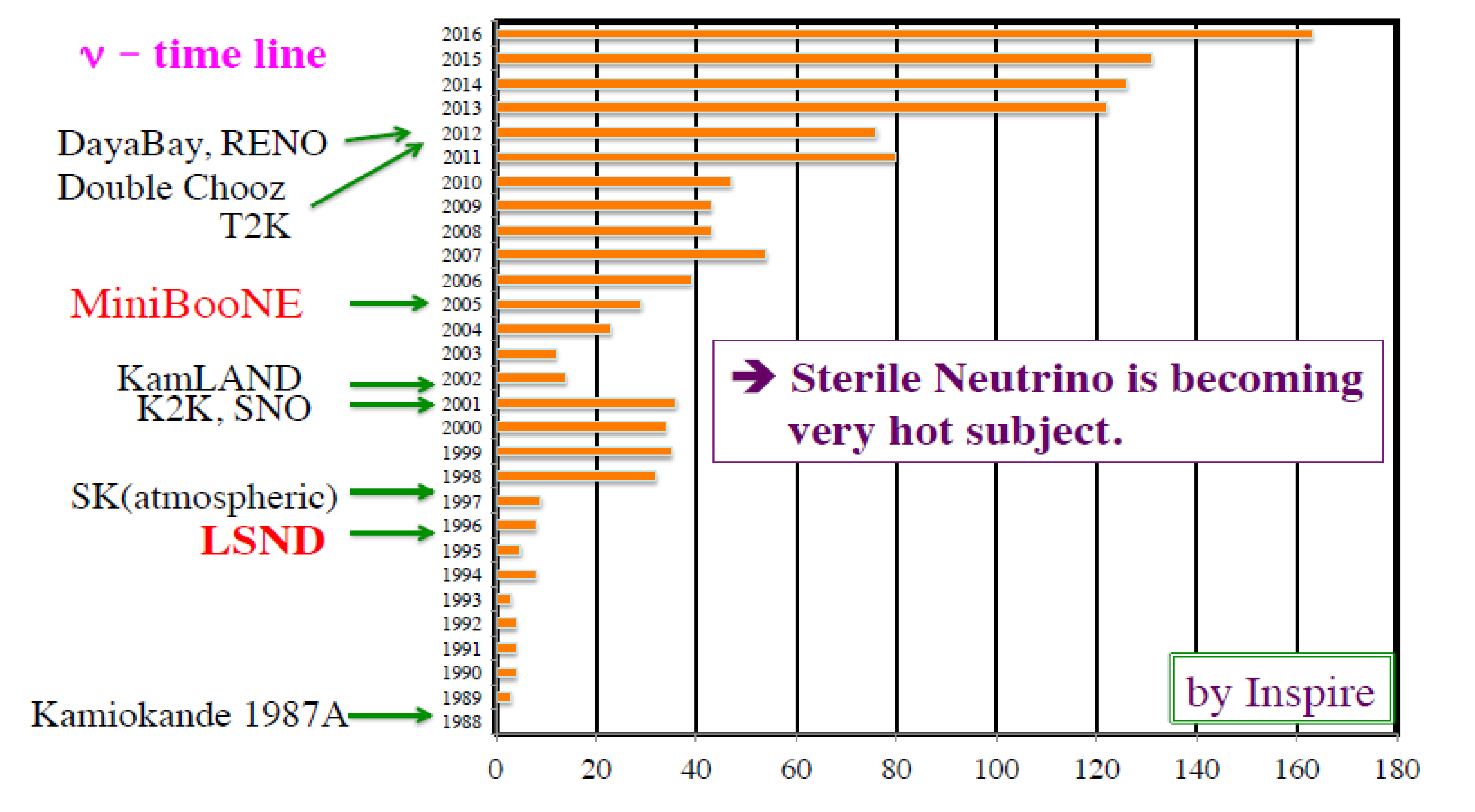
ν_μ disappearance

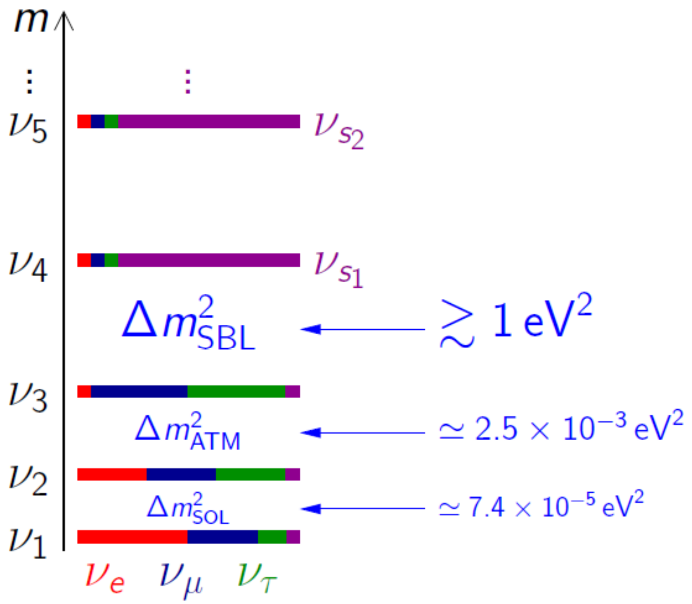
MARCO LAVEDER - June 17, 2019

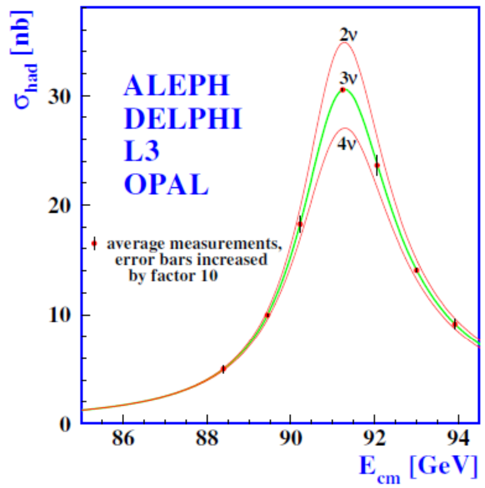
Sterile Neutrino



Sterile Neutrino

Beyond Three-Neutrino Mixing: Sterile Neutrinos





$$\boxed{N^{\text{LEP}}_{\nu_{\text{active}}} = 2.9840 \pm 0.0082}$$

Terminology: a eV-scale sterile neutrino
means: a eV-scale massive neutrino which is mainly sterile

Sterile Neutrino

Sterile Neutrinos from Physics Beyond the SM

- Neutrinos are special in the Standard Model: the only neutral fermions
- Active left-handed neutrinos can mix with non-SM singlet fermions often called right-handed neutrinos
- Light left-handed anti-ν_R are light sterile neutrinos

$$\nu_R^c \to \nu_{sL} \qquad \text{(left-handed)}$$

- Sterile means no standard model interactions

[Pontecorvo, Sov. Phys. JETP 26 (1968) 984]

- Active neutrinos $(\nu_e, \nu_\mu, \nu_\tau)$ can oscillate into light sterile neutrinos (ν_s)
- Observables:
  - Disappearance of active neutrinos (neutral current deficit)
  - Indirect evidence through combined fit of data (current indication)
- Short-baseline anomalies + 3ν-mixing:

$$\begin{array}{ccccc} & \Delta m^2_{21} \ll & |\Delta m^2_{31}| \ll & |\Delta m^2_{41}| \leq & \ldots \\ \nu_1 & \nu_2 & \nu_3 & \nu_4 & \ldots \\ \nu_e & \nu_\mu & \nu_\tau & \nu_{s_1} & \ldots \end{array}$$

3+1 Neutrino Model

Effective 3+1 SBL Oscillation Probabilities

Appearance ($\alpha \neq \beta$)

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

Disappearance

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

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

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

SBL

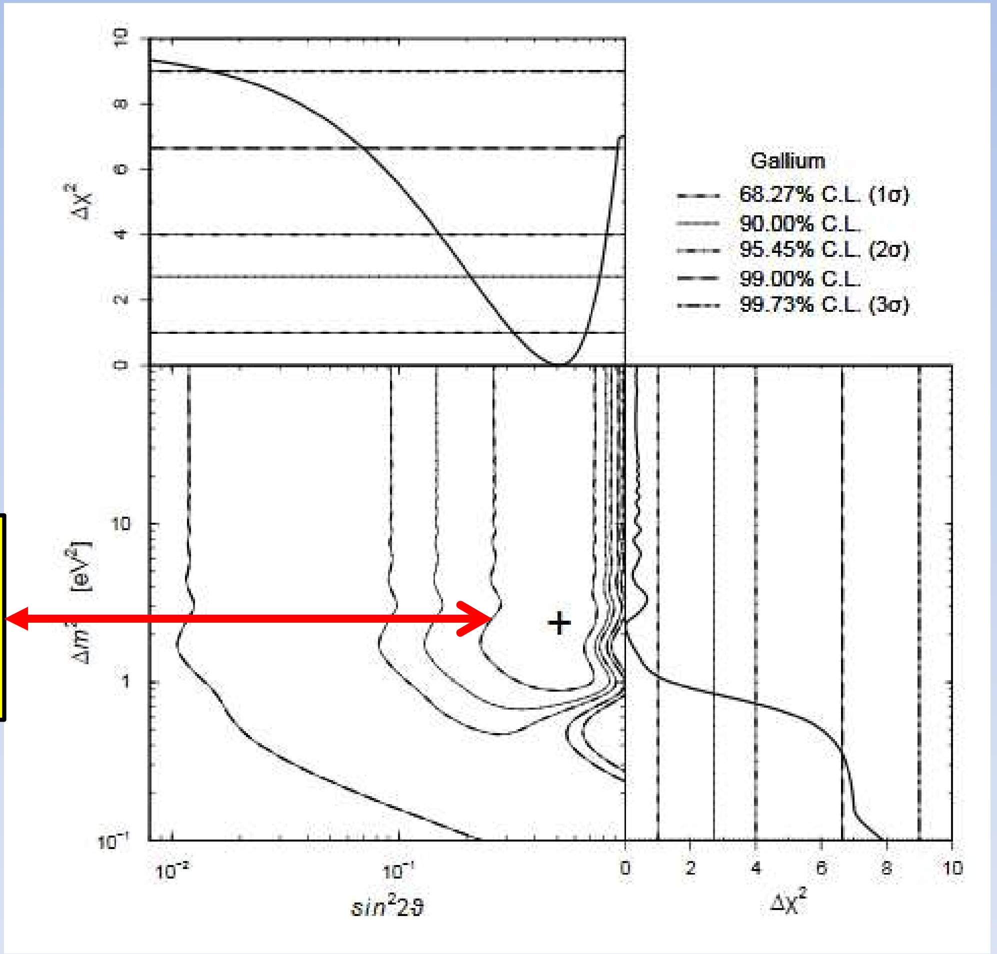
- 6 mixing angles
- 3 Dirac CP phases
- 3 Majorana CP phases

- CP violation is not observable in SBL experiments!
- Observable in LBL accelerator exp. sensitive to Δm^2_{ATM} [de Gouvea et al, PRD 91 (2015) 053005, PRD 92 (2015) 073012, arXiv:1605.09376; Palazzo et al, PRD 91 (2015) 073017, PLB 757 (2016) 142; Kayser et al, JHEP 1511 (2015) 039, JHEP 1611 (2016) 122] and solar exp. sensitive to Δm^2_{SOL} [Long, Li, CG, PRD 87, 113004 (2013) 113004]

