Double Chooz: Latest Results for Applied Antineutrino Detection

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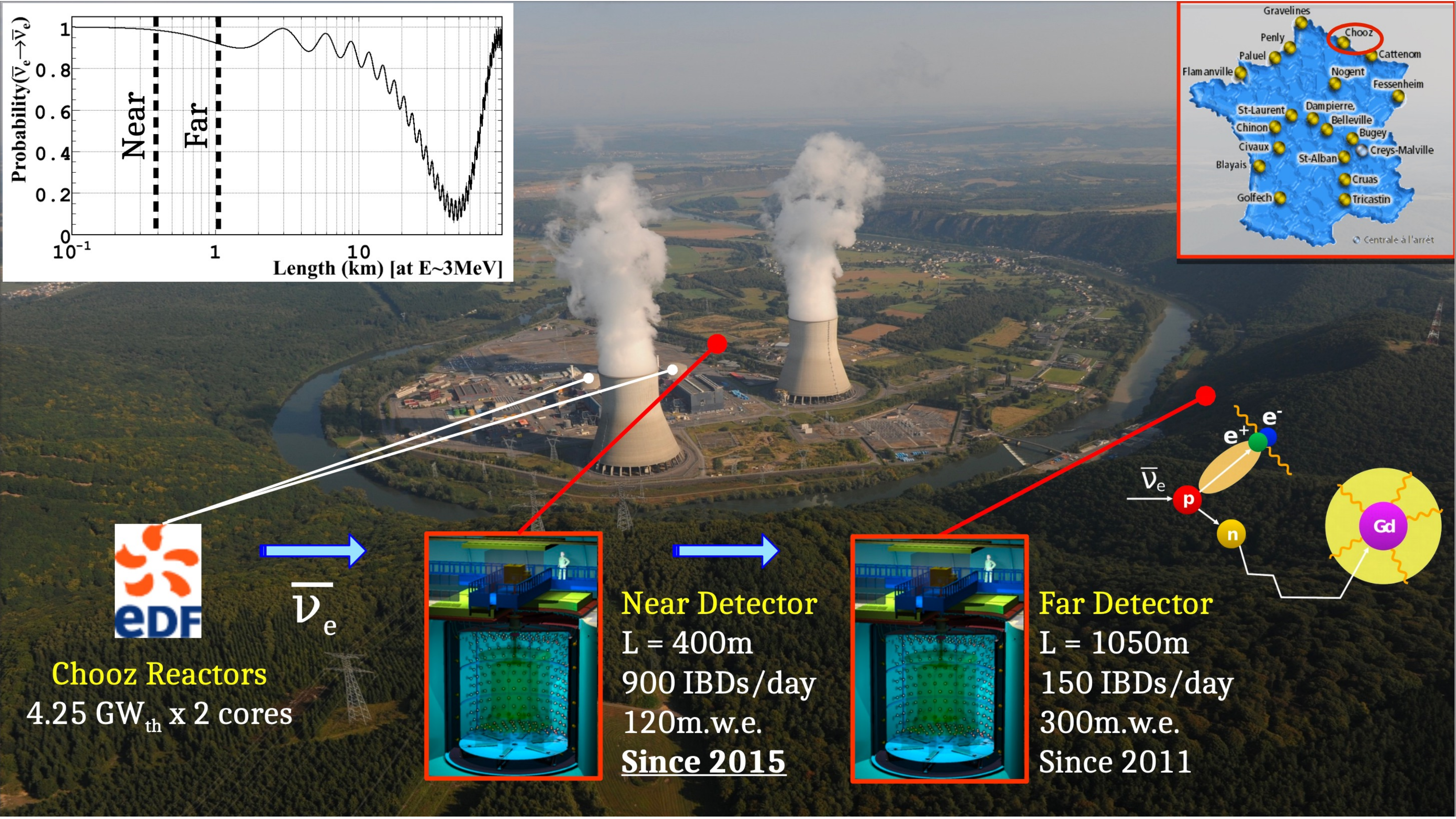
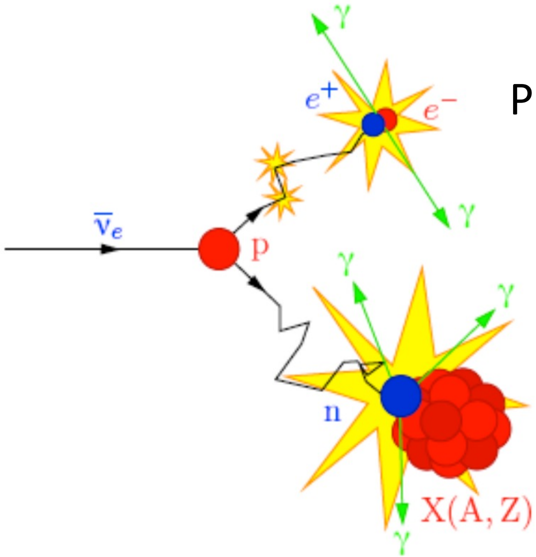
Applied Antineutrino Physics Workshop @ York

20^{th} September 2023



Probability($\bar{\nu}_e \to \bar{\nu}_e$)
1
0.8
0.6
0.4
0.2
0
10^{-1}
1
10
Length (km) [at E~3MeV]
Near
Far
Gravelines
Penly
Paluel
Flamanville
Chooz
Cattenom
Nogent
Fessenheim
St-Laurent
Dampierre
Belleville
Chinon
Bugey
Civaux
Creys-Malville
St-Alban
Blayais
Cruas
Golfech
Tricastin
Centrale à l'arrêt
eDF
Chooz Reactors
4.25 GW_{th} x 2 cores
$\bar{\nu}_e$
Near Detector
L = 400m
900 IBDs/day
120m.w.e.
Since 2015
Far Detector
L = 1050m
150 IBDs/day
300m.w.e.
Since 2011
$\bar{\nu}_e$
p
n
e^+
e^-
Gd

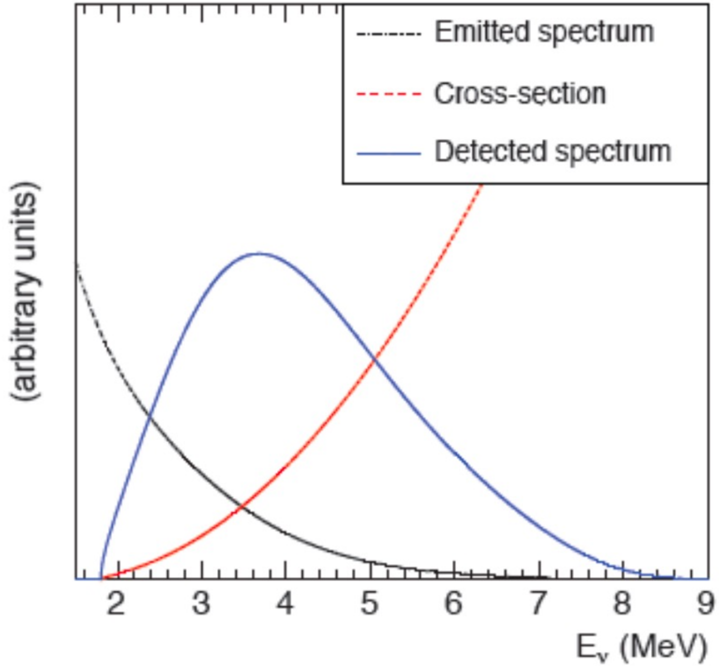
IBD signal



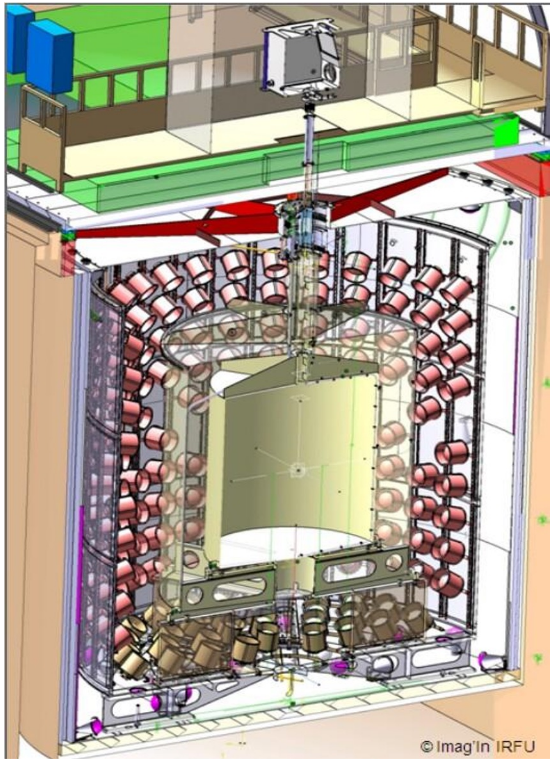
Prompt: > 1 MeV

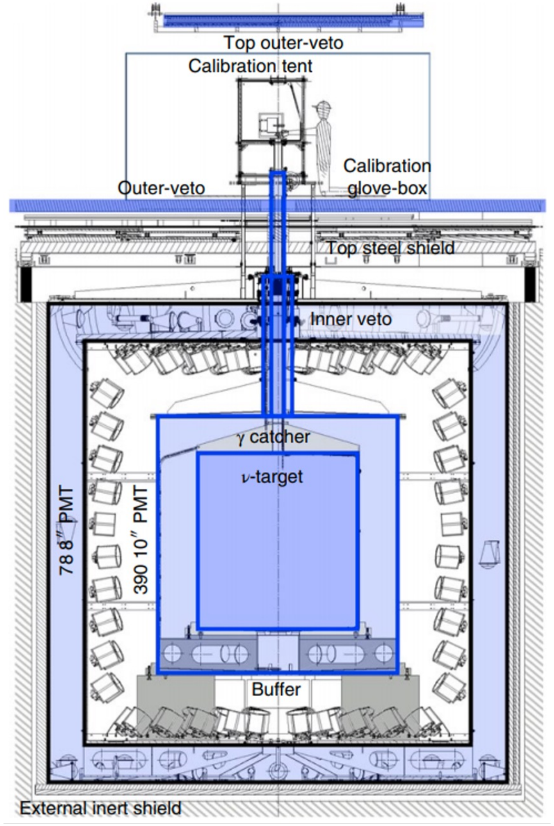
Delayed: n on Gd (H)
~30 (200) μs
8 (2.2) MeV

$$N_\nu^{\exp}(t) = \frac{\varepsilon N_p}{4\pi L^2} \times \frac{P_{th}(t)}{\langle E_f \rangle} \times \langle \sigma_f \rangle$$

