Systematic Effects on CP violation measurements

(morning session of Oct. 24)

Session Conveners

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Systematic Effects on CP violation measurements

(morning session of Oct. 24)

1. Systematic in J-PARC/Hyper-K Akihiro Minamino
2. CP Violation with Laguna - LBNO Alfons Weber
3. How accurately do we estimate the (anti)neutrino NCE and CCQE cross sections Artur Ankowski
4. Systematics at Neutrino Factories ... and global context Walter Winter
5. ν_e cross sections and νSTORM Jorge Morfin
6. Impact of systematic uncertainties for the neutrino paramter measurements in superbeam experiments Davide Meloni

$$\Delta P \equiv P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$

$$= -16\, J \sin\Delta_{12} \sin\Delta_{31} \sin\Delta_{23} \quad (\alpha,\beta = e, \mu, \tau)$$

$J \equiv s_{12}c_{12}\, s_{23}c_{23}s_{13}c_{13}^2$: leptonic Jarskog factor

$s_{ij} \equiv \sin\theta_{ij} \;\; c_{ij} \equiv \cos\theta_{ij}$

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{4E} L \qquad \Delta m_{ij}^2 \equiv m_i^2 - m_j^2$$

CP violation is a genuine three flavor phenomena

We needs to study appearance modes!

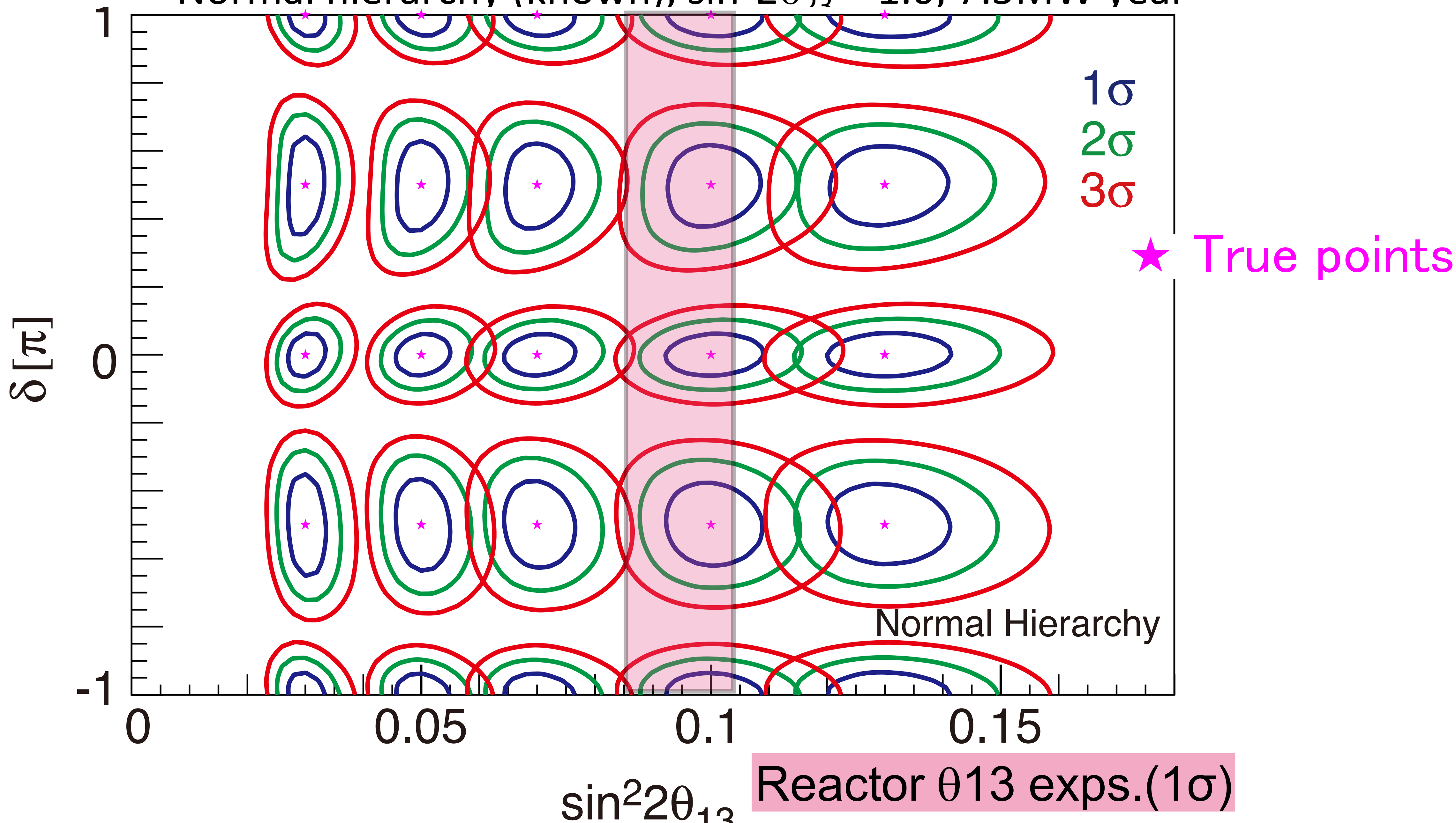
realistic options: α,β = (μ,e) or (e, μ)

We need to know well cross sections for ν_e and ν_μ and for antineutrinos!

