Directional analysis of CNO solar neutrinos in JUNO: preliminary MC approach and strategy for combination with MV fit

24.10.2022 I Luca Pelicci[1,2], Livia Ludhova[1,2], Apeksha Singhal [1,2].

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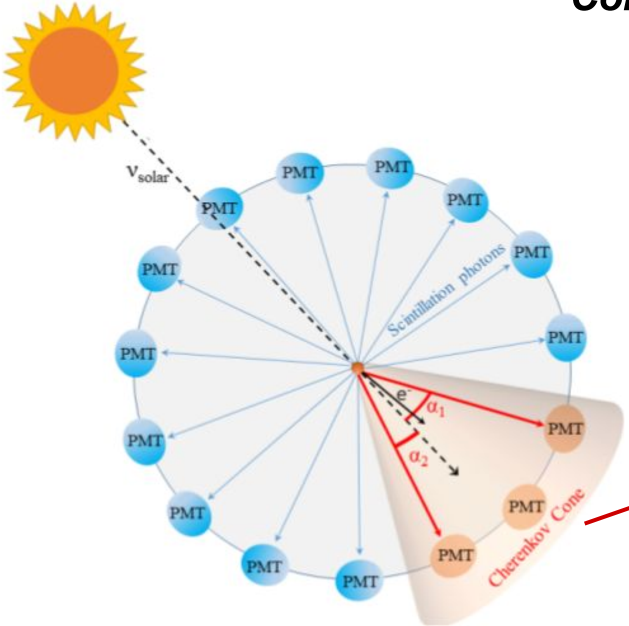
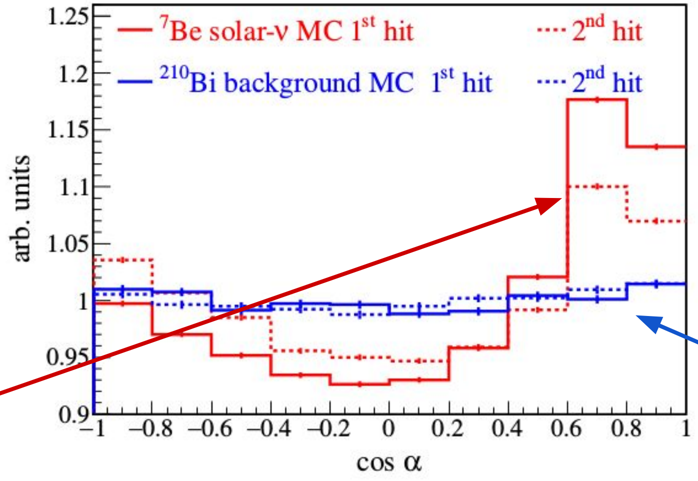
Outline

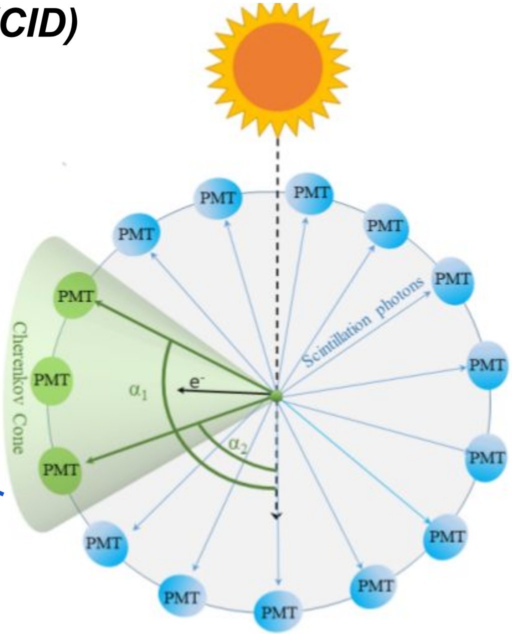
- Introduction to CID
- Cherenkov and Scintillation light in JUNO
- Workflow of CID analysis
- Application of CID as a constraint
- Summary and Outlook

Introduction

Correlated and Integrated Directionality (CID)







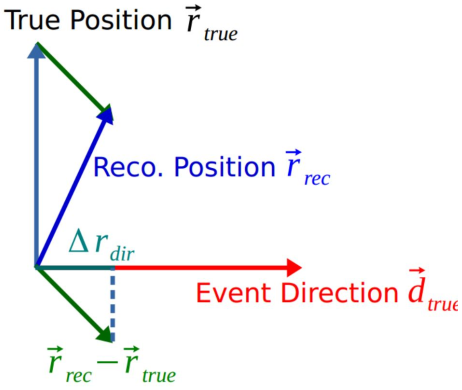
Neutrino Event

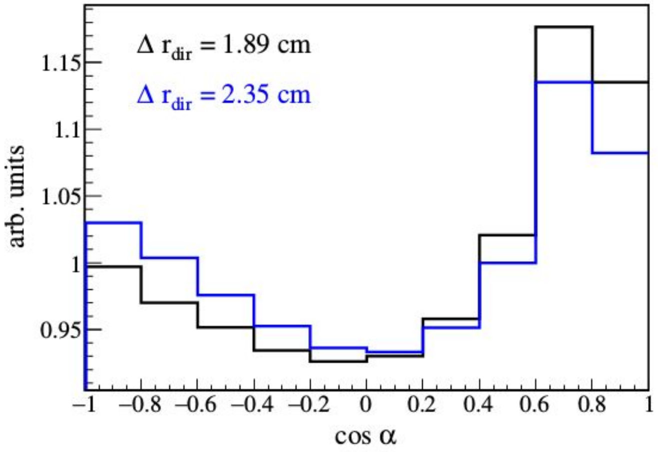
Background Event

PRL 128 (2022) 091803 + PRD 105(2022) 052002.

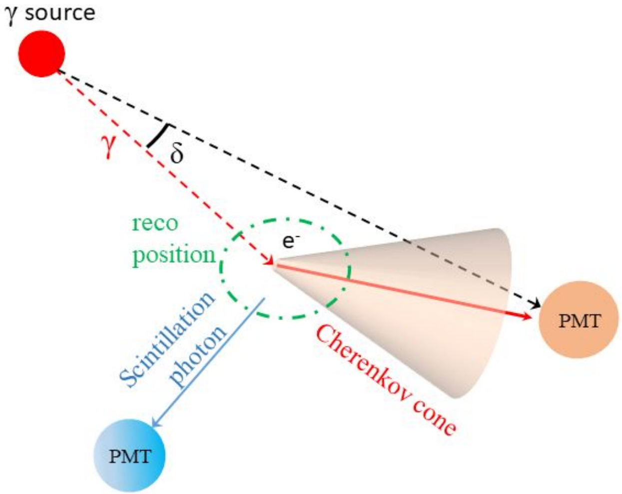
Major Systematics of CID in Borexino

1) Bias in position reconstruction





2) Effective correction on refractive index for Cherenkov photons in MC



Major Systematics of CID in Borexino

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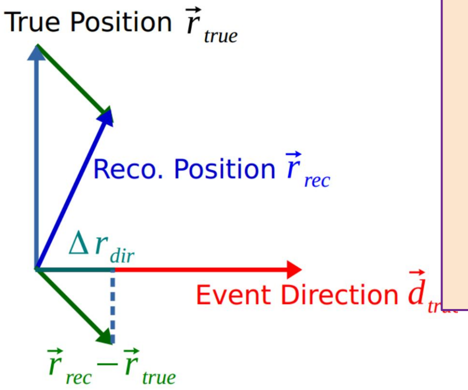
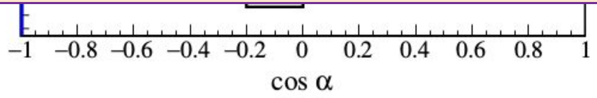
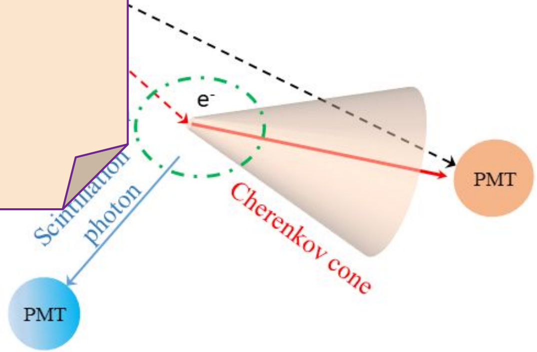




2) **Effective correction on refractive index for Cherenkov photons in MC**



These systematic effects are not included in this work!

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JUNO MC Configuration

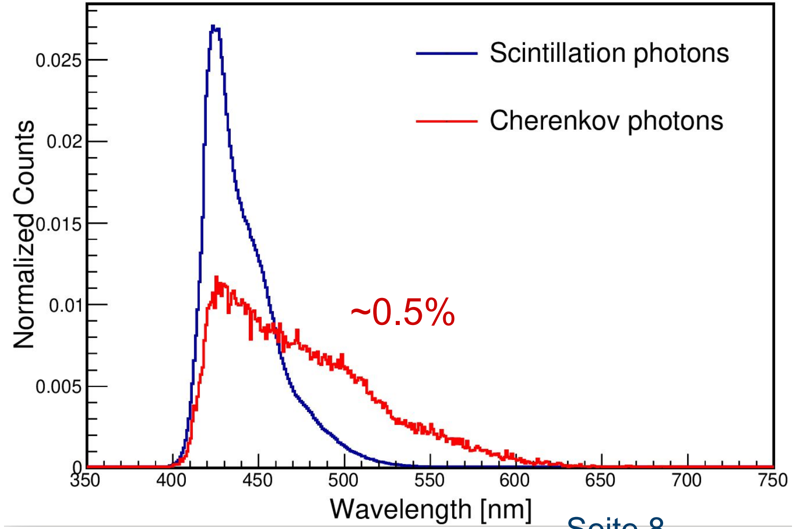
- Software Version used for simulation : J22.1.0-rc4.
- Electrons with energy range 0.8-1.4 MeV are simulated.
- Statistics of ~5000 events is considered.
- Only "Detsim" and "Elecsim" levels of simulation are performed and the corresponding files are analyzed.

