JUNO sensitivity to ^{7}Be, pep and CNO solar neutrinos

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JUNO Italia Meeting - 2022 May 05 - Milano

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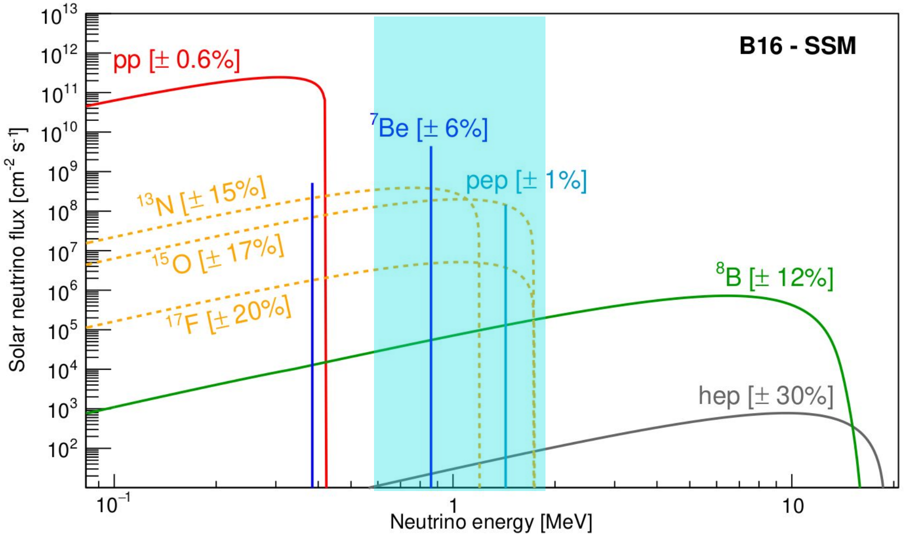
Istituto Nazionale di Fisica Nucleare

Motivation

Solar ν energy spectrum



- Solar neutrino fluxes **depend on metallicity scenario (HZ or LZ),** describing the abundance of elements heavier than He in the Sun:

  ^{7}Be-ν ~8.7% CNO-ν ~28% ^{8}B-ν ~17.4%

- Precision measurement → astrophysical implications: <u>solar metallicity discrimination</u>

- Energy ROI: **~(0.45-1.7) MeV**
  This and 8B-ν analysis are complementary
  (Feasibility and physics potential of detecting 8B neutrinos at JUNO, Chinese Phys. C 45 023004)

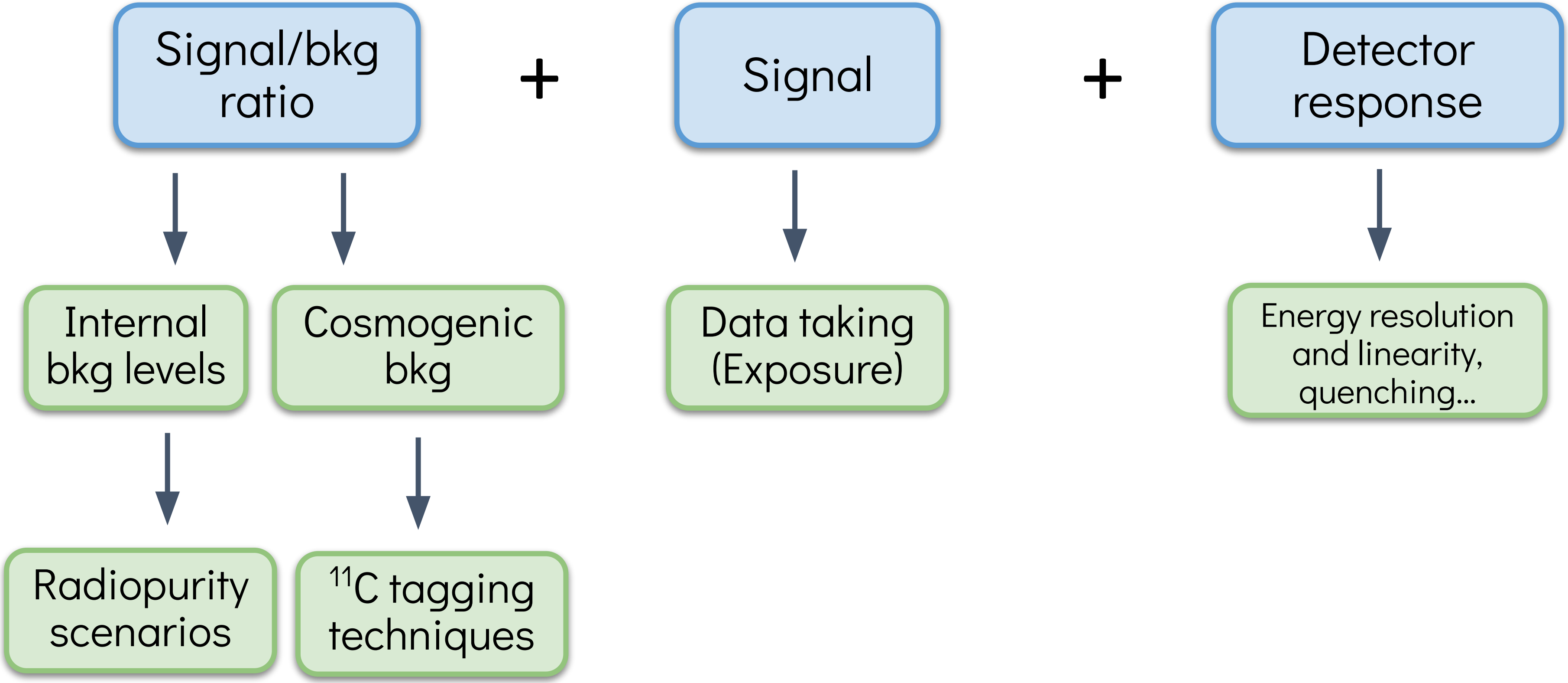
JUNO sensitivity to intermediate-energy solar neutrino fluxes
Which factors drive the JUNO sensitivity?

Analysis strategy

Which factors drive the JUNO solar ν sensitivity?

Signal/bkg ratio + Signal + Detector response

Which factors drive the JUNO solar ν sensitivity?



Signal/bkg ratio + Signal + Detector response

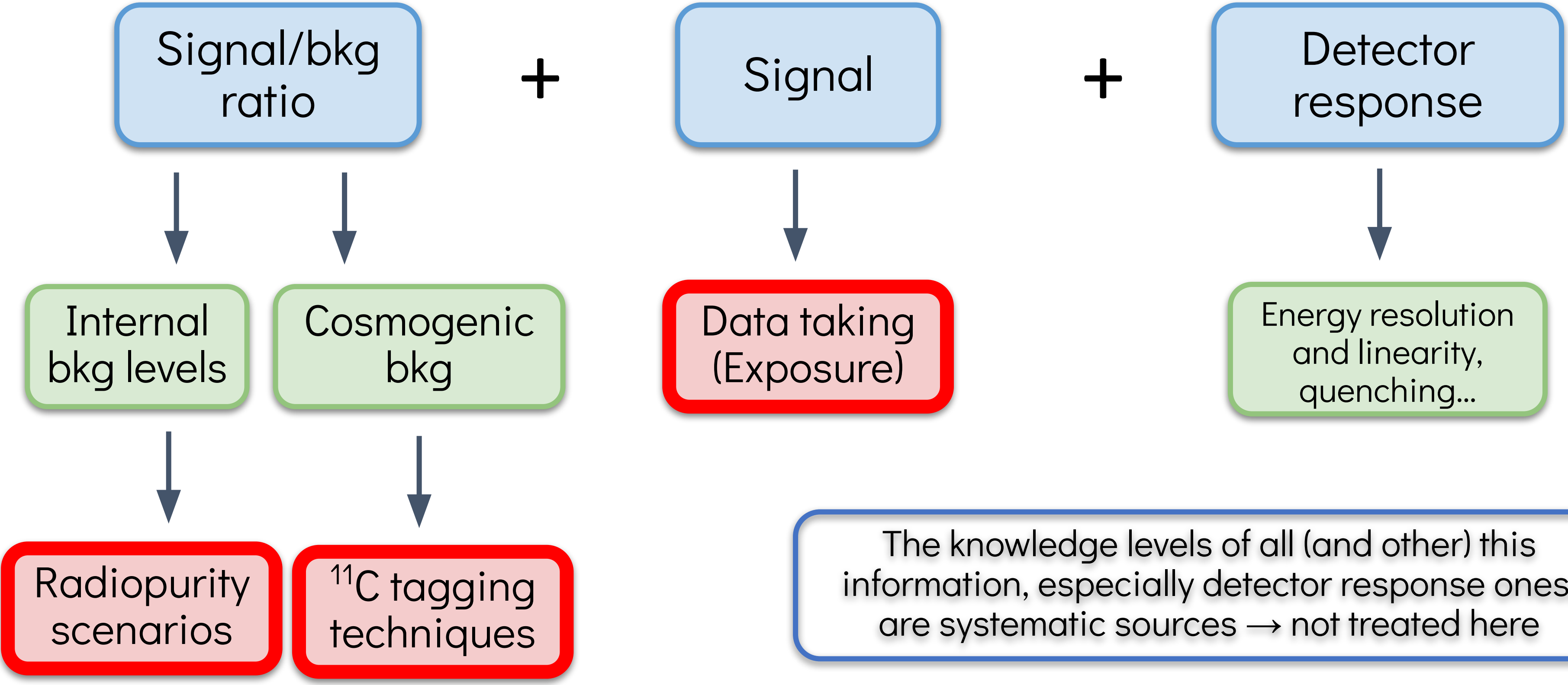
Signal/bkg ratio → Internal bkg levels → Radiopurity scenarios

Signal/bkg ratio → Cosmogenic bkg → ^{11}C tagging techniques

Signal → Data taking (Exposure)

Detector response → Energy resolution and linearity, quenching…

Which factors drive the JUNO solar ν sensitivity?



Signal/bkg ratio

+

Signal

+

Detector response

Internal bkg levels

Cosmogenic bkg

Data taking (Exposure)

Energy resolution and linearity, quenching…

Radiopurity scenarios

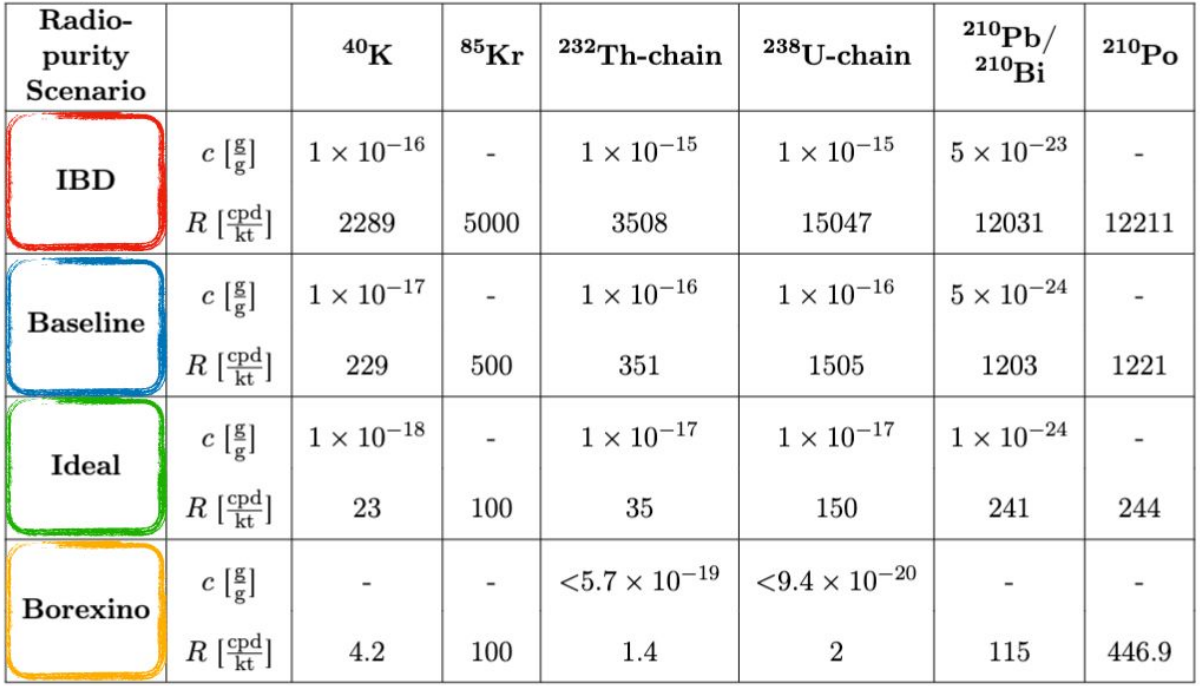
^{11}C tagging techniques

The knowledge levels of all (and other) this information, especially detector response ones, are systematic sources → not treated here

Internal bkgs budget

- Re-evaluation of backgrounds rates both radio-contaminants and cosmogenic
- Four radiopurity scenarios have been analyzed → **sensitivity for each of these scenarios**

Better radiopurity



Radio-purity Scenario		^{40}K	^{85}Kr	^{232}Th-chain	^{238}U-chain	^{210}Pb/ ^{210}Bi	^{210}Po
IBD	$c\ [\frac{g}{g}]$	1×10^{-16}	-	1×10^{-15}	1×10^{-15}	5×10^{-23}	-
	$R\ [\frac{cpd}{kt}]$	2289	5000	3508	15047	12031	12211
Baseline	$c\ [\frac{g}{g}]$	1×10^{-17}	-	1×10^{-16}	1×10^{-16}	5×10^{-24}	-
	$R\ [\frac{cpd}{kt}]$	229	500	351	1505	1203	1221
Ideal	$c\ [\frac{g}{g}]$	1×10^{-18}	-	1×10^{-17}	1×10^{-17}	1×10^{-24}	-
	$R\ [\frac{cpd}{kt}]$	23	100	35	150	241	244
Borexino	$c\ [\frac{g}{g}]$	-	-	$<5.7 \times 10^{-19}$	$<9.4 \times 10^{-20}$	-	-
	$R\ [\frac{cpd}{kt}]$	4.2	100	1.4	2	115	446.9

IBD: ~ minimum requirement for NMO ☹

Baseline: ~ 10 times Borexino Phase-I contam.

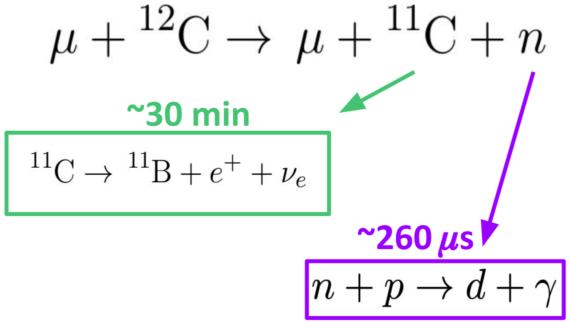
Ideal: ~ Borexino Phase-I contamination

Borexino-like: ~Borexino Phase-III contamination ☺

Cosmogenic background and ^{11}C tagging

- ^{11}C produced by μ through spallation processes on scintillator ^{12}C (Expected rate: ~10x than Gran Sasso!)

- **Effective 11C identification algorithm → Three-Fold Coincidence (TFC)** algorithm: space and time correlations between n, μ and e$^+$
- Algorithm is not implemented still
- TFC performance was assumed in an effective way



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

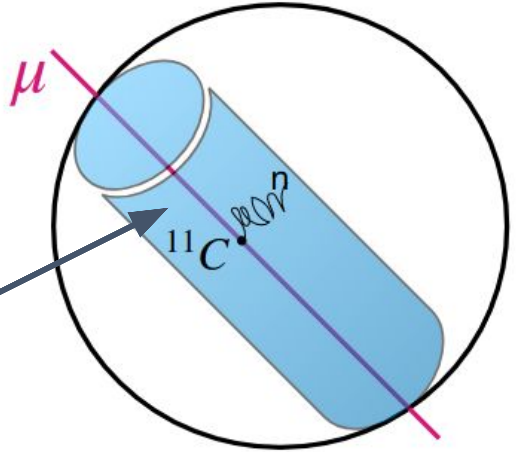
~30 min

$$\boxed{{}^{11}\mathrm{C} \rightarrow {}^{11}\mathrm{B} + e^+ + \nu_e}$$

~260 μs

$$\boxed{n + p \rightarrow d + \gamma}$$

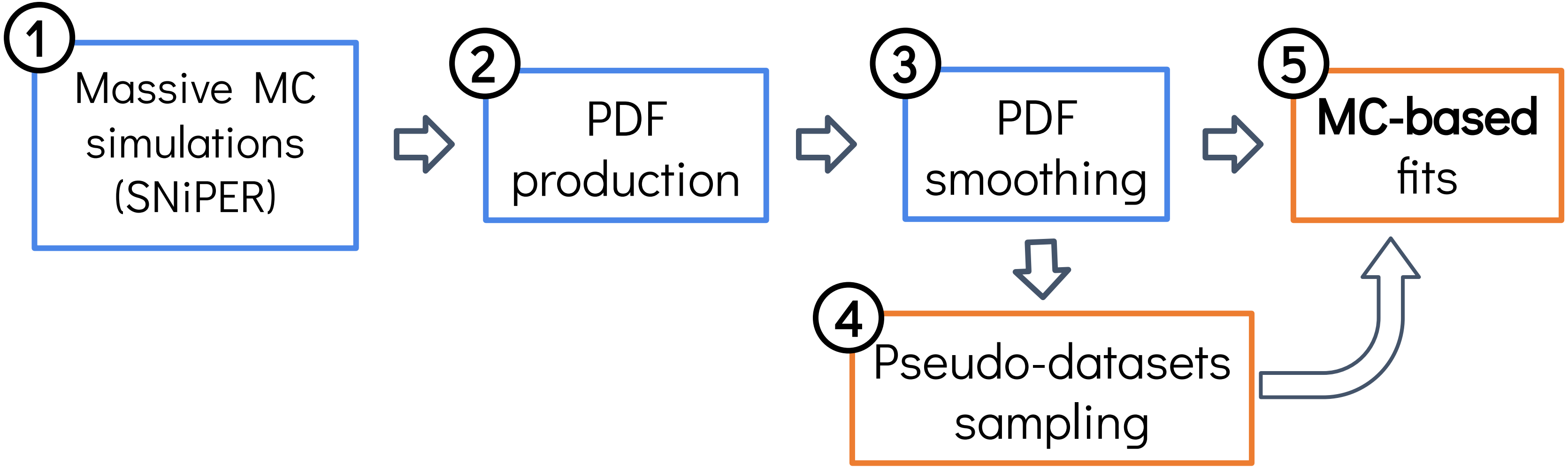
TFC application splits the JUNO solar neutrino dataset into two distinct data samples: one more populated by 11C (**TFC-tagged**) and one depleted in 11C (**TFC-subtracted**).



Spatial region (cylinder)
vetoed in TFC

Sensitivity studies work-flow

Details: docDB#7661
(NuSol Technote)



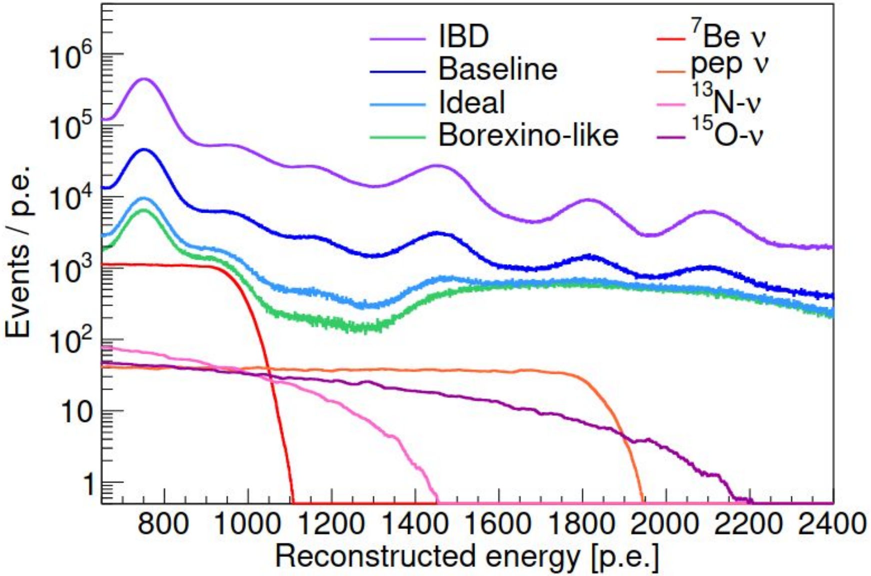
1, 2, 3: common ground

4, 5: independent software frameworks from Milano and Juelich (**MUST** and JUST tools)

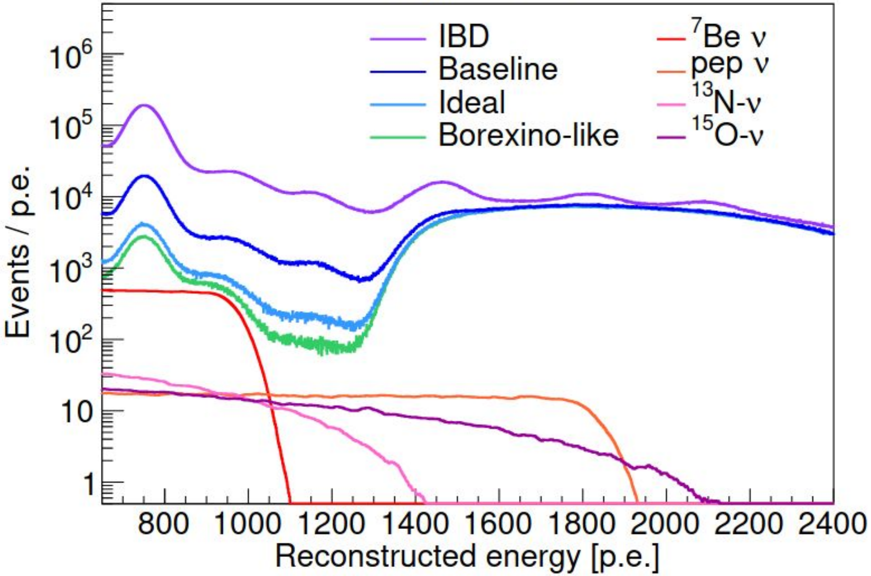
Milano nUsol Sensitivity Tool

Spectra in the four radiopurity scenarios

TFC-Subtracted spectra
(Depleted in ^{11}C)

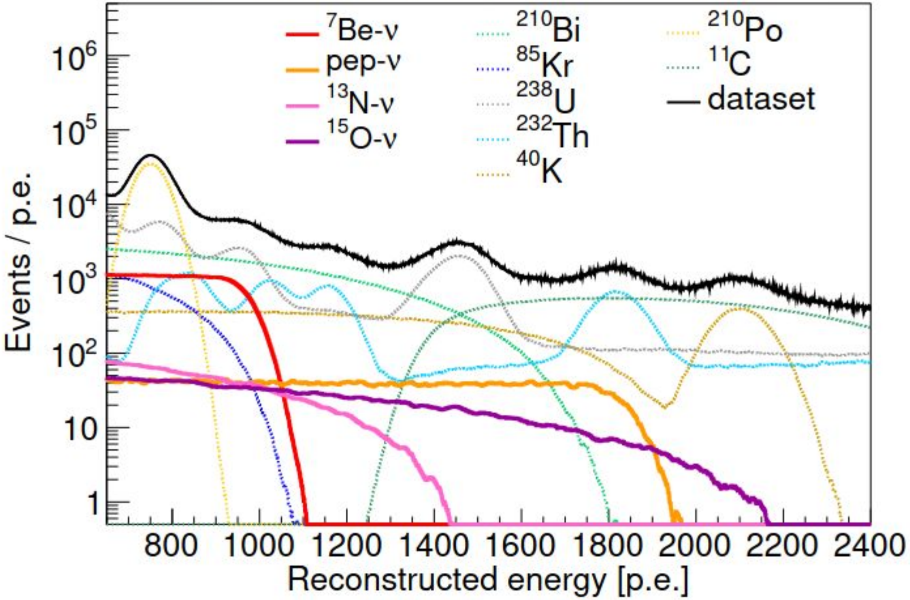


TFC-Tagged spectra
(More populated by ^{11}C)

