Double Chooz

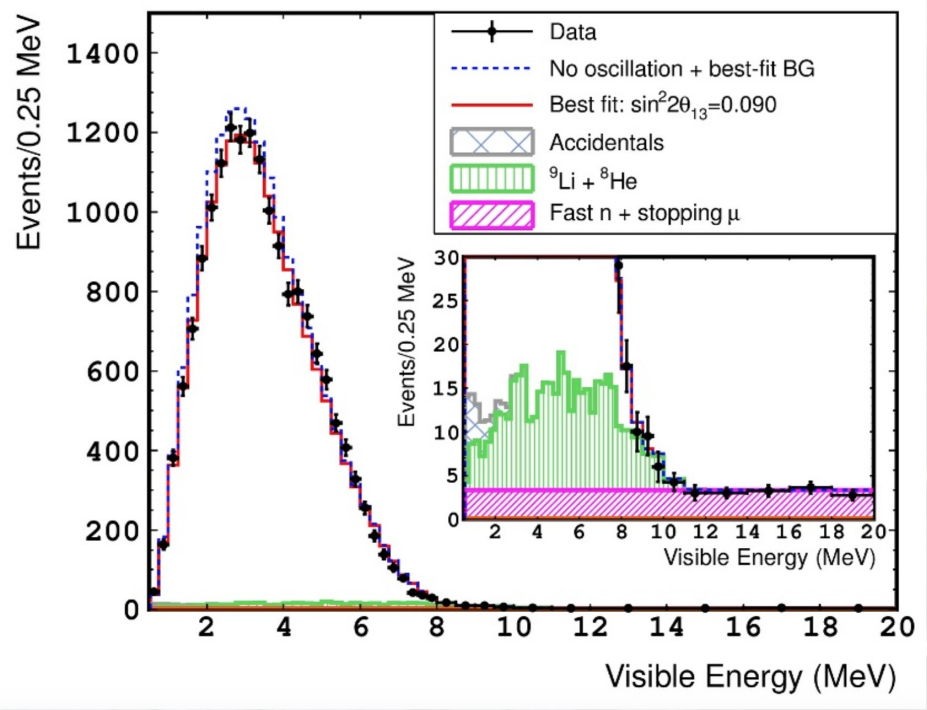
“were we were, are and will be”

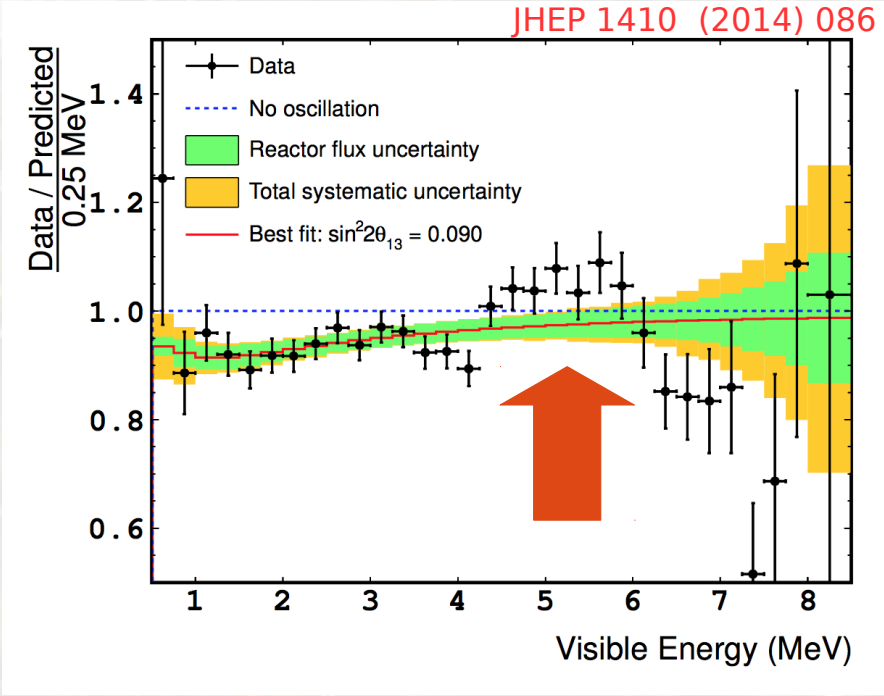
Thiago Sogo Bezerra,
on behalf of **the Double Chooz Collaboration**

GDR Neutrino Meeting

November 21st, 2017

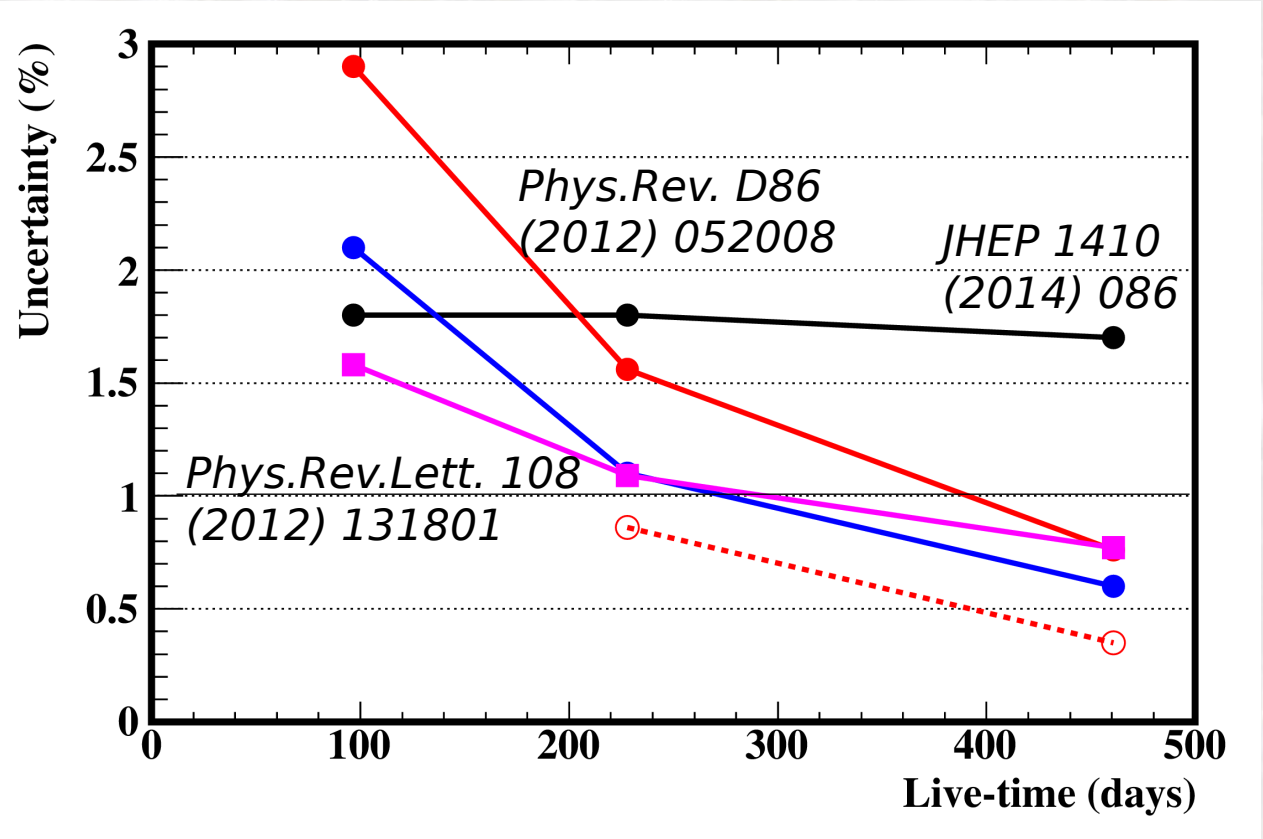
Oscillation fit on 2014





- Background and other uncertainties constrained by shape information
  - $\sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029}$
- **Unexpected spectrum distortion observed at 4-6MeV**
  - ✓ Negligible impact to θ_{13} measurement
  - ✓ Magnitude of excess proportional to reactor power
  - ✓ Same distortion later confirmed by RENO, Daya Bay and n-H capture in DC

Analysis improvements

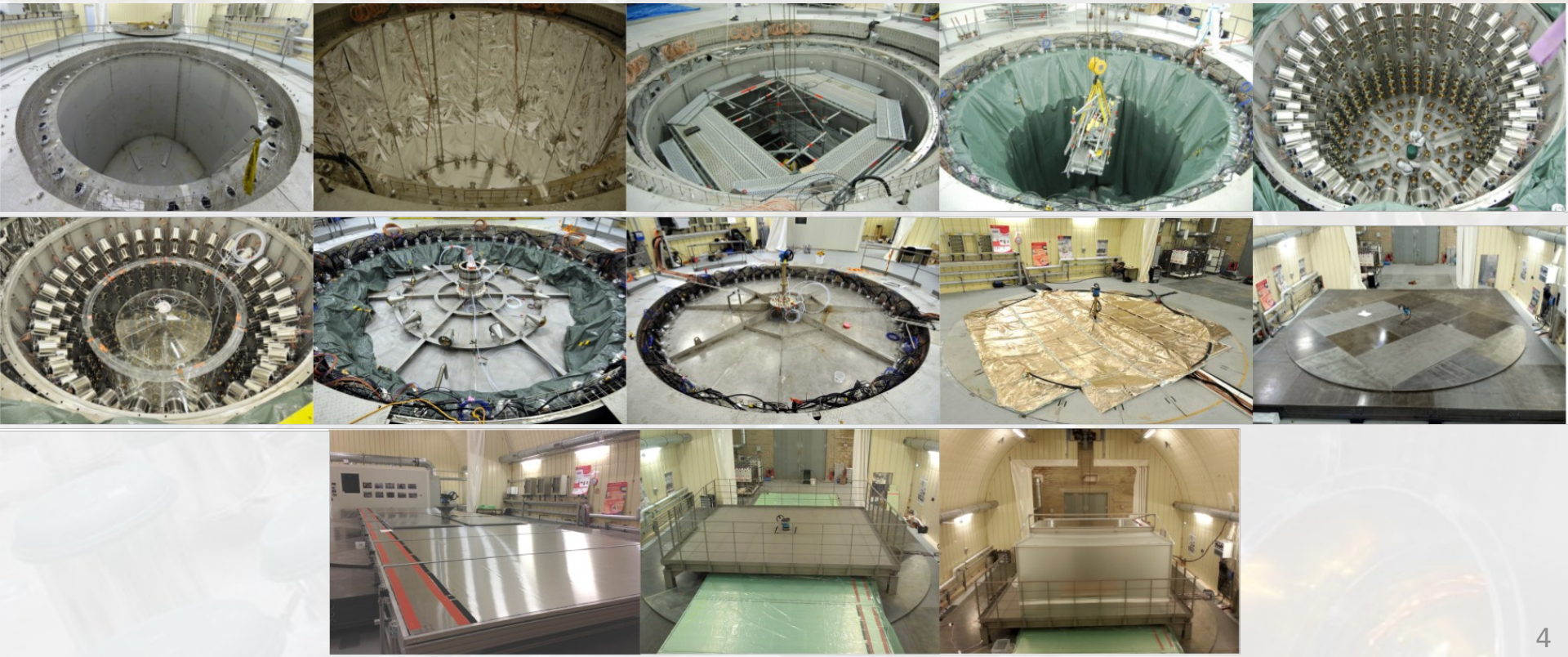


- Detector and background uncertainties are suppressed to per-mille level by analysis improvements
  - Reactor flux uncertainty (1.7%) dominant in last FD-only analysis

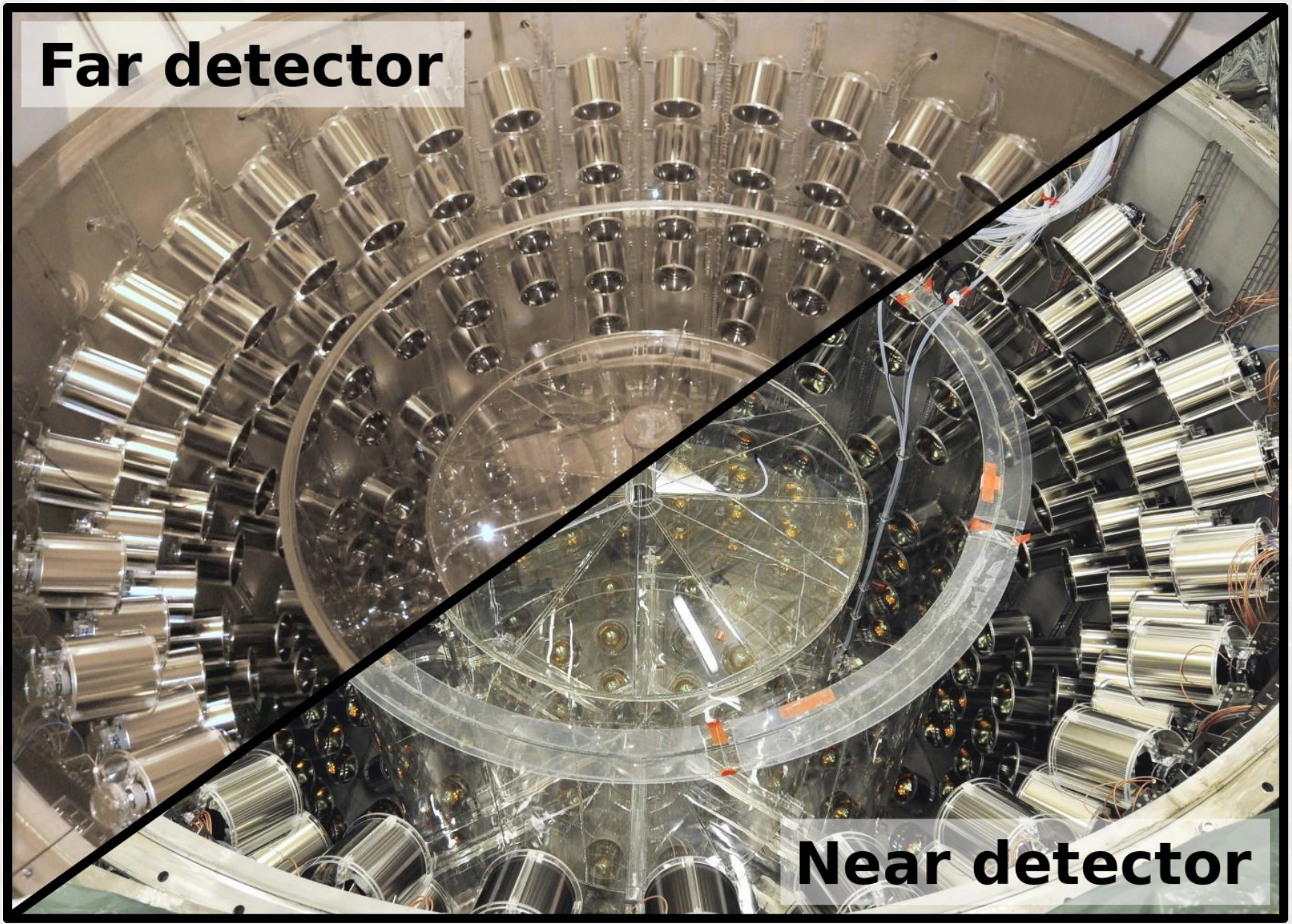
⇒ Reactor flux and detection systematics to be suppressed with two detectors

Near Lab / Detector

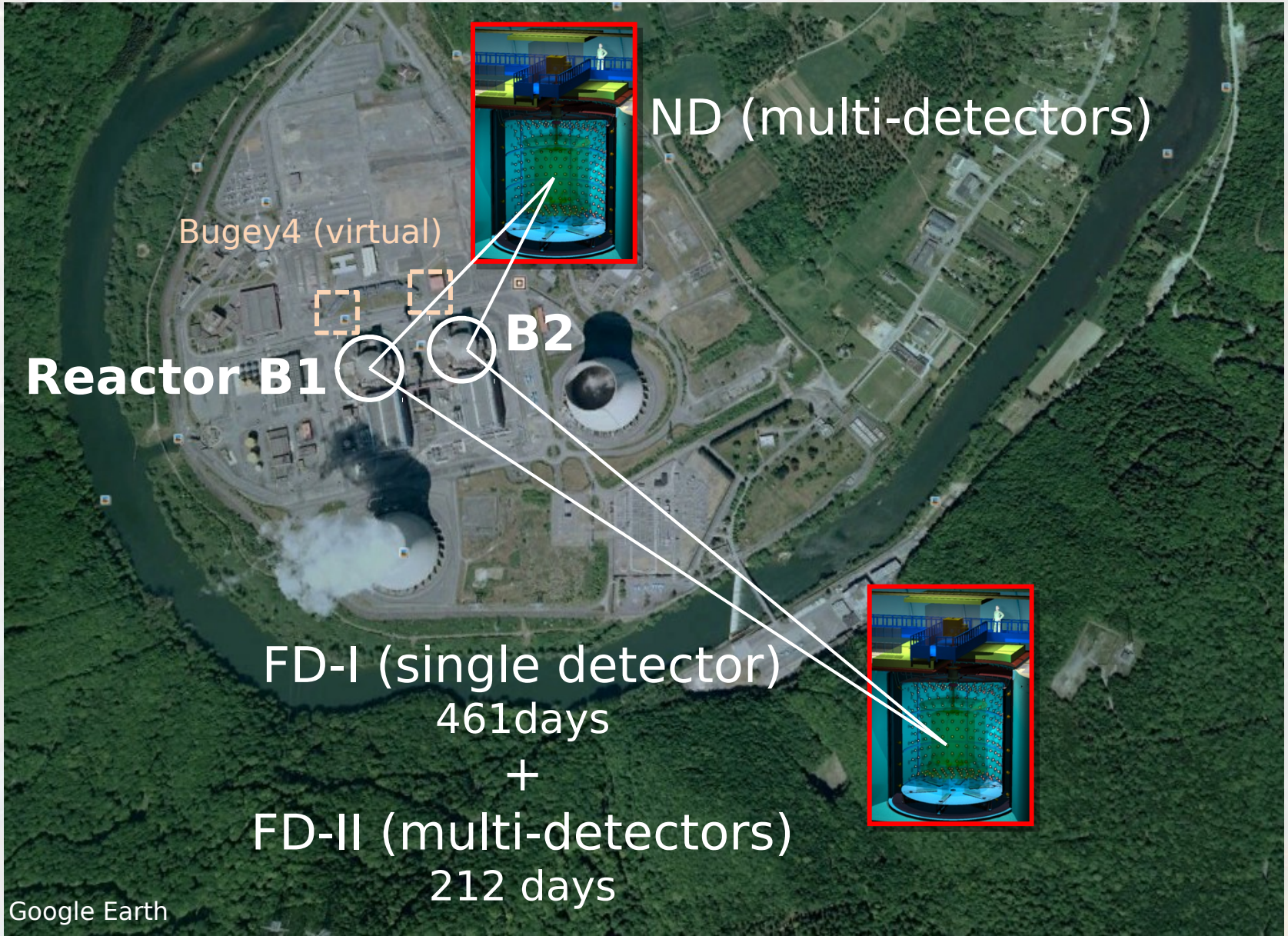
- 2011 – Tunnel and Cave digging
- 2012 – Detector pit and lab construction
- 2013 – Water shield, Inner Veto, Buffer, wall and bottom PMTs
- 2014 – Acrylics, lids, filling, commissioning, Outer Veto
- 2015 – Official data-taking starts (January)



