Double Chooz Measurement of θ_{13} and Beyond

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on behalf of **the Double Chooz Collaboration**

The 26th International Workshop on Weak Interactions and Neutrinos @ UC Irvine

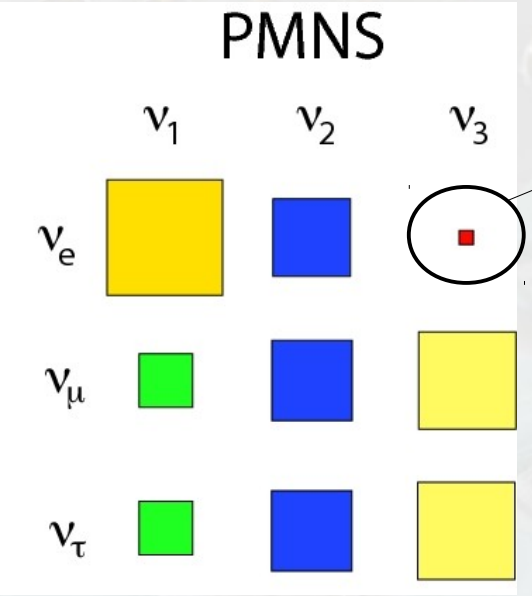
June 20th, 2017

Neutrino Oscillations and θ_{13}

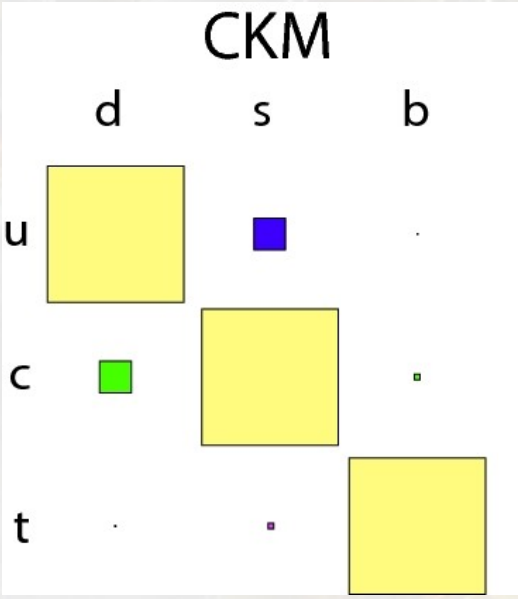
atmospheric	reactor & accelerator	solar
$P(\nu_\mu \to \nu_\mu)$	$P(\nu_e \to \nu_e)$ & $P(\nu_\mu \to \nu_e)$	$P(\nu_e \to \nu_x)$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{-i\delta} & 0 & c_{12}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

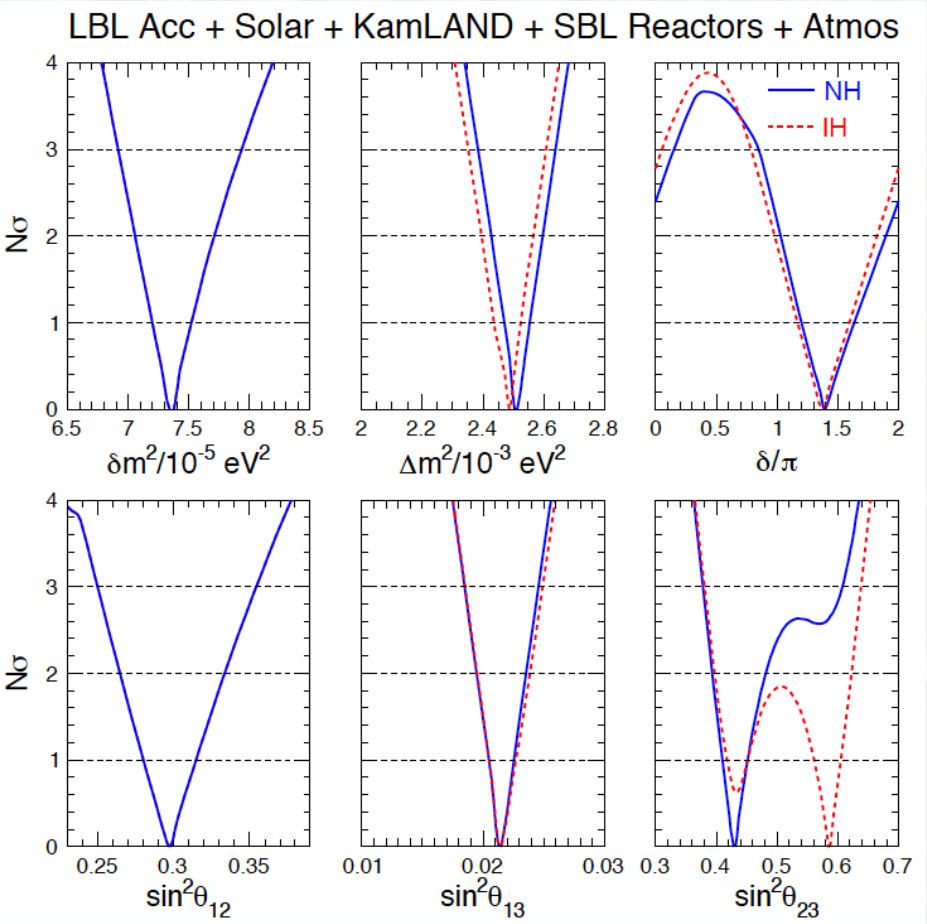
$\theta_{23} \sim 45^o$	θ_{13} & "dirac" δ_{CP}	$\theta_{12} \sim 33^o$



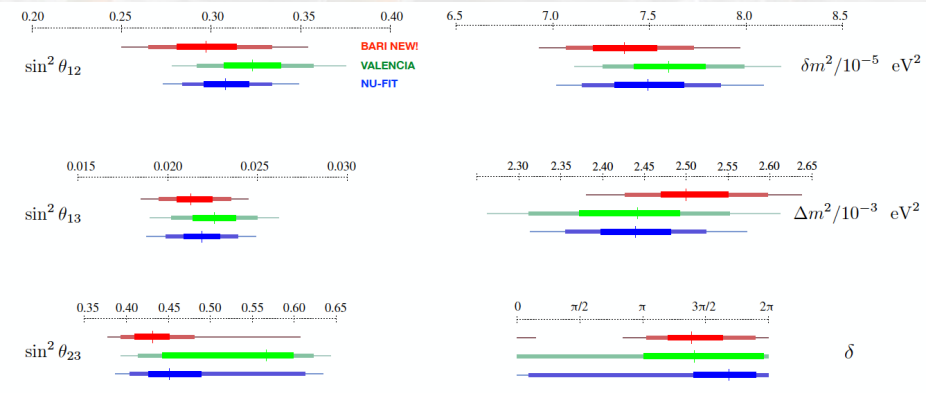
Driven by θ_{13}



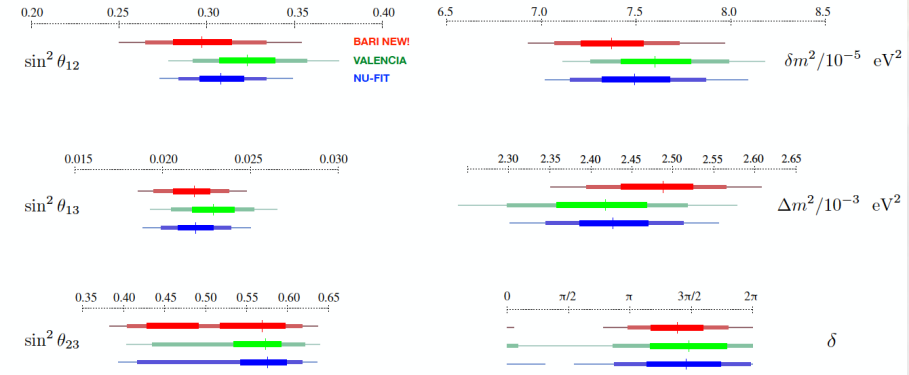
3 ν Oscillation Status (Marrone et al)



Normal ordering



Inverted ordering

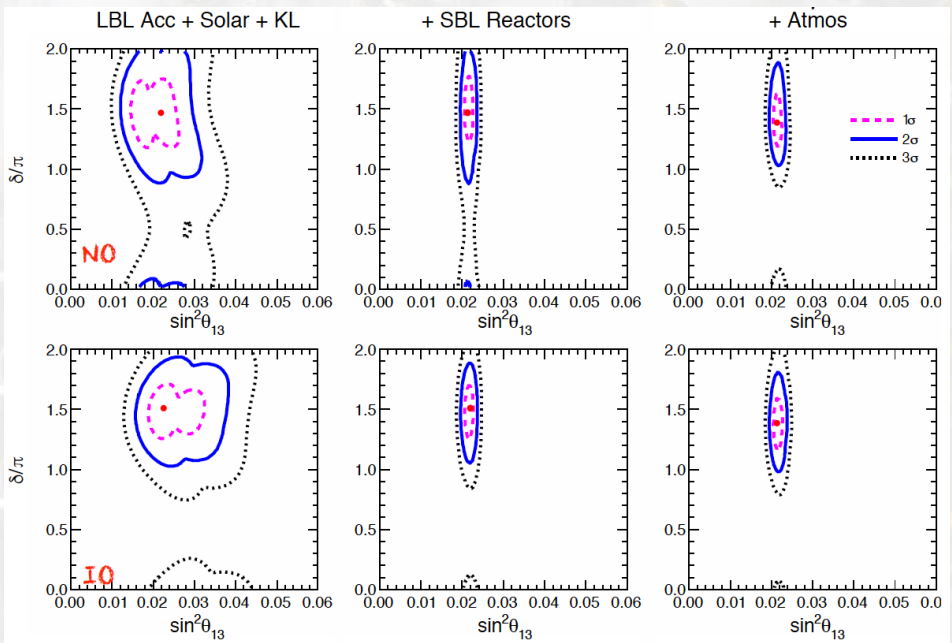


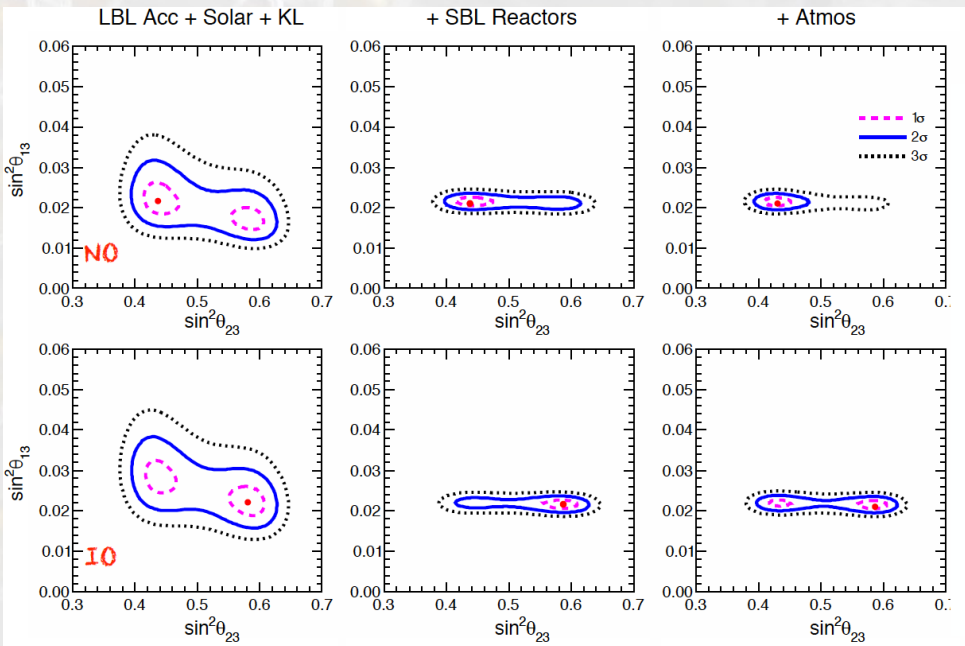
Oscillation parameters: θ_{13}, θ_{12}, θ_{23}, Δm^2, δm^2, δ_{CP}

- Remarkable precision, even a hint for δ_{CP}

3 ν Oscillation Status (Marrone et al)

Knowledge on 3ν oscillation model depends on θ_{13}





θ_{13} vs δ_{CP}
→ Maximal CP?

θ_{13} vs "octant"
→ do we know anything?

θ_{13} measurement (value & error) w/ critical implication
ex. Predict CPV correct?

Double Chooz collaboration

Brazil

CBPF
UNICAMP
UFABC

France

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

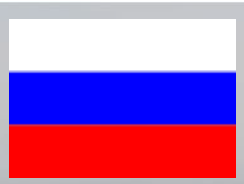
CNRS/IN2P3:
- Subatech
- IPHC

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

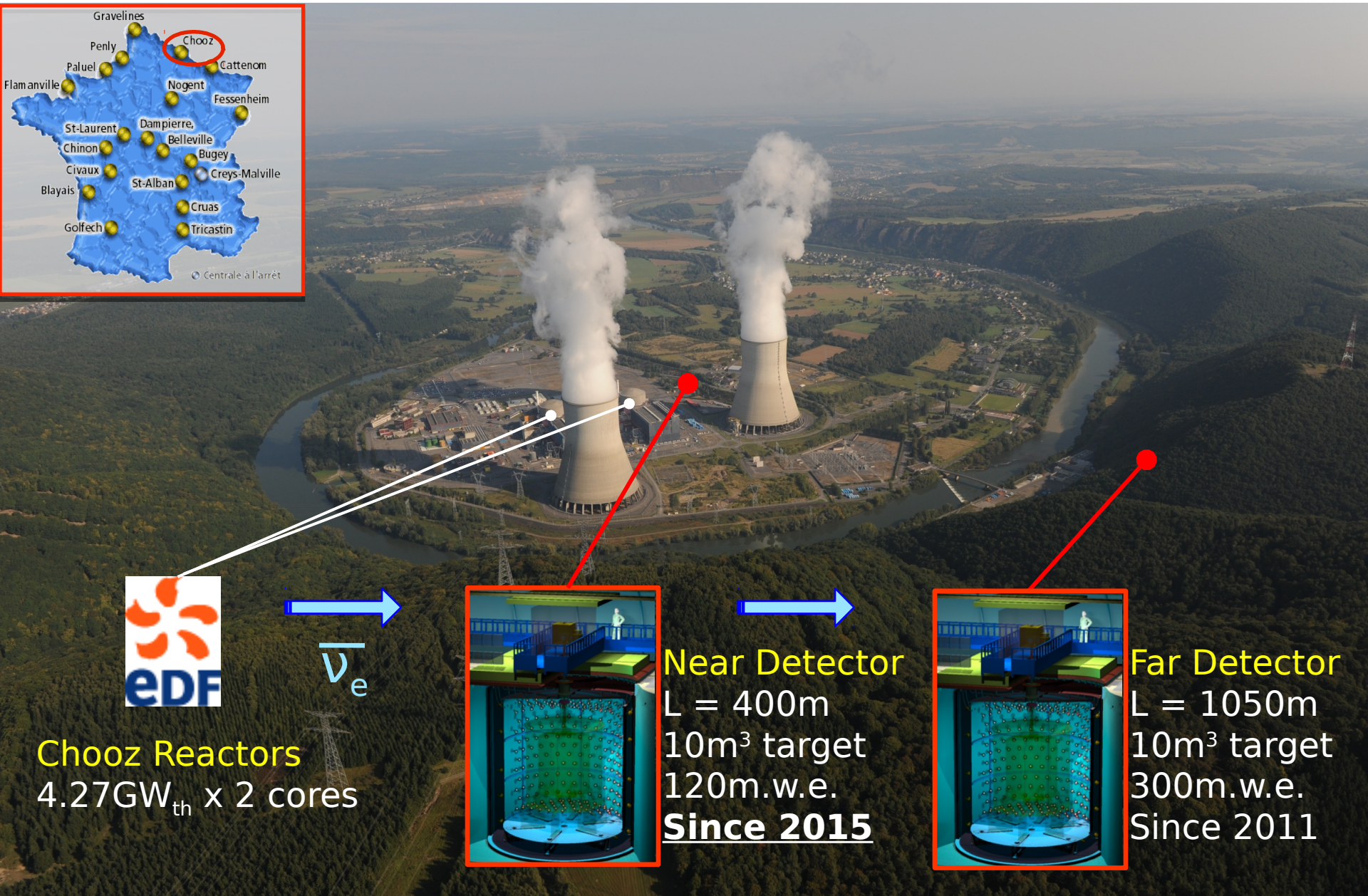
U. Alabama
ANL
U. Chicago
Columbia U.
UC Davis
Drexel U.
IIT
KSU
LLNL
MIT
U. Notre Dame
U. Tennessee

Spokesperson:
H. de Kerret (IN2P3)

Project Manager:
Ch. Veyssière (CEA-Saclay)

Web Site:
www.doublechooz.org/

Double Chooz experiment



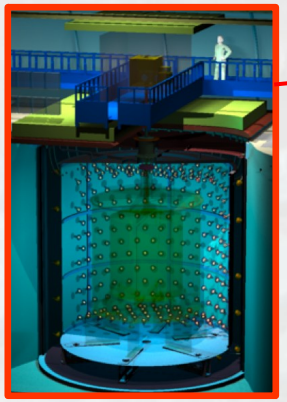
Precision measurement of θ_{13}

- 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

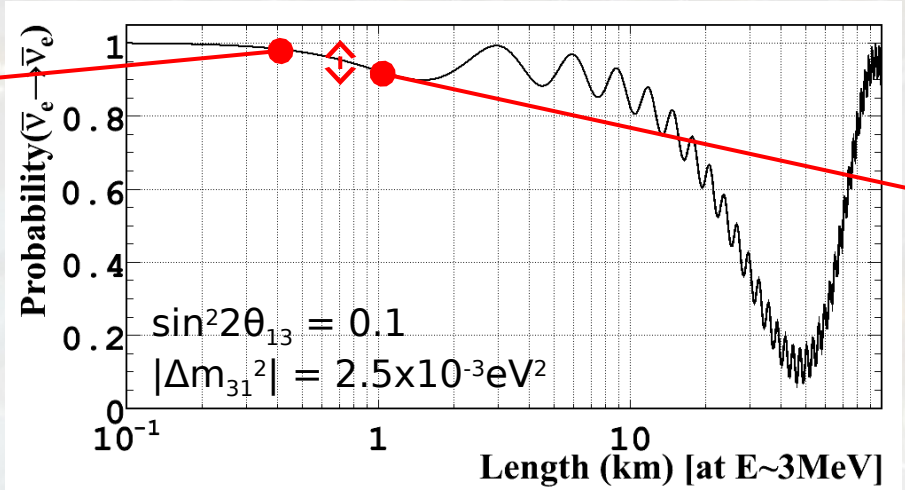
Survival probability of reactor neutrinos