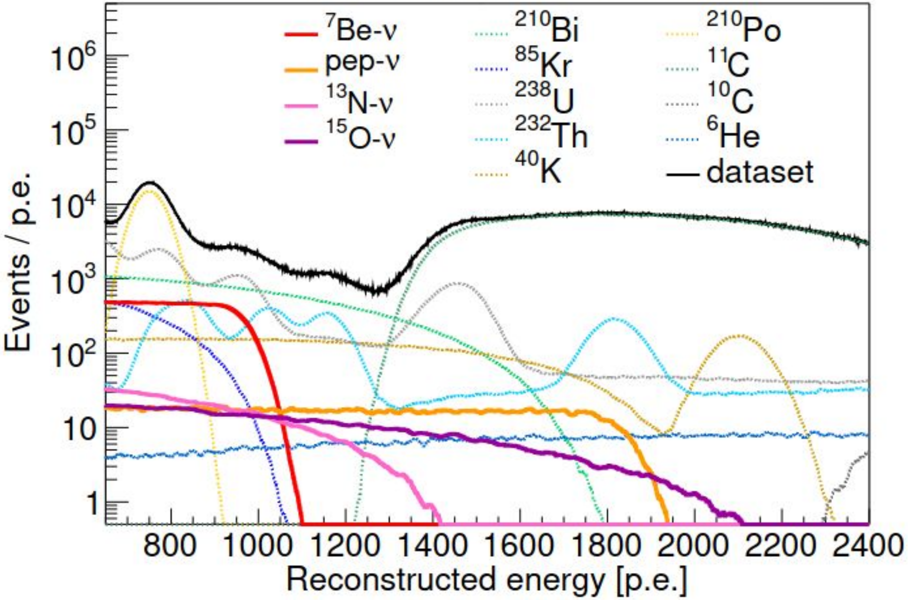


TFC-Subtracted & TFC-Tagged spectra (Baseline scenario)

Baseline TFC-Subtracted spectrum
(Depleted in ^{11}C)



Ideal TFC-Tagged spectrum
(More populated by ^{11}C)



Sensitivity results:

^{7}Be, pep, CNO

Sensitivity study: configurations

Sensitivity to Be7, pep and CNO depending on several variables of interests:

1. Impact of the exposure
2. Impact of internal backgrounds
3. Impact of TFC-related parameters: tagging power and % Subtracted Exposure

Common fit settings: 650 p.e. < E_{rec} < 2400 p.e. , 90% TFC Tagging Power, 70% TFC Subtracted Exposure, 10^4 fits for each study. **Two main fit configurations:**

①

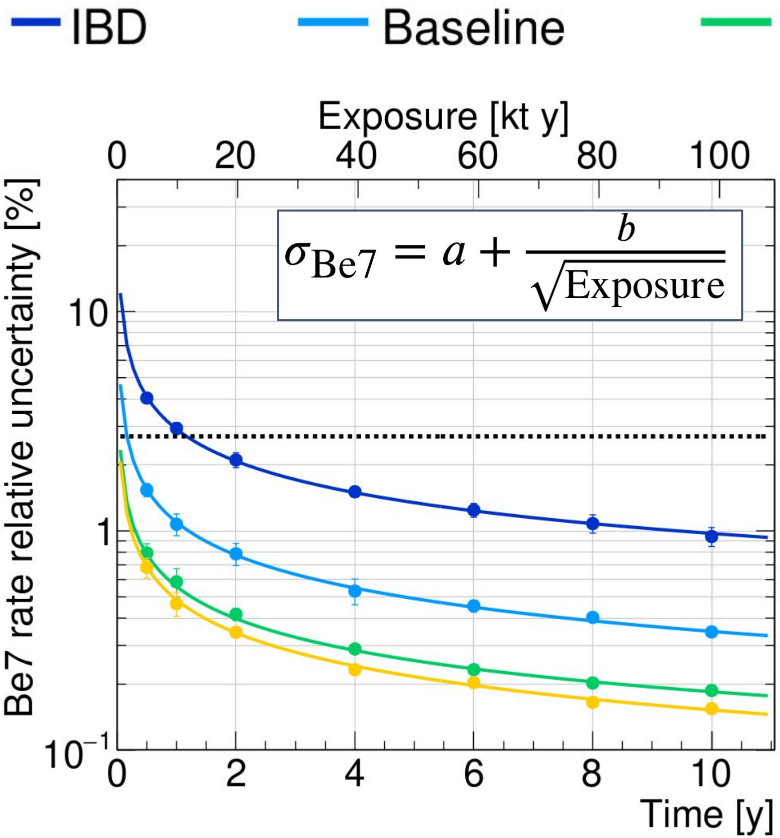
Be7, pep, CNO rates free to vary,
CNO constrained to HZ-SSM
→ **Be7, pep, CNO measurement**

②

Be7, pep, 13N, 15O free to vary
→ **13N and 15O measured independently (+ Be7, +pep)**

Also, then: costraining pep with SSM luminosity constraint for better CNO / N13 / O15 measurement

1) Impact of the exposure on 7Be sensitivity

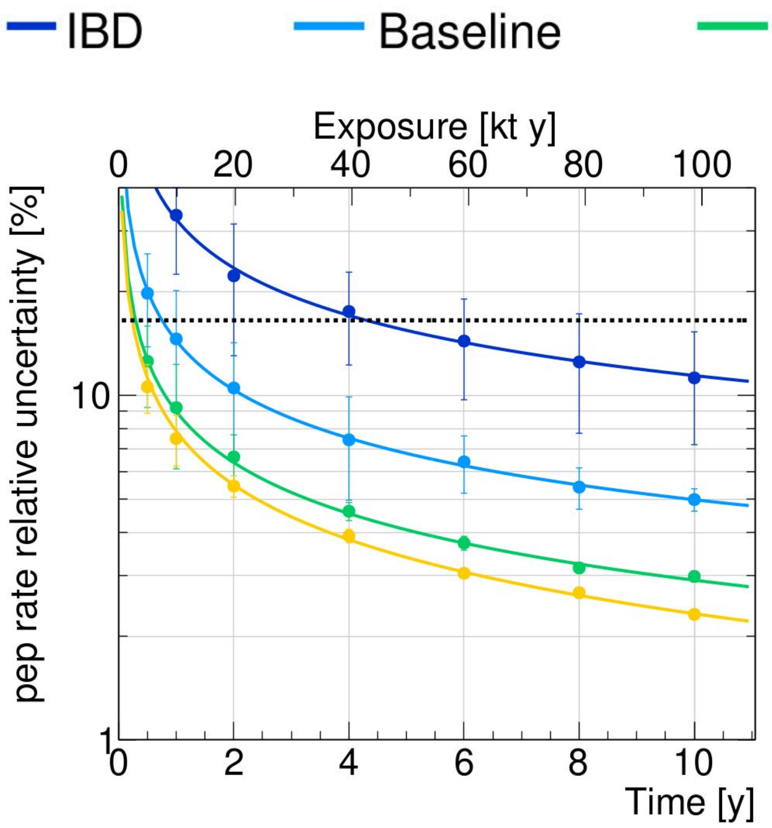


- After 1y, **Be7 stat. error**:
~0.55% (ideal), ~1% (baseline), ~2.9% (IBD)
- After 6y, **Be7 stat. error**:
~0.2% (ideal), ~0.4% (baseline), ~1.0% (IBD)

Borexino result (2.7%) is matched, for all the scenarios, after the first year of data taking: short term measurement

No significant improvement after 6 years for Ideal and Baseline
→**Systematics are driving the error budget for long data-taking !**

1) Impact of the exposure on pep sensitivity

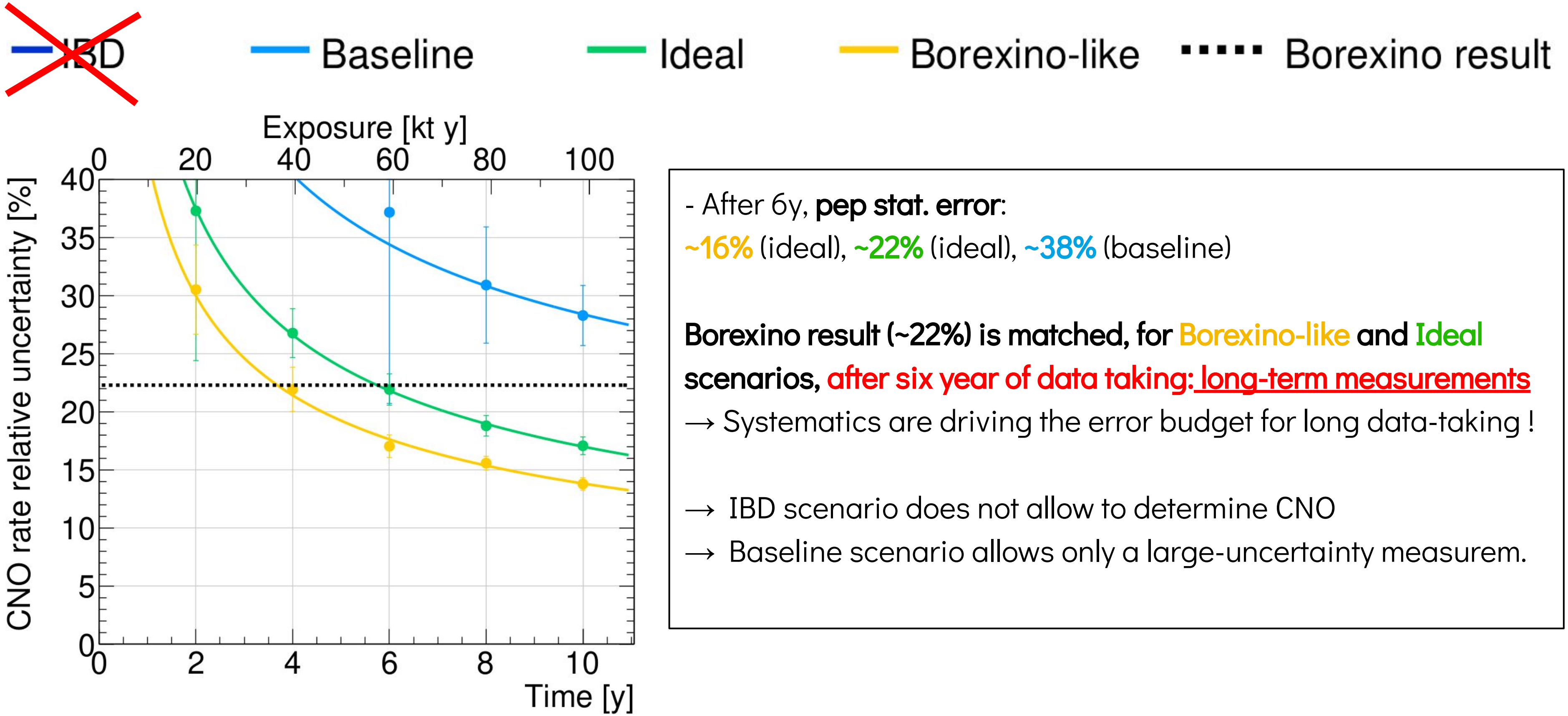


- After 1y, **pep stat. error**:
~6% (ideal), ~10% (baseline) or ~23% (IBD)
- After 6y, **pep stat. error**:
~3.5% (ideal), ~6.5% (baseline) or ~18% (IBD)

Borexino result (16%) is matched, for all the scenarios, after six year of data taking: long-term measurements

→Systematics are driving the error budget for long data-taking !

1) Impact of the exposure on CNO sensitivity



- After 6y, **pep stat. error**:
~16% (ideal), ~22% (ideal), ~38% (baseline)

Borexino result (~22%) is matched, for Borexino-like and Ideal scenarios, after six year of data taking: long-term measurements
→ Systematics are driving the error budget for long data-taking !

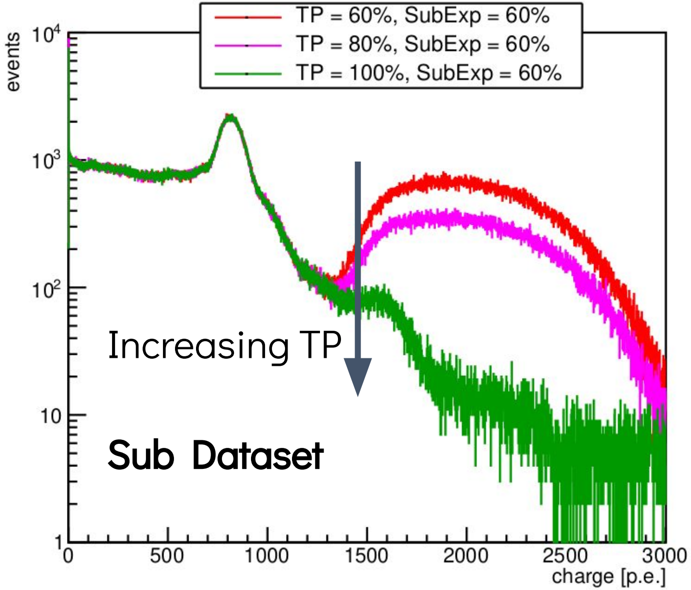
→ IBD scenario does not allow to determine CNO
→ Baseline scenario allows only a large-uncertainty measurem.

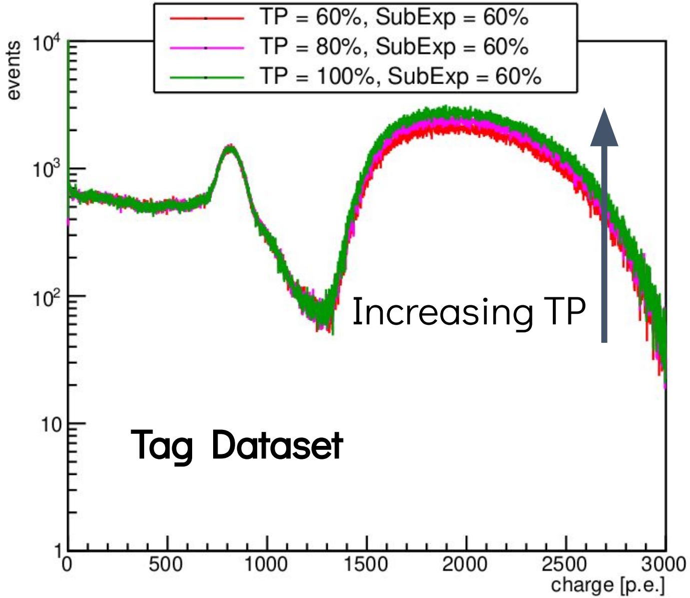
pep and CNO sensitivity: scanning the two C11-tagging parameters

Two parameters drive the 11C-tagging technique performances: **(11C rate = 1916 cpd/kt)**

- **Tagging Power (TP)**: % of 11C events identified
- **Subtracted dataset exposure (SubExp)**: remaining % exposure in the Sub dataset

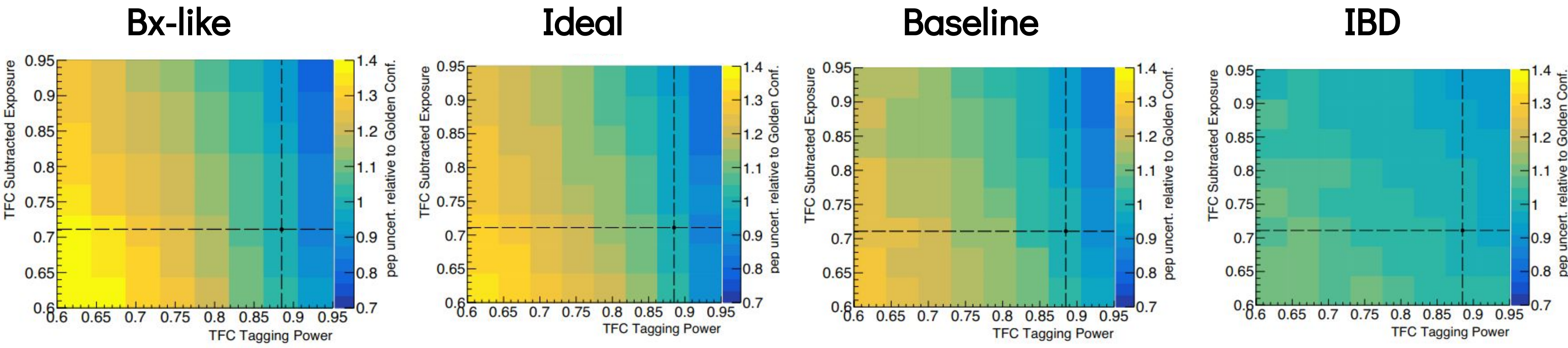
They must be as high as possible: a perfect (and unreachable) 11C tagging technique identifies 100% of 11C events (TP=1) without losing any exposure in the “subtracted” dataset (SubExp=100%)





pep sensitivity: impact of the C11-tagging performances

6Y data taking, repeated 10^4 times for each TP + SubExp configuration
Color scale: pep stat. error relative to TP = 0.90 and Sub.Exp = 0.70 (reasonable for JUNO)
as a function of Tagging Power (x axis) and Subtracted Exposure (y axis)



Bx-like **Ideal** **Baseline** **IBD**

decreasing radiopurity ⇒ internal bkg levels increase

⇒ s/b ratio is less and less influenced by C11 id. techniques

Similar behaviour has been observed for CNO neutrinos

pep sensitivity: impact of the C11-tagging performances

6Y data taking, repeated 10^4 times for each TP + SubExp configuration
Color scale: <u>pep stat. error</u> relative to TP = 0.90 and Sub.Exp = 0.70 (reasonable for JUNO)
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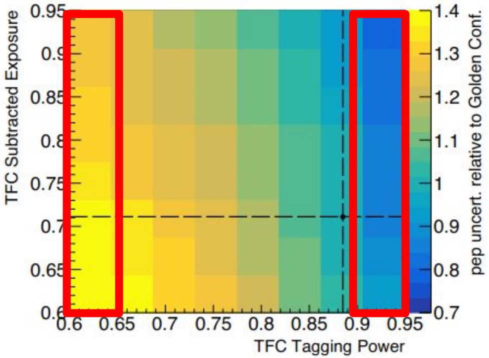
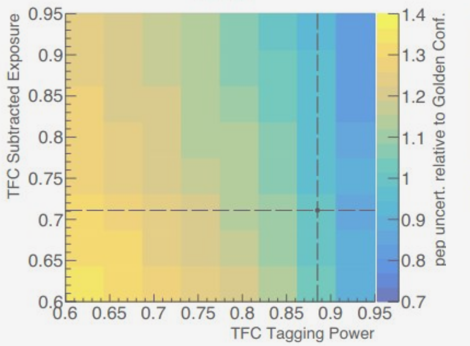
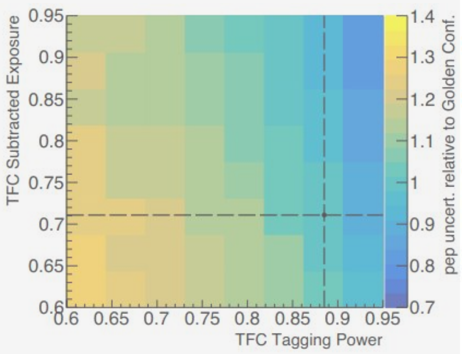
Bx-like



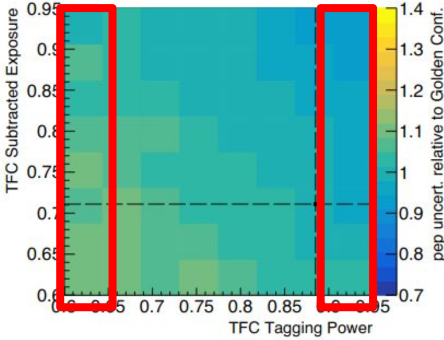
Ideal



Baseline



IBD



P impact relevantly (different
color scale)

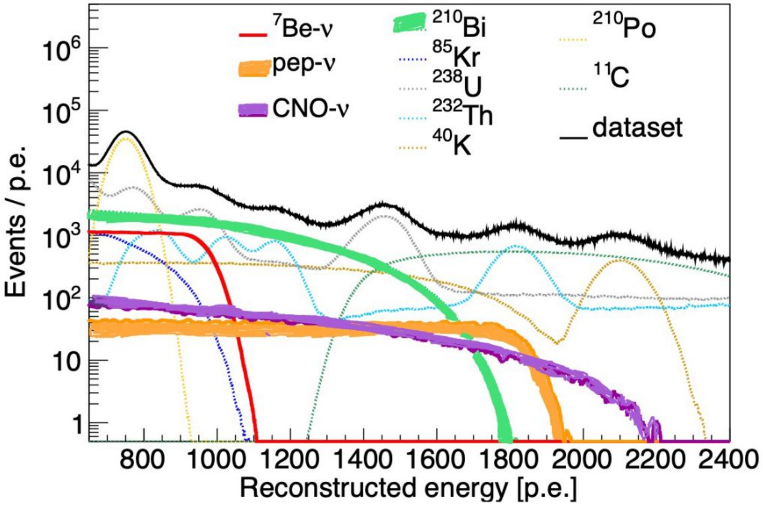
TP does not impact
(same color scale)

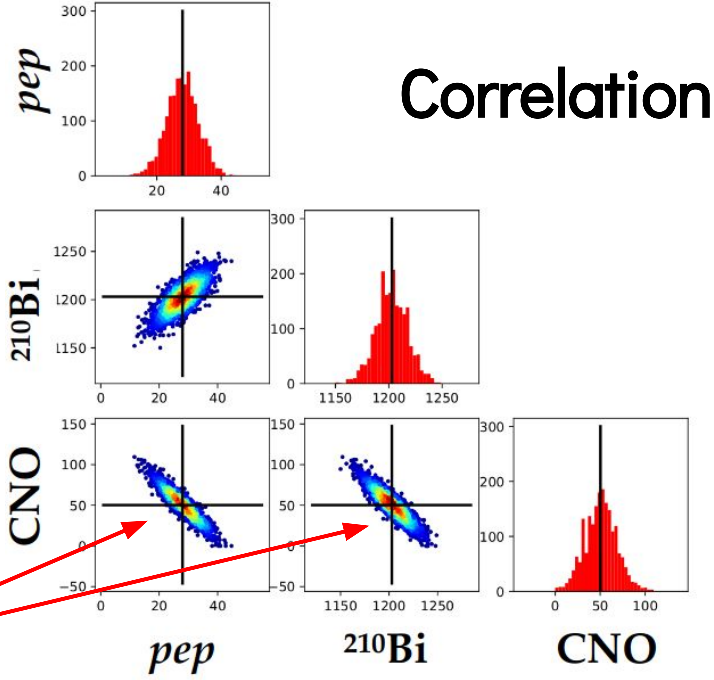
decreasing radiopurity ⇒ internal bkg levels increase
⇒ **s/b ratio is less and less influenced by C11 id. techniques**

Similar behaviour has been observed for CNO neutrinos

CNO sensitivity assuming a pep constraint

CNO sensitivity is affected by rates strong anti-correlations with Bi background and pep neutrinos



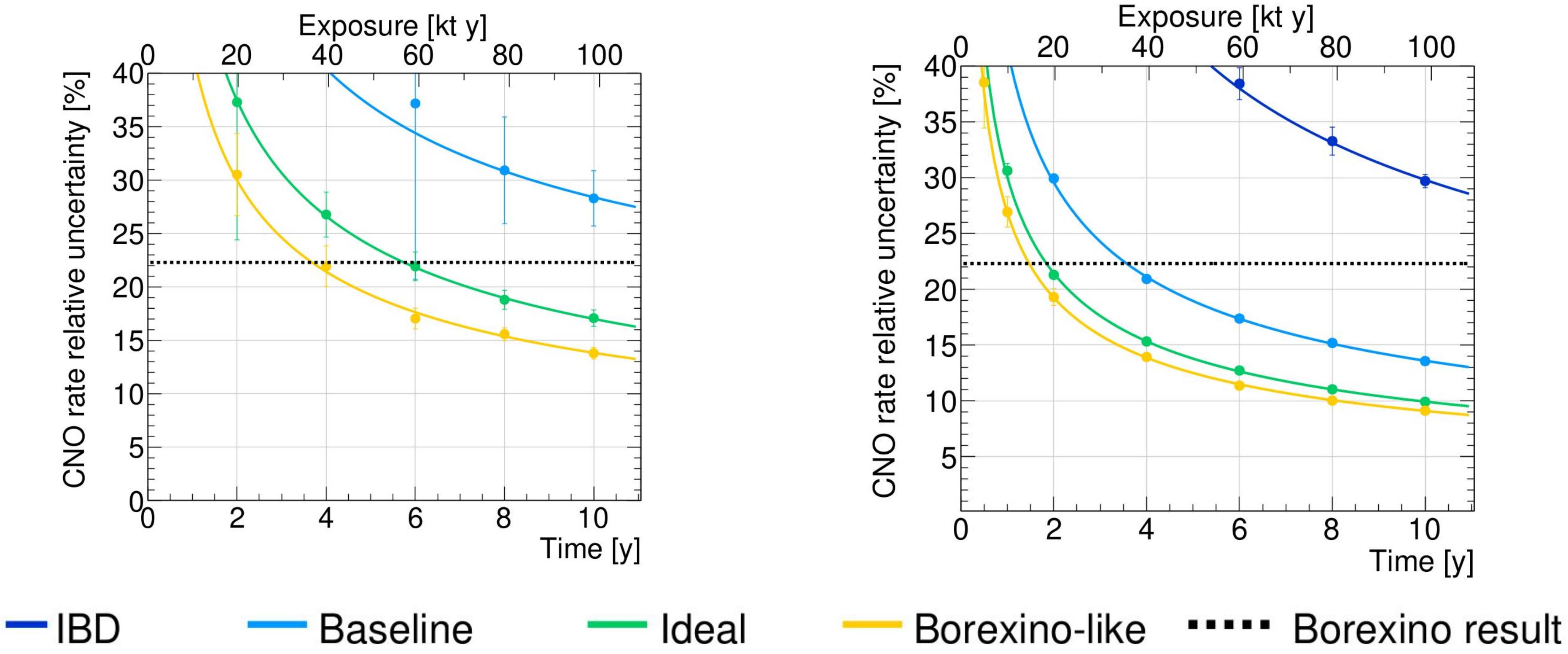


Correlation plots

Strong anti-correlations

To remove the pep-CNO degeneracy we can set a 1.4% pep constraint based on HZ-SSM predictions + oscillations

