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(for the NESSiE Collaboration)

Search for sterile neutrinos in ν_μ disappearance mode at FNAL

Is a SBL experiment à –la-NESSiE needed ?

- The "sterile" issue at 1 eV mass scale
- The NESSiE Collaboration
- Proposal P-1057
- Infrastructures, funding, schedules
- Conclusions

FNAL-PAC January 15th, 2015

The "sterile" issue

From masses to flavours:

$$\left|\nu_e\right\rangle = U_{e1}\left|\nu_1\right\rangle + U_{e2}\left|\nu_2\right\rangle + U_{e3}\left|\nu_3\right\rangle$$

$$\left|\nu_\mu\right\rangle = U_{\mu 1}\left|\nu_1\right\rangle + U_{\mu 2}\left|\nu_2\right\rangle + U_{e\mu 3}\left|\nu_3\right\rangle$$

$$\left|\nu_\tau\right\rangle = U_{\tau 1}\left|\nu_1\right\rangle + U_{\tau 2}\left|\nu_2\right\rangle + U_{\tau 3}\left|\nu_3\right\rangle$$

U is the 3 × 3 Neutrino Mixing Matrix
mixing given by 3 angles, θ_{23}, θ_{12}, θ_{13}

transition amplitudes driven by
$\Delta m^2_{solar} = \Delta m^2_{21}$
$\Delta m^2_{atm} = |\Delta m^2_{32}| \approx |\Delta m^2_{31}|$

The **framework** pinpointed for the 3 standard neutrinos, **marvellously** completed with the θ_{13} measurement, does not account for some relevant issues:

- Leptonic CP violation
- Mass values
- Dark Matter
- Anomalies and discrepancies in several results

The "sterile" issue (contd)

The previous picture is **wonderfully** working.
Oscillation frame should stay whatever extensions !

Exploit 3+1 or even 3+2 oscillating models, by adding one or more "**sterile**" neutrinos

$$\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix} \Rightarrow$$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta_{\alpha\beta} \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

APPEARANCE

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

DISAPPEARANCE

when $\Delta m_{21}^2 << \Delta m_{31}^2 << \Delta m_{41}^2$ and $\left|U_{s4}^2\right| \leq 1$

with

$$\sin^2 2\theta_{e\mu} = 4\left|U_{e4}\right|^2 \left|U_{\mu 4}\right|^2$$

for **APPEARANCE**

and

$$\sin^2 2\theta_{ee} = 4\left|U_{e4}\right|^2 \left(1 - \left|U_{e4}\right|^2\right)$$

$$\sin^2 2\theta_{\mu\mu} = 4\left|U_{\mu 4}\right|^2 \left(1 - \left|U_{\mu 4}\right|^2\right)$$

for **DISAPPEARANCE**

sterile: *not weakly interacting neutrinos* (B. Pontecorvo, JETP, 53, 1717, 1967)

The "sterile" issue (cntd)

- ➔ Experimental hints (?) for more than 3 standard neutrinos, at eV mass scale
- ➔ Strong tension with any formal extension of 3x3 mixing matrix

ν_e disappearance

Reactor anomaly ~2.5σ
Re-analysys of data on anti-ν_e flux from reactor short-baseline (L~10-100 m) shows a small deficit in expected flux
R=0.943 ±0.023
G.Mention et al, Phys.Rev.D83, 073006 (2011) , A.Mueller et al. Phys.Rev.C **83,** 054615 (2011).

Gallex/SAGE anomaly ~3σ
Deficit observed by Gallex in neutrinos coming from a ^{51}Cr and ^{37}Ar sources
***R* = 0.76+0.09 −0.08**
C. Giunti and M. Laveder, Phys.Rev. C83, 065504 (2011), arXiv:1006.3244

ν_e appearance

Accelerator anomaly ~3.8σ
Appearance of anti-ν_e in an anti-ν_μ beam (LSND). *A.Aguilar et al. LSND Collaboration Phys.Rev.D 64 112007 (2001).*

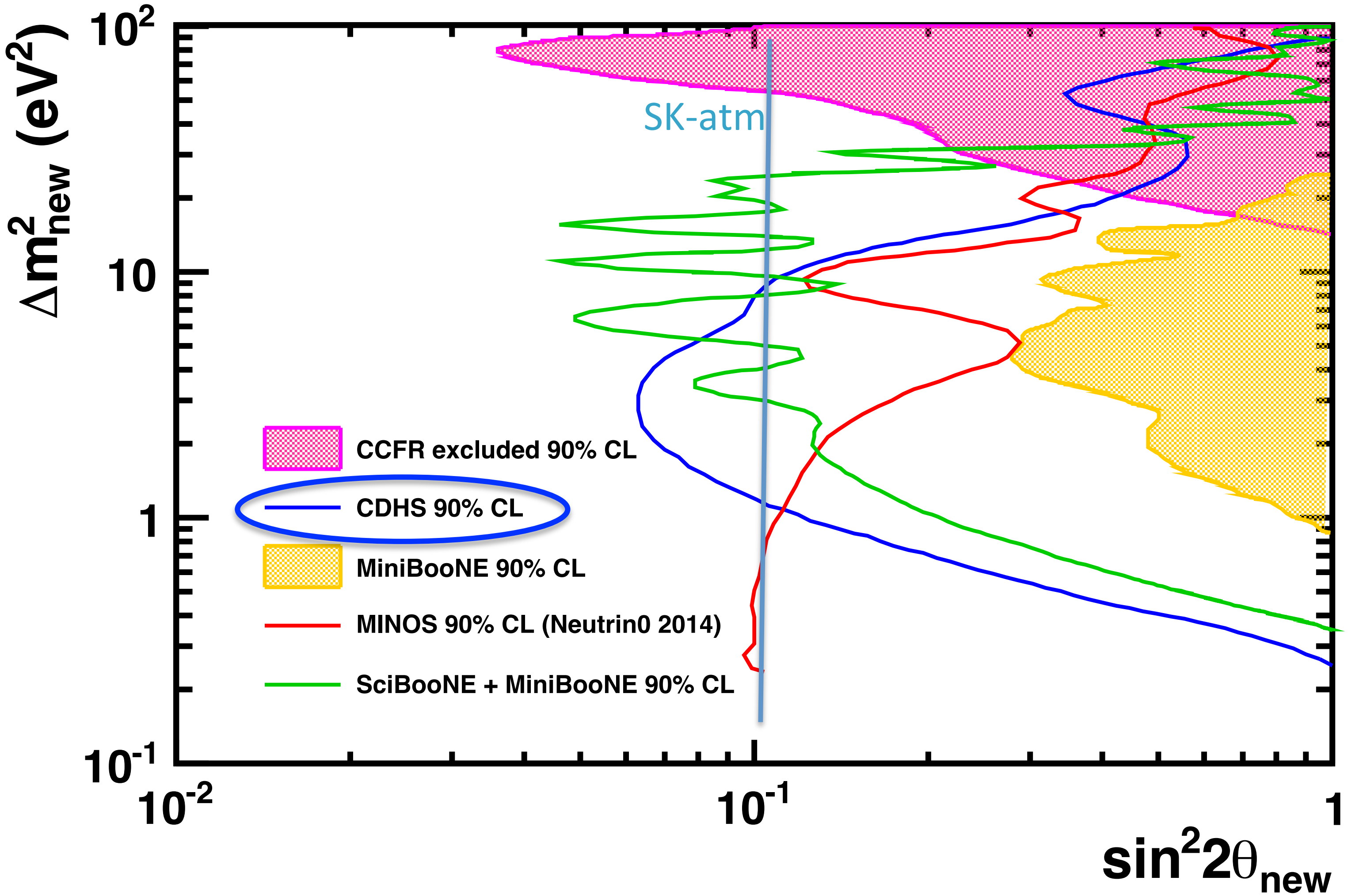
Confirmed (?) by MiniBooNE (which also sees appearance of ν_e in a ν_μ beam) *A.Aguilar et al. (MiniBooNE Collaboration) Phys.Rev.Lett. 110 161801 (2013)*

CMB/cosmology: some room for $N_\nu > 3$

?? Where is the ν_μ disappearance ??

Here are the current limits on ν_μ disappearance

Note: all the exclusion curves are at 90% C.L.

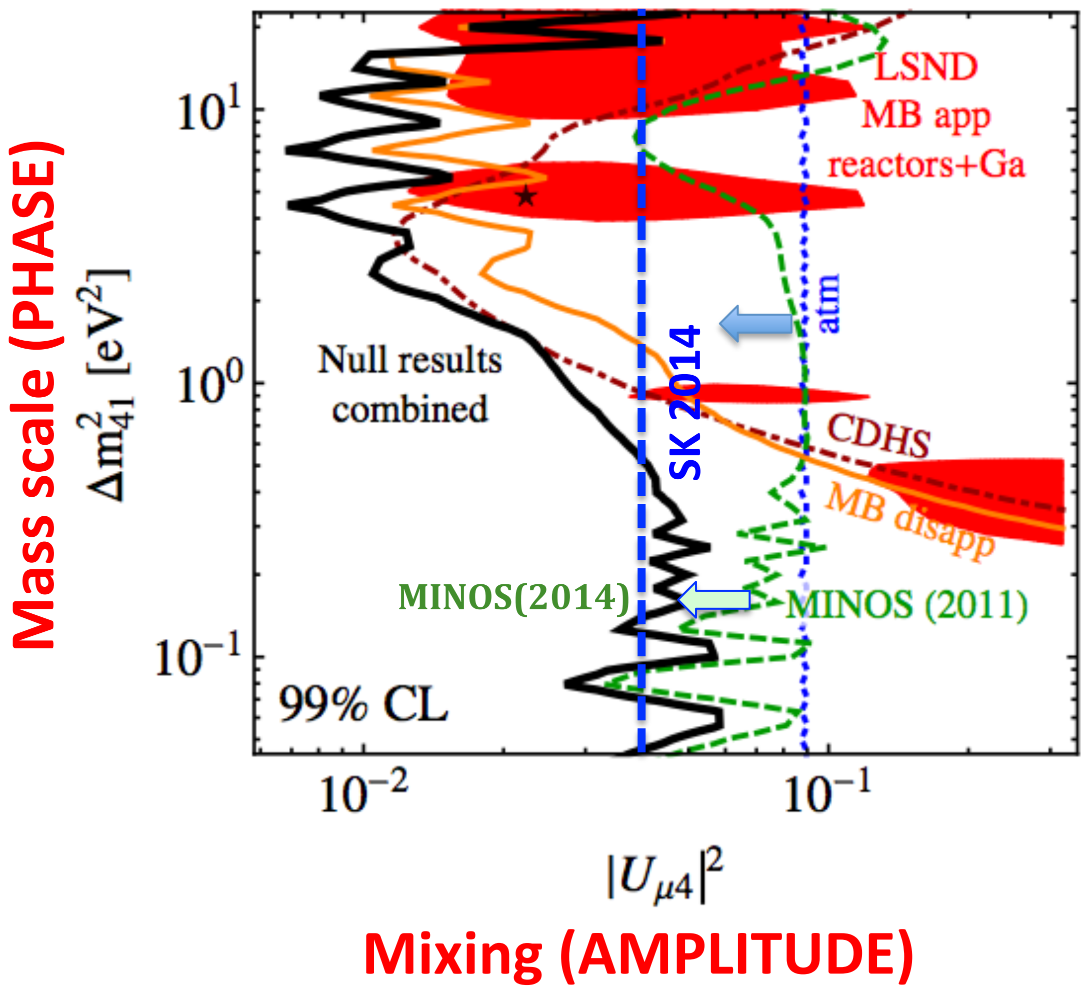


Best limit from CDHS (1984) : 3300 events, 135 m and 885 m, 1.5 m of iron but with 19.2 GeV p…

Possible explanation: mixing of the active flavours with a sterile neutrino Δm^2 ~ 1 eV^2

But STRONG tensions exist between
ν_e (appearance and disappearance) and ν_μ disappearance

(by J. Kopp at Neutrino2014 and references therein)



What is the community undertaking ?...
...many proposals and experiments
to confirm/get rid of the anomalies.

Why not directly proceeding to measure ν_μ disappearance by a dedicated experiment ?

The NESSiE Collaboration

Neutrino Experiment with SpectrometerS in Europe

⇩

Neutrino Experiment with SpectrometerS in FERMILAB

A conclusive experiment to determine the ν_μ disappearance behavior at 1 eV mass scale, with Spectrometers exploited to provide muon charge assignment and momentum measurement

Spectrometers at a neutrino beam. Extended studies:

- SPSC-P-343, arXiv:1111.2242
- SPSC-P347, arXiv:1203.3432
- ESPP, arXiv:1208.0862
- LOI CENF: https://edms.cern.ch/nav/P:CERN-0000096725:V0/P:CERN-0000096728:V0/TAB3
- L. Stanco et al., *AHEP 2013 (2013)* ID 948626, arXiv:1306.3455v2
- FNAL-P-1057, arXiv:1404.2521
- Nucl.Phys.B (Proc. Suppl.): arXiv:1410.3980
- A.Anokhina et al, submitted to Phys.Rev. D

The NESSiE Collaboration

INFN and Physics Dep. (Italy),
LPI – RAS, MSU – SINP (Russia),
RBI (Croatia),
CERN.

All groups have long experience
in Neutrino Physics and Hardware
(MACRO, CHORUS, NOMAD, OPERA, T2K…)

A. Anokhina[11], A. Bagulya[10], M. Benettoni[12], P. Bernardini[8,7], R. Brugnera[13,12], M. Calabrese[7], A. Cecchetti[6], S. Cecchini[3], M. Chernyavskiy[10], P. Creti[7], F. Dal Corso[12], O. Dalkarov[10], A. Del Prete[9], G. De Robertis[1], M. De Serio[2,1], L. Degli Esposti[3], D. Di Ferdinando[3], S. Dusini[12], T. Dzhatdoev[11], C. Fanin[12], R. A. Fini[1], G. Fiore[7], A. Garfagnini[13,12], S. Golovanov[10], M. Guerzoni[3], B. Klicek[15], U. Kose[5], K. Jakovcic[15], G. Laurenti[3], I. Lippi[12], F. Loddo[1], A. Longhin[6], M. Malenica[15], G. Mancarella[8,7], G. Mandrioli[3], A. Margiotta[4,3], G. Marsella[8,7], N. Mauri[6], E. Medinaceli[13,12], A. Mengucci[6], R. Mingazheva[10], O. Morgunova[11], M. T. Muciaccia[2,1], M. Nessi[5], D. Orecchini[6], A. Paoloni[6], G. Papadia[9], L. Paparella[2,1], L. Pasqualini[4,3], A. Pastore[1], L. Patrizii[3], N. Polukhina[1(M. Pozzato[4,3], M. Roda[13,12], T. Roganova[11], G. Rosa[14], Z. Sahnoun[3‡], S. Simone[2,1], C. Sirignano[13,12], G. Sirri[3], M. Spurio[4,3], L. Stanco[12,a], N. Starkov[10], M. Stipcevic[15], A. Surdo[7], M. Tenti[4,3], V. Togo[3], M. Ventura[6] and M. Vladymyrov[10].
(a) Spokesperson

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‡ Also at Centre de Recherche en Astronomie Astrophysique et Geophysique, Alger, Algeria

Prospects for the measurement of ν_μ disappearance at the FNAL-Booster

The NESSiE Collaboration

Submitted to FNAL-PAC:
FNAL-P-1057 and arXiv:1404.2521

6 months of works following the prescriptions of ESPG (and P5)…

Key-points of the proposal:

1. The muon-neutrino disappearance is **mandatory**
   - either in case of **null** result on electron-neutrino
     (the presence of sterile neutrino could be hidden due to interference modes and data mis-interpretation for the interplay between ν_e appearance/disappearance)
   - or in case of positive result on electron-neutrino **at SBL**
     (to address the correct interpretation of sterile neutrino oscillation, see current tension between ν_e/ν_μ appearance/disappearance)

2. **Standalone** measurement of muon-neutrinos
   (fully compatible with upstream LAr detectors, a small target might be useful at Near-site for NC/CC and absolute rate control)

3. Interplay between **systematic** and statistical errors:
   optimized configuration for NEAR and FAR sites
   (only with a magnetic detector at NEAR the muon-neutrino can be accurately normalized)

4. **IDENTICAL** NEAR and FAR detectors
   (the same iron slab will be cut in two pieces corresponding to the Near and the Far positions)

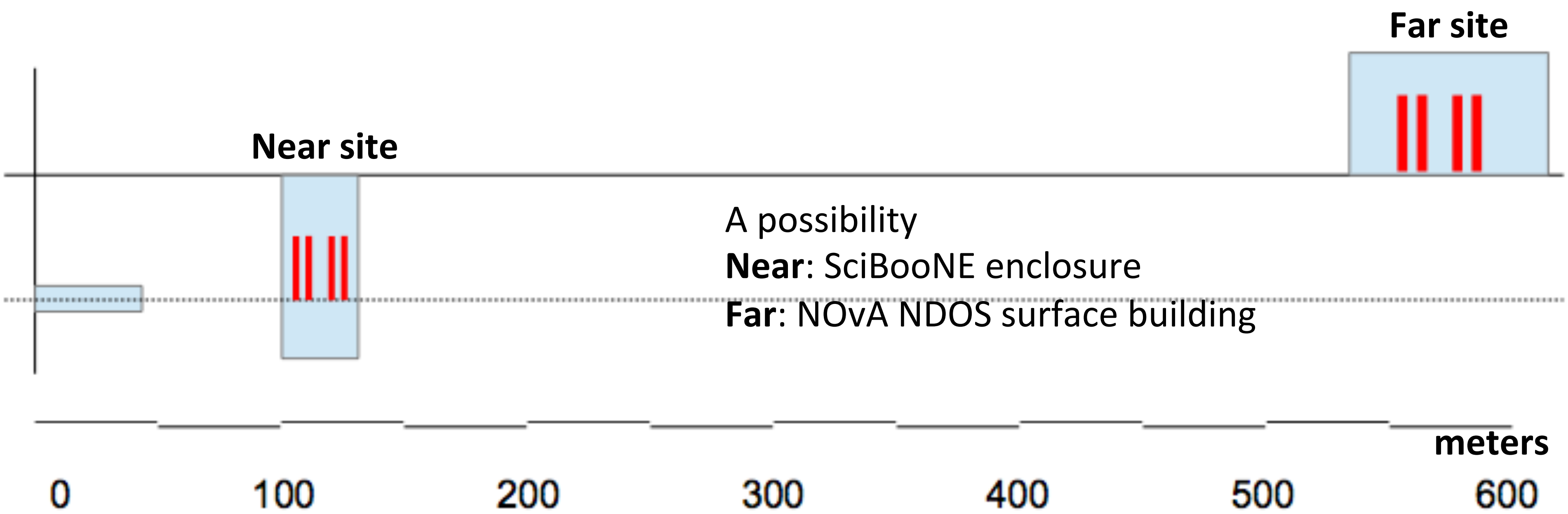
5. No R&D/refurbishing/upgrade: **robustness** of the program (both technologically, time- and cost-wise)
   (80% of re-used well proven detectors, straightforward extension;
   < 100 kWatt power needed at each site*)*

Careful study of the FNAL-Booster neutrino beam,
based on previous knowledge from MiniBooNE and SciBooNE,
and data obtained by HARP and E910.

