Double Chooz

Neutrino 2014

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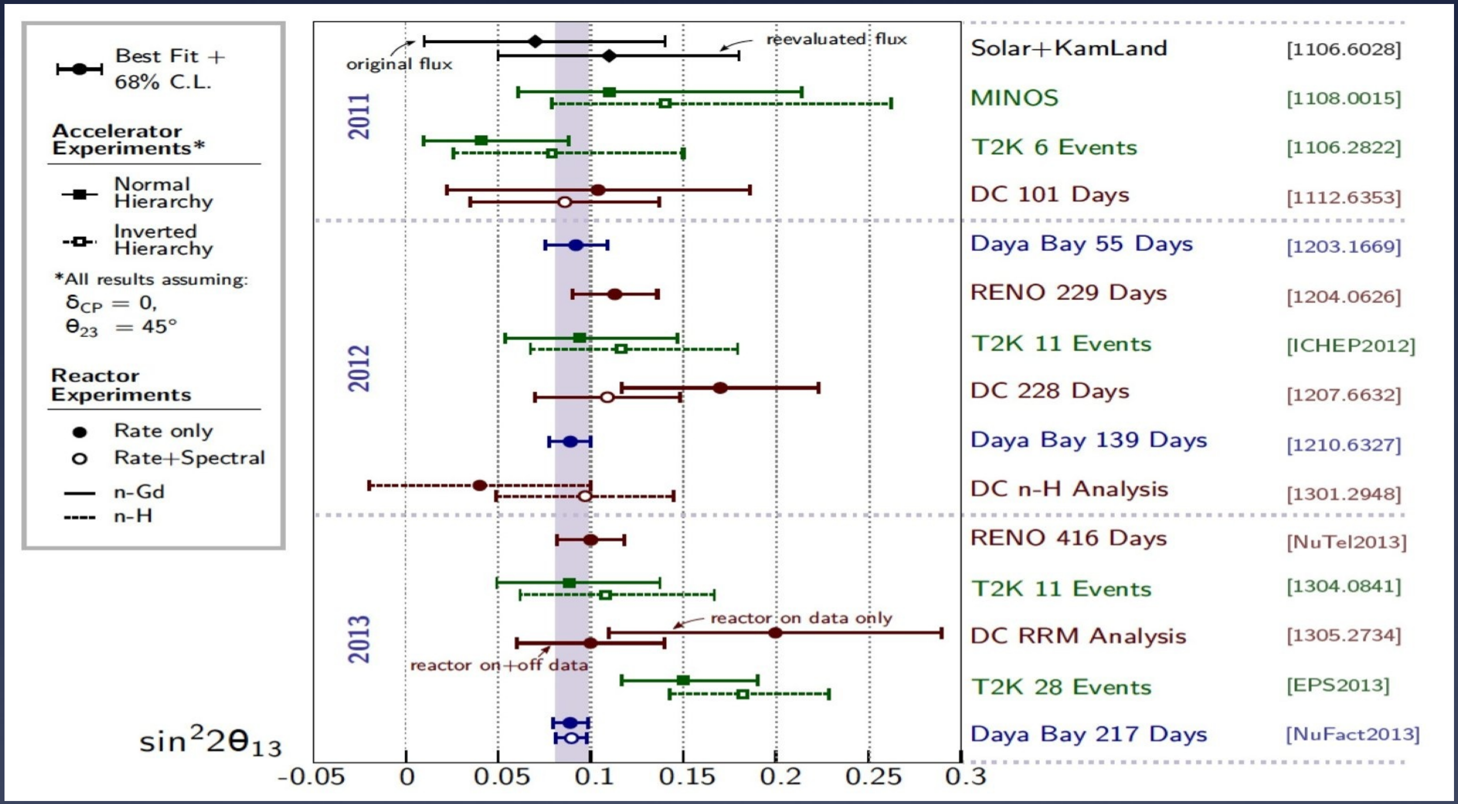
On behalf of the Double Chooz collaboration

θ_{13}-reactor measurements…



reactor precision is unsurpassable→ setting θ_{13} for several decades to go!!

(also measurement by T2K, MINOS, etc)

- future work together (DC+Daya Bay+ RENO) to help producing the world θ_{13}
- reactor-detector different length helpful for delta M23 ?

experimental setup…

Near
<L> 400m
~300ν/day
120mwe
Target: 8.2t
2014

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

Two Reactors
Power: $8.5GW_{th}$
$\Longrightarrow \sim 10^{21} \nu/s$

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.
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)

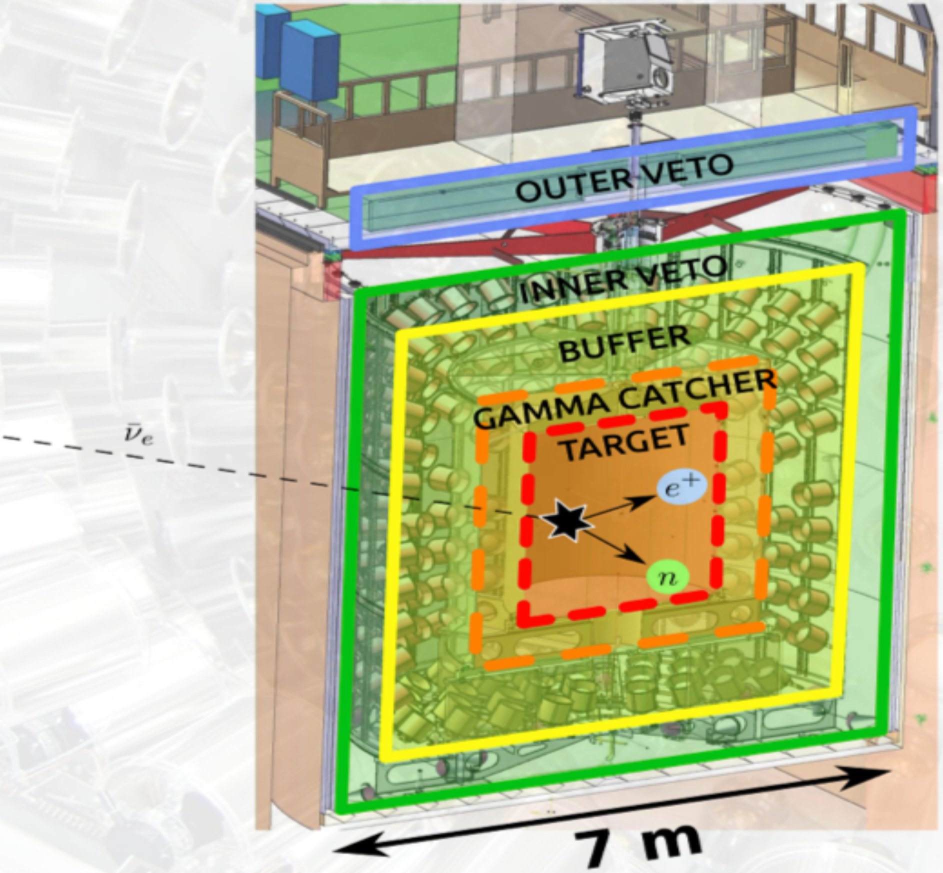
project manager: Christian Veyssière (CEA Saclay)

INVERSE BETA DECAY on proton (thresold > 1.8 MeV)

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

prompt signal: scintillation + e^+ annihilation
$E_{prompt} \approx E(\nu_e) - 0.8$ MeV

delayed signal: γ ray(s) from neutron capture
n-Gd $E_{delayed} \approx 8.0$ MeV $\Delta T \approx 30$ μs
or n-H $E_{delayed} \approx 2.2$ MeV $\Delta T \approx 200$ μs



Neutrino target:
liquid scintillator PXE + Gd

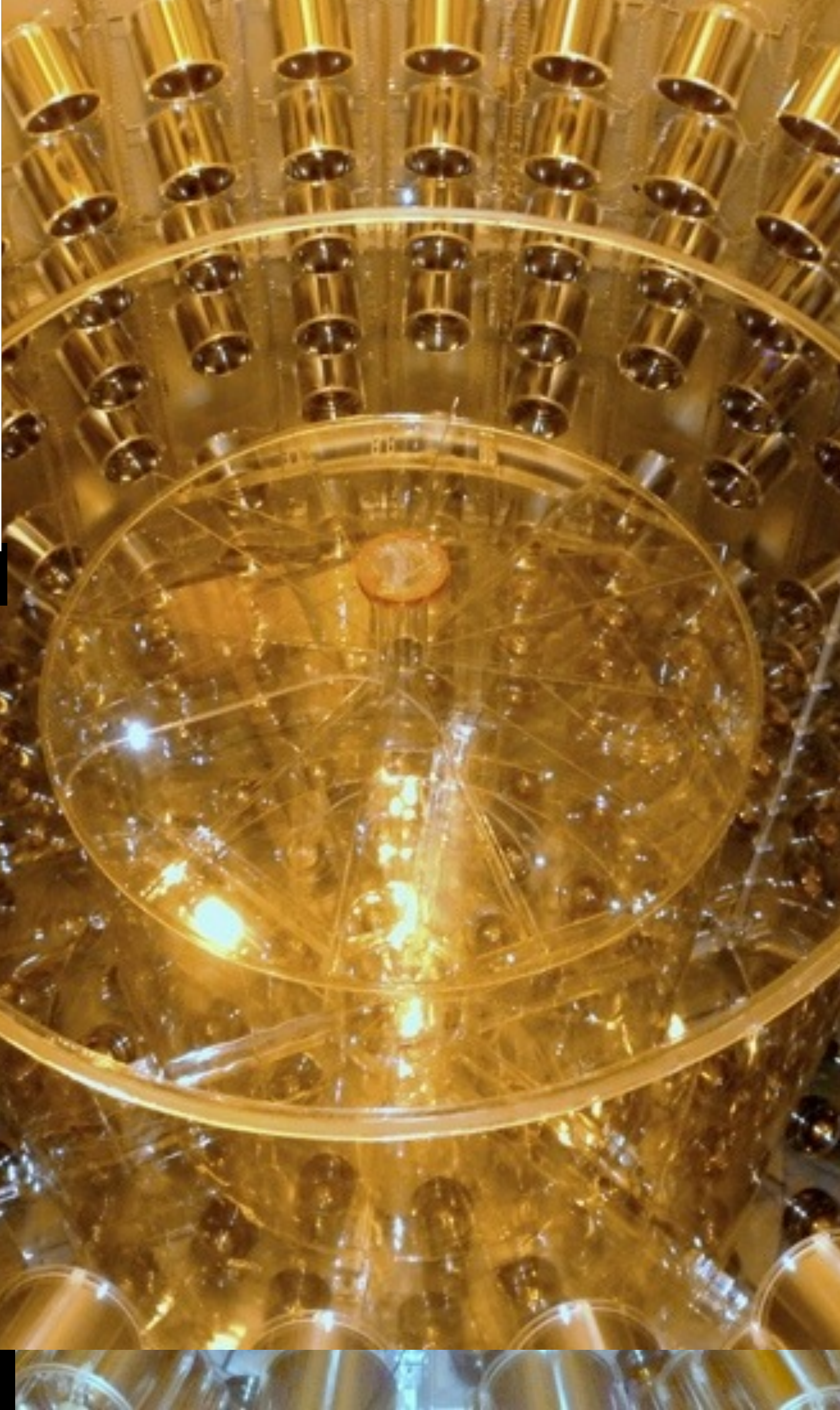
Gamma catcher:
liquid scintillator PXE (no Gd)

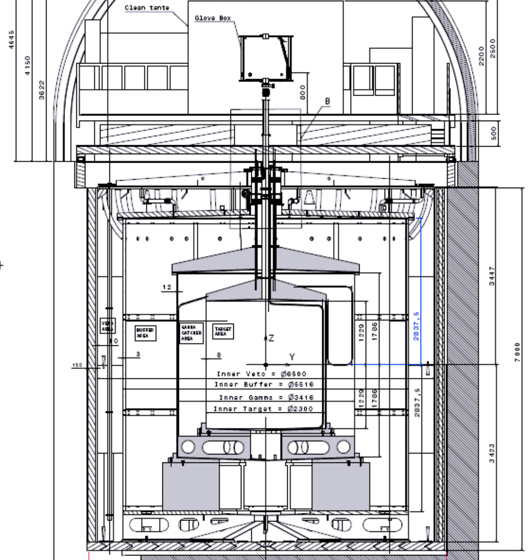
Buffer volume:
transparent mineral oil
with 390 x 10" PMTs assembly

Inner Veto:
liquid scintillator (LAB)
with 78 x PMTs 8"

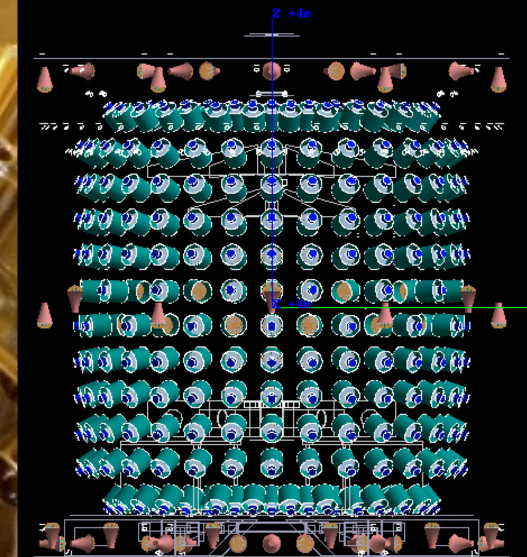
Outer Veto:
plastic scintillator strips

Letter of Intent 15 may 2004: 10th anniversary !





