Measurement of the θ_{13} neutrino mixing angle with the two detectors of the Double Chooz experiment

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On behalf of the Double Chooz collaboration

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Status on Neutrino Oscillation knowledge

- Standard Model (3 families)
- $PMNS_{3x3}$ (θ_{12},θ_{23},θ_{13} + 1 δ_{CP} phase)
- Two independent square mass differences $\pm\Delta m^2$, δm^2

PMNS Matrix

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

Flavour eigenstates (creation/detection)

Mass eigenstates (propagation)

	Experiment	NuFIT 5.0
θ_{12}	SNO+SK	2.3%
θ_{23}	NOνA	2.1%
θ_{13}	Reactor exp	1.4%
δm^2	KamLAND	2.8%
$\lvert\Delta m^2\rvert$	T2K+DYB	1.1%
Sign Δm^2	unknown	NO ~3σ
CPV	unknown	Favored ~3σ

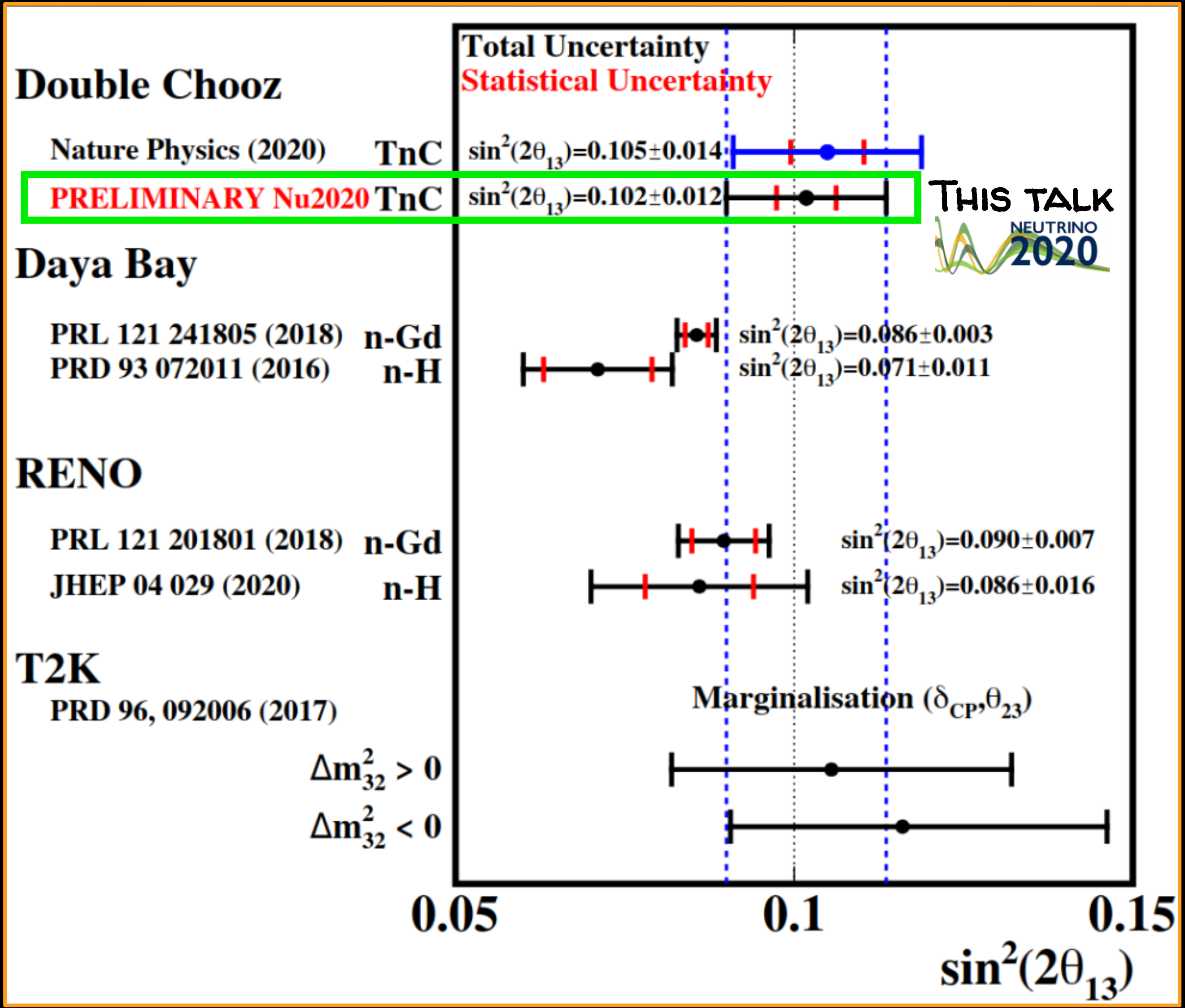
Must measure all parameters with high precision

↓

Characterise & test (i.e. over-constrain) Standard Model

θ_{13} cannot be measured by others than reactor experiments !

Status of θ_{13}

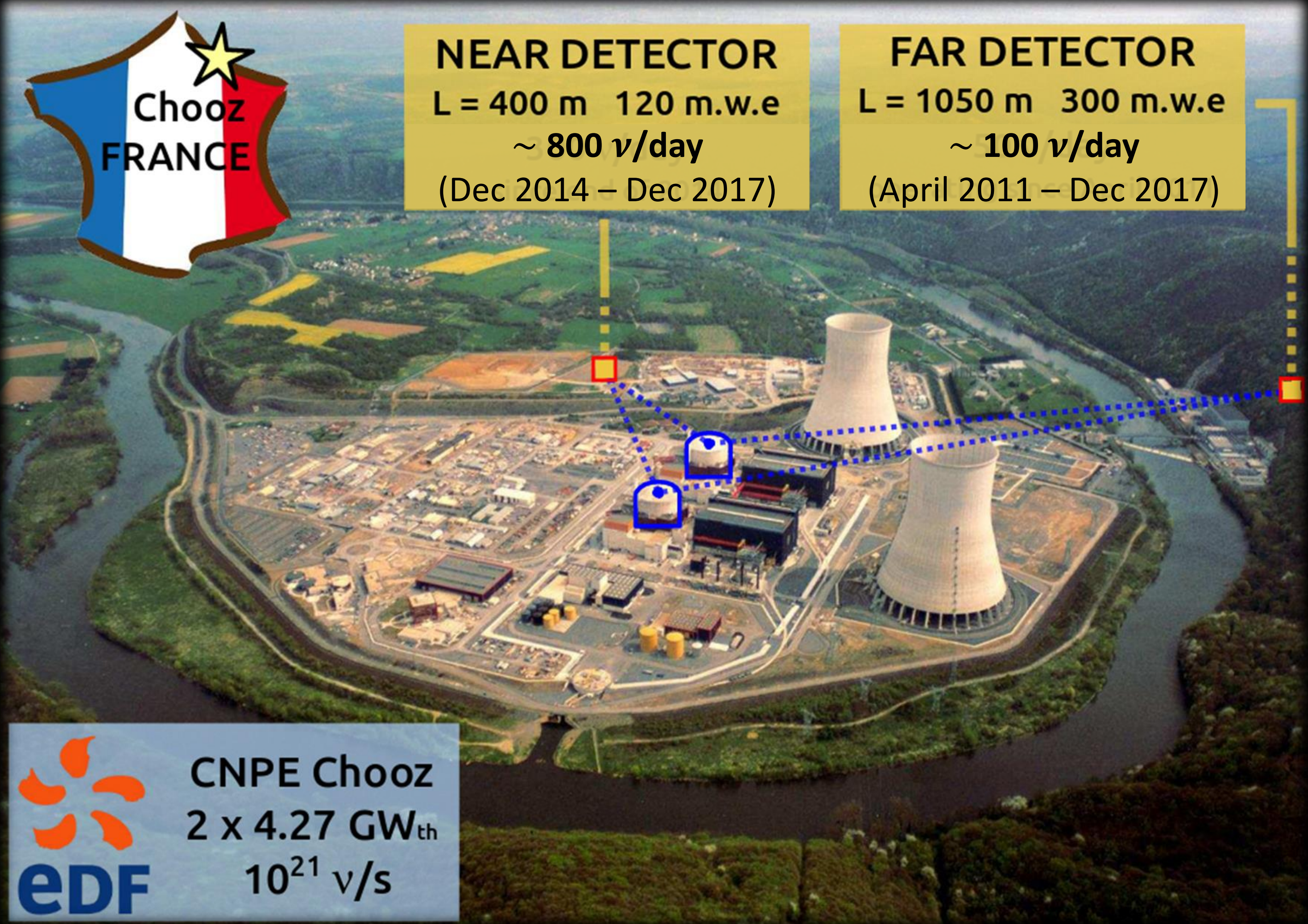


Reactor-θ_{13} experiments
Double Chooz ⊕ Daya Bay ⊕ RENO

Challenges:

