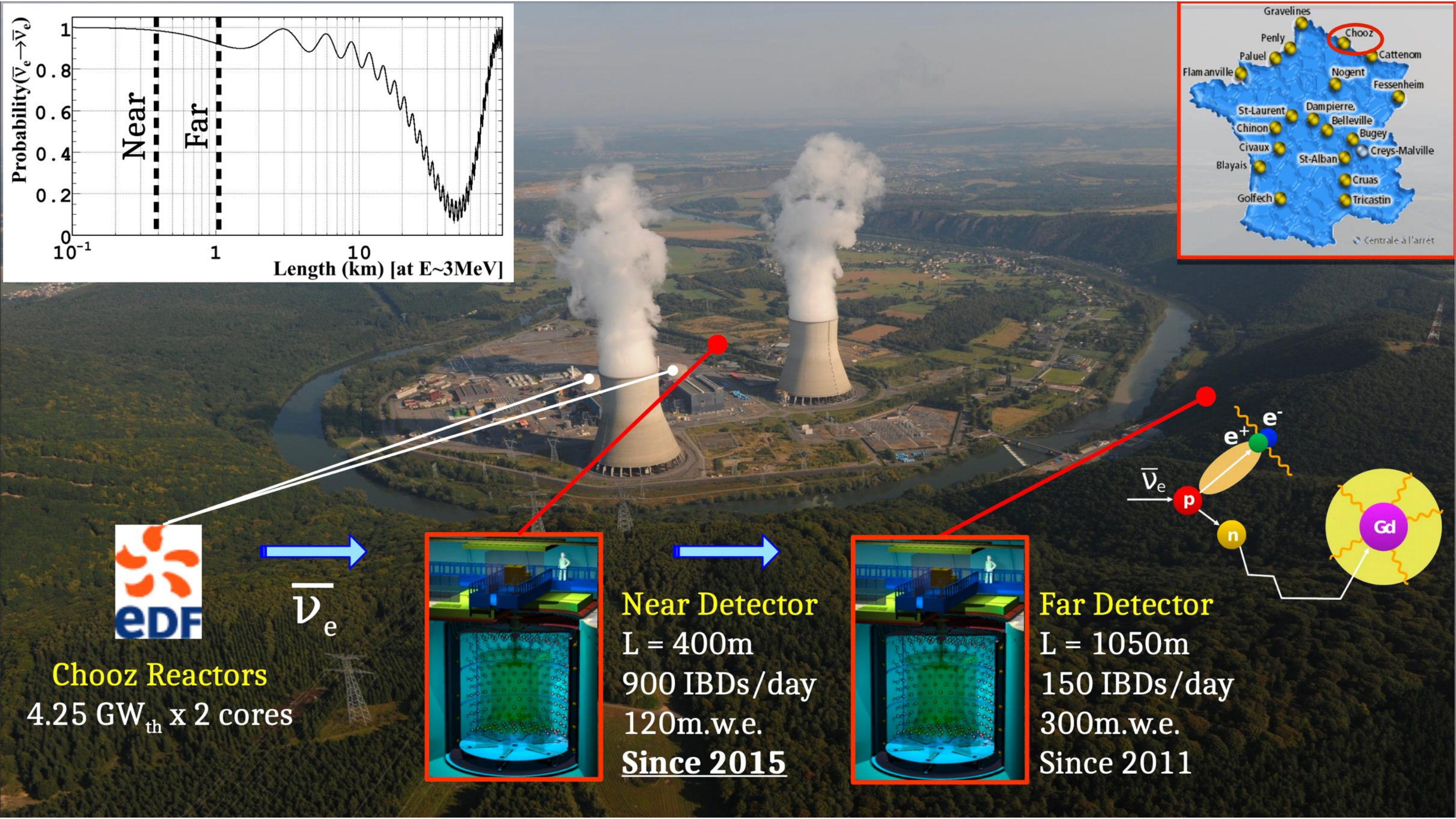
Double Chooz: Latest lessons & results for reactor antineutirno detection

UNIVERSITY OF SUSSEX

Thiago Bezerra, for the Double Chooz Collaboration

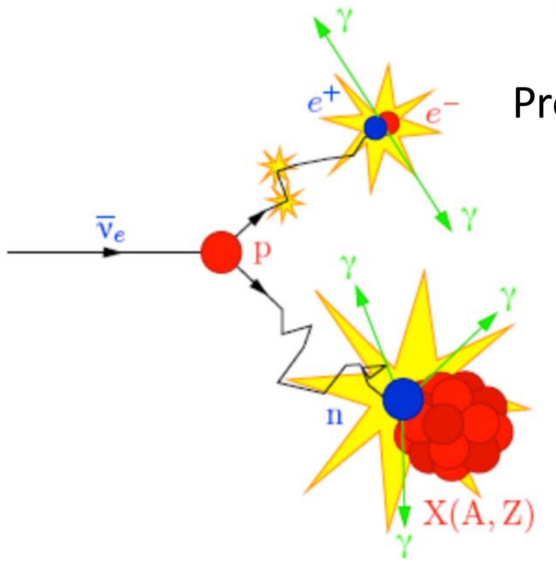
3rd IAEA Technical Meeting on Nuclear data
for antineutrino spectra applications

09th April 2024



Probability($\overline{\nu}_e \to \overline{\nu}_e$)
Near
Far
Length (km) [at E~3MeV]
Gravelines
Chooz
Penly
Paluel
Cattenom
Flamanville
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
$\overline{\nu}_e$
Near Detector
L = 400m
900 IBDs/day
120m.w.e.
Since 2015
Far Detector
L = 1050m
150 IBDs/day
300m.w.e.
Since 2011
e^-
e^+
$\overline{\nu}_e$
p
n
Gd

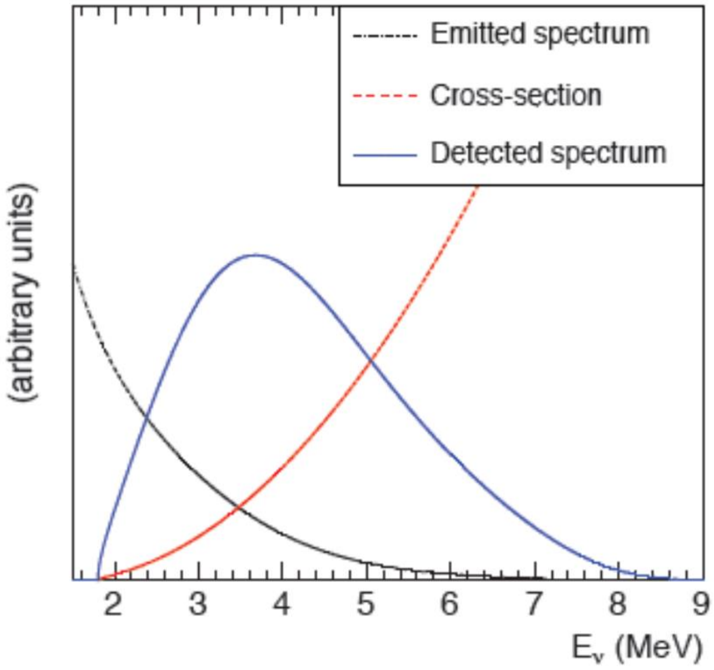
IBD signal



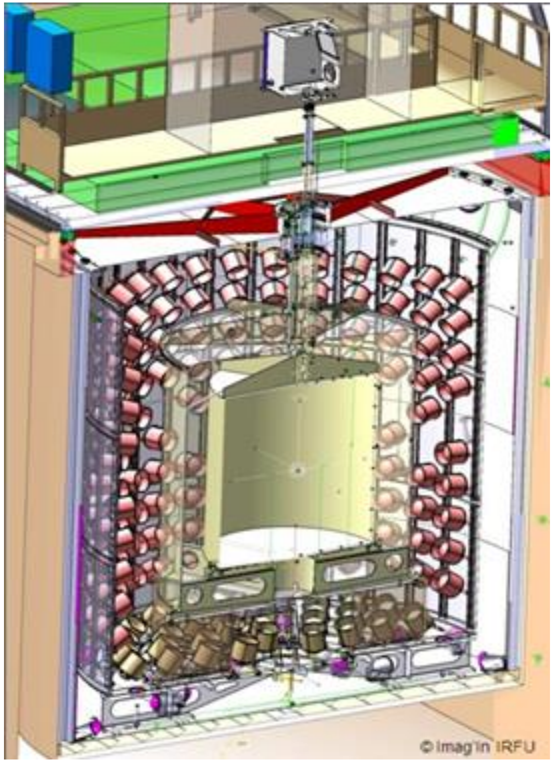
Prompt: > 1 MeV

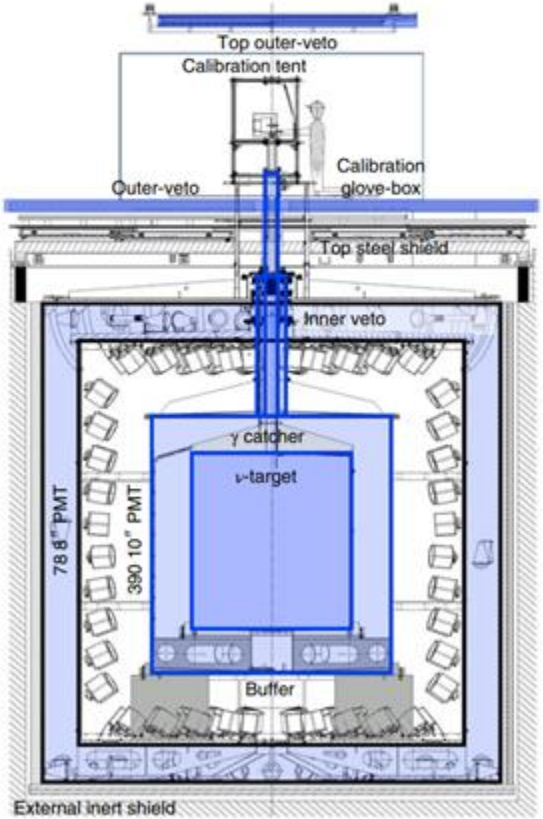
Delayed: n on Gd (H)
~30 (200) μs
8 (2.2) MeV

