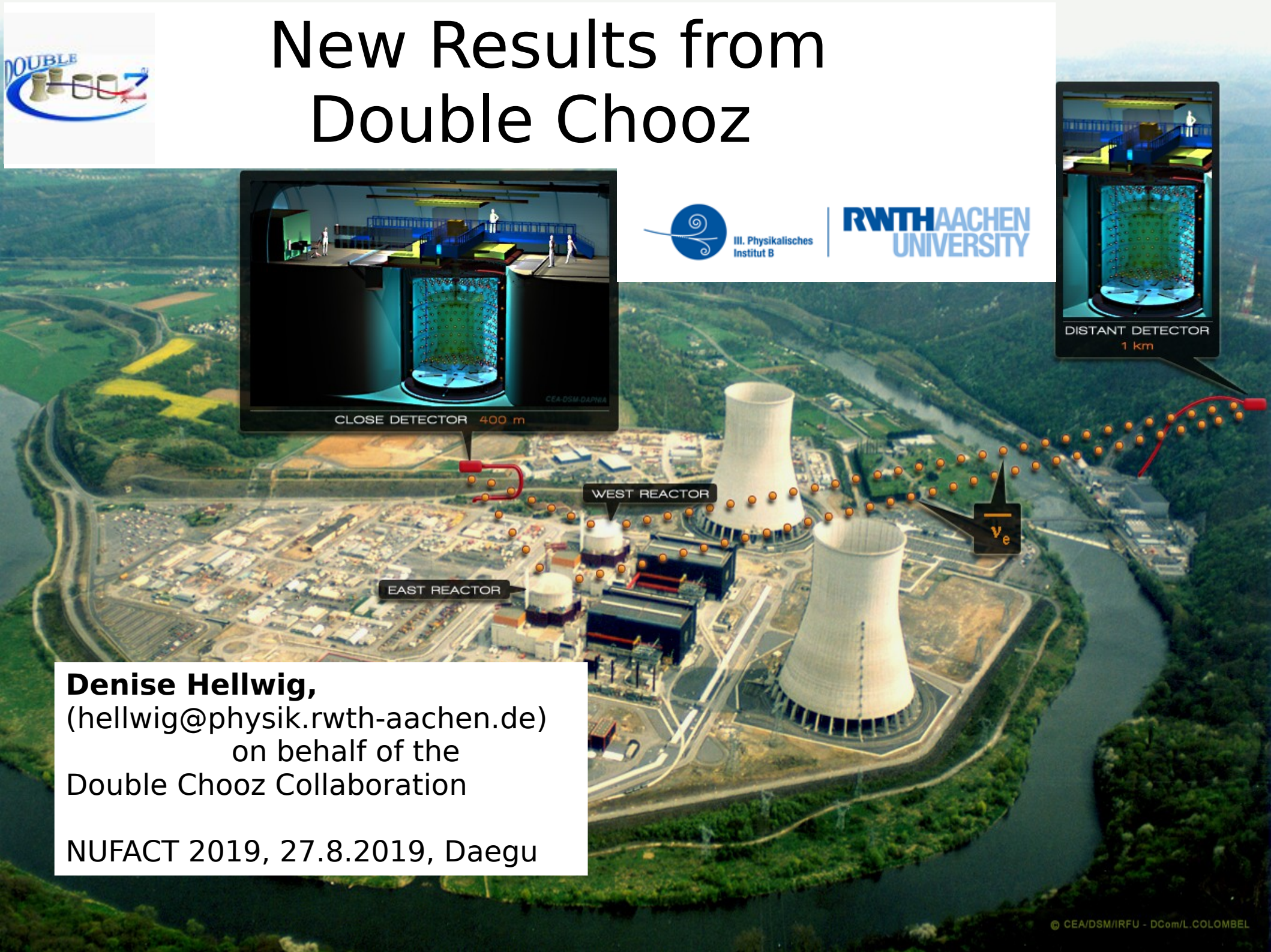
New Results from Double Chooz



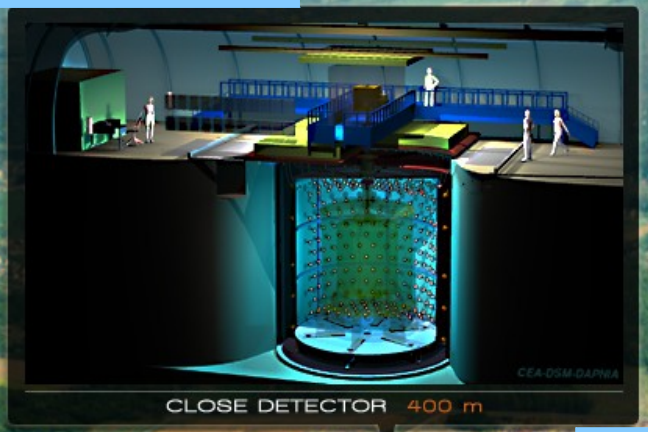
Denise Hellwig,
(hellwig@physik.rwth-aachen.de)
on behalf of the
Double Chooz Collaboration

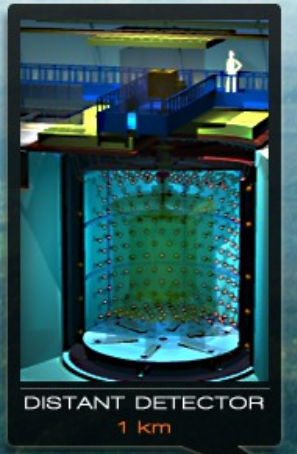
NUFACT 2019, 27.8.2019, Daegu

Experimental site

Near detector
- Operating Jan 2015 – Dec 2017
- **Baseline ~ 400 m**
- Overburden ~ 120 mwe

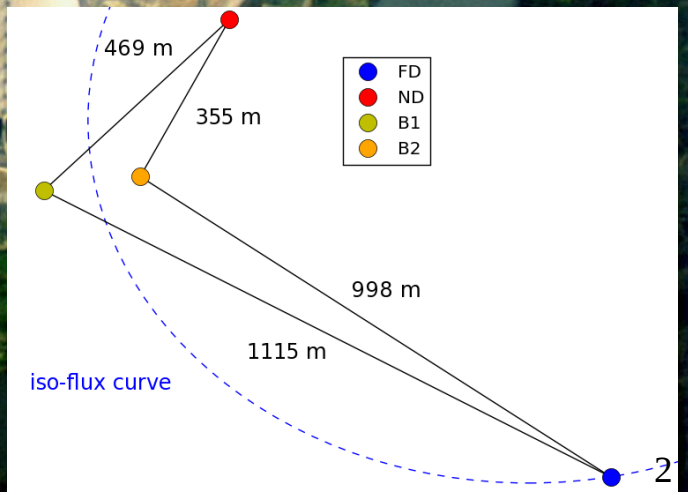
Far detector
- Operating Apr 2011 – Dec 2017
- **Baseline ~ 1050 m**
- Overburden ~ 300 mwe





Reactor B2
- 4.25 GW_{th}

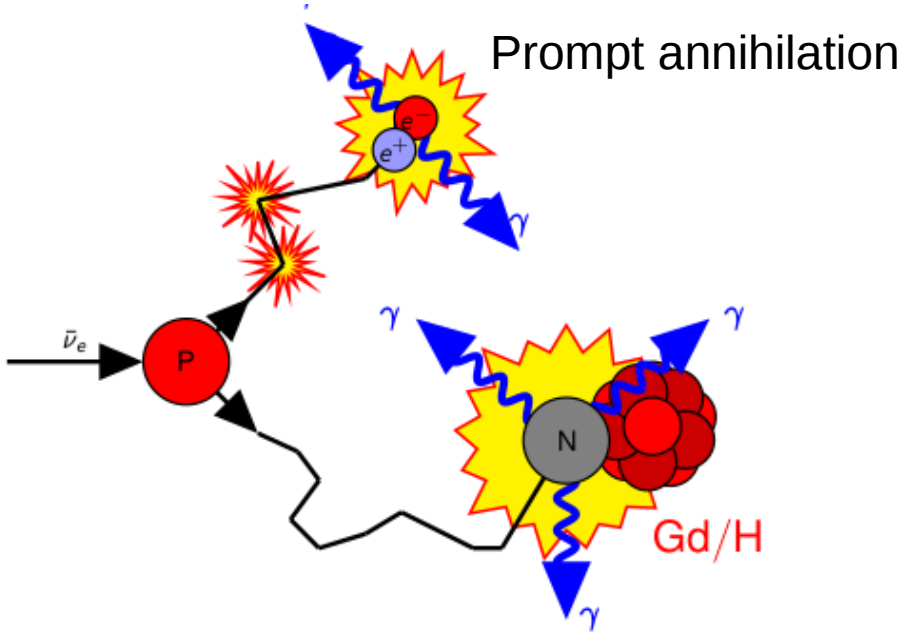
Reactor B1
- 4.25 GW_{th}



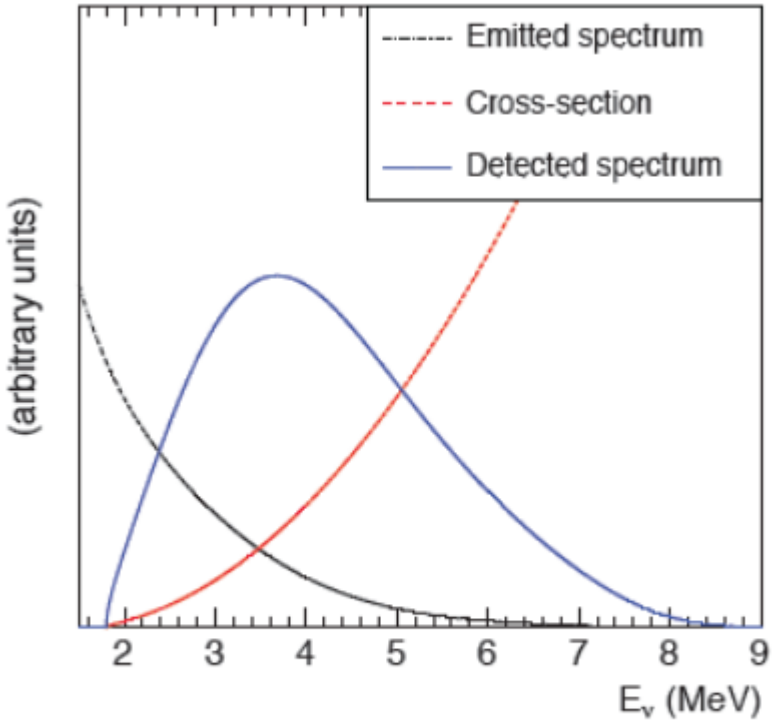
Detection principle

- Detection via inverse beta decay

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

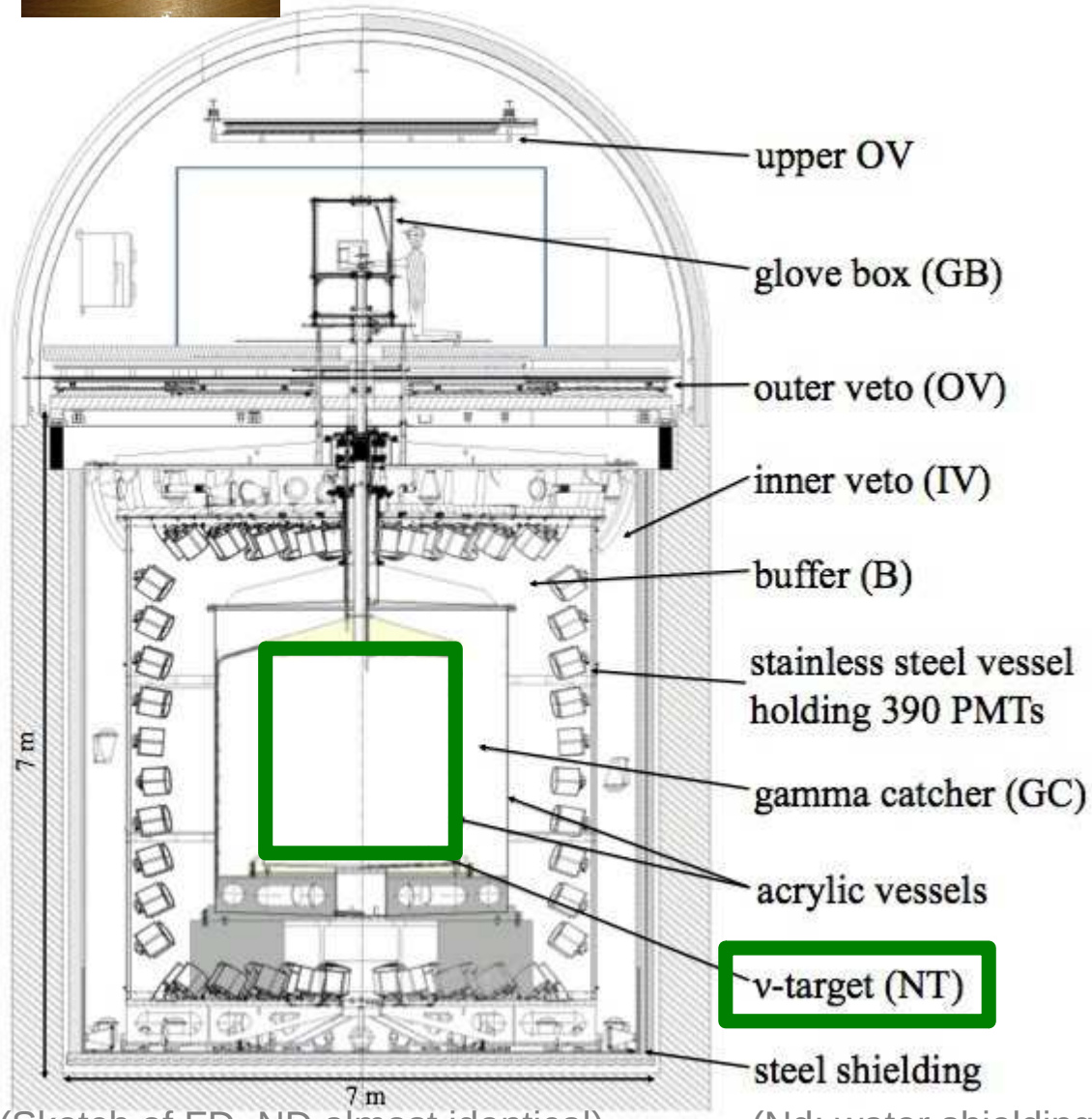


Delayed neutron capture Gd(H):
8 (2.2) MeV
30 (200) μs



$$E_{vis} = E_\nu - 0.8\,MeV$$

Detector

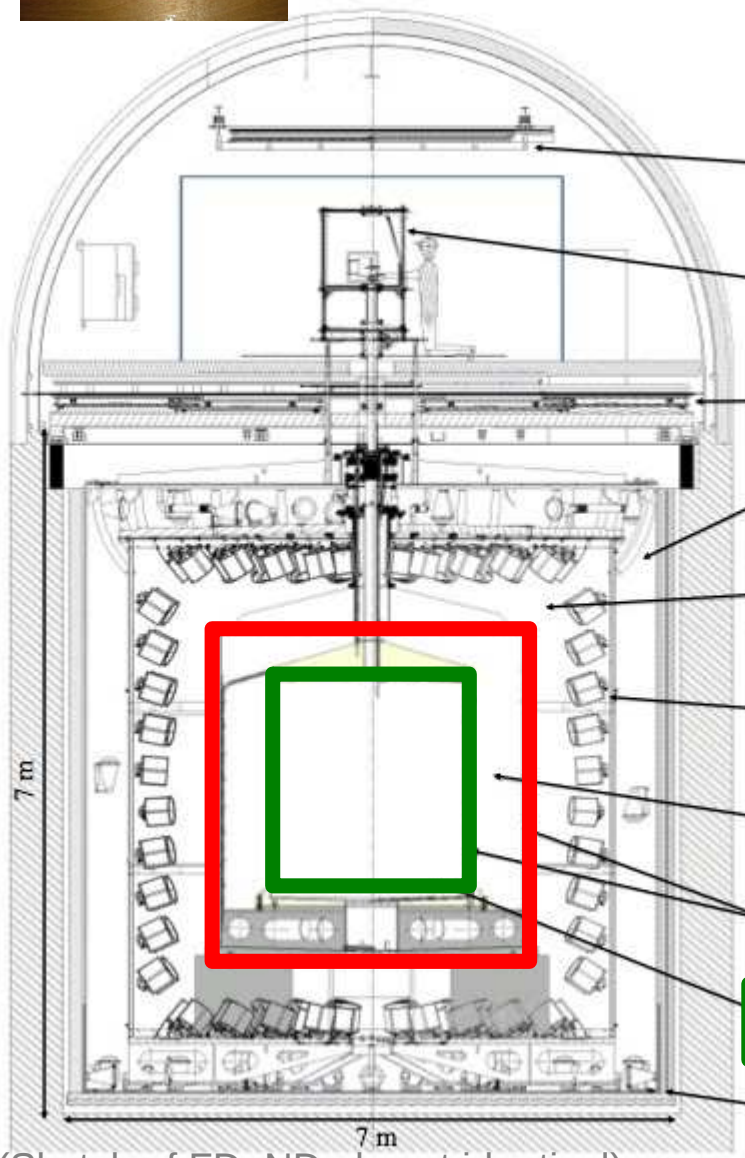


(Sketch of FD, ND almost identical)

