Double Chooz:
Latest results in the multiple detector configuration

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on behalf of the Double Chooz Collaboration

IPHC seminar
February 17, 2017

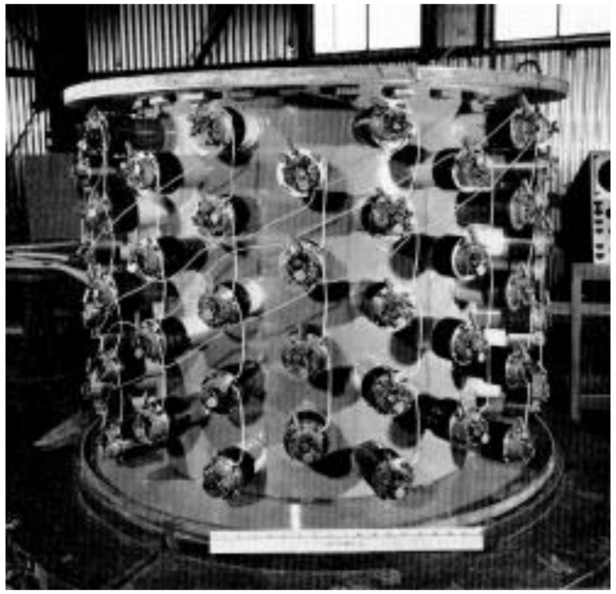
Summary

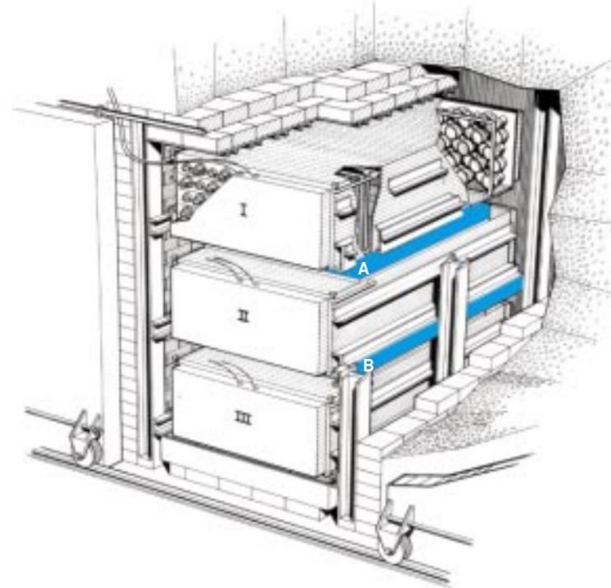
1. Introduction: neutrino oscillation and reactor antineutrinos
2. Double Chooz experimental setup
3. Reactor flux prediction
4. The detectors response
5. IBD selection and background
6. $\sin^2(2\theta_{13})$ fit
7. Reactor flux characterization
8. Conclusion

Introduction
Neutrino oscillation & reactor antineutrinos

Neutrino history

1956: Reactor antineutrinos measurement by
Cowan & Reines @Savannah River





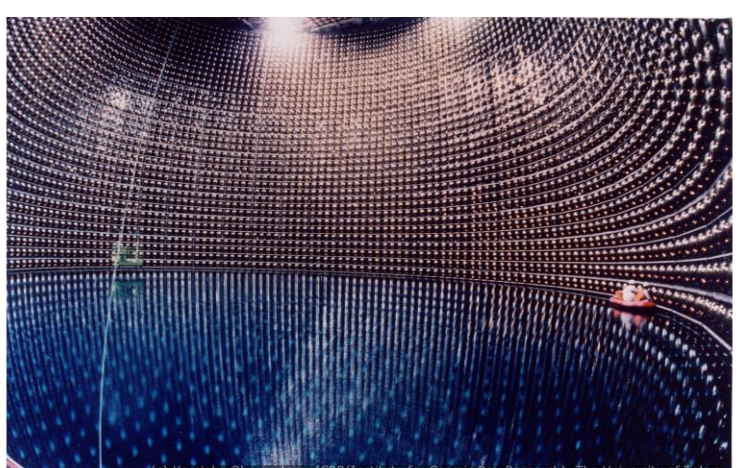
Flavors oscillation in all sectors:

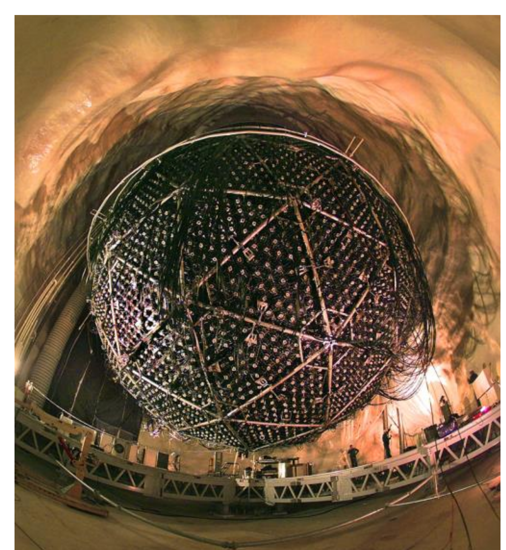
- *Atmospheric neutrinos*
- *Solar neutrinos*
- *Reactor neutrinos*
- *Accelerator neutrinos*

Neutrinos are massive ⇒ *masseless in the Standard Model !*

Neutrino oscillation:

- Homestake, Kamland, Super Kamiokande, SNO, ….





Open questions

- *Sterile neutrinos*
- *Neutrino nature: Dirac, Majorana ?*
- δ_{Cp}
- *Mass hierarchy*
- *Absolute neutrino mass*
- *…*

3 neutrino flavors, ν_e, ν_μ, ν_τ, associated to the 3 charged leptons (e^-, μ^- and τ^-)

The PMNS matrix

Flavor states

Mass eingenstates

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & C_{23} & S_{23}\\ 0 & -S_{23} & C_{23}\end{pmatrix}}_{\substack{\text{atmospheric}\\ \nu_\mu \to \nu_\mu}} \underbrace{\begin{pmatrix}C_{13} & 0 & S_{13}\, e^{-i\delta}\\ 0 & 1 & 0\\ -S_{13}\, e^{i\delta} & 0 & C_{13}\end{pmatrix}}_{\substack{\text{reactor / accelerator}\\ \nu_e \to \nu_e \quad \nu_\mu \to \nu_e}} \underbrace{\begin{pmatrix}C_{12} & S_{12} & 0\\ -S_{12} & C_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\substack{\text{solar}\\ \nu_e \to \nu_x}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

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

- **Oscillation parameters:** - 3 mixing angles: $\theta_{23}, \theta_{12}, \theta_{13}$
  - 2 squared masses differences: $\Delta m_{13}^2, \Delta m_{12}^2$
  - 1 CP phase: δ_{CP}

- Up to 2011: Limit on θ_{13} from 1st Chooz experiment: $sin^2(2\theta_{13}) < 0.14$ (90% CL)

- New generation of reactor experiments designed to search for a non vanishing angle θ_{13} with unprecedented sensitivity (multi-detector concept)

  ↳ **Daya Bay / Double Chooz / RENO**

Reactor antineutrino

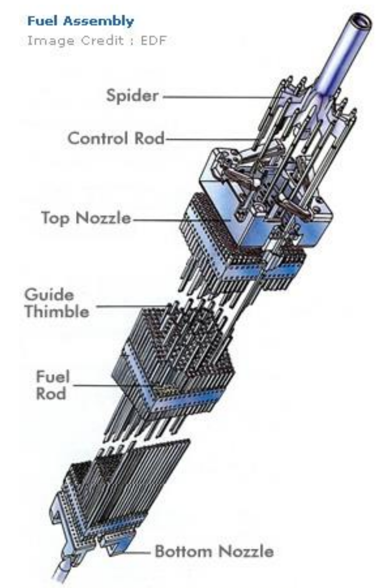
Commercial nuclear reactor

- Pressurized Water Reactor – PWR
- Fresh fuel : UO_2 (^{238}U + few percent of ^{235}U)

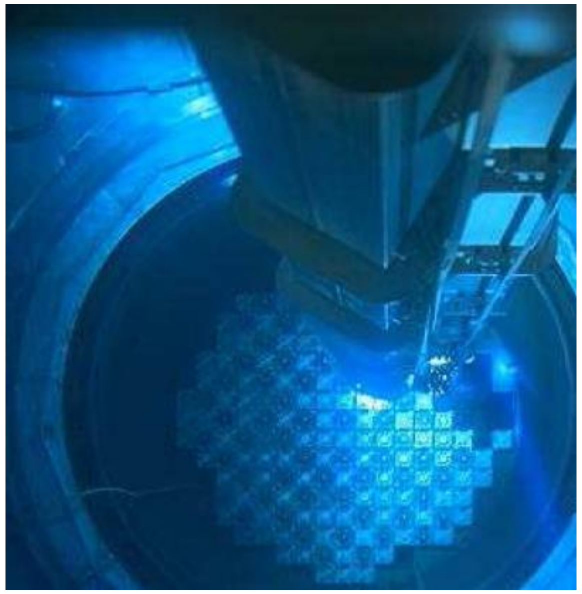
  ↳ Other fissile nuclei appears with fuel depletion (neutron capture on ^{238}U)

Thermal power mainly induced by fission of 4 nuclei:

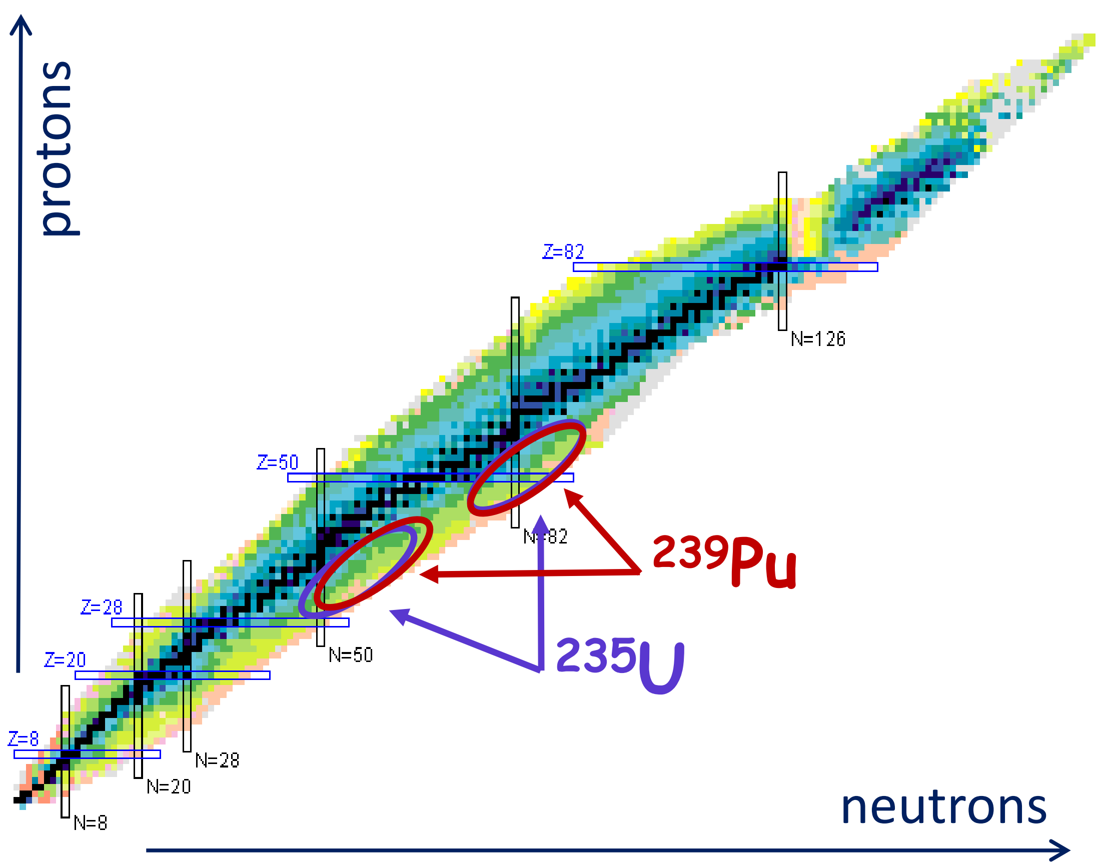
^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu



Assembly rods



N4-PWR reactor core



The fission products (FP) are neutron-rich nuclei

↳ undergoing successive β⁻ decays to reach stability:

$$\beta^- \ decay: \ {}^{A}_{Z}X \rightarrow {}_{Z+1}^{A}Y + e^- + \boxed{\bar{\nu}_e}$$

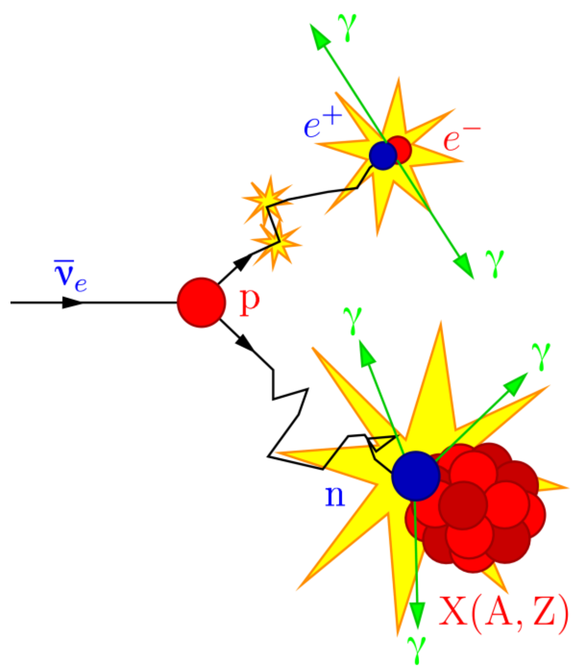
	^{235}U	^{239}Pu	^{238}U	^{241}Pu
$\langle E_\nu \rangle_k$ (MeV)	1.46	1.32	1.56	1.44
$\langle N_\nu \rangle_k$ *(E>1.8MeV)*	5.58 (1.92)	5.09 (1.45)	6.69 (2.38)	5.89 (1.83)

$\langle N_\nu \rangle_k$: *Average number of $\bar{\nu}_e$ resulting of one fission of the isotope k*

Advantages of reactor experiments

- cheap source / no matter effect
- Intense flux: $\sim 1.10^{20}\ \bar{\nu}_e$/s for a 900 MWth reactor ($\sim$2700 MWe)

$\bar{\nu}_e$ detection

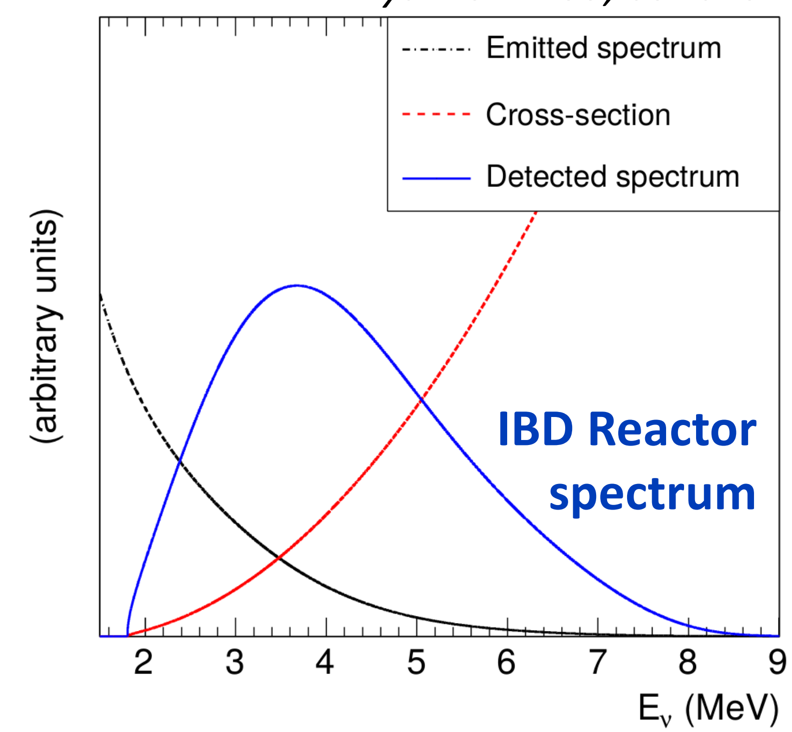


Inverse beta decay reaction (IBD) in liquid scintillator doped with gadolinium:

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

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

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

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

θ_{13} measurement with reactor experiment

-

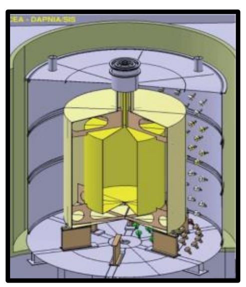
Double Chooz experimental setup

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

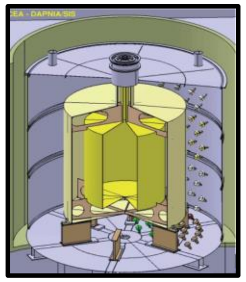
Non oscillation probability:

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

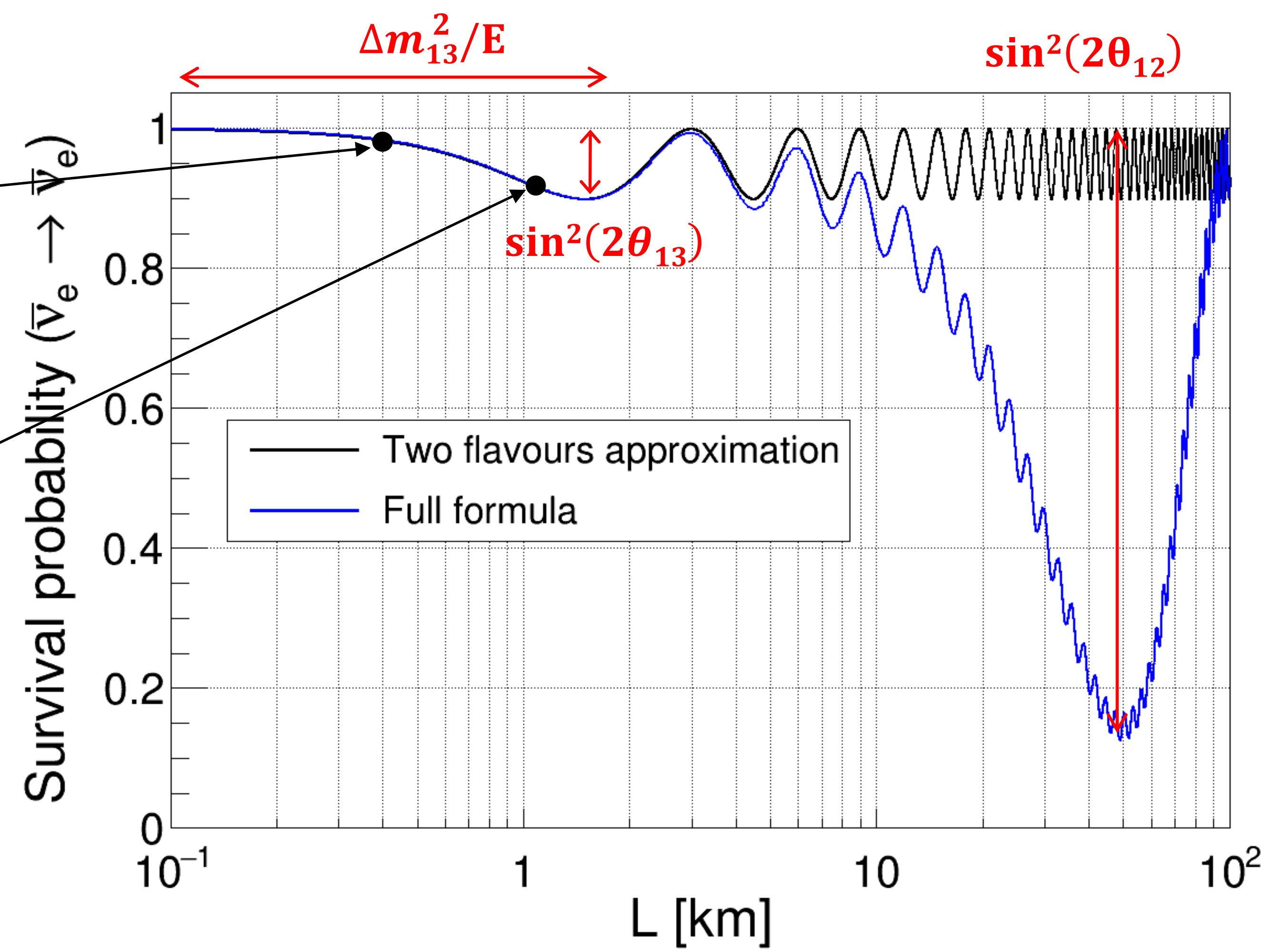
(two flavours approximation)



Near detector (ND)

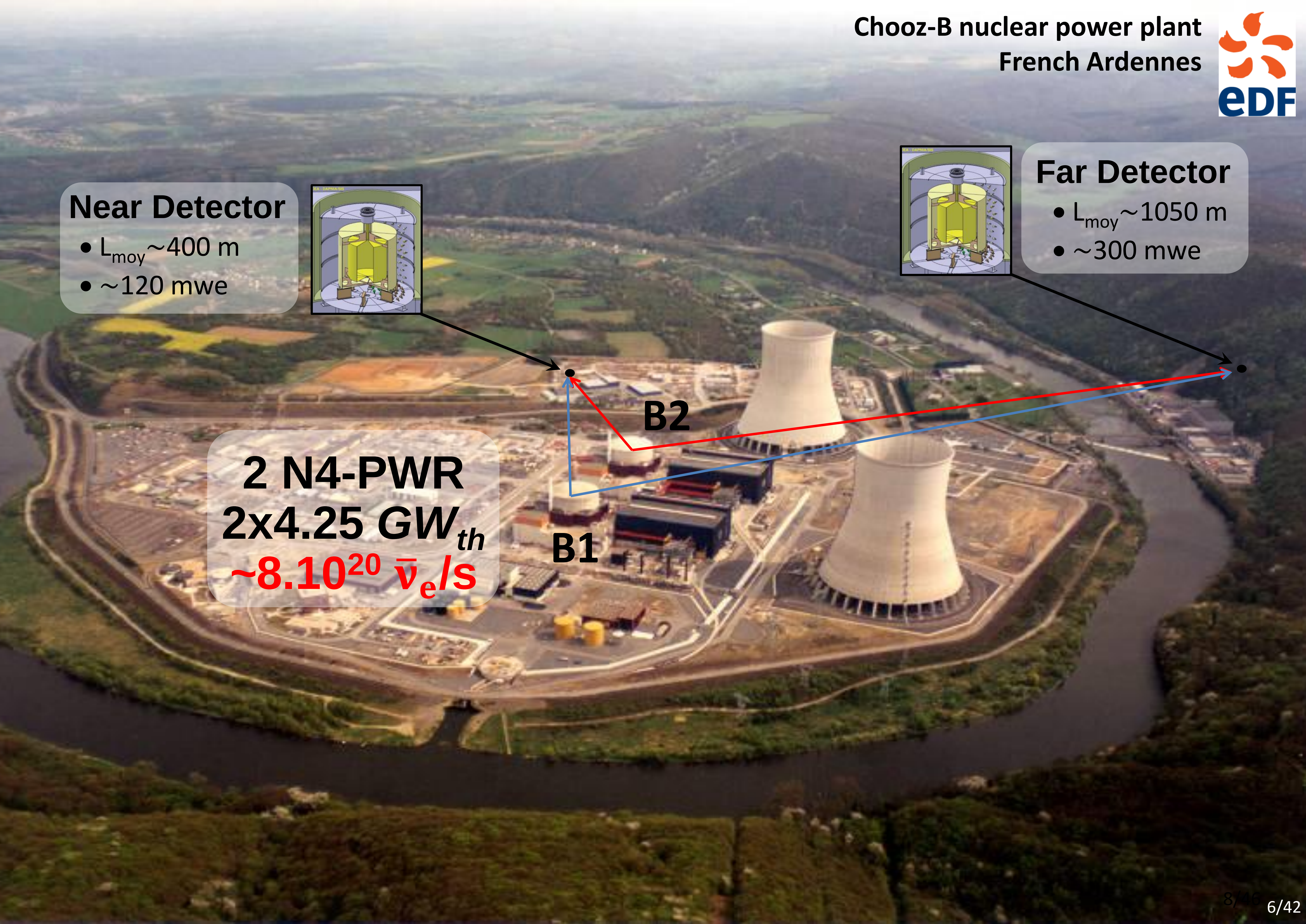


Far detector (FD)



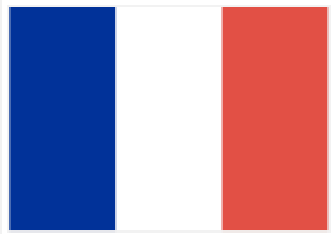
➡ **Systematics uncertainties highly suppressed in multiple detectors configuration at different baselines with identical detectors**

Experimental setup of Double Chooz



The Double Chooz collaboration

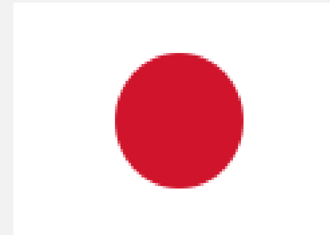
Brazil
CBPF
UNICAMP
UFABC



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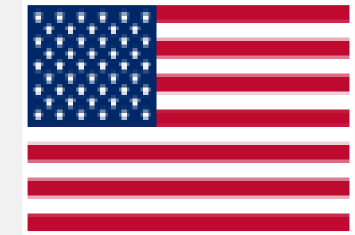
Tokyo Inst. Tech.
Tokyo Metro. U.
Kitasato U.
Kobe U.
Tohoku Gakuin U.
Hiroshima Inst.Tech.