Cherenkov and Scintillation light in JUNO

- All photons of wavelength less than ~400 nm are absorbed in the liquid scintillator and reemitted as scintillation photons.

- Photons are tagged as “Cherenkov” in elecsim only if it is **originally Cherenkov in detsim and was not re-emitted.**

Wavelength distribution of all Cherenkov and Scintillation photons

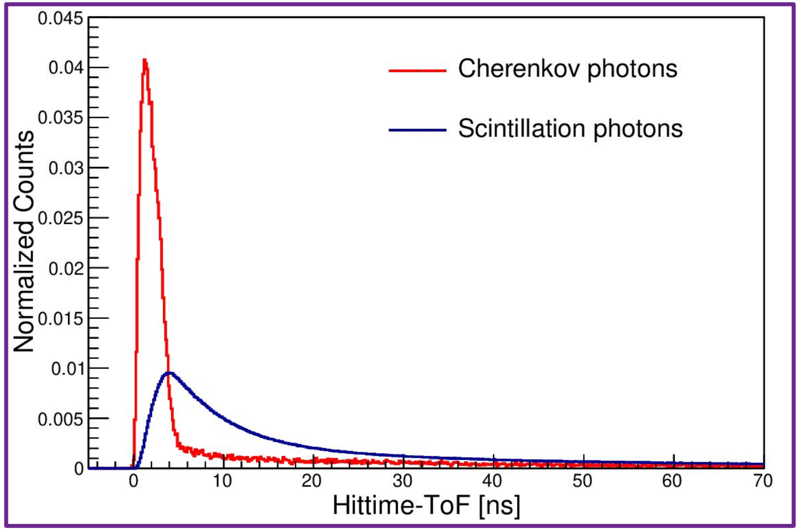


Hit time of Cherenkov and Scintillation light in JUNO

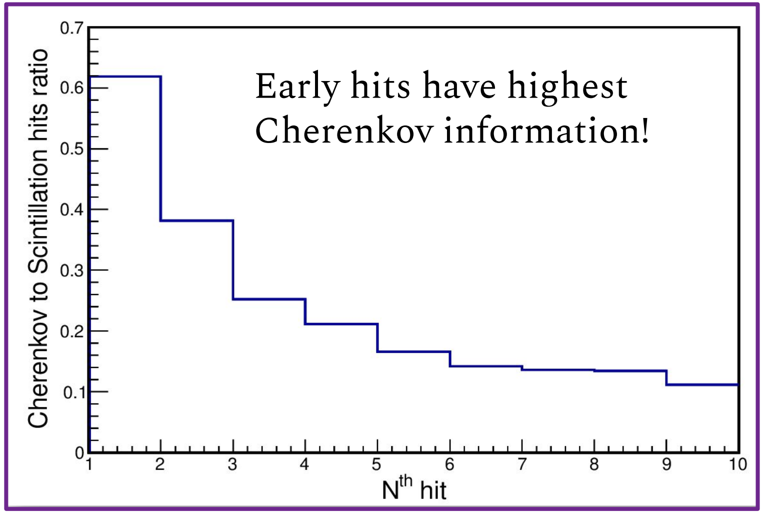
Cherenkov light is emitted instantaneously while Scintillation photons arrive the PMTs at later times.

Ideal Case: No TTS and No noise hits, All Large PMTs

Time of Flight (ToF) corrected hittime distribution



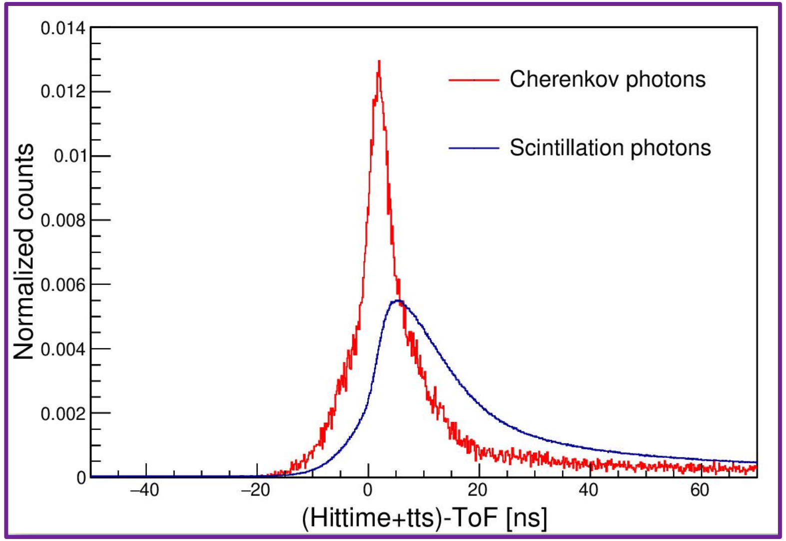
Cherenkov to scintillation ratio Vs N^{th} hit



Hit time of Cherenkov and Scintillation light in JUNO

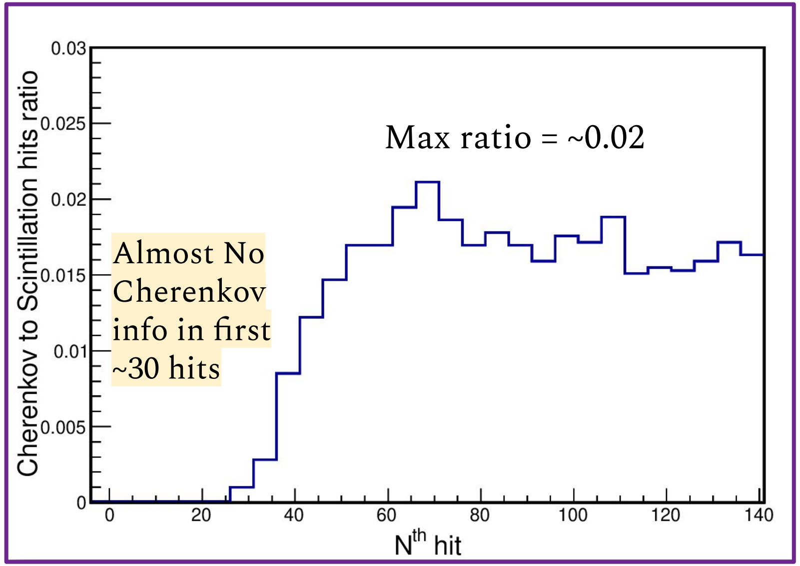
Including TTS and noise hits, All Large PMTs

ToF corrected hittime distribution



Distribution is more spreaded due to TTS

Cherenkov to scintillation ratio Vs N^{th} hit

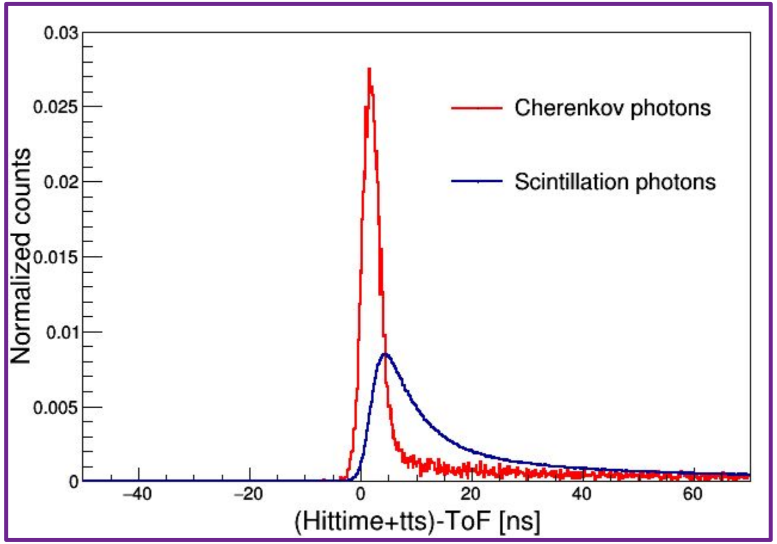


Noise hits are included as Scintillation photons

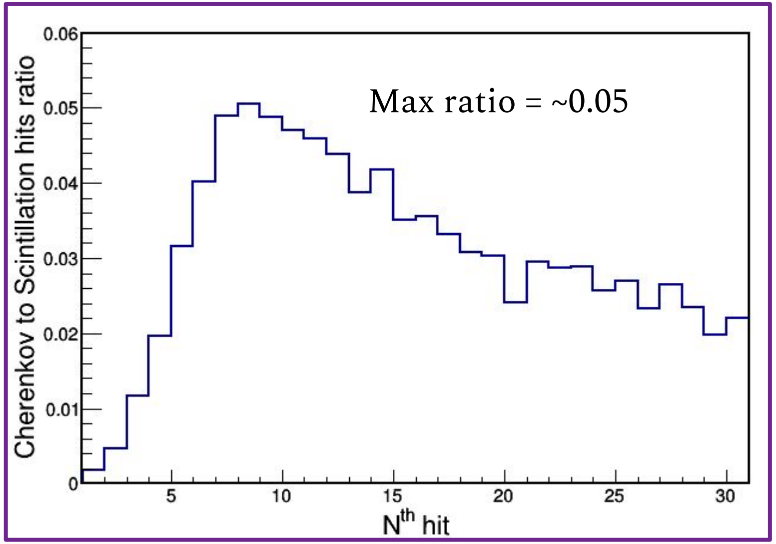
Hit time of Cherenkov and Scintillation light in JUNO