(Nd: water shielding)

Neutrino Target (NT)
Gd loaded (1 g/l) liquid scint.
(10 m³)

Detector



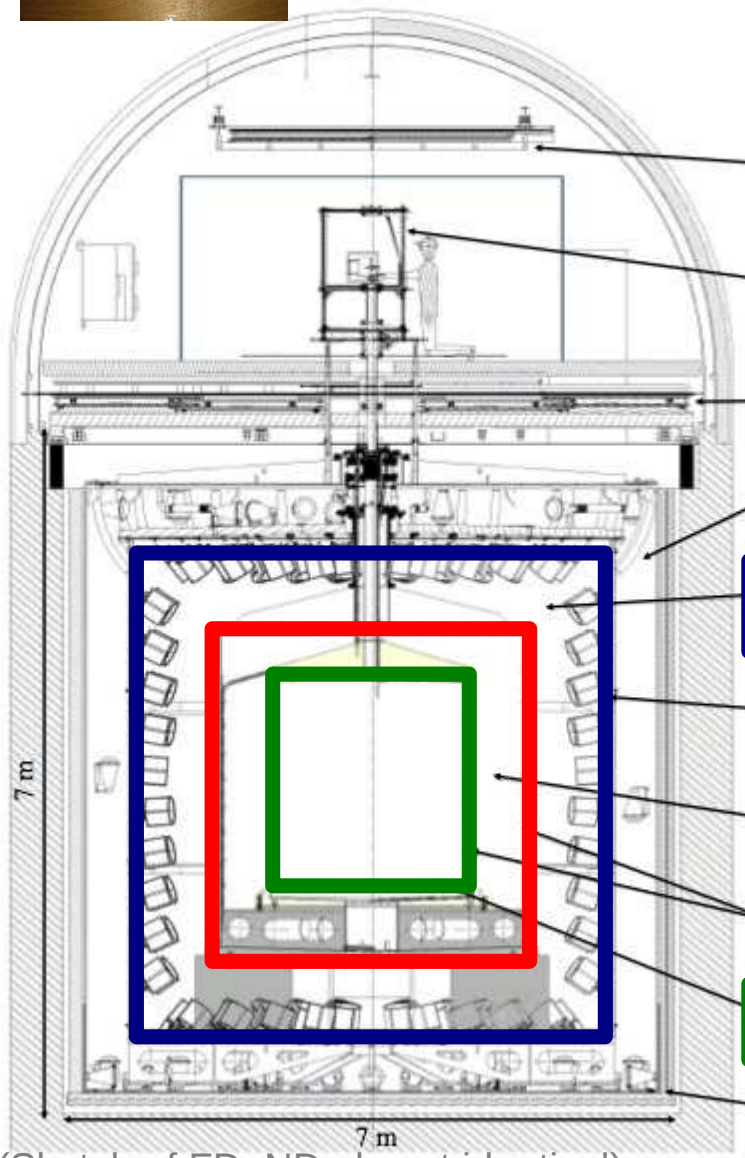
(Sketch of FD, ND almost identical)

(Nd: water shielding)

Gamma Catcher (GC)
Liquid Scintillator (22 m³)
Measures γ escaping the target

Neutrino Target (NT)
Gd loaded (1 g/l) liquid scint.
(10 m³)

Detector



(Sketch of FD, ND almost identical)

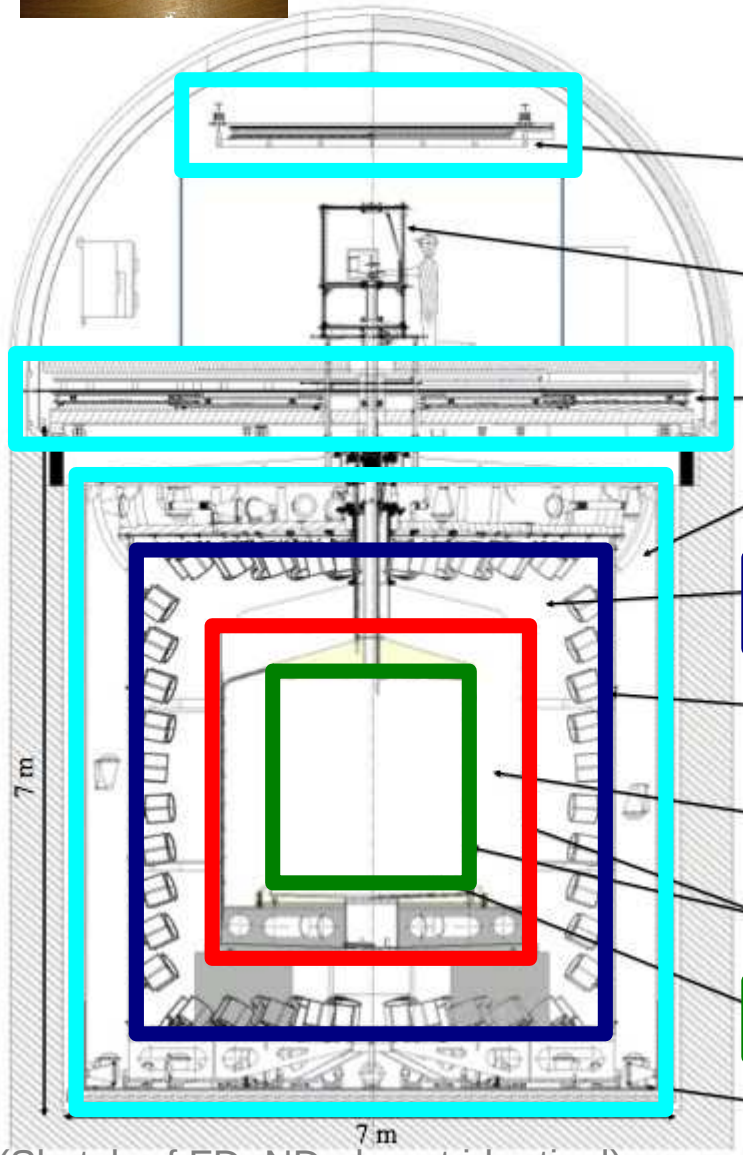
(Nd: water shielding)

Buffer (B)
Non-scintillating mineral oil
(110 m³)
390 10" PMT
Shielding against external γ

Gamma Catcher (GC)
Liquid Scintillator (22 m³)
Measures γ escaping the target

Neutrino Target (NT)
Gd loaded (1 g/l) liquid scint.
(10 m³)

Detector



(Sketch of FD, ND almost identical)

(Nd: water shielding)

Outer Veto (OV)
Plastic scintillator strips
vetos atmospheric μ

Inner Veto (IV)
Liquid Scintillator (90 m³)
78 8" PMT
Vetos atmosperic μ and neutrons
Shielding

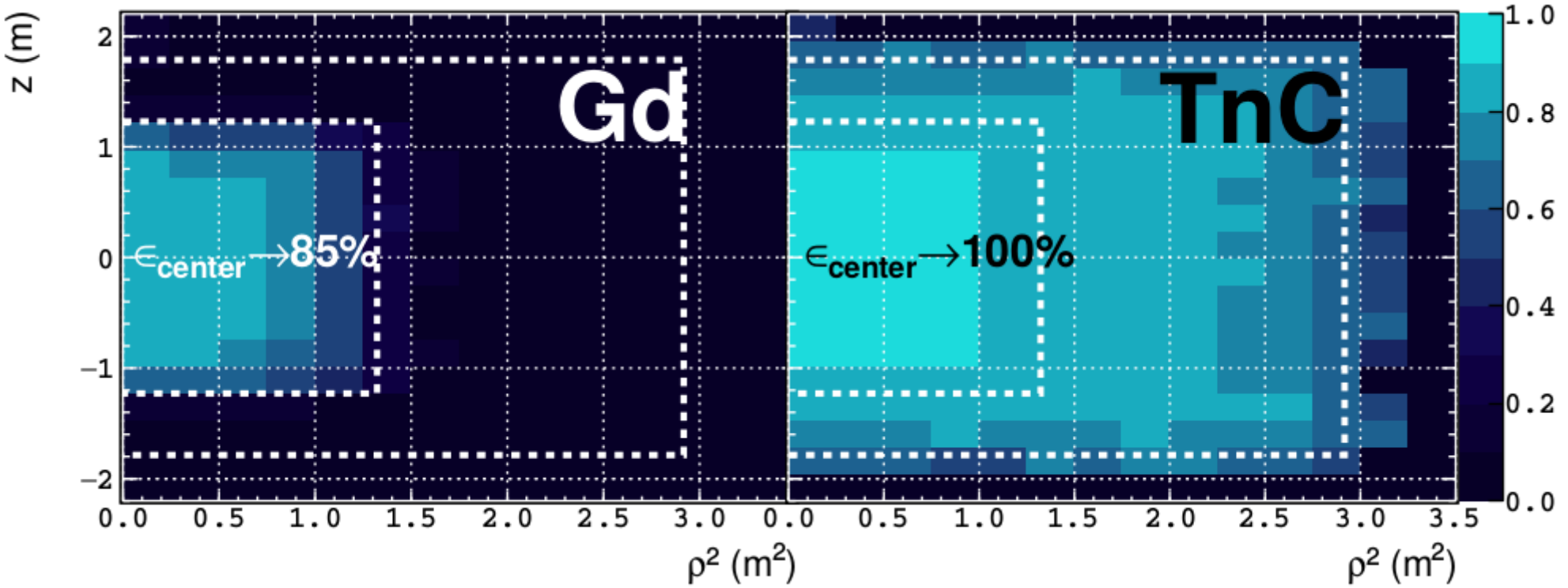
Buffer (B)
Non-scintillating mineral oil
(110 m³)
390 10" PMT
Shielding against external γ

Gamma Catcher (GC)
Liquid Scintillator (22 m³)
Measures γ escaping the target

Neutrino Target (NT)
Gd loaded (1 g/l) liquid scint.
(10 m³)

IBD Selection

NEW Selection

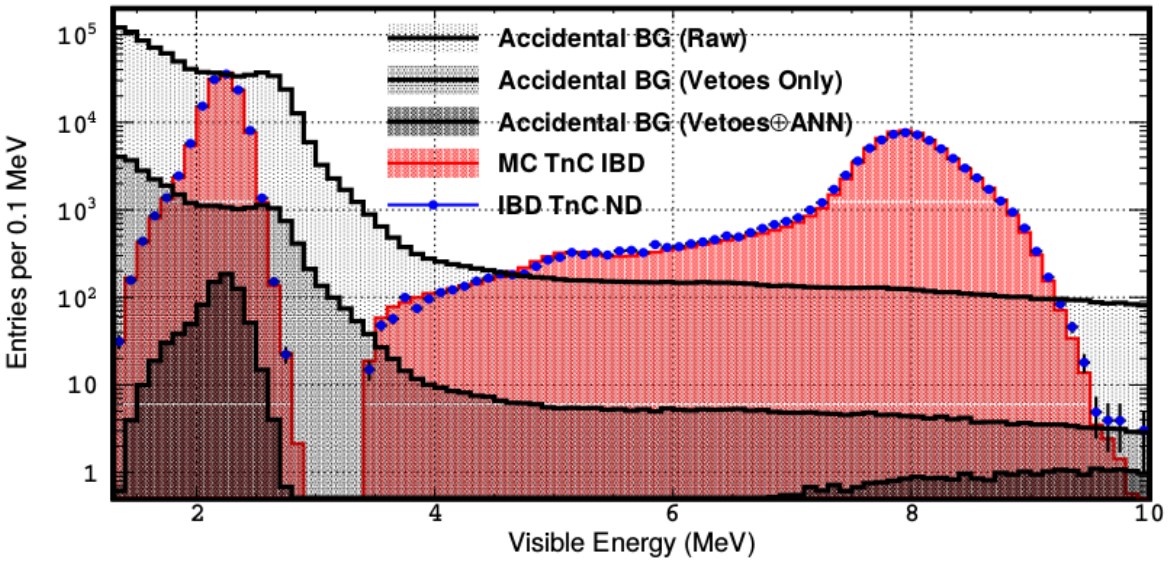


Total neutron capture (TnC) selects capures on Gd+H+C

- Increase detection efficiency (spilling irrelevant)
- Increase of active detector volume (~ 30 t)
- Increase statistics (factor ~ 2.5)
- Immune to liquid exchange in the ND