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

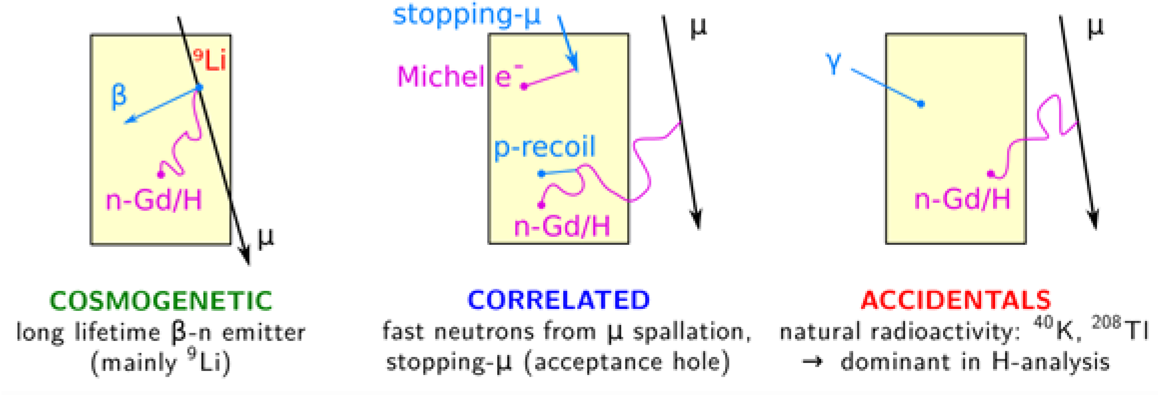


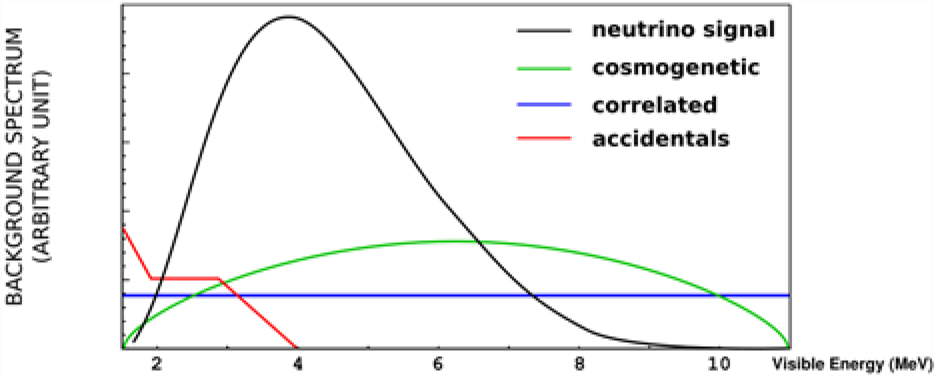
Detectors components



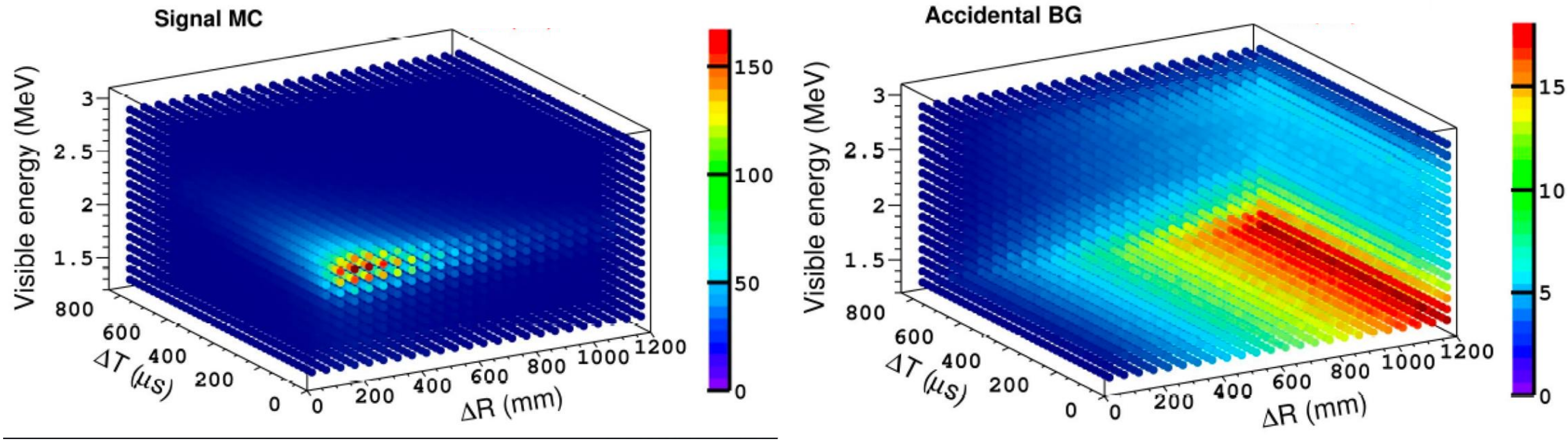


Backgrounds





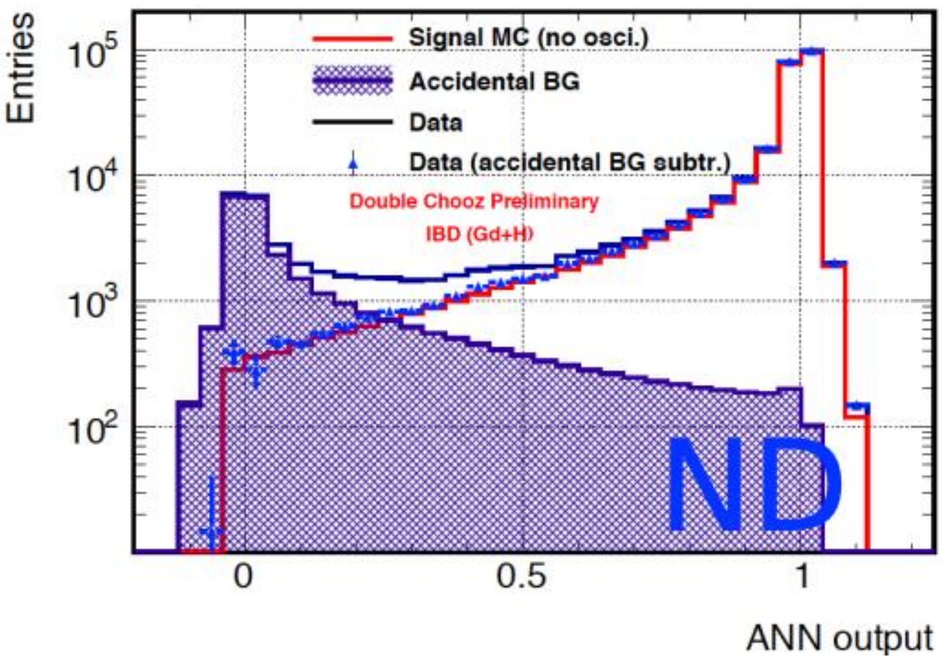
ANN training for Accidental Rejection

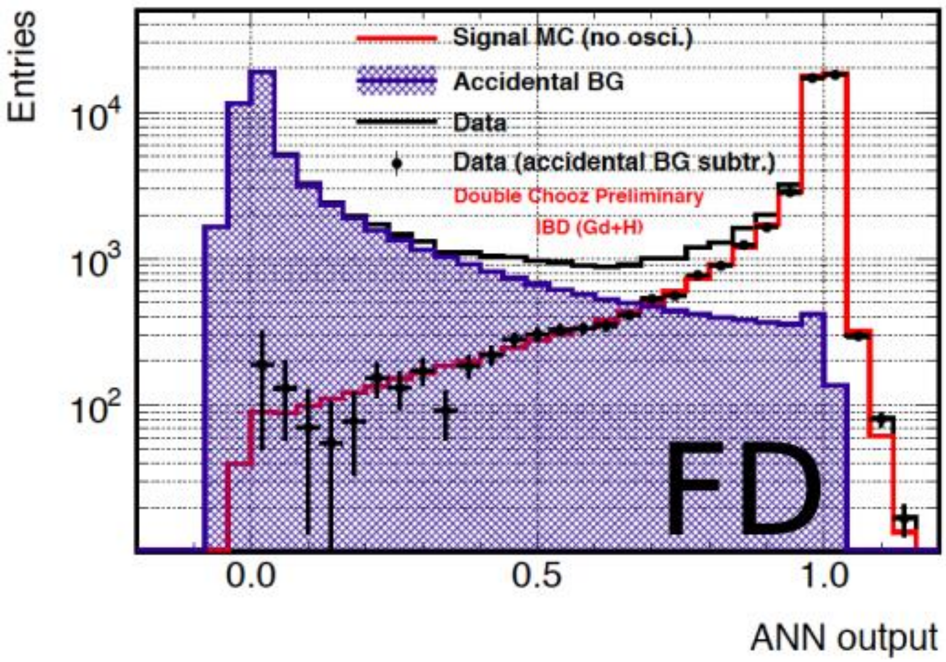


Signal: Correlated

Accidental: random

ANN training for Accidental Rejection