Including TTS and noise hits, Hamamatsu PMTs only

ToF corrected hittime distribution



Cherenkov to scintillation ratio Vs N^{th} hit



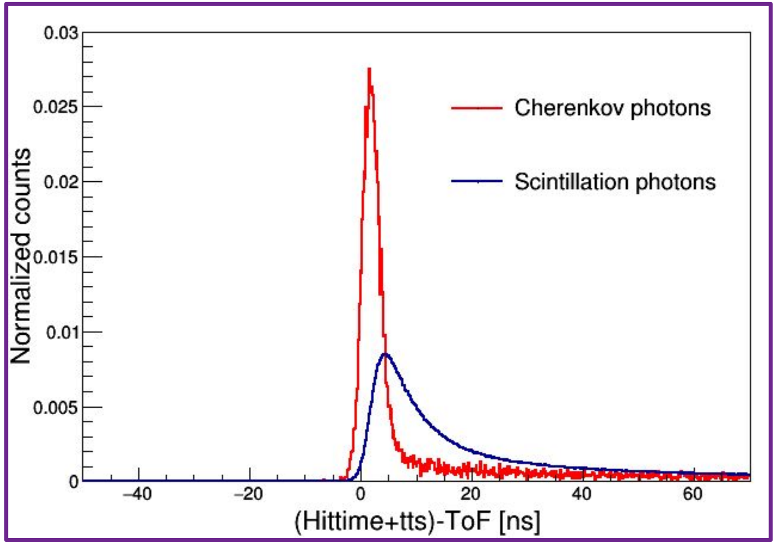
Selecting Hamamatsu PMTs lead to increase in the Cherenkov to Scintillation hits ratio at early hits!

Noise hits are included as Scintillation photons

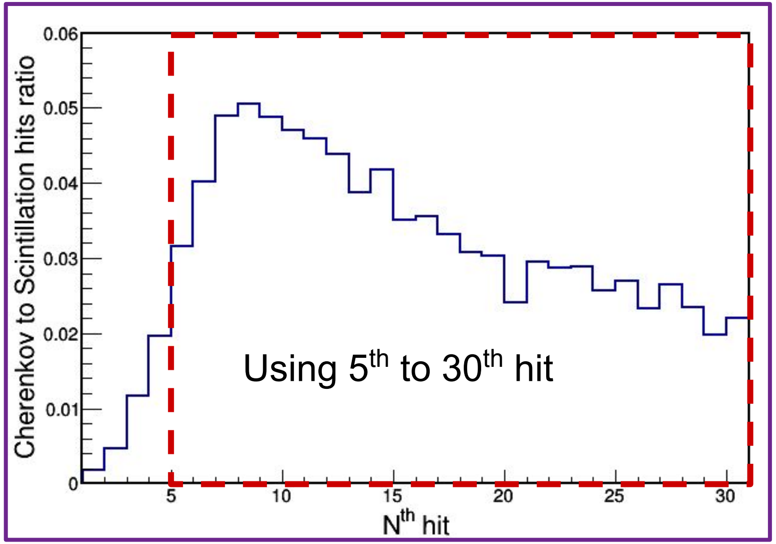
Hit time of Cherenkov and Scintillation light in JUNO

Including TTS and noise hits, Hamamatsu PMTs only

ToF corrected hittime distribution



Cherenkov to scintillation ratio Vs N^{th} hit



Noise hits are included as Scintillation photons

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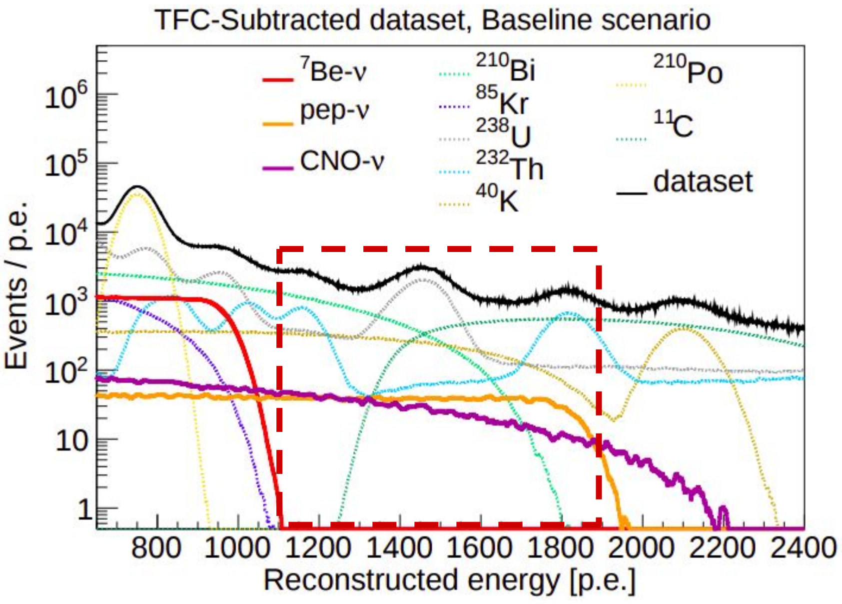
Region of Interest for CID analysis



Docdb: 7661

- Energy range: 0.8 - 1.4 MeV.
- ^{11}C-subtracted data with assumed Three-Fold Coincidence (TFC) performance: Tagging Power = 90% and Subtracted Exposure = 70%.
- FV<14m (No external backgrounds).

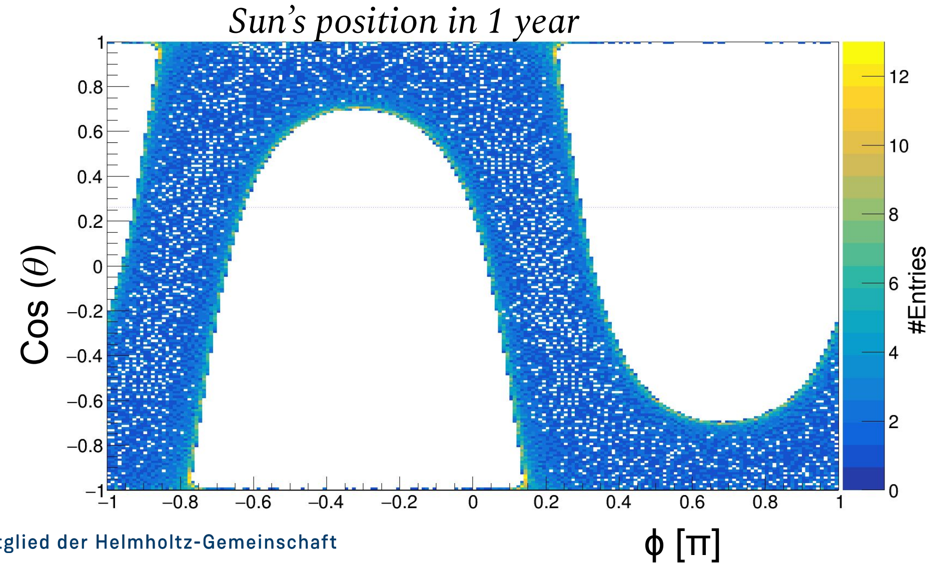
Signal: CNO and pep solar neutrinos

Background: ^{210}Bi, ^{11}C, ^{238}U, ^{232}Th, ^{40}K

Sun’s Position

1) Calculating altitude and azimuth from geographical location of JUNO site. The geographic location is 112°31’05” E and 22°07’05” N.

2) Transforming azimuth and altitude w.r.t JUNO’s cartesian coordinates to obtain θ and ϕ.



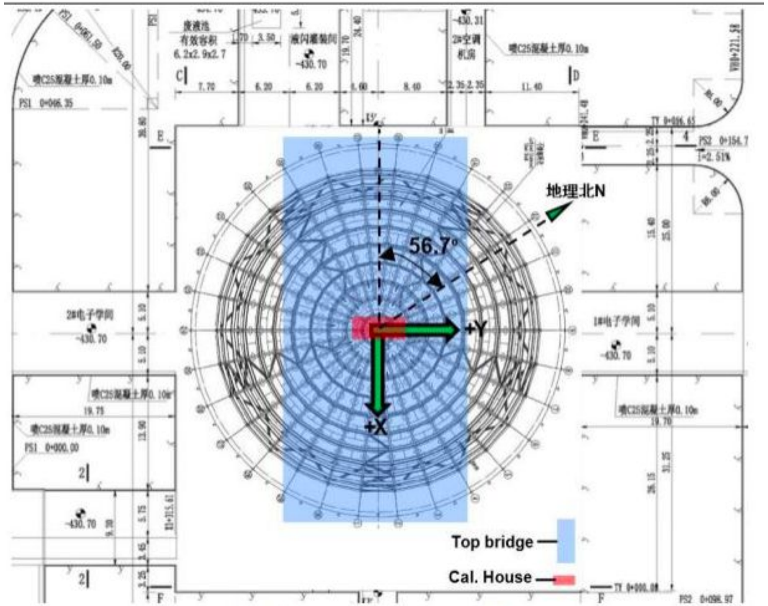


Fig.2 layout in Experimental Hall

Doc-db 4599-v1

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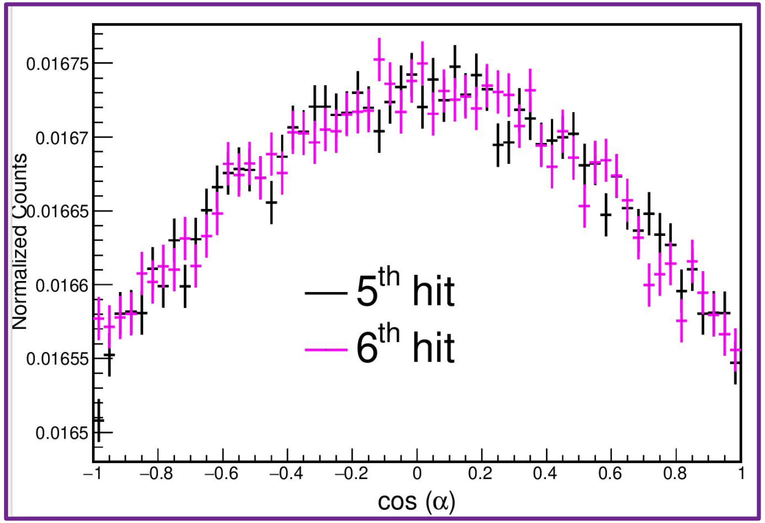
Background PDFs

cosα distribution for backgrounds from Toy MC



Using Toy Monte Carlo with ingredients:

- Sun's position.
- Generation of uniformly distributed background events.
- Real Position of Hamamatsu PMTs.

