Latest results of the Double Chooz experiment

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on behalf of the Double Chooz Collaboration

Les Rencontres de Physique de la Vallée d'Aoste
La Thuile, March 6, 2017

Summary

1. Introduction: neutrino oscillation and reactor antineutrinos
2. Double Chooz experimental setup
3. Events selection and background
4. $\sin^2(2\theta_{13})$ fit
5. Reactor flux and shape caracterization
6. Conclusion

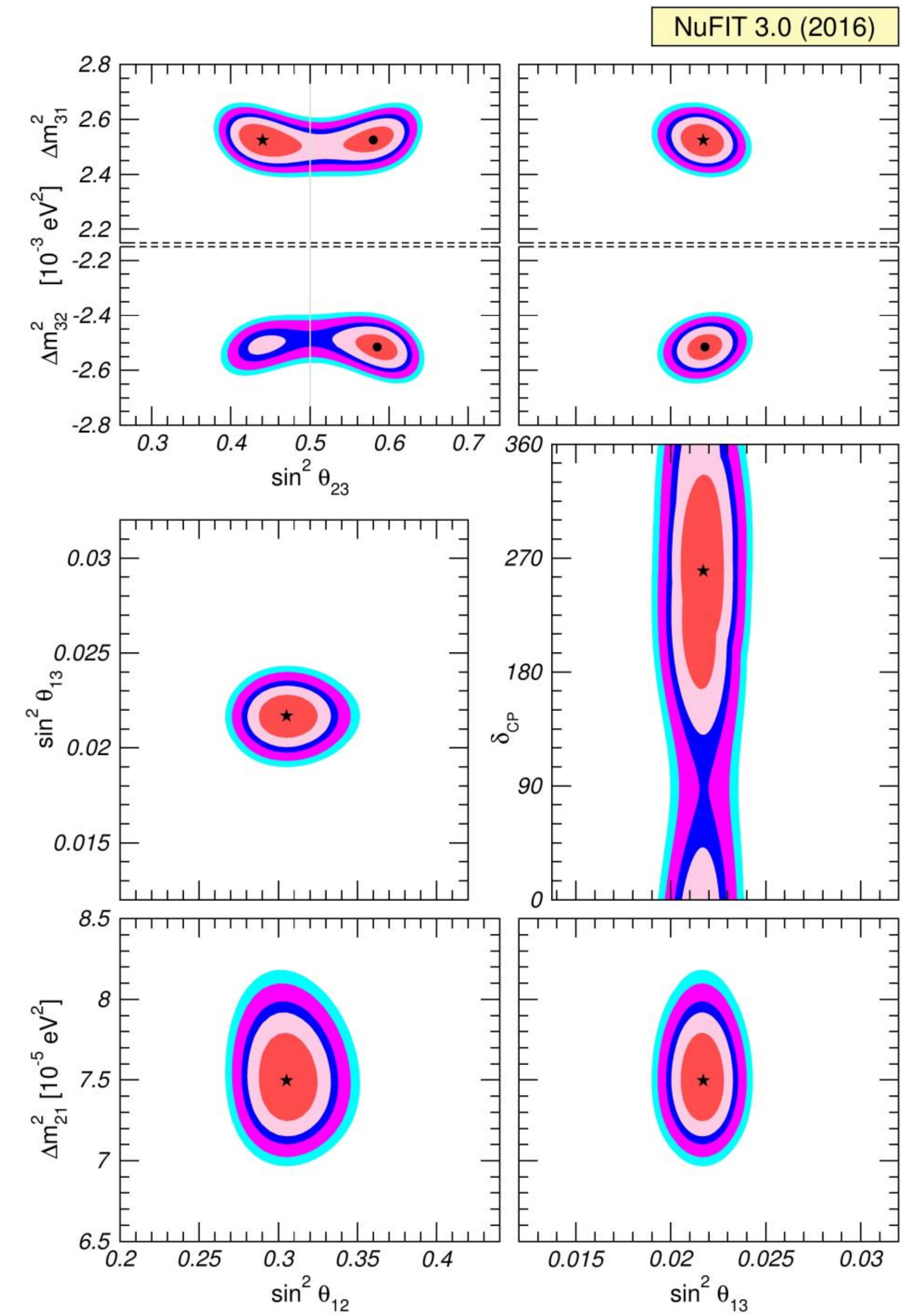
The PMNS matrix

$$|\nu_\alpha\rangle = \sum_i U^*{}_{\alpha i}\,|\nu_i\rangle$$

$c_{ij} = \cos(\theta_{ij})$
$s_{ij} = \sin(\theta_{ij})$

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{pmatrix}}_{\text{atmospheric}} \underbrace{\begin{pmatrix} \boldsymbol{C_{13}} & 0 & \boldsymbol{S_{13}}\, e^{-i\delta} \\ 0 & 1 & 0 \\ -\boldsymbol{S_{13}}\, e^{i\delta} & 0 & \boldsymbol{C_{13}} \end{pmatrix}}_{\text{reactor / accelerator}} \underbrace{\begin{pmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar}}$$

$\boldsymbol{\nu_\mu \rightarrow \nu_\mu}$ $\boldsymbol{\nu_e \rightarrow \nu_e}$ $\boldsymbol{\nu_\mu \rightarrow \nu_e}$ $\boldsymbol{\nu_e \rightarrow \nu_x}$



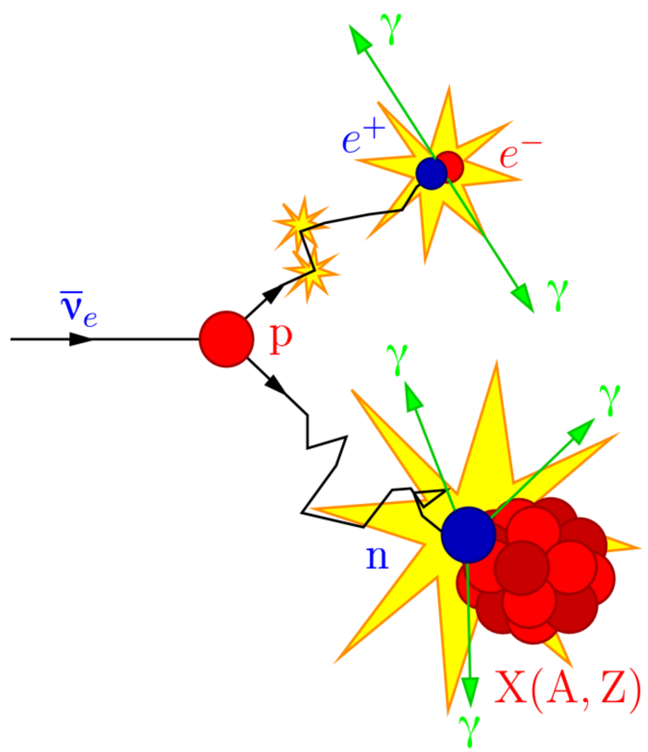
- **By 2010:** $\mathbf{\sin^2(2\theta_{13}) < 0.17}$ **at 90% CL** (Chooz)
  - ↬ **New generation of reactor experiments with unprecedented sensitivity (multi-detector concept)**
    Daya Bay, Double Chooz, RENO
  - ↬ Complementary to the long baseline oscillation experiments
- Precise θ_{13} measurement:
  - mass hierarchy determination
  - CP violation measurement
  - Understanding PMNS matrix

Reactor antineutrinos

Commercial nuclear reactor

- Pressurized Water Reactor ⇒ Thermal power from **^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu** (> 99.7% of total fission)
- Intense flux: ~5.10^{20} $\bar{\nu}_e$/s for a typical 900 MWth reactor

$\bar{\nu}_e$ detection

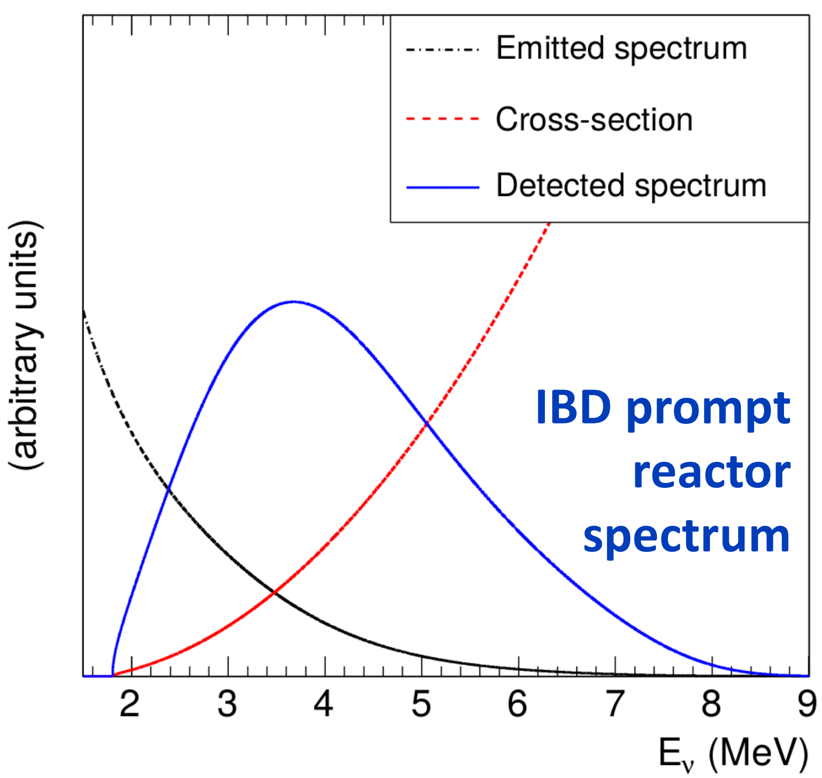


Inverse beta decay reaction (IBD) in liquid scintillator doped with gadolinium:

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

Energie threshold: 1.8 MeV
$\langle\sigma\rangle \sim 10^{-43}\mathrm{cm}^2$

Phys. Rev. C 83, 054615



$\bar{\nu}_e$ signature: spatial and temporal correlation between a prompt and a delayed signal

- **Prompt signal:** ionisation induced by positron + annihilation γ's

$$\Rightarrow \mathbf{E_{vis} = E_{\bar{\nu}_e} - 0.782\ MeV}$$

- **Delayed signal:** γ's from neutron capture on Gd or/and H
  - **Gd: 8 MeV / $\tau \sim$ 30 µs**
  - **H: 2.2 MeV / $\tau \sim$ 200 µs**

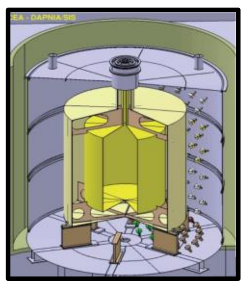
Measurement of θ_{13}

Disappearance experiment ($\bar{\nu}_e \rightarrow \bar{\nu}_e$) $\Rightarrow$ Direct measurement of θ_{13} from energy dependent deficit

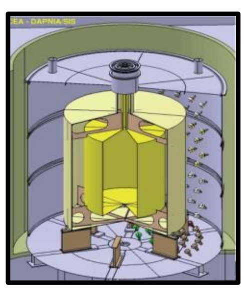
Non oscillation probability:

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}(L,E) \simeq 1 - \sin^2(2\theta_{13}) \sin^2\left(1.267 \frac{\Delta m^2_{13}(\mathrm{eV}^2)\mathrm{L(m)}}{E(\mathrm{MeV})}\right)$$

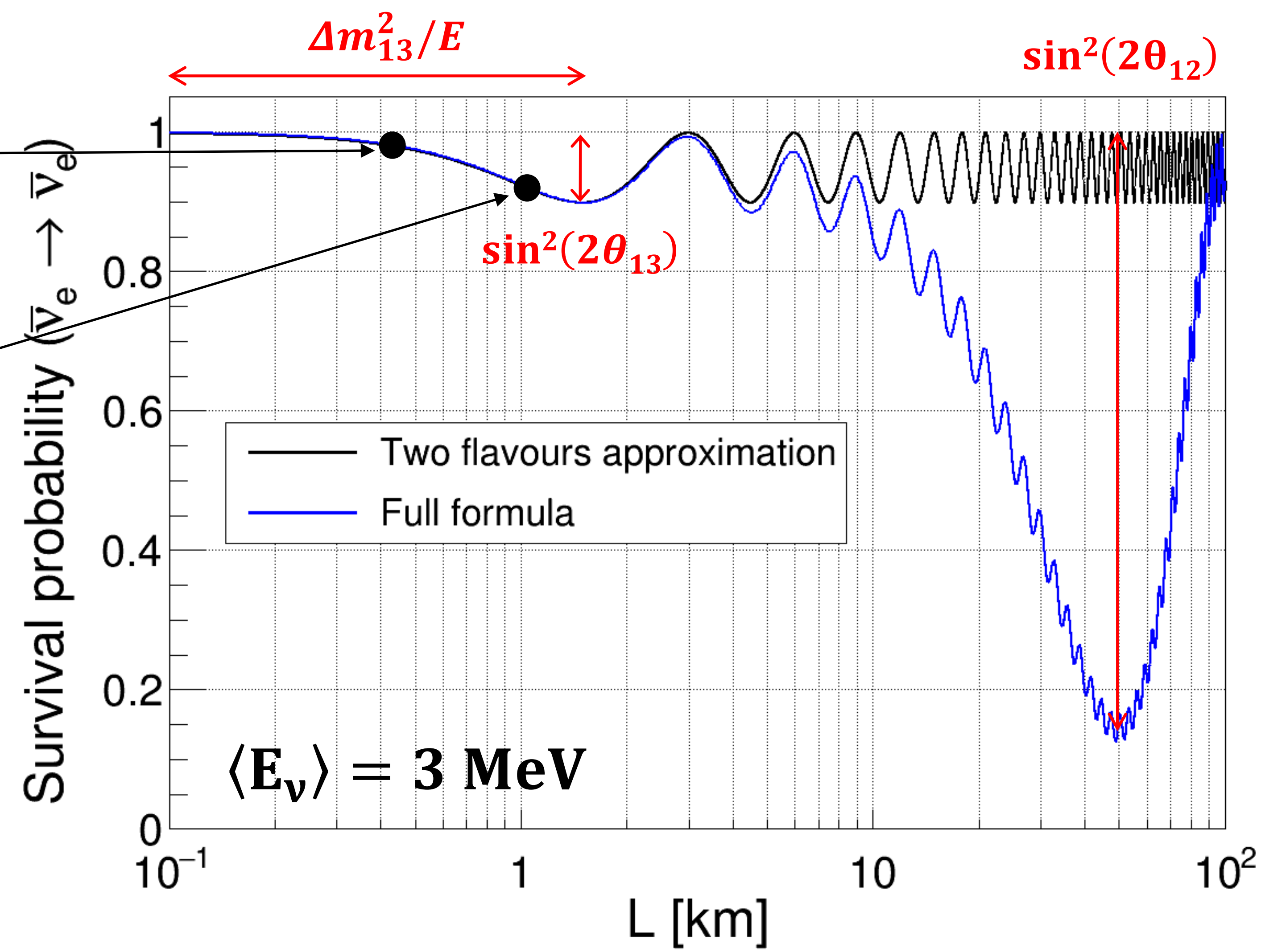
(two flavours approximation)