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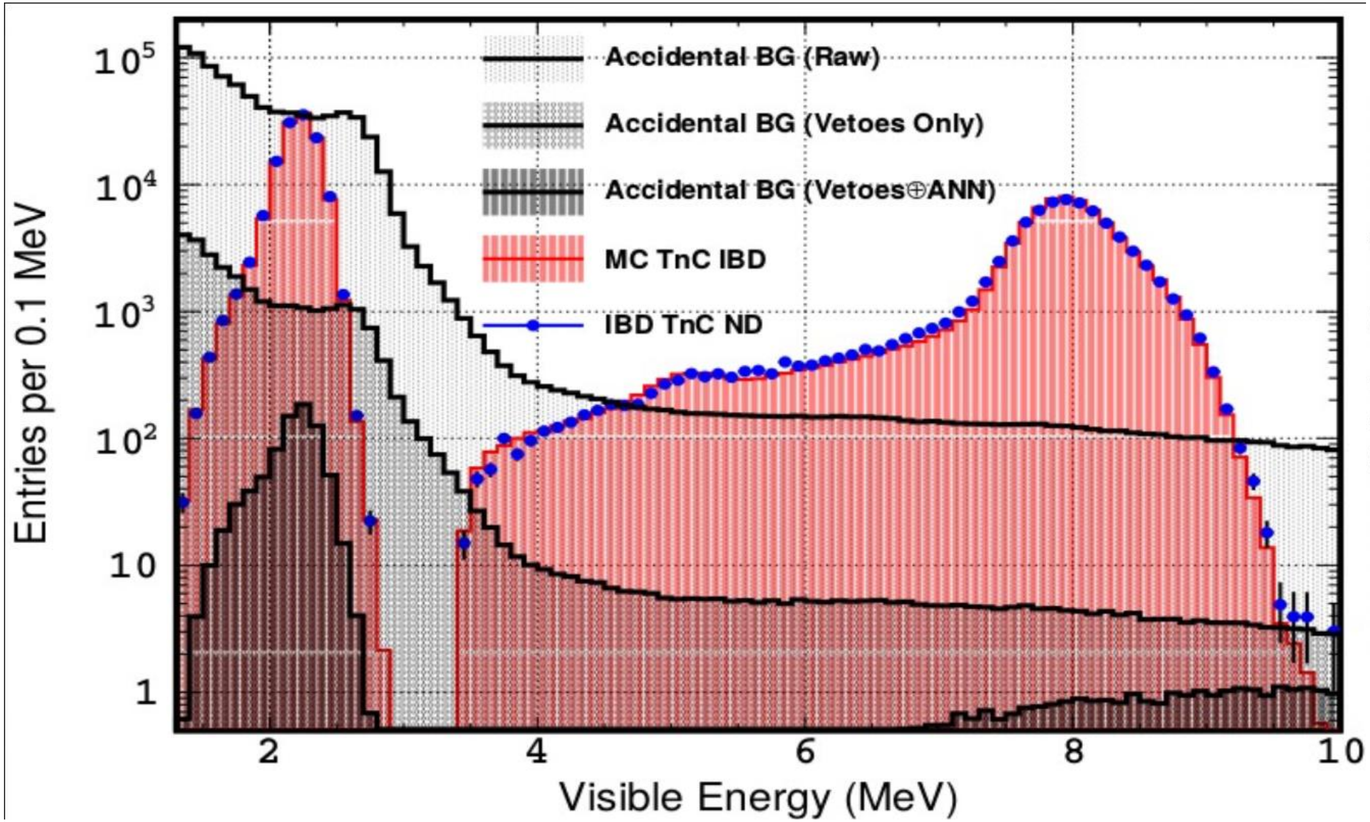
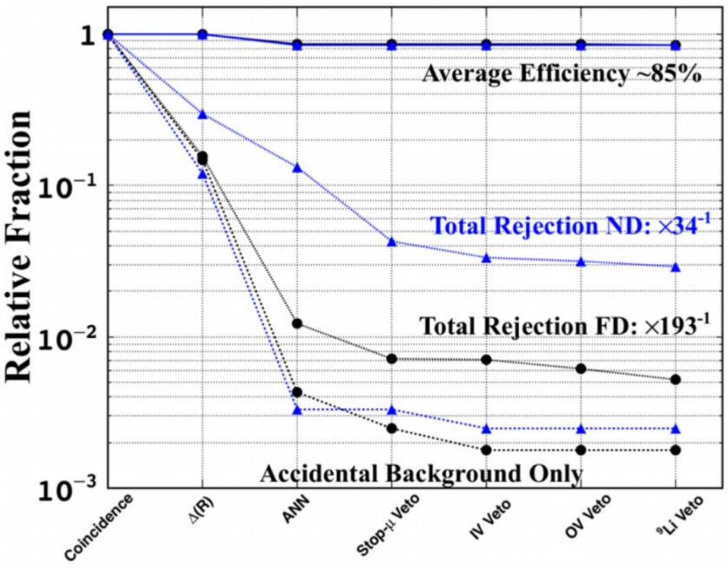
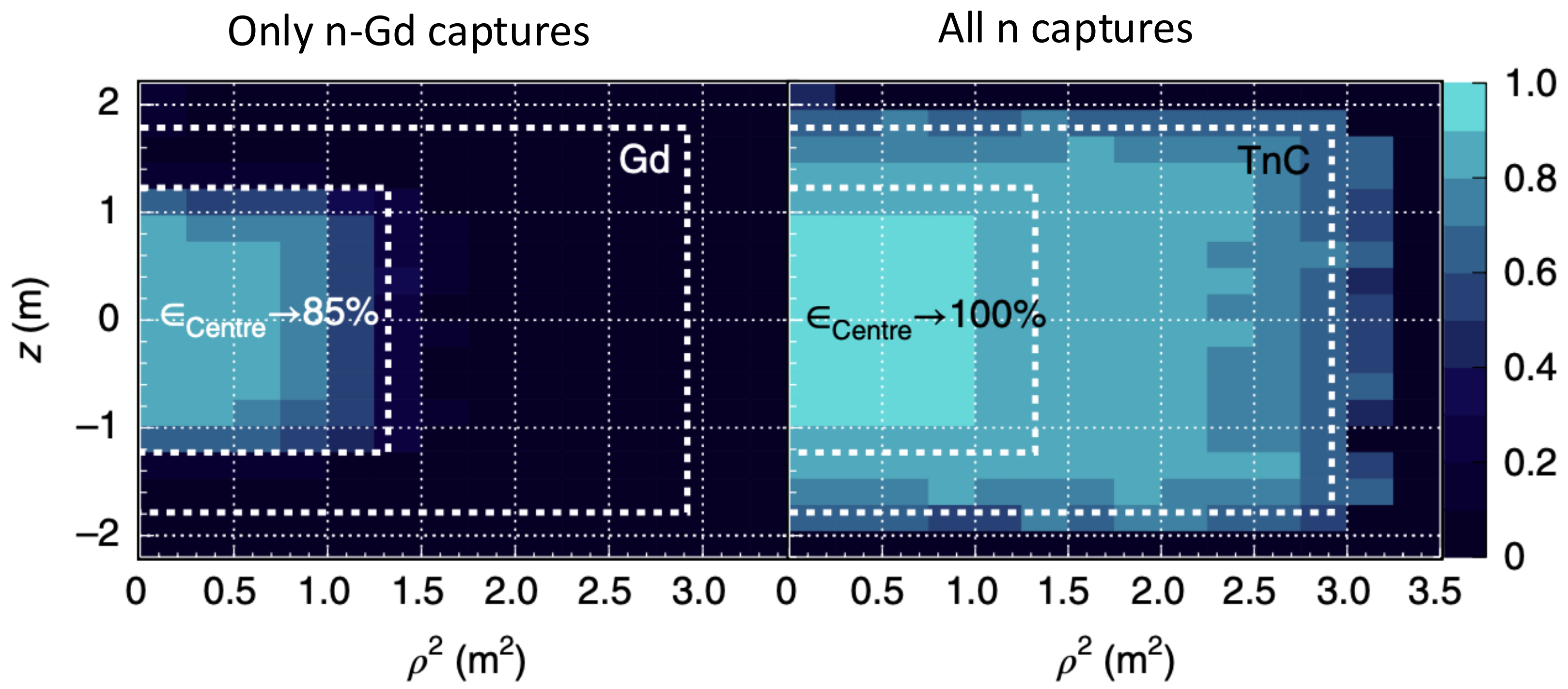


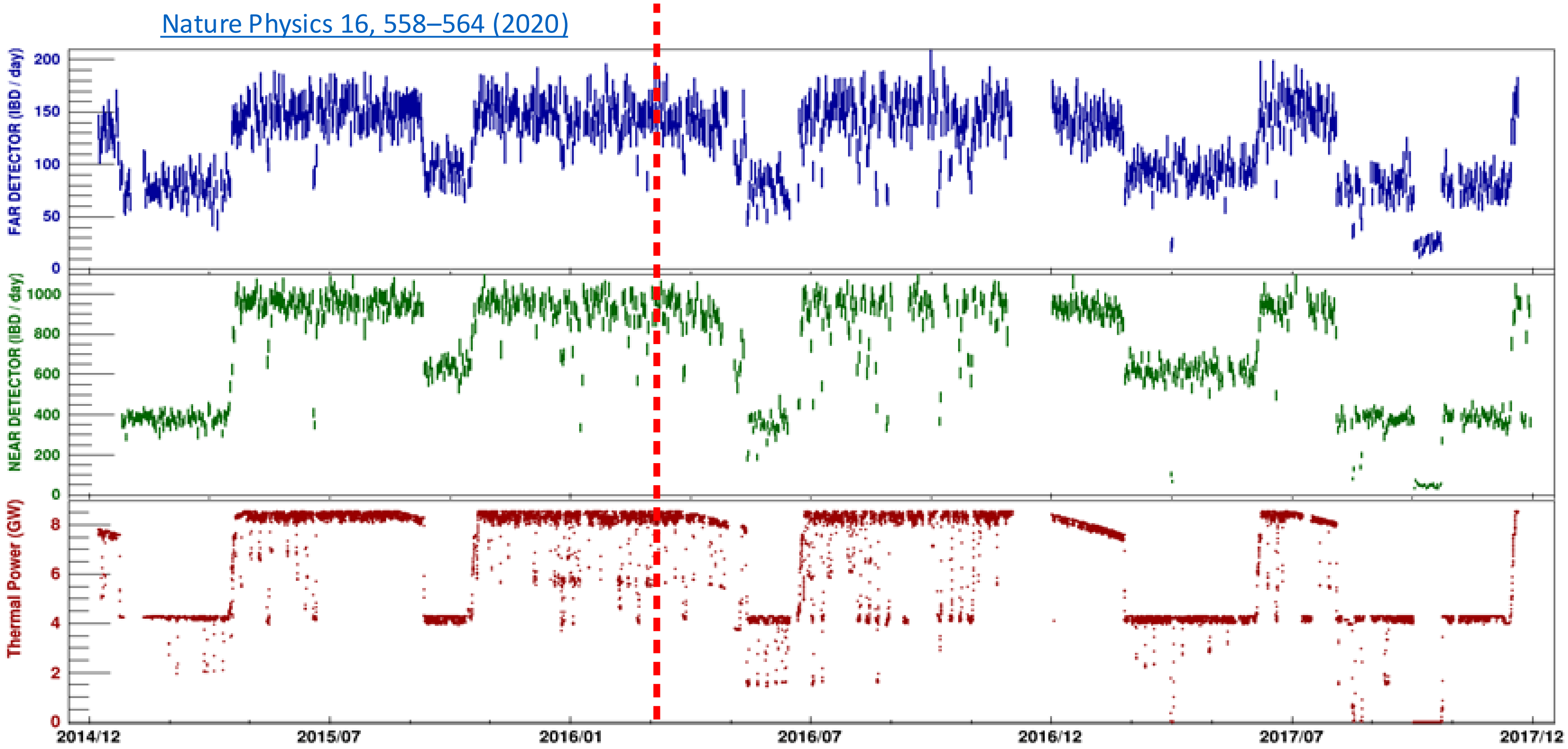


Selection efficiency



Two detector data

Nature Physics 16, 558–564 (2020)



Far Detector

Near Detector

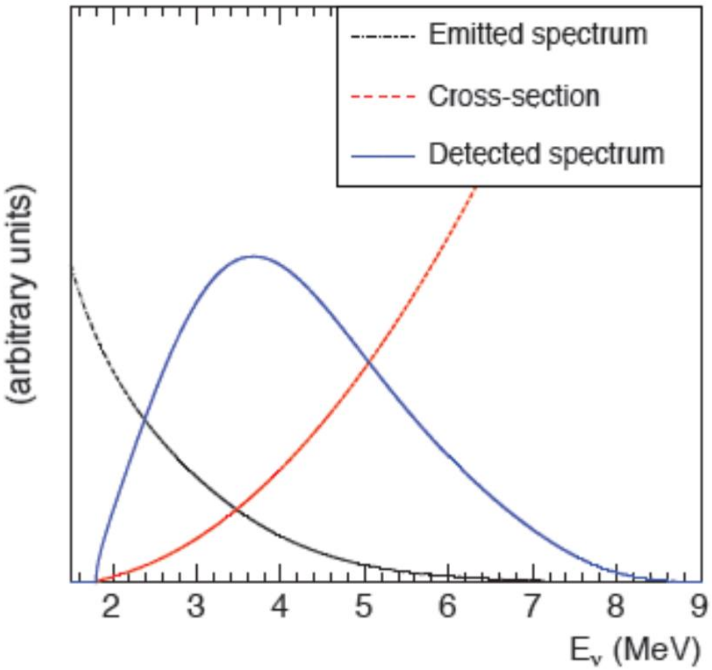
Reactor Thermal Power

Reactor ν flux

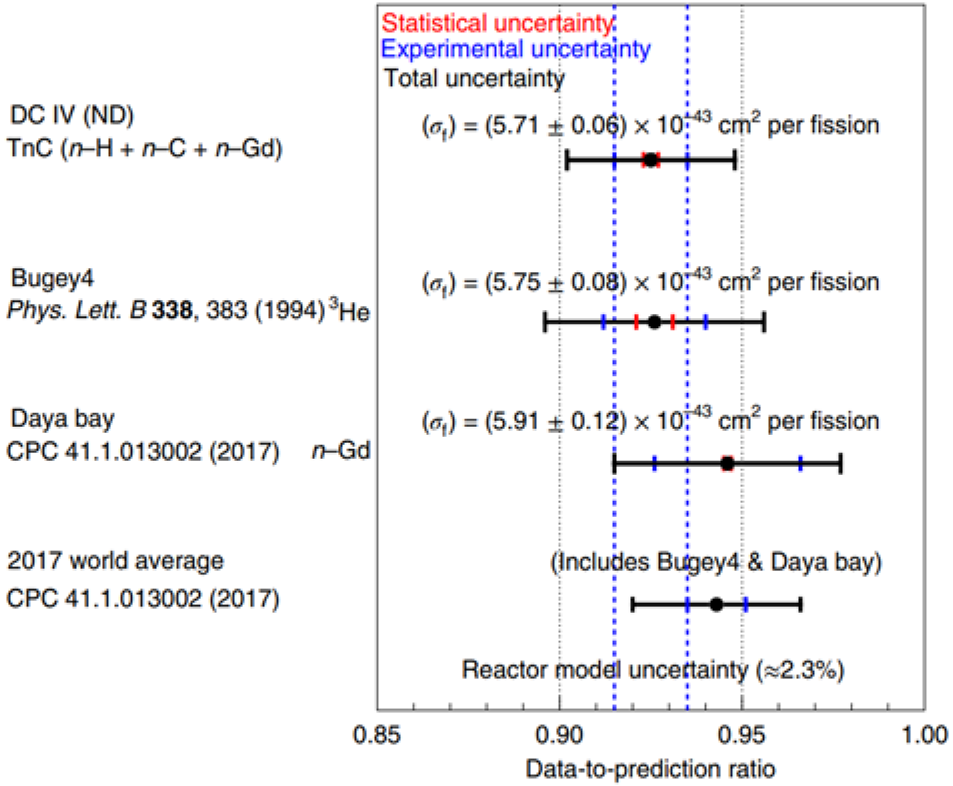
Mean cross-section per fission (MCSpF)

