Latest Results of Double Chooz

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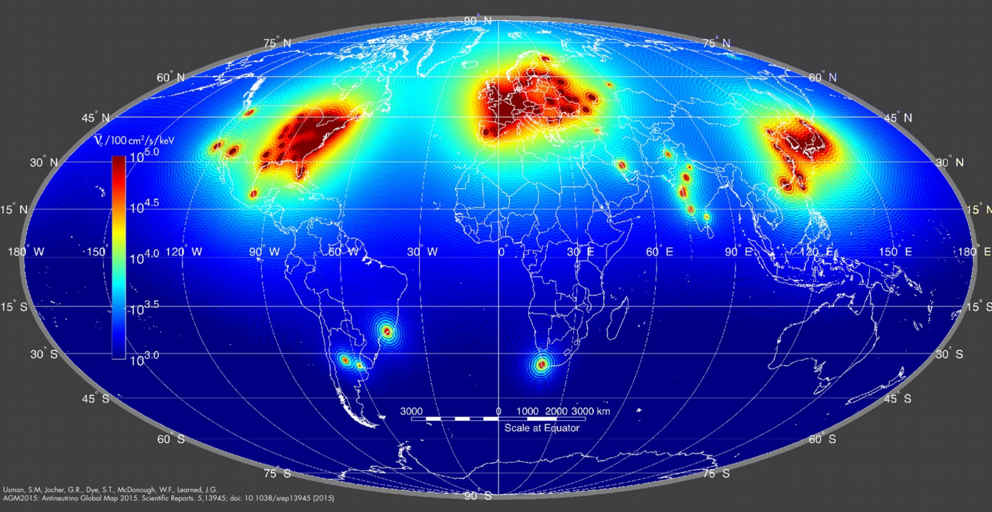
for the
Double Chooz Collaboration

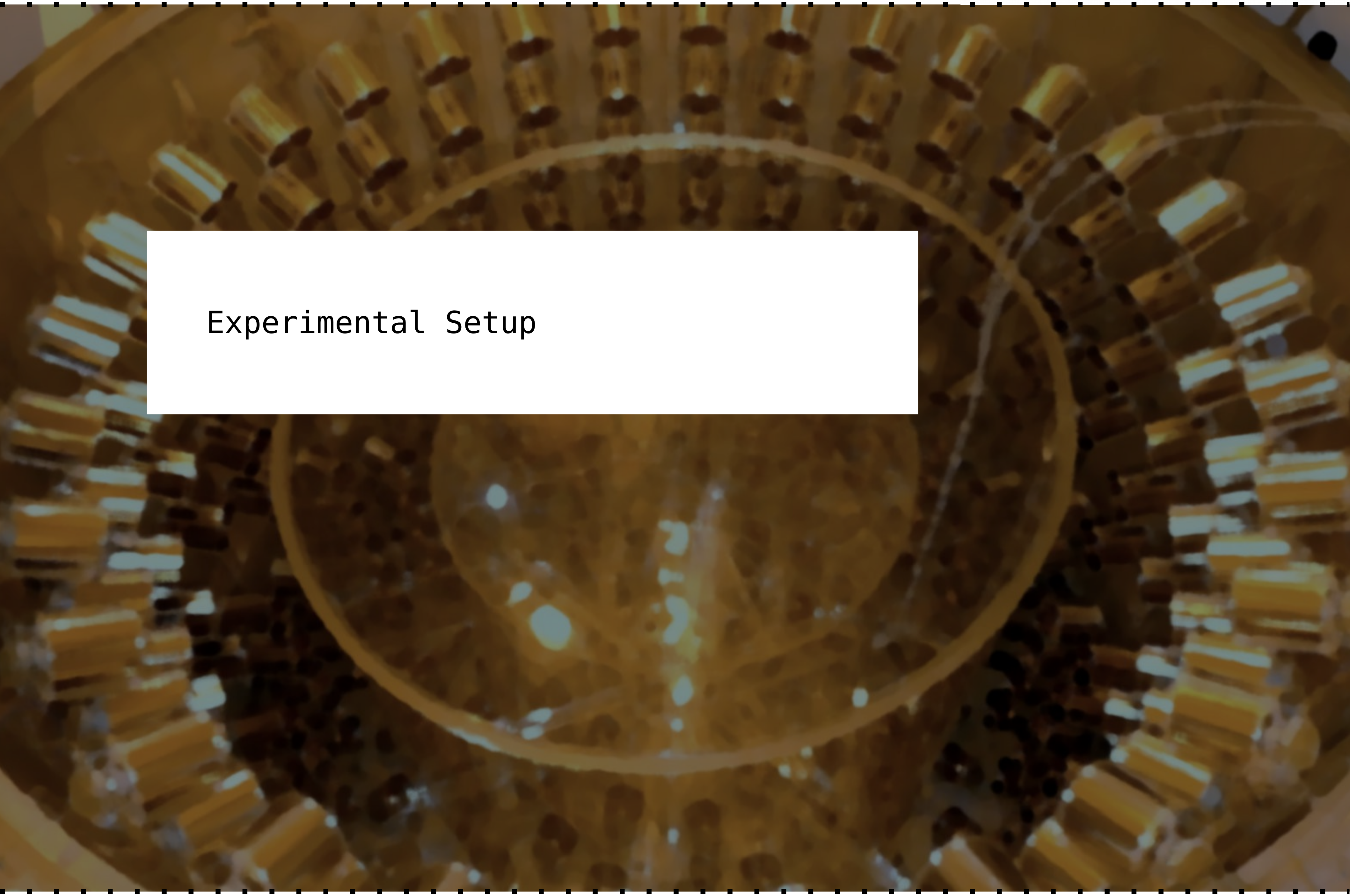
Outline

- Experimental Setup
- The Neutrino Detection
- The Two Detector Dataset
- Oscillation Analysis
- Summary/Outlook

3 MeV reactor antineutrino oscillations worldwide:



Antineutrino Global Map 2015, Sci.Rep. 5 (2015) 13945

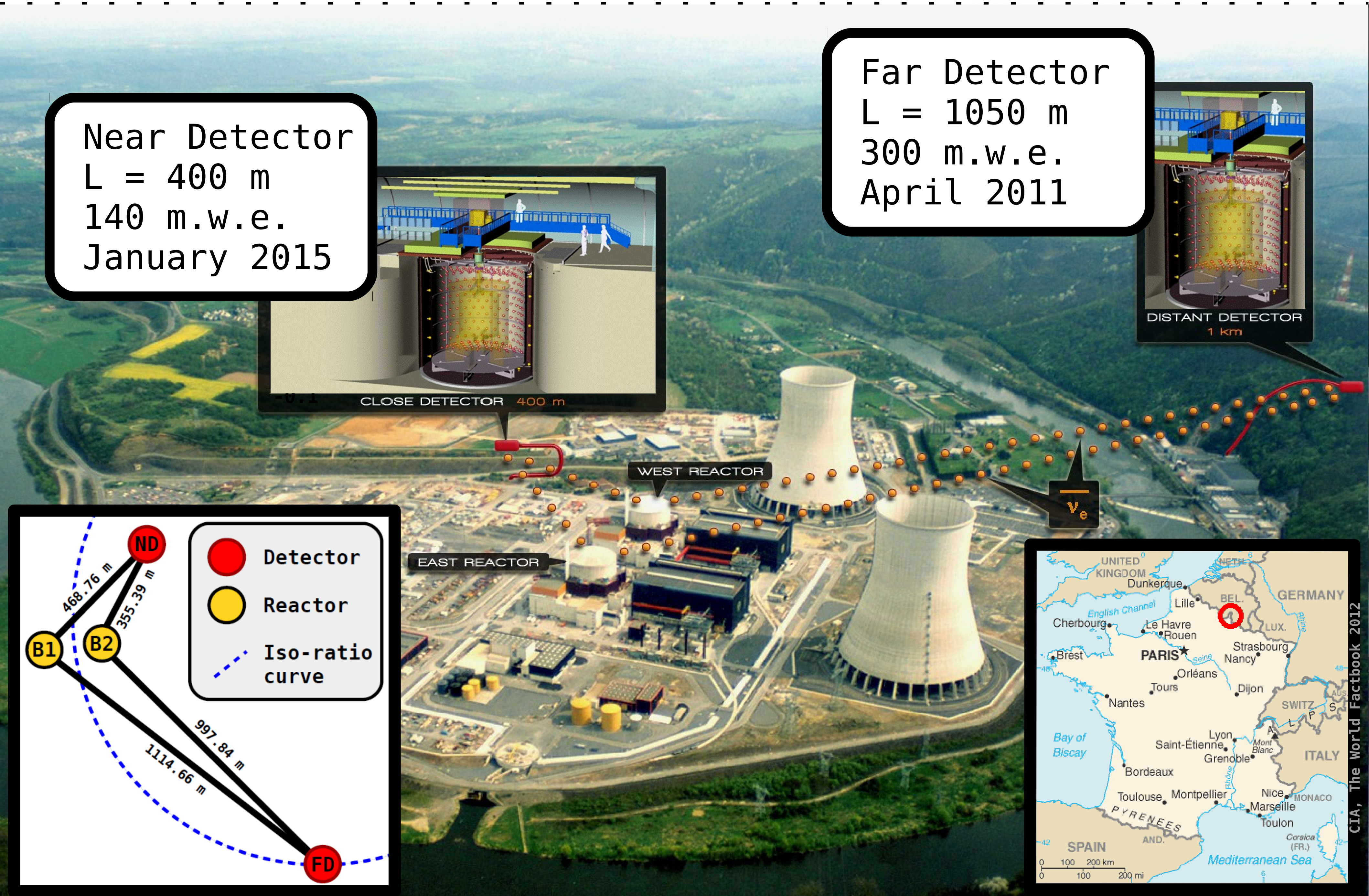


Experimental Setup

Experimental Site

Near Detector
L = 400 m
140 m.w.e.
January 2015

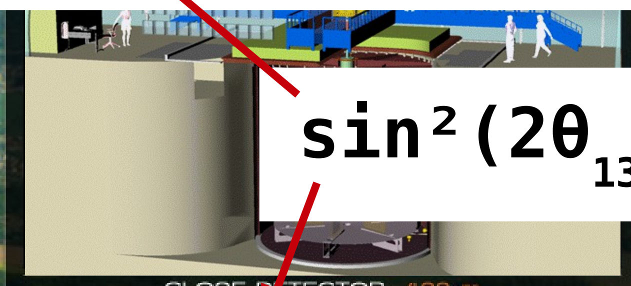
Far Detector
L = 1050 m
300 m.w.e.
April 2011