Expected Contours

assuming 5% systematics on signal, ν_μ BG, ν_e BG, ν/anti-ν

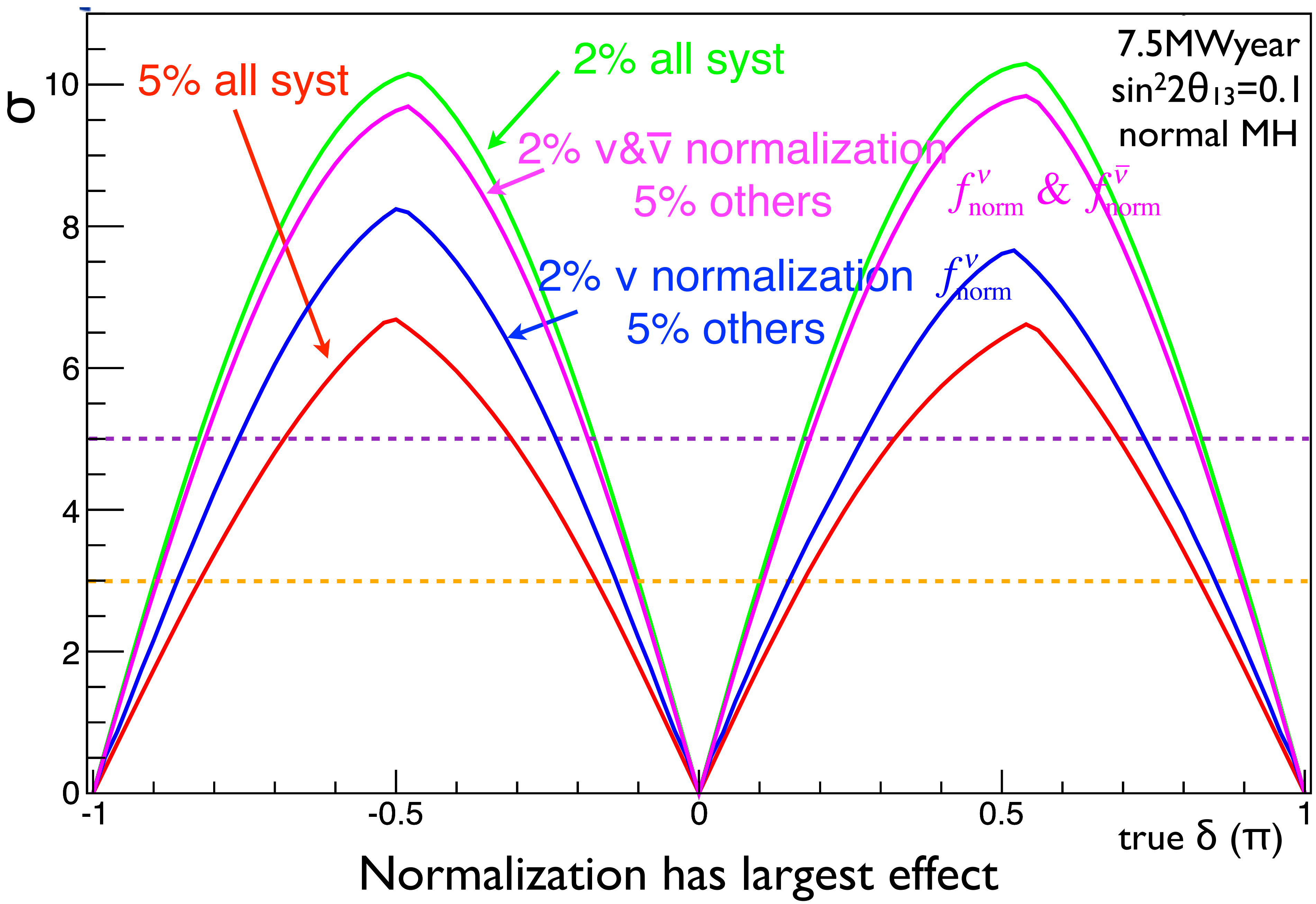
Normal hierarchy (known), $\sin^2 2\theta_{23}$ = 1.0, 7.5MW year



Good sensitivity for CPV!

CPV Discovery sensitivity

Effect of normalization



Normalization has largest effect

Corresponding T2K Systematic errors to J-PARC/Hyper-K errors

T2K sys. Errors (only ν run)

$\sin^2 2\theta_{13} = 0.1$	**Individual**	**Group**
Flux	8.0	Flux+Xsec w/ ND fit 5.0%
M_A^{QE} (GeV)	6.7	
M_A^{RES} (GeV)	1.8	
CCQE norm ($E_\nu < 1.5$ GeV)	6.2	
CC1π norm ($E_\nu < 2.5$ GeV)	3.5	
NC1π^0 norm	2.2	
CC other shape (GeV)	0.1	Xsec w/o ND fit 7.4%
Spectral function	5.5	
p_F (MeV)	0.1	
CC coherent norm	0.2	
NC coherent norm	0.6	
NC1$\pi^\pm$+NC other norm	0.8	
$\sigma_{\nu_e \mathrm{CC}}/\sigma_{\nu_\mu \mathrm{CC}}$	2.7	
W shape (MeV)	0.9	
Pionless delta decay	3.2	
1π E_ν shape	1.2	
SK detector efficiency	3.1	SK det. +FSI/SI 3.9%
FSI+SI	2.4	
SK energy scale	0.6	
Total	9.8%	

Hyper-K sys. errors

Large effect errors (target value = 5.0%)

8.8%

$f^{\nu}_{\mathrm{norm}}, f^{\bar{\nu}}_{\mathrm{norm}}, f^{\bar{\nu}}_{\mathrm{WS}}$

$f^{\nu}_{nQE}, f^{\bar{\nu}}_{nQE}$

$f^{\nu}_{\nu\mu}, f^{\bar{\nu}}_{\nu\mu}, f^{\bar{\nu}}_{\bar{\nu}_\mu}$

$f^{\nu}_{\nu e}, f^{\bar{\nu}}_{\nu e}, f^{\bar{\nu}}_{\bar{\nu}_e}$

Small effect errors

We will demonstrate J-PARC/Hyper-K feasibility with T2K.

Summary

- J-PARC + Hyper-K LBL experiment has potential to reveal full picture of neutrino oscillation.
  - CPV > $3\sigma(5\sigma)$ for 74(55)% of δ
- Systematic uncertainties are important for study of sub-leading CPV effect.
  - We will demonstrate J-PARC/Hyper-K feasibility with T2K.

NuInt 2012

Systematics

- We estimate the significance C.L. with a chi2sq method, with which we can
  1) exclude the opposite mass hierarchy and
  2) exclude $\delta_{CP} = 0$ or π (CPV)
- Minimize chi2sq w.r.t to the known 3-flavor oscillations and the nuisance parameters using Gaussian constraints

Name	Value	Error (1σ)
L	2300 km	exact
Δm^2_{21}	7.6×10^{-5} eV^2	exact
$\|\Delta m^2_{32}\|$ $\times10^{-3}$ eV^2	2.40	±0.09
$\sin^2\theta_{12}$	0.31	exact
$\sin^2 2\theta_{13}$	0.10	±0.02
$\sin^2\theta_{23}$	0.50	±0.06
Average density of traversed matter (ρ)	3.2 g/cm^3	$\pm4\%$

