Systematic Uncertainties of the NOvA Neutrino Oscillation Analysis

40th International Conference on High Energy Physics
Czech Republic, Prague

Tomas Nosek (for the NOvA Collaboration)

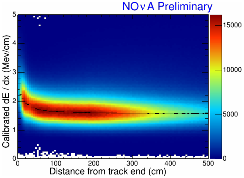
Charles University, Institute of Particle and Nuclear Physics

July 31, 2020

Sources of considered systematic uncertainties

Significant sources

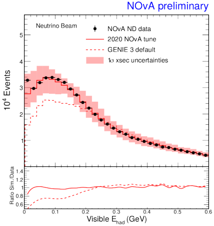
Detector calibration



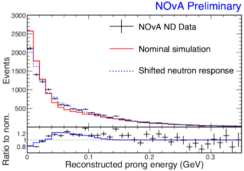
- Estimated from data/MC discrepancies in dE/dx of different particles (μ and p most importantly), up to 5%
- NOvA's test beam might address and help to reduce these uncertainties

Neutrino cross sections

- GENIE (v3.0.6, model configuration N1810k0211a) with specific NOvA tune to Near Detector data
- Uncertainties derived from estimates of NOvA model parameters for individual interaction types



Neutron uncertainty

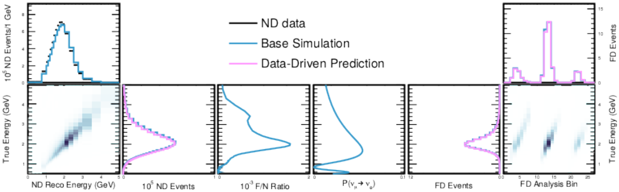


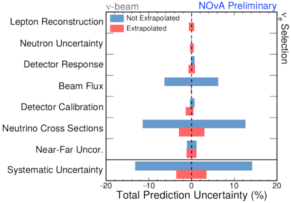
- Motivated by an observed data/MC disagreement in low energy n clusters
- 1% in $\bar{\nu}_\mu$ reconstructed energy

Other sources

- **Detector response:** light yield and cherenkov/scintillation light yield ratio, detector aging (time stability)
- **Beam flux:** hadron production constrained from external NA49 and MIPP data, beam focusing (target position etc.)
- **Lepton reconstruction:** μ energy scale (track length) and lepton angle
- **Near-Far uncorrelated:** rock (uncontained) events scale, cosmic scale, exposure counting, detector mass, detectors acceptance, Michel e identification, Near Detector data/MC selection efficiency differences

Reducing detector correlated uncertainties





- Generating nominal and systematically shifted predictions through NOvA standard Near/Far extrapolation technique:

$$\text{FD prediction} = \frac{\text{ND data corrected MC}}{\text{ND uncorrected MC}} \times \text{FD MC}$$

- Shifted predictions are generated by (depending on the implementation):

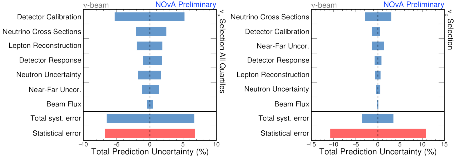
1. Weighting MC with respect to the event type, or
2. Adjusting the simulated variables, or
3. Creating a new simulated samples (detector calibration, cherenkov and light yield)

- This significantly reduces detector correlated uncertainties (especially for ν_e analysis samples)
- Beam flux and smaller neutrino cross section uncertainties are additionally treated with principal component analysis of an ensemble of randomly generated shifted predictions in energy bins of Near and Near/Far basis
- This helps to account for bin-bin correlations and to identify the largest components in order to reduce systematic nuisance included in the fit (computation time)

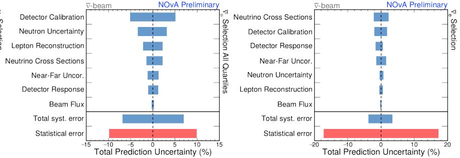
Systematic uncertainties in oscillation analysis

Far detector prediction uncertainties

ν-mode



$\bar{\nu}$-mode

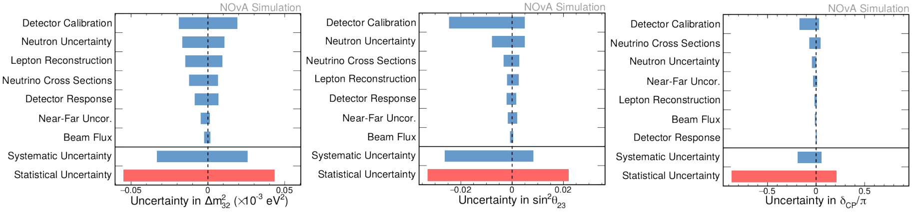


- Uncertainties are determined separately for all analysis samples $\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$
- With current analysis techniques ν_μ's ($|\Delta m^2_{32}|$, $\sin^2 2\theta_{23}$) systematic and statistical uncertainties are comparable

  ν_e samples are governed by statistic uncertainties

Uncertainties on neutrino oscillation parameters

NOvA joint fit best-fit point: Normal Ordering, $\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}$ eV^2, $\sin^2\theta_{23} = 0.57^{+0.03}_{-0.04}$, $\delta_{\mathrm{CP}} = 0.82\pi$



- In current status, further reduction of systematic uncertainties is important for precise determination of $\sin^2\theta_{23}$, whereas precision on δ_{CP} is limited by statistics and potential degeneracies in parametric space (normal and inverted ordering and $\sin^2\theta_{23} >$ or < 0.5)

CPT violation sensitivity of NOvA, T2K and INO experiments using neutrino and antineutrino oscillation parameters

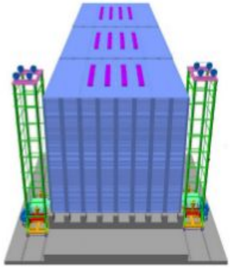
Daljeet Kaur
SGTB Khalsa college, University of Delhi, India
Email id: daljeet.kaur97@gmail.com

ICHEP 2020 | PRAGUE
40th INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS
VIRTUAL CONFERENCE
28 JULY - 6 AUGUST 2020
PRAGUE, CZECH REPUBLIC

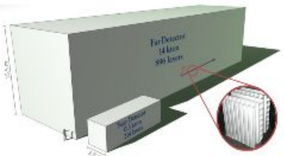
1. INTRODUCTION

- Charge-Parity-Time (CPT) symmetry → identical oscillation parameters for ν and $\bar{\nu}$
- If different mass and mixing parameters for ν and $\bar{\nu}$ → possible hint for CPT violation (Model-independent approach)
- Our focus to find sensitivity for $(\Delta m^2_{32} - \Delta \bar{m}^2_{32})$ and $(\sin^2\theta_{23} - \sin^2\bar{\theta}_{23})$ using long-baseline and atmospheric neutrino experiments in different possible combinations of octant for neutrinos and anti-neutrinos
- We show the joint sensitivity of the T2K, NOvA and INO experiments to such CPT violating observables

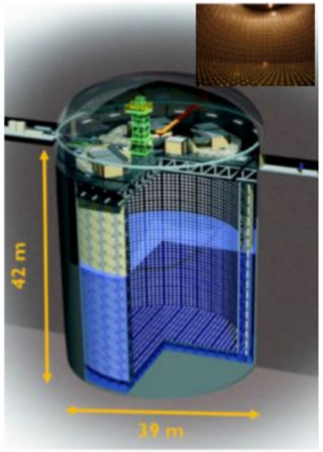
2. EXPERIMENTS



Iron-Calorimeter(ICAL)-Atmospheric neutrino experiment, Location: Tamilnadu, India



The NOvA (NuMi off-axis ν_e appearance), long-baseline neutrino experiment, Location: Ash River, Minnesota



The T2K (Tokai to Kamioka), long baseline, Location: Tokai, Japan

3. OSCILLATION PARAMETERS

Osc. parameters	True values	Marginalization range
$\sin^2(2\theta_{12})$	0.86	Fixed
Δm^2_{21} (eV^2)	7.6×10^{-5}	Fixed
$\sin^2(\theta_{13})$	0.0234	Fixed
$\sin^2(\theta_{23})$	varied	0.3-0.7
$\lvert\Delta m^2_{32}\rvert$ (eV^2)	varied	$(2.0\text{-}3.0)\times 10^{-3}$
δ_{CP}	0.0	Fixed (INO)
δ_{CP}	0.0	$[0-360^o]$ (T2K,NOvA)

Table: Oscillation parameters for both ν and $\bar{\nu}$.

