{\mu\tau}) cos(\phi_{\mu\tau}) sin^2(1.27\Delta m^2_{31} L/E) sin^2(1.27\Delta m^2_{41} L/E) \\
& + \; C sin(2\theta_{\mu\tau}) sin(\phi_{\mu\tau}) sin(2.54\Delta m^2_{31} L/E) sin^2(1.27\Delta m^2_{41} L/E)
\end{aligned}
$$

Approximation used: Δm^2_{21}=0 eV^2.

Parametrization as a function of three parameters:

$$C \;=\; 2|U_{\mu 3} U^*_{\tau 3}|$$

$$\phi_{\mu\tau} \;=\; Arg(U_{\mu 3} U^*_{\tau 3} U^*_{\mu 4} U_{\tau 4})$$

$$sin^2(2\theta_{\mu\tau}) \;=\; 4|U_{\mu 4}|^2 |U_{\tau 4}|^2$$

Oscillation probability parametrization

Limit for $\Delta m^2_{41} > 1$ eV^2 :

$$P(E) = C^2\, sin^2(1.27\Delta m^2_{32}L/E) + 0.5\, sin^2(2\theta_{\mu\tau})$$
$$+\, C\, sin(2\theta_{\mu\tau})\, cos(\phi_{\mu\tau})\, sin^2(1.27\Delta m^2_{32}L/E)$$
$$+\, 0.5\, C\, sin(2\theta_{\mu\tau})\, sin(\phi_{\mu\tau})\, sin(2.54\Delta m^2_{32}L/E)$$

$$C = 2|U_{\mu 3}U^*_{\tau 3}|$$

$$\phi_{\mu\tau} = Arg(U_{\mu 3}U^*_{\tau 3}U^*_{\mu 4}U_{\tau 4})$$

$$sin^2(2\theta_{\mu\tau}) = 4|U_{\mu 4}|^2|U_{\tau 4}|^2$$

χ^2 plot in the parameter space

$$\chi^2 = -2 \ln(L/L_0)$$

$$L = \mu^n/n!\ e^{-\mu}$$

$$L_0 = n^n/n!\ e^{-n}$$

1 degree of freedom for counting analysis.

n= the number of τ observed by OPERA

$$\mu = \int \phi(E) P(E) \sigma(E) \epsilon(E)\ dE + bkg$$

Number of expected events in OPERA (background included)