Near detector (ND)



Far detector (FD)

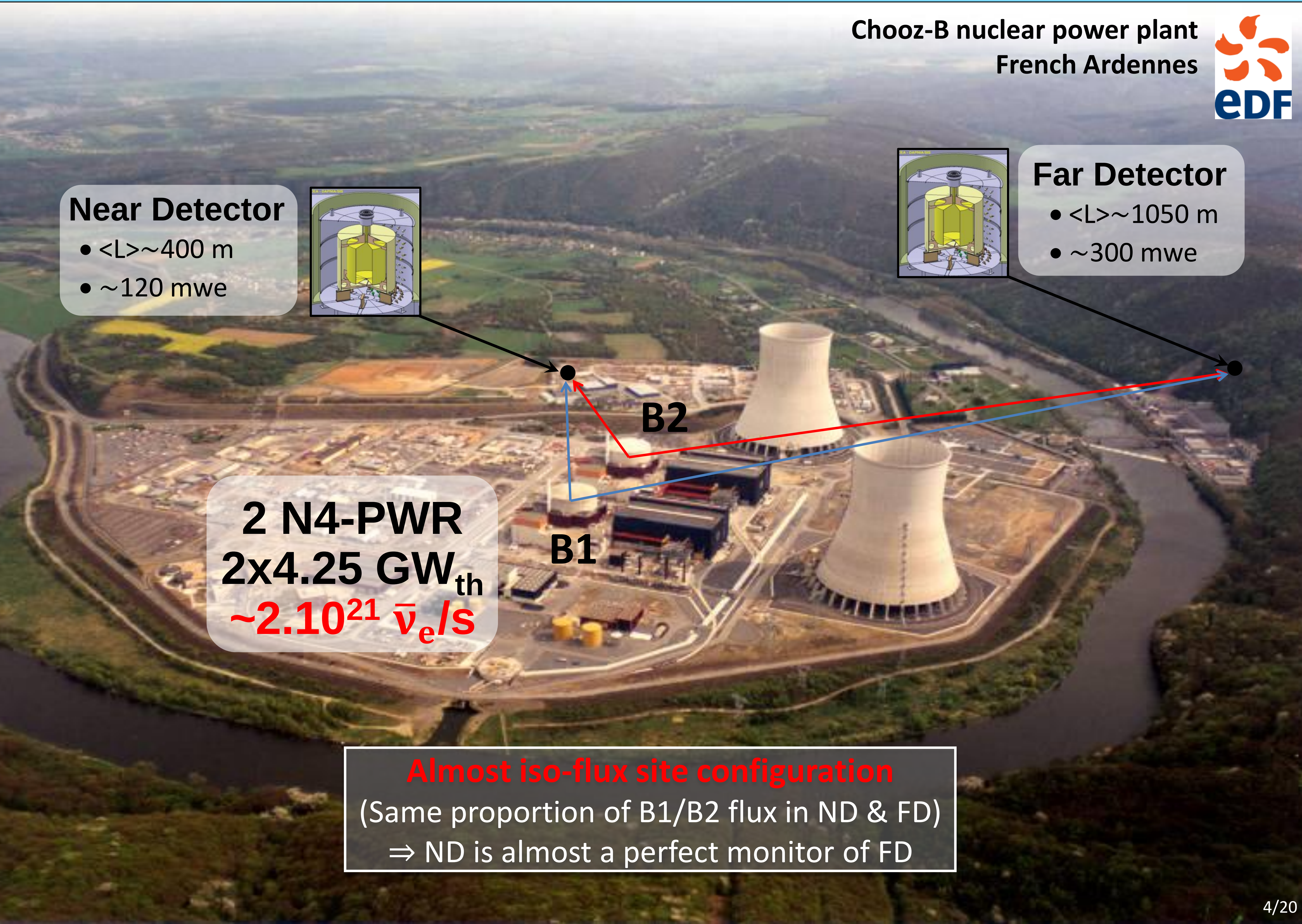


$\Rightarrow$ **Rate deficit and shape distortion between a Near and a Far detector**

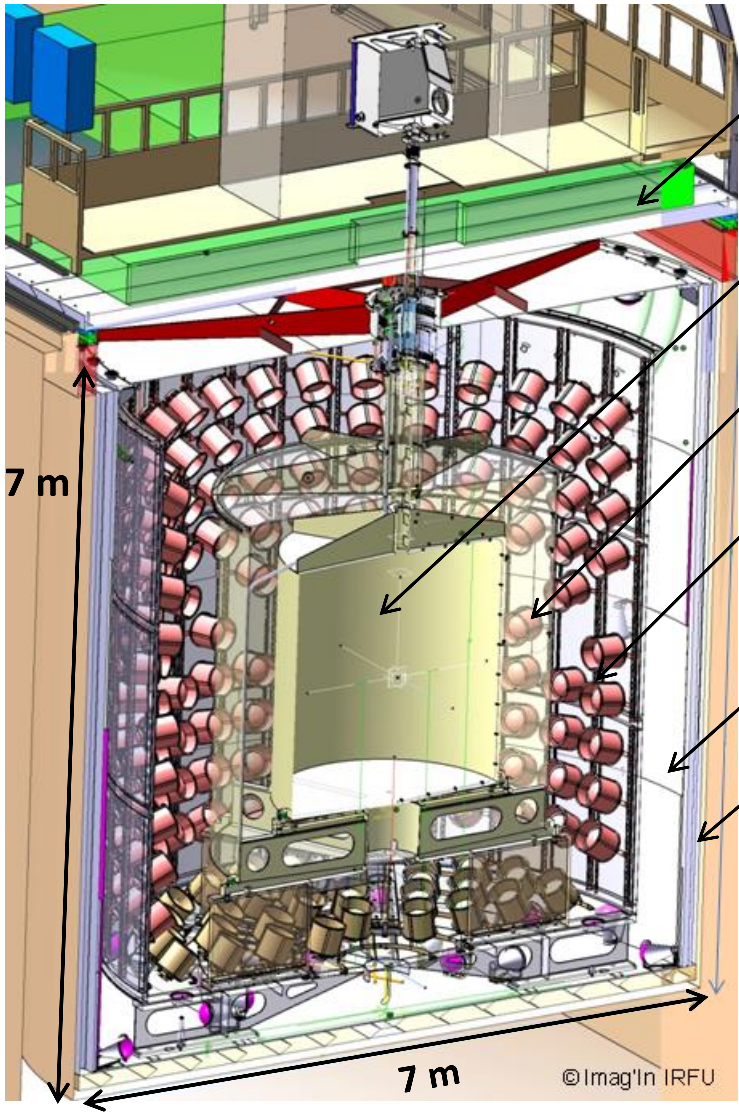
$\Rightarrow$ **No 'matter effet' and no δ_{CP} dependency**

$\Rightarrow$ **Systematics uncertainties highly suppressed in multiple detectors configuration at different baselines with identical detectors**

Experimental setup of Double Chooz



Detector design



Outer Veto: plastic scintillator strips

***ν*-Target:** liquid scintillator doped with 1 g/l of Gd (10.3 m^3)

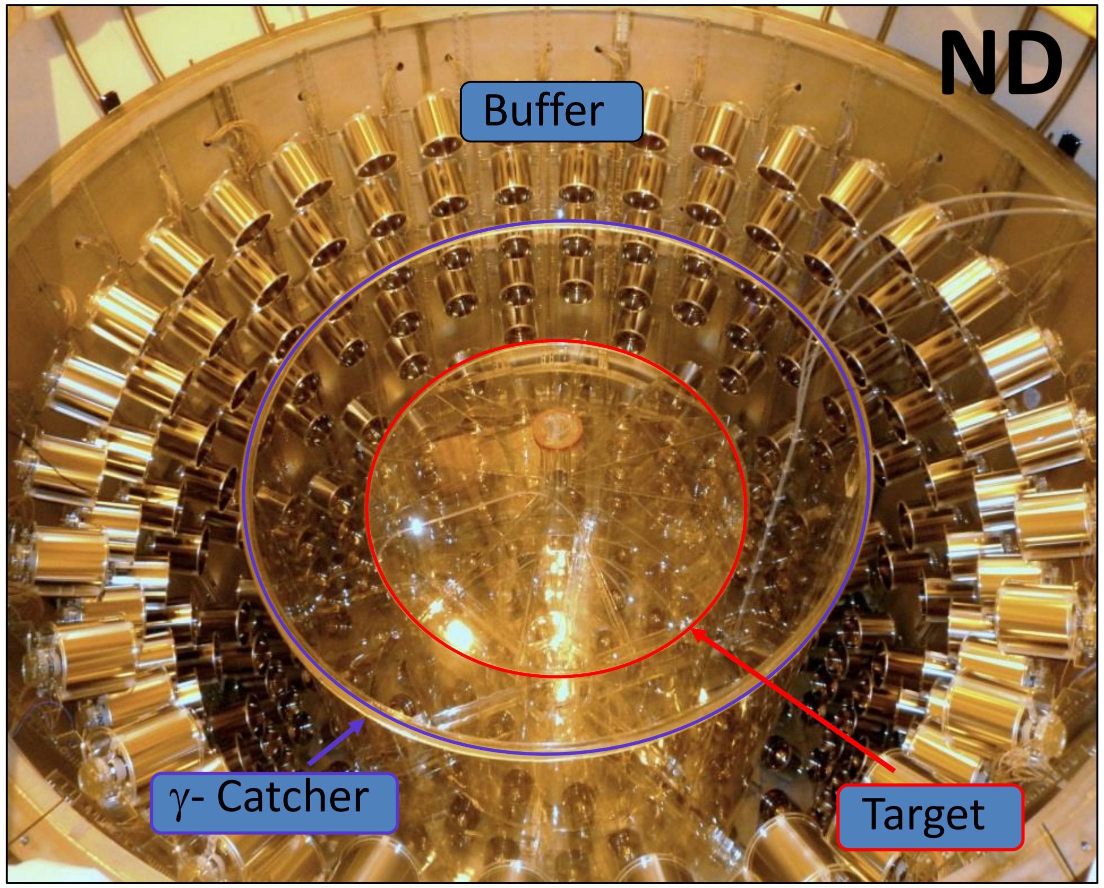
γ-Catcher: liquid scintillator (22.3 m^3)

Buffer: - mineral oil (110 m^3)
- 390 PMTs (10 inches)

Inner detector

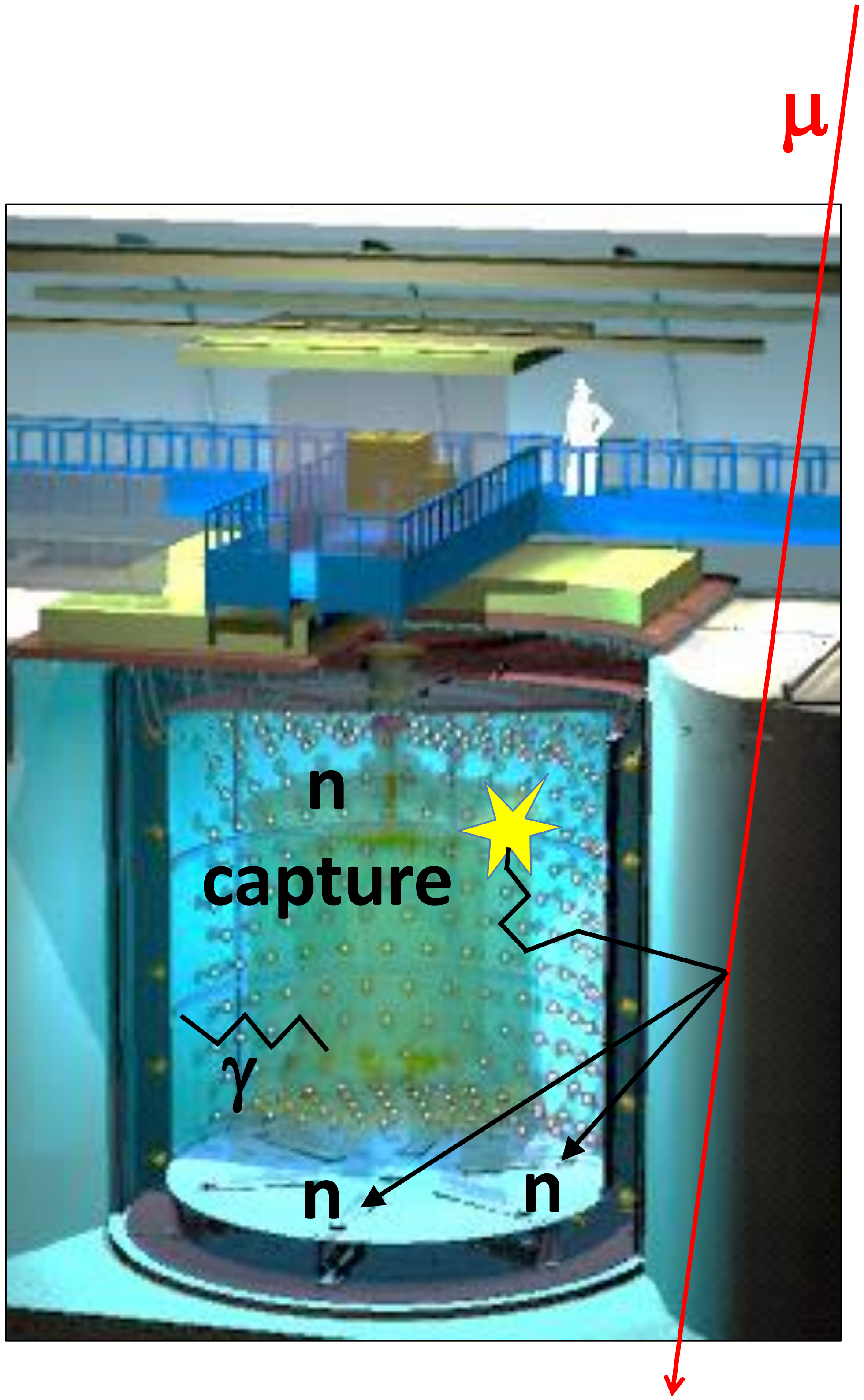
Inner Veto: liquid scintillator (90m^3) / 78 PMTs (8 inches)

Shielding: ~15 cm steel shielding (FD) / 1 m water (ND)



Experimental concept to **use two identical detectors**

- 4 layers structure (ν-Target, γ-Catcher, Buffer and IV)
- stable Gd loaded liquid scintillator developed (same batch for both detectors)



Two types of background expected

- **Accidental coincidence:**

γ (radioactivity from materials, PMTs, rock)