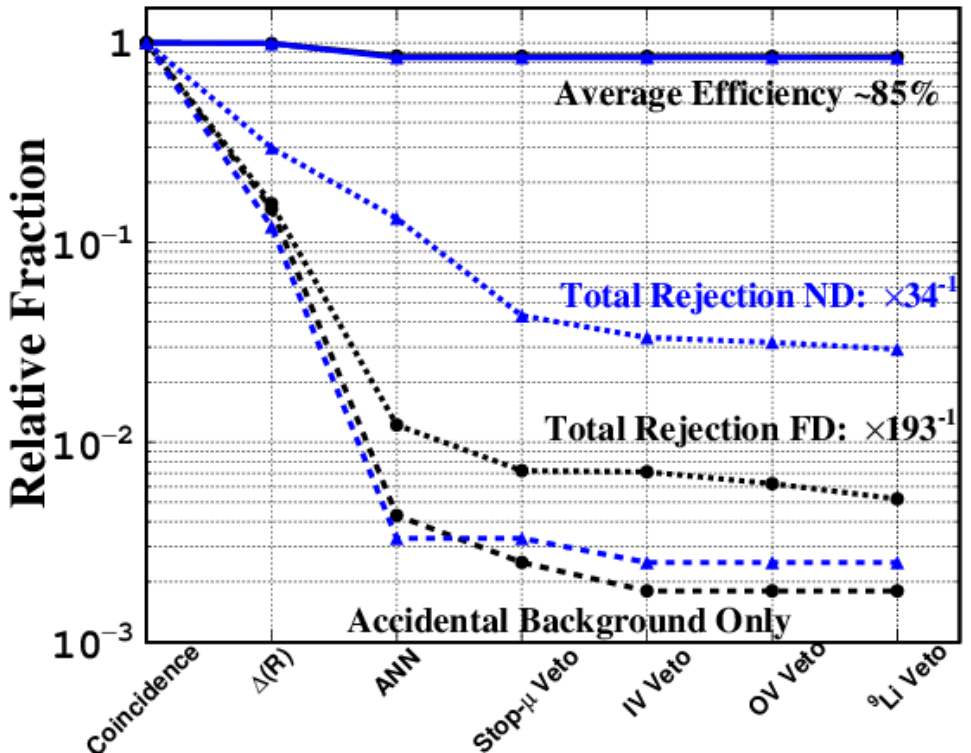
Backgroud rejection

Delayed energy spectrum before and after cuts

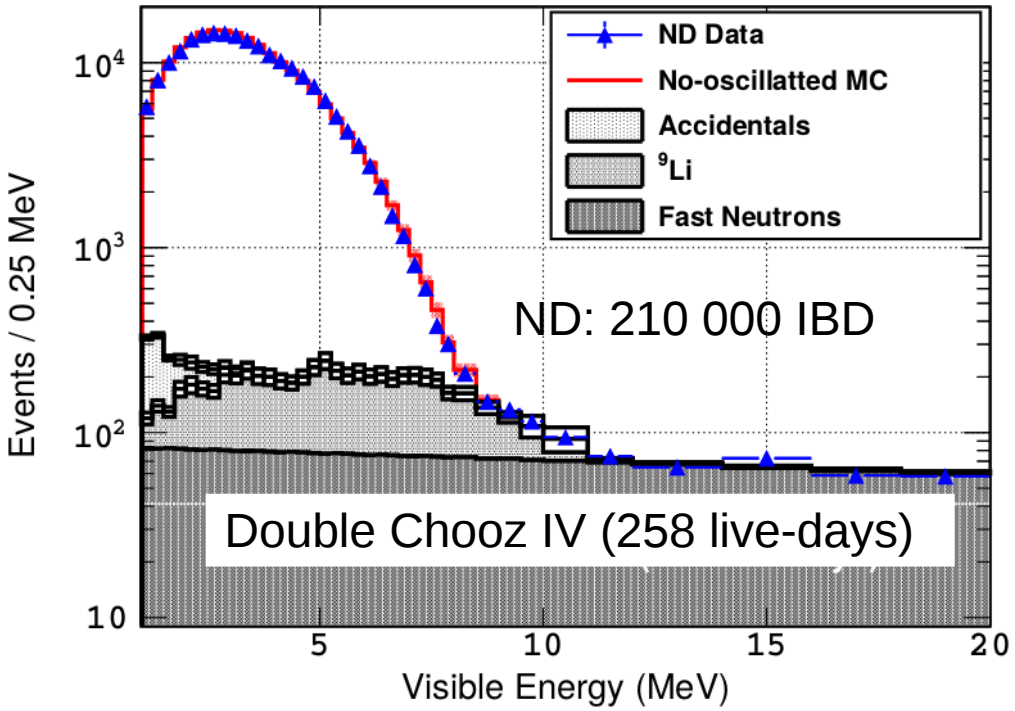


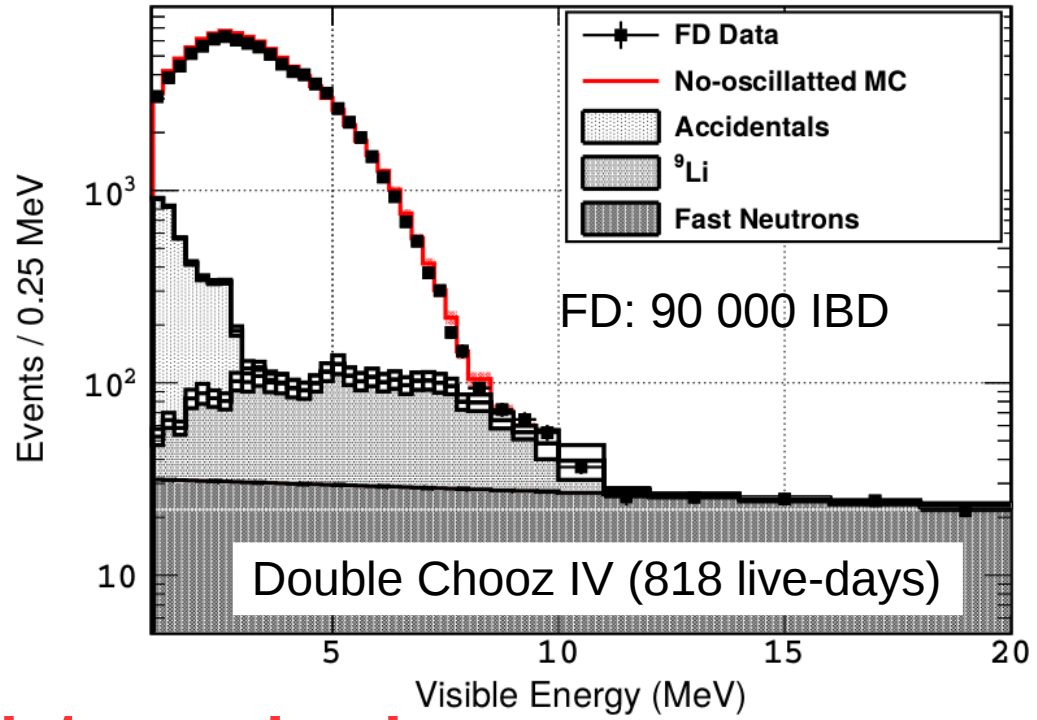
- Good data/MC agreement for IBD candidates
- Efficient background rejection with cuts and vetos
- Artificial neutronal network (ANN) used for efficient accidental background rejection

IBD efficiency and background rejection



Datasets



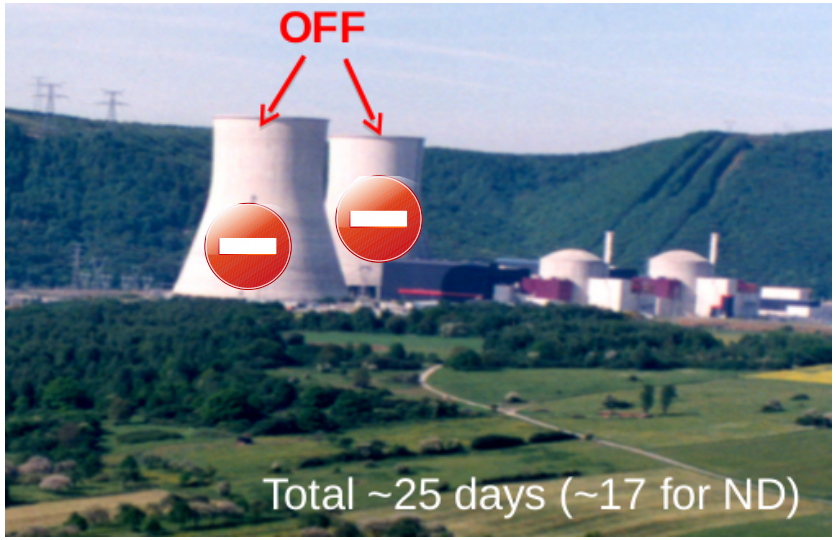


More data on disc!

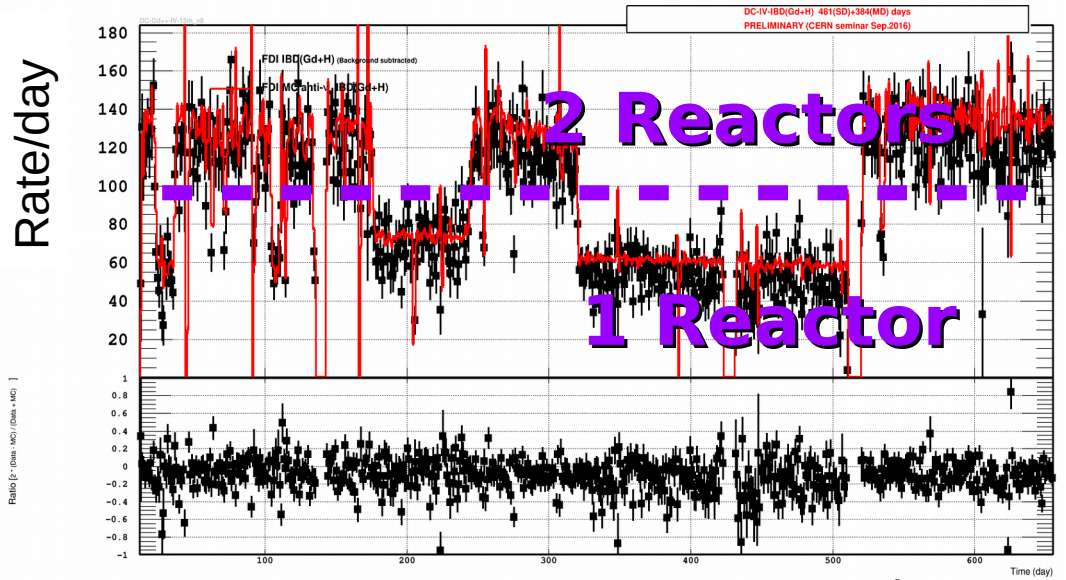
	Ev./day FD	Ev./day ND
IBD candidates	112	816
Cosmogenic BG (^{9}Li)	2.62 ± 0.27	14.52 ± 1.48
Fast n	2.50 ± 0.05	**20.85 ± 0.31**
Accidental BG	**4.13 ± 0.02**	3.11 ± 0.01

Signal/BG > 10

Reactor off data



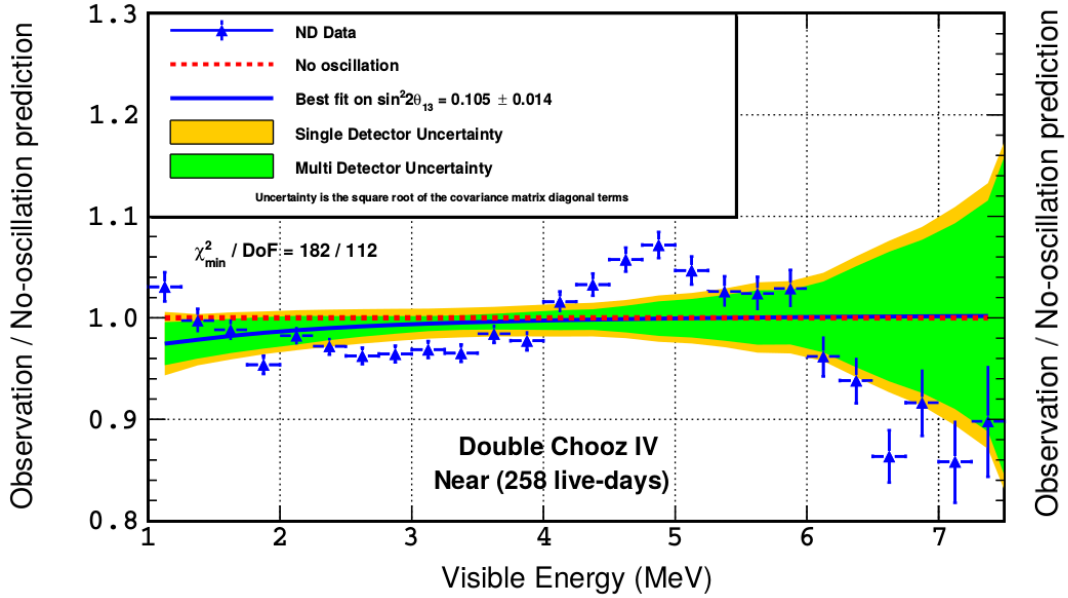
Rate[1/day] vs. time



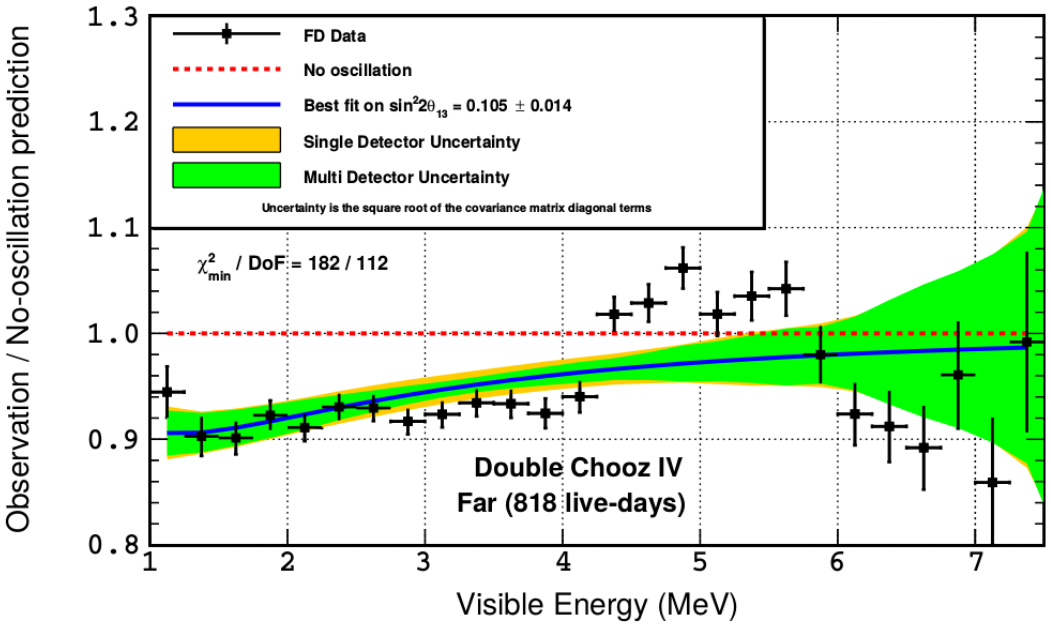
- Double Chooz is the only θ_{13} experiment with only two reactors
- One or both can be off
- 8 days of off-off data with only the far detector
- 17 additional days with both detectors
  => Background understanding

Best fit result

ND

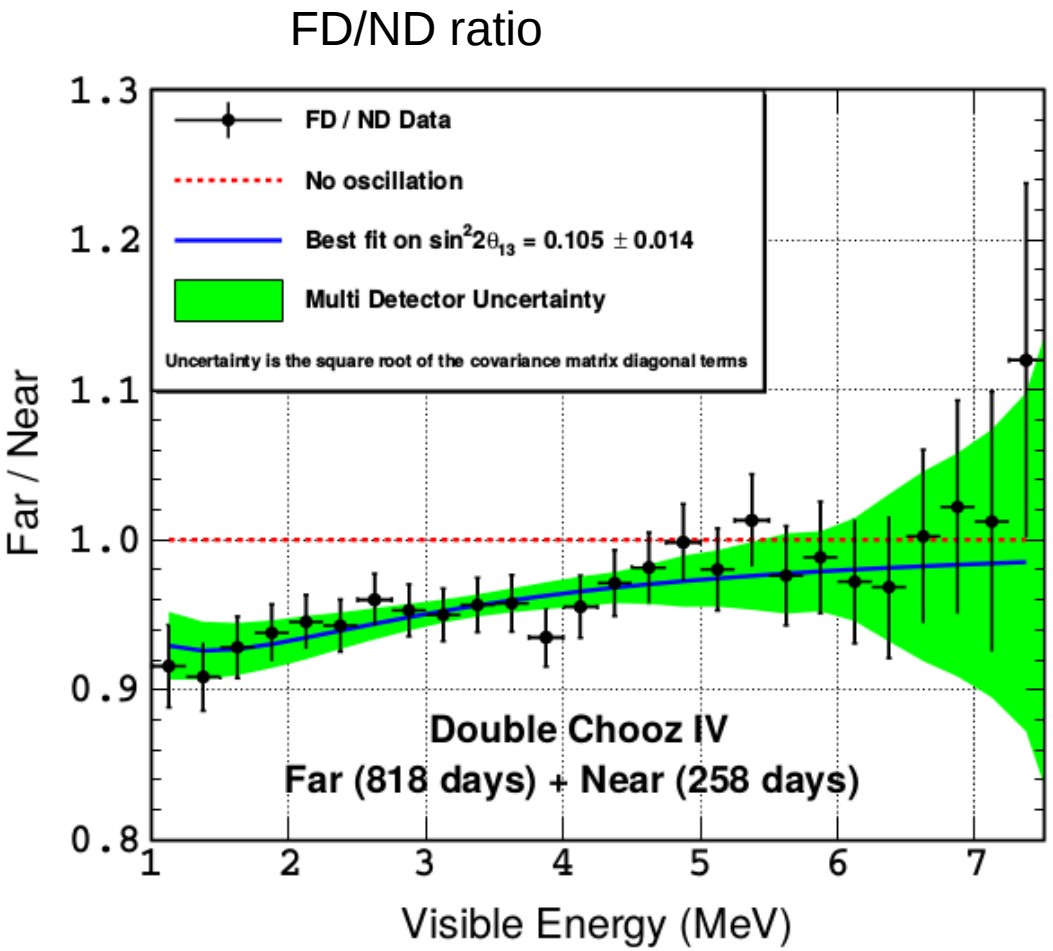


FD



- Data-MC fit using Bugey 4 normalisation
- Best fit resut: **$\sin^2 2\theta_{13} = 0.105 \pm 0.014$**
- Spectral distortion in the 4-6 MeV range

