The θ_{13} Panorama...

DAPNIA-CEA Saclay

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APC (IN2P3) - Paris

(PhD in MINOS/Oxford)

overview:

- ν status & MINOS
- Why θ_{13} important?
- θ_{13}-beams exp.
- θ_{13}-reactor exp.
- Complementarity
- Conclusions...

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- complementarity: all experiment has input into global coherent(!) picture

ν oscillations reminder

neutrino oscillations summary

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    - non-degenerate mass spectrum of 3(?) active νs
    - "mirroring" lepton-quark mixing => beyond *SM*?

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1

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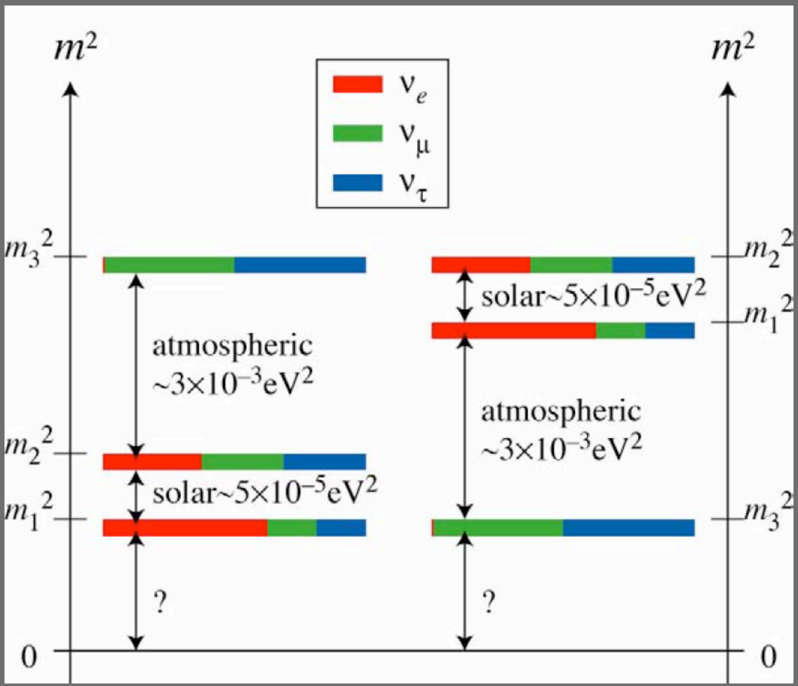

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ν-Osc. sensitive only to Δm^2's:

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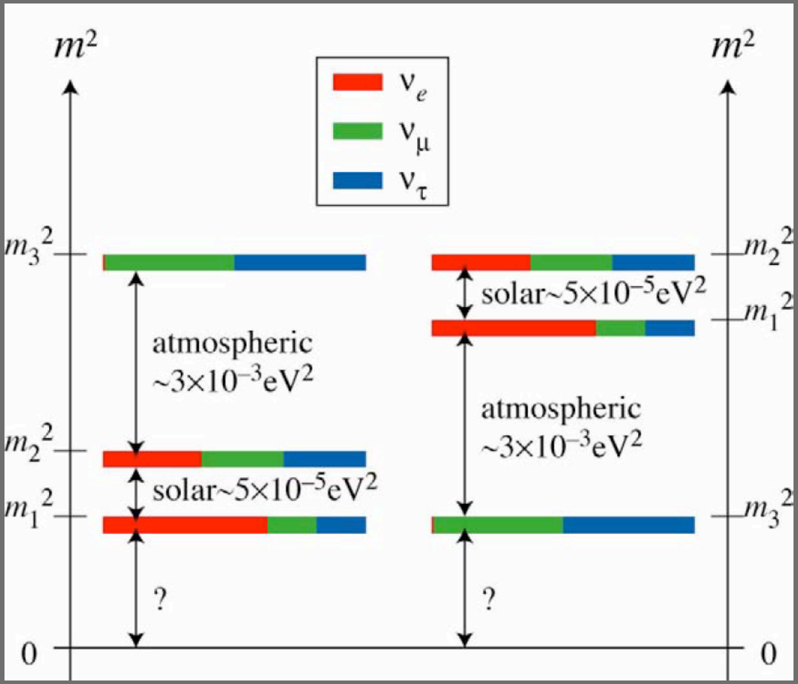

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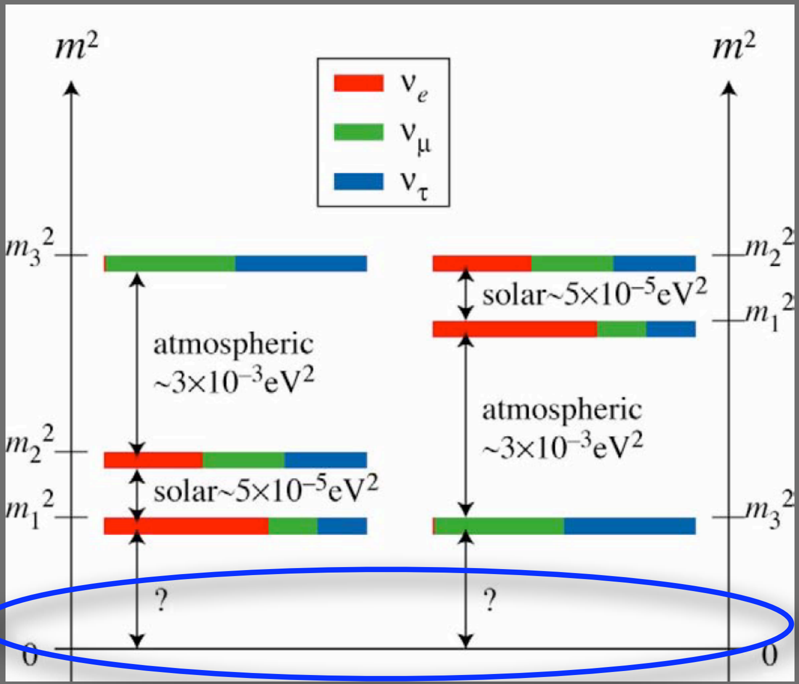

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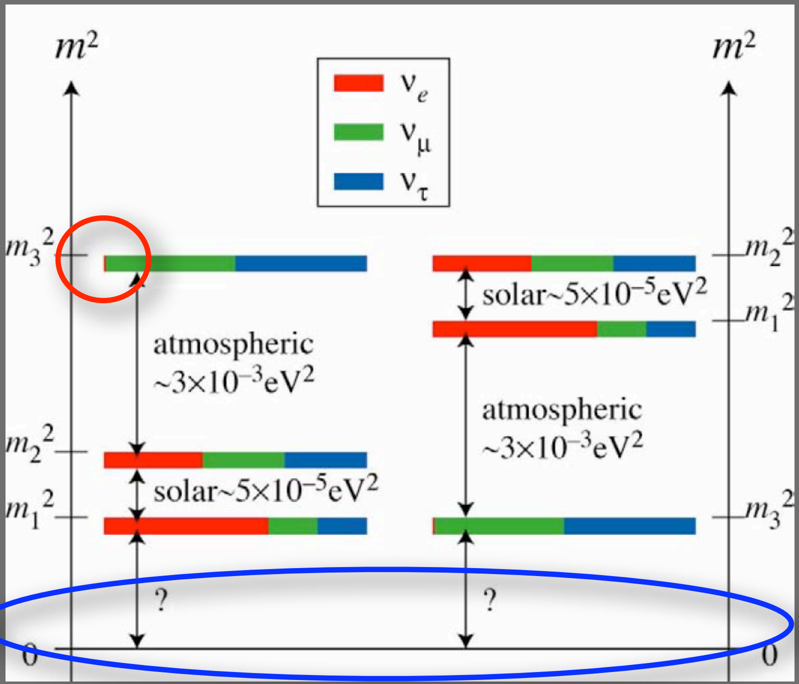

2ν oscillation probability equation:

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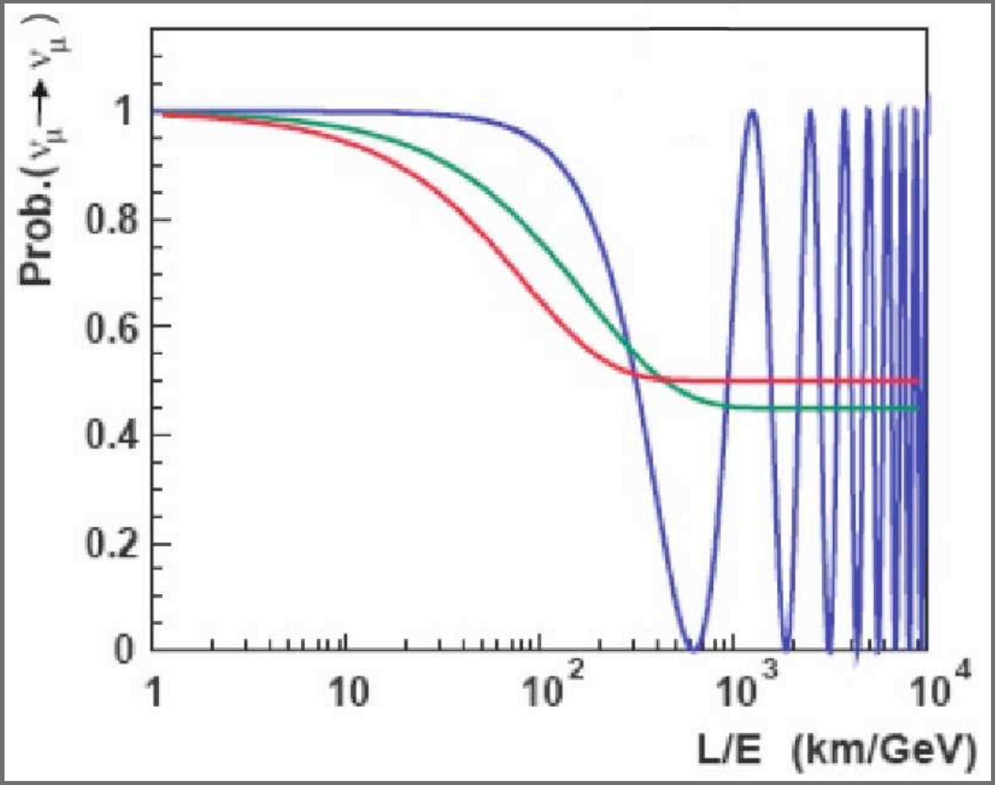

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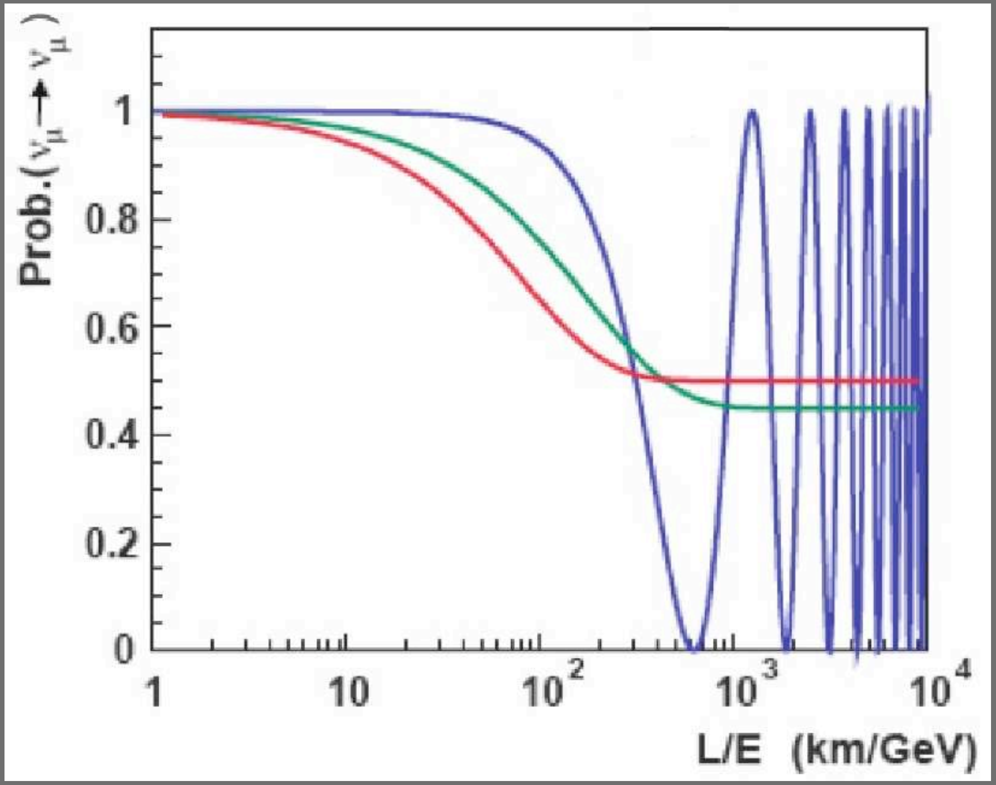
E/L modulation unique feature!



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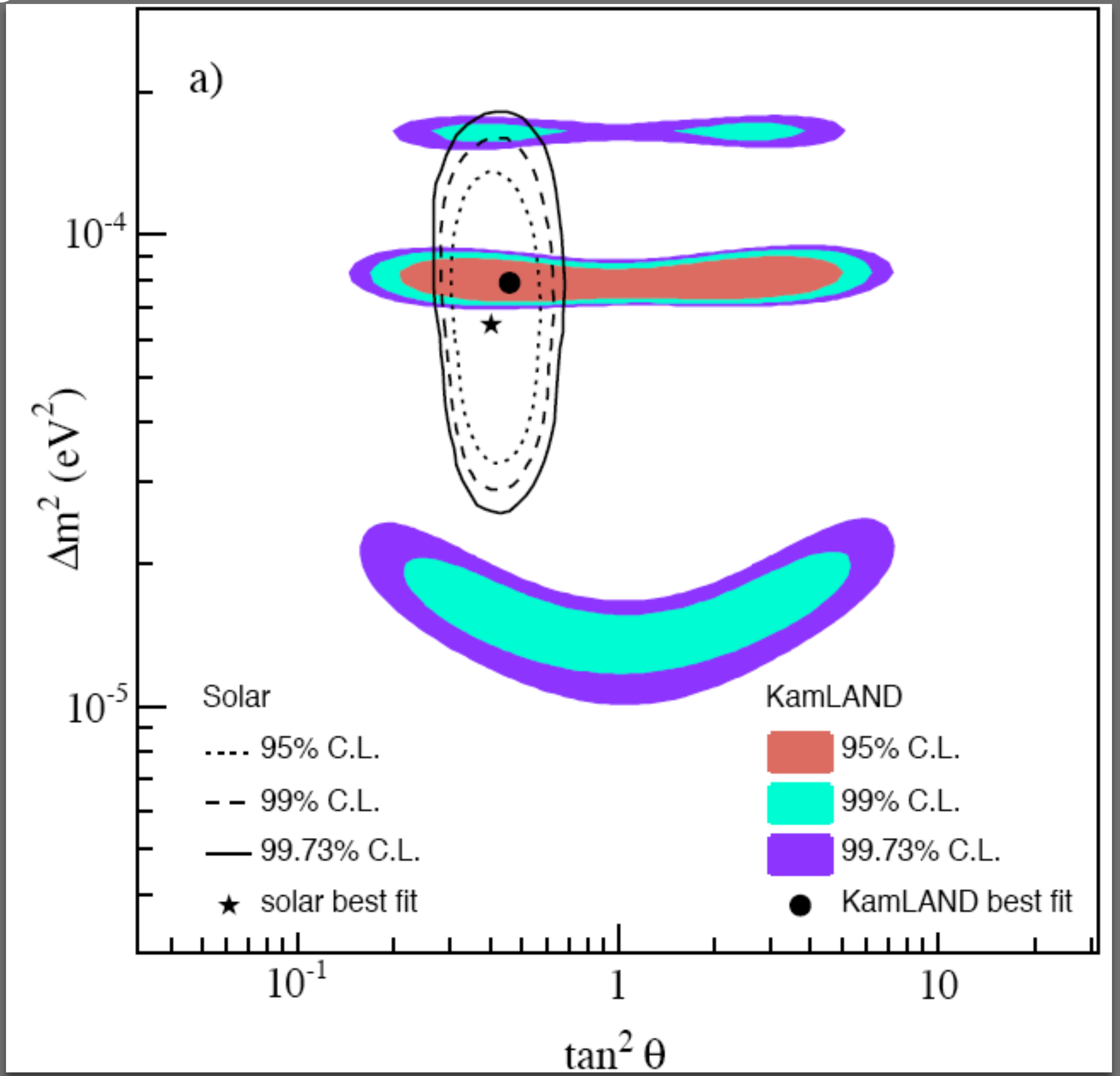
  - modify oscillation equations
  - explicit "L" dependence (not only E/L)

Believing in ν-oscillations?

The most fascinating demonstration so far...



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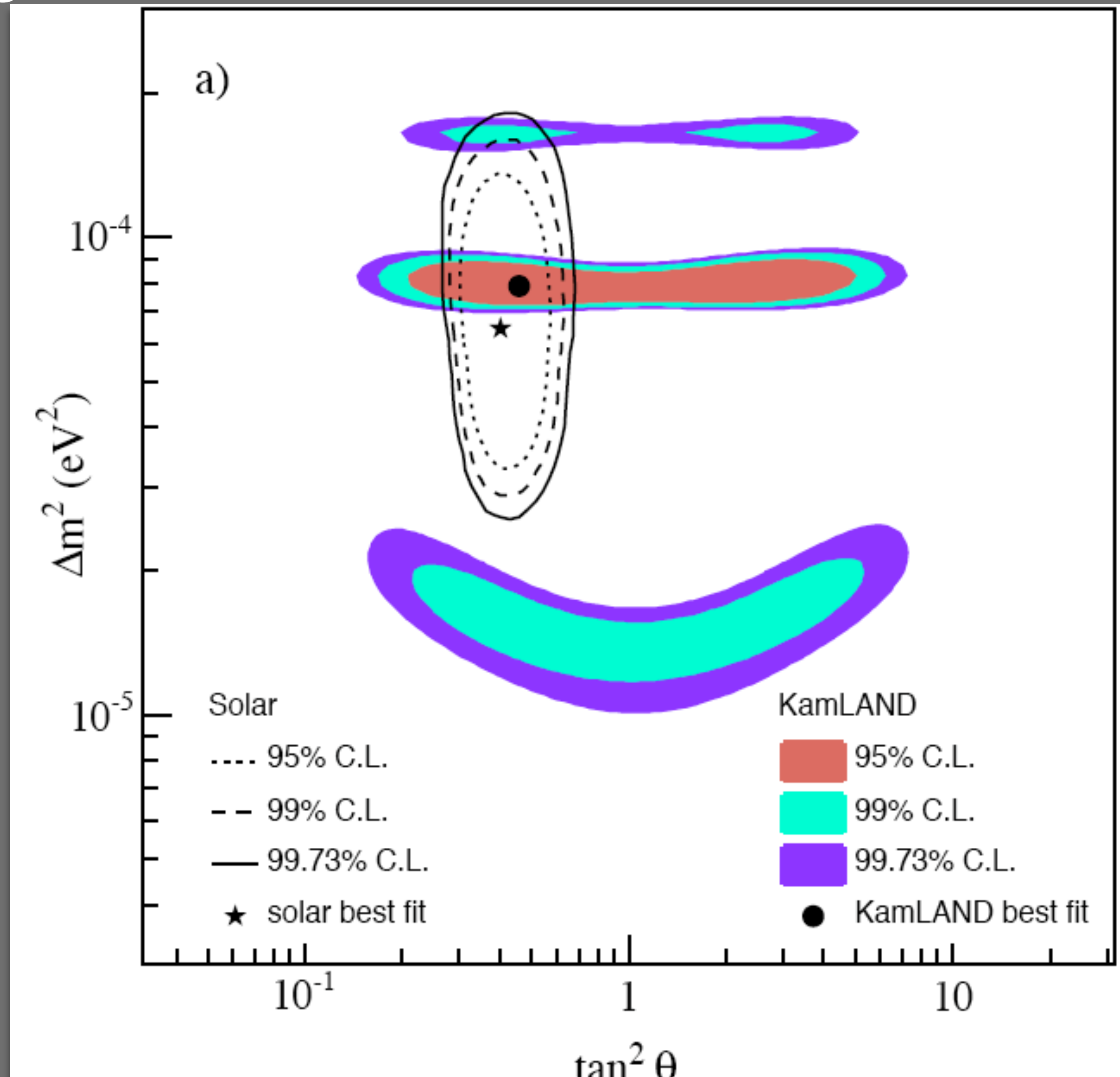
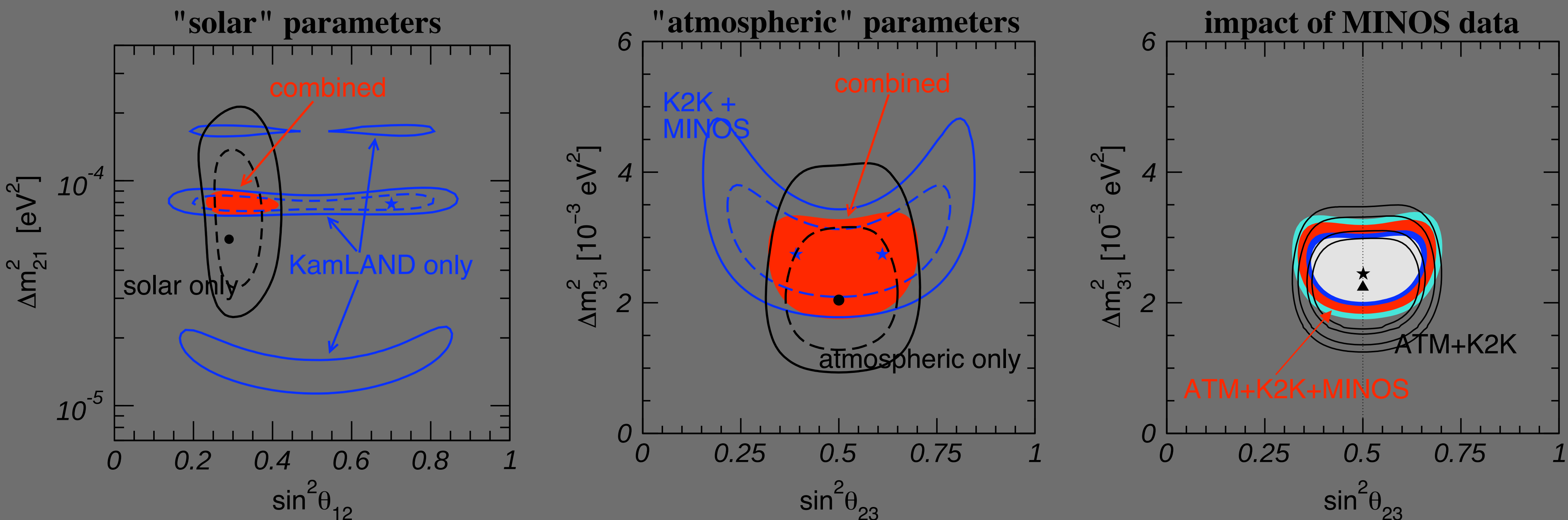


summary

PMNS: large mixing (unlike CKM)...

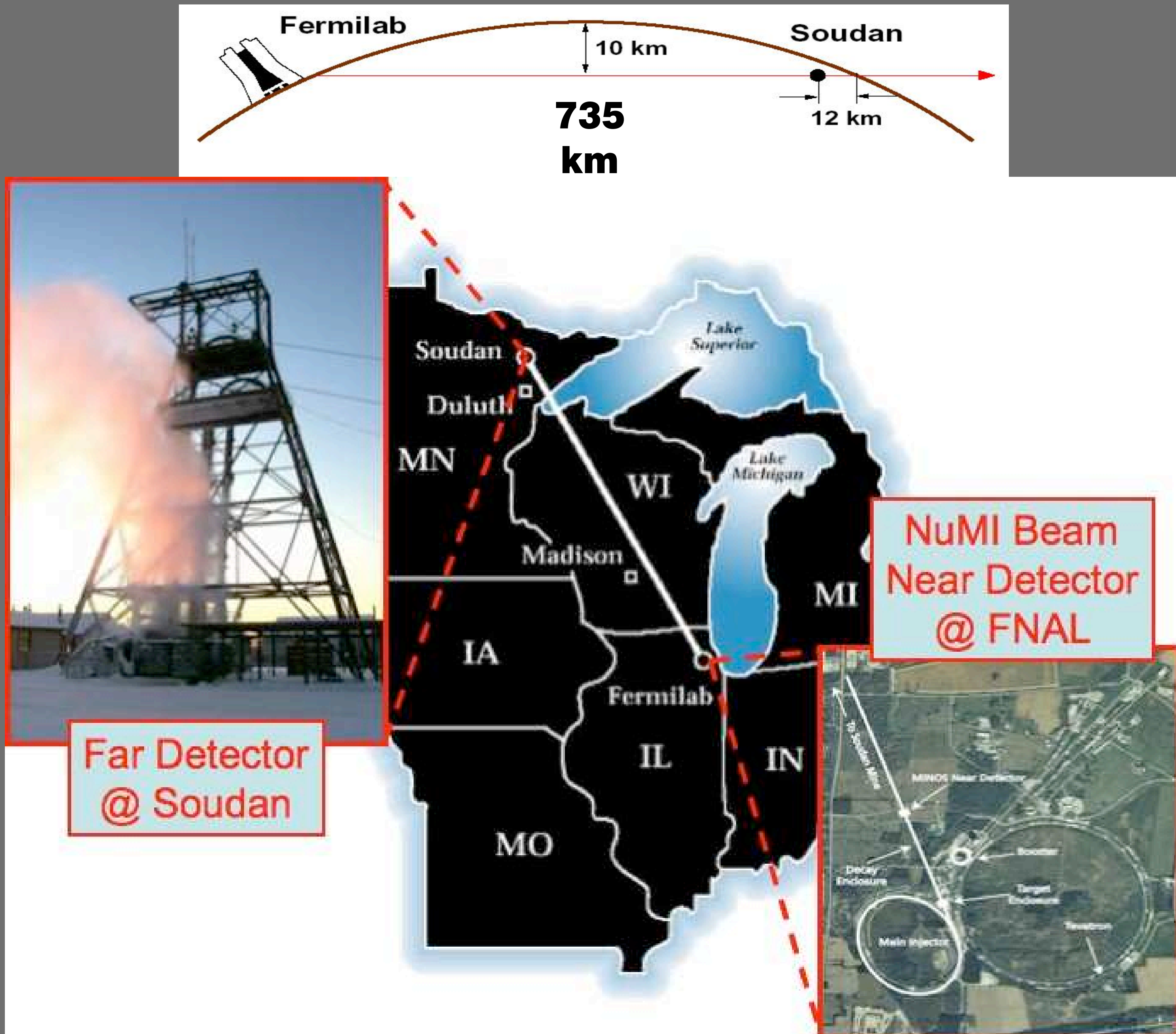
T.Schwetz hep-ph/0606060

parameter	bf$\pm 1\sigma$	1σ acc.	2σ range	3σ range
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	7.9 ± 0.3	4%	$7.3 - 8.5$	$7.1 - 8.9$
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$	$2.5^{+0.20}_{-0.25}$	10%	$2.1 - 3.0$	$1.9 - 3.2$
$\sin^2\theta_{12}$	$0.30^{+0.02}_{-0.03}$	9%	$0.26 - 0.36$	$0.24 - 0.40$
$\sin^2\theta_{23}$	$0.50^{+0.08}_{-0.07}$	16%	$0.38 - 0.64$	$0.34 - 0.68$
$\sin^2\theta_{13}$	–	–	≤ 0.025	≤ 0.041



MINOS

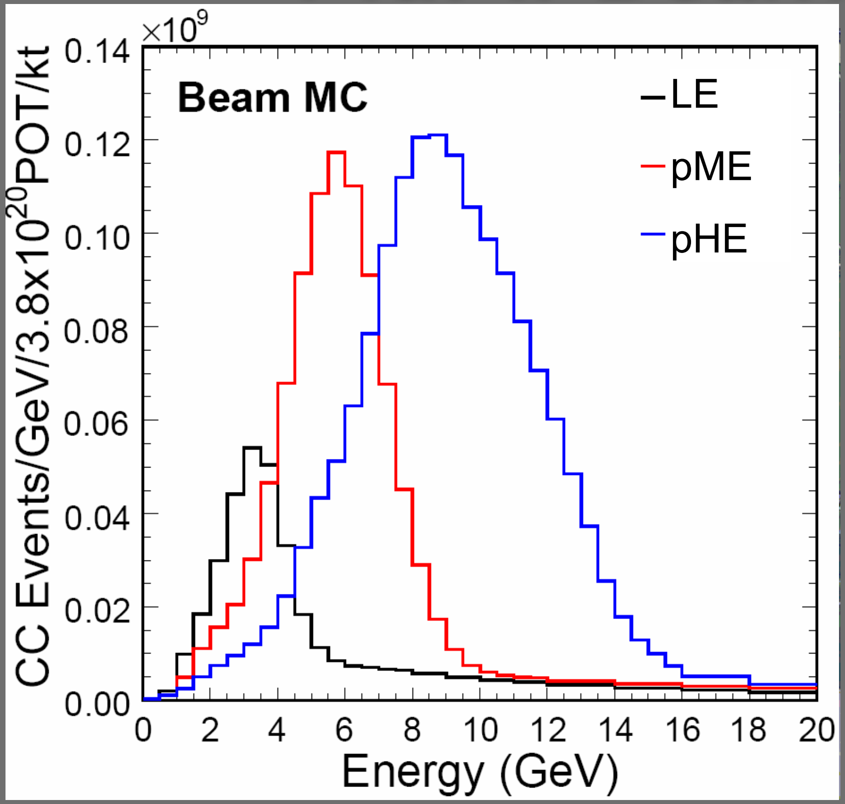
hep-ph/0607088
MINOS@Nu06
MINOS@NOW06

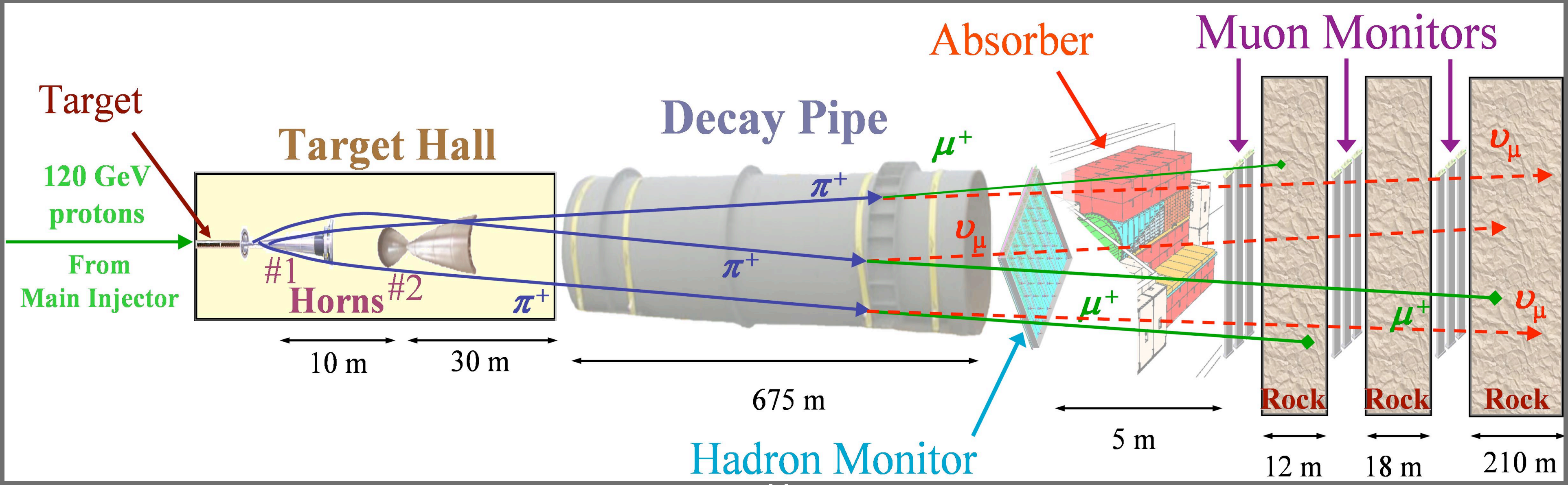


- 736km baseline
- 2 detectors
- magnetised
- beam physics
- cosmic physics
- $\sim 7\times 10^{20}$pot

NuMI Beam

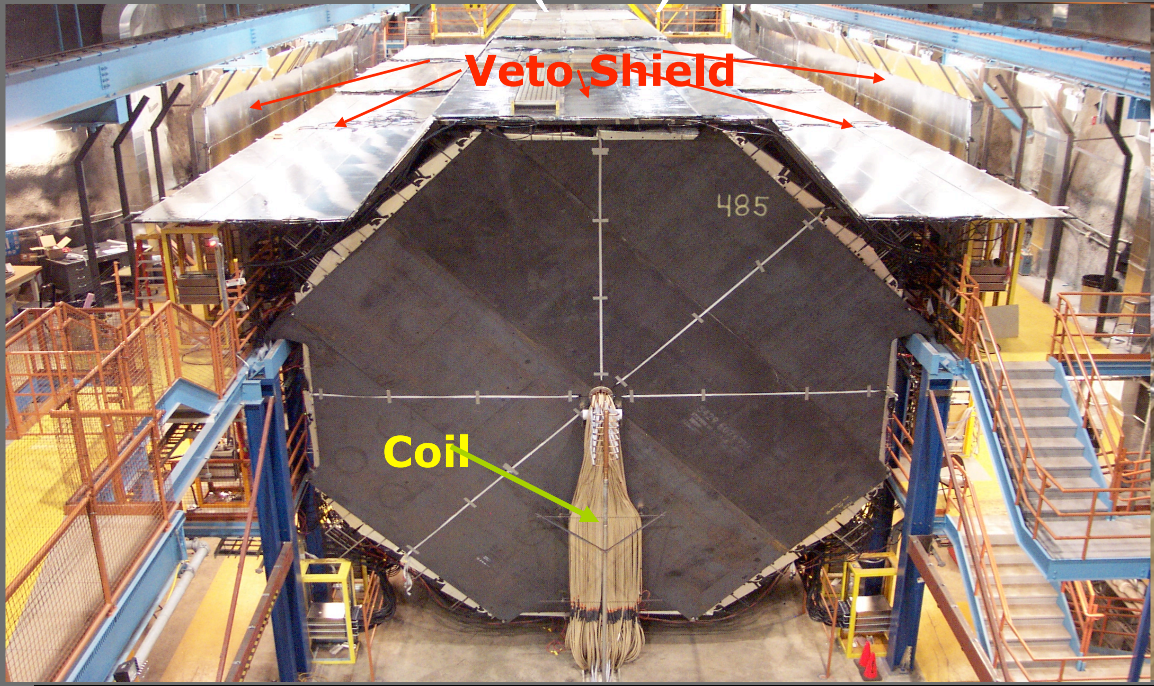
- 120 GeV protons strike graphite target
- Magnetic horns focus produced pions and kaons, pions and kaons decay into muons and neutrinos
- Target position adjusts to change beam energy
- 10 μs spills as fast as once every 2 seconds
- 2.5×10^{20} POT/year





Detectors

Far Detector (FD)



Near Detector (ND)

Far Detector (FD)	Near Detector (ND)
5.4 kton mass, 8×8×30m	1 kton mass 3.8×4.8×15m
484 steel/scintillator planes	282 steel and 153 scintillator planes
VA electronics	Robust QIE electronics

B ~1.2T

Multi-pixel (M16,M64) PMTs

GPS time-stamping to synch FD data to ND/Beam

Continuous *untriggered* readout of whole detector (only during spill for the ND)

Interspersed light injection (LI) for calibration

Software triggering in DAQ PCs (Highly flexible : plane, energy, LI triggers in use)

Spill times from FNAL to FD trigger farm

Design

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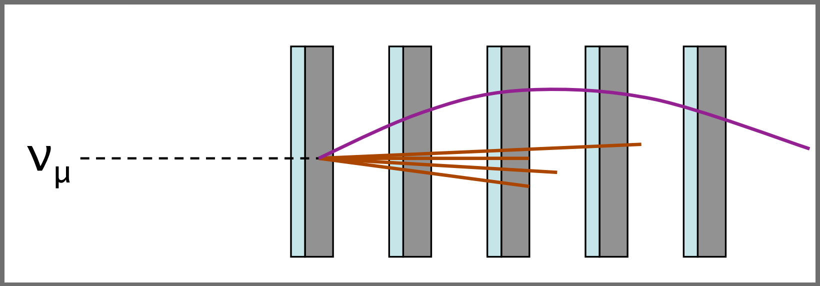
- sampling calorimeter: showers



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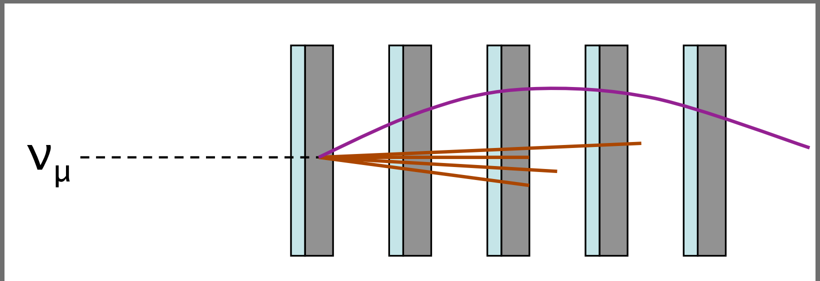

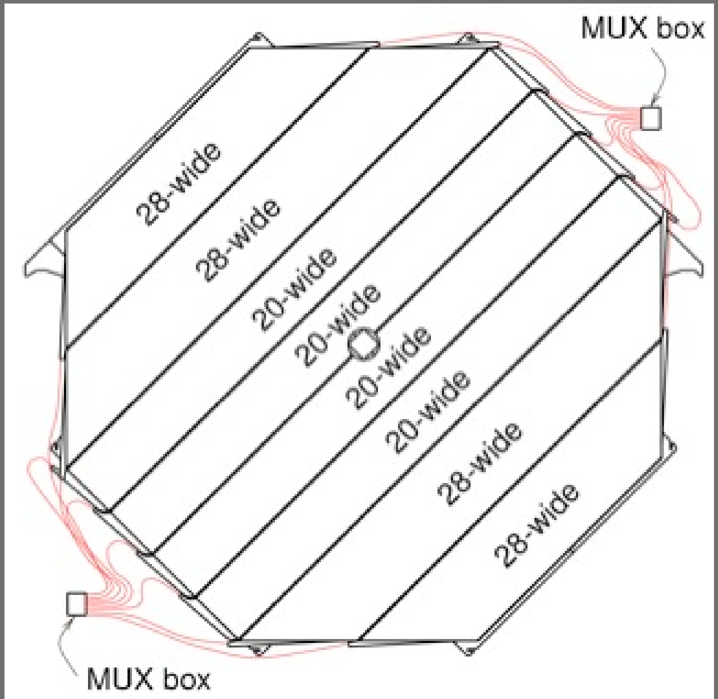

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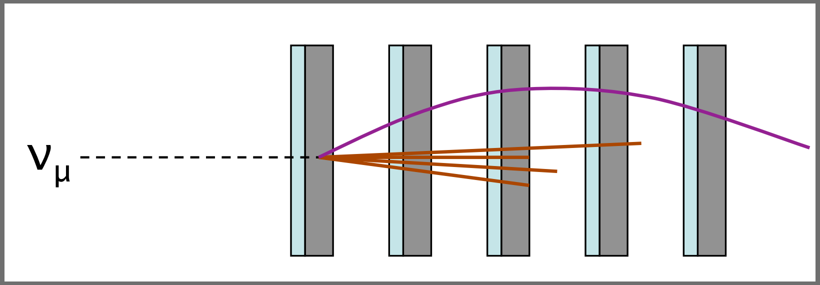