Russia
INR RAS
IPC RAS
RRC Kurchatov

Spain
CIEMAT-Madrid



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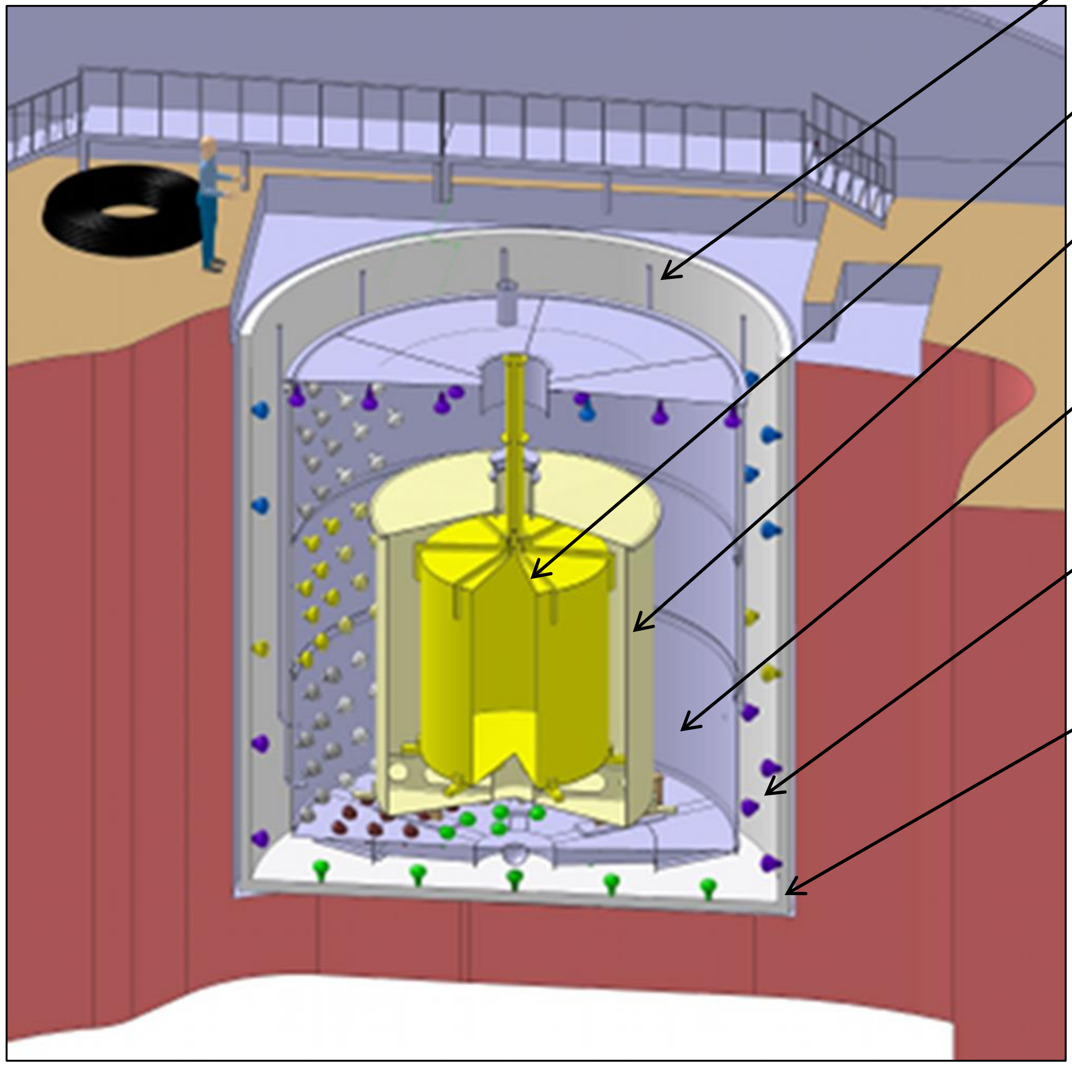
Spokesperson
H. De Kerret

Projet Manager
Ch. Veyssière

Web Site:
www.doublechooz.org

~150 physicists (35 institutions)

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)

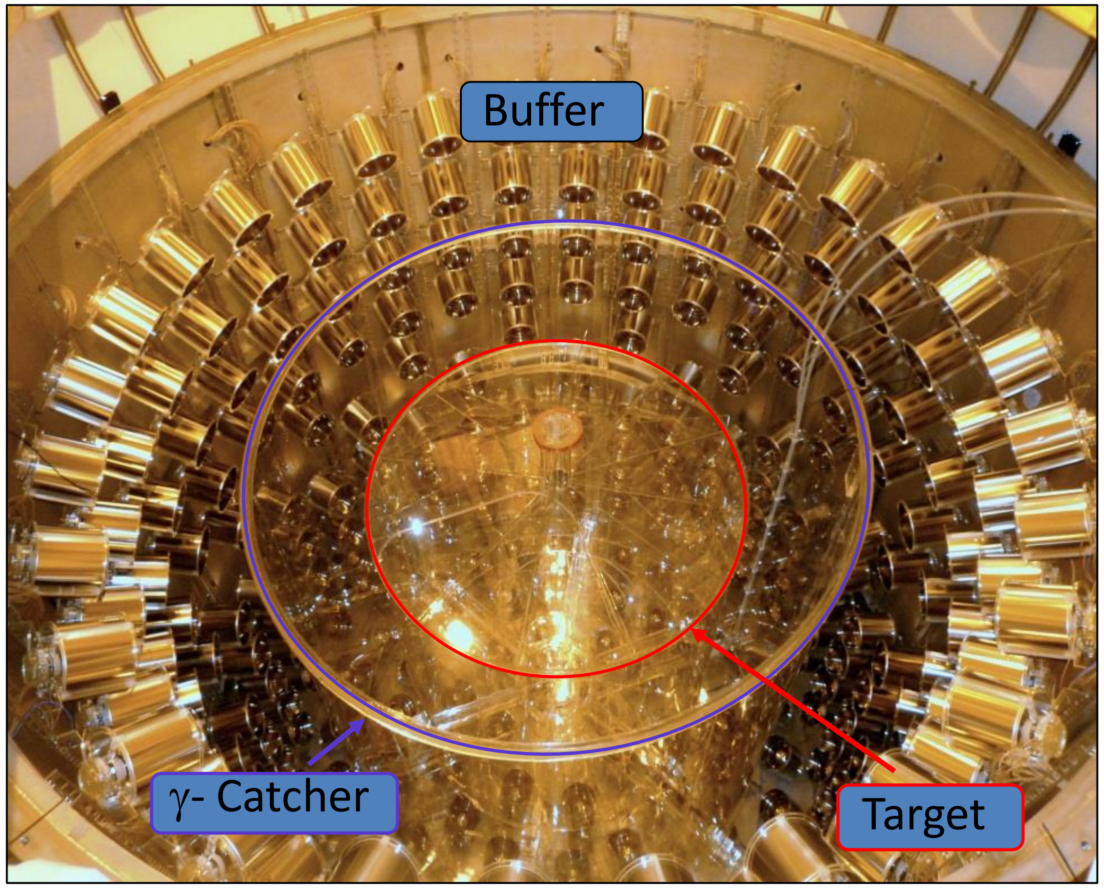
Inner detector

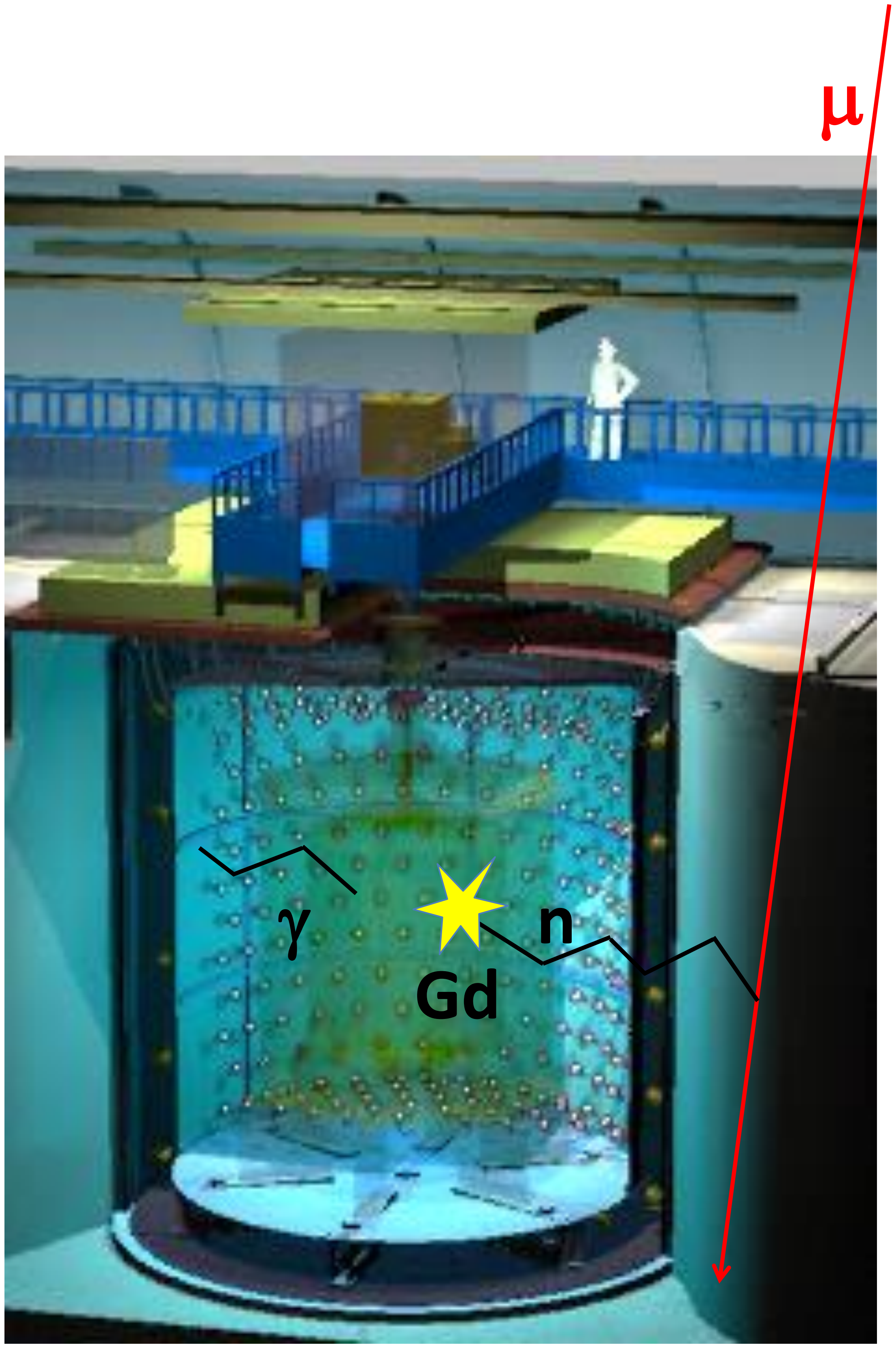
Inner Veto: - liquid scintillator (90m^3)
- 78 PMTs (8 inches)