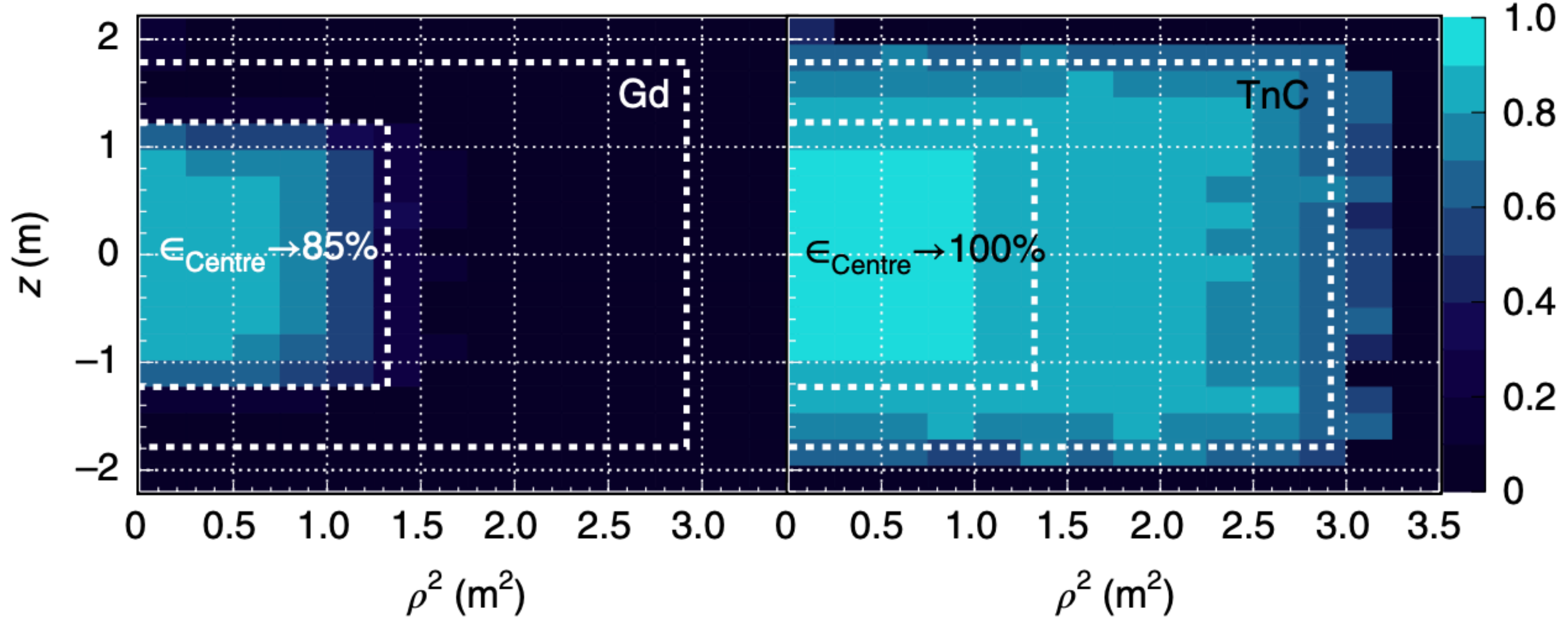


Detectors components





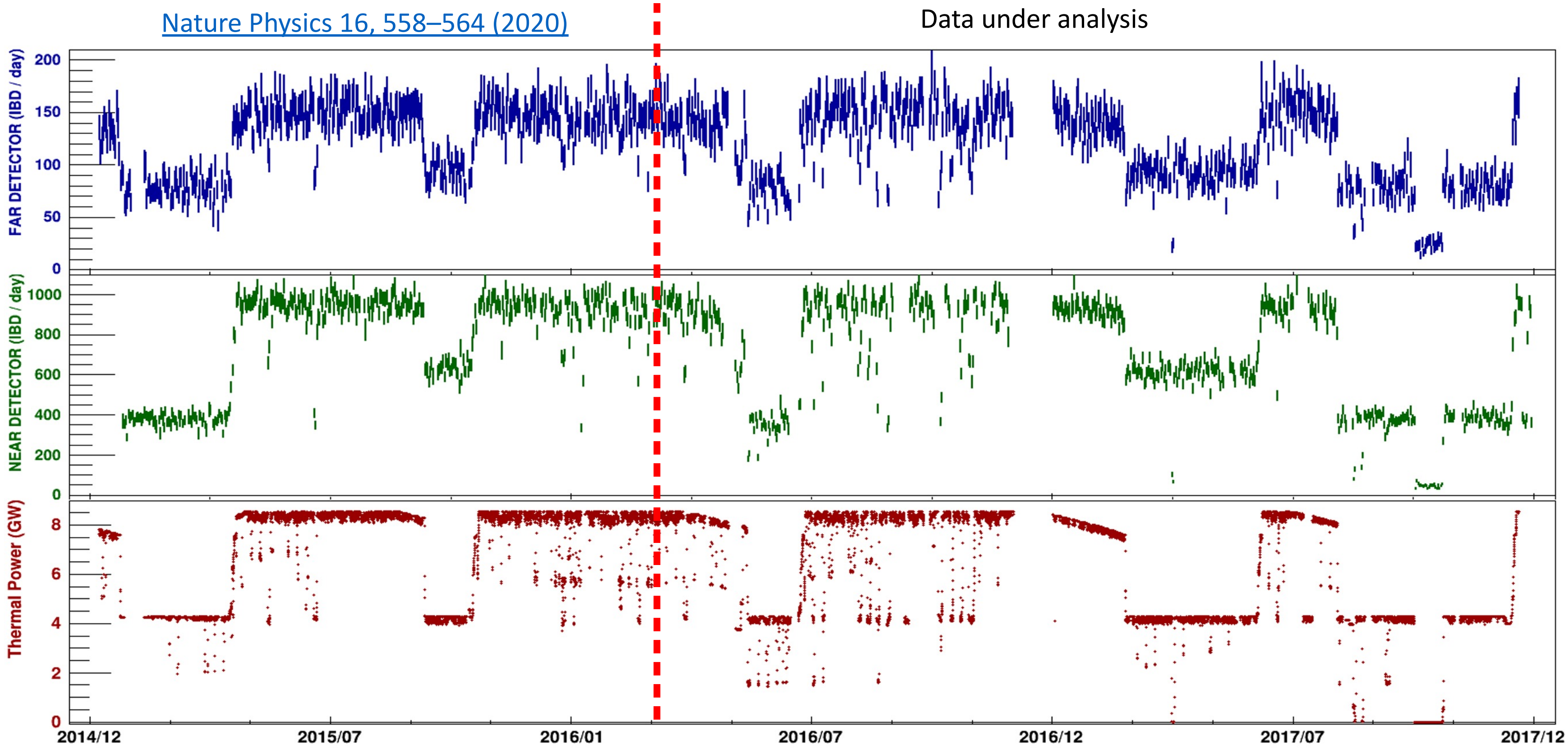
Selection efficiency



Two detector data

Nature Physics 16, 558–564 (2020)