Possible combinations of octants for ν and $\bar{\nu}$:

Case 1: ν and $\bar{\nu}$ both in Higher Octant (HO) $[\sin^2\theta_{23}(\sin^2\bar{\theta}_{23})$ in range 0.5-0.7]

Case 2: ν and $\bar{\nu}$ both in Lower Octant (LO) $[\sin^2\theta_{23}(\sin^2\bar{\theta}_{23})$ in range 0.3-0.5]

Case 3: ν in HO and $\bar{\nu}$ in LO

Case 4: ν in LO and $\bar{\nu}$ in HO

→ The experimental sensitivities for all the octants cases have been shown on a single frame with allowed regions at 1σ,2σ and 3σ Confidence Level (CL) under Normal-Hierarchy assumption.

4. SIMULATION INPUTS

Features	**INO**
Source	Atmospheric neutrino
Runtime	10 years for ν_μ and $\bar{\nu}_\mu$
Detector	50kton Iron Calorimeter
Charge-id eff.	$\sim$ 99% for μ^- and μ^+
Direction eff.	1 degree (few GeV muons)
Features	**NOvA**
Baseline	810 km
Run time	3 year ν and 3 year $\bar{\nu}$
Detector	14 kton
Signal eff.	26%(ν_e), 41% ($\bar{\nu}_e$),100% (ν_μ, $\bar{\nu}_\mu$ CC)
Background eff	as in Ref. [1]
Features	**T2K**
Baseline	295 km
Run time	5 year ν and 5year $\bar{\nu}$
Detector	22.5 kton
Signal eff.	87% (ν_e,$\bar{\nu}_e$), 100%(ν_μ, $\bar{\nu}_\mu$CC)
Background eff.	as in Ref. [1]

→ Systematics used in analysis as given in Ref [1]

→ GLoBES [2] simulation toolkit for long-baseline experiments and a c++ based based code for atmospheric ν experiment.

5. METHODOLOGY

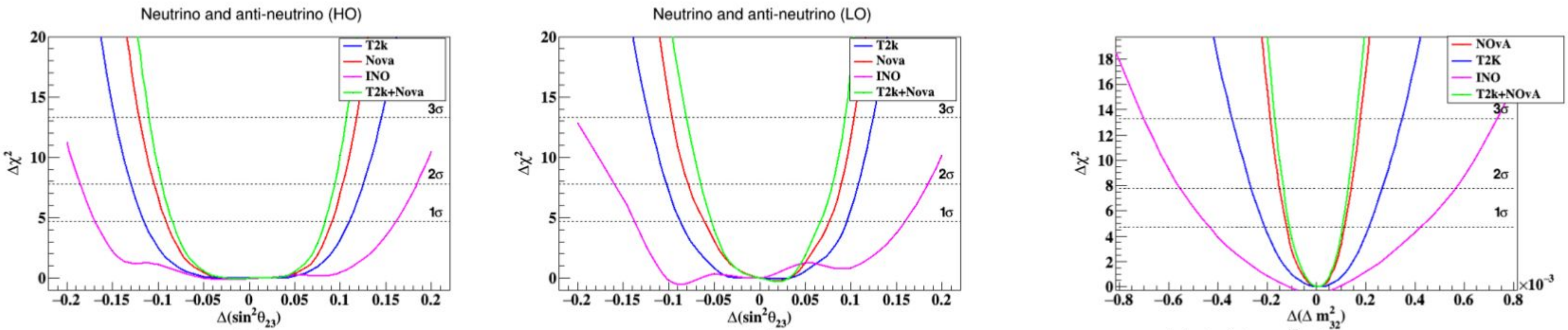
- Identical oscillation parameters for ν and $\bar{\nu}$ have been considered as null hypothesis(i.e. $[\Delta(\Delta m^2_{32}) = (\Delta m^2_{32} - \Delta\bar{m}^2{}_{32}) = 0]$, and $[\Delta\sin^2\theta_{23} = (\sin^2\theta_{23} - \sin^2\bar{\theta}_{23}) = 0]$)
- To rule out the null hypothesis, true values of neutrino and anti-neutrino oscillation parameters (Δm^2_{32}, $\sin^2\theta_{23}$, $\Delta\bar{m}^2_{32}$, $\sin^2\bar{\theta}_{23}$) have been varied within marginalisation range and generated true datasets
- A four dimensional grid search is performed for the predicted dataset. χ^2 is calculated between the true datasets and predicted datasets for each set of true values of oscillation parameters
- For each set of difference $\Delta(\Delta m^2_{32})$ or $\Delta\sin^2\theta_{23}$, we calculate $\Delta\chi^2 = \chi^2 - \chi^2_{min}$ including marginalisation and plot it as the functions of desired set of differences

REFERENCES

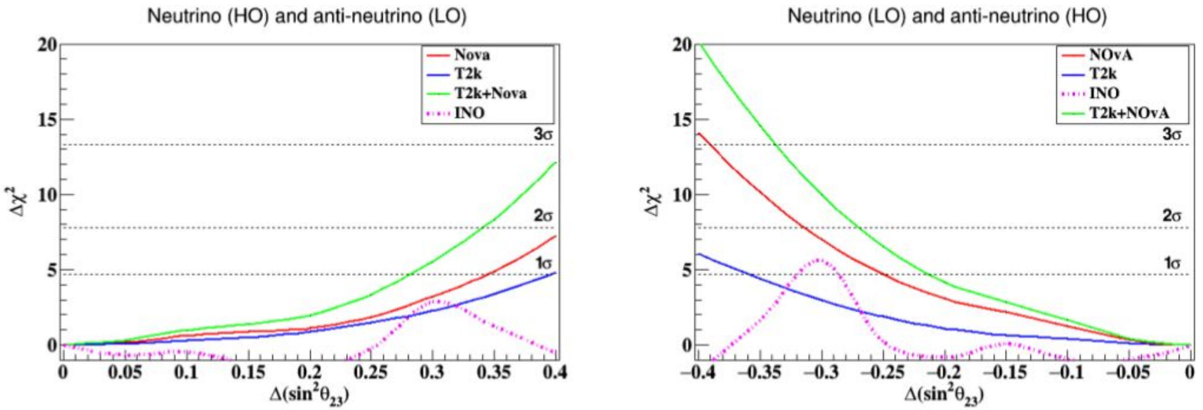
[1] Phys.Rev.D 101 (2020) 5, 5. DOI: 10.1103/PhysRevD.101.055017
[2] P. Huber et al., Comput. Phys. Commun. 167, 195 (2005)

Email id: daljeet.kaur97@gmail.com

6. RESULTS



(a) (b) (e)$\Delta(\Delta m^2_{32})$ sensitivity



(c) (d)

$\lvert\Delta(\Delta m^2_{32})\rvert \times 10^{-3}eV^2$				
Osc.parameter	NOvA	T2K	INO	T2K+NOvA
$\lvert\Delta(\Delta m^2_{32})\rvert$	0.10	0.22	0.40	0.10
$\lvert\Delta\sin^2\theta_{23}\rvert$				
Octant Case 1	0.1	0.13	0.16	0.07
Octant Case 2	0.08	0.12	0.17	0.09
Octant Case 3	0.34	0.4	$<1\sigma$	0.28
Octant Case 4	0.24	0.36	$<1\sigma$	0.21

f) 1σ sensitivity

Joint sensitivity of NOvA, T2K, INO for $\Delta\sin^2\theta_{23}$ when (a) ν and $\bar{\nu}$ in HO, (b) ν and $\bar{\nu}$ in LO, (c) ν in HO and $\bar{\nu}$ in LO and (d) when ν in LO and $\bar{\nu}$ in HO and (e)for $\Delta(\Delta m^2_{32})eV^2$ which is almost same for all octants

- Measurement of $\Delta\sin^2\theta_{23}$ is largely affected by the existence of ν and $\bar{\nu}$ in particular octant
- All considered experiments are least sensitive for different octant combinations for neutrinos and anti-neutrinos
- For similar octant combinations (either LO or HO) for both ν and $\bar{\nu}$, Precise determination of $\Delta\sin^2\theta_{23}$ for all the experiments
- Each experiment is able to measure $\Delta(\Delta m^2_{32})$ quite significantly irrespective of different octant combinations

Conclusions

- Each experiment is able to measure $\Delta(\Delta m^2_{32})$ quite significantly irrespective of different octant combinations
- But, measurement of $\Delta \sin^2\theta_{23}$ is largely affected by the existence of ν and $\bar{\nu}$ in particular octant
- For similar octant combinations (either LO or HO) for both ν and $\bar{\nu}$, Precise determination of $\Delta \sin^2\theta_{23}$ for all the experiments
- All considered experiments are least sensitive, if neutrinos and anti-neutrinos lie in different octant combinations.
- **With the proposed fiducial volume and run time, the NOvA detector found the best among all the considered experiments for constraining $\Delta(\Delta m^2_{32})$ and $\Delta \sin^2\theta_{23}$**
- NOvA+T2k joint results enhances the sensitivities for $\Delta \sin^2\theta_{23}$ if the ν and $\bar{\nu}$ are in different octants. The present CPT bounds at 1σ confidence interval are shown in Table(f)

This work has been published in: **Phys.Rev.D 101 (2020) 5, 5. DOI: 10.1103/PhysRevD.101.055017**

THANK YOU!!