Shielding: ~250t steel shielding

Experimental concept to **use two identical detectors**

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





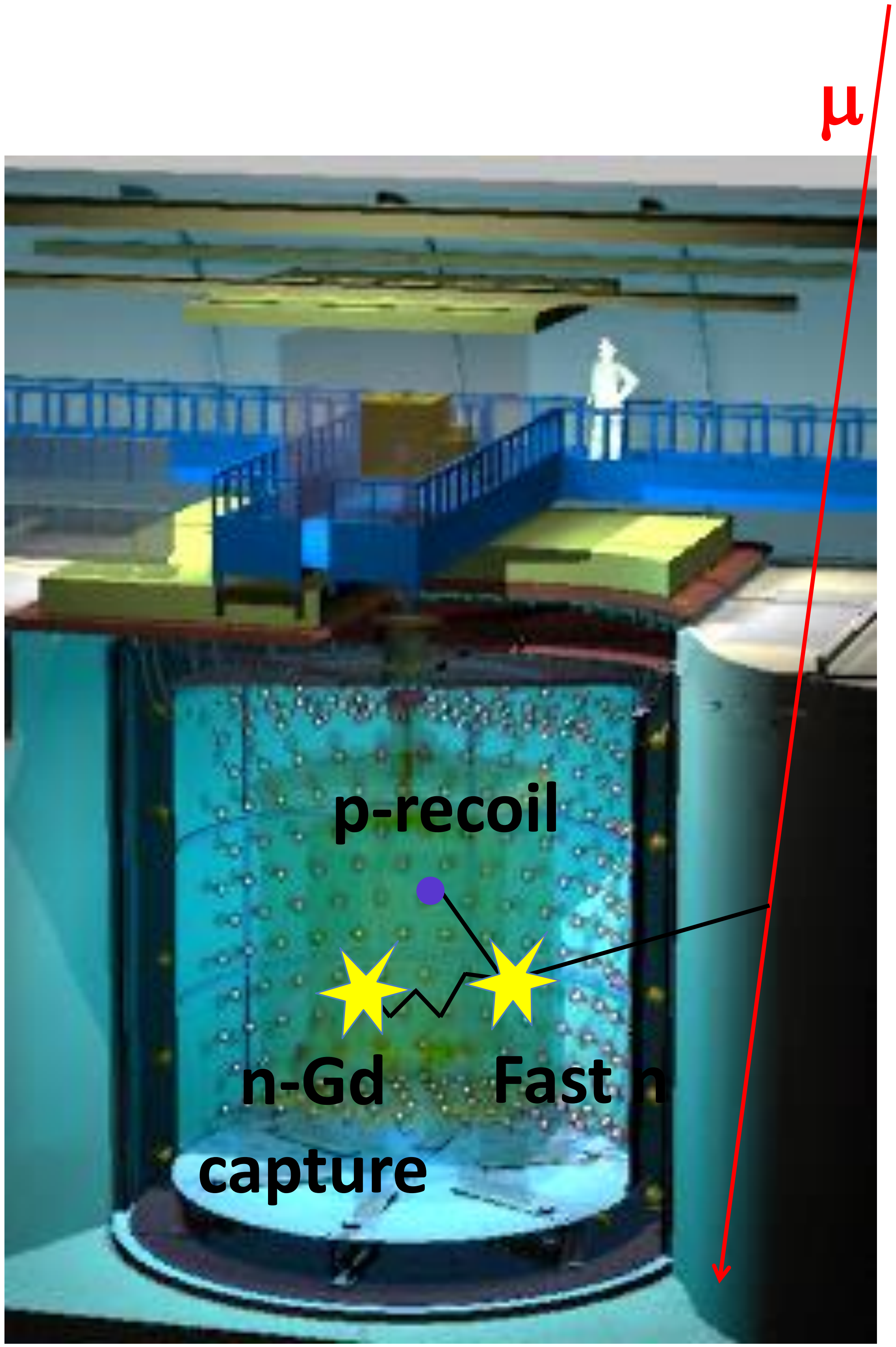
Two types of background expected

- **Accidental coincidence:**

γ + spallation n

Prompt mimic

Delayed mimic



Two types of background expected

- **Accidental coincidence:**

γ + spallation **n**

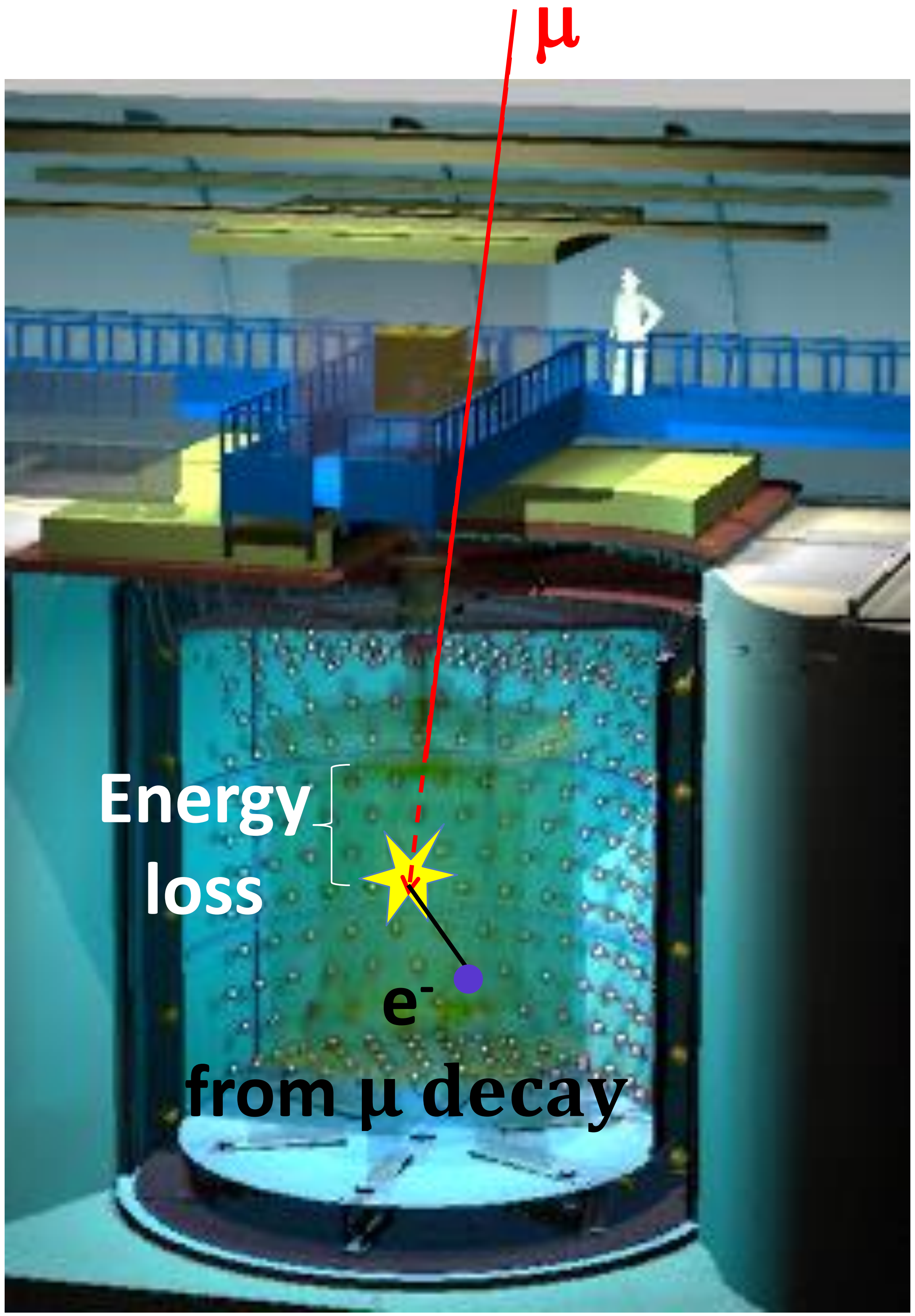
- **Fast neutron:**

n + p → **p** + **n**

correlated

Prompt mimic

Delayed mimic



Two types of background expected

- **Accidental coincidence:**

$$\gamma + \text{spallation } n$$

- **Fast neutron:**

$$n + p \rightarrow p + n$$

- **Stopping muon:**

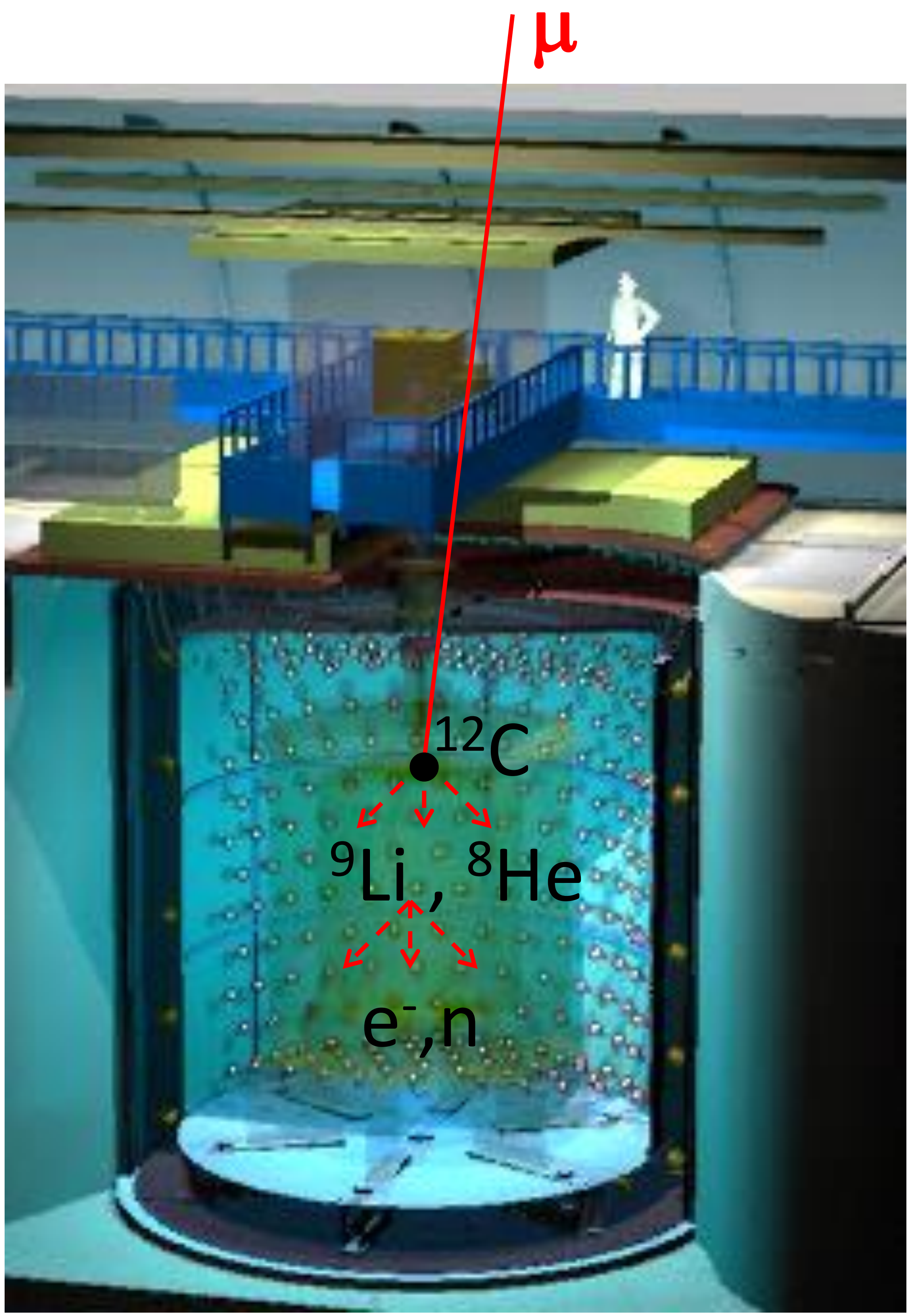
$$\mu \rightarrow e^- + \nu + \nu$$

correlated

Prompt mimic

Delayed mimic

Background



Two types of background expected

- **Accidental coincidence:**

$$\gamma + \text{spallation } n$$

- **Fast neutron:**

$$n + p \rightarrow p + n$$

- **Stopping muon:**

$$\mu \rightarrow e^- + \nu + \nu$$

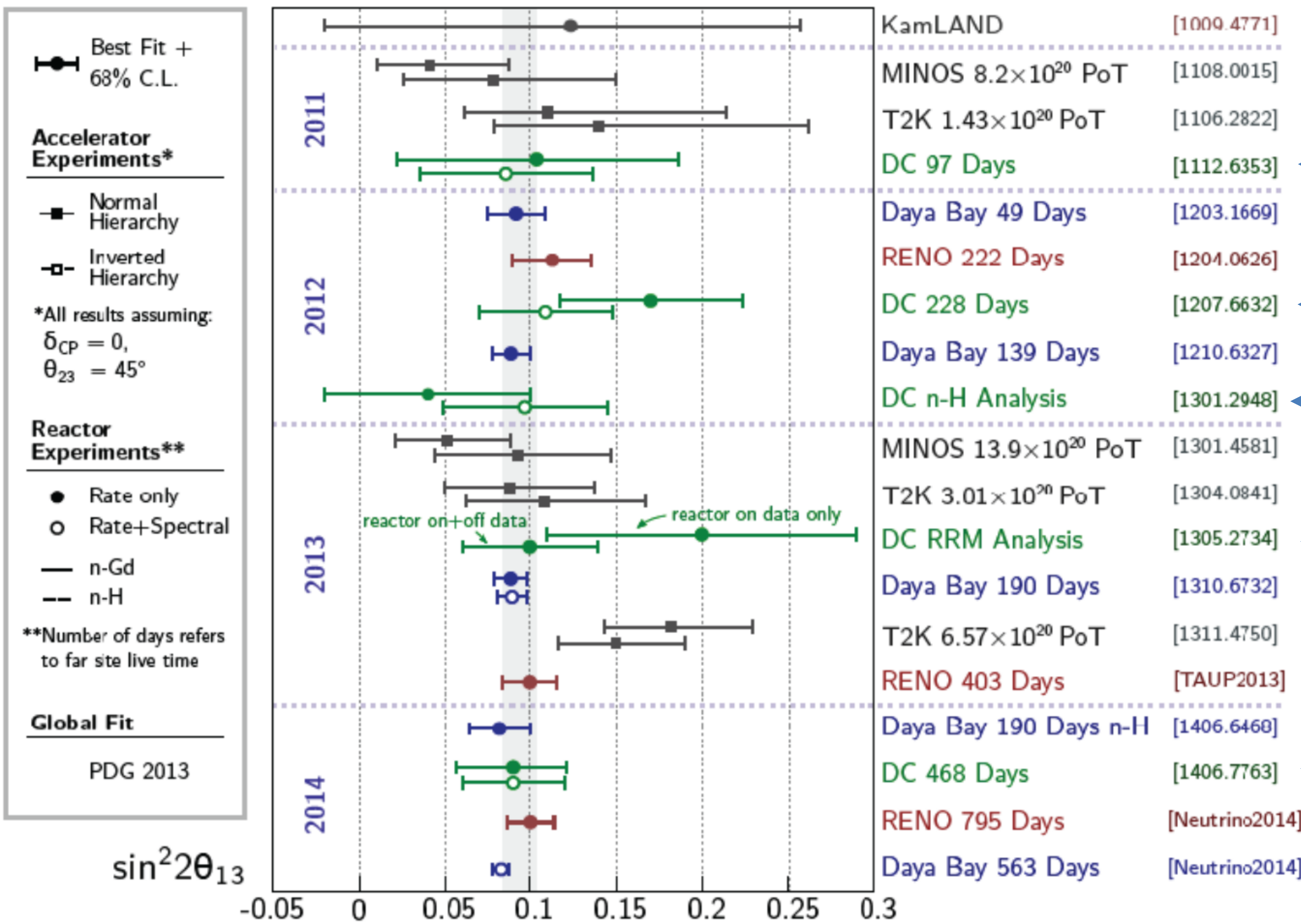
- **Cosmogenic β-n emitter:**

$$^{9}Li \rightarrow \alpha + \alpha + e^- + \nu + n$$

correlated

Prompt mimic

Delayed mimic



2011: Start of data taking with the far detector

First Gd analysis, Rate + shape fit:
Indication of non-zero value of θ_{13}

Improved Gd analysis

New analysis based on n-H capture

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

Improved Gd analysis
Observation of a spectral distortion between the data and the prediction

2015 – ND filling and start of data taking in multi-detector configuration

- 1st Preliminary results: Moriond 2016 conference (mars. 2016) – 9 months
- 2nd Preliminary results: released at a Cern seminar (sept. 2016) – **12 months ⇒ This presentation**

Detectors configurations

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

Reactor flux prediction

Reactor flux prediction

- **Expected unoscillated neutrino rate:**

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

$(k = {}^{235}U, {}^{239}Pu, {}^{238}U, {}^{241}Pu)$

- Fission fraction: $\alpha_k = FR_k / \sum_k FR_k$
- Mean energy released per fission: $\langle E_f \rangle = \sum_k \alpha_k E_{f,k}$
- Thermal power: $P_{th,r}$
- Distance, proton number and efficiency: L_r, N_p, ϵ

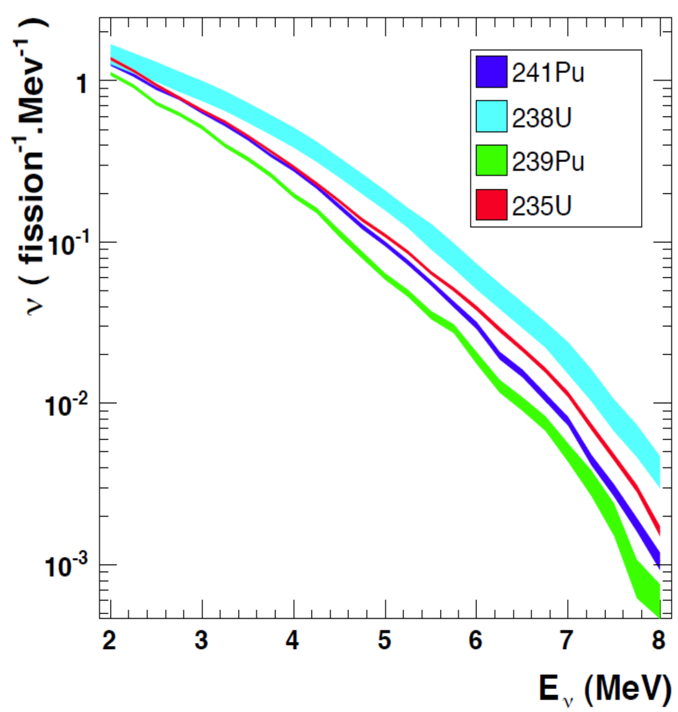
Reference $\overline{\nu}_e$ spectra

Derived from integral β measurements @ILL reactor for ^{235}U, ^{239}Pu, ^{241}Pu and from FRM-II reactor for ^{238}U

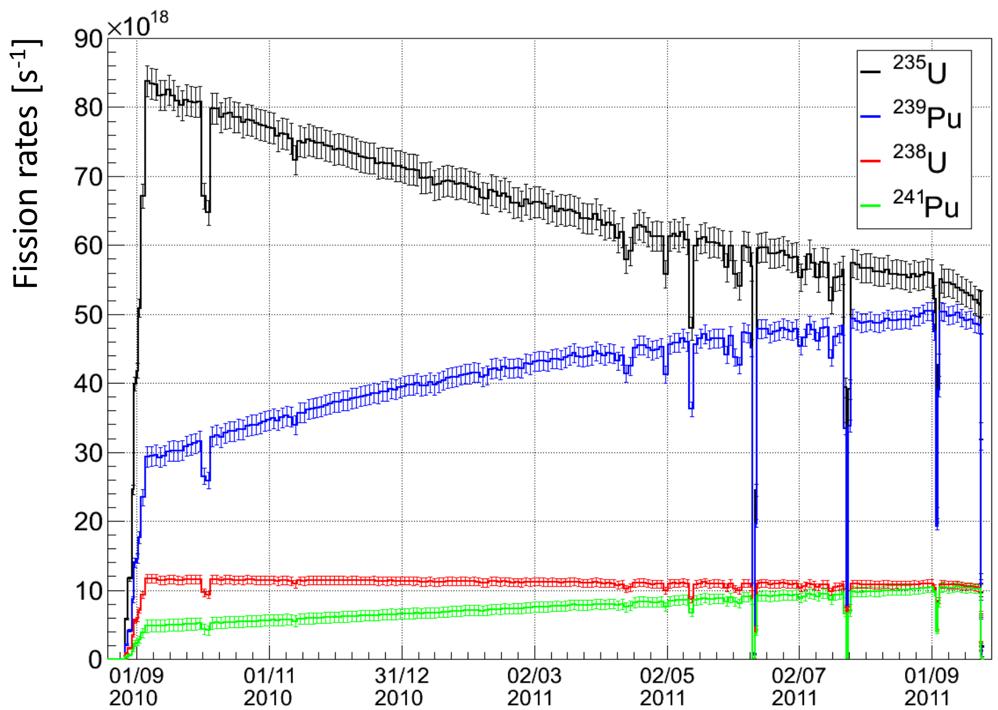
- P. Huber, Phys.Rev. C84 (2011) 024617

- N. Haag, PhysRevLett.112.122501

$$\langle \sigma_f \rangle = \int_0^x dE\, \alpha_k S_k(E)\, \sigma_{IBD}(E)$$



Reference anti-neutrinos spectra



Typical fission rates evolution over a full reactor cycle

Fission fraction and associated error predicted through simulation of the reactors during the period of data taking

- **The MURE Code *(MCNP Utility for Reactor Evolution)*:** Fuel depletion code. Interface to the Monte Carlo code MCNP (static particle transport code)

- Agreement with French EDF company: design data, operating parameters, instrumental core measurement , simulation results ...

- **Expected unoscillated neutrino rate:**

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

$(\boldsymbol{k = {}^{235}U, {}^{239}Pu, {}^{238}U, {}^{241}Pu})$

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➡ **Bugey-4 measurement used as an anchor point for the mean cross-section per fission $\langle \boldsymbol{\sigma_f} \rangle$**

$$\langle \sigma_f \rangle(t) = \langle \sigma_f \rangle^{Bugey} + \sum_k \left(\alpha_k^{DC}(t) - \alpha_k^{Bugey} \right) \langle \sigma_f \rangle_k$$

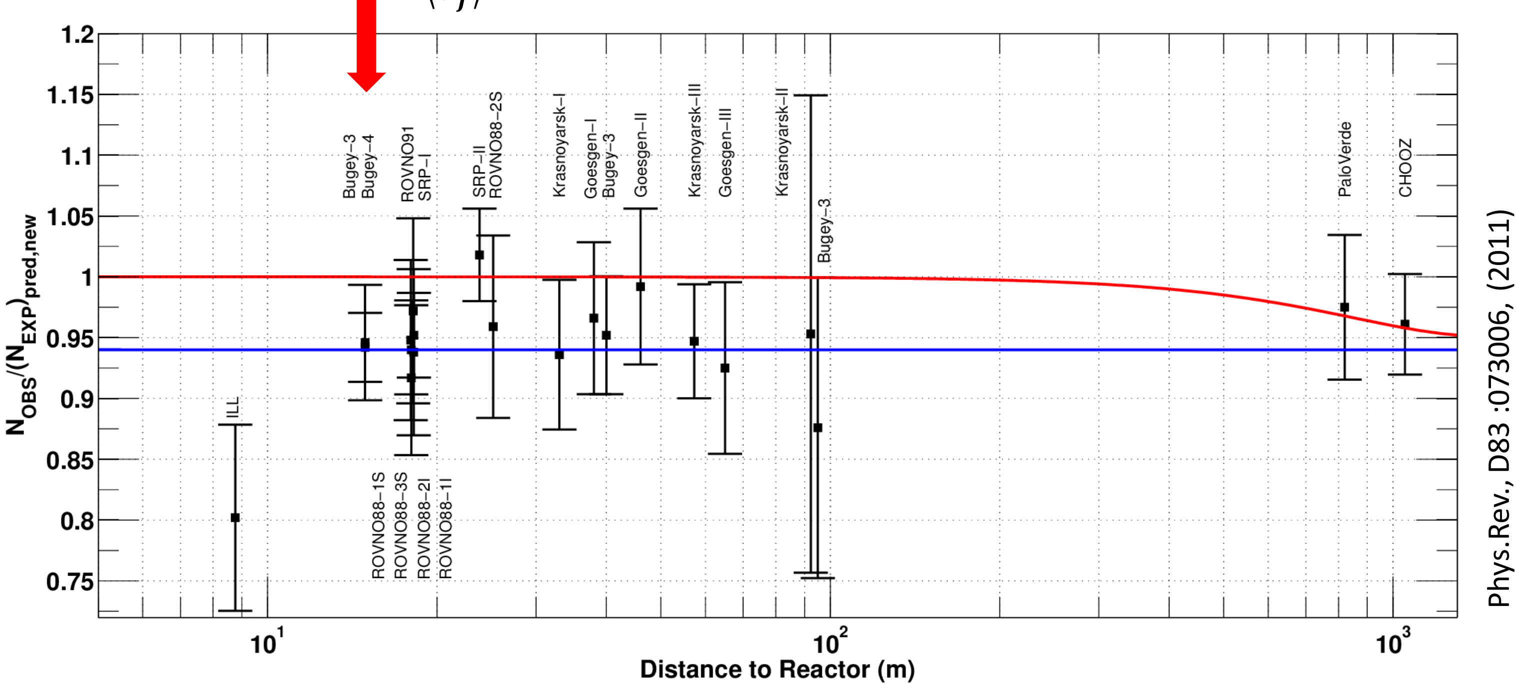
$$\langle \sigma_f \rangle_k = \int_0^x dE \; \boldsymbol{S_k(E)} \; \sigma_{IBD}(E)$$

IBD cross section

Reference antineutrinos spectra

Bugey-4: most precise IBD reactor flux measurement

$\boldsymbol{\sigma_{\langle \sigma_f \rangle} = 1.4\%}$



Reactor anomaly

$\sim$6% flux discrepencies between prediction and reactor flux measurement with short baseline reactor experiments.

B4 normalization in single detector phase

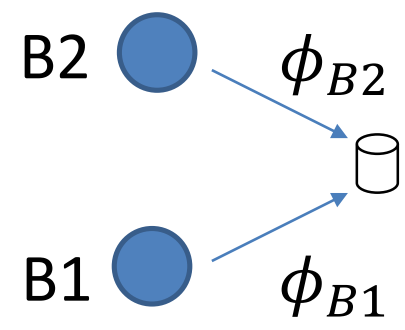
- Suppression of reference anti-neutrino spectra uncertainties
- Insensitive to sterile neutrino with $\Delta m^2 \sim 1 \text{ eV}^2$

Flux error cancellation in multiple detectors configuration

Single detector configuration:

- $\sin^2(2\theta_{13})$ from comparison of far detector data to MC
- Flux systematics: dominant uncertainty on $\sin^2(2\theta_{13})$ measurement

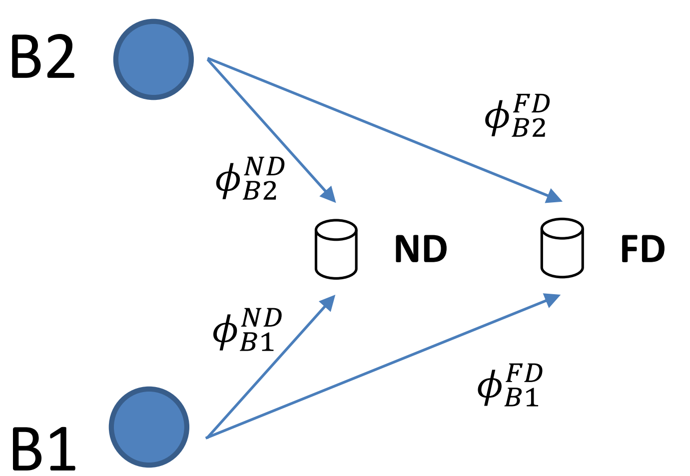
$\Rightarrow \boldsymbol{\sigma_{flux} \sim 1.7\%}$



DC like experimental setup – 1st phase

Multi-detector configuration:

- Flux prediction still require for $\sin^2(2\theta_{13})$ fit
  - ↳ proportion of flux coming from each reactor on each detector



DC like experimental setup – 2nd phase

Near/Far prediction:

- $\phi_{tot}^{ND} = \phi_{B1}^{ND} + \phi_{B2}^{ND}$
- $\phi_{tot}^{FD} = \phi_{B1}^{FD} + \phi_{B2}^{FD}$

$$\left\{\begin{array}{l}
\phi_{B1}^{ND} = f(Pth_{B1}, L_{B1_{ND}}, \alpha_{k_{B1}}, \langle E_f\rangle_{B1}, \langle\sigma_f\rangle^{B4}, S_k(E)\sigma_{IBD}(E)) \\
\phi_{B2}^{ND} = f(Pth_{B2}, L_{B2_{ND}}, \alpha_{k_{B2}}, \langle E_f\rangle_{B2}, \langle\sigma_f\rangle^{B4}, S_k(E)\sigma_{IBD}(E)) \\
\phi_{B1}^{FD} = f(Pth_{B1}, L_{B1_{FD}}, \alpha_{k_{B1}}, \langle E_f\rangle_{B1}, \langle\sigma_f\rangle^{B4}, S_k(E)\sigma_{IBD}(E)) \\
\phi_{B2}^{FD} = f(Pth_{B2}, L_{B2_{FD}}, \alpha_{k_{B2}}, \langle E_f\rangle_{B2}, \langle\sigma_f\rangle^{B4}, S_k(E)\sigma_{IBD}(E))
\end{array}\right.$$

- Flux prediction parameters can be correlated across: B1 & B2 reactors / ND & FD detectors

⇒ In multiple detectors configuration, most of the uncertainty on the flux prediction is canceled

Flux error cancellation in multiple detectors configuration

The multi-detectors and multi-reactors configuration (simultaneous period of data taking)

Isoflux condition

Error suppression factor (SF) in non-isoflux configuration site can be analyticaly computed

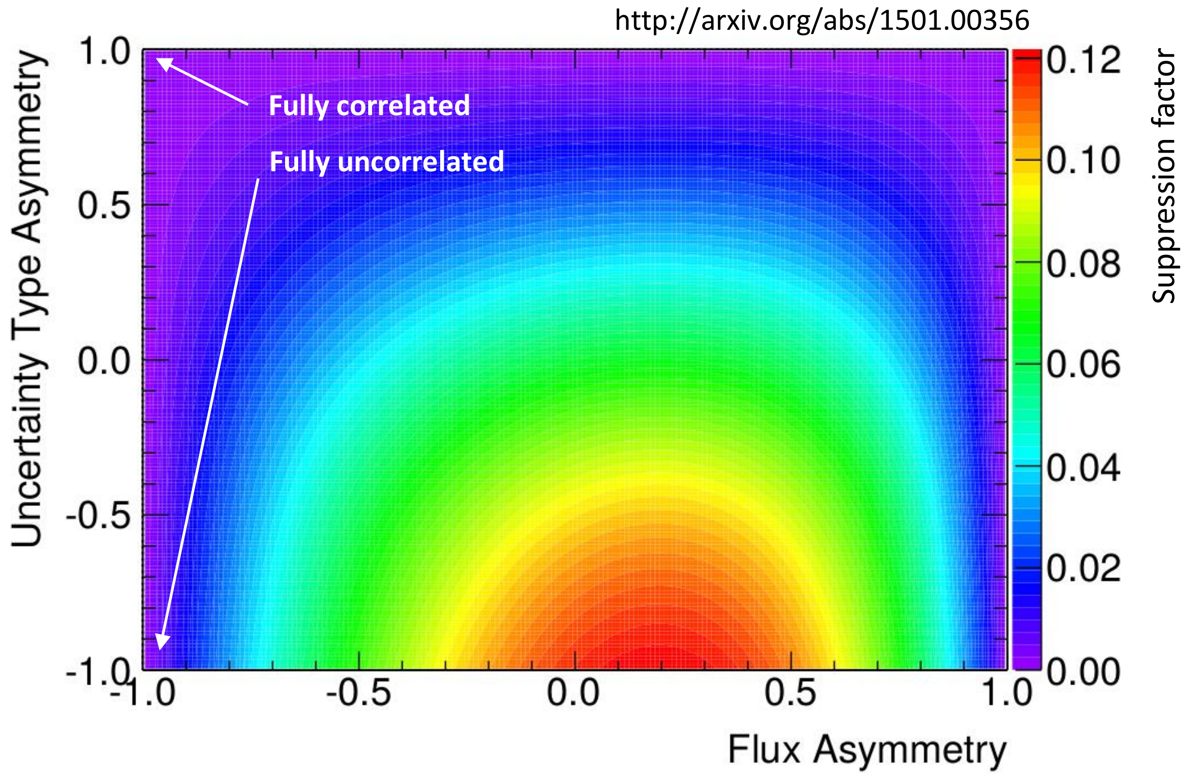
- This factor reflects the ability of each experiment to minimise the reactor uncertainty relative to the simple case of a single detector and a single reactor, where no cancellation is expected