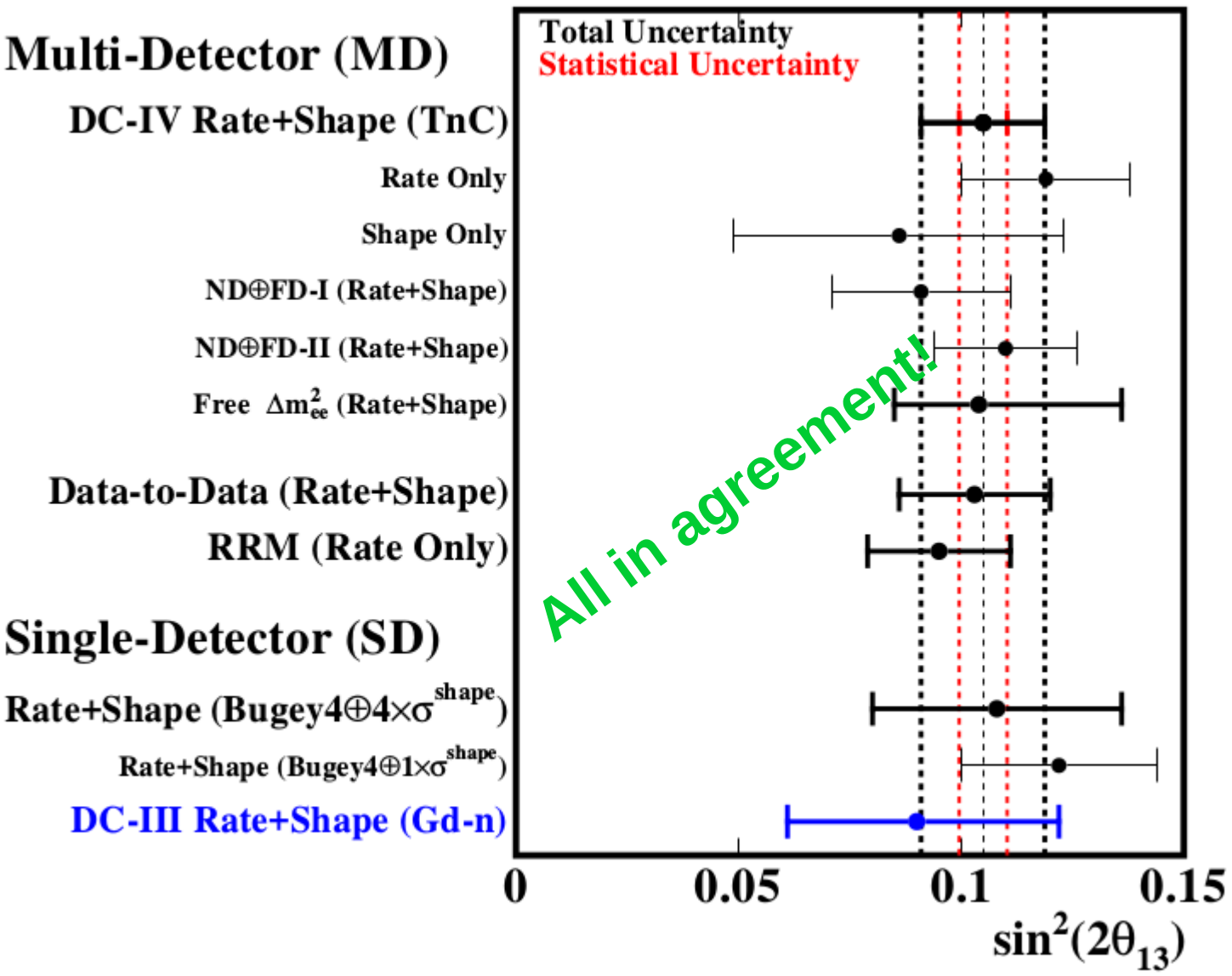
Near-far ratio



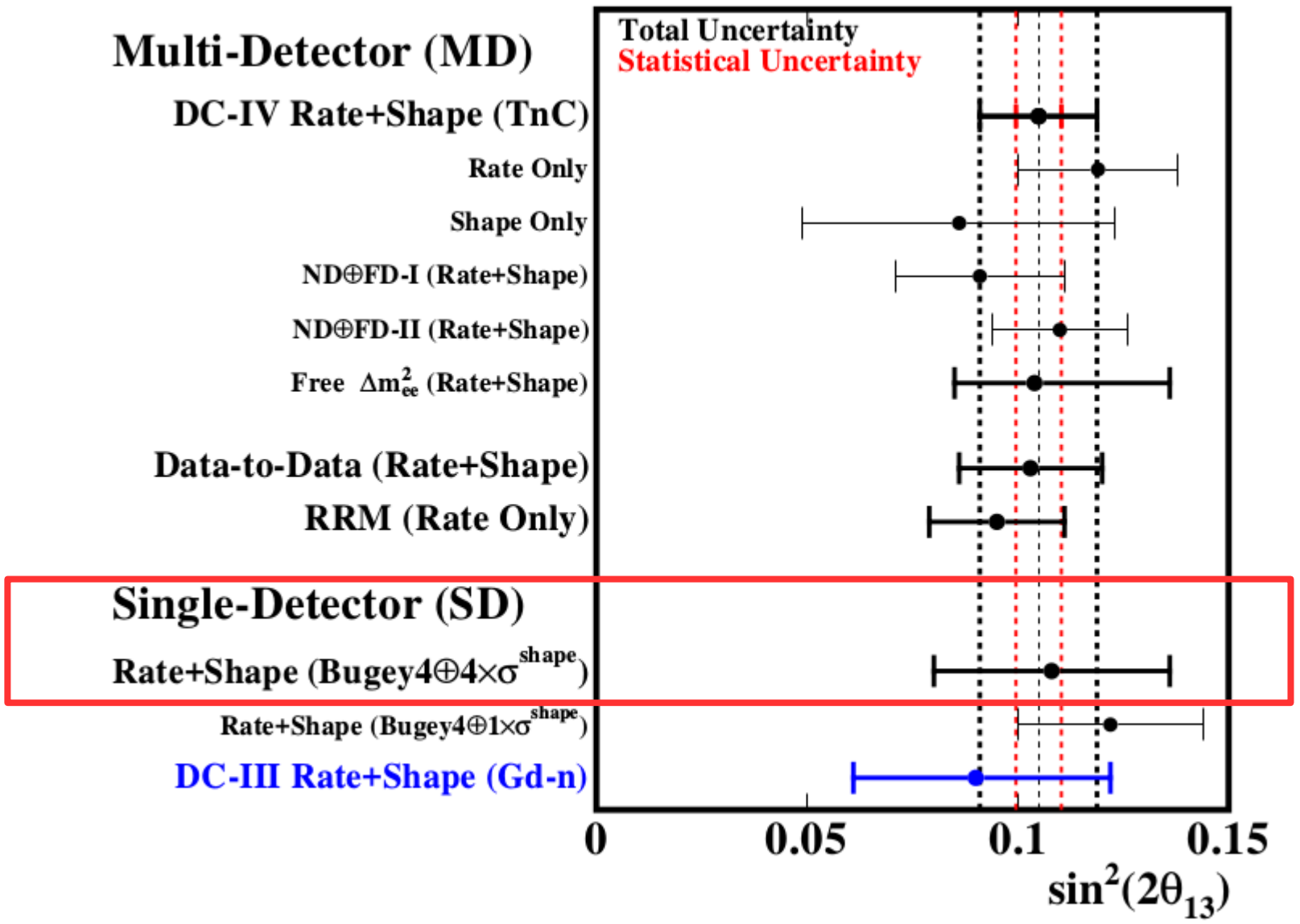
- Observed distortion chancels out in ratio of experimental data
  - Other experiments make the same observation
- **Fit based on near-far ratio: $\sin^2 2\theta_{13} = 0.103 \pm 0.017$**

  => consistent with nominal result

Internal crosschecks



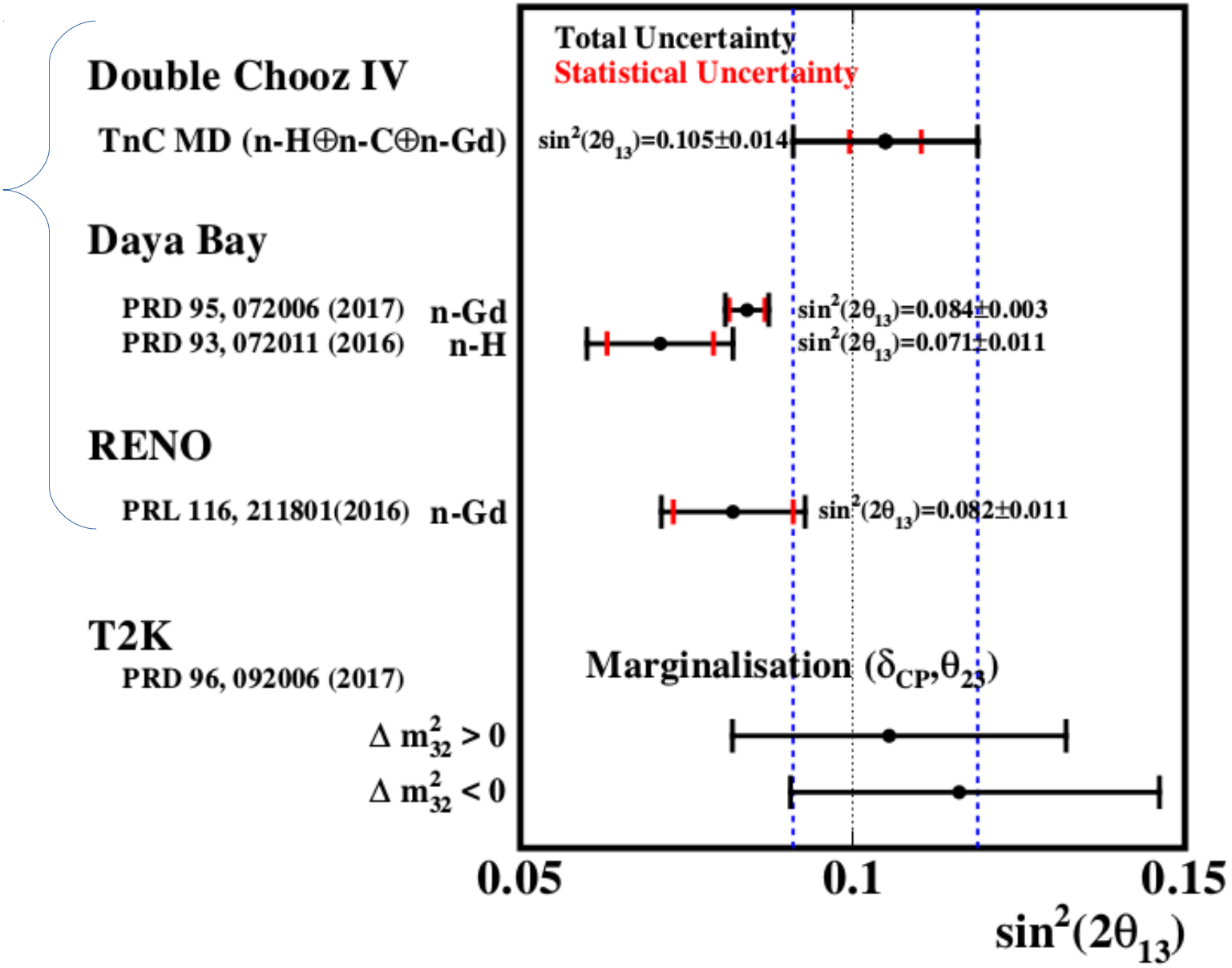
Internal crosschecks



- Most precise single detector measurement!
- Single detector fit with increased error budget becomes effectively unbiased from distortion