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

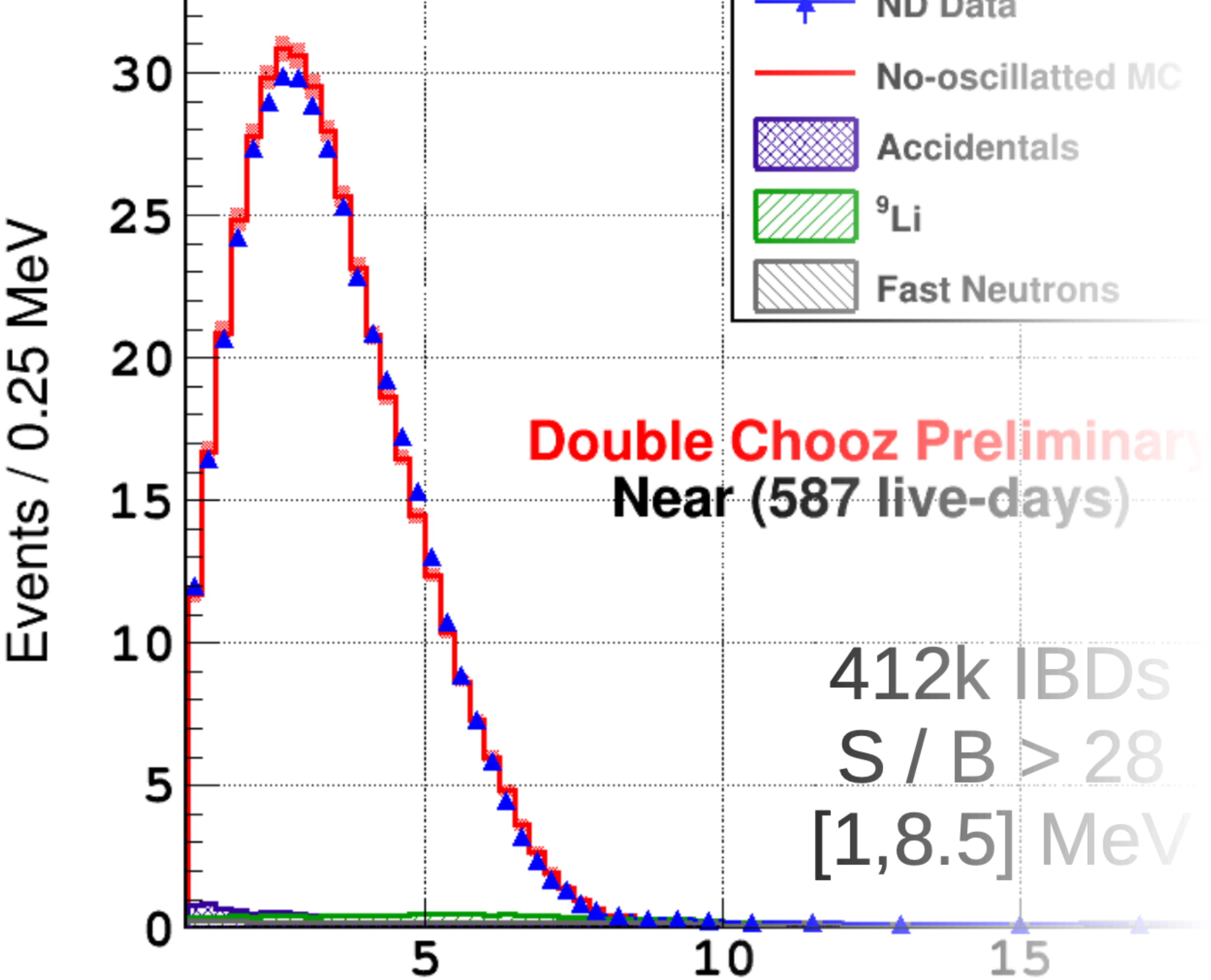
$$\langle \sigma_f \rangle = \frac{N(\overline{\nu}_e)}{N_p \epsilon} \left(\sum_{r=\mathrm{B1,B2}} \frac{\langle P_{th} \rangle_r}{4\pi L_r^2 \langle E_f \rangle_r} \right)^{-1} \mathrm{cm}^2 \text{ per fission}$$



Improved MCSpF measurement

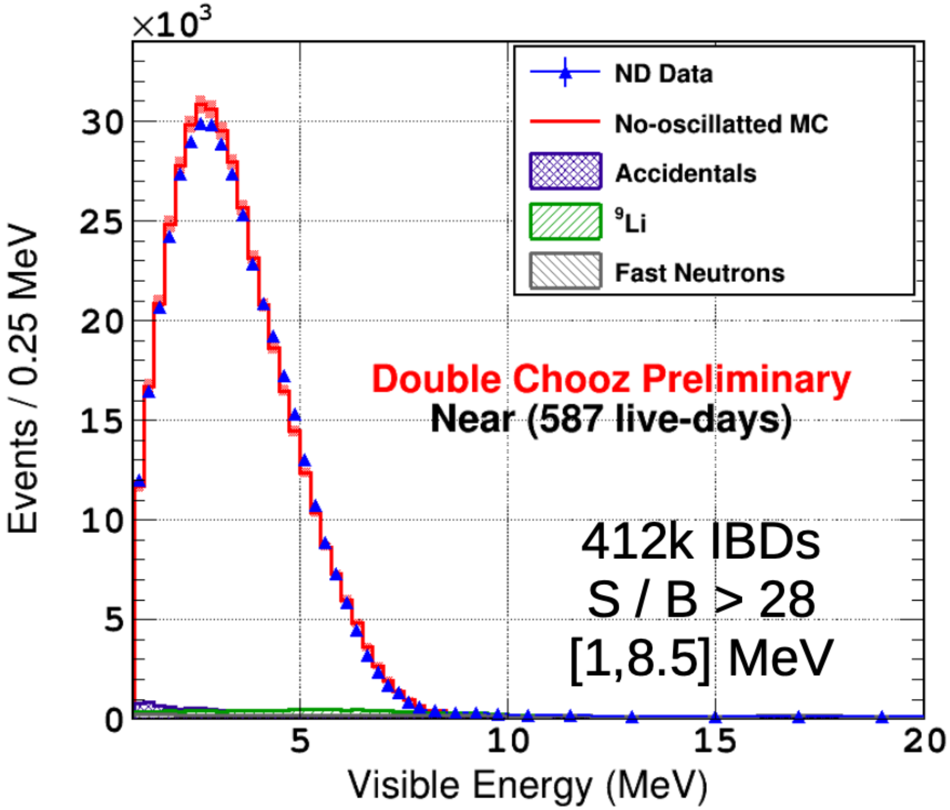


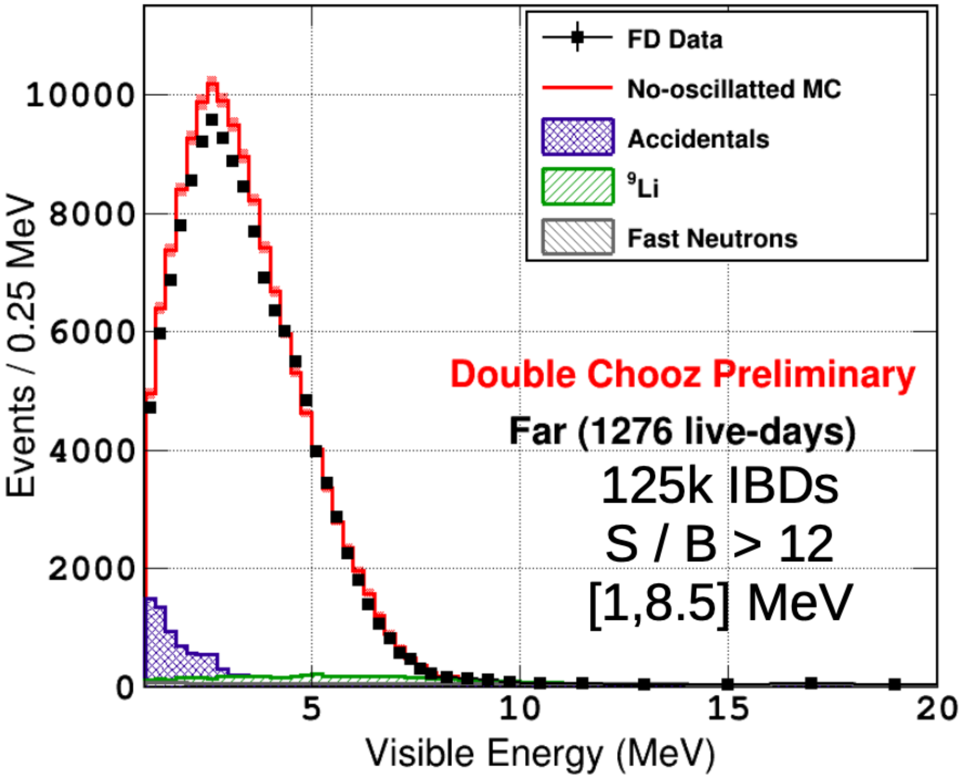
Uncertainty (%)	ND
Proton Number	0.66
Thermal Power	0.47
TnC Selection	0.24
Background	0.18
Energy per Fission	0.16
θ_{13} Correction	0.16
Statistics	0.22
Total	0.97