3+1 Model Dependent Results: ν_e

$\sin^2 2\theta \approx 0.5$

$\Delta m^2 \approx 2\ eV^2$

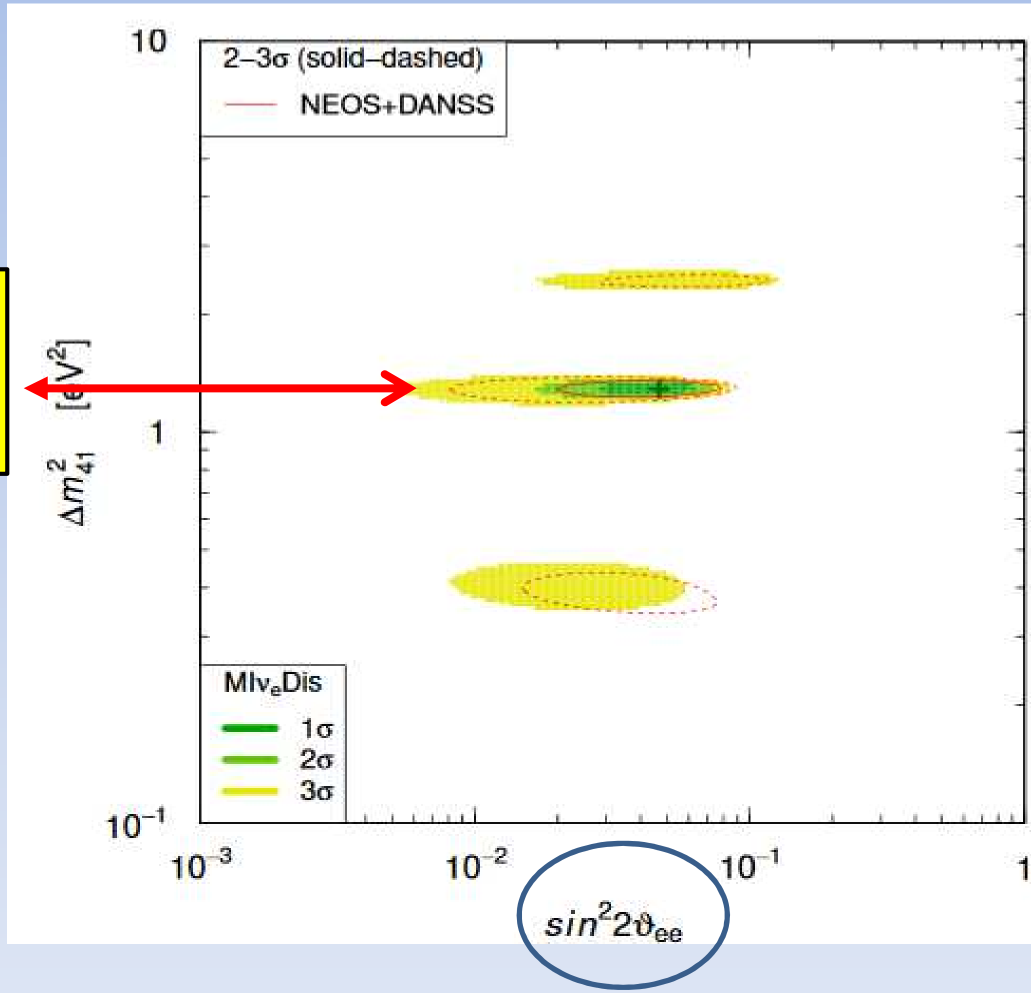


arXiv:1006.3244

3+1 Model Independent Results: $\bar{\nu}_e$

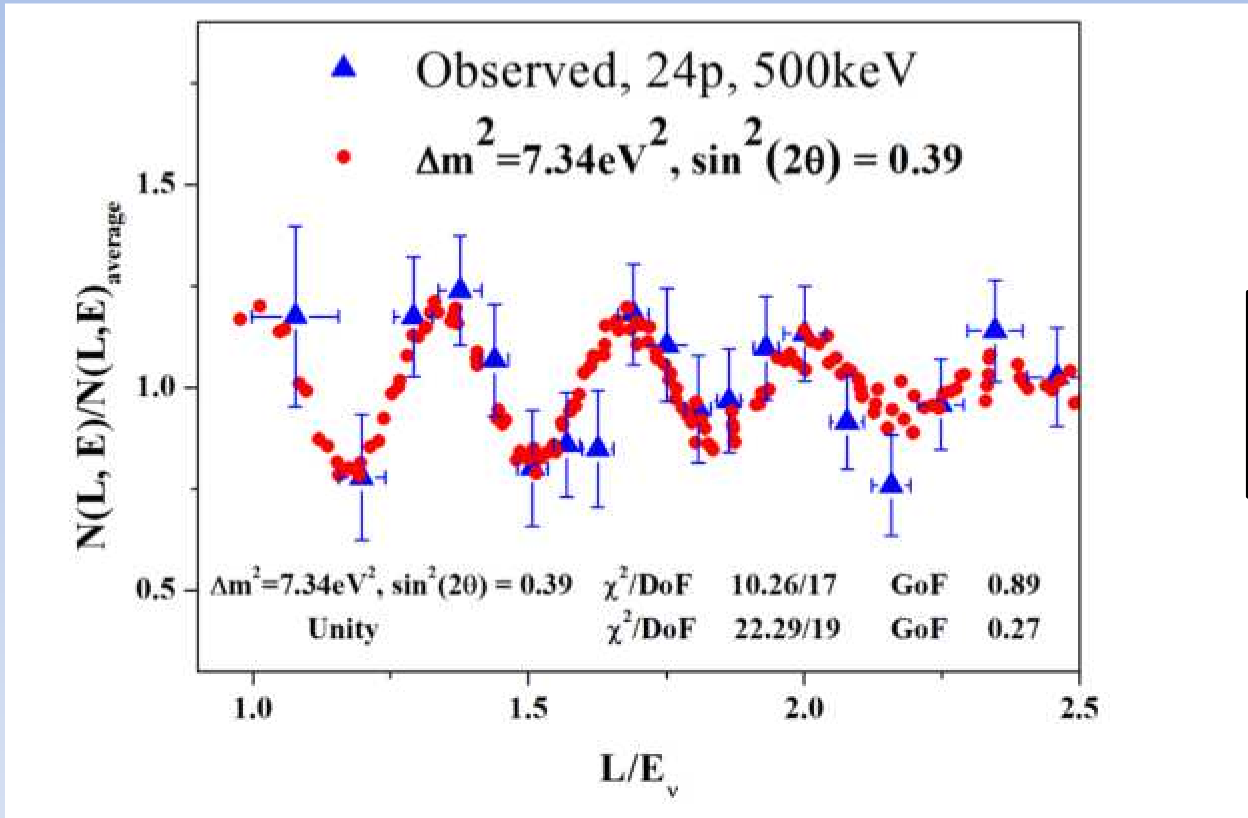
$sin^2 2\theta \approx 0.05$

$\Delta m^2 \approx 1.3\ eV^2$



arXiv:1801.06467

3+1 Model Independent Result: $\bar{\nu}_e$

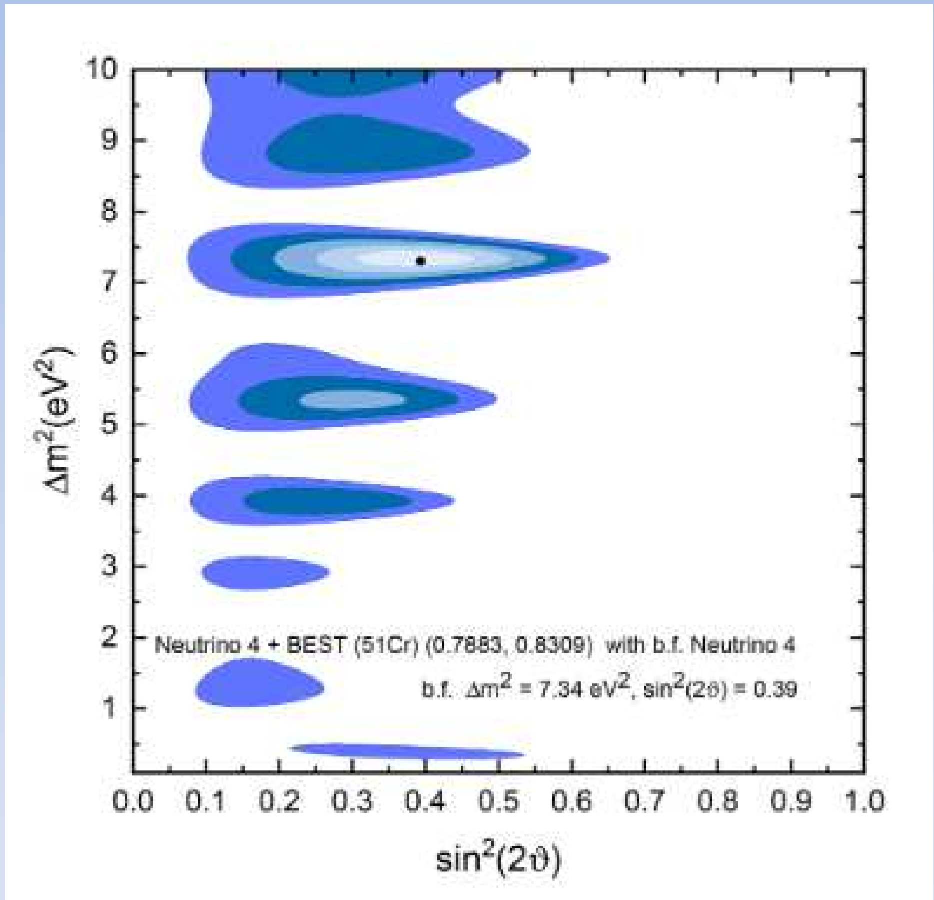


NEUTRINO-4

$sin^2 2\theta \approx 0.4$
$\Delta m^2 \approx 7\ eV^2$

1809.10561

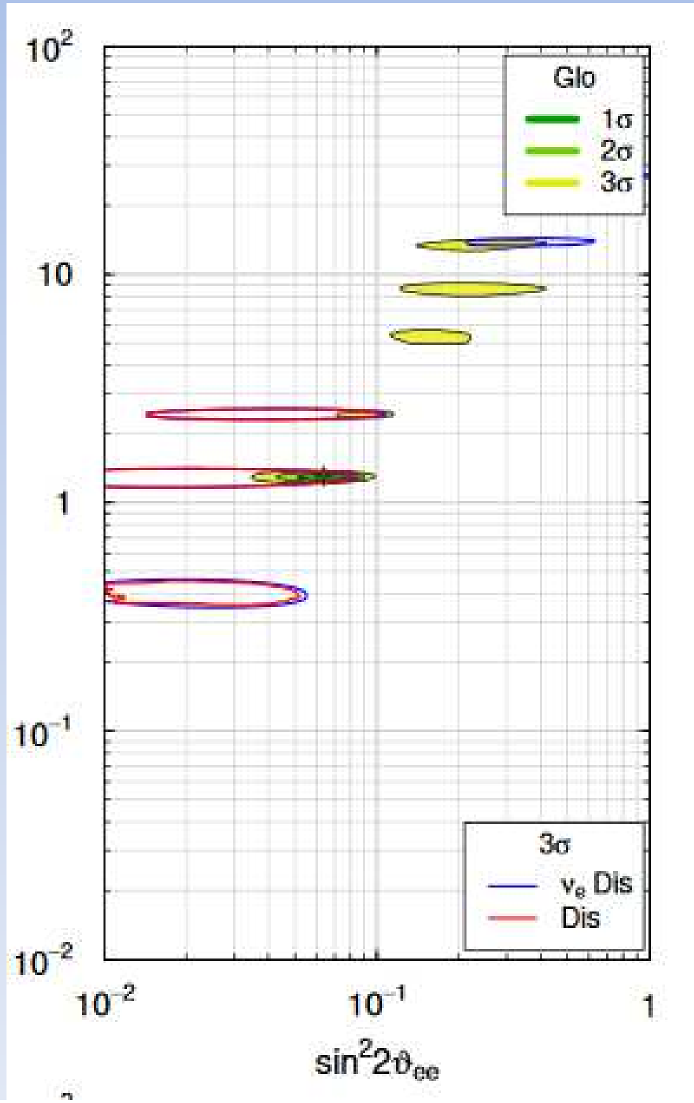
3+1 Model Independent Predictions: ν_e & $\bar{\nu}_e$



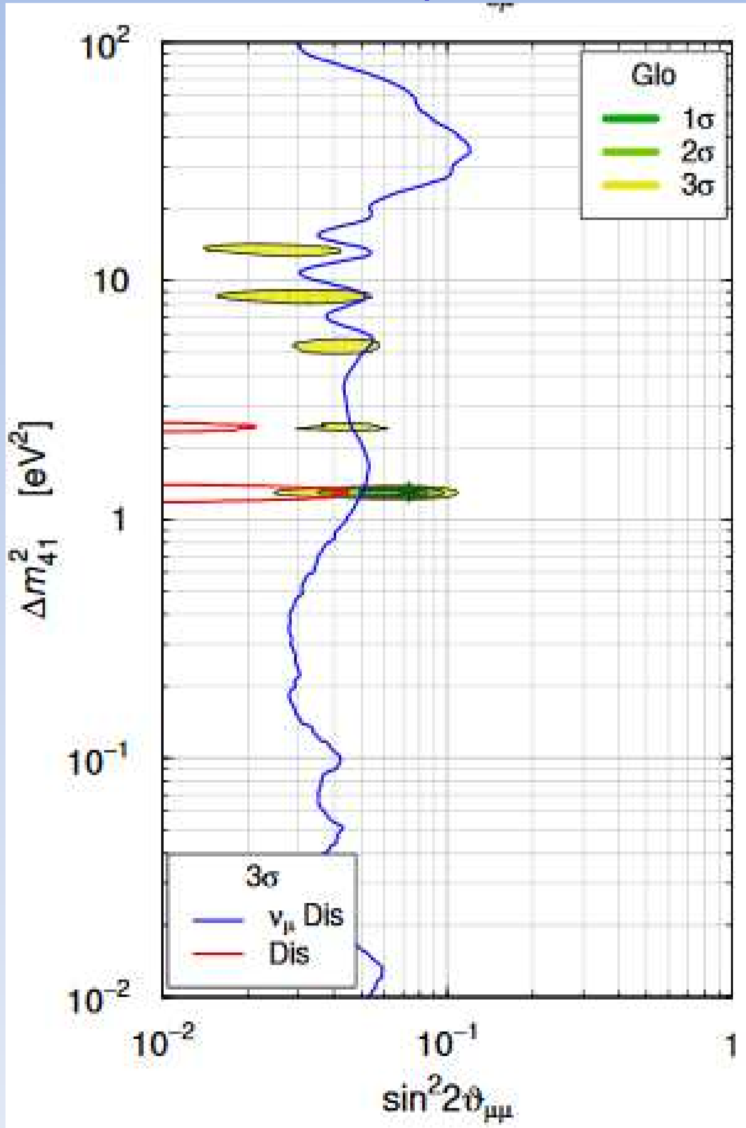
1905.07437

GALLIUM+BEST

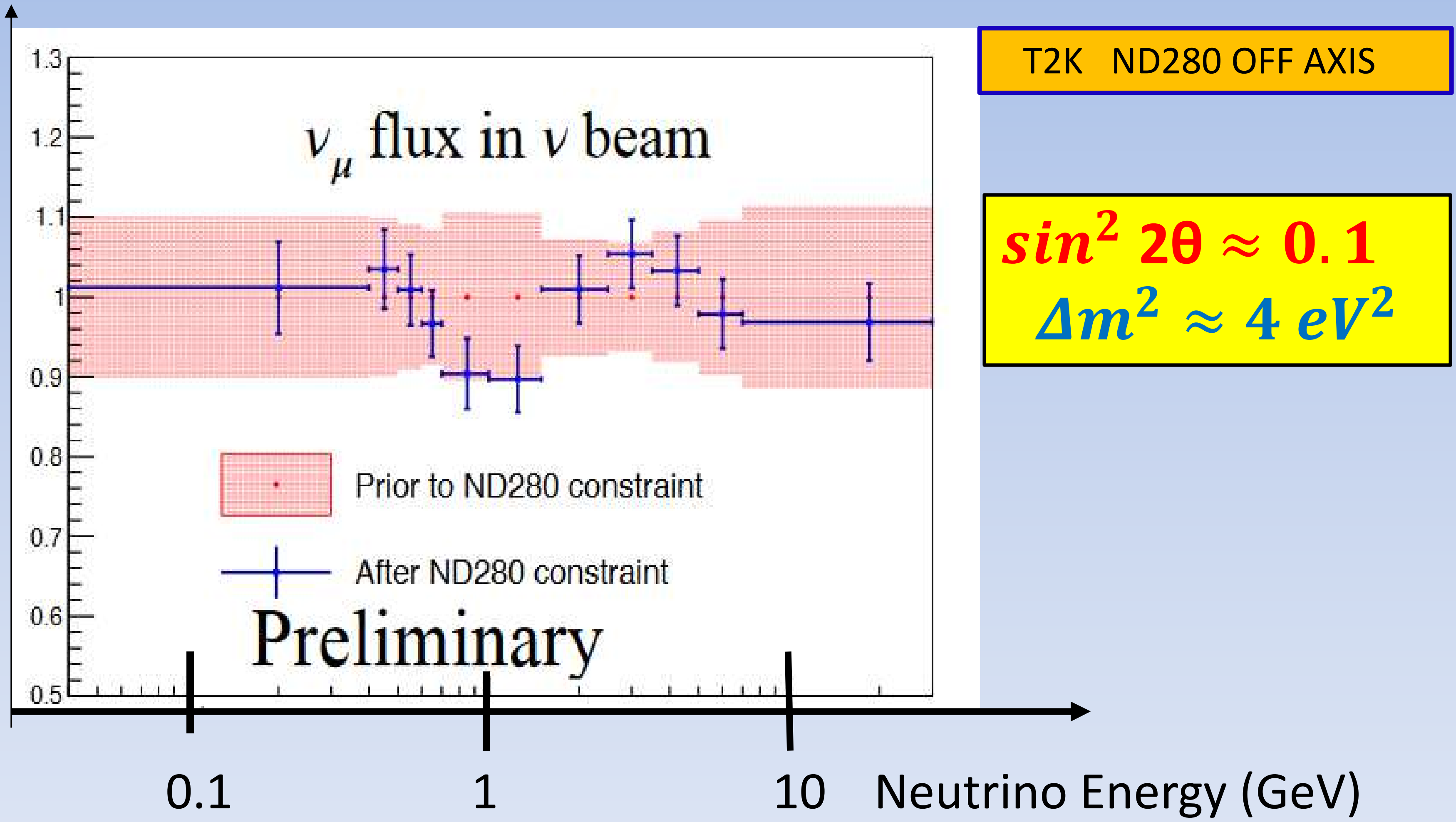
STATUS 3+1 Model nonpragmatic: ν_e & $\bar{\nu}_e$



STATUS 3+1 Model nonpragmatic: ν_μ



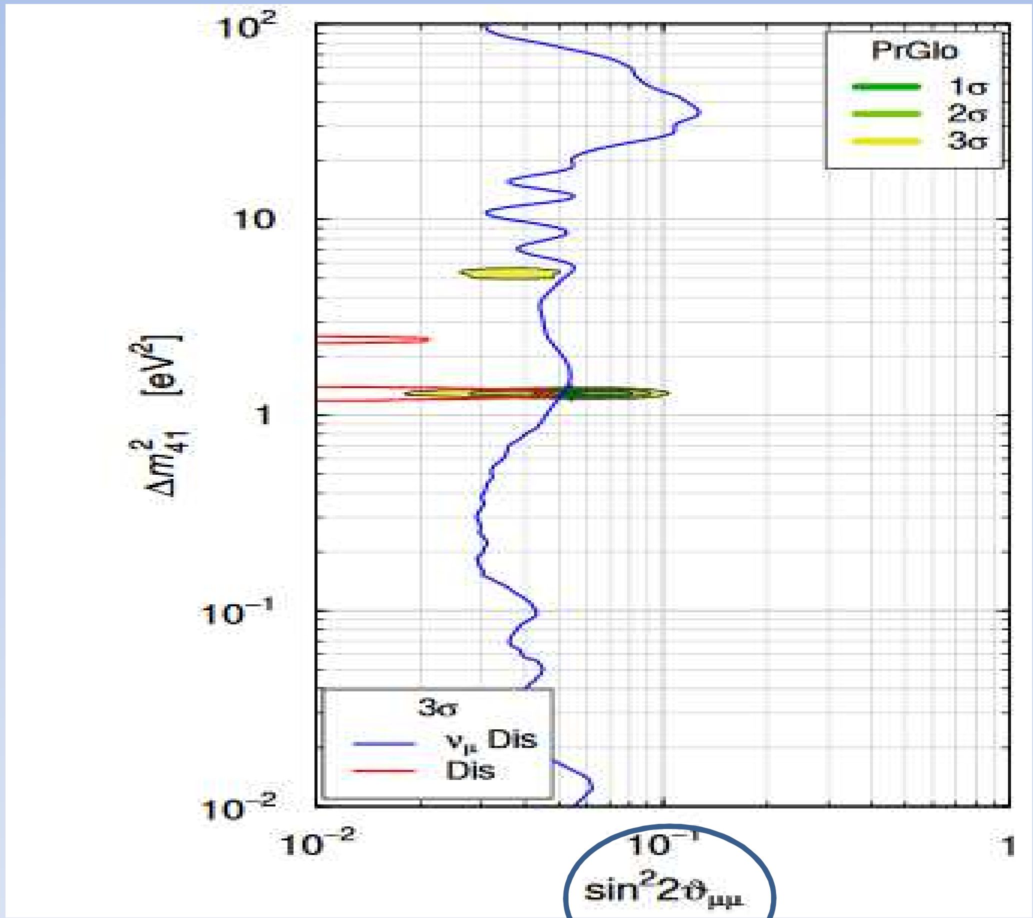
3+1 Model Independent Result: ν_μ



$sin^2 2\theta \approx 0.1$

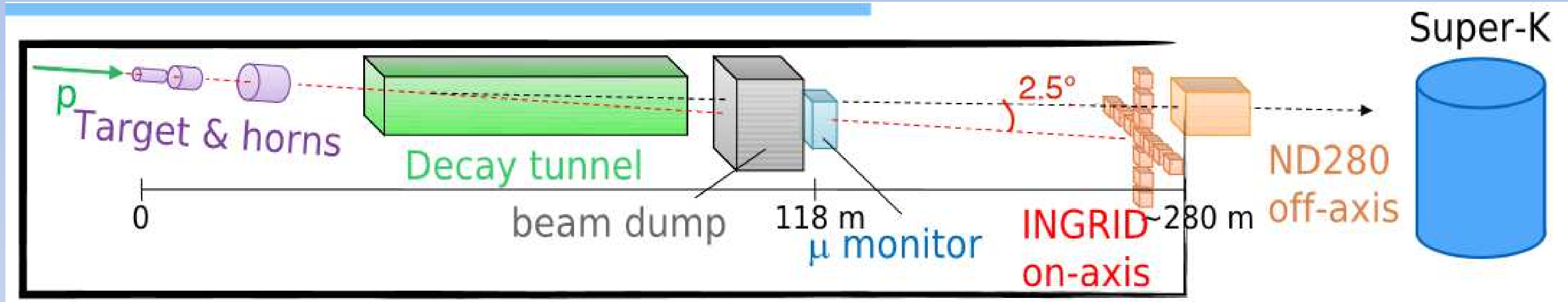
$\Delta m^2 \approx 4\ eV^2$

Problems with MINOS/MINOS+ limit



T2K Experiment

T2K Beam



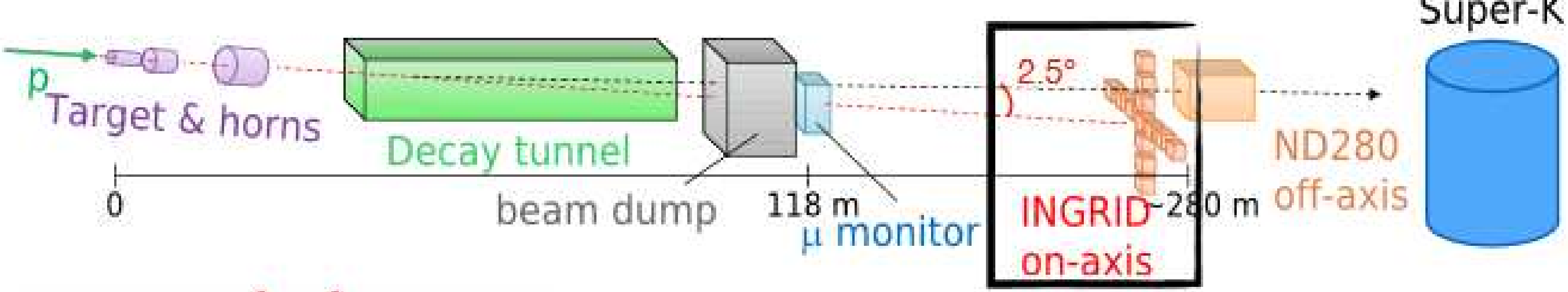
30 GeV proton beam from J-PARC Main Ring extracted onto a graphite target producing hadrons (mainly pions and kaons)