  - flux asymmetry

  - uncertainty type asymmetry: $\frac{\delta_c - \delta_u}{\delta_c + \delta_u}$

DC case:

- **Worst case (highest SF): SF is ~0.12**
  - *0.12*1.7% = 0.2%*
- **Best case (lowest SF): SF=0 ⇒ Total cancellation**
  - uncertainties are reactor correlated maximally (Unc. Type = 1)
  - one reactor is off (flux asymmetry = -1 or 1)
  - *Mathematically identical as having one effective reactor as source, perfectly monitored by the near, regardless of the experimental setup geometry*



Evolution of SF against both the reactor power flux asymmetry (x-axis), defined as $(\Phi_{R2} - \Phi_{R1})/(\Phi_{R2} + \Phi_{R1})$ (i.e. the flux difference between reactor R1 and R2), and the reactor uncertainty type asymmetry (y-axis)

Reactor flux systematics

Flux systematics breakdown: only inter-reactors correlations included in this table

		FD-I [%]		FD-II [%]		ND[%]	
		SD	MD	SD	MD	SD	MD
Bugey4 [%]	$\langle \sigma_f \rangle^{B4}$	1.41	-	1.41	-	1.40	-
Energy per fission [%]	$\langle E_f \rangle$	0.16	-	0.16	-	0.16	-
Spectrum$\otimes$ σ_{IBD} [%]	$S_k(E) \otimes \sigma_{IBD}$	0.06	-	0.05	-	0.05	-
Baselines [%]	L_r		<0.01		<0.01		<0.01
Fission fraction [%]	α_k	0.78	0.55	0.78	0.56	0.78	0.57
Thermal power [%]	$P_{th,r}$	0.47	0.33	0.47	0.33	0.47	0.33
Total [%]		**1.68**	**0.64**	**1.68**	**0.65**	**1.68**	**0.66**

Correlated across reactors and detectors

$\Rightarrow$ suppressed in multi-detector analysis

MD: $\rho_{B1B2} = 0$

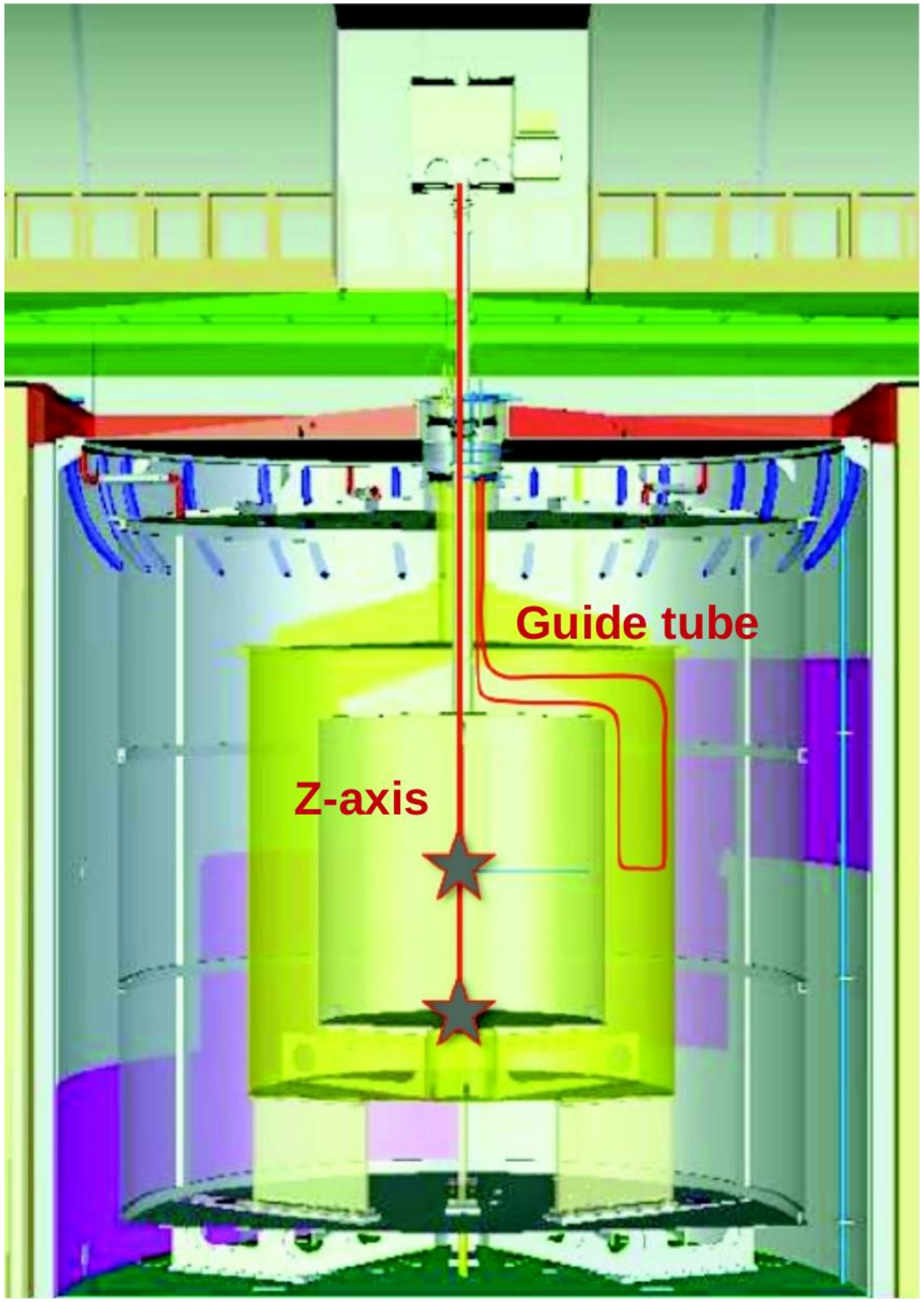
Black: error in single detector analysis

Blue: remaining error in multi-detector analysis

Reduced to 0.13% due to isoflux condition

- Cancellation between FDII & ND (isoflux) $\begin{cases} \rho = 0.993 \\ error[\%] = 0.13 \text{ (SF = 0.08)} \end{cases}$

Detectors response



Several calibration systems

- **Light injection system**

  multi-wavelength LED ⇒ IV/ID PMTs

- **Radioactive sources**

  - γ-sources: ^{68}Ge, ^{37}Cs, ^{60}Co
  - n-source: ^{252}Cf

  Deployed in the target-volume (Z-axis) and in the gamma-catcher volume (guide tube)

- **Natural sources**

  spallation neutrons capture on Gd, H, C

Energy scale

$$E_{vis} = N_{pe} \times f_u(\rho, z) \times f_{PE/MeV} \times f_{stab}^{DATA}(t) \times f_{qnl} \times f_{equ} \times f_{lnl}^{MC}$$

- **N_{pe}: linearised PE calibration**

  - Gain non-linearities at low charge

- **$f_{PE/MeV}$: absolute energy scale**

  - H capture with ^{252}Cf @center detector (~200 PE/MeV)

- **$f_u(\rho, z)$: non-uniformity correction**

  - map with n-captures on H (2.2 MeV)

- **$f_{stab}^{DATA}(t)$: data stability correction (drifts)**

- **f_{qnl}: charge non-linearity correction**

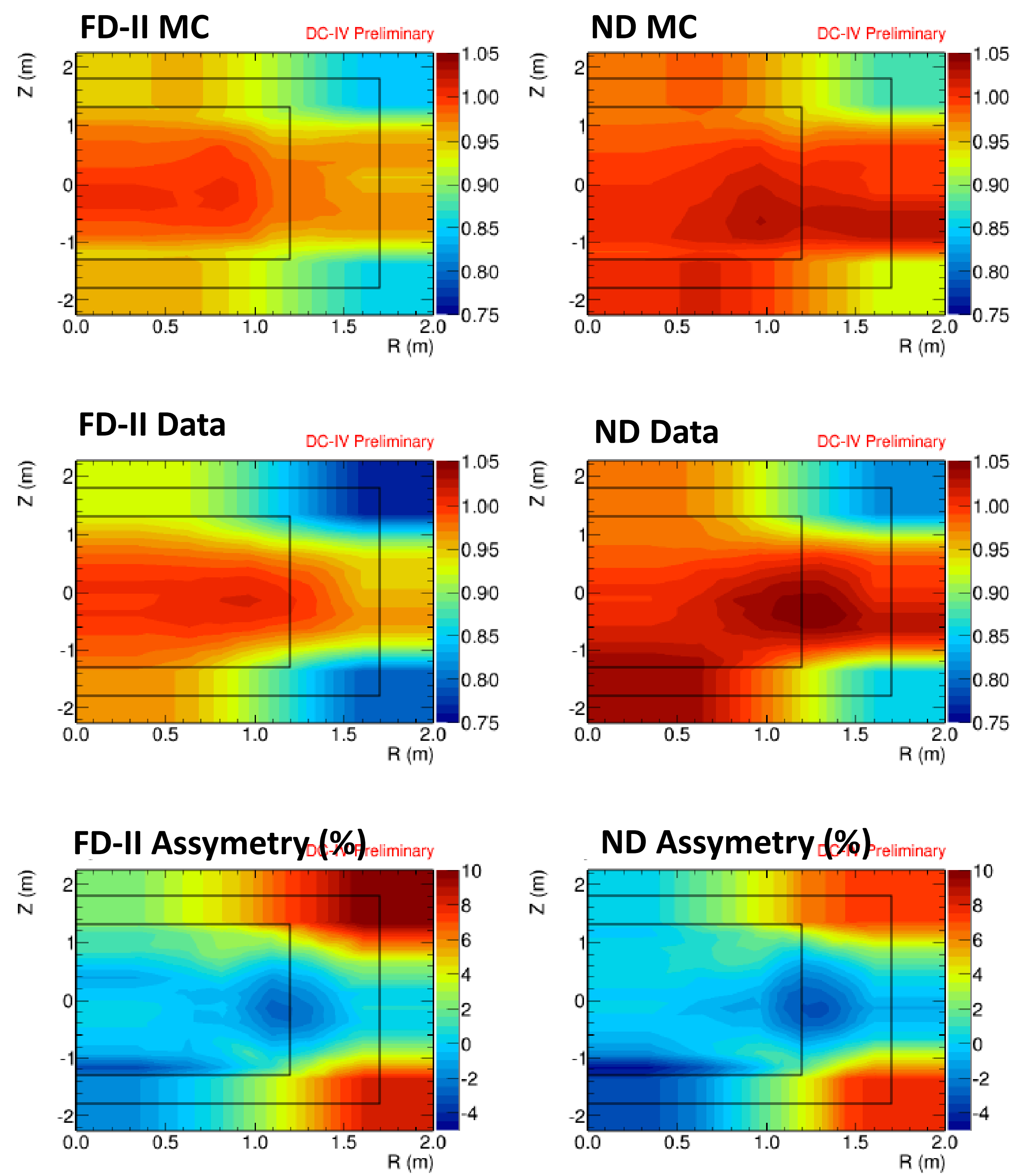
  - charge non-linearity mainly arise from electronics

- **f_{equ}: equalisation of absolute energy scale**

  - 2.2 MeV peak of n from 252 Cf

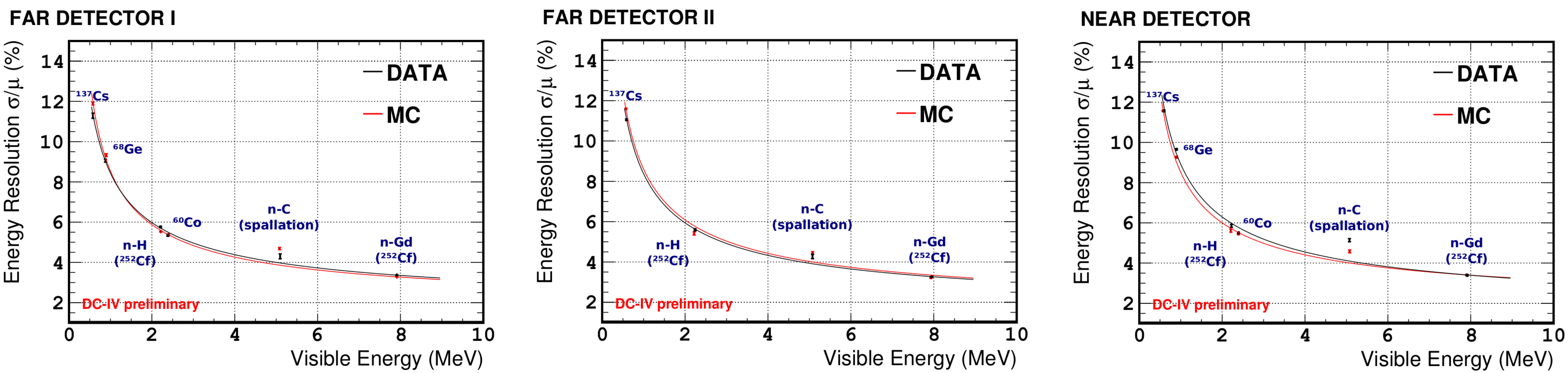
- **f_{lnl}^{MC}: MC light non-linearity correction**

  - Read-out / scintillator model related



response uniformity
(systematics ~0.25%FD & ~0.40%ND)

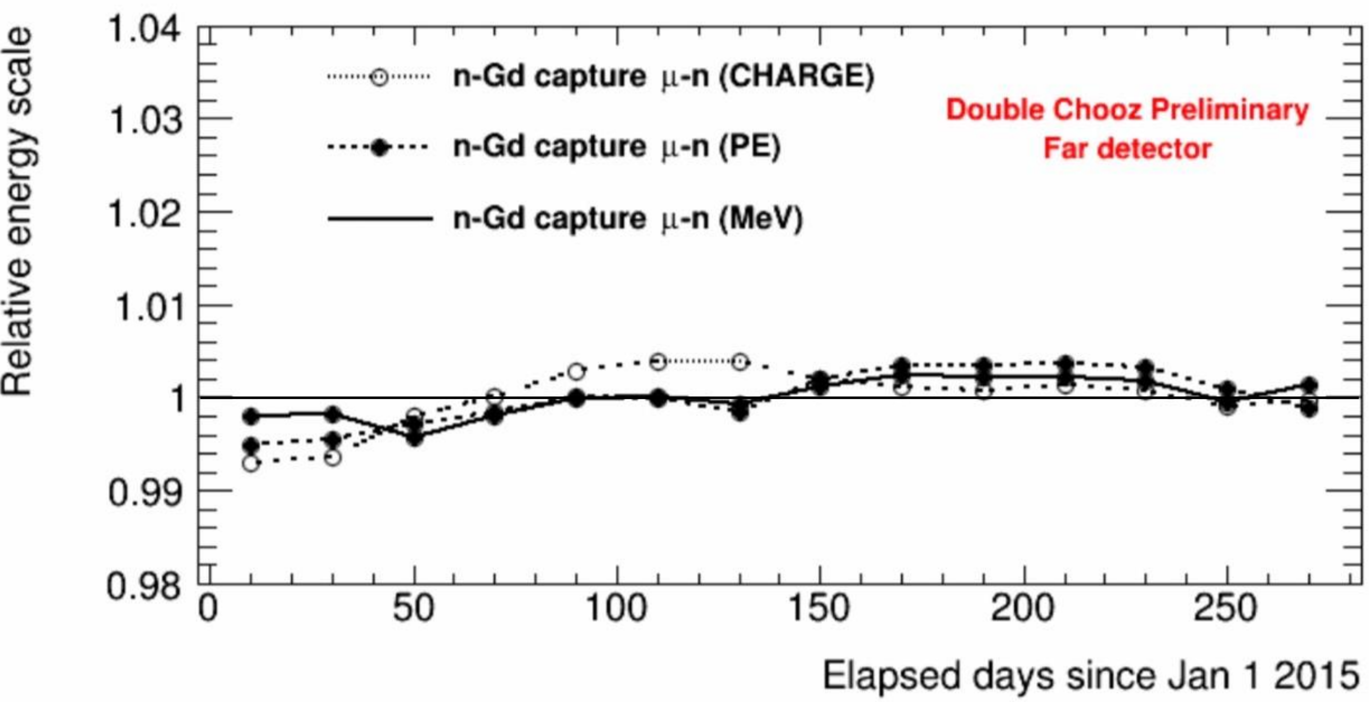
Detector response – energy resolution



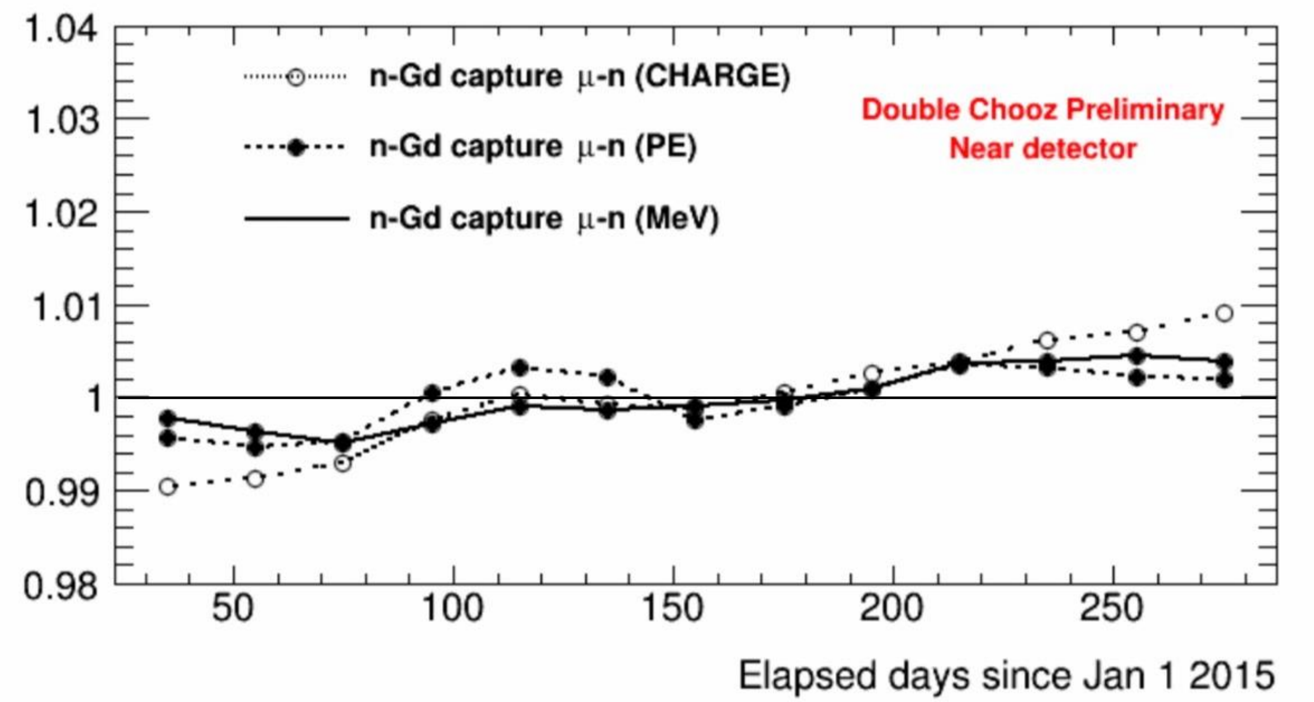
- All calibration points @ target center, except ^{137}Cs in guide tube

- Fit function: $\frac{\sigma}{E_{vis}} = \sqrt{\frac{a^2}{E_{vis}} + b^2 + \frac{c^2}{E_{vis}{}^2}}$
  - a: statistical
  - b: constant
  - c: electric noise

Detector response – time stability



Far detector



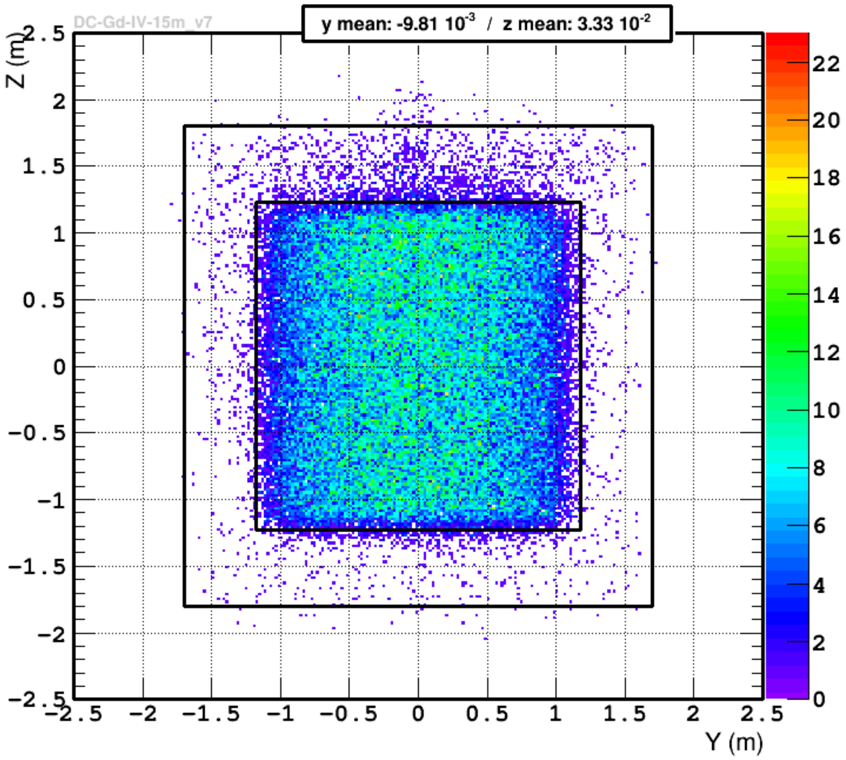
Near detector

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

  ↳Liquide from the same batch in both detectors

IBD selection

IBD[Gd]



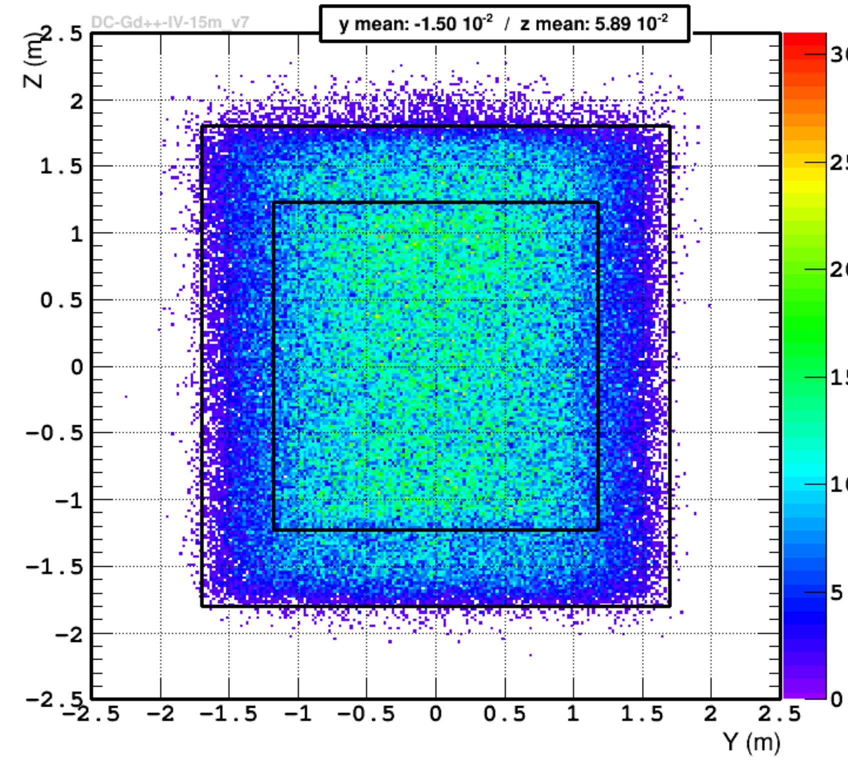
Detection volume: ~8t

ν-Target

New Analysis

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

IBD[Gd+H]



