Double Chooz

(first multi-detector appetiser)

FNAL laboratory (Chicago, USA)
March 2016

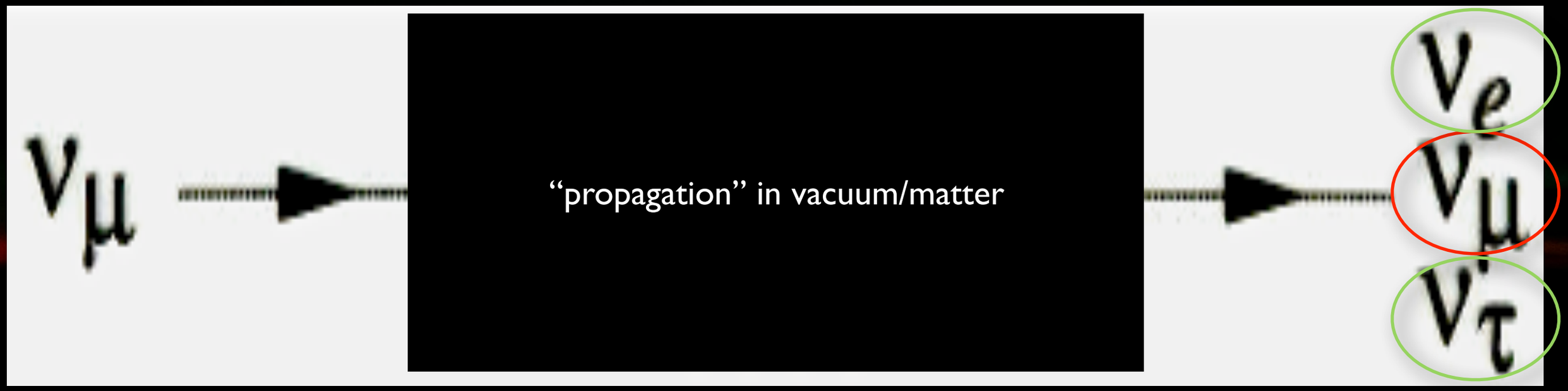
Anatael Cabrera

CNRS / IN2P3 @ APC (Paris)

neutrino oscillations in a nut shell

Let's take ν_μ (a popular example) to start with…

disappearance
appearance



observations: **disappearance** (→ **Nobel Prize 2015**) & **appearance** (>2010)

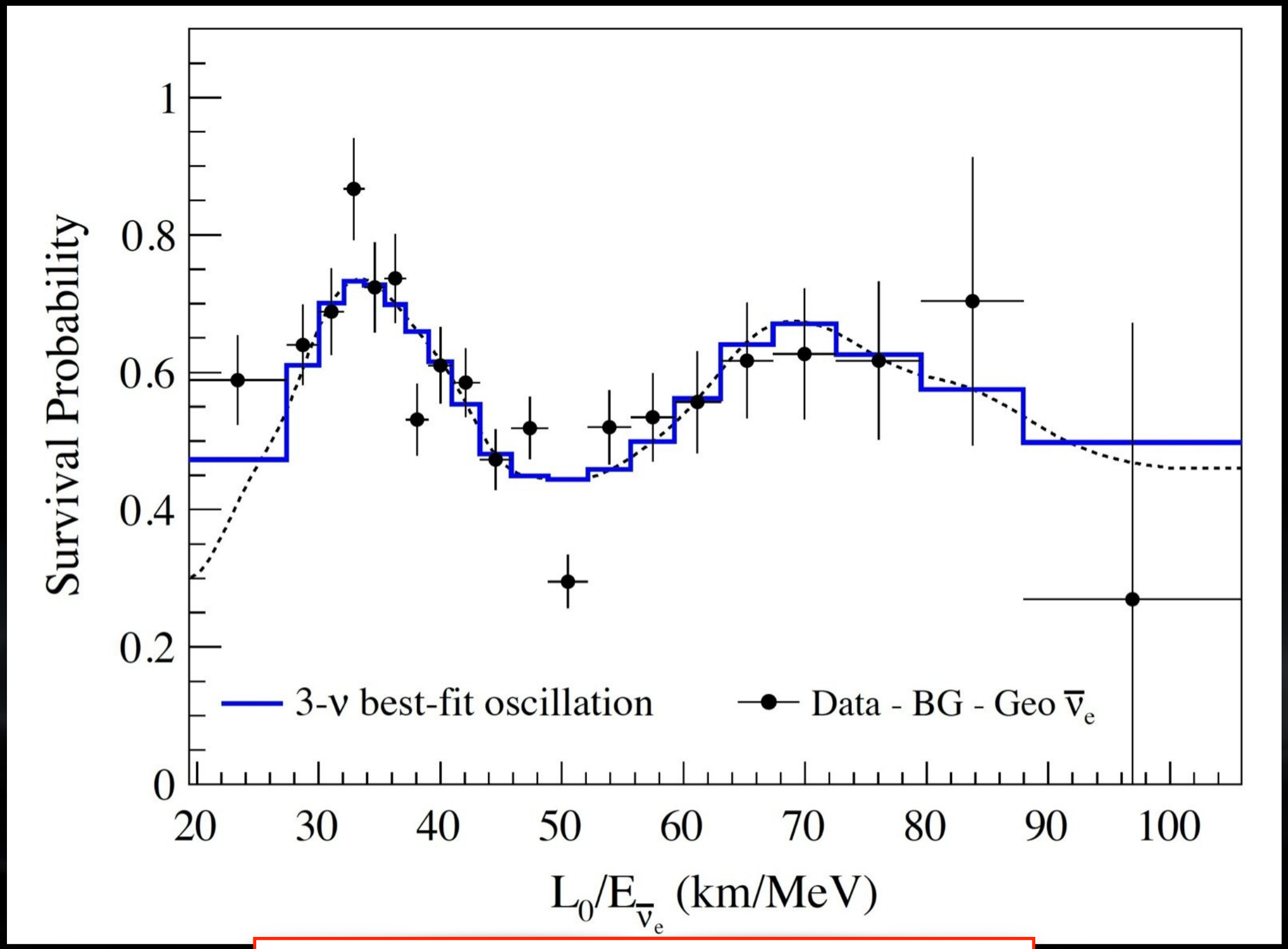
all observations (many!) follow well one model: 3ν oscillation

"mixing": a common phenomenon…

$$\nu_\alpha = 0.5 \bullet \nu_1 + 0.5 \bullet \nu_2$$

the latest KamLAND's $P(\nu_e \rightarrow \nu_e)$…

the most beautiful E/L disappearance so far… (to me)



arguably a Noble prize worth E/L…

"atmospheric" $\Longrightarrow$ $\theta_{23}\sim45^\circ$

θ_{13} & "dirac" δ_{CP}

"solar" $\Longrightarrow$ $\theta_{12}\sim33^\circ$

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

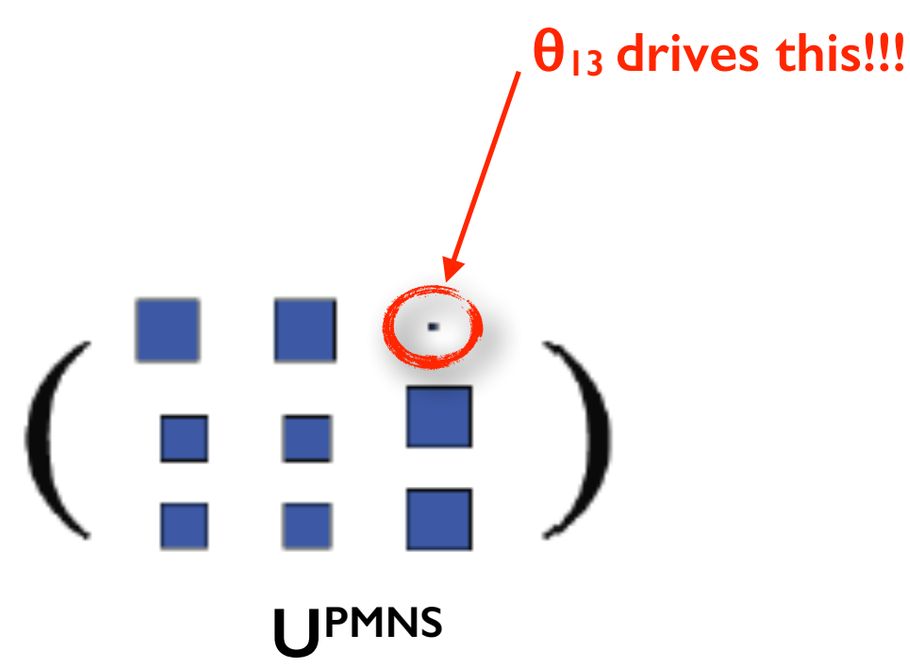
Δm^2_{31} — atmos+LBL(dis) — $P(\nu_\mu\rightarrow\nu_\mu)$

Δm^2_{31} — Chooz+LBL(app) — $P(\nu_e\rightarrow\nu_e)$ & $P(\nu_\mu\rightarrow\nu_e)$

Δm^2_{21} — solar+KamLAND — $P(\nu_e\rightarrow\nu_x)$

knowledge on
θ_{13} & δ_{CP}
[**this talk**]

$(\nu_e,\nu_\mu,\nu_\tau)^T = U(\nu_1,\nu_2,\nu_3)^T$, where U^{PMNS} looks like



note: θ_{13} dominant term @ position "1-3" of matrix (not mixing of m_1 and m_3 states)

why to measure θ13?...

@PDG

$\sin^2(\theta_{13})$

At present time direct measurements of $\sin^2(\theta_{13})$ are derived from the reactor $\overline{\nu}_e$ disappearance at distances corresponding to the Δm^2_{32} value, i.e. L $\sim$ 1km. Alternatively, limits can also be obtained from the analysis of the solar neutrino data and accelerator-based $\nu_\mu \rightarrow \nu_e$ experiments.

VALUE (units 10^{-2})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
2.19± 0.12 OUR AVERAGE					
2.15± 0.13		[1] AN	15	DAYA	DayaBay, Ling Ao/Ao II reactors
$2.3 \pm^{0.9}_{0.8}$		[2] ABE	14H	DCHZ	Chooz reactors
2.12± 0.47		[3] AN	14B	DAYA	DayaBay, Ling Ao/Ao II reactors
2.5 ± 0.9 ±0.9		[4] ABE	13C	DCHZ	Chooz reactors
2.9 ± 0.3 ±0.5		[5] AHN	12	RENO	Yonggwang reactors
• • • We do not use the following data for averages, fits, limits, etc. • • •					

Citation: K.A. Olive *et al.* (Particle Data Group), Chin. Phys. C, **38**, 090001 (2014) and 2015 update

(the boring but still real argument)

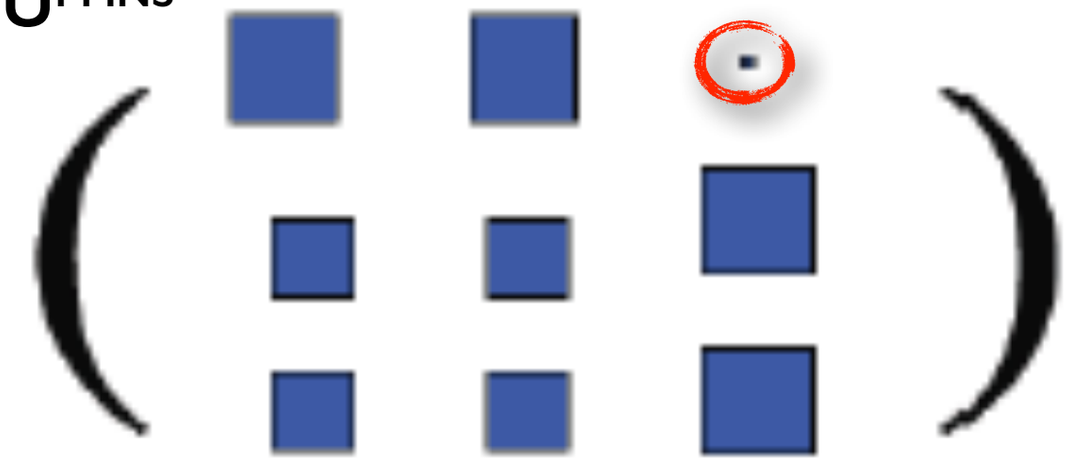
as all parameters in SM are to be measured and plug-in (i.e. no prediction from SM)

(but models beyond-SM might have predictions our SM values)

our knowledge on θ_{13} dominated by DYB

also linked to bigger questions…

U^{PMNS}



U^{CKM}

⇒ ~maximal mixing ⇒ ~minimal mixing

why are CKM and PMNS so?

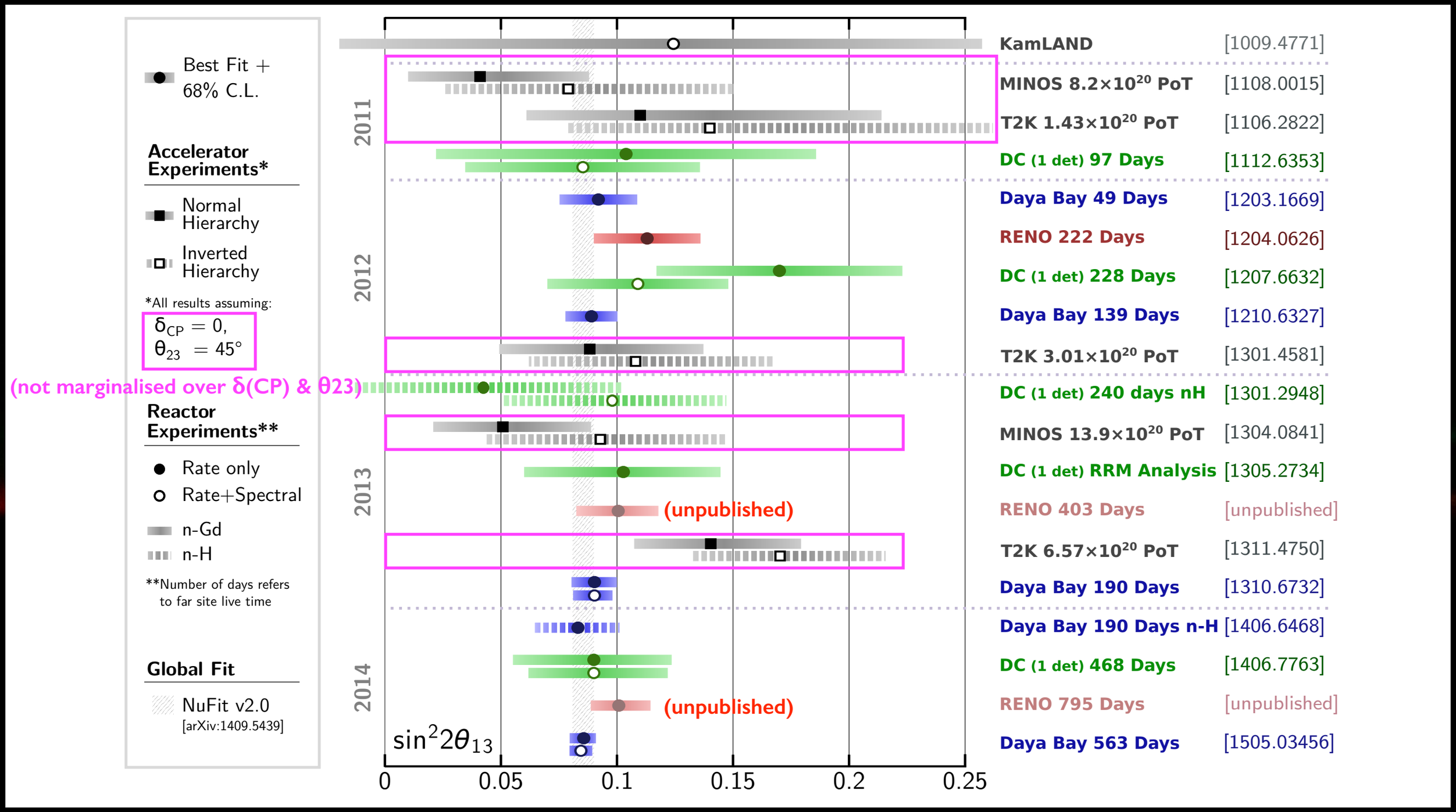
if 3 families ⇒ **unitary** (really?)

CKM unitarity being tested to high precision
PMNS very early stages

if not unitary ⇒ indirect evidence of >3 families?

the world's θ_{13} knowledge…

θ_{13}-reactor measurements (summer 2015)…



unsurpassable reactor precision→ "reactor-θ_{13}" for several decades to go!

(measurement by T2K+MINOS+NOvA, KamLAND⊕Solar, etc)

T2K⊕MINOS⊕NOνA vs reactors: a CPV hint…?

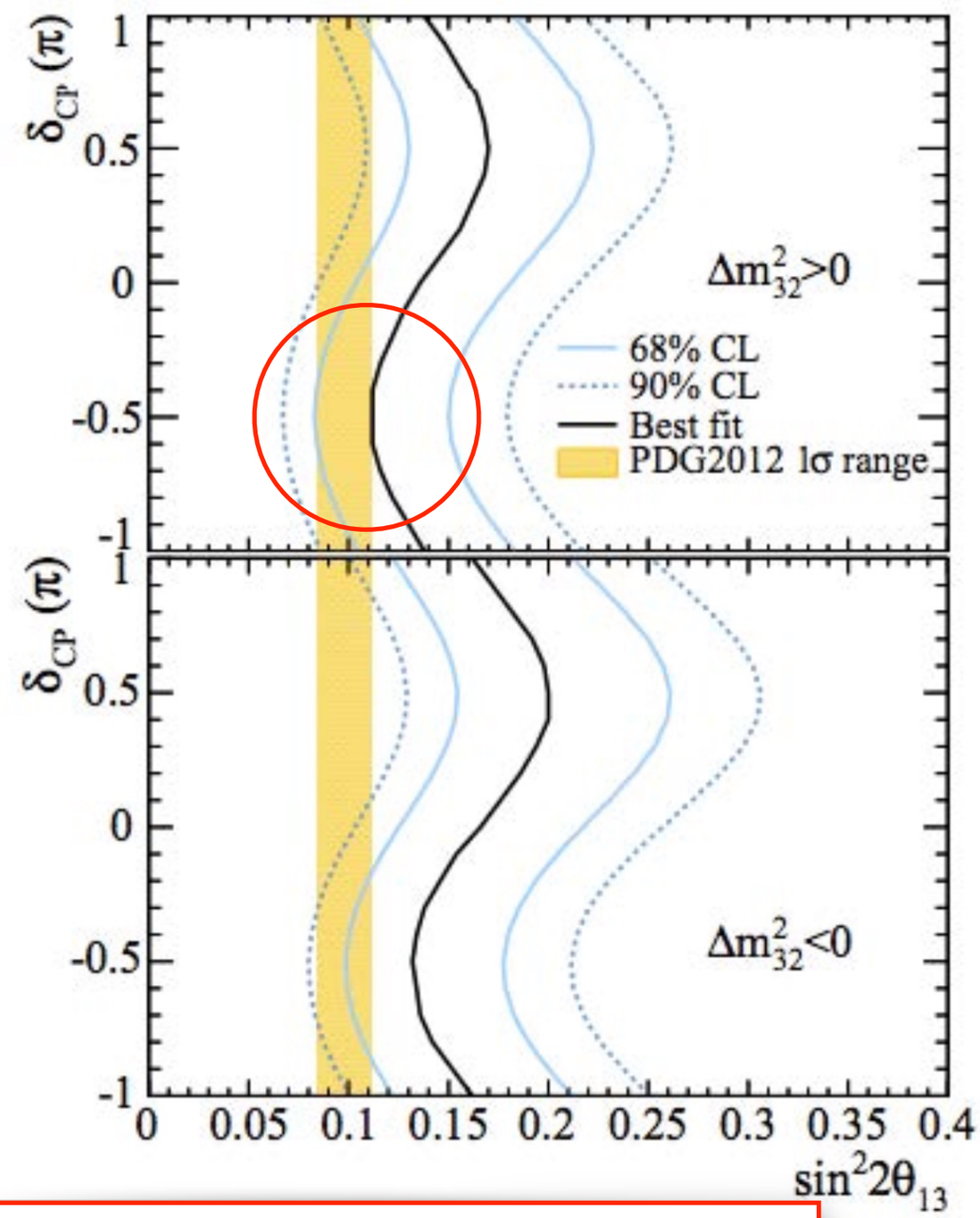
Comparing T2K results with reactors

T2K $\sin^2 2\theta_{13}$ result computed assuming $\sin^2\theta_{23}=0.5$, $\delta_{CP}=0$, and normal hierarchy (top), and inverted hierarchy (bottom)

Consistent at 90% CL (1.6σ)

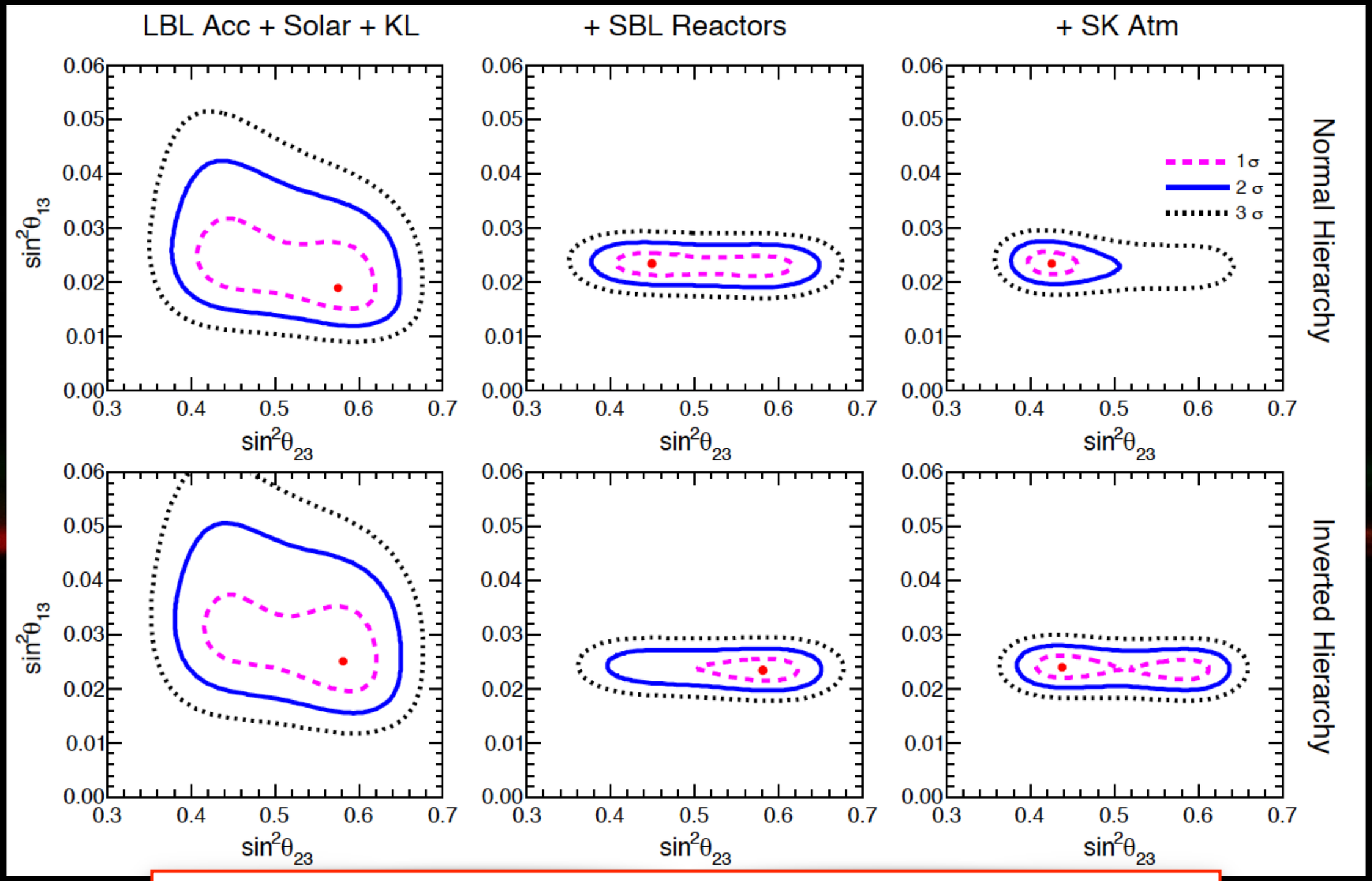
…but excess by T2K nudges all remaining unknowns in direction to increase rates

- normal hierarchy
- $\theta_{23}>45°$
- $\delta_{CP}=-\pi/2$ (aka $3\pi/2$)



interplay between reactors & beams → critical phenomenology

(Lisi et al Jan. 2014) impact to the θ_{23} octant…



reactors (again): may help to resolve θ_{23}-octant ambiguity?

reactor data (only θ_{13}) orthogonality aids beam data⇒ a deeper sight together

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)

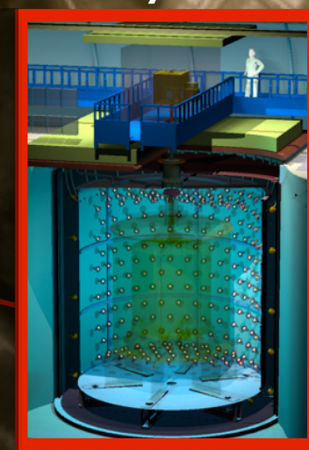
Project Manager:
Ch. Veyssière (CEA-Saclay)

Web Site:
www.doublechooz.org/

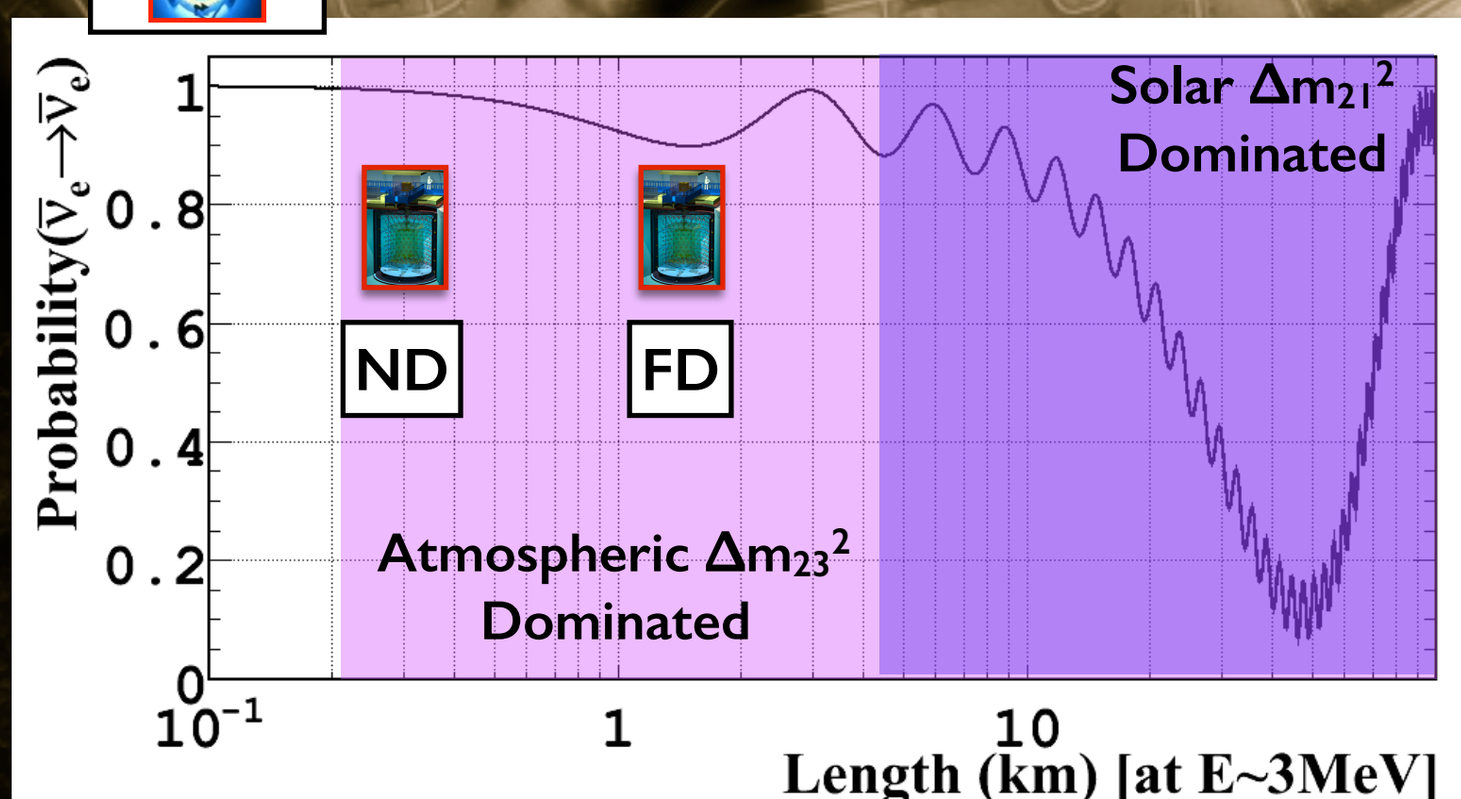
DC @ LNCA laboratory…

Chooz Reactors
Power: 8.5GWth
$\Longrightarrow$ ~$10^{21}\nu$/s
(N4s: very powerful)

Near
<L>≈410m
~250 IBD/day
~120 mwe
Target: 8.2t
Dec.2014



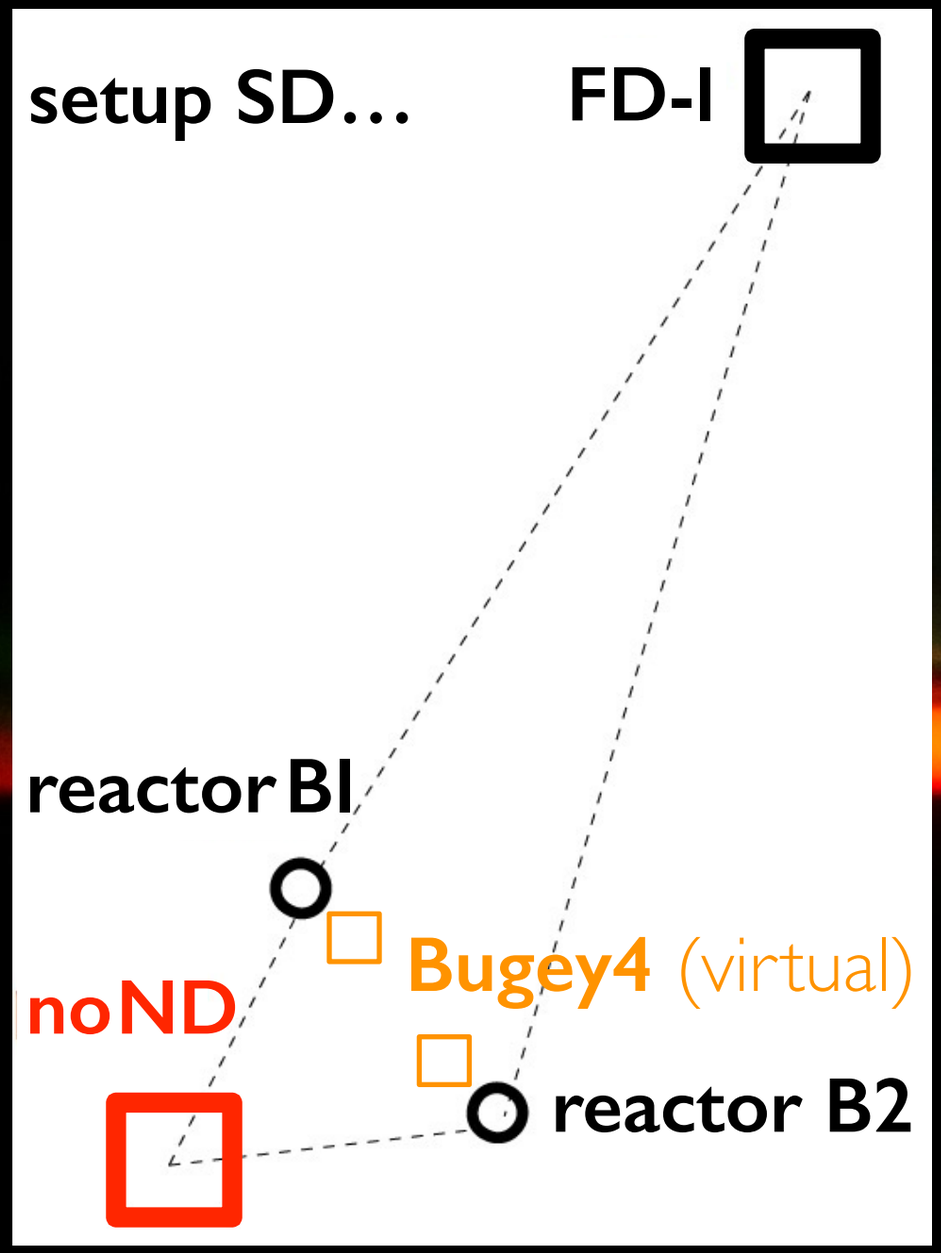
reactor



Far
<L>≈1050m
~40 IBD/day
~300 mwe
Target: 8.2t
April 2011

our experiment @ DC-IV: 2 setup…

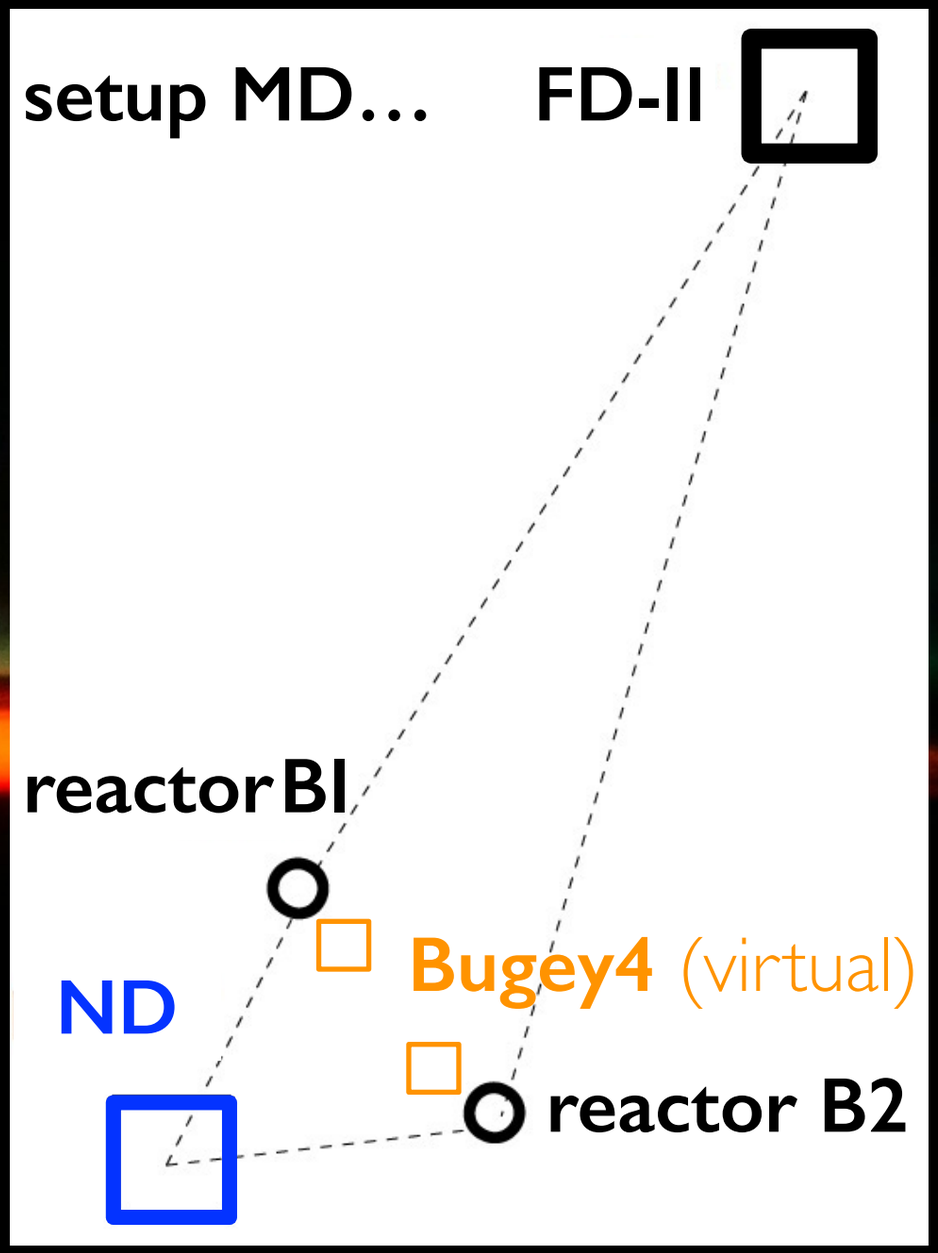
(exposure used: ~48months)



- IBD's @ FD→ θ13 info [no ND monitor but B4]
- Li+He BG + Reactor-OFF→ δ(BG) systematics
- cross-check on BG, detection, etc (common FD)

@Gd-III: $1\sigma[\sin^2(2\theta_{13})] \approx 0.03$

(exposure used: ~9months @ Moriond)



- IBD's @ FD→ θ13 info [ND monitor]
- Li+He BG 2 detectors→ δ(BG) systematics
- lowest δ(flux) using ND monitor
- cross-check on BG, detection, etc (FD vs ND)

reactor θ13 multi-detector rationale…

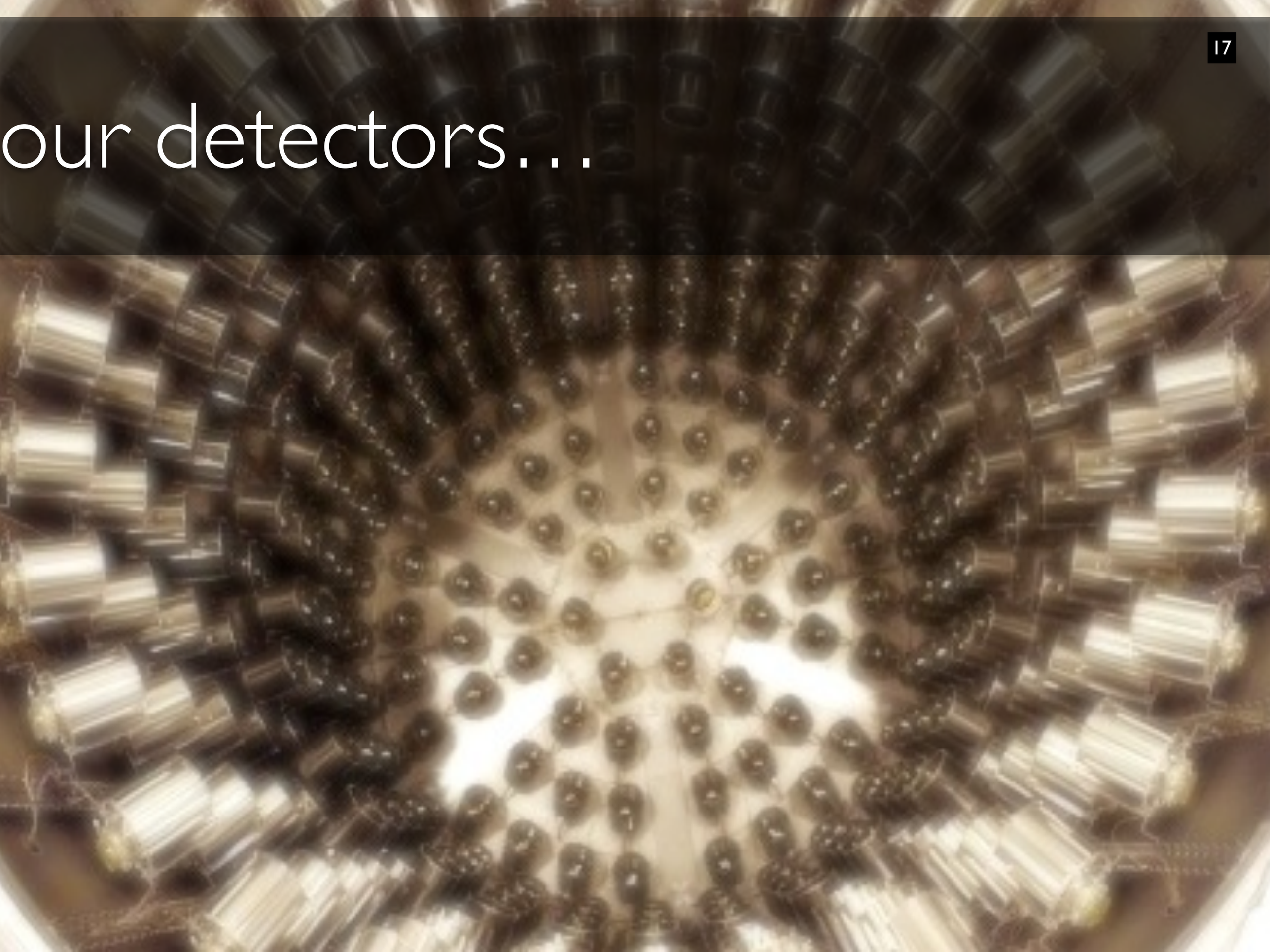
systematics	single detector (SD) (%)		multi-detector (MD) (%)
δ(detection)	**~2.0** (no fiducial volume)	→	**~0.2** (**identical detectors**)
δ(flux)	**~3.0** (prediction) [**~1.7** via **Bugey4**]	→	**≤0.5** (**ND reactor monitor**)
δ(background)	**≤1.0** (radio-purity+overburden)	↛	**≤1.0** (**no suppression**)

— systematics uncertainties ~1‰ each —

only one experiment providing θ_{13} with a few ‰ errors?