Data under analysis



Far Detector

Near Detector

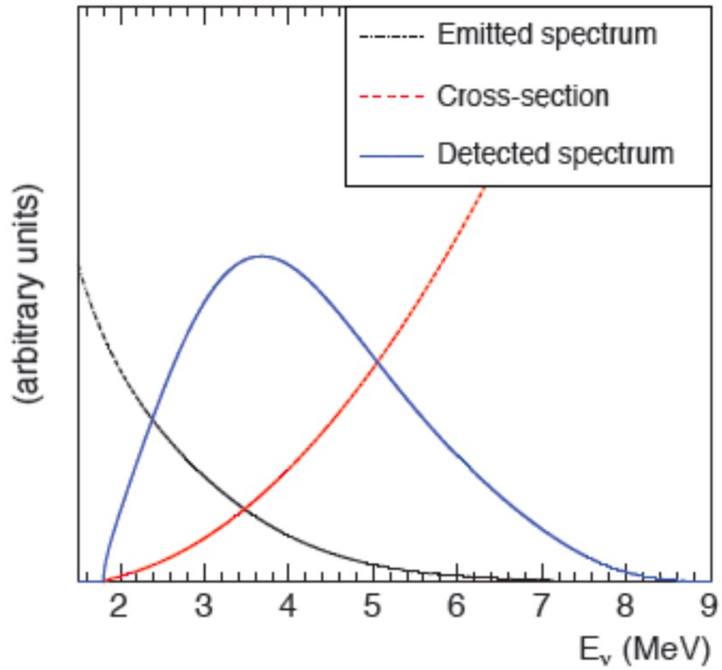
Reactor Thermal Power

Reactor ν flux

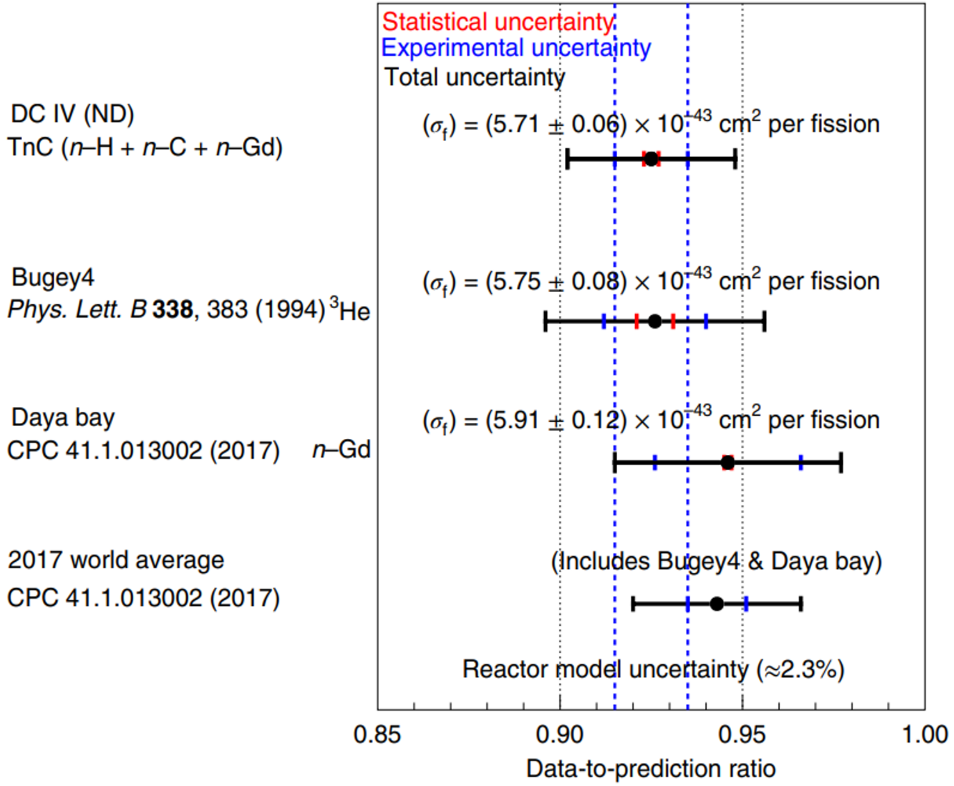
Mean cross-section per fission (MCSpF)

$$N_{\nu}^{\exp}(t) = \frac{\varepsilon N_p}{4\pi L^2} \times \frac{P_{th}(t)}{\langle E_f \rangle} \times \langle \sigma_f \rangle$$

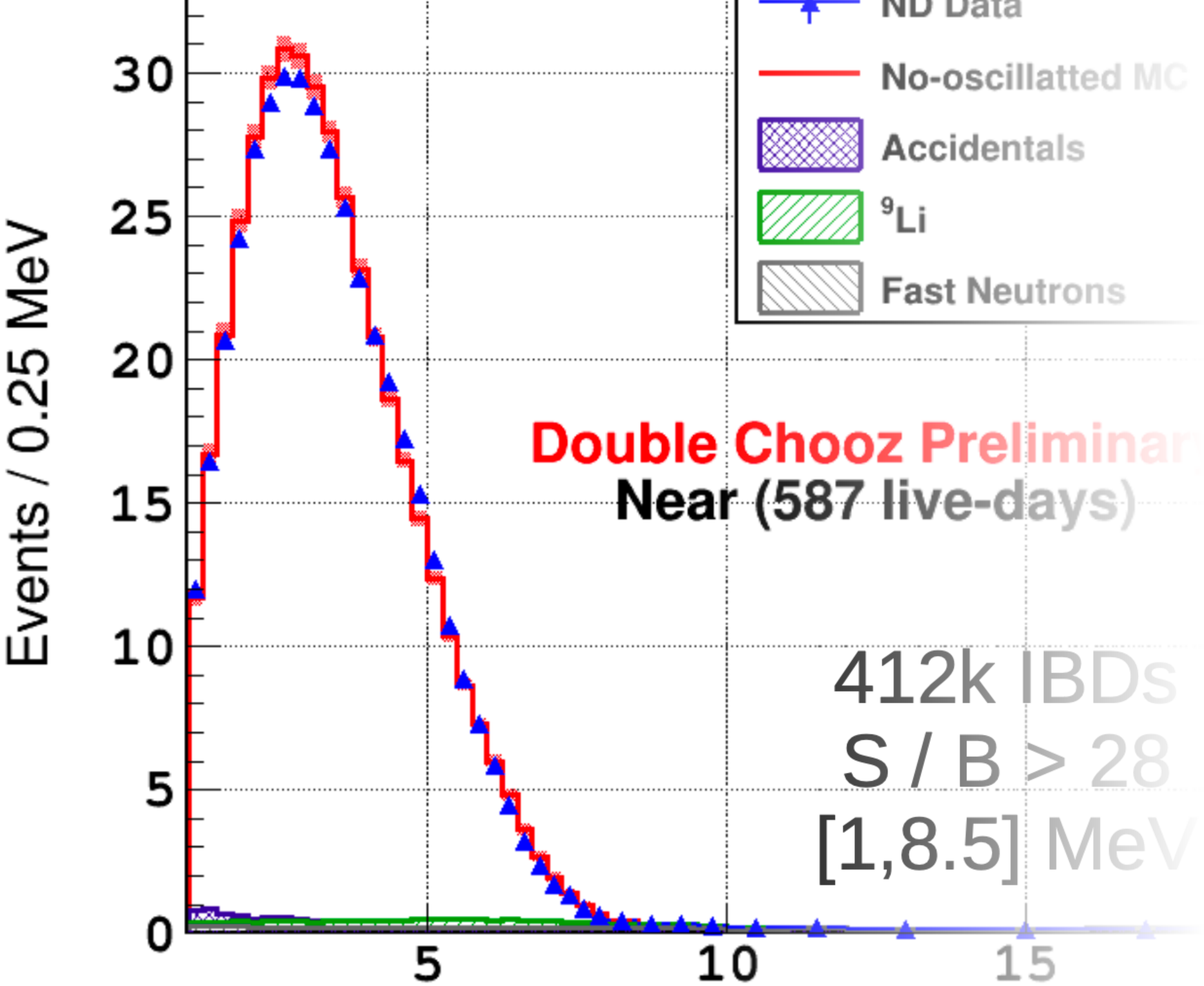
$$\langle \sigma_{\mathrm{f}} \rangle = \frac{N(\overline{\nu}_e)}{N_p \epsilon} \left(\sum_{r=\mathrm{B1,B2}} \frac{\langle P_{\mathrm{th}} \rangle_r}{4\pi L_r^2 \langle E_{\mathrm{f}} \rangle_r} \right)^{-1} \mathrm{cm}^2 \text{ per fission}$$



Improved MCSpF measurement



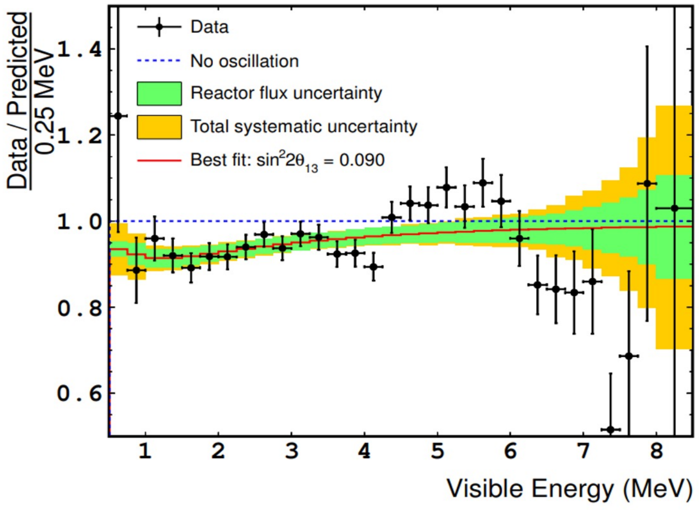
Uncertainty (%)	ND
Proton Number	0.66
Thermal Power	0.47
TnC Selection	0.24
Background	0.18
Energy per Fission	0.16
θ_{13} Correction	0.16
Statistics	0.22
Total	0.97

