NEW RESULTS OF DOUBLE-CHOOZ MULTI-DETECTOR

Carmen Palomares

CIEMAT

Madrid (Spain)

GOBIERNO DE ESPAÑA

MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

Ciemat

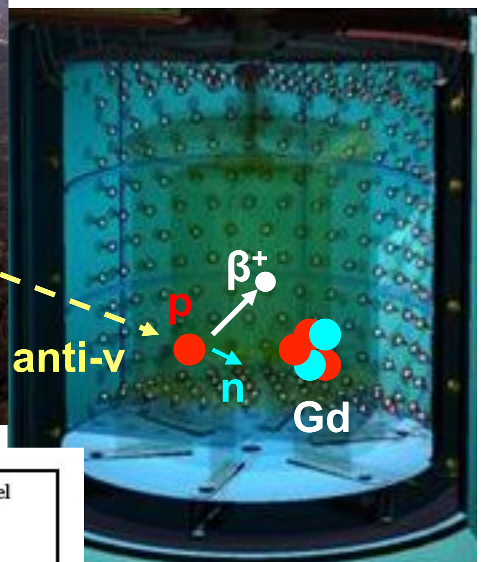
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

EXCELENCIA MARÍA DE MAEZTU

cfp CIEMAT física de partículas

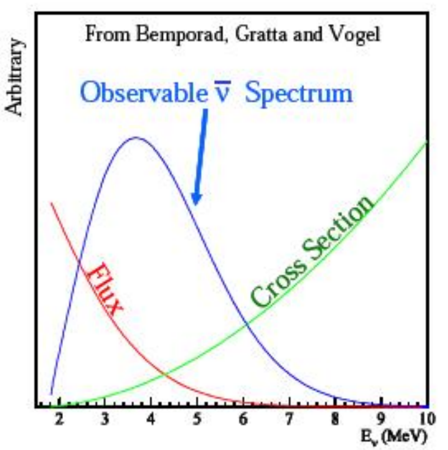
Nuclear reactor neutrino experiments

The commercial nuclear reactors produces 10^{21} anti-ν_e/s



The anti-ν_e are detected **via inverse β-decay (IBD) reaction:**

- Cross-section well known
- Prompt signal: positron + annihilation γ's ($E_\nu \sim E_{signal}$ + 0.8MeV)
- Delayed signal:
  → **8 MeV γ's from n-Gd** (well above natural radioactivity)
  → 2.2 MeV γ's from n-H



Background is strongly suppressed by requiring time/space correlation

Measurement of θ_{13}

Nuclear reactors:

Survival probability

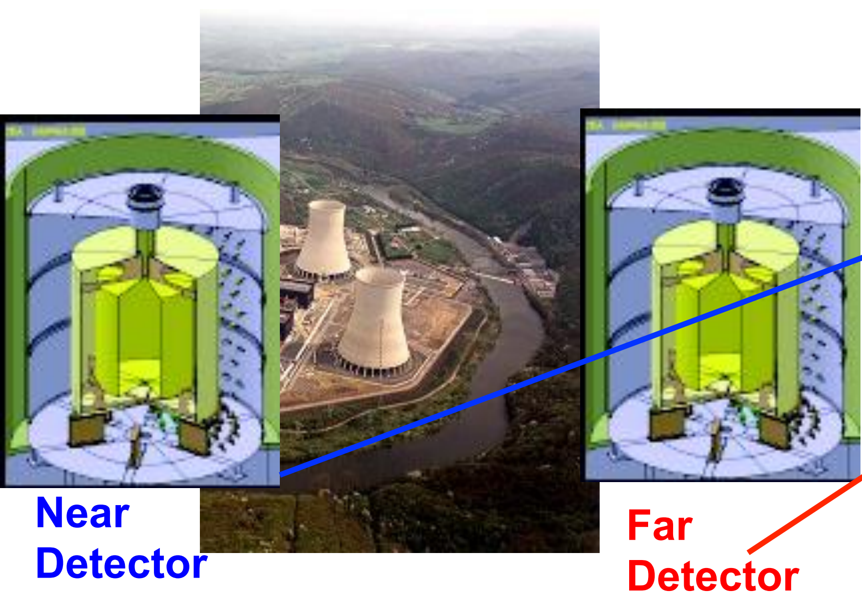
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{13}^2 L}{4E}$$

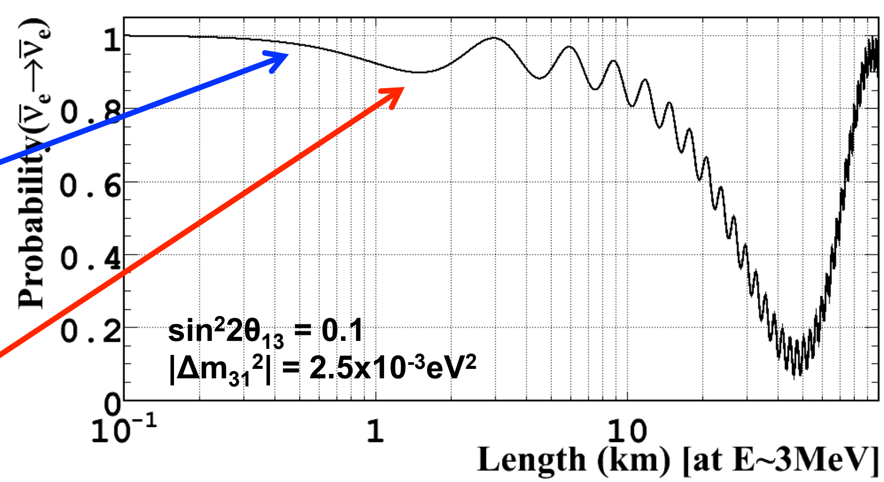
- L/E match Δm_{31}^2 (L~1.5 Km)
- θ_{13} independent of CP-violation
- Weak dependence on Δm_{12}^2
- Negligible matter effects

- Unambiguous measurement of θ_{13} complementary to beams
- The only limitation comes from **systematic errors**

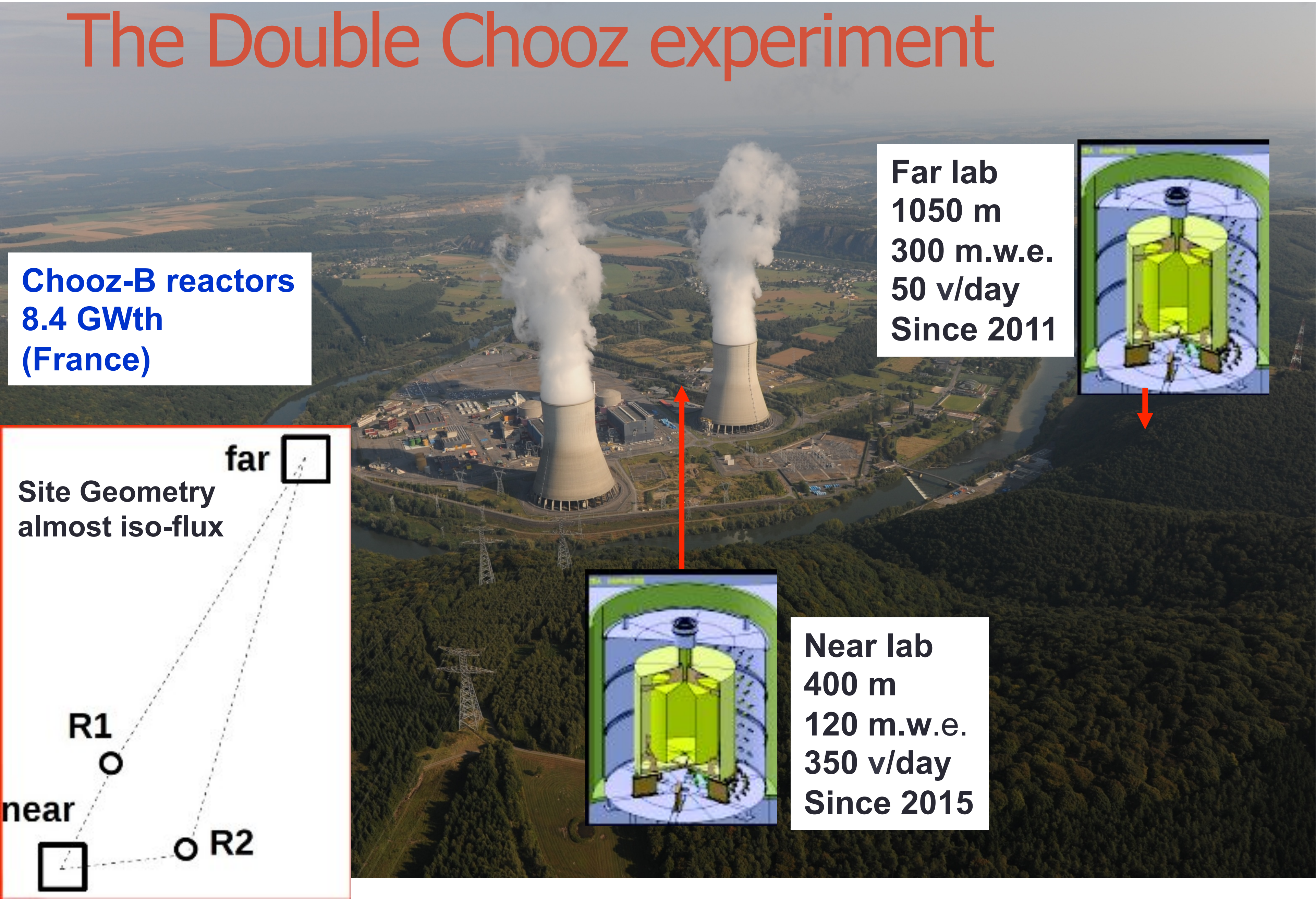
Precision measurement of θ_{13}

- **Two detectors** to remove uncertainties of the reactor flux
- **Identical detectors** to reduce errors due to detector acceptance





