Feasibility study for ^{7}Be and CNO solar neutrino directional measurement with JUNO

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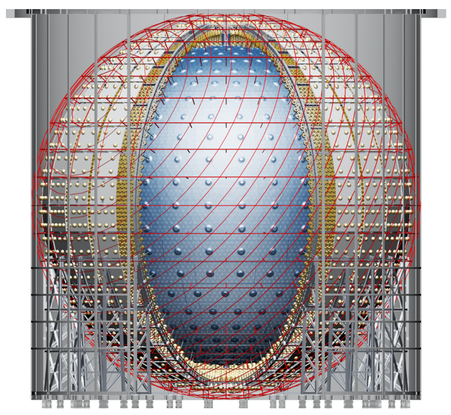
Introduction: solar neutrino detection in JUNO

Jiangmen Underground Neutrino Observatory



- Construction to be completed this year
- Located **underground** in **south China,** vertical overburden of **650 meters**
- **20 kton** organic liquid **scintillator detector**
- 17612 20″ photomultiplier tubes (LPMTs) 25600 3″ photomultiplier tubes (SPMTs)
- **Unprecenteted energy resolution** of 3% @ 1 MeV
- **Excellent target radiopurity** of all its components
- Multipurpose neutrino physics experiment
- **MAIN GOAL:** determination of **neutrino mass ordering** with reactor antineutrinos

Perfect candidate to study solar neutrinos

Solar Neutrinos

- Produced in the core of the **Sun** in **fusion reactions**
  $$4p \rightarrow {}^{4}He + 2e^{+} + 2\nu_e$$
- Staggering flux on Earth of $\Phi_\nu = 6 \cdot 10^{10}$ cm^{-2} s^{-1}
- Crucial to probe physical quantities of the **Sun**, i.e. its **metallicity** [2]
- Helpful to study **neutrinos properties** [3], i.e. their **survival probability** P_{ee}

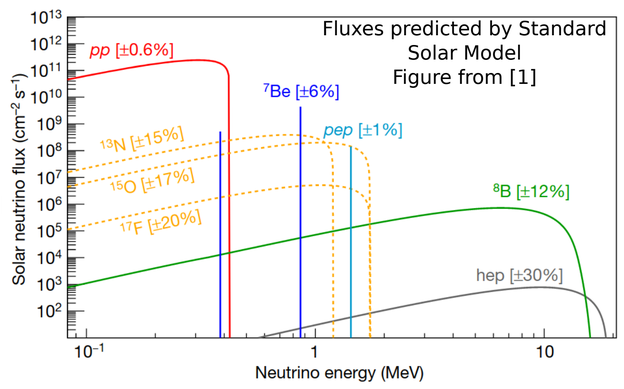
Main **interaction** in JUNO

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

x = e, μ, τ

Interaction rate in JUNO

neutrinos	R [day^{-1} kton^{-1}]
pp	1340
^{7}Be	490
pep	28
^{8}B	4.4
hep	0.01
^{13}N	23.9
^{15}O	26.4
^{17}F	0.7
total	1913

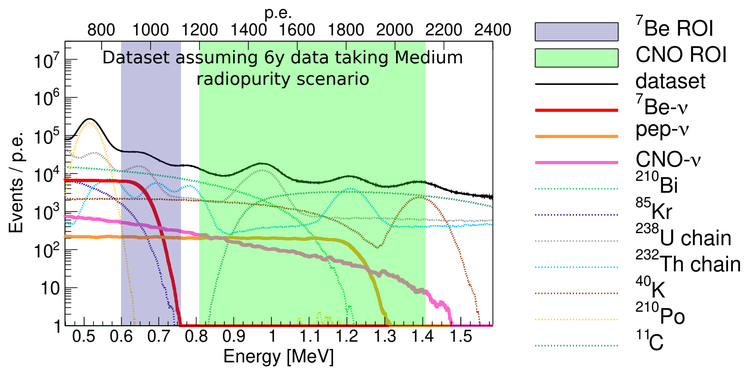


Backgrounds: decays of all the **unstable nuclei**
Detection of solar neutrinos strongly depends on cosmogenics and on the radiopurity of the detector
We consider the so-called Medium radiopurity scenario [4] that assumes realistic contaminations of the scintillator and cosmogenics decay rates

Correlated and Integrated Directionality: motivation and principle

I. Spectral analysis

Different energy spectra among all the species
Energy and vertex **reconstruction from isotropic scintillation light**



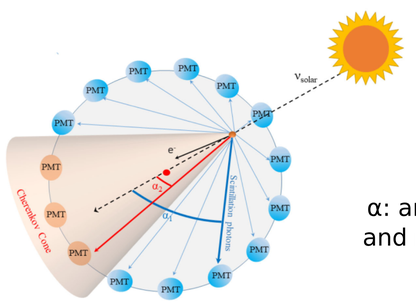
Great **potential to improve** current measurements on ^{7}**Be**, **pep** and **CNO** neutrinos [4]
→ see Davide Basilico's poster