Funded by the Horizon 2020
Framework Programme of the
European Union

Updates on the ESSνSB Target Station potentialities for CP violation discovery

Julie Thomas, IPHC, Université de Strasbourg,
CNRS/IN2P3, 67037 Strasbourg, France.

On behalf of the ESSνSB Collaboration

The ESSνSB project [1]

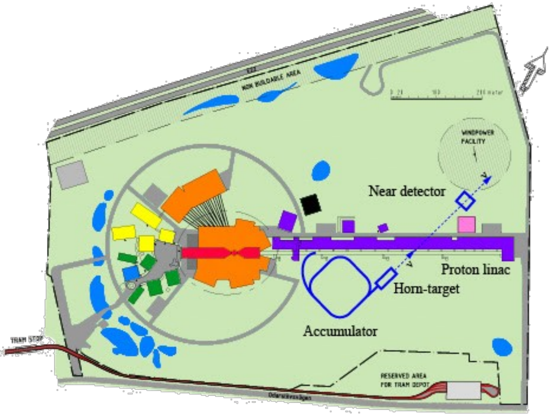


Fig. 1 : ESSνSB site in Lund

CP violation in leptonic sector is a candidate to explain the asymmetry between matter and anti-matter observed in the Universe : $P(\nu_i \rightarrow \nu_j) \neq P(\bar{\nu}_i \rightarrow \bar{\nu}_j)$.

The ESS Neutrino Super Beam project proposes to use the linac of ESS[2] to produce a high-intensity and low-energy neutrino beam.

Facility parameters	
Proton beam kinetic energy (GeV)	2.5
Total beam power (MW)	5
Beam intensity (ppp)	8.9×10^{14}
Beam pulse duration Linac / accumulator (ms/μs)	2.86 / < 1.5
Pulse repetition rate (Hz)	14
Distance target station - detector (km)	540
FD fiducial volume (kt)	540

This combination of high intensity and low energy will allow to access the second maximum in the neutrino oscillation probability.

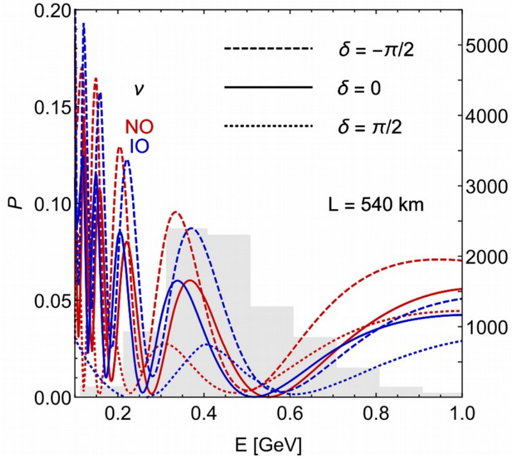
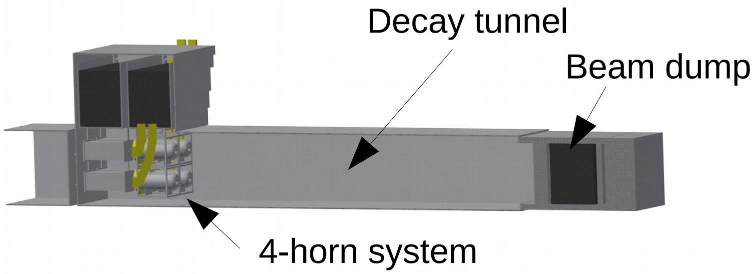


Fig. 2 : Oscillation probability as function of neutrino energy for different values of δ_{CP}[3]

References :
[1] https://essnusb.eu
[2] https://europeanspallationsource.se
[3] M. Blennow et al, Eur. Phys. J. **C 80** 190 (2020) [arXiv:1912.04309].

The Target Station



The target station is made of three major elements : the hadron collector, the decay tunnel and the beam dump.

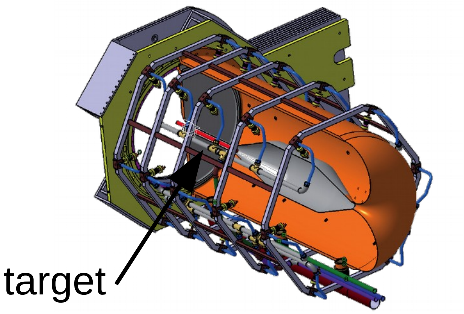


Fig. 3 : A magnetic horn[4][5]

Hadron collector complex :

- 4 magnetic horn-target systems,
- 350 kA pulsed current,
- 2 focusing modes,
- Packed-bed targets : 3 mm diameter titanium spheres, 78 cm long, 1.5 cm radius.

Decay tunnel : 25 m long

Beam dump : one-block graphite (4*4*3.2 m^3)

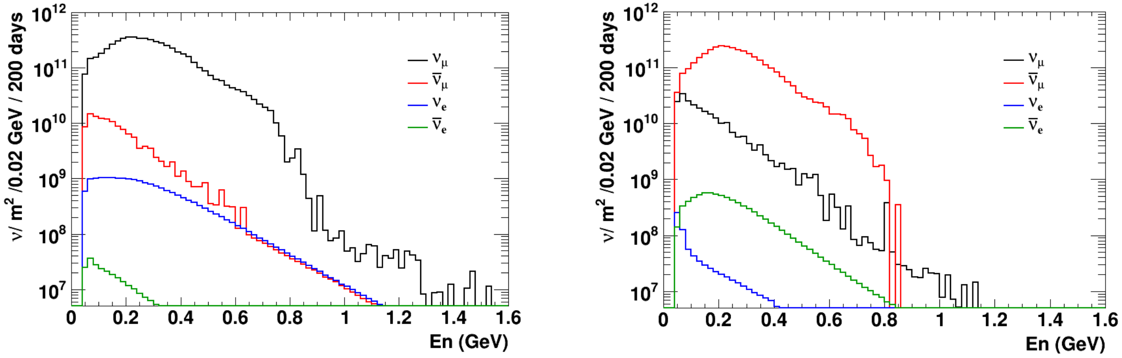


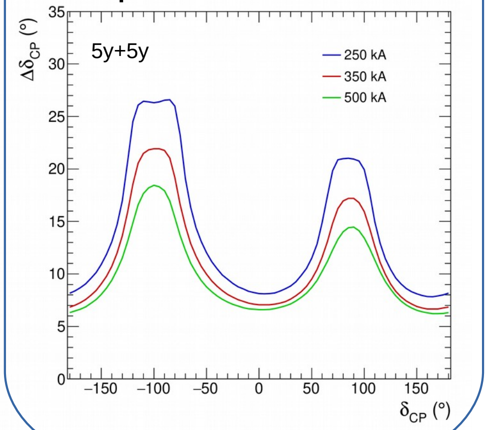
Fig. 4 : Neutrino fluxes as function of energy for a year of running time for positive and negative focusing respectively.[6]

References :
[4] T. R.Edgecock et al, Phys. Rev. ST Accel. Beams **16** (2013), 021002, [arXiv:1305.4067 [physics.acc-ph]].
[5] E.Baussan et al, Phys. Rev. ST Accel. Beams **17** (2014), 031001, [arXiv:1212.0732 [physics.acc-ph]]
[6] L. D'Alessi, PoS, NuFact2019:062, 2020.