Detection volume: ~30t

ν-Target+ γ-Catcher

- Simultaneous selection of event 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 contaminated with Gd in the near detector)
  - increase statistic: ~3x

Events collected
- Near detector: ~**200 k**
- Far detector (since 2011): ~**80 k**

IBD selection

IBD[Gd] selection

Accidental BG negligible

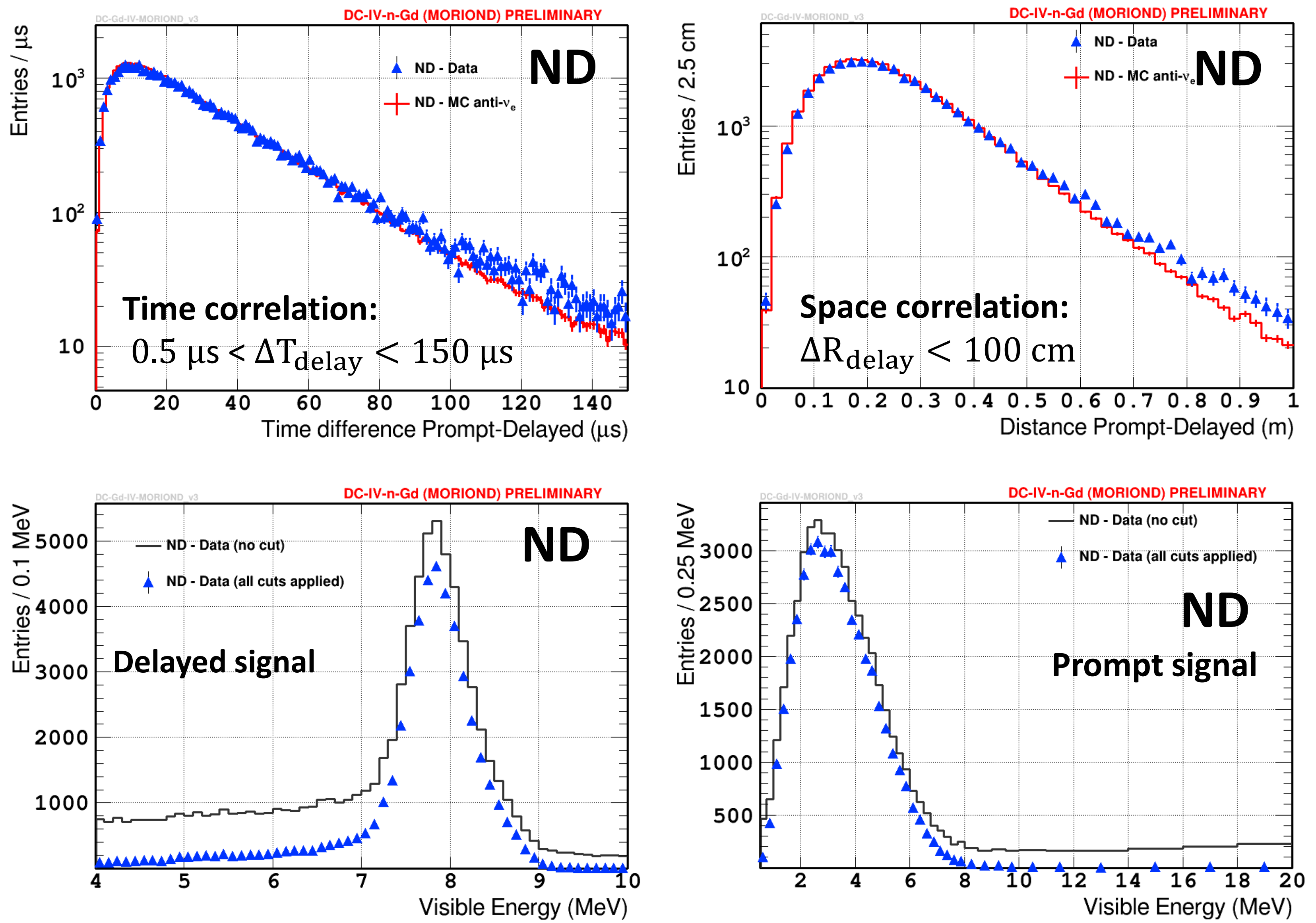
↳ cut based selection

- Delayed energy:

  4 < Evis < 10 MeV
- Correlation time:

  0.5 < ΔT < 150 μsec
- Correlation distance:

  Δ R < 100 cm



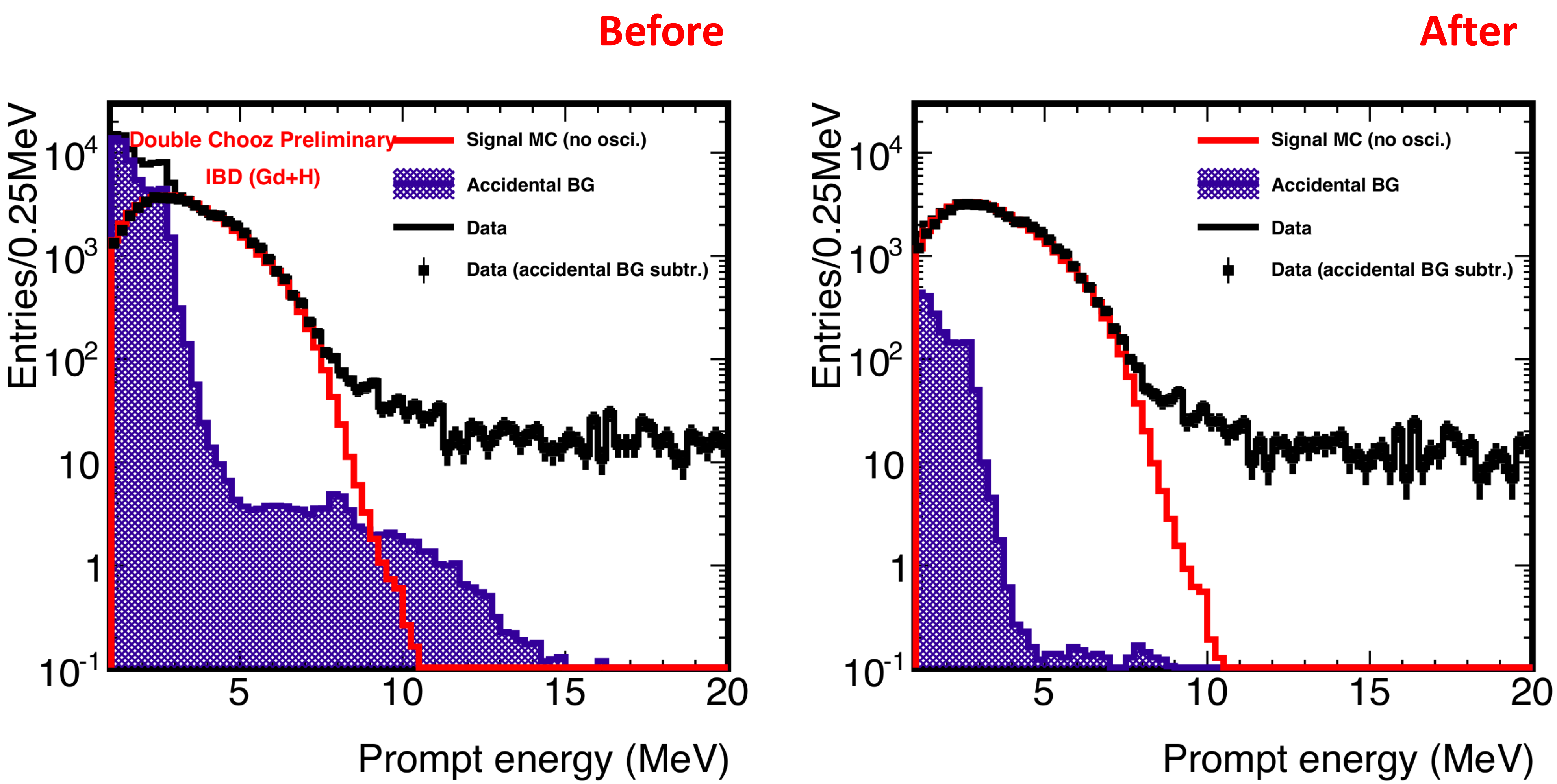
IBD[Gd+H] selection

Accidental BG dominant

↳ multivariate analysis: **Artificial Neural Network (ANN)**

Artificial neural network (ANN)

- Cut on ANN based on the 3 uncorrelated variables: ΔR, ΔT, delayed energy
- More than factor 10 reduction of accidental background



Prompt signal before and after the ANN

Comparison of unoscillated flux prediction with data

(background substracted)

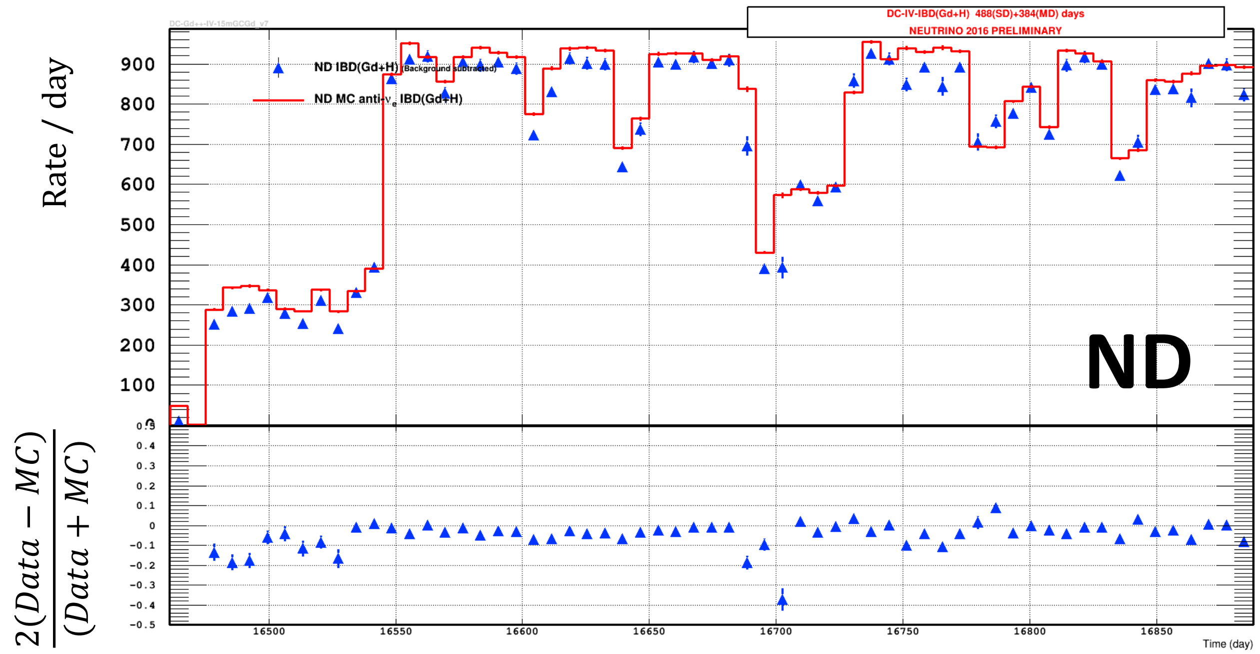
Near detector IBD[Gd+H]

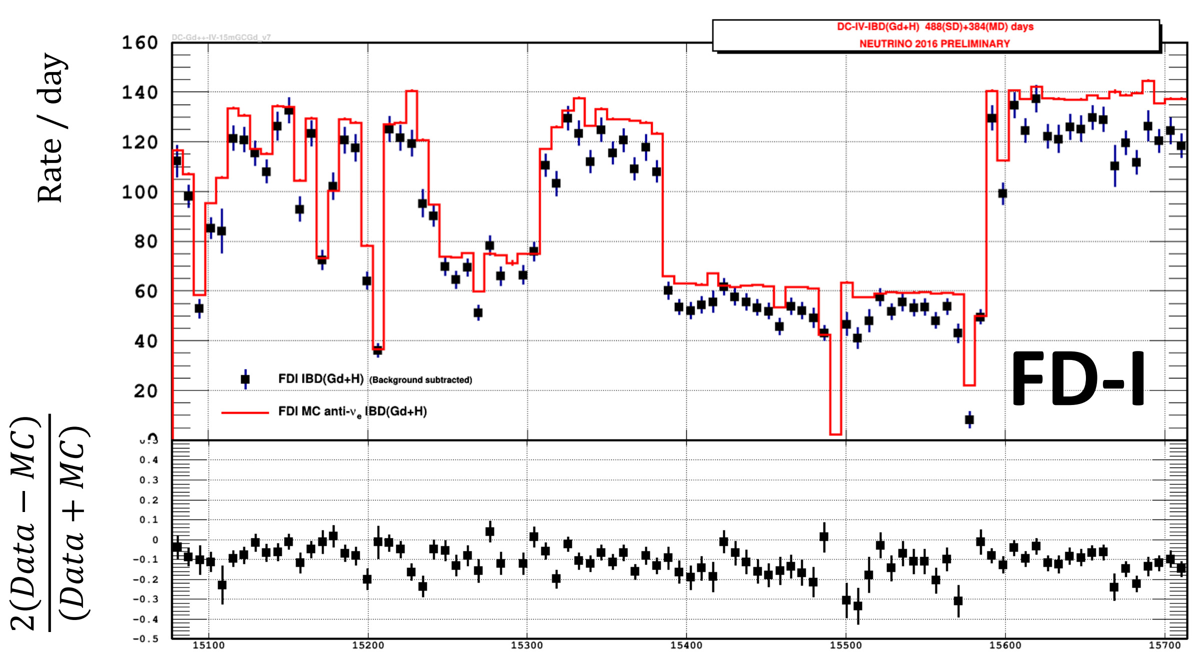
- $\sim$900 events per day ($\sigma_{stat}\sim 0.2\%$)

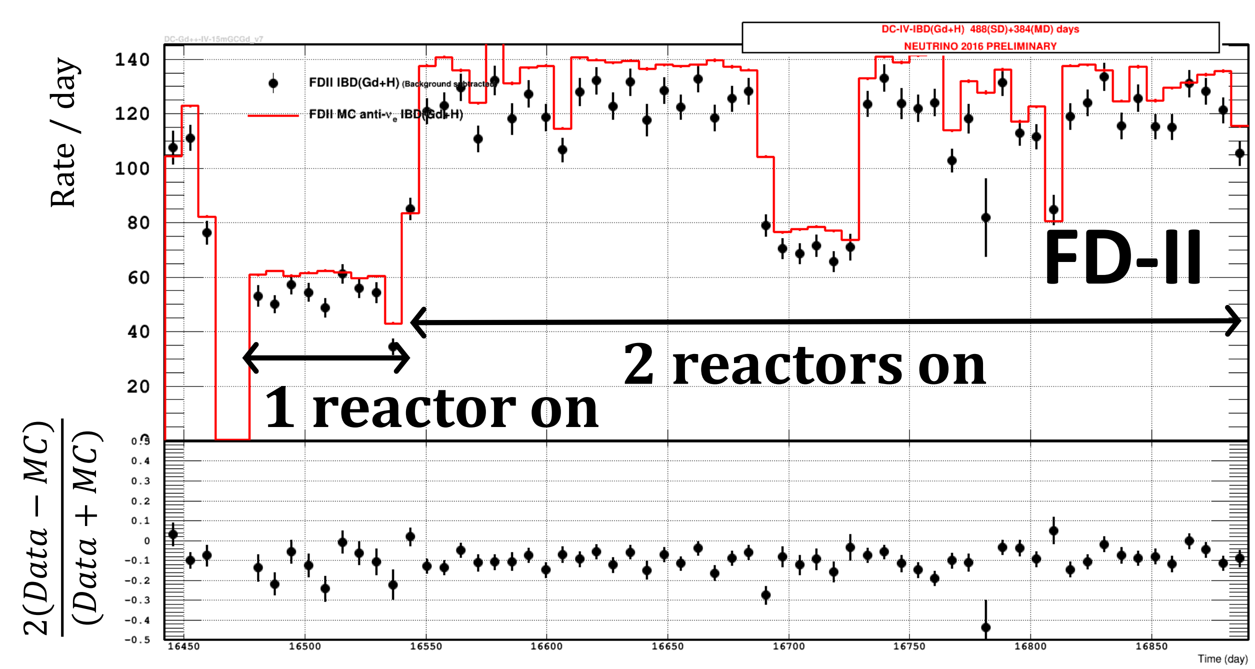
Far detector IBD[Gd+H]

- $\sim$150 events per day ($\sigma_{stat}\sim 0.4\%$)

- ND is almost a perfect monitor of FD
  - Discrenpencies between FDII and ND induced by the time exposure







Detection systematics

Double Chooz Preliminary

	IBD[Gd] – Last results @DC first phase	IBD[Gd+H]
DAQ⊕Trigger	<0.1%	<0.1%
BG vetoes (%)	0.1%	0.05%
Gd fraction (%)	0.4%	-
IBD selection (%)	0.4%	0.27% (0.26%)
Spill in/out (%)	0.3%	-
GC Boundary	-	0.2% (0%)
Proton number (%)	0.3%	0.74% (0.56%)
Total (%)	**∼0.7%**	**∼0.8%** (0.6%)

Numbers in parentheses are uncorrelated uncertainties in multi-detectors analysis

↳Correlated uncertainties across detectors are canceled!

- Drawback of the IBD[Gd+H] analysis: worst proton number estimate

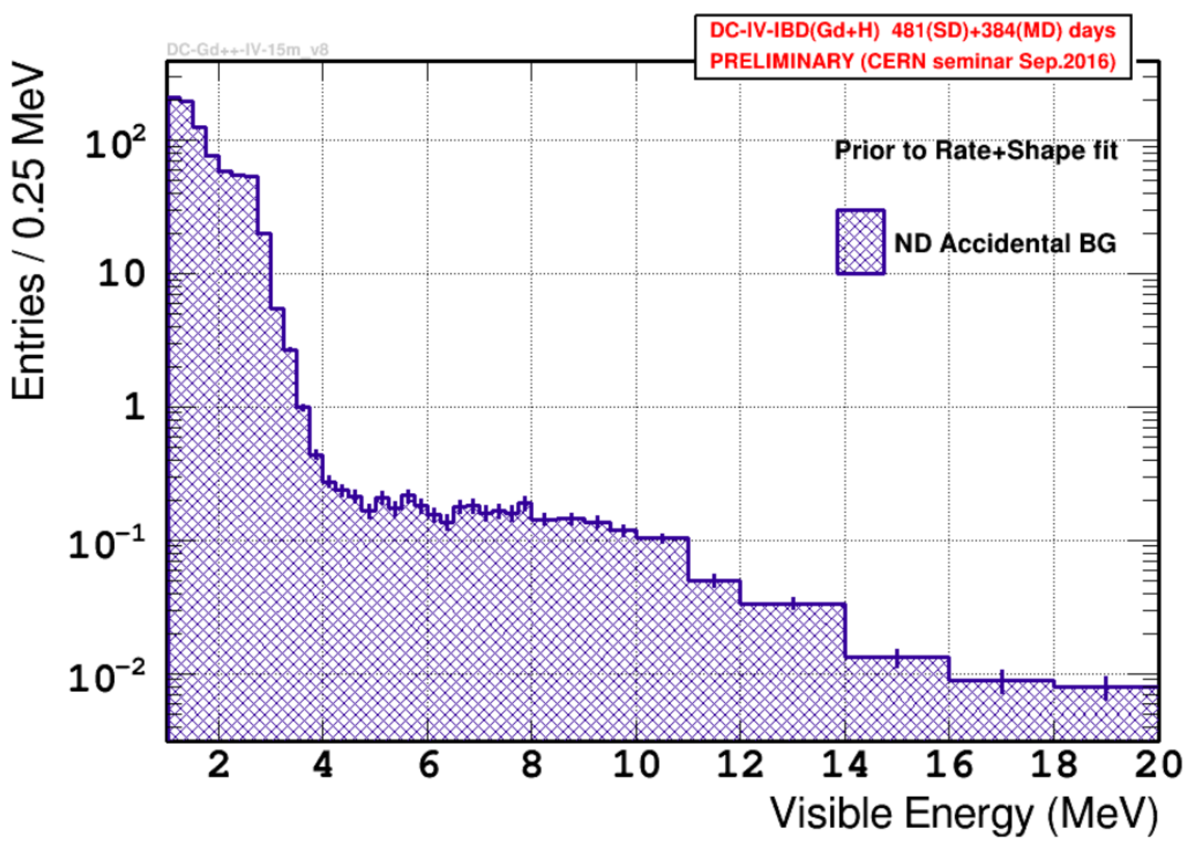
  - **ν-Target:** $\sigma_{N_p} = 0.3\%$
  - **γ-Catcher:** $\sigma_{N_p} = 0.9\%$

  remains our challenge!