CNO sensitivity over exposure:



without pep constraint
(same plot seen before):

with pep constraint

Sensitivity results:

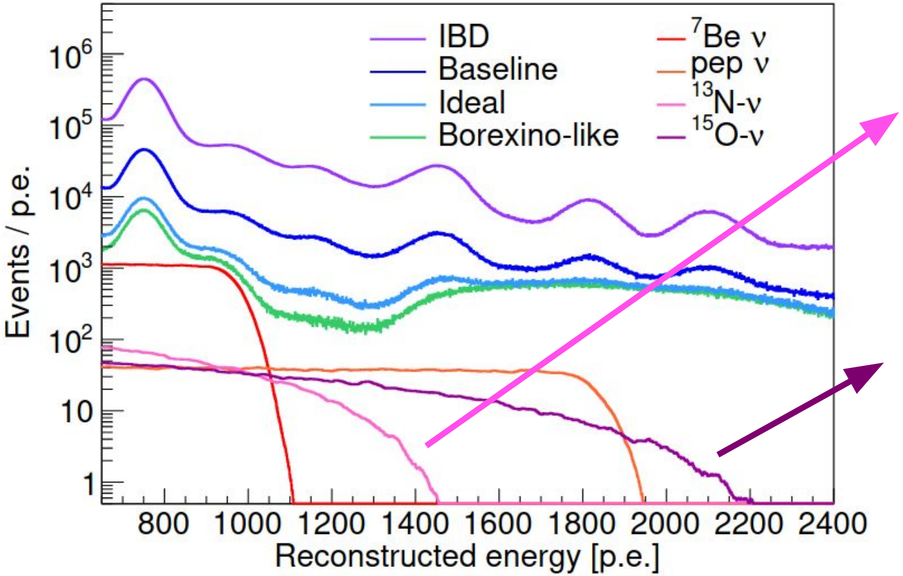
^{13}N and ^{15}O separately

Sensitivity to 13N and 15O separately

→ **possible first separate detection ever**

→ astrophysical importance to infer the direct C and N abundances in the Sun

→ allowed by the huge JUNO statistics, only for the two radiopurest scenarios (Bx-like and Ideal)



13N neutrinos:

Pro: lower Q-value, **lower s/b ratio**

Con: less anti-correlation with pep

15O neutrinos:

Con: **strong anti-correlation** with pep due to shape similarity, lower rate

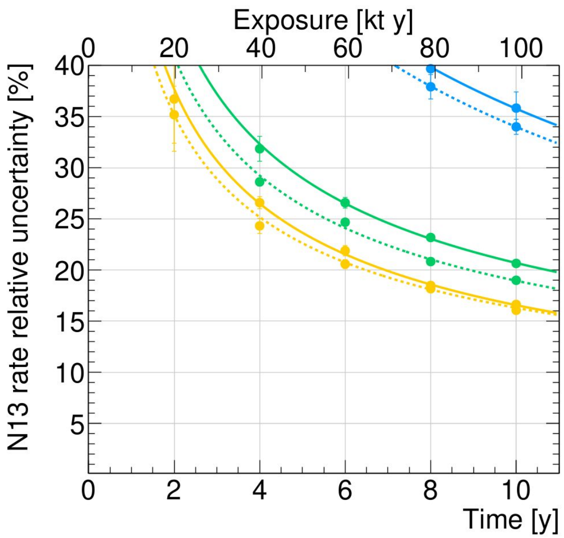
Pro: **degeneracy can be broken** via pep constraint

Sensitivity to 13N and 15O separately

— Baseline
— Ideal
— Borexino-like

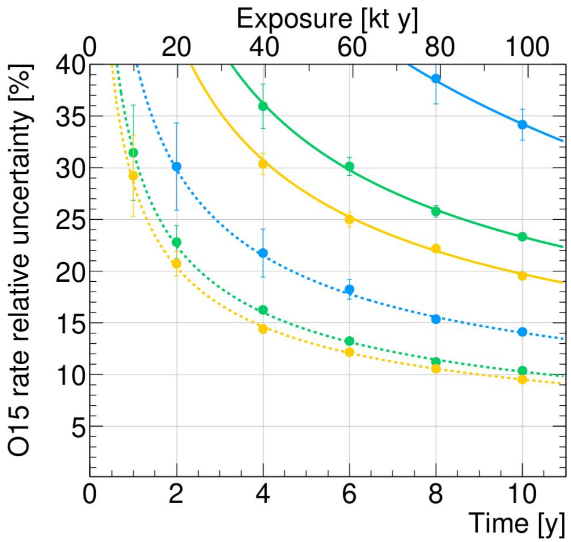
solid: all rates free to vary
dashed: pep constraint applied

N13 neutrinos



pep constraint (dashed) does not help significantly

O15 neutrinos

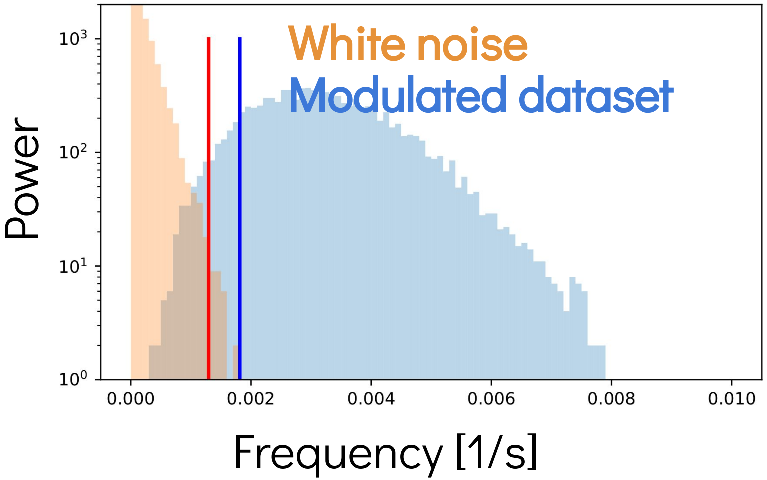


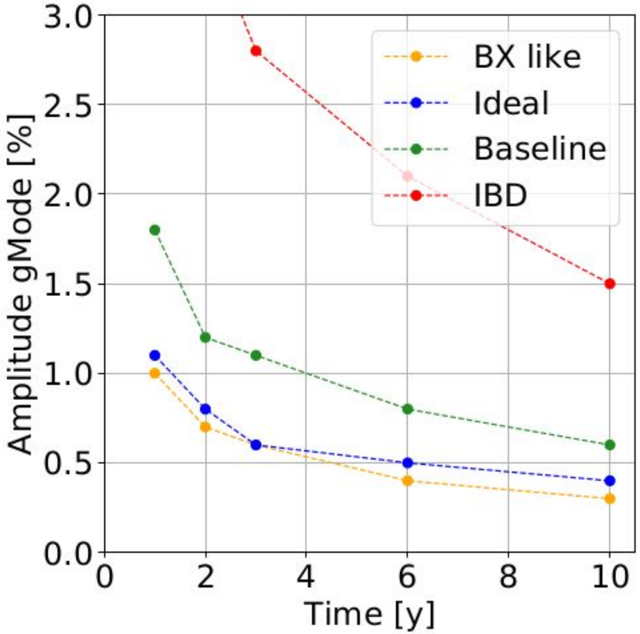
pep constraint (dashed) improves significantly

Bonus: Modulation analysis in solar neutrino rate

Search for hour-period modulation in simulated time dataset, for Be7 energy region
→ based on Lomb-Scargle periodogram analysis
→ independent work by groups of Milano and Munich (TUM)

1. “Time” dataset generation → 2. Periodogram generation and analysis → 3. C.L. extraction



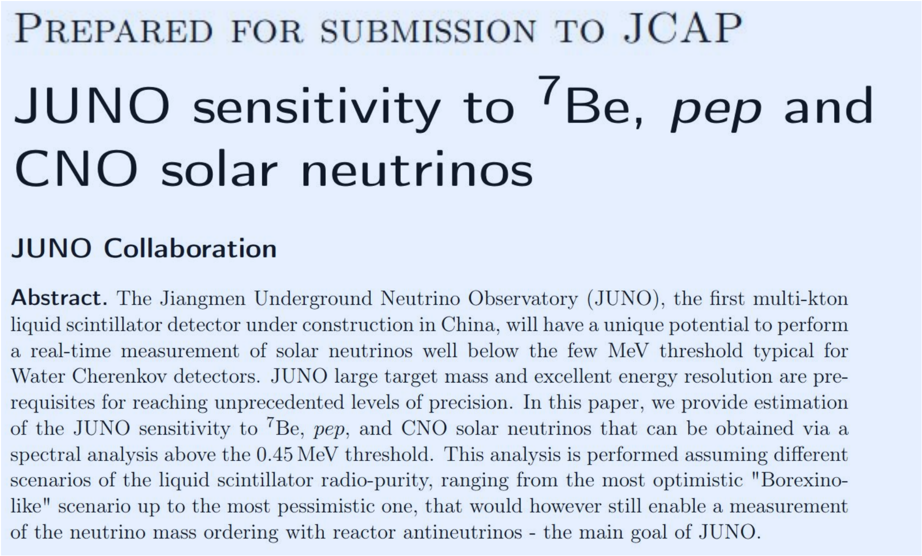


Timeline and status

1) Technote shared to the JUNO collaboration and approved by internal referees, DocDB#7661
Analysis performed **independently by Milano and Jülich groups**, but based on common starting points

2) Paper to be finalized in few weeks, to be submitted to JCAP

(also contain a neutrino signal modulation part which is not described in this talk)



PREPARED FOR SUBMISSION TO JCAP

JUNO sensitivity to ^{7}Be, *pep* and CNO solar neutrinos

JUNO Collaboration

Abstract. The Jiangmen Underground Neutrino Observatory (JUNO), the first multi-kton liquid scintillator detector under construction in China, will have a unique potential to perform a real-time measurement of solar neutrinos well below the few MeV threshold typical for Water Cherenkov detectors. JUNO large target mass and excellent energy resolution are prerequisites for reaching unprecedented levels of precision. In this paper, we provide estimation of the JUNO sensitivity to ^{7}Be, *pep*, and CNO solar neutrinos that can be obtained via a spectral analysis above the 0.45 MeV threshold. This analysis is performed assuming different scenarios of the liquid scintillator radio-purity, ranging from the most optimistic "Borexino-like" scenario up to the most pessimistic one, that would however still enable a measurement of the neutrino mass ordering with reactor antineutrinos - the main goal of JUNO.

Conclusions

- Multivariate fit analysis to extract the solar neutrino rate on thousands of pseudo-datasets simulated with the official JUNO MonteCarlo code
  → independently by Milano and Juelich groups

1) **Short-term**: during the **first data-taking year**, JUNO will match the best **Be7** and (except for worst radiopurity scenario) **pep** results

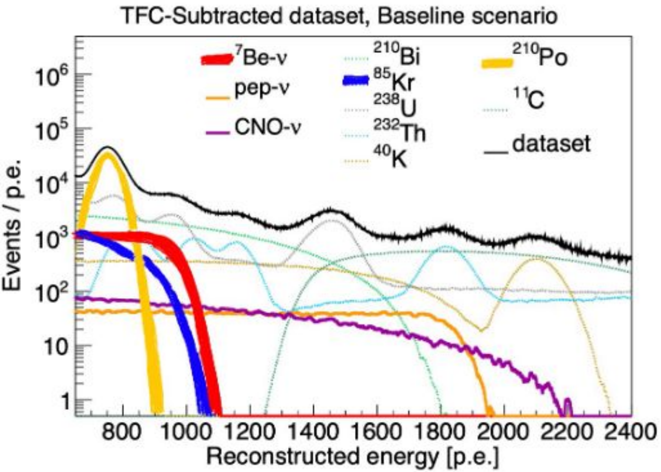
2) **Long-term:** In case of optimistic radiopurity scenario, the **CNO** precision will be significantly improved for **> six years** data taking (first simultaneous Be, pep, CNO meas.)
   - The first separate detection of **N13** and **O15** neutrinos is also possible!

Collaboration paper writing is going to be finalized in the next few weeks.

Backup

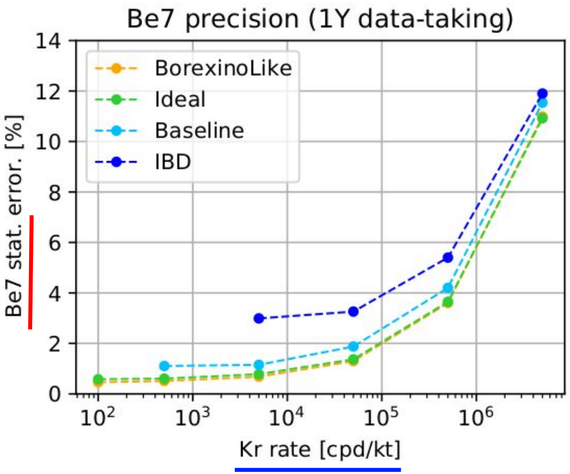
2) Background impact to 7Be sensitivity

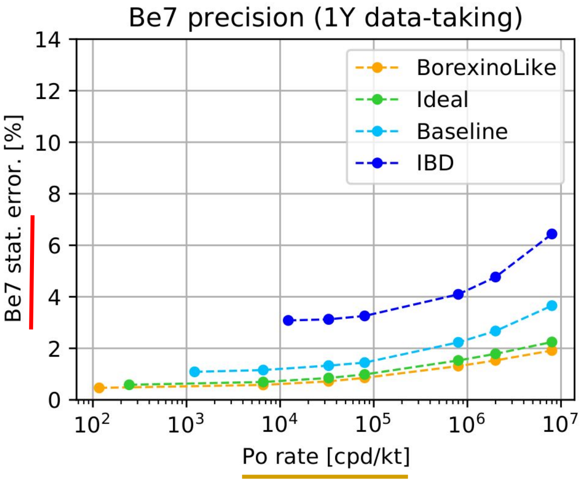
7Be neutrinos sensitivity depends on the backgrounds insisting in the same energy region



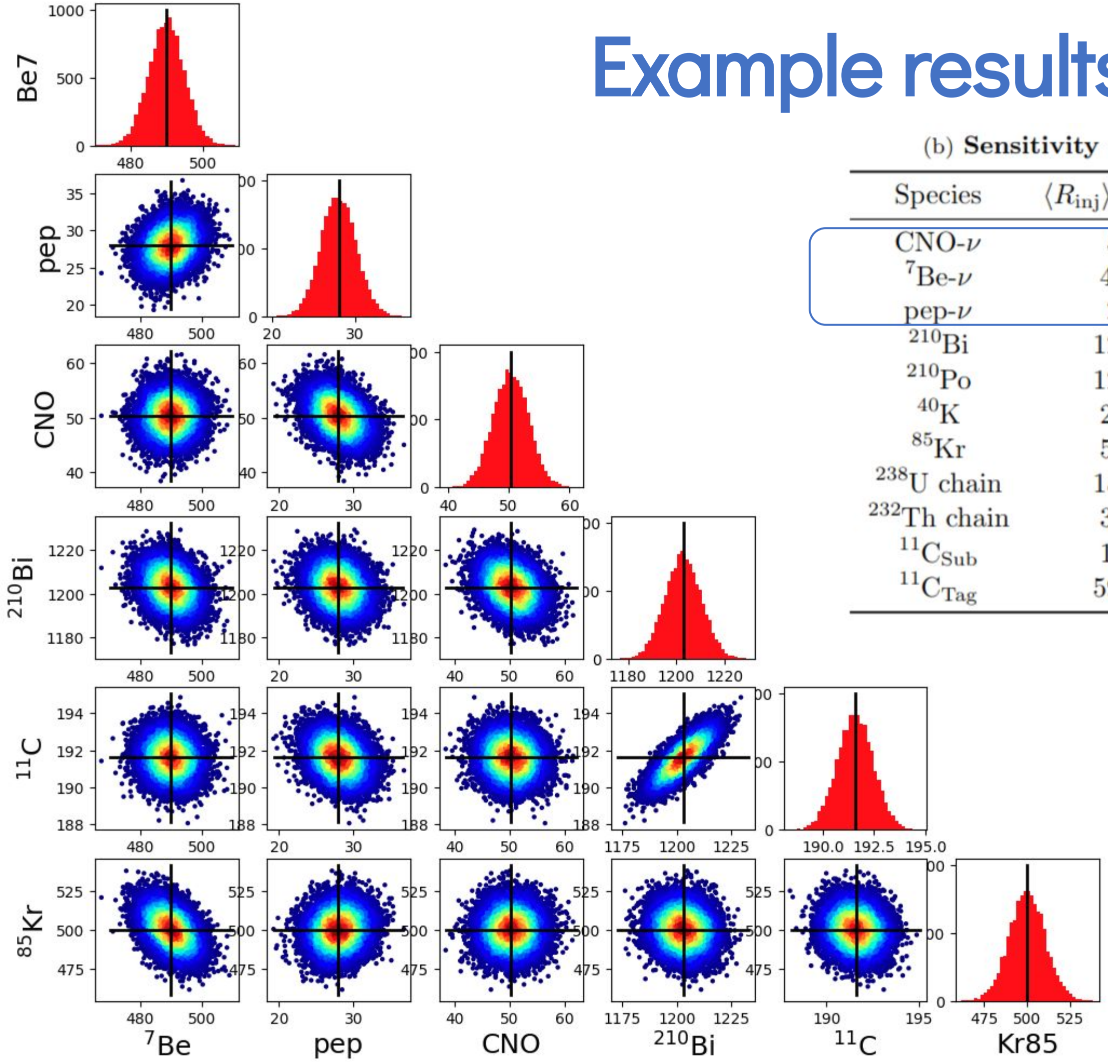
85Kr could be absorbed by the acrylic surface due to air exposures, then emanated through the scintillator

Out-of-equilibrium **210Po** washed out from the surface of the pipes during the detector filling → unsupported 210Po





Example results - Baseline scenario



(b) **Sensitivity to CNO neutrinos with MUST in the baseline scenario**

Species	$\langle R_{\text{inj}}\rangle$ [cpd/kt]	$\langle R\rangle$ [cpd/kt]	σ_R [cpd/kt]	σ_R [%]	Bias [%]
CNO-ν	50.3	50.9	17.82	34.99	1.2
^{7}Be-ν	490.0	490.0	5.20	1.06	9.2×10^{-4}
pep-ν	28.0	27.9	4.91	17.62	-0.5
^{210}Bi	1203.0	1202.4	15.29	1.27	-4.6×10^{-2}
^{210}Po	1221.0	1221.0	0.92	0.08	8.1×10^{-4}
^{40}K	229.0	229.0	2.21	0.96	9.8×10^{-3}
^{85}Kr	500.0	500.1	10.36	2.07	2.0×10^{-2}
^{238}U chain	1505.0	1505.0	4.21	0.28	-5.9×10^{-4}
^{232}Th chain	350.8	350.9	2.13	0.61	1.3×10^{-2}
^{11}C$_{\text{Sub}}$	191.6	191.6	0.97	0.51	-1.3×10^{-2}
^{11}C$_{\text{Tag}}$	5939.6	5939.5	2.90	0.05	-1.2×10^{-3}

Relative errors

All biases are under control

Backgrounds estimations

Internal bkgs

- Contaminants:
  - ^{85}Kr
  - ^{40}K
  - 238U and 232Th chains
  - ^{210}Pb sub-chain (^{210}Bi and ^{210}Po)
- Low energy region of pp neutrinos is excluded → 14C and its pileup neglected

- **4 radiopurity scenarios:**
  - **“Borexino-like”**
  - **“Ideal”**
  - **“Baseline”**
  - **“IBD”**

Cosmogenic bkgs

- Spallation of atmospheric μ on C atoms
- Scaled rates from previous experiments (KamLAND and Borexino):
  - ^{11}C
  - ^{10}C
  - ^{6}He

External bkgs

γ from 208Tl, 214Bi, and 40K isotopes in the PMT glass and light cones.

Can be neglected in our Fiducial Volume (r < 14 m sphere)

Backgrounds estimations

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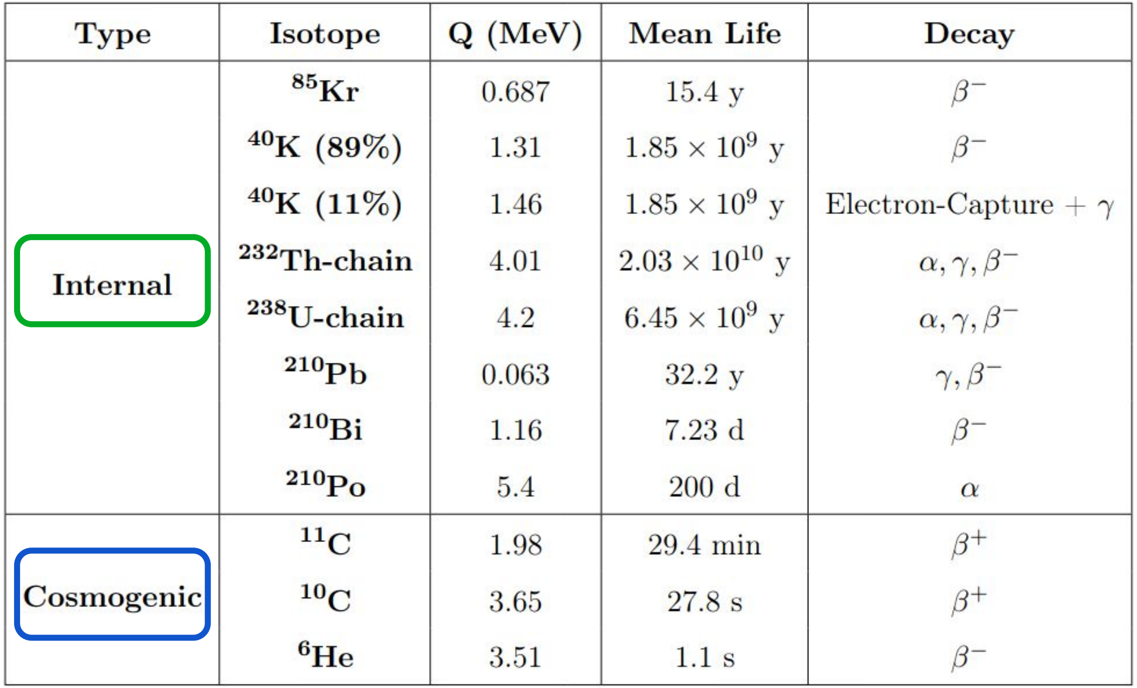
~~External bkgs~~

~~γ from 208Tl, 214Bi, and 40K isotopes in the PMT glass and light cones.~~

~~**Can be neglected in our Fiducial Volume** (r < 14 m sphere)~~

Backgrounds estimations



Type	Isotope	Q (MeV)	Mean Life	Decay
Internal	^{85}Kr	0.687	15.4 y	β^-
	^{40}K (89%)	1.31	1.85×10^9 y	β^-
	^{40}K (11%)	1.46	1.85×10^9 y	Electron-Capture + γ
	^{232}Th-chain	4.01	2.03×10^{10} y	α, γ, β^-
	^{238}U-chain	4.2	6.45×10^9 y	α, γ, β^-
	^{210}Pb	0.063	32.2 y	γ, β^-
	^{210}Bi	1.16	7.23 d	β^-
	^{210}Po	5.4	200 d	α
Cosmogenic	^{11}C	1.98	29.4 min	β^+
	^{10}C	3.65	27.8 s	β^+
	^{6}He	3.51	1.1 s	β^-

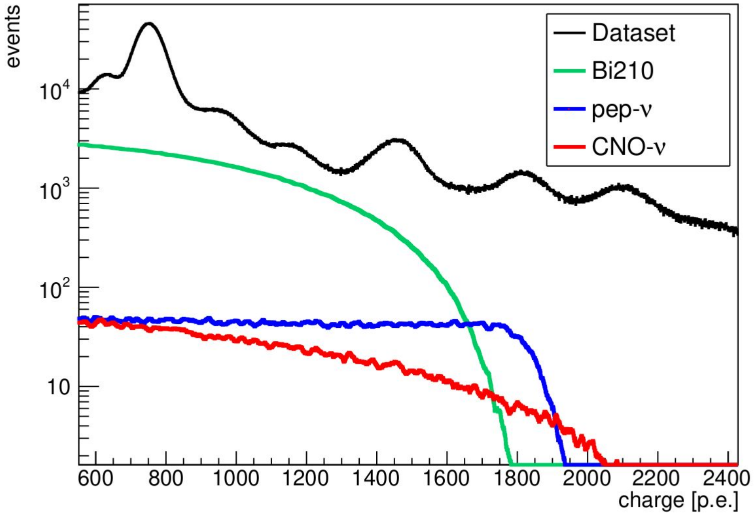
Low energy region of pp neutrinos is excluded → 14C and its pileup neglected