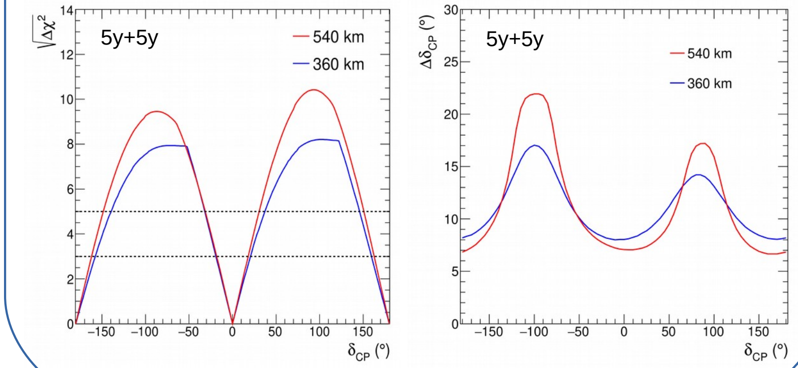
A parameter study for physics optimization

Different studies have been done at the level of the target station facility and the magnetic horns in order to improve the sensitivity of ESSνSB for the measurement of δ_{CP}. ν fluxes were generated with Geant4[7][8][9] and sensitivity plots obtained with GLoBES[10][11].

1. Influence of the current delivered to the horn on the performances.

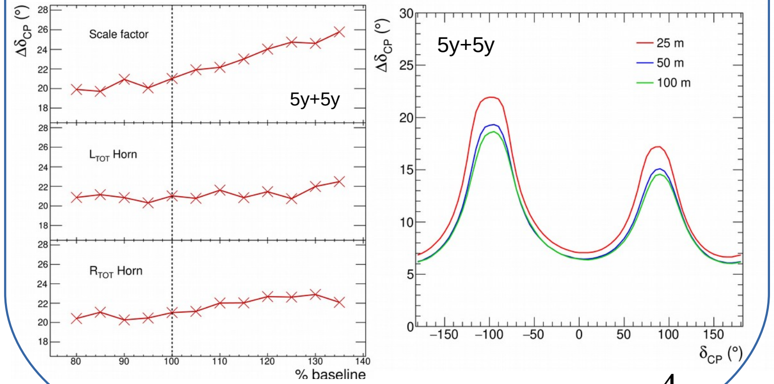


2. Influence of different baselines. There are two predominent choices : the mine of Garpenberg at 540 km and the mine of Zinkgruvan at 360 km.



3. A parametric study on the horn dimensions and the decay tunnel :

- Both total length and radius of the horn are modified (Scale Factor),
- Only the total length of the horn is modified (L_{TOT} Horn),
- Only the total radius of the horn is modified (R_{TOT} Horn).



References :

[7] S. Agostinelli et al, Nucl. Instrum. Methods A 506, 250-303 (2002) DOI:10.2172/799992

[8] S. Agostinelli et al, IEEE Trans. Nucl. Sci. 53, 70-278 (2006) DOI:10.1109/TNS.2006.869826

[9] J. Allison et al, Nucl. Instrum. Methods A 835, 186-225 (2016) DOI:10.1016/j.nima.2016.06.125

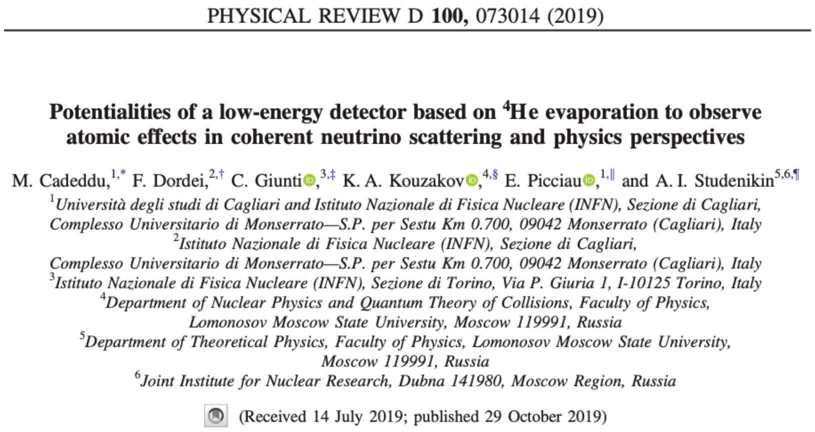
[10] P. Huber et al, Comput. Phys.Commun. **167** 195 (2005) [arXiv:hep-ph/0407333].

[11] P. Huber et al, Comput. Phys. Commun. **177** 432–438 (2007) [arXiv:hep-ph/0701187].

REVEALING NEW PROCESSES WITH SUPERFLUID LIQUID HELIUM DETECTORS: THE COHERENT ELASTIC NEUTRINO ATOM SCATTERING

Emmanuele Picciau

Università degli Studi di Cagliari
Istituto Nazionale di Fisica Nucleare (CA)



PHYSICAL REVIEW D **100,** 073014 (2019)

Potentialities of a low-energy detector based on ^{4}He evaporation to observe atomic effects in coherent neutrino scattering and physics perspectives

M. Cadeddu,[1,*] F. Dordei,[2,†] C. Giunti,[3,‡] K. A. Kouzakov,[4,§] E. Picciau,[1,∥] and A. I. Studenikin[5,6,¶]

[1] *Università degli studi di Cagliari and Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Cagliari, Complesso Universitario di Monserrato—S.P. per Sestu Km 0.700, 09042 Monserrato (Cagliari), Italy*
[2] *Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Cagliari, Complesso Universitario di Monserrato—S.P. per Sestu Km 0.700, 09042 Monserrato (Cagliari), Italy*
[3] *Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Torino, Via P. Giuria 1, I-10125 Torino, Italy*
[4] *Department of Nuclear Physics and Quantum Theory of Collisions, Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia*
[5] *Department of Theoretical Physics, Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia*
[6] *Joint Institute for Nuclear Research, Dubna 141980, Moscow Region, Russia*

(Received 14 July 2019; published 29 October 2019)

ICHEP: 31st July 2020, Virtual Conference, Prague, Czech Republic

COHERENT ELASTIC NEUTRINO ATOM SCATTERING

$$\nu + A \longrightarrow \nu + A$$

Kinematic condition:

