First double-detector results from Double Chooz experiment

38th ICHEP @ Chicago, 4 August 2016

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on behalf of the Double Chooz collaboration

Double Chooz collaboration...

BRAZIL
CBPF
UNICAMP
UFABC

FRANCE
APC
CEA/DSM/IRFU:
SPP, SPhN, SEDI,
SIS, SENAC.
CNRS/IN2P3:
Subatech, IPHC.

GERMANY
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MPIK Heidelberg
RWTH Aachen
TU München
U. Hamburg

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Tokyo Inst. Tech.
Tokyo Metro. U.
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Kobe U.
Tohoku Gakuin U.
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IPC RAS
RRC Kurchatov

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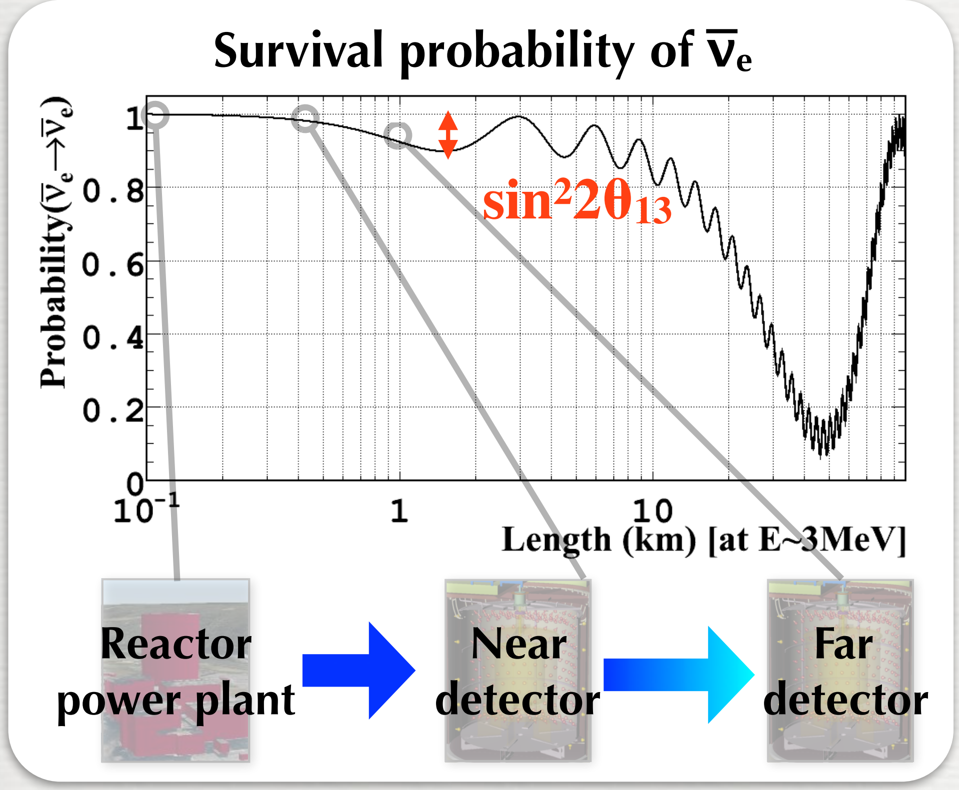
Columbia U.
UC Davis
Drexel U.
U. Hawaii
IIT
KSU
LLNL
MIT
U. Notre Dame
U. Tennessee

150 scientist in 7 countries

spokesman: Hervé de Kerret (CNRS/IN2P3 - APC)

project manager: Christian Veyssière (CEA Saclay)

θ_{13} measurement with reactor neutrinos



Features of reactor θ_{13} measurement

- Reactor is free and rich $\bar{\nu}_e$ source
- Direct measurements of θ_{13} with $\bar{\nu}_e$ disappearance at 1 km baseline as:

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \mathrm{O}(10^{-3})$$

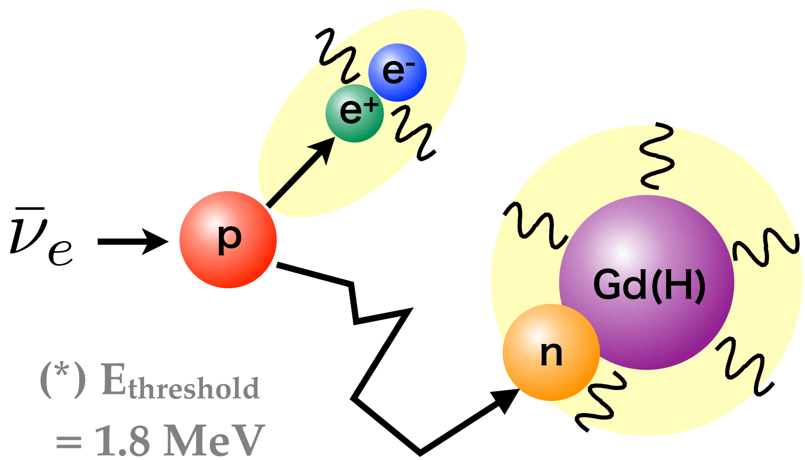
- Background is strongly suppressed by delayed coincidence technique
- Systematic uncertainties are further reduced by two identical detectors

Double Chooz is pioneer of reactor experiments to measure the θ_{13}

- Improvements from Chooz w/ stable Gd-LS & new det. structure (Proposal@2006)
- First indication of non-zero θ_{13} at 94% C.L. (LowNu@2011, PRL 108 (2012) 131801)
- First θ_{13} results using Hydrogen capture signal (PLB 723 (2013) 66-70)
- Report of spectral distortion around E_ν = [5, 7] MeV (JHEP 1410 (2014) 086)
- θ_{13} measurements with multi-detector setup (Since 2015, this talk)

Detection principle of reactor neutrinos

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



(*) $E_{threshold}$ = 1.8 MeV

Two independent samples of Gd/H capture measured by delayed coincidence technique

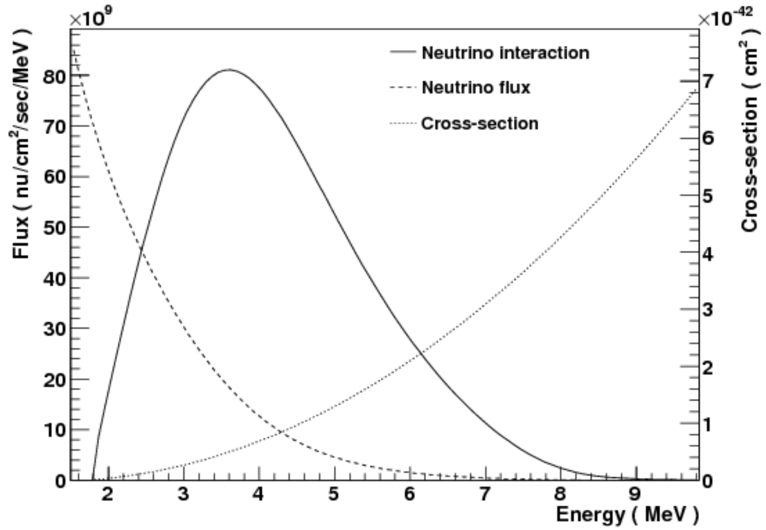
- **Prompt signal (e^+ ionization & annihilation)**
  E_{prompt} = 1~8 MeV
- **Delayed signal (Neutron capture)**
  $E_{delayed}$ = ~8 (2.2) MeV for Gd (H) capture
- **Time coincidence of those**
  τ ~ 30 (200) μs for Gd (H) capture