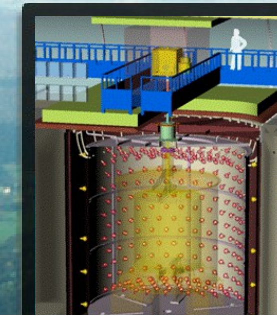


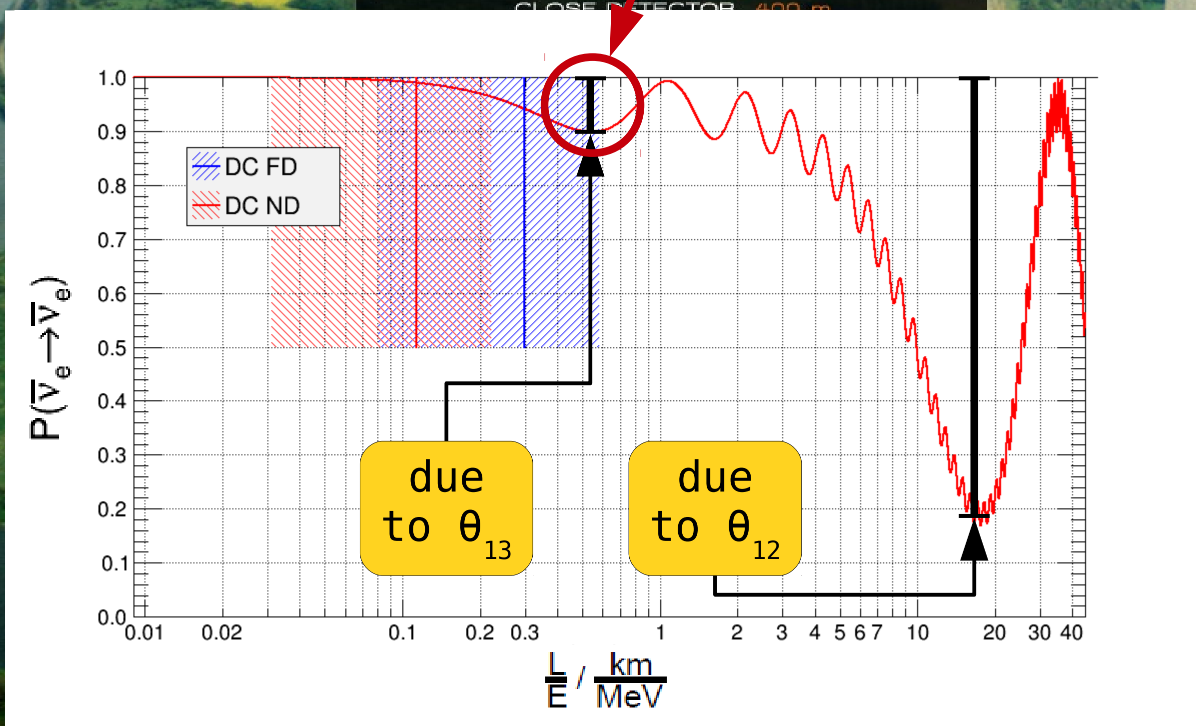
Double Chooz: $\bar{\nu}_e$ disappearance

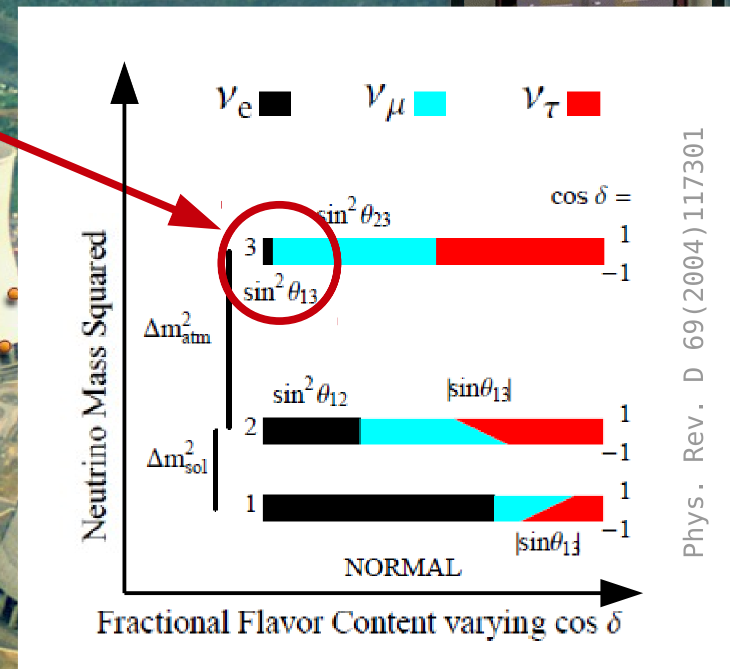
$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \alpha^2 \left(\frac{\Delta m^2_{31} L}{4E}\right)^2 \cos^4(\theta_{13}) \sin^2(2\theta_{12}).$$

$\sin^2(2\theta_{13})$

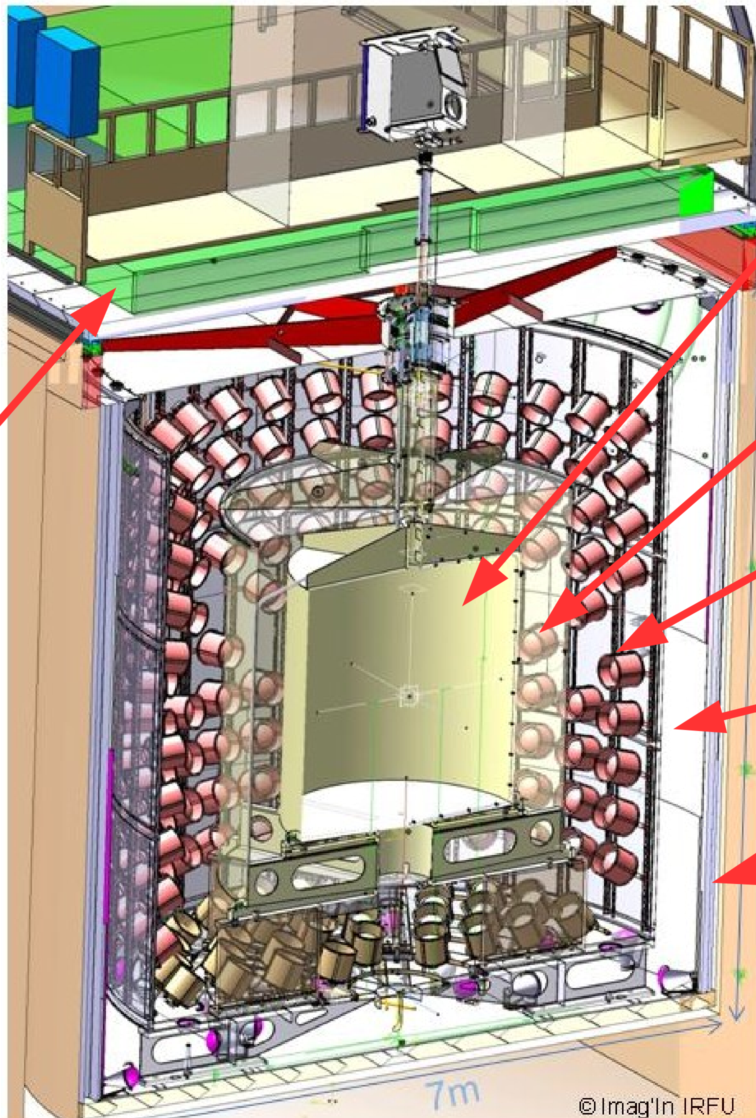








The Detectors



Onion Shape:

Target
→ fiducial volume
→ 10.3 m³ liquid scintillator
→ doped with Gadolinium (Gd)

transparent acrylic vessel

γ-Catcher
→ 22.4 m³ liquid scintillator
→ w/o Gd

transparent acrylic vessel

Buffer
→ 110 m³ non-scintillating oil
→ 390 PMTs (10”)

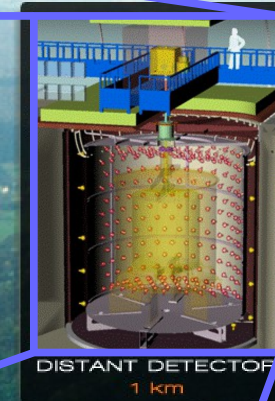
steel tank

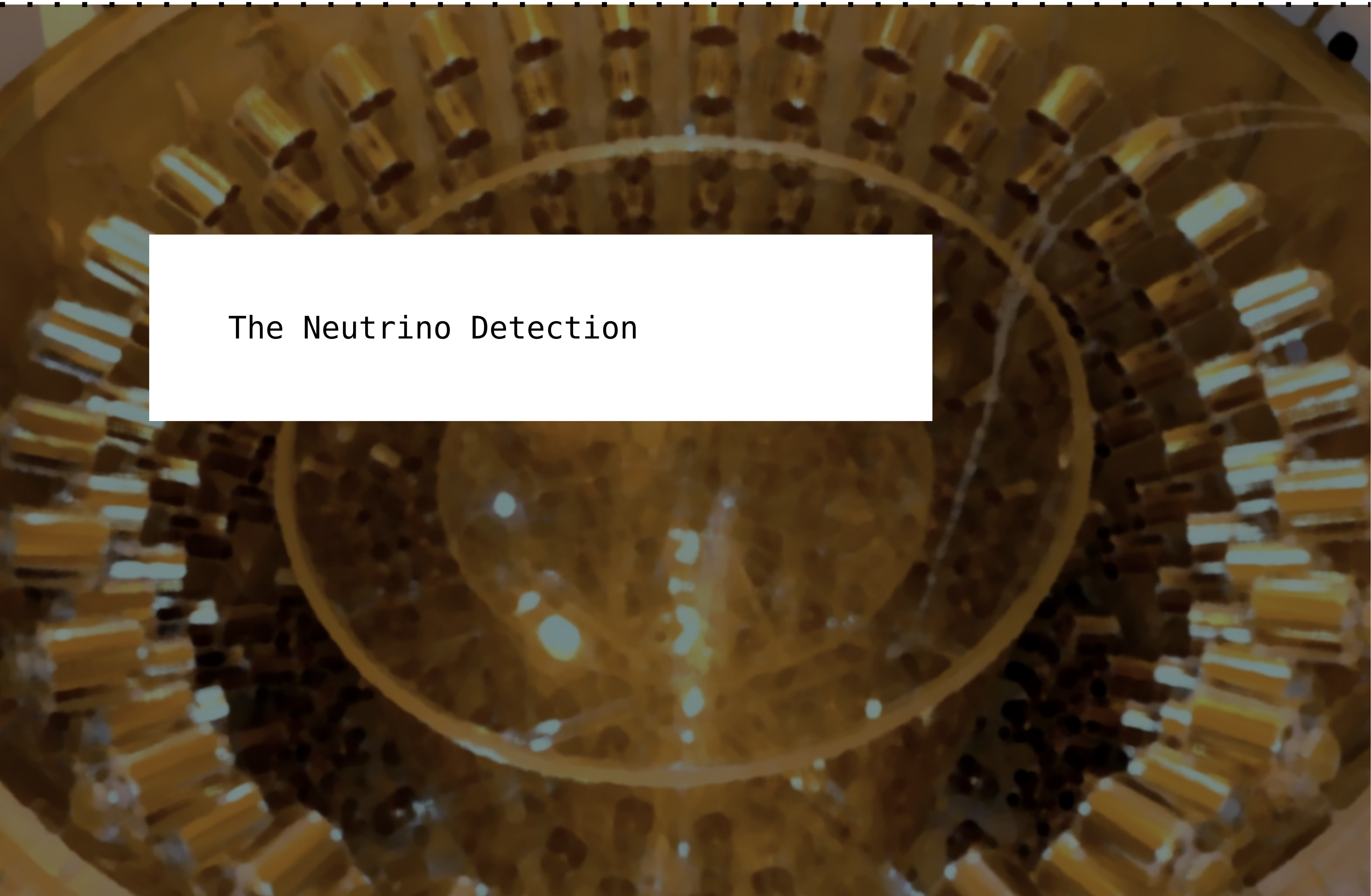
Inner Veto
→ 90 m³ liquid scintillator
→ 78 PMTs (8”)