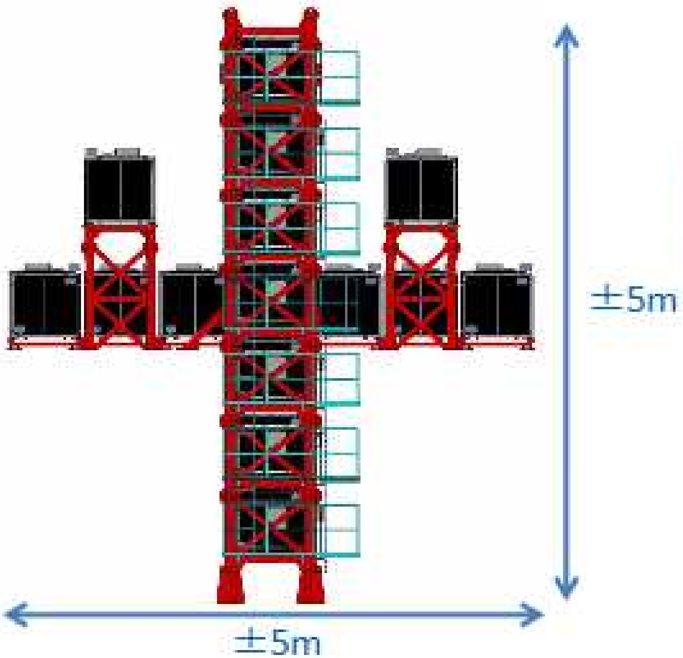
Hadrons are focused and selected in charge by 3 electromagnetic horns:

- ν_μ beam created by π^+ and $\bar{\nu}_\mu$ beam by π^- decay

T2K 280 Near Detector ON-axis

The on-axis near detector (INGRID)



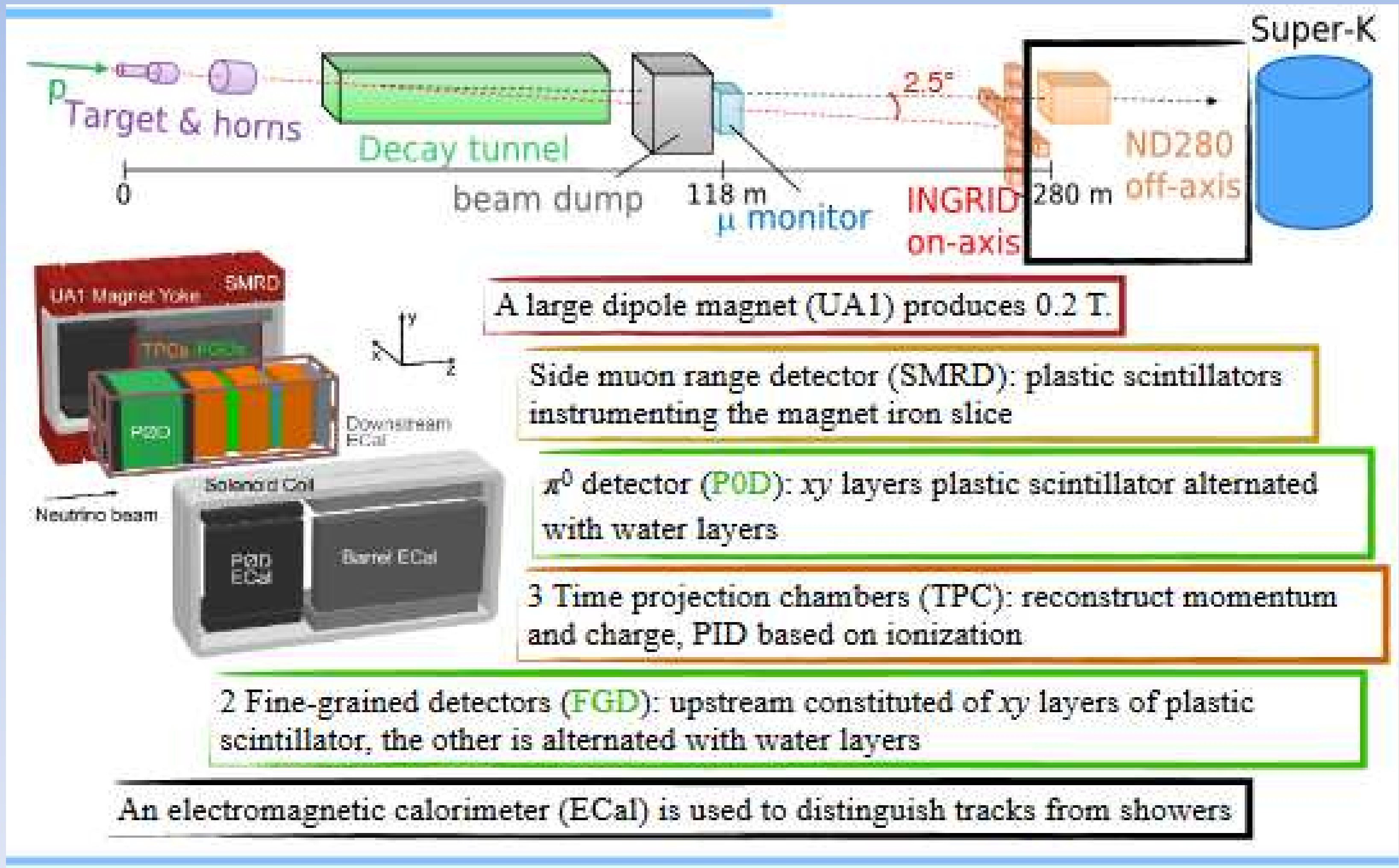


Monitor the beam stability and direction day-by-day looking at ν ($\overline{\nu}$) interactions

14 modules arranged in a cross; two others placed at off-diagonal positions

1 extra module made of scintillators and water at the center of the cross

T2K 280 Near Detector OFF-axis



ν_μ Interactions – P0D

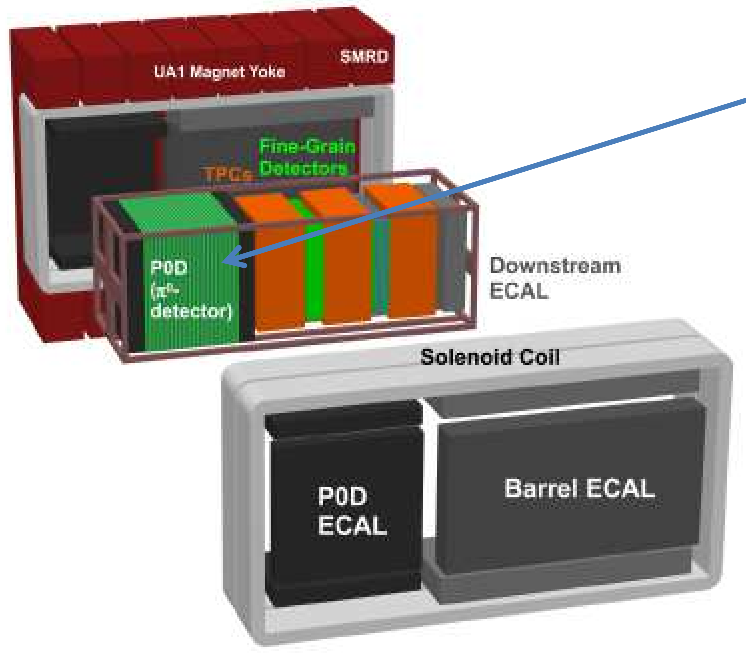
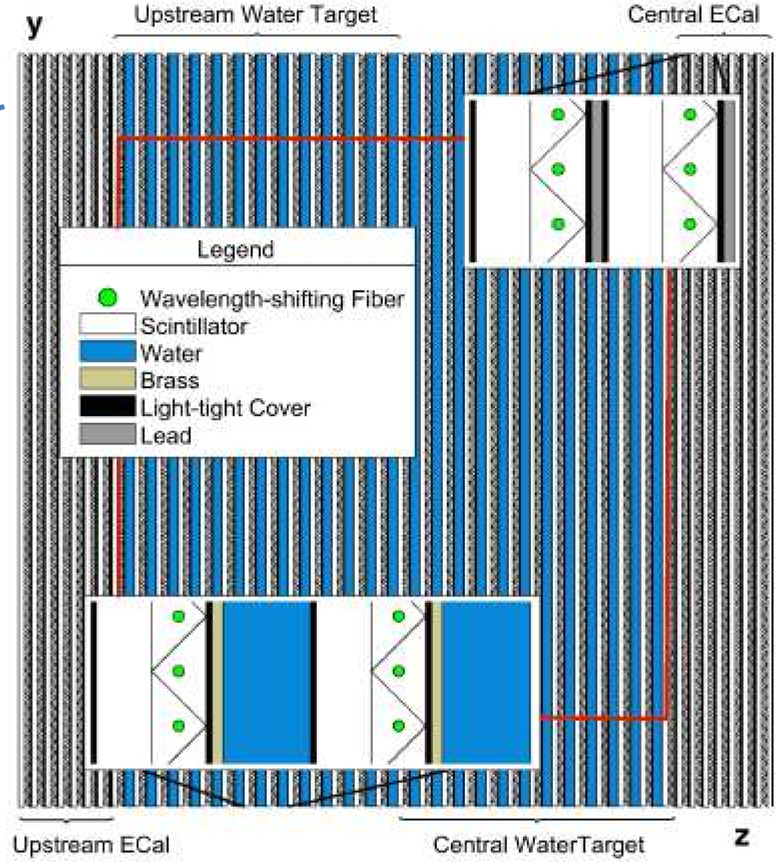
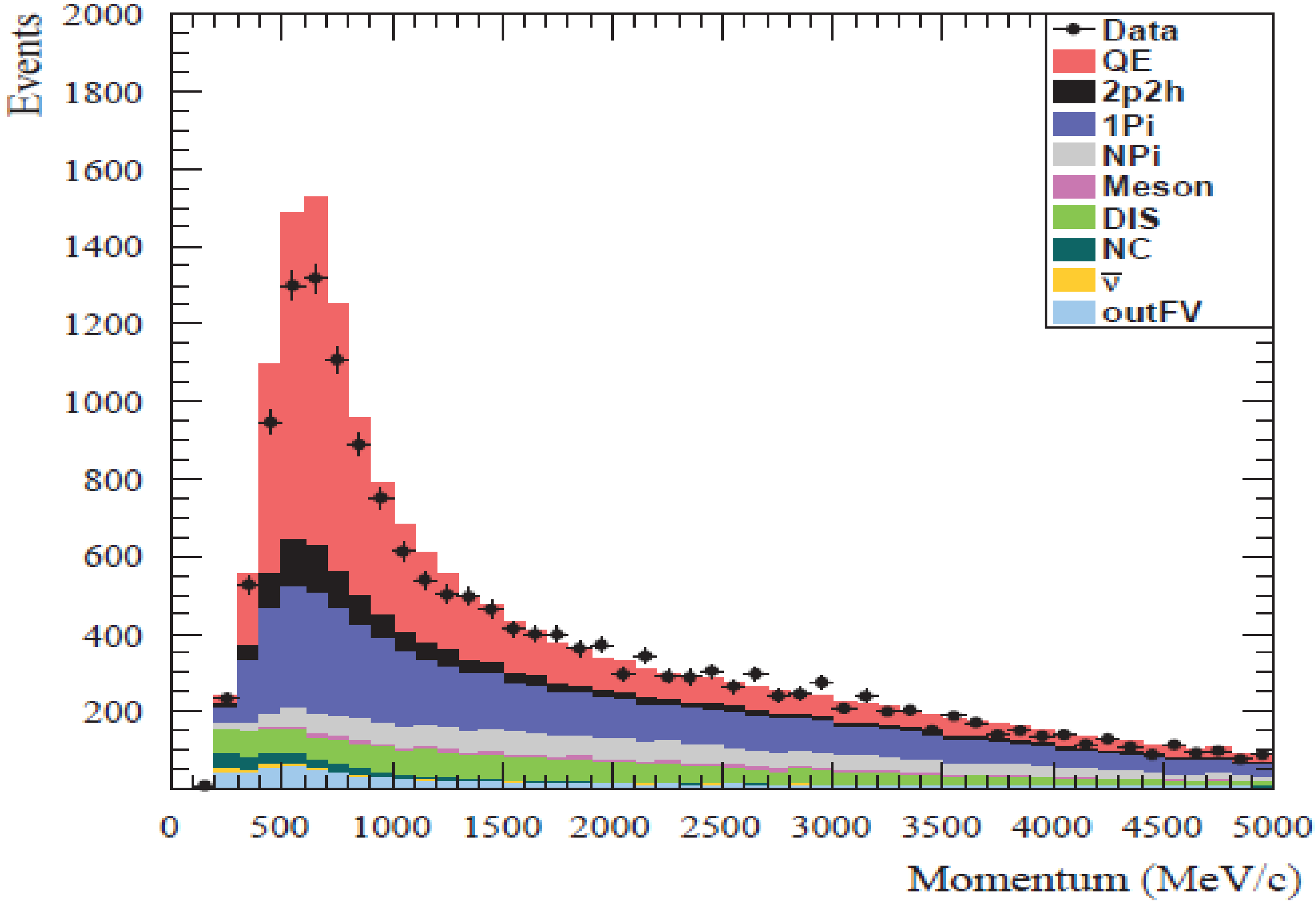


FIG. 1. An exploded view of T2K's off-axis near detector.