In this IBD process, prompt energy is related to neutrino energy

$$
\begin{aligned}
E_{vis} &= E(kin)_{e^+} + 2m_e \\
&\simeq E_{\bar{\nu}_e} - (M_n - M_p) + m_e \\
&\simeq E_{\bar{\nu}_e} - 0.782\,\mathrm{MeV}
\end{aligned}
$$

→ **Spectral shape of the prompt signal gives us further information.**

Spectral shape of ν energy



Experimental site

Reactors

Two reactor cores
4.27 GW_{th} for each core

Near detector

L = ~ 400 m
~120 m.w.e.
10 m^3 target

Operating since 2015

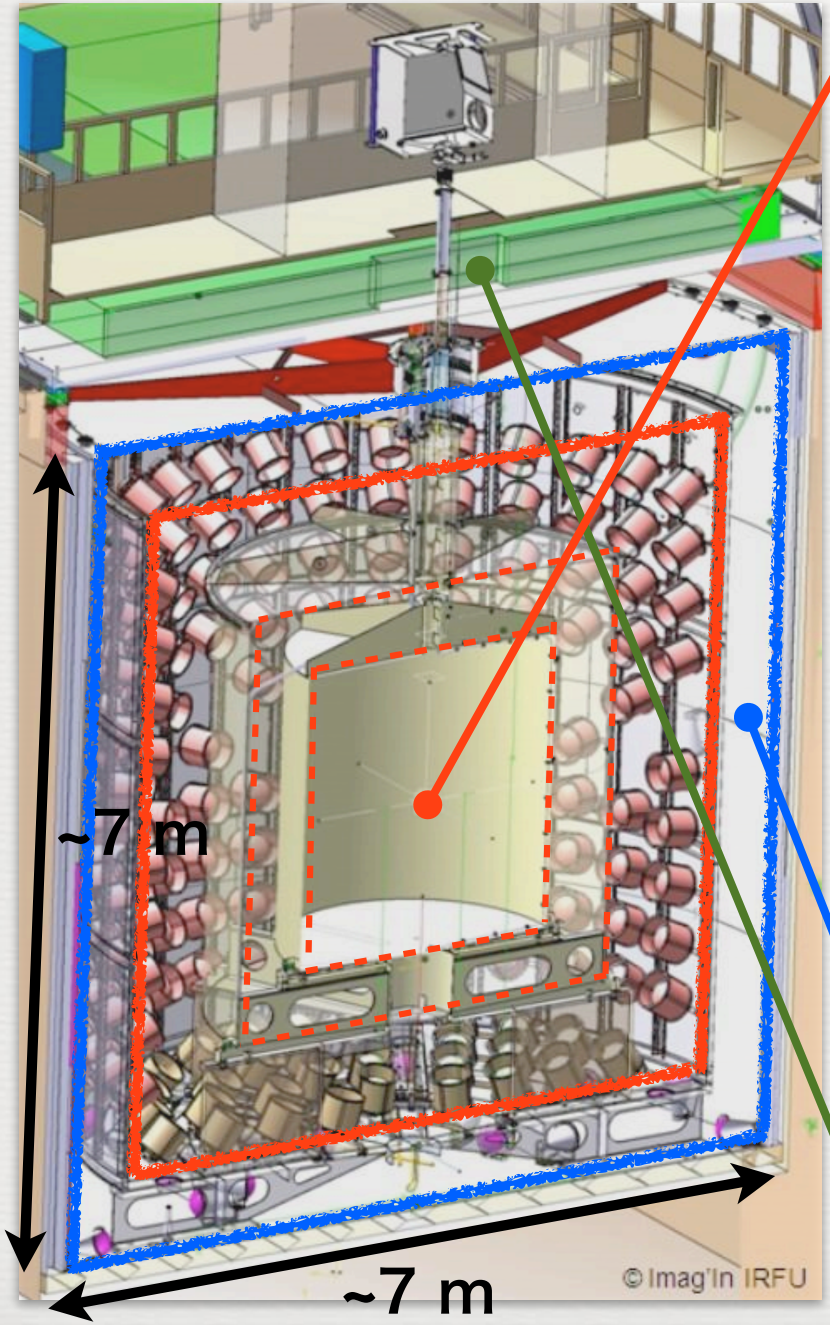
Far detector

L = ~ 1050 m
~300 m.w.e.
10 m^3 target

Operating since 2011

Started Double-detector data taking since early-2015

Double Chooz detector



Inner Detector (ID) - three cylindrical layers

ν-target (Gd capture) region
- Gd-loaded (1 g/l) liquid scintillator (10.3 m^3)

γ-catcher (H capture) region
- 22.3 m^3 liquid scintillator

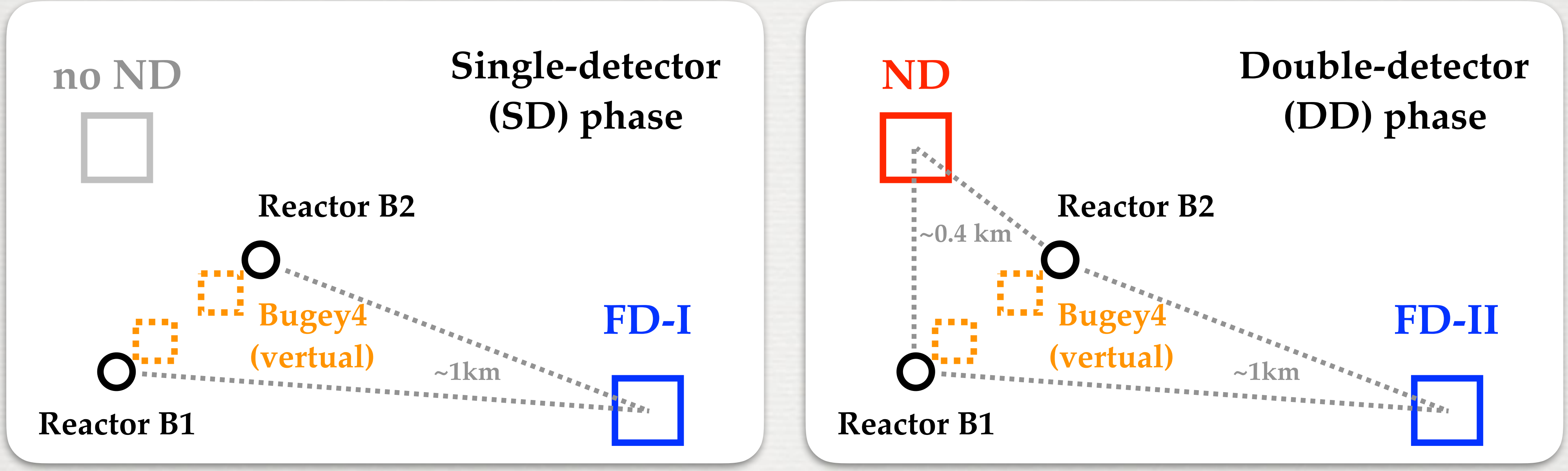
Buffer region
- 110 m^3 mineral oil & 390 low-BG 10″ PMTs

Detectors for background veto

Inner veto (IV)
- Liquid scintillator & 78 8″ PMTs in steel tank

Outer veto (OV)
- Plastic scint. strip + WLS fiber + MAPMT

Single-detector & Double-detector phase



SD: Bugey4 is used as an anchor of reactor ν flux (1.7% precision)