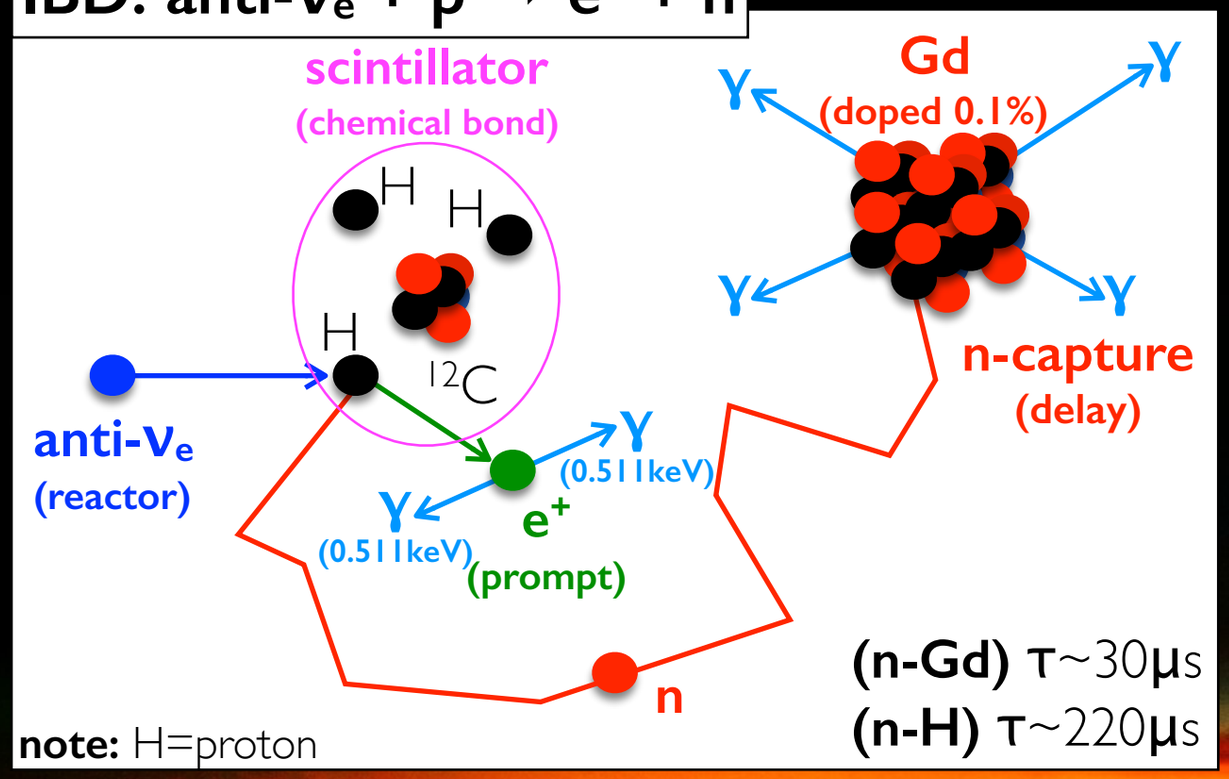
(remember: LEP, etc)

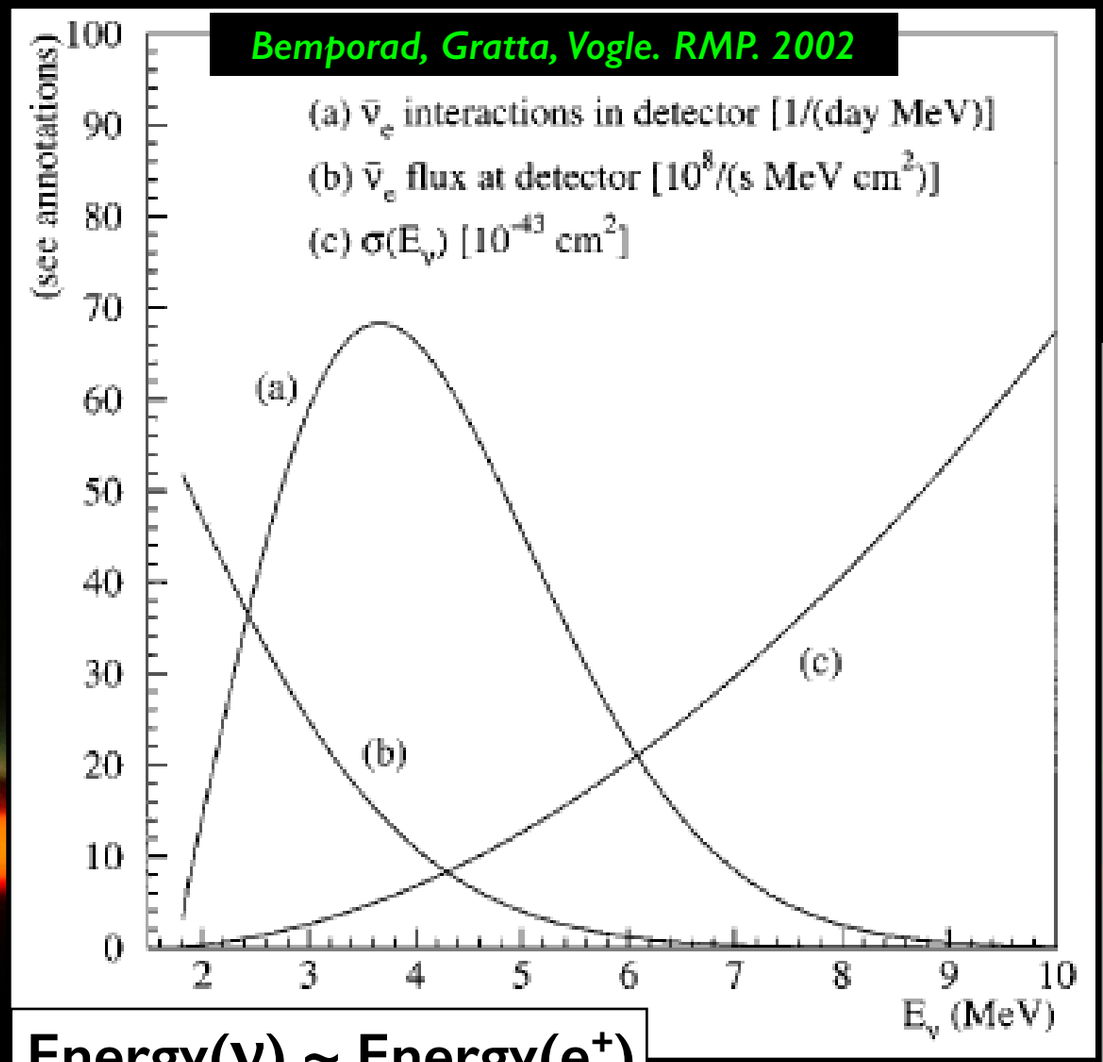
our detectors…



inverse-β decay (IBD) interaction…

IBD: anti-ν_e + p → e^+ + n





Energy(ν) ~ Energy(e^+)

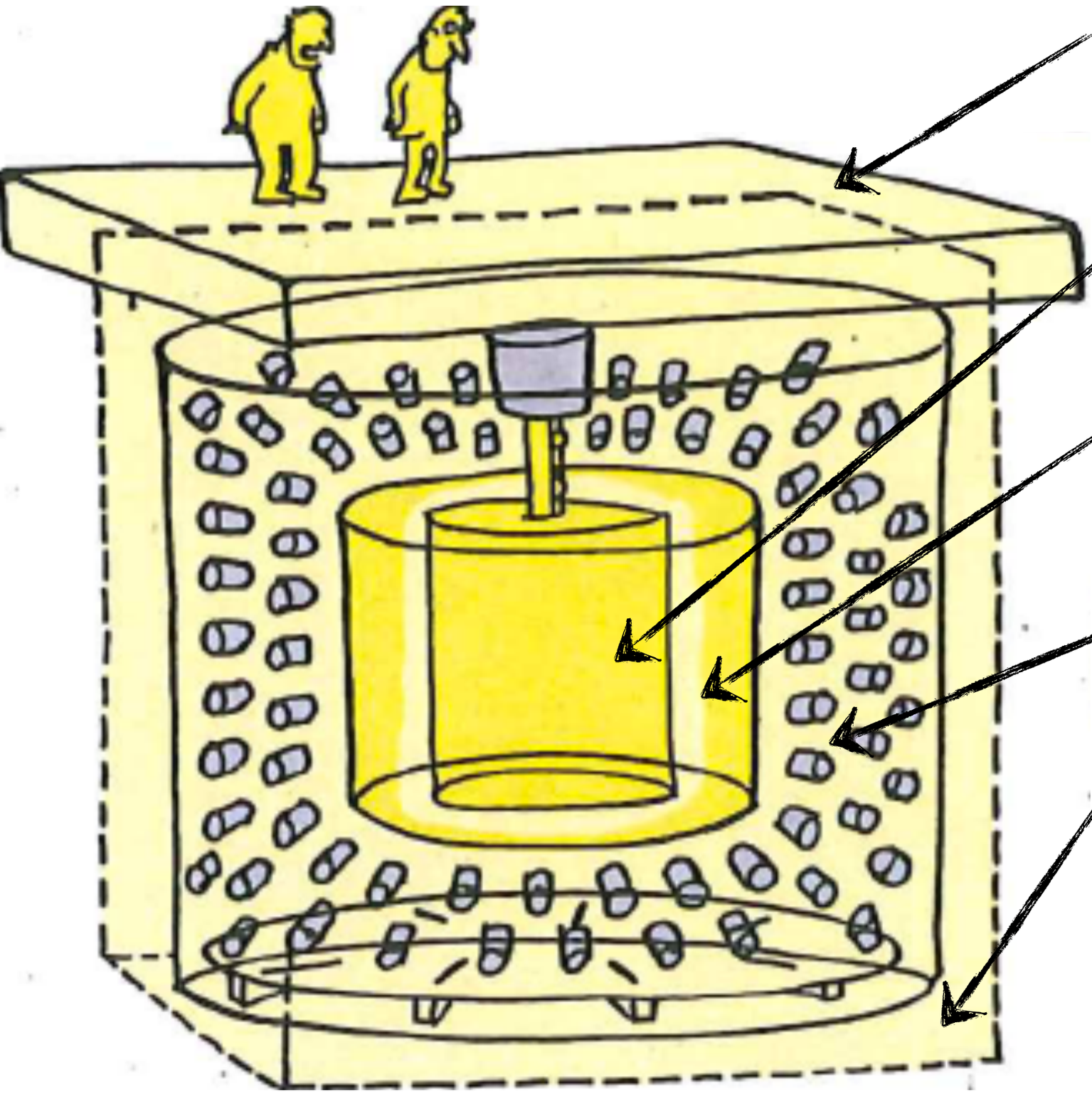
- **high & well known σ^{IBD}** [$\tau_{neutron}$=(881.5±1.5)s]
- IBD manifests via **trigger-coincidence**
  - 1st trigger→ **e+(prompt)** [ionisation ⊕ annihilation]
  - 2nd trigger→**n-Gd capture (delay @ ~8MeV)**
- **Energy(ν) ~ Energy(e+) + 0.8MeV**
- major rejection of radioactivity background…
  - time/space coincidence
  - delay @ 8MeV (radioactivity dominates ≤3MeV)

why IBD ⊕ Gd?

- small & shallow (high S/BG)
- no need for ultra-purity

⟹ **inexpensive ‰ precision!!**

a generic θ_{13}-LAND…



Outer μ-Veto (OV)

Plastic-Scintillator: strips (→tracking)

ν-Target (NT)

Liquid-Scintillator + Gd (0.1%)

γ-Catcher (GC)

Liquid-Scintillator

Light Buffer

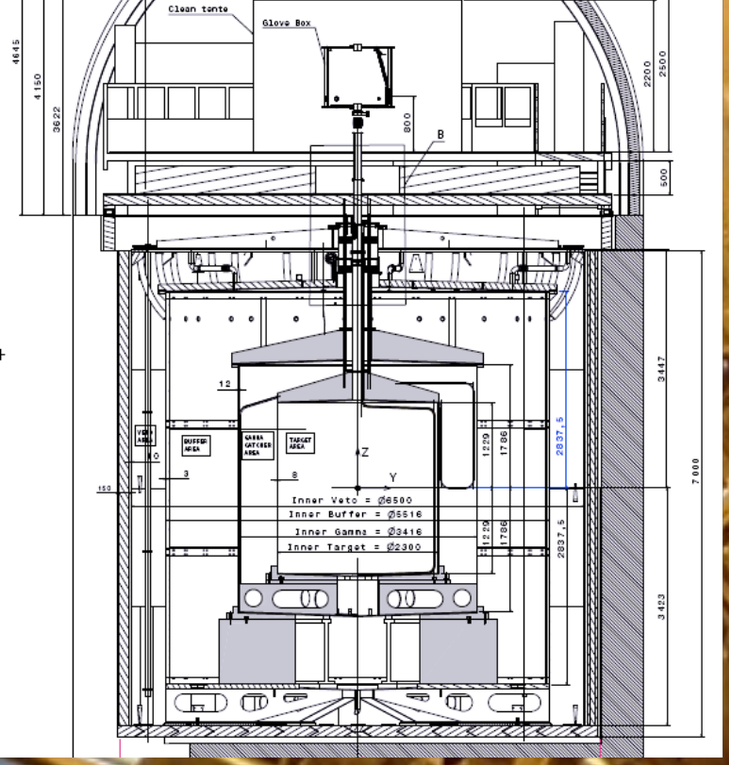
Oil (negligible scintillation)

Inner μ-Veto (IV)

Liquid-Scintillator

Inert γ-Shield

15cm of steel (around all detector)



engineer's view

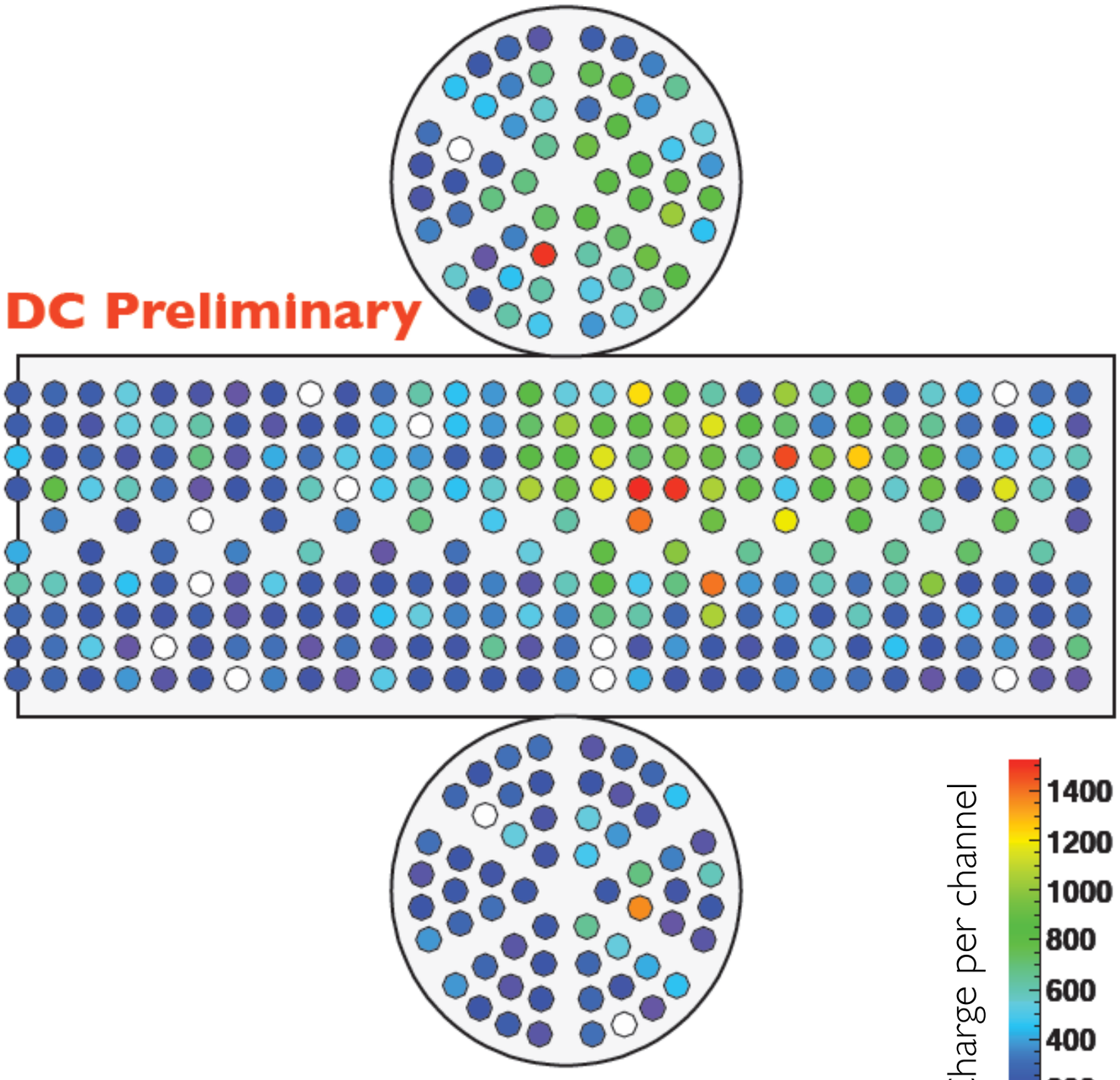
MC's view

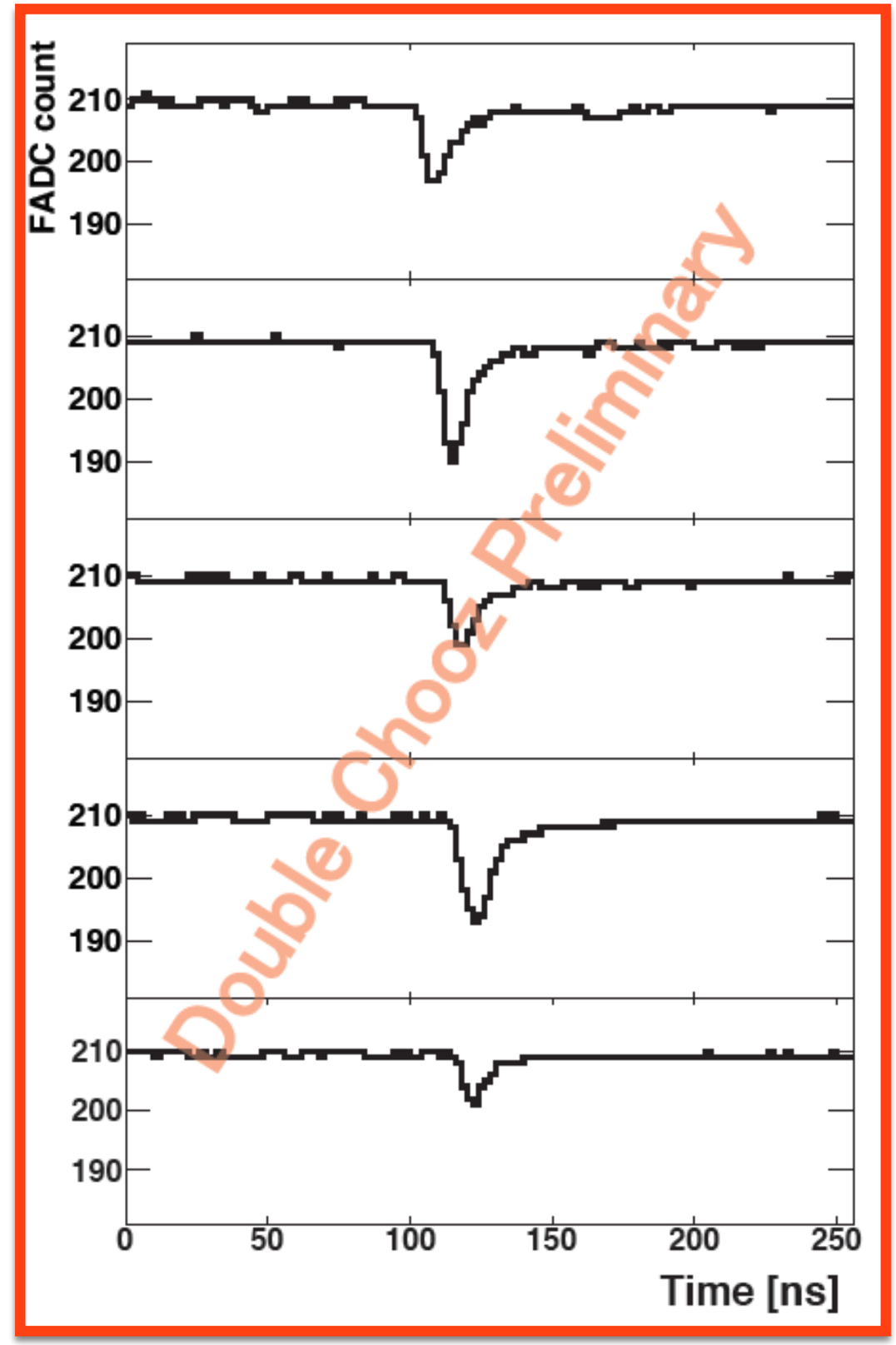
our favourite view…

readout...

a point like event (no IV activity)…

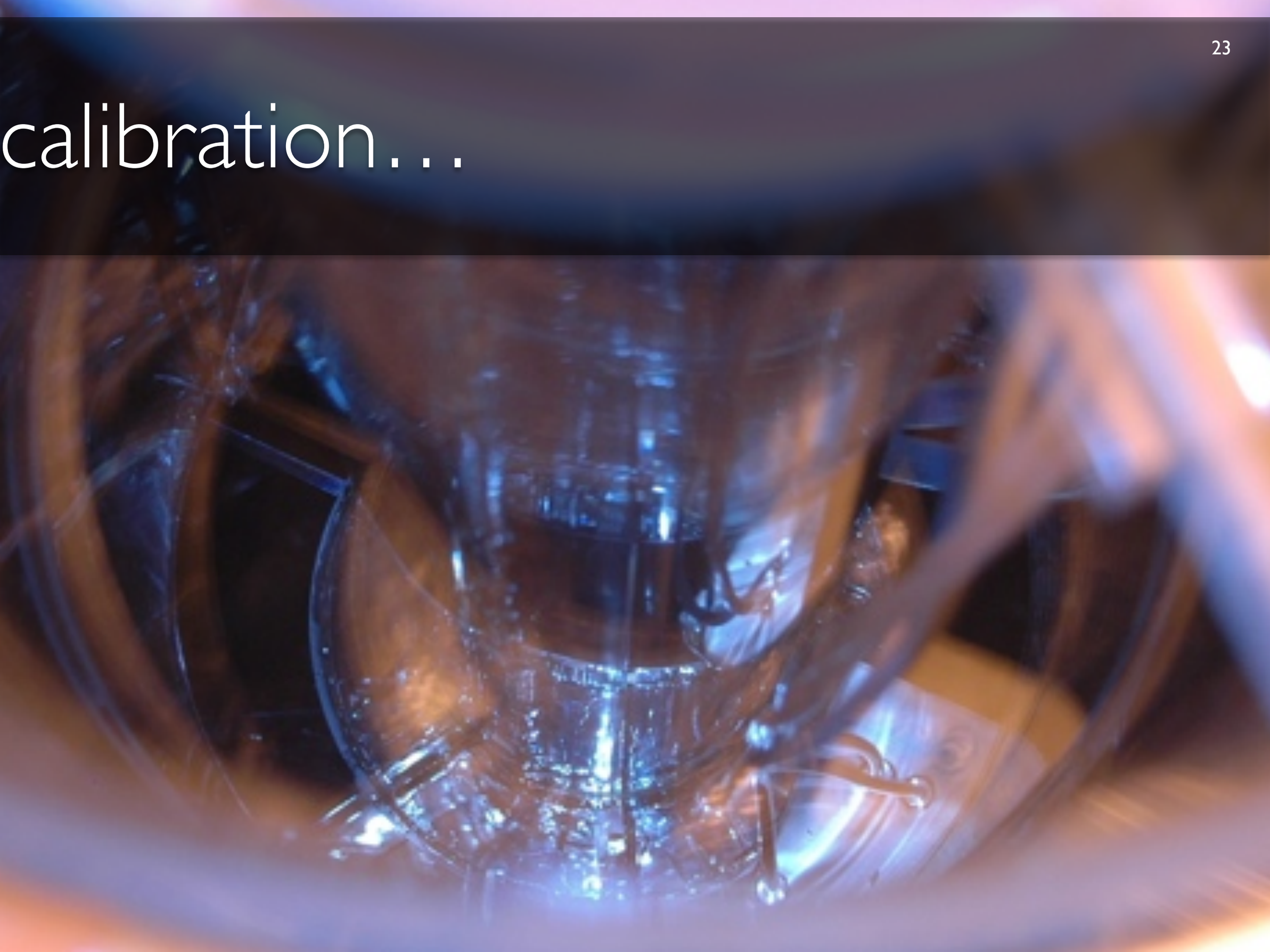
Energy ~8MeV





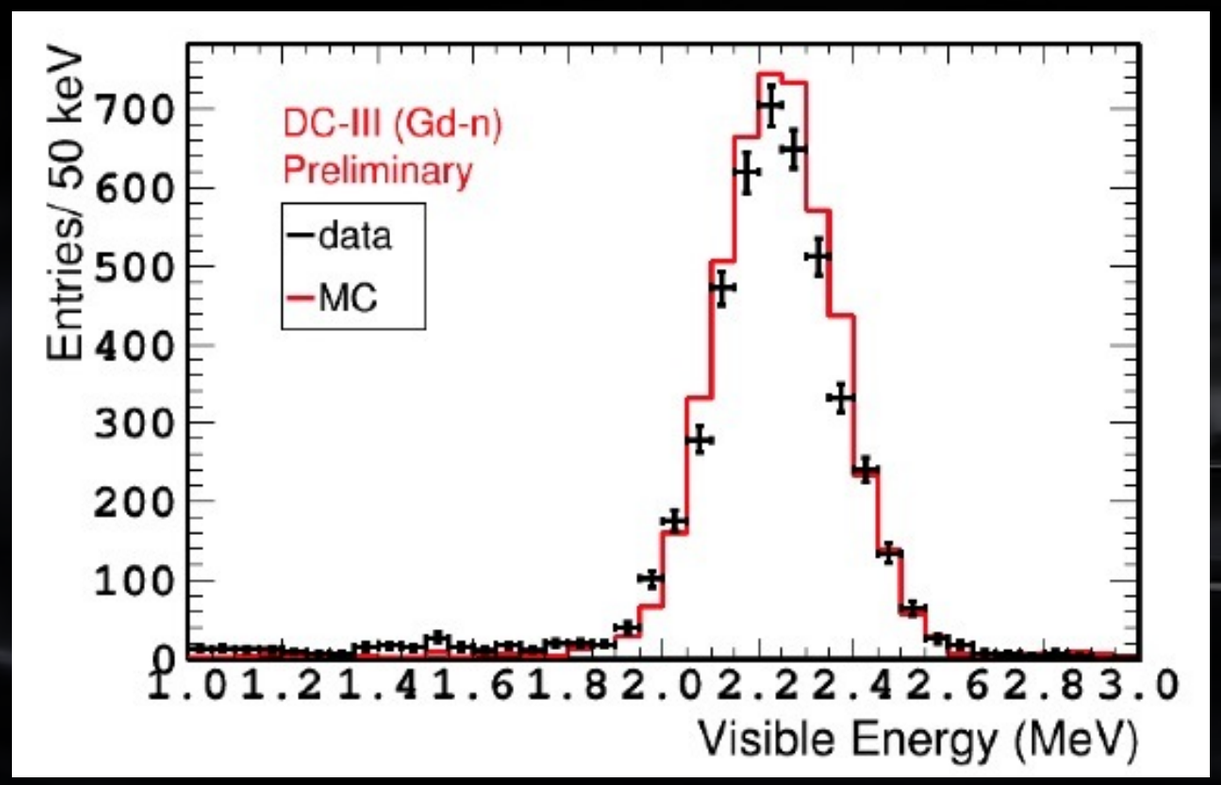
NOTE: all PMTs working (white means: no charge)

calibration…

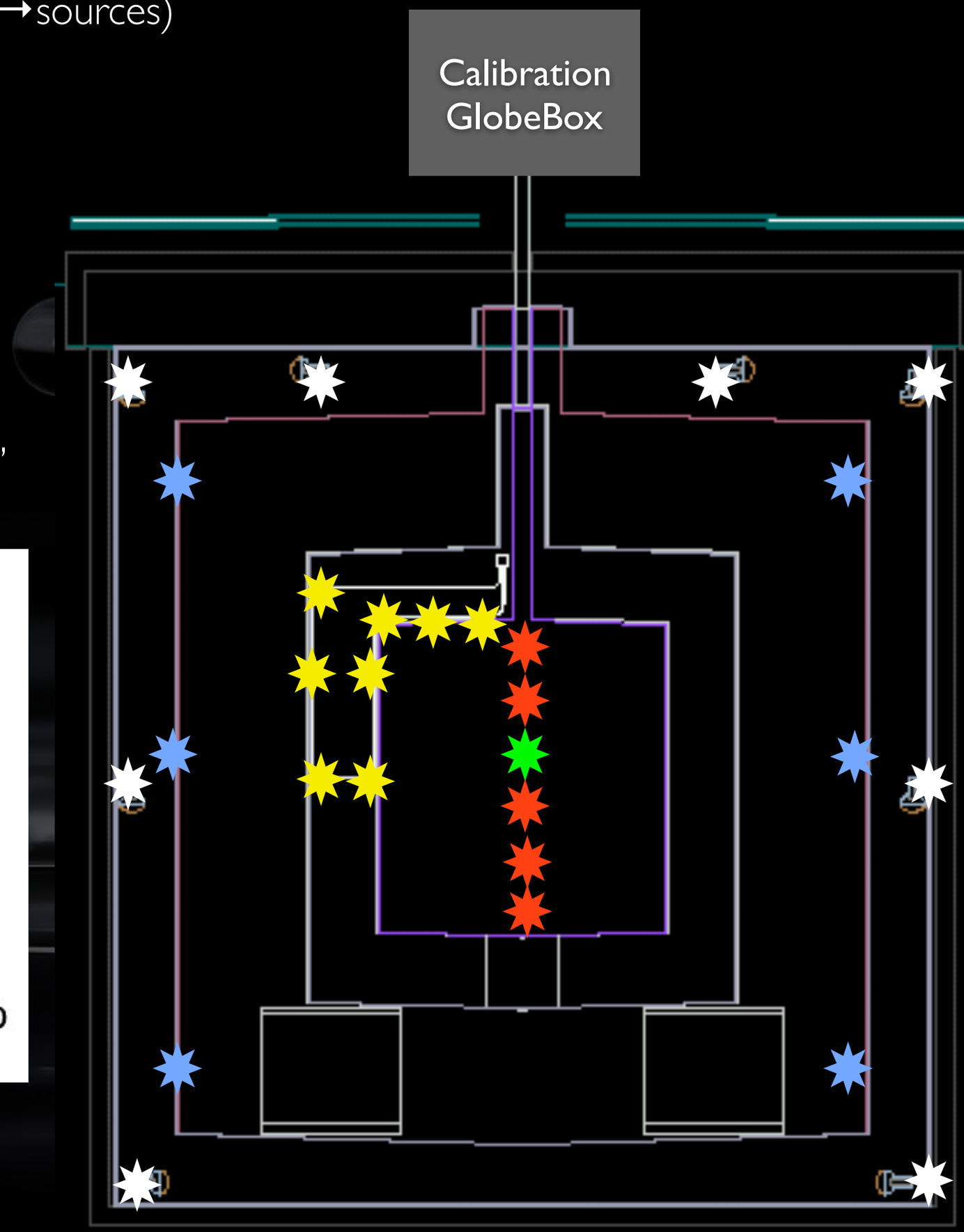


calibration system…

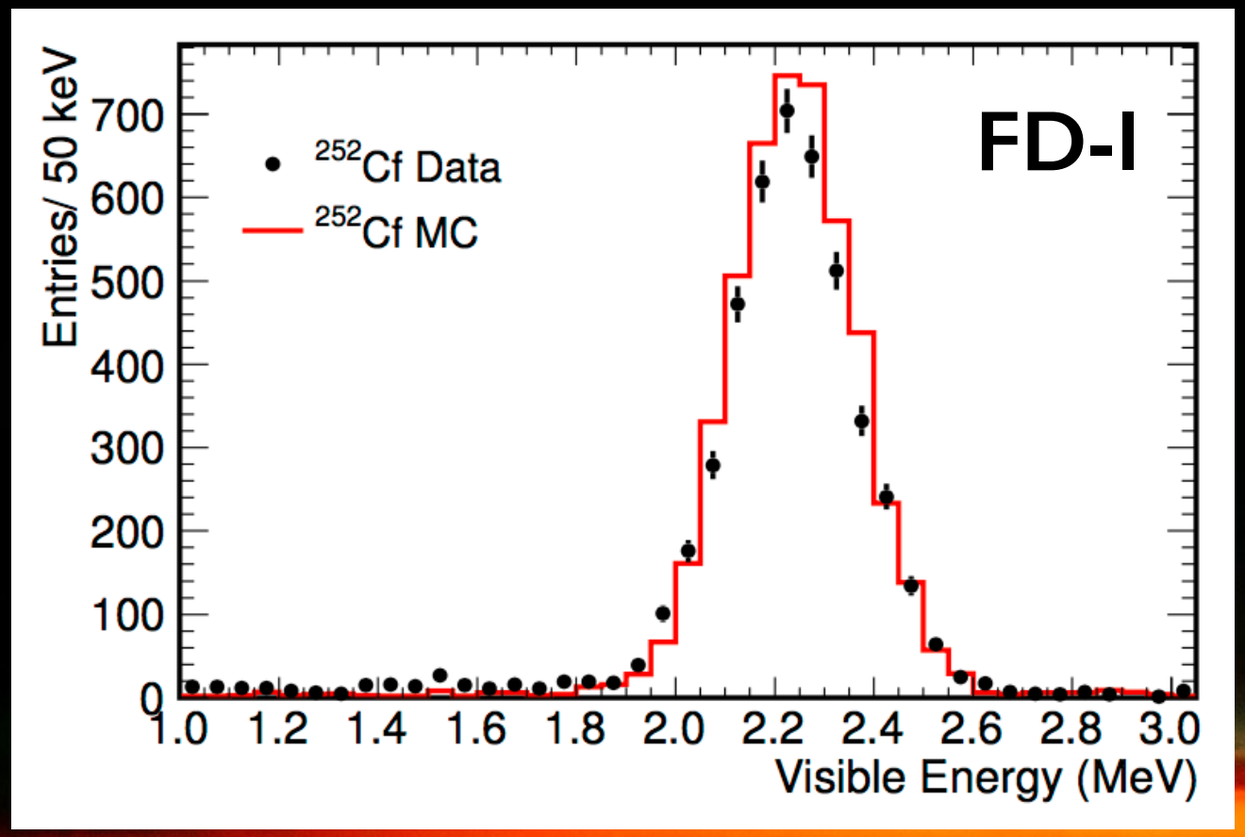
- **principle:** redundancy critical for systematics (→sources)
- **in-built:** light LED (**ID** + **IV**)
- **deployable** (^{137}Cs, ^{68}Ge, ^{60}Co, **^{252}Cf**, lasers)
  - **z-axis** (→ ν-target sampling)
  - **GC guide-tube** (→ GC sampling)
  - (not yet used) **Articulated Arm**
- **natural:** H-n, C-n, Gd-n peaks (μ's fast-n), BiPo, IBD (delay spectrum→validation)

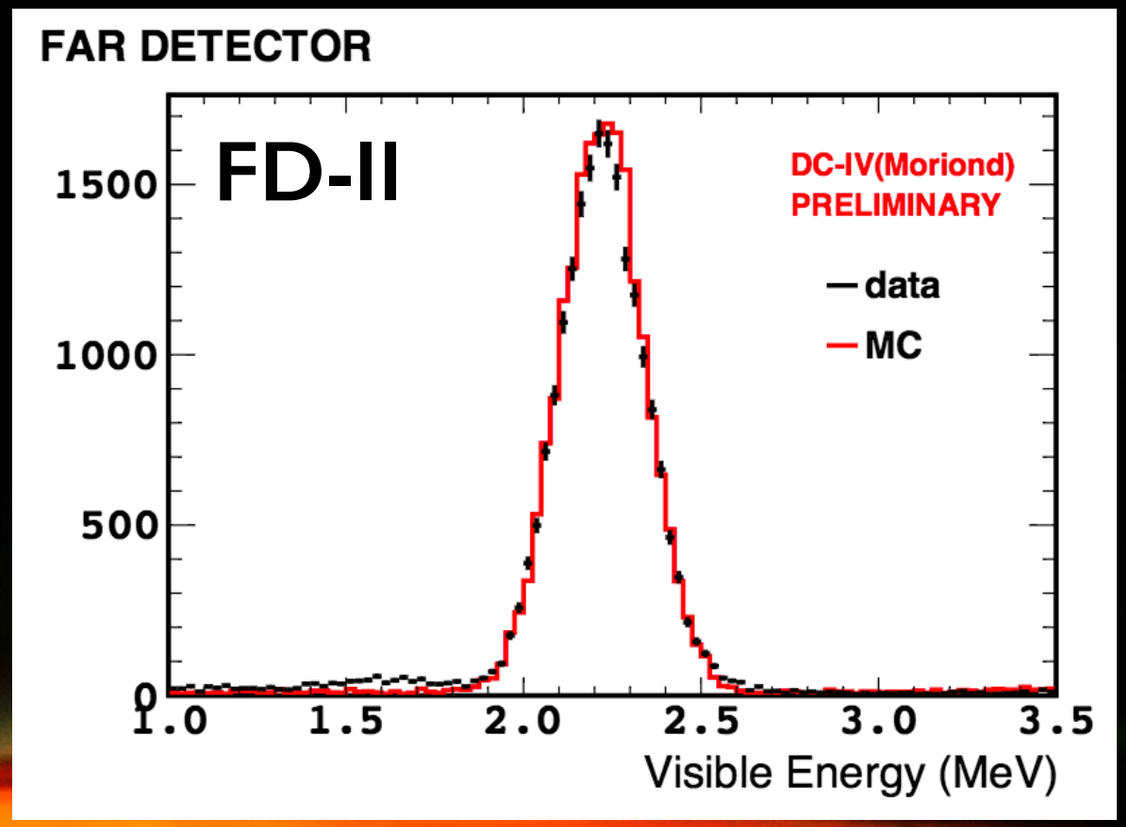


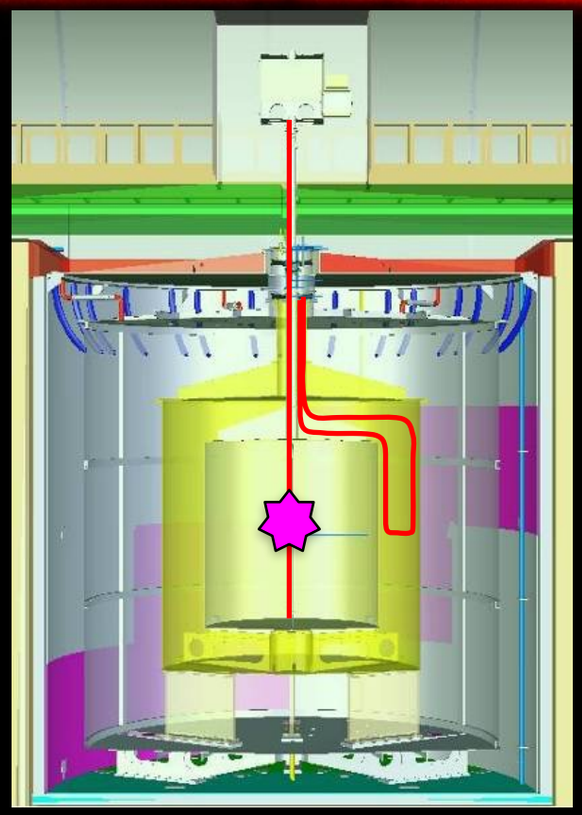
MeV definition (H-n peak @ center)
(our *standard candle*)



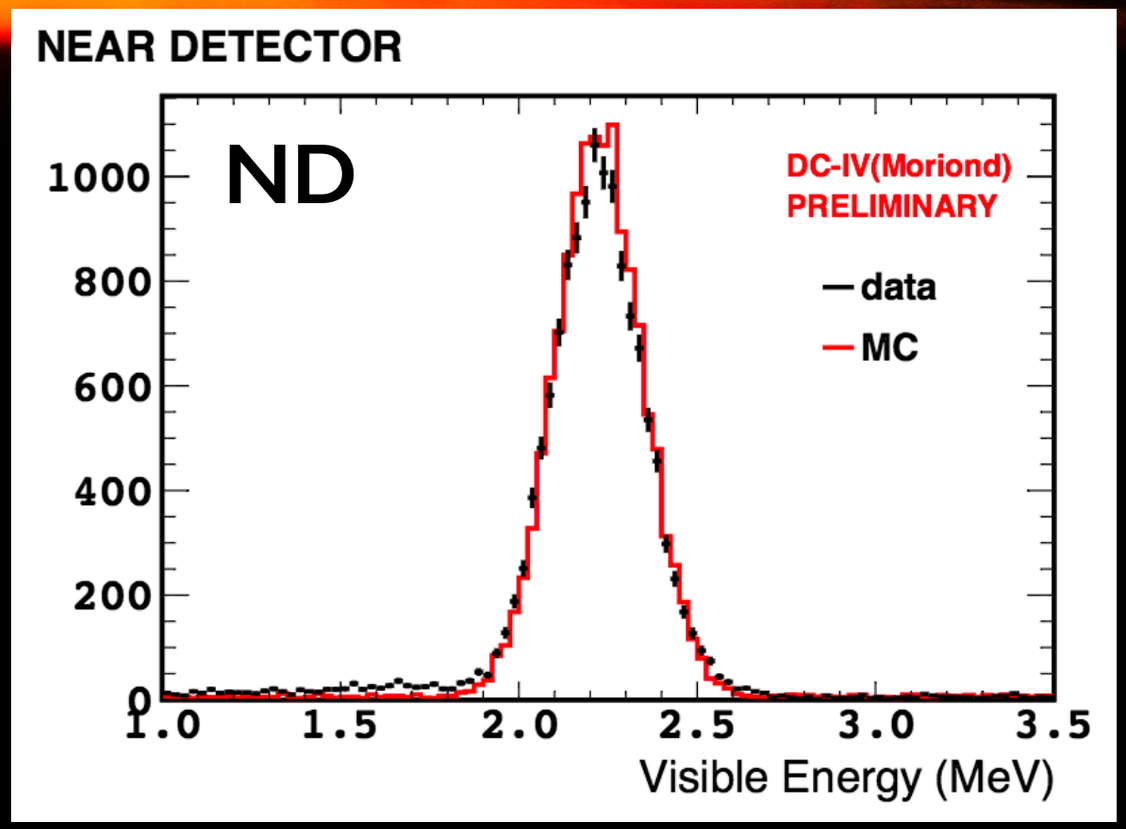
energy reference: 2.2MeV H-n peak





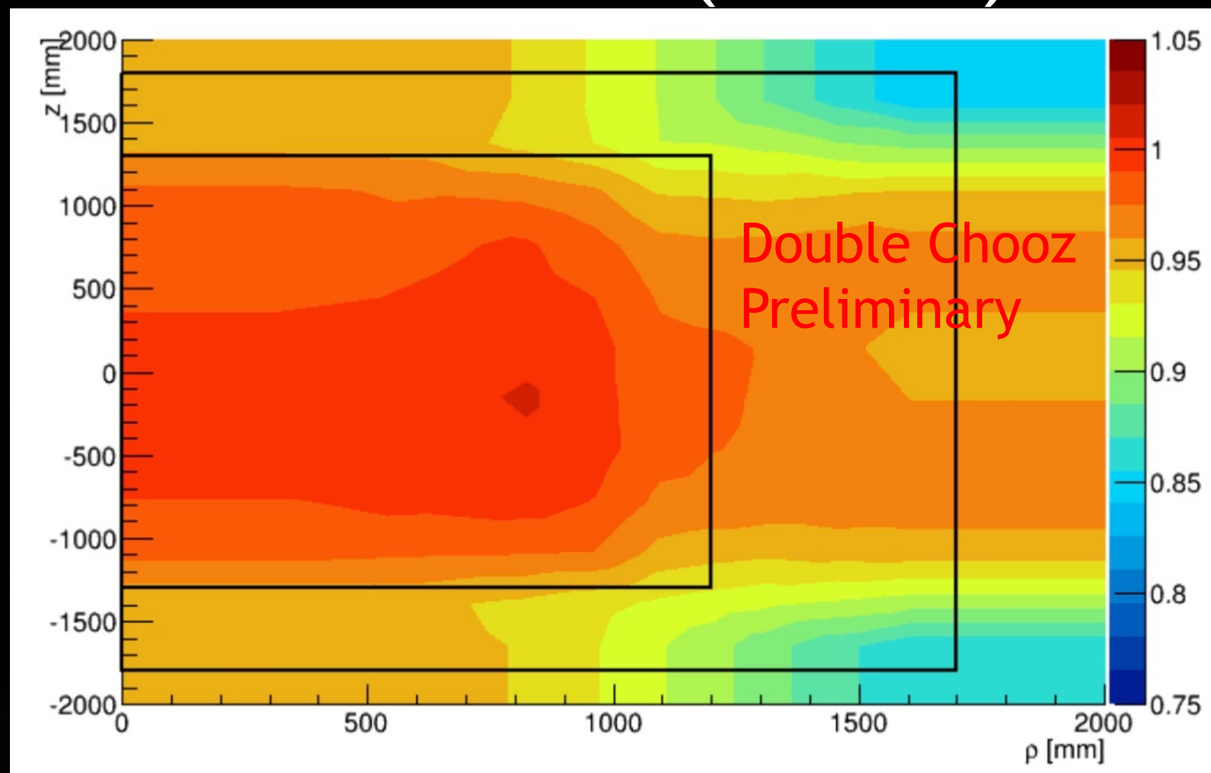


Cf neutron source deployed at center

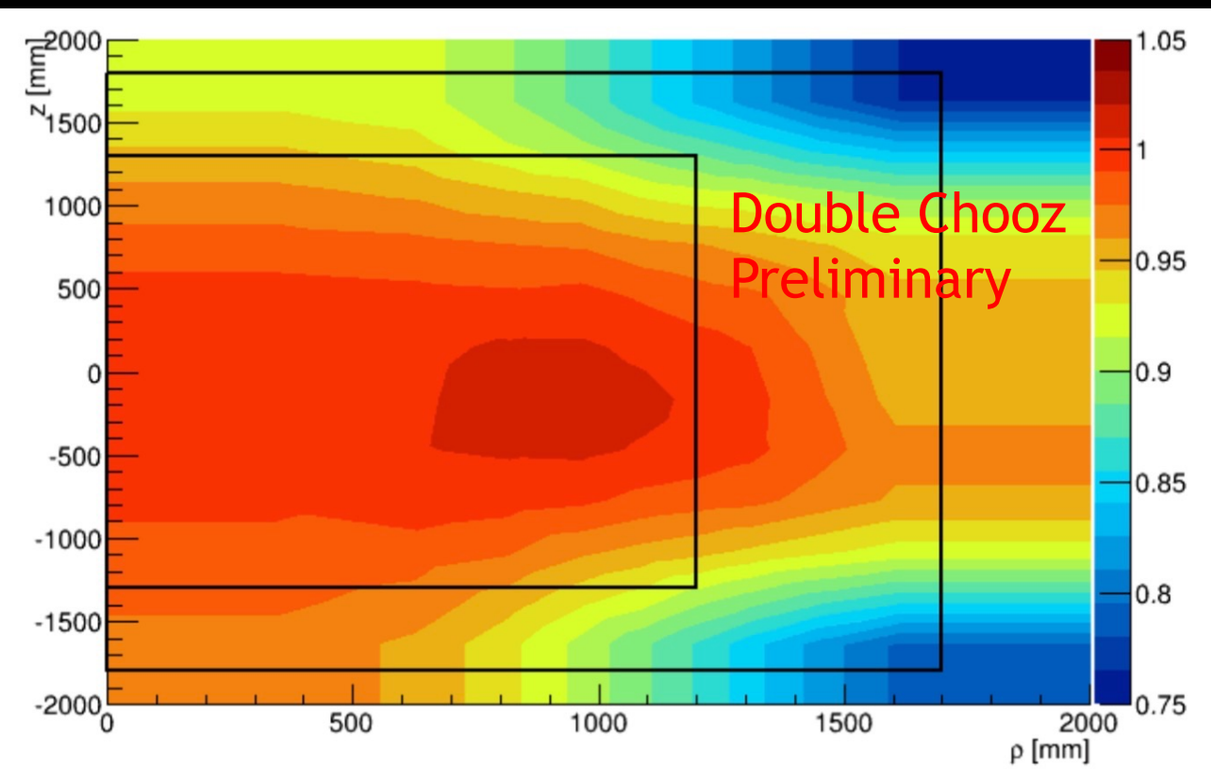


uniformity (2.2MeV H-n peak)