steel tank

Shielding
→ top: 17cm steel
→ bottom/side: 17 cm steel/1 m water

Outer Veto
→ plastic scintillator strips
→ extents beyond cylindrical parts



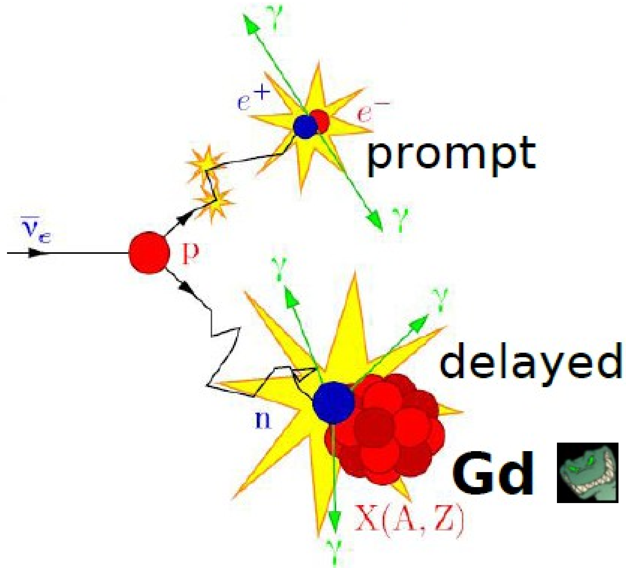


The Neutrino Detection

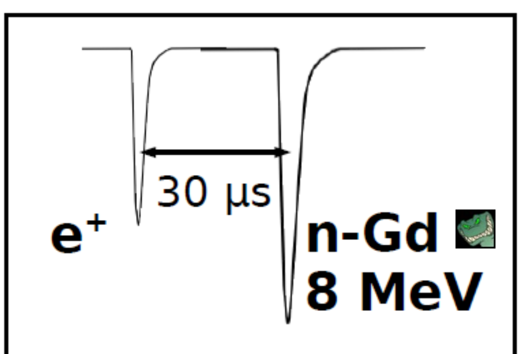
Neutrino signal

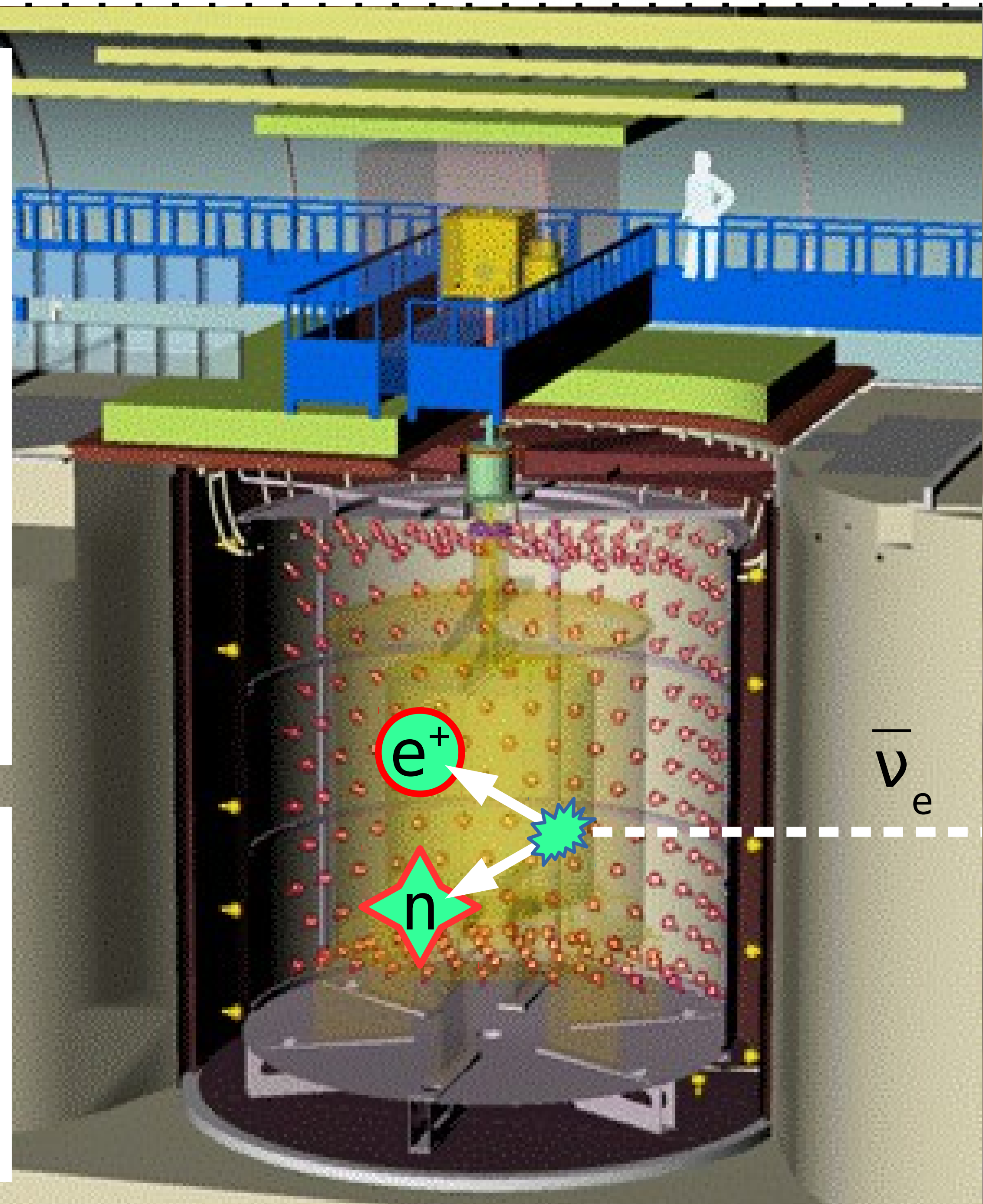
Inverse beta-decay:

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



Delay due to thermalisation of neutron before capture





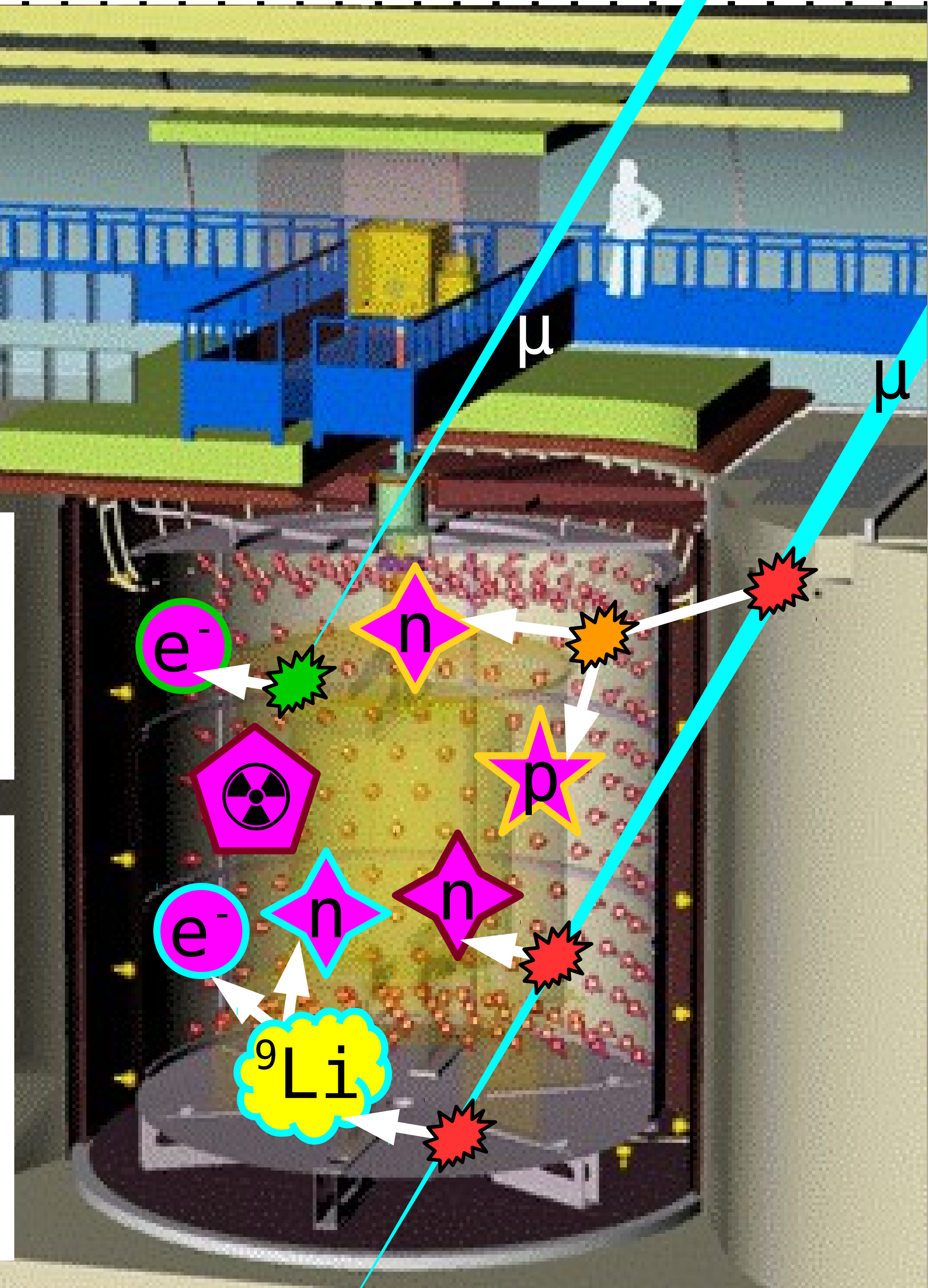
Backgrounds

Detection:
→ measured in experiment
→ vetoed by Outer or Inner Veto
Sources:
→ atmospheric muons
→ intrinsic radioactivity

