DC@2017

(where are we?)

39th International School of Nuclear Physics @ Erice

(Neutrino in Cosmology, Astrophysics & Nuclear Physics)

Erice, Sicilia, Italia — SEPT-2017

Anatael Cabrera

CNRS / IN2P3 @ APC (Paris)

(nut-shell) experiment's rationale & history…

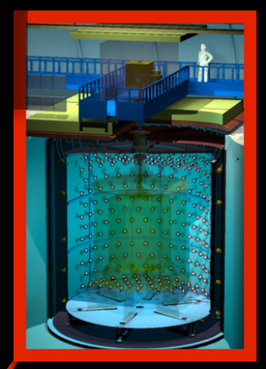
Chooz Reactors

~10^{21} ν/s

<L>=0m

Bugey4 (~ND)

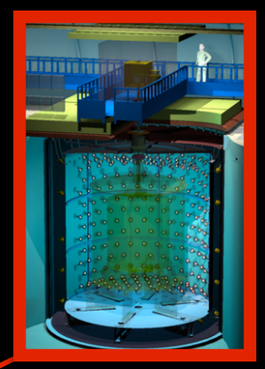
Near Detector (ND)



≲1000 ν/day
Dec.2014

<L>≈400m

Far Detector (FD-I & FD-II)

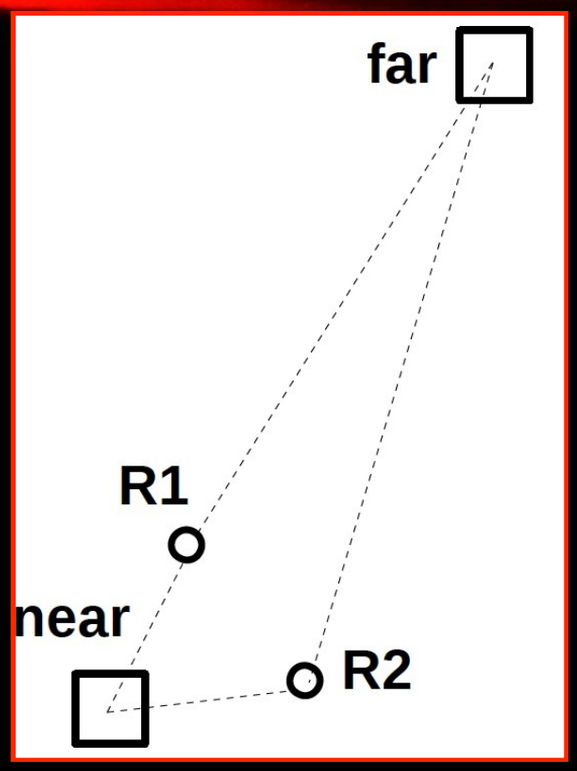


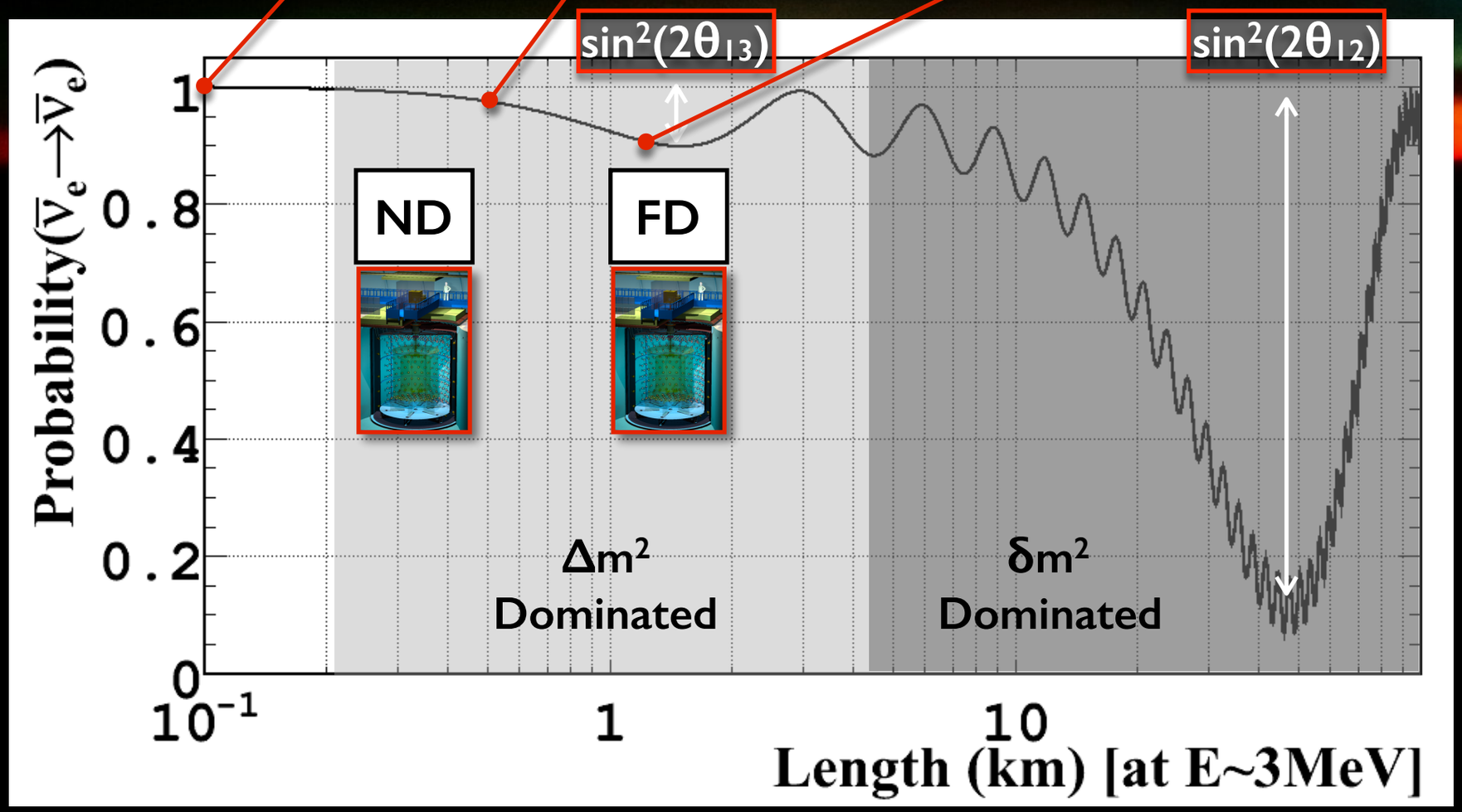
≲140 ν/day
April 2011

<L>≈1050m

FD-I ⊕ Bugey4
FD-II ⊕ ND

Site Geometry
(~iso-flux)





DC achievements (so far)…

- **(2011-OCT) first positive indication of θ13 (~2σ) with FD-I** [**arXiv:1112.6353**]
  - same location & similar statistics **CHOOZ** claimed: no observation
  - combined **DC-2010(disappearance)⊕T2K-2010(appearance) ~3σ consistent observation**
  - **DYB-2012 ≳5σ** followed by RENO-2012 (≲5σ)→ θ13 observed beyond doubts!!

  NOTE: central value of DC-I(Bugey4) & DYB almost identical [RENO claimed higher value]

- **(2014-MAY) first indication of reactor spectral distorsion with FD-I** [**arXiv:1406.7763**]
  - no choice since no ND (still): **DC ≳3σ via rate+shape analysis** [≲20k IBD's]
  - confirmed by RENO (June) & DYB (July) with ND [>100k's IBD's] via shape-only analysis (≲4σ's)

- **(2016-SEPT) first θ13 measurement with FD⊕ND [FD-I⊕FD-II: ≳7σ's Preliminary@CERN]**
  - θ13 seems higher (similar to RENO-I)→ DC-DYB discrepancy @ ~2σ's ["ok agreement"?]
  - also: **most precise $\langle\sigma^{IBD}_{fission}\rangle$**, **R+S spectral distorsion** & **most precise IBD-directionality**

DC achievements (so far)…

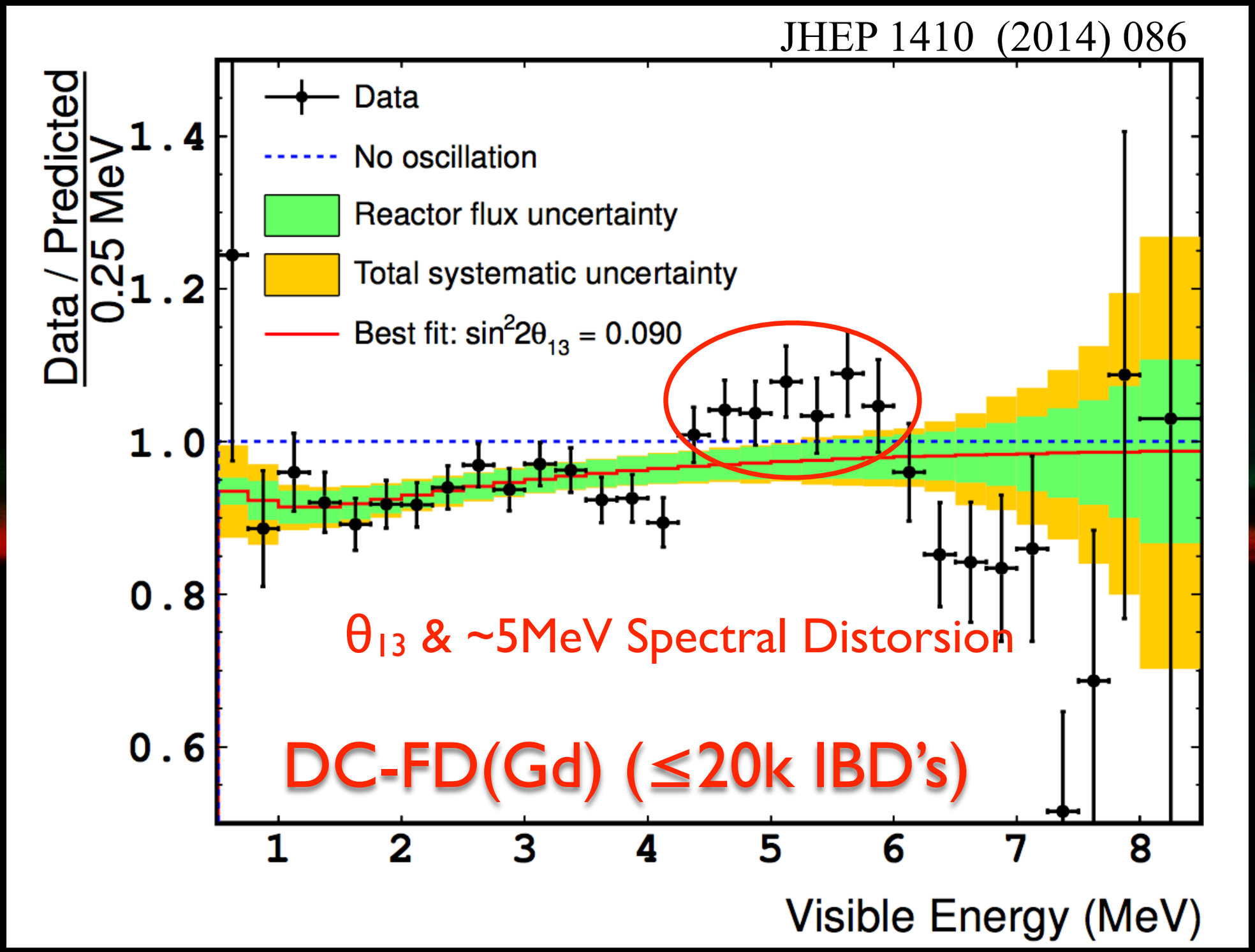
- **(2011-OCT) first positive indication of θ13 (~2σ) with FD-I** [**arXiv:1112.6353**]
  - same location & similar statistics **CHOOZ** claimed: no observation
  - combined **DC-2010(disappearance)⊕T2K-2010(appearance) ~3σ observation**
  - **DYB-2012 ≳5σ** followed by RENO-2012 (≲5σ)→ θ13 observed beyond doubts!!

  NOTE: central value of DC-I(Bugey4) & DYB almost identical [RENO claimed higher value]

- **(2014-MAY) first indication of reactor spectral distorsion with FD-I** [**arXiv:1406.7763**]
  - no choice since no ND (still): **DC ≳3σ via rate+shape analysis** [≲20k IBD's]
  - confirmed by RENO (June) & DYB (July) with ND [>100k's IBD's] via shape-only analysis (≲4σ's)

- **(2016-SEPT) first θ13 measurement with FD⊕ND [FD-I⊕FD-II: ≥7σ's Preliminary@CERN]**
  - θ13 seems higher (similar to RENO-I)→ DC-DYB discrepancy @ ~2σ's ["ok agreement"?]
  - also: **most precise $\langle\sigma^{IBD}_{fission}\rangle$**, **R+S spectral distorsion** & **most precise IBD-directionality**

the original observation…



confirmed by RENO & DYB a few months later [more info later]

DC achievements (so far)…

- **(2011-OCT) first positive indication of θ13 (~2σ) with FD-I** [**arXiv:1112.6353**]
  - same location & similar statistics **CHOOZ** claimed: no observation
  - combined **DC-2010(disappearance)⊕T2K-2010(appearance) ~3σ observation**
  - **DYB-2012 ≳5σ** followed by RENO-2012 (≲5σ)→ θ13 observed beyond doubts!!

  NOTE: central value of DC-I(Bugey4) & DYB almost identical [RENO claimed higher value]

- **(2014-MAY) first indication of reactor spectral distorsion with FD-I** [**arXiv:1406.7763**]
  - no choice since no ND (still): **DC ≳3σ via rate+shape analysis** [≲20k IBD's]
  - confirmed by RENO (June) & DYB (July) with ND [>100k's IBD's] via shape-only analysis (≲4σ's)

- **(2016-SEPT) first θ13 measurement with FD⊕ND [FD-I⊕FD-II: ≳7σ's Preliminary@CERN]**
  - θ13 seems higher (similar to RENO-I)→ DC-DYB discrepancy @ ~2σ's ["ok agreement"?]
  - also: **most precise $\langle\sigma^{IBD}_{fission}\rangle$, R+S spectral distorsion** & **most precise IBD-directionality**

this talk…

our θ13 experimental site…

Anatael Cabrera (CNRS-IN2P3 & APC)

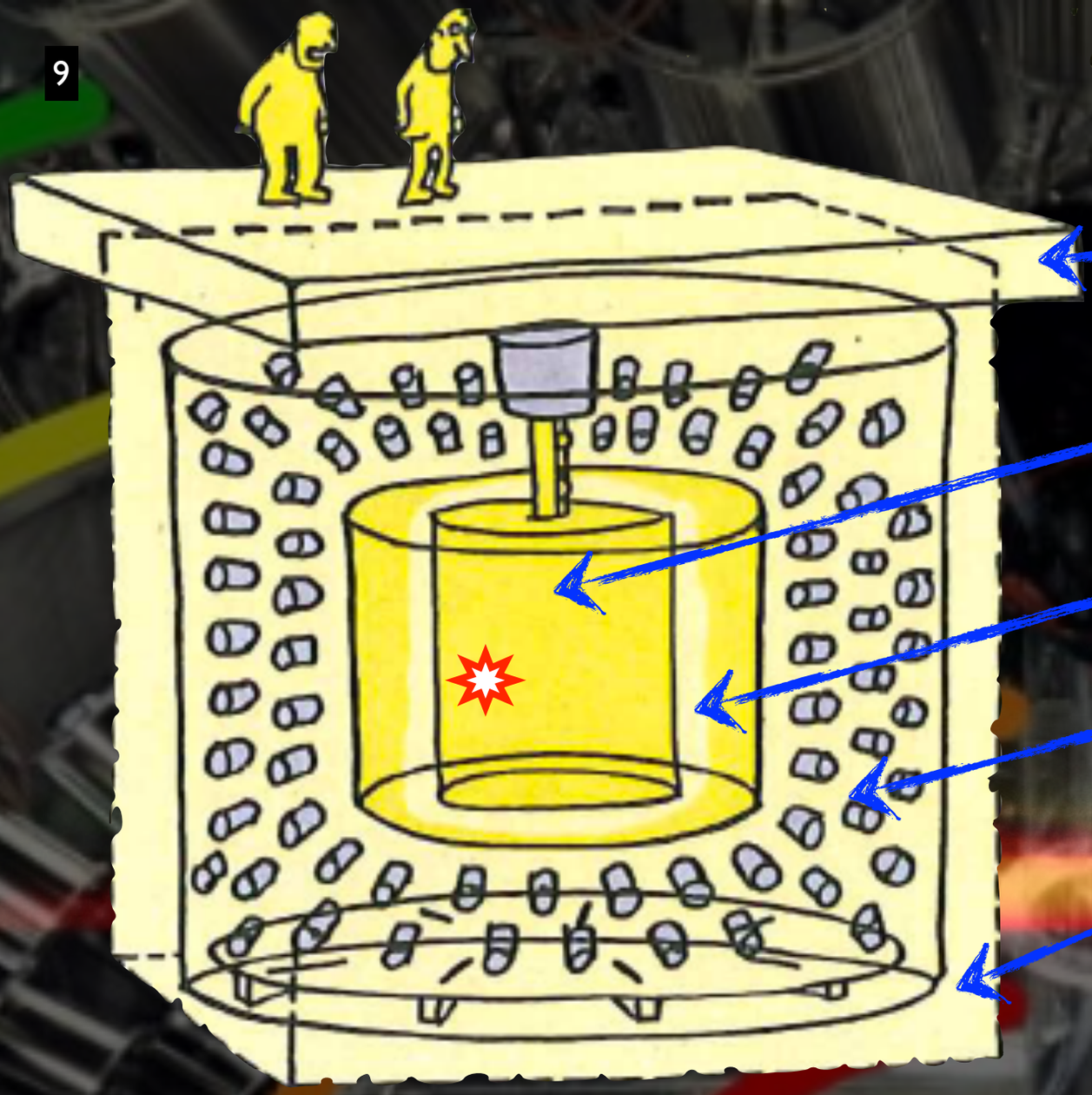
DC's LNCA laboratory…

Near Lab
<L>≈410m
~30ν day^{-1} ton^{-1}
~120 mwe

Far Lab
<L>≈1050m
~6ν day^{-1} ton^{-1}
~300 mwe

Chooz Reactors
Power: 8.5GW^{thermal}⇒ ~10^{21}ν/s
(2x N4 reactor)

DC a θ_{13}-LAND...



Outer μ-Veto (OV)
plastics-scintillator: strips (→tracking)

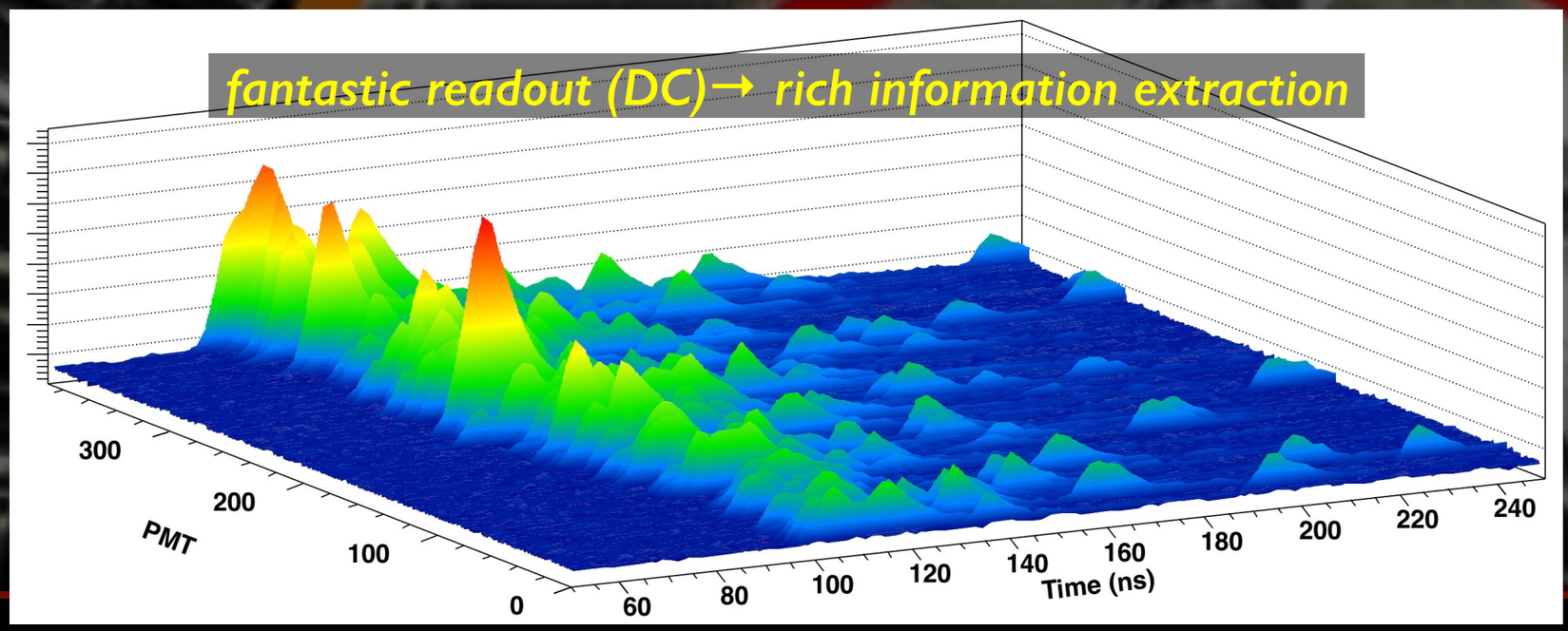
ν-Target (NT)
~10m³ Liquid-Scintillator + Gd (0.1%)

γ-Catcher (GC)
~20m³ Liquid-Scintillation

Light Buffer
~100m³ oil (no scintillation)

Inner μ-Veto (IV)
~90m³ Liquid-Scintillator

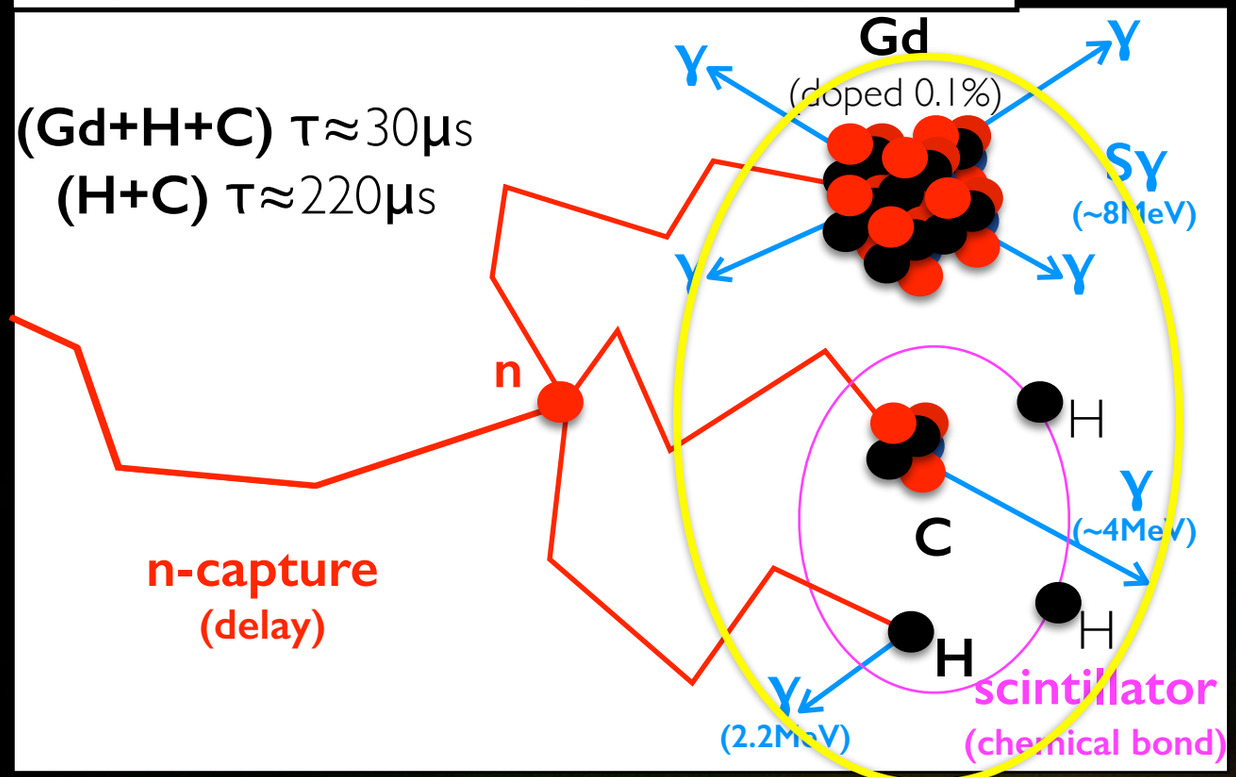
Inert γ-Shield
15cm steel [FD] / 1m water [ND]



Liquid Scintillator
⊕
10" PMTs
⊕
FADC readout
⊕
offline reconstruction
(time,charge,position,PS,multiplicity,etc)

