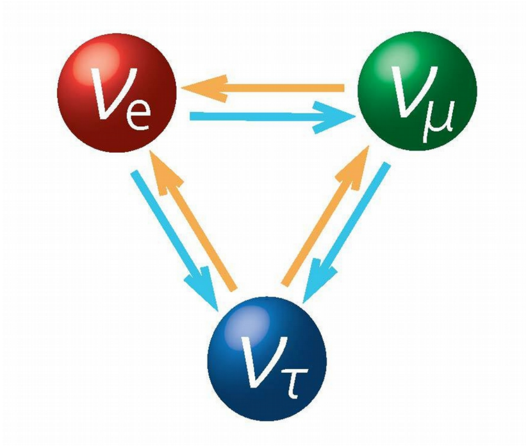
Double Chooz: θ_{13} measurement and Spectral shape analysis

LAPP, Annecy - February 10th 2017

Timothée Brugière
IPHC

Overview

- **Neutrino physics**
  - → Oscillations
  - → Recent results
  - → θ_{13} in the global picture



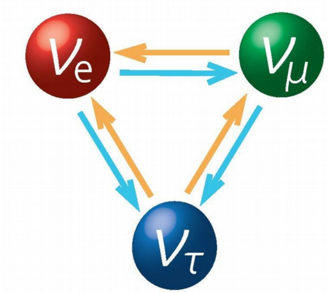
- **The Double Chooz experiment**
  - → General presentation
  - → θ_{13} measurement and results
  - → Reactor shape study

- **Conclusion and perspectives**

Neutrinos oscillations

Neutrino oscillations → The neutrino flavor periodically transforms to an other one

→ Analogy with quarks (simplified 2ν case: α, β = e, μ τ) :



$$i\frac{d}{dt}\begin{pmatrix}\nu_\alpha \\ \nu_\beta\end{pmatrix} = \frac{1}{\gamma}\begin{pmatrix}\mu_\alpha & \tau^*_{\alpha\beta} \\ \tau_{\alpha\beta} & \mu_\beta\end{pmatrix}\begin{pmatrix}\nu_\alpha \\ \nu_\beta\end{pmatrix}$$

Amplitude of the $\nu_\alpha \leftrightarrow \nu_\alpha$ transition (= neutrino masses if $\tau_{\alpha\beta}$=0)

Amplitude of the $\nu_\alpha \leftrightarrow \nu_\beta$ transition

→ Mass eigenstates ν_1 and ν_2 becomes a mixture of ν_α and ν_β :

$$\begin{pmatrix}|\nu_1> \\ |\nu_2>\end{pmatrix} = \begin{pmatrix}\cos\theta & -e^{-i\phi}\sin\theta \\ e^{-i\phi}\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}|\nu_\alpha> \\ |\nu_\beta>\end{pmatrix}$$

Mixing angle

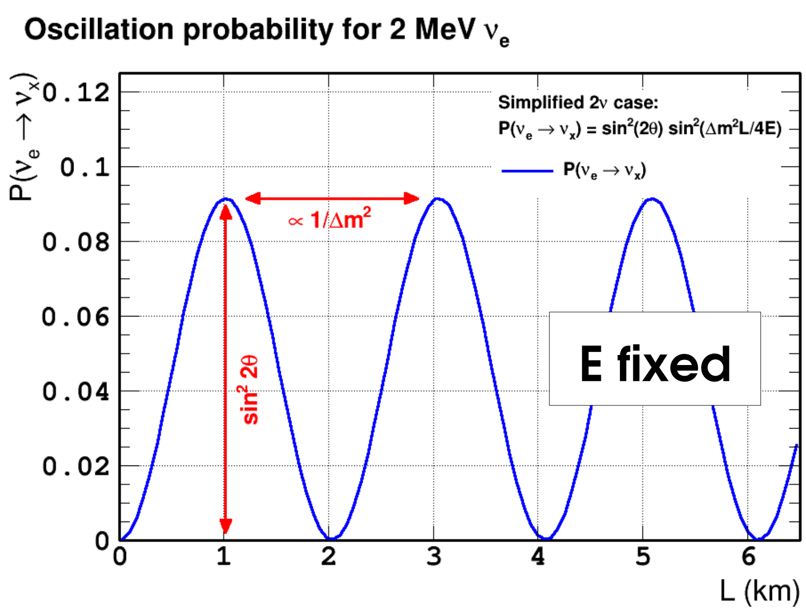
→ Relations between the mixing angle and neutrino masses :

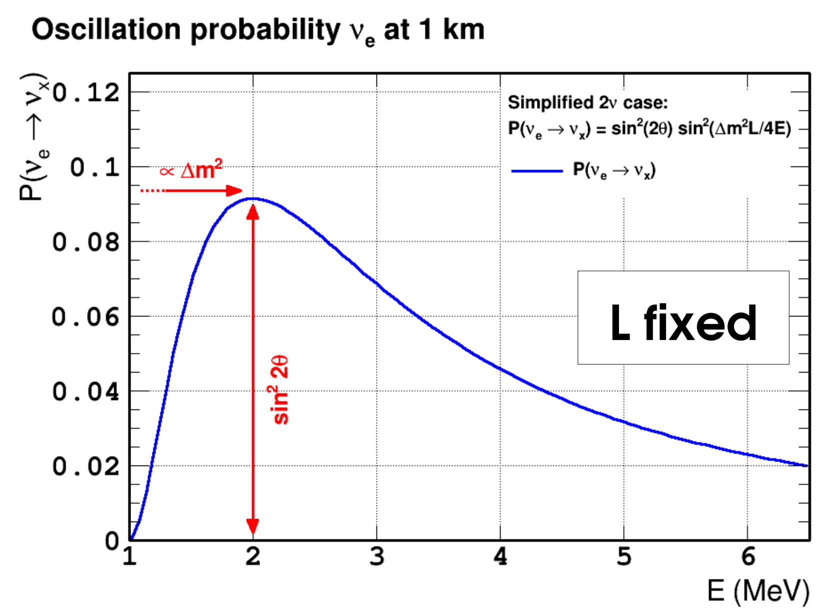
$$\tan 2\theta = \frac{2|\tau_{\alpha\beta}|}{\mu_\beta - \mu_\alpha} \qquad \begin{pmatrix}\mu_\alpha \\ \mu_\beta\end{pmatrix} = \begin{pmatrix}\cos^2\theta & \sin^2\theta \\ \sin^2\theta & \cos^2\theta\end{pmatrix}\begin{pmatrix}m_1 \\ m_2\end{pmatrix}$$

$$\Rightarrow \quad P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2\left((m_2^2 - m_1^2)\frac{L}{4E_\nu}\right)$$

Measuring the oscillation

Simplified 2ν case: $P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left((m_2^2 - m_1^2)\frac{L}{4E_\nu}\right)$

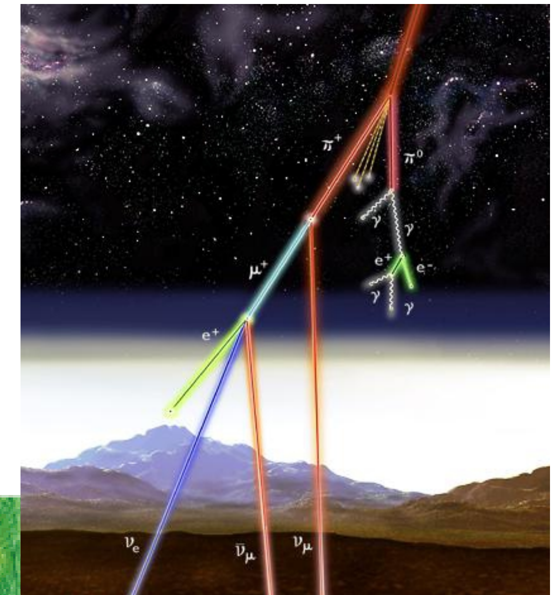


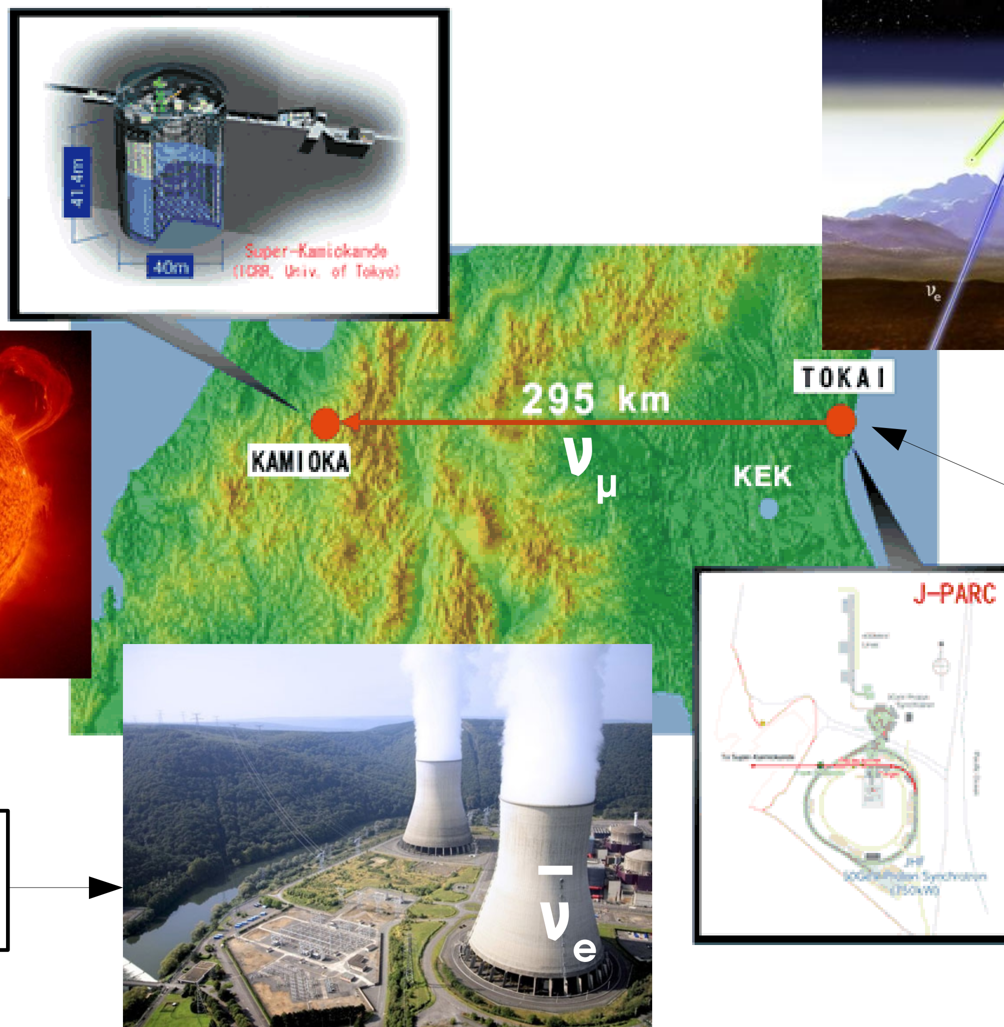


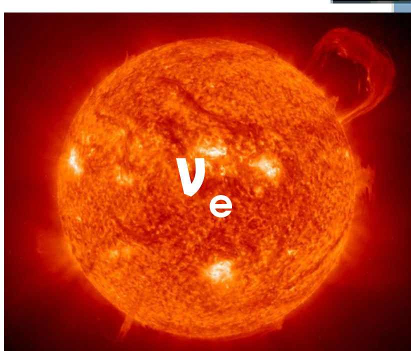
- Oscillation parameters:
  - → Mixing angles **θ** fix the oscillation amplitudes
  - → Squared mass differences **Δm^2** fix oscillation frequencies
- The L/E ratio (+ν flavor) defines the observed "sector": Atmospheric, Solar, Reactor

Measuring the oscillation

$$\nu_\alpha \xrightarrow[L]{E_\nu} \nu_\beta$$







Δm^2_{atm} , θ_{atm}

Δm^2_{sol} , θ_{sol}

Exploring the neutrino mixing

$$\underbrace{\nu_{\alpha L}}_{e,\,\mu,\,\tau} = \sum_i U_{\alpha i}\, \underbrace{\nu_{iL}}_{1,\,2,\,3}$$

Etats de saveurs — Etats de propagation

Oscillation parameters :
- → θ_{12}, θ_{13}, θ_{23}
- → Δm^2_{21}, Δm^2_{31}
- → δ_{CP}

$\Delta m^2_{ij} = m^2_i - m^2_j$

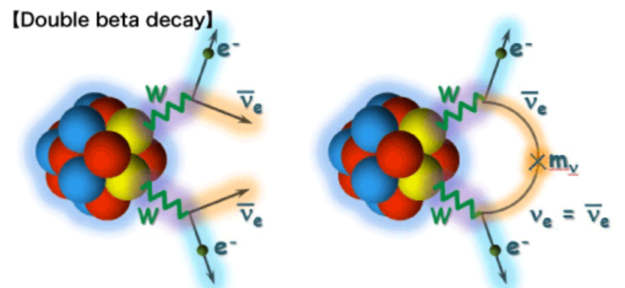
Oscillation physics

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

sub-leading — sub-leading

Atmospheric sector	Interference sector	Solar sector
Atmos. + LBL (dis.)	Reactor + LBL (app.)	Solar + KamLAND
$\nu_\mu \rightarrow \nu_\mu$	$\nu_e \rightarrow \nu_e$ & $\nu_\mu \rightarrow \nu_e$	$\nu_e \rightarrow \nu_x$

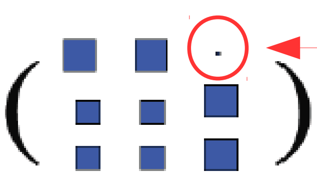
0νββ



Double beta decay which emits anti-neutrinos

Neutrinoless double beta decay

U looks like:



θ_{13} drives this !

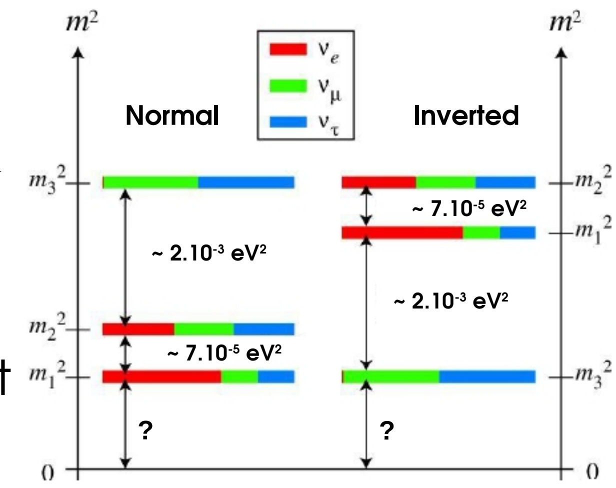
$c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$

Exploring the neutrino mixing

Next important steps:

→ Mass hierarchy ($m_1<m_2<m_3$?), θ_{23} octant

→ δ_{CP}



δ_{CP} measurement:

→ Matter - antimatter asymmetry (leptogenesis)

→ CP violation effect proportional to the Jarlskog invariant

$$J = s_{12}c_{12}s_{23}c_{23}s_{13}c_{13}^2 \times \sin\delta_{CP}$$

→ Observed in quark mixing: but too small (J_q ~ 3 10^{-5})

→ Could be large enough in neutrino mixing

$$J_\nu \sim 0.12 \times \cos\theta_{13}\sin 2\theta_{13} \times \sin\delta_{CP}$$
$$\sim 0.036 \times \sin\delta_{CP}$$

→ Need of a model independent measurement, from the difference between an **oscillation** and its **CP-inverted oscillation.**

→ Eg: $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ in a long-baseline accelerator **appearance** experiment

$$\frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \sim \frac{0.087}{\sin 2\theta_{13}}\sin\delta_{CP}$$

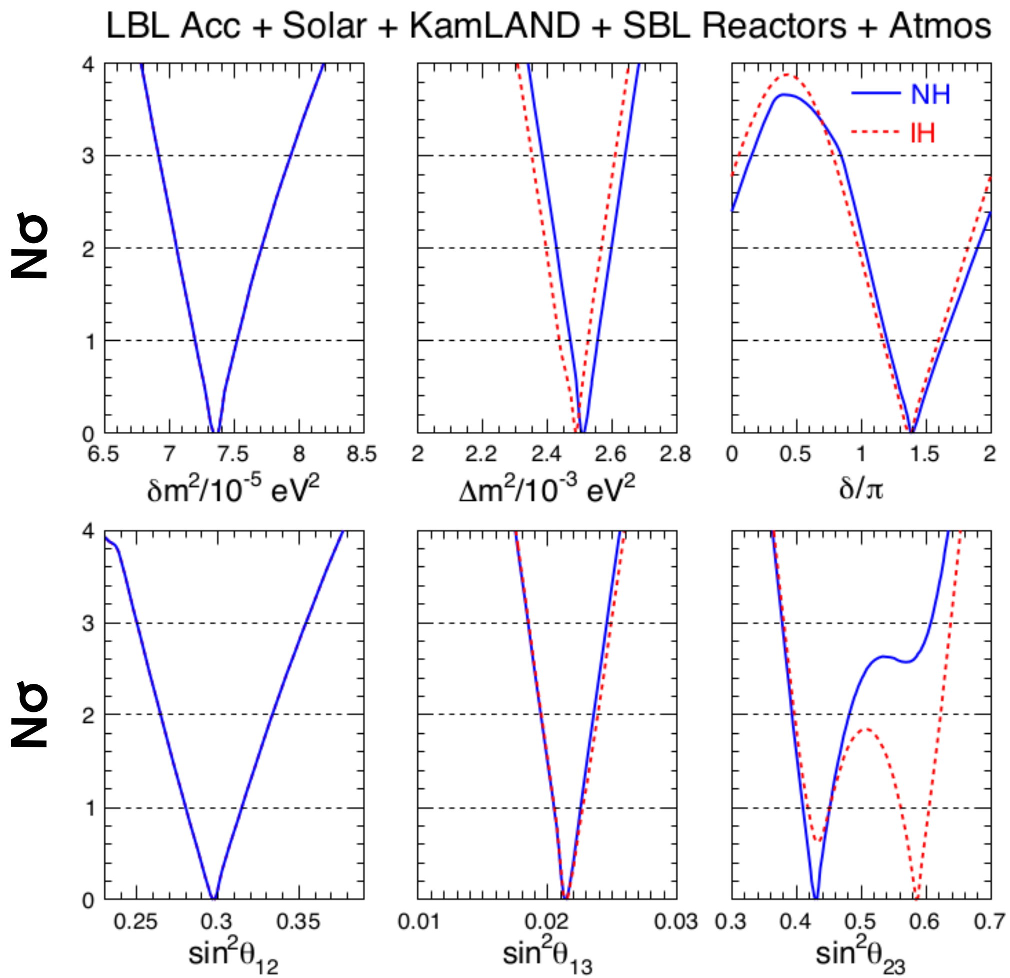
θ_{13} → key parameter for the feasibility of the future experiments

Global picture

A. Marrone et al. @ Neutrino 2016

Bounds on single oscillation parameters

(preliminary @ Neutrino 2016)



CP phase

- δ_{CP} ~ 1.4π at best fit
- CP-conserving cases (0, π) disfavored at ~2σ or more
- Significant fraction of the (0,π) range disfavored at >3σ

θ_{23}

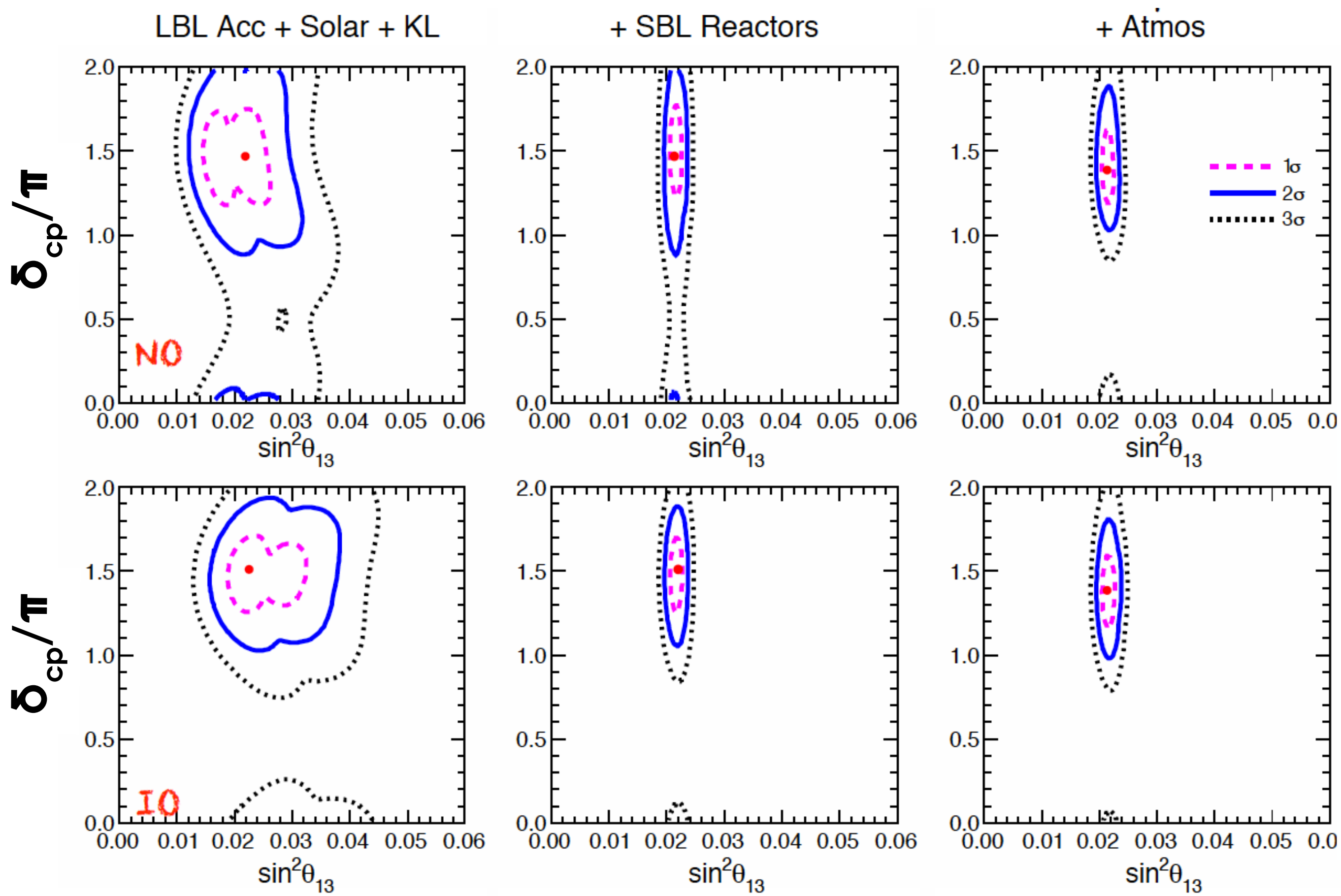
- Maximal mixing disfavored at ~2σ
- Best fit octant flips with mass ordering