Far / Near Detectors

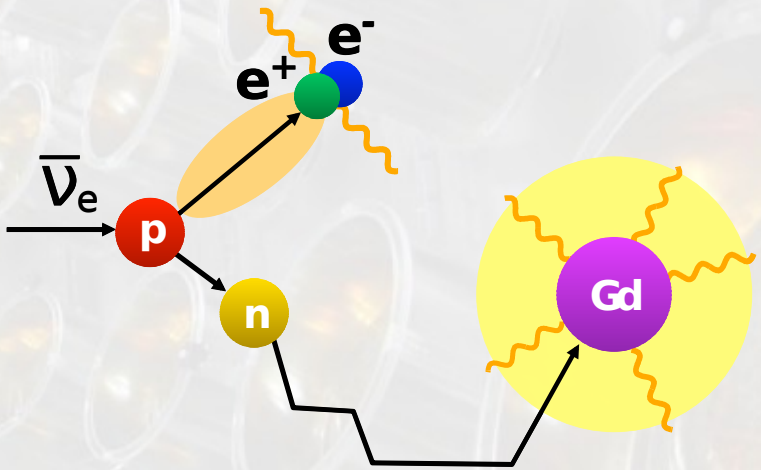


Multi-detectors analysis (2015~)



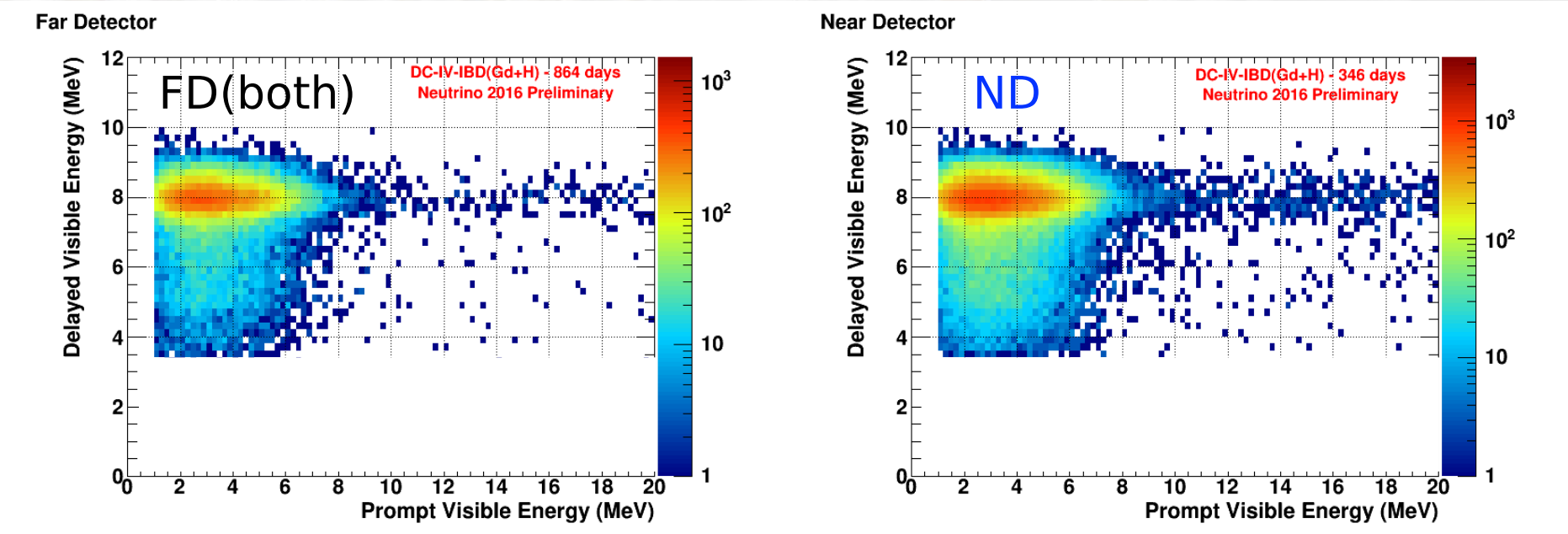
Detection Mode

- Inverse Beta Decay (IBD):
  - $\bar{\nu}_e + p \rightarrow n + e^+$
- Prompt signal: E_{e^+} + annihilation γ's ($1 \sim 9$ MeV, $E_{vis} \simeq E_{\bar{\nu}_e} - 0.8\,\mathrm{MeV}$)
- Delayed signal: γ's from neutron capture on Gd
- Delayed coincidence



Gd channel

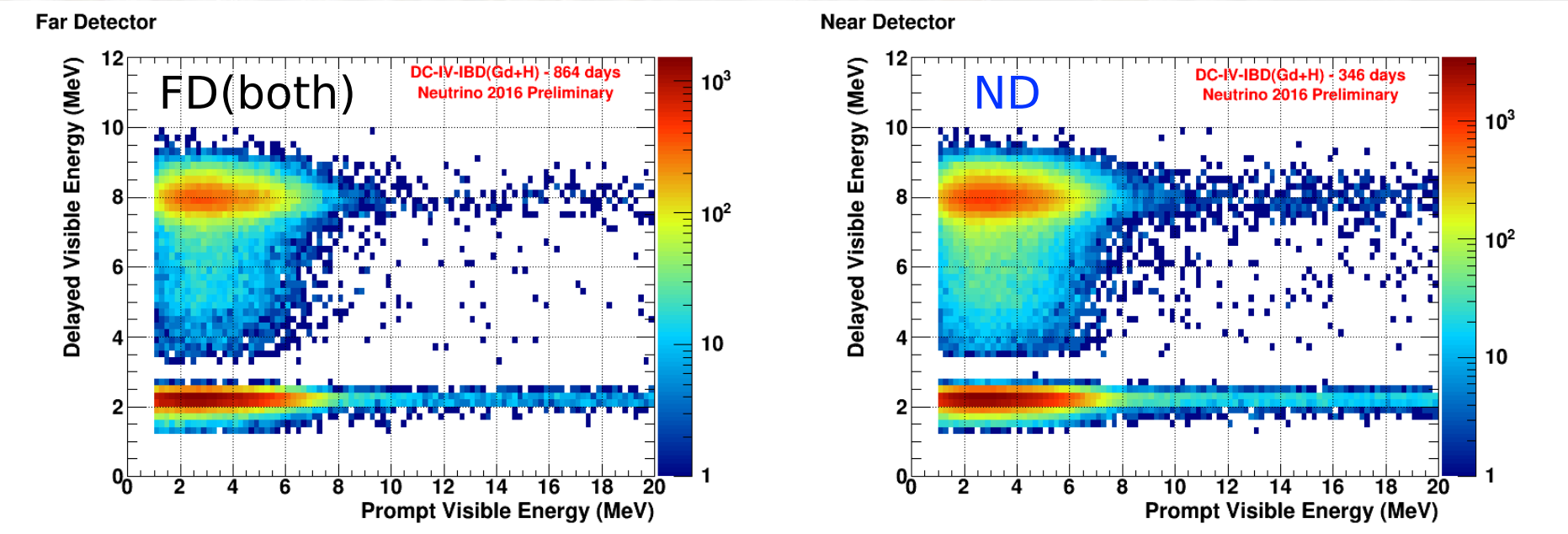
The Largest Single θ_{13} Target



IBD (Gd)

Target: ~8t (smallest θ_{13} target)

The Largest Single θ_{13} Target



IBD (Gd)

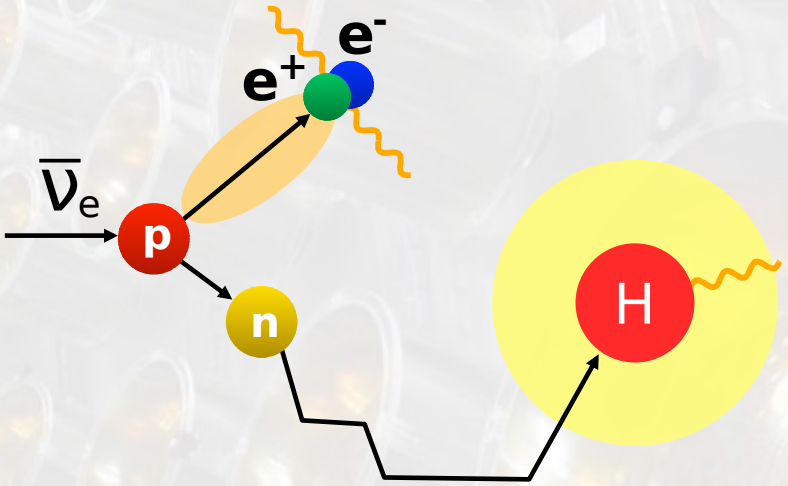
Target: ~8t (smallest θ_{13} target)

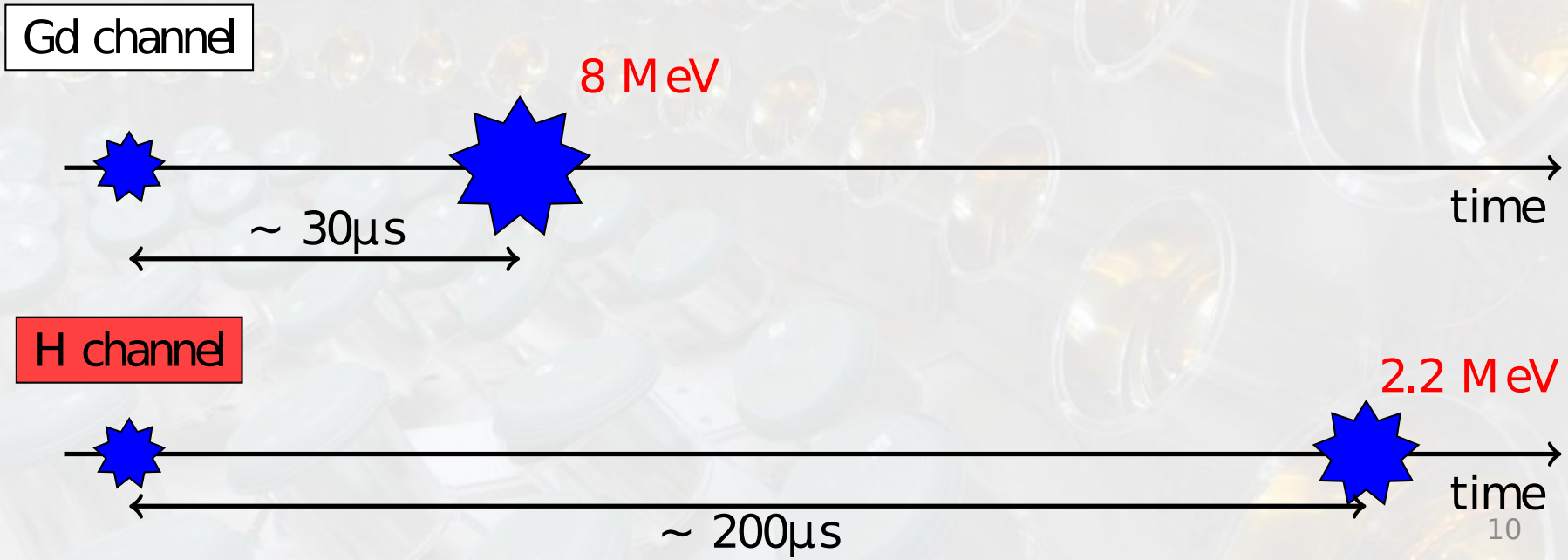
IBD (Gd+H)

Target: ~30t (largest θ_{13} single detector target)

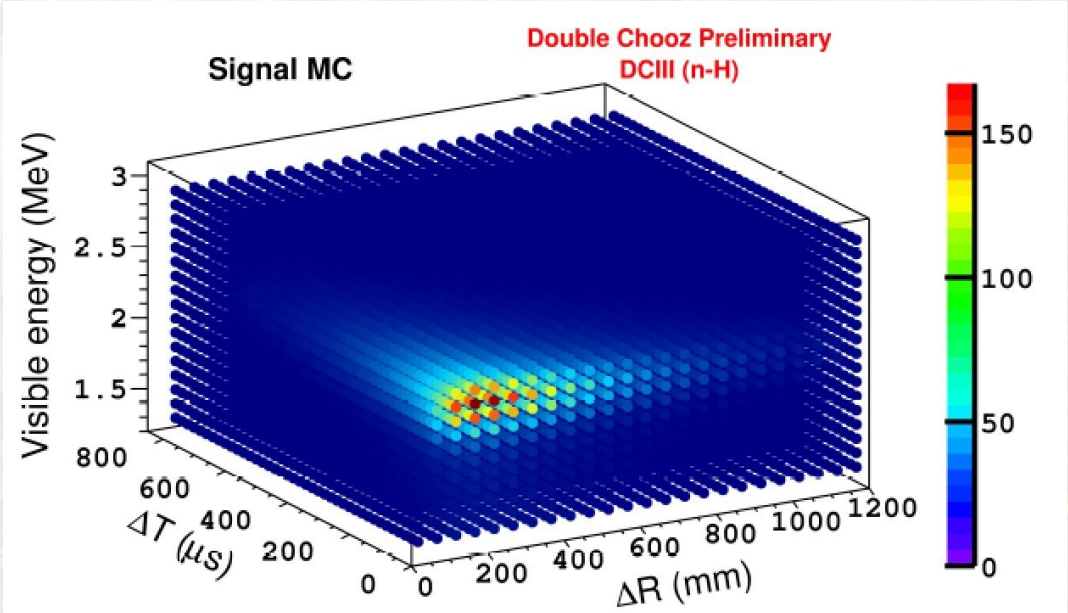
Detection Mode

- Inverse Beta Decay (IBD):
  - $\bar{\nu}_e + p \rightarrow n + e^+$
- Prompt signal: E_{e^+} + annihilation γ's (1 ~ 9 MeV, $E_{vis} \simeq E_{\bar{\nu}_e} - 0.8\,\mathrm{MeV}$)
- Delayed signal: γ's from neutron capture on Gd or H
- Delayed coincidence

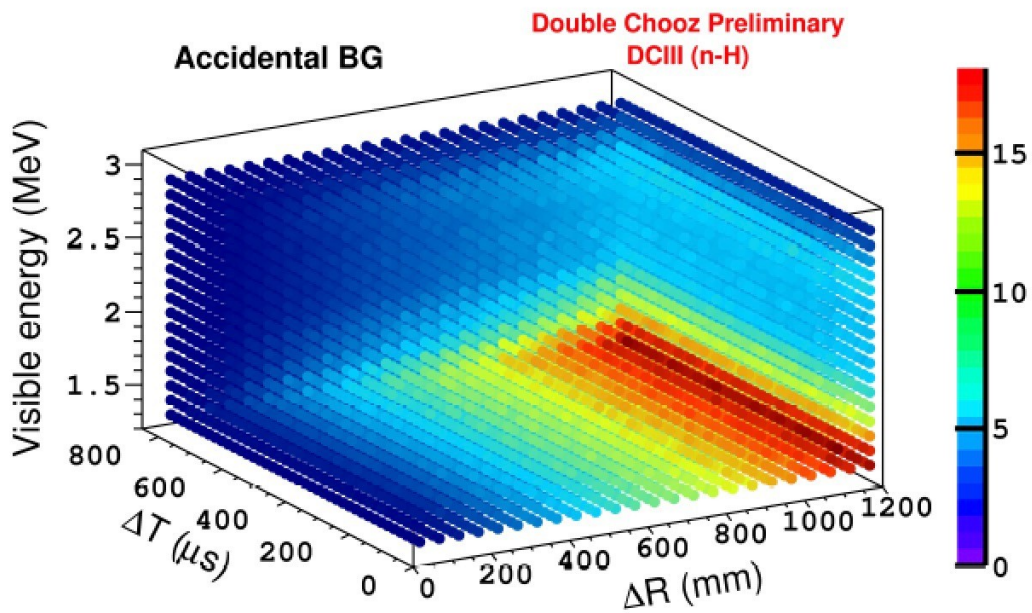




ANN Accidental BG Regection

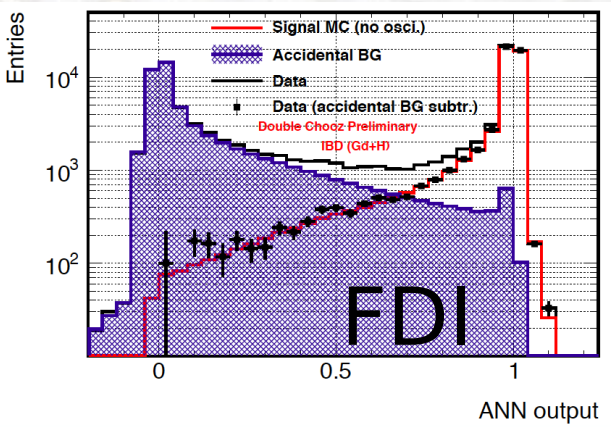


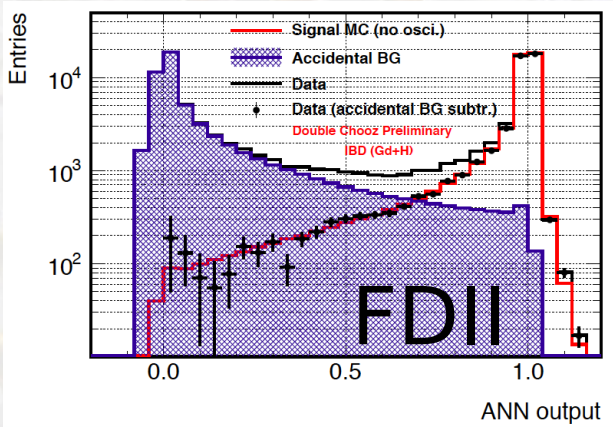
IBD (signal)
(correlated)

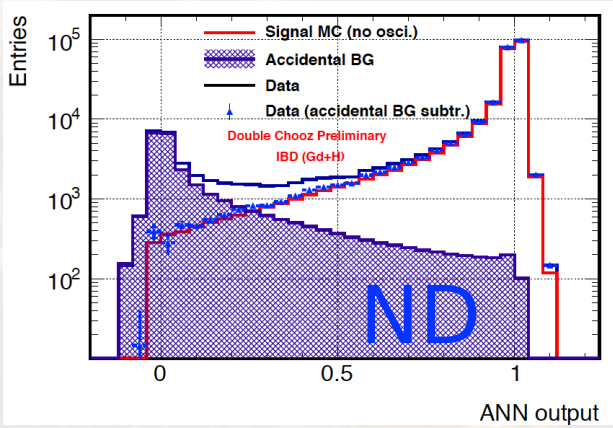


Accidental BG
(Random)
(i.e. longer Δt, ΔR)