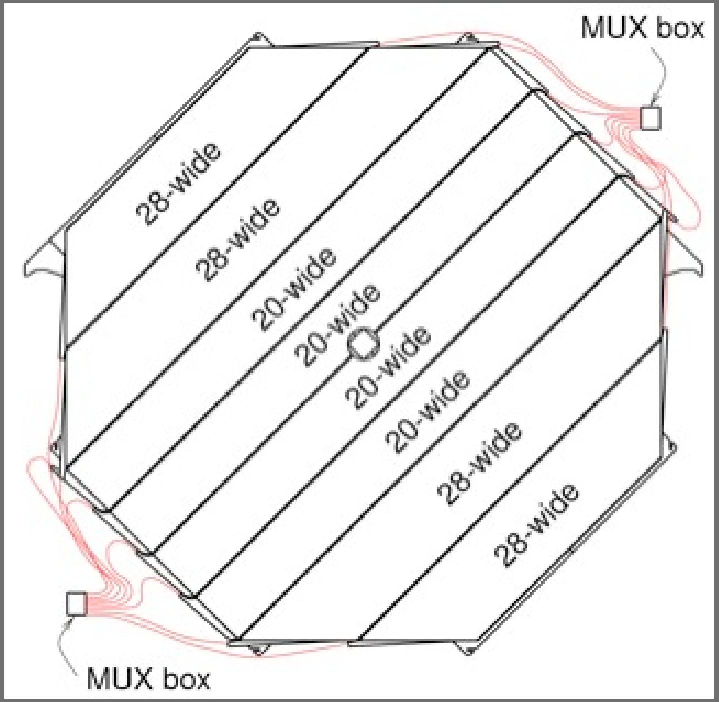

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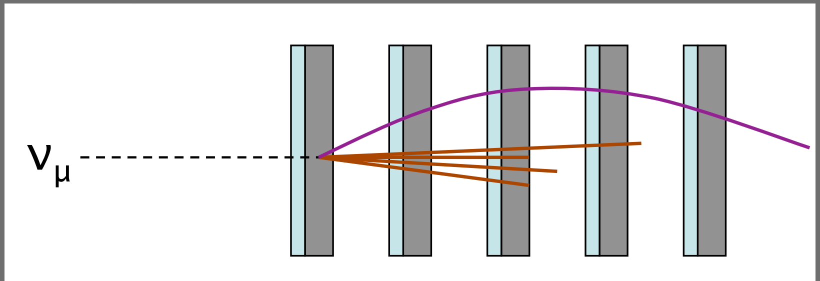

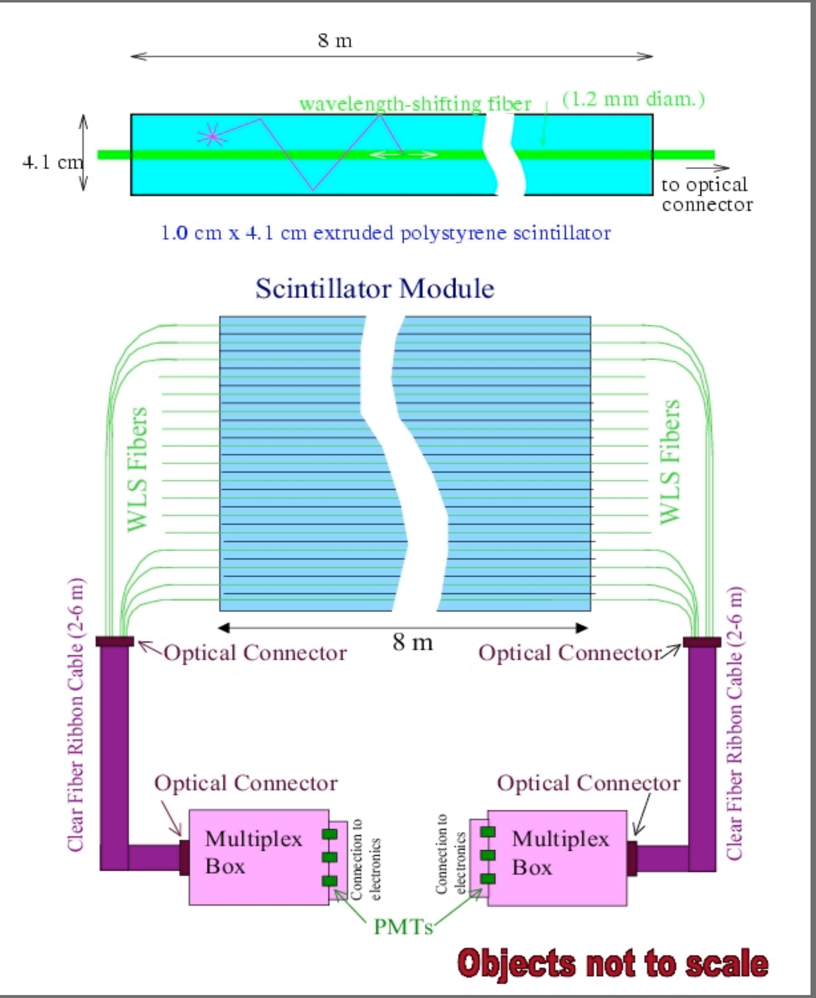

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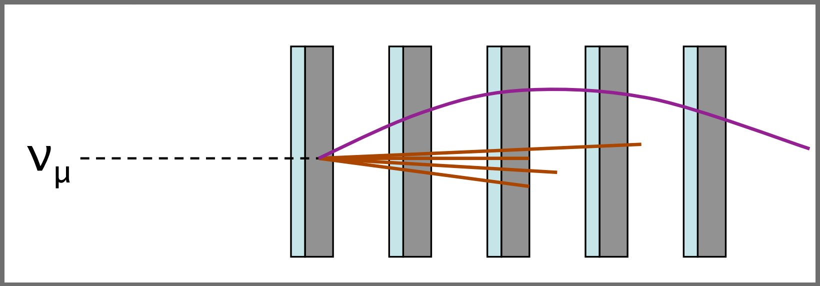

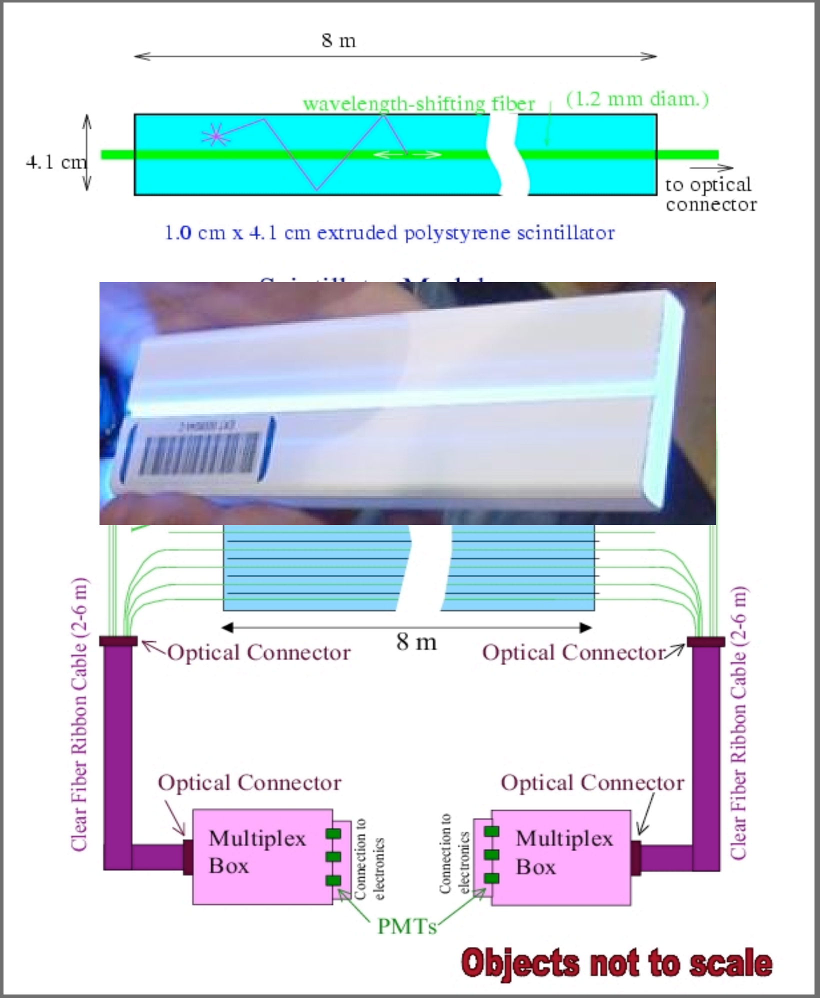

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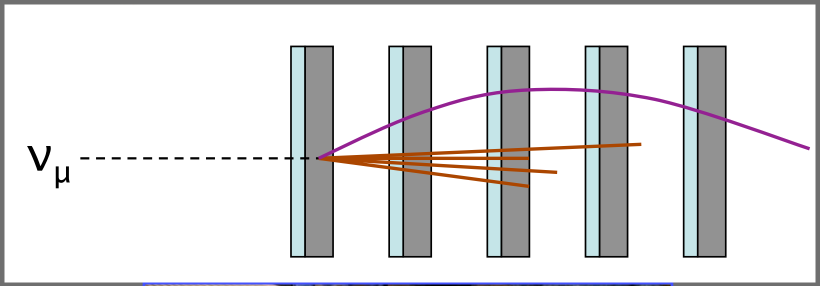

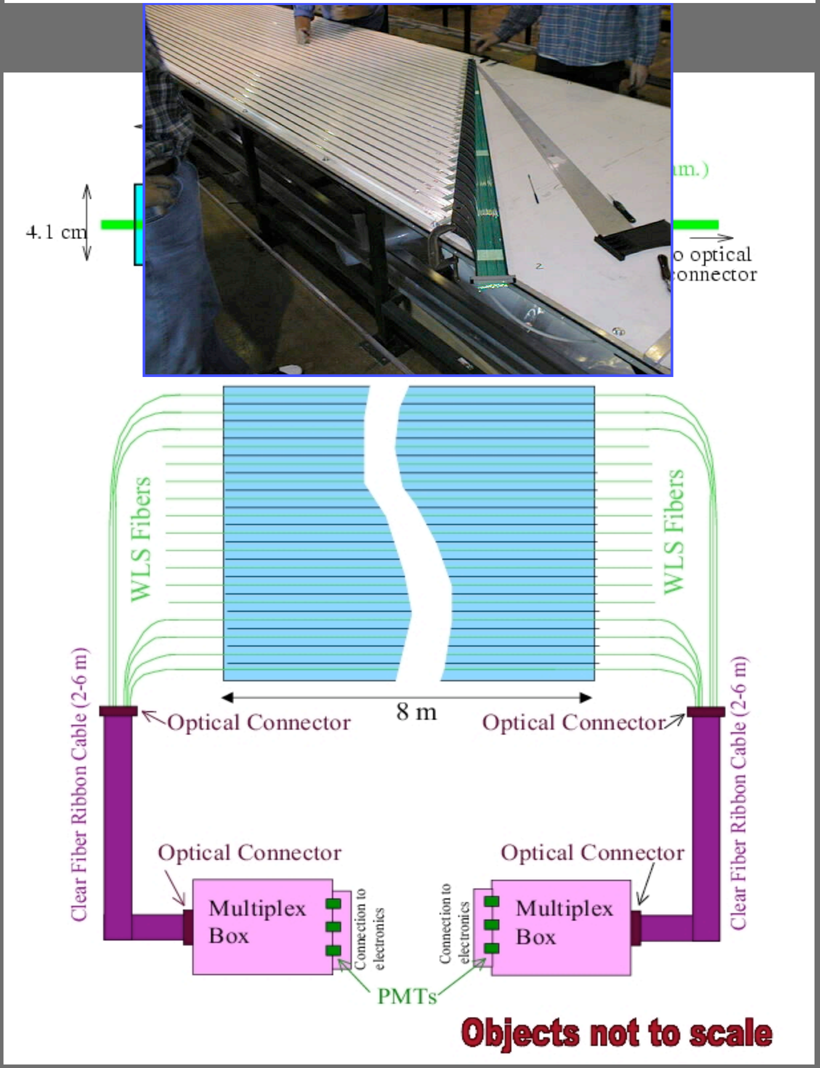

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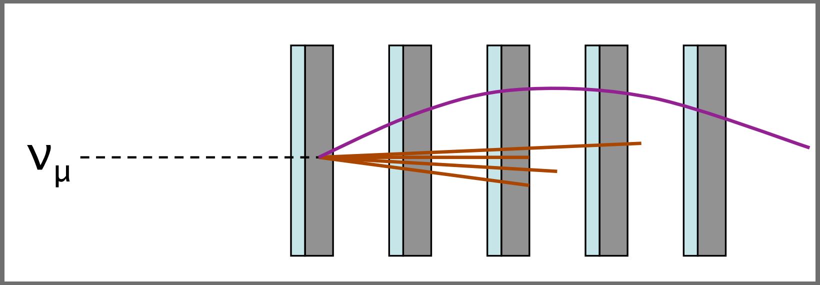

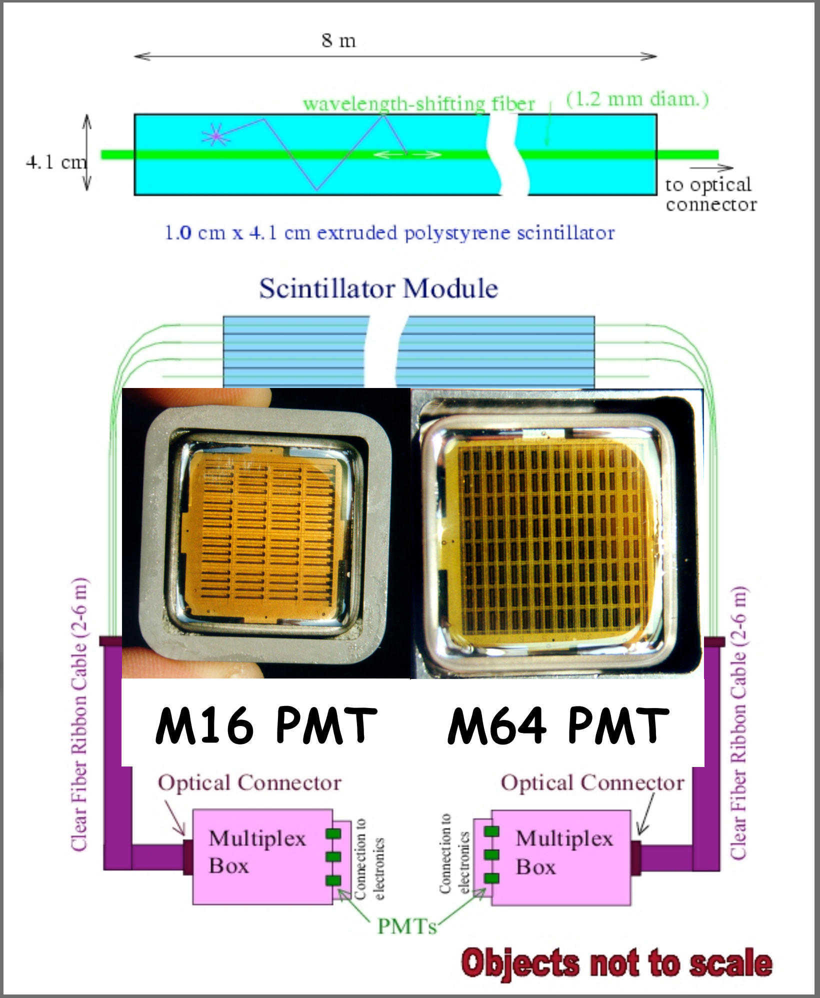

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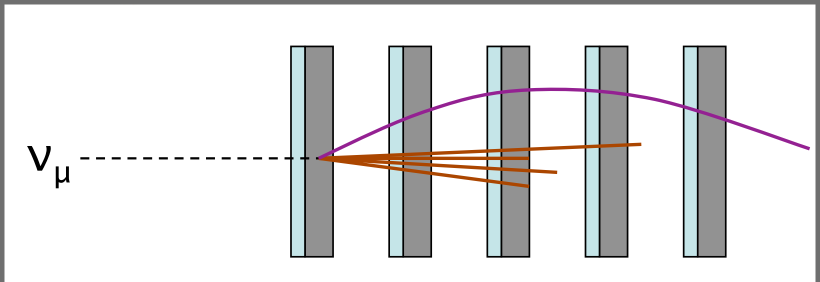
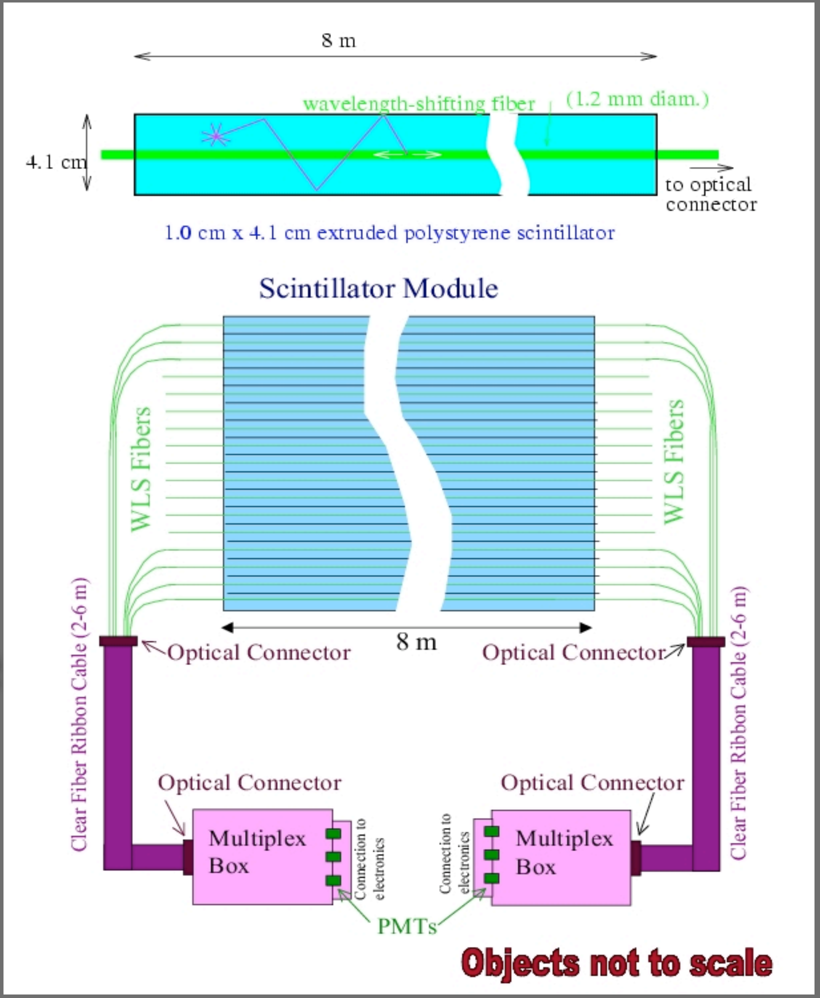
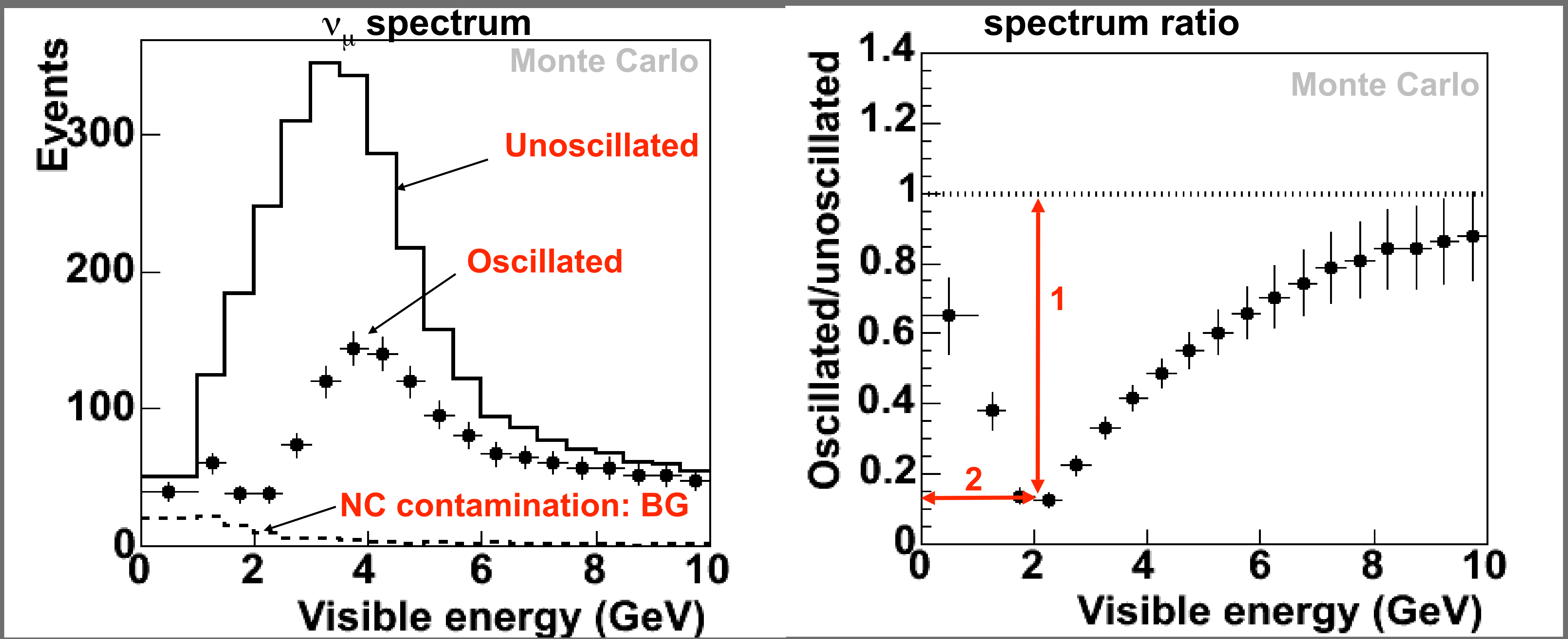




Golden Channel: Δm^2

$$P(\nu_\alpha \rightarrow \nu_\beta) = \overset{1}{\boxed{\sin^2 2\theta}} \sin^2\left(\frac{1.27 \overset{2}{\boxed{\Delta m^2}} L}{E}\right)$$



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      hep-ex/0701045
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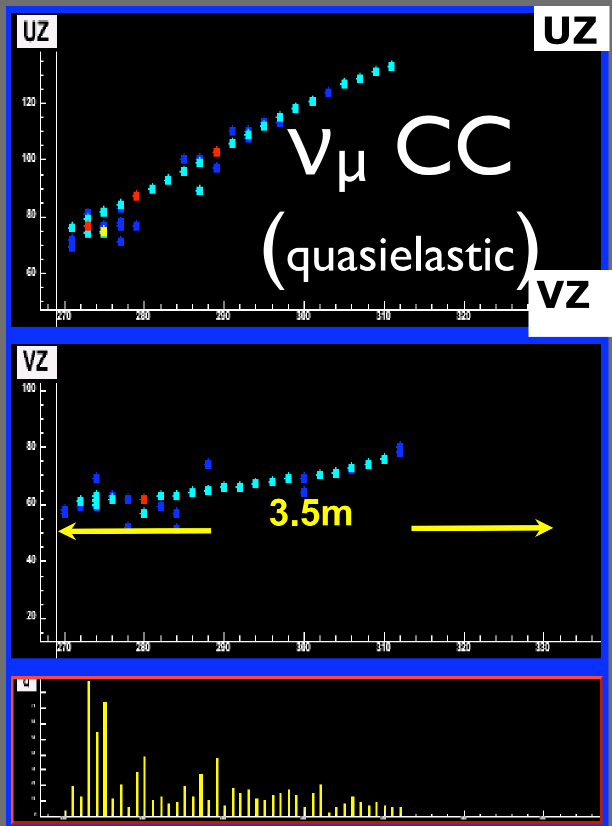
  hep-ex/0512036

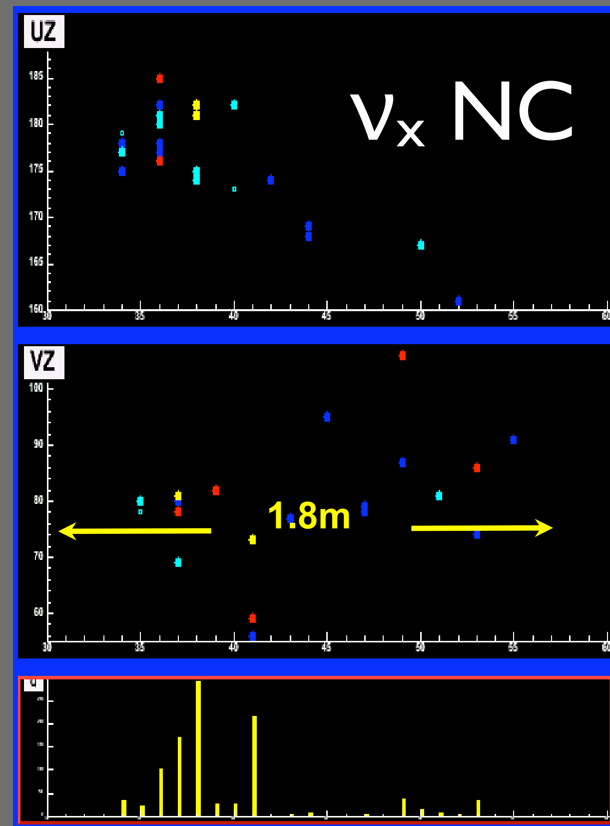
$$\nu_\lambda + N \xrightarrow{W^\pm} \lambda + X \; : \; CC \; Interaction$$

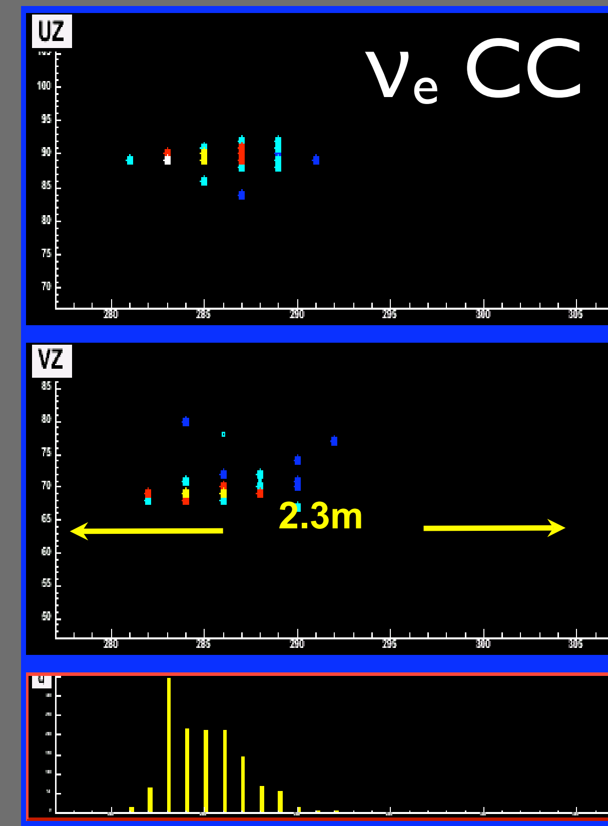
$$\nu_x + N \xrightarrow{Z^o} \nu_x + X \; : \; NC \; Interaction$$

Event Topology

Monte Carlo





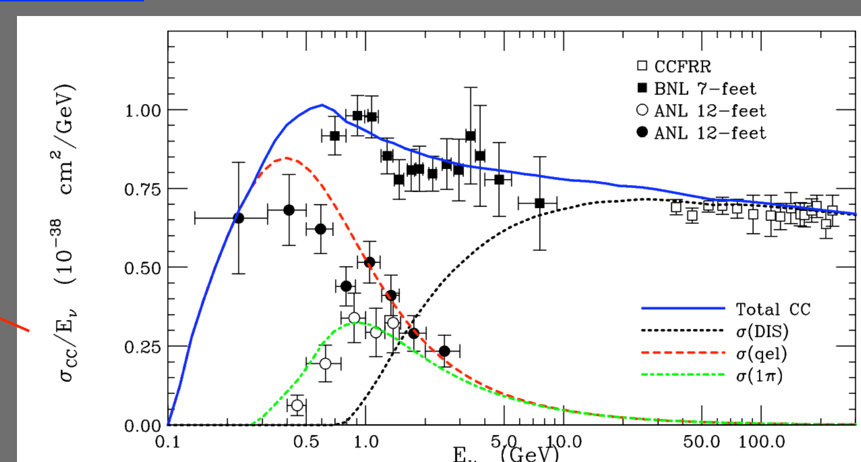


$$E(\nu_\mu\text{-CC}) = f(E_{shower}, P_\mu, \text{interaction-ID})$$

55%/$\sqrt{E}$

6% range

10% curvature



Atmospheric Physics

hep-ex/0701045

Oscillations and a CPT test...

hep-ex/0701045

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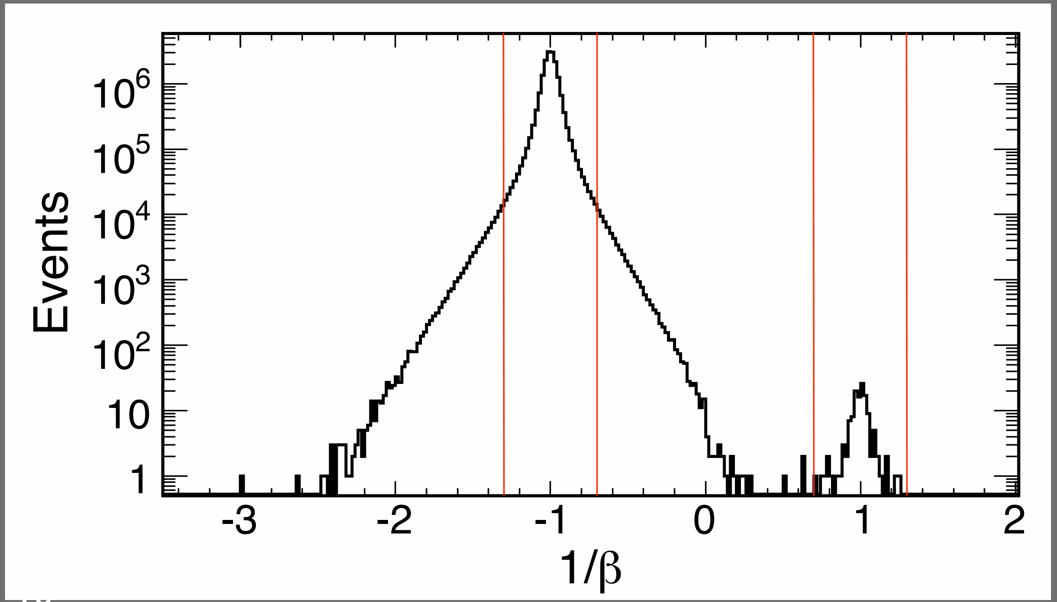

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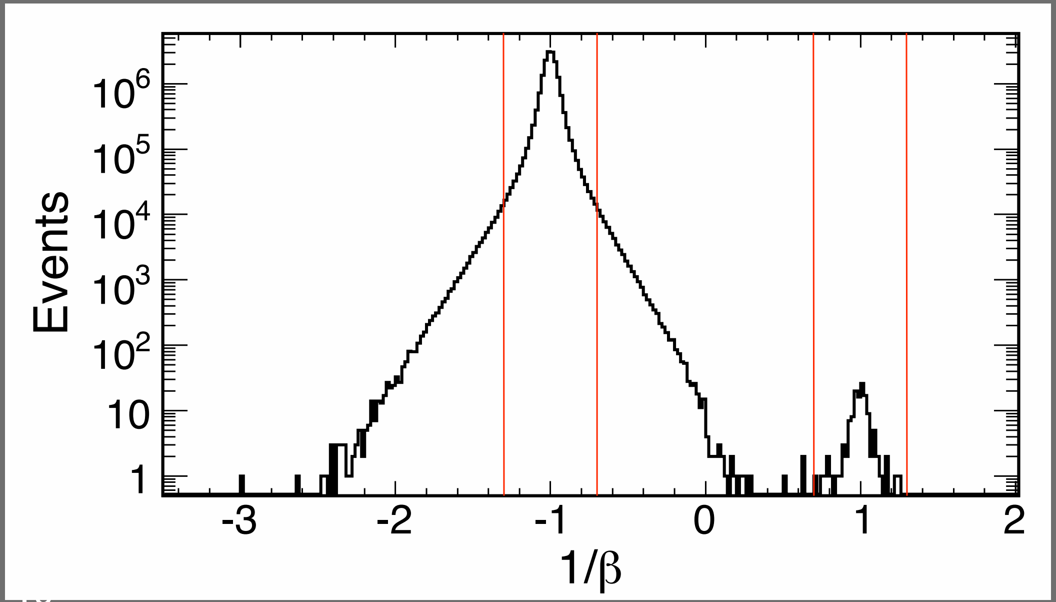

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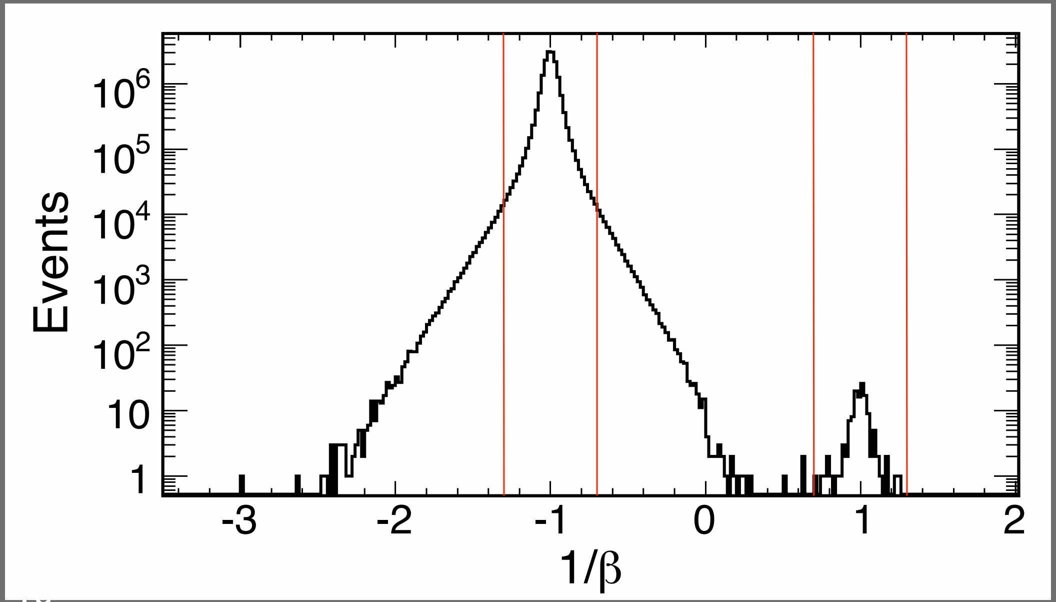
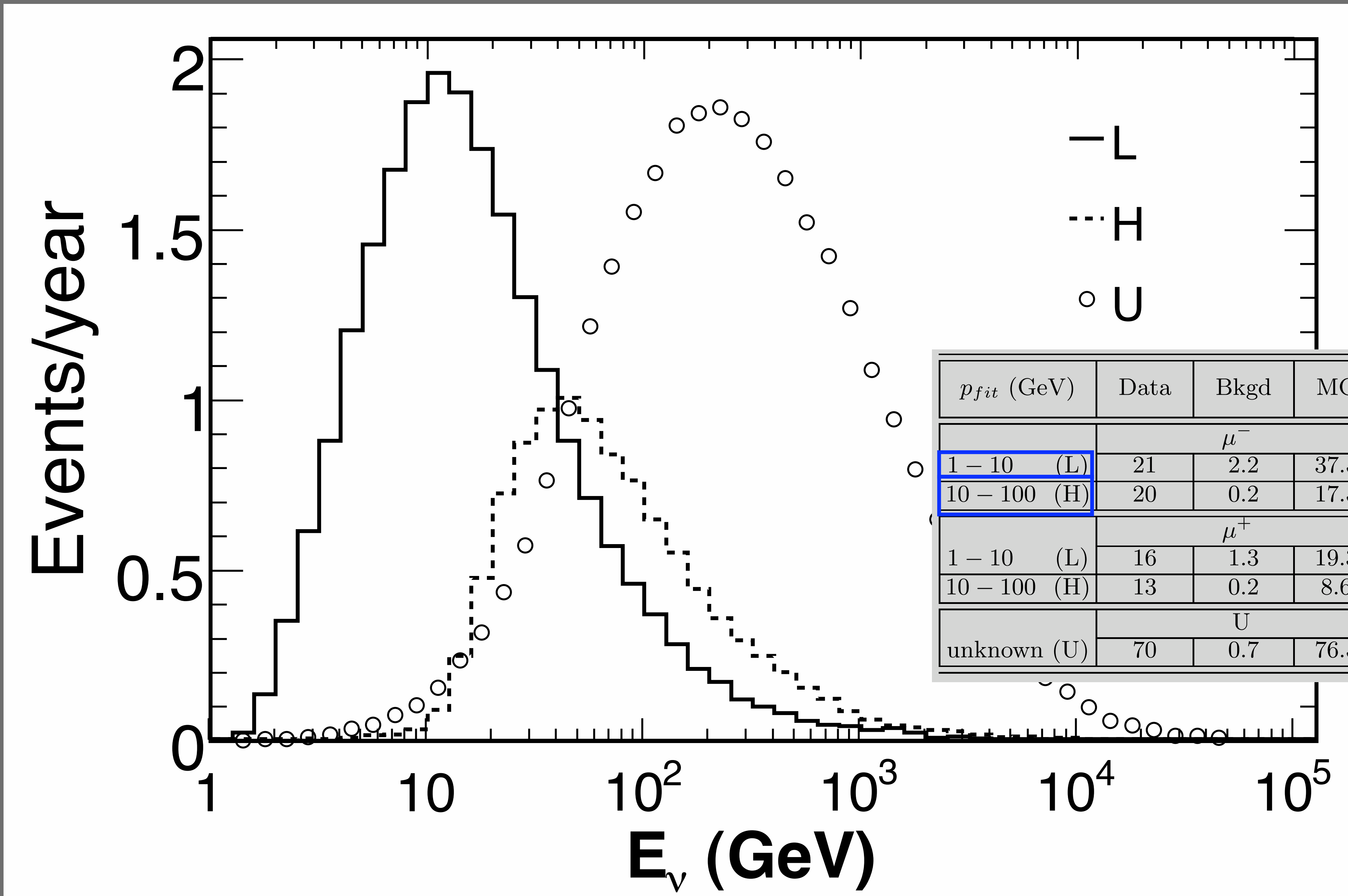
- Results...

$$\mathcal{R} = \frac{R^{data}_{L/H+U}}{R^{MC}_{L/H+U}} = 0.65^{+0.15}_{-0.12}(\mathrm{stat}) \pm 0.09(\mathrm{syst})$$

$$\hat{\mathcal{R}}_{CPT} = 0.72^{+0.24}_{-0.18}(\mathrm{stat})^{+0.08}_{-0.04}(\mathrm{syst})$$



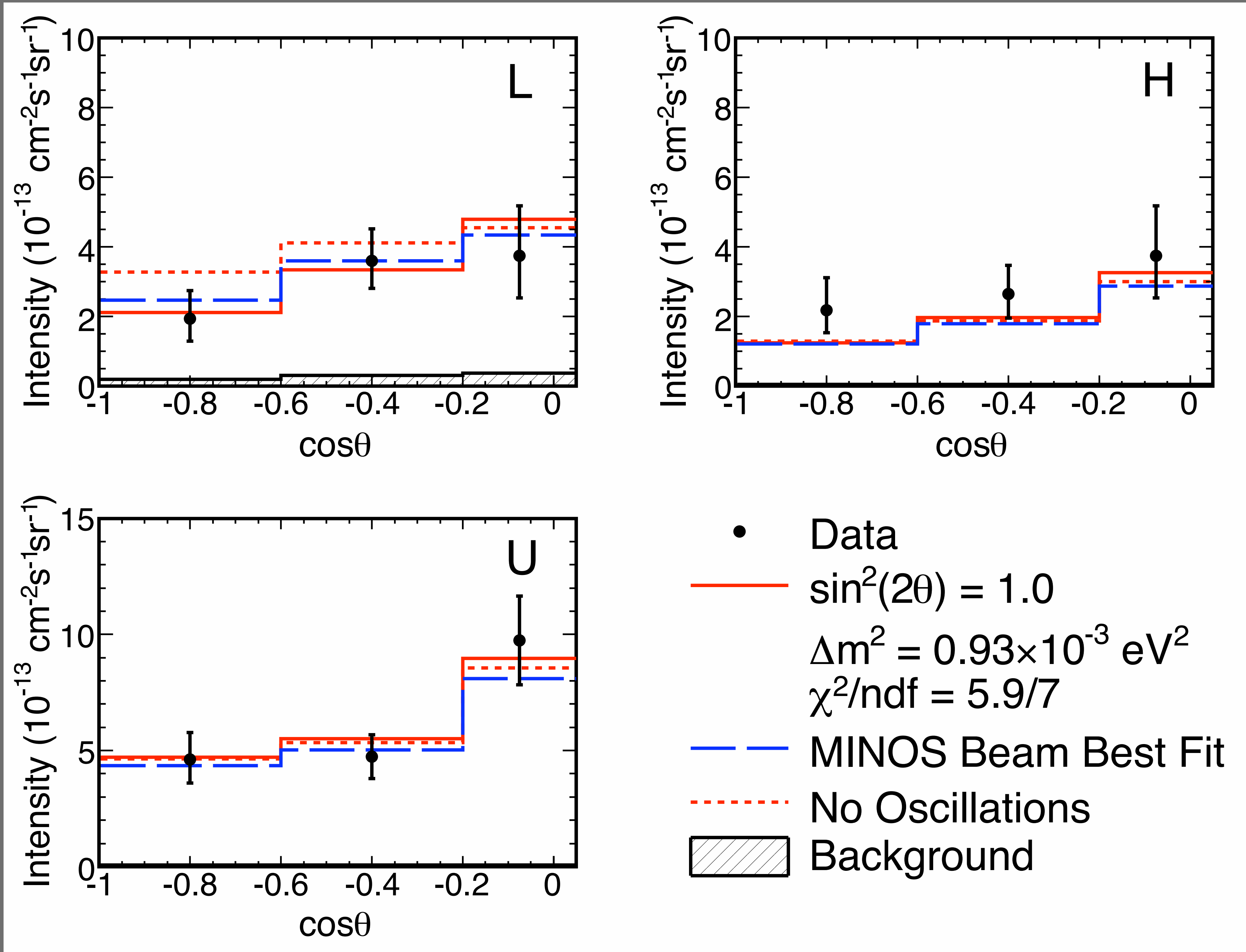
ν Energy Distribution



p_{fit} (GeV)	Data	Bkgd	MC
	μ^-		
1 – 10 (L)	21	2.2	37.5
10 – 100 (H)	20	0.2	17.5
	μ^+		
1 – 10 (L)	16	1.3	19.3
10 – 100 (H)	13	0.2	8.6
	U		
unknown (U)	70	0.7	76.5