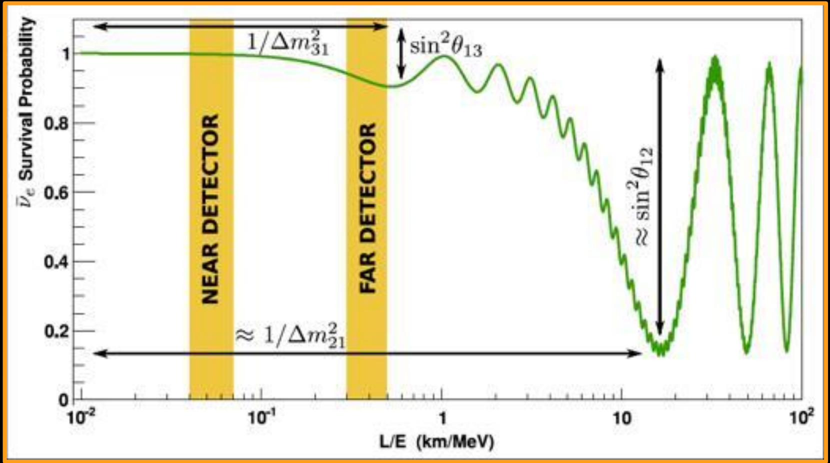
- Statistics: ~10^5 (far) [$<10^6$]
- Systematics: order of 0.1% (each)
  - Detection
  - Flux
  - BG
- Energy control: <1% precision

The Double Chooz site



$\bar{\nu}_e$ disappearance is directly related with θ_{13}

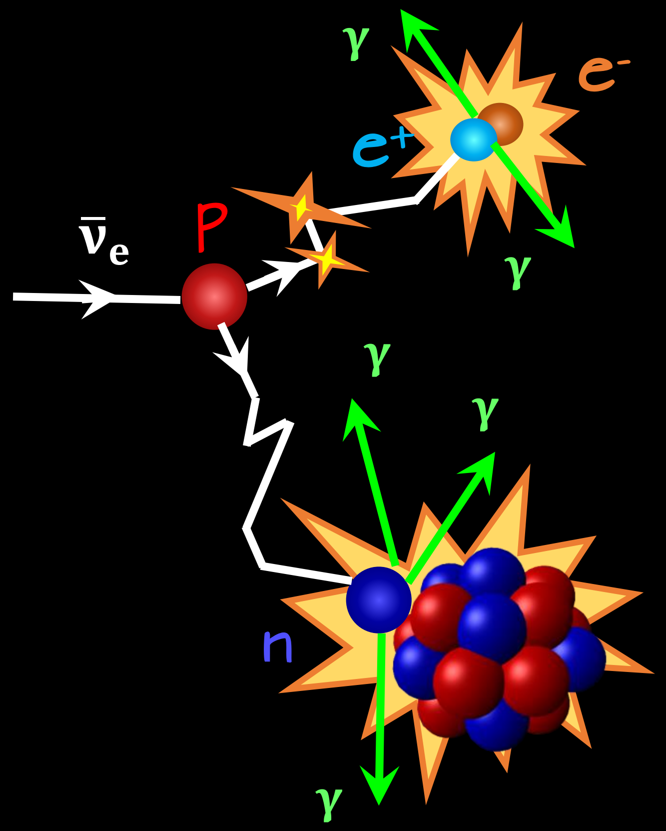
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2\left[\frac{1.27\Delta m^2_{13}(eV^2)L(m)}{E_\nu(MeV)}\right]$$



Antineutrinos are produced in nuclear reactors by the β-decay of the fission products:

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

Inverse β decay



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

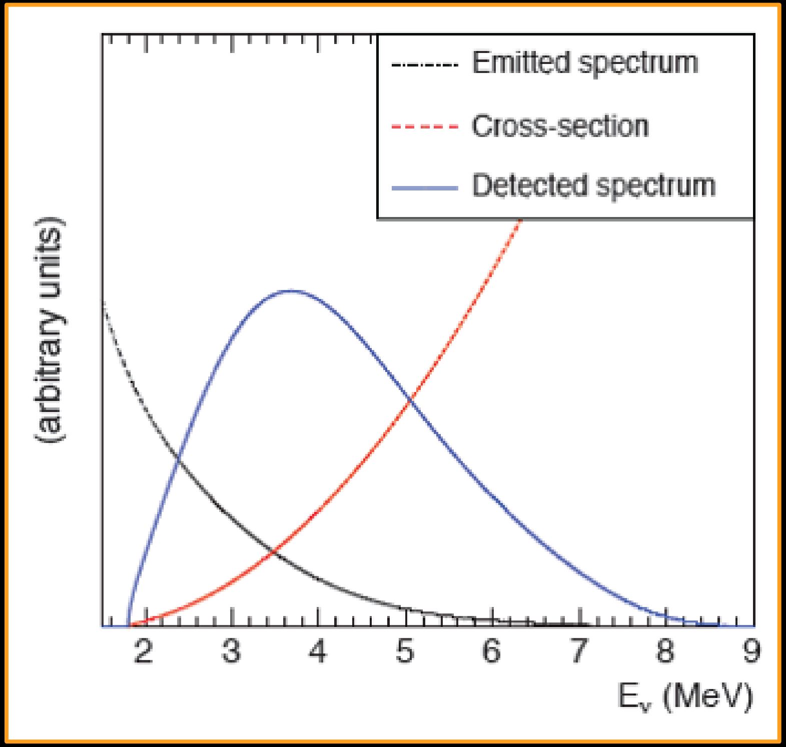
- Prompt signal

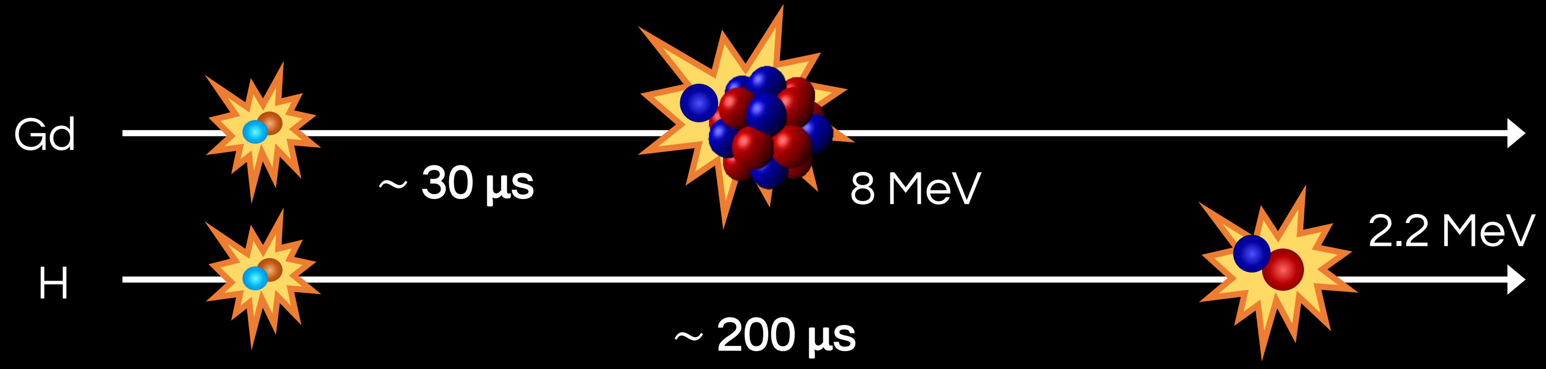
  Energy losses + e^+ anihilation
  E(prompt)≃ E($\bar{\nu}_e$) - 0.8 MeV