- full simulation of the beam with GEANT4 and FLUKA
  (from protons to neutrinos)

- detailed analysis of sources of systematic errors
  (use of Sanford-Wang parametrization)

- Several configurations analyzed, on/off-axis including MicroBooNE site and different detector sizes

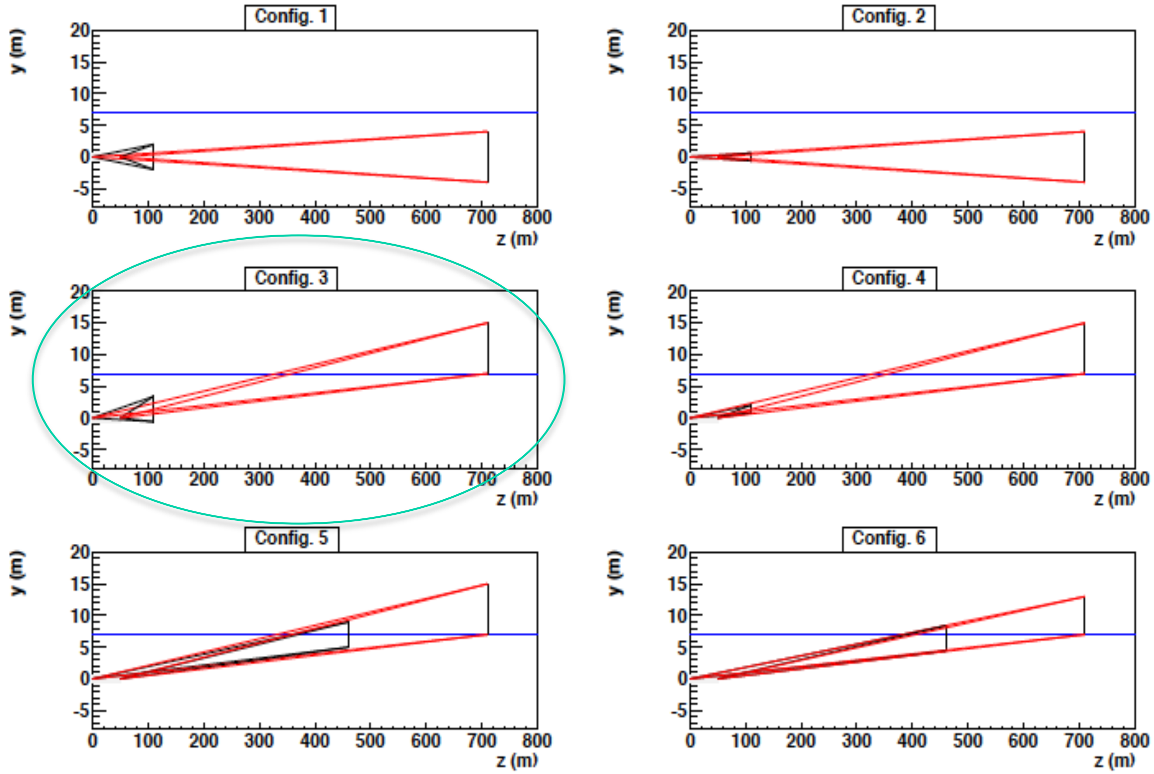


Near-site Far Near-off Far Near-size Far

configuration	L_N (m)	L_F (m)	y_N (m)	y_F (m)	s_N (m)	s_F (m)
1	110	710	0	0	4	8
2	110	710	0	0	1.25	8
3	110	710	1.4	11	4	8
4	110	710	1.4	11	1.25	8
5	460	710	7	11	4	8
6	460	710	6.5	10	4	6

Table 2: *Near-Far detectors configurations. $L_{N(F)}$ is the distance of the Near (Far) detector from the target. $y_{N(F)}$ is the vertical coordinate of the center of the Near (Far) detector with respect to the beam axis which lies at about -7 m from the ground surface. $s_{N(F)}$ is the dimension of the Near (Far) detector.*

NEAR almost on axis
FAR on surface,
"NESSiE" configuration



Sanford-Wang parametrization

Major estimator: FAR/NEAR

chosen configuration

Estimated 1%-2% systematic error

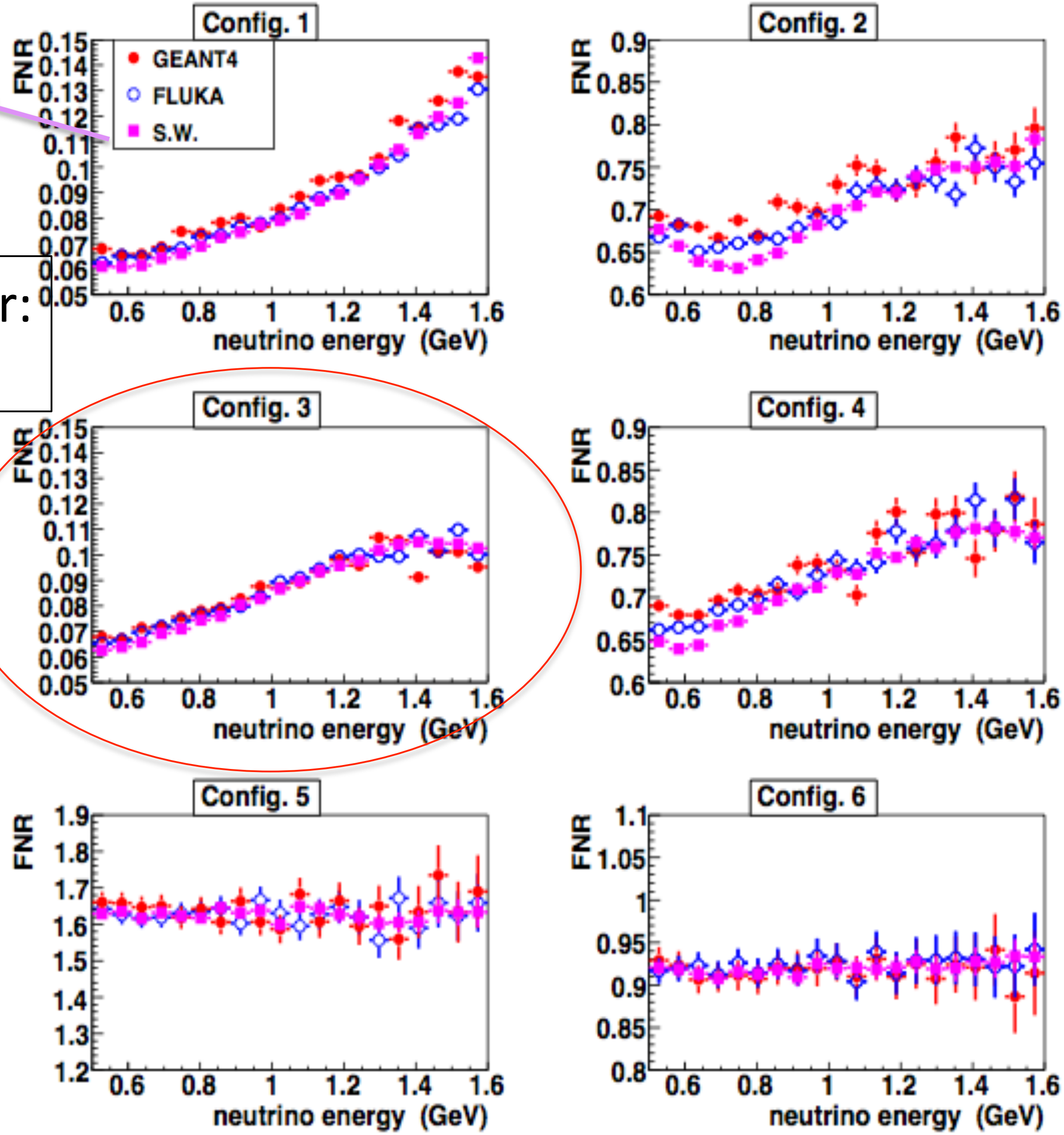
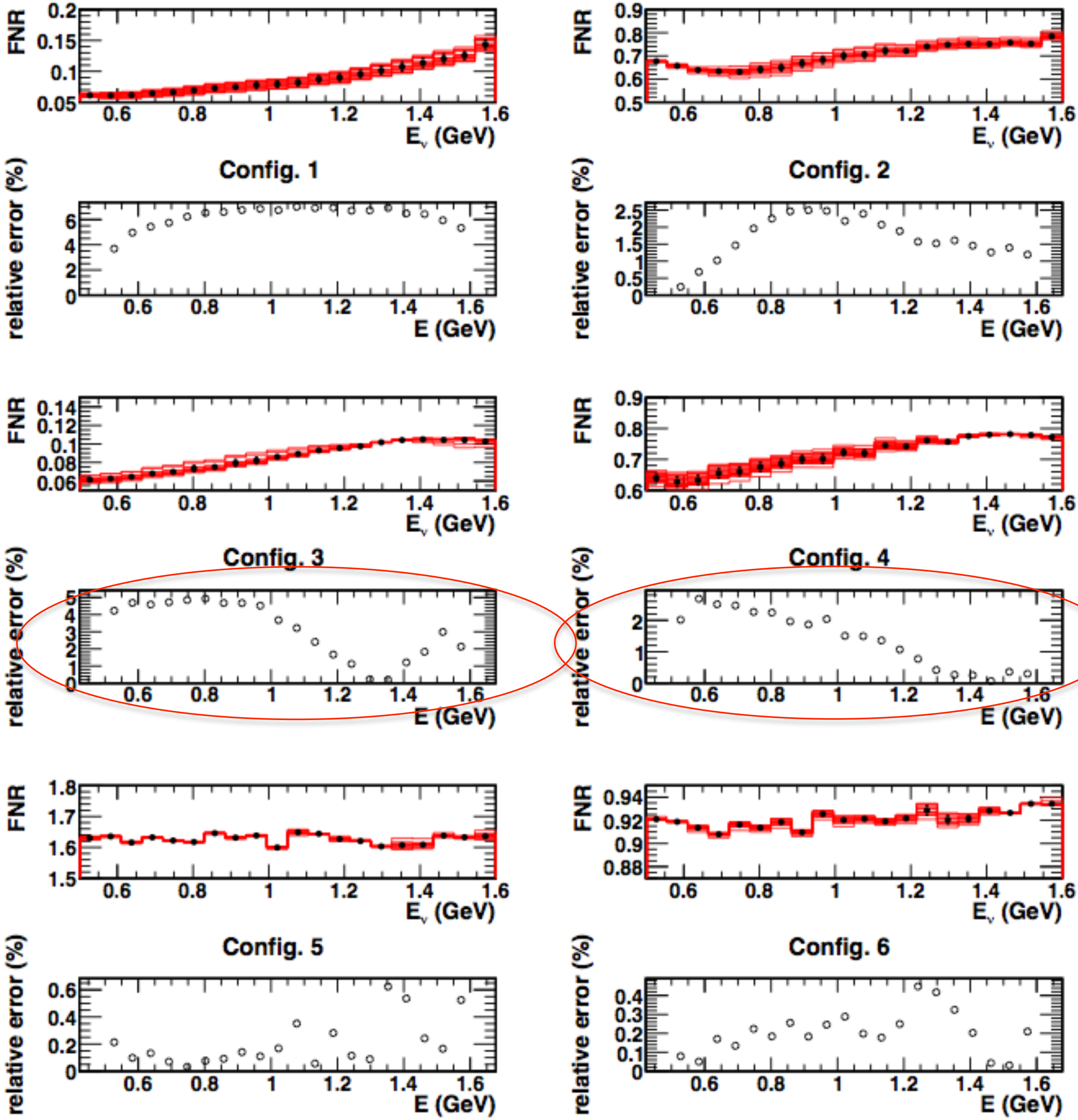


Figure 10: *Far-to-Near ratios for the six considered configurations. Comparison of FLUKA and GEANT4 for hadroproduction.*

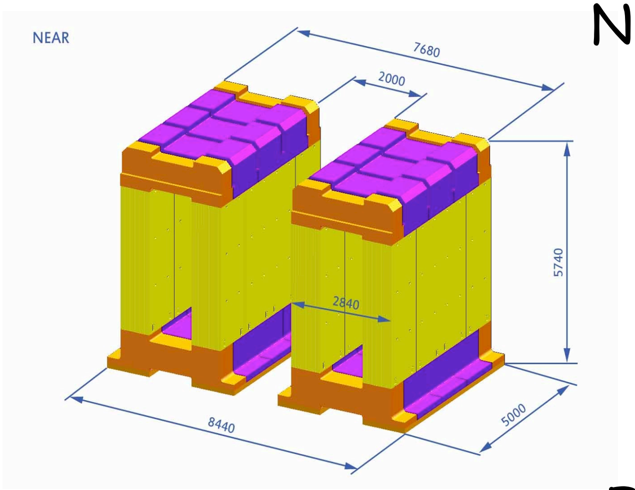


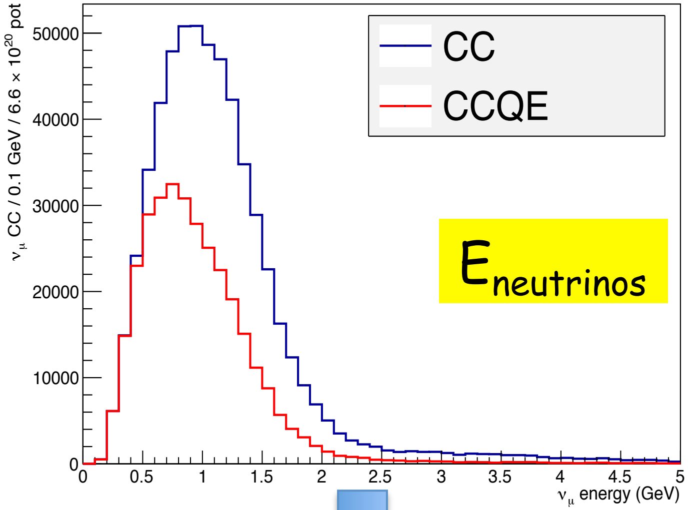
PDF due to hadroproduction uncertainties on F/N computed with Sanford-Wang (full correlation matrix)

O: mean
| : deviation
—: throw sampling

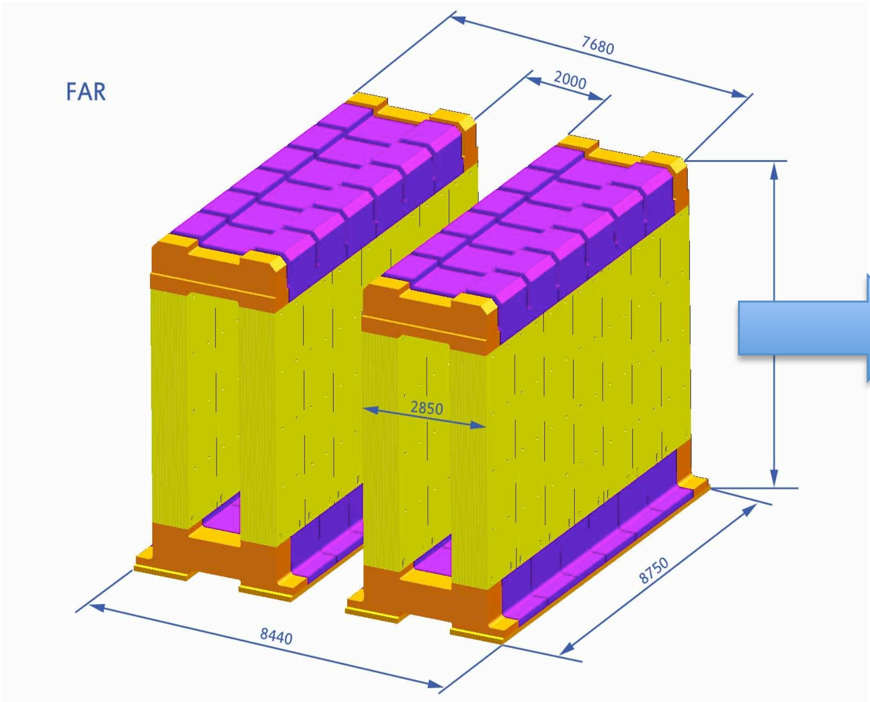
Near-to-Far matching gives 1%-2%,
Far off-axis is ok,
need high statistics.