Backgrounds:
→ mimic inverse-β-decays (IBDs)

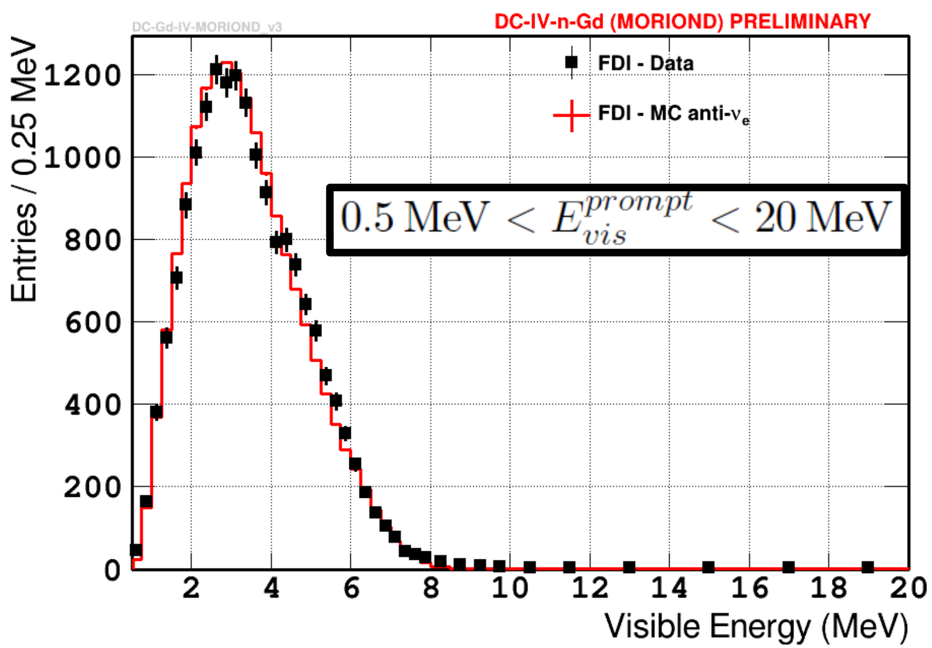
Uncorrelated (accidentals):
→ intrinsic radioactivity + spallation neutrons

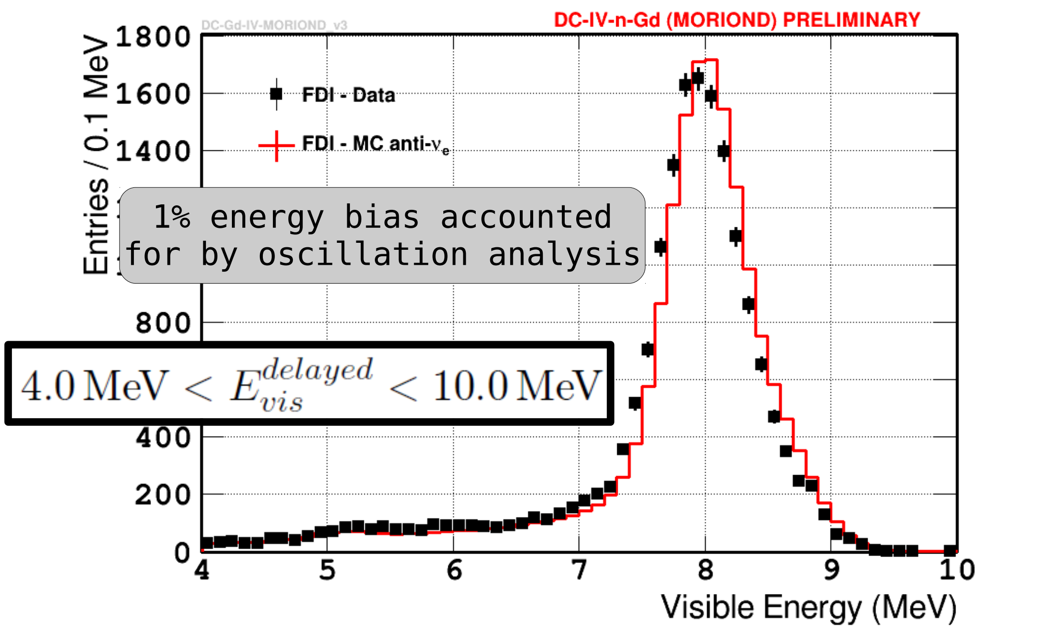
Correlated:
→ fast neutrons (FN): p recoil + n capture
→ stopping μ (SM): μ + Michel electron
→ unstable isotopes (9Li/8He): β-n decay

