Latest results from Double Chooz

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Neutrino Telescope

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Neutrino mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

PMNS matrix (Pontecorvo-Maki-Nakagawa-Sakata)

ν_e, ν_μ, ν_τ : flavor eigenstates.

ν_1, ν_2, ν_3 : mass eigenstates of $m = m_1, m_2, m_3$.

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

$c_{23} = \cos\theta_{23}$, etc.

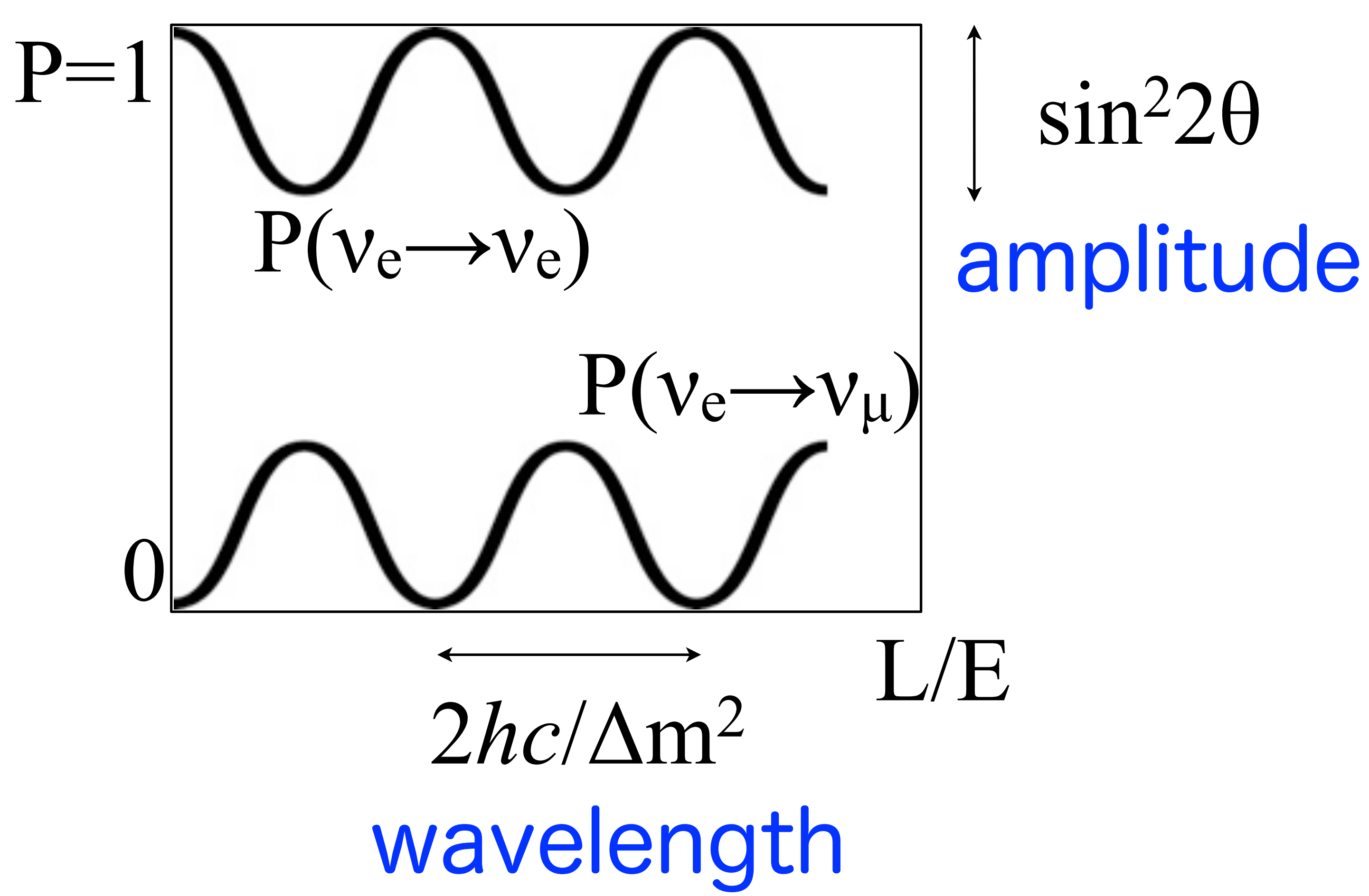
3 mixing angles (θ_{12}, θ_{23}, θ_{13}) + 1 complex phase (δ) ←CP violation

Neutrino oscillation

IF $\theta \neq 0$ AND $\Delta m^2 \neq 0$, flavor transmutation occurs.

$P(\nu_i \rightarrow \nu_j) = \sin^2 2\theta_{ij} \times \sin^2(1.27\Delta m^2 L/E)$ (2 flavor approx.)

Δm^2 in (eV^2), L/E in (km/GeV or m/MeV)



- 3 mixing angles
  θ_{12}, θ_{23}, θ_{13}
- 2 (independent) mass^2 differences
  $\Delta m^2_{32} = m_3^2 - m_2^2$
  $\Delta m^2_{21} = m_2^2 - m_1^2$
  $(\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21})$
- 1 complex phase (CPV) δ

Oscillation parameters

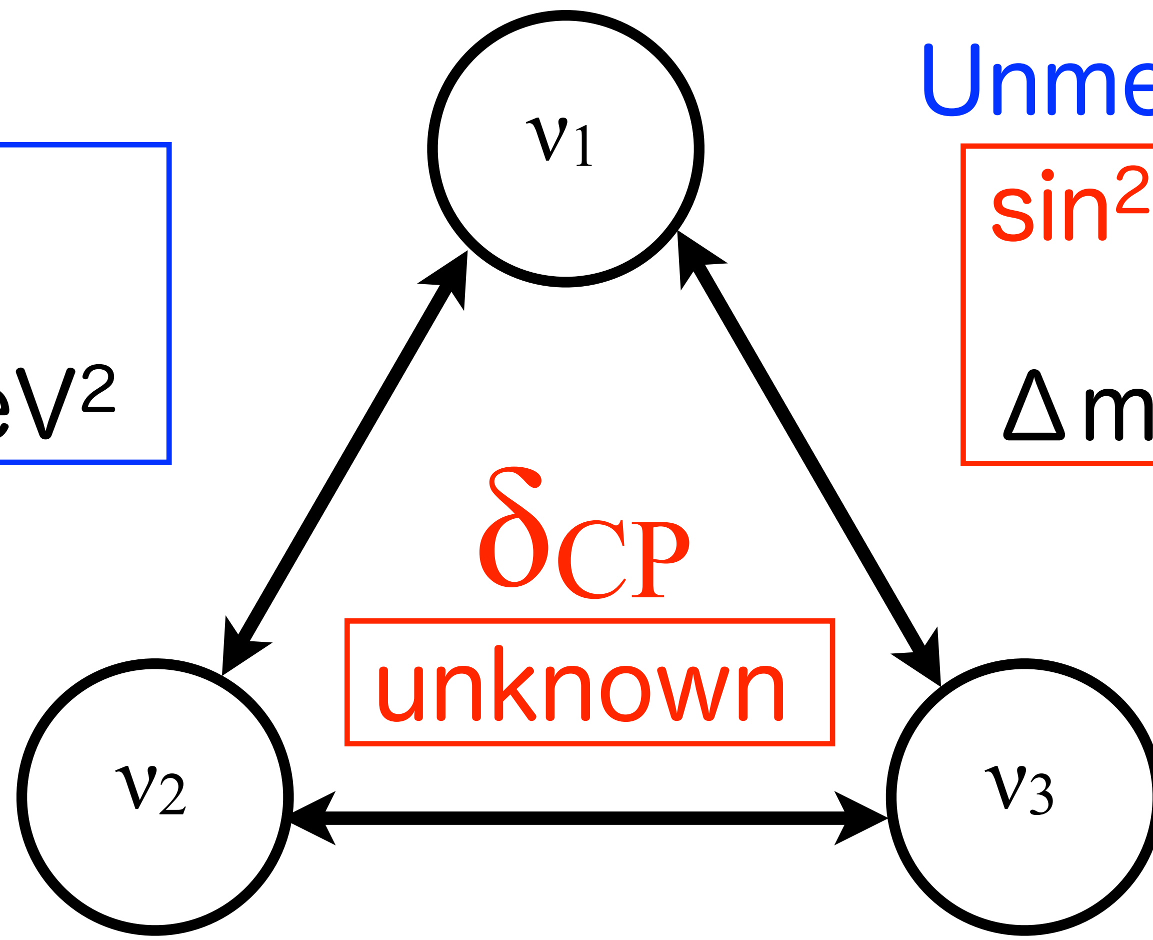
Unmeasured <2011

$\sin^2(2\theta_{12})\sim0.8$

$\Delta m^2_{21}\sim8\times10^{-5}\mathrm{eV}^2$

Solar-ν

Reactor-ν



$\sin^2(2\theta_{13})\sim0.1$

$\Delta m^2_{31}\sim\Delta m^2_{32}$

Reactor-ν

Acc-ν

Atm-ν

Acc-ν

$\sin^2(2\theta_{23})\sim1.0$

$|\Delta m^2_{32}|\sim2.5\times10^{-3}\mathrm{eV}^2$

unknown

mass ordering:

$m_3 >> m_2 > m_1$ or

$m_2 > m_1 >> m_3$

- $\theta_{12}\sim33°$, $\theta_{23}\sim45°$, but $\theta_{13}\sim9°$
- $|\Delta m^2_{32}| >> |\Delta m^2_{21}|$ (by factor ~30)

Importance of θ_{13}

- Last measured mixing angle:
  PMNS matrix structure is very different from
  CKM matrix in quark sector (mostly diagonal)
  → key to the origin of flavor (generation)

- To measure CP-violation phase δ experimentally,
  the condition $\theta_{12}\theta_{23}\theta_{13}\neq 0$ is necessary.
  → key to the matter-antimatter asymmetry of Universe
  (quark CP violation is too small)

- Accelerator appearance probability is a function of θ_{13} and CP δ → by combining with reactor θ_{13}, one can already have handle on δ (with mass hierarchy degeneracy)

Oscillation maximum:

$$1.27\Delta m^2(eV^2)L(km)/E(GeV)=(2n+1)\pi/2$$

1st maximum at $L \sim E/\Delta m^2$ (×1.57/1.27)

- For $\Delta m^2_{32(31)} \sim 2.5\times10^{-3}$ eV^2 and E ~ 1 GeV,
  → L ~ O(400km): accelerator long-baseline experiments
  (T2K, MINOS, NOvA)

- For $\Delta m^2_{32(31)} \sim 2.5\times10^{-3}$ eV^2 and E ~ 4 MeV,
  → L ~ O(1.5km): reactor mid-baseline experiments
  (Daya Bay, DC, RENO)

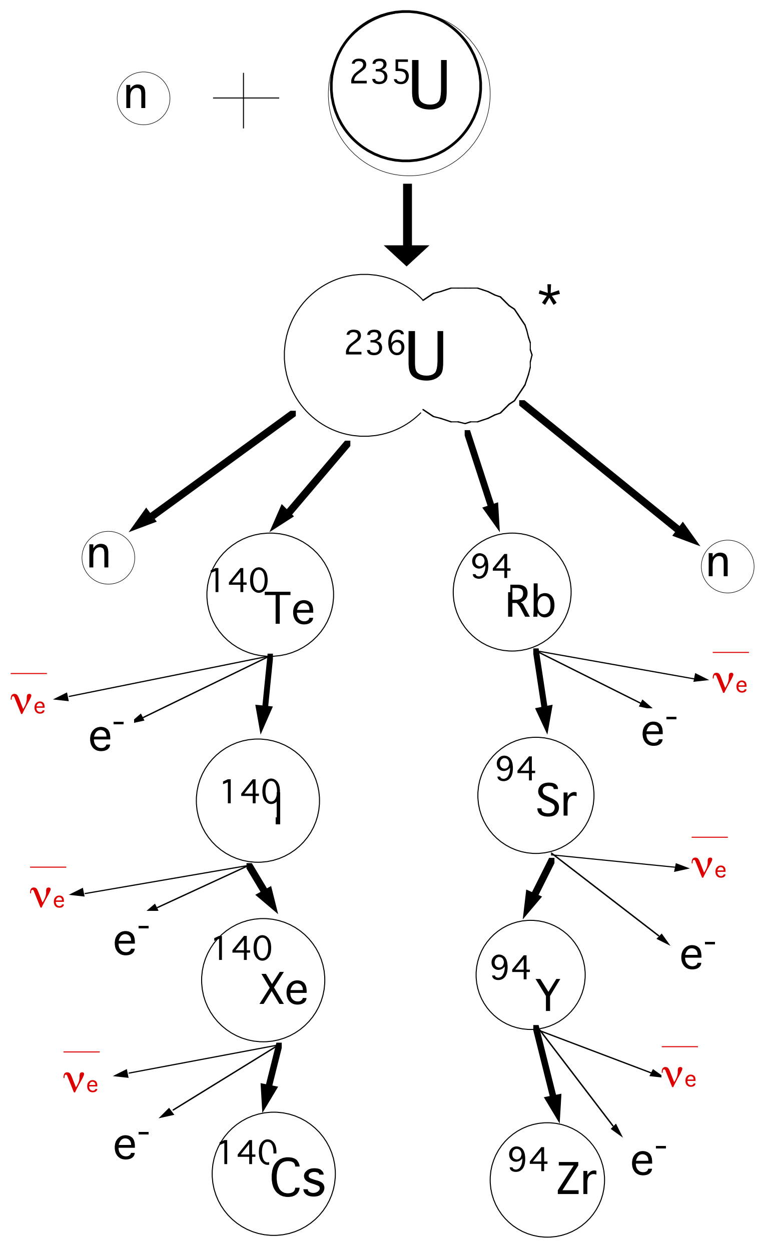
- For $\Delta m^2_{21} \sim 0.8\times10^{-4}$ eV^2 and E ~ 4 MeV,
  → L ~ O(50km): reactor long-baseline exp't (KamLAND)

Why reactors?