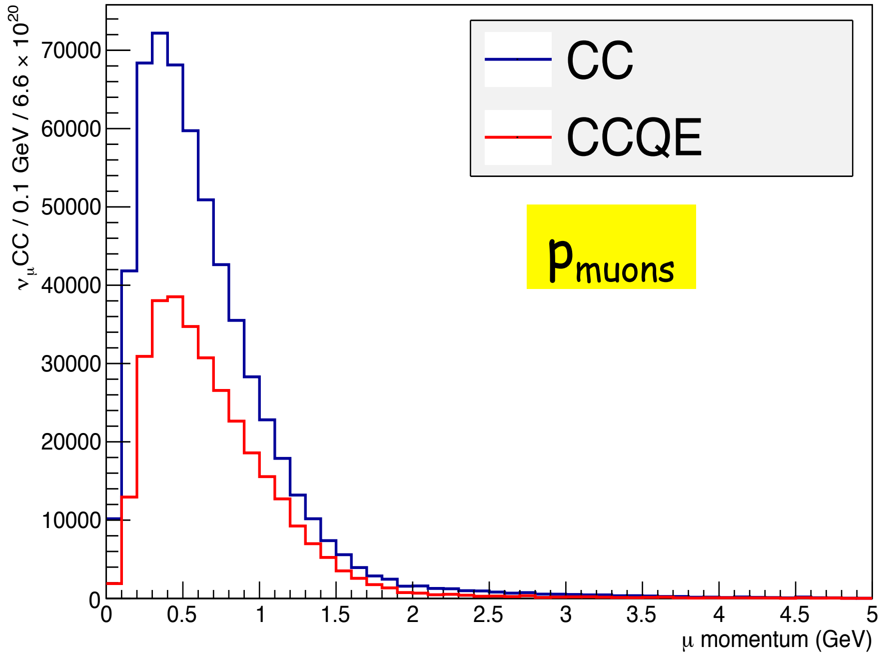
Near site





Far site



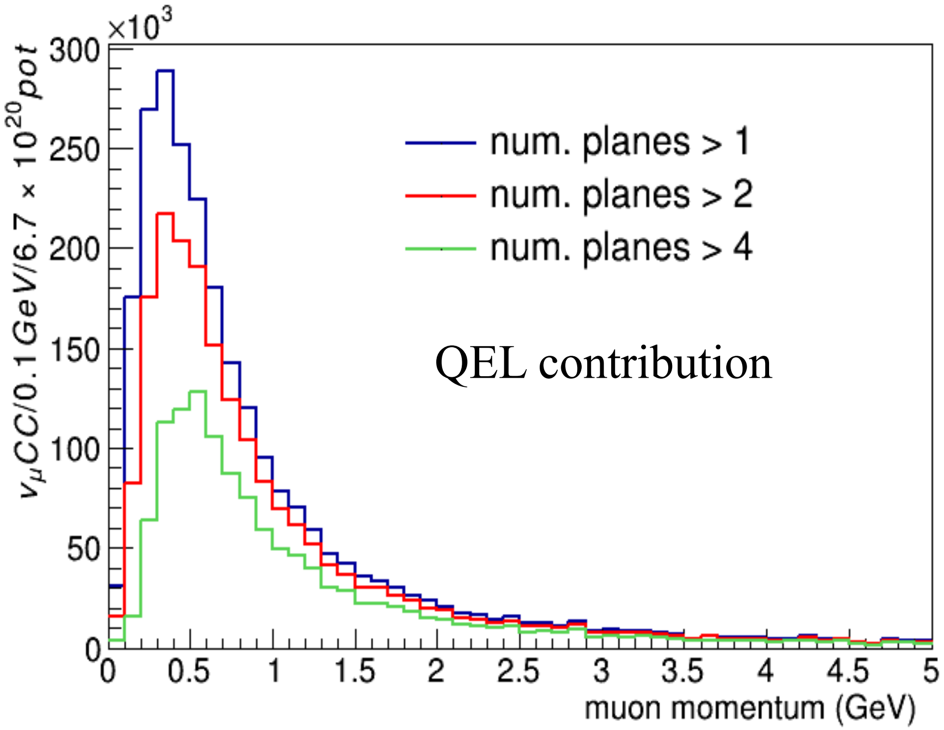


ABSOLUTE interactions in the FAR fiducial volume, 3 years data taking

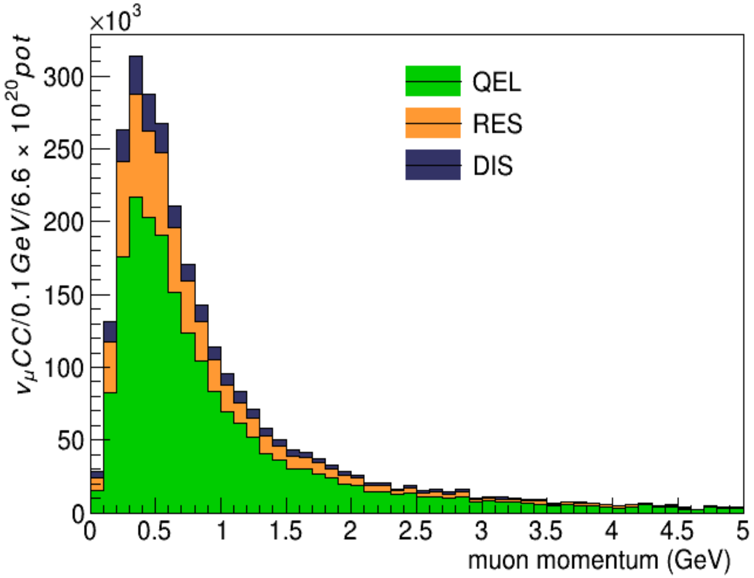
Evts vs Muon MOMENTUM at NEAR site

(3 years data taking)

Muon momentum for different trigger configurations



Muon momentum for trigger configuration num. planes > 2



(including NC background)

DATA COLLECTION

Absolute number of ν_μ CC interactions,
seen by the NEAR detector at 110 m and the FAR detector at 710 m,
(either in the E_ν or the p_μ variables)
normalized to the expected luminosity in 3 years of data taking
at FNAL–Booster, or 6.6×10^{20} p.o.t.
(full simulation including RPC digitization)

	Number of events in 3 year (6.6×10^{20} pot)		NC
Trigger	NEAR	FAR	background
num. planes ≥ 2	5.1×10^6	2.8×10^5	4.2%
num. planes ≥ 3	4.1×10^6	2.3×10^5	3.0%
num. planes ≥ 5	2.7×10^6	1.5×10^5	1.0%

that can be used for:

- Charge-misID at **≤ 8**% from 0.5-1.5 GeV,
  around **3%** in 1.5-4.0 GeV

- Momentum resolution at **4%-10%** from 0.5-3.5 GeV,
  about **30%** above 3.5 GeV (above 1.5 GeV using only 1 magnet)

- High statistics for robust control of ν_μ
  (and possible “calibration” of LAr data)

- Robust control of anti-ν_μ contamination

- High statistics and controlled sample of ν_μ CC events
  to study systematics
  (similar or better than Minerνa for NuMI due to larger mass)

Control of SYSTEMATIC ERRORS

1) Beam systematic error for Far/Near is about 1% for the chosen site configuration
(see previous slide 14 and slide 45 in Backup)

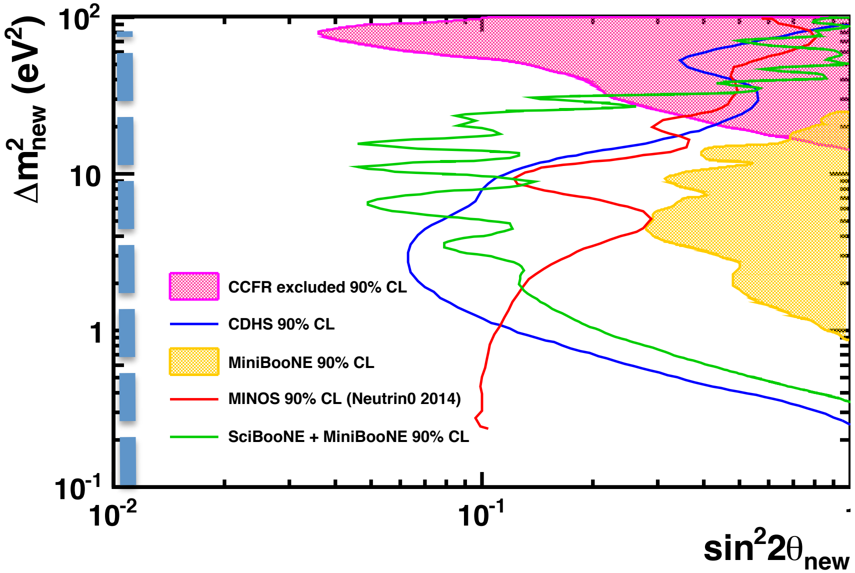
2) Detailed apparatus-simulation (GLoBES & GEANT)
for the matricial treatment of the errors (see slides 50-51 in Backup)

CONCLUSIONS:

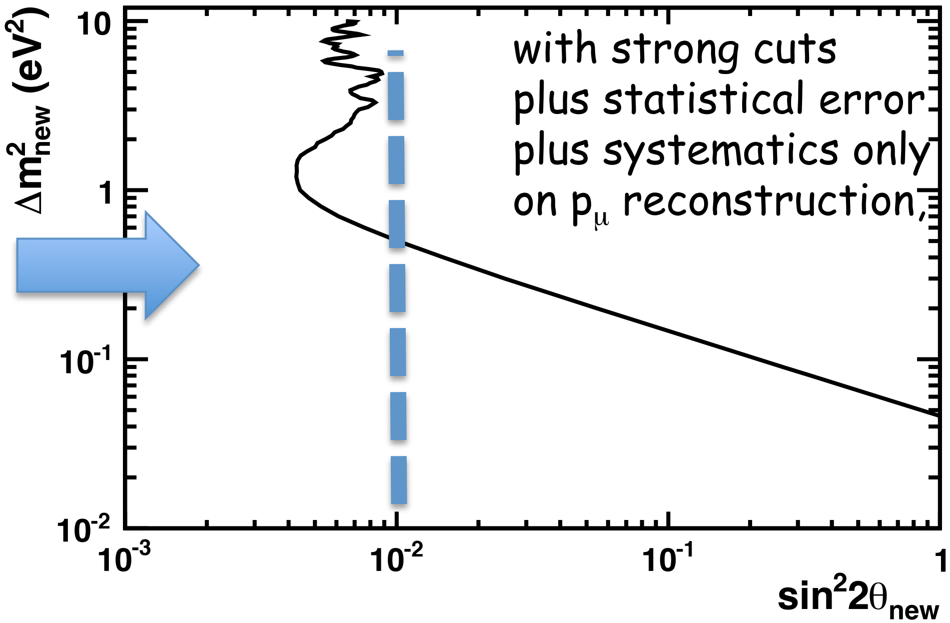
- 1% systematic error is quickly saturating the systematic contribution for correlated systematic error on the Far/Near estimator
- Neutral Current background under control (steel-dE/dx:11.4 MeV/cm to be compared with LAr-dE/dx:2.1 MeV/cm)
- Geometrical-acceptance systematics is <1% with detailed MC simulation
- Detector-material differences for Near and Far under control (exactly the same iron slab, in a ordered way, foreseen to be used)
- Reconstruction dependences on energy are kept under control by large statistical sample and experience with OPERA

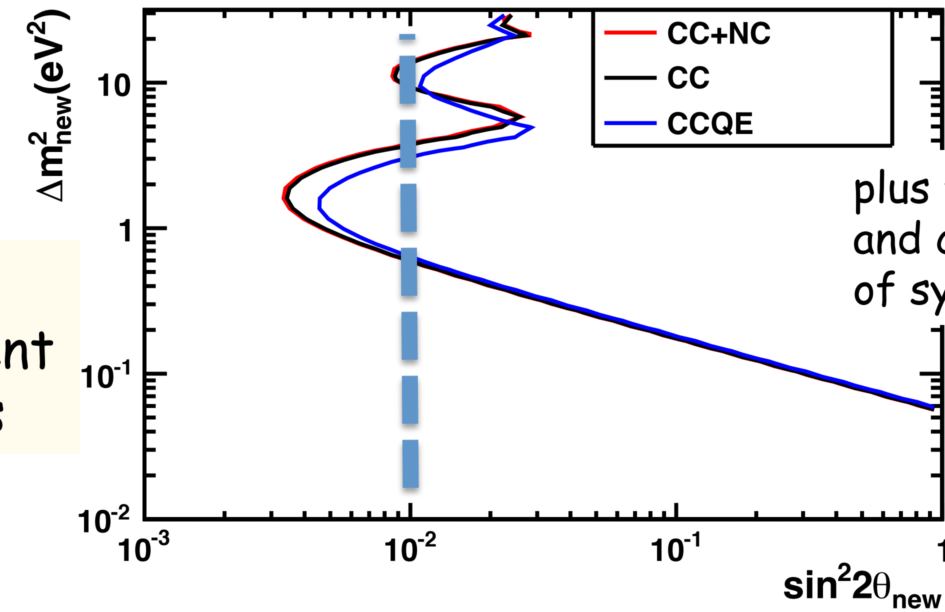
Sensitivity

from here (now)



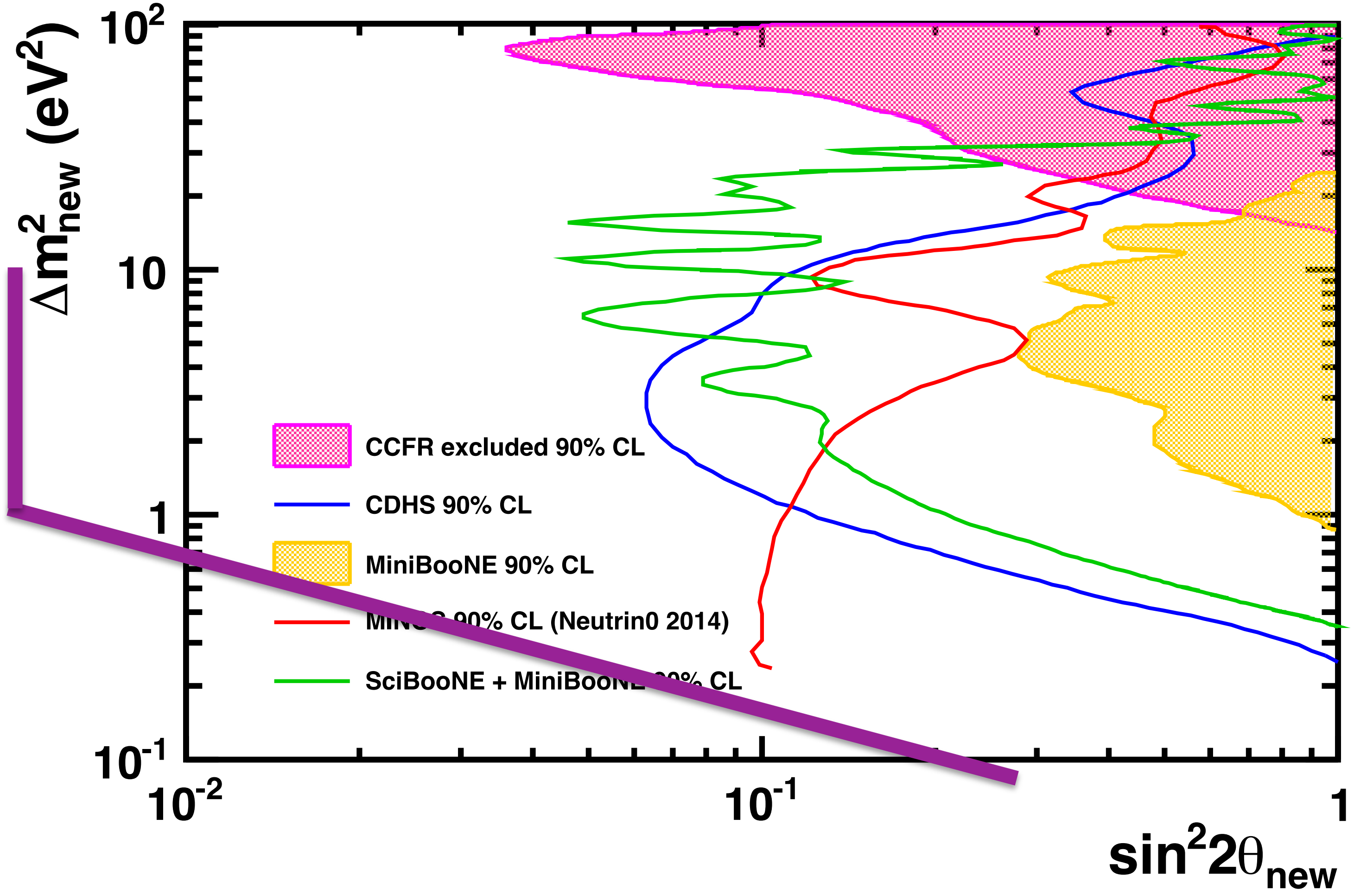
to here (NESSiE)