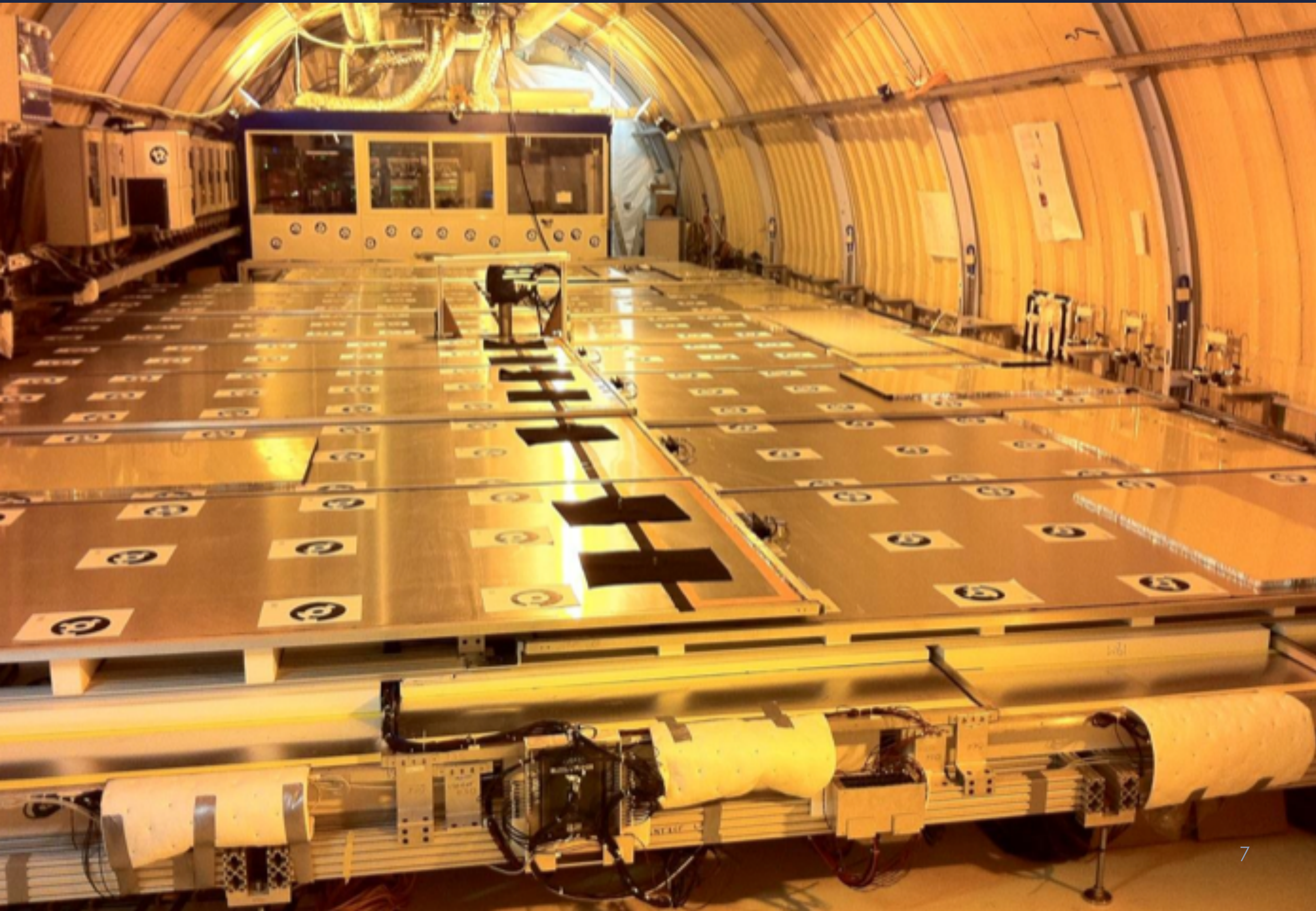
engineer's view



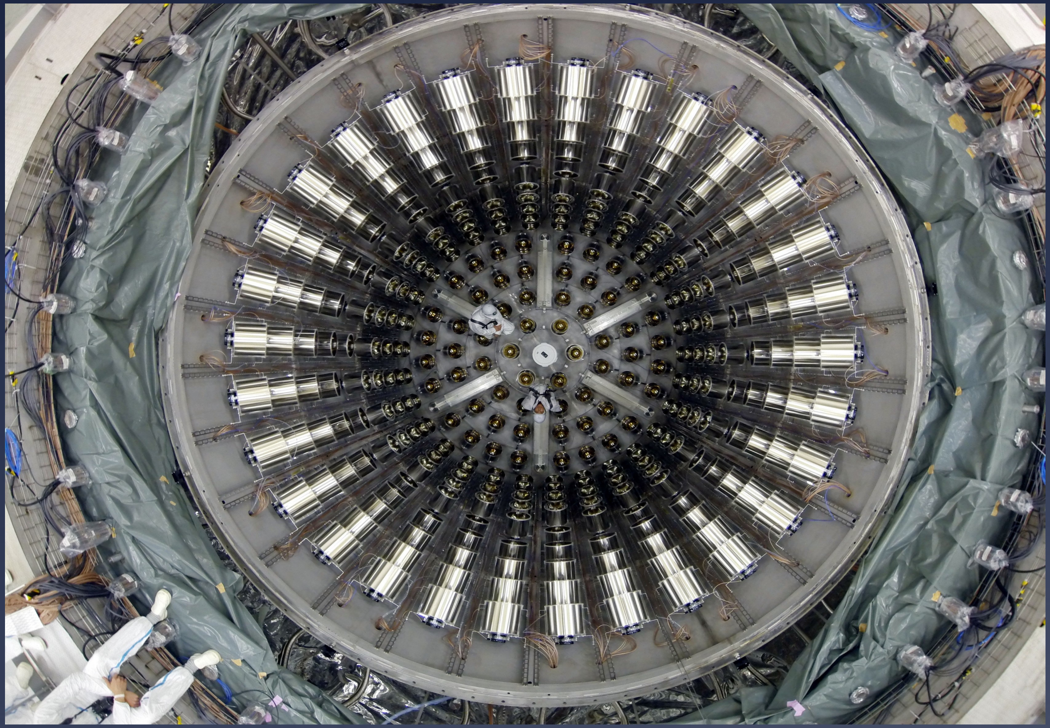
MC's view

our favourite view...

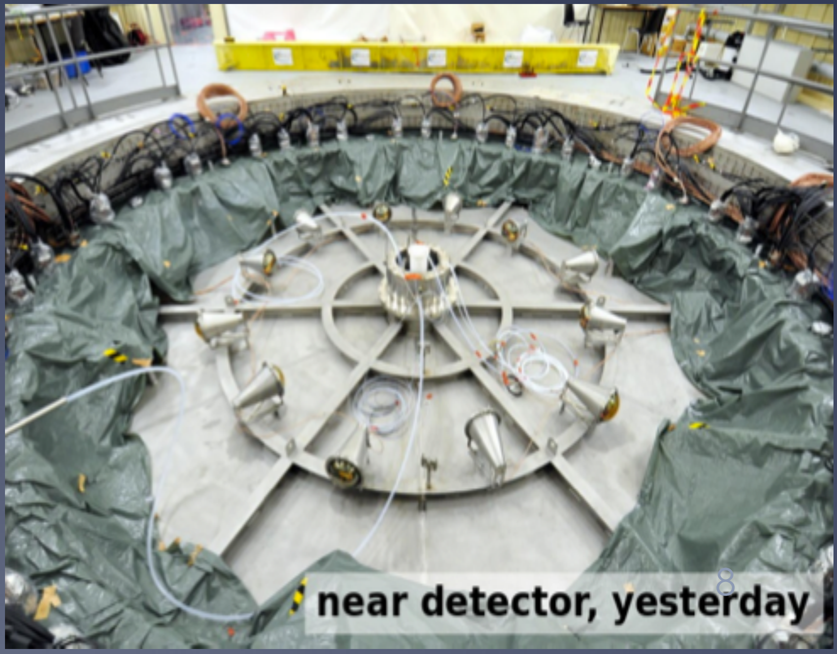
our top μ-tracker/veto (Outer-Veto)...



NEAR DETECTOR : READY SOON



Buffer closed
main tank to be closed this week

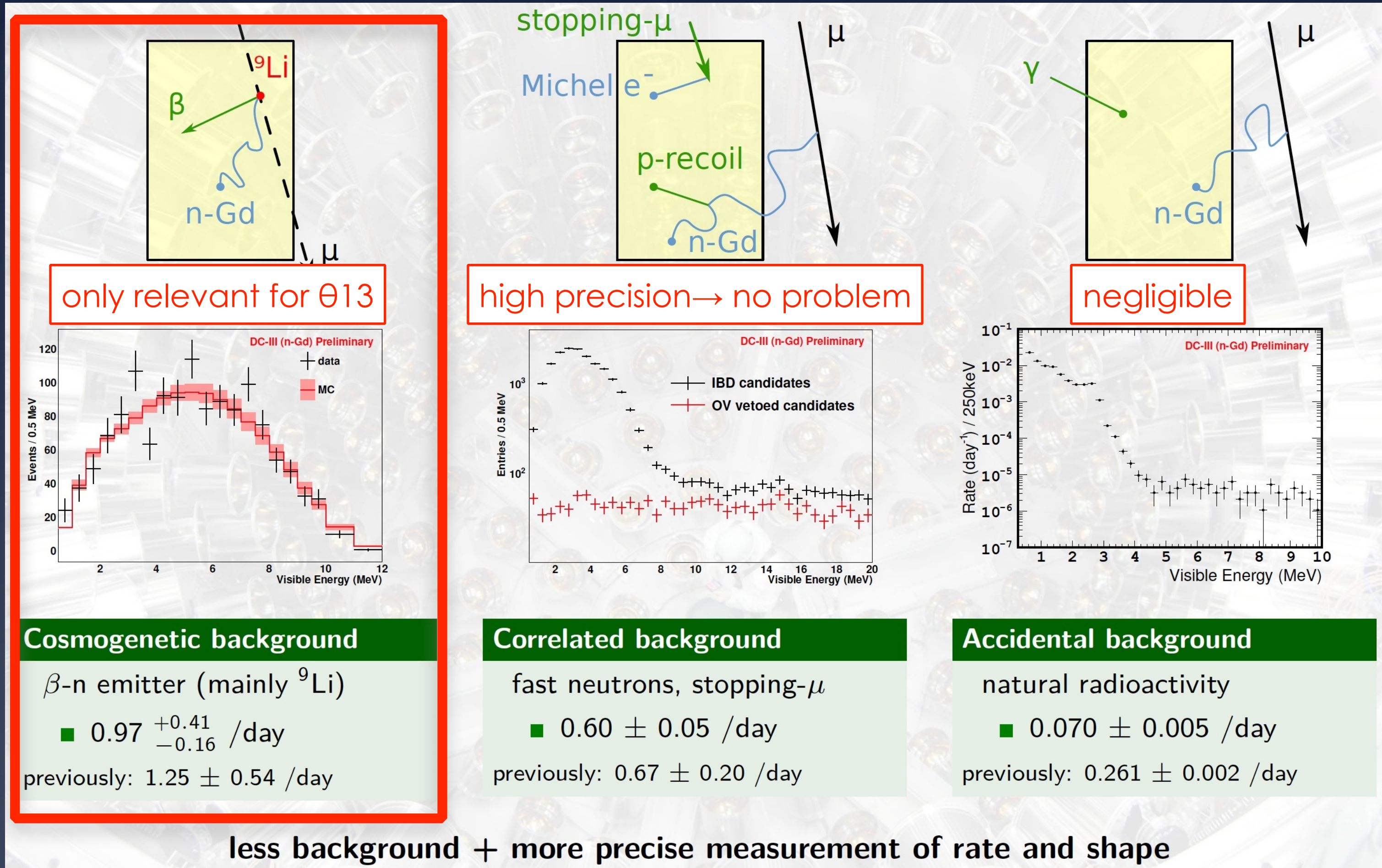


Fill this summer →
Neutrinos in september/October

BACKGROUNDS

All components measured separately (exclusive background)

Then entered in the rate + shape fit → more precise value obtained

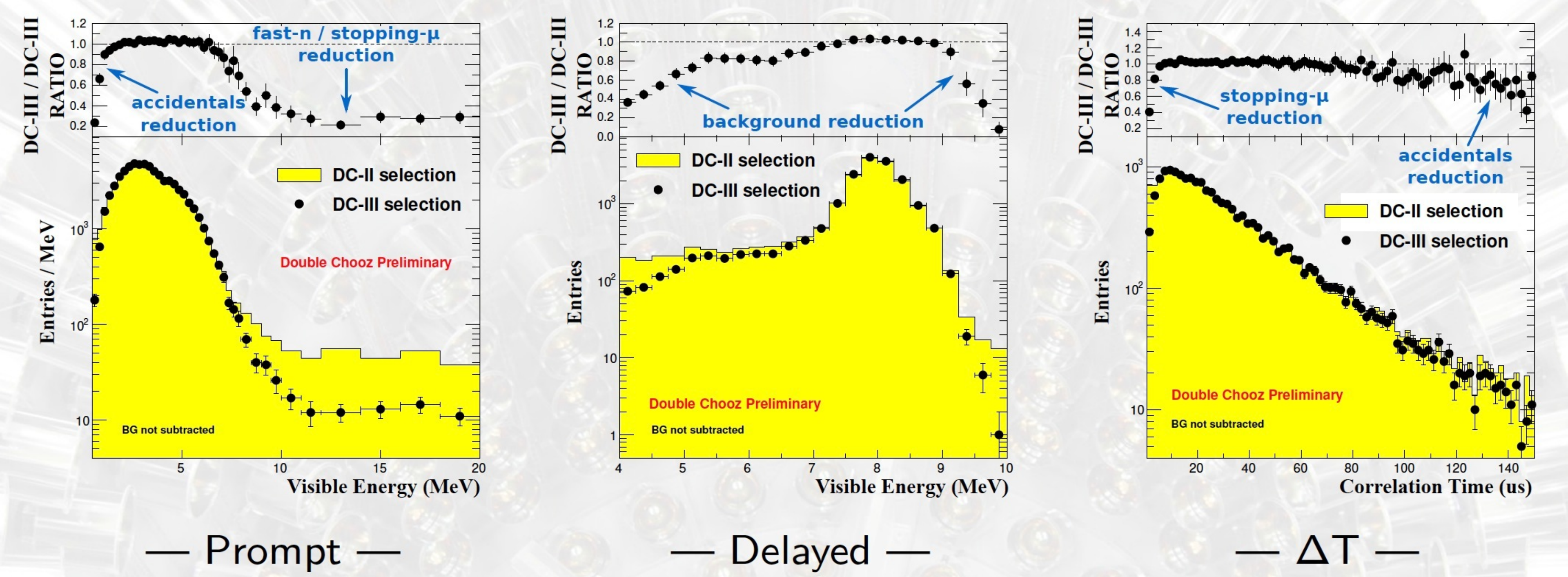


fast-neutrons→ identified by bugey 3 → CHOOZ design
Lithium+Helium→ identified by KamLAND and CHOOZ → DC design

- current reactor experiment generation→ **no new background seen**
- detectors strong rejection to cope with specificities (light noise, stop-μ, accidental,etc..)