- ~6 $\bar{\nu}$'s/fission, ~200MeV/fission

→ 6×10[20] $\bar{\nu}$/sec for a typical commercial reactor

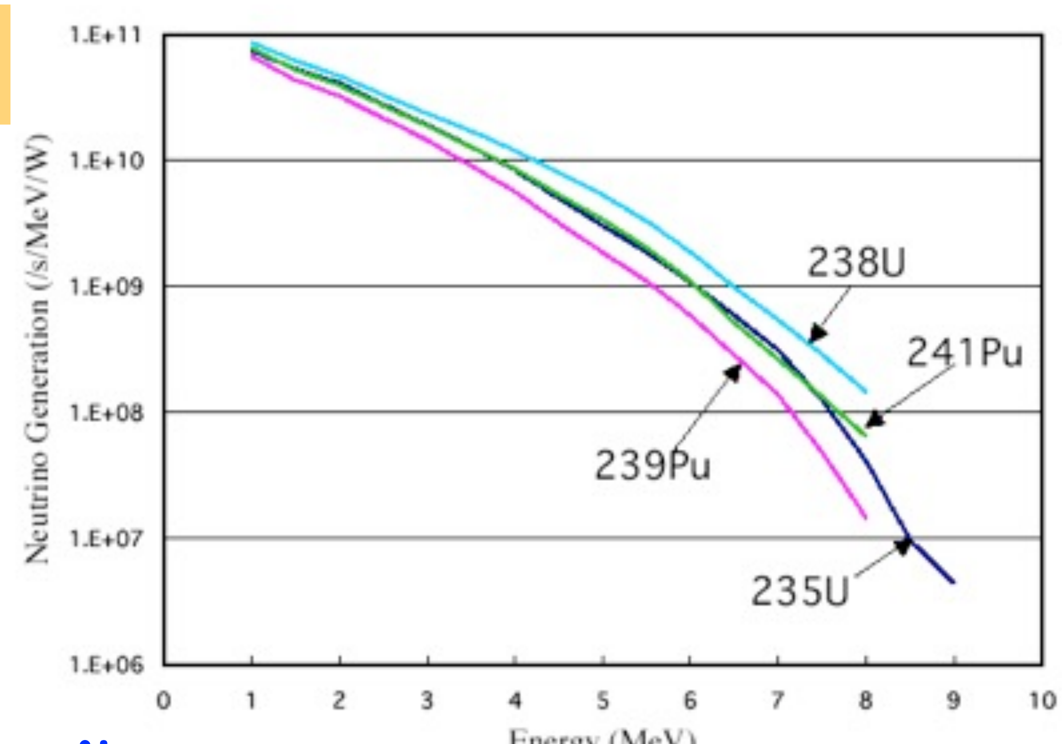
(1GW power ~ 3GW thermal)



(example)

Reactors are powerful and "free" sources of low-energy (isotropic) neutrinos

E_ν~ a few MeV



Always full power

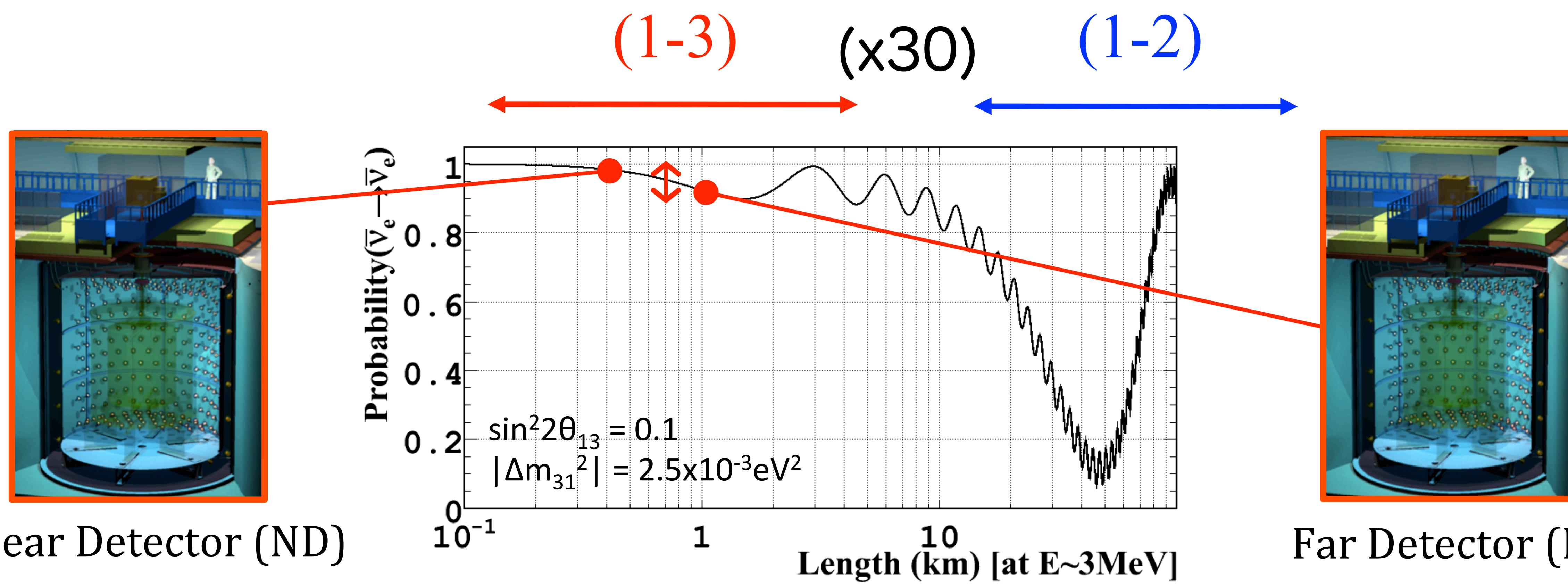
↕

Can't switch off easily

Principle of reactor-ν exp.

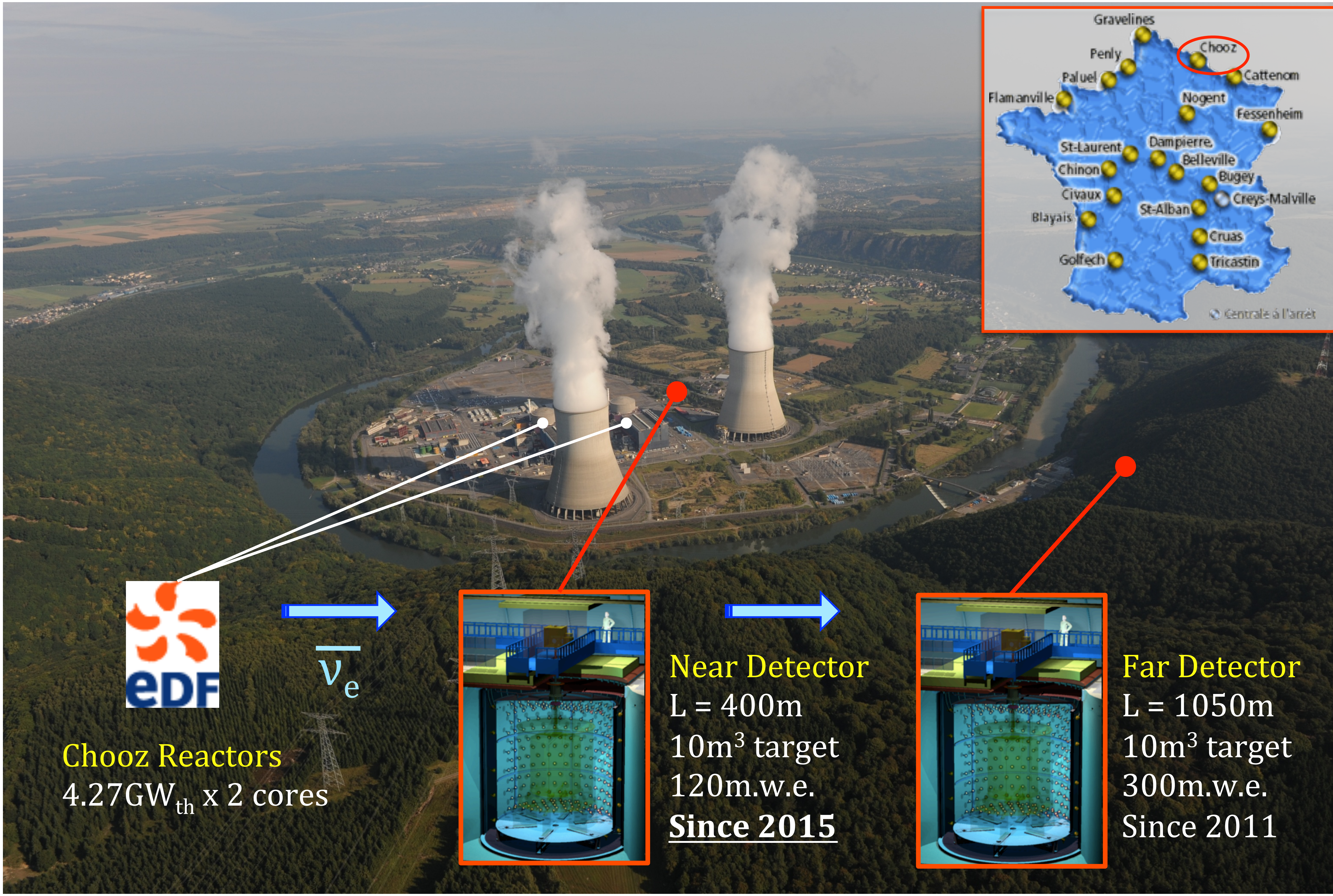
- Disappearance at (1-3) osc. maximum (L=1~2km) (Energy is too low for appearance)
- Thanks to Δm^2 hierarchy, it is a pure θ_{13} measurement

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E}$$ $+O(10^{-3})$ from Δm^2_{21} oscillation



- Cancel flux uncertainty by placing Near and Far detectors

Double Chooz experiment



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

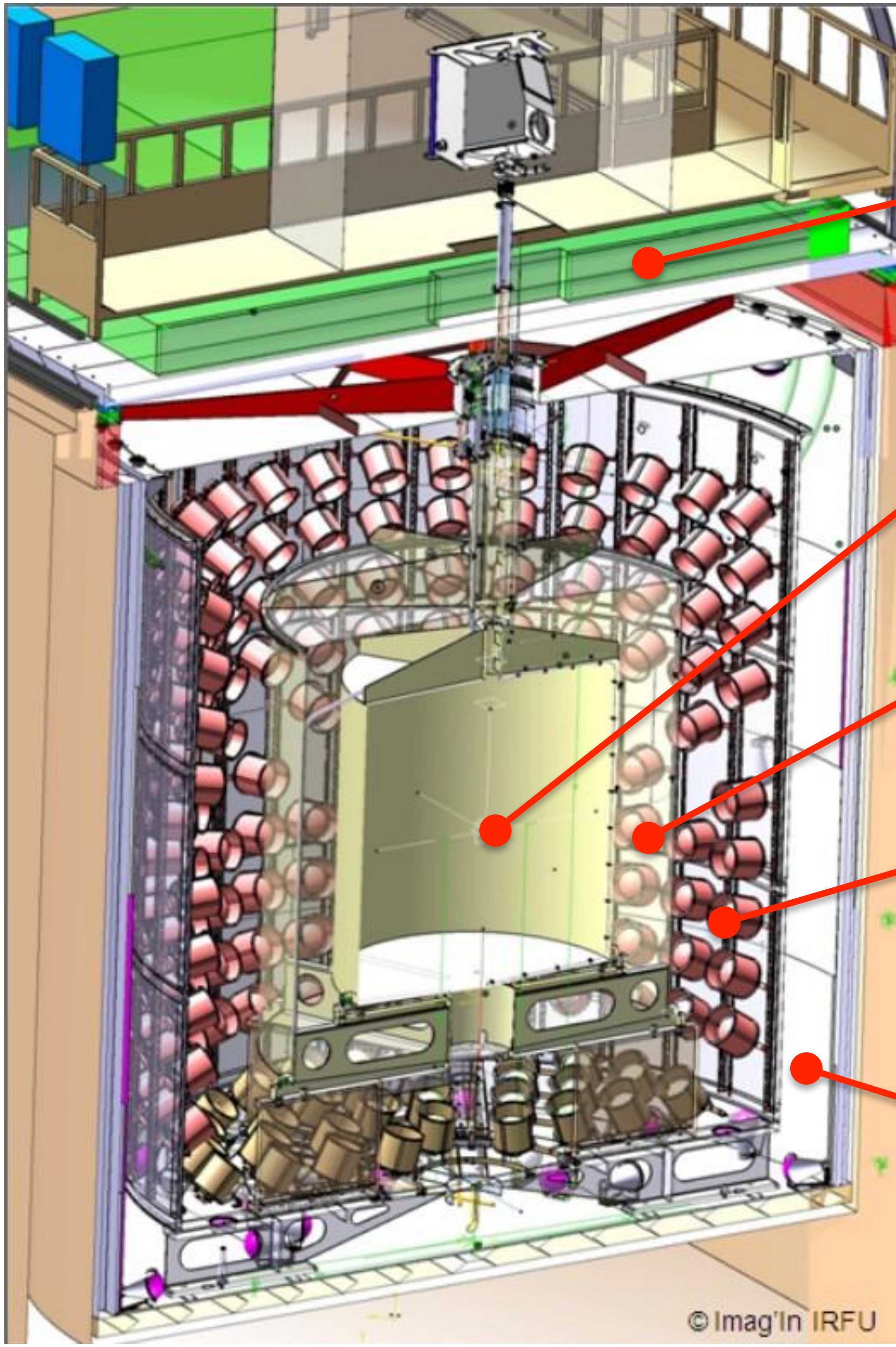
Japan
Tohoku U.
Tokyo Inst. Tech.
Tokyo Metro. U.
Kitasato U.
Kobe U.
Tohoku Gakuin U.
Hiroshima Inst.
Tech.