Control of systematic errors will be fundamental

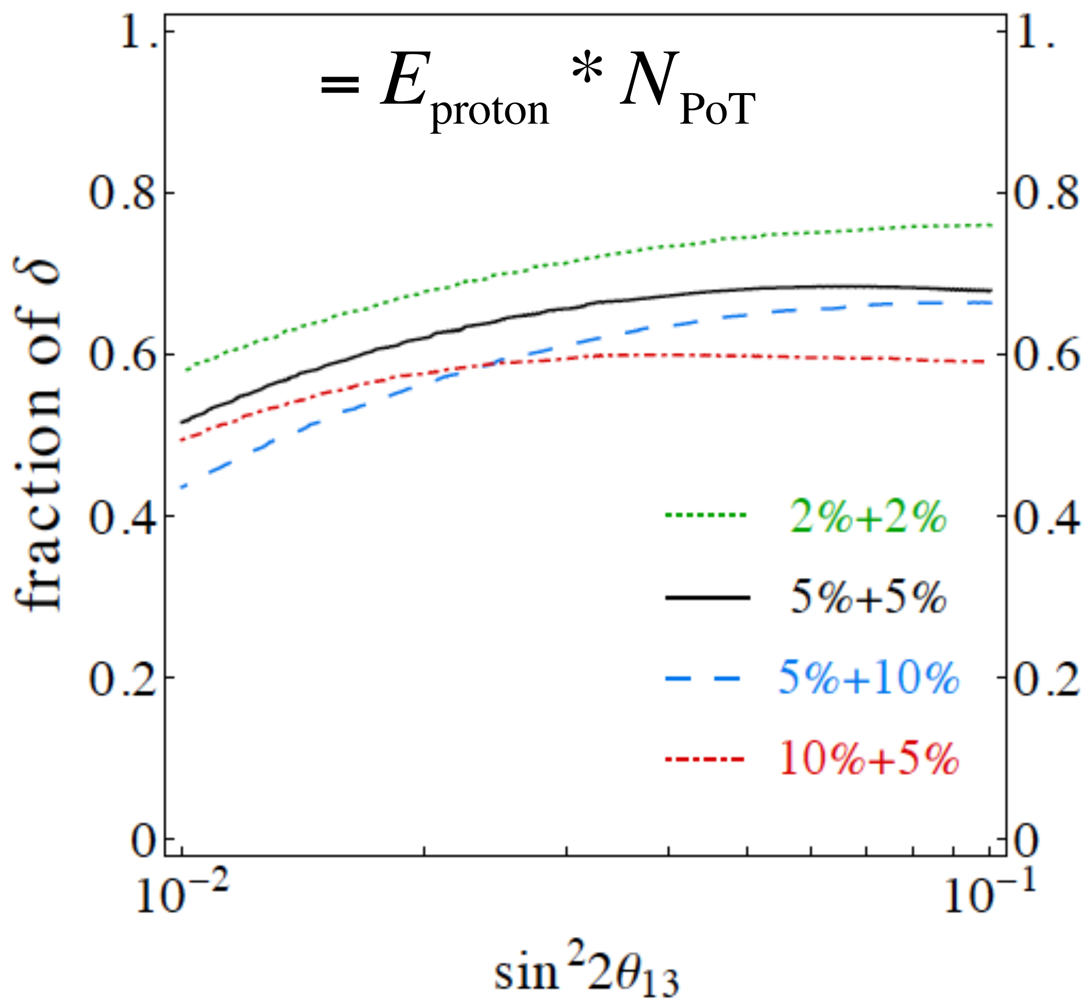
Name	MH determination Error (1σ)	CP determination Error (1σ)
Bin-to-bin correlated:		
Signal normalization (f_{sig})	$\pm5\%$	$\pm5\%$
Beam electron contamination normalization ($f_{\nu_e CC}$)	$\pm5\%$	$\pm5\%$
Tau normalization ($f_{\nu_\tau CC}$)	$\pm50\%$	$\pm20\%$
ν NC and ν_μ CC background ($f_{\nu NC}$)	$\pm10\%$	$\pm10\%$
Relative norm. of "+" and "-" horn polarity ($f_{+/-}$)	$\pm5\%$	$\pm5\%$
Bin-to-bin uncorrelated	$\pm5\%$	$\pm5\%$

Conservative errors

NuInt 2012

Effect of Uncertainty

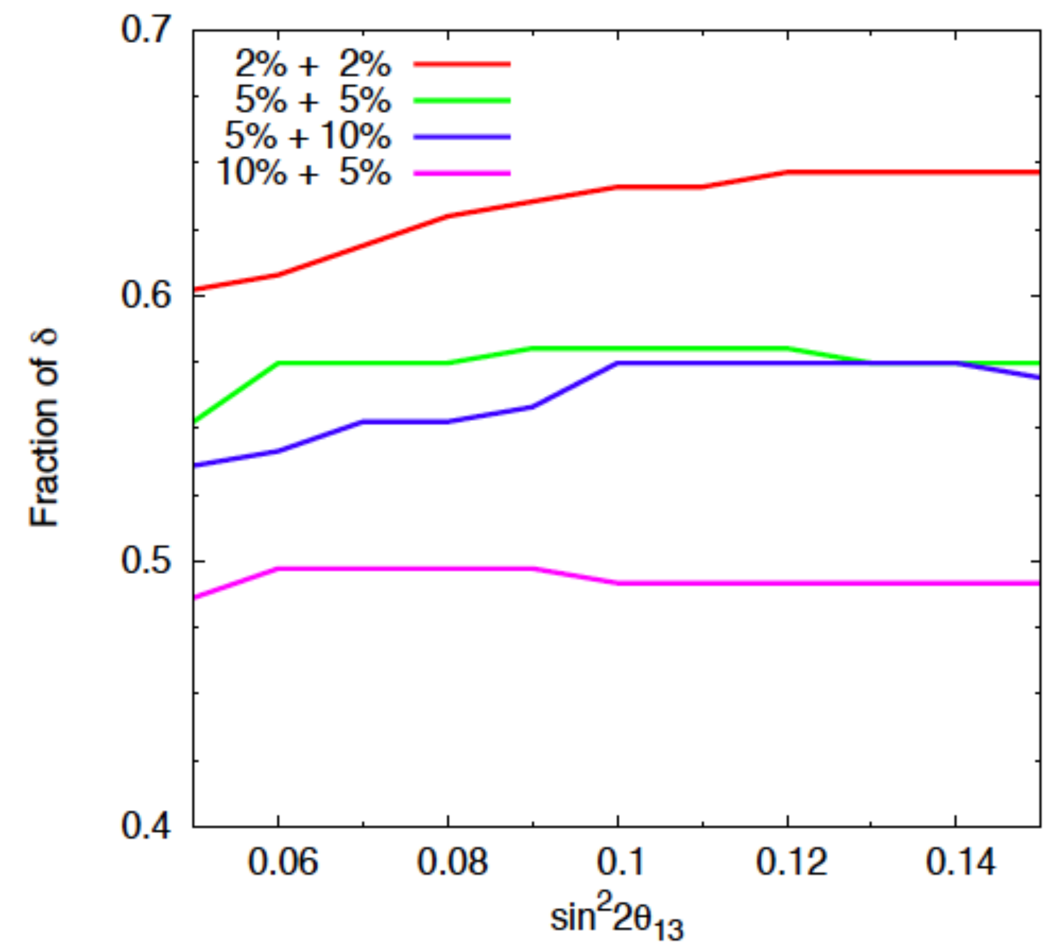
150×10^{22} GeV total, 100 kt:



P. Coloma, T. Li, S. Pascoli, [1206.4038].

CP fraction ranges from $\sim 60\% - 75\%$.

50×10^{22} GeV total, 100 kt:



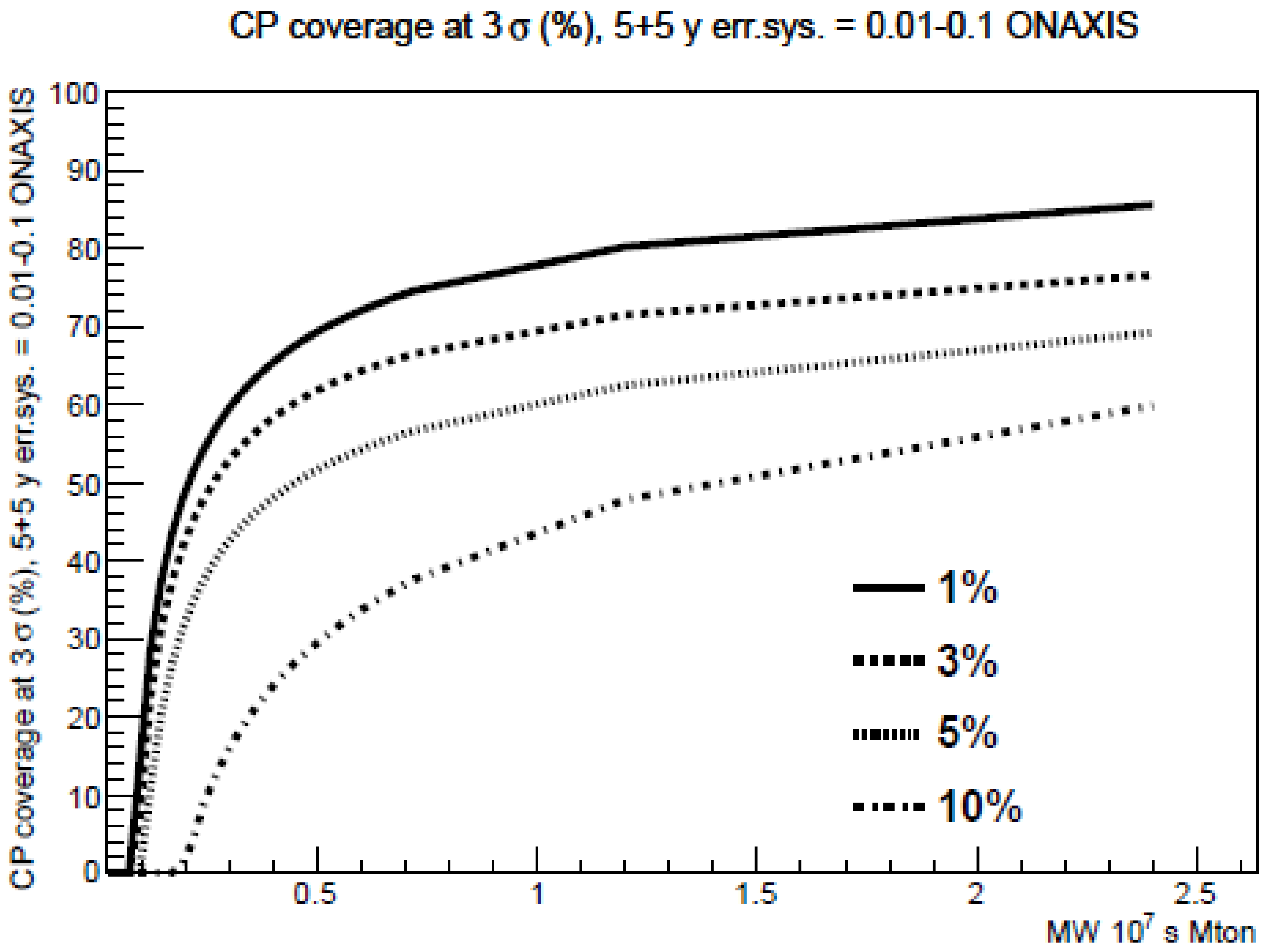
P. Coloma, T. Li, S. Pascoli.

CP fraction ranges from $\sim 48\% - 65\%$.

NuInt 2012

Effect of Systematics (II)

- From Dusini et al. (arXiv:1209.7010)



NuInt 2012

Main Points

- Systematic are important and will determine the amount of CP coverage
- Important
  - Hadron production experiments to predict neutrino flux
  - Near detector to reduce systematics
  - Dedicated cross section measurements especially for electron neutrino cross sections

3. How accurately do we estimate the (anti)neutrino NCE and CCQE cross sections   Artur Ankowski

Axial mass from shape analysis

- 1.20 ± 0.12 GeV for ^{16}O, <*E*> = 1.3 GeV,
  R. Gran *et al.* (K2K), PRD **74**, 052002 (2006)
- 1.144 ± 0.077 GeV for ^{12}C,
  C. Mariani (K2K), AIP Conf. Proc. **981**, 247 (2008)
- 1.23 ± 0.20 GeV for ^{12}C, <*E*> = 0.8 GeV,
  Aguilar-Arevalo *et al*. (MiniBooNE),PRL **100**, 032301 (2008)
- 1.07 ± 0.06(stat)± 0.07(syst) GeV for ^{12}C,<*E*>= 25.9 GeV
  V.Lyubushkin *et al.* (NOMAD), EPJ C **63**, 355 (2009)
- $1.19^{+0.09}_{-0.10}$(fit)$^{+0.12}_{-0.14}$(syst) GeV for ^{56}Fe, all Q^2, peak at 3 GeV
  M. Dorman (MINOS), AIP Conf. Proc. **1189**, 133 (2009)
- 1.35 ± 0.17 GeV for ^{12}C, <*E*> = 0.8 GeV,
  Aguilar-Arevalo *et al*. (MiniBooNE), PRD **81**, 092005 (2010)

3. How accurately do we estimate the (anti)neutrino NCE and CCQE cross sections   Artur Ankowski

Axial mass determination

- The analysis based on the absolute cross section shows **stronger model dependence** than the shape analysis
- The shape analysis yields an effective axial mass when multinucleon processes are not modeled accurately
- The cross section uncertainties increase in the low-Q^2 region

3. How accurately do we estimate the (anti)neutrino NCE and CCQE cross sections   Artur Ankowski

Summary

1. The cross section uncertainties increase in the low Q^2 region due to multinucleon processes.

2. The available calculations of multinucleon contribution to the antineutrino cross section differ *qualitatively*.

3. The uncertainty of the neutrino (antineutrino)-carbon cross section is estimated to be 22% (37%). The cross sections ratio is then known with the 43% uncertainty.