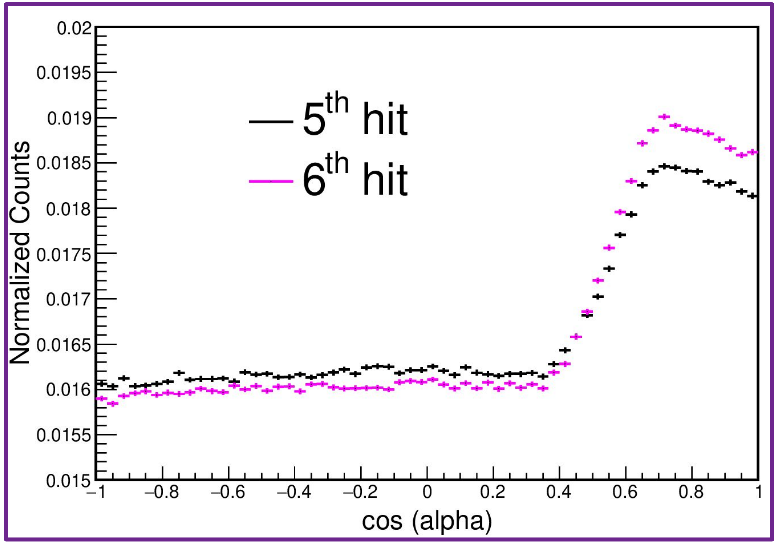
Shape of PDFs do not depend on N^{th} hit and the background species!

Signal PDFs

Using Toy Monte Carlo with ingredients:

- Sun's position.
- Generation of events with uniform position.
- Real Position of Hamamatsu PMTs.
- Energy of scattered electrons and their angle of recoil.
- N^{th} hit dependency of number of Cherenkov and scintillation photons.
- Wavelength dependent refractive index. Refractive index and velocity of particle dependent Cherenkov angle.

cosα distribution for signal from Toy MC



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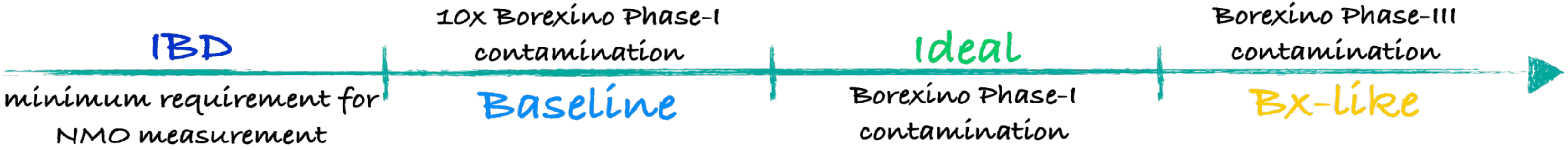
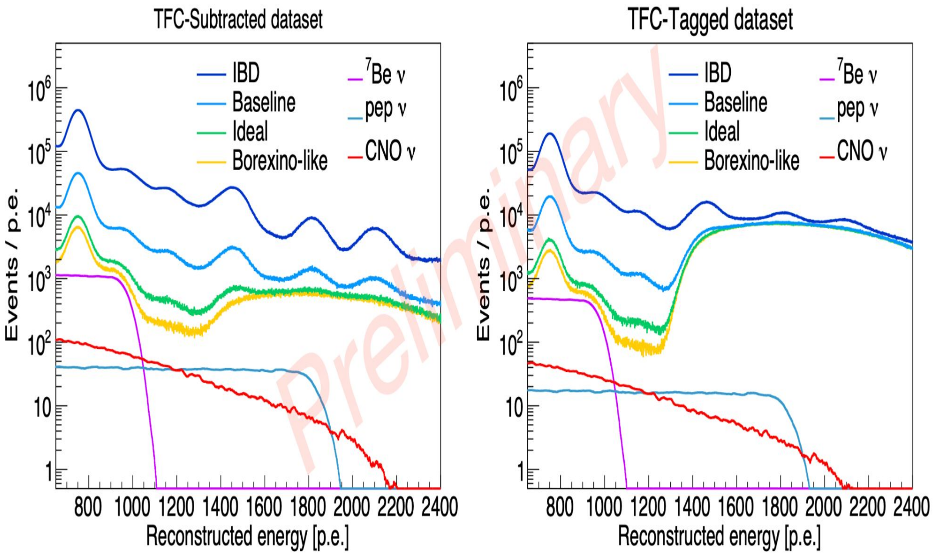
Solar analysis

Radio-purity scenarios considered (from worst to best):





Sensitivity studies:

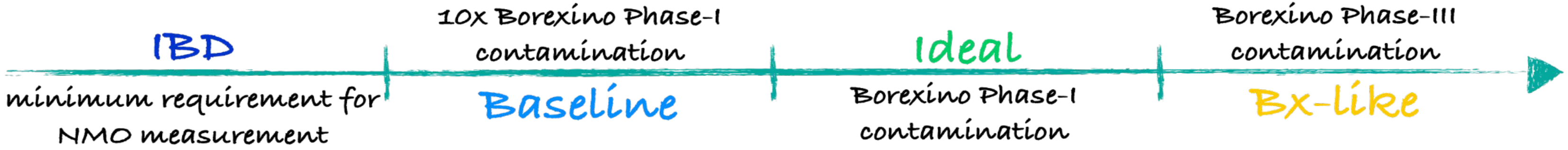
1. Generate **Monte Carlo PDFs** (Juno Offline software)
2. Create thousands **toy-experiments** sampling each PDF
3. **Simultanoeus fit** based on binned Poisson likelihood:

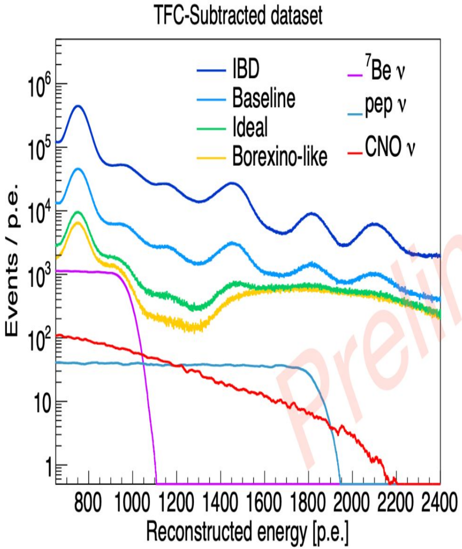
$$\mathscr{L} = \mathscr{L}_{E-sub} \cdot \mathscr{L}_{E-tag}$$

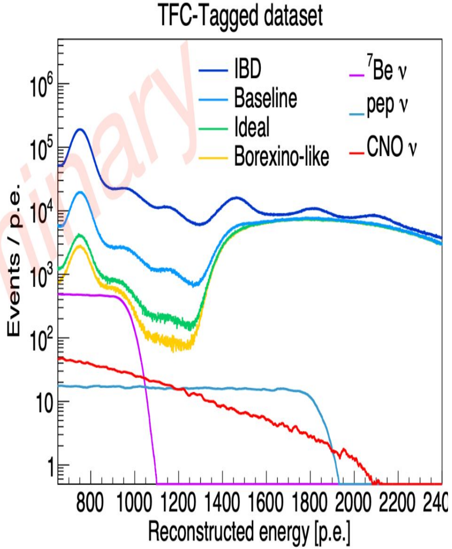
Technote in Docdb: 7661

Solar analysis

Radio-purity scenarios considered (from worst to best):







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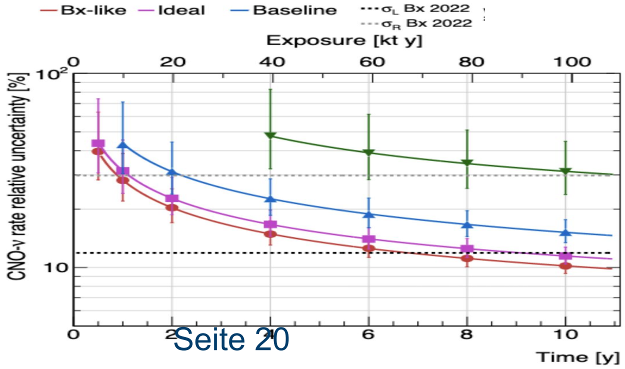