Russia
INR RAS
IPC RAS
RRC
Kurchatov

Spain
CIEMAT-
Madrid

USA
U. Alabama
ANL,U. Chicago
Columbia U.
UC Davis
Drexel U.
IIT, KSU, MIT,
U. Notre Dame
U. Tennessee
Virginia Tech

The Double Chooz detector



Outer Veto (OV):
Plastic scintillator strips

Inner Detector

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

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

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

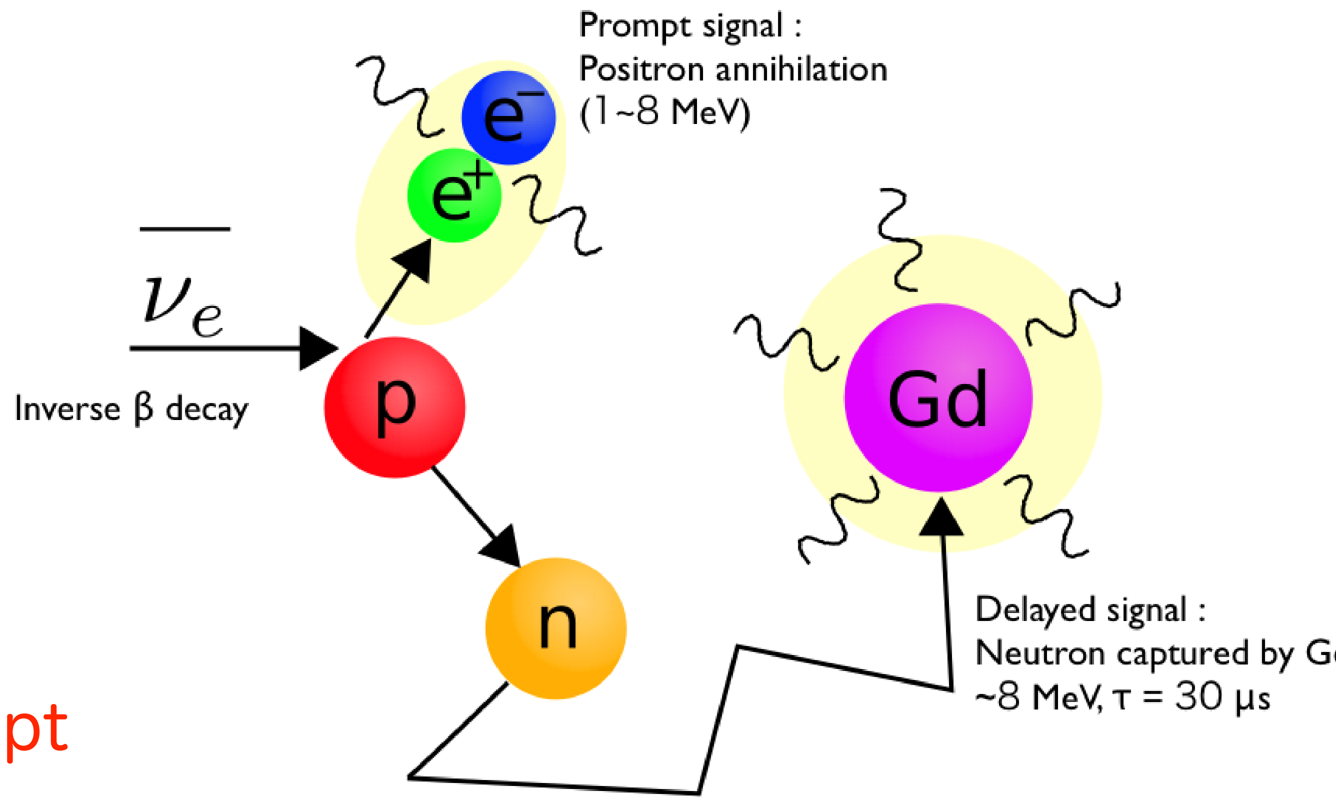
Inner Veto (IV):
- Liquid scintillator ($90m^3$)
- 78 8-inch PMT

Detection Principle

- Inverse-beta decay

  (E_{thresh}=1.8MeV)

  E_ν information carried by e^+



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

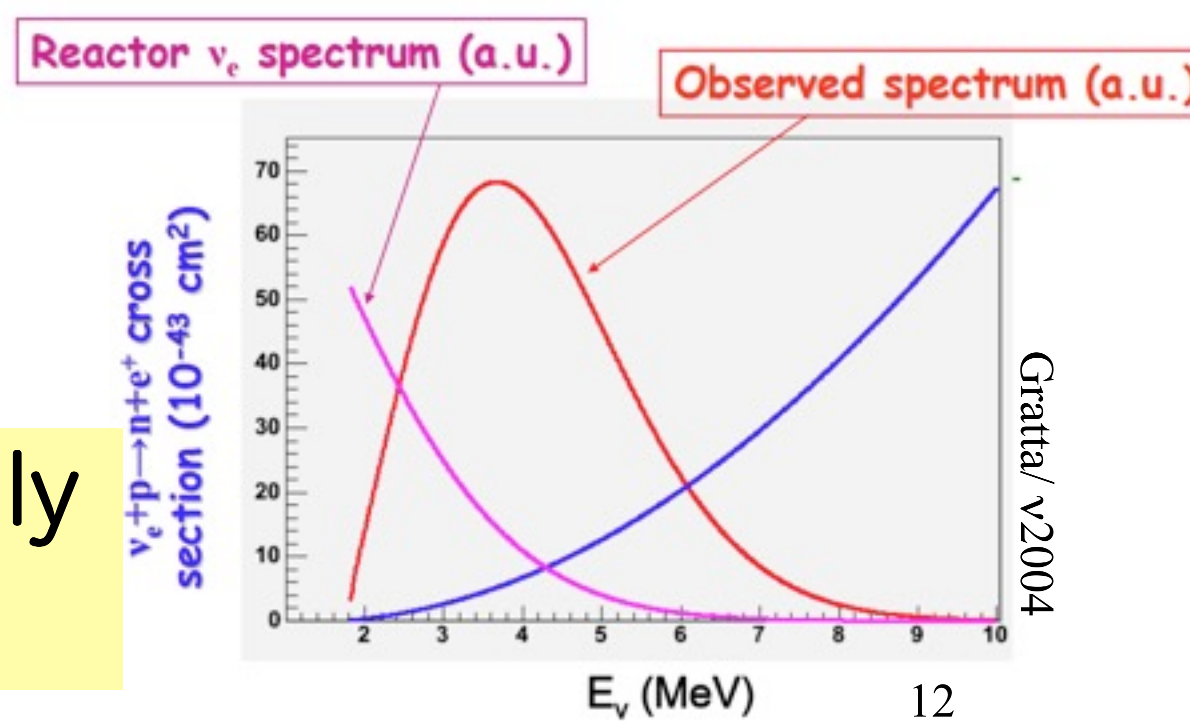
$$e^+ + e^- \rightarrow 2\gamma \quad \text{Prompt}$$

$$\left(E_\nu - 0.8MeV\right)$$

$$n + Gd \rightarrow Gd' + \gamma s\left(\sum E = 8MeV\right) \quad \text{Delayed}$$

n thermalization time
τ ~ 30 μsec (H: 220 μsec)

In Gamma-Catcher volume, use Hydrogen capture as delayed
n+p→d+γ(2.2MeV)



"Delayed coincidence" drastically reduces the background.

Double Chooz brief history

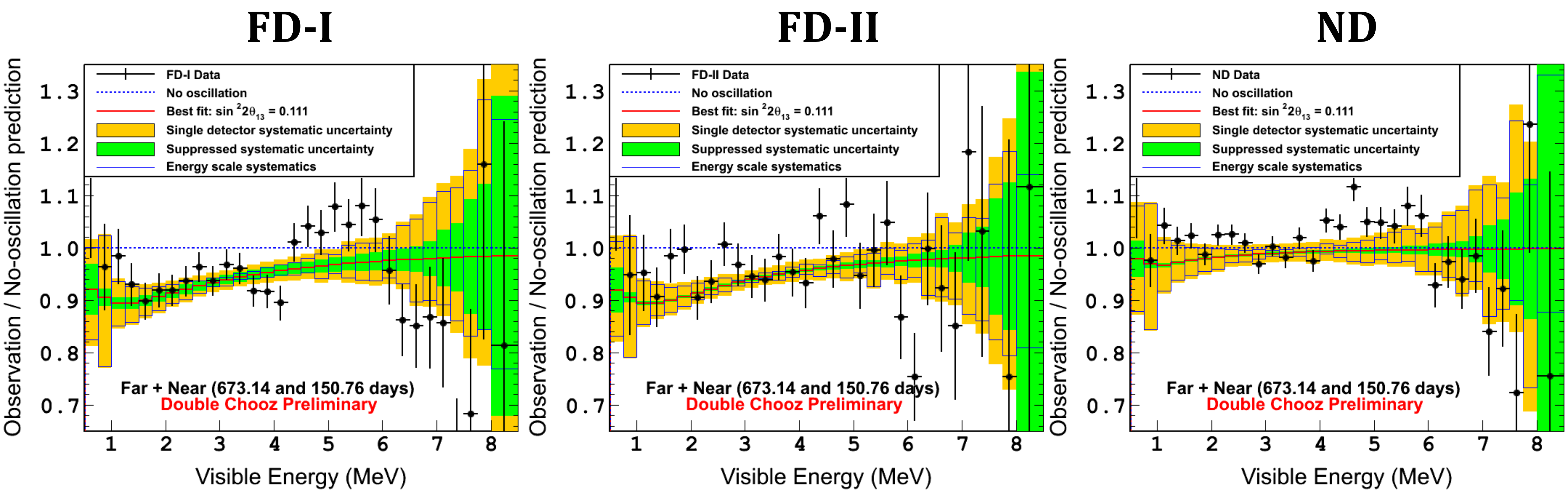
- Nov/2011 Reported 1st reactor-θ_{13} indication
  - arXiv:1112.6353 (PRL) : $\sin^2(2\theta_{13})=0.086\pm0.05$ (94.6%CL)
  - Jun/2011 T2K ν_e appearance indication (6 events)
- 1st Hydrogen-capture analysis (arXiv:1301.2948)
- Latest FD-only results
  - arXiv:1406.7763 (JHEP) : 0.090±0.03
    Gd-capure events in target volume
  - arXiv:1510.08937 (JHEP) : 0.088±0.03
    H-capture events in gamma-catcher (combined with Gd)

Final goal in DC LoI in 2005 was ±0.03 (with ND+FD!)

- Start to take ND+FD data since 2015, first results:
  - Moriond 2016 : 0.111±0.018 (Gd), 5.8σ observation
- Today's results based on
  - 20/Sep/2016 CERN seminar indico.cern.ch/event/548805/

Multi-detector analysis

Energy spectrum (Moriond '16)



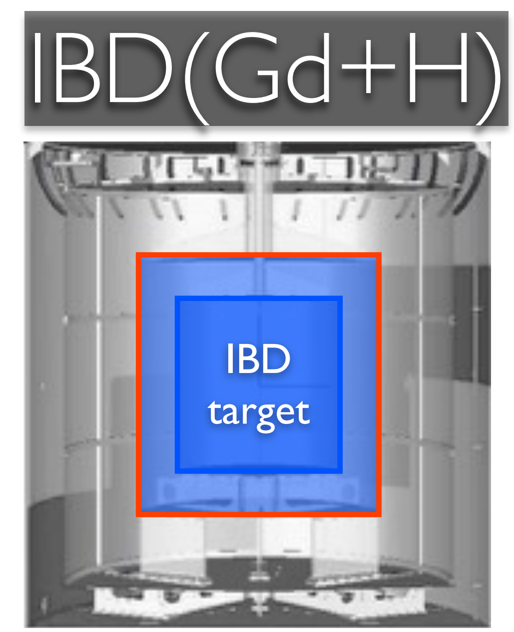
- Best-fit: $\mathbf{\sin^2 2\theta_{13} = 0.111 \pm 0.018}$ (stat.+syst.) (χ^2/dof = 128.8/120)
  - **Non-zero θ_{13} observation at 5.8σ C.L.**