Mass ordering

- $\Delta\chi^2_{IO-NO} = 3.1$
- Inverted ordering slightly disfavored

θ_{13} impact

A. Marrone et al. @ Neutrino 2016



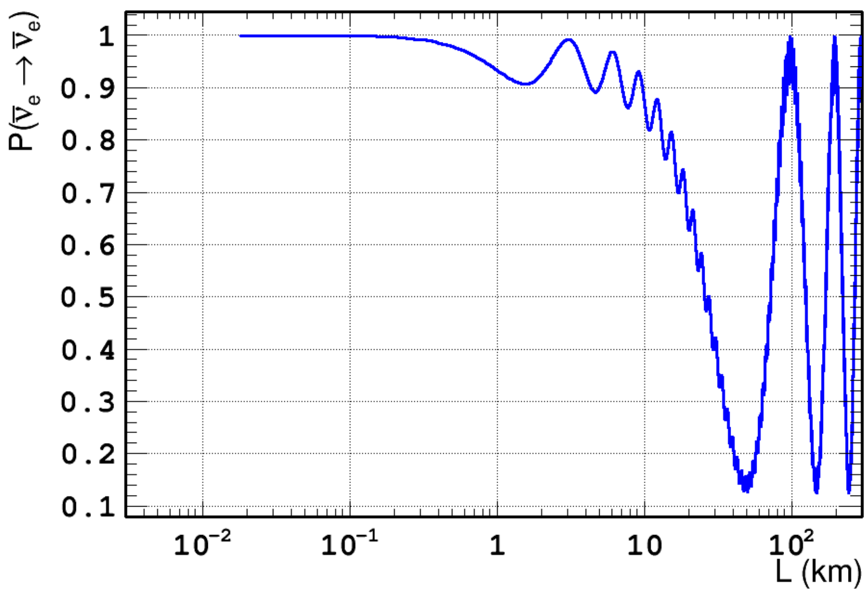
θ_{13} vs. δ_{CP}

- δ_{CP} ~ depends on θ_{13} in long baseline experiments (LBL)
- Maximal CP? ($\delta_{CP} = 3\pi/2$)
- **θ_{13} measurement (value and error) → critical implications !**

θ_{13} and the mass hierarchy

- θ_{13} value is large enough to be observed at medium distance from reactors:
  → Observation of both θ_{13} and θ_{12} (solar) driven oscillations with the same experiment

Non-oscillation probability for 3 MeV $\bar{\nu}_e$

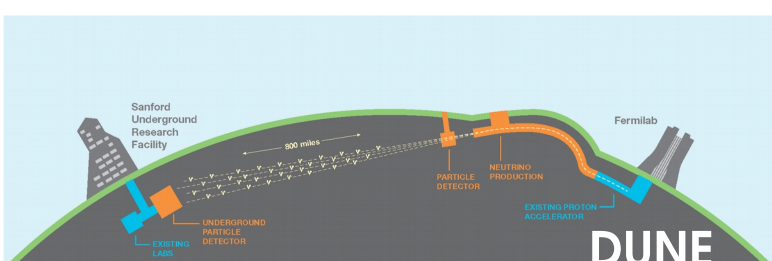


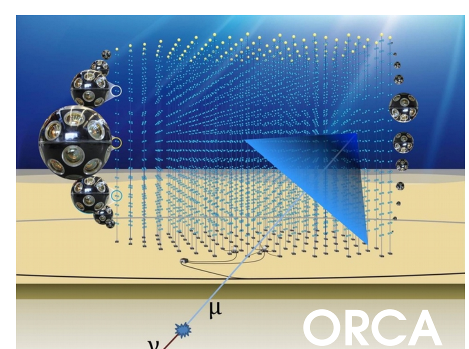
$$P_{ee} = 1 - \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21})$$
$$- \sin^2(2\theta_{13})\sin^2(\Delta_{31})$$
$$- \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{21})\cos(2|\Delta_{31}|)$$
$$\pm \frac{\sin^2(\theta_{12})}{2}\sin^2(2\theta_{13})\sin(2\Delta_{21})\sin(2|\Delta_{31}|).$$

$$\Delta_{ij} \equiv \frac{\delta m^2_{ij} L}{4E_\nu}, \quad (\delta m^2_{ij} \equiv m^2_i - m^2_j)$$

Measurement of the mass hierarchy independent from matter effects and δ_{CP}

→ not true with acc. or atm. experiments





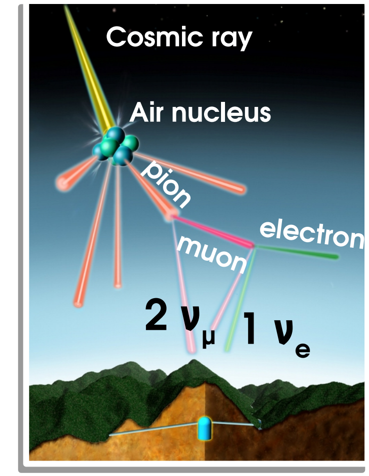
Why θ_{13} with reactor experiments?

- **1980's:** Atmospheric neutrino anomaly (Kamiokande, IMB, Soudan)
  - ν_μ/ν_e **ratio** lower than expected: oscillation $\nu_\mu \rightarrow \nu_e$?

2002

  → If yes: CPT inverted $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ **should exist at same L/E** !

  → **Reactor $\bar{\nu}_e$** ~ few MeV → L ~ few km



- **1990's:** Chooz and Palo Verde tried to observe $\bar{\nu}_e \rightarrow \bar{\nu}_e$
  - No significant deficit → $\sin^2 2\theta_{13} < 0.1$ (end of 90's)

- **1998:** SuperKamiokande → evidence of neutrino oscillation (atm.)

2015

- **2002:** SNO (solar) + KamLAND (reactor) measure solar oscillations

  → Possibility to measure δ_{CP} in long baseline experiments if θ_{13} is not too small:

$$P(\nu_\mu \to \nu_e) \sim \sin^2\theta_{23}\left(\frac{\sin 2\theta_{13}}{1-\rho_m L}\right)^2 - 0.04 \sin\delta_{CP}\frac{\sin 2\theta_{13}}{1-\rho_m L}$$

  → Sign of ρ_m depends on (ν_μ or $\bar{\nu}_\mu$) and on the mass hierarchy

  → Difficult to correct this fake CP asymmetry and measure δ_{CP} + θ_{13} with acc. only

- **2003:** measure θ_{13} with a reactor experiment using a 2-detectors configuration

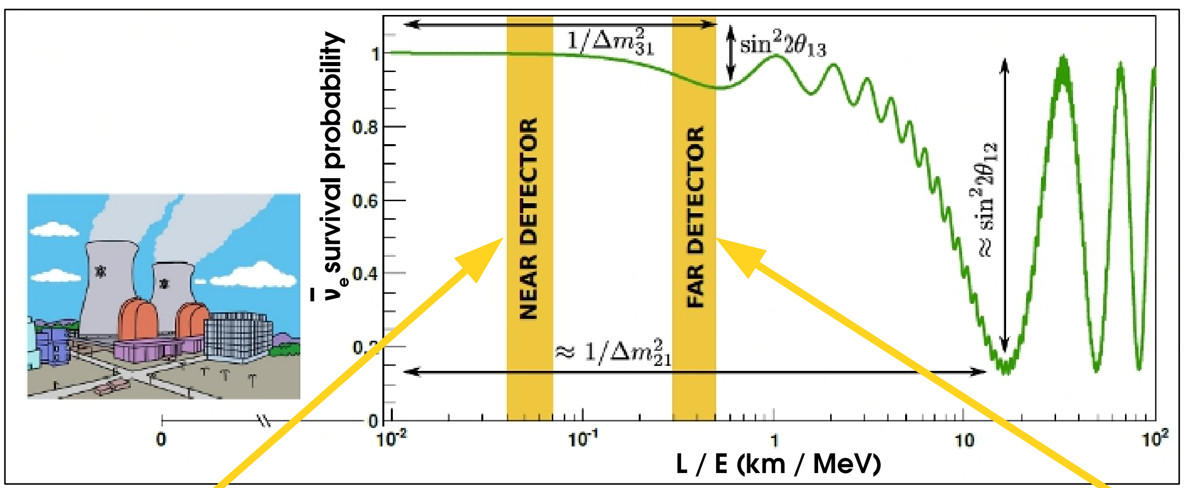
The Double Chooz experiment

Aim of the Double Chooz experiment:

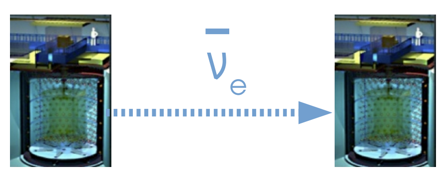
→ Measurement of θ_{13} through the observation of $\bar{\nu}_e \rightarrow \bar{\nu}_e$ transition according to the survival probability :

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + O(10^{-3}) \quad \text{for } L/E \lesssim 1$$

- **Reactors:** Pure $\bar{\nu}_e$, low energy, high intensity (10^{21} $\bar{\nu}_e$/s), "Cheap"
- **Short baseline** (~ 1km): no matter effect



Unoscillated flux & spectrum
→ Cancel flux and efficiency uncertainties



Oscillated flux & spectrum
→ θ_{13} measurement

→ Suppression of systematic uncertainties (<< 1%) with identical detectors

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

Spokesperson:
H. de Kerret (IN2P3)

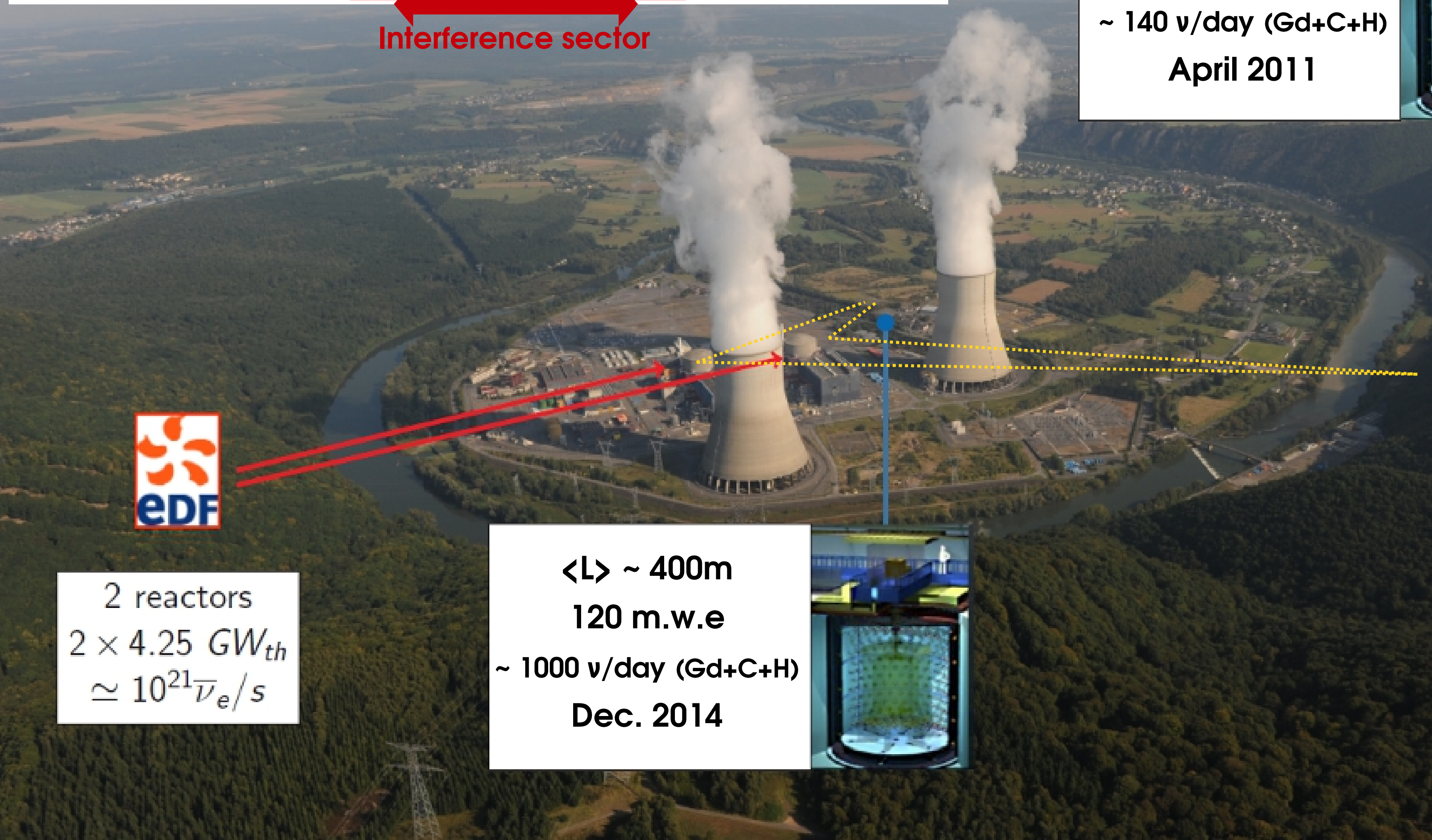
Project Manager:
Ch. Veyssière (CEA-Saclay)

Web Site:
www.doublechooz.org/

Power plant @ Chooz (France)

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Interference sector

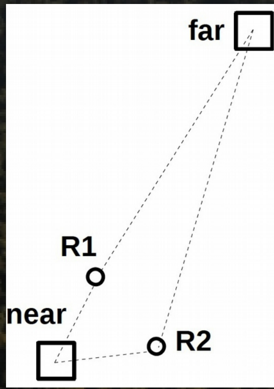


<L> ~ 1050m
300 m.w.e
~ 140 ν/day (Gd+C+H)
April 2011

<L> ~ 400m
120 m.w.e
~ 1000 ν/day (Gd+C+H)
Dec. 2014

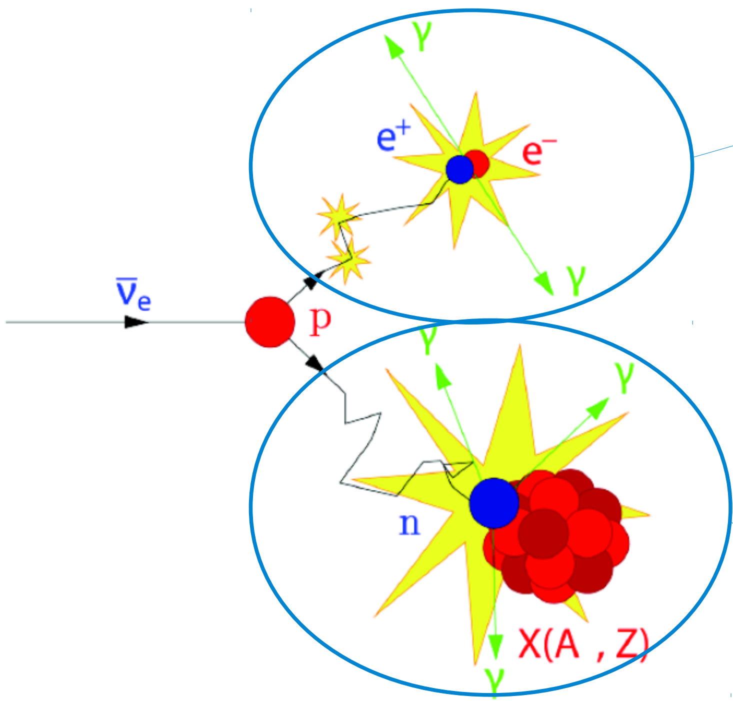
2 reactors
$2 \times 4.25\ GW_{th}$
$\simeq 10^{21} \overline{\nu}_e / s$

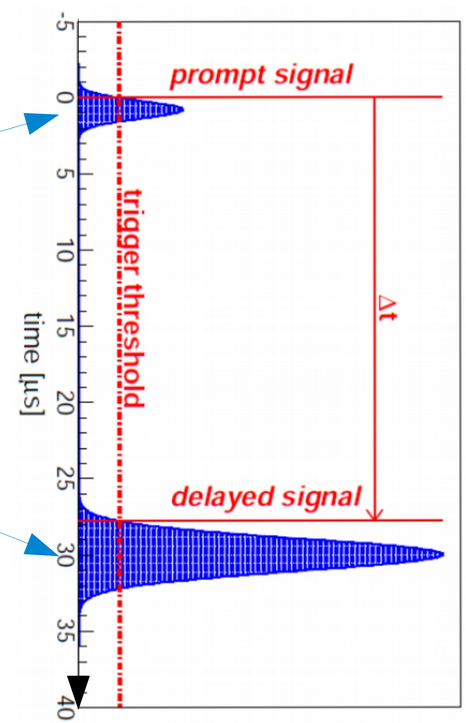
Site geometry
(~ iso-flux)



Inverse β decay (IBD)

IBD: $\bar{\nu}_e + p \rightarrow e^+ + n$ → **Clear twofold coincidence signature**





Prompt signal:

- e⁺ ionization and annihilation
- Energy proportional to E_ν

→ $\mathbf{E_{prompt} = E_\nu} - E_n - 0.8$ MeV

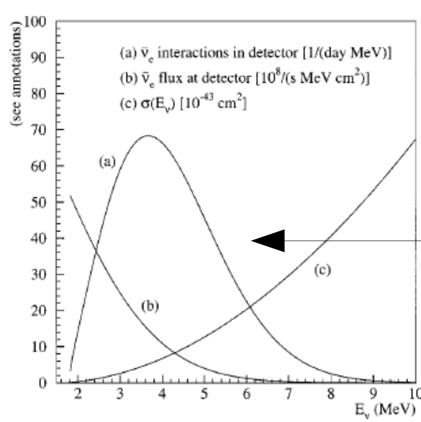
10-40 keV

Delayed signal:

- γ rays from neutron capture

→ On **Gd : 8 MeV / τ ~ 30µs**

→ On **H : 2.2 MeV / τ ~ 200µs**



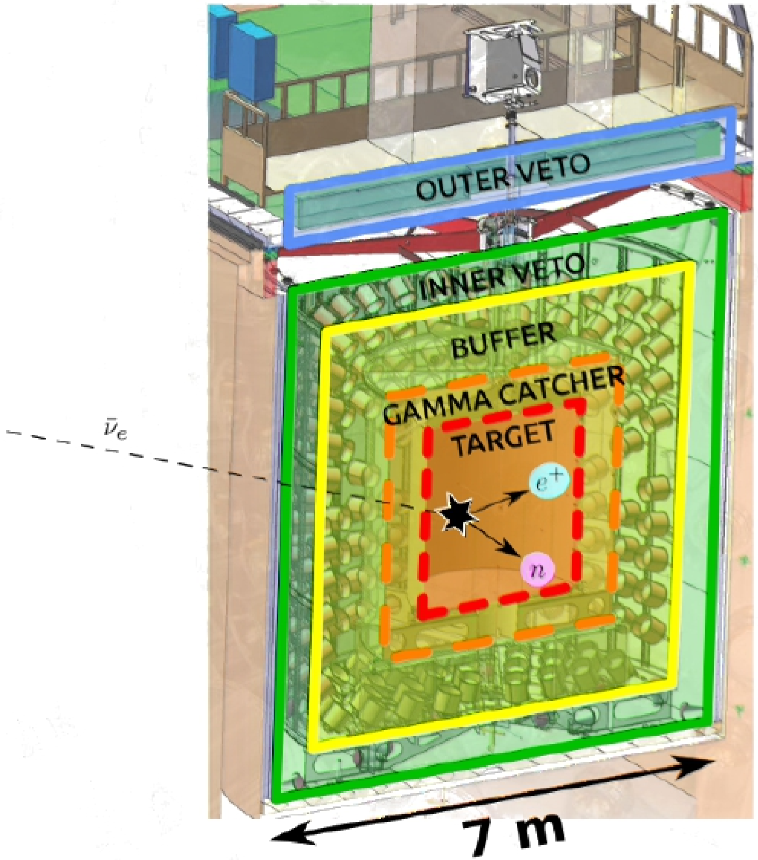
Detected $\bar{\nu}_e$ energy spectrum (if no oscillations)

The Double Chooz detectors

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

prompt signal: scintillation + e⁺ annihilation
$E_{prompt} \approx E(\nu_e) - 0.8$ MeV

delayed signal: γ ray(s) from neutron capture
n-Gd $E_{delayed} \approx 8.0$ MeV $\Delta T \approx$ 30 μs
or n-H $E_{delayed} \approx 2.2$ MeV $\Delta T \approx 200$ μs



Neutrino target:
liquid scintillator PXE + Gd

Gamma catcher:
liquid scintillator PXE (no Gd)