The Double Chooz experiment



Chooz-B reactors
8.4 GWth
(France)

Far lab
1050 m
300 m.w.e.
50 ν/day
Since 2011

Near lab
400 m
120 m.w.e.
350 ν/day
Since 2015

Site Geometry
almost iso-flux

The Double Chooz Collaboration

Spokesman: Hervé de Kerret (APC)

France: APC, CEA/DSM/IRFU, IN2P3(Subatech, IPHC)

Germany: RWTH Aachen, MPIK Heidelberg, TU München, EKU Tübingen, u. Hamburg

Spain: CIEMAT

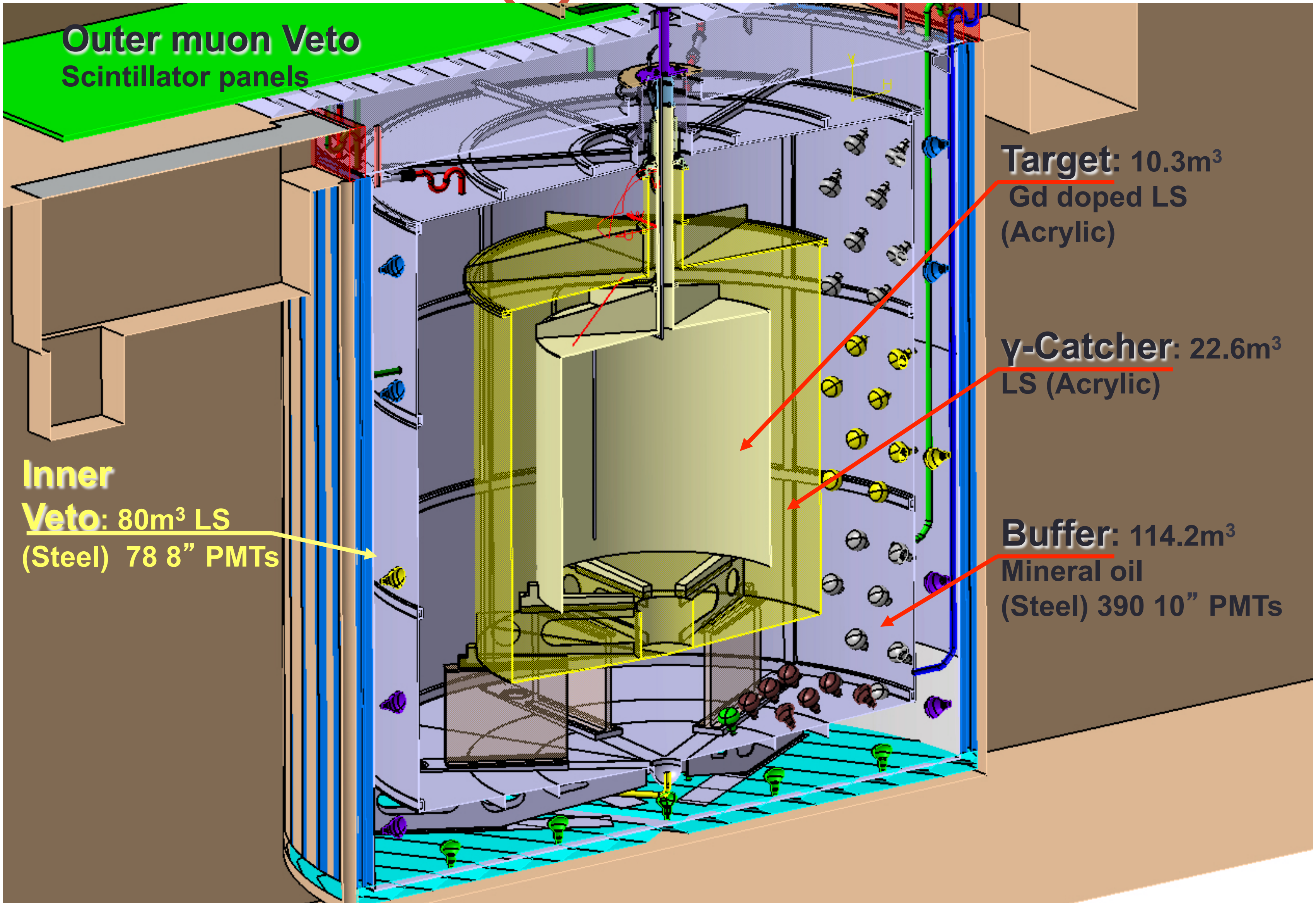
Japan: Kobe U., Niigata U., TGU, Tokyo IT, Tokyo MU, Tohoku U., Hiroshima IT.

Russia: RAS, RRC Kurchatov Institute

USA: U. Alabama, ANL, U. Chicago, Columbia U, Drexel U, ITT, MIT, Kansas S U, LLNL, U. Notre Dame, U. Tennessee, UC Davis

Brazil: CBPF, UNICAMP,UFABC

The Detector(s)



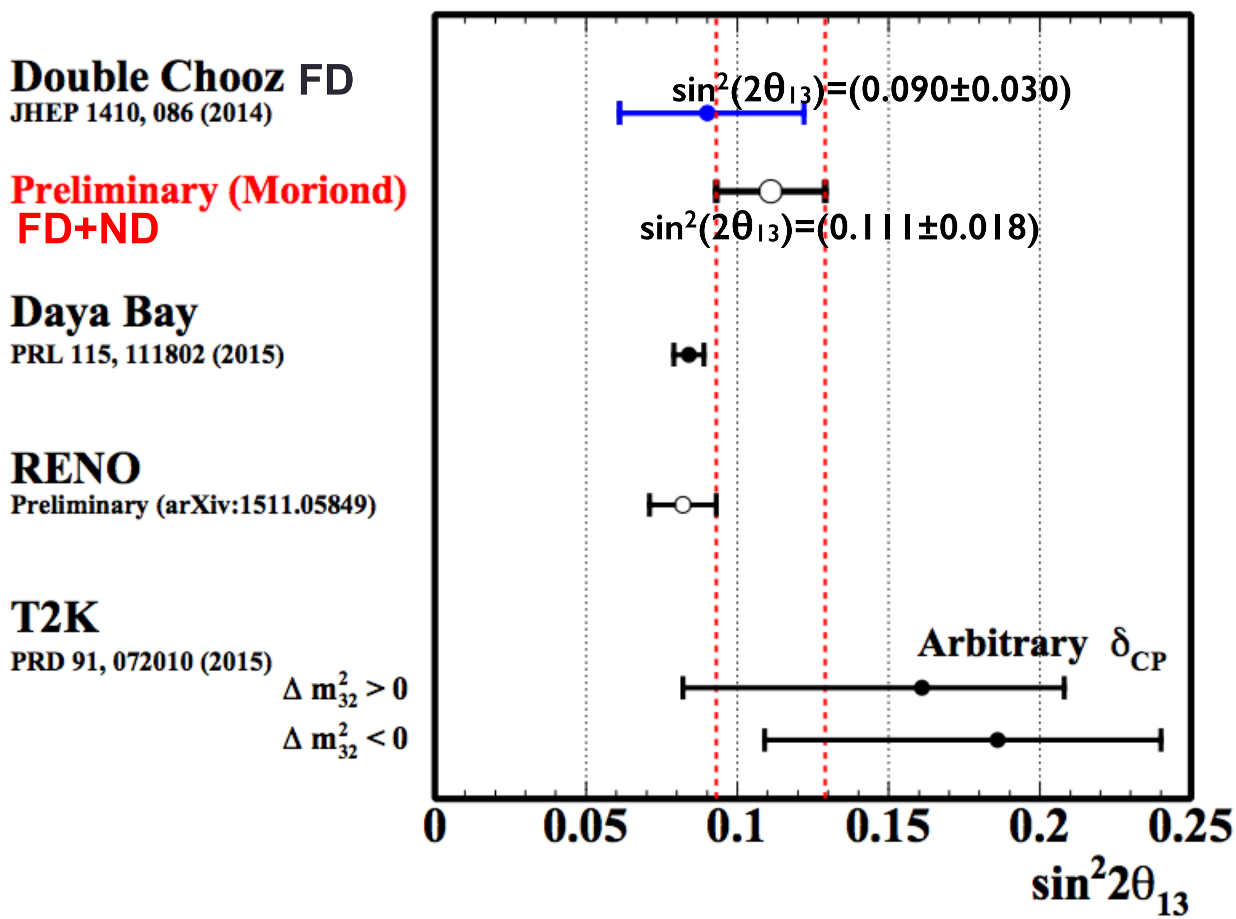
Achievements single detector (Far)