~850 days: 140 ν_μs

zenithal distribution



hep-ex/0701045

Beam Physics

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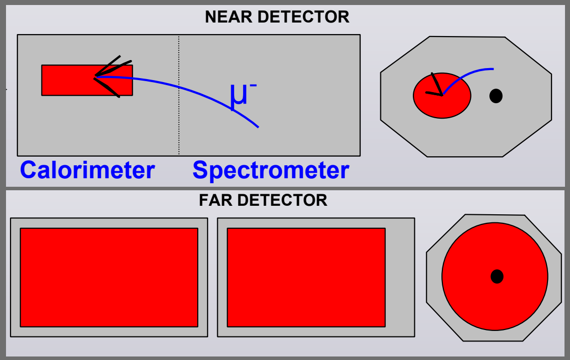

Event Selection

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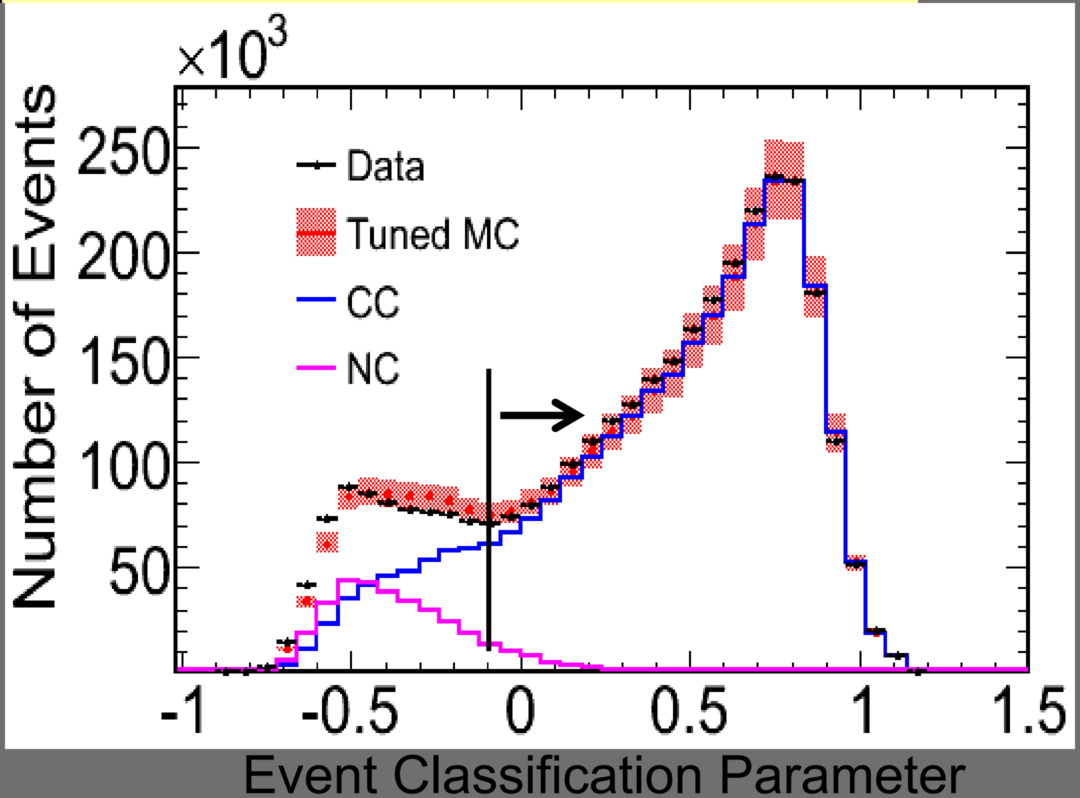
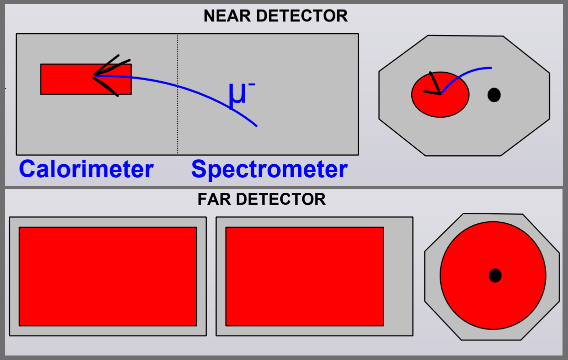
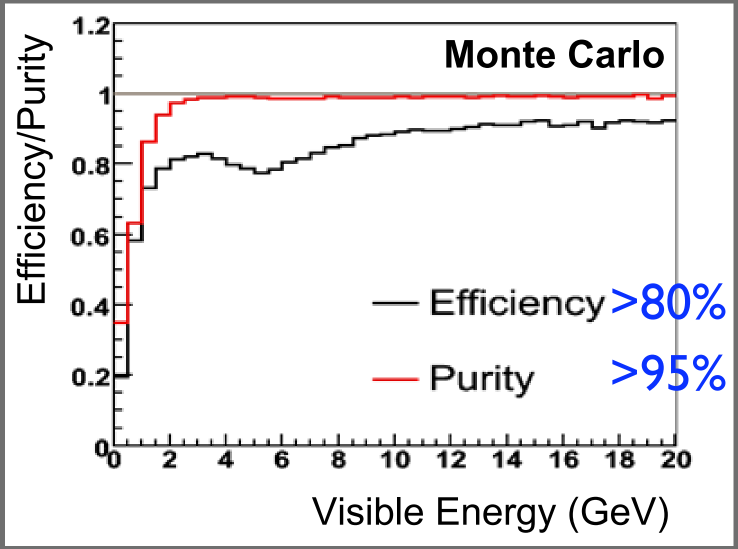
  - observed μ-: CC-quasielastic and low-“y”
  - NC contamination: pattern-ID hard <1.5GeV

$$PID = -(\sqrt{-\log(P_\mu)} - \sqrt{-\log(P_{NC})})$$







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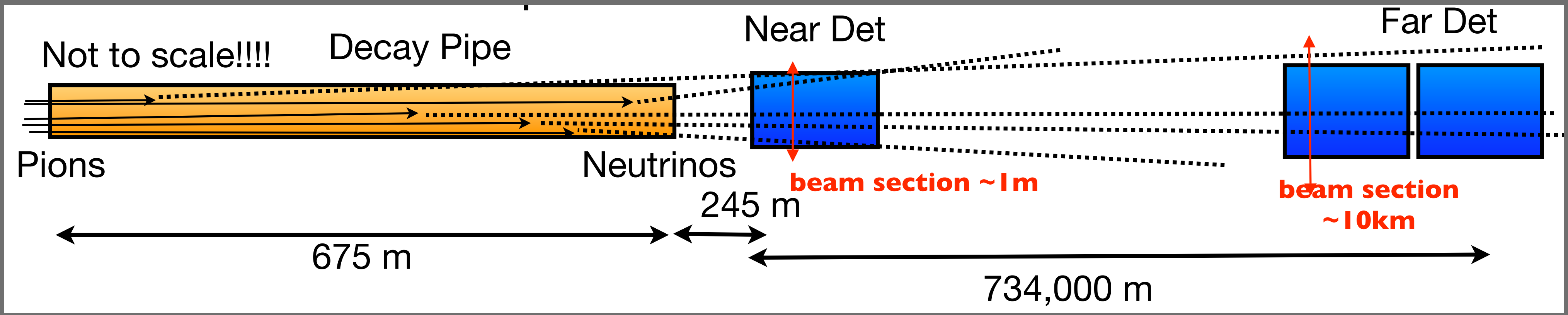

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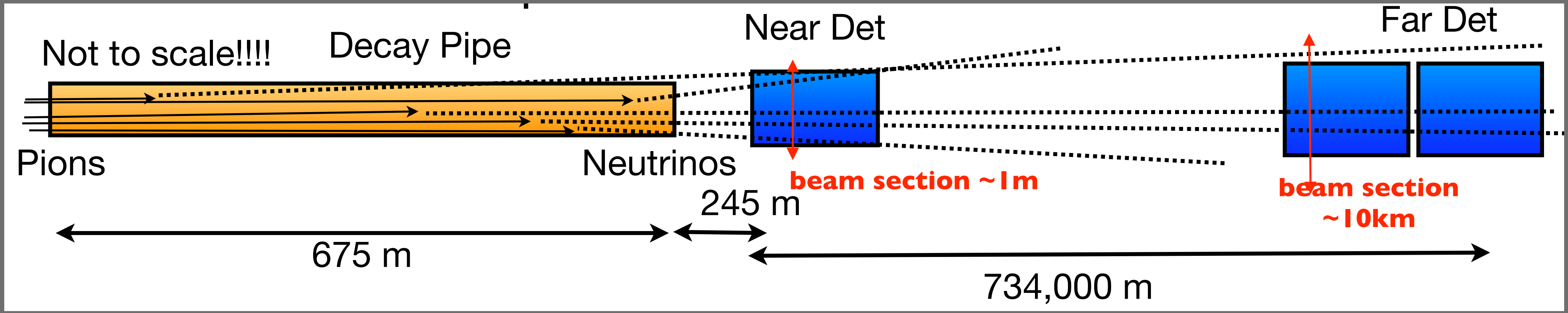

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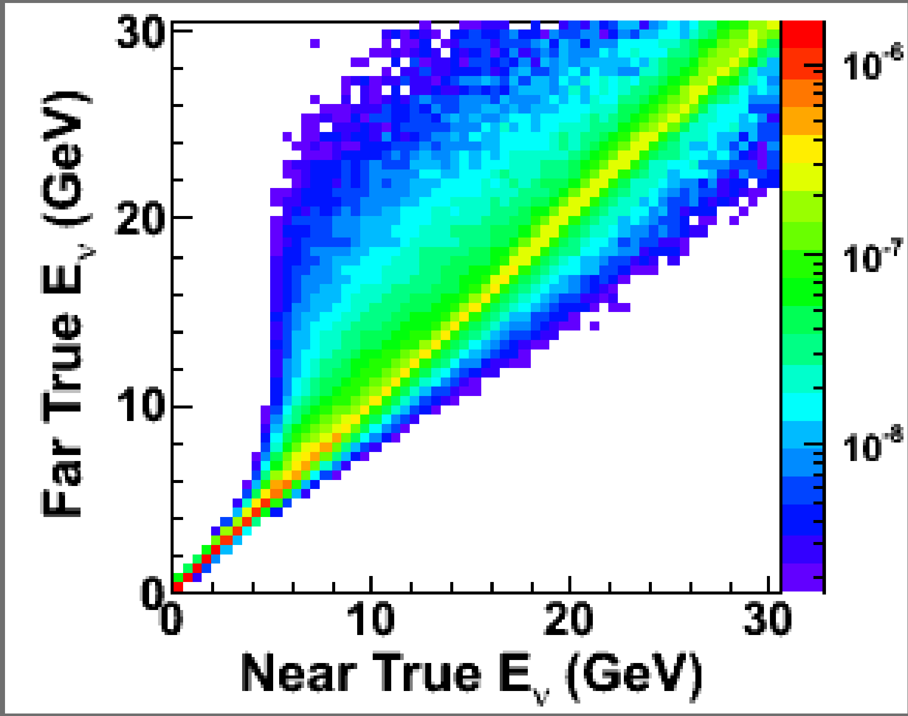

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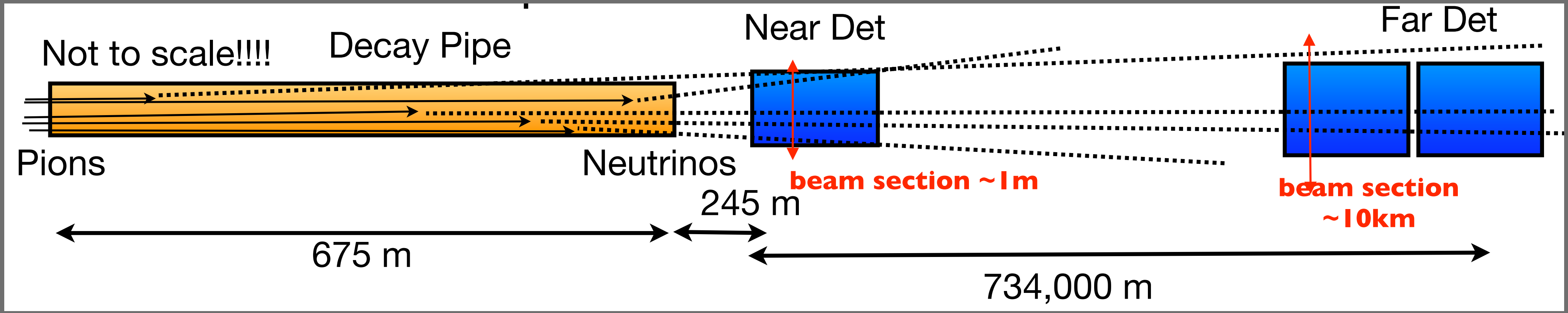

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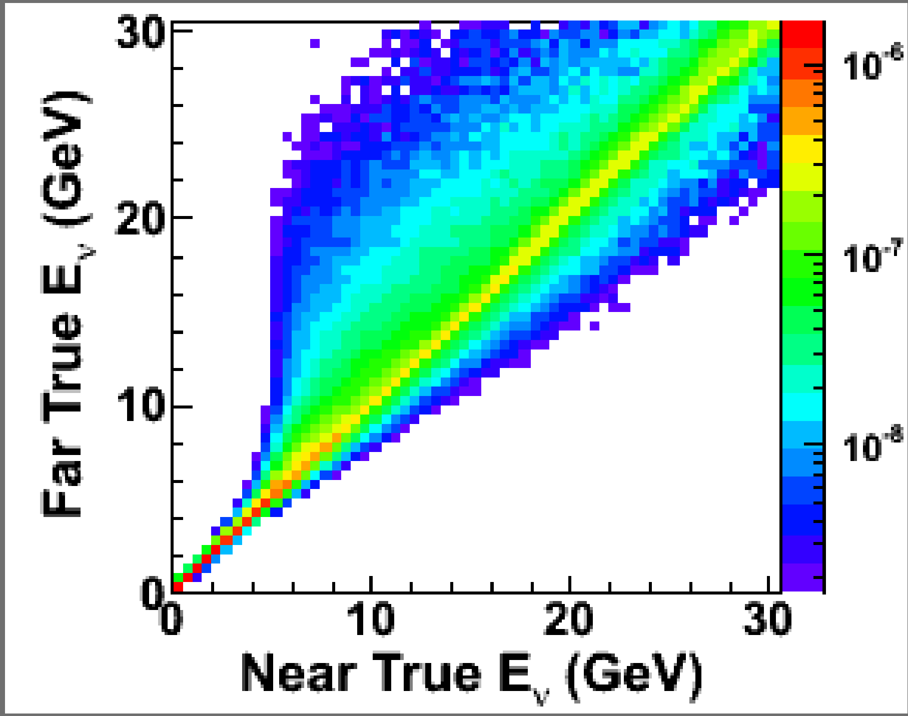
- ND more low E νs (high angle)
- ND-νs ≠ FD-νs!!!



ND to FD extrapolation

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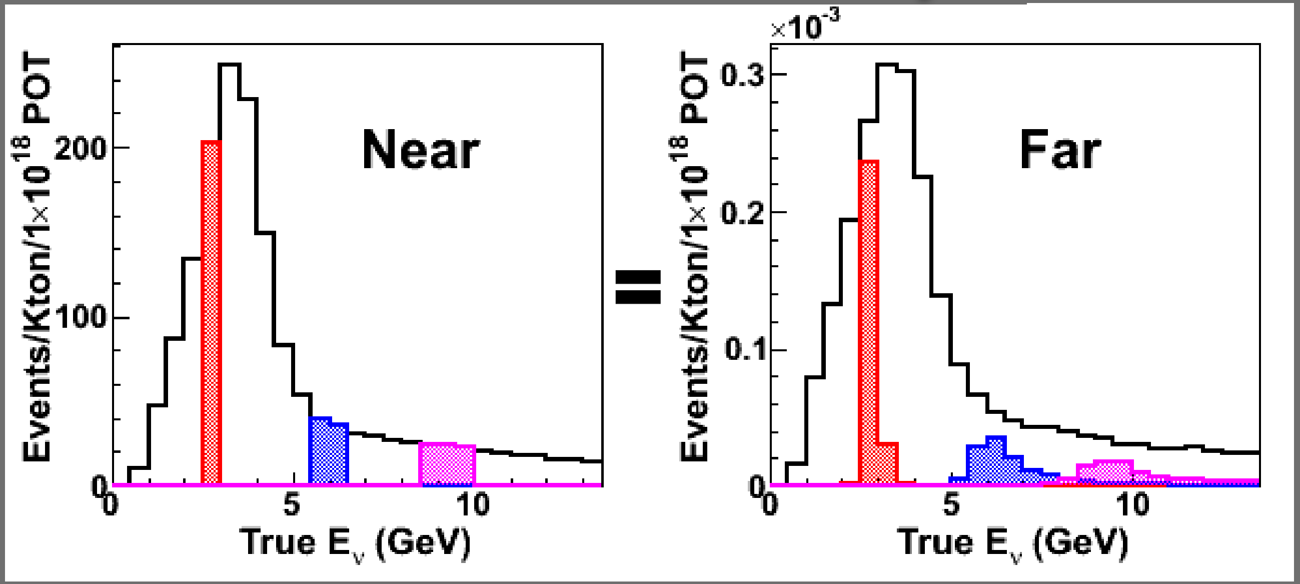

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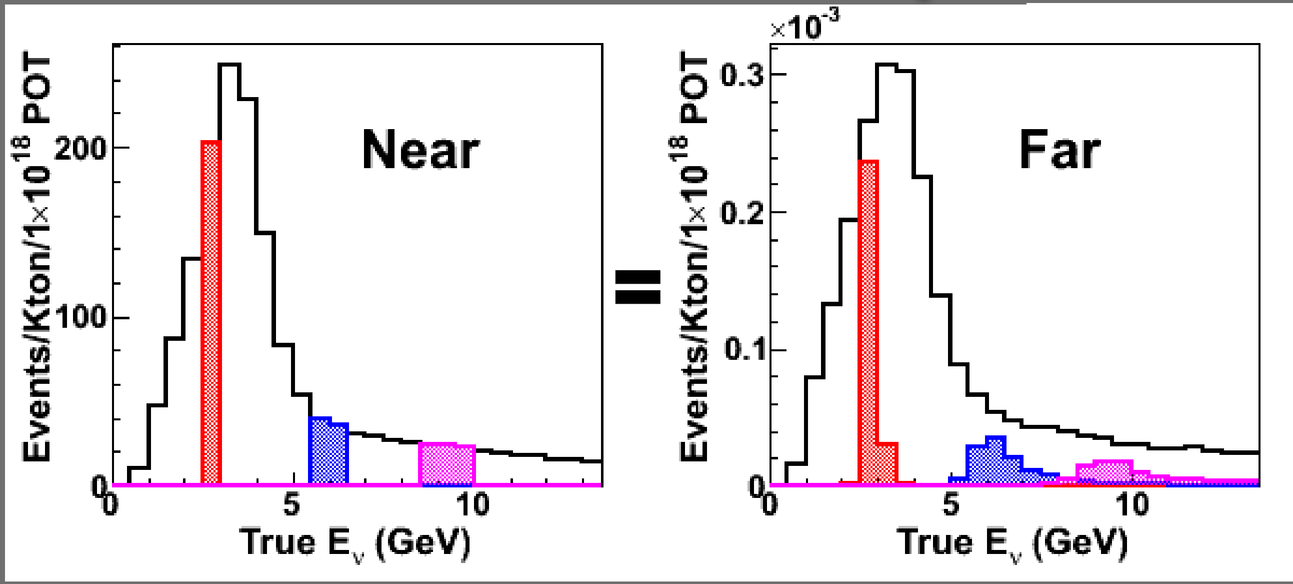
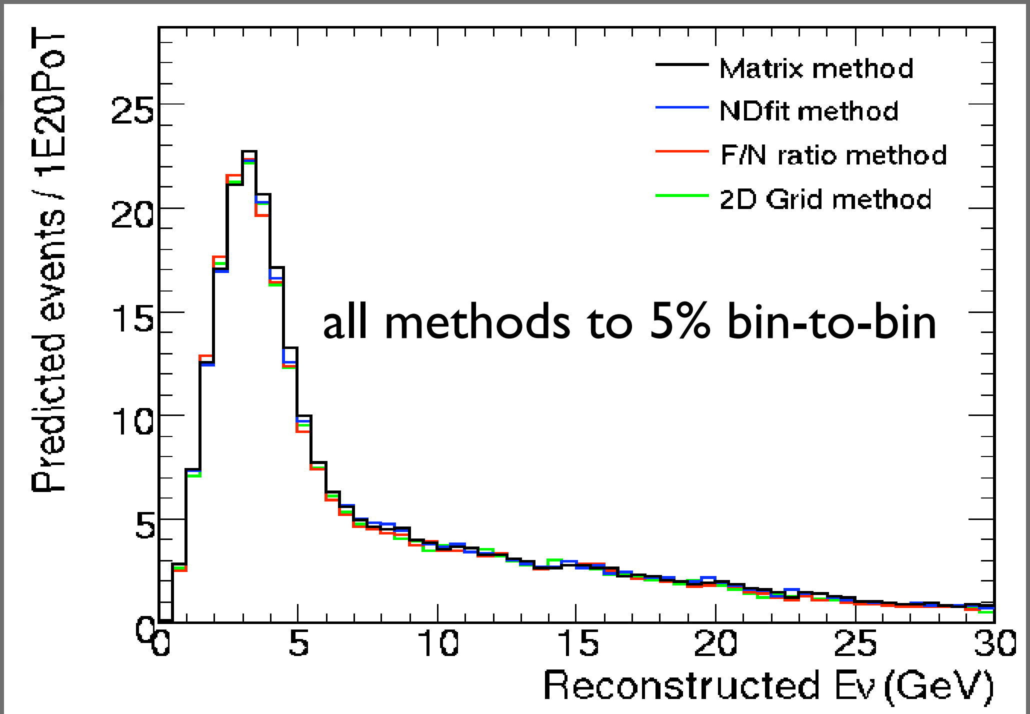


- Detector MC:
  - acceptances & responses
- Predict $\nu_{ND} \Rightarrow \nu_{FD}$
- Verify with 3 more methods
  - Fitting ND PDFs
  - More direct extrapolation



MINOS: rate information

Data sample	observed	expected	ratio
ν_μ only (< 30 GeV)	215	336.0 ± 14.4	0.64 ± 0.05
ν_μ only (< 10 GeV)	122	238.7 ± 10.7	0.51 ± 0.05
ν_μ only (< 5 GeV)	76	168.4 ± 8.8	0.45 ± 0.06

- Energy dependent deficit of events
- 49% deficit below 10 GeV - 6.2σ (stat+sys)

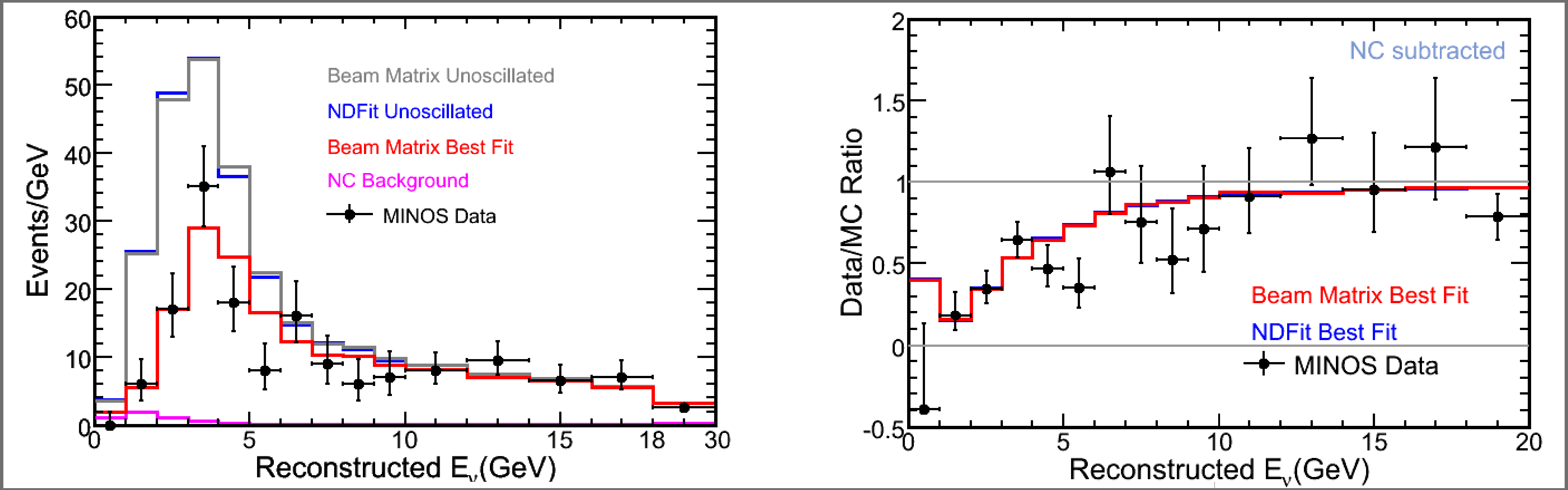
hep-ph/0607088
MINOS@Nu06

Δm^2 Measurement

$$\chi^2 = \sum_{i=1}^{\text{nbins}} \left[2(e_i - o_i) + 2o_i \ln(o_i / e_i) \right] + \boxed{\sum_{j=1}^{\text{nsys}} \Delta s_j^2 / \sigma_{s_j}^2}$$

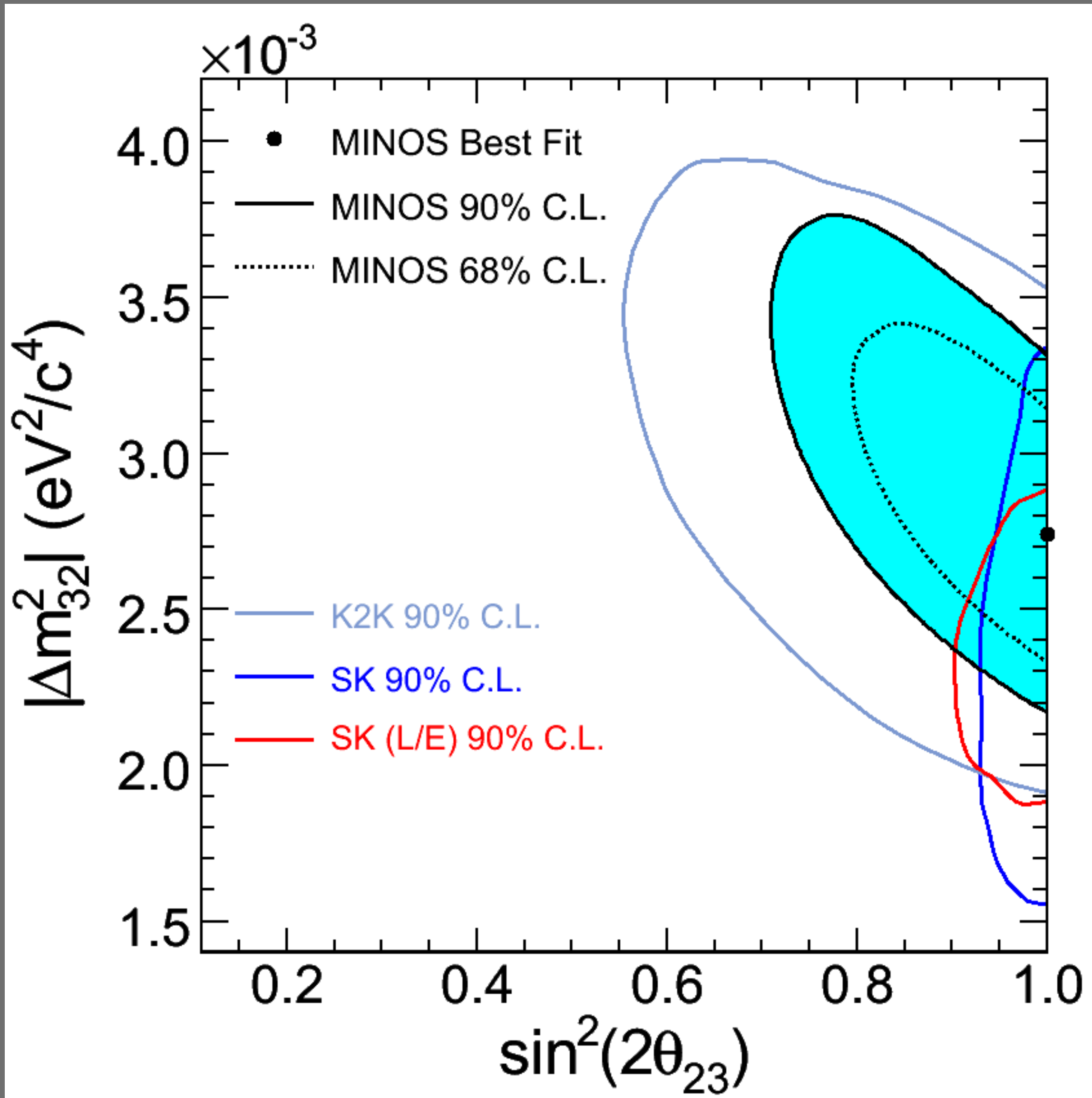
Penalty terms for systematic uncertainties

E/L modulation

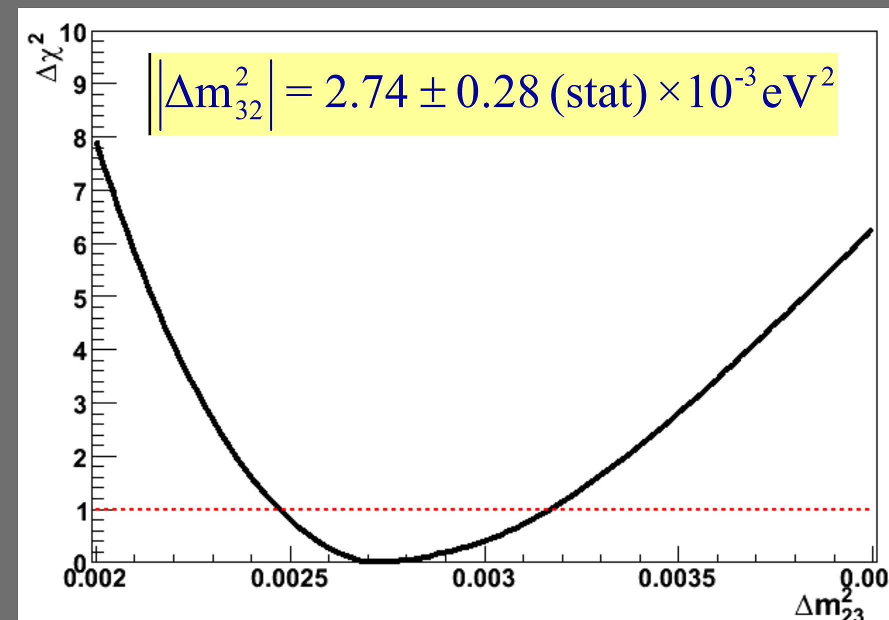


(also @: K2K, SK and KamLAND)

Δm^2 Measurement



1 d.o.f.: $\sin^2(2\theta_{23})=1$



$$|\Delta m^2_{32}| = 2.74^{+0.44}_{-0.26}\ (\text{stat}+\text{syst}) \times 10^{-3}\ \text{eV}^2$$

$$\sin^2 2\theta_{23} = 1.00_{-0.13}\ (\text{stat}+\text{syst})$$

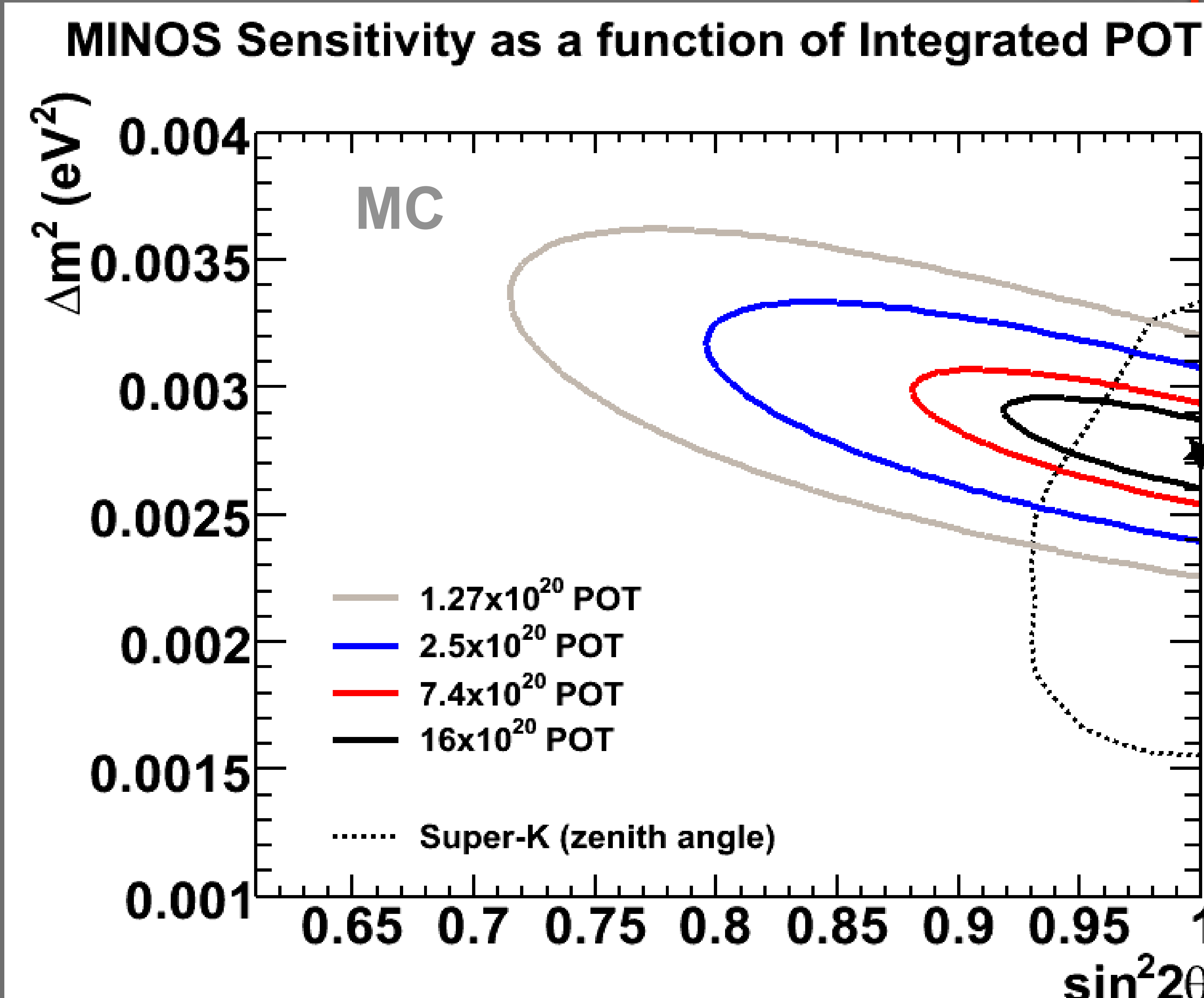
$$\text{Normalization} = 0.98$$

Fit constrained to physical region

$2x\sigma_{syst} \sim \sigma_{stat}$

potential ~5%measurement

Prospects


MINOS Sensitivity as a function of Integrated POT
MC
Δm² (eV²)
0.004
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
sin²2θ
1.27x10²⁰ POT
2.5x10²⁰ POT
7.4x10²⁰ POT
16x10²⁰ POT
Super-K (zenith angle)

looking for θ_{13}...