Background

Accidental background

- >90% of accidental background rejected by ANN cut
- Further ~30% of accidental background are tagged and rejected by IV
- Rate and spectrum shape of remaining contamination precisely measured by off-time coincidence method
  ↳ Multiple time windows with different offset (T_{offset} >1s)

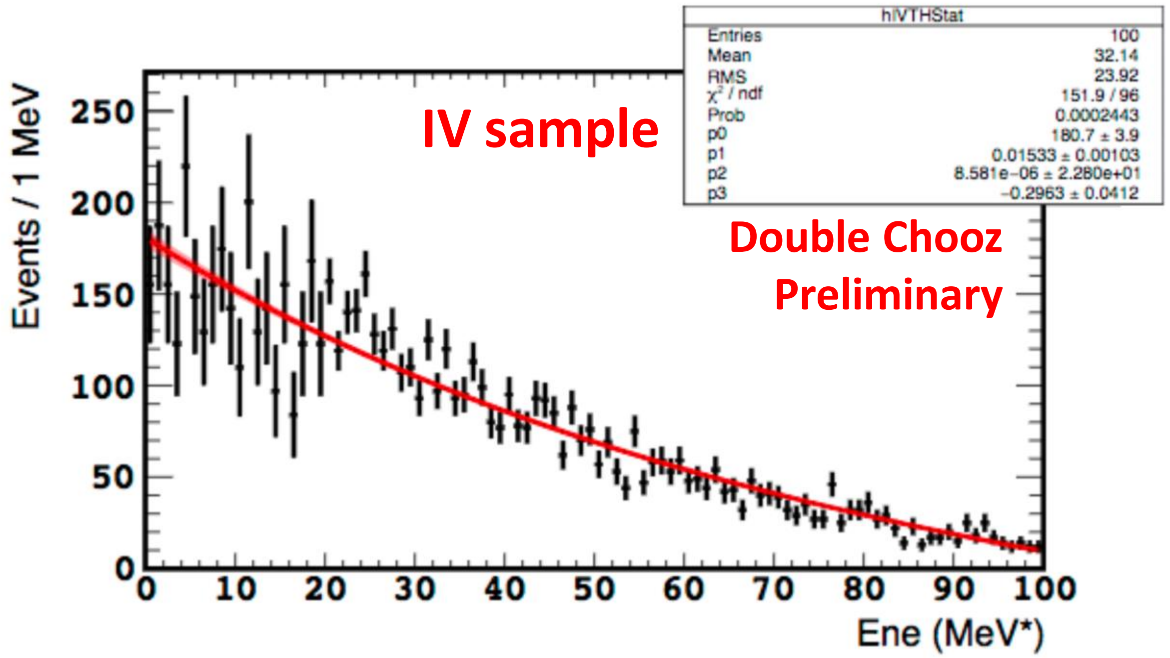


ND accidental prompt spectrum

Residual accidental rate
- **FD-I/FD-II: 3.93±0.01 d^{-1}**
- **ND: 3.11±0.04 d^{-1}**

Fast neutrons:

- Multiple tagging from IV, OV and ID of fast neutrons:
  - ⇒ rejected as background
  - ⇒ used to measure BG rate and shape



- Energy spectrum measured by IV tagged sample (up to 100 MeV) with empirical function
$$a \cdot \exp(-b \cdot E_{vis}) + c + d \cdot E_{vis}$$
- More important rate in the near detector due to the lower overburden

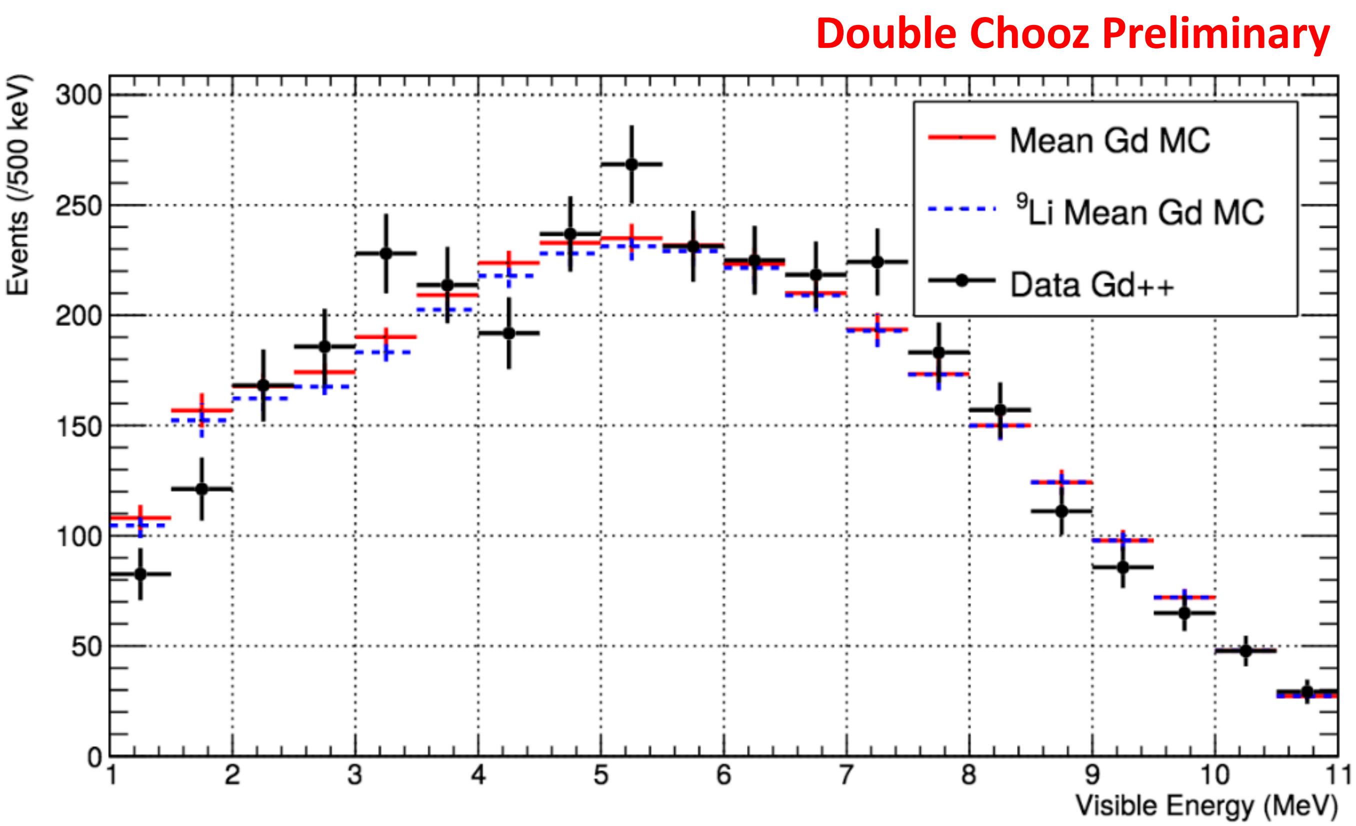
Stopping μ:

- Rejection: muon identified by Inner Veto / Muon entering from chimney identified by PMT hit patern / coincidence with OV activity

  ⇒ Negligible contamination after rejection for both detectors

Residual FN rate
- **FD-I/FD-II: 2.54±0.07 d^{-1}**
- **ND: 20.77±0.43 d^{-1}**

Cosmogenic isotopes



Lithium likelihood calculated to muon – IBD candidate pairs based on :

- Number of neutrons in 1ms following muon
- Distance between muon track and prompt vertex

Li-events partialy rejected by Li likelihood

↳ Residual Li rate estimated by ΔTμ analysis (excess of τ~257ms component)

- Contribution of ^{8}He compatible with 0 (comparison with prediction)

Residual Li rate

- **FD-I/FD-II: 2.57 ±0.60 d^{-1}**
- **ND: 11.05 ±1.95 d^{-1}**

Signal and background summary

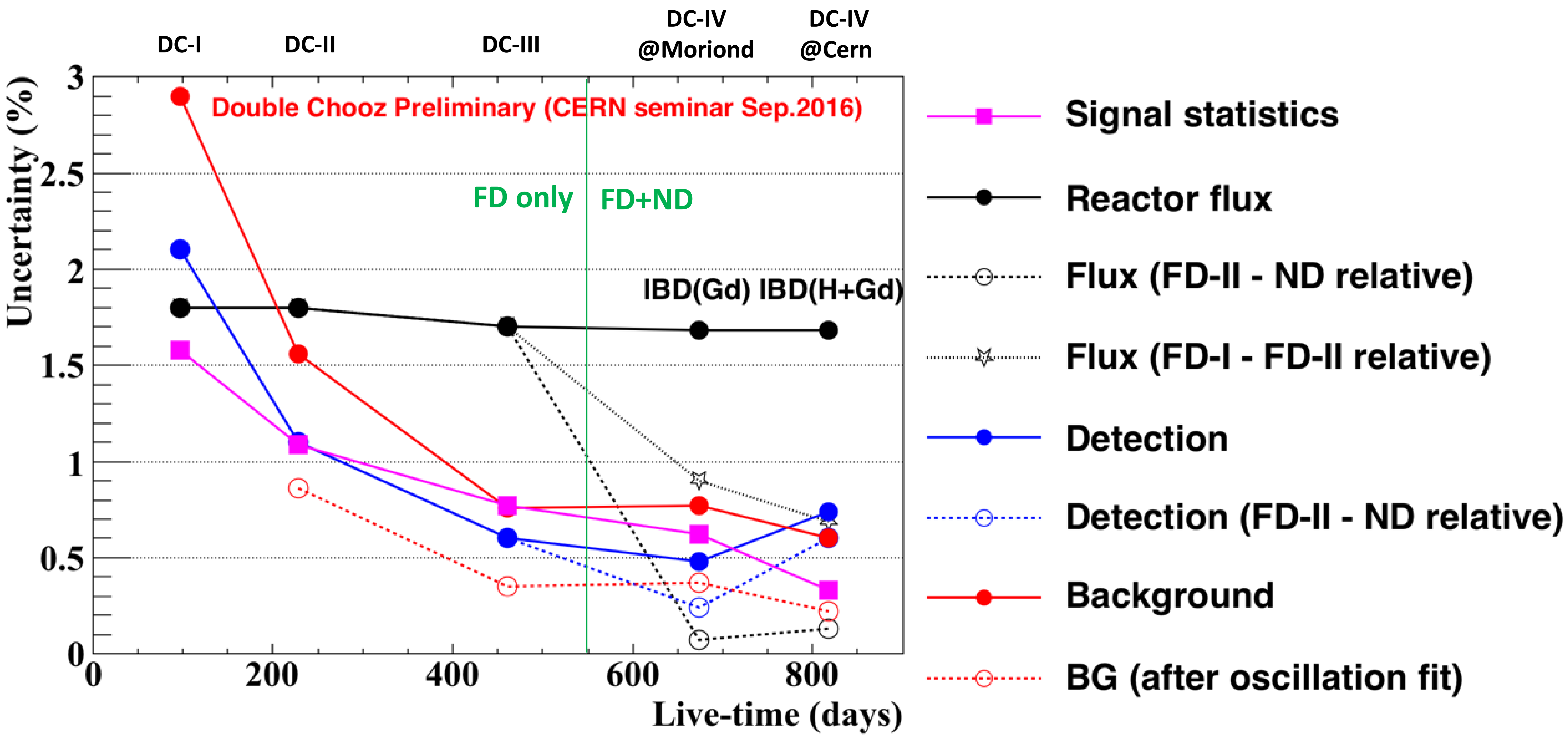
Double Chooz Preliminary

	FD-I	FD-II	ND
Live-time (d)	455.3	366.4	259.3
signal (d^{-1})	112.0	128.8	1118.9
Accidental BG (d^{-1})	3.93 ± 0.01	4.32 ± 0.02	3.11 ± 0.04
Fast-n + stop-μ (d^{-1})	2.54 ± 0.07		20.77 ± 0.43
Cosmogenic (d^{-1})	2.57 ± 0.60		11.05 ± 1.95
BG total (d^{-1})	9.06 ± 0.61	9.45 ± 0.61	34.99 ± 2.99
Signal/BG	**10.7**	**11.4**	**22.3**
σ(BG)/Signal	**0.5%**	**0.5%**	**0.3%**

- Background errors are reduced in oscillation fit by spectrum shape information

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

Flux systematics for DC-IV@Cern

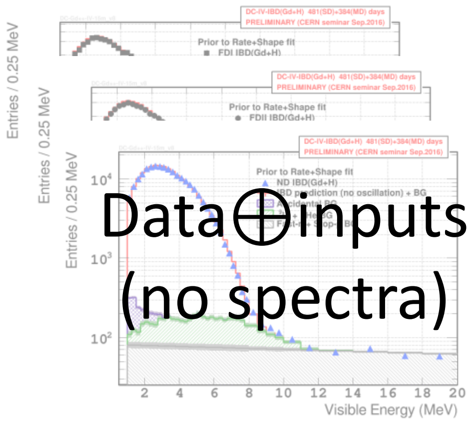


- Detector and background uncertainties are suppressed to per-mille level by analysis improvements
- Reactor flux uncertainty dominant in last single detector analysis (1.7%)

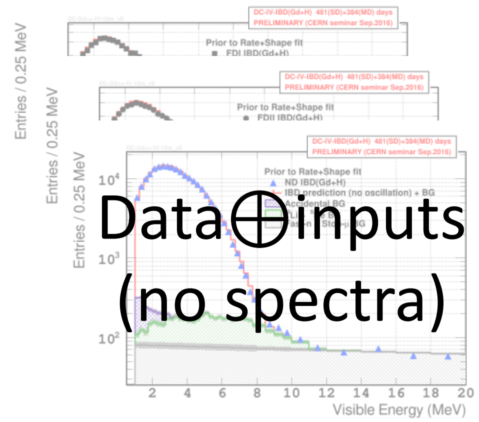
↳ Multiple detector analysis: - partial suppression between FDI/FDII

- almost maximal suppression between ND/FDII (isoflux condition)

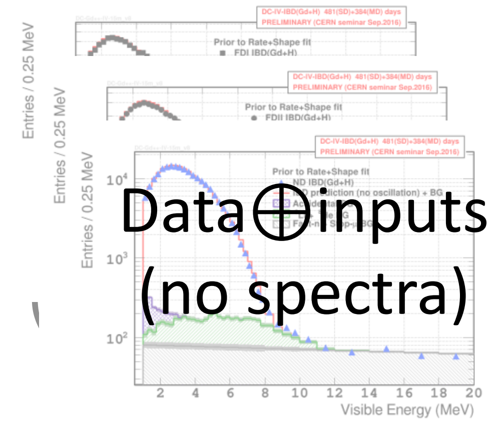
Fit methods in Double Chooz



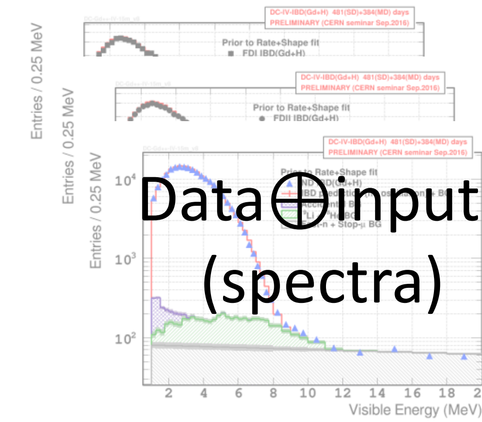
Rate Only
(1bin)



RRM-I
(+ reactor power)



RRM-II
(+[1,8.5]MeV+extra BG)



Rate + Shape
(38 bins)

<u>Rate + shape fit:</u>

- Data-to-MC: Individual and simultaneous comparison of FD-I, FD-II and ND with the folded reactor flux prediction
- Data-to-Data: direct comparison of ND data with FD data

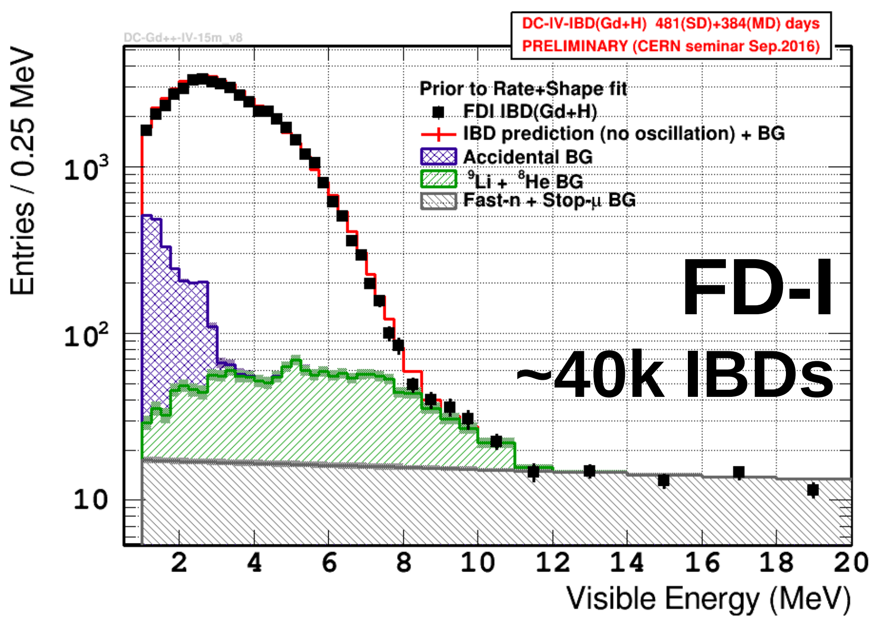
unbiassed analysis articulation
(blinding each inputs till fit agreed→sensitivity→measurement)

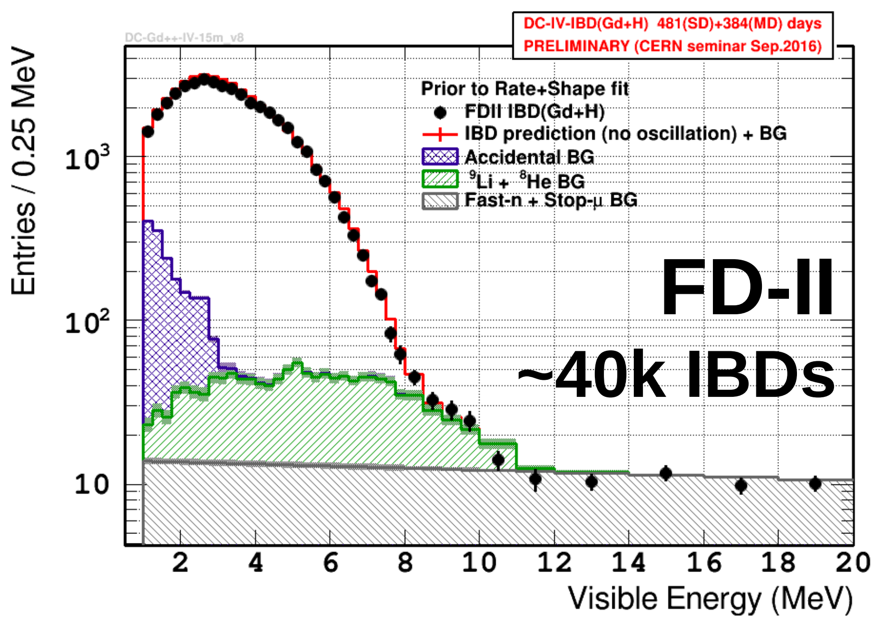
Data-to-MC fit (Rate + Shape):

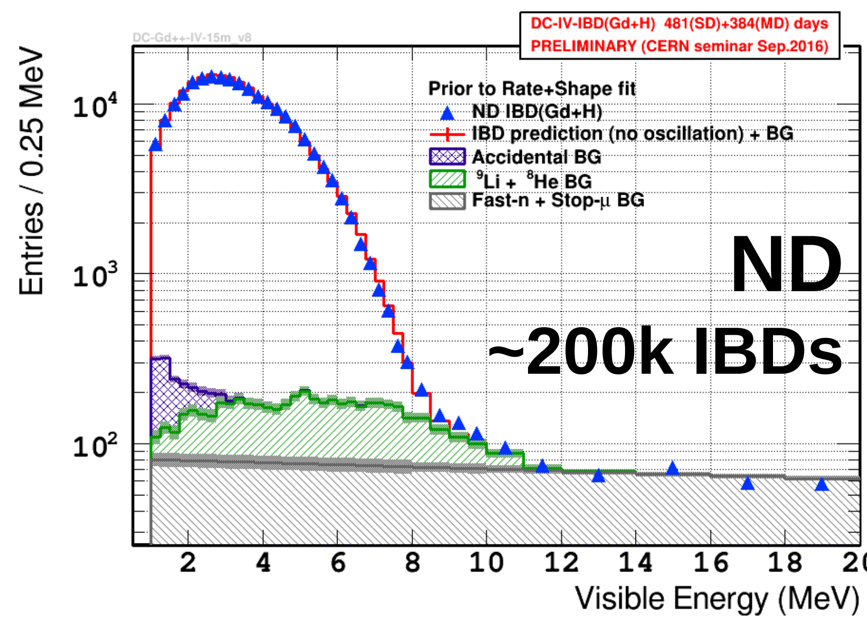
- Simultaneously comparison of FD-I, FD-II and ND data to un-oscillated flux predictions

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

- Background rate and shape estimated by data but Li and FN rate unconstrained in the fit
- BG constraint from 7.24 days of both reactor off (FD-I)







FD-I:FD-II

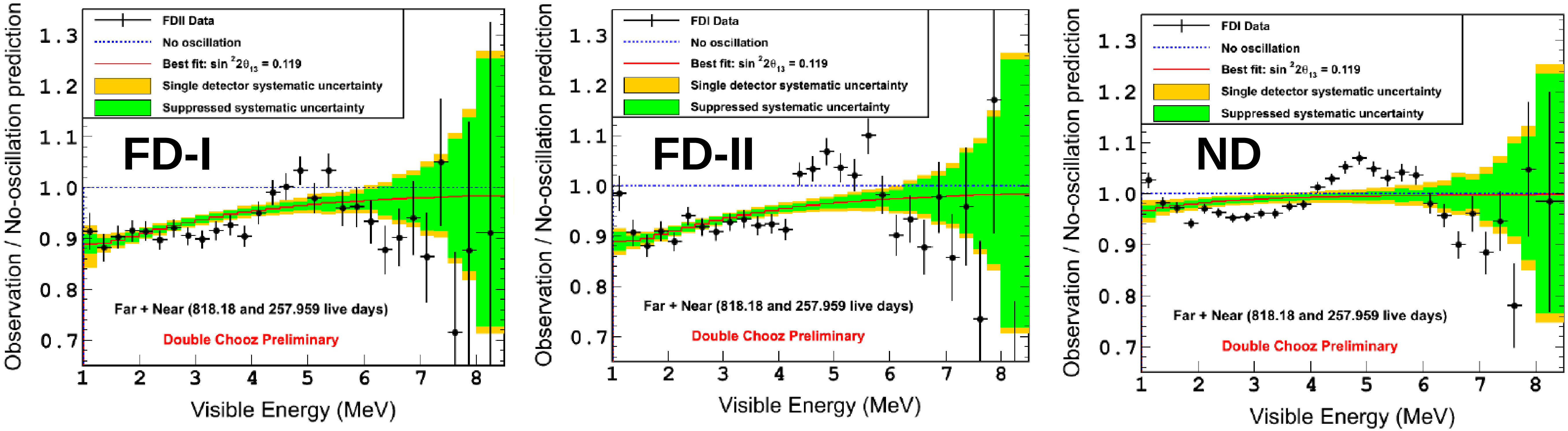
FD-II:ND

- Correlation of systematic uncertainties (flux predictions and detector systematics) are taken into account
- Energy: - non-linearity effectively corrected in the fit

  - **non-linearity assumed correlated across all detectors**

θ_{13} fit

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



Ratio of the data versus the unoscillated prediction

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

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

- High χ^2/ndf induced by the distortion between the MC and the data
- Background constraint after fit