plus full simulation and careful treatment of systematics errors

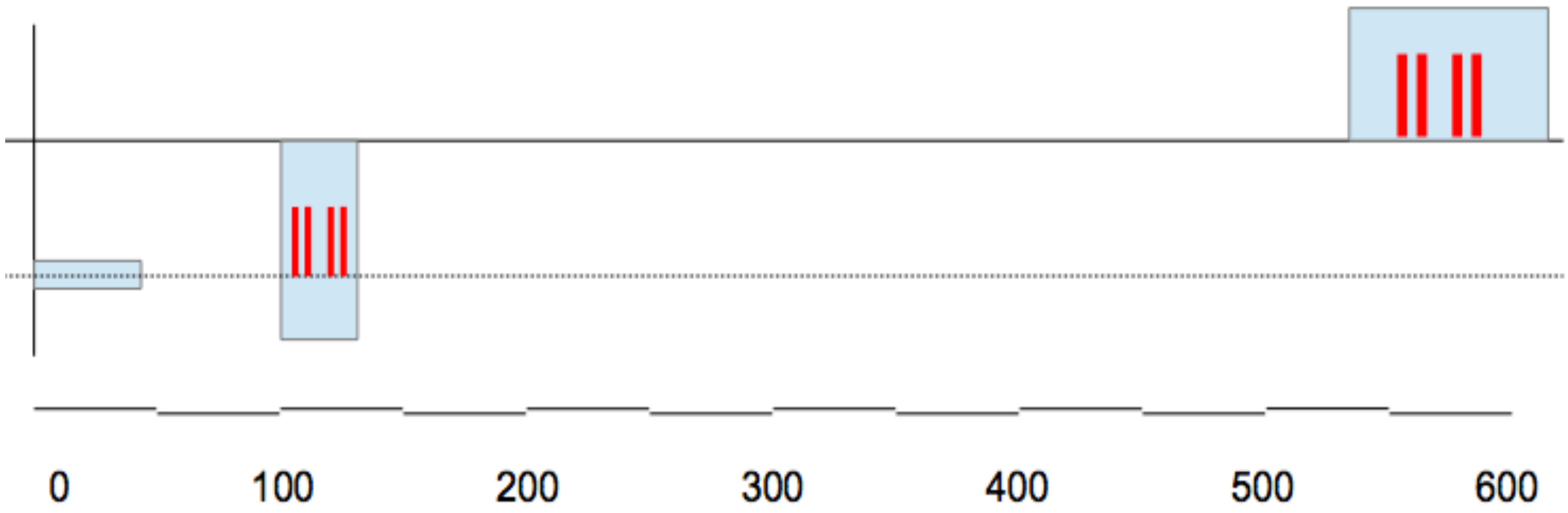
Three independent analyses, with different statistical approaches



NESSiE at 95% C.L. (sketched purple line)

Possible logistics for NESSiE at FNAL

Near: SciBooNE (enlarged) enclosure
Far: NOvA NDOS surface building

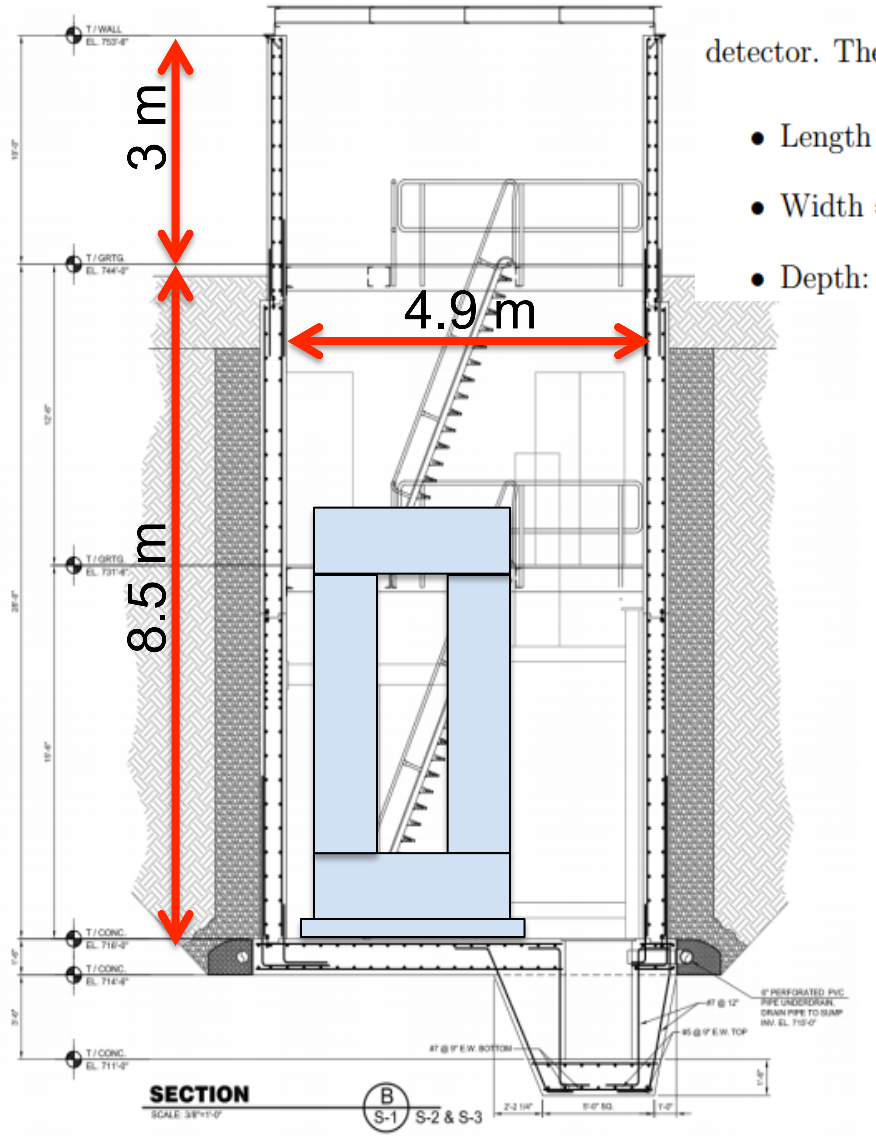


NEAR

FAR

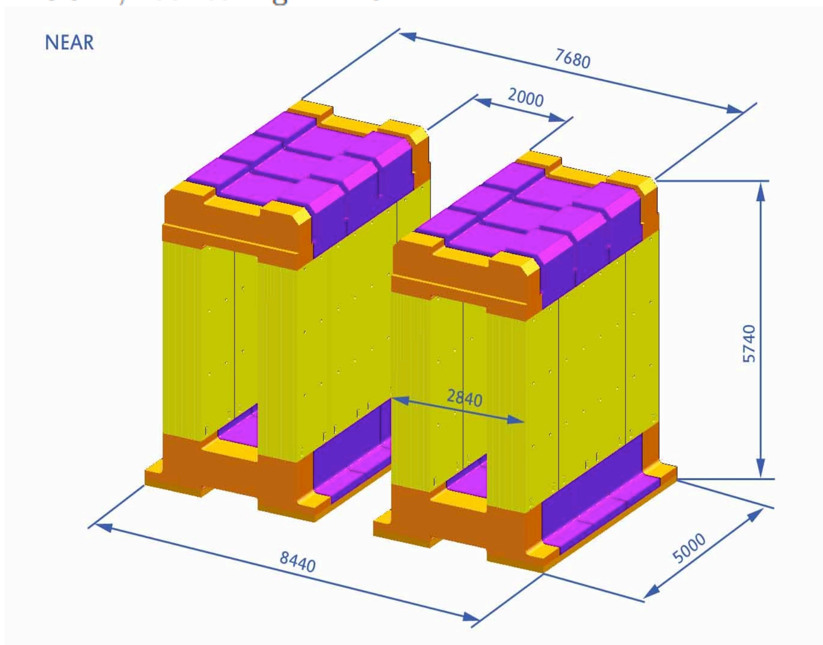
NESSiE Near at SciBooNE enclosure

http::/arxiv.org/pdf/1309.7987.pdf



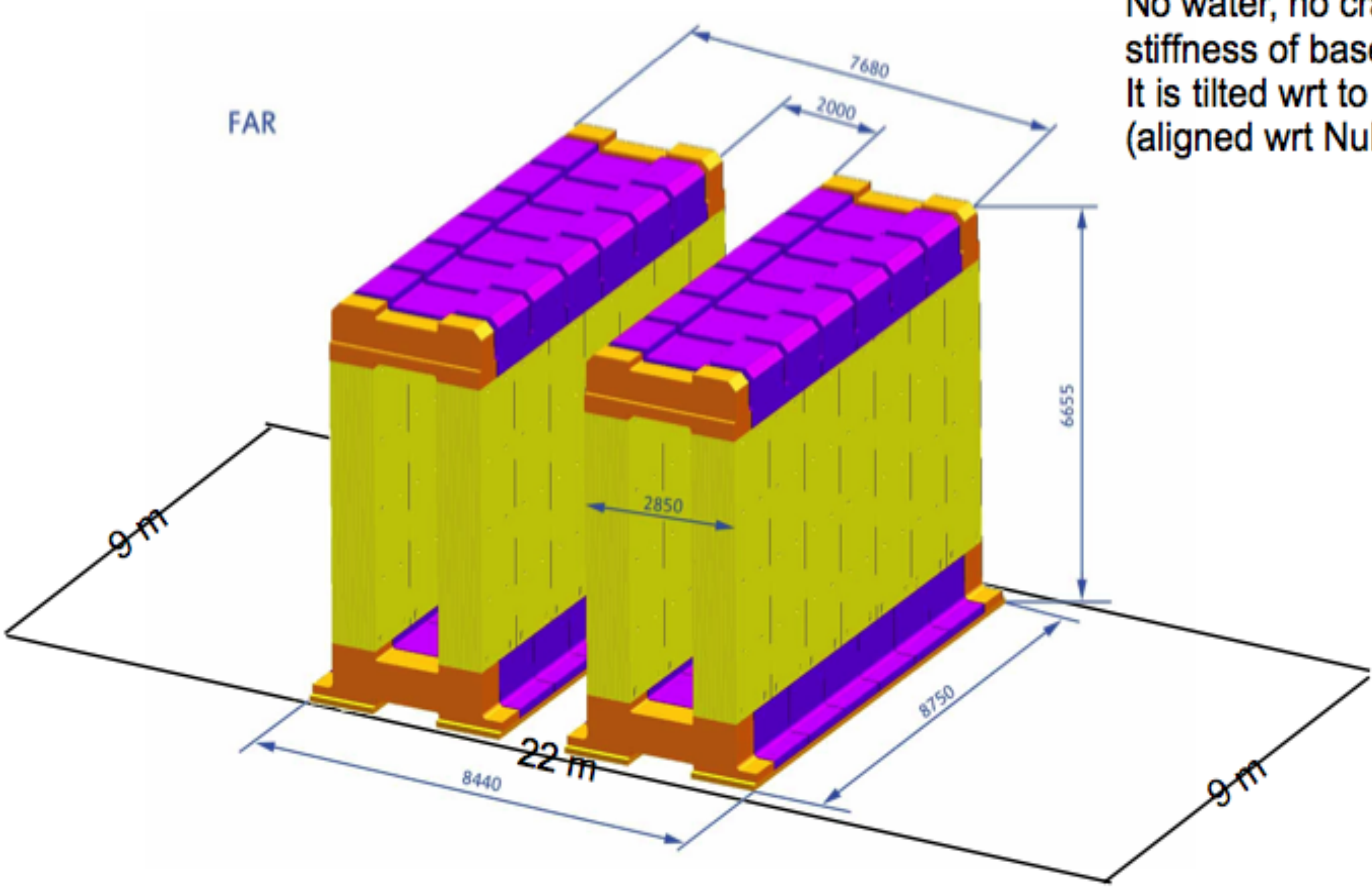
detector. The SciBooNE enclosure, shown in Fig. 13, has the following interior dimensions:

- Length (beam direction) = 4.9 m
- Width = 7.0 m
- Depth: floor-grade = 8.5 m, floor-ceiling = 11.6 m.



Only 1/2 will fit in,
sufficient from the statistics point of view,
shorter range for muon-momentum measure

NESSiE Far at NOvA NDOS surface building

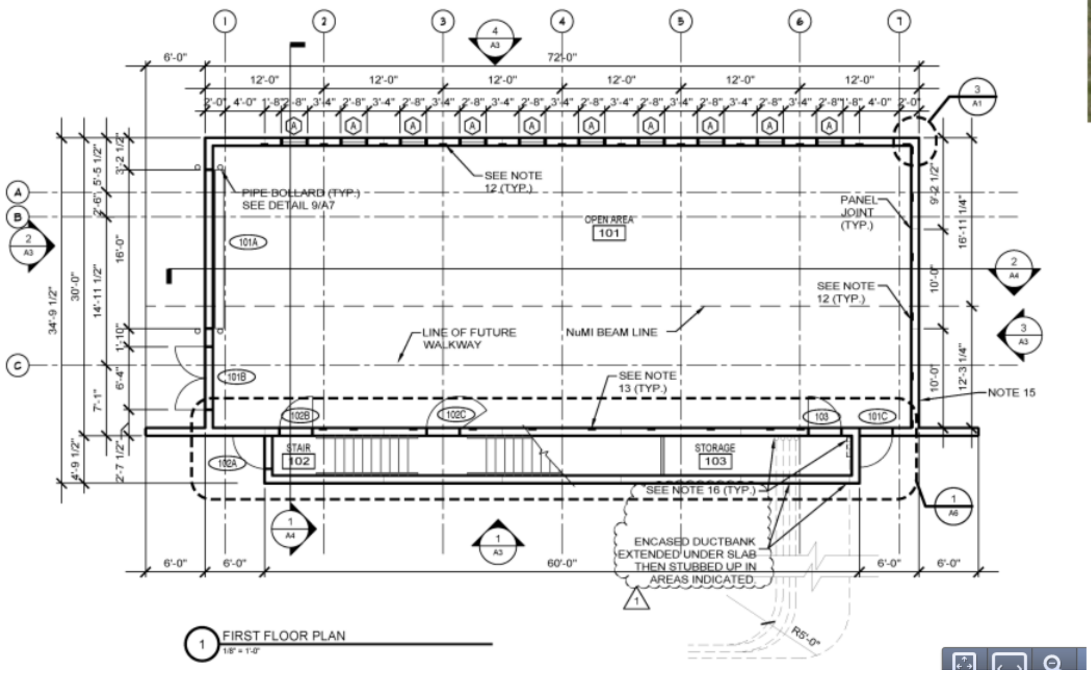


No water, no crane, stiffness of basement ?
It is tilted wrt to BNB (aligned wrt NuMI)

Note: statistics at the FAR site is an issue

NOvA Surface Building (72 x 30 ' ~ 22 x 9 m^2)

