CNO solar neutrino detection with Borexino: directionality measurement and spectral analysis

Luca Pelicci[1,2] on behalf of the Borexino Collaboration

1 Institut für Kernphysik, Forschungszentrum Jülich, Germany
2 RWTH Aachen University - Physics Institute III B, Aachen, Germany

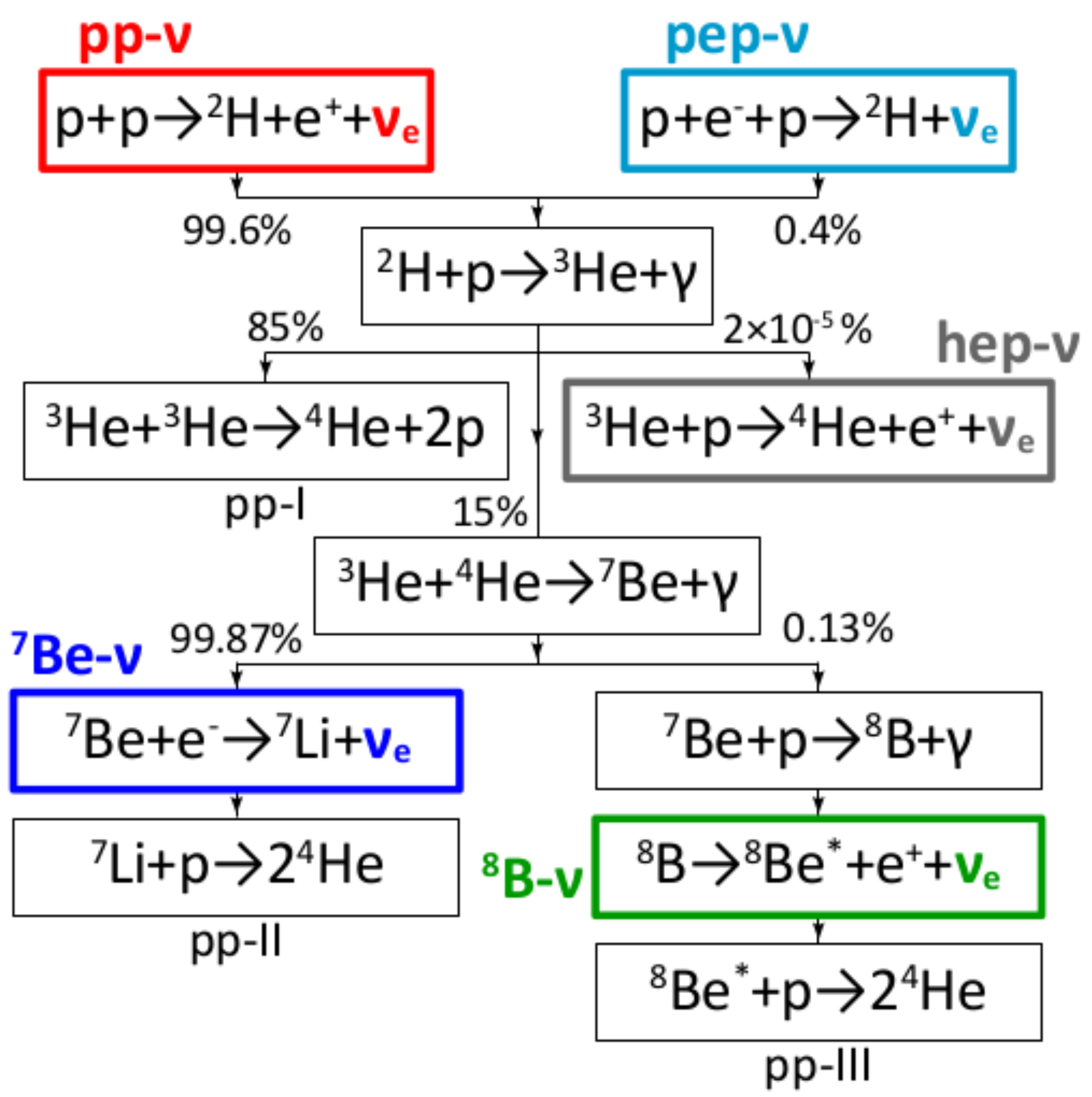
INTERNATIONAL WORKSHOP ON NEUTRINO TELESCOPES 2023 - 26.10.2023

Mitglied der Helmholtz-Gemeinschaft

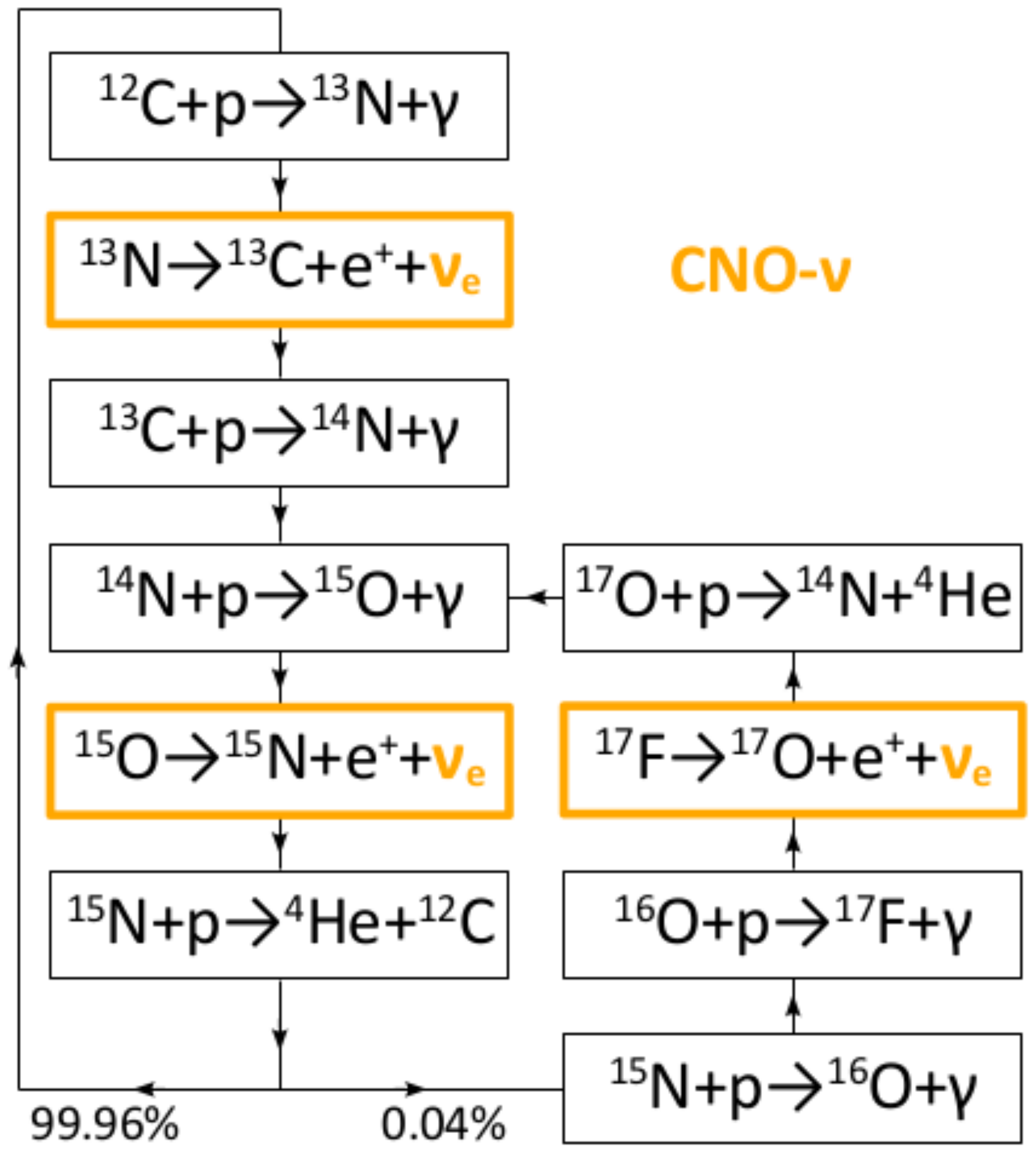
SOLAR NEUTRINOS

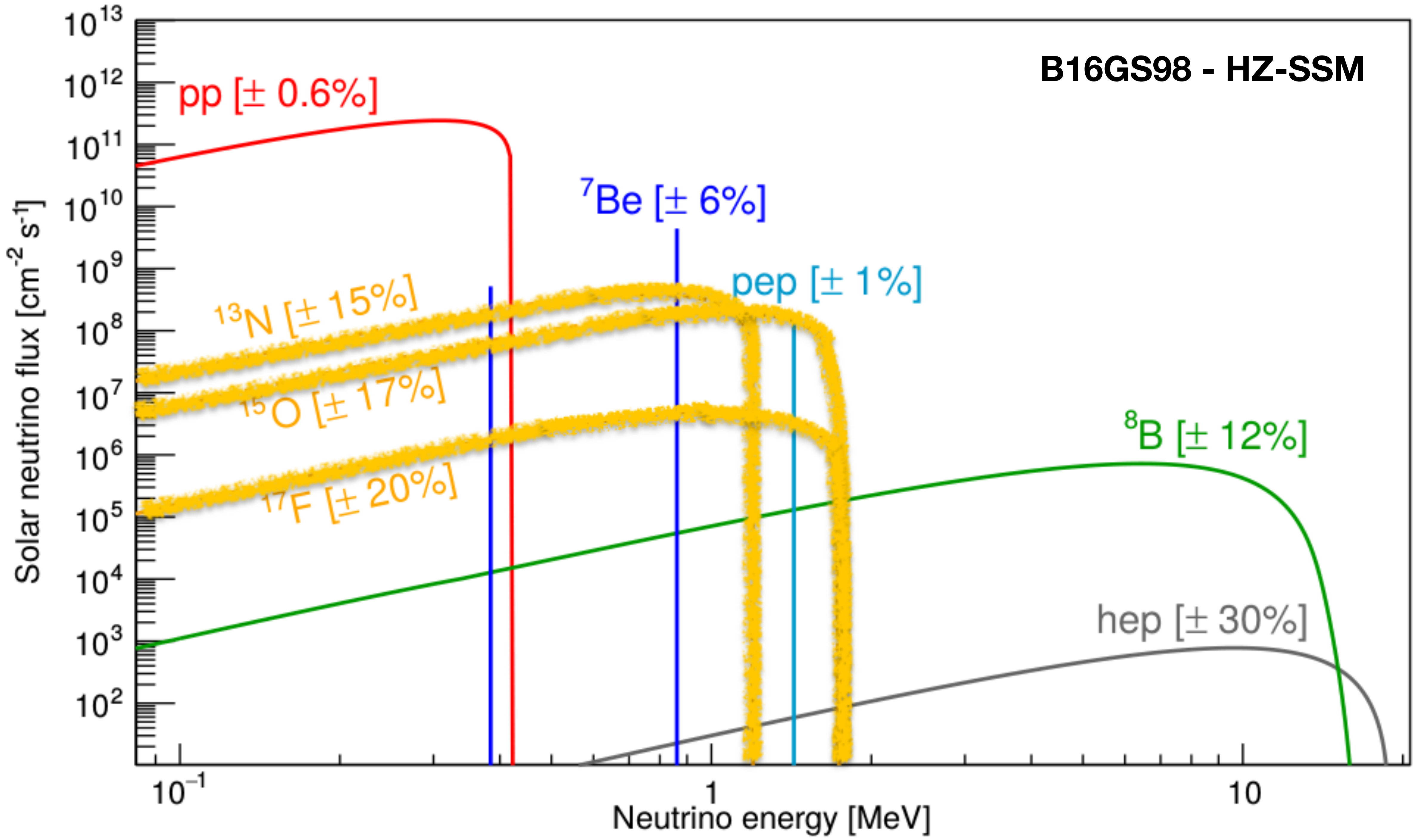
The Sun is powered by two sequences of thermonuclear reactions:

pp chain reaction (~99% $E_\odot$)



CNO cycle (~1% $E_\odot$)





Net reaction: $4p \rightarrow \; ^4He + 2e^+ + 2\nu_e \qquad Q \approx 26.7 MeV$

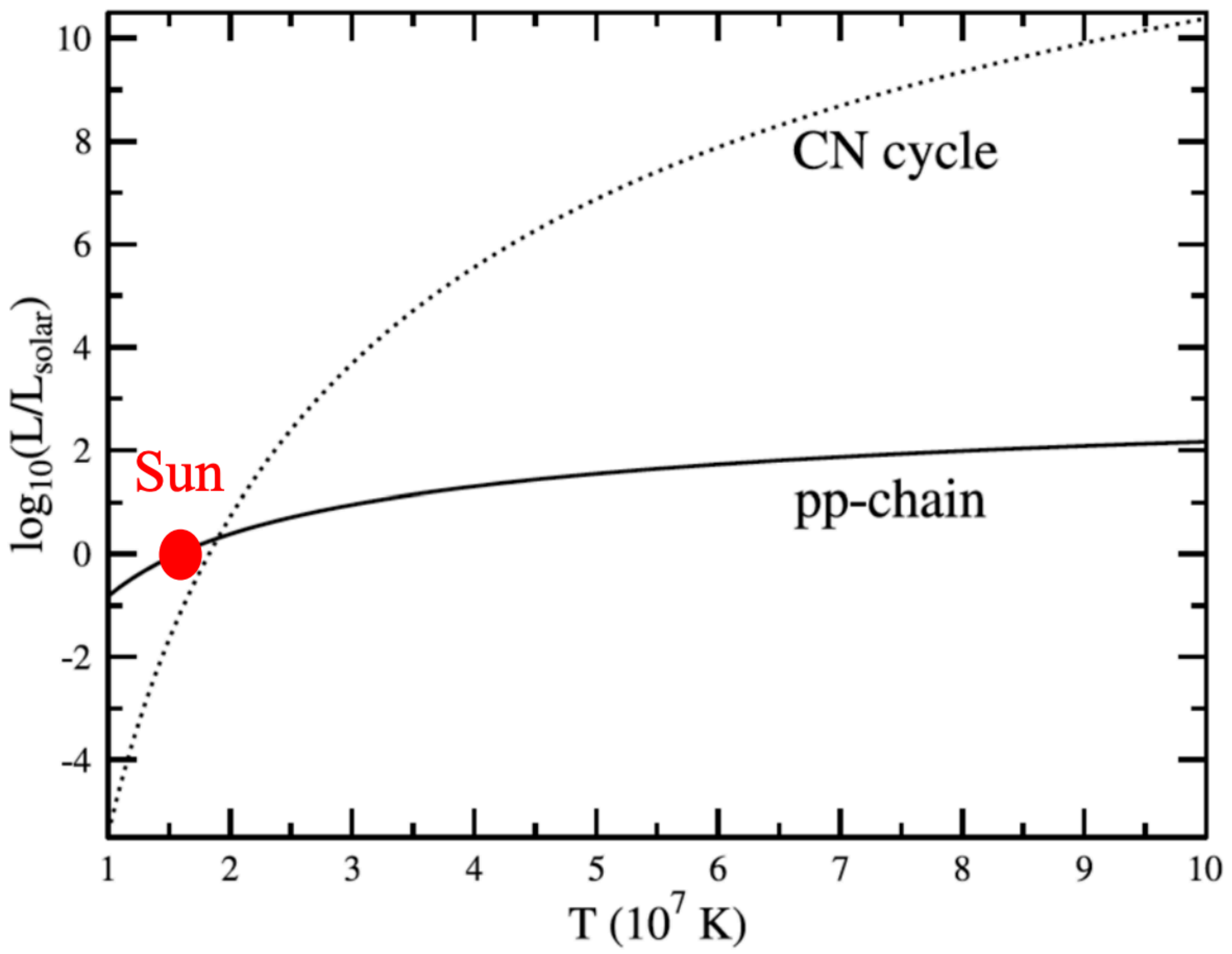
SOLAR NEUTRINOS

The Sun is powered by two sequences of thermonuclear reactions:

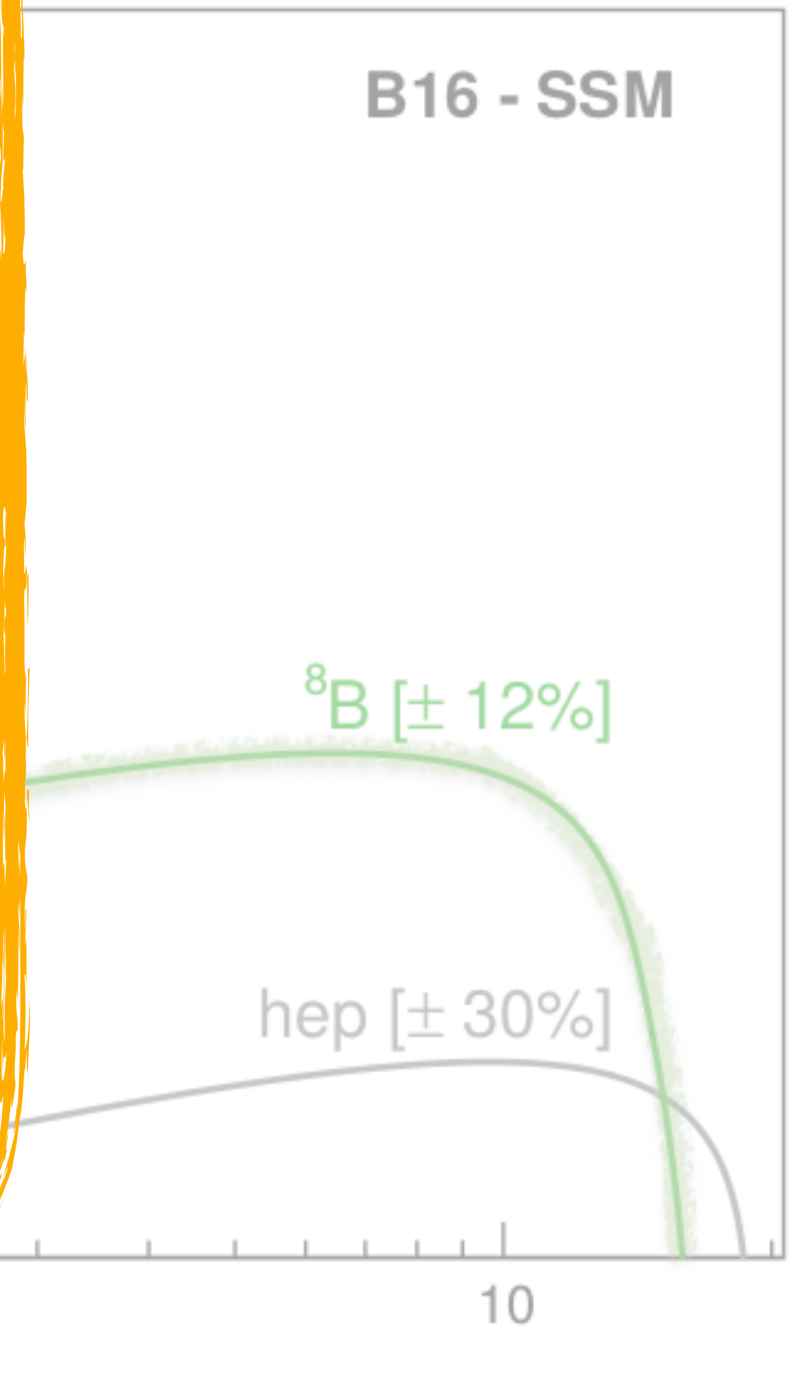
pp chain

pp-ν
p+p→^{2}H+e$^+$+ν$_e$
99.6%
^{2}H+p→^{3}H
85%
^{3}He+^{3}He→^{4}He+2p
pp-I
15%
^{3}He+^{4}He→
^{7}Be-ν 99.87%
^{7}Be+e$^-$→^{7}Li+ν$_e$
^{7}Li+p→2^{4}He
pp-II
^{8}B-ν

The importance of CNO neutrinos



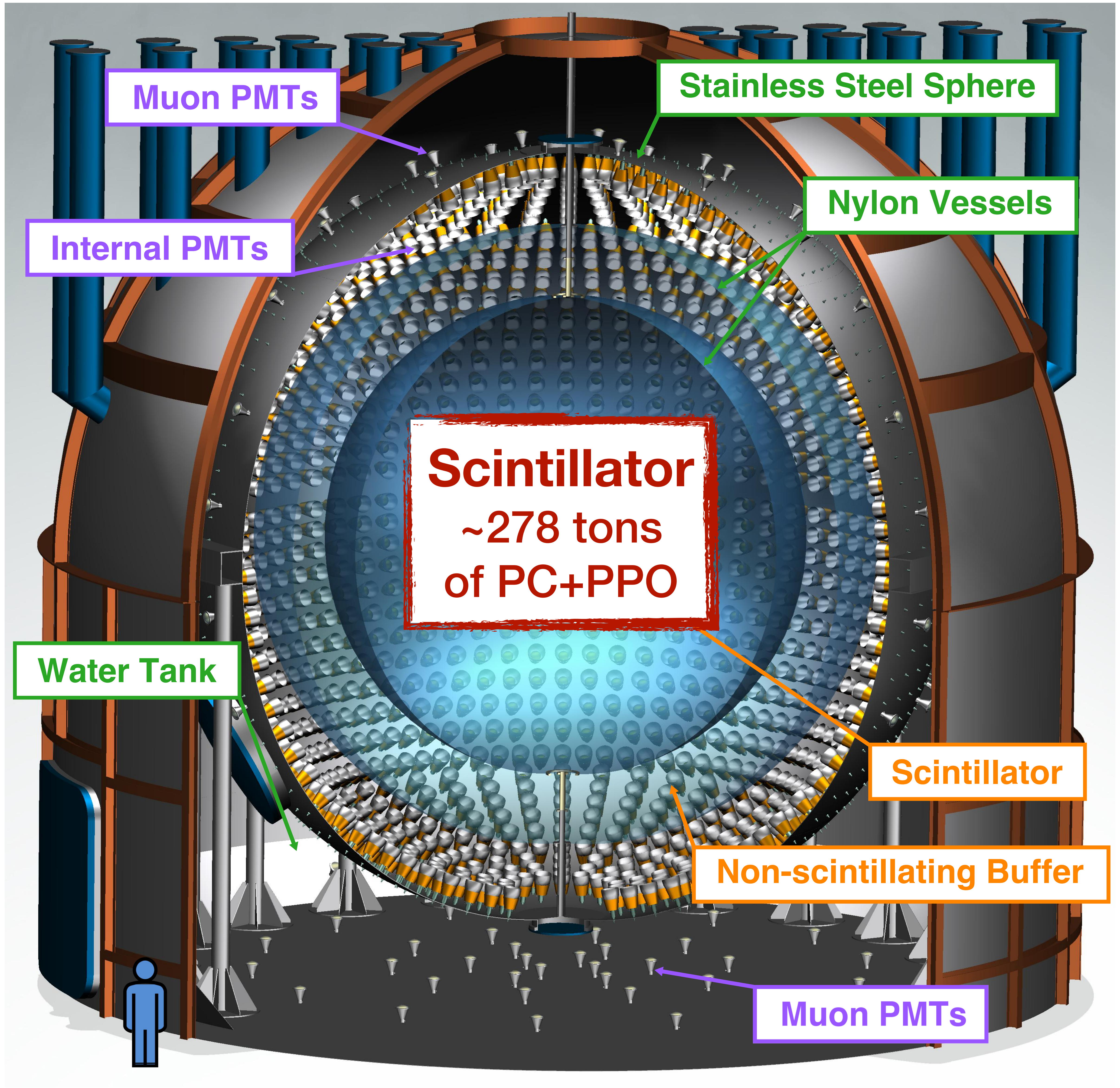
- **Proof of existance** of Carbon - Nitrogen - Oxygen (CNO) cycle in nature
- CNO cycle is expected to be dominant for stars with $M \geq 1.3\ M_\odot$
- Sensitive to Sun's core **metallicity problem**



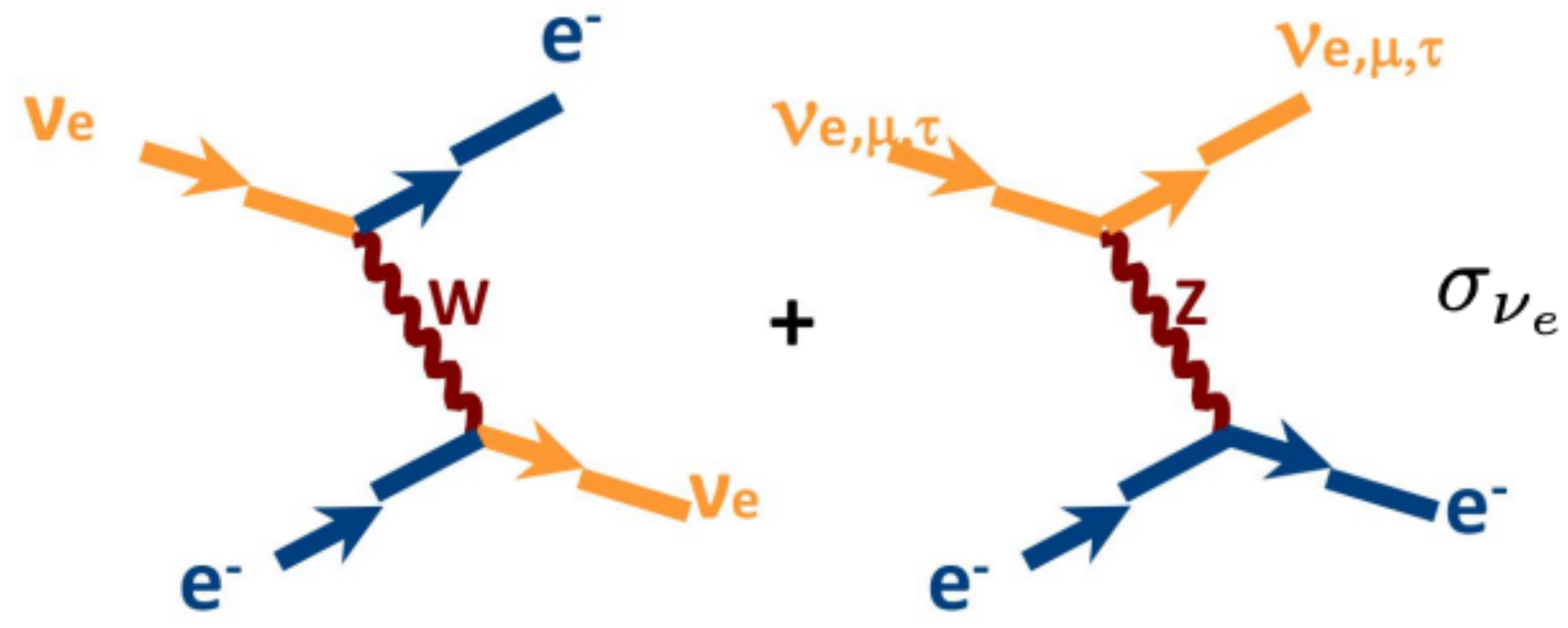
Net reaction: $4p \rightarrow\ ^4He + 2e^+ + 2\nu_e \qquad Q \approx 26.7MeV$

BOREXINO DETECTOR

Location: Laboratori Nazionali del Gran Sasso (LNGS), Italy



Detection channel: neutrino-electron elastic scattering



$$\sigma_{\nu_e} : \sigma_{\nu_{\mu,\tau}} :\cong 1 : 0.16$$

Unique features:

- ☑ **The Most radio-pure liquid scintillator detector in the world**: $c(^{232}\mathrm{Th}) < 7.2 \cdot 10^{-19}\ g/g$ and $c(^{238}\mathrm{U}) < 9.5 \cdot 10^{-20}\ g/g$
- ☑ **High effective light yield** (~500 p.e./MeV with 2000 PMTs)
- ☑ Low energy threshold (~0.15 MeV)
- ☑ Good energy (~6% at 1 MeV) and position resolutions (~11 cm at 1 MeV)
- ☑ DAQ period: 2007 - 2021

JÜLICH Forschungszentrum

SOLAR NEUTRINOS WITH BOREXINO: A LONG JOURNEY

- ☑ **1990**: Start of R&D for innovative radiopurity methods
- ☑ **1995**: Counting Test Facility (CTF) testing the radiopurity
- ☑ **1997**: Approval of the experiment
- ☑ **2007**: Begin of data taking

Liquid scintillator purification campaign

Phase-I (2007 - 2010)

Solar neutrinos:
- $^7Be\ \nu$: 1st observation (5%) + no Day/Night asymmetry;
- pep ν: 1st observation;
- ^{8}B ν with low threshold;
- CNO ν : best limit;

Liquid scintillator purification campaign

Phase-II (2012 - 2016)

Solar neutrinos:
- pp ν: 1st observation;
- $^7Be\ \nu$ flux seasonal modulation;
- **Comprehensive measurement of pp-chain (Nature 2014 and 2018)**

Thermal insulation and active temperature control

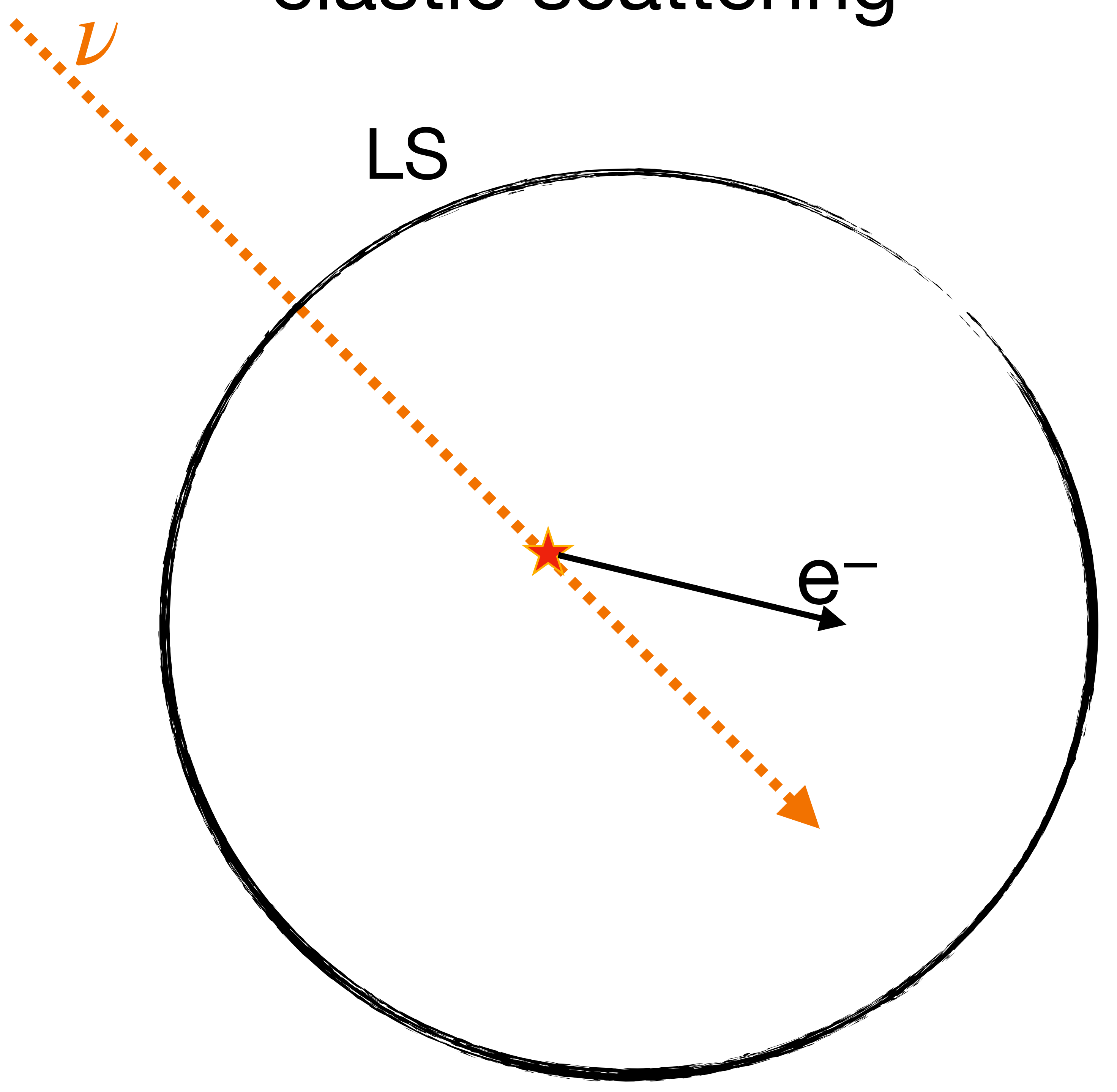
Phase-III (2016 - 2021)

End of data taking

Solar neutrinos:
- First direct experimental evidence of CNO neutrinos (Nature 2020)
- Updated CNO measurement (2022)
- **Directional measurement of CNO solar neutrinos**