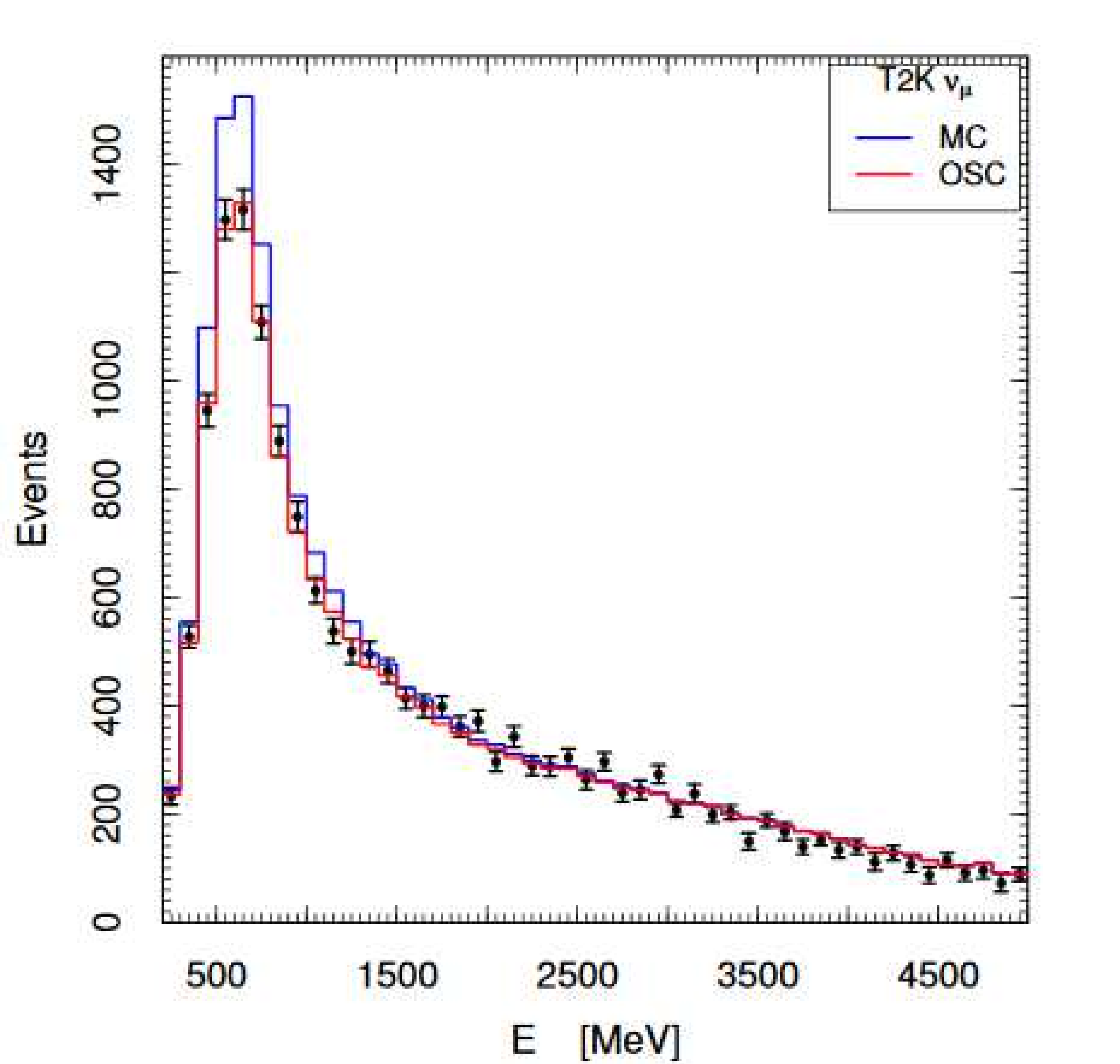


arXiv:1706.04257

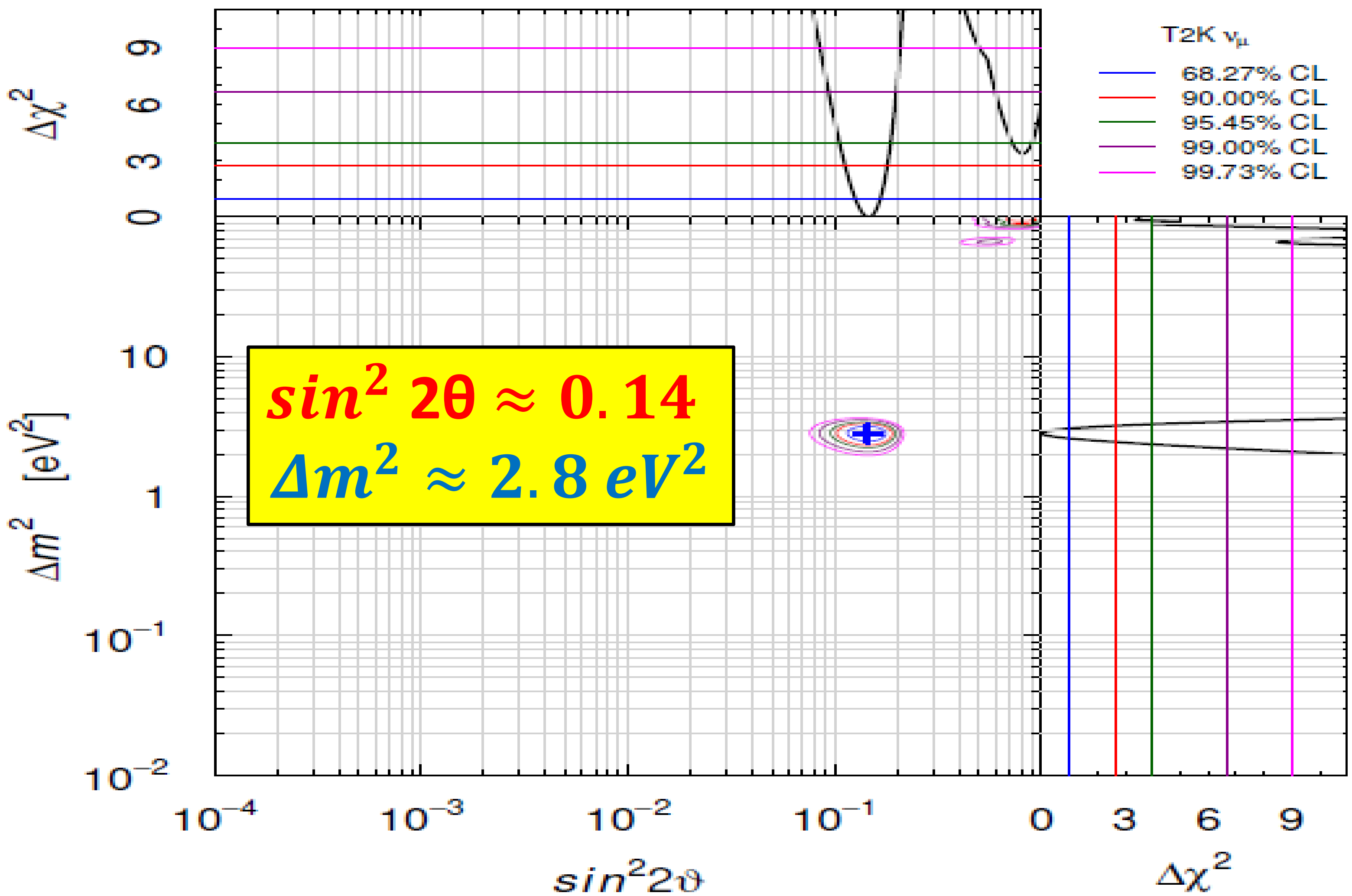
ν_μ Disappearance – P0D



ν_μ Disappearance – P0D



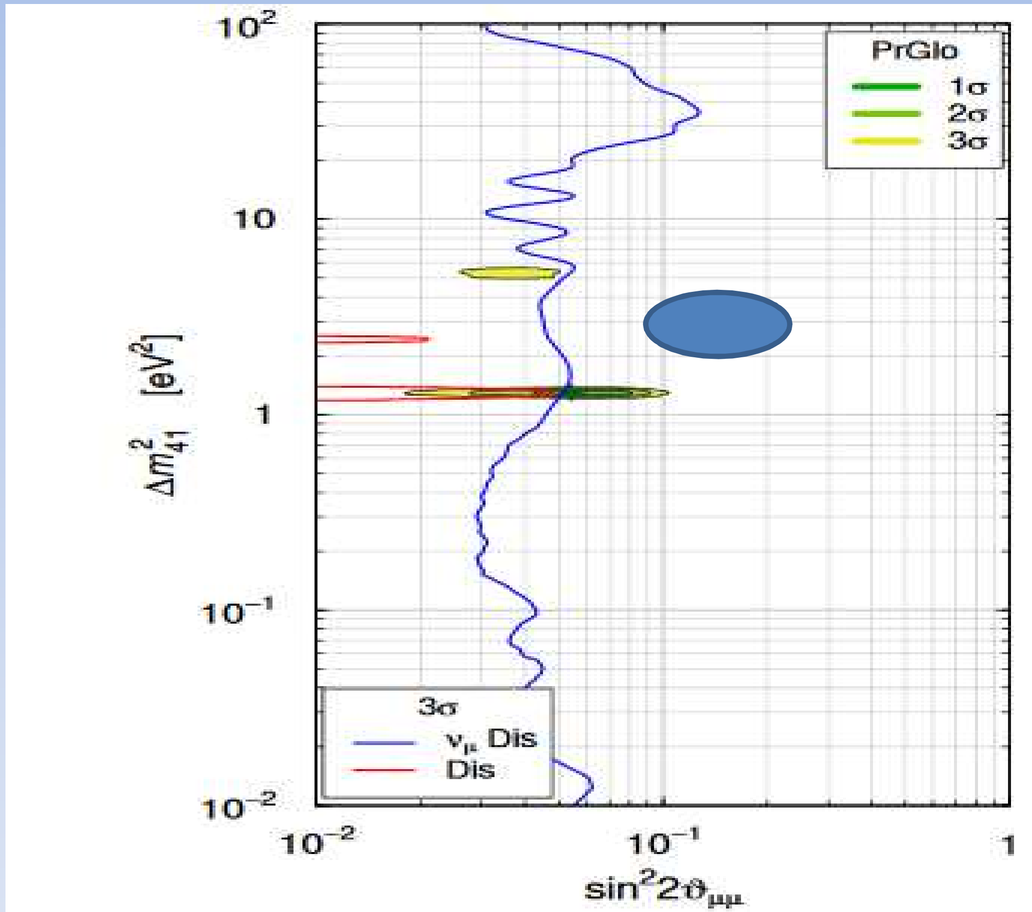
3+1 Model Dependent Result: ν_μ



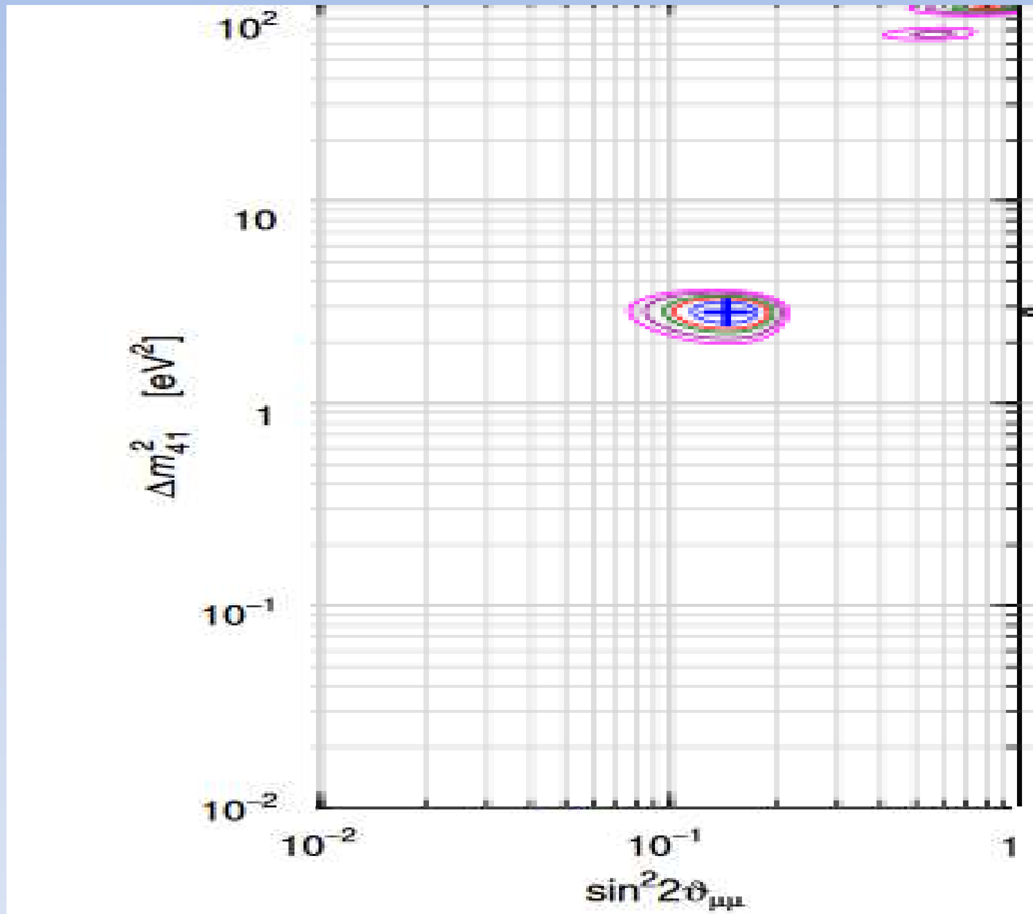
3+1 Fit Parameters

No Osc.	χ^2	114.7
	NDF	48
	GoF	$2e-07$
Osc.	χ^2_{min}	63.1
	NDF	46
	GoF	0.05
	$\sin^2 2\vartheta$	0.14
	Δm^2	2.8
No Osc. − Osc.	$\Delta\chi^2_{\mathrm{NO}}$	51.5
	$\mathrm{NDF}_{\mathrm{NO}}$	2
	$n\sigma_{\mathrm{NO}}$	6.9σ

Problems with MINOS/MINOS+ limit



Problems with MINOS/MINOS+ limit



MINOS+ constraints ν_μ flux using MINERVA νe scattering data

NEW !

Constraint of the MINERvA Medium Energy Neutrino Flux using Neutrino-Electron Elastic Scattering

E. Valencia,[1,2] D.Jena,[3] Nuruzzaman,[4,5] F. Akbar,[6] L. Aliaga,[1,7] D.A. Andrade,[2] M. V. Ascencio,[7] A. Bashyal,[8] L. Bellantoni,[3] A. Bercellie,[9] A. Bodek,[9] J. L. Bonilla,[2] A. Bravar,[10] H. Budd,[9] G. Caceres,[11] T. Cai,[9] M.F. Carneiro,[8] J. Chaves,[12] D. Coplowe,[13] H. da Motta,[11] S.A. Dytman,[14] G.A. Díaz,[9,7] J. Felix,[2] L. Fields,[3] A. Filkins,[1] R. Fine,[9] N. Fiza,[15] A.M. Gago,[7] R.Galindo,[5] H. Gallagher,[16] A. Ghosh,[5,11] T. Golan,[17,9] R. Gran,[18] D.A. Harris,[3] S. Henry,[9] S. Jena,[15] J. Kleykamp,[9] M. Kordosky,[1] D. Last,[12] T. Le,[16,4] X.-G. Lu,[13] E. Maher,[19] S. Manly,[9] W.A. Mann,[16] C. Mauger,[12] K.S. McFarland,[9,3] A.M. McGowan,[9] B. Messerly,[14] J. Miller,[5] J.G. Morfín,[3] D. Naples,[14] J.K. Nelson,[1] C. Nguyen,[20] A. Norrick,[1] A. Olivier,[9] V. Paolone,[14] J. Park,[9] G.N. Perdue,[3,9] M.A. Ramírez,[2] R.D. Ransome,[4] H. Ray,[20] D. Rimal,[20] P.A. Rodrigues,[21,9] D. Ruterbories,[9] H. Schellman,[8,22] C.J. Solano Salinas,[23] H. Su,[14] M. Sultana,[9] V.S. Syrotenko,[16] B. Yaeggy,[5] and L. Zazueta[1]
(The MINERνA Collaboration)

arXiv:1906.00111

Neutrino Flux and Cross-section Measurement

MINERvA

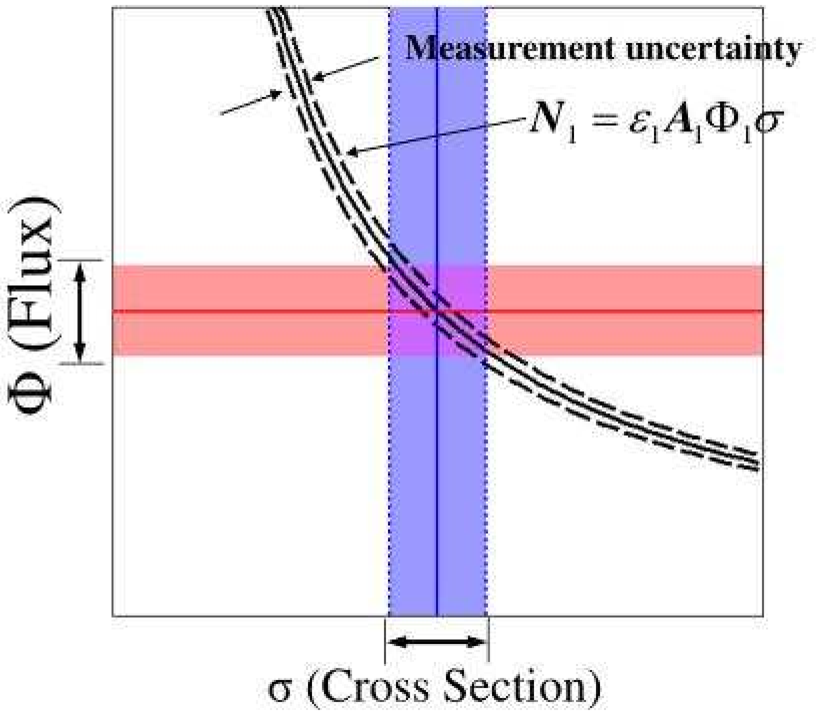
$$\sigma = \frac{N}{\varepsilon A \Phi}$$

Flux uncertainty goes into cross-section uncertainty

Flux constraint using Near Detector

$$\Phi = \frac{N}{\varepsilon A \sigma}$$

Cross-section uncertainty goes into flux uncertainty

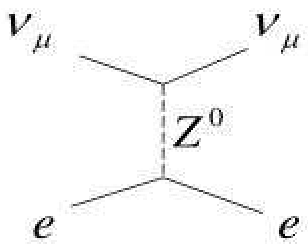


N: Events
ε: Efficiency
A: Acceptance
σ: signal cross section

- Flux and cross-section are anti-correlated with given Near Detector constraint

J.Park – FNAL seminar , Dec 20, 2013

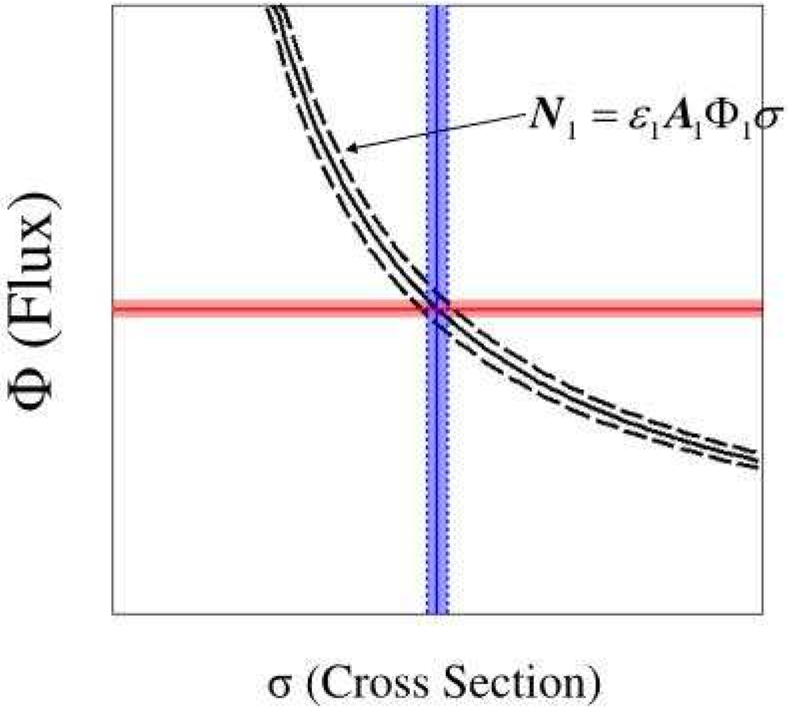
Known Interaction (Standard Candle)