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

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



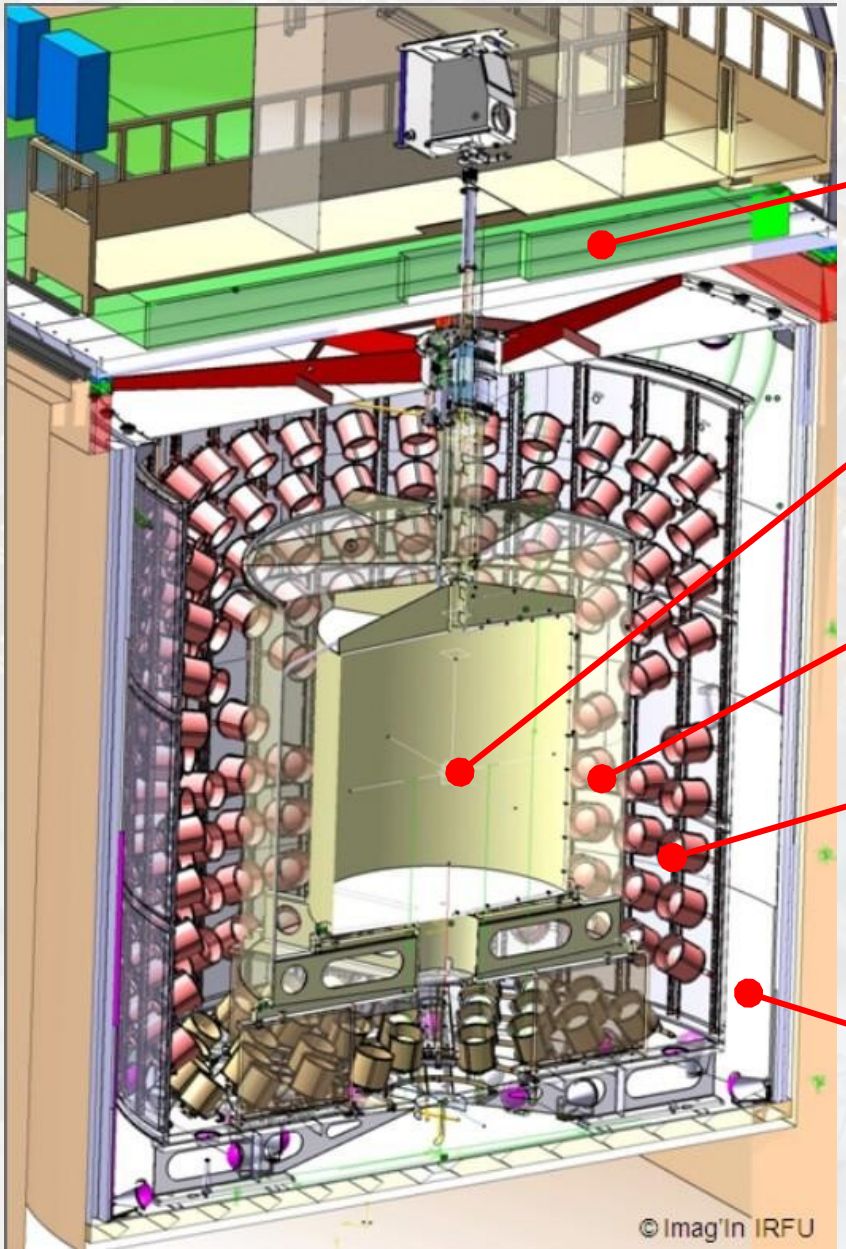
Near Detector (ND)



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)

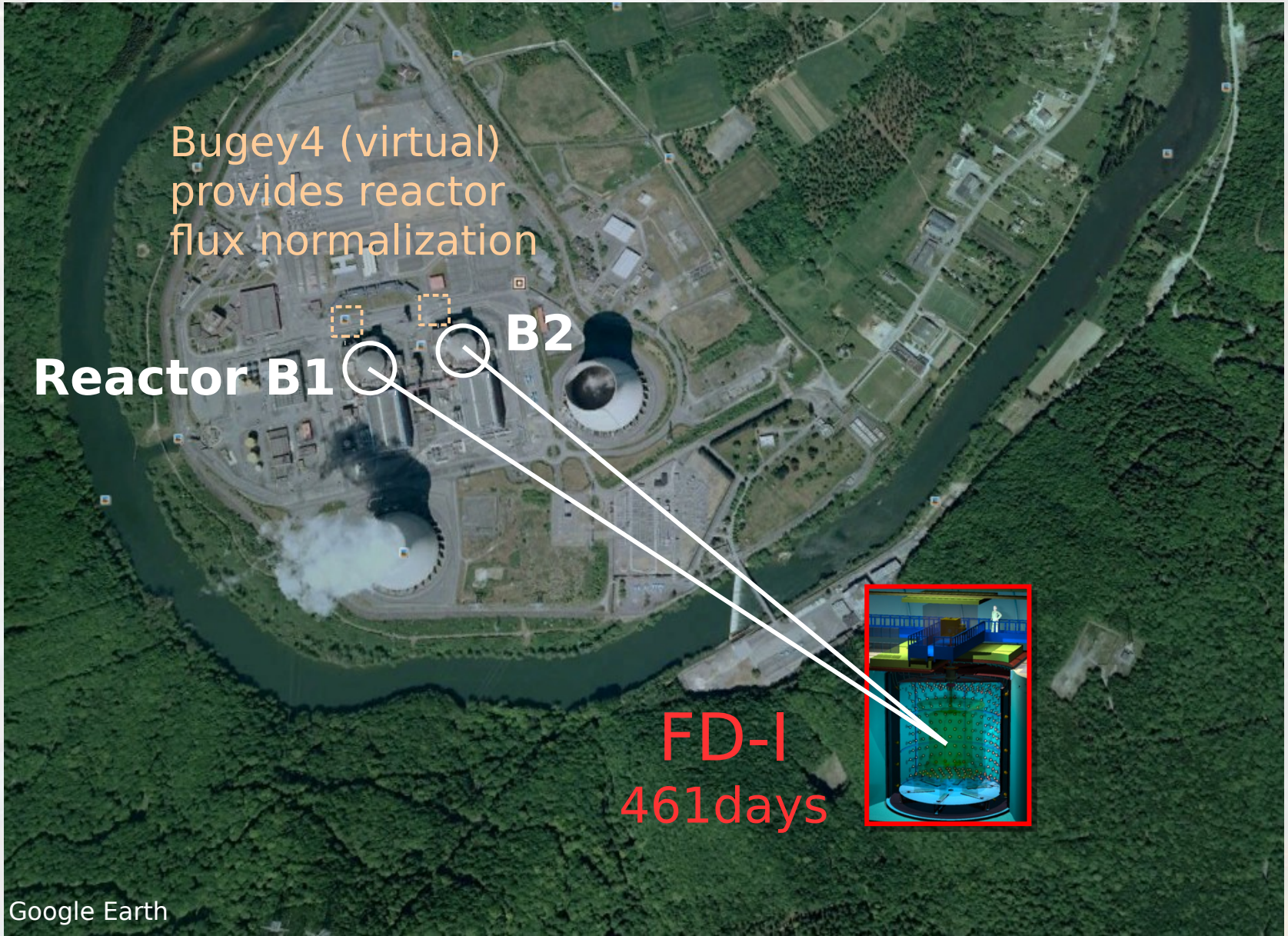
ν-target (NT)
- Gd loaded liquid scintillator (10m^3)

γ-catcher (GC)
- Liquid scintillator (22m^3)

Buffer
- Mineral oil (110m^3)
- 390 10-inch PMT

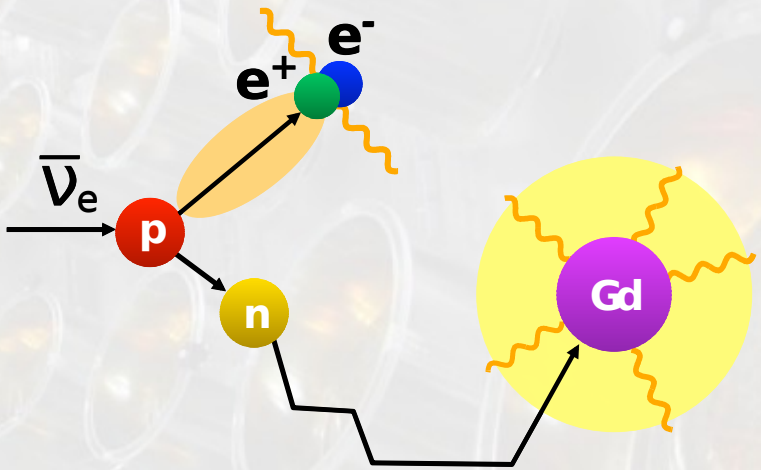
Inner Veto (IV)
- Liquid scintillator (90m^3)
- 78 8-inch PMT

Single detector analysis



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



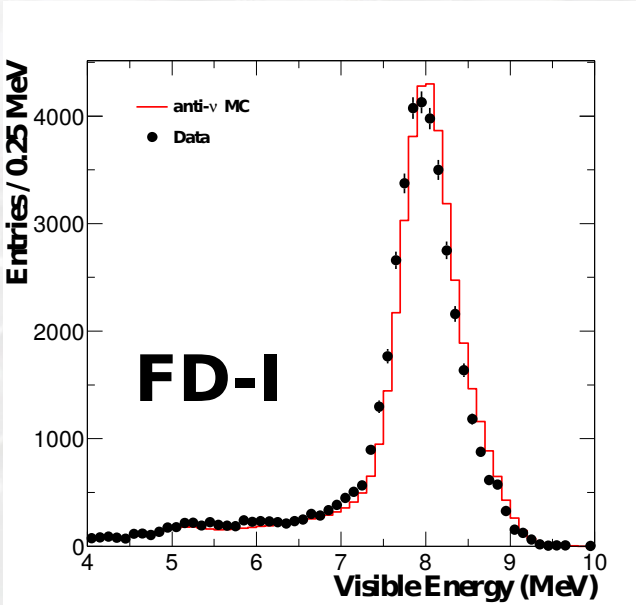
Gd channel

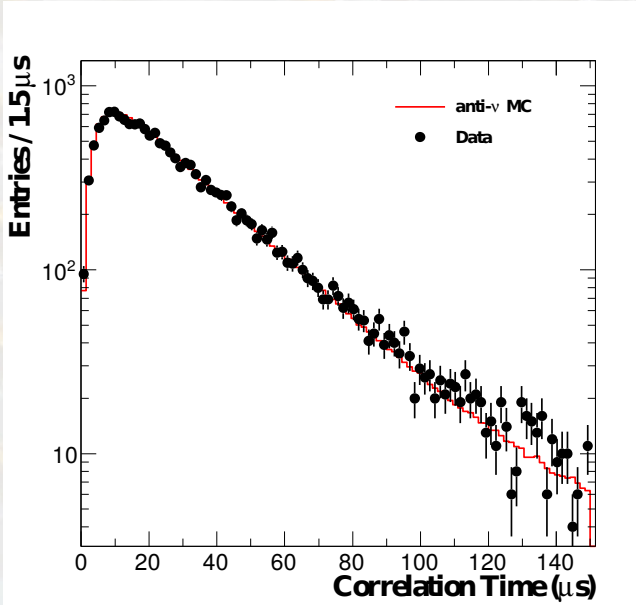
IBD coincidence condition

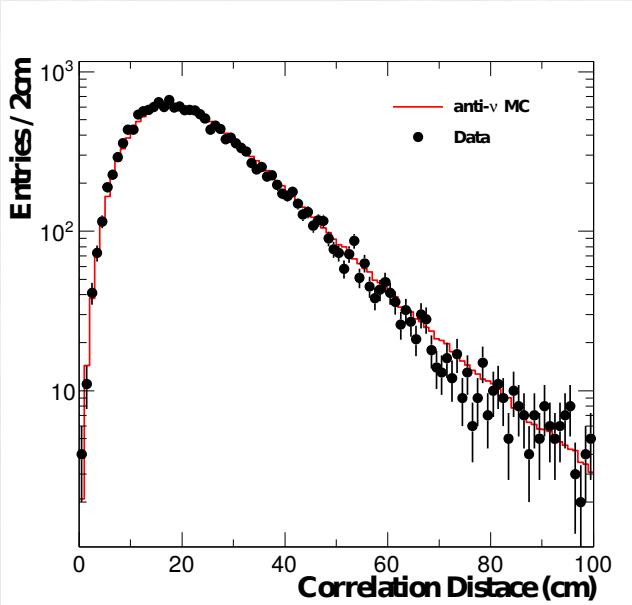
Delayed signal energy
$4 < E_{vis} < 10$MeV

Correlation time
$0.5 < \Delta T < 150\mu$sec

Correlation distance
$\Delta R < 100$cm







⇒ Remaining BG

Cosmogenic β-n emitter: $^{9}Li \rightarrow \alpha + \alpha + e + \nu + n$

Fast neutron: $n + p \rightarrow p + n$

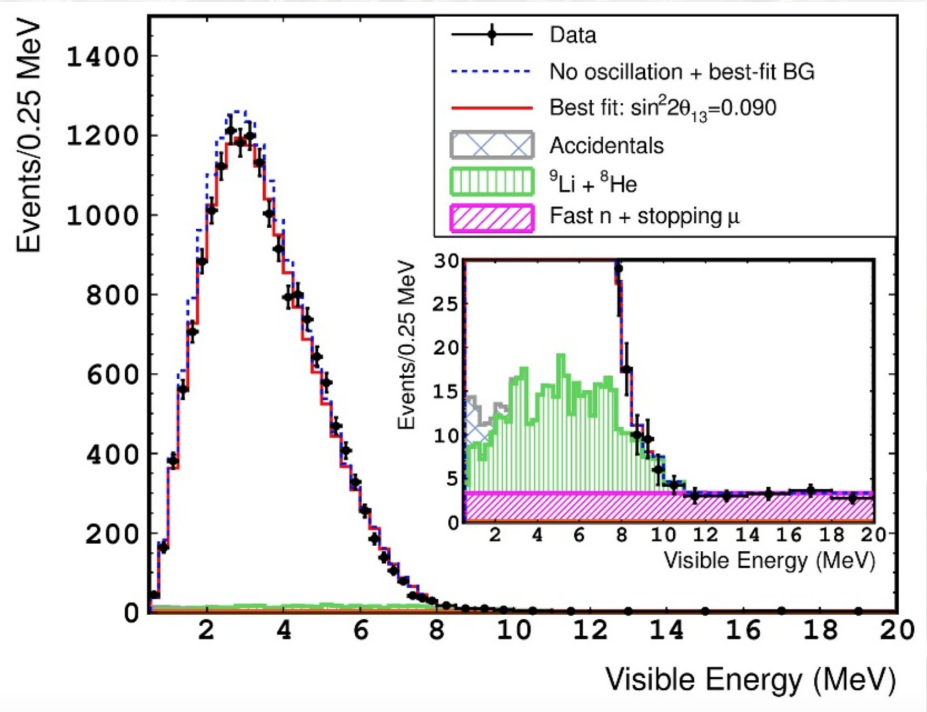
Stop-μ: $\mu \rightarrow e + \nu + \nu$

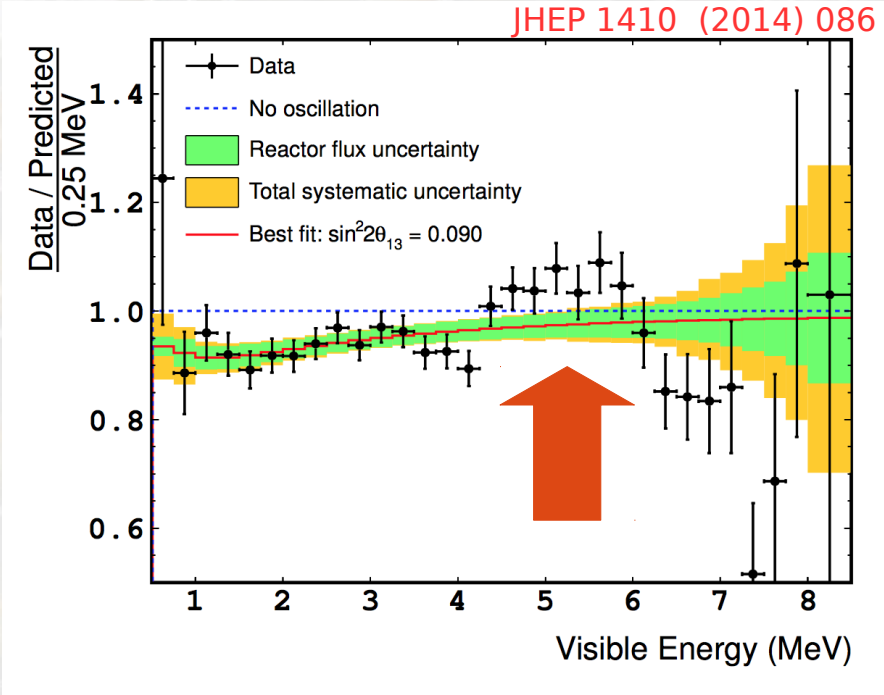
Accidental coincidence: e.g. γ + spallation n