→ some information come from the DC-III data [next slides]

new major background rejection...



much better active background rejection/control→ wide open selection

⟹ **major reduction of all systematics**

17351 IBD candidates (background included) in 460.67 days

selection details…

	Gd-III IBD candidate criteria
μ-tagging	Energy(ID)≥20MeV NEW!! & Charge(IV)≥30k(a.u.) NEW!!
Δt(μ)	1ms NEW!!
QmQt	≤0.12 NEW!!
RMS(time,charge)	2D cut NEW!!
ΔQ	30k(a.u.) NEW!!
Δt(n~e	[0.5,150]μs NEW!!
Δd(n~e	≤1m NEW!!
E(delay)	[4,10]MeV NEW!!
E(prompt)	[0.5,20.0]MeV NEW!!
Multiplicity	[-0.2,0.6]ms (relative to prompt) NEW!!
OV veto	yes
IV veto	yes NEW!!
FV veto	yes NEW!!
Li+He veto	yes NEW!!

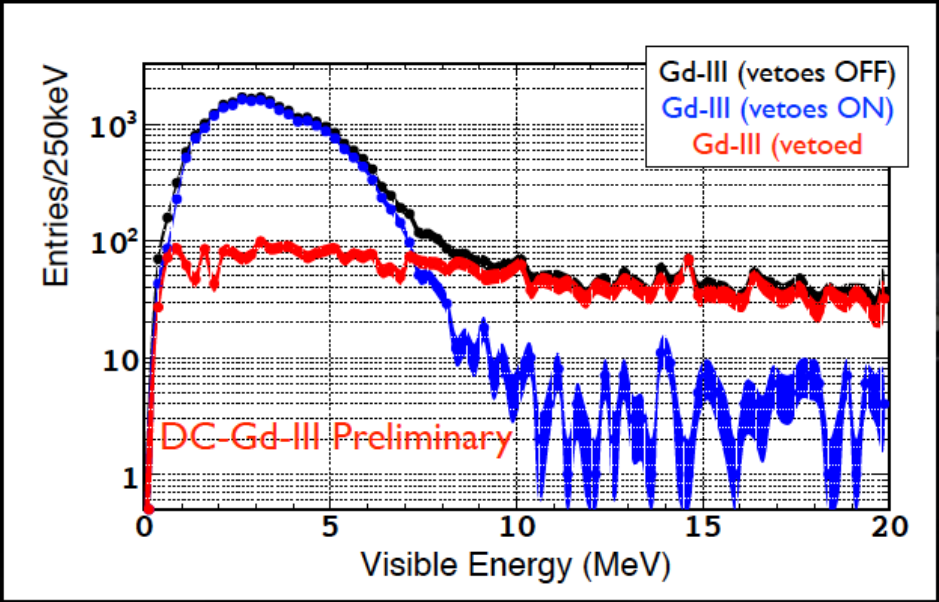
μ-Veto Selection

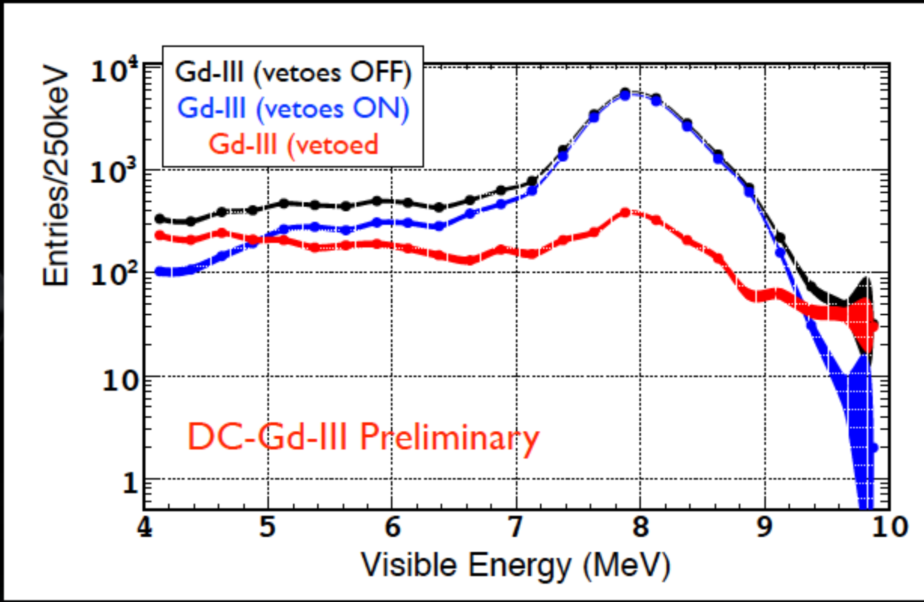
Light Noise Selection

IBD Selection

BG Rejection

our BG active BG rejection vetoes…



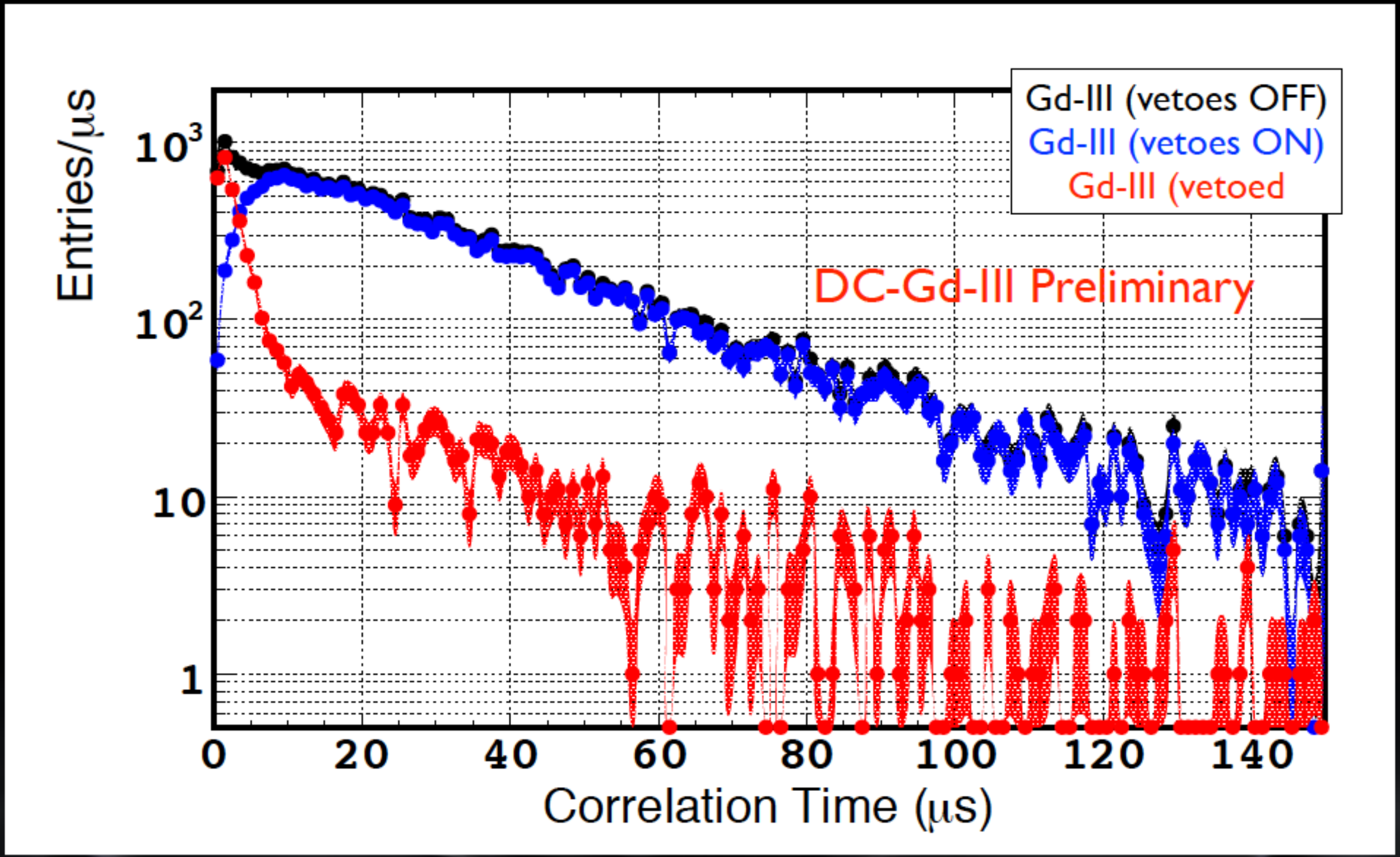


veto efficiency (%)	absolute (per veto)	uncorrelated fraction	relative (with all other vetoes)
IV veto	24	7	40
OV veto	62	7	41
FV veto	71	19	66
all vetoes	90	33	

Power(rejection) ~90%, estimated [12,20]MeV (high redundancy)

(VERY unusual for LS detector→ a volume of liquid flashing)

correlated events vetoes (all)…



vetoes reject correlated events (very challenging→ accidentals are much easier)

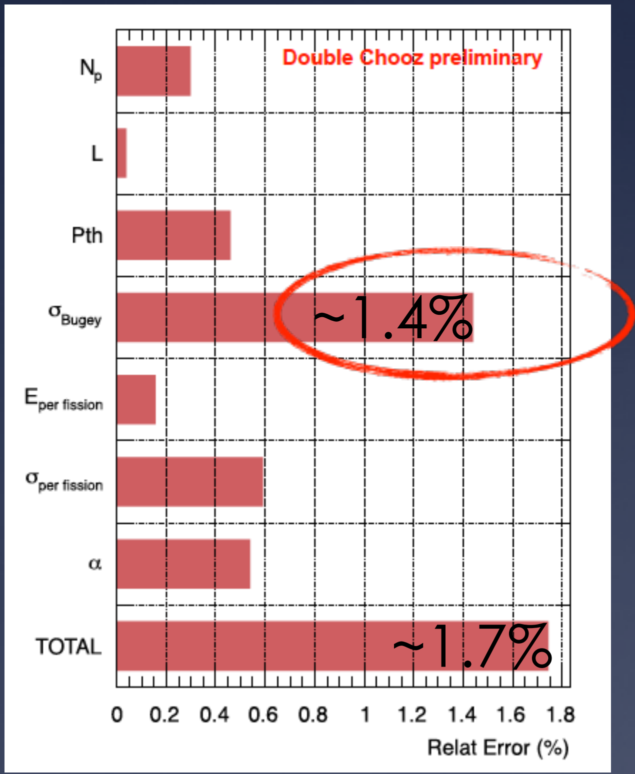
slow correlation→ neutrons in final state

fast correlation→ stopped-μ's (lifetime of a μ)

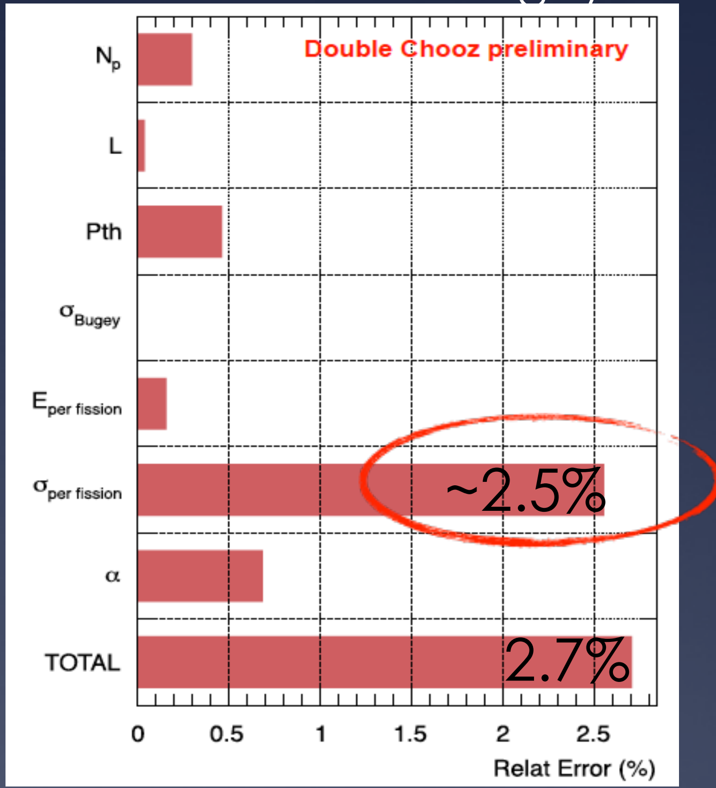
SYSTEMATICS

Bugey our "near" detector now…

With Bugey 4



Without Bugey 4



DC used Bugey as effective ND (via MC)