Neutrino flux

Oscillation probability

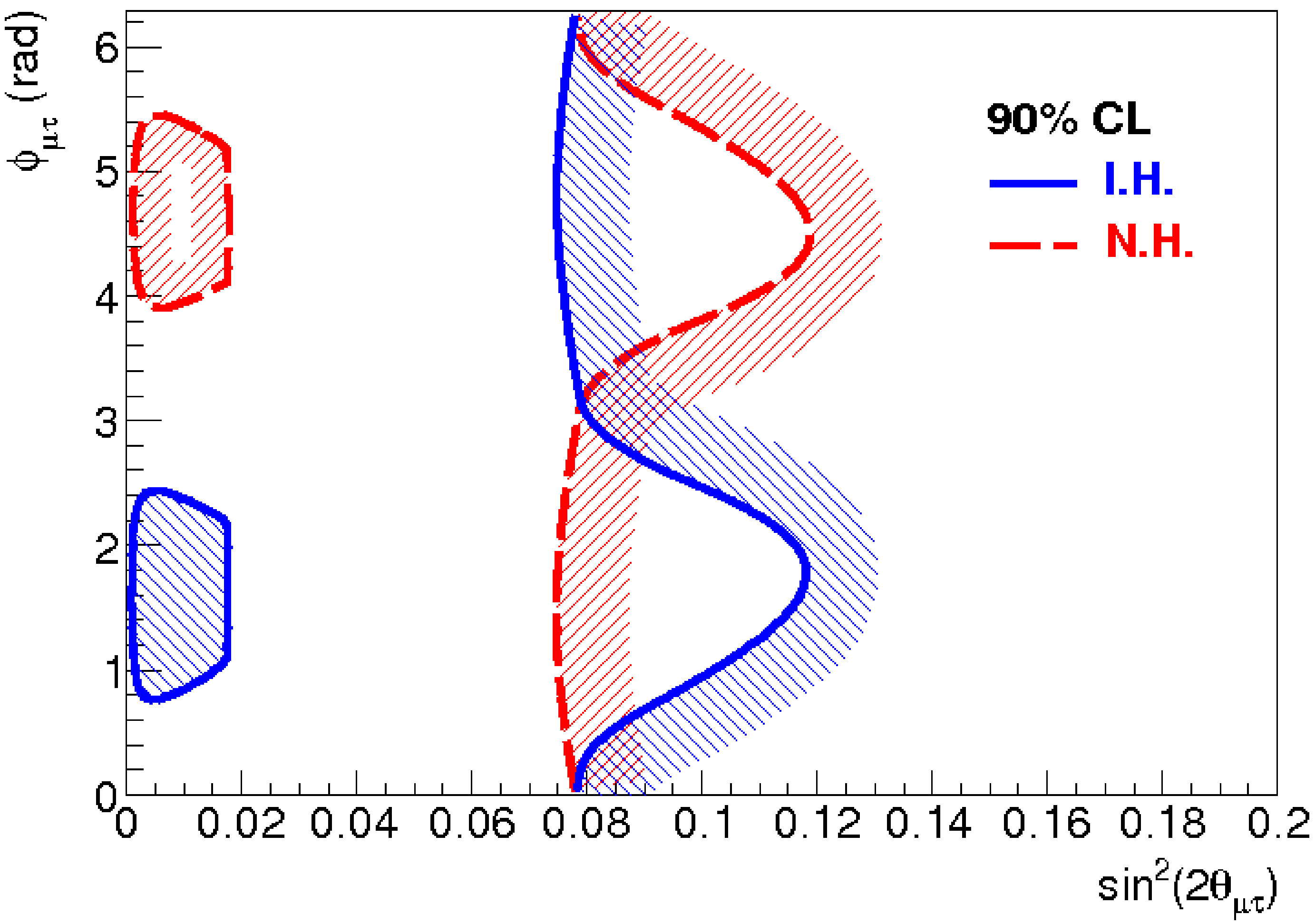
τ Cross-section

Efficiency

Many thanks to Giuliana for support with cross sections and efficiencies.

High Δm^2_{41} analysis.

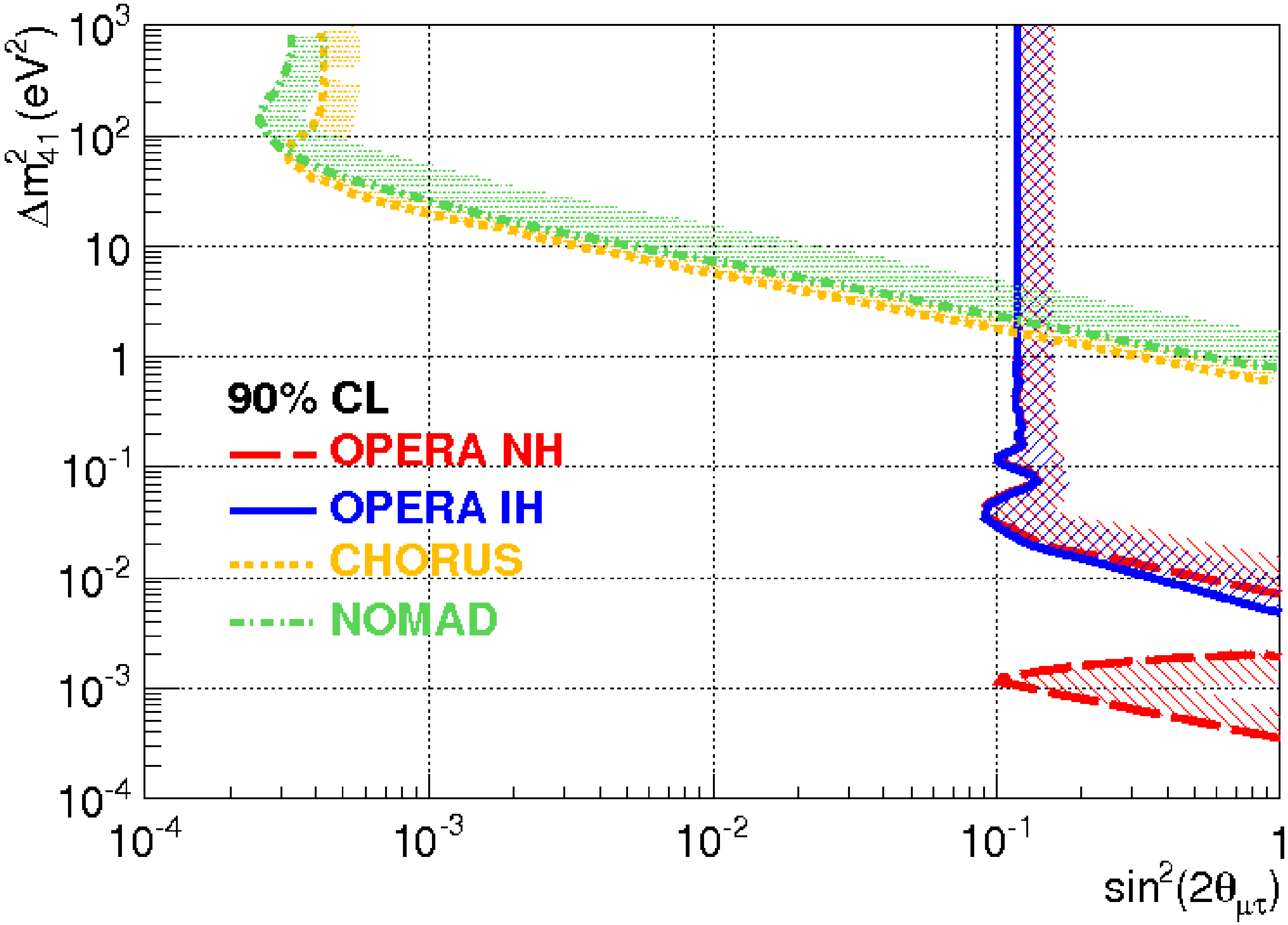
Profile likelihood: for every (δ,$\sin^2(2\theta_{\mu\tau})$) minimize χ^2 wrt to C between 0 and 1.