Prompt

Delayed

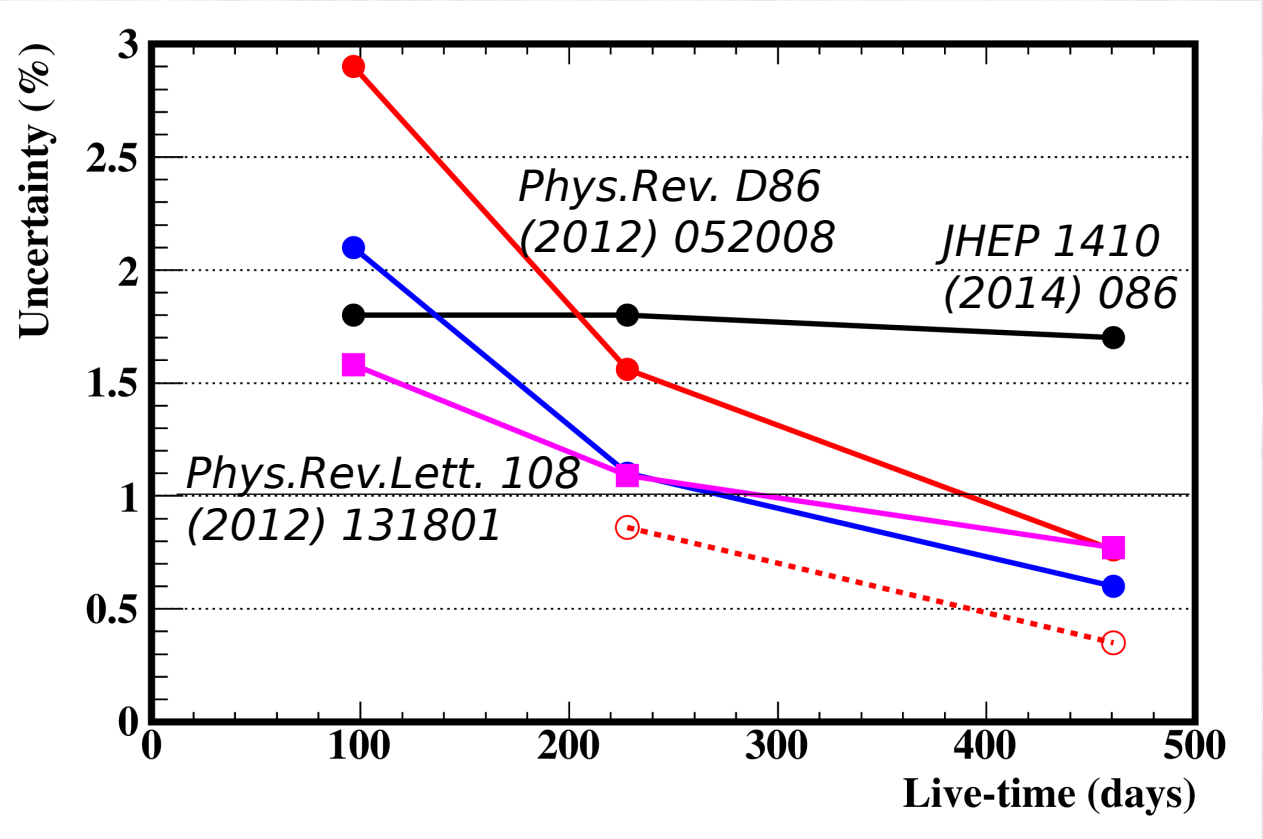
Oscillation fit: rate + spectrum shape





- 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

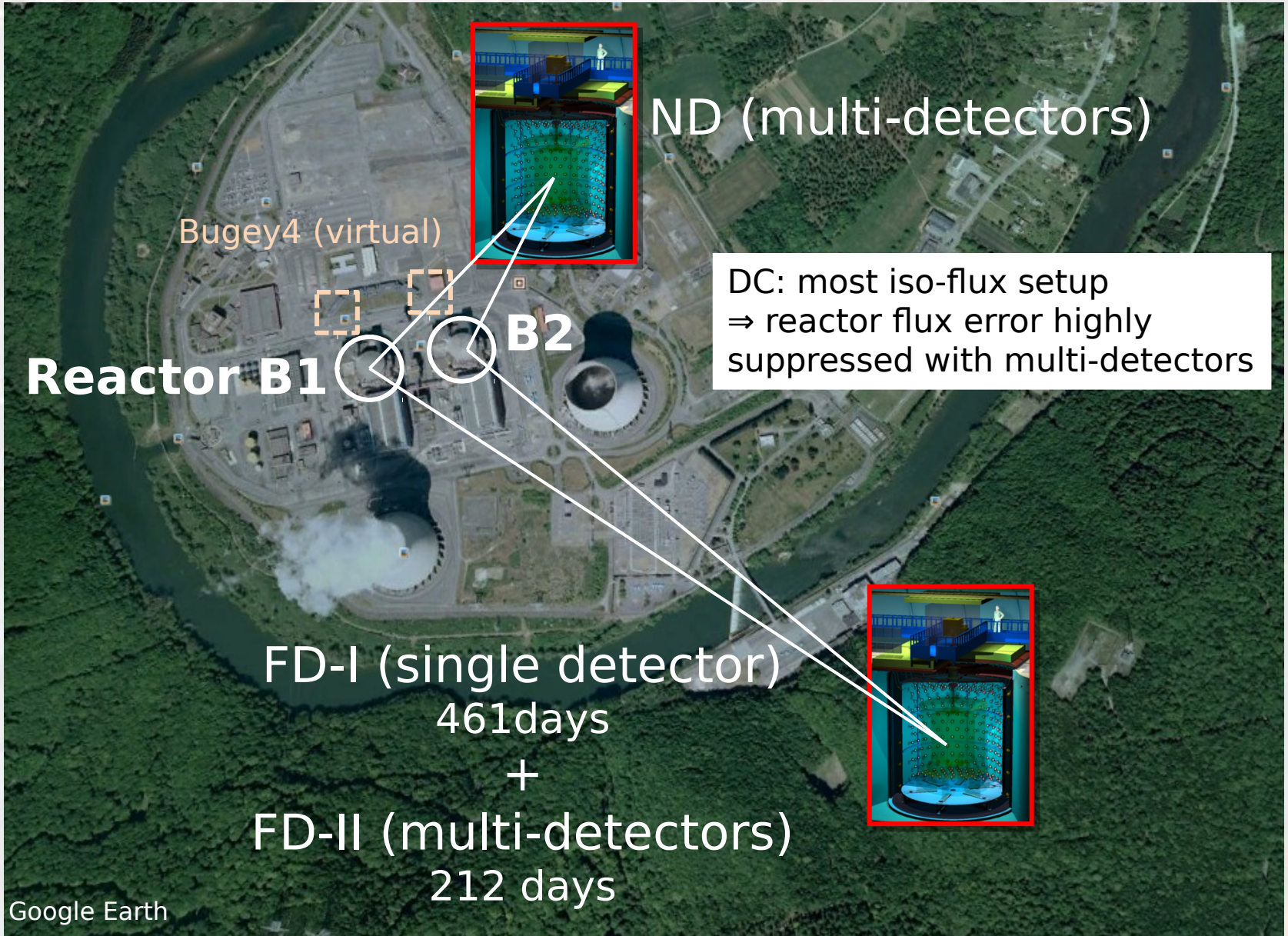
Analysis improvements



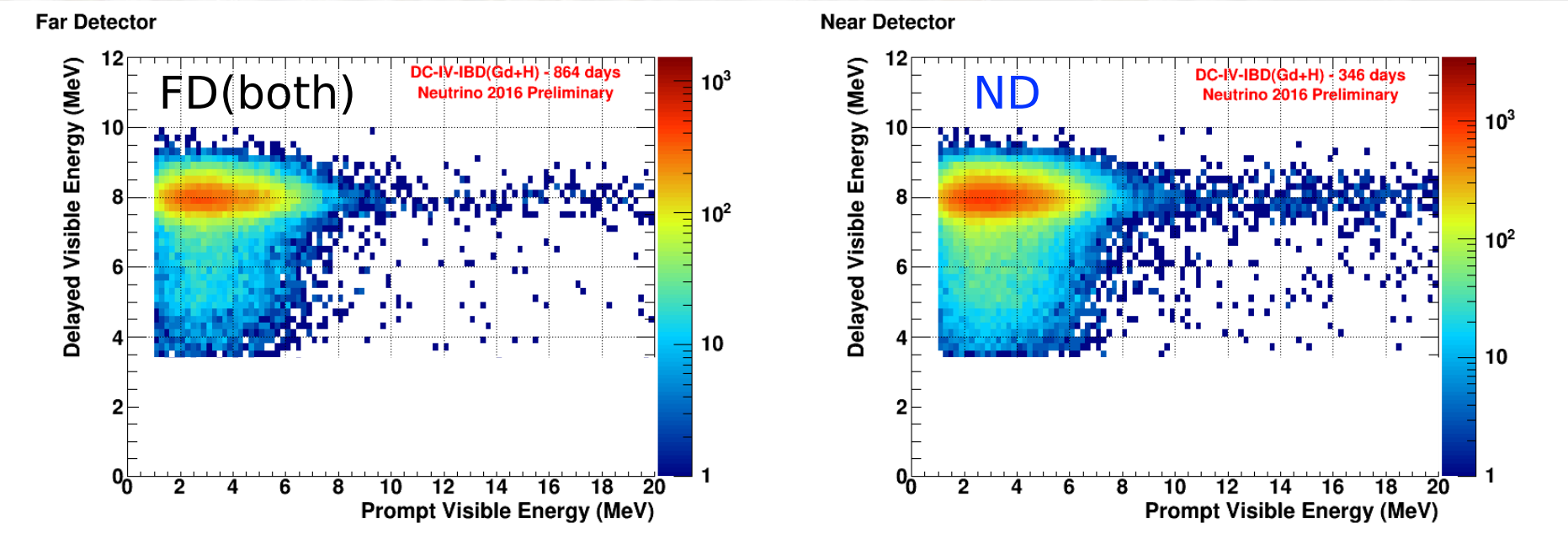
- Detector and background uncertainties are suppressed to per-mille level by analysis improvements
  - Reactor flux uncertainty (1.7%) dominant in last FD-only analysis

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

Multi-detectors analysis



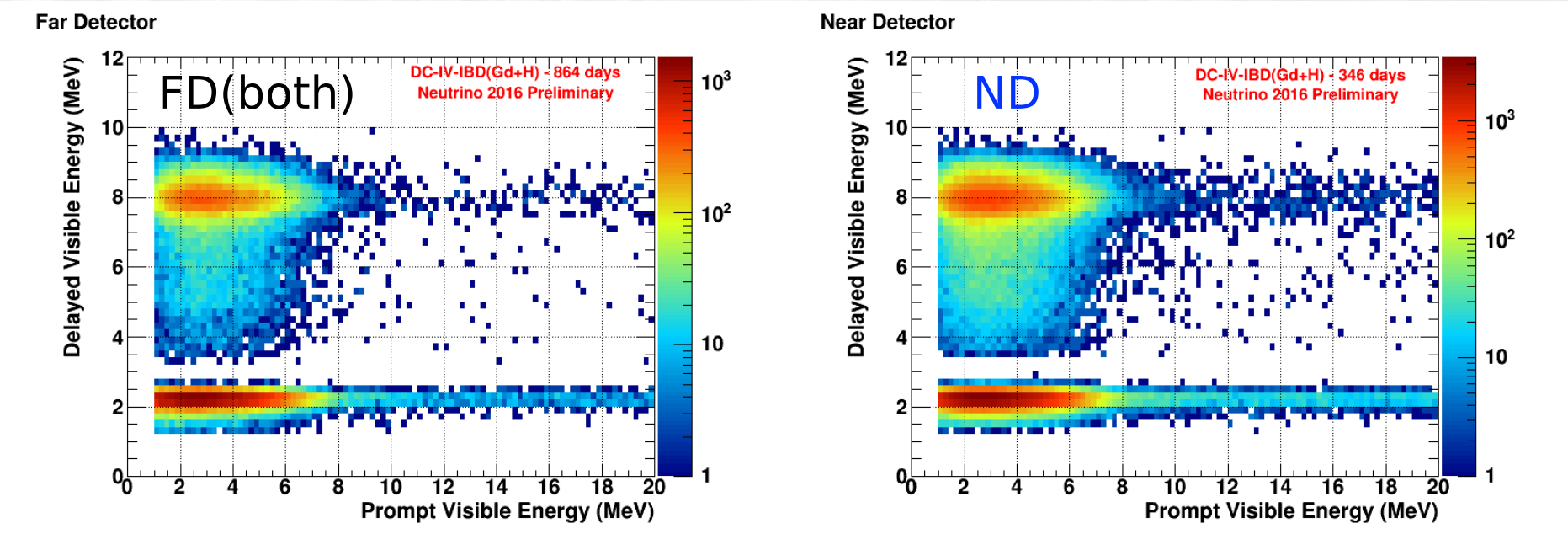
The Largest Single θ_{13} Target



IBD (Gd)

Target: ~8t (smallest θ_{13} target)

The Largest Single θ_{13} Target



IBD (Gd)

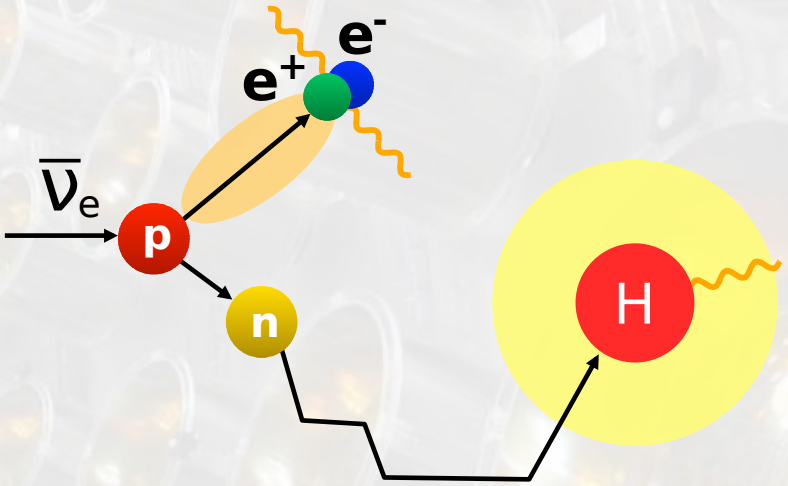
Target: ~8t (smallest θ_{13} target)

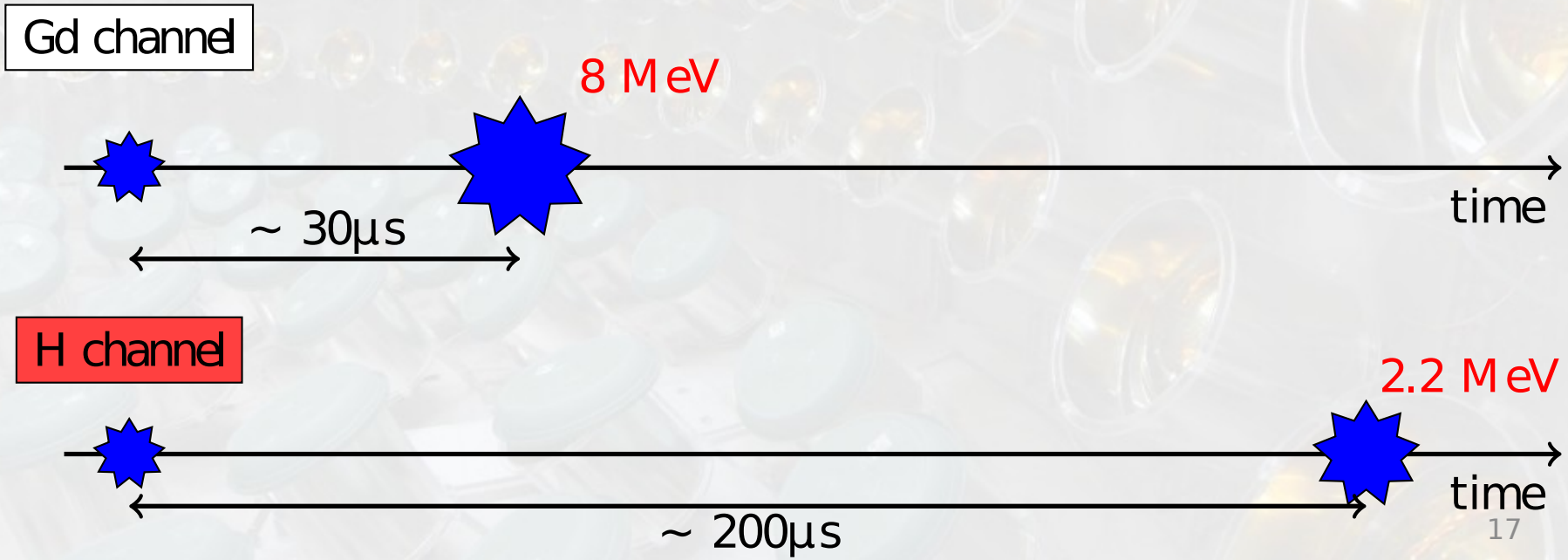
IBD (Gd+H)

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

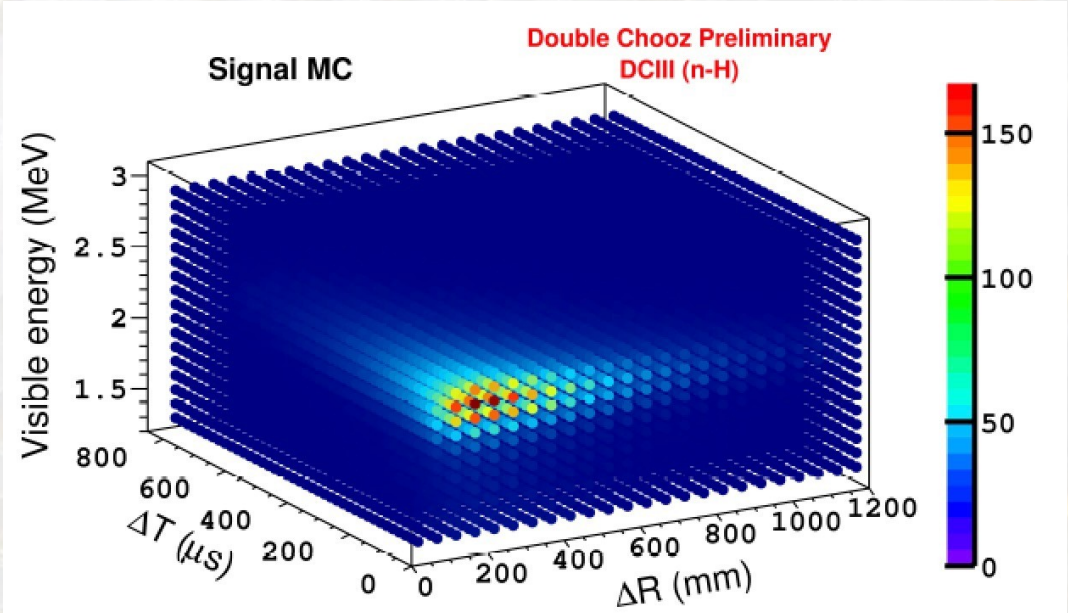
Detection Mode

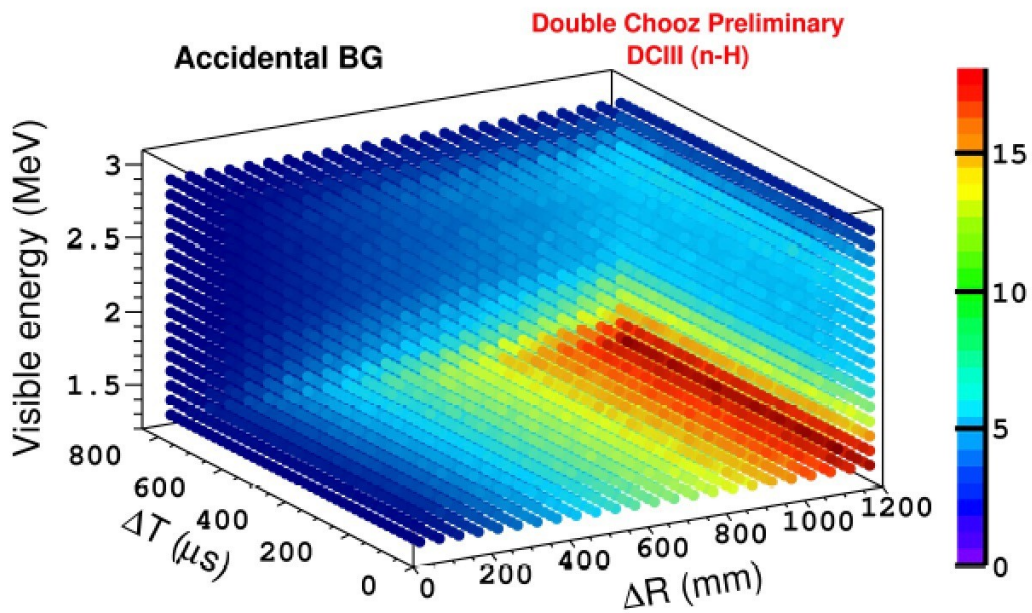
- Inverse Beta Decay (IBD):
  - $\bar{\nu}_e + p \rightarrow n + e^+$
- Prompt signal: E_{e^+} + annihilation γ's (1 ~ 9 MeV, $E_{vis} \simeq E_{\bar{\nu}_e} - 0.8\,\mathrm{MeV}$)
- Delayed signal: γ's from neutron capture on Gd or H
- Delayed coincidence