It reduces ~30% the dominant flux uncertainty→ used by KamLAND…

note: Bugey4 precise reactor flux measurement on purpose after Bugey3 (2 detectors) for CHOOZ experiment (only one far detector)

systematics recapitulation…

systematics	DC-Gd-II (%)		DC-Gd-III (%)	
δ(flux)	1.7		1.7	
δ(detection)	~1.0		~0.6	
exposure (days)	227.9 (8249 IBDs)		467.9 (17358 IBDs)	
Δ(background) (input | output)	1.6	0.9 (R+S) 0.11 (RRM)	0.8	**0.3** (R+S) **0.5** (RRM)

RRM input

R+S input

Δ(background) independent estimation: <u>no spectral info used</u>

⟹ input to Rate+Shape (mandatory) and RateRateModulation (optional)

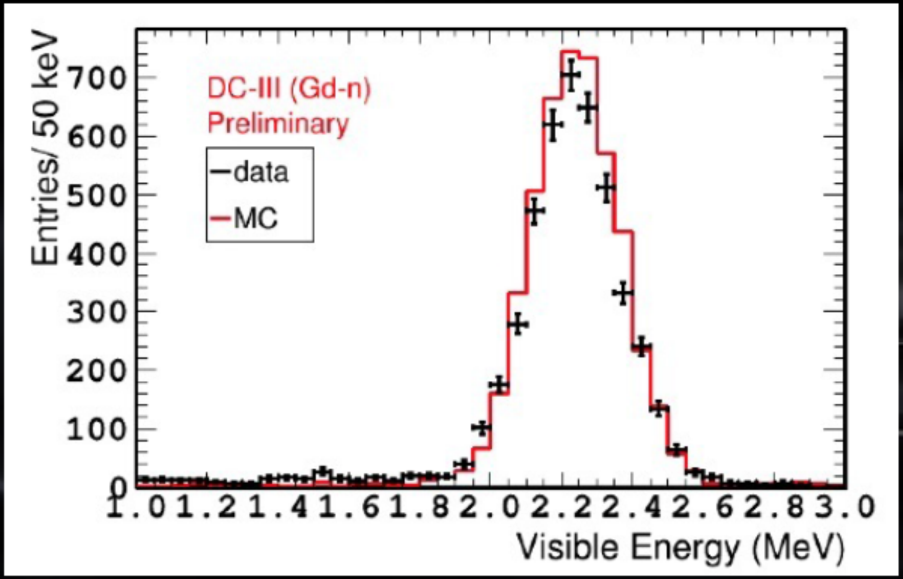
Δ(background) re-estimated by the final fit

(R+S and RRM are 2 methods described later)

Energy Reconstruction

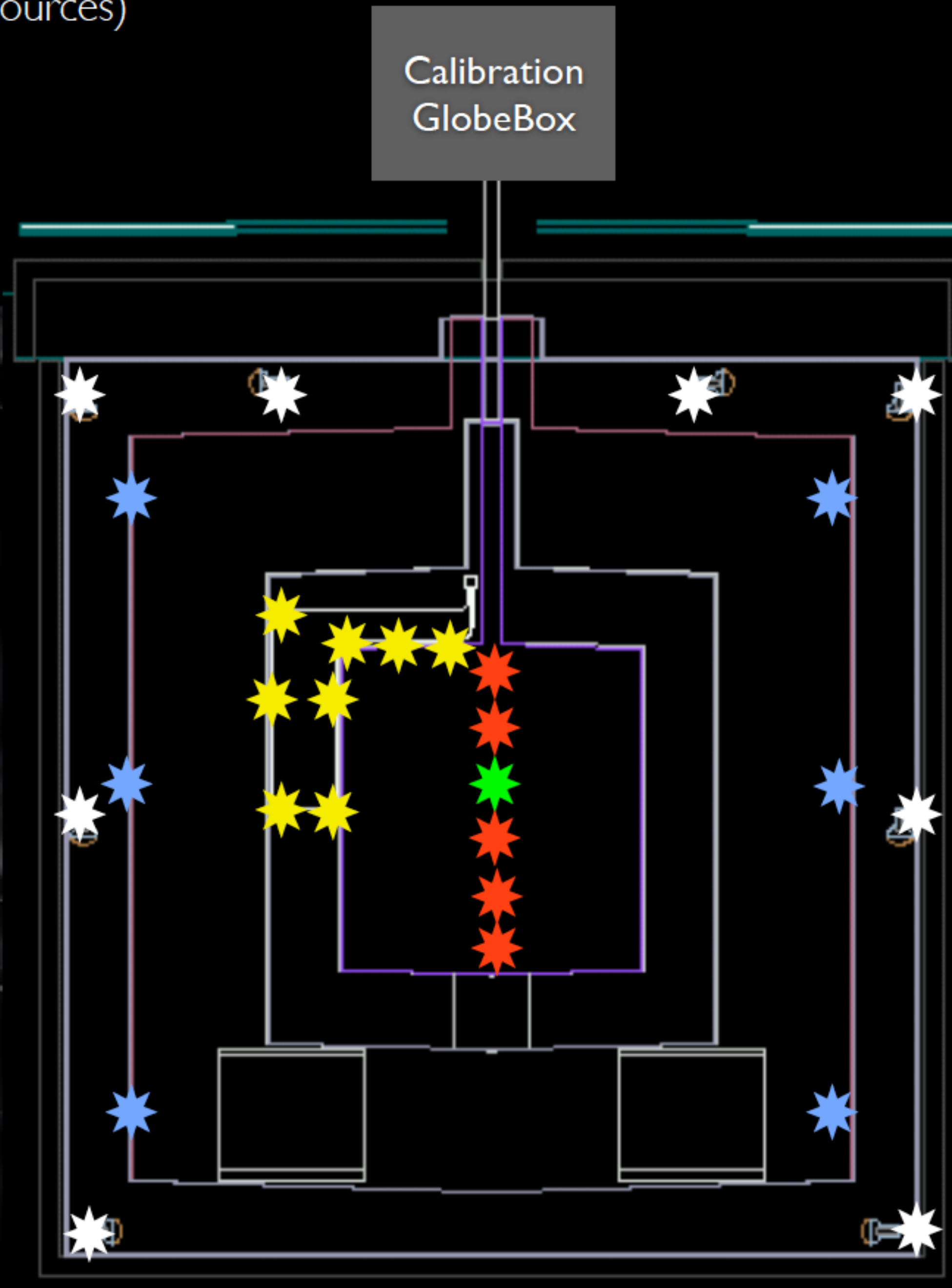
calibration system...

- **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)



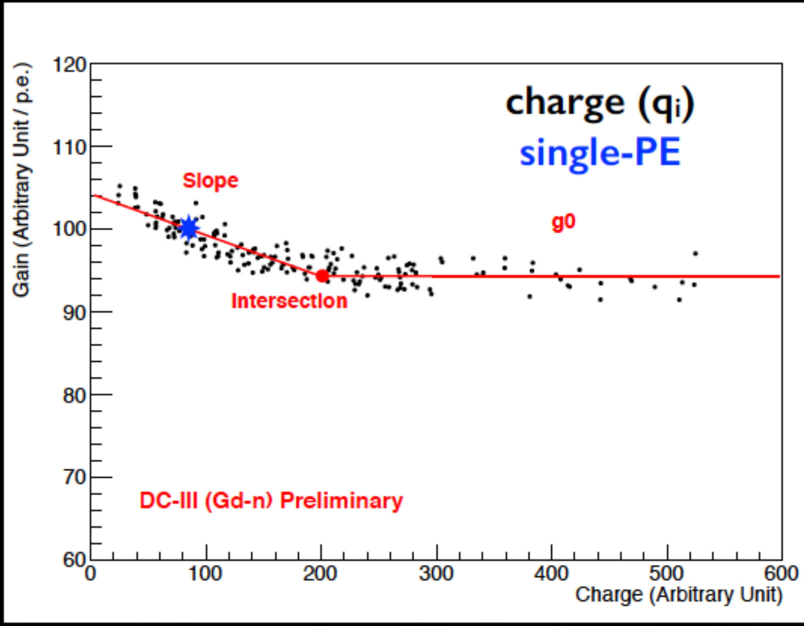
MeV definition (H-n peak @ center)

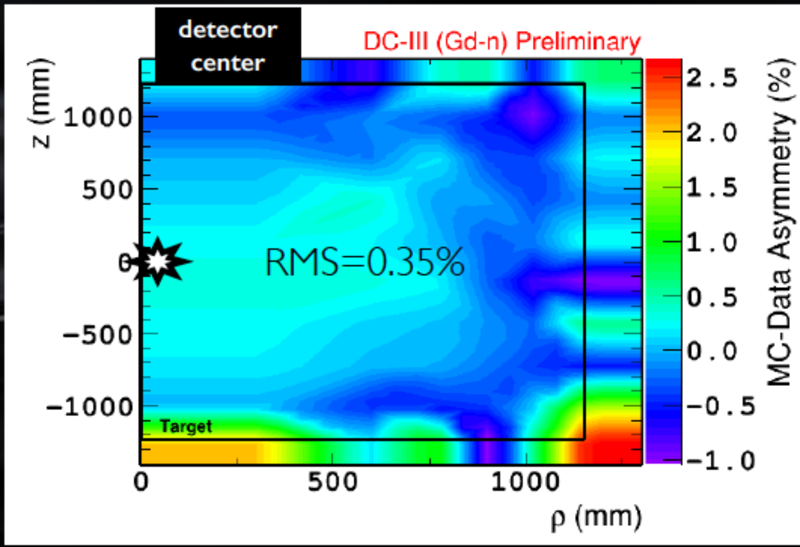
(our *standard candle*)



energy reconstruction (I)...

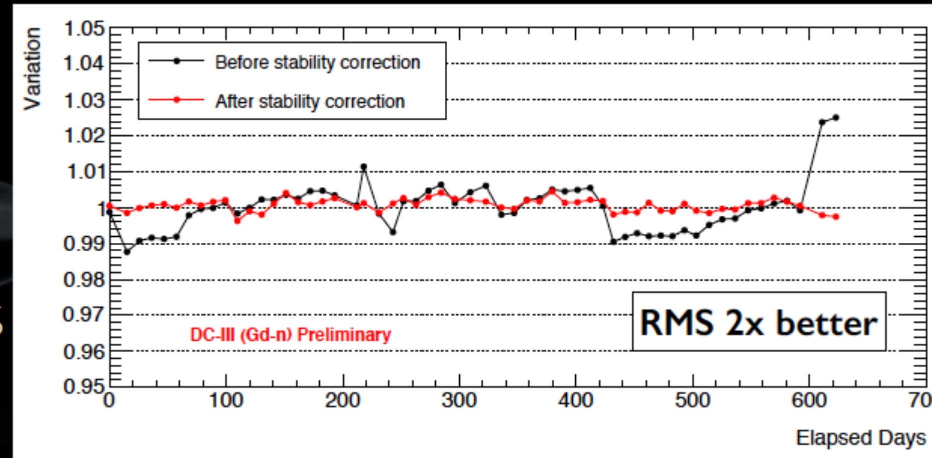
- **integrated data and MC calibration scheme...**
  - MC treated independently (as two detectors)
  - MC (no free knobs → lab measurement + calibration)
- **Linearised-PE & Alpha Calibration...**
  - def: **PE = α(PE,#PMT hit) x [Σqi x g(qi)]**
  - conversion **Q[Δ~5%]→PE[Δ≤0.5%]** @ H-n peak center
  - 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)