CNO relative uncertainty

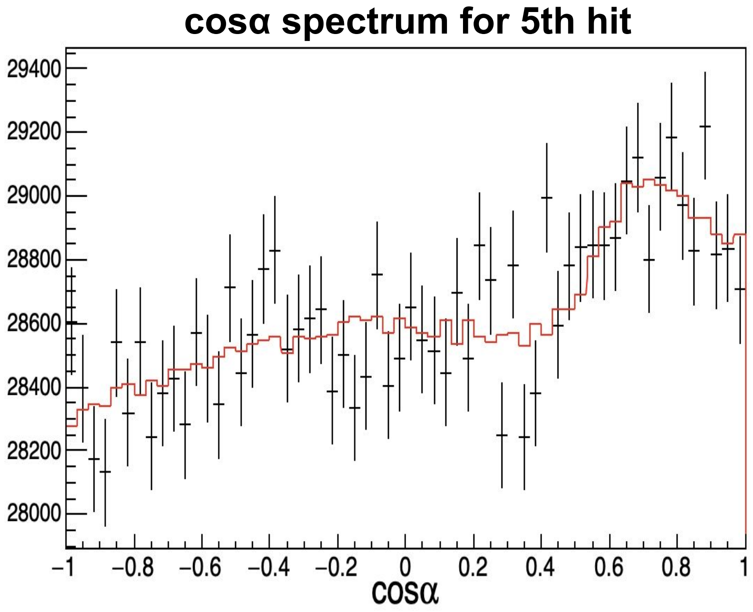
(pep constrained at 1.4% level)

Technote in Docdb: 7661

Extracting the constraint

Toy datasets produced sampling toy-MC PDFs

Contributions of signals and backgrounds is weighted with number of events expected in the ROI



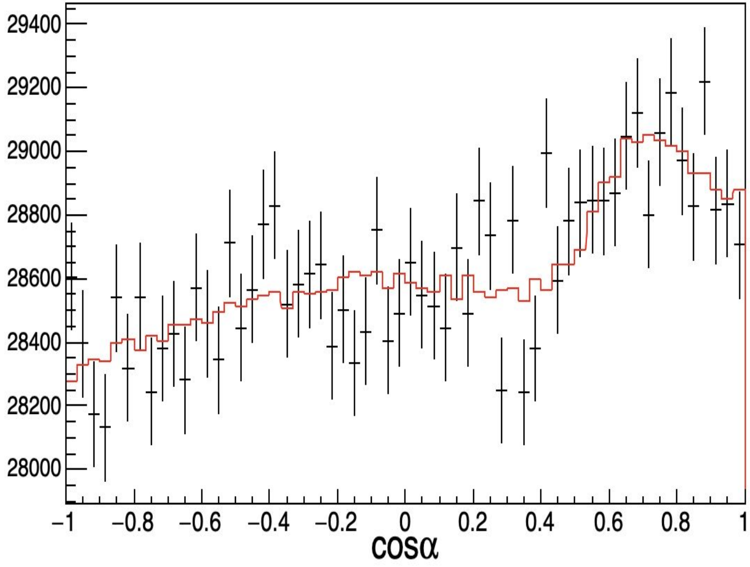
Extracting the constraint

Can you show also spectrum 3 to 39

Toy datasets produced sampling toy-MC PDFs

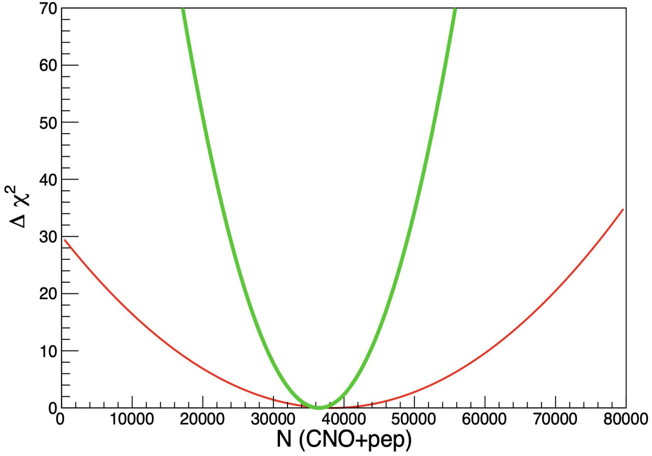
Contributions of signals and backgrounds is weighted with number of events expected in the ROI

cosα spectrum for 5th hit



CID constraint:

N(sig) profile with simultaneous fit of 26 cosα spectra (5th to 30th hit)

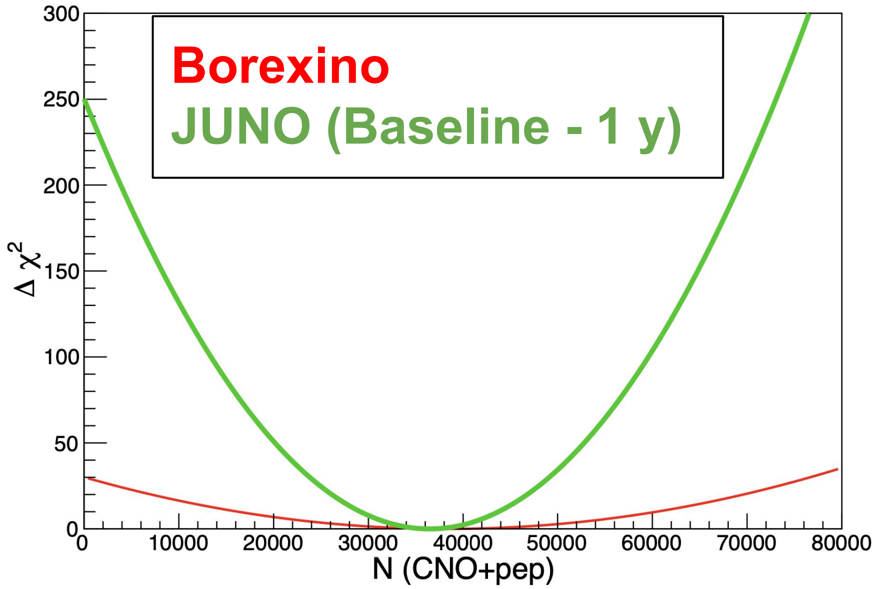


Borexino

JUNO (Baseline for 1 year)

CID constraint

Directional measurement of CNO+pep can be used to put additional constraint on solar neutrinos number of events in the MV fit.



Implemented in the fitter as additional likelihood term:

$$\mathscr{L} = \mathscr{L}_{E-sub} \cdot \mathscr{L}_{E-tag} \cdot \mathscr{L}_{CID}$$

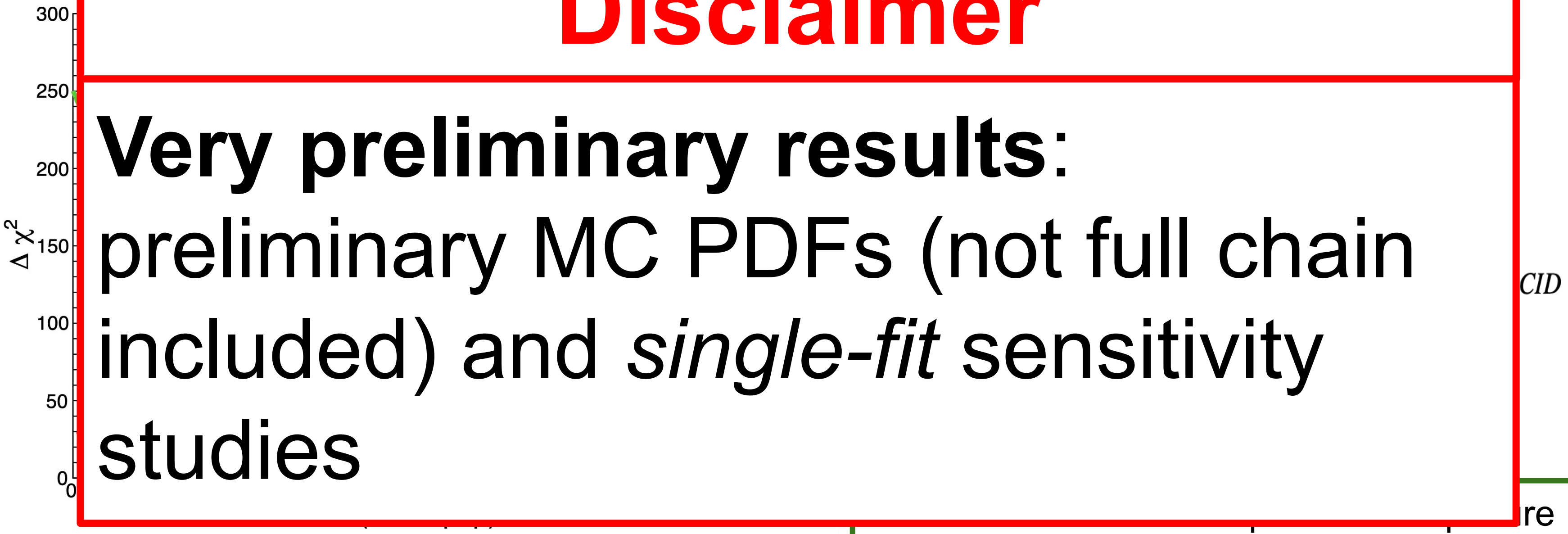
$$N(\text{CNO+pep}) = (w_{pep}R_{pep} + w_{CNO}R_{CNO}) \cdot \text{exp}_{CID}$$

w = weight (portion of signal in the ROI)
R = interaction rate (cpd/1kt)
exp = exposure (mass * days)

Note: CID constraint depends on exposure
More exposure → better CID precision

CID constraint

Directional measurement of CNO+pep can be used to put additional constraint on solar neutrinos number of events in the MV fit.