- First indication of non-zero θ_{13} at 94% CL in reactor experiment
- First measurement of θ_{13} using hydrogen capture
- Observation of spectral distortion at 4-6 MeV
- Precise measurement of θ_{13} with single far detector
  - High purity IBD selection (n-Gd: S/N ~ 23, n-H: S/N~10)
  - Well controlled systematics at per-mille level (energy, detection, BG)
  - Use of Bugey4 as anchor of reactor flux normalization

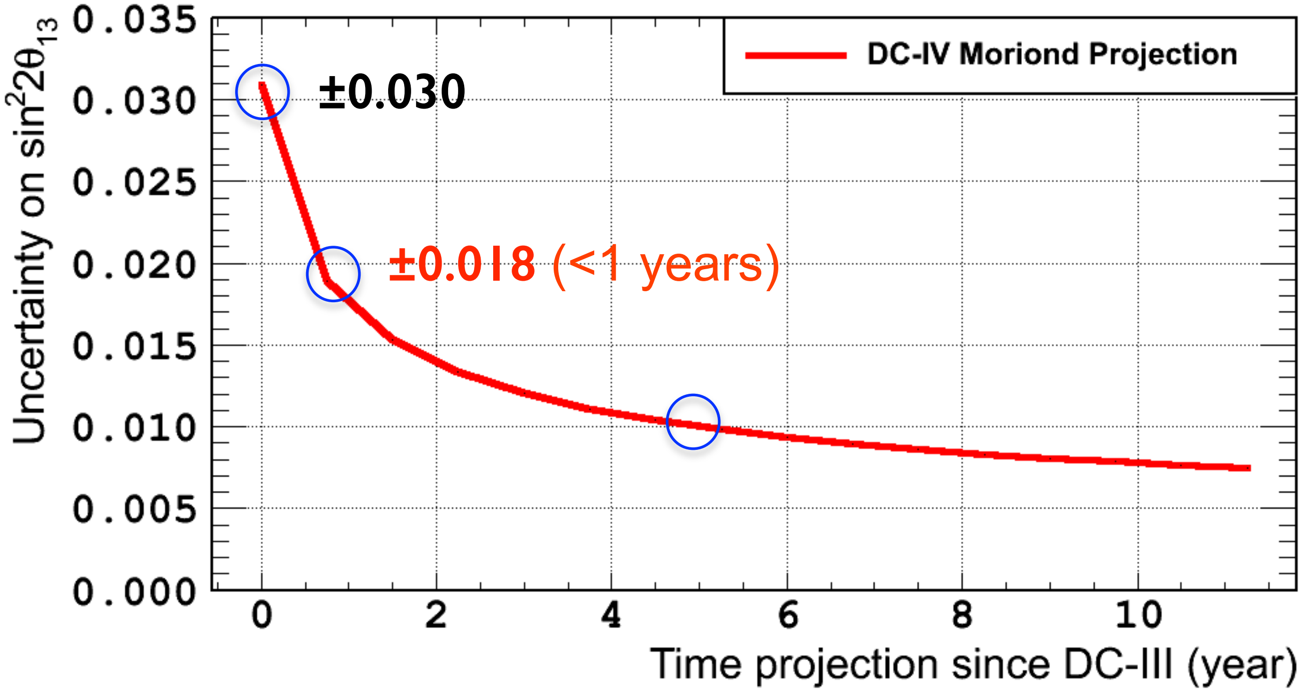
Multidetector measurement:

- **First data set using n-Gd presented at Moriond (March-2016)**
- **New analysis with higher statistics:**
  More data and a larger Neutrino-Target TODAY

Double Chooz results



DC sensitivity evolution



Dominated by statistics
~5 years to reach ±0.010

New analysis Larger DC Neutrino Target

IBD(Gd)

Target: ~8t
smallest θ_{13} target

IBD(Gd+H)

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

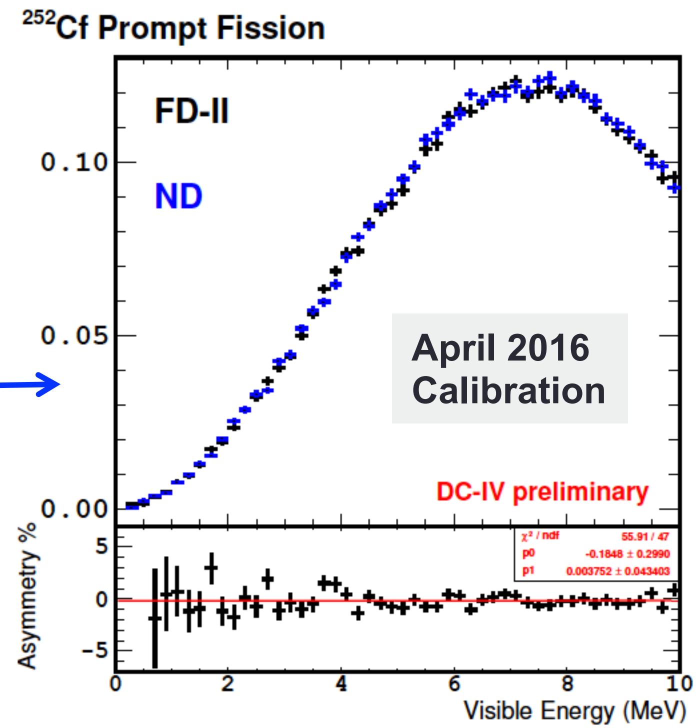
DC result is not dominated by statistics any more

ND performance

ND has (small) leak **Target → GC**

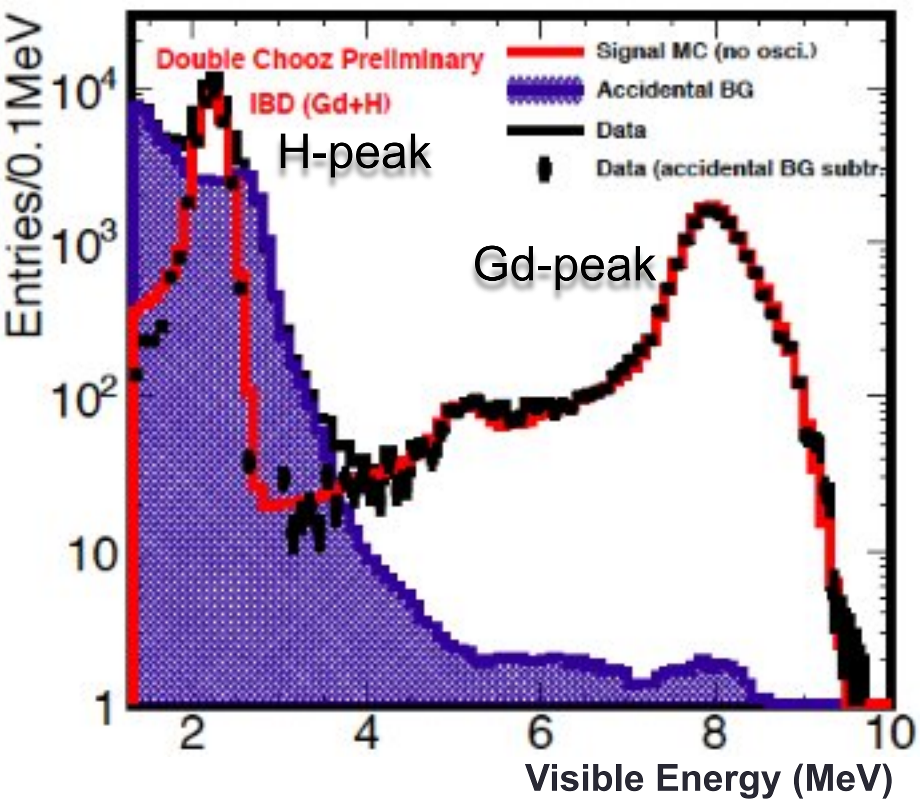
- Target-GC liquids in contact (we don't know the cause yet)
- Small fraction of Gd in GC
- Diffusion is expected
- No effect on the new analysis Gd+H
  [effect on Gd analysis under study]

April 2016 Calibration: same ^{252}Cf source in both detectors
Ex: Relative response linearity <0.3% at [1,10] MeV



IBD Selection (Gd+H)