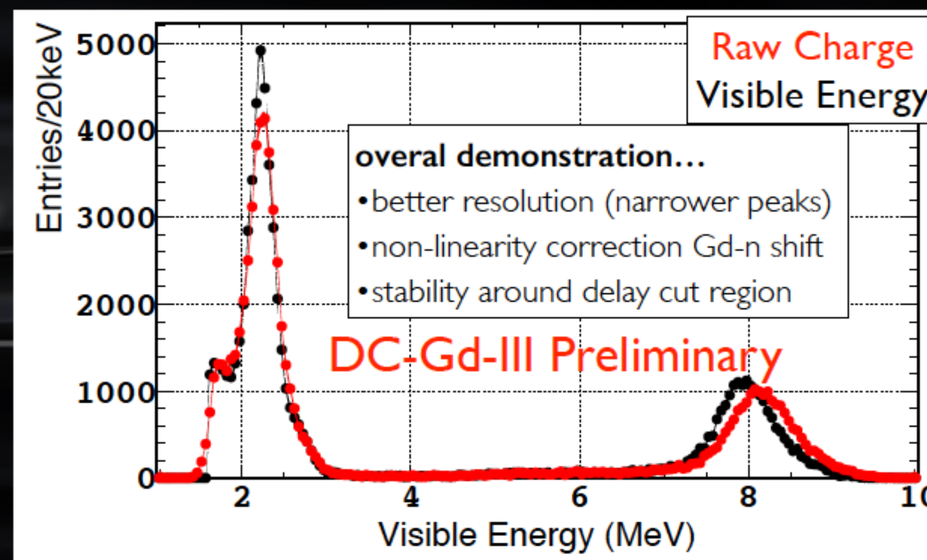




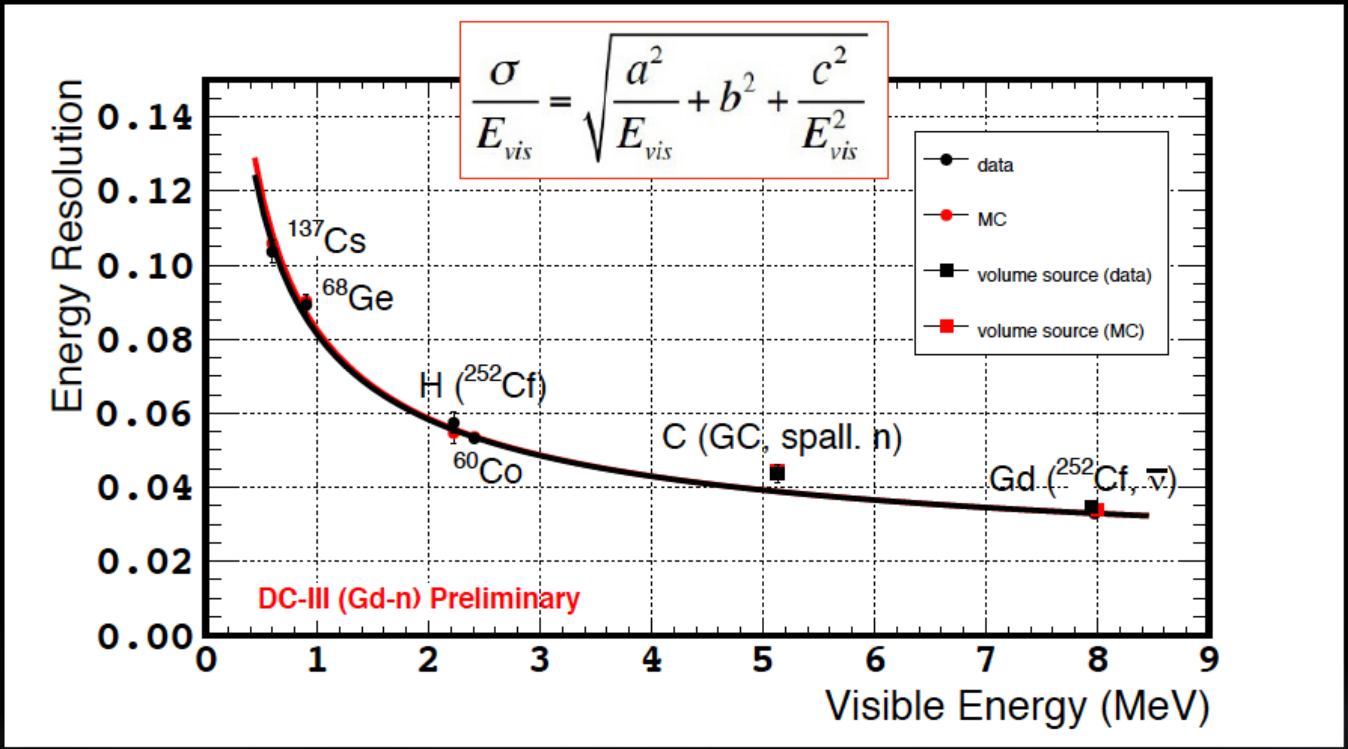
energy reconstruction (2)...

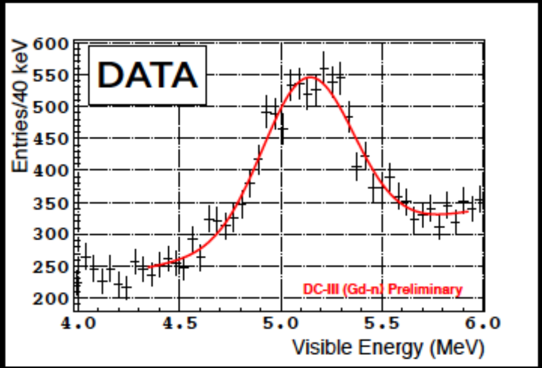
- **Drift Stability Calibration...**
  - def: **PE(t)→PE(τ)**, where **τ**: time MeV definition
  - response drift by +0.5%/years (unknown)
  - impact: **stability (+)**
- **Charge Non-Linearity Calibration...**
  - readout driven-non-linearity→ Δ(H-n,Gd-n)=~1%
  - validation with C-n peak @ 5MeV & ^{12}B spectrum
  - impact: **linearity (+)**
- **Light Non-Linearity Calibration...**
  - single-γ scintillation quenching measurement
    - many calibration sources @ center
  - conversion: **MeV(e+)→MeV(single-γ)** [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.

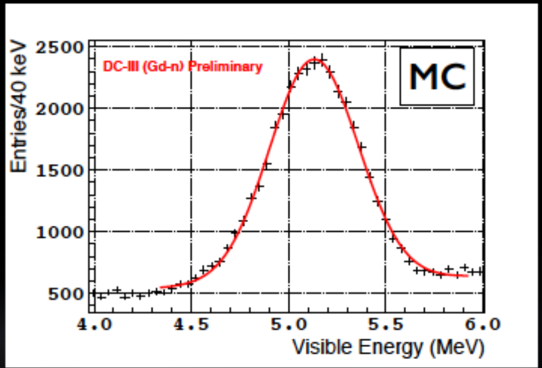




response coherence all throughout…







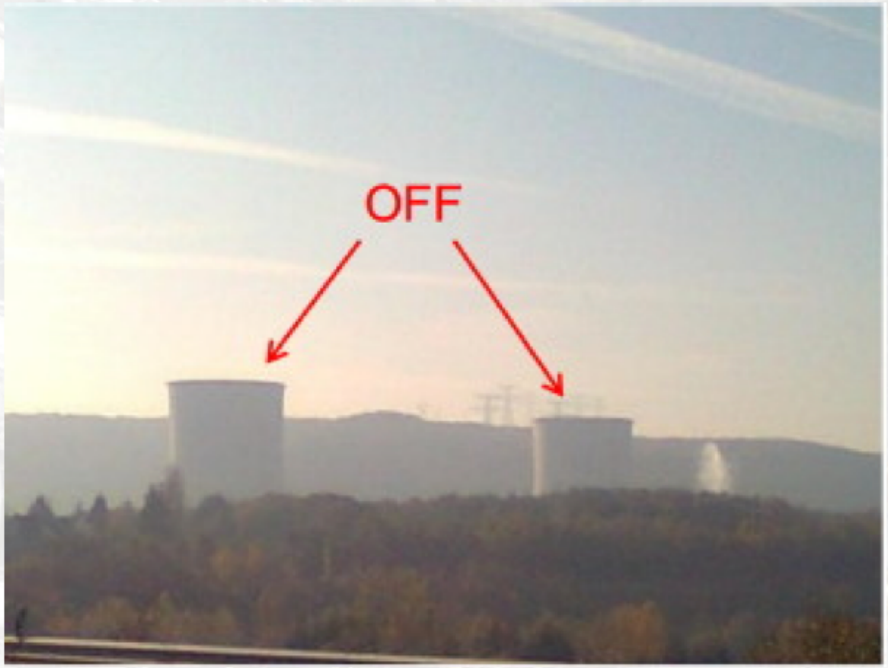
a: statistical term
b: constant term
c: e.g. electric noise

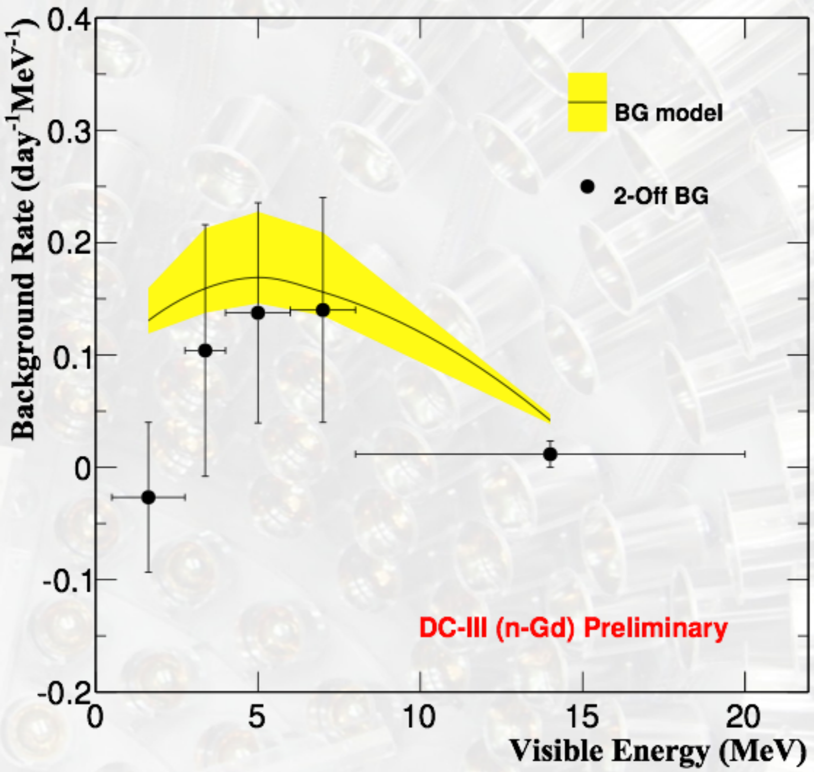
Data
a=0.0773±0.0025
b=0.0182±0.0014
c=0.0174±0.0107

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 anywhere in NT and GT
  - C-n peak (mainly from GC)→ slight different response in GC (worse)
- **constant term of resolution ~1.8%** (powerful calorimetry)
  - dominated by stochastic term

IBD candidates with reactors OFF





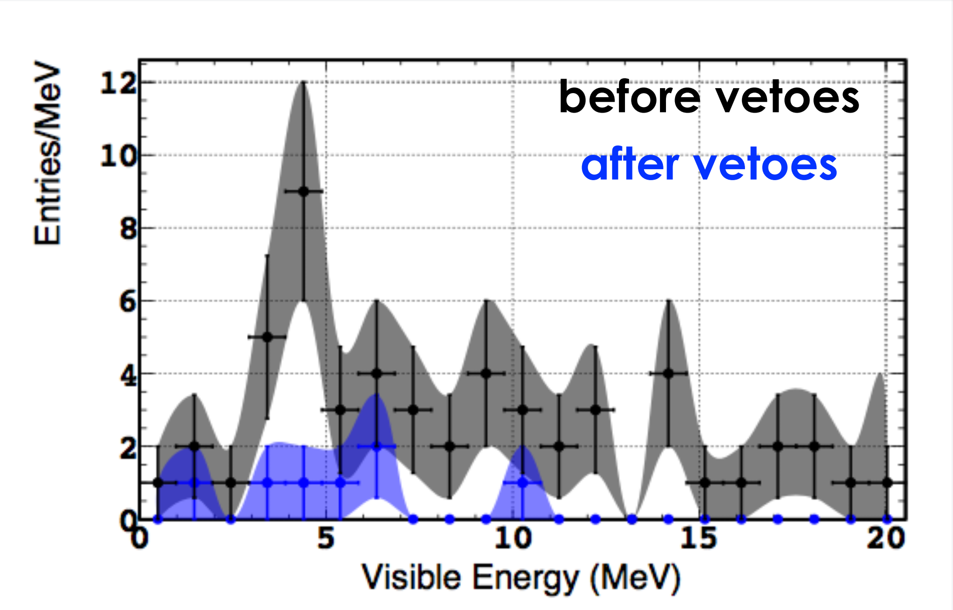
agreement between reactor fully OFF and background model

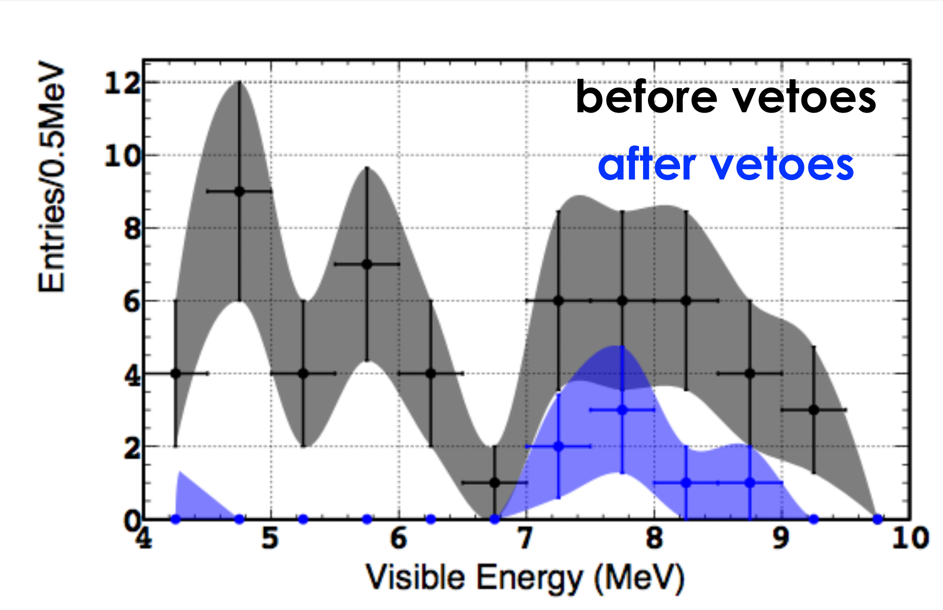
(poor spectral info→ mainly rate)

tension **$BG(OFF)^{inclusive} < \Sigma\, bg_i^{exclusive}$** @ ~2σ

⟹ it implies no (or very little) room for any <u>unknown background</u>

reactor 2xOFF data…





7 events in 7.238 days - 13.4 expected

2xOFF data: powerful information before/after veto evolution

(scrutinising a few event-wise BG-only)