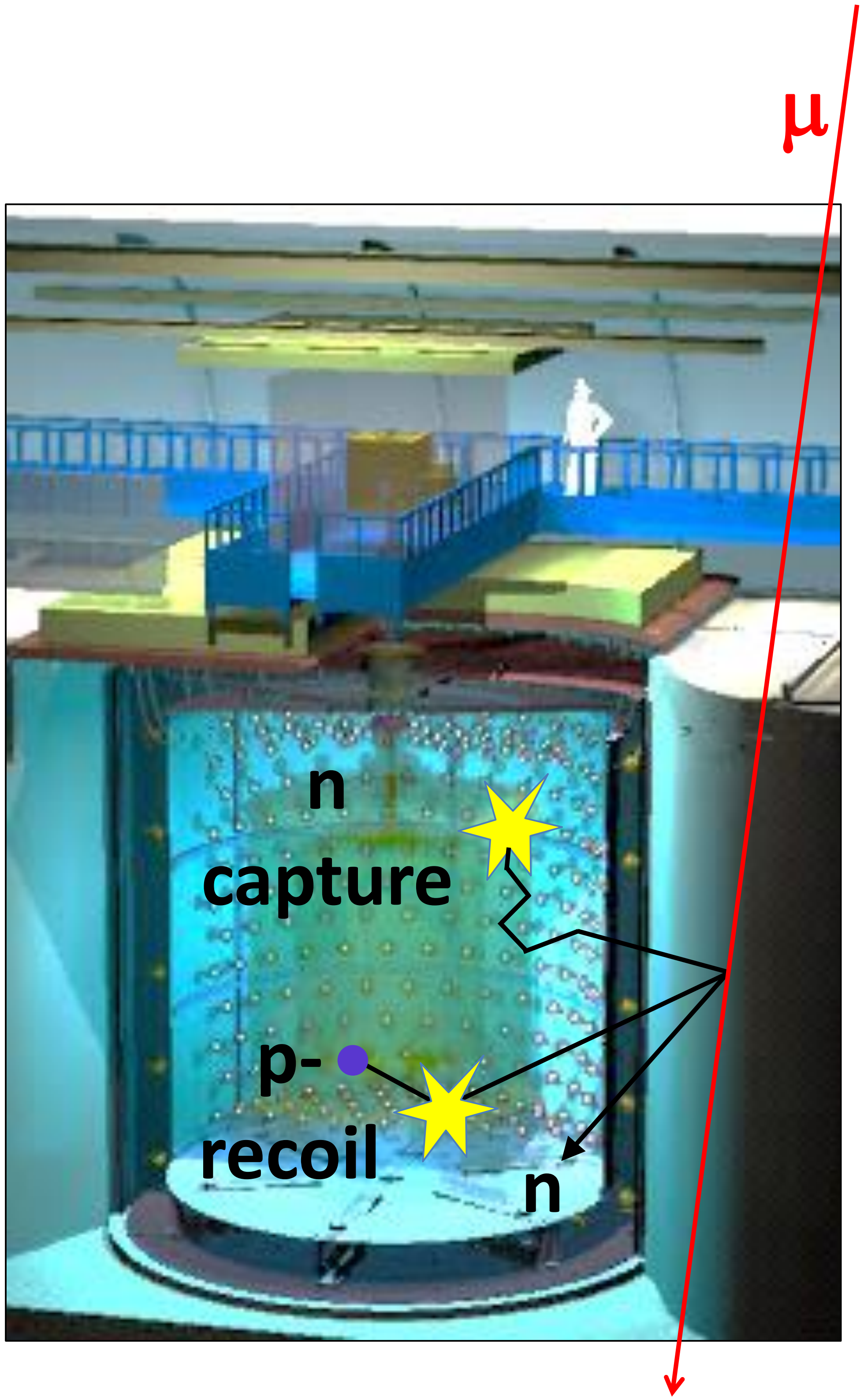
Neutrons (from cosmic μ spallation) captured on Gd/H or γ like prompt fake signal in case of H

Prompt mimic

Delayed mimic

Background

Two types of background expected



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γ (radioactivity from materials, PMTs, rock)

Neutrons (from cosmic μ spallation) captured on Gd/H or γ like prompt fake signal in case of H

- **Fast neutron:**

Neutrons (from cosmic μ spallation) gives recoil protons (low energy)

Neutrons (from cosmic μ spallation) captured on Gd/H or γ like prompt fake signal in case of H

correlated

Prompt mimic | **Delayed mimic**

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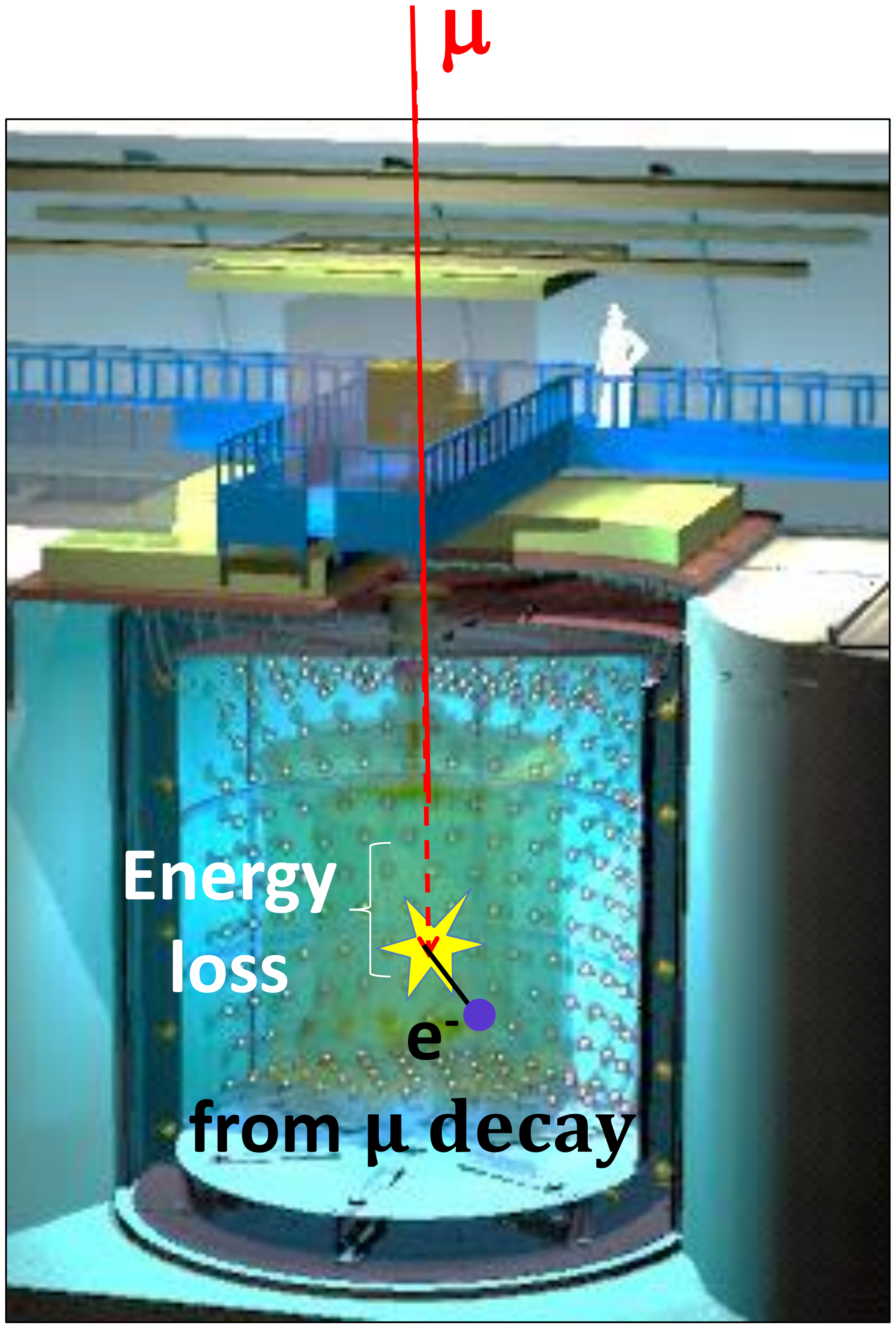

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- **Stopping muon:**

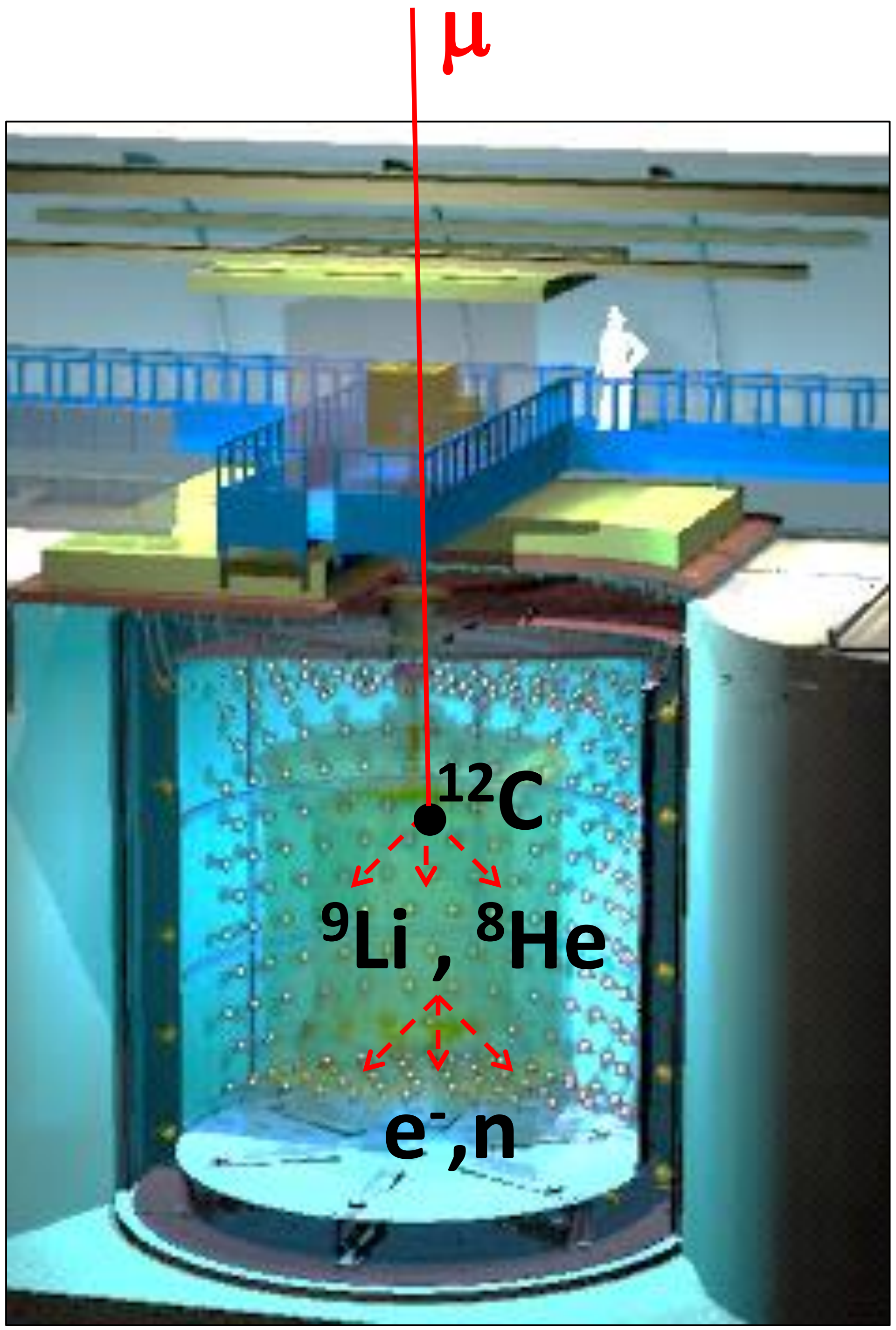
Cosmic μ entering from the chimney

Michel electrons (μ decay)

correlated

Prompt mimic | **Delayed mimic**

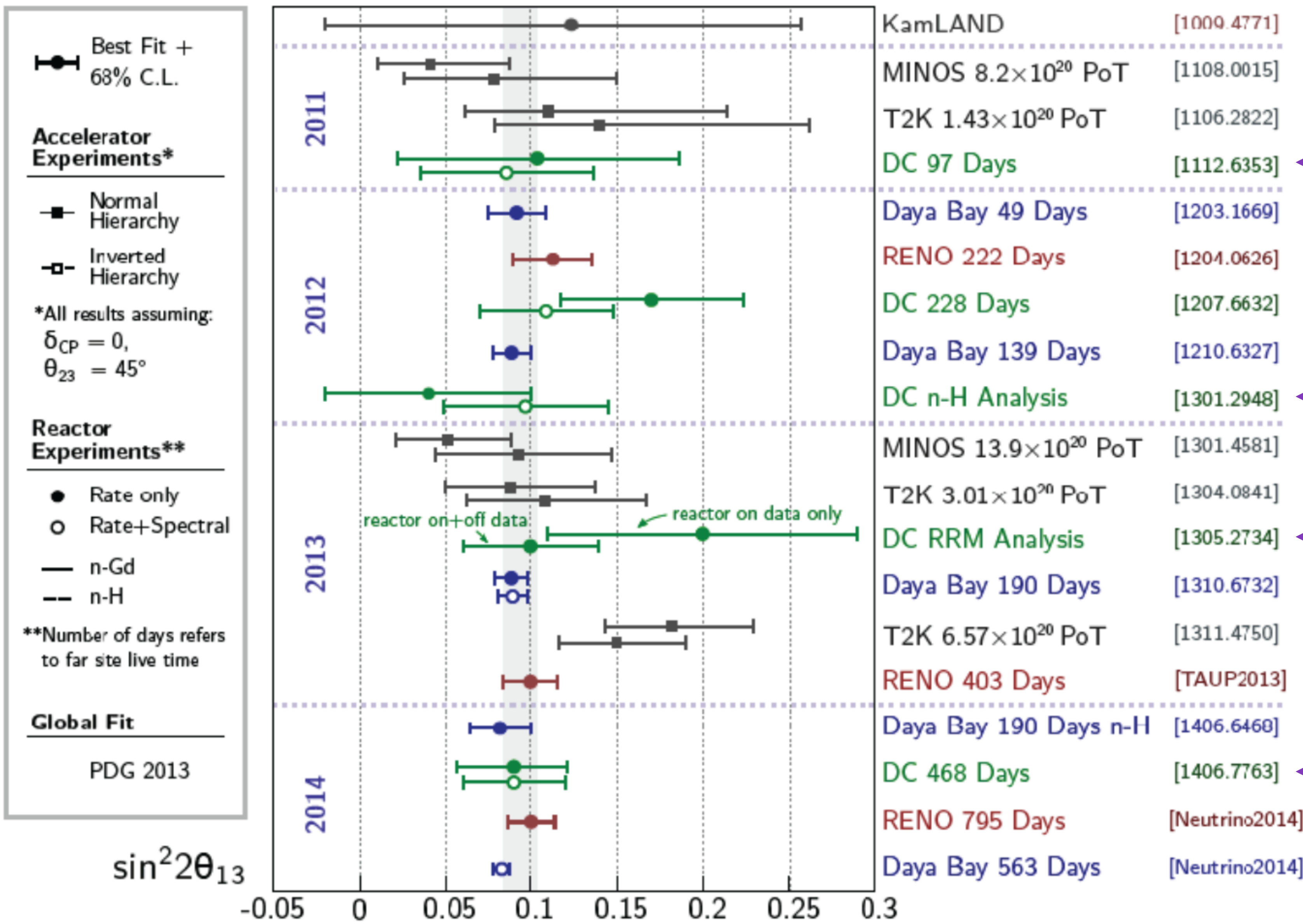
Two types of background expected



	Prompt mimic	Delayed mimic
• Accidental coincidence:	γ (radioactivity from materials, PMTs, rock)	Neutrons (from cosmic μ spallation) captured on Gd/H or γ like prompt fake signal in case of H
• Fast neutron:	Neutrons (from cosmic μ spallation) gives recoil protons (low energy)	Neutrons (from cosmic μ spallation) captured on Gd/H or γ like prompt fake signal in case of H
• Stopping muon:	Cosmic μ entering from the chimney	Michel electrons (μ decay)
• Cosmogenic β-n emitter:	e^- from $^9Li/^8He$ β + n decays	Neutrons from $^9Li/^8He$ β + n decays captured on Gd/H

correlated

Double Chooz milestone



First n-Gd analysis (Rate + Shape fit): **Indication of non-zero value of θ_{13}**