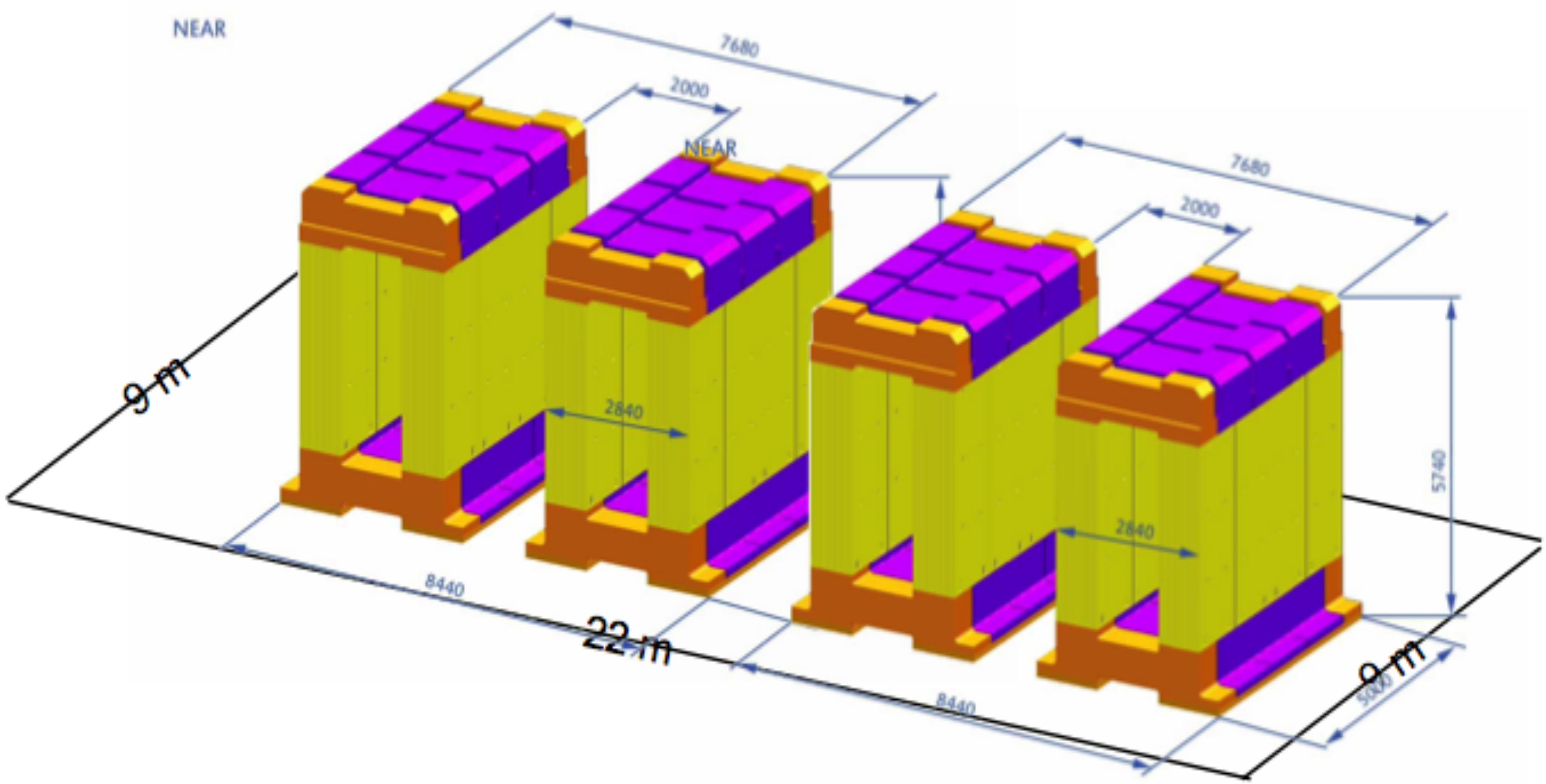
- Constructed in 2010
- $1,500,012
- 2,160 square feet
- $762/square foot



NESSiE Far at NOvA NDOS surface building

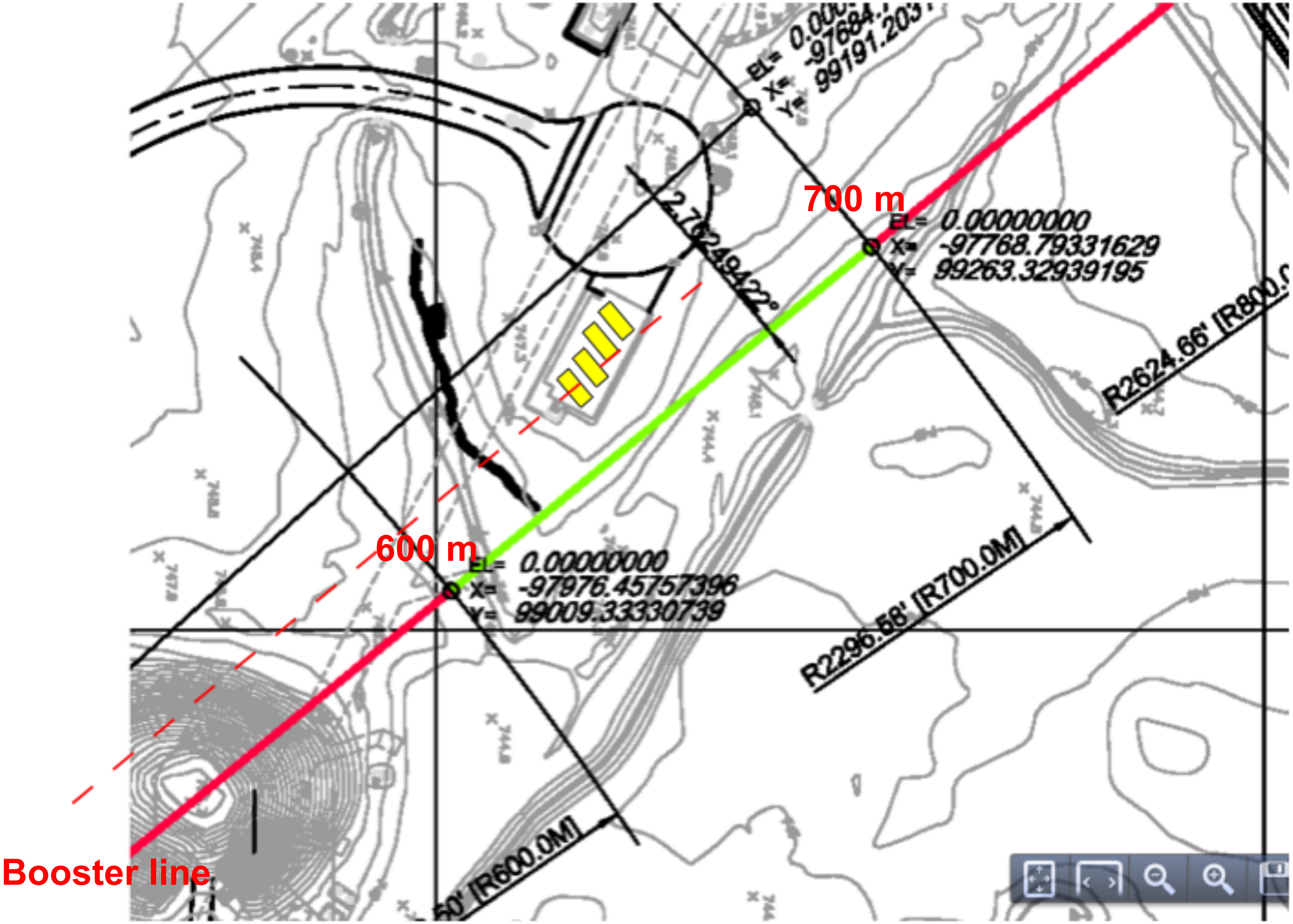
24 yokes

No water, no crane, stiffness of basement ?
It is tilted wrt to BNB
(aligned wrt NuMI)



(sketch, the precise height be 4/3 of the Near spectrs)

Horizontal off-axis angle ~1 degree ~ 5-7 m (horizontally)



Schedule

A bit aggressive, but reliable schedule
based on successful experience with OPERA

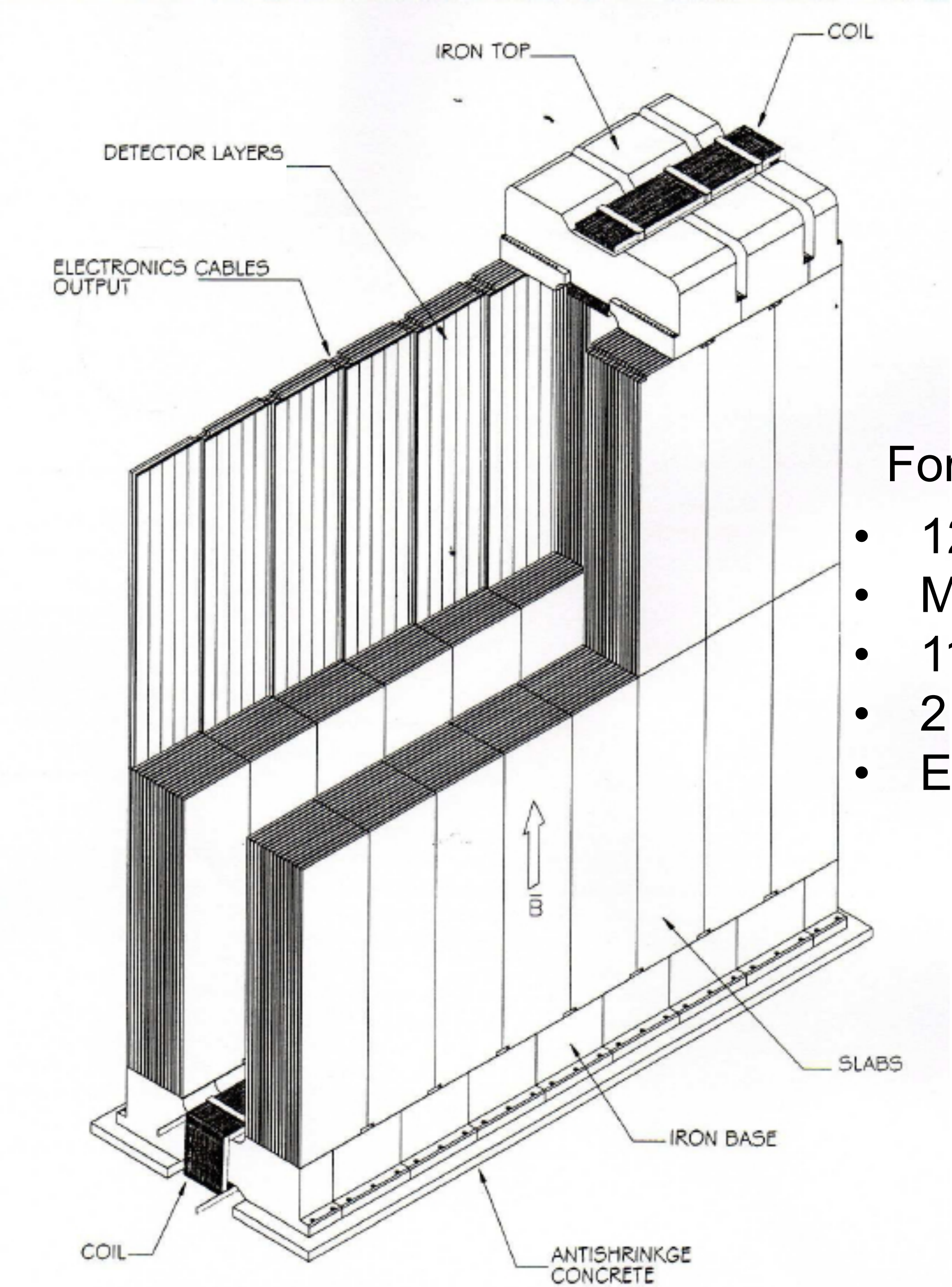
Year(portion)	Action
1^{rst} half 2015	Define tenders/contracts
2^{nd} half 2015	Site preparation Setting up Detectors Test-stands
1^{rst} half 2016	Mechanical Structure construction Start Magnet installation Start detectors installation
2^{nd} half 2016	End installation
1^{rst} half 2017	Commissioning and Starting Run
2^{nd} half 2019	End Data Taking

Costs

(both Near and Far)

Item	Cost (in M €)
Far	
Magnet	2.5 (in–kind)
RPC detectors	0.8 (in–kind)
Strips	0.3 (in–kind)
New Electronics	0.2
Data Acquisition	0.1
Near	
Magnet	2.0 (in-kind)
Top/bottom yokes	1.0
Coils, Power Supplies	0.2
RPC detectors	0.6 (in–kind)
New detectors	0.2
Strips	0.2 (in–kind)
New Electronics	0.1
Data Acquisition	0.1
Transportation	0.6
Total	2.5 + 6.4 (in–kind)

(new Electronics,
new DAQ,
x 2 coil number)



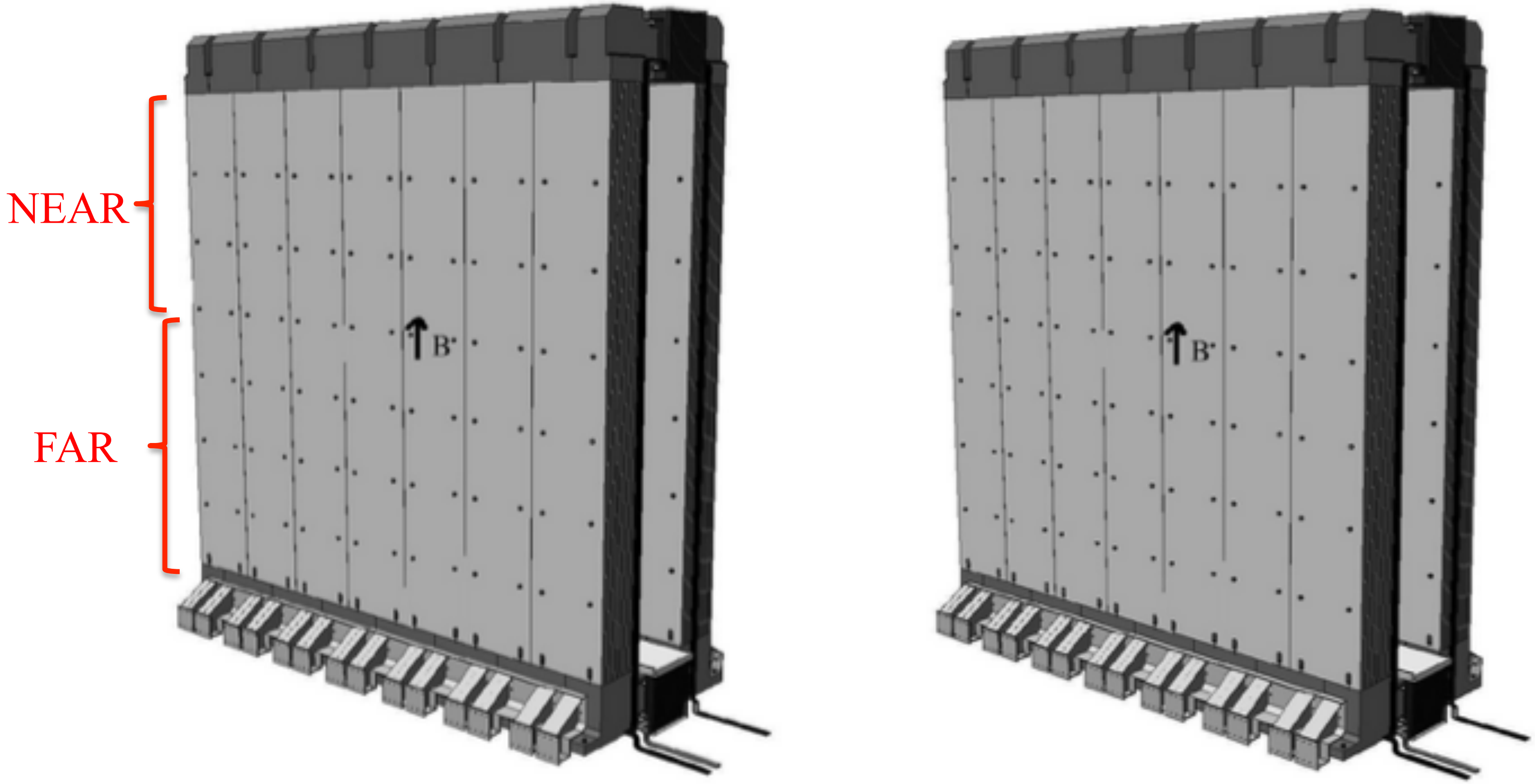
(obsolete width)

OPERA MAGNET

For each of the two Spectrometers:

- 12+12 iron planes, 5 cm thick
- Magnetic field of 1.5 T
- 11+11 bakelite RPC planes
- 21 RPC per layer: 462 chambers
- Each chamber 3 m^2, streamer mode

Available materials from INFN



OPERA
7 x 11 x 4 = 308 slabs
6 x 2 x 2 = 24 yokes
4 x 2 = 8 semi-yokes
21 x 22 x 2 = 924 RPC

NESSiE
NEAR: 6 yokes + 4 semi-yokes + 88(3/7)slabs
FAR: 4 x (6 yokes + 4 semi-yokes + 88(3-or-4/7)slabs)
----
30 yokes + 20 semi-yokes + ~188 (or 239) slabs =
TO BE PROD.: 6 yokes + 12 semi-yokes

OPERA

1rst Spectrometer

2nd Spectrometer

One OPERA spectrometer

Bottom YOKES

(Coils)

Top YOKES

Internal frame used for assembling, to be removed after

Assembling issues

- Assembling on site by using 5-ton crane for iron-slabs
- Use 30-ton movable-crane for large pieces of 25 tons
- Needed lateral clearance of 1 m, each side
- Procedure to be endorsed by FNAL, needed a 3-people workgroup
- 2 coupled planes of iron-RPC per week (22 weeks per Spectrometer)
- Internal steel-structure to be extracted (!)

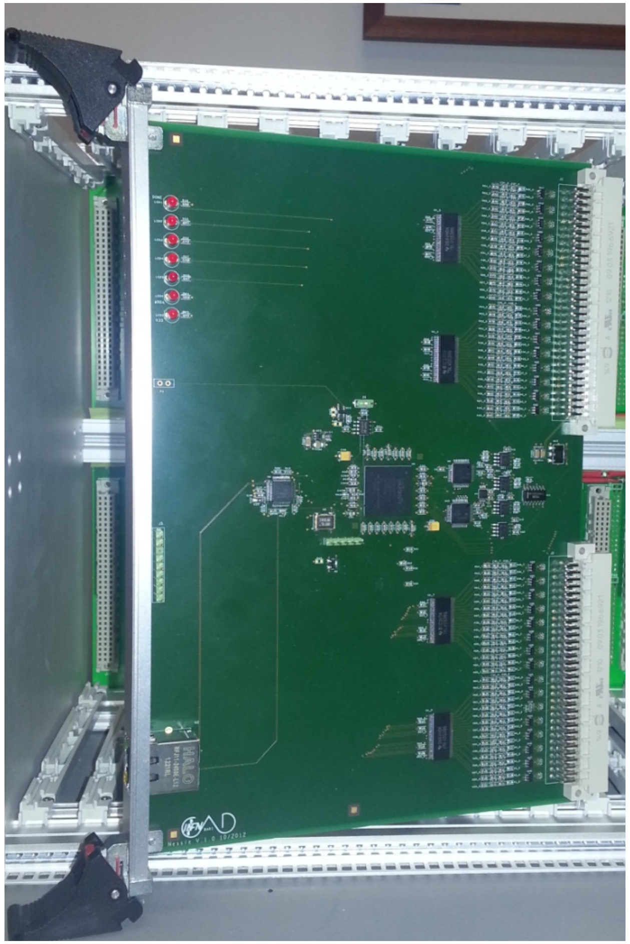
OPERA will start its dismantling THIS January (19th).
First pieces of the spectrometers available about December

Call opened by INFN to reuse the OPERA Spectrs.