$$|\,\vec{\mathbf{q}}\,| \cdot R_{\mathrm{atom}} \ll 1$$

$|\,\vec{\mathbf{q}}\,|$: 3-momentum transfer

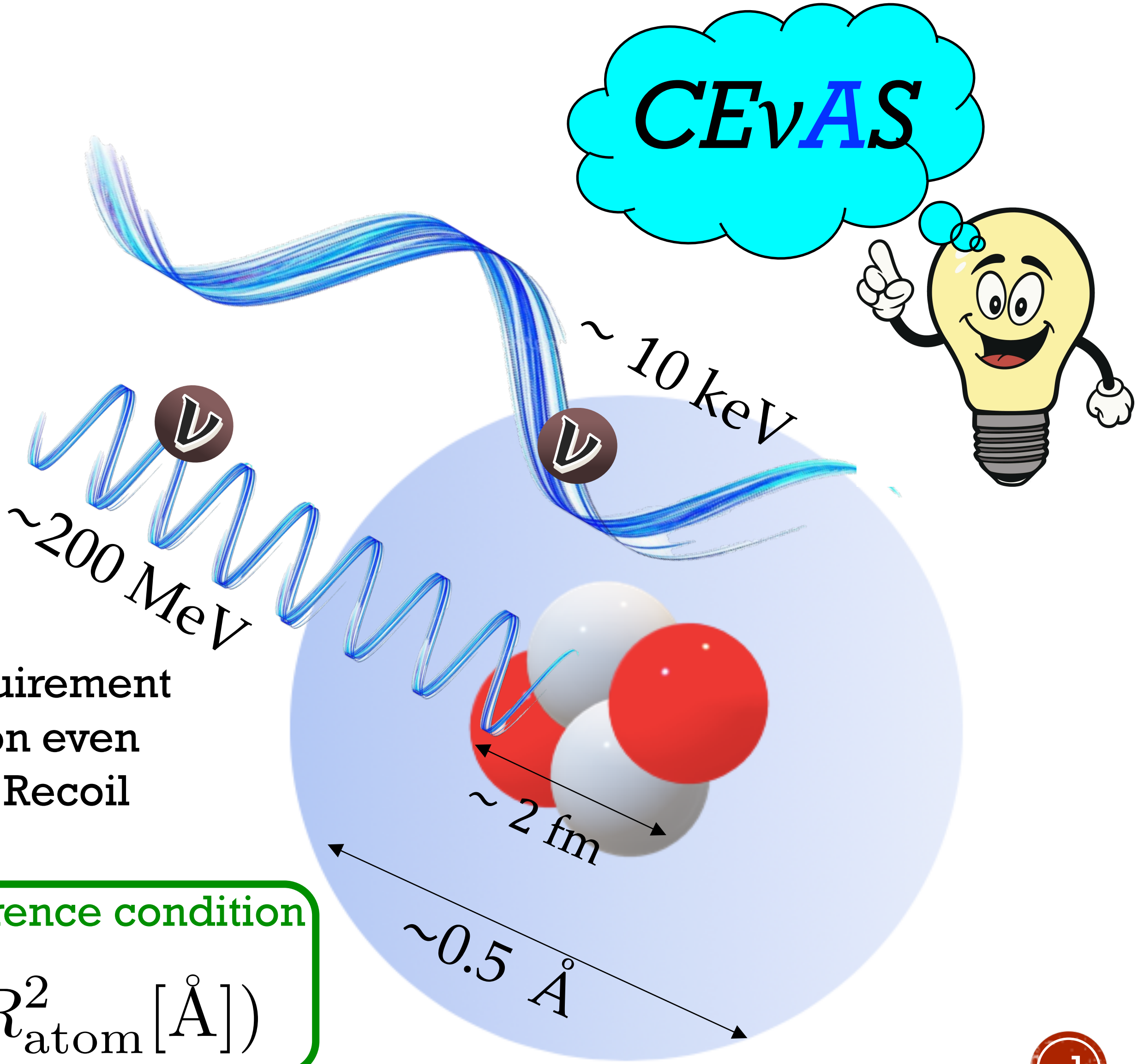
R_{atom} : atomic radius

The kinematic requirement makes the detection even more challenging! Recoil energies of **meV!**

$$|\,\vec{\mathbf{q}}\,| \cdot R_{\mathrm{atom}} \sim 1$$

Coherence condition

$$T_R \sim 2\ \mathrm{meV}/(A R^2_{\mathrm{atom}}[\text{Å}])$$



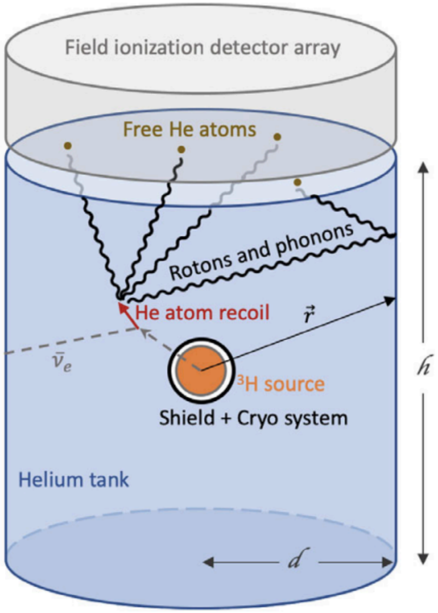
THE REAL QUESTION: IS THE PROCESS DETECTABLE NOWADAYS?

…or maybe in the future?

What do we need?

Shopping List

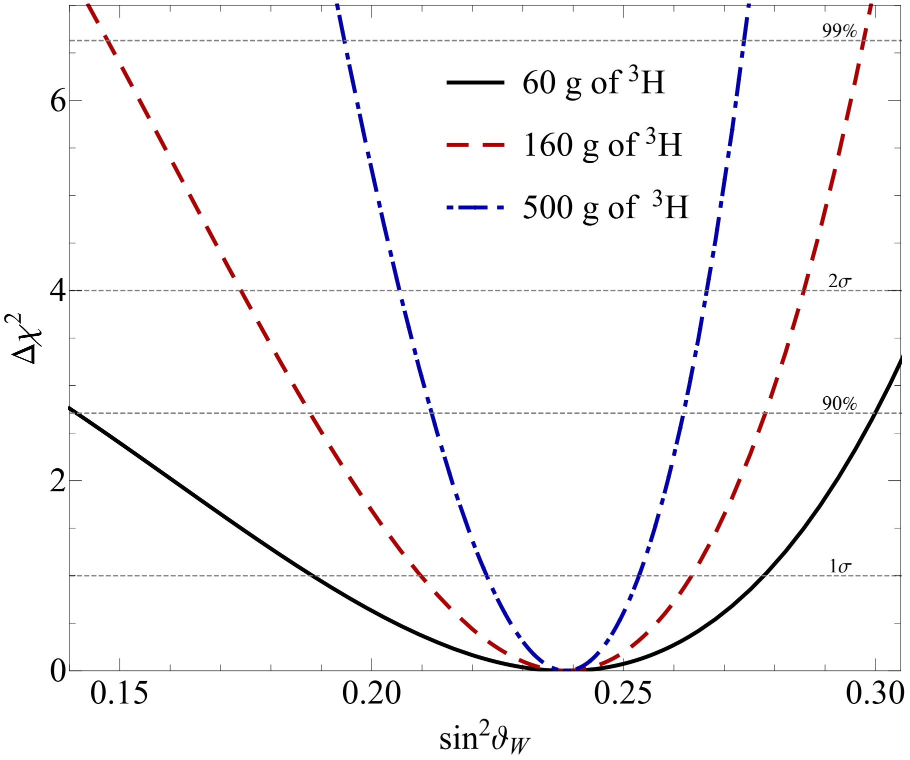
- *A* ***source*** *of low energy neutrinos to achieve the coherence with the whole atom:* *Tritium source*
- *A* ***target*** *with mass number and atomic radius as small as possible:* *Superfluid liquid helium*
- *A* ***detector****, based on the same target, with threshold to detect such a small energy releases:* *Helium evaporation*