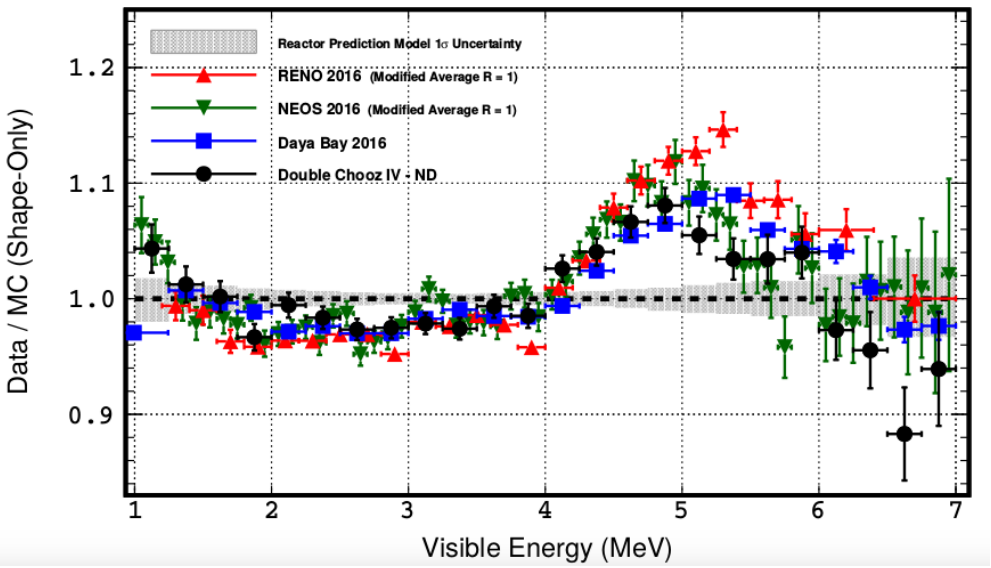
World Comparison

Difference < 2σ

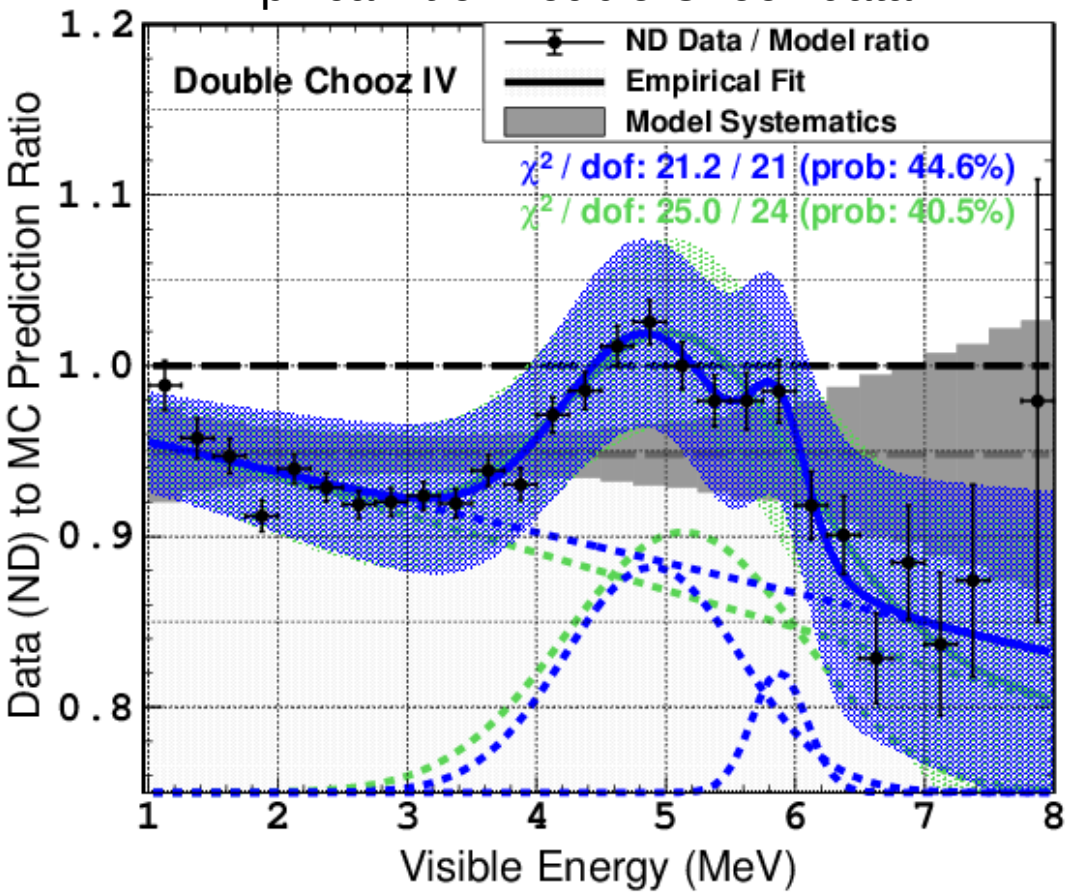


Spectral distortion

Comparison between reactor experiments

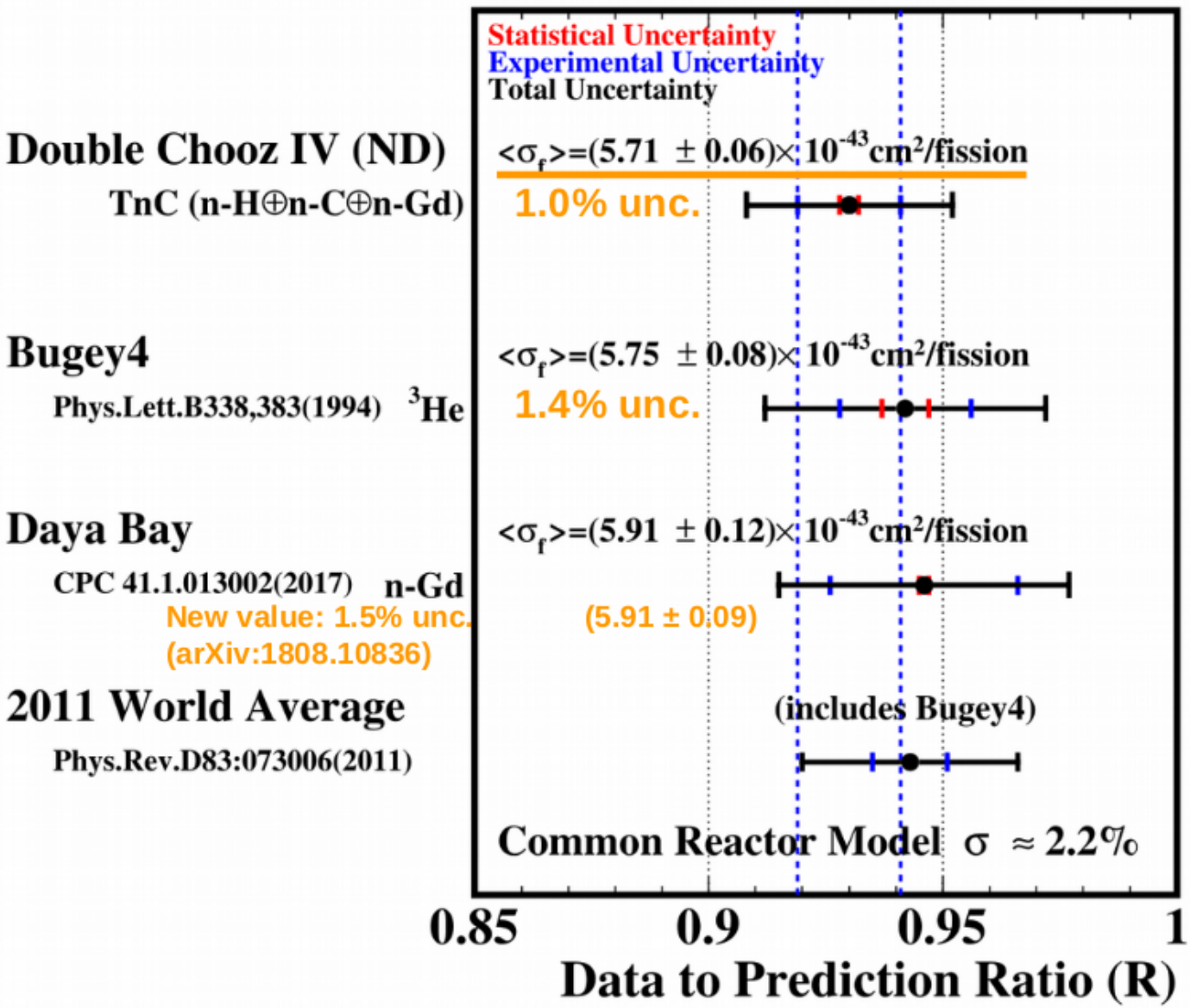


Empirical fit of Double Chooz data



- Observation by other experiments are very similar
- Empirical fit of Double Chooz data is consistent with a negative slope and a double or single Gaussian peak structure

Mean cross section per fission



- **World's most precise measurement is from Double Chooz**

Summary

- Three years of Double Chooz data with two detectors: 2015 – 2017
- Novel IBD selection : Total Neutron Capture (H+Gd+C)
  - Improved statistics
- Good background control (S/B > 10)
  - Background model confirmed with reactor off data
  - ~25 days reactor off data in the final dataset
- New result based on 15 month of data:

  $\sin^2 2\theta_{13} = 0.105 \pm 0.014$

  See also:
  arXiv:1901.09445 [hep-ex]
- Spectral distortion investigation
- Most precise mean cross section per fission results to date:

  $$\langle \sigma_f \rangle = 5.71 \pm 0.06 \cdot 10^{-43} cm^2/\text{fission}$$

- Double Chooz is unfortunately decommissioned
- Analyze the remaining data → increase statistics
- Improve systematics by proton number calibration during dismantling

In Memory of

Herve de Kerret
(Spokesperson 2004 – 2017)

Double Chooz collaboration

Brazil

CBPF
UNICAMP

France

APC (IN2P3)
CEA/IRFU:
- SPP
- SPhN
- SEDI
- SIS
- SENAC

CENBG (IN2P3)
LNCA (IN2P3/CEA)
Subatech (IN2P3)

Germany

EKU Tübingen
MPIK Heidelberg
RWTH Aachen
TU München

Japan

Tohoku U.
Tokyo Inst. Tech.
Tokyo Metro. U.
Tokyo U. Science
Kitasato U.
Kobe U.

Russia

INR RAS
RRC Kurchatov

Spain

CIEMAT-Madrid

USA

Alabama U.
ANL
Chicago U.
Drexel U.
Hawaii U.
Notre Dame U.
Virginia Tech.

Spokesperson:
A. Cabrera (IN2P3/CNRS)

Project Manager:
Ch. Veyssière (CEA)

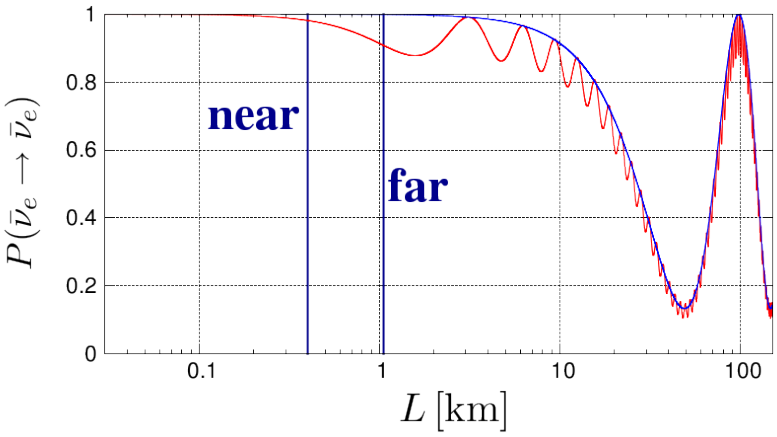
97 scientists 25 institutions (Americas, Asia, Europe)

web: doublechooz.in2p3.fr

Backup

Reactor Neutrino θ_{13} Experiments

- Systematic uncertainties below 1% required to measure small θ_{13} oscillation
- Can not use reactor flux prediction only
- **Several identical detectors at different distances**
  - Near detector measures unosillated flux
  - Far detector measures energy dependent deficit due to disappearance
  - Identical detector design cancels systematics!



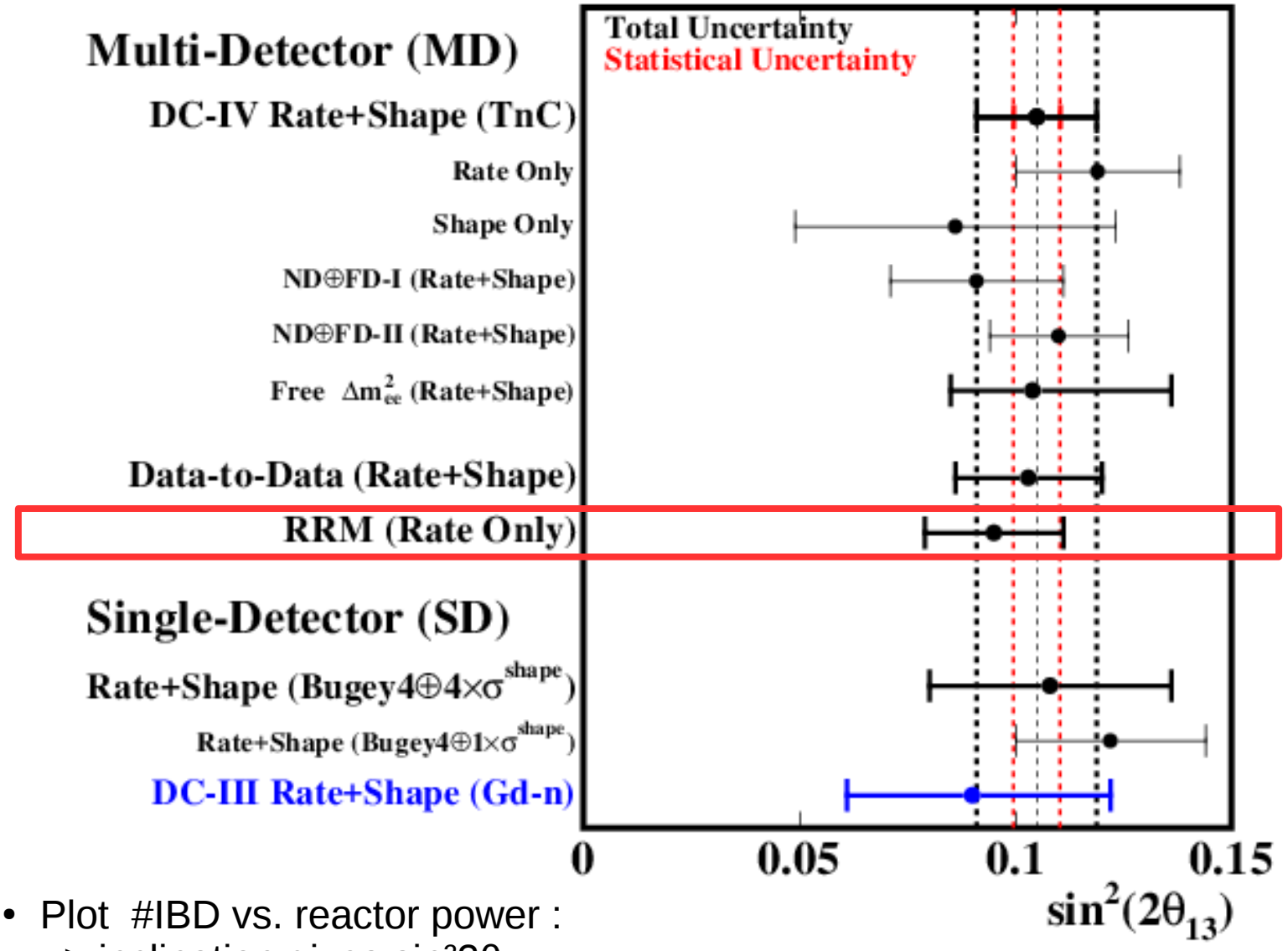
Three major experiment: Double Chooz, RENO, Daya Bay

Chooz reactors
France /Ardenne

YonGwang reactors
South Korea

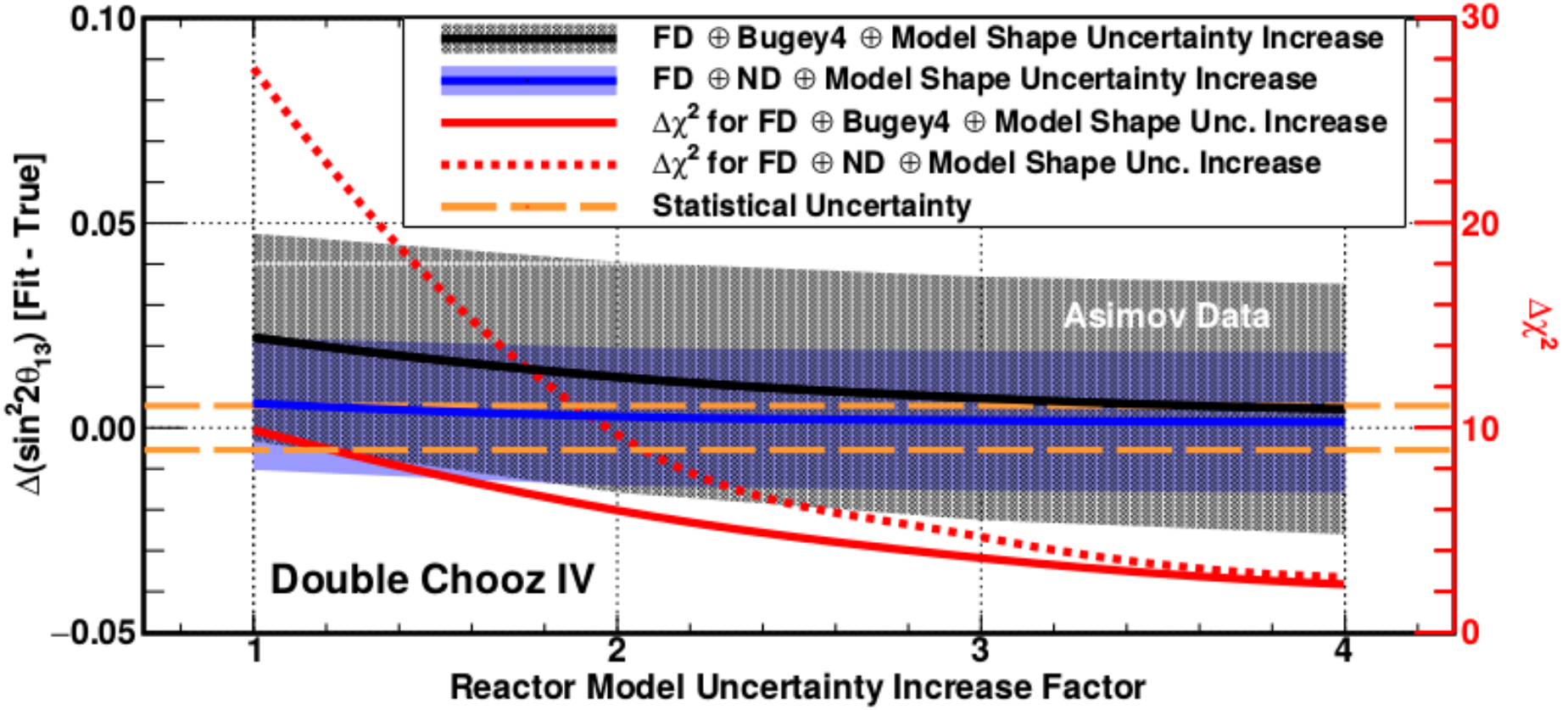
Daya Bay reactors
South China (close Hong Kong)

