Towards precision neutrino physics

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A dangerous journey

into uncharted waters.

CP violation

There are only very few parameters in the νSM which can violate CP

- CKM phase – measured to be $\gamma \simeq 70^\circ$
- θ of the QCD vacuum – measured to be $< 10^{-10}$
- Dirac phase of neutrino mixing
- Possibly: 2 Majorana phases of neutrinos

At the same time we know that the CKM phase is not responsible for the Baryon Asymmetry of the Universe…

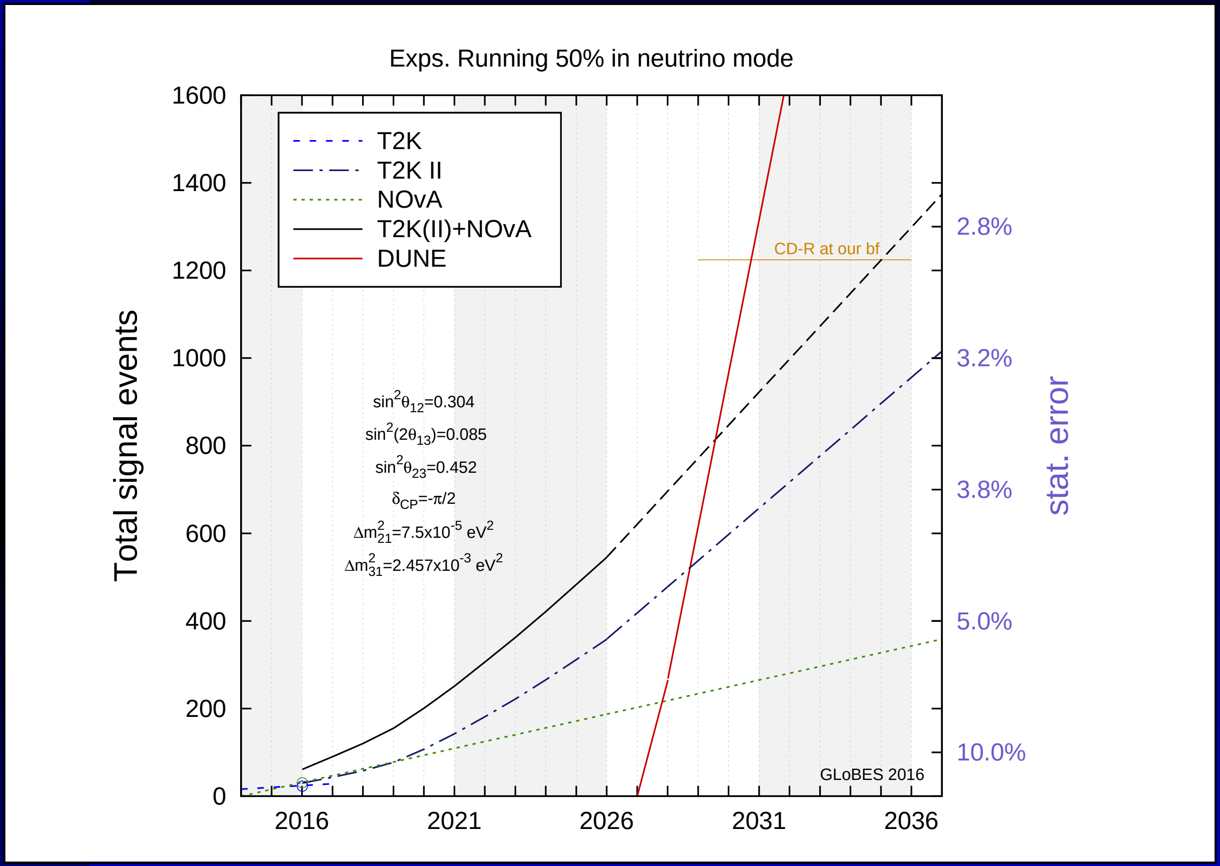
What can we learn from that?

– If we refute three flavor oscillation with significance, we have found new physics, but this requires great precision.

– If we confirm three flavor oscillation with great precision, we need the context of specific models to learn anything about BSM physics.

Corollary: Only if we do this precisely we really will learn something!

The way forward



Clearly, we are on the (slow) road towards 3% measurements of the event rates

Translating this into a 3% measurements of the oscillation probability is very difficult

Note, T2HK would reach 1000 ν_e signal events very quickly.

The basic concept

In order to measure CP violation we need to reconstruct one out of these

$$P(\nu_\mu \to \nu_e) \text{ or } P(\nu_e \to \nu_\mu)$$

and one out of these

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) \text{ or } P(\bar{\nu}_e \to \bar{\nu}_\mu)$$

and we'd like to do that at the percent level accuracy

The reality

We do not measure probabilities, but event rates!

$$R^\alpha_\beta(E_{\text{vis}}) = N \int dE \, \Phi_\alpha(E) \, \sigma_\beta(E, E_{\text{vis}}) \, \epsilon_\beta(E) \, P(\nu_\alpha \to \nu_\beta, E)$$

In order the reconstruct P, we have to know

- N – overall normalization (fiducial mass)
- Φ_α – flux of ν_α
- σ_β – x-section for ν_β
- ϵ_β – detection efficiency for ν_β

Note: $\sigma_\beta \epsilon_\beta$ always appears in that combination, hence we can define an effective cross section $\tilde{\sigma}_\beta := \sigma_\beta \epsilon_\beta$

The problem

Even if we ignore all energy dependencies of efficiencies, x-sections *etc.*, we generally can not expect to know any ϕ or any $\tilde{\sigma}$. Also, we won't know any kind of ratio

$$\frac{\Phi_\alpha}{\Phi_{\bar{\alpha}}} \quad \text{or} \quad \frac{\Phi_\alpha}{\Phi_\beta}$$

nor

$$\frac{\tilde{\sigma}_\alpha}{\tilde{\sigma}_{\bar{\alpha}}} \quad \text{or} \quad \frac{\tilde{\sigma}_\alpha}{\tilde{\sigma}_\beta}$$