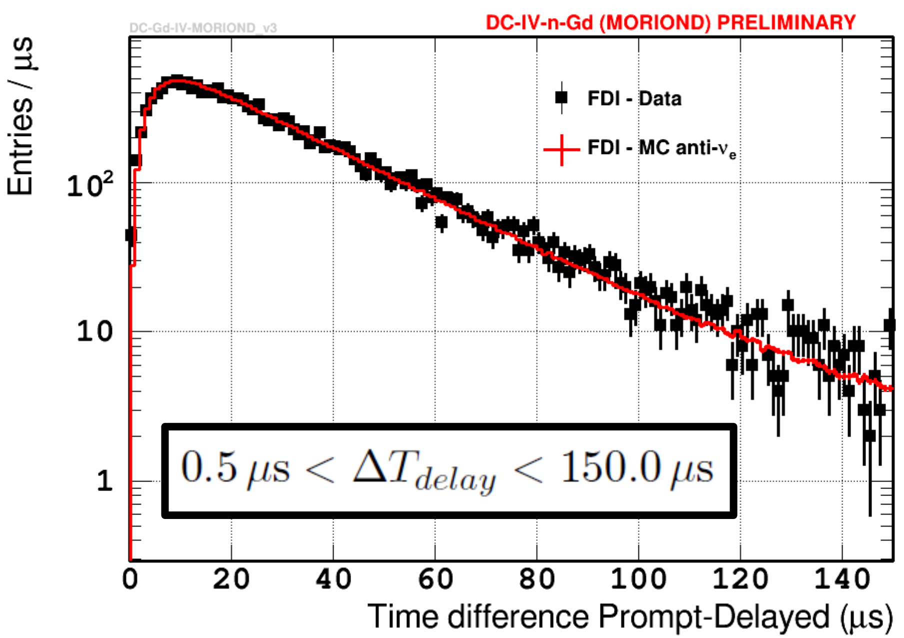


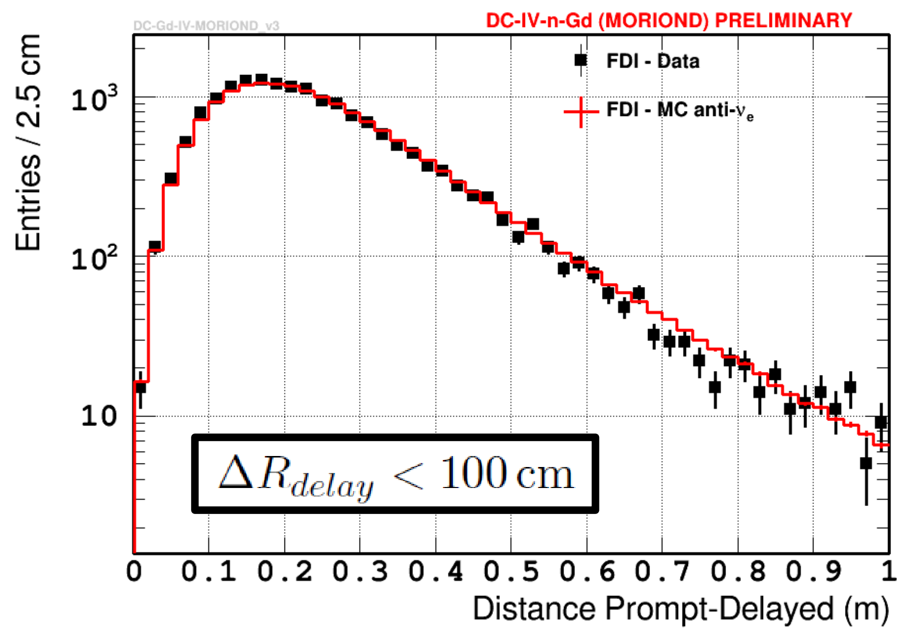
The Two Detector Dataset

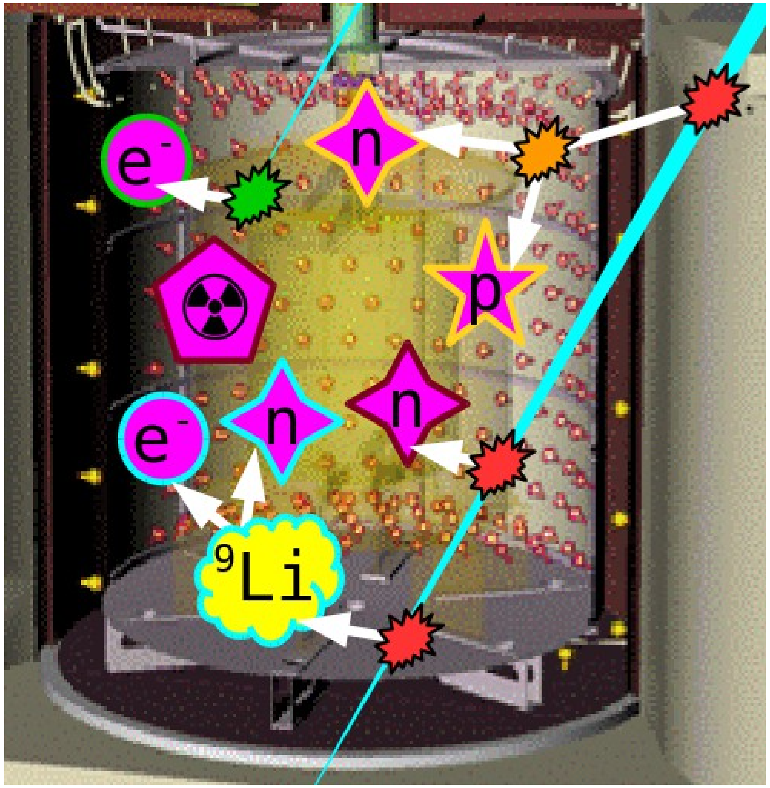
IBD selection





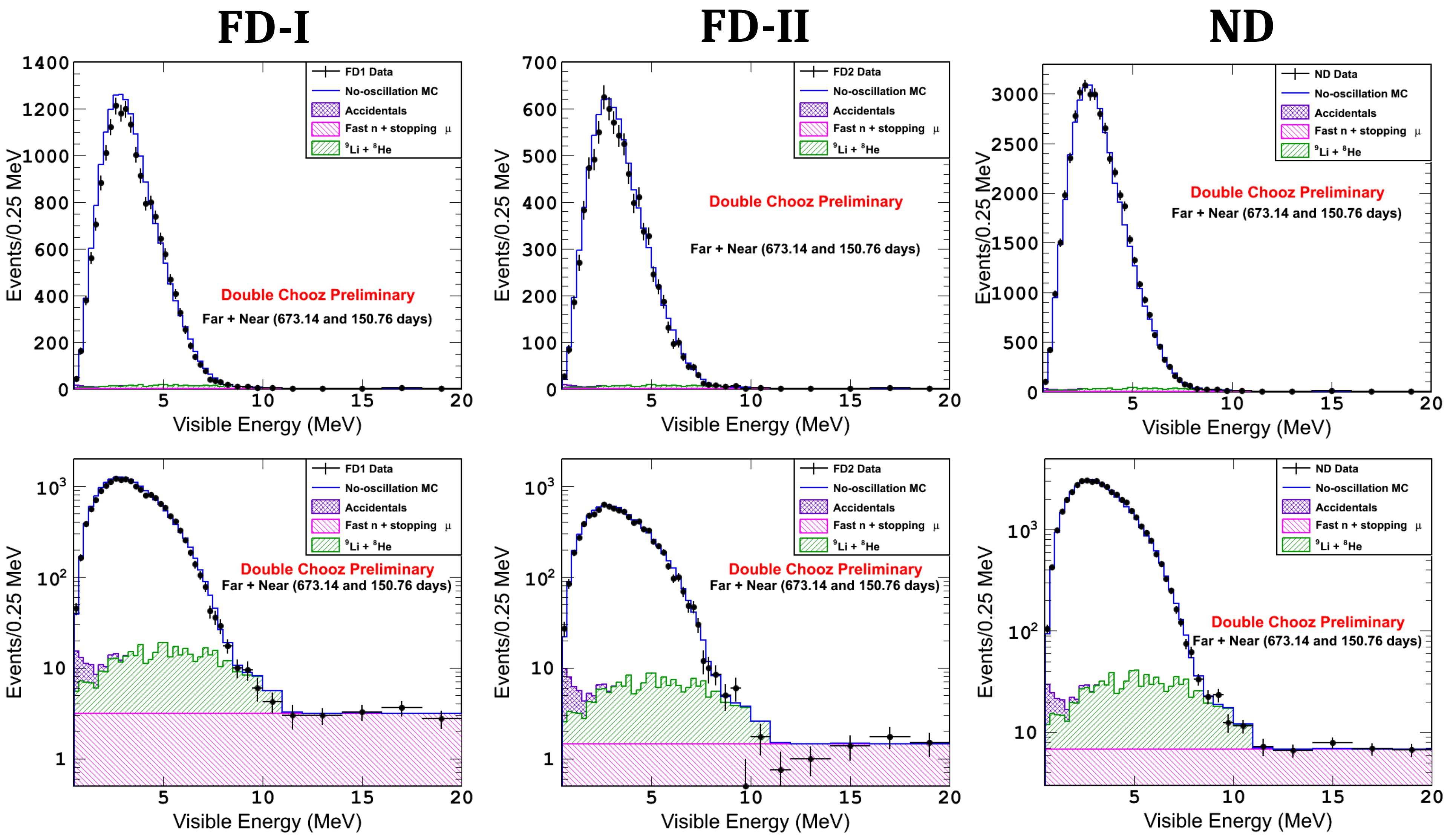






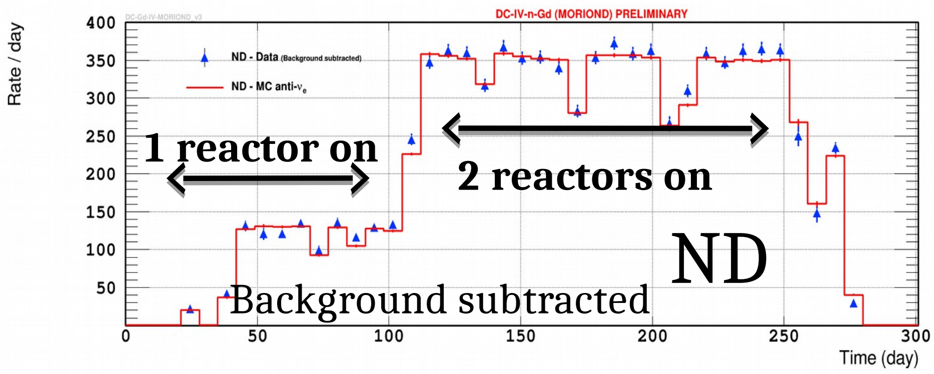
Cut name	Information used	Target of cut
μ veto	1ms veto after μ	μ, cosmogenic
Multiplicity	unicity condition	multiple-n
FV veto	vertex likelihood	chimney stop-μ
IV veto	IV activity	fast n, stop-μ, γ scattering
OV veto	OV activity	fast n, stop-μ
Li veto	Li-likelihood	cosmogenic
LN cut	PMT hit pattern & time	light emission from PMT
(CPS veto)	chimney likelihood	stop-μ
(Qratio)	Max Q/Tot. Q	ND buffer stop-μ

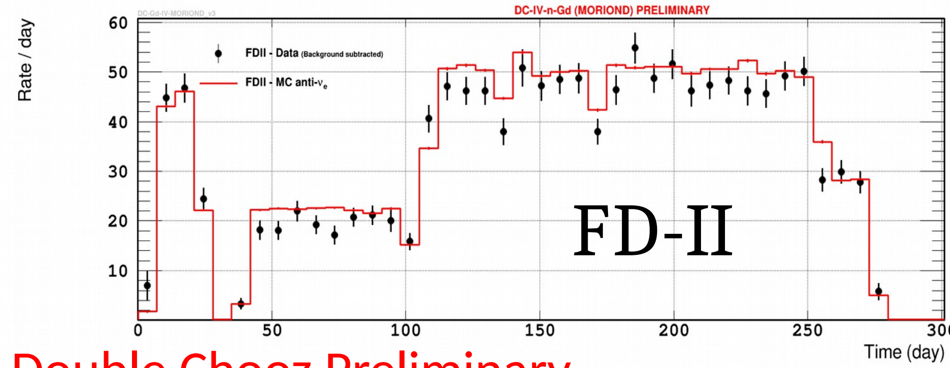
(only applied in multi-detector analysis)



Remark: spectra before the oscillation analysis are shown

New Extended Dataset



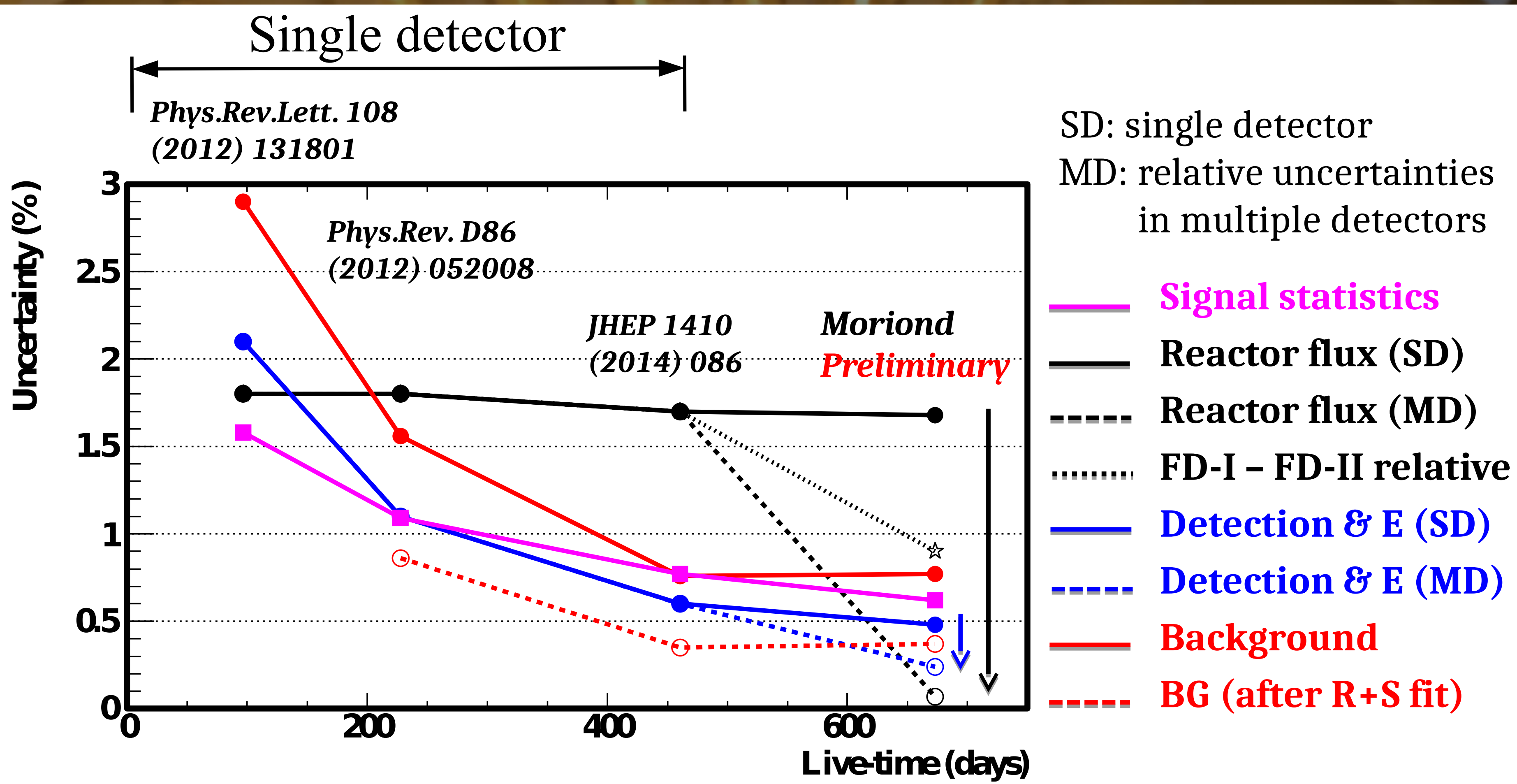


Double Chooz Preliminary

	FD-I	Reactor-off	FD-II	ND
Live-time (d) (after μ veto)	460.93	7.24	212.21	150.76
IBD prediction (d^{-1})	38.04±0.67	0.217±0.065	40.39±0.69	280.5±4.7
Accidental BG (d^{-1})	0.070±0.003		0.106±0.002	0.344±0.002
Fast-n + stop-μ (d^{-1})	0.586 ±0.061			3.42 ±0.23
Cosmogenic (d^{-1})	$(0.97^{+0.41}_{-0.16})$			(5.01 ±1.43)
Total prediction (d^{-1})	**39.63±0.73**	**1.85±0.30**	**42.06±0.75**	**289.3±4.9**
IBD candidates (d^{-1}) (number of events)	**37.64** (17351)	**0.97** (7)	**40.29** (8551)	**293.4** (44233)