5 τ analysis, from OPERA note n.180 (September 2015)

Δm^2_{41} vs $\sin^2(2\theta_{\mu\tau})$ analysis.

Profile likelihood: for every ($\Delta\mu 241$, $\sin^2(2\theta_{\mu\tau})$) minimize χ^2 wrt to C and ϕ.



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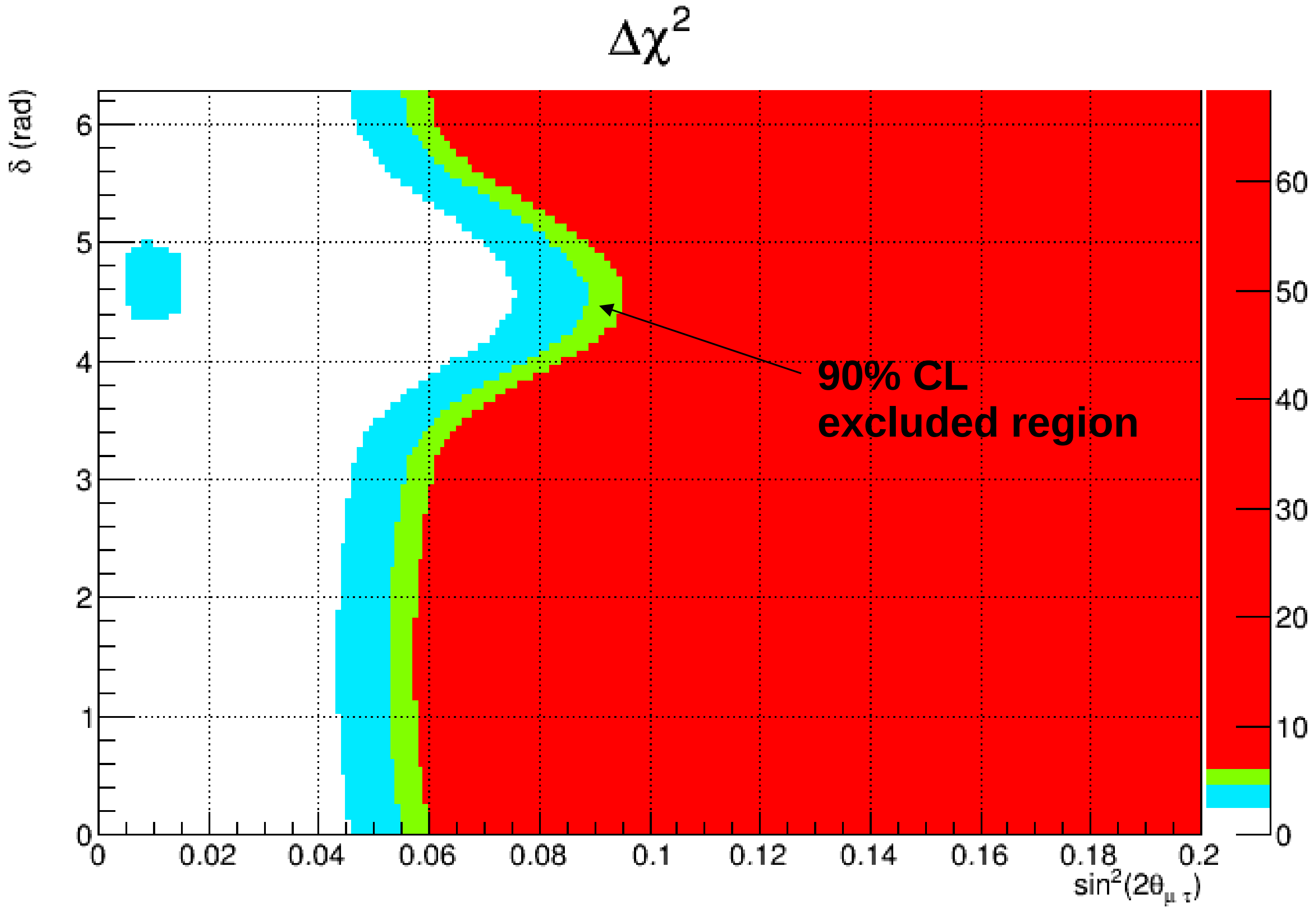
NH