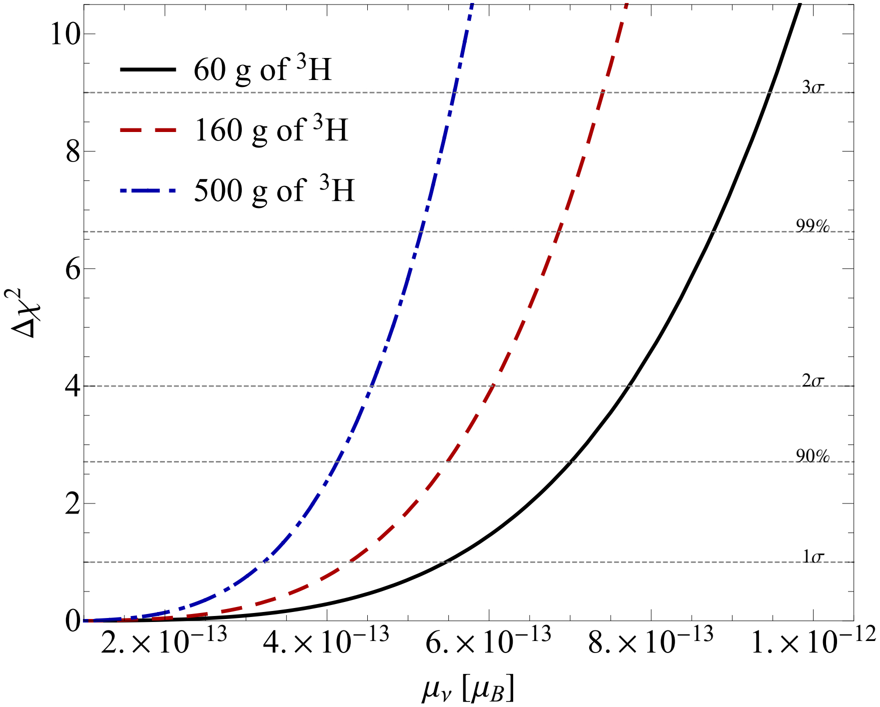


POSSIBLE MEASUREMENT EXPLOITING CEνAS

Weak Mixing Angle

…at energy scales never reached before



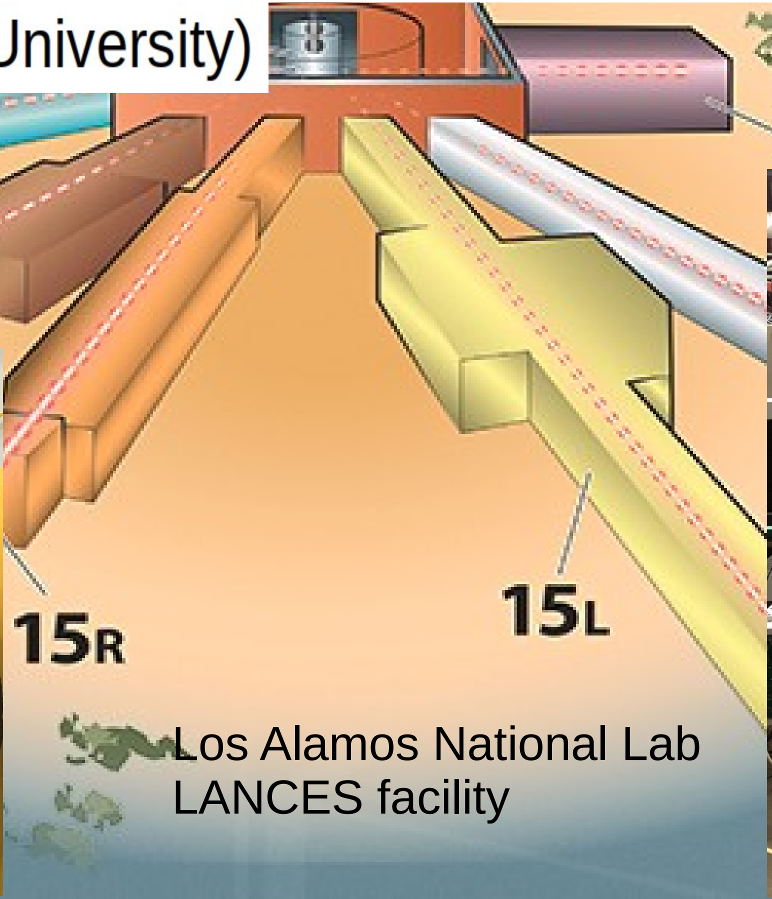


Neutrino Magnetic Moment

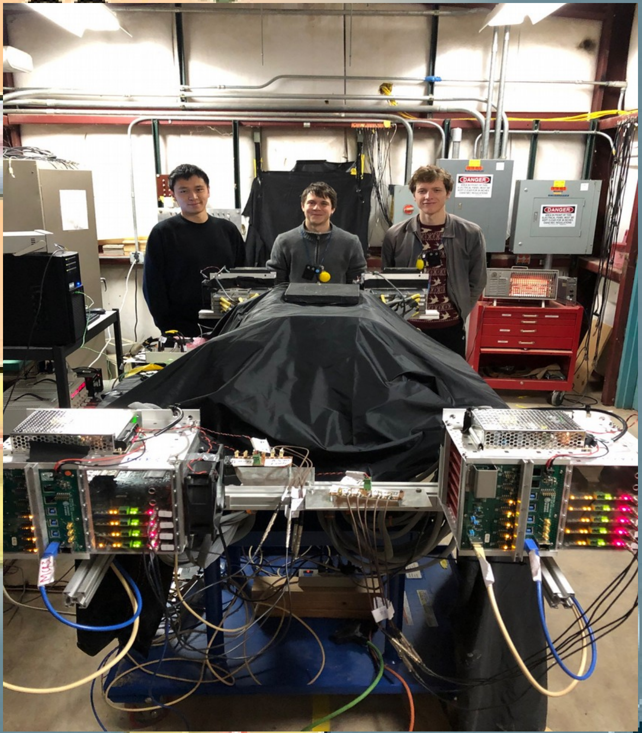
…2 order of magnitude lower than current experiments

Neutron Beam Test with 3D-Projection Scintillator Tracker Prototypes for Long-Baseline Neutrino Oscillation Experiments

Guang Yang (Stony Brook University)



Los Alamos National Lab
LANCES facility



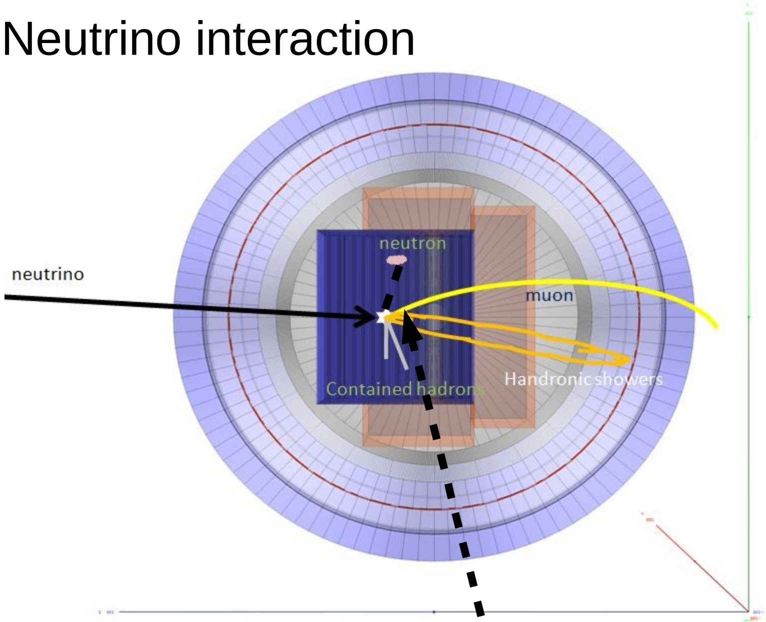
Motivation

- Missing neutron energy : one of the dominant systematic uncertainties in the long-baseline neutrino oscillation analyses

- In the precision era, neutrino interaction measurement including neutron information desired in the near detectors of the long-baseline experiments

- Neutron kinetic energy measurement enabled by the ToF technique with a low-threshold, fast-timing and fine-granularity 3D projection tracker

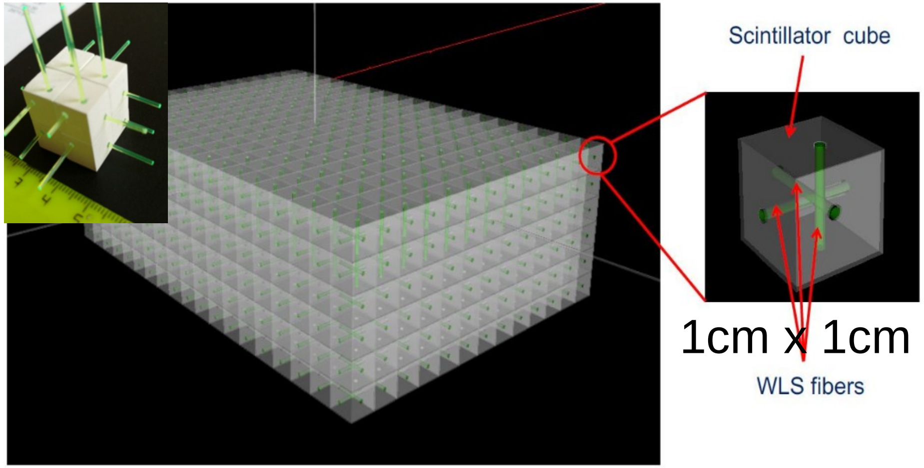
Neutrino interaction



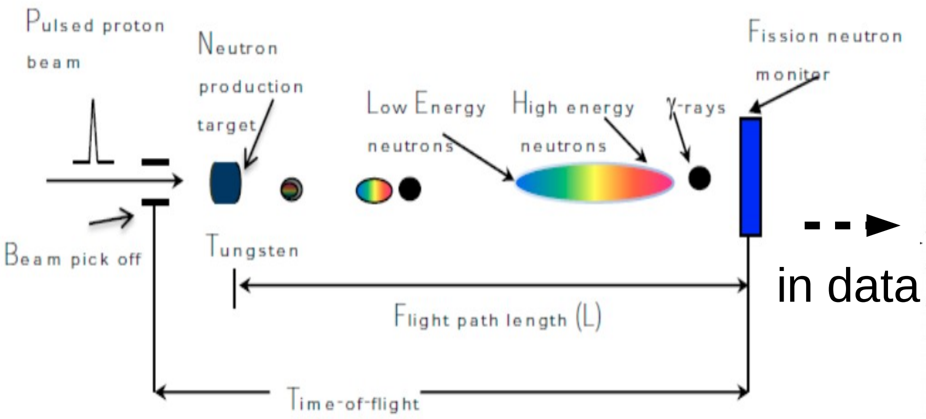
- Neutron kinetic energy can be obtained by measuring the neutron-induced hit distance and time