FD-II DATA (9months)

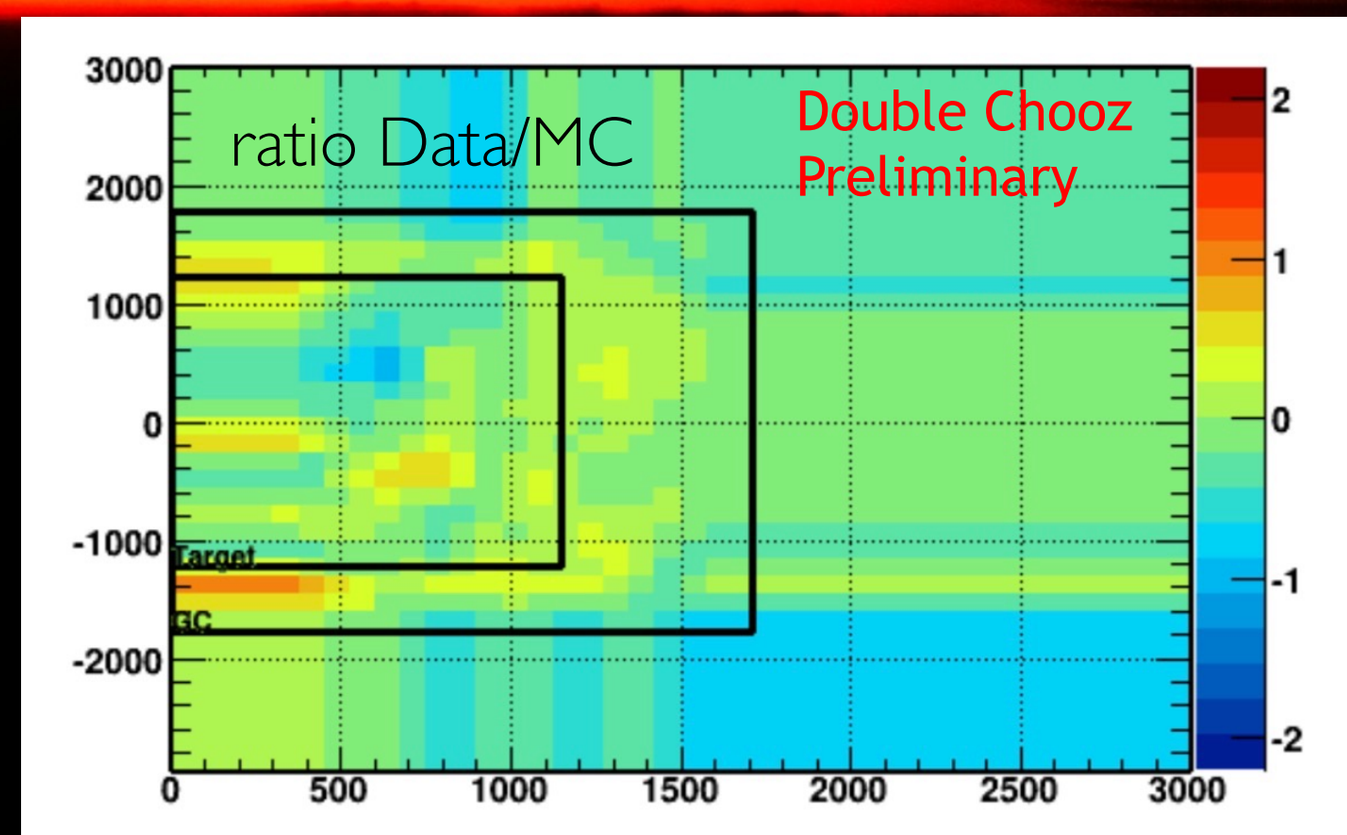


FD-II MC

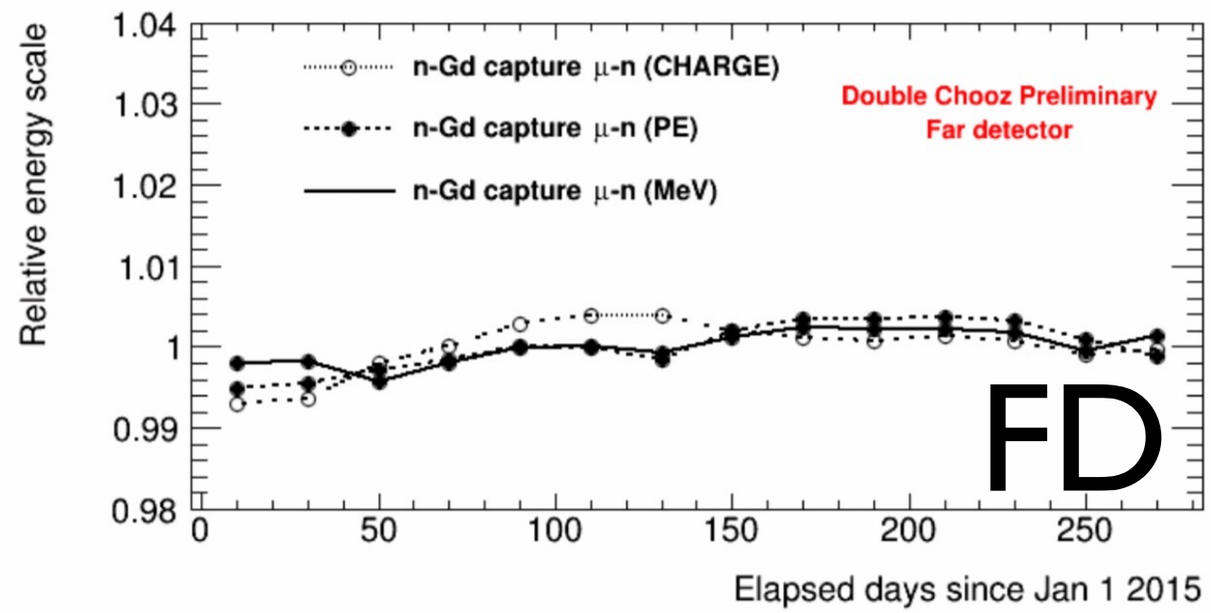


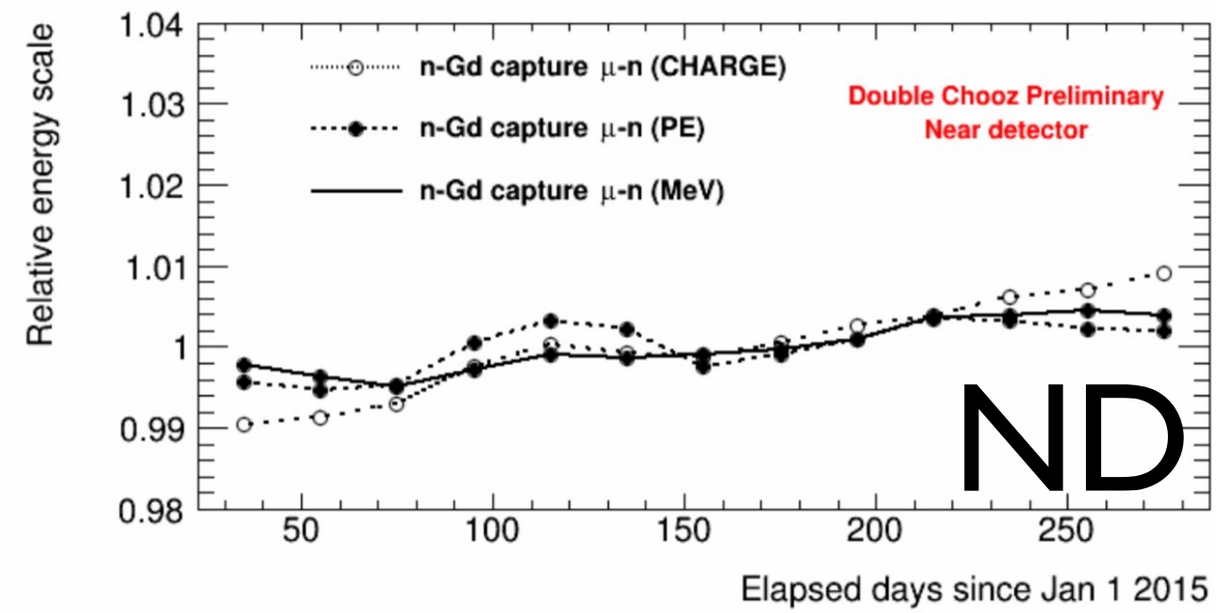
(swamped by **μ**'s and after-**μ** stuff)

- most DC calibration uses cosmogenic signals (i.e. self-calibrated)
- fast-n H-n captures map:
- ratio DATA /MC: **0.25%^{FD}** & **0.39%ND**



detector/response stability…



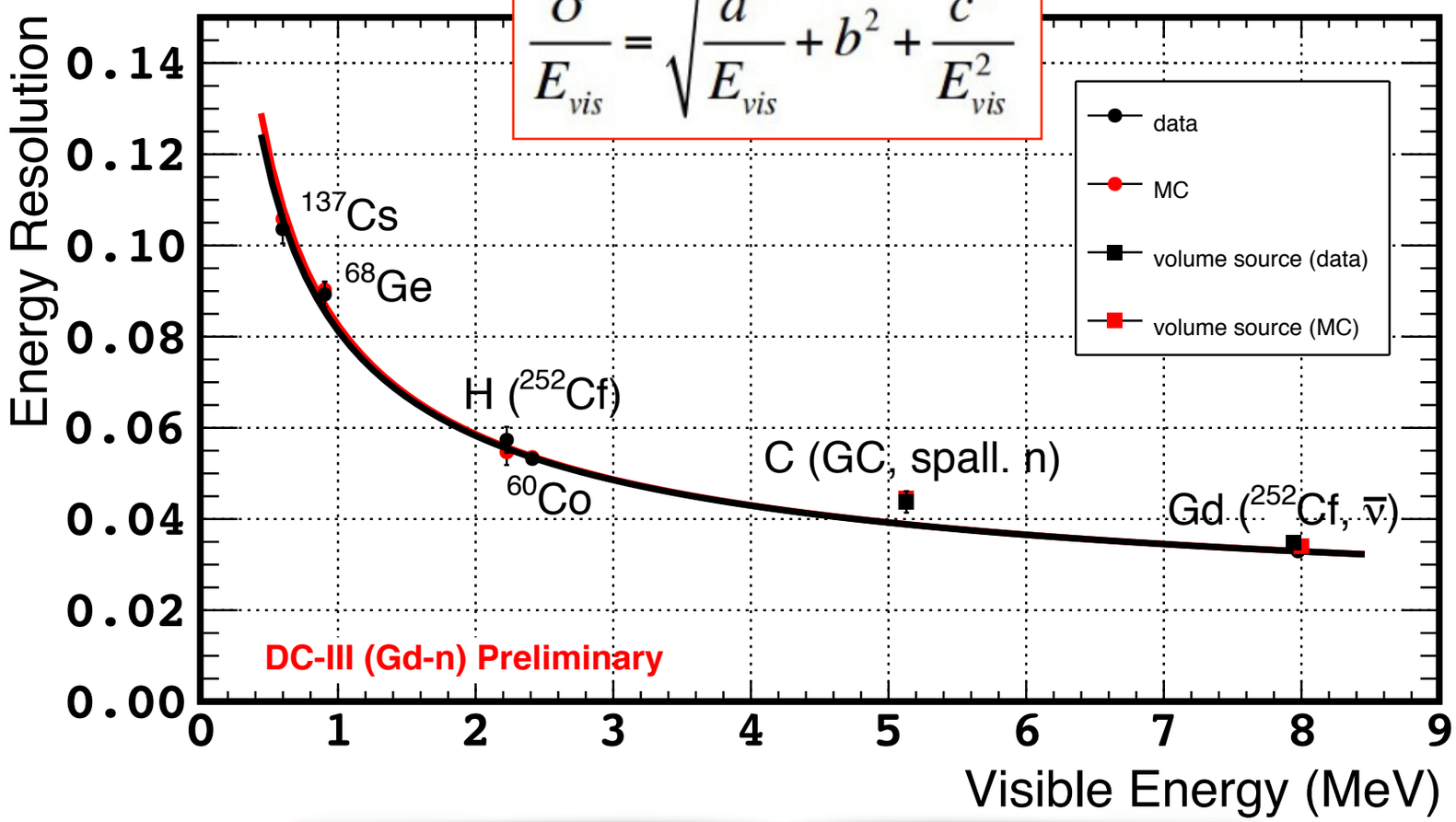


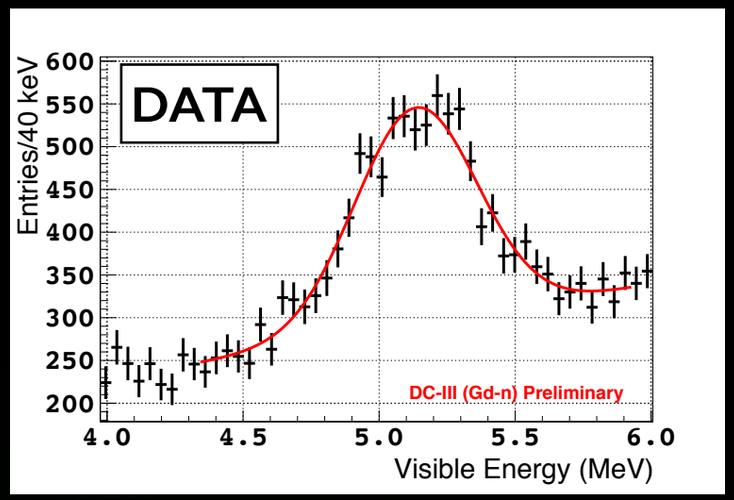
response increases with time (≲1%/year)

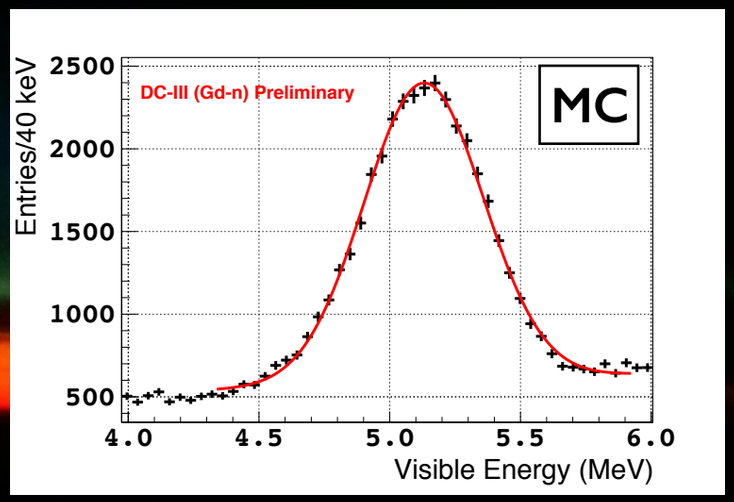
DC: the only loaded-LS detector not deteriorating?

(FRosT-16 workshop @ FNAL)

response demonstration…







excellent MC precision & accuracy

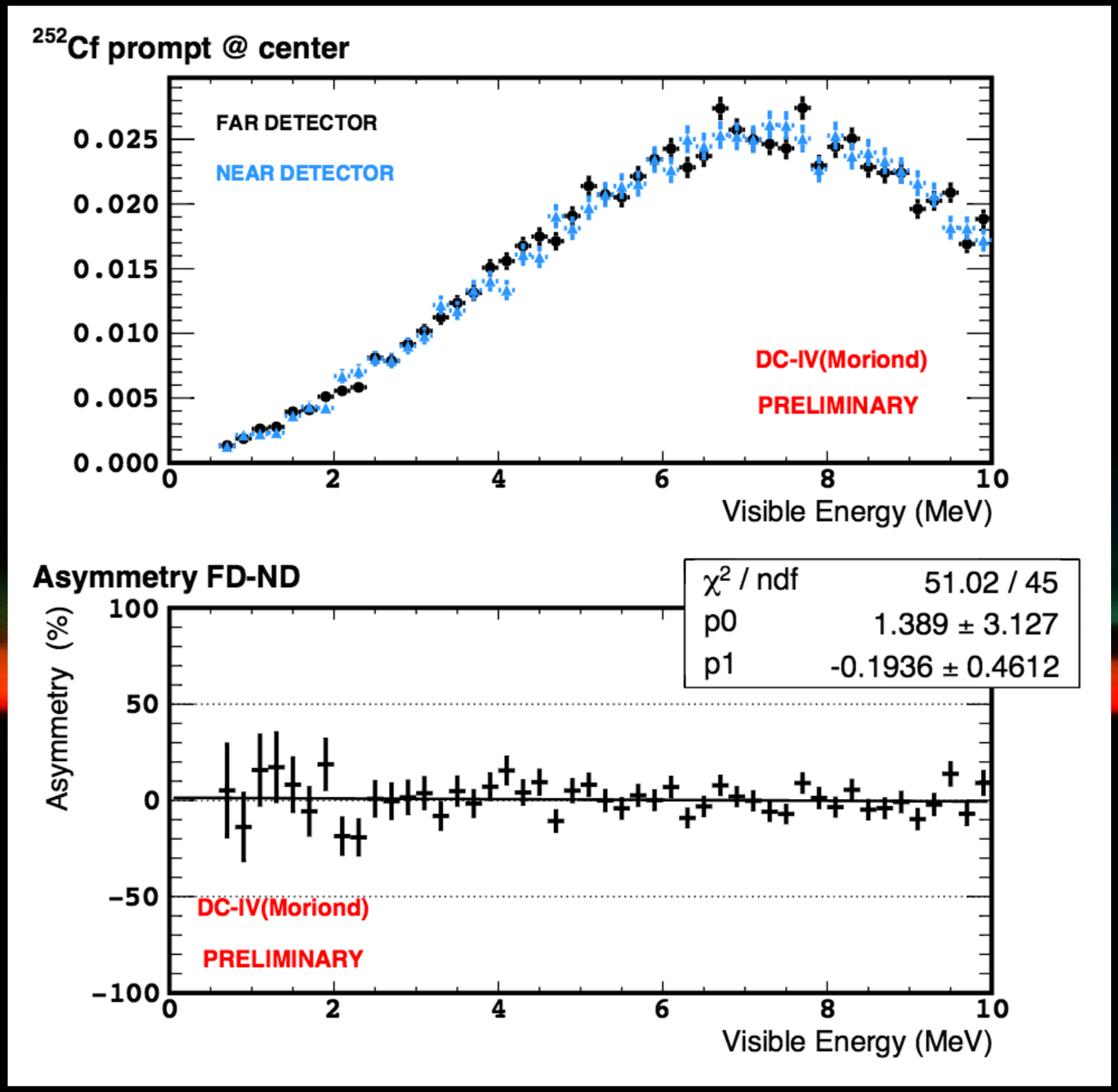
a: statistical term
b: constant term
c: e.g. electric noise

Data
a=0.0773±0.0025
b=0.0182±0.0014
c=0.0174±0.0107

MC
a=0.0770±0.0018
b=0.0183±0.0011
c=0.0235±0.0061

- **remarkable agreement data to MC** throughout full energy range
  - identical curves (→ no free knobs in MC)
  - most relevant region for θ_{13} is ≤4MeV
- **excellent precision:** peak position and widths (highly non-trivial)
  - true for peaks in center or <u>anywhere in NT and GT</u>
  - C-n peak (mainly from GC)→ slight different response in GC (worse)
- **constant term of resolution ~0.018** (powerful calorimetry)
  - largely dominated by stochastic term

prompt energy of ^{252}Cf data (same source)…



- ^{252}Cf emits ~10 γ with 1MeV in average.
- **comparison FD to ND data (no MC) ^{252}Cf @ the center**→ identical

more calibration needed (poor-ish statistics)

our **new** analyses (I,II,III→**IV**)…

@51st Moriond (March 2016)

PRELIMINARY

(further details in our 2014 paper→ similar)

Improved measurements of the neutrino mixing angle θ_{13} with the Double Chooz detector

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Double Chooz Collaboration

arXiv:1406.7763v1 [hep-ex] 30 Jun 2014

reactor θ13 multi-detector rationale…

systematics	single detector (SD) (%)	multi-detector (MD) (%)
δ(detection)	~2.0 (~0.4$^{DC\text{-}IV}$)	~0.2 (~0.3$^{DC\text{-}IV}$) (identical detectors)
δ(flux)	~3.0 (~1.7$^{DC\text{-}IV}$ via Bugey4)	≤0.5 (<0.1$^{DC\text{-}IV}$) (~iso-flux site)
δ(background)	≤1.0 (~0.4$^{DC\text{-}IV}$) (active BG rejection)	≤1.0 (~0.4$^{DC\text{-}IV}$) (active BG rejection)

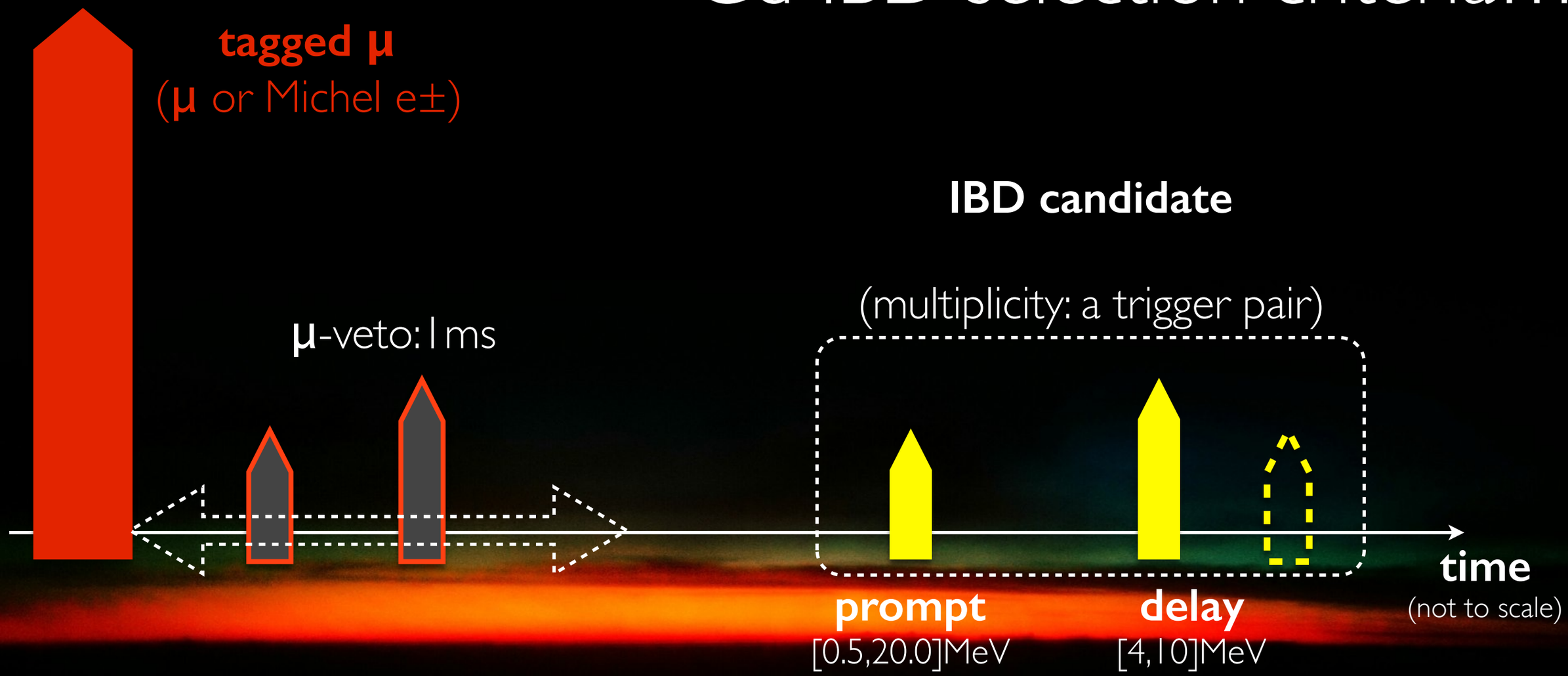
DC challenge: statistics (systematics are too good)

BG & detection systematics dominated by statistics too (this analysis)

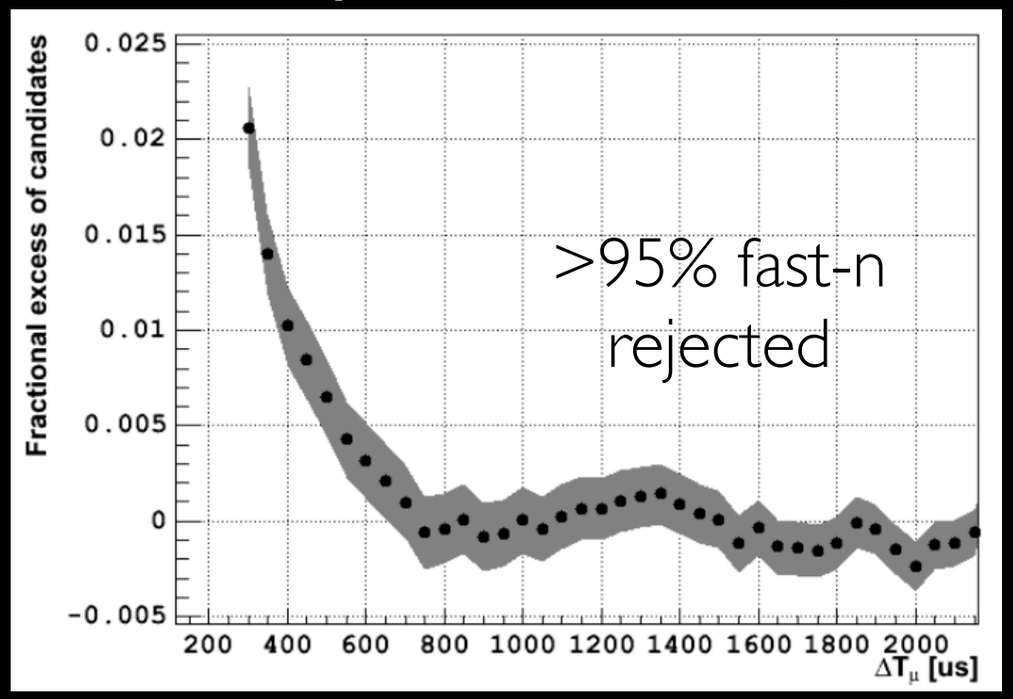
let's get those neutrinos…

— event selection —

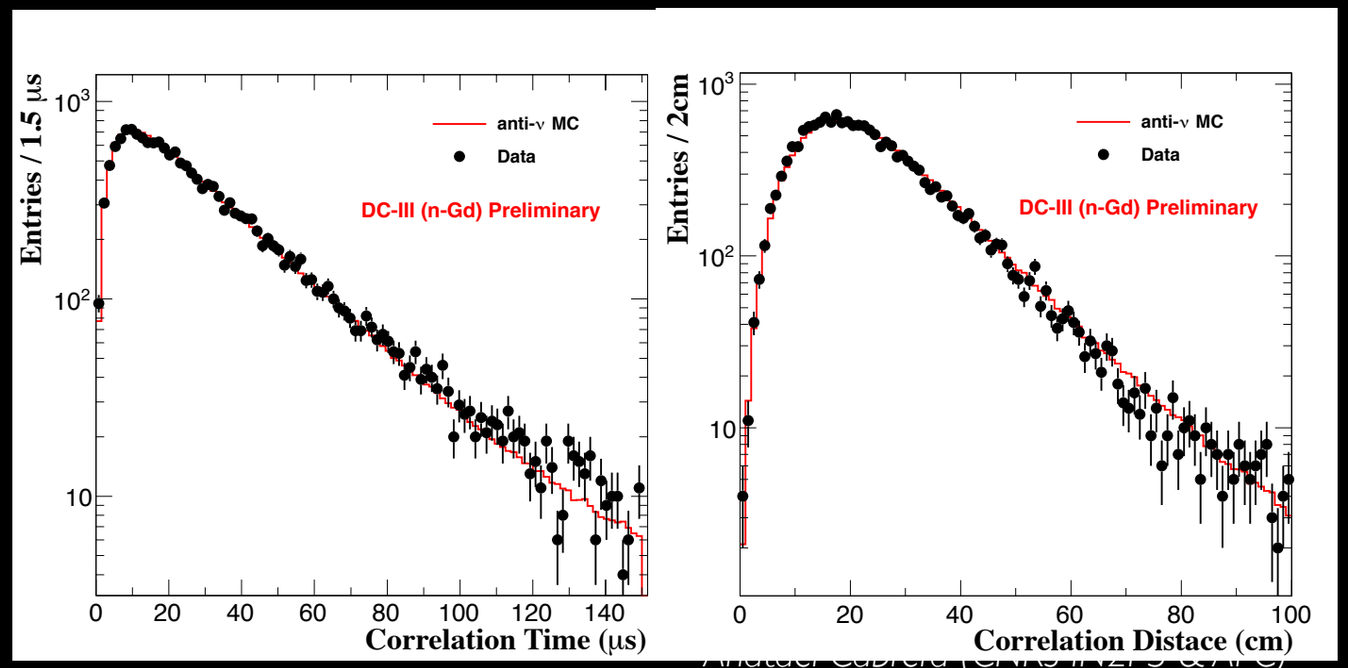
Gd-IBD selection criteria…



after-μ correlated IBDs



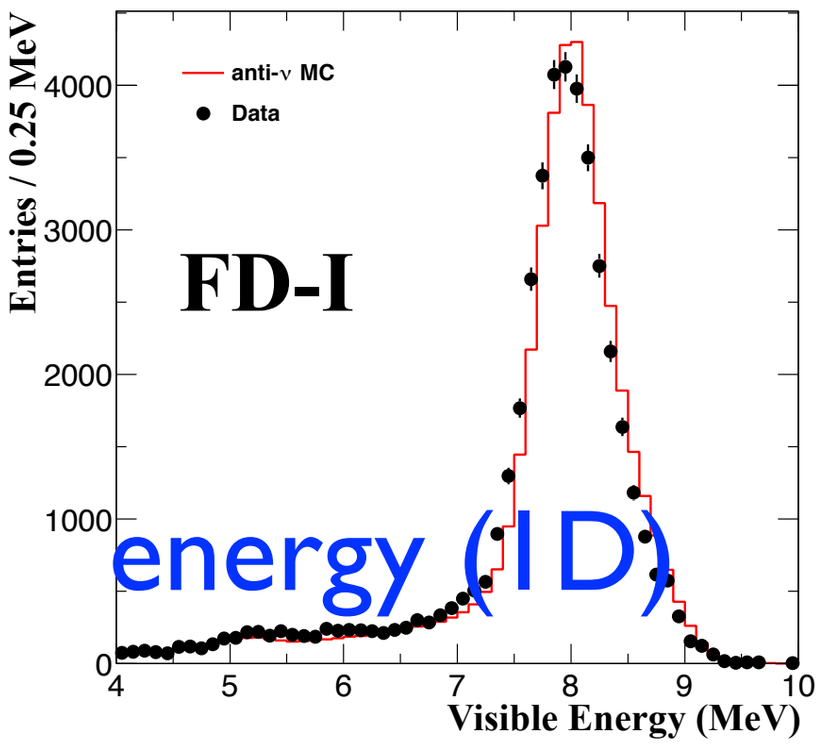
IBD time/space (e^+~n) correlation



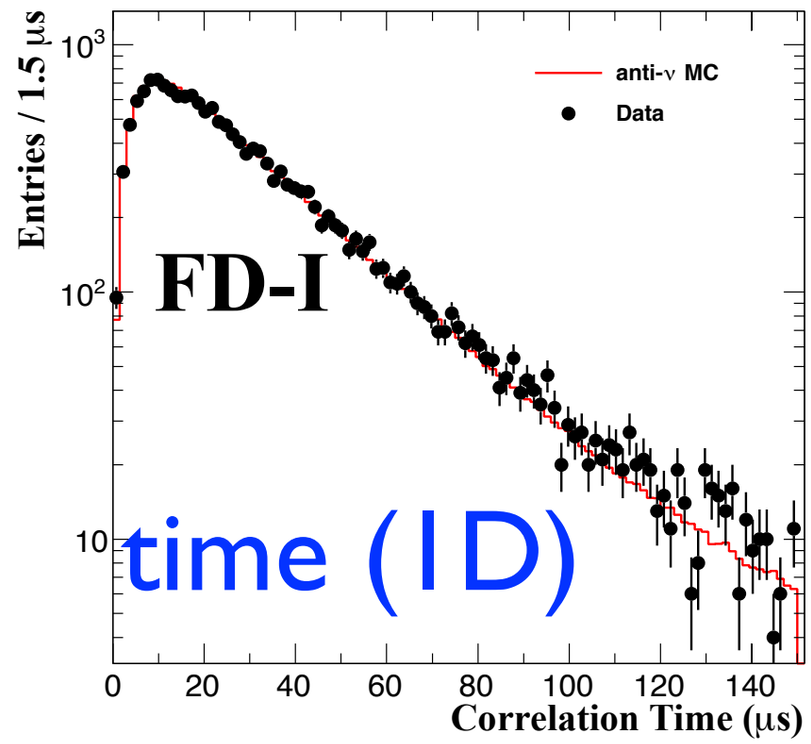
IBD coincidence: 5D definition

stunning data-MC agreement

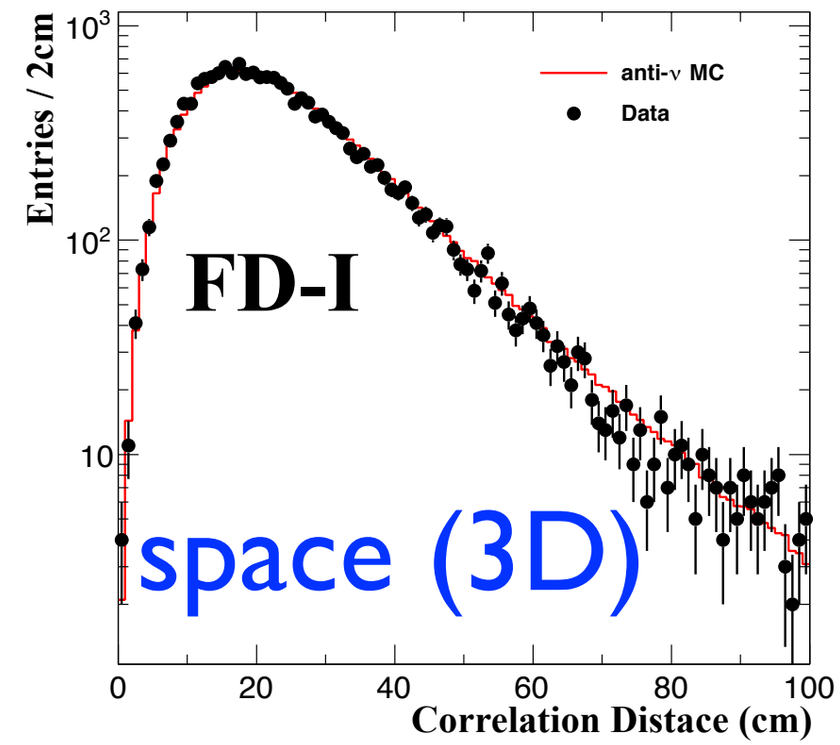
Delayed signal energy
$4 < E_{vis} < 10$MeV



Correlation time
$0.5 < \Delta T < 150\mu$sec



Correlation distance
$\Delta R < 100$cm



⇒ **Remaining BG…**

Cosmogenic β-n emitter: $^{9}Li \rightarrow \alpha + \alpha + e + \nu + n$

Fast neutron: $n + p \rightarrow p + n$

Stop-μ: $\mu \rightarrow e + \nu + \nu$

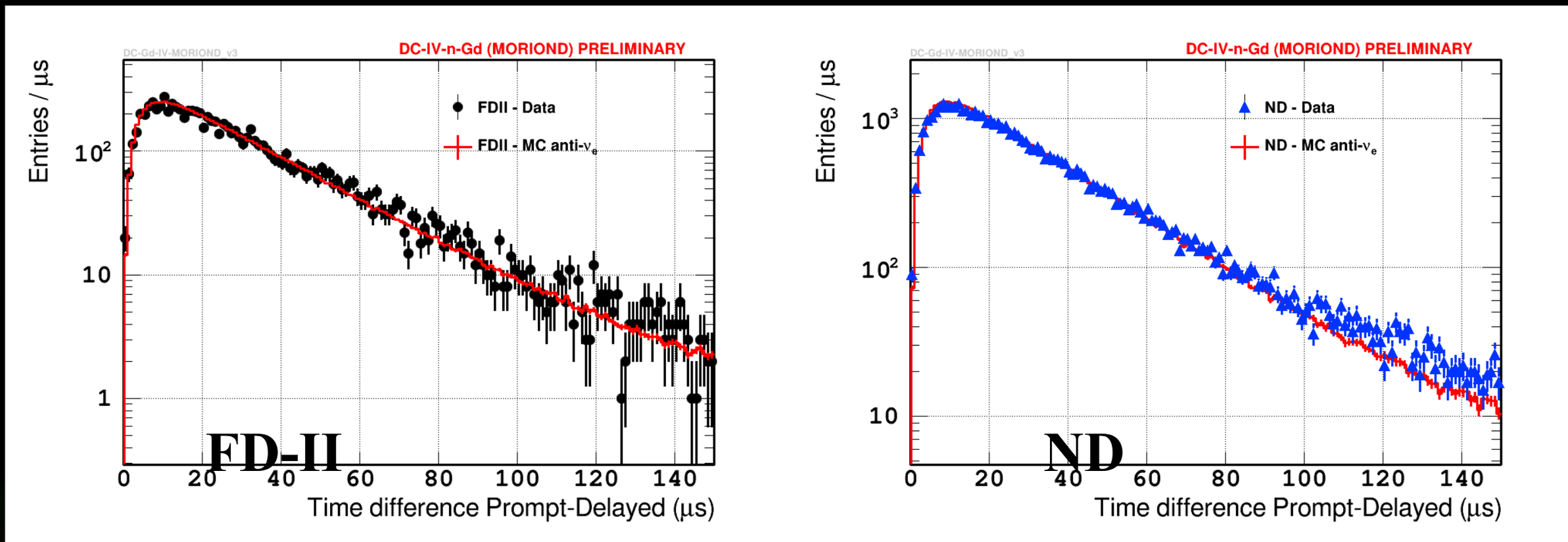
Accidental coincidence: e.g. γ + cosmogenic (^{12}B, fast-n) & radiogenic