New analysis based on n-H capture

First θ_{13} fit based on reactor thermal power modulation –RRM– (rate only)

Improved n-Gd analysis: **Observation of a spectral distortion between the data and the prediction**

2011-2015: 1st phase of DC, data taking with only the far detector

- $\sin^2(2\theta_{13})$ measurement: comparison of FD data with a prediction of the expected non-oscillated $\bar{\nu}_e$ flux ⇒ **Flux systematics dominated ($\sigma_{flux}\sim1.7\%$)**

2015: 2nd phase of Double Chooz, data taking in a multi-detector configuration

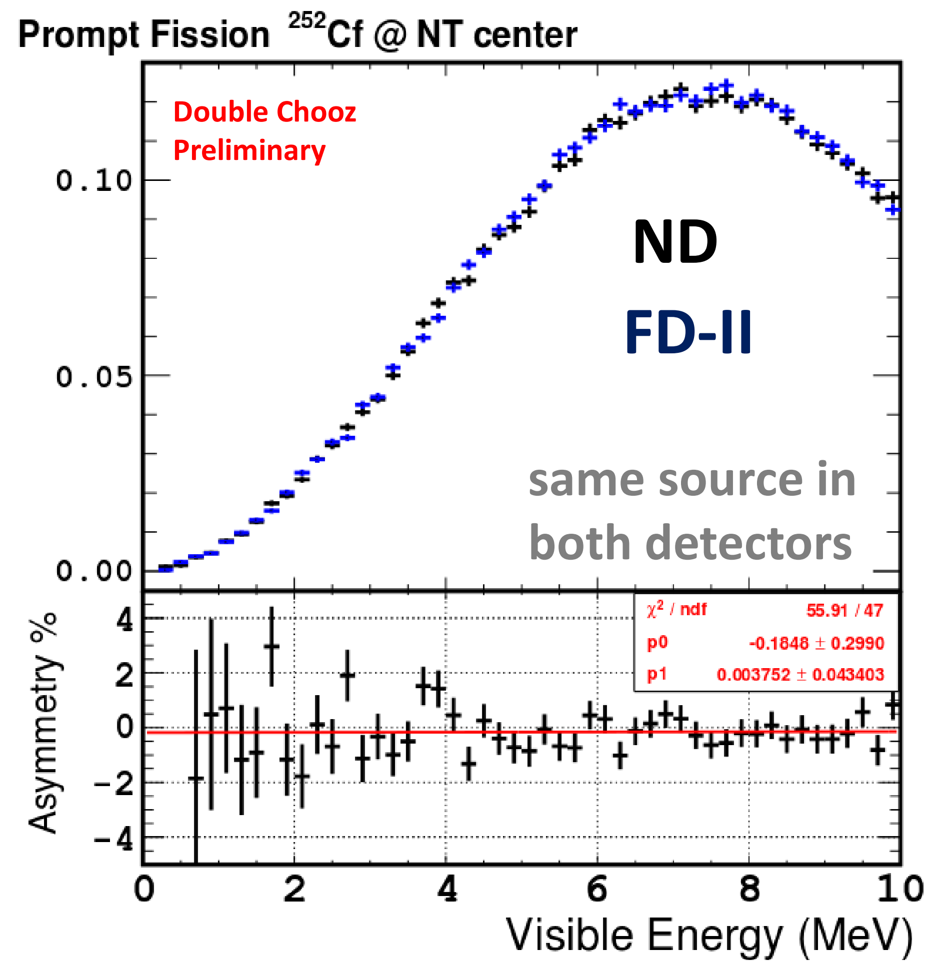
- 1st analysis released at the Moriond 2016 conference (mars. 2016) – 9 months
- **2nd analysis released at a Cern seminar (sept. 2016) – 15 months ⇒ This presentation**

Detectors configurations

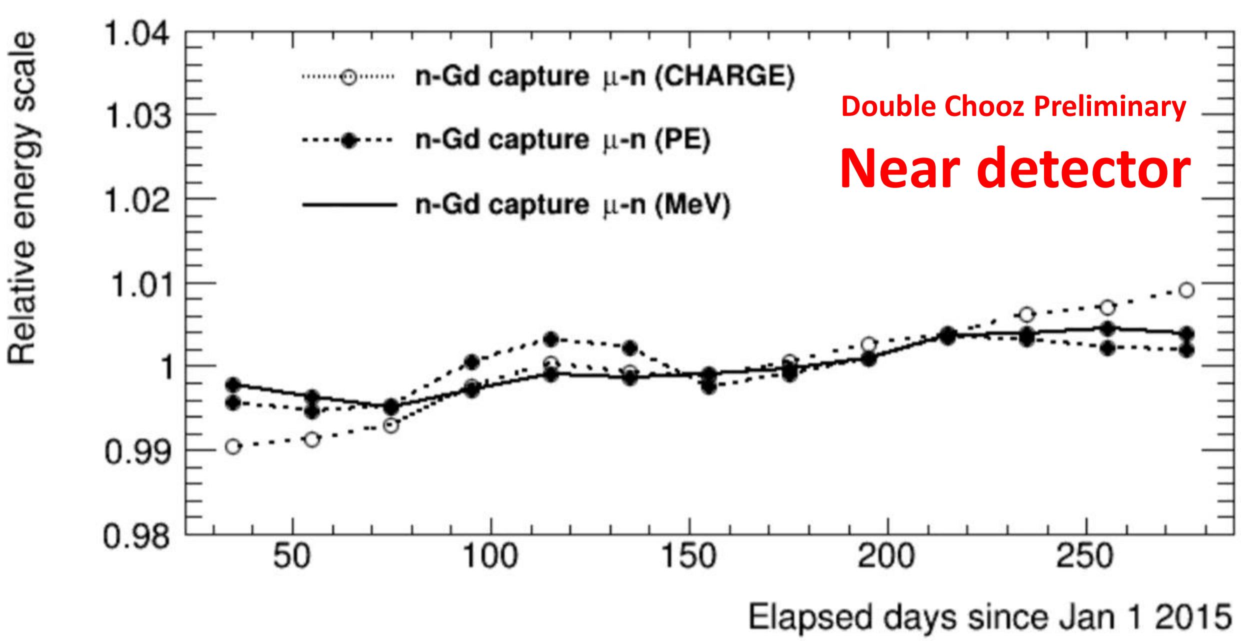
1st phase ⇒ FD-I
2nd phase ⇒ FD-II / ND

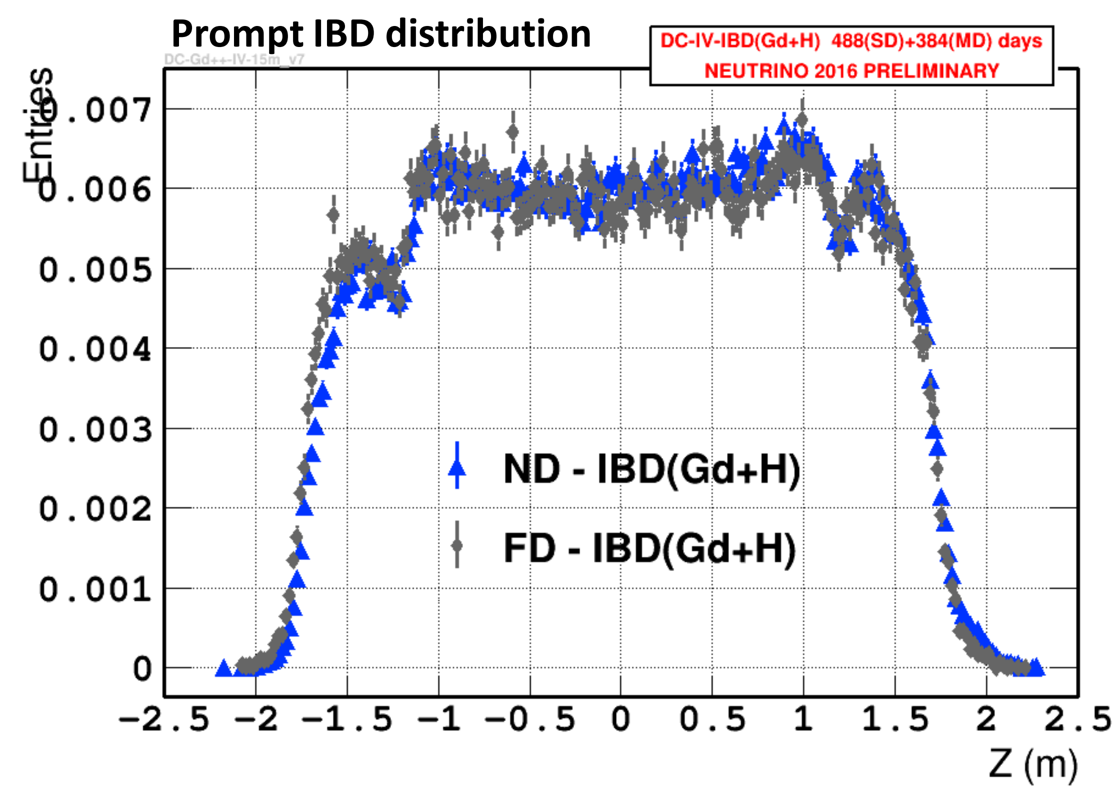
Detectors performance

- Very similar response for both the far and near detectors
  - ↳ ^{252}Cf calibration campaign: **relative response linearity** $\leq$ **0.3%** within [1,10] MeV
  - ↳ Good agreement of events distribution after background rejection

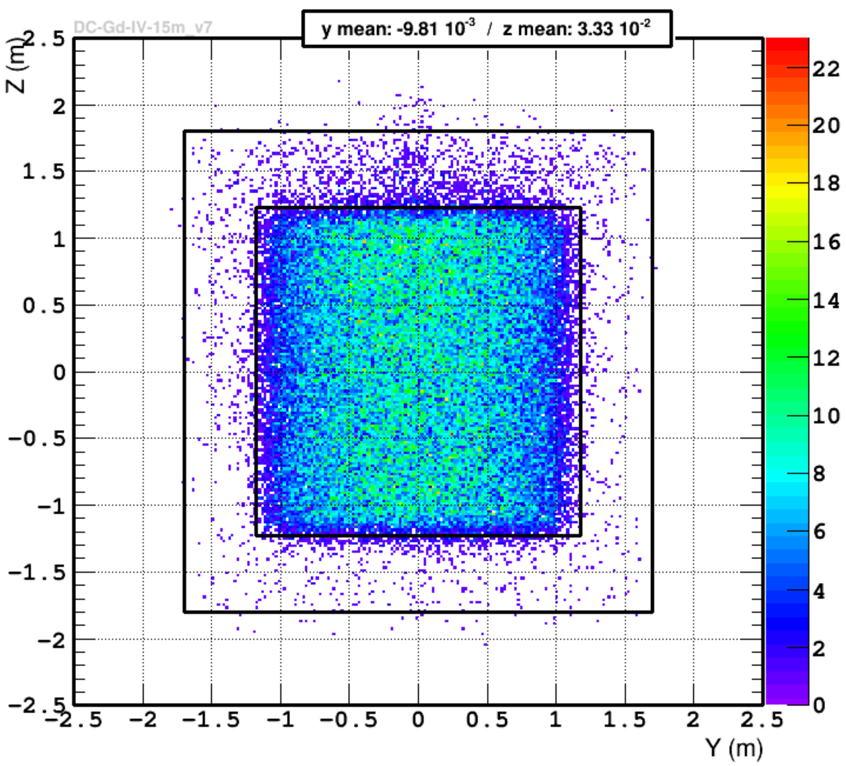


- **Detector response variation with time** $\lesssim 1\%/\text{year}$
- **Stable scintillator**: Gd-fraction unchanged since > 5 years (within 0.2%)





IBD[Gd]

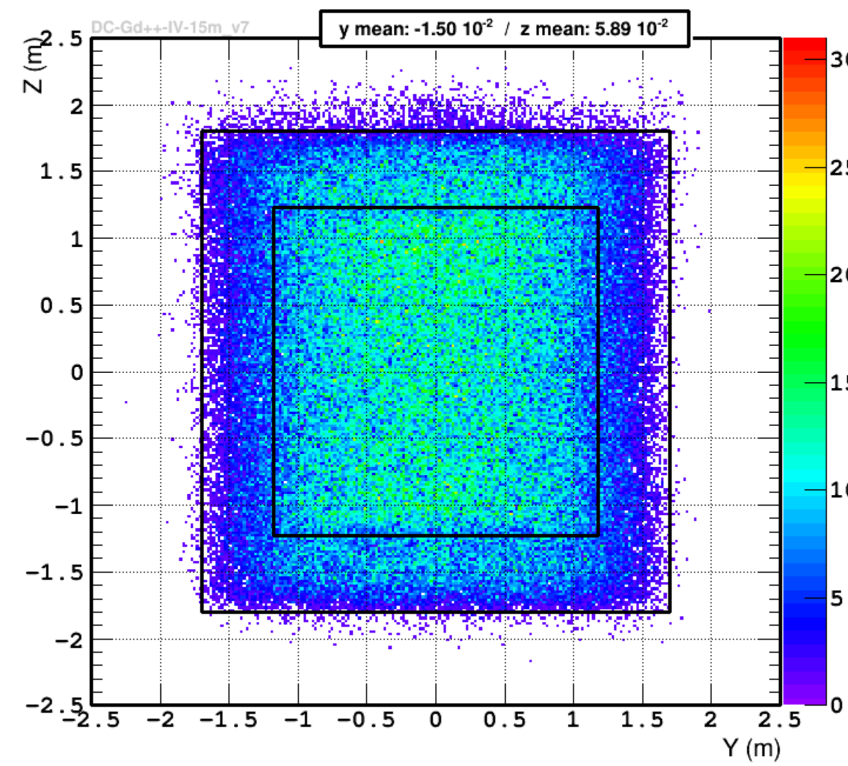


Detection volume: ~8t

ν-Target

New Analysis

IBD[Gd+H]



Detection volume: ~30t

ν-Target + γ-Catcher

- Simultaneous selection of events with neutron capture on Gd and H ⇒ Open delayed energy window
- New IBD[Gd+H]: - Immune to liquide exchange between ν-Target and γ-Catcher (γ-Catcher slightly contaminated with Gd in the Near detector)

  - Increased statistic: $\sim$3x

⇒ ***Drawback:*** *worse proton number estimation*

- **- ν-Target:** $\sigma_{N_p} = 0.3\%$
- **- γ-Catcher:** $\sigma_{N_p} = 0.9\%$

remains our challenge!