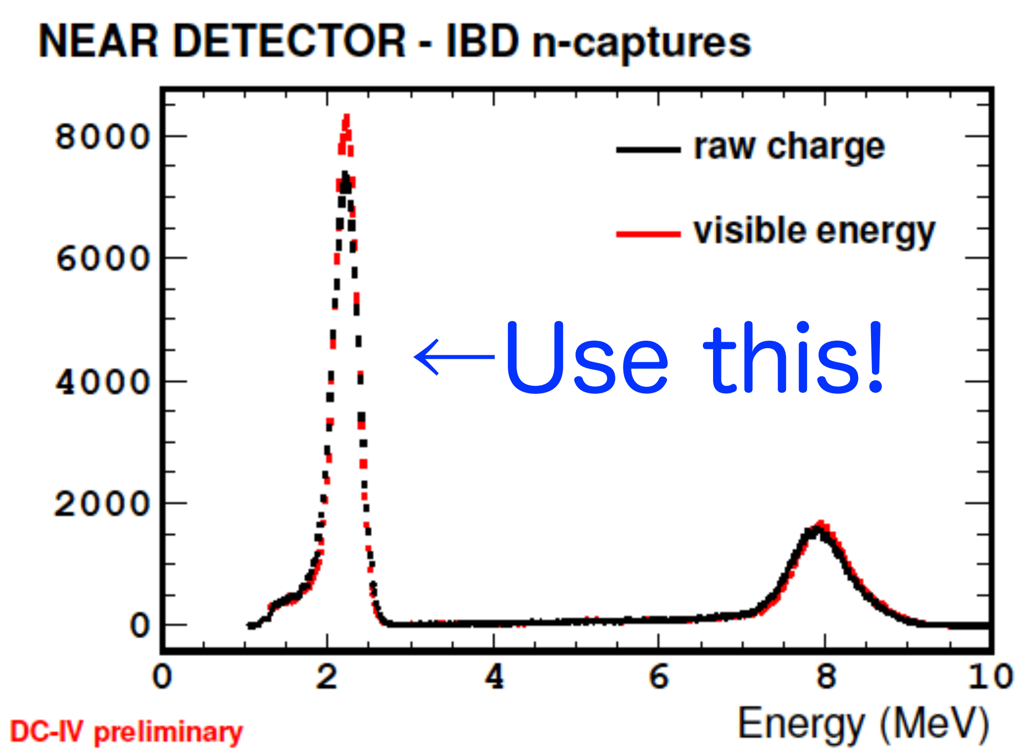
Double Chooz Preliminary

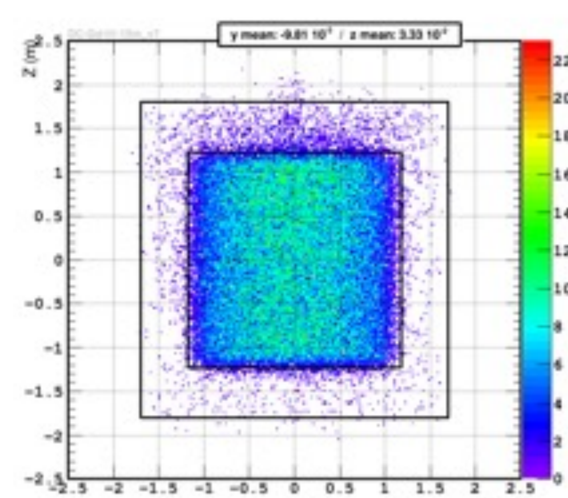
- Fit 3 data sets simultaneously: ~2x more precise than FD paper
- Many systematics, especially flux error, strongly suppressed
- Use also 7-days reactor-off BG measurement (only DC has it)

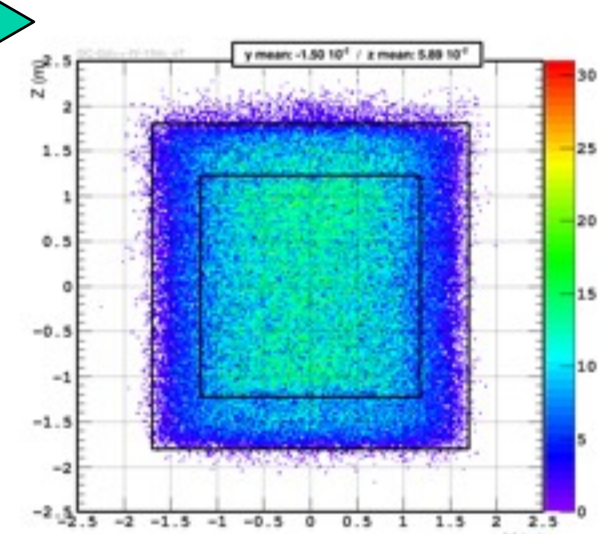
New strategy : Gd+H analysis

- Daya Bay & RENO advance in statistics
  → increase the fiducial volume from target (8t)
  to target + gamma-catcher (~30t)
- More data added:
  ~480days (FD-I)
  ~380days (FD+ND)



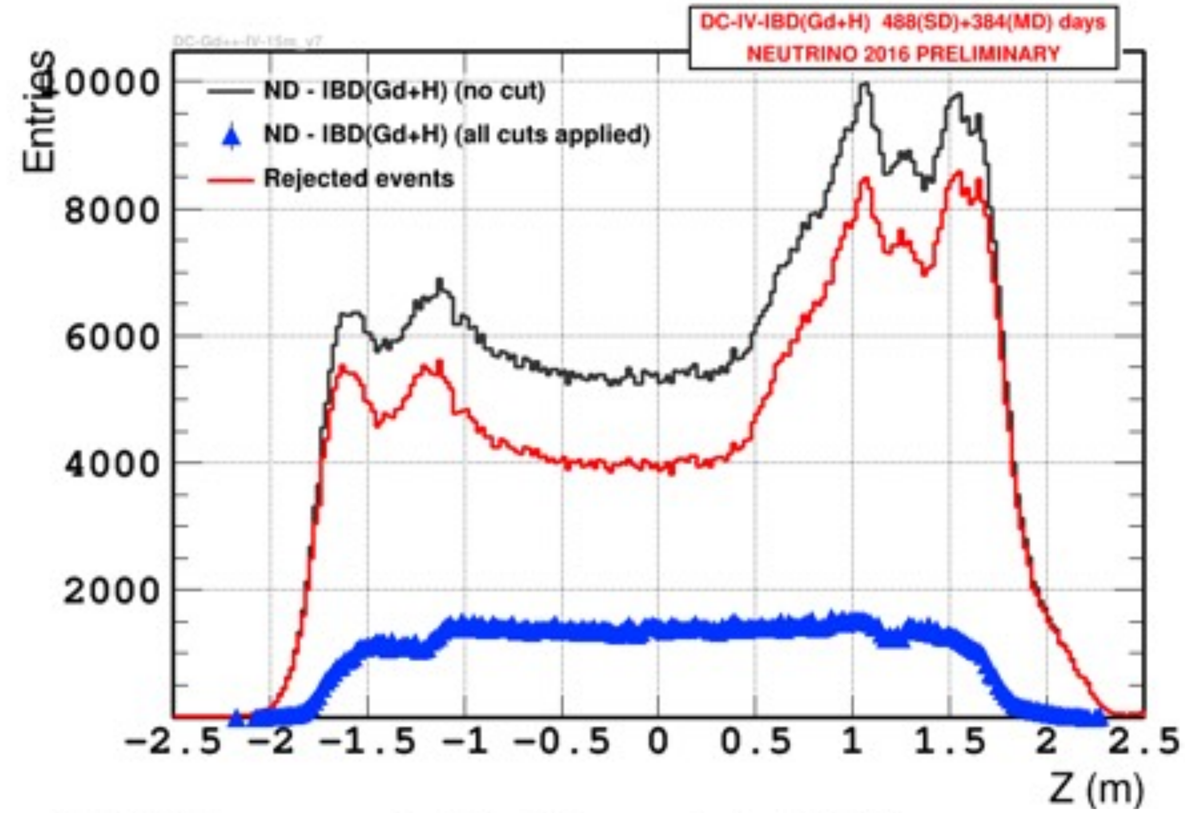




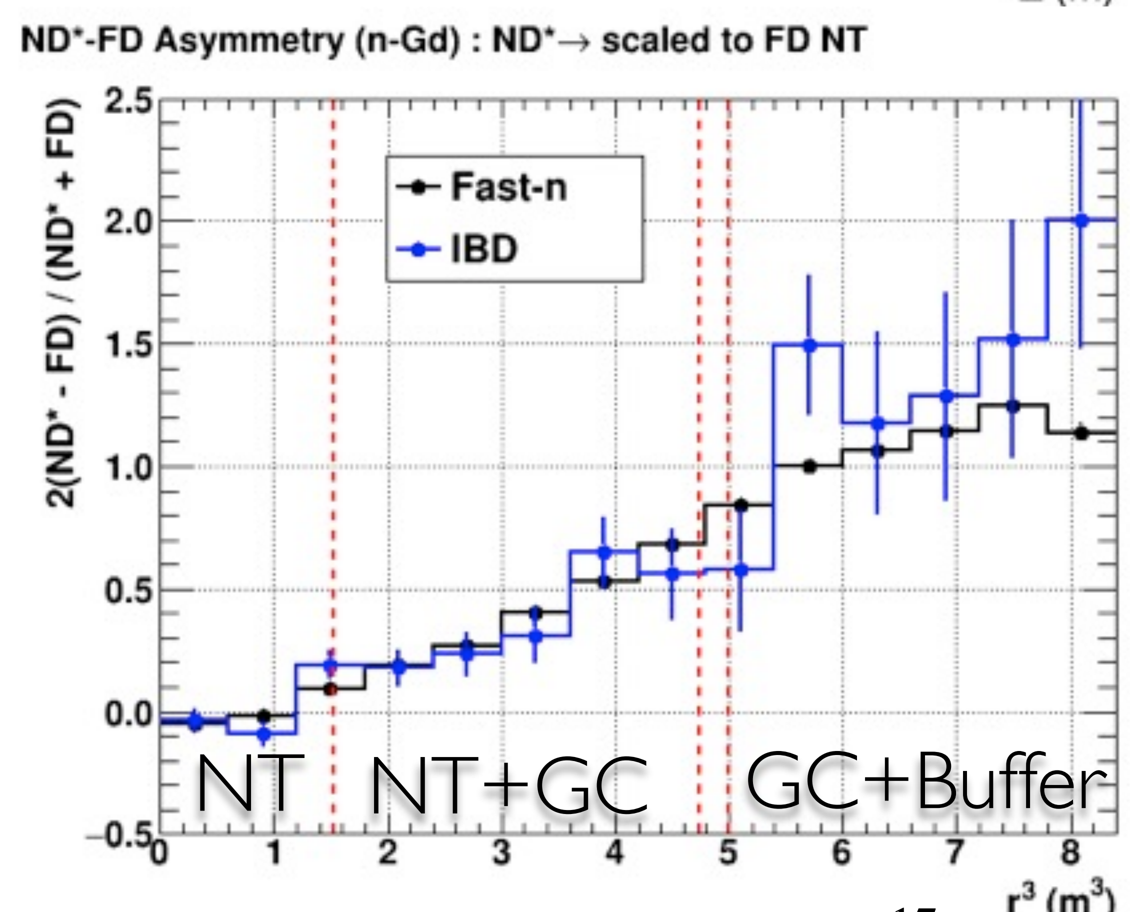


On the leaks in ND

- Small amount of LS in the upper buffer ("buffer events") → easy to reject with event pattern (mainly cosmic muons)



- Small amount of Gd exists in gamma-catcher volume → Gd+H analysis immune to it (effect to Gd analysis under investigation)



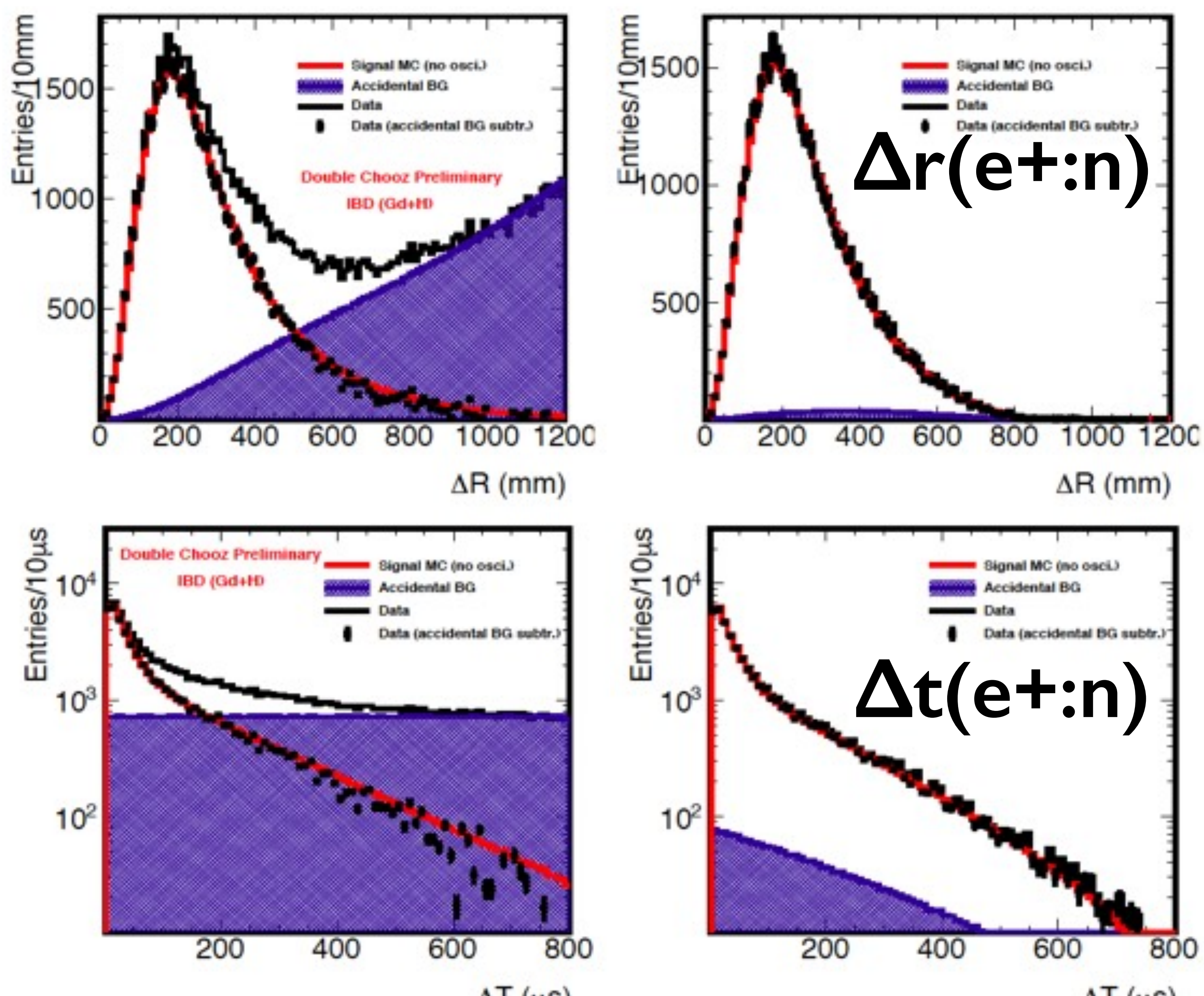
Gd+H simultaneous analysis

- Dominant BG at low-E is accidental coincidence
  $\rightarrow$ ANN (artificial neutral network) developed using distance, time difference and $E_{delayed}$