ANN Accidental BG Regection



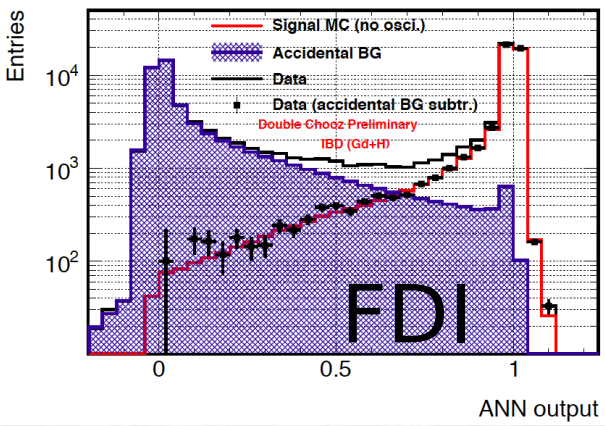


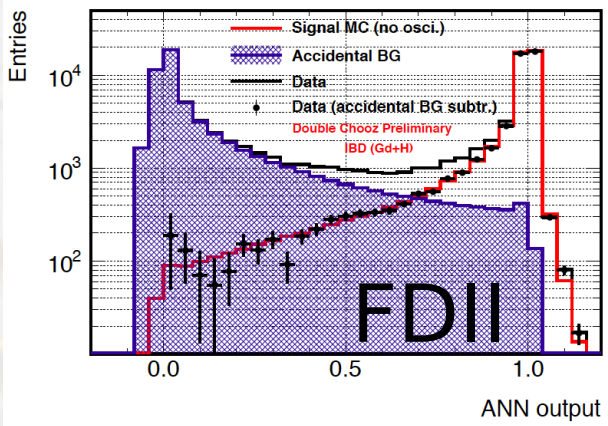
IBD (signal)
(correlated)

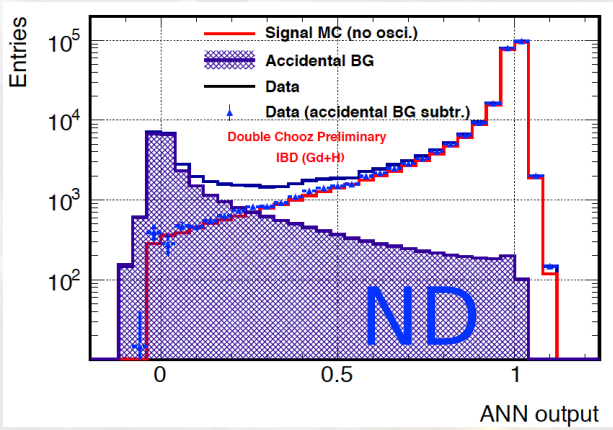
Accidental BG
(Random)

(i.e. longer Δt, ΔR)

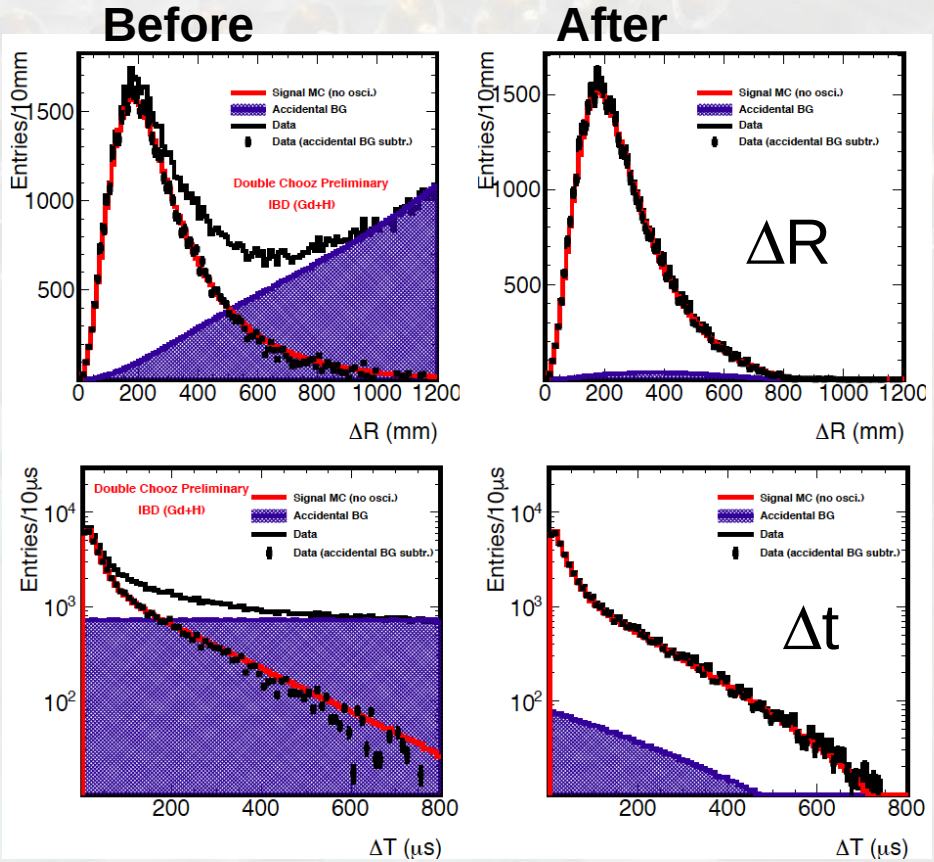
IBD(Gd+H) definition: Multi-variable cut





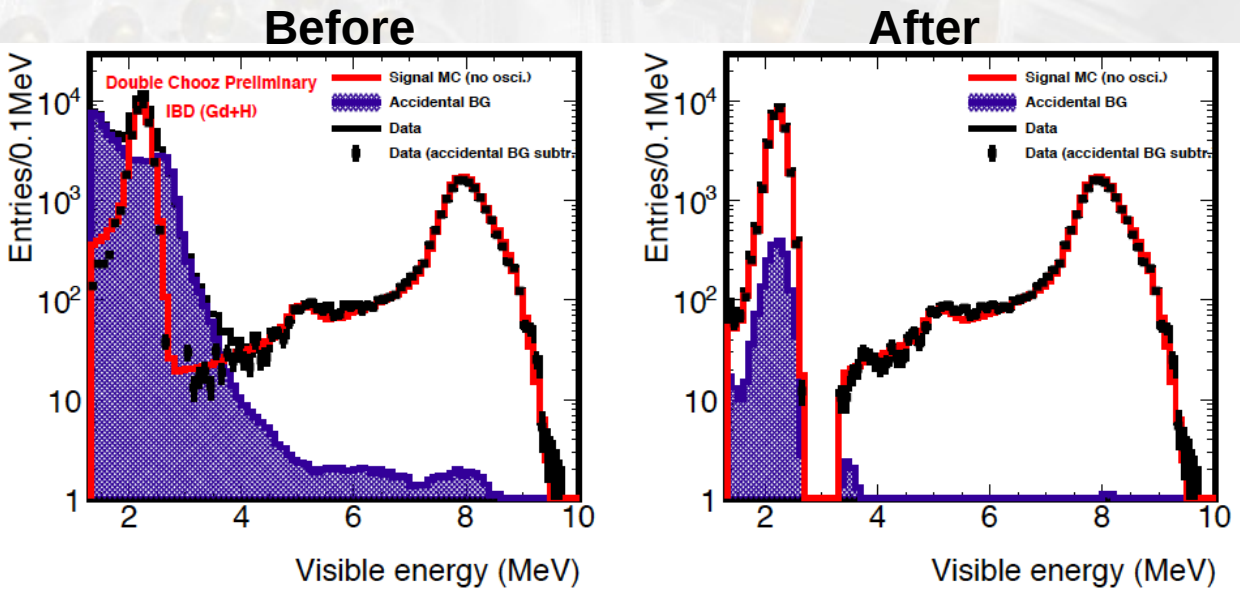


ANN IBD definition



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

Energy Spectrum IBD(Gd+H) Selection

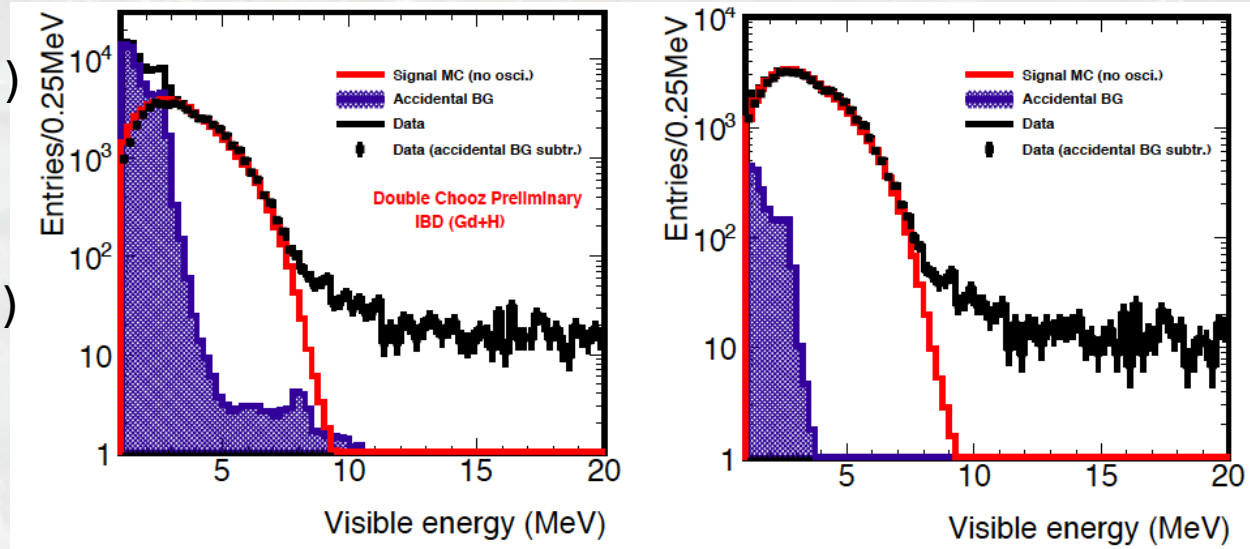


IBD(Gd+H) integrates over all captures

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

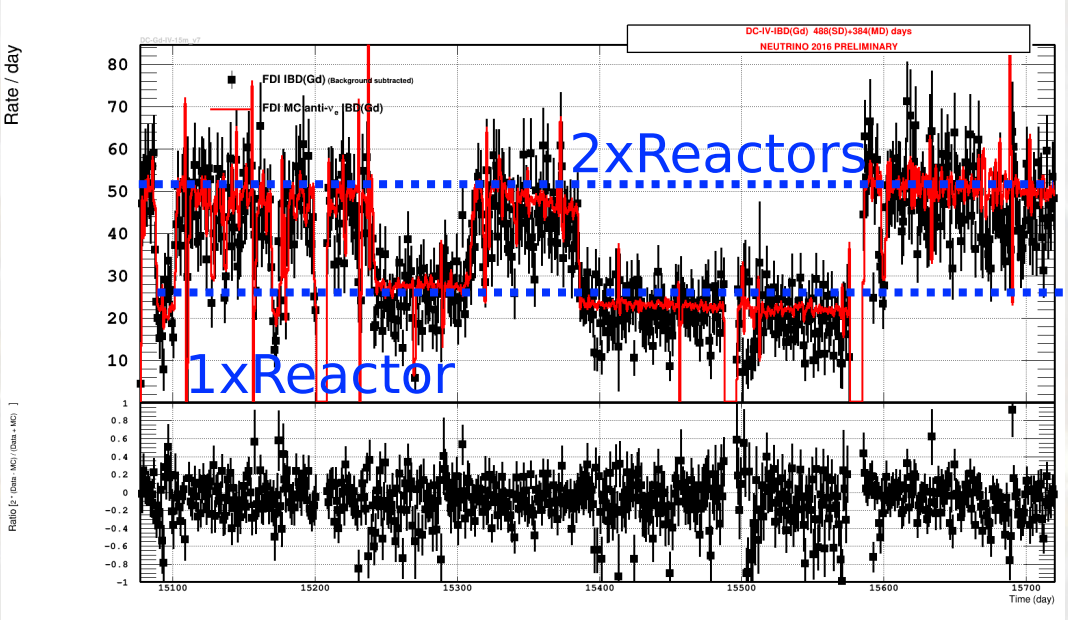
IBD(Gd+H+C):
≲140day^{-1}(FD)
≲1000day^{-1}(ND)

~2.5x IBD(Gd)



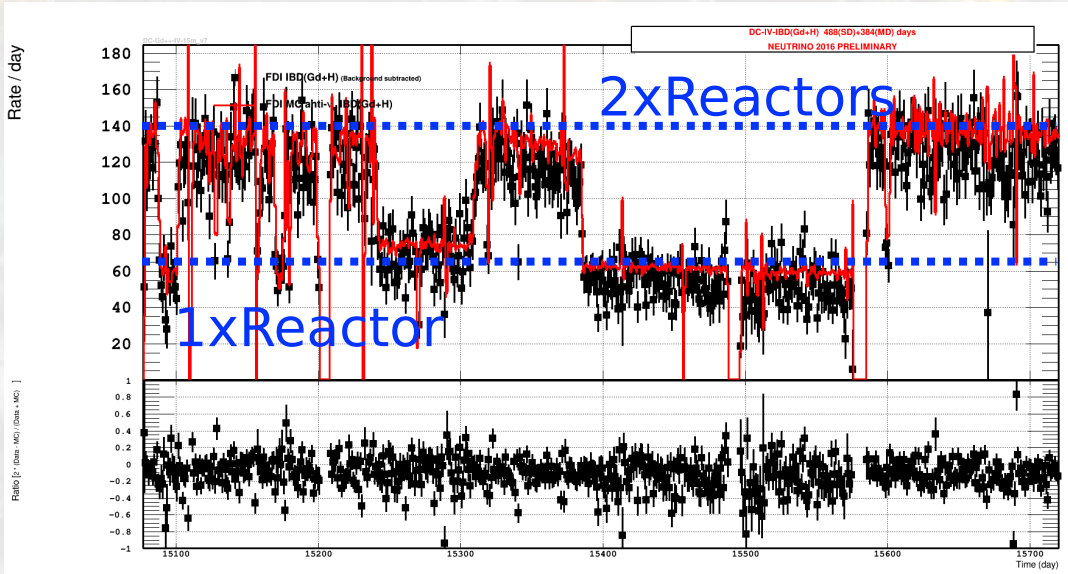
IBD (Gd+H) and IBD (Gd) vs Time

IBD(Gd)
$\lesssim$50day-1@ FD
σ^{stat} = 0.56%^{now}

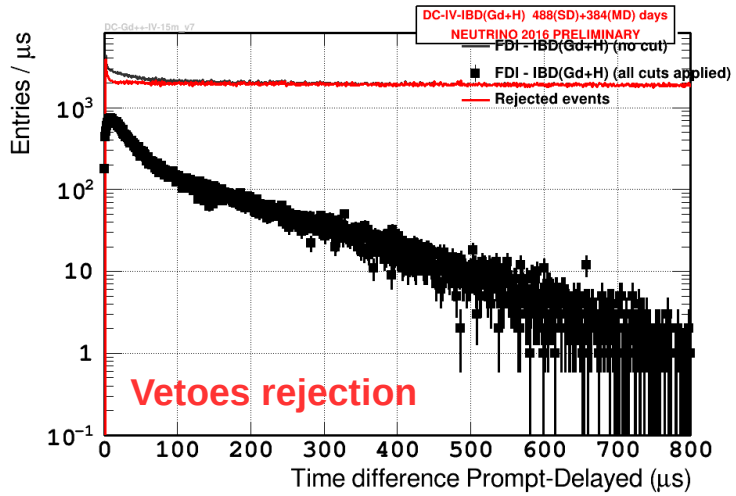


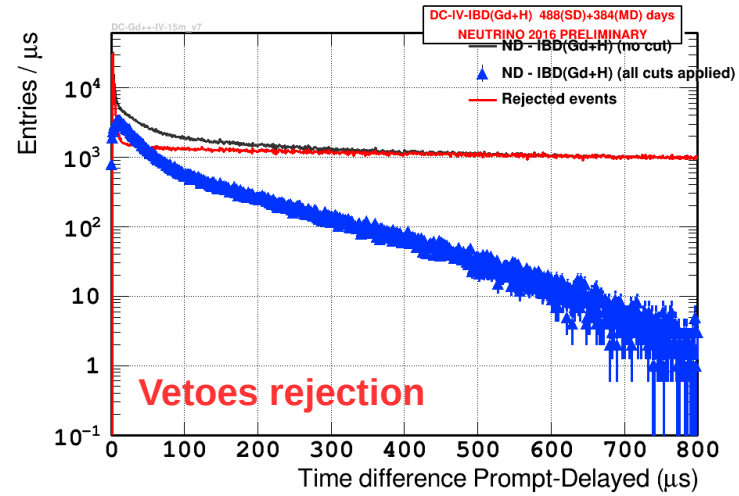
IBD(Gd+H)
$\lesssim$140day^{-1}@ FD
σ^{stat}=0.35%^{now}

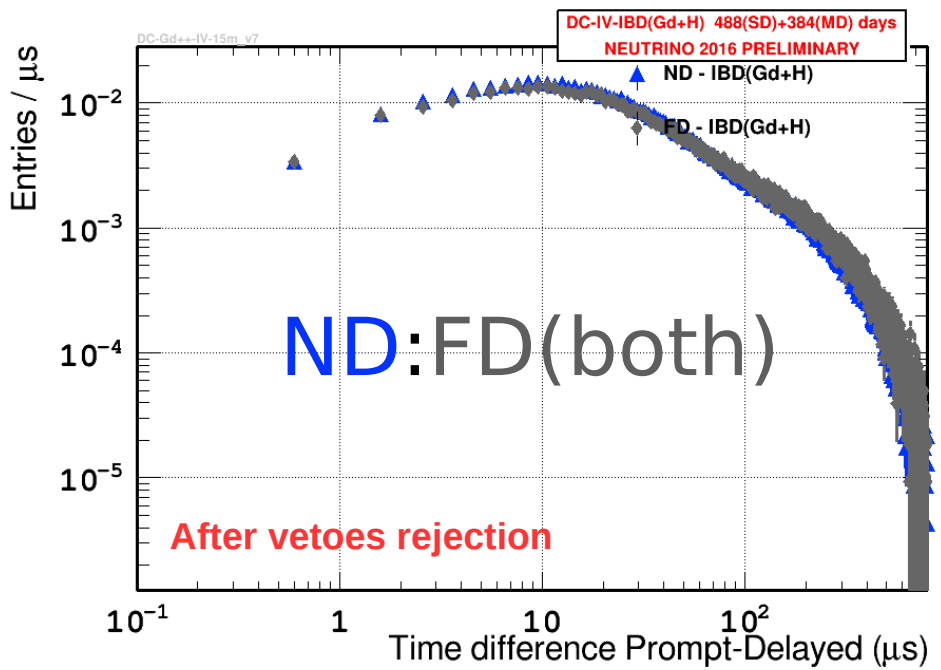
[$\Rightarrow$~0.2%^{stat} final]