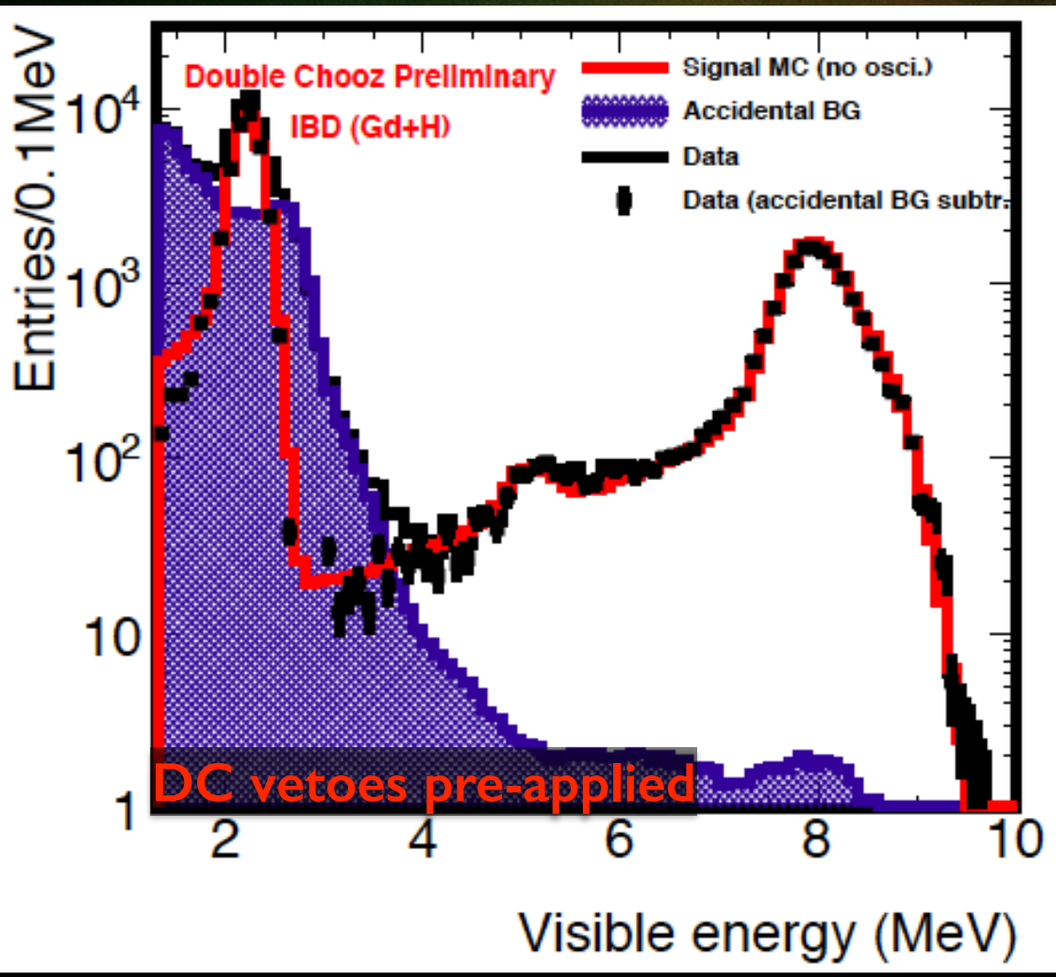
multi-isotope captures IBD's…

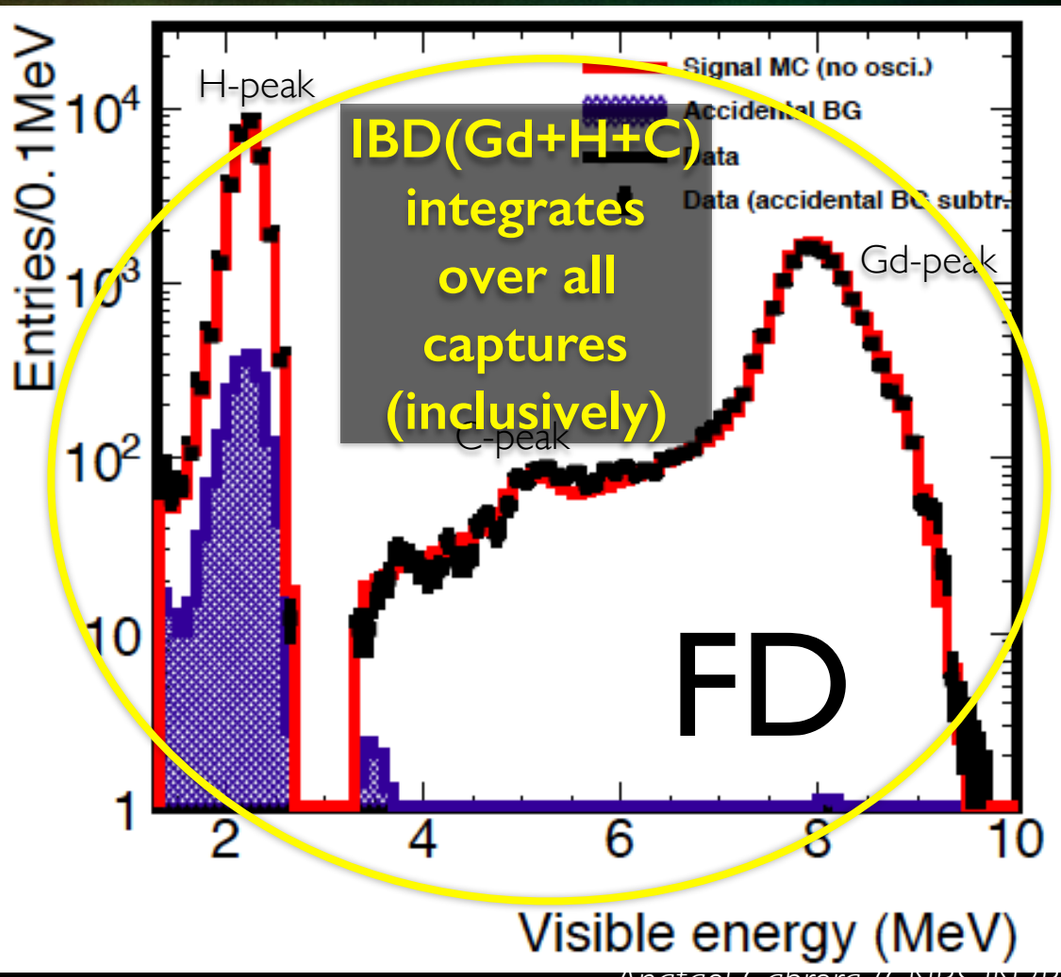
Capture: n + X → (process) → γ's



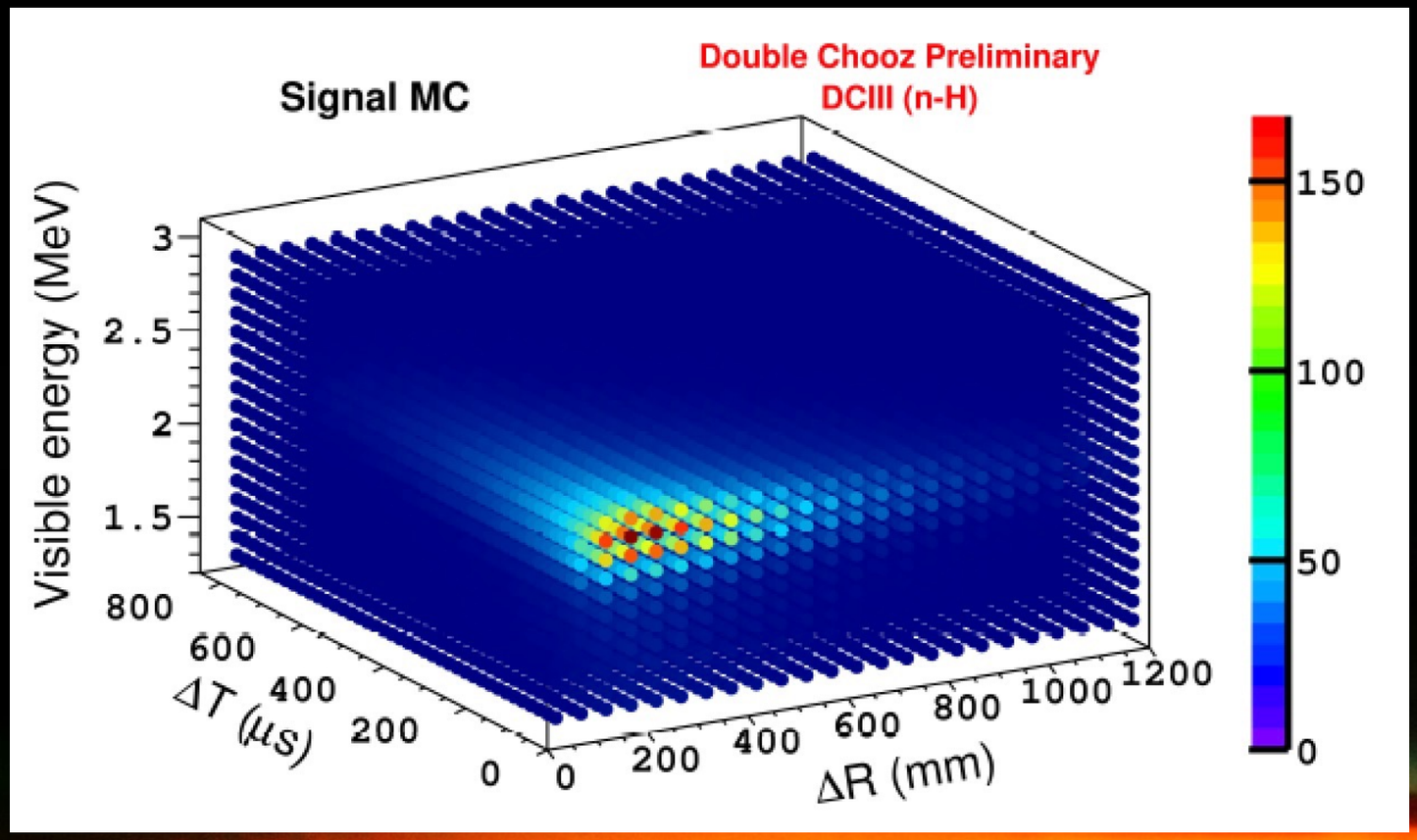
IBD selection (n-capture driven):

IBD	DC	DYB	RENO
Gd	≥2011	≥2012	≥2012
H	≥2012	≥2014	2014??
Gd+C	≥2014	—	—
Gd+C+H	≥2016	—	—

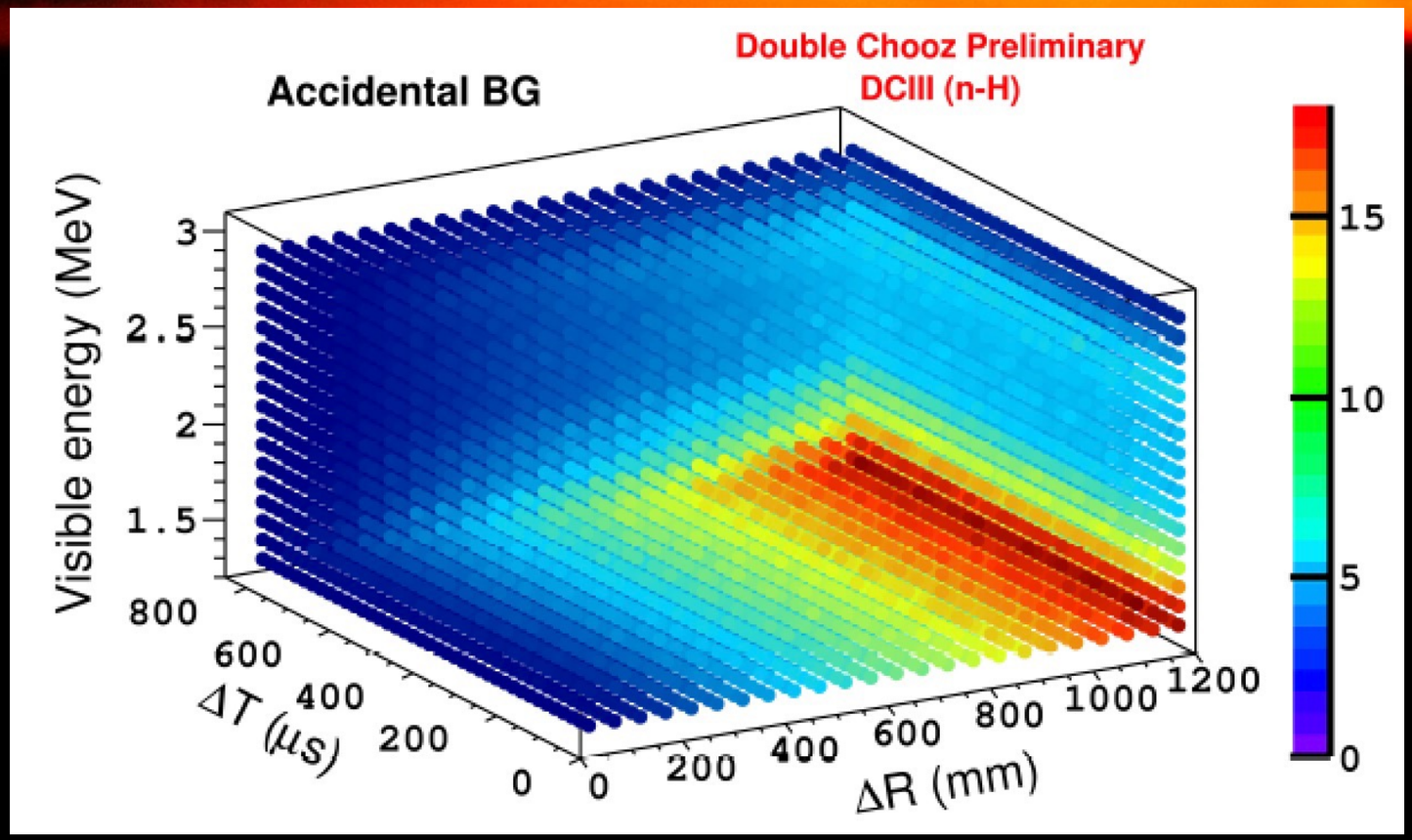




ANN discrimination rationale…



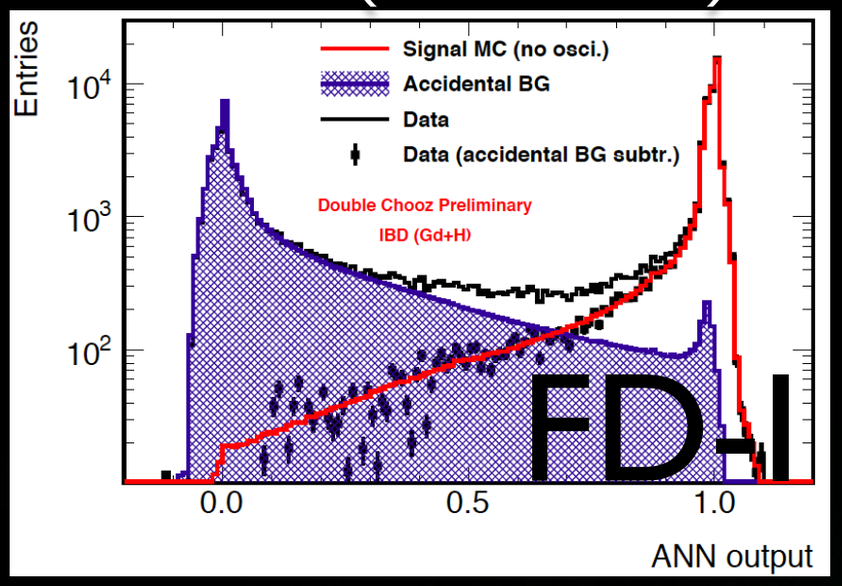
IBD (signal)
(correlated)

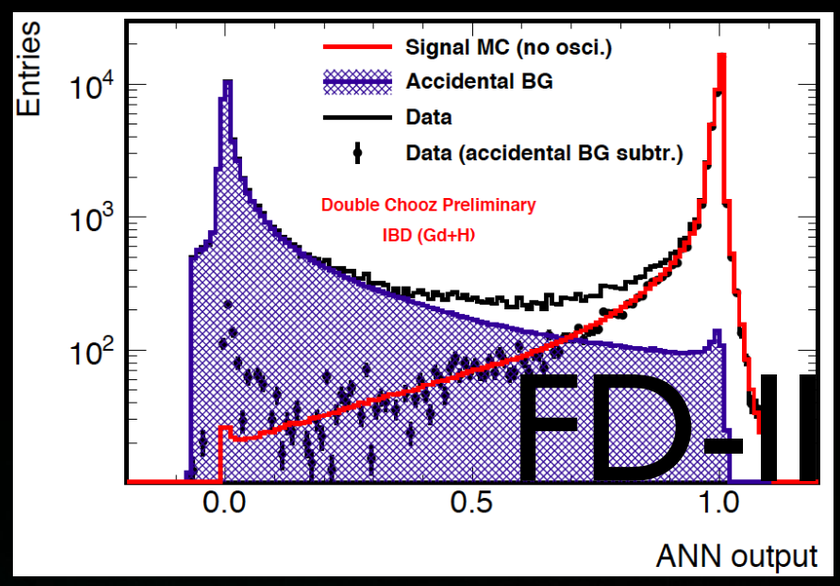


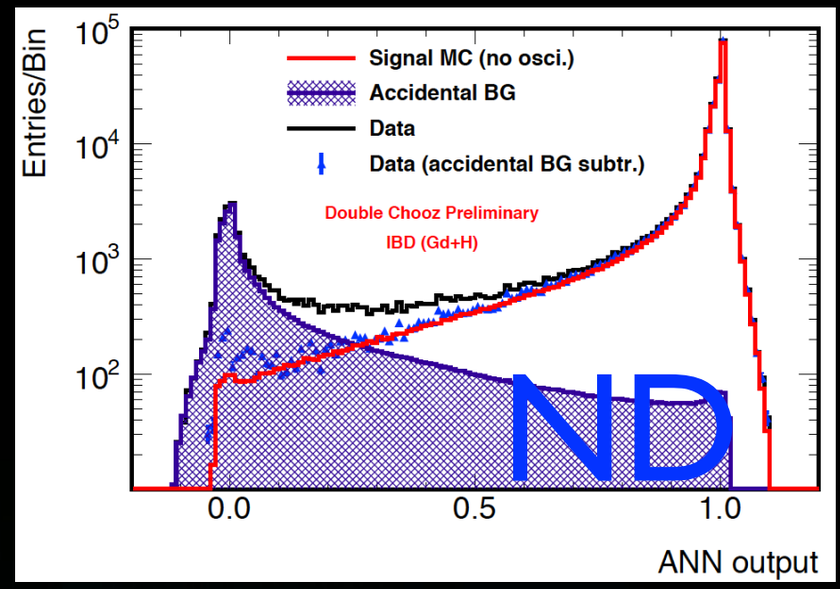
Accidental BG
(random)

(i.e. longer **Δ**t, longer **Δ**r, etc)

IBD(Gd+H) definition: 5D coincidence⊕ANN…



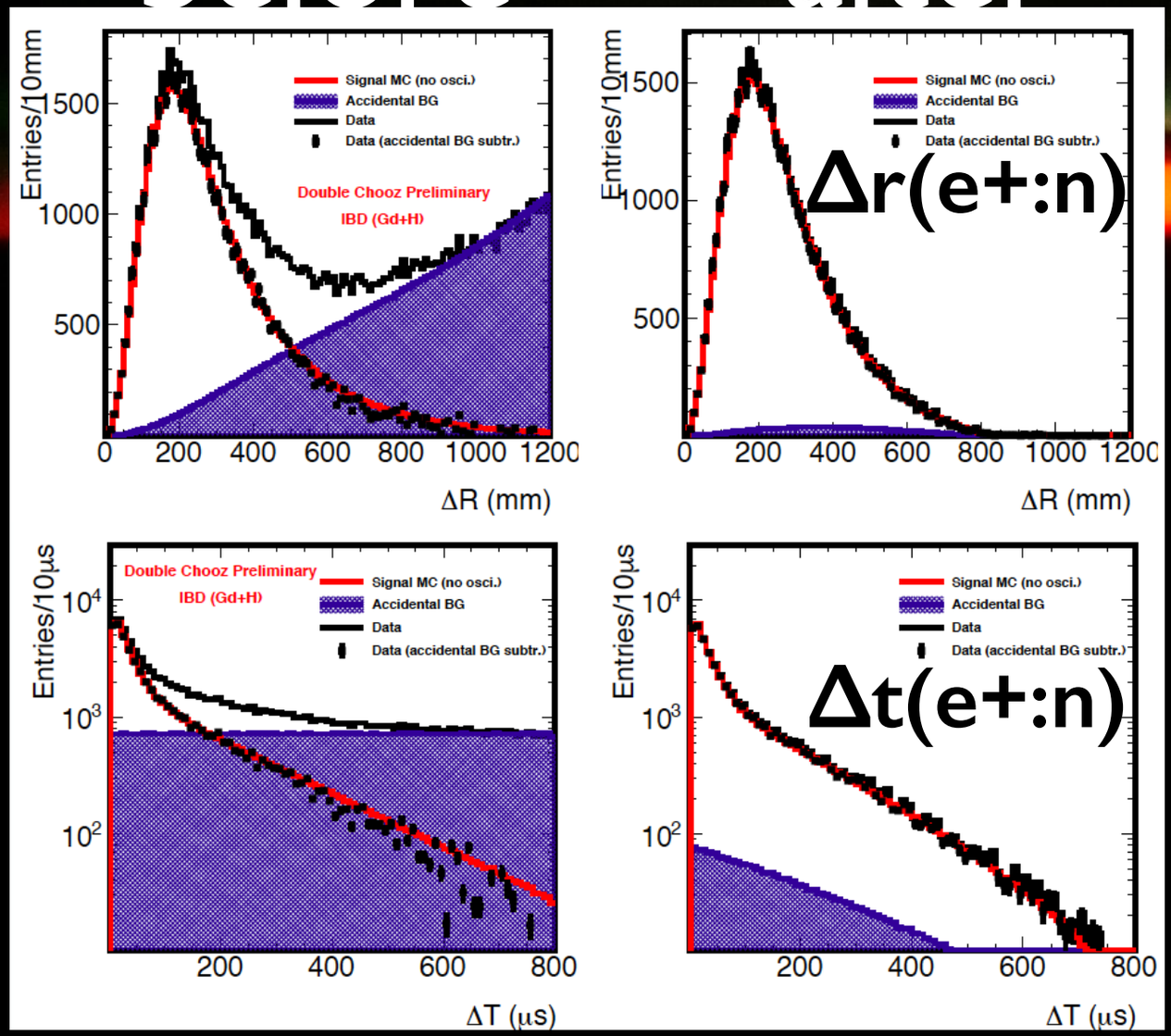




ANN IBD definition

before

after



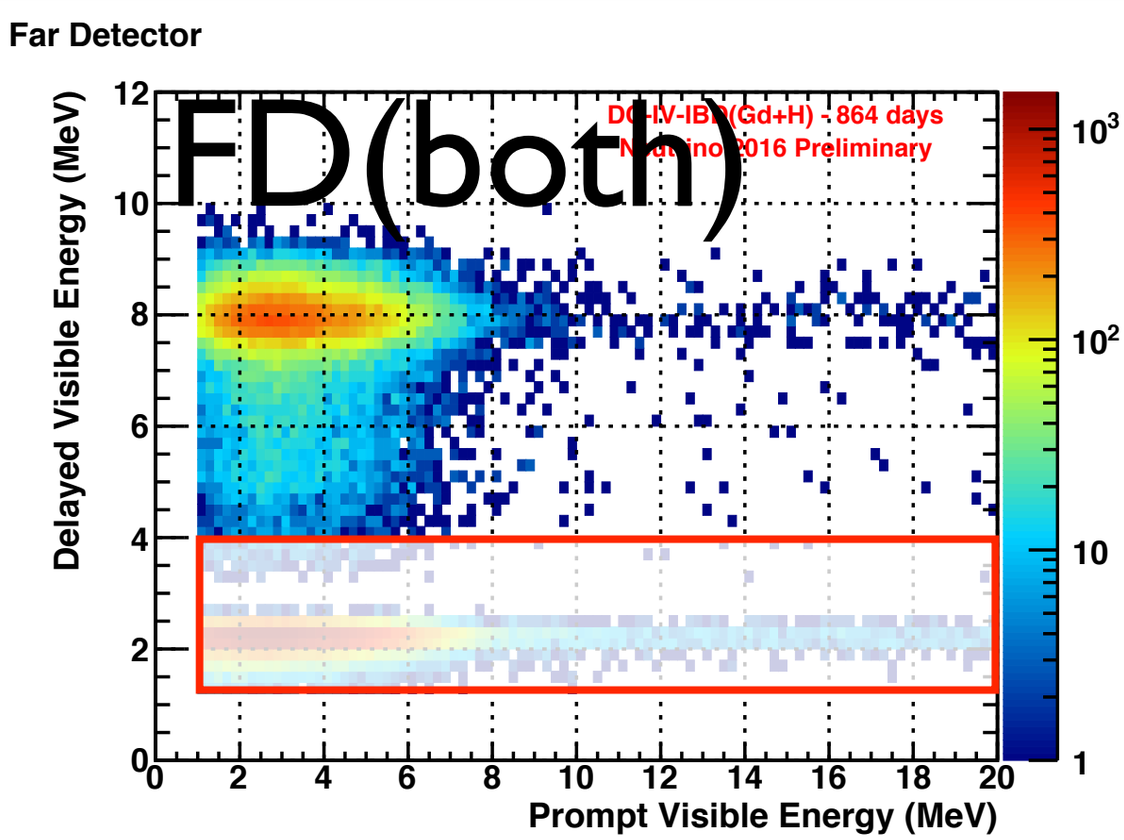
IBD:3D coincidence

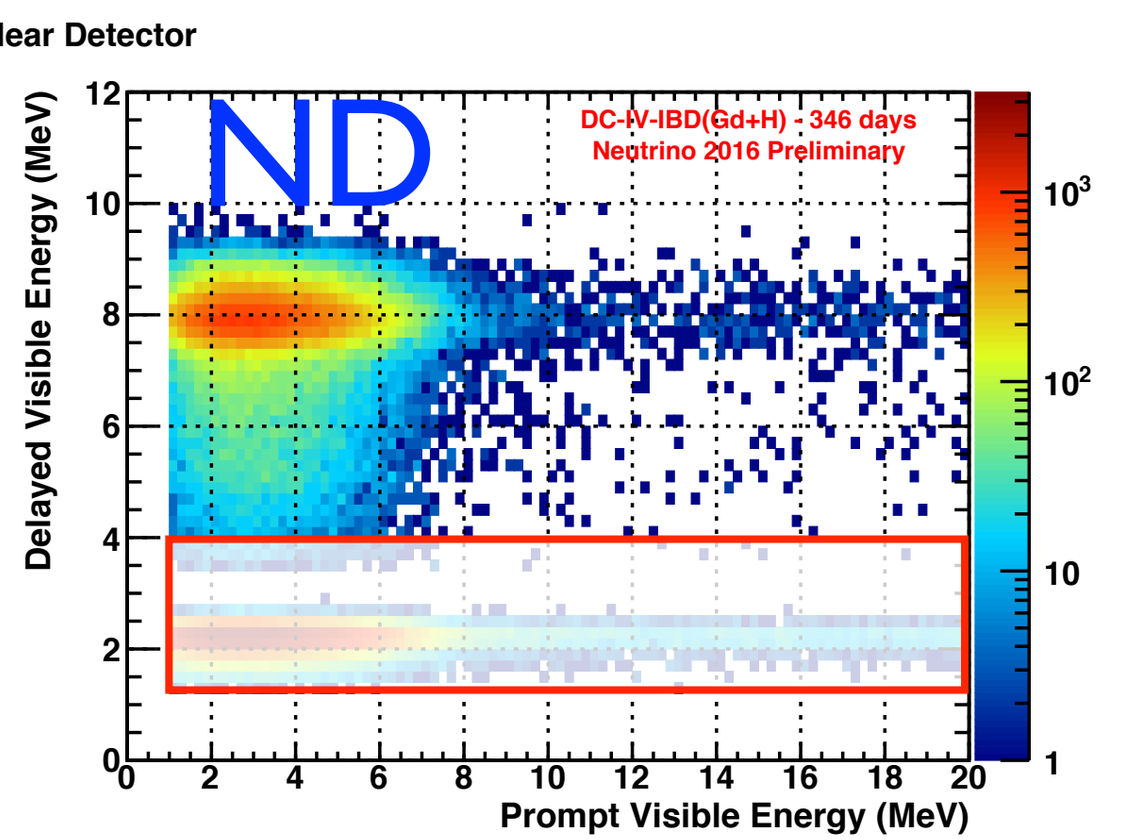
(exploits accurate MC)

- **ΔE(delay)** [1D]
- **Δt(e+:n)** [1D]
- **Δr(e+:n)** [3D]
- **ANN** [1D]

(⇒ **ANN multi-D**)

larger single-θ_{13}-target...