distance

before ANN

Δtime



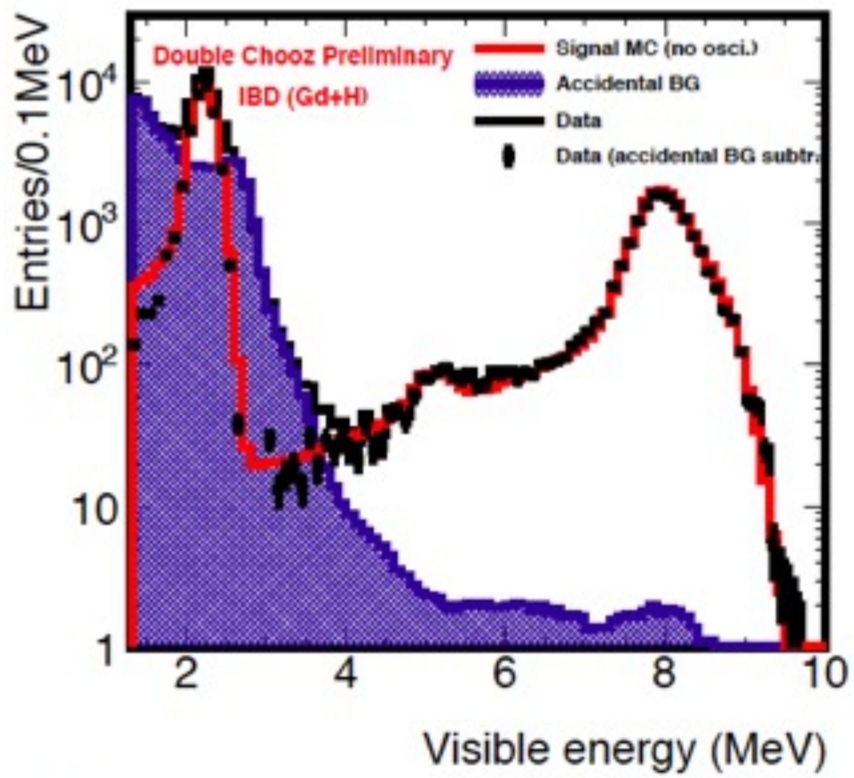
after ANN

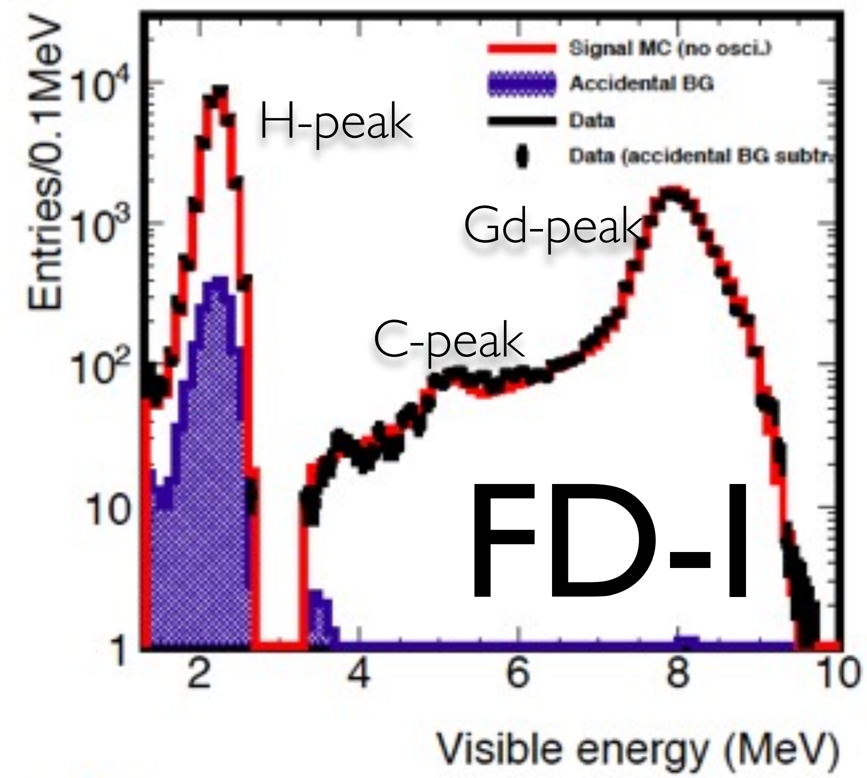
violet: acc. coincidence

ANN analysis: energy spectra

- $E_{delayed}$ → simultaneously analyze captures on Gd, H (and small amount C)

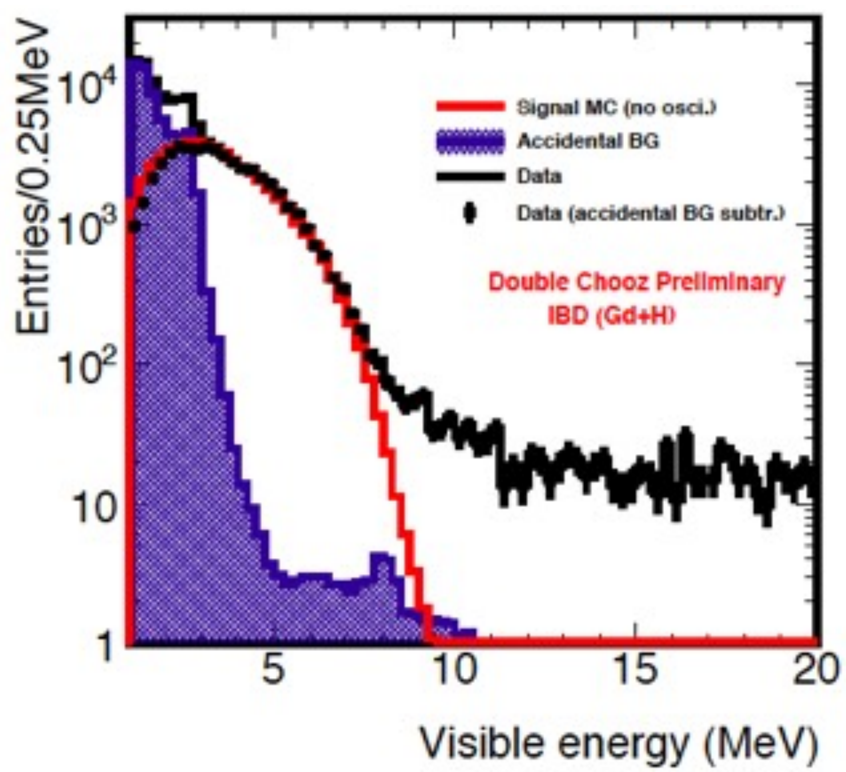
- E_{prompt} → ANN reduces low-E acc. BG dramatically

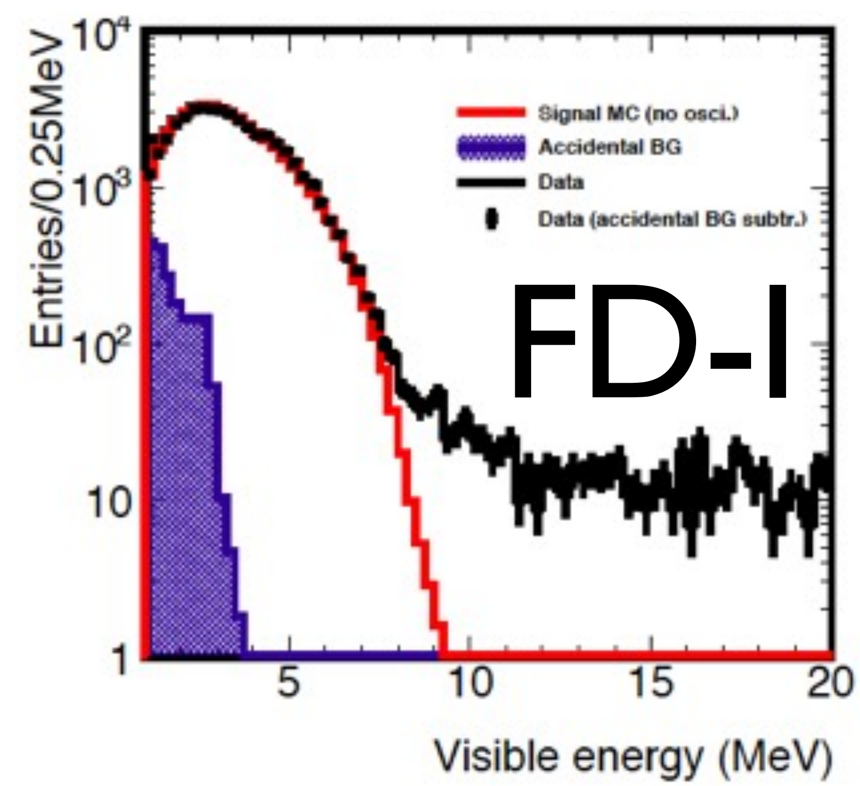




before ANN cut

after ANN cut





Detector response

- Important to understand the difference of ND/FD
- ^{252}Cf calibration →
- Energy resolution data/MC comparison