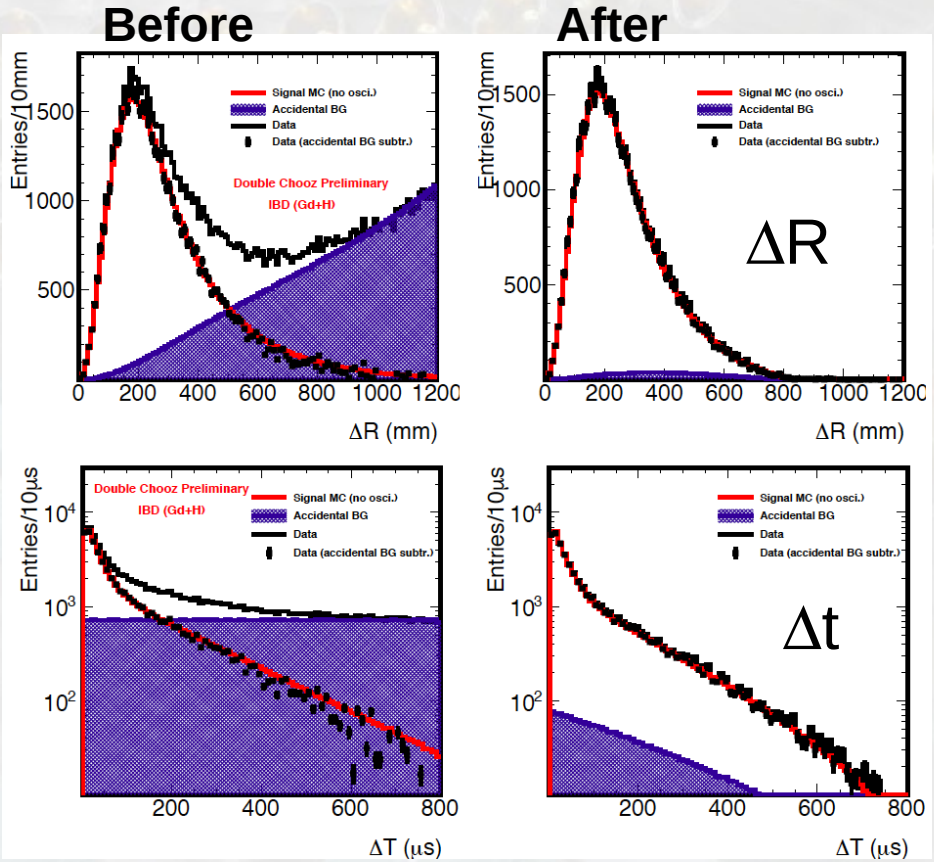
IBD(Gd+H) definition: Multi-variable cut







ANN IBD definition

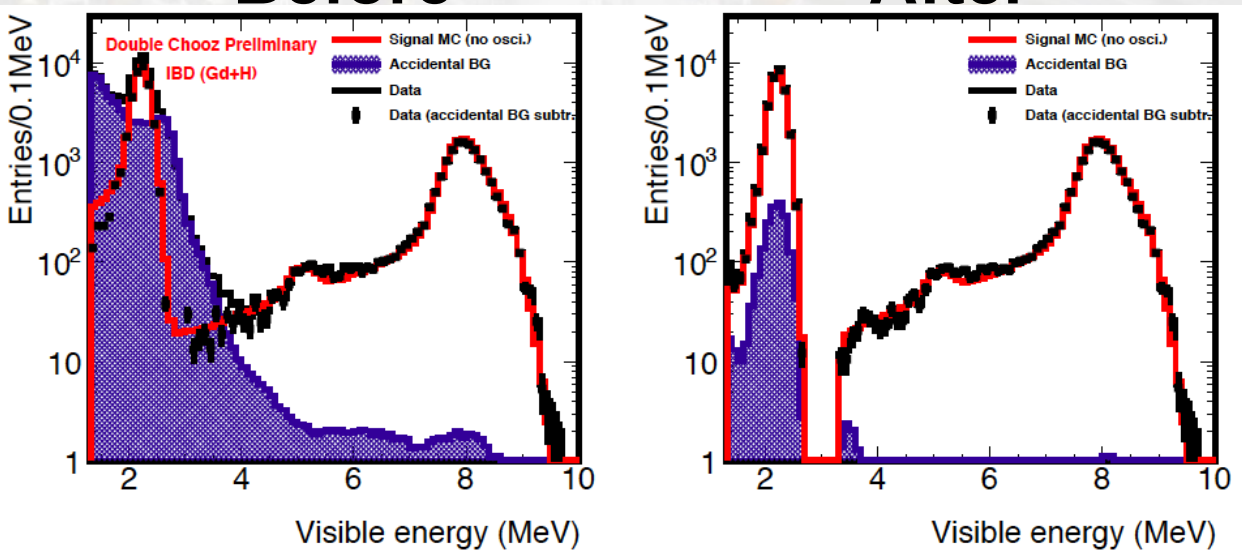


- E_{vis} (delay)
- Δt (prompt:delay)
- ΔR (prompt:delay)
- ANN

Energy Spectrum IBD(Gd+H) Selection

Before **After**

Delayed

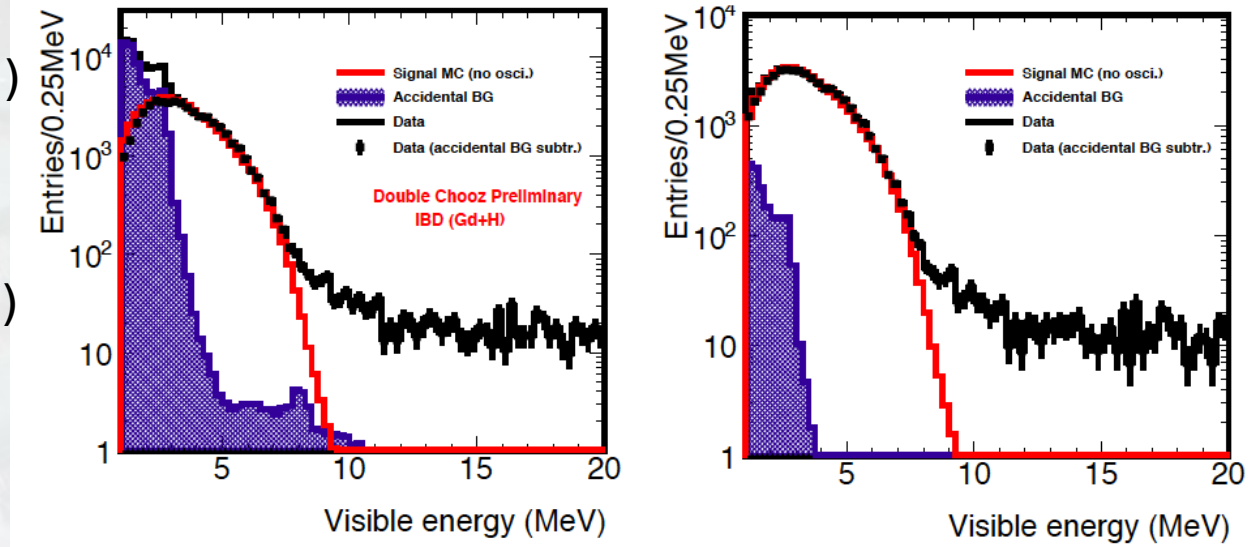


IBD(Gd+H) integrates over all captures

AccBG:
~4day^{-1} (FD/ND)

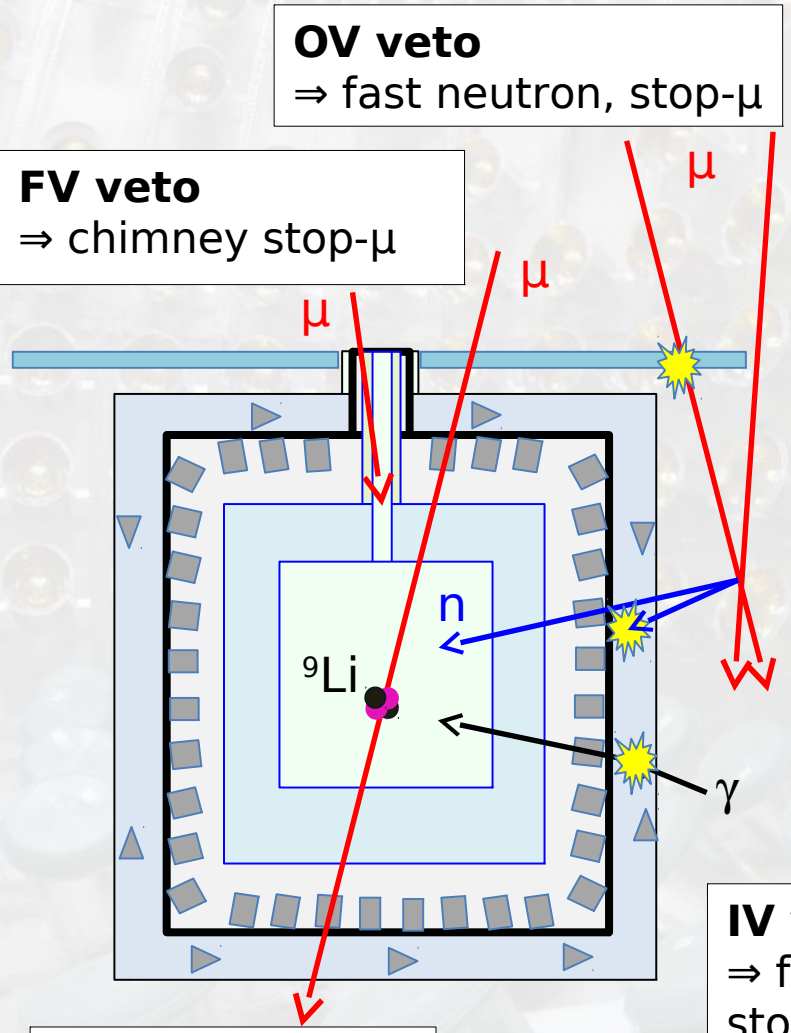
IBD(Gd+H+C):
≲140day^{-1}(FD)
≲1000day^{-1}(ND)

~2.5x IBD(Gd)



Prompt

Background Vetoes

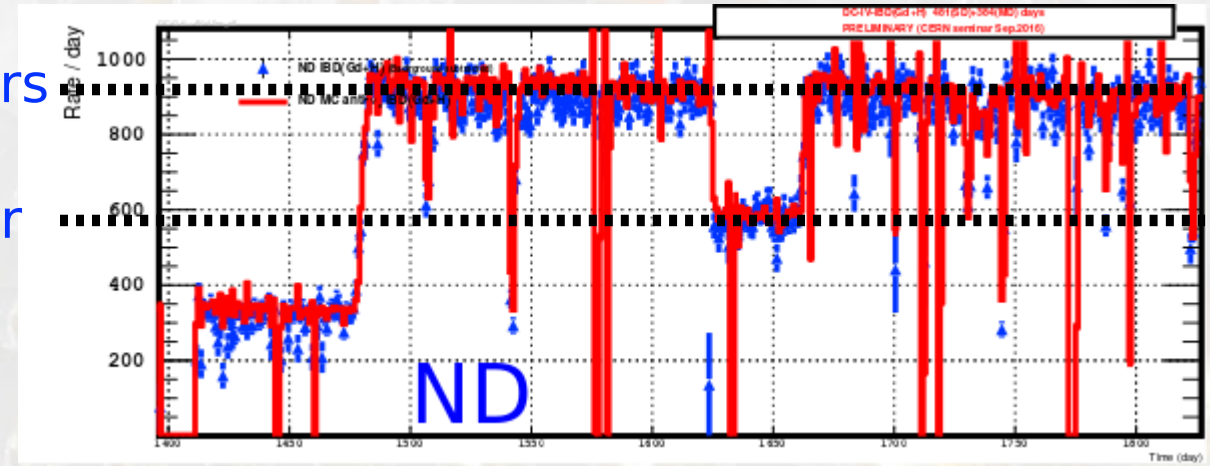


Cut	Information used	Target of cut
μ veto	1ms veto after μ	μ, cosmogenic
Multiplicity	unity condition	multiple-n
FV veto	vertex likelihood	chimney stop-μ
IV veto	IV activity	fast n, stop-μ, γ scattering
OV veto	OV activity	fast n, stop-μ
Li veto	Li-likelihood	cosmogenic
LN cut	PMT hit pattern & time	light emission from PMT

IBD (Gd+H) vs Time (Near & Far)

2xReactors

1xReactor

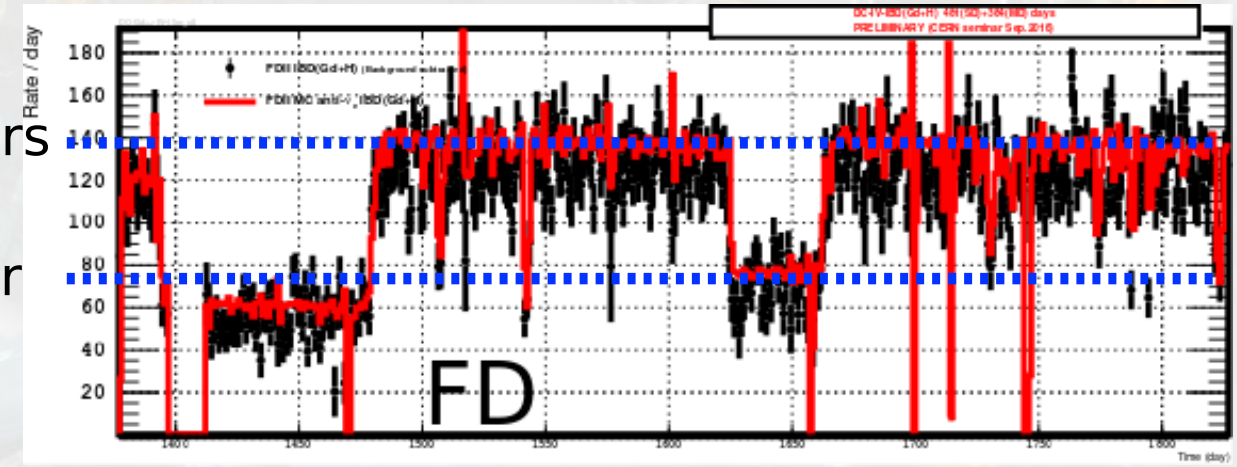


$\lesssim 140 day^{-1}$ @ FD

$\sigma^{stat} = 0.35\%^{now}$

2xReactors

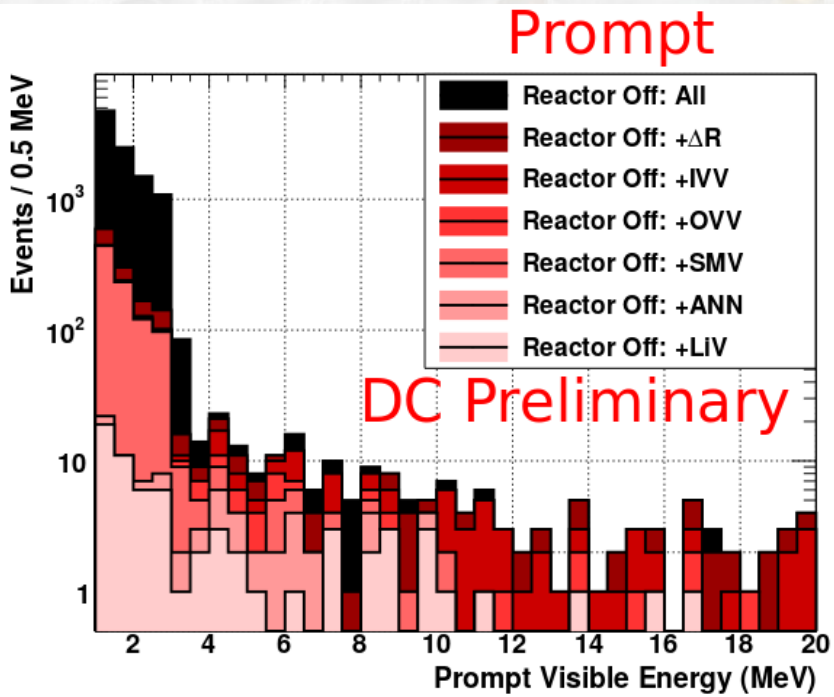
1xReactor

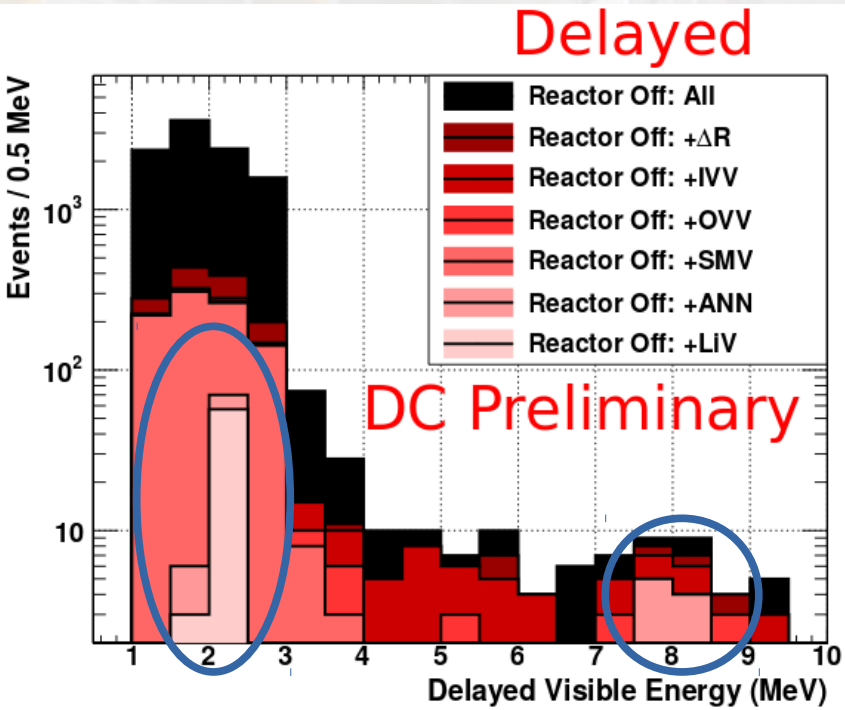


[⇒~0.2%^{stat} final]