- Delayed signal

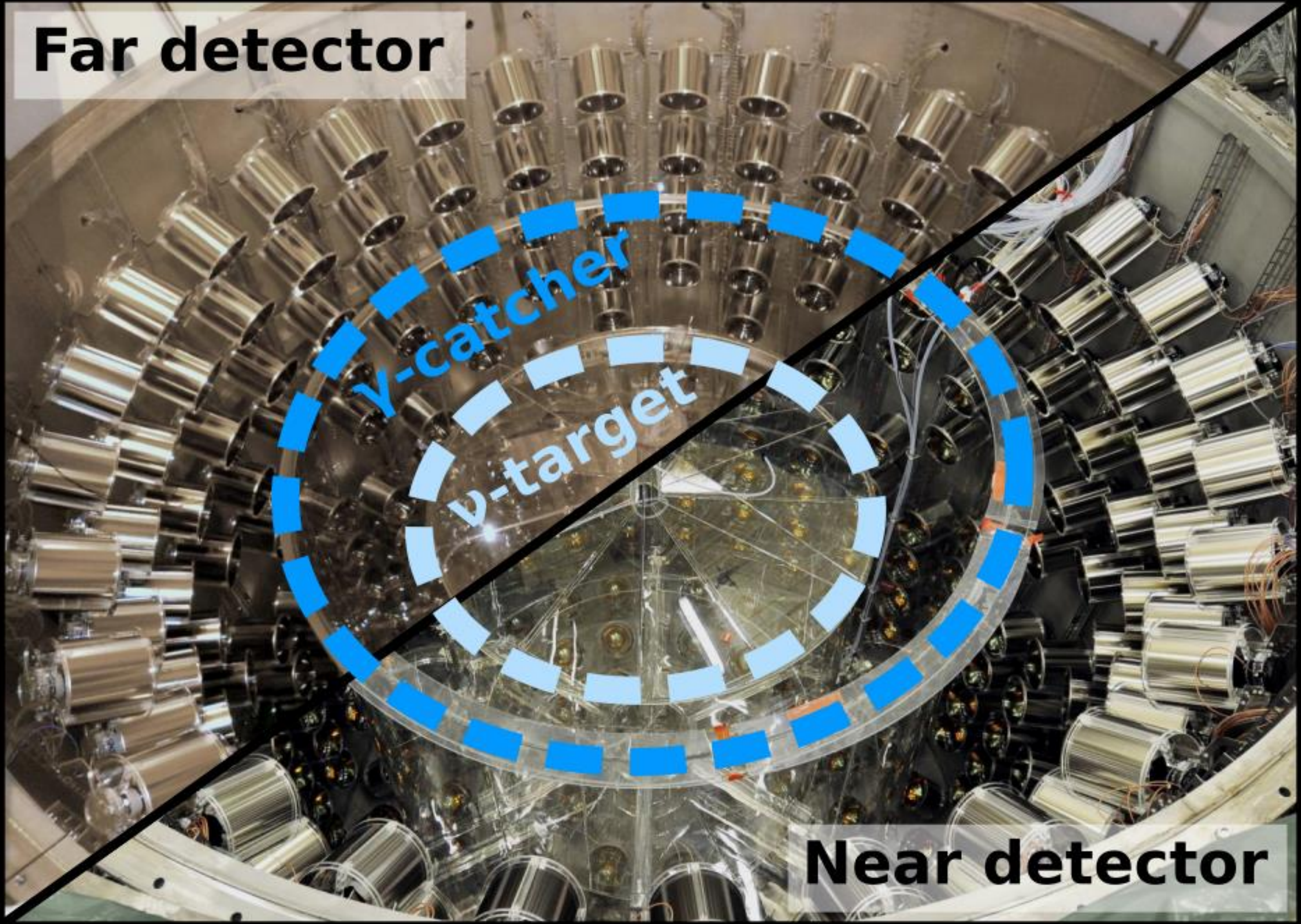
  Neutron capture on Gadolinium (Gd), emission of 8 MeV γ rays

  * Alternatively, n-capture on Hydrogen (H) (~2.2 MeV)





The Double Chooz detectors



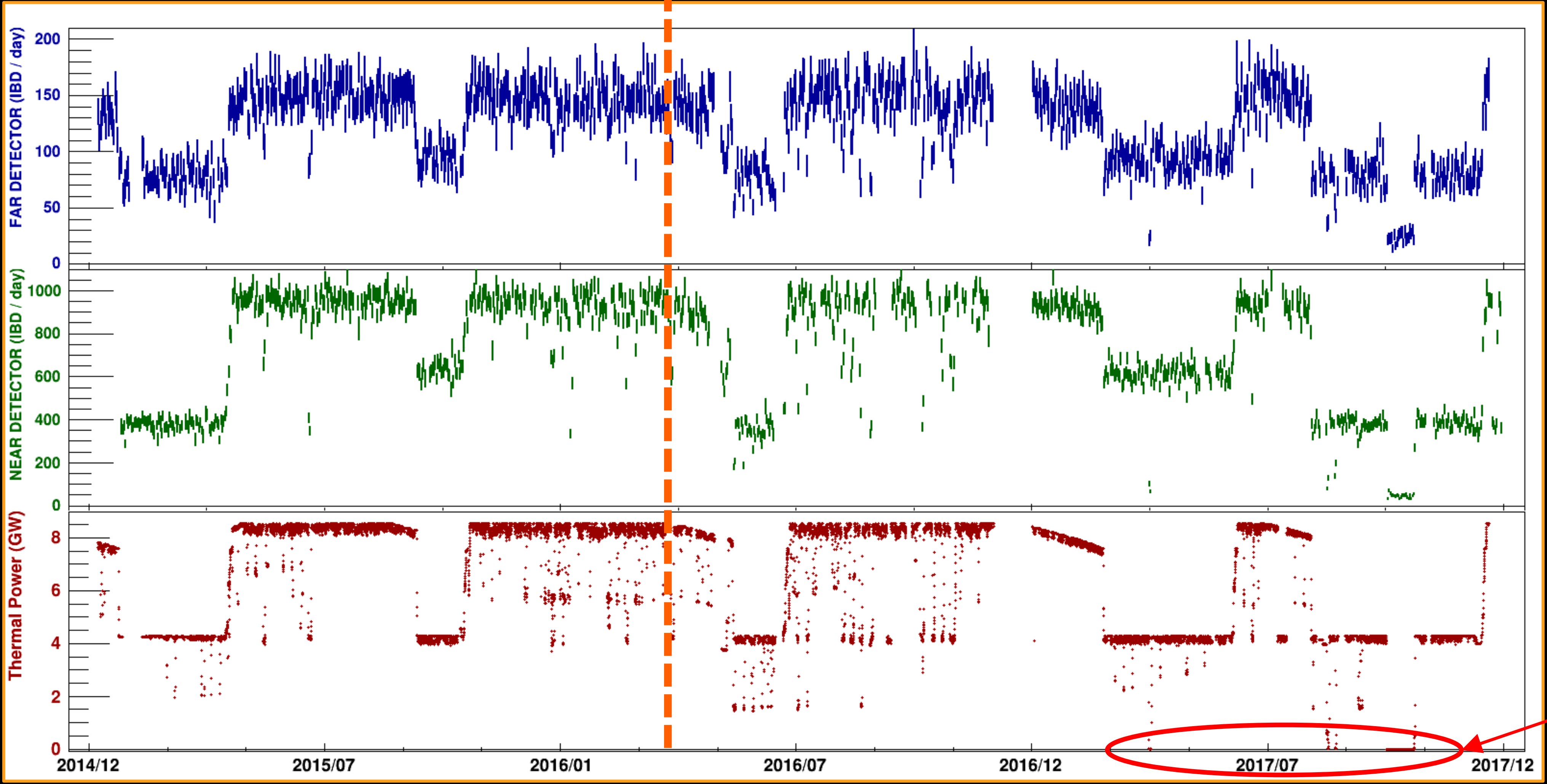
Smallest ν-target θ_{13} reactor experiments

New Data

nature physics

Nature Physics Data Set
(+1.5y of Far only data)