→ 9 month of two detector data added to previous single detector dataset

→ Cosmogenic background rate not used as input
  → constrained by oscillation analysis



- Systematic errors suppressed with two detectors and in rate+shape fit

  ⇒ All systematic uncertainties below < 0.4% (after R+S fit)
- Current precision (9 months ND) is limited by the statistical uncertainty

Reactor flux uncertainty

- → Uncertainty in reactor flux normalisation suppressed by adding Bugey4 (15m baseline) flux measurement
- → Reactor flux uncertainty in two detector setup further suppressed due to nearly iso-flux ratio between ND and FD-II

Double Chooz Preliminary

	FD-I (%)	FD-II (%)	ND (%)
Bugey4	1.40	1.40	1.40
Energy per fission	0.16	0.16	0.16
Spectrum$\oplus\sigma_{IBD}$	0.20	0.20	0.20
Baselines	< 0.01	< 0.01	0.01
Fission fraction (α_k)	0.82	0.74	0.73
Thermal power (P_{th})	0.44	0.44	0.44
Total	**1.70**	**1.66**	**1.66**
ρ(FD-I:FD-II)	**0.72 (0.90% relative)**		
ρ(FD-II:ND)		**>0.99 (0.07% relative)**	

Correlated across FD-I, FD-II and ND

Uncorrelated
⇒ suppressed with two detectors (in parallel operation)

Inter-reactor correlation for α_k and P_{th}: $\rho_{B1/B2} = 0.78$
(most conservative assumption with current data set)

Detection Systematics

Double Chooz Preliminary

	FD-I	FD-II	ND
BG vetoes (%)	0.11 (0.11)	0.09 (0.09)	0.02 (0.02)
Gd fraction (%)	0.25 (0.14)	0.26 (0.15)	0.28 (0.19)
IBD selection (%)	0.21 (0.21)	0.16 (0.16)	0.07 (0.07)
Spill in/out (%)	0.27 (0)	0.27 (0)	0.27 (0)
Proton number (%)	0.30 (0)	0.30 (0)	0.30 (0)
Total (%)	**0.49 (0.26)**	**0.47 (0.22)**	**0.38 (0.15)**

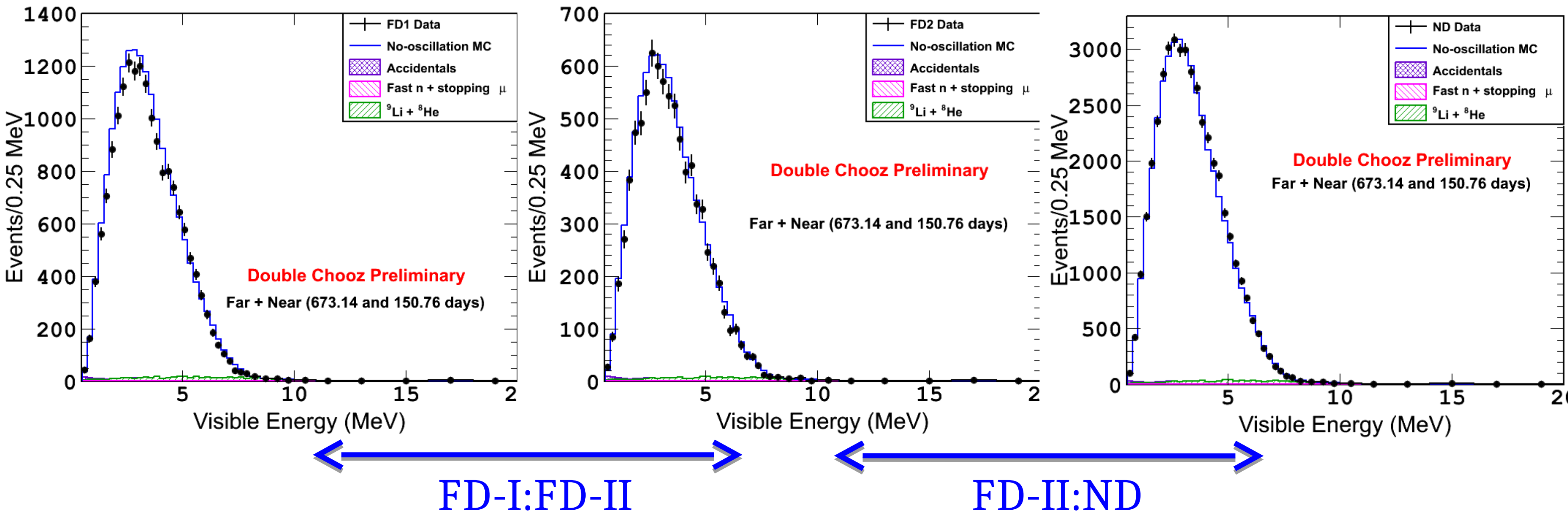
Numbers in parentheses are uncorrelated uncertainties
in multi-detectors analysis (FD-I, FD-II and ND)

→ identical design of detectors suppresses uncorrelated uncertainties

Oscillation Analysis

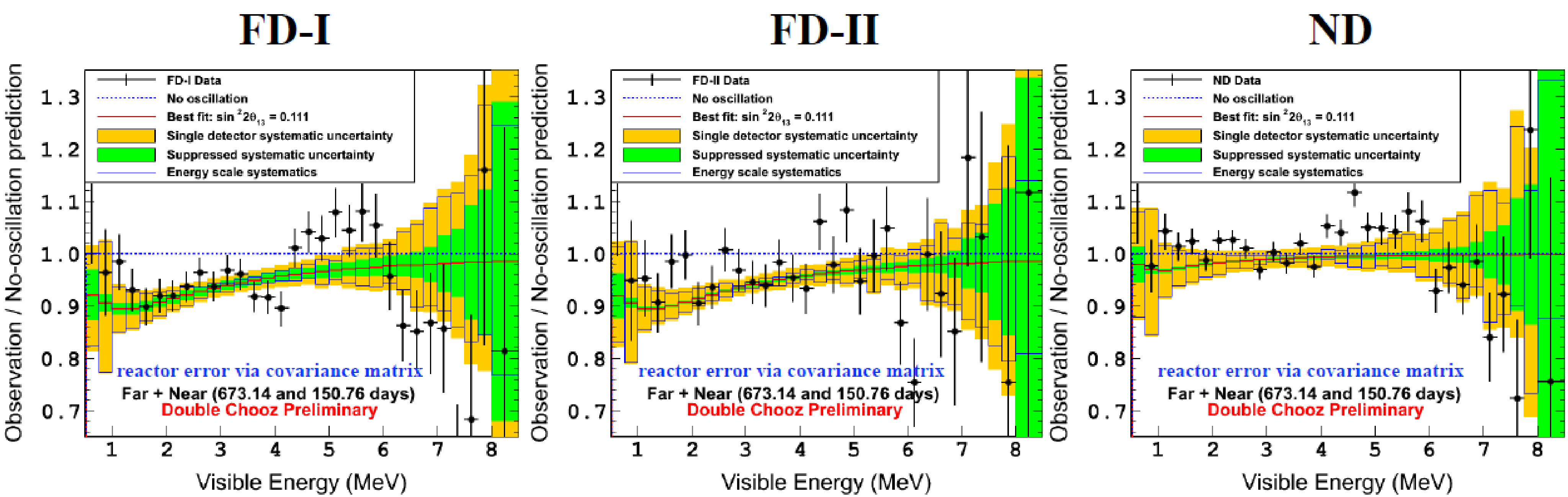
General Analysis Strategy

→ Compare FD-I, FD-II, ND data simultaneously to predictions
  → Background rate and shape estimated by data
    → cosmogenic rate not constrained
  → Observed data in reactor off sample as separate background constraint



→ energy non-linearities corrected in oscillation analysis
→ energy scale across detectors uncorrelated (conservative approach)
→ many cross-checks (data-only, bkgrd constraint &c)
→ independent analyses using different implementations of statistical and systematic uncertainties

Oscillation Results



$\sin^2(2\theta_{13})$=0.111 ± 0.018 (stat.+syst.)

→ χ^2/dof = 128.8/120

→ non-zero θ_{13} observation at 5.8σ C.L.

→ cosmogenic ^{9}Li bkgrd: 0.75 ± 0.14 d^{-1}(FD), 4.89 ± 0.78 d^{-1}(ND)

→ fast-n+stop-μ bkgrd: 0.535 ± 0.035 d^{-1}(FD), 3.53 ± 0.16 d^{-1}(ND)

→ energy non-linearity: outcome consistent across data sets and with calibration

Double Chooz collaboration reported first θ_{13} measurement with two Detectors (FD-I: 460.93 days + FD-II: 212.21days + ND: 150.76days)

- $\sin^2(2\theta_{13})=0.111 \pm 0.018$ (stat.+syst.)

- reactor flux uncertainty strongly suppressed to < 0.1%
- other systematic uncertainties ≤ 0.5%
- ND: un-oscillation spectrum direct observable by experiment

- precision now limited by statistics
  (estimate of systematics also dominated by statistics)
  ⇒ further improvements expected from Double Chooz

Double Chooz Collaboration

III. Physikalisches Institut B

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Brazil
CBPF
UNICAMP
UFABC

France
APC
CEA/DSM/IRFU:
SPP
SPhN
SEDI
SIS
SENAC
CNRS/IN2P3:
Subatech
IPHC

Germany
EKU Tübingen
MPIK
Heidelberg
RWTH Aachen
TU München
U. Hamburg

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Tokyo Metro. U.
Niigata U.
Kobe U.
Tohoku Gakuin U.
Hiroshima Inst. Tech.