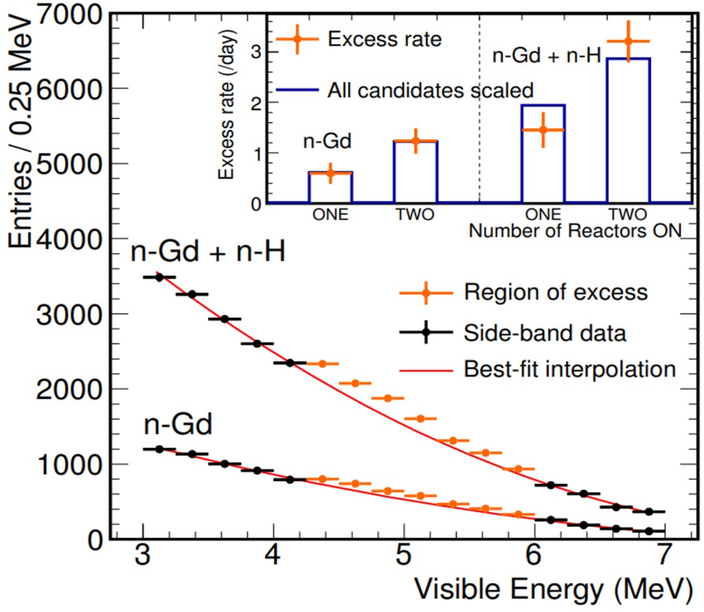


Spectral shape

First evidence of spectral distortion

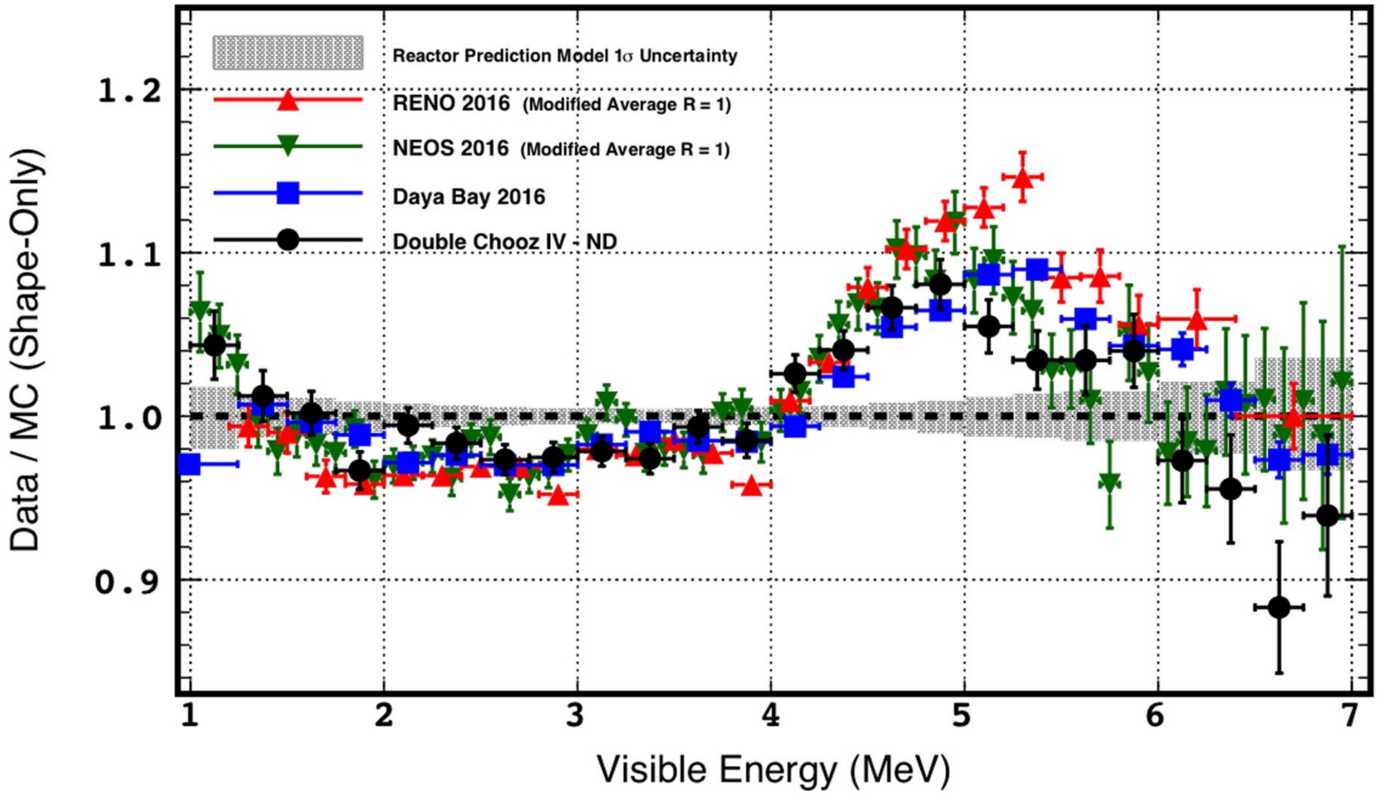
~*18,000* IBD candidates in Far detector (2014)



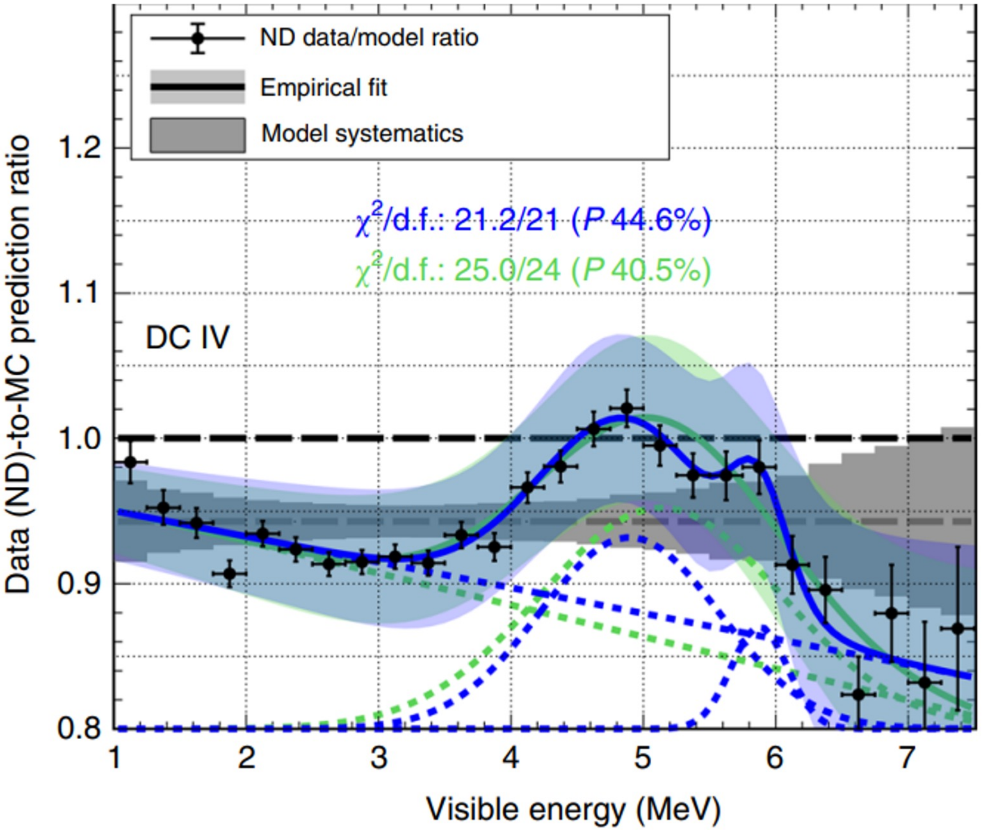


JHEP10(2014)086 arXiv:1406.7763

Near detectors shape comparison



Spectrum ~~Bump~~ Distortion



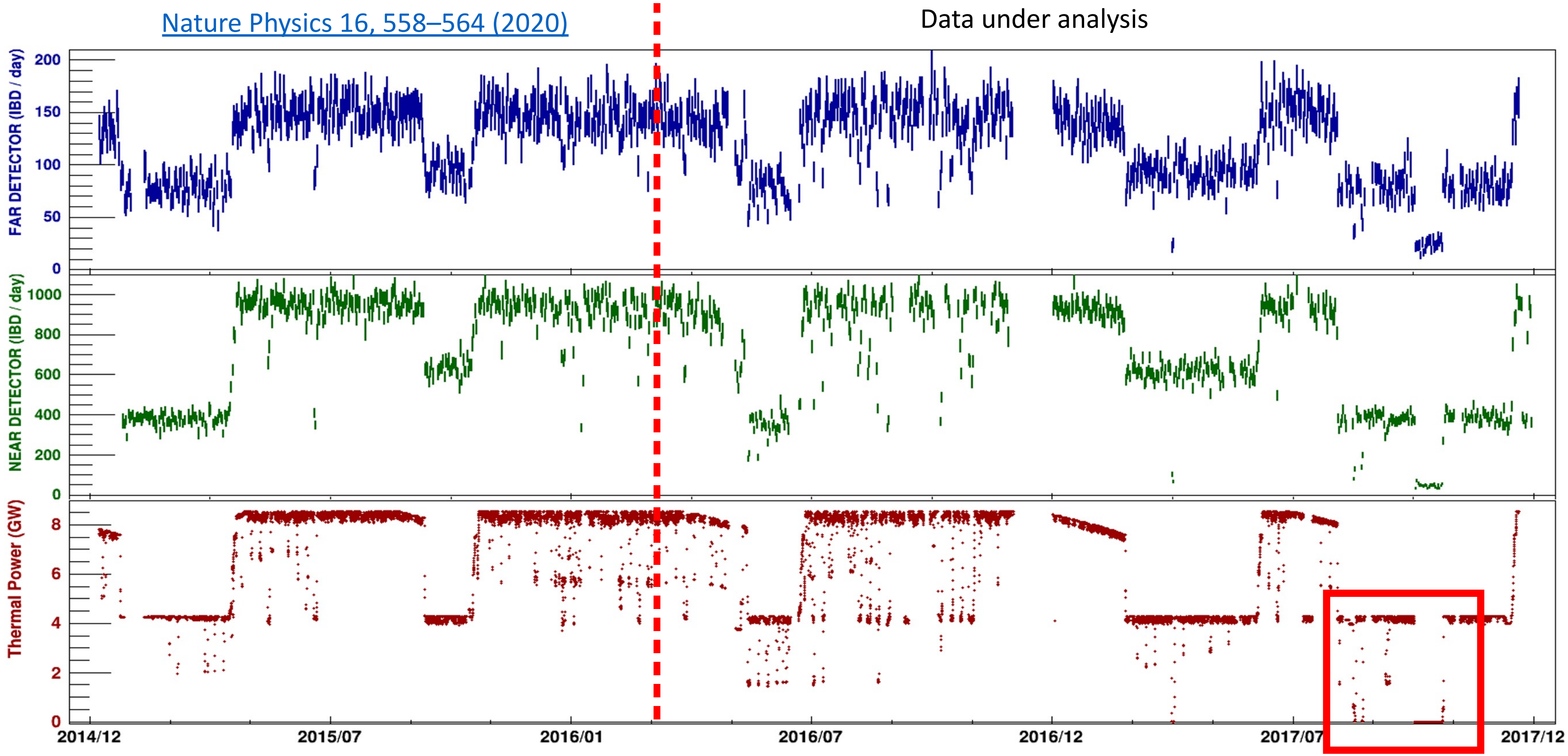
Reactor off

For full details see: A. Onillon talk at 2023 IAEA Technical Meeting

Two detector data

[Nature Physics 16, 558–564 (2020)]