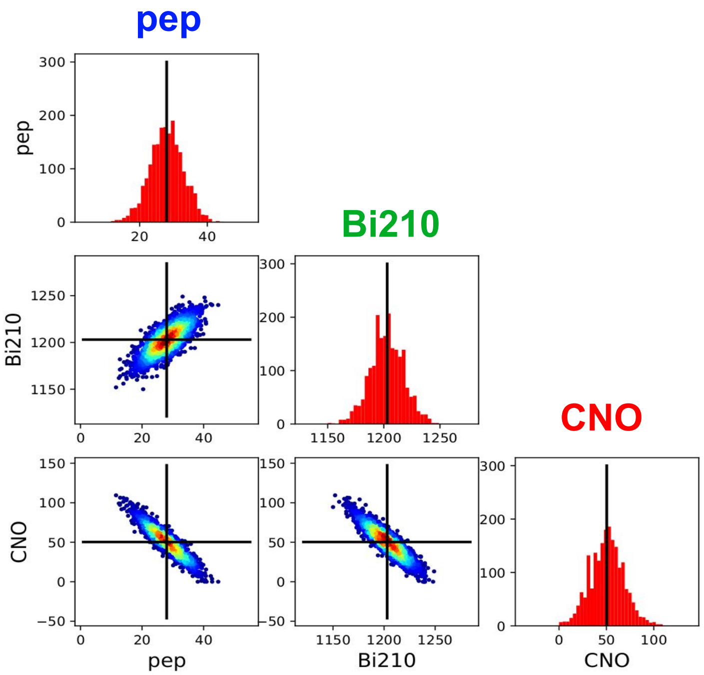
Four radiopurity scenarios:

1. **“Borexino-like”**
2. **“Ideal”**
3. **“Baseline”**
4. **“IBD”**

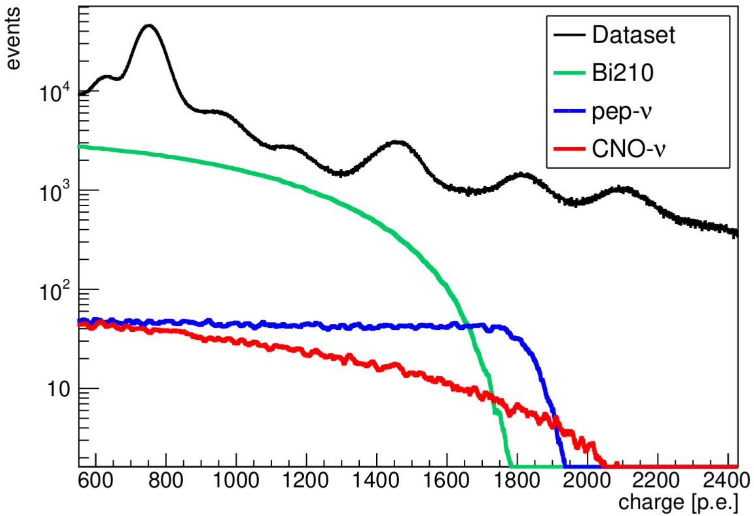
Due to Spallation of atmospheric μ on 12C → scaled rates from previous exp. (KamLAND and Borexino):

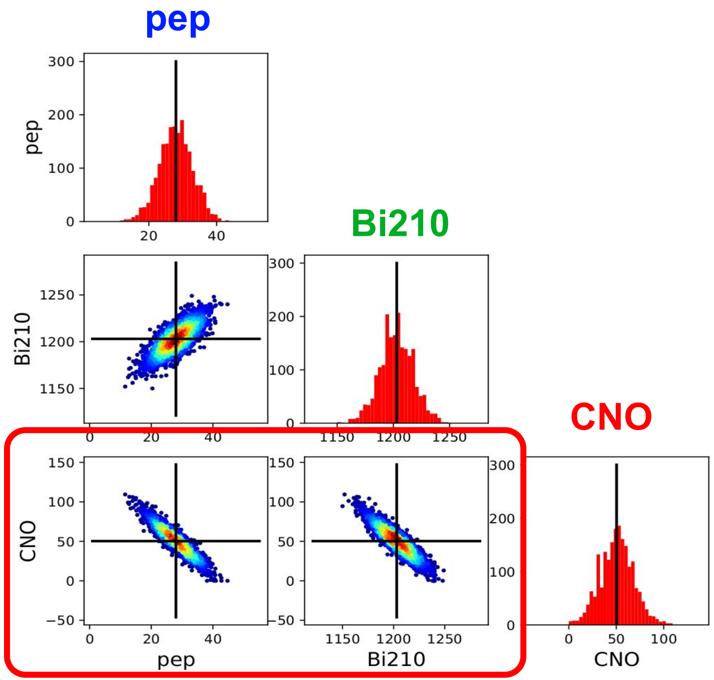
Golden fit configuration - The CNO constraint





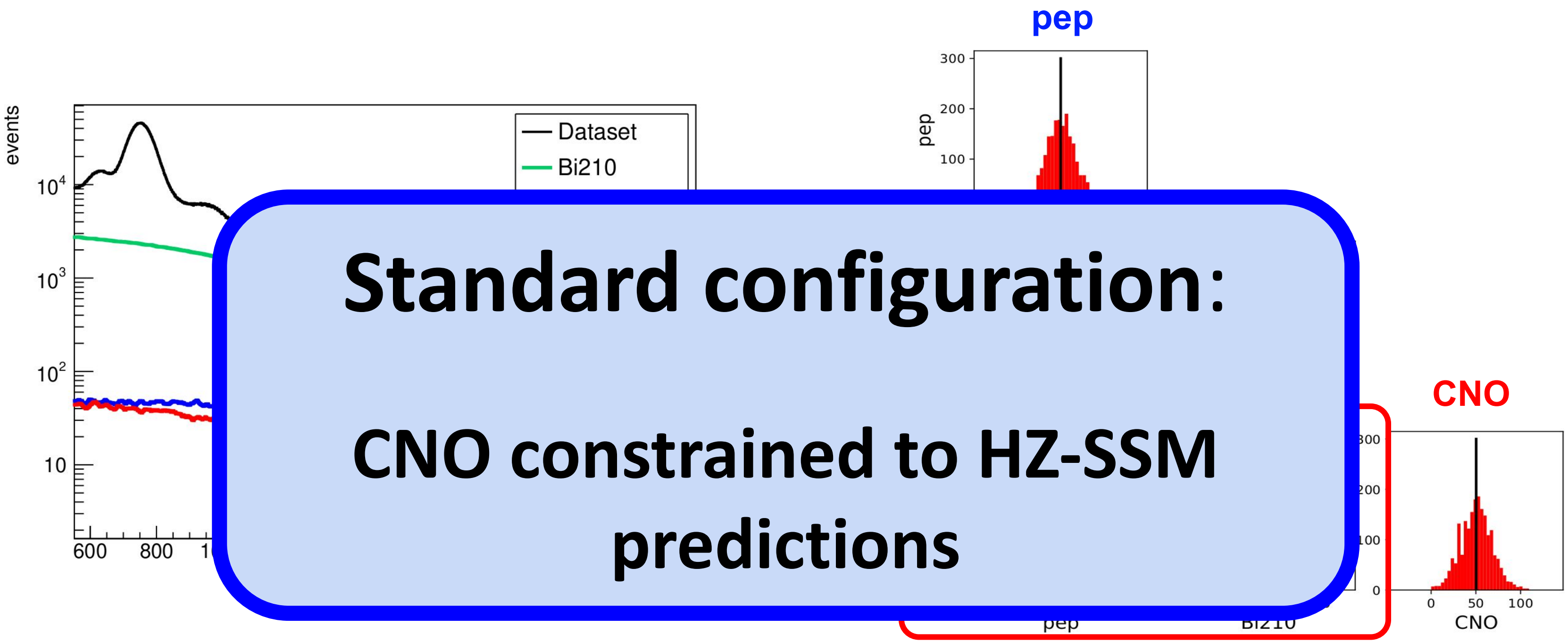
Golden fit configuration - The CNO constraint





CNO interaction rate is strictly **anti-correlated** with pep and Bi210

Golden fit configuration - The CNO constraint



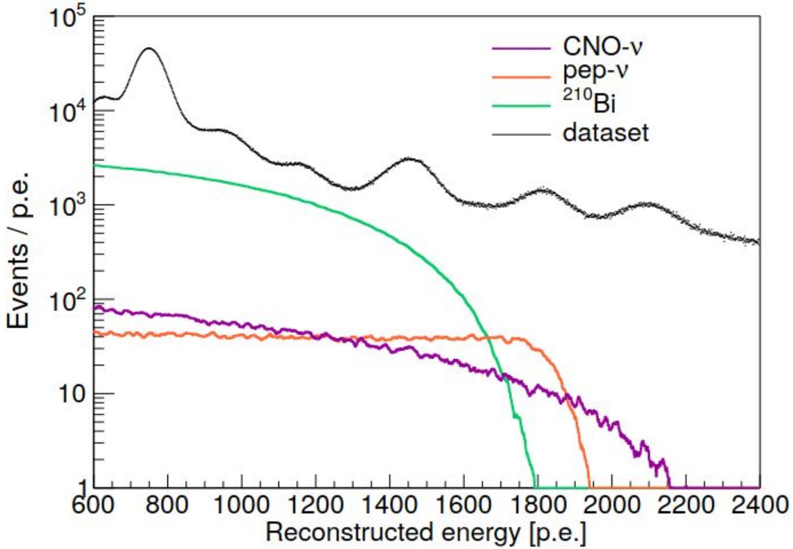
Standard configuration:

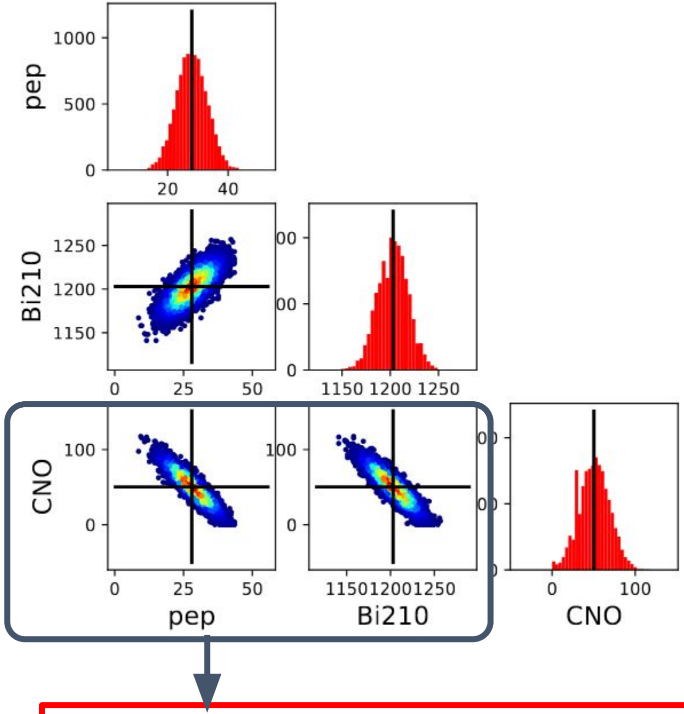
CNO constrained to HZ-SSM predictions

CNO interaction rate is strictly **anti-correlated** with pep and Bi210

CNO sensitivity

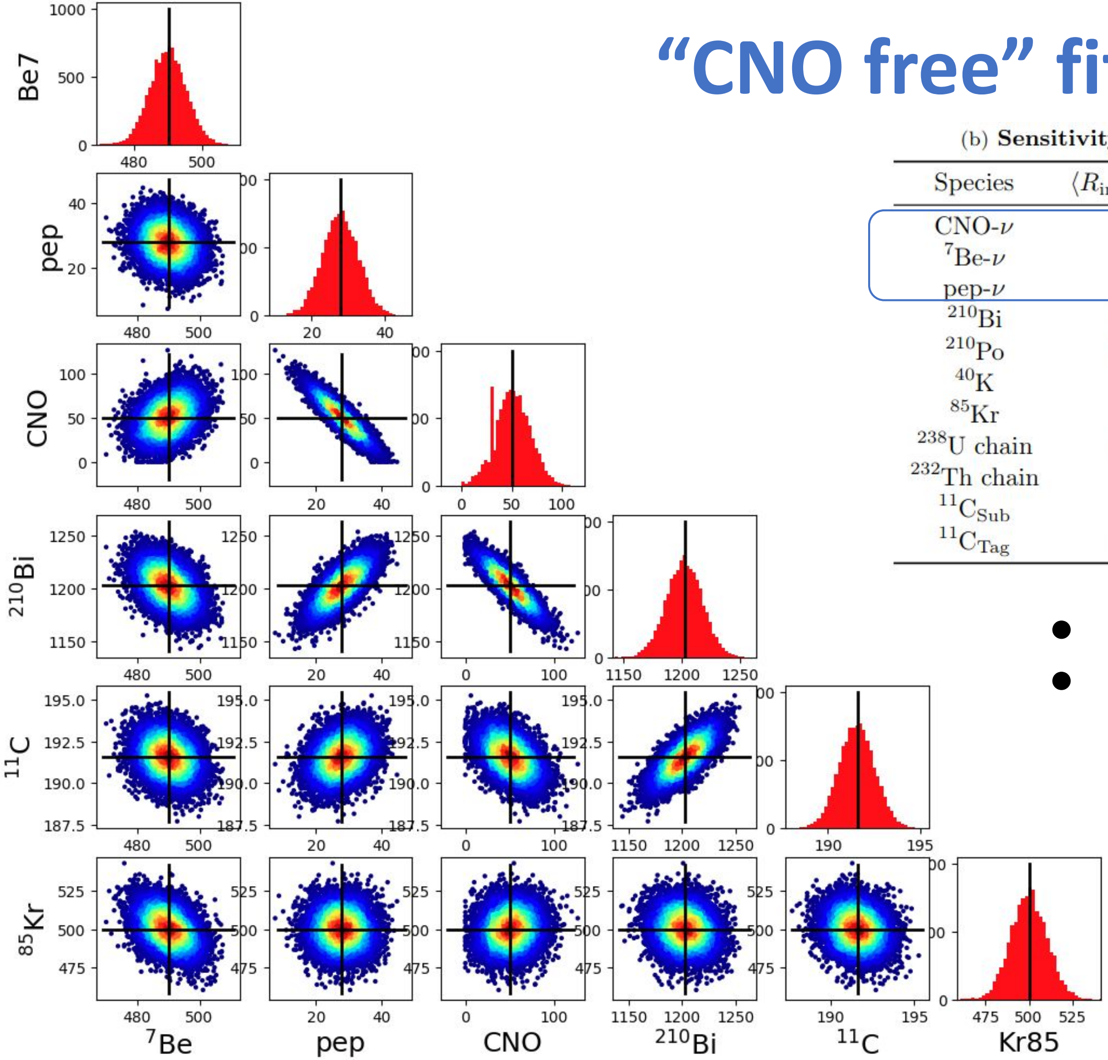
Exemplary 1Y baseline dataset, fitted leaving pep, Bi210 and CNO rates as free parameters





strict anti-correlation between CNO rate vs pep rate and CNO rate vs Bi210 rate

“CNO free” fit results - Baseline sc.



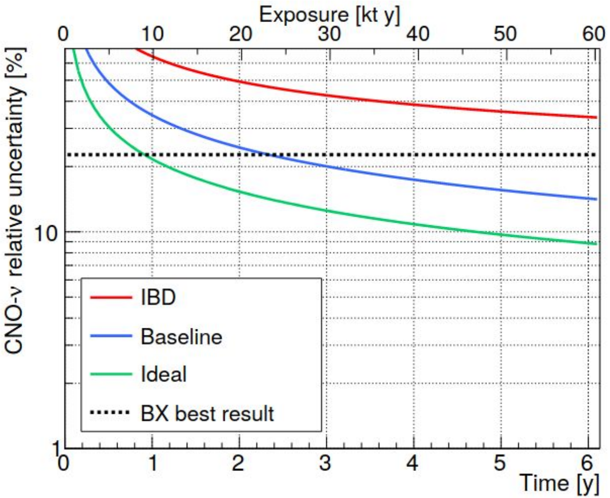
(b) **Sensitivity to CNO neutrinos with MUST in the baseline scenario**

Species	$\langle R_{\mathrm{inj}} \rangle$ [cpd/kt]	$\langle R \rangle$ [cpd/kt]	σ_R [cpd/kt]	σ_R [%]	Bias [%]
CNO-ν	50.3	50.9	17.82	34.99	1.2
^{7}Be-ν	490.0	490.0	5.20	1.06	9.2×10^{-4}
pep-ν	28.0	27.9	4.91	17.62	-0.5
^{210}Bi	1203.0	1202.4	15.29	1.27	-4.6×10^{-2}
^{210}Po	1221.0	1221.0	0.92	0.08	8.1×10^{-4}
^{40}K	229.0	229.0	2.21	0.96	9.8×10^{-3}
^{85}Kr	500.0	500.1	10.36	2.07	2.0×10^{-2}
^{238}U chain	1505.0	1505.0	4.21	0.28	-5.9×10^{-4}
^{232}Th chain	350.8	350.9	2.13	0.61	1.3×10^{-2}
^{11}C$_{\mathrm{Sub}}$	191.6	191.6	0.97	0.51	-1.3×10^{-2}
^{11}C$_{\mathrm{Tag}}$	5939.6	5939.5	2.90	0.05	-1.2×10^{-3}

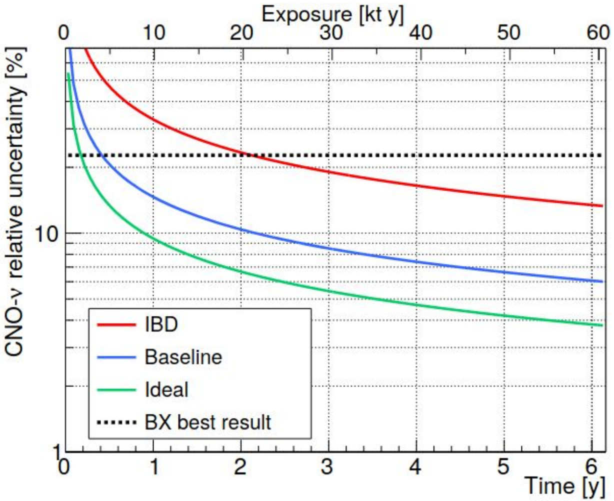
- All biases are under control
- JUNO would be able to measure simultaneously Be, pep and CNO

Impact of the exposure on the sensitivity to CNO neutrinos

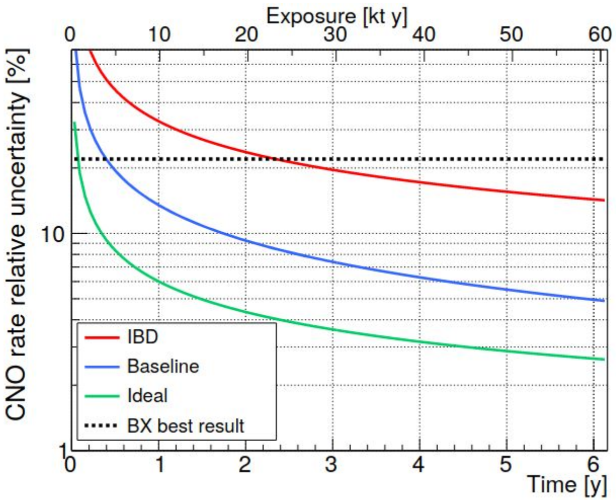
^{210}Bi and pep free



^{210}Bi free, pep constrained



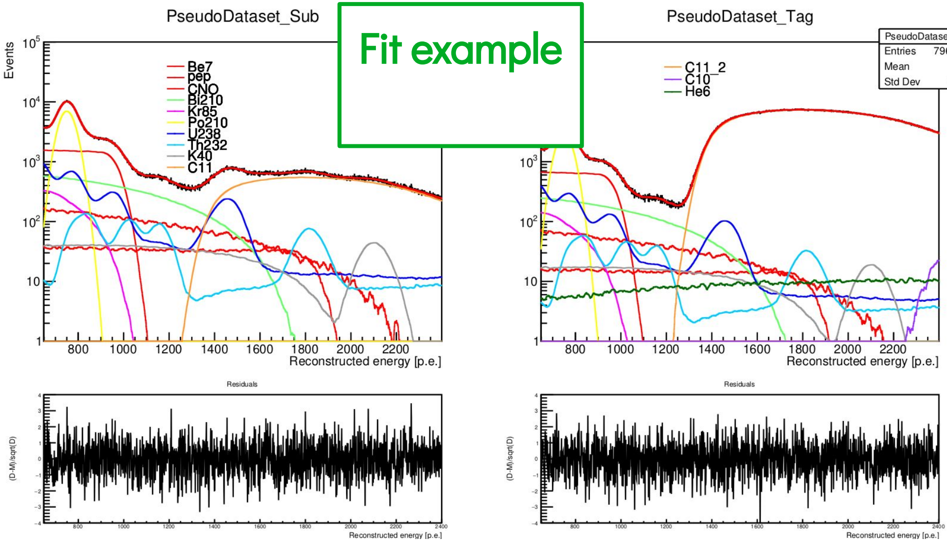
^{210}Bi and pep constrained (Bi 1% precision)



The pep constraint is crucial to achieve a precise CNO measurement for the IBD scenario
After 6y, **Ideal scenario**: ~9% (Bi and pep free), ~4% (Bi free, pep constrained), ~2.7% (Bi constrained at 1% level, pep constrained

Multivariate fit: MUST and JUST

- Performed by using **MUST** (**M**ilano n**U**sol **S**ensitivity **T**ool) and **JUST** (**J**ülich n**U**sol **S**ensitivity **T**ool): tools developed **independently** of each other by the two groups. They have completely different structures.
- Based on binned poisson likelihood optimization
- Based on MC PDFs used to generate pseudo-datasets and to fit them.
- To improve the sensitivity, 2 histograms (^{11}C-sub and ^{11}C-tag) are *simultaneously* fitted



Fit example

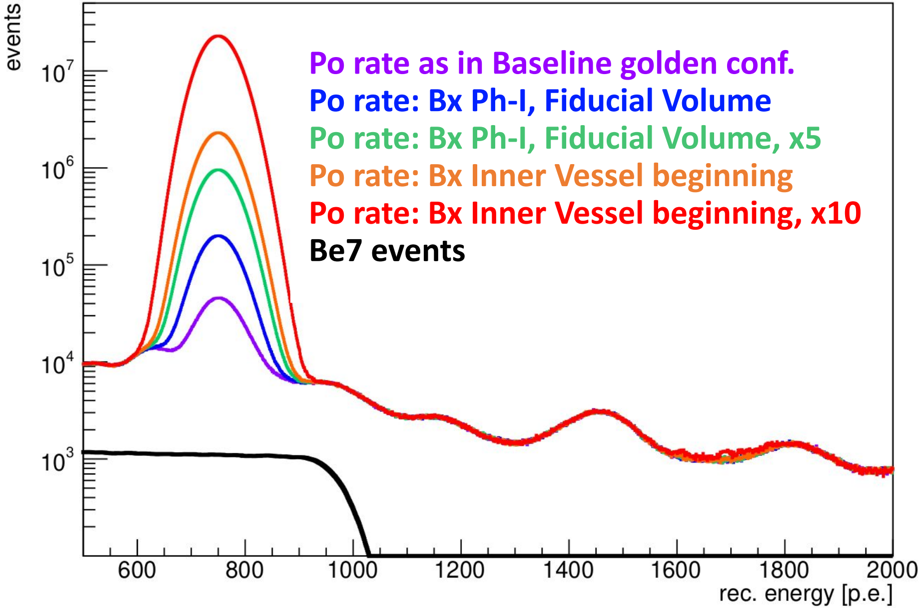
$$\mathcal{L}(\vec{k}|\vec{\lambda}) = \mathcal{L}_{\text{sub}}(\vec{k}|\vec{\lambda}) \cdot \mathcal{L}_{\text{tag}}(\vec{k}|\vec{\lambda})$$

$$\mathcal{L} = \prod_{i=1}^{N} \frac{\lambda_i^{k_i} e^{-\lambda_i}}{k_i!}$$

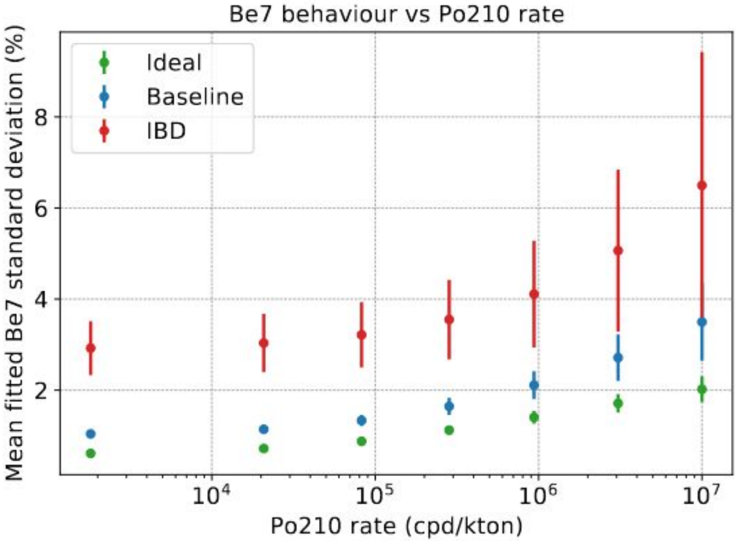
$$\mathcal{L} = \prod_{i=1}^{N} \frac{\lambda_i^{k_i} e^{-\lambda_i}}{k_i!}$$