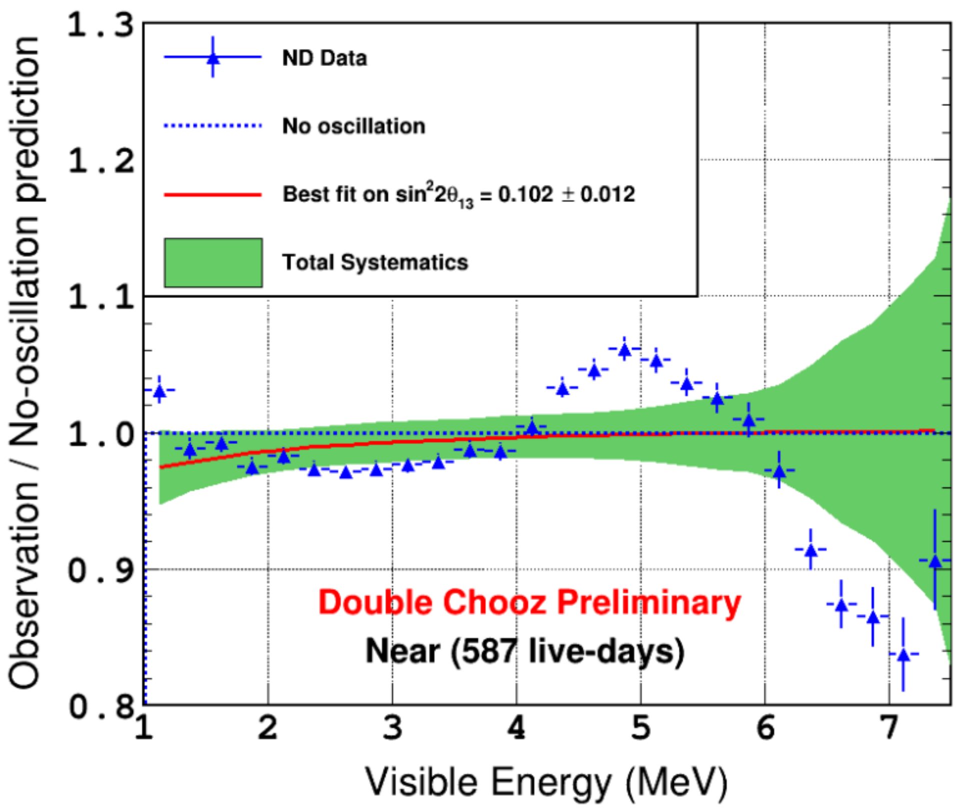
Spectral shape

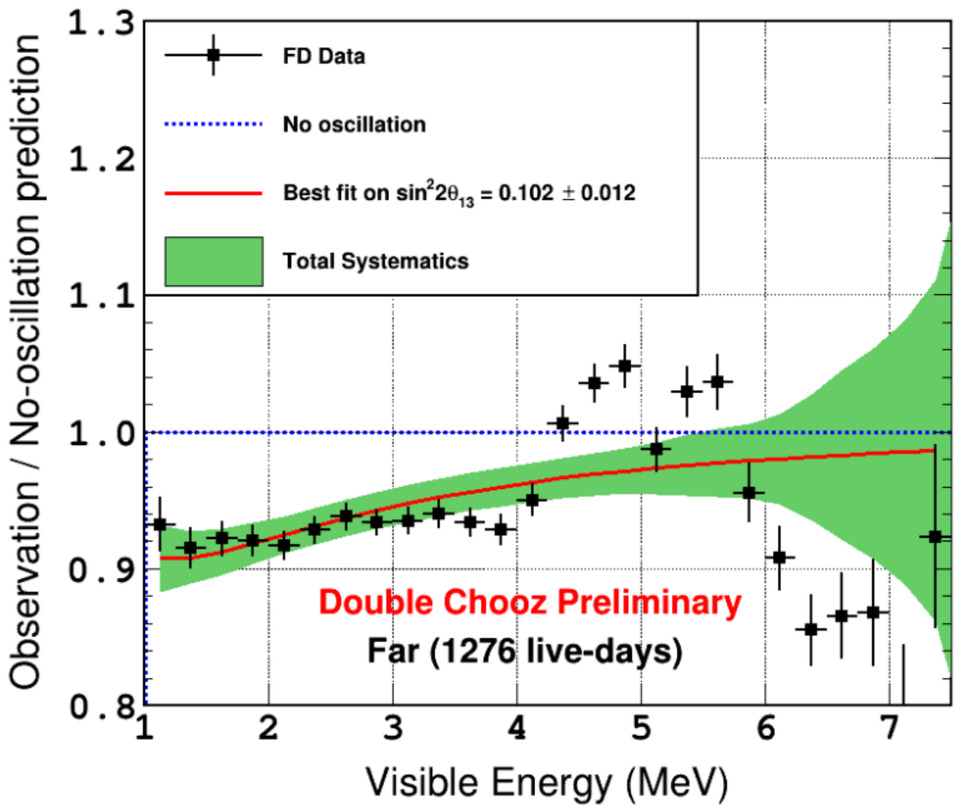
Measured spectra



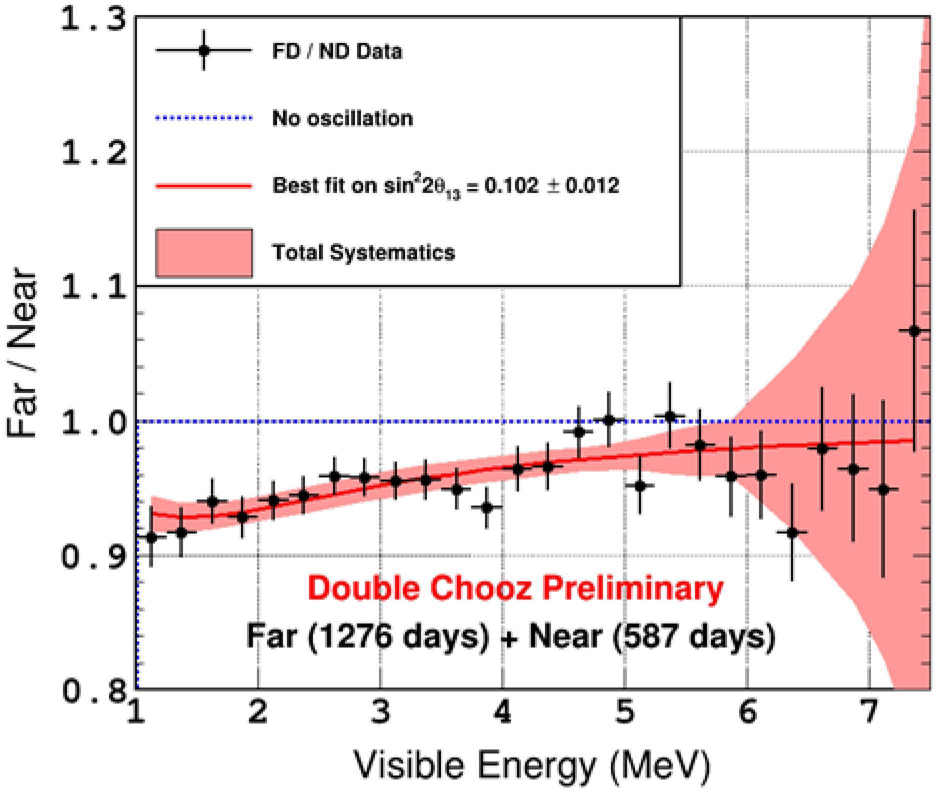


Measured spectra, ratio to prediction



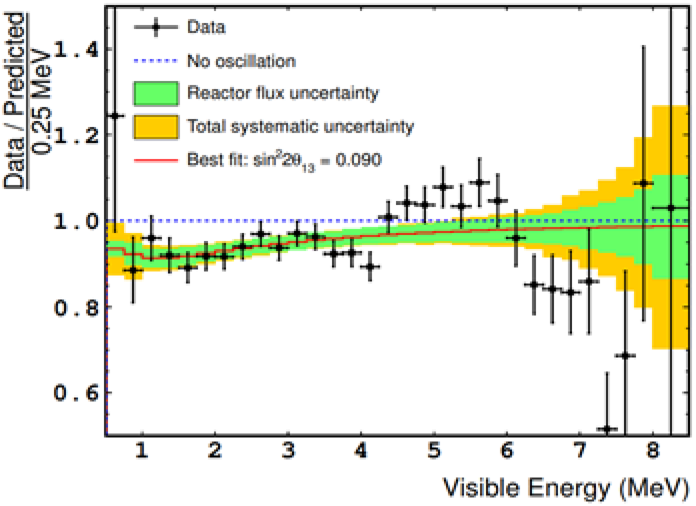


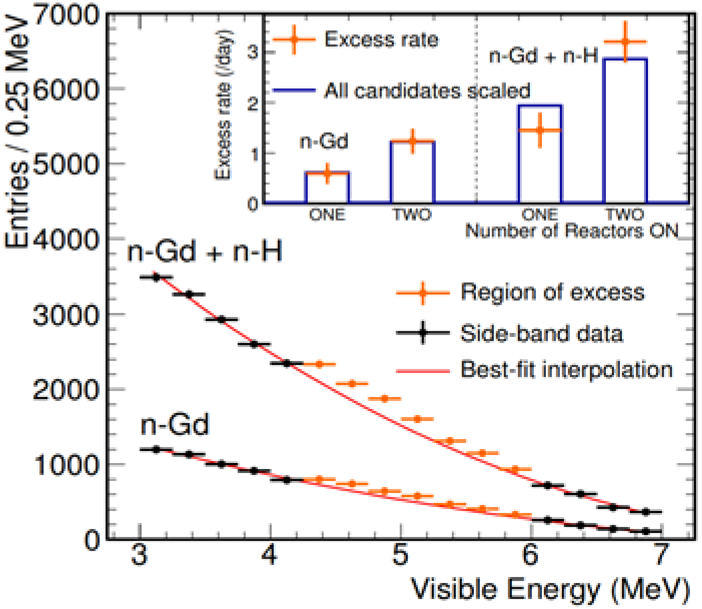
Oscillation analysis protected



First evidence of spectral distortion

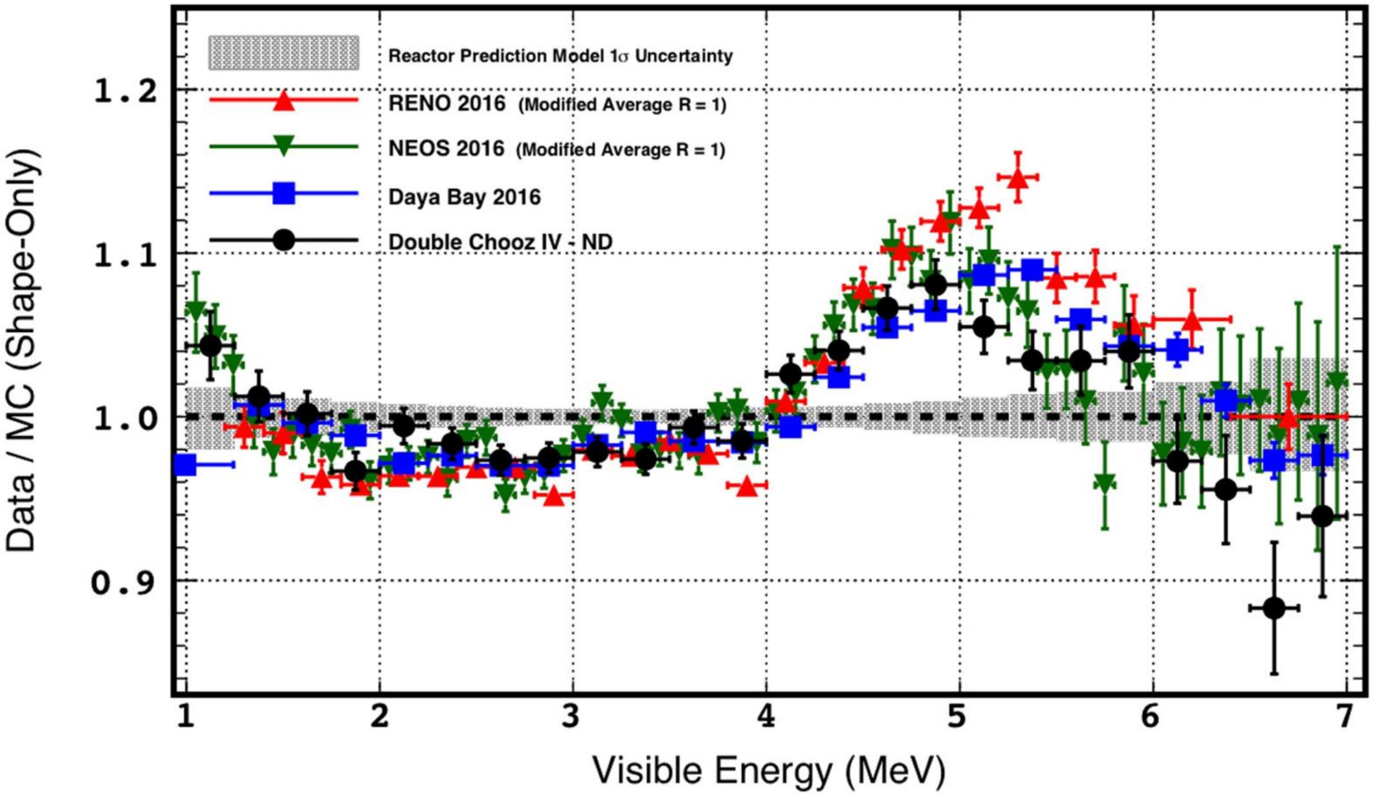
~*18,000* IBD candidates in Far detector (2014)