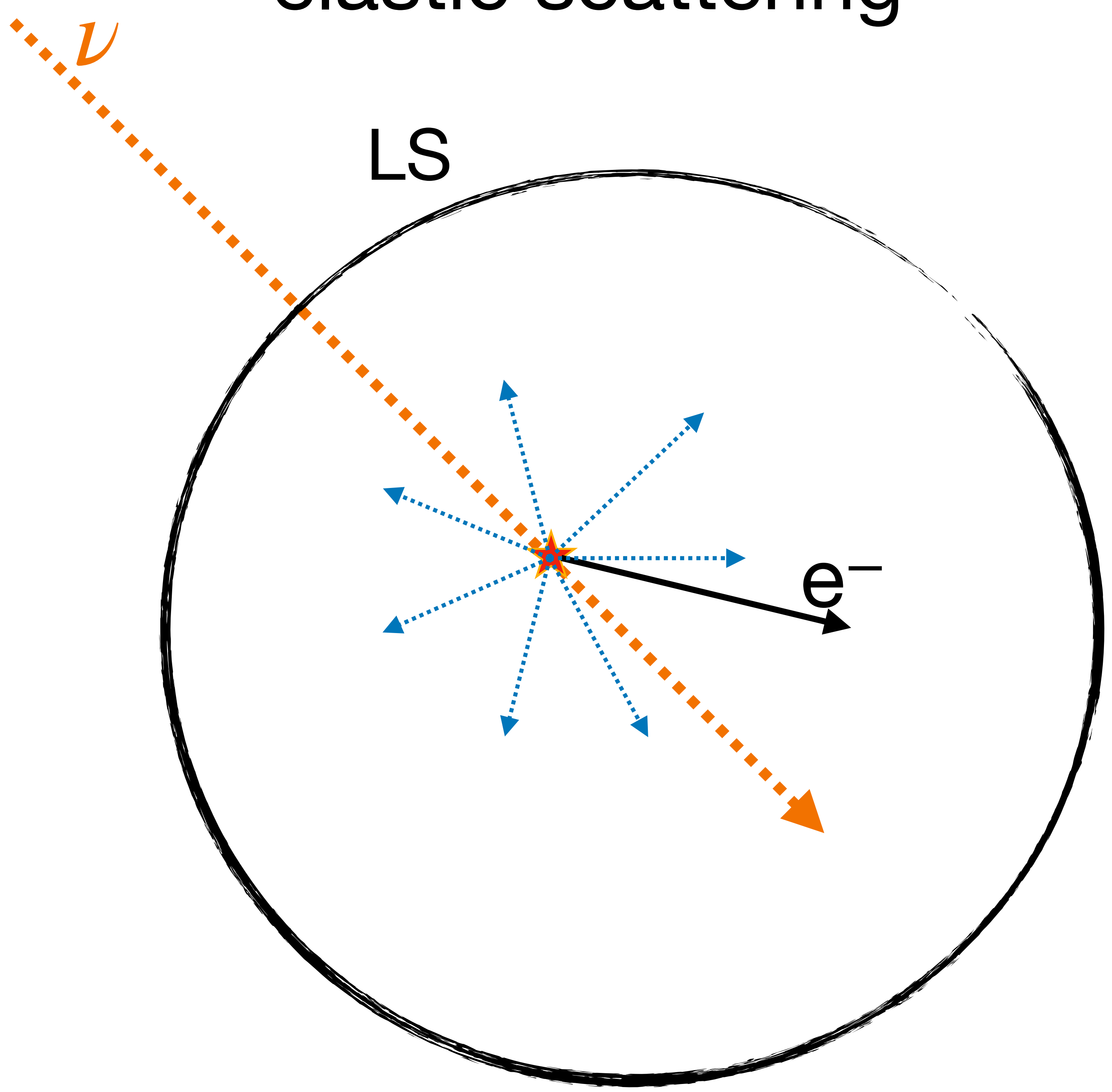
SOLAR NEUTRINO DETECTION IN BOREXINO

Solar neutrino interact in liquid scintillator (LS) with electrons via elastic scattering



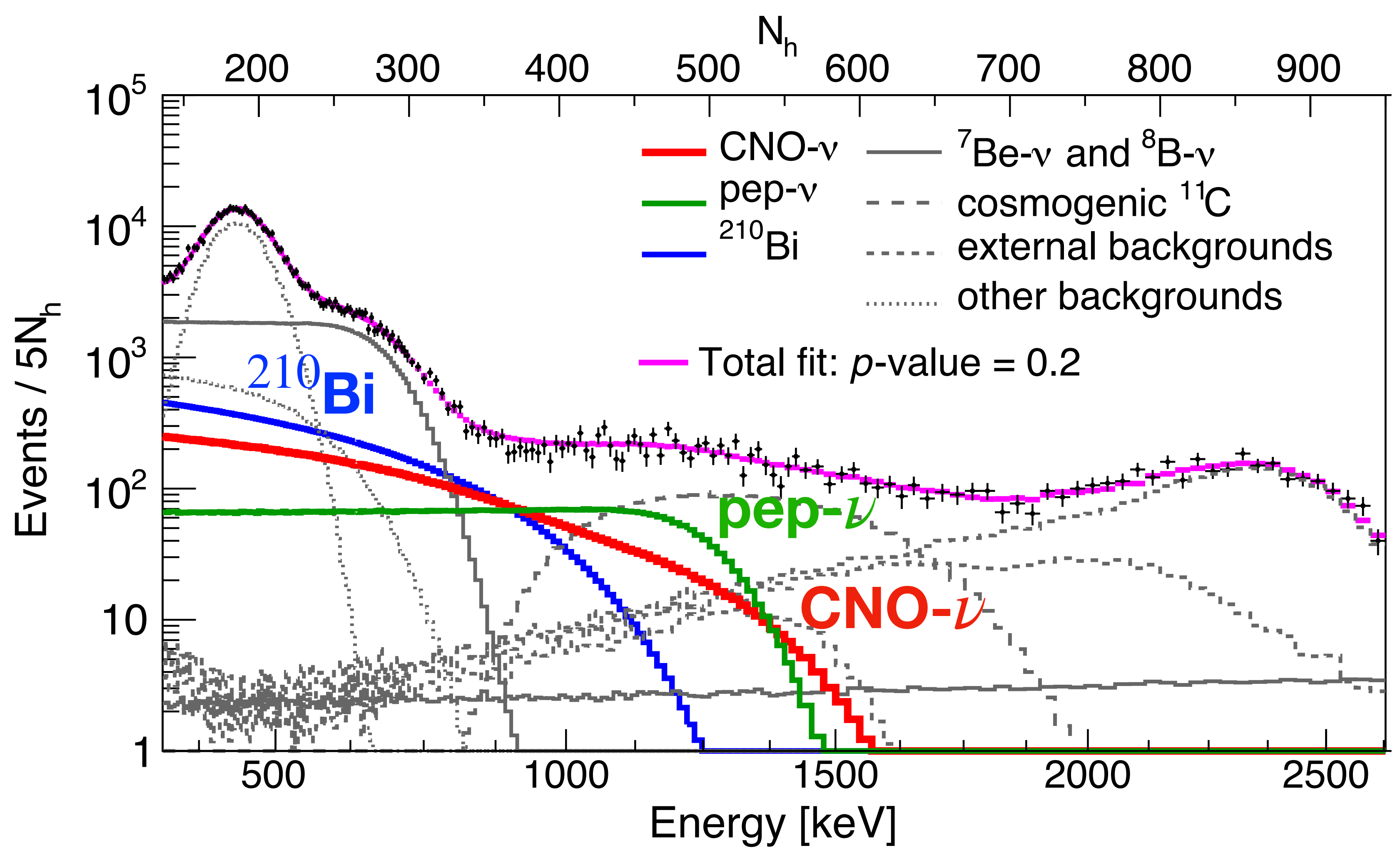
SOLAR NEUTRINO DETECTION IN BOREXINO

Solar neutrino interact in liquid scintillator (LS) with electrons via elastic scattering



No directional information

Scintillation light (dominant): spectral fit analysis



- Phase-III: January 2017 - October 2021
- **Likelihood fit** of energy and radial distributions
- Fit parameters: interaction rates of solar neutrinos and backgrounds
- **Constraints:**

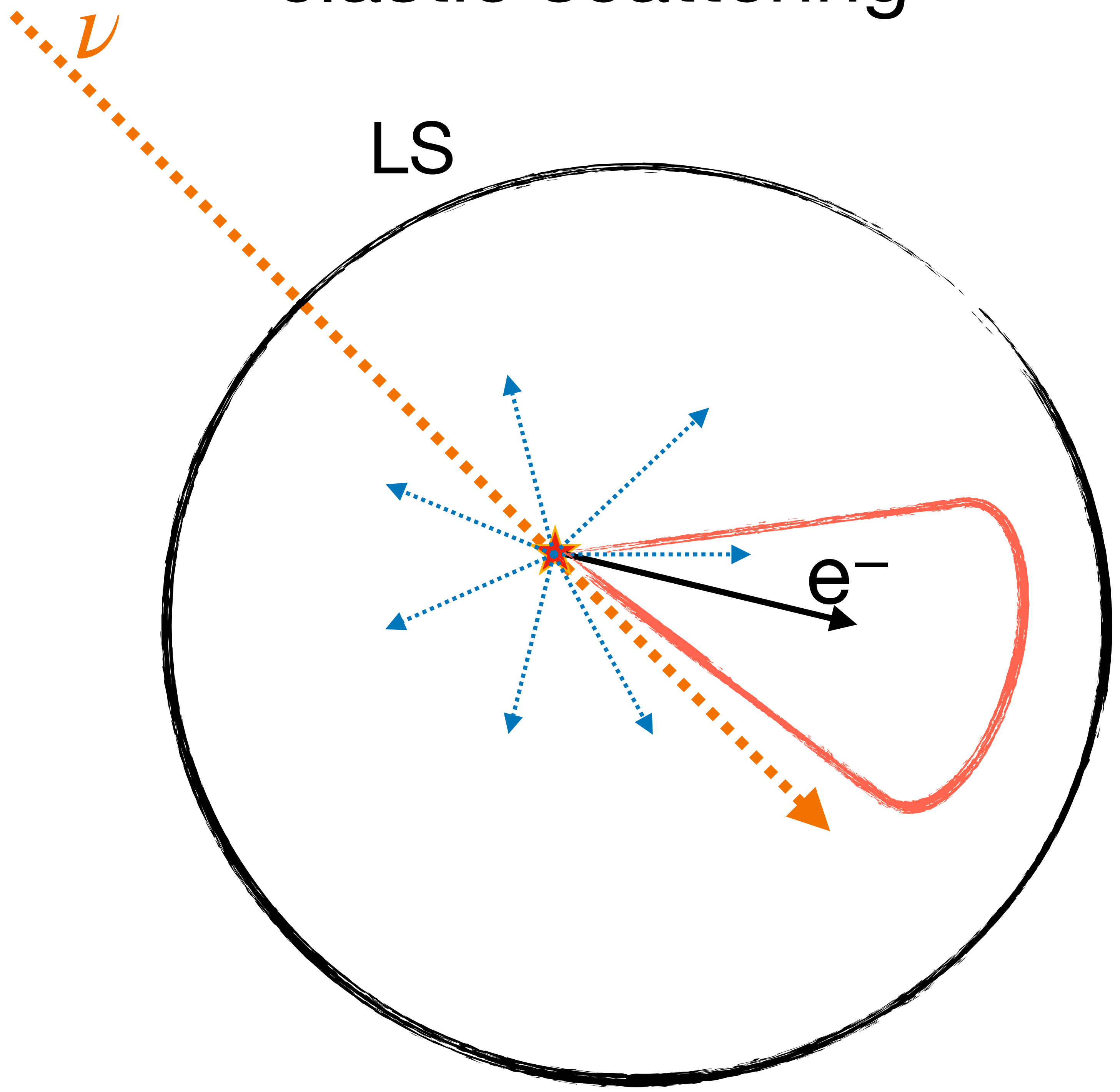
$\nu(pep) = 2.74 \pm 0.04$ **cpd/100 t**

$R(^{210}\mathrm{Bi}) = 10.8 \pm 1.0$ cpd/100t

Phys. Rev. Lett. 129 (2022) 252701.

SOLAR NEUTRINO DETECTION IN BOREXINO

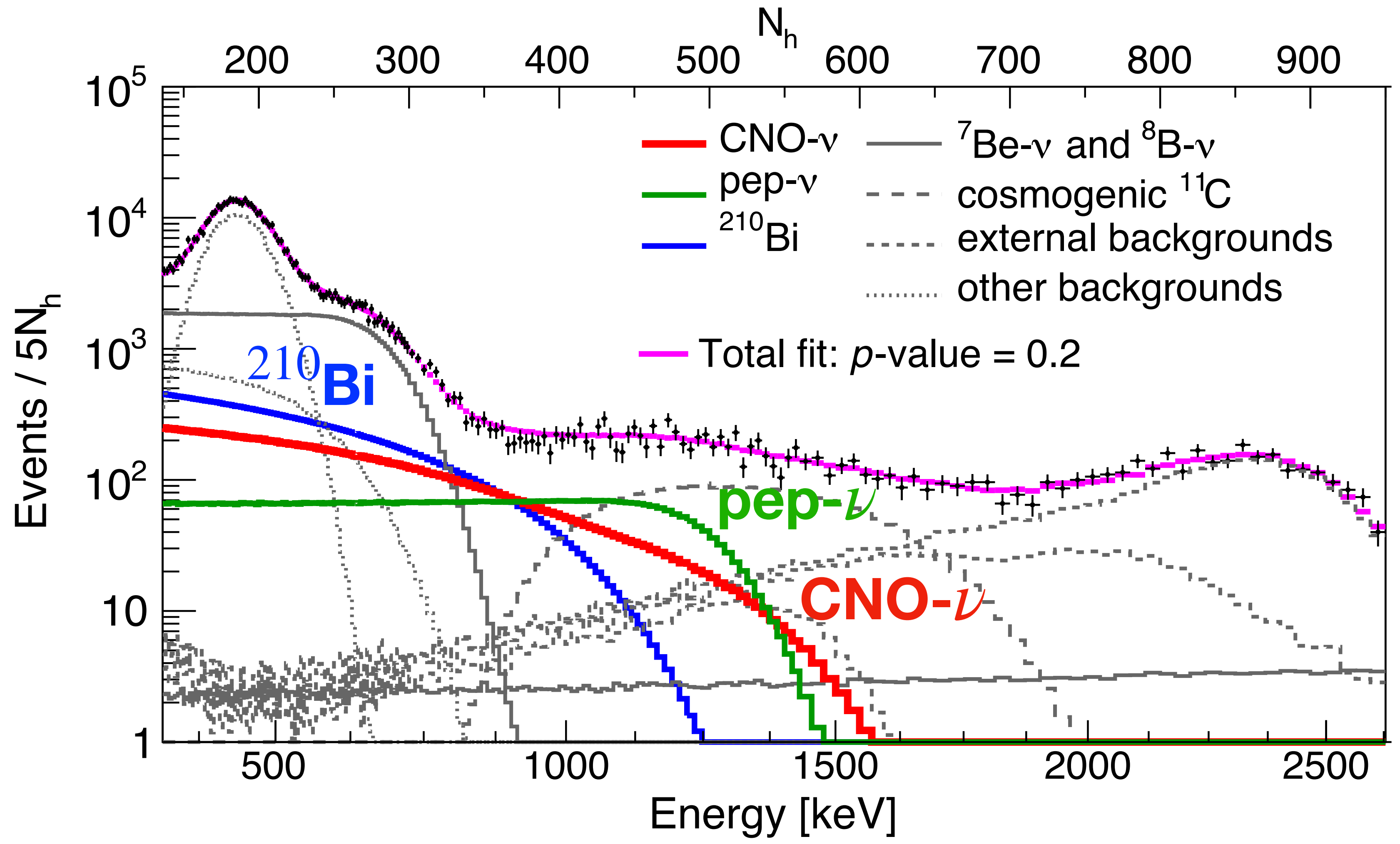
Solar neutrino interact in liquid scintillator (LS) with electrons via elastic scattering



No directional information

Directional information

Scintillation light (dominant): spectral fit analysis



- ☑ Phase-III: January 2017 - October 2021
- ☑ **Likelihood fit** of energy and radial distributions
- ☑ Fit parameters: interaction rates of solar neutrinos and backgrounds
- ☑ **Constraints:**

$\nu(pep) = 2.74 \pm 0.04$ **cpd/100 t**

$R(^{210}\mathrm{Bi}) = 10.8 \pm 1.0$ cpd/100t

Phys. Rev. Lett. 129 (2022) 252701.

Cherenkov light: Correlated Integrated Directionality (CID)

Novel technique introduced by Borexino to **exploit sub-dominant Cherenkov emission** (independent information wrt spectral fit)

Proof of principle measuring ^{7}Be flux

Phys. Rev. Lett. 128 (2022) 091803 and *Phys. Rev. D* 105 (2022) 052002.

New!

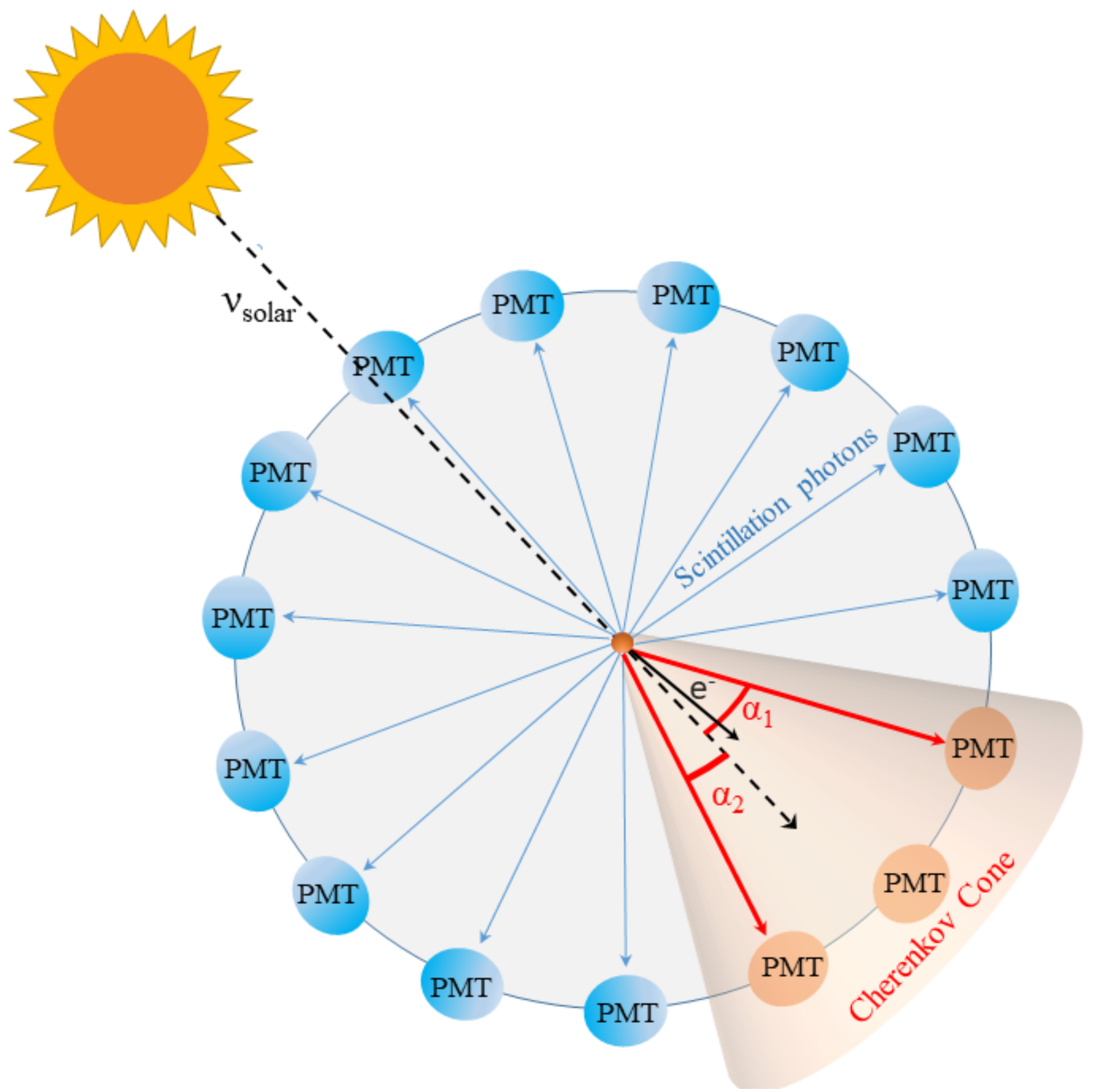
Exploit its potential for **CNO detection**

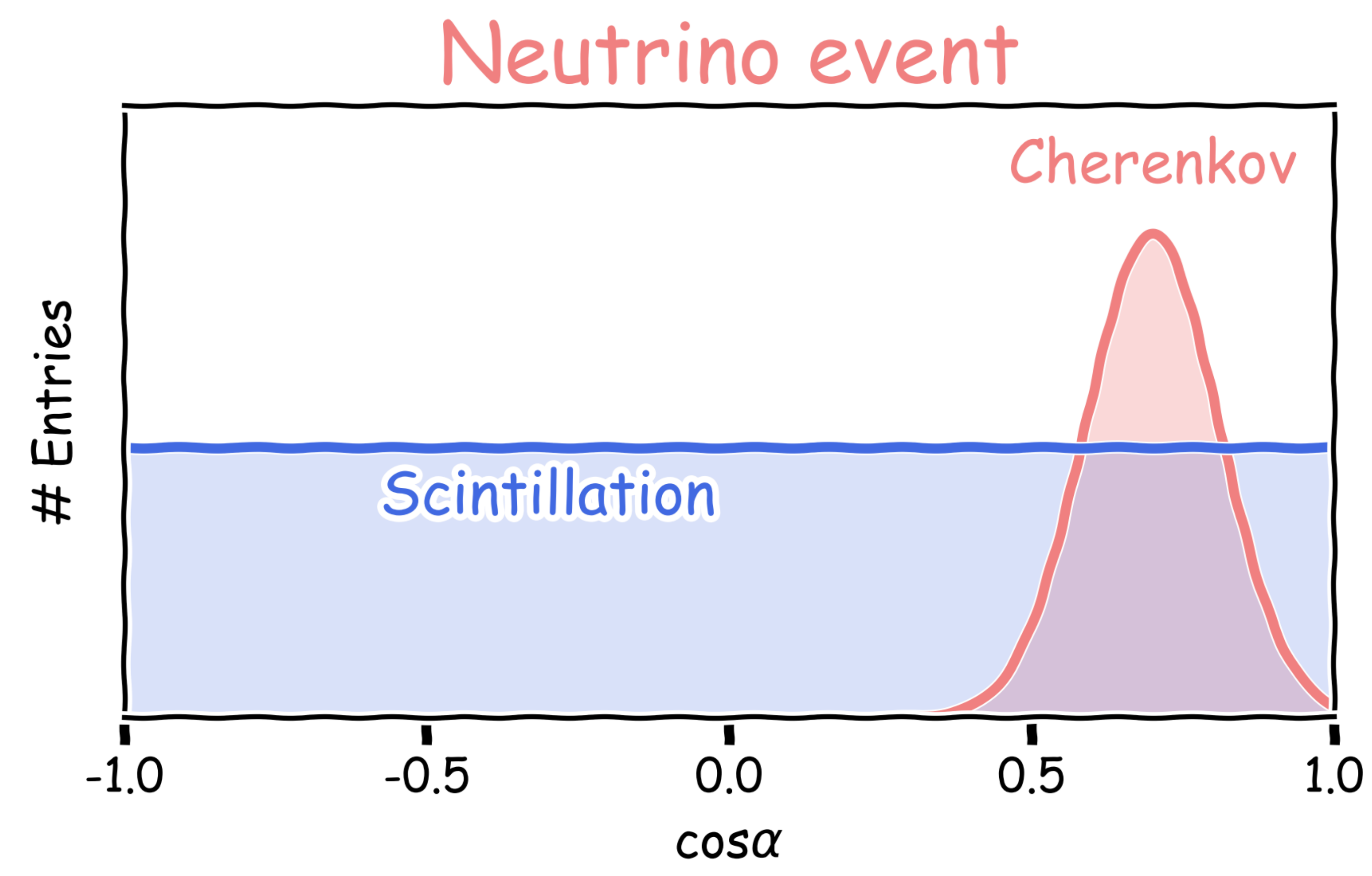
Accepted on Phys. Rev. D

CORRELATED INTEGRATED DIRECTIONALITY (CID)

Newly developed method by Borexino:

Exploit fast **Cherenkov light emission for** statistical separation of solar neutrinos and background





Neutrino Event:

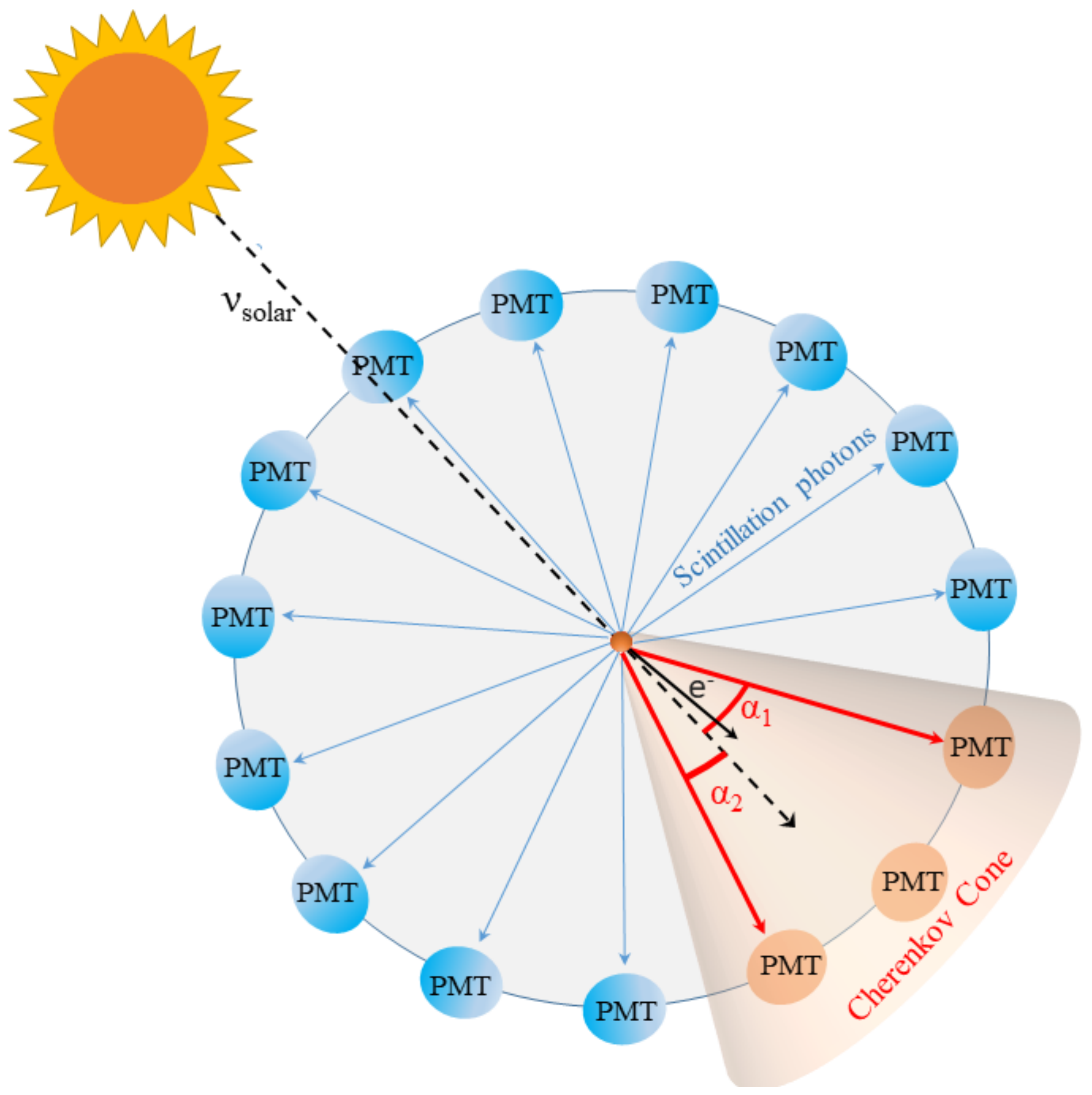
Cherenkov light correlated to the position of the Sun (non flat $\cos\alpha$)

JÜLICH Forschungszentrum

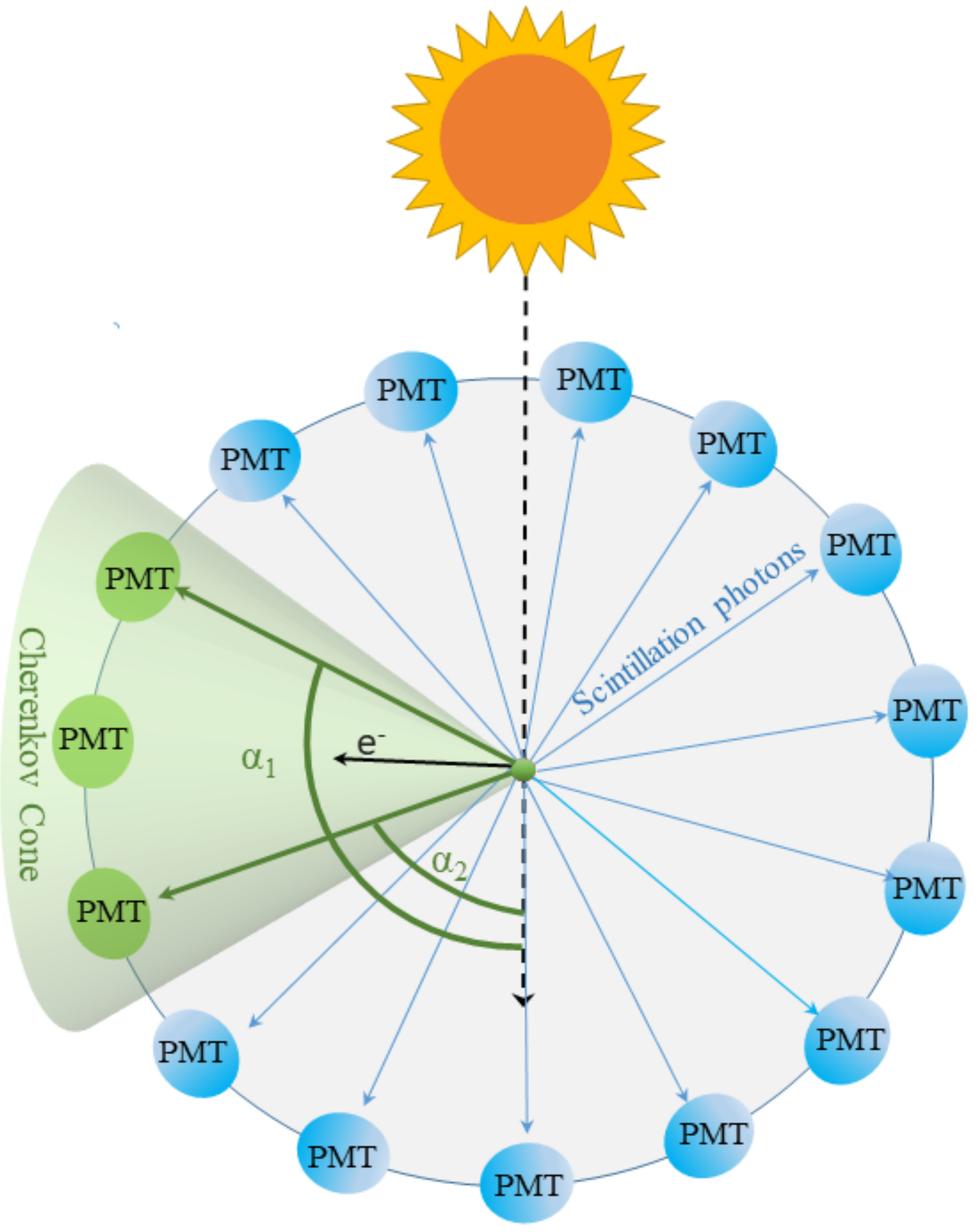
CORRELATED INTEGRATED DIRECTIONALITY (CID)

Newly developed method by Borexino:

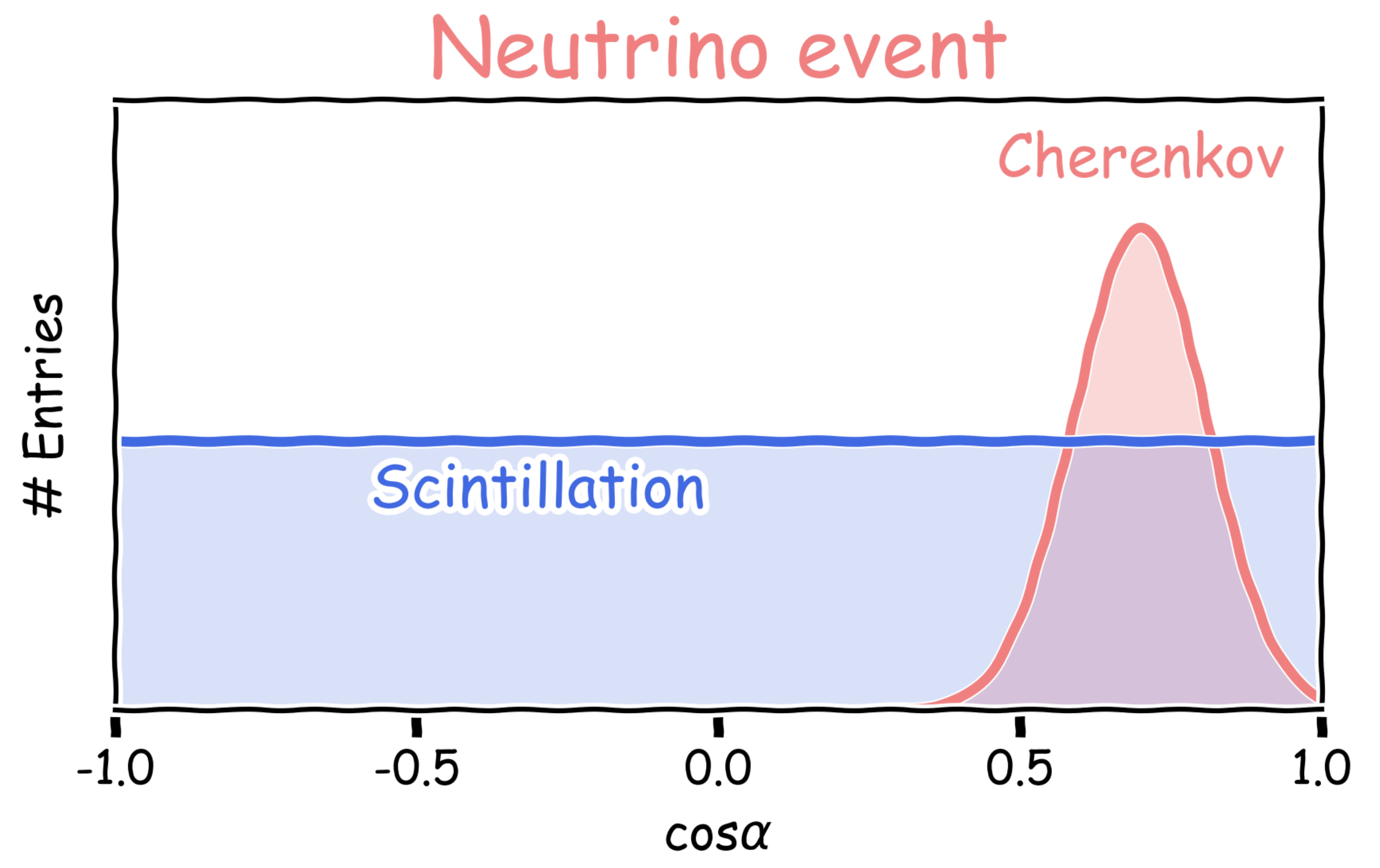
Exploit fast **Cherenkov light emission for** statistical separation of solar neutrinos and background

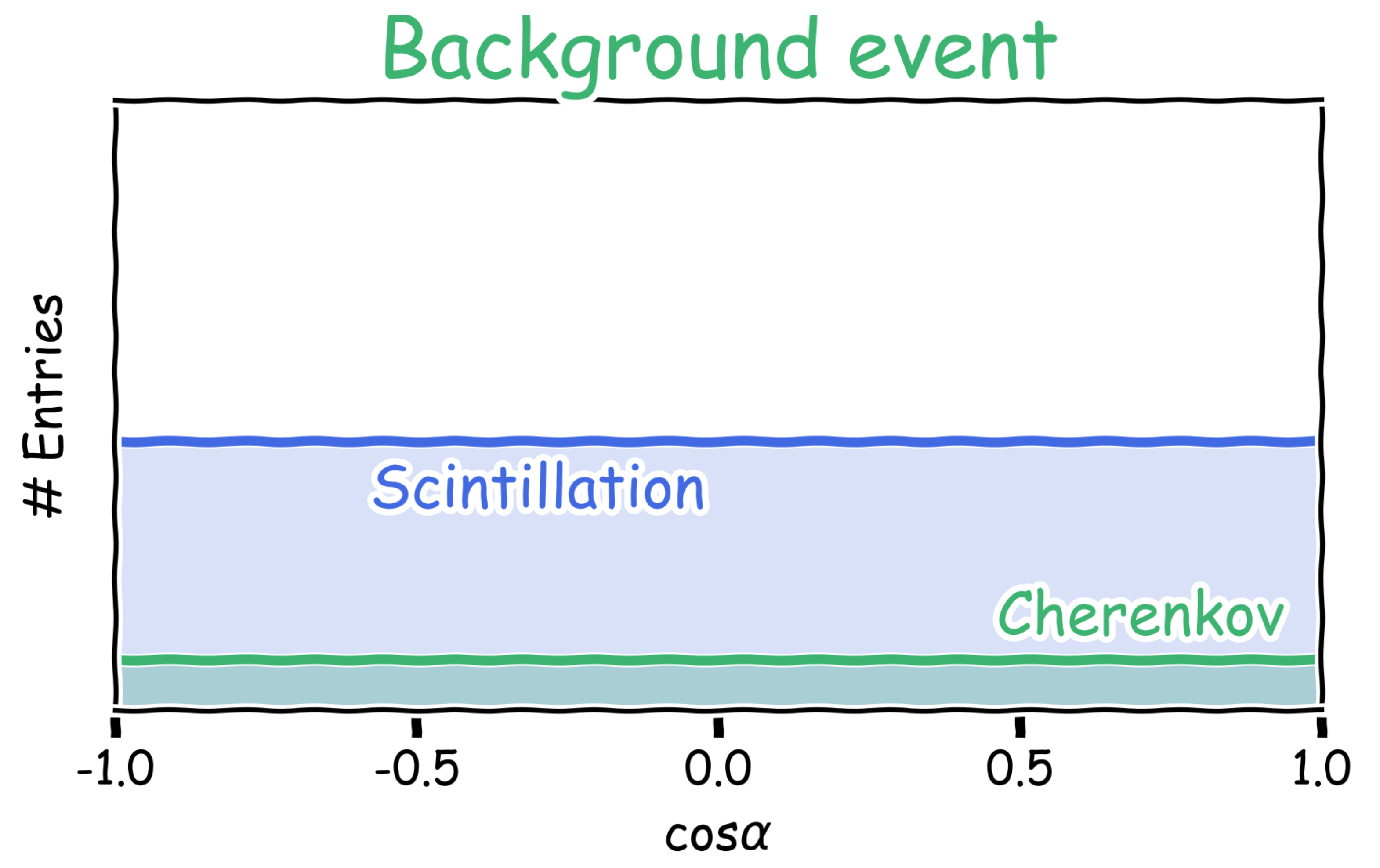


Neutrino Event:
Cherenkov light correlated to the position of the Sun (non flat $\cos\alpha$)



Background Event:
Cherenkov light uncorrelated to the position fo the Sun (flat $\cos\alpha$)





CORRELATED INTEGRATED DIRECTIONALITY (CID)

Scintillation and Cherenkov photons (PMT hits) are indistinguishable on an event-by-event basis

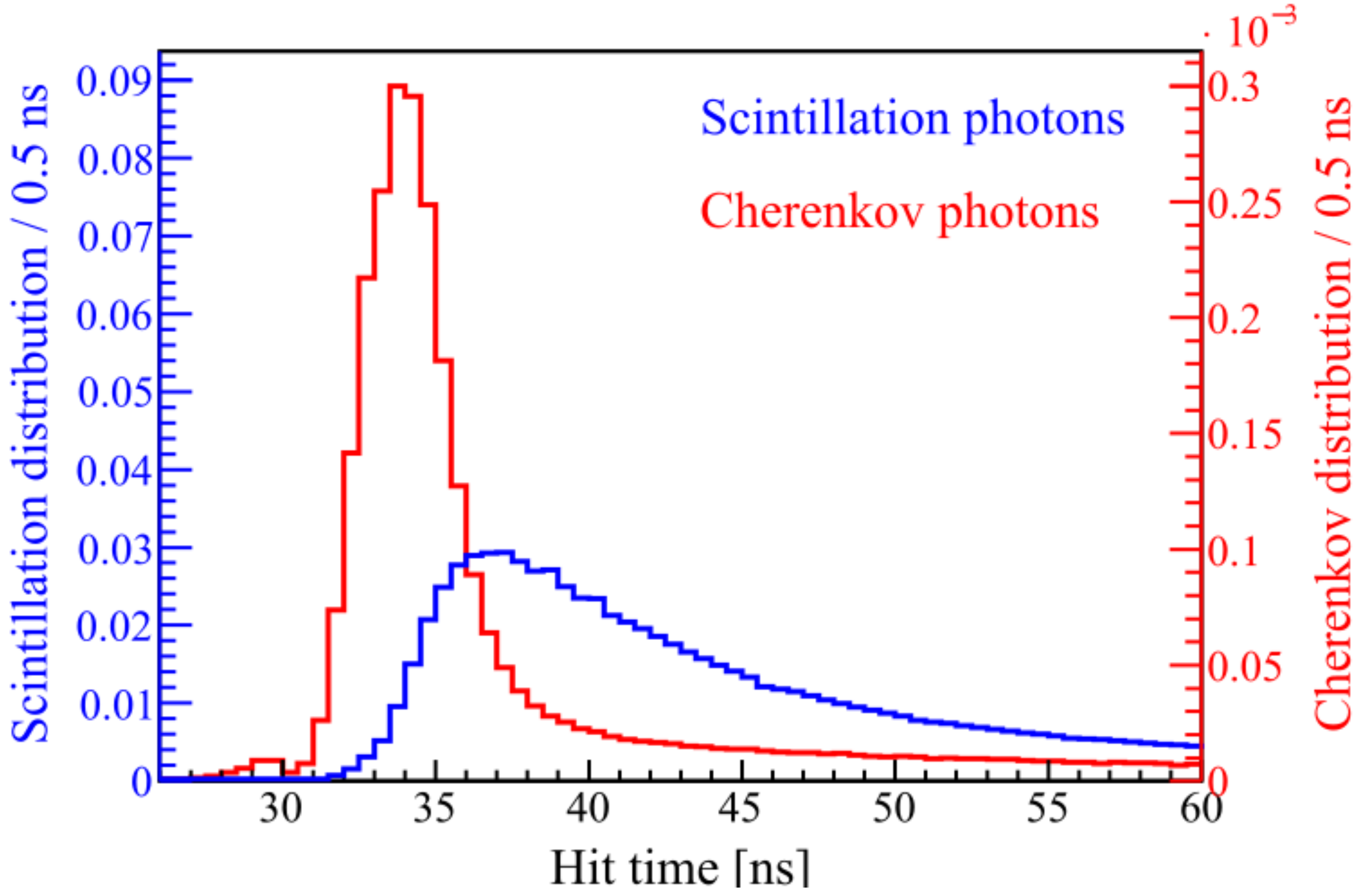
Ch/Sc separation optimized through **time ordering** of PMT hits

JÜLICH
Forschungszentrum

CORRELATED INTEGRATED DIRECTIONALITY (CID)

Scintillation and Cherenkov photons (PMT hits) are indistinguishable on an event-by-event basis

Ch/Sc separation optimized through **time ordering** of PMT hits

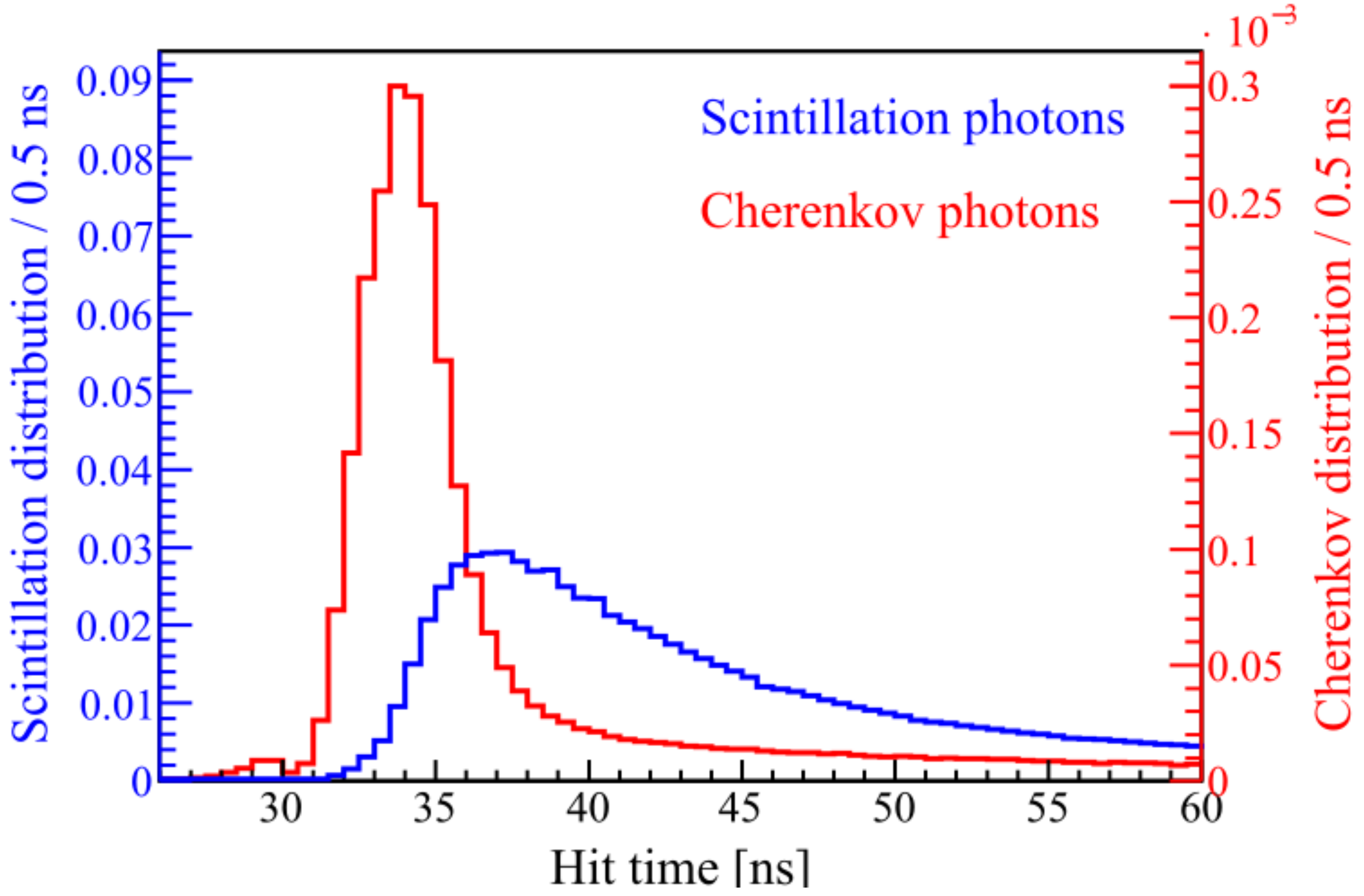


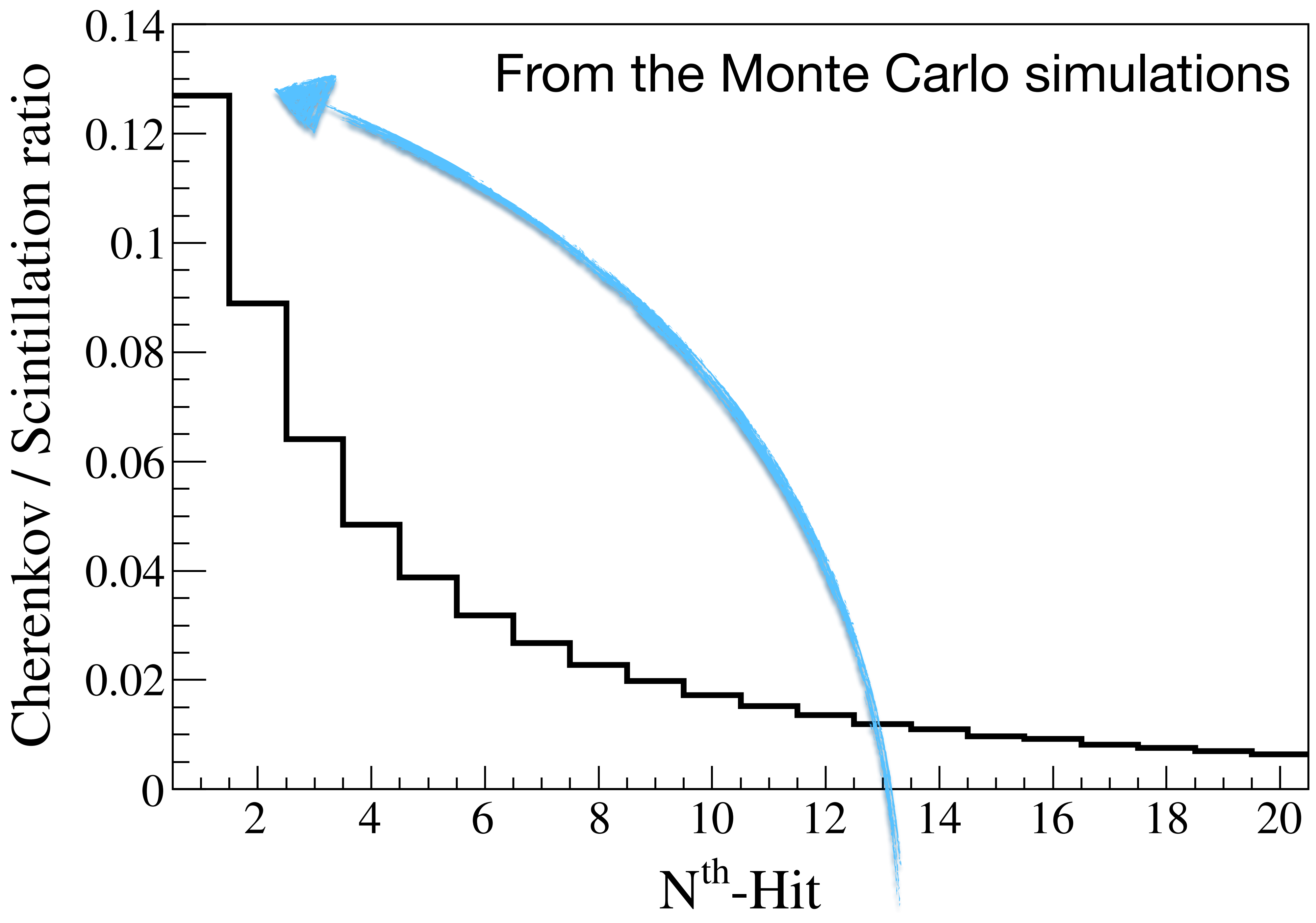
- ☑ Sub-dominant Cherenkov photons are emitted earlier
- ☑ Time ordering of PMT hits after time of flight (ToF) subtraction (wrt reconstructed position)

CORRELATED INTEGRATED DIRECTIONALITY (CID)

Scintillation and Cherenkov photons (PMT hits) are indistinguishable on an event-by-event basis

Ch/Sc separation optimized through **time ordering** of PMT hits





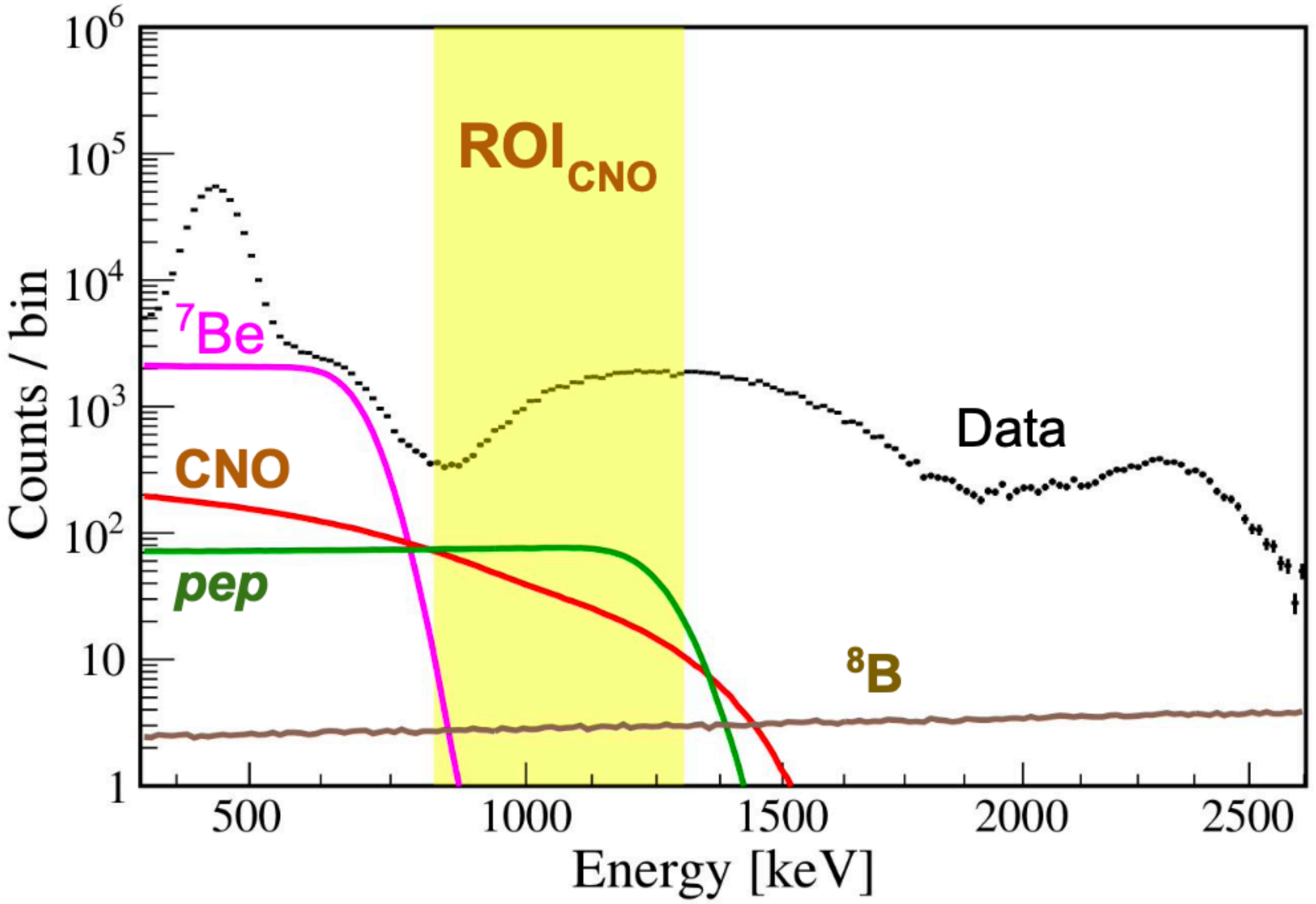
- Sub-dominant Cherenkov photons are emitted earlier
- Time ordering of PMT hits after time of flight (ToF) subtraction (wrt reconstructed position)

- Early hits have **higher Ch/Sc ratio**
- Build $\cos\alpha$ distributions for each **Nth-Hit**
- extract number of solar neutrnios (N_ν) via **simultaneous fit** of the produced $\cos\alpha$ spectra

$$\text{N}^{\text{th}}\text{-Hit} \begin{cases} \in [1-15] \text{ for Phase-I} \\ \in [1-17] \text{ for Phase-II+III} \end{cases}$$

DATA SELECTION AND MONTE CARLO MODEL FOR CID

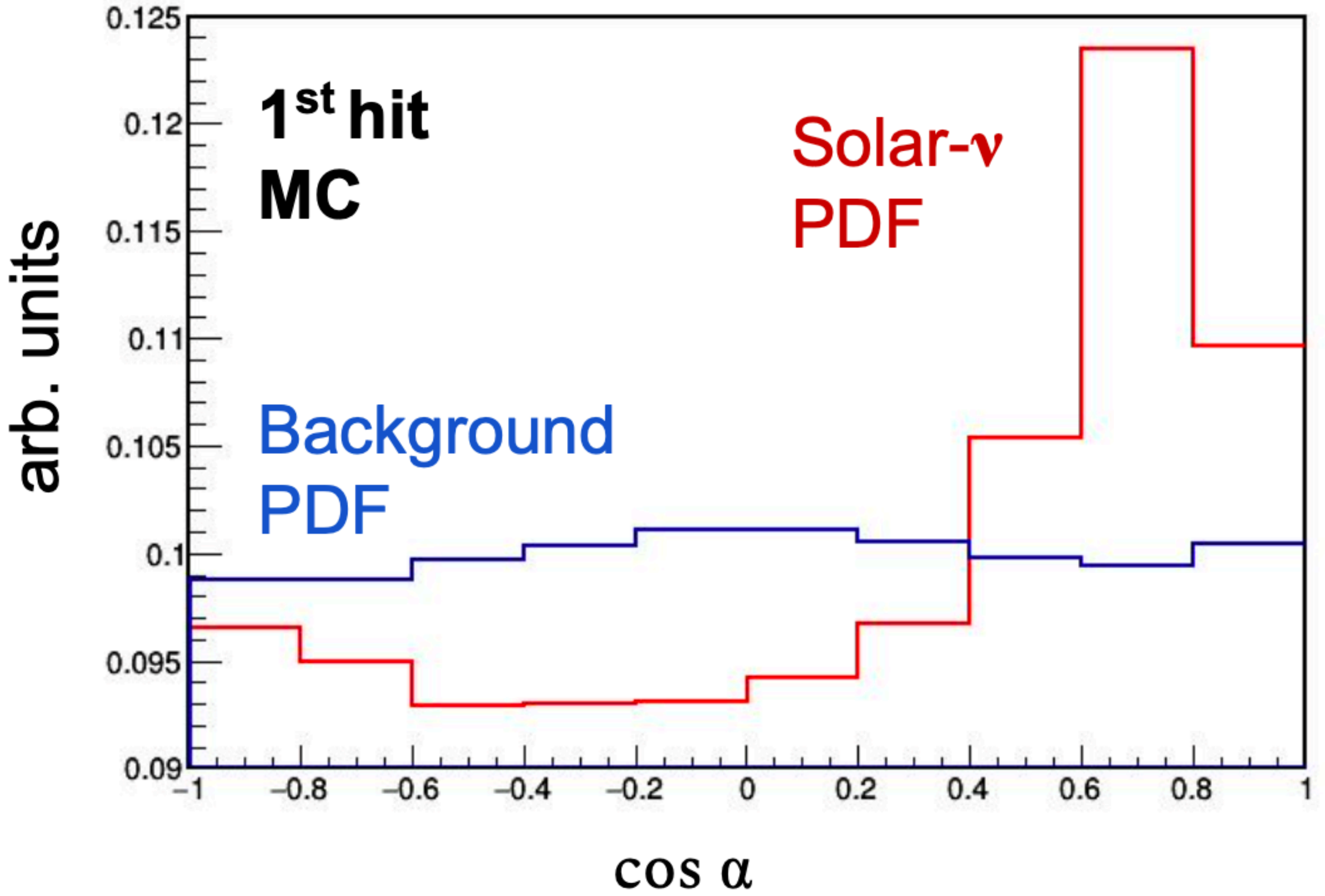
Region of Interest for CNO analysis (RoI_{CNO}) is optimised according to signal-to-noise ratio:



- Free parameters of the fit:
  - **Signal**: N_ν = pep-ν (~64%) + CNO-ν (~33%) + ^{8}B-ν (~3%)
  - **Bacgkround**: N_{bkg} (no preliminary information on **backgrounds** is needed)
- Whole Borexino DAQ: **Phase-I and PhaseII+III** analysis performed separately due to treatment of nuisance parameter (see next slide)

cos α PDFs produced with a Geant4-based Borexino Monte Carlo simulation

CID distribution of Phase-II+III from MC



All processes from neutrino interaction to Scintillation/**Cherenkov light production and propagation,** and electronic simulations are performed

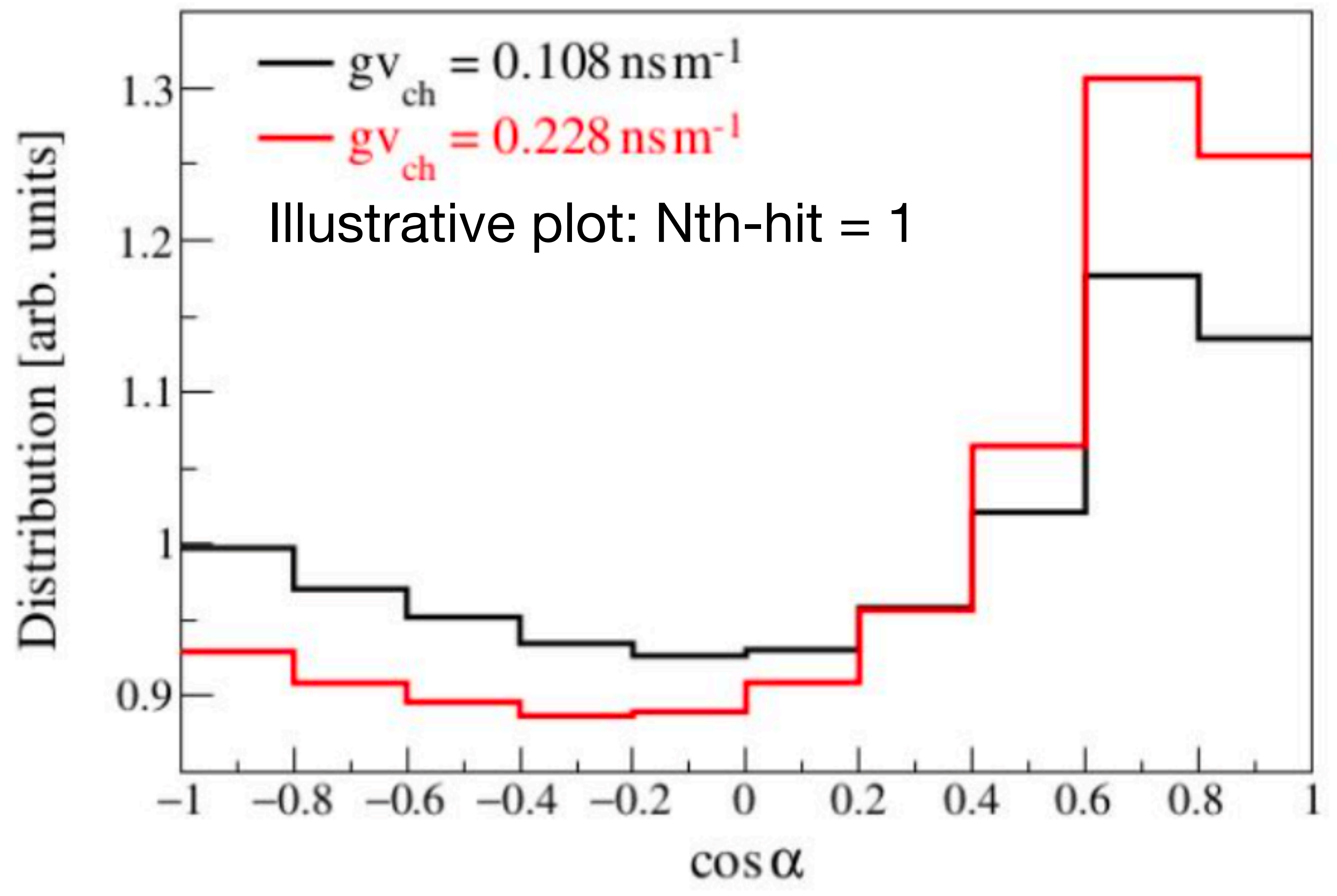
MAIN SYSTEMATIC EFFECTS OF CID

1. Group velocity correction for Cherenkov photons (gv_{ch}^{corr})

Sc/Ch relative group velocities needs calibration in Monte Carlo:

$$(gv_{Ch}^{data} - gv_{Sc}^{data}) \neq (gv_{Ch}^{MC} - gv_{Sc}^{MC})$$

gv_{ch} effective correction: $t_{new}^{ToF} = t_{MC}^{ToF} - gv_{ch}^{corr} \cdot L_{MC}$



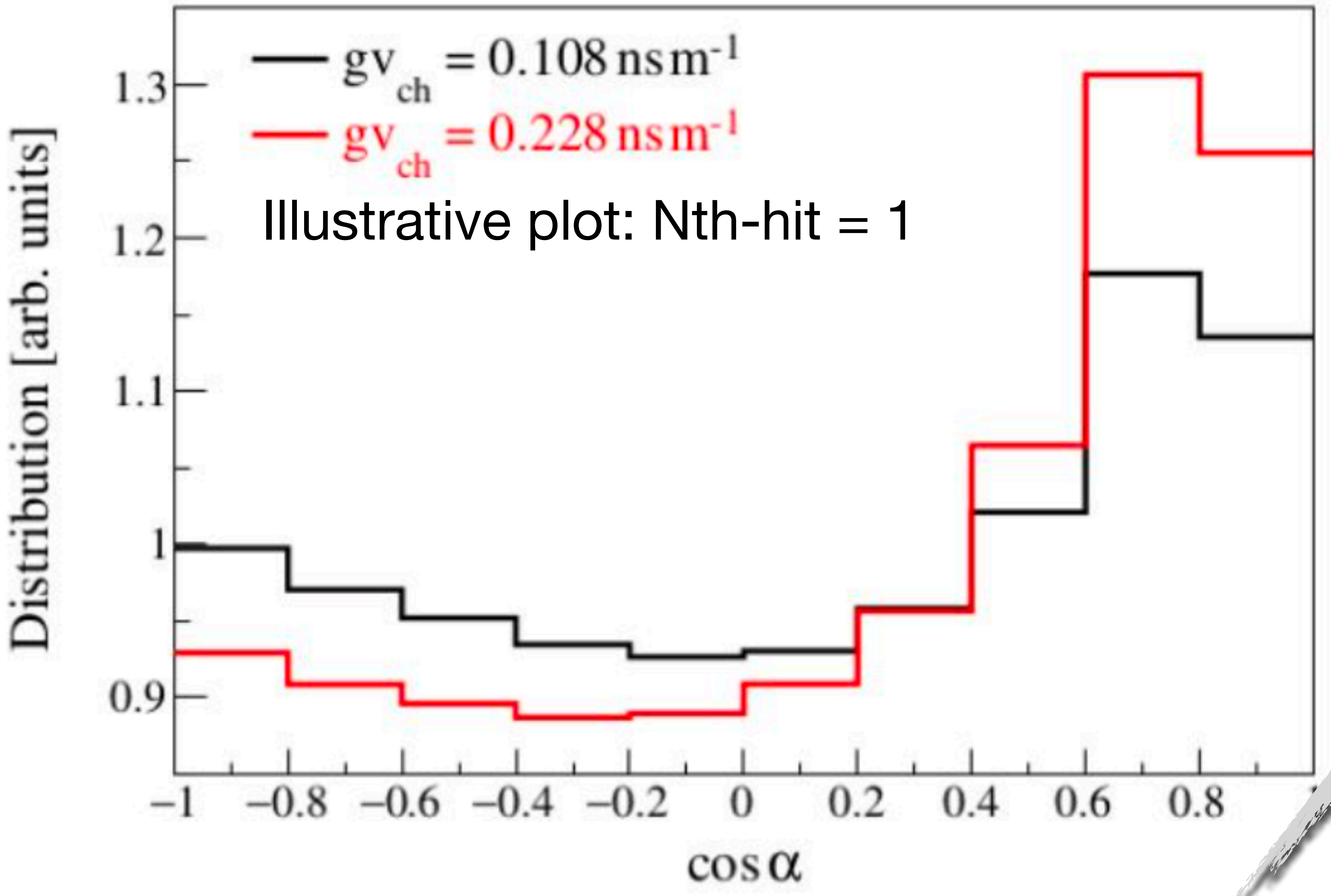
MAIN SYSTEMATIC EFFECTS OF CID

1. Group velocity correction for Cherenkov photons (gv_{ch}^{corr})

Sc/Ch relative group velocities needs calibration in Monte Carlo:

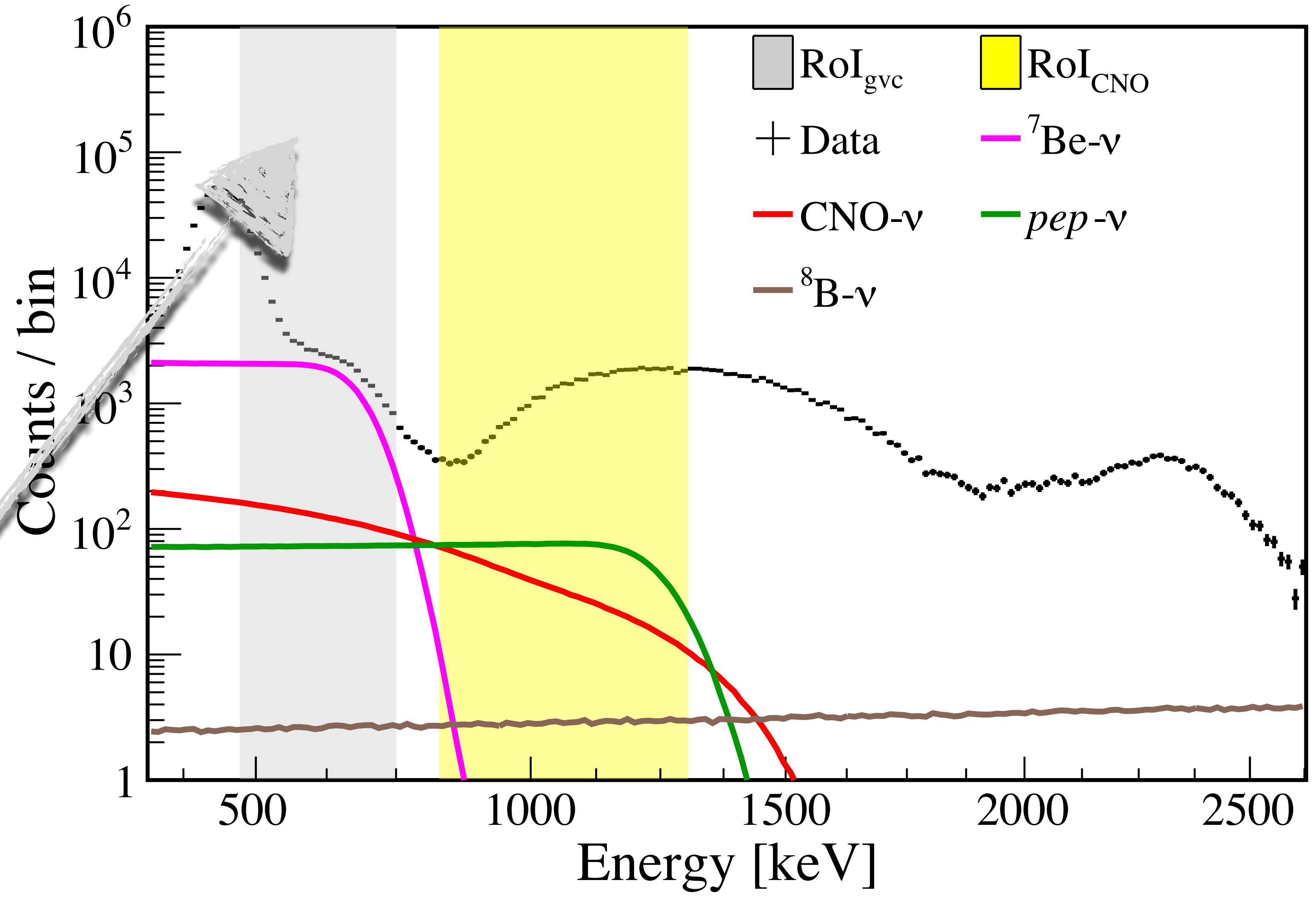
$$(gv_{Ch}^{data} - gv_{Sc}^{data}) \neq (gv_{Ch}^{MC} - gv_{Sc}^{MC})$$

gv_{ch} effective correction: $t_{new}^{ToF} = t_{MC}^{ToF} - gv_{ch}^{corr} \cdot L_{MC}$



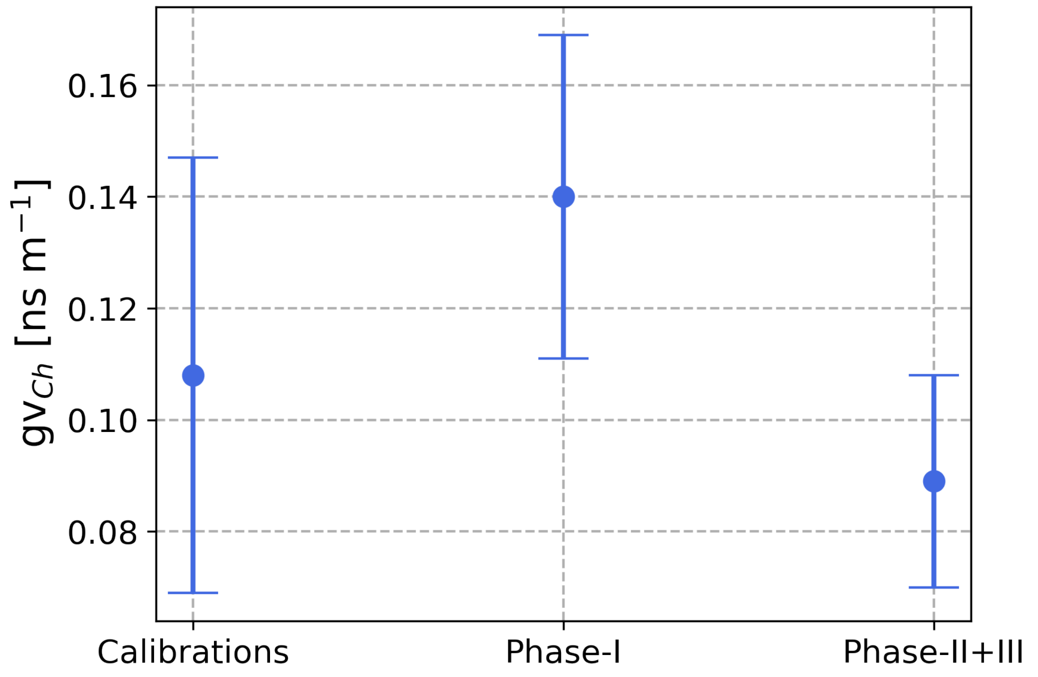
Can be calibrated on ^{7}Be shoulder: RoI_{gvc}

Treated as a **constrained nuisance parameter** in the fit



CID analysis constraining N_ν to the Standard Solar Model predictions using Phase-I and PhaseII+III

Previously: gv_{Ch} calibrated on γ calibration sources in Phase-I



Different methods give **compatible results in PhaseI**

Analysis performed with two time periods (PhaseI and PhaseII+III)

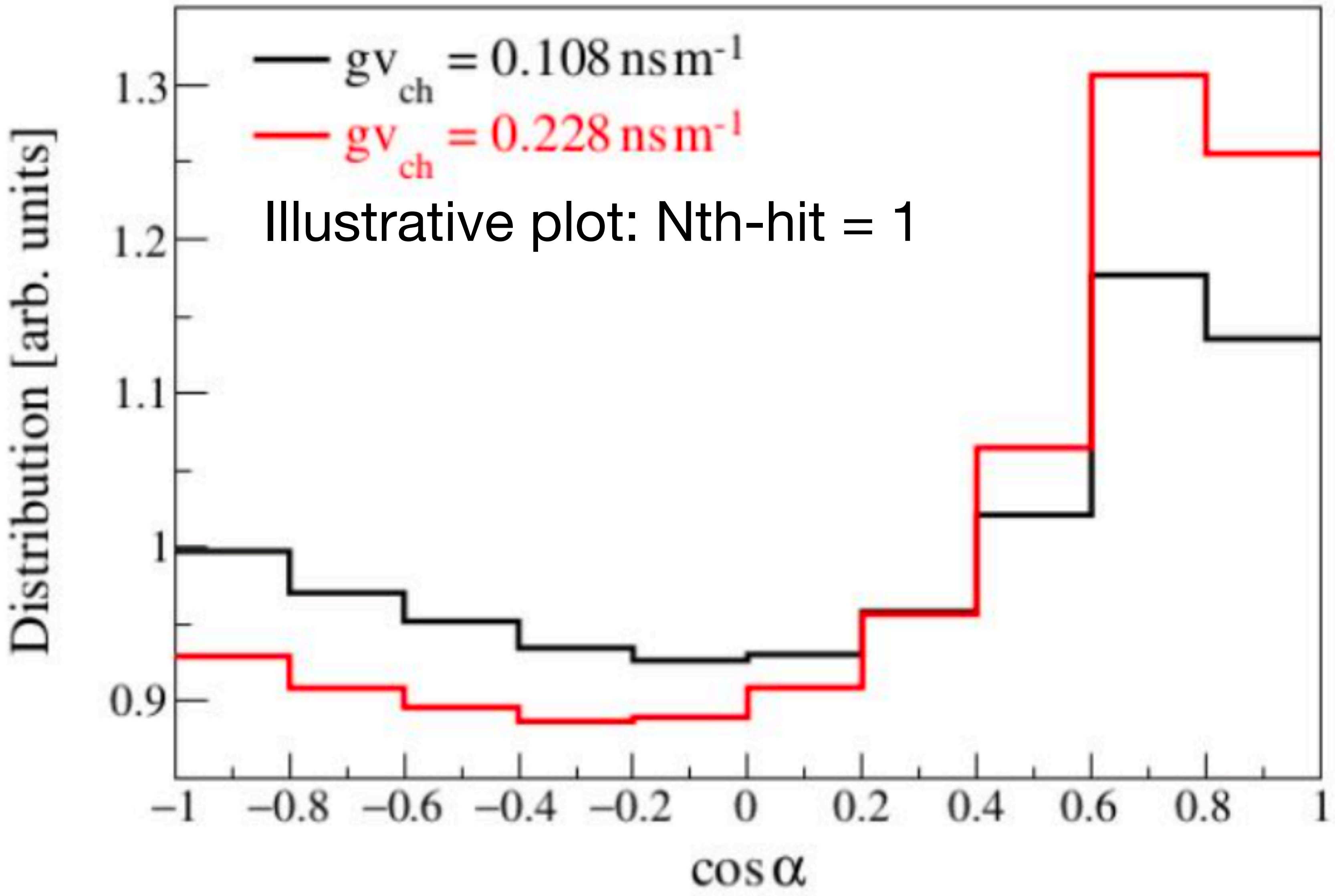
MAIN SYSTEMATIC EFFECTS OF CID

1. Group velocity correction for Cherenkov photons (gv_{ch}^{corr})

Sc/Ch relative group velocities needs calibration in Monte Carlo:

$$(gv_{Ch}^{data} - gv_{Sc}^{data}) \neq (gv_{Ch}^{MC} - gv_{Sc}^{MC})$$

gv_{ch} effective correction: $t_{new}^{ToF} = t_{MC}^{ToF} - gv_{ch}^{corr} \cdot L_{MC}$



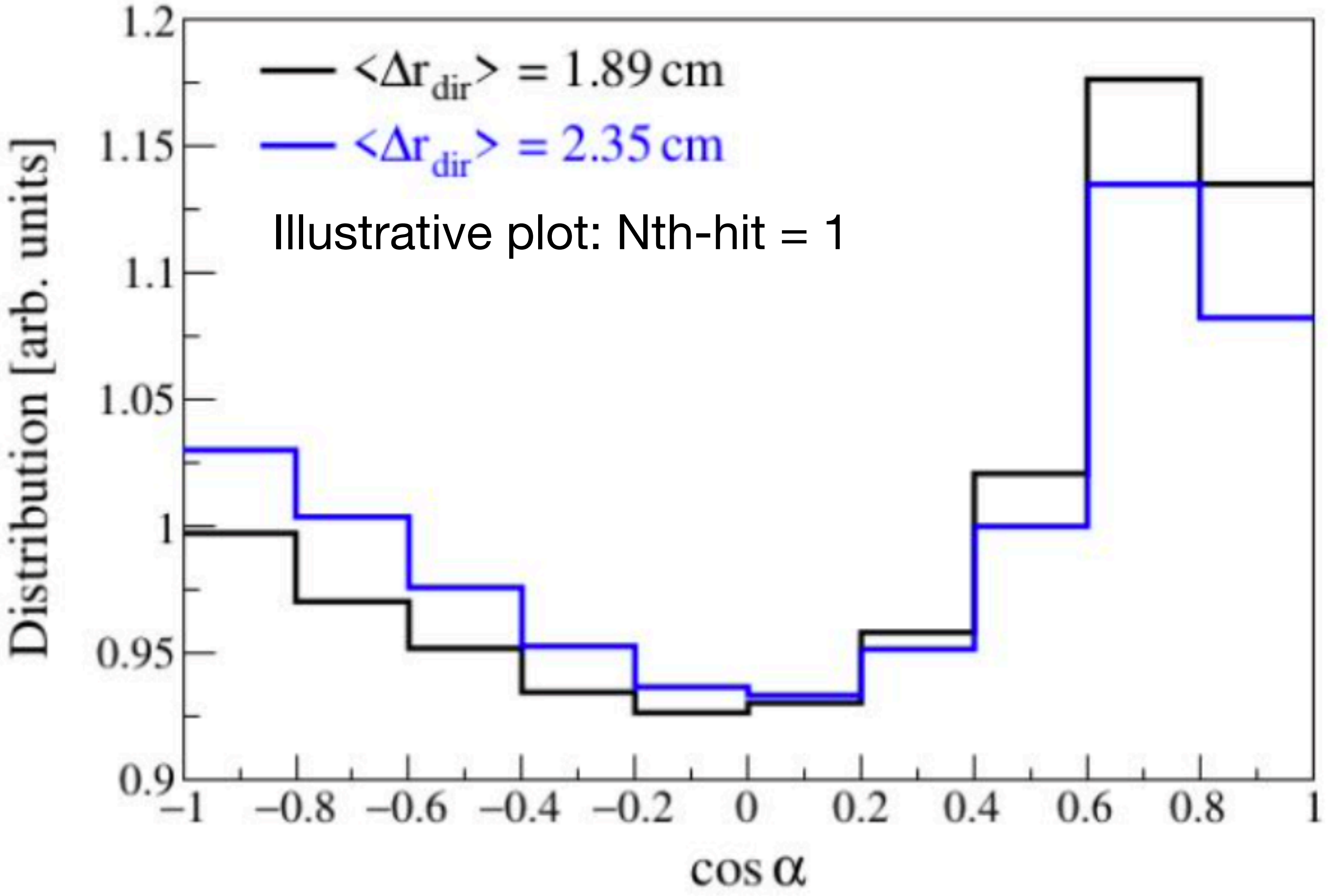
Can be calibrated on ^{7}Be shoulder: RoI_{gvc}

Treated as a **constrained nuisance parameter** in the fit

2. Event position reconstruction bias (Δr_{dir})

Reconstructed position pulled towards early hits (with *high* Cherenkov contribution)

Additonal ***indirect information*** in solar-ν $\cos\alpha$ distribution

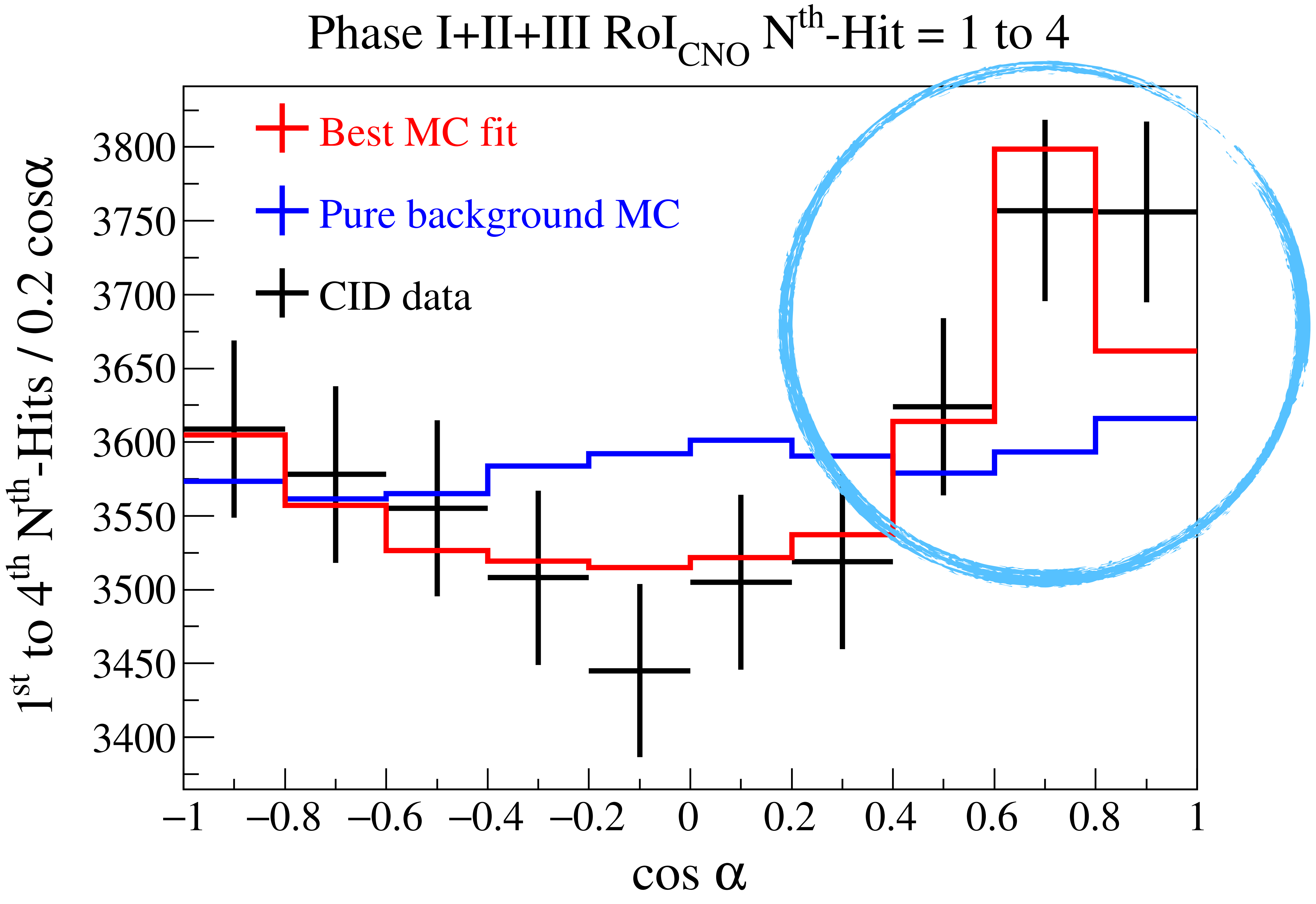


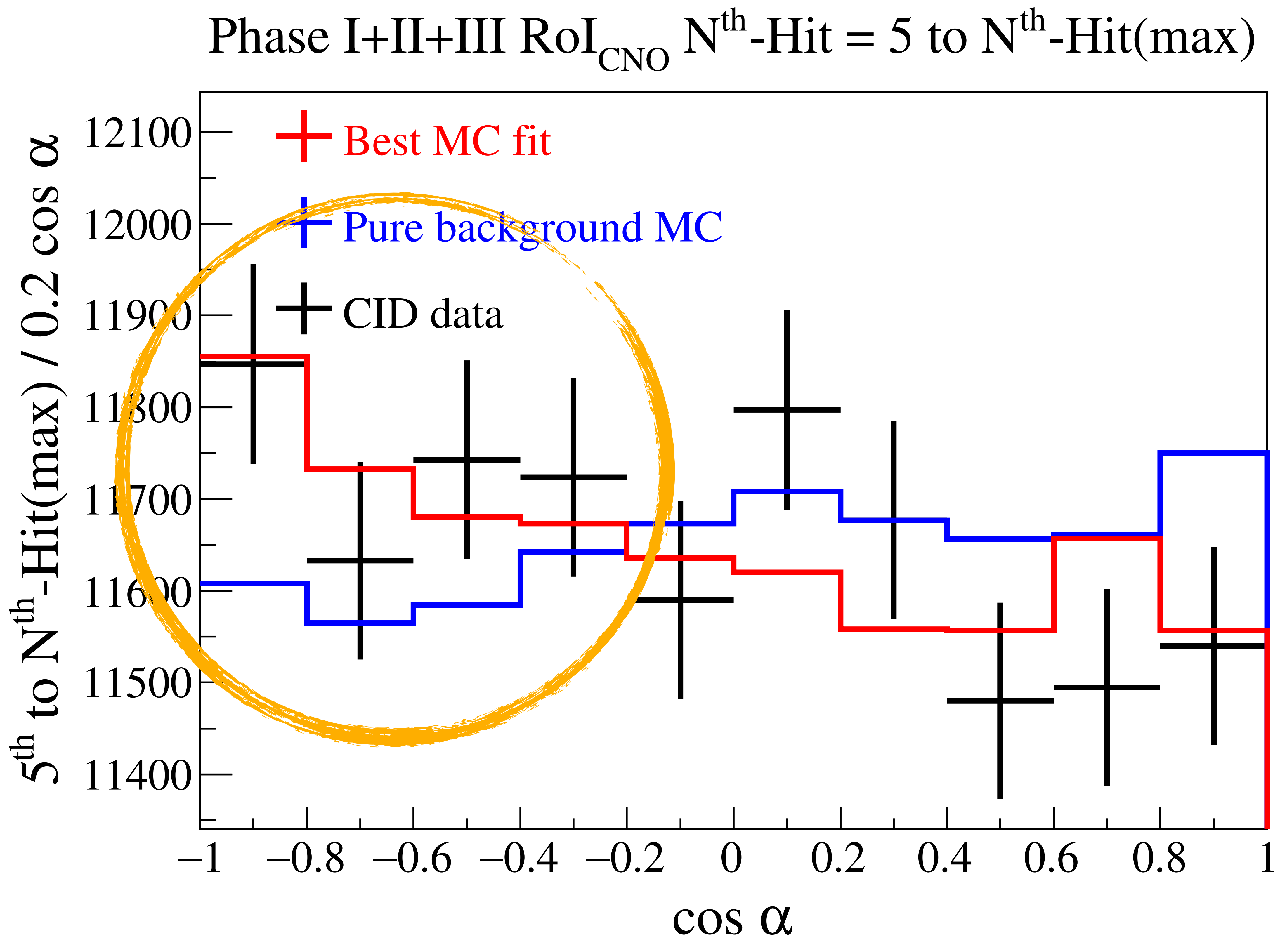
Can't be calibrated (no Cherenkov calibration source)

Treated as a **free nuisance parameter** in the fit

CID FIT IN ROI$_{CNO}$

Number of solar neutrinos (N_ν) extracted through χ^2-fit of the considered N^{th}-hit





Early hits [1 - 4]:
direct Cherenkov information

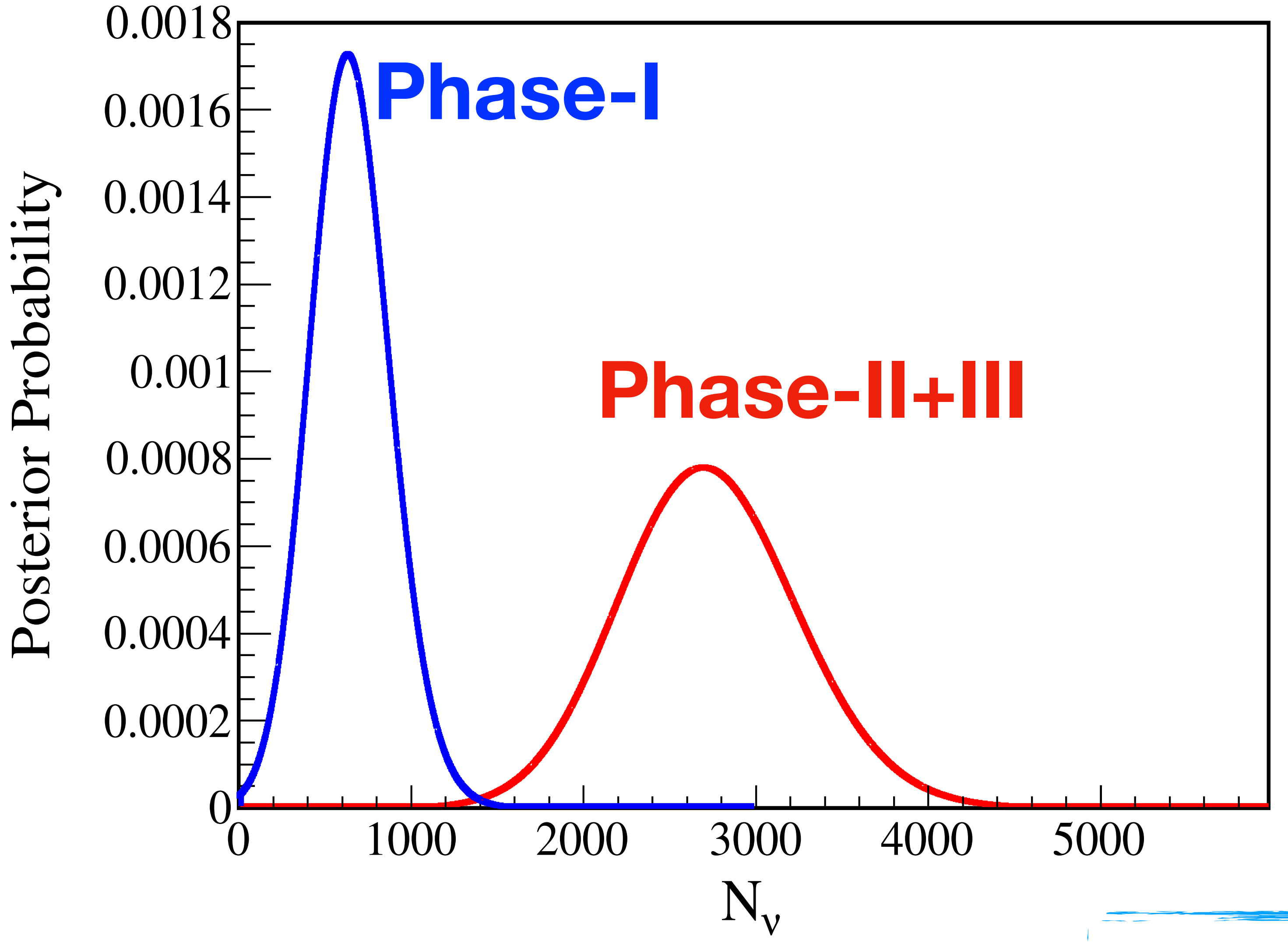
Late hits [5 - Nth-Hit(max)]:
indirect Cherenkov information (Δr_{dir})

CNO$-\nu$ RESULTS FROM CID

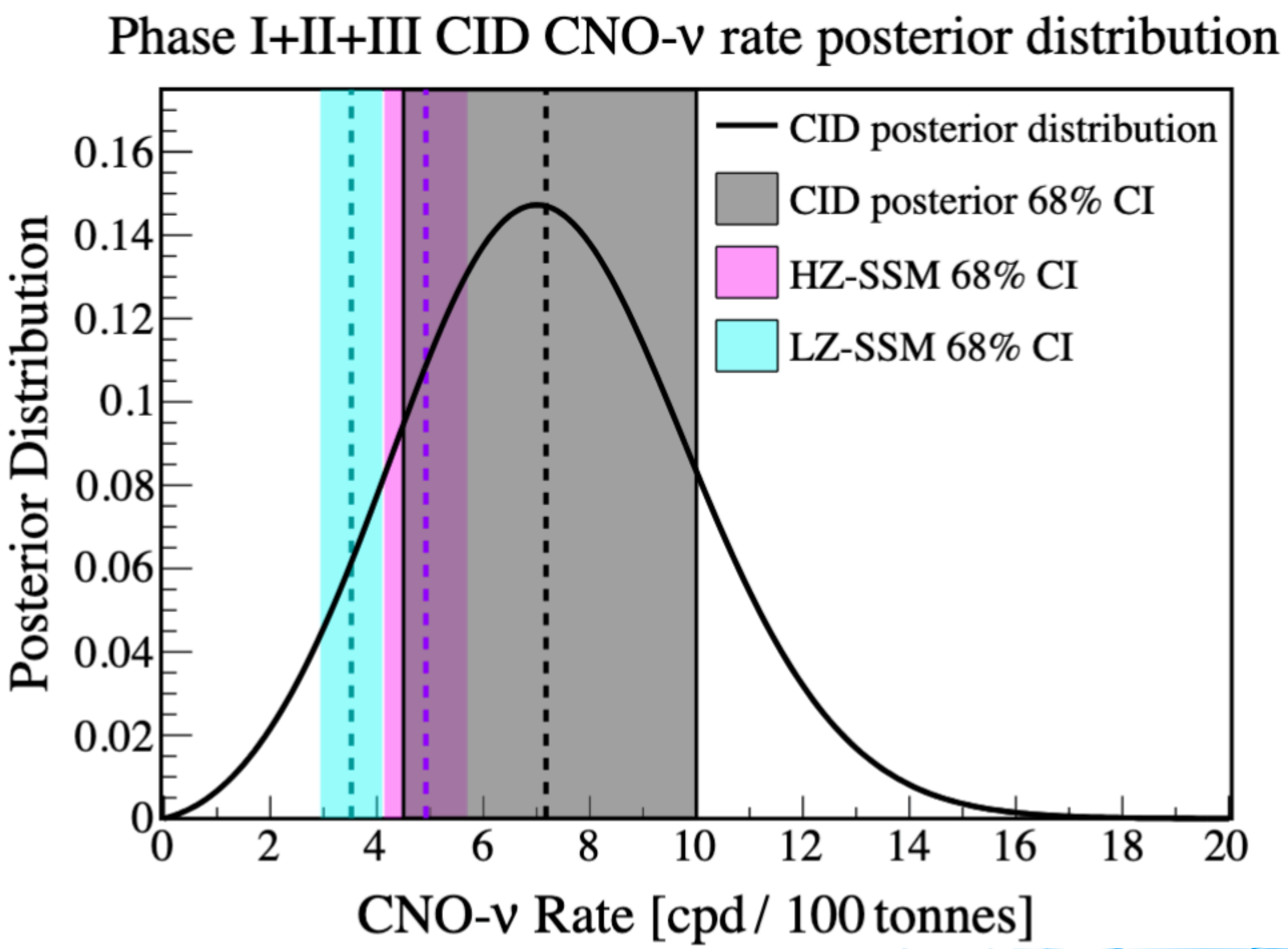
Results of CID analysis (N_ν in RoI_{CNO}):

Bayesian approach:

N_ν posterior probability



- Constrain Non-CNO-ν to SSM
- combine all phases
- convert to rate



CID-only results (PhaseI+II+III)