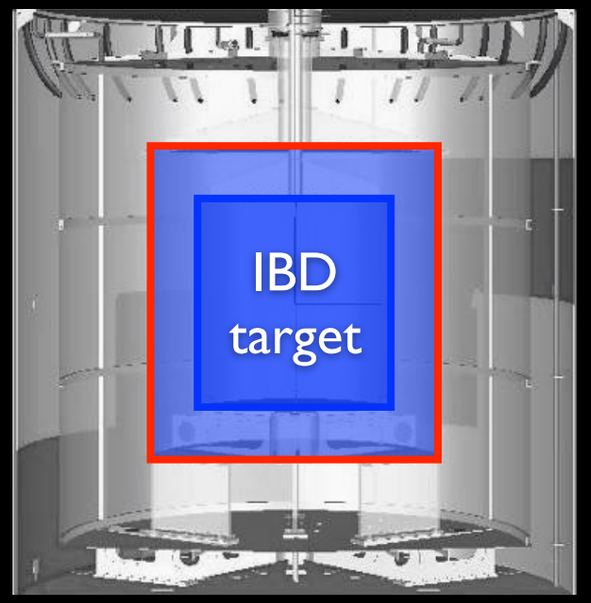




IBD(Gd)

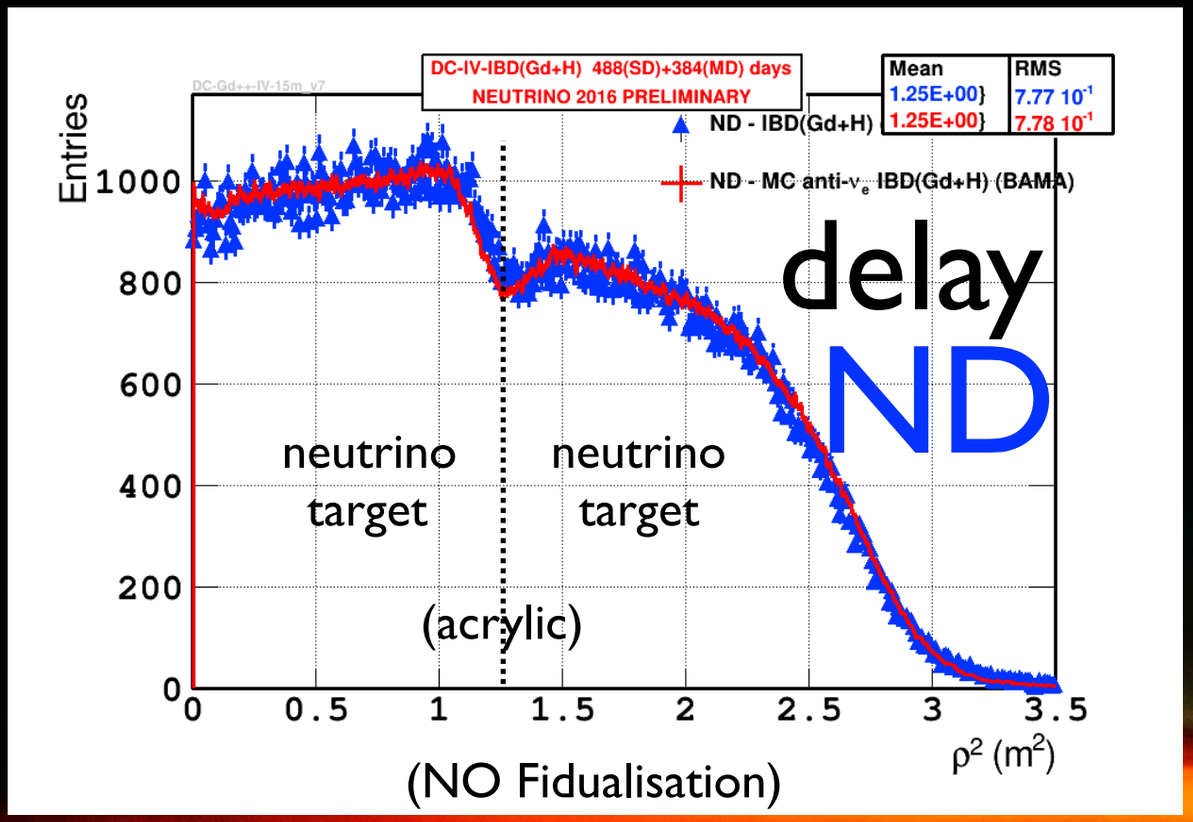
target: ~8t (smallest θ13 target)

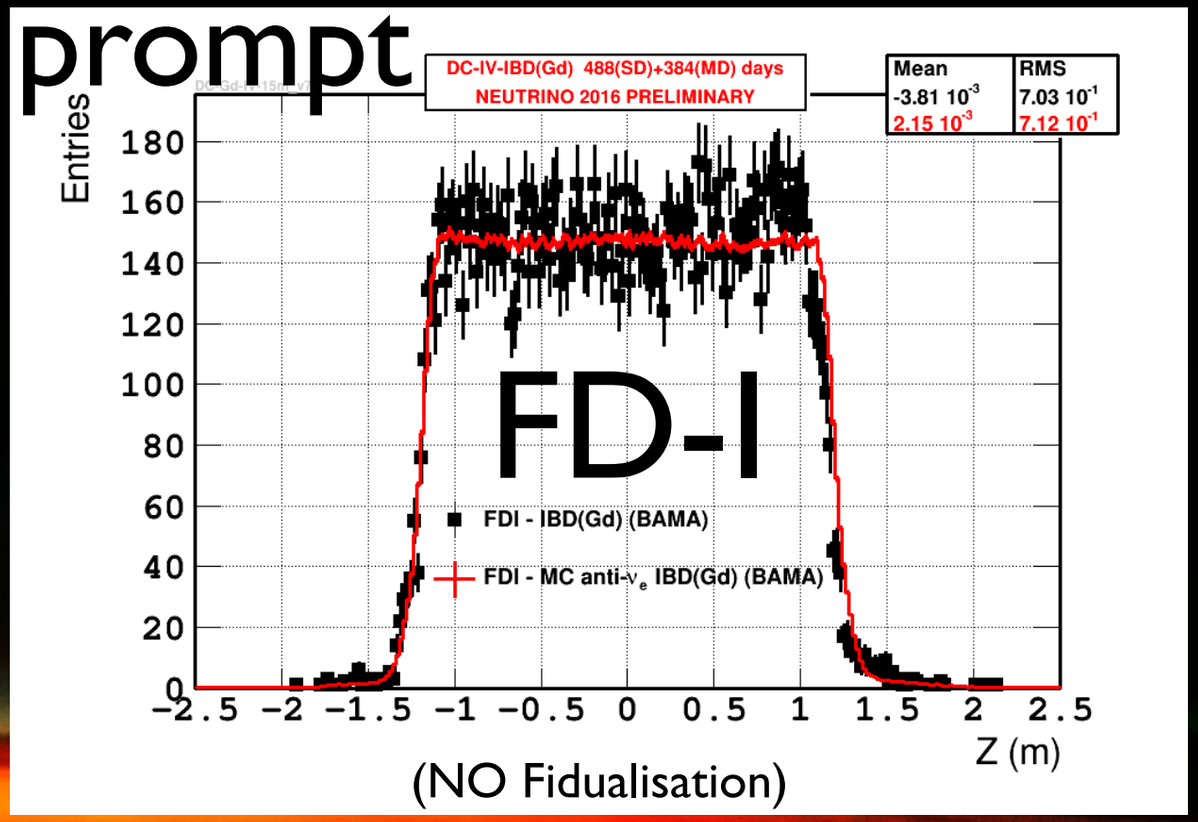
IBD(Gd⊕H⊕C)



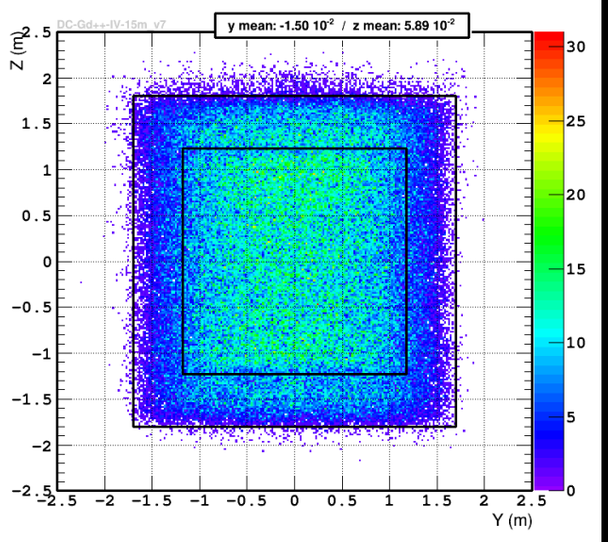
target: ~30t (large θ13 single detector target)

IBD(Gd+H)-large vs IBD(Gd)-small ν-target…





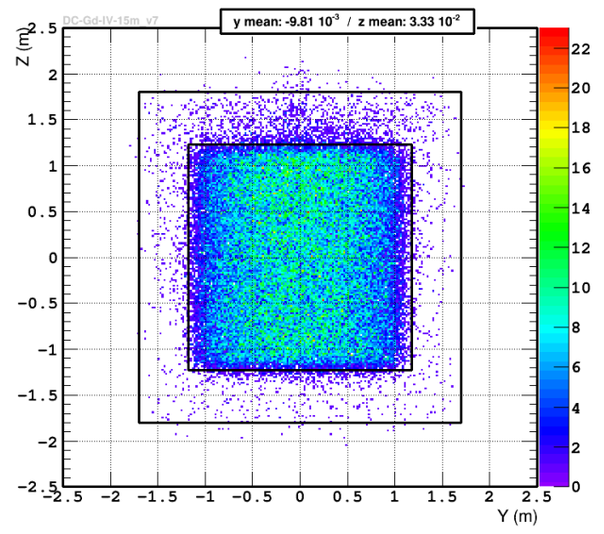
IBD(Gd⊕H⊕C)



target: ~30t (large θ13 single detector target)
Signal/BG: ~10^FD and ~20^ND

target: ~8t (smallest θ13 target)
Signal/BG: ~25^FD and ~30^ND
IBD(Gd) reference to tune IBD(Gd+H)

IBD(Gd)

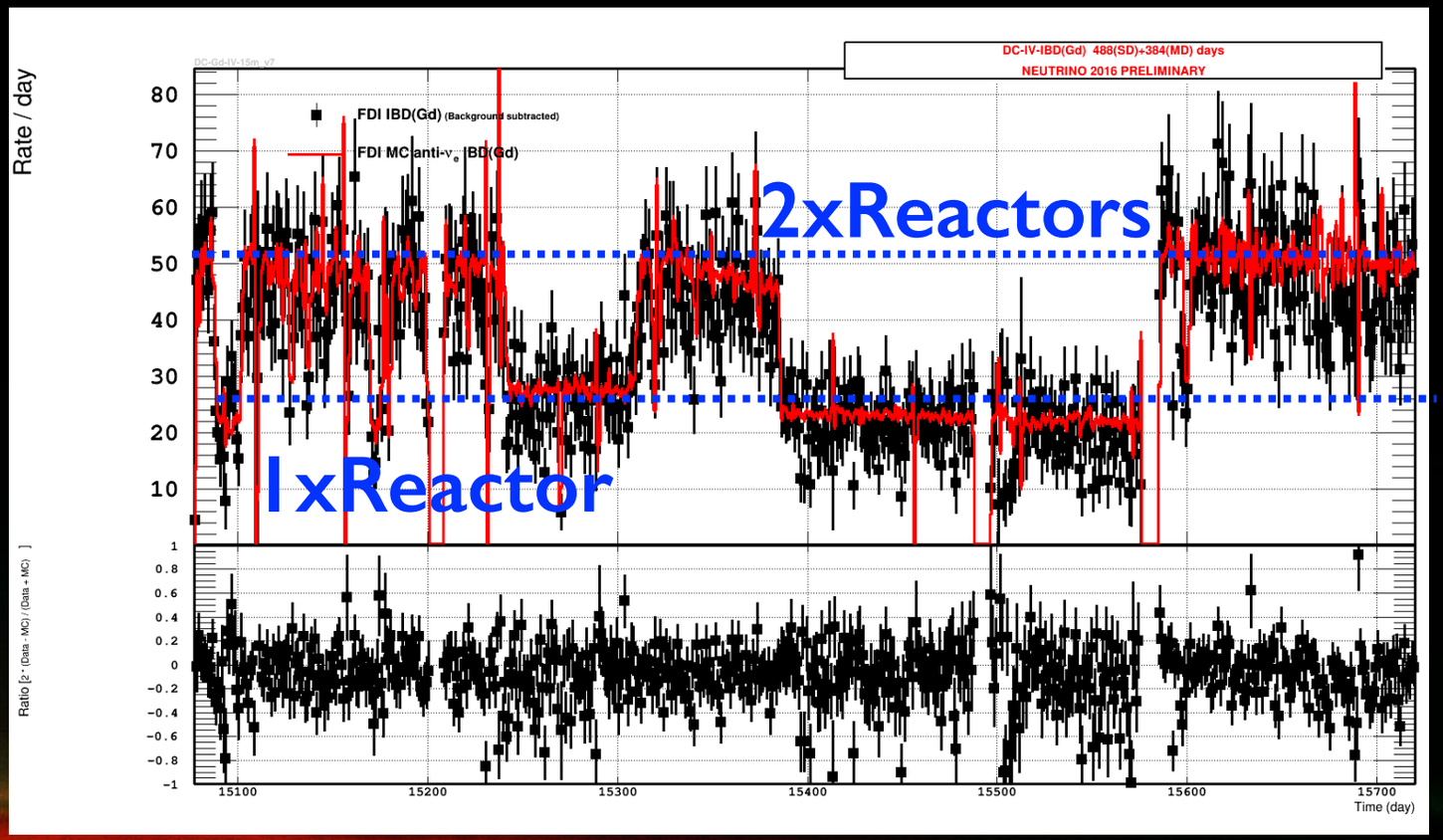


IBD(Gd+H) & IBD(Gd) vs time…

IBD(Gd)

≲50day^{-1}@ FD

σ^{stat}=0.56%^{now}

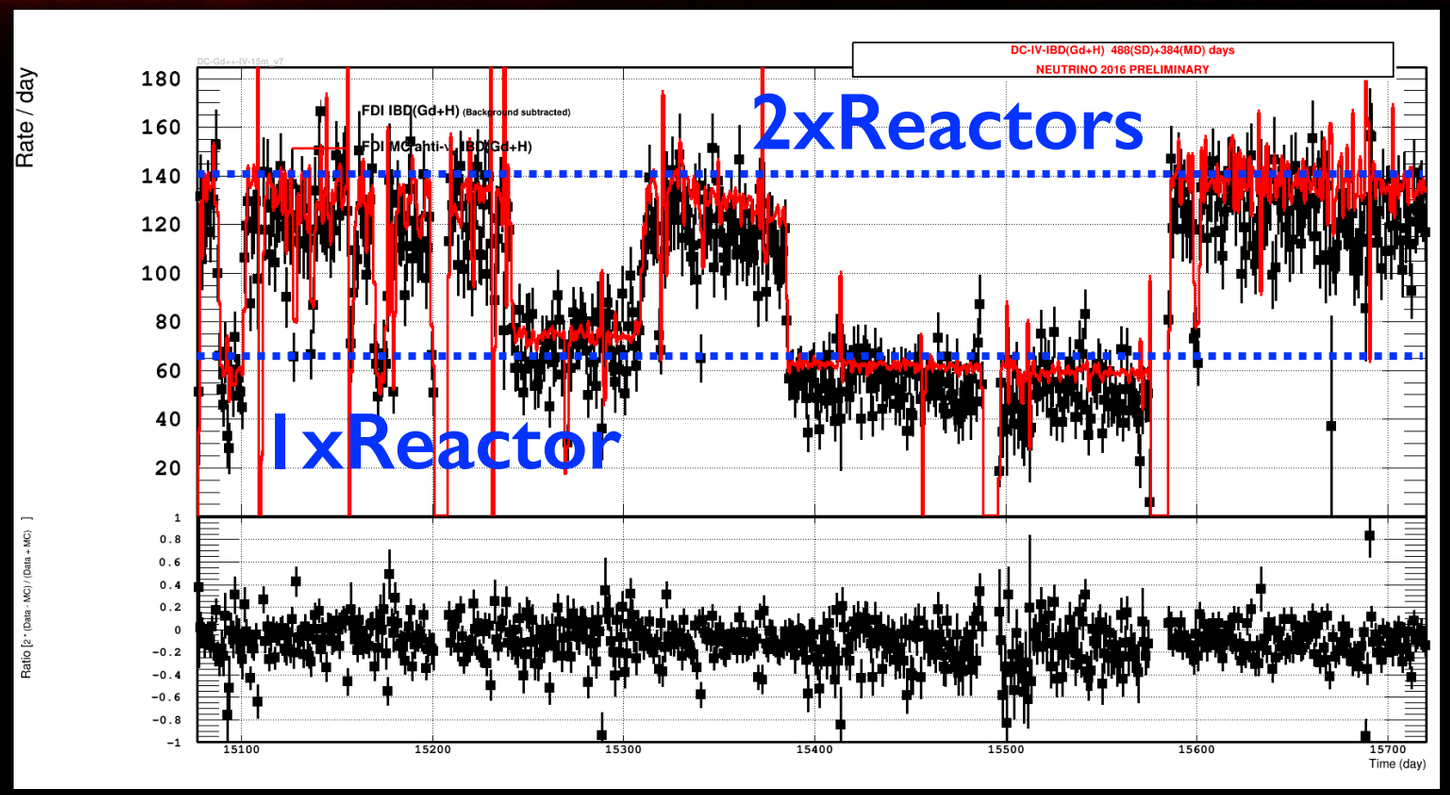


IBD(Gd⊕C⊕H)

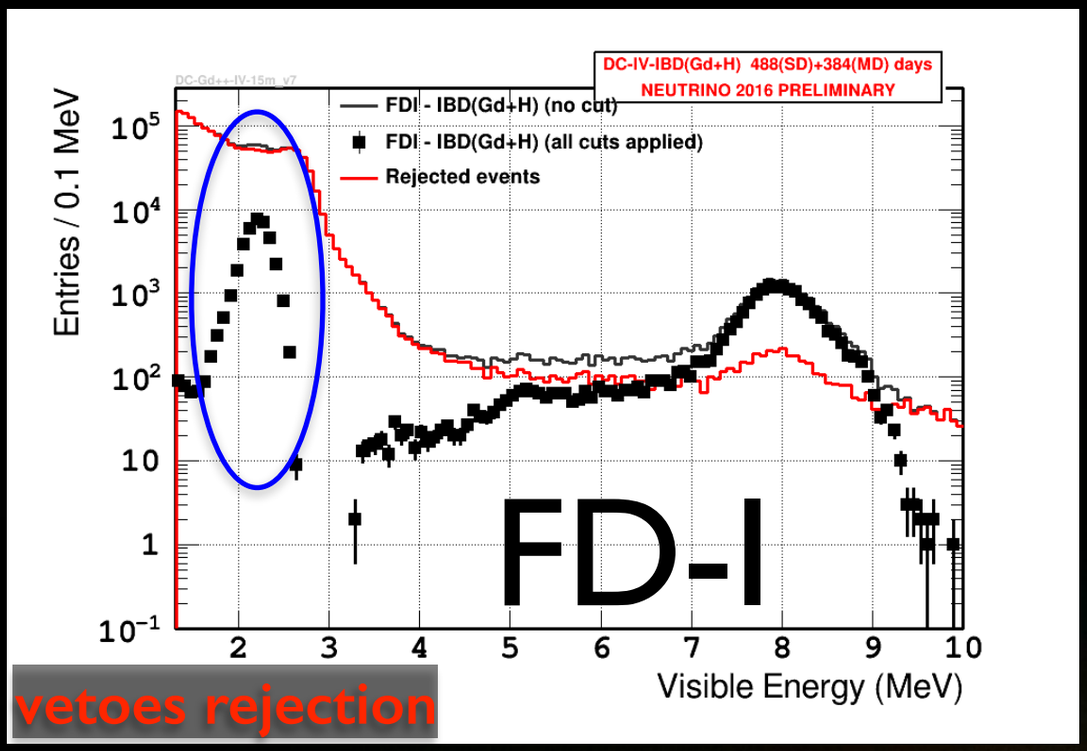
≲140day^{-1}@ FD

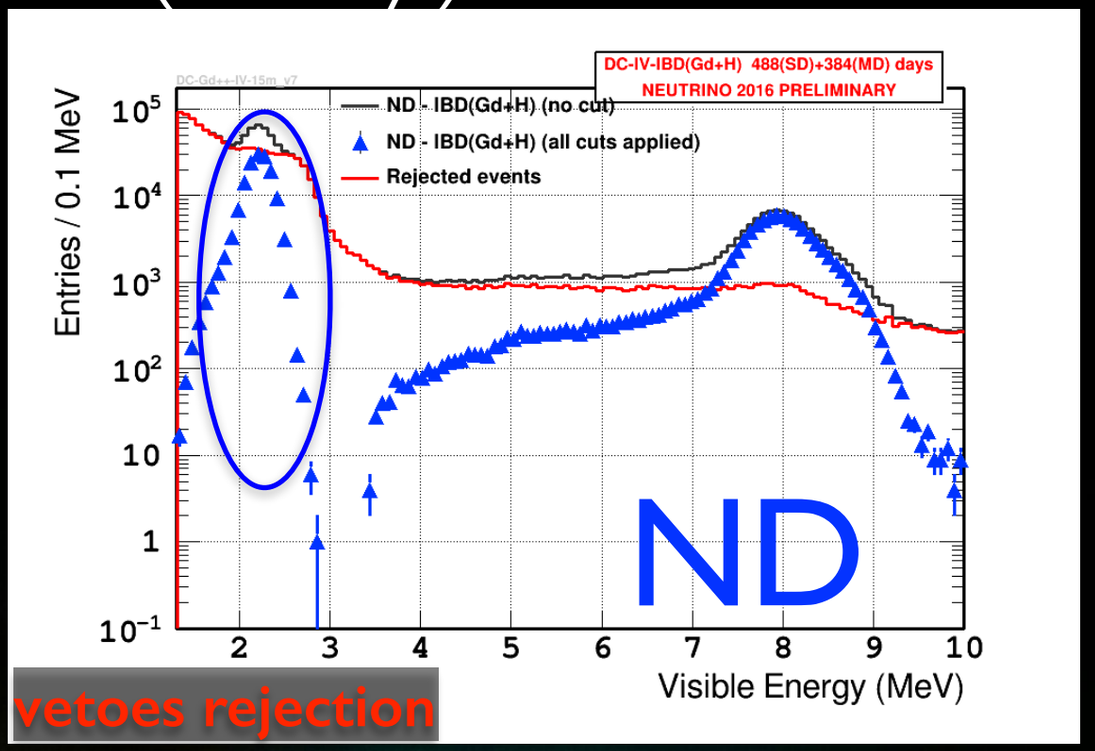
σ^{stat}=0.35%^{now}

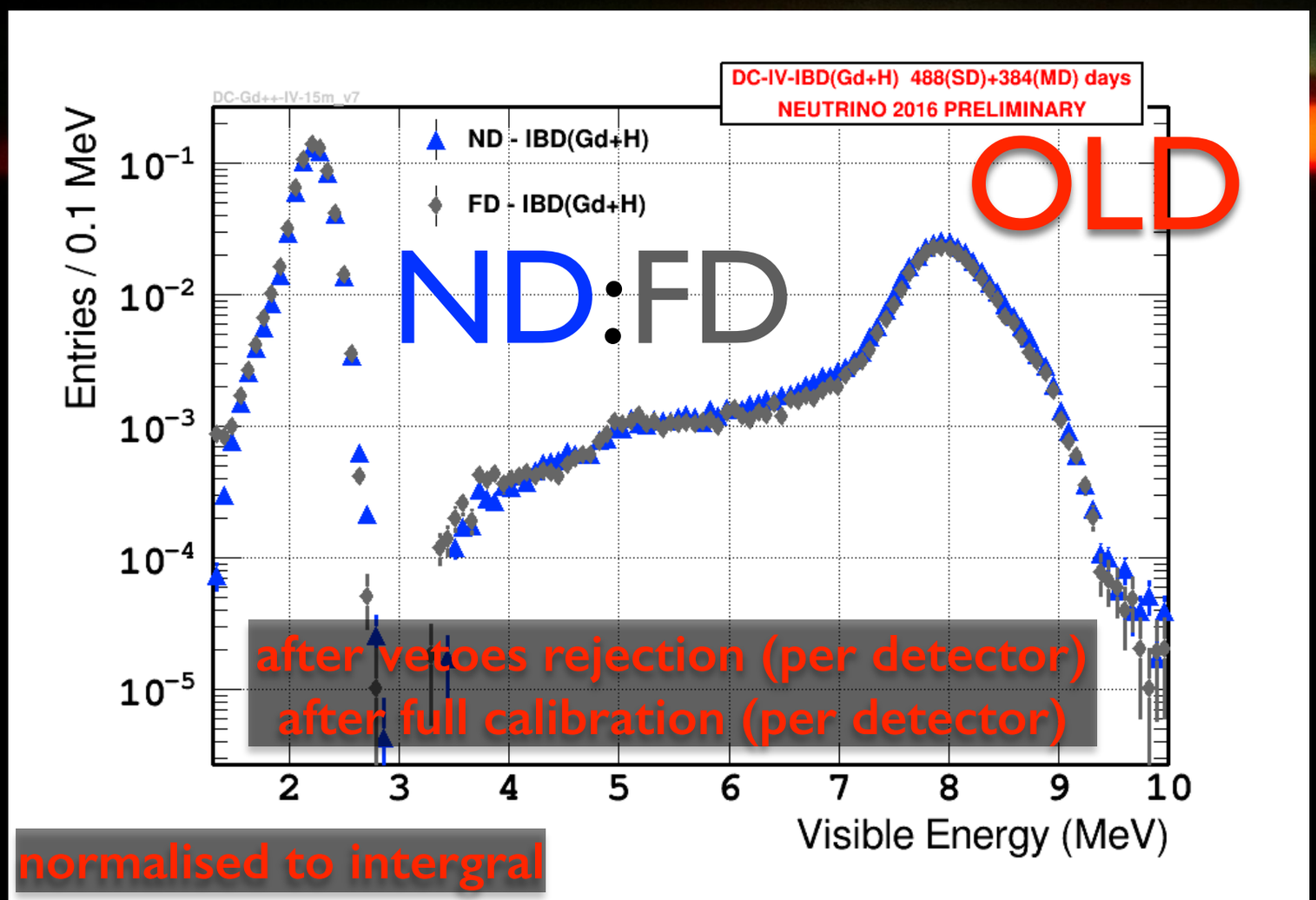
[⇒~0.2%^{stat} final]