4. Systematics at Neutrino Factories ... and global context Walter Winter

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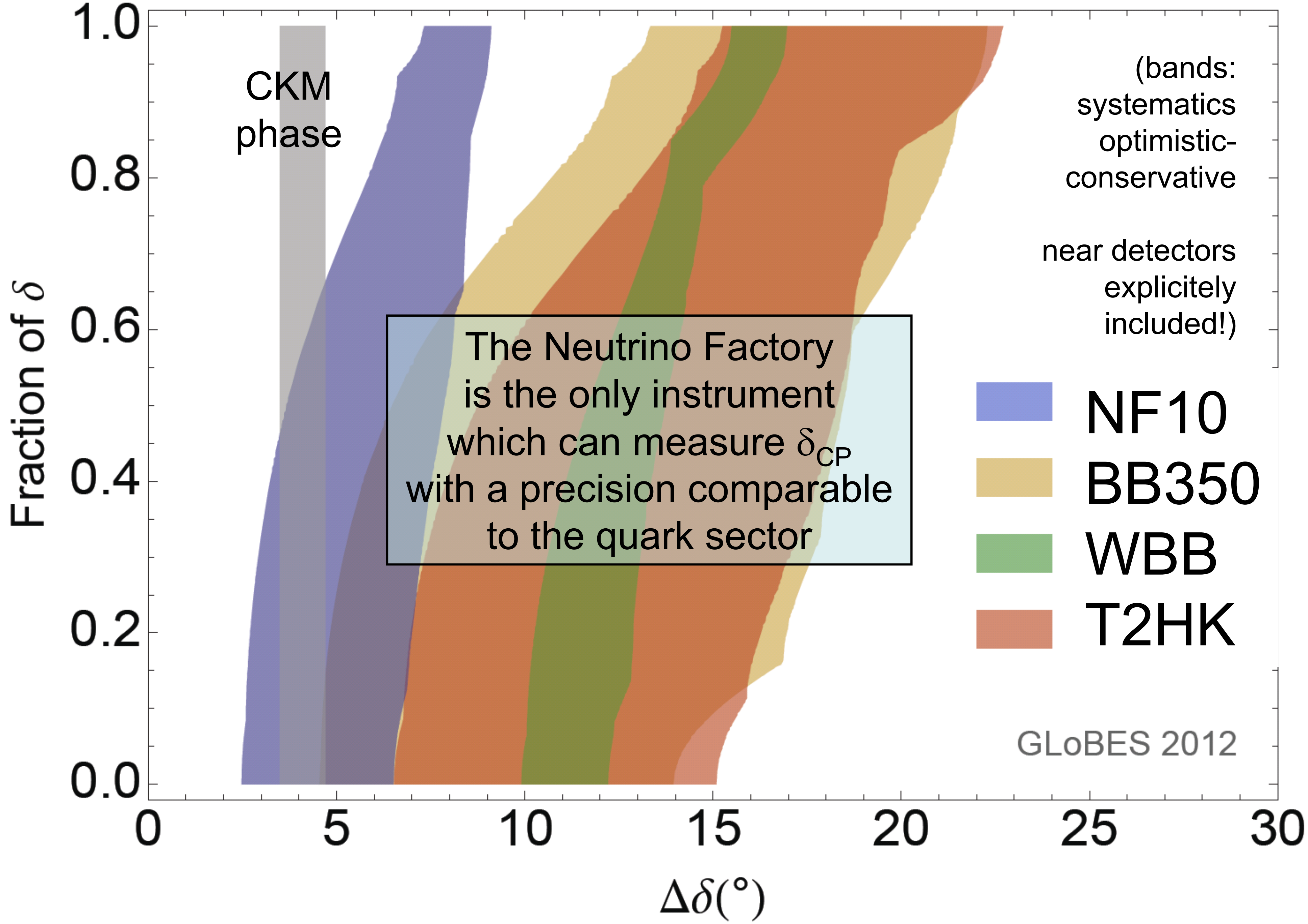
Precision: Worldwide comparison

W. Winter



(Coloma, Huber, Kopp, Winter, arXiv:1209.5973)

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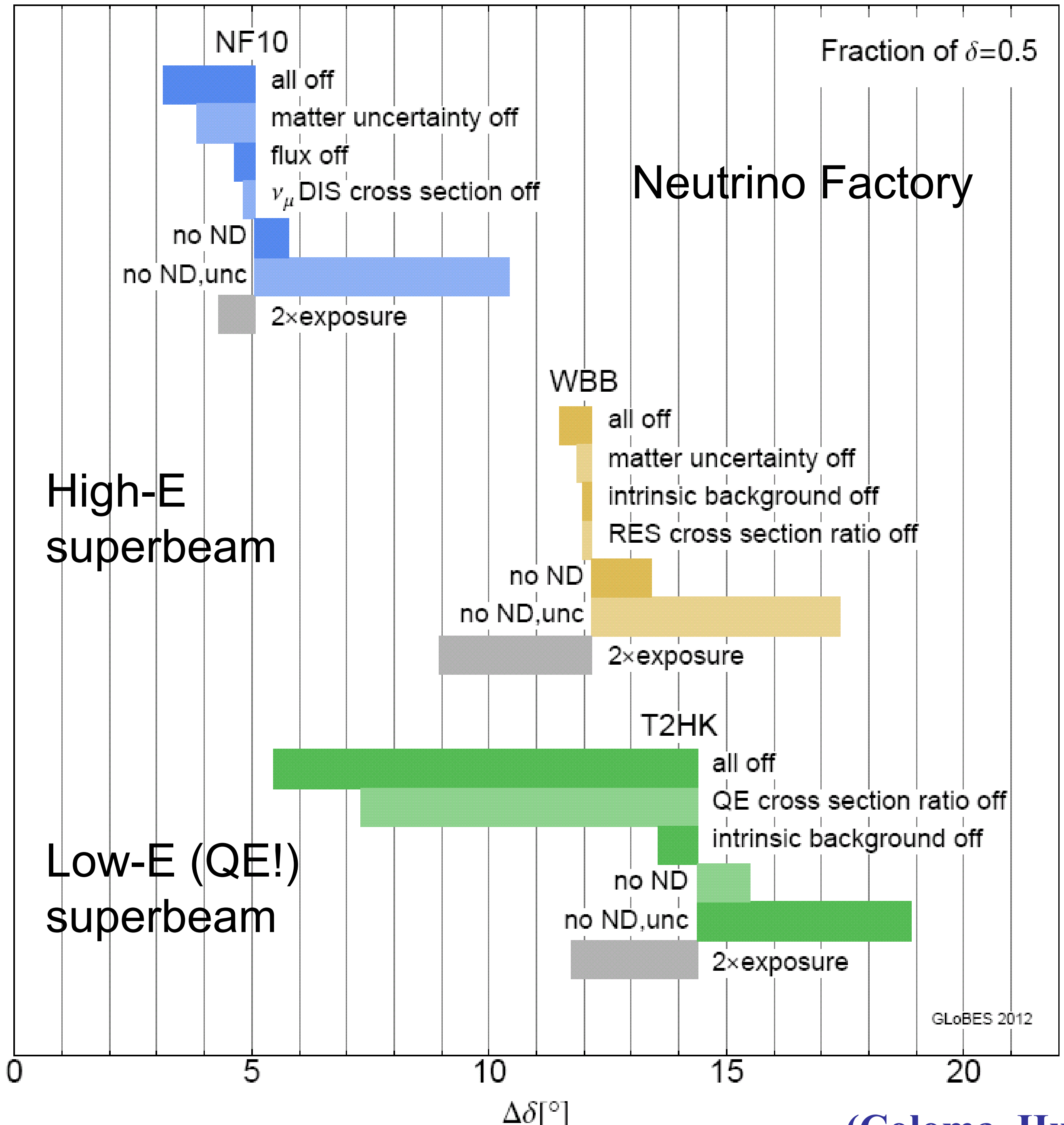
Systematics summary

W. Winter



Robust wrt systematics

Main impact:
Matter density uncertainty

Operate in statistics-limited regime

Exposure more important than near detector

QE ν_e X-sec critical:
no self-consistent measurement

Theory: ν_e/ν_μ ratio?
Experiment: νSTORM?