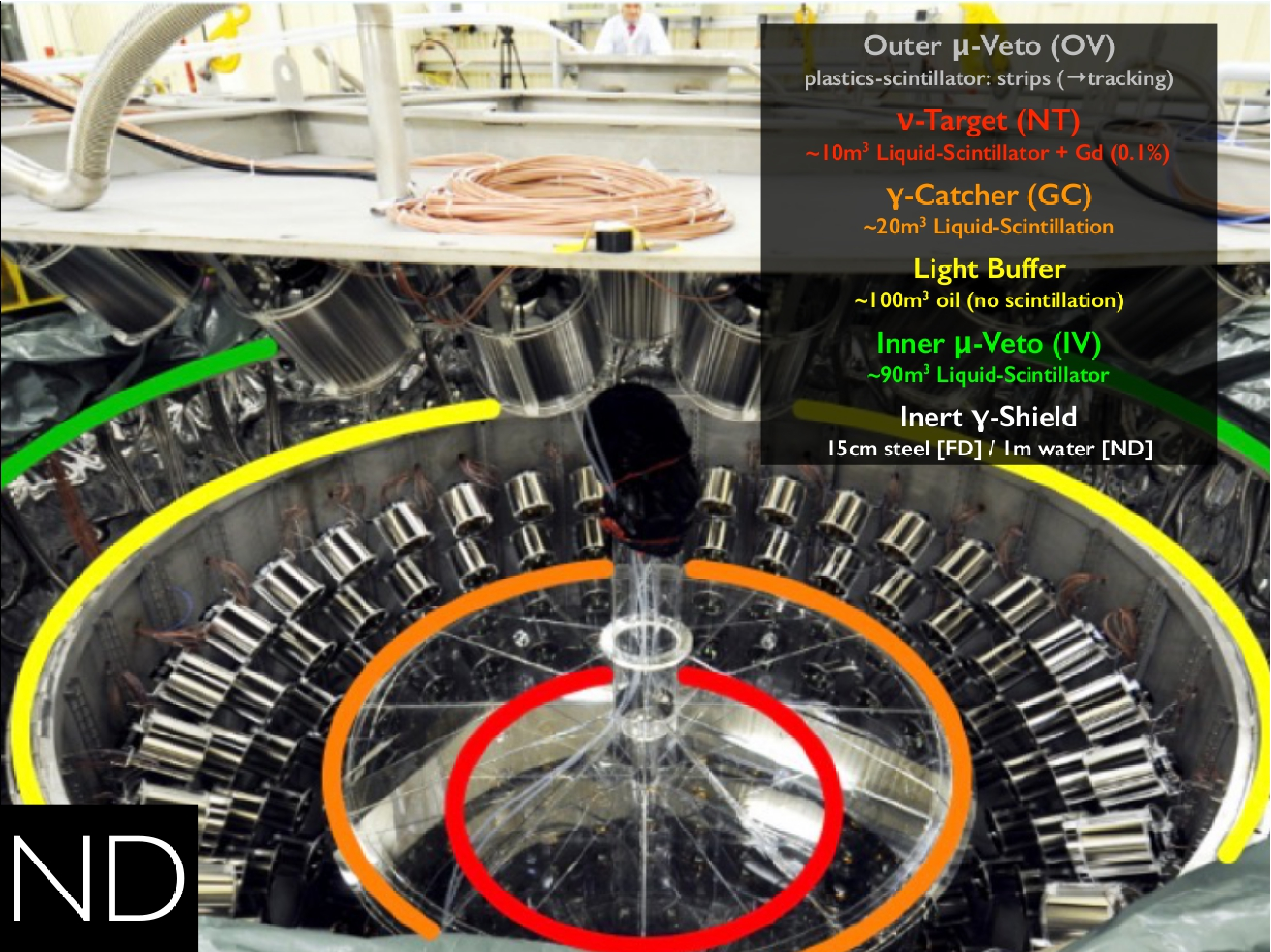
Buffer volume:
transparent mineral oil
with 390 x 10" PMTs assembly

(Neutrino target, Gamma catcher, Buffer volume: **Inner detector**)

Inner Veto:
liquid scintillator (LAB)
with 78 x PMTs 8"

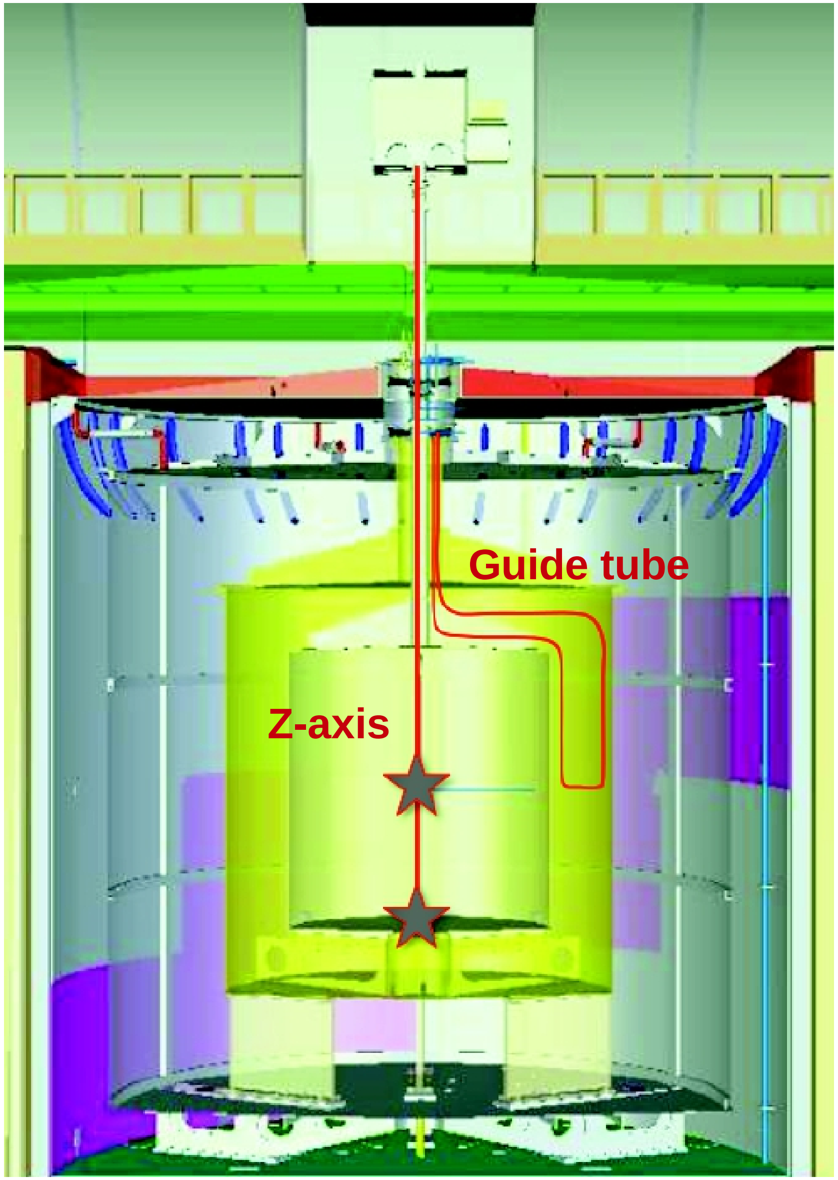
Outer Veto:
plastic scintillator strips

- **IBD threshold**: 1.8 MeV
- **Inert external Shielding**: @Far → 150 mm of steel / @Near → 1 m of water


Outer μ-Veto (OV)
plastics-scintillator: strips (→tracking)
ν-Target (NT)
~10m^3 Liquid-Scintillator + Gd (0.1%)
γ-Catcher (GC)
~20m^3 Liquid-Scintillation
Light Buffer
~100m^3 oil (no scintillation)
Inner μ-Veto (IV)
~90m^3 Liquid-Scintillator
Inert γ-Shield
15cm steel [FD] / 1m water [ND]
ND

Detector calibration

- **Light injection system:**
  - LED + Fibers
  - Multi-wavelength (≥ fiber per PMT)
  - PMT / scintillator calibration IV+ID
- **Source + LASER injection system:**
  - Radioactive sources
    - → γ (^{60}Co, ^{137}Cs, ^{68}Ge), neutron (^{252}Cf)
  - Target (chimney) + γ-catcher (guide tube)
  - LASER diffuser ball
- **Natural sources:**
  - Spallation n capture on *Gd, H, C*
  - α's from ^{210}Po decays

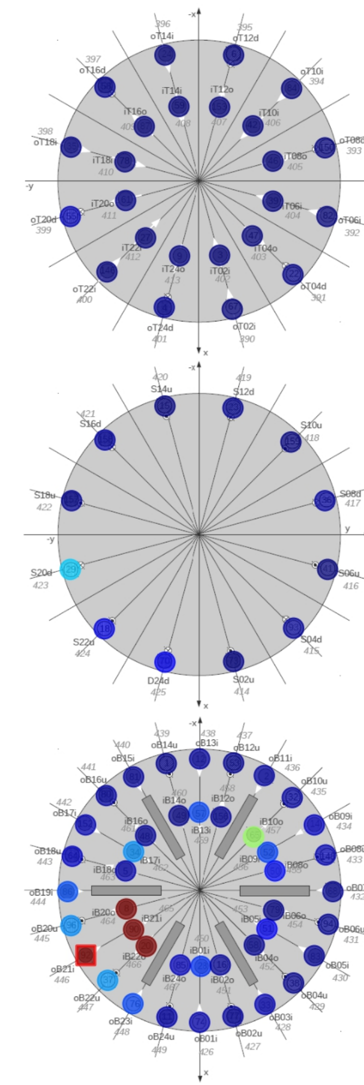


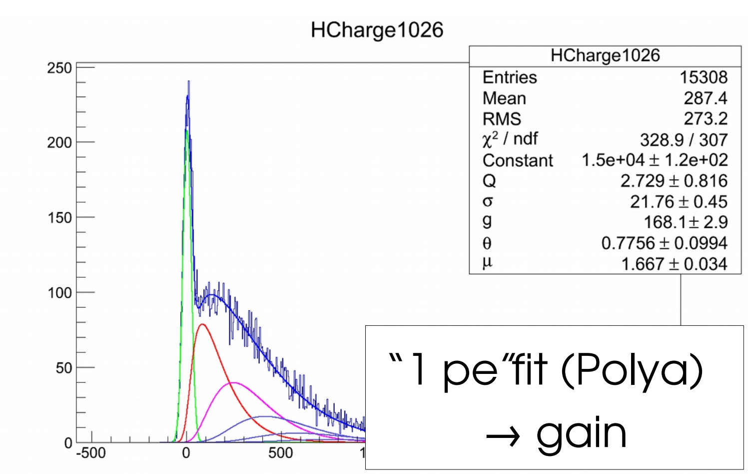
IVLI calibration system

- **Inner veto:**
  → 78 PMTs (24 top, 12 middle, 42 bottom)
- **IVLI system:**
  → 84 LED (+ 12 UV)

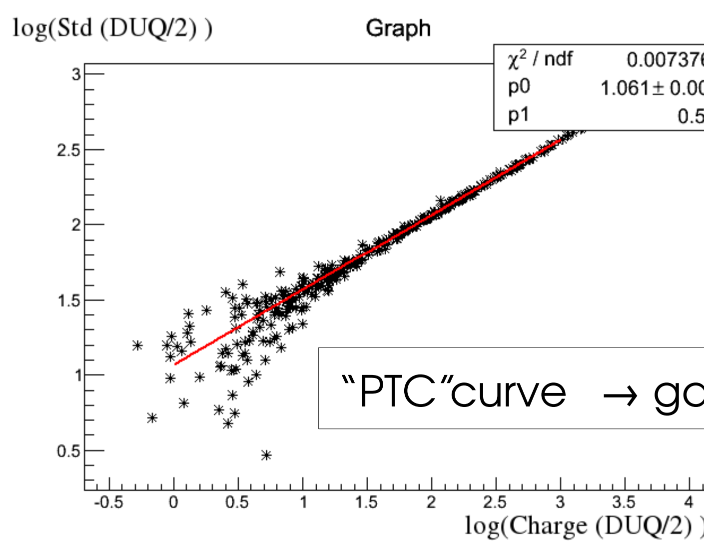
  - At least 1 LED / PMT
  - **Low intensity** runs → **gain** calibration
  - **High intensity** runs → **T_0** calibration
  - LED UV → scintillator response

→ Gain calibration every week !





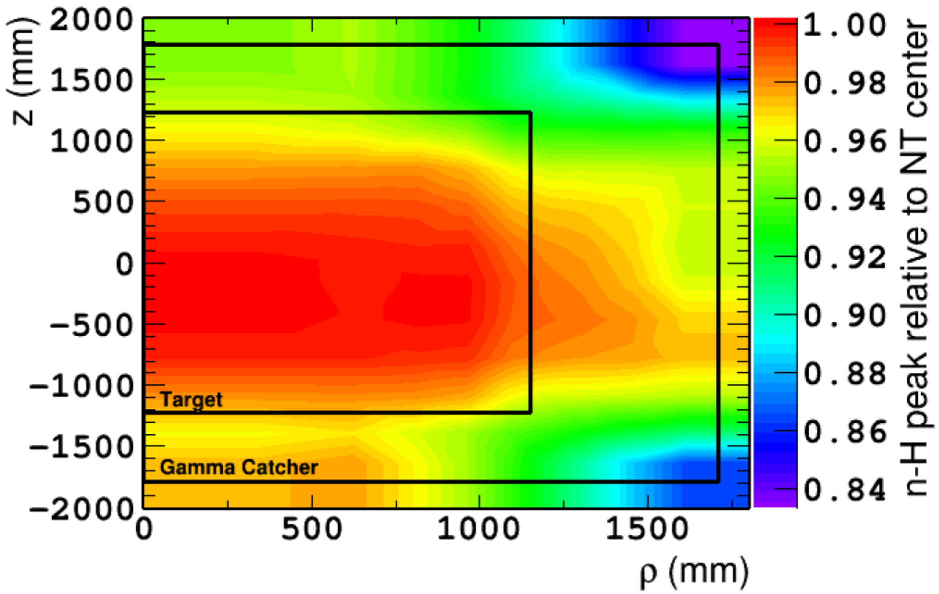
"1 pe" fit (Polya)
→ gain

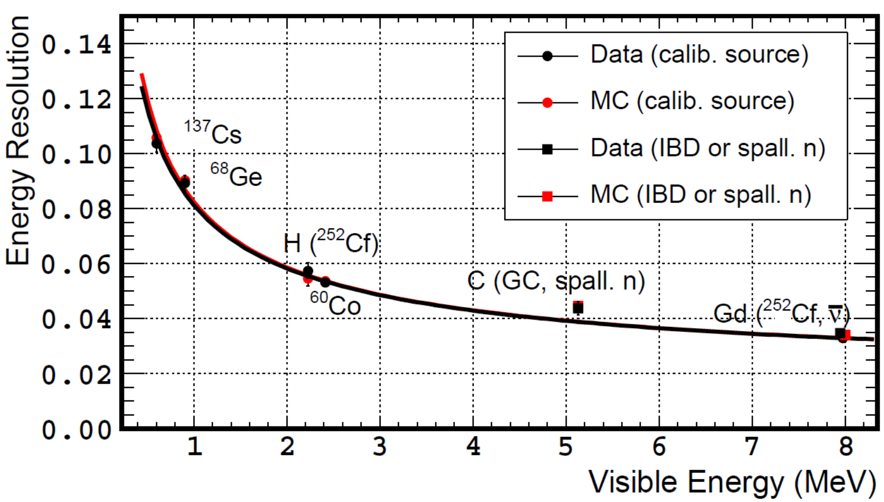


"PTC" curve → gain & linearity

Energy resolution

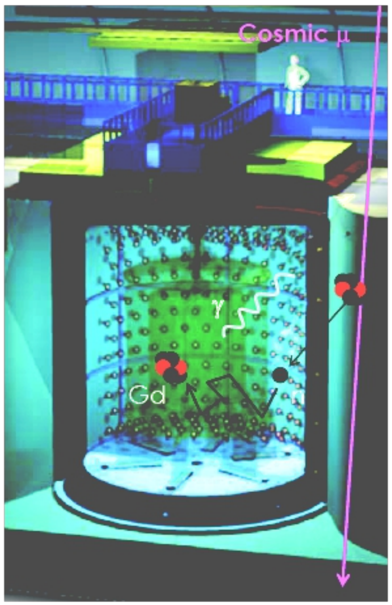
- **Linearized N_{pe}:**
  - Gain non-linearities at low charge
- **Uniformity correction:**
  - Position dependency of N_{pe} estimation
  - Map using neutron captures on H (2.2MeV)
- **Absolute energy scale alignment:**
  - Using 2.2 MeV peak of n from ^{252}Cf
- **Time stability (data only)**
  - Calibrate variation of mean gain
  - Weekly and monthly dedicated set of runs
- **Non-linearity (MC only)**
  - Read-out / scintillator model related





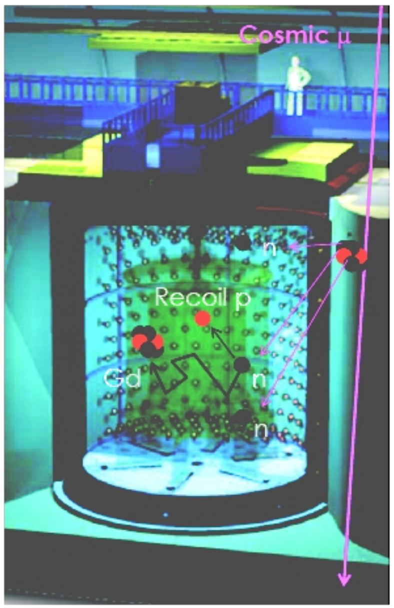
Background sources

Accidental BG

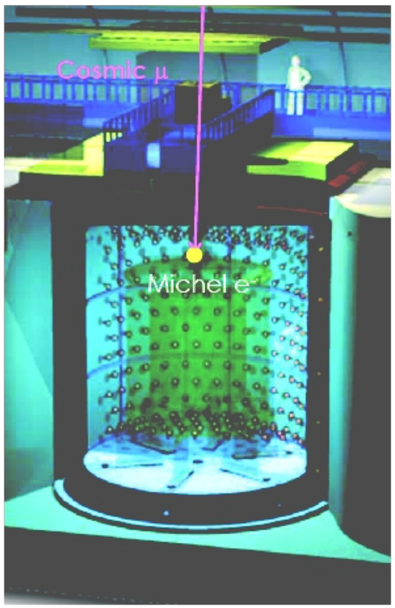


Correlated BG

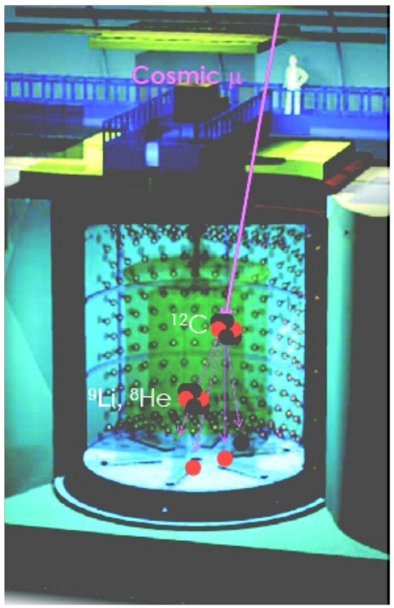
Fast neutrons



Stopping μ



Cosmogenics

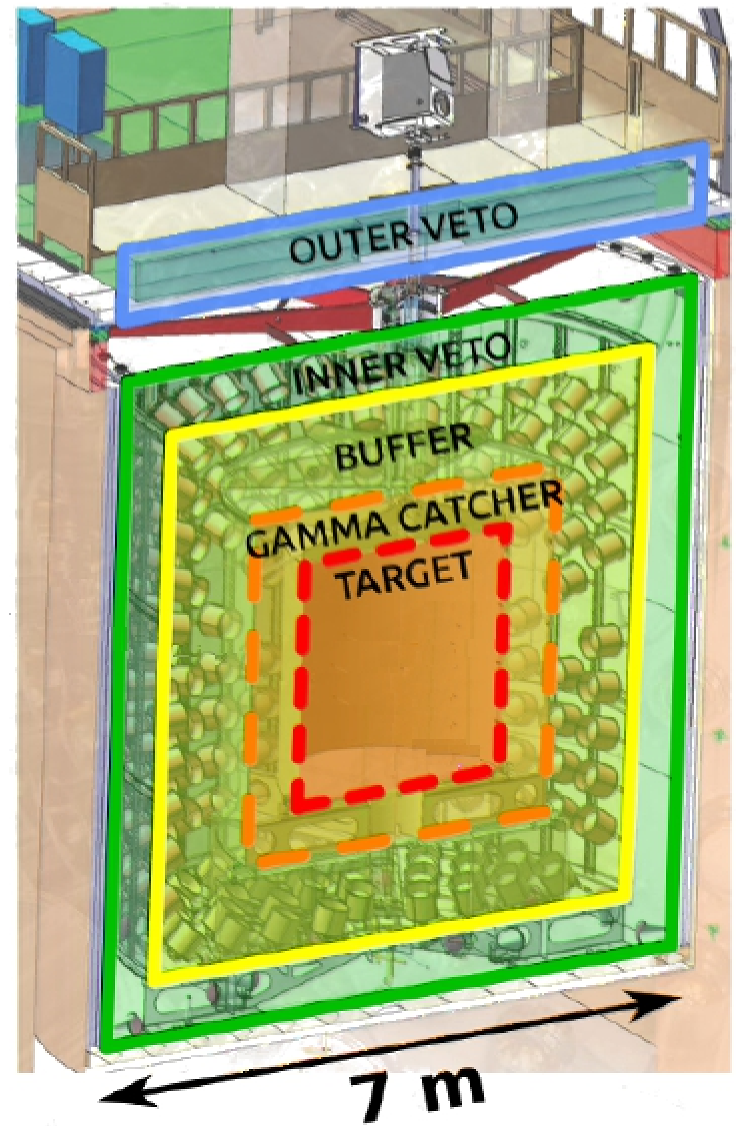


	Accidental BG	Fast neutrons	Stopping μ	Cosmogenics
Prompt	Radioactivity from materials, PMTs, surrounding rock (^{208}Tl).	Neutrons from cosmic μ spallation gives recoil protons (low energy).	Cosmic μ entering from the chimney.	Electrons from ^{9}Li/^{8}He β + n decays.
Delay	Neutrons from cosmic μ spallation captured on Gd/H, or γ like prompt fake signal in case of H analysis.	Neutrons from cosmic μ spallation captured on Gd/H, or γ like prompt fake signal in case of H analysis.	Michel electrons.	Neutrons from ^{9}Li/^{8}He β + n decays captured on Gd/H.