Prompt

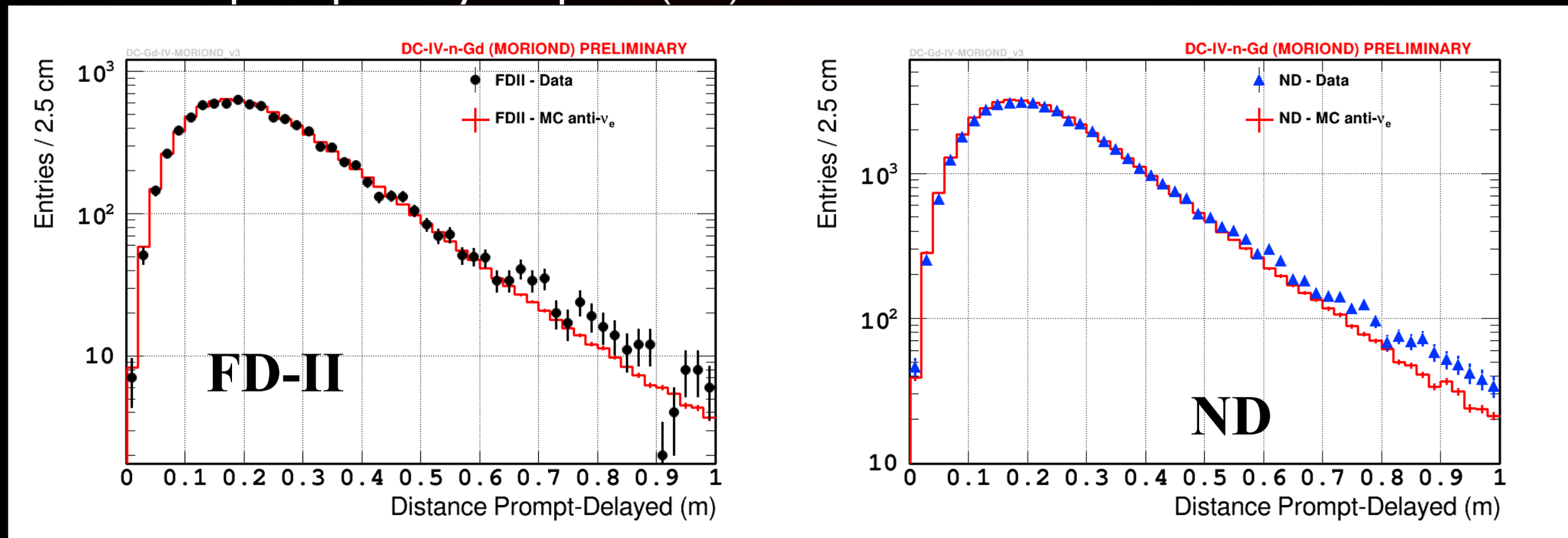
Delayed

IBD selection

Correlation prompt-delay in time (1D)…

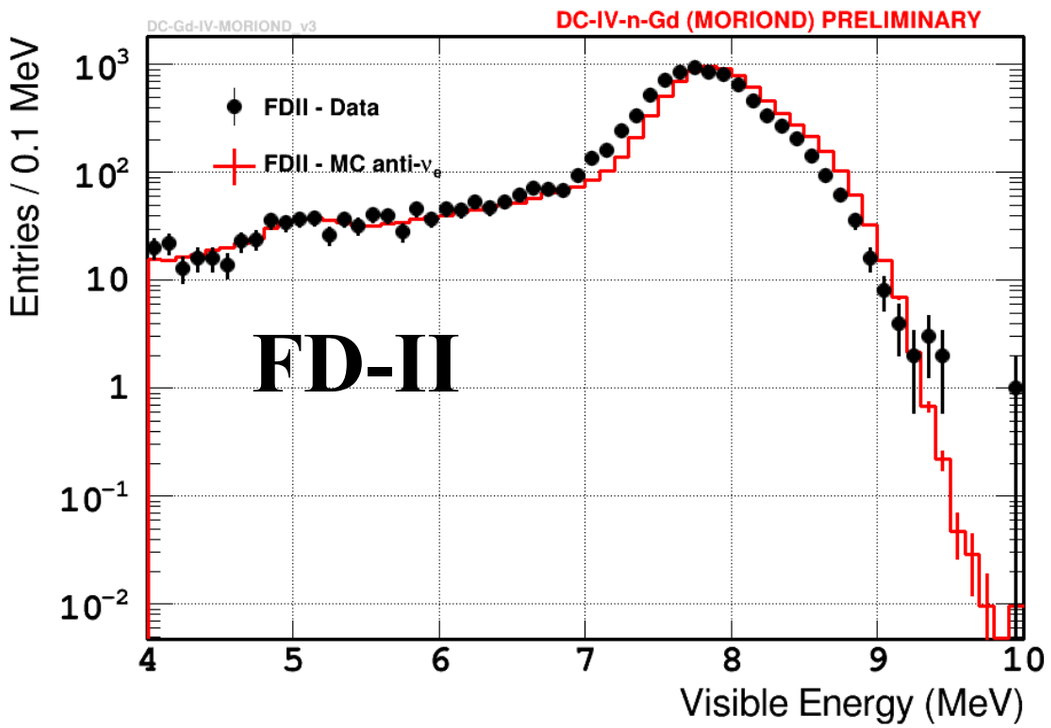


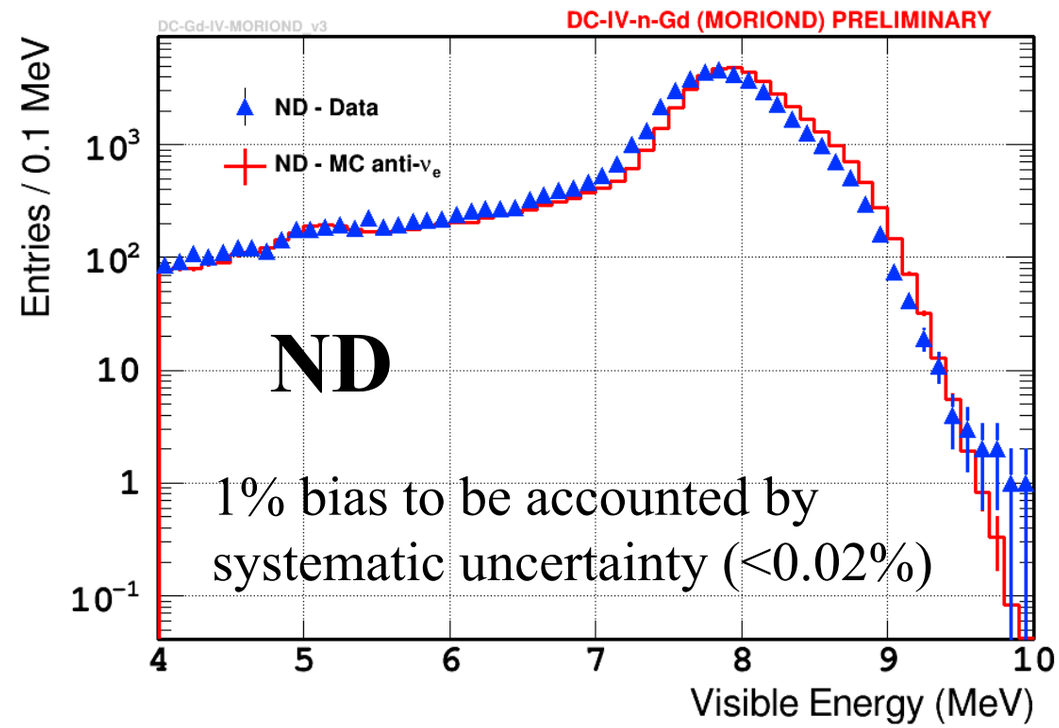
Correlation prompt-delay in space (3D)…



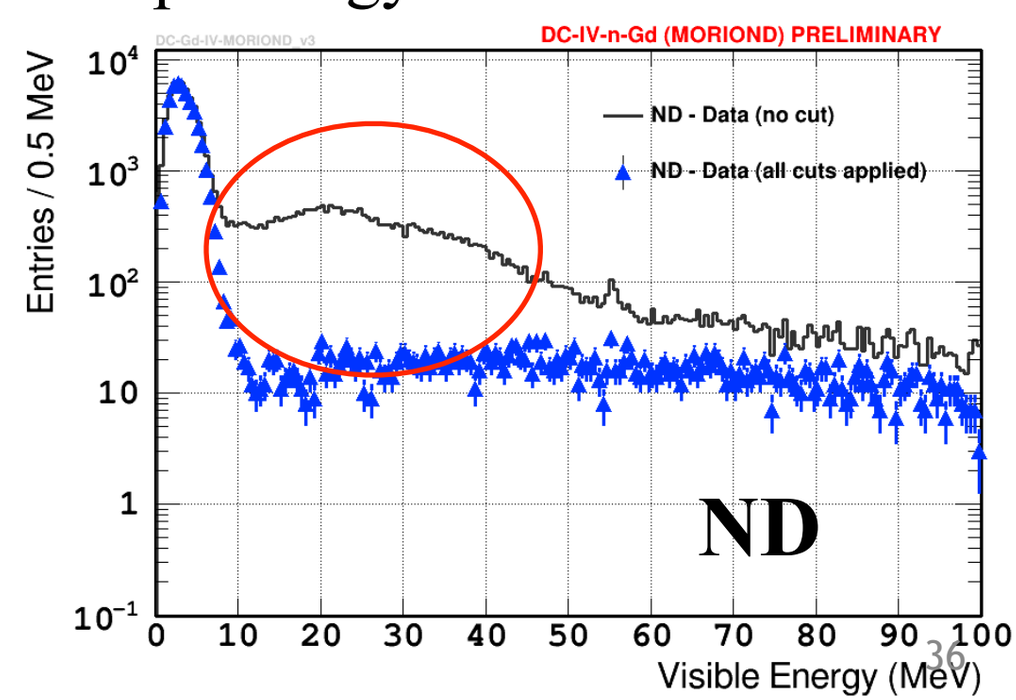
IBD selection

Delayed energy





Prompt energy



contamination of liquid scintillator (leak?) in ND buffer causes buffer stop-μ background

⇒ almost all such backgrounds are rejected

by new selections based on

- Energy dependent MaxQ/TotQ cut
- Likelihood at chimney vs. vertex (CPS veto)

Detection systematics

Double Chooz Preliminary

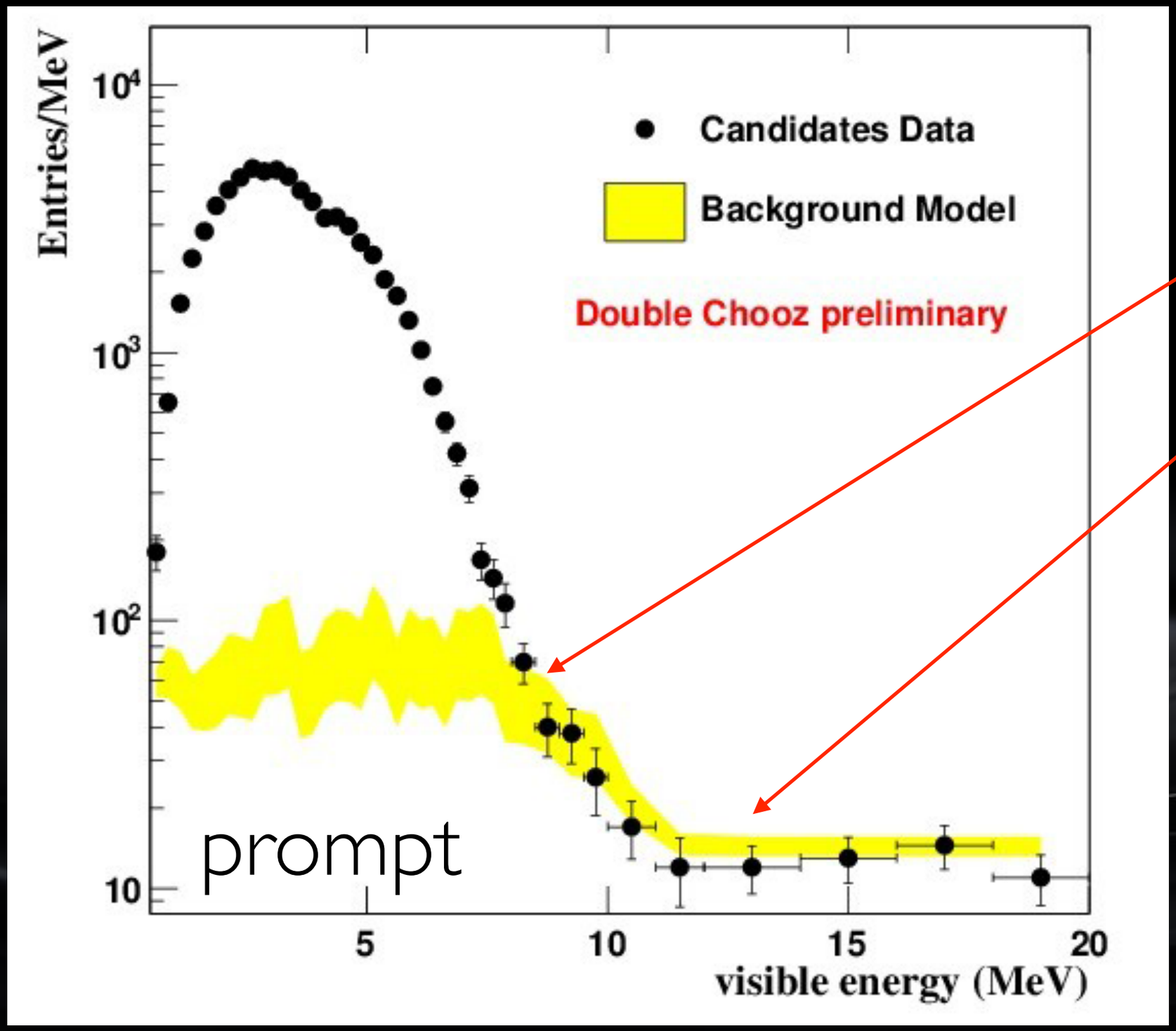
	FD-I	FD-II	ND
BG vetoes (%)	0.11 (0.11)	0.09 (0.09)	0.02 (0.02)
Gd fraction (%)	0.25 (0.14)	0.26 (0.15)	0.28 (0.19)
IBD selection (%)	0.21 (0.21)	0.16 (0.16)	0.07 (0.07)
Spill in/out (%)	0.27 (0)	0.27 (0)	0.27 (0)
Proton number (%)	0.30 (0)	0.30 (0)	0.30 (0)
Total (%)	**0.49 (0.26)**	**0.47 (0.22)**	**0.38 (0.15)**

Numbers in parentheses are uncorrelated uncertainties in multi-detectors analysis (FD-I, FD-II and ND)

ND and FD identical within statistical dominated errors (0.29%)

BACKGROUNDs

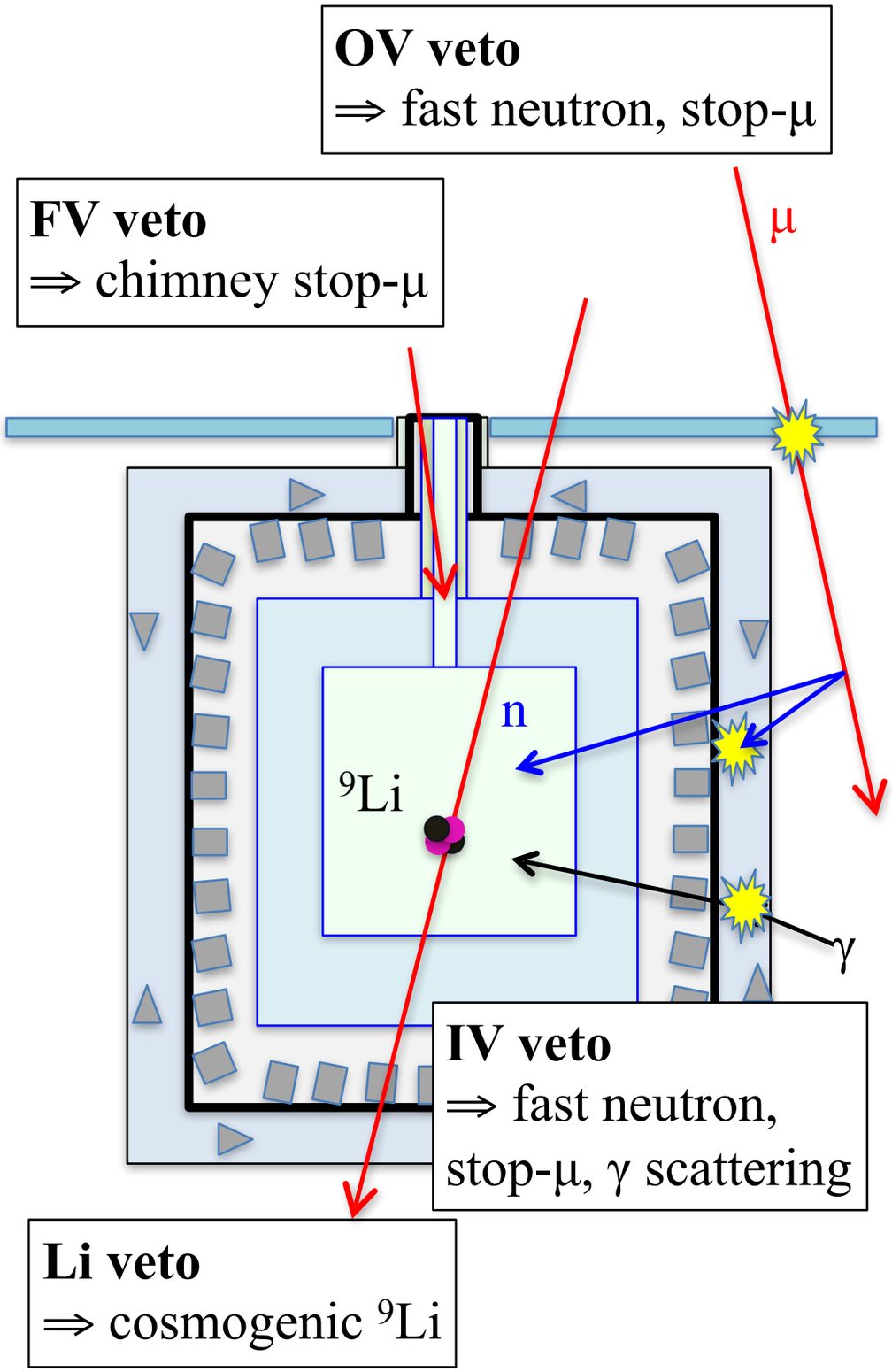
our background model…



- **^{9}Li (+ a little ^{8}He)**
  (dominant & knowledge @ 20%)
- **fast-n (+ little stopped-μs)**
  (still visible & knowledge @ <10%)
- **stopping-μ:** mostly rejected
- **other BGs…**
  - accidentals
  - $^{13}C(\alpha,n)^{16}O$
  - ^{12}B related

active BG rejection…

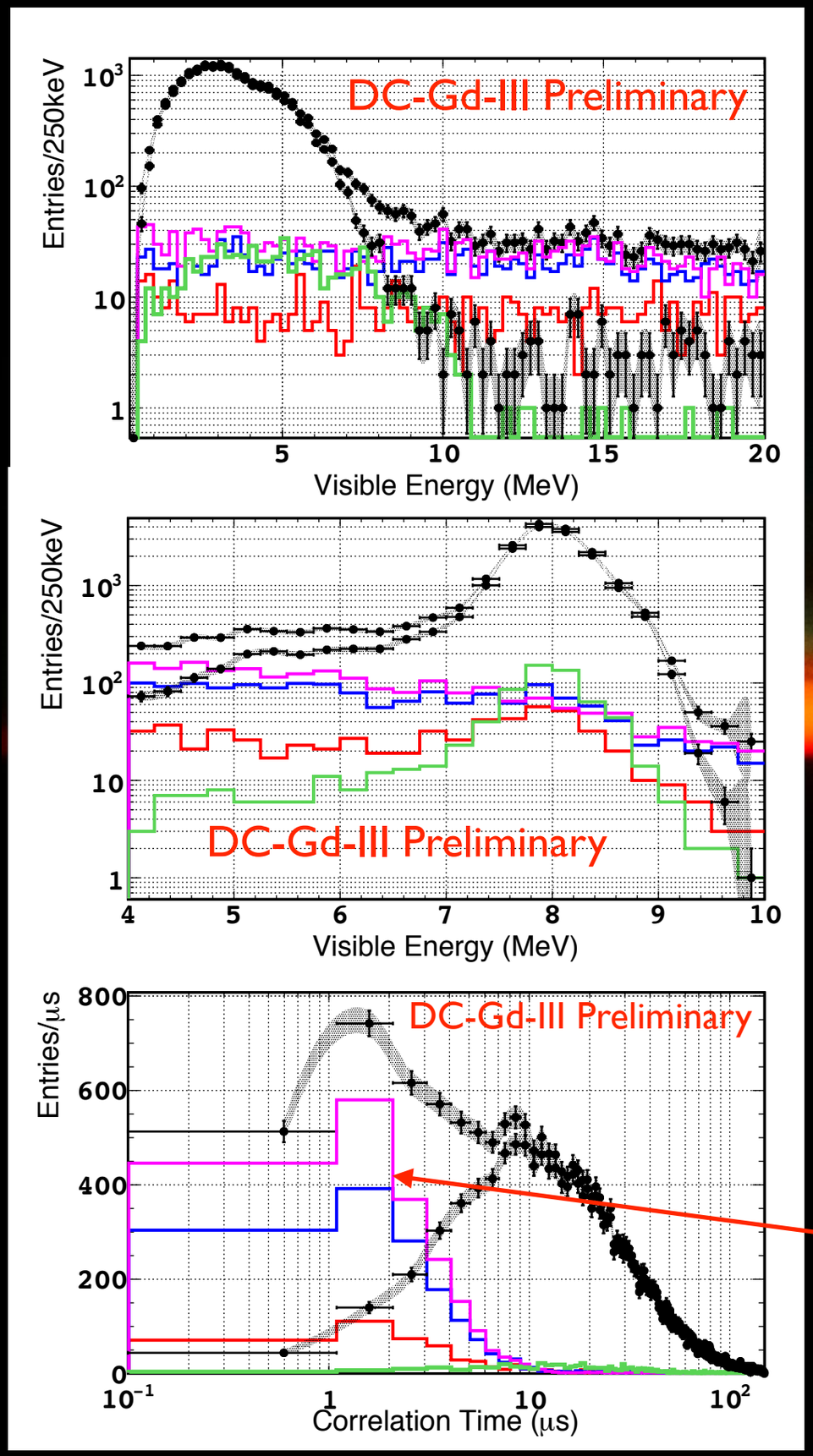
Background vetoes



Cut	Information used	Target of cut
μ veto	1ms veto after μ	μ, cosmogenic
Multiplicity	unicity condition	multiple-n
FV veto	vertex likelihood	chimney stop-μ
IV veto	IV activity	fast n, stop-μ, γ scattering
OV veto	OV activity	fast n, stop-μ
Li veto	Li-likelihood	cosmogenic
LN cut	PMT hit pattern & time	light emission from PMT
(CPS veto)	chimney likelihood	stop-μ
(Qratio)	Max Q/Tot. Q	ND buffer stop-μ

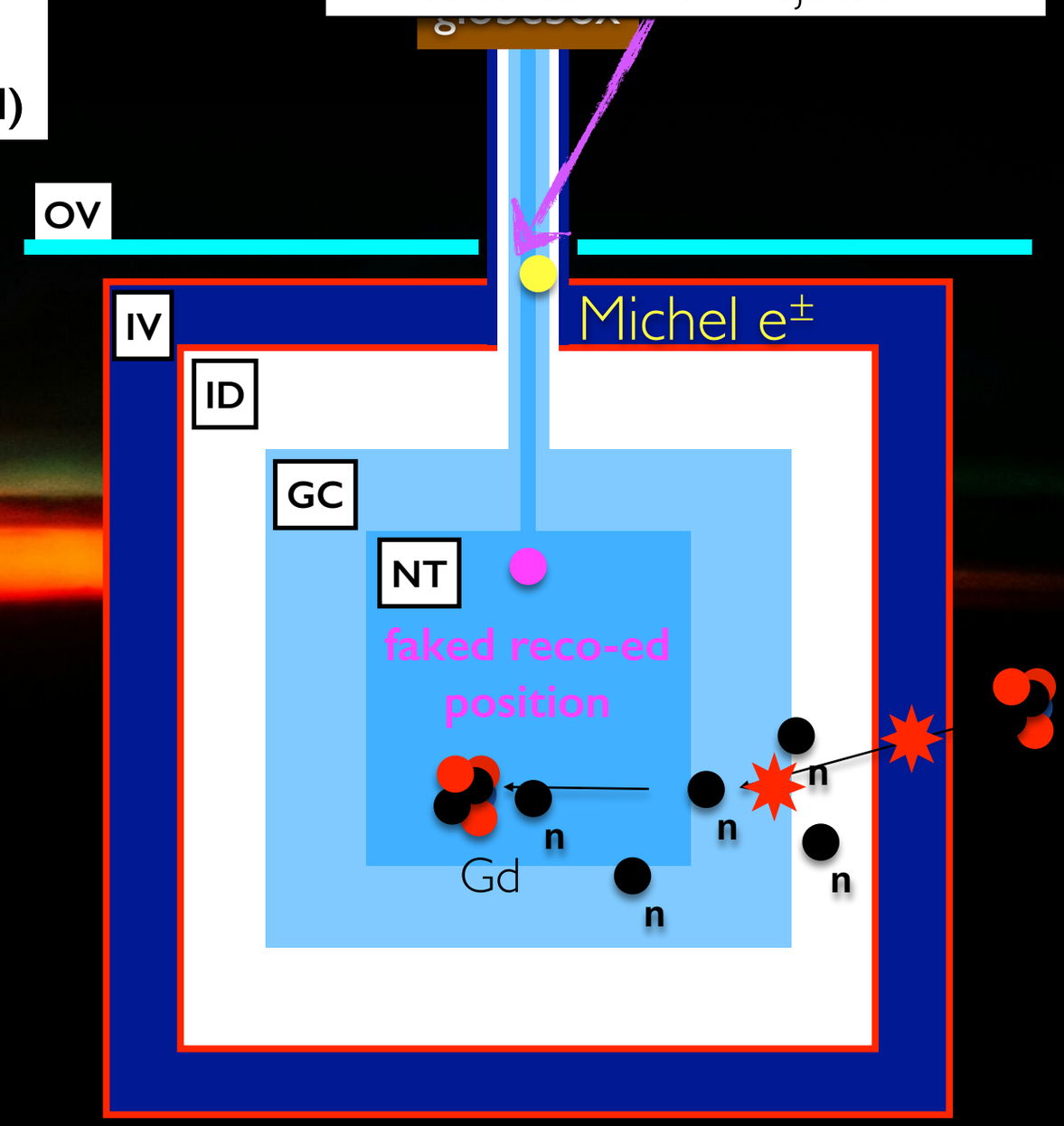
(only applied in multi-detector analysis)

our vetoes in action (one by one)…



Gd-III (vetoes OFF)
FVV veto
Li+He veto
OV veto
IV veto
Gd-III (vetoes ON)

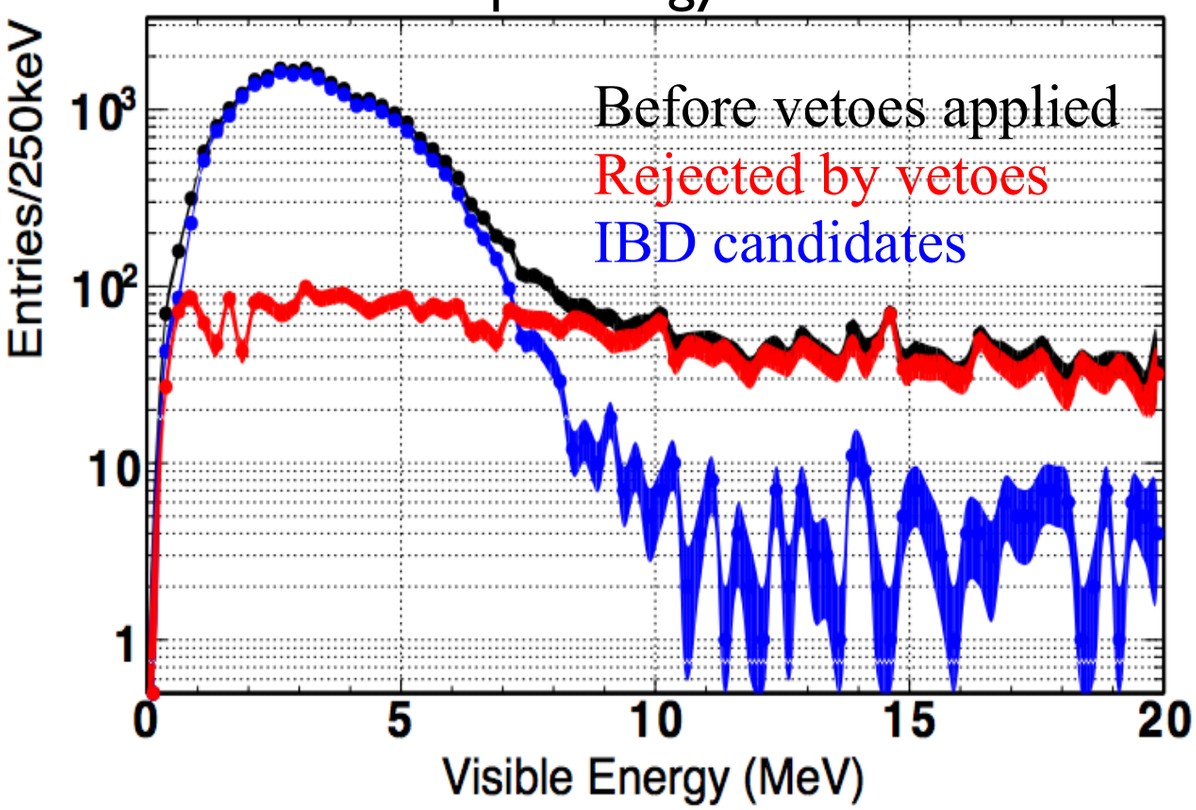
BG rejection…
- Li/He→ ~50% rejection
- fast-n + stop-μ→ ~10x rejection
- accidental→ >10x rejection



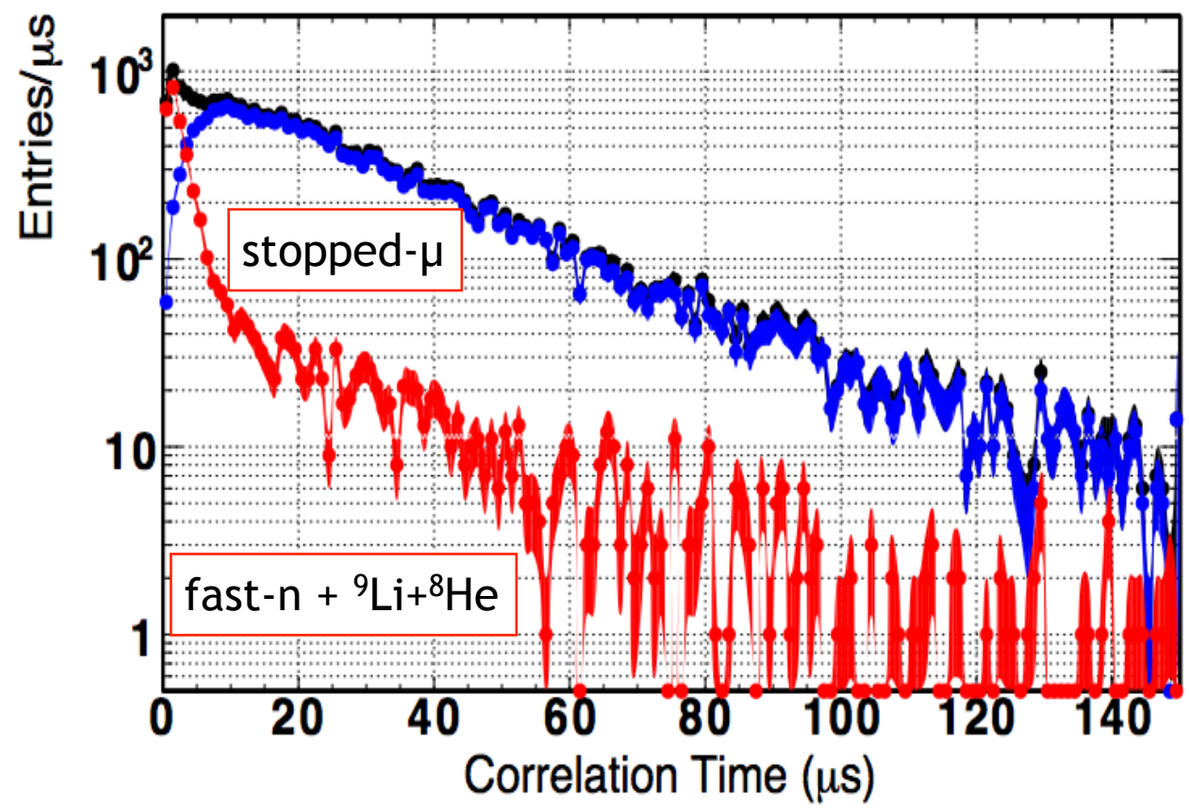
stopped-μ largest BG
(if not vetoed→ ~fully rejected)

Background vetoes

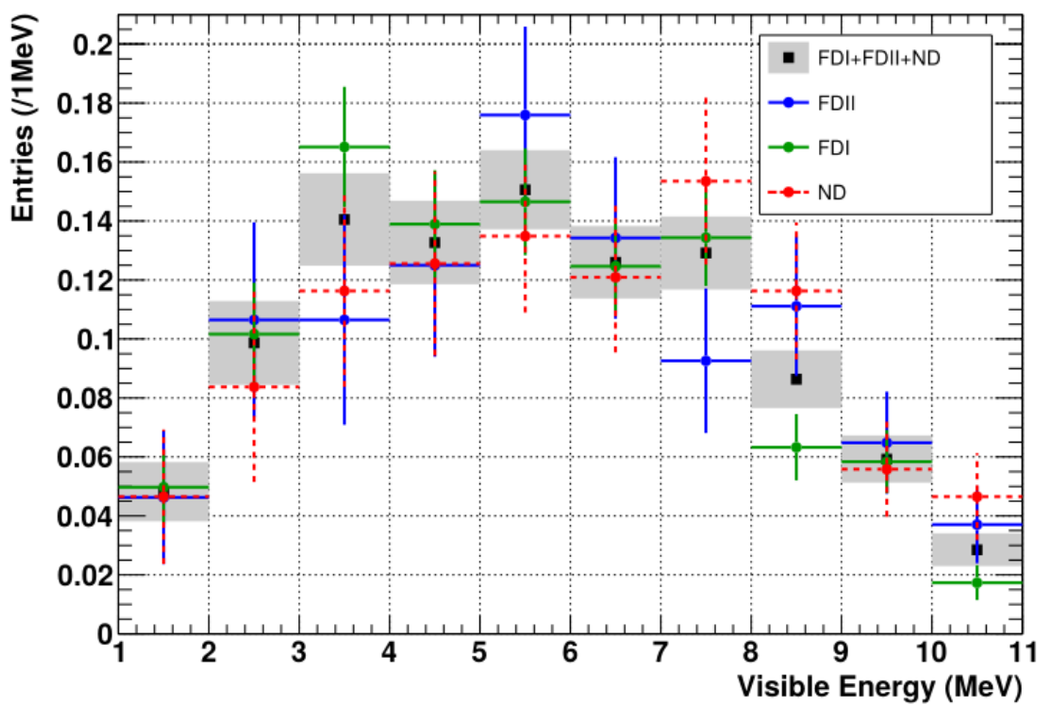
Prompt energy



Correlation time

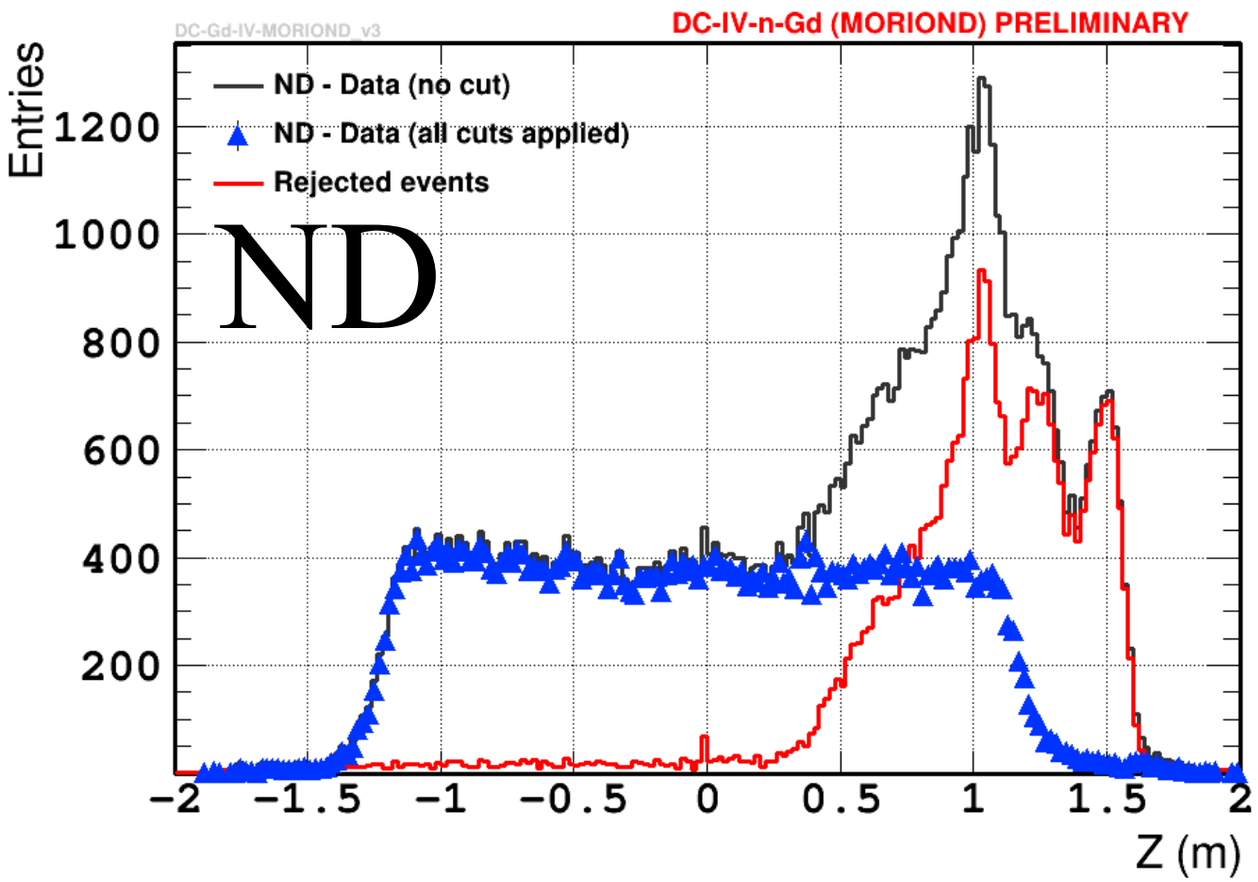


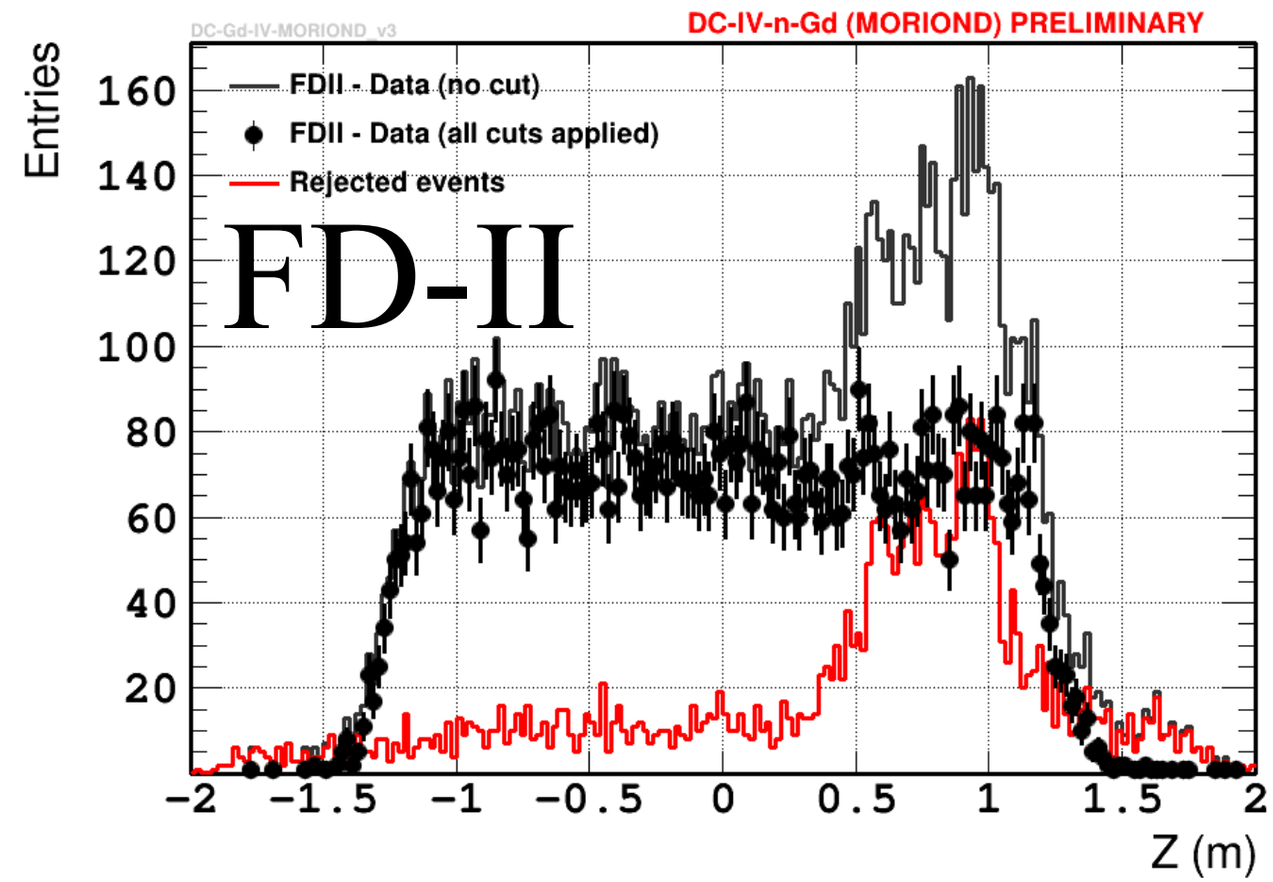
prompt energy (rejected by ^{9}Li veto)



- Significant reduction of background: stop-μ, fast n, ^{9}Li, natural radioactivity
  ⇒ Rejected (tagged) events are used to evaluate residual background
- IBD inefficiency: <1% (besides μ veto)

stopped-μ contamination





inefficiency: **97.53±0.02** (all vetoes)
rejection power **>10x**

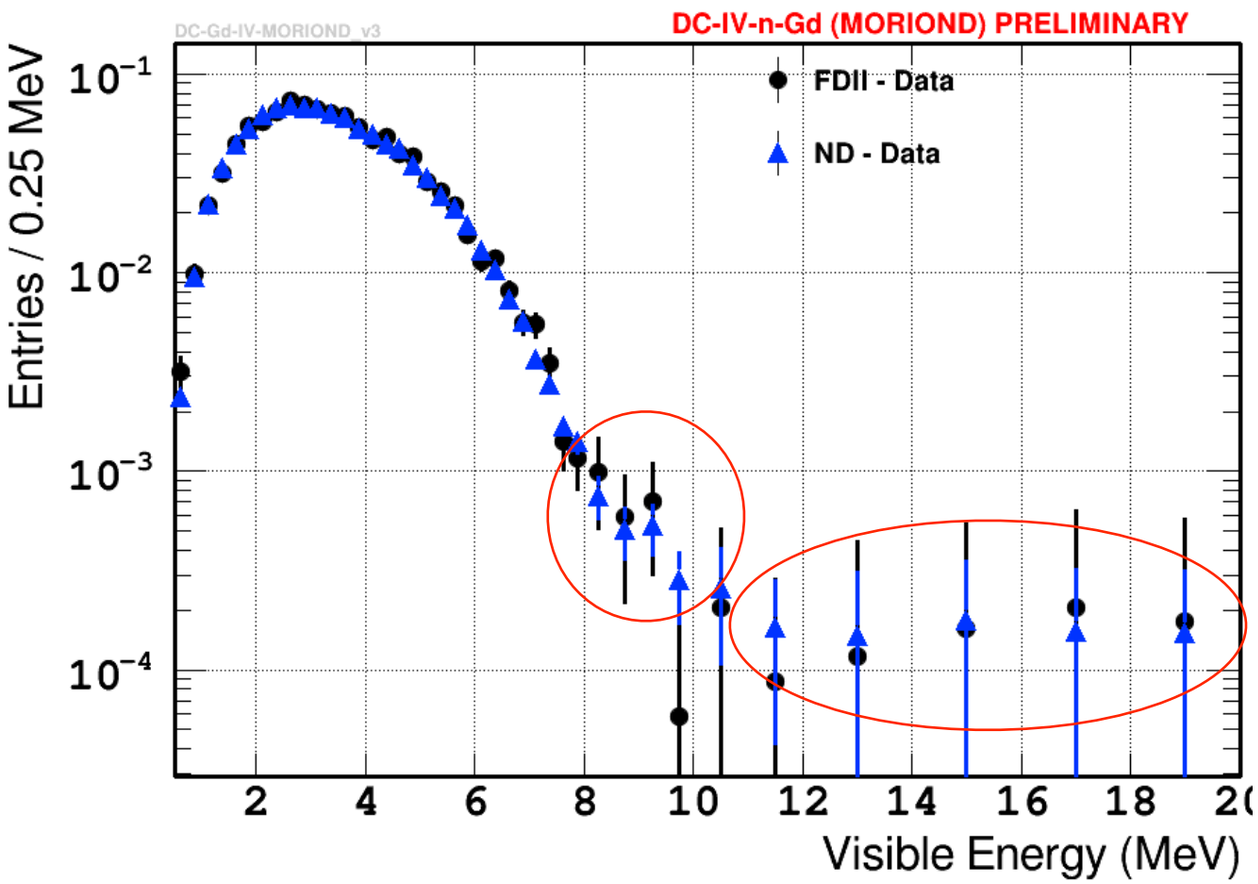
inefficiency: **97.27±0.09** (all vetoes)
rejection power **~10x**