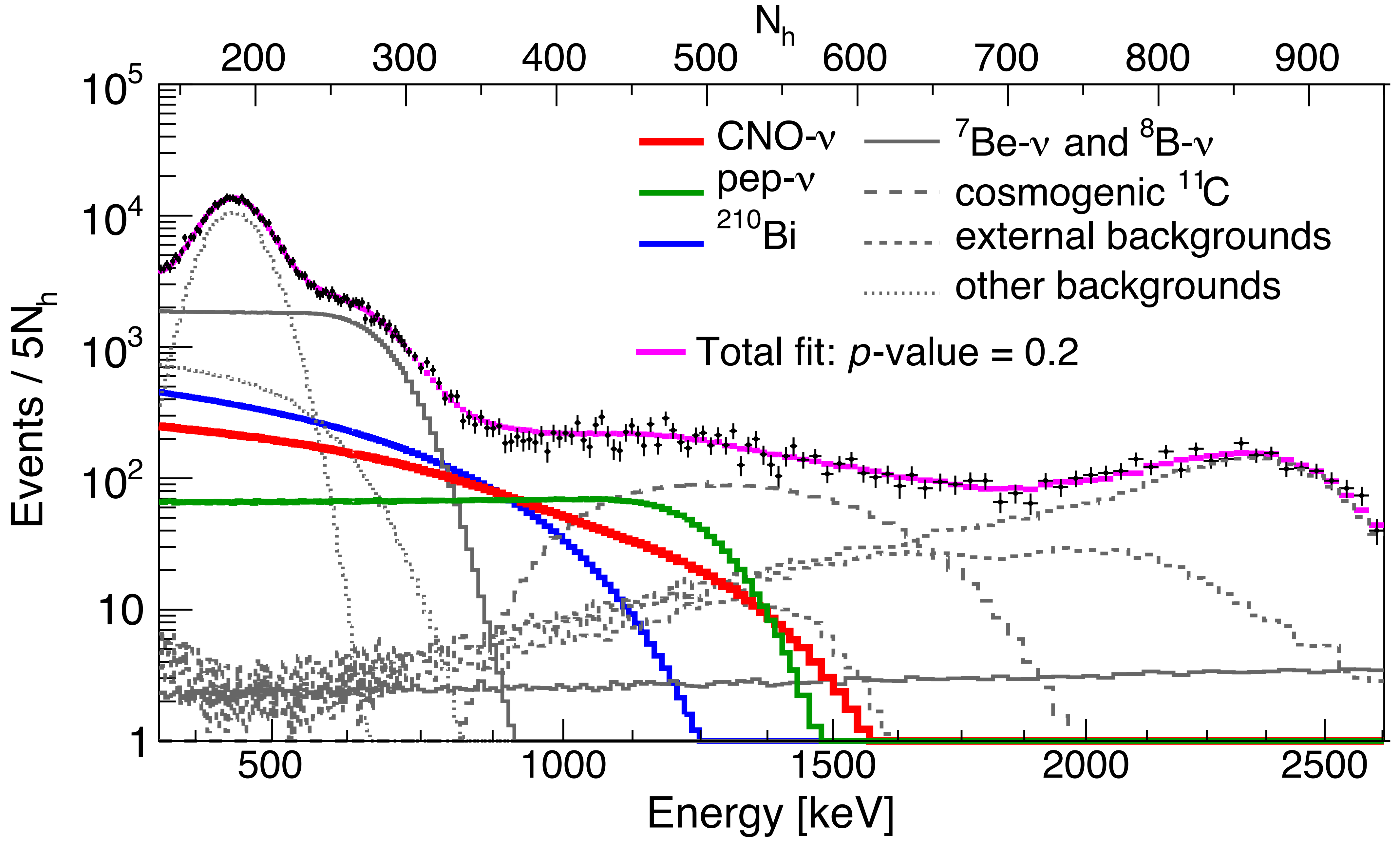
- ☑ **R(CNO) = $7.2^{+2.8}_{-2.7}$ cpd/100t**
- ☑ No assumption on backgrounds (^{210}Bi)
- ☑ No-CNO hypothesis disfavoured at $\sim 5.3\sigma$

CNO CID + SPECTRAL COMBINED ANALYSIS

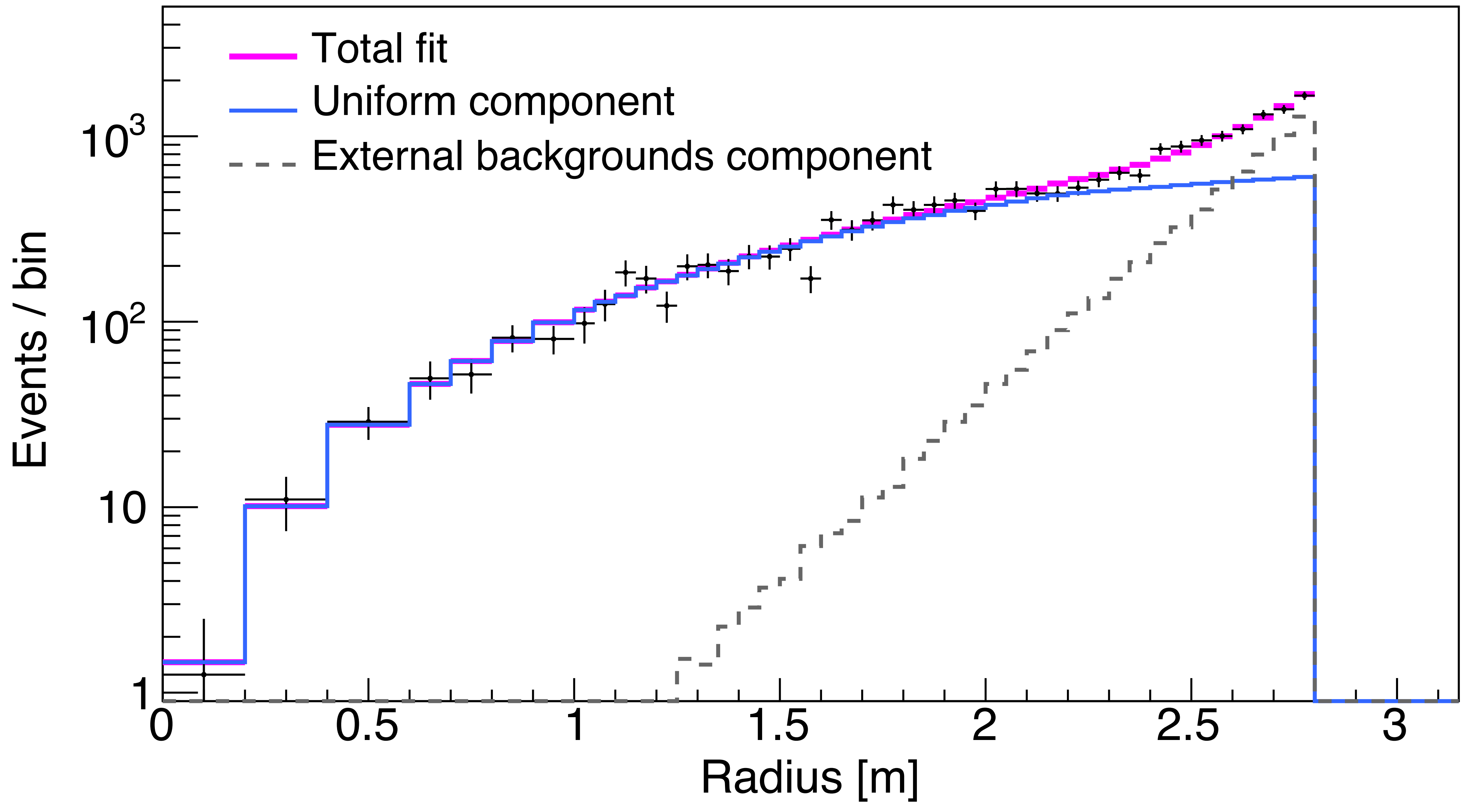
Multivariate spectral fit: rates obtained through minimization of a full 2D likelihood function with non-equidistant binning

$$\mathscr{L}_{MV} = \mathscr{L}^{2D}_{E-Sub} \cdot \mathscr{L}_{E-Tag} \cdot \mathscr{L}_{pep} \cdot \mathscr{L}_{^{210}Bi}$$

Energy projection



Radial projection



JÜLICH Forschungszentrum

CNO CID + SPECTRAL COMBINED ANALYSIS

Multivariate spectral fit: rates obtained through minimization of a full 2D likelihood function with non-equidistant binning

$$\mathscr{L}_{MV} = \mathscr{L}^{2D}_{E-Sub} \cdot \mathscr{L}_{E-Tag} \cdot \mathscr{L}_{pep} \cdot \mathscr{L}_{^{210}Bi}$$

1. pep$-\nu$ constraint:

$\nu(pep) = 2.74 \pm 0.04$ **cpd/100 t** (solar luminosity constraint + global analysis of solar data)

cpd=counts per day

2. ^{210}Bi constraint through ^{210}Po:

$$^{210}\mathrm{Pb} \xrightarrow[Q_\beta = 63.5\ \mathrm{keV}]{\beta,\ \tau \approx 32\ \mathrm{y}} \boxed{^{210}\mathrm{Bi} \xrightarrow[Q_\beta = 1160\ \mathrm{keV}]{\beta,\ \tau \approx 7.23\ \mathrm{d}} {}^{210}\mathrm{Po}} \xrightarrow[Q_\alpha = 5.3\ \mathrm{MeV}]{\alpha,\ \tau \approx 199.1\ \mathrm{d}} {}^{206}\mathrm{Pb}$$

Temperature gradient caused **convective motions** in the LS

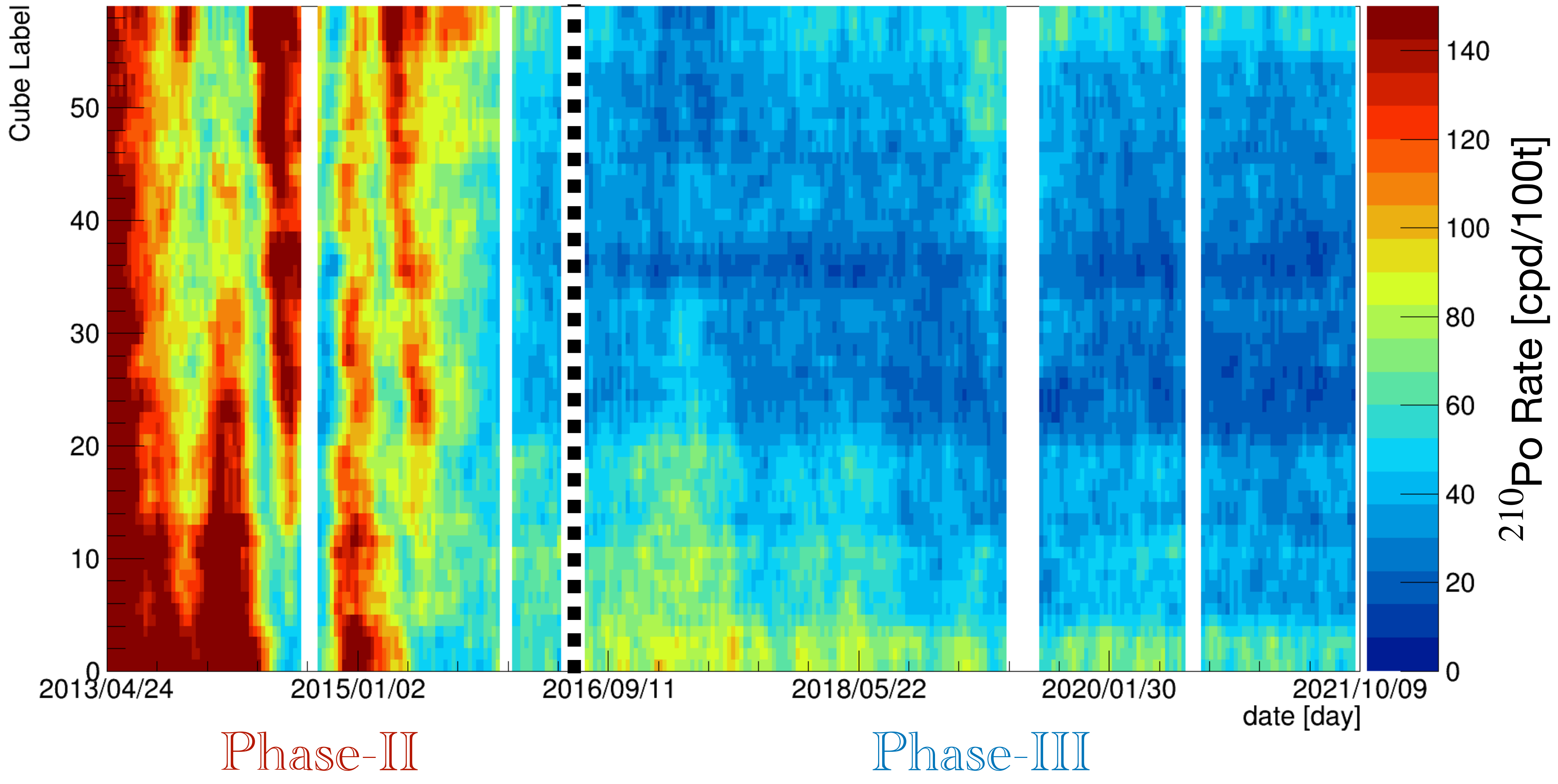
↓

Unknown amount of **out-of-equlibrium ^{210}Po** in the FV

↓

Thermal insulation of the detector

Low Polonium Field (LPoF):



$R(^{210}\mathrm{Bi}) = 10.8 \pm 1.0$ cpd/100t
(11.3 ± 1.5 cpd/100t for first CNO measurement)

JÜLICH Forschungszentrum

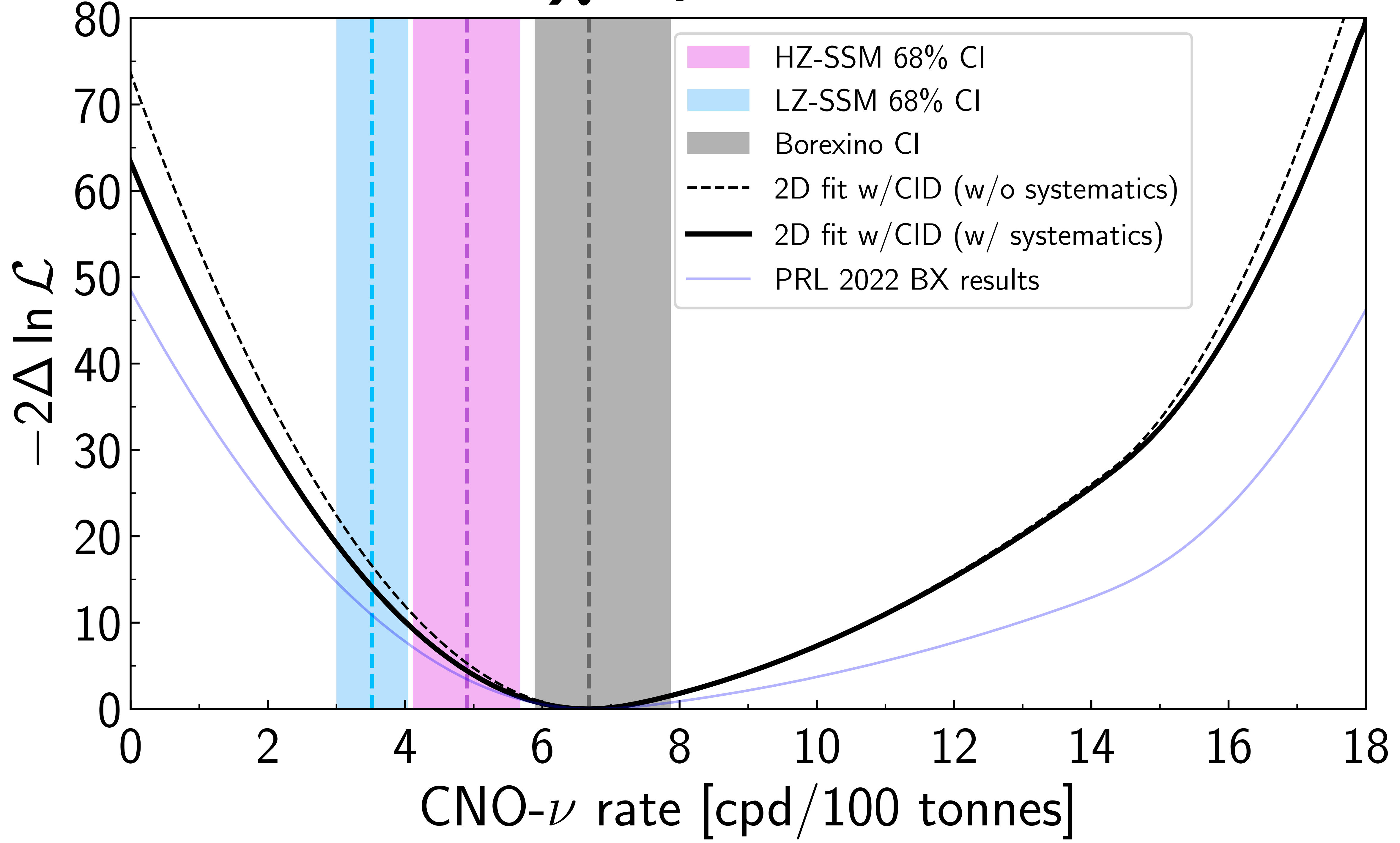
CNO CID + SPECTRAL COMBINED ANALYSIS

Multivariate spectral fit: rates obtained through minimization of a full 2D likelihood function with non-equidistant binning

$$\mathscr{L}_{MV} = \underbrace{\mathscr{L}^{2D}_{E-Sub} \cdot \mathscr{L}_{E-Tag} \cdot \mathscr{L}_{pep} \cdot \mathscr{L}_{^{210}Bi}}_{\text{Phase-III dataset}} \cdot \mathscr{L}^{P-I}_{CID} \cdot \mathscr{L}^{P-II+III}_{CID}$$

New!
External pull terms based on CID posteriors

$\Delta\chi^2$ profiles



Φ(CNO) = $6.7^{+1.2}_{-0.8} \cdot 10^8$ cm^{2}s^{-1}

- ☑ **Most precise CNO measurement so far**
- ☑ Significance to no-CNO hypothesys > 8σ
- ☑ LZ-SSM disfavoured at 3.2σ level

JÜLICH
Forschungszentrum

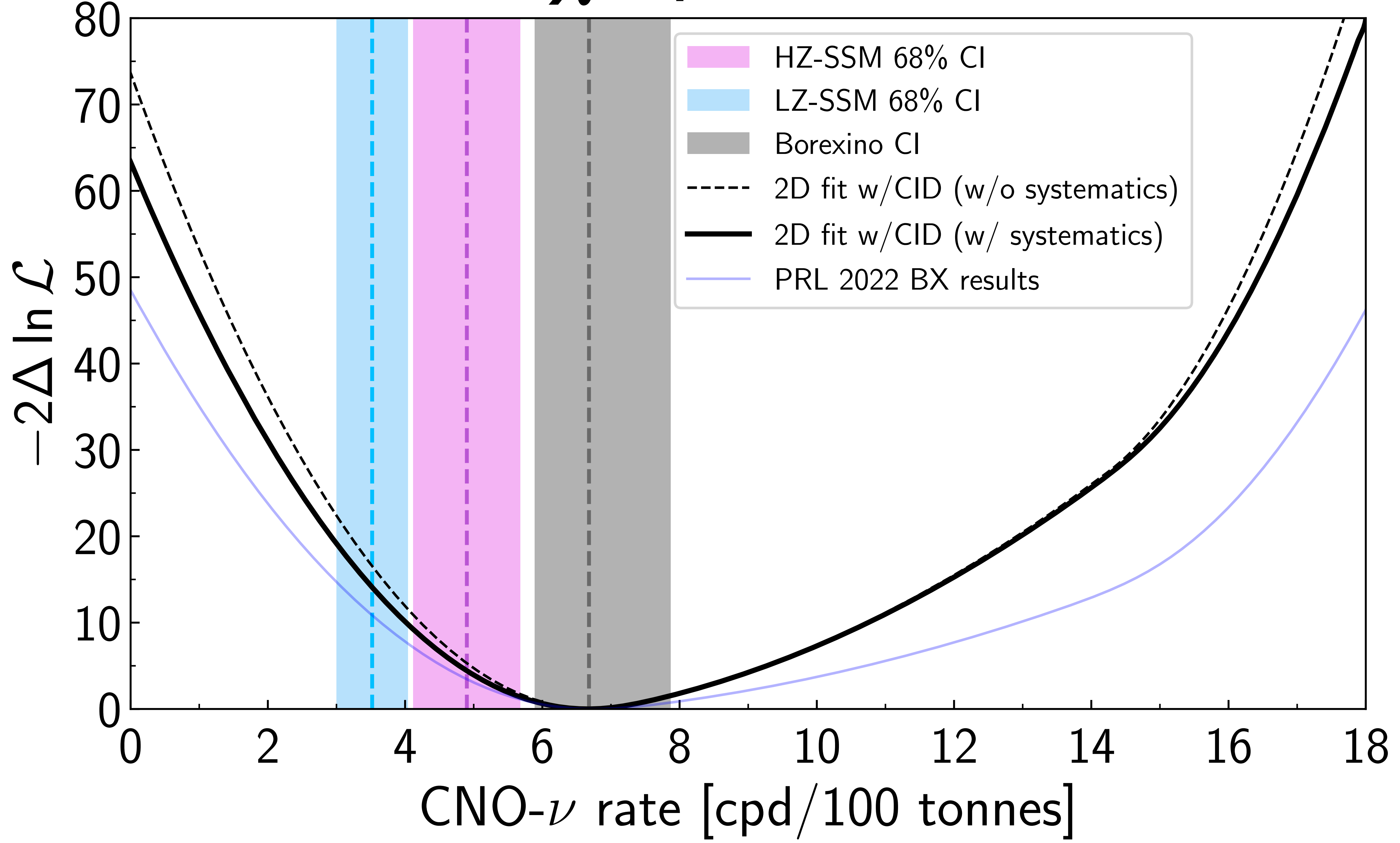
CNO CID + SPECTRAL COMBINED ANALYSIS

Multivariate spectral fit: rates obtained through minimization of a full 2D likelihood function with non-equidistant binning

$$\underbrace{\mathscr{L}_{MV} = \mathscr{L}^{2D}_{E-Sub} \cdot \mathscr{L}_{E-Tag} \cdot \mathscr{L}_{pep} \cdot \mathscr{L}_{^{210}Bi}}_{\text{Phase-III dataset}} \cdot \mathscr{L}^{P-I}_{CID} \cdot \mathscr{L}^{P-II+III}_{CID}$$

New!
External pull terms based on CID posteriors

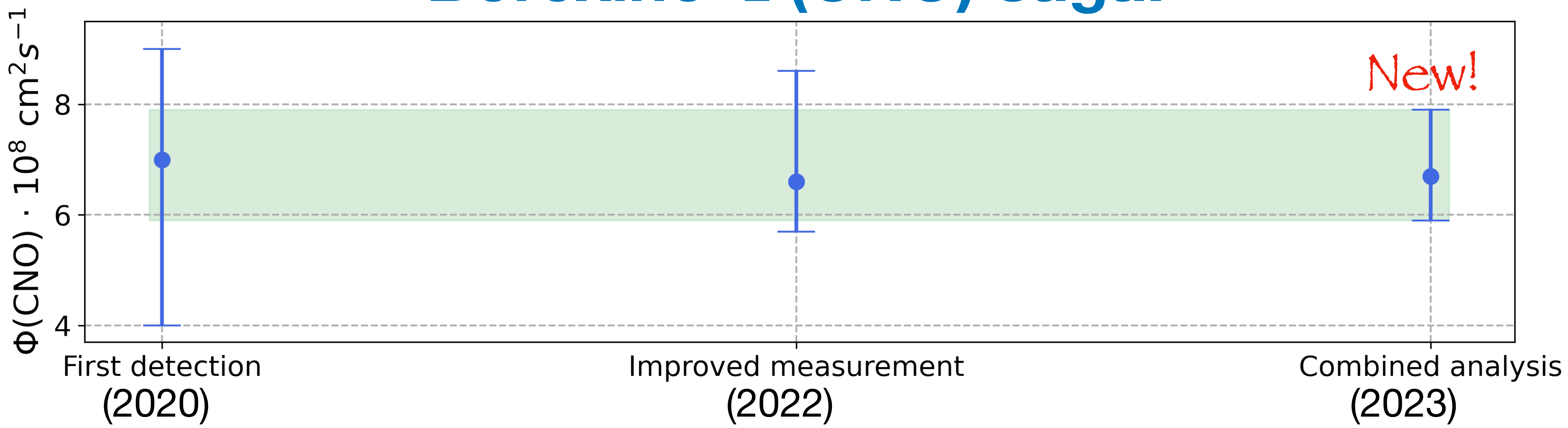
$\Delta\chi^2$ profiles



Φ(CNO) = $6.7^{+1.2}_{-0.8} \cdot 10^8$ cm^{2}s^{-1}

- ☑ **Most precise CNO measurement so far**
- ☑ Significance to no-CNO hypothesys > 8σ
- ☑ LZ-SSM disfavoured at 3.2σ level

Borexino Φ(CNO) saga:



CONCLUSIONS

- ☑ **Solar neutrinos** are a crucial ingredient for a complete understanding of the reactions taking place in the Sun.

- ☑ Over more than 10 years of data taking, Borexino has performed a complete spectroscopy of solar neutrinos (pp-chain and CNO cycle).

- ☑ Directionality measurement, using the **Correlated Integrated Directionality (CID) method** for solar neutrinos:

  Independet CNO measurement: R(CNO) = $7.2^{+2.8}_{-2.7}$ cpd/100 t without any assumption on backgrounds.

- ☑ **Final Borexino result on CNO neutrinos:** combined analysis of spectral fit with CID results leads to unprecendented precision

  R(CNO) = $6.7^{+1.2}_{-0.8}$ cpd/100t.


Thank you for your attention!

BACKUP

SOLAR PHYSICS: THE SOLAR METALLICITY PUZZLE

Metallicity: abundance of elements with Z > 2 in the Sun (wrt Hydrogen), quantified with **metal-to-hydrogen ratio (Z/X)**.
Can be inferred from spectroscopic measurements of the photosphere.

High Metallicity

(1998) **Z/X(GS98) = 0.023**
- **HZ-Scenario**
- Helioseismology ✓

→

Low Metallicity

(2009) **Z/X(AGS09) = 0.018**
- **LZ-Scenario**
- Helioseismology ✗

→

Low Metallicity

(2021) **Z/X(AG21) = 0.0187**
- **LZ-Scenario**
- Helioseismology ✗

→

High Metallicity

(2022) **Z/X(MB22) = 0.0225**
- **HZ-Scenario**
- Helioseismology ✓

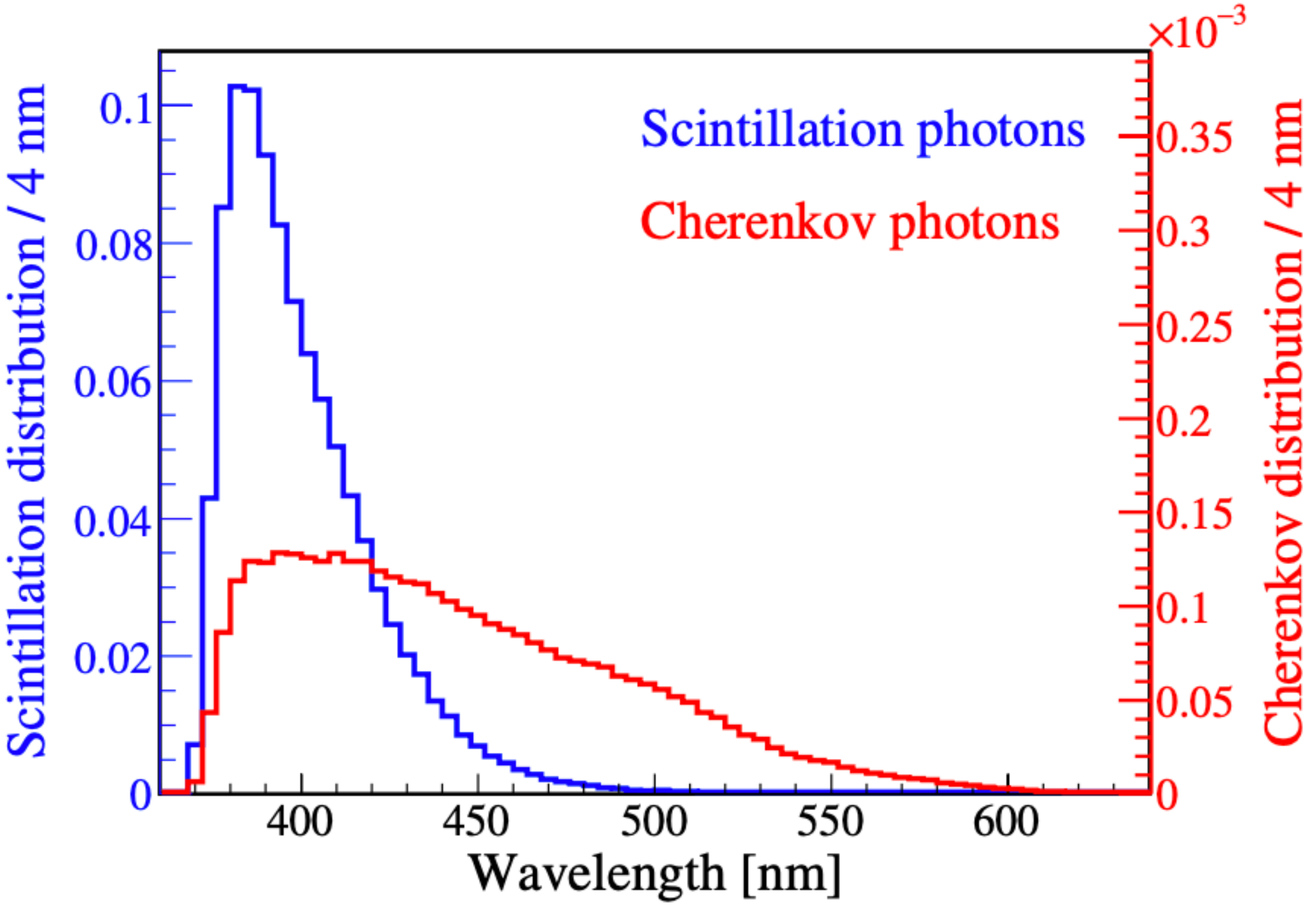
Solar neutrino fluxes depends on the metallicity input in SSM:

Flux	**BGS98 (HZ) [$cm^{-2}s^{-1}$]**	**AGSS09 (LZ) [$cm^{-2}s^{-1}$]**	**% diff**
pp	$5.98(1 \pm 0.006) \cdot 10^{10}$	$6.03(1 \pm 0.005) \cdot 10^{10}$	0.83
pep	$1.44(1 \pm 0.01) \cdot 10^{8}$	$1.46(1 \pm 0.009) \cdot 10^{9}$	1.4
^{7}Be	$4.93(1 \pm 0.006) \cdot 10^{10}$	$4.50(1 \pm 0.06) \cdot 10^{10}$	8.7
^{8}B	$5.45(1 \pm 0.12) \cdot 10^{6}$	$4.50(1 \pm 0.12) \cdot 10^{6}$	17.4
^{13}N	$2.78(1 \pm 0.15) \cdot 10^{8}$	$2.04(1 \pm 0.14) \cdot 10^{8}$	26.6
^{15}O	$2.05(1 \pm 0.17) \cdot 10^{8}$	$1.44(1 \pm 0.16) \cdot 10^{8}$	29.8
^{17}F	$5.29(1 \pm 0.20) \cdot 10^{6}$	$3.26(1 \pm 0.18) \cdot 10^{6}$	38.6
All CNO	$4.88(1 \pm 0.16) \cdot 10^{8}$	$3.51(1 \pm 0.15) \cdot 10^{8}$	28.1

^{7}Be, **^{8}B**, and CNO neutrinos are the best candidates to unravel the metallicity puzzle

JÜLICH
Forschungszentrum

Scintillation and Cherenkov photons have different wavelenght distribution



gv_ch accounts for small differences in the relative hit time distribution of Ch and Sc between data and MC

n depends on wavelenght -> **Ch and Sc have different average v_g**

In CID only the difference is important: $\Delta v_g = v_g^{Ch} - v_g^{Sc}$

It can be different in Data and MC:

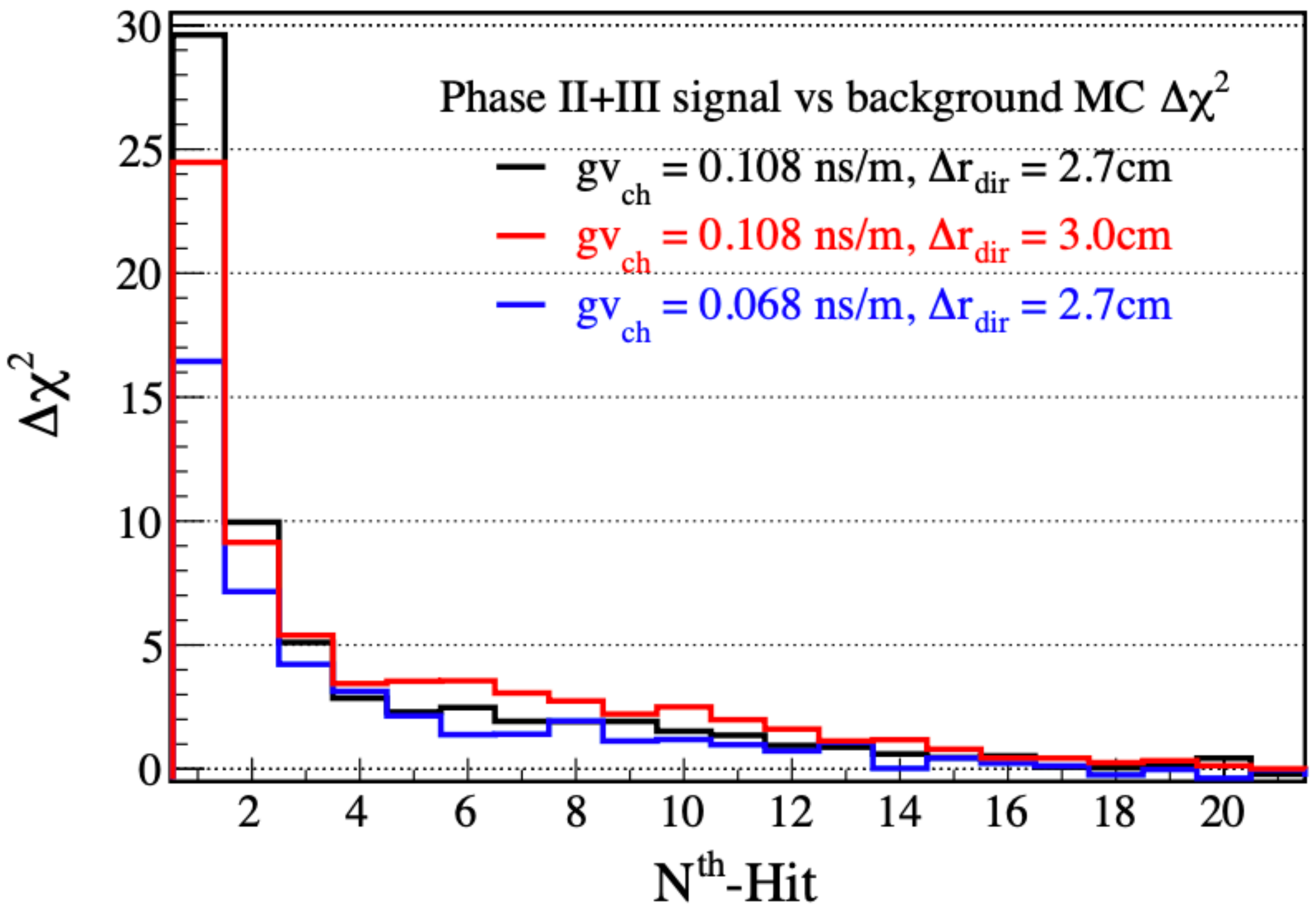
$$\Delta v_g(data) \neq \Delta v_g(MC)$$

gv_ch is an effective correction of v_g^{Ch} so that $\Delta v_g(data) = \Delta v_g(MC)$

It is implemented in the MC on the PMT hit time: $t_{new}^{ToF} = t_{MC}^{ToF} - gv_{ch}^{corr} \cdot L_{MC}$

Hit time of Cherenkov photons

MC track lenght of the photon



JÜLICH
Forschungszentrum

Source of uncertainty	Phase-I	Phase-II+III
For N_ν		
PMT selection	1.3%	0.6%
PMT time corrections	4.2%	2.4%
Low number of signal events	2.2%	–
CNO-ν vs. *pep*-ν MC	2.2%	2.0%
For N_{CNO}		
pep+^{8}B-ν constraint	4.6%	1.8%
For R_{CNO}		
Fiducial mass	$\left(^{+0.2}_{-1.2}\right)$%	$\left(^{+0.2}_{-1.2}\right)$%
Fraction of CNO-ν in RoI	1.4%	1.4%

TABLE II. Systematic uncertainties on the number of solar neutrino events N_ν in $\mathrm{RoI_{CNO}}$, relative to the best fit value. The uncertainty from *pep*+^{8}B-ν constraint is relevant only for N_{CNO}. The last two rows are relevant only for the CNO-ν rate (R_{CNO}) calculation.