DC “singles” selection

Veto on single triggers:

- **Muon veto**
  → No triggers 1.25 ms after a muon
- **OV**
  → No coincidence with the Outer Veto
- **Li+He veto**
  → Likelihood trained on ^{12}B : 50% rejection
- **IV**
  → No coincidence with IV activity (fast n, stopped μ, γ scattering)
- **FV+CPS**
  → Stopped μ rejection
- **PMT light emission**
  → Rejection based on PMTs charge/time distribution



IBD candidates selection:

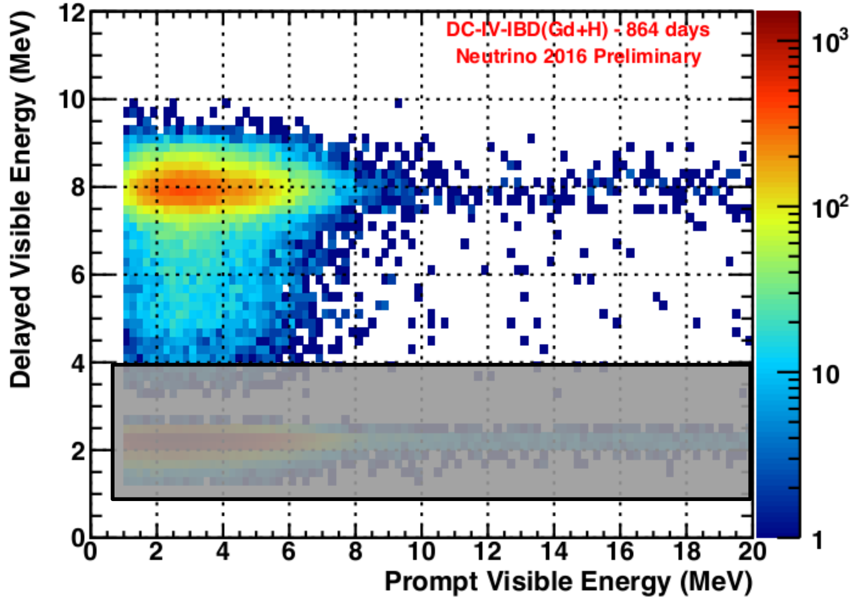
Prompt energy (1, 20) MeV

\+ **Isolation window** (prompt) (-800, +900) μs

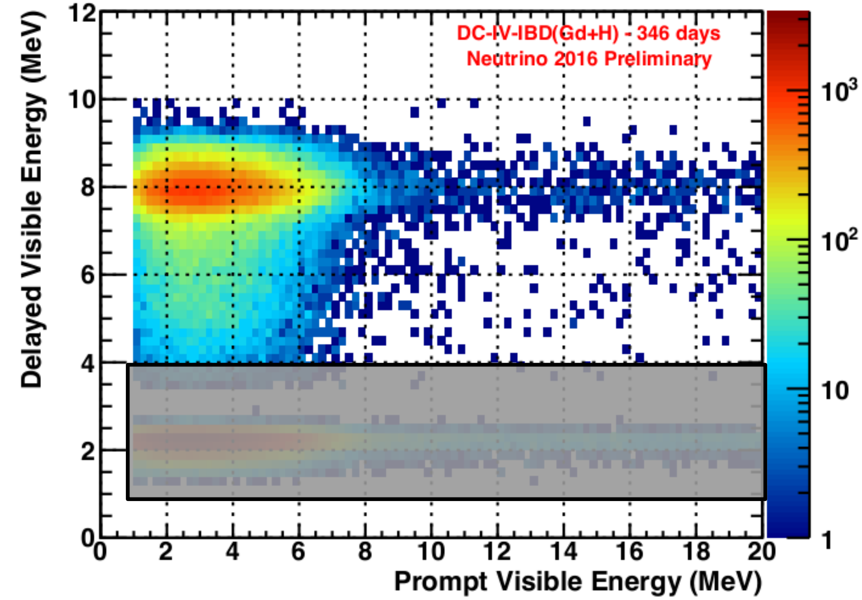
\+ **Multivariate cut →** Acc. vs. corr. events ID, see next slides

DC IBD selection

Far detector



Near detector



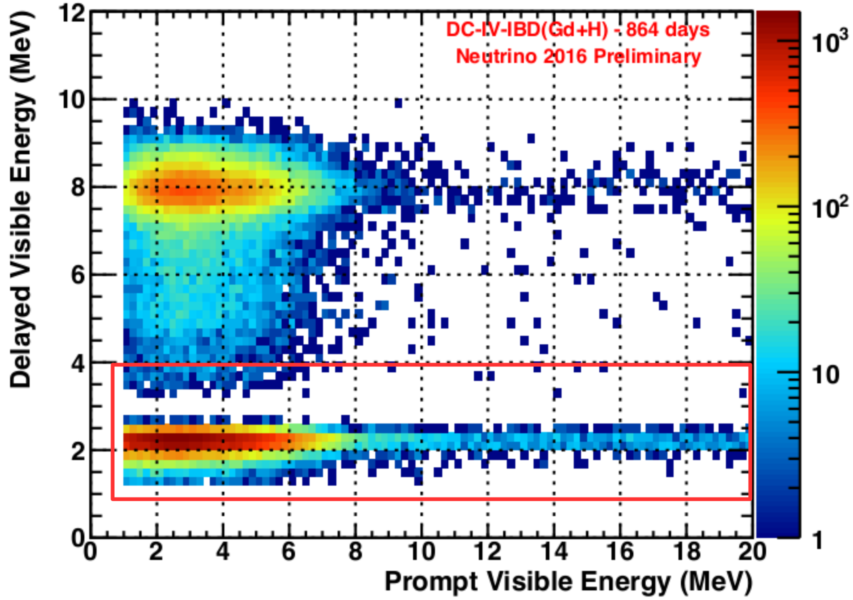
IBD (Gd+C)

Target:

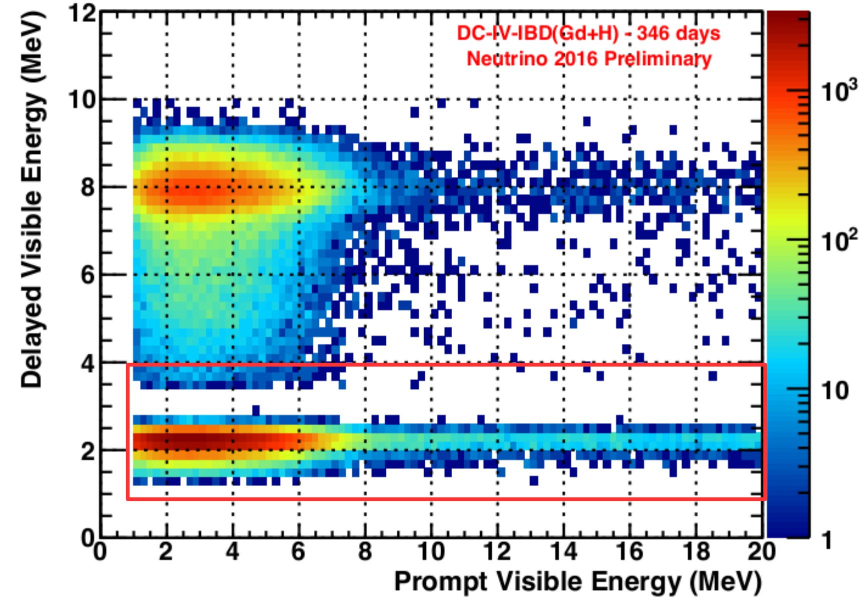
- **~ 8t**
- Smallest θ_{13} target

DC IBD selection

Far detector



Near detector

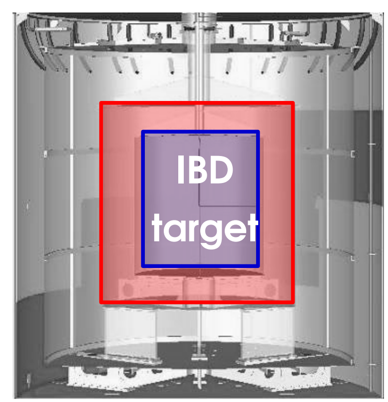


IBD (Gd+C)

Target:

- **~ 8t**
- Smallest θ_{13} target

IBD (Gd+C+H)

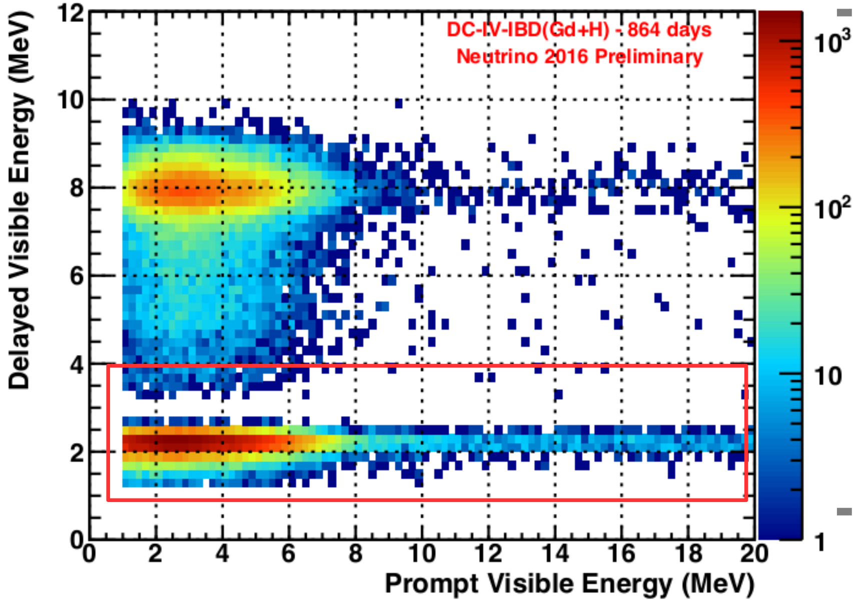


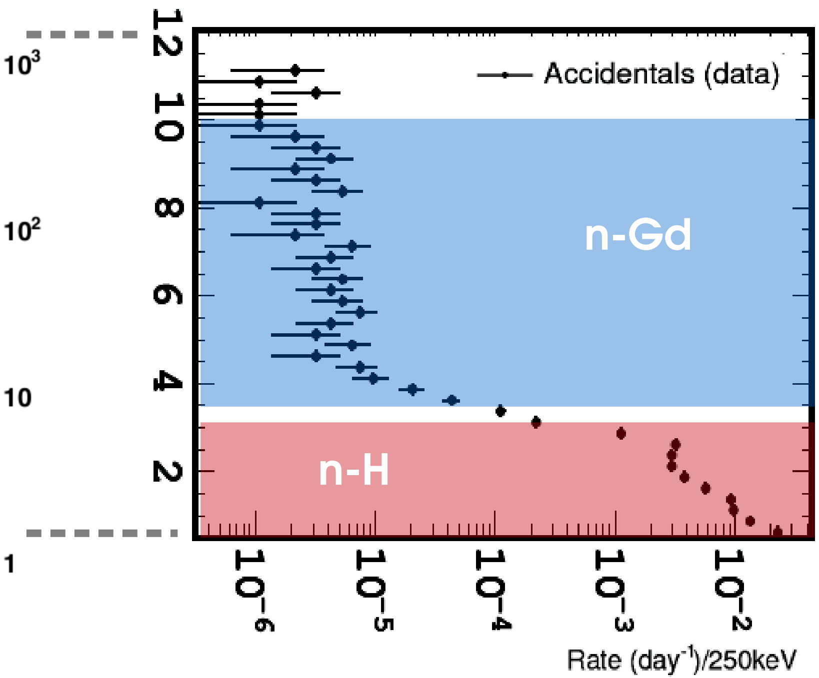
Target:

- **~ 30t**
- Largest θ_{13} target (for single detector)
- Gd-fraction independent

DC IBD selection

Far detector



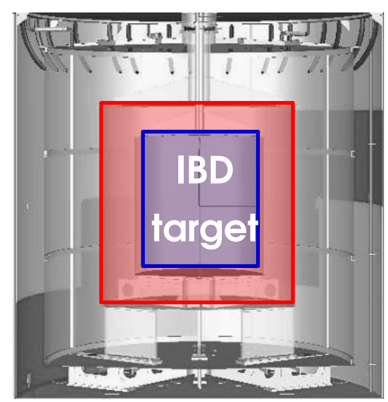


IBD (Gd+C)

Target:

- **~ 8t**
- Smallest θ_{13} target

IBD (Gd+C+H)



Target:

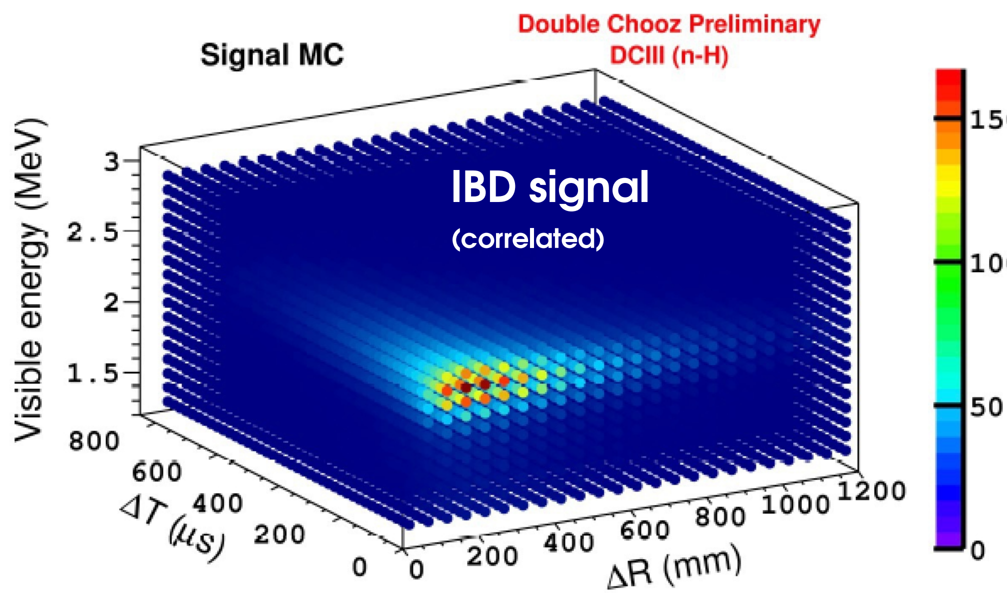
- **~ 30t**
- Largest θ_{13} target (for single detector)
- Gd-fraction independent
- But large accidental contribution around 2eV

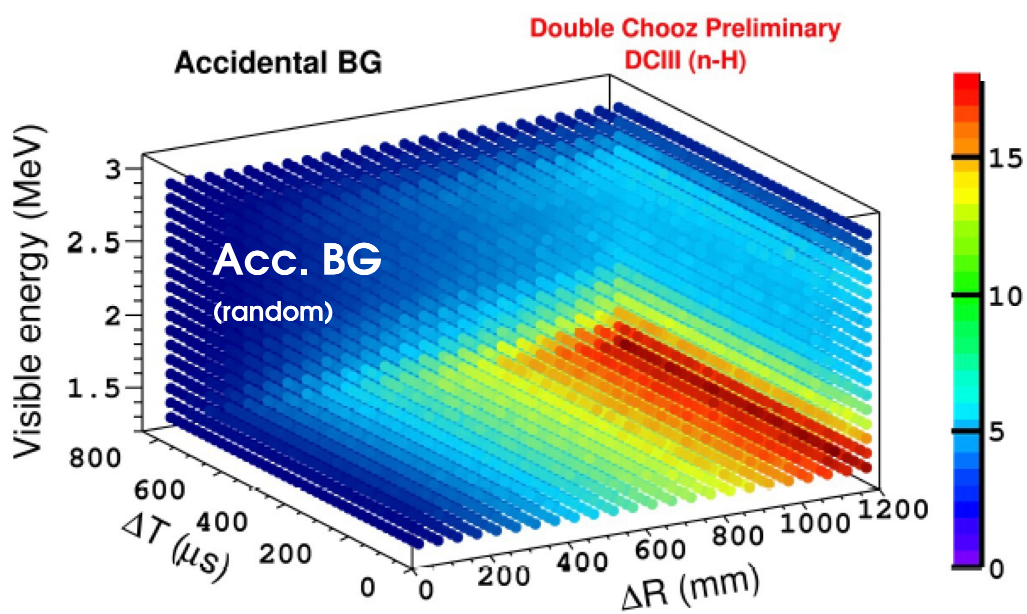
DC IBD selection

- Accidental rejection → Multivariate analysis (ANN) to reject random coincidences

Signal:

- Peak @ 2.2MeV
- Short ΔT
- Short ΔR





Accidental BG:

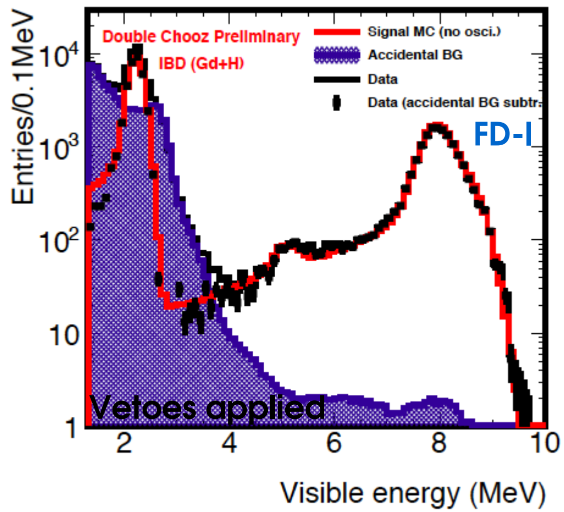
- High contribution @ low energy
- Flat ΔT
- Large ΔR

DC IBD selection

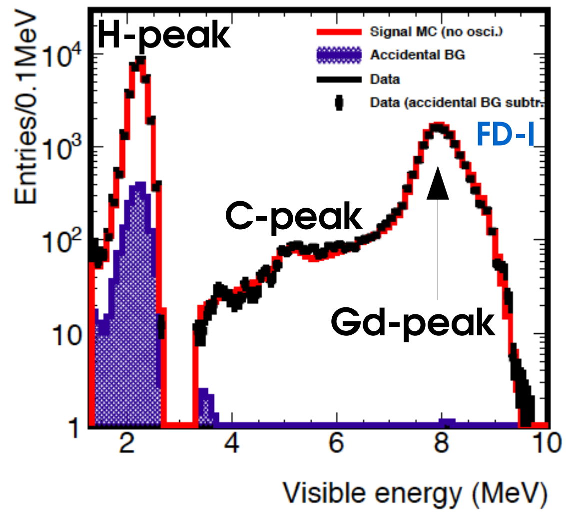
- Delayed energy:

Signal MC / DATA / Accidental BG

Before ANN



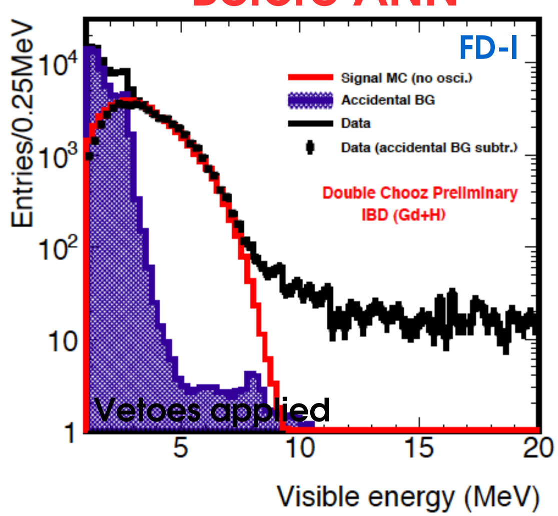
After ANN



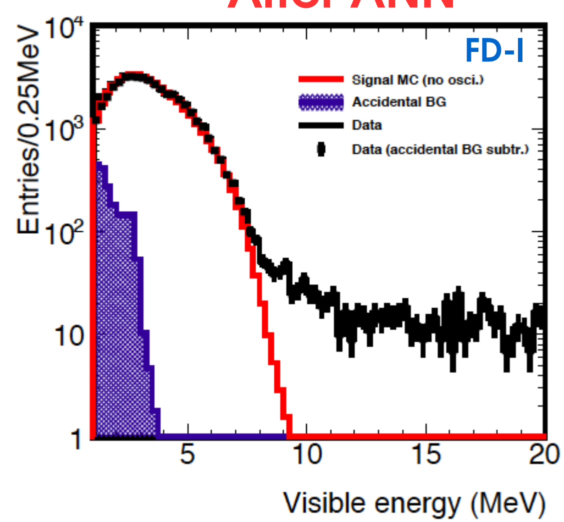
IBD selection uses all captures: on Gd, C and H.