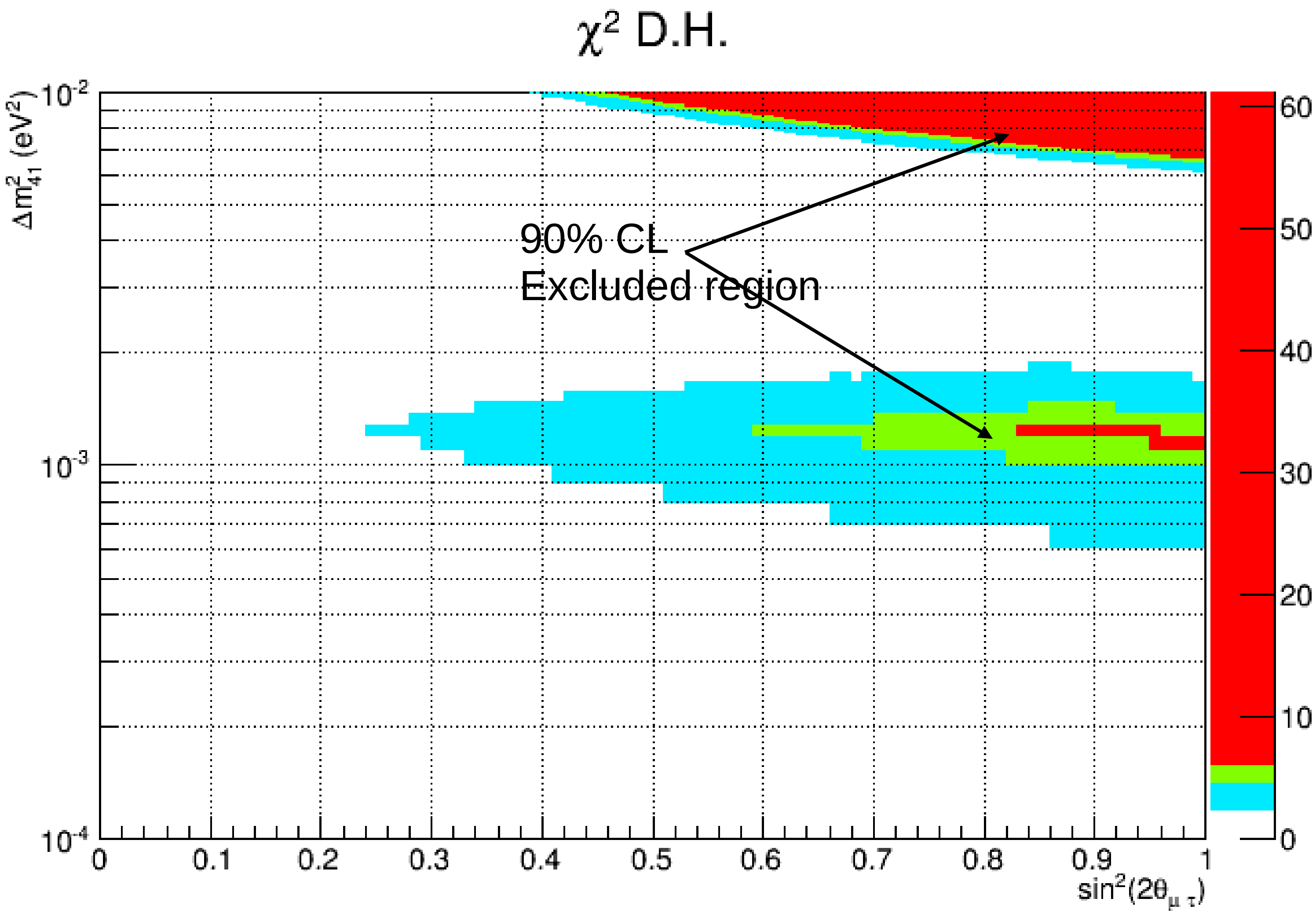


10 τ analysis, preliminar

Δm^2_{41} vs $\sin^2(2\theta_{\mu\tau})$ analysis.

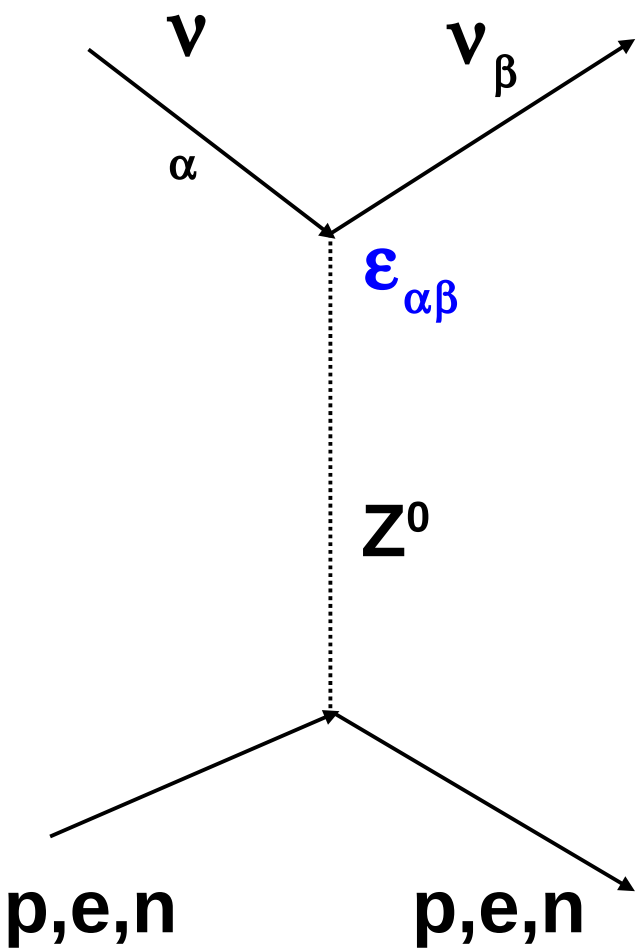
Profile likelihood: for every ($\Delta\mu 241$, $\sin^2(2\theta_{\mu\tau})$) minimize χ^2 wrt to C and ϕ.