Extra set included in this talk



Far Detector
$\sim 150\nu$/day

Near Detector
$\sim 1000\nu$/day

Reactor
Thermal Power

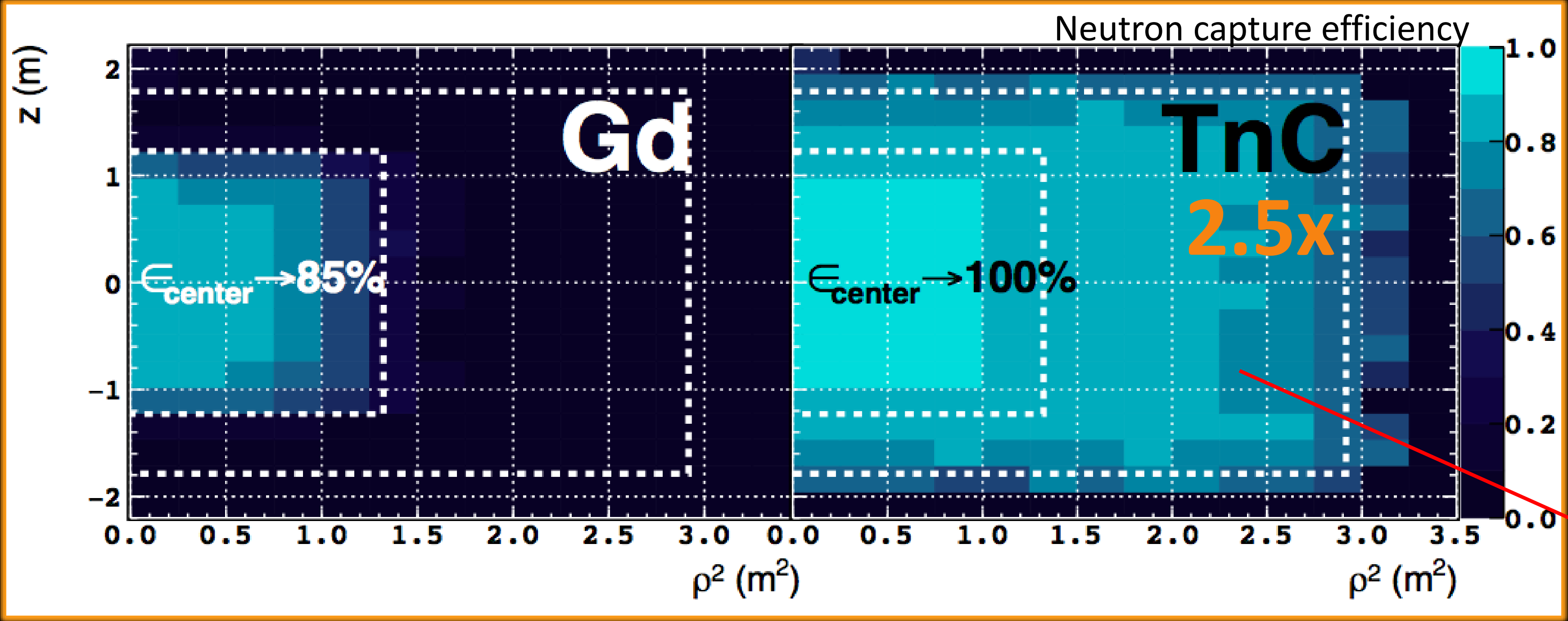
2 reactors off

Motivation for the TnC technique

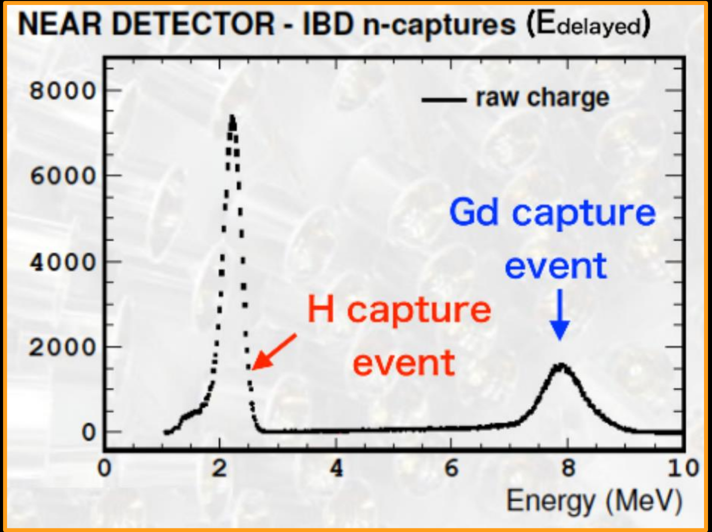
Statistics is limiting factor in the sensitivity of θ_{13}

- Major increase of the detection volume
  - Increase of signal statistics by more than a factor of 2.5 (Gd-only)

Small Gd-target (8.3 t) Gd+H+C-target (~30 t)



Delayed energy window maximally open

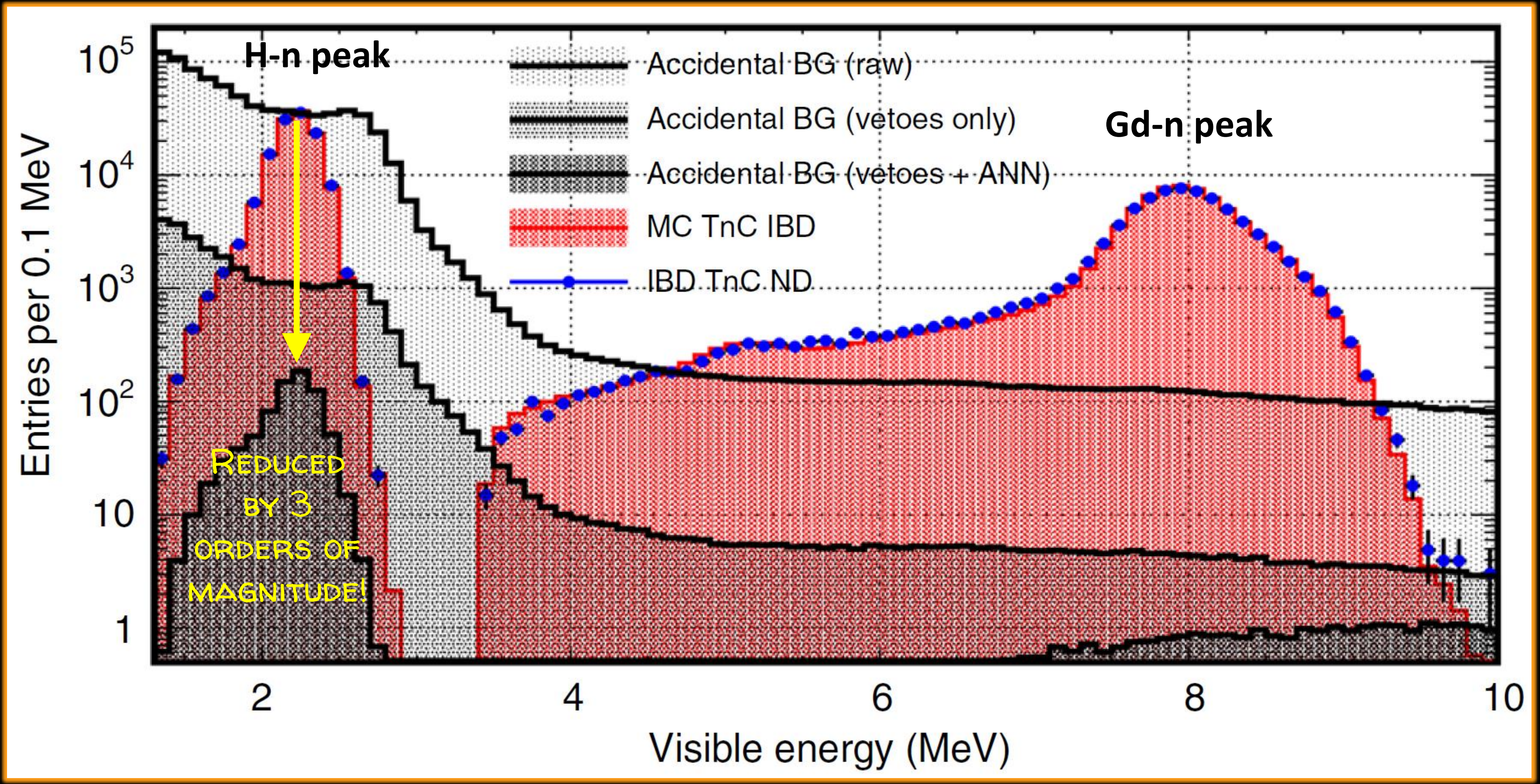


Large Gamma Catcher proton number uncertainty ~0.6%

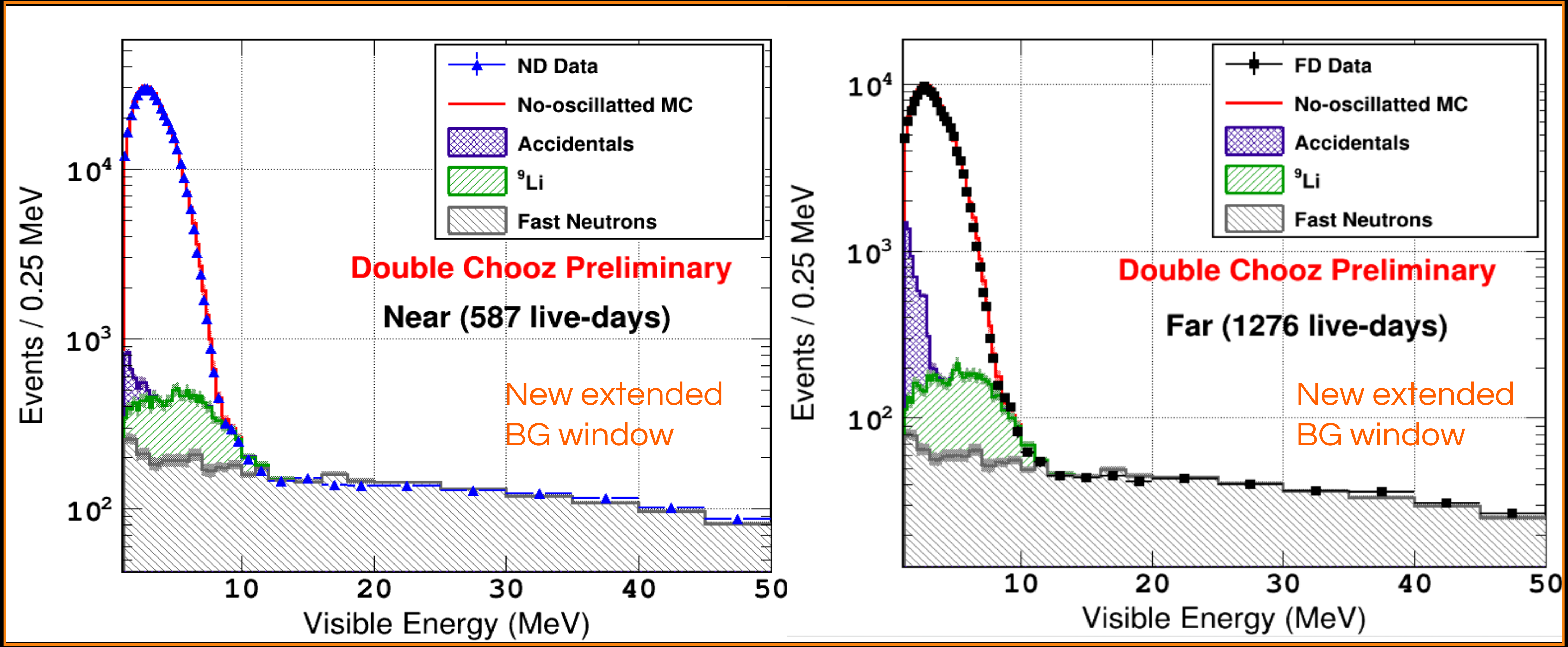
4 layers detector structure → 3 layers detector structure