Data under analysis



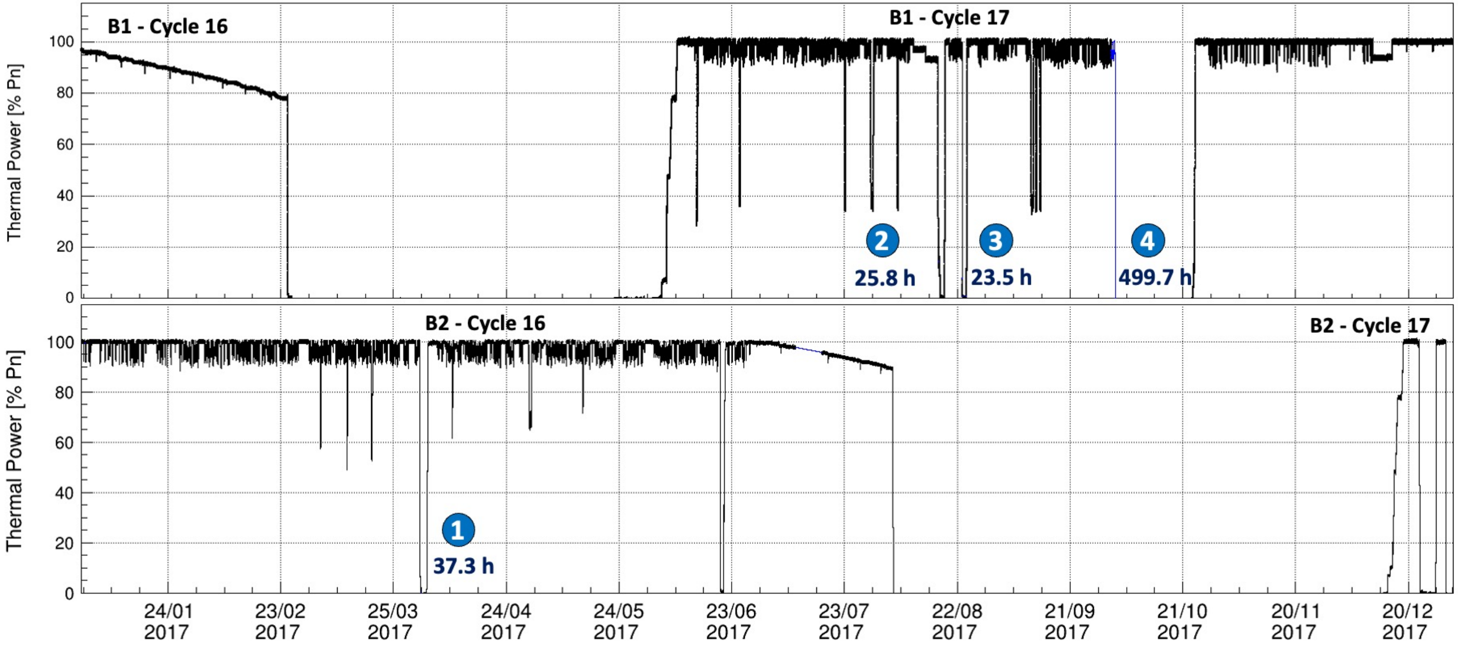
Far Detector

Near Detector

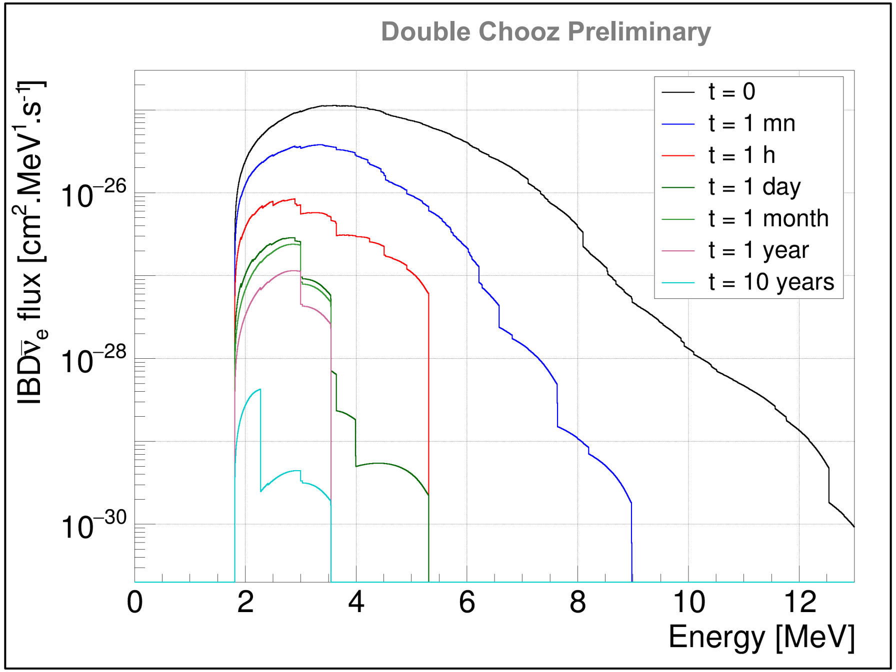
Reactor Thermal Power

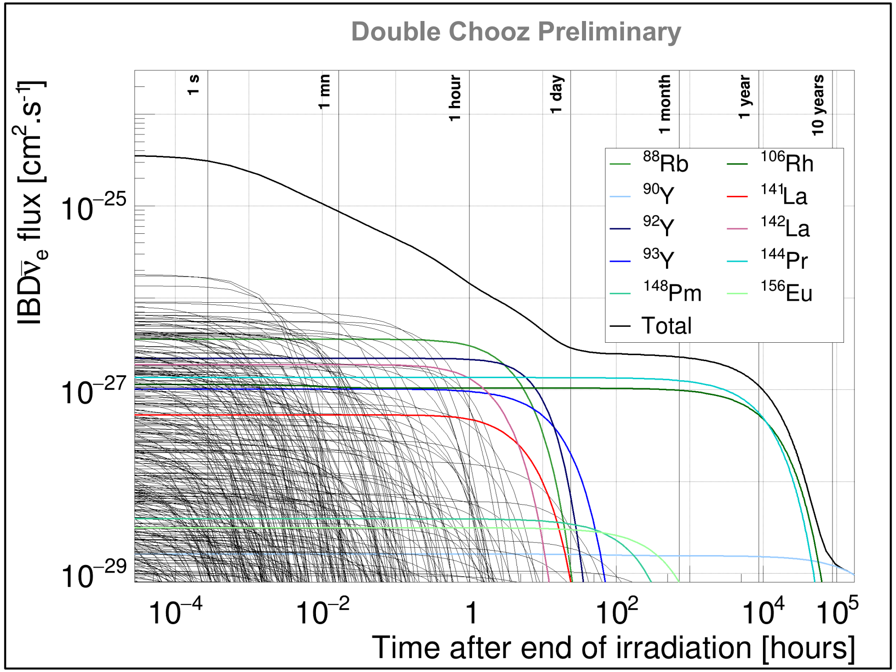
The 4 off-off periods of Chooz-B in 2017

- ①: 1 April: ~ 37 h ⇒ Planned shutdown of B2. Maintenance control on reactor building.
- ②: 17 August: ~ 26 h ⇒ Planned shutdown of B1. Maintenance operation in the engine room.
- ③: 23 August: ~ 24 h ⇒ Unplanned automatically shutdown of B1. Unexpected closure of a steam valve
- ④: 3 October: ~ 500 h ⇒ Unplanned shutdown of B1. Unexpected electric grid disconnection