NO ADDITIONAL TIME available for the final decision (NESSiE).

Meanwhile a full new electronics has been developed:

FRONT-END BOARD



- Eurocard 6U form factor
- 64 Input channels
- Positive & negative input signals
- Threshold range -500mV / +500mV
- Input pulse width ~ 2 ns
- Memory depth 4096 samples / channel
- Timing resolution 10 ns
- Ethernet interface for data read and configuration (every FEB is an ethernet node)
- Remote firmware upgrade
- Test pulse circuit
- FastOR generation (groups of 32 channels)

CONCERNS and next ACTIONS

1) FNAL decision needed **now**

2) In case of FNAL positive answer, INFN-CSNII ready to support us after a check on the human resources:
   a formal call will be opened to both Italian groups and interested US groups (1 month time)

3) In case of a positive response MOU’s has to be signed between major agencies, FNAL-INFN-CERN (2-3 months time)

4) Sites to be ready by end of 2015

PRO and CONS

PRO:

1. Valuable physics outcome
   (full disentangling of sterile issue at accelerators)
2. Conservative experimental approach, > 80% in-kind material
   (robust measurement of ν_μ disappearance)
3. Light interference (infrastructures, resources …) with other exps
4. Possible synergy with Liquid-Argon exps
   (Spectrs can be put downstream)
5. Availability of human resources
   (and keeping alive the large NESSiE neutrino community)

CONS:

- None ?

Conclusions

1) Necessary to do (finally) an SBL experiment on ν_μ disappearance

2) Extend by one order of magnitude previous result from CDHS

3) By using “brute force”

4) 1 kton of iron in 2 sites (large and compact masses)

5) NESSiE has shown that it can be done at FNAL Booster beam

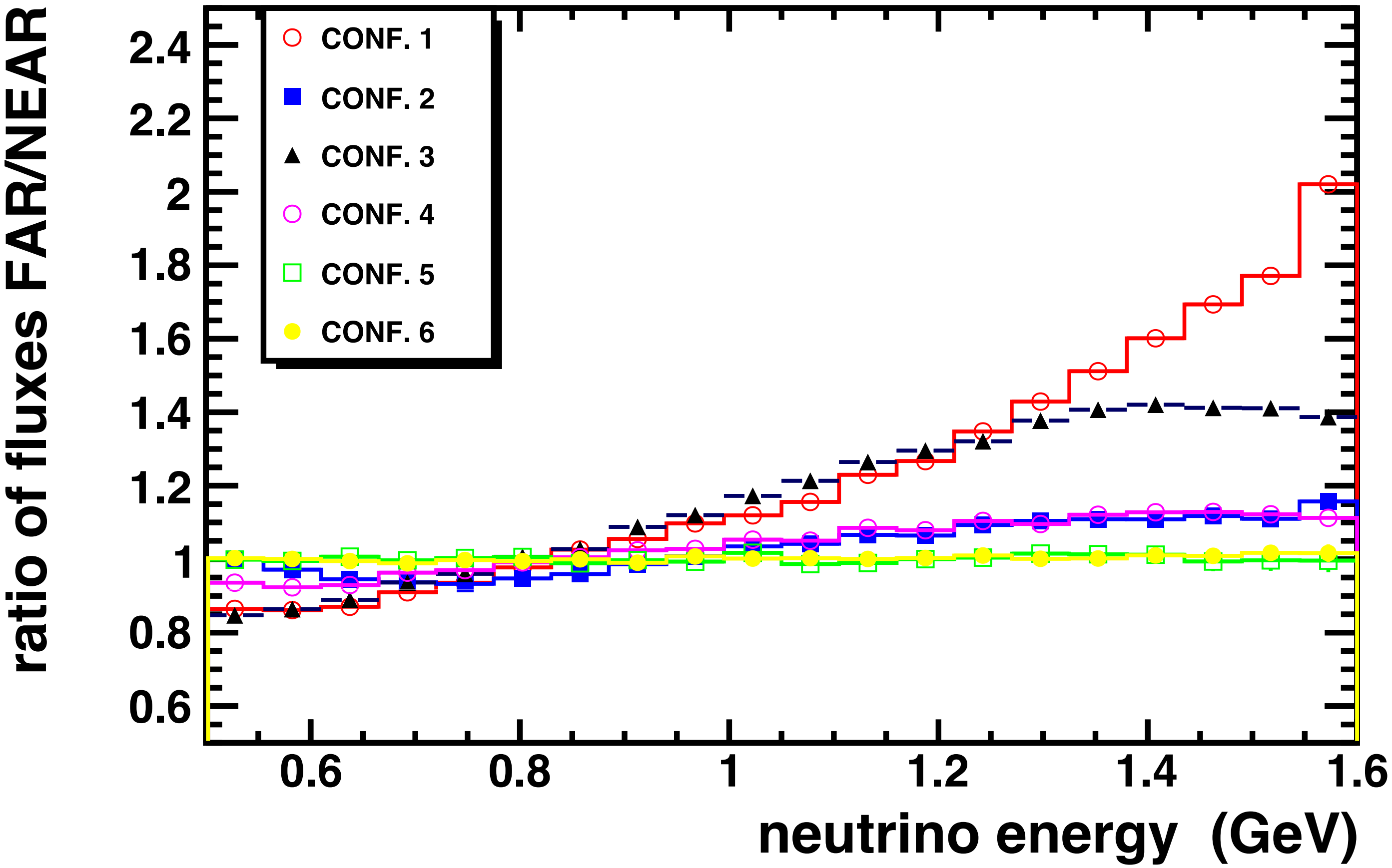
6) Detectors fully available/funded, but…

7) A very prompt action needed from FNAL

Thank you !

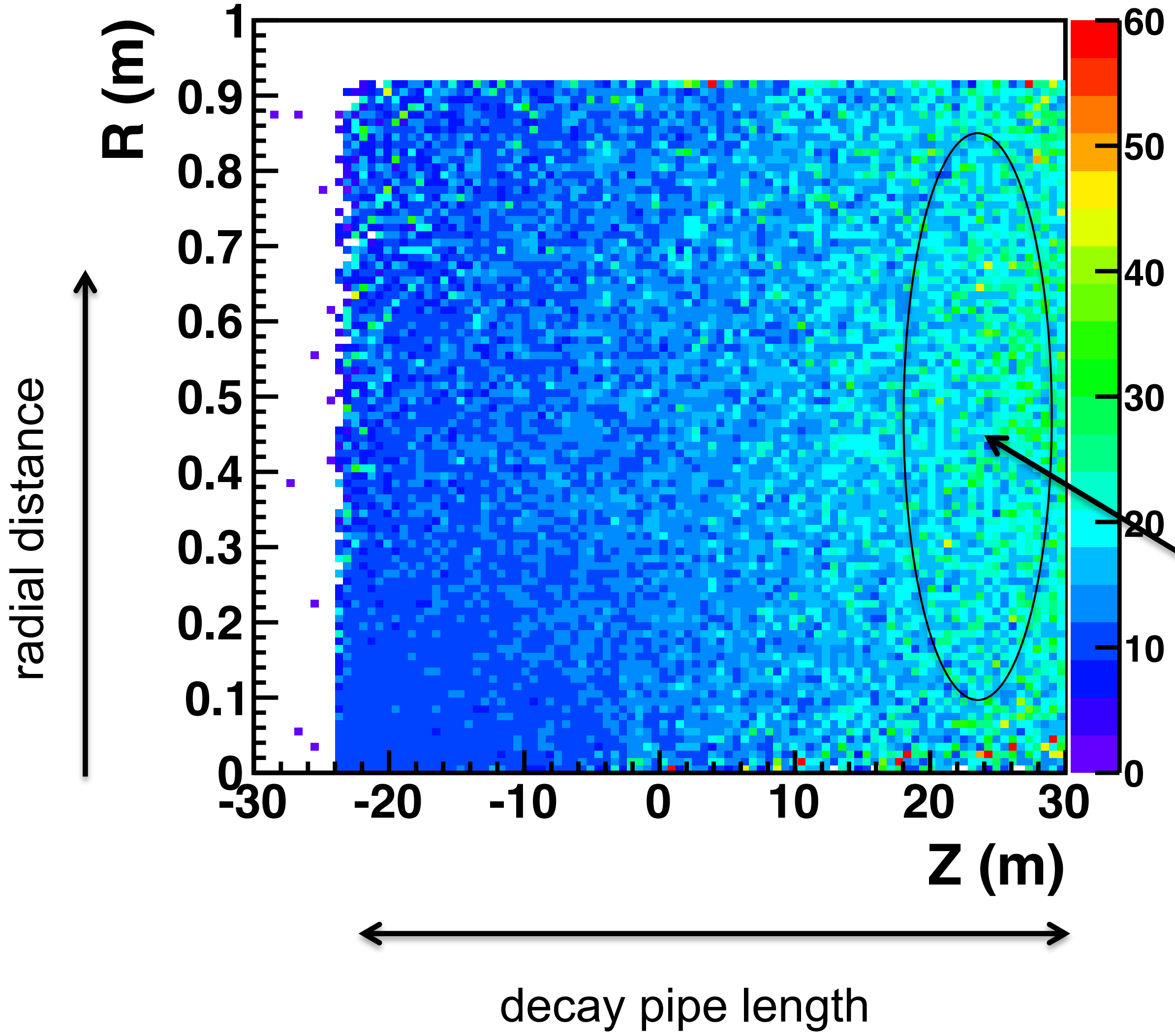
NESSiE at FNAL

BACKUP



ratio of fluxes FAR/NEAR
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.6
0.8
1
1.2
1.4
1.6
neutrino energy (GeV)
CONF. 1
CONF. 2
CONF. 3
CONF. 4
CONF. 5
CONF. 6

Far/Near systematic error
due to transverse position of ν production



The **NEAR/FAR** dependence is only due to the z-value of the production point

The **NEAR** owns larger acceptance for neutrinos produced in the downstream part of the decay pipe, and which have less energy

Iron slabs thinner than those available by OPERA NOT worth

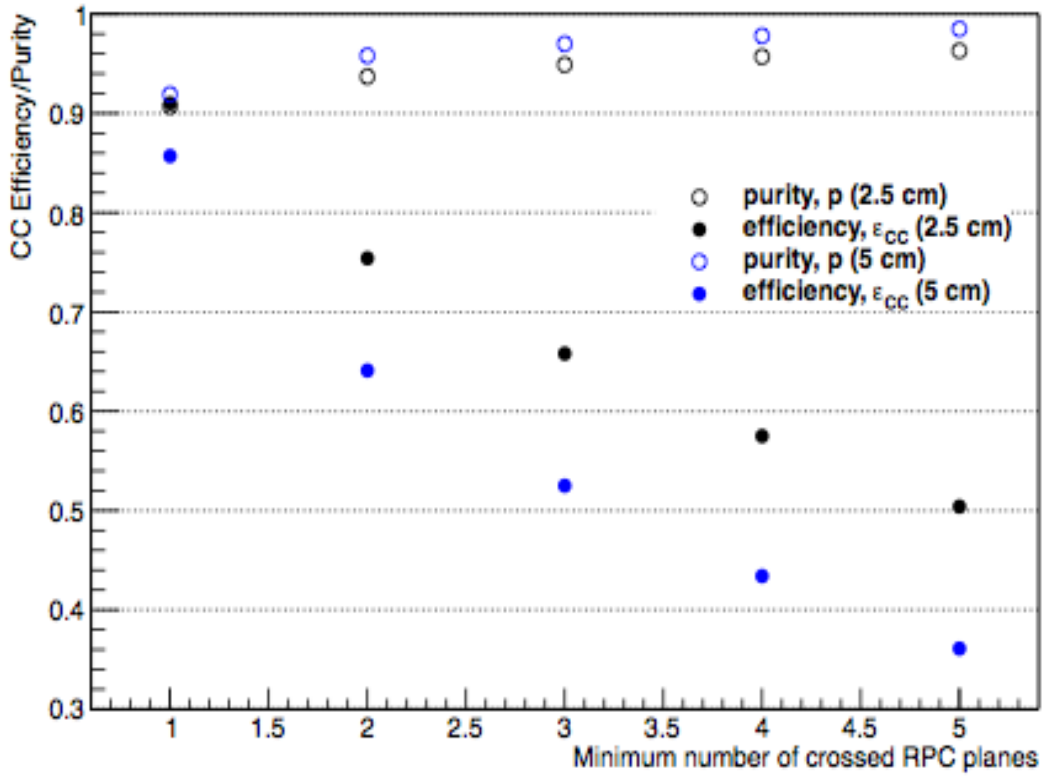
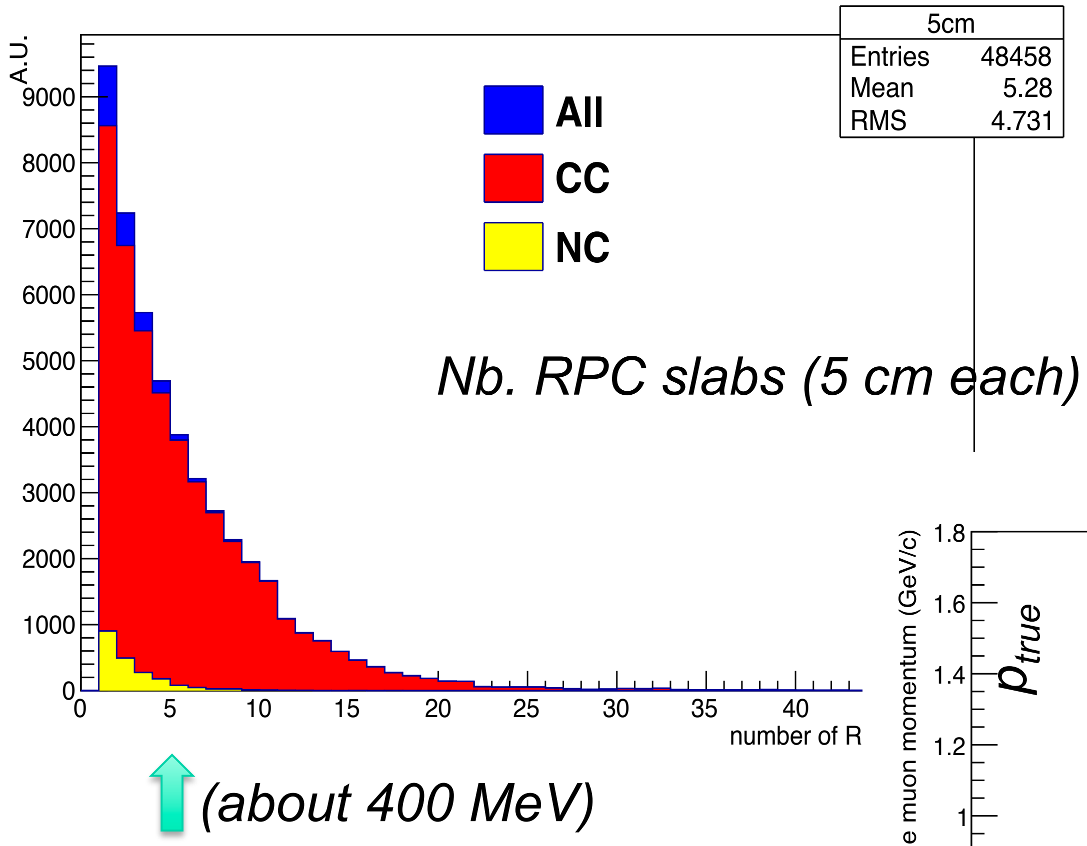
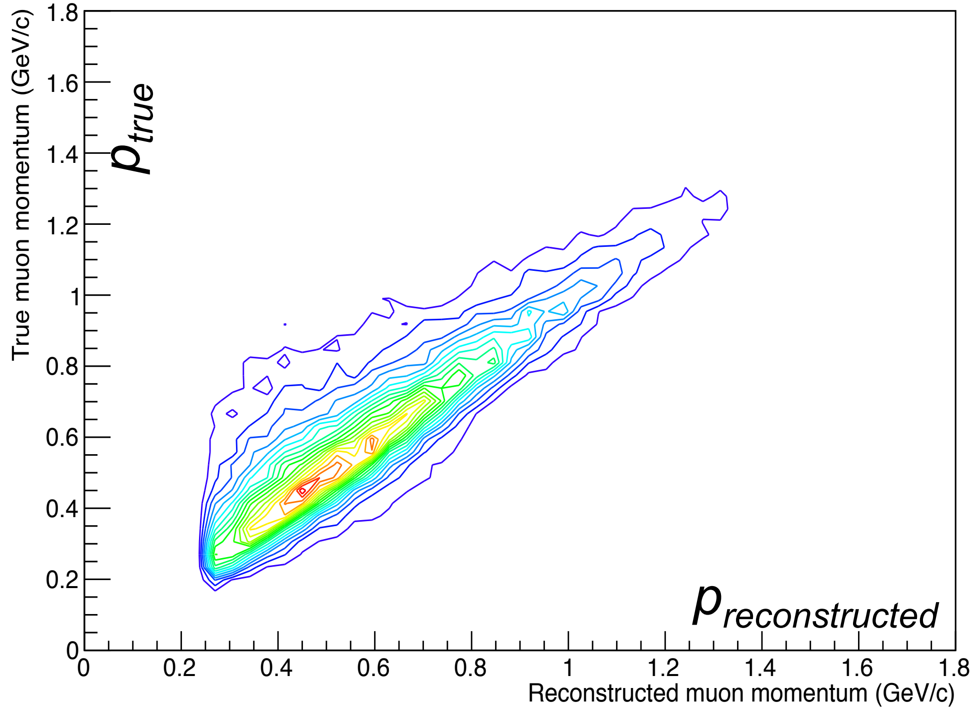