NH



10 τ analysis, preliminar

NSI Theory in a nut-shell



Z potential, V modified by $\varepsilon_{\alpha\beta}$.

$\varepsilon_{\alpha\beta}$ could be a complex number.

Oscillation probability (to the first order):

$P_{\alpha\beta} = | \sin 2\theta_{23} \ \Delta_{32} + V \varepsilon_{\alpha\beta} L |^2$

$\Delta_{32} = 1.27 \Delta m^2_{32} (eV^2) L(km) / E (GeV)$

τ counting $\rightarrow$ access to $\varepsilon_{\mu\tau}$.

MINOS results published.

Note: in principle NSI could be also in CC interactions, eg: $\nu_\mu \rightarrow \tau$

Limits of order of 10^{-2} on $\varepsilon^W_{\mu\tau}$ can be derived from CHORUS/NOMAD.

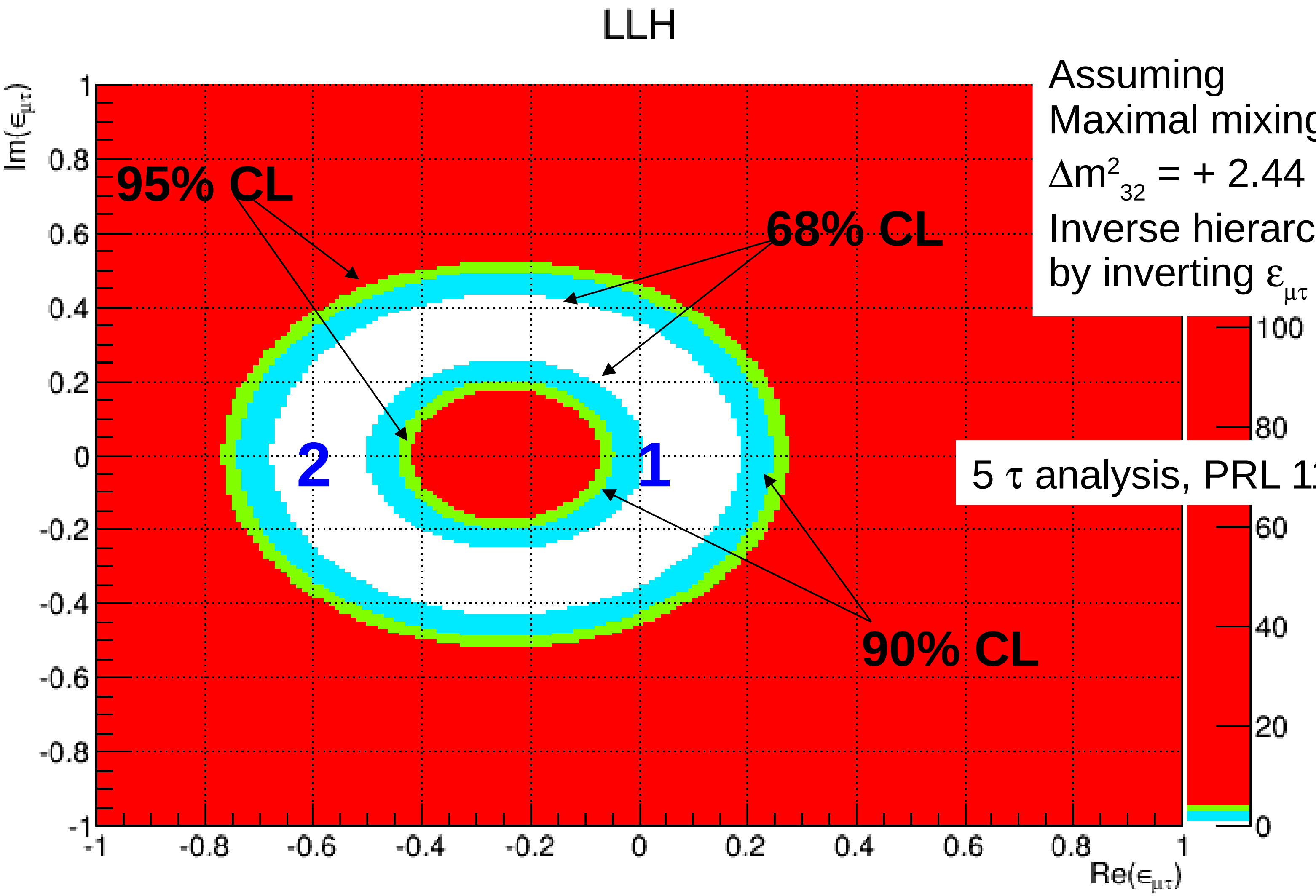
OPERA NSI analysis

Similar to sterile neutrino analysis.

τ counting.

Likelihood construction and global scan with 1 dof.