Reactor Rate Modulation



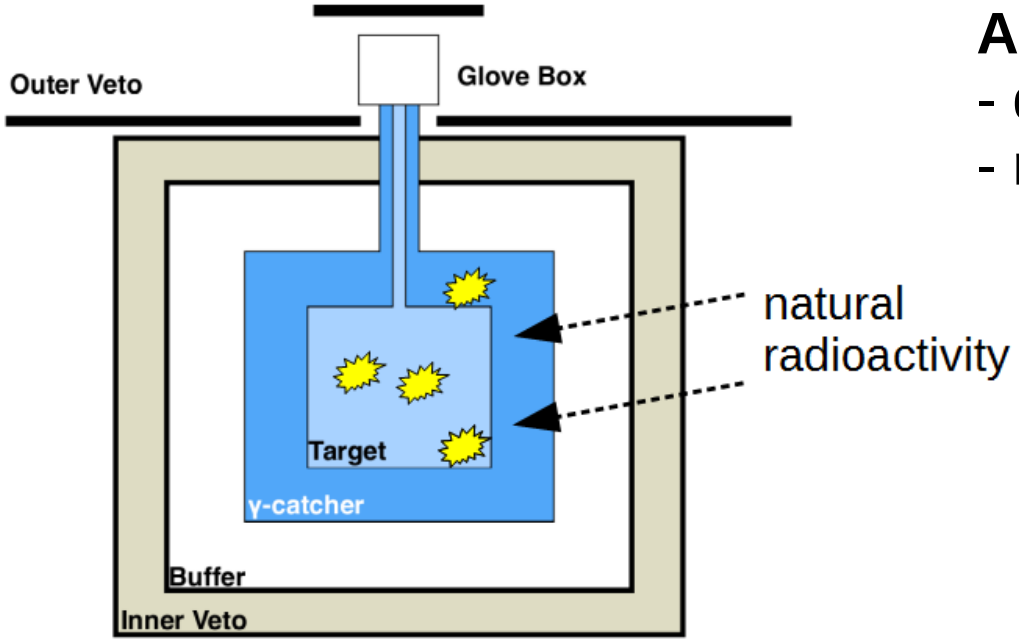
- Plot #IBD vs. reactor power :
  => inclination gives $\sin^2 2\theta_{13}$
- Two detector result: $\sin^2 2\theta_{13}$=

Reactor flux error budget



- 4σ uncertainty increase efficiently removes bias

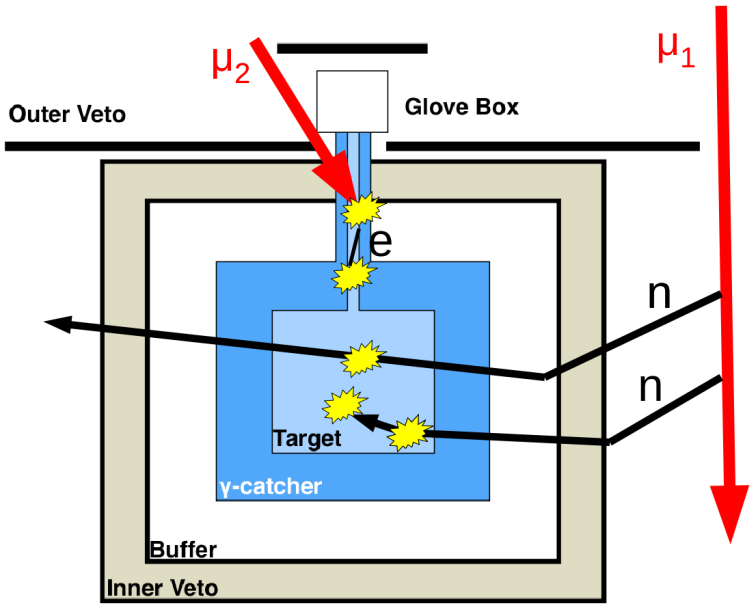
Backgrounds



Accidentals

- due to natural radioactivity
- random coincidence

Backgrounds



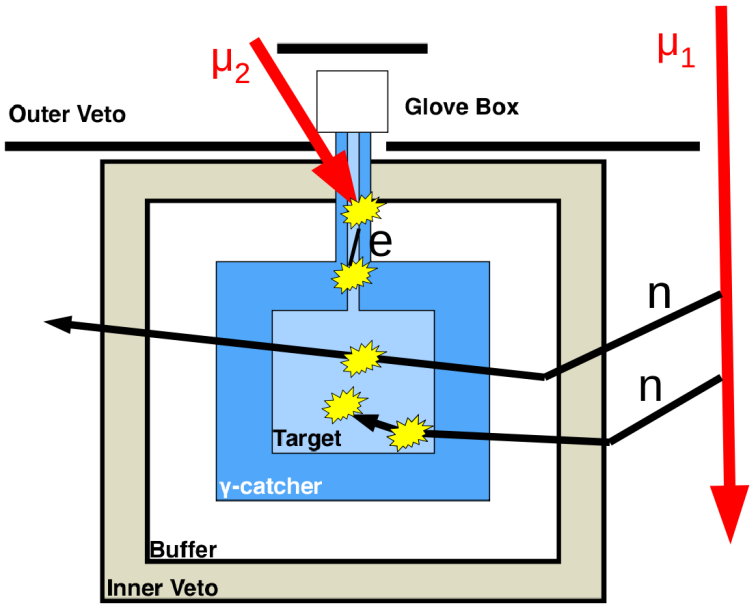
Fast neutrons (FN)

- induced by spallation due to atm. μ (cf. μ_1)
- protein recoil and n-capture may mimic IBD signal

Stopping Muons (SM)

- May enter in particular throught the chimney (cf. μ_2)
- end off the μ-track mimics prompt event
- Michel electron mimics delayed event

Backgrounds



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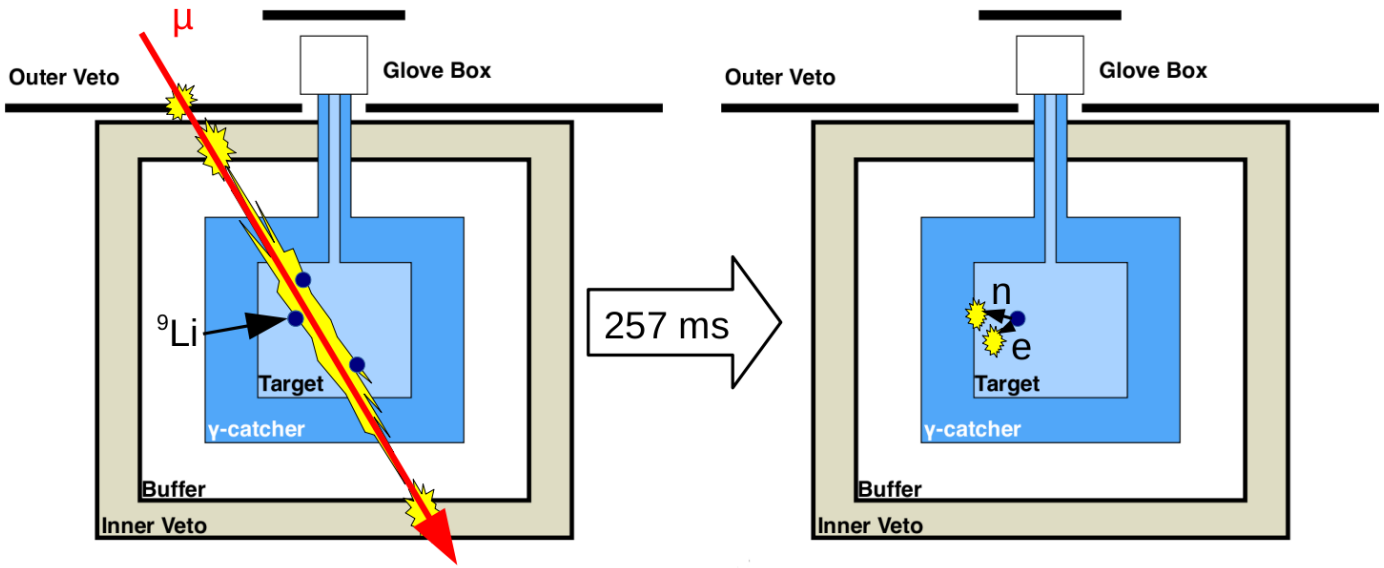


Lithium (Li)
- atm. μ produce long lived β-n decay isotopes ^{9}Li, ^{8}He (257 ms resp. 172 ms mean live time)
- electrons cannot be distinguished from positrons

IBD selection

Single event selection

- Not light noise, muon, or random trigger
- Not within 1.25 ms after a muon

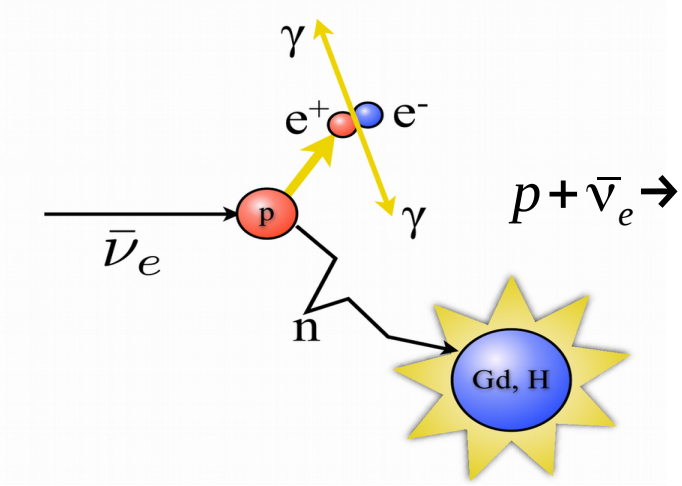
IBD prompt-delayed pair selection

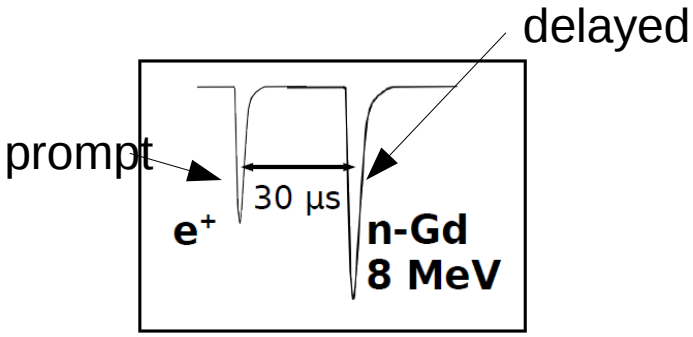
- E_{prompt} , $E_{delayed}$, ΔT, ΔR

Background rejection:

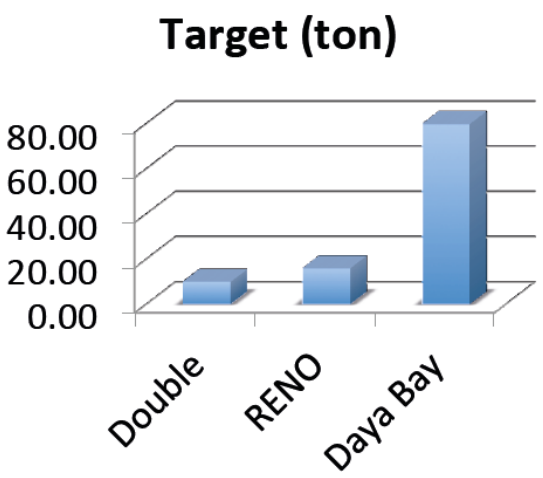
- Multiplicity cut
- No IV, OV coincidence
- Artificial neuronal network (ANN) using $E_{delayed}$, ΔT, ΔR
- Stopping μ veto cut
- Lithium veto cut

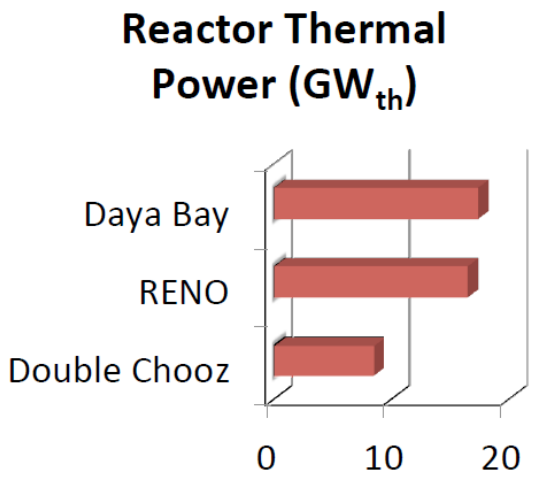
Inverse beta decay IBD





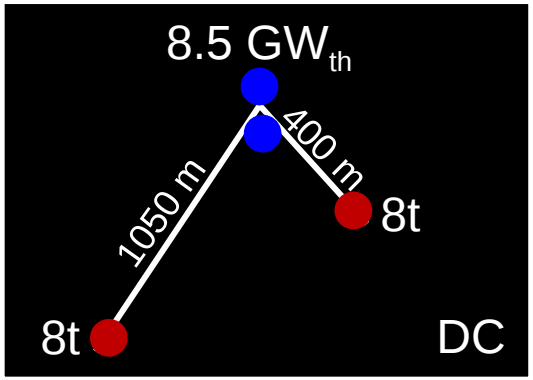
Comparision of Experiments

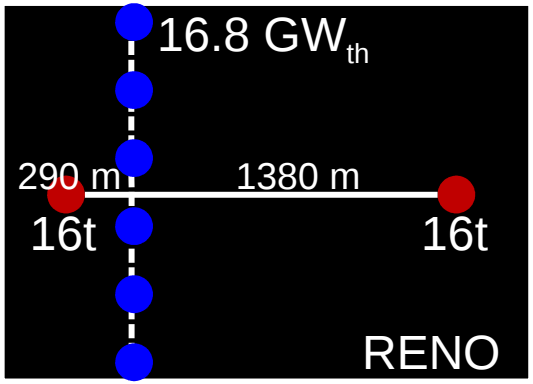


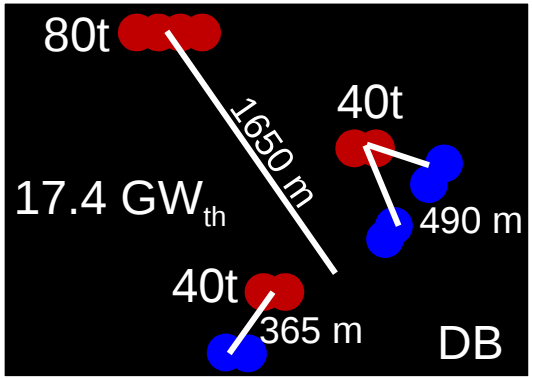


Experiment	Thermal Power (GW)	Distance Near/Far (m)	Depth Near/Far (mwe)	Target mass (ton)
Double Chooz	8,5	400/1050	120/300	8/8
RENO	16,8	290/1380	120/450	16/16
Daya Bay	17,4	360(500)/ 1985(1613)	260/860	40x2/80