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CHOOZ @ 90%CL

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CHOOZ @ 90%CL

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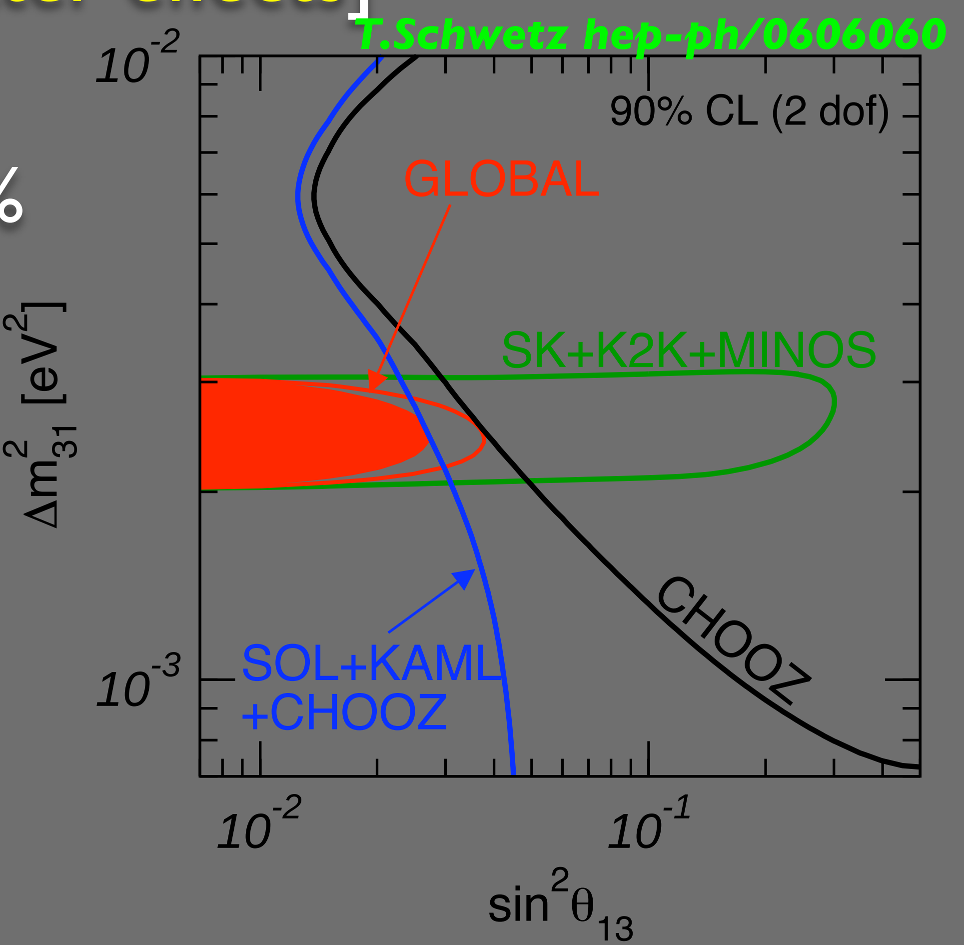
Global Analysis @ 90%CL



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Lindner@NOW2006

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  - correlation: δ_{CP}, θ_{13},θ_{23} degeneracy and matter effects*

$$\begin{aligned} P(\nu_\mu \to \nu_e) \simeq\ & \boxed{\sin^2 2\theta_{13}}\boxed{\sin^2 \theta_{23}} \sin^2 \Delta \\ \boxed{\mp}\ & \alpha \boxed{\sin 2\theta_{13}}\boxed{\sin \delta_{CP}} \sin 2\theta_{12} \boxed{\sin 2\theta_{23}} \Delta \sin^2 \Delta \\ +\ & \alpha \boxed{\sin 2\theta_{13}}\boxed{\cos \delta_{CP}} \sin 2\theta_{12} \boxed{\sin 2\theta_{23}} \Delta \cos \Delta \sin \Delta \\ +\ & \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \Delta^2 \end{aligned}$$

$$\Delta \equiv \Delta m^2_{31} L/(4E_\nu)$$

$$\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$$

beam sensitivity illustration

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- appearance

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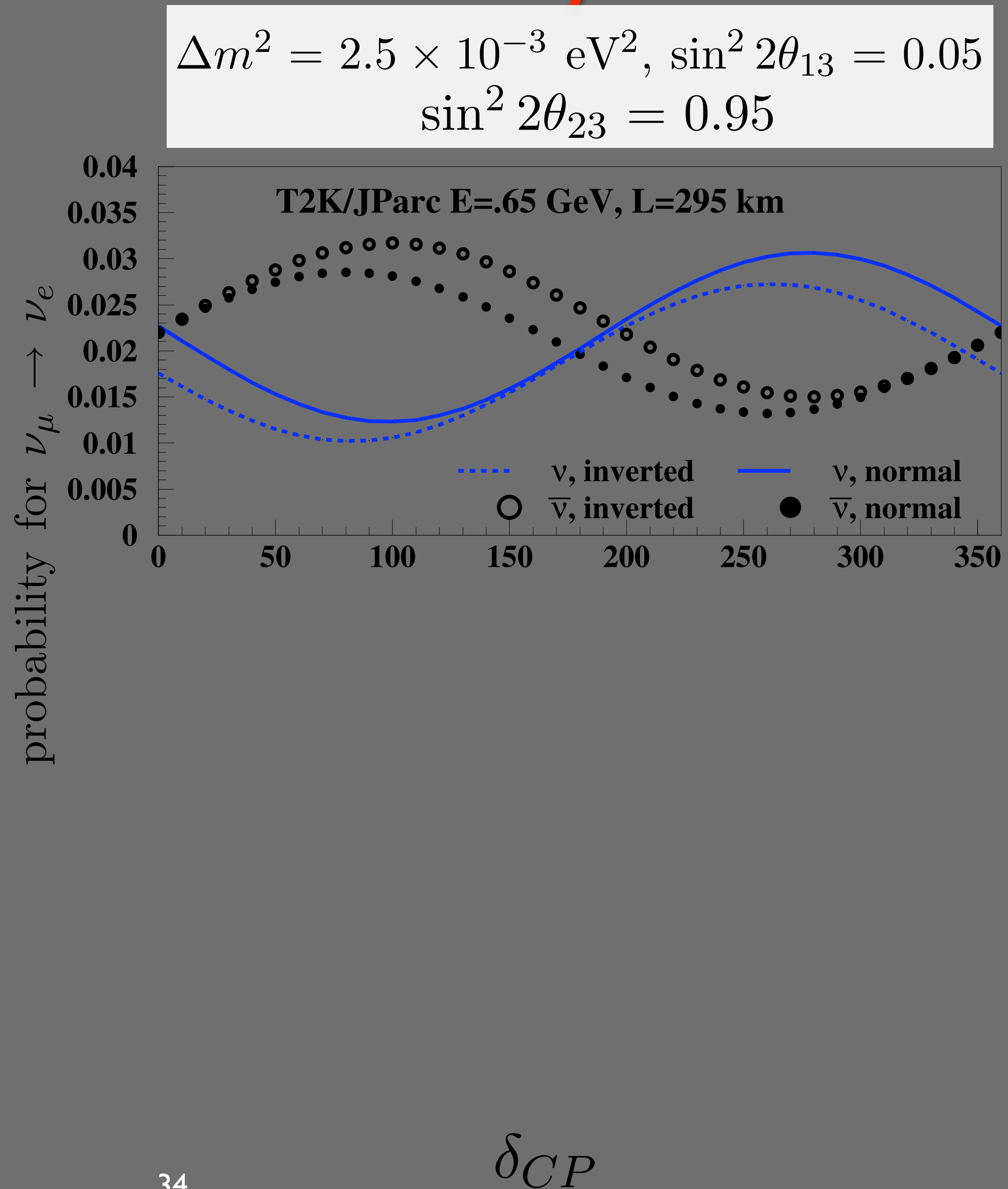

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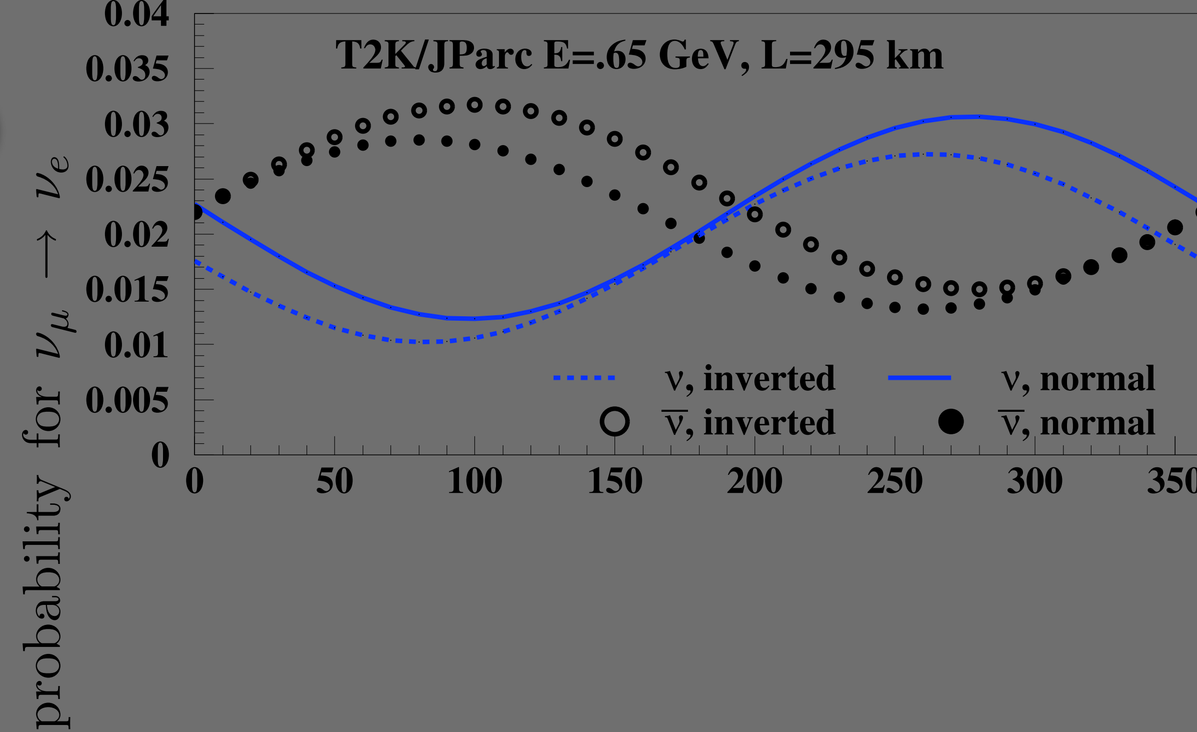

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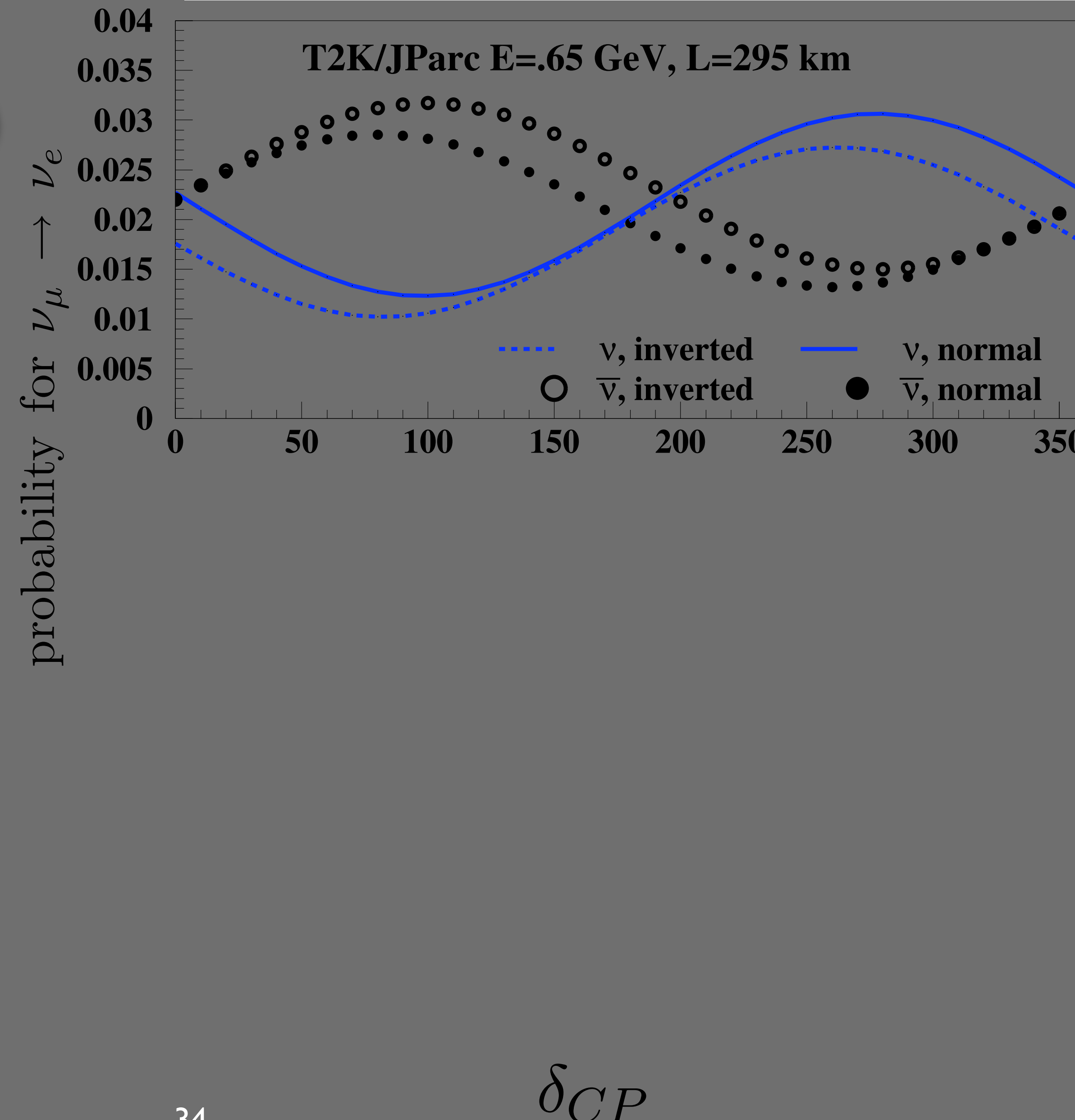

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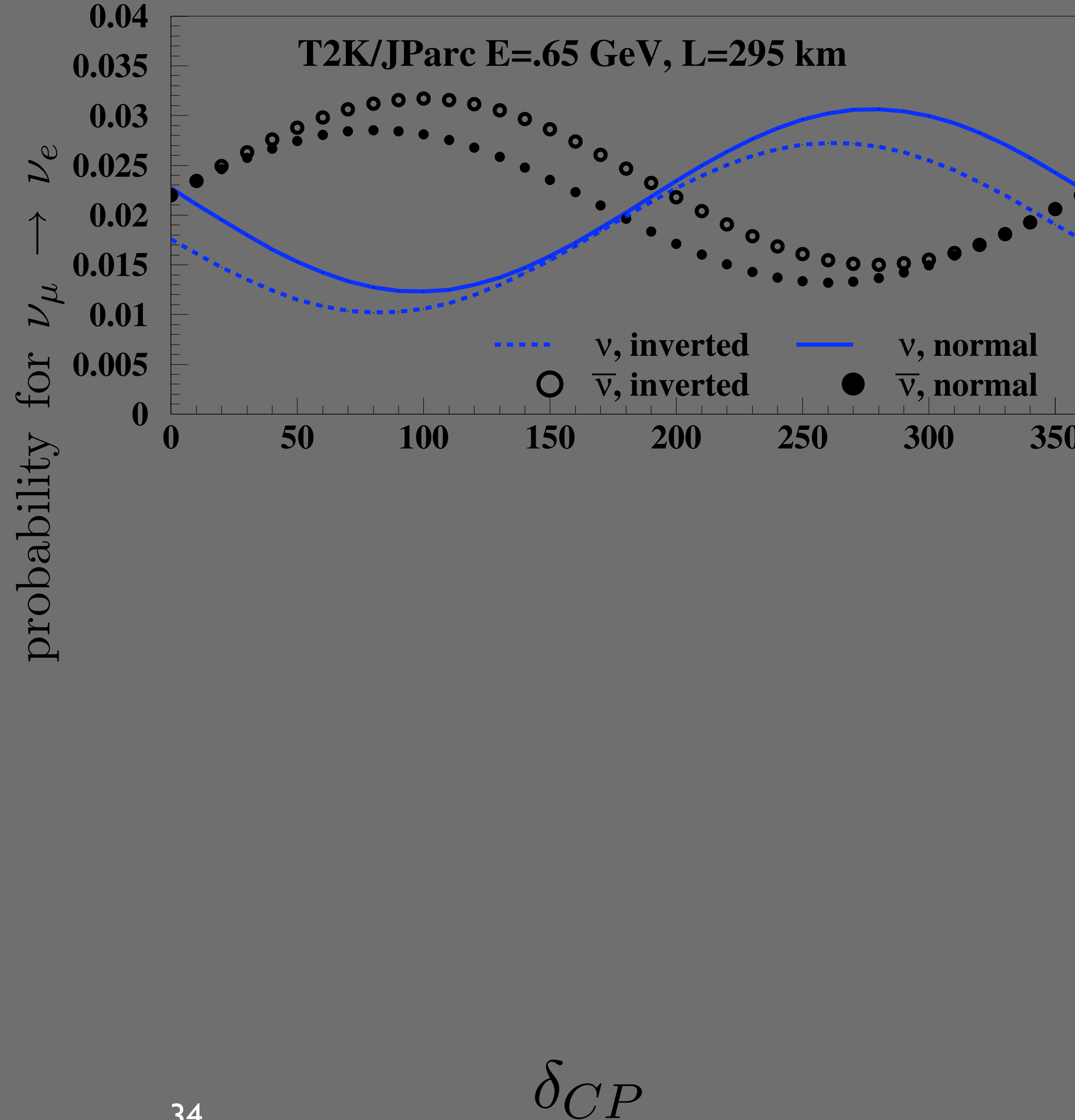

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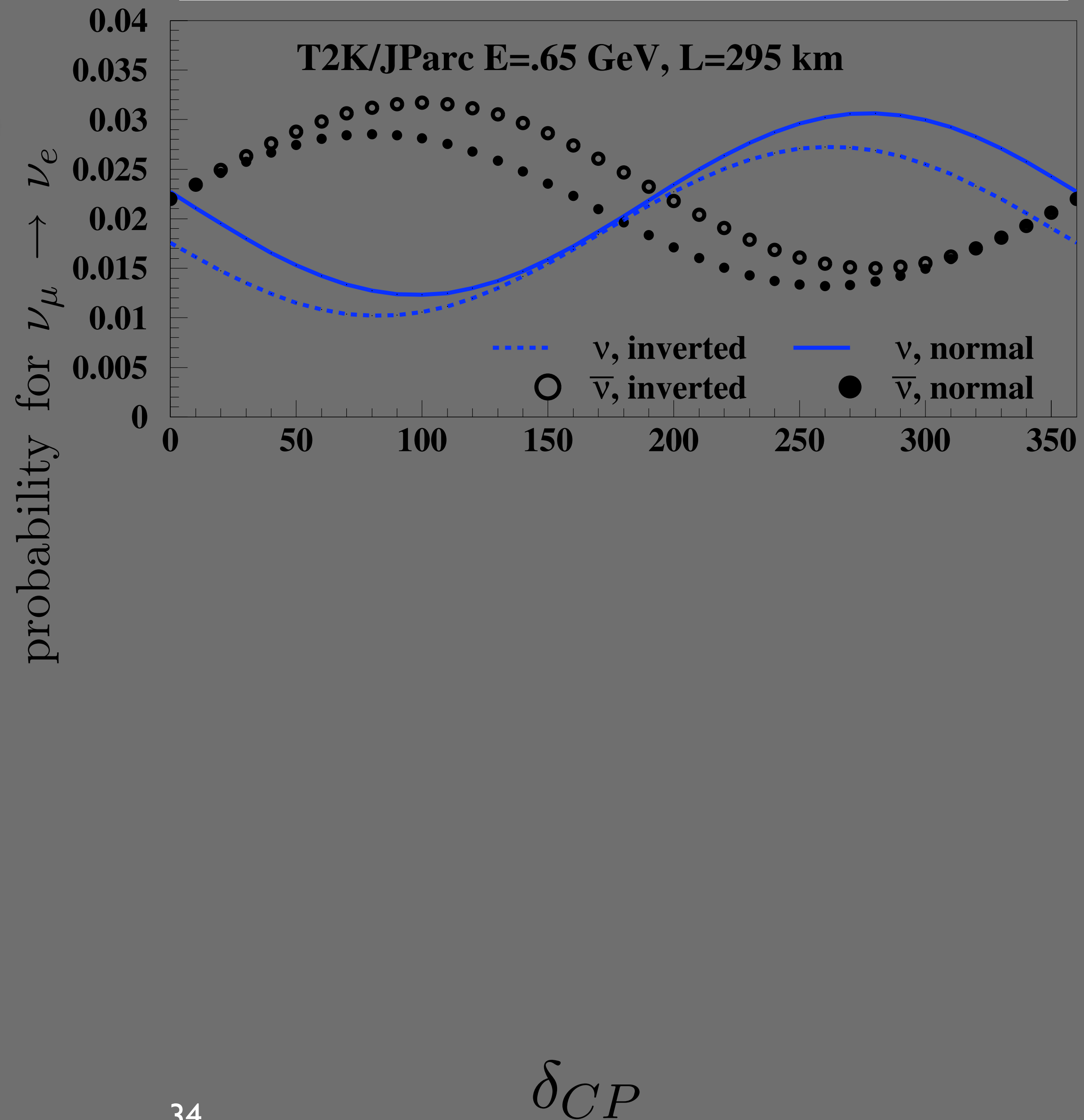

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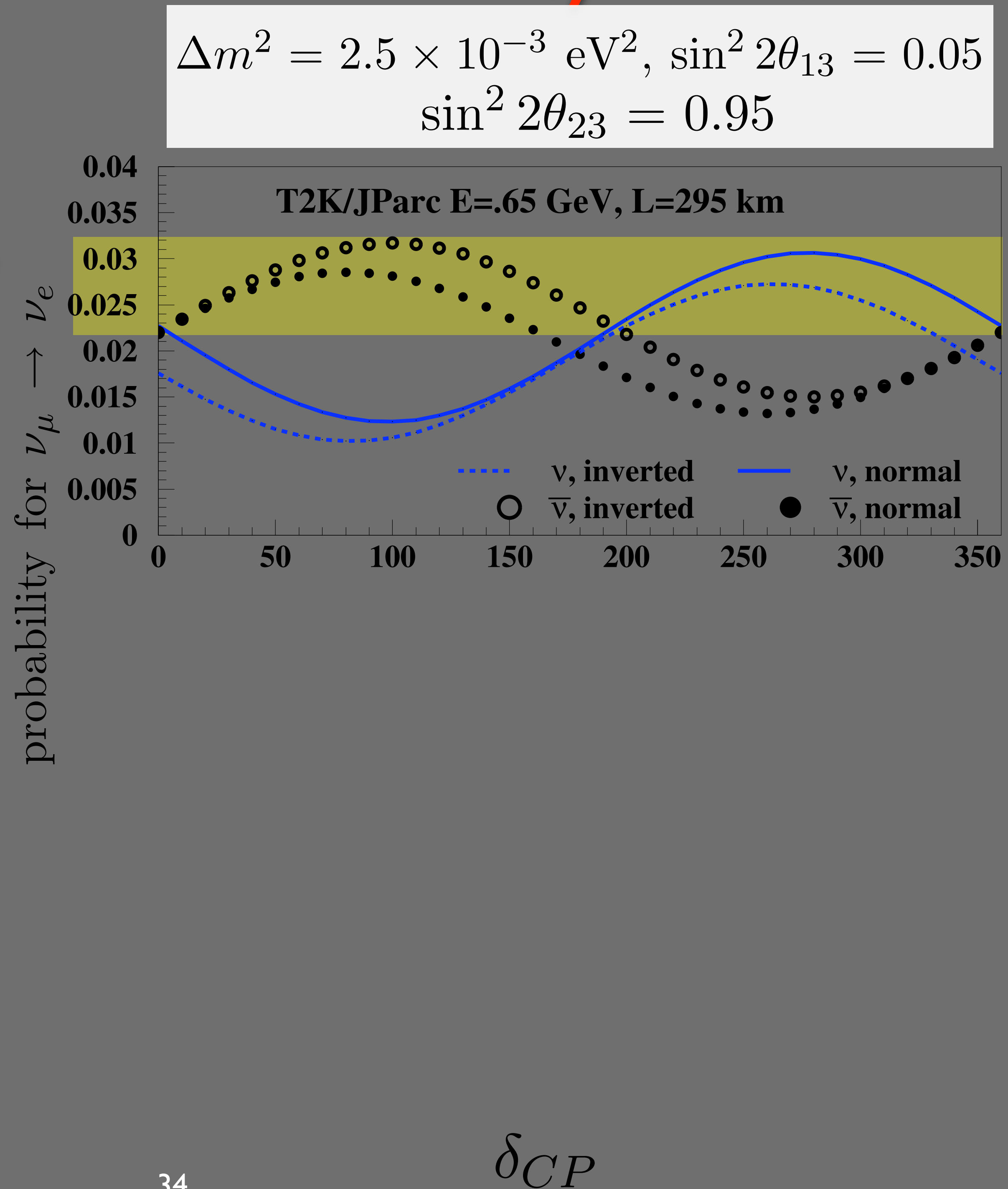

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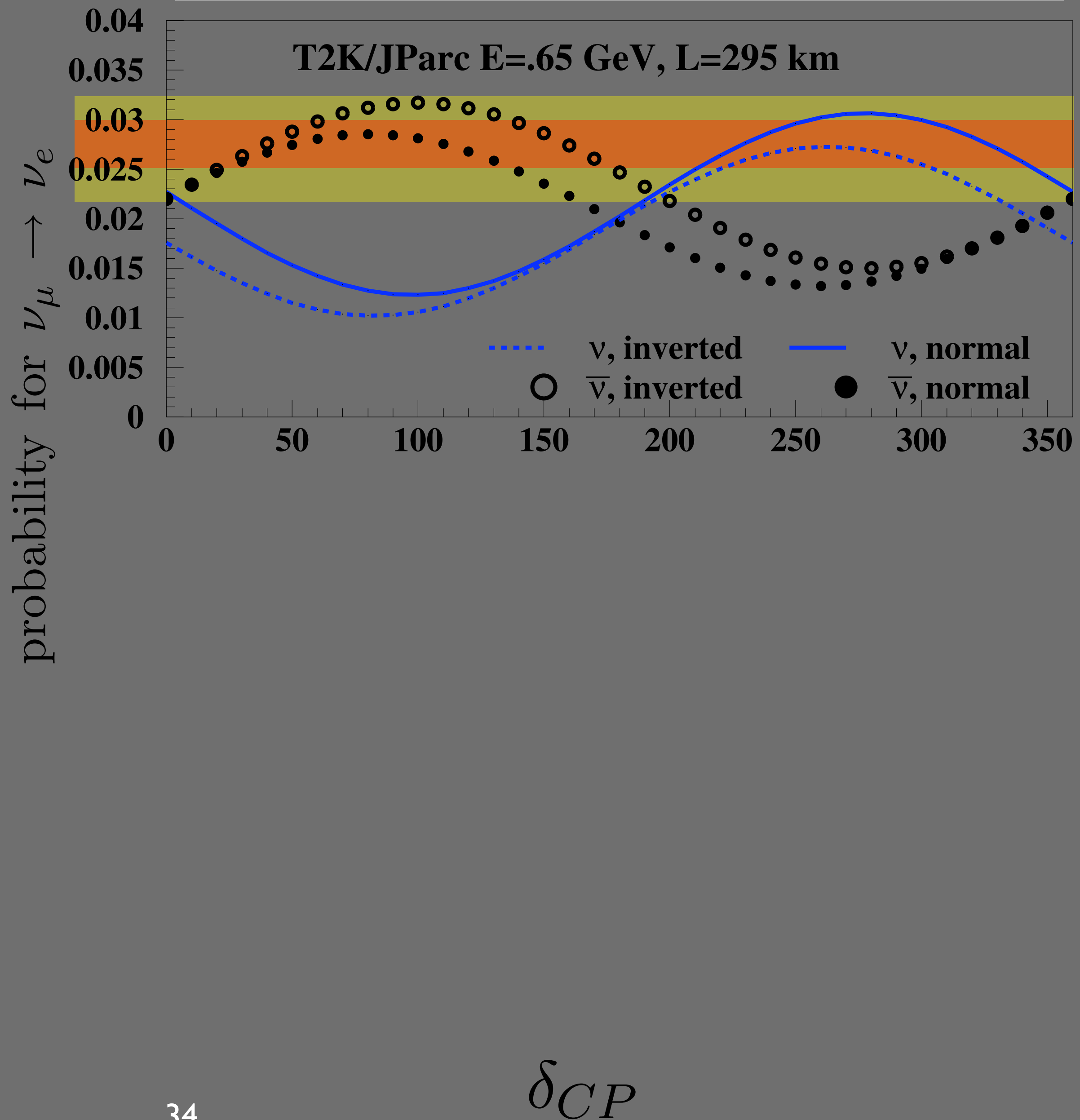

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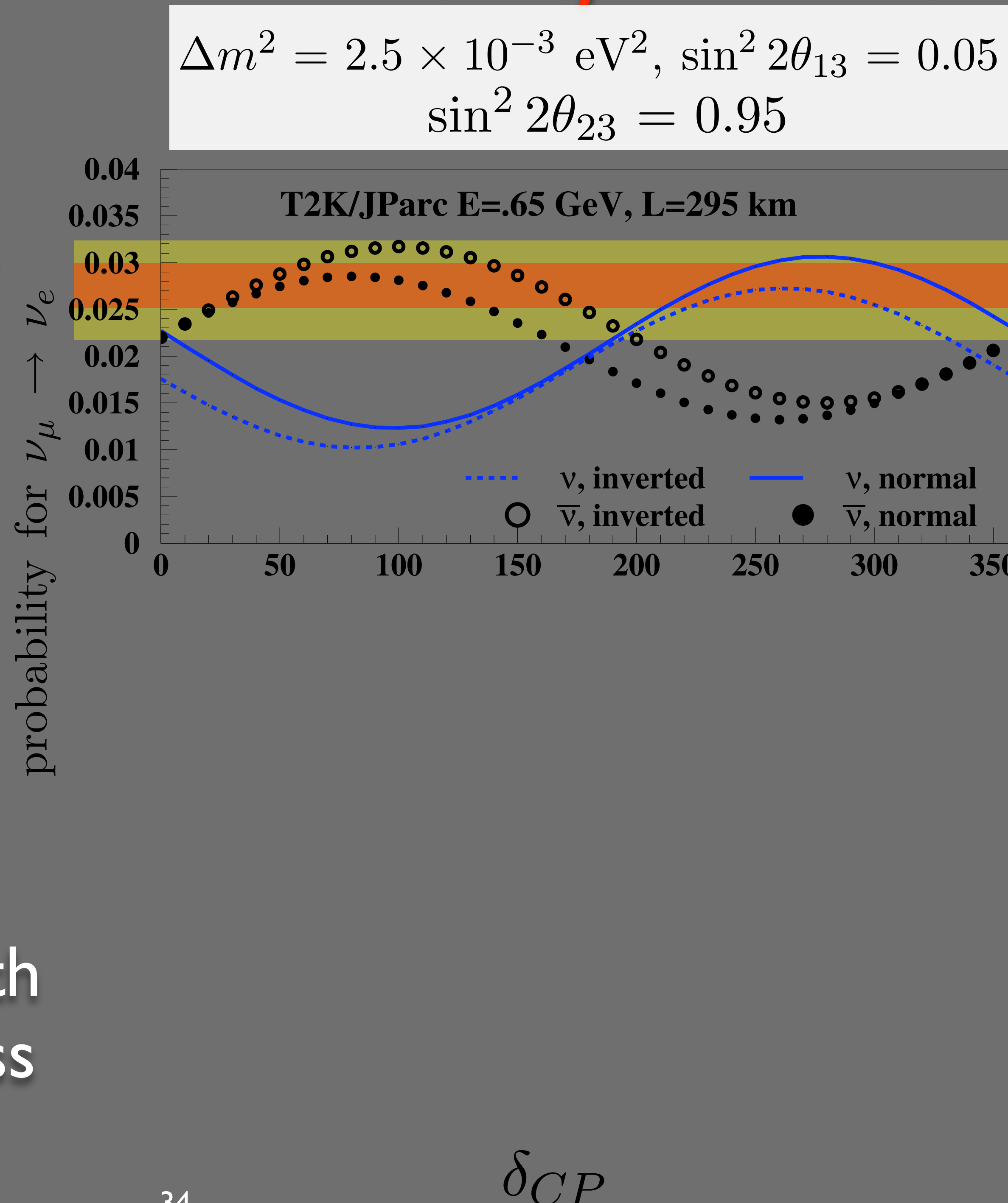

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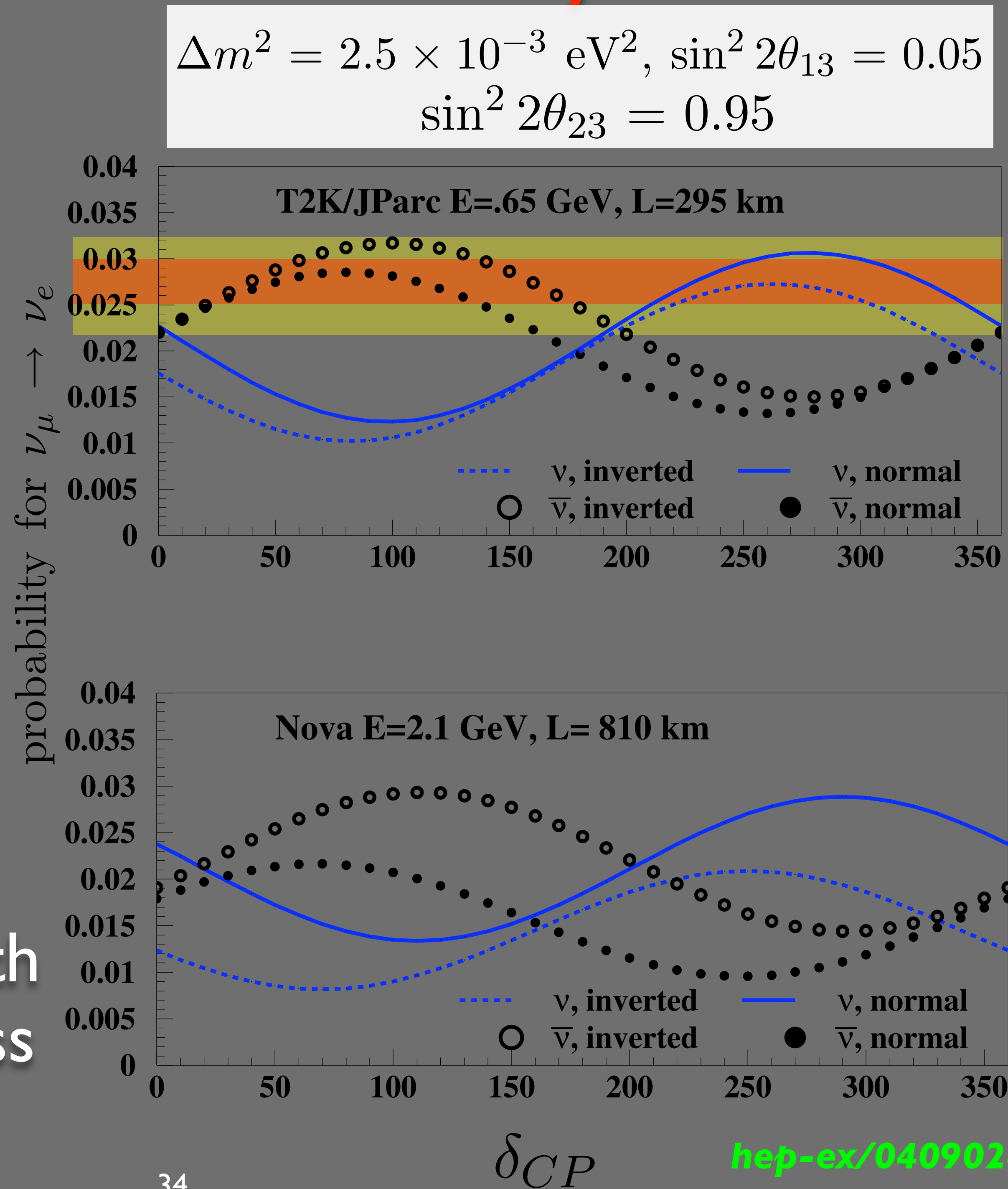
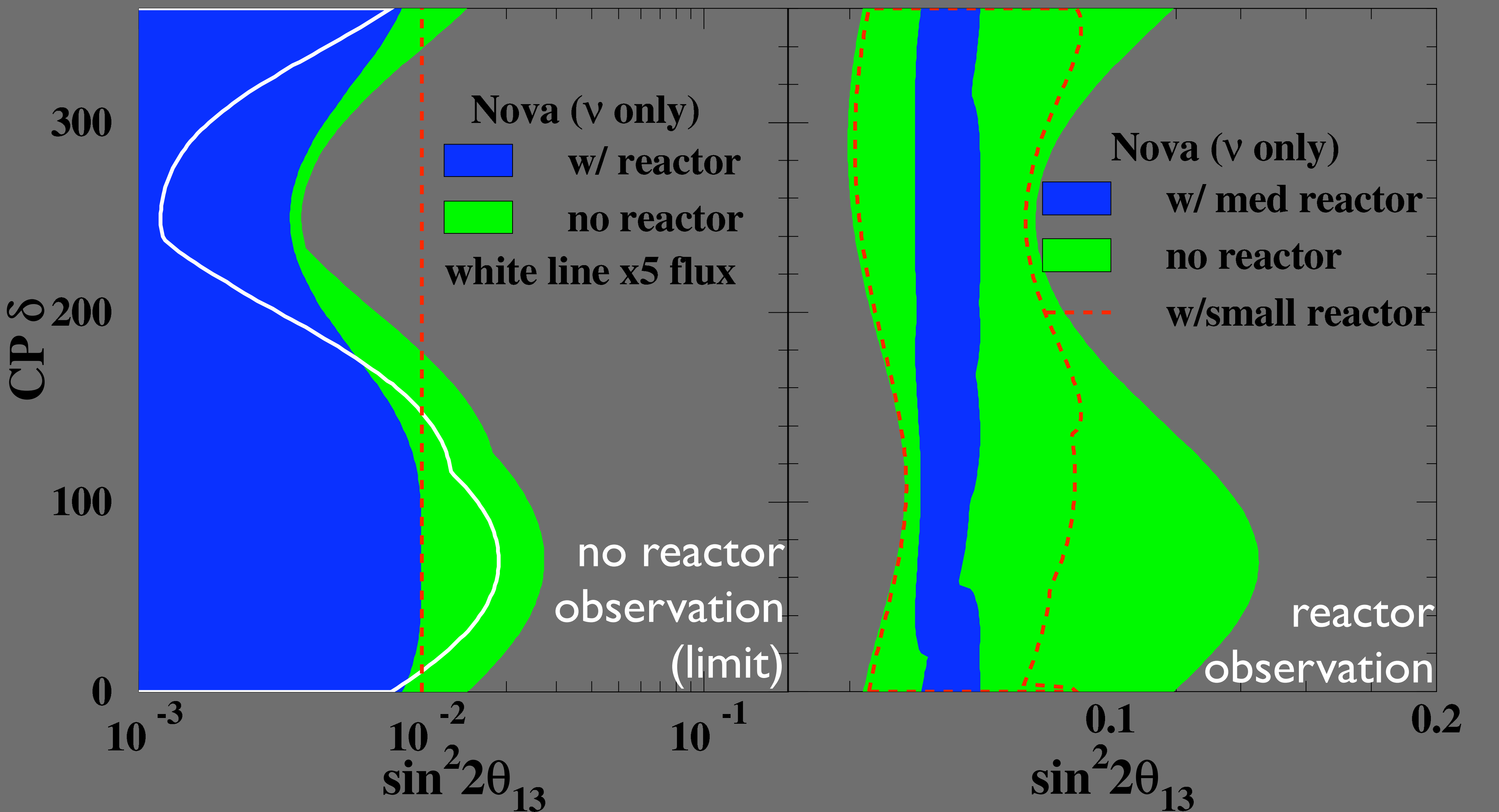


hep-ex/0409028

complementarity illustration

beam + reactor experiments combination



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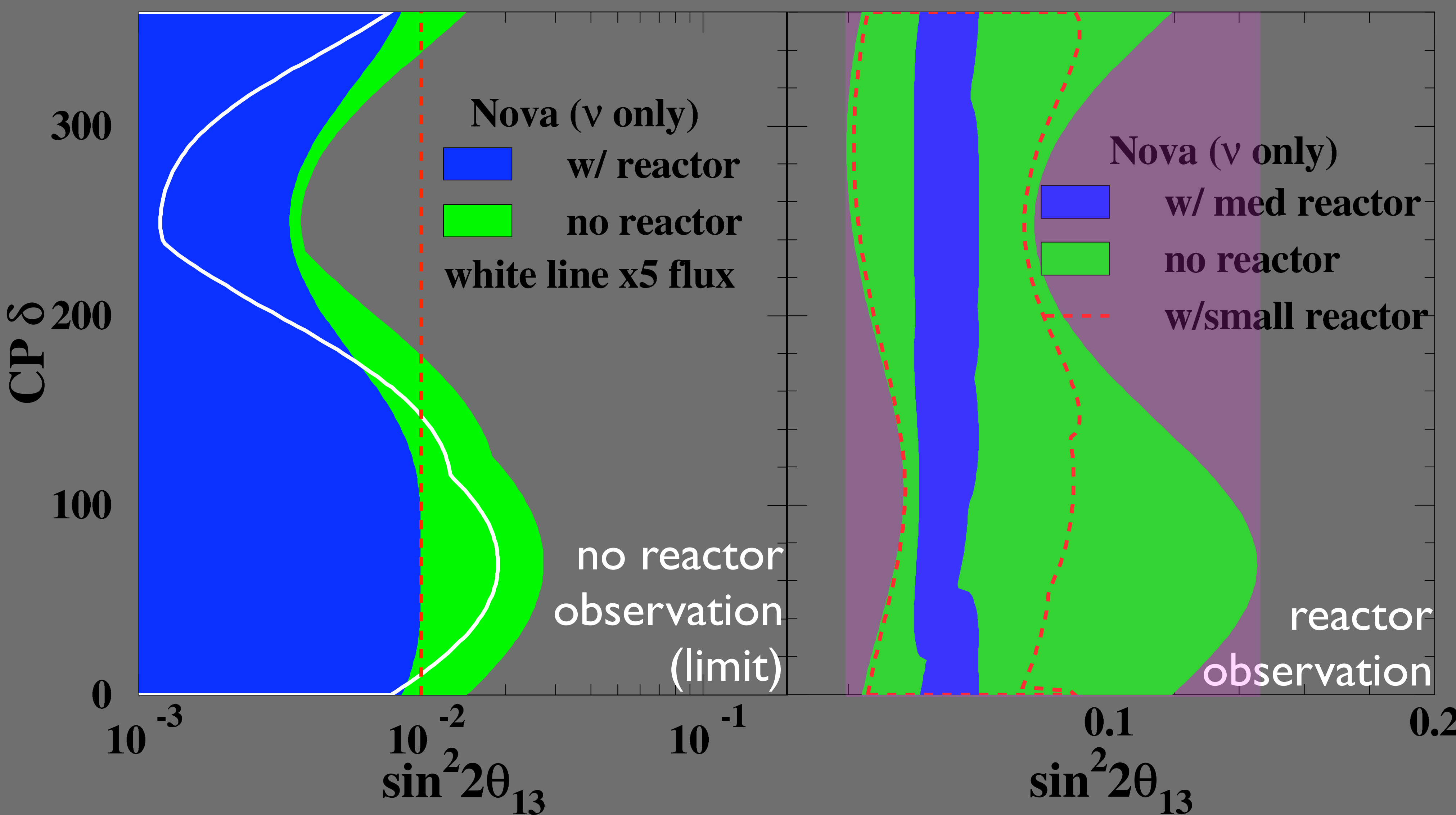