(Coloma, Huber, Kopp, Winter, arXiv:1209.5973)

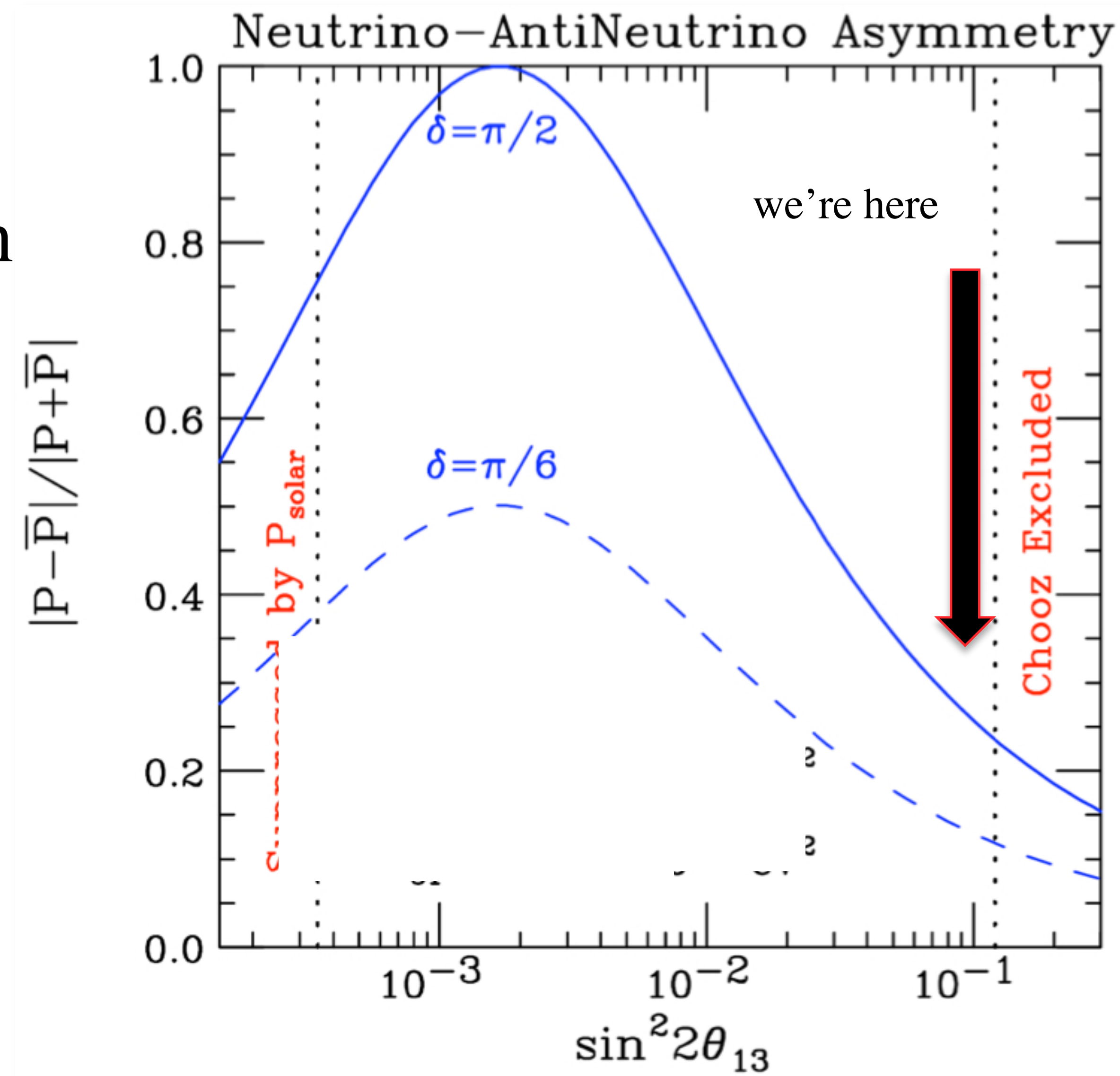
Julius-Maximilians-UNIVERSITÄT WÜRZBURG

Summary

- The Neutrino Factory is the only experiment which can measure the CP phase with CKM-like precision
- Main impacts (NF):
  - Matter density uncertainty
  - Exposure
  - Near detector (low-E NuFact). In no other experiment the near detector has found to be the dominant impact factor!
  - ➢ Can control systematics in self-consistent way!
- Comparsion to alternatives:
  - BB+SPL: Best alternative performance, better than γ=350 beta beam. Self-consistent cross-section measurements
  - Low-E superbeams (T2HK): QE cross section ratio critical
    - ➢ Theoretical: Better predictions/models especially for this ratio?
    - ➢ Experimental: Measure ν_e cross sections? **νSTORM? Systematics *from* Neutrino Factory?**
  - High-E superbeams (such as LBNE): Exposure seems more important than the near detector …

Why are ν_e and $\bar{\nu}_e$ Cross Sections Important?

- Large θ_{13} means we could have reasonable statistics.
- However, as the now-well-known plot at right suggests, the asymmetry between ν and $\bar{\nu}$ will be small and the goal of constraining the range of δ will demand minimal systematic errors.
- One of these systematics will be our knowledge of ν_e and $\bar{\nu}_e$ cross sections in the relevant energy range.