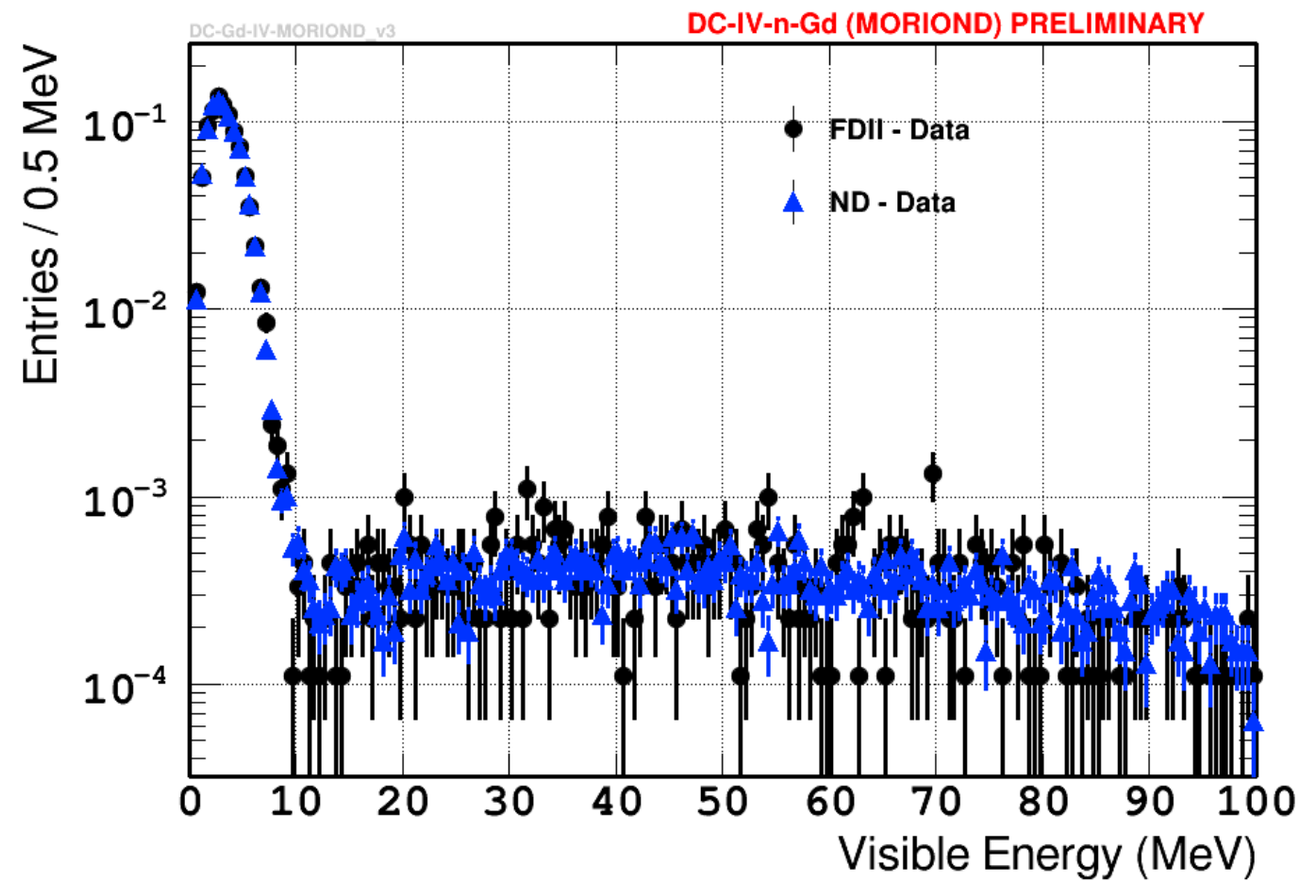
(validated with reactor-OFF data)

vetoes are treated as totally uncorrelated (same cuts though)

after cuts: FD vs ND

relatively normalise→ hide θ13 disappearance



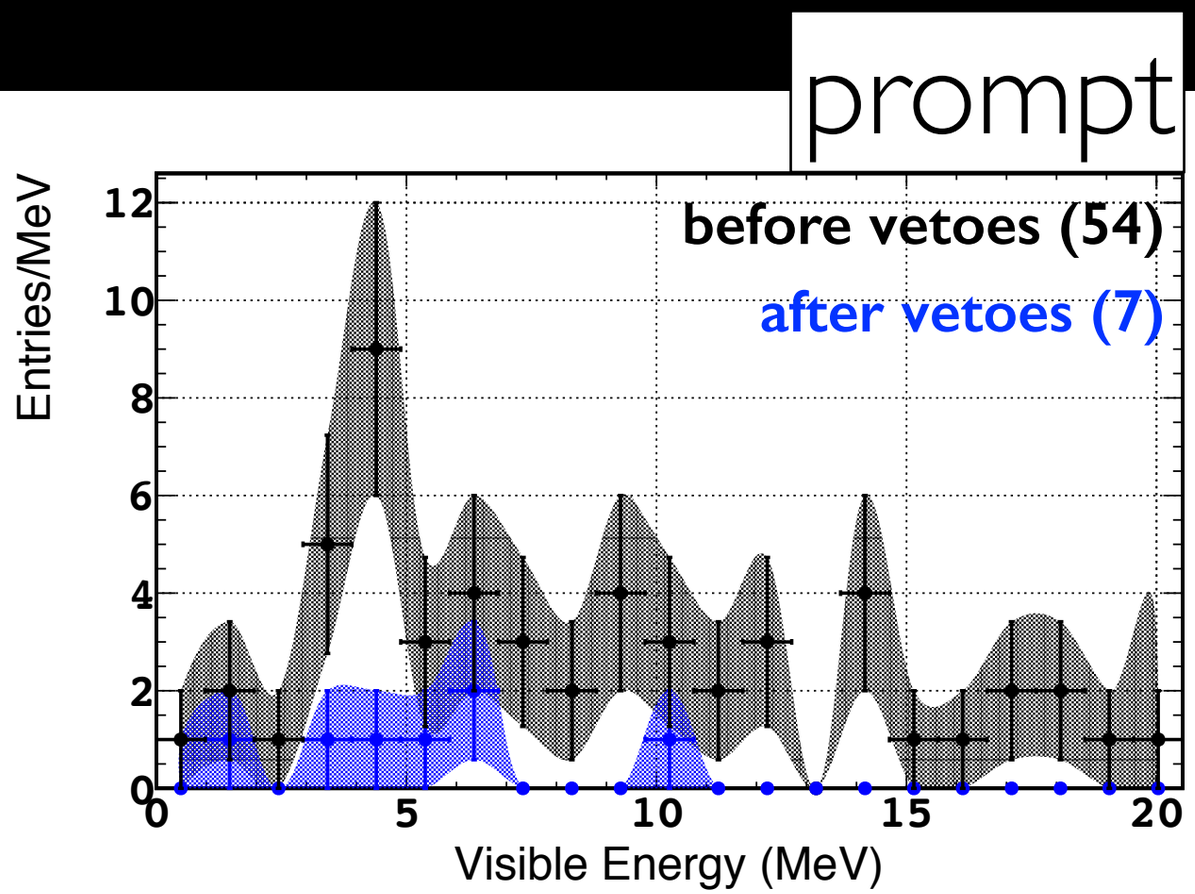


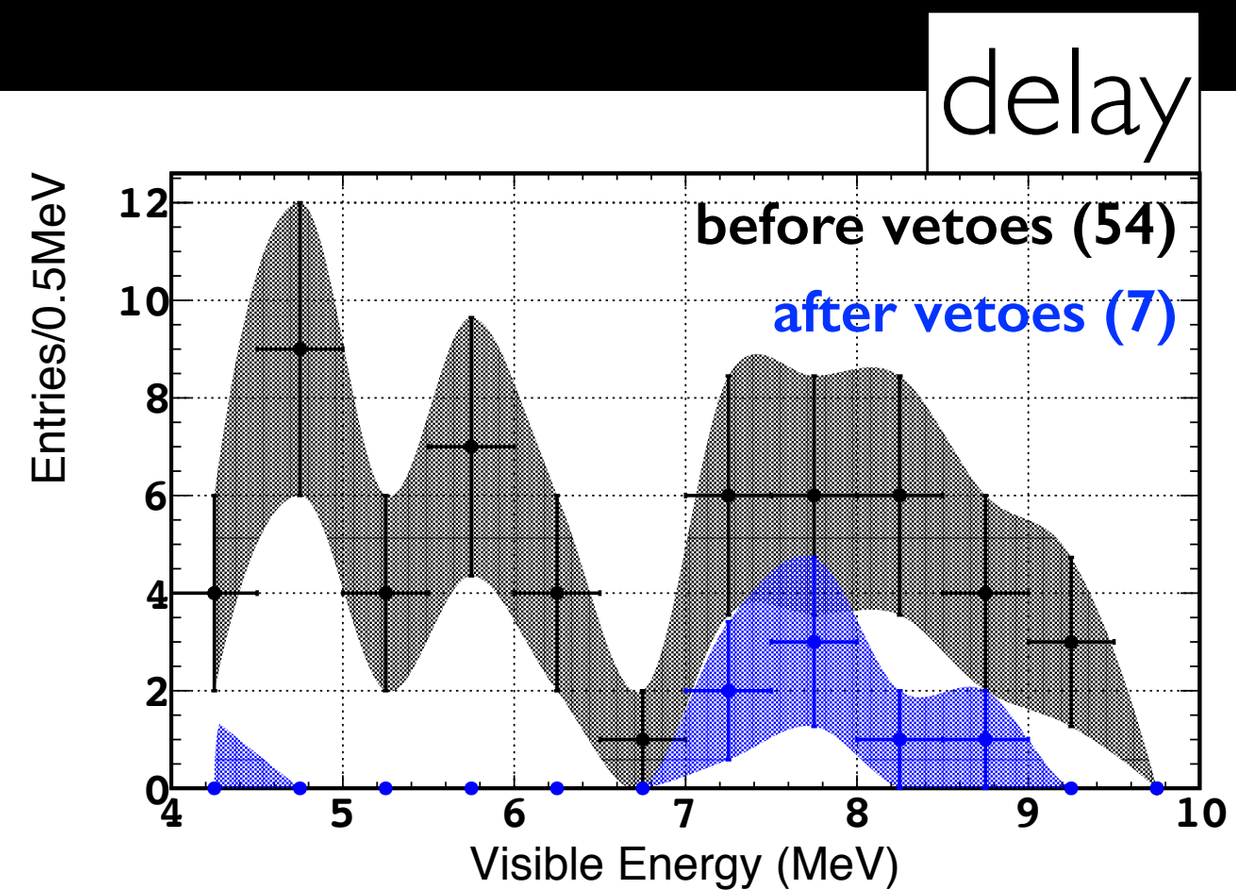
remarkable consistency (signal & BG are different) across FD & ND full dynamics

@ND ~7x more IBDs than @FD

reactor OFF data (only FD)…

reactor-OFF data…





2x reactor-OFF data: powerful information before/after veto evolution
(scrutinising a few event-wise BG-only)

1 week→**poor stats** (spectral info fluctuations dominated)→ inconclusive

P(rejection)=(7.7±3.1) @ Gd-III
(in agreement with (9.9±1.0) estimated between [12,20]MeV)

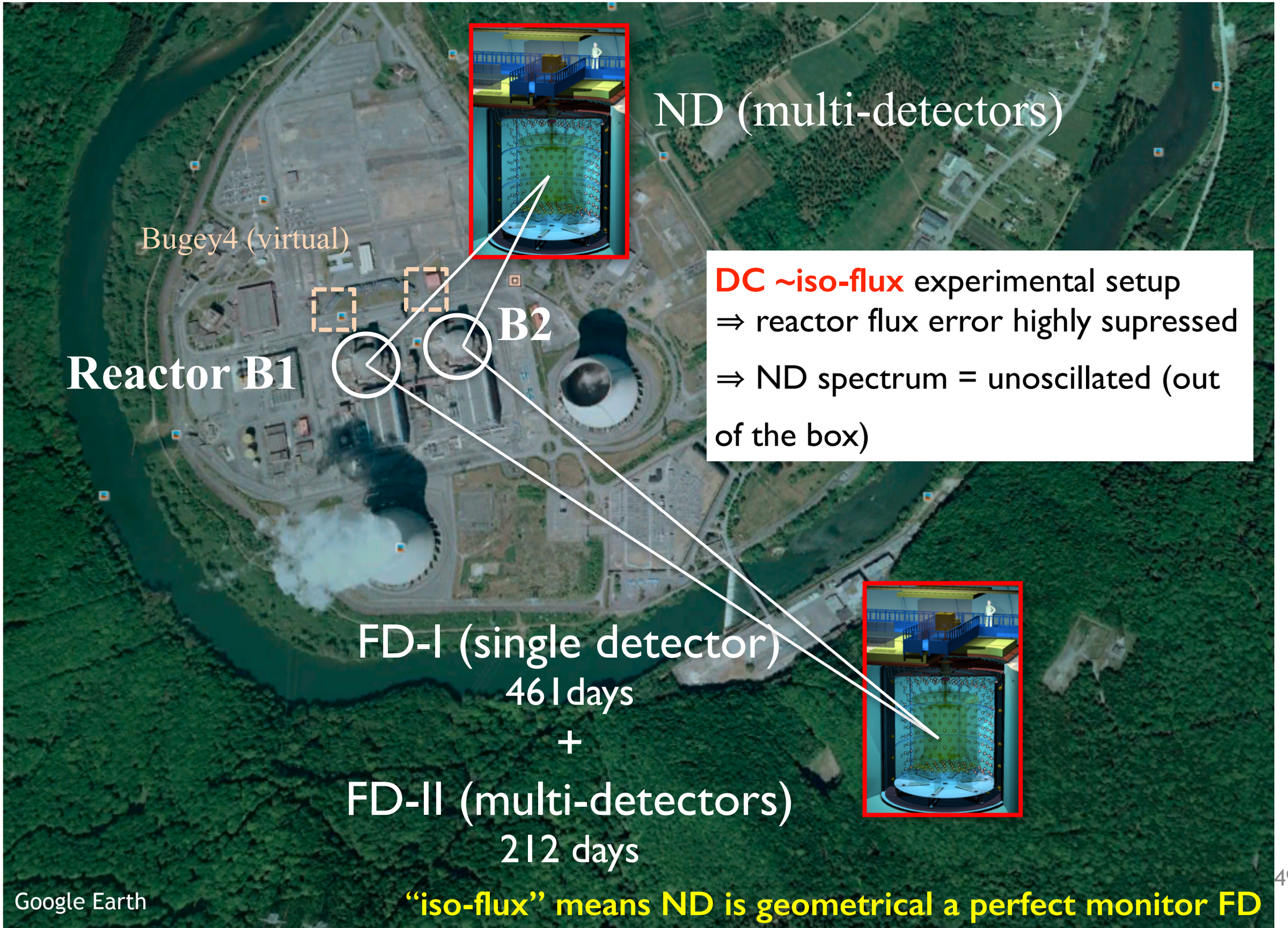
Signal and background

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)

- **all BG shapes measured with data** (no MC used)
- cosmogenic BG ($^{9}Li+^{8}He$): rate not used as input to rate+shape fit (independent)
  ⇒ rates are constrained directly in fit via rate+shape information (data spectrum)

Multi-detectors analysis (today)



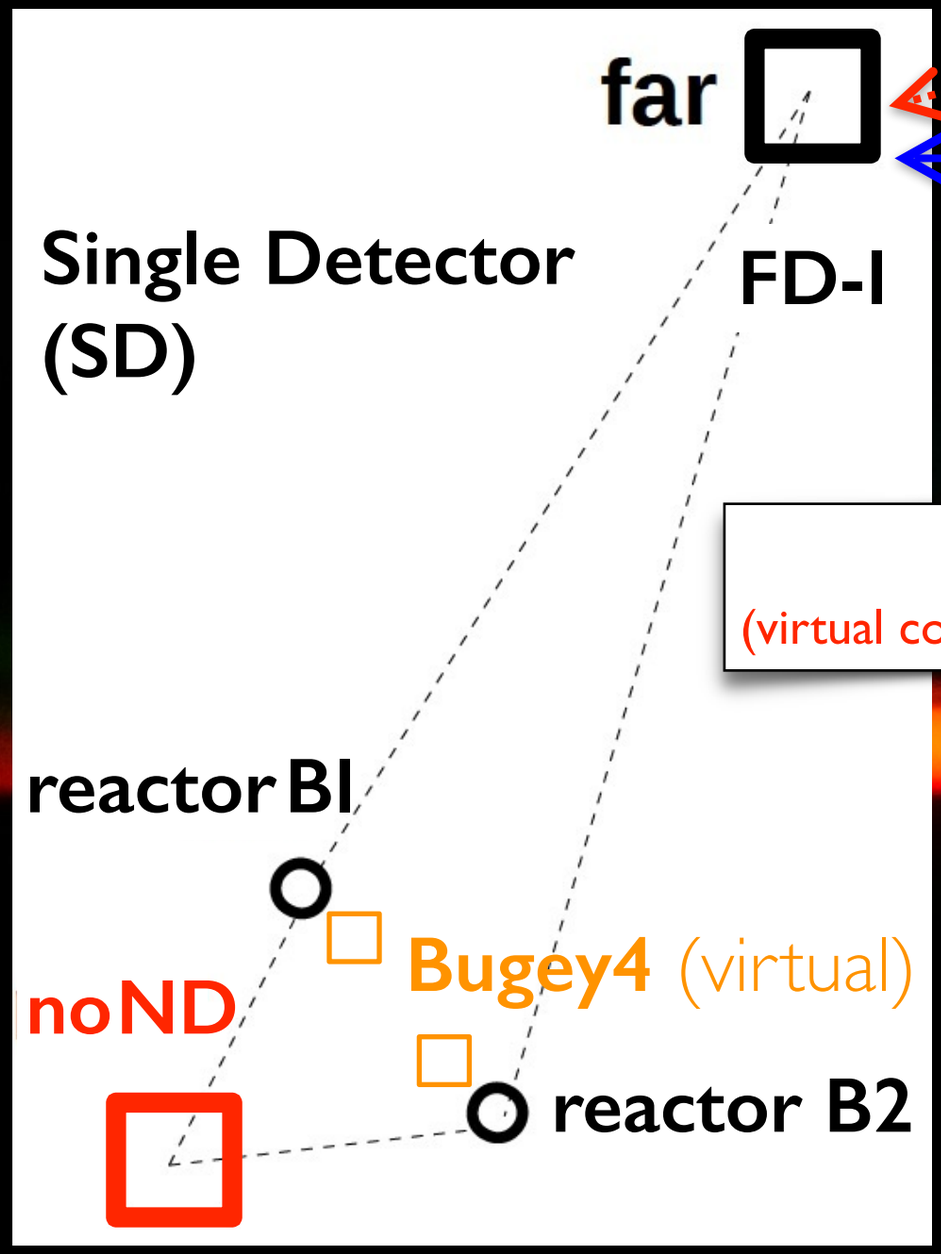
DC ~iso-flux experimental setup
⇒ reactor flux error highly supressed

⇒ ND spectrum = unoscillated (out of the box)

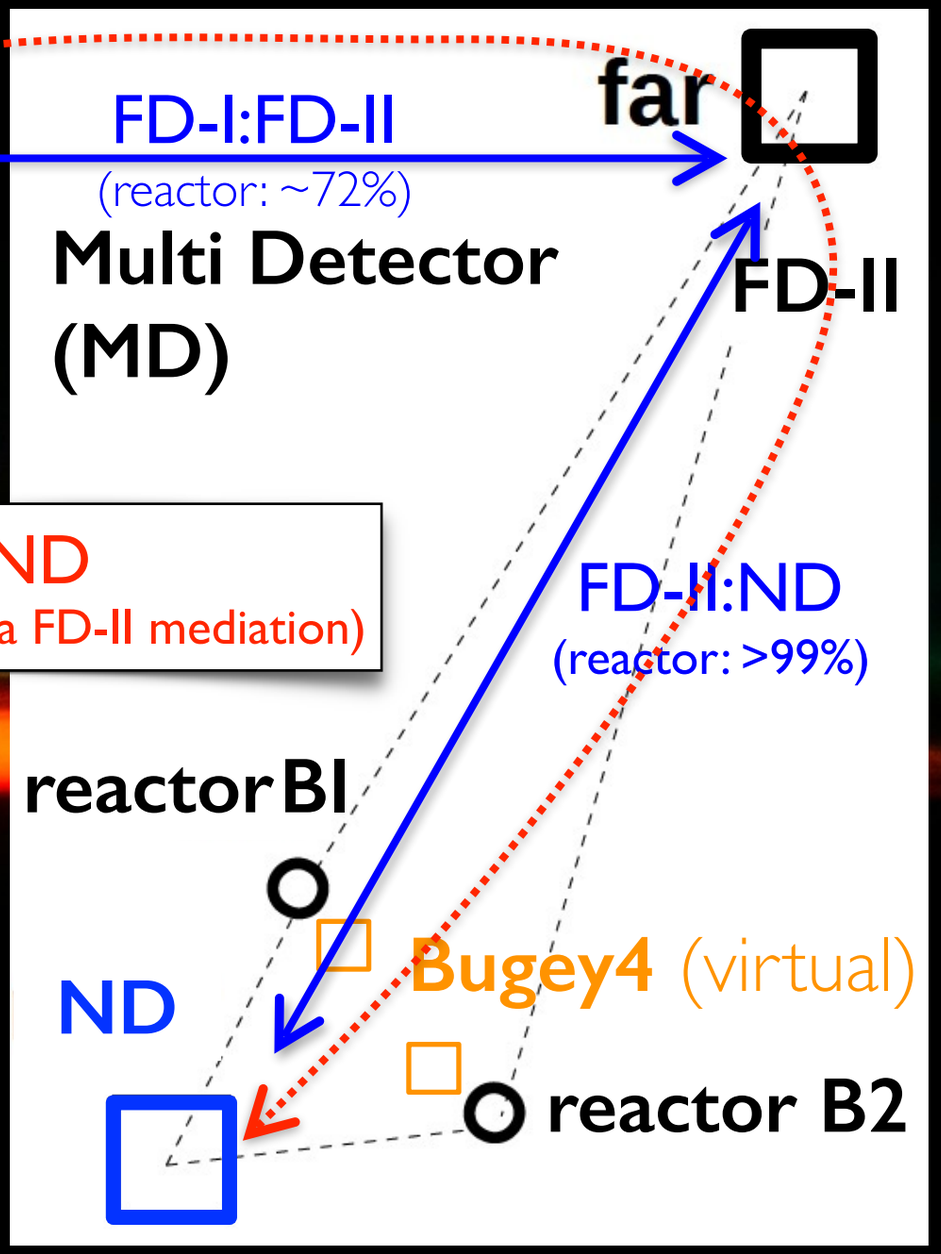
"iso-flux" means ND is geometrical a perfect monitor FD

DC-IV setup correlations…

(exposure used: ~48months)



(exposure used: ~9months @ Moriond)



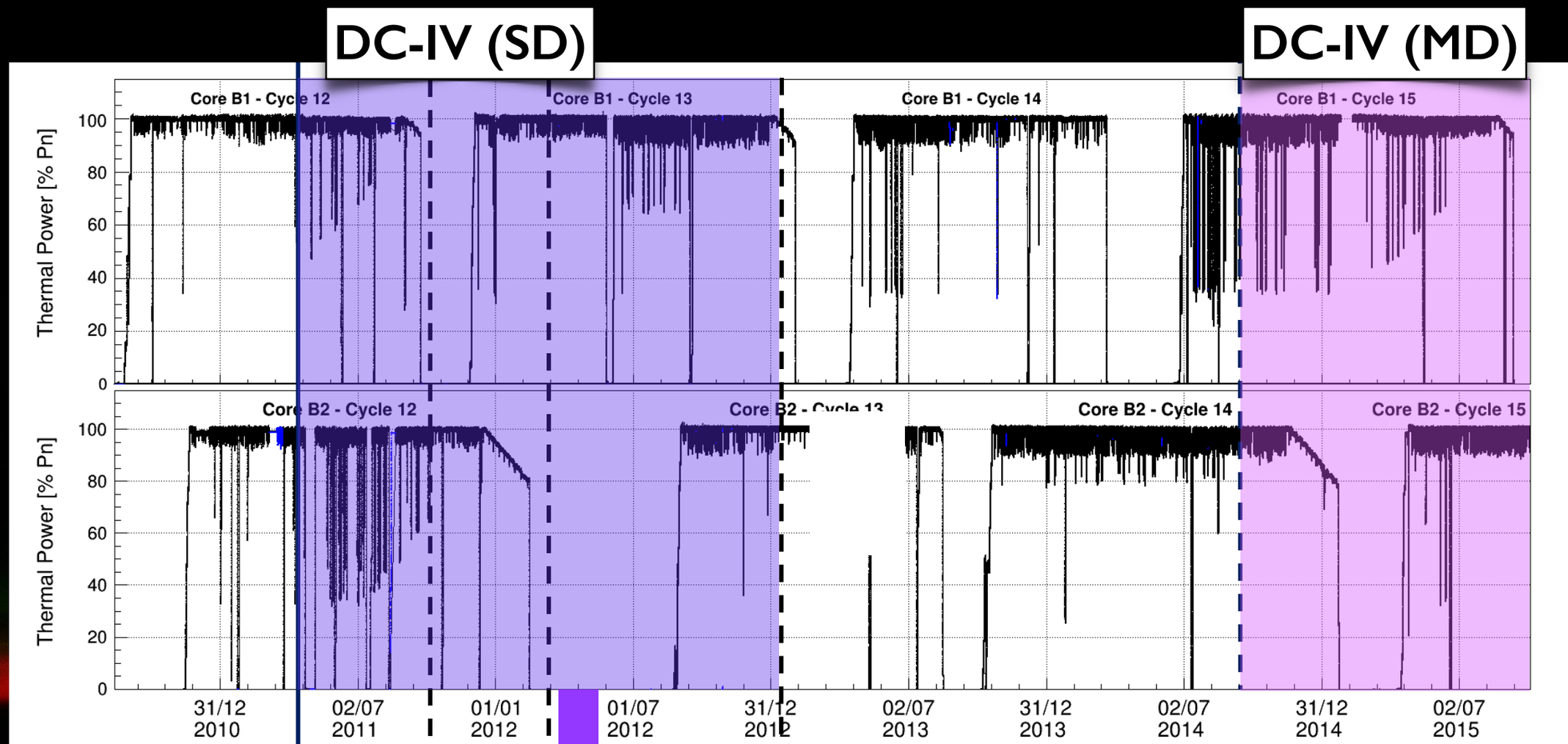
- FD-I≈FD-II (same)→ strongly correlated BG & response
  - precious extra Li+He BG & **Reactor-OFF** info
  - FD-II hardware upgraded (2x more gain & all PMTs ON)
- **indirect ND monitored:** new error **~0.9%** (1.7% before)

- FD-II **directly ND monitored**
- correlation FD-II with FD-I and with ND
  - unknown inter-reactor error correlation
  - **use value maximising $\sigma[\sin^2(2\theta_{13})]$**

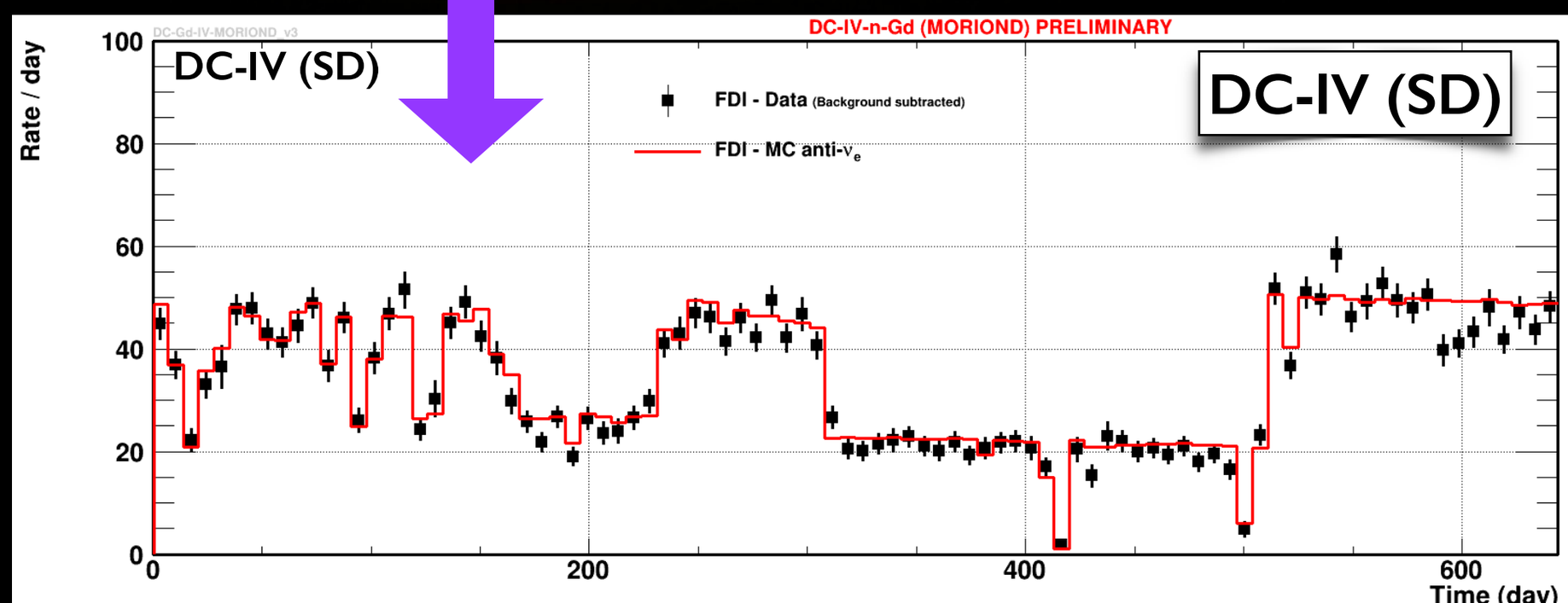
Anatael Cabrera (CNRS-IN2P3 & APC)

reactors luminosity…

reactor power information



measured IBD's



Anatael Cabrera (CNRS-IN2P3 & APC)

Reactor flux uncertainties

Double Chooz Preliminary

without Bugey4
total error ~3.0%

	FD-I (%)	FD-II (%)	ND (%)
Bugey4	1.40	1.40	1.40
Energy per fission	0.16	0.16	0.16
Spectrum$\oplus\sigma_{IBD}$	0.20	0.20	0.20
Baselines	< 0.01	< 0.01	0.01
Fission fraction (α_k)	0.82	0.74	0.73
Thermal power (P_{th})	0.44	0.44	0.44
Total	**1.70**	**1.66**	**1.66**
ρ(FD-I:FD-II) (error)	**0.72 (0.90% relative)**		—
ρ(FD-II:ND) (error)	—	**>0.99 (0.07% relative)**	

Correlated across FD-I, FD-II and ND

Uncorrelated
⇒ suppressed with two detectors (in parallel operation)

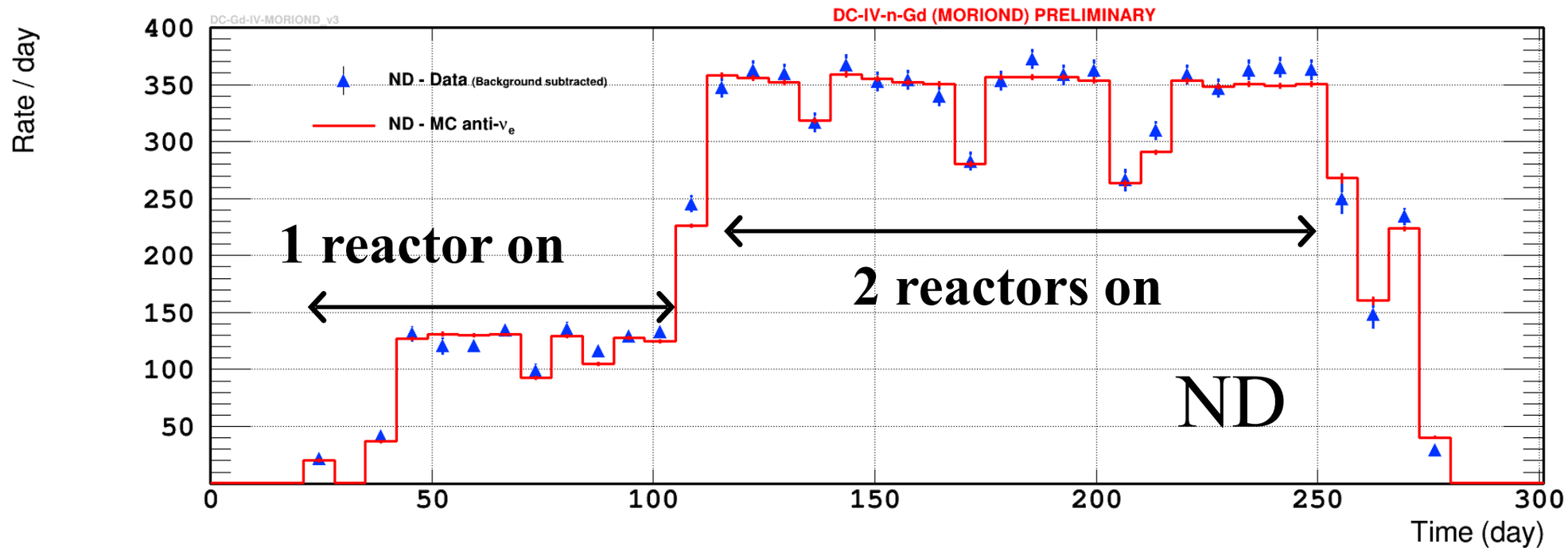
inter-reactor correlation for α_k and P_{th}: $\rho_{B1/B2}$ = 0.78
(most conservative assumption with current data set)

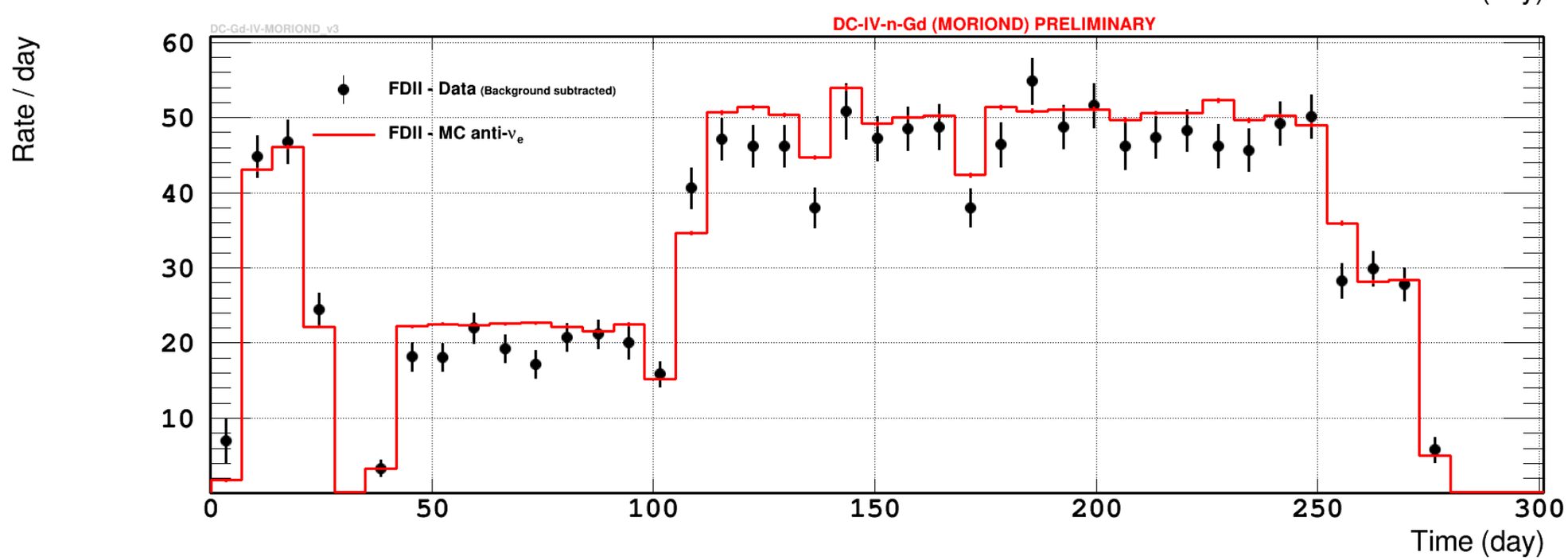
- reactor flux uncertainty suppressed to **< 0.1%** in multi-detector analysis thanks to nearly **iso-flux** experimental setup in DC

IBD rate vs. time

Background subtracted

Double Chooz Preliminary

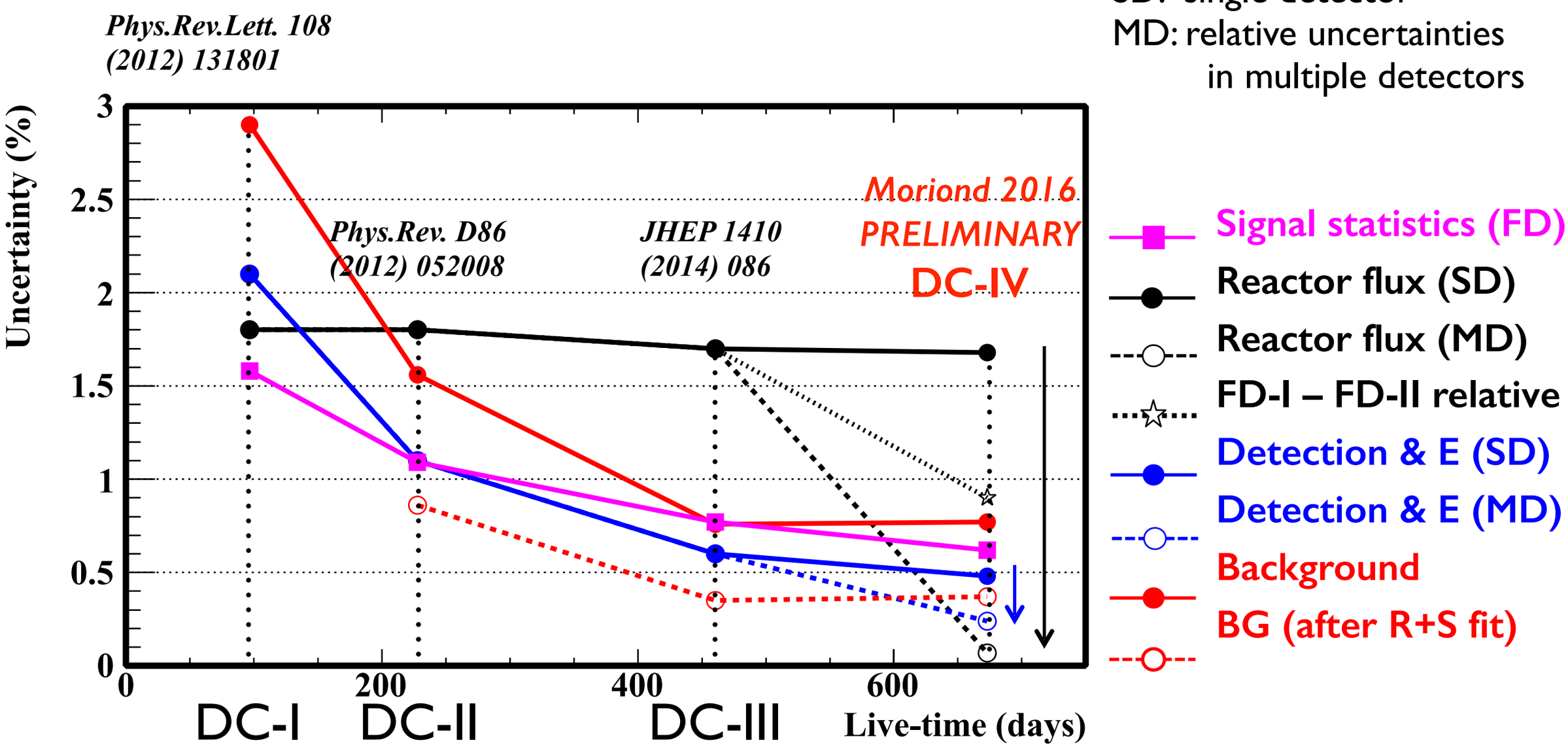




ND is ~perfect monitor of FD (rate & shape): ~iso-flux configuration

uncertainties in multi-detectors analysis

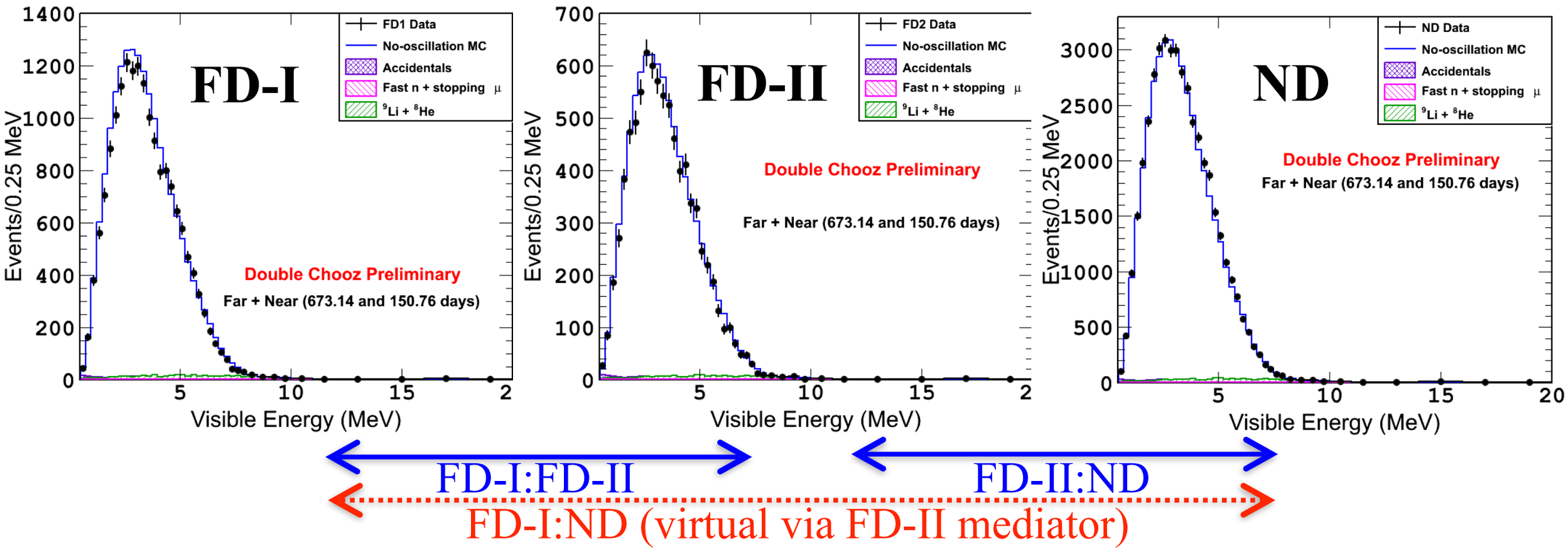
SD: single detector
MD: relative uncertainties in multiple detectors