BG rejection: E(delay)MeV view…





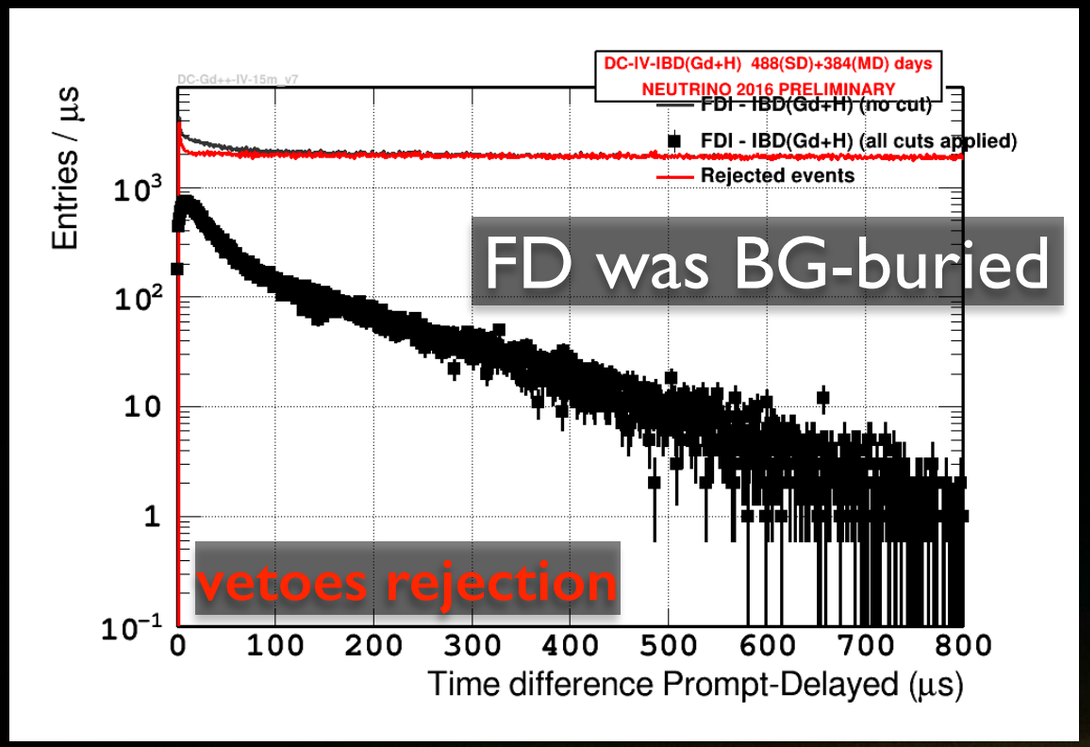


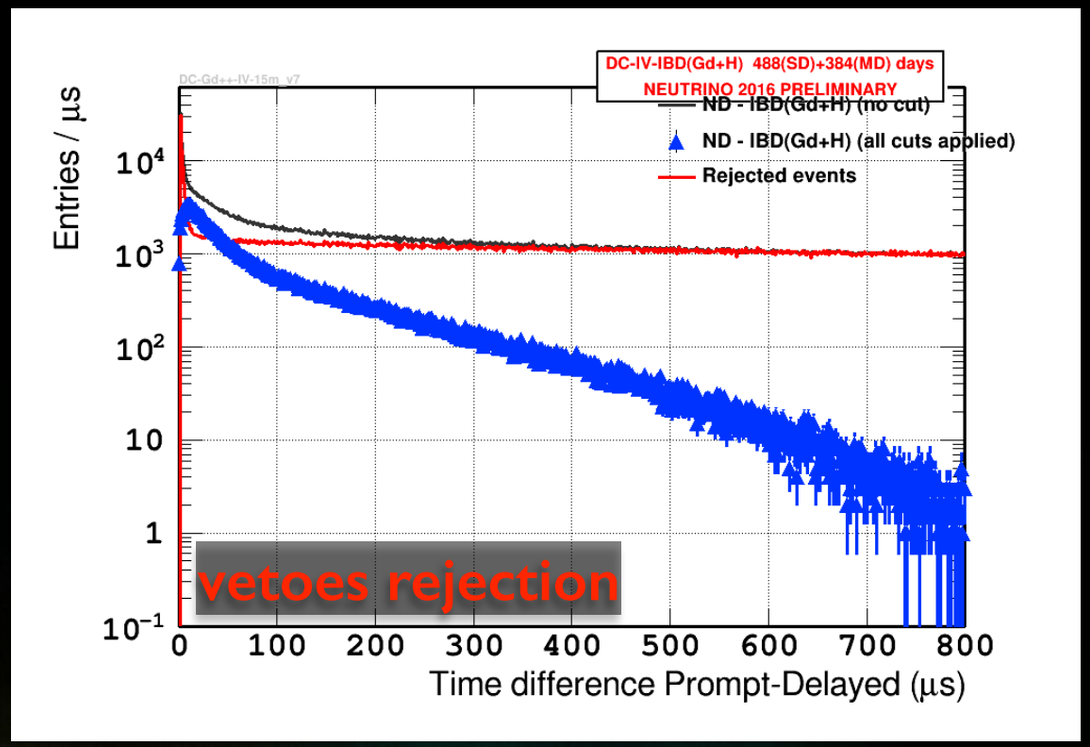
E(delay)

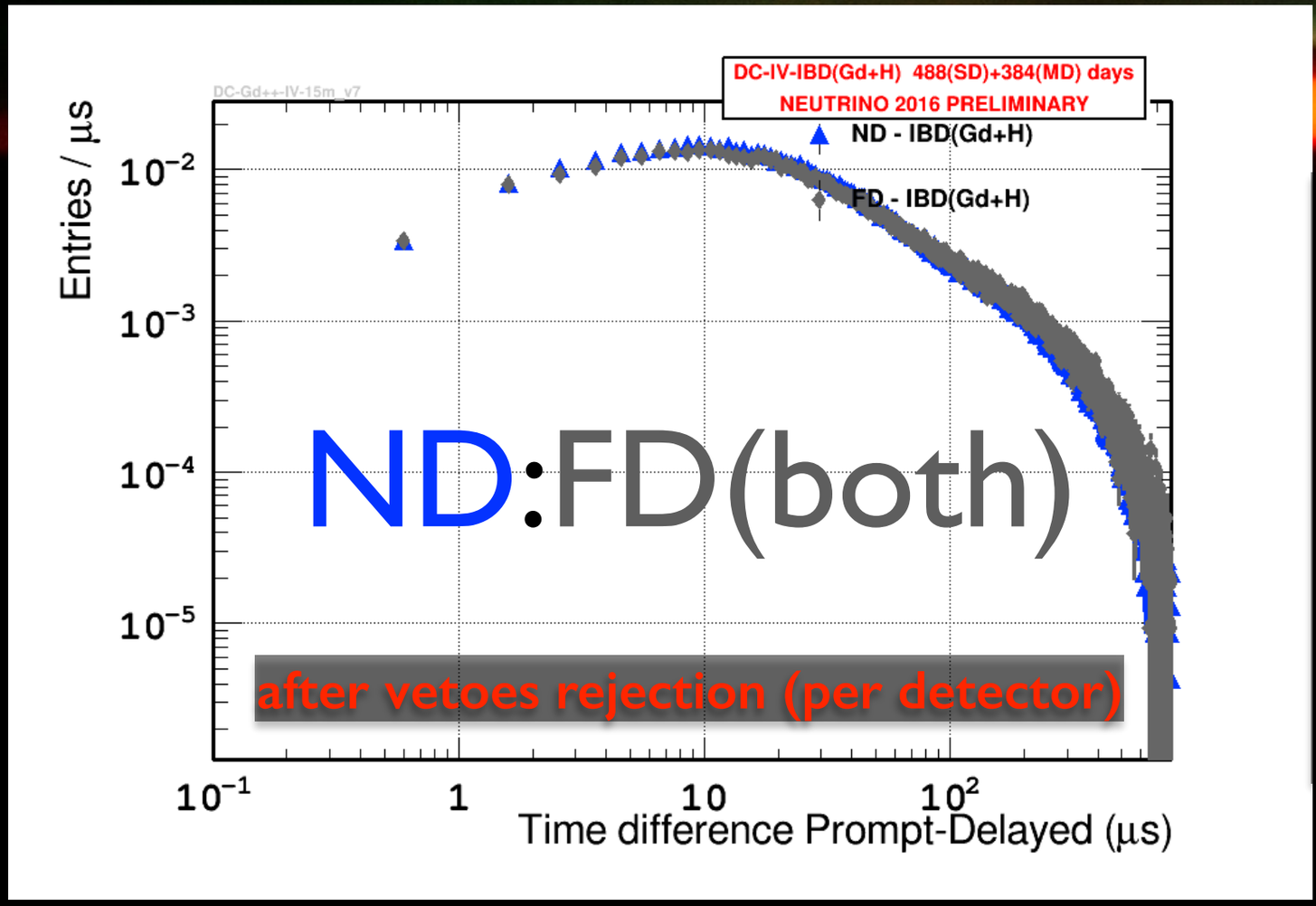
vetoes rejection impact
(demonstration >10^3 range)

ND ≈ FD(both)
(after vetoes)

BG rejection: Δt(e+:n) view…





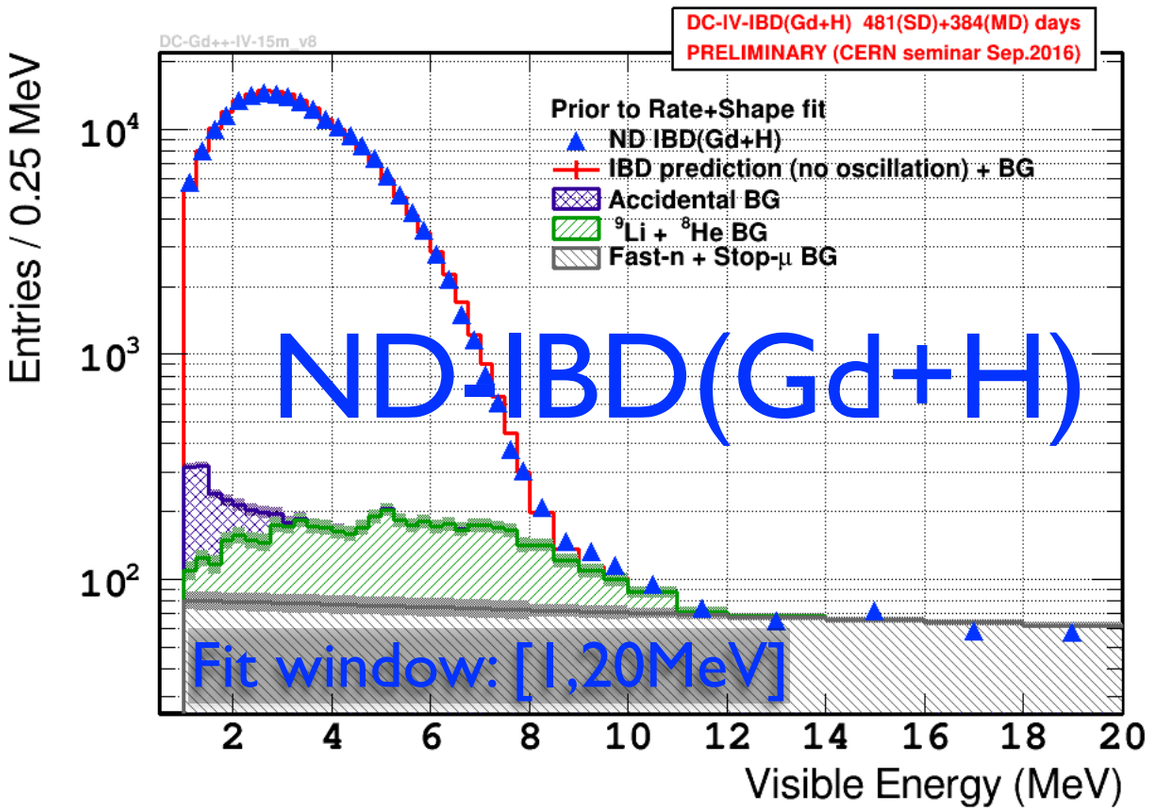


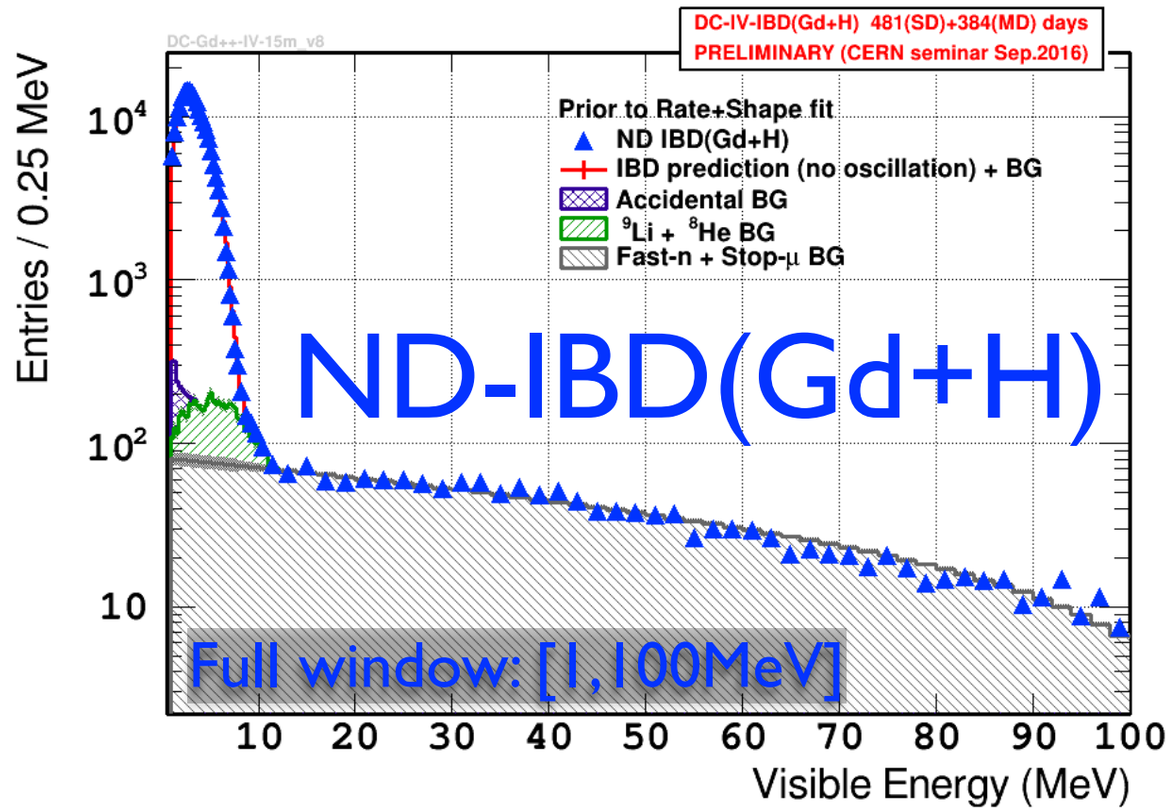
Δt(prompt:delay)

vetoes rejection impact
(demonstration >10^3 range)

ND ≈ FD(both)
(after vetoes)

remaining BG measurement…





BG model: BG(∑) = BG(accidental)+BG(fast-neutron)+BG(^{9}Li)

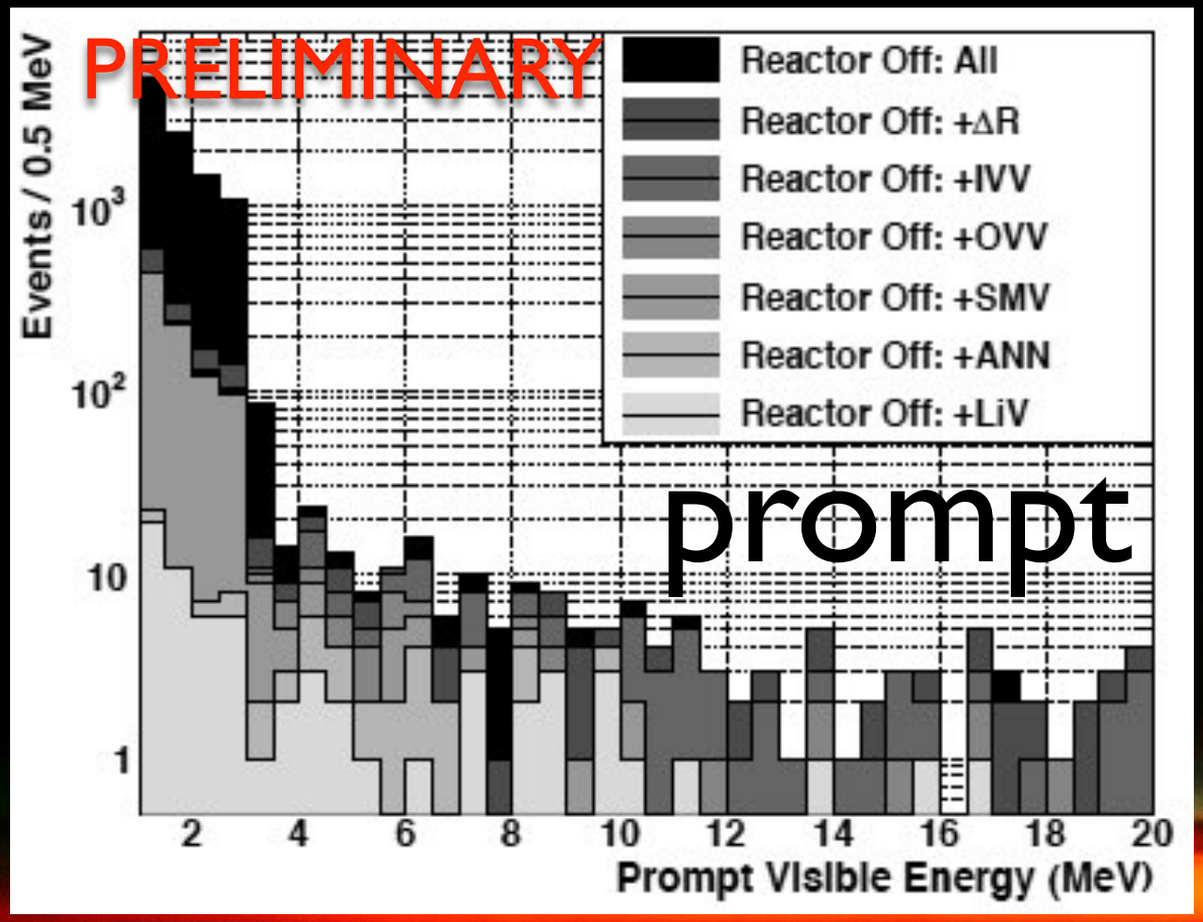
BG(acc): via **OFF-time coincidence** [**σ(BG)→~0%**]
BG(fast-n): via **μ-detector tagging** (IV checked by OV) up to 100MeV [**σ(BG)→~small**]
BG(^{9}Li): via **μ-spallation correlated production** (≤50% vetoed) [**σ(BG):~0.3%FD**]

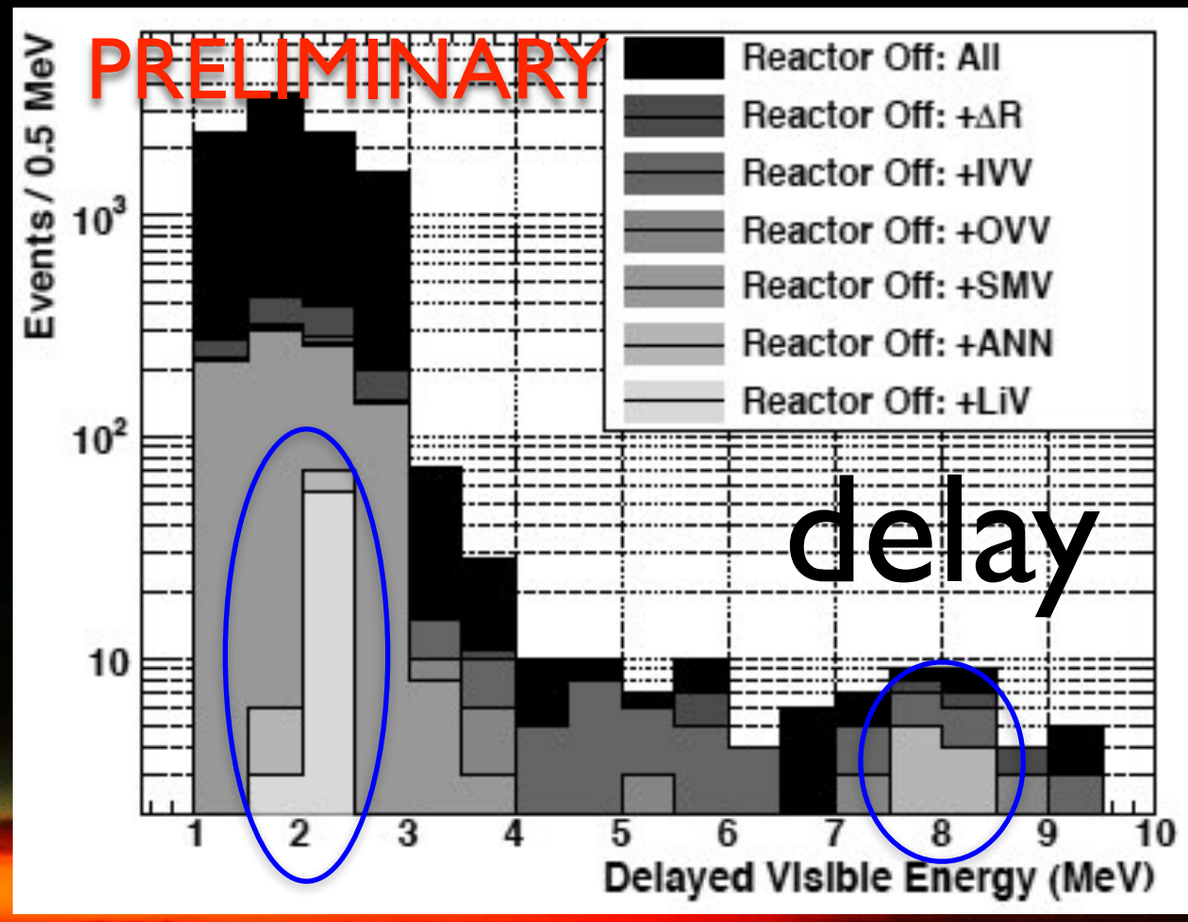
BG(∑)^{exclusive} ≈ BG(reactor-OFF)^{inclusive} ⇒ BG-model is complete

(implies **BG(stopped-μ)**, **BG(^{12}B)**, **BG(BiPo)**, **BG(multi-captures): all negligible!!**)

precious reactor-OFF (~7 days) validation…

FD-IBD(Gd+H)





Rejection Power estimation (total and per-veto)

IBD(Gd⊕C⊕H): 158x (6:1000 selection) while efficiency: 95.00±0.03

[IBD(Gd): 11x (9:100 selected)]

IBD(Gd+H) allows BG strategy validation of IBD(Gd) by an one extra order of magnitude

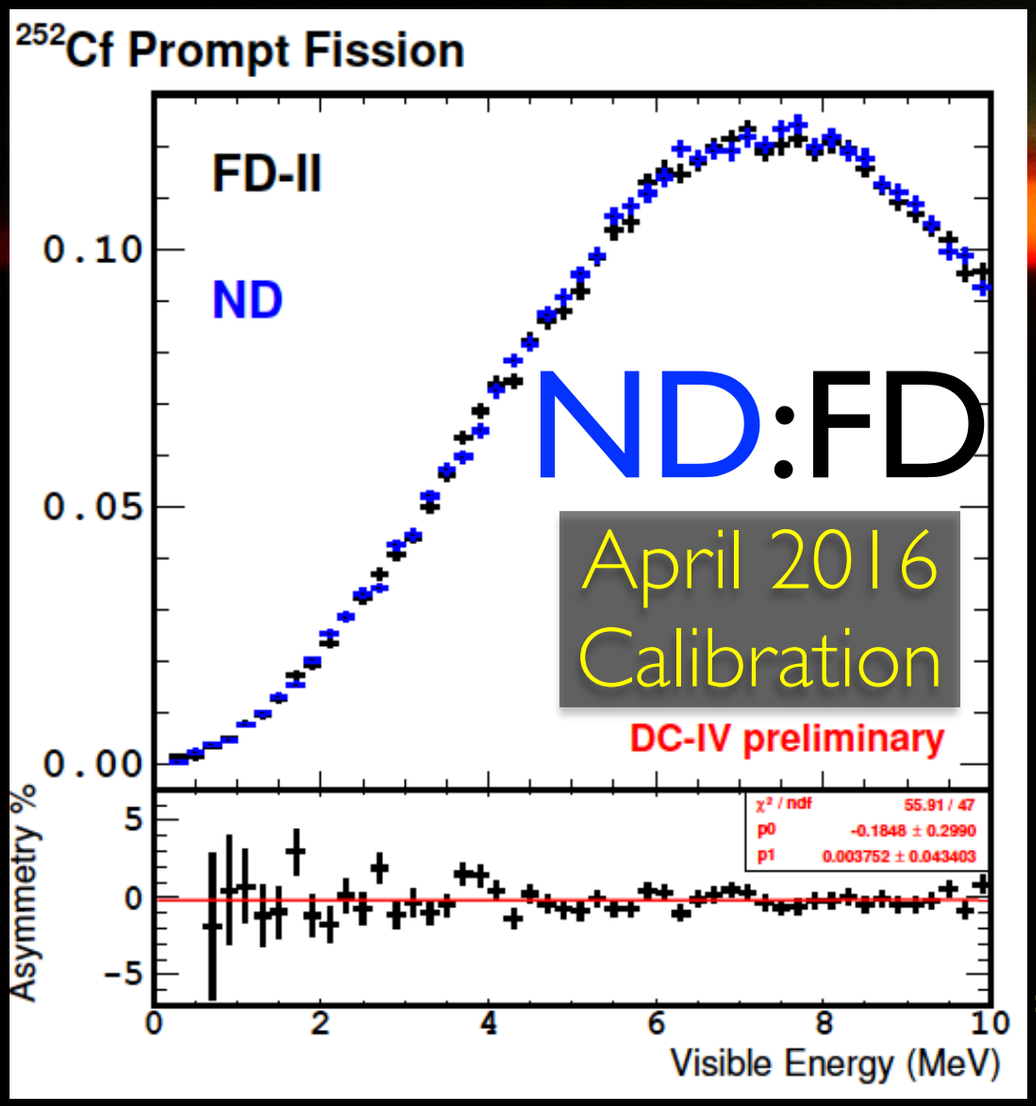
BG-model inclusiveness validation [done]

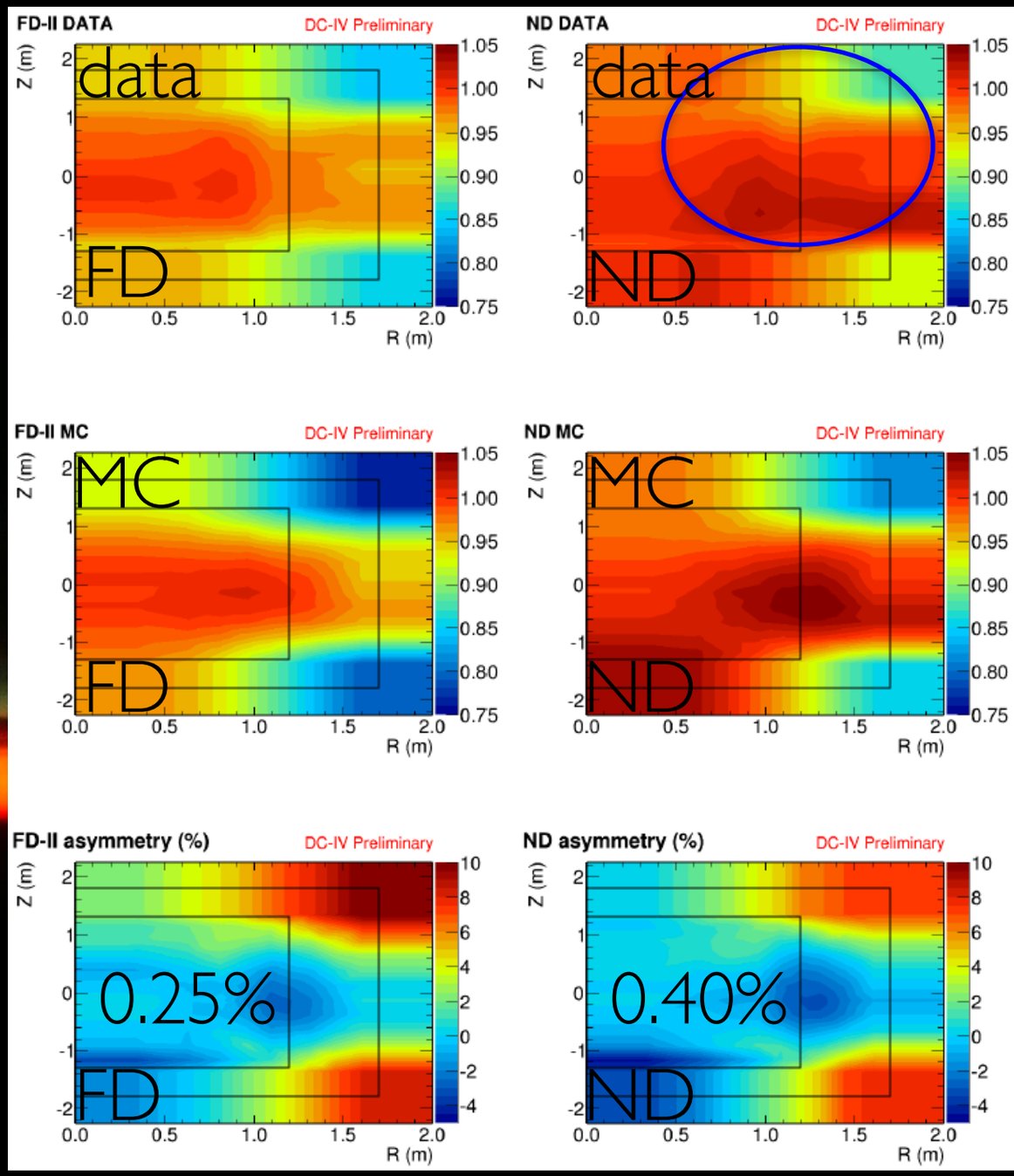
~1 day reactor-OFF ND…

(a few weeks ago)

detector response uniformity & linearity…

response uniformity
(systematics ~0.25%^{FD} & ~0.40%ND)