OPERA NSI results



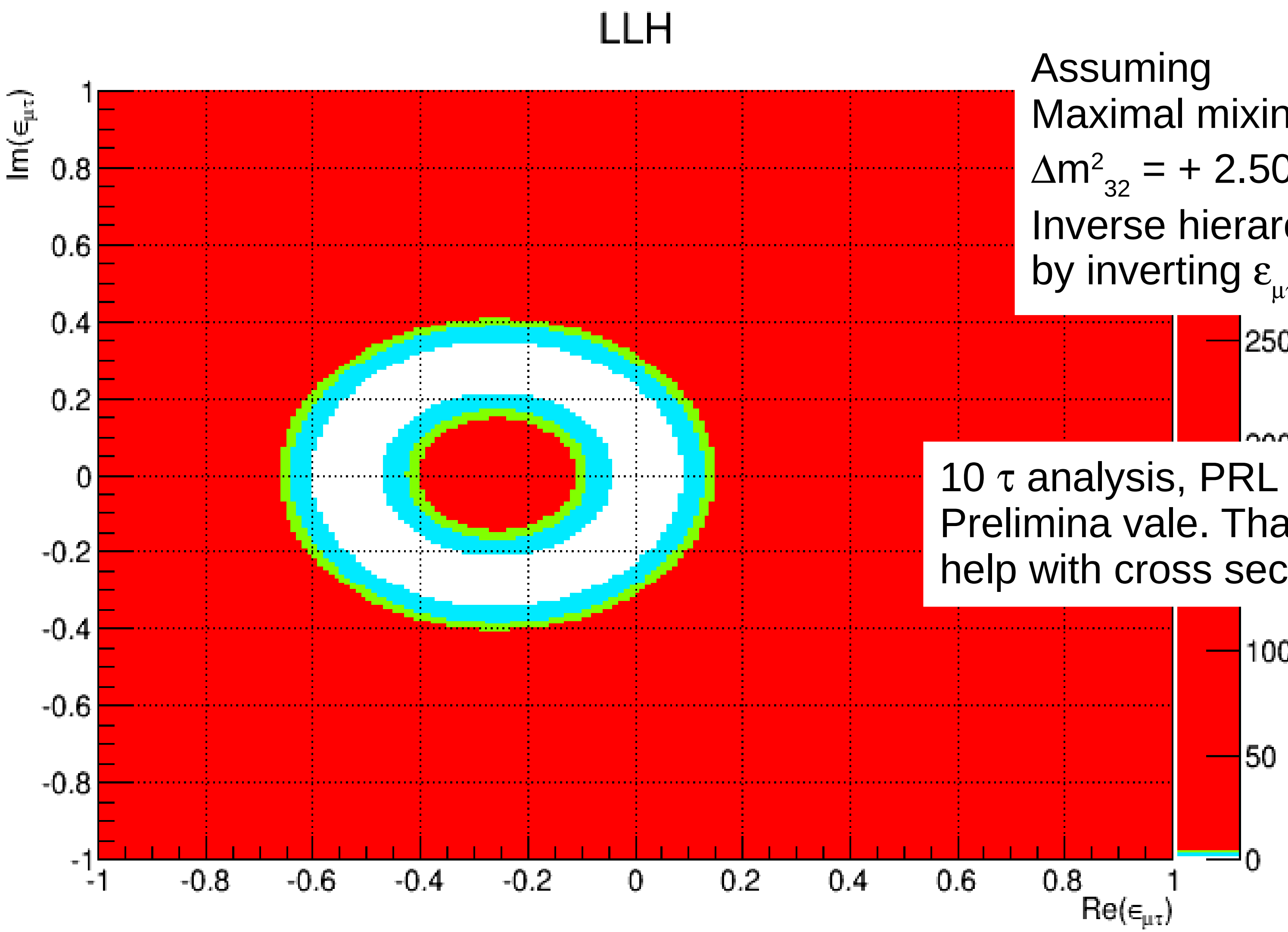
Assuming
Maximal mixing and
Δm^2_{32} = + 2.44 10^{-3} eV^2
Inverse hierarchy result obtained by inverting $\varepsilon_{\mu\tau} \rightarrow - \varepsilon_{\mu\tau}$

5 τ analysis, PRL 115, 121802 (2015)

Region 1: No NSI for $\varepsilon_{\mu\tau}$ = 0

Region 2: maximal NSI effect for $\varepsilon_{\mu\tau}$ = -2 sin2θ_{23} Δ_{32} / (VL)

OPERA NSI results



Assuming
Maximal mixing and
Δm^2_{32} = + 2.50 10^{-3} eV^2
Inverse hierarchy result obtained by inverting $\varepsilon_{\mu\tau} \rightarrow -\varepsilon_{\mu\tau}$

10 τ analysis, PRL 120, 211801 (2018)
Prelimina vale. Thanks to Giuliana for her help with cross sections and efficiencies.

The 90% CL allowed region is shrinked.