- Very similar design

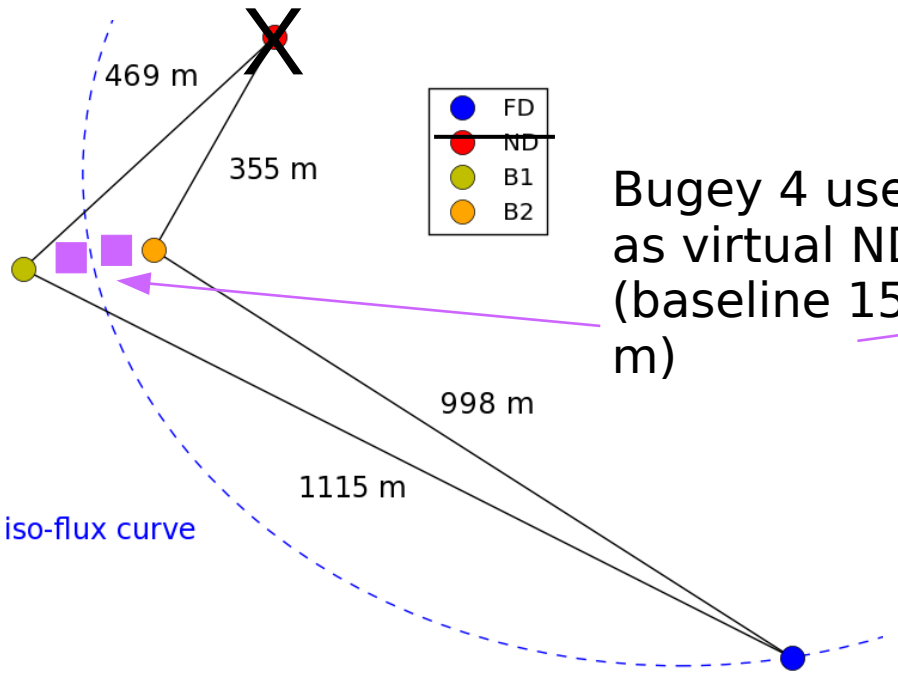






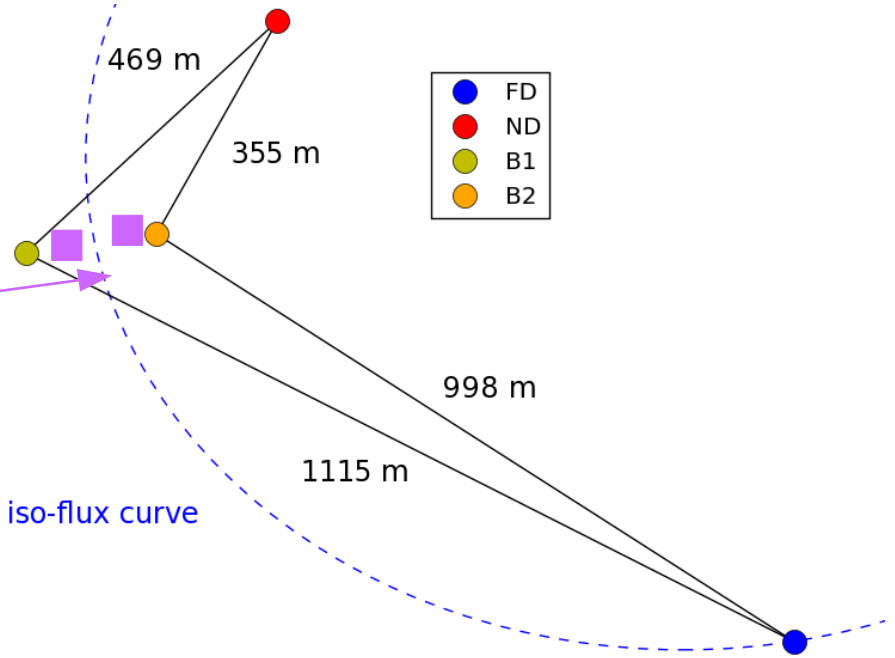
Datasets

Before 2015



Bugey 4 used as virtual ND (baseline 15 m)

Since 2015



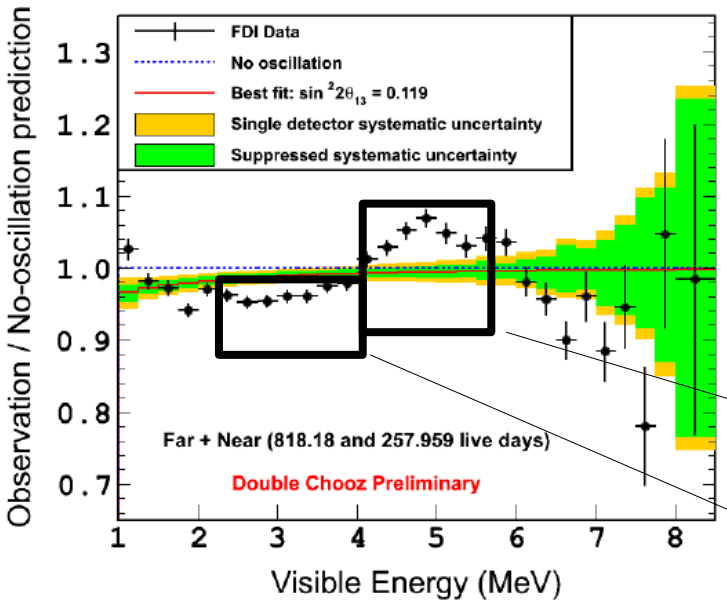
FDI 455 days lifetime
+ 7 days lifetime reactor off

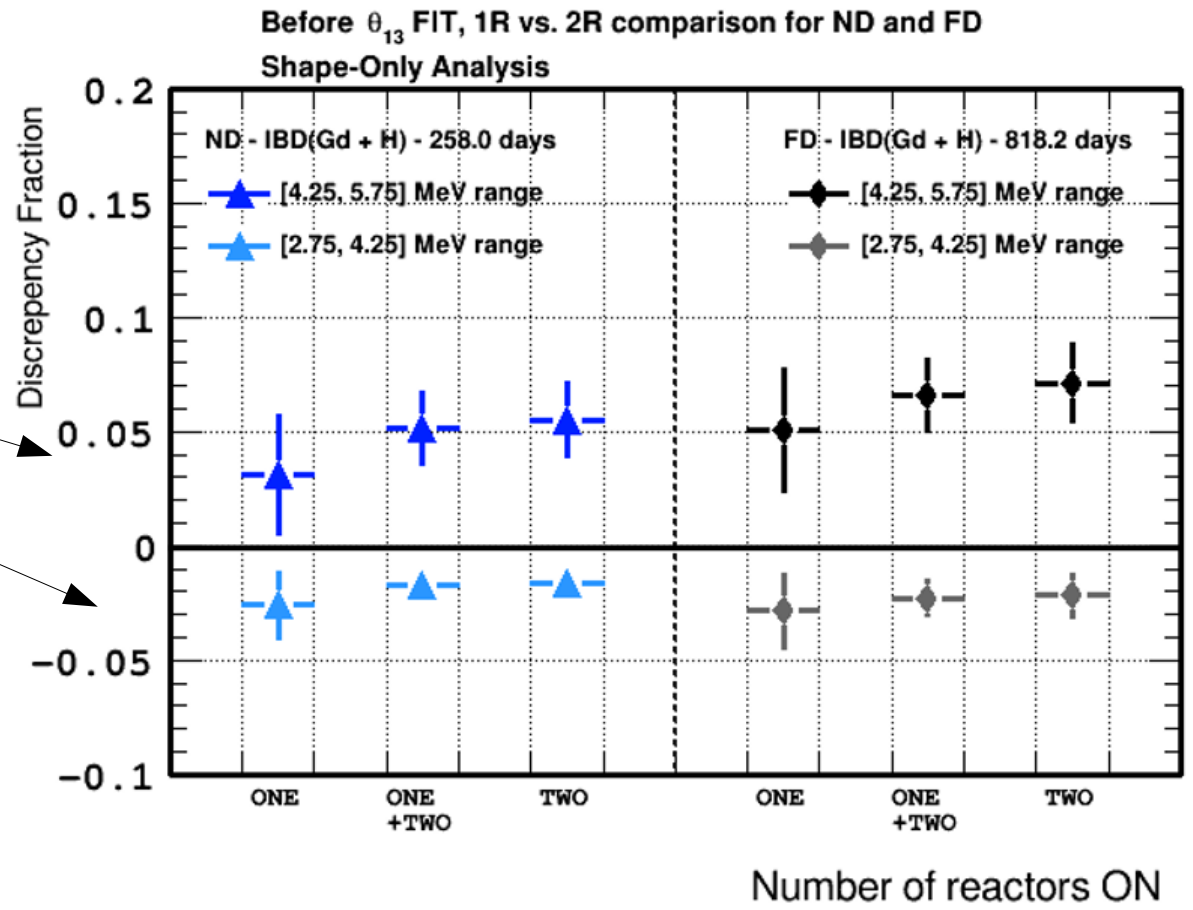
ND 258 days lifetime
FDII 363 days lifetime

Double Chooz has been operated 3 years in full configuration (detectors still running)

Datasets can be combined!

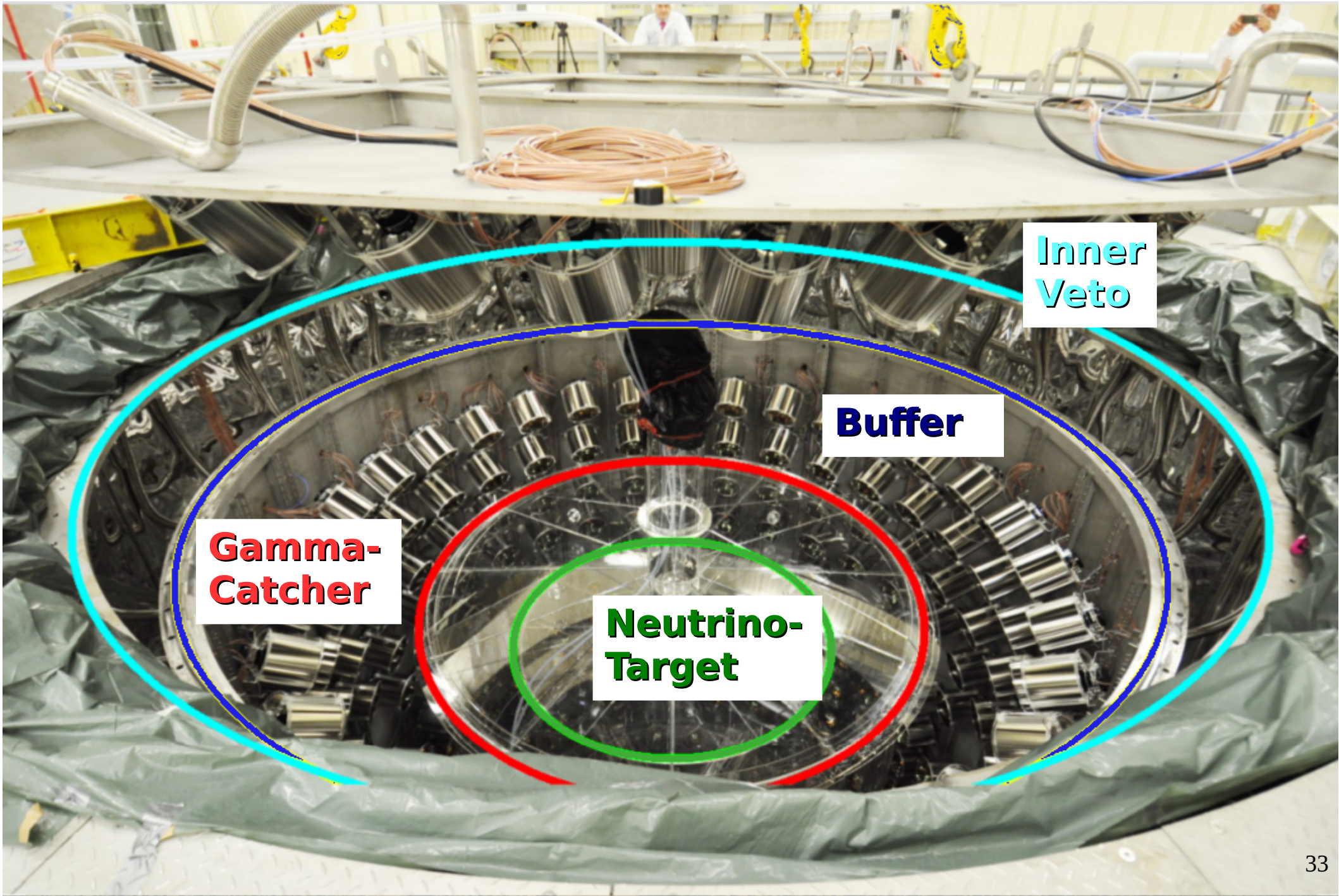
Spectral Distortion vs. Reactor Power



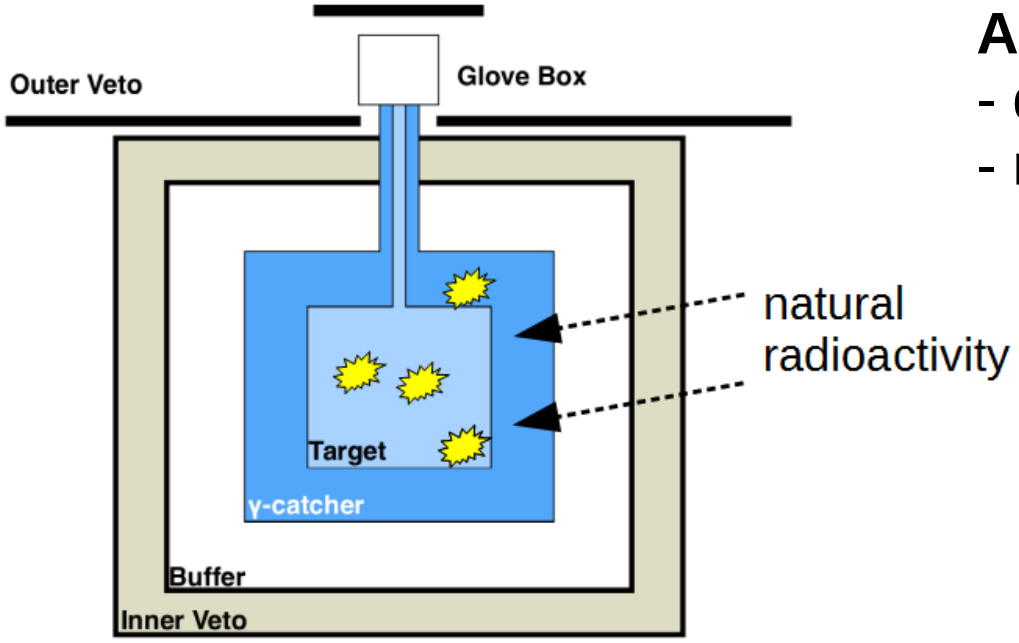


Excess/deficit is consistent to be proportional to reactor power

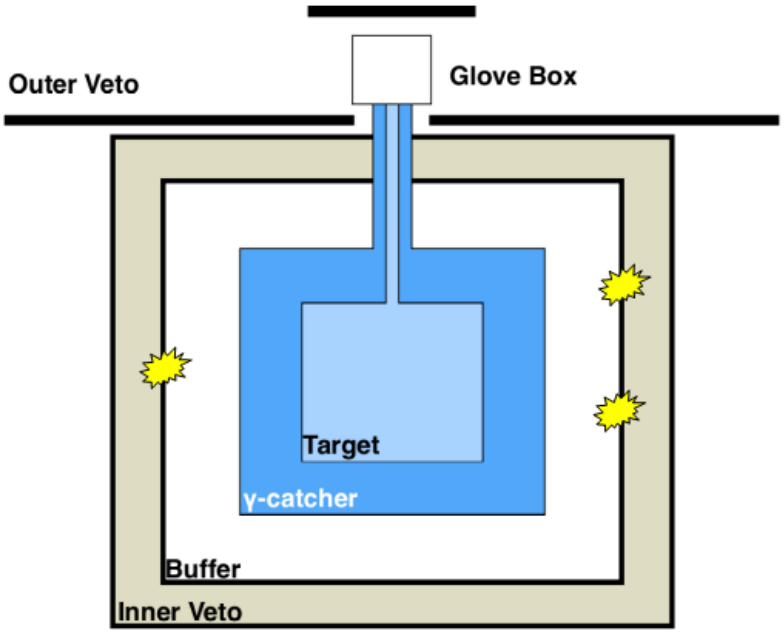
Detector



Uncorrelated Backgrounds

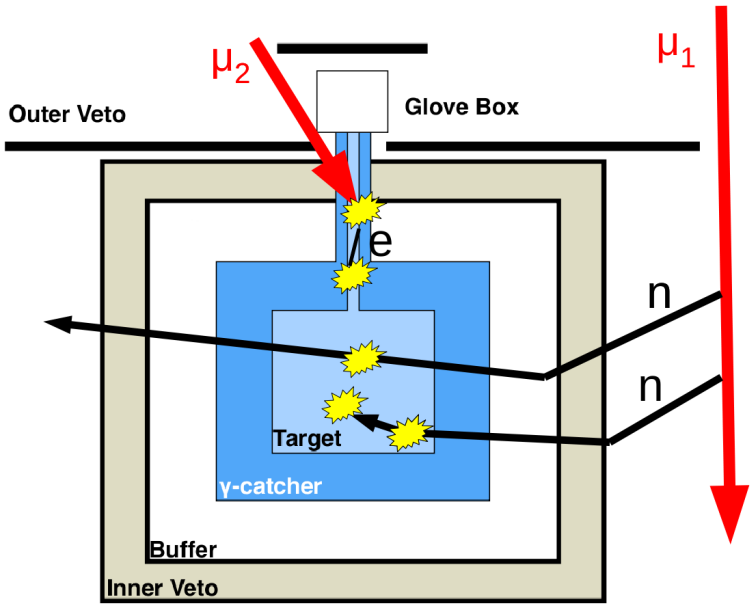


Accidentals
- due to natural radioactivity
- random coincidence



Light Noise
- Light emission by the PMTs themselves
- PMTs mostly light up themselves
  => easy to reject