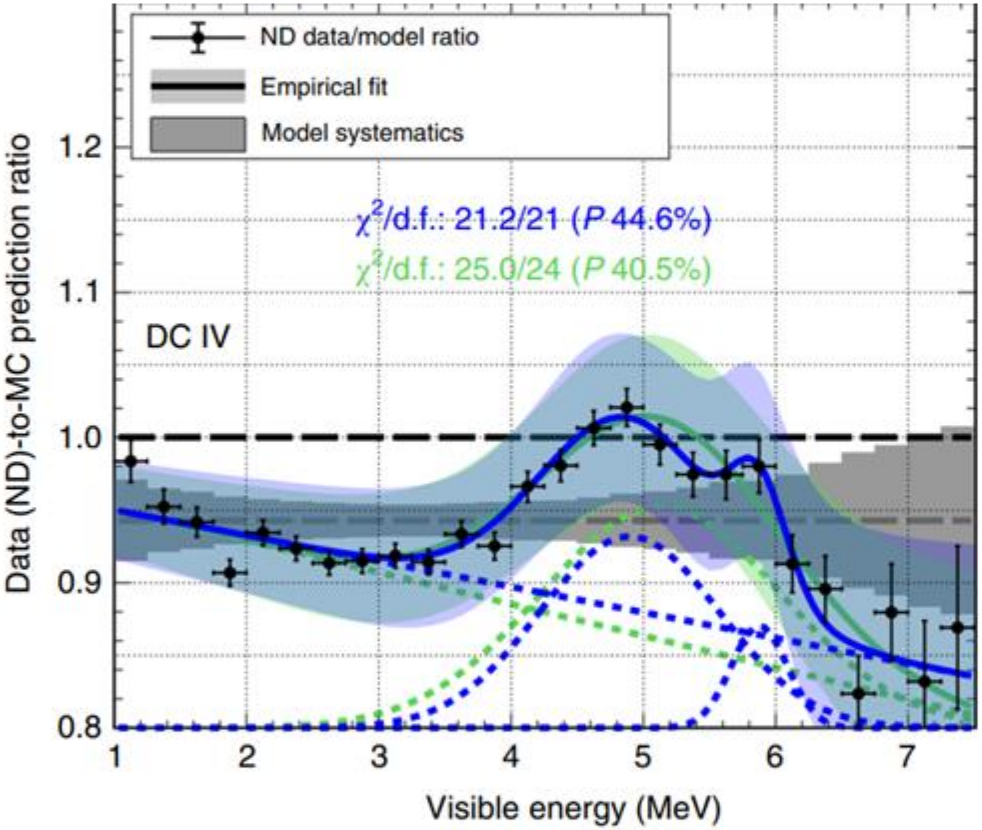


JHEP10(2014)086 arXiv:1406.7763

Near detectors shape comparison



Spectrum ~~Bump~~ Distortion

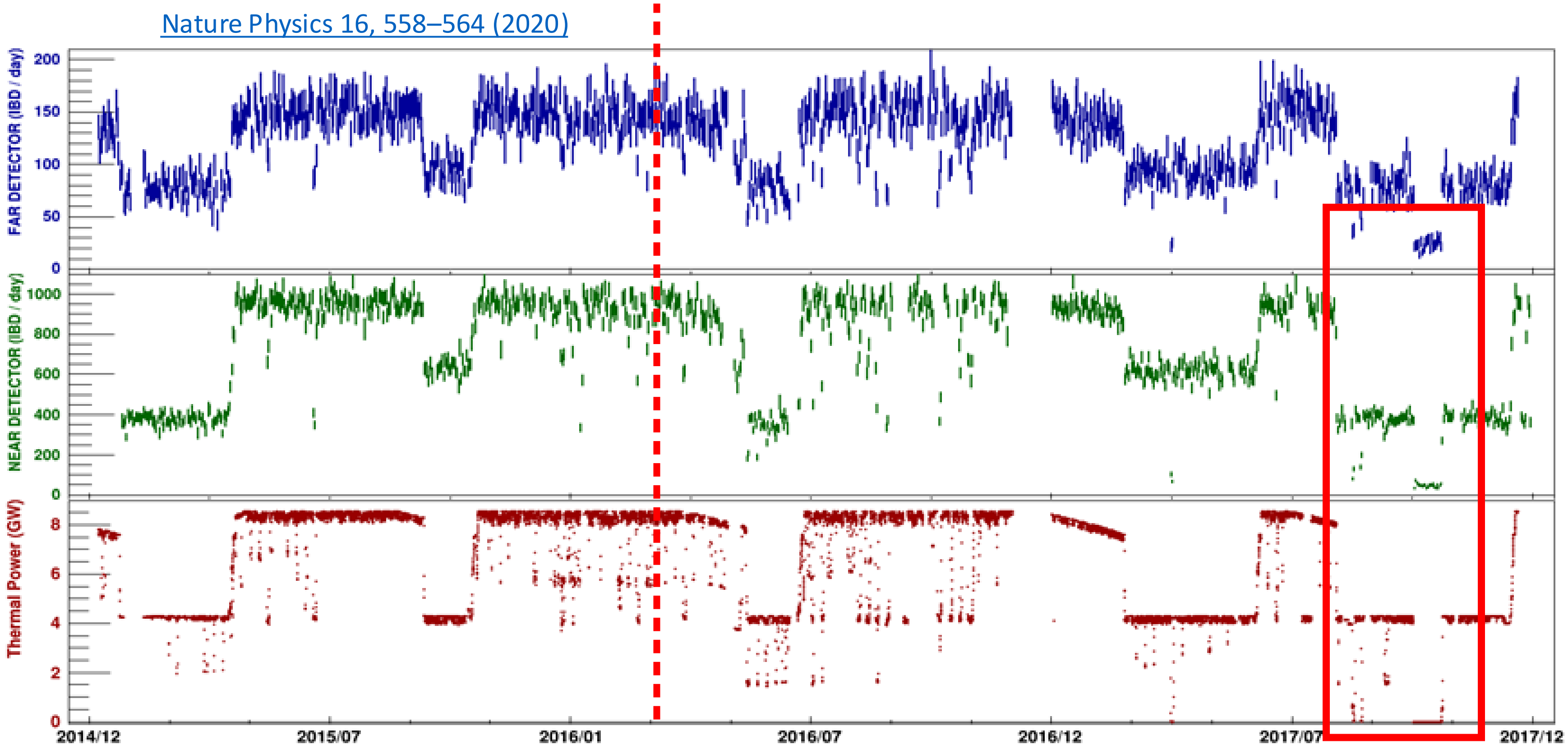


Reactor off

For full details see: Double Chooz talk at 2023 IAEA Technical Meeting

Two detector data

Nature Physics 16, 558–564 (2020)