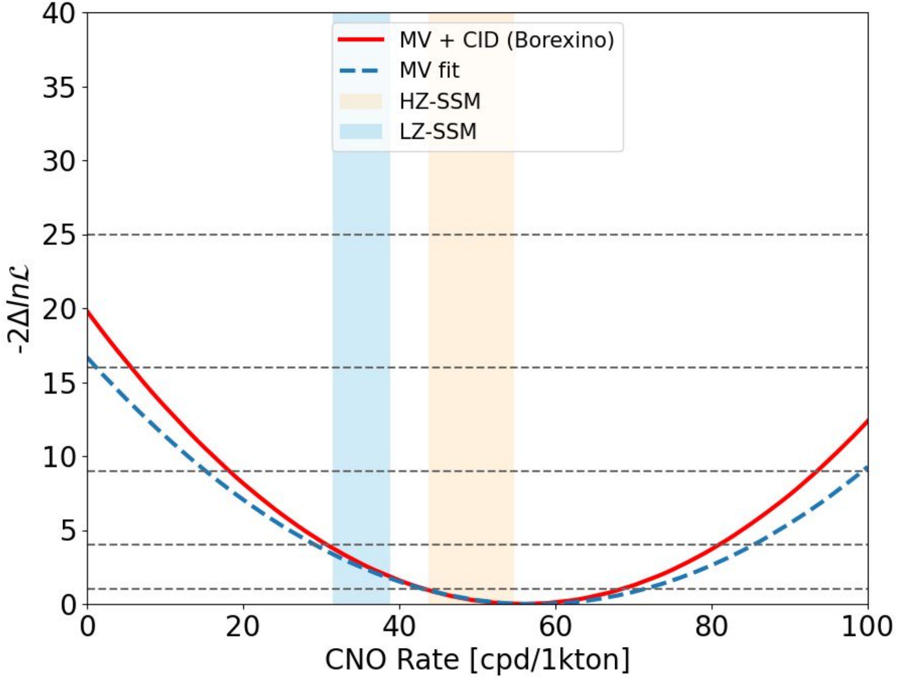
Disclaimer

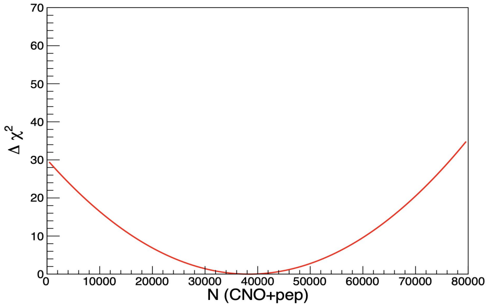
Very preliminary results: preliminary MC PDFs (not full chain included) and *single-fit* sensitivity studies

re
More exposure → better CID precision

Inclusion of CID constraint

Bx-like radiopurity scenario
1 year of data taking





CID profile used as additional constraint

Significance to no-CNO hypothesis:

MV fit = 4.1 sigma

Bx-CID constraint = 4.4 sigma

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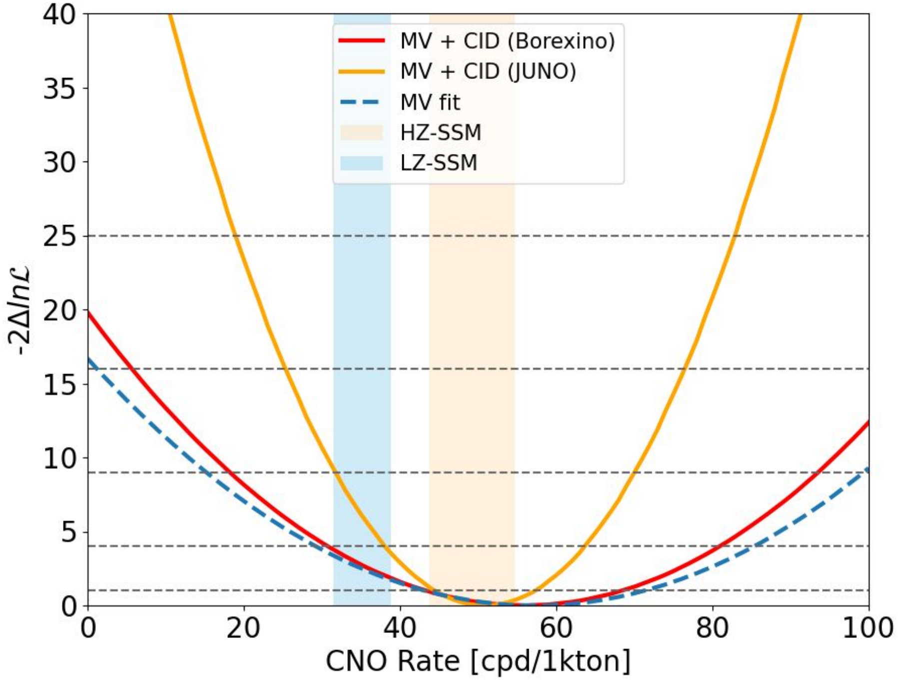
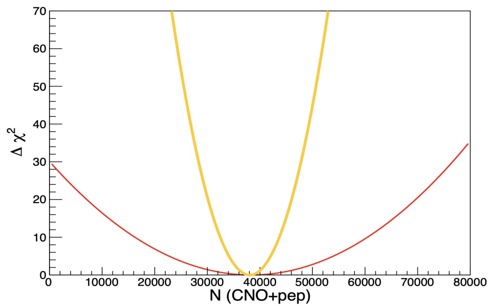
Inclusion of CID constraint

Bx-like radiopurity scenario
1 year of data taking





CID profile used as additional constraint

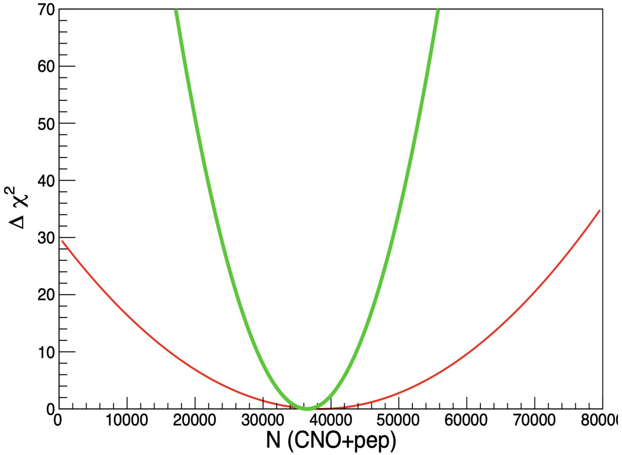
Significance to no-CNO hypothesis:

MV fit ~ 4.1 sigma
Bx-CID constraint ~ 4.4 sigma
Juno constraint ~ 8.0 sigma

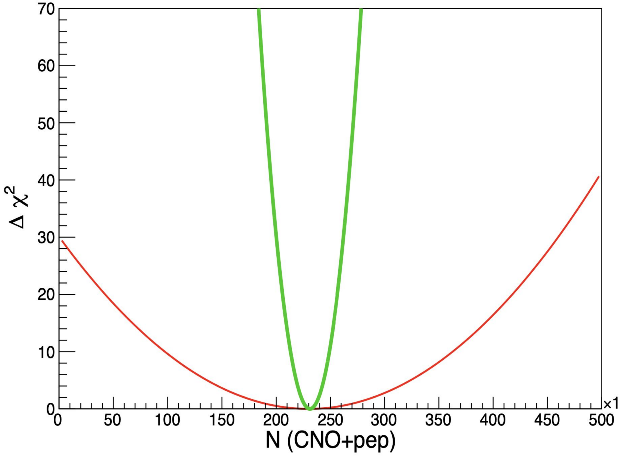
Bx-like is (too) optimistic radiopurity scenario. **Is CID constraint effective with more backgrounds?**

CID constraints

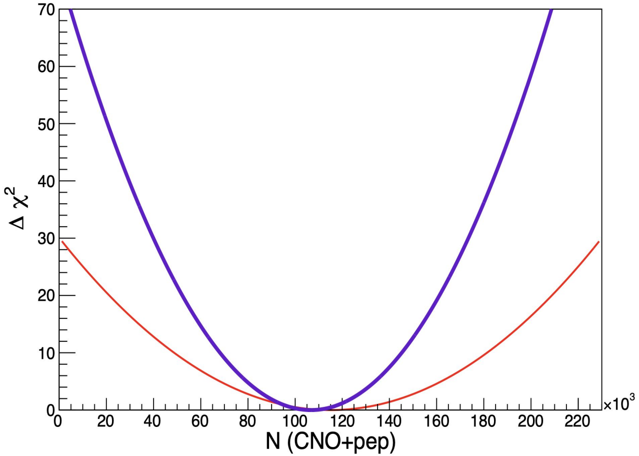
Baseline (1 year)



Baseline (6 years)



IBD (3 years)



More statistics

More background

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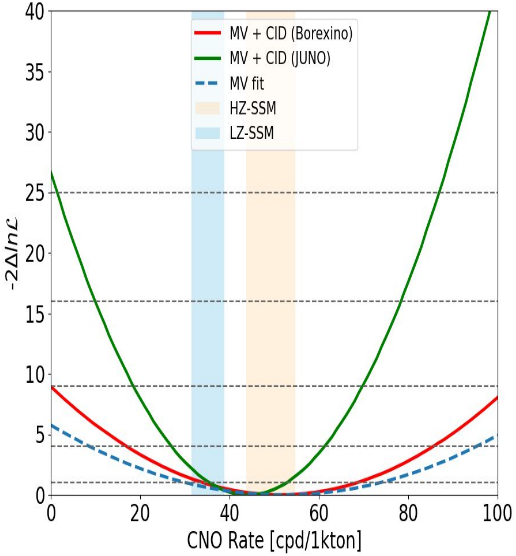
Fit results