Lorentz invariance violation (LIV) analysis

MINOS Phys.Rev.Lett.105:151601,2010

Slides from A. Longhin talk at OPERA General Meeting of 17th June 2015

A Search for Lorentz Invariance and CPT Violation with the MINOS Far Detector

$m_p \cong 10^{19}$ GeV. One promising category of Planck-scale signals is the violation of the Lorentz and CPT symmetries that are central to the SM and General Relativity. The Standard Model Extension (SME) is the comprehensive effective field theory that describes Lorentz (LV) and CPT violation (CPTV) at attainable energies [3].

The SME predicts behaviors for neutrino flavor change that are different from conventional neutrino oscillation theory. The probability of flavor change in the SME depends on combinations of L, the distance traveled by the neutrino, and the product of distance and the neutrino energy, $L \times E_\nu$. For conventional oscillation theory the transition probability depends only on L/E_ν. The SME also predicts that the neutrino flavor change probability depends on the angle between the direction of the neutrino and the LV/CPTV field in the sun-centered inertial frame in which the SME is formulated [4]. Ex-

Advantage wrt MINOS: E (3 → 17), Same L

Lorentz violation analysis

MINOS Phys.Rev.Lett.105:151601,2010

Slides from A. Longhin talk at OPERA General Meeting of 17th June 2015

A Search for Lorentz Invariance and CPT Violation with the MINOS Far Detector

Additive term to standard oscillation probability:

$$P^{(1)}_{\mu\tau} = 2L\Big\{(P^{(1)}_{\mathcal{C}})_{\tau\mu} + (P^{(1)}_{\mathcal{A}_s})_{\tau\mu}\sin\omega_\oplus T_\oplus + (P^{(1)}_{\mathcal{A}_c})_{\tau\mu}\cos\omega_\oplus T_\oplus + (P^{(1)}_{\mathcal{B}_s})_{\tau\mu}\sin 2\omega_\oplus T_\oplus + (P^{(1)}_{\mathcal{B}_c})_{\tau\mu}\cos 2\omega_\oplus T_\oplus\Big\}$$

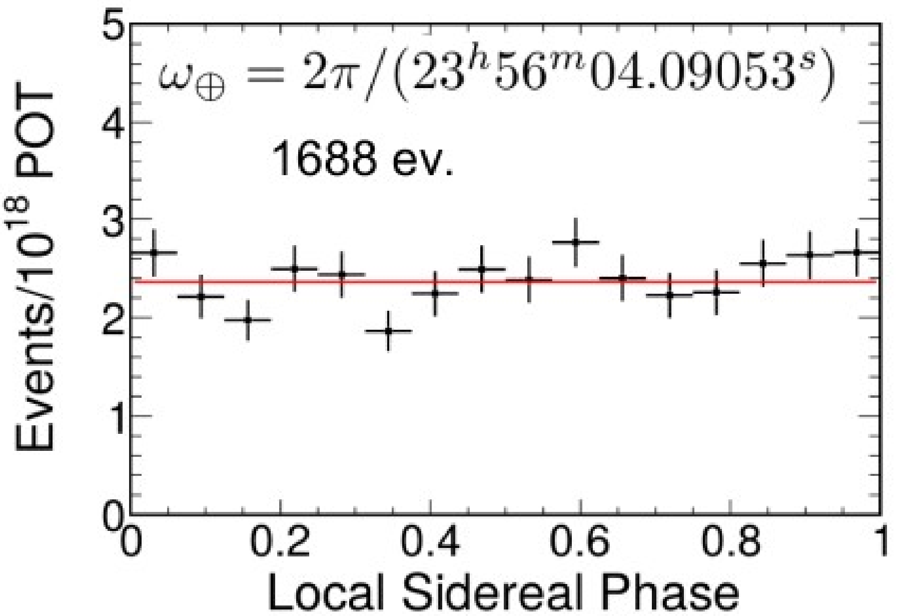


TABLE III: 99.7% C.L. limits on SME coefficients for $\nu_\mu \to \nu_\tau$; $(a_L)^\alpha_{\mu\tau}$ have units [GeV]; $(c_L)^{\alpha\beta}_{\mu\tau}$ are unitless. The columns labeled $\mathcal{I}$ show the improvement from the near detector limits.

Coeff.	Limit	$\mathcal{I}$	Coeff.	Limit	$\mathcal{I}$
$(a_L)^X_{\mu\tau}$	5.9×10^{-23}	510	$(a_L)^Y_{\mu\tau}$	6.1×10^{-23}	490
$(c_L)^{TX}_{\mu\tau}$	0.5×10^{-23}	20	$(c_L)^{TY}_{\mu\tau}$	0.5×10^{-23}	20
$(c_L)^{XX}_{\mu\tau}$	2.5×10^{-23}	220	$(c_L)^{YY}_{\mu\tau}$	2.4×10^{-23}	230
$(c_L)^{XY}_{\mu\tau}$	1.2×10^{-23}	230	$(c_L)^{YZ}_{\mu\tau}$	0.7×10^{-23}	170
$(c_L)^{XZ}_{\mu\tau}$	0.7×10^{-23}	190	–	–	–