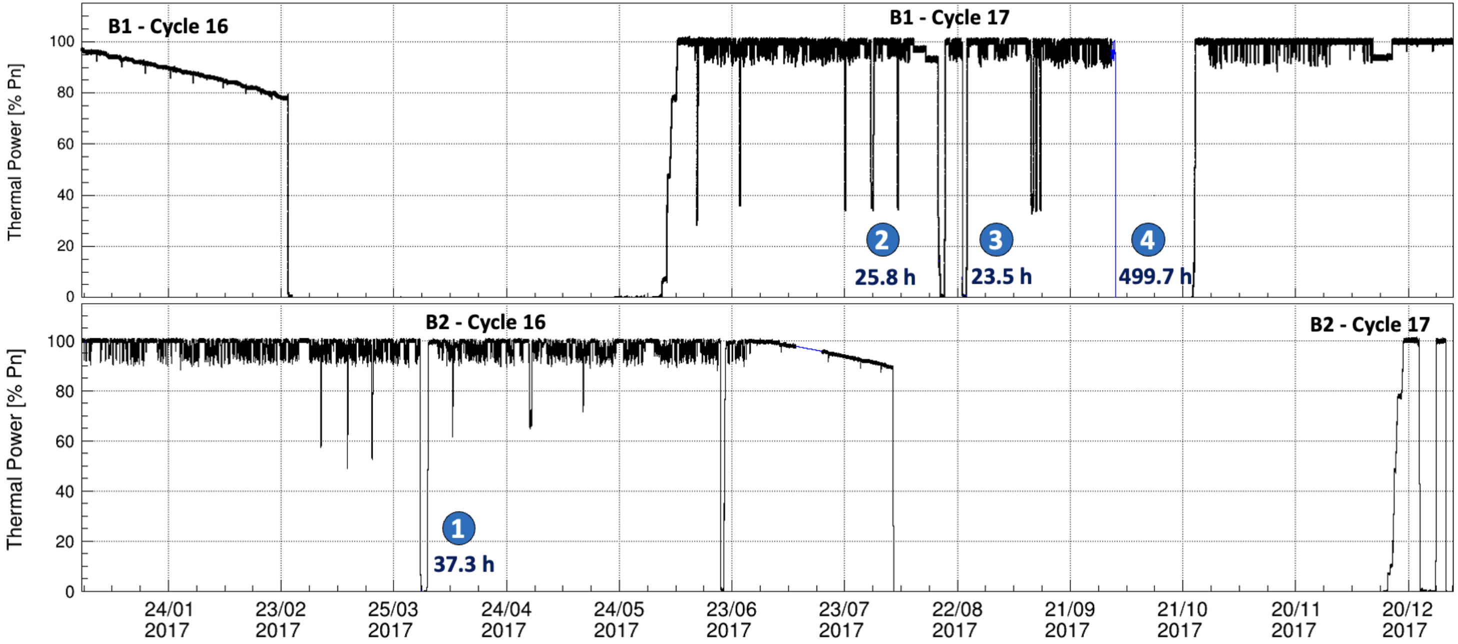
Far Detector

Near Detector

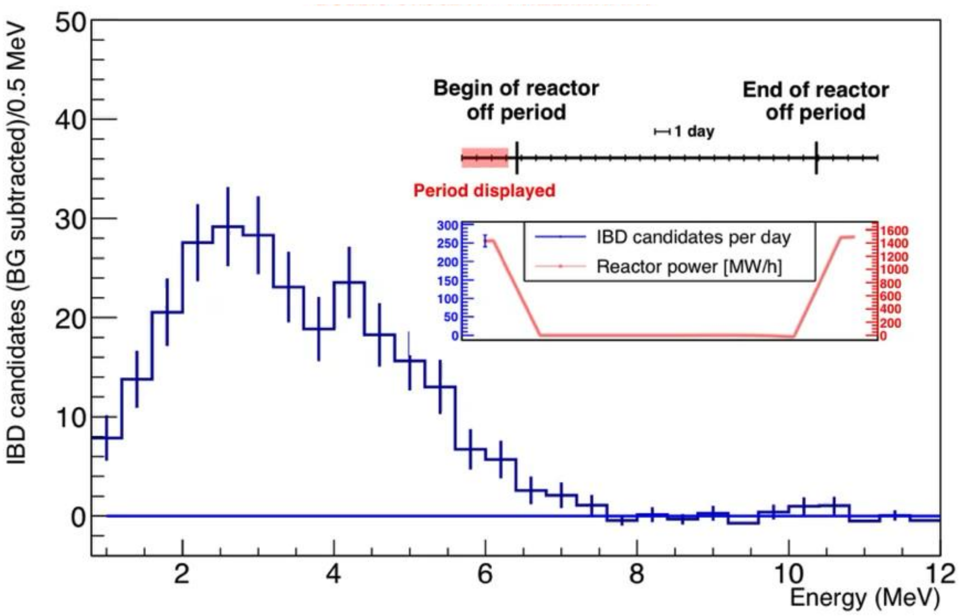
Reactor Thermal Power

The 4 off-off periods of in 2017

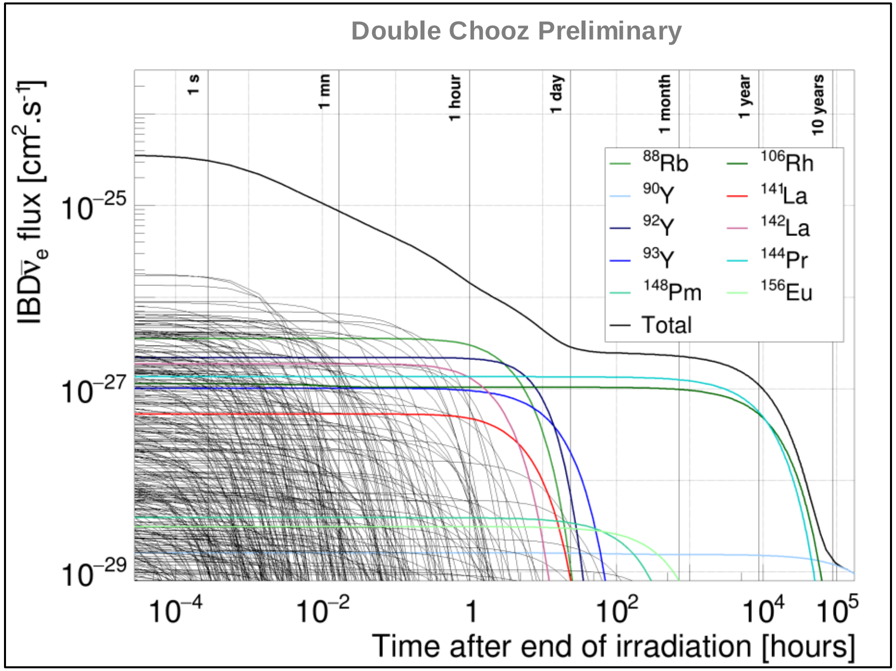
- ①: 1 April: ~ 37 h ⇒ Planned shutdown of B2. Maintenance control on reactor building.
- ②: 17 August: ~ 26 h ⇒ Planned shutdown of B1. Maintenance operation in the engine room.
- ③: 23 August: ~ 24 h ⇒ Unplanned automatically shutdown of B1. Unexpected closure of a steam valve
- ④: 3 October: ~ 500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

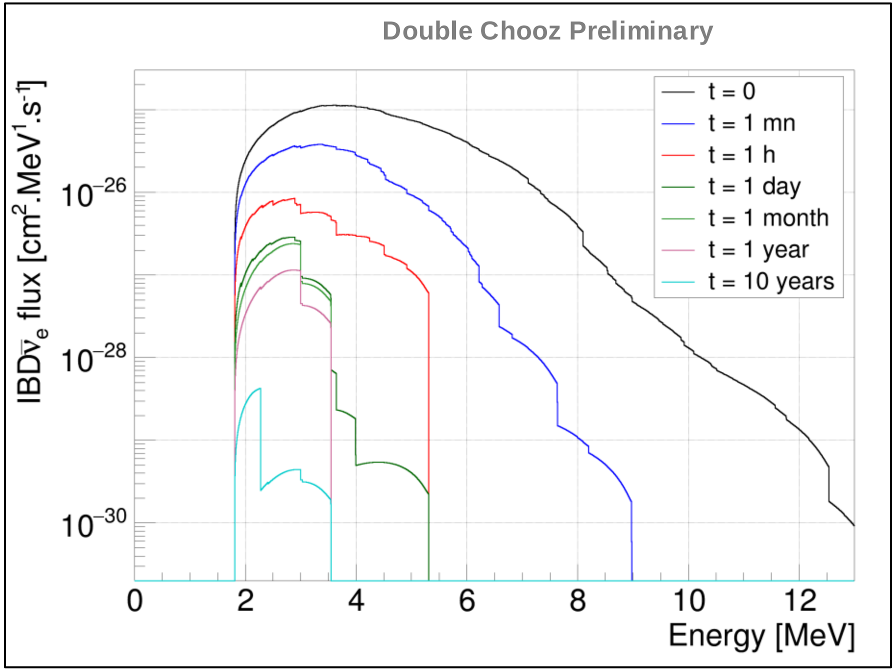


IBD rate and reactor power down/up



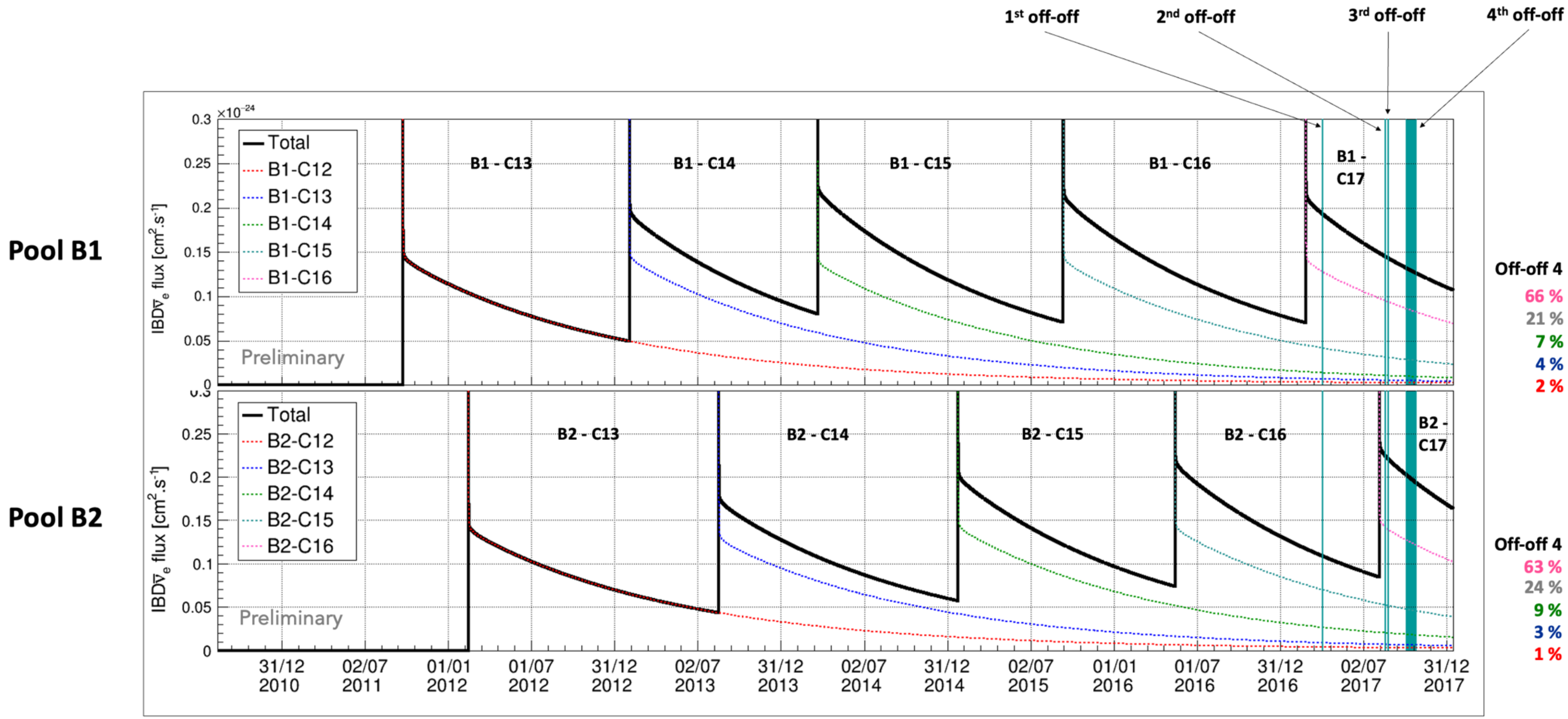
Residual IBD spectrum prediction





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



Expected IBD at reactor-off period

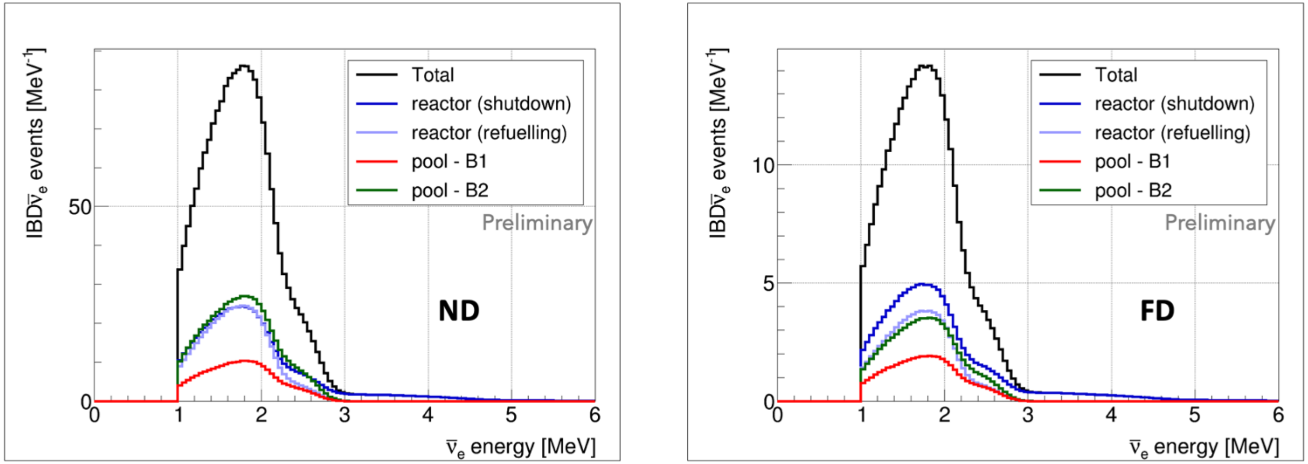
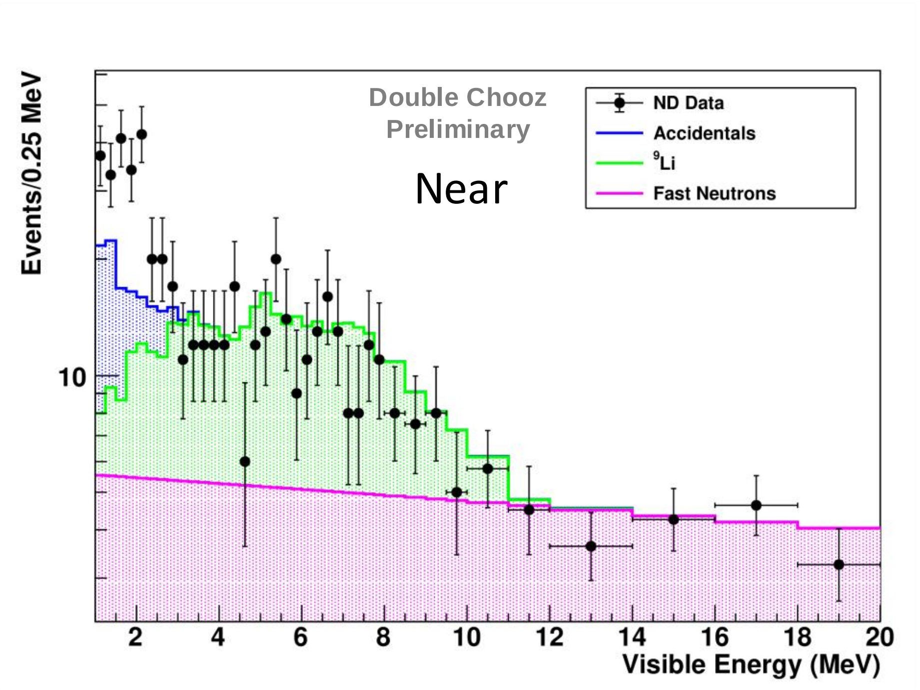