Residual IBD spectrum prediction



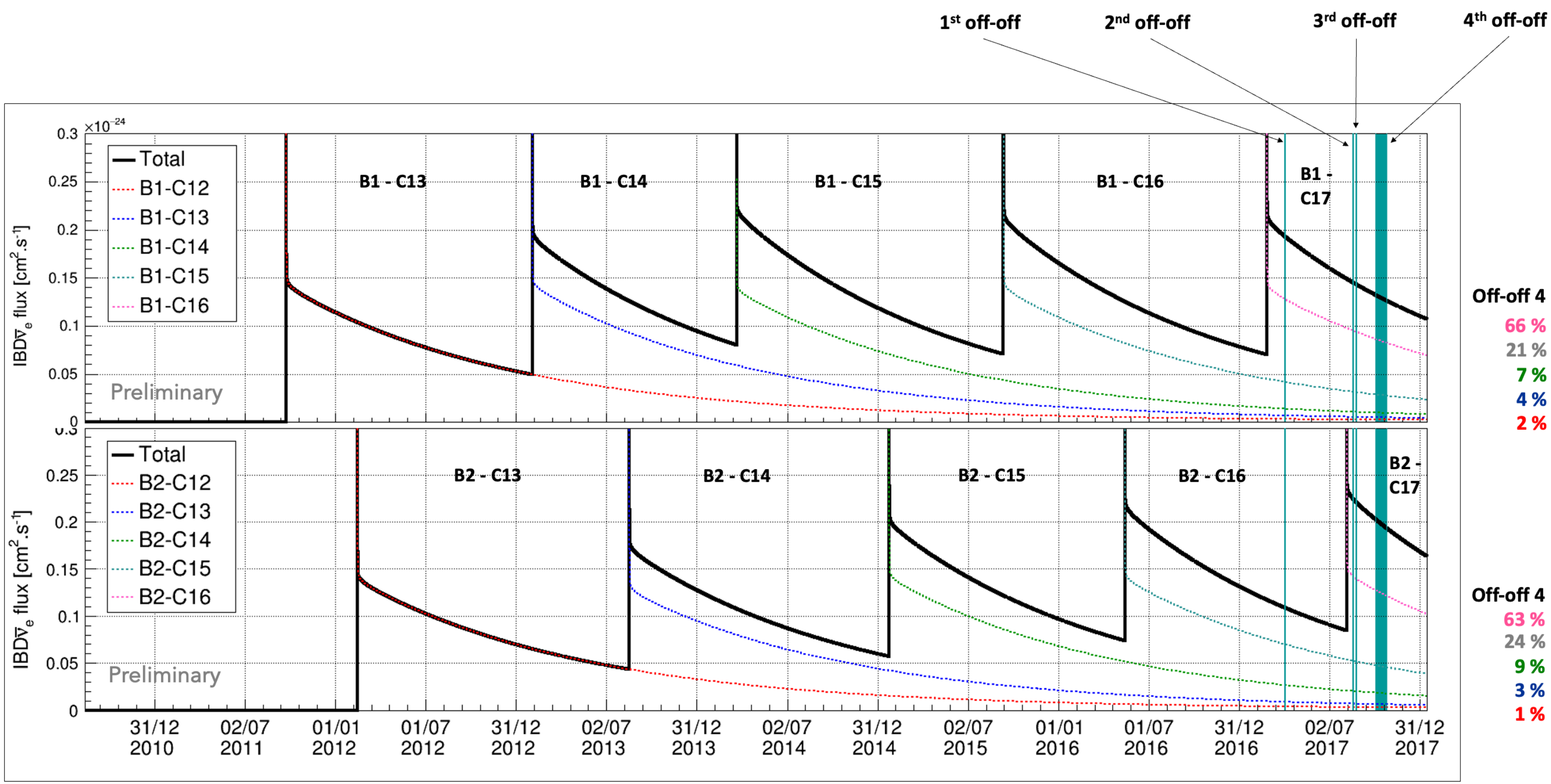


$IBD_{\bar{\nu}_e}$ flux from a UO_2 (4%) spent fuel assembly irradiated for 45 GWd/t.

IBD from spent fuel assemblies in pools

Pool B1

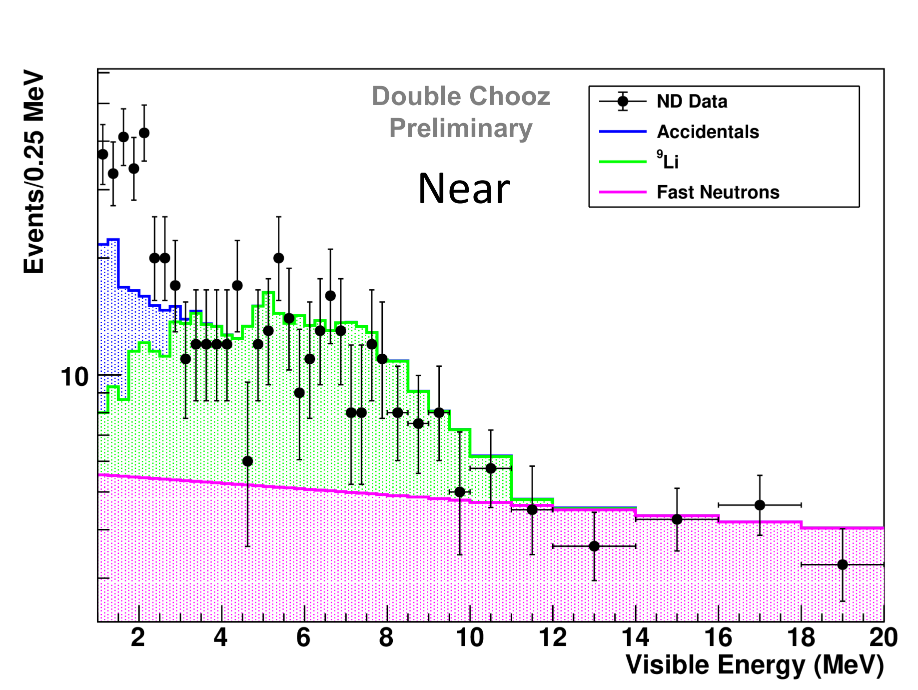
Pool B2

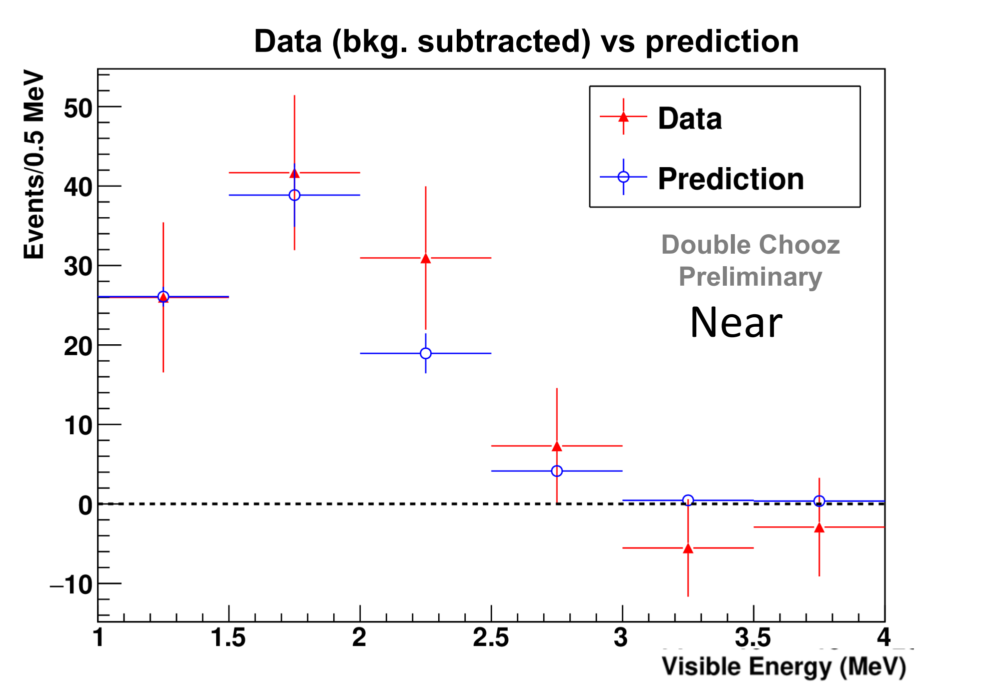


Off-off 4
66 %
21 %
7 %
4 %
2 %

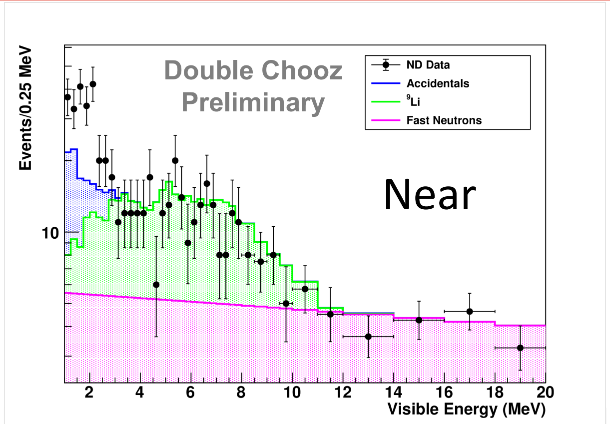
Off-off 4
63 %
24 %
9 %
3 %
1 %

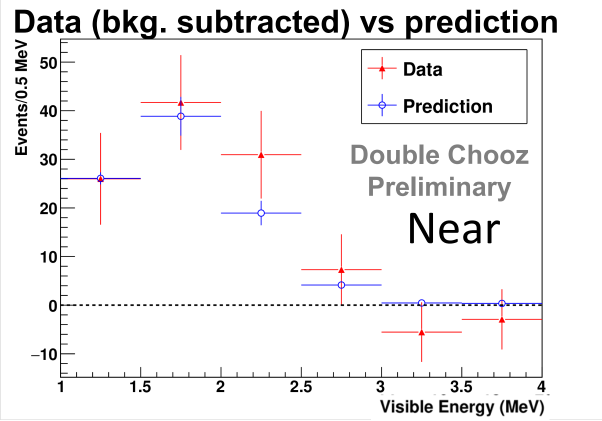
Two reactors-off spectrum

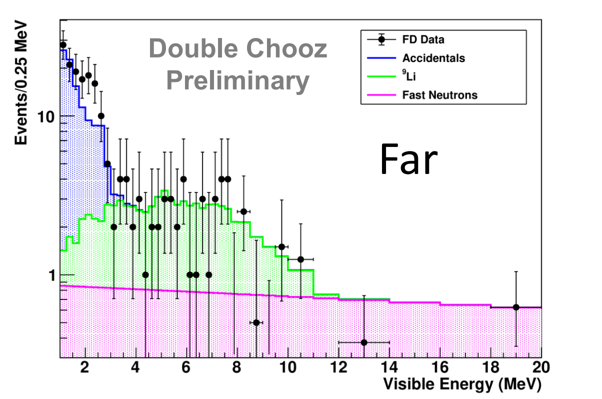


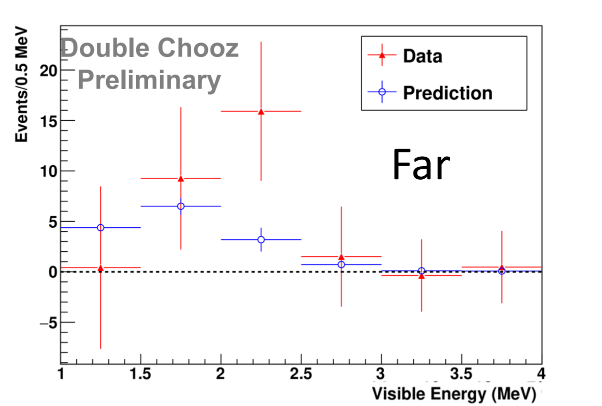


Two reactors-off spectrum









$IBD_{\overline{\nu}_e}$ 1-3 MeV

	Data	Prediction	Difference
ND	106 ± 18	88 ± 6	18 ± 19
FD	27 ± 14	15 ± 1	12 ± 14

Limited statistic: $\sigma_{stat}^{ND} \sim 17\%$, $\sigma_{stat}^{FD} \sim 52\%$
Good data/prediction agreement