Background rejection

Challenge: control of larger BGs



Better constraint of cosmogenic BG



^{9}Li Rate uncertainty 7%
Fast-neutron Rate uncertainty 1%
Accidental Rate uncertainty < 1%

- Help to further constraint the FN rate
- Data driven spectra (~~model~~)

Reactors OFF data

Direct measurement of the backgrounds

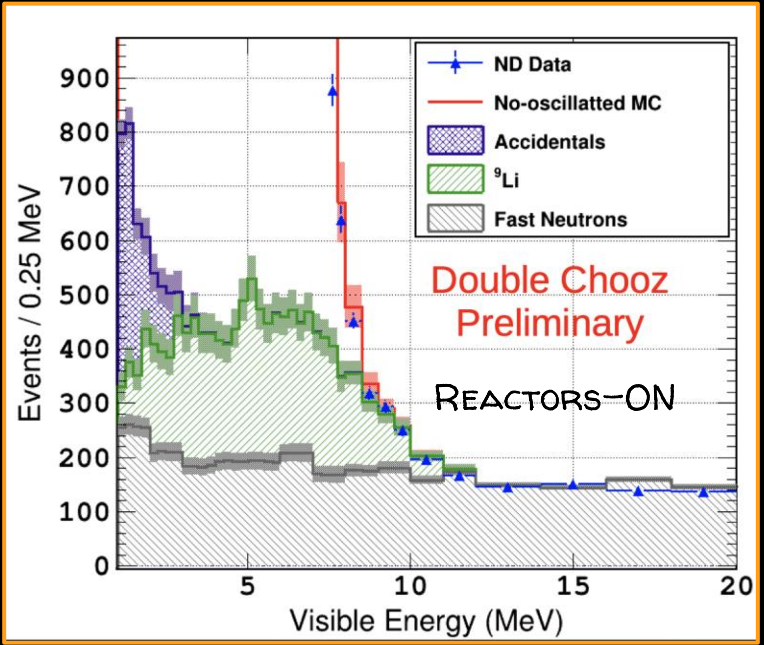
2-OFF

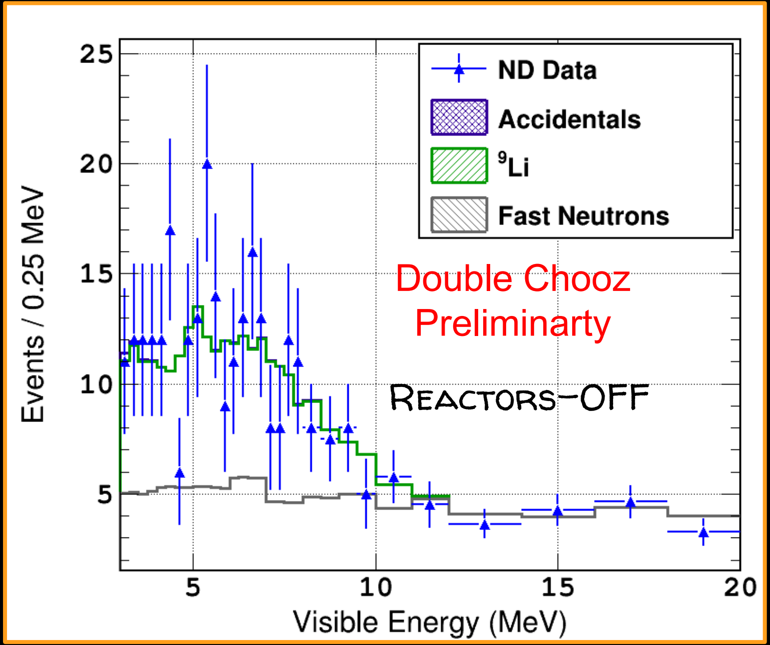
Background understanding

	Events/day FD	Events/day ND
OFF-OFF (2012)	8.9 ± 1.2	---
OFF-OFF (2017)	9.8 ± 0.9	39.6 ± 2.5
BG estimated (fit)	9.3 ± 0.3	38.5 ± 1.5

Good agreement, all numbers within 1σ

Acc + FN + Li^9





- ~7 days of 2-Off data (only FD working)
- ~23 days of 2-Off data (FD & ND)

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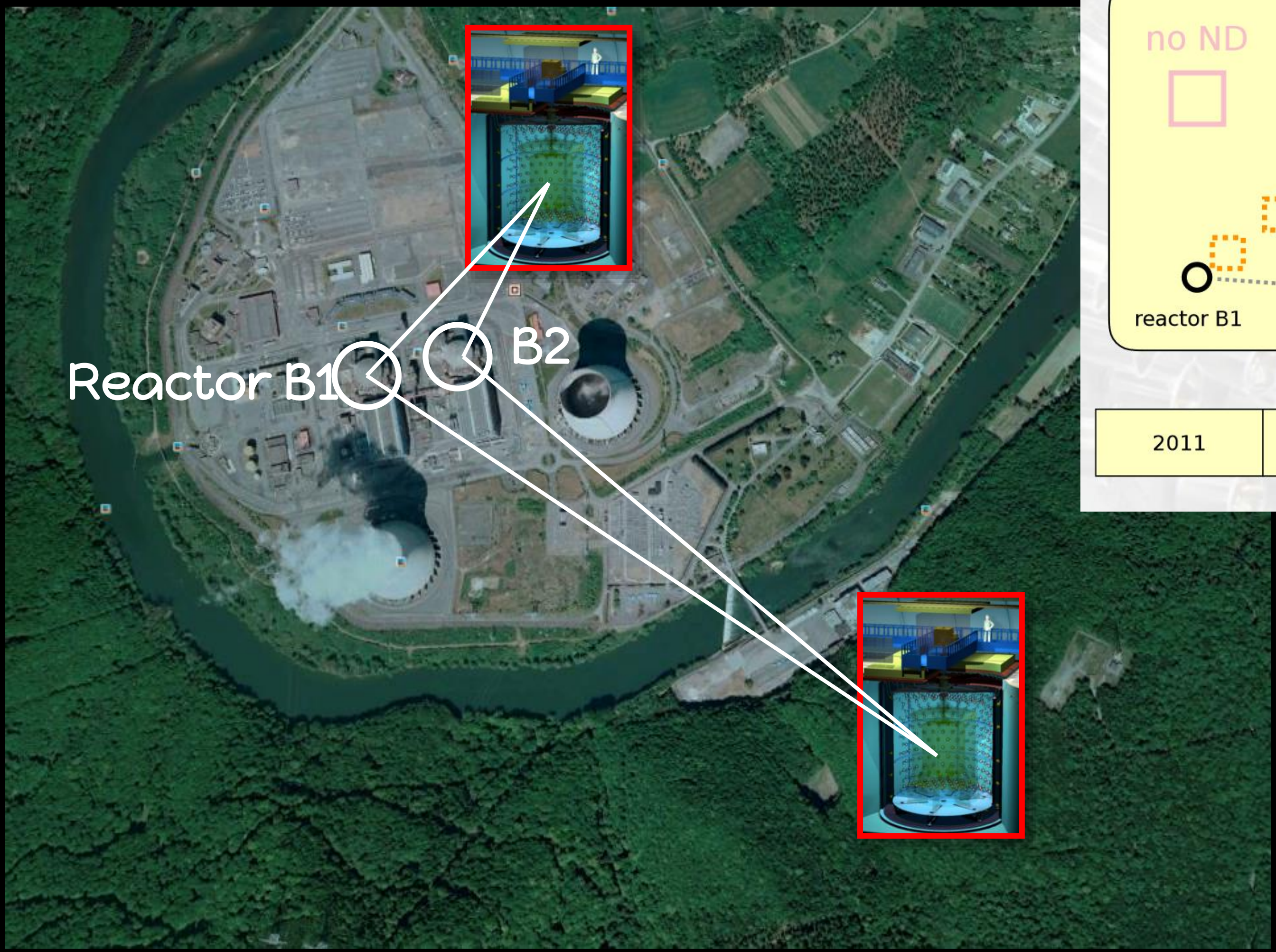
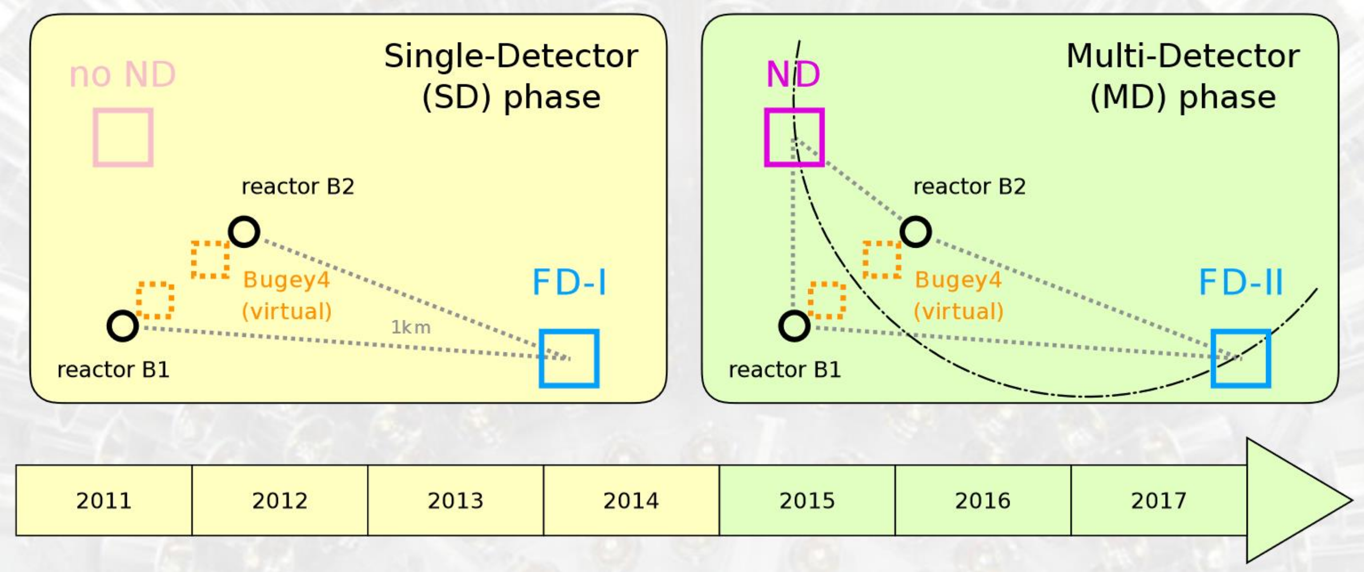
Shape info used for first time in the Rate+Shape θ_{13} fit