DC Background Suppression

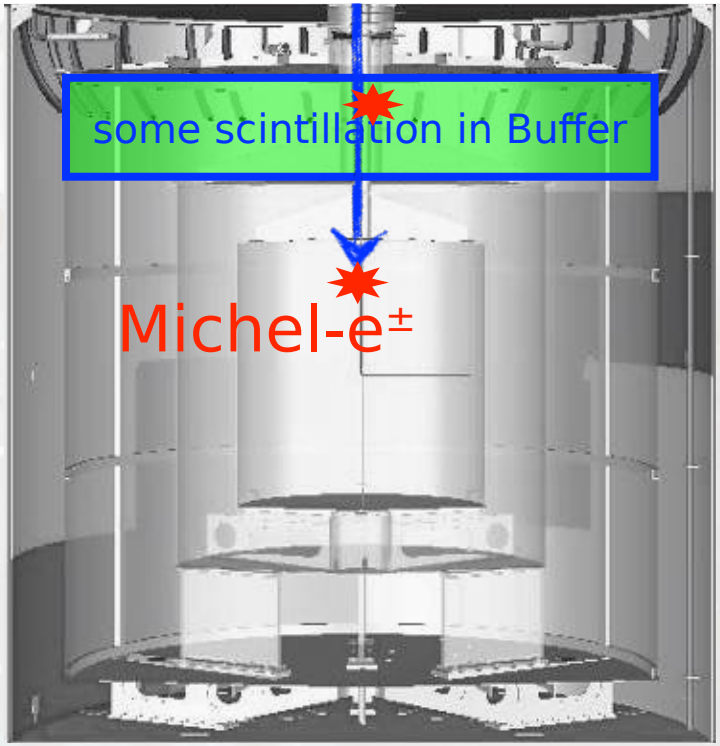
Two Reactors Off Data (Far Detector)

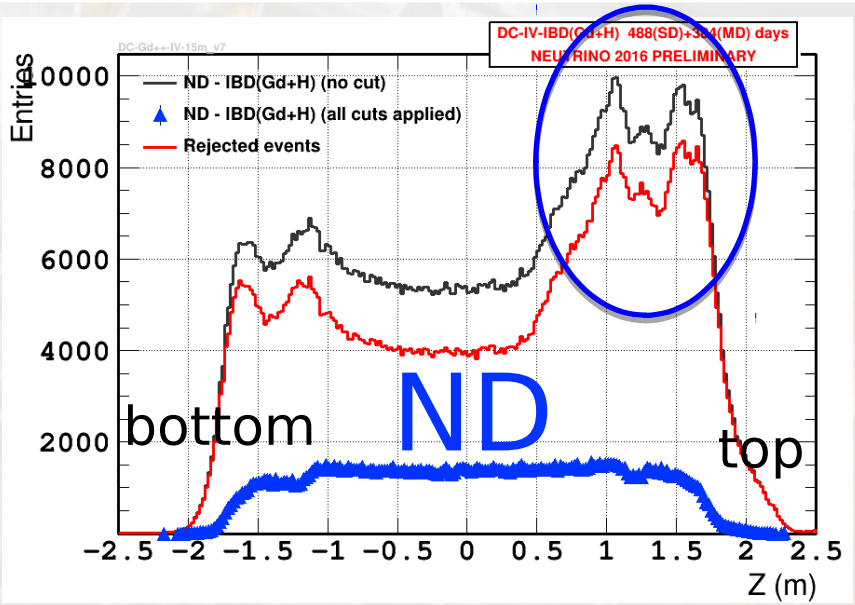


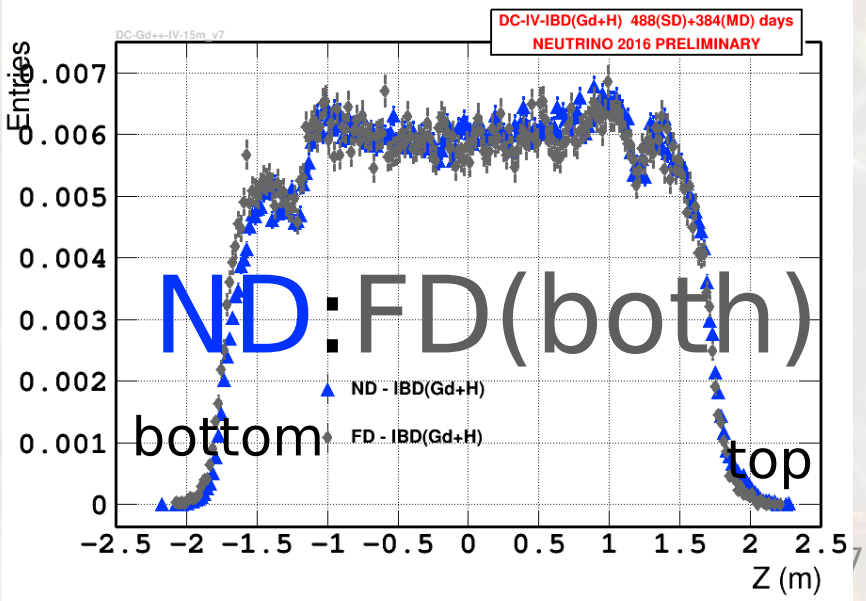


- DC Precious Reactor-off data (about 7 days on FD);
- From 10^4 to $<10^2$ BG suppression;
- 6:1000 selection with 95.00±0.03 of IBD efficiency.

Scintillator accumulates on Buffer top



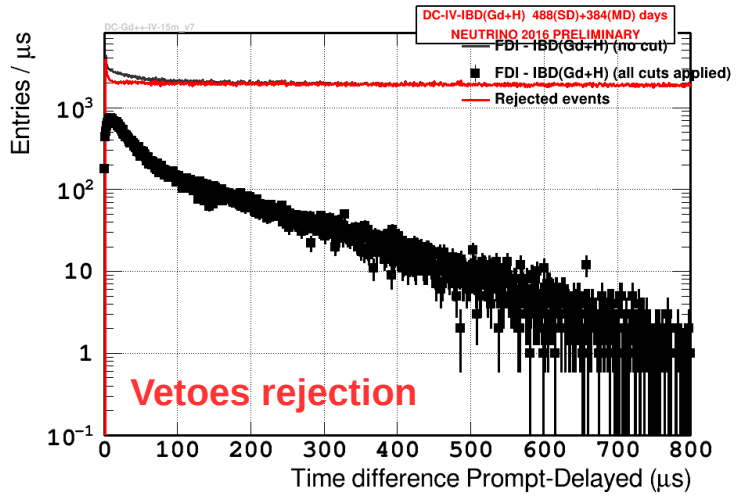


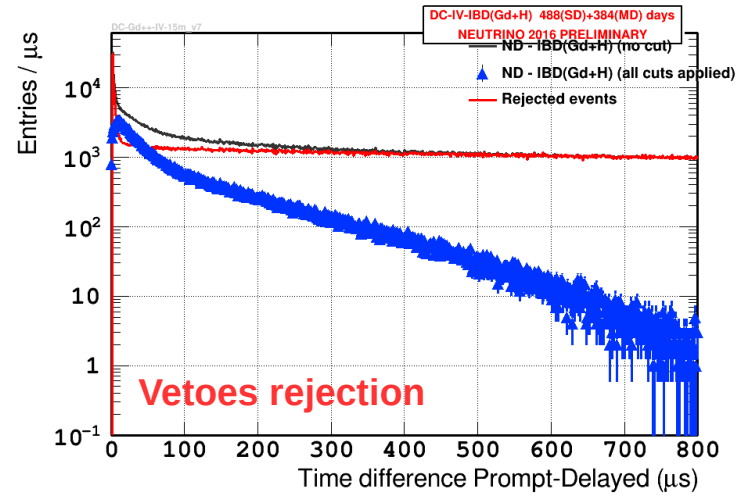


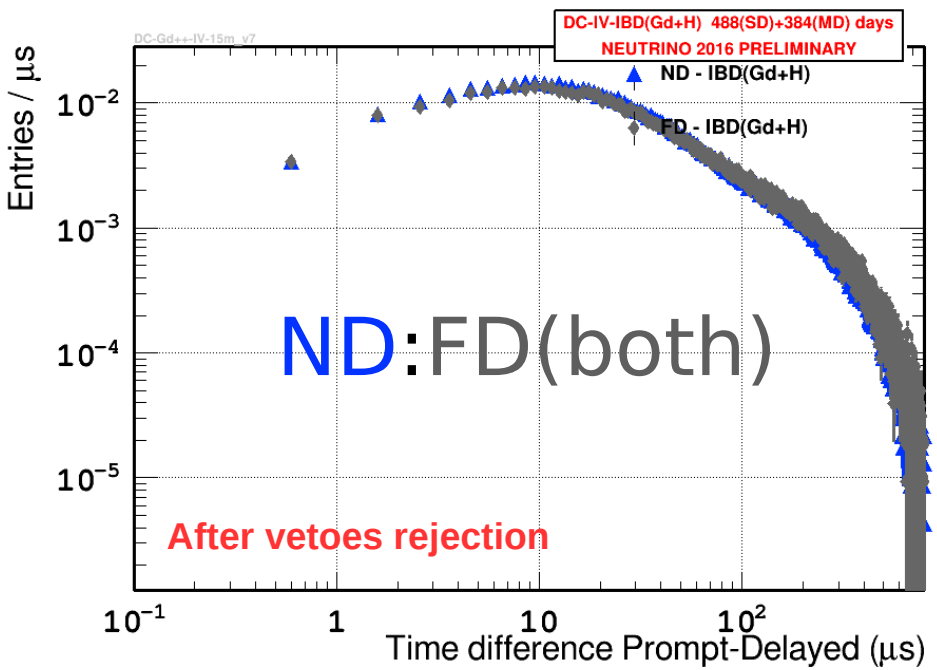
most μ-decay @ rest (Michel-e±)
rate(ND/FD)~100x

stopped-μ (all) contamination
→ negligible!
(ND≈FD after rejection)

BG rejection: Δt(e⁺:n) view







Δt(prompt:delay)

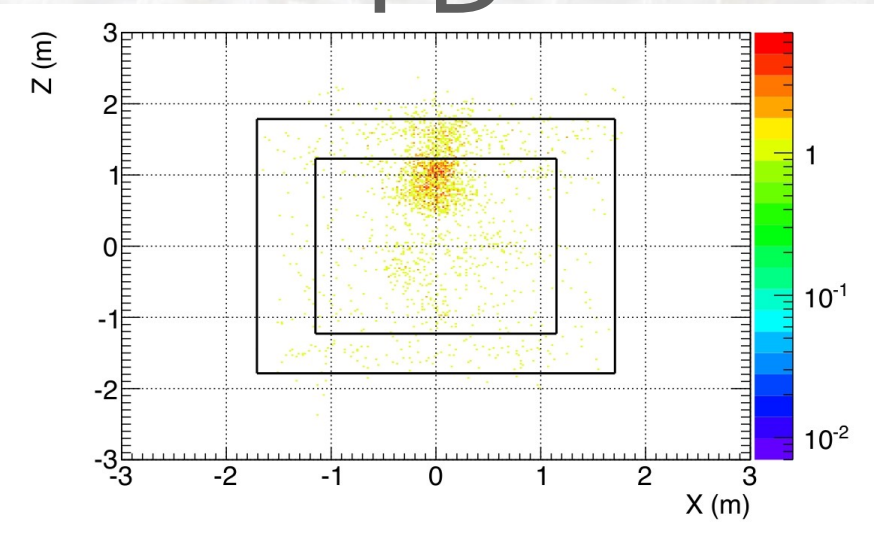
vetoes rejection impact
(demonstration >10^3 range)

ND ≈ FD(both)
(after vetoes)

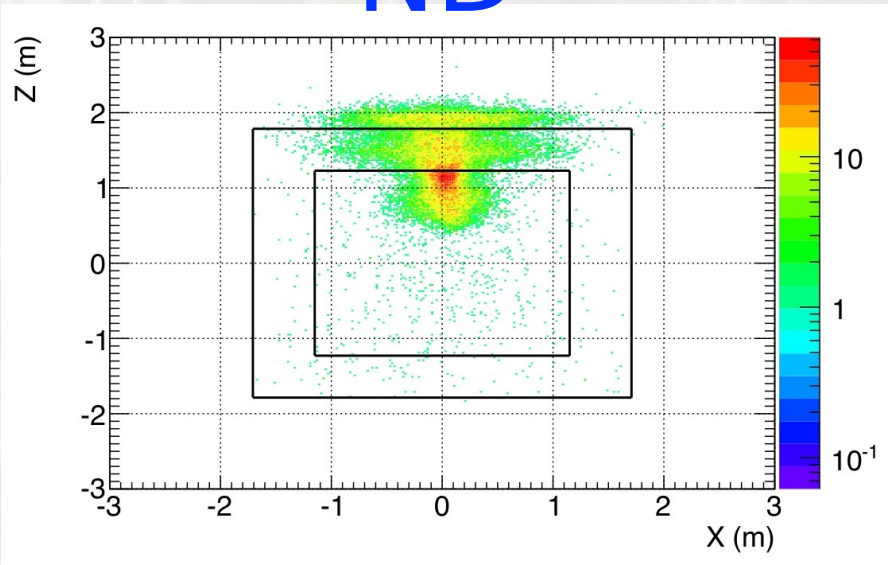
Stopping-μ Rejected

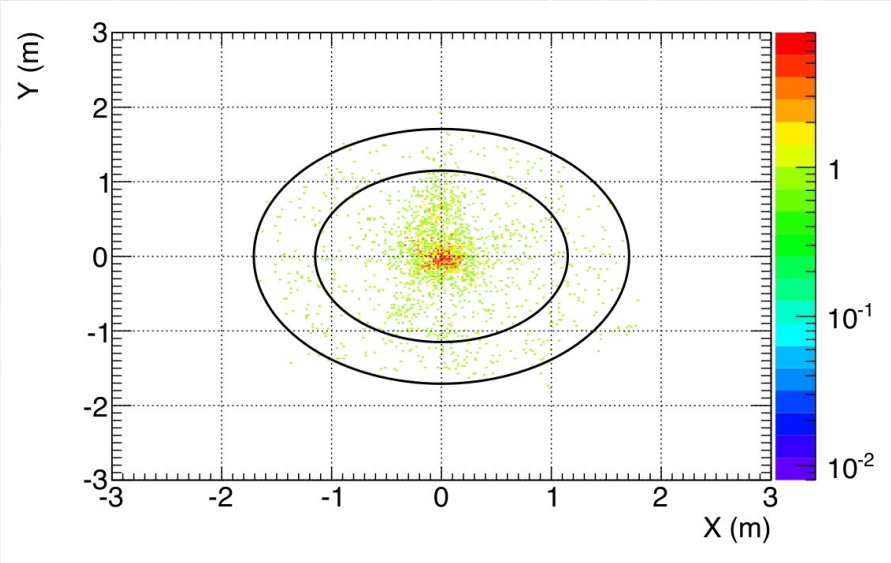
Reconstructed Vertex

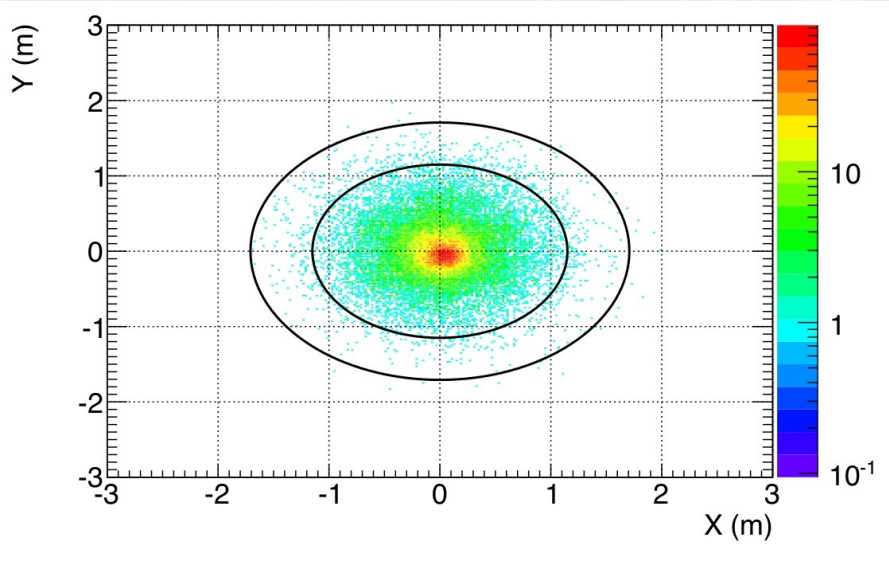
FD



ND







Recapitulation (~10 years)

DC was…

- **smallest target (~8t)**
  (smallest signal)
- **lowest overburden**
  (largest BG)

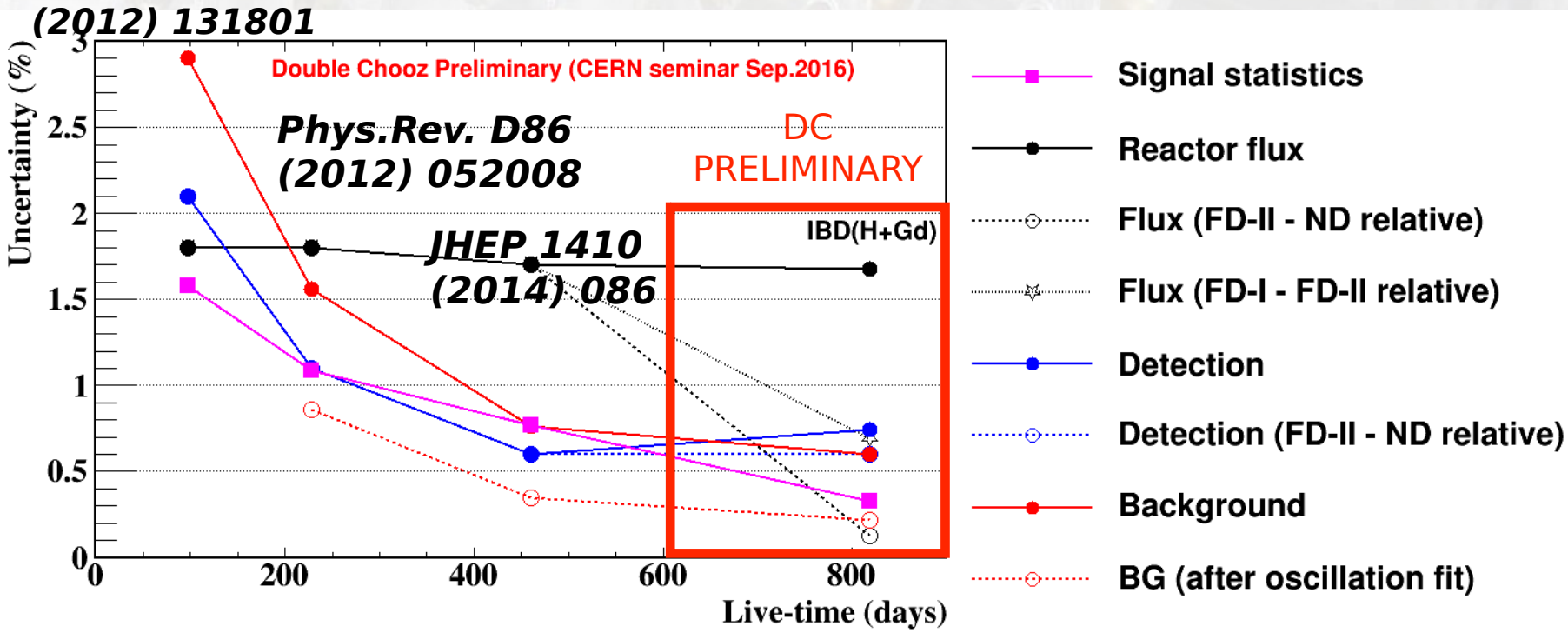
& worse…

- **ND (tiny) leak**
  (complex normalisation)
- **delayed ND laboratory**
  (~3years)