Misbehavior of hit time distribution for some PMTs (identified by fitting individual hit time distr (with C11 strict sample)
Evaluated by varying the selection of usable PMTs

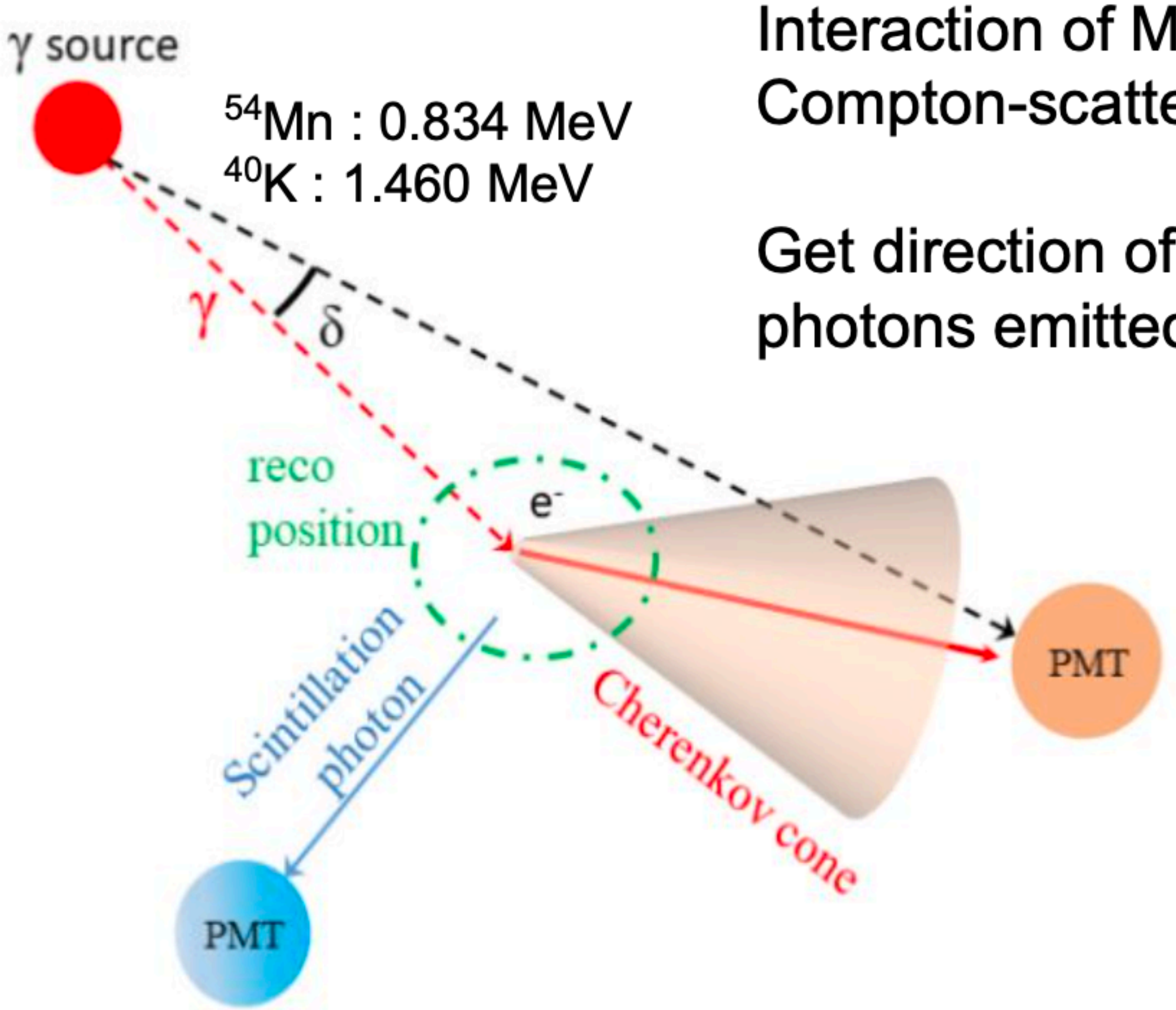
In data, PMTs have time offset ~0.3 pm 0.1 ns (not in MC)
Correct in data and propagate the uncertainty

Ch/Sc hits ratio is 0.475% for CNO and 0.469% for pep due to different energy distribution in $\mathrm{ROI_{CNO}}$ + different angular distribution of recoiled electrons.
Analysis performed with pep MC and syst evaluated redoing it with CNO MC

Source of gv_{ch} uncertainty	Phase-I	Phase-II+III
PMT selection	2.1%	1.6%
PMT time corrections	3.7%	2.1%
MLP event selection	1.0%	1.0%
Fiducial mass	$\left(^{+0.2}_{-1.2}\right)$%	$\left(^{+0.2}_{-1.2}\right)$%
Fraction of neutrinos in RoI	1.3%	0.9%

TABLE I. Systematic uncertainties of the gv_{ch} measurement in the $\mathrm{RoI_{gvc}}$, relative to the best fit value.

Calibration for Cherenkov photons using γ-sources



^{54}Mn : 0.834 MeV
^{40}K : 1.460 MeV

Interaction of MeV γs in LS via several Compton-scattered electrons

Get direction of γ via the Cherenkov photons emitted by the Compton-scattered e-

Calibration source data from 2009 calibration campaign
(H. Back et al. 2012, JINST 7, P10018)

$$\cos\delta_i = \frac{\left(\vec{r}_i^{\,\mathrm{PMT}} - \vec{r}_{\mathrm{source}}\right)\cdot\left(\vec{r}_{\mathrm{rec}} - \vec{r}_{\mathrm{source}}\right)}{\left|\left(\vec{r}_i^{\,\mathrm{PMT}} - \vec{r}_{\mathrm{source}}\right)\right|\left|\left(\vec{r}_{\mathrm{rec}} - \vec{r}_{\mathrm{source}}\right)\right|}.$$

Note: unlike solar neutrinos, here we reconstruct the direction of the gamma -> major source of uncertainty

$$\chi^2(gv_{\mathrm{ch}}^{\mathrm{corr}}) = \sum_{n=1}^{N}\sum_{i=1}^{I}\frac{\left((\cos\delta)_{n,i}^{D} - (\cos\delta)_{n,i}^{M}(gv_{\mathrm{ch}}^{\mathrm{corr}})\right)^2}{(\sigma_{n,i}^{D})^2 + (\sigma_{n,i}^{M})^2}$$

gv^{ch} = 0.108 ± 0.006 (stat.) ± 0.039 (syst.) ns m^{-1}

Error due to direction mis-reconstruction = 36% relative uncertainty-> estimated via MC studies

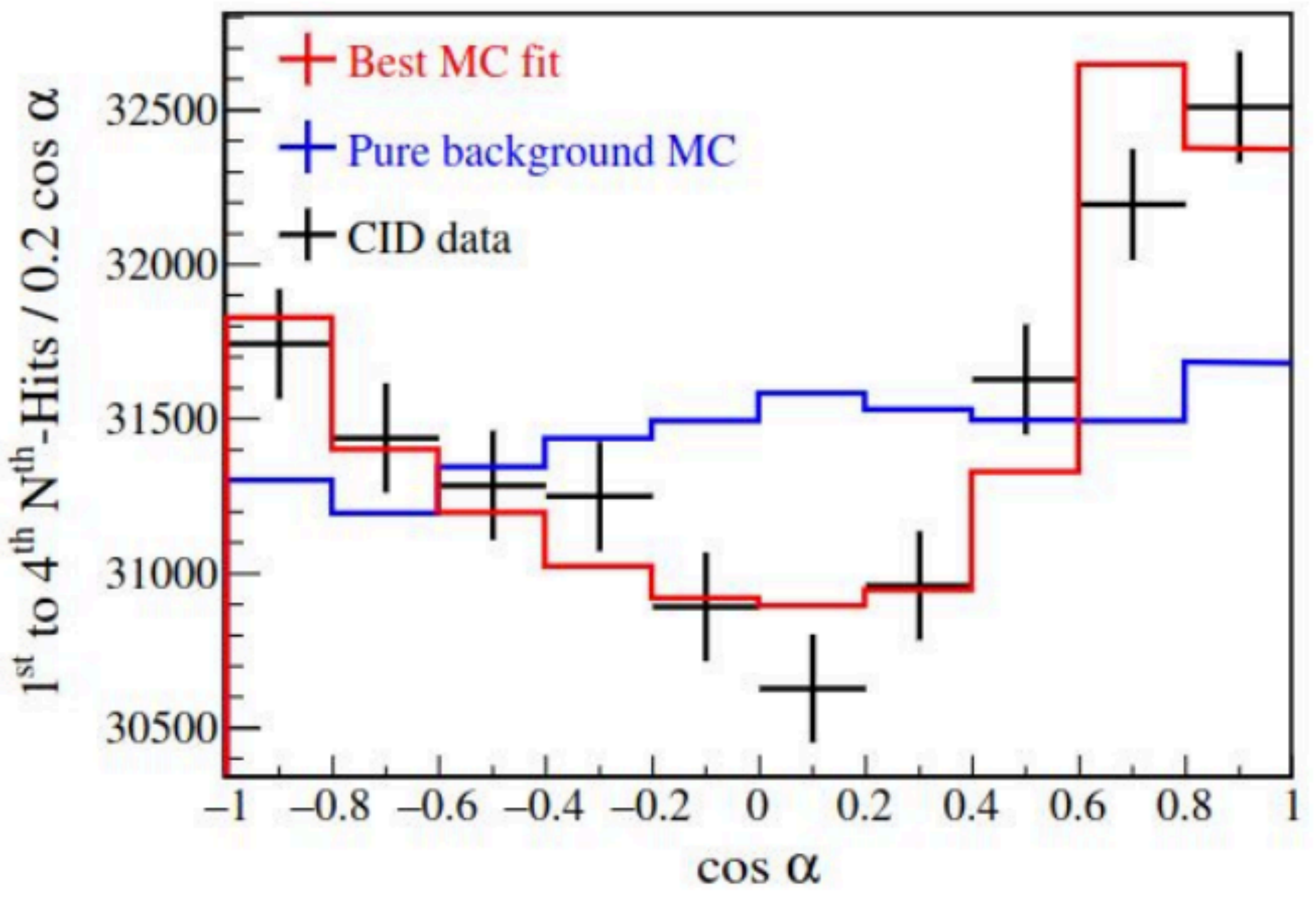
CID method: nuisance parameters, gv$_{ch}$ calibration

How to extract gv$_{ch}$? 7Be shoulder ROI (0.5 MeV ≲ T_e ≲ 0.8 MeV), rich in neutrinos

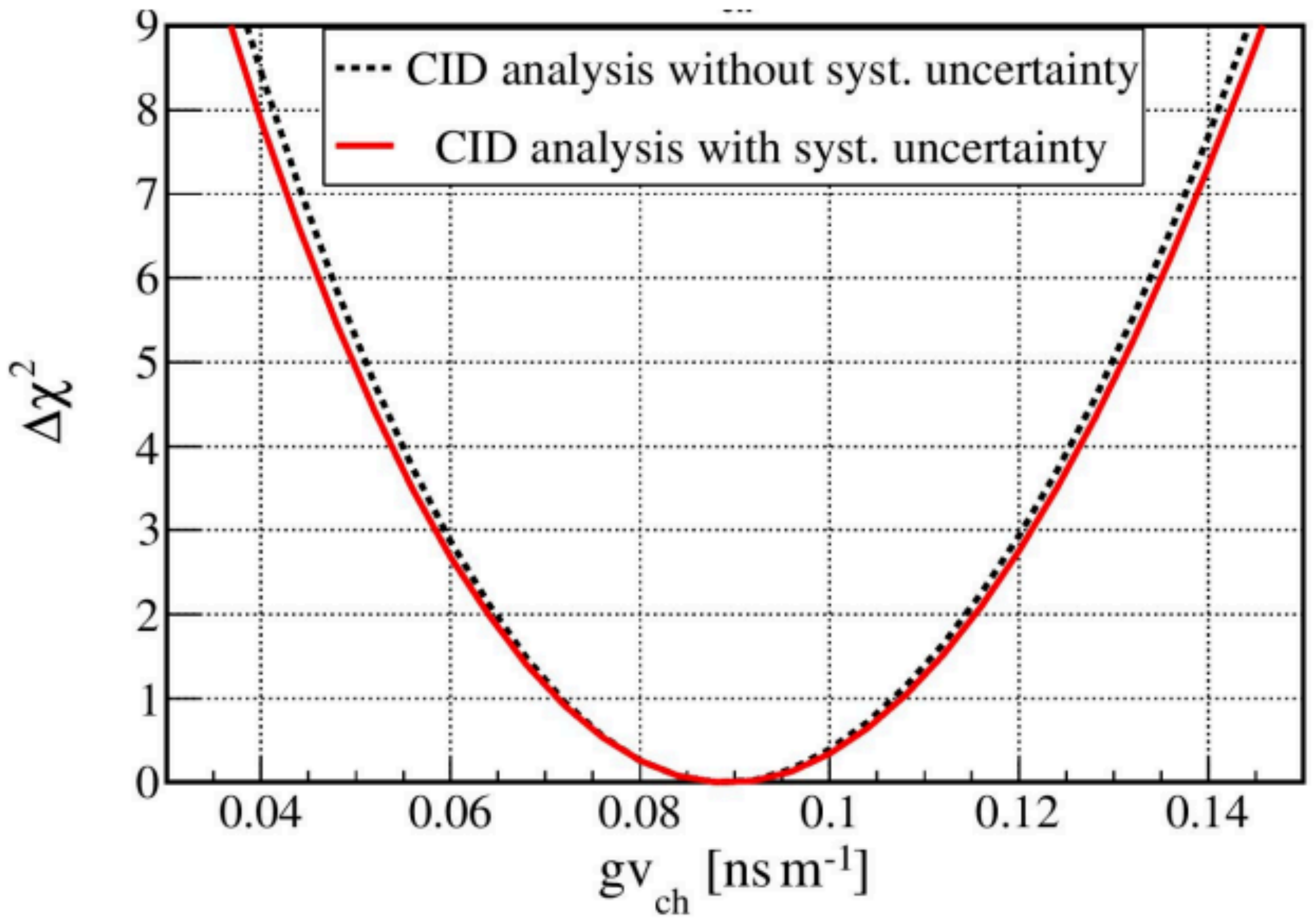
$$\chi^2_{\mathrm{gv_{ch}}}(N_\nu, \mathrm{gv_{ch}}, \Delta r_{\mathrm{dir}}) =$$
$$= \sum_{n=1}^{N^{\mathrm{th}}\text{-hit(max)}} \sum_{i=1}^{I} \left(\frac{\left(\mathcal{N} \cdot M_i^n - D_i^n\right)^2}{\mathcal{N} \cdot M_i^n + \mathcal{N}^2 \cdot M_i^n} \right) - 2\ln\left(P(N_\nu)\right)$$

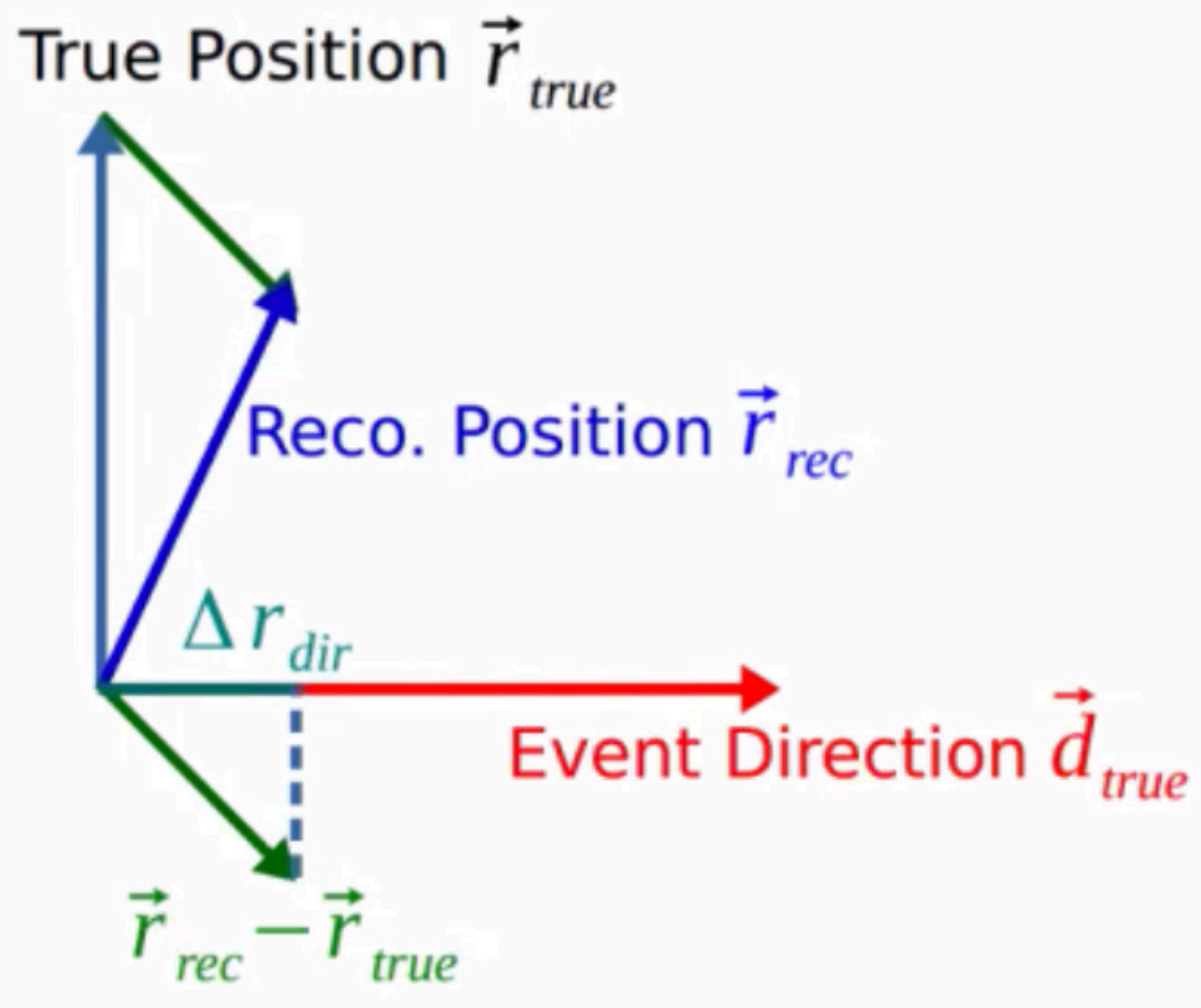
- M_i^n, D_i^n: MC and data in cos α distrib. for i-th bin and n-th hits
→ ν contribution to M_i^n explicitly depends on gv$_{ch}$, N_ν Δr_{dir}
- N_ν constrained by SSM
- Δr_{dir} free to vary

cos α fit (1 to 4 hit)

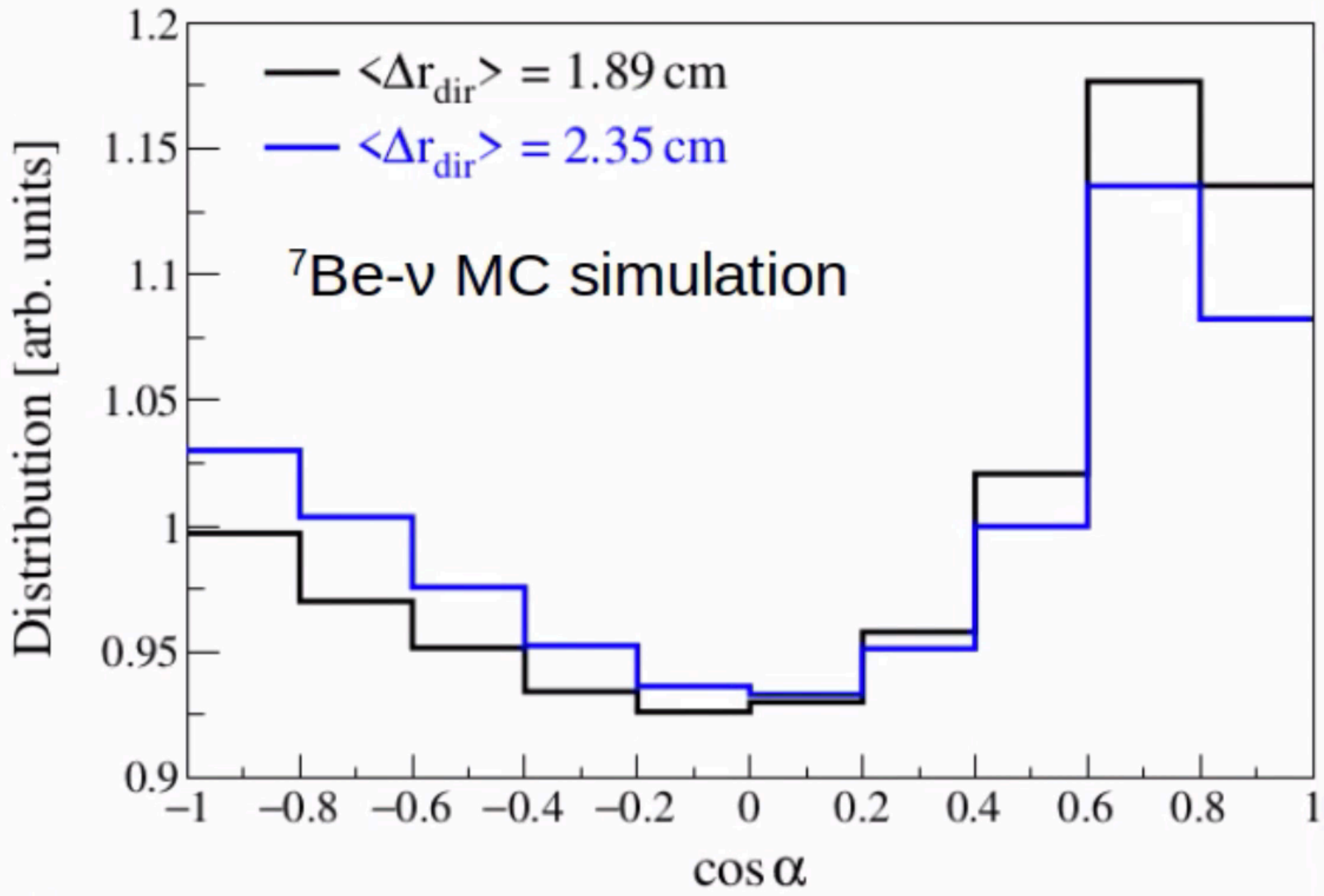


Δχ² profile for gv$_{ch}$

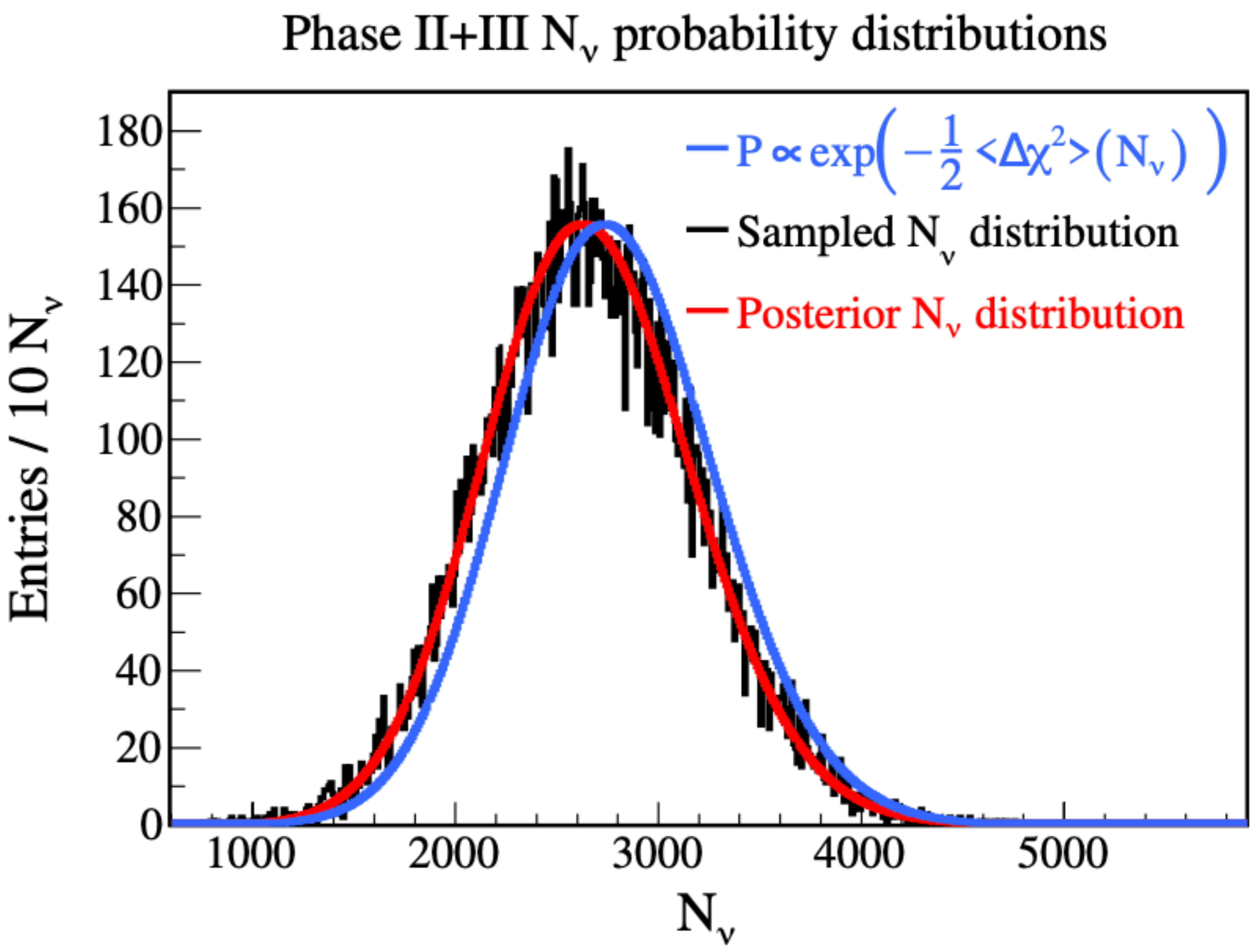




$$\Delta r_{\mathrm{dir}} = (\vec{r}_{\mathrm{rec}} - \vec{r}_{\mathrm{true}}) \cdot \vec{d}_{\mathrm{true}}$$



- Position reconstruction is based on PMT hit times, using likelihood fit
- Early hit PMTs tend to pull reconstructed position towards them
- Čerenkov hits are earlier than scintillation hits:
  - → Small bias in position reconstruction towards the true e^- direction
- Only visible for large sum of events. ~2 cm over ~10 cm position resolution
- Free nuisance parameter in the cos α fit, as Δr_{dir} cannot be calibrated



Bayesian posterior distributon is produced using Monte Carlo rejection sampling method

MC generated pseudo-data based on priors:
N = uniform (0 - total number of events)
Dr_dir = uniform
gv_ch = measurement in ROI_Be7

- pseudo-data inputs (N,Dr,gv)_sim sampled from priors
- Perform analysis and obtain (N,Dr,gvch)_fit

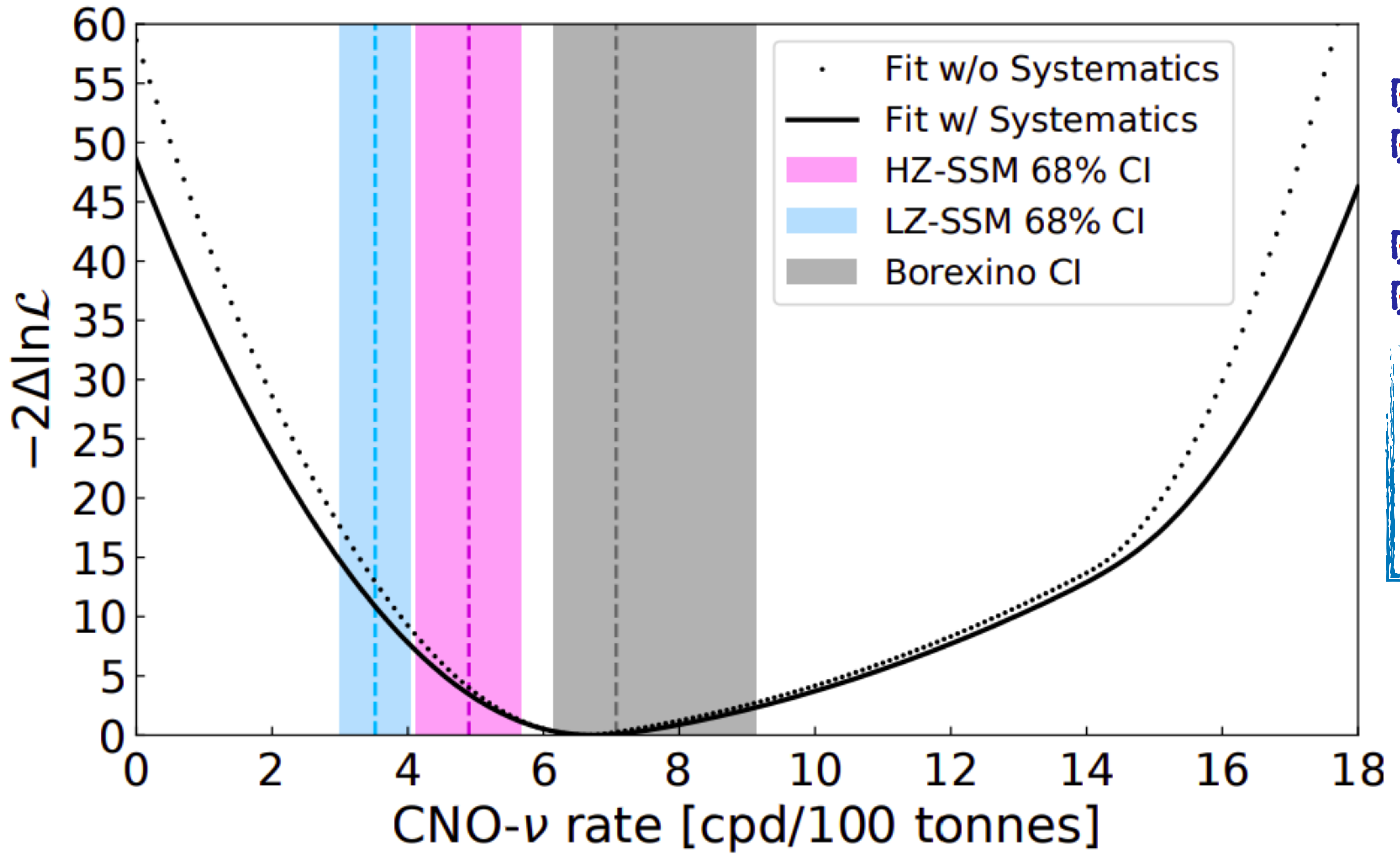
- Save triplet_sim only with a Pr = P(triplet_fit)