- New Reactor-off Data gives extra constrains on BG above 3 MeV

Major cancellation of reactor flux



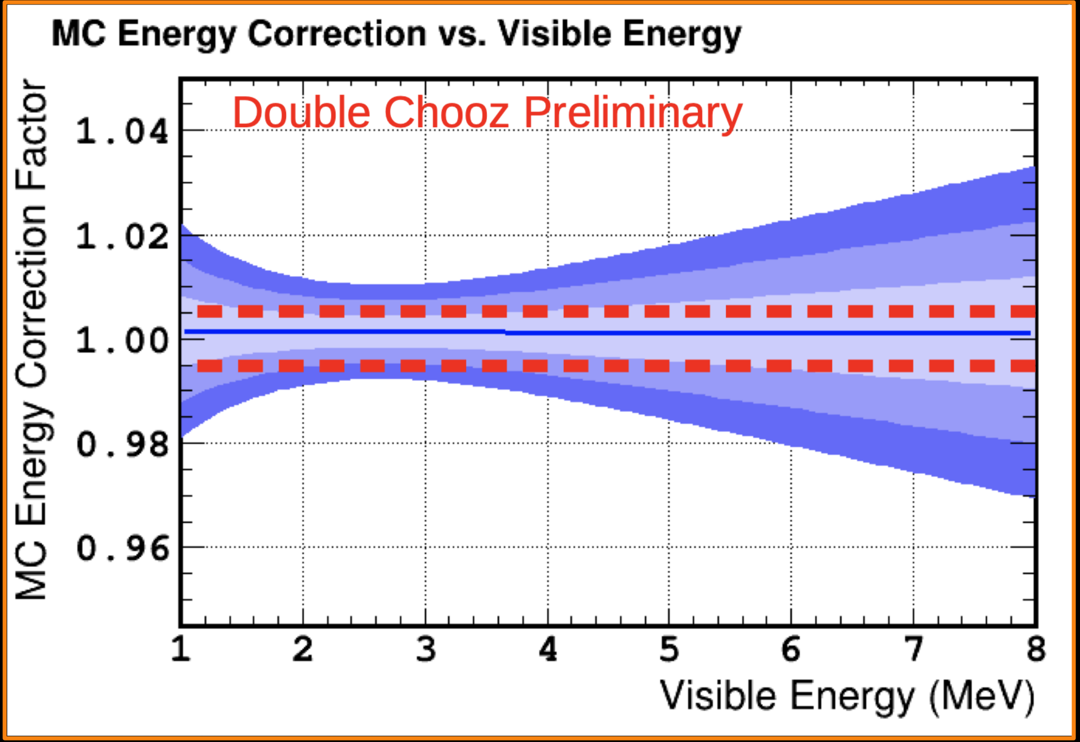


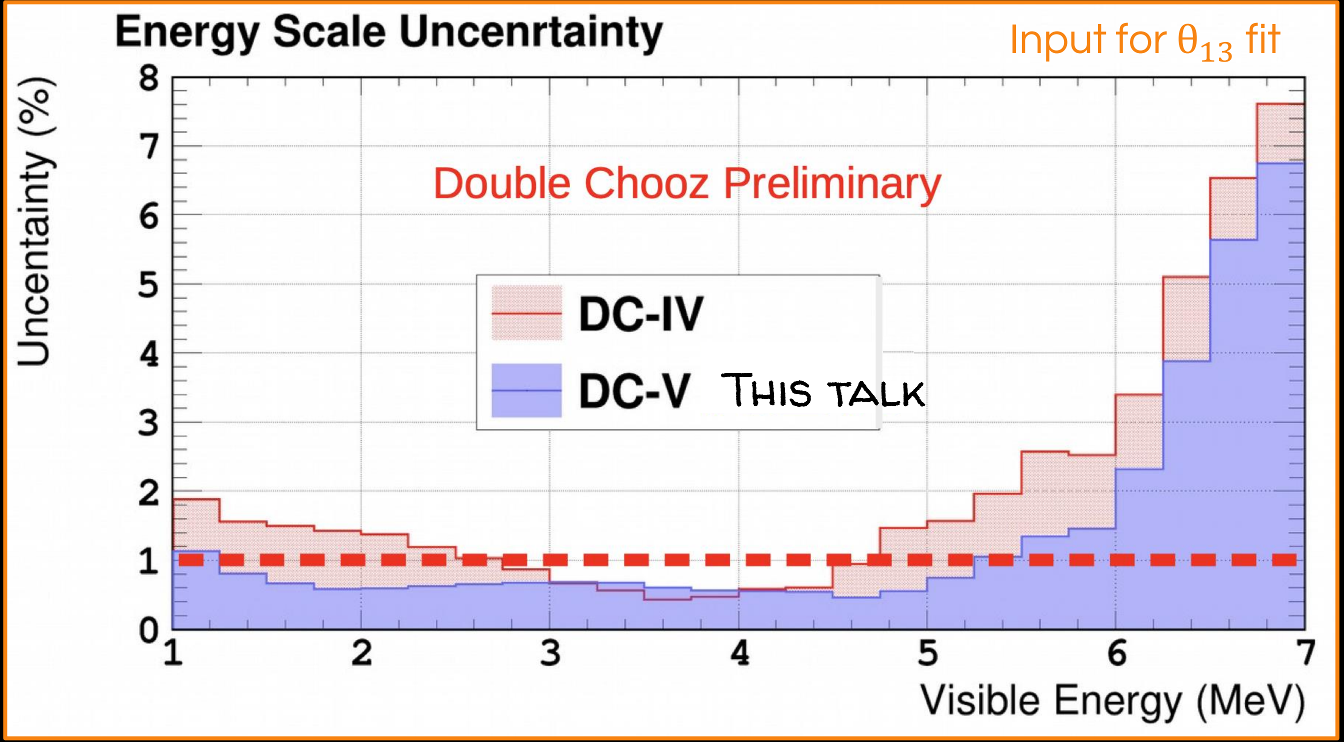
Isoflux configuration

- Relative contribution by each reactor to the total detected $\bar{\nu}_e$ flux is almost the same for both detectors. The ND becomes an effective monitor of the FD.
- Reactor flux error highly suppressed with multi-detectors