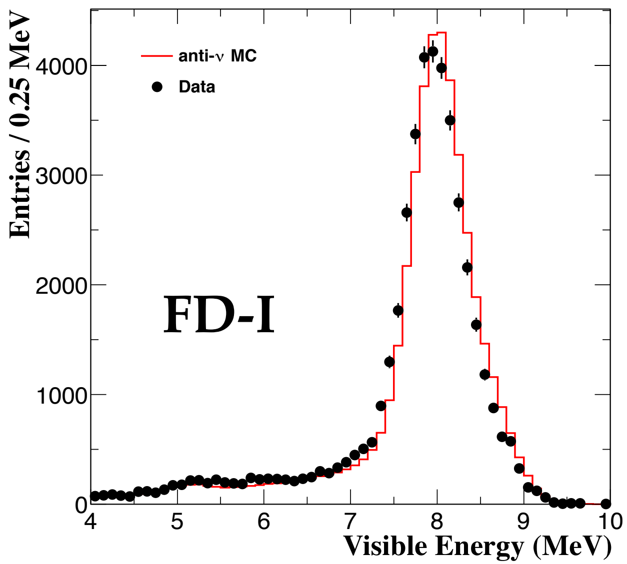
→ Nearly iso-flux setup of ND & FD can suppress ν flux error (< 0.1%)

→ Identical detector can cancel correlated systematics like det. efficiency.

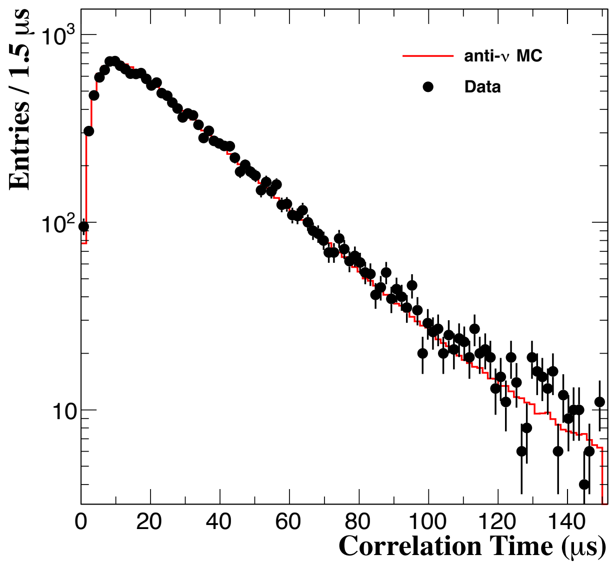
Preliminary results using FD-I, FD-II and ND data (~461, 212, 150 days of live time) are shown in this talk.

IBD selection & BG veto

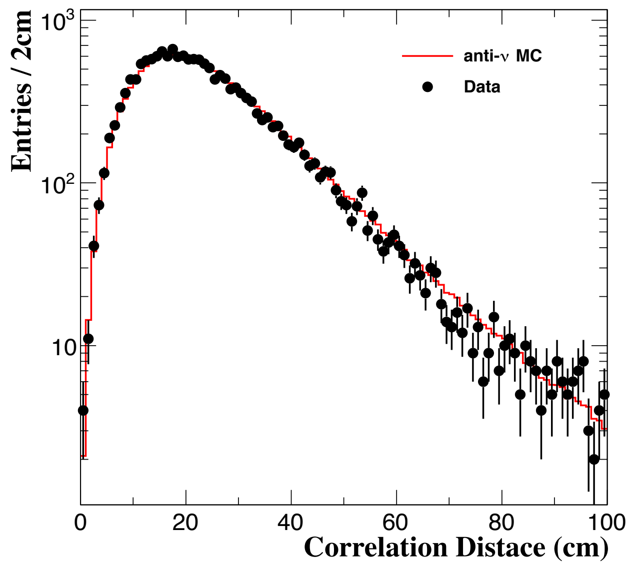
Delayed signal energy



Correlation time



Correlation distance



Observed IBD rate: ~40 d^{-1} (FD) and ~300 d^{-1} (ND)

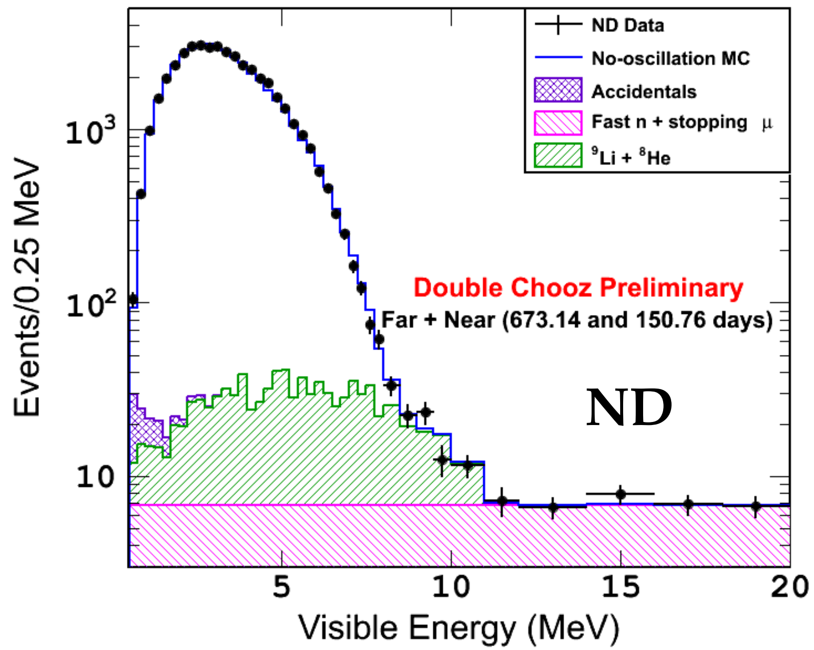
Remaining BG are:

- **Accidental coincidence:** e.g.) environmental γ + spallation n
- **Fast neutron:** $\mathrm{n} + \mathrm{p} \rightarrow$ recoil $\mathrm{p} + \mathrm{n}$
- **Stopping muon:** $\mu \rightarrow \mathrm{e} + \nu + \nu$
- **(β, n) emitter from spallation products :** e.g.) ${}^{9}\mathrm{Li} \rightarrow {}^{8}\mathrm{Be} + \mathrm{e} + \nu + \mathrm{n}$