- Resulting distribution is the posterior distribution (black to red)

LATEST CNO MEASUREMENT

- **Phase-III Dataset:** January 2017 - October 2021: exposure increased by ~ 33% (wrt first CNO measurement);
- **Monte Carlo:**
  - data - MC agreement improved
  - Improved energy non linearities and non-uniformities estimation (based on cosmogenic neutrons) for systematics evaluation
- In 2021 temperature is more stable, thus less unsupported ^{210}Po (and larger LPoF)

More stringent limit on ^{210}Bi: $R(^{210}Bi) = 10.8 \pm 1.0$ **cpd/100t** ($R(^{210}Bi) = 11.3 \pm 1.5$ cpd/100t for first CNO measurement)



Sources of systematic error:

- **fitting method systematics** (great stability of the fit)
- **detector energy response** (non linearity, light yield stability and spatial non uniformity, energy scale, and ^{210}Bi spectral shape)
- **method of extraction and uniformity of ^{210}Bi upper limit**
- **N/O fixed ratio** in CNO spectral shape (negligible)

Results (stat. + syst.):
R(CNO) = $6.7^{+2.0}_{-0.8}$ cpd/100t
$\phi(CNO) = 6.6^{+2.0}_{-0.9} \cdot \nu \cdot cm^{-2}s^{-1}$

no-CNO hypotesis rejected with **>7σ significance at 90% C.L.**

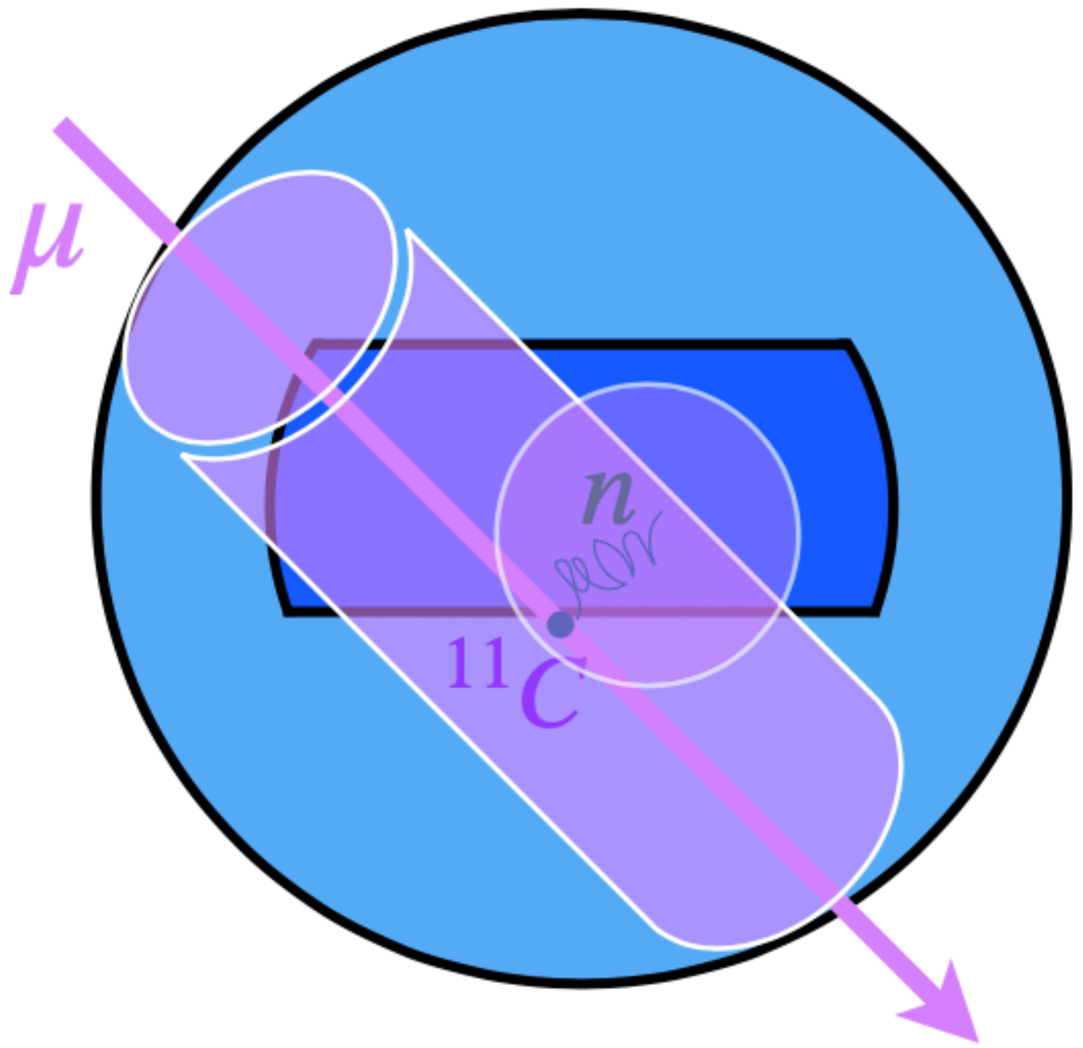
Solar implications:

- First **determination of C+N abundance** in the Sun using neutrinos
  - **(~2σ tension with SSM-LZ)**
- **Frequentist hypothesis test** based on a likelihood-ratio test statistics including only Borexino results
  - **(SSM-LZ disfavoured at ~3.1σ)**

- **Signal**: CNO solar neutrinos
- **Backgrounds**:
  - **Internal backgrounds**: ^{210}Bi, ^{210}Po, ^{85}Kr
  - **External backgrounds**: γ's produced from ^{208}Tl , ^{214}Bi and ^{40}K nuclei (mainly from the stainless steel sphere and PMTs)
  - **Cosmogenic backgrounds**: mainly ^{11}C produced by cosmic muons spallations, identified via **three fold coincidence (TFC)**

$$\mu + {}^{12}C \rightarrow \mu + {}^{11}C + n$$

$$^{11}C \rightarrow {}^{11}B + e^+ + \nu_e \qquad n + p \rightarrow d + \gamma_{2.2\ MeV}$$

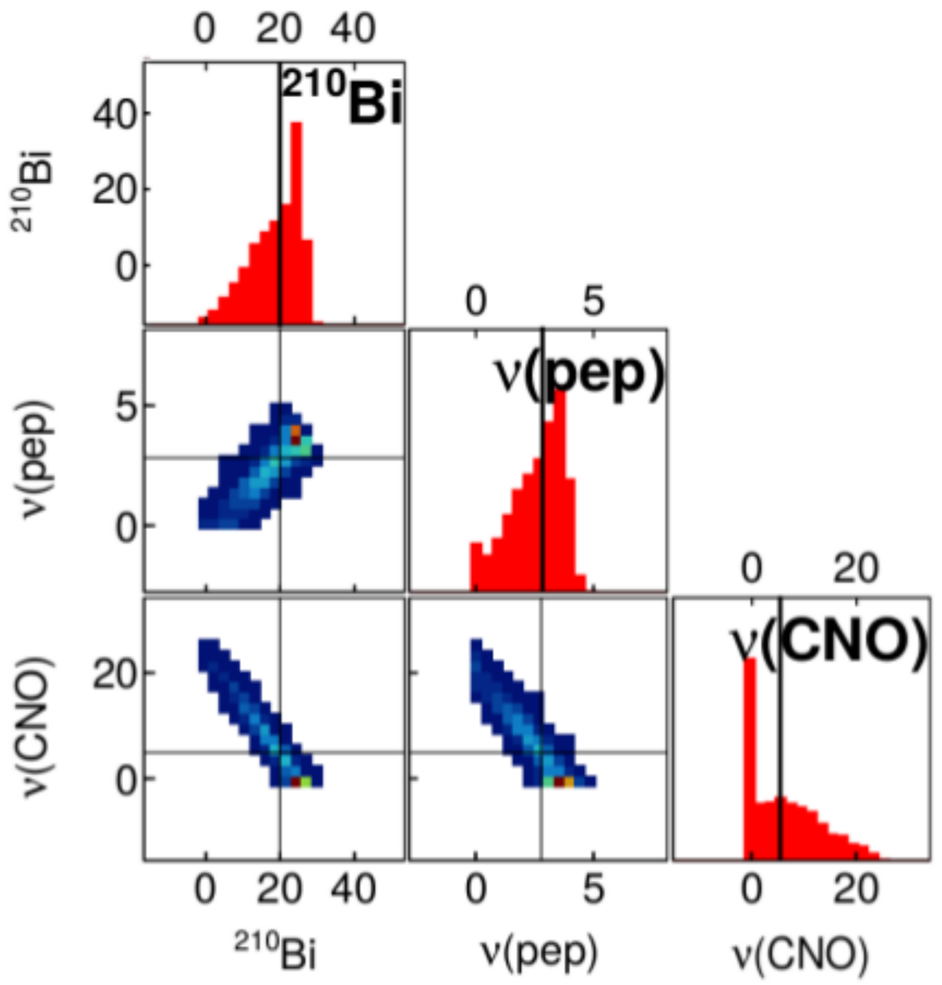


Data-set divided in two samples:
TFC-tagged (enriched in ^{11}C) and
TFC-subtracted (depleted in ^{11}C)

  - **pp-chain Solar neutrinos**: $pep-\nu$ and $^{7}Be-\nu$

LATEST CNO MEASUREMENT

Most important backgrounds: $\nu(\text{pep})$ and ^{210}Bi



Strong anti-correlation

Indipendent constraints:

- $\nu(pep) = 2.74 \pm 0.04$ **cpd/100t** (solar luminosity constraint + global analysis of solar data excluding Borexino Phase III);
- **^{210}Bi constraint is the main challenge of the analysis.**

^{210}Bi constrain through ^{210}Po:

$^{210}\text{Pb} \xrightarrow[Q_\beta = 63.5\ \text{keV}]{\tau \approx 32\ \text{y}} \boxed{^{210}\text{Bi} \xrightarrow[Q_\beta = 1160\ \text{keV}]{\tau \approx 7.23\ \text{d}} {}^{210}\text{Po}} \xrightarrow[Q_\alpha = 5.3\ \text{MeV}]{\tau \approx 199.1\ \text{d}} {}^{206}\text{Pb}$

Temperature gradients inside the detector

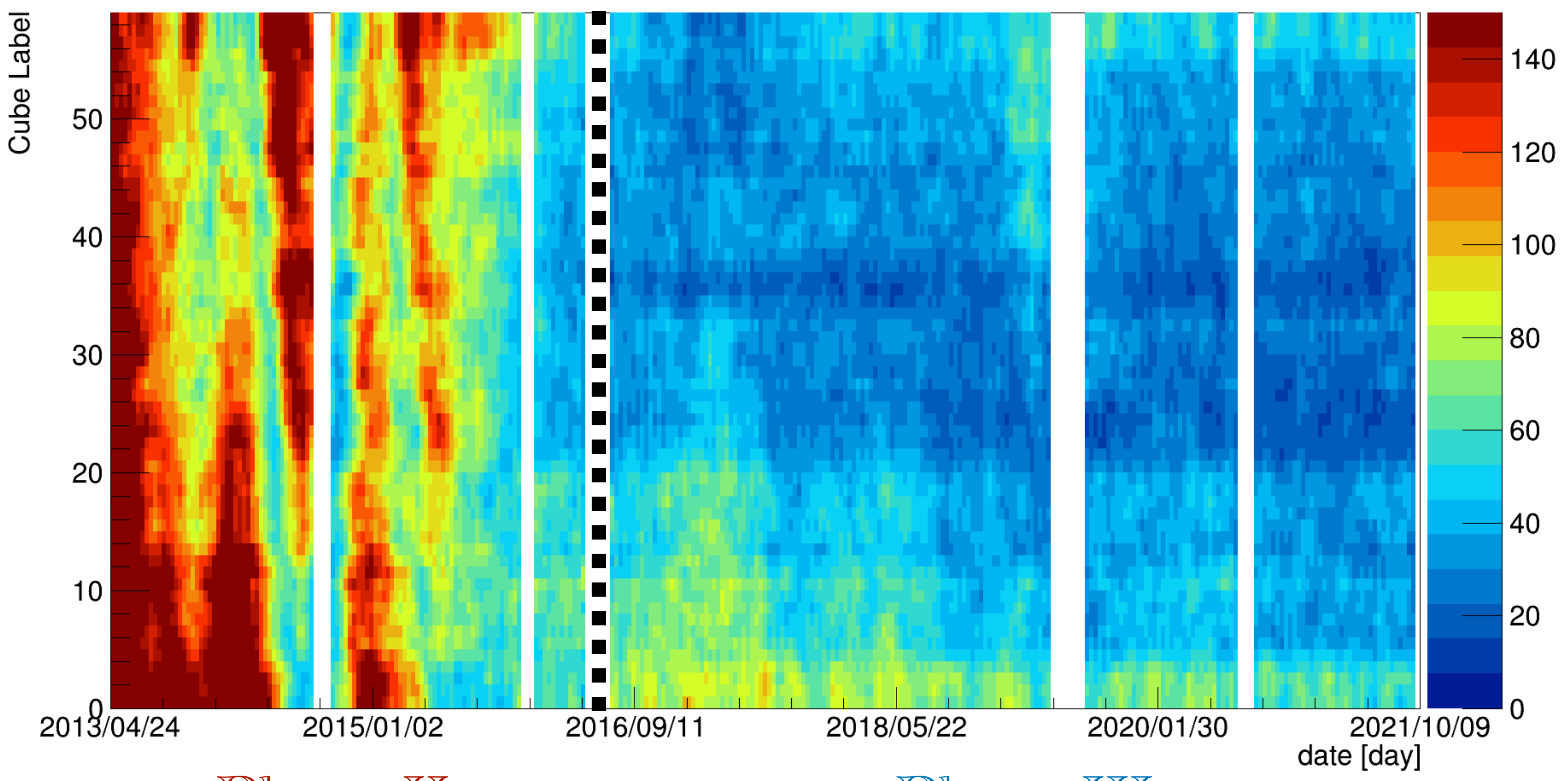
Convective motions in the liquid scintillators

Unknown amount of out-of-equlibrium ^{210}Po inside the FV

Secular equilibrium is broken: $R(^{210}\textbf{Po}) \geq R(^{210}\textbf{Bi})$

Thermal insulation of the detector:

^{210}Po Rate [cpd/100t] in Cubes



Phase-II Phase-III

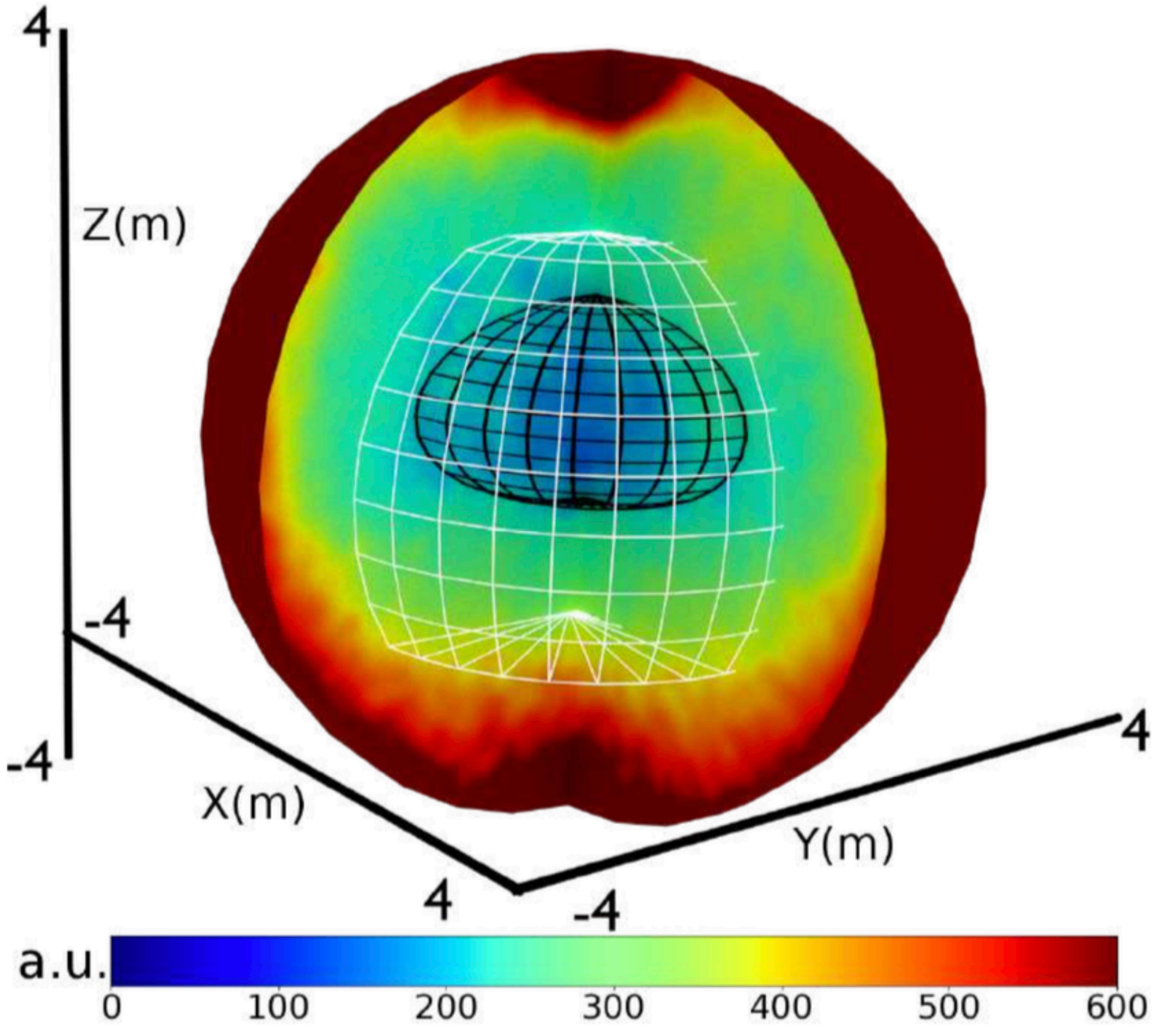
Low Polonium Field (LPoF):

Region inside the FV where the additional ^{210}Po contribution is minimum

$R(^{210}\textbf{Bi})$ **upper limit**

THE LOW POLONIUM FIELD

In this condition, the challenge is to find a region inside the FV where the additional ^{210}Po contribution is minimum:



Low Polonium Field (LPoF):

20 tons above the equator ($z_{center} \sim 80$ cm)

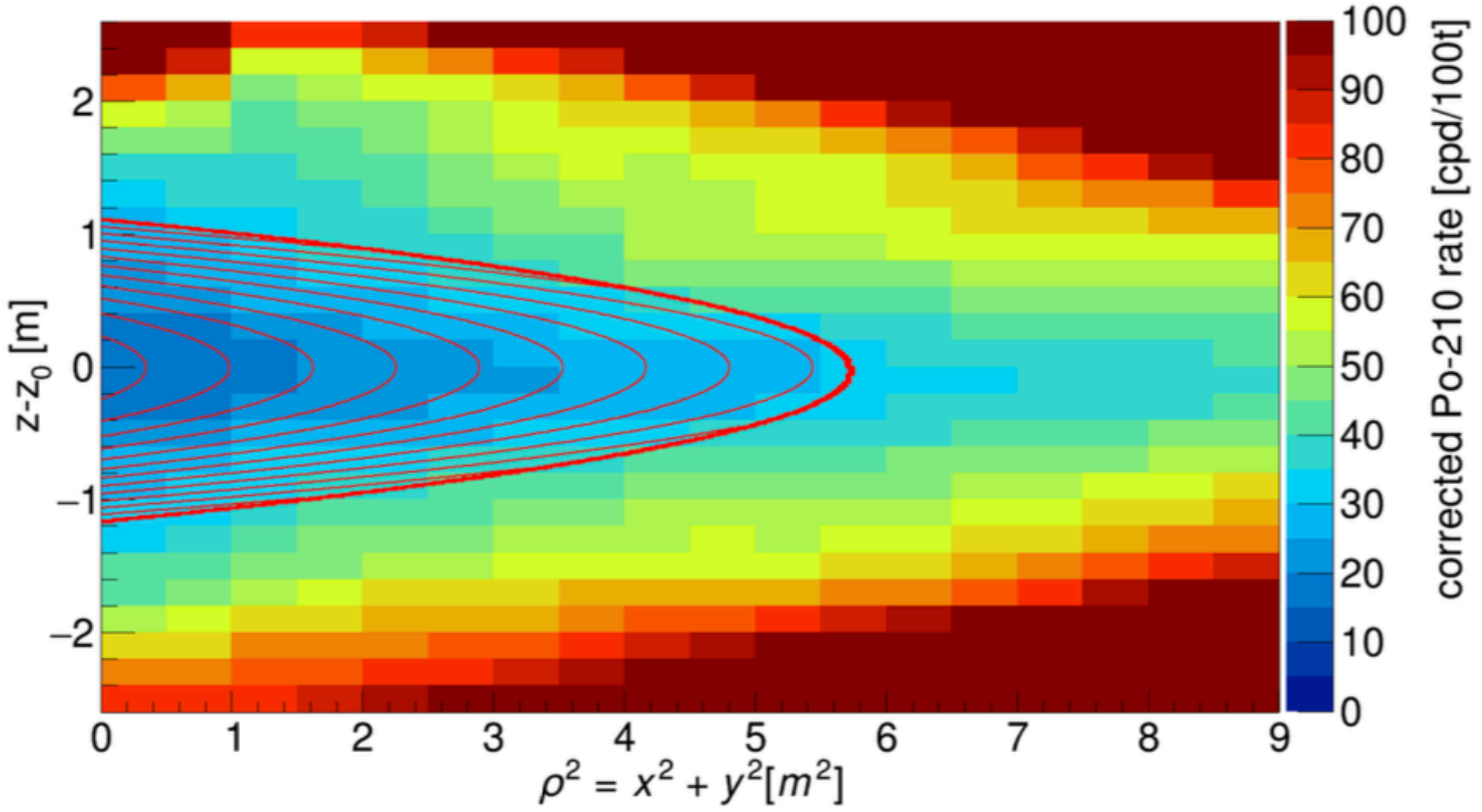
Cross-checked with fluid dynamic simulations

^{210}Po minimum is determined with **two methods**:

1) fitting LPoF with a 2D paraboloidal function:

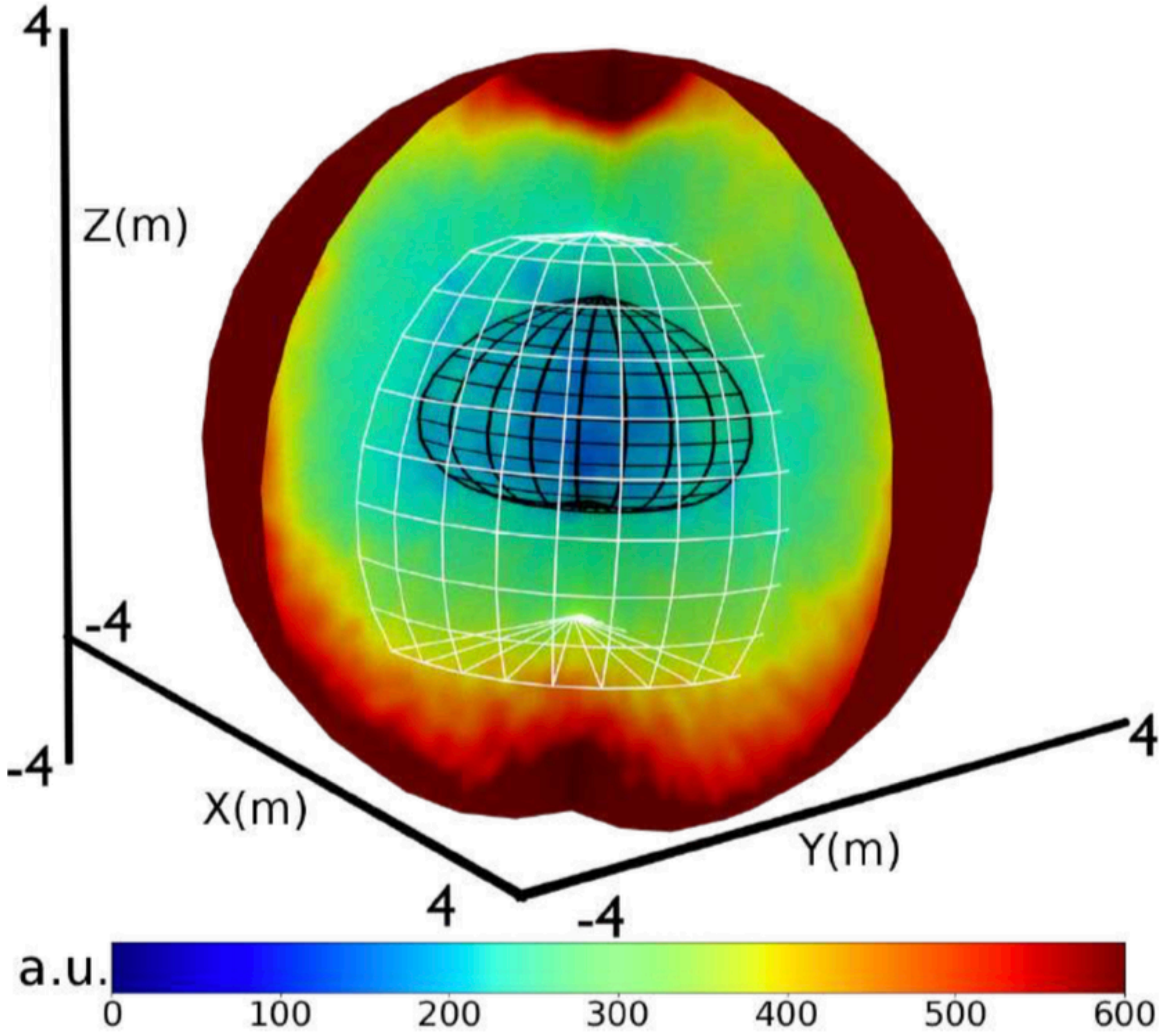
$$\frac{d^2R(^{210}Po)}{d(\rho^2)dz} = [R(^{210}Po)\epsilon_E\epsilon_M LP + R_\beta] \times \left(1 + \frac{\rho^2}{a^2} + \frac{(z-z_0)^2}{b^2}\right)$$

- Fit performed in data bins of one month: extract z_0 position vs time
- Sum up the time bins, alignin distributions wrt z_0
  - **Aligned dataset:** blindly align data according to z_0 from previous month to minimize possible biases



THE LOW POLONIUM FIELD

In this condition, the challenge is to find a region inside the FV where the additional ^{210}Po contribution is minimum:



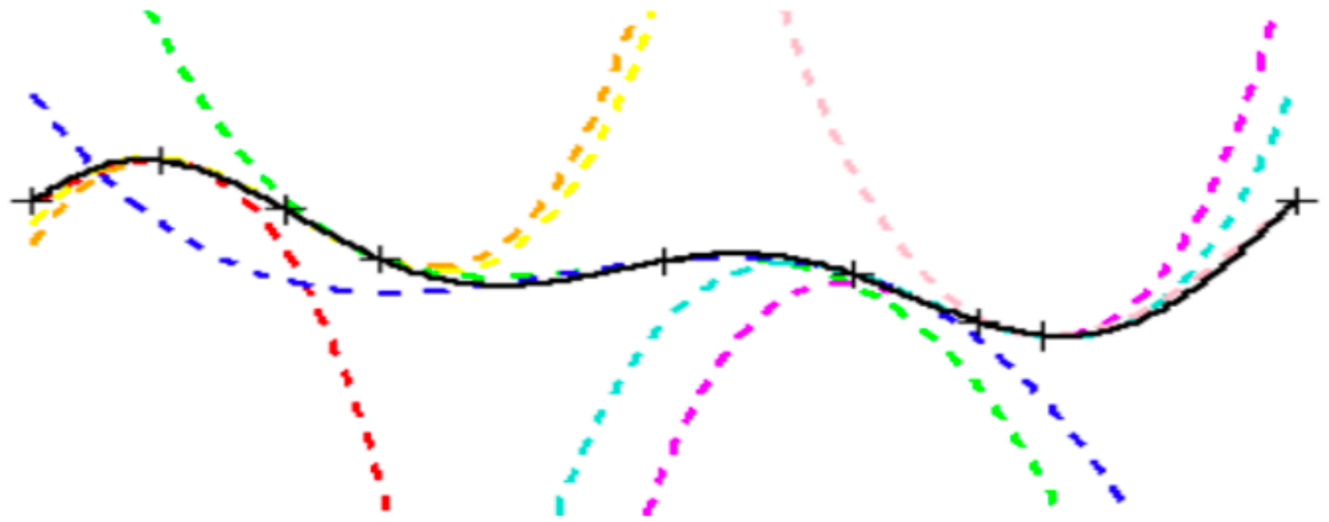
Low Polonium Field (LPoF):

20 tons above the equator ($z_{center} \sim 80$ cm)

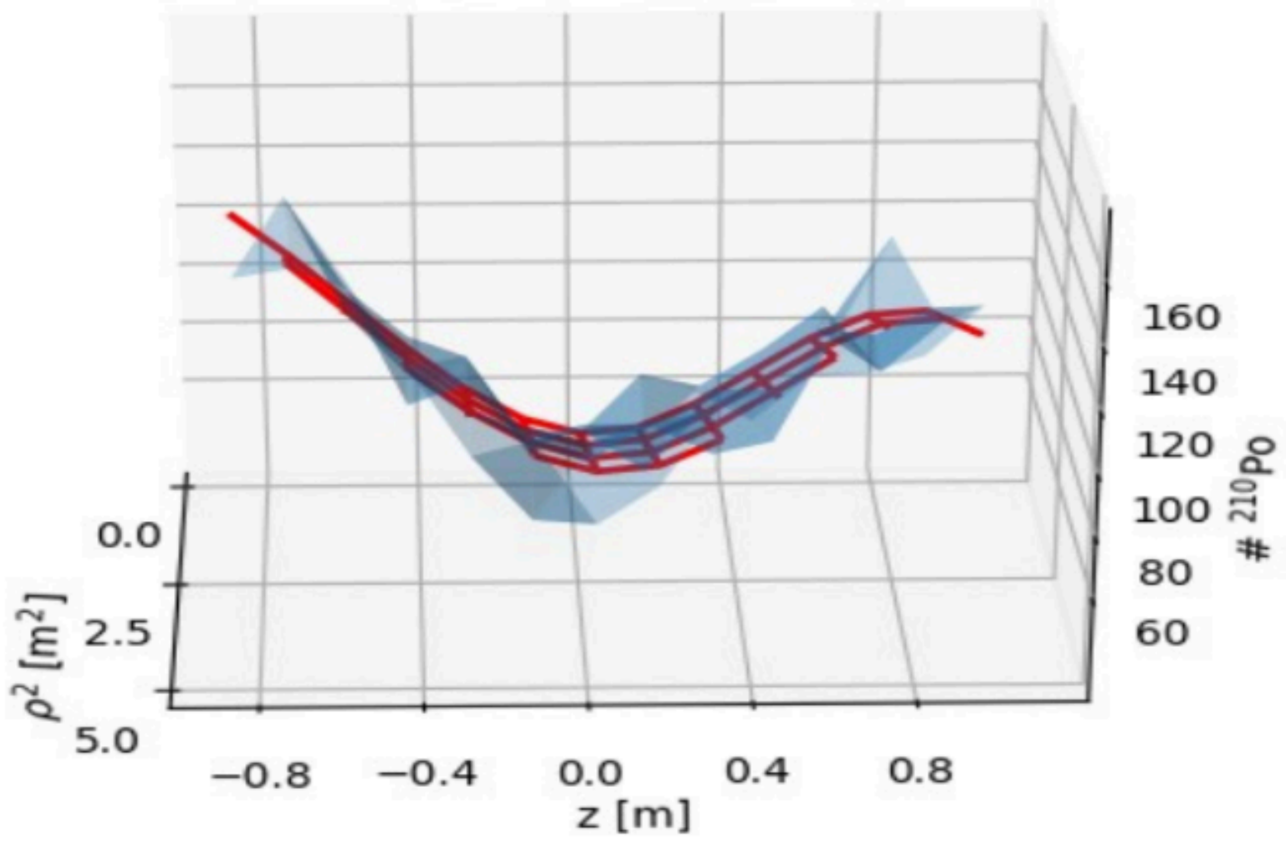
Cross-checked with fluid dynamic simulations