1 week→**poor stats** (spectral info fluctuations dominated)→ <u>inconclusive</u>

P(rejection)=(7.7±3.1) @ Gd-III

(in agreement with (9.9±1.0) estimated between [12,20]MeV)

θ_{13} RESULTS

several analyses sensitive to θ_{13}…

- **Rate+Shape Analysis (R+S)**
  - Exploit full spectra and E/L signature of θ_{13} (ν-oscillations)
  - BG measured in-situ → further constrained by shape information
    - x2 precise BG estimate (w.r.t. Gd-II) → x3 precise δ(BG) after R+S fit
  - **Provides most precise measurement of θ_{13}**
- **Reactor Rate Modulation Analysis (RRM)** (**Double Chooz only**)
  - Exploits variations of reactor power: fit a straight line in the neutrino rate/reactor power
  - **Background- and spectrum shape-independent measurement of θ_{13}**
    - BG (and θ_{13}) constrained by Rector-OFF data
  - **Precision improved with input BG estimates**
  - (**unique DC**) remarkable cross-check θ_{13} with and without BG model
- (RO) **rate-only analysis** (**cross-check only**)

- The same 3 analyses using neutron H-n captures
  - **first such analysis published Jan 13 [hep-ex 1301.2948]**

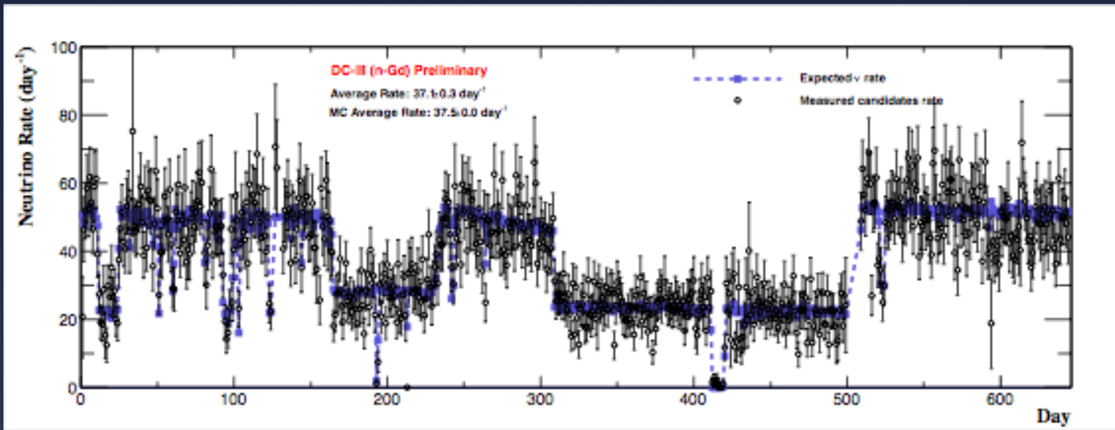
Several Analyses…

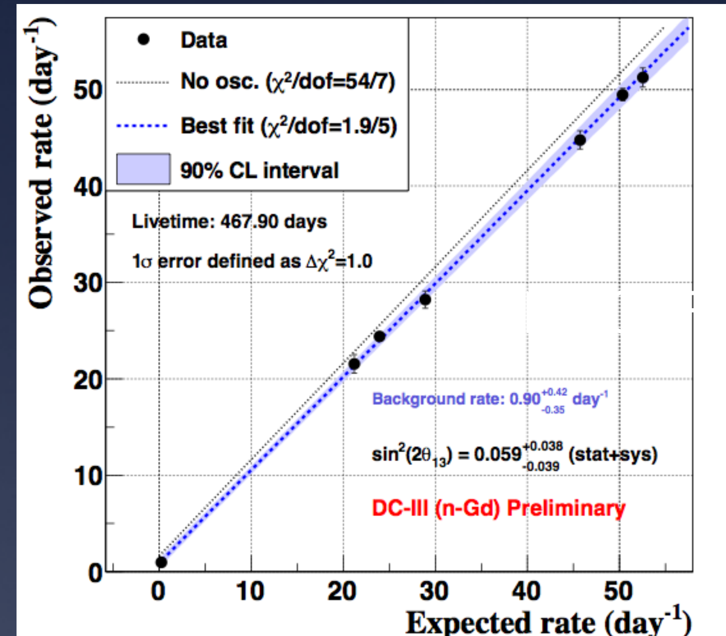
Gd-n analysis	Background		Theta 13
	input	output	
Rate + Shape (**R+S**)	BG model	background further constrained by shape	
Reactor Rate Modulation (**RRM**)	no	background independant teta 13 Measurement	
	full reactor off	no	Precision improved from this BG input
Rate Only (**RO**)	no	no	cross check
	full reactor off	no	cross check

same with H-n analysis

also Gd-n$\oplus$H-n combined analysis

Reactor Rate Modulation analysis…

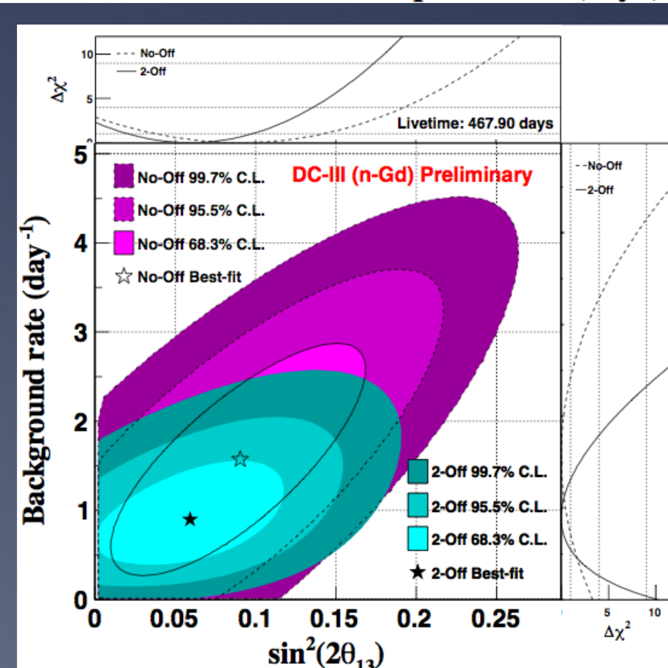




- exploit our 100% variations in reactor power…
  - **measure BG and $\sin^2(2\theta_{13})$ simultaneously**
  - **Background is inclusive**→ even unknown
  - $\Longrightarrow$ background measurement without model

- fit is straight line…
  - **BG^{inclusive}**→ intercept
  - **$\sin^2(2\theta_{13})$**→ slope

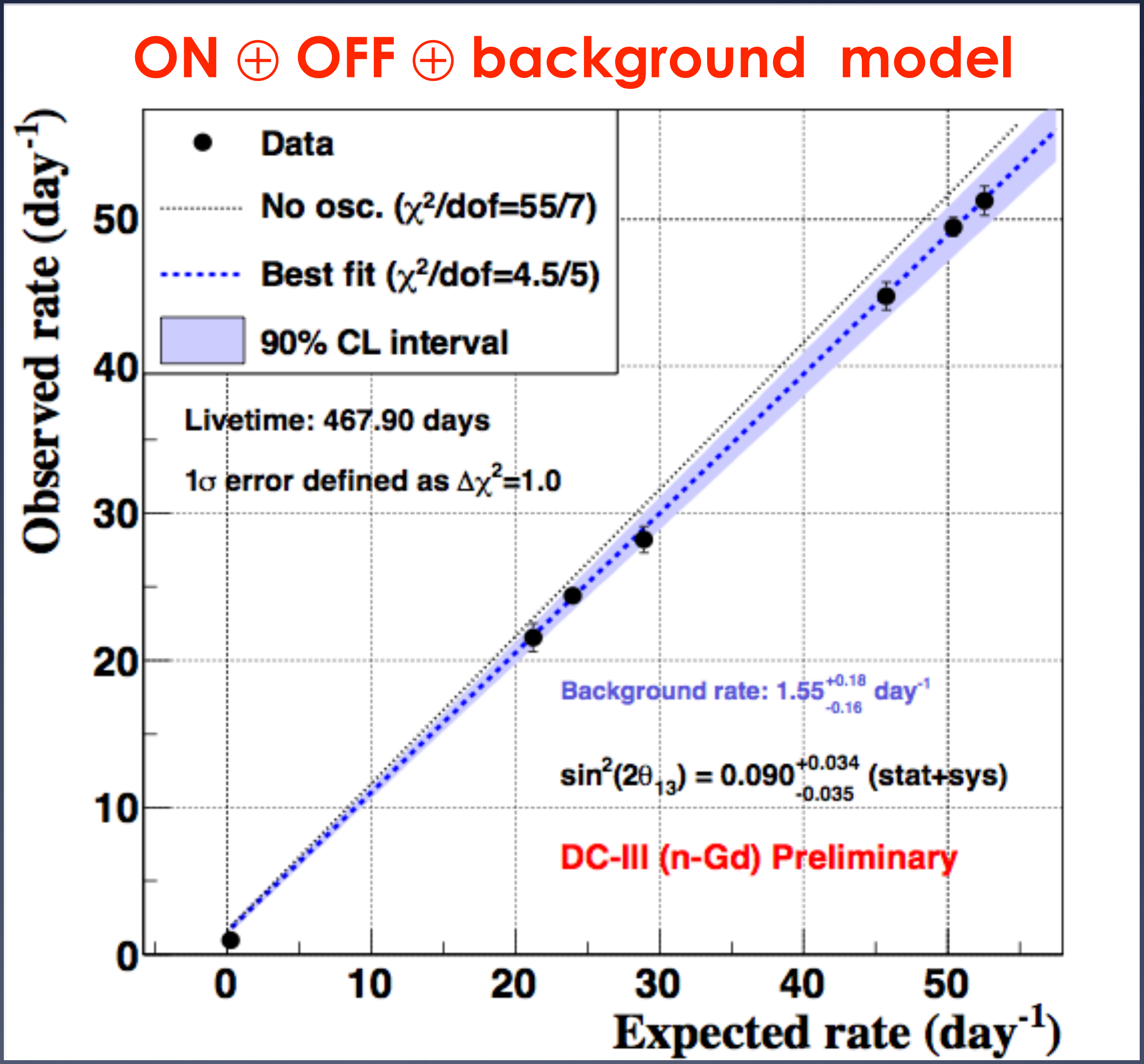
- unique analysis of DC (remarkable validation)



the ultimate Reactor Rate Modulation results…

3 ways to constrain BG…

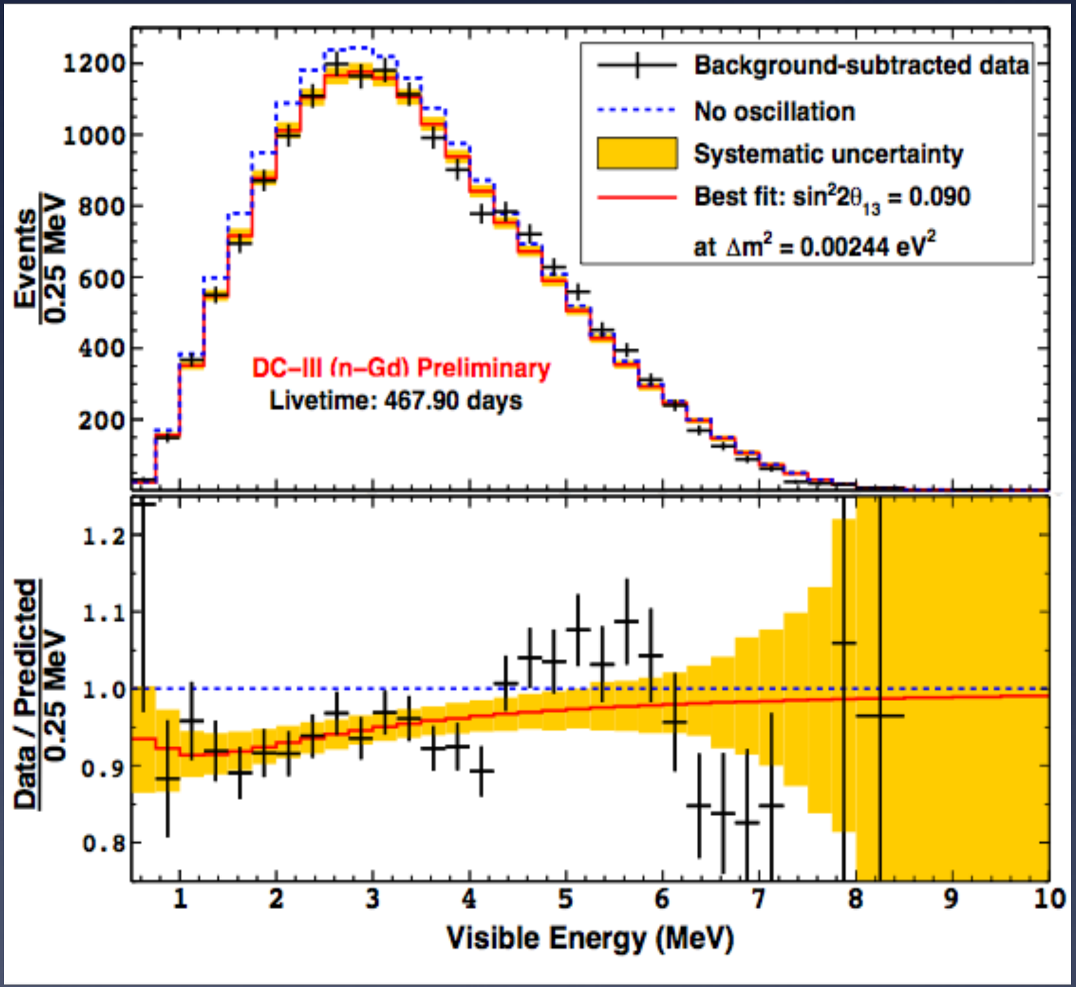
- ON data extrapolation
- reactor 2xOFF data
- independent BG model measurements



most precise rate-only→ i.e. not spectral info used
(independent technique + complementary to R+S)

Rate+Shape results

- **many improvements…**
  - NEW!! 250keV binning and [0.5,20]MeV
  - NEW!! **BG fully data driven** (first time)
- **signal treatment…**
  - NEW!! new spectrum with ^{238}U (low energy)
  - Δm^2 from MINOS (confirmed T2K)
- **BG treatment…**
  - NEW!! **full** OFF data constraint (extra bin)
  - **accidental pull term**
    - NEW!! **rate:** syst. dominated
    - **shape:** data measured
  - **fast-n pull term** (~no stopping μs) NEW!!
    - **rate:** stats dominated
    - **shape:** data measured
  - **Li+He pull term**
    - NEW!! **rate:** statistics driven
    - NEW!! **shape:** data measured (no MC!!!)
  - negligible ^{12}B and BiPo
- **energy treatment…**
  - e+ energy model (via tuned MC) NEW!!
  - scintillator non-linearity NEW!!