Neutron capture signal



The new analysis integrates over all captures inclusively

8 MeV n-Gd signal Low BG

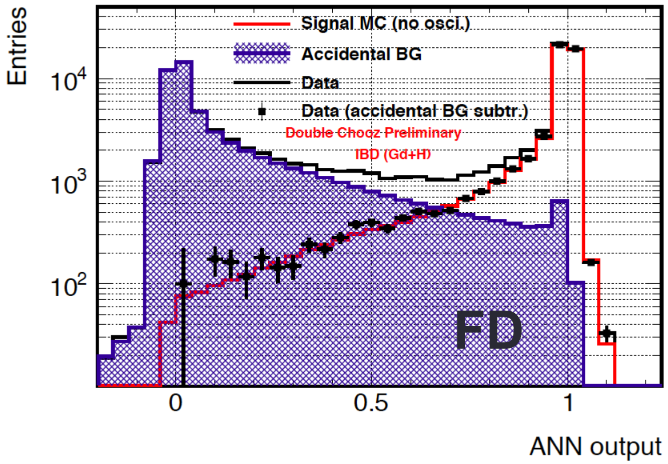
2.2 MeV n-H signal Hidden by Acc. BG

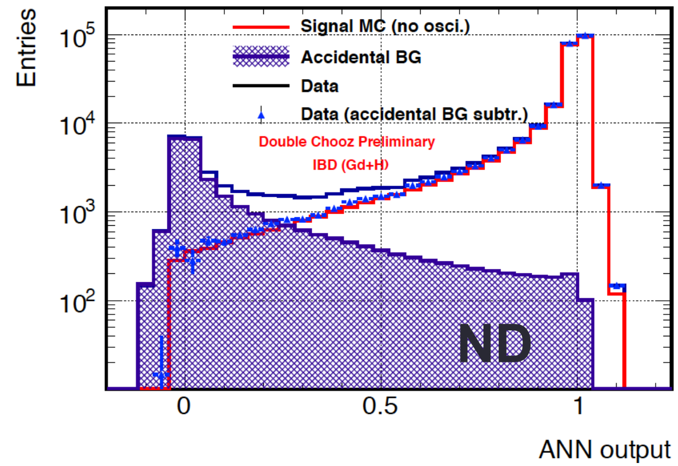
Artificial Neural Network (ANN)

based on the 3 characteristic variables of the IBD reaction:

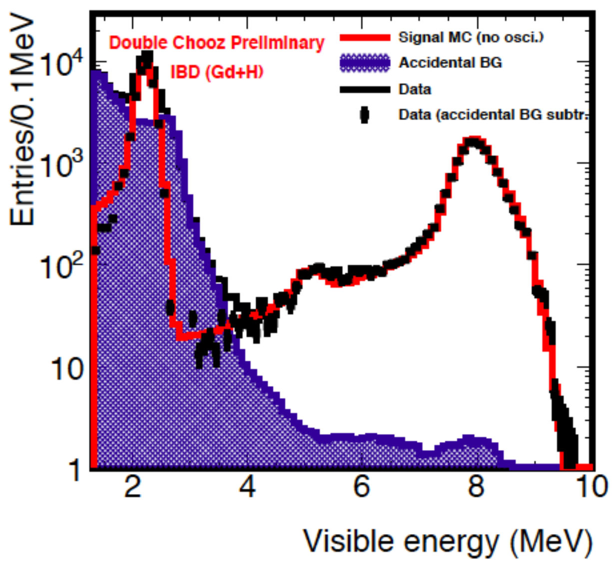
- **Energy neutron capture (delayed)**
- **Distance prompt-delayed ΔR**
- **Time difference prompt-delayed ΔT**