Figure 18: *CC efficiency (ε_{CC}, points) and purity (p, open circles) as a function of the minimum number of RPC planes for the two spectrometer geometries, 5 cm slabs (in blue) and 2.5 cm slabs (in black). For a given level of purity p the efficiencies for the two geometries are similar, therefore no advantage in statistics is taken requiring the same NC contamination suppression.*

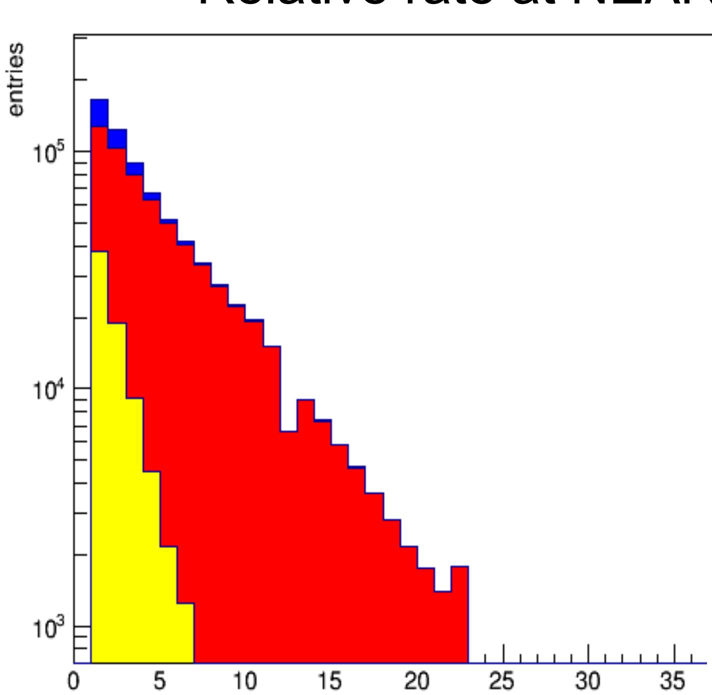
The collected neutrino interactions:





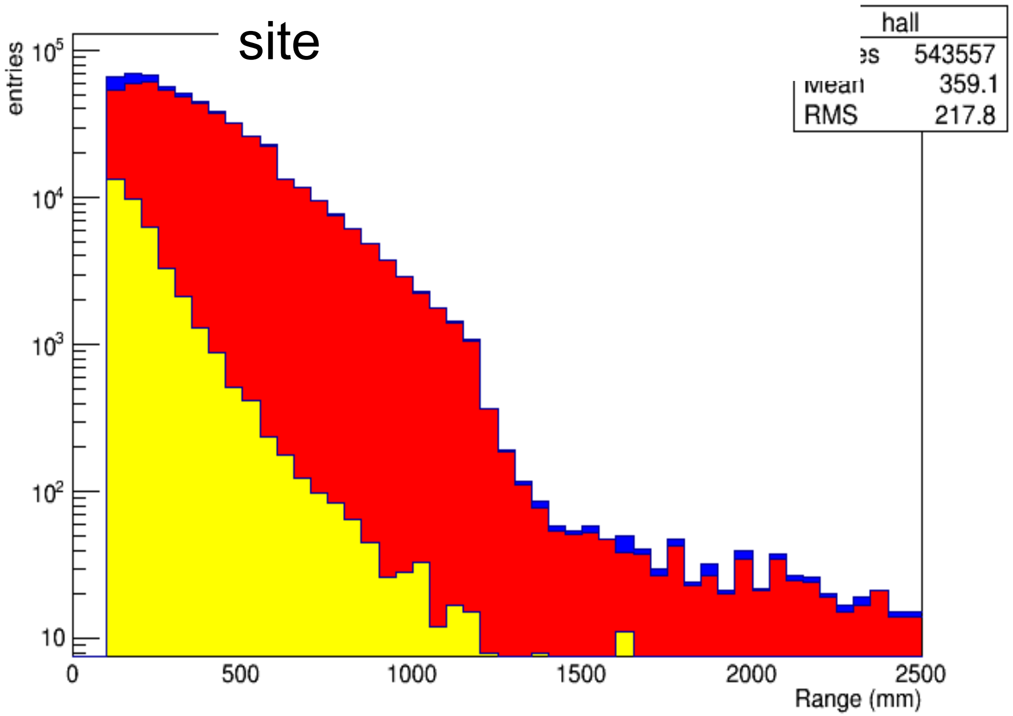
The collected neutrino interactions:

Relative rate at NEAR site



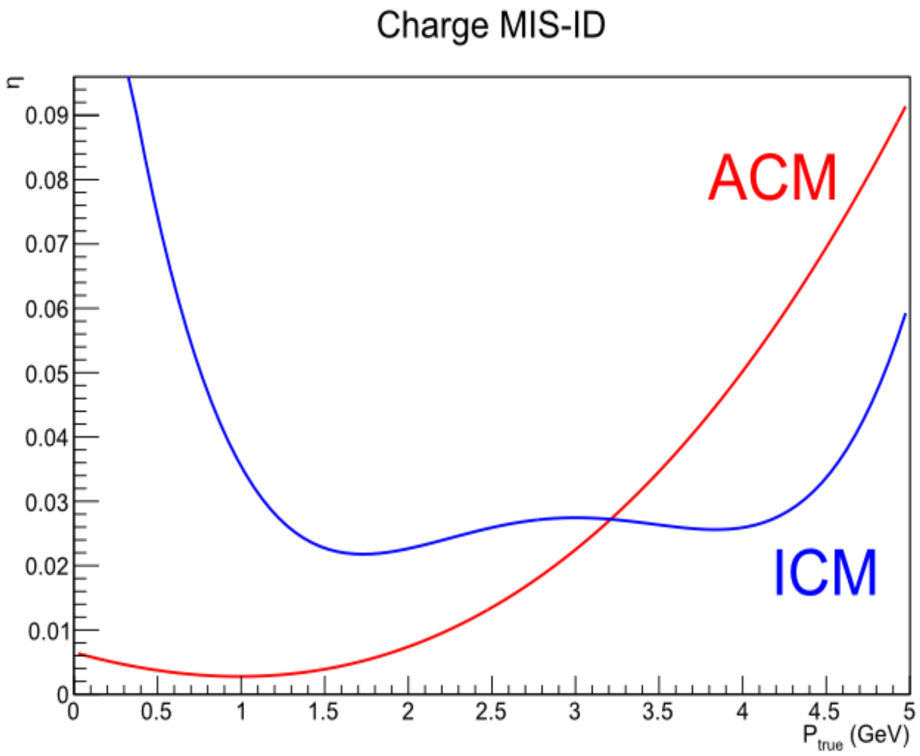
nb. of iron slabs

Relative rate at NEAR site

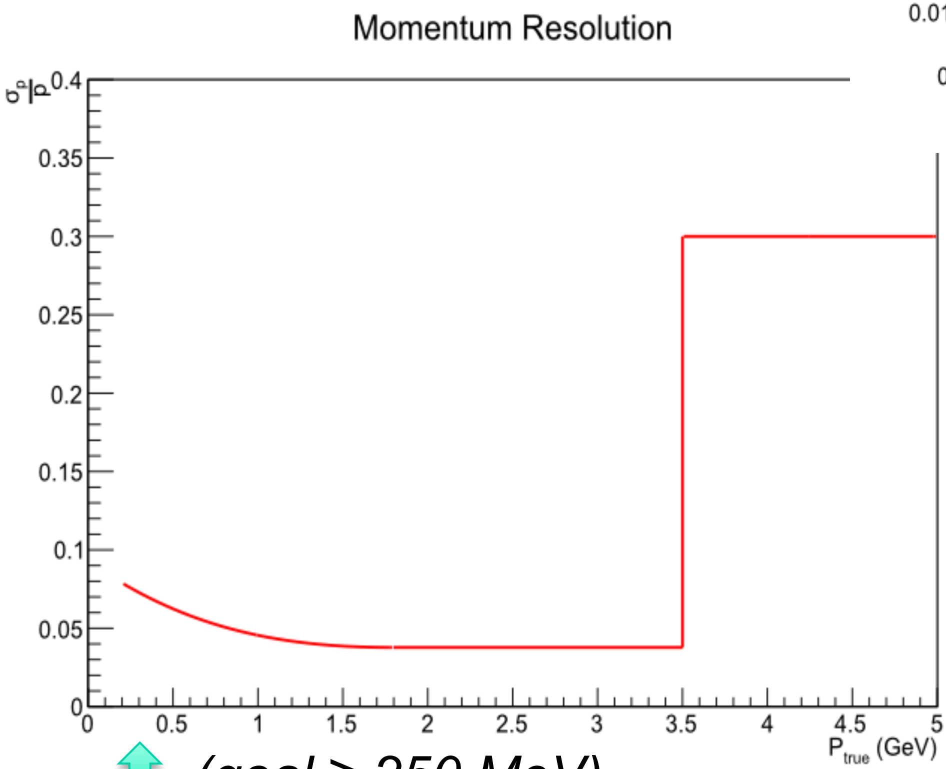


Resolutions:

Sensitivities from the actual NESSiE configurations
(full simulation, with neutrino beam)



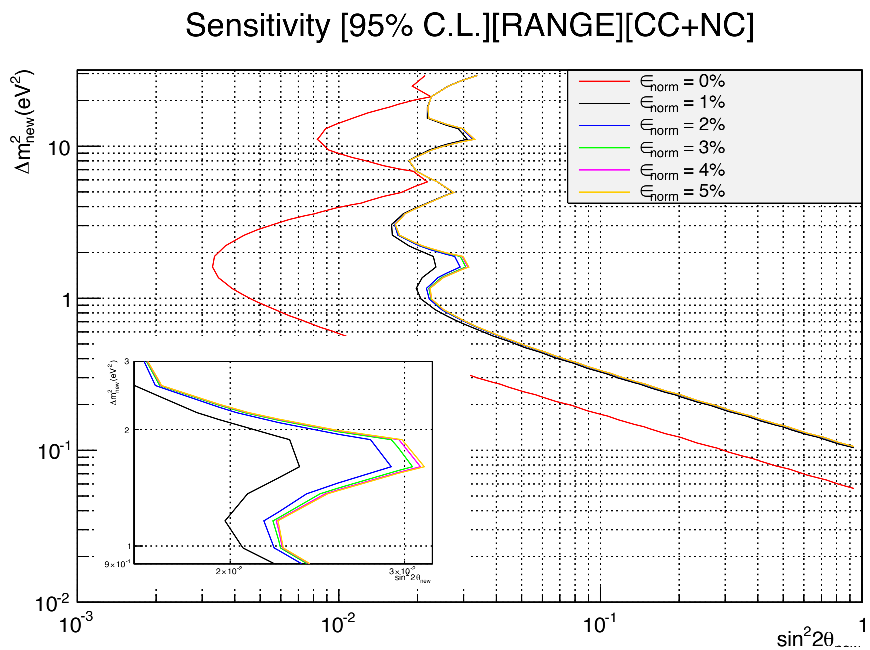
Charge-ID measured by iron slabs (ICM: blue line)

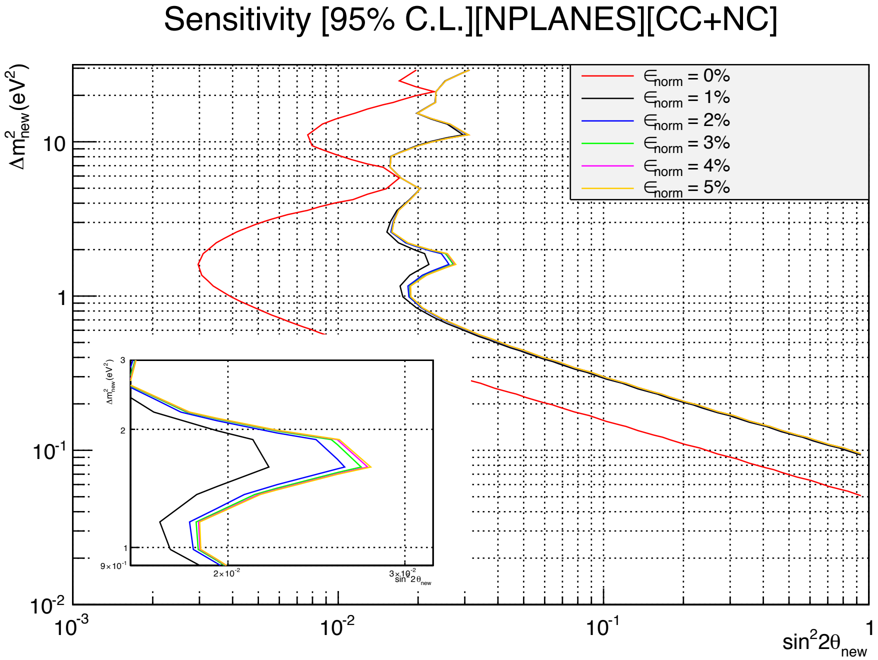


(goal ≥ 250 MeV)

Momentum measured by range (ICM) up to 3.5 GeV, then ≈30% are provided

DATA Analysis systematic error



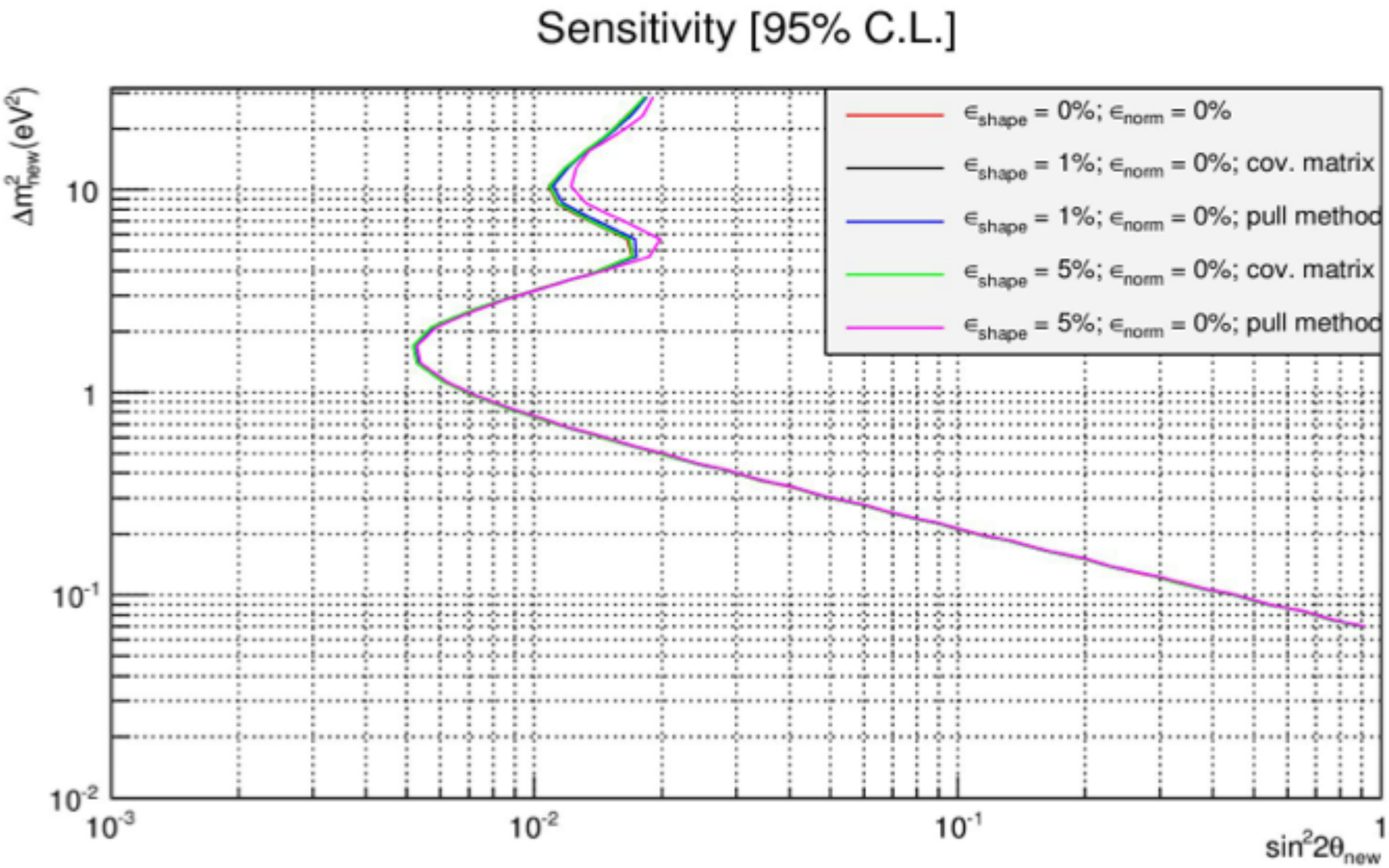


Distinct effect of systematic error
for NPLANES and RANGE parameters

Method II of the proposal:
- full MC simulation,
- matricial treatment

(systematic error on normalization)