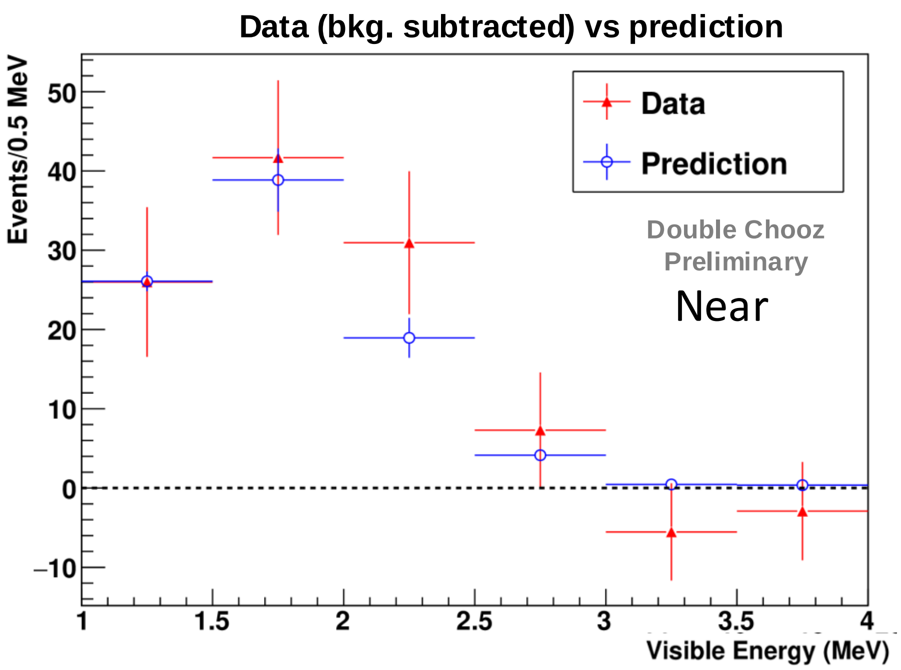
Fig. Expected IBD$\bar{\nu}_e$ spectrum in the ND (left) and FD (right) for all off-off period combined (no runlist).

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

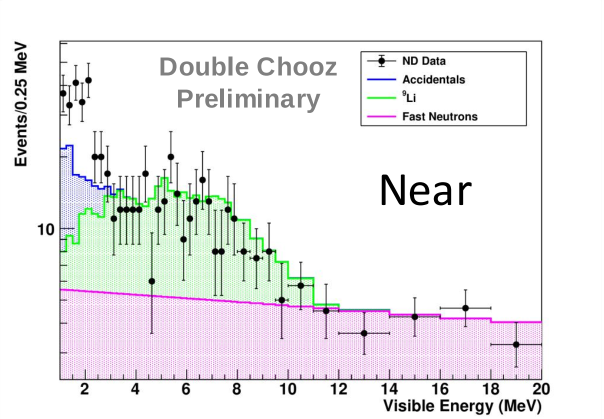
Tab. Expected number of IBD$\bar{\nu}_e$ in the ND and FD for all off-off periods combined.

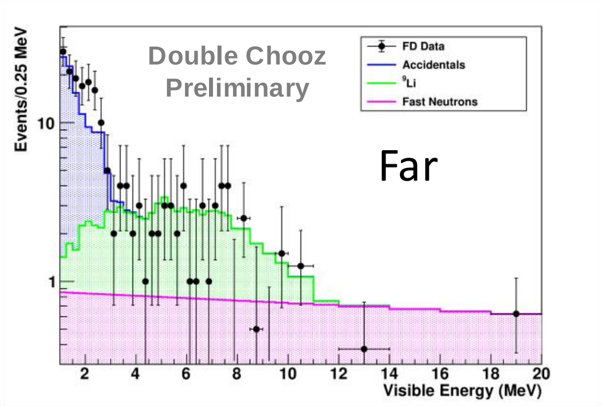
Two reactors-off spectrum



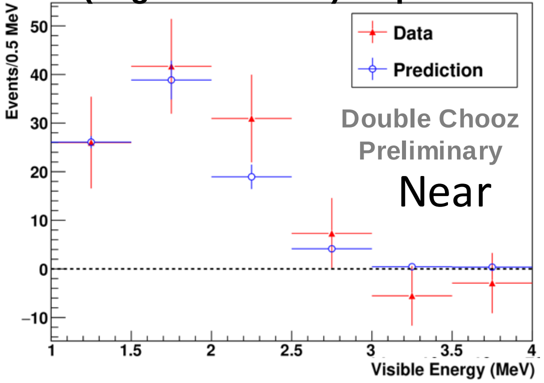


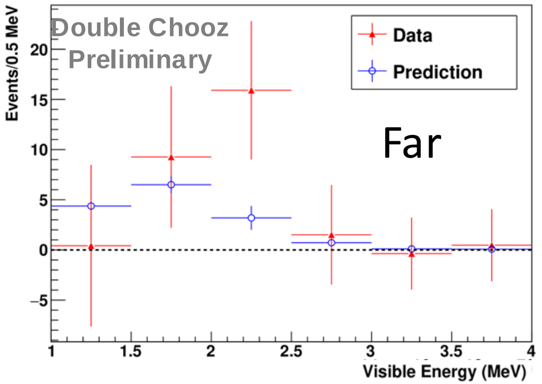
Two reactors-off spectrum





Data (bkg. subtracted) vs prediction





$IBD_{\bar{\nu}_e}$ 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

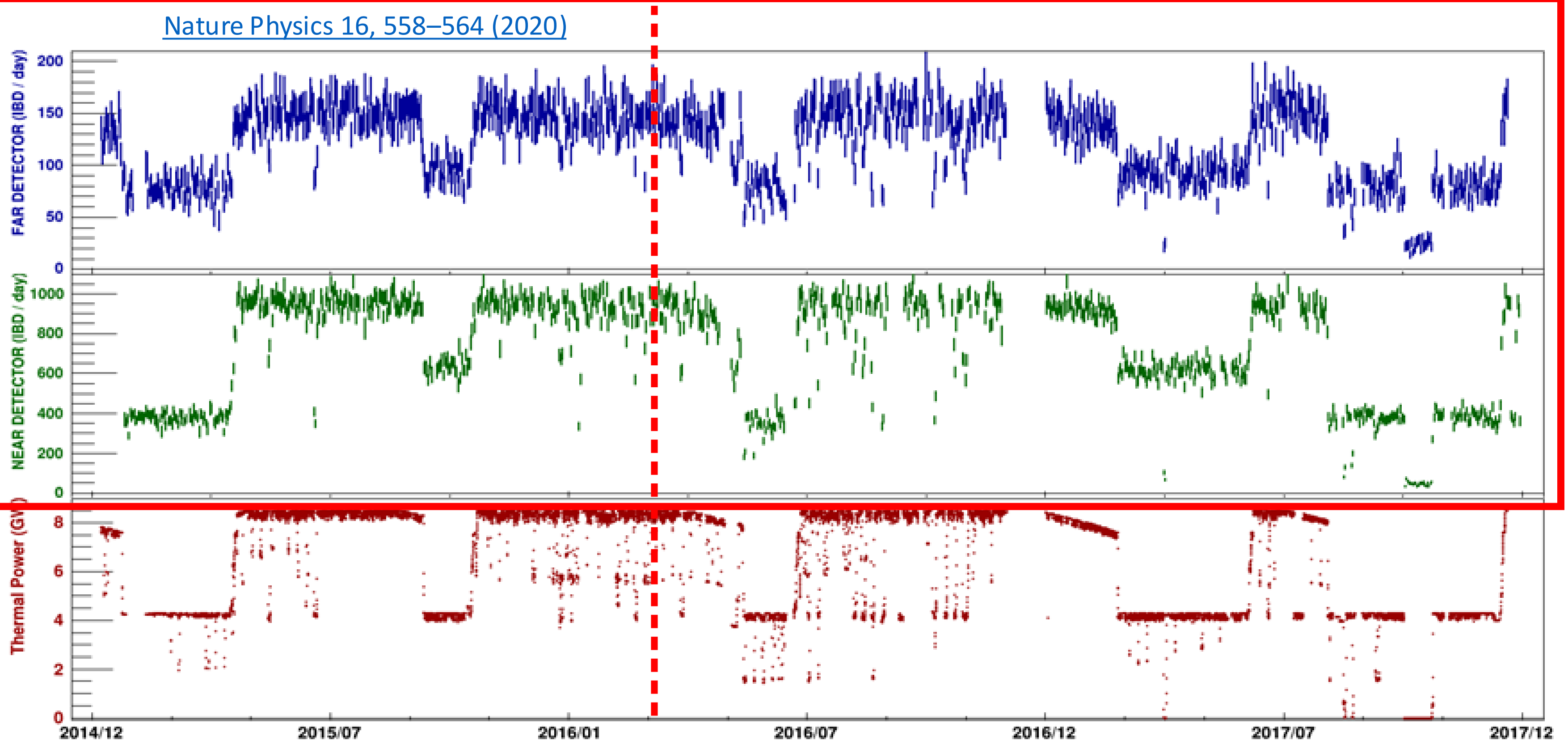
		ND	FD
Chooz site	- Distance assemblies-detectors	**2.9**	**0.9**
	- θ_{13} oscillation	0.1	0.3
Detector	- detection efficiency	0.3	0.4
	- proton number	0.7	0.7
Reactor	- Thermal power	0.5	0.5
	- Reactor stop time	0.2	0.2
	- IBD cross-section	0.1	0.1
	- Fission product inventory	**2.1**	**2.1**
	- Amount 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

Improvements

Final results underway

Nature Physics 16, 558–564 (2020)



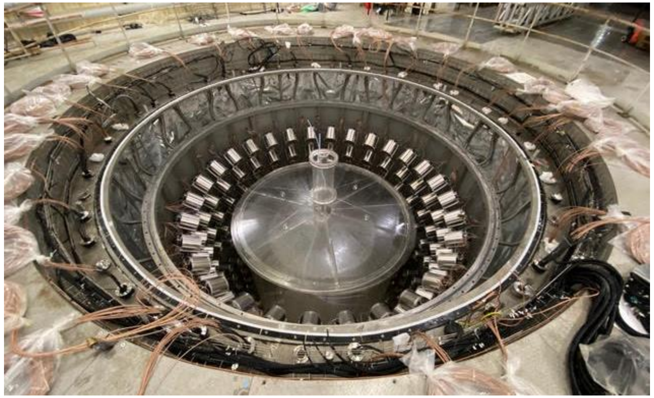
Far Detector

Near Detector

Reactor Thermal Power

Final results underway

- Final Double Chooz publication:
  - Uses all data, 2x the statistics of latest publication
- Improved systematics
  - New measurements of the number of protons
    - Factor 2 improvement achieve at decommissioning
  - Better control of energy reconstruction
  - Better control of backgrounds
- New release soon (summer)
  - Improvement of both ν flux (<1% unc) and θ_{13} measurement



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: $\langle \boldsymbol{\sigma_f} \rangle = \mathbf{(5.75 \pm 0.06) \times 10^{-43}\ cm^2}$
- $\sim$24 days with both reactor off ⇒ very unique data set in the framework of reactor experiments
- Detailed residual 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!