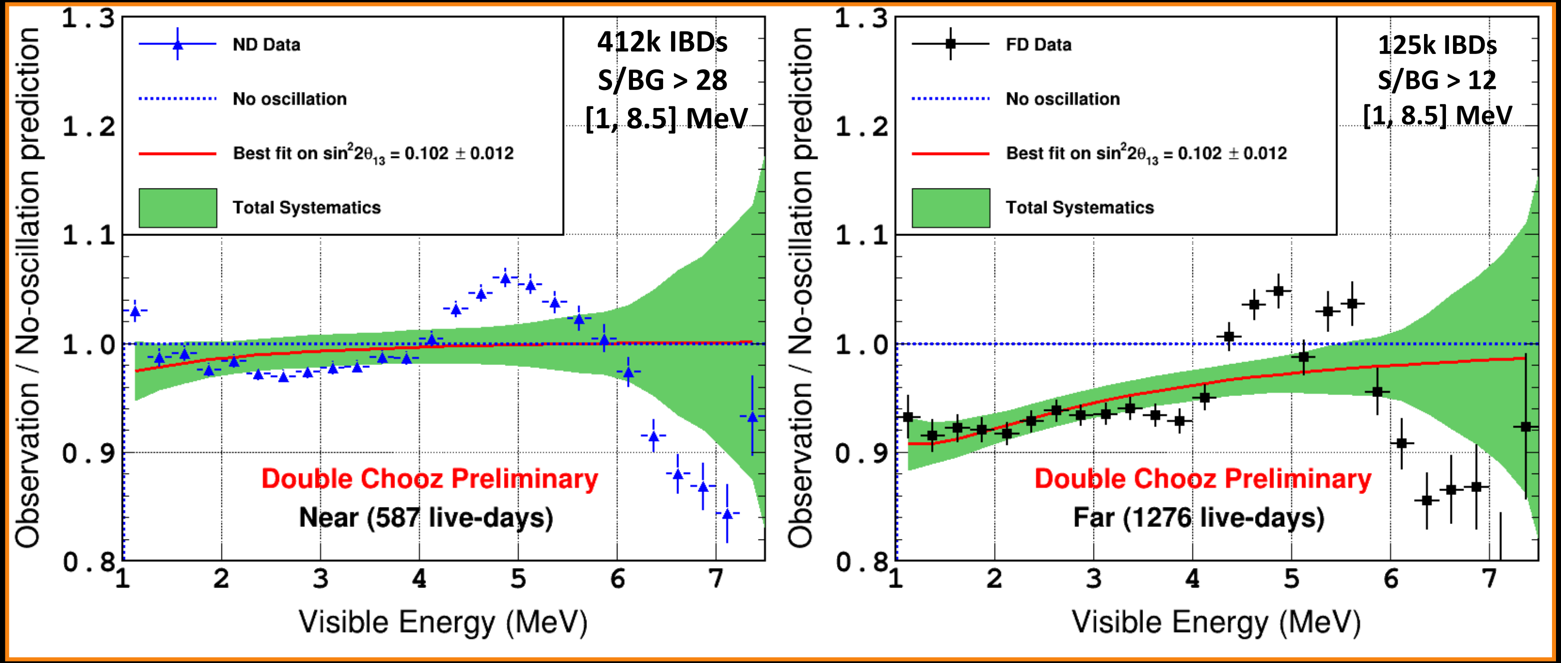
Positron Energy Model

- More Data allowed:
  - Better understanding of detector stability & uniformity
- Deticated calibration campaigns allowed:
  - Extra constrain of light & charge non-linearities
- Energy controlled ~0.5% in θ_{13} region





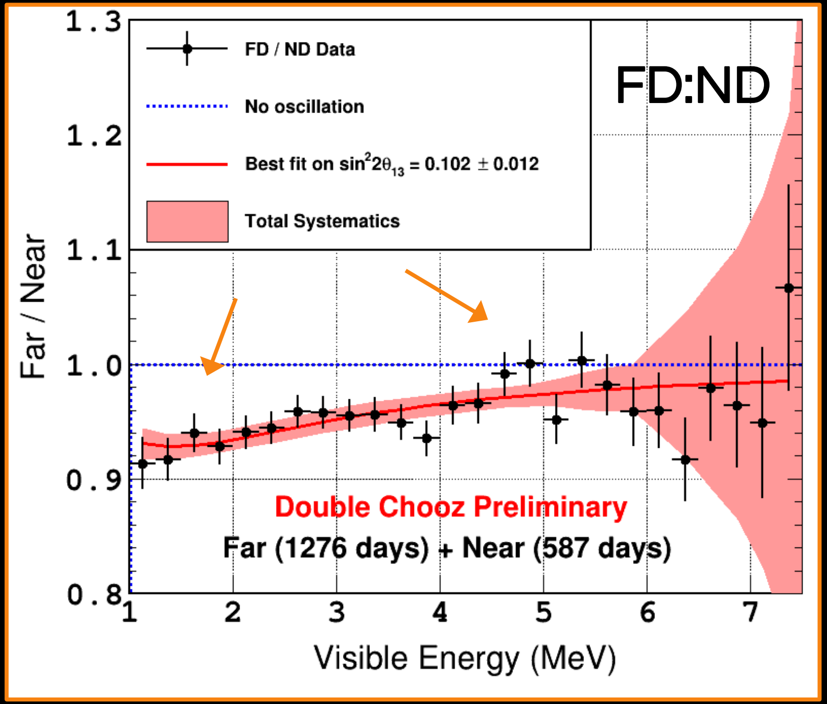
θ_{13} Rate+Shape Oscillation fit



$$\sin^2(2\theta_{13}) = 0.102 \pm 0.012$$

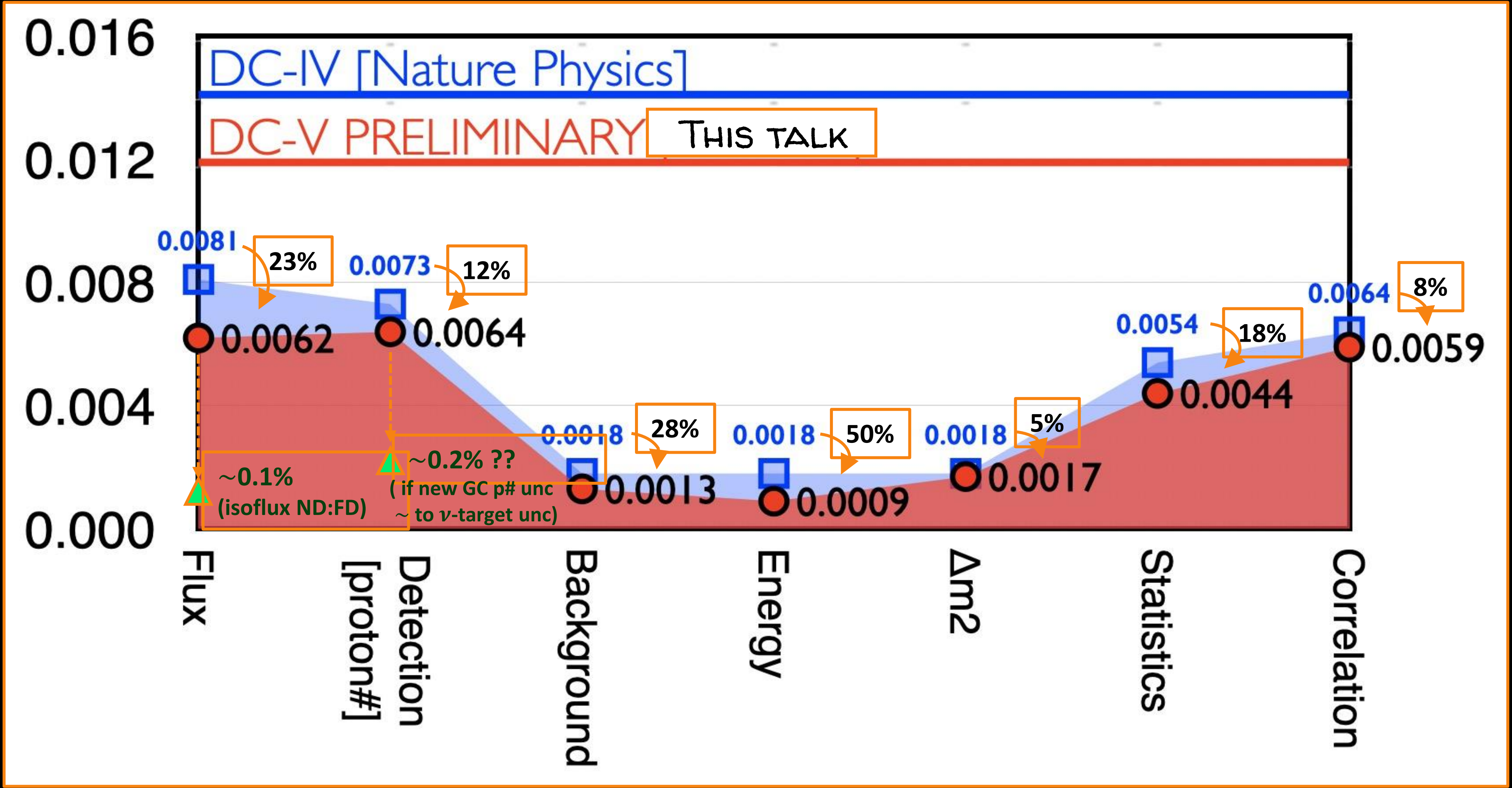
$$\sin^2(2\theta_{13}) = 0.102 \pm 0.011\ (\text{syst}) \pm 0.004\ (\text{stat})$$