Prediction systematics

		ND	FD
Chooz site	- Distance assemblies-detectors	**2.9**	**0.9**
	- θ_{13} oscillation	0.1	0.3
Detector	- detection efficiency	0.3	0.4
	- proton number	0.7	0.7
Reactor	- Thermal power	0.5	0.5
	- Reactor stop time	0.2	0.2
	- IBD cross-section	0.1	0.1
	- Fission product inventory	**2.1**	**2.1**
	- Amount of spent fuel in the pool	**2.0**	**1.5**
	- $\bar{\nu}_e$ spectra	**6.0**	**6.0**
	Total	**7.4 %**	**6.7 %**

- Total uncertainty dominated by the uncertainty associated to the $\bar{\nu}_e$ spectra modelling (NSC ^{144}Pr)
- Request to EDF to lift approximations associated to the pool dimension and fuel content in the pools
  - ↳ Status of spent fuel from old reactor cycles unknown ⇒ treated as systematic

Summary

- $\mathbf{sin^2(2\theta_{13}) = 0.102 \pm 0.011\ (syst.) + 0.04\ (stat.)}$ (limited by number of targets unc.)
- Best reactor flux measurement to date: $\langle \boldsymbol{\sigma_f} \rangle = (\mathbf{5.75 \pm 0.06})\times\mathbf{10^{-43}\ cm^2}$
- First report of reactor spectrum distortion
- $\sim$24 days with both reactor off ⇒ very unique data set in the framework of reactor experiments
- Detailed prediction, including nuclear structure calculation for ^{144}Pr isotope
- Very good preliminary data/prediction agreement:
  - $\mathbf{N_{IBD}^{data,ND} = 106 \pm 18}$ **evts measured /** $\mathbf{N_{IBD}^{pred,ND} = 88 \pm 6}$ **evts**

  ⇒ Demonstrate the great progress in detection and prediction over the last 20 years!

- Analyses under finalisation – publication foreseen soon with improved target mass

The Double Chooz Collaboration

Thank you!

Backup

Expected IBD at reactor-off period

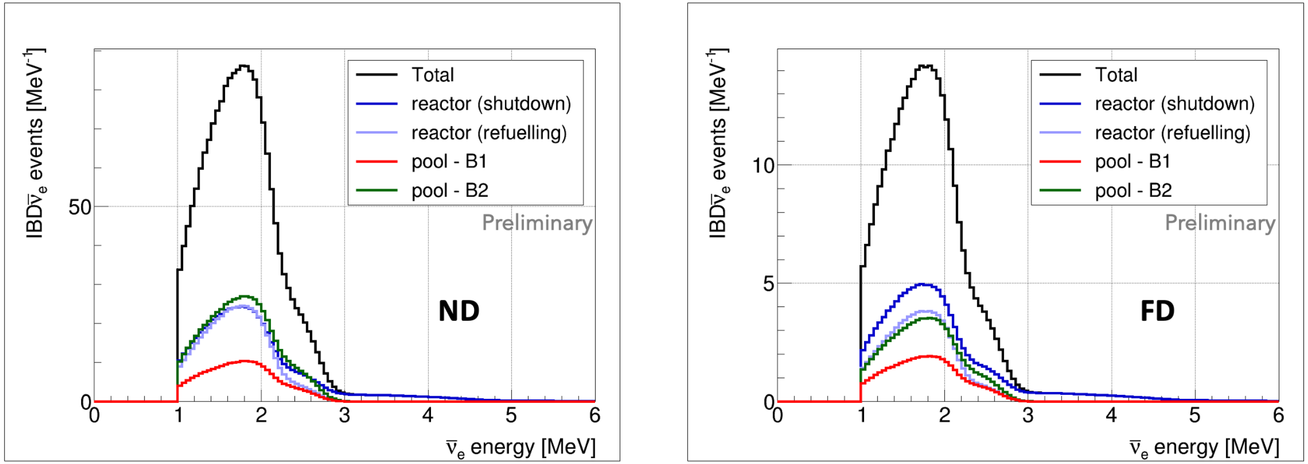
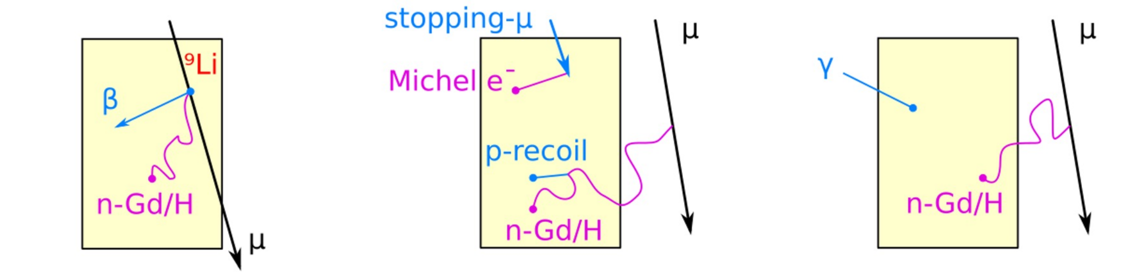


Fig. Expected IBD$_{\bar{\nu}_e}$ spectrum in the ND (left) and FD (right) for all off-off period combined (no runlist).

	Relative contribution [%]	
	Reactors	**Pools**
Near	56.5	43.5
Far	61.7	38.3

Tab. Expected number of IBD$_{\bar{\nu}_e}$ in the ND and FD for all off-off periods combined.

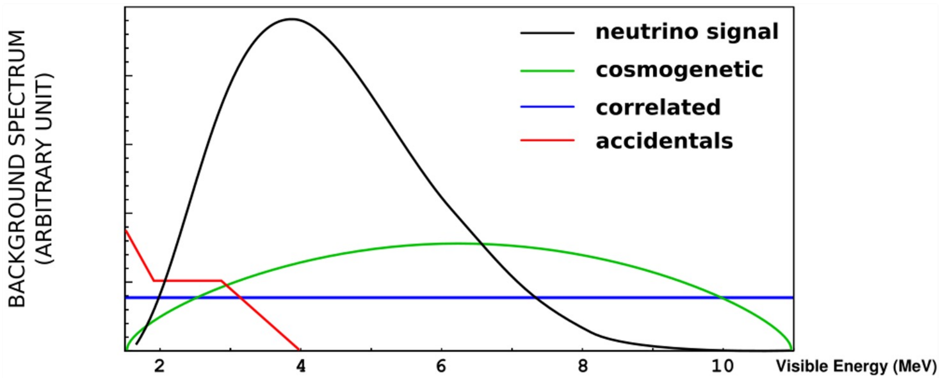
Backgrounds



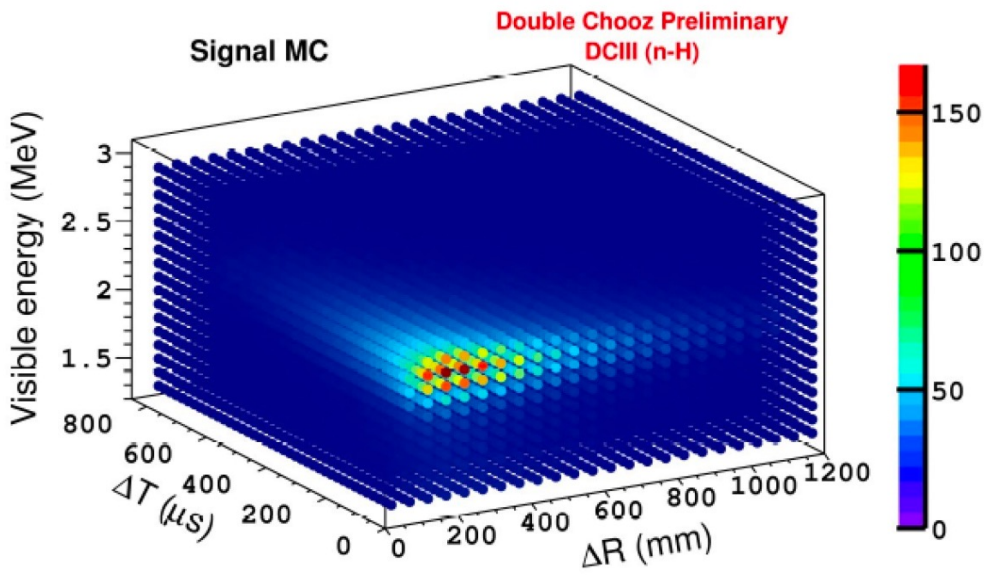
COSMOGENETIC
long lifetime β-n emitter
(mainly ^{9}Li)