Flux constraint using ND

$$\Phi = \frac{N}{\varepsilon A \sigma}$$

Cross-section uncertainty goes into flux uncertainty

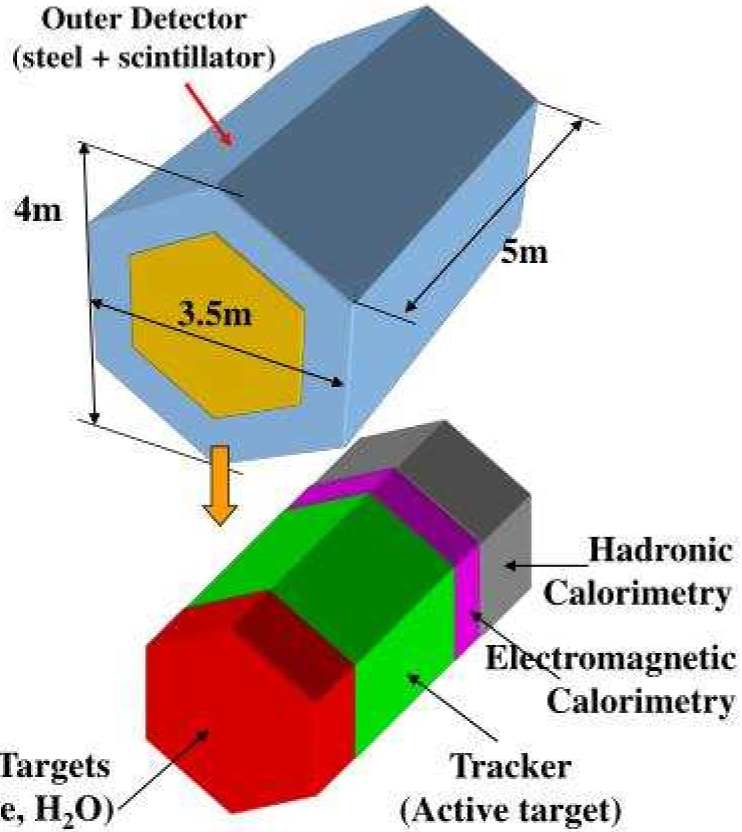


- ν-e scattering is well known interaction we can use to constrain the neutrino flux

ν-e Scattering

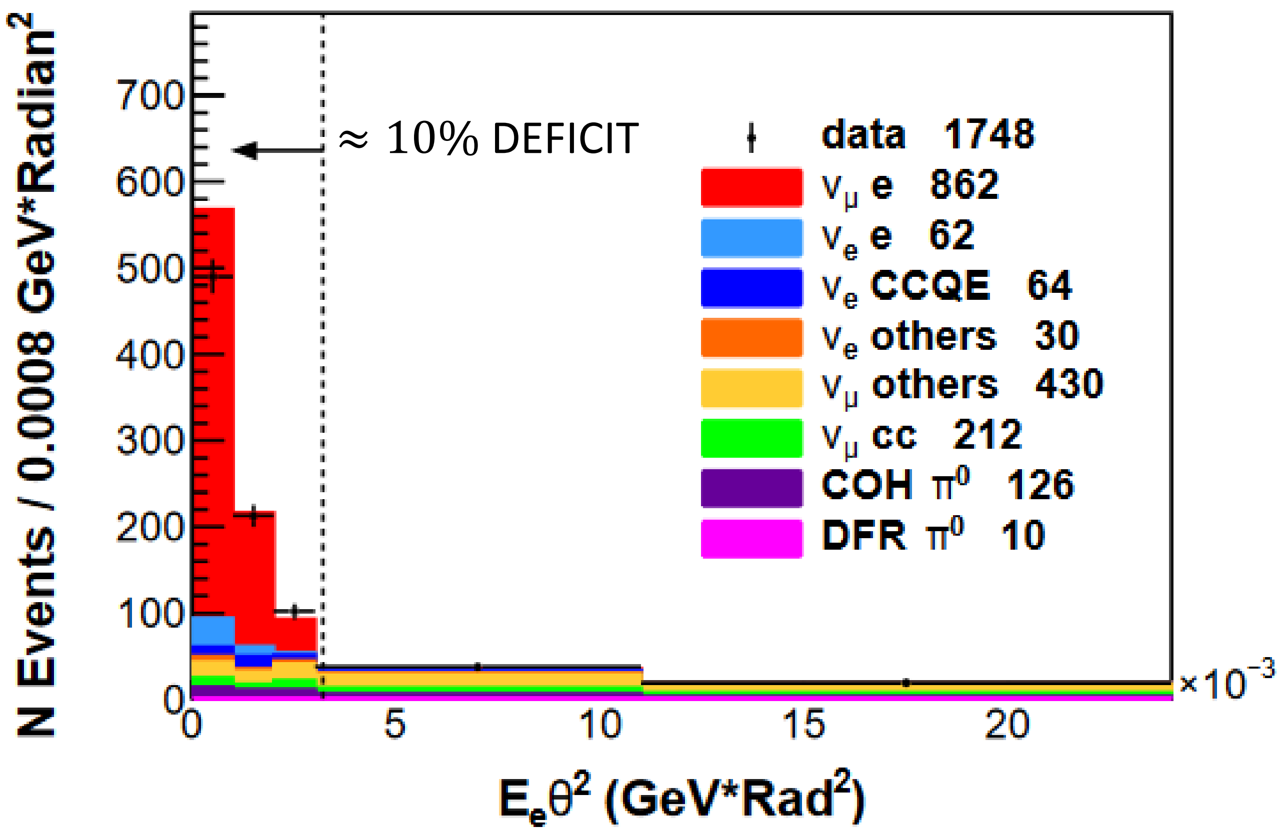
J.Park – FNAL seminar , Dec 20, 2013

MINERνA Detector



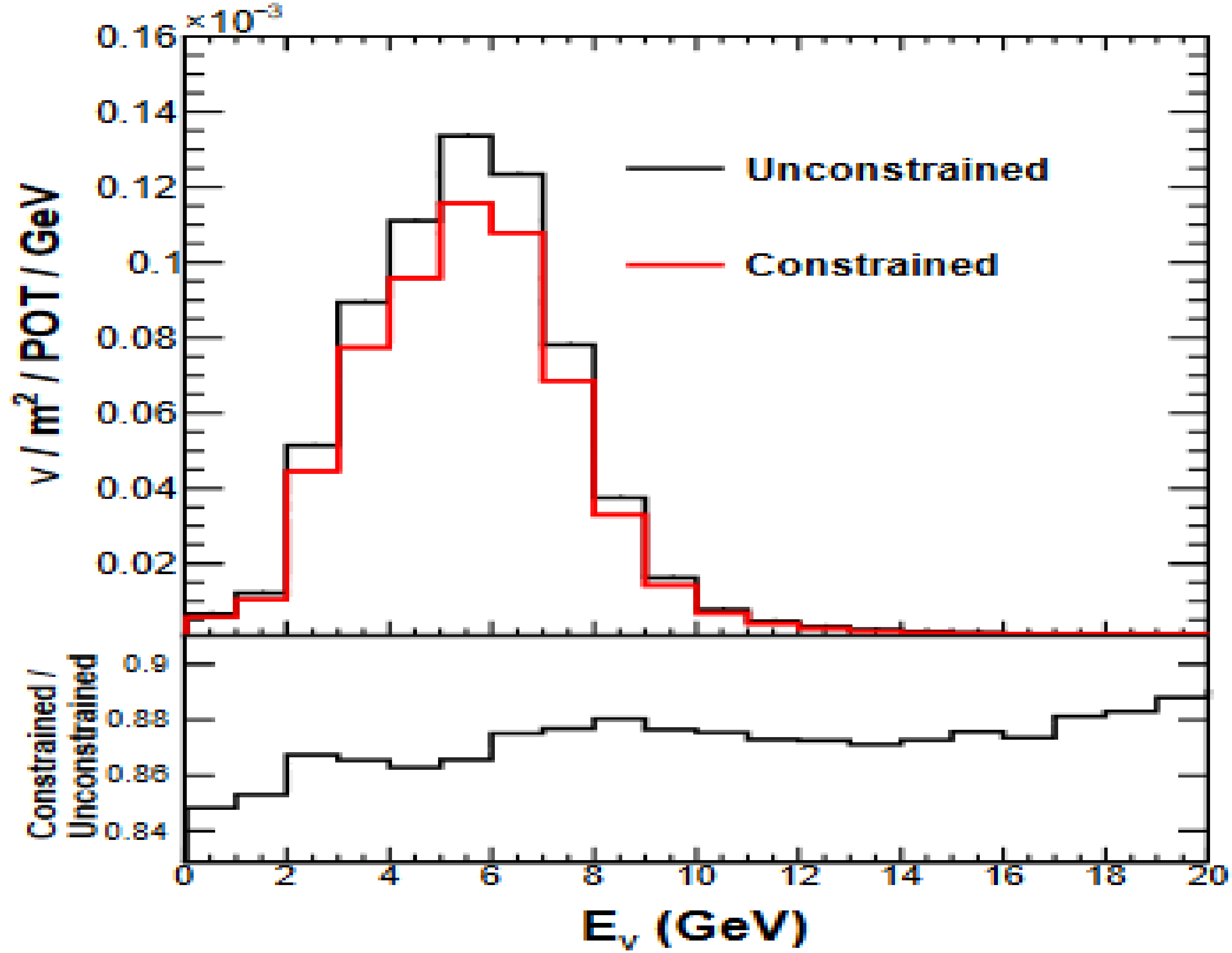
J.Park – FNAL seminar , Dec 20, 2013

MINOS+ constraints ν_μ flux using MINERVA νe scattering data

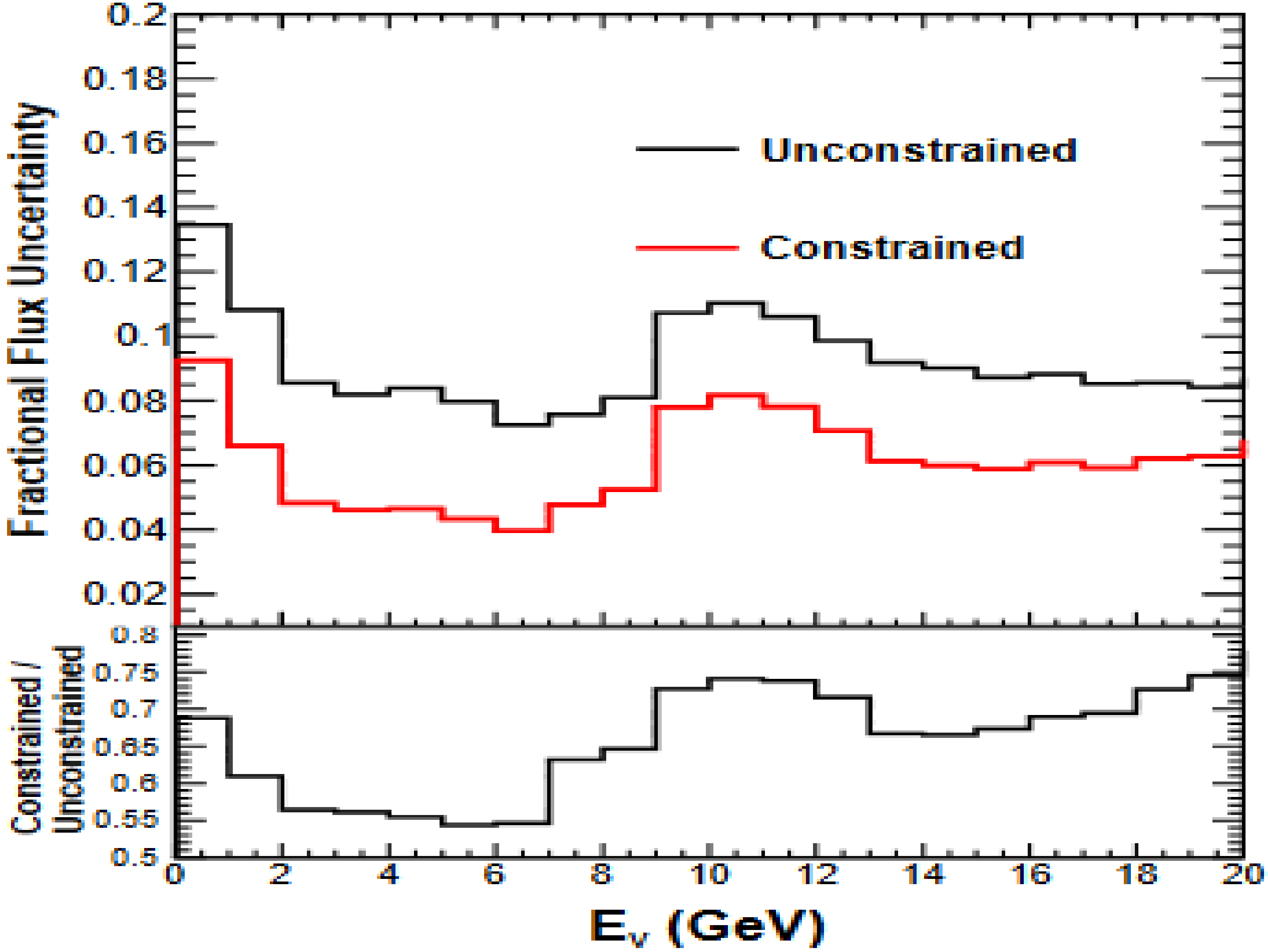


arXiv:1906.00111

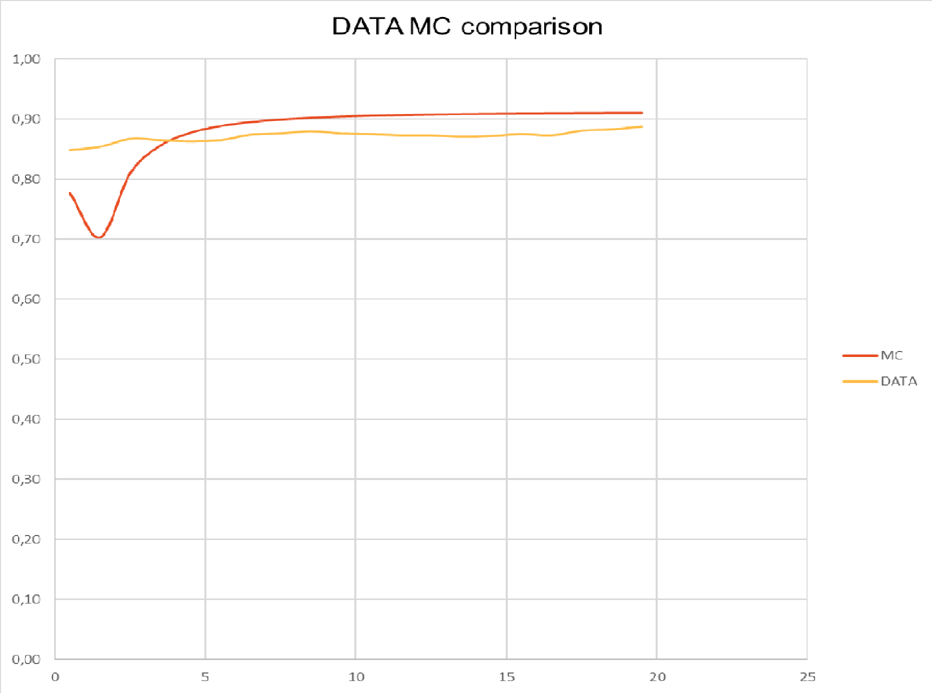
Minerva ve scatering constraints the v_μ flux