Events collected

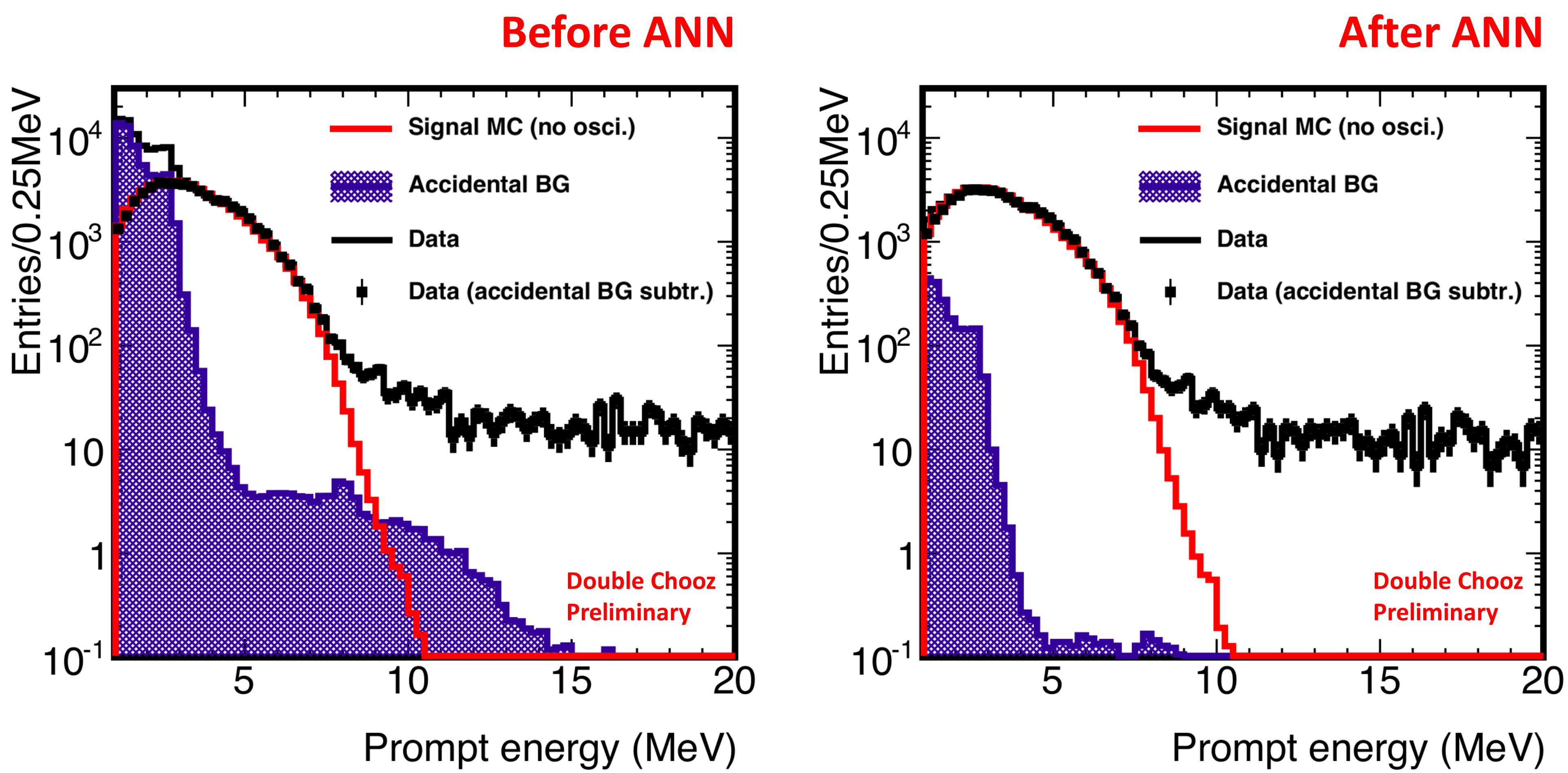
- Near detector: **$\sim$200 k**
- Far detector (since 2011): **$\sim$80 k**

IBD[Gd+H] selection

Accidental Background dominant ⇒ IBD selection through multivariate analysis: **Artificial Neural Network (ANN)**

- Cut on ANN based on the 3 uncorrelated variables: **ΔR, ΔT, delayed energy**
  - ↳ Train on MC with accidental background sample
- **More than factor 10 reduction of accidental background**

Prompt Energy	1 - 20 MeV
Delayed Energy	1.3 - 10 MeV
Δt	0.5 - 800 μs
ΔR	< 1.2 m
Isolation windows (prompt)	[-800, +900] μs
Δt after a muon	> 1250 μs



Prompt signal before and after the ANN (Near detector)

Background rejection

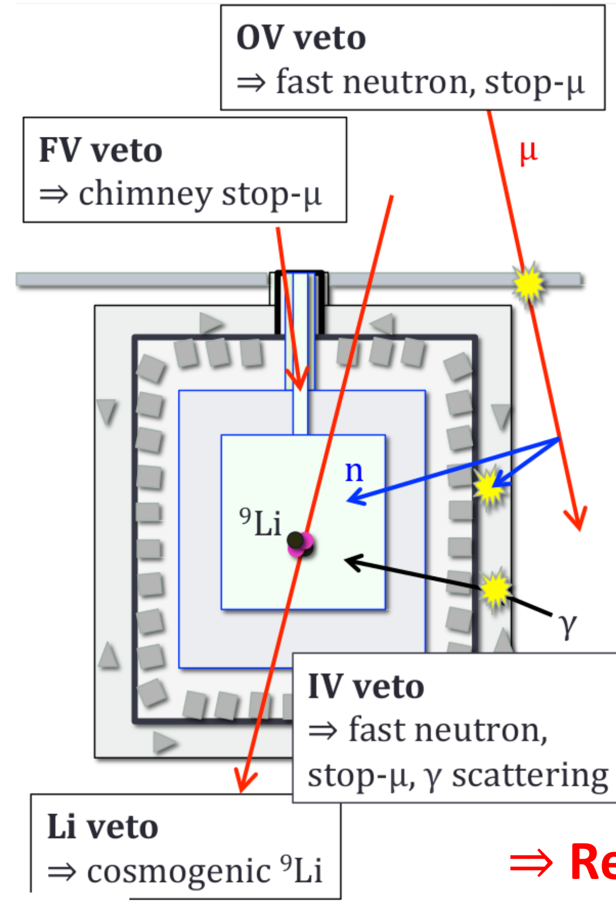
- Backgrounds rejected with multiple vetoes
  - ⇒ negligible stopping-μ contamination after rejection (both detectors)

- Remaining contamination

Acc:
- FD: $3.93 \pm 0.01\ d^{-1}$
- ND: $3.11 \pm 0.04\ d^{-1}$

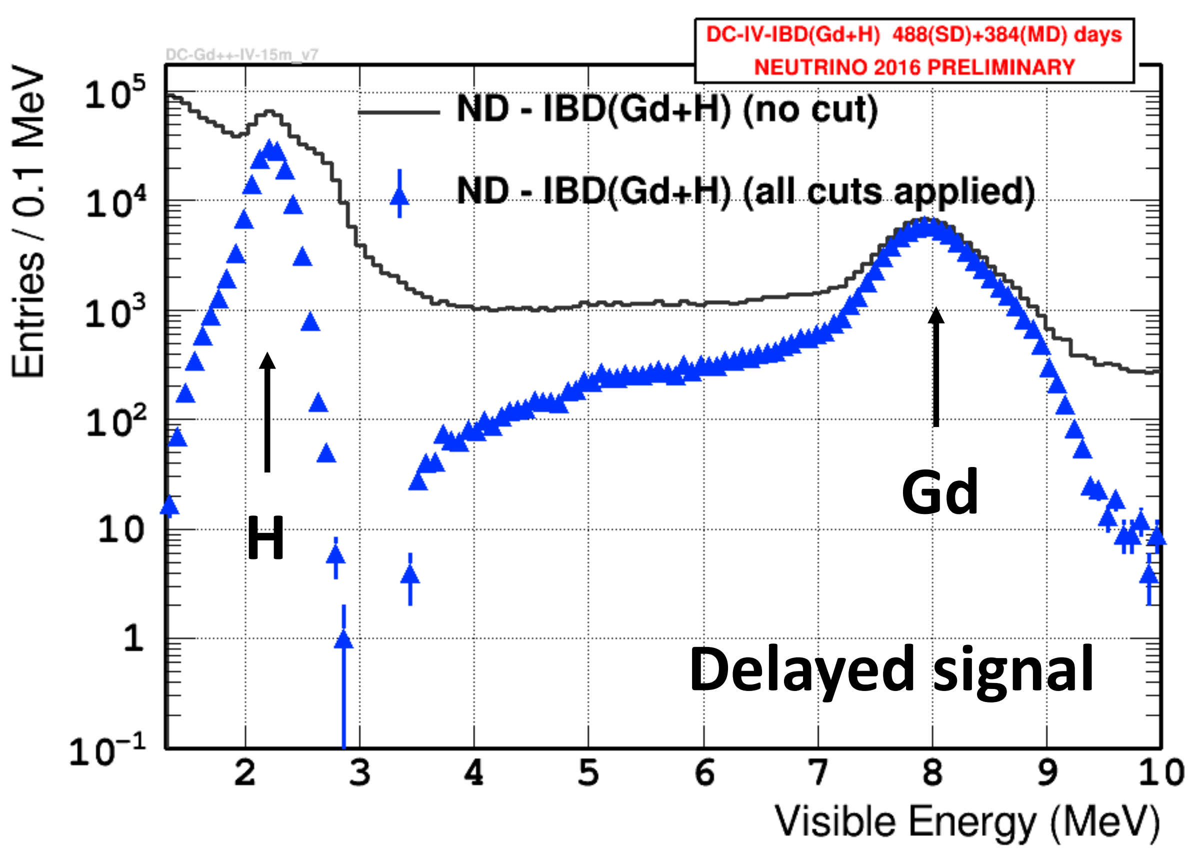
FN:
- FD: $2.54 \pm 0.07\ d^{-1}$
- ND: $20.77 \pm 0.43\ d^{-1}$

Li:
- FD: $2.57 \pm 0.60\ d^{-1}$
- ND: $11.05 \pm 1.95\ d^{-1}$



Cut	Information used	BG removed
μ veto	1.25ms veto after μ	μ, cosmogenic
Multiplicity	e^{+}/n signals isolated	multiple-n
FV veto	vertex reconst. likelihood	chimney stop-μ
IV veto	IV – ID signal coincidence	fast n, stop-μ, γ scattering
OV veto	OV activity	fast n, stop-μ
Li veto	Li-likelihood	^{9}Li, ^{12}B
LN cut	PMT hit pattern & time	light emission from PMT
(CPS veto)	chimney likelihood	stop-μ

⇒ Rejection Power estimation: 158x



		FD	ND
Signal/BG		~11	~22
σ(BG)/Signal	**(data)**	**0.5%**	**0.3%**
	(after fit)	**0.2%**	**0.1%**

⇒ Additionnal constraint after $\sin^2(2\theta_{13})$ fit

IBD candidates versus time

Comparison of unoscillated flux prediction with data

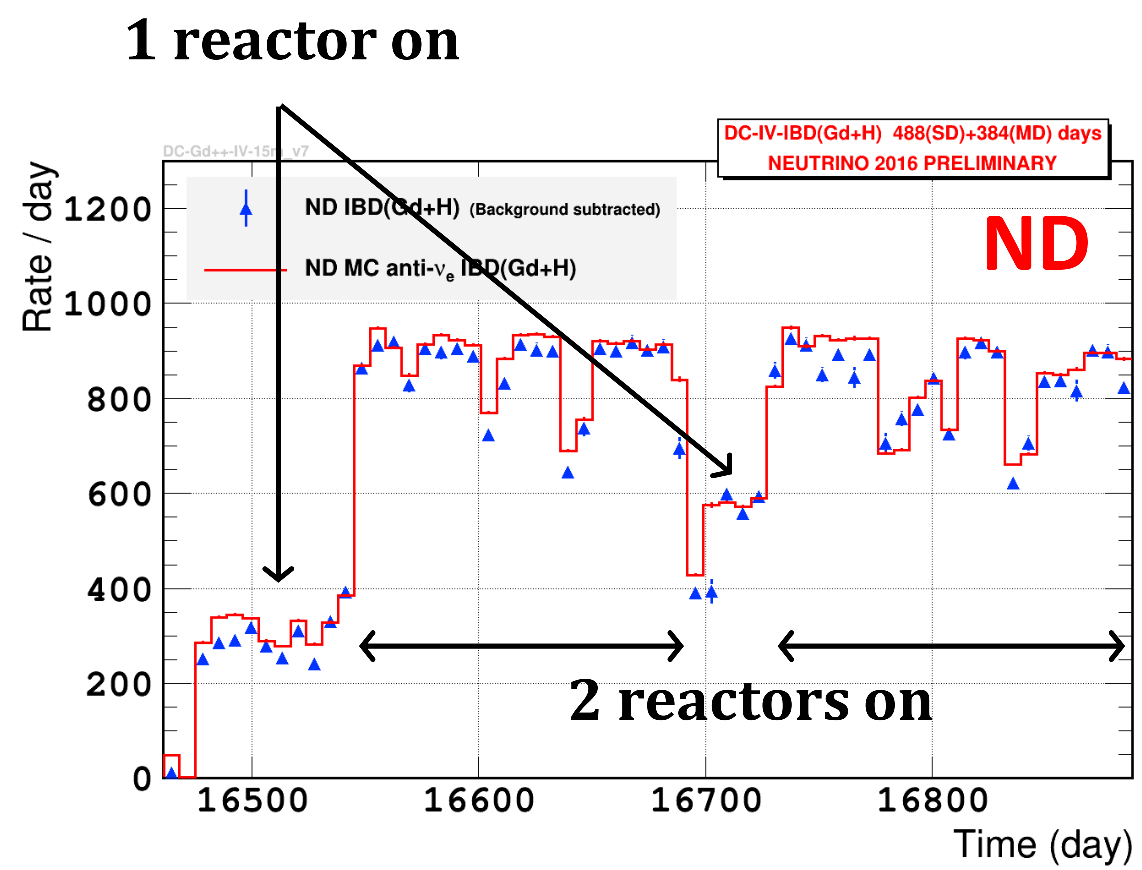
(background substracted)

Near detector IBD[Gd+H]

- $\sim$900 events per day ($\sigma_{stat}\sim$0.2%)