ANN

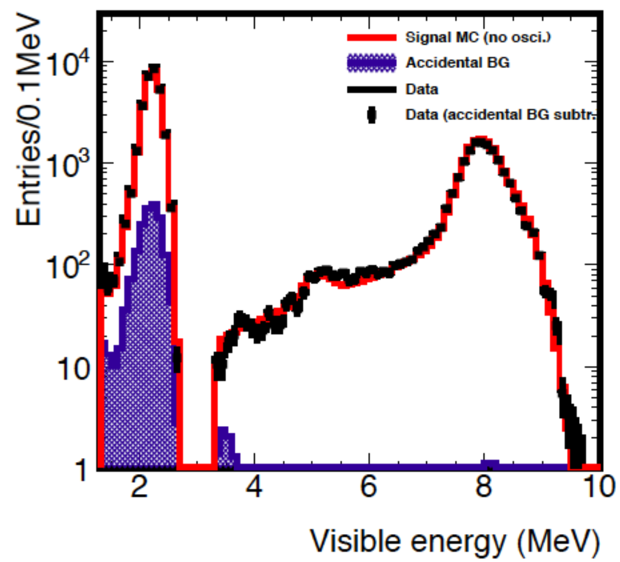




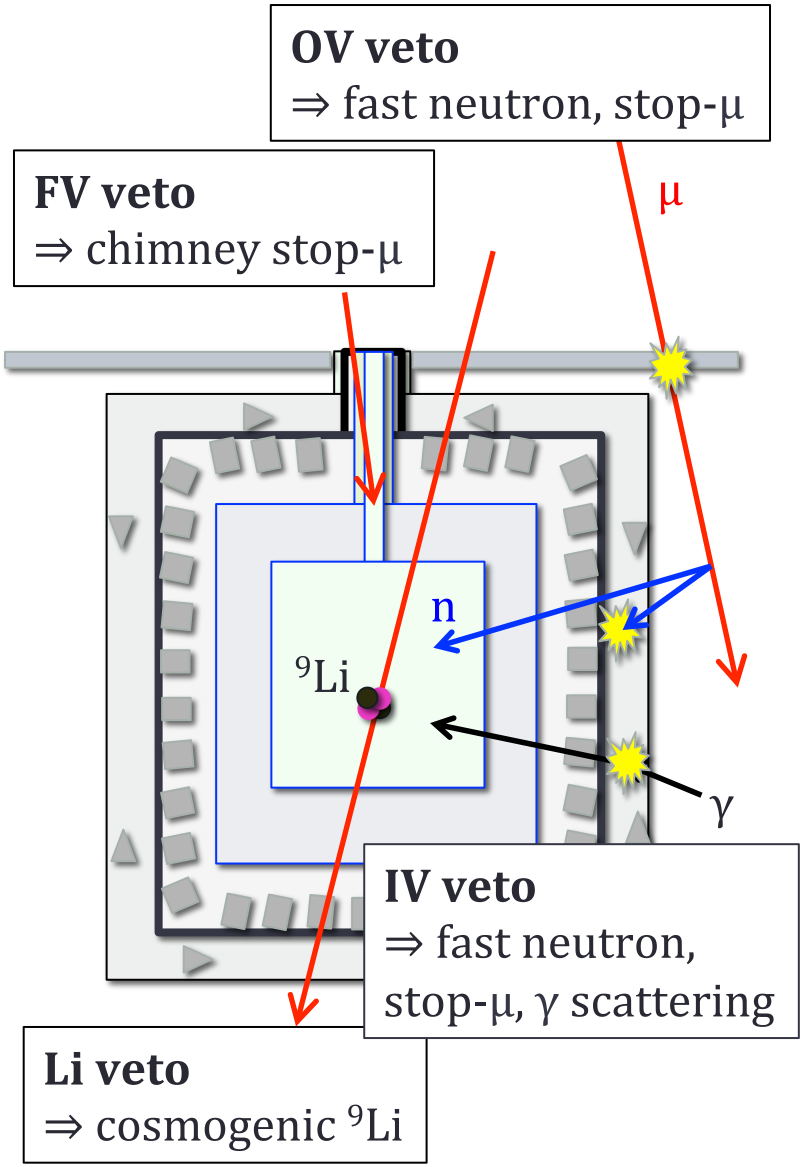
Before ANN cut



After ANN cut

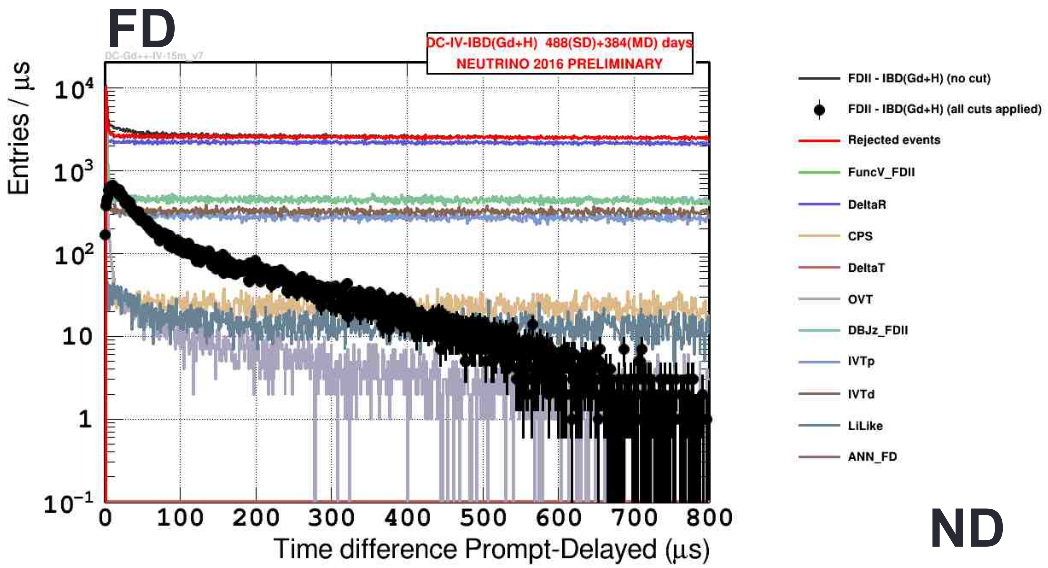


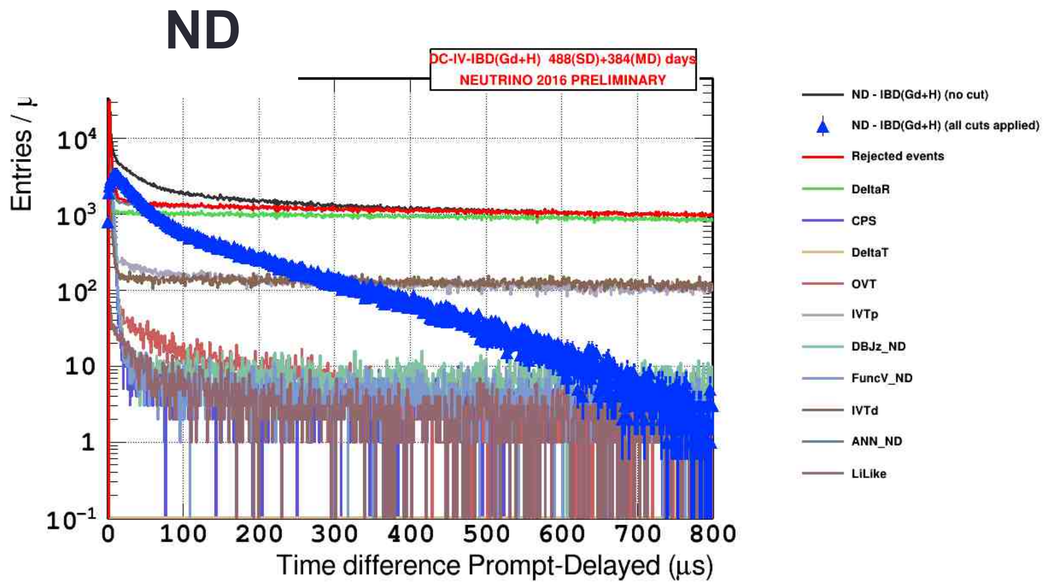
IBD Selection: Background vetoes



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

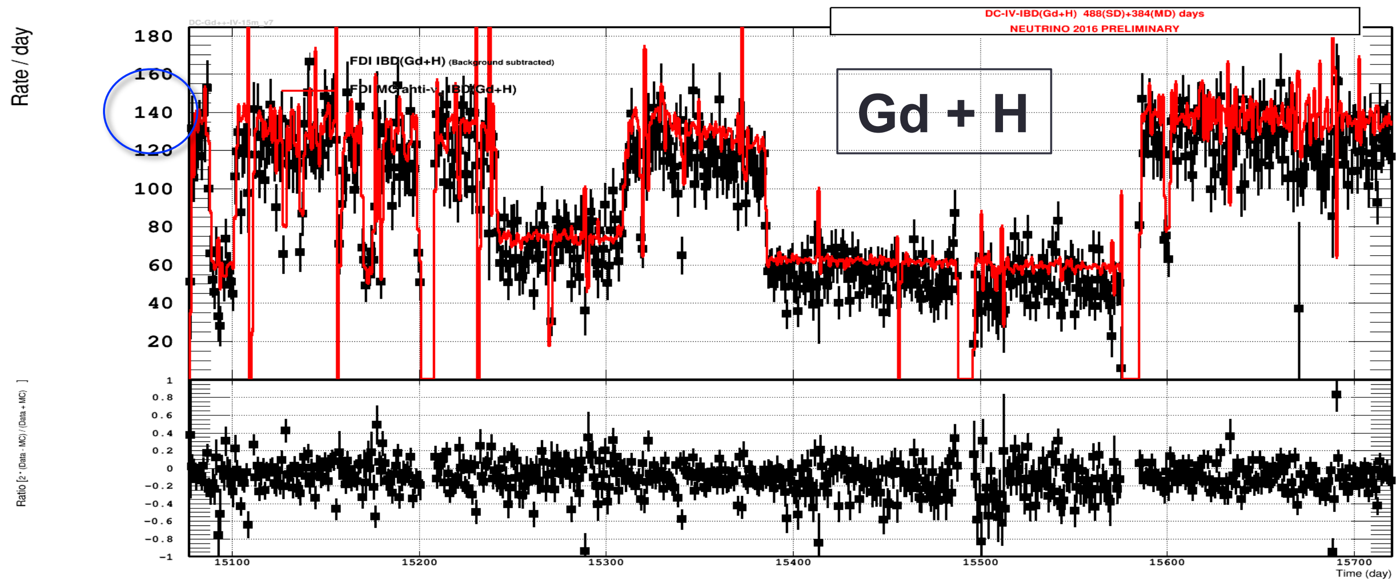
IBD Selection



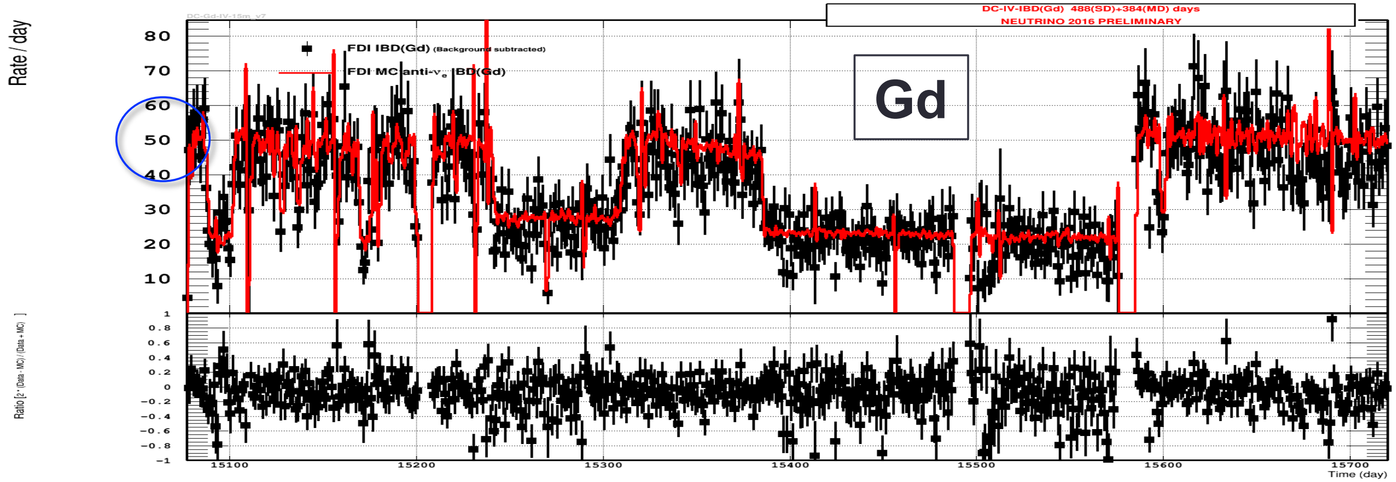


FD anti-neutrino sample

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



$\sigma^{stat}=0.56\%$



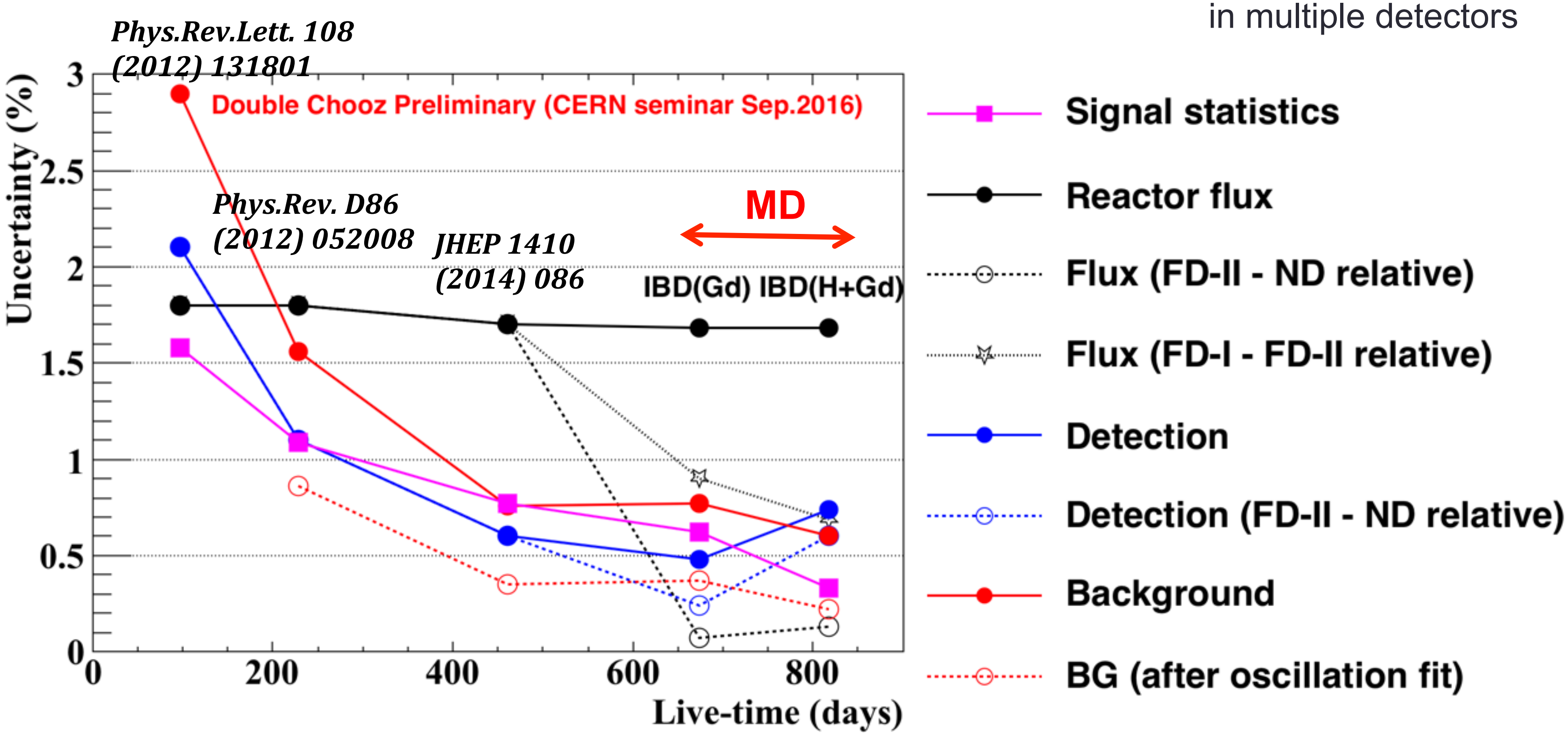
Signal + BG

	FD-I (SD)	FD-II (MD)	ND
Live-time (days)	455.207	362.974	257.959
IBD prediction (day^{-1})	101.39	115.21	782.10
^{9}Li (β-n) BG (day^{-1})	2.59 ± 0.61	2.59 ± 0.61	11.11 ± 2.96
Correlated BG (day^{-1})	2.60 ± 0.11	2.48 ± 0.10	20.77 ± 0.43
Accidental BG (day^{-1})	3.93 ± 0.01	4.32 ± 0.02	3.110 ± 0.004