BG rejection: $\Delta t(e^+:n)$ view





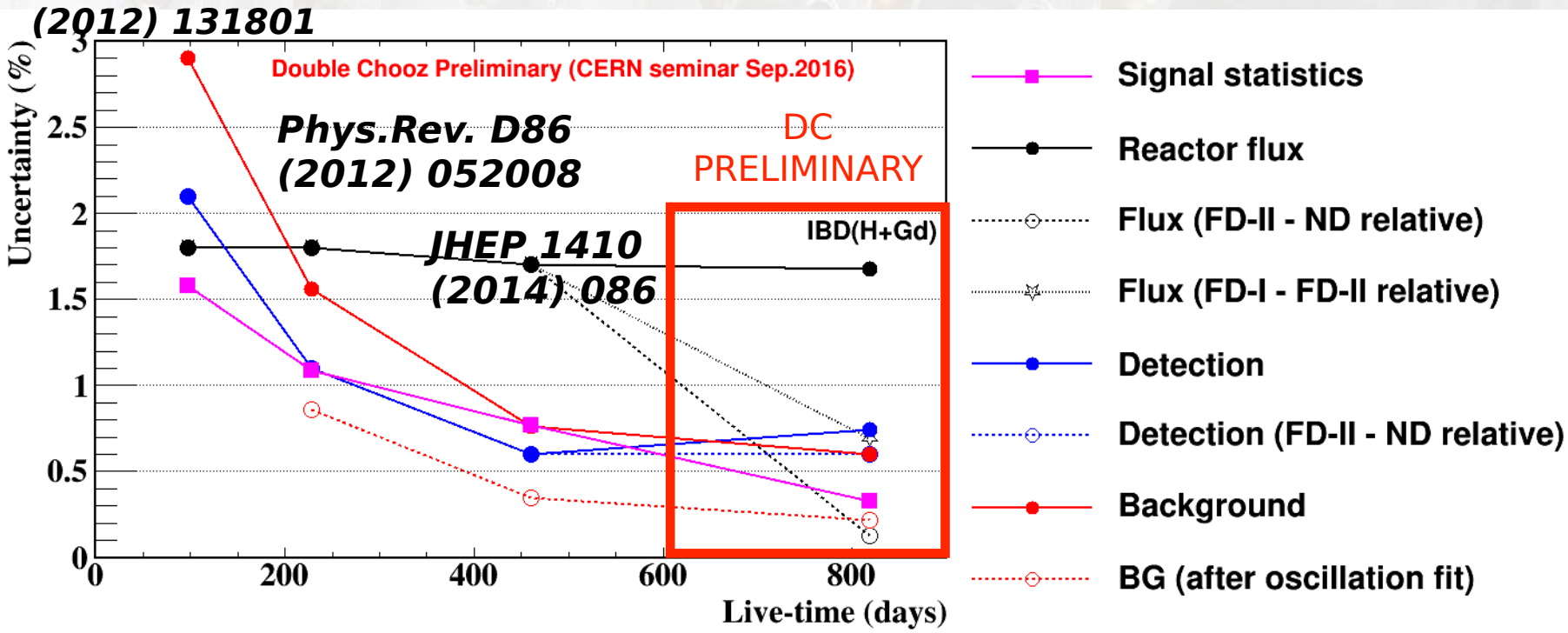


Δt(prompt:delay)

vetoes rejection impact
(demonstration $>10^3$ range)

ND ≈ FD(both)
(after vetoes)

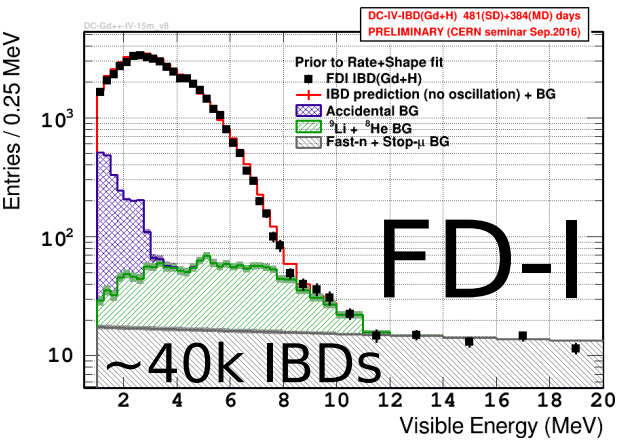
Systematic error evolution

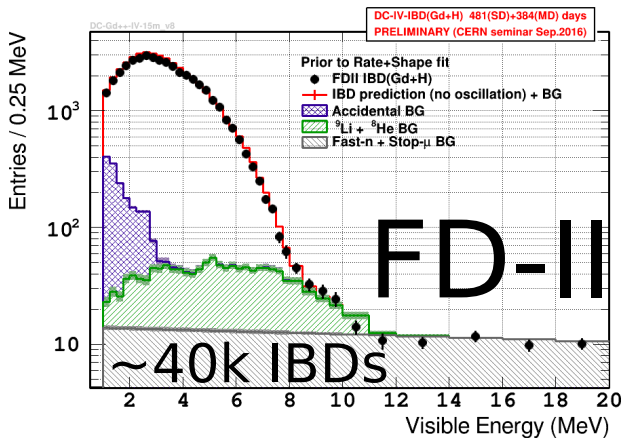


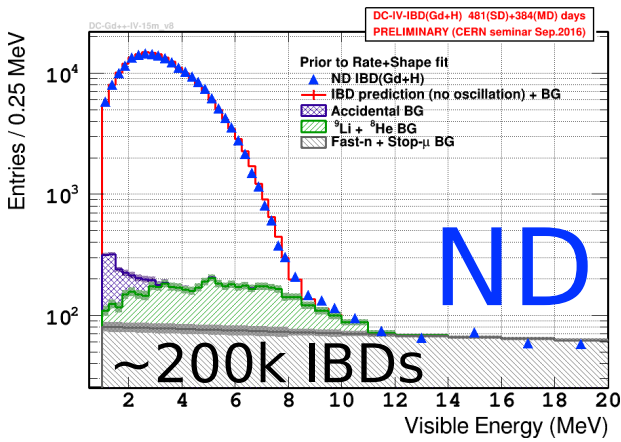
proton# (full volume) is largest uncertainty

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

(R+S Fit) All Detector Spectra



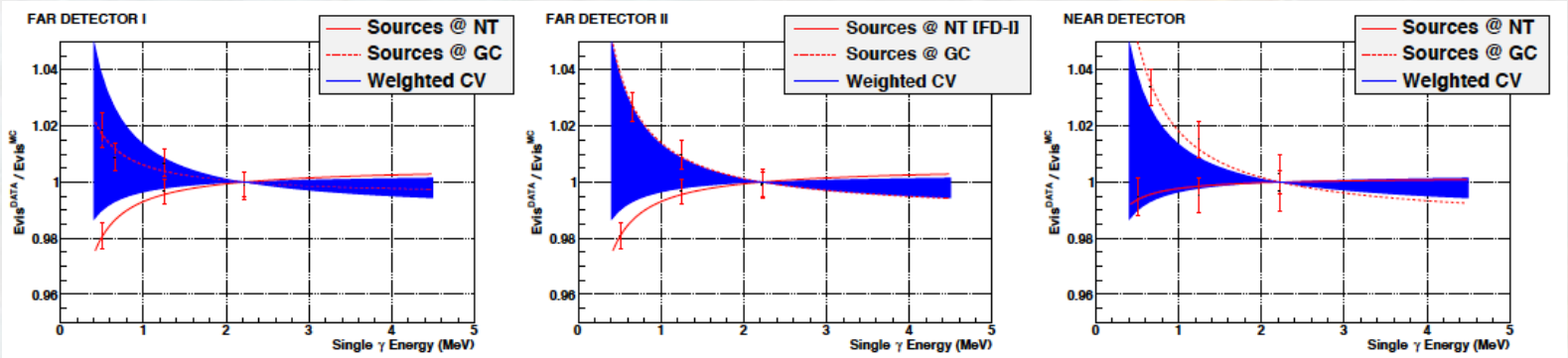




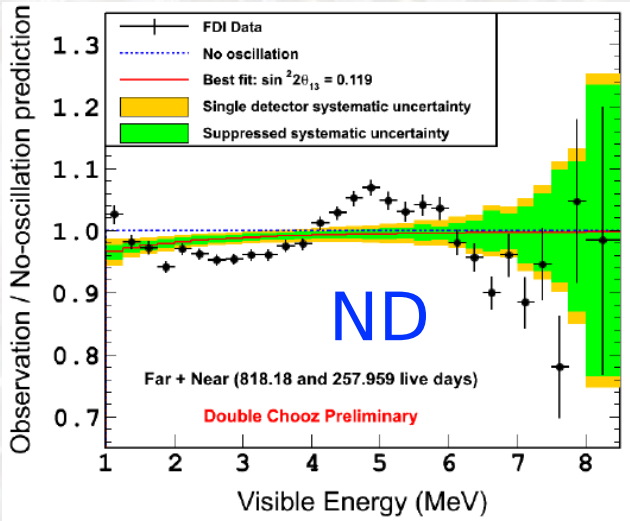
θ_{13} fits (R+S & RRM) fold all information simultaneous

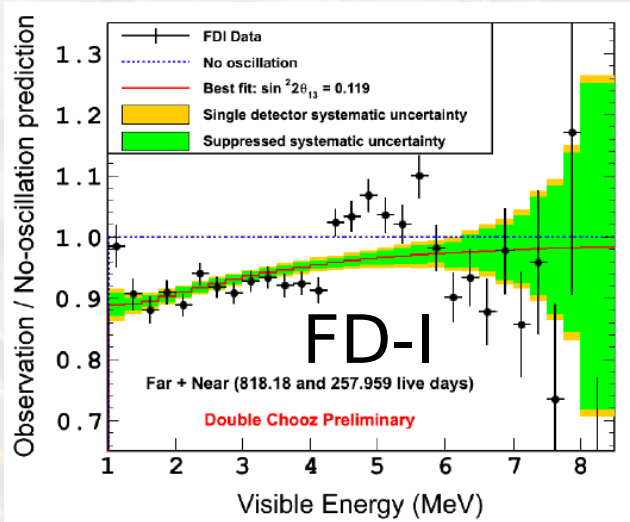
- **MD**(FD-II:ND)⊕**SD**(FD-I:FD-II:ND) [SD uses MC→ minimal impact]
  ⇒ MC-e+ non-linearity model [NT vs NT⊕GC volume]
- each BG (^{9}Li measurement ≳7MeV) ⊕ reactor-OFF constraint
- full flux error w/ and w/o Bugey4 constraint

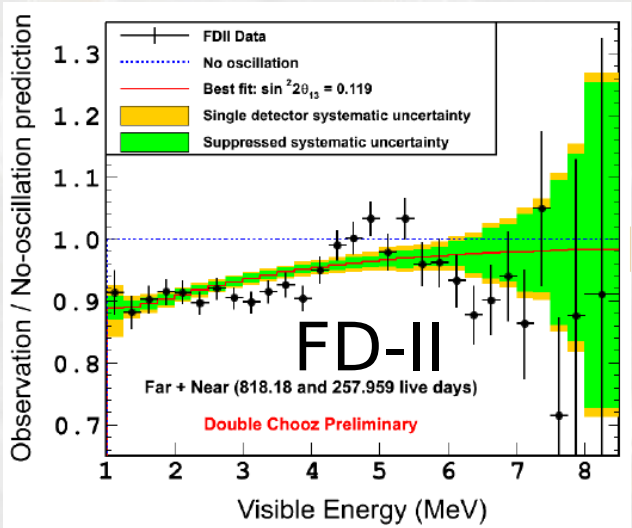
all correlations energy⊕reactors⊕detectors⊕backgrounds



θ_{13} R+S Fit Result







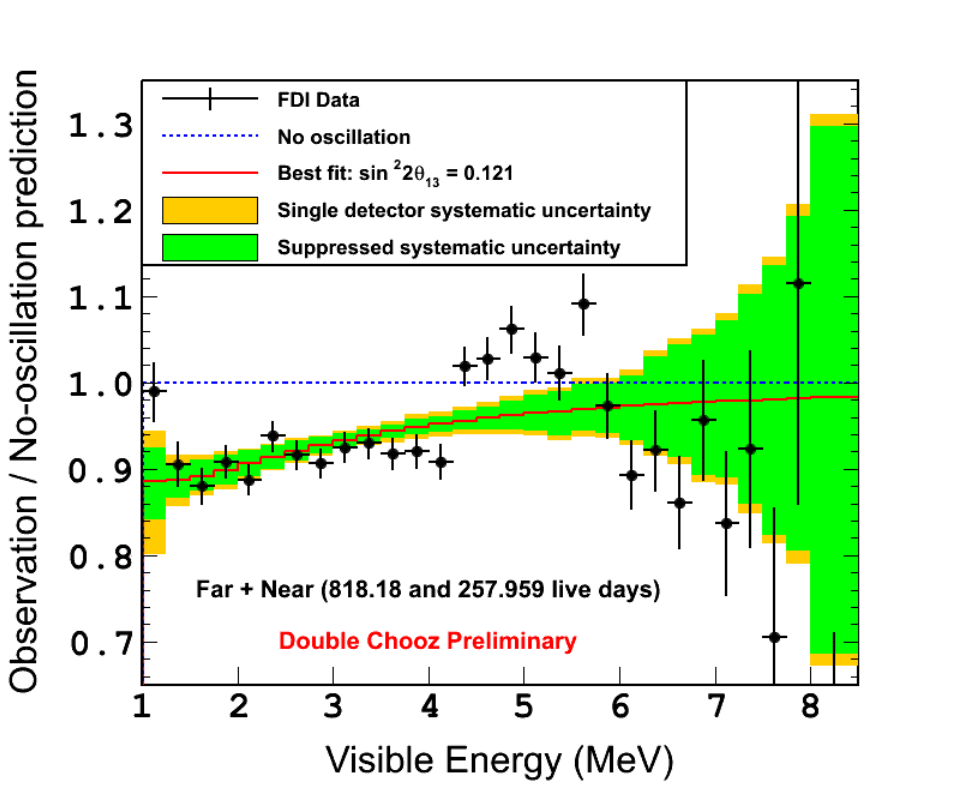
$\sin^2(2\theta_{13})^{R+S}=(0.119\pm0.016)$ with χ^2 / ndf: 236.2 / 114

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

Parke et al. arXiv:1601.07464)