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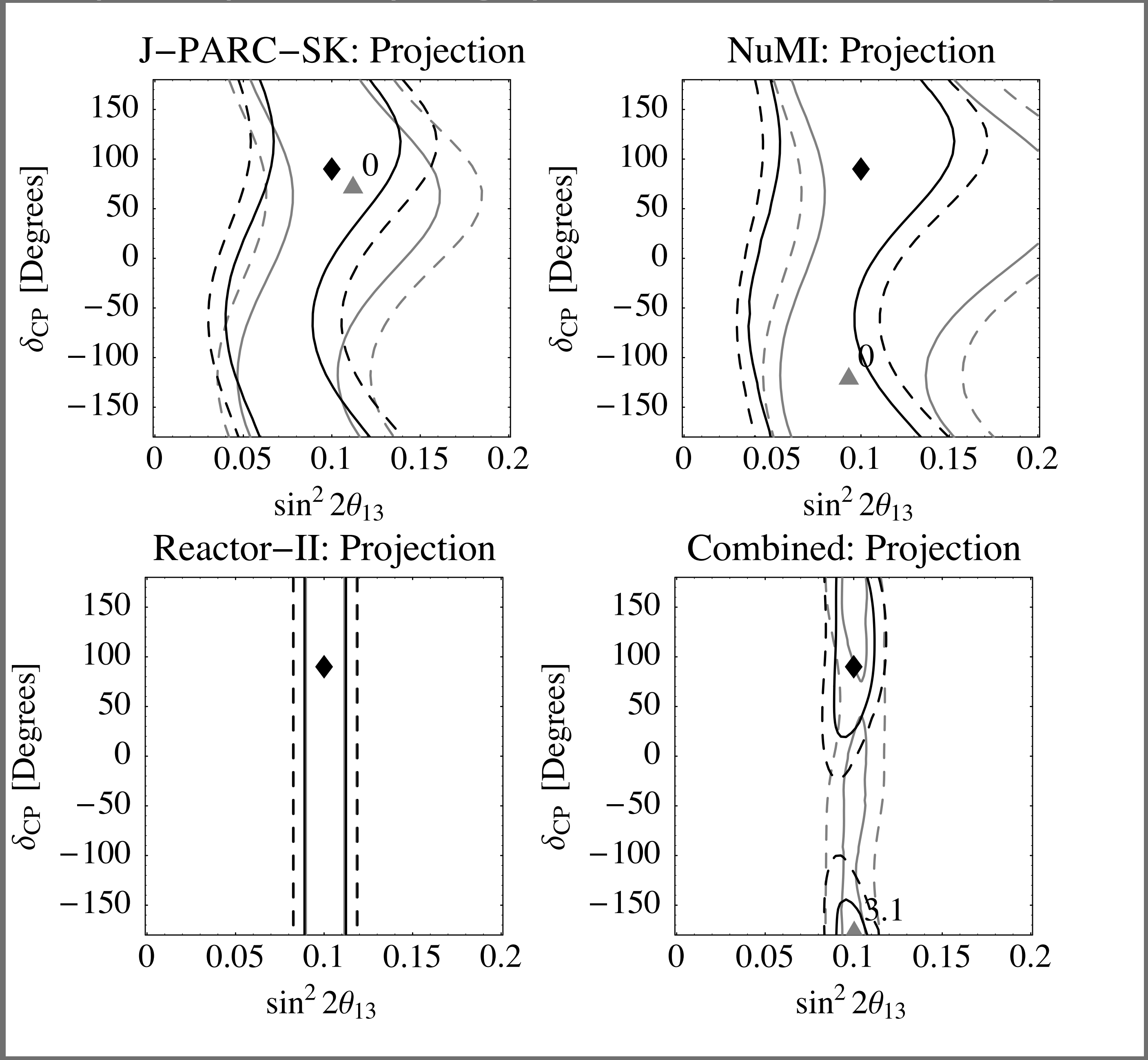
Reactor+T2K+NOvA

δ_{CP}=90, $\sin^2(2\theta_{13})$=0.1 (large), $\Delta m^2>0$, $\Delta m^2<0$ (ν only)



hep-ph/0403068

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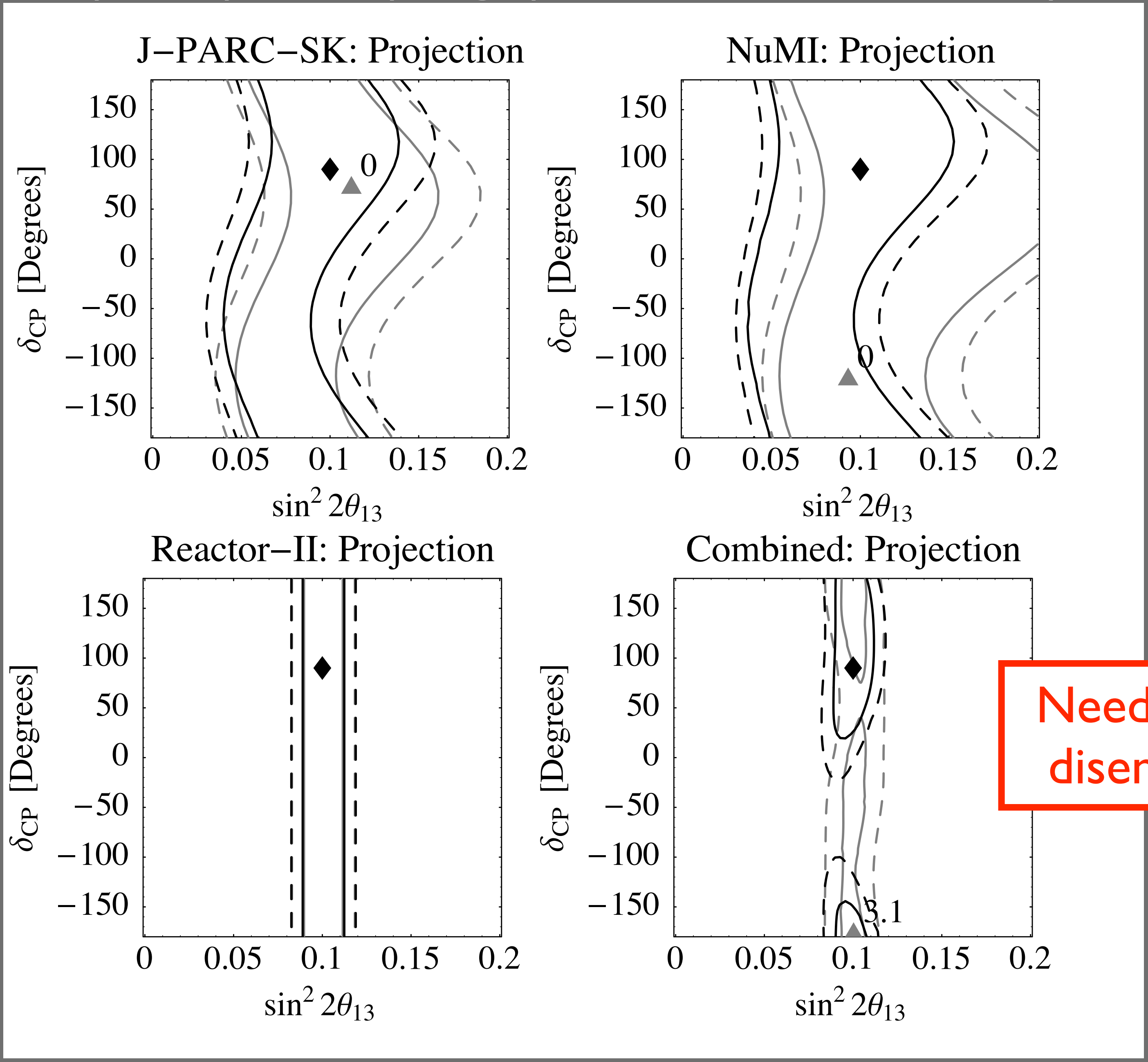
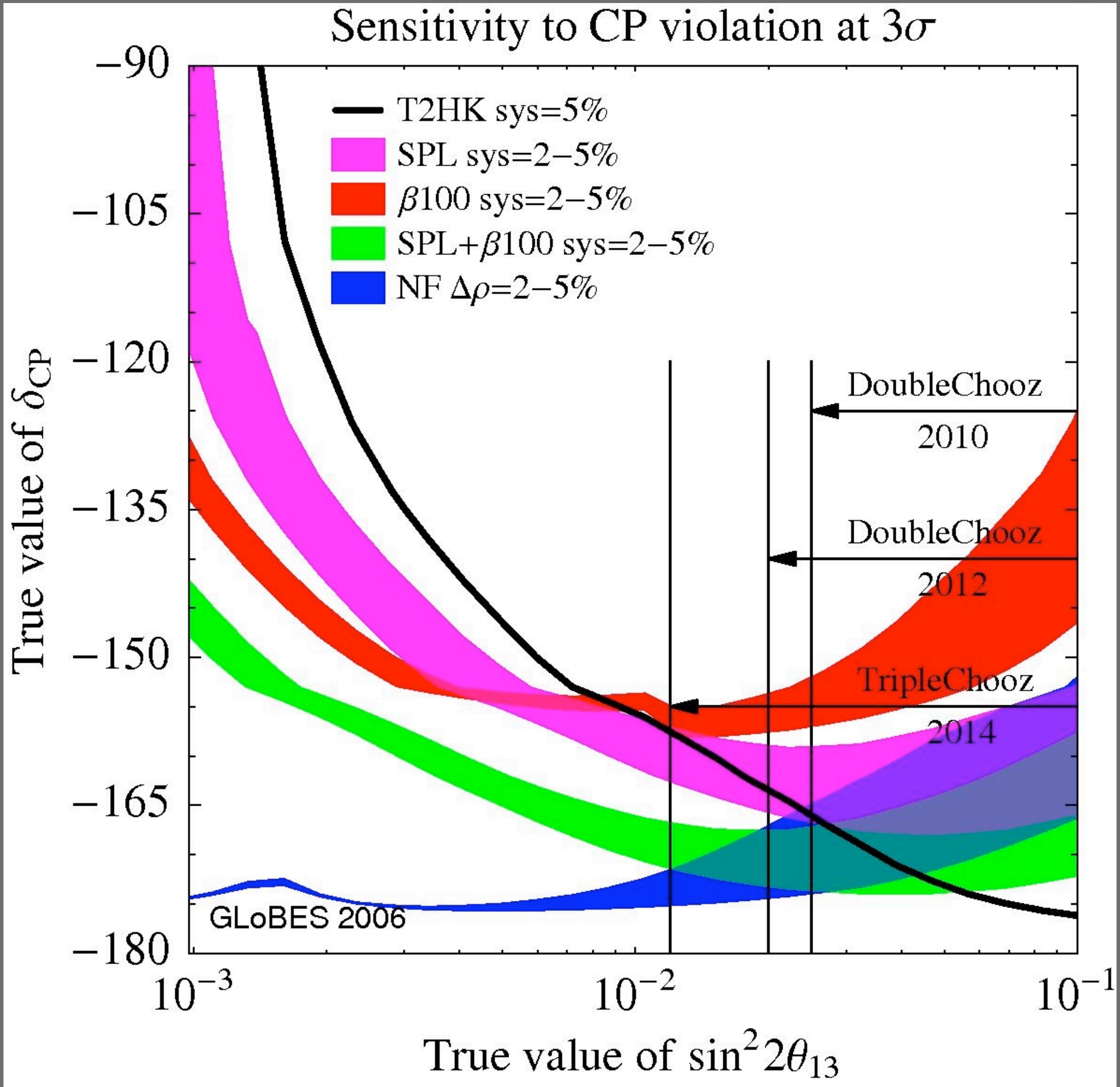


Needs all to disentangle

hep-ph/0403068

Another way to complement...



choose the most suitable next step
upon previous experience

experiments θ_{13}
(next 5 years)

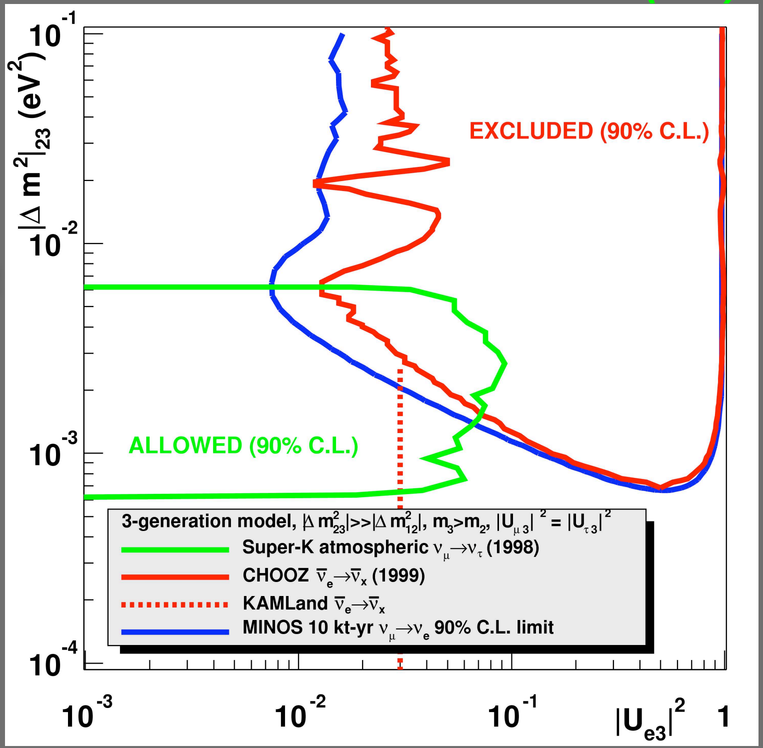
beam experiments

MINOS & OPERA
(“conventional beams”)

Conventional Beams (running)

- MINOS: measure Dm2: E/L tuning!
- Statistically limited (full set by 2010)
- If no observation: improved by ~2x the CHOOZ limit
- BG$_{OPERA}$: DIS & lower E from signal
- BG$_{MINOS}$: from ND extrapolation
- Off-axis: lower BG

MINOS TDR (old)



OPERA@NOW06

θ_{13}	signal	$\tau \to e$	ν_μCC	ν_μNC	ν_eCC beam
9º	9.3	4.5	1.0	5.2	18
8º	7.4	4.5	1.0	5.2	18
7º	5.8	4.6	1.0	5.2	18
5º	3.0	4.6	1.0	5.2	18
Efficiency	0.31	0.032	0.34×10^{-4}	7.0×10^{-4}	0.082

T2K & NOvA
(“off-axis beams”)

Why off-axis beams?

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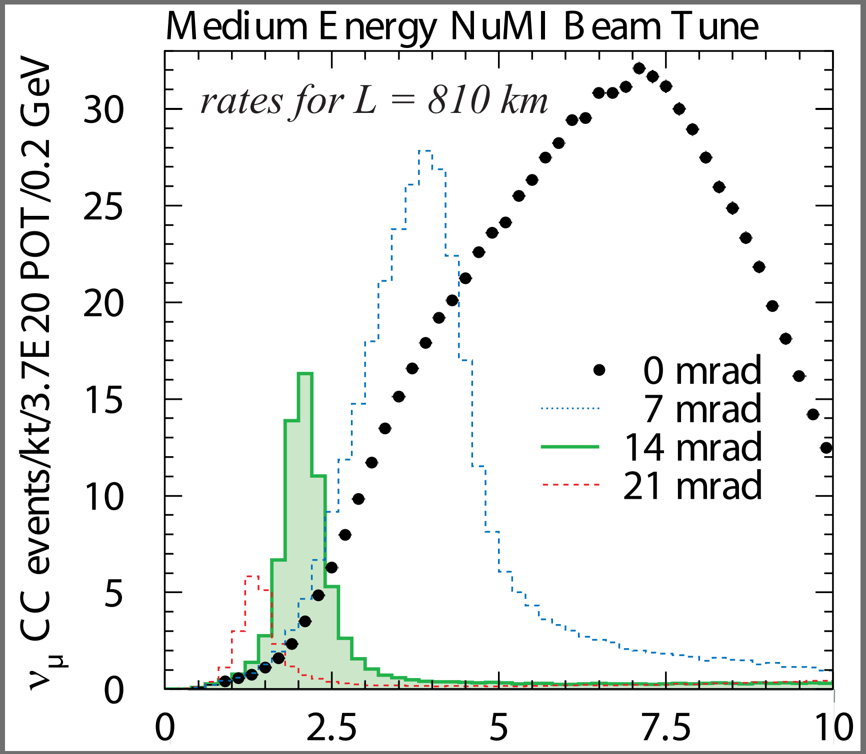
- Off-axis: narrow band aimed to oscillation maximum



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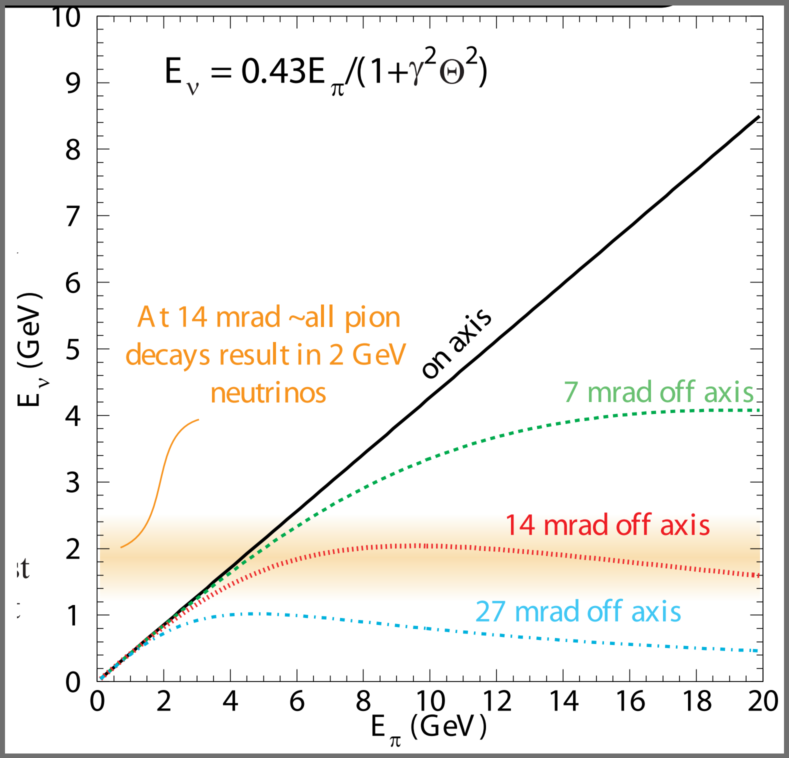

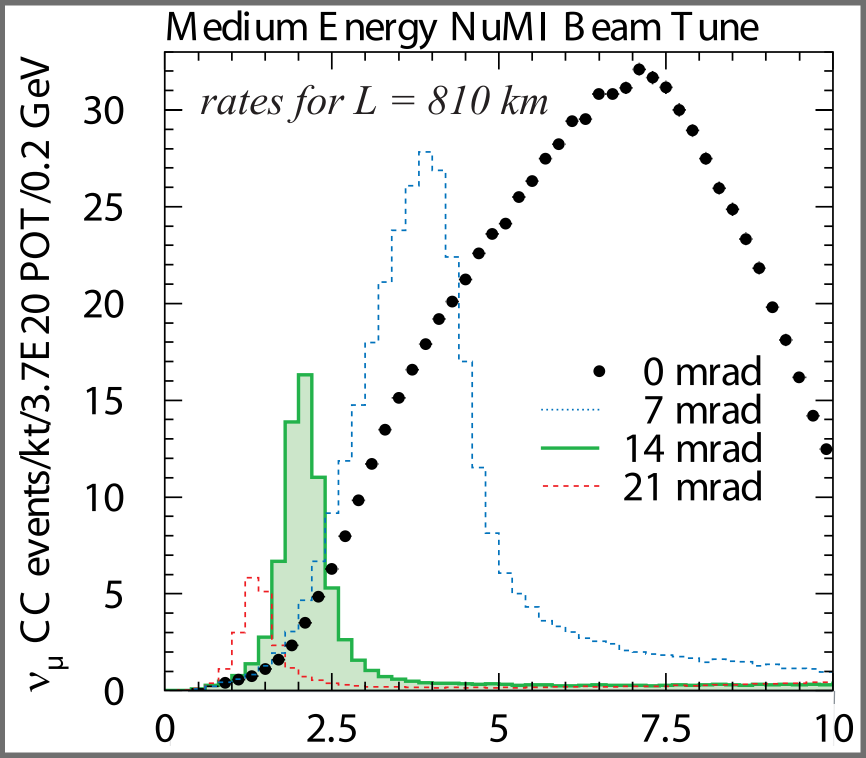

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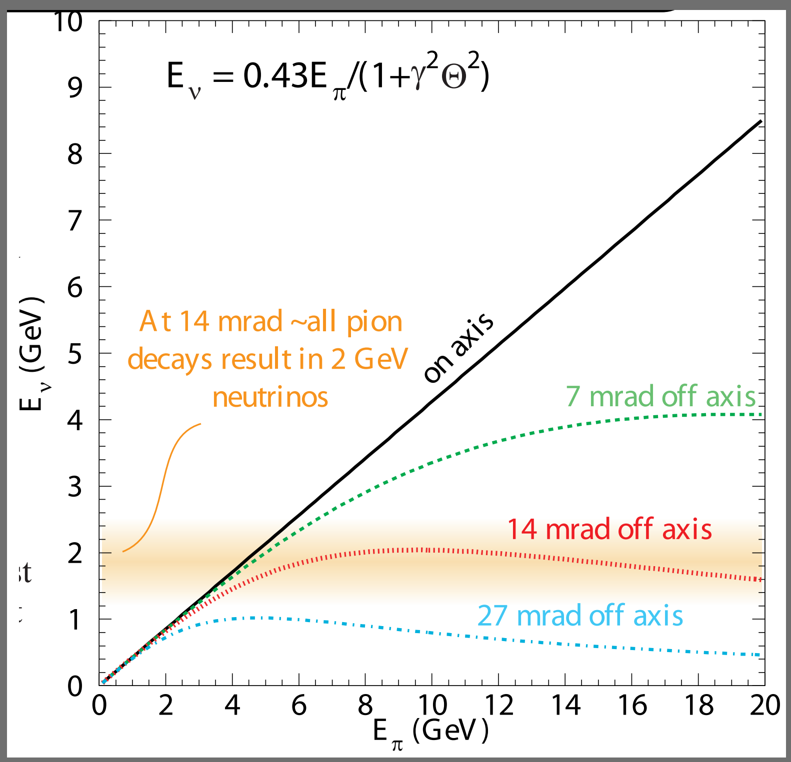

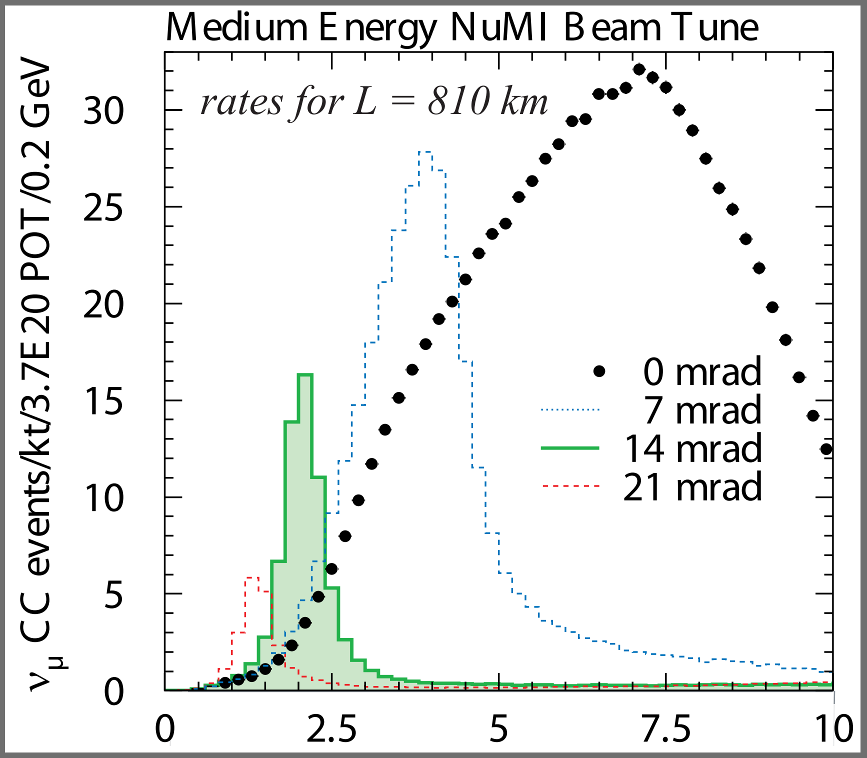

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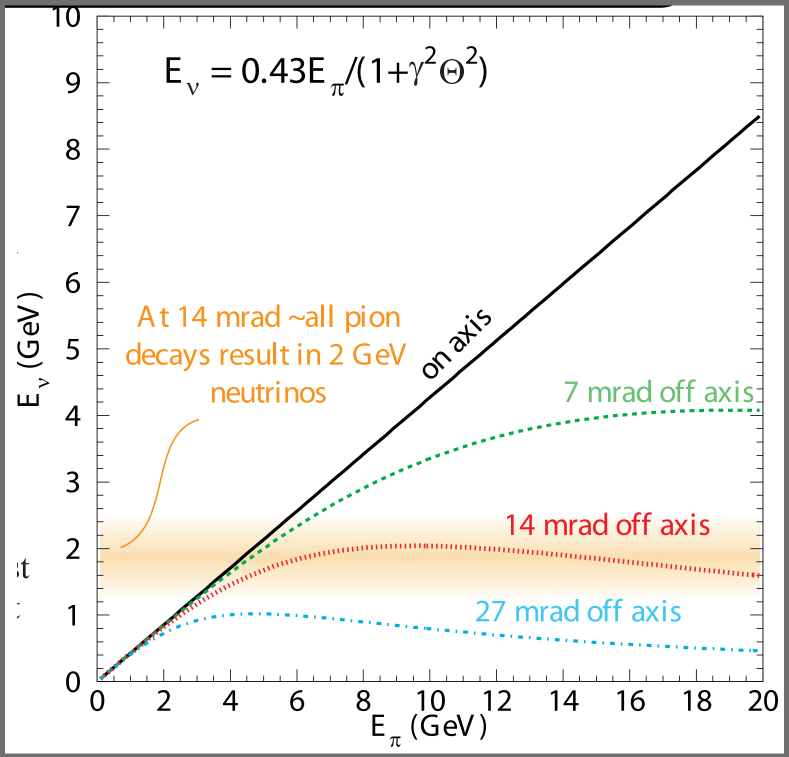
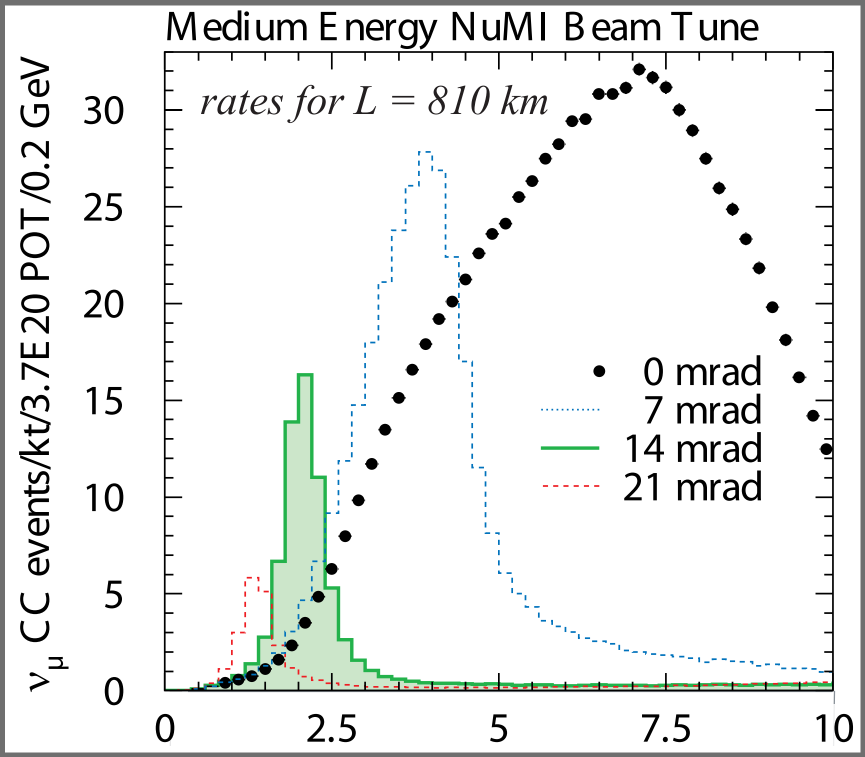
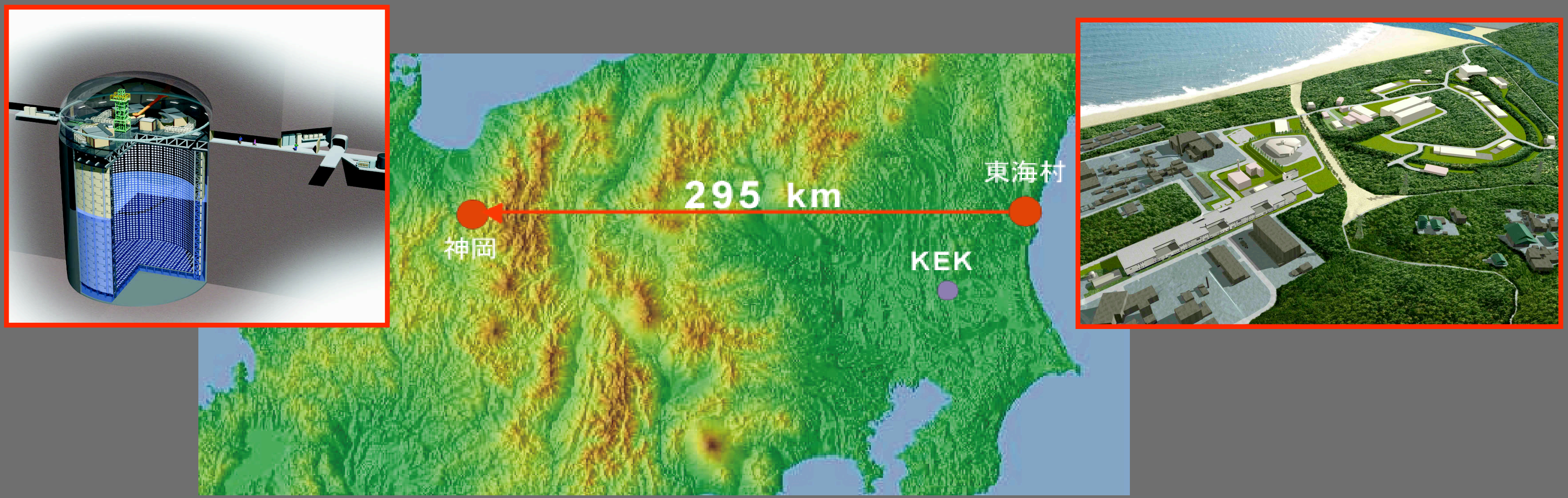




T2K

JPARC beam + SuperK



Kajita@NOW2006

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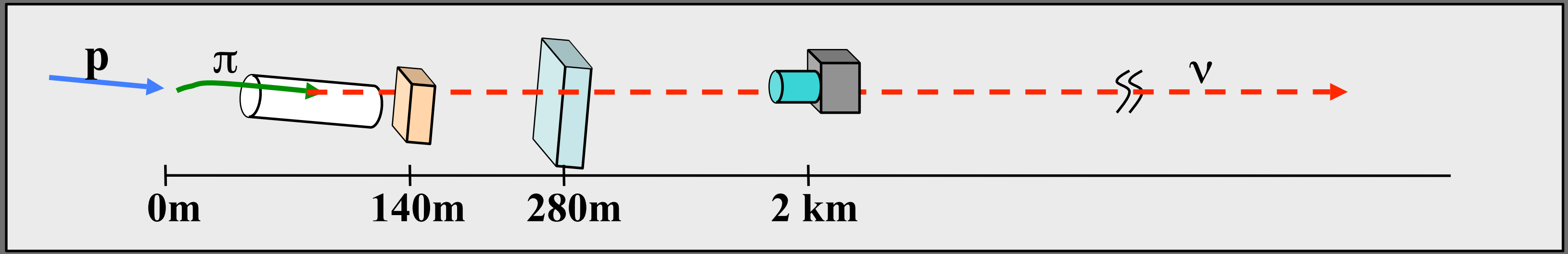

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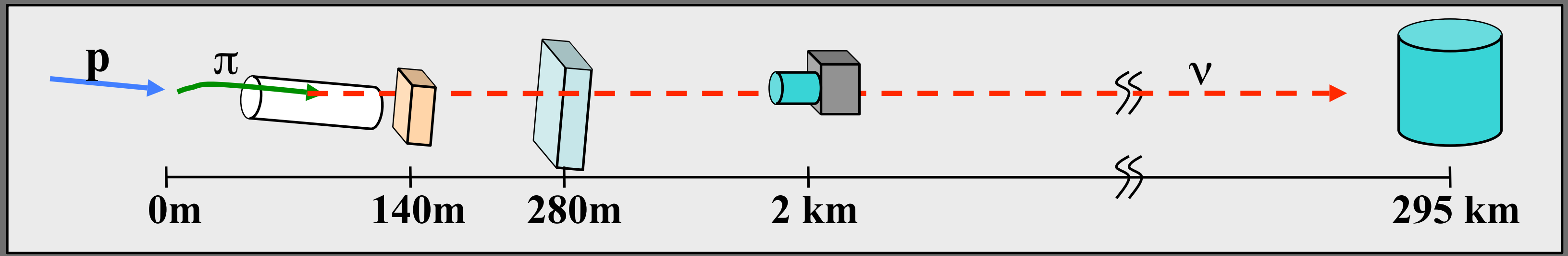

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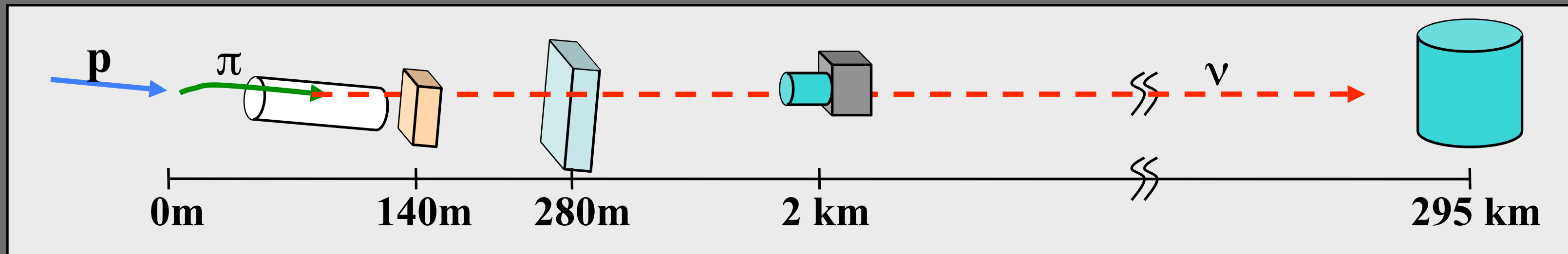

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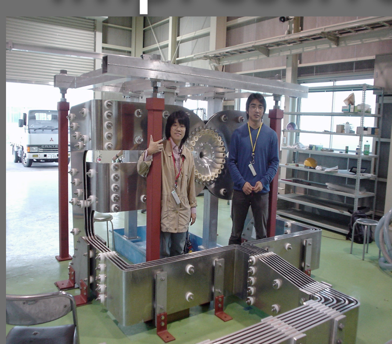
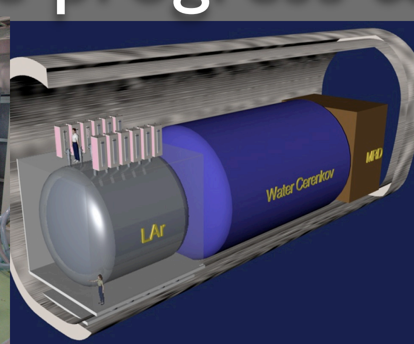
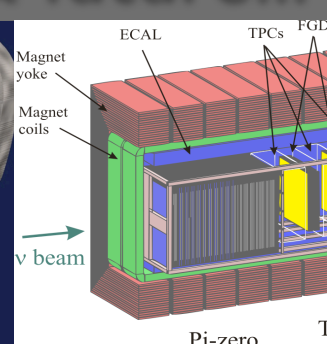
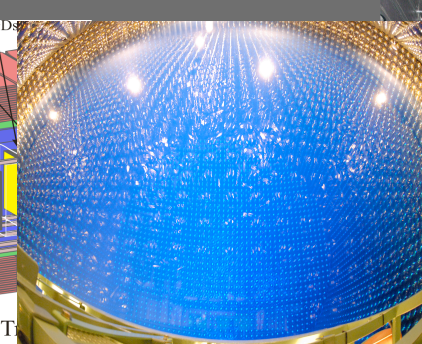
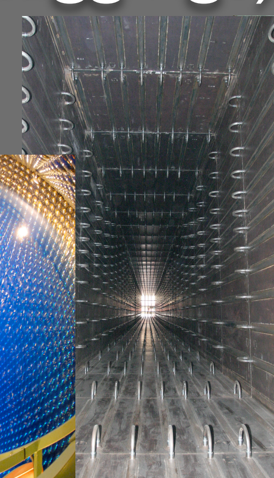
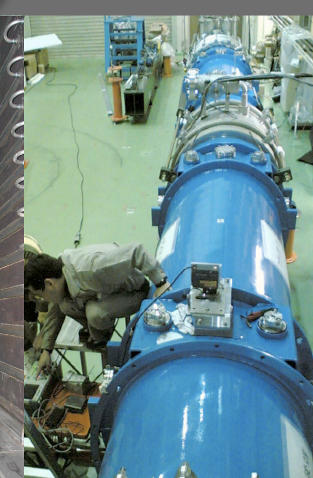
- Impressive progress & future...