Total Prediction (day^{-1})	**110.51**	**124.60**	**817.09**
IBD candidates observ. (day^{-1})	**105.77** (48147)	**117.53** (42660)	**815.94** (210480)

SD: single detector
MD: multiple detectors

Systematic errors

SD: single detector
MD: relative uncertainties in multiple detectors



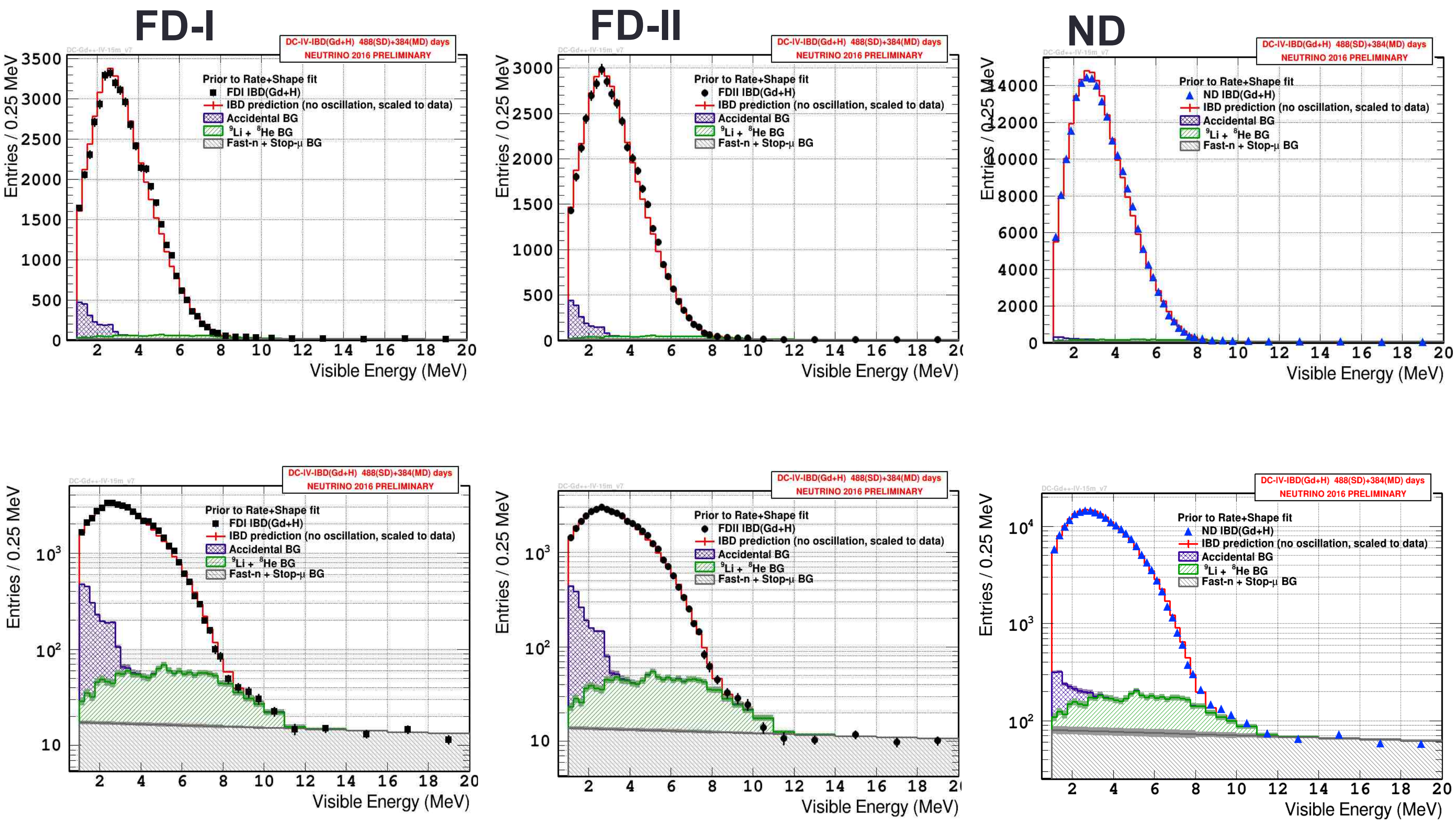
Main systematic errors:

- **Detection:** due to the uncertainty in proton# in GC, limiting sensitivity in Gd+H

[Full volume: 0.53%(uncorrelated)/0.76%(total) [NT: 0.1%(uncorrelated)/0.3%(total)]

- **Background:** β-n (^{9}Li) rate estimations are not used as input to rate+shape fit
  ⇒ rates are constrained in the fit with the shape information

Anti-neutrino energy spectrum



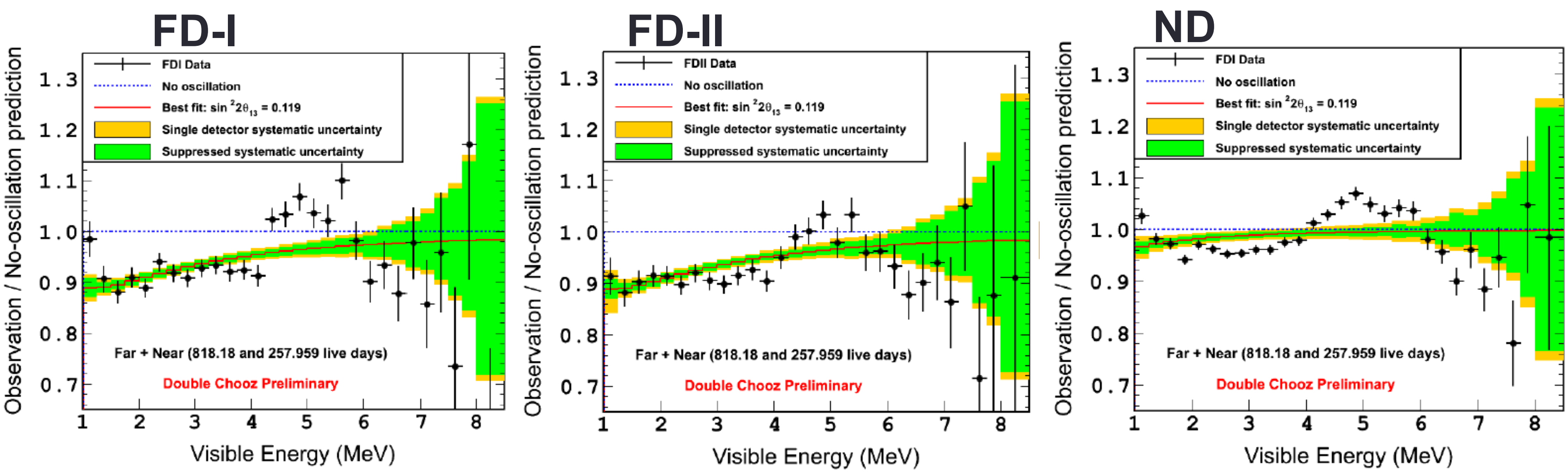
Measurement of θ_{13} Rate + anti-neutrino spectrum shape