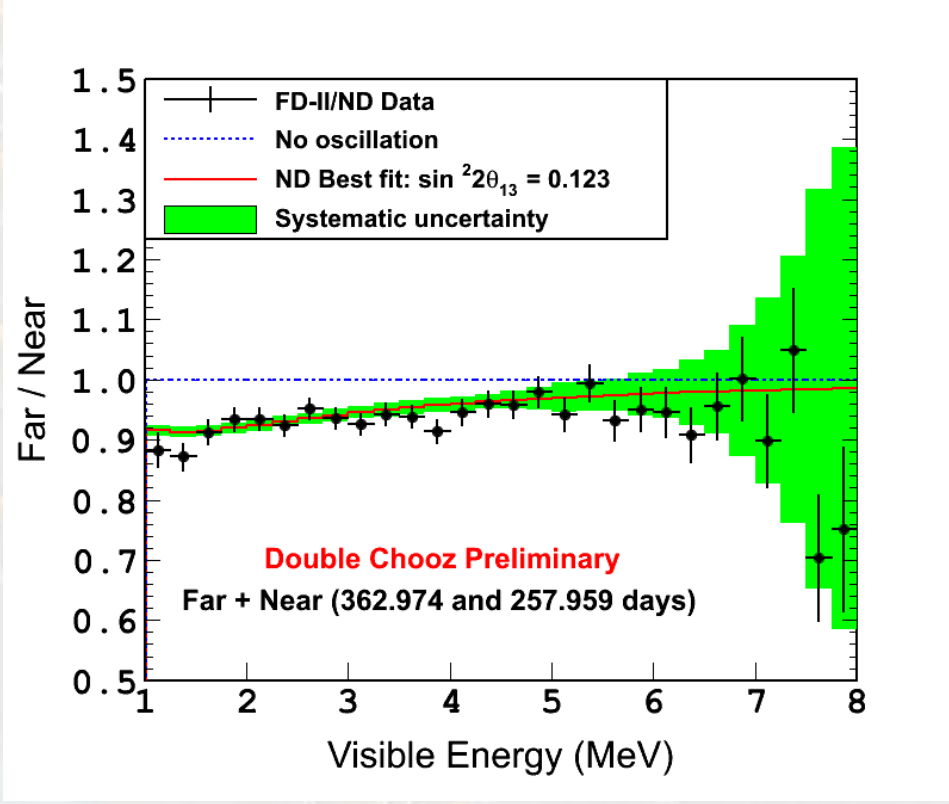
θ_{13} Fit Validation

Data | MC



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

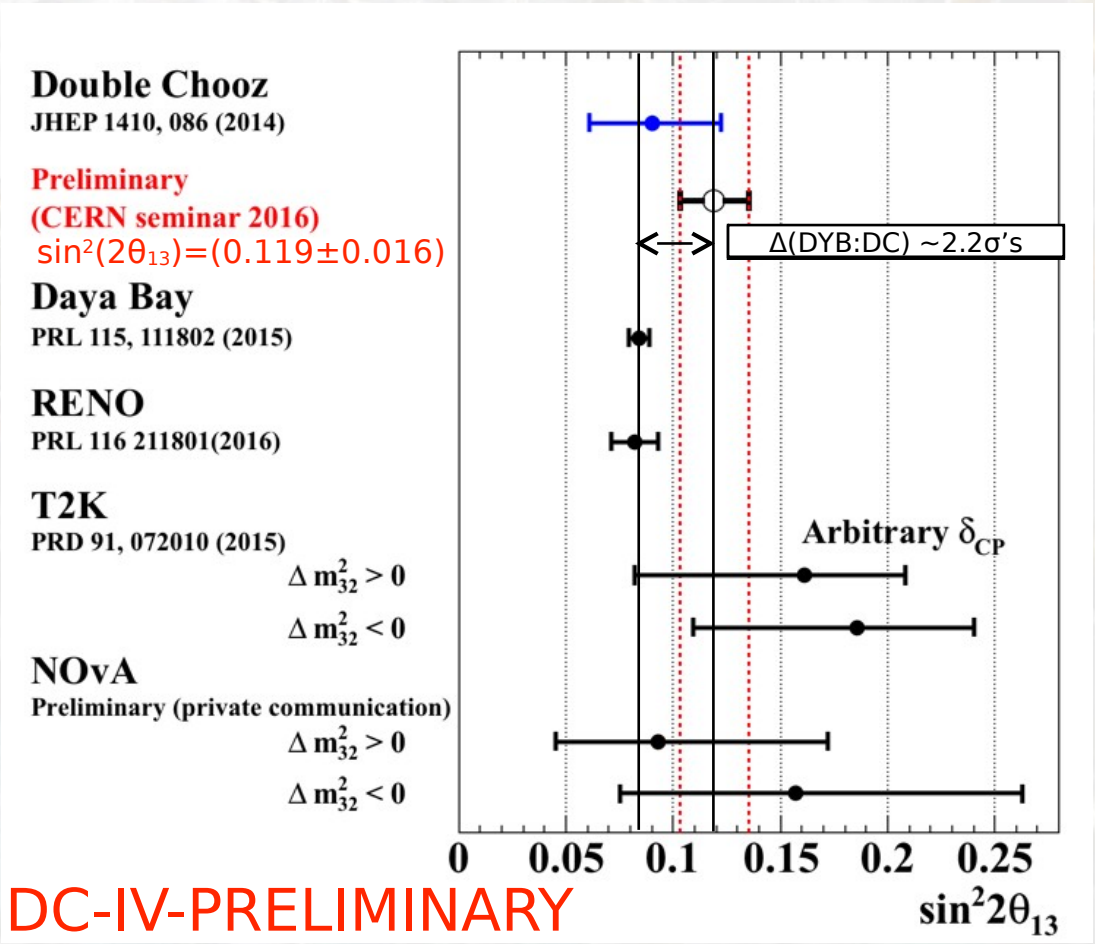
Data | Data

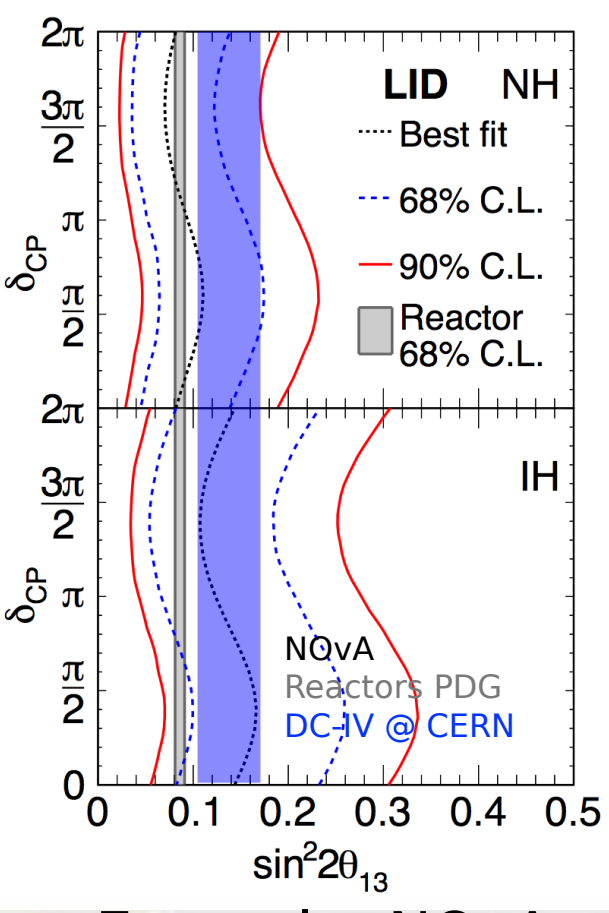


$\sin^2(2\theta_{13}) = (0.123 \pm 0.023)$

(spectral distortions cancel across ND:FD)

Comparison with others





Example: NOvA

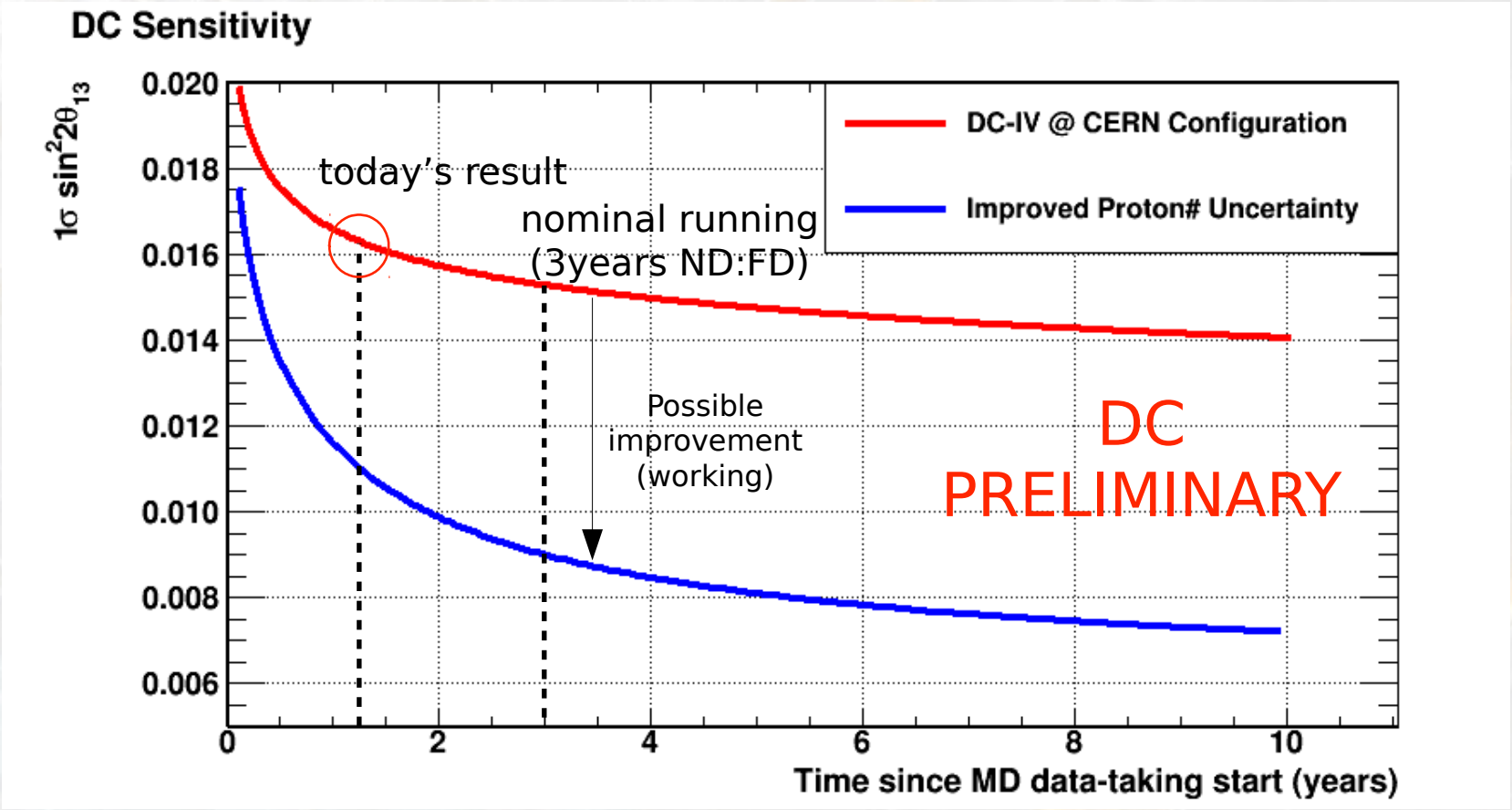
DC & beams might prefer a higher θ_{13}?

(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?

collaboration is committed improve to resolve (internally & together with DYB+RENO)

Beyond θ_{13}

Reactor spectral characterization

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

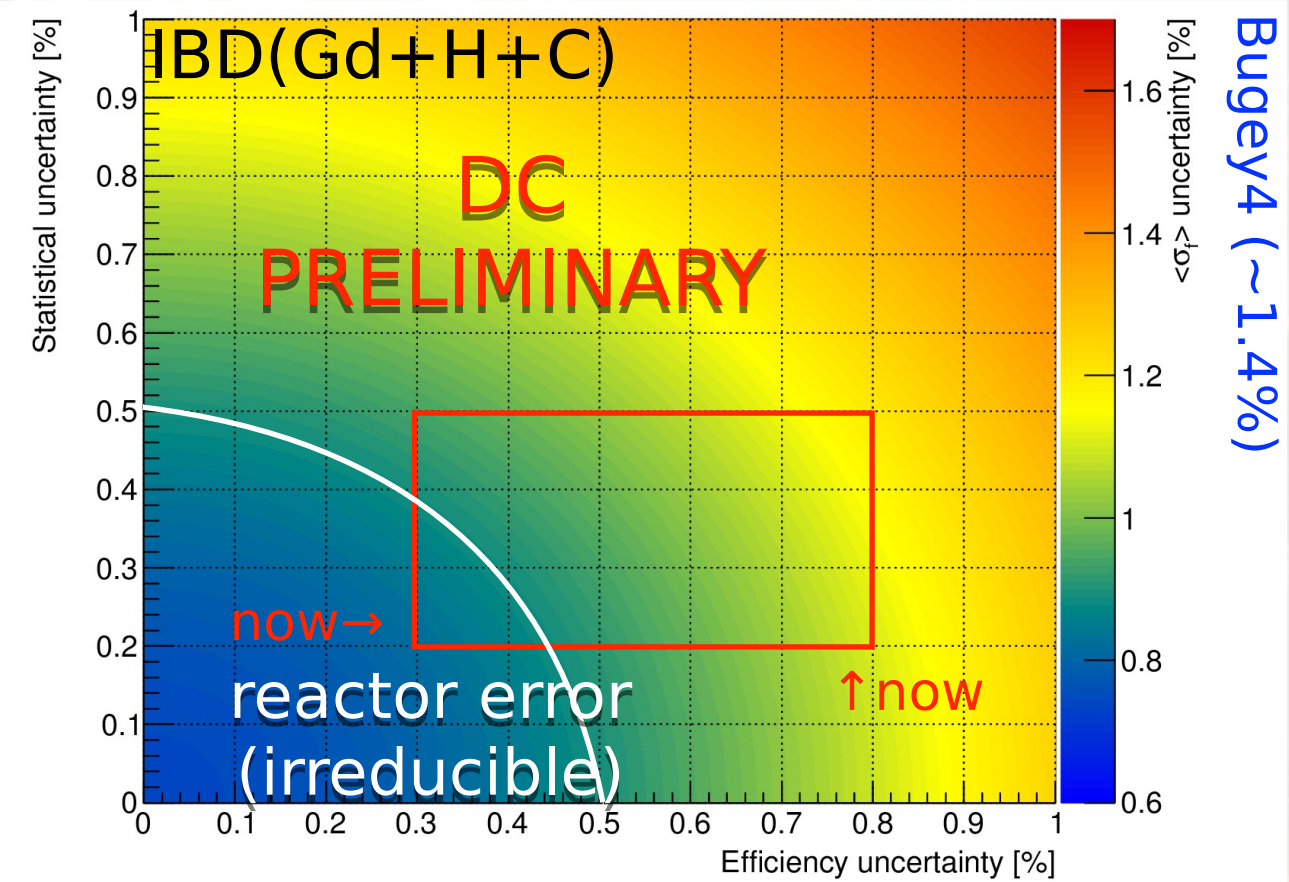
reactor luminosity

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

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)

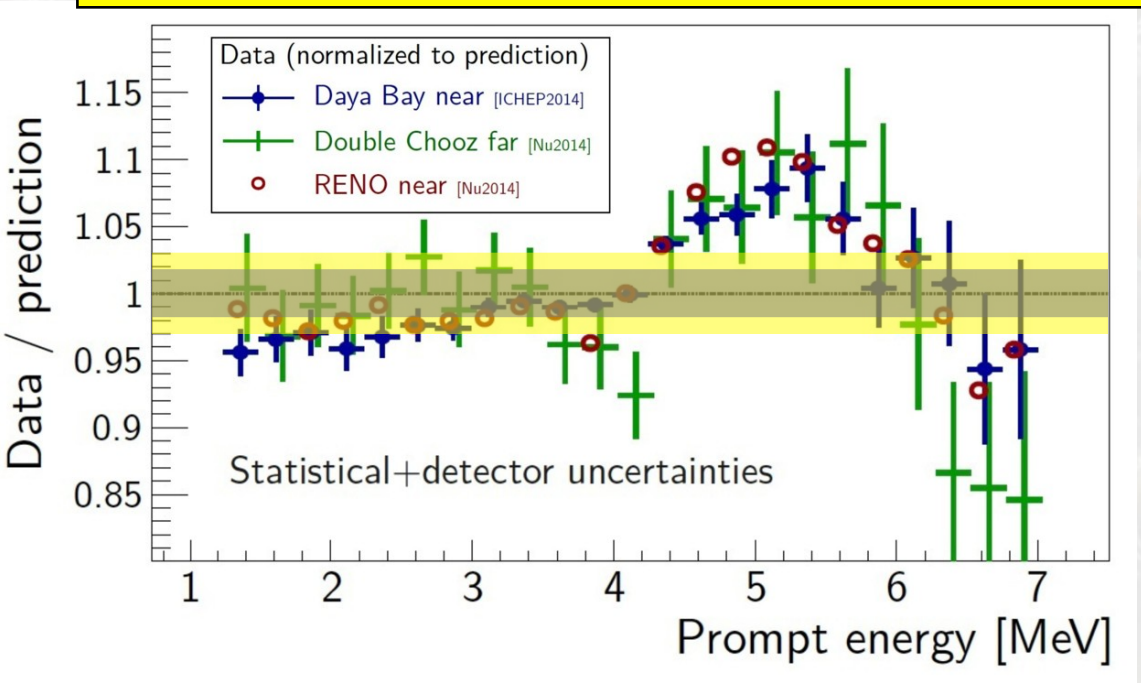


precision limit $\langle \sigma_f \rangle^{DC}$: total error ≈ reactor error (irreducible)

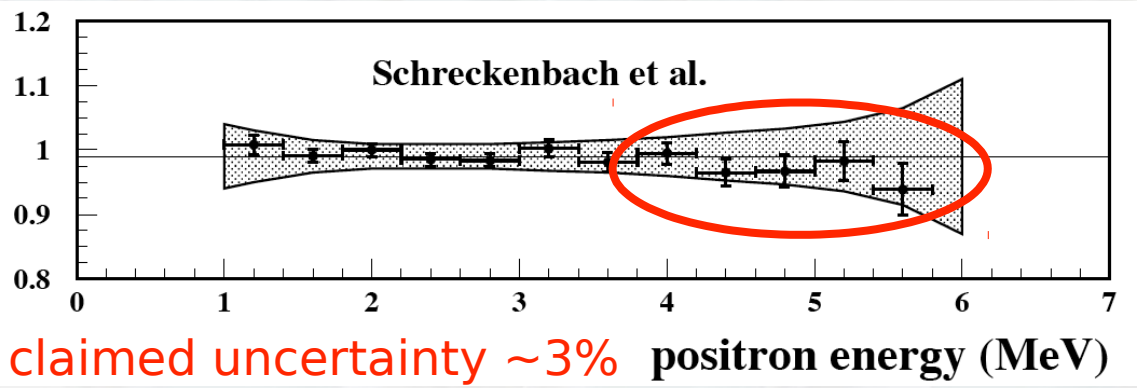
(Reactor Thermal Power ~0.47% @ Chooz)

(2014) 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)

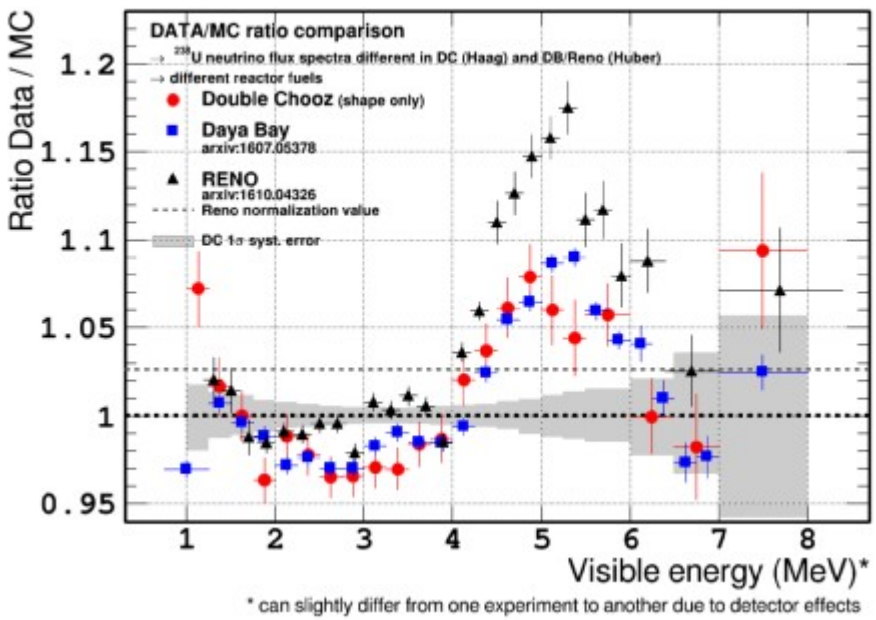
MAIN ISSUE
features >1σ(flux) ILL-based prediction uncertainties
⇒ error is (likely) underestimated
(hard to believe otherwise)

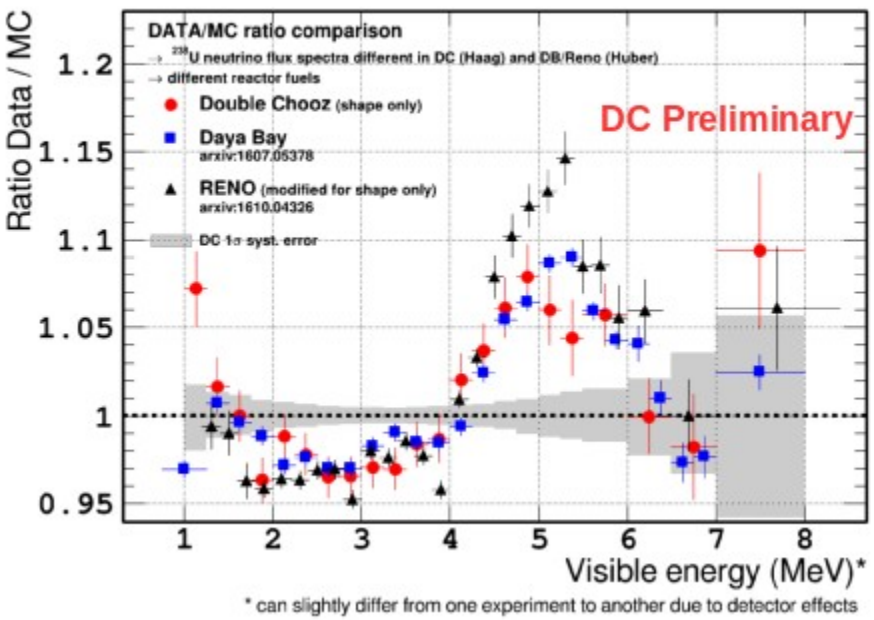
QUESTION
why Bugey3 data did not see it?
(best world shape reference)
[DC⊕B3 working to reconcile]