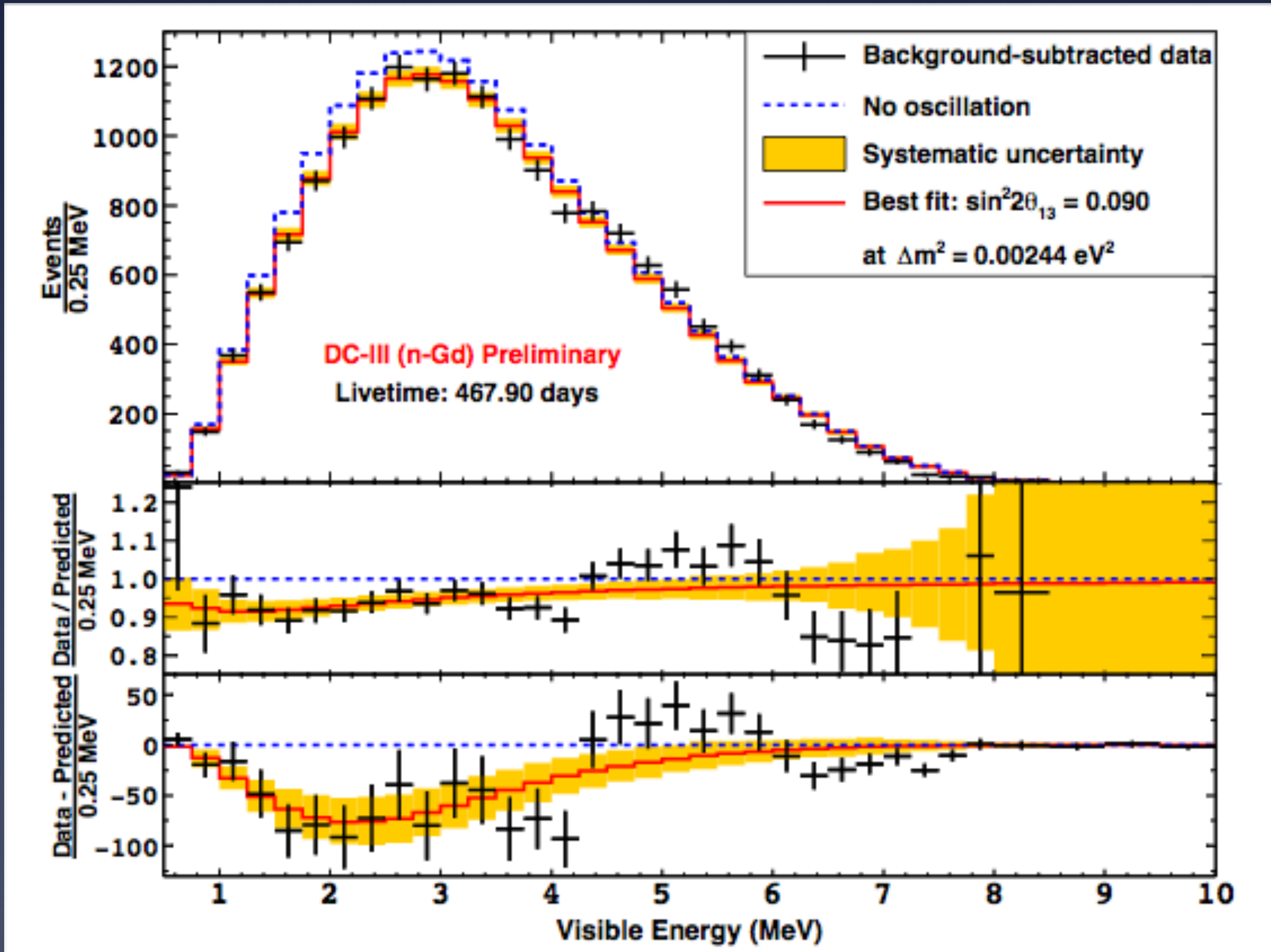


$\sin^2(2\theta_{13})=(0.09\pm0.03)$

(χ^2/n.d.f. = 51.4/40)

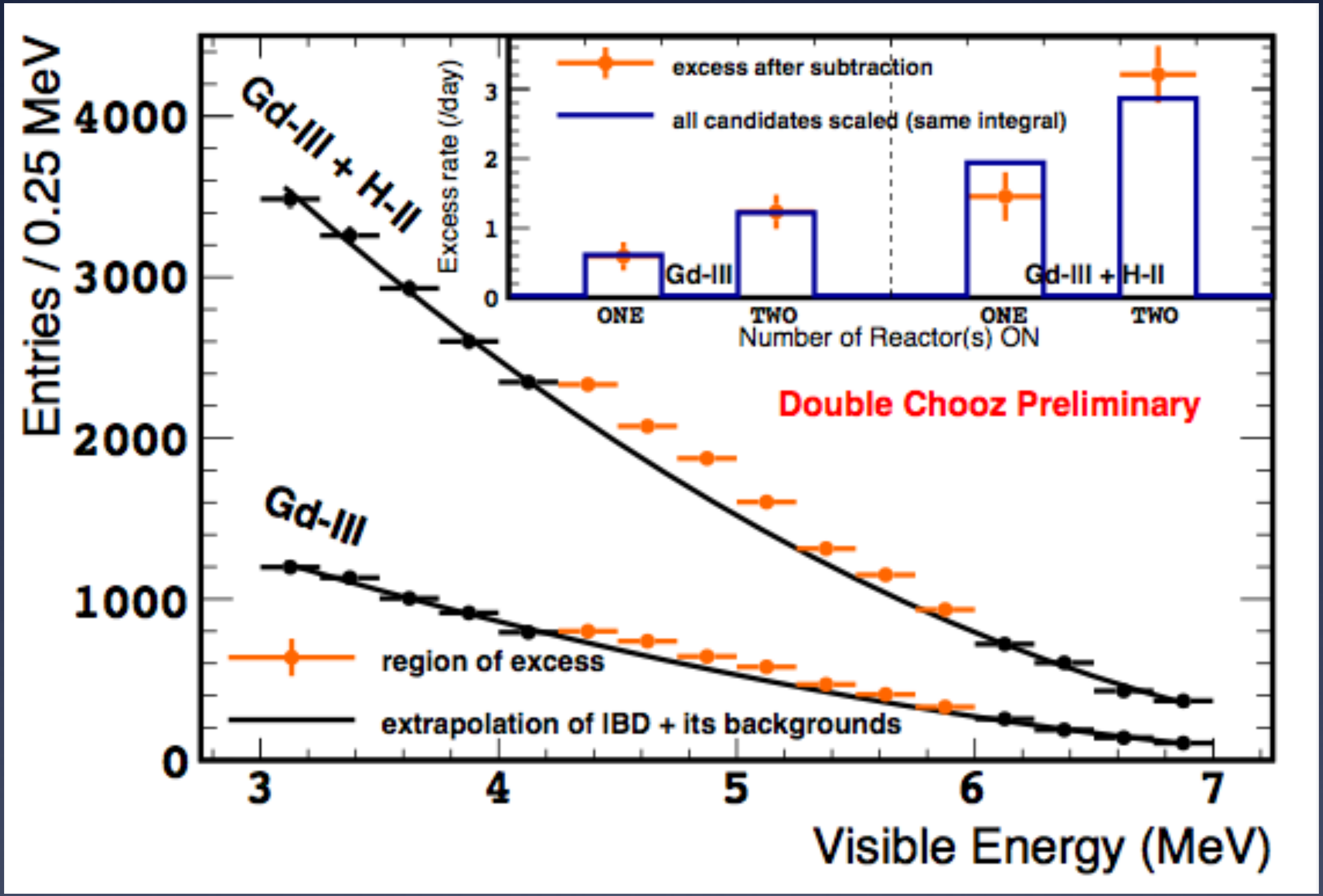
background subtracted

(BG systematic 3x smaller than previous results)



Background-subtracted data
No oscillation
Systematic uncertainty
Best fit: $\sin^2 2\theta_{13} = 0.090$
at $\Delta m^2 = 0.00244\ \mathrm{eV}^2$
DC-III (n-Gd) Preliminary
Livetime: 467.90 days
Events / 0.25 MeV
Data / Predicted / 0.25 MeV
Data - Predicted / 0.25 MeV
Visible Energy (MeV)

targeted studies…



search for empirical correlations in "excess" region ~[4,6]MeV
(deficit region: no enough statistics)

no correlation was found on any BG-sensitive variable (time to last μ, etc)

strong correlation with reactor power→ <u>more data (H) stronger correlation</u>
(empirical data-driven observation)

observed structure in data/MC over [4,6]MeV is **not yet understood**
but, NOT impact on θ13 measurement (many tests→ very robust)

source	status
detection	discarded
energy	disfavoured
background	tension
flux	possible?
combination	possible

considering only IBD neutrinos ($\nu+p\rightarrow n+e^{+}$), this is consistent with an unaccounted reactor neutrino flux effect @ ~1.5σs.

other possible explanations (background, energy, etc) are disfavoured by dedicated consistency checks or tension

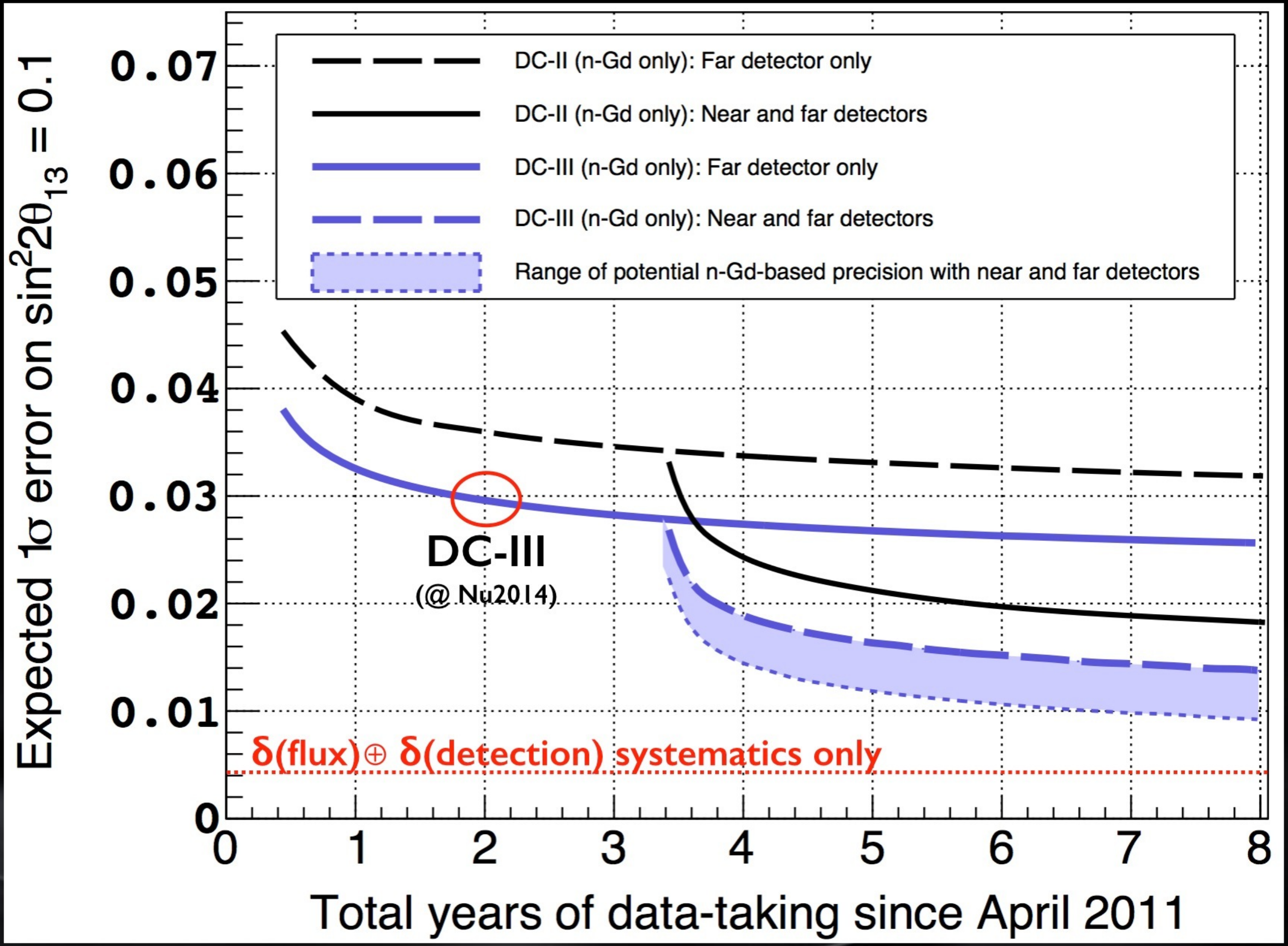
Prospected 1σ Error with ND

Gd-n analysis FD+ND prospect inputs

- **δ(flux)~0.1%** (**preliminary**)
  - iso-flux suppression dominated
- **δ(detection)~0.2%**
  - 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**