( ) : mimic prompt (delayed) signal

IBD candidates & BG estimation

Prompt signal energy w/ BG



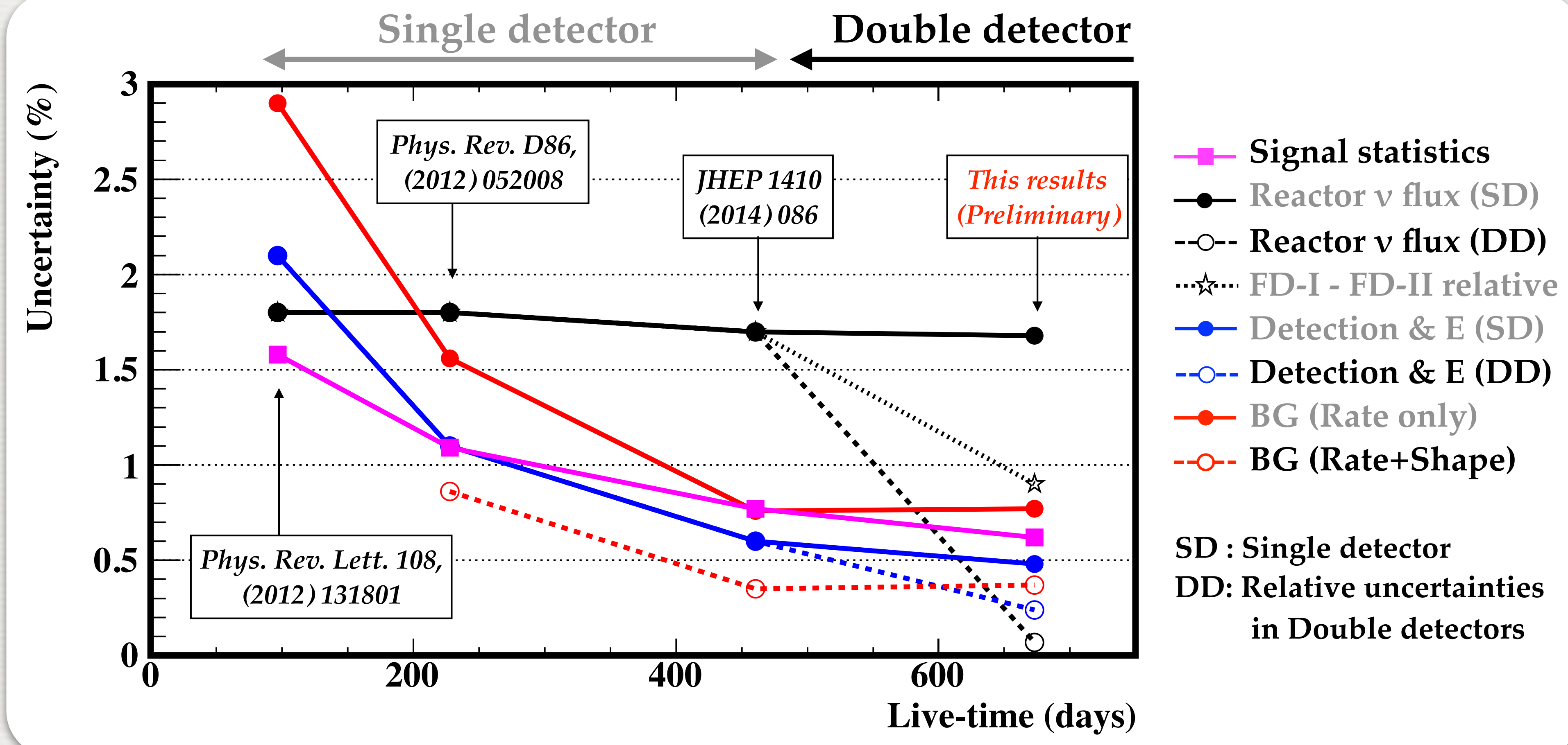
Populations and errors (Double Chooz Preliminary)

	FD-I	Reactor off	FD-II	ND
Live time (d)	460.93	7.24	212.21	150.76
IBD prediction (d^{-1})	38.04±0.67	0.217±0.0065	40.39±0.69	280.5±4.7
Accidental BG (d^{-1})	0070±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 BG (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})	37.64	0.97	40.29	293.4
(Number of events)	(17351)	(7)	(8551)	(44233)

All BG are measured from data:

- Accidental BG: Off-time coincidence (rate & shape)
- Fast-n + stop-μ: High energy window (rate), IV/OV tagged events (shape)
- Cosmogenic BG: ⁹Li-enriched data (shape)
  → ⁹Li BG rate is not used in the fit, which is constrained by shape in the fit

Suppression of systematic uncertainties



SD phase: we improved uncertainties. Reactor ν flux error was dominant.

→ It is strongly suppressed with two detectors

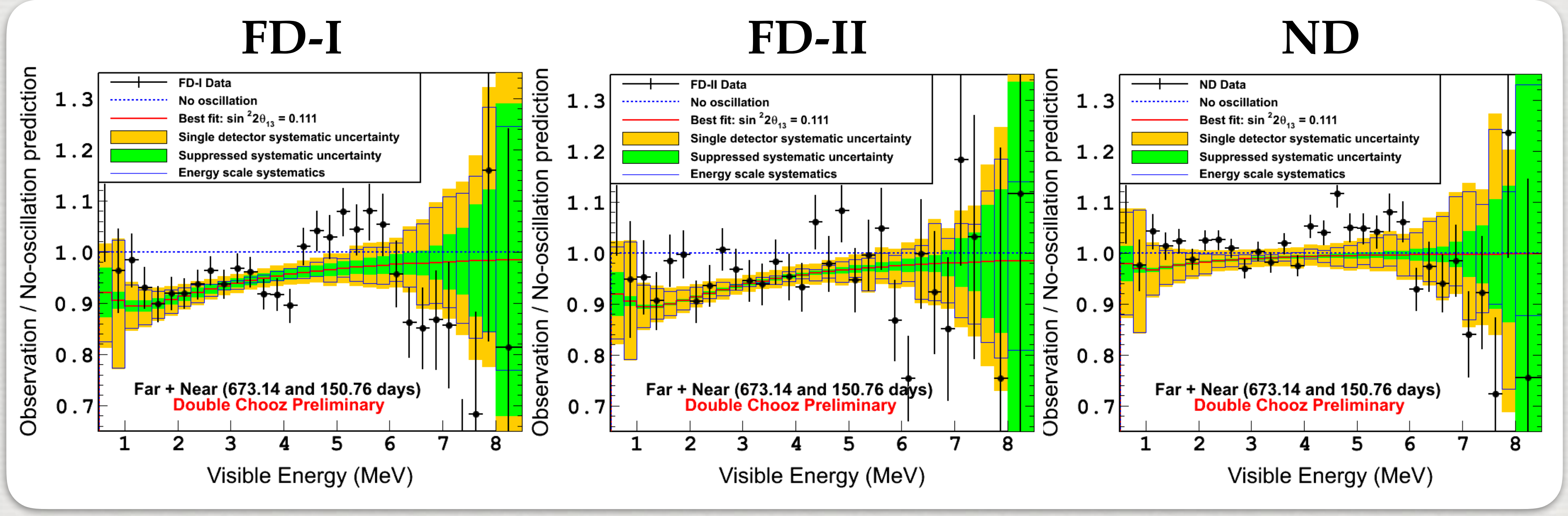
DD phase: All systematic uncertainties are < 0.4% (after Rate + shape analysis)

→ Precision is now limited by Statistics. Further improvement is expected!

Preliminary results

Fit FD-I, FD-II and ND data simultaneously w/ predictions

- Chi-square method with systematic errors by pull term & covariance matrix
- Correlation of systematic uncertainties b/w detector periods are considered
- BG rate and shape are estimated from data (Li9 rate is not constrained)
- Observed data in reactor-off period is used → Further BG constraint