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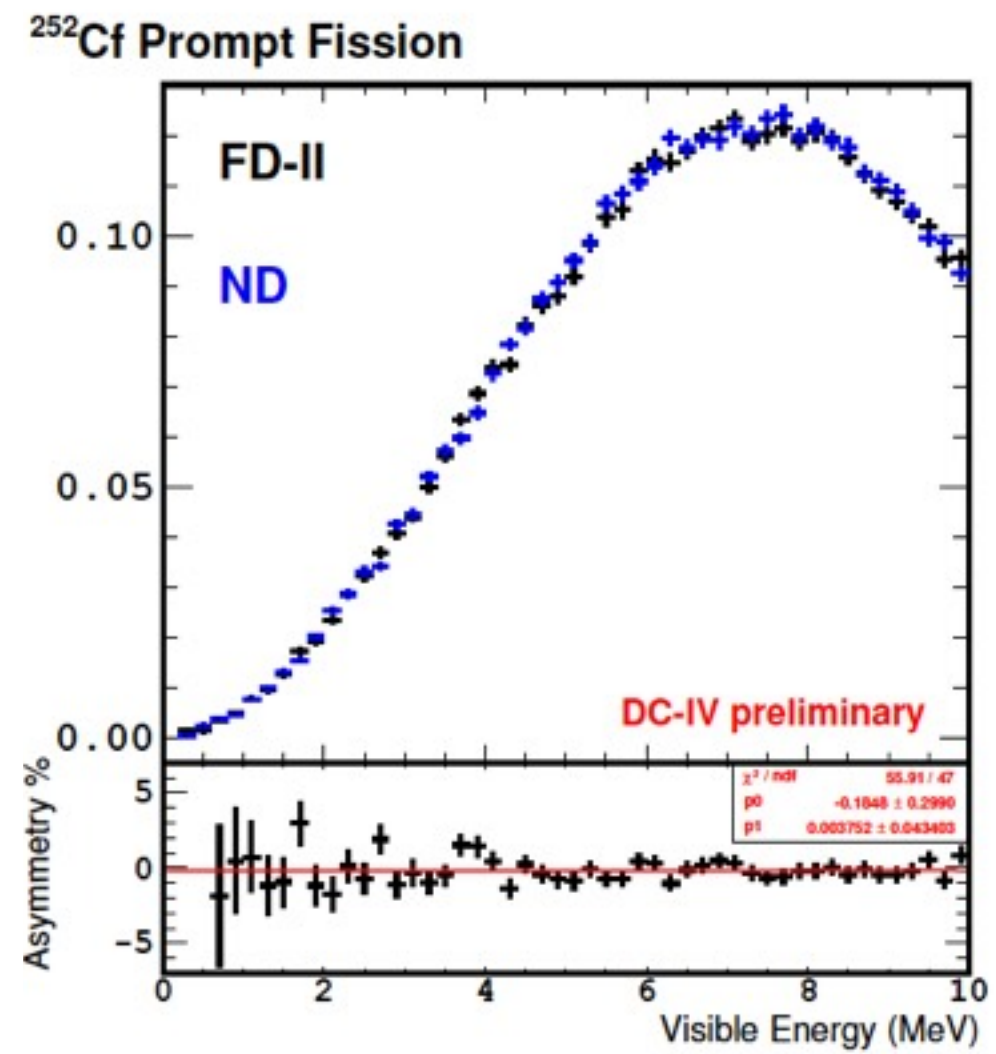
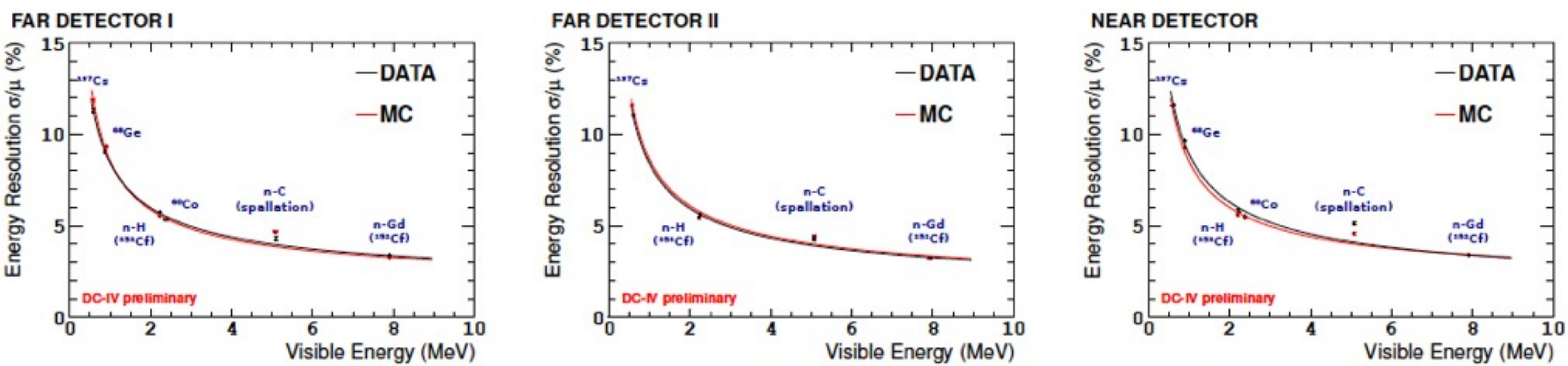
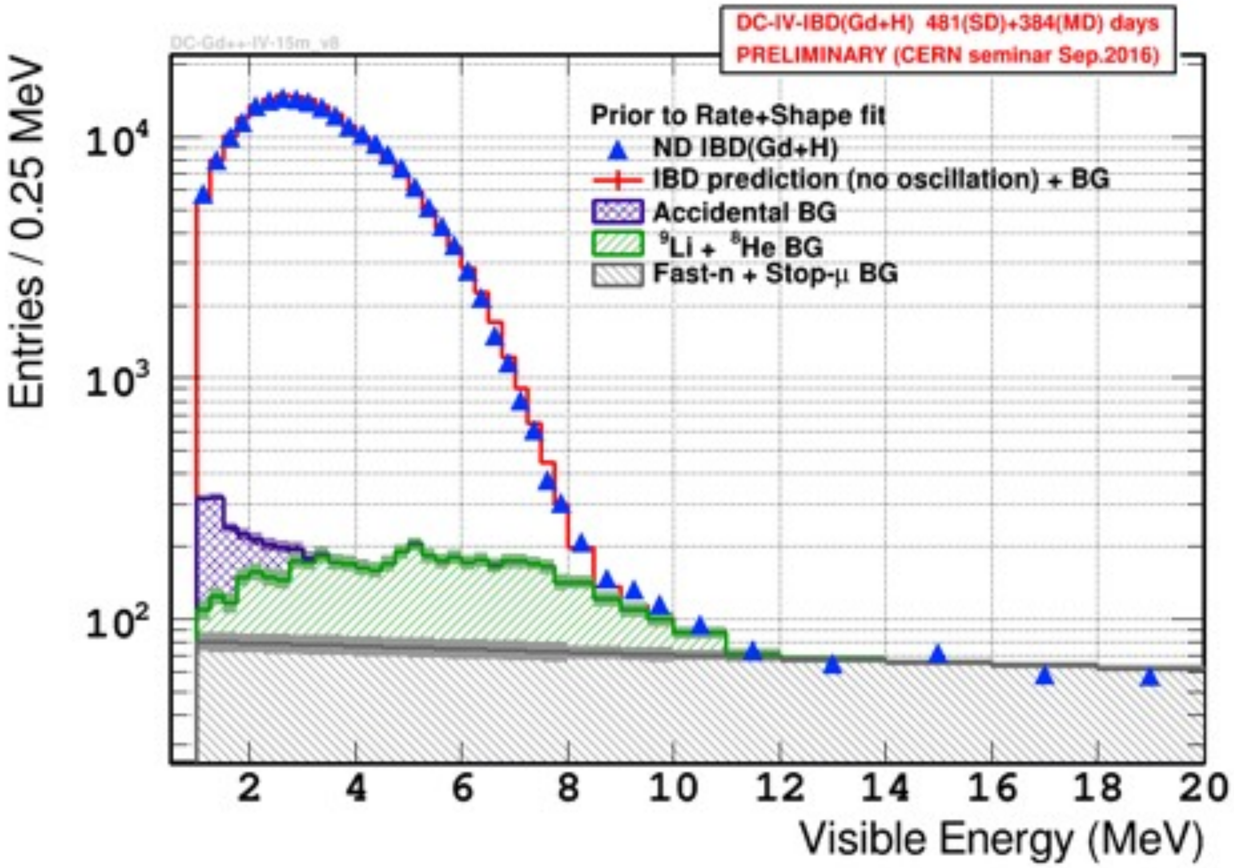
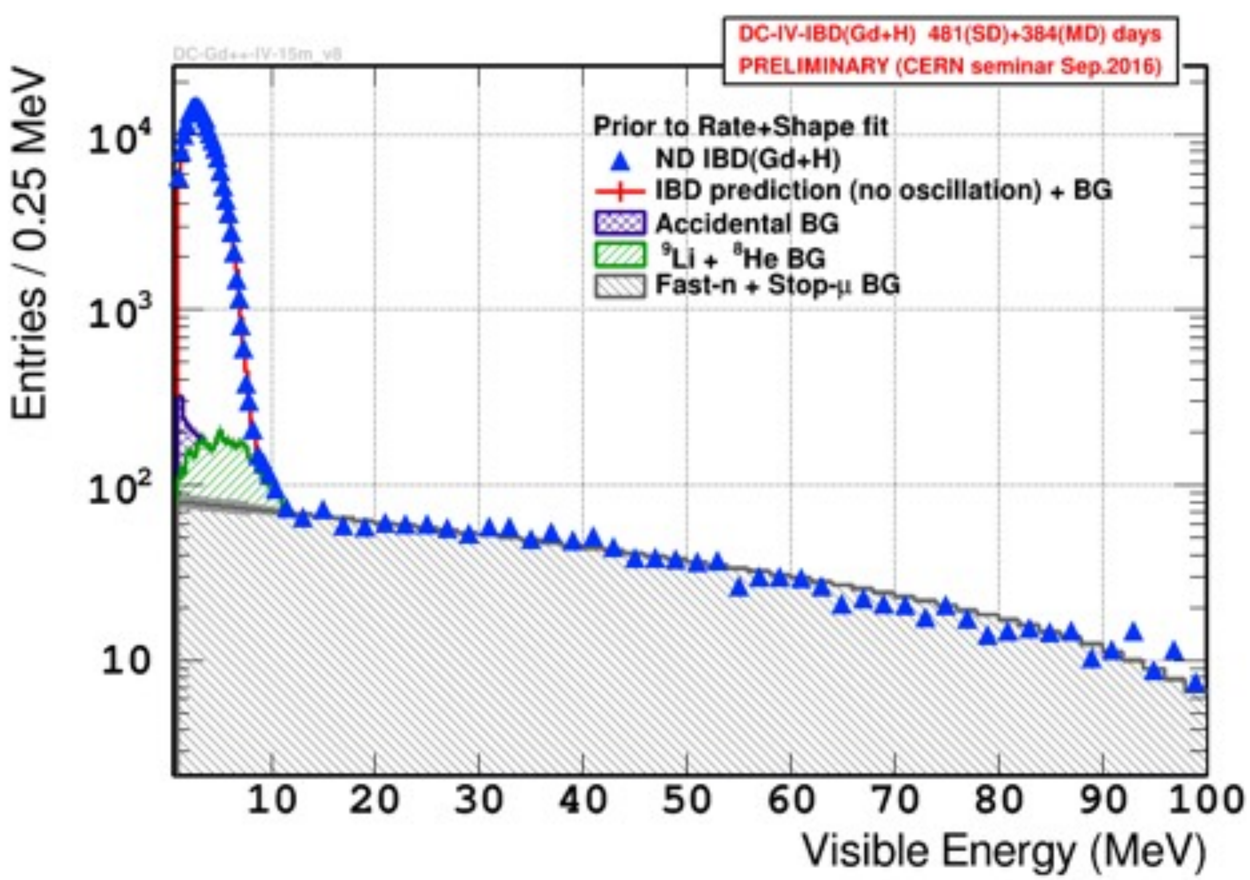