3D projection scintillator tracker

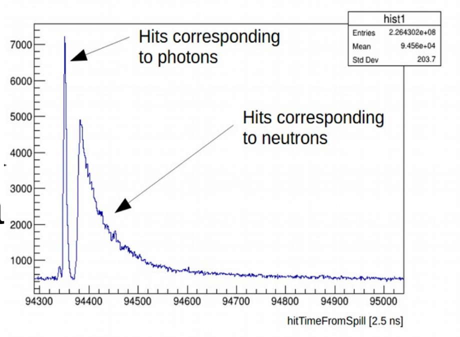
3 fiber light yield: > 100 pe
MIP time resolution ~0.5 ns



Beamline setup



in data



- We have two separate beamline time allocations at 90 m and 20 m locations from the proton target.

- A gamma flash (providing t0) comes before the neutron arrives, which allows a neutron energy measurement with the time-of-flight.

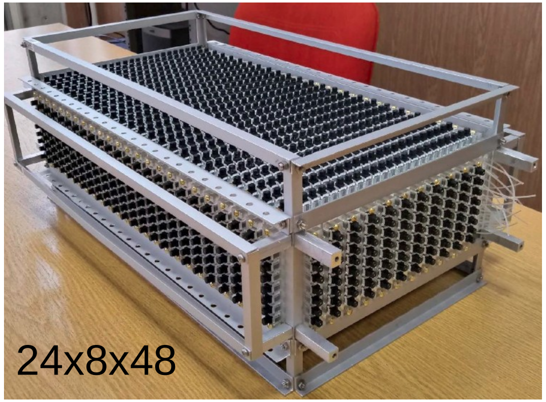
- Two prototypes were proposed and built by a collaboration and exposed to the beamline for a total time of 90 hours.

Collaborating institutions

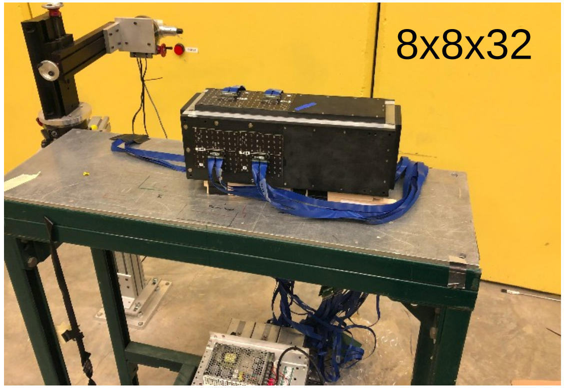
- CERN
- University of Geneva, Switzerland
- High Energy Accelerator Research Organization (KEK), Japan
- Institute for Nuclear Research (INR), Russia
- Imperial College, UK
- Louisiana State University, USA
- University of Pennsylvania, USA
- University of Pittsburgh, USA
- University of Rochester, USA
- Stony Brook University, USA
- University of Tokyo, Japan
- ETH Zurich, Switzerland
- Chung-Ang University, S. Korea
- South Dakota School of Mines and Technology, USA
- A lot thanks to the LANSCE's WNR facility

LANSCE neutron beam test

SuperFGD prototype

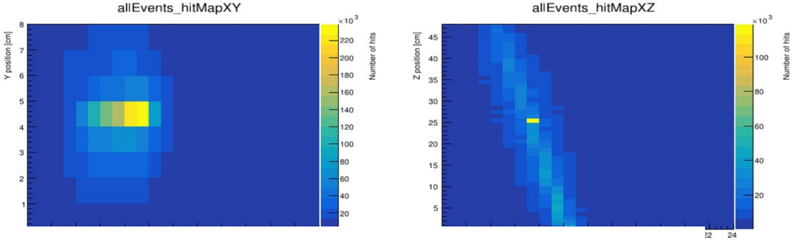


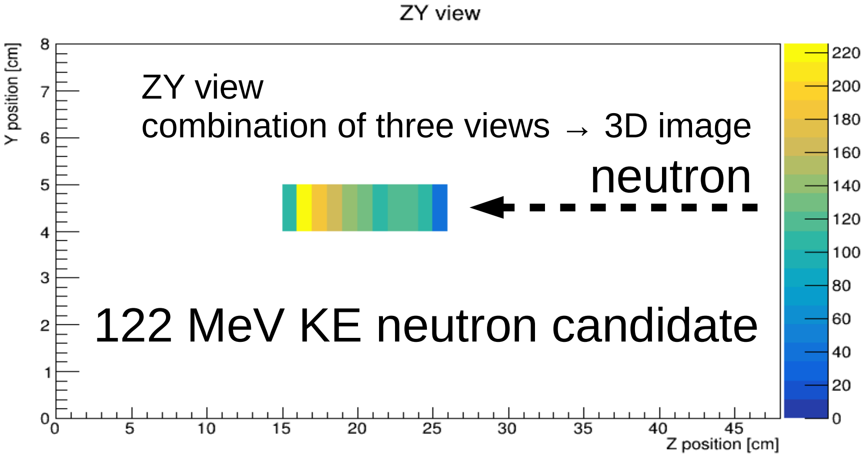
US-Japan prototype



- A ~0-800 MeV KE neutron beam provided by LANSCE in LANL; Our detectors capable to achieve an energy resolution measurement at 2% level
- Goals: Neutron detection response, neutron cross section and neutron double scattering; Data analysis is on-going and we expect a publication by the end of this year.