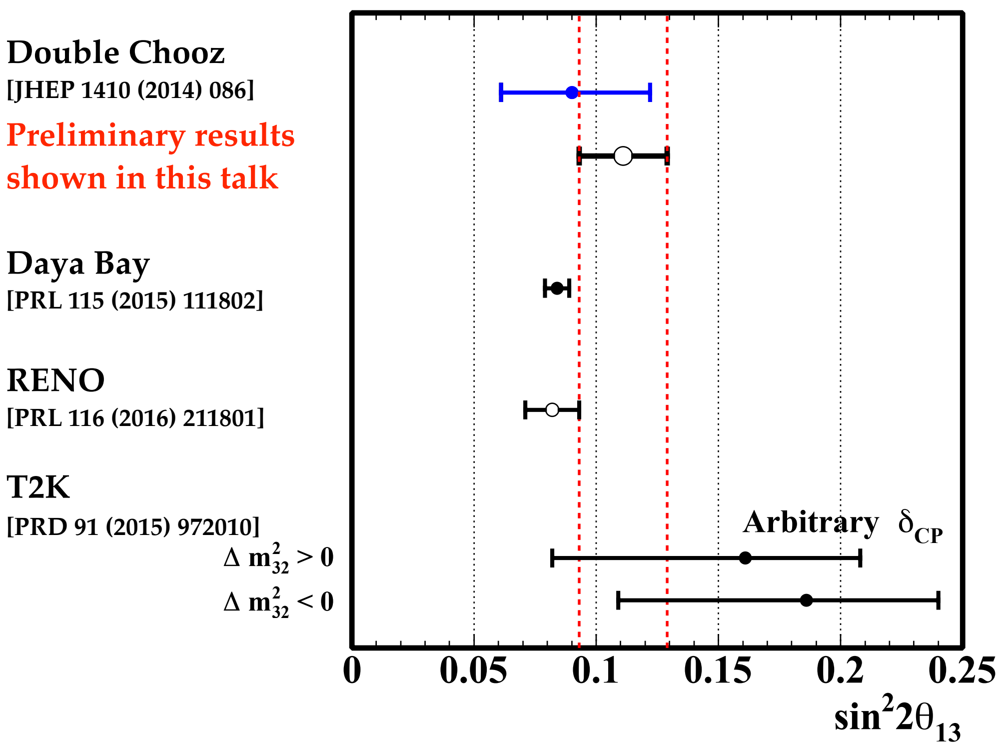
Best-fit: $\sin^2 2\theta_{13} = 0.111 \pm 0.018$ (χ^2/dof = 128.8/120)

Non-zero θ_{13} observation at 5.8 σ C.L.

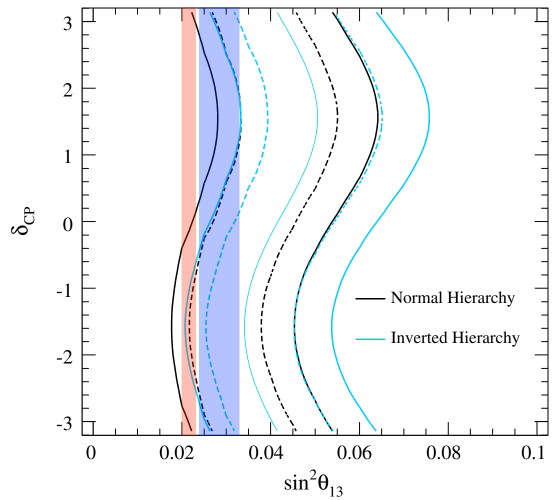
Double Chooz Preliminary

Current θ_{13} in the world

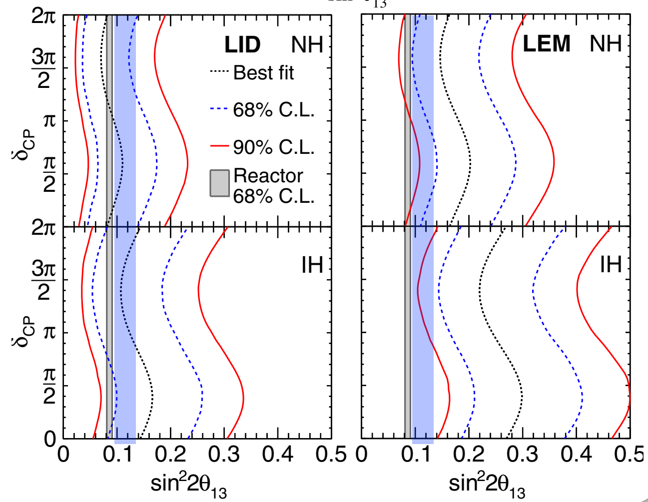
Comparison of θ_{13} measurements



T2K results
w/ Reactor θ_{13}
[PRD 91 (2015) 972010]



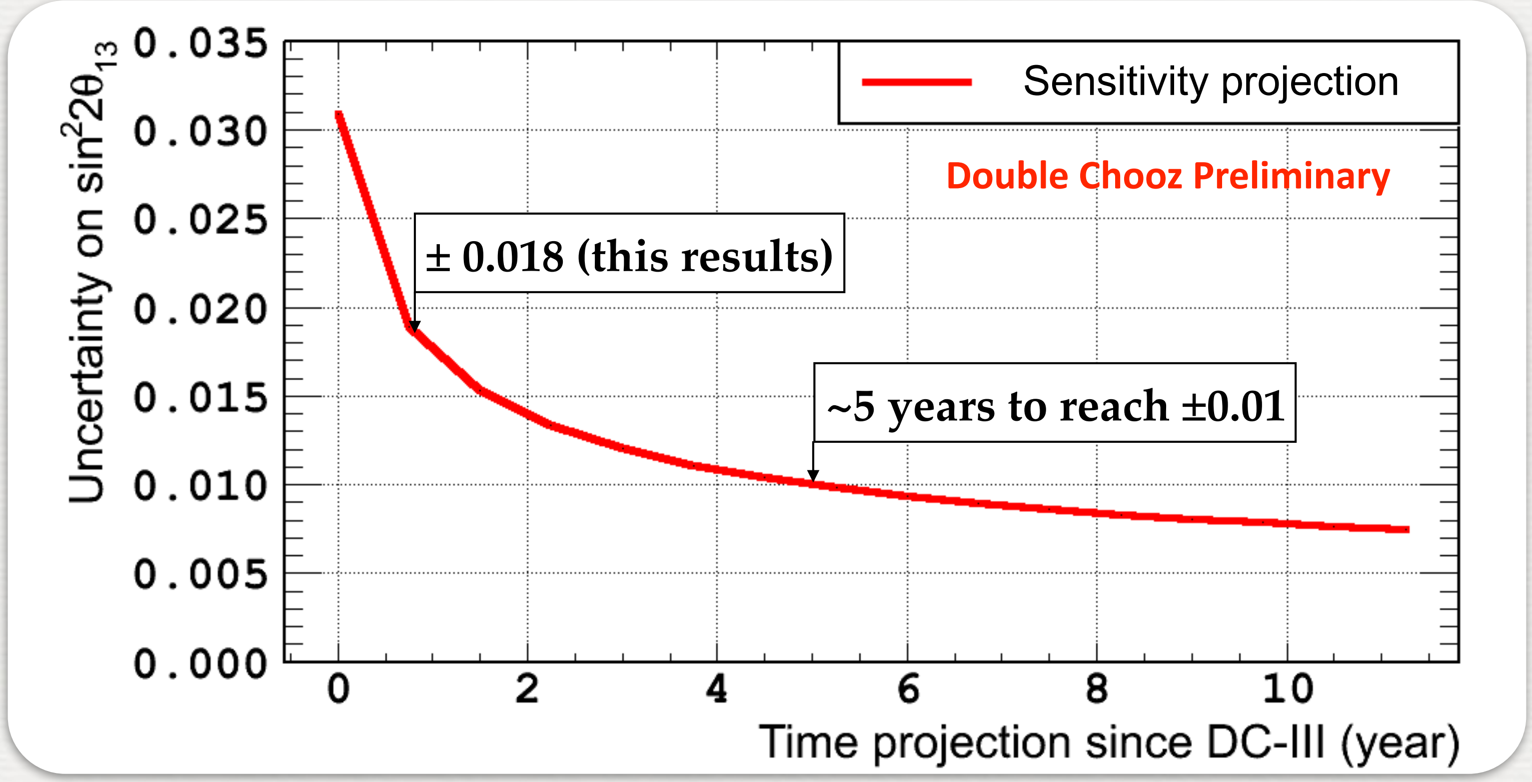
NOvA results
w/ Reactor θ_{13}
[PRL 116 (2016) 151806]



Precise measurement of θ_{13} by reactor experiments is still a key for current/future ν projects for CP violation and mass hierarchy

→ Validation with multiple experiments is essential.