Unsupported ^{210}Po studies

- At the beginning of the data-taking, we expect an additional Po contribution (named "unsupported"), found out of the secular equilibrium of 210Pb sub-chain or 238U chain
- Study of the sensitivity to Be7 as a function of **unsupported Po rate**



Unsupported ^{210}Po studies



Configuration	Po rate cpd/1kt	Be7 relative RMS [%]		
		Ideal	Baseline	IBD
JUNO YB	-	0.52	0.97	2.83
Bx Ph-I (FV)	6600	0.59	1.05	2.83
Bx Ph-I (FV) x5	33000	0.74	1.15	2.86
Bx Ph-I (IV)	8.00E+04	0.84	1.26	3.01
Bx Ph-I (IV) x10	8.00E+05	1.30	1.88	3.87
Bx Ph-I (IV) x25	2.00E+06	1.58	2.48	4.59
Bx Ph-I (IV) x50	4.00E+06	1.78	2.89	5.16
Bx Ph-I (IV) x100	8.00E+06	2.06	3.34	6.02

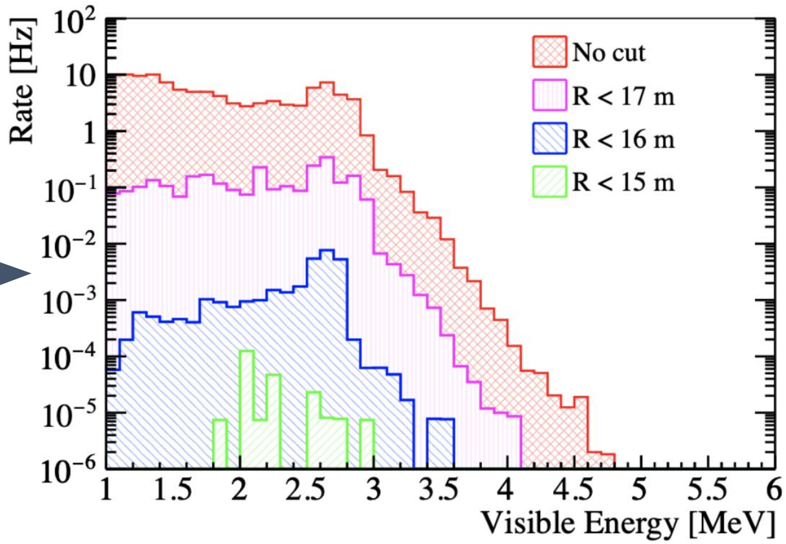
- The Be7 rate is identified by the fit thanks to its spectral “shoulder”, which is only partly covered by Po events
- Unsupported Po impacts on Be7 stat. error **only for very large contributions** (Bx Ph-I IV or more)
- pep rate precision (not shown here) is unaffected by the unsupported Po increase

External backgrounds

Can be removed with offline fiducial volume cut

→ we can always afford to cut deep enough, into the cleanest region of the detector
→ analysis “external background free”

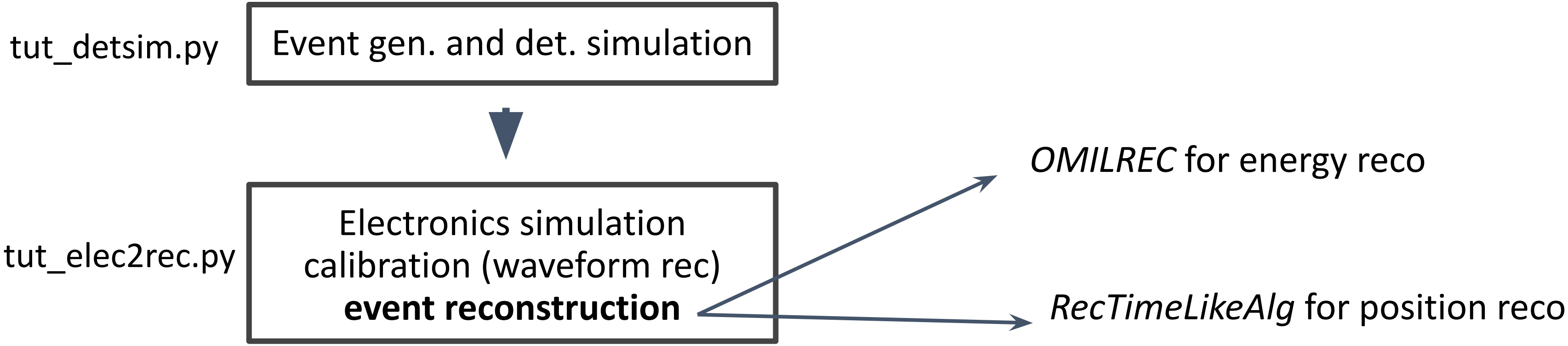
Simulations of the ext γ energy spectrum
→ r<15 m spherical FV would be large enough to completely suppress the external γ contributions.



To be conservative, in the following analysis we will include only events in **r_{FV}< 14 m FV sphere**.

Monte Carlo simulations

- JUNO Offline version **J21v1r0-Pre0** is used
- Major improvements in the understanding of the SNiPER simulations details
- Complete inclusion of **detector response**
- Energy variable of interest: **m_NQE** (OMILREC, total charge in p.e., corrected for the event radial position without usage of SPE).



tut_detsim.py

Event gen. and det. simulation

tut_elec2rec.py

Electronics simulation
calibration (waveform rec)
event reconstruction

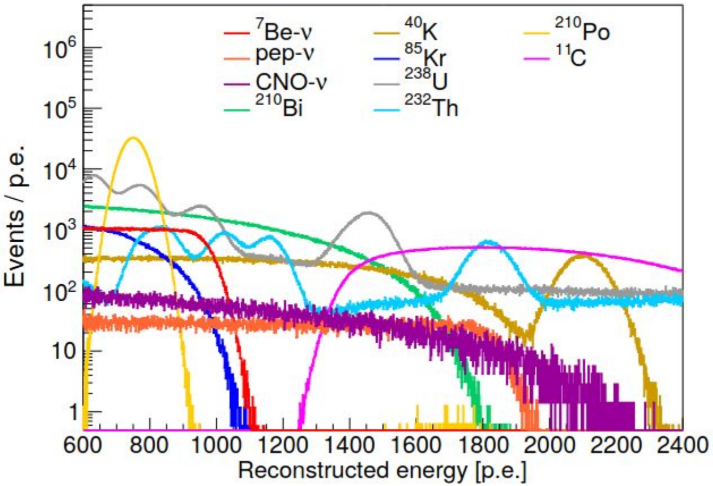
OMILREC for energy reco

RecTimeLikeAlg for position reco

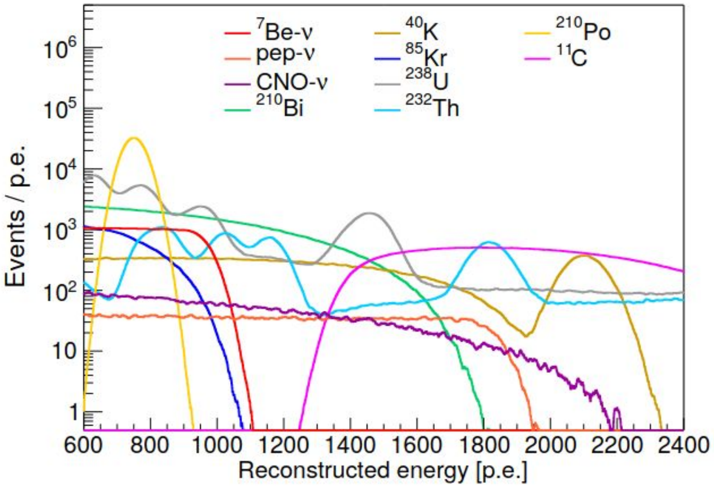
PDFs comparison: before and after smoothing

- **Why smoothing?**
  MC PDFs are built with statistics similar to the one for data-taking of interest.
  But PDFs events should be at least **1 order of magnitude higher than data** ➛ risk of "reproducing" the PDFs statistical fluctuations in an uncontrolled manner on data.
- After many tests, the optimal level of smoothing was chosen.

Before the smoothing



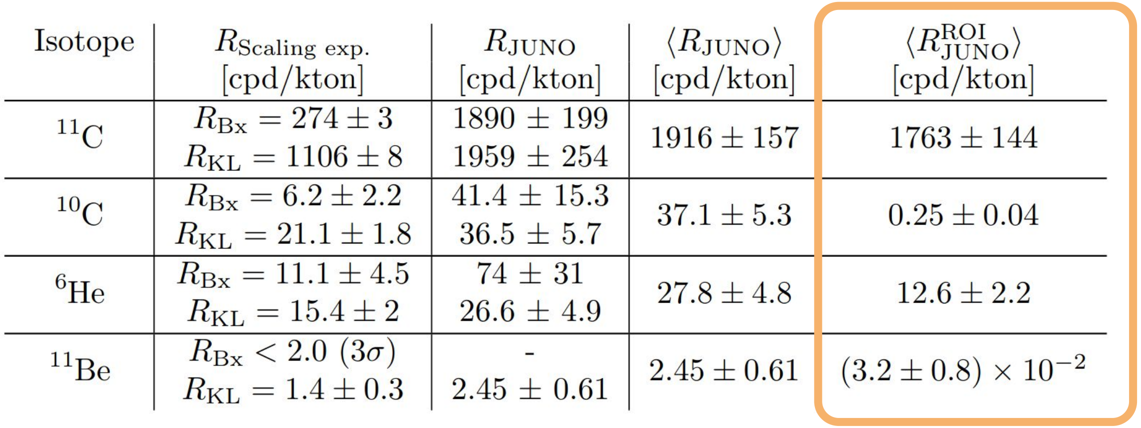
After the smoothing



Cosmogenic backgrounds

- Scaled rates from previous experiments: KamLAND and Borexino

$$R^{\mathrm{JUNO}} = R^{X} \cdot \left(\frac{\bar{E}_{\mu}^{\;\mathrm{JUNO}}}{\bar{E}_{\mu}^{\;X}} \right)^{\alpha} \cdot \frac{\Phi(\mu)^{\mathrm{JUNO}}}{\Phi(\mu)^{X}} \cdot \frac{\epsilon_{C}^{\mathrm{JUNO}}}{\epsilon_{C}^{X}}$$



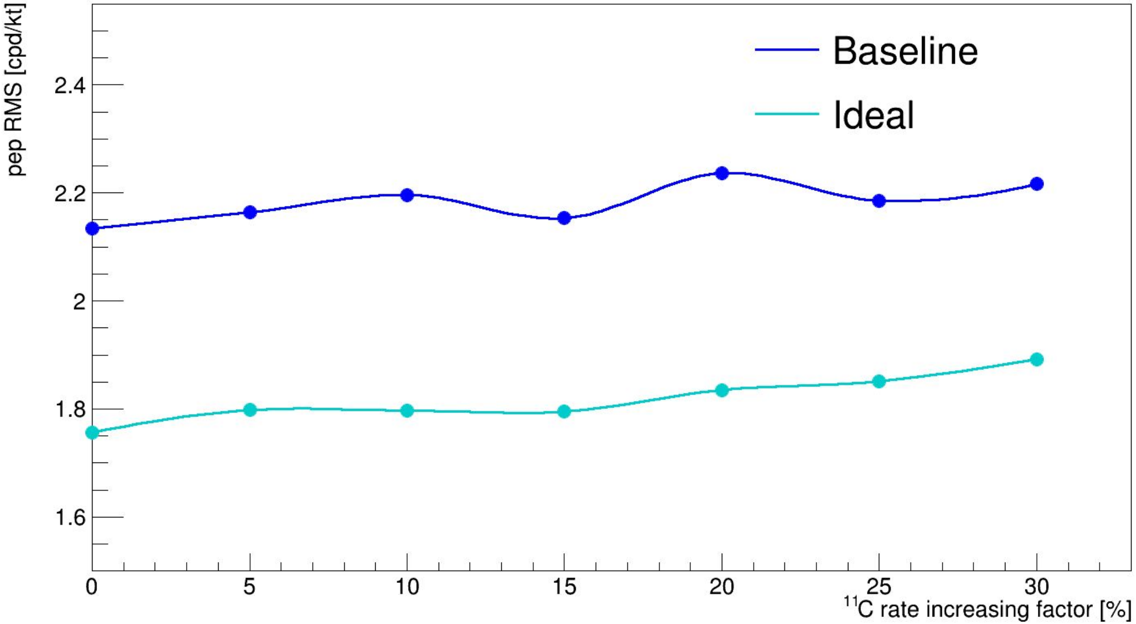
Isotope	$R_{\text{Scaling exp.}}$ [cpd/kton]	R_{JUNO} [cpd/kton]	$\langle R_{\text{JUNO}} \rangle$ [cpd/kton]	$\langle R^{\text{ROI}}_{\text{JUNO}} \rangle$ [cpd/kton]
^{11}C	$R_{\text{Bx}} = 274 \pm 3$ $R_{\text{KL}} = 1106 \pm 8$	1890 ± 199 1959 ± 254	1916 ± 157	1763 ± 144
^{10}C	$R_{\text{Bx}} = 6.2 \pm 2.2$ $R_{\text{KL}} = 21.1 \pm 1.8$	41.4 ± 15.3 36.5 ± 5.7	37.1 ± 5.3	0.25 ± 0.04
^{6}He	$R_{\text{Bx}} = 11.1 \pm 4.5$ $R_{\text{KL}} = 15.4 \pm 2$	74 ± 31 26.6 ± 4.9	27.8 ± 4.8	12.6 ± 2.2
^{11}Be	$R_{\text{Bx}} < 2.0$ (3σ) $R_{\text{KL}} = 1.4 \pm 0.3$	- 2.45 ± 0.61	2.45 ± 0.61	$(3.2 \pm 0.8) \times 10^{-2}$

pep rate precision: scanning the C11 rate

Due to the possibility of atmospheric muons to reach the detector in bundles and of a single muon to create multiple ^{11}C isotopes along its path, variations up to 30% in the ^{11}C rate have been considered.

Configuration:

MV fit, 1Y data taking, repeated 5000 times for each point. TP = 0.9 and Sub.Exp = 0.7 are assumed



Most of the sensitivity to pep ν comes from the TFC_sub spectrum.

The increase of the ^{11}C rate has to be multiplied by a 10% efficiency in the TFC_sub spectrum.

Cross-checks between MUST and JUST

Goal: validate these two **independent fitters** by proving that they lead to **compatible results**.

How we proceeded:

1. **Fitter validation**: we run a single fit with the same input parameters in the two fitters: exposure, pseudo-dataset, “injected rates”, fitting range. Both **single-histo** and **double-histos fit (sub+tag)** cases were analyzed.
2. **Toy MC validation**: generation of samples by comparing the number of generated events species-by-species + comparison of the results’ distributions.

Cross-checks between MUST and JUST

Fitter validation: results

1-histo fit case

Species	Bias on the rec. rate MUST/JUST	% error difference MUST/JUST
Be7	-4E-06	0,00%
pep	-1E-04	-0,07%
Bi210	2E-04	-0,04%
K40	-7E-04	-0,54%
Kr85	-9E-05	-0,04%
U238	-3E-05	-0,01%
Th232	-4E-04	-0,09%
Po210	0E+00	0,00%
C11	5E-06	0,00%

2-histo fit case

Species	Bias on the rec. rate MUST/JUST	% error difference MUST/JUST
Be7	4E-06	-0,01%
pep	9E-05	0,04%
Bi210	1E-04	0,00%
K40	-6E-04	-0,01%
Kr85	-4E-06	0,10%
U238	-4E-05	0,00%
Th232	-1E-04	0,11%
Po210	-1E-05	0,00%
C10	-3E-04	0,06%
He6	8E-05	0,12%
C11 (Sub)	-1E-05	0,00%
C11_2 (Tag)	3E-05	0,00%

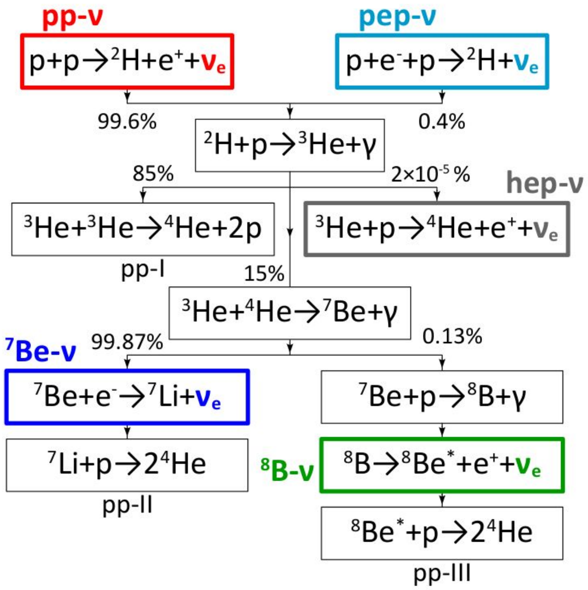
The mean level of agreement MUST/JUST is **$\sim 10^{-4}$**

MUST and **JUST** lead to **independent** and **compatible results**

Solar neutrinos

- Sun is powered by nuclear fusion reactions → neutrino emission
- “Photography” of the Sun core
- Two sequences: pp-chain (primary in the Sun, ~99% lum.) and the secondary CNO cycle

pp chain



pp-ν
$p+p \rightarrow {}^2H+e^++\nu_e$

pep-ν
$p+e^-+p \rightarrow {}^2H+\nu_e$

99.6%
0.4%

${}^2H+p \rightarrow {}^3He+\gamma$

85%
2×10^{-5} %

hep-ν

${}^3He+{}^3He \rightarrow {}^4He+2p$
pp-I

${}^3He+p \rightarrow {}^4He+e^++\nu_e$

15%

${}^3He+{}^4He \rightarrow {}^7Be+\gamma$

⁷Be-ν
99.87%
0.13%

${}^7Be+e^- \rightarrow {}^7Li+\nu_e$

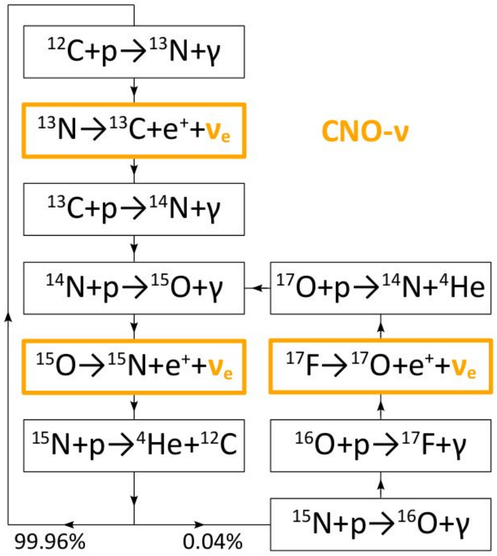
${}^7Be+p \rightarrow {}^8B+\gamma$

${}^7Li+p \rightarrow 2{}^4He$
pp-II

⁸B-ν
${}^8B \rightarrow {}^8Be^*+e^++\nu_e$

${}^8Be^*+p \rightarrow 2{}^4He$
pp-III

CNO cycle



${}^{12}C+p \rightarrow {}^{13}N+\gamma$

${}^{13}N \rightarrow {}^{13}C+e^++\nu_e$

CNO-ν

${}^{13}C+p \rightarrow {}^{14}N+\gamma$

${}^{14}N+p \rightarrow {}^{15}O+\gamma$

${}^{17}O+p \rightarrow {}^{14}N+{}^4He$

${}^{15}O \rightarrow {}^{15}N+e^++\nu_e$

${}^{17}F \rightarrow {}^{17}O+e^++\nu_e$

${}^{15}N+p \rightarrow {}^4He+{}^{12}C$

${}^{16}O+p \rightarrow {}^{17}F+\gamma$

${}^{15}N+p \rightarrow {}^{16}O+\gamma$

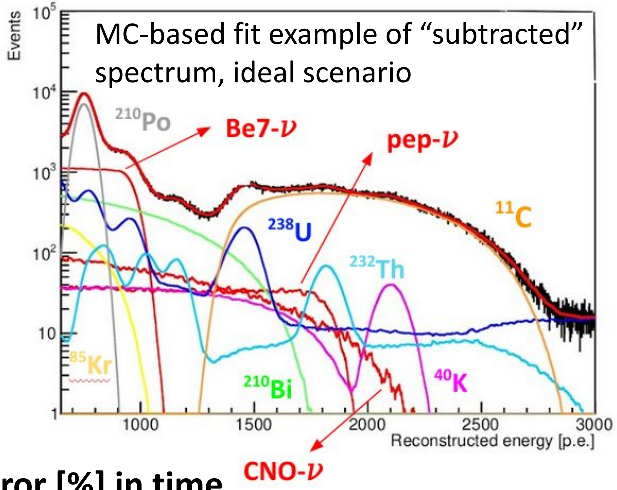
99.96%
0.04%

Net reaction:

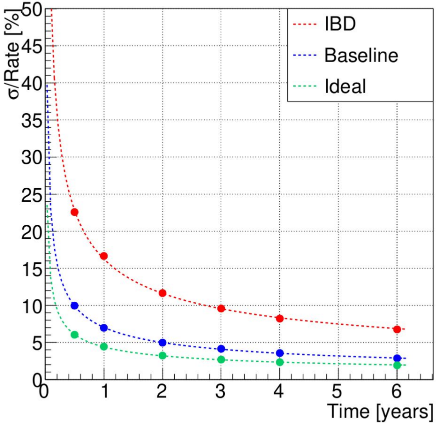
$$4p \rightarrow {}^4\mathrm{He} + 2e^+ + \boxed{2\nu_e} + \underset{26.731\,\mathrm{MeV}}{\underset{\downarrow}{Q}}$$

Intermediate energy solar ν - summary (docDB#7312)

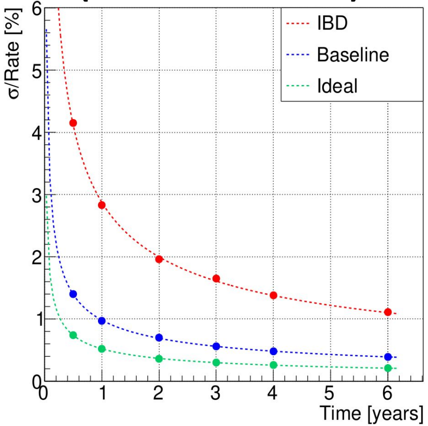
- Significant improvements wrt Jan 2021: full inclusion of detector response
- Outstanding JUNO performances for solar-ν spectroscopy (Be7-ν, pep-ν, CNO-ν), depending on the radioactive contamination scenarios
  - "Ideal": best scenario achievable, quoted in YB
  - "Baseline": scenario quoted in YB (~ ideal levels x10)
  - "IBD": minimum requirement for MH discrimination (baseline levels x10)
- **Timeline: technote in Autumn; Collaboration paper in Spring 2022**


MC-based fit example of "subtracted" spectrum, ideal scenario

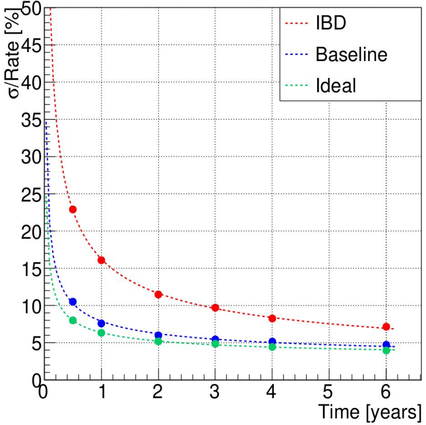
CNO stat error [%] in time (210Bi and pep constrained)



Be7 stat error [%] in time (CNO constrained)

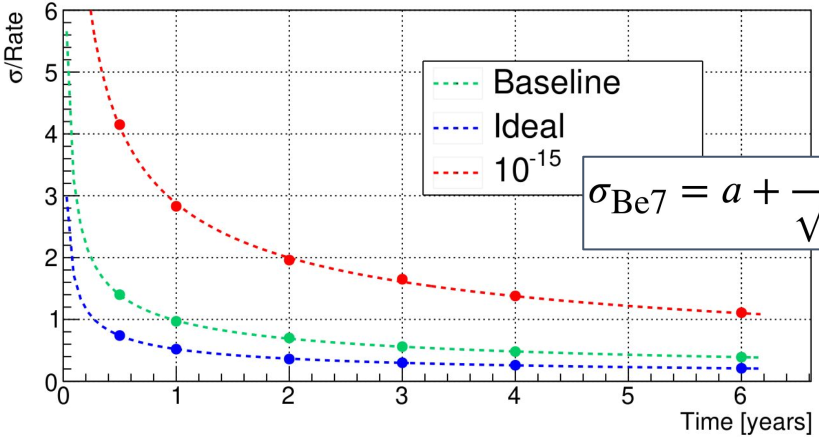


pep stat error [%] in time (CNO constrained)