- systematic errors suppressed with two detectors and in rate+shape fit
  ⇒ All systematic uncertainties below < 0.4% (after R+S fit)
- current precision (9 months ND) is limited by the statistical uncertainty

Extraction of θ_{13} by oscillation fit

- Compare FD-I, FD-II and ND data simultaneously to predictions
  - Background rate and shape estimated by data (Li rate not constrained)
  - Observed data in reactor off as separate term ⇒ BG constraint



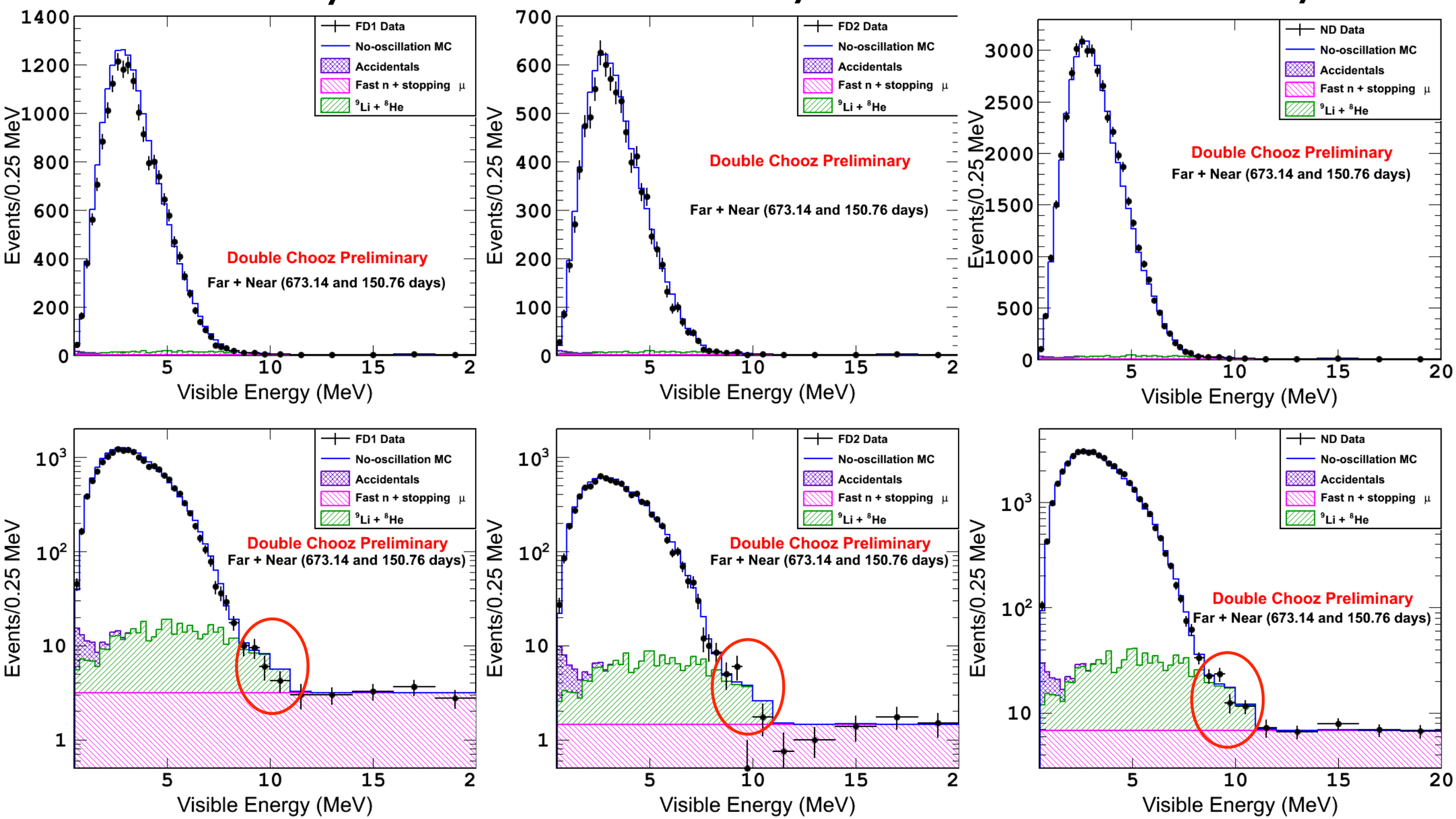
- correlation of systematic uncertainties are taken into account
- energy: **non-linearity uncorrected across all detectors** (→conservative)
- many cross-checks (data-only, BG constraint etc) & independent χ^2 and likelihood fits (→different implementation of systematics)

prompt energy spectrum

FD-I
460.93days

FD-II
212.21days

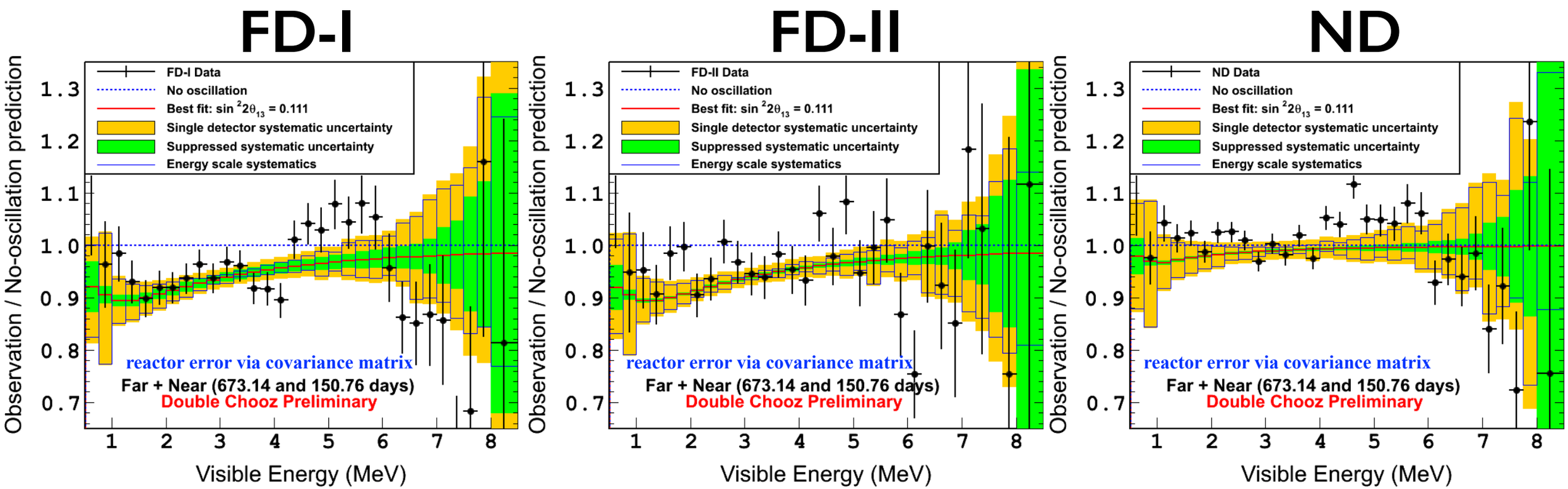
ND
150.76days



SD fit: R+S most precise measurement ^{8}Li+^{9}He & θ_{13} (for each)

Fit results

Double Chooz Preliminary

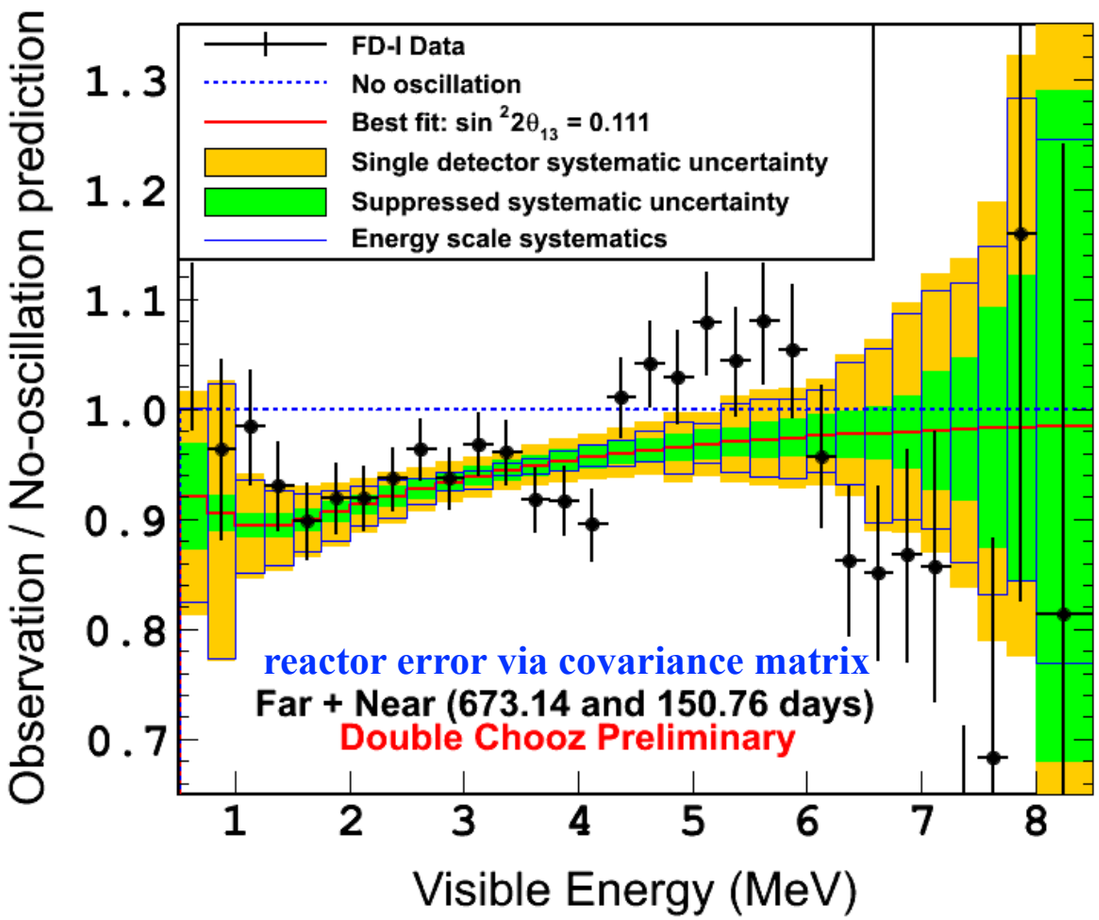


best-fit: $\sin^2 2\theta_{13}$=0.111 ± 0.018 (stat.+syst.) (χ^2/dof = 128.8/120)

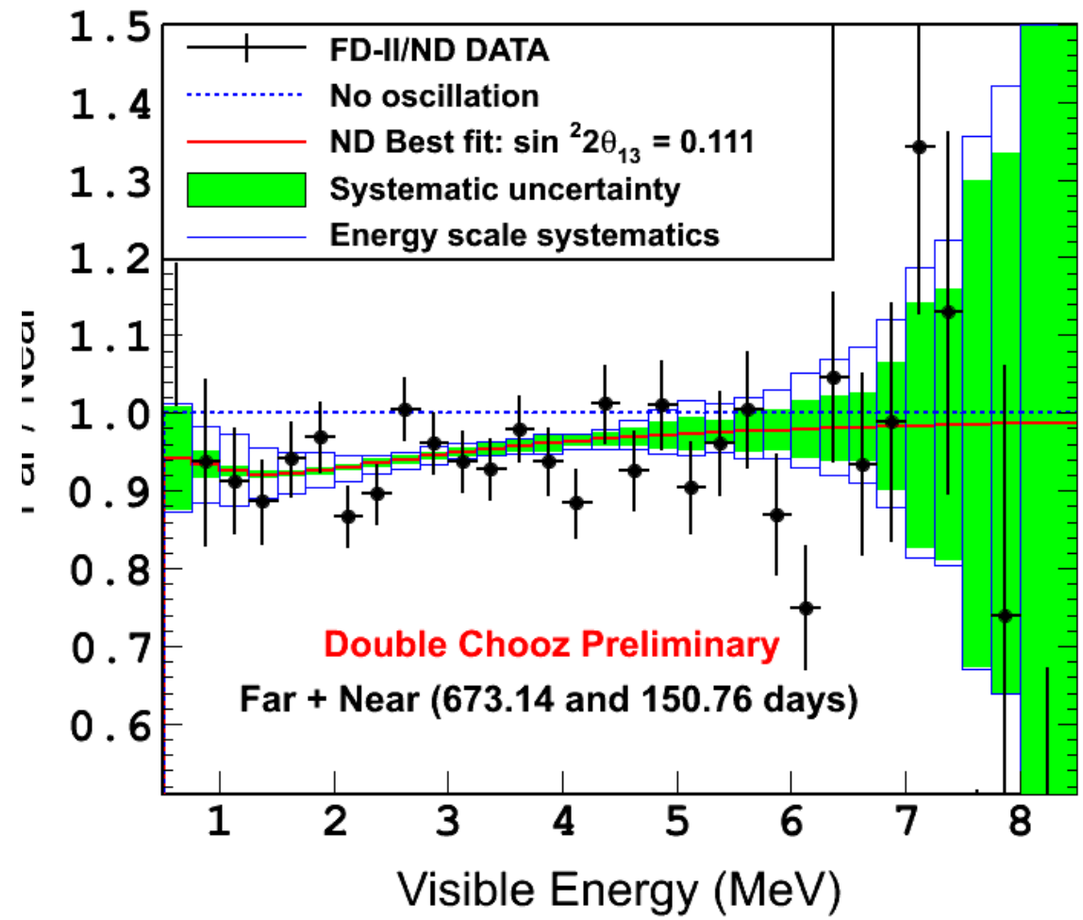
- marginalised over latest MINOS' **$|\Delta m_{23}^2|$ = [2.28−2.46]×10^{-3}eV^2** (Normal Ordering)
- non-zero θ_{13} observation at 5.8σ C.L.
- **cosmogenic ^{9}Li+^{8}He BG: 0.75±0.14 d^{-1}(FD), 4.89±0.78 d^{-1}(ND)**
- **fast-n (stop-μ) BG: 0.535±0.035 d^{-1}(FD), 3.53±0.16 d^{-1}(ND)**
- **energy non-linearity:** consistent across all detector as well as calibration data (non-trivial)

FD-I ⊕ FD-II / ND ratio

FD-I data/prediction



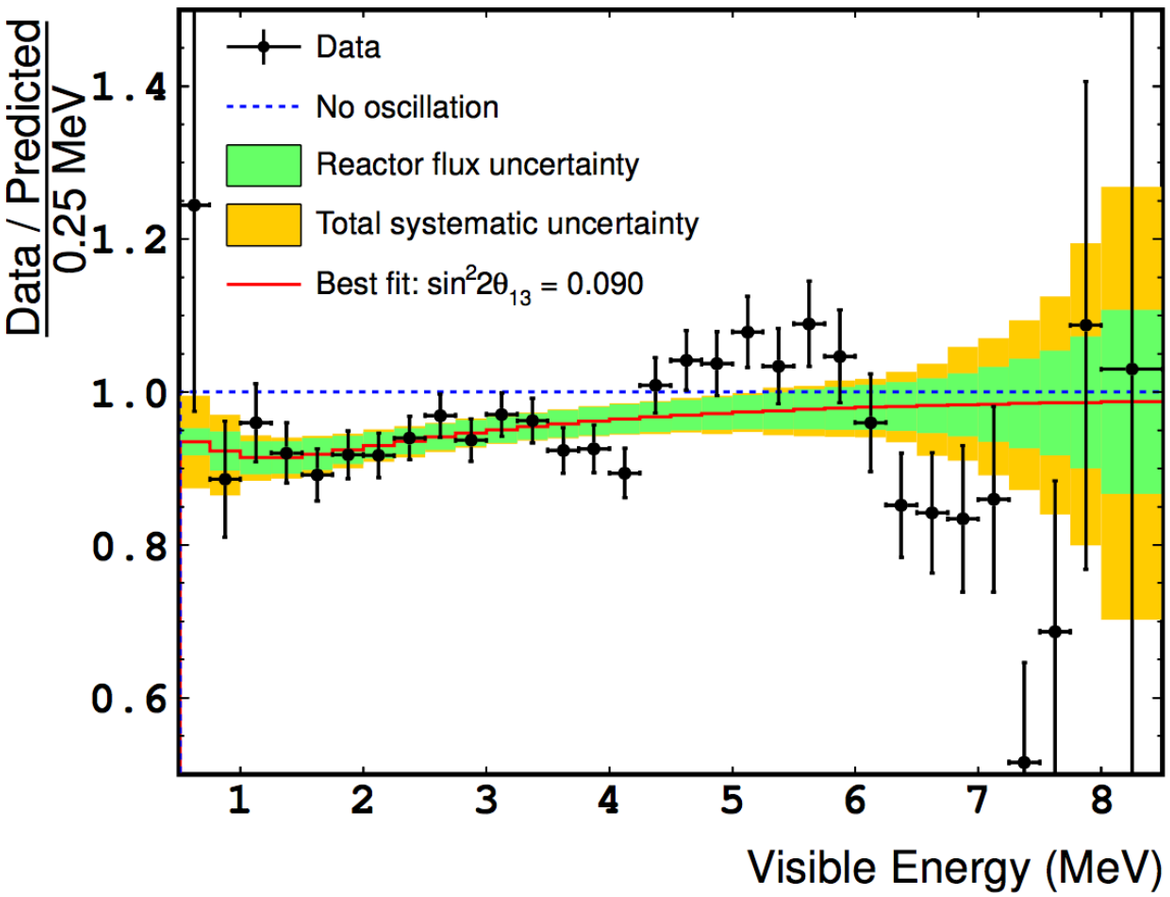
FD-II data/ ND data



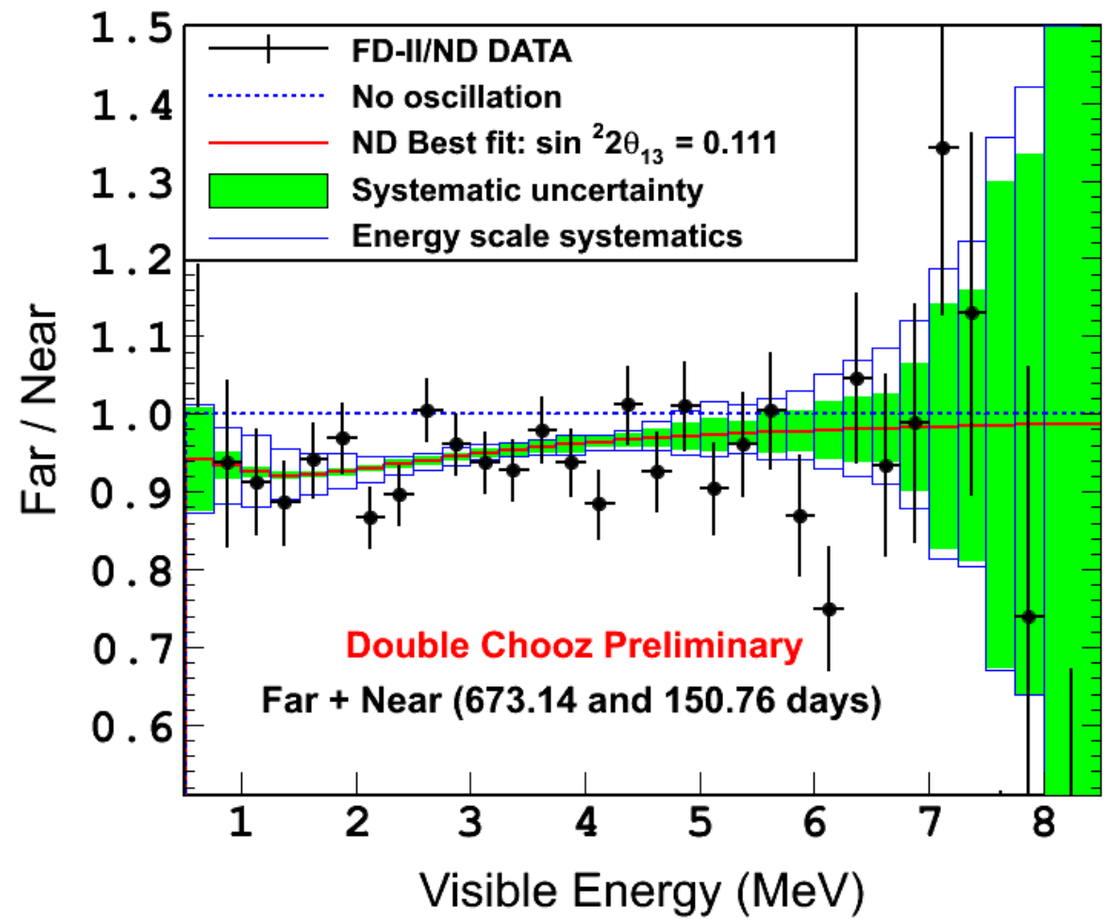
- Systematic uncertainties suppressed in FD-ND relative comparison
- Currently energy uncertainties are assumed to be uncorrelated across detectors (conservative approach)
  ⇔ strong correlation expected with the same scintillator and electronics

DC-Gd-III (SD) vs DC-Gd-IV (MD)

FD-I data/prediction MC (Gd-III)

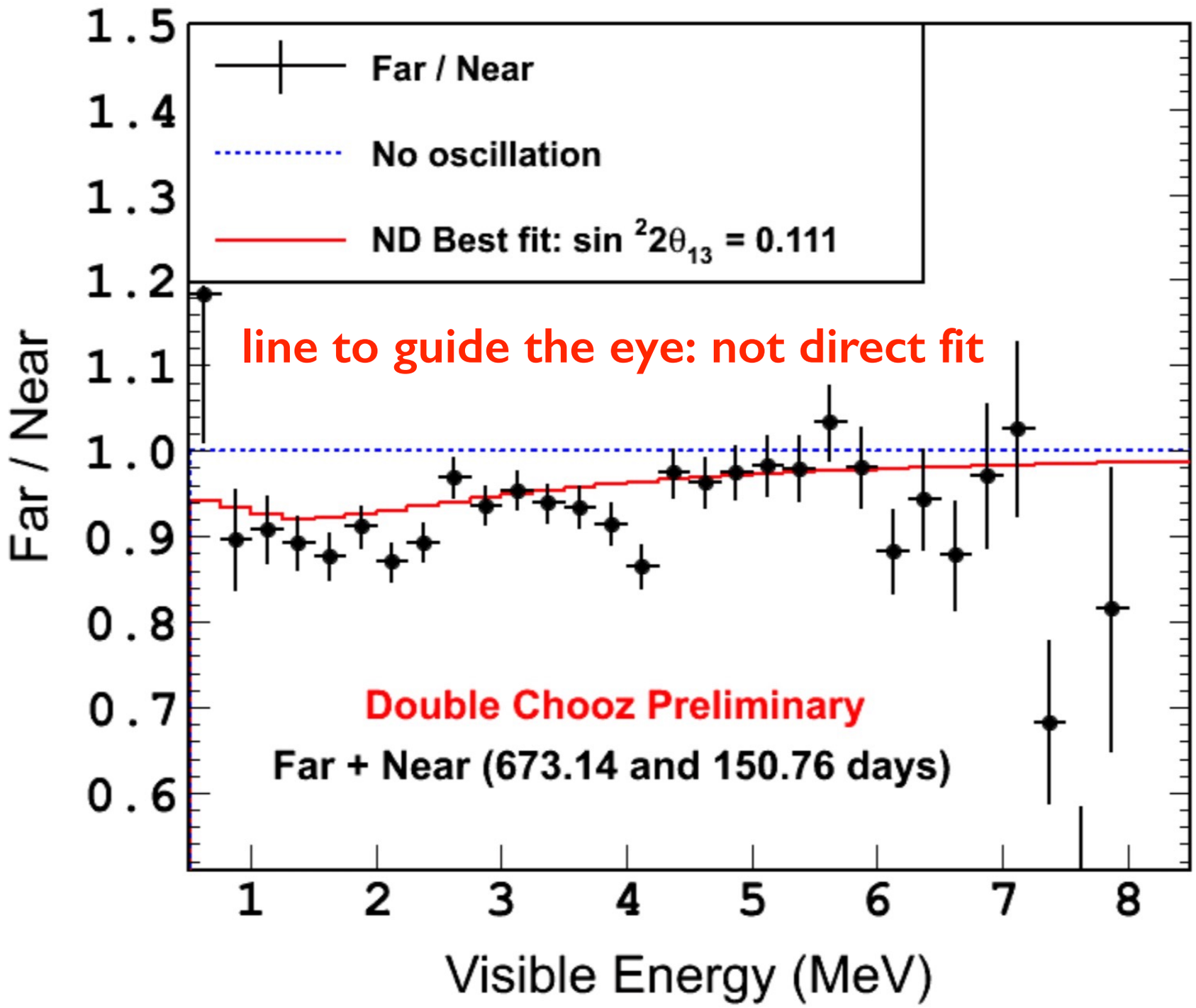


FD-II data/ ND data (Gd-IV)



- **DC-IV:** remarkable systematics suppression across ND:FD (flux: 0.07%)
  - very conservative treatment of energy-linearity: uncorrelated all detectors
  - lack of statistics in FD-II (9months only)
- **DC-III:** very precise single-detector analysis (detection⊕energy: ~0.6%)

(FD-I⊕FD-II) / ND ratio



consistency guideline with additional FD-I (higher stats→ shape)

$\theta_{13}^{\text{DC-IV-Moriond}}$ vs $\theta_{13}^{\text{DYB4}}$…

in terms of $\sin^2(2\theta_{13})$…

Δ(DC:DBY) ~+35%
[significance ~1.6σ]

$$\sin^2(2\theta_{13})^{\text{DC-IV-M}} = (0.111 \pm 0.018)$$
$$\sin^2(2\theta_{13})^{\text{DB4}} = (0.084 \pm 0.005)$$

in terms of $\sin^2(\theta_{13})$…

$$\sin^2(\theta_{13})^{\text{DC-IV-M}} = (0.0286 \pm 0.0048)$$
$$\sin^2(\theta_{13})^{\text{DYB4}} = (0.0215 \pm 0.0013)$$

implications…?

Double Chooz θ_{13} in the world

World θ_{13} comparison

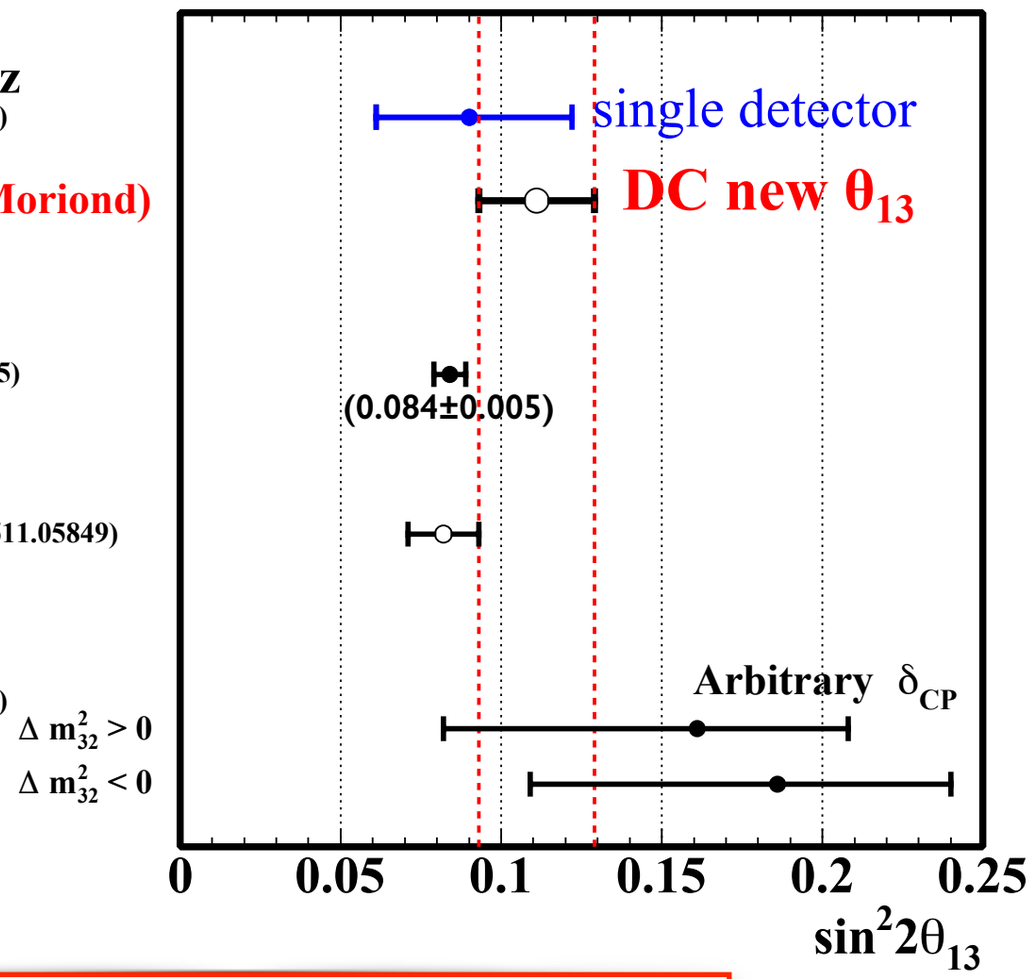
Double Chooz
JHEP 1410, 086 (2014)

Preliminary (Moriond)

Daya Bay
PRL 115, 111802 (2015)

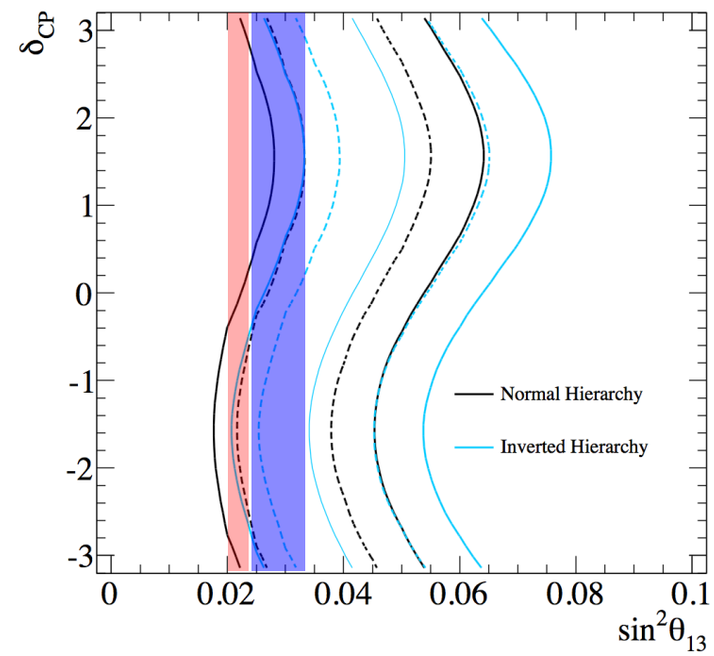
RENO
Preliminary (arXiv:1511.05849)

T2K
PRD 91, 072010 (2015)



● published
○ preliminary

@Moriond-2016: DYB Gd-n⊕H-n: (0.082±0.004)



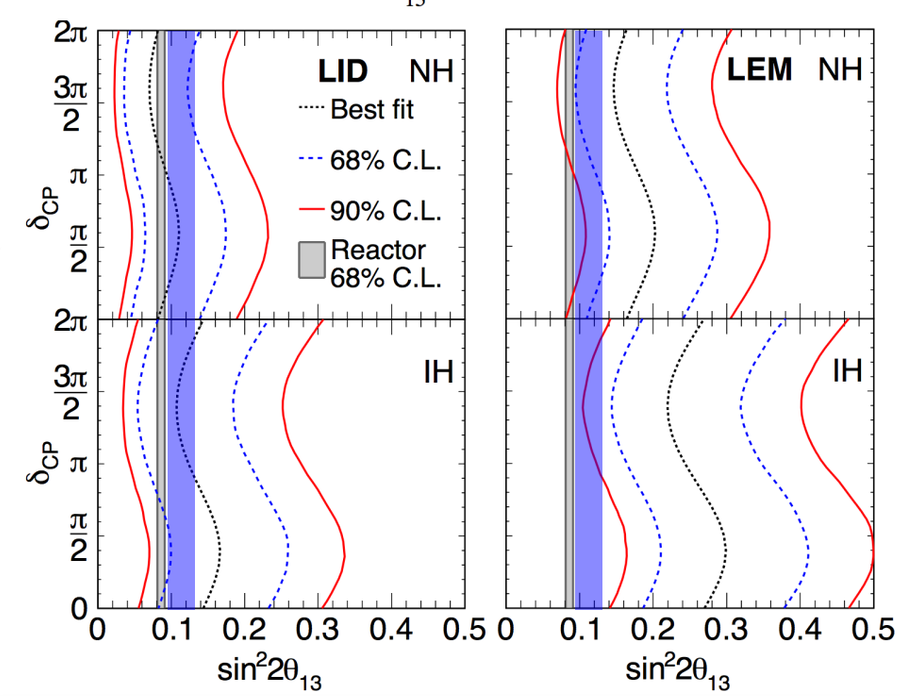
Reactor vs. T2K

PRD91 072010 (2015)

Double Chooz 1σ
Daya Bay 1σ

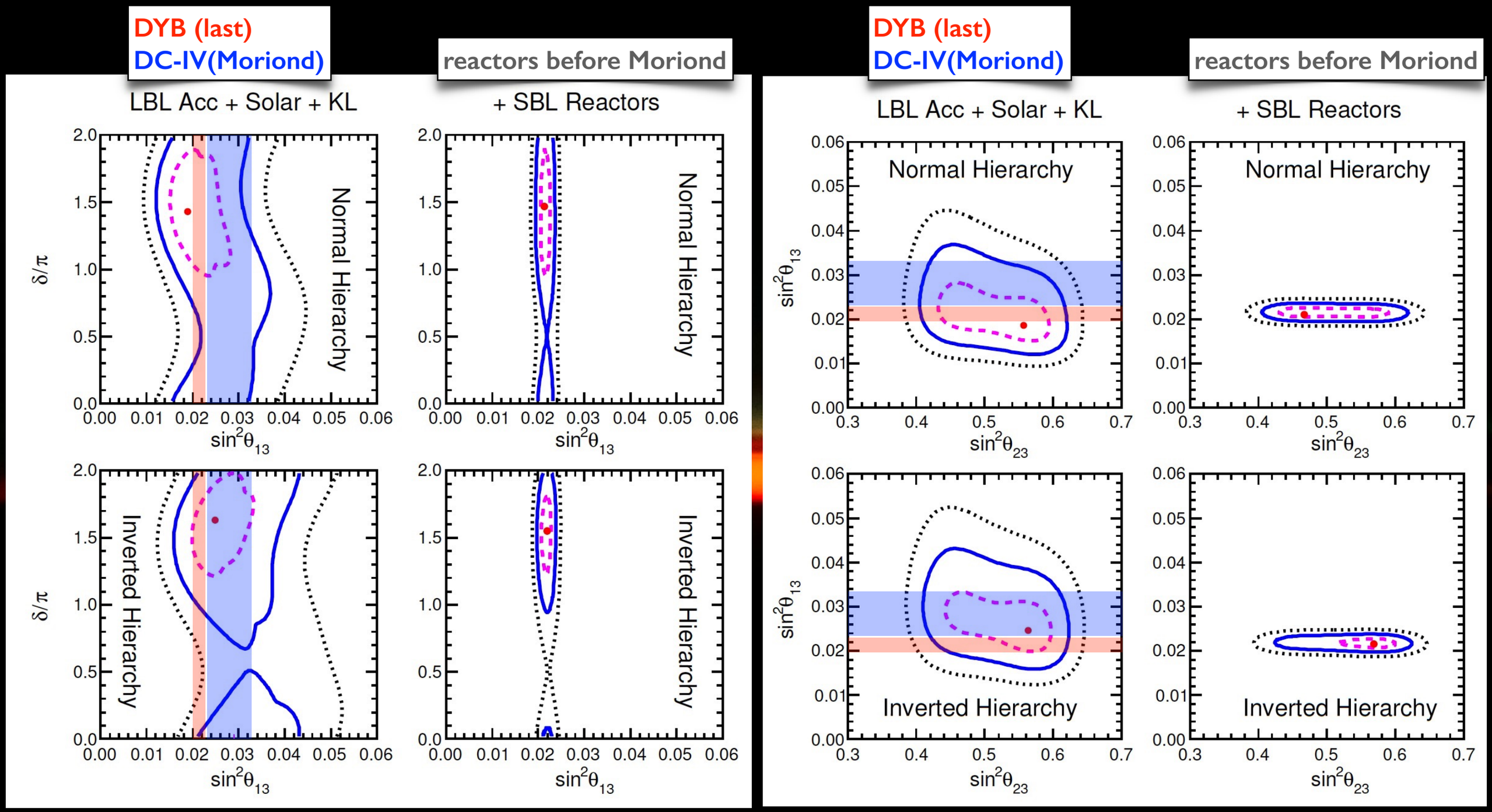
Reactor vs. NOvA

arXivL1601.05522
(accepted by PRL)



- DC θ_{13} is higher than other reactor θ_{13} by **~35% (1.4σ→1.6σ wrt DYB)**
- Long baseline (T2K, NOvA) weakly favours higher θ_{13} than reactor average
- Reactor θ_{13} is key parameter to solve CP-violation and mass hierarchy

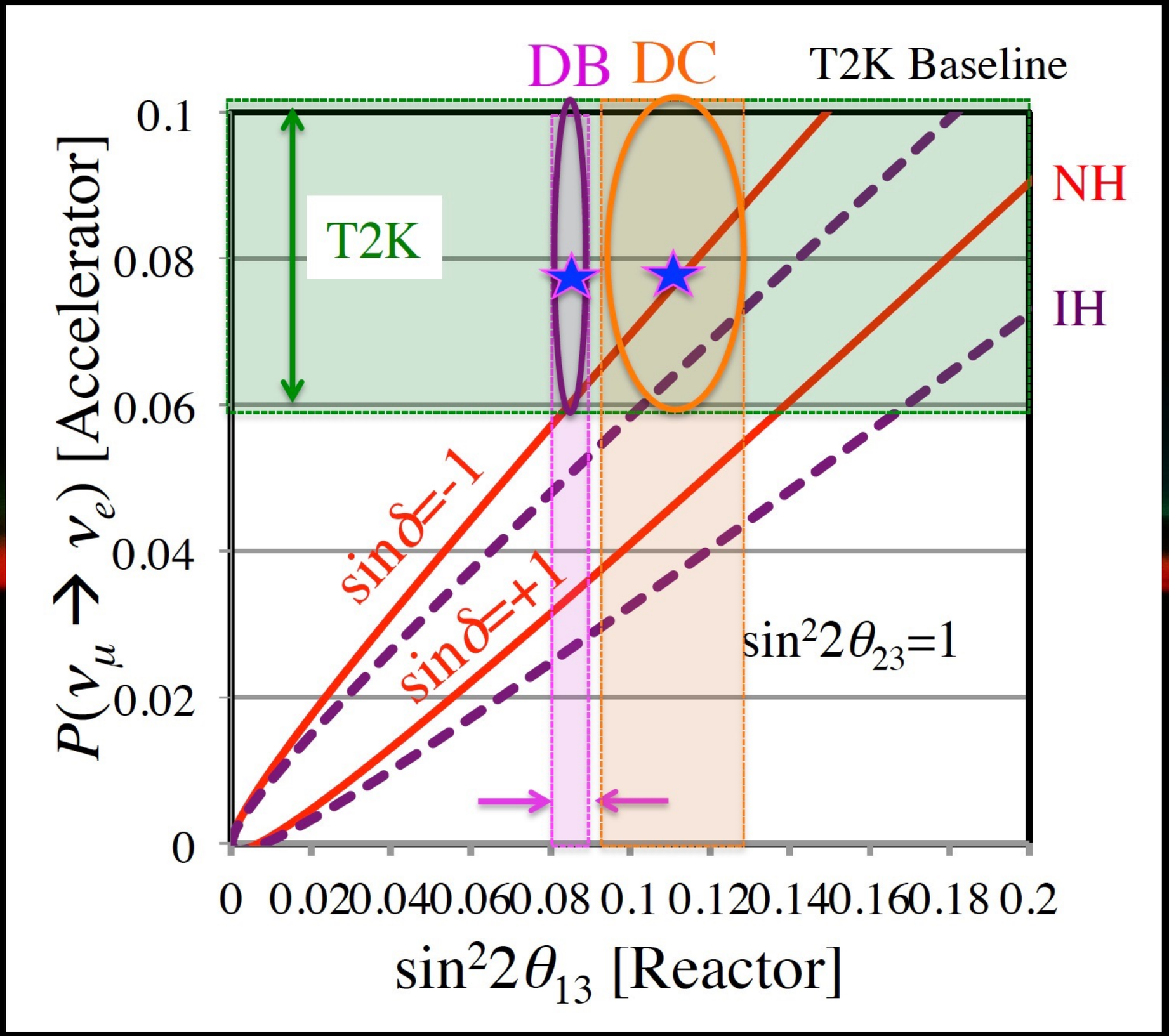
DC-IV implications to the global picture…



(**caveat:** drawn regions are very approximative→ overlaid)

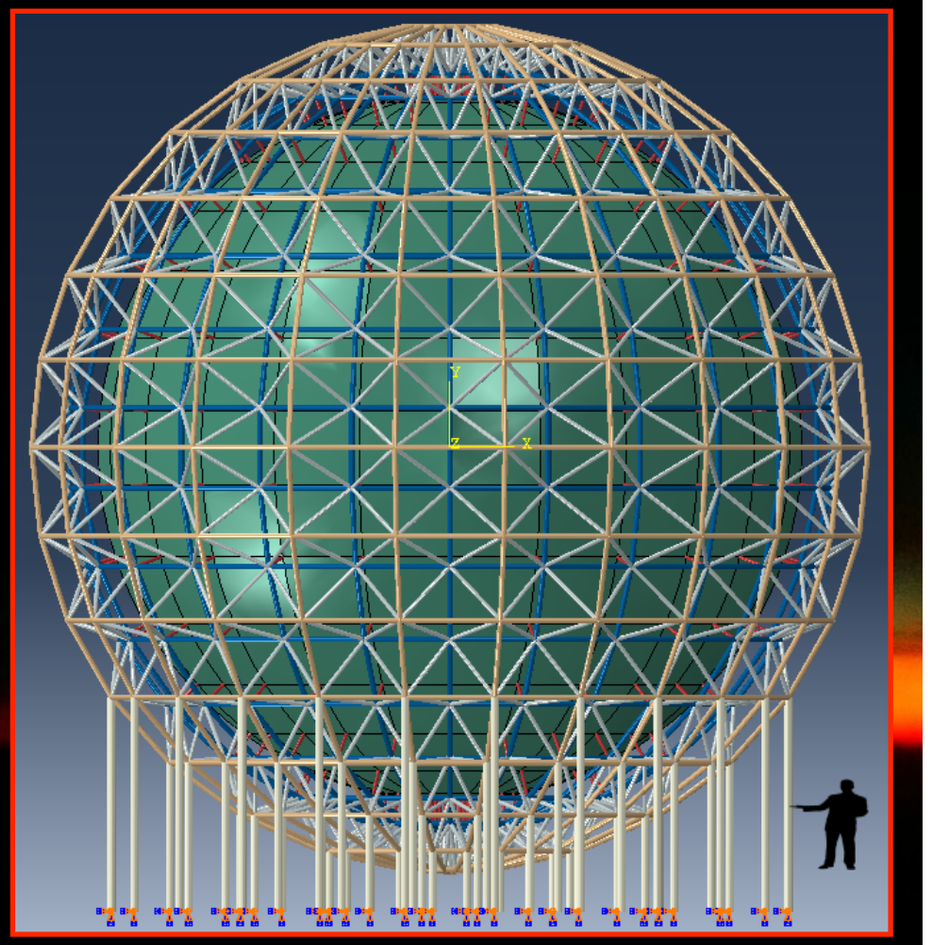
solution phase-space might change if θ13 was larger (not yet)