Physics

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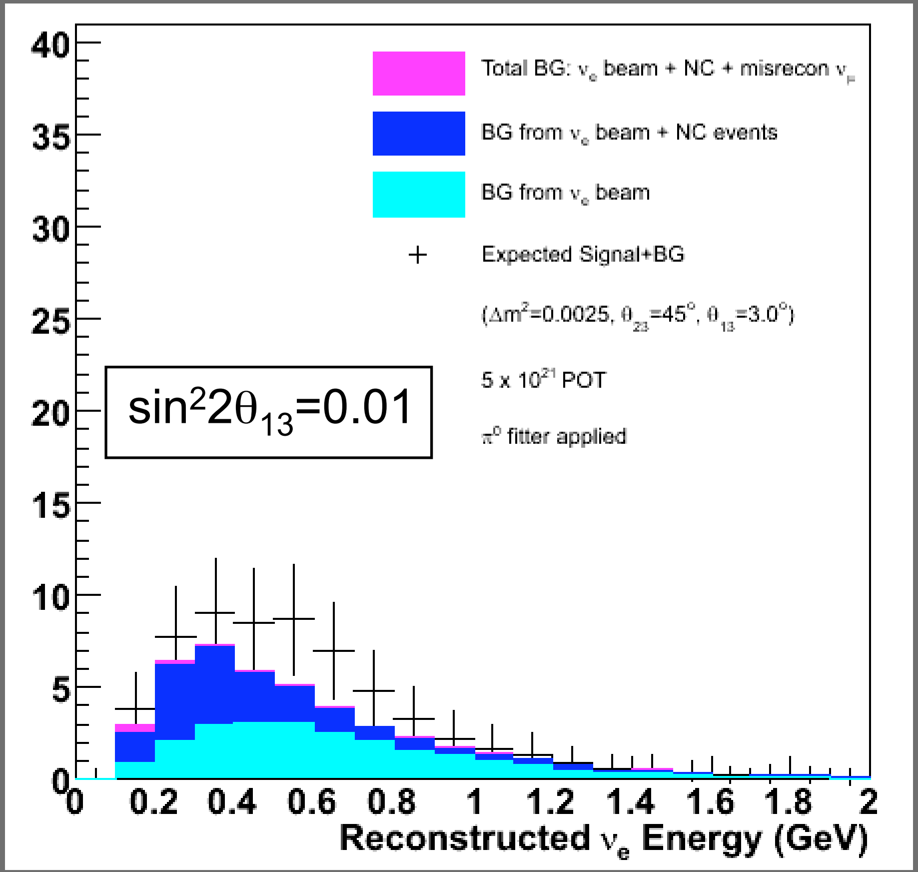

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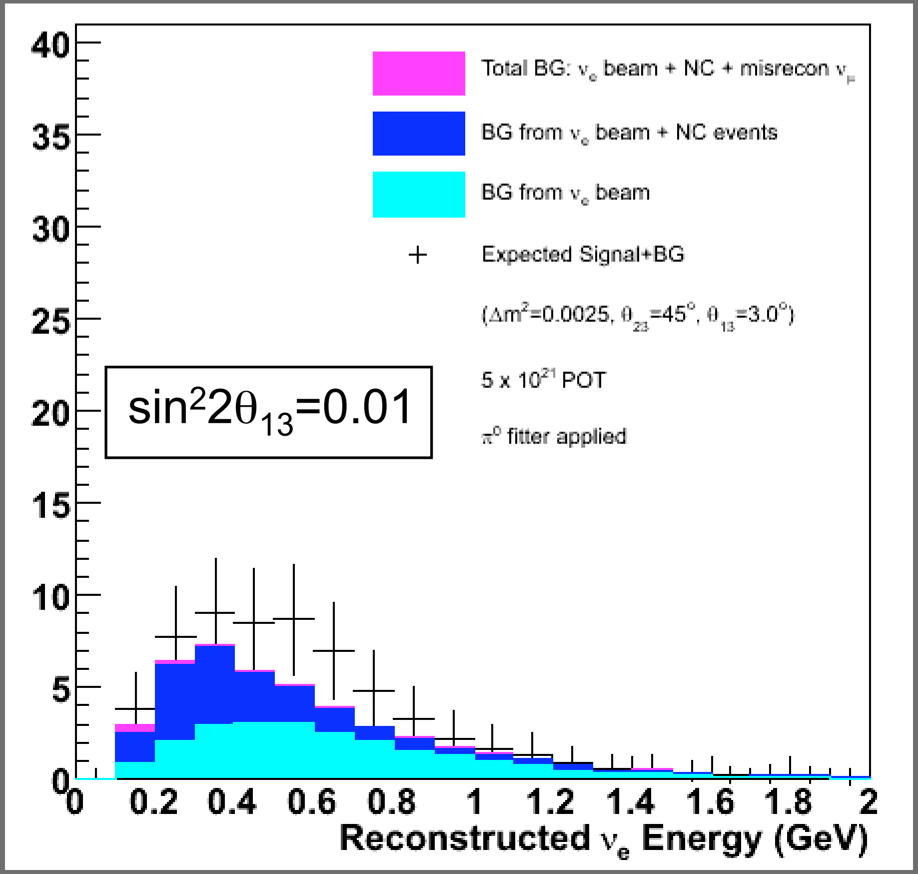

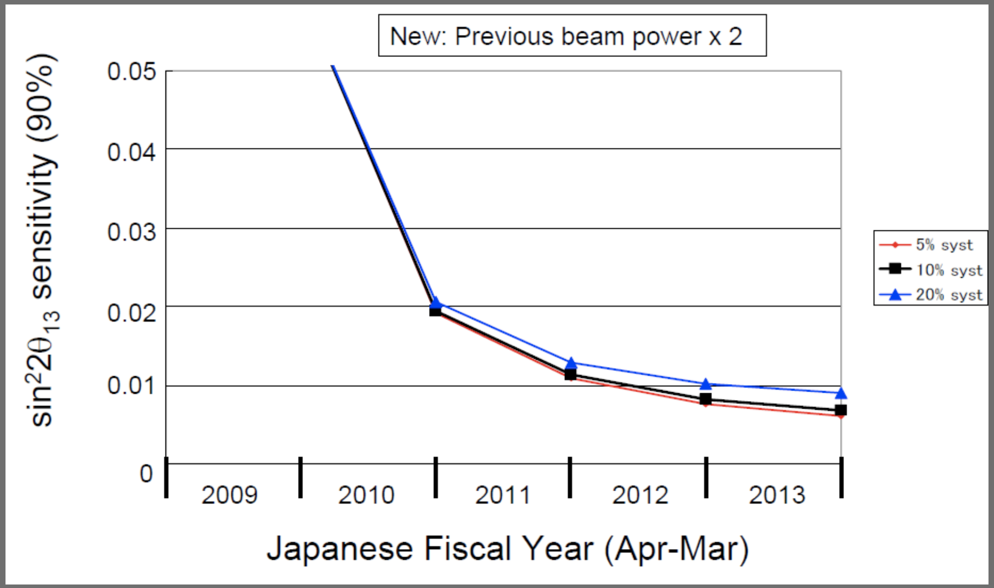

NOνA

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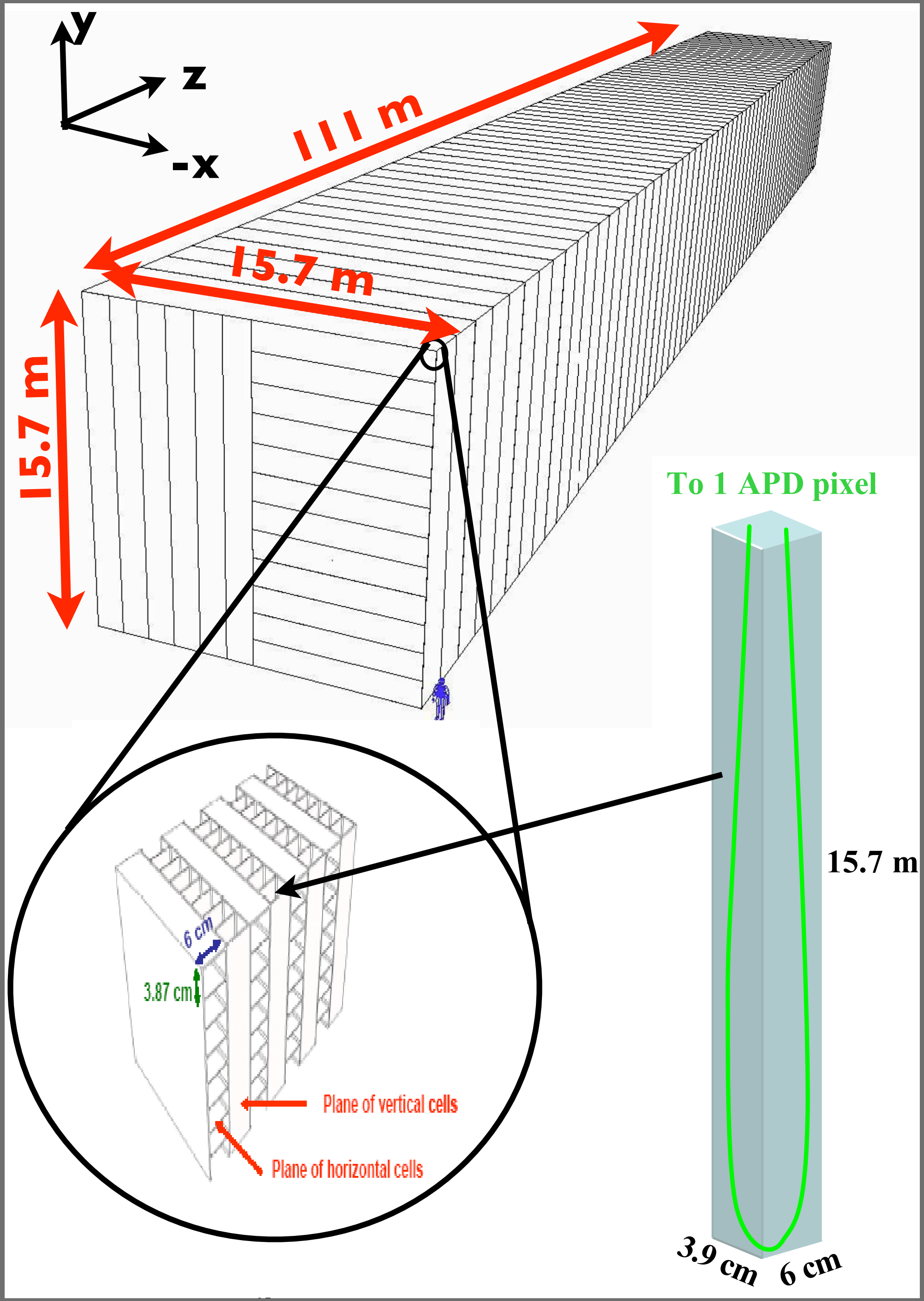

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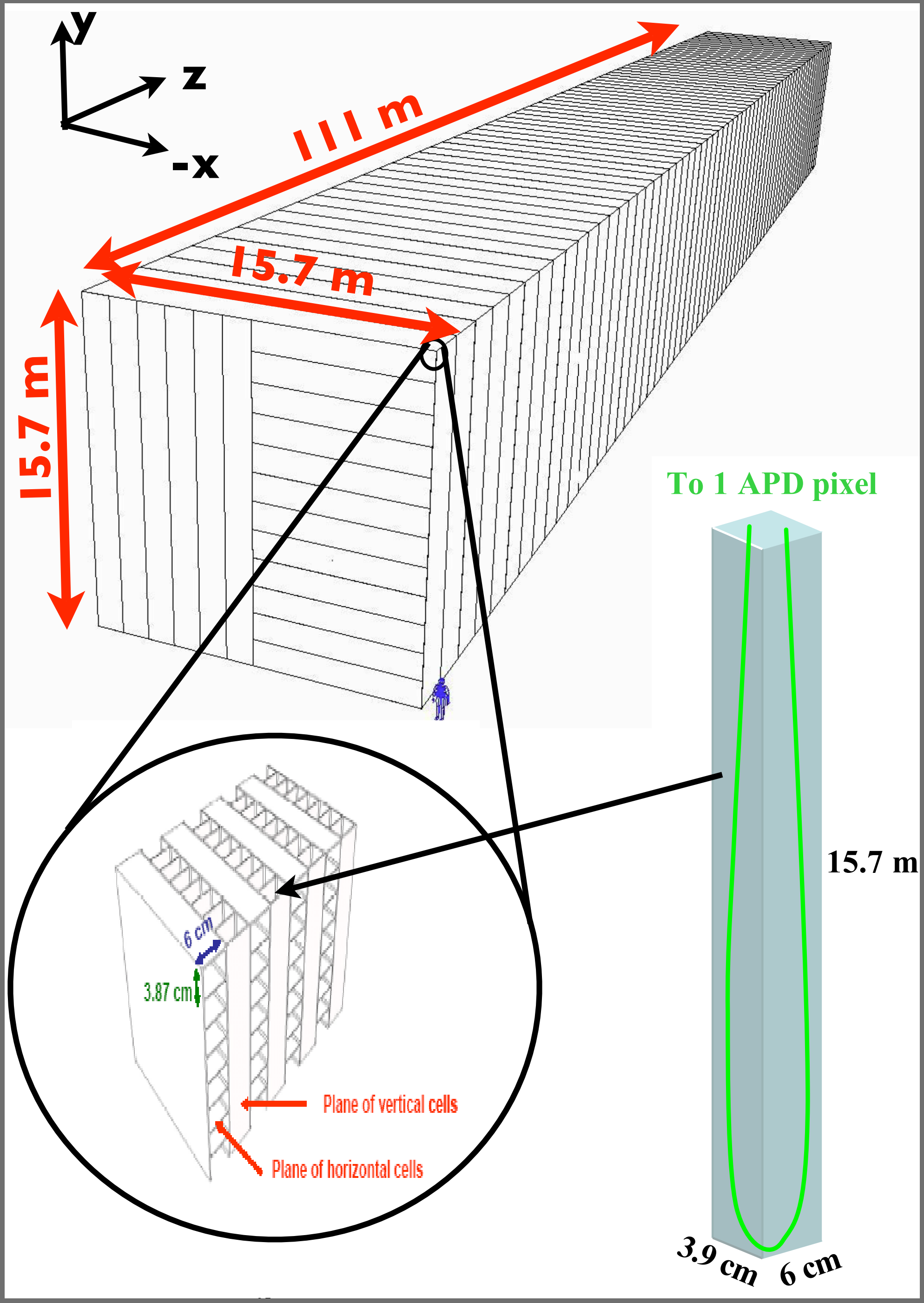

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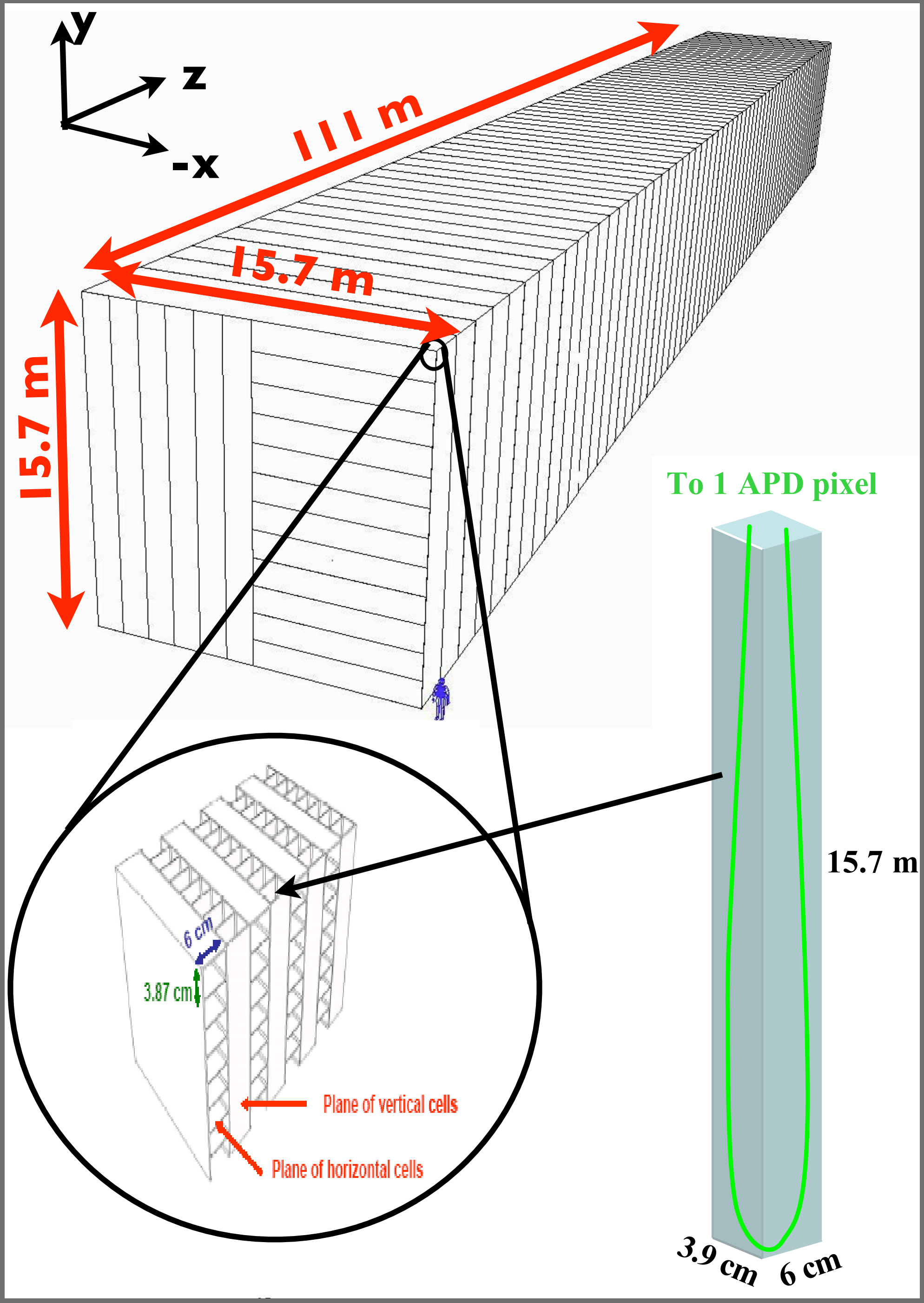

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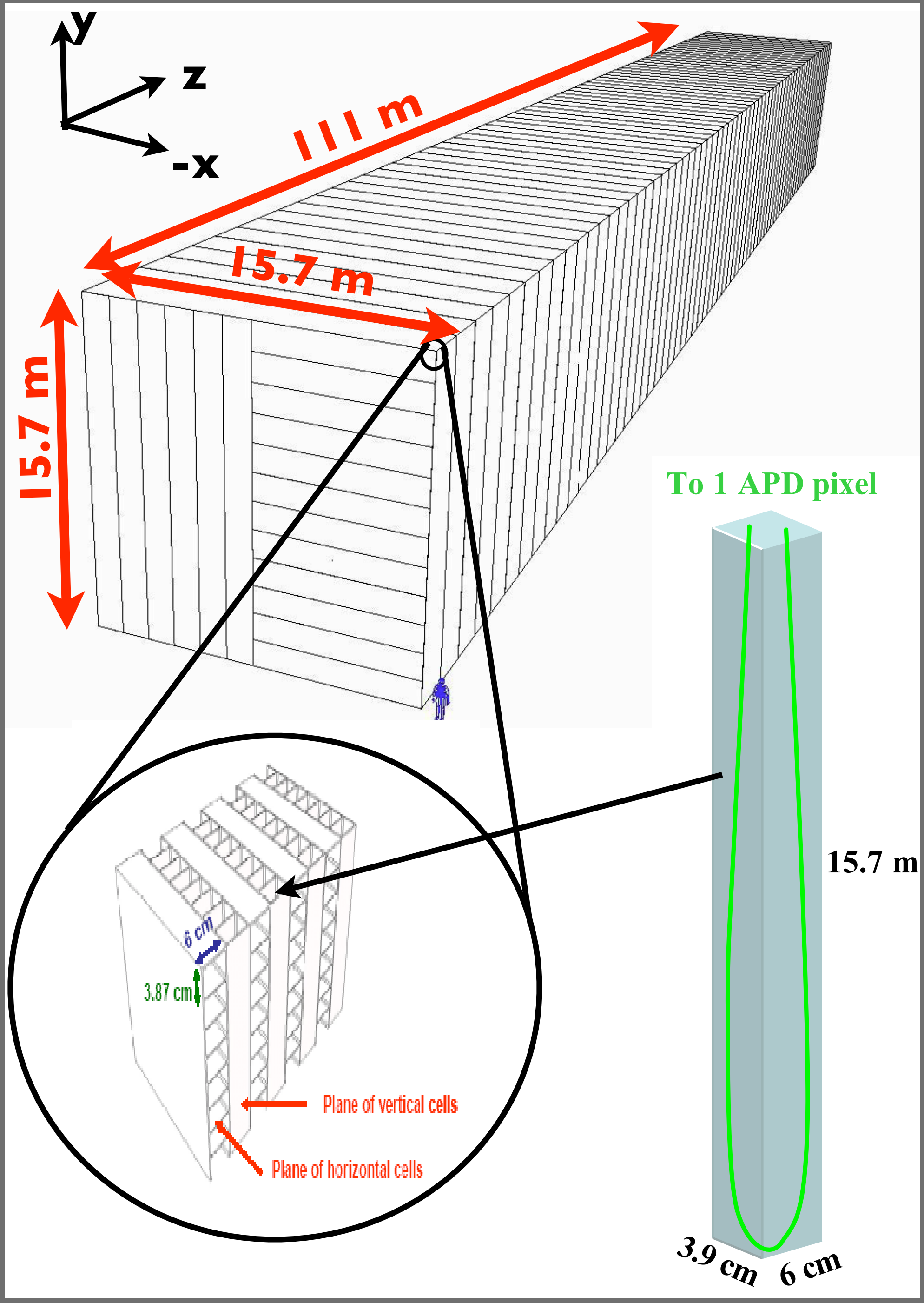

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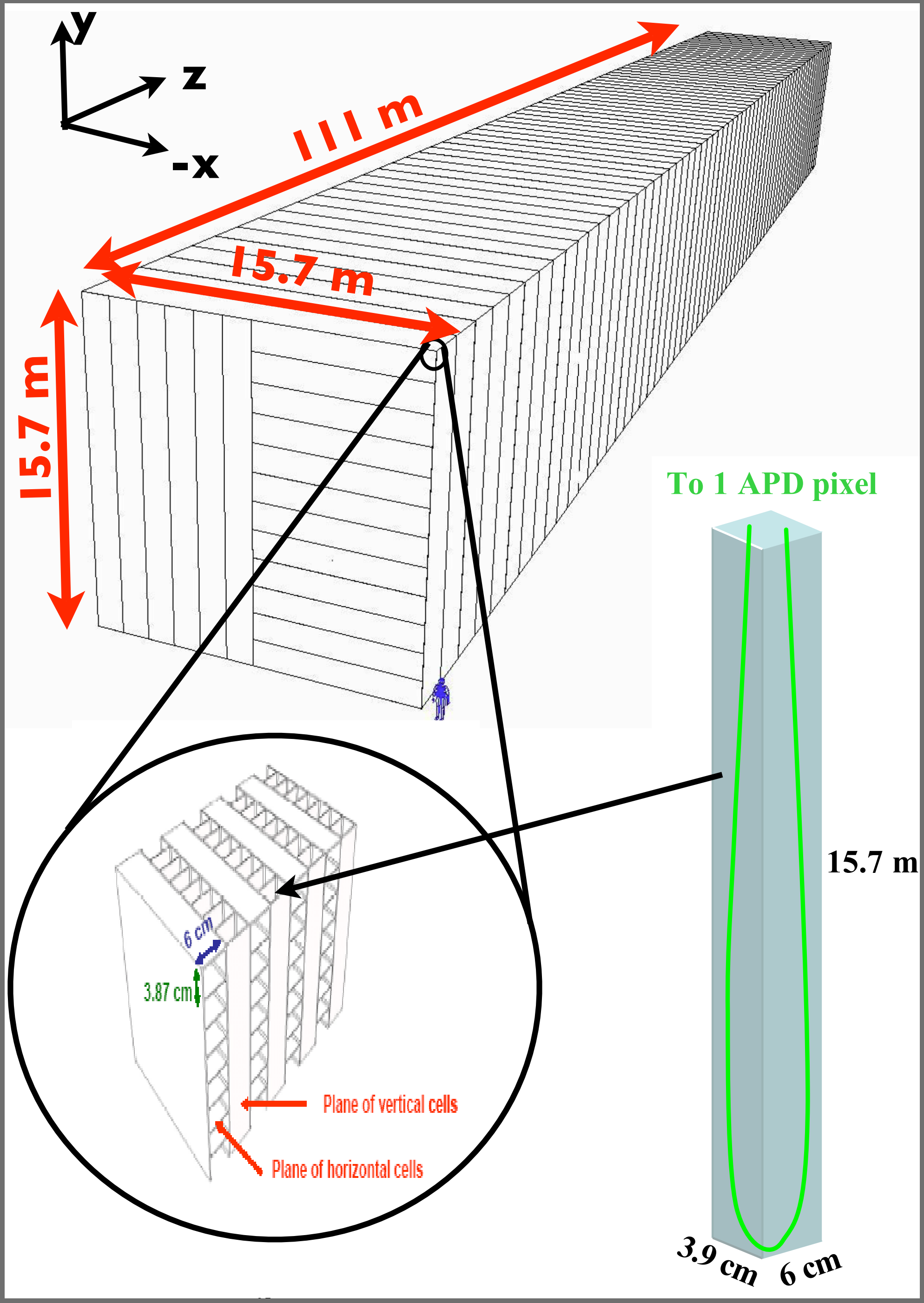
  - MINOS-like but...



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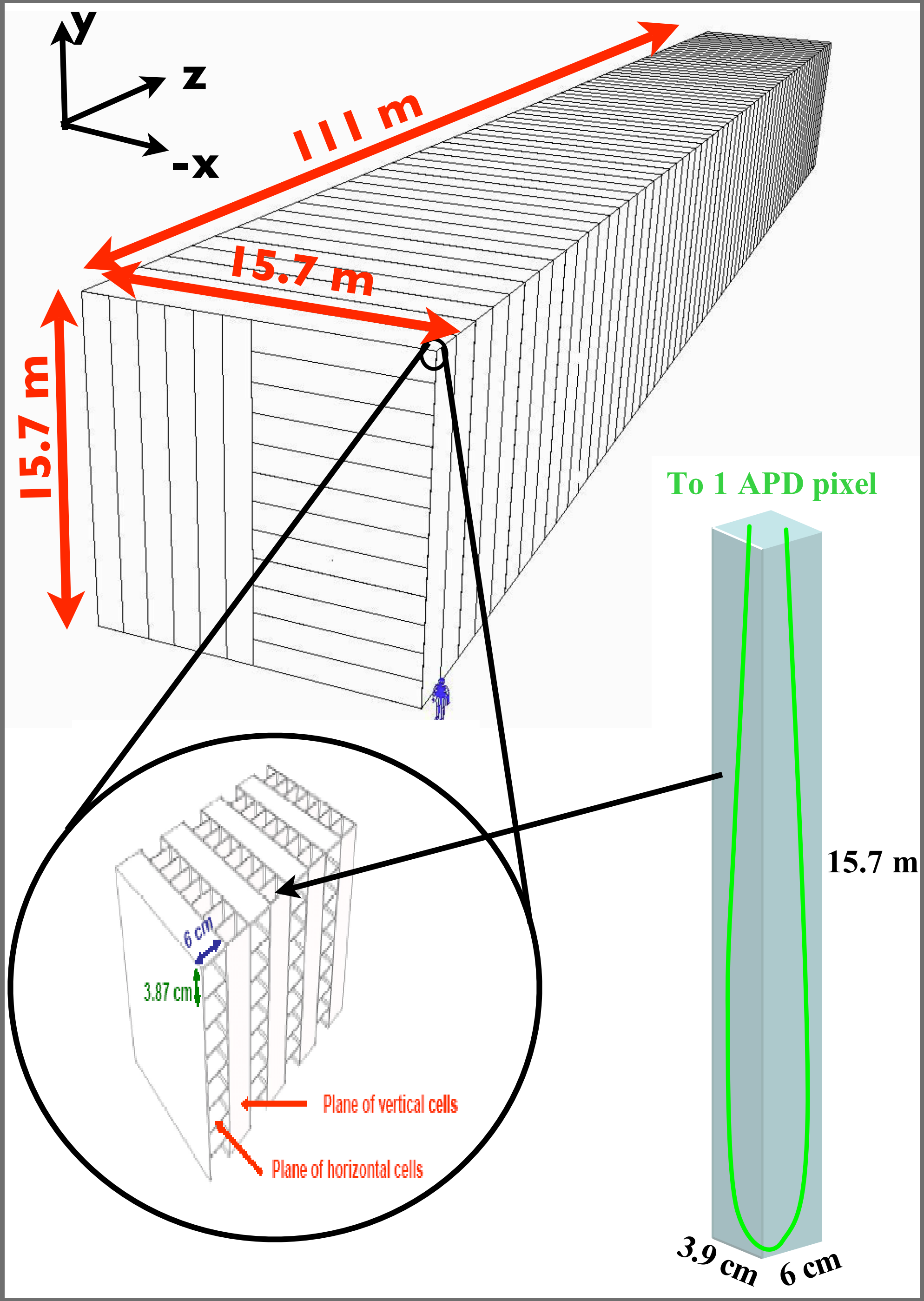

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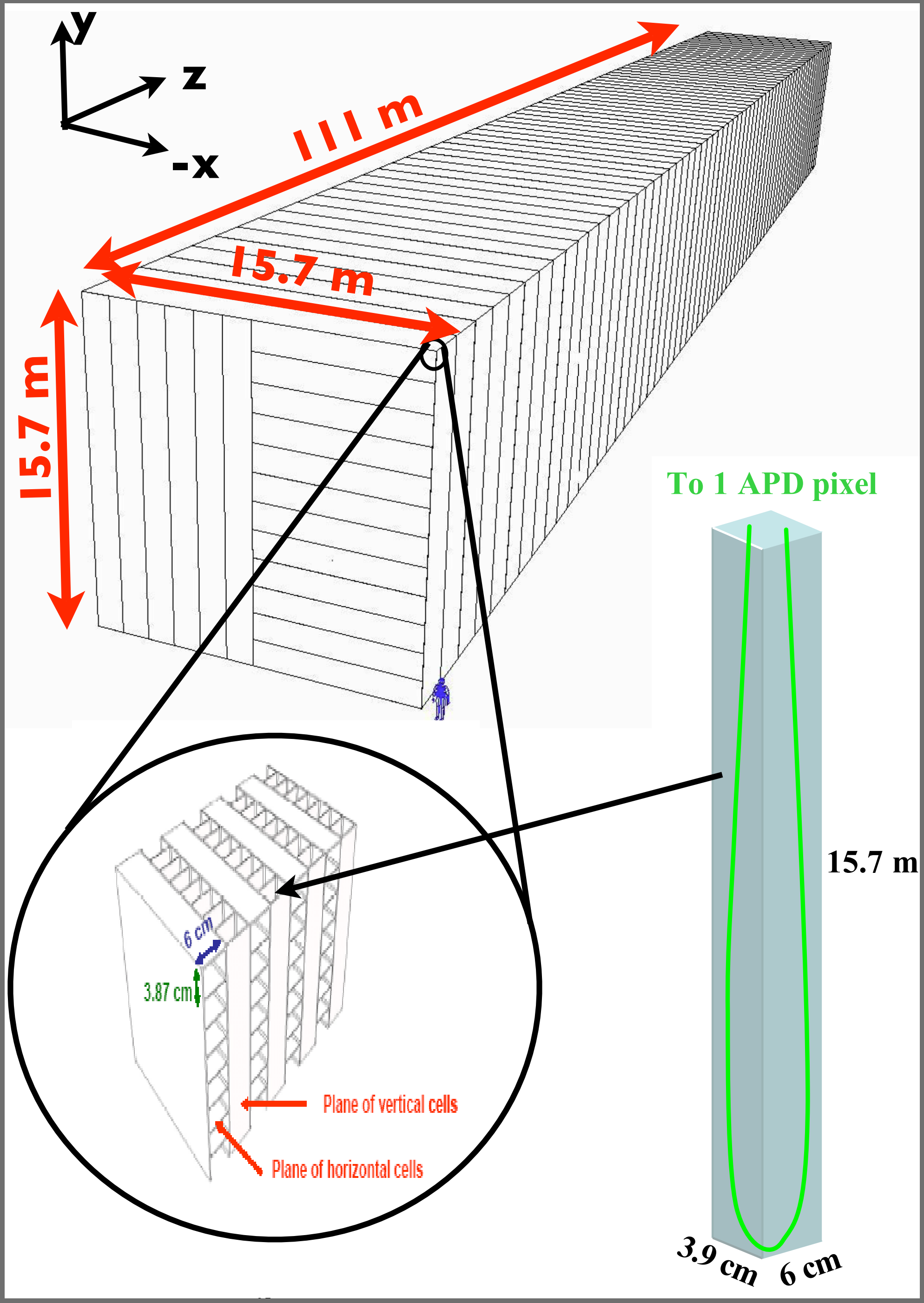

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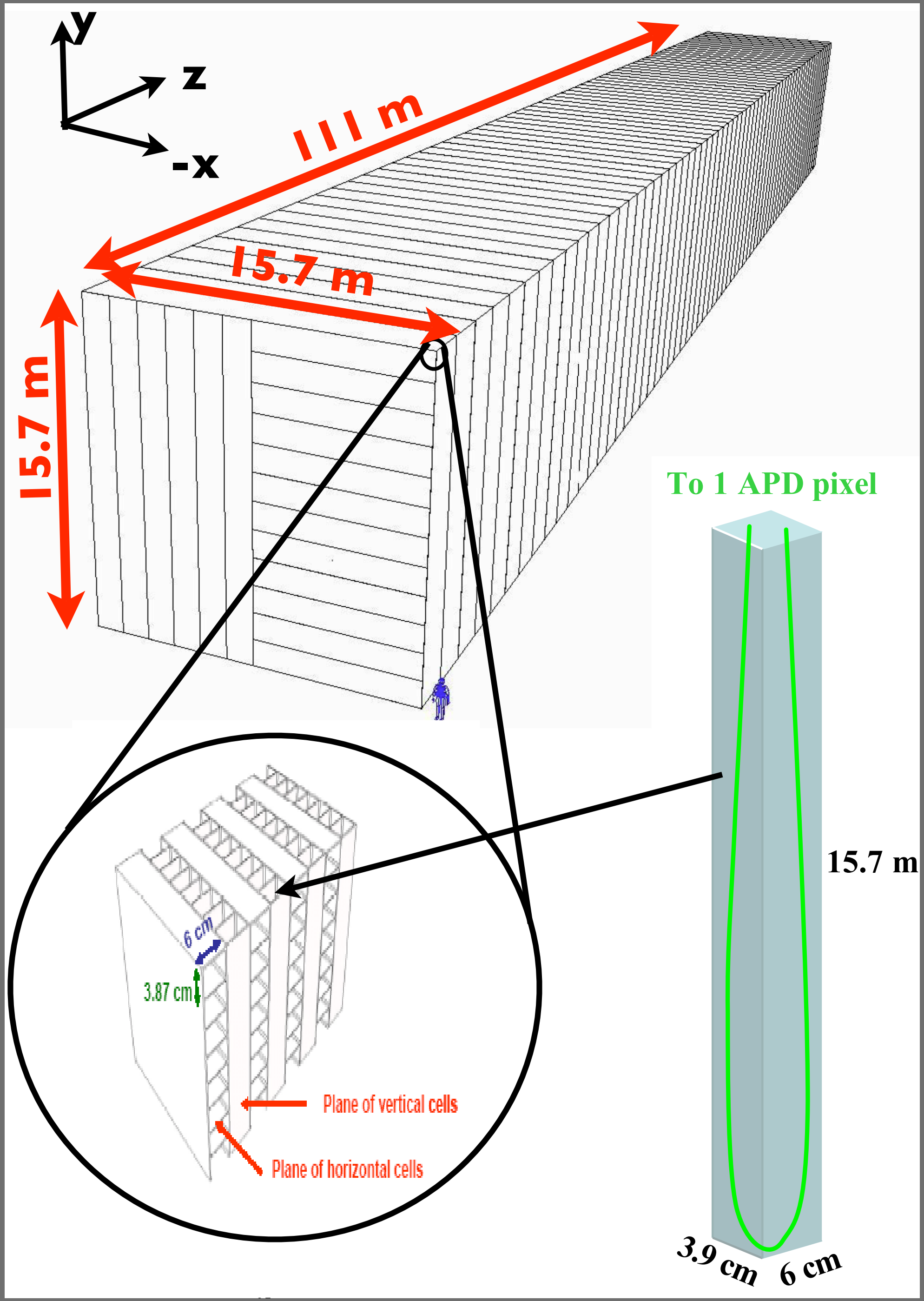

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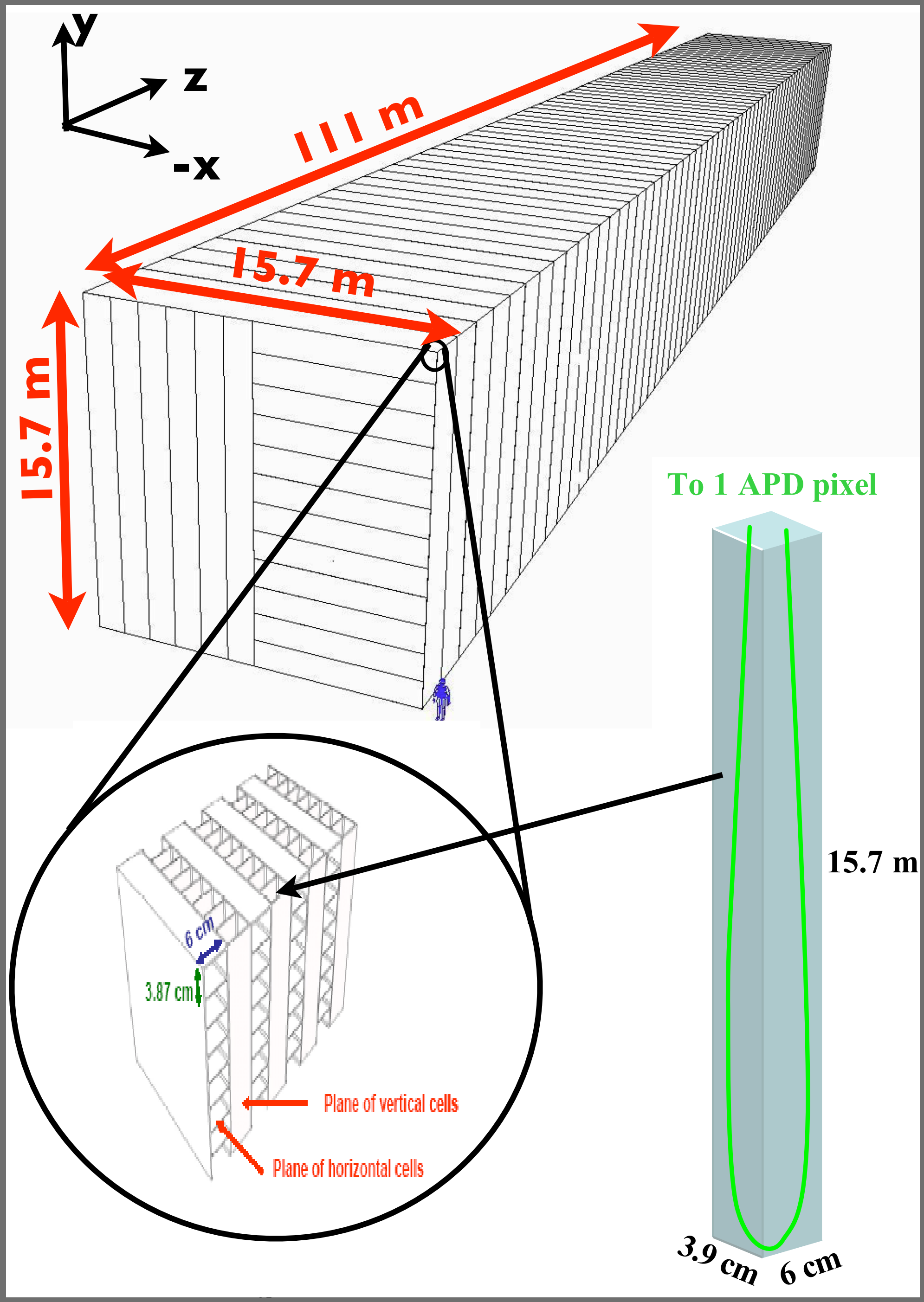

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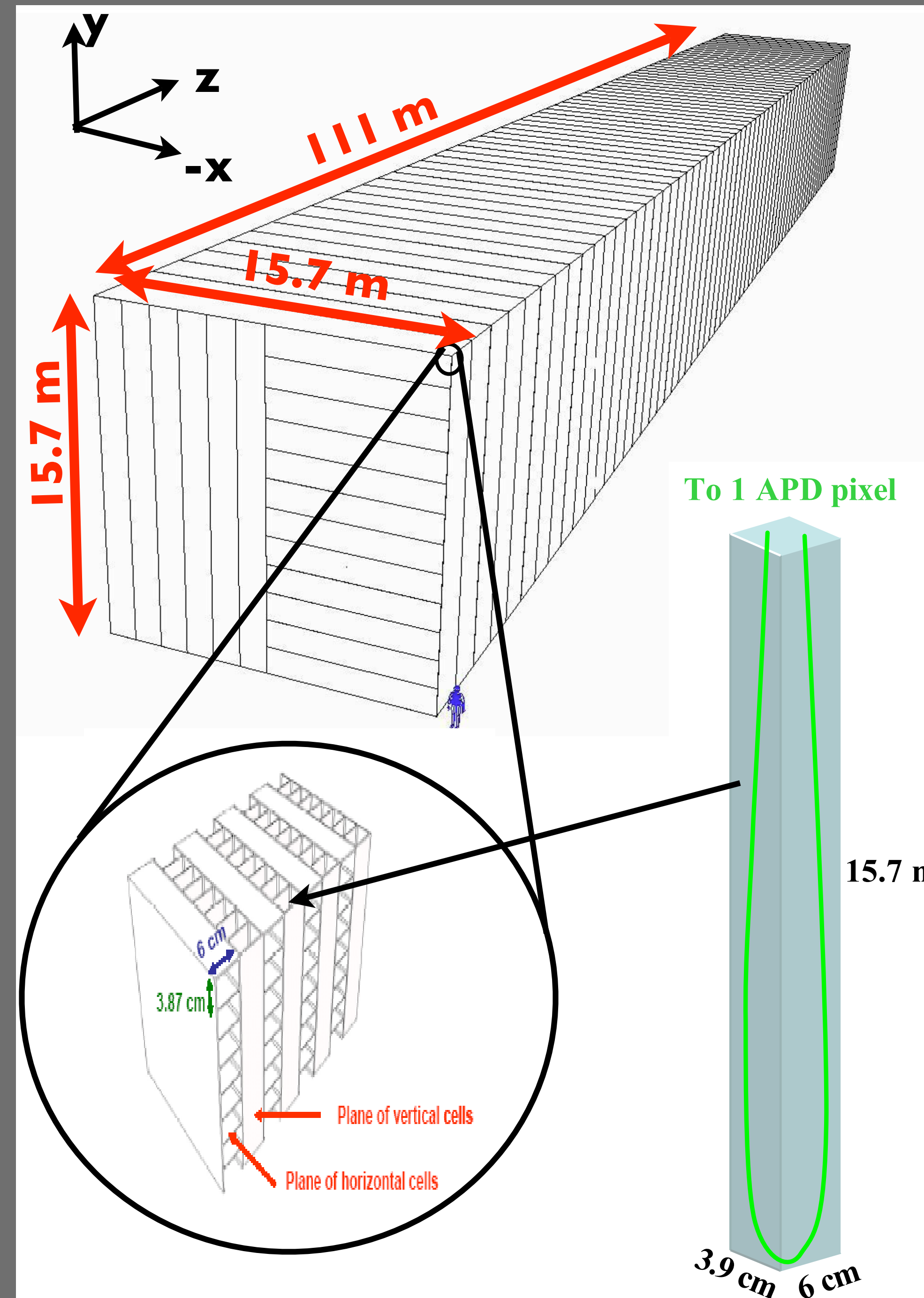