(stable result also for Rate or Shape only analysis)

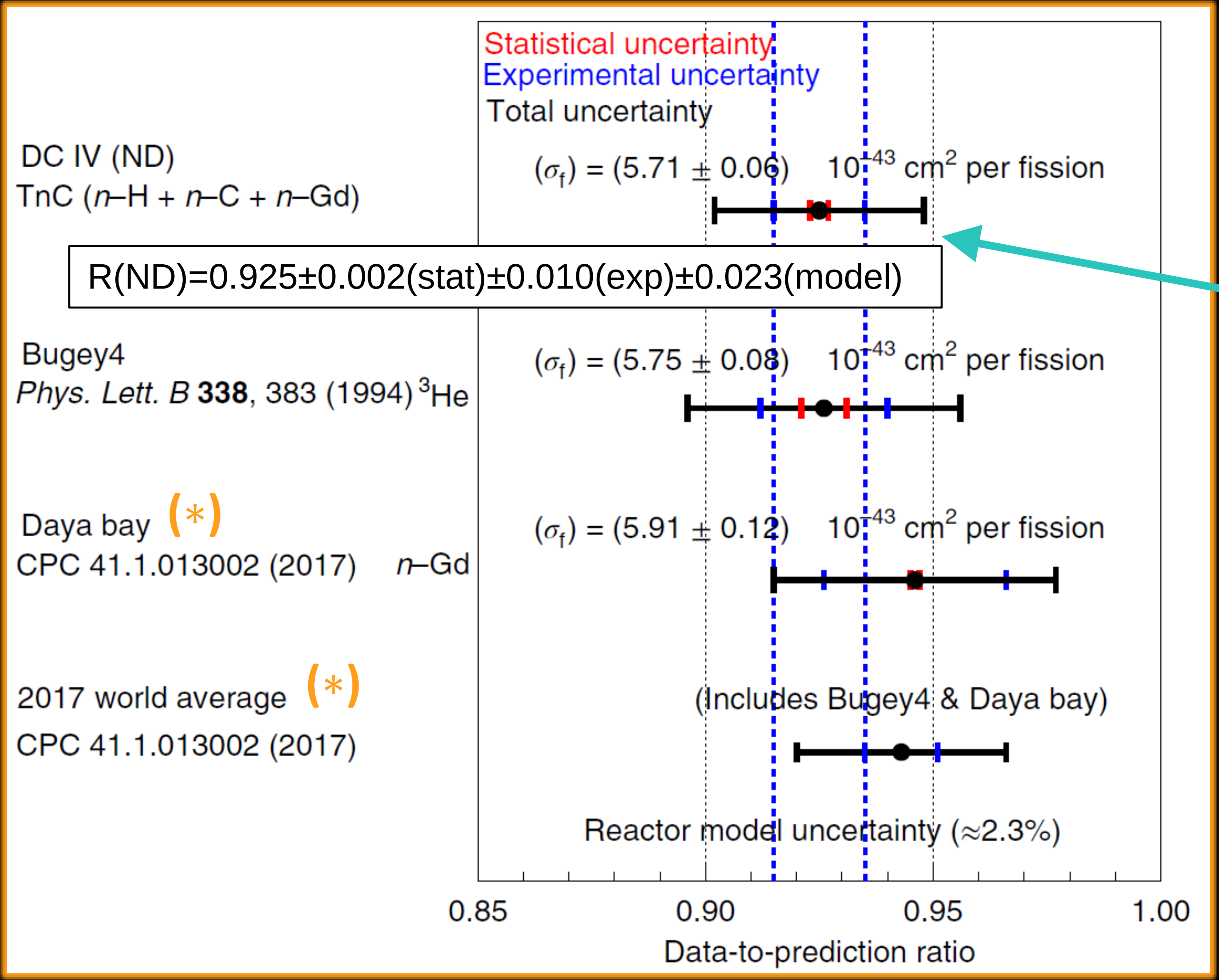


Inter-detector ratio
(reactor model cancellation)

Systematics Breakdown



Mean cross-section per fission



$$N_{\nu}^{exp}(t) \propto \epsilon \frac{N_p}{L_R^2} \frac{P_{th}^R}{\langle E_f \rangle_R} \langle \sigma_f \rangle_R$$

Best Integral Flux Measurement to Date

Excellent agreement with Bugey4 and Daya Bay

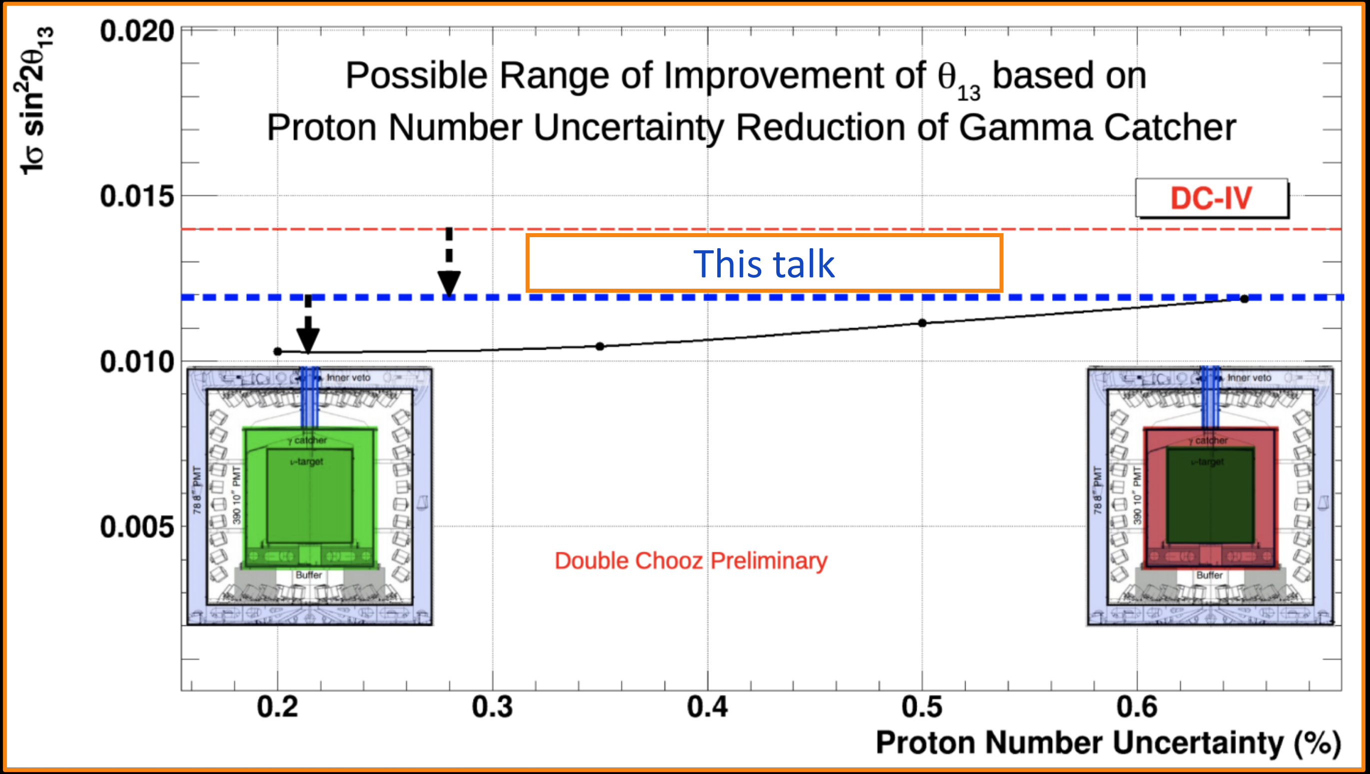
DC ND Fission fraction
(2 reactors weighted)

^{235}U → 0.520
^{238}U → 0.087
^{239}Pu→ 0.333
^{241}Pu→ 0.060

(*) Results before Neutrino 2018

Prospects and Conclusions

- Extra statistics → Better bkg constraint, detection systematics, flux cancellation and stability
- Reactor off → Better bkg constraint
- Improved energy systematics
- New result: $\sin^2(2\theta_{13}) = 0.102 \pm 0.012$ (w/ full two detectors data)



- Detector dismantling underway. Goal: a better GC proton number measurement
- Still room for $\sin^2(2\theta_{13})$ improvement ($1\sigma \lesssim 0.01$)

Thank you!


Brazil
CBPF
UNICAMP
France
APC (IN2P3)
CEA/IRFU:
SPP
SPhN
SEDI
SIS
SENAC
CENBG (IN2P3)
LNCA (IN2P3/CEA)
Subatech (IN2P3)
Germany
EKU Tübingen
MPIK Heidelberg
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