Future prospects



To reach better precision, earlier:

Current analysis (Gd-only) is statistically limited

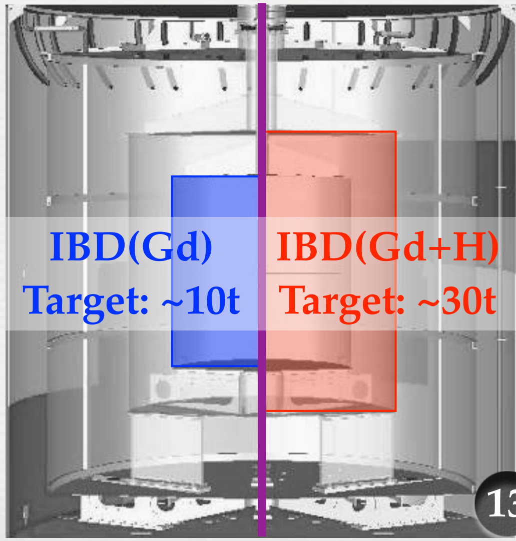
→ Inclusion of H-capture event (Gd+H analysis!)

Pros: Larger volume as target

Cons: Increase of Accidental BG by lowering E_d window

Systematic error is also challenging

→ Analytical effort is on going… (Next page)

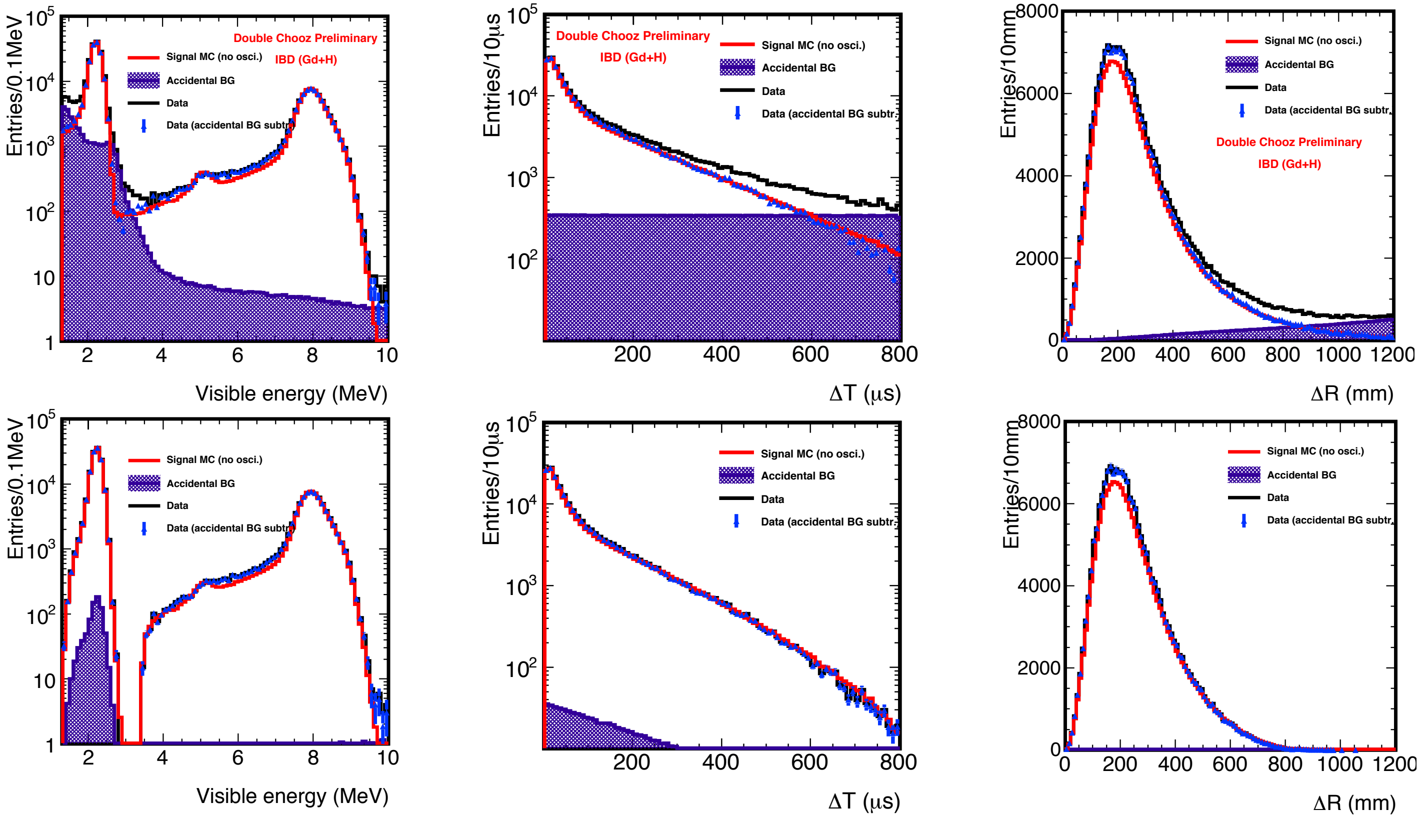


To reach better precision…

Delayed signal energy | Correlation time | Correlation distance

Before ANN cut

After ANN cut



- Accidental BG is dramatically reduced by ANN
  → Almost negligible impact to θ_{13} measurement after ANN
- Confirmed x2.5 of IBD rate than Gd only analysis

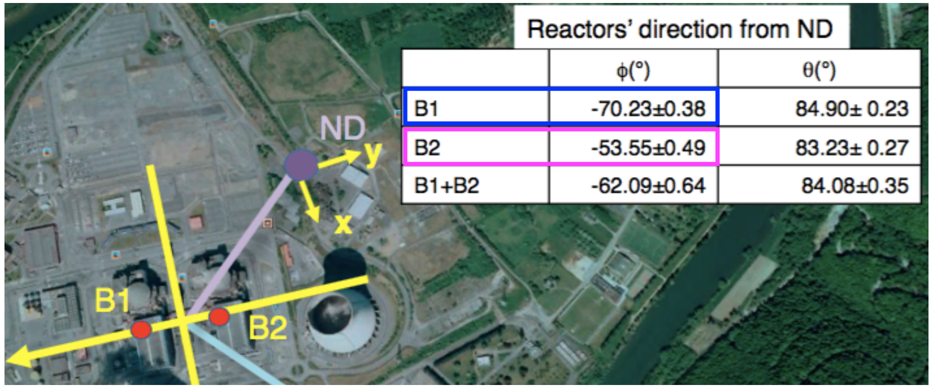
IBD rate	Gd analysis	Gd+H analysis
FD	$\sim$40 d^{-1}	$\sim$100 d^{-1}
ND	$\sim$300 d^{-1}	$\sim$800 d^{-1}

New analysis is ongoing w/ more stat. & better understandings of syst.
→ We aims to release our results at CERN seminar (20th Sep.) Stay tuned!