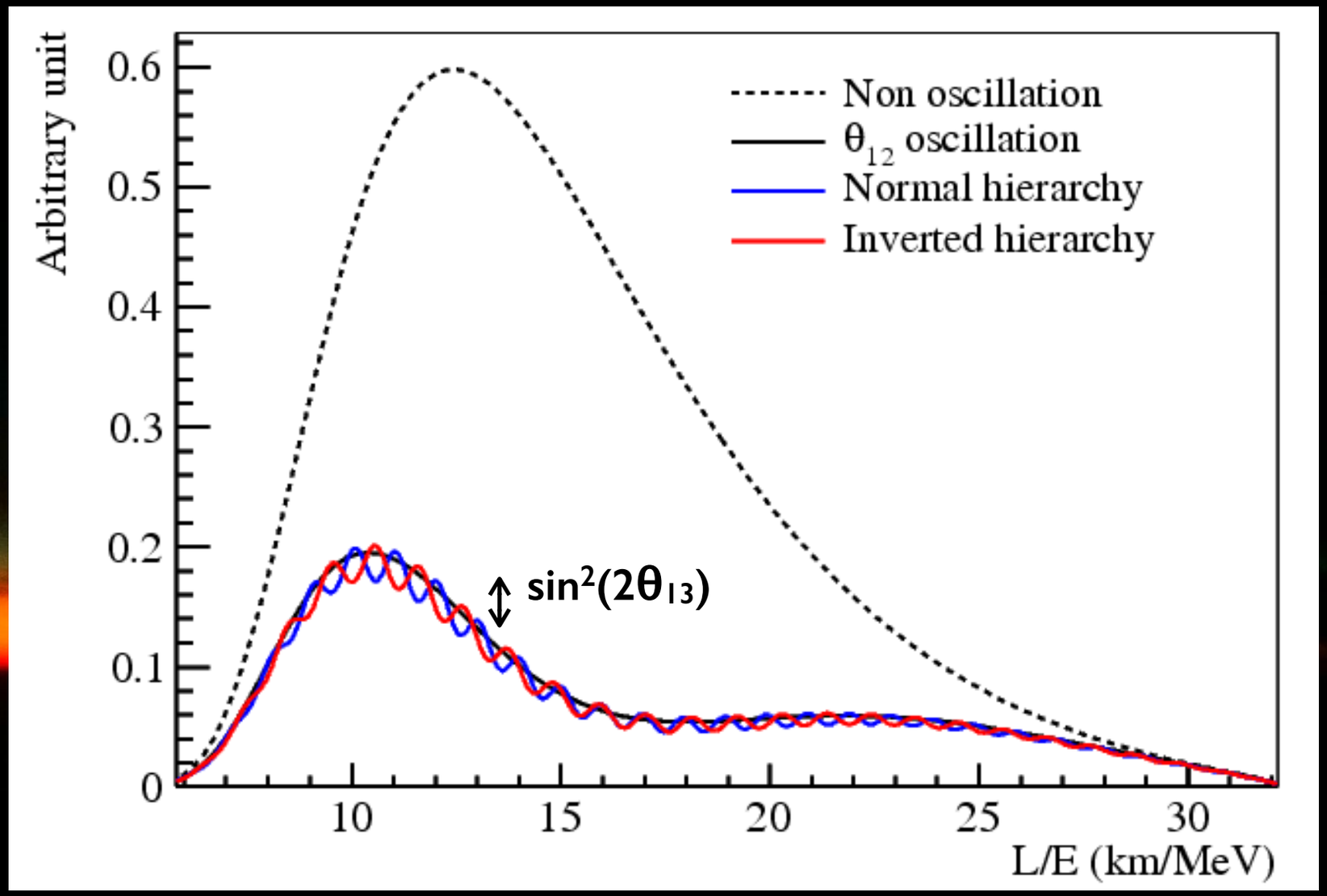
interplay beams⊕reactors…



courtesy by Suekane-san

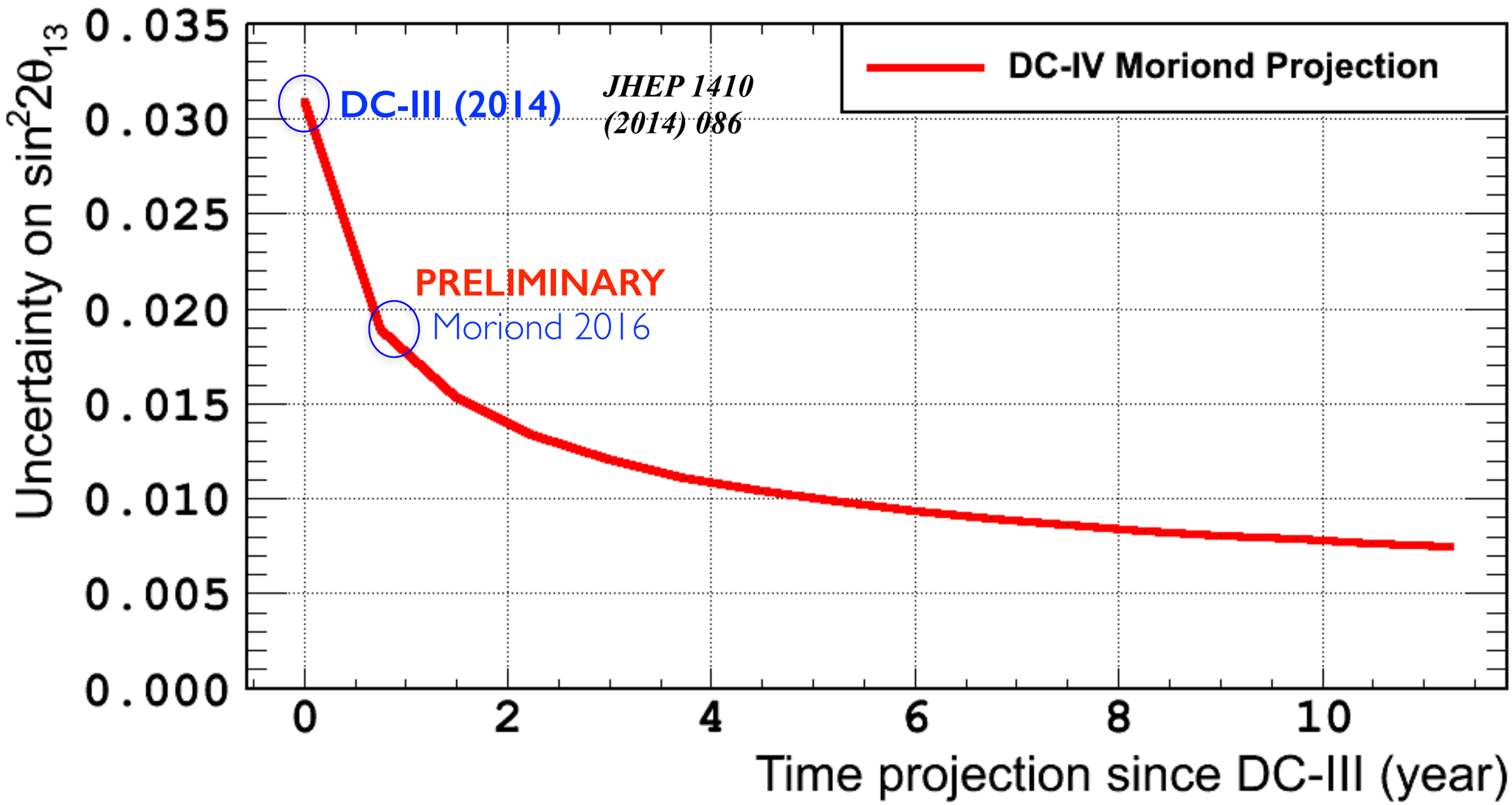
…and JUNO?





JUNO will benefit from larger θ_{13}… (if true)

DC-IV improvement with statistics…



DC-IV can go for >10years without hitting systematics (≲0.005)

(⇒ analysis is too good for detector's size)

— working on higher stats sample —

Reactor-θ_{13}

(combining results)

Daya Bay⊕Double Chooz⊕RENO

1st workshop→ Autumn 2016 (Seoul, South Korea)
(systematics, results, etc)

2nd workshop→ later on (allow full statistics samples)
(towards the combined θ13)

[*the best θ_{13} value for a long while*]

BUMP

AHEAD

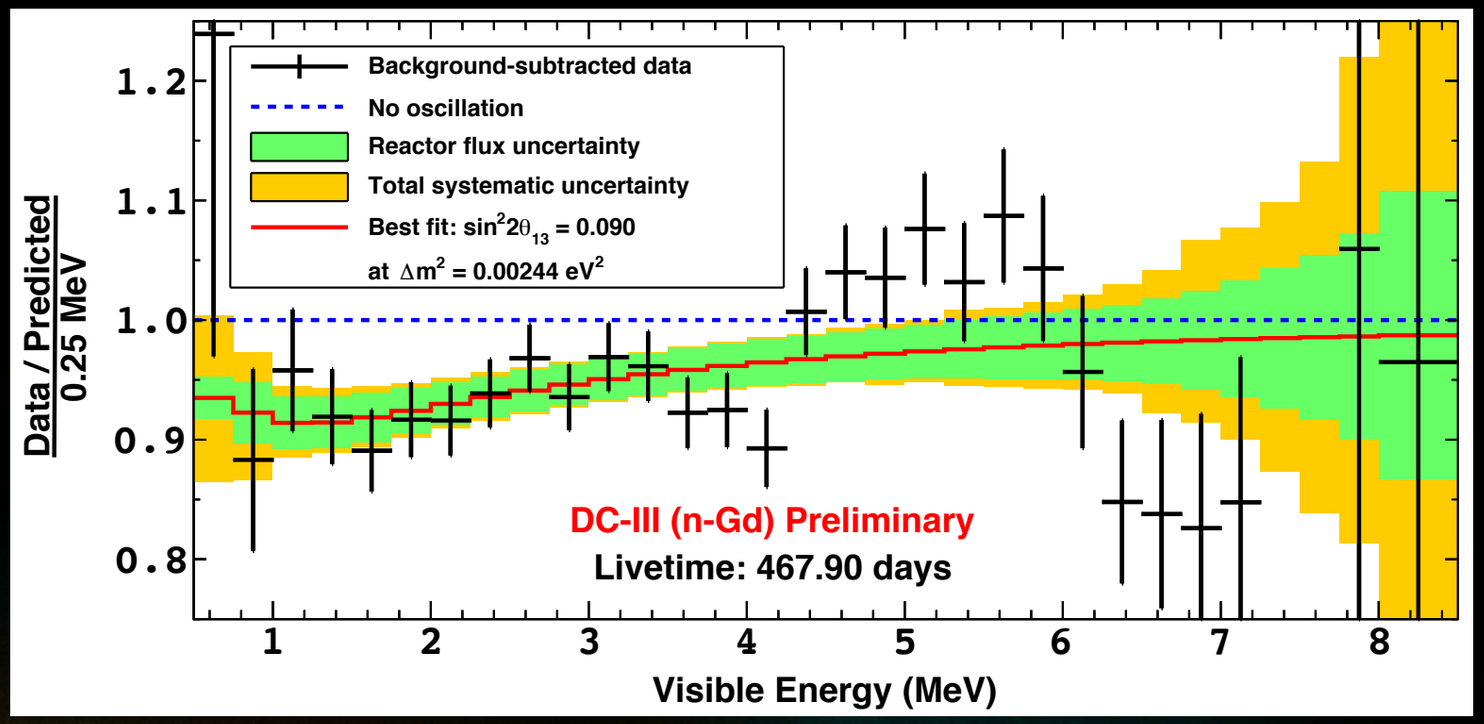
θ_{13} experiments → high precision spectrum…

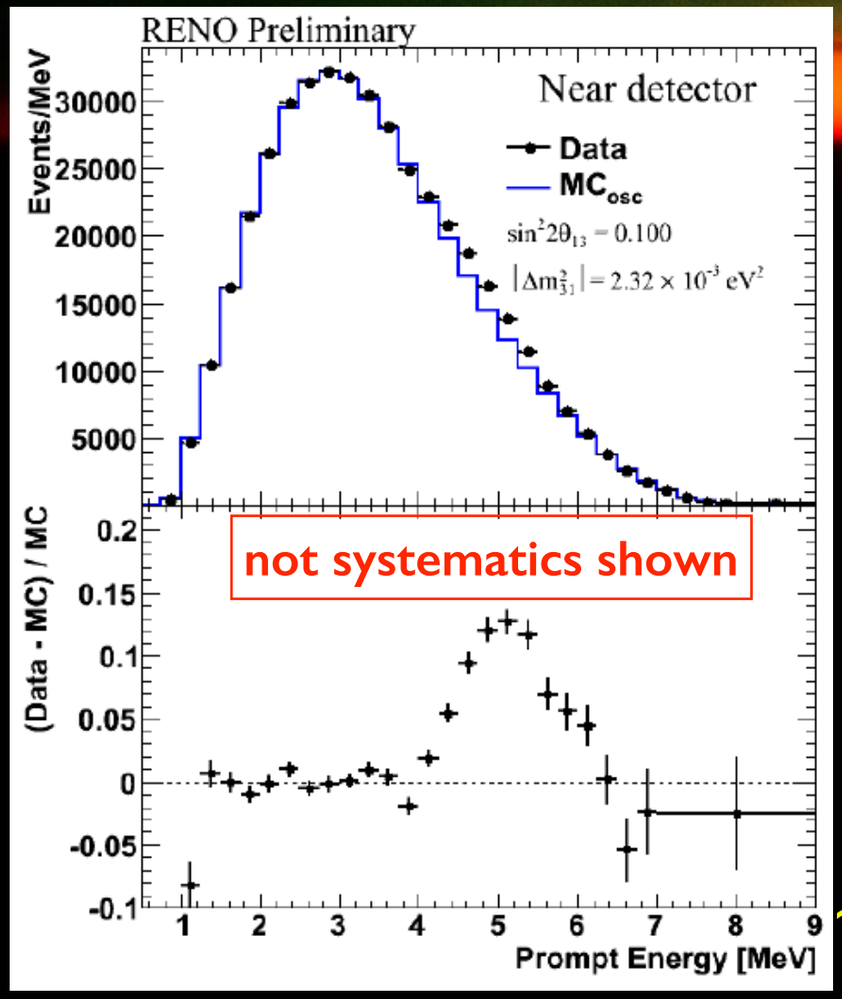
Double Chooz (**May 2014**)

~3.0σ (~17k events @ FD)

σ(stat): ~0.8%

σ(detection): ~0.6% (0.4%)





RENO (**June 2014**)

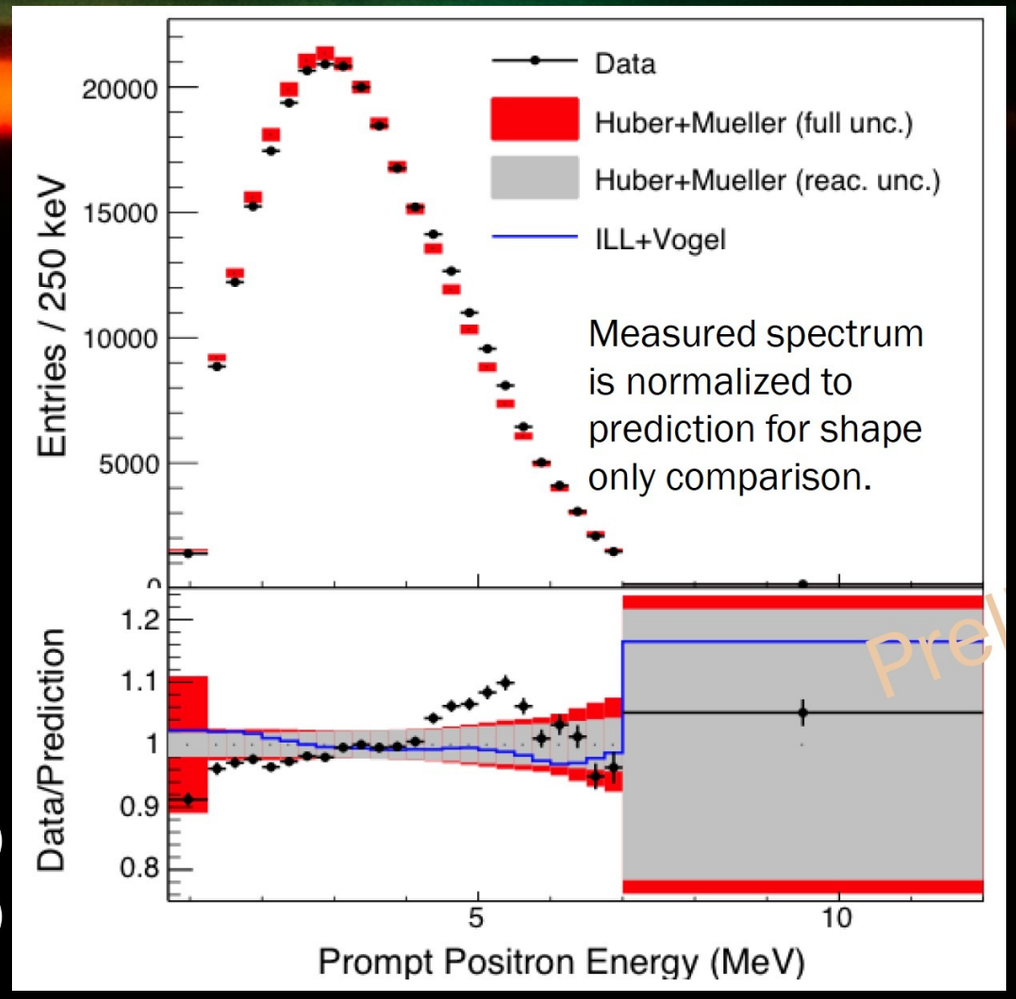
~3.6σ (~500k events @ ND)

σ(stat): ≳0.2%

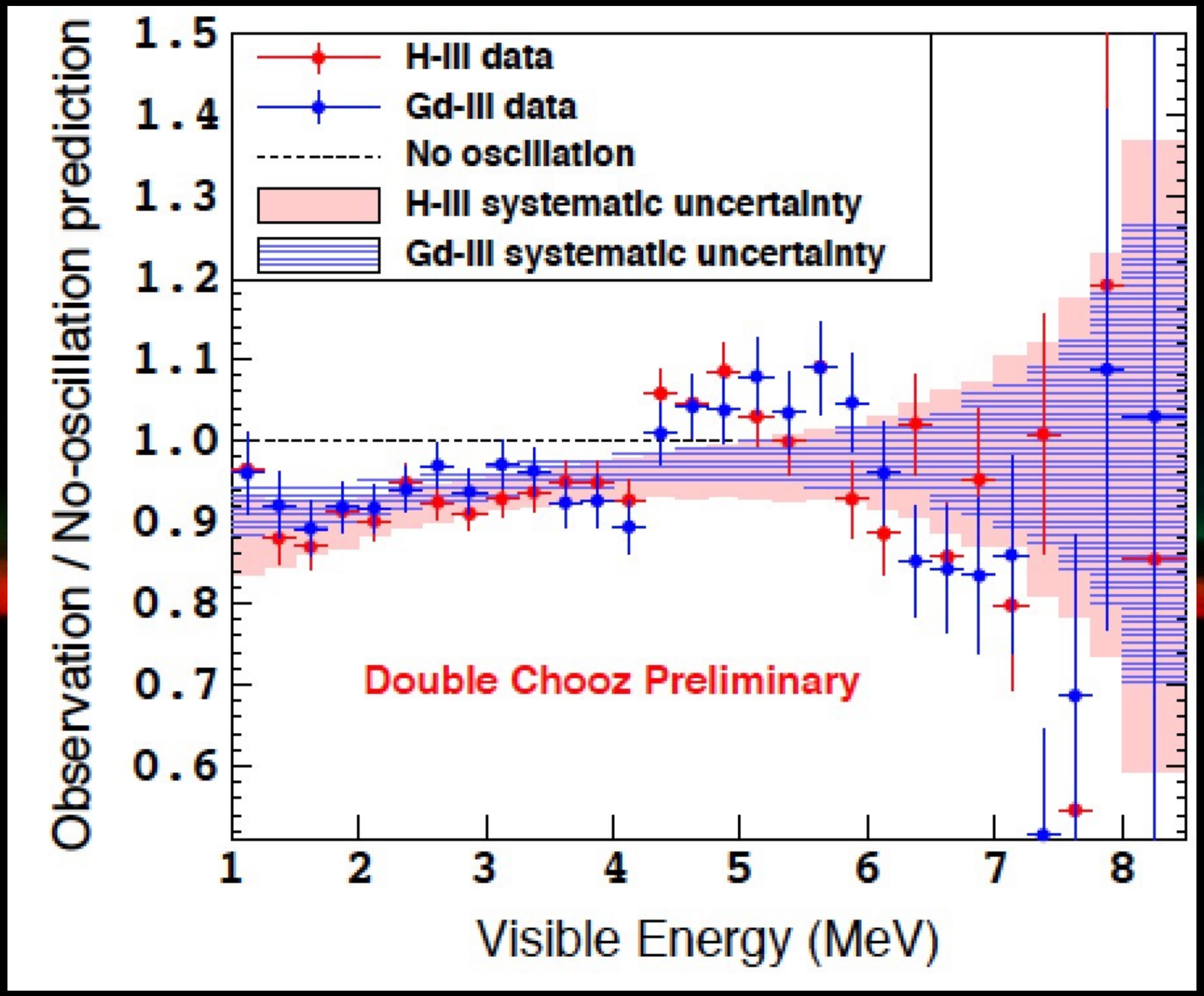
σ(detection): ≳2.0%

Daya Bay (**July 2014**)

~4.0σ (~300k events @ 3xNDs)



[4,6]MeV energy distorsion…

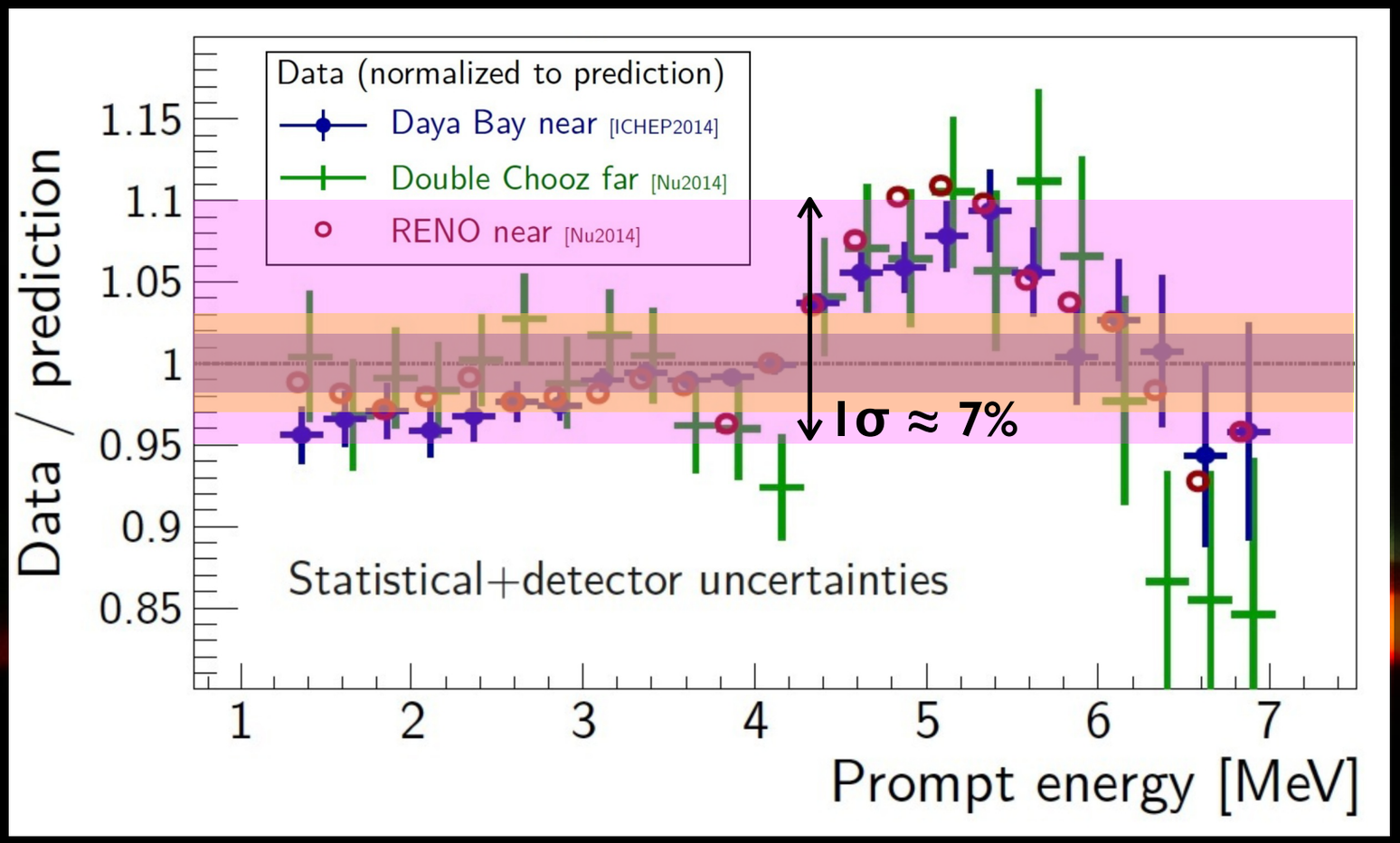


consistent result with both Gd-n and H-n IBDs (independent)

(but **different BGs, detection volume, capture mechanism**)

(θ13 experiments) spectral distorsion [4,8]MeV…

1σ of δ(flux)→ ±3% (DB & RENO) & ±1.7% (DC⊕Bugey4)

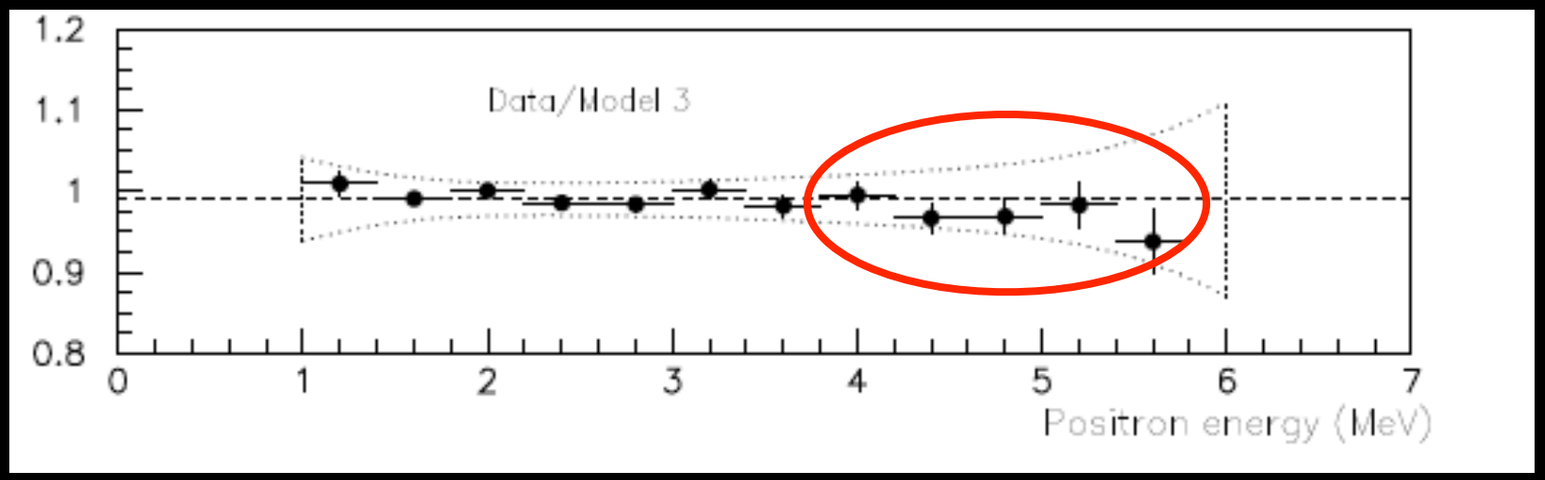


3 different experiments in agreement
(not trivial: not the same fuel)

δ(flux) error is very likely to increase
(hard to believe otherwise)

⇒ necessity for neutrino-sterile hypothesis (reactor-data): insignificant?

how to set new (reasonable) error?



…and what do we do with Bugey3?
(could we ever reconcile?)

5MeV distortion implies…

(the problem)
- its origin might likely entail a complex explanation (nuclear, bias, etc…)
  → likely beyond any particle physics interest (not clear yet though)

(applied neutrino physics)
- reactor neutrino physics precision surpasses reactor nuclear knowledge?
  → neutrino data use to understand better reactor physics (first time ever)

(effective fact)
- incompatible with the ~3% error (conversion method) → **error must be larger**
  → how to set a new error? (not easy)
  → **~(3,7]% error** to be used as effective reference (in the meantime)

(particle physics implication)
- any fundamental physics conclusion/hypothesis relying on reactor-spectrum knowledge (error budget) must be taken with extreme caution — to say the least.

(my opinion)

BUMP

tip: don't go too fast...!

AHEAD

symmetry claims a "discovery"… which one?

A joint Fermilab/SLAC publication

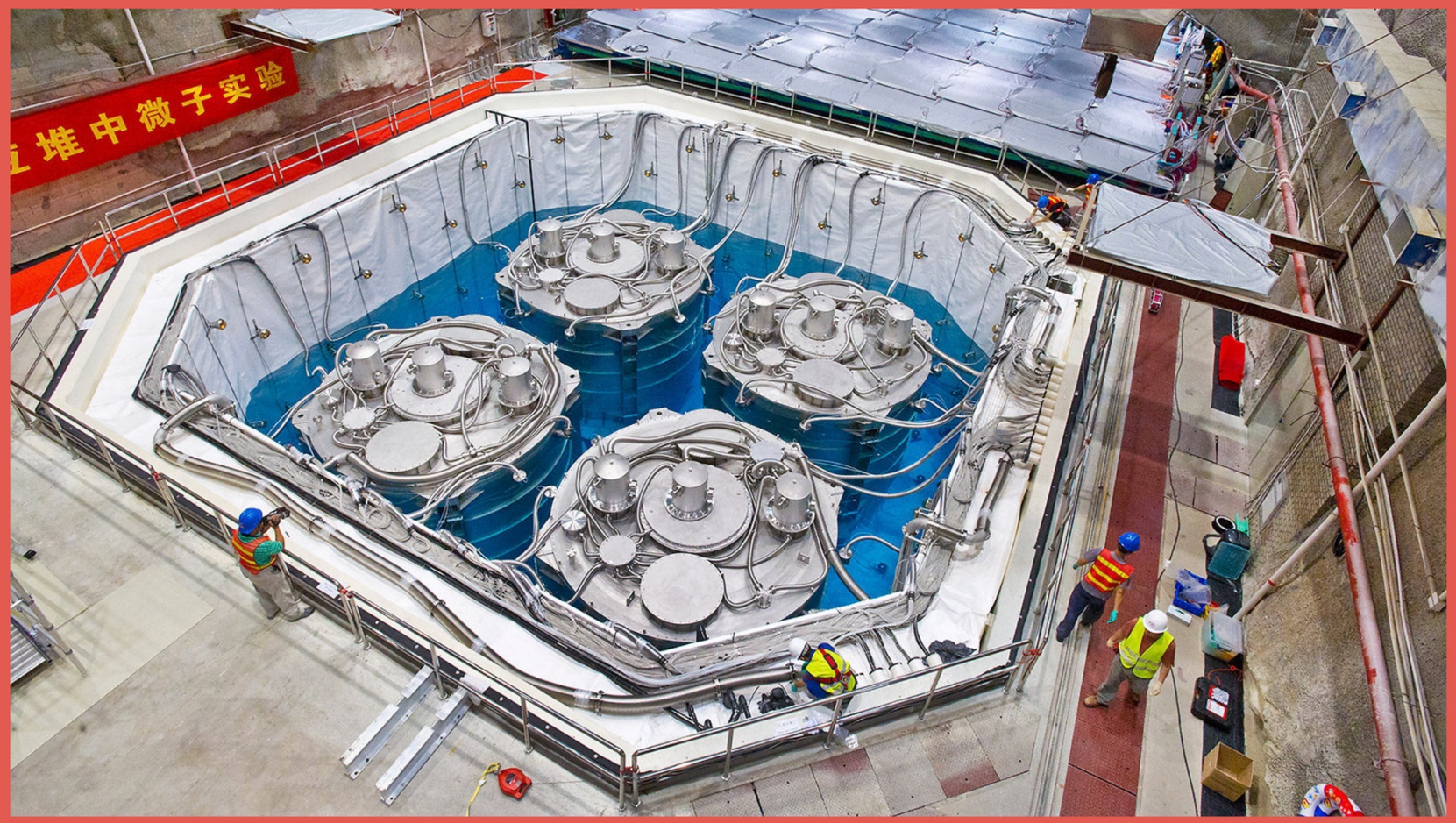


Photo courtesy of Brookhaven National Laboratory

Daya Bay discovers a mismatch

02/12/16 | By Kathryn Jepsen

The latest measurements from the Daya Bay neutrino experiment in China don't align with predictions from nuclear theory.

actually, prediction is (much) based on data (ILL, fits, etc)

no collaboration (so far) has claimed any "discovery" → **why symmetry does?**

what to remember?

DC goals @ proposal…

DC Proposal: hep-ex/0606025

θ_{13}" [6]. But since its publication the worldwide situation has changed and the projects still being considered are Angra [7] in Brazil, Daya Bay [8] in China, Double Chooz in France (see [9, 10] and this proposal), KASKA [11] in Japan and RENO [12] in South Korea. A recent comparison of the capabilities of these experiments can be found in [13, 14]. Double Chooz is particularly attractive because it could limit $\sin^2(2\theta_{13})$ to 0.022-030 (for $\Delta m^2_{31} = 3.5 - 2.5 \times 10^{-3}\ eV^2$), within an unrivaled time scale and a modest cost. Installation of the experiment will start with the far detector located

Double Chooz performance is better than ever…

reached proposal goal (@3years) with only 9months of ND+FD data
(indeed with a "unrivalled time scale")

(DC delays arguably not worse than most HEP experiment→ DYB & RENO superb timing!!)

Summary

- Double Chooz collaboration reported first θ_{13} measurement with two detectors (FD-I: 460.93 days + FD-II: 212.21days + ND:150.76days)
  - **$\sin^2 2\theta_{13}$=0.111 ± 0.018** (stat.+syst.)
  - **reactor flux uncertainty strongly suppressed to < 0.1%** (almost iso-flux)
    - ND: **un-oscillation spectrum direct observable** of experiment
  - **other systematic uncertainties ≤0.5%** (soon: improvements expected) (after analysis improvements made in single detector phase)

- reactor-θ_{13} is a key for current and future neutrino projects aim to solve still unknown CP-violation and mass hierarchy (and other observables) ⇒ **validation by multiple-experiments is essential: agreement?**

- precision now limited by statistics (systematics also dominated by stats) ⇒ **further improvements expected from Double Chooz (very soon!)**

caution…

1.6σ means 1.6σ

(no more & no less)

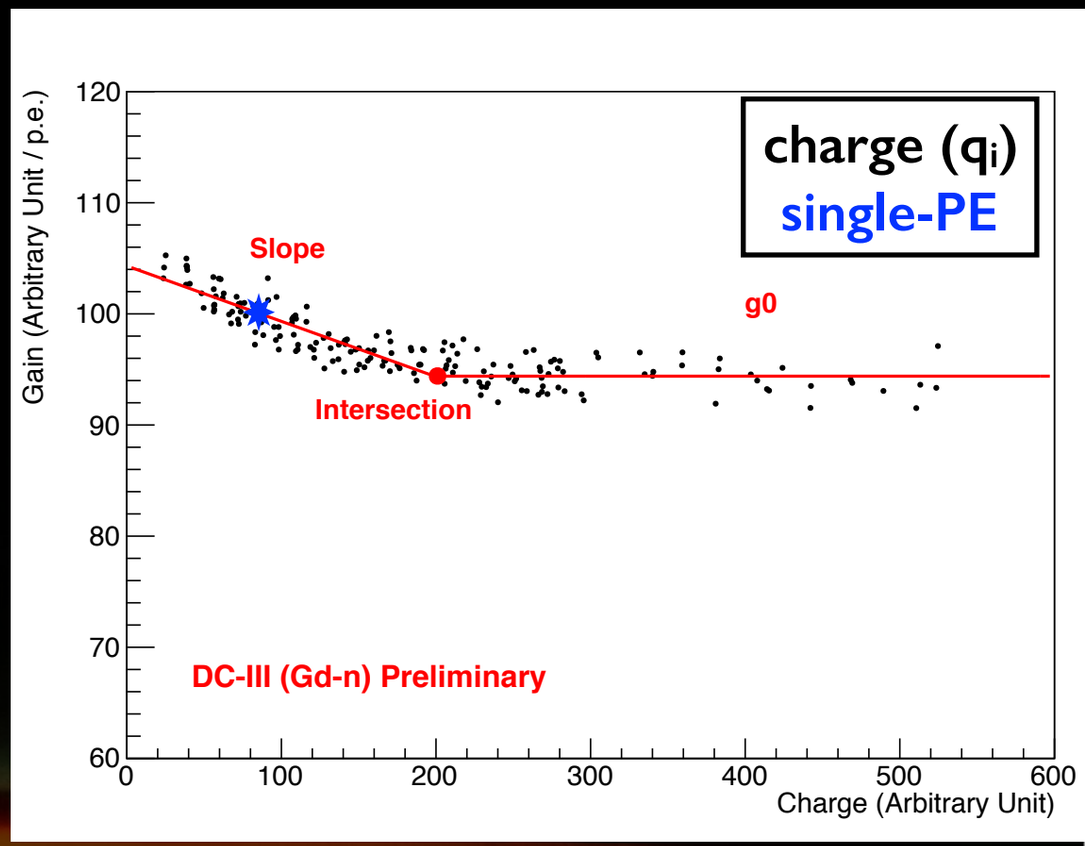
DC: much better error **soon**!