DC is presented *now* as…

- **largest single-θ_{13}-target (~30t)**
  - √ 2nd largest world IBD sample
  - √ excellent energy control (<1% accuracy)
- **(no miracles) lowest overburden**
  - √ remarkable reco (great readout)
  - √ most precise BG control (reactor-OFF)
  - √ most powerful BG veto system
- **ND (tiny) leak…**
  - √ leak-immune selection IBD(Gd+H+C)
- **iso-flux site (2 reactors only)**
  - √ ND as a direct reactor flux monitor

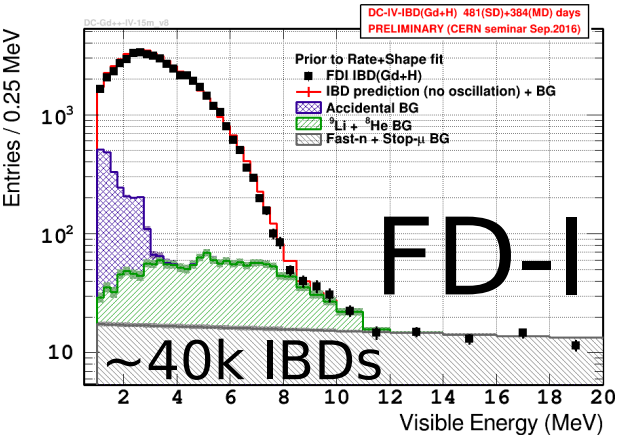
Systematic error evolution

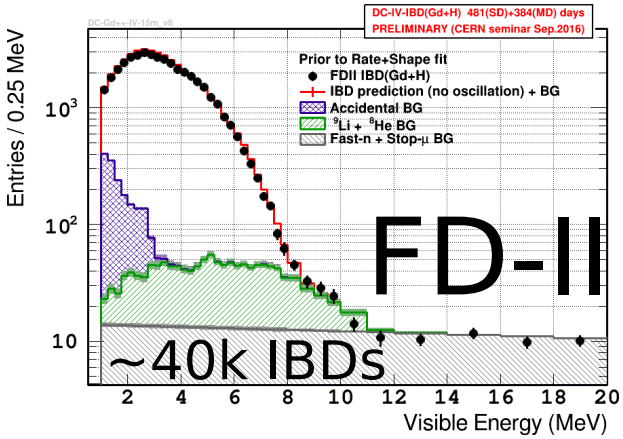


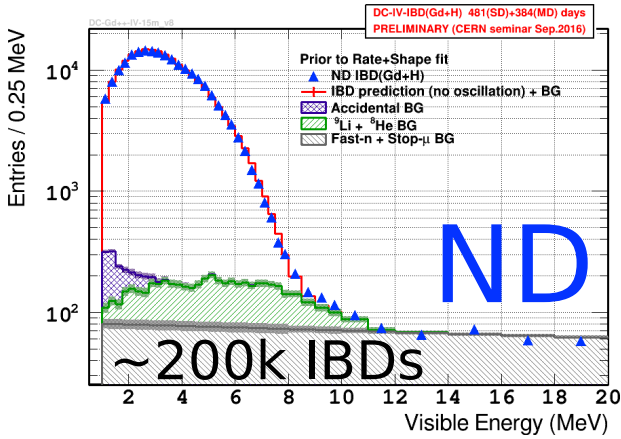
proton# (full volume) is largest uncertainty

(beyond DC-IV) dedicated campaign proton#
(analysis⊕hardware→ even decommissioning)

(R+S Fit) All Detector Spectra



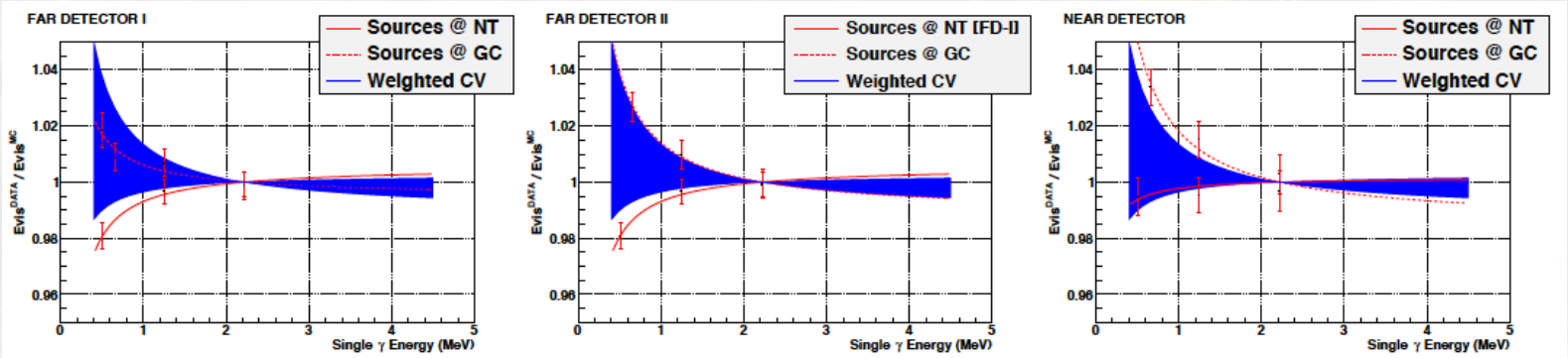




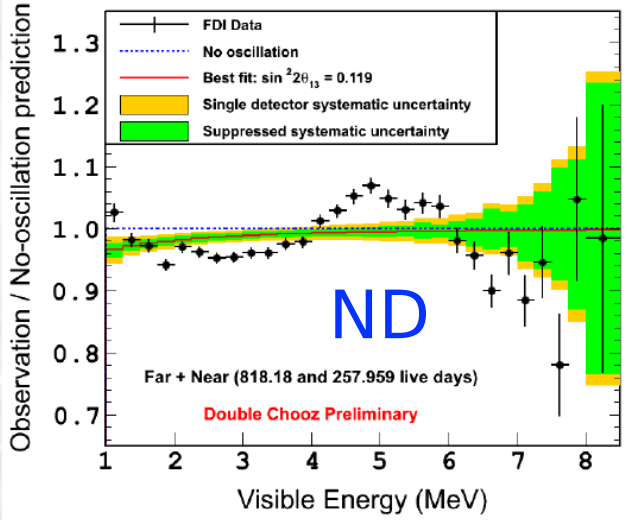
θ_{13} fits (Rate+Shape & Rate Only) fold all information simultaneous

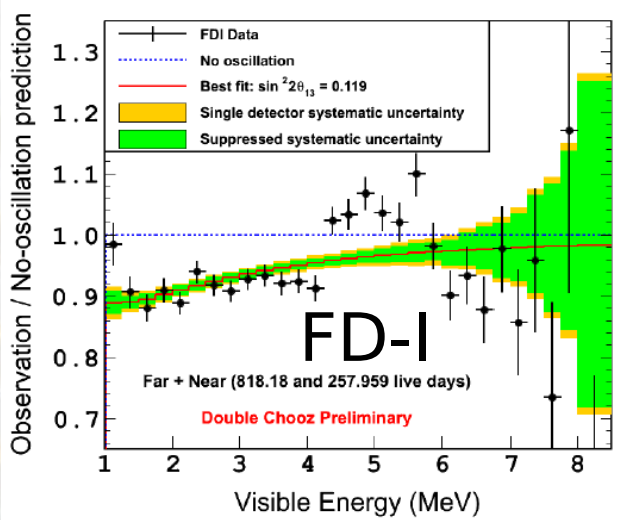
- **MD**(FD-II:ND)⊕**SD**(FD-I:FD-II:ND) [SD uses MC→ minimal impact]
  ⇒ MC-e+ non-linearity model [NT vs NT⊕GC volume]
- each BG (^{9}Li measurement ≳7MeV) ⊕ reactor-OFF constraint
- full flux error w/ and w/o Bugey4 constraint

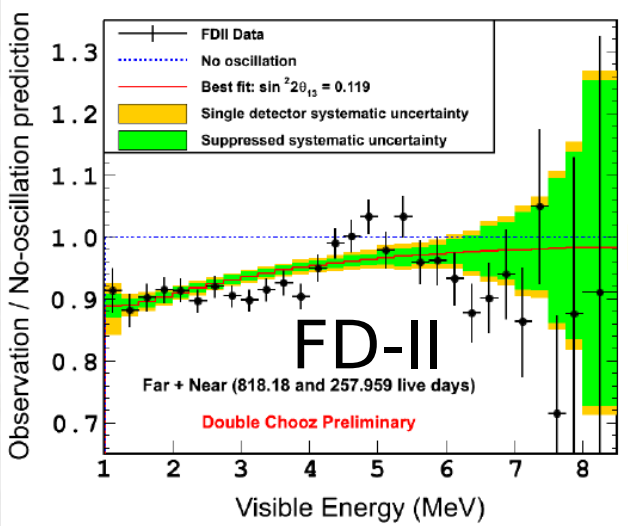
all correlations energy⊕reactors⊕detectors⊕backgrounds



θ_{13} R+S Fit Result







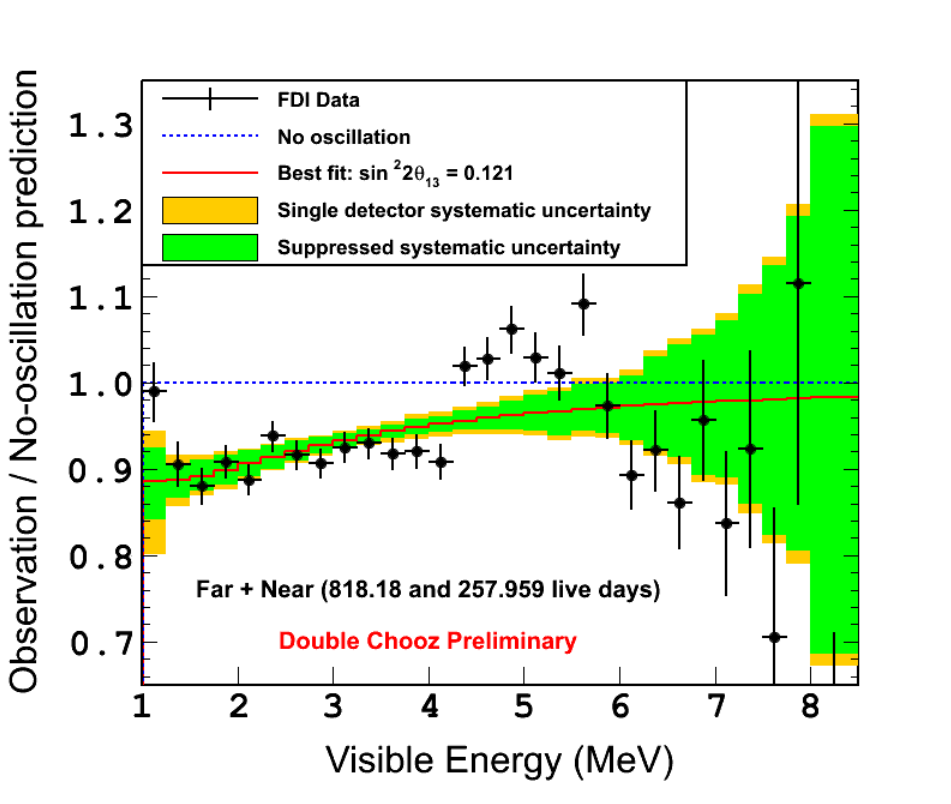
$\sin^2(2\theta_{13})^{R+S}=(0.119\pm0.016)$ with χ^2 / ndf: 236.2 / 114

(marginalised over $\Delta m^2=(2.44\pm0.09)eV^2$

Parke et al. arXiv:1601.07464)

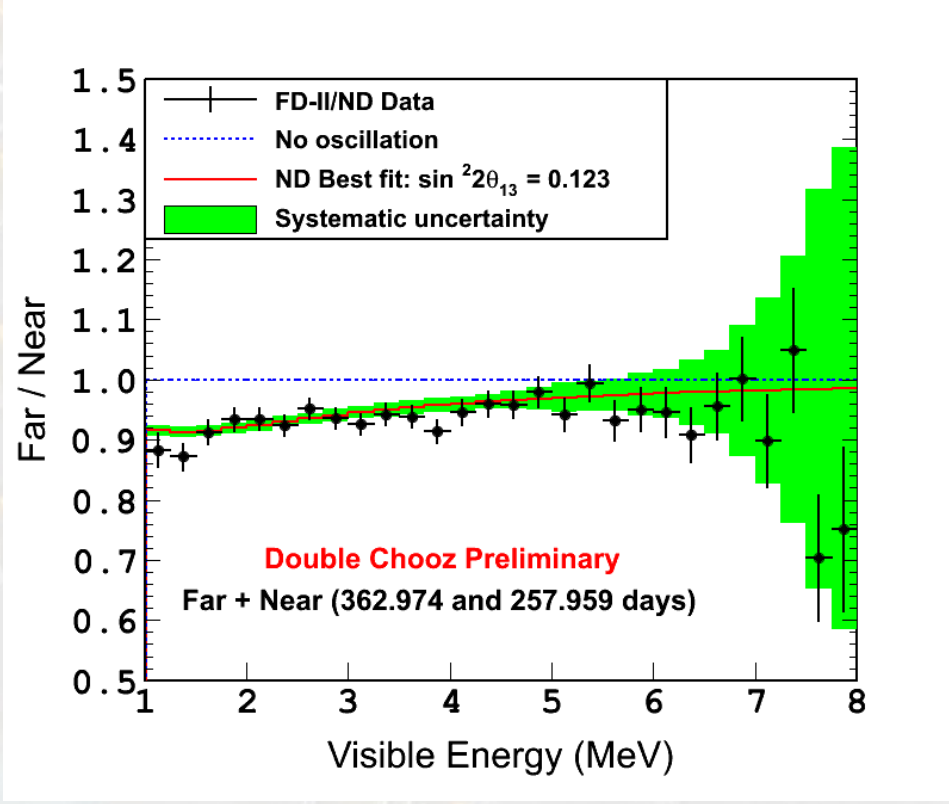
θ_{13} Fit Validation

Data | MC



$\sin^2(2\theta_{13}) = (0.119 \pm 0.016)$

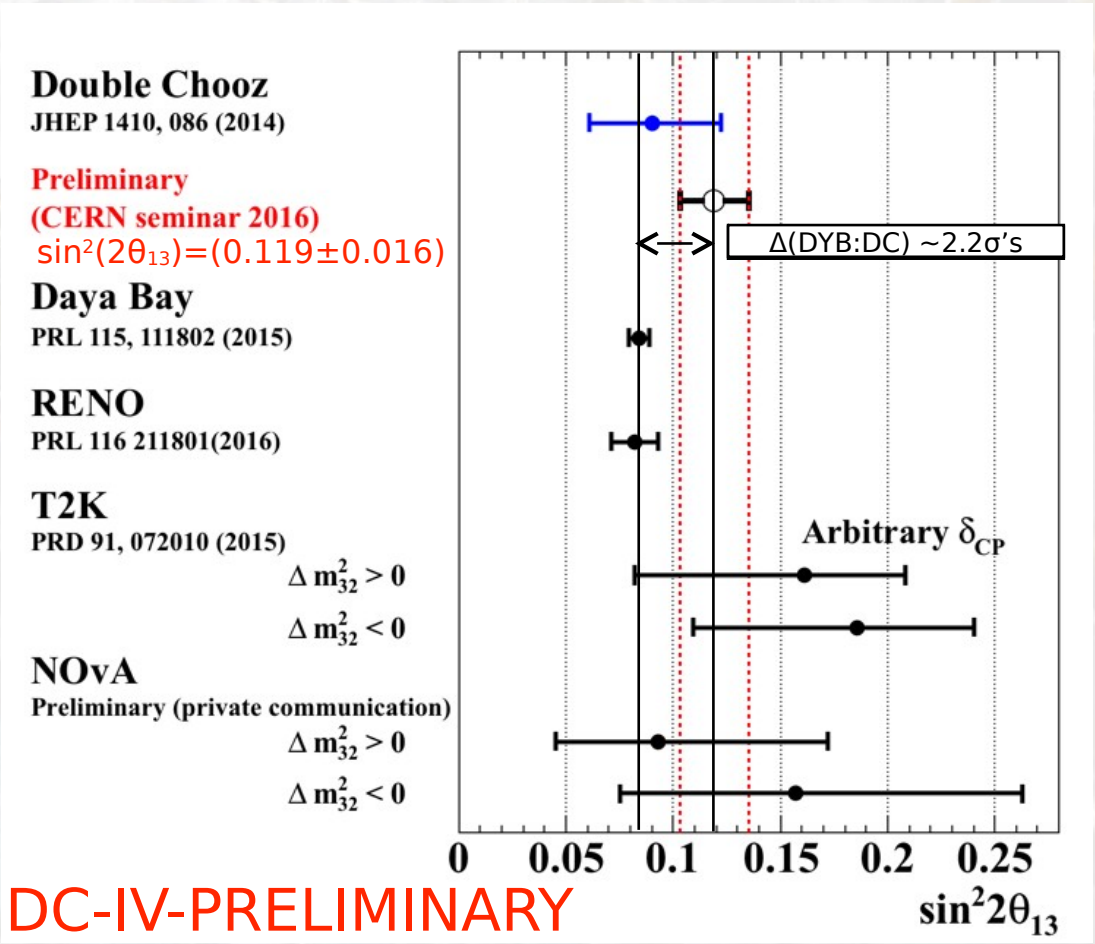
Data | Data

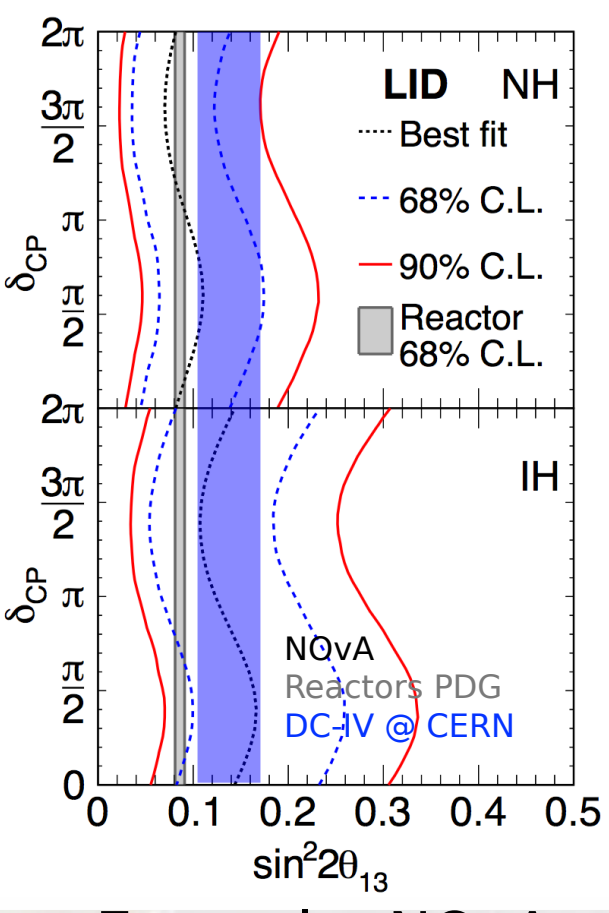


$\sin^2(2\theta_{13}) = (0.123 \pm 0.023)$

(spectral distortions cancel across ND:FD)