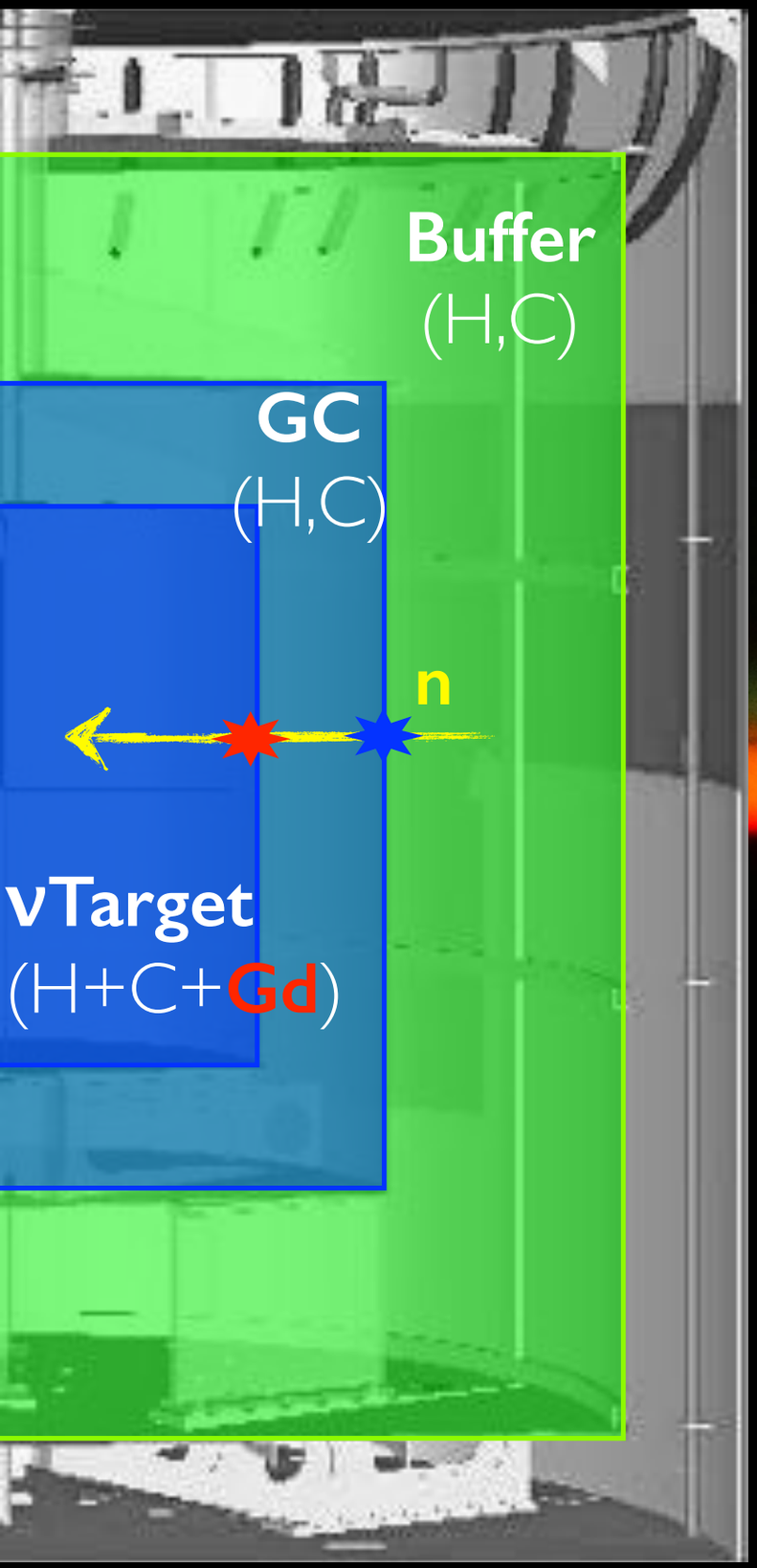


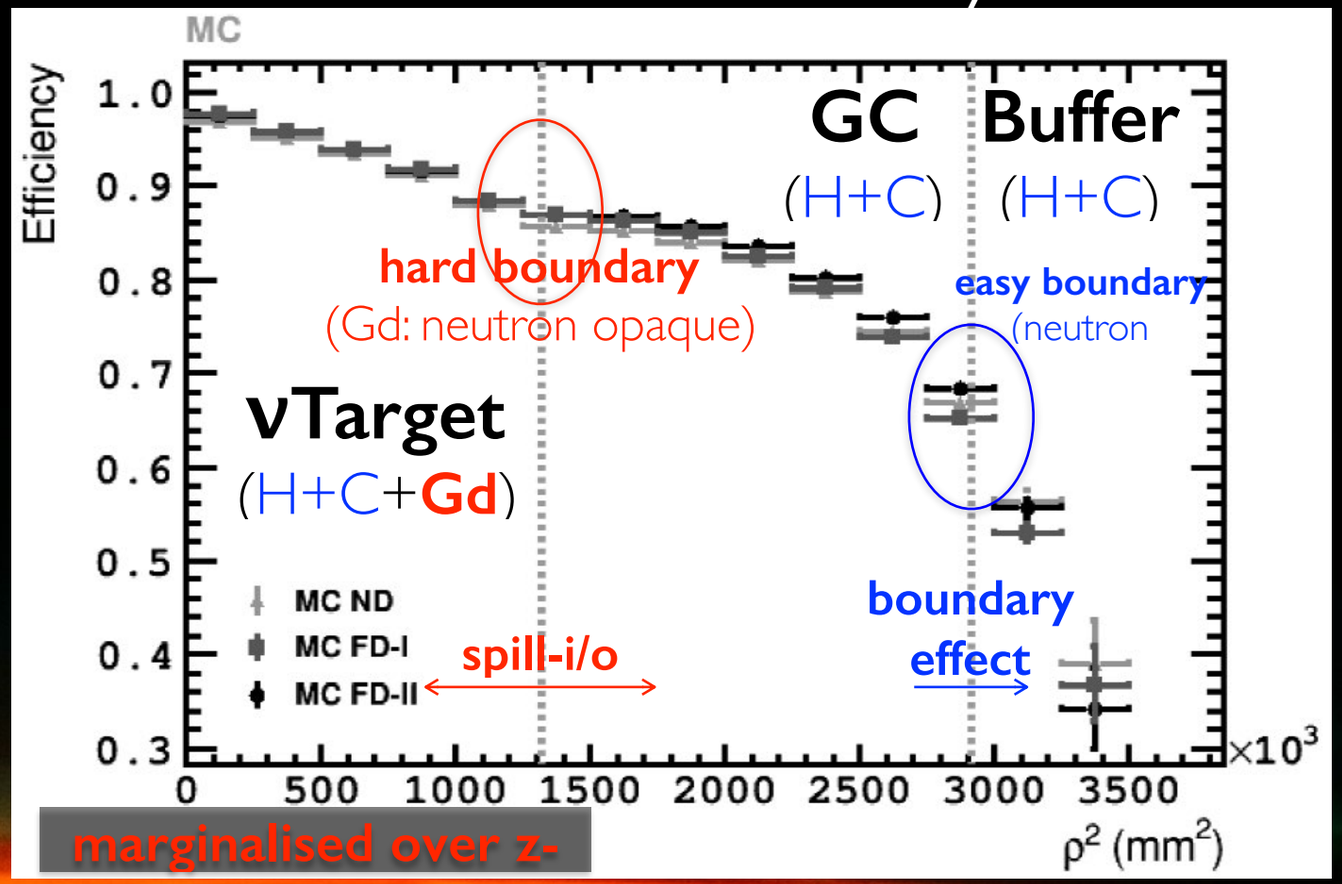


response linearity
(relative ≤0.3% within [1,10]MeV)

⇒ **same ^{252}Cf source** (both detectors)

IBD(Gd+H+C) yields lower detection systematics…





IBD(Gd⊕H⊕C) smooth neutron interface

⇒ major systematics reduction!!

(systematics)	IBD(Gd+C)	IBD(Gd+H+C)
DAQ⊕Trigger	negligible (<0.1%)	<0.01%
BG rejection veto	small (0.1%)	<0.05%
Gd Fraction	largest (0.4%) →	irrelevant
Efficiency IBD (ANN)	large (0.3%)	0.26%/0.27%
Spill I/O	large (0.3%)	irrelevant
GC Boundary	—	0.00%/0.20%
Proton# (NT+GC)	small (0.3%)	0.56%/0.74% !!!

IBD(Gd+C+H) selection…

- **most robust multi-isotope n-capture strategy…**
(H vs G vs C exclusive inaccurate predictions⇒ **multi-detector goal**)

⇒ **forces excellent DATA:MC agreement**
(MC inaccuracies do not manifest→ inclusive H+Gd+C contribution)

⇒ **robust inter-detector selection normalisation**
(in both single/absolute and multi/relative detector configurations)

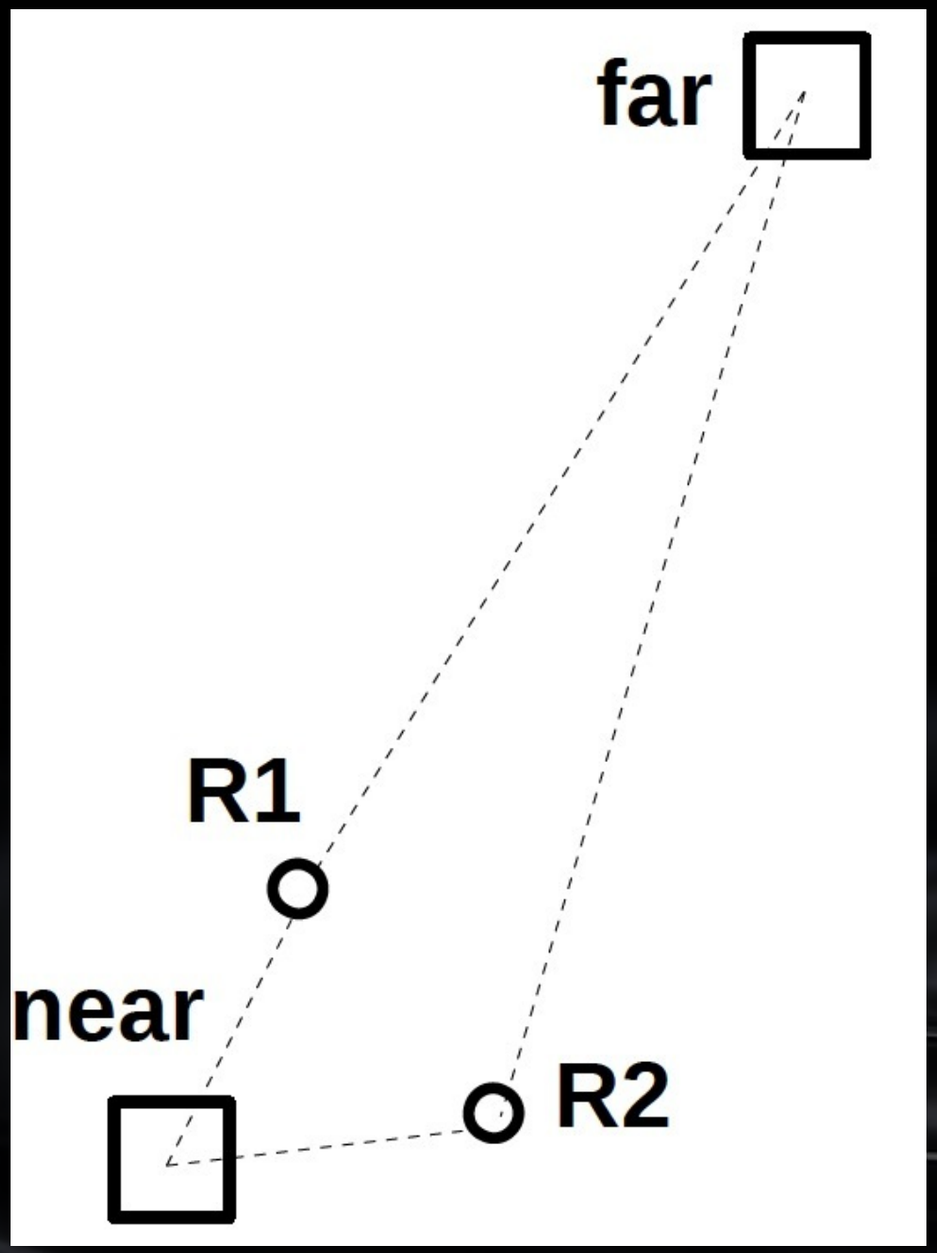
⇒ (gratis) **inter-volume leak immunity (if any)**

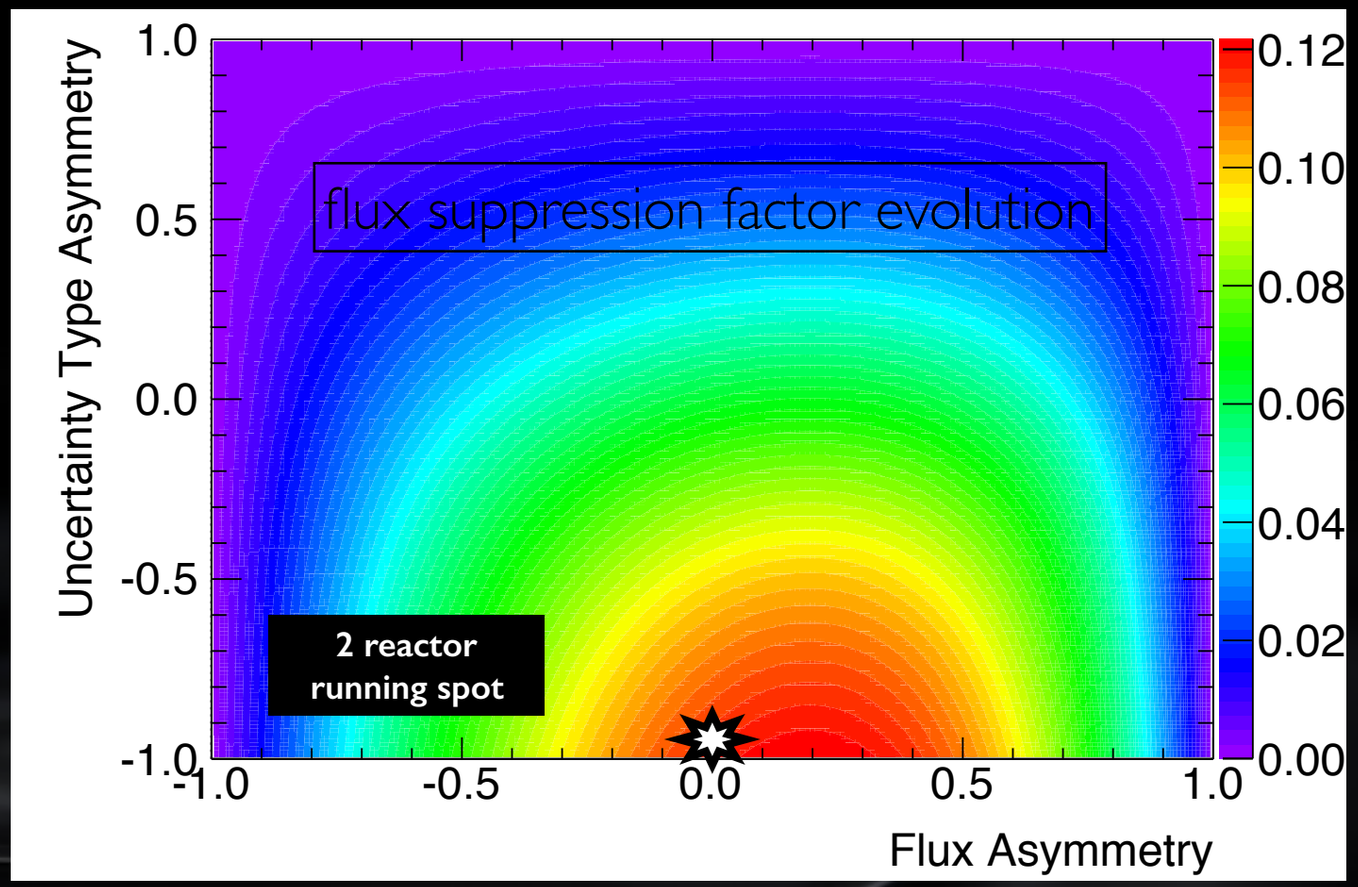
(to 1st order: all neutrons are caught — regardless of isotope)

major δ(flux) cancellation (with ND)…

DC most isoflux experimental setup

$\Longrightarrow$ ≈90% δ(flux) suppression





reactor error correlations → δ(flux) suppression

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

"Reactor Induced Systematics for Multi-Detector θ13 Experiments"

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

IBD(Gd⊕C⊕H) implies…

DC statistics solved!
(better systematics)

extremely delicate interplay
detector⊕analysis
—lucky too—

physics now…

our latest references...

latest Multi-Detector analysis

DC-IV @ CERN (2016) [publication(s) in preparation]
https://indico.cern.ch/event/548805/

(most of the techniques used @ CERN→ Gd-III⊕H-III analyses)

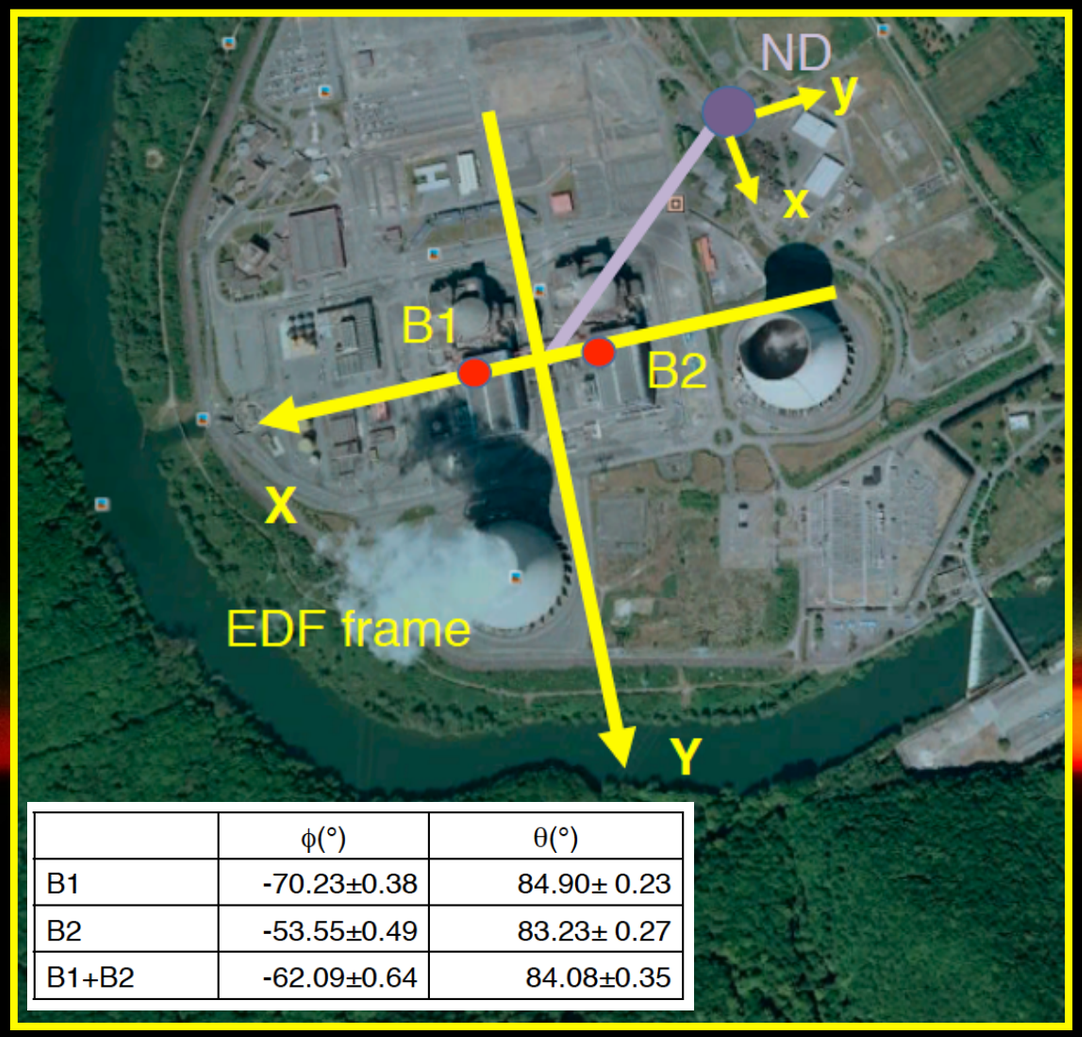
latest Single-Detector analyses

DC-III Gd-IBD's only: publication@JHEP (2014) [long paper]
https://arxiv.org/abs/1406.7763

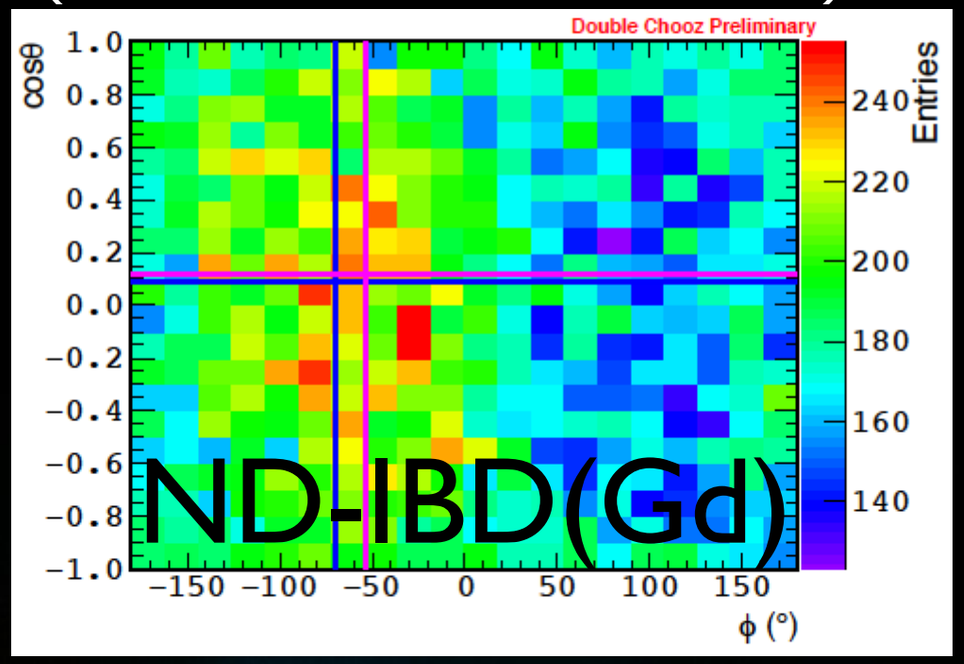
DC-III H-IBD's only: publication@JHEP (2015) [long paper]
https://arxiv.org/abs/1510.08937

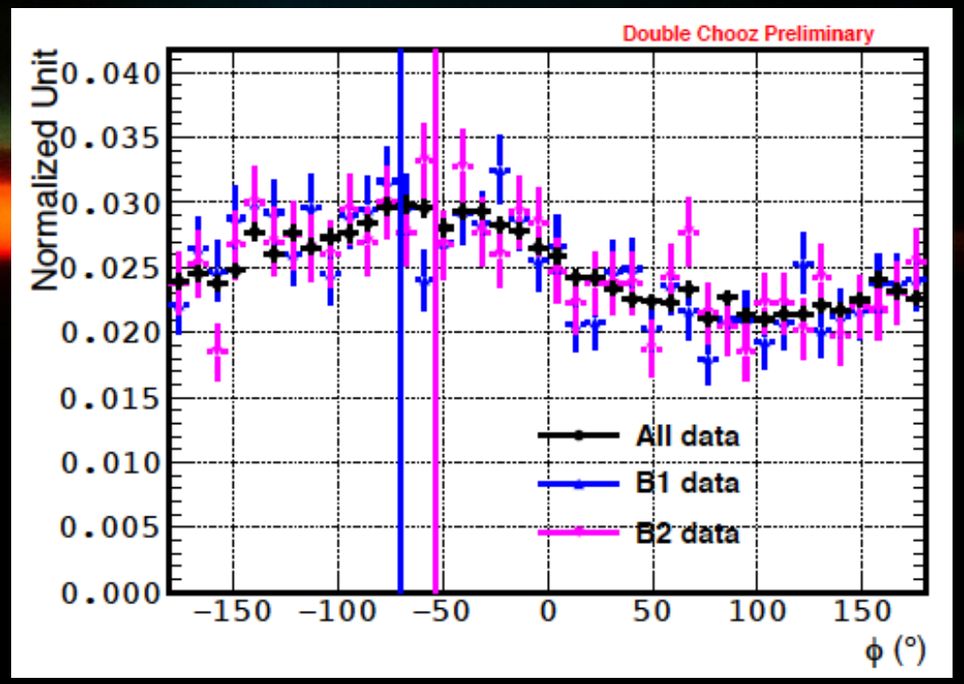
IBD (un)directionality (**world ref: DC**)…

IBD($\nu_e + p \rightarrow e^+ + n$) **incident direction** from linear momentum defined by **Δl(e⁺:n) vector**



	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





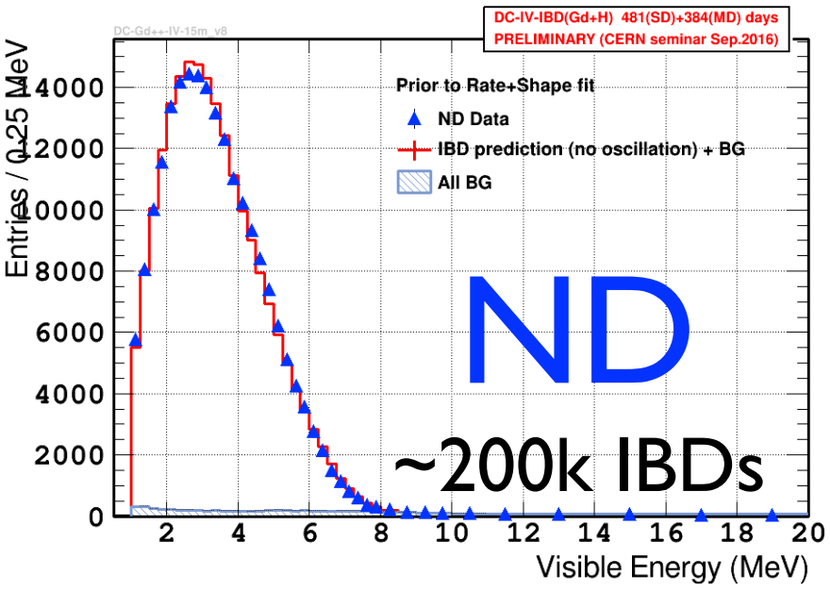
IBD directionality regarded as a statistical deformation (rather than event-wise pointing)

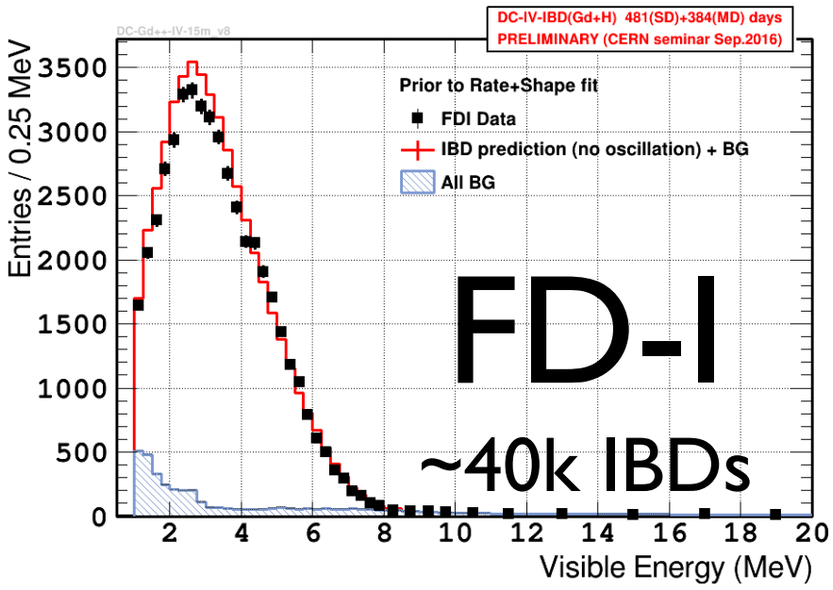
	Events	ϕ(°)	θ(°)	Stat(°)	Sys(°)	Δl(mm)
B1	4616	-81.0	101.8	9.4	1.4	21.2± 4.5
B2	4001	-69.2	96.6	12.0	3.3	21.8± 4.6
All	73869	-69.3	87.5	2.8	0.6	17.2± 1.0

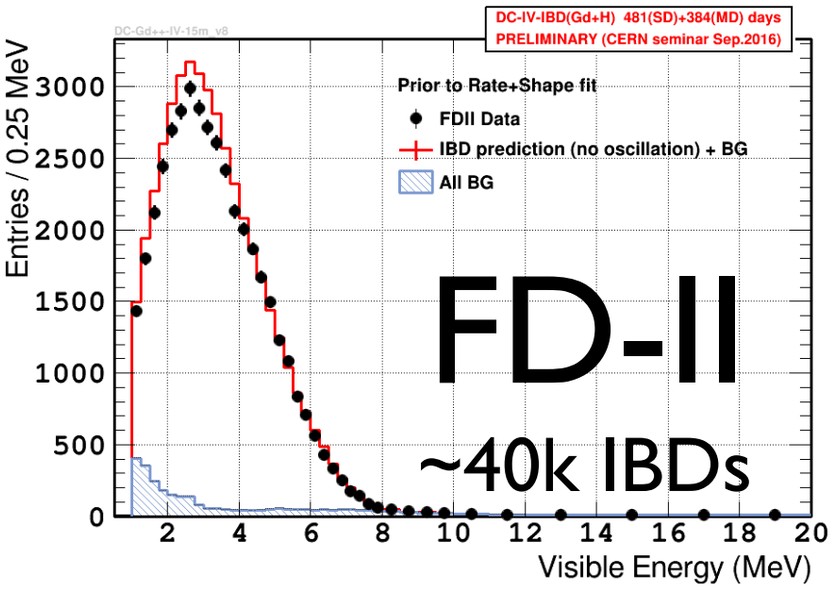
measuring θ_{13} with DC...