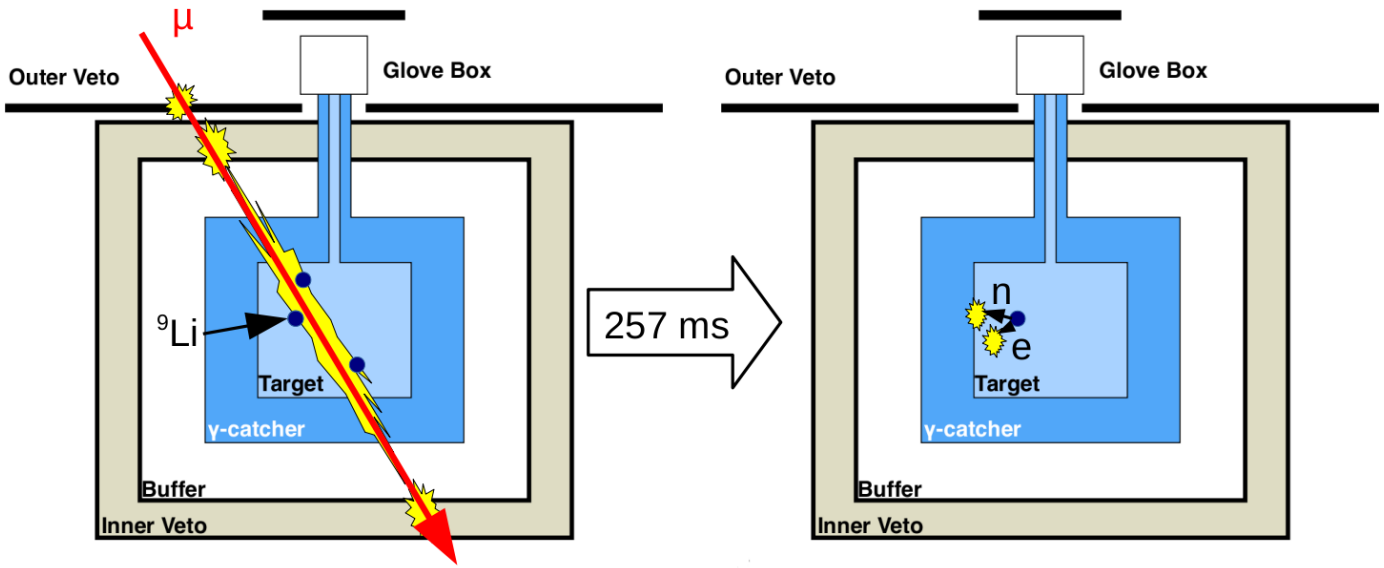
Muon Induced Backgrounds



Crossing muon
- large energy deposit => efficiently rejected

Fast neutrons (FN)
- induced by spallation due to atm. μ (cf. μ_1)
- protein recoil and n-capture may mimic IBD signal

Stopping Muons (SM)
- May enter in particular throught the chimney (cf. μ_2)
- end off the μ-track mimics prompt event
- Michel electron minimcs delayes event

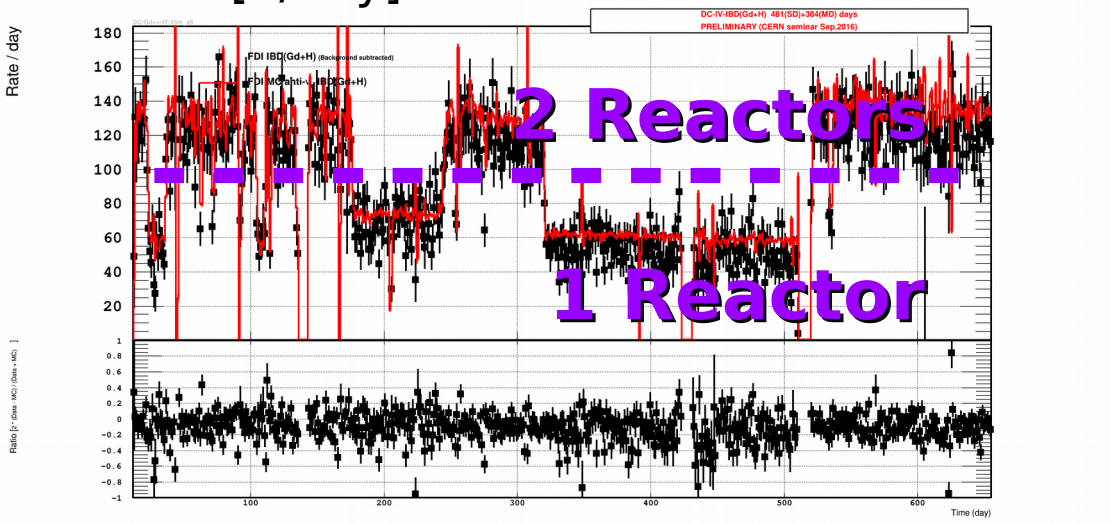


Lithium (Li)
- atm. μ produce long lived β-n decay isotopes ^{9}Li, ^{8}He (257 ms resp. 172 ms mean live time)
- electrons cannot be distinguished from positrons

Datasets

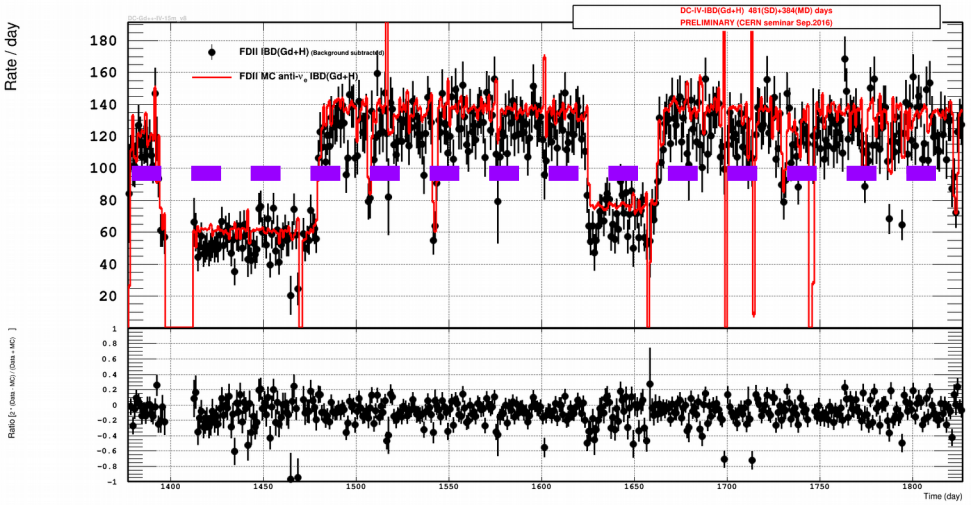
FDI (FD before ND existed) 455 days lifetime + 7 days lifetime reactor off

Rate[1/day] vs. time



FDII (FD parallel to ND) 363 days lifetime

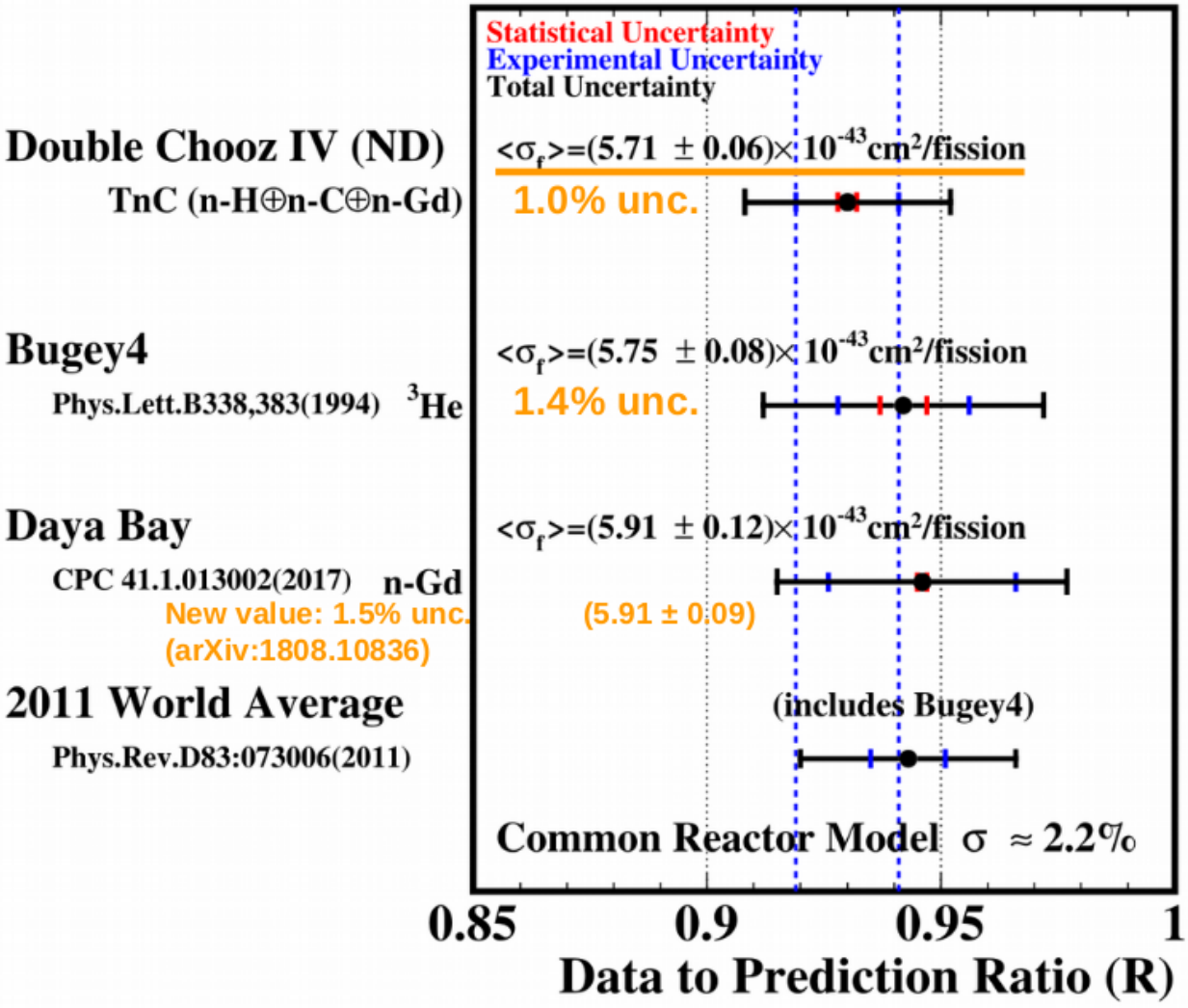
Rate[1/day] vs. time



ND 258 days lifetime

Rate[1/day] vs. time

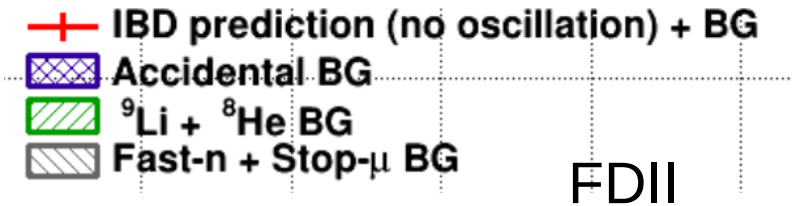
Mean cross section per fission



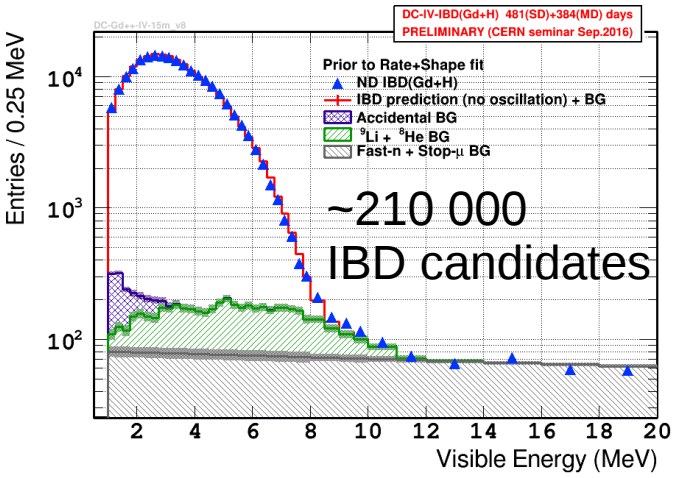
$$N_\nu^{\exp}(t) = \frac{\varepsilon N_p}{4\pi L^2} \times \frac{P_{th}(t)}{\langle E_f \rangle} \times \langle \sigma_f \rangle$$

- **World‘s most precise measurment is from Double Chooz**

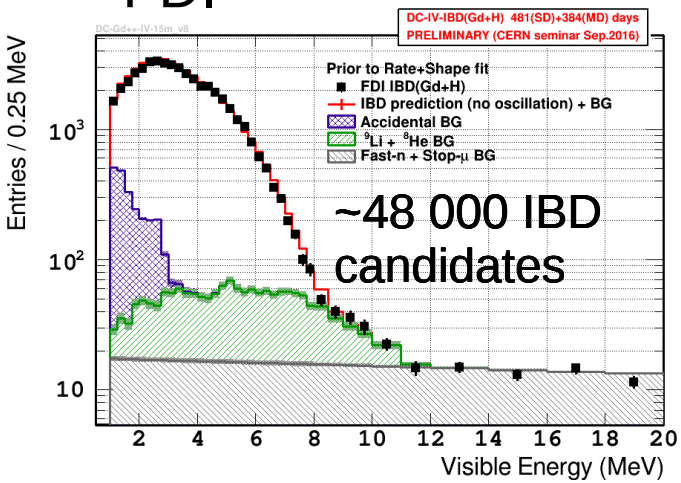
Datasets



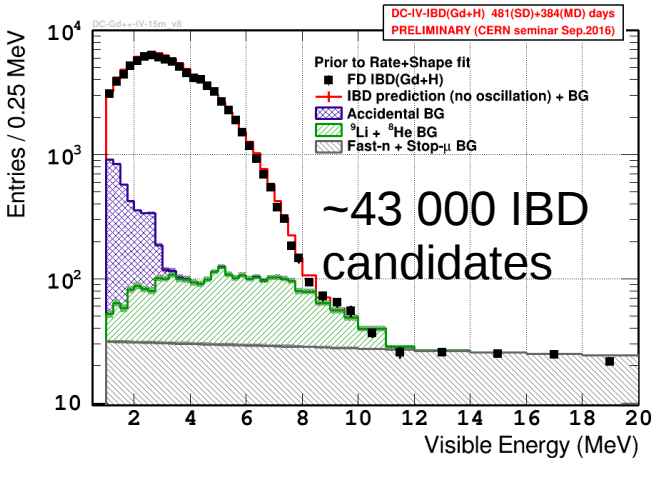
ND



FDI



FDII



+ FDI Reactor-Off dataset
(highly constrainting backgrounds!!!)

- Official data taking ended
- More data on disc! (~ Factor 2 for ND and FDII)