	FD-I	FD-II	ND
σ(BG)/Signal	0.5% → **0.2%**	0.5% → **0.2%**	0.3% → **0.2%**

→ **values after fit**

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

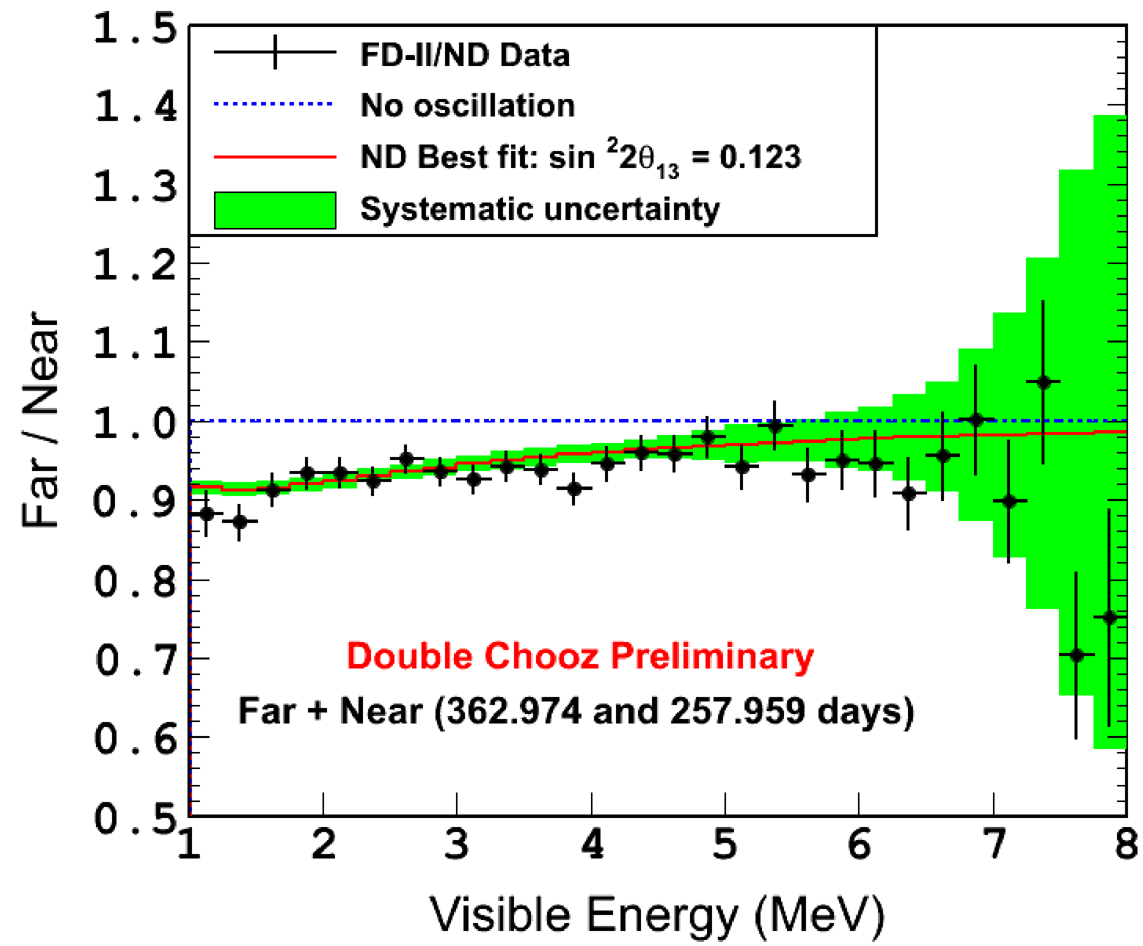
- FD-II directly compared to ND data (FDI excluded)

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

+ Penalty Pulls

ω_i scaling factor

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

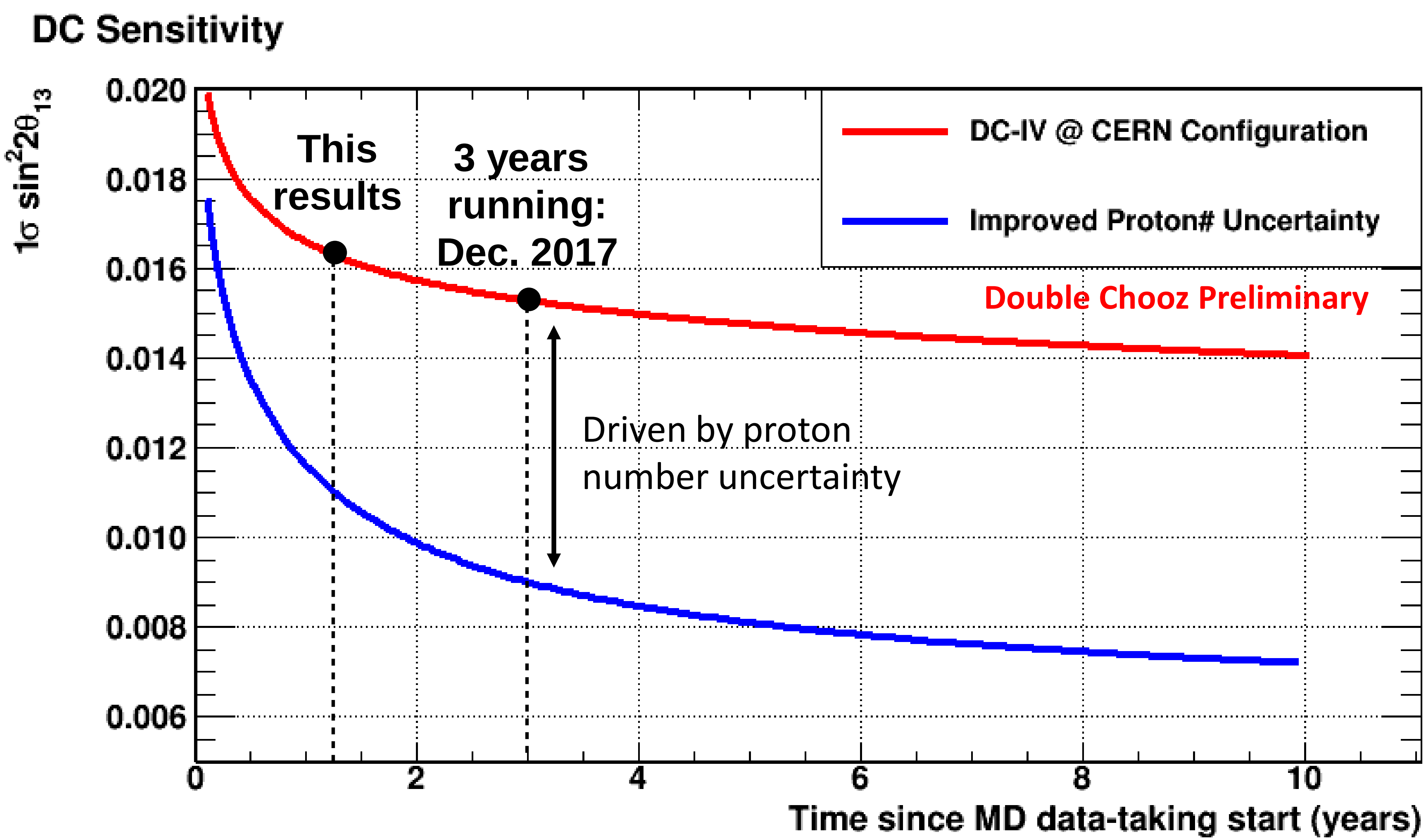


Ratio of the FDII data versus the ND data

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

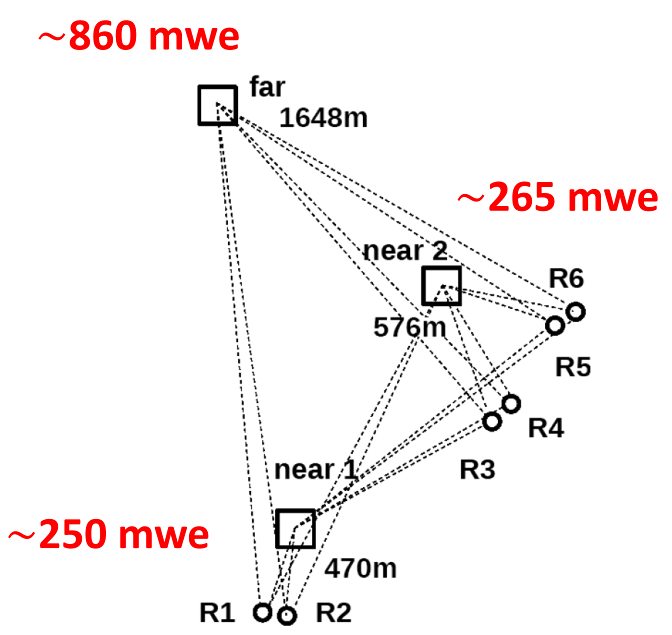
- Good agreement of Data-to-MC fit and Data-to-Data fit

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



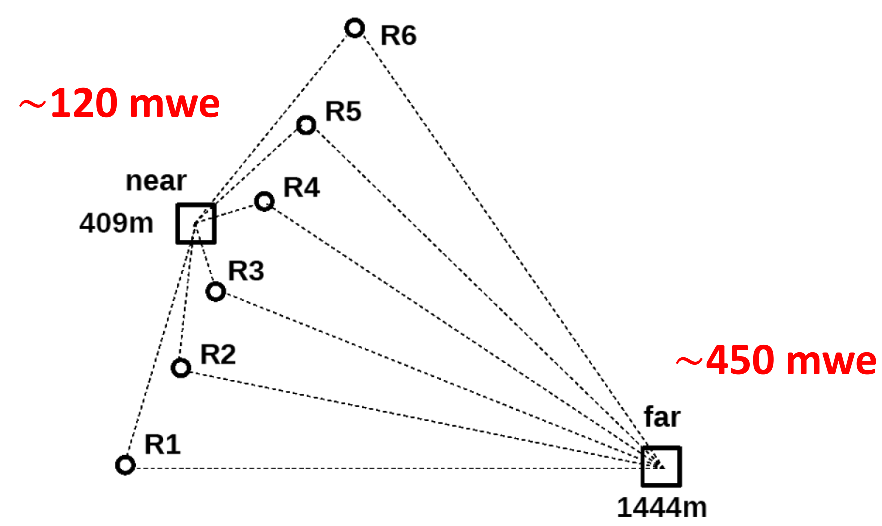
- Blue line: assumption on the proton number uncertainty ($\sigma_{Np} = 0.1\%$)
  - ↳ Potential room for improvement of DC sensitivity with a best proton number estimate (work in progress)

Daya Bay
(China)



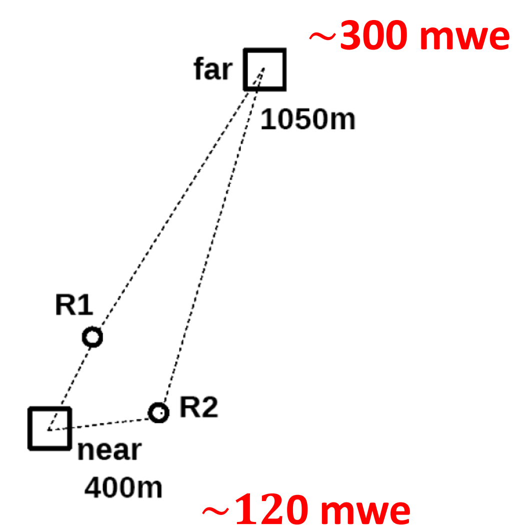
4 far detectors (1 site)
4 near detectors (2 sites)

RENO
(South Korea)



1 far detector
1 near detector

Double Chooz
(France)



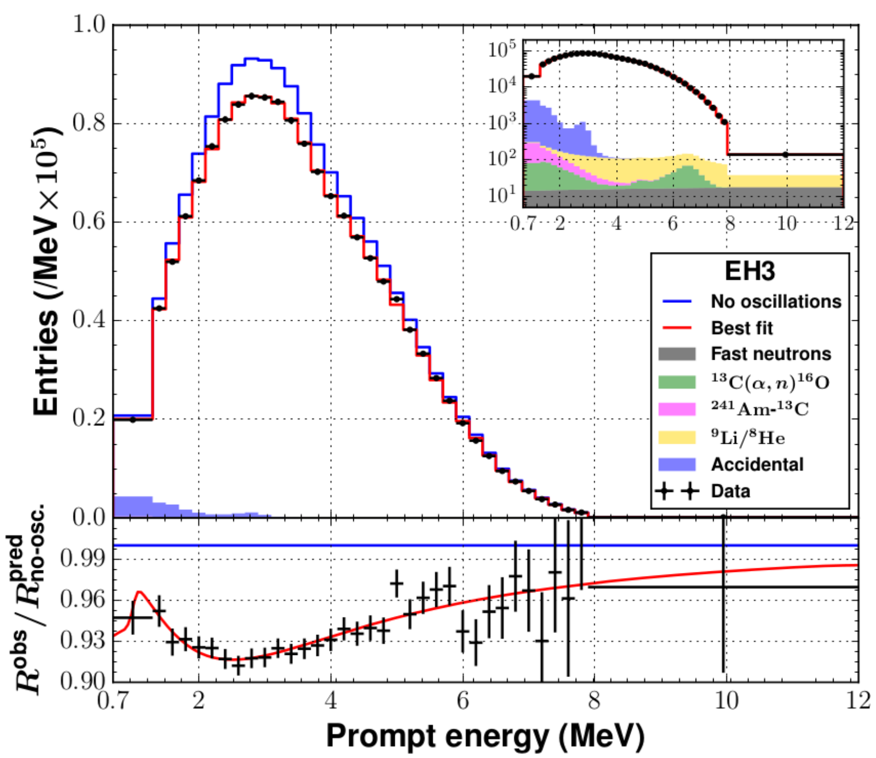
1 far detector
1 near detector

	N_{det}	$M_{\nu\text{-target}}$	Reactors	Total power
Double Chooz	2	~8t	2×4.25 GW_{th}	8.5 GWth
RENO	2	~16t	6×2.8 GW_{th}	16.8 GWth
Daya-Bay	8	~20t	6×2.9 GW_{th}	17.4 GWth

θ_{13} with reactor experiments

Daya Bay

[arXiv:1610.04802v1 / 1230 days]

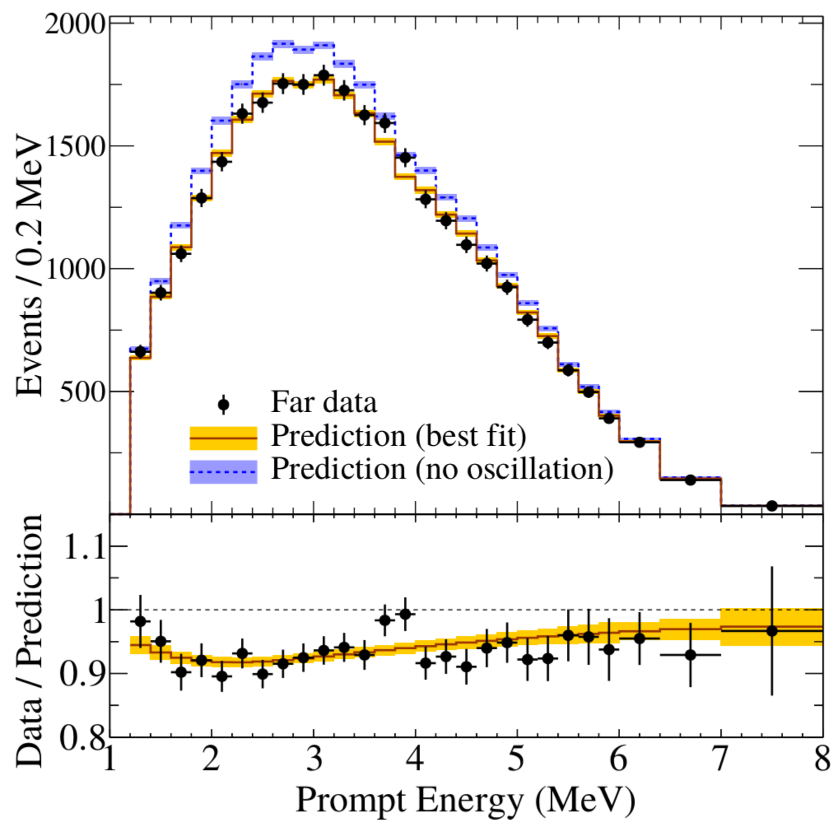


Ratio of events measured in the far hall to the unoscillated prediction

- Near Hall-1: ~1.2 million events
- Near Hall-2: ~1.0 million events
- Far Hall: ~ 300 k events

RENO

[Phys. Rev. Lett. 116, 211801 / 500 days]

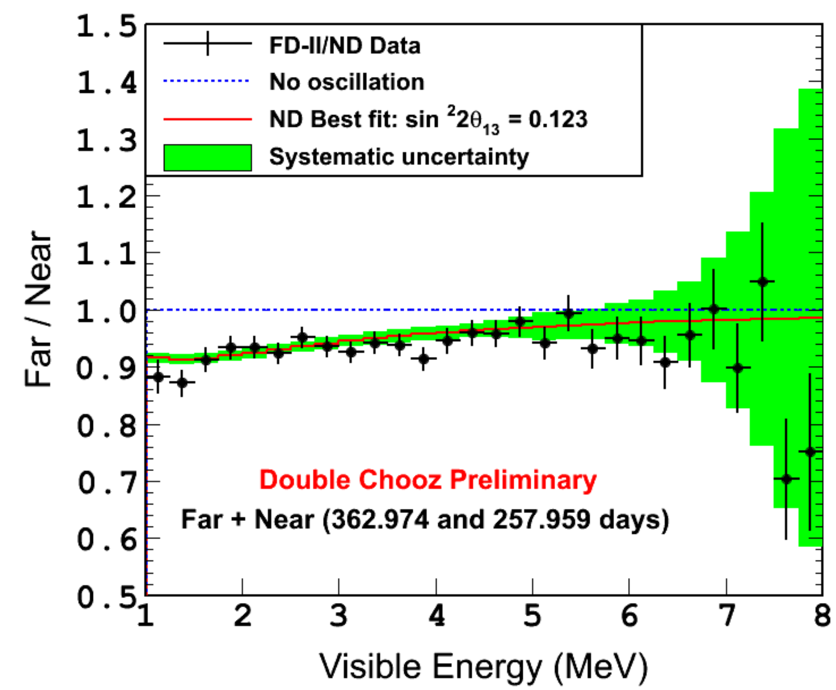


Ratio of events measured in the far detector to the unoscillated prediction

- Near det.: ~300 k events
- Far det.: ~30 k events

Double Chooz

[Preliminary results– Cern seminar - 820/250 (FD/ND) days]



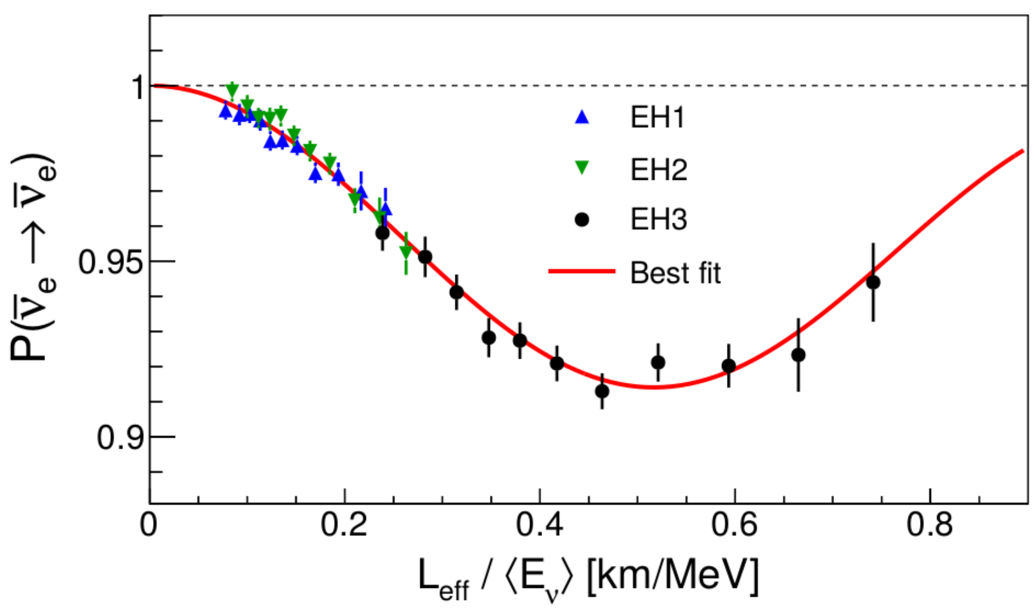
Ratio of events measured in the far detector to the events measured in the near

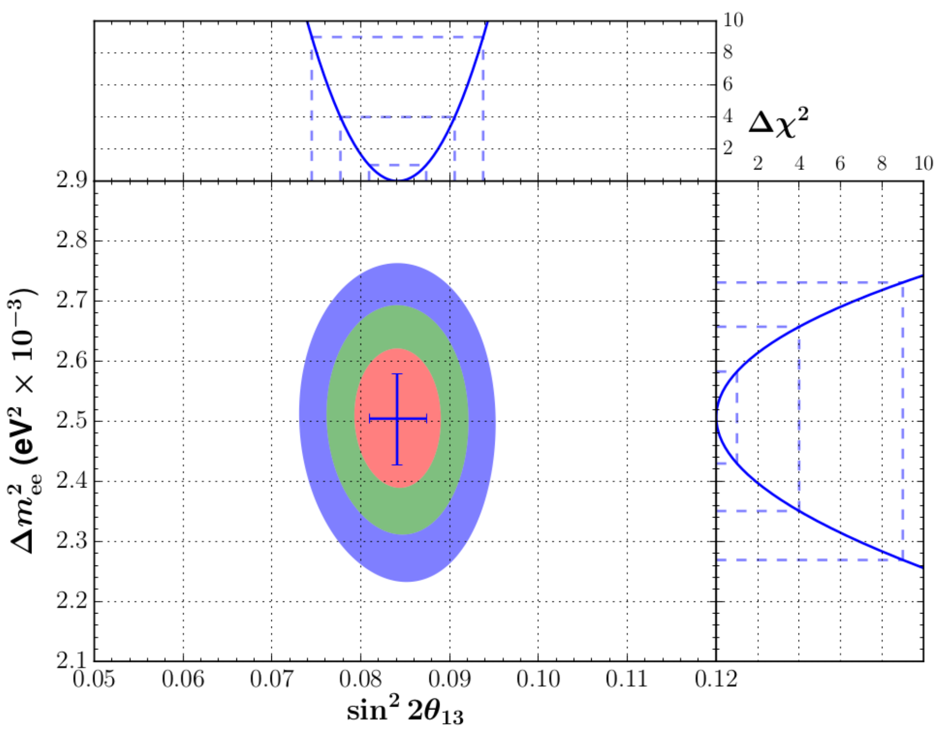
- Near det.: ~200 k events
- Far det.: ~80 k events

θ_{13} with reactor experiments

Daya Bay

(arXiv:1610.04802v1 / 1230 days)