Feldman@WIN05
Howcroft@NuFact06
Kopp@NOW06

Physics reach

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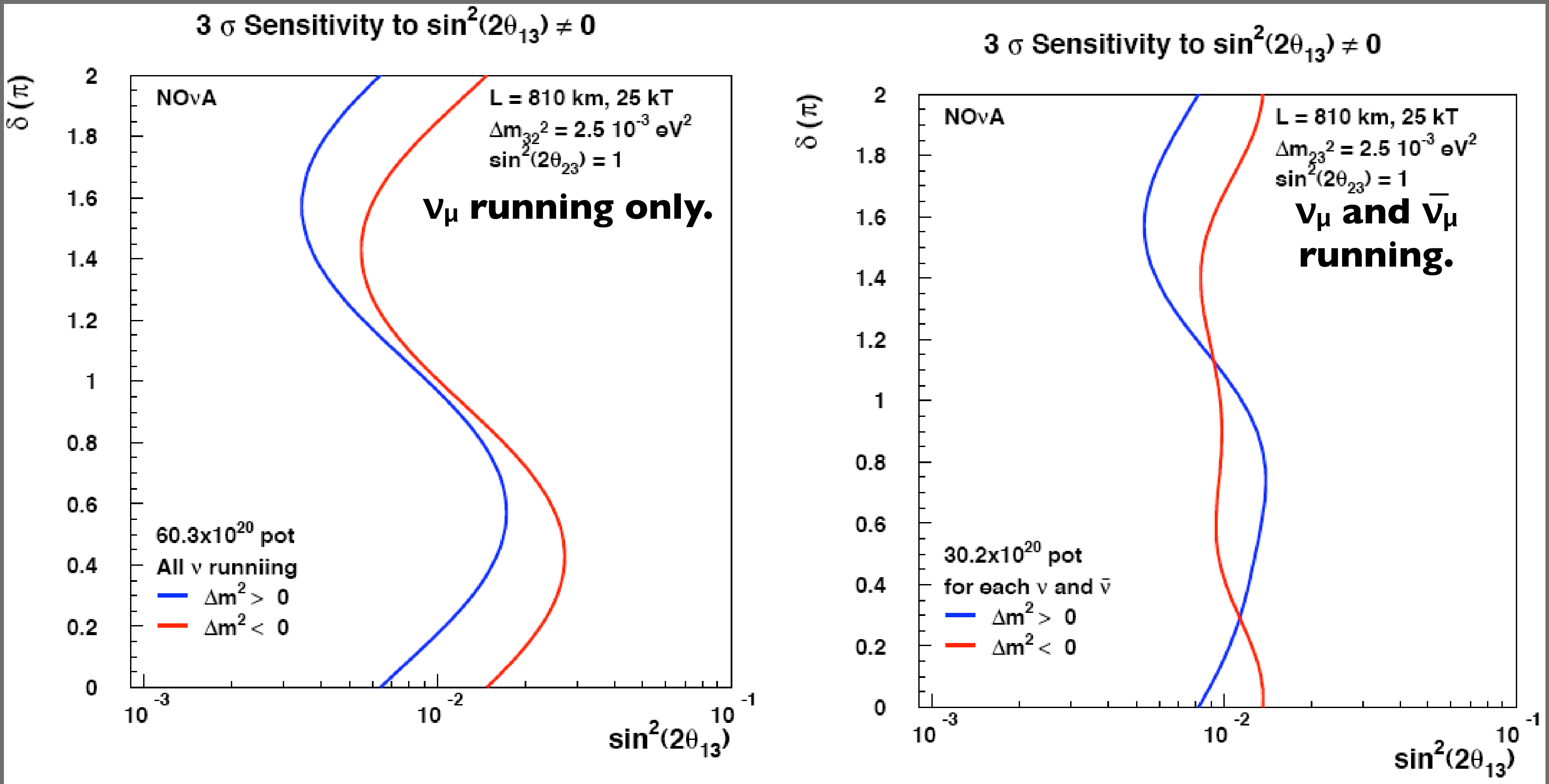
- Correlation among θ_{13},δ_{CP},$\pm\Delta m^2$ => to disentangle



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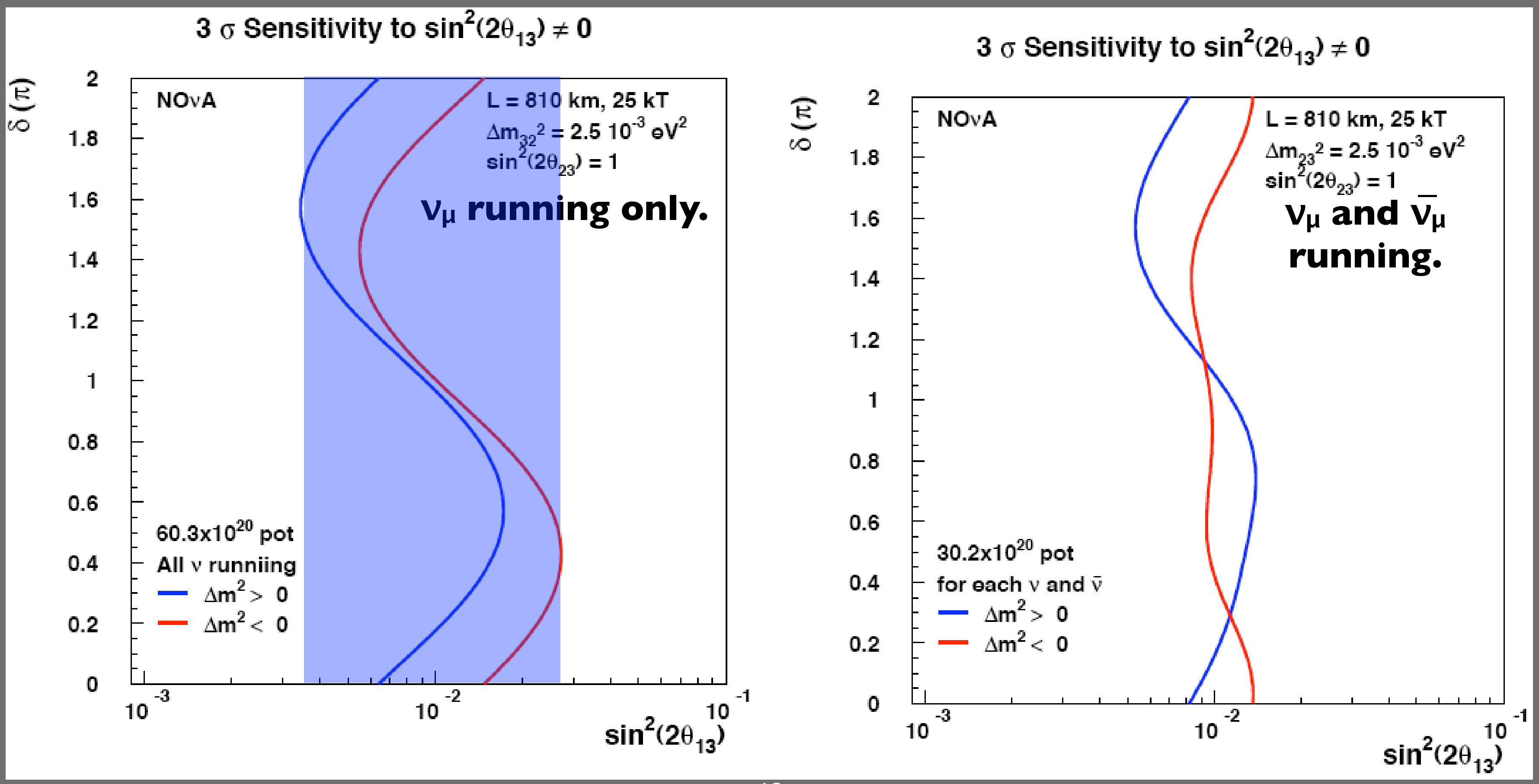

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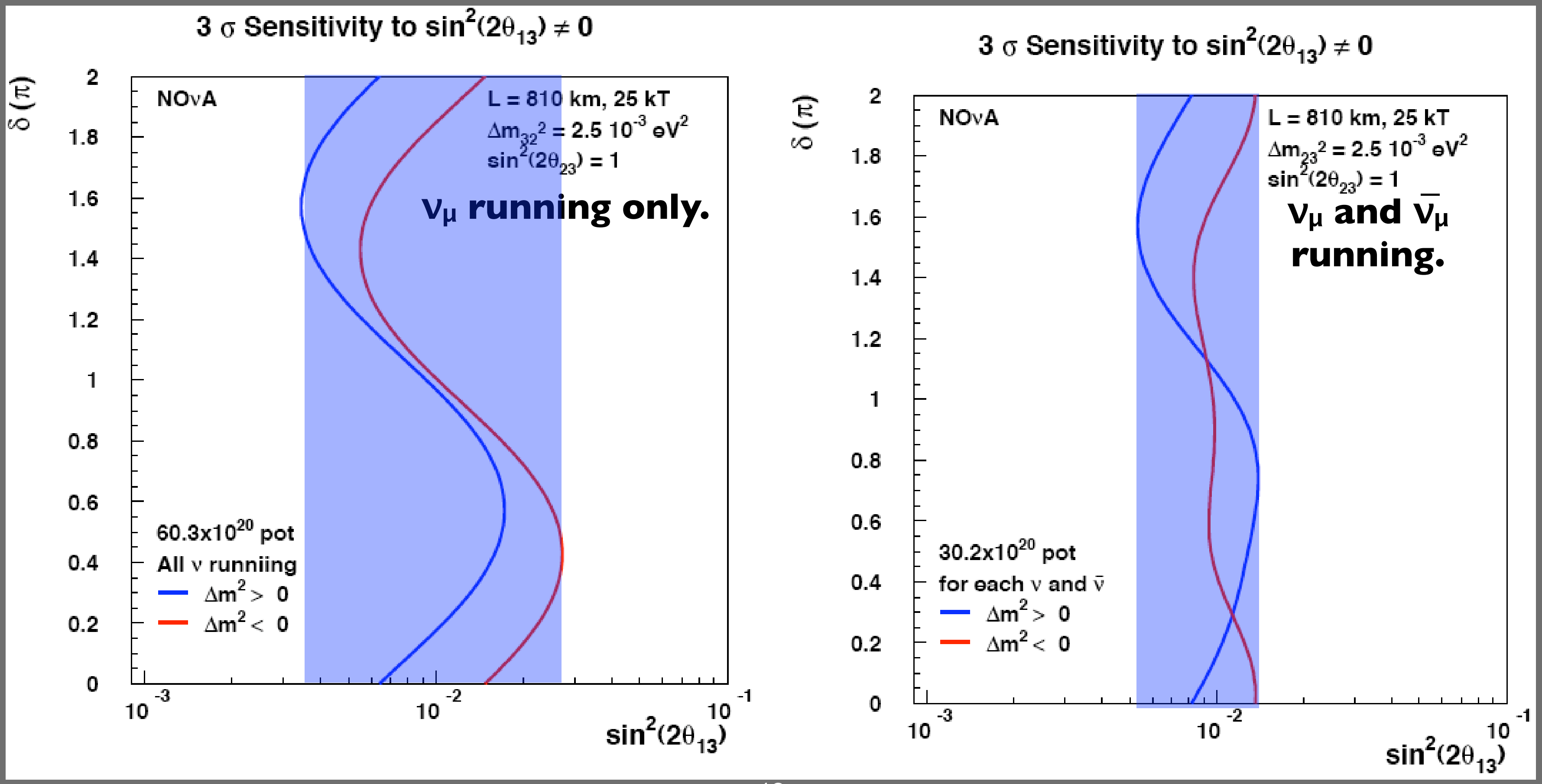

Physics reach

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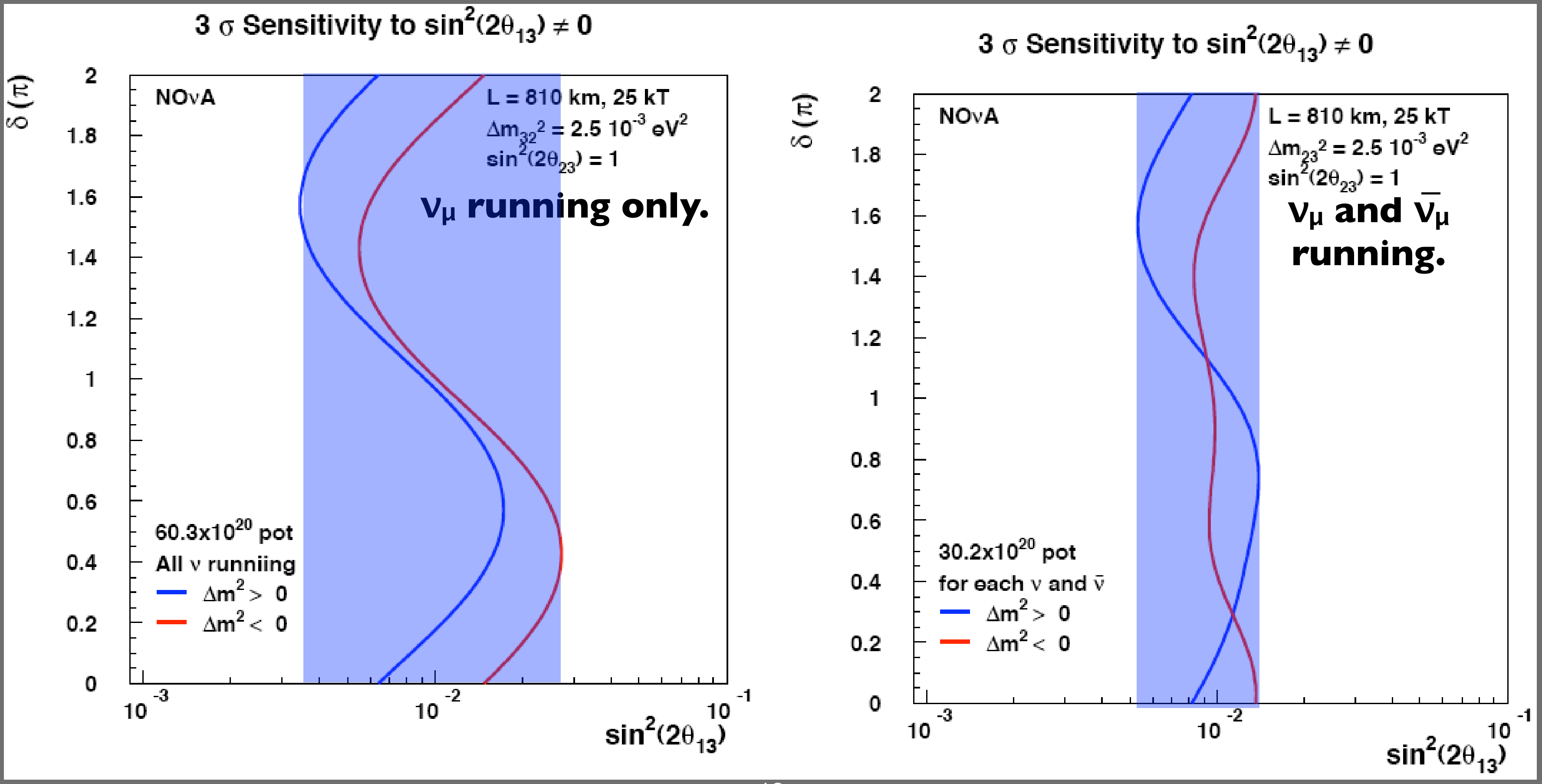
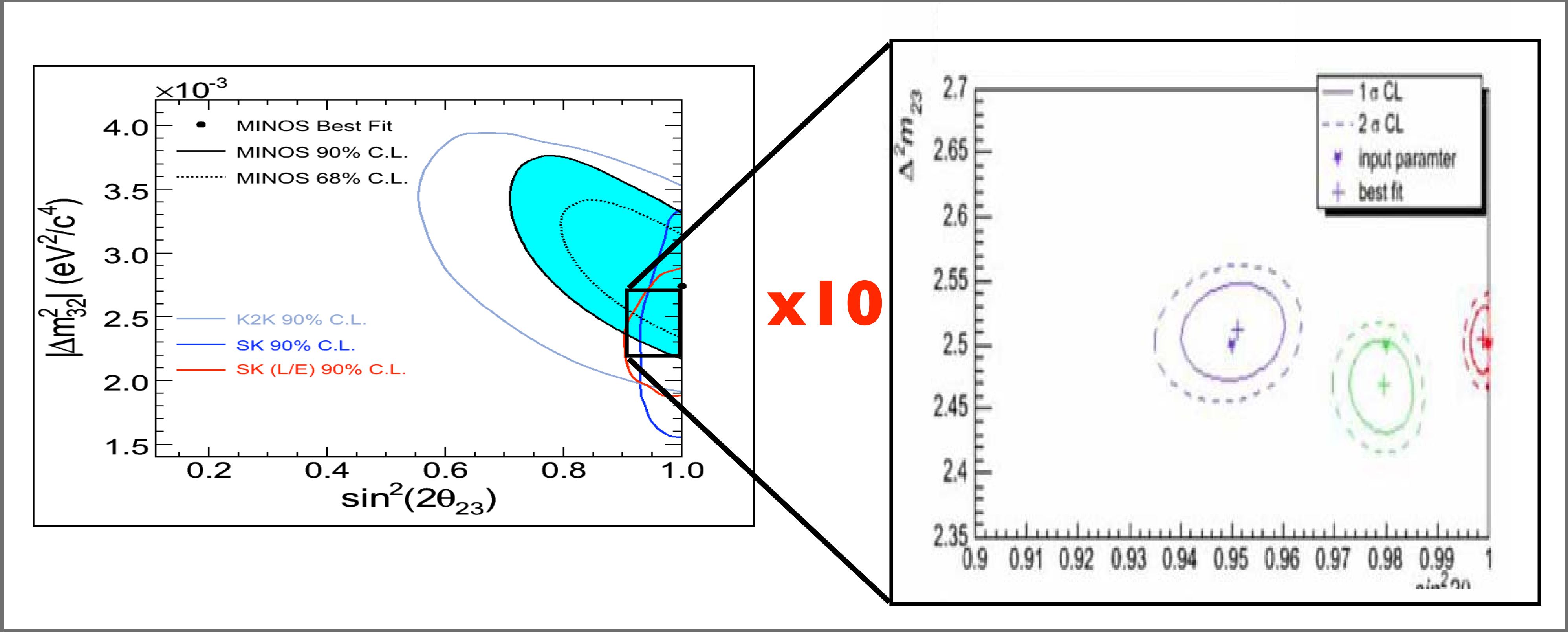
    - comparison with T2K and reactors



Measure

Measure $\sin^2(2\theta_{23})$ to ~1% and $\Delta m^2(\text{atm})$ to ~2%



Time Scale

- **April 2006:** DOE CD1 review. Recommends approval
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http://www-nova.fnal.gov/NOvA_Proposal/NOvA_P929_March21_2005.pdf

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  NuMI upgrade I (700kW): duty cycle better (~2009)
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Reactor Experiments:

Double Chooz
Daya Bay
RENO

reactor experiments: goals

“White Paper”: hep-ex/0402041

reactor experiments: goals

- make flux uncertainty negligible: multi-detector

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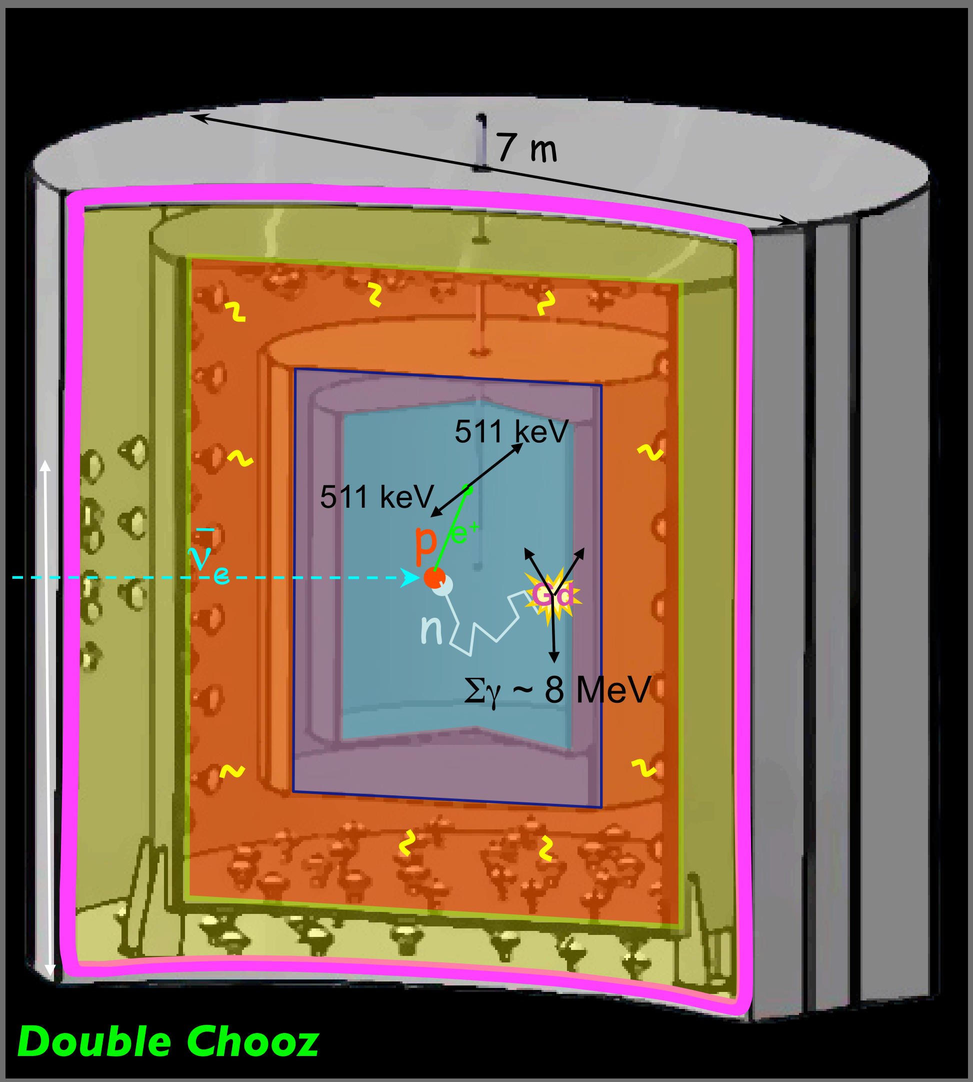
"White Paper": hep-ex/0402041

The standard θ_{13}-LAND: Double Chooz

θ_{13} dedicated detector => systematics well <1%



DC Proposal: hep-ex/0606025

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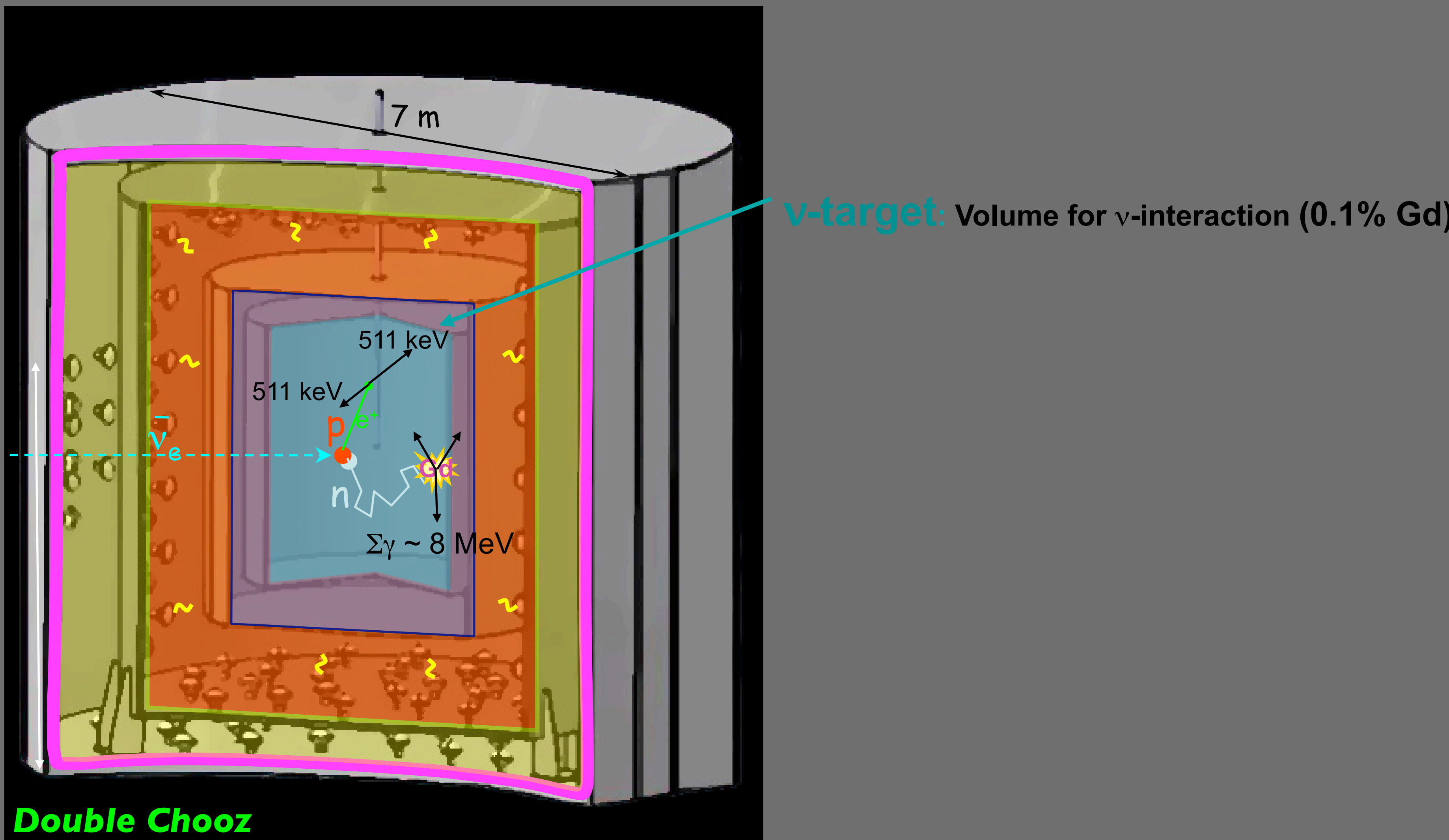

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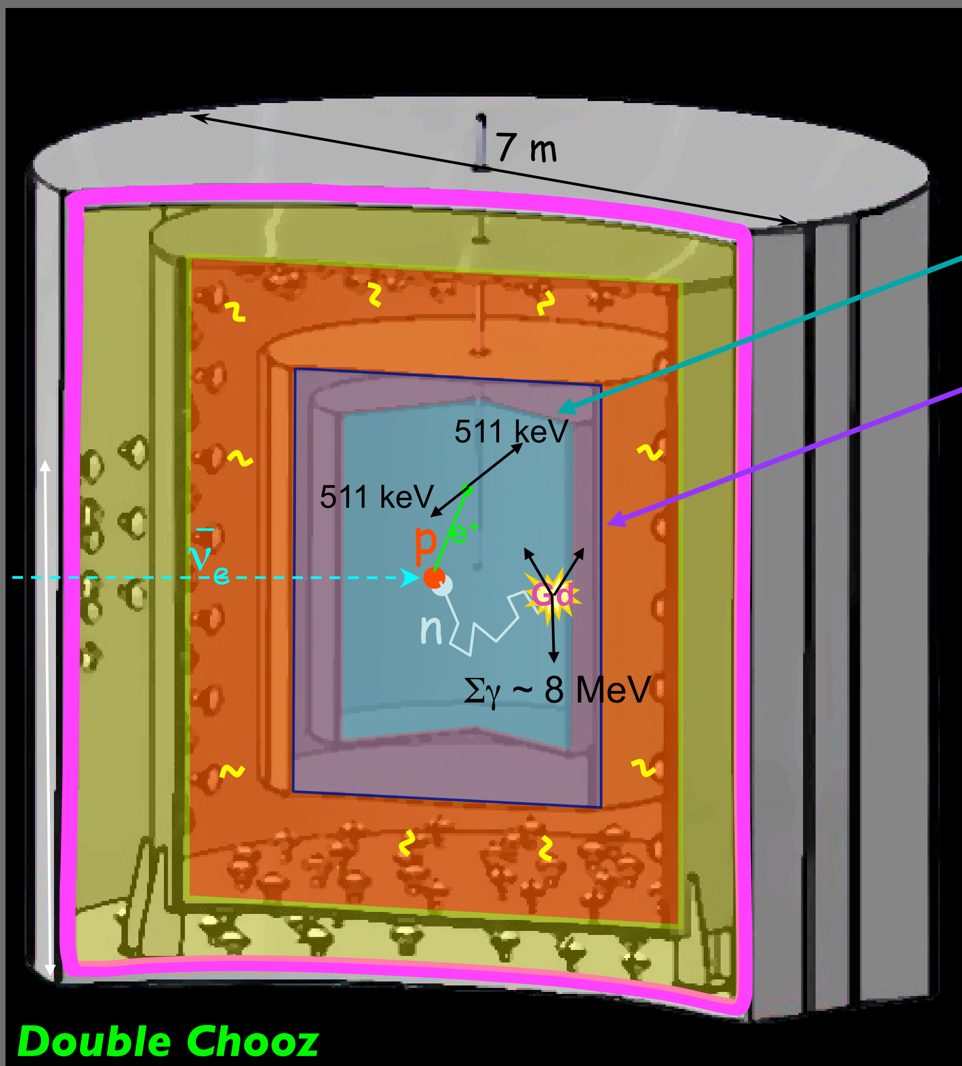

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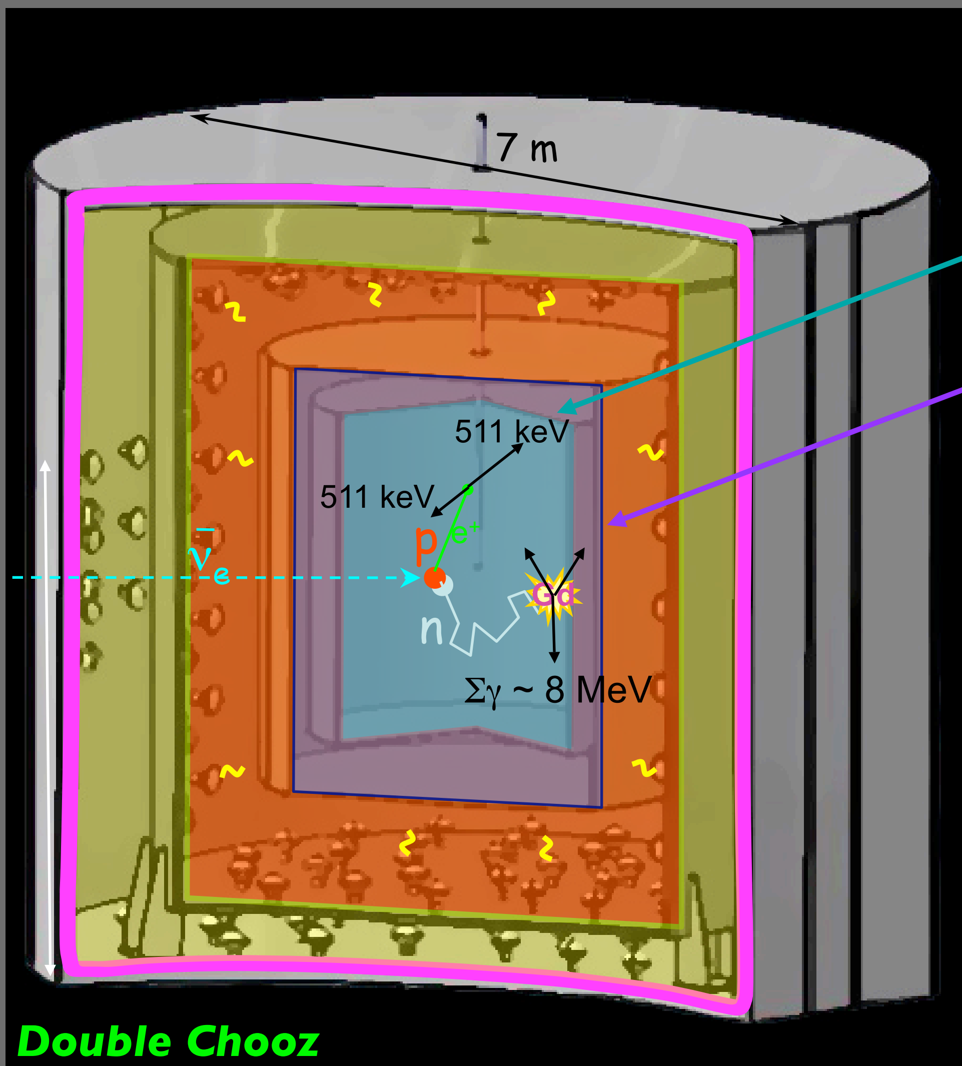

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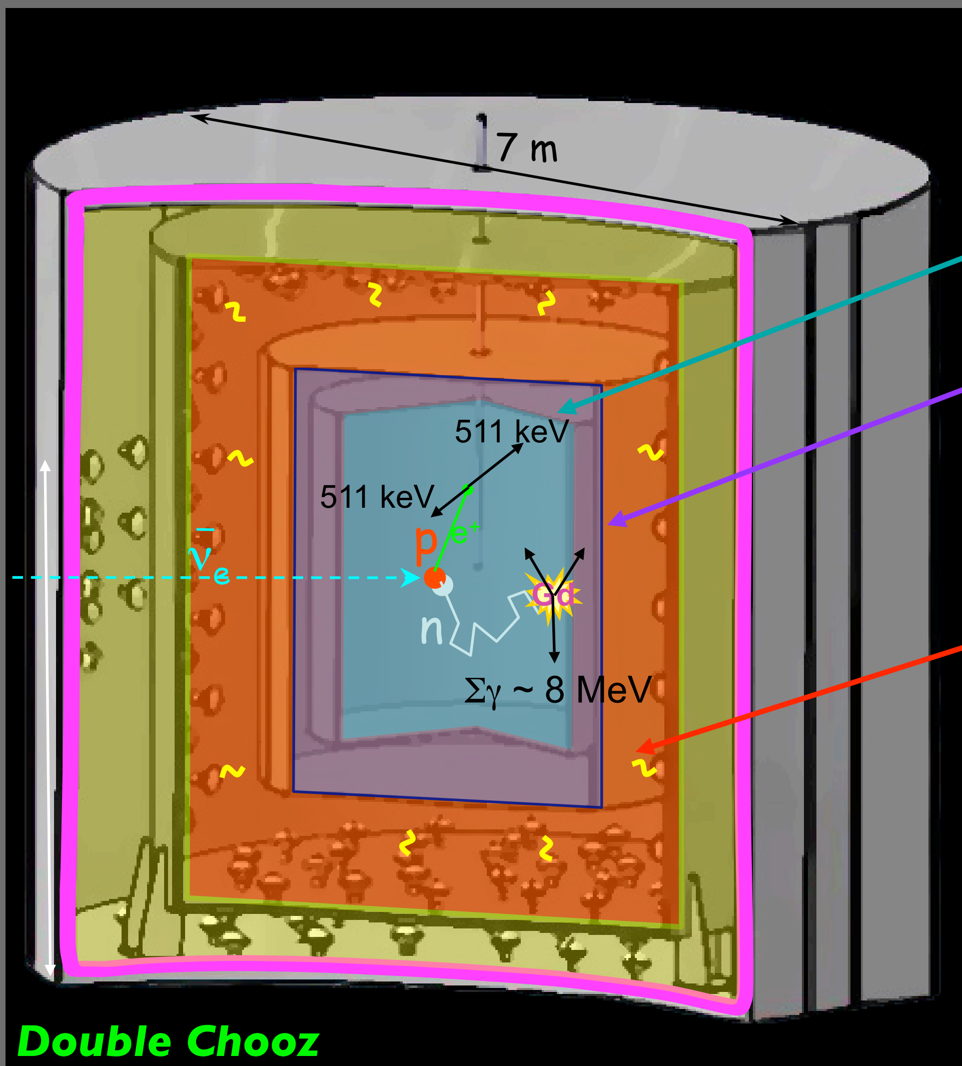

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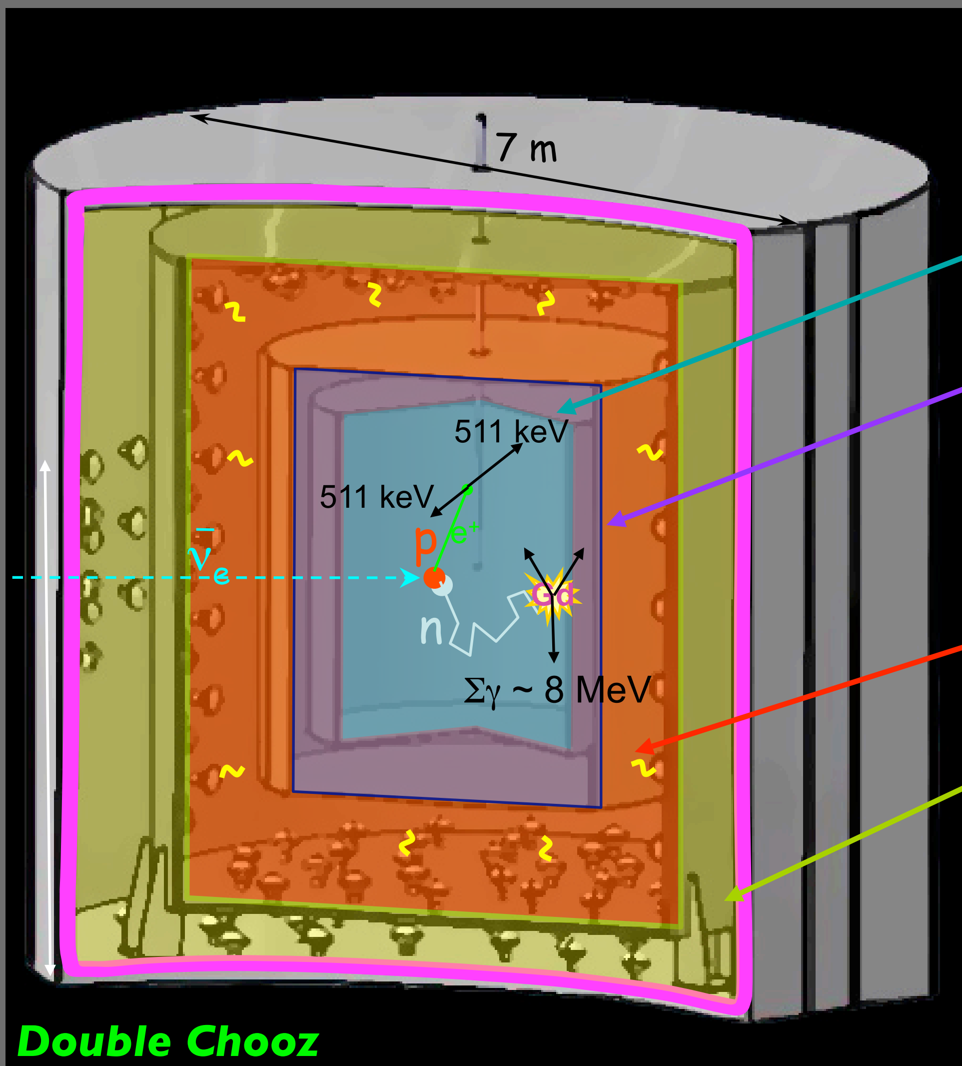