- χ^2 **fit** comparing FD-I, FD-II and ND **data** to (**MC** prediction + BG estimation)
- Correlation of systematic errors are included in the fit:
  FD-I / FD-II and FD-II / ND
- Energy non-linearity effectively corrected in rate+shape fit
- Simple extension of SD analysis

- ○ Background rate and shape estimated by data
- ○ ^{9}Li (β-n) BG rate not constrained (only limited by shape information)
- ○ Observed data in reactor off as separate term ⇒ BG constraint
- ○ Background error is further suppressed by rate+shape fit

Cross-checked by independent fits based on χ^2 and likelihood and a fit based on comparison of FD **data** and ND **data**

Results



$\sin^2(2\theta_{13}) = 0.119 \pm 0.016$ (stat.+syst.) (χ^2/dof = 236.2/114)

Background	Estimation FD	Fit output FD	Estimation ND	Fit output ND
^{9}Li (β-n)	2.59 ± 0.61	2.55 ± 0.23	11.11 ± 2.96	14.4 ± 1.2
Correlated	2.54 ± 0.10	2.51 ± 0.05	20.77 ± 0.43	20.85 ± 0.31

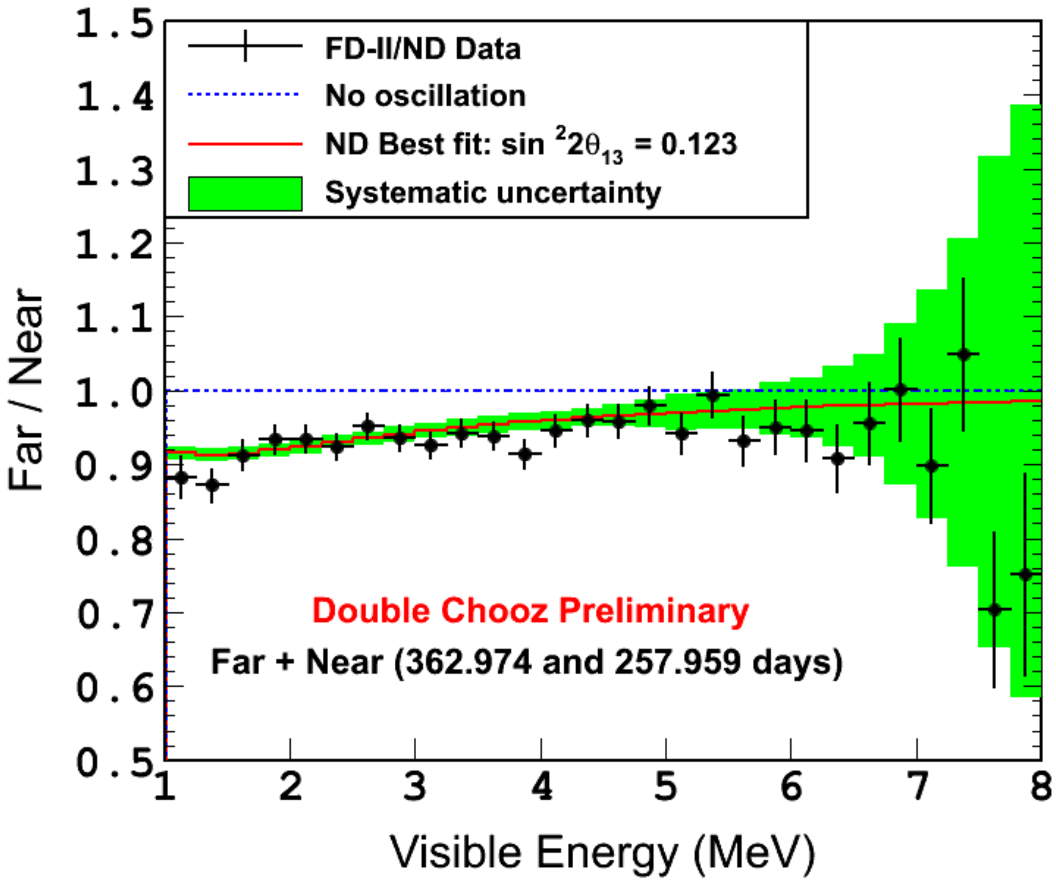
Cross-check data-to-data fit

FD-II:ND only

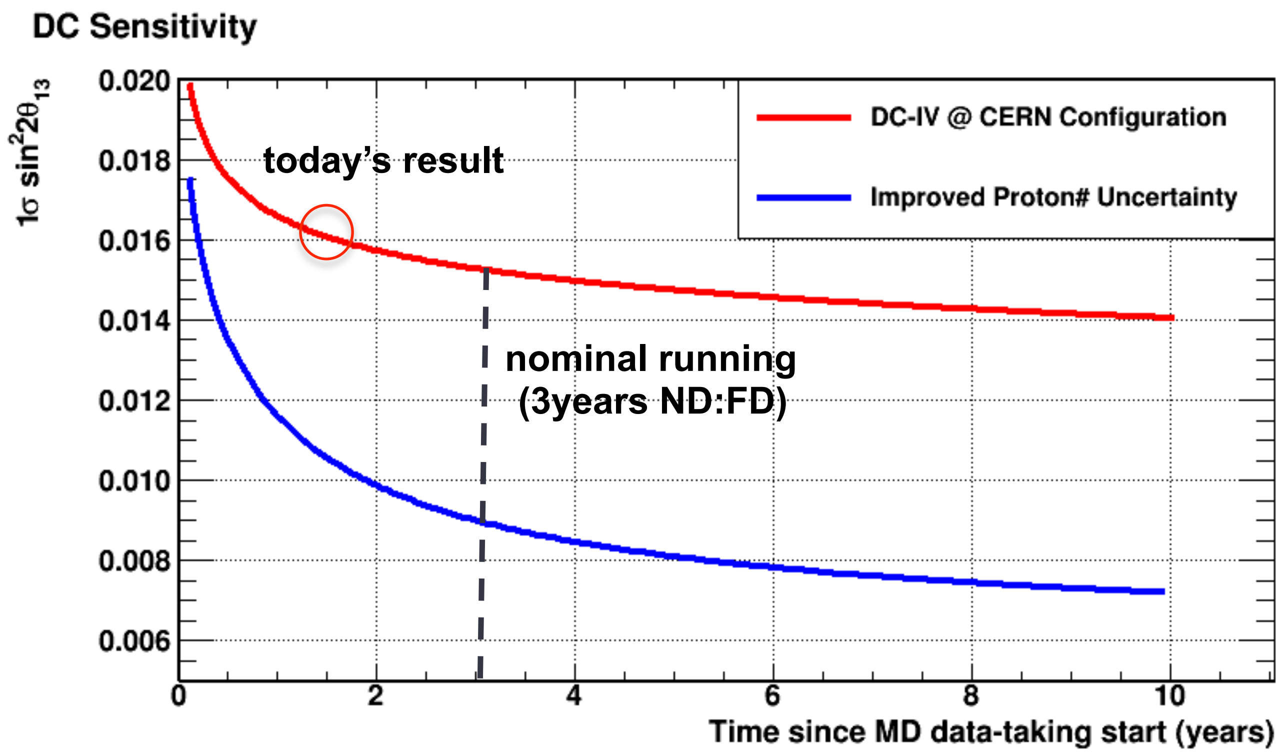
$\sin^2(2\theta_{13})$ = 0.123 ± 0.023

(χ^2/dof = 10.6 / 38)