Anatael Cabrera (CNRS-IN2P3 & APC)

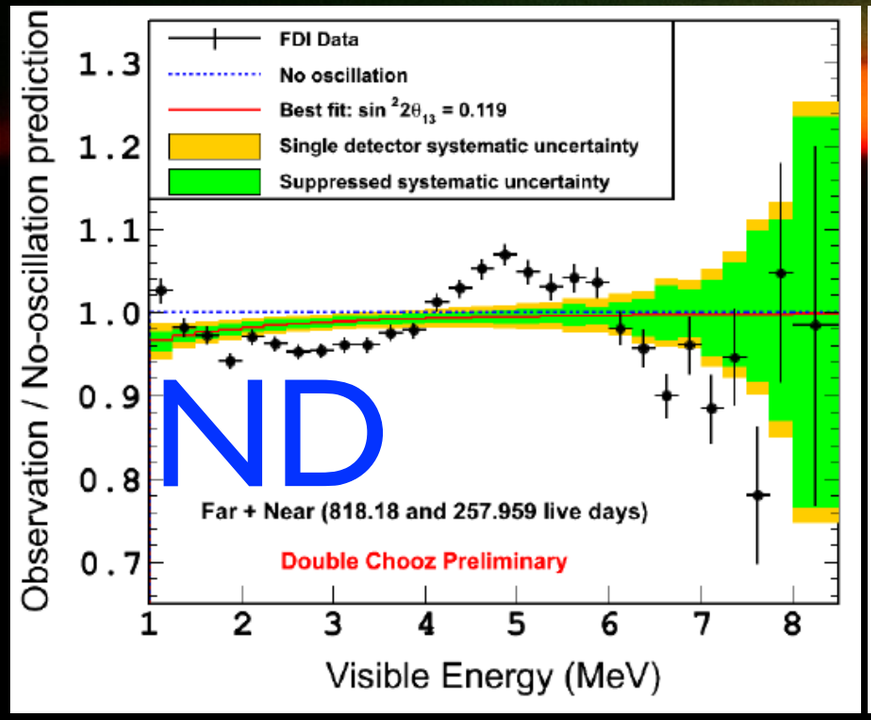
θ13 R+S fit result…

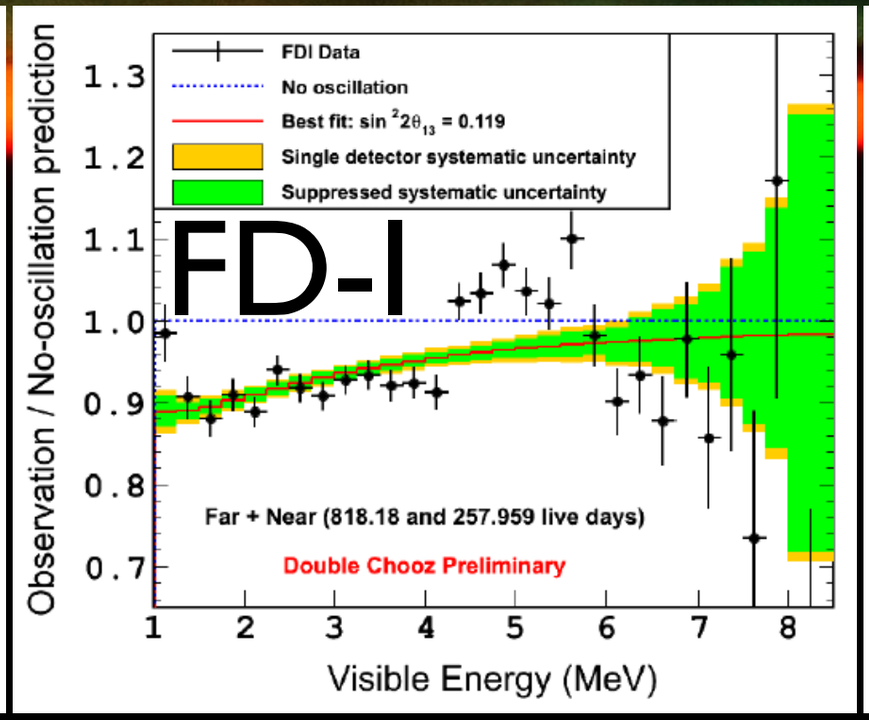


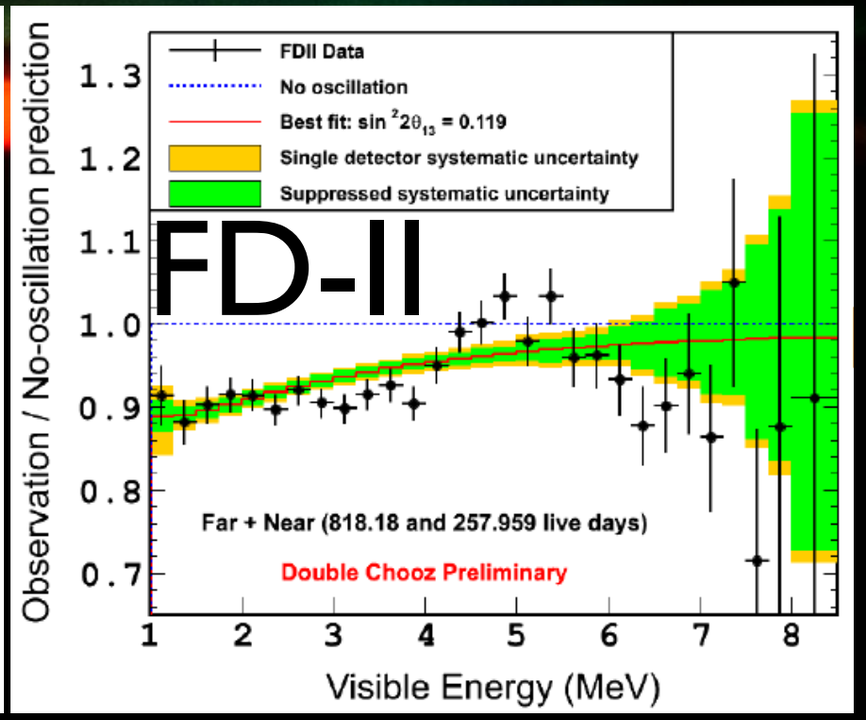




3x SD-fits (MC) ⊕ MD-fit (inter-detector correlations)



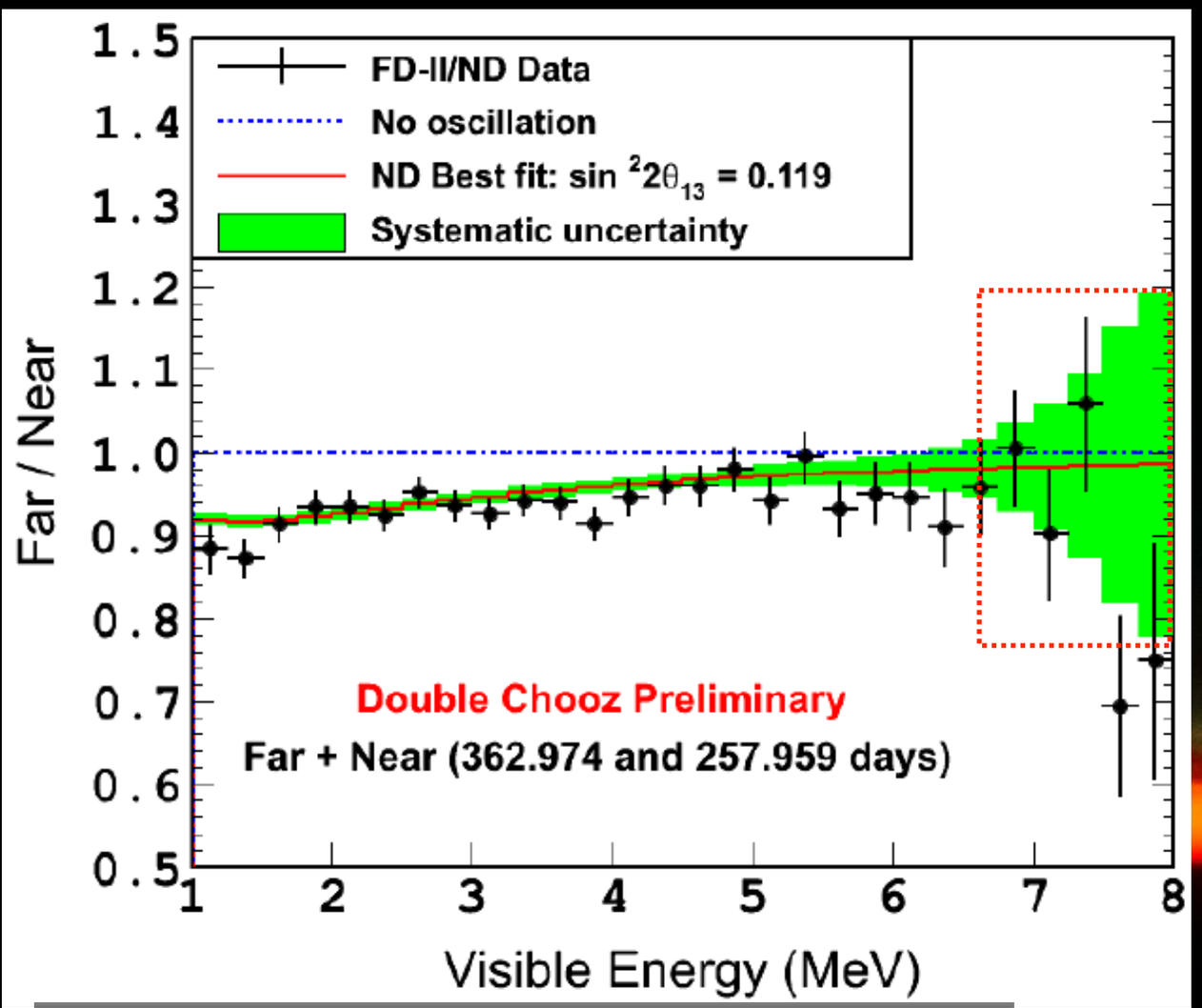




$\sin^2(2\theta_{13})^{R+S}=(0.119\pm0.016)$ with χ^2 / ndf: 236.2 / 114

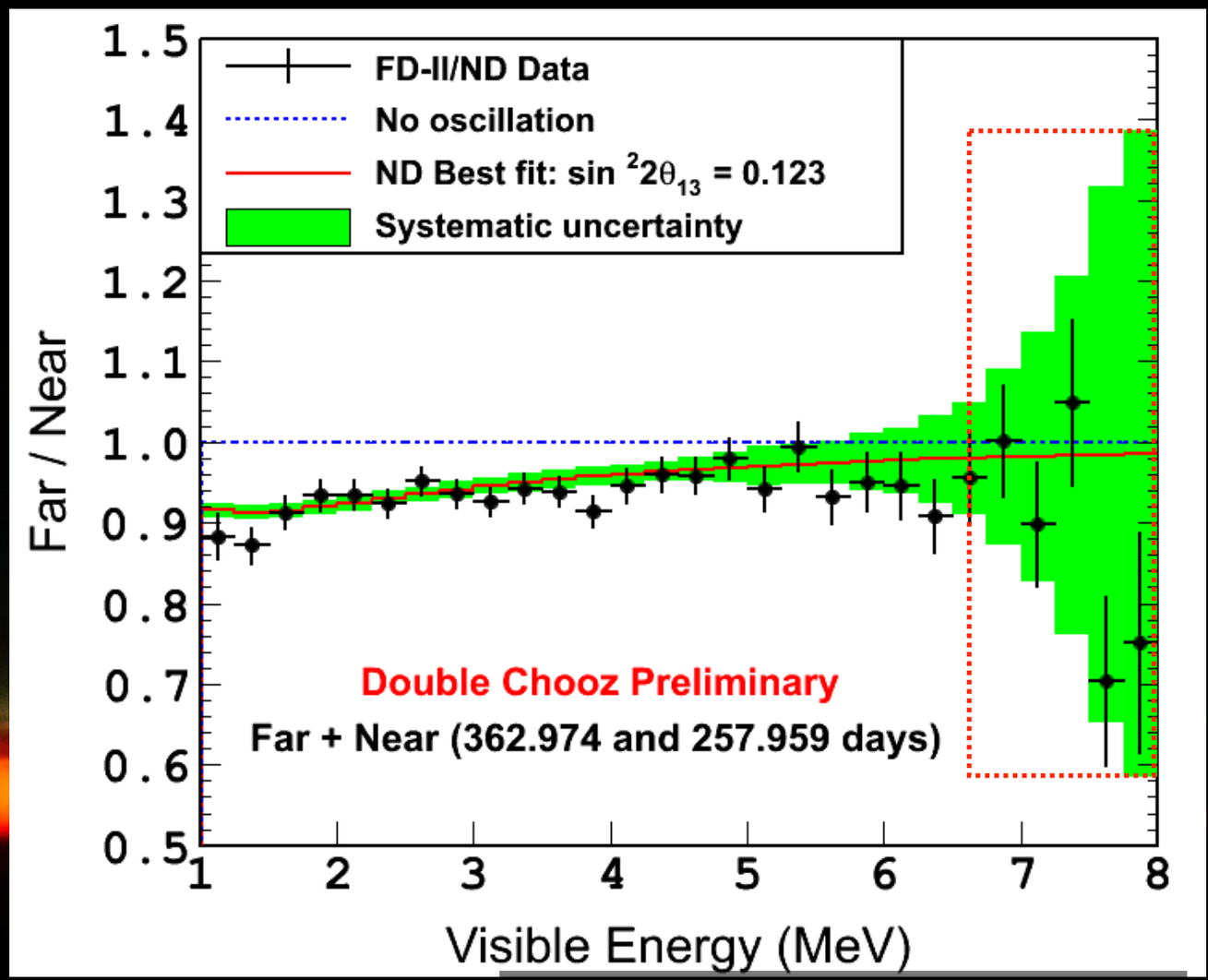
(marginalised over $\Delta m^2=(2.44\pm0.09)eV^2$ → **arXiv:1601.07464**)

θ13 energy distorsion & Li measurement…



Data to MC FIT

FD-I⊕FD-II⊕ND each SD



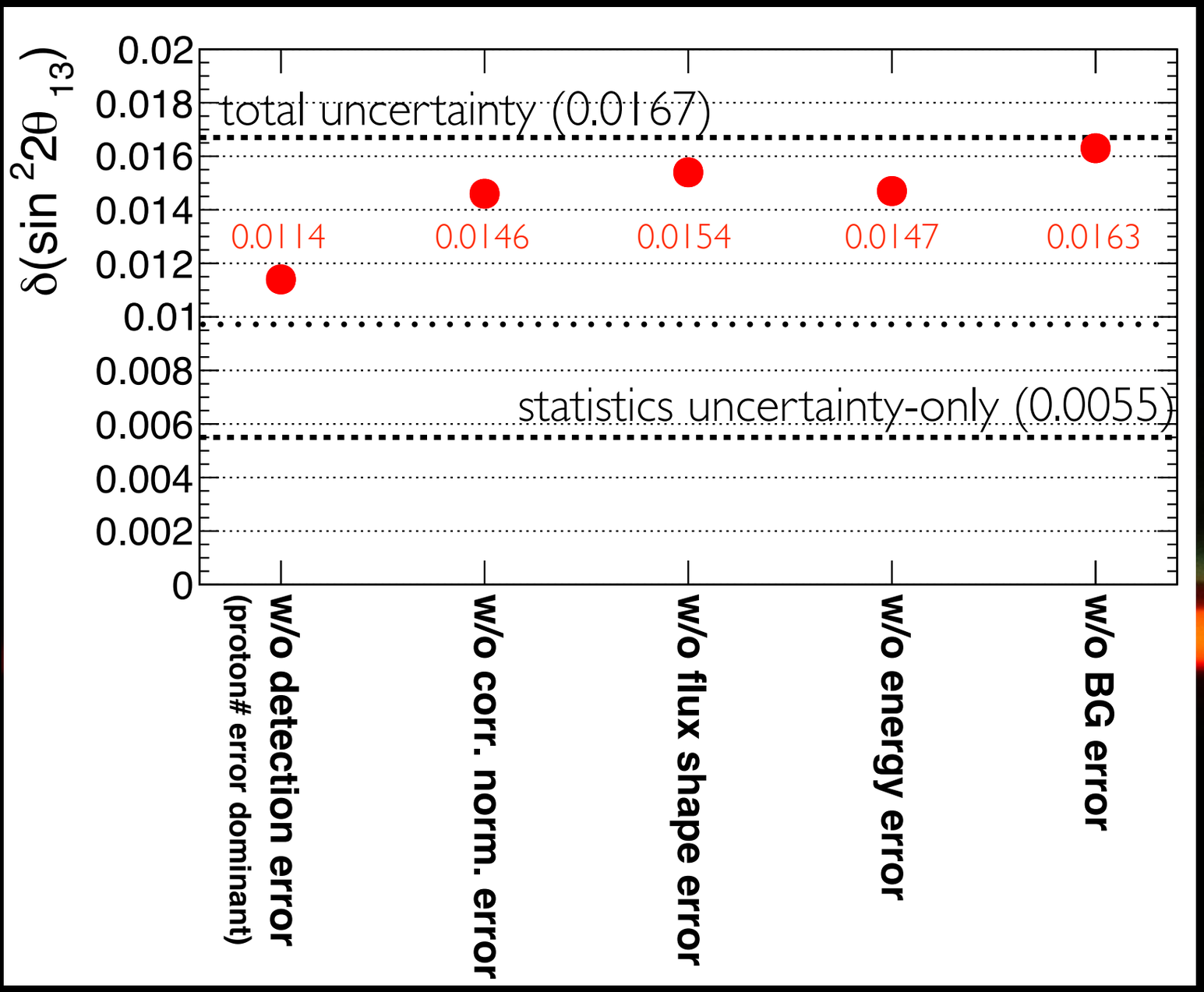
Data to Data FIT

FD-II⊕ND

both methods are similar but not identical

(agreement is expected→ **important cross-check**)

θ13 systematics: much room for improvement…



DC largely dominated by proton#

(conservative→ working to improve — if possible)

statistical error (1σ≈0.005)…

→@FD ~80k IBDs [0.35%] with S/BG>10

→@ND ~200k IBDs [0.22%] with S/BG>20

SYSTEMATICS…

- **detection** (**1σ≈0.012**)

→driven by proton# (very conservative)

now 0.75%/0.53% full volume

- **correlated-norm** (1σ≈0.008)

→driven by ND statistics un-oscillated normalisation constraint to FD [improving]

- **energy** (1σ≈0.008)

→driven by scintillator linearity [improving]

- **flux error** (1σ≈0.007)

→driven by poorer FD-I:ND correlation

→iso-flux (FD-II:ND) limitations are tiny

- **background** (1σ≈0.004)

→driven by Li constraint [improving]

our CERN result (SEPT-2016)…

Double Chooz
JHEP 1410, 086 (2014)

Preliminary DC-IV
(CERN seminar 2016)
$\sin^2(2\theta_{13})=(0.119\pm0.016)$

Daya Bay [Kam-Biu's talk]
PRL 115, 111802 (2015)

updated

RENO
PRL 116 211801(2016)

T2K [Kobayashi's talk]
PRD 91, 072010 (2015)

updated

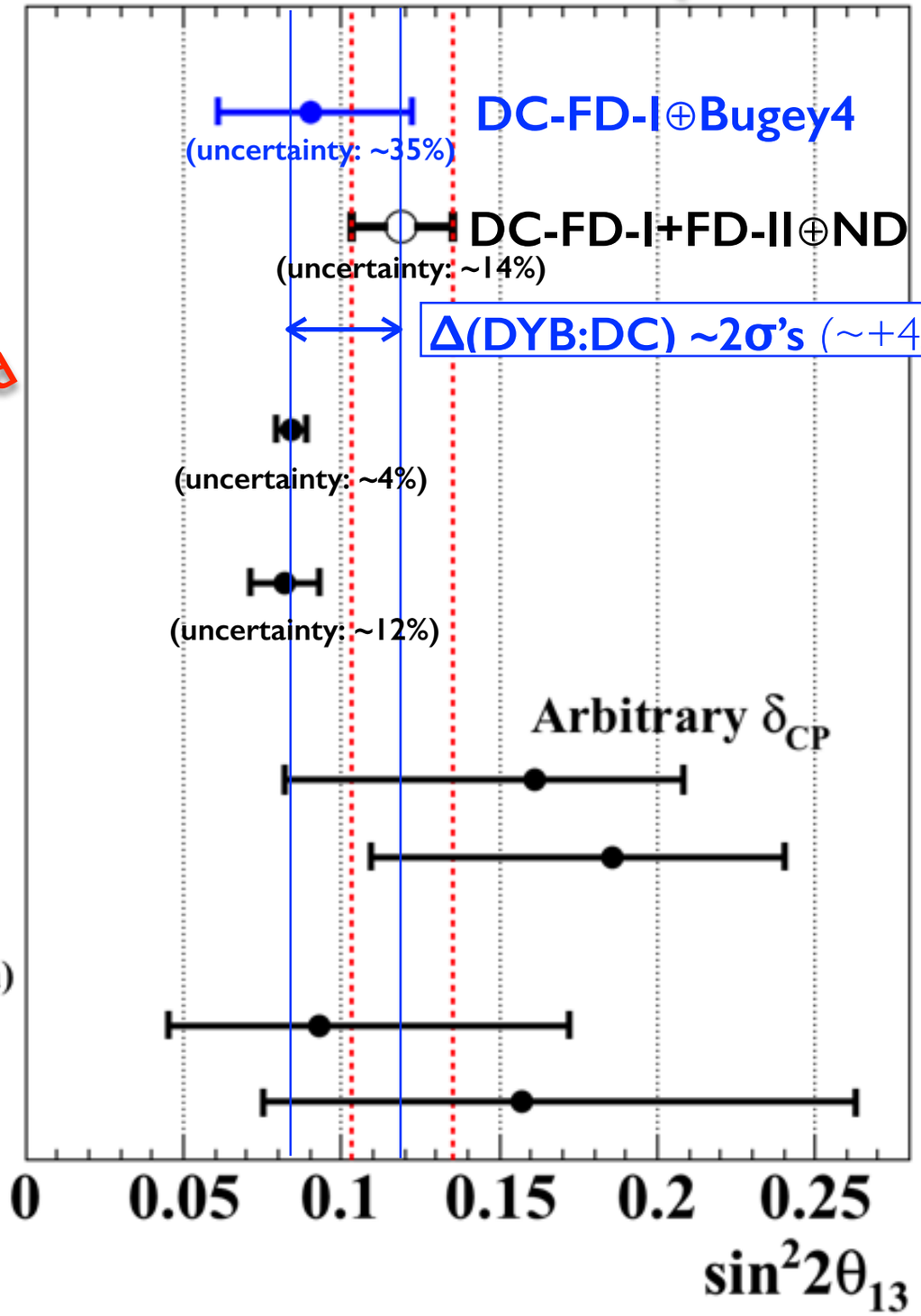
$\Delta m^2_{32} > 0$

$\Delta m^2_{32} < 0$

NOvA [Peter's talk]
Preliminary (private communication)

$\Delta m^2_{32} > 0$

$\Delta m^2_{32} < 0$



DC-IV-PRELIMINARY @ CERN

statistical fluctuation ruled out >5σ's ⇒ it's all about systematics @ ‰ level (complex)

(i.e. more IBD statistics is expected to drive little change)

caution…

~2σ means ~2σ

(no more & no less → inconclusive still)

"issue" vs "poor-ish agreement"

(1 year reviewing our systematics → new cross-checks)

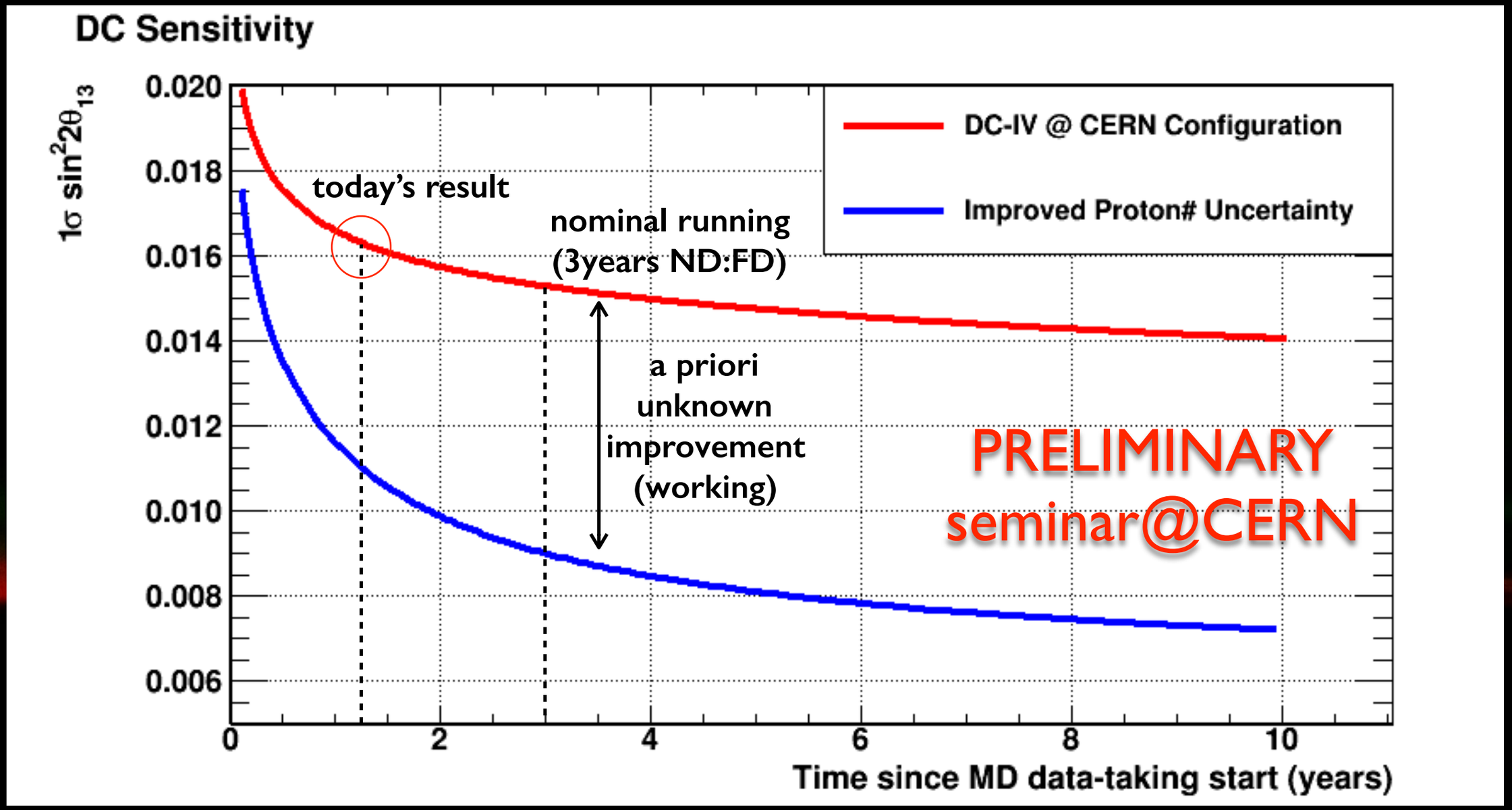
new results imminent on our publication

DC record (so far)…

[Nov. 2011] ~2σ on θ_{13} → confirmed DYB+RENO 2012

[May 2014] ~3σ spectral distorsion reactor ("bump") → confirmed RENO+DYB

DC prospects (improve proton#)…



DC largely dominated by proton#→ improvement possibility?