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INR RAS
IPC RAS
RRC
Kurchatov

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U. Tennessee

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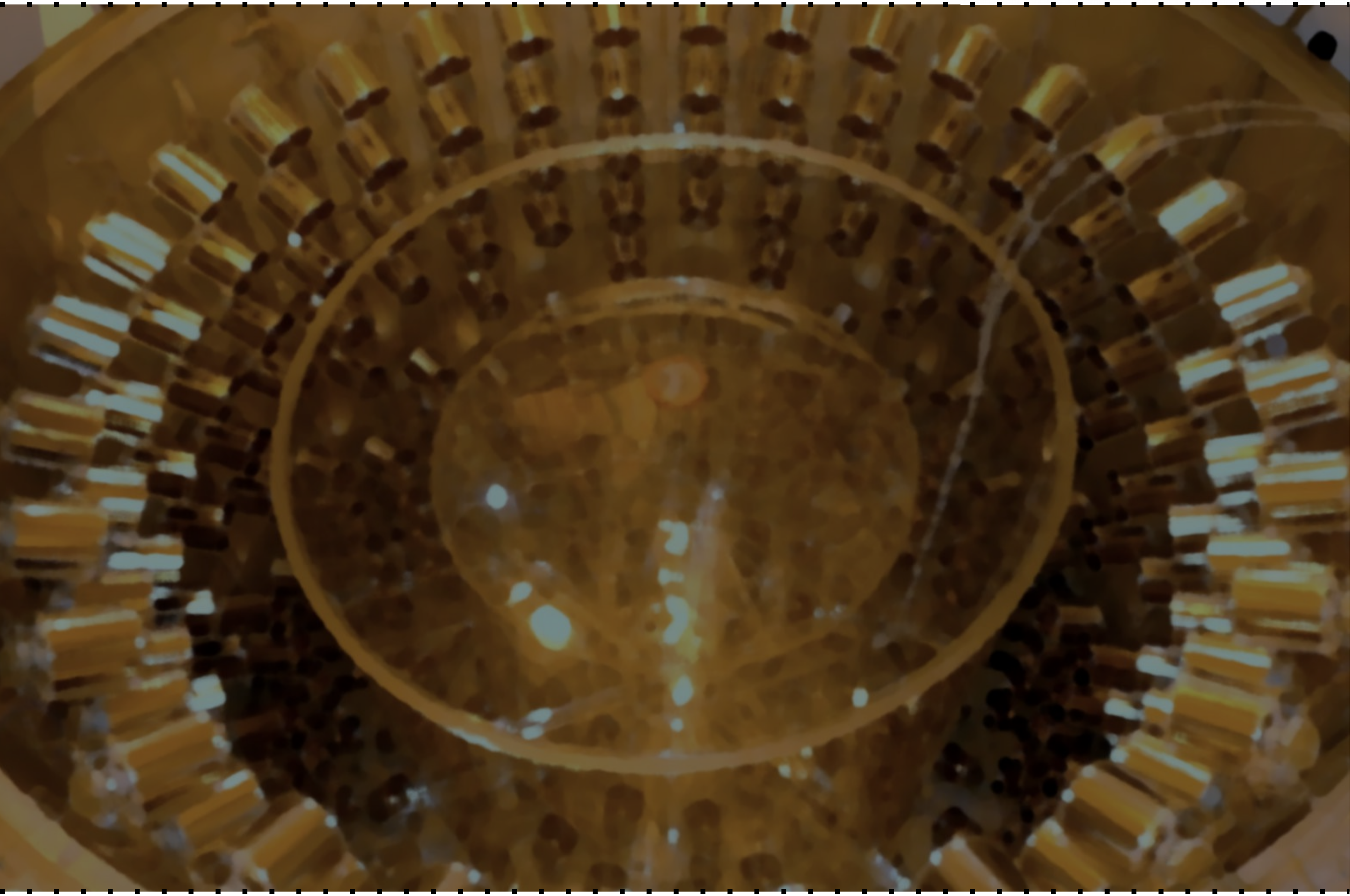
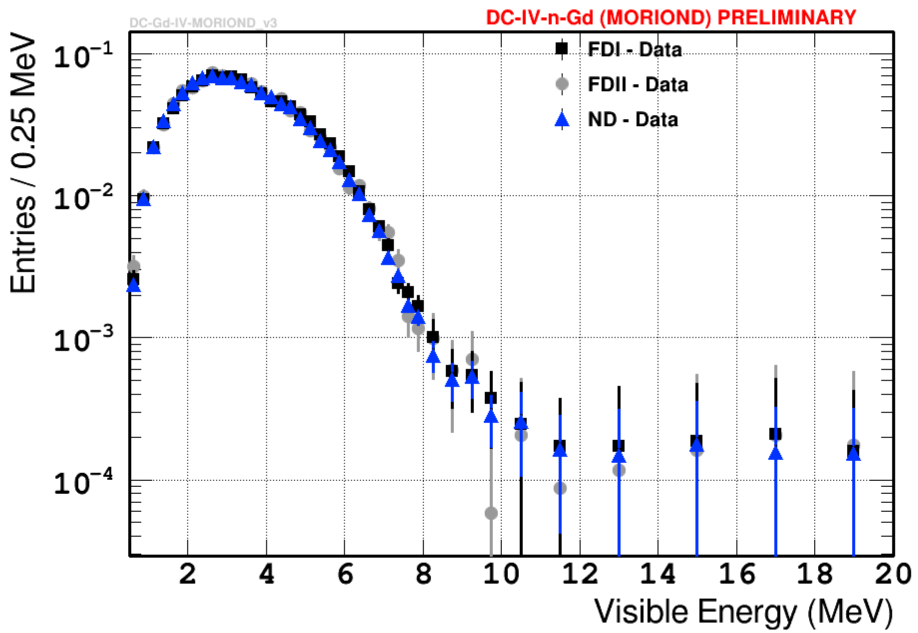
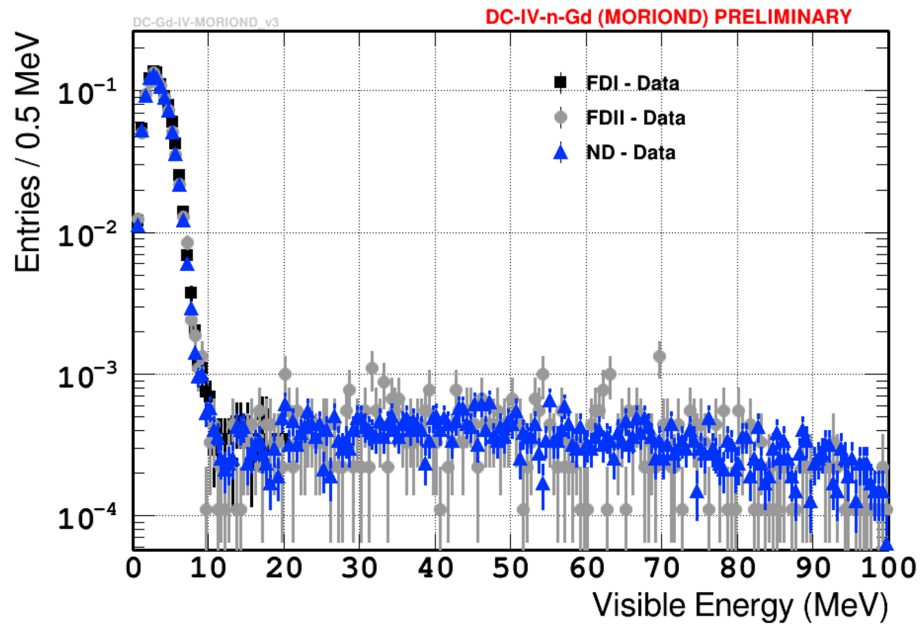
Web Site:
www.doublechooz.org/