SuperFGD proto. Beam spot XY and XZ

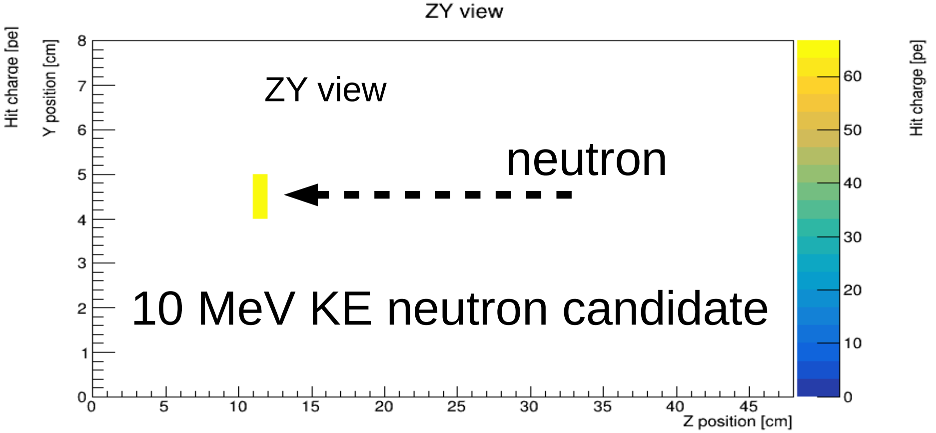




ZY view
combination of three views → 3D image

neutron

122 MeV KE neutron candidate



ZY view

neutron

10 MeV KE neutron candidate

SuperNEMO Calorimeter Commissioning

Malak HOBALLAH on behalf of the SuperNEMO Collaboration

Jul 31 2020

ICHEP 2020 | PRAGUE

40th INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS

VIRTUAL CONFERENCE

28 JULY - 6 AUGUST 2020

PRAGUE, CZECH REPUBLIC

cnrs

université PARIS-SACLAY

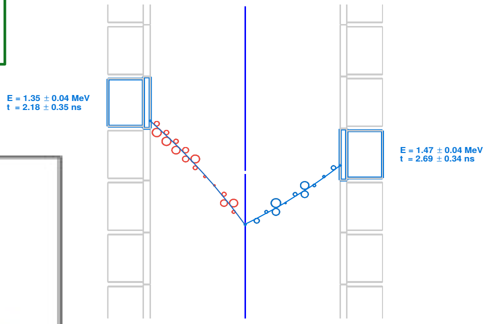
IJCLab Irène Joliot-Curie

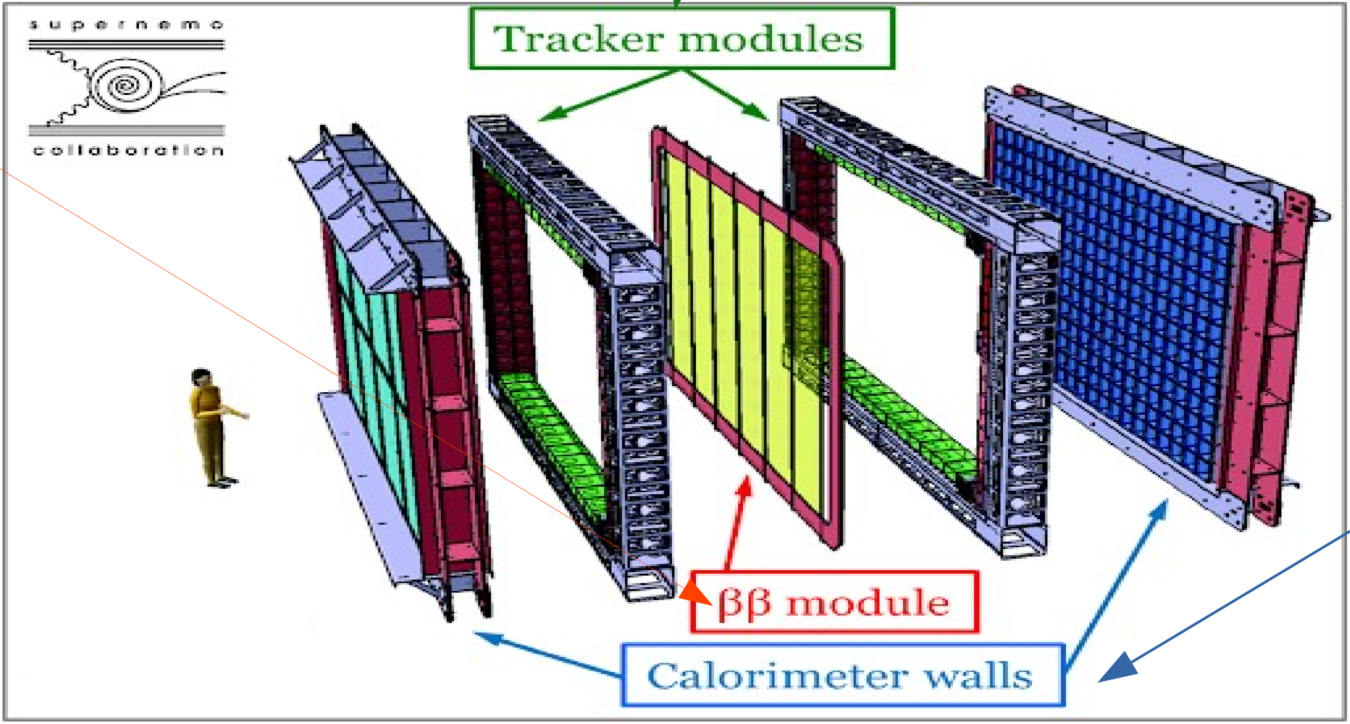
Laboratoire de Physique des 2 Infinis

supernemo collaboration

SuperNEMO and Neutrinoless Double Beta Decay (0νββ)

Full topological reconstruction → **High background rejection**
(expected <10^{-4} events/keV/kg.yr)





Source separate from detector → ability to **study several isotopes**

Measure individual energies giving access To decay mechanism

Main goal to reach a sensitivity of $\mathbf{T^{0\nu}_{1/2} > 5 * 10^{26}}$ **y** with 500 kg.y exposure of ^{82}Se

The SuperNEMO Demonstrator & Calorimeter

Demonstrator module with ~ 6 kg of ^{82}Se :

Expected sensitivity **$T^{0\nu}_{1/2} > 6.5 * 10^{24}$ y, $<m_\nu>$ < (0.15 – 0.4) eV** (90% CL) for a 17.5 kg.y exposure of ^{82}Se

Reachable background sensitivity Source radio-purity A(^{208}Tl) < 2 µBq/kg & A(^{214}Bi) < 10 µBq/kg A(^{222}Rn) < 0.15 mBq/m^3

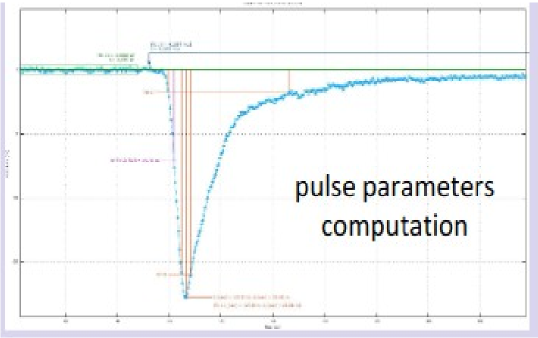
The Calorimeter of the Demonstrator :

Specifications

Energy resolution
8% FWHM at 1 MeV

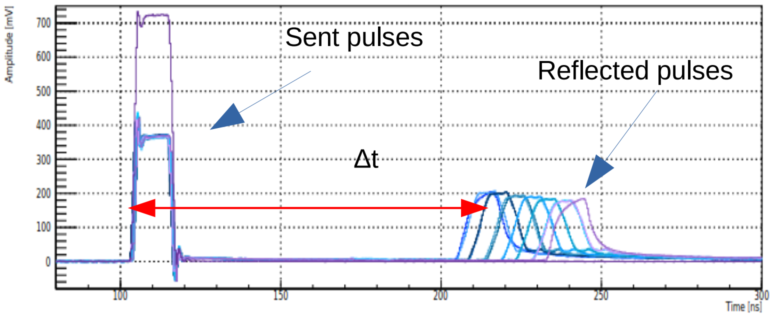
Time resolution **σ** < 400 ps
for 1 MeV electrons

712 optical modules → Pulse digitization: pedestal and pulse shape tested using background runs

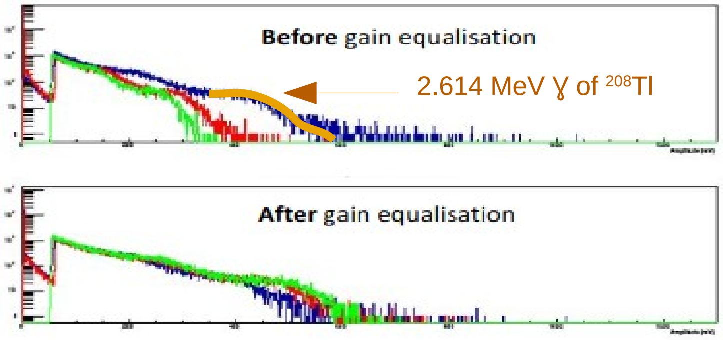


Tracker on its final steps towards commissioning, magnetic field, anti-Radon tent, gamma and neutron shielding to be installed

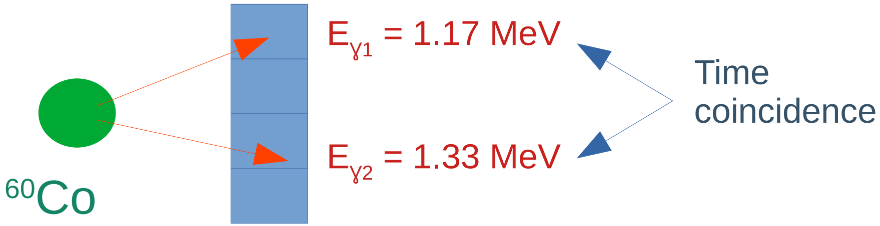
Calorimeter Commissioning analysis



Reflectometry tests to test signal attenuation and time delays between PMT channels using electronics generated pulses



PMT Gain equalization with a dedicated method using ^{208}Tl Compton edge, giving a spread in gain < 10% with gammas, better results expected with electrons



$E_{ɣ1}$ = 1.17 MeV

$E_{ɣ2}$ = 1.33 MeV

Time coincidence

^{60}Co

Time resolution *primarily results* using ^{60}Co give a **σ** < 600 ps for ɣs @ 1 MeV

Better results expected with an electron source and tracker commissioned

Thanks for your attention