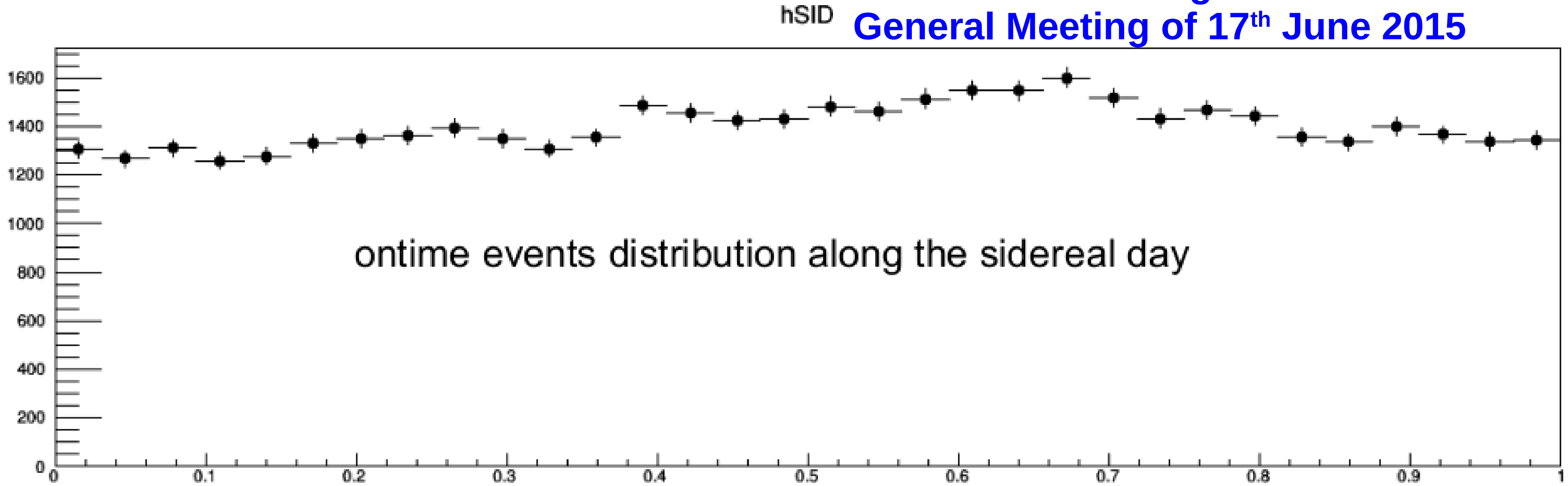
MINOS anti-nu ND analysis:

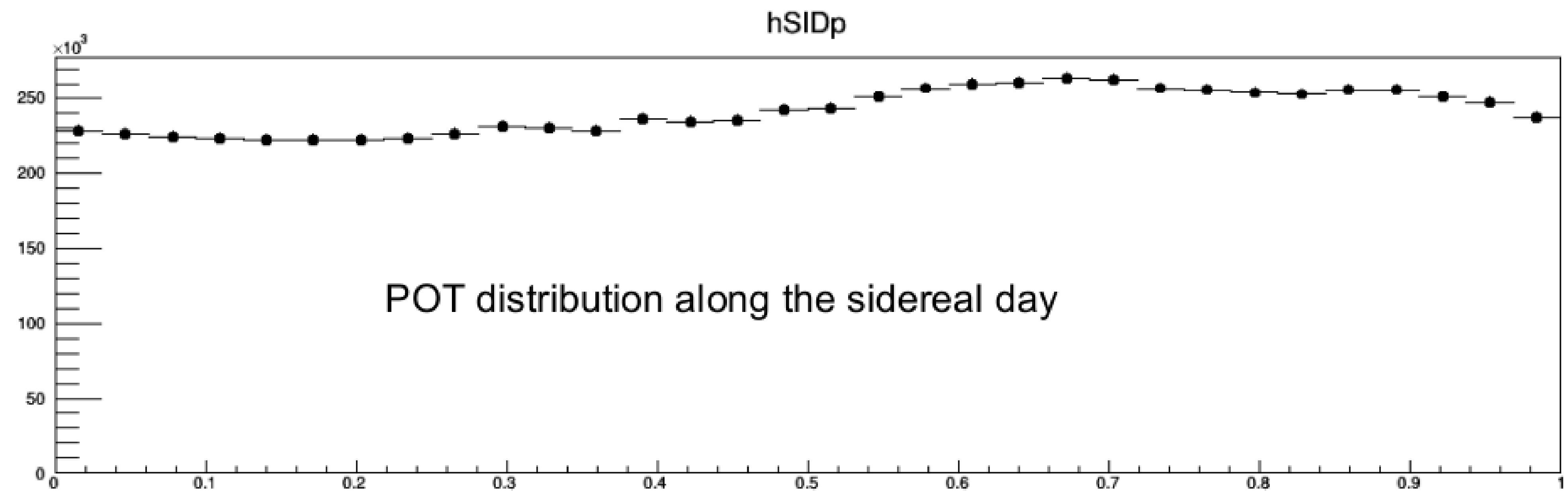
Phys.Rev. D85 (2012) 031101

OPERA sidereal time distributions

Selection: ontime events (including rock muons)

Slides from A. Longhin talk at OPERA General Meeting of 17th June 2015





OPERA sidereal time distributions

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