Comparison with others





Example: NOvA

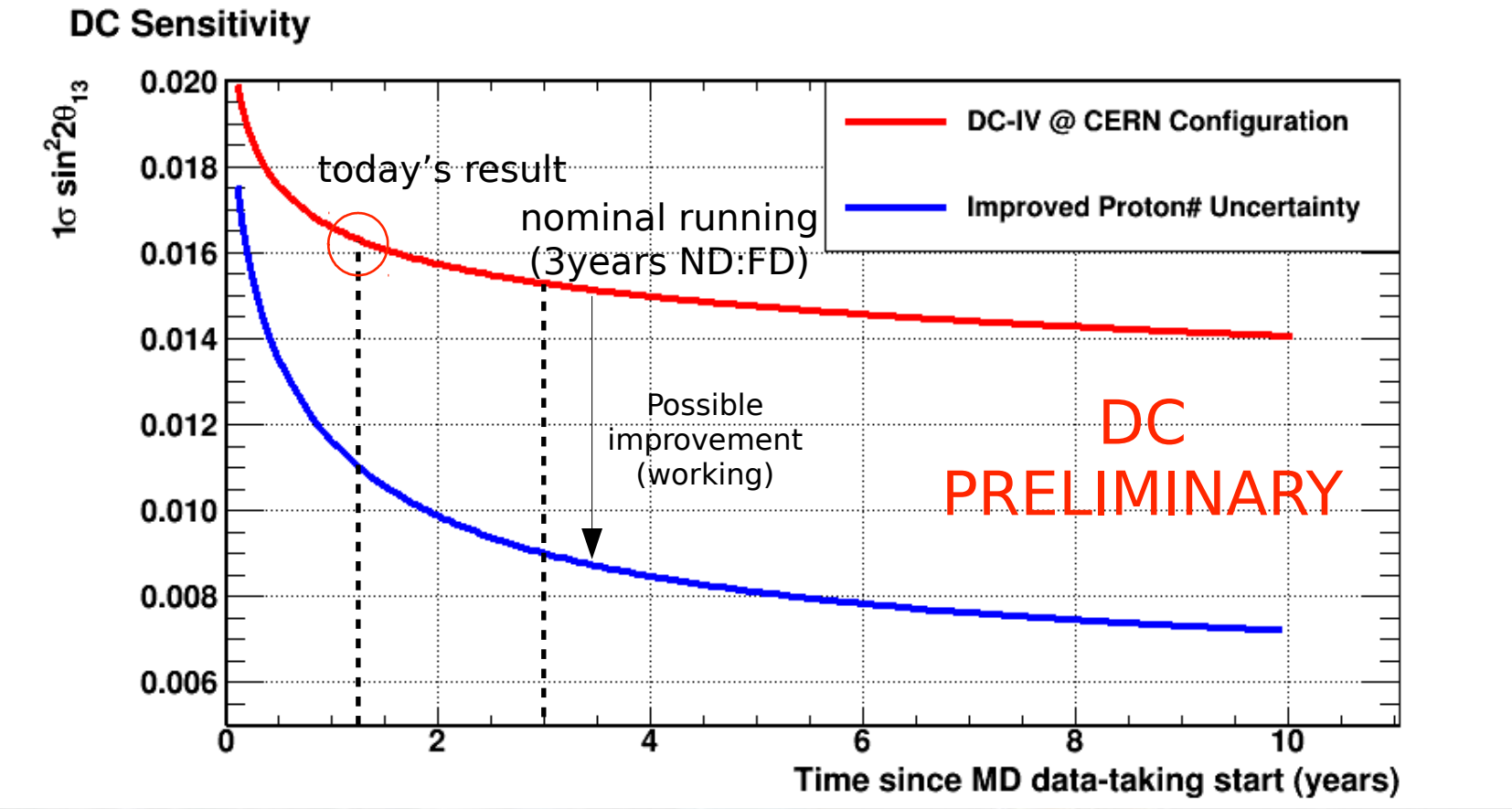
DC & beams might prefer a higher θ_{13}?

(beam "handicapped" by unknowns(δ_{CP}) / uncertainties)

reactor-θ_{13} key to solve CP-violation & mass hierarchy→ redundancy fundamental

(reactor-θ 13 experiments work together to resolve)

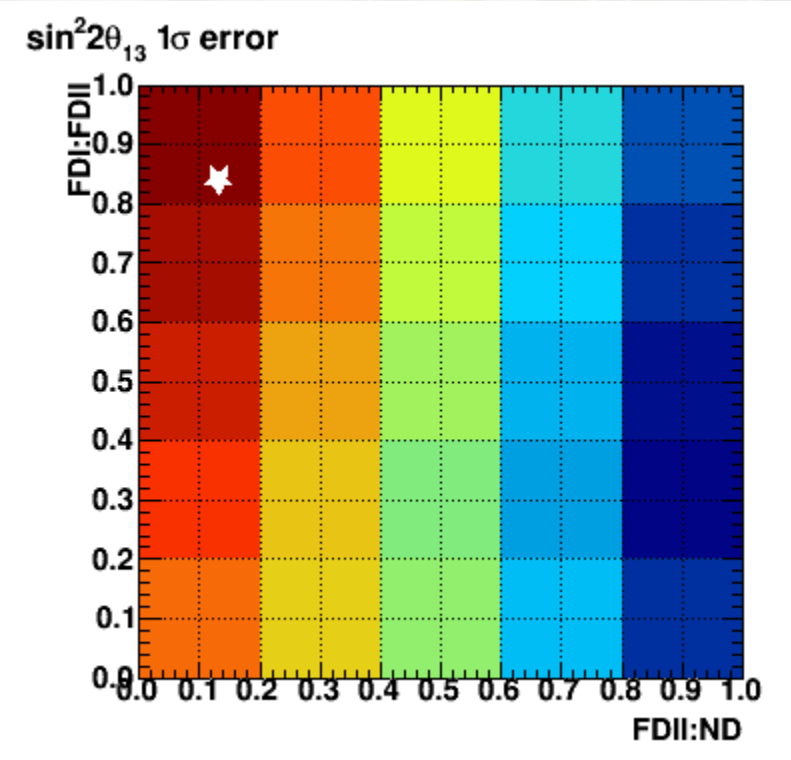
Prospects to the Future



DC largely dominated by proton#→ improvement possibility?

Prospects to the Future

We know that current result is conservative

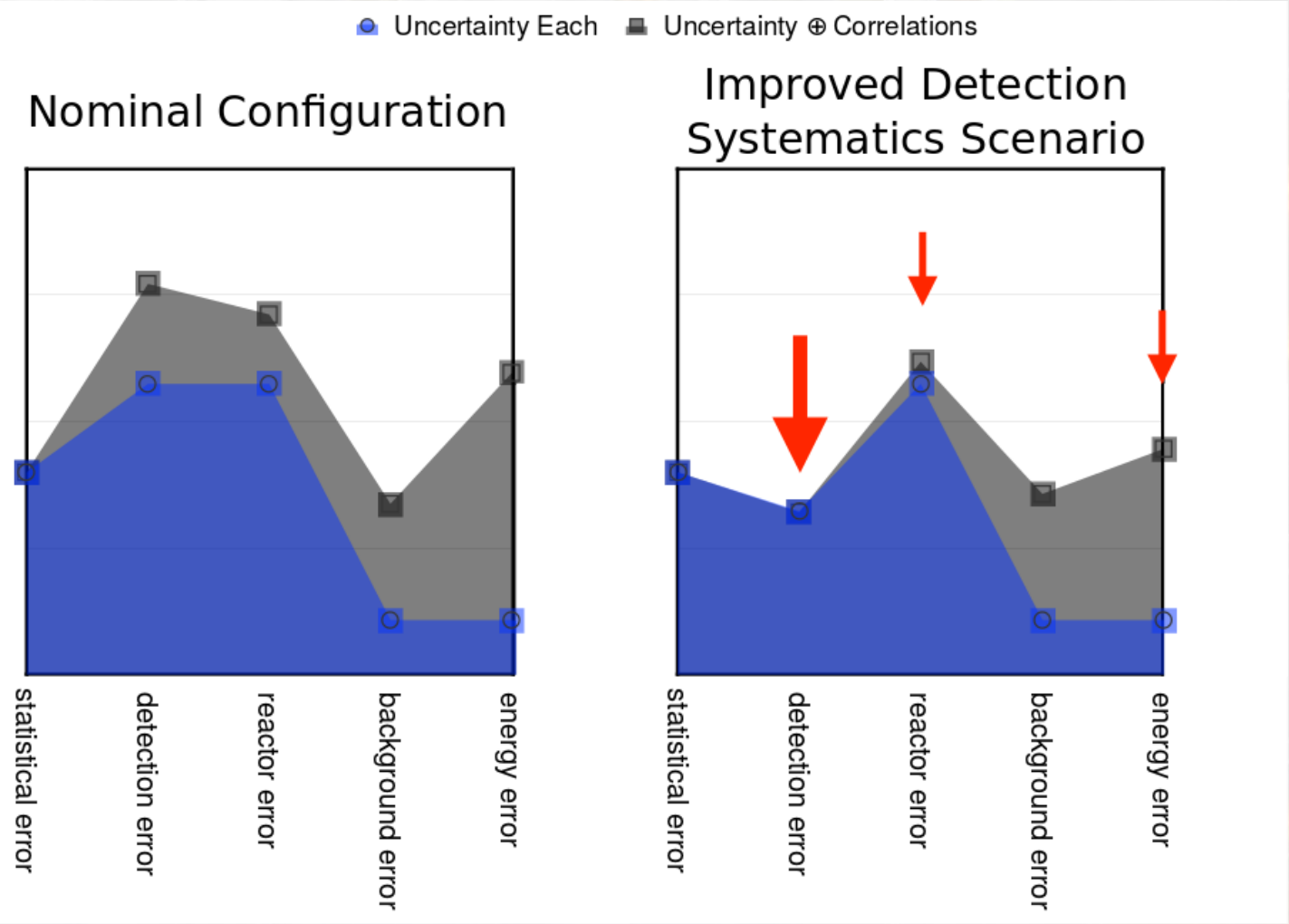


Detection systematics correlation btw FD:ND highly impacts θ_{13} sensitivity

(expected → "error cancellation" strategy)

Prospects to the Future

Further improvement, via systematics correlation



Prospects to the Future

What else is coming (θ_{13} front)?

- >2weeks of reactor off data (further validate ND BG)

http://www.lunion.fr/46034/article/2017-08-23/la-centrale-de-chooz-un-incident-provoque-l-arret-du-reacteur-et-l-inquietude-d

Reactor-θ_{13} *(combining results)*

Daya Bay⊕Double Chooz⊕RENO

0th discussion/planning → Neutrino 2016 Conference, London (UK)

1st workshop → October 2016 (Seoul, South Korea)
(systematics, results consistency)

2nd workshop → June 2017 (APC, France)
(articulation the start of 1st common analysis: cosmogenic BG)

final goal: combination of reactor-θ_{13} (many results)

(likely) most precise input to θ_{13} for several decades…

Double Chooz

Beyond θ_{13}

High Precision Reactor-IBD Rate (world ref. Bugey4)

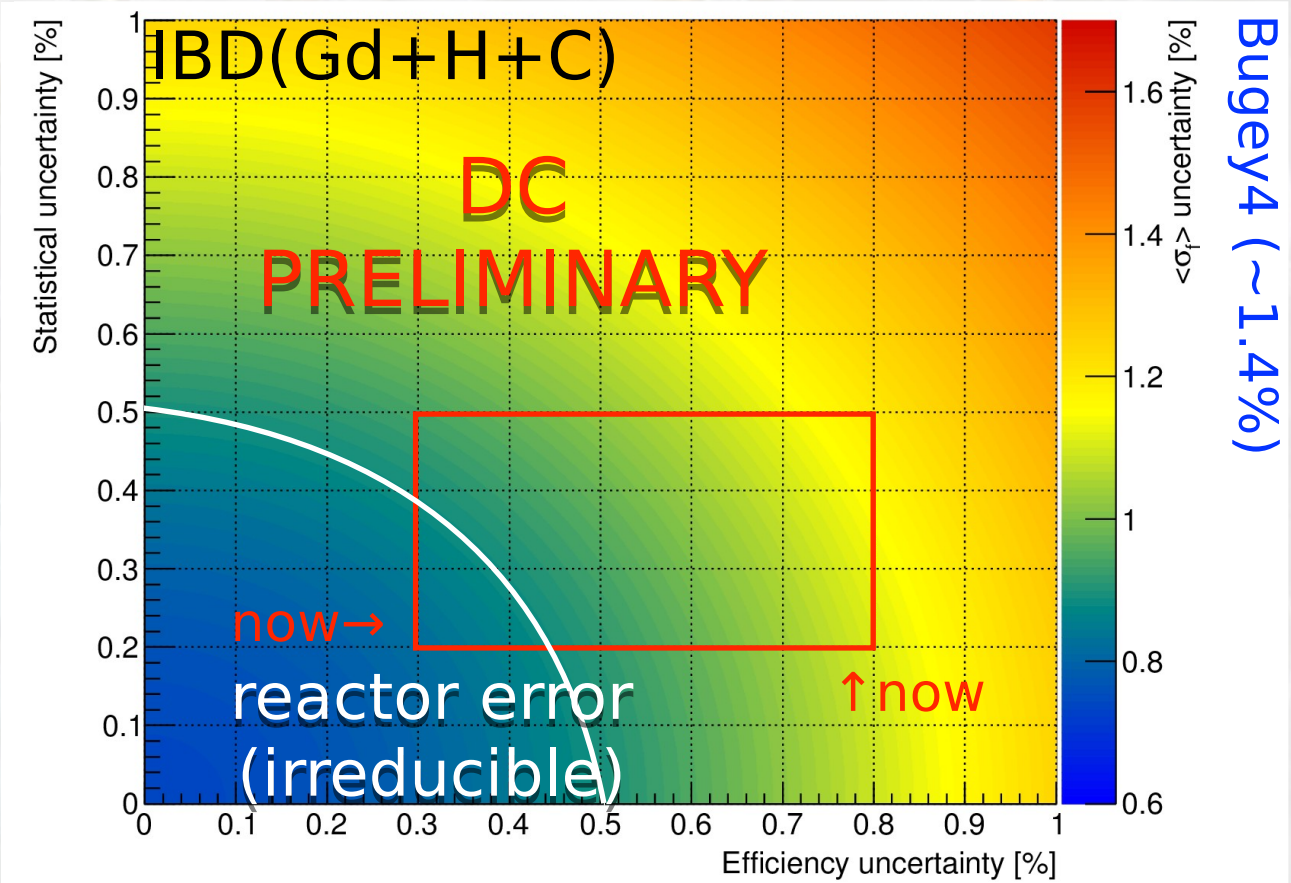
reactor luminosity

$$\langle \sigma_f \rangle = \frac{n_\nu}{N_p \times \epsilon} \times \frac{1}{\sum_{p=1}^{2} \frac{\langle P_{th} \rangle_p}{\langle E_f \rangle_p \times 4\pi R_p^2}}$$

n_ν: IBD rate **without** oscillation $[\bar{\nu}_e . s^{-1}]$

p: iterator over the reactor B1 & B2

DC expected to supersede Bugey4 (world reference today)



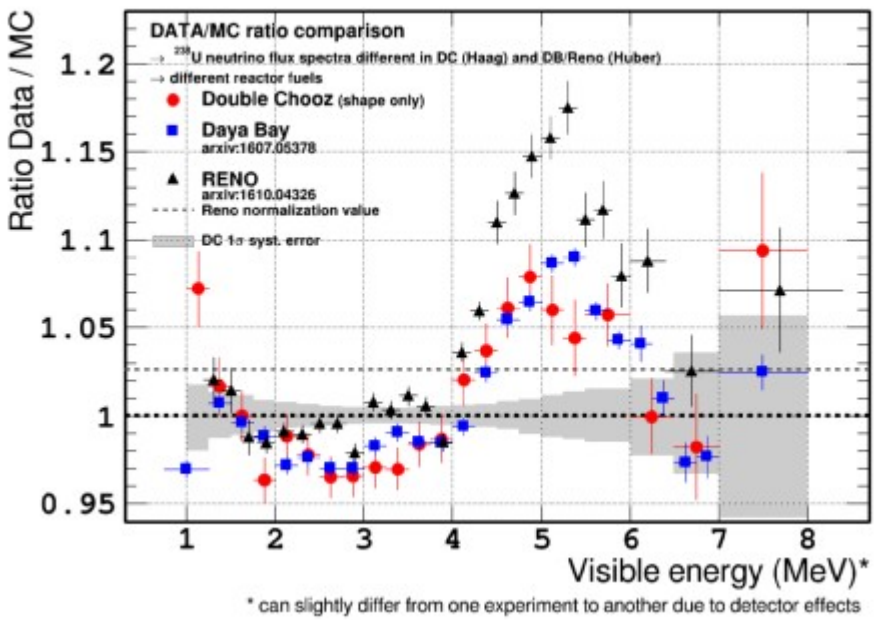
Details at A. Onillon talk this afternoon

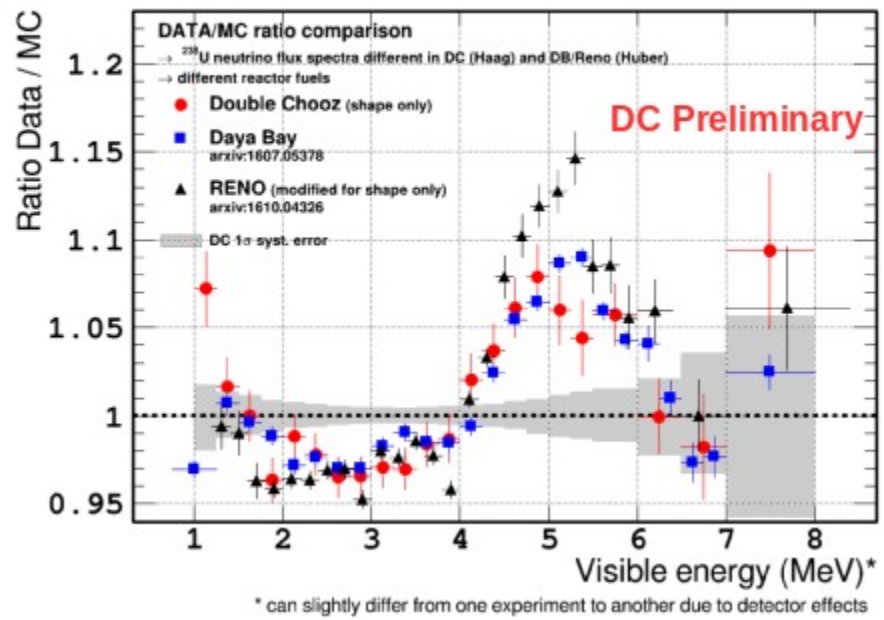
precision limit $\langle \sigma_f \rangle^{DC}$: total error ≈ reactor error (irreducible)