(most conservative inputs/assumptions adopted @ CERN)

collaboration is **committed improve to resolve** (internally & together with DYB+RENO)

pushing for **multi-experiment reactor-θ13 forum** (→next slide)

possible implications…

against the latest T2K results…

T2K Best Fit:

$$\sin^2\theta_{13} = 0.0277^{+0.0054}_{-0.0047} \text{ (NH)}$$

PDG 2016:

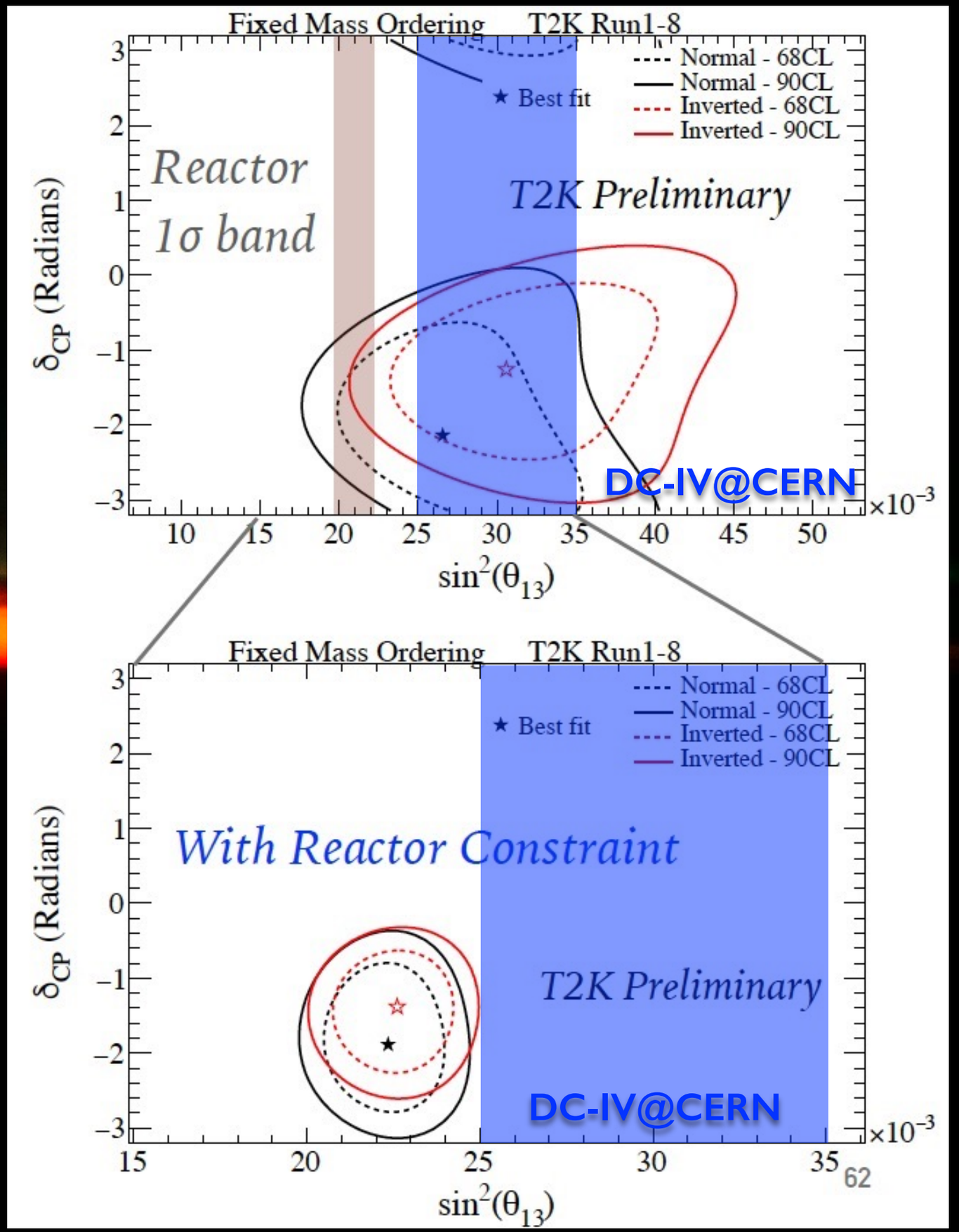
$$\sin^2\theta_{13} = 0.0210 \pm 0.0011$$

T2K's θ_{13} (alone) central value higher (~25%)
(wider uncertainty due to θ_{23}, δ_{CP}, NO/IO)

T2K's result uses "reactor-θ_{13}" (DYB driven)
⇒ major improved insight on δCP

(marginalised over θ_{23} & NO/IO)

[Concha's talk] "T2K doing better than expected"
(overall consistency critical to conclude on δ_{CP})



Reactor-θ_{13} *(combining results)*

Daya Bay⊕Double Chooz⊕RENO

0th discussion/planning→ @ Neutrino-2016, London (UK)

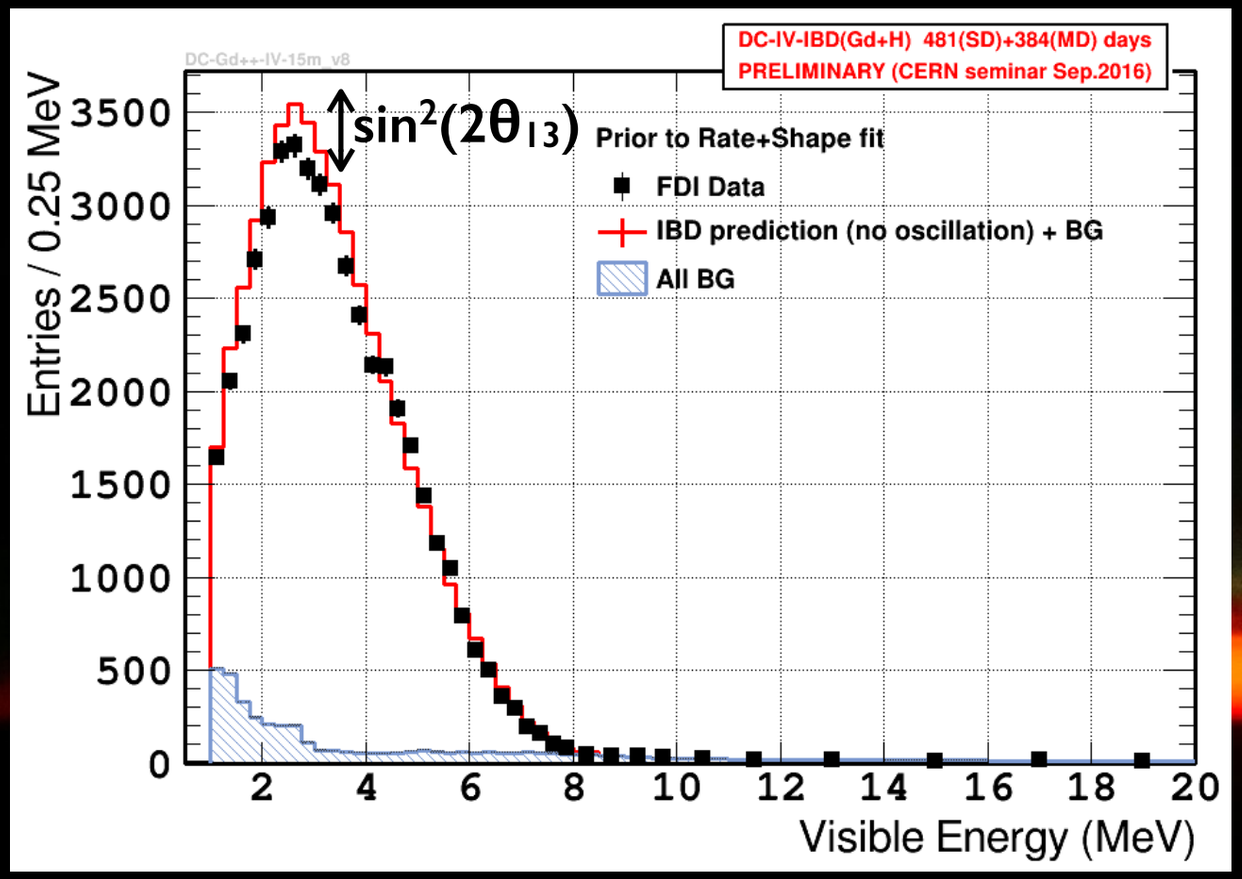
1st workshop→ October 2016 (Seoul, South Korea)
(systematics, results consistency)

2nd workshop→ June 2017 (Paris, France)
(further θ_{13} systematics consistency)

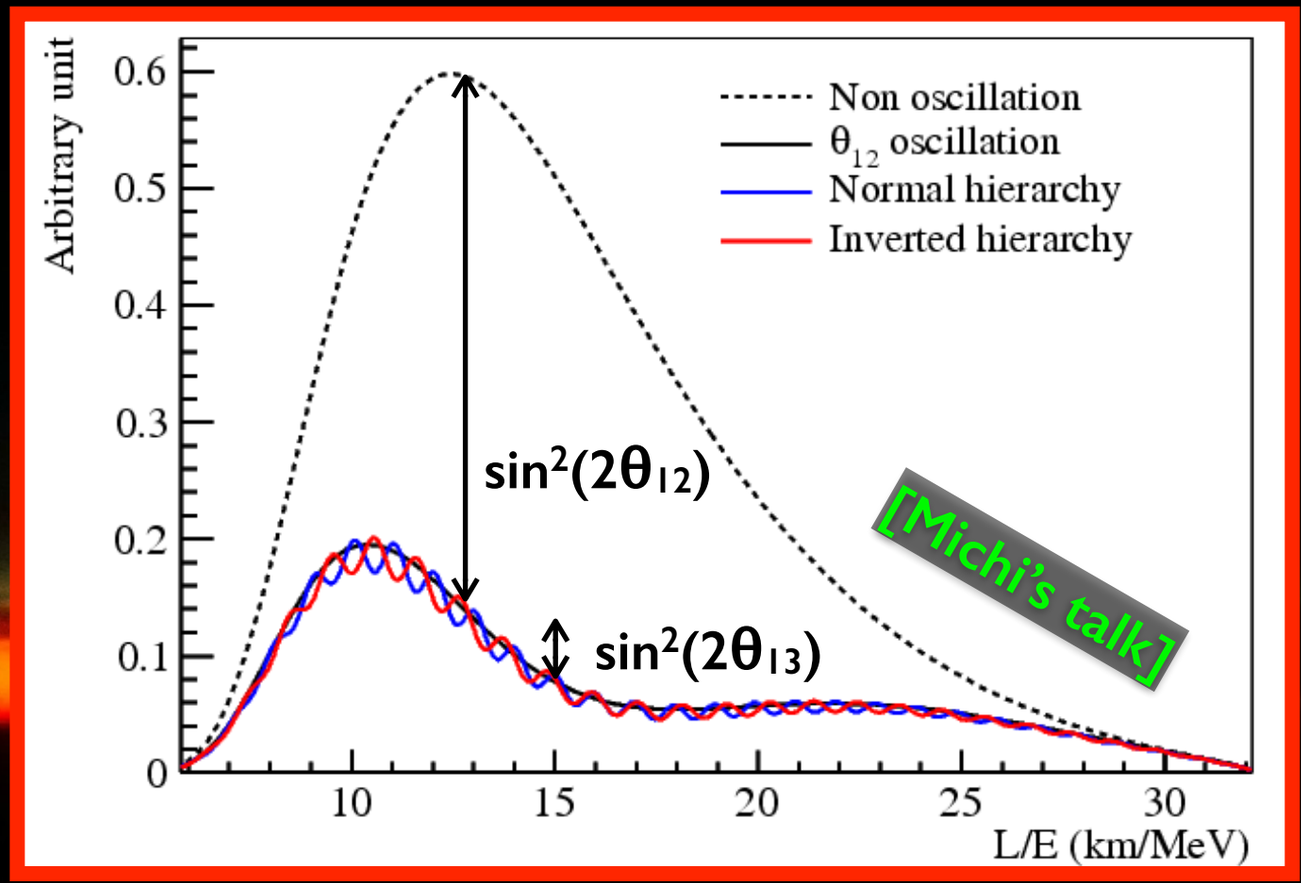
3rd workshop→ X 2018 (Hong Kong, China)

(likely) most precise input to θ_{13} for several decades…

JUNO scrutinise θ13-experiments…



Double Chooz (alike)
(FD⊕ND R+S analysis)

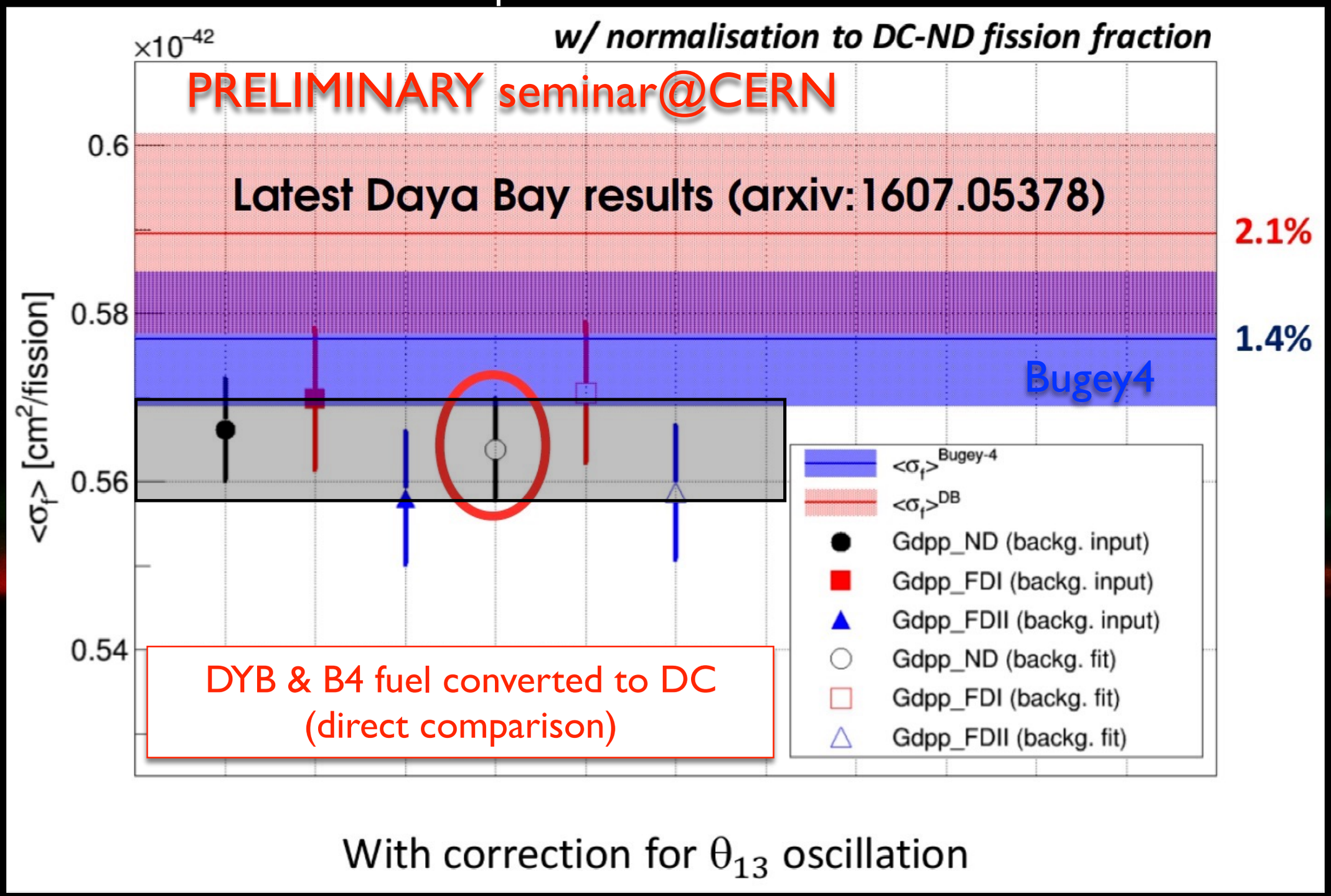


JUNO
(FD shape-only analysis)

reactor spectral characterisation…

Anatael Cabrera (CNRS-IN2P3 & APC)

the most precise reactor normalisation…



$\langle\sigma_f\rangle^{ND}=0.564\times10^{-42}\text{cm}^2/\text{fission}$

[Christian's talk]

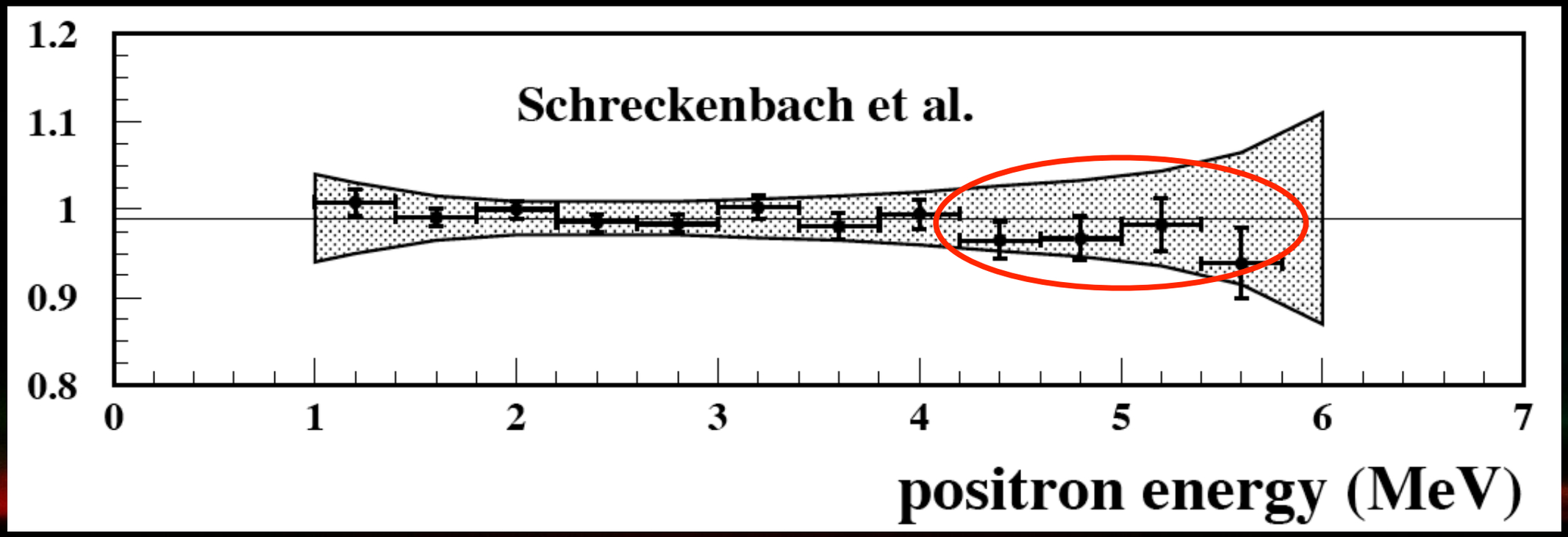
uncertainty: ±1.1%→ world most precise measurement

BUMP?

AHEAD

up to Bugey3: no problem…

SHAPE-ONLY (i.e. normalisation = 1)



KNOWLEDGE priori θ13-experiments

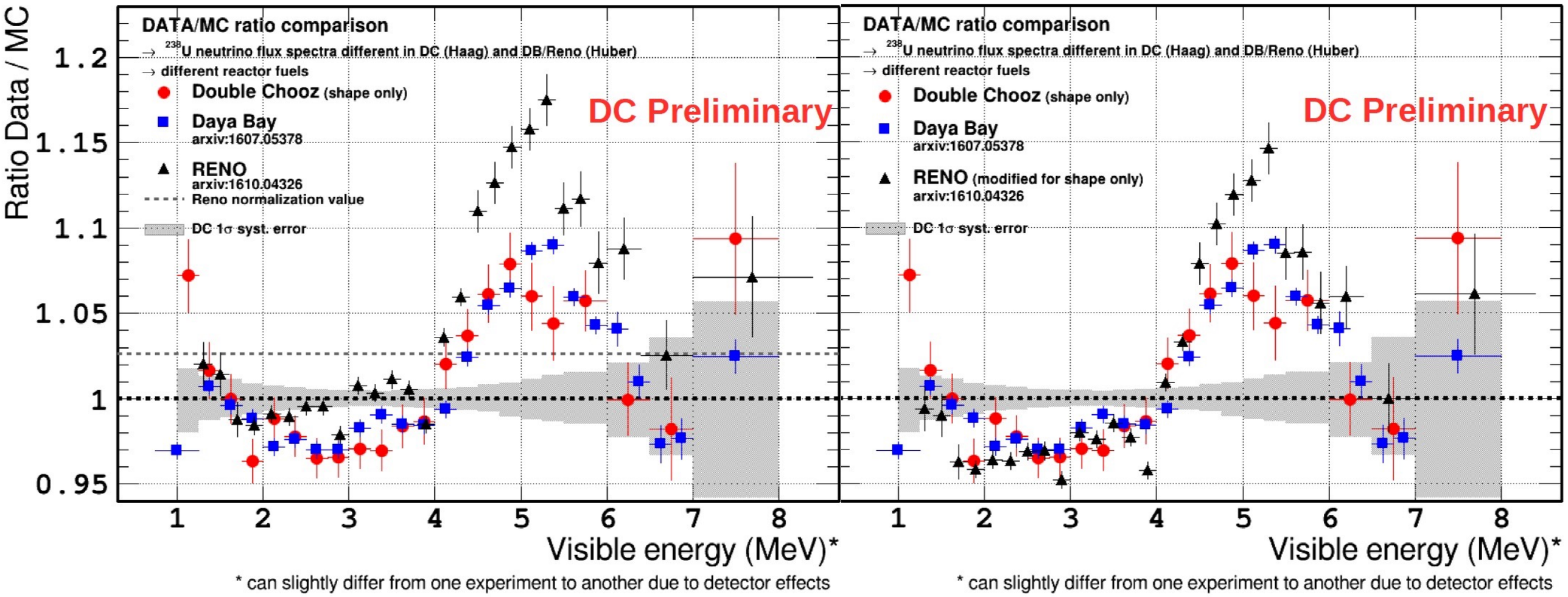
ILL-based prediction (≈ Bugey3 IBD data)⇒ 1σ budget of prediction reliable?

can we use reactor neutrinos to probe (new) physics (amplitude ≤5%)?