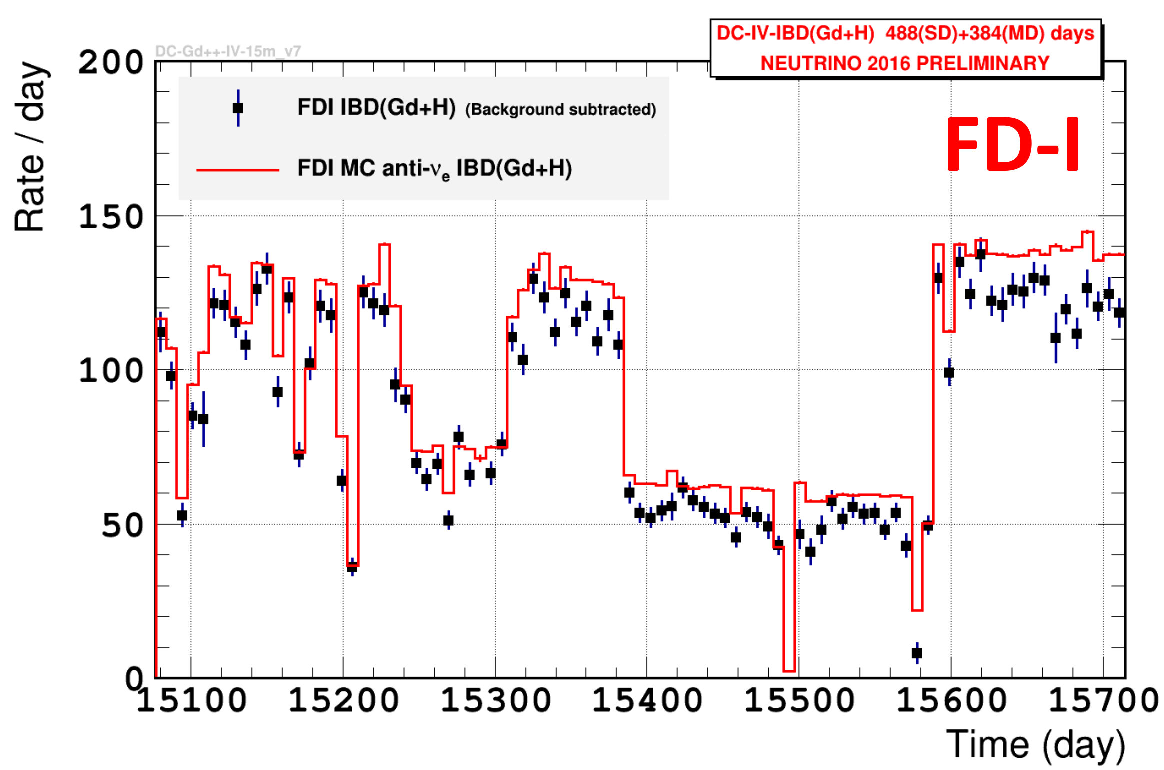
Far detector IBD[Gd+H]

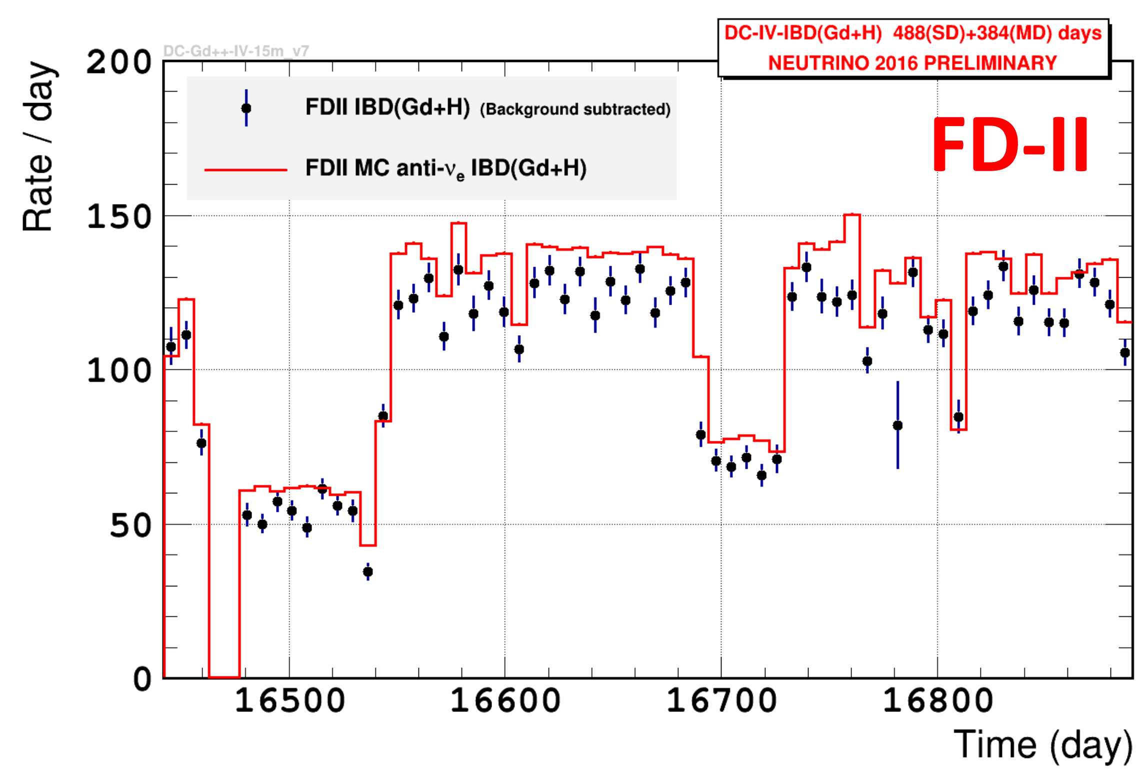
- $\sim$130 events per day ($\sigma_{stat}\sim$0.4%)



⇒ ND is almost a perfect monitor of FD-II

Discrenpancies induced by the time exposure



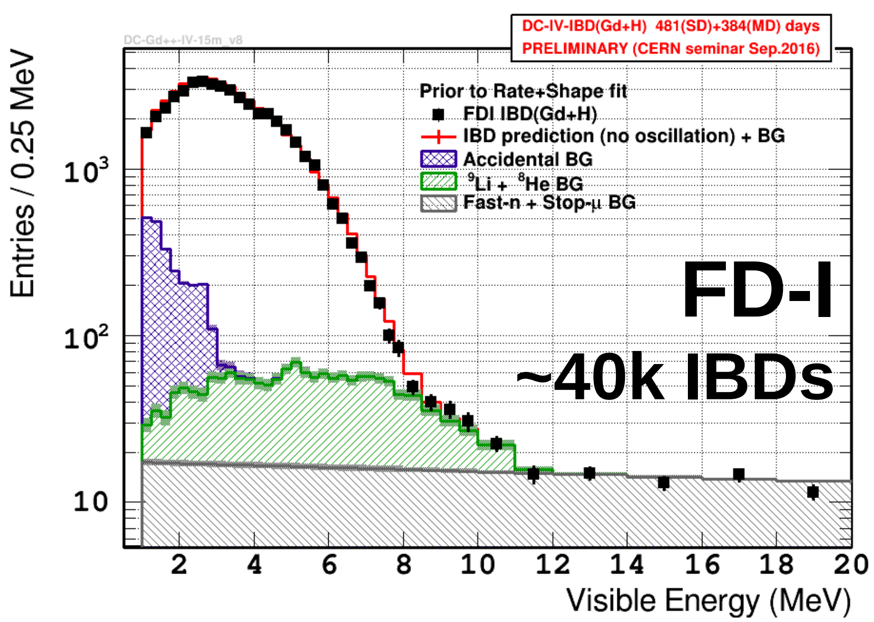


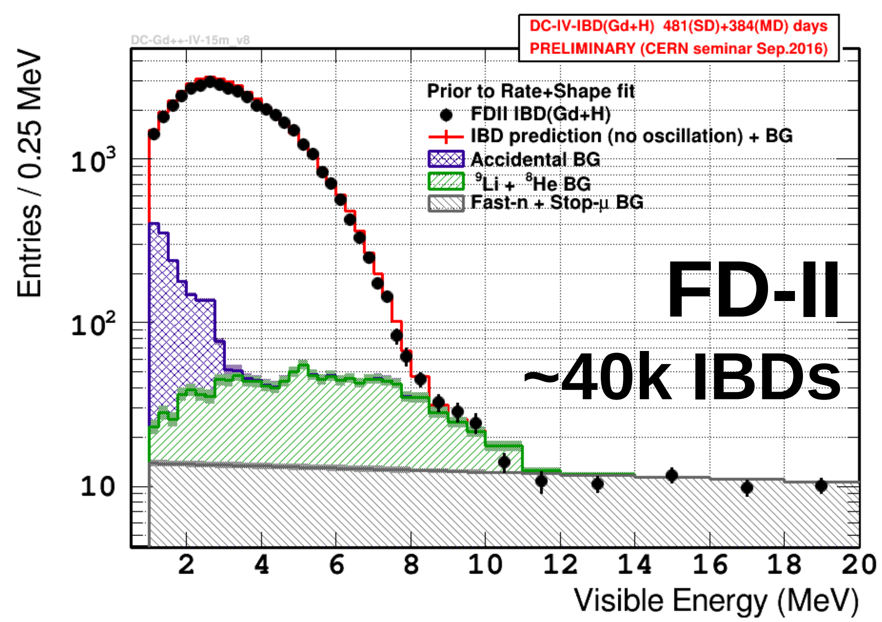
Data-to-MC fit (Rate + Shape):

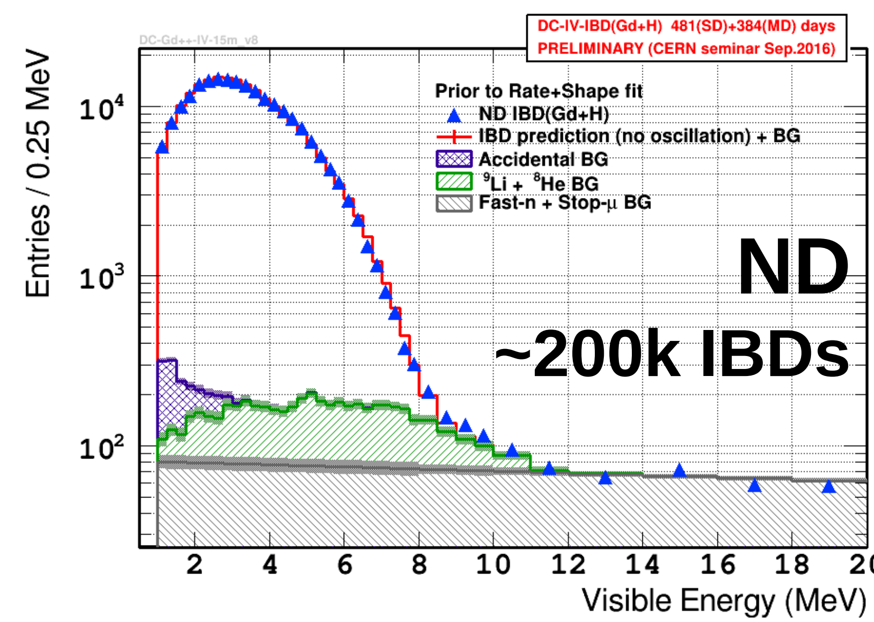
- Simultaneous comparison of FD-I, FD-II and ND data to non-oscillated flux predictions

$$\chi^2(\theta_{13}, R^d_{Li}) = (\overline{Data} - \overline{Pred}) M^{-1}_{cov} (\overline{Data} - \overline{Pred})^T$$
$$+ \text{Penalty Pulls}$$
$$+ \text{Reactor off}$$

- BG rate and shape estimated by the data but in fit:
  - Li rate unconstrained
  - FN rate and shape parameters treated as pulls
- BG constraint from 7.24 days with both reactor off (FD-I)







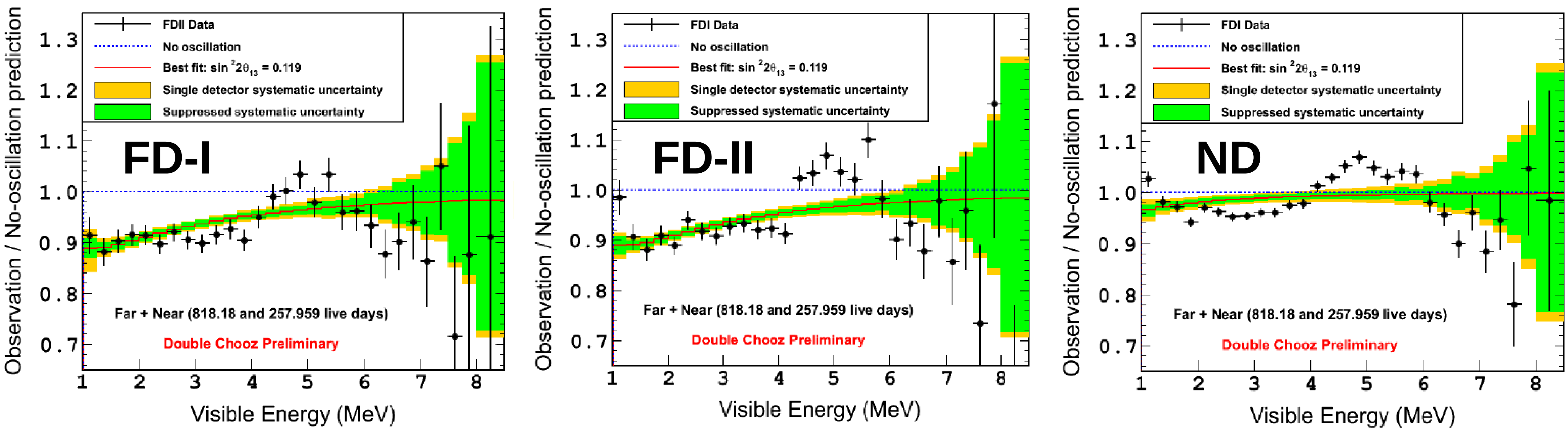
FD-I:FD-II

FD-II:ND

- Correlation of systematic uncertainties (flux predictions, detection, energy response, backgrounds) are taken into account

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

Data-to-MC fit (Rate + Shape):