(Reactor Thermal Power ~0.47% @ Chooz)

Shape Distortion Comparison (DC Near)

DC: 210 000 events / DB: 1.2 million events / Reno: 280 000 events

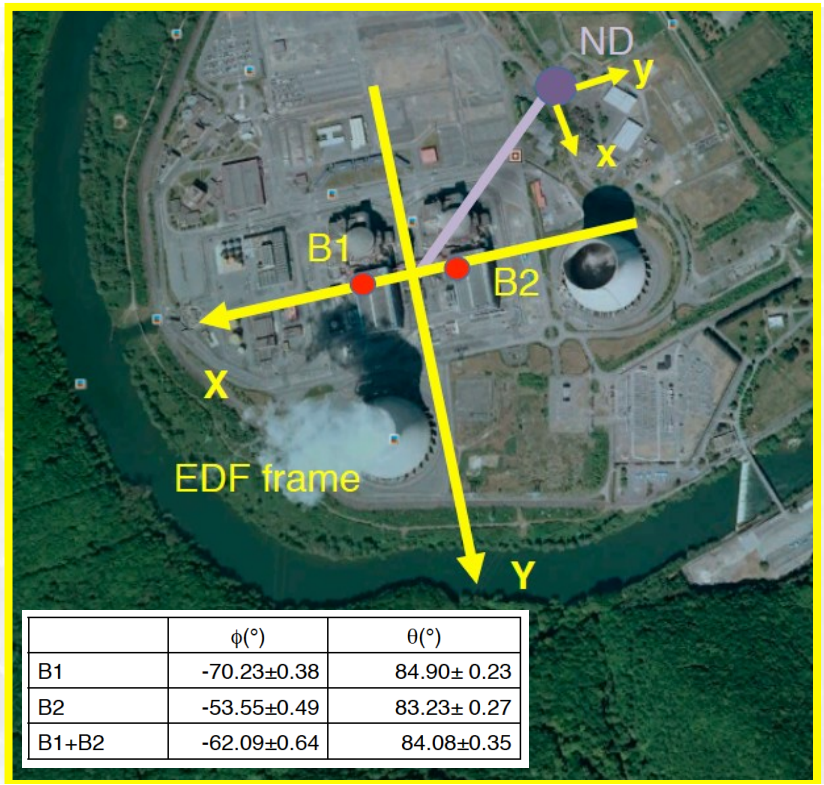




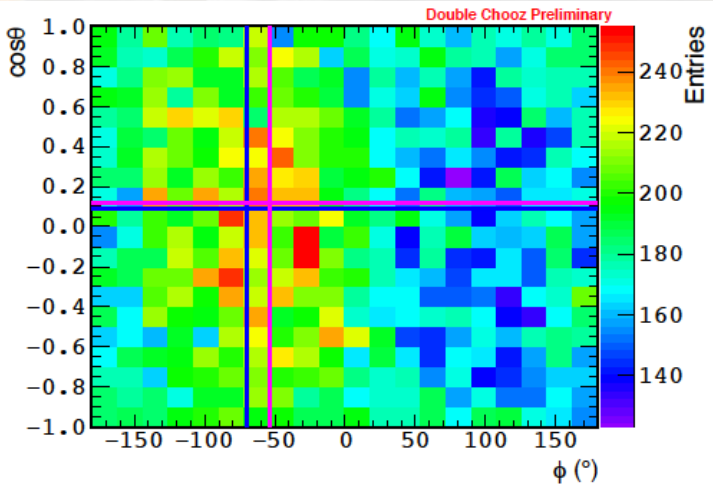
- **Consistency between Double Chooz and Daya Bay** results !
  → **not trivial**: θ_{13} correction, background, energy, ...
- Due to the normalization used, RENO points are close to 1 up to 4 MeV
- But good agreement with RENO when area are normalized to 1 for E < 4.5MeV
- Some discrepancy remains with RENO around 5 MeV:
  → DC and DB reactors are similar (Areva), not Reno reactors
  → Reactor fuels? Other?

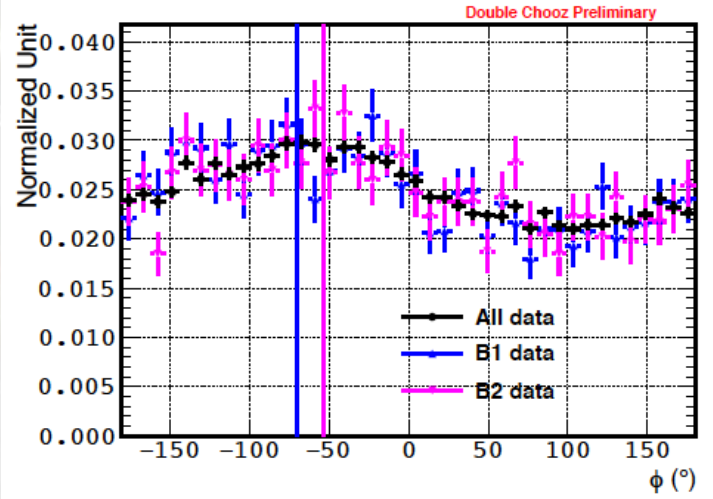
Details at A. Onillon talk this afternoon

IBD Directionality (Near Detector, Gd)



	ϕ(°)	θ(°)
B1	-70.23±0.38	84.90± 0.23
B2	-53.55±0.49	83.23± 0.27
B1+B2	-62.09±0.64	84.08±0.35





	Events	ϕ(°)	θ(°)	Stat(°)	Sys(°)	Δl(mm)
B1	4616	-81.0	101.8	9.4	1.4	21.2± 4.5
B2	4001	-69.2	96.6	12.0	3.3	21.8± 4.6
All	73869	-69.3	87.5	2.8	0.6	17.2± 1.0

IBD(ν_e+p→e^++n) incident direction from linear momentum defined by Δl(e^+:n) vector

IBD directionality regarded as a statistical deformation (rather than event-wise pointing)

DC-IV Preliminary

DC results with new IBD(Gd+H+C) selection

- **largest-single-θ_{13}-target now** [statistics comparable to ~2x DYB-FD's & 2x larger than RENO]
- DC will NOT be limited by statistics: systematics challenge
- **conservative systematic scenario adopted** → expected to improve (ongoing work)

DC-IV PRELIMINARY results

- new sin2(2θ13) = (0.119±0.016) [many cross-checks: all consistent all across to our best ability]
  - **non-statistical discrepancy @ ~2.2σ** → must address internally & reactor-θ_{13} forum
- result understood as conservative. Better one expected soon;
- new reactor spectrum characterization (rate⊕shape) major improvement
- **DC questions ILL-based prediction error budget**: <u>limitation to reactor single-detectors to yield (some) fundamental particle physics issue</u>: **neutrino(sterile) hypothesis?**

DC world best IBD-directionality measurements → still improving!

Double Chooz collaboration

Brazil

CBPF
UNICAMP
UFABC

France

APC
CEA/DSM/IRFU:
- SPP
- SPhN
- SEDI
- SIS
- SENAC

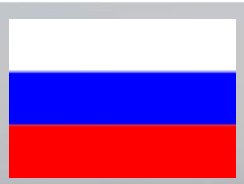
CNRS/IN2P3:
- Subatech
- IPHC

Germany

EKU Tübingen
MPIK
Heidelberg
RWTH Aachen
TU München
U. Hamburg

Japan

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



Russia

INR RAS
IPC RAS
RRC Kurchatov

Spain

CIEMAT-Madrid

USA

U. Alabama
ANL
U. Chicago
Columbia U.
UC Davis
Drexel U.
IIT
KSU
LLNL
MIT
U. Notre Dame
U. Tennessee

Spokesperson:
H. de Kerret (IN2P3)

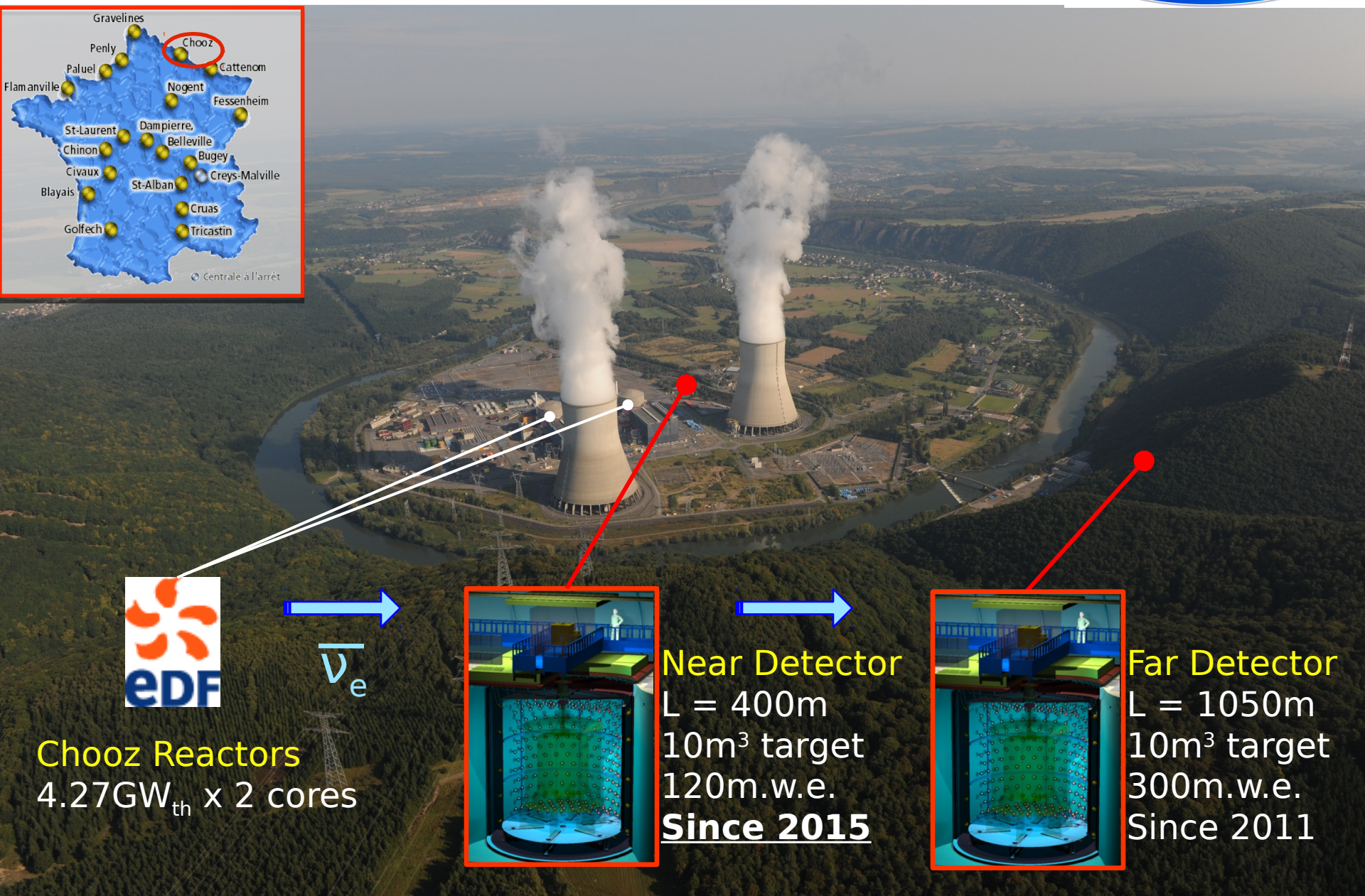
Project Manager:
Ch. Veyssière (CEA-Saclay)

Web Site:
www.doublechooz.org/


Thank you!

Backup

Double Chooz experiment



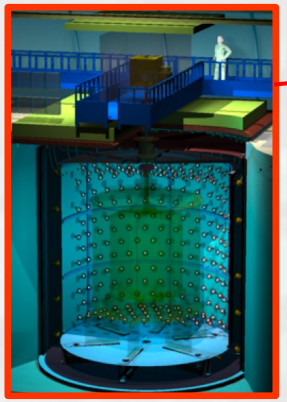
Precision measurement of θ_{13}

- Direct measurement of θ_{13} from energy dependent deficit
  - No parameter degeneracy/matter effects
- Suppression of systematic uncertainties (<< 1%) with multi-detectors at different baselines

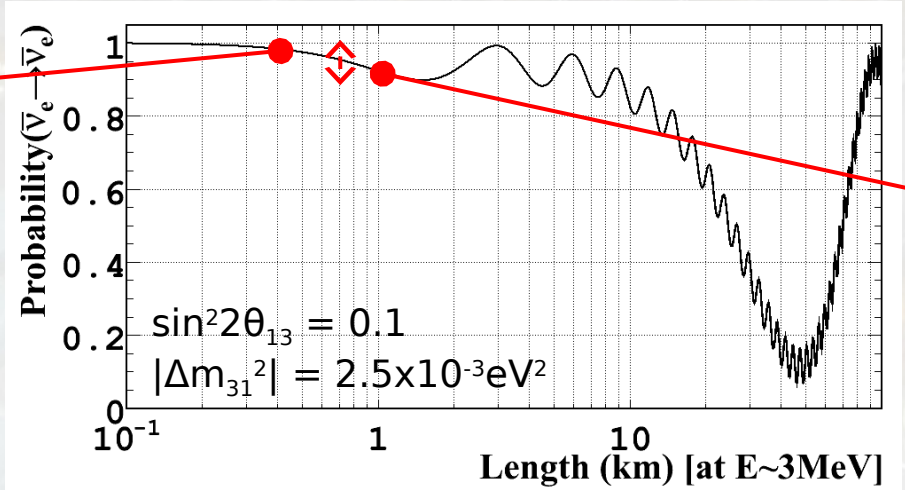
Survival probability of reactor neutrinos

$$P\left[\overline{\nu}_e \rightarrow \overline{\nu}_e\right] \cong 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) \quad \ldots$$

Simple two flavor oscillation formula is valid at L ~ 1km



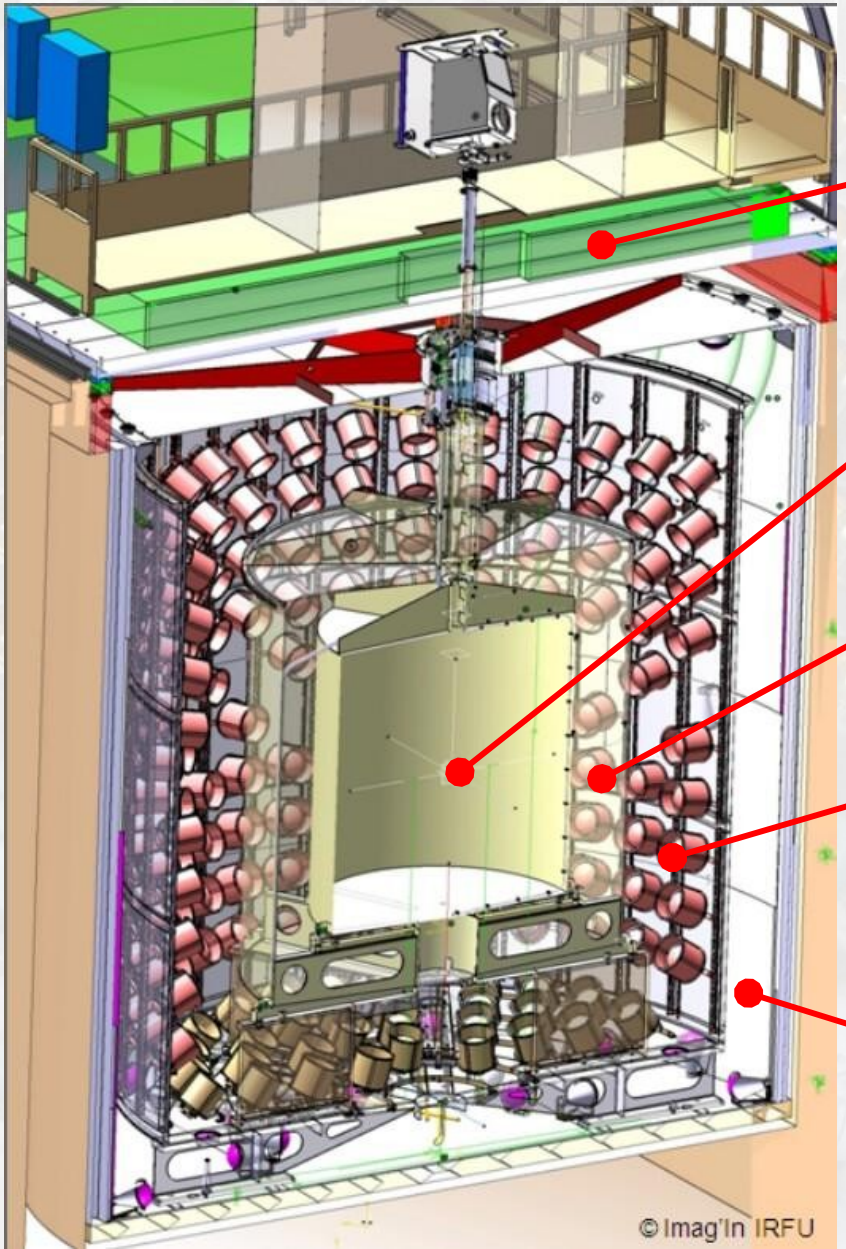
Near Detector (ND)



Far Detector (ND)

- Reactor θ_{13} (most precise) used as reference in current and future projects which aim to search for CP violation and mass hierarchy in neutrino sector.