Minerva ve scatering error budget



3+1 Model Dependent Fit : Good news

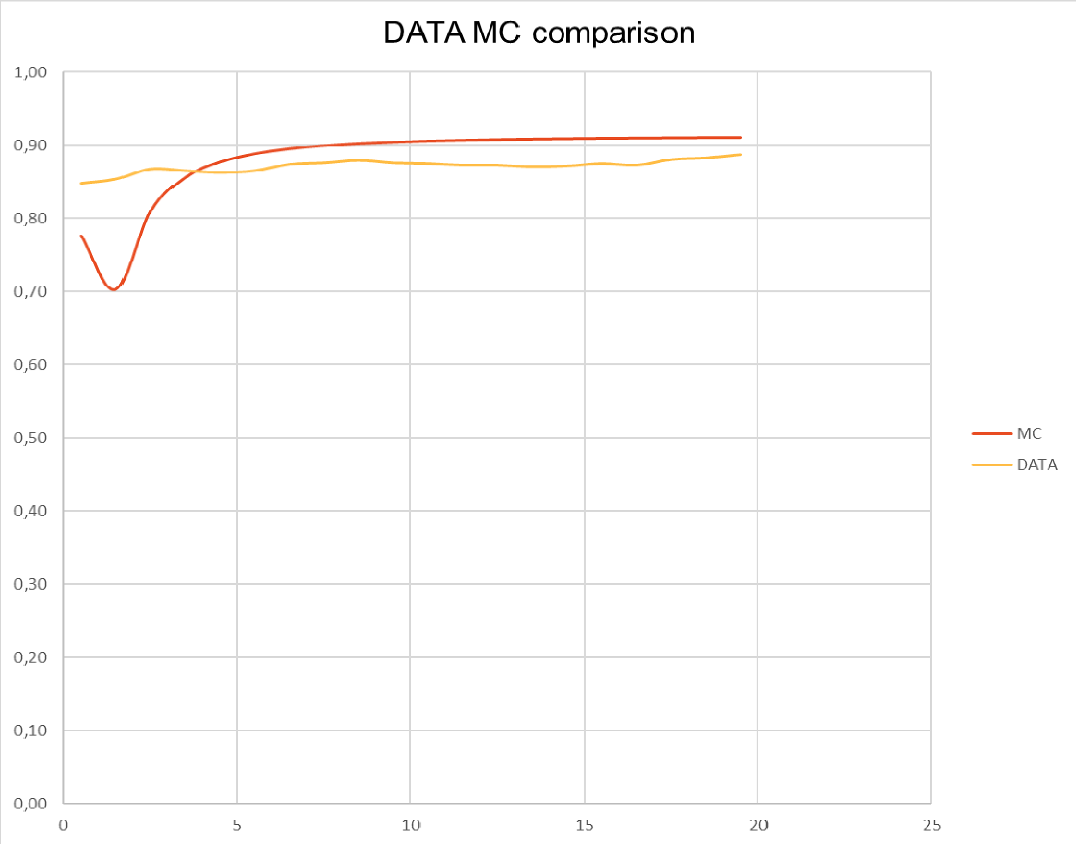


$$\chi^2(0,0,A=1) \quad = 104.53$$

$$\chi^2(bf,A=1) = 11.13$$

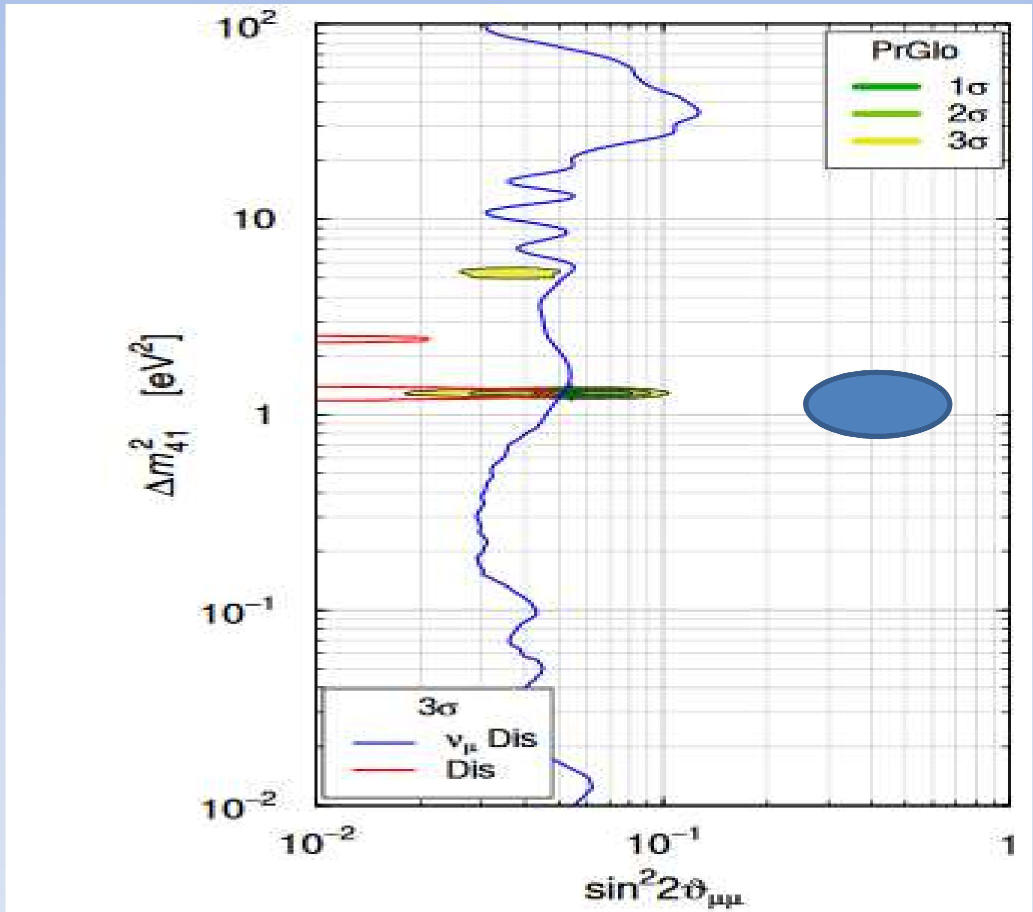
$$\Delta\chi^2 = 93.40$$

3+1 Model Dependent Results: muon channel : neutrinos

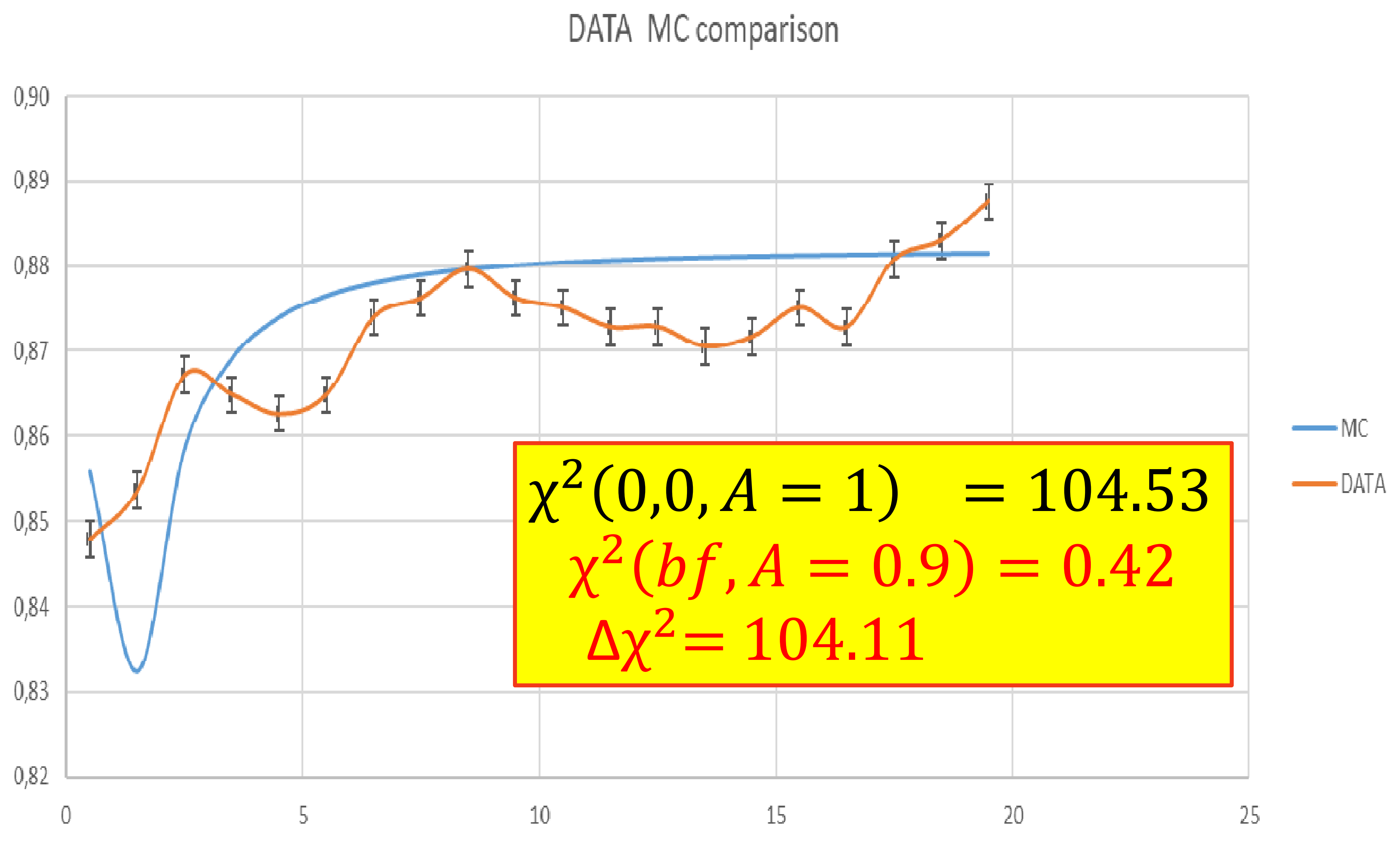


$$sin^2 2\theta \approx 0.4$$
$$\Delta m^2 \approx 1.2\ eV^2$$

Problems with MINOS/MINOS+ limit



3+1 with Decay Model Dependent Results: muon channel : neutrinos

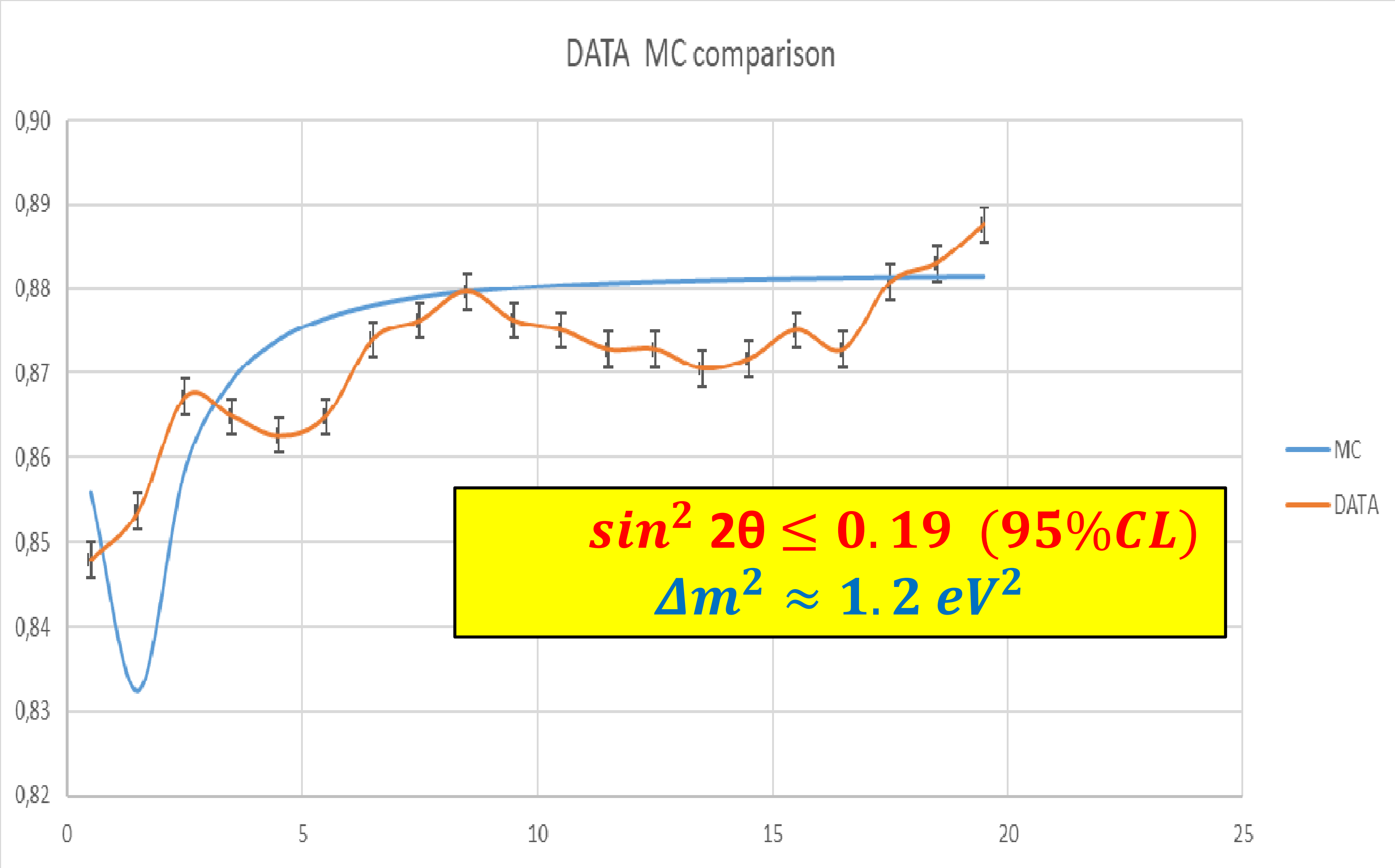


$$\chi^2(0,0,A=1) \quad = 104.53$$

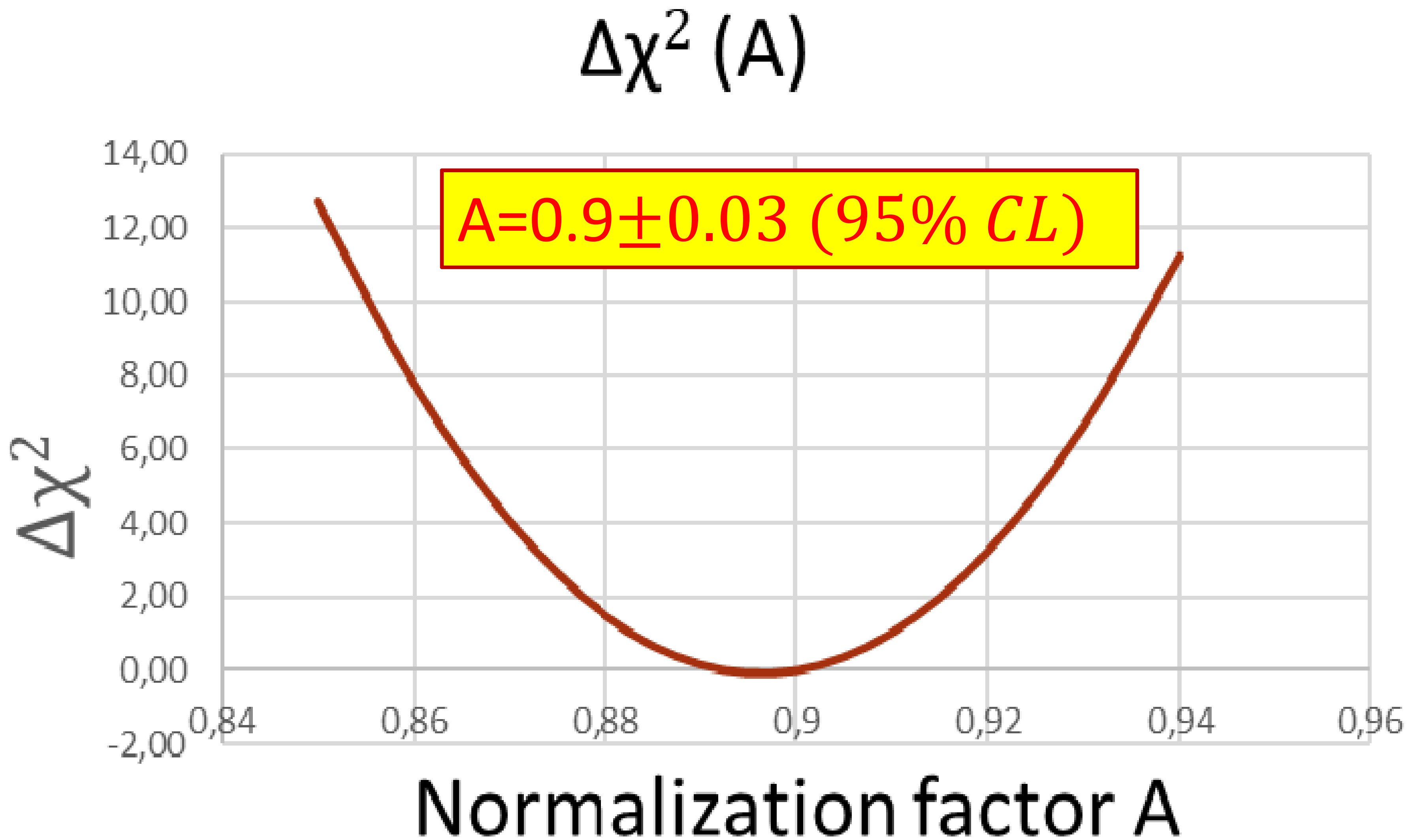
$$\chi^2(bf, A=0.9) = 0.42$$

$$\Delta\chi^2 = 104.11$$

3+1 with Decay Model Dependent Results: muon channel : neutrinos



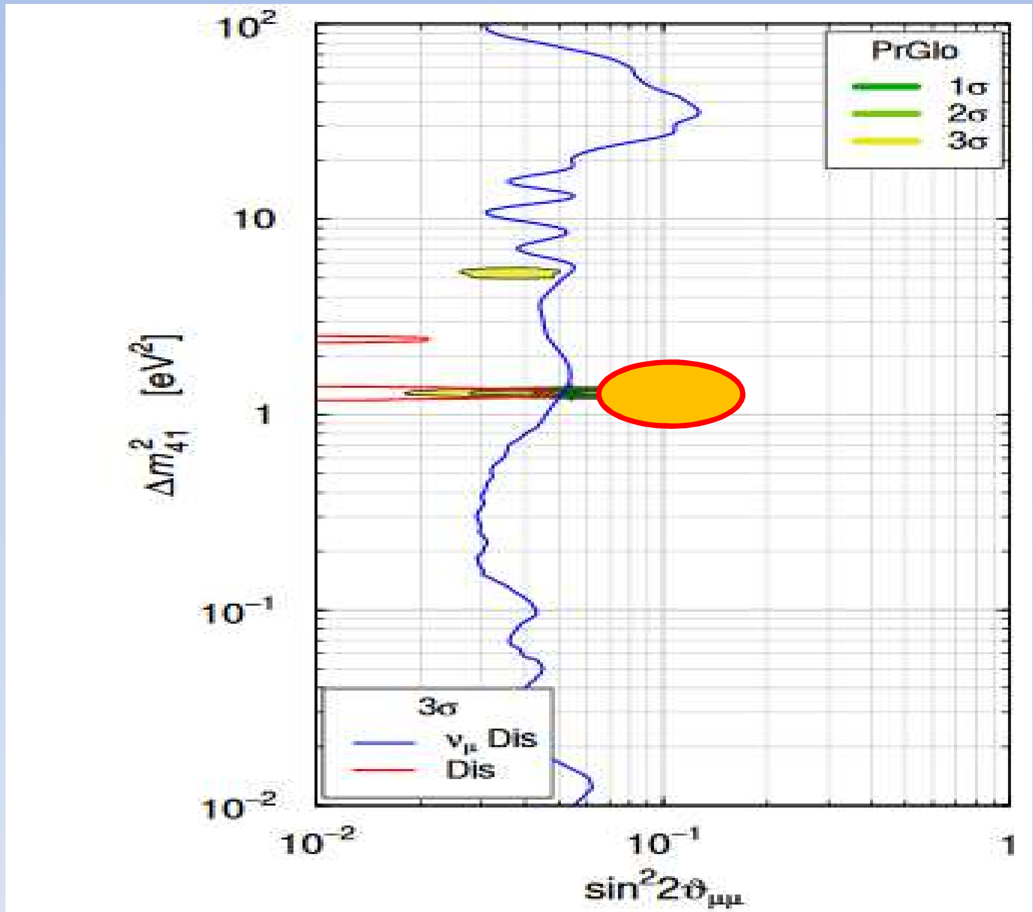
A dependance



P-value (A)