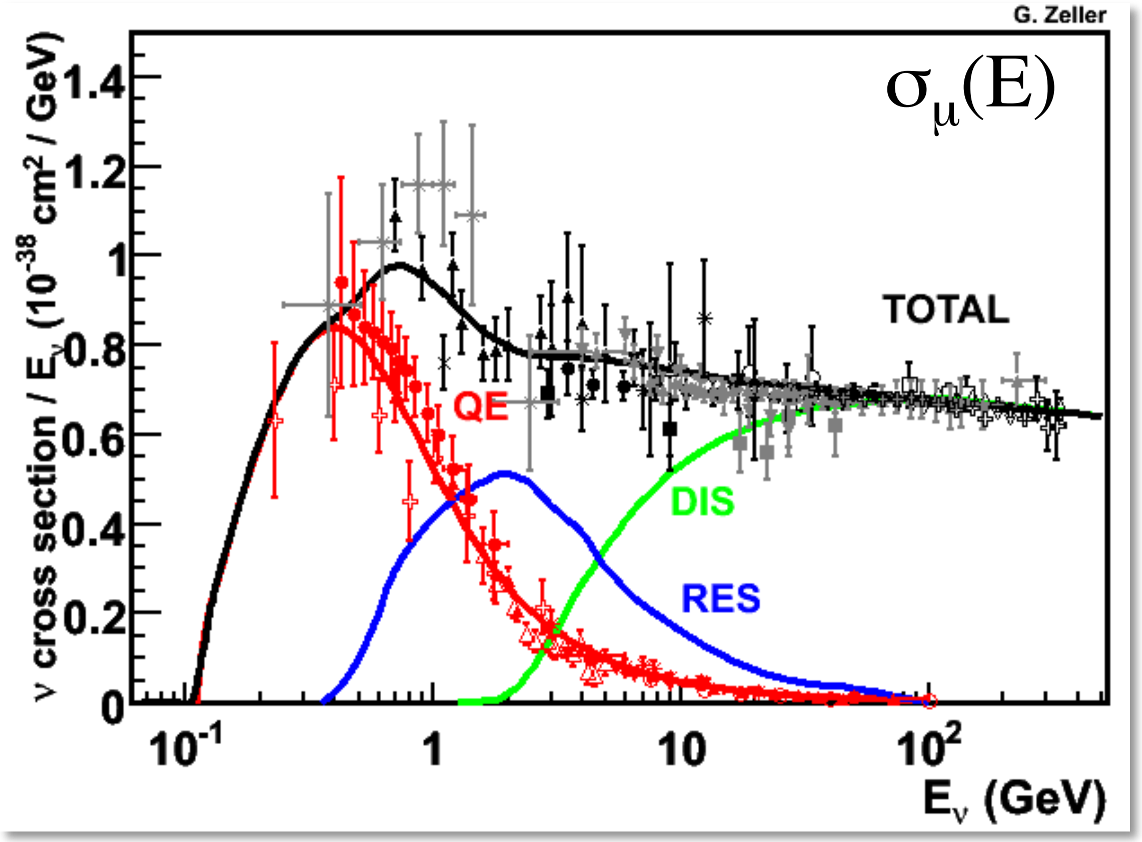


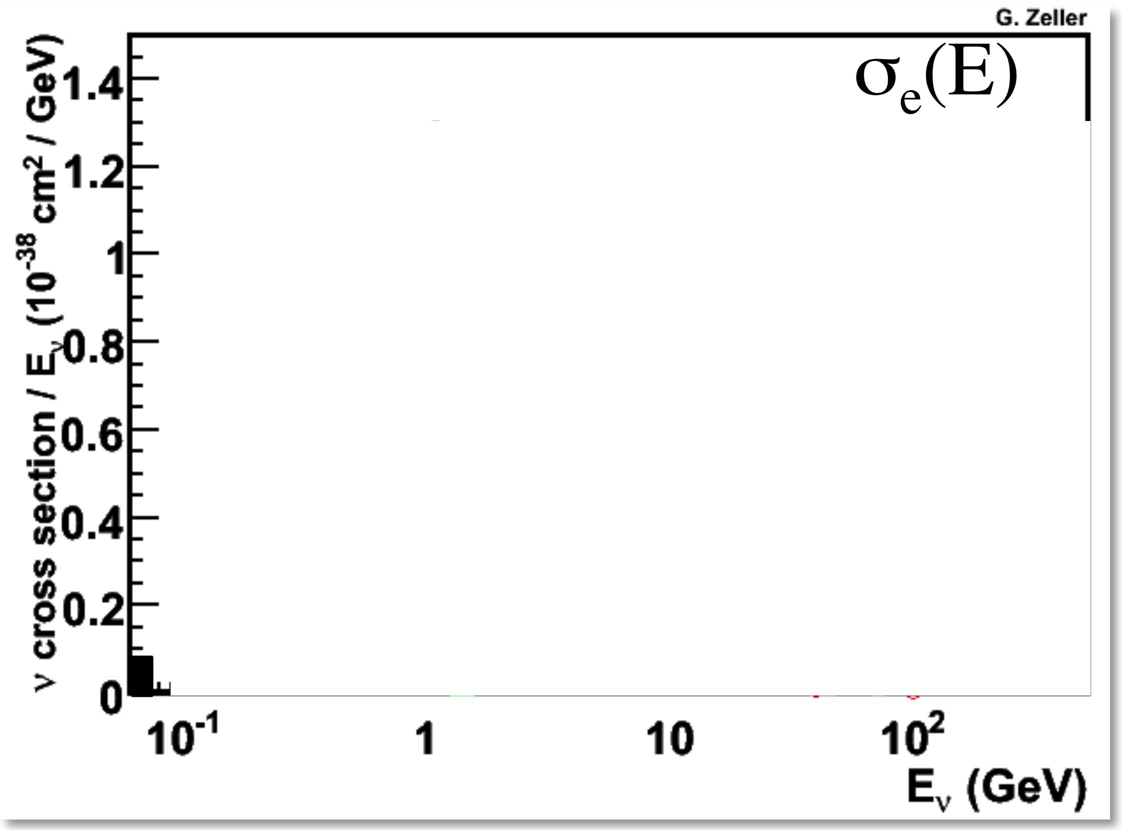
(not including matter effects & backgrounds)

(S. Parke)

Can we Actually MEASURE these Differences in the 0.5 – 6 GeV region

- Need to measure the $\sigma_e(E)$ of multiple channels to predict spectrum at the far detector.
  - Want an intense source of ν_e events.
  - Would like to know the flux of ν_e (and ν_μ, by the way) to order 1%.

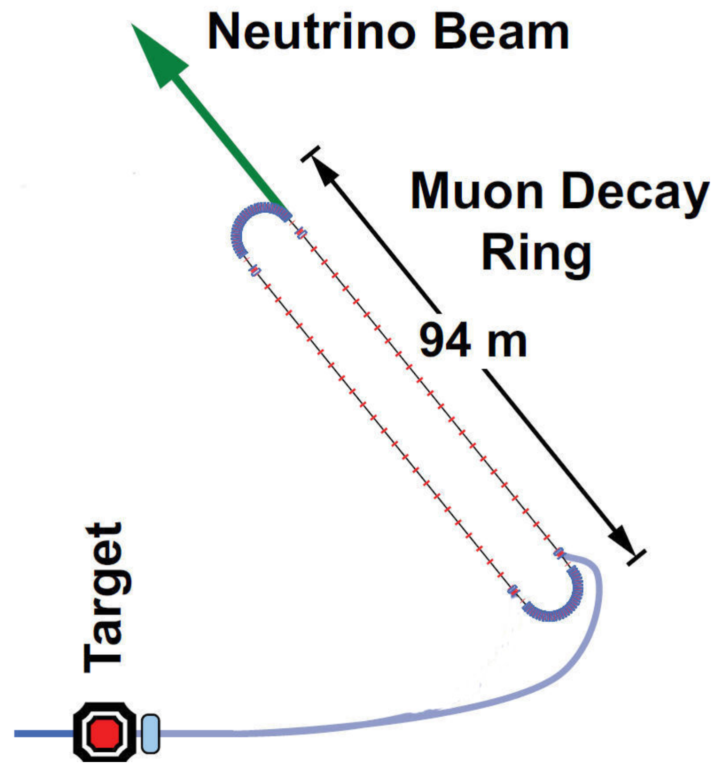




Enter - νSTORM

Neutrinos from Stored Muons – Alan Bross Presentation on Friday

- High-Precision ν interaction physics program.
  - ν_e and $\overline{\nu}_e$ cross-section measurements.
- Address the large Δm^2 oscillation regime, make a major contribution to the study of sterile neutrinos.
  - Either allow for precision study (in many channels), if they exist in this regime.
  - Or greatly expand the dis-allowed region.