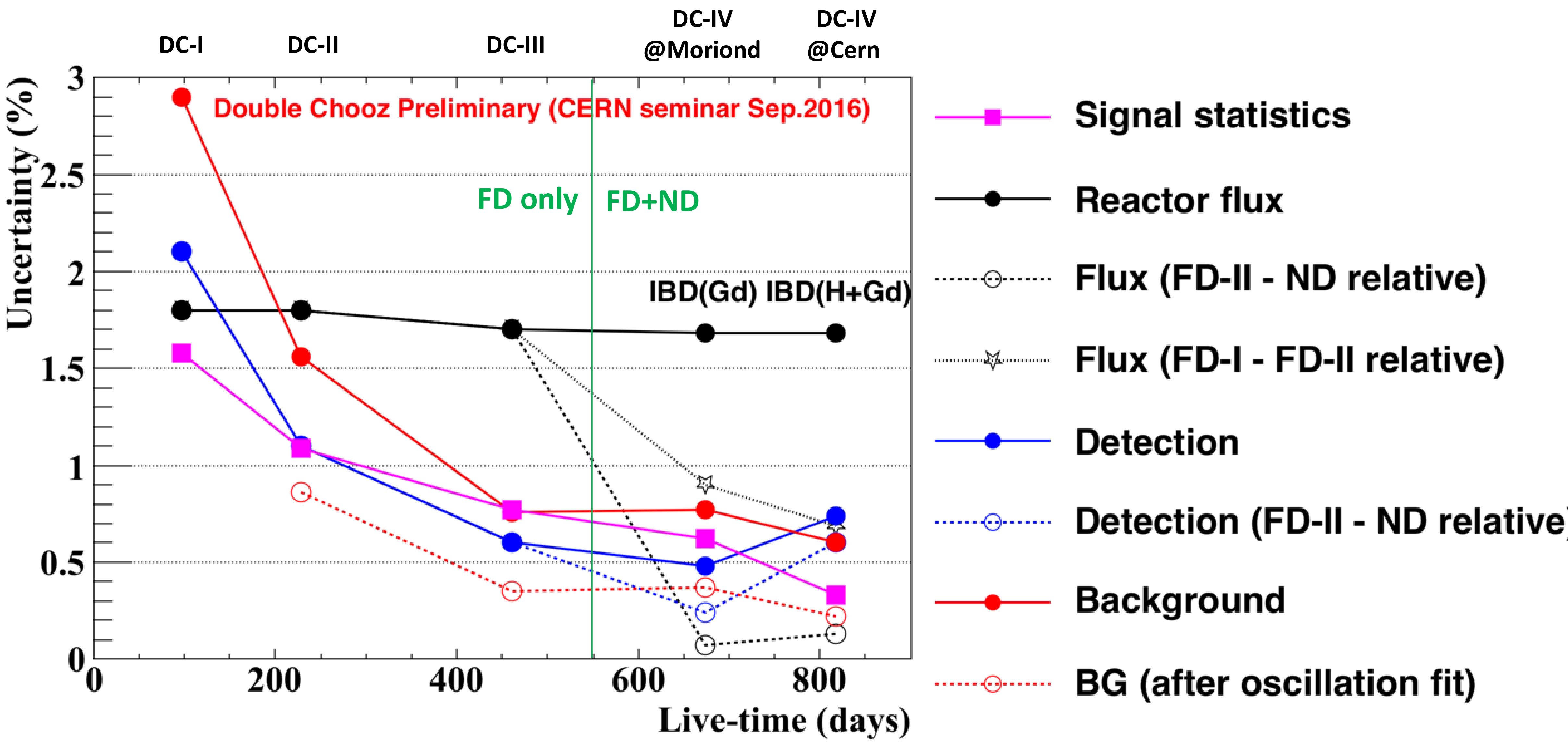
Ratio of the data to the unoscillated flux prediction

$$\sin^2(2\theta_{13}) = 0.119 \pm 0.016 \;\; \text{with} \;\; \chi^2/\text{dof} = 236.2/114$$

(marginalised over Δm^2=(2.44±0.09)eV^2 — Parke et al. arXiv:1601.07464)

- High χ^2/dof induced by the distortion between the MC and the data
- Crosscheck with a data-to-data fit (insensitive to the distorsion): $\sin^2(2\theta_{13}) = 0.123 \pm 0.023$ ($\chi^2/dof = 10.6/38$)

Systematics overview

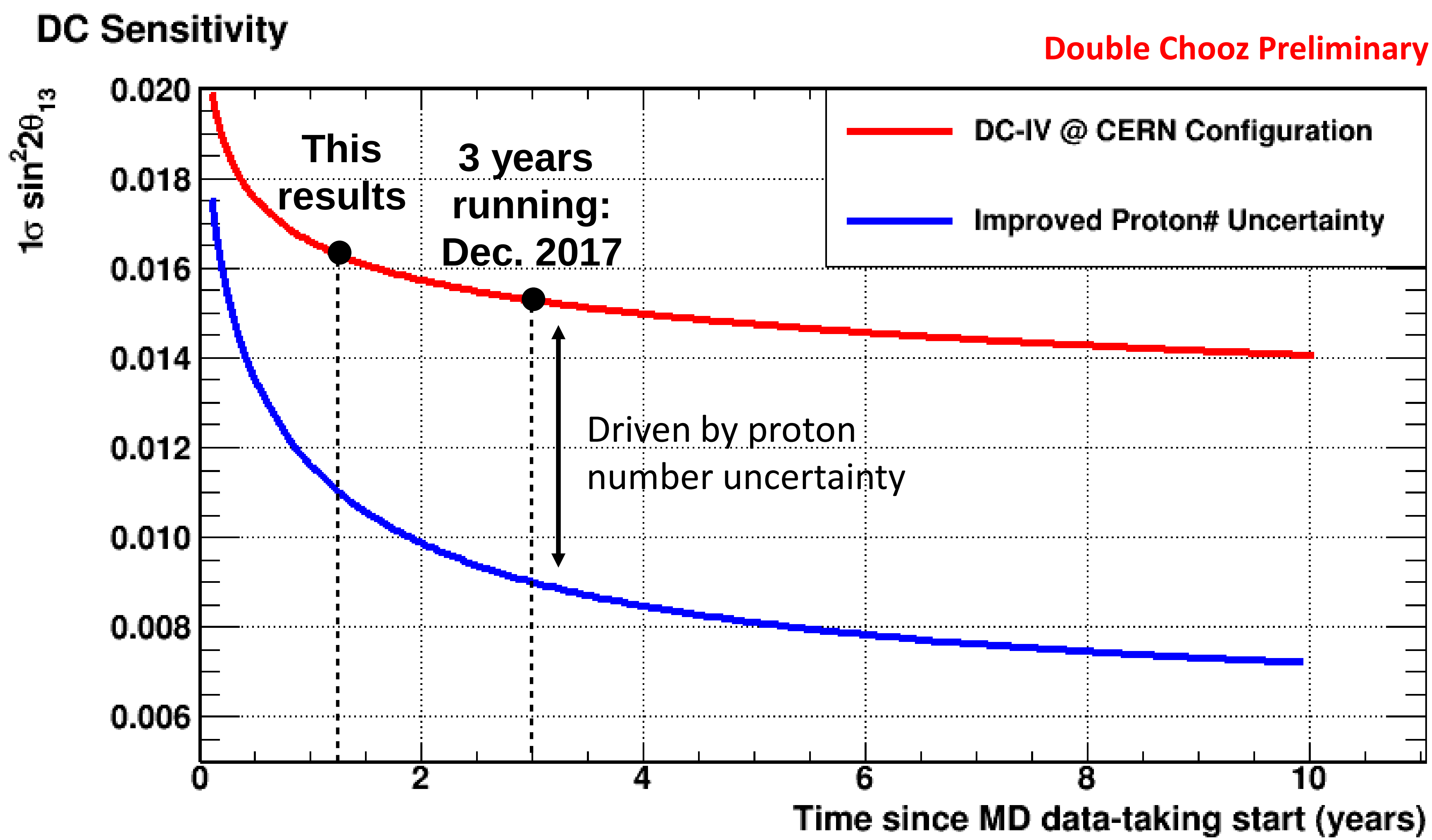


- Detection and background uncertainties suppressed to per-mille level by analysis improvements
- Detection systematic dominated by the proton number uncertainty
- Reactor flux uncertainty dominant in last single detector analysis (1.7%)

↳ Multiple detector: - partial suppression between FDI/FDII **(~62% of uncertainties suppressed)**

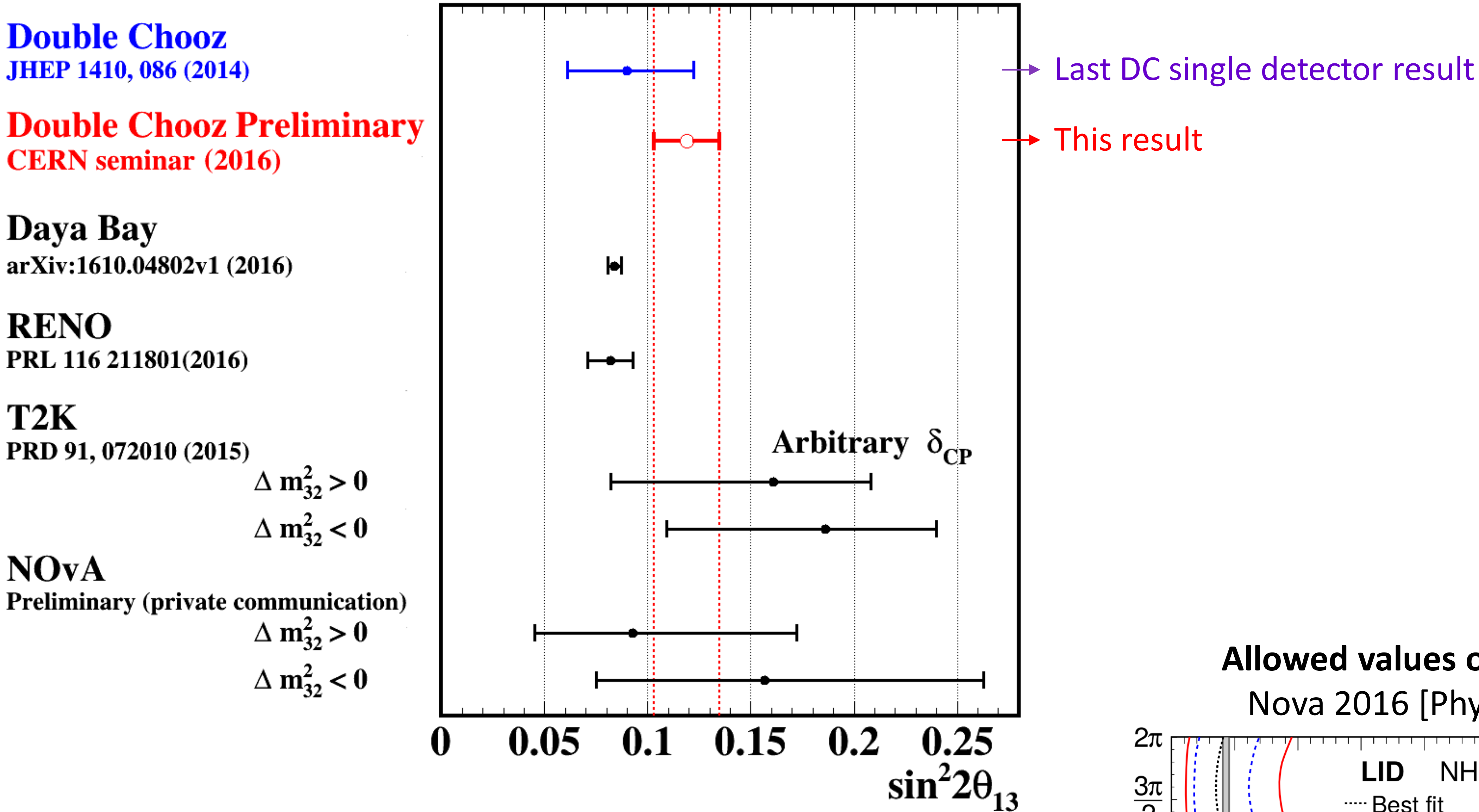
- almost maximal suppression between ND/FDII (isoflux condition): **(~92% of uncertainties suppressed)**

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



- $\sin^2(2\theta_{13})$ uncertainty dominated by the proton number uncertainty
- Blue line: assumption on the proton number uncertainty ($\sigma_{Np} = 0.1\%$)
  - ↳ Potential room for improvement of DC sensitivity with a best proton number estimate (work in progress)

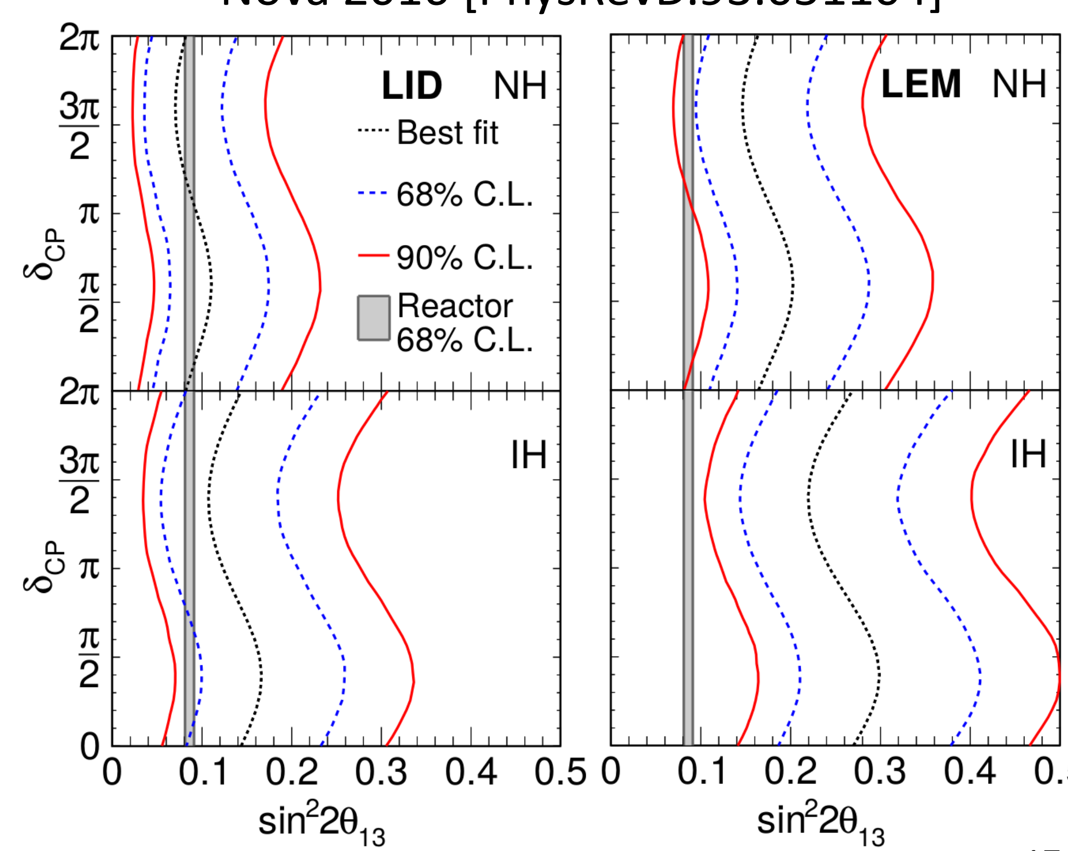
Summary of θ_{13} measurement



- Double Chooz value is 2.2σ above Daya Bay (statistical effect ruled out @6σ)