A	p-value
1	0,00E+00
0,99	5,10E-13
0,98	1,12E-10
0,97	1,37E-08
0,96	9,38E-07
0,95	3,62E-05
0,94	7,90E-04
0,93	9,85E-03
0,92	7,15E-02
0,91	3,11E-01
0,9	1,00E+00
0,89	6,86E-01
0,88	2,18E-01
0,87	4,37E-02
0,86	5,21E-03
0,85	3,58E-04
0,84	1,41E-05
0,83	3,11E-07
0,82	3,88E-09
0,81	2,70E-11
0,8	1,05E-13
0,79	0,00E+00

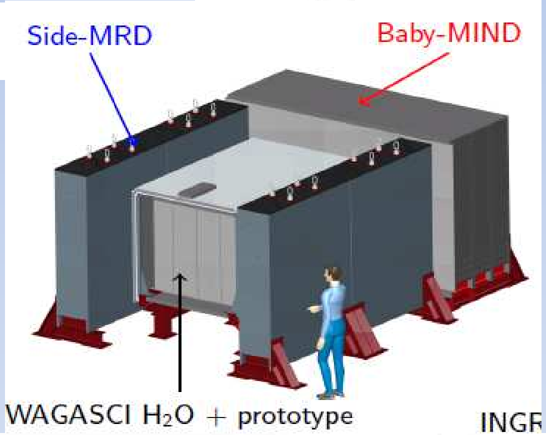
cfr with MINOS/MINOS+ limit



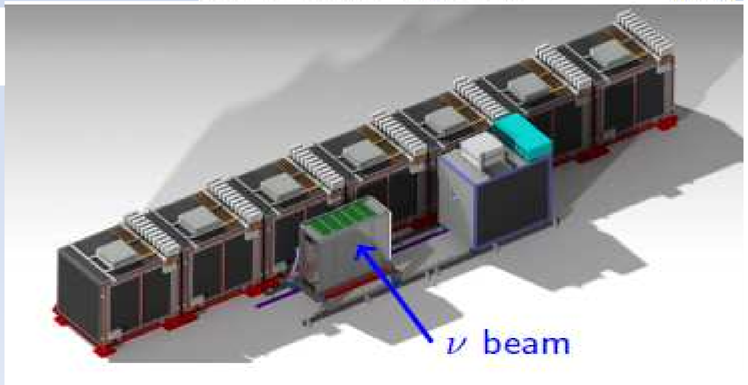
T2KND280 is a 3 detector complex

@ 2.5 deg

@ 1.5 deg



@ 0 deg



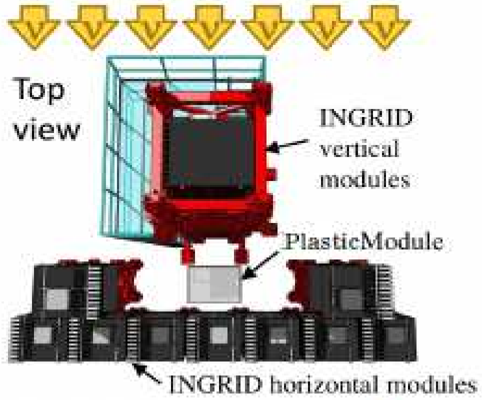
T2KND280 is a 3 detector complex @fixed L with 3 beams of different E_ν

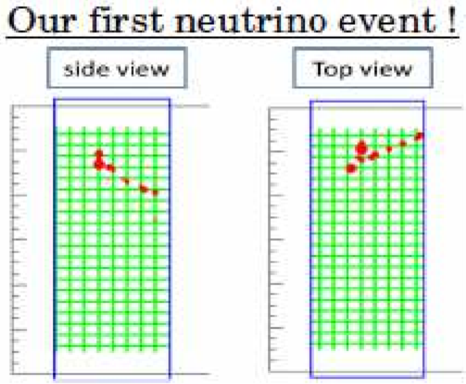
- 1) INGRID+PM+WM ON-AXIS @ 0 deg
  <E_ν> = 1.5 GeV $\rightarrow$ $\Delta m^2 \sim 5\ eV^2$

- 2) WAGASCI+Baby MIND OFF-AXIS @1.5 deg
  <E_ν> = 0.7 GeV $\rightarrow$ $\Delta m^2 \sim 2\ eV^2$

- 3) ND280 OFF-axis @ 2.5 deg
  <E_ν> = 0.6 GeV $\rightarrow$ $\Delta m^2 \sim 2\ eV^2$

ν_μ Interactions – On-axis detector

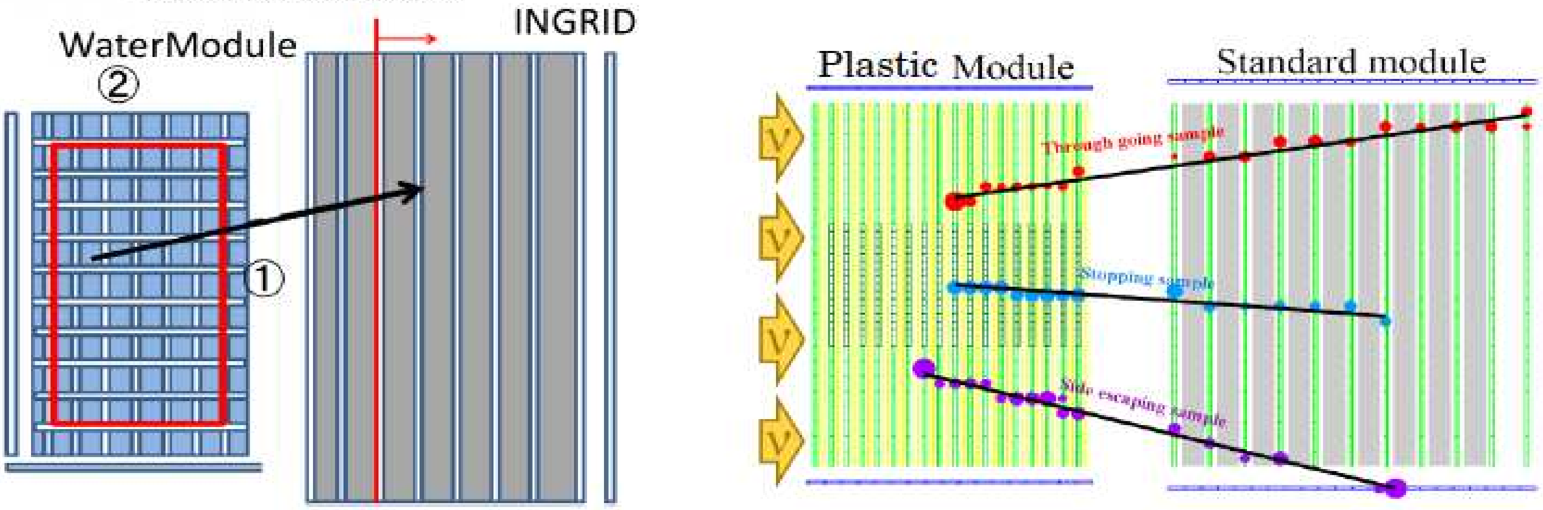




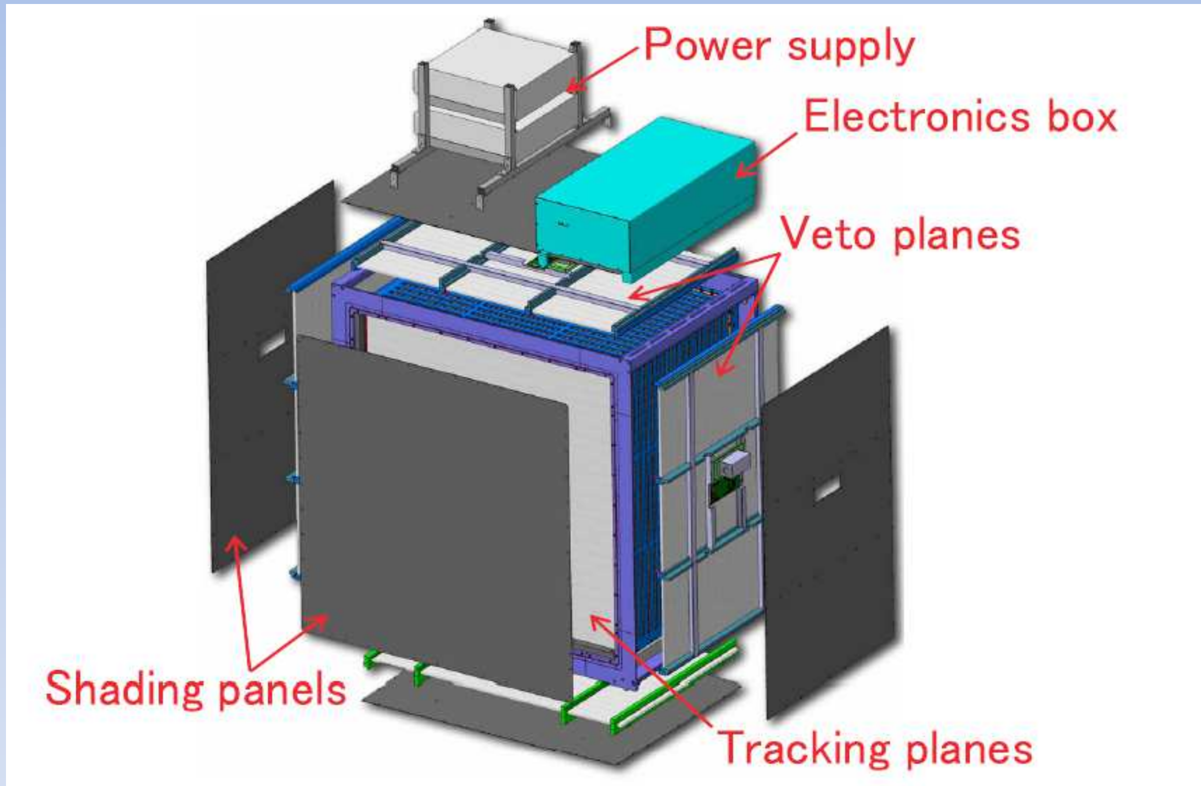
Goals :

1. Demonstrate module performances

2. Measure absolute XSection of ν / $\bar{\nu}$ on H_2O and H_2O/CH ratio on-axis (E~1.5 GeV)



Proton Module (PM)

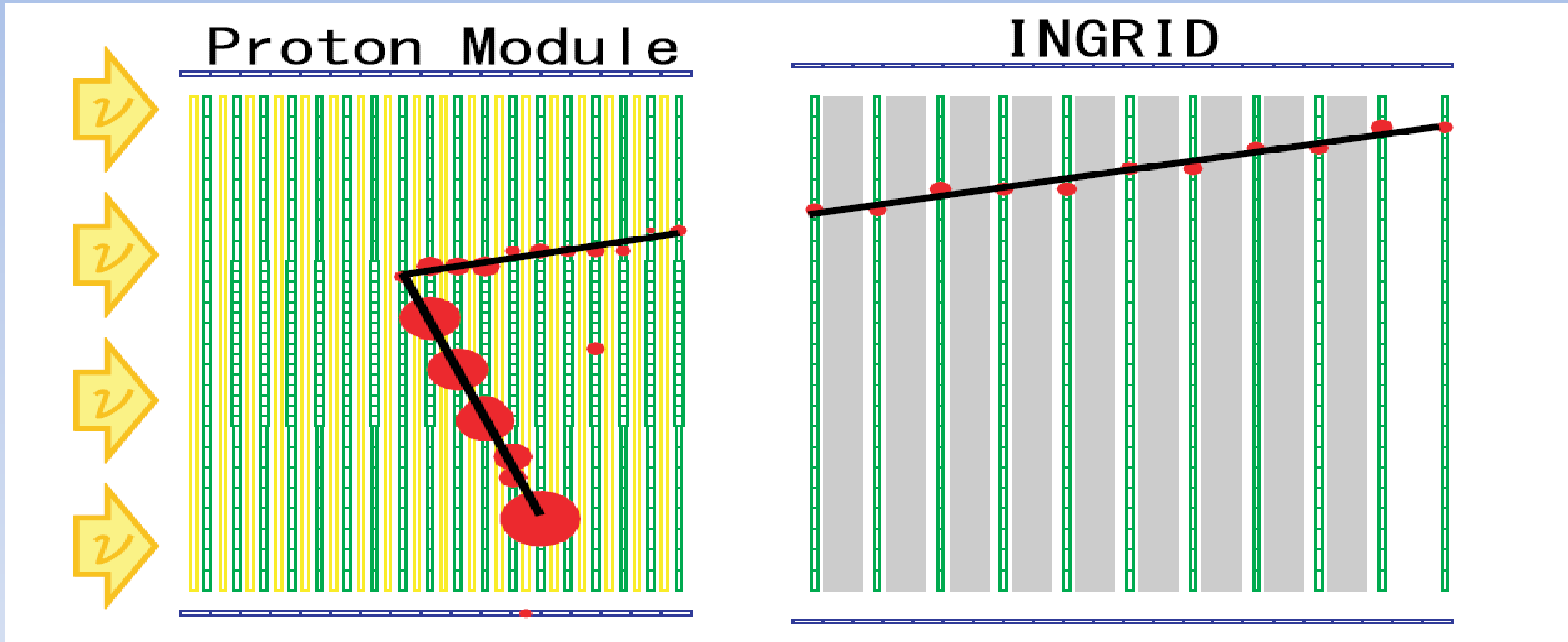


Study of neutrino interaction with T2K on-axis neutrino detector proton module

T2K Collaboration (T. Kikawa (Kyoto U.) for the collaboration). 2013. 4 pp.

Published in J.Phys.Conf.Ser. 408 (2013) 012082

ν_μ Interactions – Proton Module



Study of neutrino interaction with T2K on-axis neutrino detector proton module

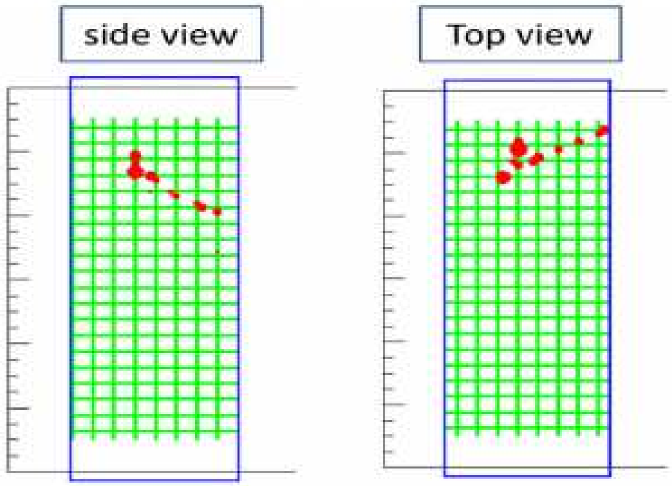
T2K Collaboration (T. Kikawa (Kyoto U.) for the collaboration). 2013. 4 pp.

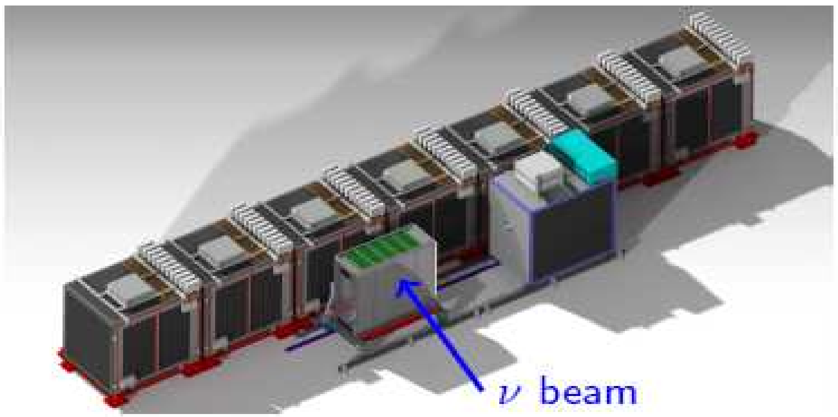
Published in J.Phys.Conf.Ser. 408 (2013) 012082

ν_μ Interactions – Water Module (WM)

- First H_2O module installed @ beam-axis in autumn 2016 w/ INGRID electronics (Trip-T front-end boards [TFBs])
- Goals :
  - Demonstrate module performance
  - Measure absolute cross section of $\nu/\bar{\nu}$ on H_2O and H_2O/CH ratio on-axis ($E \sim 1.5$ GeV) using INGRID module as muon calorimeter

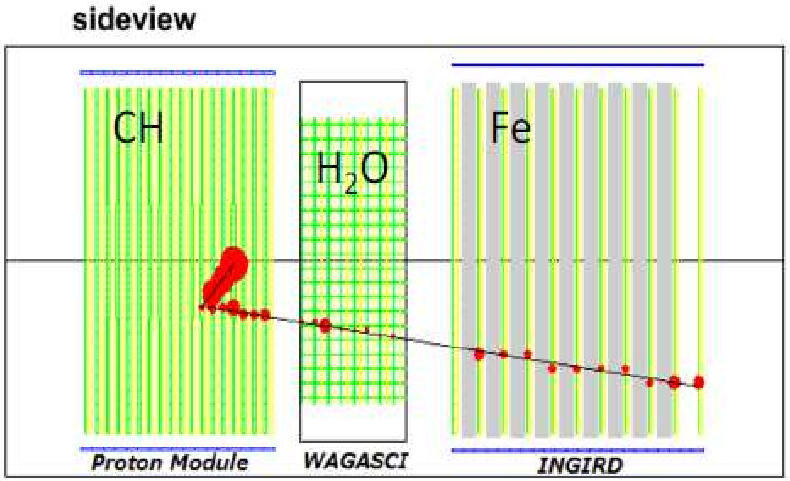
Our 1^{st} ν event



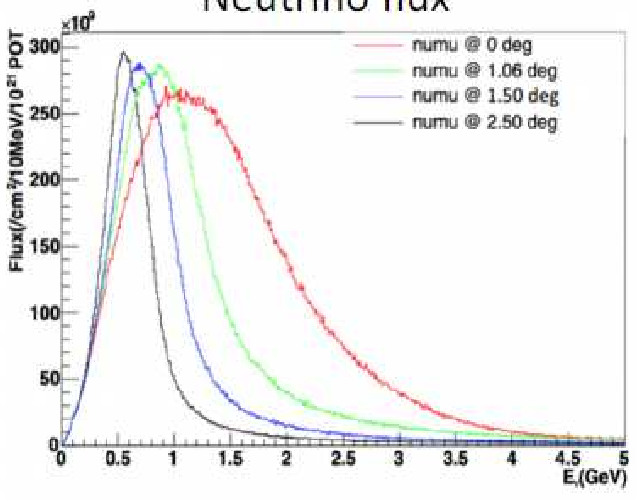


ν_μ Interactions – Off-axis WAGASCI detector @ 1.5 deg

- $H_2O/CH/Fe$ CC cross sections (and their ratio) at 1.5° off-axis angle.