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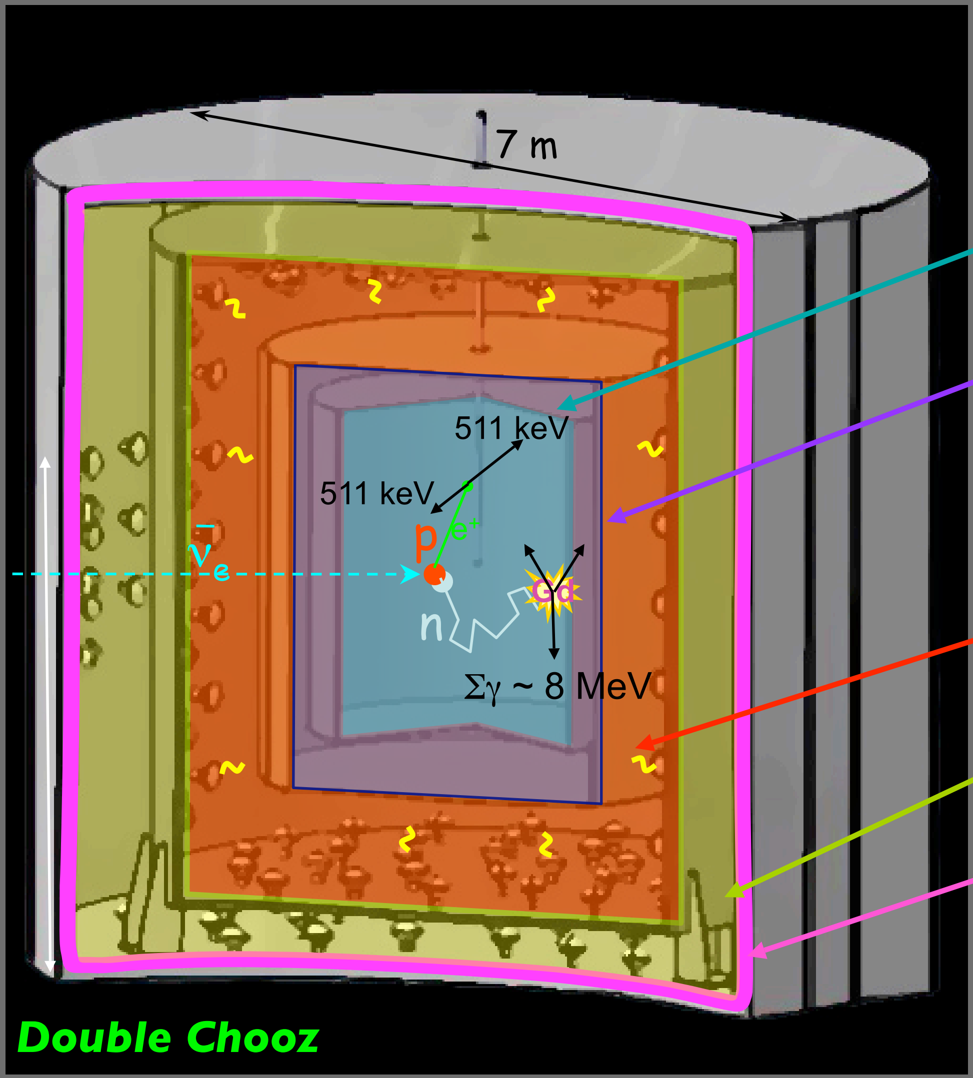

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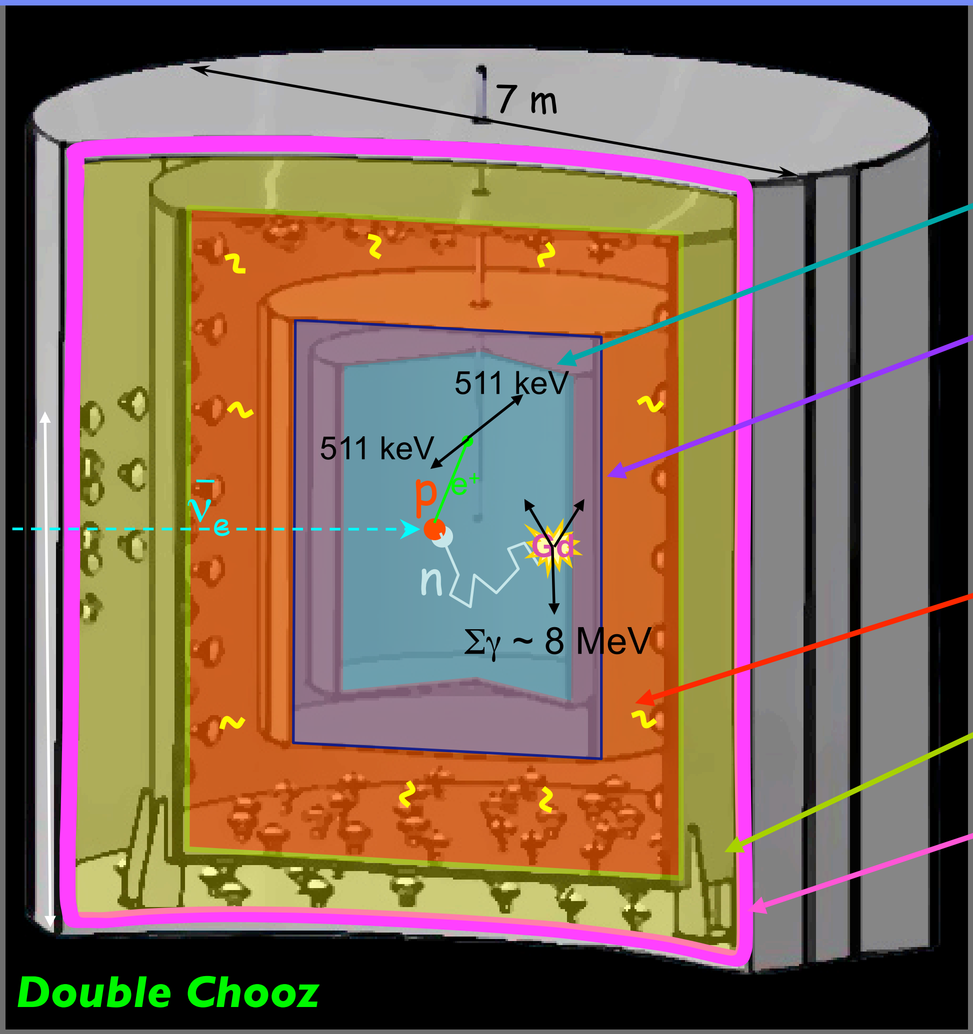

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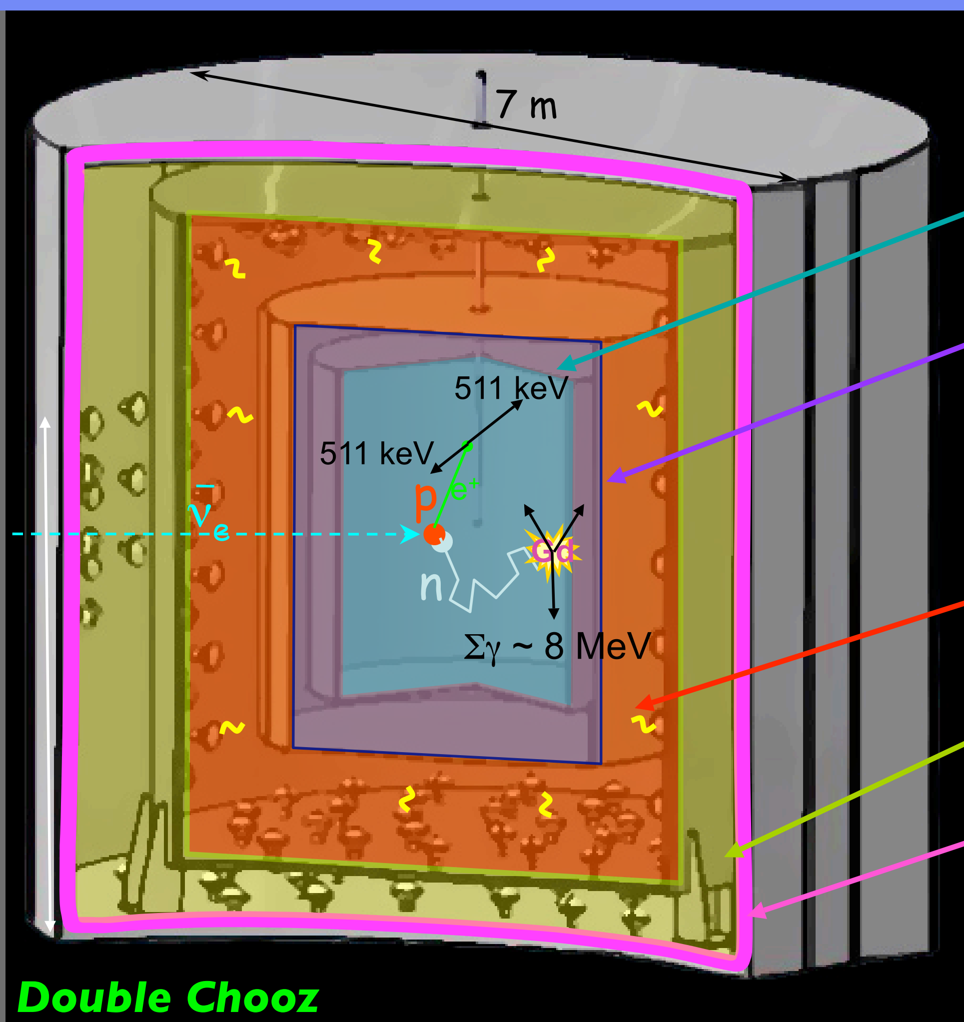
"near-miss" μ tagging



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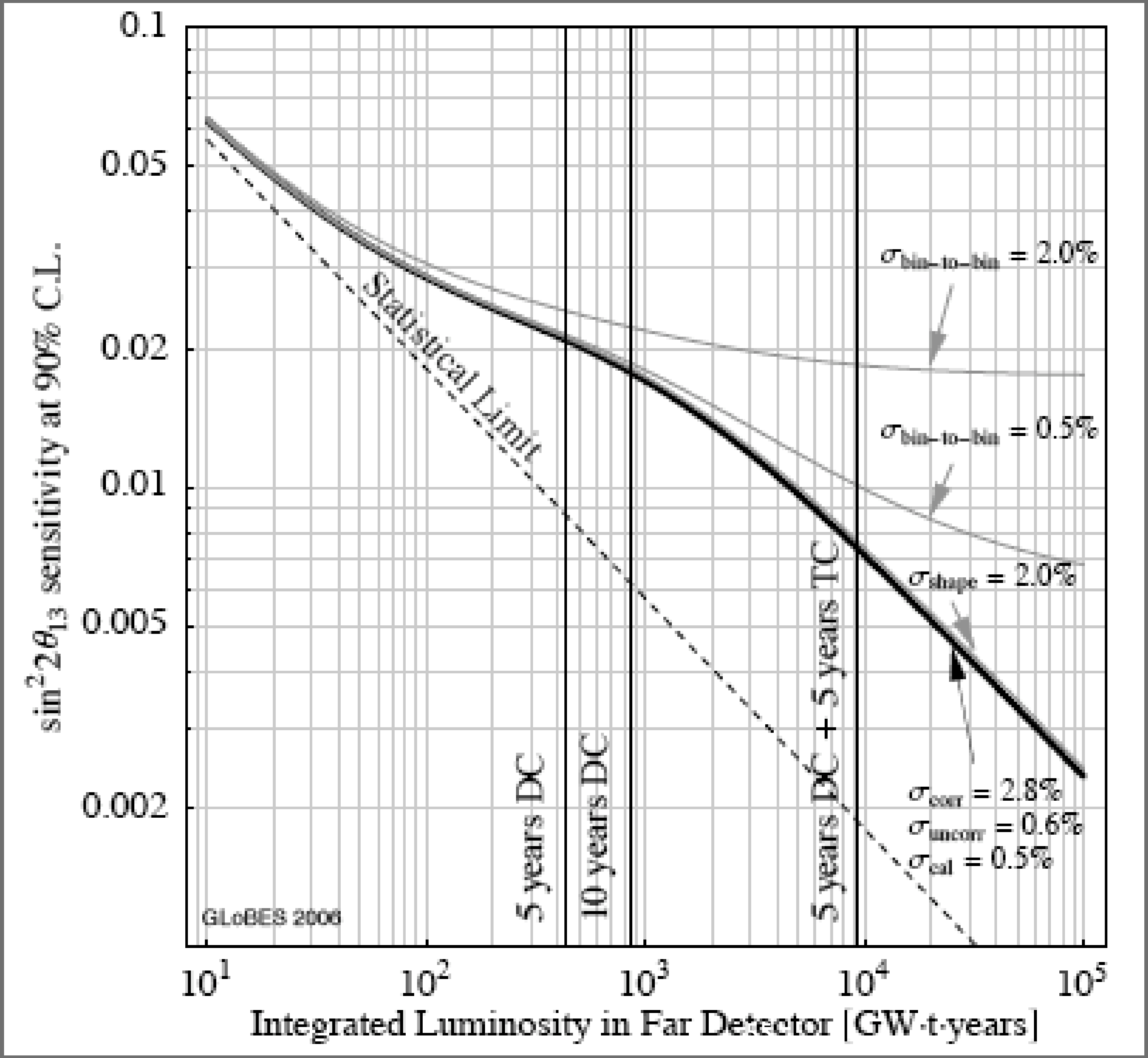

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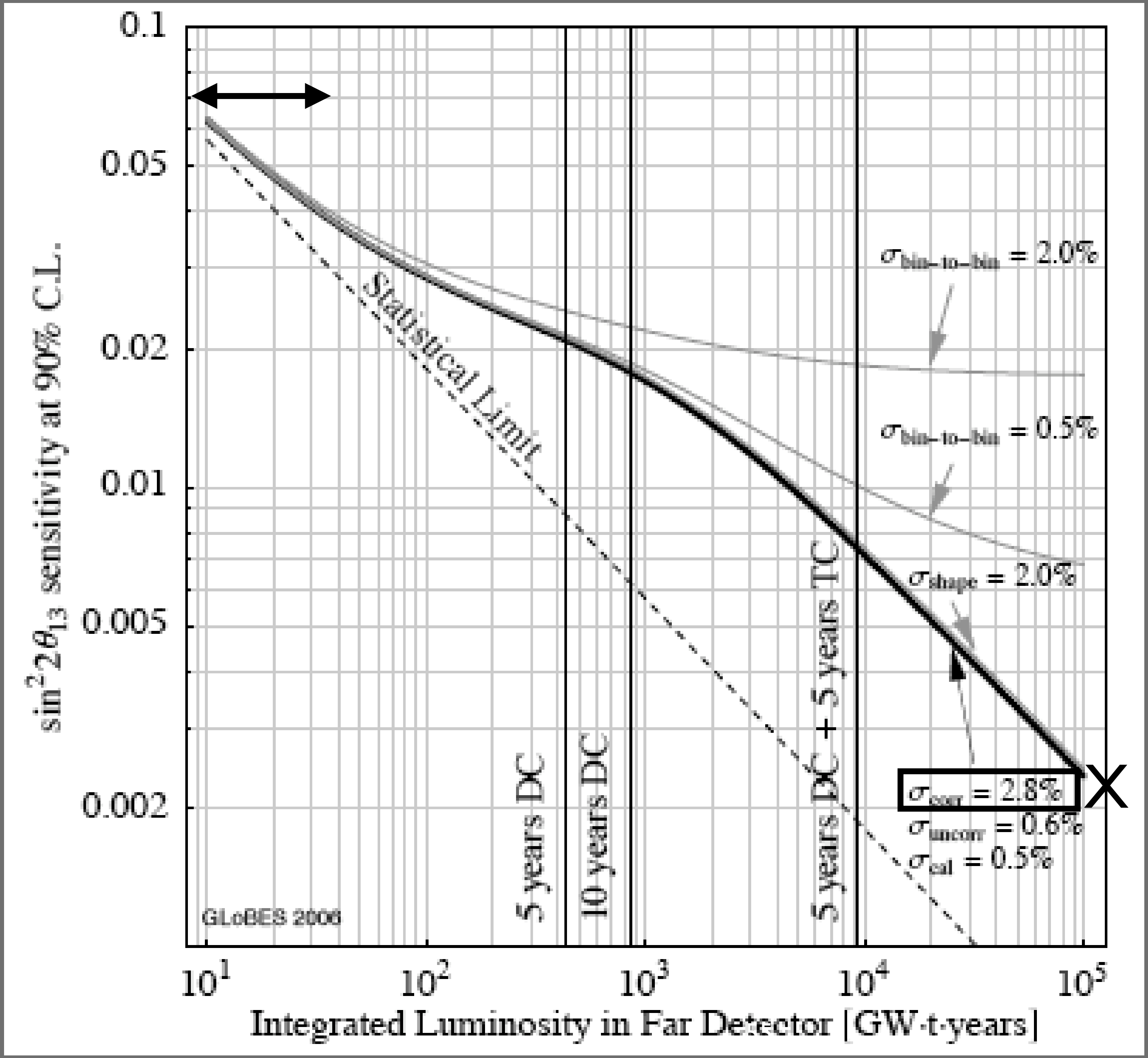

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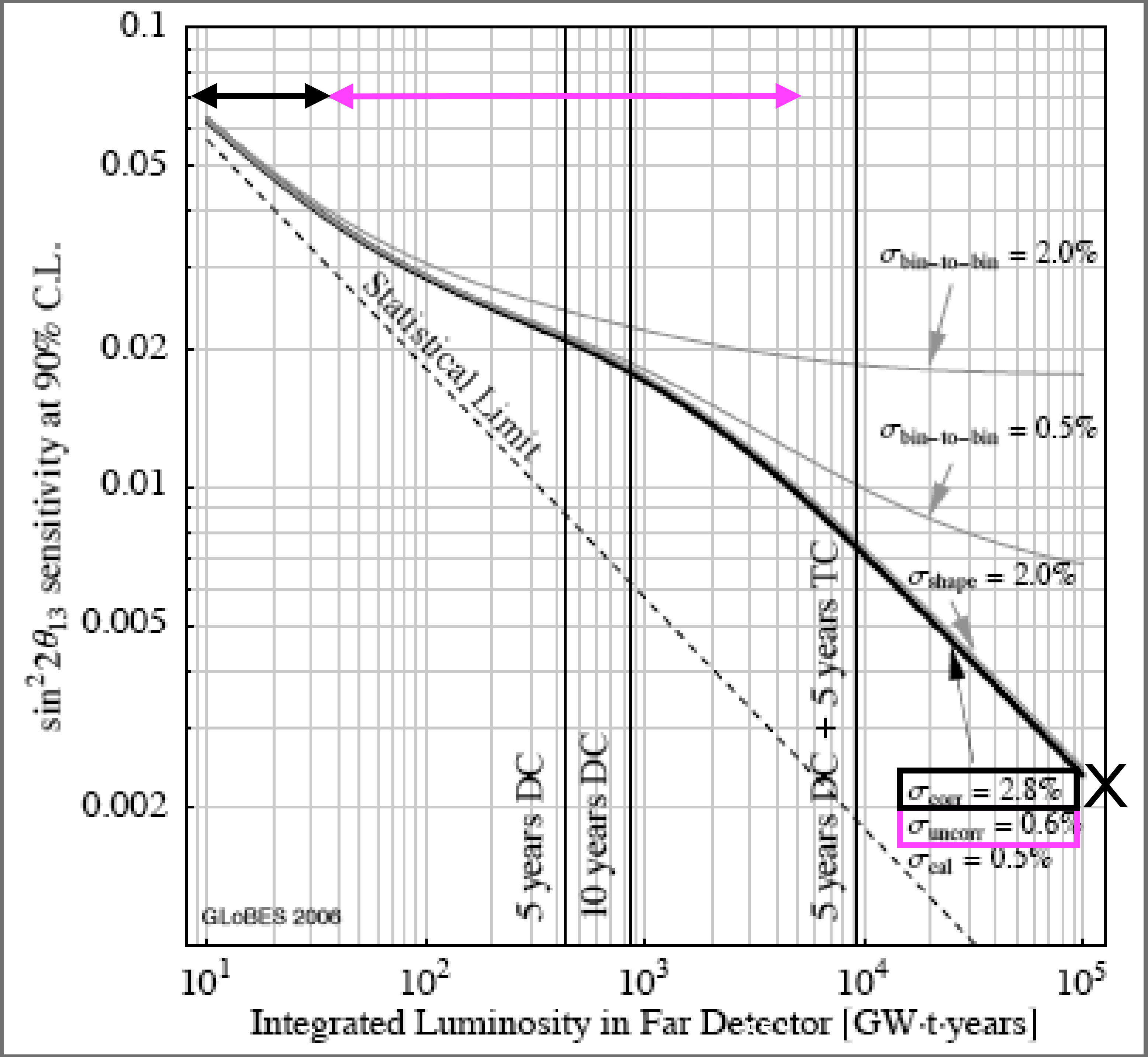

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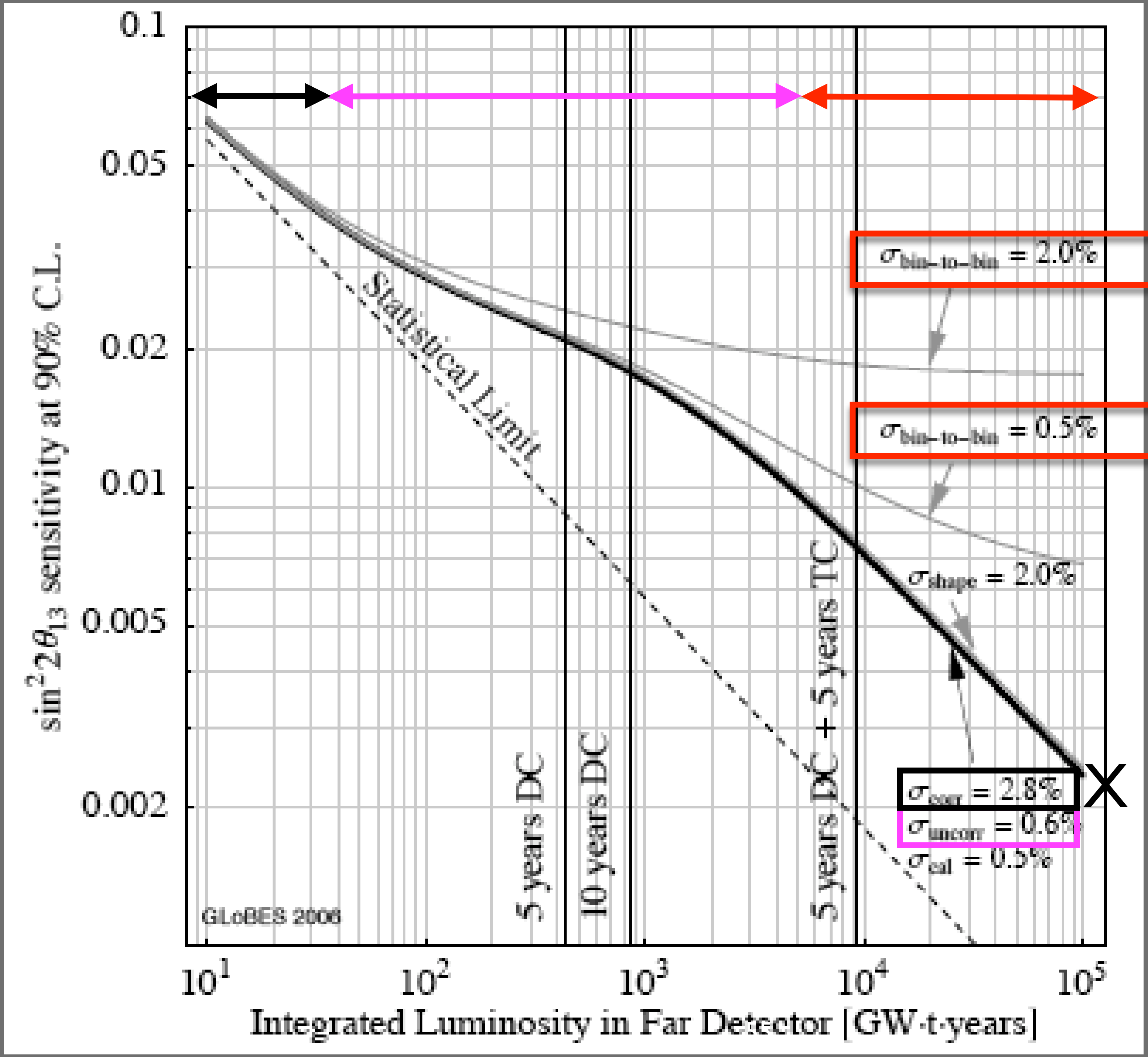

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&
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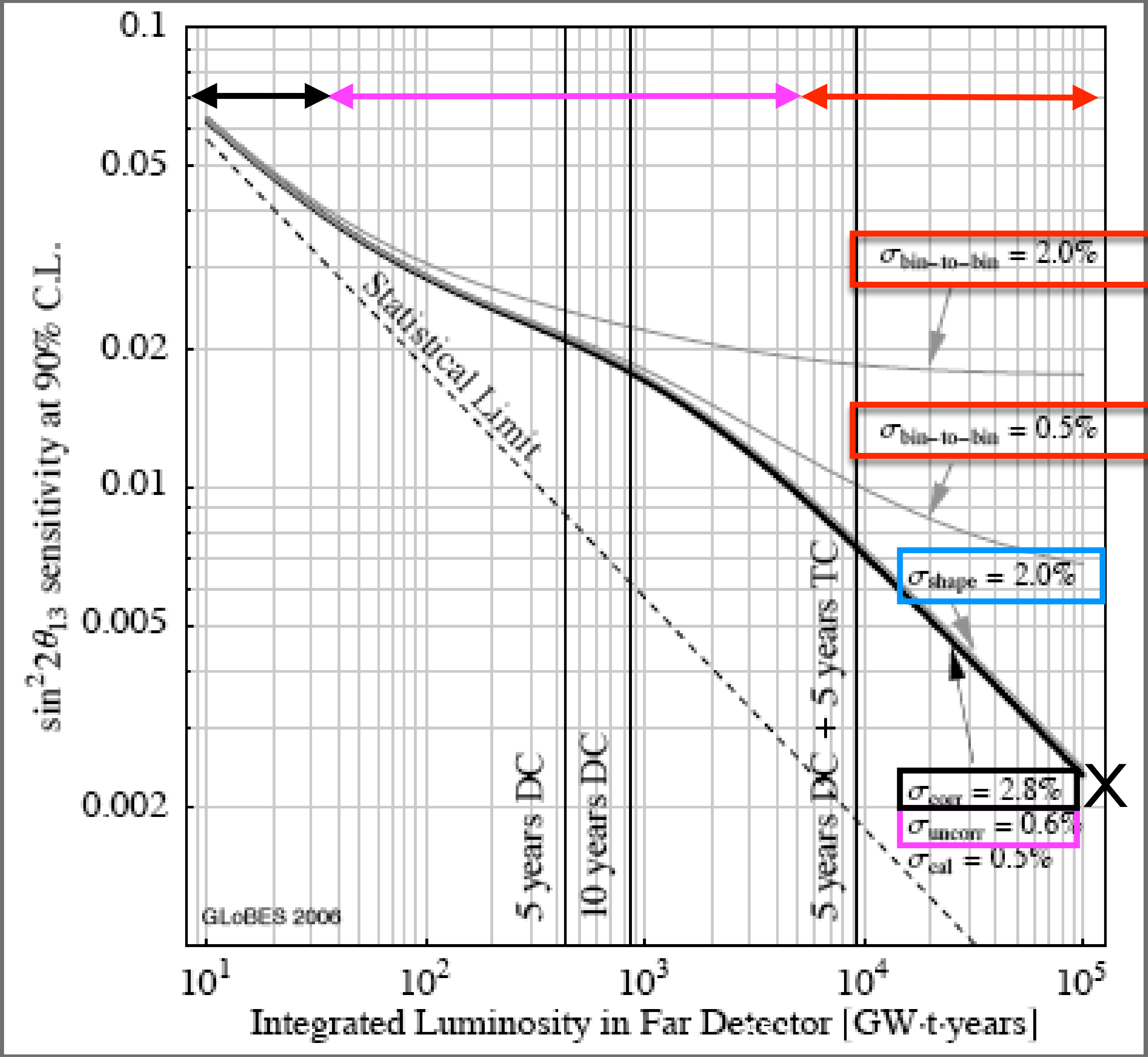

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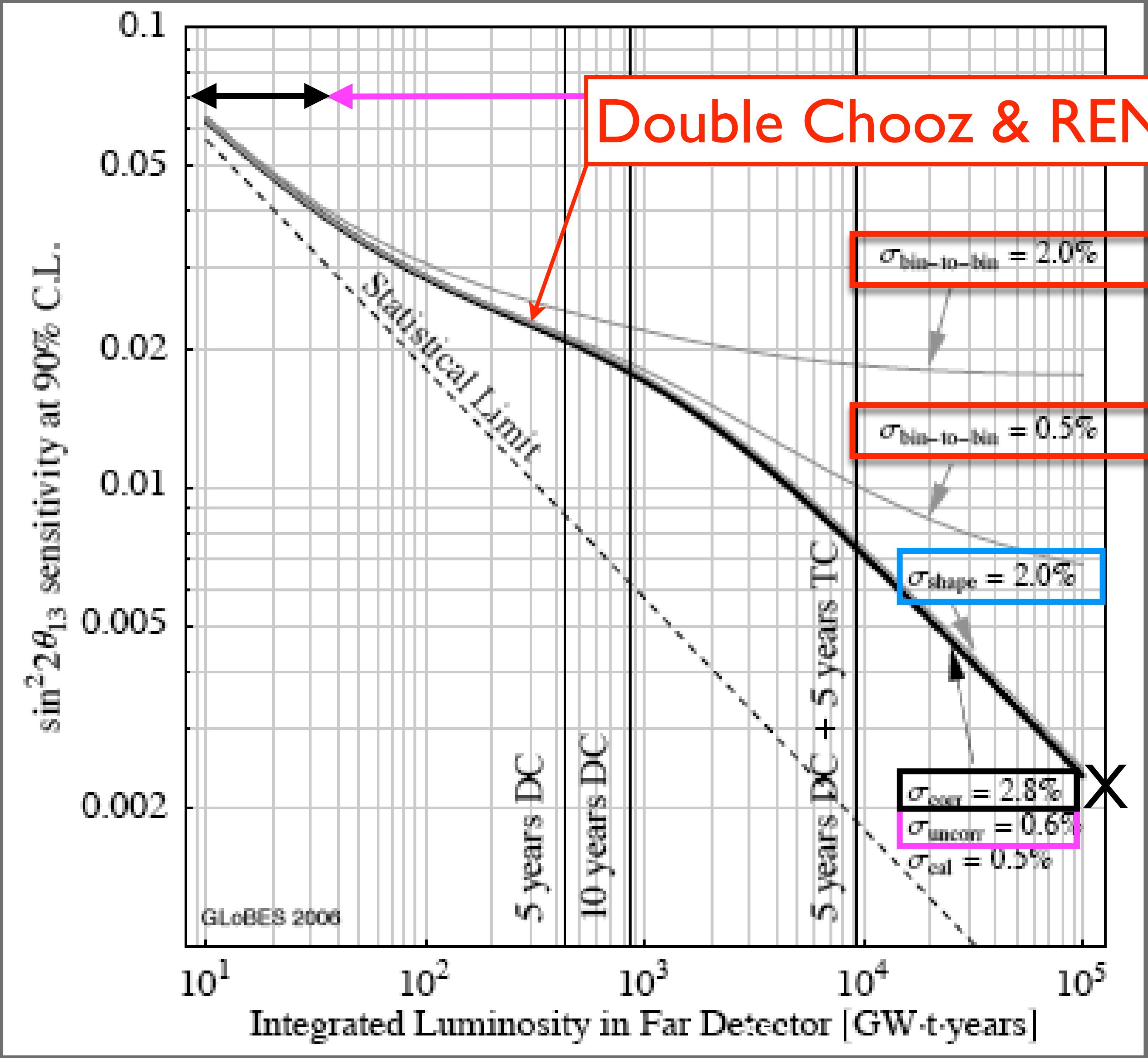

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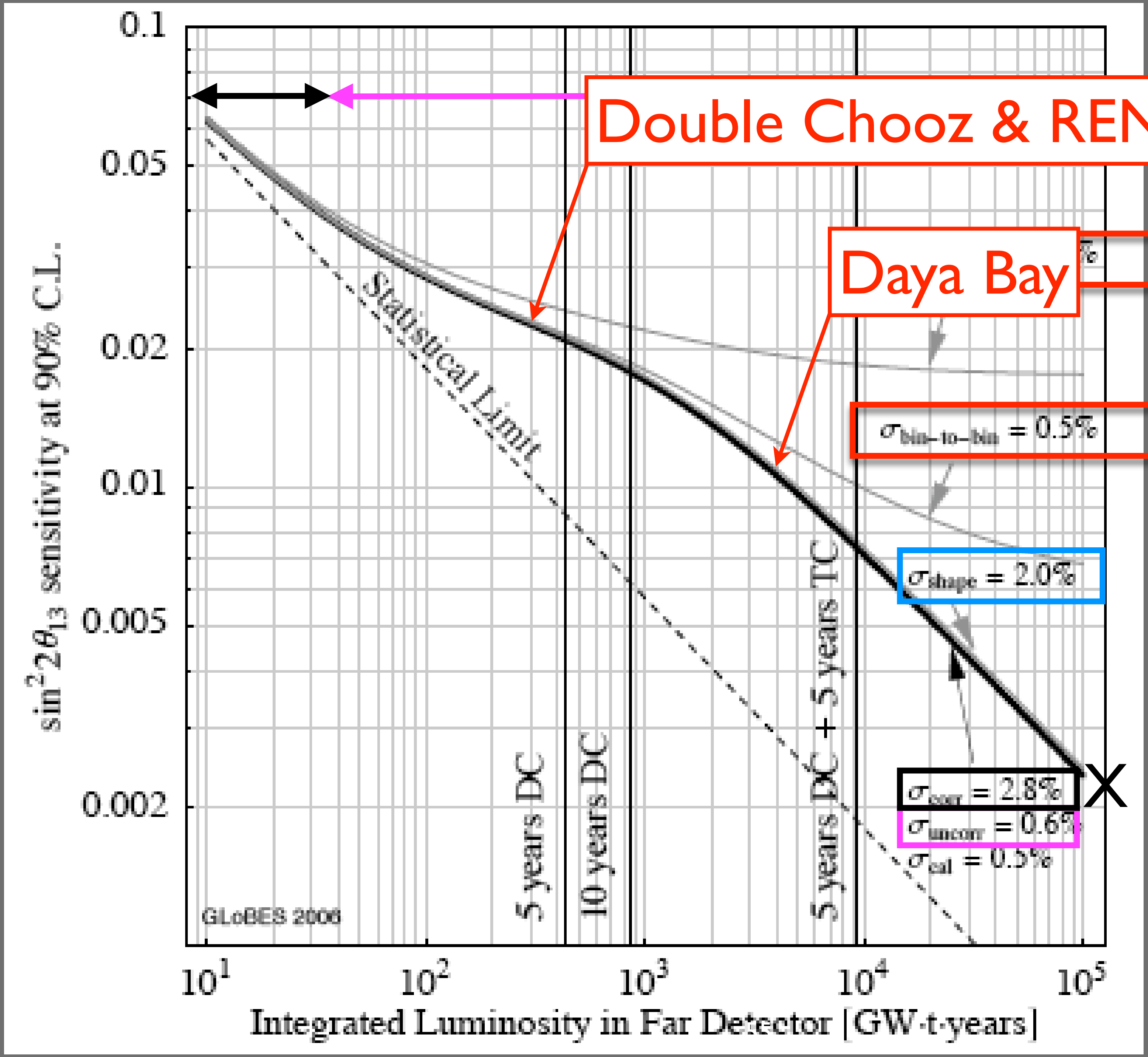

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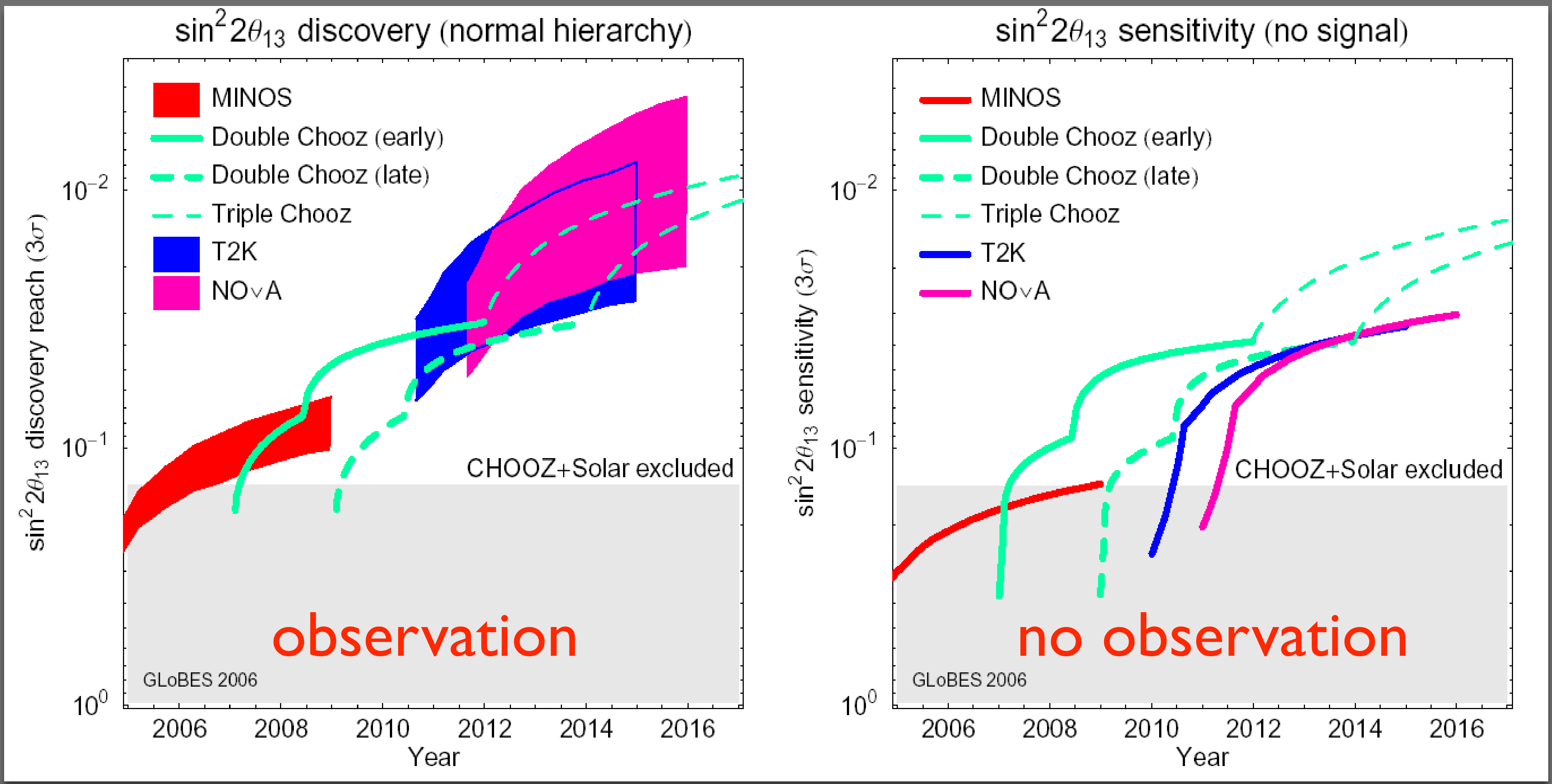
What to remember?

beams + reactors = deeper insight

Competitive & overlapping coverage by both techniques!



Similar time scale

P. Huber et al: hep-ph/0601266

no time for...

no time for...

- Angra (reactor): θ_{13} [hep-ex/0511059]

no time for...

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- And more...