No affected by MC spectrum distortion at [4,6] MeV



DC sensitivity evolution for Gd+H analysis

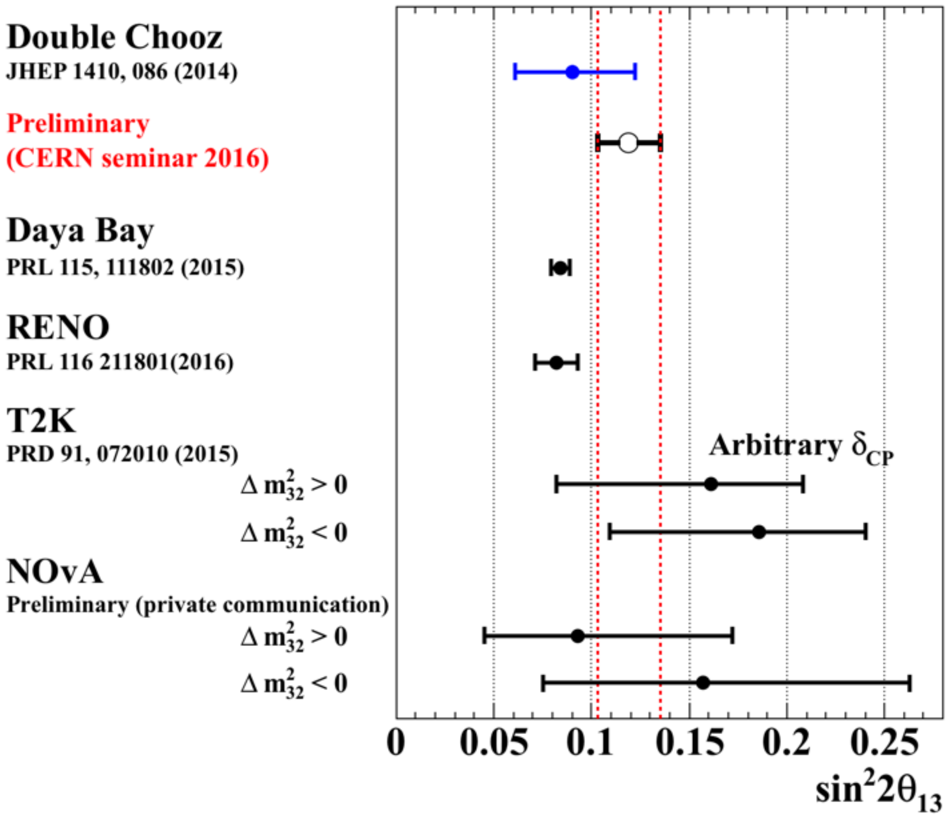


DC largely dominated by proton# uncertainty

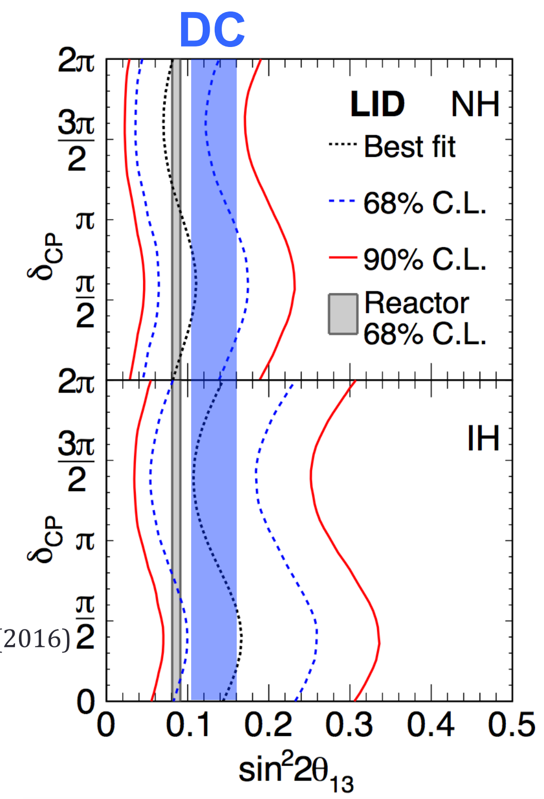
Most conservative inputs/assumptions has been adopted so far

(There is room from improvement)

Double Chooz results in the world



Reactor vs. NOvA
Phys.Rev.Lett.116 (2016)



DC θ_{13} is higher than other reactor θ_{13} by ~45% (2.2σ wrt DYB)

Reactor θ_{13} is key parameter to solve CP-violation and mass hierarchy

Summary

- Double Chooz has presented a new measurement of θ_{13} with the multi-detector configuration
- A new analysis integrating over all neutron capture (Gd+H) has been used to increase the anti-neutrino statistics and to avoid the effect of a tiny leak of Gd in the GC
  - $\mathbf{\sin^2(2\theta_{13}) = 0.119 \pm 0.016}$ (stat.+syst.)
  - The statistical error is reduced ~40%
  - Reactor flux uncertainty is strongly suppressed to < 0.1% thanks to nearly iso-flux condition
  - But the new measurement is dominated by proton# uncertainty
- Reactor θ_{13} is a key for current and future neutrino projects aim to solve still unknown CP-violation and mass hierarchy
  $\Rightarrow$ Validation by multiple-experiments is essential

EXTRA SLIDES

Reactor systematic errors (%)
Fully correlated

	SD	MD
Bugey4	1.4	--
E / fission	0.16	--
Baselines	≤0.01	≤0.01
Spectrum + σ_{IBD}	0.05	--

Reactor systematic errors (%)
Unknown physical correlations

	FD-I		FD-II		ND	
	SD	MD	SD	MD	SD	MD
Fission fraction	0.78	0.55	0.78	0.56	0.78	0.57
Thermal power	0.47	0.33	0.47	0.33	0.47	0.34

Systematic error Flux (FD-II:ND) = 0.198 %

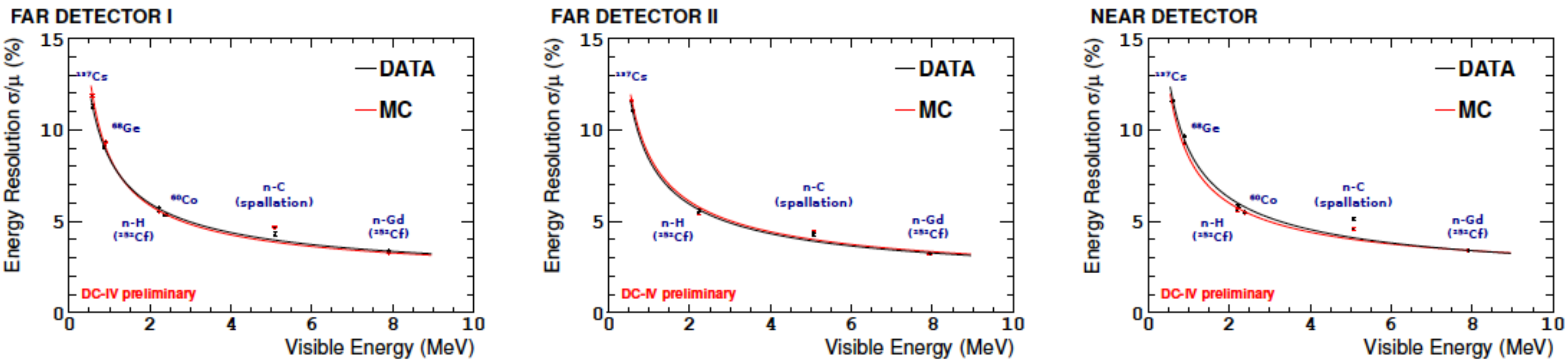
Detection systematics

	FD-I	FD-II	ND
BG (%)	0.60 (0.5)	0.5 (0.5)	0.38 (0.3)
Gd fraction (%)	0.25 (0.14)	0.26 (0.15)	0.28 (0.19)
IBD selection (%)	0.31 (0.30)	0.27 (--)	0.30
Spill in/out (%)	0.20 (0)	0.20 (0)	0.20 (0)
Proton number (%)	0.76 (0.53)	0.76 (0.53)	0.76 (0.53)
Total (%)	**0.75 (0.60)**	**0.75 (---)**	**0.74 (0.60)**

Systematic errors

Error on IBD normalization

	MD (%)	SD(%)
Flux	0.13/0.65	1.56
proton# (FD+ND)	0.53	0.76
Energy (delay)	<0.01	
Detection (FD)	0.30	0.31
BG (FD)	0.60	0.60
Detection (ND)	0.30	---
BG (ND)	0.38	0.38

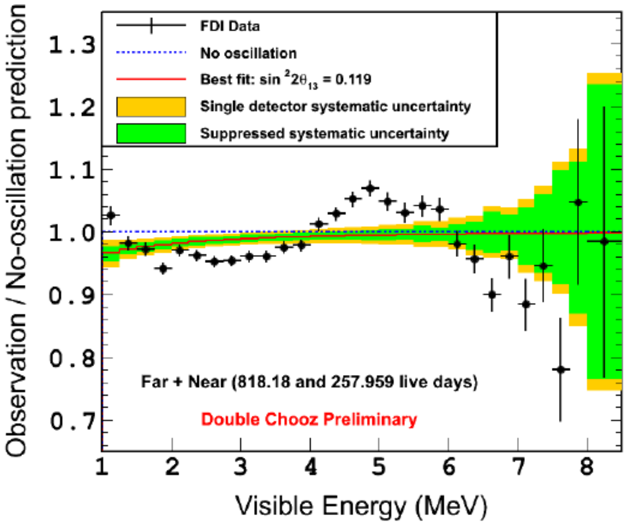


$$\sigma / E_{vis} = \sqrt{\frac{a^2}{E_{vis}} + b^2 + \frac{c^2}{E_{vis}^2}}$$

a: statistical
b: constant term
c: electric noise

	FD-I	FD-II	ND
a	7.84 ± 0.10 %	7.92 ± 0.17 %	8.46 ± 0.09 %
b	1.87 ± 0.06 %	1.66 ± 0.11 %	1.58 ± 0.10 %
c	2.49 ± 0.29 %	2.13 ± 0.35 %	2.32 ± 0.21 %

Spectrum distortion



Excess proportional to reactor power