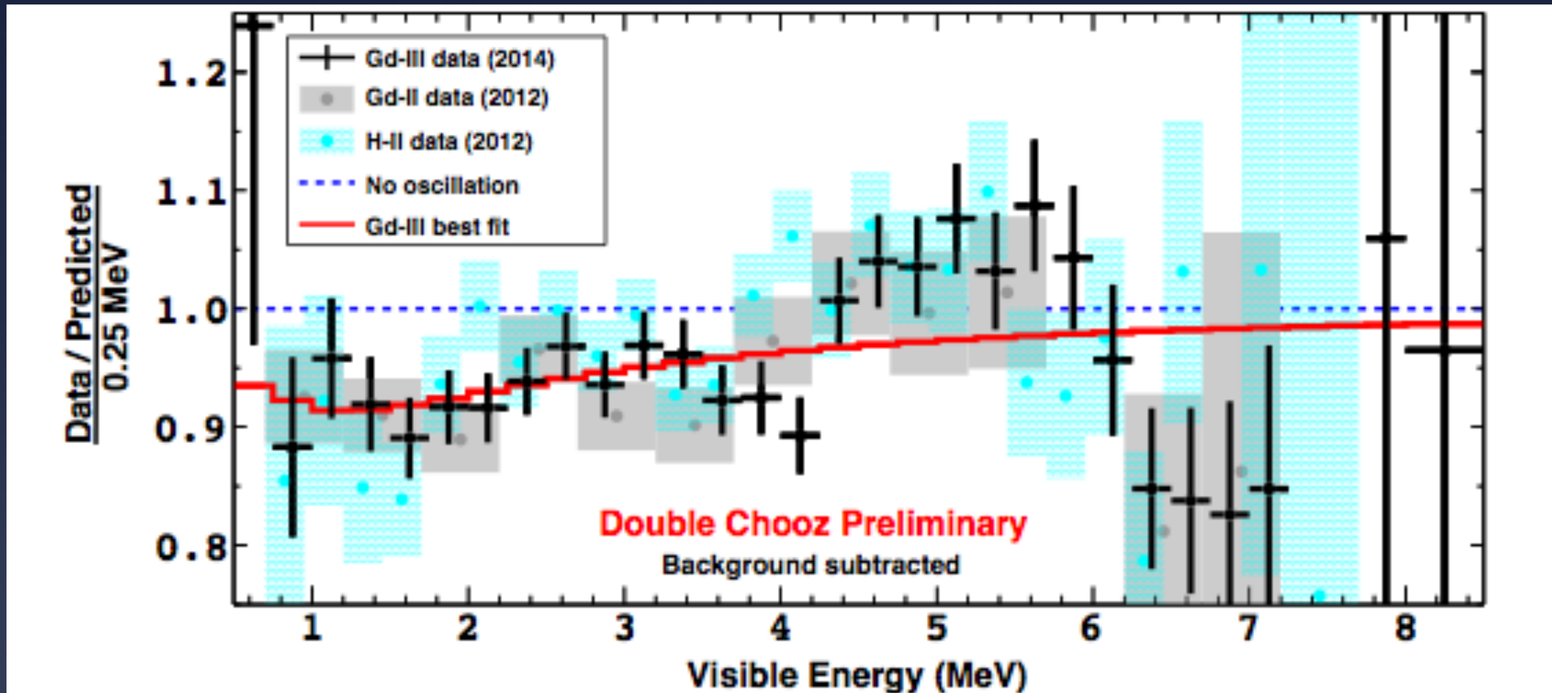
(rate+spectrum projection uses latest BG model fromDC-III)

conclusions

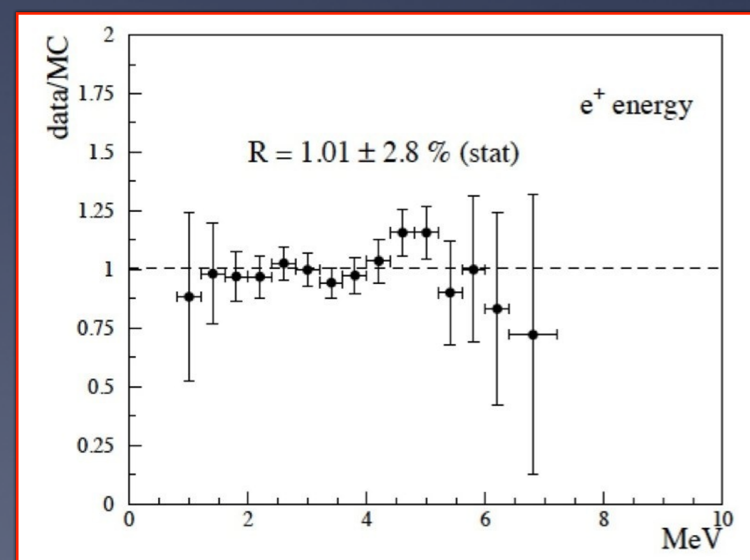
- **DC-Gd-III improvements…**
  - 2x more statistics
  - improves everything by factors relative to Gd-II (Kyoto, Nu2012)
    - higher efficiency, less BG (active BG rejection), data-driven BG estimations, etc
    - **δ(detection)^{III} ~2x more precise**
    - **δ(background)^{III} ~3x more precise**
    - **better energy reconstruction** (non-linearities fully accounted)
  - analysis ready for ND (more under preparation)
  - other studies in progress: neutrino direction (thanks to the small number of reactors).. See the poster
- **DC-Gd-III results…**
  - **R+S:** $\sin^2(2\theta_{13})=(0.09\pm0.03)$ [for BG=(1.43 ± 0.15)day^{-1}]
  - **RRM:** $\sin^2(2\theta_{13})=(0.09^{+0.03}_{-0.04})$ [for BG=(1.55 ± 0.17)day^{-1}]
    - **RRM**(no BG model)**:** $\sin^2(2\theta_{13})=(0.06\pm0.04)$ [for BG =(0.90 ± 0.39)day^{-1}]
- **DC projections…**
  - ND from end of summer 2014
  - major systematic cancellation boosting DC **$\geq$0.01 as 1σ error on $\sin^2(2\theta_{13})$ (Gd-n only)**
    - improvements in analysis→ already in preparation

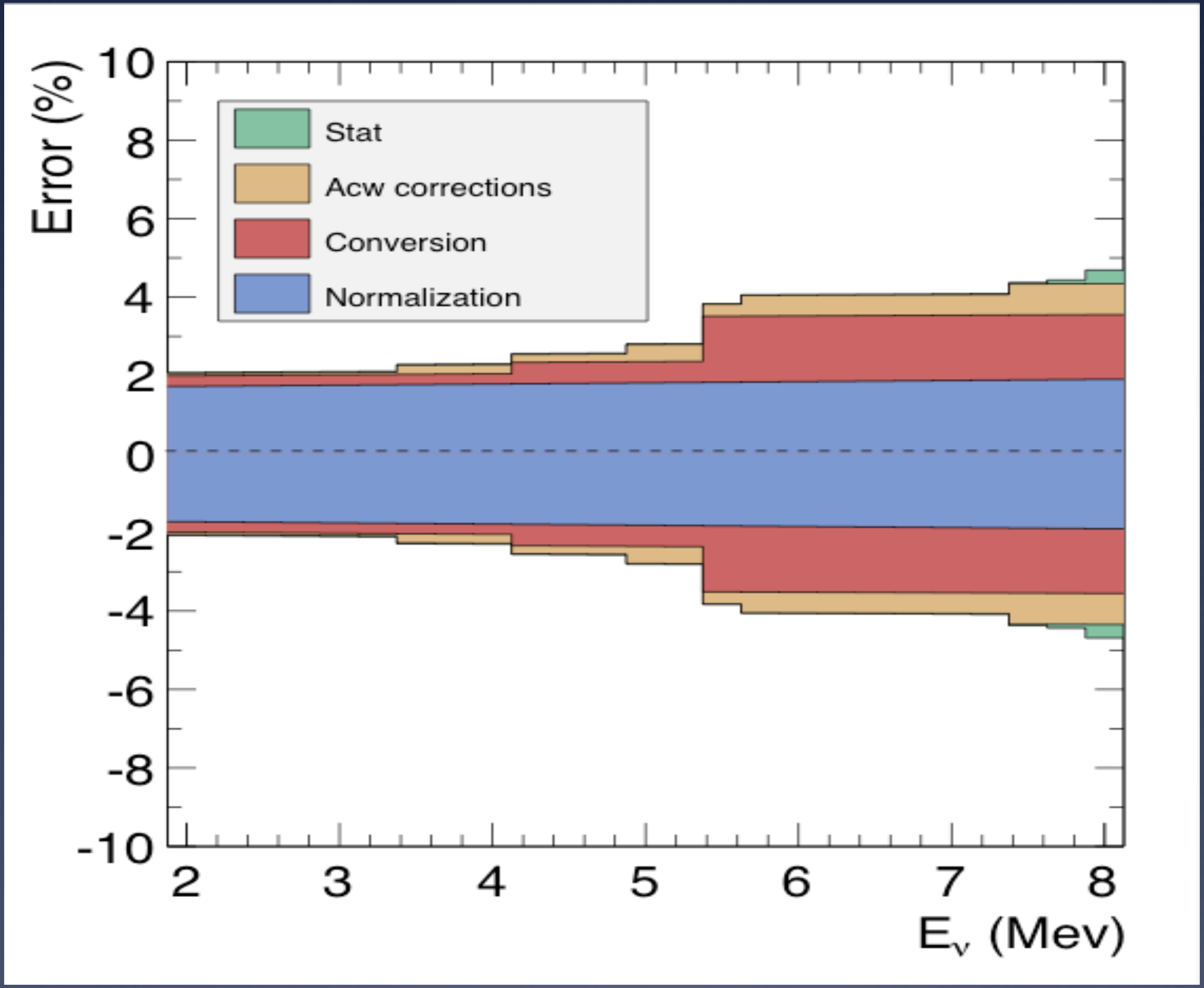
BACK UP

DC-III-Gd vs DC-II-Gd and DC-II-H



- **not new!! just better resolved…**
  - better stats (x2) (same flux info)
  - better energy (+50% better systematics)
  - better BGs (x3 better systematics)
- same DC-III-Gd pattern visible with…
  - **DC-II-Gd…** [also **DC-I-Gd**]
    - different selection (→ different BGs)
  - **DC-II-H…**
    - very different BGs
    - different detector volume (less precision)
  - **also CHOOZ?** (same reactors, different everything)





Error (%)
10
8
6
4
2
0
-2
-4
-6
-8
-10
Stat
Acw corrections
Conversion
Normalization
2
3
4
5
6
7
8
E_ν (Mev)

Parameter	Input C.V.	Input Error	Output C.V.	Output Error
E-scale a'	-0.027	0.006	-0.026	$+0.006, -0.005$
E-scale b'	1.012	0.008	1.011	$+0.004, -0.007$
E-scale c'	-0.0001	0.0006	-0.0006	$+0.0006, -0.0005$
FN+SM rate (d^{-1})	0.60	0.05	0.56	0.04
Li+He rate (d^{-1})	0.97	$+0.41, -0.16$	0.80	$+0.15, -0.13$
Accidentals rate (d^{-1})	0.0701	0.0054	0.0708	0.0053
Residual $\bar{\nu}_e$	1.57	0.47	1.49	0.47
Δm^2 (10^{-3} eV^2)	2.44	$+0.09, -0.10$	2.44	$+0.09, -0.10$
$\sin^2 2\theta_{13}$	—	—	0.090	$+0.033, -0.028$
χ^2/d.o.f.	—	—	51.4/40	—

improvement of Li+He constraint using spectral information (aided by rate)
→ lower rate and more precise (improve S/BG too)

all results consistent between input and output (no tensions >1σ)

all about ^{7}Li (the rest is ~negligible)…

BG	rate (day	shape	energy range	S/BG (%)	δ(BG) (%)	suppresion (wrt Gd-II)
9	**0.97**	data (Li+He tag)	[0,12]MeV	2.61	**0.78**	1.3
fast-n stopped-μ	**0.60±0.05**	data (IV tag)	[0,20]MeV	1.62	0.13	1.9
accident al	0.070±0.005	data (off-time)	<3MeV	0.19	0.01	3.7
12	<0.003@68CL	neglected	[0,13]MeV	-	-	>7.0
BiPo	<0.1	neglected	<2MeV	-	-	same

Li+He (He ≤10%) dominates BG systematics budget by >90%

(energy spectrum data-driven→ poor statistics)

all other BG becoming negligible→ DC-III = IBDs + ^{9}Li

(effectively)

(fast-n is high but well know spectrum makes it innocuous)