Combination of spectral results with CID **analysis** in ^{7}Be and CNO ROIs could yield even better precision

II. Correlated and Integrated Directionality (CID) analysis

Statistical separation of **solar neutrinos** and **background** events based on **directional Cherenkov light**

Solar neutrino events

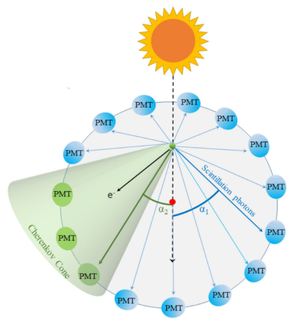


Typical ν - e scattering angle <20°

Typical Cherenkov cone angle ~40°

α: angle between direction and reconstructed position-hit PMT vector

Background events

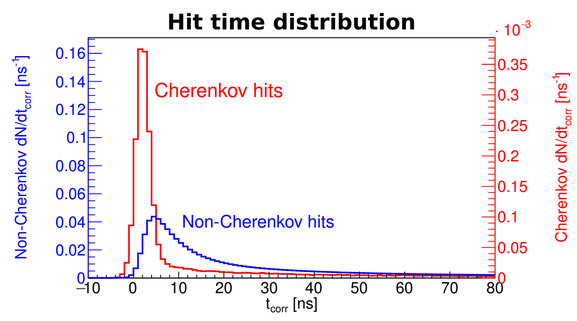


Direction of **Cherenkov light correlated** with **Sun's position**

Scintillation light is **uncorrelated** to **Sun's position**

Direction of **Cherenkov light uncorrelated** with **Sun's position**

Hit time distribution



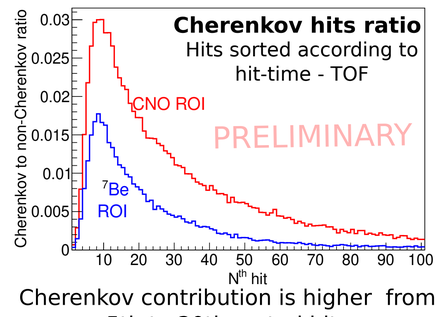
Cherenkov light subdominant (<0.5%); Faster emission → most **contribution** in the **early PMT hits**

Method developed and successfully exploited by the Borexino collaboration [5-7] → see Luca Pelicci's poster

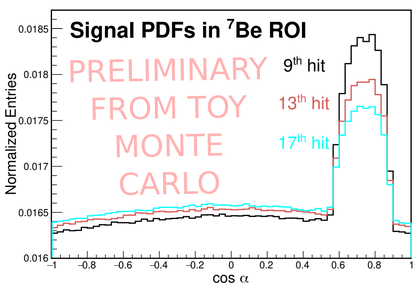
CID in JUNO: workflow and strategy for combination with spectral analysis

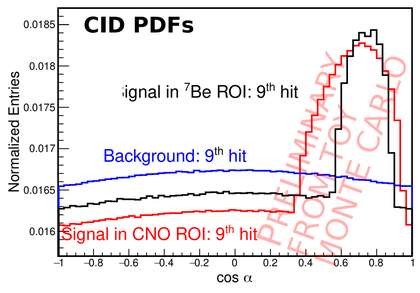
1. CID PDFs creation:

PDFs produced with toy Monte Carlo that simulates correct Sun's positions, ν-e and Cherenkov angles; INPUTS: hit-time and Cherenkov ratio distributions from full Monte Carlo



Cherenkov contribution is higher from 5th to 30th sorted hits





SIGNAL PDFs:
- **peak** at cosα ~ 0.7
- peak **more pronounced** where the **Cherenkov contribution** is **higher**

BACKGROUND PDFs:
- ~ **flat**
- **independent from Nth hit**

Warning: PDFs built not considering Multiple Coulomb scattering of e-, Rayleigh scattering of γ, position reconstruction

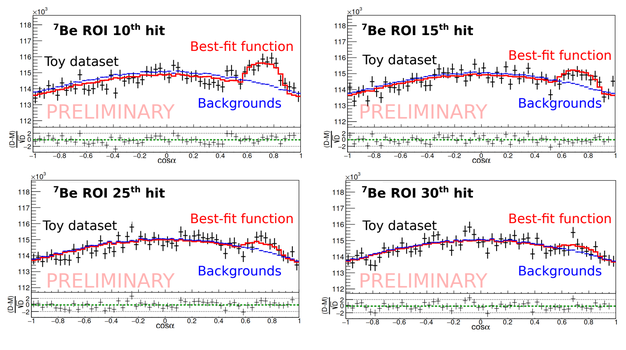
2. Pseudodatasets generation:

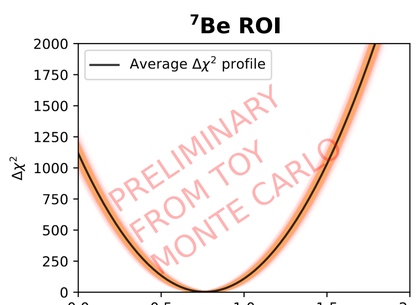
Spectral and CID **pseudodatasets** are generated **from the PDFs** assuming 6 years of data-taking and Medium radiopurity scenario
No systematic are considered in the generation of pseudodatasets

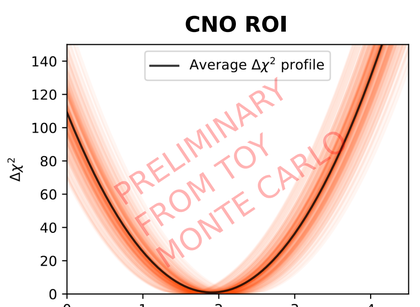
CID pseudodataset → one cosα histogram for each Nth hit from 5th to 30th

3. CID pseudodataset fitting:

All the cosα histograms are fitted simultaneously
Extraction of **Δχ² profiles** as a **function** of solar neutrino events N_ν





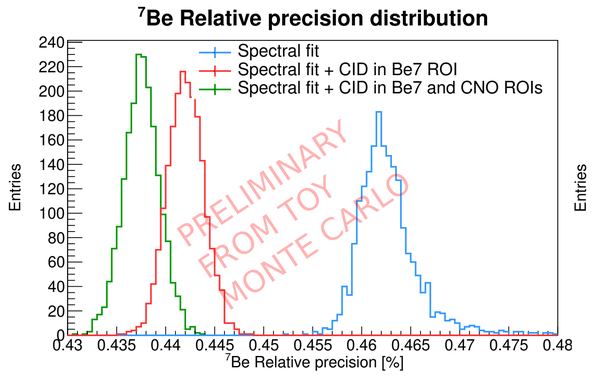


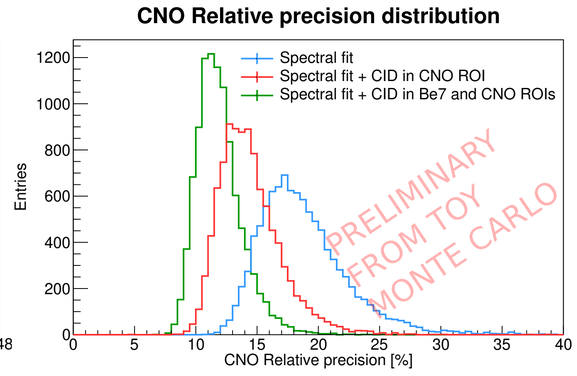
4. CID and spectral analyses combination:

CID likelihood profiles used as an **external constraint in the spectral analysis**

$$\mathcal{L} = \mathcal{L}_{\text{spectral}} \cdot \mathcal{L}_{\text{CID-CNO}} \cdot \mathcal{L}_{\text{CID-Be7}}$$

$$\mathcal{L}_{\text{CID}} = e^{-\Delta\chi^2_{\text{CID}}/2}$$





CID has a **modest** impact on ^{7}**Be** neutrinos

CID has a **significant** impact on **CNO** neutrinos

Conclusions

- The **CID** analysis provides a method of **statistical separation** between **solar neutrinos** and **background** events [5-7]
- The feasibility of CID application in JUNO has been studied with the use of a toy Monte Carlo
- **First results** indicate that **CID** will **improve** the previously studied **JUNO sensitivity to solar neutrinos** with spectral fit [4 and Davide Basilico's poster], in **particular** to **CNO** neutrinos
- Systematics not yet fully considered, expected impact of the known systematic to be small from initial tests

Next steps

- Final **evaluation** of the physics **potential** of **CID** in JUNO with the **full Monte Carlo simulation**
- Detailed **evaluation** of **all** the **systematic** effects
- Development of a **Cherenkov calibration source** to maximise the CID potential

References

[1] M. Agostini et al., Comprehensive measurement of pp-chain solar neutrinos, Nature 562 (2018) 496
[2] Núria Vinyoles et al. "A new Generation of Standard Solar Models". In: Astrophys. J. 835.2 (2017). arXiv: 1611.09867 [astro-ph.SR]
[3] I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler, and T. Schwetz, "Updated fit to three neutrino mixing: exploring the accelerator-reactor complementarity," JHEP, vol. 01, p. 087, 2017
[4] A. Abusleme et al., JUNO sensitivity to 7Be, pep, and CNO solar neutrinos, J. Cos. Astro. Phys. 10 (2023) 022
[5] M. Agostini et al., First Directional Measurement of sub-MeV Solar Neutrinos with Borexino, Phys. Rev. Lett. 128 (2022) 091803
[6] M. Agostini et al., Correlated and Integrated Directionality for sub-MeV solar neutrinos in Borexino, Phys. Rev. D 105 (2022) 052002
[7] D. Basilico et al., Final results of Borexino on CNO solar neutrinos, Phys. Rev. D 108 (2023) 102005