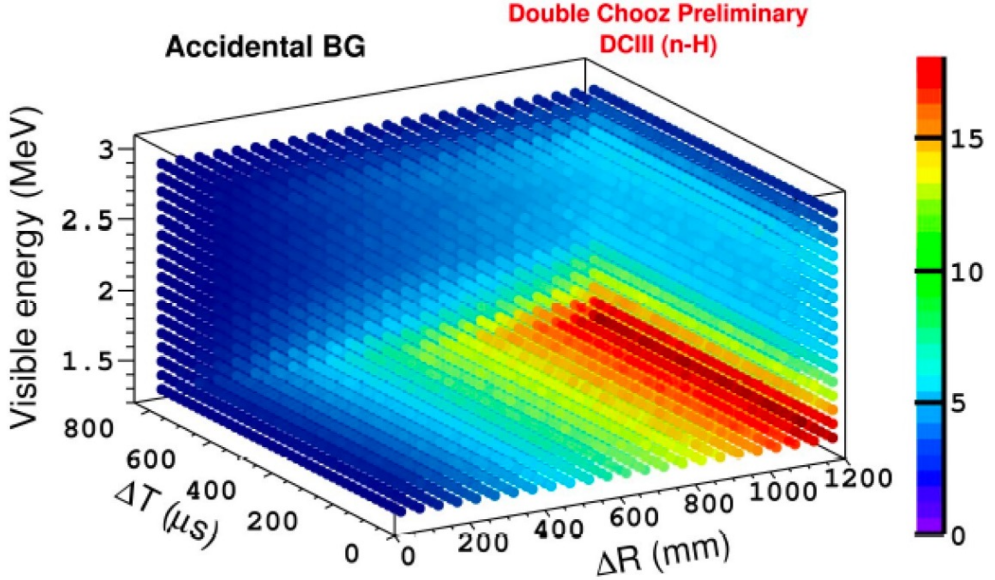
CORRELATED
fast neutrons from μ spallation,
stopping-μ (acceptance hole)

ACCIDENTALS
natural radioactivity: ^{40}K, ^{208}Tl
→ dominant in H-analysis



ANN training for Accidental Rejection

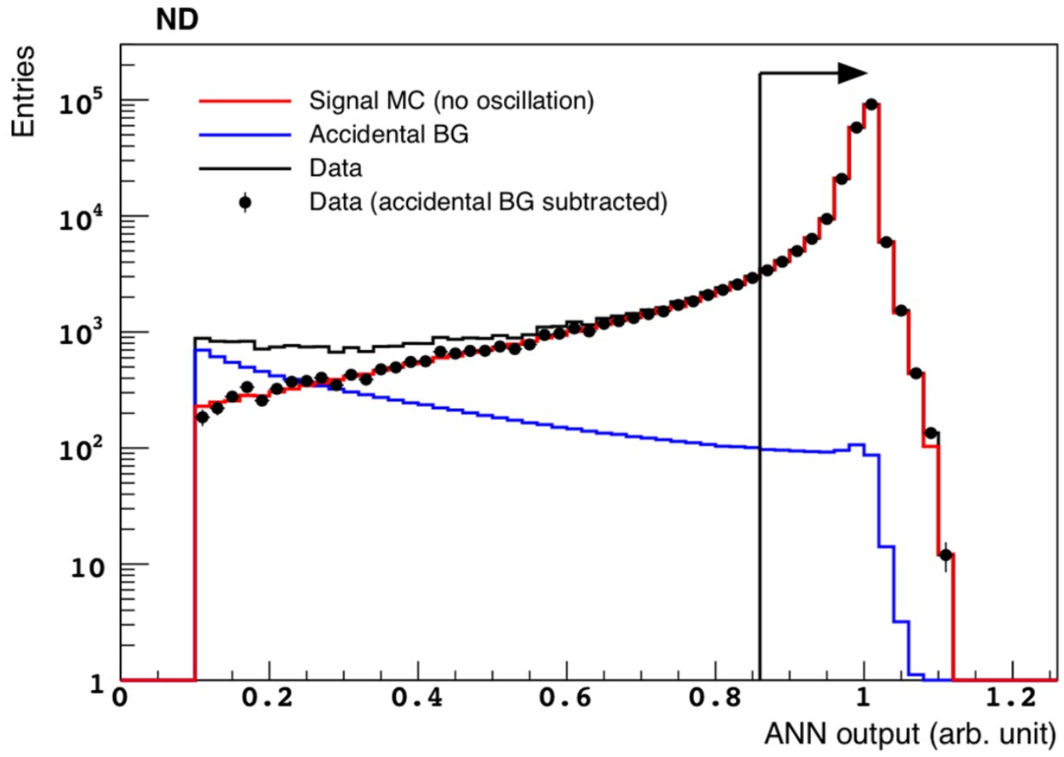




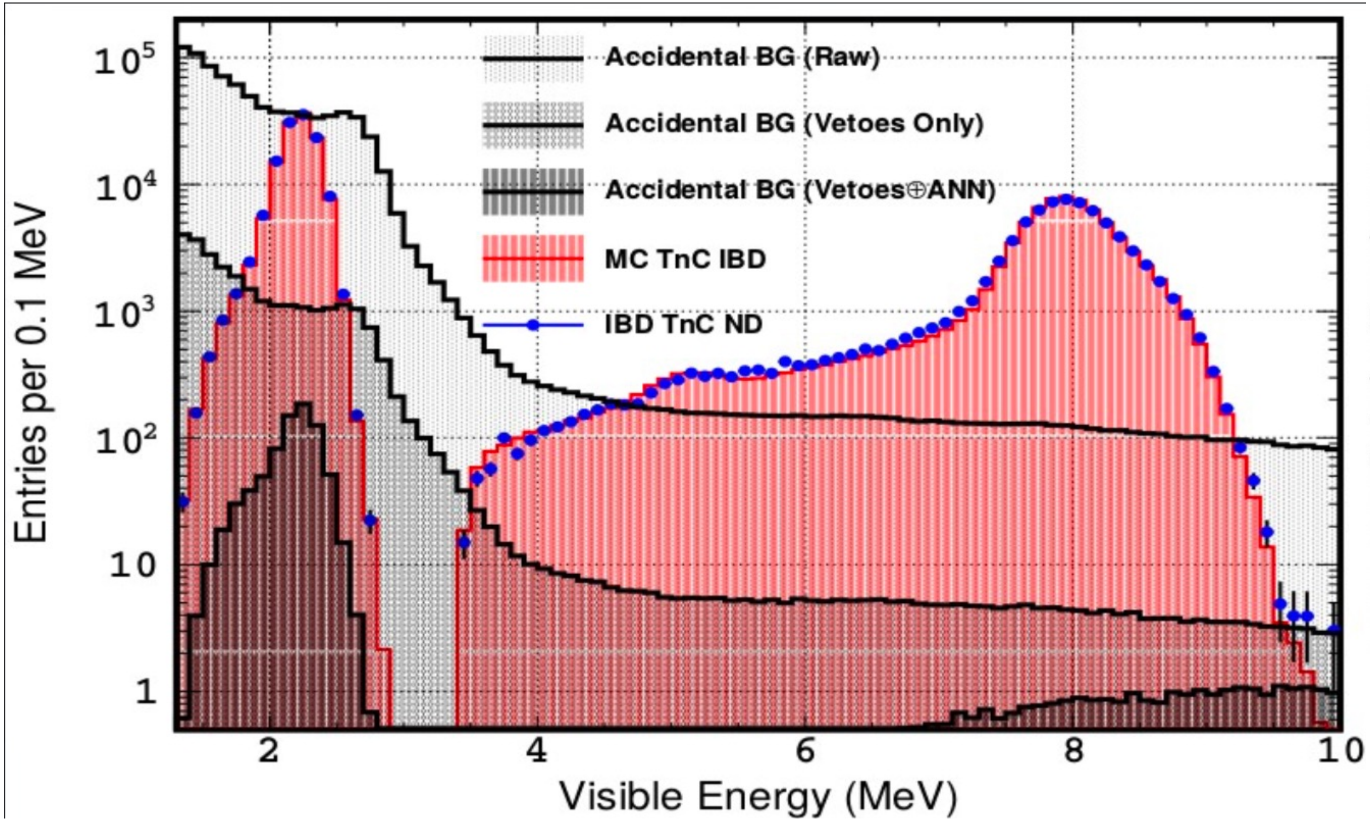
Signal: Correlated

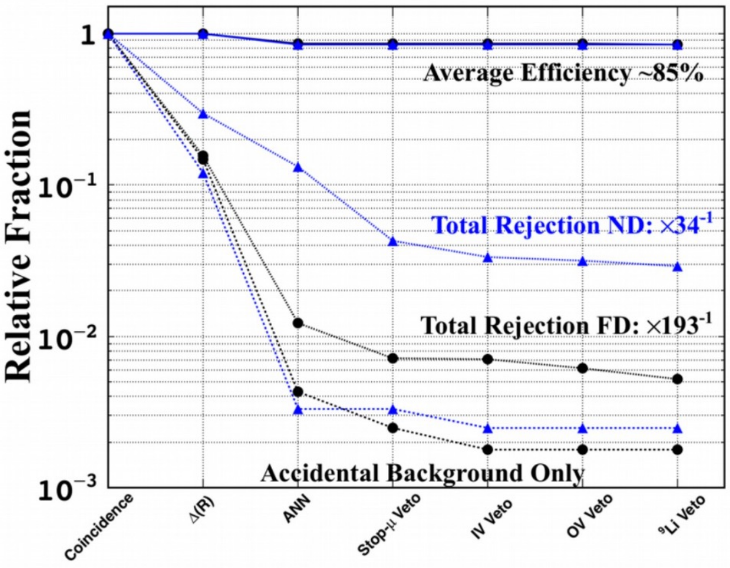
Accidental: random

ANN training for Accidental Rejection



ANN training for Accidental Rejection





Oscillation Analysis