Background understanding

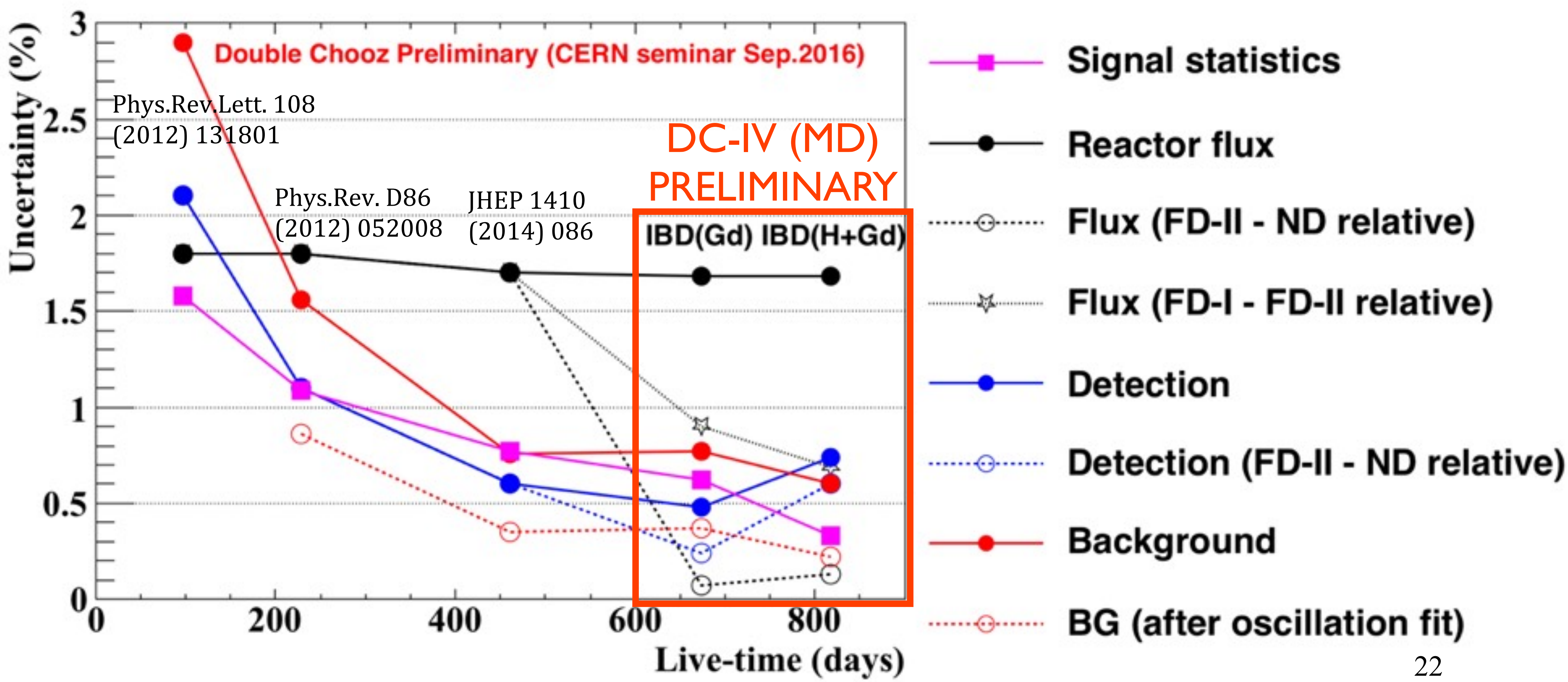




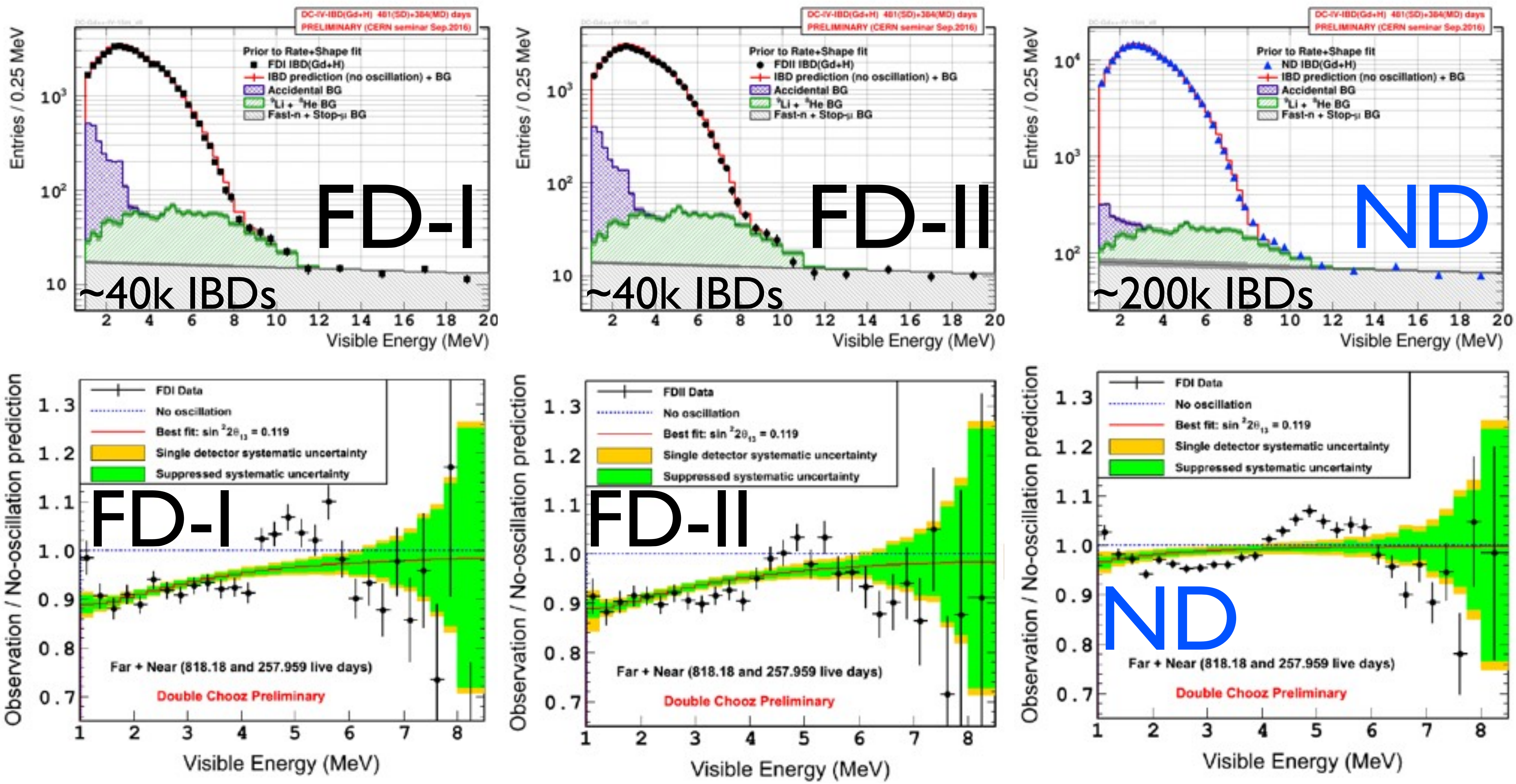
- 3 components (environ. γ and cosmic induced)
  - Accidental coincidence low-energy region
  - Fast-n, Stopped μ high-energy region
  - Spallation ^{9}Li (long life) (green) β-n decay
- Characteristic spectra
  - Fit together with ν signal and obtain fractions

Systematic uncertainty

- Flux uncertainty largely cancel in ND-FD analysis
- Currently larger detection systematics than Moriond (conservative proton number error for Gd+H analysis)



Fit results

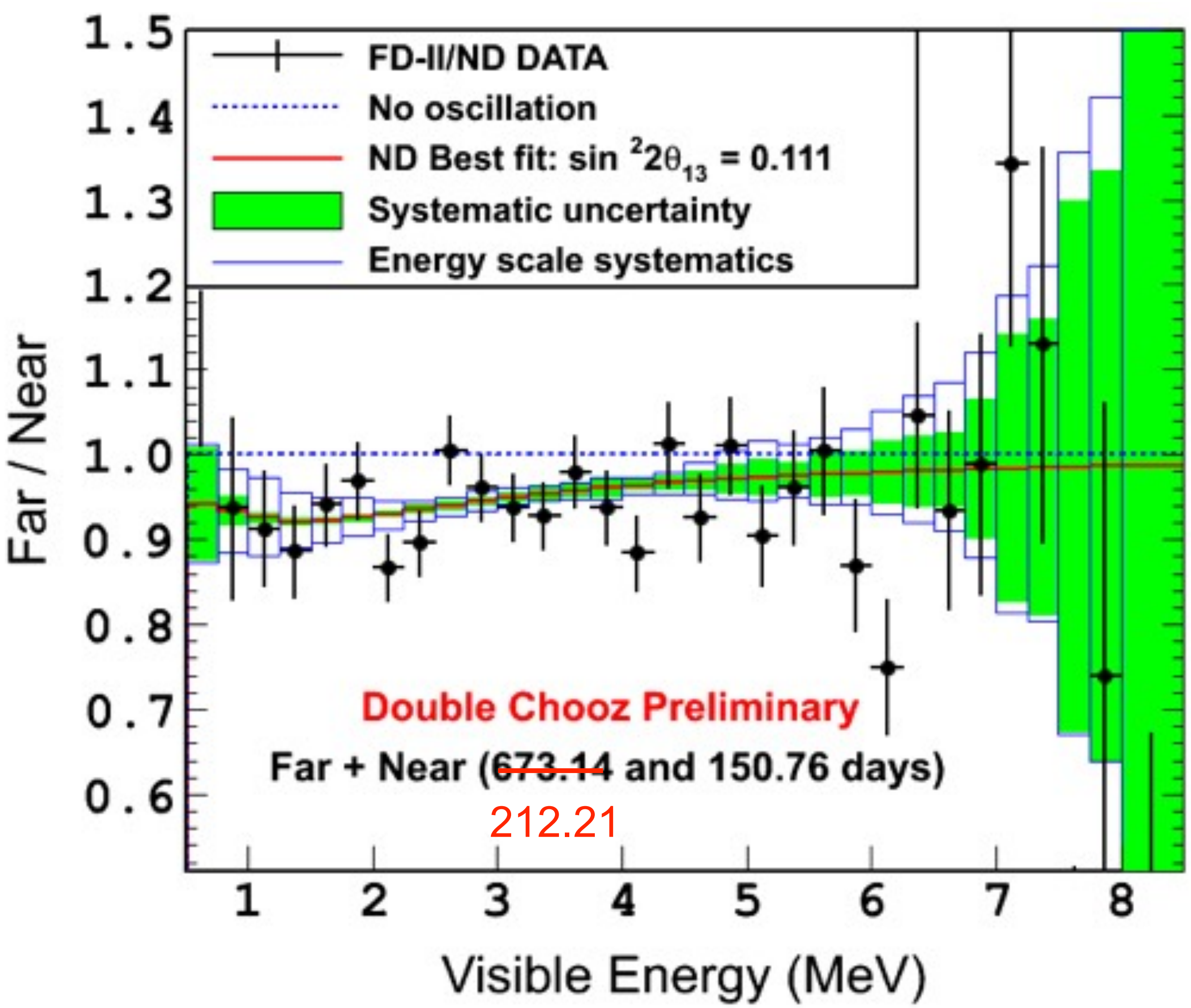


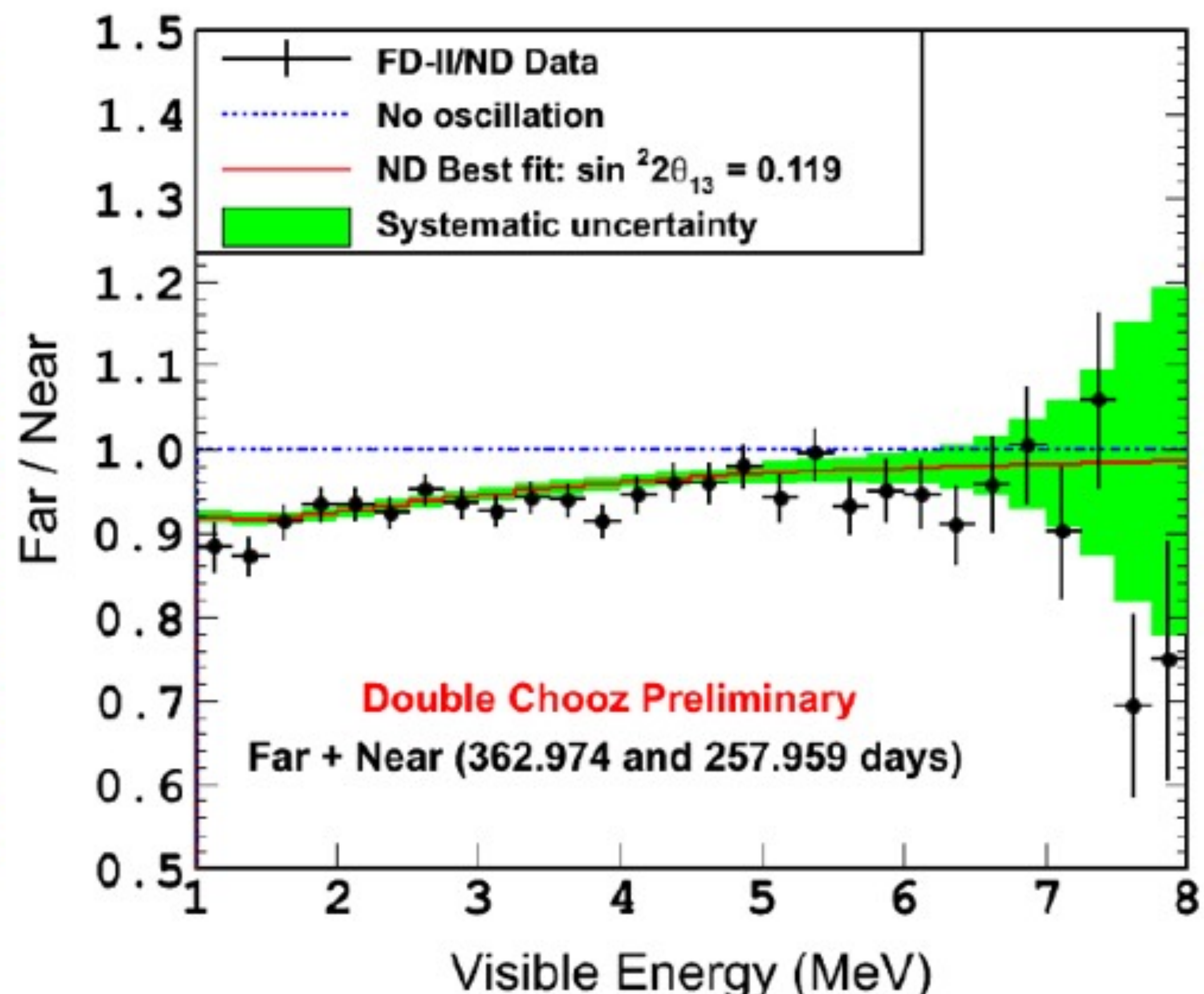
- $\sin^2(2\theta_{13}) = 0.119 \pm 0.016$
- cf. Moriond $\sin^2(2\theta_{13}) = 0.111 \pm 0.018$

FD-II/ND ratio

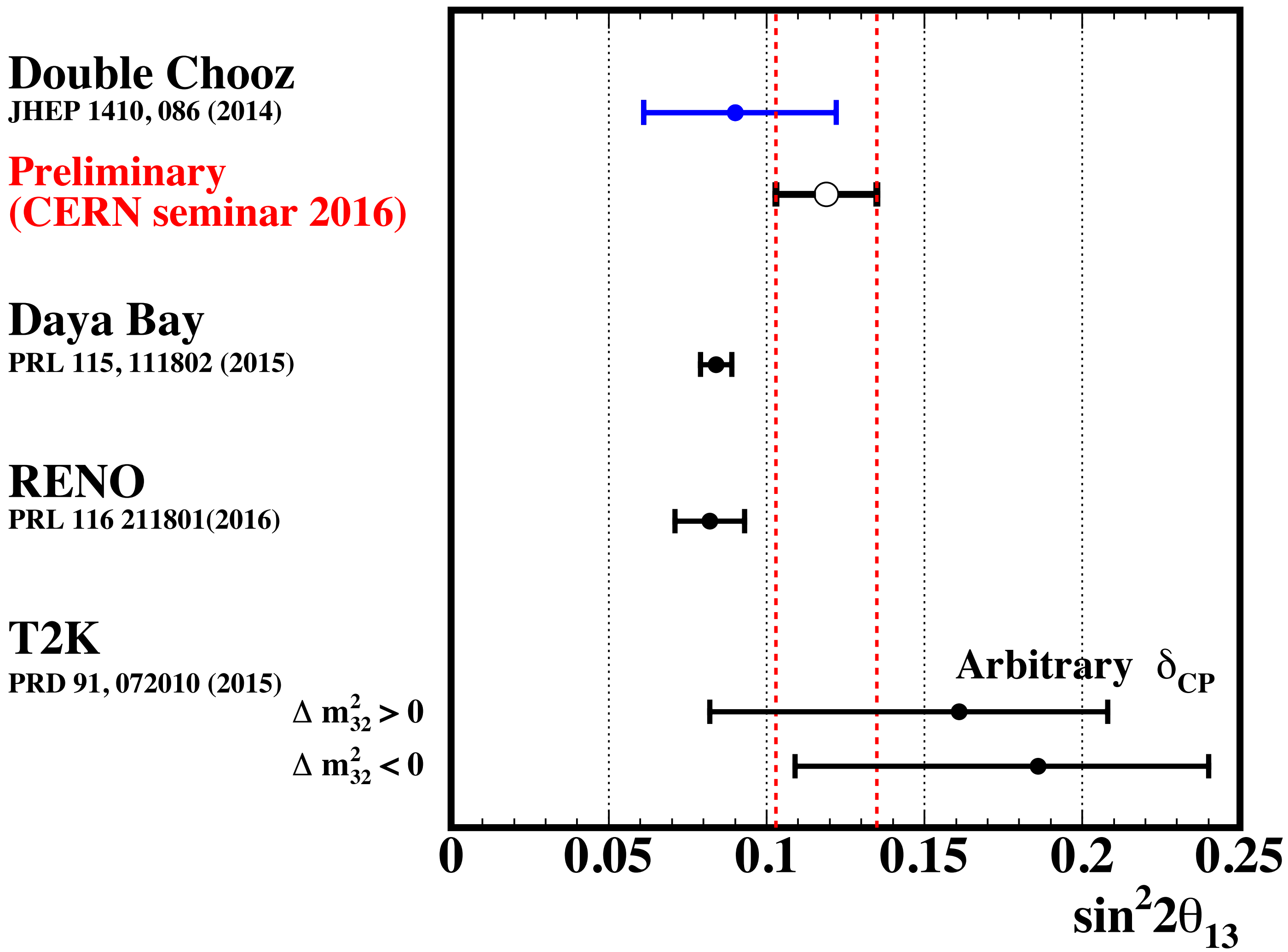
- "5MeV bump" cancels, seen in both data
- #events: FD-II/ND ~8k/~40k → ~40k/~200k