Double Chooz Detectors



Outer Veto (OV)
Plastic scintillator strips

Inner Detector (ID)

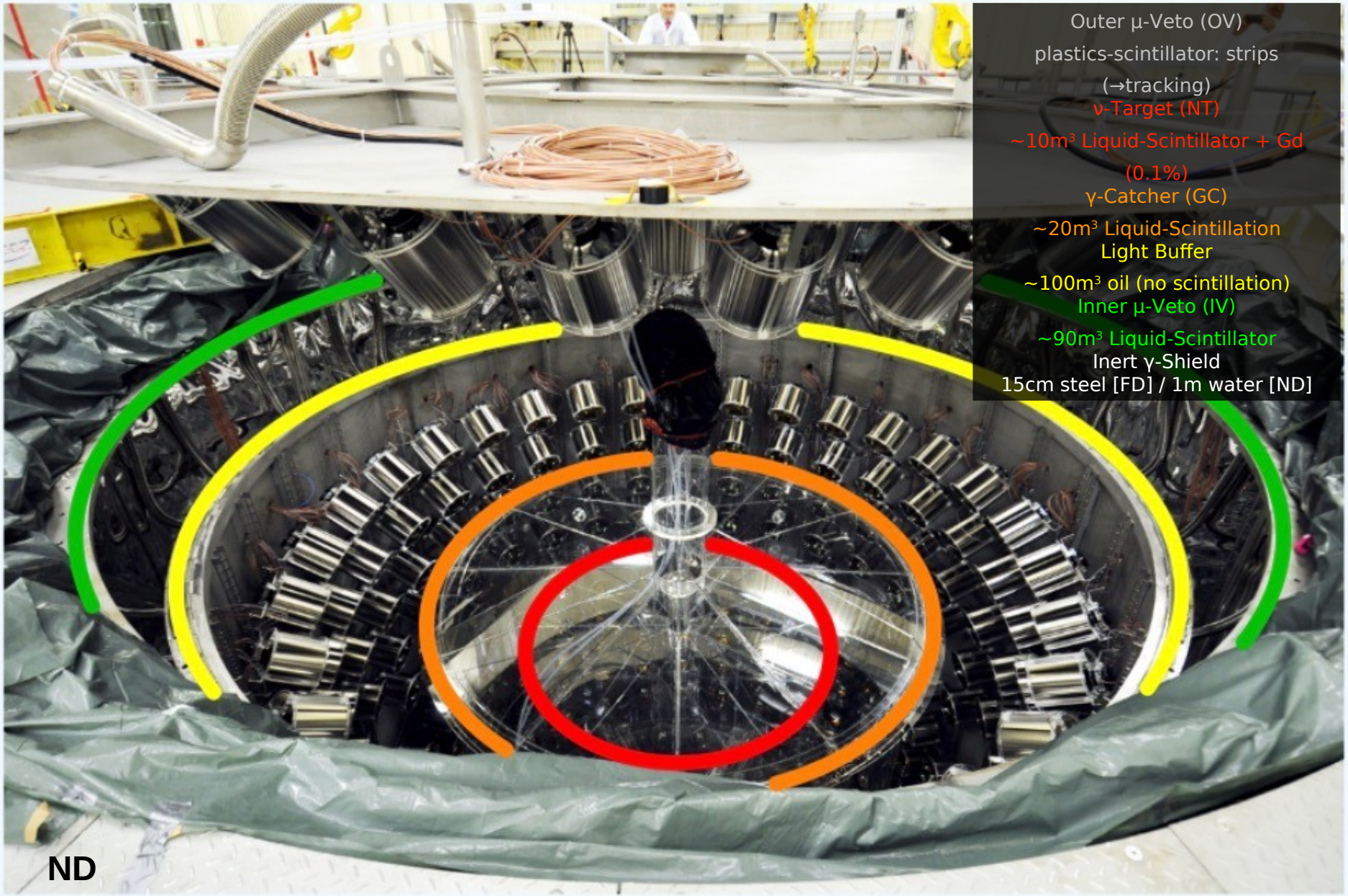
ν-target (NT)
- Gd loaded liquid scintillator (10m³)

γ-catcher (GC)
- Liquid scintillator (22m³)

Buffer
- Mineral oil (110m³)
- 390 10-inch PMT

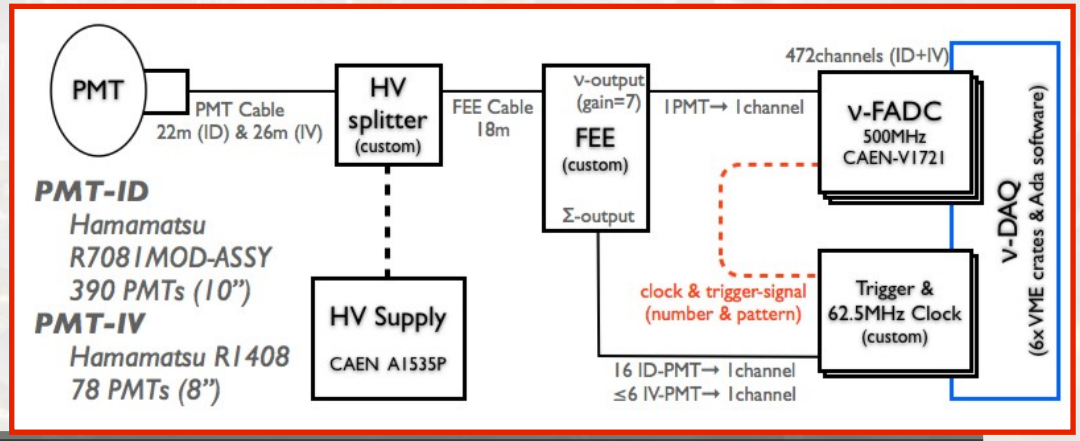
Inner Veto (IV)
- Liquid scintillator (90m³)
- 78 8-inch PMT

Double Chooz Detectors

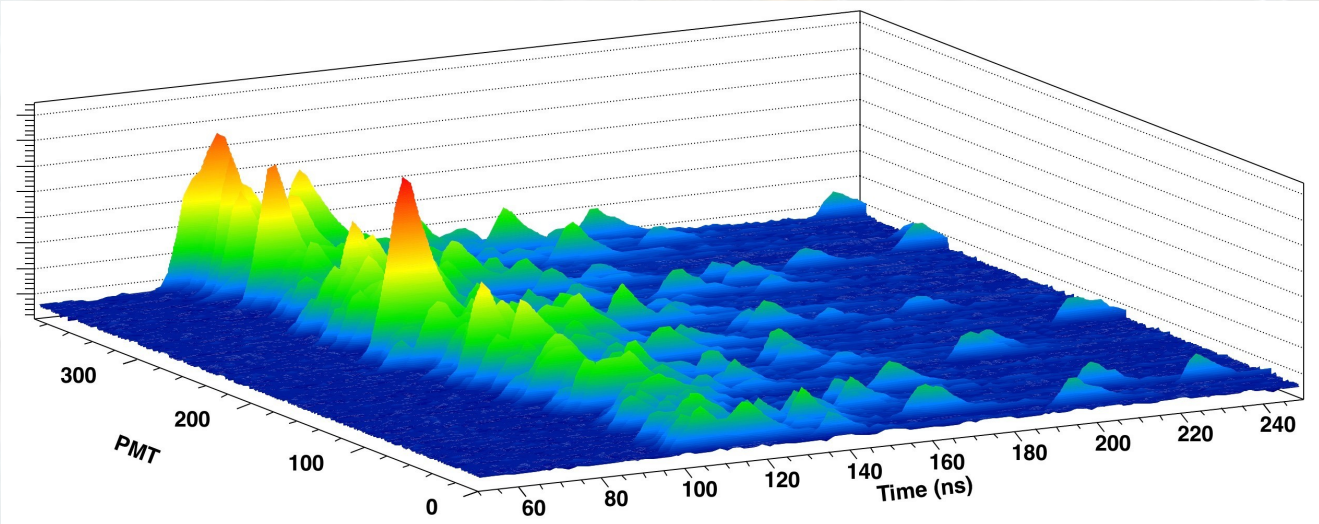


Double Chooz Read-out

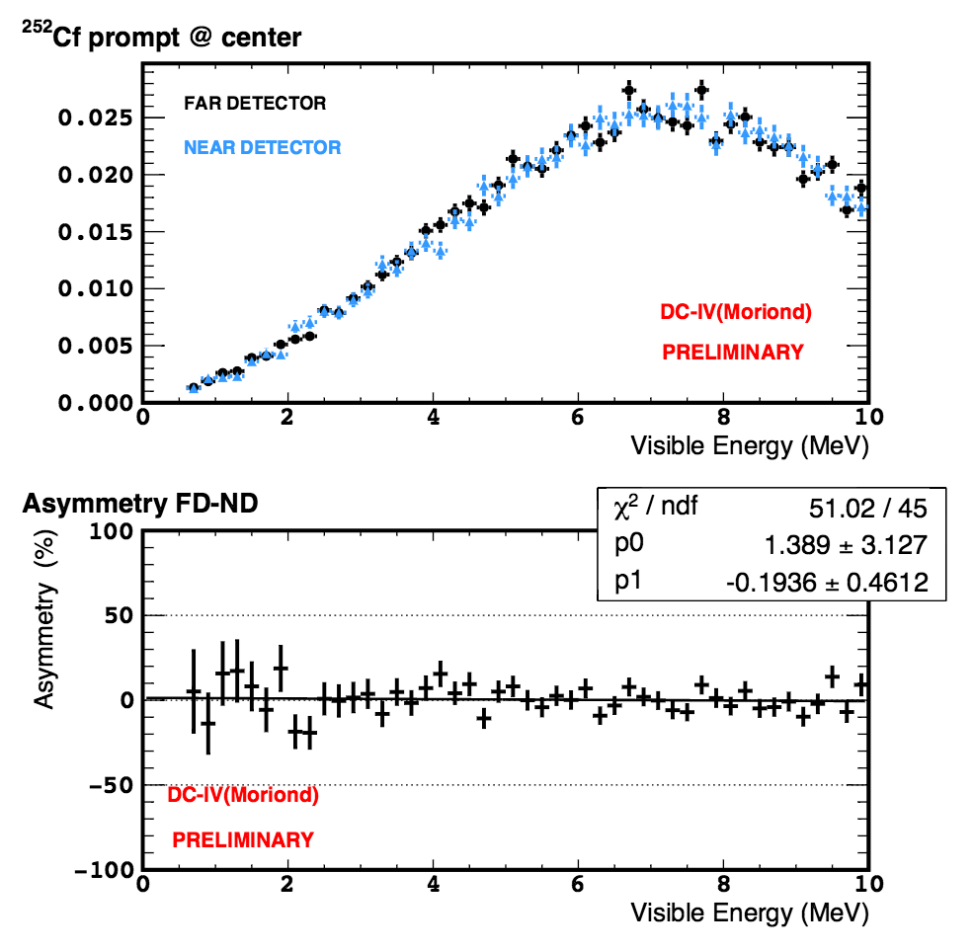
Liquid Scintillator
⊕
10” PMTs
⊕
analogue electronics
(clean & μ-handling)
⊕
500MHz FADC readout



Rich off-line reconstruction: energy & BG reduction
- time,charge [multiple methods]→ control of linearity
- position (x,y,z,t) [multiple methods]→ uniformity & BG vetoes
- PSD & PID [time and frequency domain]→ BG vetoes
- multiplicity & inter-detector-layer correlation→ BG vetoes



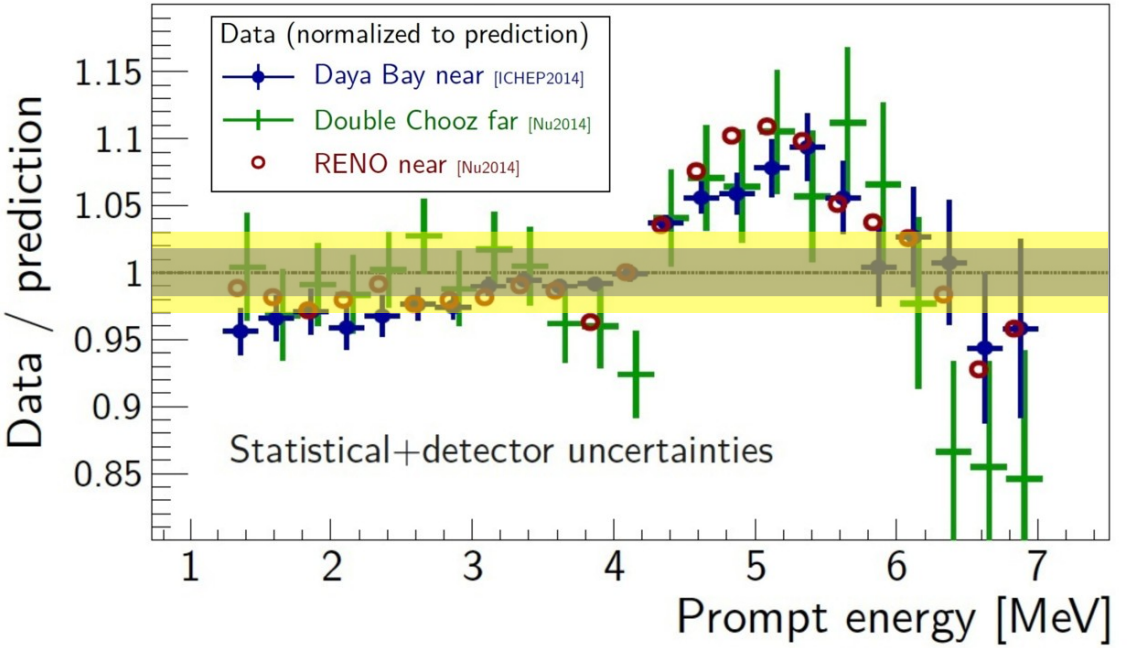
Prompt energy of ^{252}Cf data



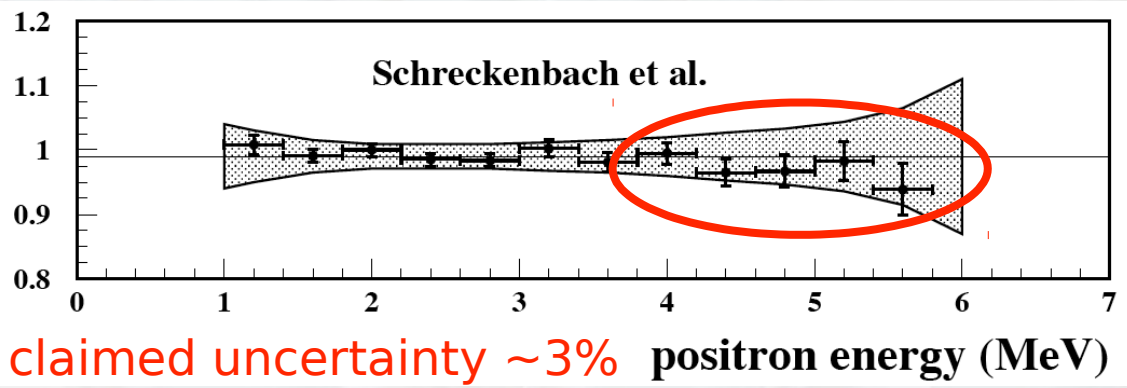
- ^{252}Cf emits ~10 γ with 1MeV in average.
- Comparison of FD and ND data with ^{252}Cf at the center of detector

Reactor-θ_{13} found spectral distortions

1σ of δ(flux)→ ±3% (DYB & RENO) & ±1.7% (DC⊕Bugey4)



DC first paper on the subject @JHEP 1410 (2014) 086



claimed uncertainty ~3%

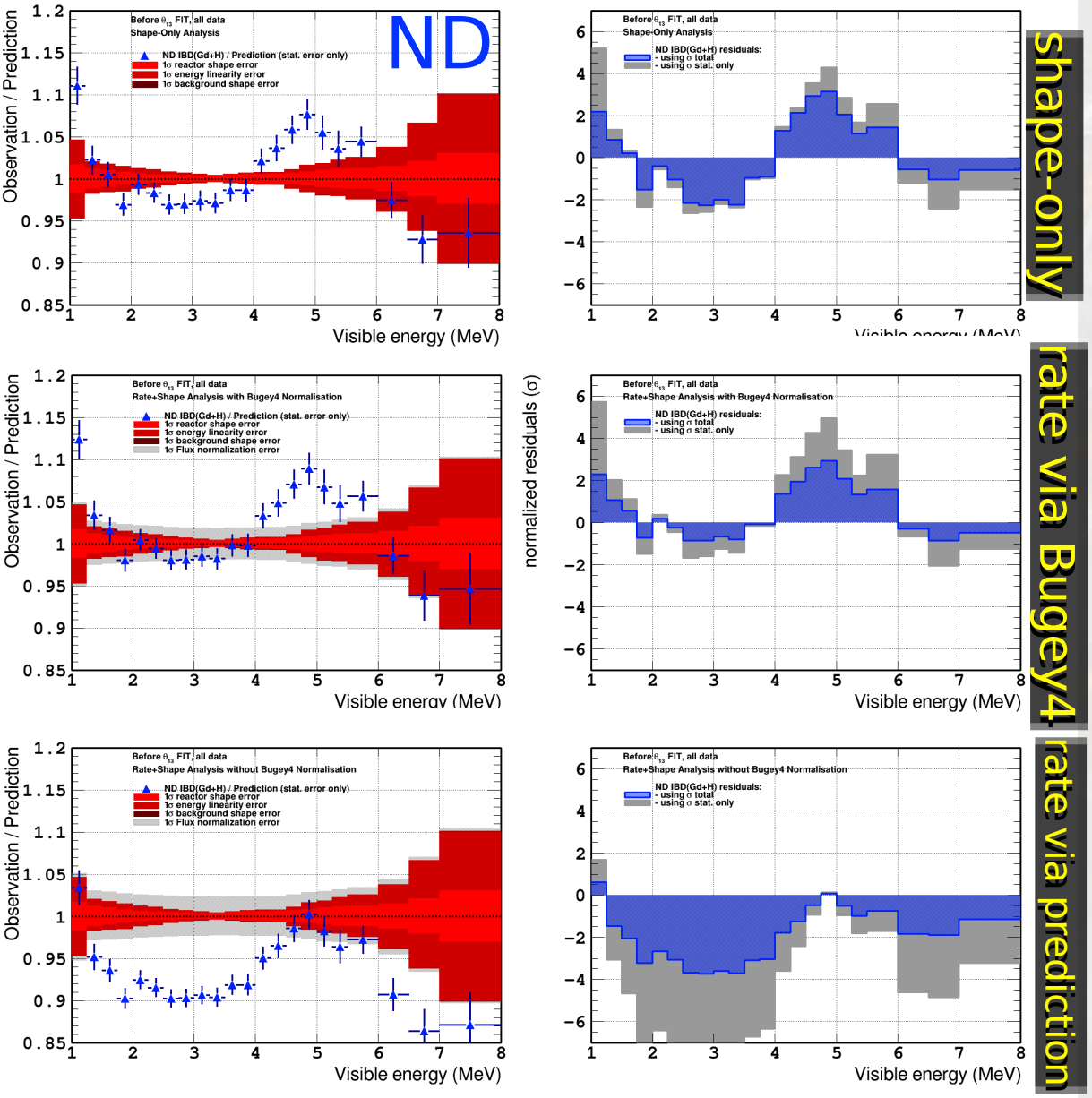
3 different experiments in agreement
(not trivial→ not identical fuels)

MAIN ISSUE
features >1σ(flux) ILL-based prediction uncertainties
⇒ error is (likely) underestimated
(hard to believe otherwise)

QUESTION
why Bugey3 data did not see it?
(best world shape reference)
[DC⊕B3 working to reconcile]

⇒LIMITATION?
our ability to address ν(sterile) hypothesis with reactor-data
(single detector)

Distortion analysis with ND rate+shape



test the existence of features not biased by shape-only assumption (i.e. smaller errors)

shape-only≈Bugey4 (consistency of Bugey4?)

non-statical features
- which is deficit?
- which excess?
- which is OK?

⇒ less evident!!

careful analysis before stating the "trouble region" is bump problem really? (maybe no bump whatsoever)

(bias question⇒bias answer)