Baseline (1 year)

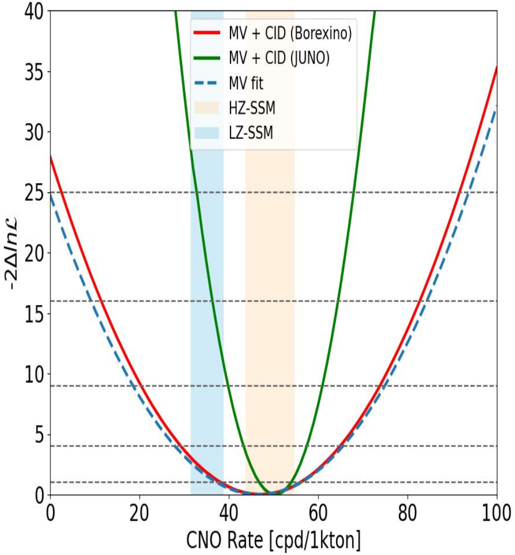


Significance to no-CNO hypothesis:
MV fit ~ 2.4 sigma
Bx-CID constraint ~ 3.0 sigma
Juno constraint ~ 5.2 sigma

Relative impact of CID constraint is higher for baseline scenario (~79%) than Bx-like (~74%)

More statistics

Baseline (6 years)

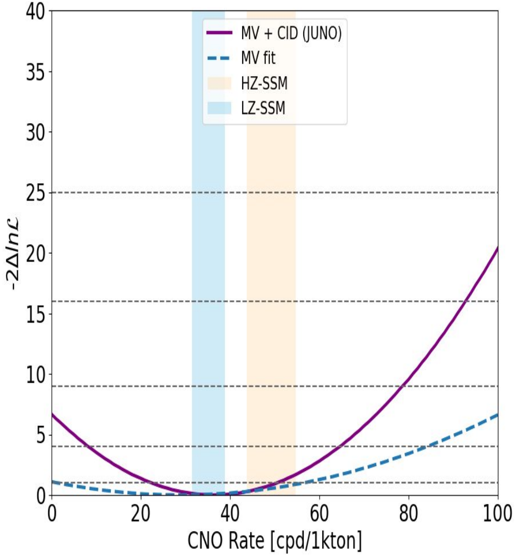


Significance to no-CNO hypothesis:
MV fit ~ 4.9 sigma
Bx-CID constraint ~ 5.3 sigma
Juno constraint > 10 sigma

Increasing statistics we get better sensitivity from MV fit and **CID importance is enhanced (relative impact ~88%)**

More background

IBD (3 years)



Significance to no-CNO hypothesis:
MV fit < 1.0 sigma
Juno constraint ~ 2.6 sigma

Including CID constraint we can look for CNO neutrinos **even for IBD scenario with low statistics**

Conclusions and outlook

- We presented the properties of **Cherenkov and scintillation light in JUNO** with Monte Carlo.

- PDFs produced with set of MC parameters (N^{th} dependency using effect of tts and noise hit, refractive index, wavelength of photons) using Juno Offline software until electronic simulation stage.

- A simultaneous fitting technique (based on the original idea implemented by Borexino collaboration) has been developed to obtain the **CID constraint to be added to the MV fit** used by Solar Group to extract JUNO sensitivity to CNO neutrinos

- **Preliminary studies** shows that additional constraint based on directionality measurement leads to an **improved sensitivity for CNO neutrinos.** CID constraint is more impactful for worst radipurity scenarios: potential of being a powerful tool for background discrimination for **high precision solar neutrino measurements**

- **Next steps:**
  - Include full MC simulations
  - Analysis of most important source of systematic errors (e.g. position reconstruction bias and refractive index for Cherenkov photons)
  - Developing calibration strategy for Cherenkov photons

Backup

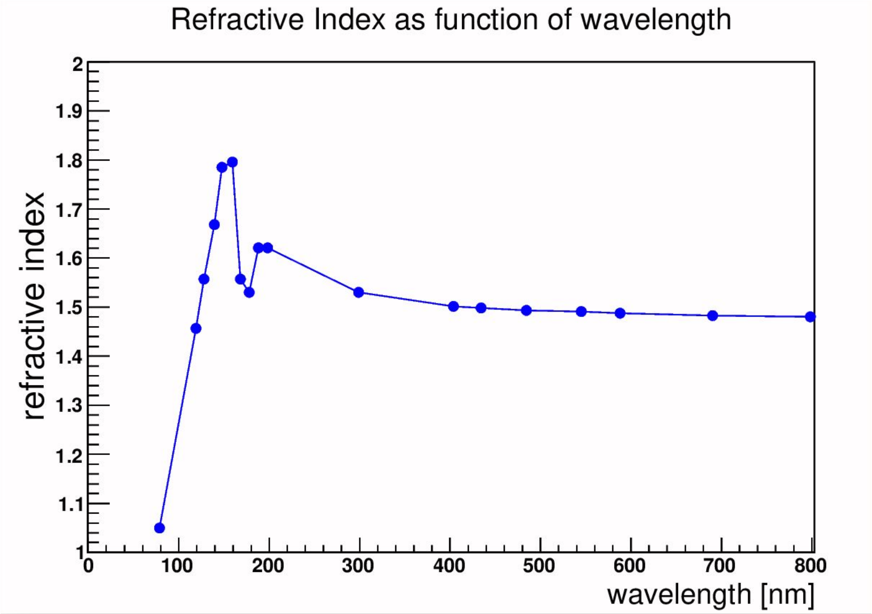
Signal-to-noise ratio

1 year

	NS/sqrt(NS+NB)	NS/(NS+NB) [%]
Borexino P2+3	21,00	40,00
JUNO - Bx like	67,79	11,99
JUNO - ideal	56,82	8,42
JUNO - baseline	32,39	2,74
JUNO - IBD	11,33	0,33

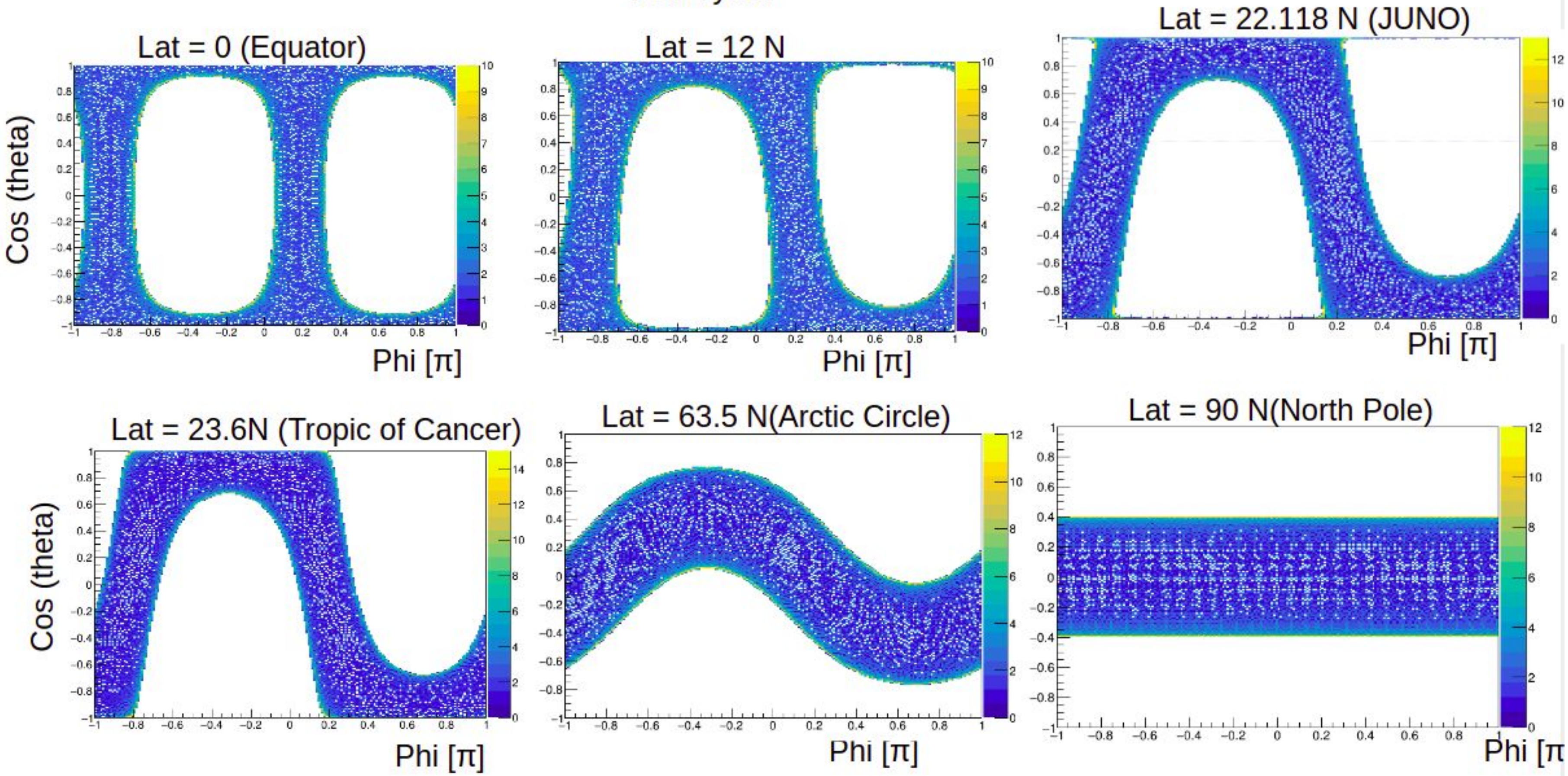
6 years

	NS/sqrt(NS+NB)	NS/(NS+NB) [%]
Borexino P2+3	21,00	40,00
JUNO - Bx like	166,05	11,99
JUNO - ideal	139,19	8,42
JUNO - baseline	79,35	2,74
JUNO - IBD	27,75	0,33