- Prompt energy:

Before ANN



After ANN



Acc. BG:

- ~ 4 / day (FD and ND)

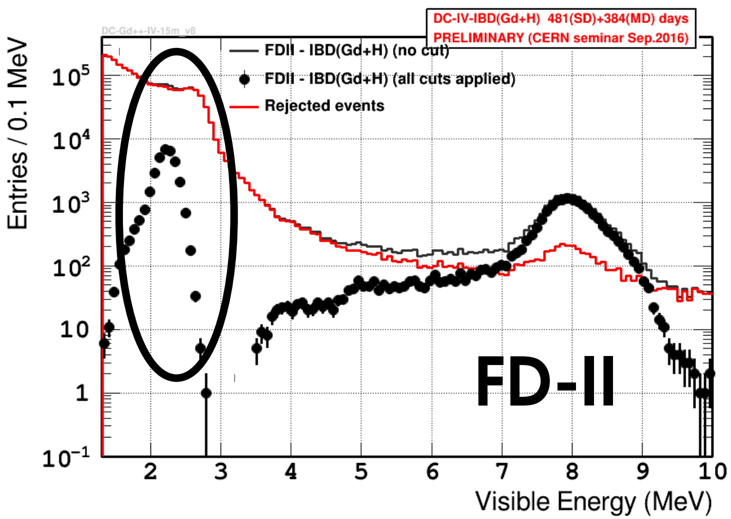
IBD (GD+H+C):

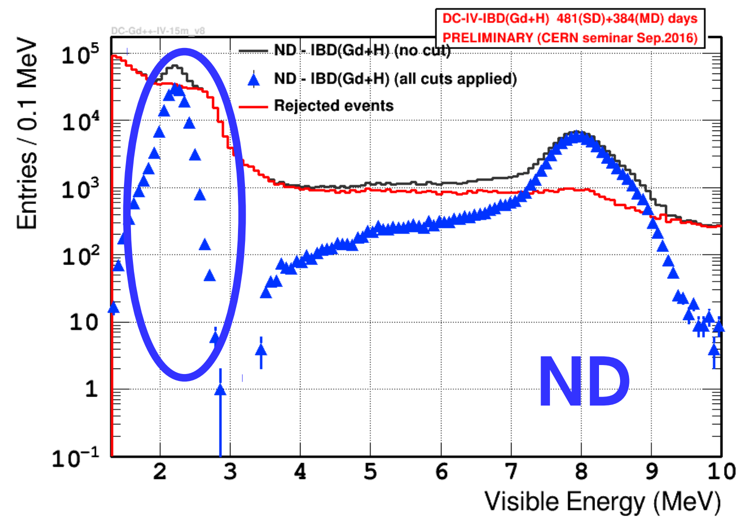
- ~ 140 / day @ FD
- ~ 1000 / day @ ND

x 2.5 stat. compared to Gd+C

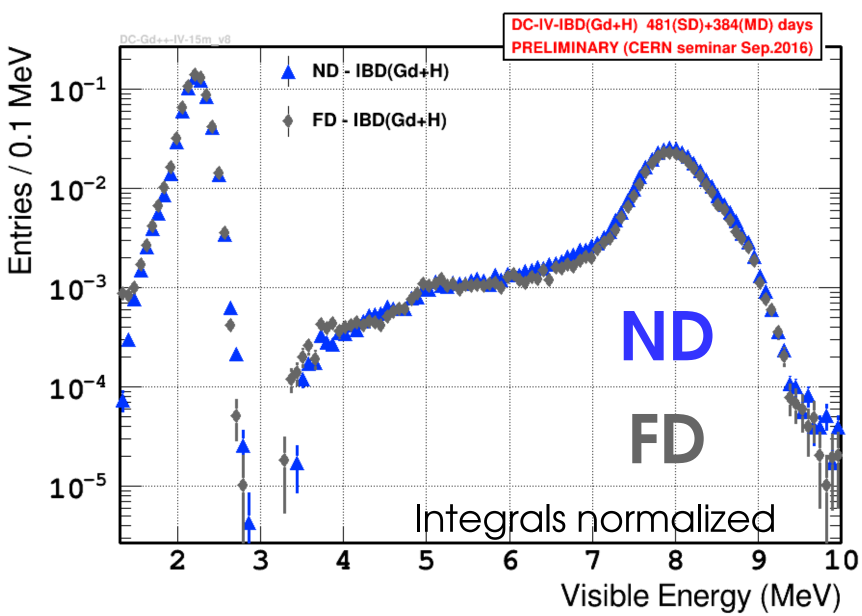
BG control

- **$E_{delayed}$** (MeV) before / after all cuts:





- ND –FD comparison:

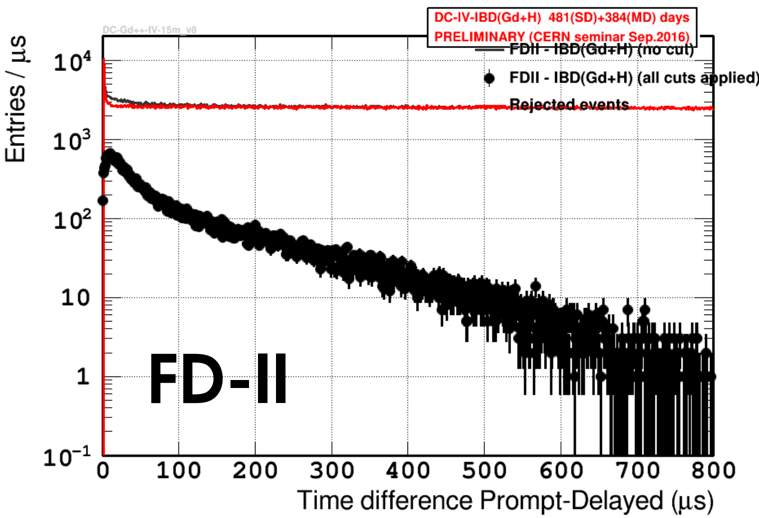


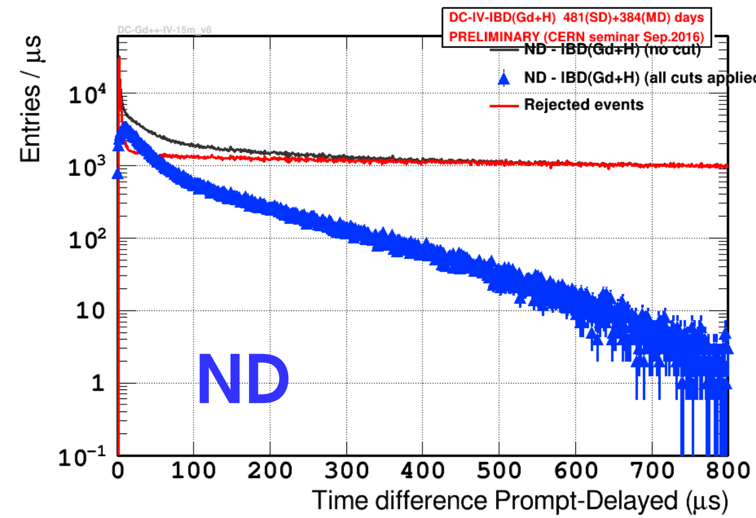
After all vetoes (per detector)
After full calibration (per detector)

ND ~ FD

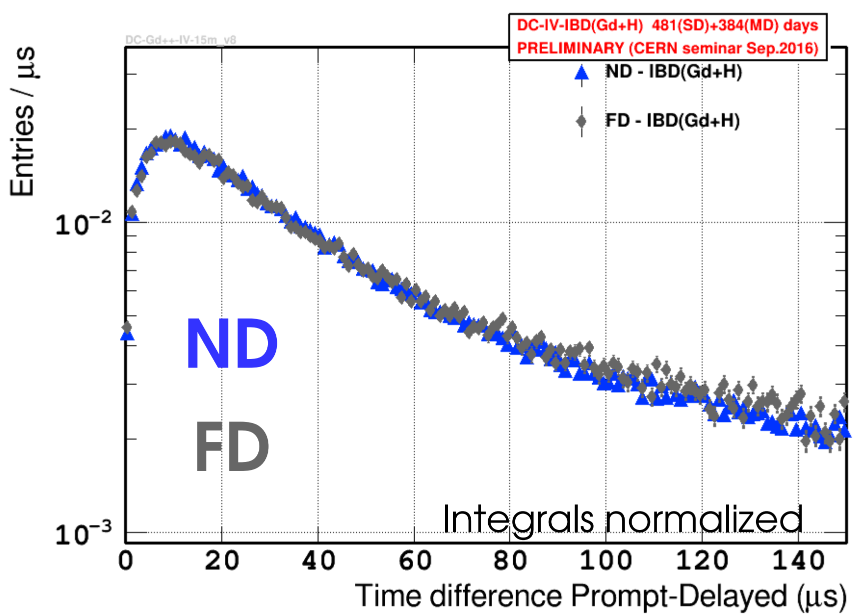
BG control

- **Δt (prompt → delayed)** (µs) before / after all cuts:



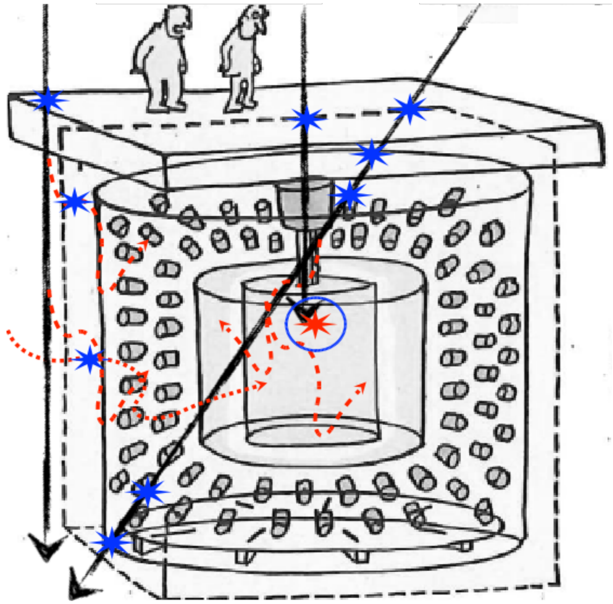


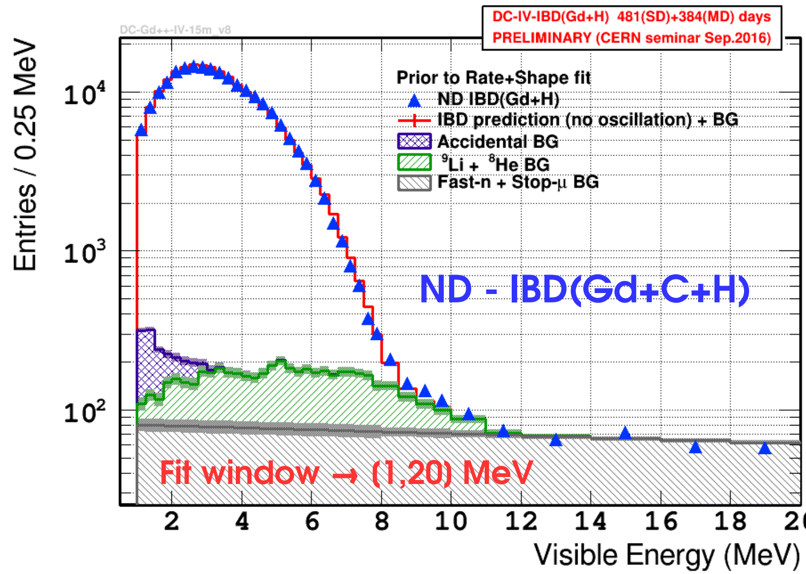
- ND –FD comparison:

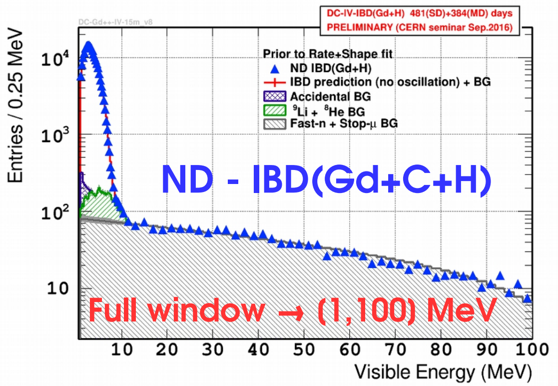


After all vetoes (per detector)

ND ~ FD







Remaining BG contributions (irreducible BG):

	prompt	delayed	~1000 IBD candidates/day @ND (day⁻¹)	~140 IBD candidates/day @FD (day⁻¹)
^{9}Li	e^- + α's	n	~11	~2.5
Fast-n	p-recoil	n	~24	~2.5
Accidental	radioactivity	radioactivity, n, ^{12}B, …	~3	~4

μspallation correlated production (~50% vetoed)
σ(BG)/S → ~dominant

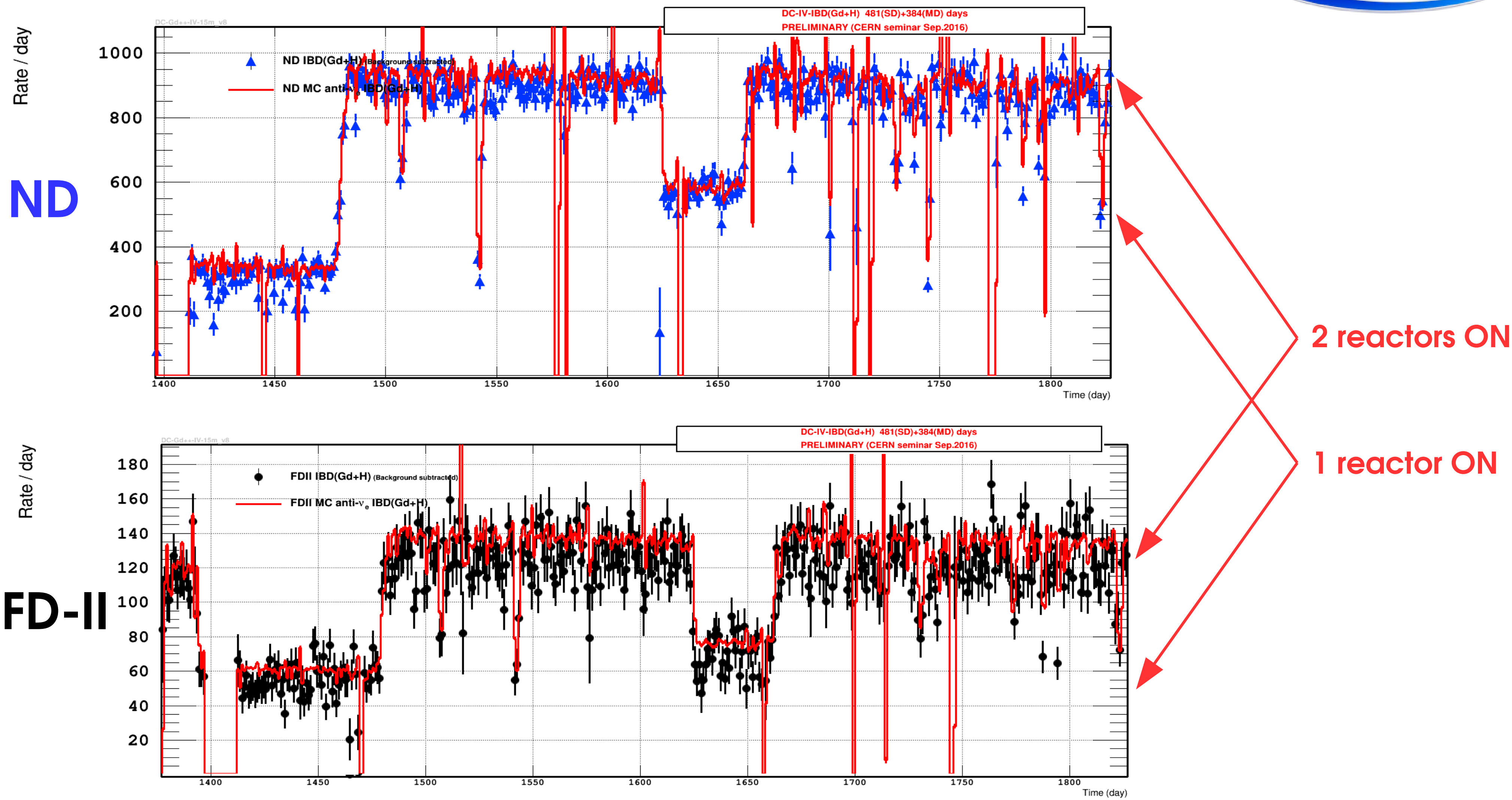
μtagging (IV+check OV) up to 100MeV
σ(BG)/S → ~small

OFF-time coincidences
σ(BG)/S → ~0%

$\sigma(BG_{tot})/S$ ~0.2% @ FD

- Other contributions (stopped-μ ^{12}B, BiPo, multi-captures) → all negligible !
- BG model confirmed by **reactor-OFF data**

IBD vs. time



Rate @ FD:

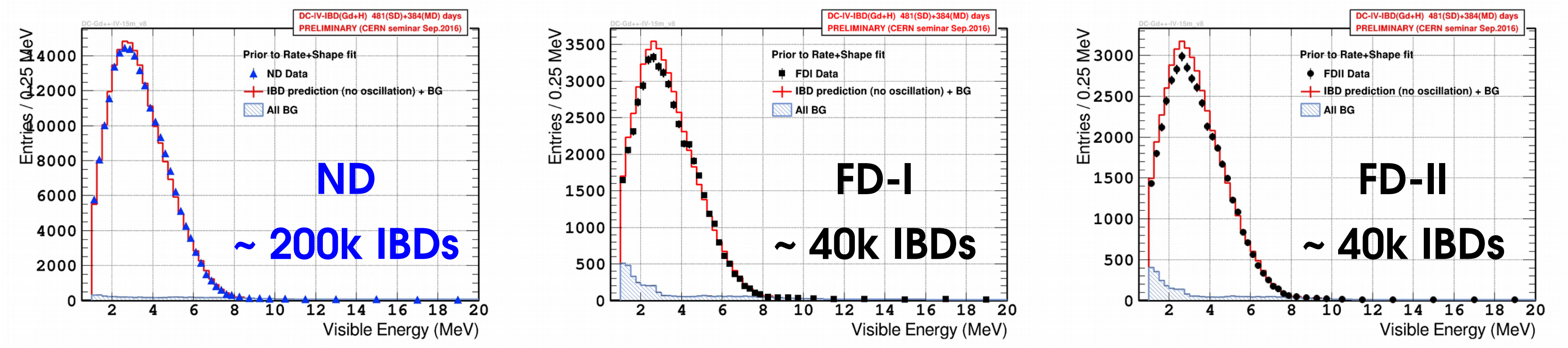
- ~ 140 events / day in Gd+C+H analysis
- ~ 50 events / day in Gd+C analysis
- ~ 0.2% stat. error on the final result

+ FD-I DATA (~3 years)

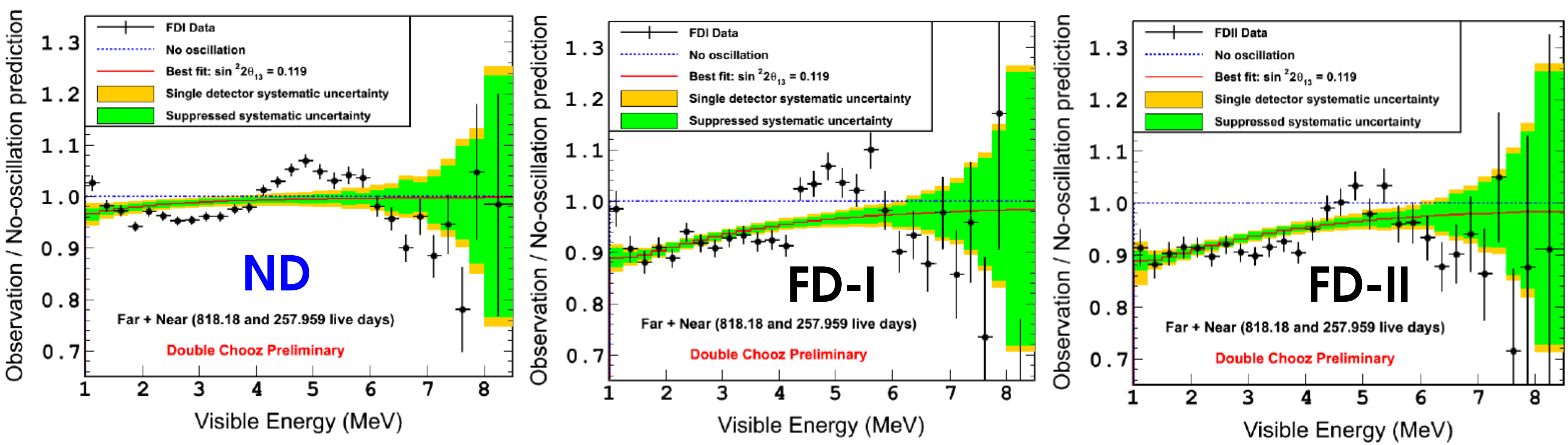
~ 210 000 IBD candidates @ND

~ 90 000 IBD candidates @FD

θ_{13} Rate+Shape fit results



→ 3 x SD-fits (MC) + MD-fits (inter-detector correlations)



$\sin^2(2\theta_{13})^{R+S} = 0.119 \pm 0.016$ (χ^2/ndf = 236.2 / 114)

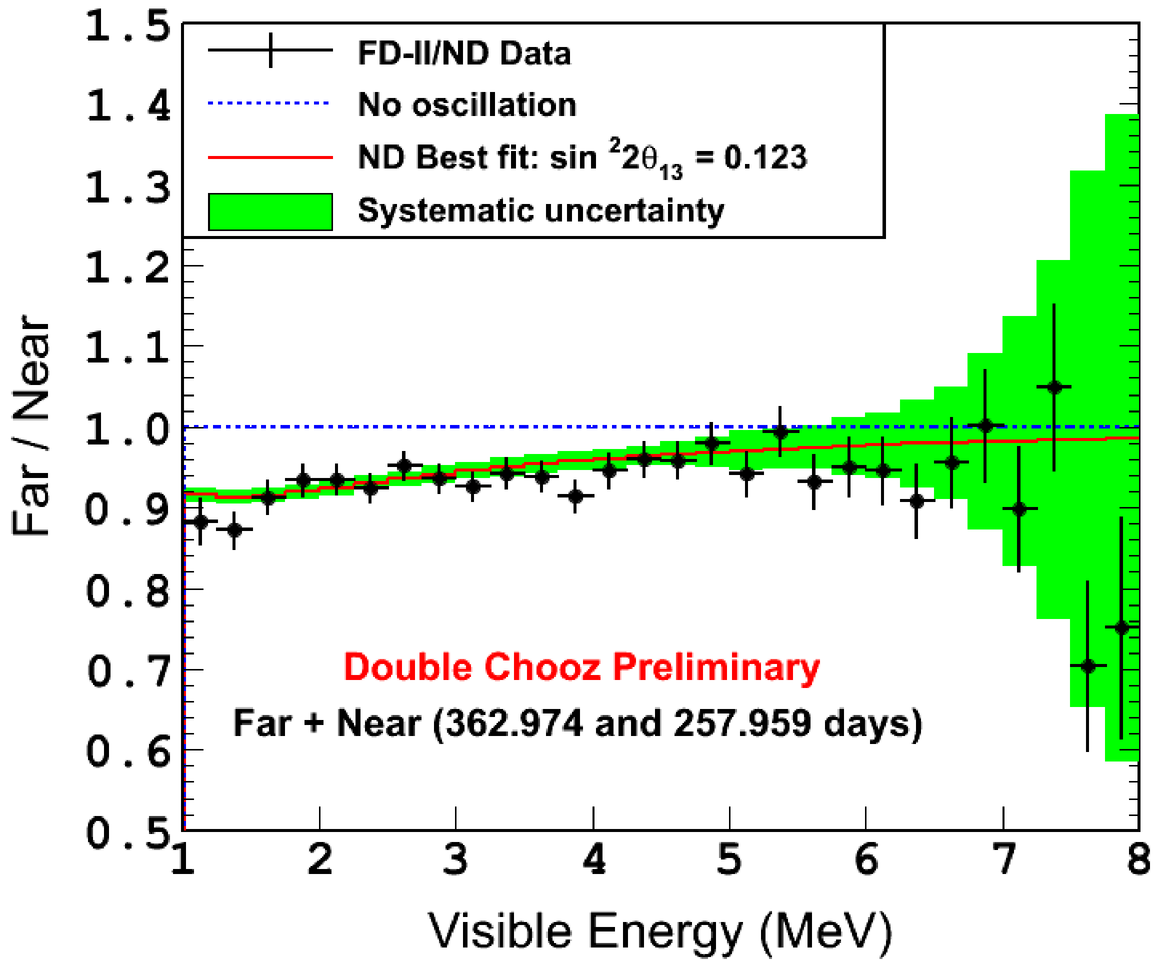
θ_{13} Rate+Shape fit results

DATA/DATA fit:

→ **Cross-check / validation**

→ FDII/ND fit:

- **$\sin^2(2\theta_{13})^{R+S} = 0.123 \pm 0.023$**
- X^2 / ndf = 10.6 / 38



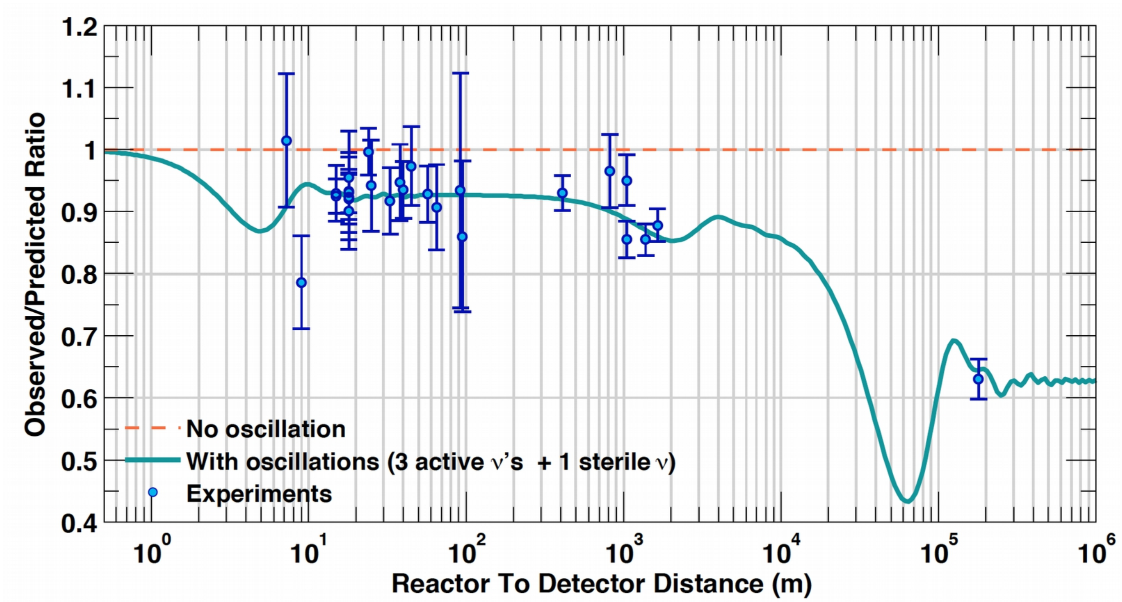
- **Large χ^2 / ndf when using MC**:
  → Mainly due to distortions in the spectral structure (large deviation wrt ILL-based model)

- **Too good χ^2 / ndf for data-to-data fit**:
  → Systematics estimation too conservative?

Comparison to MC

→ 2 main issues when data from reactor experiments are compared to the model:

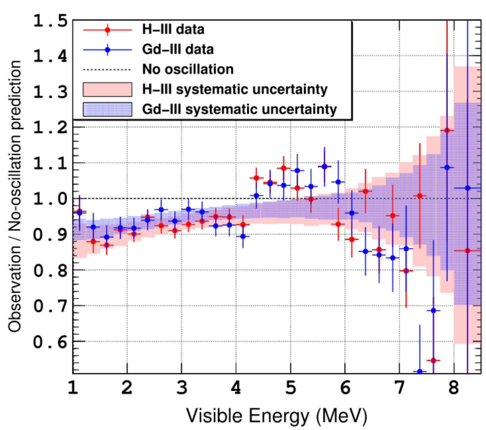
- Rate is lower than expected by ~ 6%: (reactor anomaly)



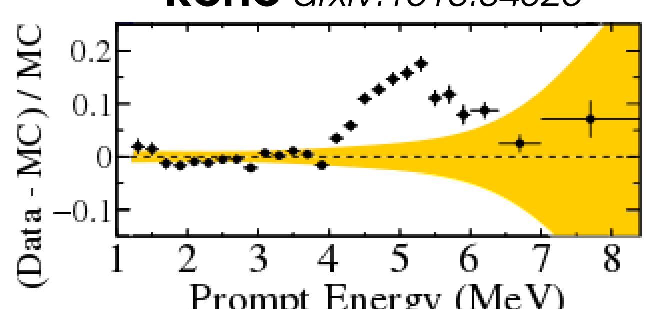
ν sterile?

- Energy shapes are not consistent: (5MeV excess)

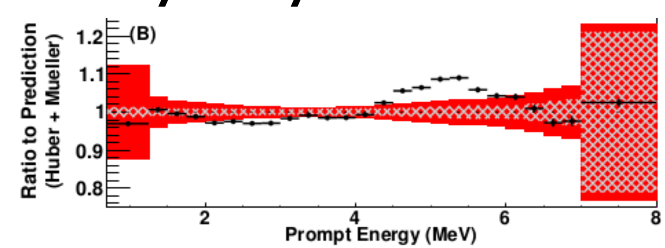
Double Chooz



Reno *arxiv:1610.04326*

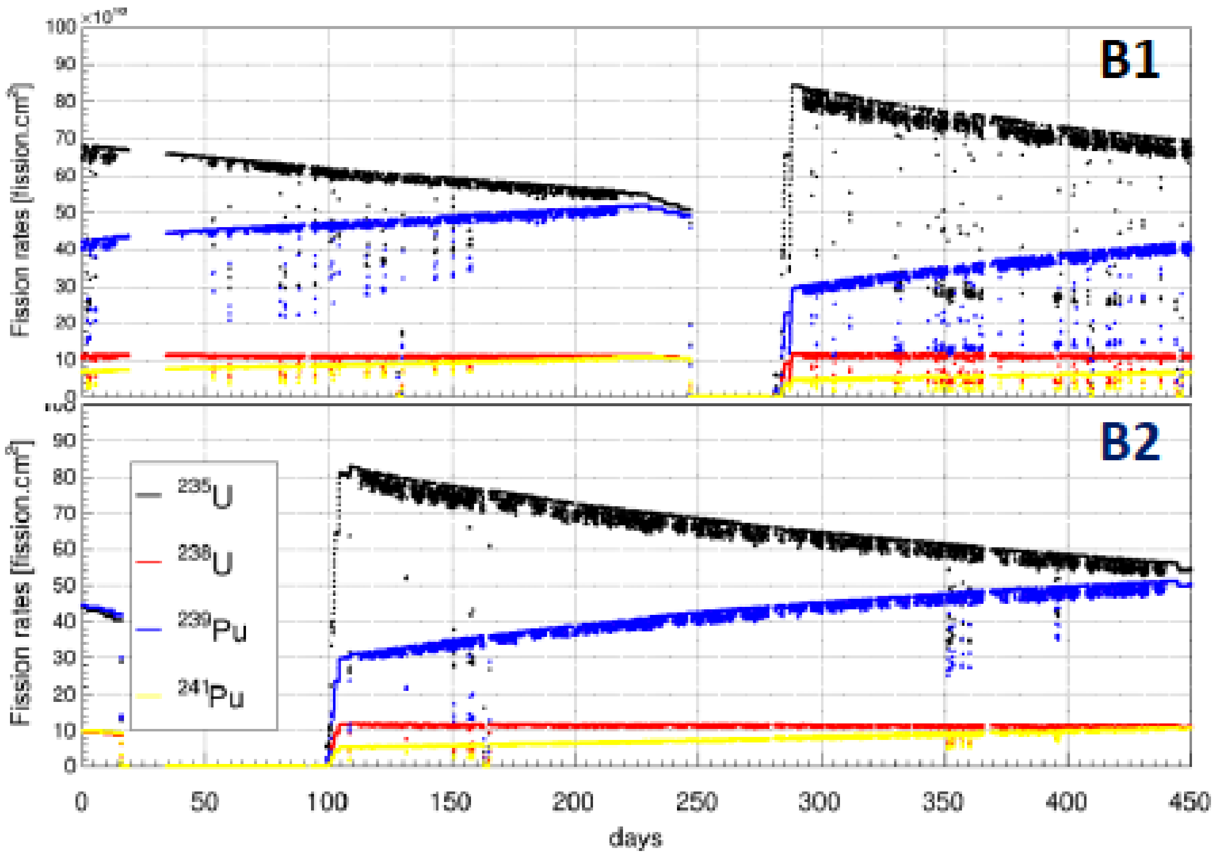


Daya Bay *arxiv:1607.05378*



How to build $\bar{\nu}$ spectra?

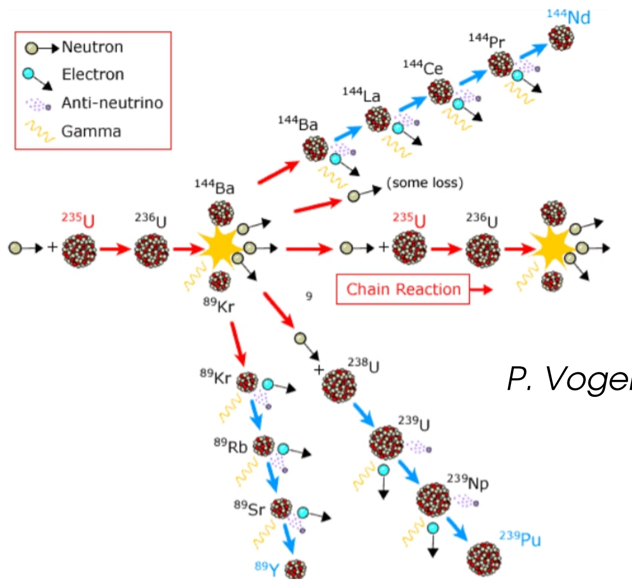
Reactor cycles @ Chooz power plant:



- 4 main isotopes in reactor fuel:
  → ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu
- Need to know the ν spectrum of each one

How to build $\bar{\nu}$ spectra?

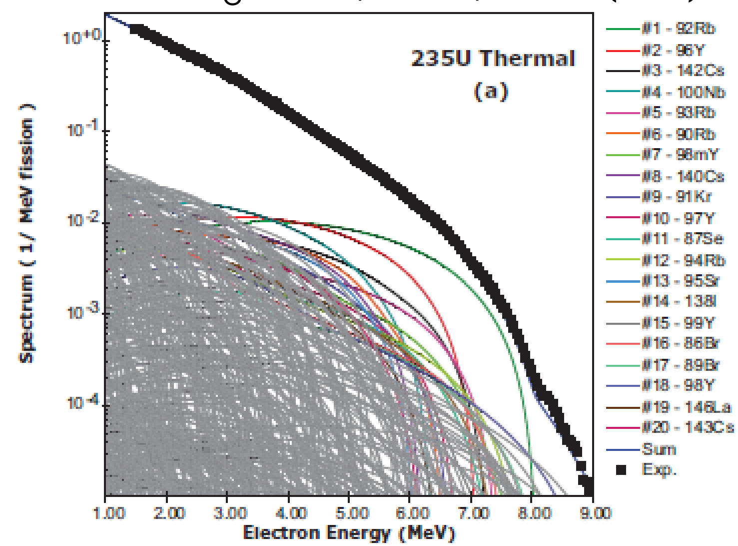
- The summation method:



Weighted sum of contributions of each decay using nuclear data bases (JEFF, ENDF)

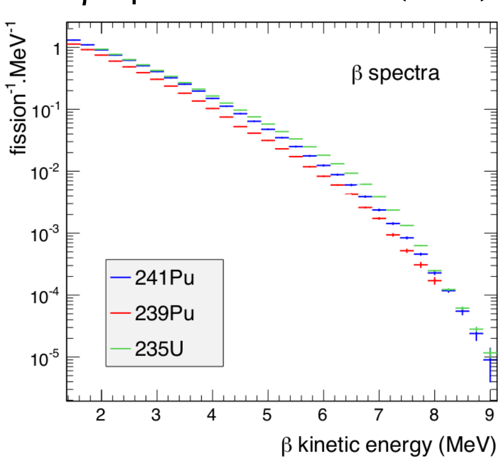
P. Vogel et al, Phys. Rev. C 24, 1543 (1981)

A.A. Sonzogni et al., PRC91, 011301 (2015)



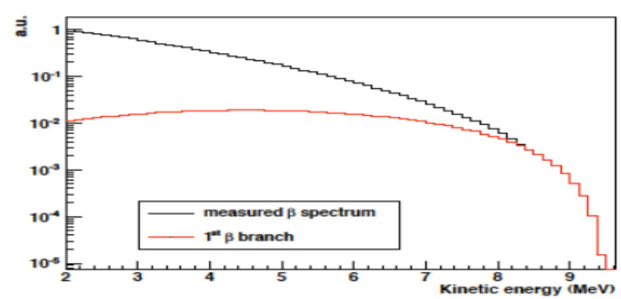
- The conversion method:

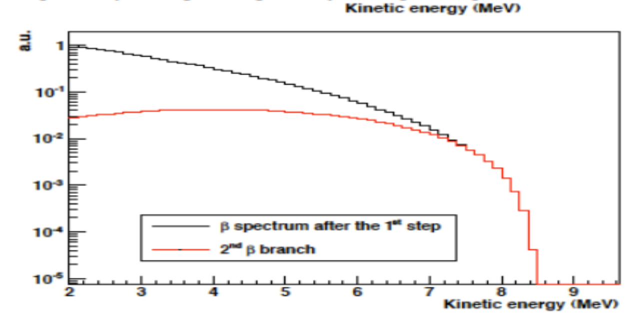
β spectra @ ILL (80's)



Fit with a set of hypothetical decay branches

+ Effective Z using nuclear data as a function of end point energy

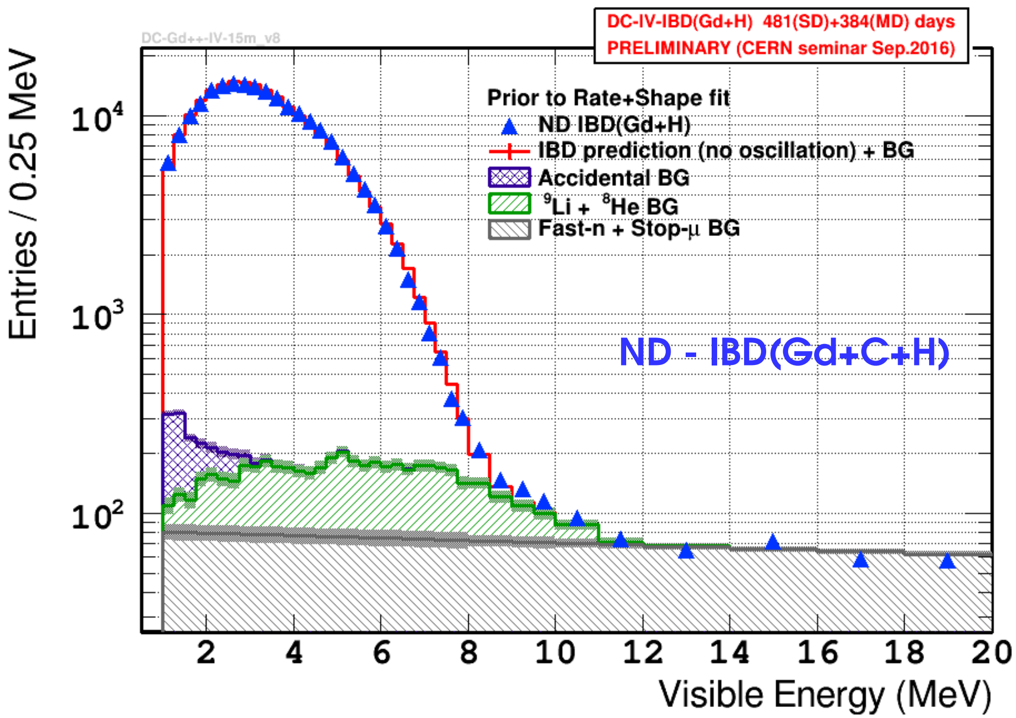


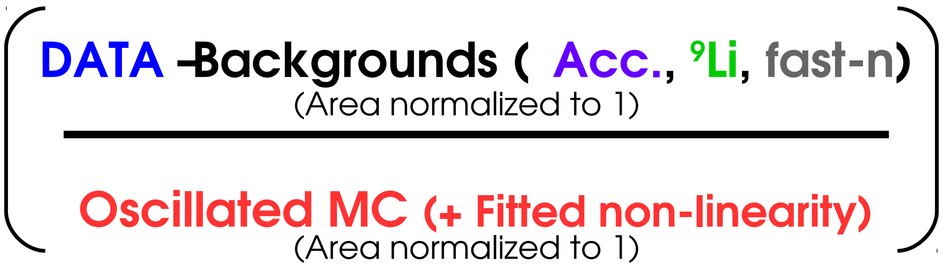


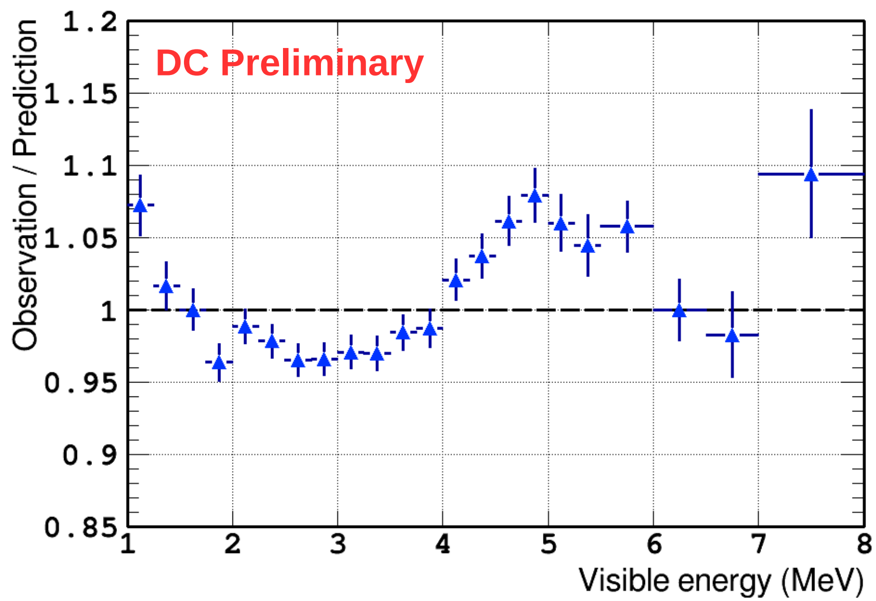
… 30 effectives branches

P. Hubert, Phys. Rev. C 84, 024617 (2011)

Build the DATA/MC ratio

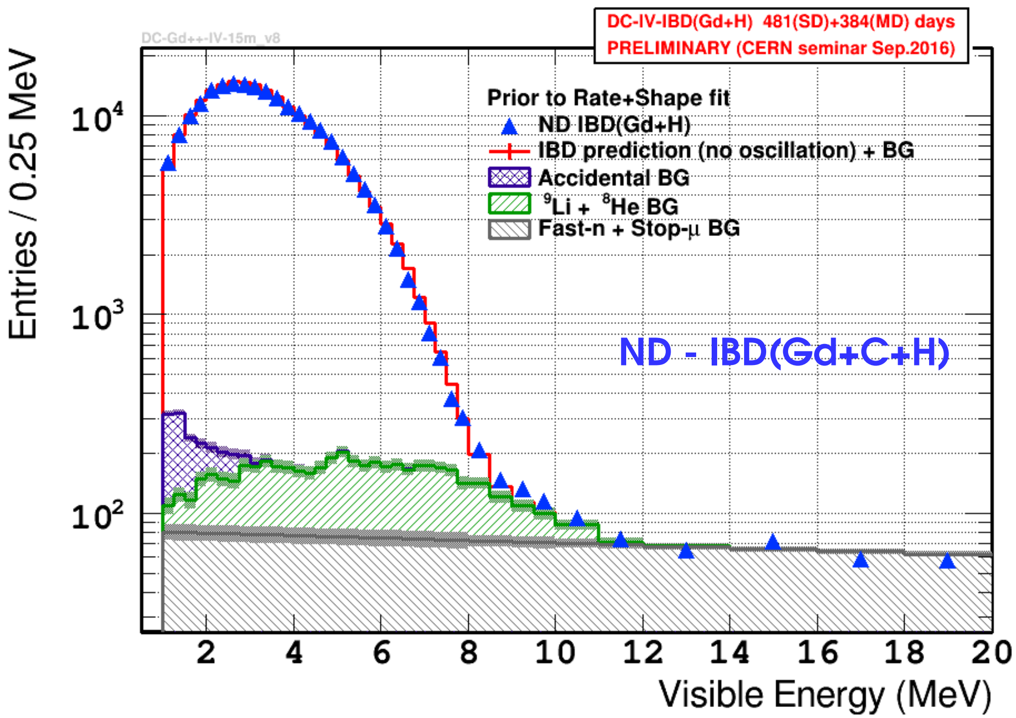






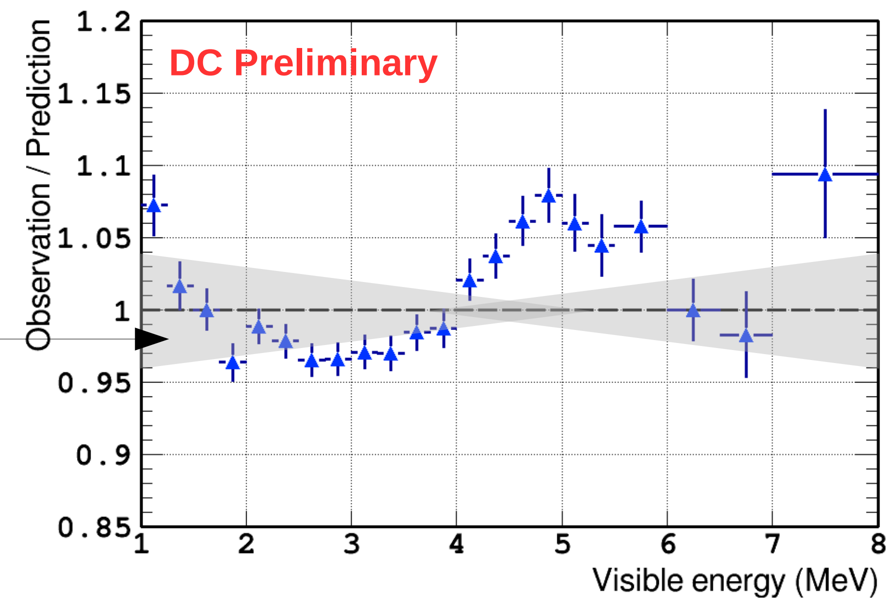
- Area normalized to 1:
  - → Shape only analysis (no rate effect)
- Only statistical error reported here