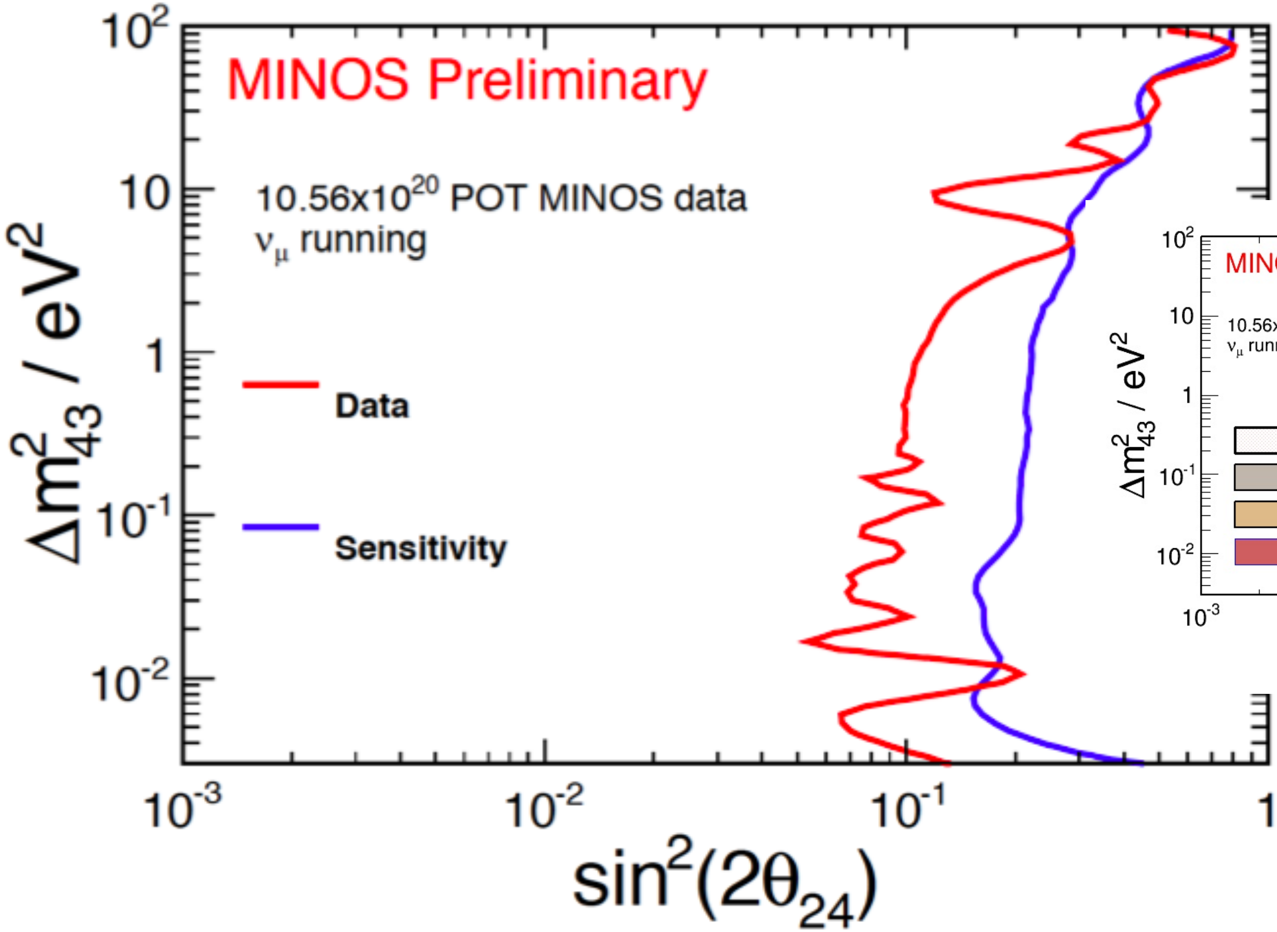
DATA Analysis systematic error (cntd)

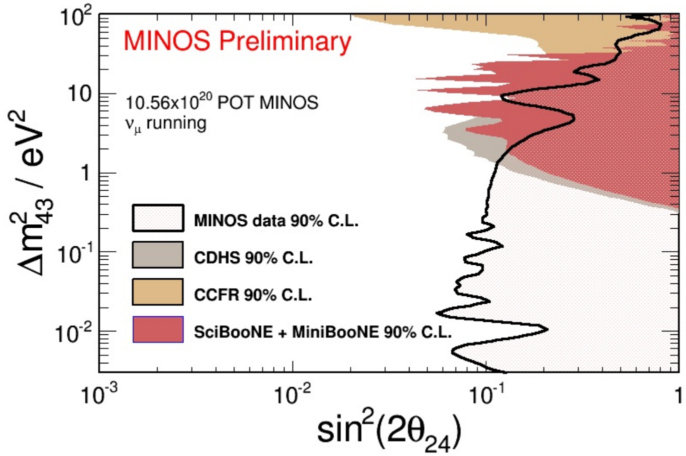


Method II of the proposal:
- full MC simulation,
- matricial treatment

(systematic error on shape)

Sterile Limit Data and Sensitivity

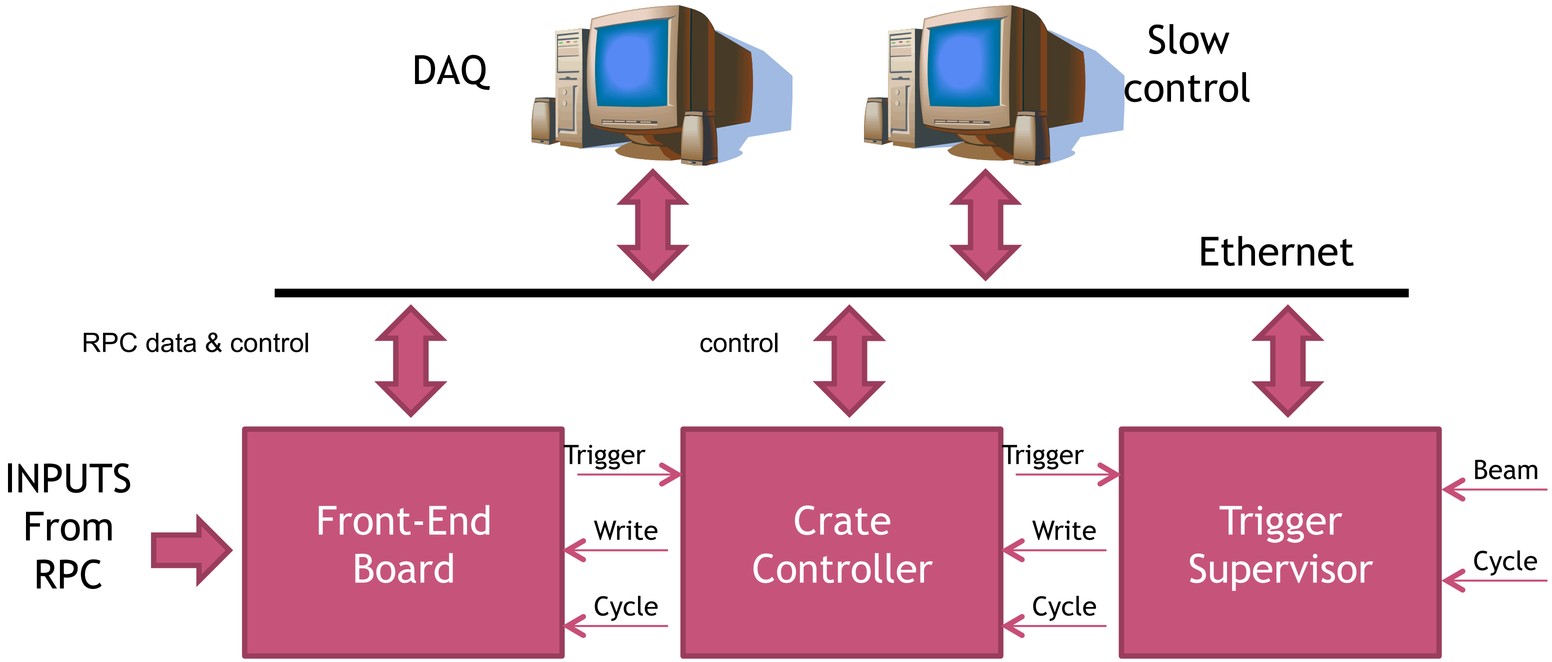




at 90% C.L.

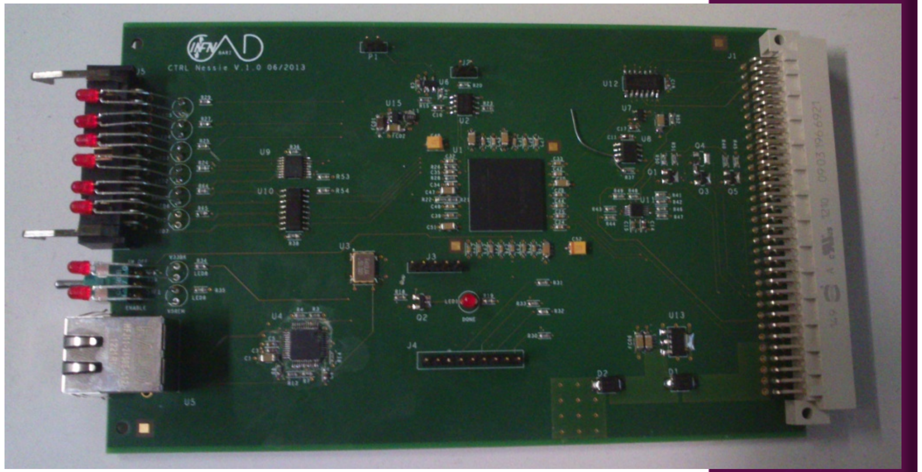
MINOS at NEUTRINO 2014 Conference, Boston, USA

SYSTEM ARCHITECTURE



CRATE CONTROLLER

- Eurocard 3U form factor
- Ethernet controlled
- Power supply management and monitoring
- Control signal distribution
- Collects fastOR from 19 FEBs combining them in a programmable manner to generate 4 trigger outputs (plane-ORs)



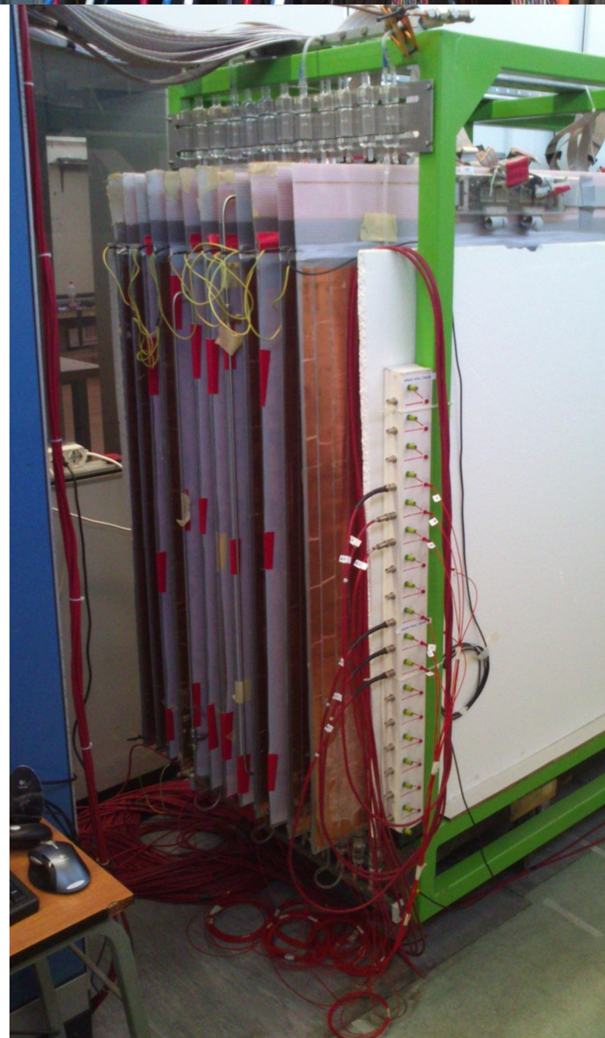
TRIGGER SUPERVISOR

- Ethernet interface
- General DAQ synchronization
- Control signal generation (CYCLE, WRITE, ABORT)
- Collects plane-ORs from Crate Controller board
- External/internal trigger mode
- Can operate in “beam” mode or in “cosmic” mode

TESTS WITH RPCs

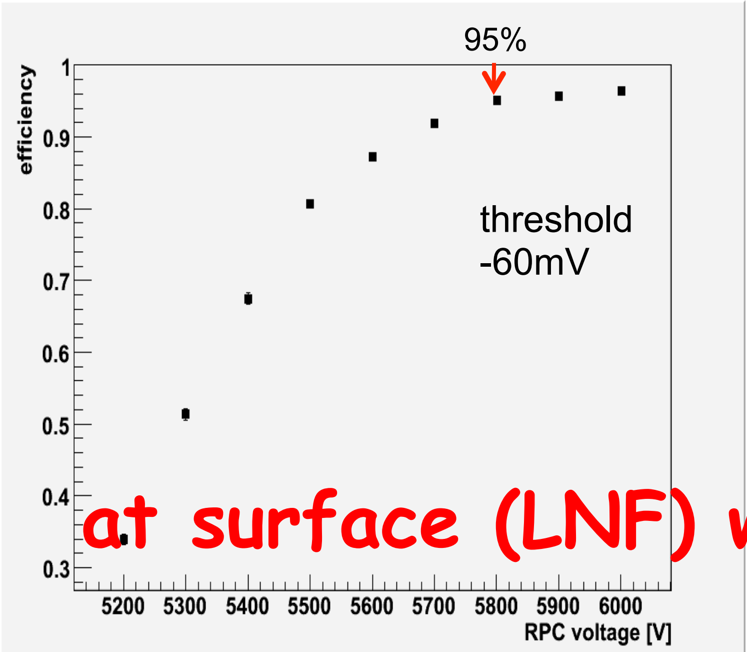
- With the help of A. Paoloni we performed three sessions of tests at LNF in December 2013, March 2014 and July 2014 (new FEBs + Trigger Supervisor)
- In the first two sessions we tested the behavior of the electronics in connection with two RPCs of small dimensions (60x70 cm^2)

- At the end of July, a stack of 12 (spare) OPERA RPCs was transported from LNGS to LNF. Every chamber (~ 3x1 m^2) has 32 horizontal strips, 96 vertical strips and is read by 2 FEBs.
- 6 RPCs were connected to our electronics. Test still in progress.

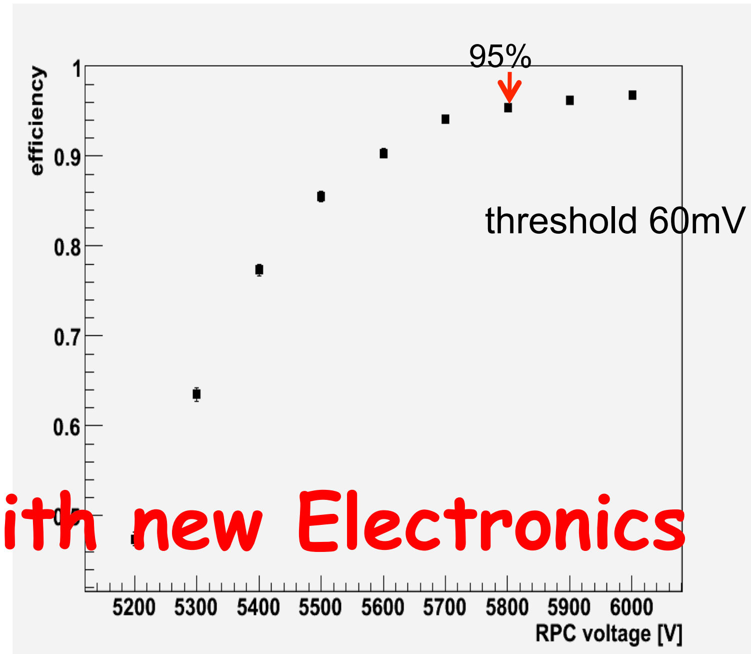


OPERA-RPC still wonderfully working

efficiency RPC1 (negative strips)



efficiency RPC2 (positive strips)



at surface (LNF) with new Electronics