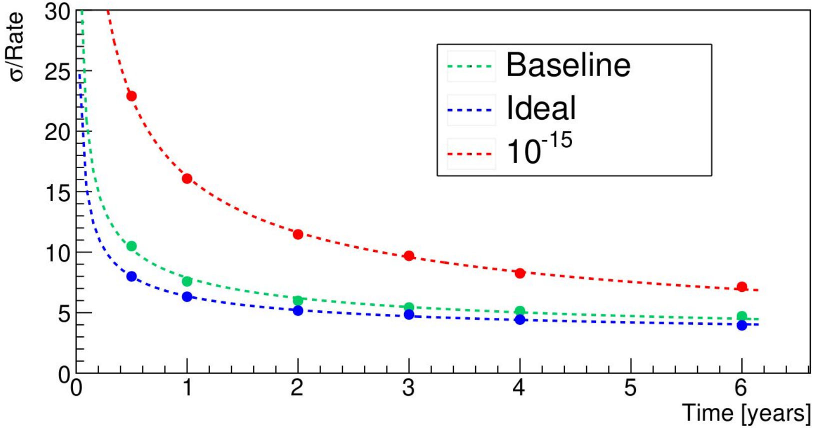
Time evolution: Be7 and pep rate uncertainty

Be7 stat error [%] in time



$$\sigma_{\mathrm{Be7}} = a + \frac{b}{\sqrt{\mathrm{Exposure}}}$$

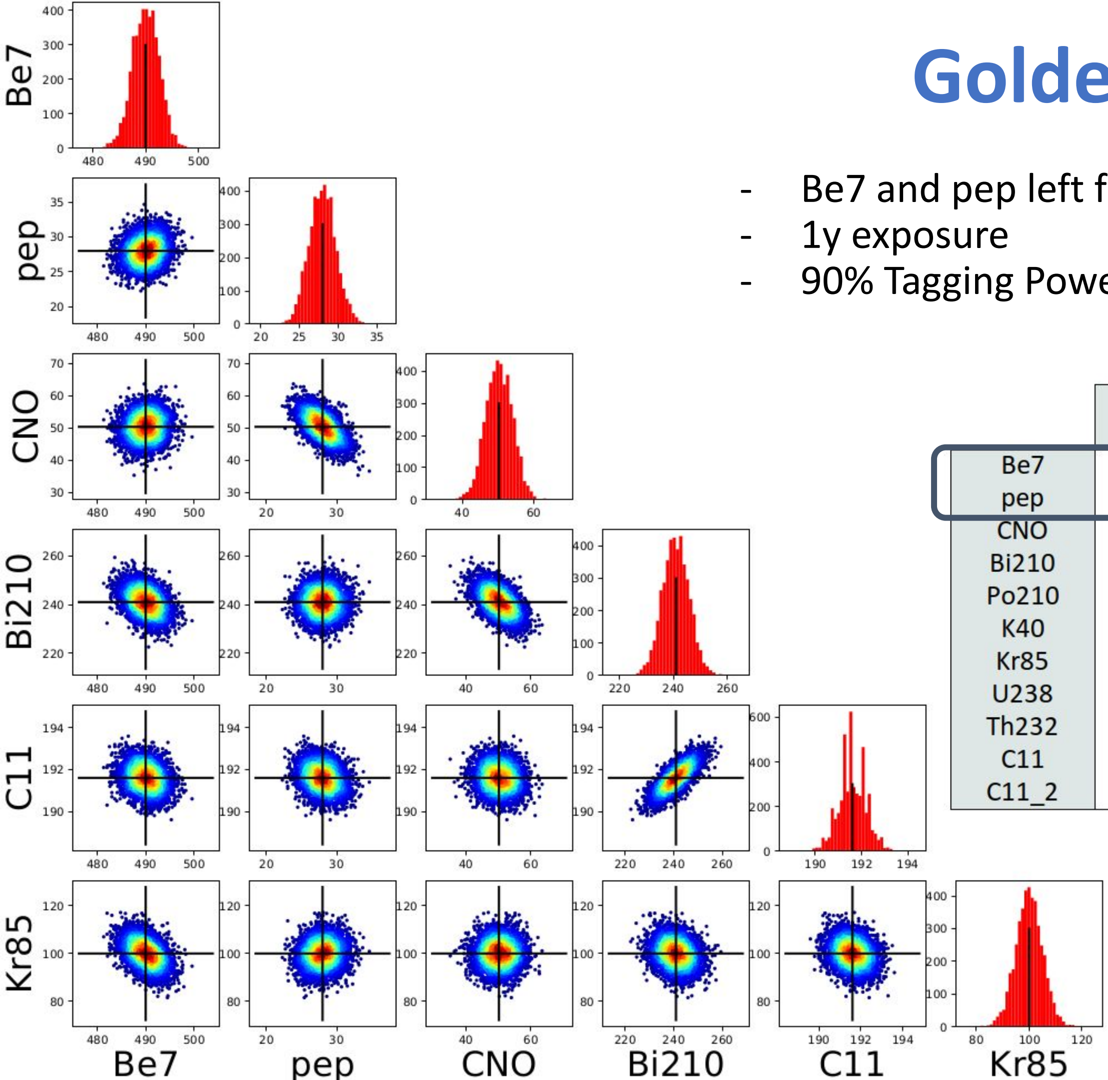
pep stat error [%] in time



- After 1y, Be7 stat. error: **~0.7%** (ideal), **~1.4%** (baseline) or **~4.2%** (10^{-15})
- After 1y, pep stat. error: **~8%** (ideal), **~11%** (baseline) or **~23%** (10^{-15})
- No significant improvement after 3 years
- **Systematics are driving the error budget for long data-taking !**

Golden fit results - Ideal sc.

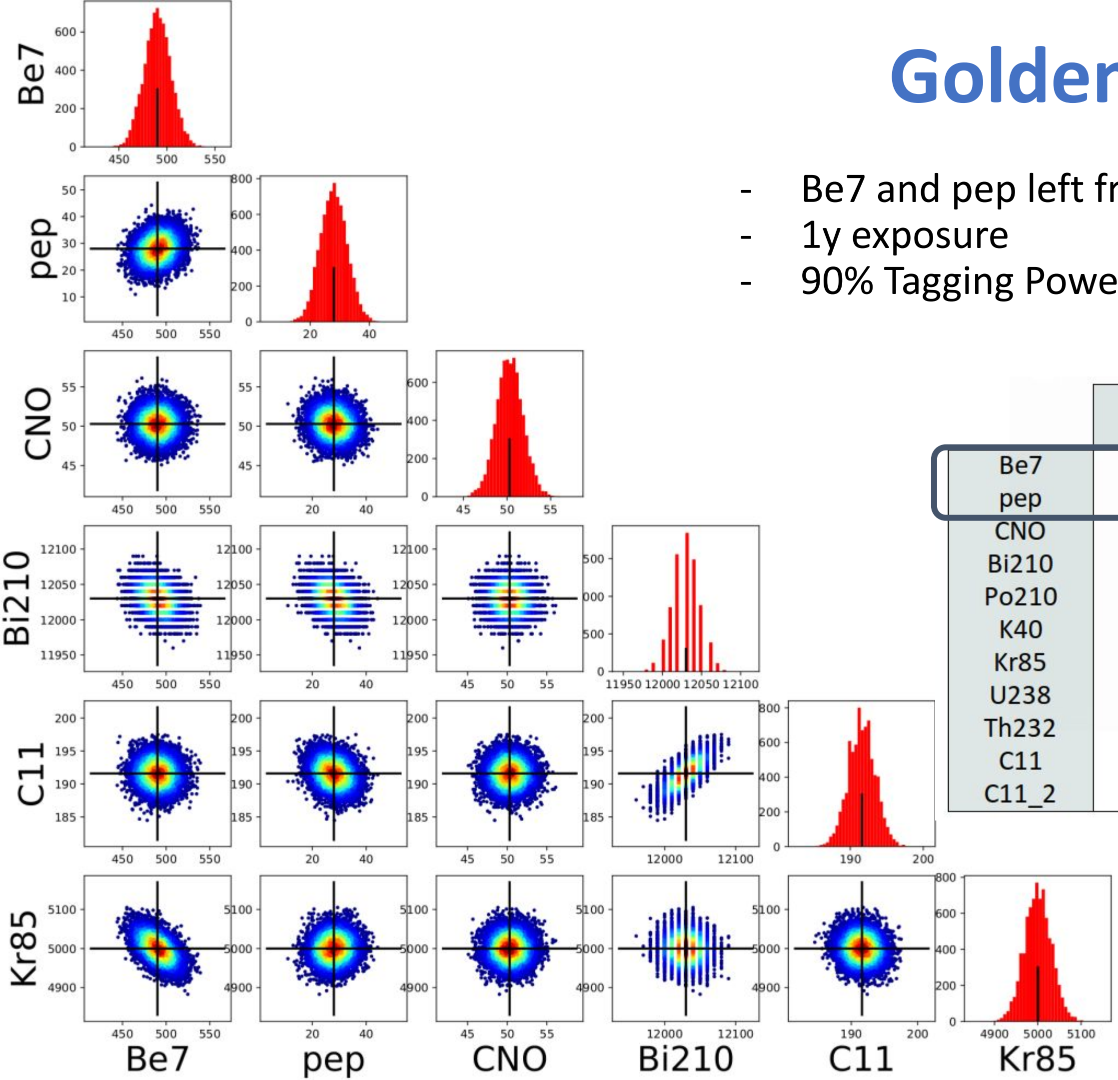
- Be7 and pep left free to vary, CNO penalty to SSM-HZ
- 1y exposure
- 90% Tagging Power, 70% Subtracted Exposure



	Inj rate cpd/kt	Avg rec rate cpd/kt	Avg RMS cpd/kt	Avg RMS %	Avg Bias %
Be7	490.0	490.0	2.52	0.51	0.01
pep	28.0	28.0	1.73	6.19	-0.03
CNO	50.3	50.4	3.75	7.44	0.12
Bi210	241.0	240.9	4.99	2.07	-0.03
Po210	244.2	244.2	0.42	0.17	0.00
K40	22.9	22.9	1.54	6.70	0.00
Kr85	100.0	100.0	5.08	5.08	-0.01
U238	150.5	150.5	1.61	1.07	-0.01
Th232	35.1	35.1	1.12	3.18	0.01
C11	191.6	191.6	0.58	0.30	0.00
C11_2	5939.6	5939.6	1.84	0.03	0.00

Golden fit results - “IBD“ sc.

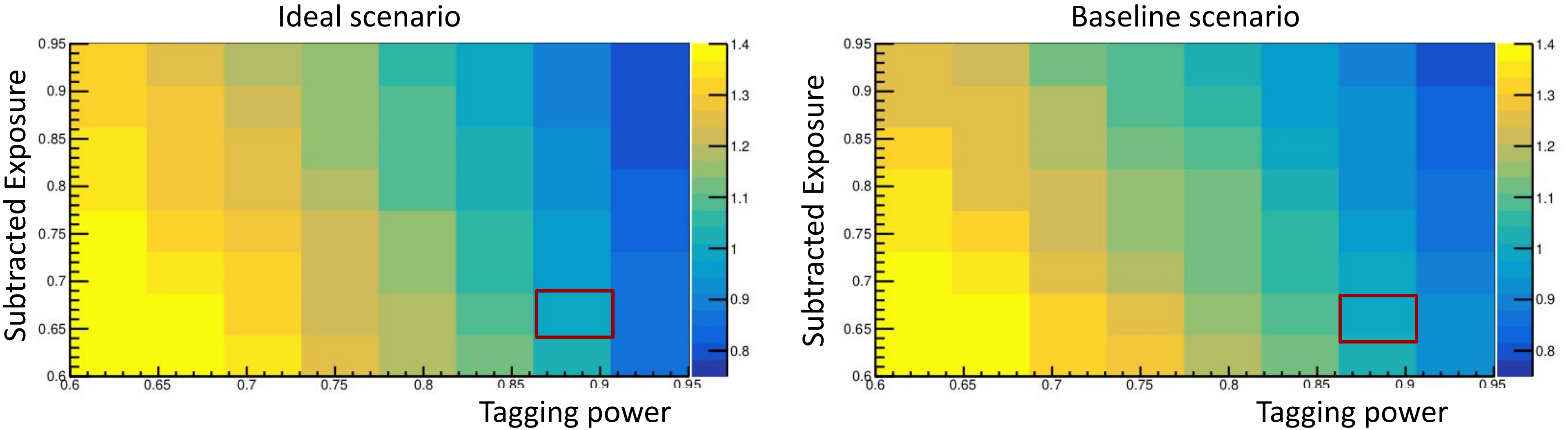
- Be7 and pep left free to vary, CNO penalty to SSM-HZ
- 1y exposure
- 90% Tagging Power, 70% Subtracted Exposure



	Inj rate cpd/kt	Avg rec rate cpd/kt	Avg RMS cpd/kt	Avg RMS %	Avg Bias %
Be7	490.0	490.3	13.89	2.83	0.05
pep	28.0	27.9	4.49	16.08	-0.24
CNO	50.3	50.3	1.53	3.04	0.04
Bi210	12030.0	12029.8	17.06	0.14	0.00
Po210	12210.0	12209.9	2.76	0.02	0.00
K40	2290.0	2290.1	4.86	0.21	0.00
Kr85	5000.0	5000.0	30.83	0.62	0.00
U238	15050.0	15050.0	10.23	0.07	0.00
Th232	3508.0	3508.1	5.05	0.14	0.00
C11	191.6	191.6	1.83	0.95	-0.01
C11_2	5939.6	5939.5	5.91	0.10	0.00

pep rate precision: scanning the two C11-tagging parameters

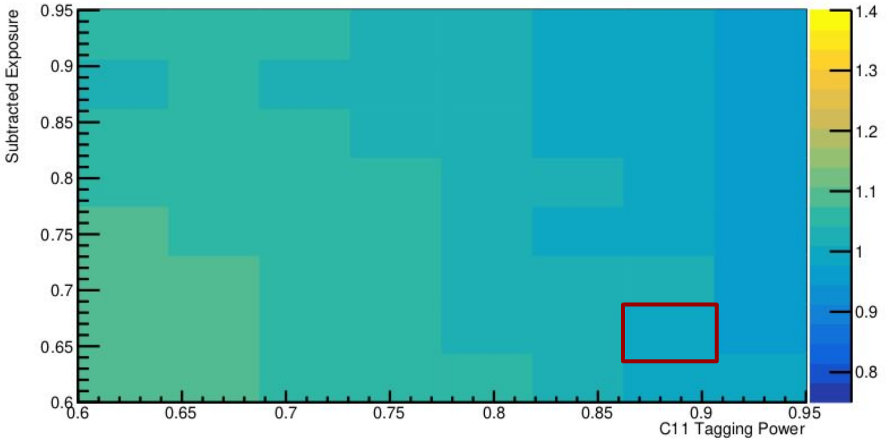
MV fit, 1Y data taking, repeated 5000 times for each TP + SubExp configuration
<u>pep rate RMS</u> (color scale) relative to TP = 0.90 and Sub.Exp = 0.65 (reasonable range for JUNO) as a function of Tagging Power (x axis) and Subtracted Exposure (y axis)

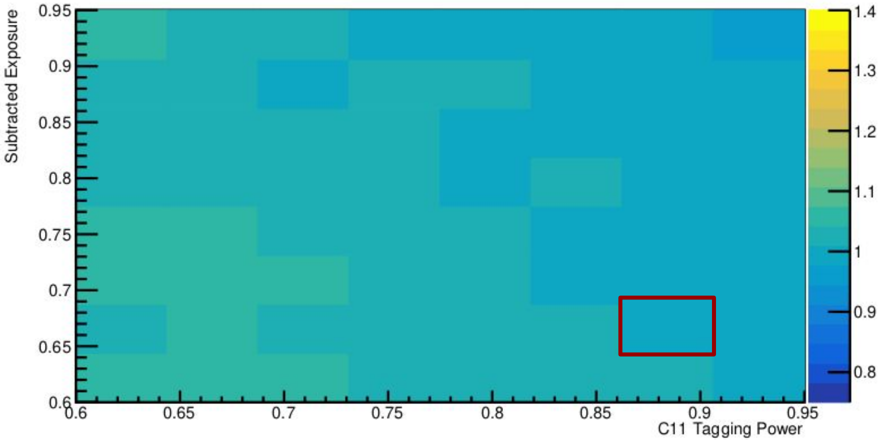


- Tag. Power is more important than Sub. Exp: pep precision is almost doubled from TP = 0.6 to 1.0
- Be7 rate precision (not shown here) not relevantly affected: max variations ~5%

Be7 rate precision: scanning the two C11-tagging parameters

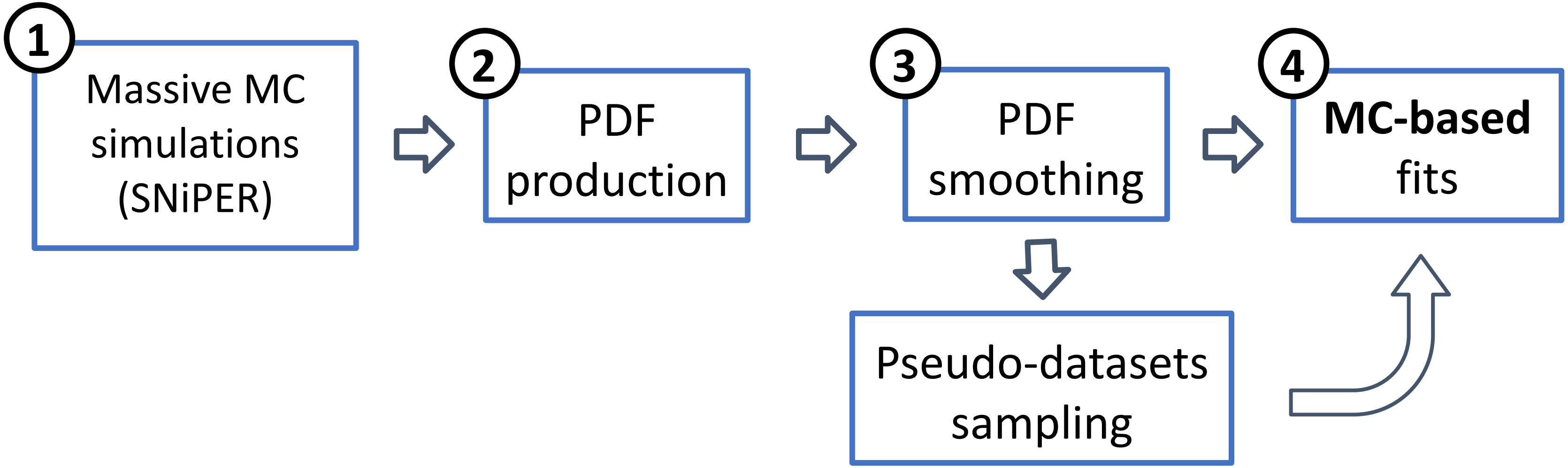
MV fit, 1Y data taking, repeated 5000 times for each TP + SubExp configuration
Be7 rate RMS (color scale) relative to the TP = 0.90 and Sub.Exp = 0.65 (reasonable range for JUNO) as a function of Tagging Power (x axis) and Subtracted Exposure (y axis)


Ideal scenario


Baseline scenario

- Be7 rate precision not relevantly affected by TP and Sub Exp: max variations ~5%

Sensitivity studies work-flow



① Massive MC simulations (SNiPER)

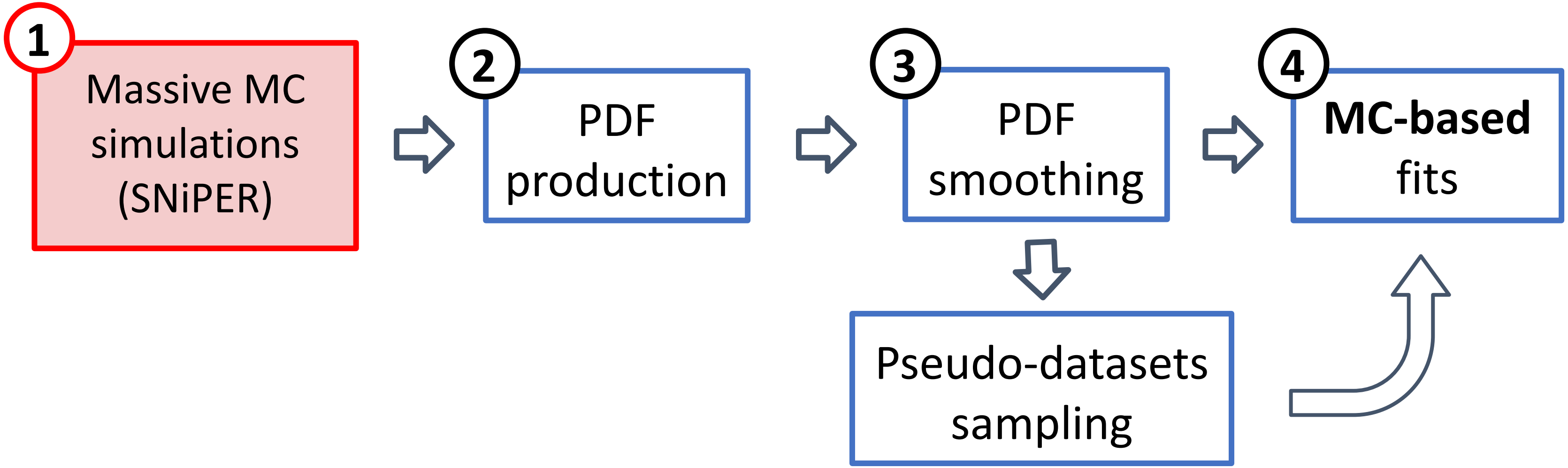
② PDF production

③ PDF smoothing

Pseudo-datasets sampling

④ **MC-based** fits

Sensitivity studies work-flow



① Massive MC simulations (SNiPER)

② PDF production

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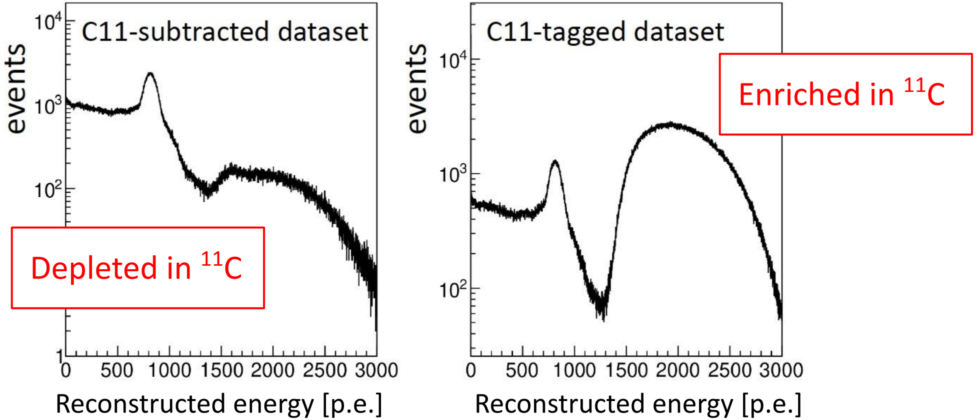
④ **MC-based** fits

Toy data sampling

For each species:

- consider its PDF produced via MC;
- sample a number of event given by **N = R*Exp** (R is the “injected rate” and the data-taking exposure).

The dataset is built by summing each of the contribution for each species.