Other physics programs

Neutrino directionality

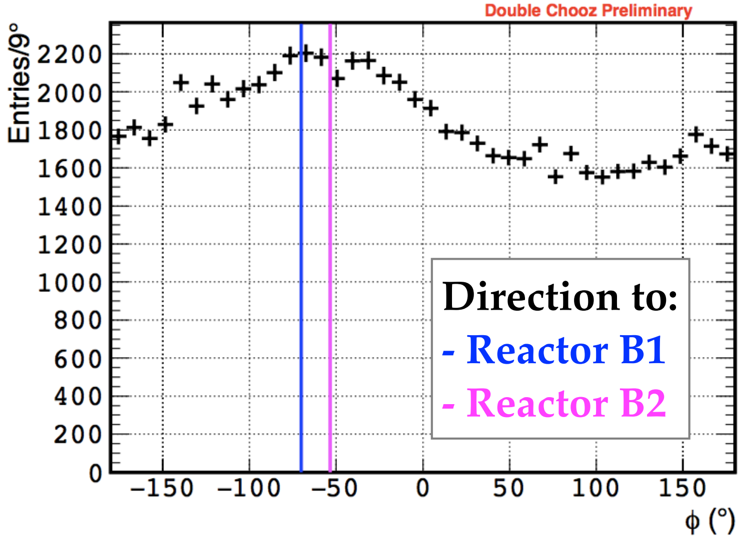
Direction of incoming ν can be observed by a vector from delayed to prompt signals



Reactors' direction from ND

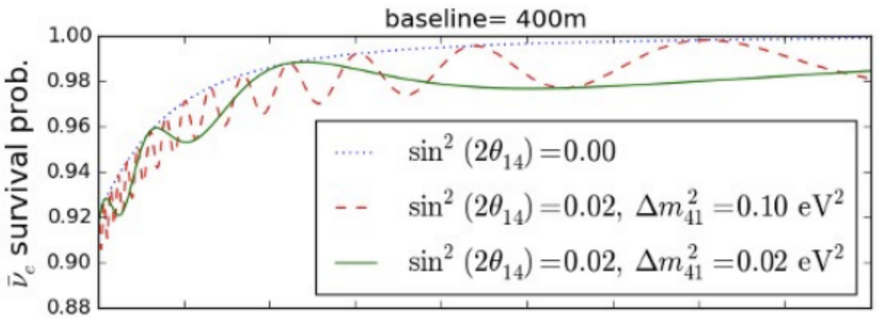
	ϕ(°)	θ(°)
B1	-70.23±0.38	84.90± 0.23
B2	-53.55±0.49	83.23± 0.27
B1+B2	-62.09±0.64	84.08±0.35

Observed angle ϕ from ND data

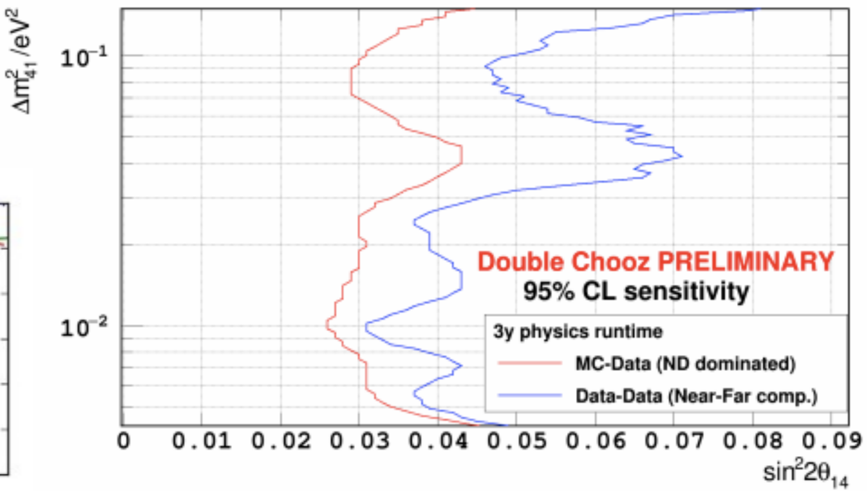


Sterile neutrino search

Sterile ν hypothesis can be tested by DC detectors located in ~400 m baseline (ND) and ~ 1 km baseline (FD)



Expected sensitivity for 3 years operation



Conclusion

- Reactor θ_{13} is a key for current and future neutrino projects
  → Validation by multi-experiment is essential

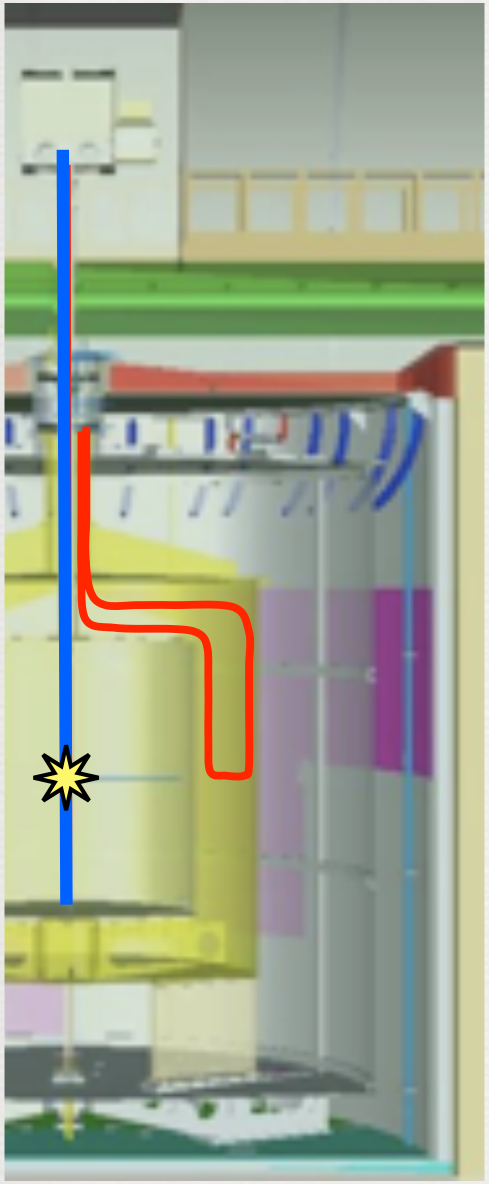
- First θ_{13} results is reported with the double-detector setup in Double Chooz experiment (FD-I: 460.93 d + FD-II: 212.21 d+ ND: 150.76 d)
  → $\sin^2 2\theta_{13} = \sin^2 2\theta_{13} = 0.111 \pm 0.018$
  - Reactor flux is strongly suppressed to <0.1 % by ND
  - Other systematic uncertainties are suppressed well below 1%

- The precision is currently limited by Statistics
  → New θ_{13} results with Gd+H analysis will come soon
  - Other physics programs are also expected

Poster presentations from Double Chooz experiments:

D. Kaplan et al. , Reactor spectral rate and shape measurement in Double Chooz detectors
A. Meregaglia et al., IBD background rejection and tagging at the Double Chooz experiment
G. Yang, et al. , θ_{13} oscillation analysis in Double Chooz with two detectors
T. Matsubara et al. , Sterile neutrino search in the Double Chooz experiment