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

Shape Distortion Comparison (DC Near)

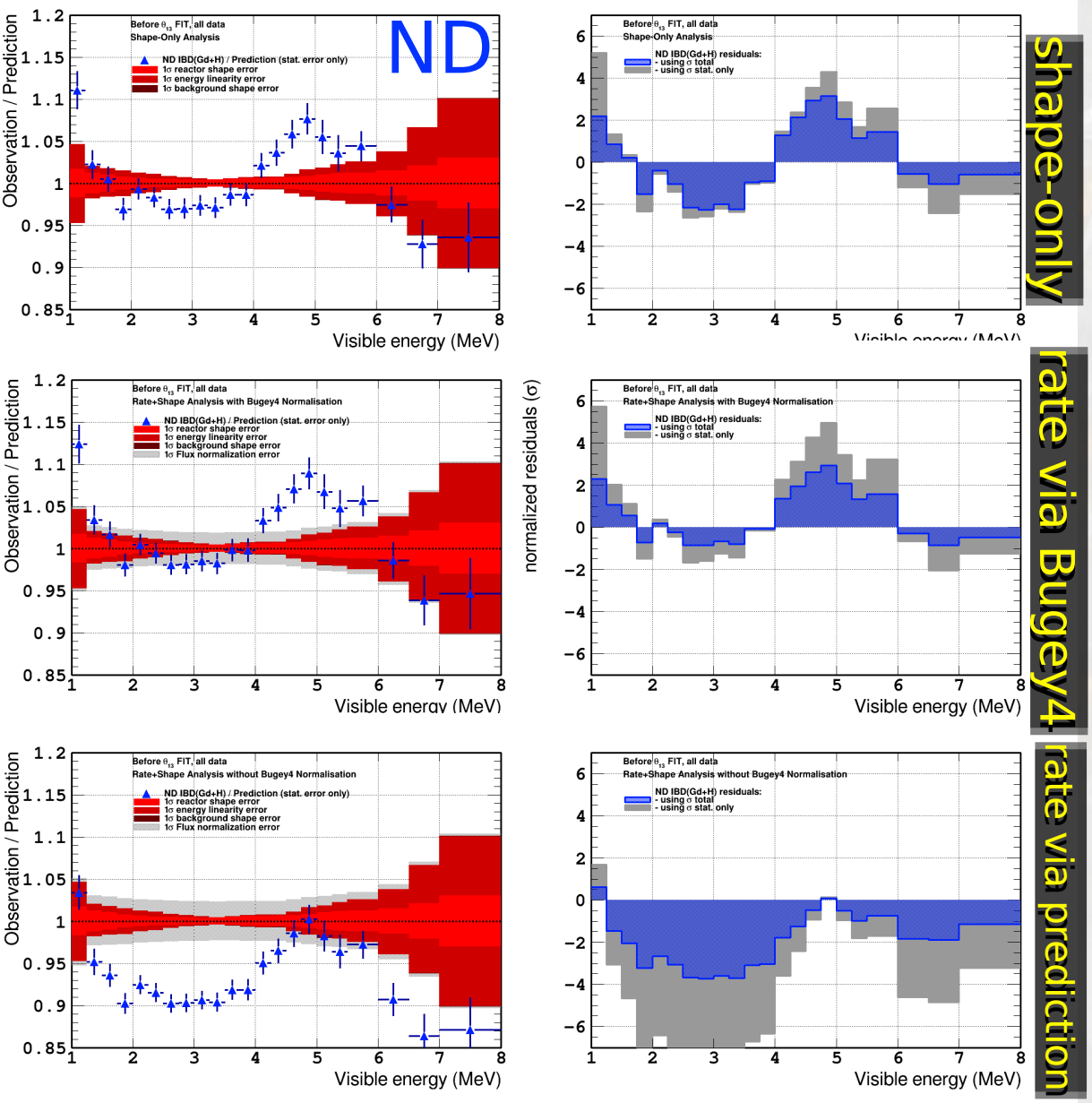
DC: 210 000 events / DB: 1.2 million events / Reno: 280 000 events





- **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?

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)

DC-IV Preliminary

DC first results with new IBD(Gd+H+C) selection [big challenge]

- **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
- new reactor spectrum characterization (rate⊕shape) major improvement
  - most precise reactor normalization & rate⊕shape analyses: **intriguing spectral distortions**
    - **DC-ND** superseding world best reactor references **Bugey4** & **Bugey3**
- **DC questions ILL-based prediction error budget**: <u>limitation to reactor single-detectors to yield (some) fundamental particle physics issue</u>: **neutrino(sterile) hypothesis?**

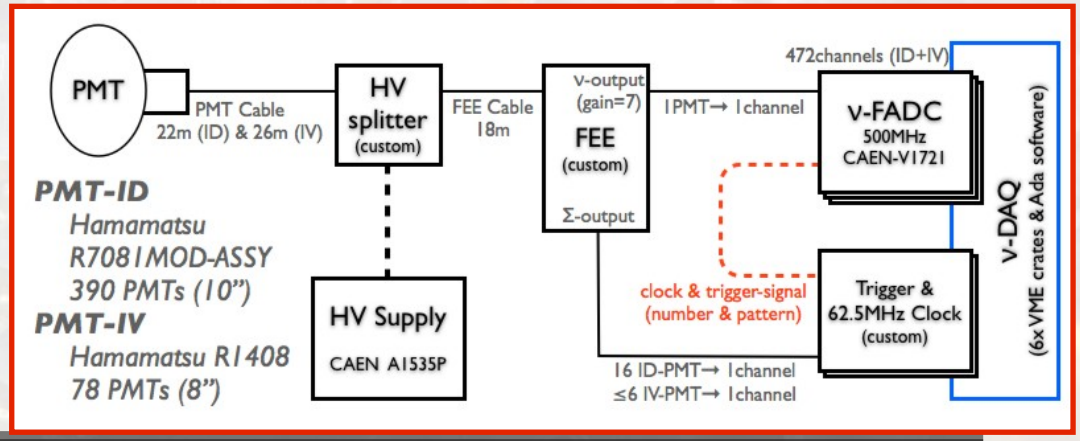
DC world best IBD-directionality measurements → still improving!


Thank you!

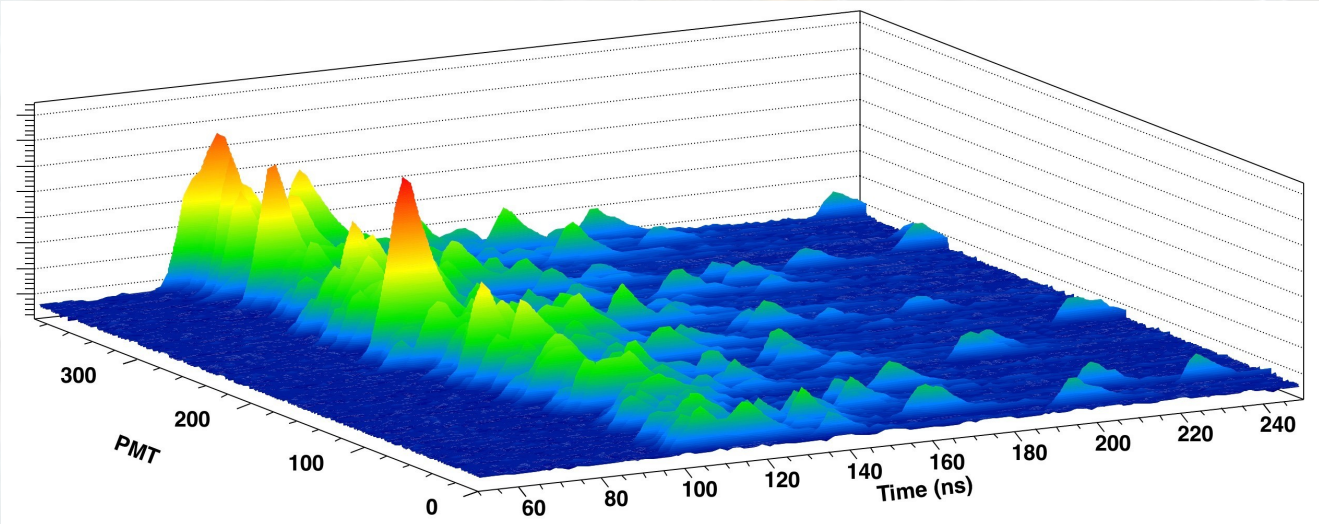
Backup

Double Chooz Read-out

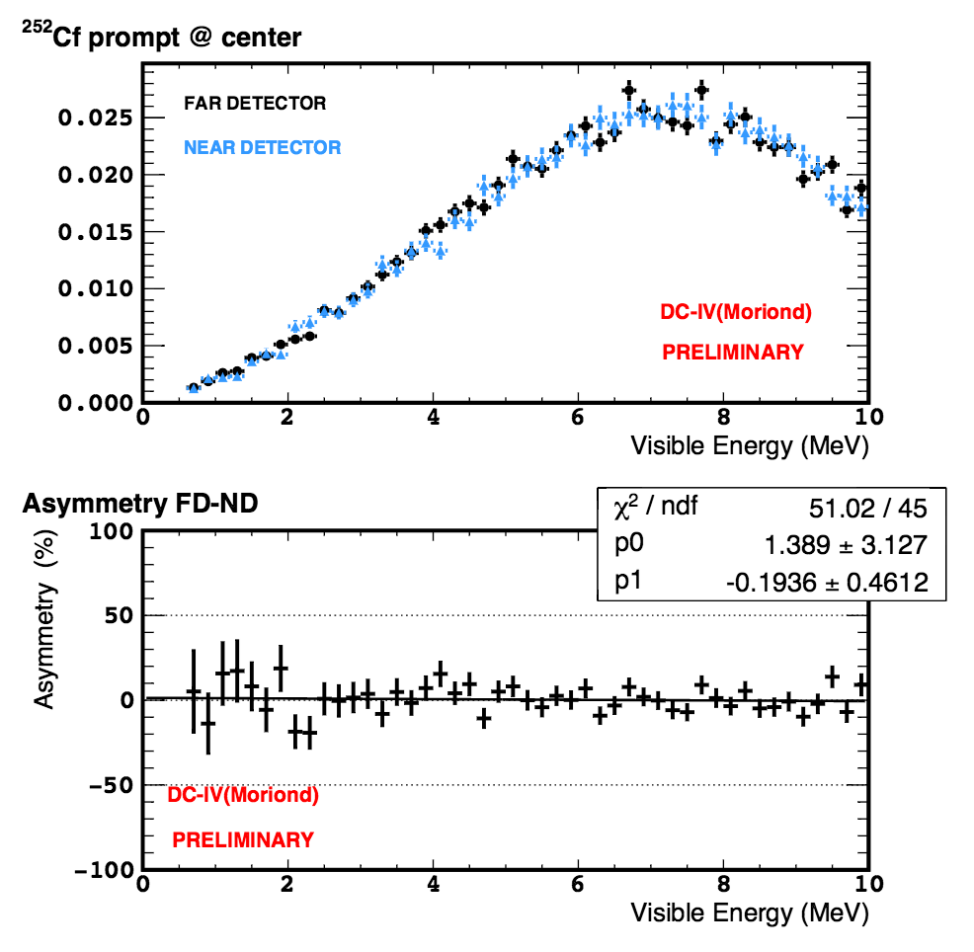
Liquid Scintillator
⊕
10” PMTs
⊕
analogue electronics
(clean & μ-handling)
⊕
500MHz FADC readout



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

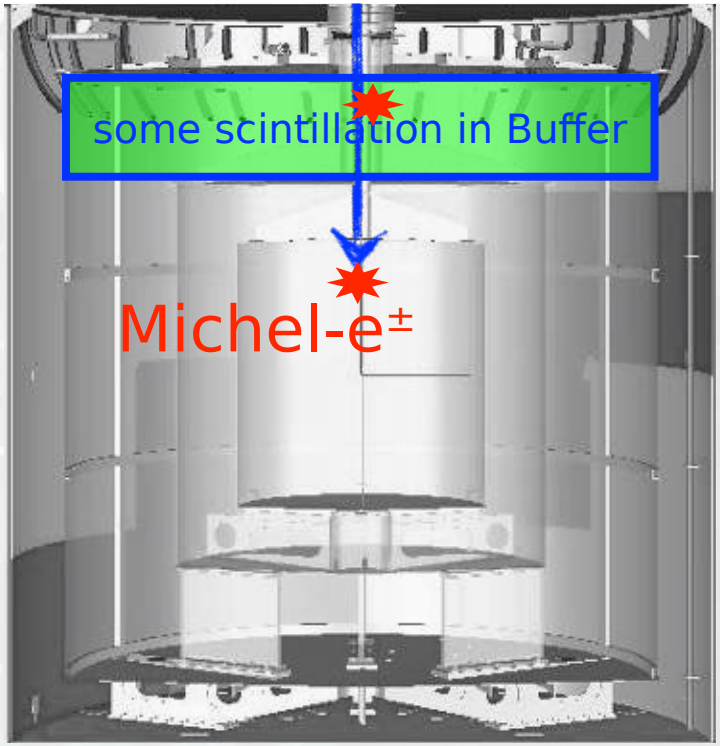


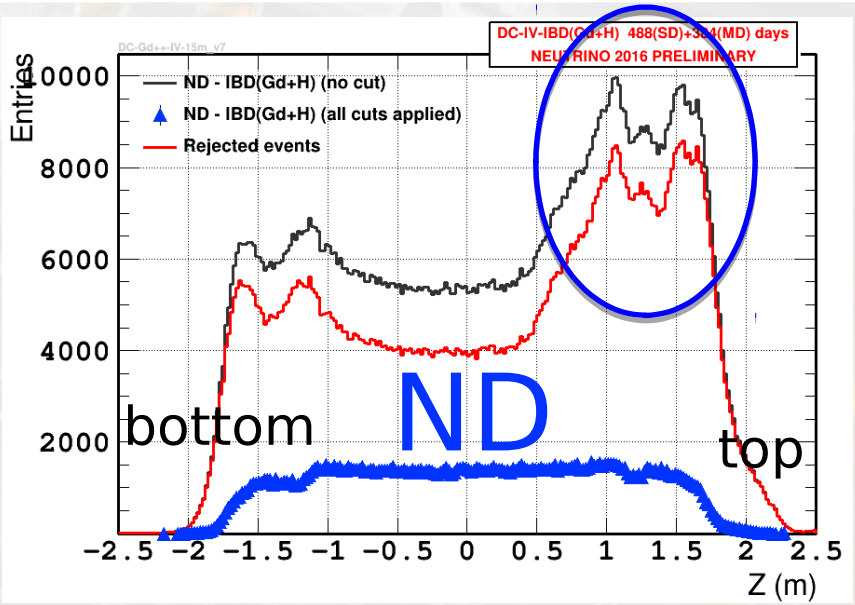
Prompt energy of ^{252}Cf data

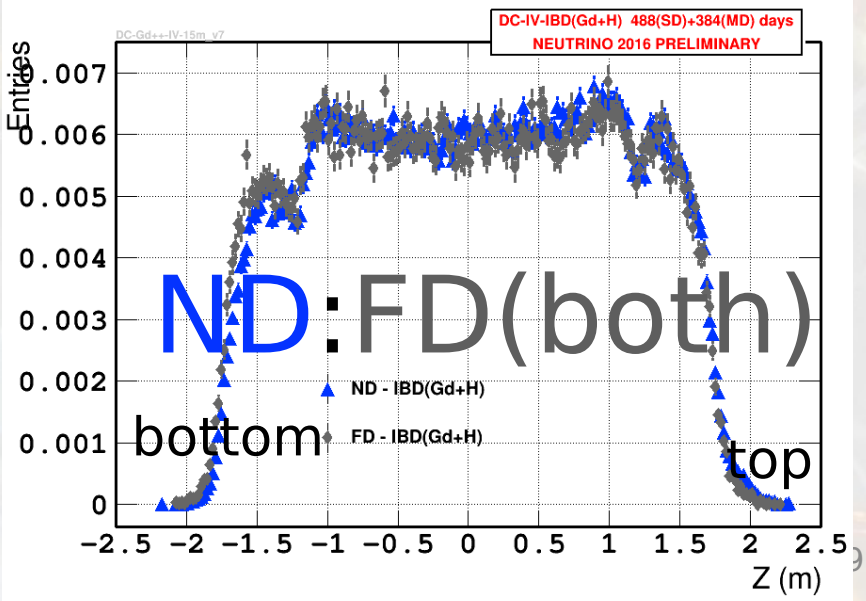


- ^{252}Cf emits ~10 γ with 1MeV in average.
- Comparison of FD and ND data with ^{252}Cf at the center of detector