Neutrino flux



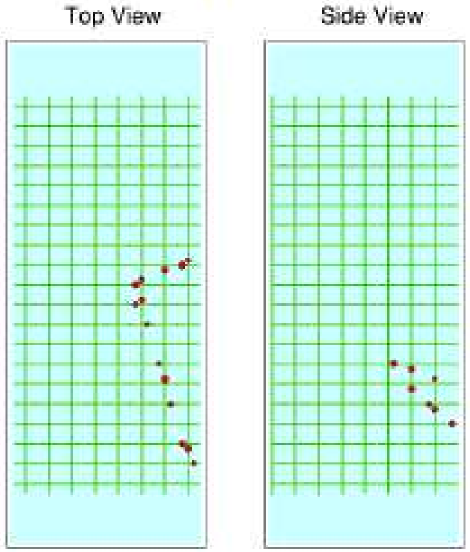
ν_μ Interactions – Off-axis WAGASCI detector @ 1.5 deg

- Second H_2O module installed @ 1.6° off-axis angle (Oct. 2017) w/ new DAQ (SPIROC2d chips)
- Goals : reproduce on-axis measurement at lower energy (~ SK neutrinos) using proton module as CH target and INGRID module as calorimeter

INGRID module

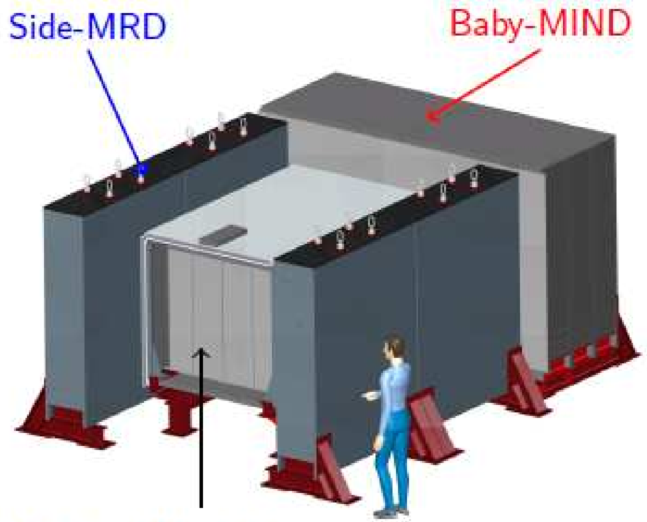
proton module WAGASCI H_2O module

2017/10/16, our 1st CCQE $\bar{\nu}$ event

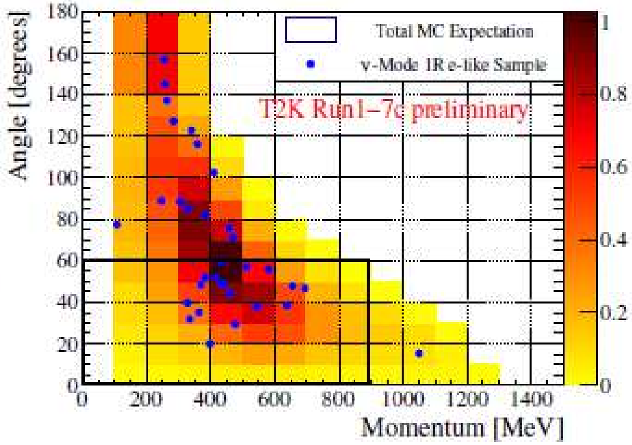


ν_μ Interactions – Off-axis WAGASCI detector @ 1.5 deg

- Final goal : 4π cross-section on H_2O @ 1.6° off-axis ⇒ cover SK phase space



WAGASCI H_2O + prototype

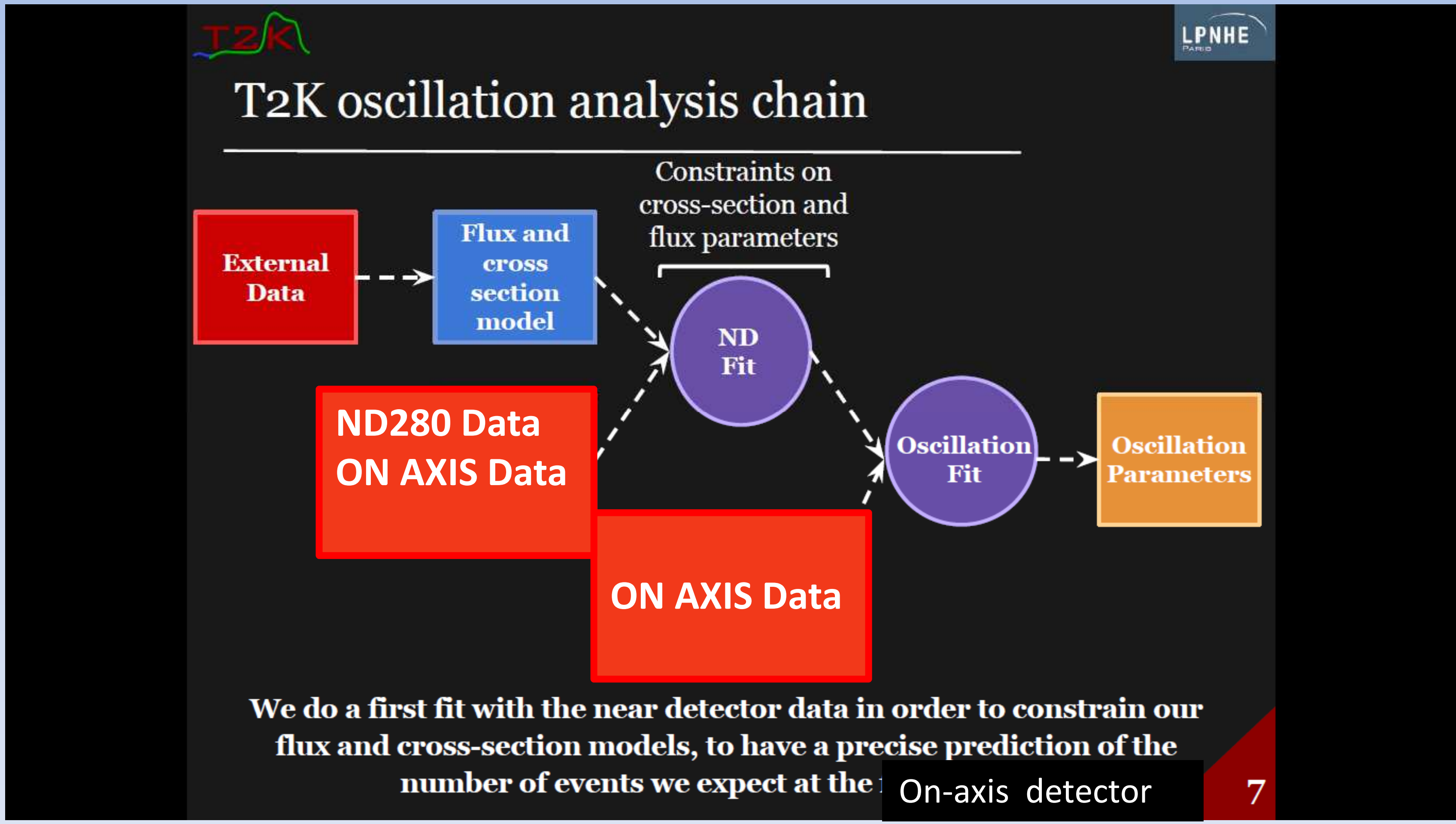


INGRID only : no $\nu/\bar{\nu}$ sep. + 150 MeV/c res.

- Measure momentum up to 2 GeV/c with 50 MeV resolution
- Separate 25% ν contamination in $\bar{\nu}$-mode (Baby-MIND)
- High angle muon range detectors (Side-MRD)

FY 2018

T2K strategy for SBL – ON AXIS



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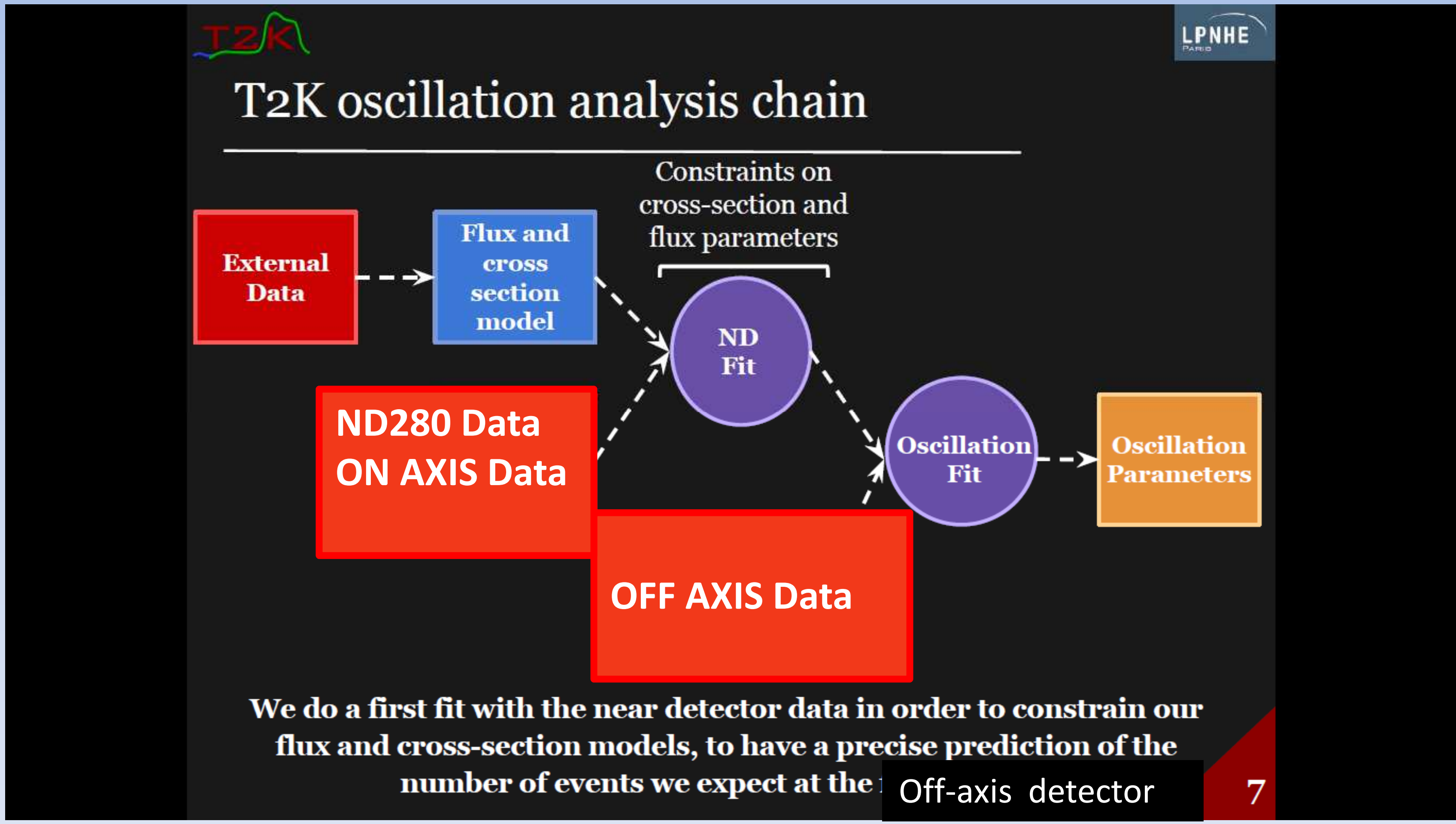
T2K strategy for SBL – OFF AXIS



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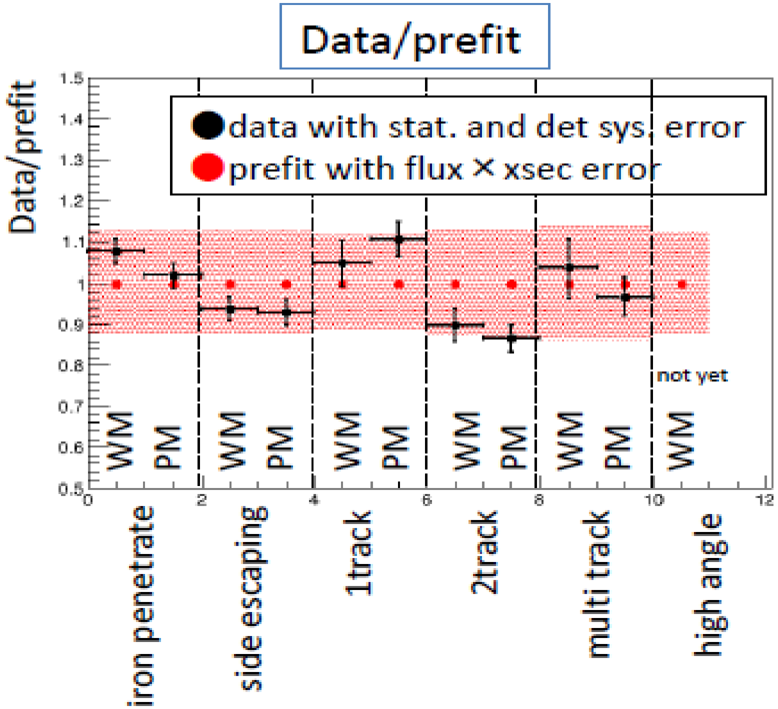
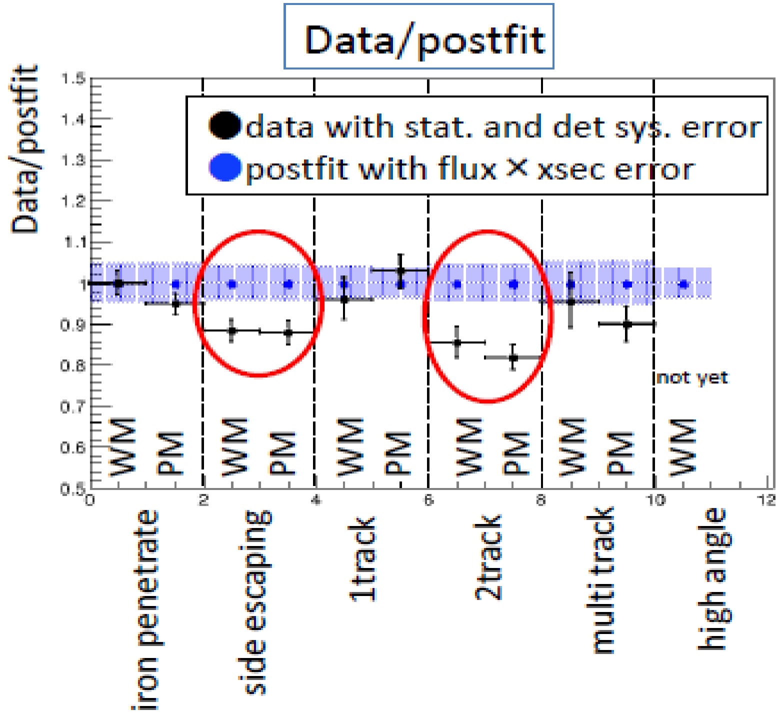
MODEL INDEPENDENT Results pending

-For side escaping sample, data/postfit = 0.885(-2.2σ) for WM, 0.880(-2.3σ) for PM
-For 2track sample, data/postfit = 0.857(-2.3σ) for WM, 0.820(-3.2σ) for PM
-Tendency is similar between WM and PM





T.Koga General Meeting 8.10.2017

… if they're roses they'll bloom!

T H A N K S !

References

- C.Giunti - Seminar @ Roma , Nov 2017
- C.Riccio - WIN 2019 conf. – Bari , Jun 2019
- F.Suekane – GRD meeting – Paris, Nov 2017
- T.Muller – GRD meeting – Paris, Nov 2017
- B.Quilain – NNN17 – Coventry - UK, Oct 2017
- A.Minamino – JPARC meeting – JP , April 2017