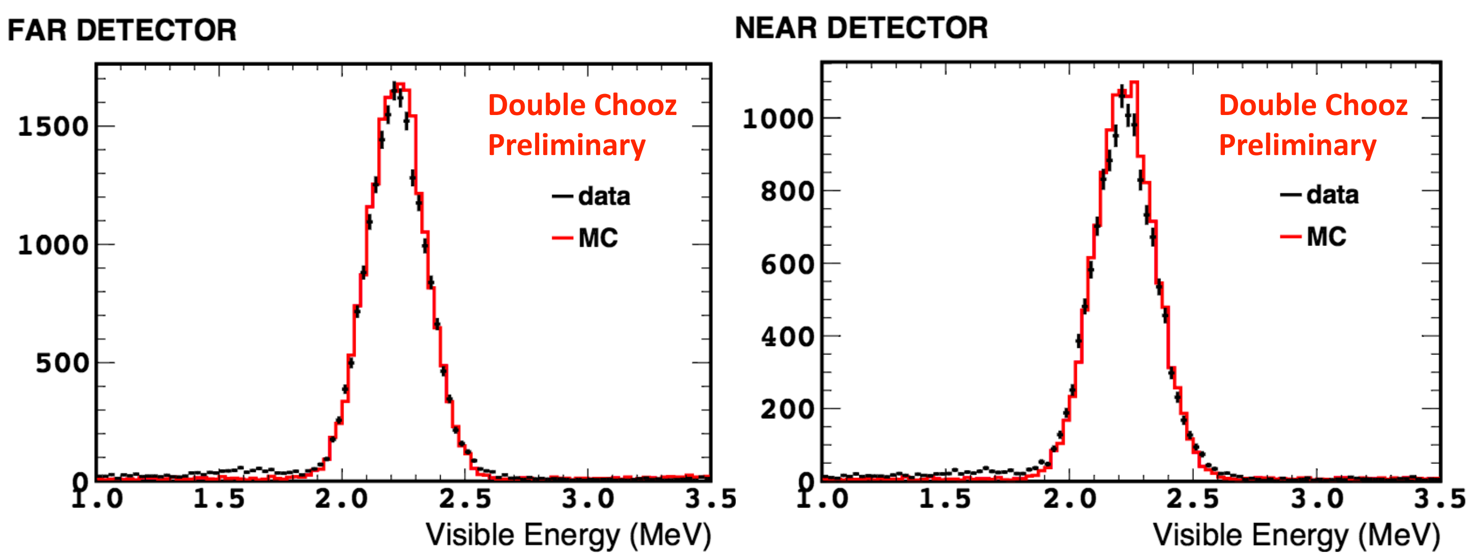
Detector performance



Detector performance is evaluated by

- Various sources like ^{60}Co, ^{68}Ge, ^{137}Cs, ^{252}Cf with two deployment systems: Z-axis system & Guide tube system
- Natural sources like neutron capture on H/Gd or BiPo

Cf-252 source deployed at detector center

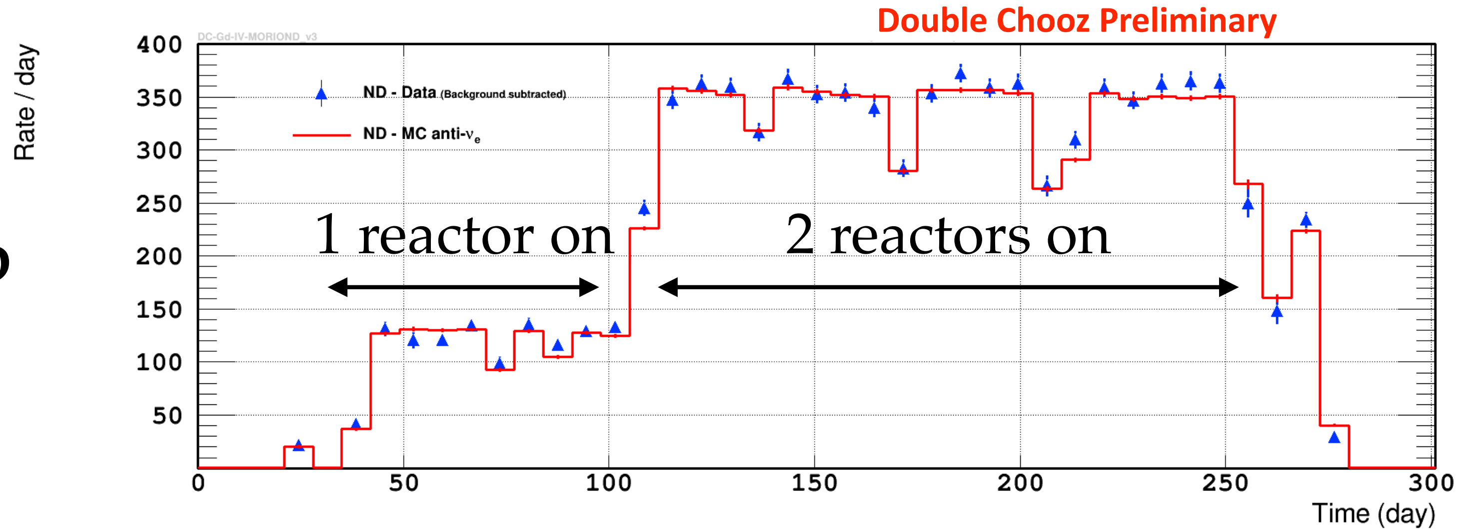


We precisely evaluated detection efficiency, energy scale, uniformity and stability from the systems and/or sources

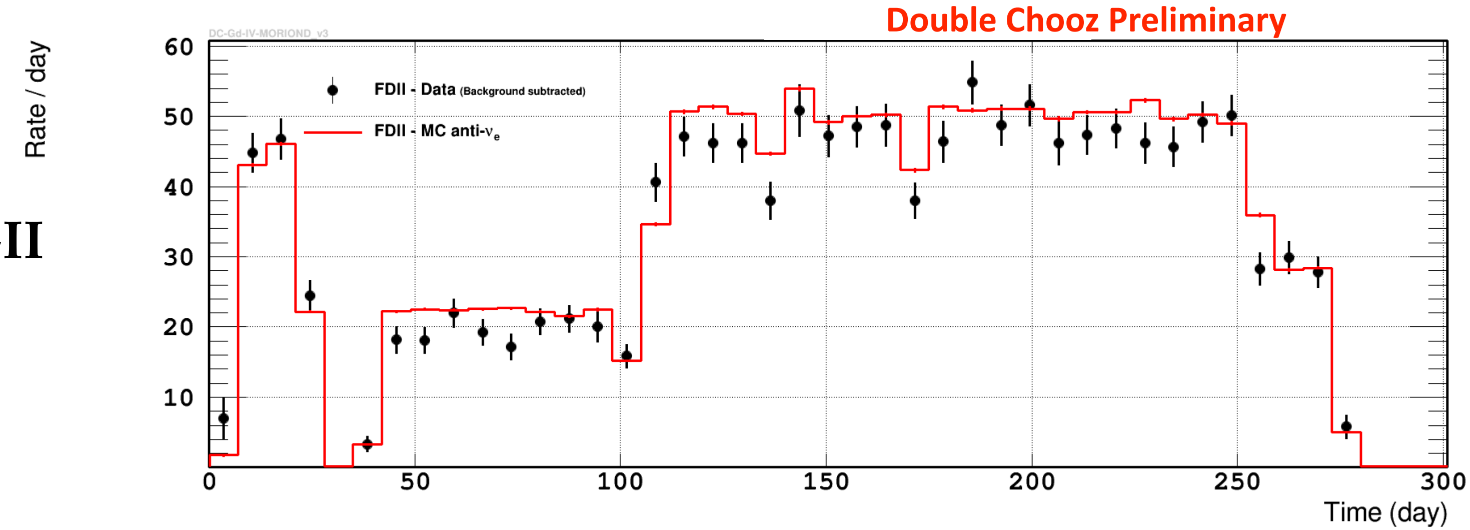
IBD candidates vs time

Rate of IBD candidates with background subtracted

ND



FD-II



Same variation of IBD candidates in double detector phase