^{210}Po minimum is determined with **two methods**:

2) fitting LPoF with splines (cubic functions defined by *knots*) along z:

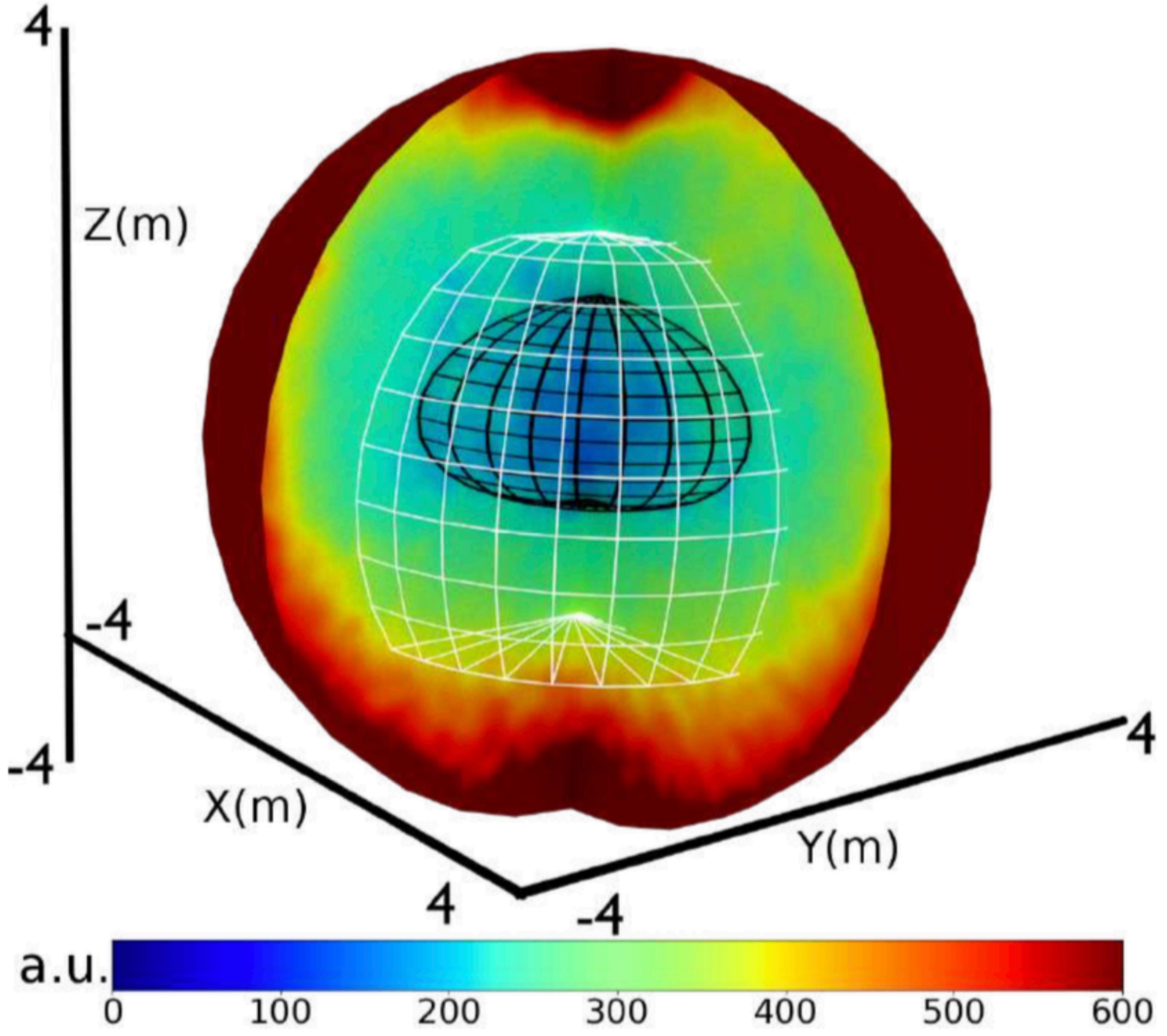


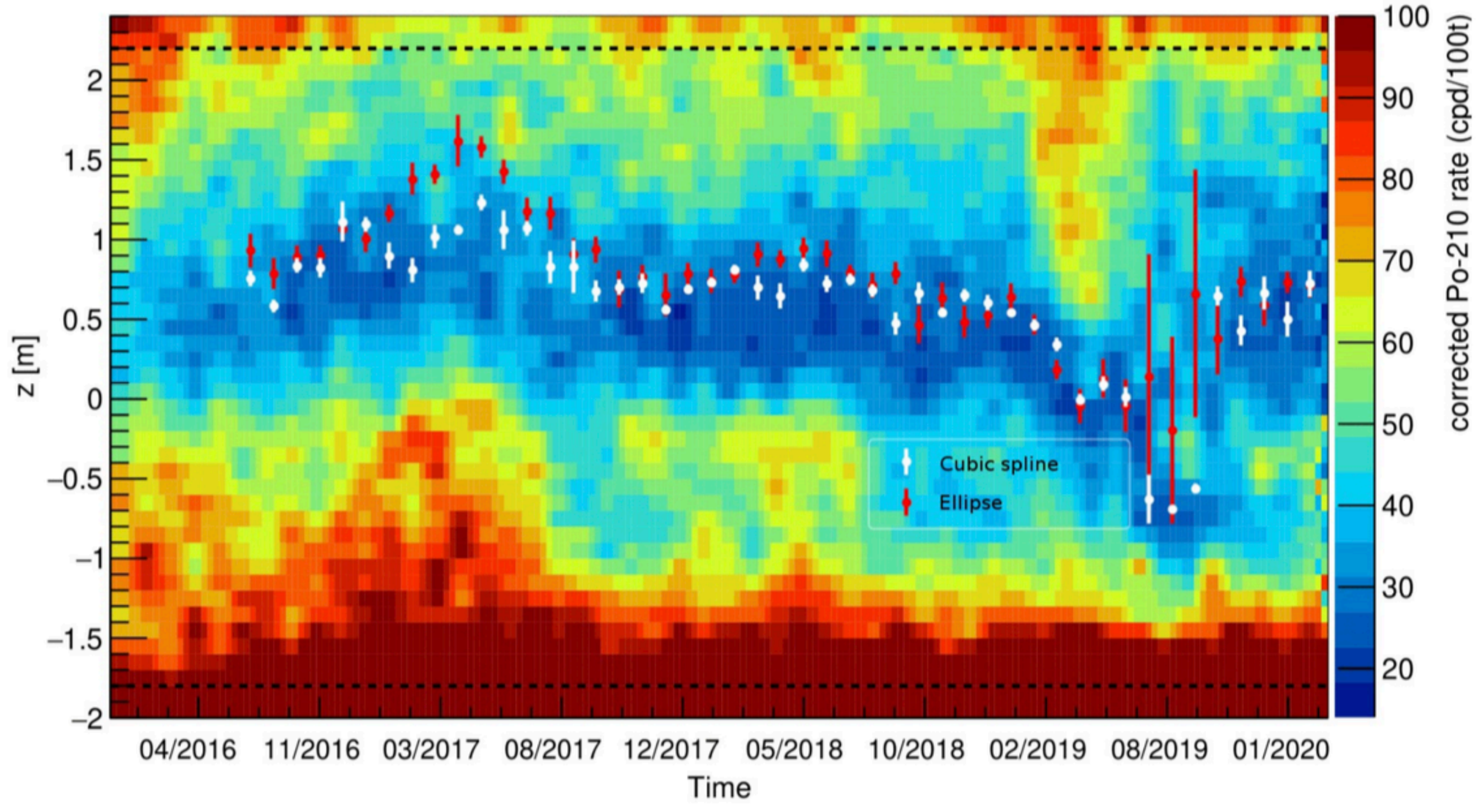
$$\frac{d^2R(^{210}Po)}{d(\rho^2)dz} = [R(^{210}Po)\epsilon_E\epsilon_M LP + R_\beta] \times \left(1 + \frac{\rho^2}{a^2} + spline(z)\right)$$



Mitglied der Helmholtz-Gemeinschaft

In this condition, the challenge is to find a region inside the FV where the additional ^{210}Po contribution is minimum:





Low Polonium Field (LPoF):

20 tons above the equator ($z_{center} \sim 80$ cm)

Cross-checked with fluid dynamic simulations

The two methods give consistent results:

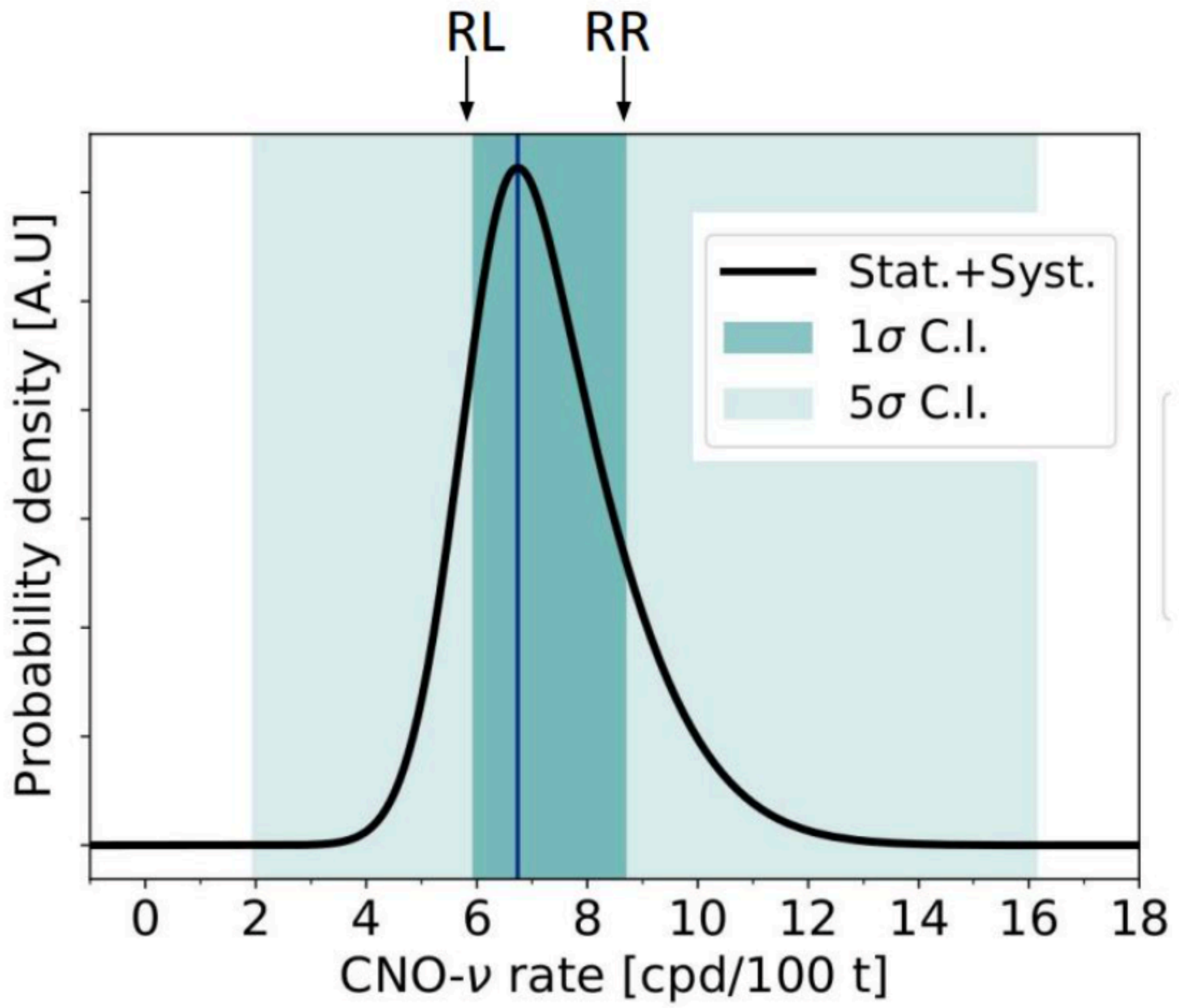
$R(^{210}\text{Bi}) \leq R(^{210}\text{Po}) = 11.5 \pm 1.0$ cpd/100t

Quantiles approach for CNO confidence interval

Procedure: quantiles of the CNO likelihood profile assuming Wilks approximation (same as 2020 CNO Nature paper)

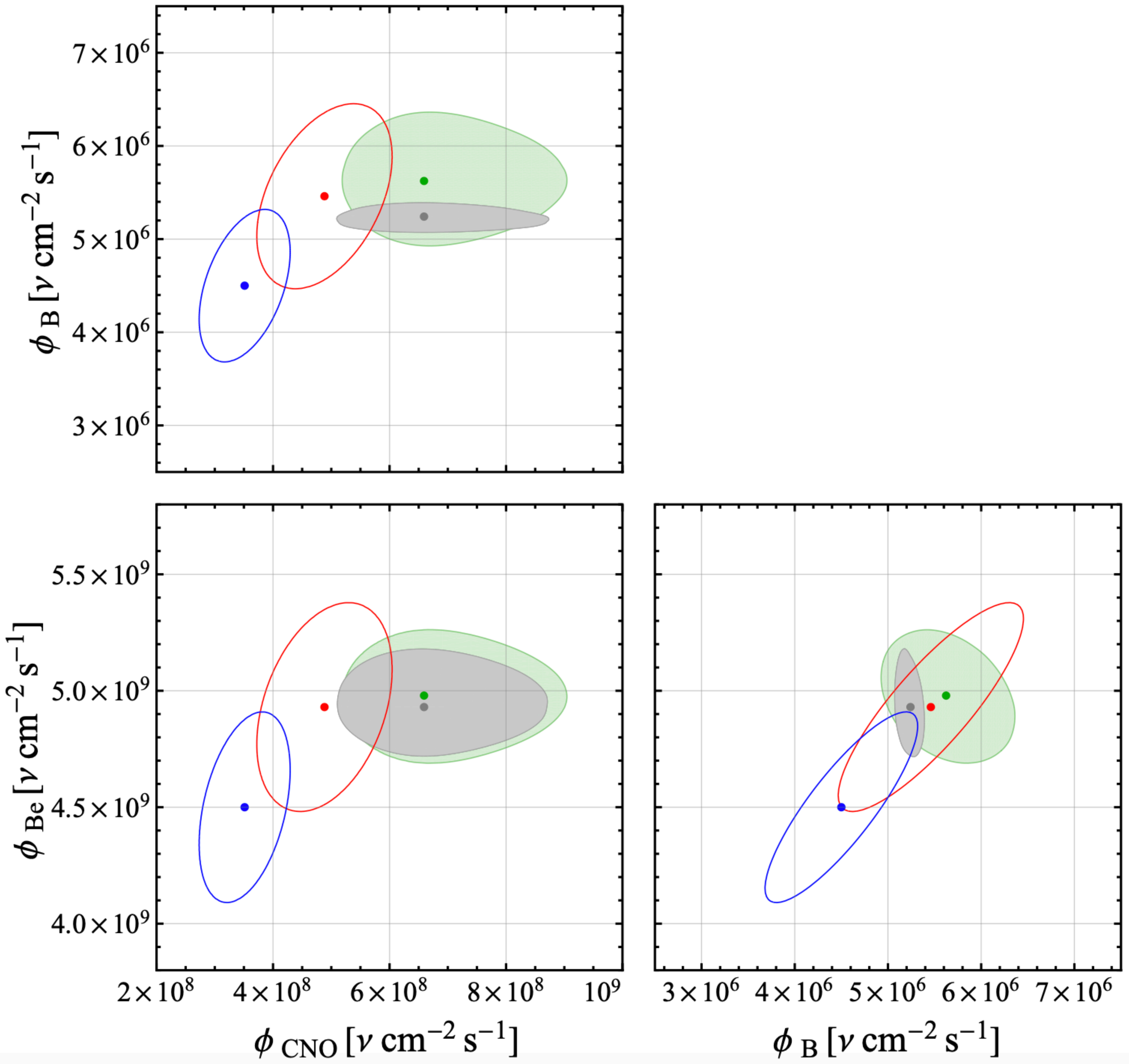
Central value → mode value: maximum of CNO rate likelihood / minimum of CNO rate $\Delta\chi^2$
C.I.→ calculating quantile of CNO density probability starting from the tail, separately for the left side and from the right side.

- 1σ C.I. left boundary: Rate RL such as area from 0 to RL is (1-0.68)/2 ~ 0.16
- 1σ C.I. right boundary: Rate RR such as area from RR to ∞ is (1-0.68)/2 ~ 0.16



SOLAR IMPLICATIONS: GLOBAL ANALYSIS

Results of **global analysis** fits in Φ_B, Φ_{Be}, and Φ_{CNO} planes



Test compatibility of solar ν data with SSM B16 predictions:

- Global analysis of all solar neutrino + Kamland reactor $\overline{\nu}_e$
- Borexino only + Kamland reactor $\overline{\nu}_e$
- SSM B16 predictions using HZ inputs (GS98)
- SSM B16 predictions using LZ inputs (AGSS09met)

Agreement with SSM-HZ predictions.
Small **tension** (adding CNO results) **with SSM-LZ**

JÜLICH Forschungszentrum

SOLAR IMPLICATIONS: HZ VS LZ TENSION

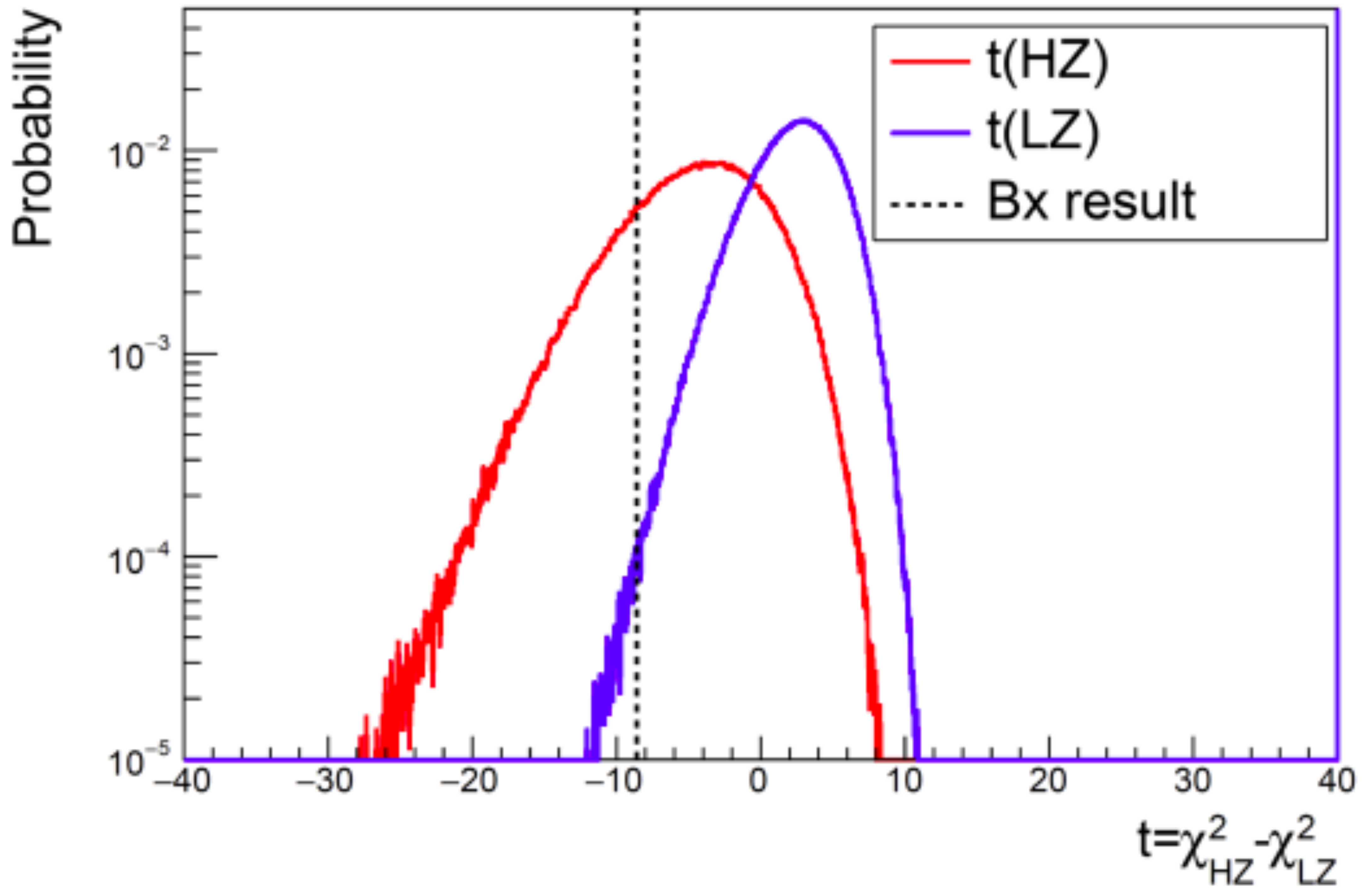
Frequentist hypothesis test based on a likelihood-ratio test statistics for SSM-LZ (null hypothesis H_0) and SSM-HZ (alternative hypothesis H_1)

Test statistics t is built using only ^8B, ^7Be, and CNO Borexino's results:

$$t = -2log[\mathscr{L}(HZ)/\mathscr{L}(LZ)] = \chi^2(HZ) - \chi^2(LZ)$$

Model and experimental uncertainties included

Assuming SSM-HZ, Borexino results (^7Be, ^8B and CNO) **disfavour SSM-LZ at ~3.2σ.**



SOLAR IMPLICATIONS: C+N ABUNNDANCE

Metallicity ⟷ Radiative Opacity ⟷ Tcore ⟷ $\Phi(^7\mathrm{Be}), \Phi(^8\mathrm{B})$

Tcore ⟷ $\Phi(\mathrm{CNO})$

Metallicity ⟷ $\Phi(\mathrm{CNO})$: Direct dependence

$$\frac{\Phi_i}{\Phi_i^{SSM}} \propto \left(\frac{T_C}{T_C^{SSM}}\right)^{\tau_i}$$

$$\frac{\Phi_B}{\Phi_B^{SSM}} \propto \left(\frac{T_C}{T_C^{SSM}}\right)^{\tau_B} \qquad \tau_{^8B} \approx 24$$

$$\frac{\Phi_O}{\Phi_O^{SSM}} \propto \frac{n_{CN}}{n_{CN}^{SSM}} \cdot \left(\frac{T_C}{T_C^{SSM}}\right)^{\tau_O} \qquad \tau_{^{15}O} \approx 20$$

Φ_B as thermometer

$$\boxed{\frac{\Phi_O/\Phi_O^{SSM}}{(\Phi_B/\Phi_B^{SSM})^k} \propto \frac{n_{CN}}{n_{CN}^{SSM}} \cdot \left(\frac{T_C}{T_C^{SSM}}\right)^{\tau_O - k\tau_B}}$$

k to minimize impact of T_C

$k = \tau_O/\tau_B \approx 0.83$

JÜLICH Forschungszentrum

SOLAR IMPLICATIONS: C+N ABUNNDANCE

Metallicity ⟷ Radiative Opacity ⟷ Tcore ⟷ $\Phi(^7\mathrm{Be}), \Phi(^8\mathrm{B})$

Tcore ⟷ $\Phi(\mathrm{CNO})$

Metallicity ⟷ $\Phi(\mathrm{CNO})$: Direct dependence

$$\frac{\Phi_i}{\Phi_i^{SSM}} \propto \left(\frac{T_C}{T_C^{SSM}}\right)^{\tau_i}$$

$$\frac{\Phi_B}{\Phi_B^{SSM}} \propto \left(\frac{T_C}{T_C^{SSM}}\right)^{\tau_B} \qquad \tau_{^8B} \approx 24$$

$$\frac{\Phi_O}{\Phi_O^{SSM}} \propto \frac{n_{CN}}{n_{CN}^{SSM}} \cdot \left(\frac{T_C}{T_C^{SSM}}\right)^{\tau_O} \qquad \tau_{^{15}O} \approx 20$$

Φ_B as thermometer

$$\frac{\Phi_O/\Phi_O^{SSM}}{(\Phi_B/\Phi_B^{SSM})^k} \propto \frac{n_{CN}}{n_{CN}^{SSM}} \cdot \left(\frac{T_C}{T_C^{SSM}}\right)^{\tau_O - k\tau_B}$$

k to minimize impact of T_C
$k = \tau_O/\tau_B \approx 0.83$

Reality is much more complicated than this...

$$\frac{\Phi_O/\Phi_O^{SSM}}{(\Phi_B/\Phi_B^{SSM})^k} \propto \frac{N_{CN}}{N_{CN}^{SSM}} \cdot [1 \pm (0.097(\mathrm{nucl}) + 0.005(\mathrm{env}) + 0.027(\mathrm{diff})]$$

Optimal k
$k = 0.769$

S-factors of nuclear properties

Diffusion

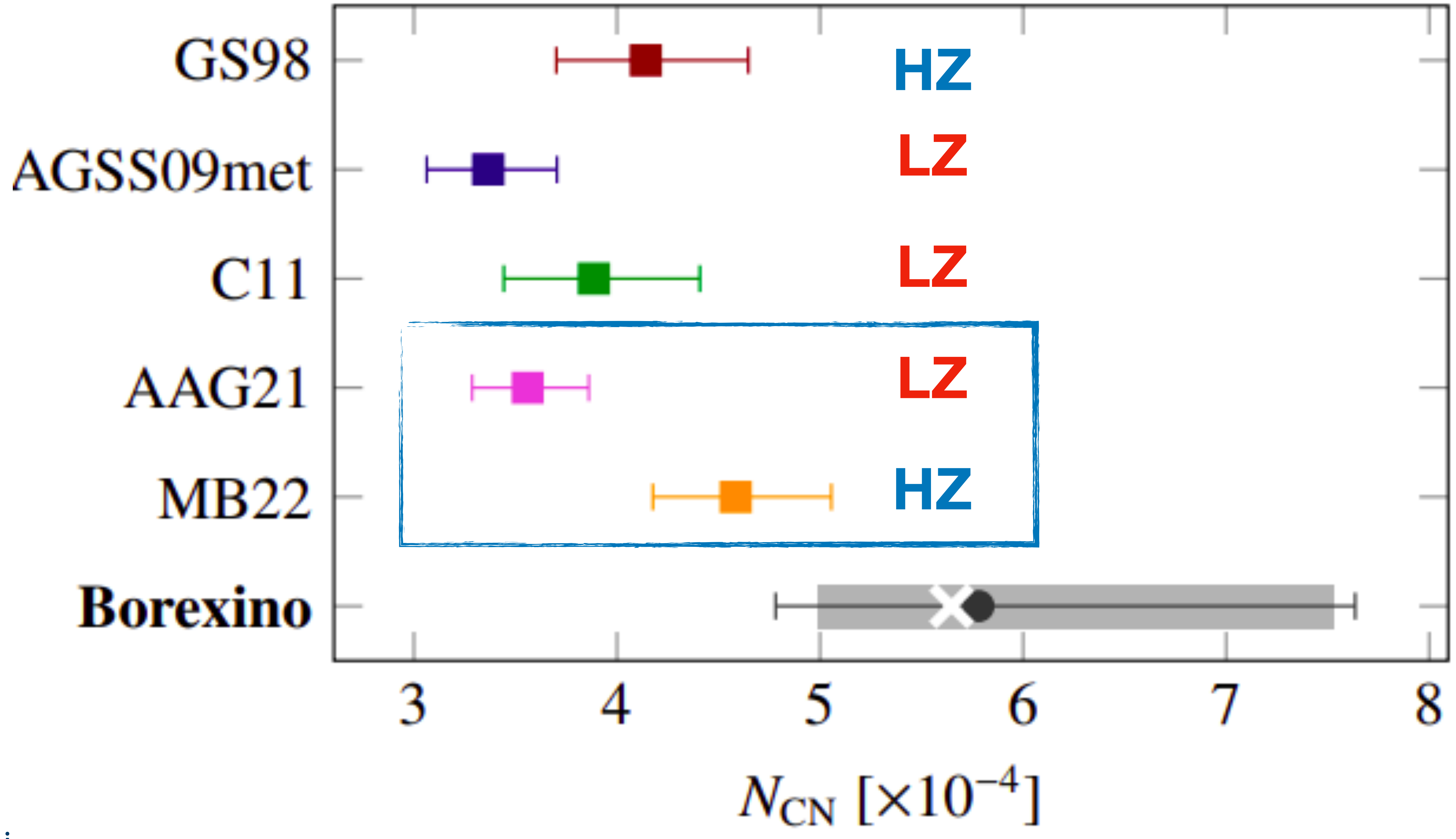
47 Elements abundances + Solar properties

SOLAR IMPLICATIONS: C+N ABUNNDANCE

With $(\Phi_B/\Phi_B^{SSM}) = 0.96 \pm 0.03$ from global analysis and $(\Phi_O/\Phi_O^{SSM}) = 1.35^{+0.41}_{-0.18}$ from CNO measurement

$$N_{CN} = (5.81^{+1.22}_{-0.94}) \cdot 10^{-4}$$

First **determination of C+N abundance** in the Sun using neutrinos
Can be directly compared with measurements from solar photosphere

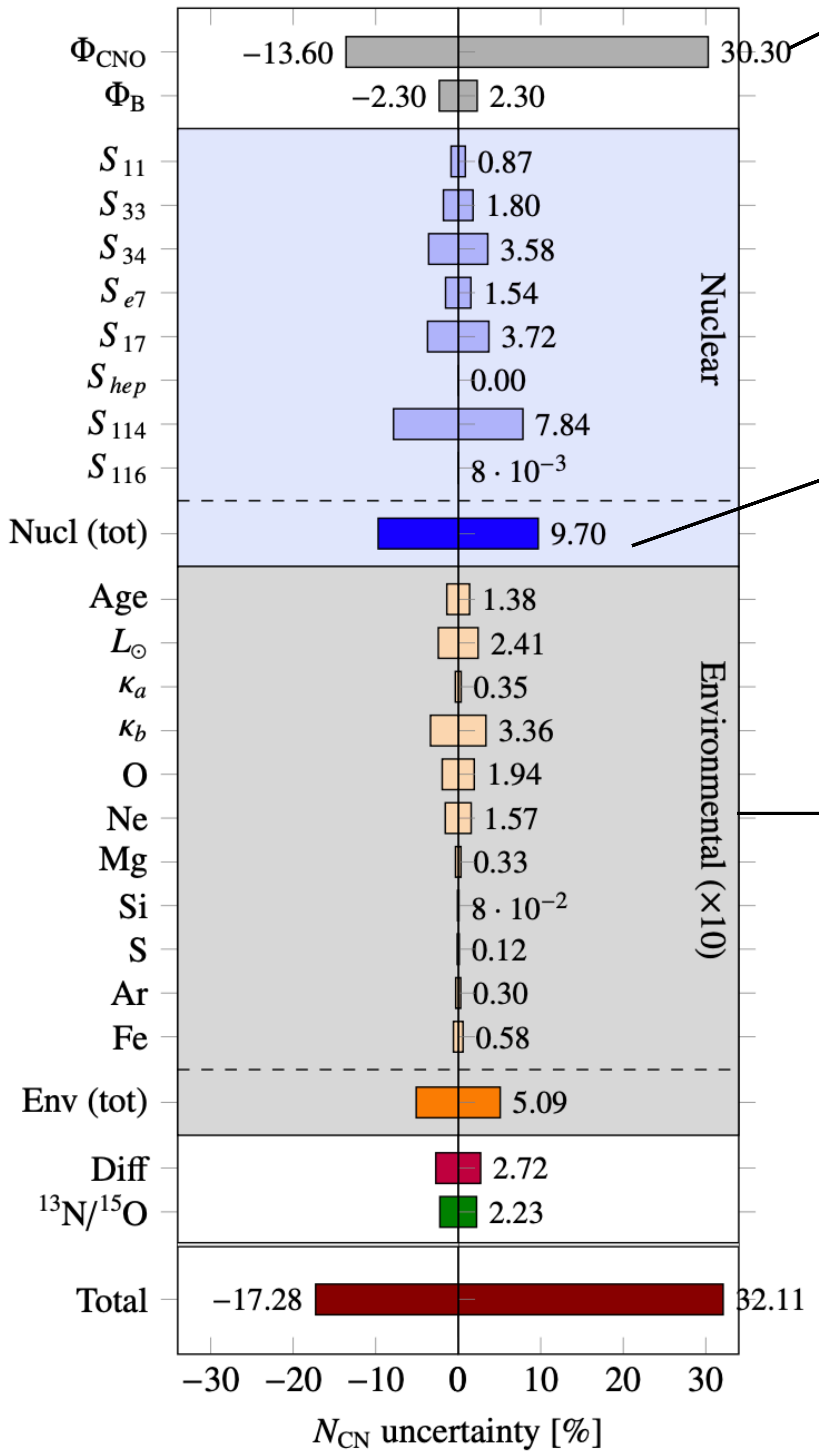


● Calculation performed with B16-GS98
× Calculation performed with B16-AGSS09met

Agreement with SSM-HZ predictions.
Moderate ~2σ **tension with SSM-LZ**

SOLAR IMPLICATIONS: C+N ABUNNDANCE

Error budget on N_CN



CNO flux determination accuracy (critical)

Limited precision on nuclear cross sections

As expected, environmental parameters doesn't affect the uncertainty much (0.5%)

JÜLICH Forschungszentrum