(best value: up to Nature's will)

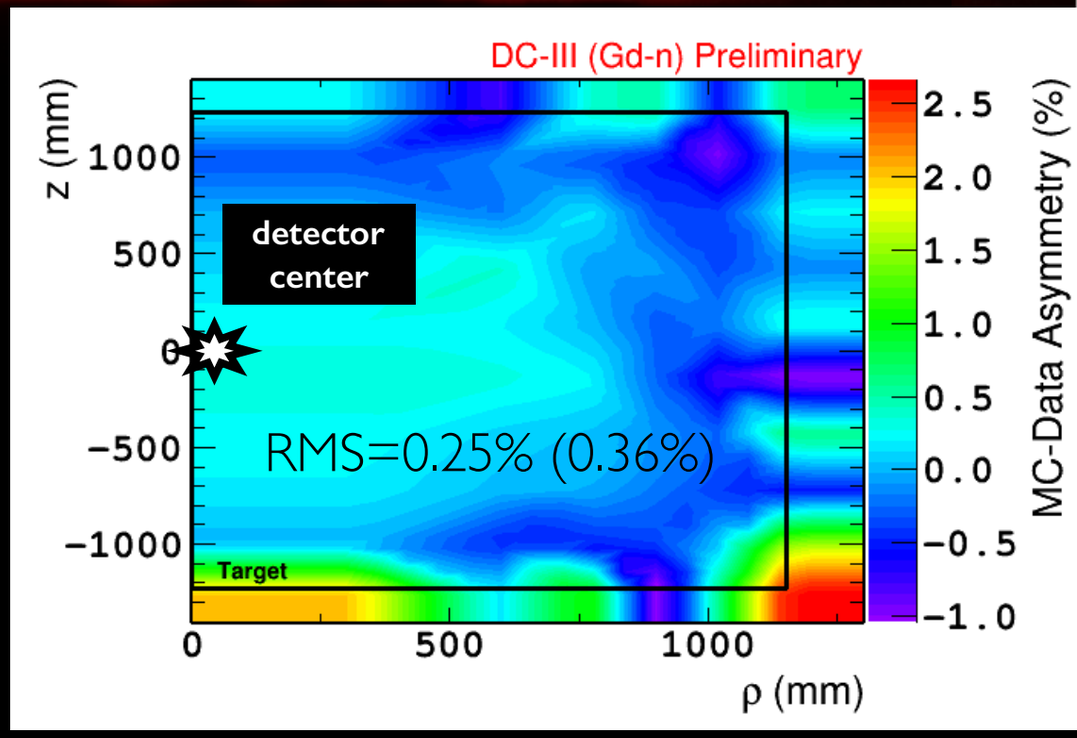
merci…
thank you…

energy reconstruction (I)…

- **integrated data and MC calibration scheme…**
  - MC treated independently (as two detectors)
  - MC (no free knobs→ lab measurement + calibration)
- **Linearised-PE & "α" Calibration…**
  - def: **PE = α(PE,#PMT hit) x {Σqi x g(qi)}**
  - conversion **Q[Δ~5%]→PE[Δ≤0.5%]** @ H-n peak center
  - impact: **stability (+++)**, **linearity (++)**, **uniformity (+)**
  - source: gain non-linear [@electronics] + other (zeroes, etc)

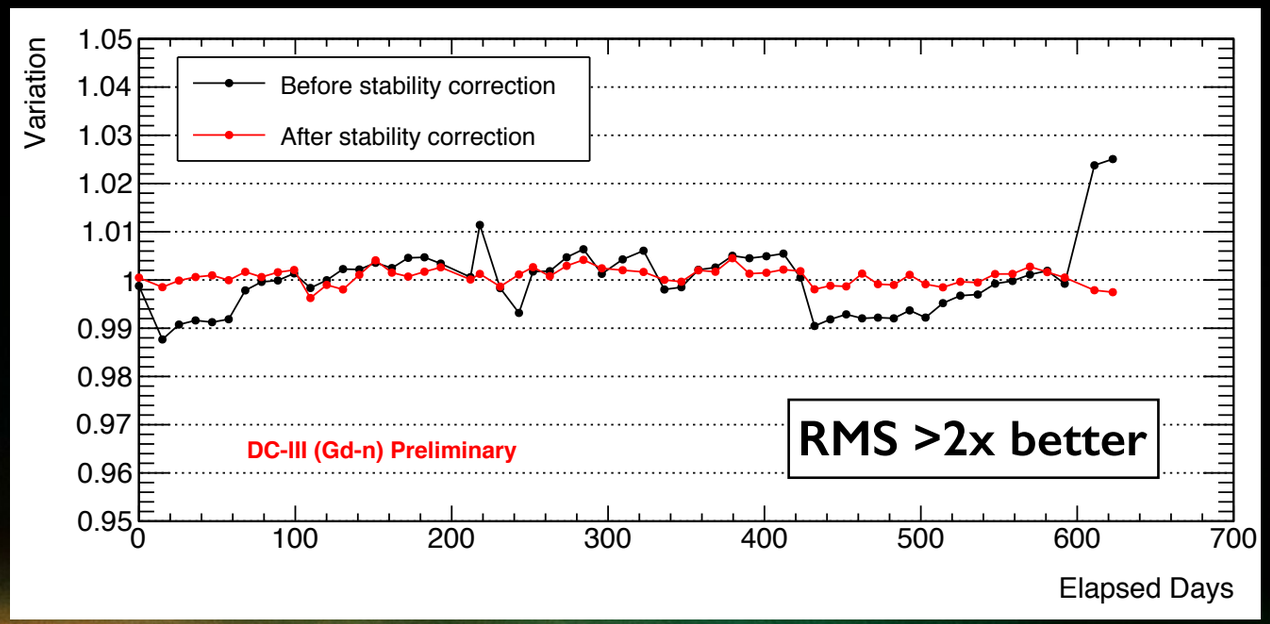


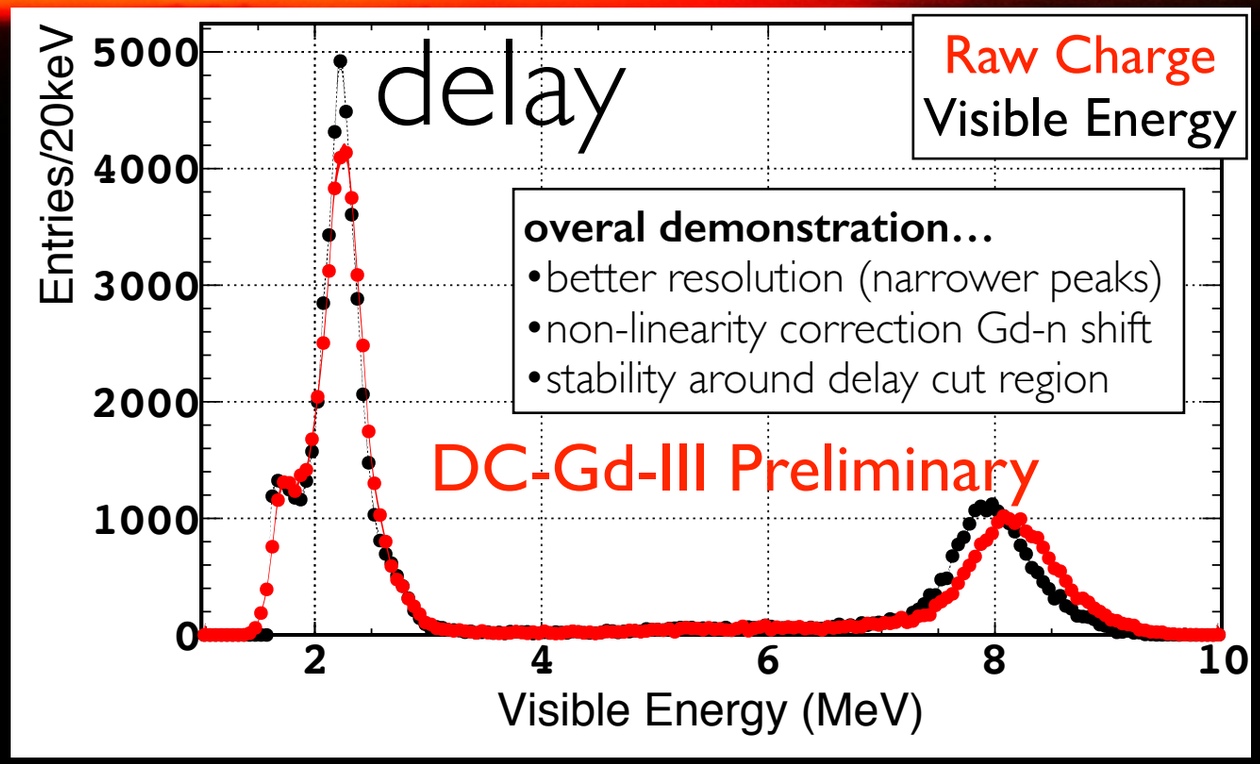
- **Uniformity Calibration…**
  - def: create H-n response full volume MAP
  - conversion **PE(ρ,z)[Δ≤8%]→PE(center)** [Δ≤0.5%]
  - impact: **uniformity (+++)**
- **MeV (or absolute) Energy Calibration…**
  - conversion: PE(0,τ)→MeV(0, τ)
  - use ^{252}Cf @ (ρ=0, z=0, t=τ)→ H-n peak: 2.223MeV
  - DATA to MC equalisation (prior <0.5% agreement)



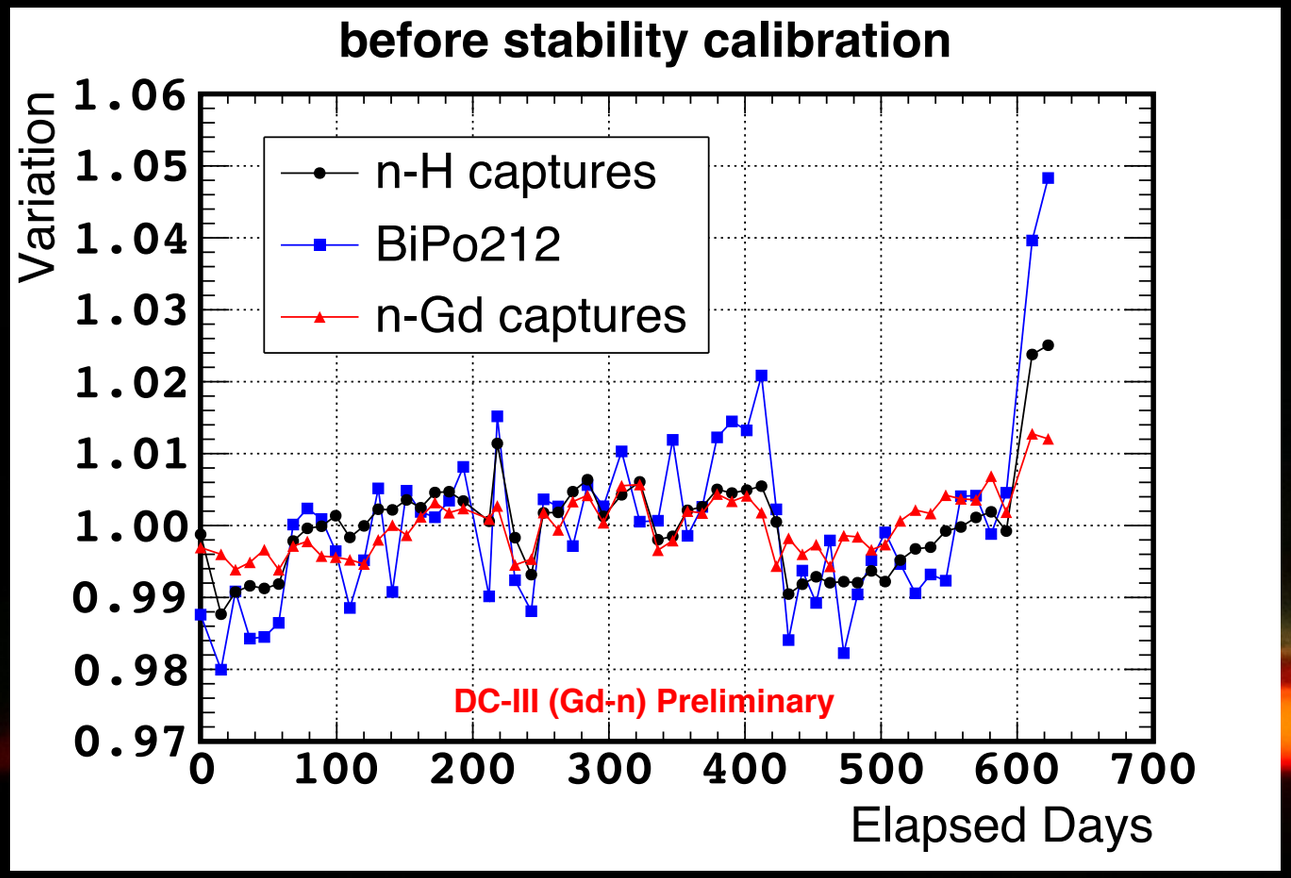
energy reconstruction (2)…

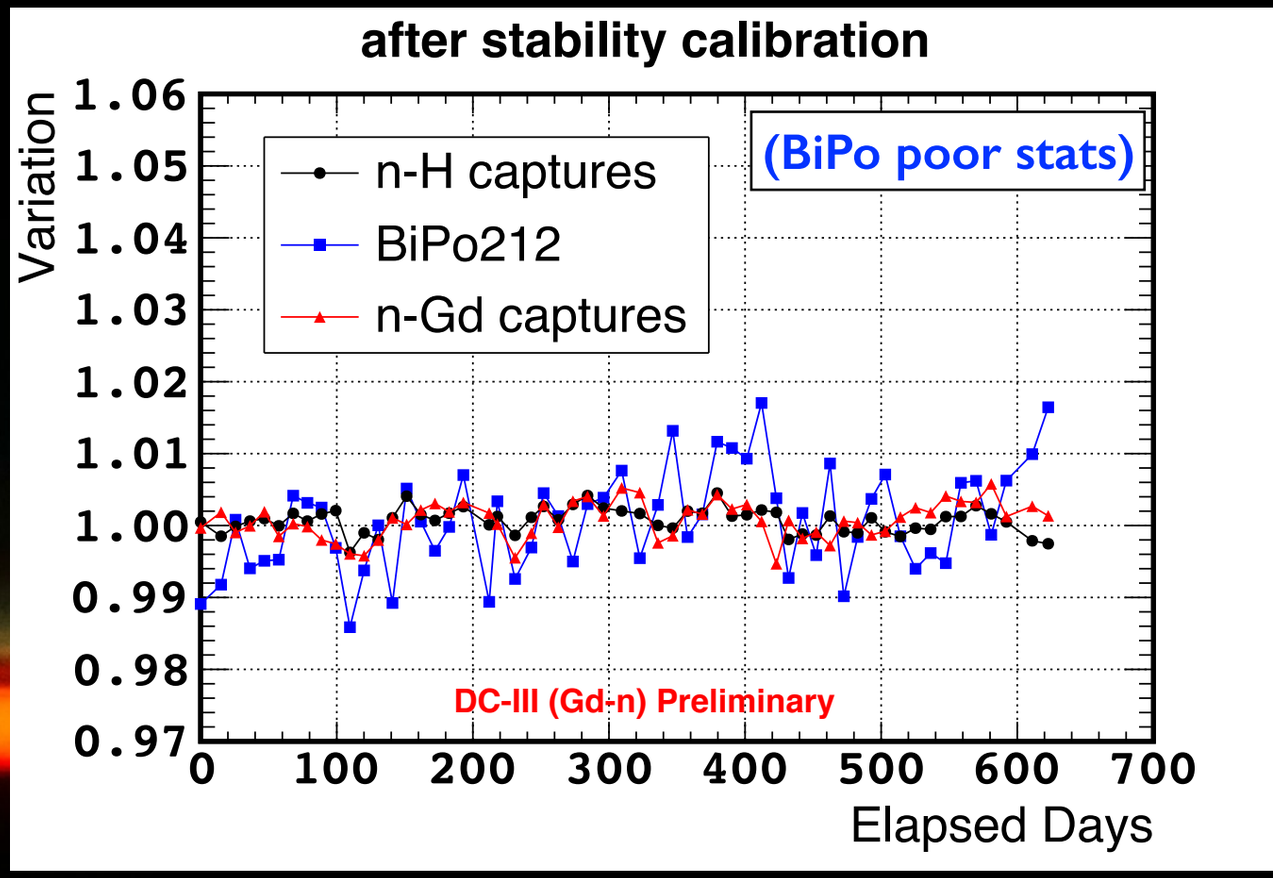
- **Drift Stability Calibration…**
  - def: **PE(t)→PE(τ)**, where τ: time MeV definition
  - response drift by +0.5%/years (unknown)
  - impact: **stability (+)**
- **Charge Non-Linearity Calibration…**
  - readout driven-non-linearity→ Δ(H-n,Gd-n)=~1%
  - validation with C-n peak @ 5MeV & ^{12}B spectrum
  - impact: **linearity (++)**
- **Light Non-Linearity Calibration…**
  - single-γ scintillation quenching measurement
    - many calibration sources @ center
  - conversion: **MeV(single-γ)→MeV(e+)** [only MC]
  - impact: **linearity (++)**
- **Overall performance…**
  - from Q(q,ρ,z,t) [RMS~10%] to MeV [RMS≤1.0%]
  - better detection systematics→ θ^{13}, BGs, Δm^2.





response stability (with energy dependence)…





raw response stability→ large non-statistical variations (electronics power cycle)

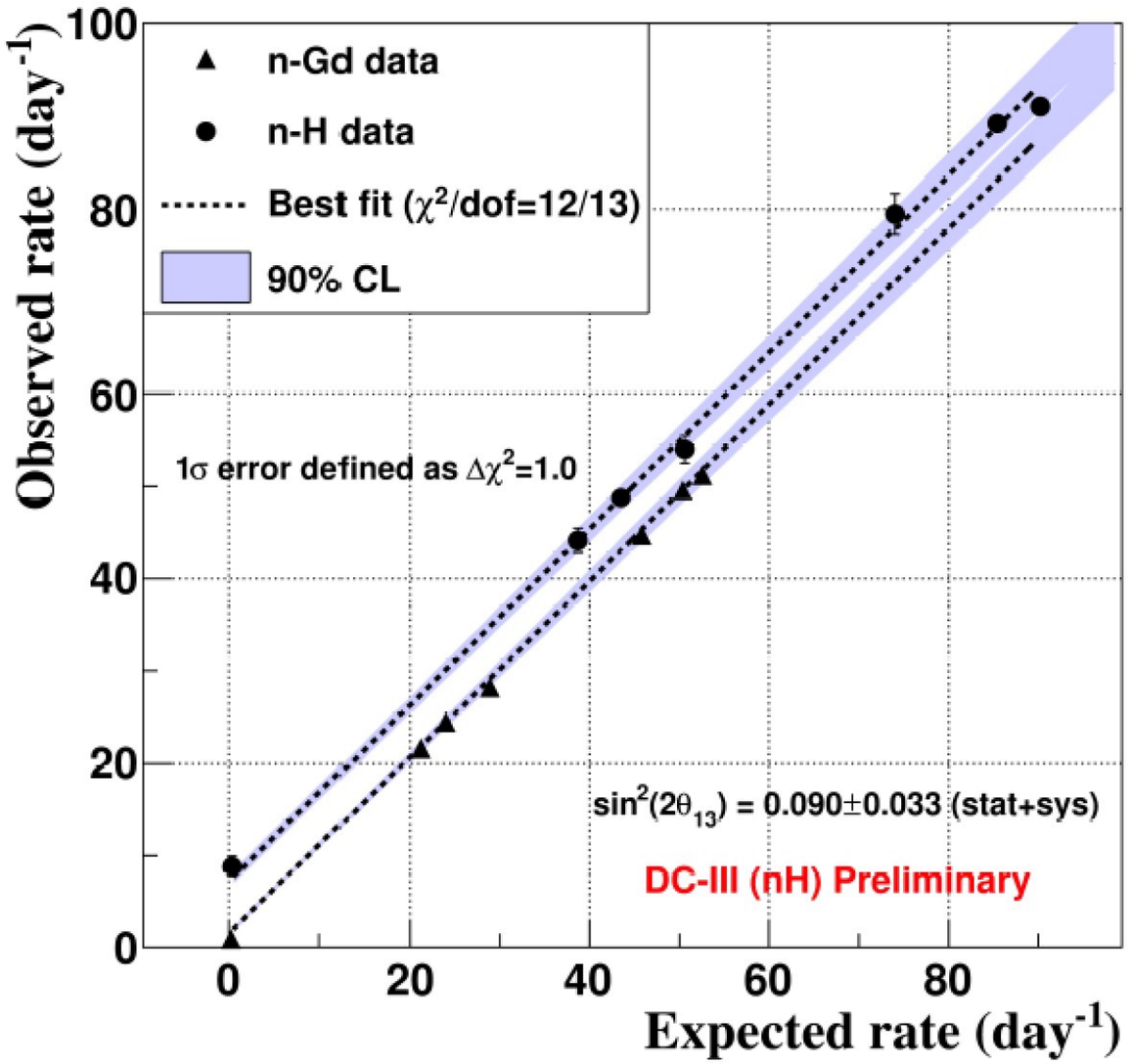
(**Δ up to 7%**)

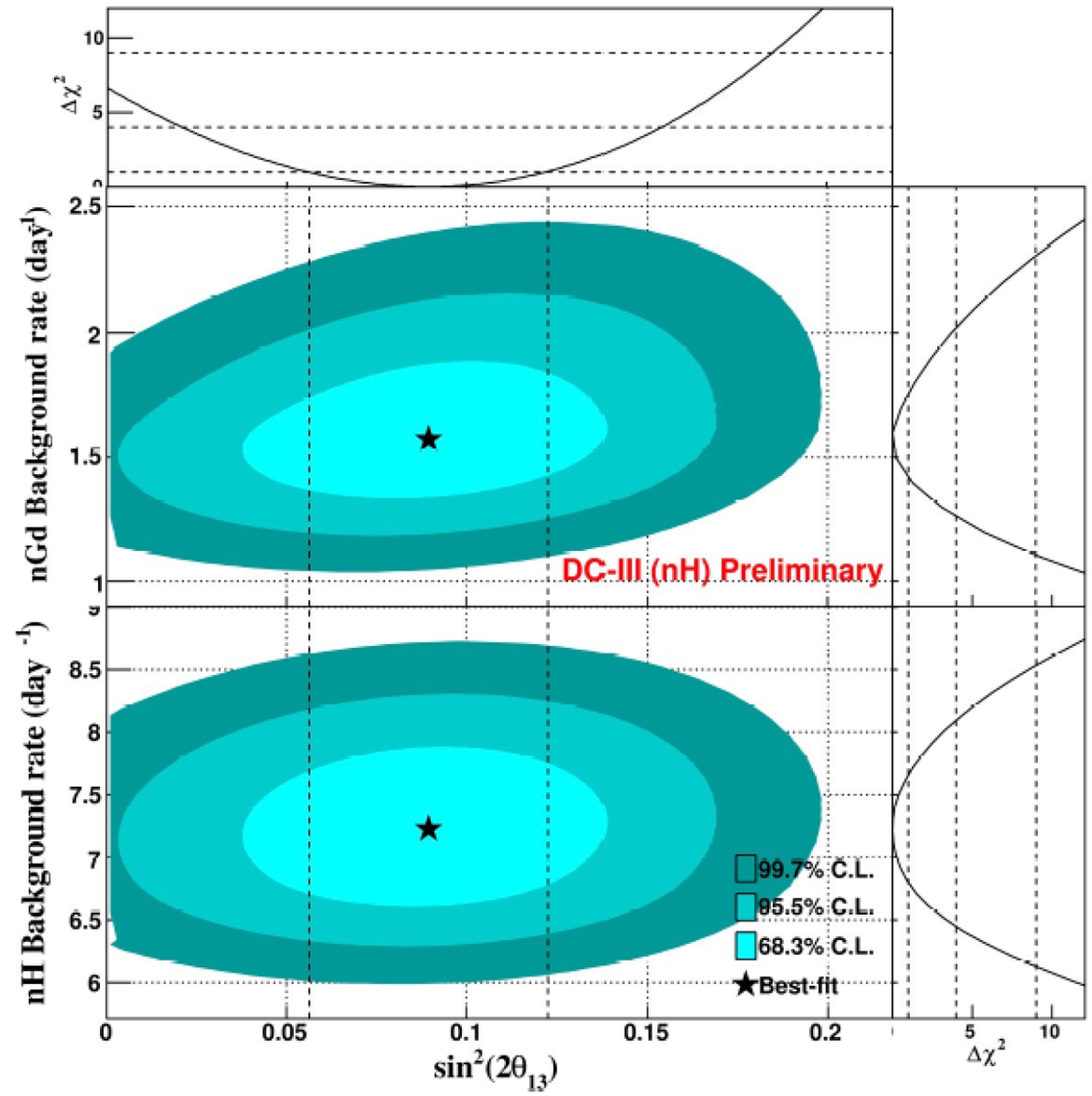
corrected response→ pattern consistent with <u>statistics dominated</u>

(**Δ≤0.5% + RMS >2x better**)

Gd-III⊕H-III RRM…

Combining this H-based result with latest Gd-based result (2014):





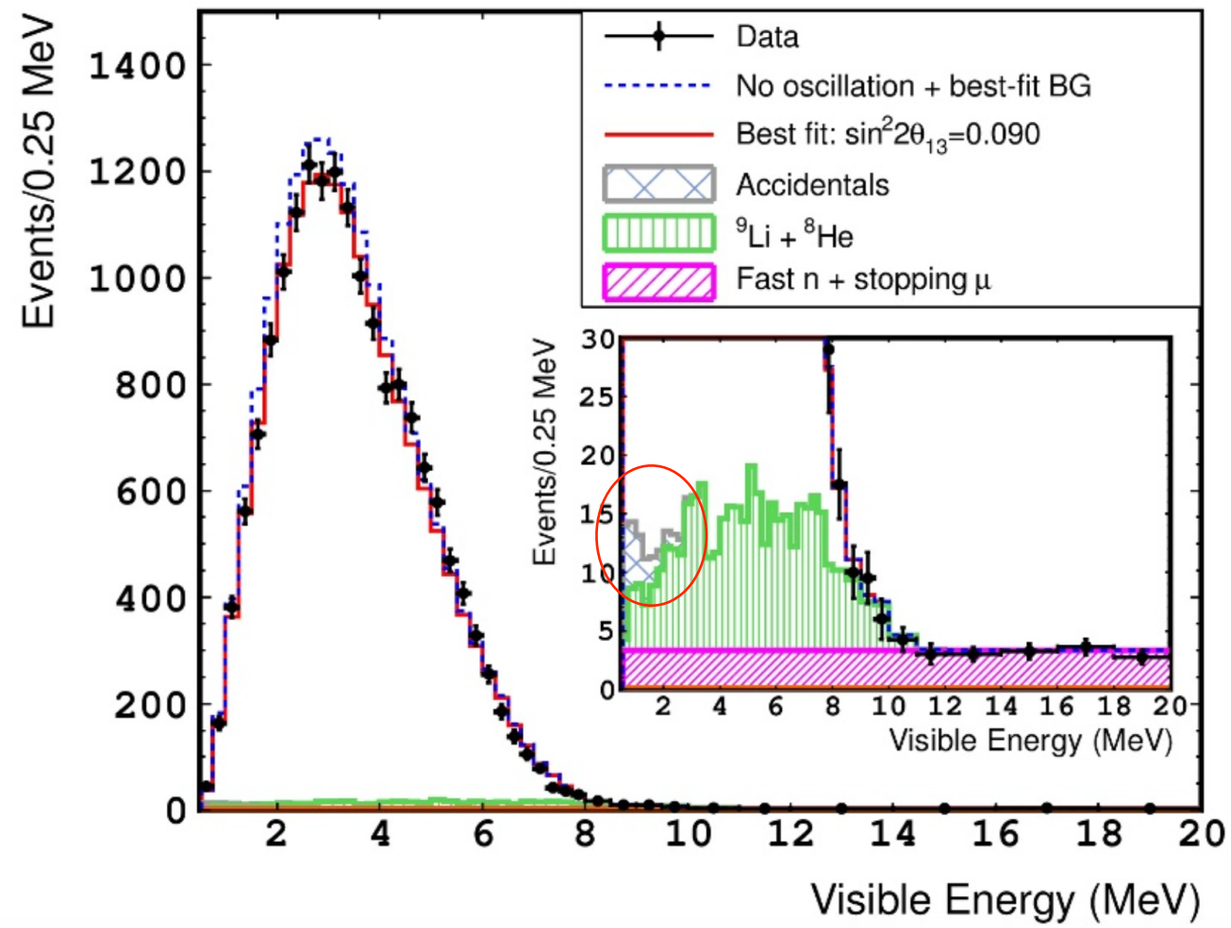
$$\sin^2 2\theta_{13} = 0.090 \pm 0.033$$

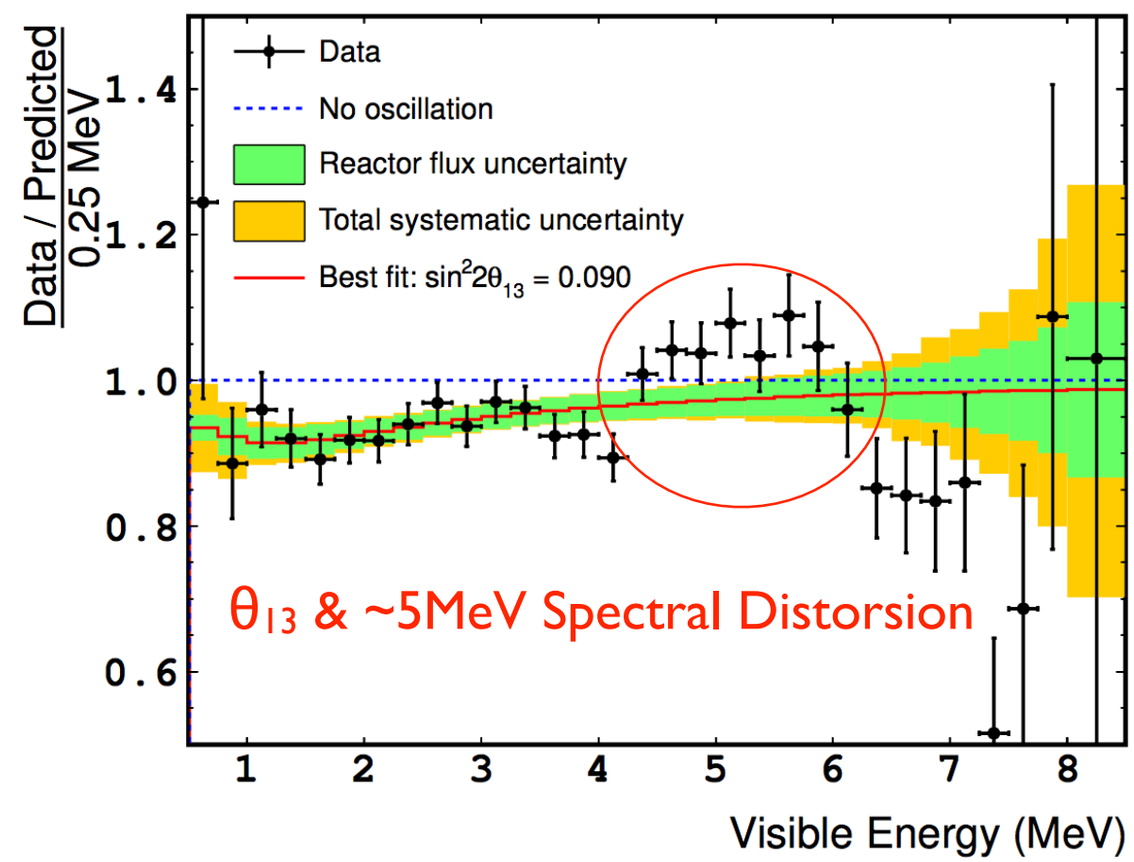
H only: $\sin^2 2\theta_{13} = 0.098^{+0.038}_{-0.039}$, Gd only: $\sin^2 2\theta_{13} = 0.090^{+0.034}_{-0.035}$

Correlations between Gd and H have minimal impact. This result assumes no correlation.

Oscillation fit: rate + spectrum shape

JHEP 1410 (2014) 086

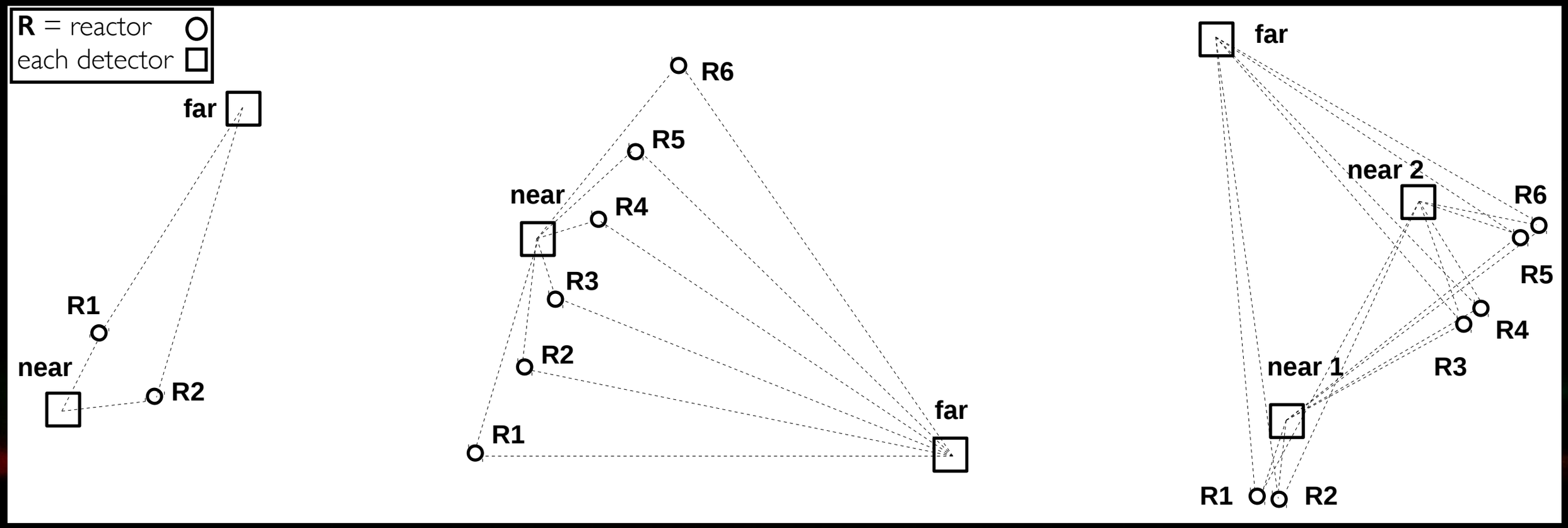




- background and other uncertainties constrained by shape information
  - **$\sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029}$**
- **unexpected spectrum distortion observed at 4-6MeV (May 2014)**
  - ✓ Negligible impact to θ_{13} measurement
  - ✓ Magnitude of excess proportional to reactor power
  - ✓ Same distortion confirmed by RENO (June-14), Daya Bay (July-14) and our n-H analysis

reactor systematics→ **geometry**…

Double Chooz | **RENO** | **Daya Bay**



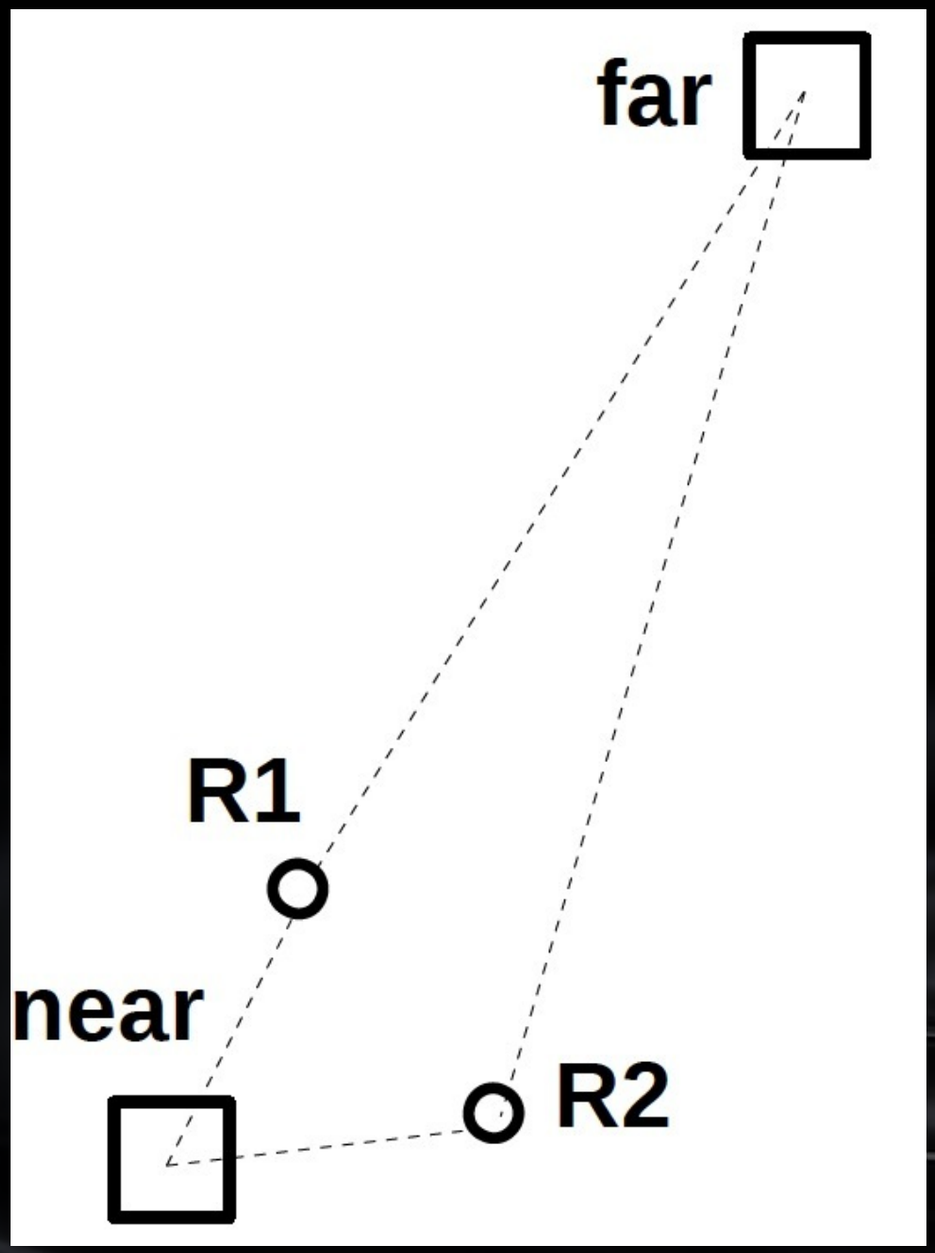
FD @ 300mwe (target: 8t) | FD @ 450mwe (target: 16t) [2x DC] | FD @ 850mwe (target: 80t) [10x DC]

key design feature of experiment: **multi-detector(s) error cancellation**

- (if identical) **detection-systematics** (target composition, efficiency, response, etc)**: ~2%→~0.2%**
- (if near/far) **flux systematics: ~3.0%(raw?)→~1.0% (uncorrelated)→<<0.1% (geometry)**

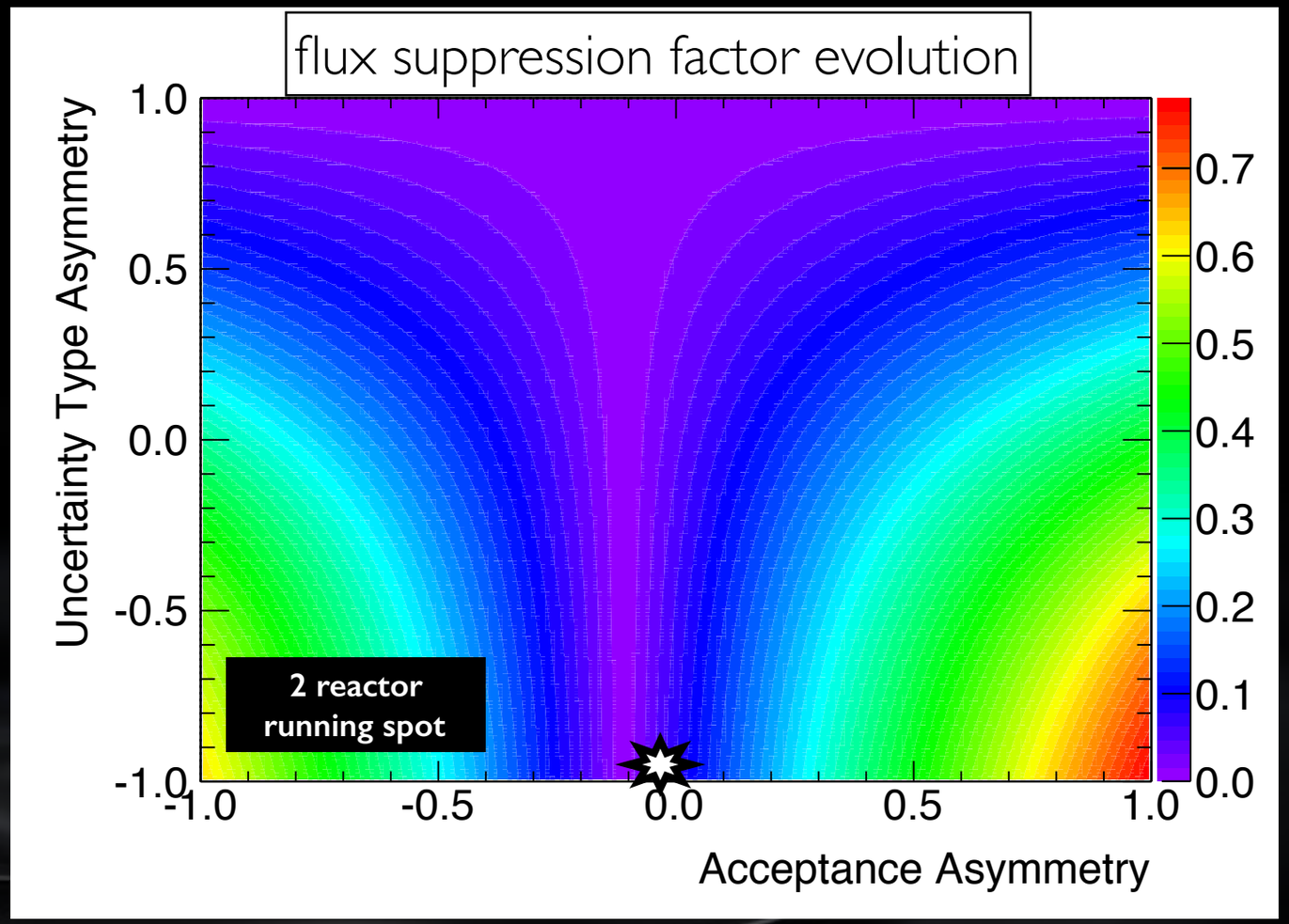
[deeper underground + radio-purity⇒ less background per detector]

DC major δ(flux) cancellation with ND…



DC most iso-flux experimental setup

⟹ ~90% δ(flux) suppression



reactor error correlations→ δ(flux) suppression

$\delta(\text{flux})^{FD}$=1.7% → $\delta(\text{flux})^{FD+ND}\leq$0.1% (preliminary)

"Reactor Neutrino Flux Uncertainty Suppression on Multiple Detector Experiments"

Cucoanes, Novella, Cabrera et al. (**arXiv:1501.00356**)

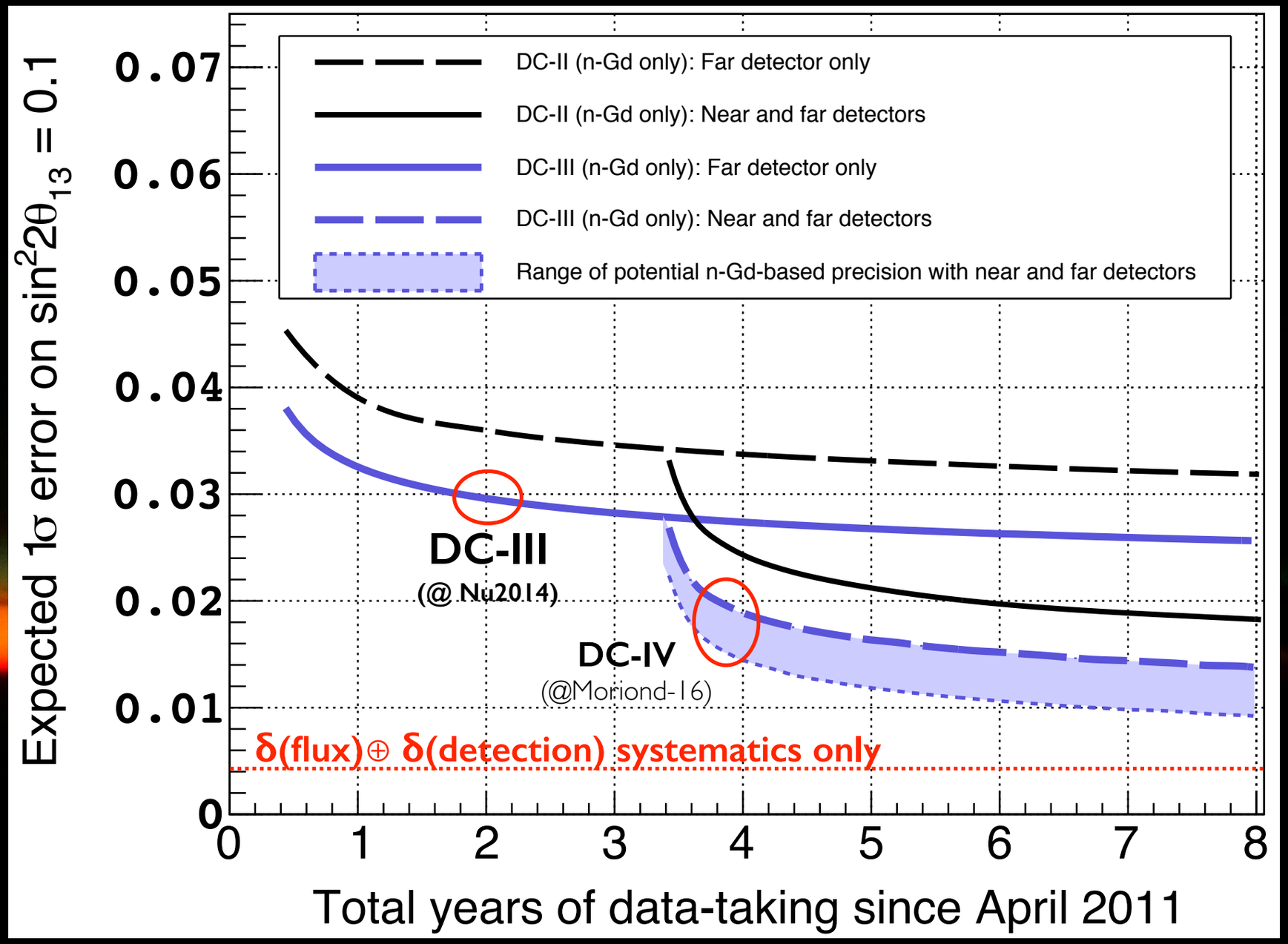
1σ error projection (via R+S analysis)…

Gd-n analysis FD+ND prospect inputs

- **δ(flux)~0.1%** (**preliminary**)
  - iso-flux suppression dominated
- **δ(detection)~0.2%** (**preliminary**)
  - à la Daya Bay / RENO
- **δ(BG)~ DC-III + R+S constraint**
  - @DC-III~0.3% (2 years data)

note:

- **δ(stat) not just $1/\sqrt{N^{FD}}$ (dominant)**
  - several effects N^{BG}, N^{ND}, etc



remarkable improvement of DC-III new analysis (wrt DC-II)

1σ within [0.010,0.014] with 3years FD+ND: BG systematics dependent→ **statistics dominated**

(rate+spectrum projection uses latest BG model fromDC-III)