[absolute measurement means data to prediction(data) ratio]

situation upon θ13 experiments…

DC: 210 000 events / DB: 1.2 million events / Reno: 280 000 events



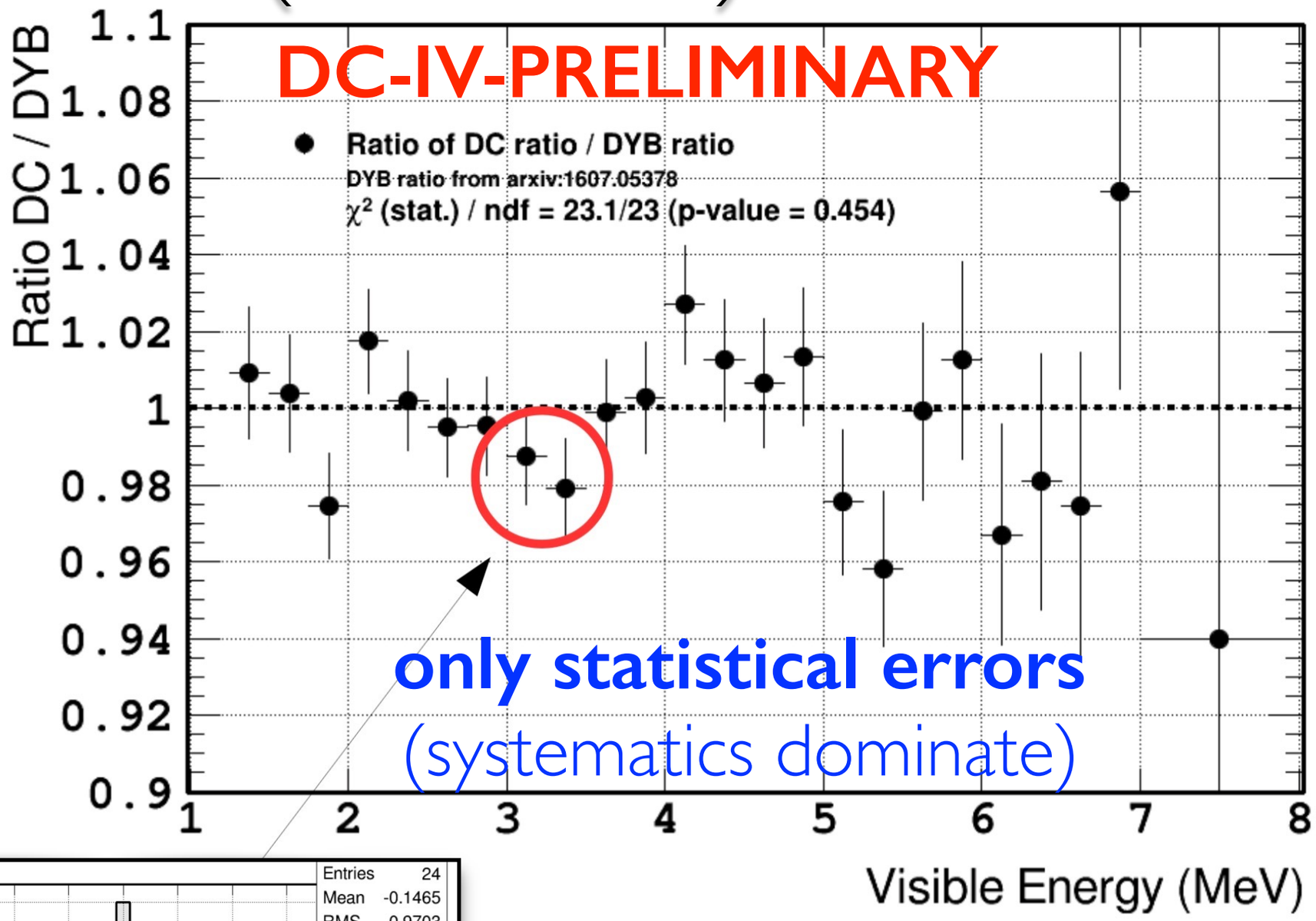
observation: **θ13 experiments disagree** (i.e. energy distorsion)

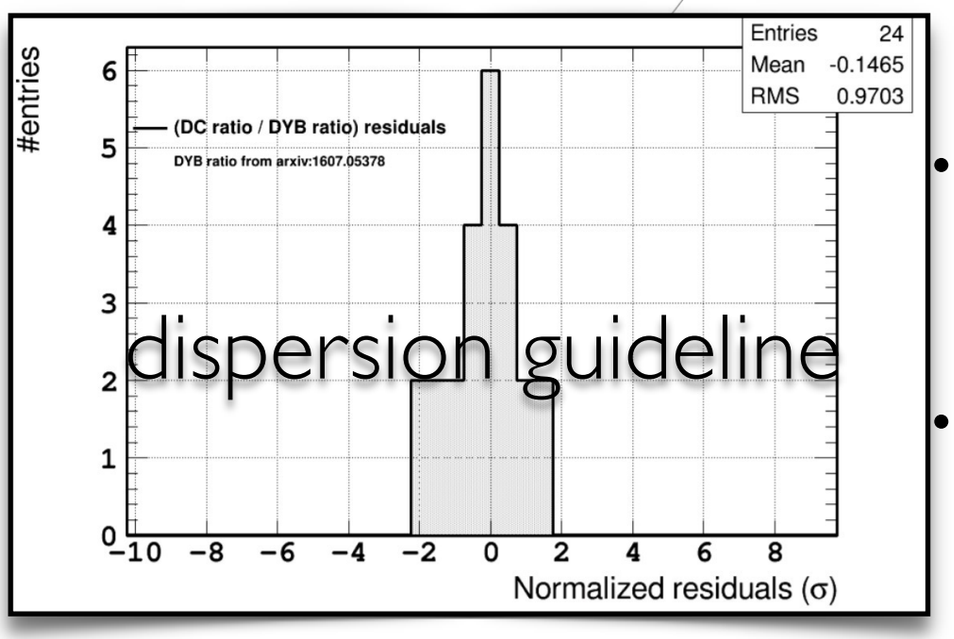
if(!) "ILL-based" predicted shape is inaccurate → **trust normalisation?**

[answer: **not evident!**]

[Yoomin's talk → NEOS]

(anecdotical) it seems DC ≈ DYB…





- **DC & DYB very different readout** (known non-linearities)
  - if wrongly calibrated → <u>should not agree</u> (fine tuning)
  - ⇒ energy driven effects are <u>very unlikely</u> (my opinion)
- **DC & DYB similar reactors AREVA** (the "French connection")
  - implication on refuelling strategy⇒**similar ratio?** (as observed)
  - RENO differences due to different reactors? [not known]

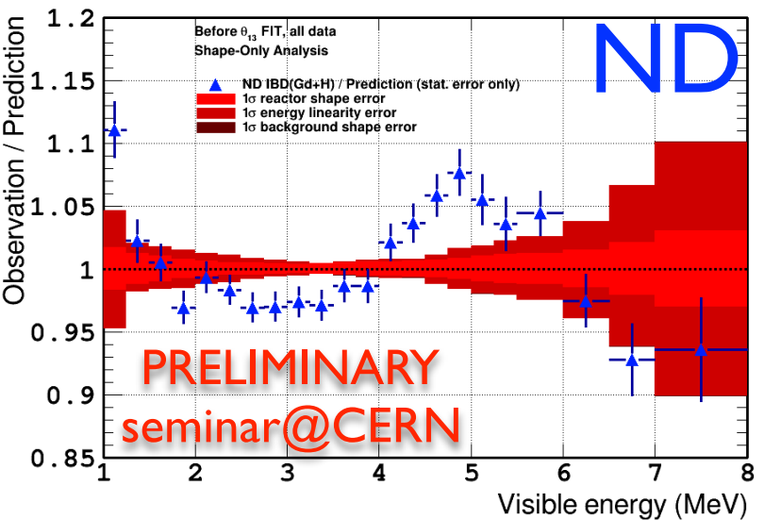
rate-only: deficit is anomalous?
[necessity for **ν**(sterile) hypothesis]

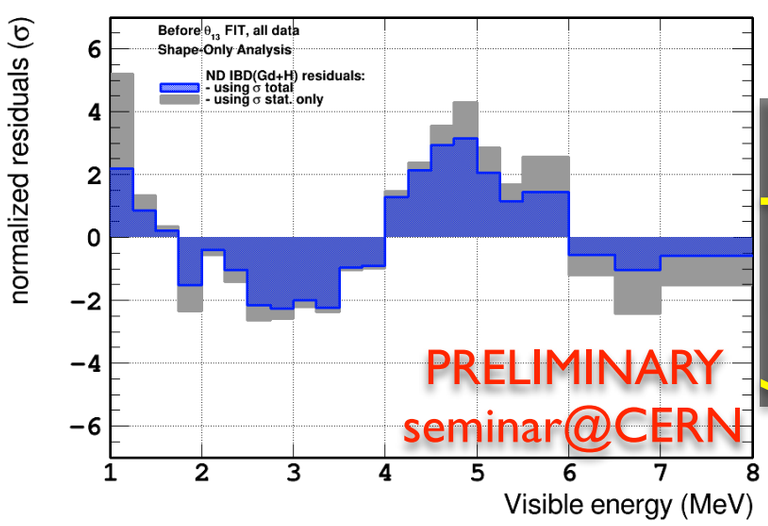
[Christian's talk]

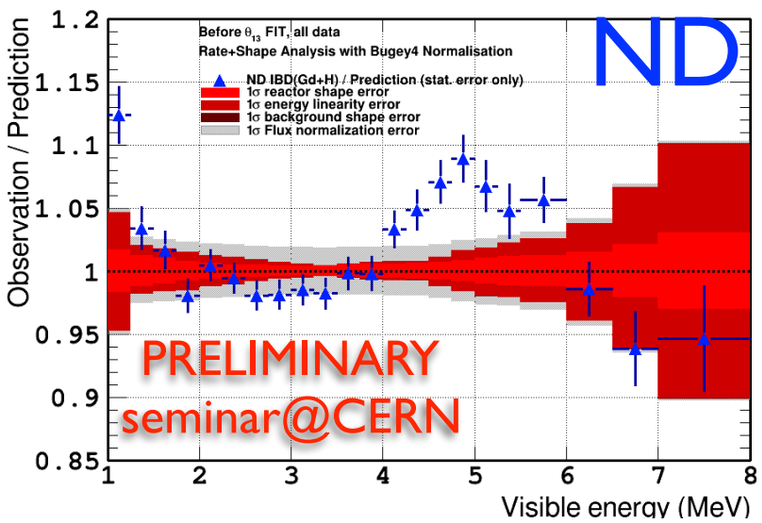
shape-only: ~5MeV bump?

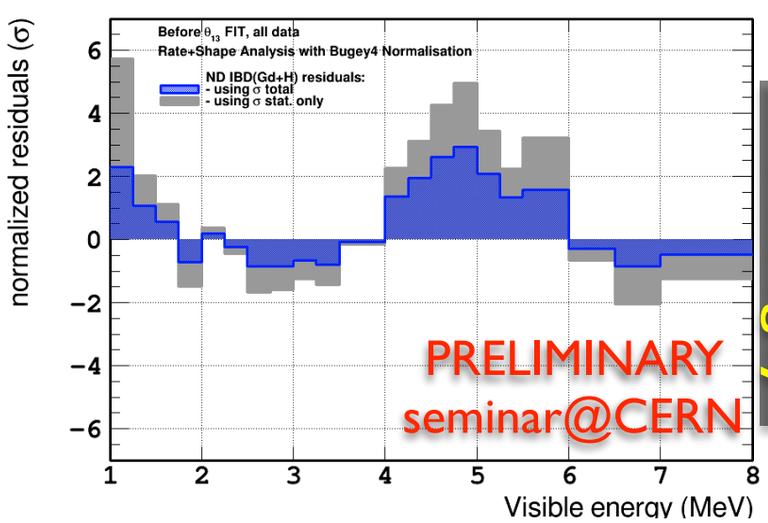
rate+shape analysis?
(a complete story)

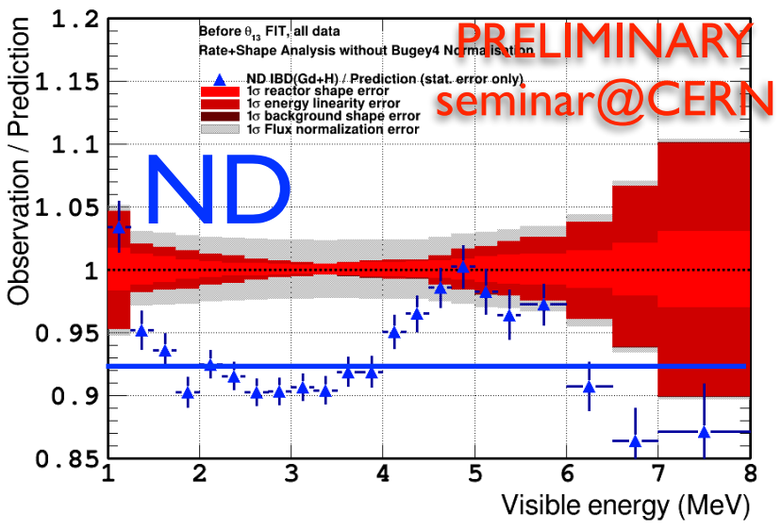
distorsions analysis with ND rate⊕shape…

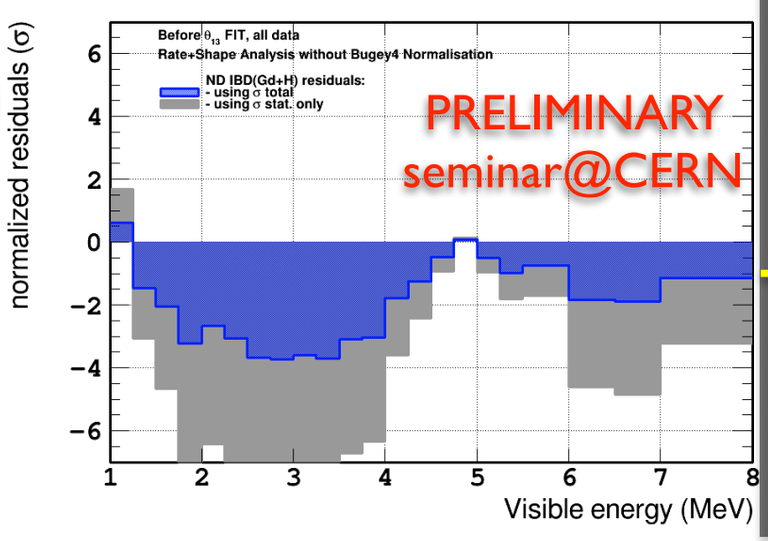












test the existence of features
not biassed by shape-only assumption
(i.e. smaller errors)

shape-only≈Bugey4
(consistency of Bugey4?)

non-statical features
- which is deficit?
- which excess?
- which is OK?

⇒ less evident!!

careful analysis before stating the "trouble region"
is bump problem really?
(maybe no bump whatsoever)

(**bias question⇒bias answer**)

what's going (i.e. mechanism)?

answer: **nobody knows for sure!**
(several suggestions, but none conclusive)

a few cases (not exhaustive — sorry)…

- [nuclear] (un/mis)accounted β branches (Ru, etc) **[R+S]**
- [Hayes et al] unaccounted transition (forbidden, etc) **[R+S]**
- [Hayes et al] Z(effective) correction **[R+S]***
- [DYB⊕Giunti et al] ^{235}U off by ≳2σ **[R+S?]**

[Alejandro's talk]

[Kam-Biu's talk]

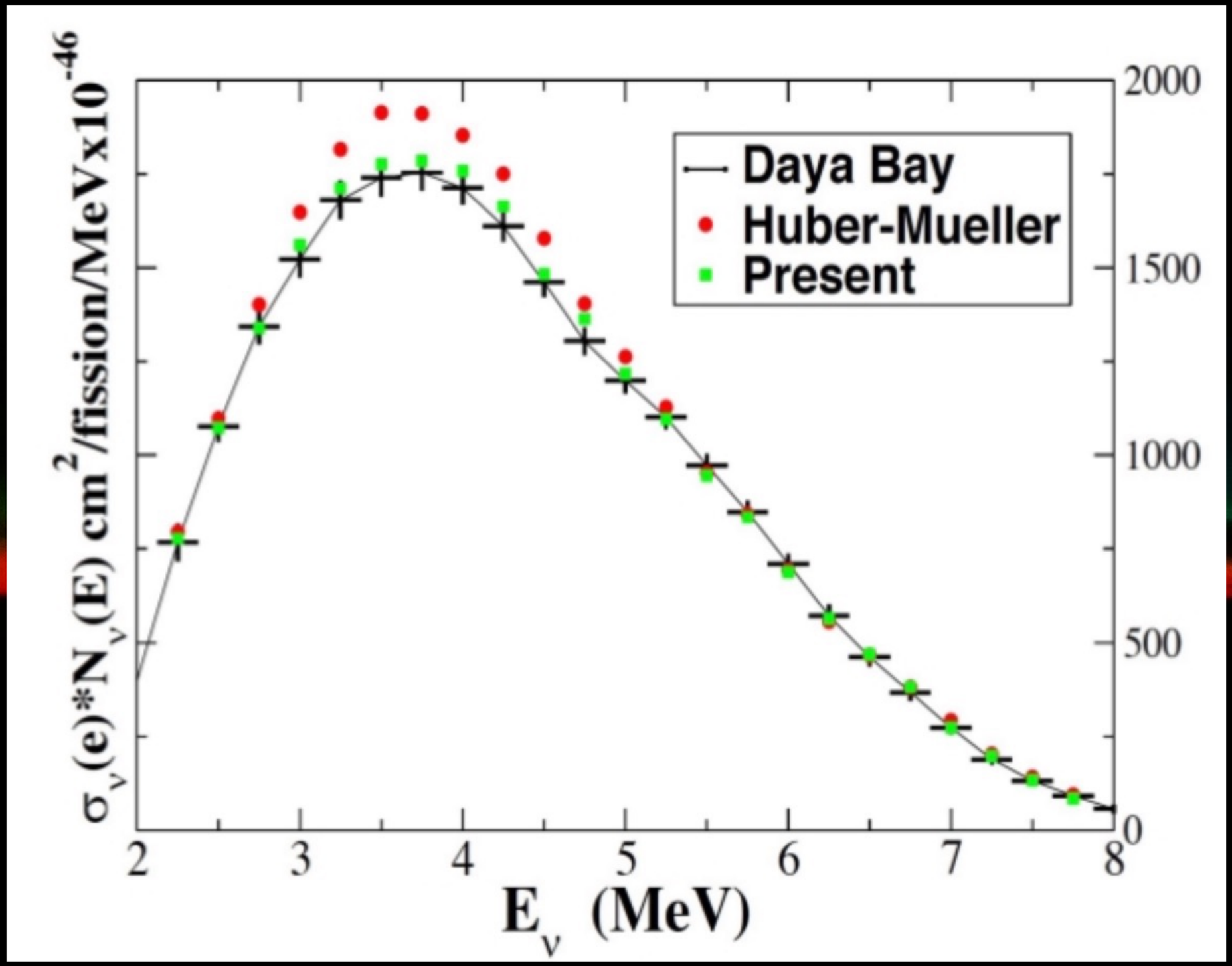
(very long etc…)

and/or

- [Mention et al] energy distorsion **[Shape-Only protect]**

[Vogel might like to add further]

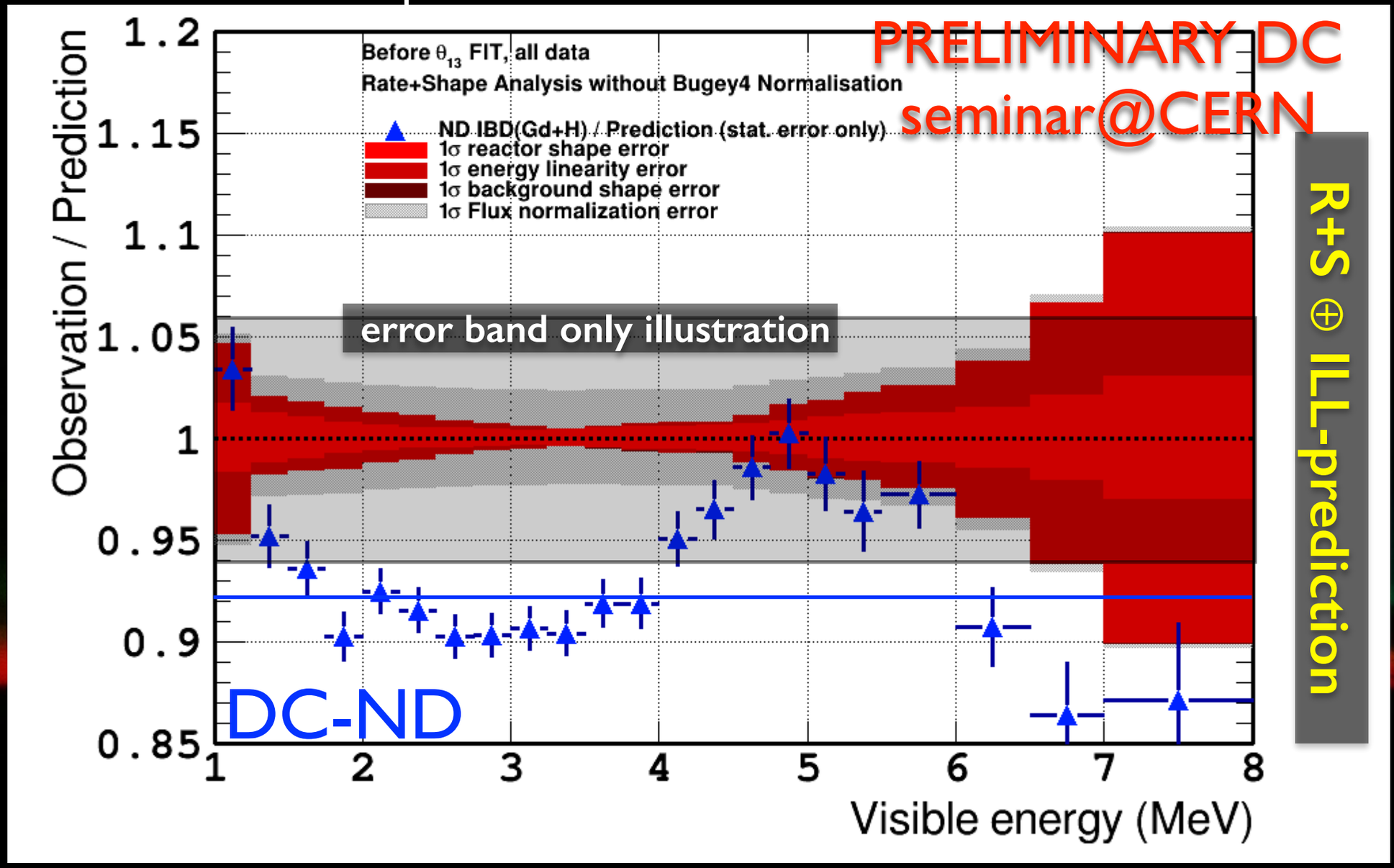
Hayes et al @ NuPhys-2016 (London, UK)…



Z(efficient) correction alone: solve all?

(likely solution is combination of several effects)

R+S reactor spectral issue → **new uncertainty?**



reactor spectrum is prediction complex issue [well motivated issues→uncertainties]

⇒ exact mechanism behind R+S features (deficit⊕distorsion) is unknown

a (combined) solution ever? likely combination of several issues

(my opinion)

new uncertainty budget is most important (while mechanism's remain unclear)

reactor neutrino measurement vs prediction: no uncertainty better ~6% (rough)

[Christian's talk]

(⇒ probe sterile neutrino hypothesis only via data-driven measurements; i.e. no predictions)

STRUCTURE

careful!

AHEAD

symmetry claims a "discovery"… which one?

A joint Fermilab/SLAC publication

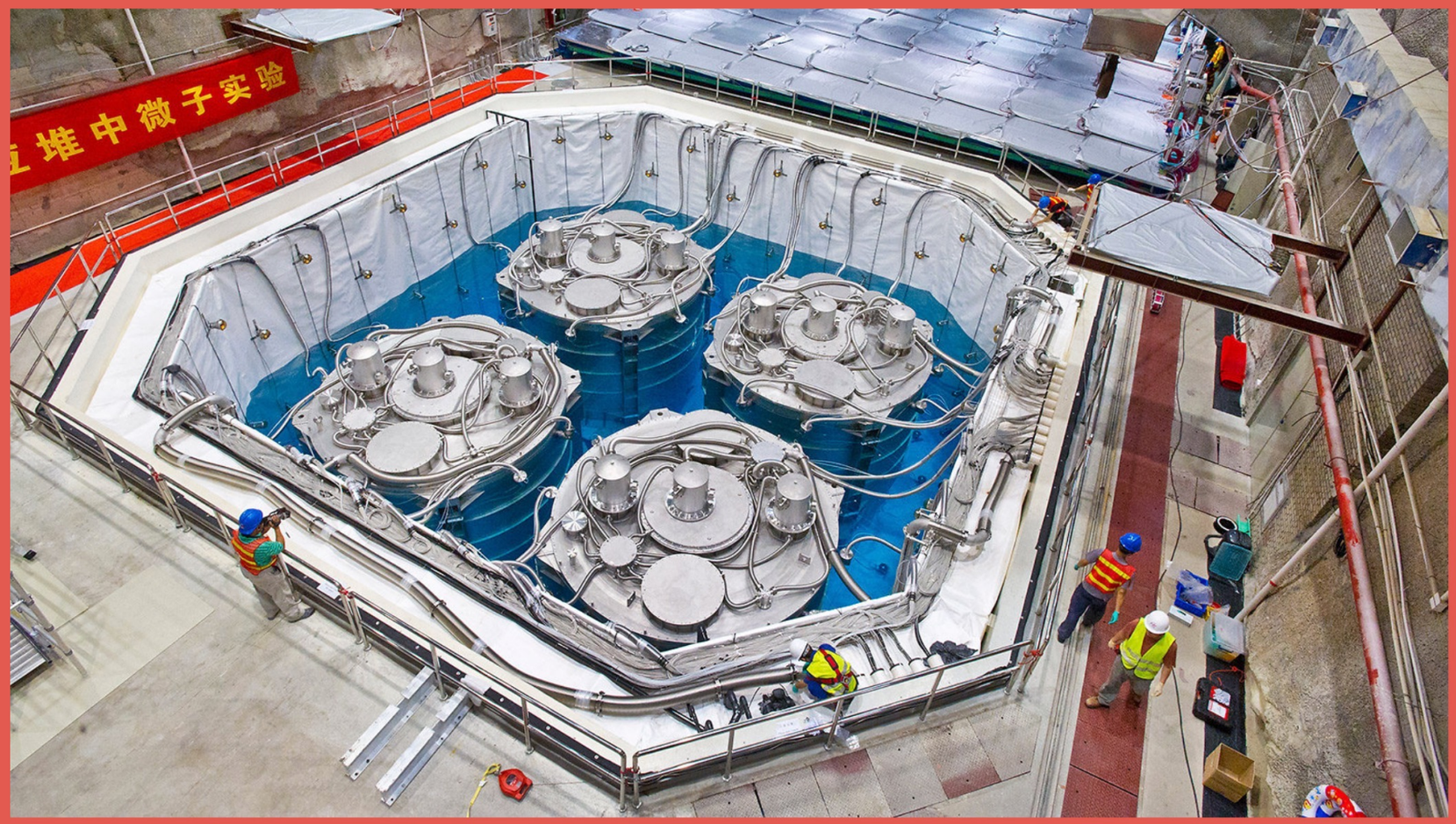


Photo courtesy of Brookhaven National Laboratory

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" → but **symmetry** does**!**

what to remember...?

DC-IV PRELIMINARY @ CERN (Sept.2016)…

- DC (despite ND delay) **delivering high precision & accuracy physics**… (more to come)
  - **high quality analyses demonstrated** (all though our history)…
    - every-single "inconsistency" found has been indeed an issue: ≳2σ suffice? (surprising)
  - latest **H⊕C⊕Gd IBD a master piece→** yield higher precision (stats & systematics)
    - **DC-FD(30tons)** comparable **~2x DYB-FD** and **~2x larger than RENO-FD**

- **DC-IV PRELIMINARY results @ CERN**… (publication's soon)
  - **new $\sin^2(2\theta_{13})$: non-statistical ~2.0σ wrt DYB: ok agreement? [systematics review]**
  - **new reactor spectrum characterisation (rate⊕shape): major improvement…**
    - **intriguing spectral distorsions behaviour & implications**
      - **DC-ND** superseding past world best reactor references ~~**Bugey4**~~ & ~~**Bugey3**~~
      - complementary info to DYB (powerful statistics @ ND)
    - **ILL-based prediction error budget is questioned: new error budget?**
- (@NEUTRINO) **DC world best IBD-directionality measurements** [backup]→ **still improving!!**

more in our paper(s) very soon…

stay tune!

[our DC languages]
obrigado…
merci…
danke…
ありがとう…
Спасибо…
gracias…
thank you…
谢谢…
hvala…