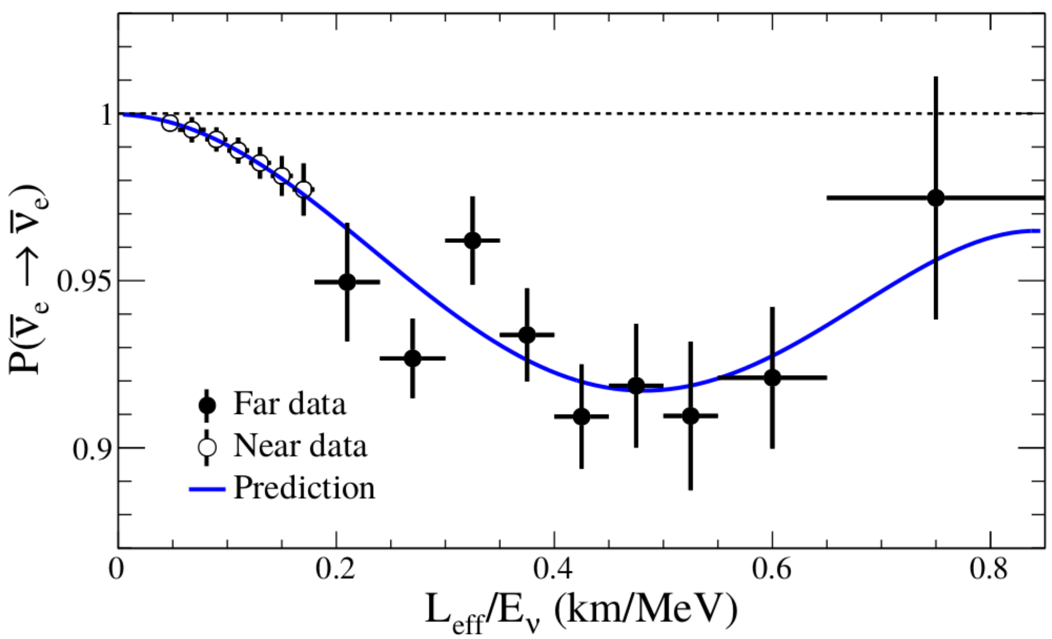


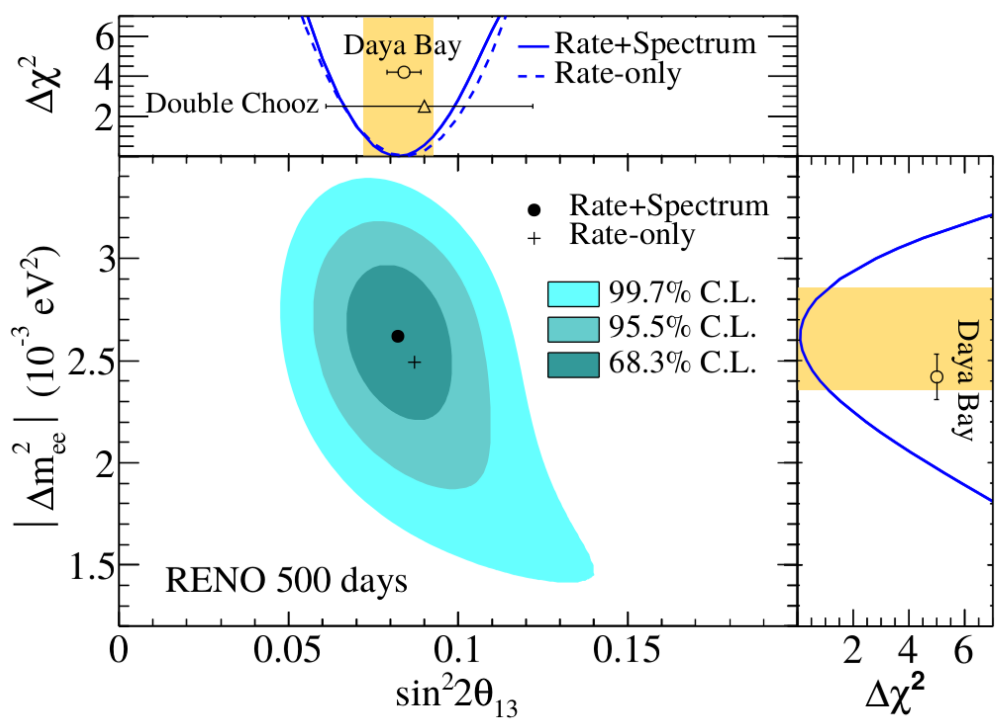


$$\sin^2(2\theta_{13}) = 0.084 \pm 0.003$$
$$|\Delta m^2_{ee}| = (2.50 \pm 0.08)\mathrm{eV}^2$$

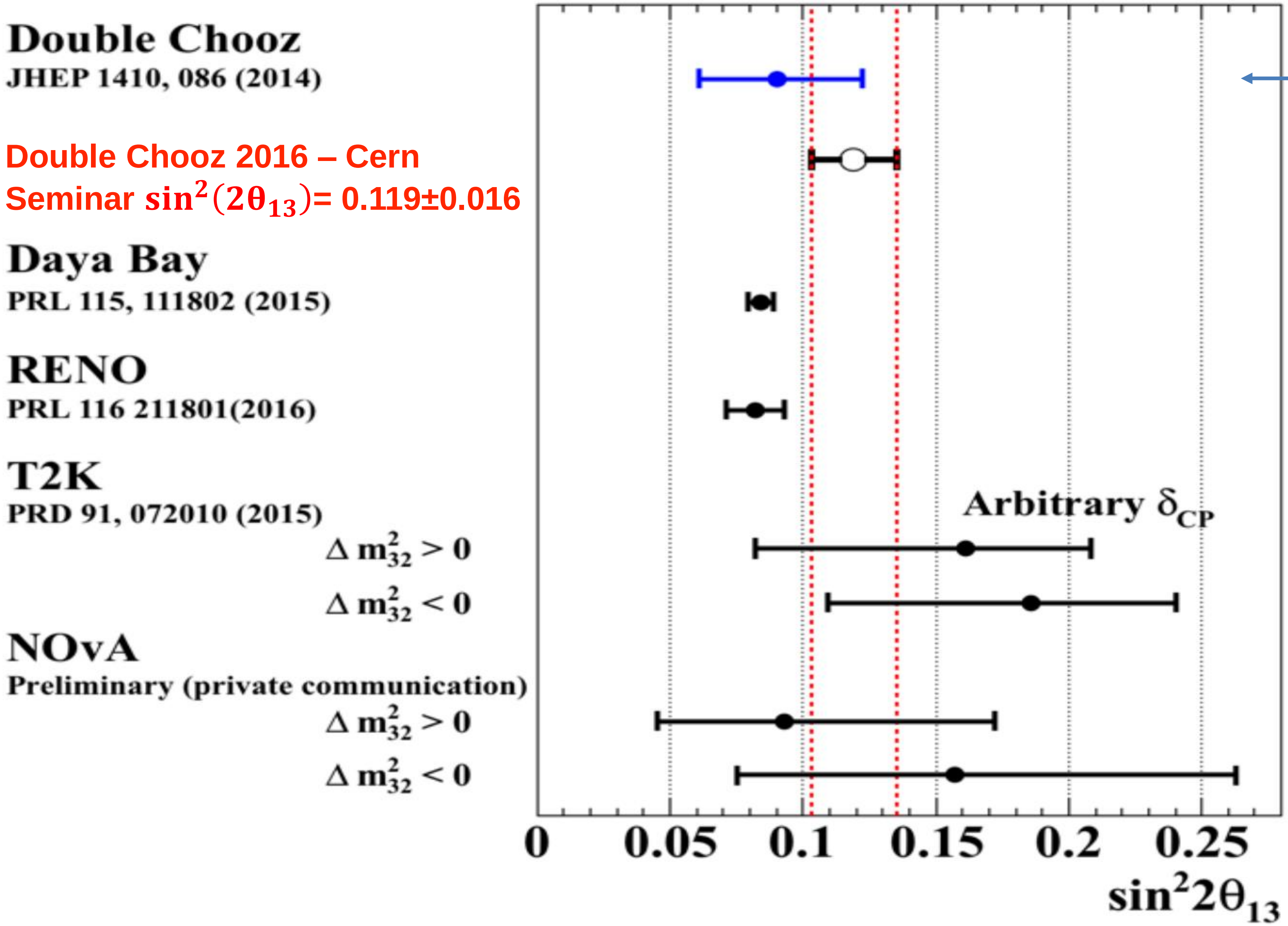
RENO

(Phys. Rev. Lett. 116, 211801 / 500 days)





$$\sin^2(2\theta_{13}) = 0.082 \pm 0.010$$
$$|\Delta m^2_{ee}| = (2.62 \pm 0.24)\mathrm{eV}^2$$



Double Chooz 2016 – Cern Seminar $\sin^2(2\theta_{13})$= 0.119±0.016

Last Double Chooz result in single detector configuration (flux systematic dominated)

- Double Chooz value is 2.2σ above Daya Bay

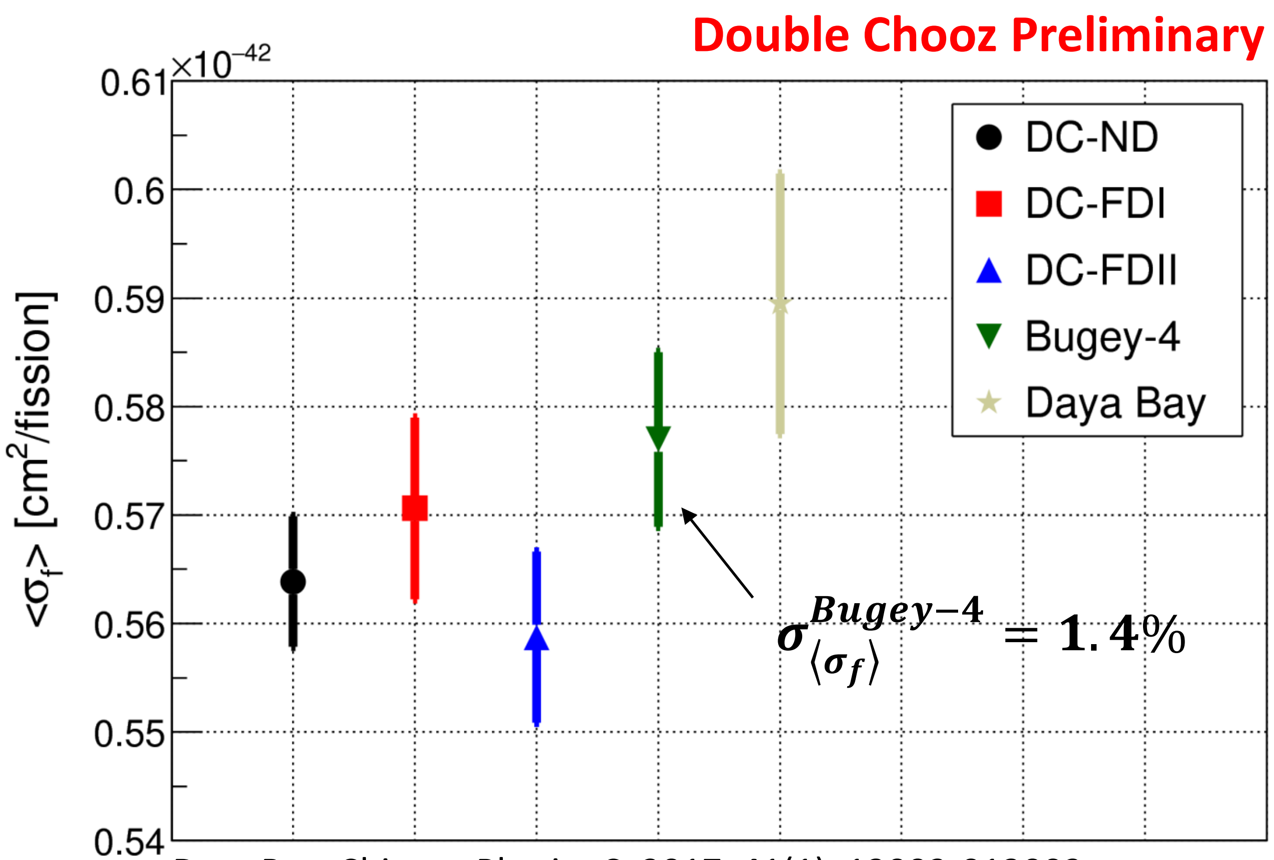
Reactor flux characterization

Reactor rate characterization:

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



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

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

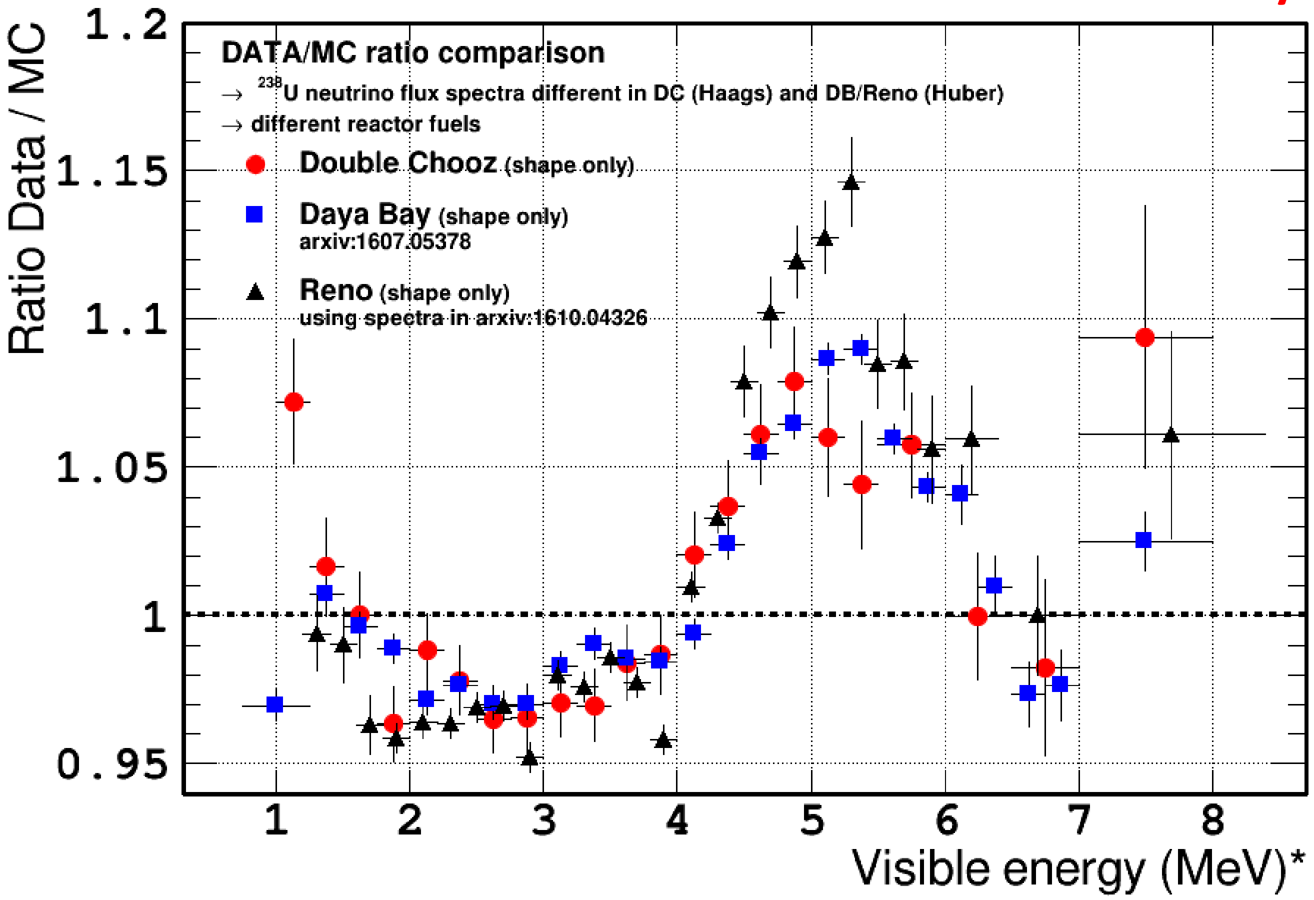
$$\langle \sigma_f \rangle^{ND} = (5.64 \pm 0.06) \times 10^{-42} \text{cm}^2/\text{fission}$$

Relative error: 1.1%

Reactor shape characterization: the [4,8] MeV distortion

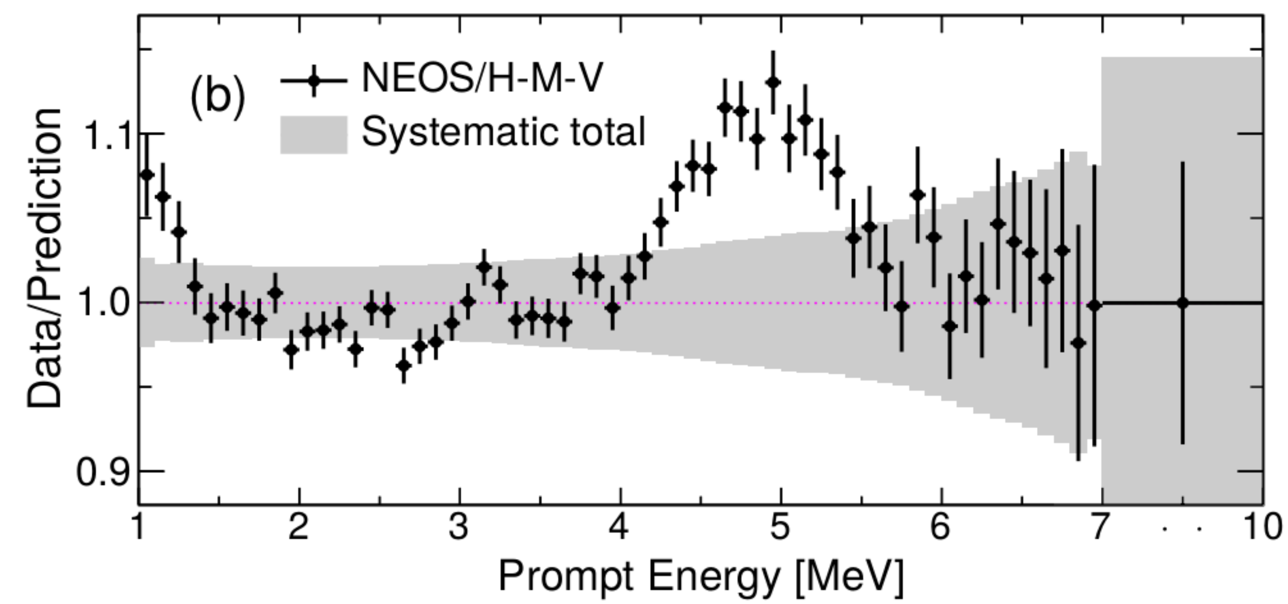
- All reactor experiments observed a spectral distortion between the expectation and the data

Double Chooz Preliminary



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

arXiv:1610.05134v3



NEOS experiment: - 24m of 2.8GWth PWR
- 1ton of Gd-loaded liquid scintillator

- Normalized ratio: only shape distortion
- Reference antineutrino spectra: - ^{235}U, ^{239,241}Pu: Huber
  - ^{238}U: Huber (Day Bay/RENO/NEOS), Haag (DC)

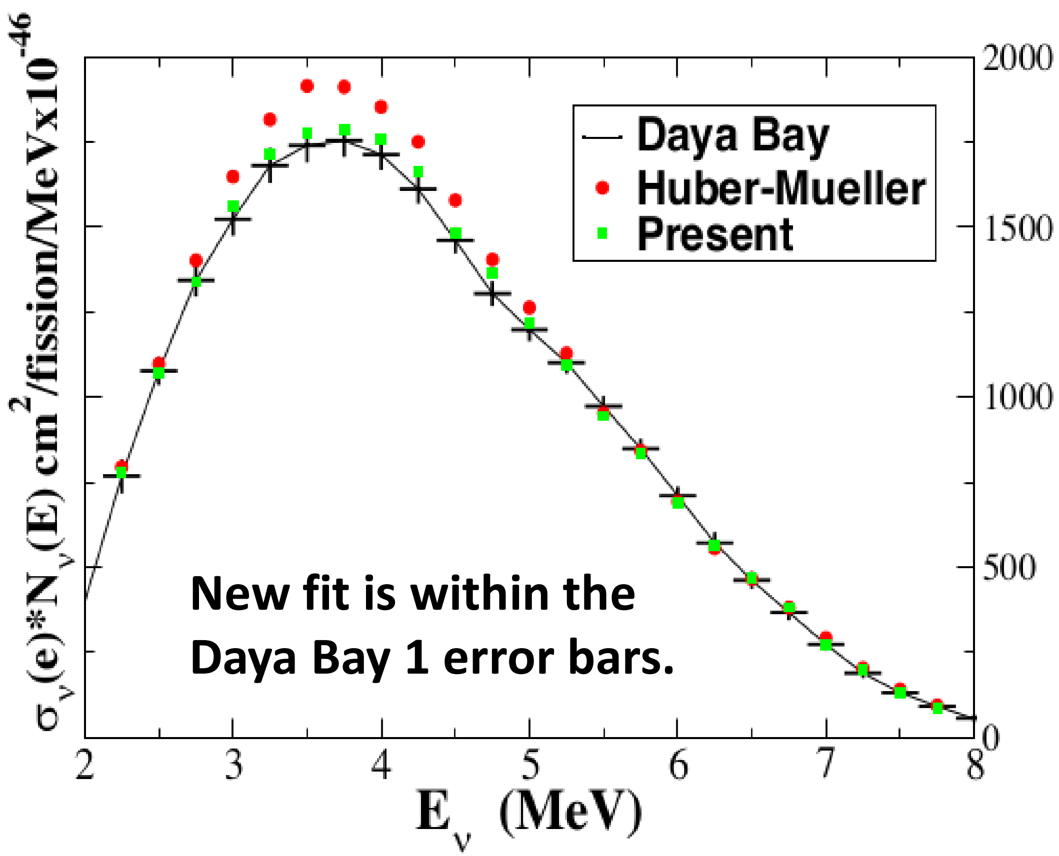
↳ Maximal effect: $\leq$ 2% in the range [1, 7] MeV

Reactor flux and shape characterization

Hypothesis for the distortion origin

From A. Hayes,
talk at ν-Phys2016

- **Other background:**
  - excluded, distortion correlated with reactor thermal power
- **Antineutrinos produce by non-fission sources of antineutrinos in the reactor:**
  - excluded from MC study with MCNP
- **Harder PWR spectrum**
  - Not excluded even if not predicted by standard fission theory
- **Conversion of β-spectrum from ILL measurements based on the Z of the fission fragments: treatment of Z in the conversion**
  - possible: recent dedicated study from A. Hayes
- **Error in the ILL β-decay measurements**
  - ‘Unlikely’
- **^{238}U responsible of the shoulder**
  - possible. More experiments required to validate / invalidate



Simultaneous fit to Daya Bay and the beta spectra, with improved description of the average charge Z, significantly lowers the Anomaly

Better understanding and characterization of the distortion can be achieved with:

↳ Experiments at very short baseline of experimental reactors (^{235}U spectrum measurement)

↳ Study of the distortion with time (i.e. fuel inventory) with commercial reactors

Conclusion

Conclusion

- **Double taking data with both detectors since beginning of 2015**
  - ↳ 1st Preliminary results: Moriond 2015 conference (mars. 2016) – 9 months
  - ↳ 2nd Preliminary results: released at a Cern seminar (sept. 2016) – 12 months

⇒ Strong reduction of flux systematics and statistic

- **New analysis:** IBD[Gd+H]
  - ↳ Immune to γ-Catcher contamination with Gd in the near detector
  - ↳ Improved statistic: $\sim \times 2.5$
  - ↳ New measurement of $\sin^2(2\theta_{13})$ based on a rate+shape fit

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

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

- **Additionnal results**
  - ↳ Precise measurement of the reactor IBD mean cross section per fission

$$\langle \sigma_f \rangle^{ND} = (5.64 \pm 0.06) \times 10^{-42} \text{cm}^2/\text{fission} \ (\sigma = 1.1\%)$$

  - ↳ Improved caracterization of the shape distortion between the prediction and the data

Thank you for your attention!