Scintillator accumulates on Buffer top



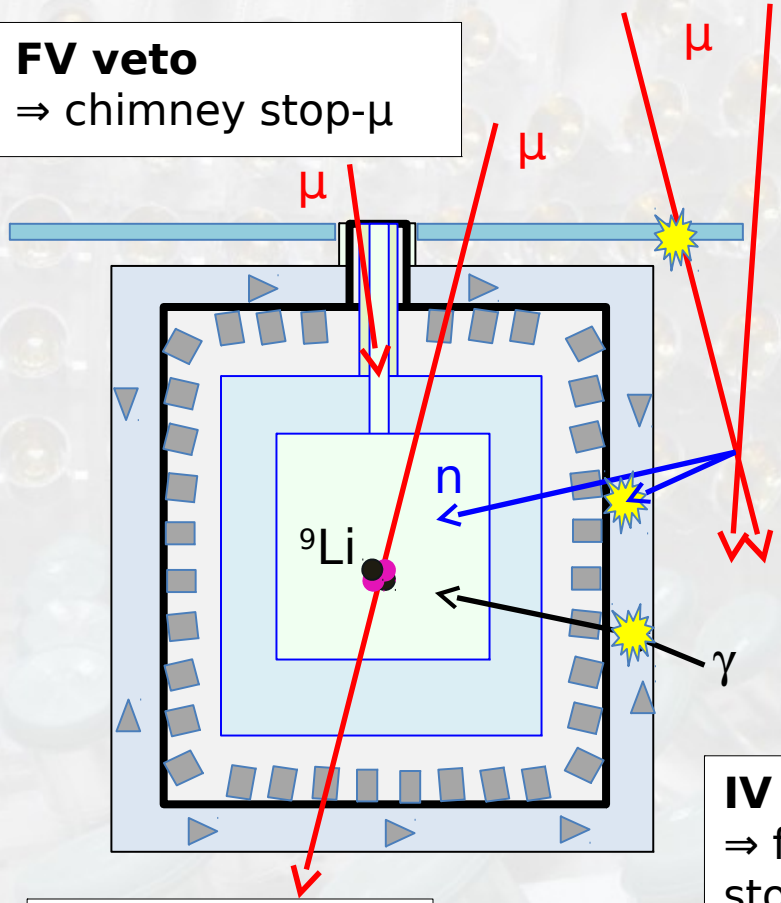




most μ-decay @ rest (Michel-e±)
rate(ND/FD)~100x

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

Background Vetoes



OV veto
⇒ fast neutron, stop-μ

FV veto
⇒ chimney stop-μ

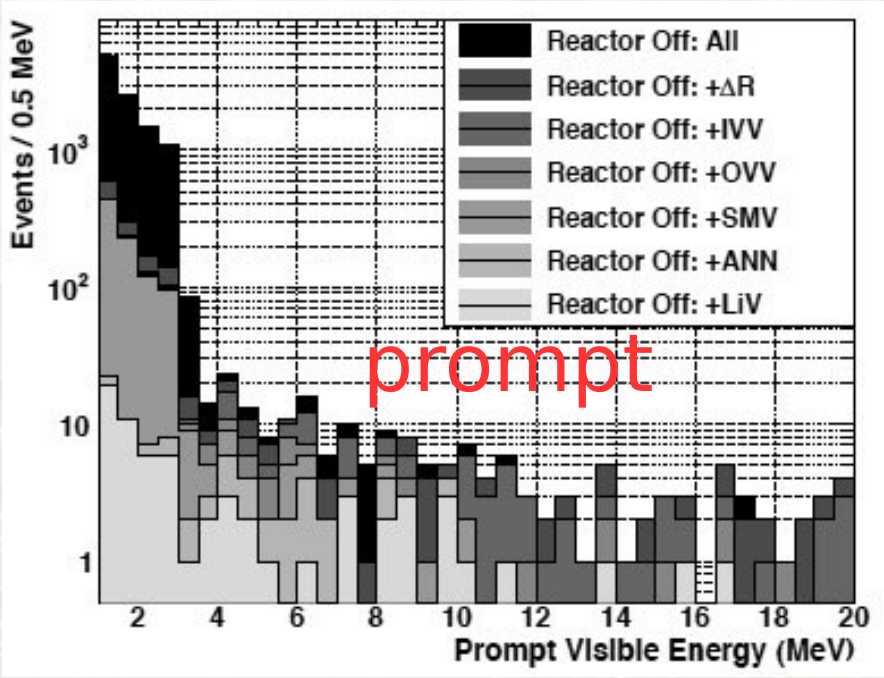
IV veto
⇒ fast neutron, stop-μ, γ scattering

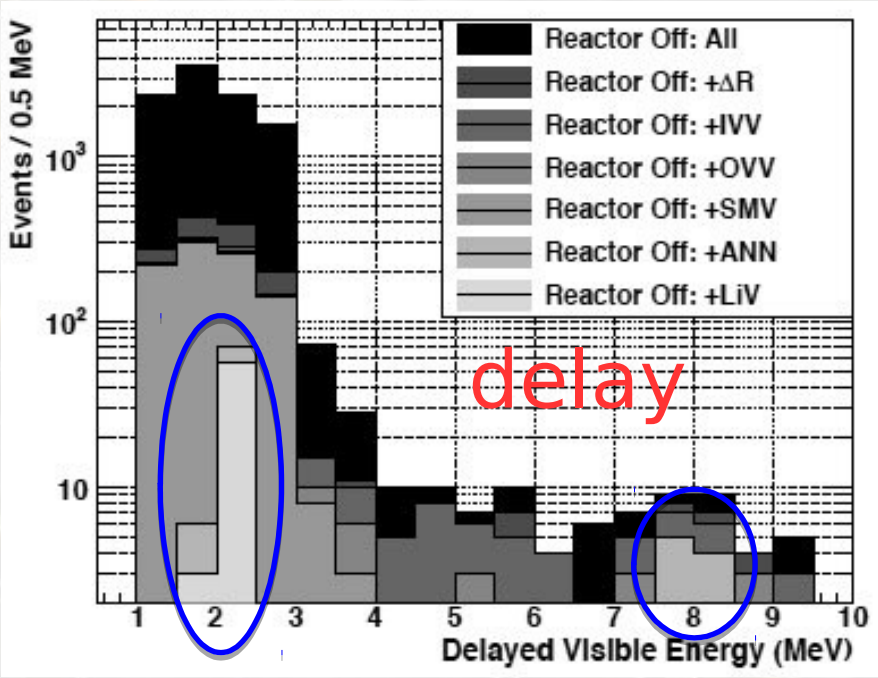
Li veto
⇒ cosmogenic ^{9}Li

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

Precious reactor-off data

FD-IBD(Gd+H)





Rejection Power estimation (total and per-veto)

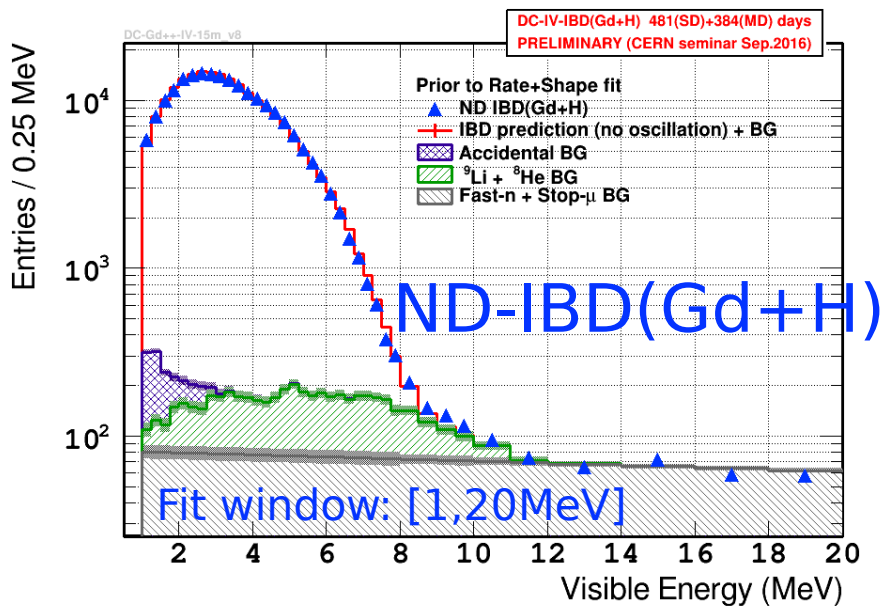
IBD(Gd+H): 158x (6:1000 selection) & efficiency≈(95.00±0.03)

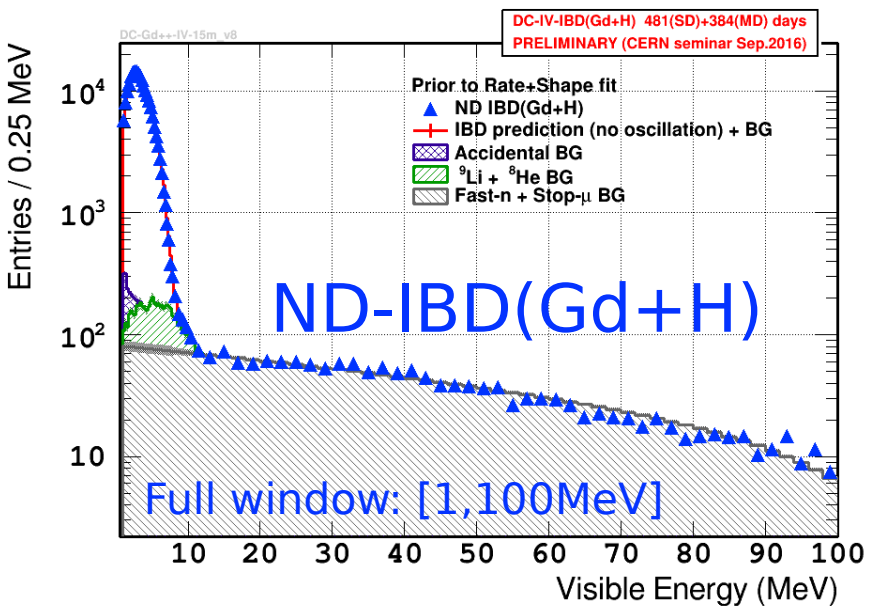
[IBD(Gd): 11x (9:100 selected)]

IBD(Gd+H) allows BG strategy validation of IBD(Gd) by an one extra order of magnitude

BG-model inclusiveness validation [next]

Remaining BG Measurement





BG model: BG(∑) = BG(accidental)+BG(fast-neutron)+BG(^{9}Li)

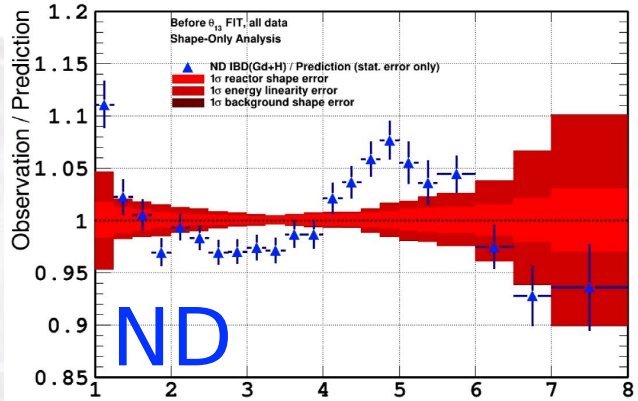
σ(BG)/Signal ≈0.2%(FD)

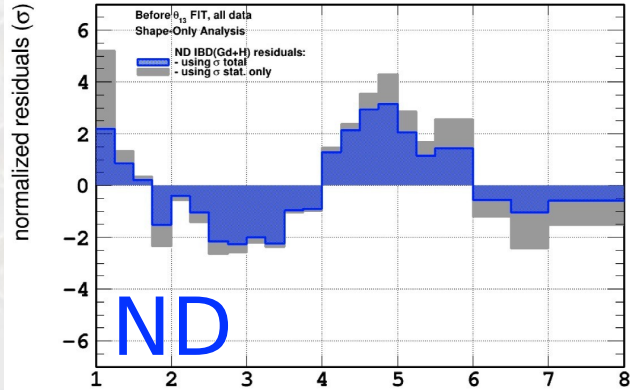
BG(acc): via OFF-time coincidence [σ(BG)/S→~0%]
BG(fast-n): via μ-detector tagging (IV checked by OV) up to 100MeV [σ(BG)/S: ~small]
BG(^{9}Li): via μ-spallation correlated production (≤50% vetoed) [σ(BG)/S:~dominant]

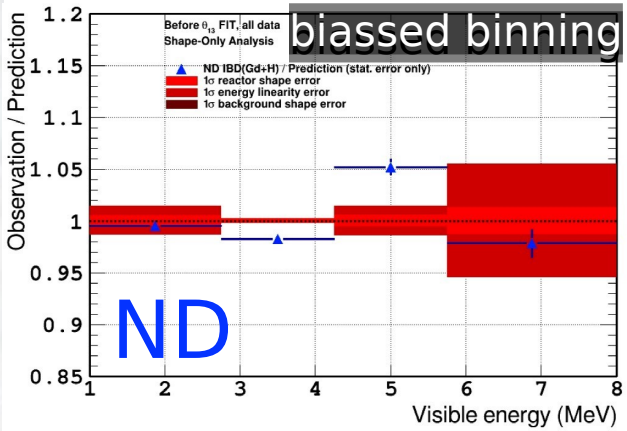
BG(∑)^{exclusive}≈BG(reactor-OFF)^{inclusive}⇒ BG-model is complete

(implies BG(stopped-μ), BG(^{12}B), BG(BiPo), BG(multi-captures): all negligible!!)

Reactor spectal distortions (shape only)





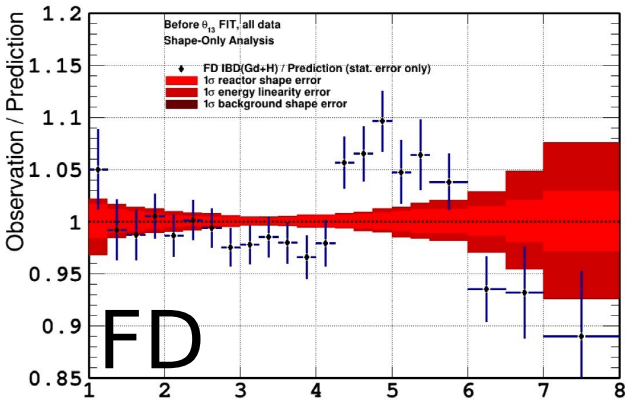


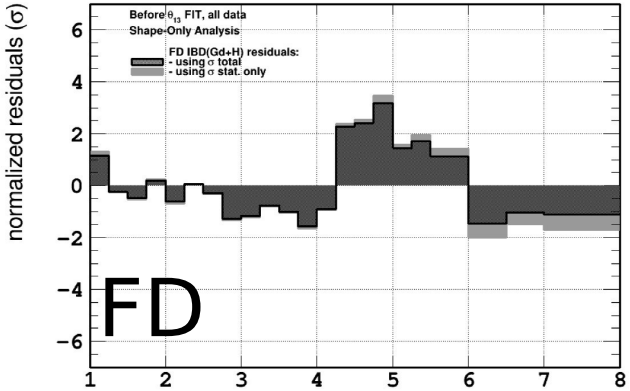
shape-only analysis (i.e. norm integral=1)

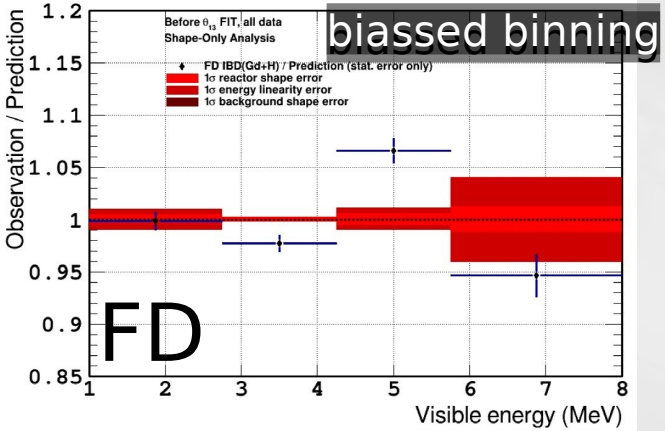
non-statical features
- lowest bin: high?
- deficit [2,4]MeV
- excess [4,6]MeV

(non-trivial)
ND≈FD: same features
(possible combination)

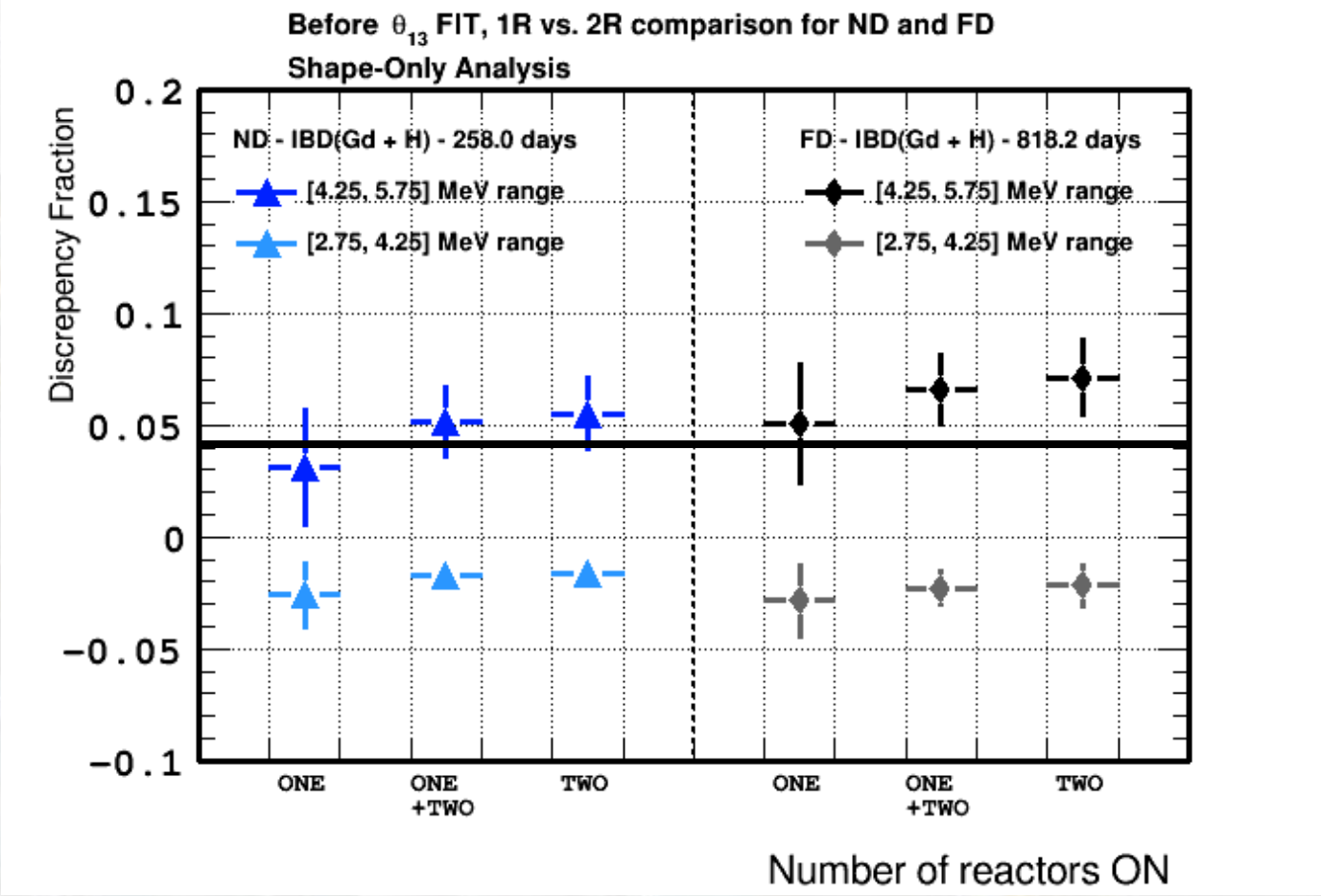
note
significance and interpretation depends highly on the normalization strategy
⇒shape-only likely incomplete
(no physical motivation)







Features scaling with reactor



consistent with our observations in 2014 @JHEP 1410 (2014) 086 (only FD)

features scaling fractionally constant with reactor#
(i.e. reactor power)

- deficit [2,4]MeV
- excess [4,5]MeV