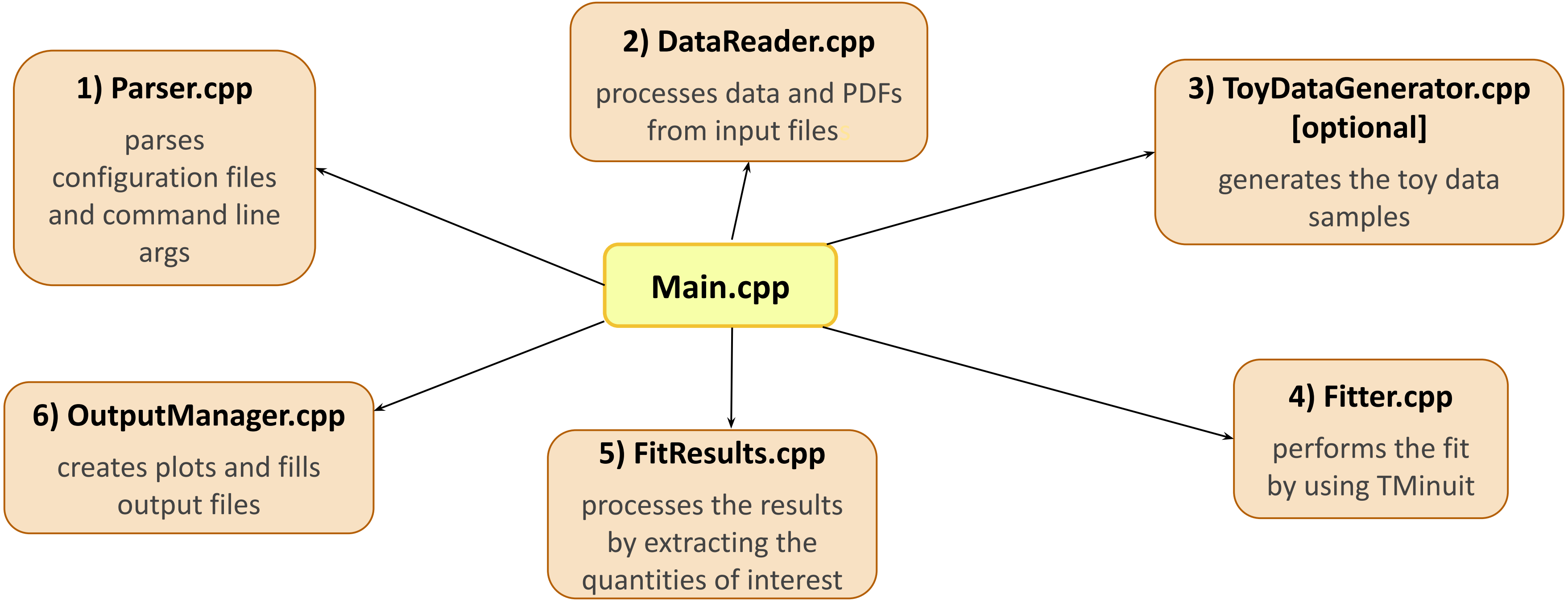
Depleted in ^{11}C

Enriched in ^{11}C

Two sub-datasets which differ for the ^{11}C rate and for the overall exposure

A little deeper into JUST: how it works

Structure



Main.cpp

1) Parser.cpp

parses configuration files and command line args

2) DataReader.cpp

processes data and PDFs from input files

3) ToyDataGenerator.cpp [optional]

generates the toy data samples

4) Fitter.cpp

performs the fit by using TMinuit

5) FitResults.cpp

processes the results by extracting the quantities of interest

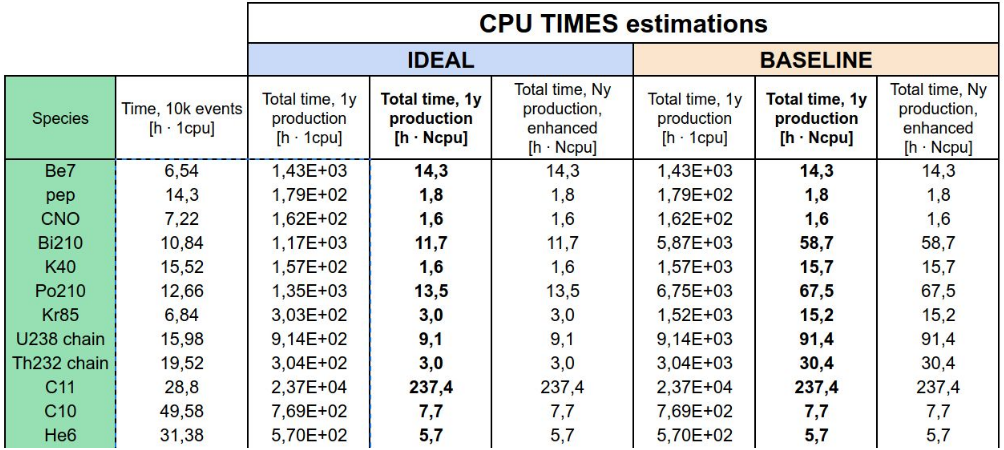
6) OutputManager.cpp

creates plots and fills output files

1 - Massive MC production

Configurations and relevant parameters

- J21v1r0-Pre0 offline version
- Exposure: spherical FV r < 15 m and data-taking = 1 y (100% duty cycle)
- Trigger threshold ~235 PMTs, trigger window 300 ns
- Dark noise removal: dark noise filter (set as default); no clustering algorithms activated
- Event reconstruction: OMILREC (energy) and RecTimeLikeAlg (position)
- GRDM (Geant4 Radioactivity Decay Module)
- WFs are not saved
- Backgrounds scenarios (ideal and baseline): all the estimations can be found at this Google Spreadsheet **(link)**



CPU TIMES estimations

		IDEAL			BASELINE		
Species	Time, 10k events [h · 1cpu]	Total time, 1y production [h · 1cpu]	**Total time, 1y production [h · Ncpu]**	Total time, Ny production, enhanced [h · Ncpu]	Total time, 1y production [h · 1cpu]	**Total time, 1y production [h · Ncpu]**	Total time, Ny production, enhanced [h · Ncpu]
Be7	6,54	1,43E+03	**14,3**	14,3	1,43E+03	**14,3**	14,3
pep	14,3	1,79E+02	**1,8**	1,8	1,79E+02	**1,8**	1,8
CNO	7,22	1,62E+02	**1,6**	1,6	1,62E+02	**1,6**	1,6
Bi210	10,84	1,17E+03	**11,7**	11,7	5,87E+03	**58,7**	58,7
K40	15,52	1,57E+02	**1,6**	1,6	1,57E+03	**15,7**	15,7
Po210	12,66	1,35E+03	**13,5**	13,5	6,75E+03	**67,5**	67,5
Kr85	6,84	3,03E+02	**3,0**	3,0	1,52E+03	**15,2**	15,2
U238 chain	15,98	9,14E+02	**9,1**	9,1	9,14E+03	**91,4**	91,4
Th232 chain	19,52	3,04E+02	**3,0**	3,0	3,04E+03	**30,4**	30,4
C11	28,8	2,37E+04	**237,4**	237,4	2,37E+04	**237,4**	237,4
C10	49,58	7,69E+02	**7,7**	7,7	7,69E+02	**7,7**	7,7
He6	31,38	5,70E+02	**5,7**	5,7	5,70E+02	**5,7**	5,7

W/ elec2rec (2 steps, 4 output rootfiles)

tut_detsim.py — Event gen. and det. simulation

tut_elec2rec.py — Electronics simulation
calibration (waveform rec)
event reconstruction

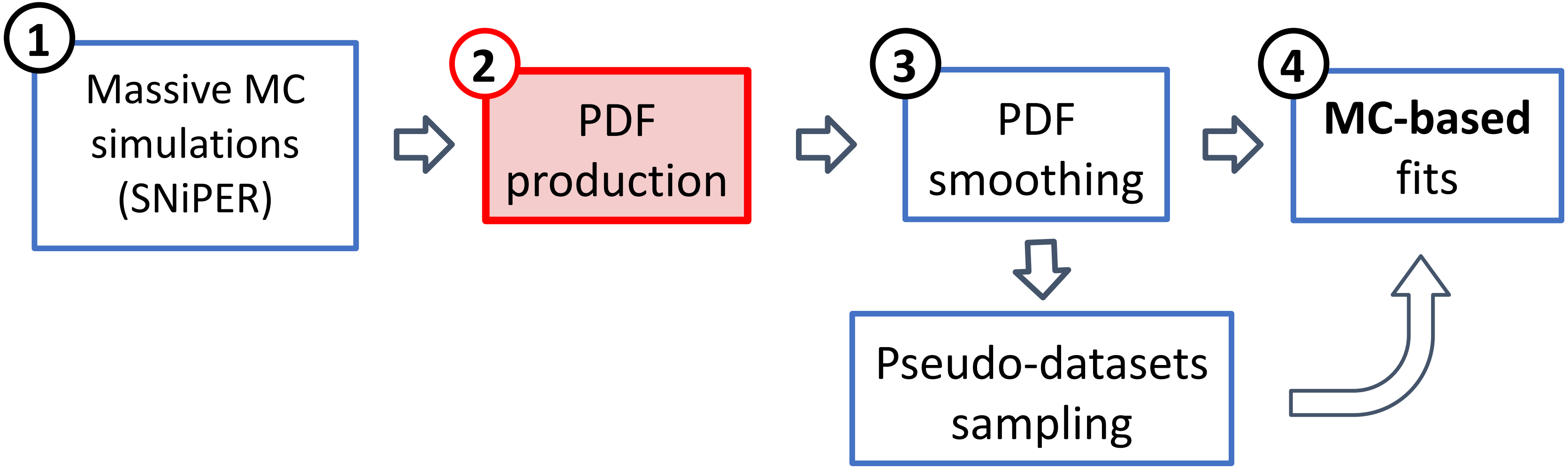
1 - Massive MC production

Simulations outputs have been now stored in a common area:

/storage/gpfs_data/juno/junofs/simulations/Pre-Release/J21v1r0-Pre0/Solar/

and can be exploited by all the interested users

Sensitivity studies work-flow



① Massive MC simulations (SNiPER)

② PDF production

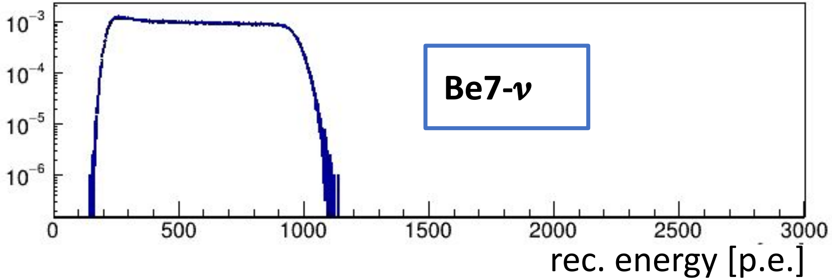
③ PDF smoothing

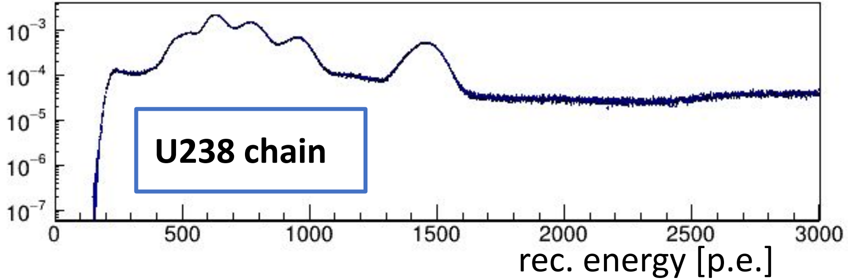
Pseudo-datasets sampling

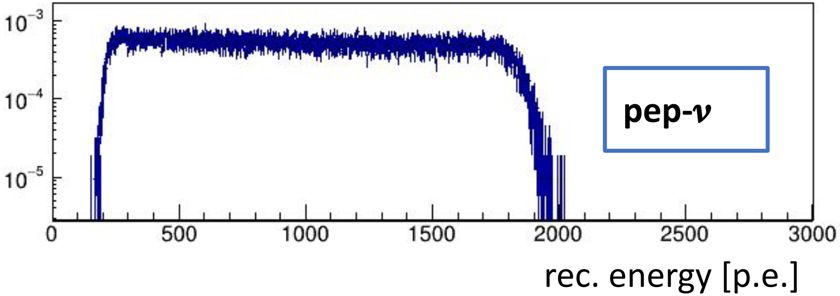
④ **MC-based** fits

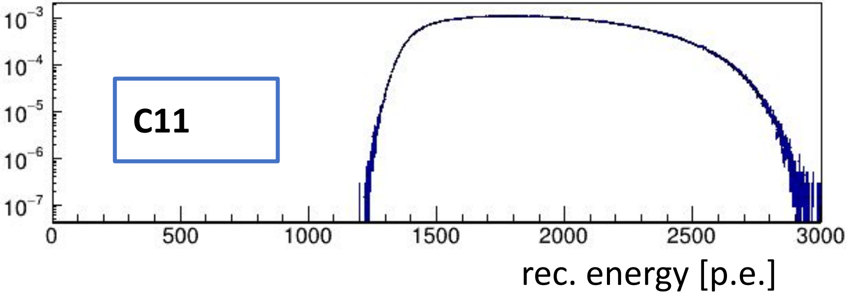
2 - PDF production

- A separate macro has been used to merge the rec rootfiles for each of the species and normalize properly (FV of the analysis: r < 14 m)
- Energy variable: m_NQE (OMILREC, total charge in p.e., corrected for the event radial pos.)
- Examples (12 PDFs in total):

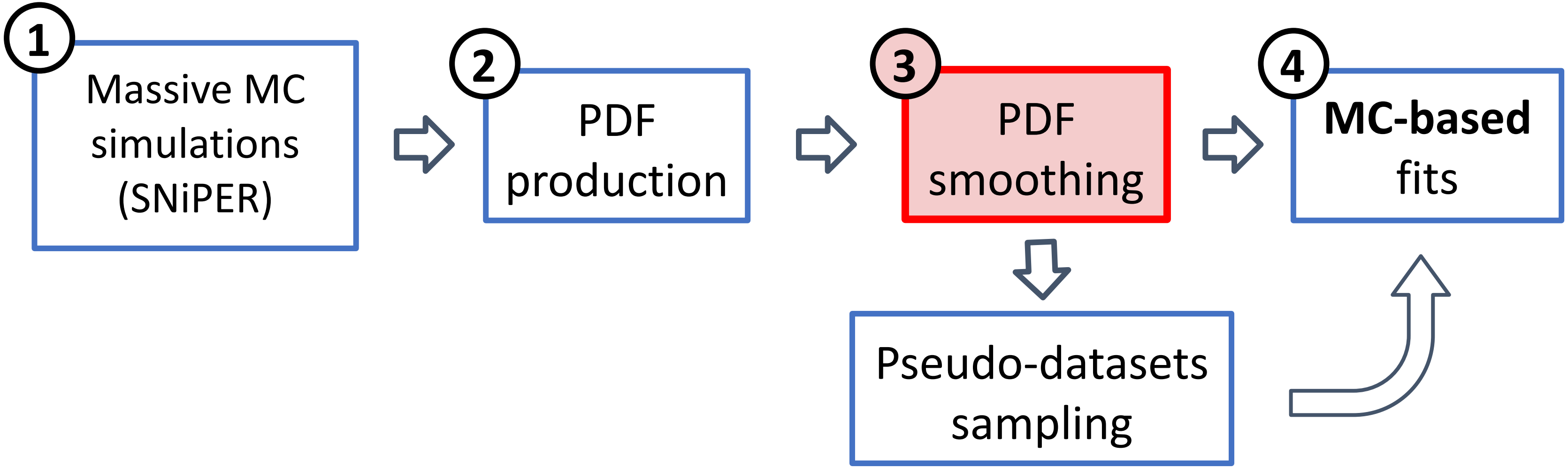








Sensitivity studies work-flow



① Massive MC simulations (SNiPER)

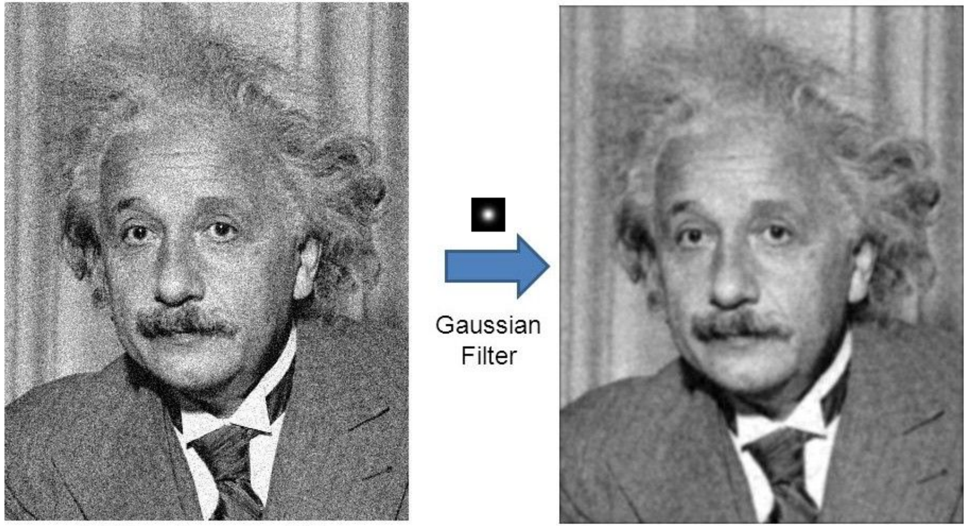
② PDF production

③ PDF smoothing

Pseudo-datasets sampling

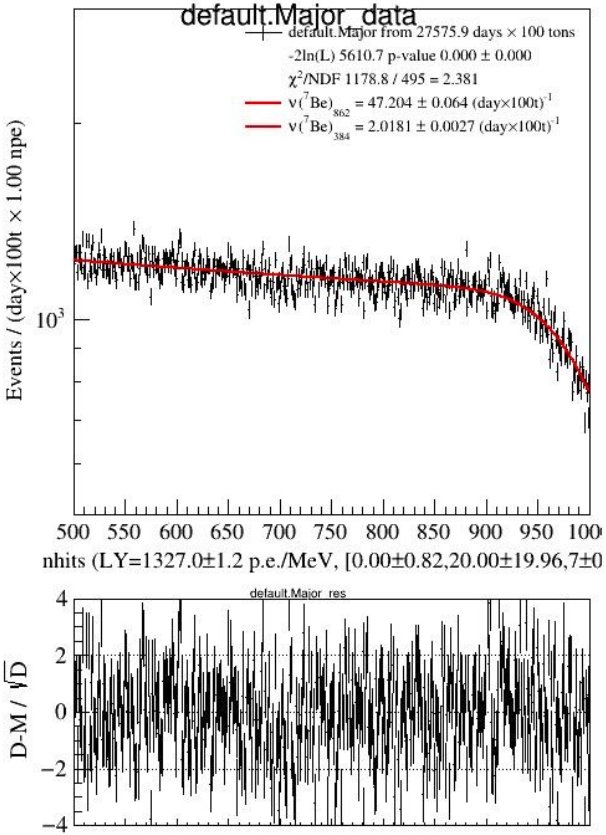
④ **MC-based** fits

3) PDF smoothing



Additive Gaussian Noise

The “oversampling” problem



The dataset is sampled from MC PDFs, built with statistics similar to the one for data-taking of interest

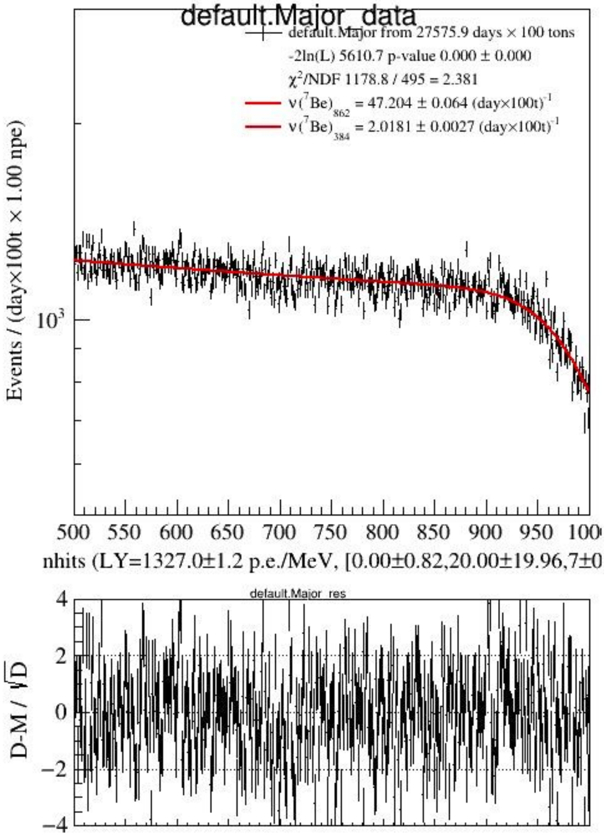
→ limited statistics: in principle, the PDFs events should be at least 1 order of magnitude higher than the data ones.

If this latter condition is not satisfied: **“oversampling”** the PDF: artificially “reproducing” the PDFs statistical fluctuations, in a way that we don’t expect on data.

In general, this is not be a problem for MC fits if we assume that the MC follows perfectly the energy response.

But we want also to perform systematic studies, where we will assume detector response will be not perfectly known.

The “oversampling” problem



What does “smooth” really mean?

The term is related to the statistical fluctuations for adjacent bins

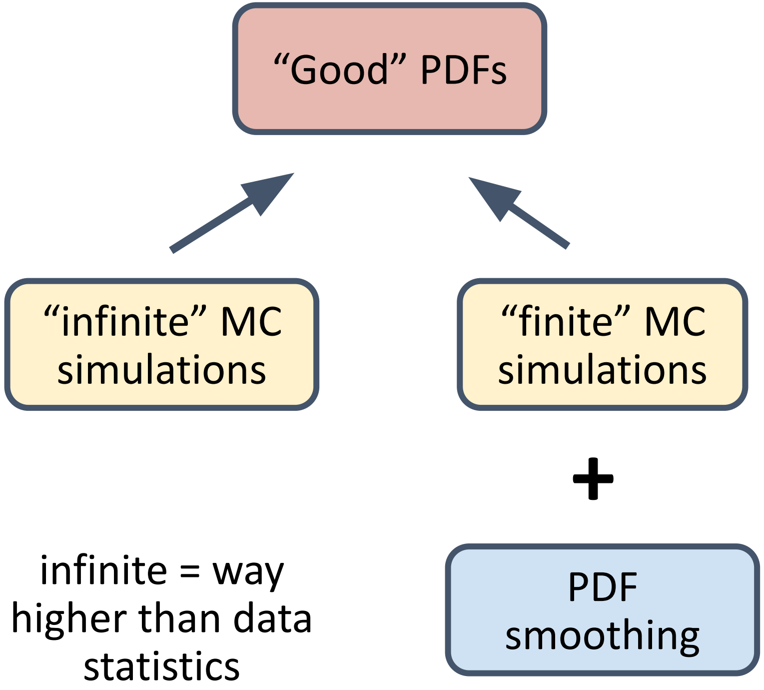
- With the smoothing, these fluctuations should be comparable with the bin statistical uncertainty ~√N

- Without the smoothing, these fluctuations would be way more sparse, due to limited statistics.

How to deal with statistical fluctuations?

1) Simulating more and more events
   - at least 10 times the ones currently simulated
   - currently, not feasible due to computational limits

2) Smoothing the PDFs in such a way that
   - statistical fluctuations for near bins are damped;
   - the main features of the PDFs are not smeared out
   → we don't want to distort the signal features


“Good” PDFs

“infinite” MC simulations

“finite” MC simulations

+

PDF smoothing

infinite = way higher than data statistics

Several filter algorithms

Many algorithms can be chosen:

1) **Savitzky-Golay filter**
2) Convolution-based filters
3) Cubic Regression Spline
4) Wiener filter

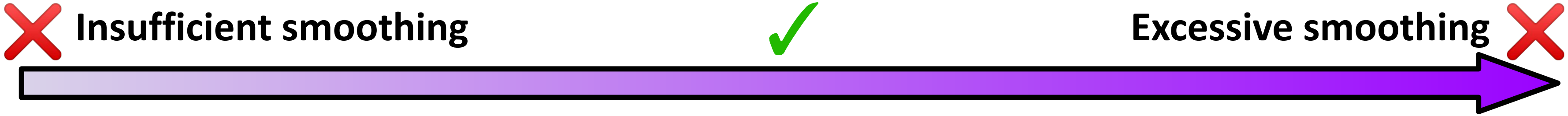
Used for this analysis, best performances trade-off

Further discussion and details on filters choice can be found here.

and so on…

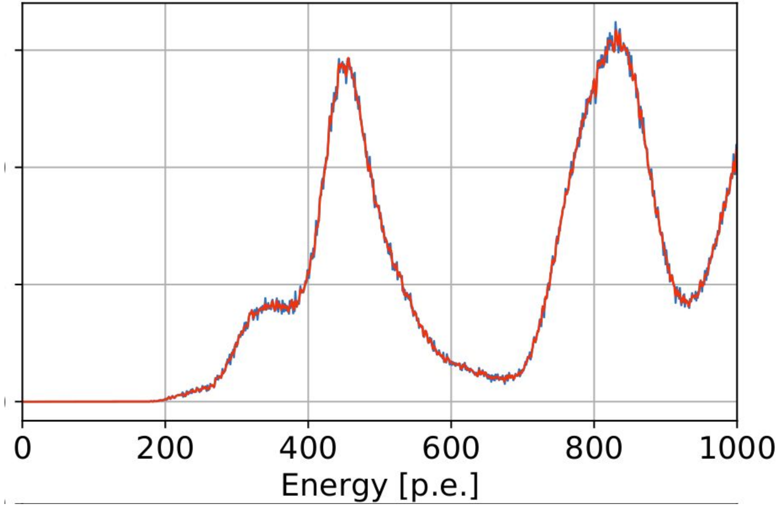
- Wide choice in literature: 2D image processing, signal processing
- Filters can be less or more useful, according to the kind of noise we want to remove

Tuning of filter parameters

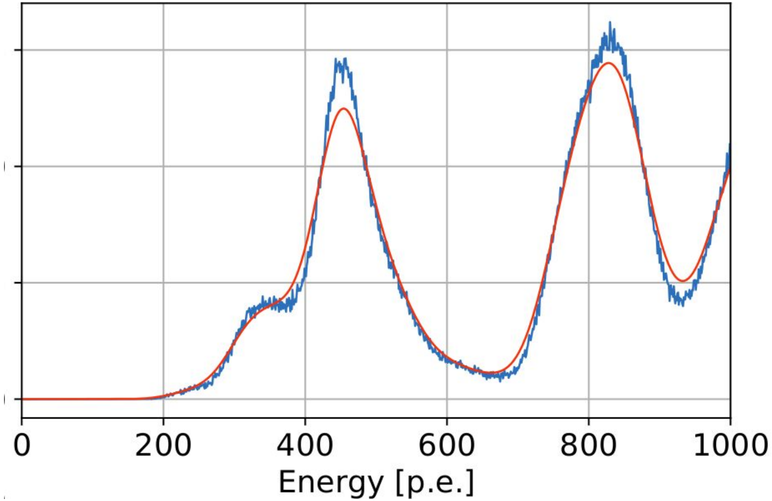


✗ **Insufficient smoothing** ✓ **Excessive smoothing** ✗

Statistical fluctuations not removed, filtered profile too adherent to the original one

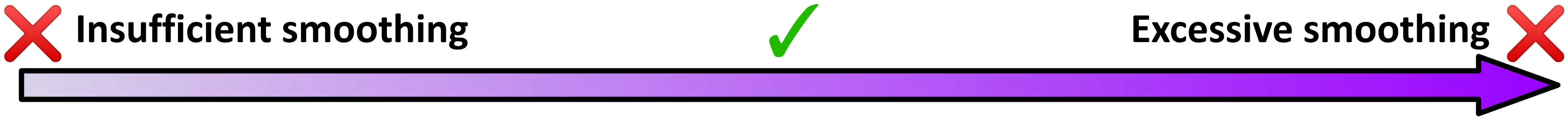


Spectral features softened, loss of resolution



How can we quantify the filter goodness and performances?