Refractive Index as function of wavelength
refractive index
wavelength [nm]
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0
100
200
300
400
500
600
700
800

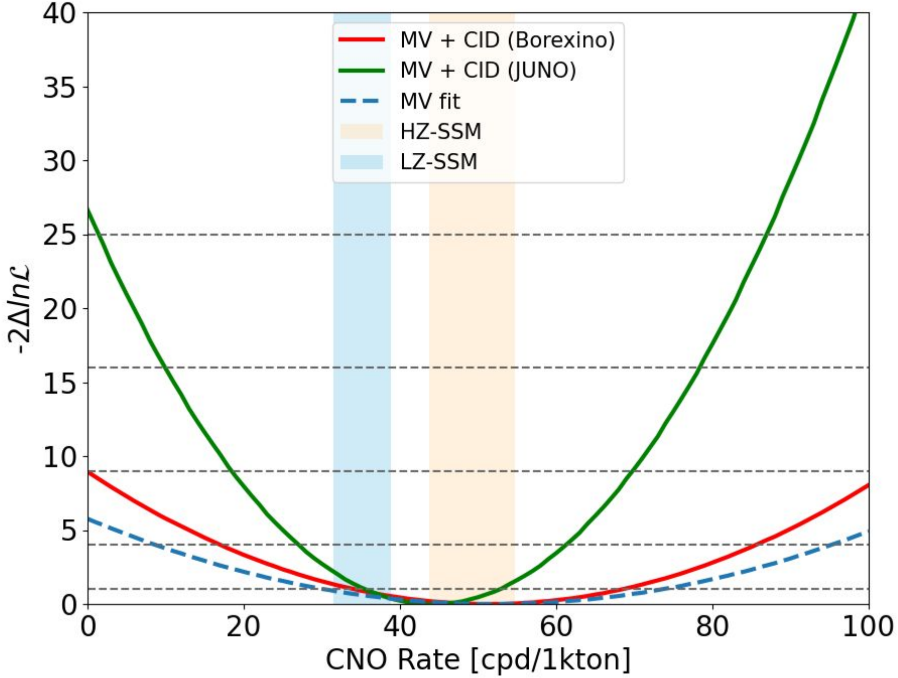
Variation as function of Latitude (Using JUNO's coordinate system and JUNO's longitude)

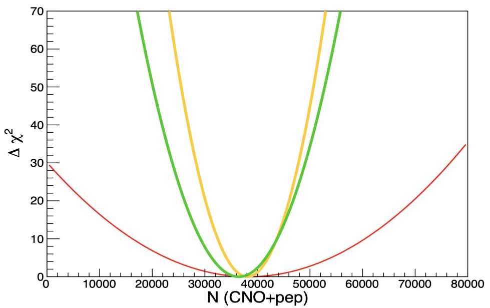
For 1 year



Results

Baseline radiopurity scenario
1 year of data taking





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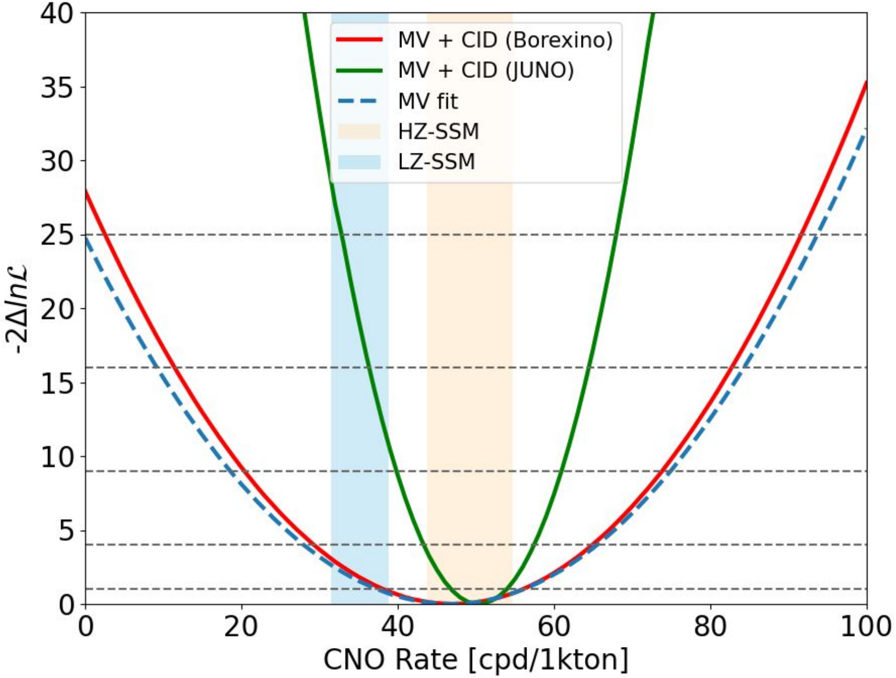
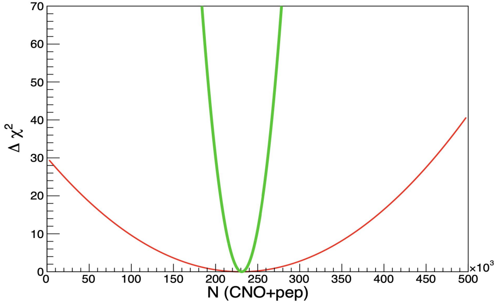
Juno constraint ~ 5.2 sigma

- With more realistic backgrounds, CID constraint can help **JUNO reach 5σ in only one year!**
- Relative impact of CID constraint is higher for baseline scenario (~79%) than Bx-like (~74%)
  - Sensitivity lowers with increasing background but **CID constraint has more impact**

Results

Baseline radiopurity scenario
6 years of data taking





CID profile used as additional constraint

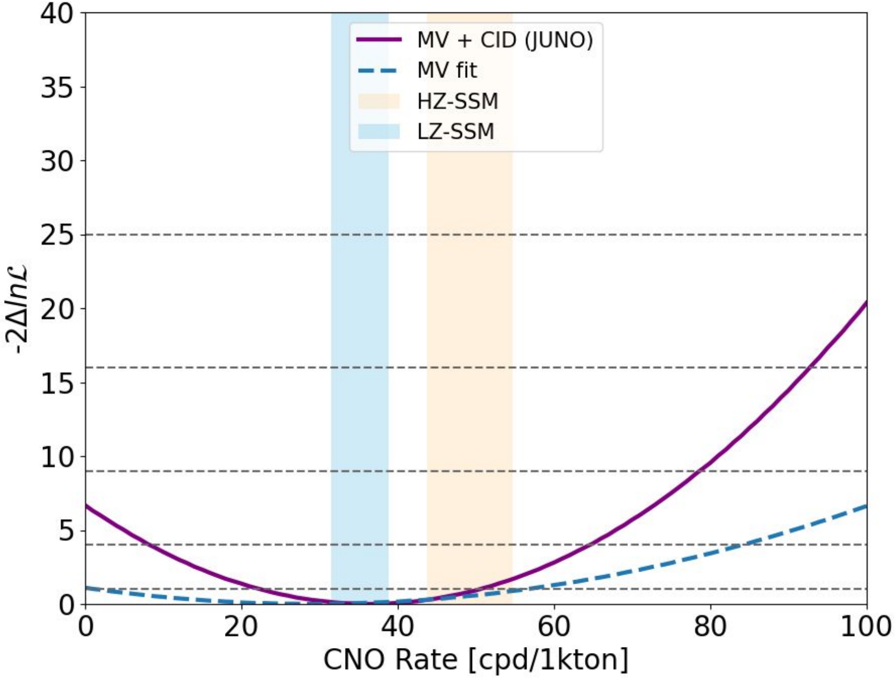
Significance to no-CNO hypothesis:

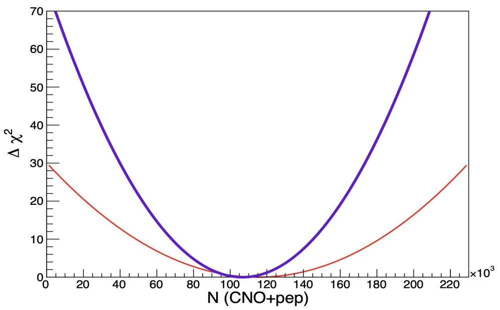
MV fit ~ 4.9 sigma
Bx-CID constraint ~ 5.3 sigma
Juno constraint > 10 sigma

Increasing statistics we get better sensitivity from MV fit and **CID importance is enhanced (relative impact ~88%)**

Results

IBD radiopurity scenario
3 years of data taking





CID profile used as additional constraint

Significance to no-CNO hypothesis:

MV fit < 1.0 sigma
Juno constraint ~ 2.6 sigma

Including CID constraint we can look for CNO neutrinos even for IBD scenario with low statistics