- Provide a technology test demonstration (μ decay ring) and μ beam diagnostics test bed.
- Provide a precisely understood ν beam for detector studies.
- **Change the conception of the neutrino factory.**

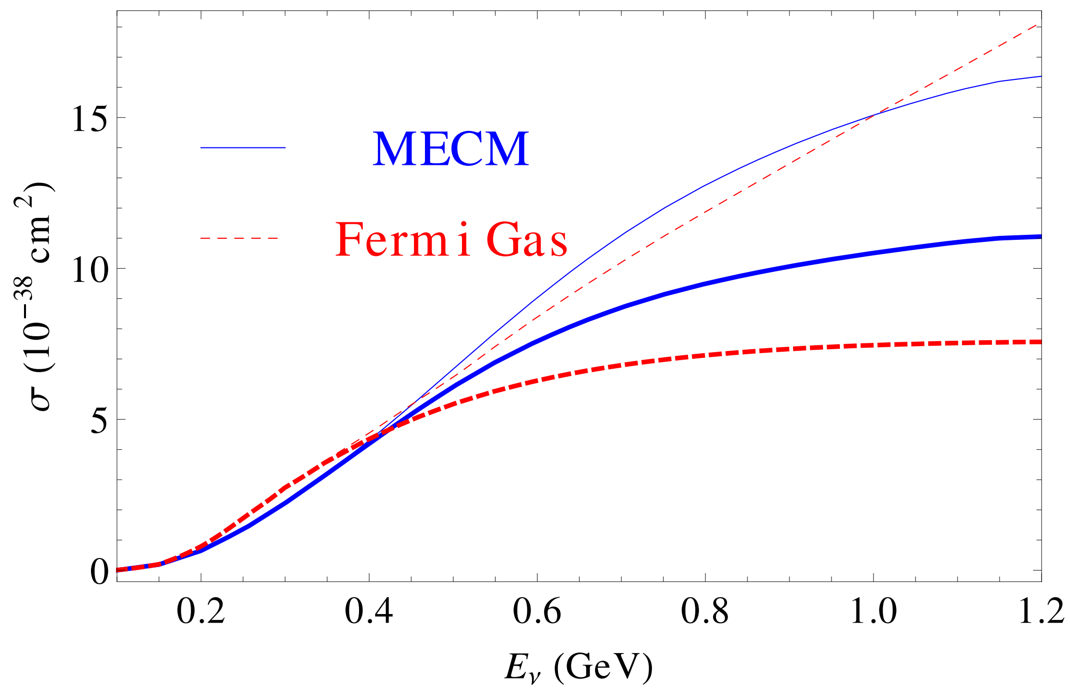
Conclusions

- An important systematic error in measurement of CP-violations could be our knowledge of ν_e cross sections.
  - Simply assuming we can infer ν_e cross sections from ν_μ cross sections is unjustified.
  - Simply correcting cross section for the difference in lepton mass is not necessarily sufficient.
- There is then a need to actually measure ν_e cross sections to minimize the systematic error from this source.
- νSTORM, based on the decay of a circulating beam of muons, could provide an intense beam of well-know flux (order 1%) of ν_e (and $\bar{\nu}_\mu$) for ν_e and $\bar{\nu}_\mu$ cross section measurements in a single experiment.
- Stay-tuned for the presentation of Alan Bross on Friday afternoon for details of the νSTORM facility and agenda.

Fit to the T2K appearance data using different cross sections

- MECM: M. Martini et al., Phys. Rev. **C80**, 065501 (2009)

solid: inclusive xs



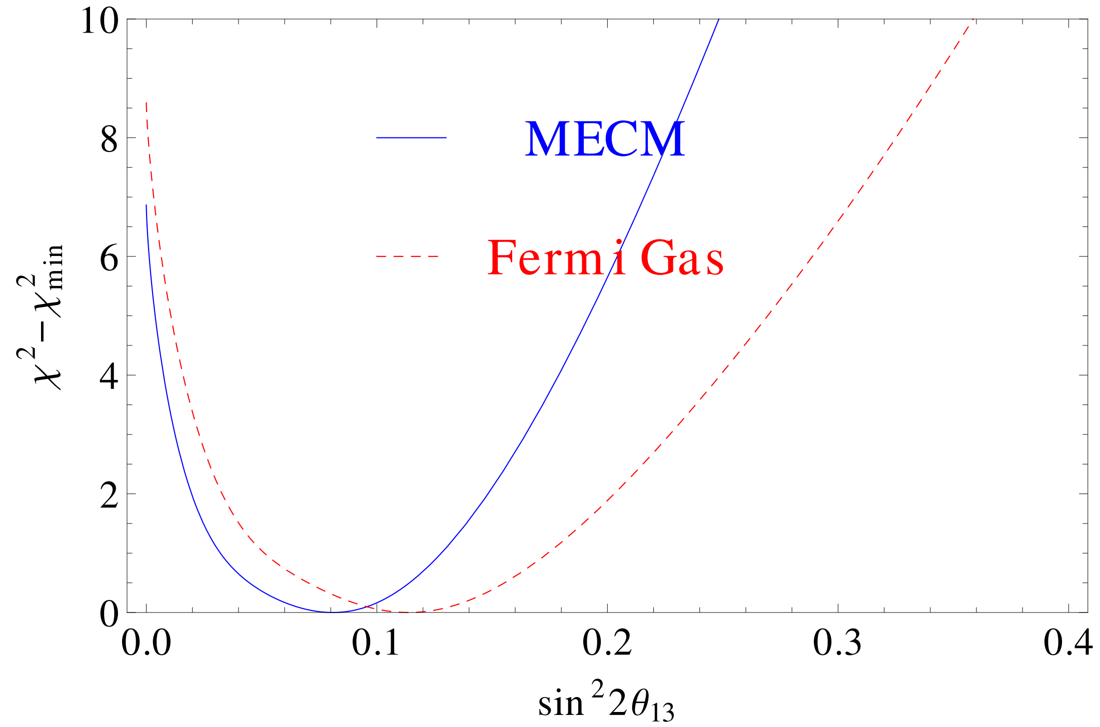
- total rates for $\sin^2 2\theta_{13}$=0.1

channel	exp result	MECM
$\nu_\mu \to \nu_e$	8.65	11.08
$\nu_e \to \nu_e$	1.5	1.97
NC	1.25	$1.25^\star$

Playing with the T2K appearance data

comparing FG and MECM models

- showing the $\chi^2 - \chi^2_{min}$ function for 1 dof ($\delta_{CP} = 0$, good for both models)



$$\sin^2 2\theta_{13}^{MECM} = 0.081\left({}^{+0.047}_{-0.049}\right)$$
$$\sin^2 2\theta_{13}^{FG} = 0.114\left({}^{+0.060}_{-0.063}\right)$$

- results are clearly compatible but central values such that $\delta\theta_{13}/\theta_{13}^{FG} \sim 30\%$

Summary

- we played a bit with the T2K data, comparing the results for θ_{13} and δ_{CP} obtained with the FG and MECM models
  - idea: give an estimate of the systematic effects encoded in the knowledge of the ν-N cross section (rough estimate)

	$\|\Delta\theta_{13}\|/\theta_{13}^{FG}$	$\|\Delta\theta_{23}\|/\theta_{23}^{FG}$	$\|\Delta\Delta m_{23}\|/(\Delta m_{23}^2)^{FG}$
X 1	30%	6.0%	2.3%
X 10	28%	4.6%	1.5%

- $\Delta\delta_{CP}/\delta_{CP}^{FG} \sim 15\%$

Systematic Effects on CP violation measurements

Open Questions
(what needs to be done?)

Needs to improve (controle) more our knowledge (uncertainty) of ν_e and $\bar{\nu}_e$ corss sections

Experimental Efforts: reduce sys err as much as possible

impacts for J-Parc/HK reported by A. Minamino

impacts for LBNO reported by A. Weber

comparison of superbeam, beta beam, Nufact reported by W. Walter

Theoretical considerations

impacts of different models reported by D. Meloni

theoretical review reported by A. Ankowski

Ideal is to measure all the necessary cross sections in a single experiment such as in Neutrino Factory (as stressed by W. Winter)

νSTORM discussed by J. Morfin and A. Bross can do such a task