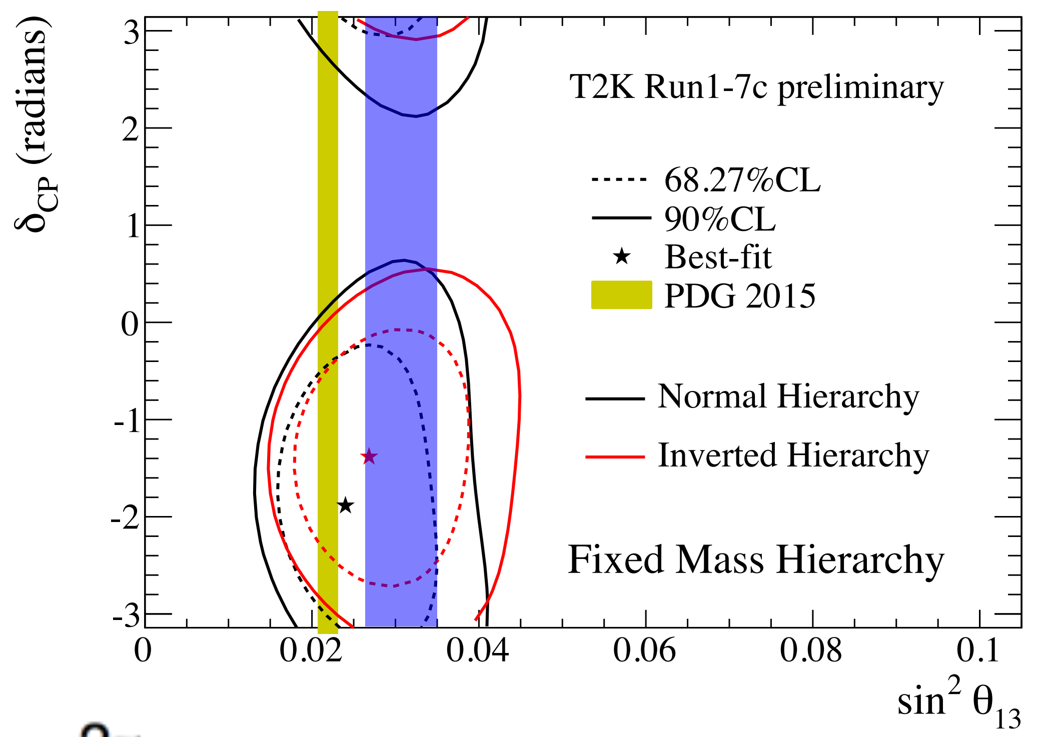
Moriond(Gd) → Now (Prel. Sep2016)

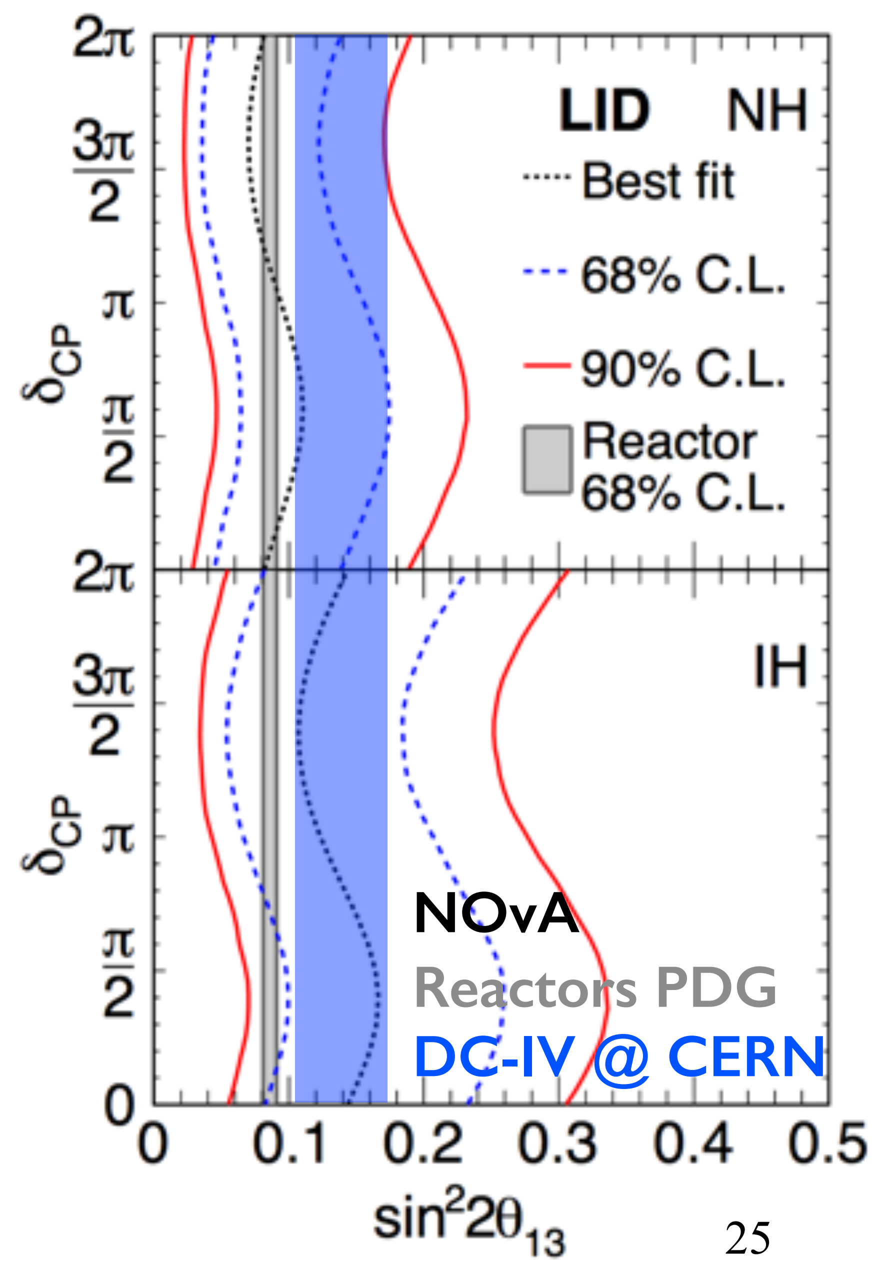




DC θ_{13} in world context



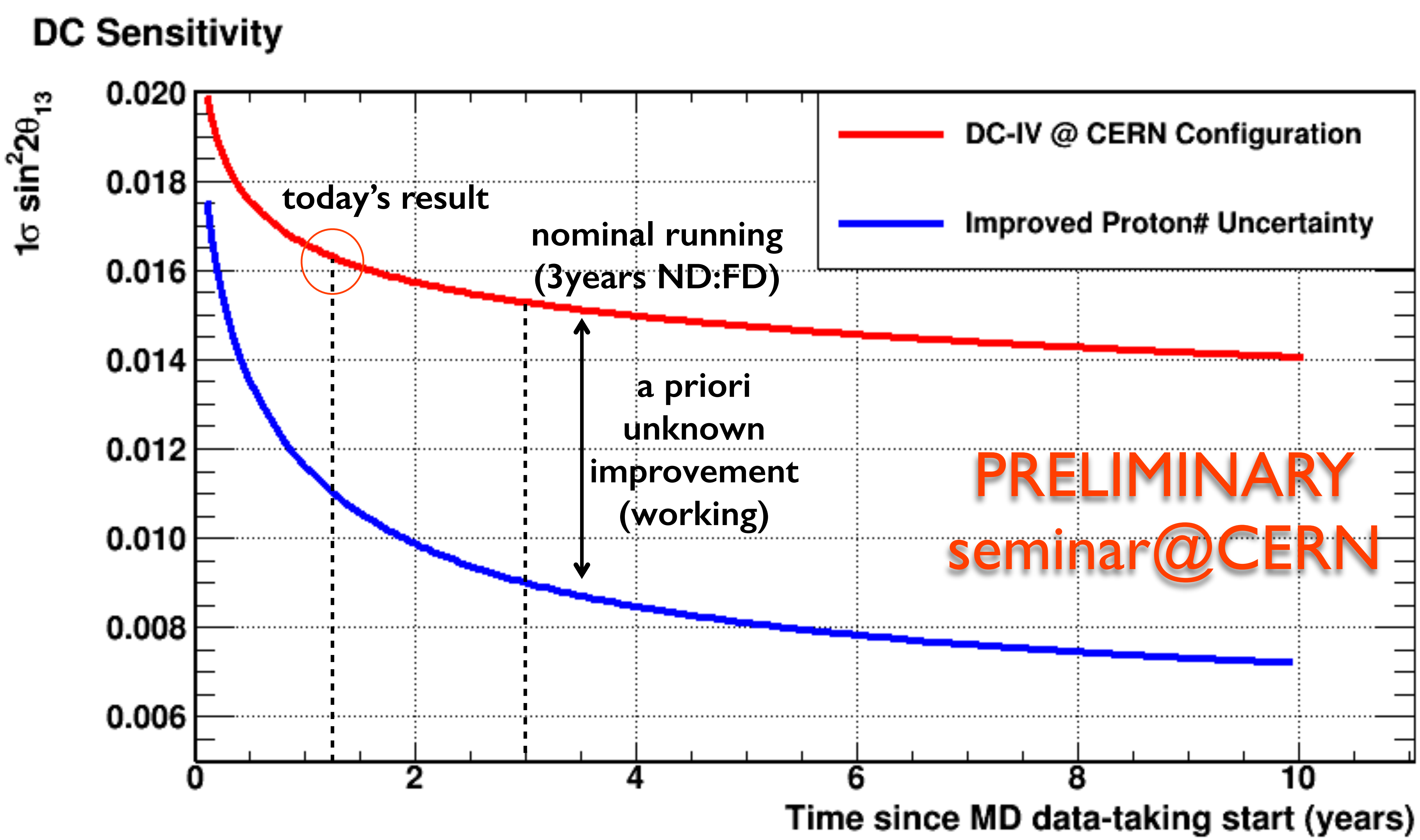




- 2.2σ tension to Daya Bay (0.082±0.004)
- Larger δ_{CP} range allowed for larger θ_{13}
- LBL experiments' best fit larger than DB

Next steps

- Reduce detection systematics of Gd+H analysis (driven by proton number uncertainty)
- Understanding improves with more data



Reactor experiments' synergy

- Experts from Daya Bay, Double Chooz and RENO had 1st inter-experiment workshop in Seoul, Oct. 2016
- In-depth discussions brought better understanding of each other experiment's analysis technical details $\rightarrow$ should help all three experiments for strong results
- Next workshop planned in Paris in 2017
- DC is very much motivated for a combined θ_{13} as the ultimate goal

Summary

- Latest θ_{13} results from ND+FD data of Double Chooz
- Gd and H captures are simultaneously selected with ANN
  → 3 times larger fiducial volume than original ν target
- $\sin^2(2\theta_{13})=0.119\pm0.016$
- DC is really "double" since 2015: high-statistics phase
  - ~2x better precision than FD-only measurement (±0.03)
  - High-stat ND data gives more physics opportunities:
    Very precise reactor-ν spectra, Sterile-ν, ν-directionality, ...
- Latest θ_{13} value somewhat larger than world average
  - θ_{13} is a key parameter for δ_{CP} together with acc. experiments
  - Important to measure with multiple reactor experiments
  - Aim to reach <0.01 with reduced syst. and stat. errors

- backup

Signal and BG (Moriond '16)

Double Chooz Preliminary

	FD-I	Reactor-off	FD-II	ND
Live-time (d) (after μ veto)	460.93	7.24	212.21	150.76
IBD prediction (d^{-1})	38.04±0.67	0.217±0.065	40.39±0.69	280.5±4.7
Accidental BG (d^{-1})	0.070±0.003		0.106±0.002	0.344±0.002
Fast-n + stop-μ (d^{-1})	0.586 ±0.061			3.42 ±0.23
Cosmogenic (d^{-1})	($0.97^{+0.41}_{-0.16}$)			(5.01 ±1.43)
Total prediction (d^{-1})	**39.63±0.73**	**1.85±0.30**	**42.06±0.75**	**289.3±4.9**
IBD candidates (d^{-1}) (number of events)	**37.64** (17351)	**0.97** (7)	**40.29** (8551)	**293.4** (44233)

- ND detects 7 times more neutrinos than FD
- Also larger BG due to more cosmic μ (but S/B better)