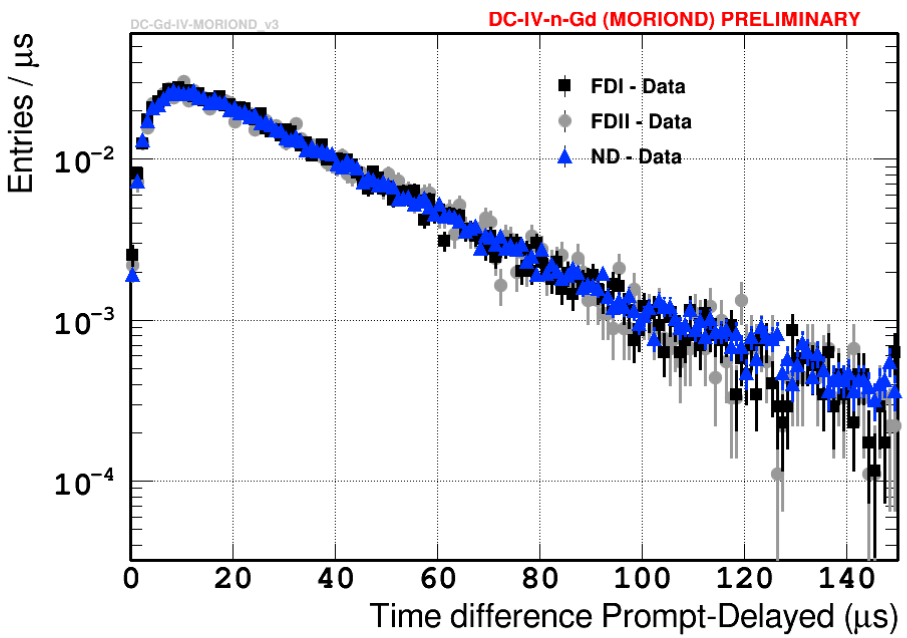
Appendix



IBD-candidate comparison





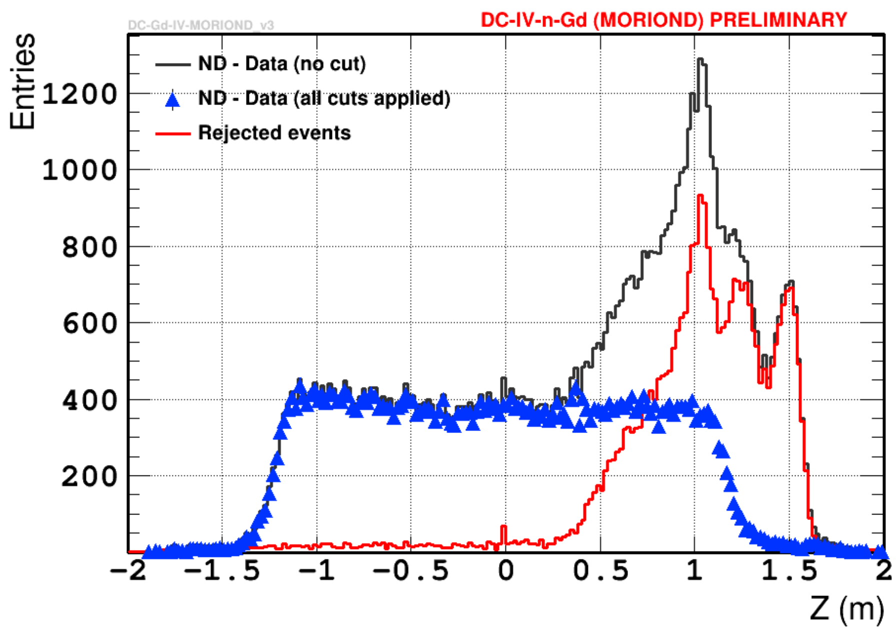


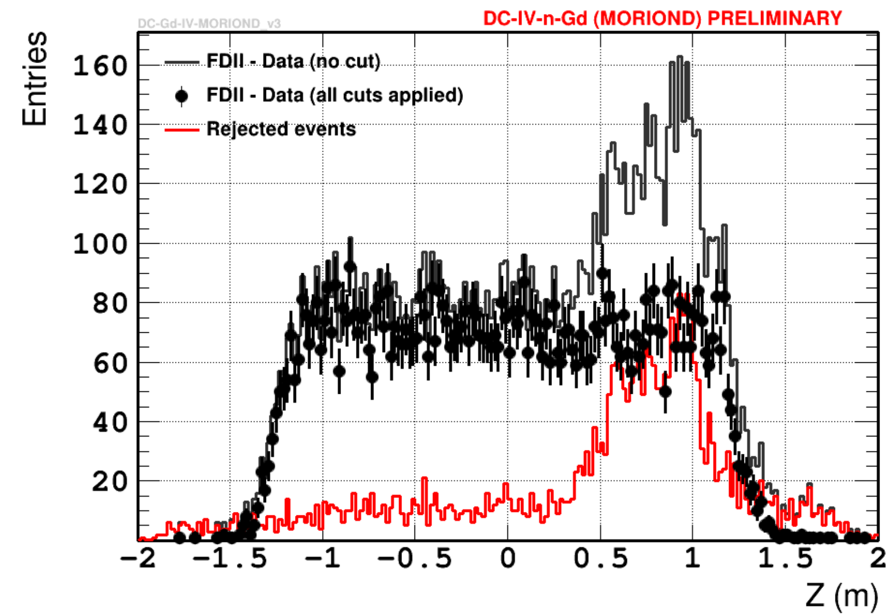
Excellent agreement between all three detectors in

→ signal-dominated low energy
→ bkgrd-dominated high energy
→ delay time
→ and all other variables

Remark:
prompt energy spectrum normalised to integral, i.e. oscillation effect hidden

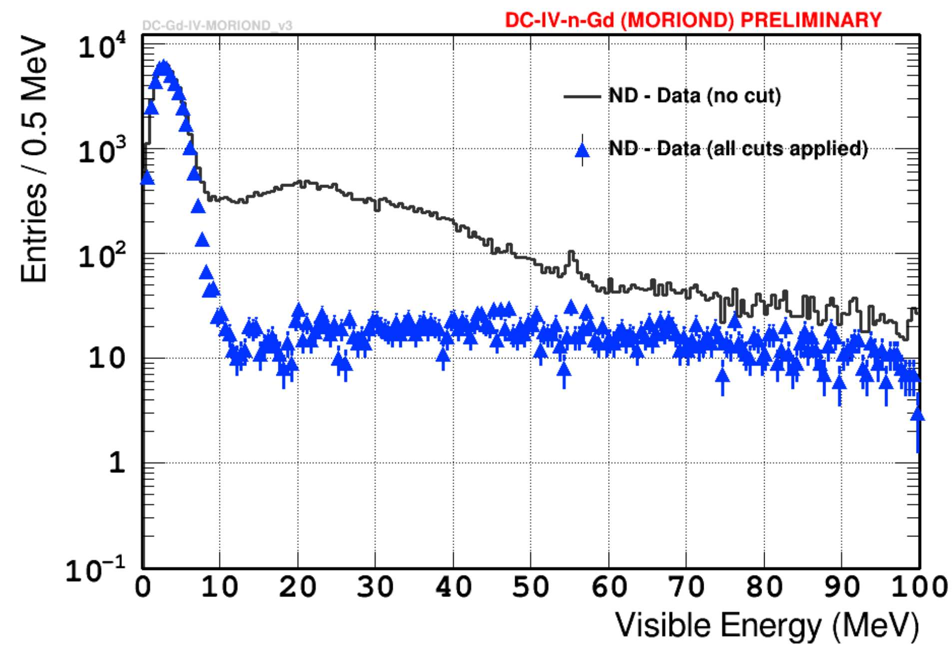
Example: stop-μ reduction



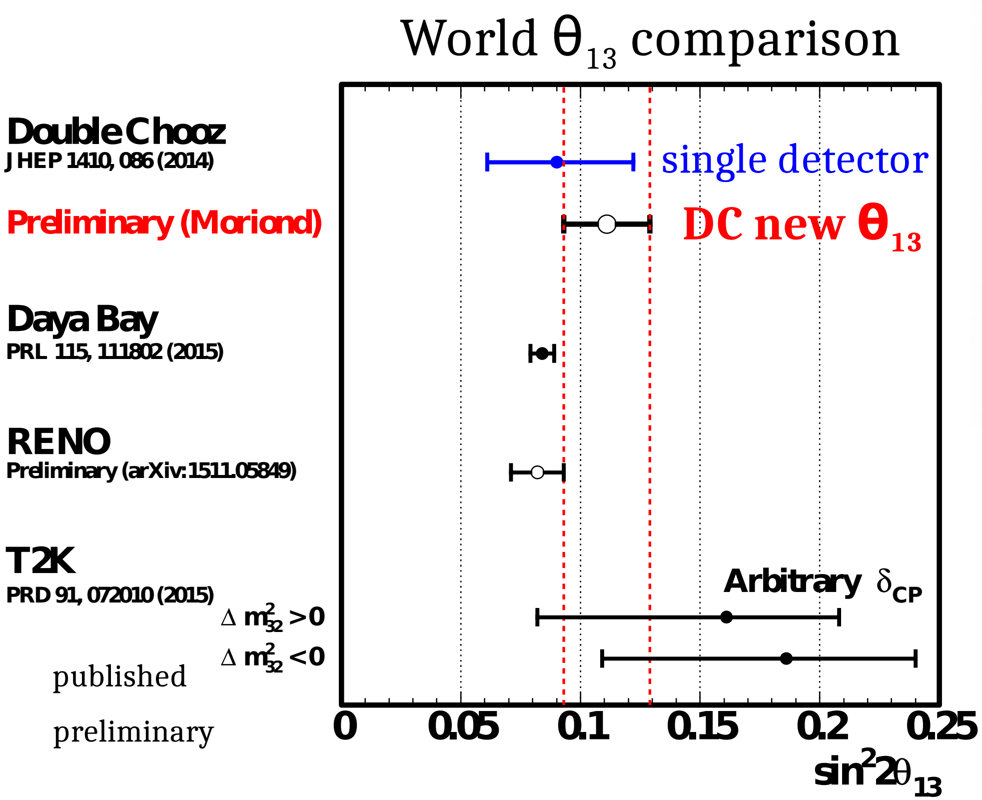


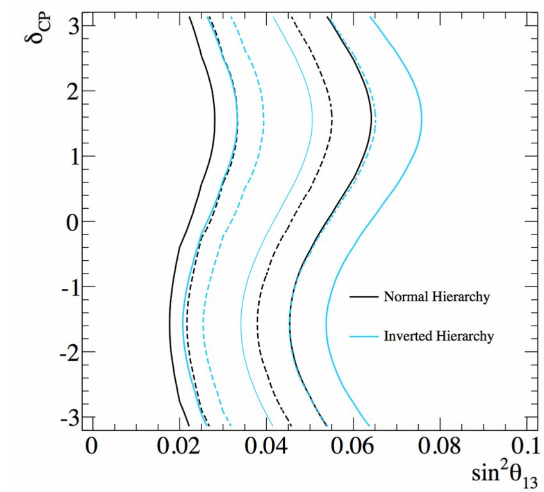
Contamination of liquid scintillator in ND Buffer causes buffer stop-μ background

⇒ Almost all such backgrounds are rejected by new selections based on
  - → Energy dependent MaxQ/TotQ cut
  - → Likelihood at chimney vs. vertex (CPS veto)



Global comparison





Reactor vs. T2K

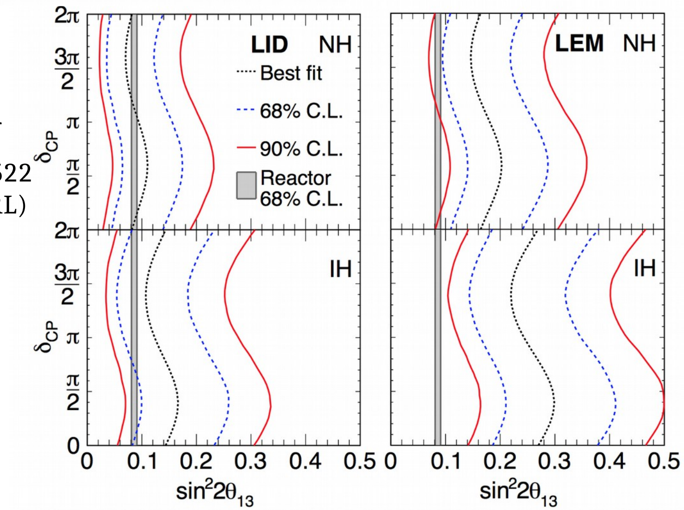
PRD91 072010 (2015)

Double Chooz 1σ

Daya Bay 1σ

Reactor vs. NOvA

arXivL1601.05522 (accepted by PRL)



→ DC θ_{13} is higher than other reactor θ_{13} by ~30% (1.4σ wrt Daya Bay)

→ Long baseline (T2K, NovA) weakly favours higher θ_{13} than reactor average

→ Reactor θ_{13} is key parameter to solve CP-violation and mass hierarchy