Tuning of filter parameters



❌ **Insufficient smoothing** ✓ **Excessive smoothing** ❌

Statistical fluctuations not removed, filtered profile too adherent to the original one

Spectral features softened, loss of resolution

How can we quantify the filter goodness and performances?

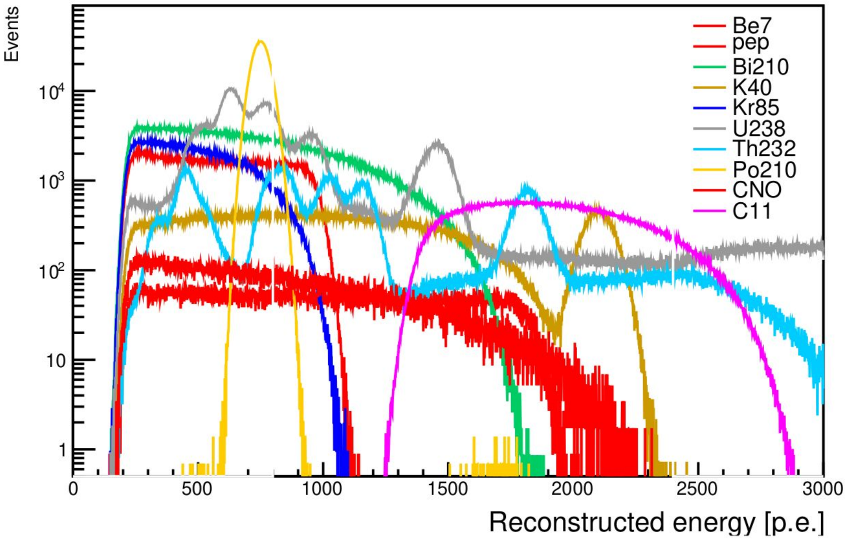
We want to remove the statistical fluctuations
⟶ a good filter satisfies a trade-off of these two conditions
⟶ particular focus to avoid signal distortions
⟶ in the following, some estimators to quantify the filters performances are proposed

Further discussion and details on filters choice can be found here.

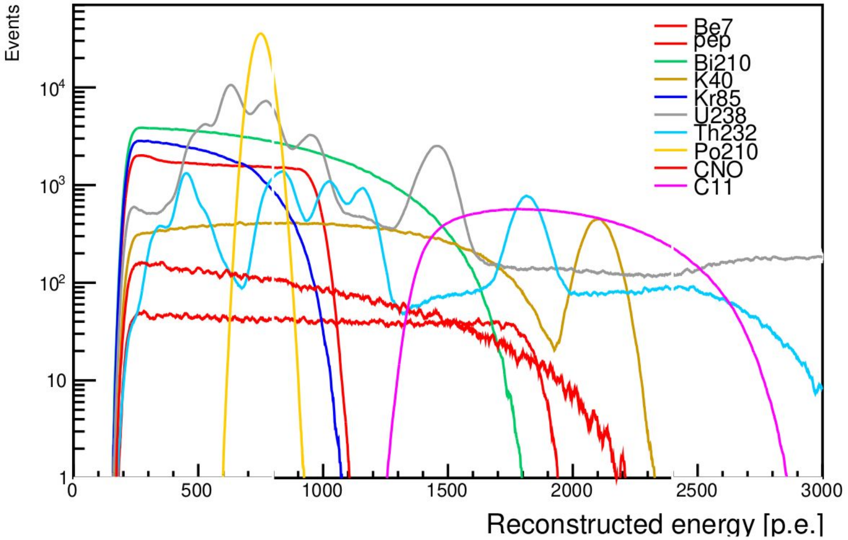
PDFs comparison: before and after smoothing

- Energy variable: m_NQE (OMILREC, total charge in p.e., corrected for the event radial pos.)
- Examples (12 PDFs in total):

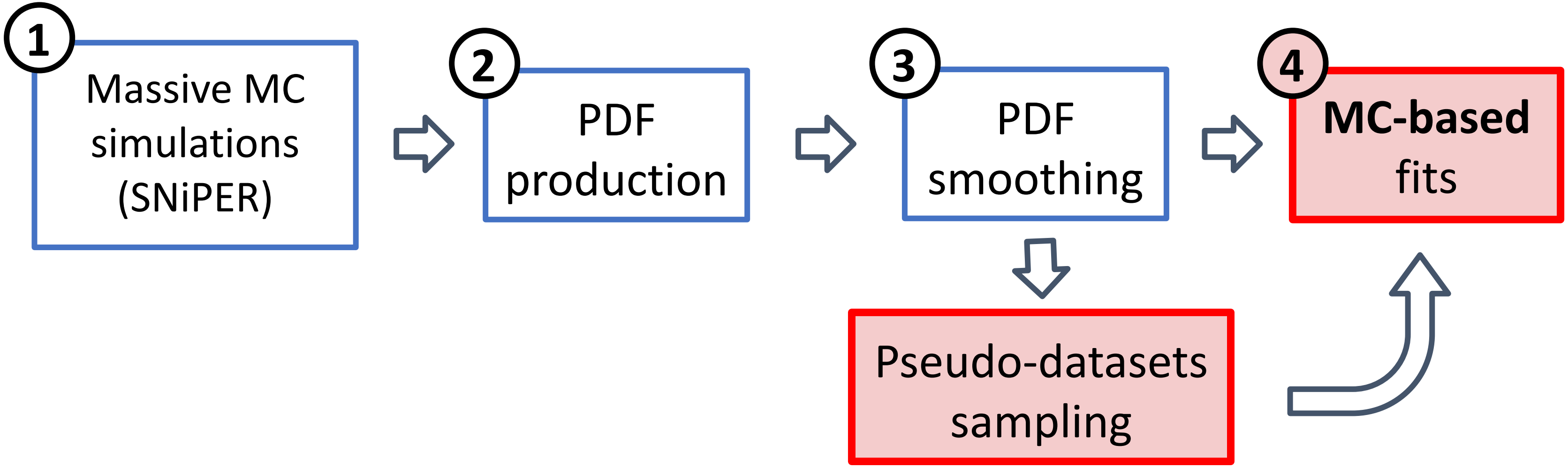
Not smoothed



Smoothed (SG)



Sensitivity studies work-flow



① Massive MC simulations (SNiPER)

② PDF production

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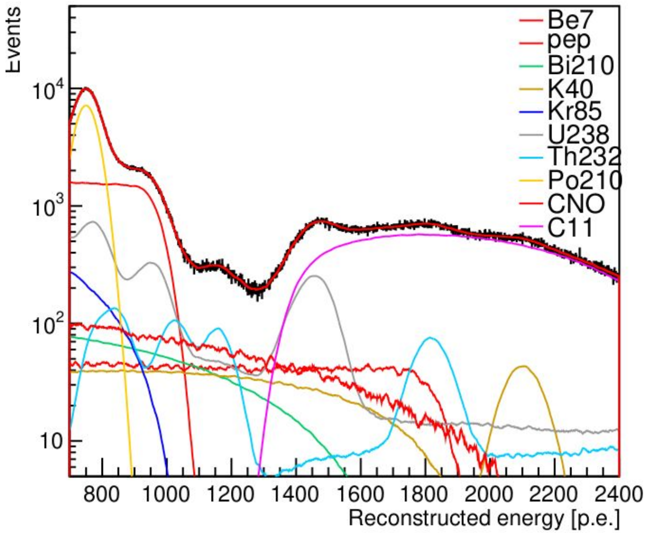
Pseudo-datasets sampling

④ **MC-based** fits

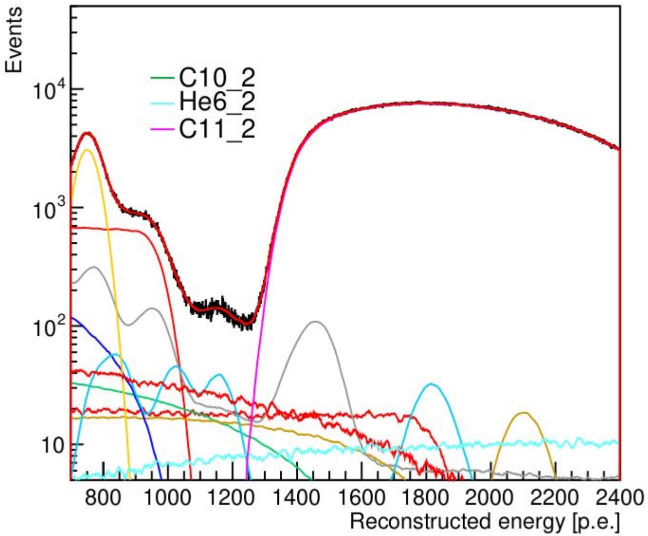
4 - Multivariate fit

- Based on binned likelihood maximization of two Poisson distributions
- Performed using a Milano local tool (“**MUST**” - **M**ilano n**U**sol **S**ensitivity **T**ool) or Juelich official fitter (**JUST**) → Anita is going to describe the performances and differences
- In these slides, only results obtained with MUST will be shown

C11-subtracted dataset



C11-tagged dataset



Example

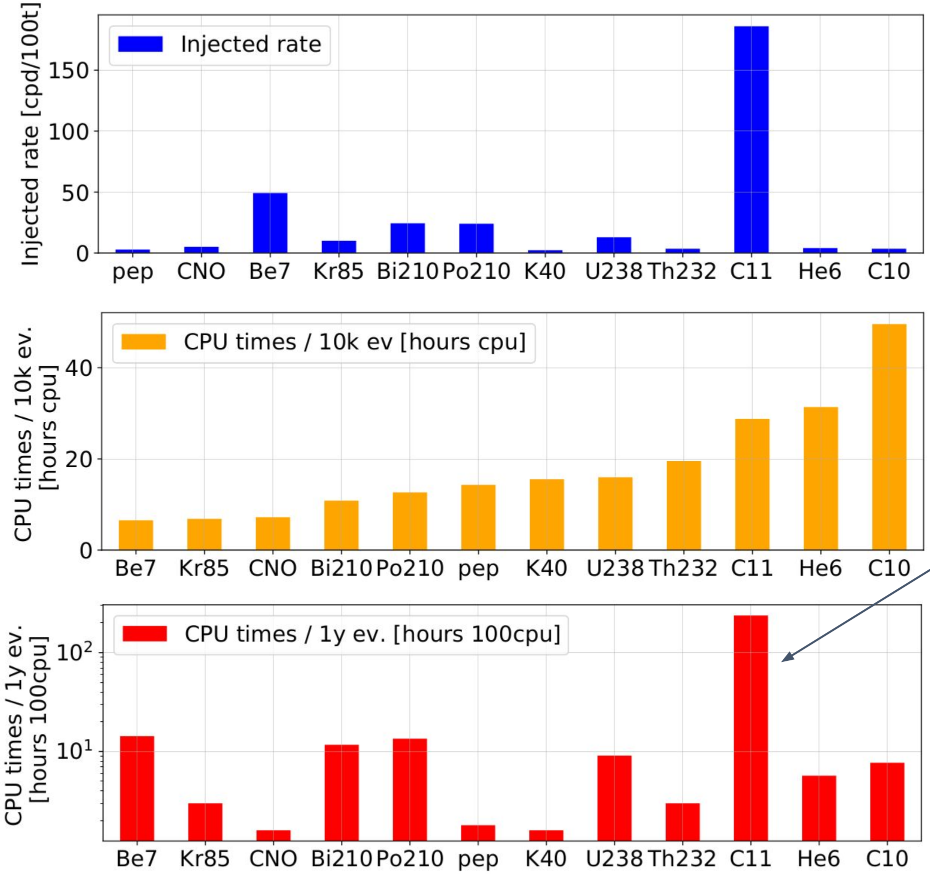
Results comparison

- Exposure: r < 14 m FV,
- 1 year data-taking
- Energy Tag + TFC Sub fit
- Energy range [p.e.]: 700 < charge < 2400
- 1000 pseudo-datasets
- Ideal radiopurity

Average std dev in cpd/100t

Species	Old PDFs	New PDFs	New PDFs w/smoothing
Be7	0.33	0.36	0.30
pep	0.21	0.16	0.21
Bi210	1.01	0.51	0.60
C11	0.11	0.06	0.07
K40	0.30	0.07	0.15
U238	0.23	0.22	0.21
Th232	0.22	0.12	0.12

MC production requirements



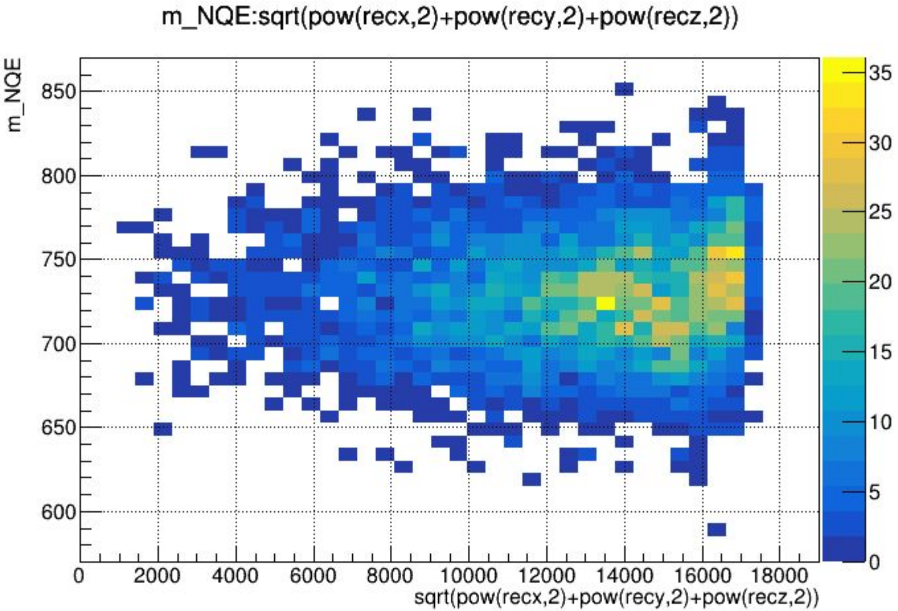
Legend:
Injected rate
CPU times for 10k events, 1 cpu
CPU times for 1 year production, 100 cpus

Because of the highest injected rate + high energy range, C11 is by far the most time consuming species overall

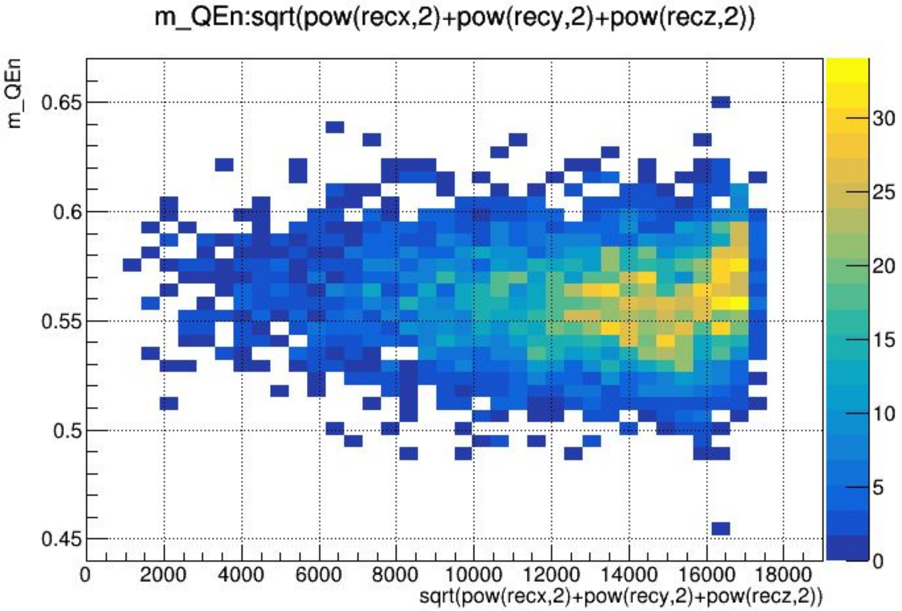
Note the log scale here!

4000 mono-energetic e- events, E=0.5 MeV, r < 17 m, J21v1r0_Pre0, OMILREC

Charge, m_NQE [p.e.]



m_QEn [MeV]

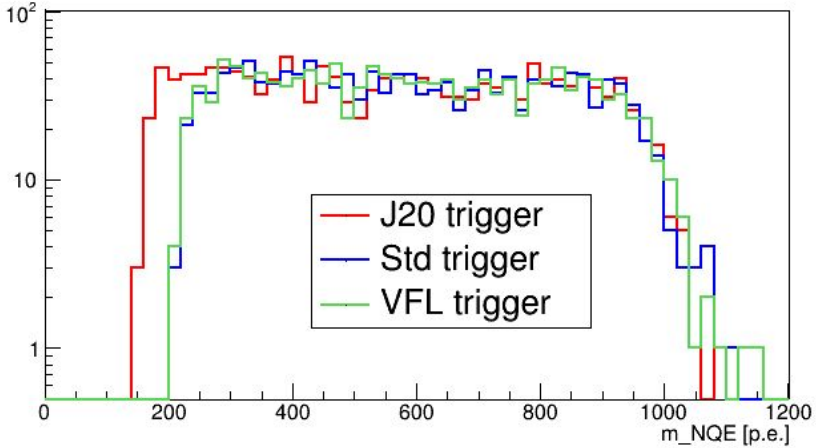


Simulations configurations

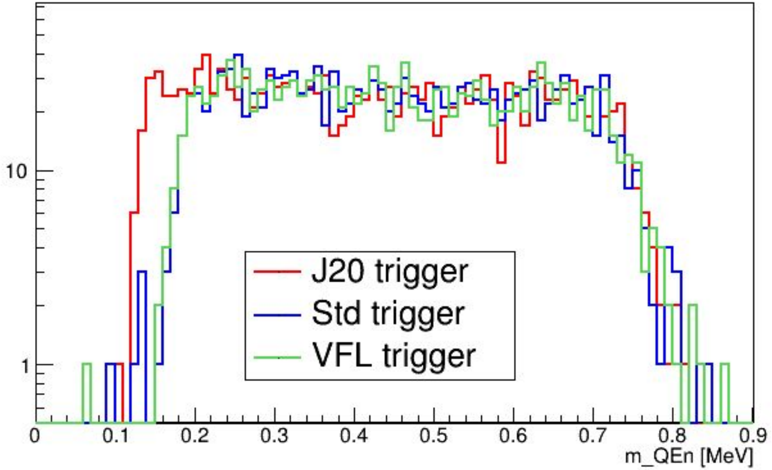
2000 Be7 events considering three trigger configurations, summarized below:

- "J20-like trigger" (**red**): effective trigger implemented in J20 version, default settings (200 FiredPMTs, trigger window 80 ns). Trigger efficiency for Be7 events = 1554/2000 = 0.777
- "Standard trigger" (**blue**): implemented only in J21 version, default settings (300 FiredPMTs, trigger window 300 ns, slip window 16 ns). Trigger efficiency for Be7 events = 1434/2000 = 0.717
- "VFL trigger" (**green**): implemented in J21 version, standard settings (100 FiredPMTs, trigger window 48 ns, slip window 16 ns). Trigger efficiency for Be7 events = 1435/2000 = 0.718

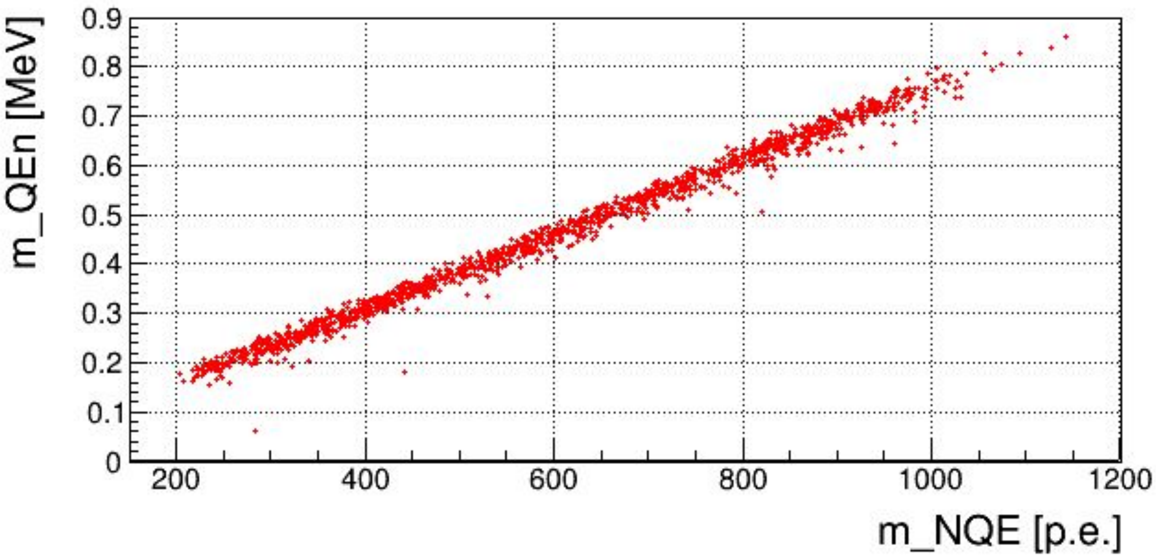
m_NQE [p.e.]



m_QEn [MeV]

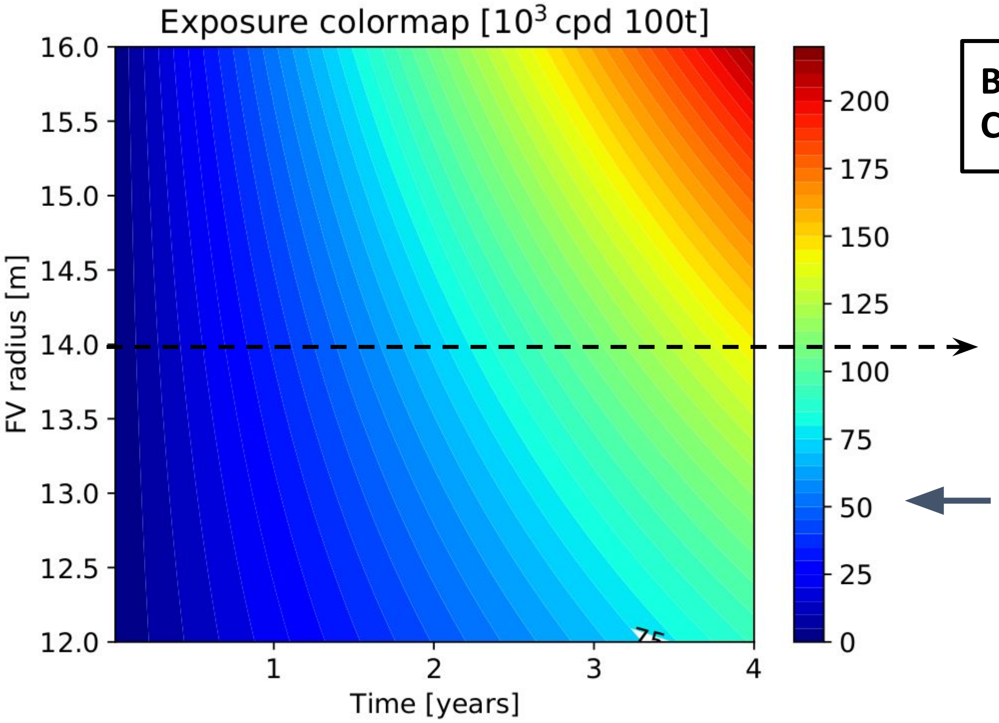


Scatter plot: m_NQE [p.e.] vs m_QEn [MeV]



For intermediate energy neutrinos, assuming a fit starting point around ~0.4-0.5 MeV, the trigger choice (Standard or VFL) should not impact to our spectrum. This would mean that for what concerns the intermediate energy neutrinos, we should be safe against the trigger choice

Exposure vs Time vs FV radius



Borexino Phase-I exposure = 550 days 100t
Can be achieved in ~6 JUNO days

FV chosen for this analysis

100 x Borexino Phase-I exposure