Build the DATA/MC ratio



DATA – Backgrounds (Acc., ^{9}Li, fast-n)
(Area normalized to 1)

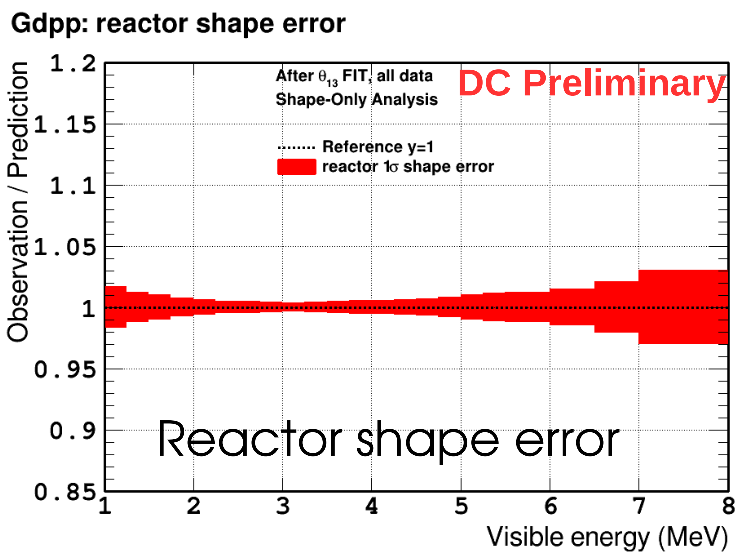
Oscillated MC (+ Fitted non-linearity)
(Area normalized to 1)

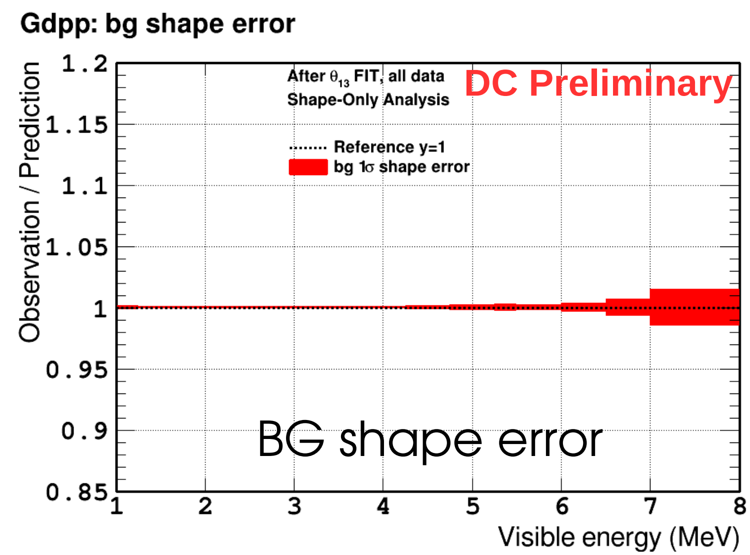


- Area normalized to 1:
  - → Shape only analysis (no rate effect)
- Only statistical error reported here
- Need also to compute the syst. errors associated to the knowledge of the shape:
  - → Reactor model
  - → Backgrounds
  - → Energy correction

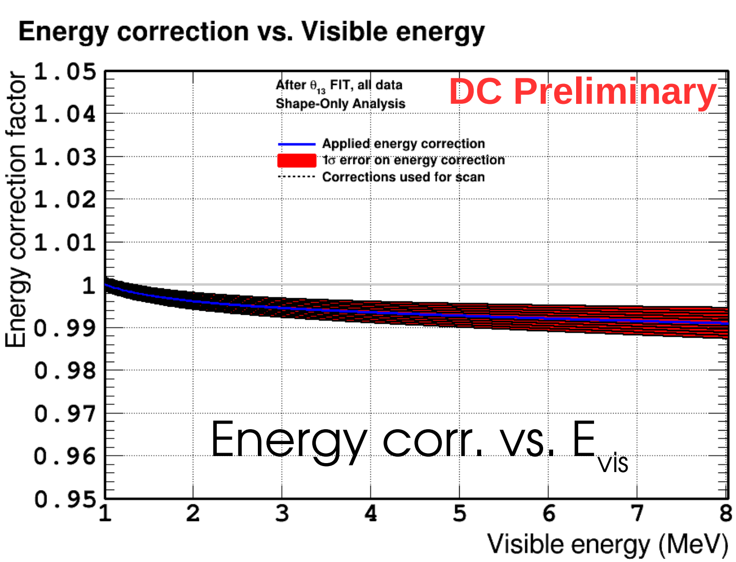
Shape errors (After fit)

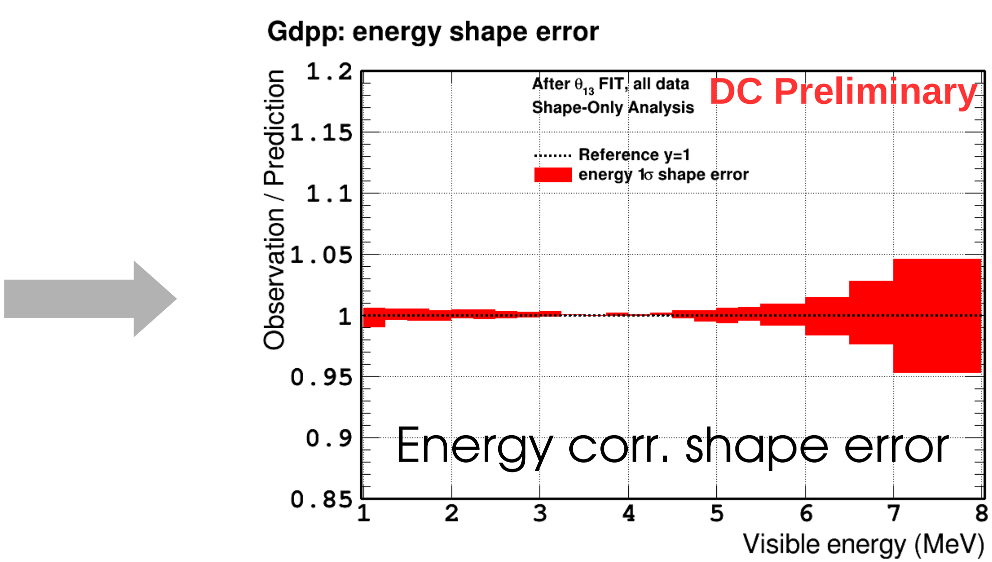
- Rector and background shape errors:



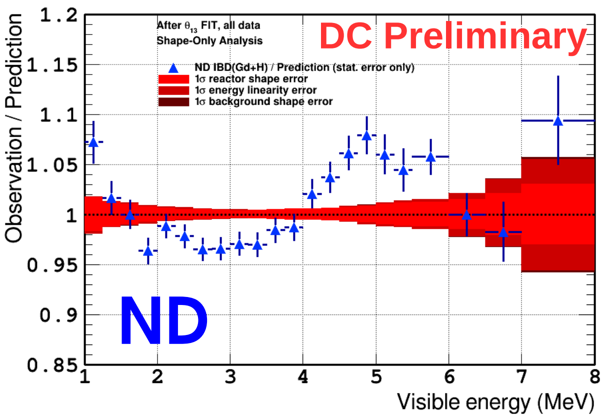


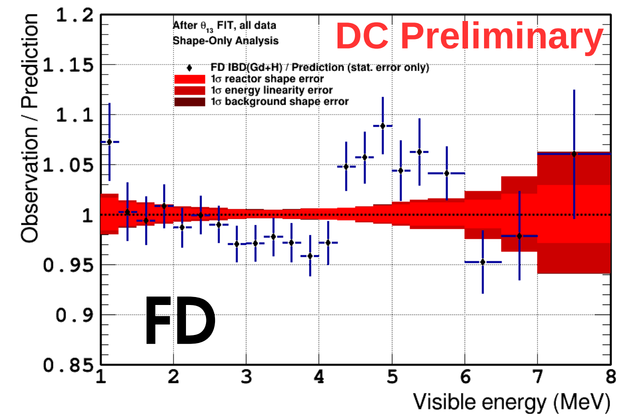
- Energy correction + associated error propagation:





Reactor spectral distortions





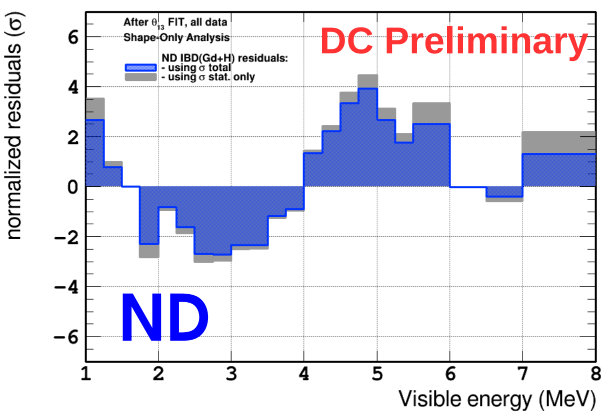
Shape-only analysis

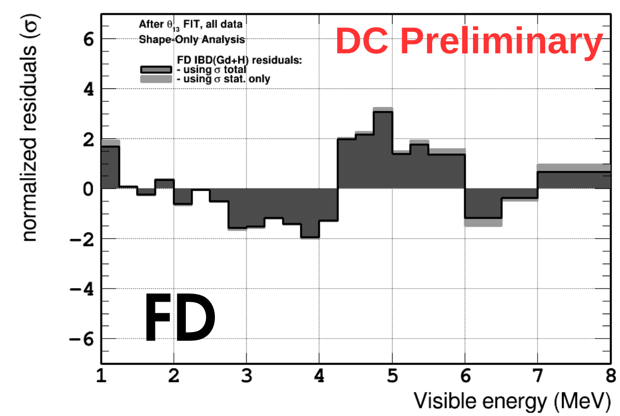
DATA and MC spectra normalized to 1

Ratio is not flat

→ Distortion relative DATA/MC

Not a statistical pattern





Same features observed

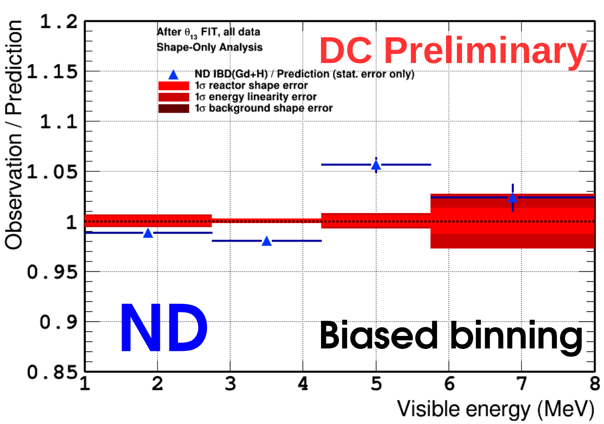
in ND and FD

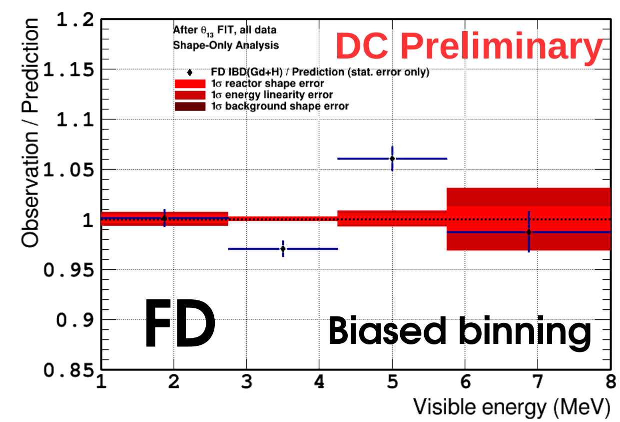
(possible combination)

But:

Shape only paradigm **allows only limited interpretation with possible risk of misleading**!

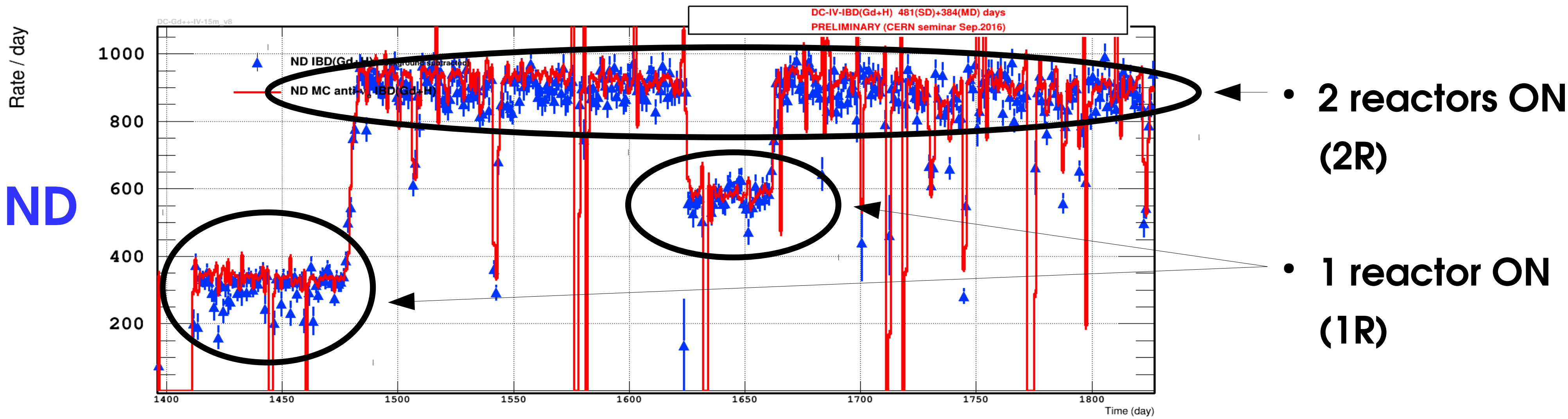
Final conclusion depends highly of the **normalization strategy**!





Scaling with reactor power

- Data are split in 2 samples:

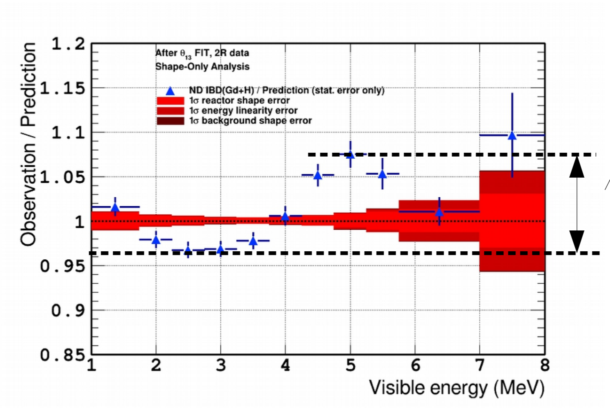


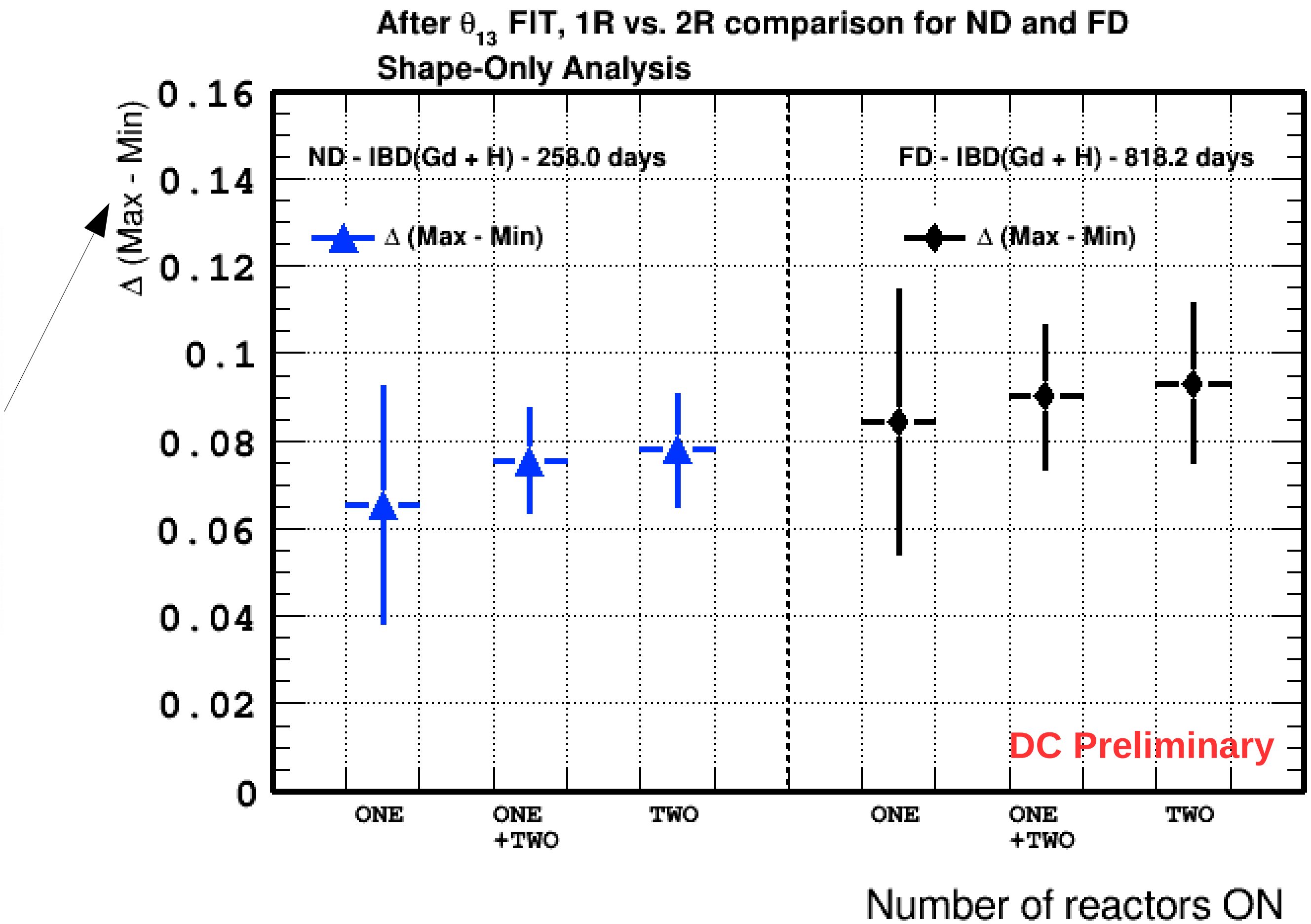
- Next "shape-only" DATA/MC ratio are computed for each case

Goal: Check if the distortions come from a reactor effect or from an external source

- If distortions are related to the reactor signal:
  → ratio is expected to be the same in the 1R and 2R cases
- If distortions are due to an external contribution:
  → larger effect expected in the 1R case (~2x less signal compared to 2R case for a constant unknown background contribution)

Scaling with reactor power

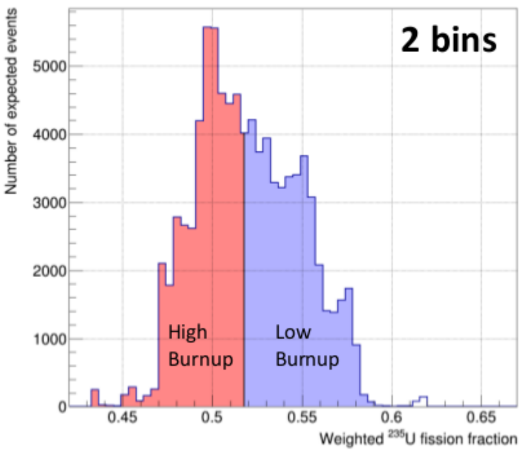




→ Features scaling fractionally constant with the reactor number (reactor power)

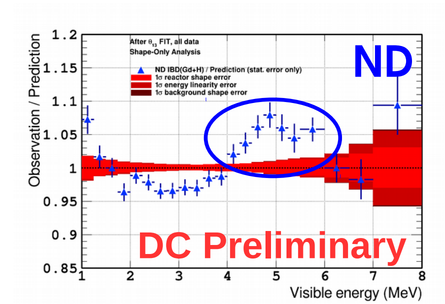
→ Statistics for 1 reactor ON is low: should be improved soon with latest DC data