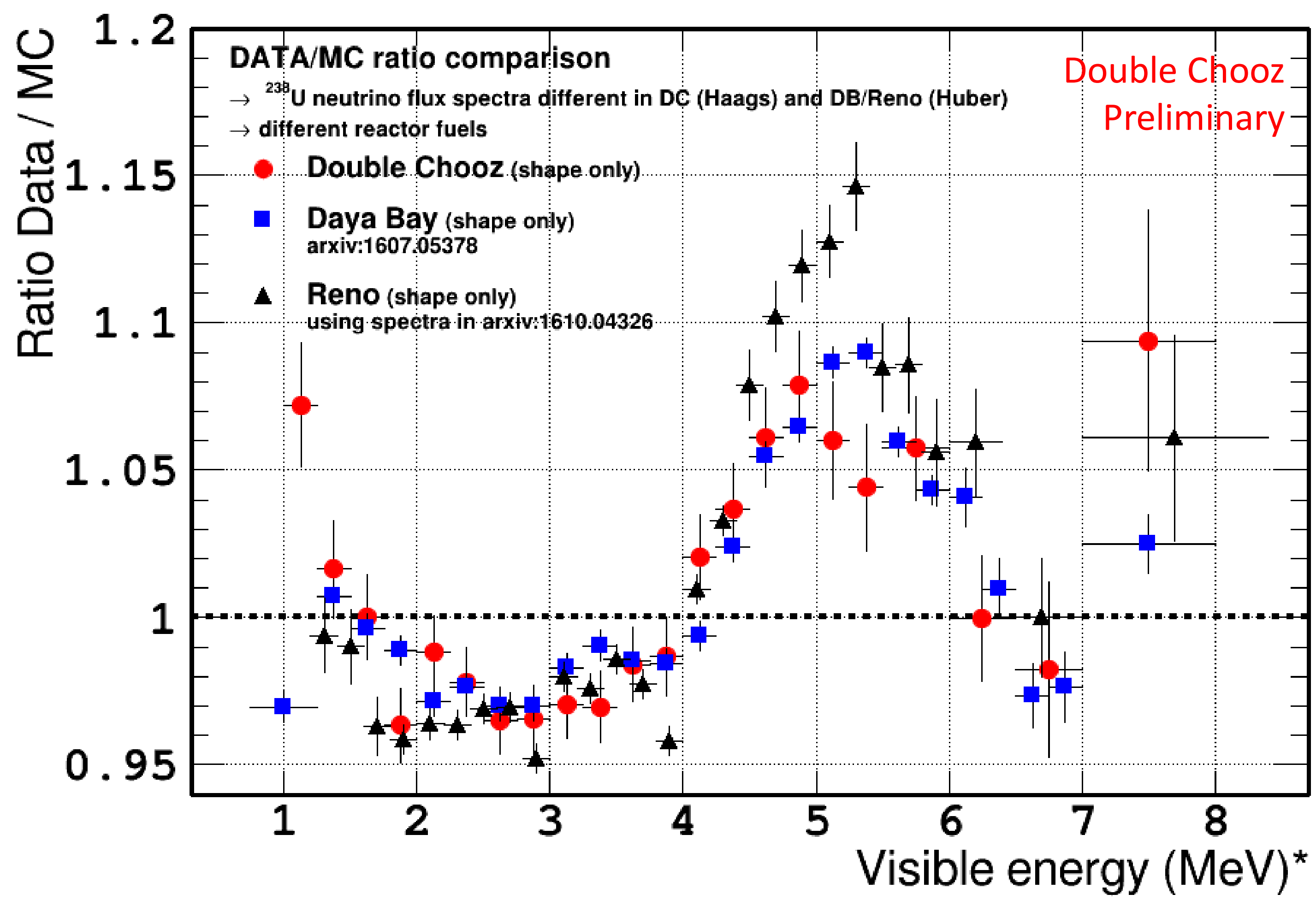
- Precise θ_{13} required for δ_{CP} measurement
  Beam experiments ⇒ degeneracy between δ_{CP} and θ_{13}

Allowed values of δ_{CP} vs $\sin^2(2\theta_{13})$
Nova 2016 [PhysRevD.93.051104]



Reactor flux and shape characterization

The spectral distortion



* can slightly differ from one experiment to another due to detector effects

Reference antineutrino spectra:

- ^{235}U, ^{239,241}Pu: Huber
- ^{238}U: Huber (Day Bay/RENO), Haag (DC)

  (Δmax: ≤ 2% within [1,7] MeV)

⇒ ***Possible explanation in the treatment of the Z of the fission fragments in the conversion of integral β-spectrum?***
A. Hayes talk @v-Phys2016

⇒ **Consistent distortion between all experiments**: dominated by flux inaccuracies modelling

↳Lack of knowledge on the reactor flux prediction: experimental data more precise than the prediction

- Better understanding and characterization of the distortion can be achieved with:
  - ↳ Very short baseline experiments at research reactors (^{235}U spectrum measurement)
  - ↳ Study of the distortion with time (i.e. fuel inventory) with commercial reactors

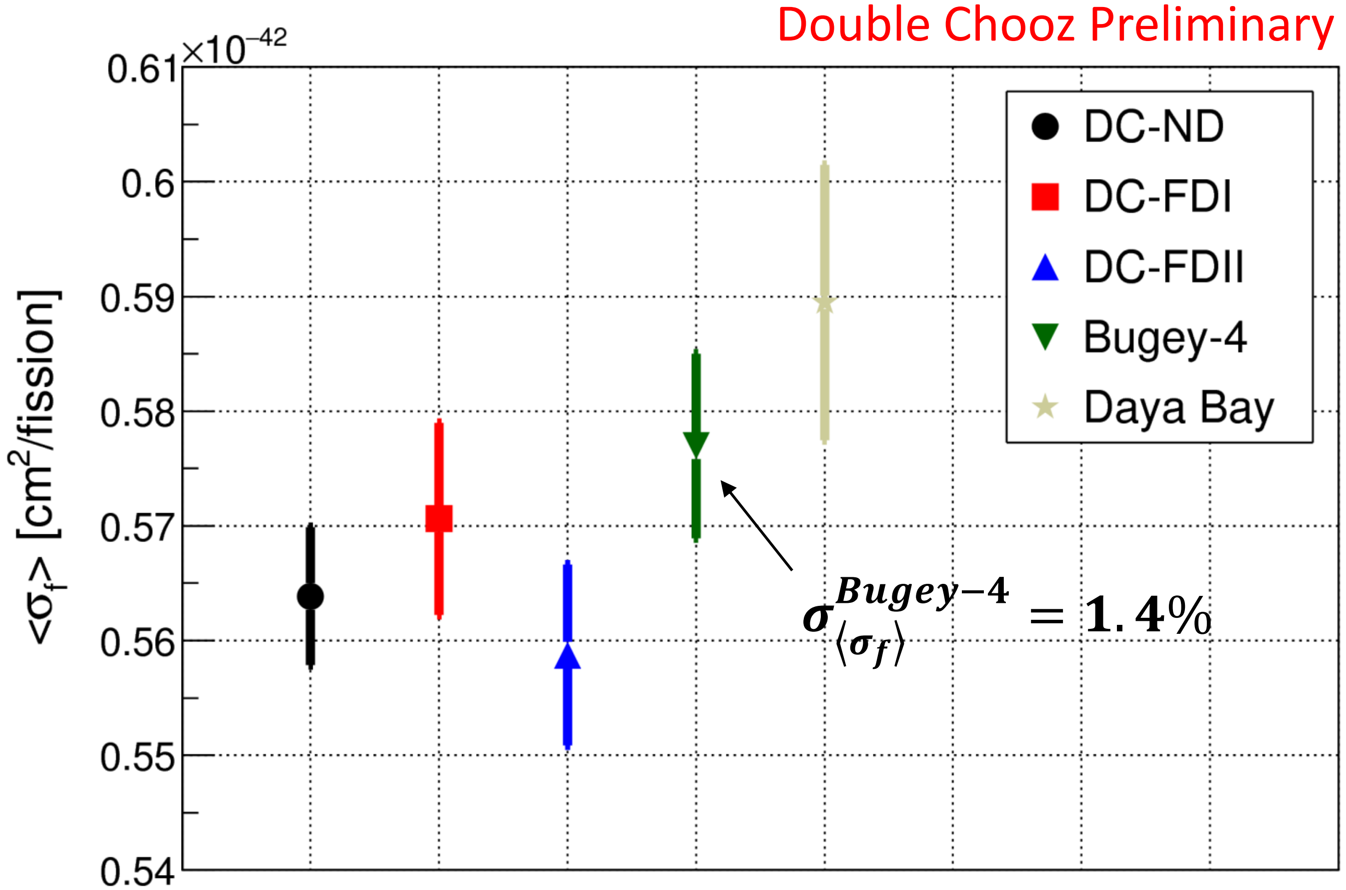
Reactor flux and shape characterization

Reactor IBD mean cross-section per fission

$$\langle \sigma_f \rangle = \frac{n_\nu}{N_p \times \epsilon} \times \frac{1}{\sum_{p=B1,B2} \frac{\langle P_{th} \rangle_p}{\langle E_f \rangle_p \times 4\pi R_p^2}}$$

n_ν: IBD rate corrected for θ_{13} oscillation
ϵ: detector efficiency
R: reactor-detector distance
$\langle P_{th} \rangle$: mean reactor thermal power
$\langle E_f \rangle$: mean energy released per fission

Double Chooz Preliminary



Daya Bay: Chinese Physics C, 2017, 41(1): 13002-013002

- DYB & B4 converted to DC fuel inventory (direct comparison)
- Higher uncertainties for FD-I and FD-II induced by the statistic and the θ_{13} correction
- Precision limit from reactor thermal power uncertainty: $\sigma_{P_{th}}$ ~0.5%

Near detector: $\langle \sigma_f \rangle^{DC} = (5.64 \pm 0.06) \times 10^{-43}$ $\mathbf{cm^2/fission}$

⇒ **World most precise reactor normalization - Relative error: 1.1%**

Conclusion

- **Double taking data with both detectors since beginning of 2015**
- **New analysis: IBD[Gd+H]**

  ↳ Immune to γ-Catcher contamination with Gd in the Near detector / Improved statistic: $\sim$3x

  ↳ New measurement of $\sin^2(2\theta_{13})$ based on a rate+shape fit

$$\mathbf{\sin^2(2\theta_{13}) = 0.119 \pm 0.016 \;\; (\chi^2/ndf = \;\; 236.2/114)}$$

  ⇒ Strong reduction of flux systematic and statistic

  ⇒ Uncertainty dominated by proton number uncertainty / work in progress for an improvement

- **Precise characterization of the reactor IBD rate and shape**
- **Other Double Chooz analysis**
  - Cosmic-muon characterization (JCAP02 (2017) 017)
  - Muon capture (PRC 93 (2016) 054608)
  - Ortho-positronium (JHEP 10 (2014) 032)
  - Background studies (PRD 87 (2013) 11102(R))
  - Lorentz violation (PRD 86 (2012) 112009)
  - Neutrino directionality
  - Sterile neutrino

Thank you for your attention!

The 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.
Kitasato 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.
UCDavis
Drexel U.
IIT
KSU
LLNL
MIT
U. Notre Dame
U. Tennessee

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www.doublechooz.org

~150 physicists (35 institutions)

Backup

$\sin^2(2\theta_{13})$ fit - crosscheck

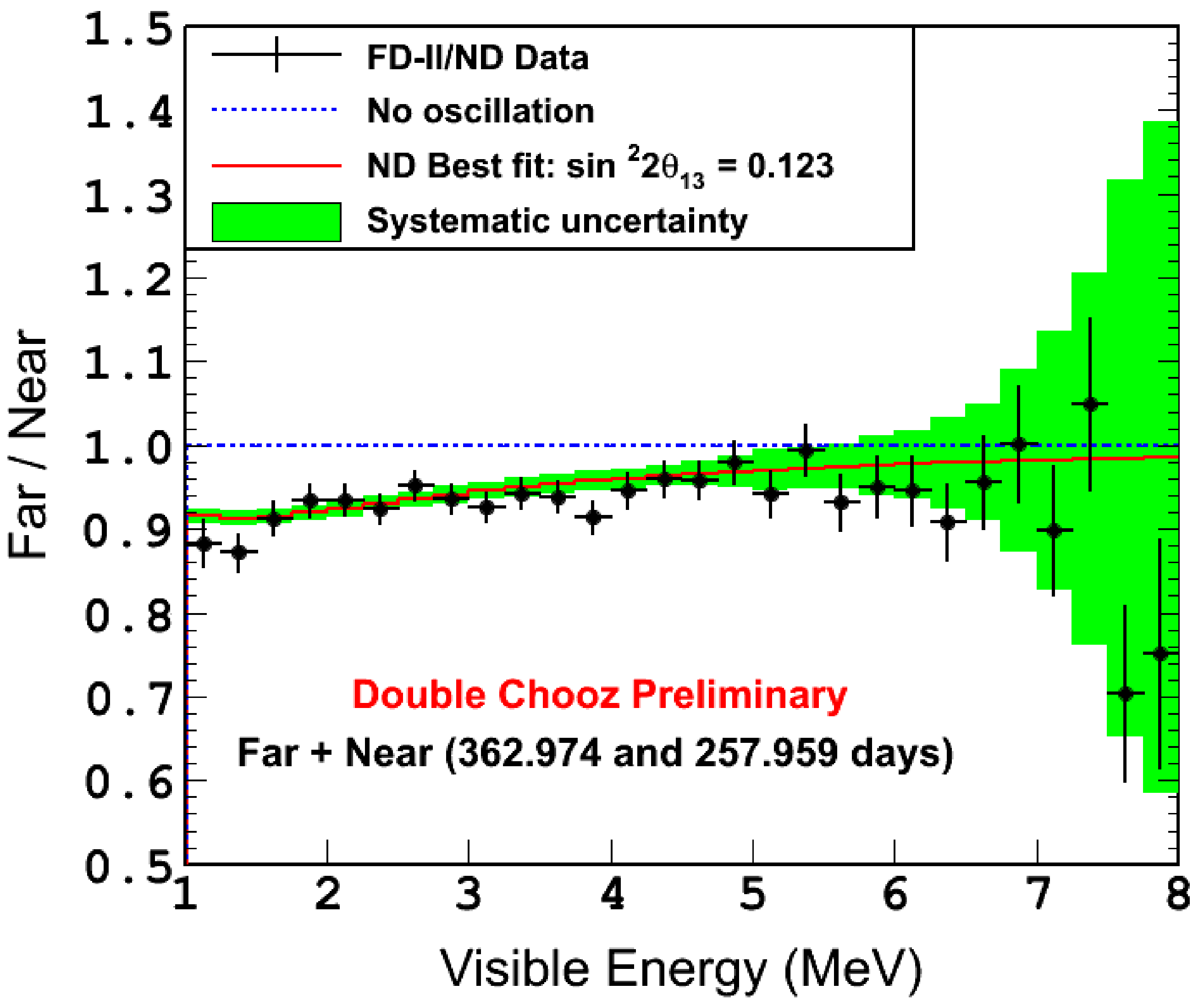
Data-to-Data fit (Rate + Shape):

- FD-II directly compared to ND data (FDI excluded)

$$\chi^2 = \sum_{ij} (N_i^{FD} - \omega_i N_i^{ND}) M_{ij}^{-1} (N_j^{FD} - \omega_j N_j^{ND})^T$$

+ Penalty Pulls

ω_i scaling factor
- proton number
- vetoes
- baseline
- live time
- expected flux (baseline, survival probability, reactors power)



$$\sin^2(2\theta_{13}) = 0.123 \pm 0.023 \text{ with } \chi^2/\text{ndf} = 10.6/38$$

$\Rightarrow$ **Good agreement of Data-to-MC fit and Data-to-Data fit**