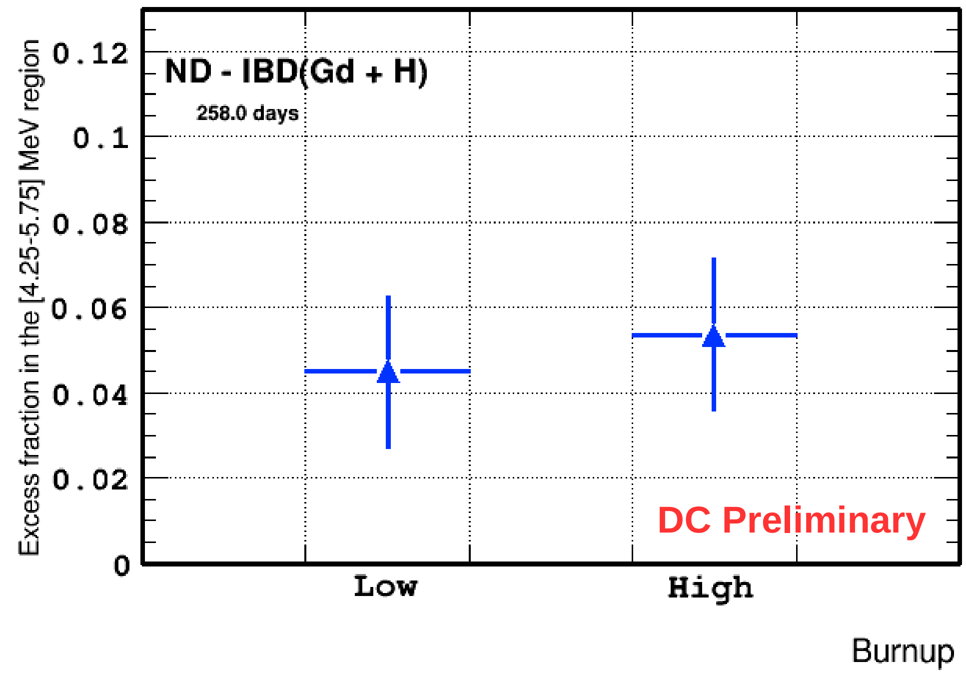
Scaling with ^{235}U fission fraction



	« High burnup »	« Low burnup »
235U	49.6	54.4
238U	8.7	8.8
239Pu	35.2	31.3
241Pu	6.5	5.5

Fission fraction





- Split DATA in two sets as a function of the fission fraction in reactors
  - → No effect seen
  - → But sensitivity too low, need more stats to split the in more samples

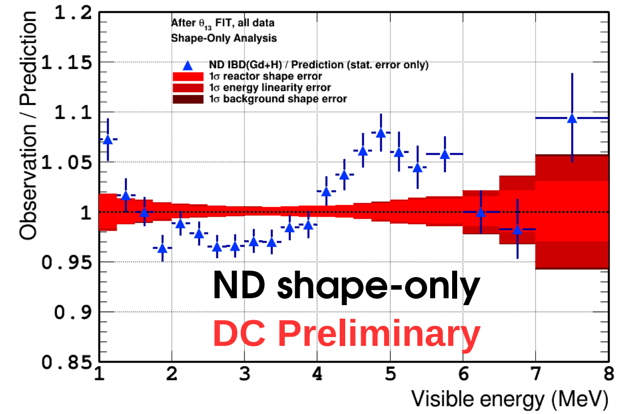
Reactor spectral distortions

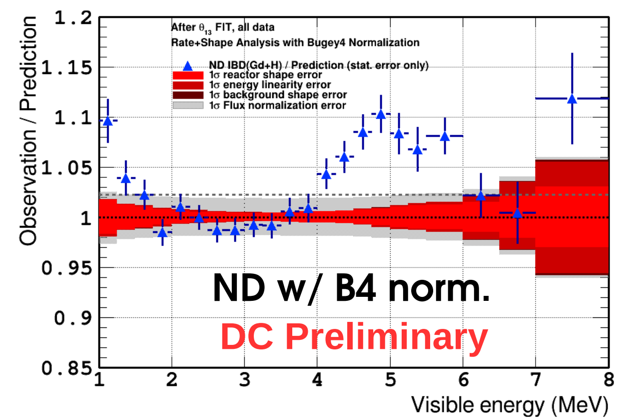
- **Shape-only**:
  → Data and MC spectra **normalized to 1**
- **By definition**, in absolute over the energy range:
  → Integral(DATA) = Integral(MC)
  → Integral("Excess") = Integral("Deficit") !
  → Values of the ratio depend of the statistics in the bin
- **But**:
  → What happens if I use a normalization?
  → **What is the real problem? Deficit? Excess? Both?**
  → "**Excess**"and " **Deficit**"notions are **driven by normalization**
  → In shape-only analysis, **only distortions remain !**

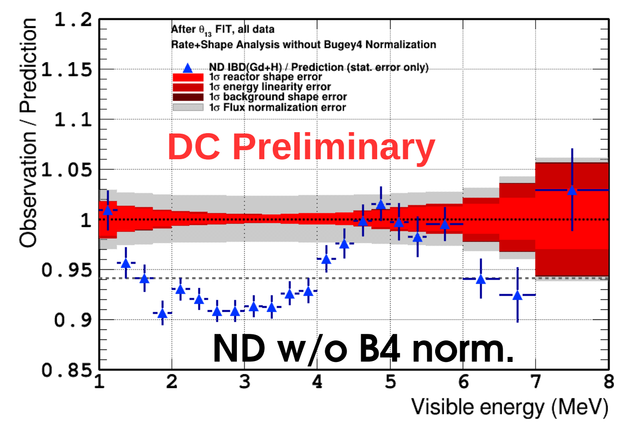
- **Conclusion**:

→ **In Shape only, some characterizations of the distortions can be done:** scaling with reactor power, fission fraction dependence, …

→ **But normalization + shape is a must** for physics interpretation, and the uncertainties associated to the normalization has to be taken into account.

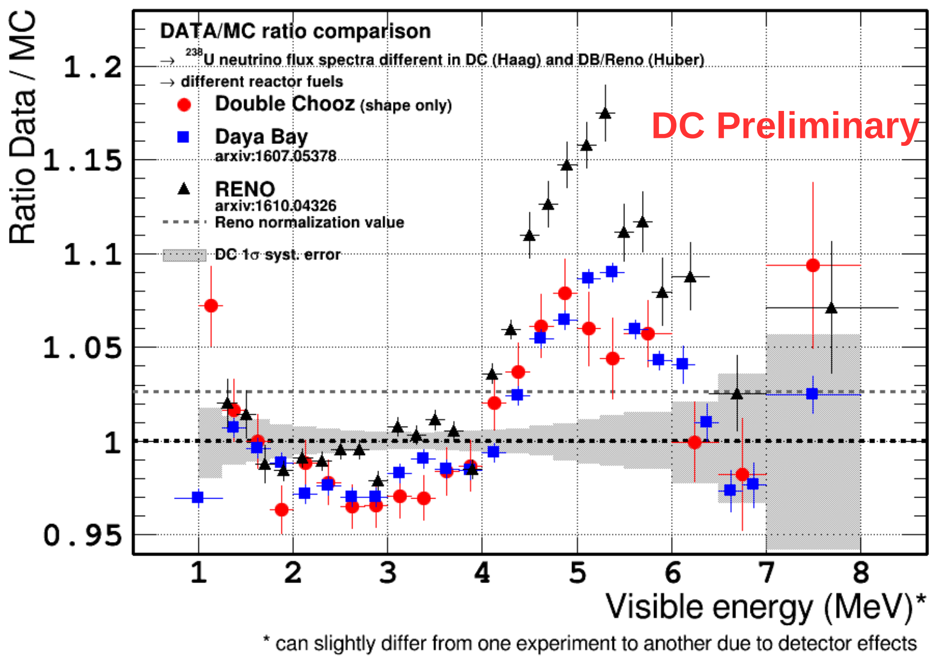


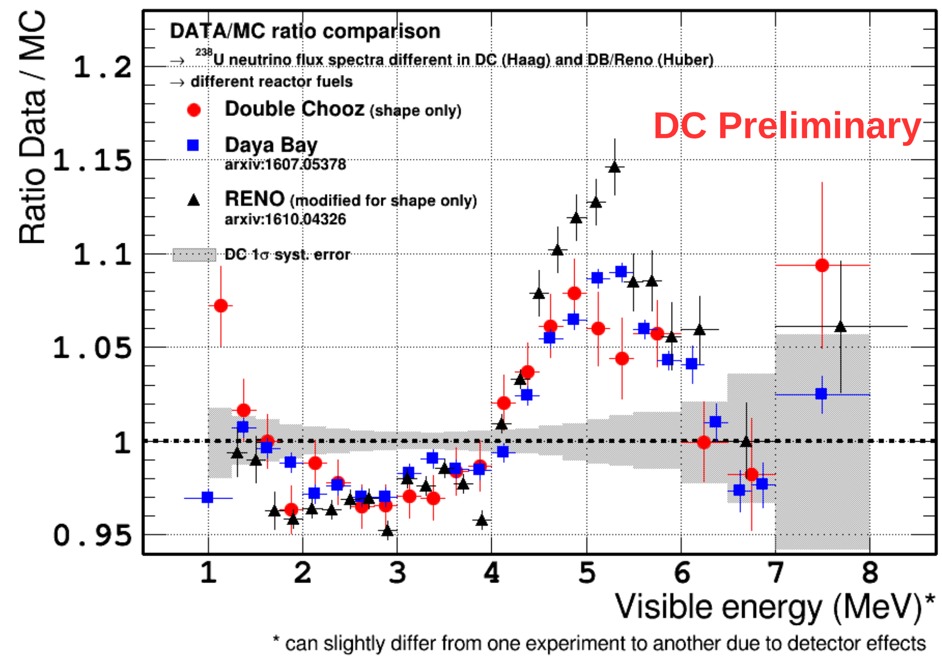




Comparison with DYB and Reno

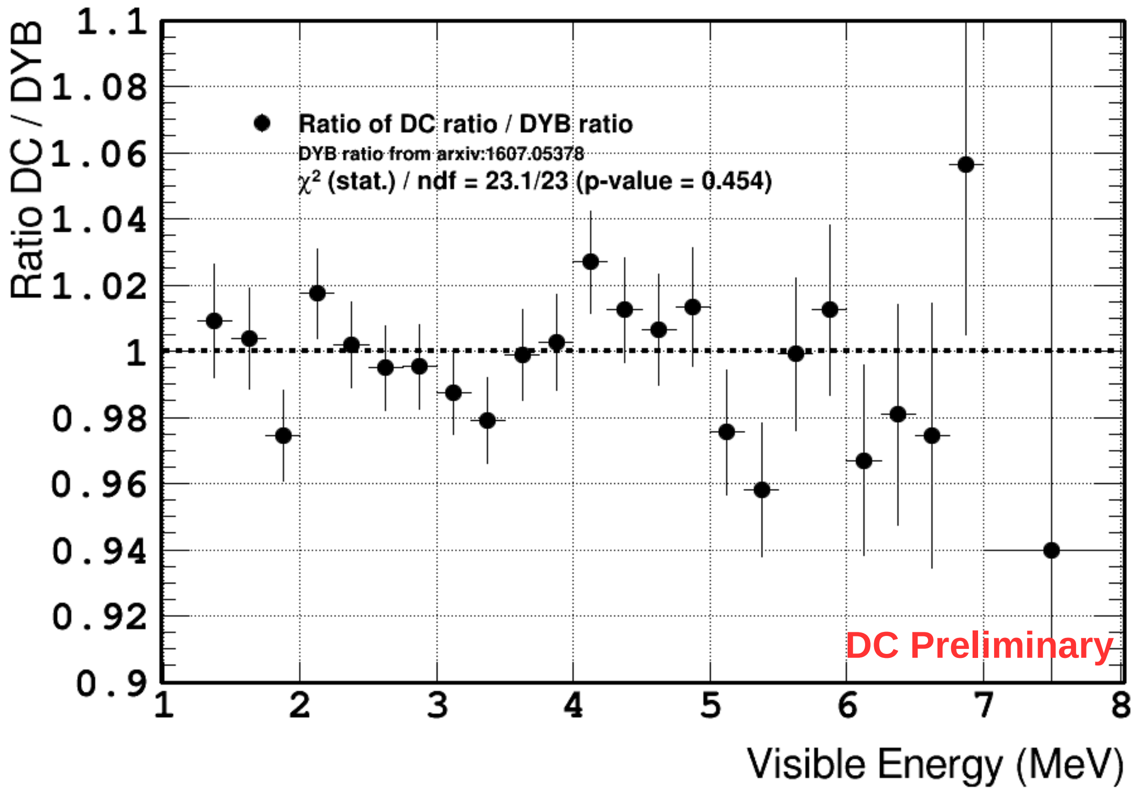
DC: 210 000 events / DB: 1.2 million events / Reno: 280 000 events



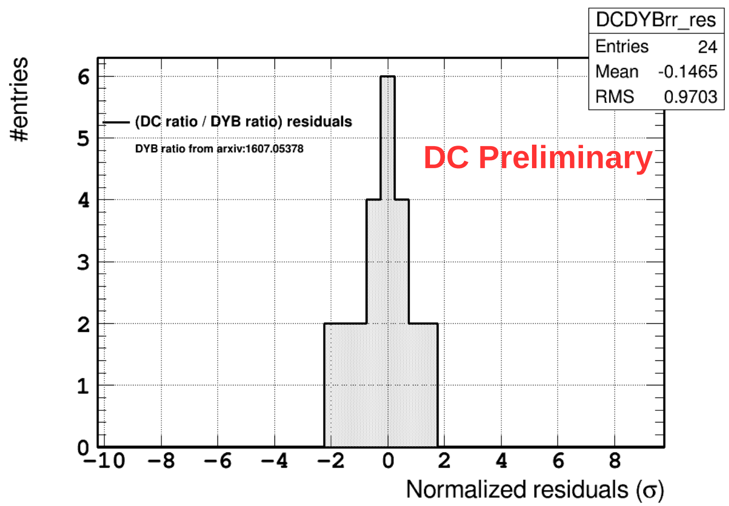


- **Consistency between Double Chooz and Daya Bay** results !
  - → **Not trivial**: θ_{13} correction, background, energy, ...
- Due to the normalization used, RENO points are close to 1 up to 4 MeV
- But better agreement with RENO when area are normalized to 1 (for E < 4.5MeV)
- Some discrepancy remains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

DC vs. DYB



1D residuals distribution



- DC and DYB ratio in remarkable agreement given the possible sources of discrepancies!

Conclusion

θ_{13} measurement:

- Double Chooz has now its first result using the 2-detector configuration
  → $\sin^2(2\theta_{13})^{R+S} = 0.119 \pm 0.016$
- Work is on going to understand the χ^2/ndf
- Publication planned soon

Reactor shape study:

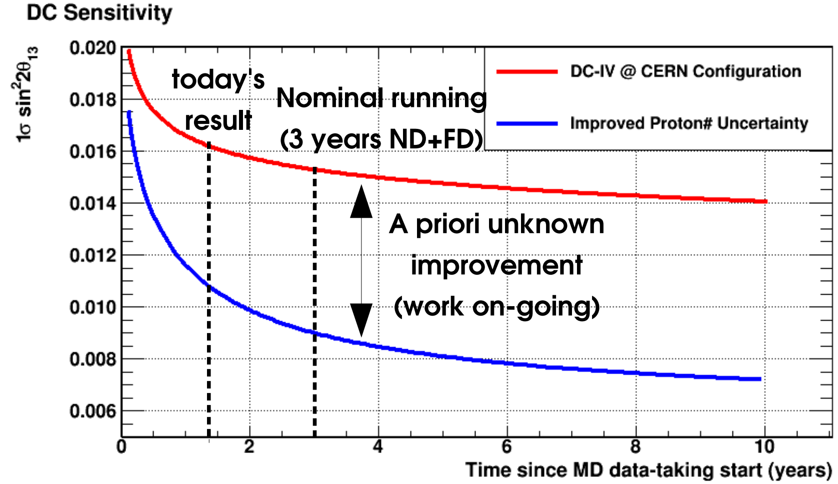
- Double Chooz results (as other experiment results, even if it's not express in the same way) point toward a correlation between the distortion of the ratio and the reactor power:
  → This correlation with the reactor power disfavors the possibility of an unaccounted background component and points towards an unaccounted component of the reactor flux.
- Consistency between DC and DYB spectra has been demonstrated.
- But shape-only analysis is inconclusive (and risk to be misleading) on the existence of an excess or a deficit when we compare DATA and MC:
  → Normalization information must be articulated to allow a full interpretation of the data.
  → Work is on-going to provide further information on the spectral distortion (upcoming publication).

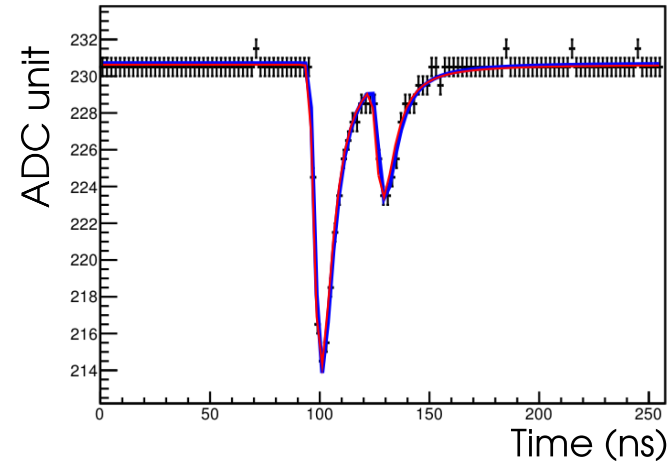
Perspectives

Double Chooz will continue to take data for 1 year and the decommissioning should start by the end of 2017

<u>θ_{13} measurement:</u>

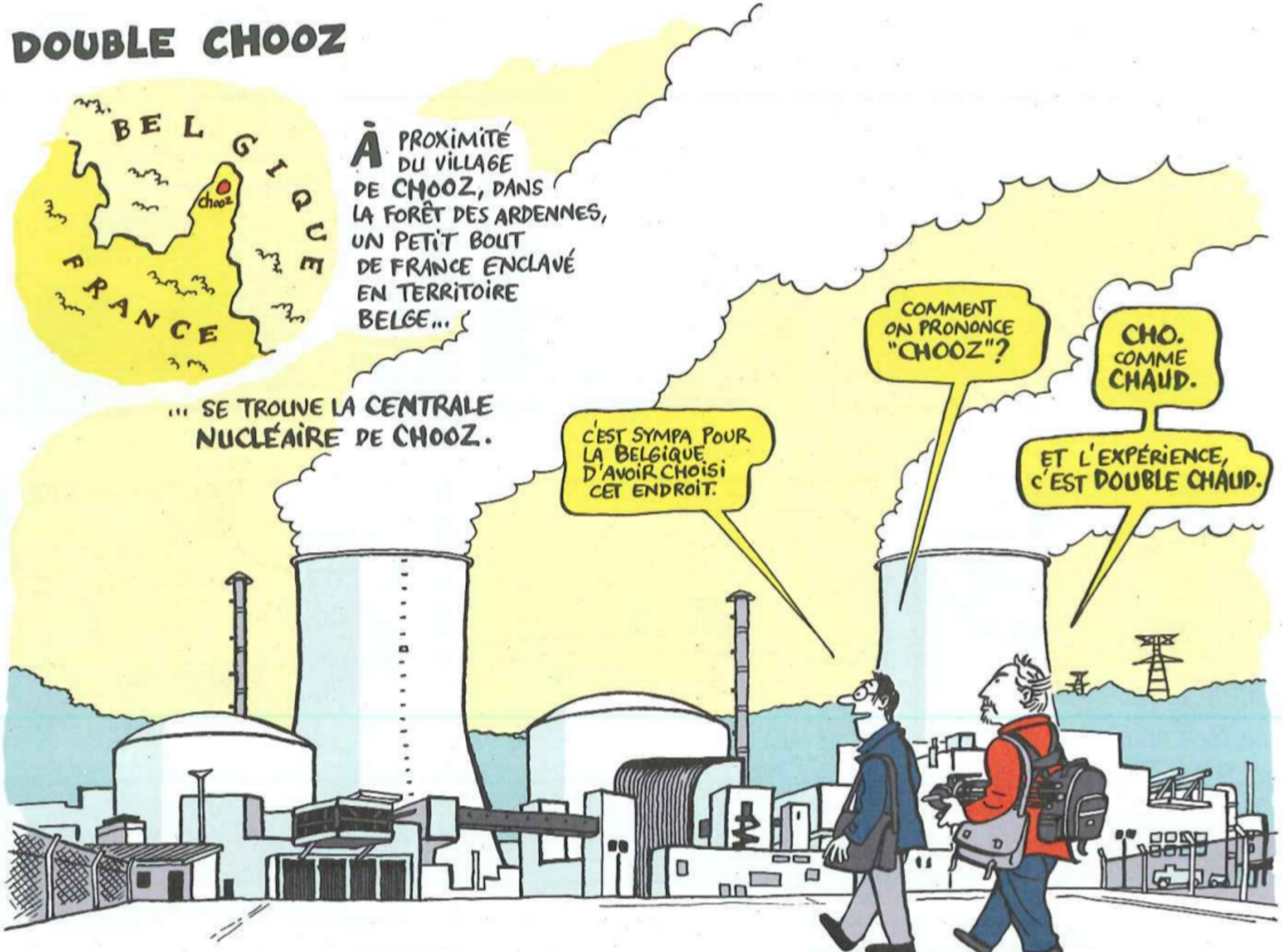
- 1.5 years of additional data are expected
  - → Almost at the syst. limit
- New pulse shape reconstruction
  - → DC has Flash ADC: fit of the waveforms
  - → Photon counting
  - → Robust baseline estimation
  - → More information (time info per pe)
  - → Remove most of the non-linearities
  - → Work on-going and first results expected mid-2017





<u>Reactor shape study:</u>

- High precision quantification on-going
- Ratio using Hubert + Mueller modeling (instead of Hubert + Haag, for comparison with DYB)
- Test of the new model proposed by A. Hayes
- Comparison with very short baseline experiments (Neos, STEREO, ..)
- Unfolding, ...


DOUBLE CHOOZ
BELGIQUE
FRANCE
Chooz
À PROXIMITÉ DU VILLAGE DE CHOOZ, DANS LA FORÊT DES ARDENNES, UN PETIT BOUT DE FRANCE ENCLAVÉ EN TERRITOIRE BELGE...
... SE TROUVE LA CENTRALE NUCLÉAIRE DE CHOOZ.
C'EST SYMPA POUR LA BELGIQUE D'AVOIR CHOISI CET ENDROIT.
COMMENT ON PRONONCE "CHOOZ"?
CHO. COMME CHAUD.
ET L'EXPÉRIENCE, C'EST DOUBLE CHAUD.

Thank you !

...


MAIS LA MATIÈRE A PRIS LE DESSUS, ET ON NE SAIT PAS POURQUOI.
LES NEUTRINOS POURRAIENT NOUS DONNER L'EXPLICATION ...
L'INFINIMENT PETIT POUR EXPLIQUER L'INFINIMENT GRAND !
Duhoo