Note: Even if we may be able to know σ_e/σ_μ from theory, we won't know the corresponding ratio of efficiencies ϵ_e/ϵ_μ

The solution

Measure the un-oscillated event rate at a near location and everything is fine, since all uncertainties will cancel, (provided the detectors are identical and have the same acceptance)

$$\frac{R^\alpha_\alpha(\text{far})L^2}{R^\alpha_\alpha(\text{near})} = \frac{N_{\text{far}}\Phi_\alpha\,\tilde{\sigma}_\alpha\,P(\nu_\alpha \to \nu_\alpha)}{N_{\text{near}}\Phi_\alpha\,\tilde{\sigma}_\alpha 1}$$

$$\frac{R^\alpha_\alpha(\text{far})L^2}{R^\alpha_\alpha(\text{near})} = \frac{N_{\text{far}}}{N_{\text{near}}}P(\nu_\alpha \to \nu_\alpha)$$

And the error on $\frac{N_{\text{far}}}{N_{\text{near}}}$ will cancel in the ν to $\bar{\nu}$ comparison. Real world example: Daya Bay.

Some practical issues

- Same acceptance may require a not-so-near near detector
- Near and far detector cannot be really identical
- Energy dependencies will remain

But . . .

This all works only for disappearance measurements!

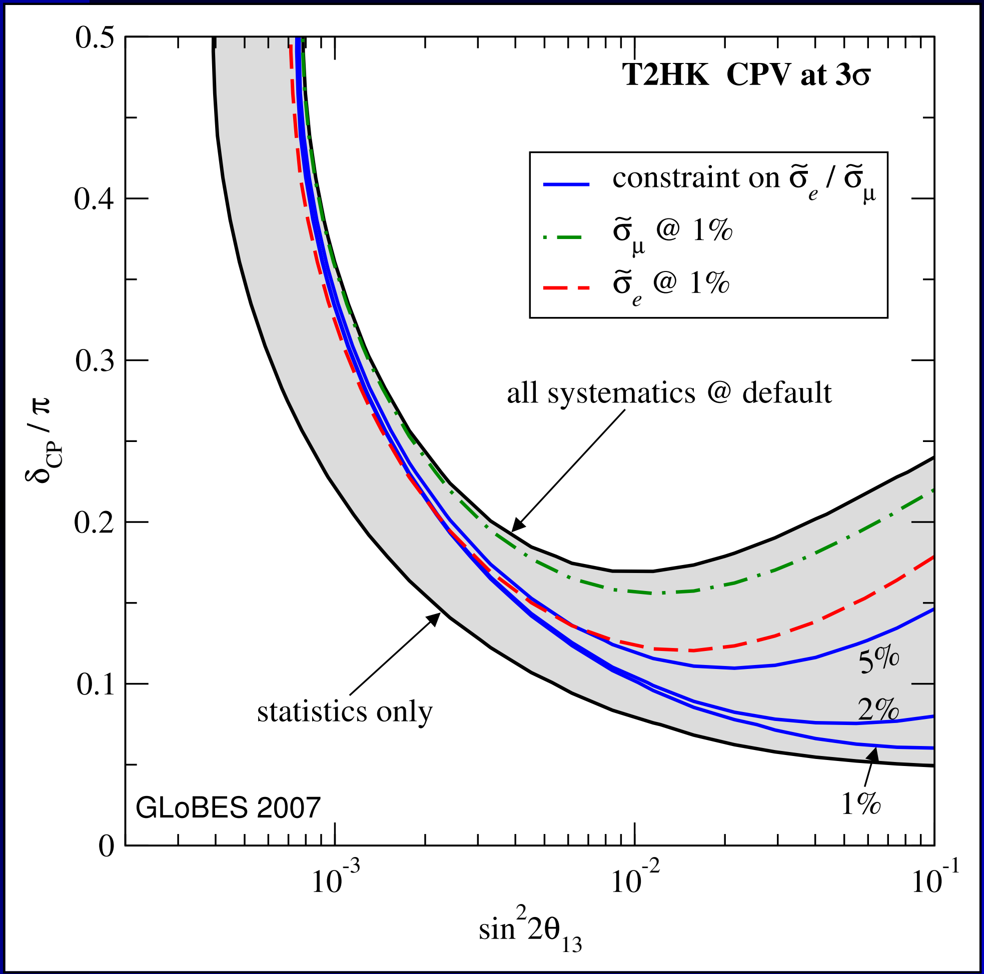
$$\frac{R^\alpha_\beta(\text{far})L^2}{R^\alpha_\beta(\text{near})} = \frac{N_{\text{far}}\Phi_\alpha\,\tilde{\sigma}_\beta\,P(\nu_\alpha \to \nu_\beta)}{N_{\text{near}}\Phi_\alpha\,\tilde{\sigma}_\alpha\,1}$$

$$\frac{R^\alpha_\beta(\text{far})L^2}{R^\alpha_\beta(\text{near})} = \frac{N_{\text{far}}\,\tilde{\sigma}_\beta\,P(\nu_\alpha \to \nu_\beta)}{N_{\text{near}}\,\tilde{\sigma}_\alpha\,1}$$

Since $\tilde{\sigma}$ will be different for ν and $\bar{\nu}$, this is a serious problem. And we can not measure $\tilde{\sigma}_\beta$ in a beam of ν_α.

NB: Using many different event samples to constrain the interaction model requires that we have a reliable cross section model.

Neutrino cross sections



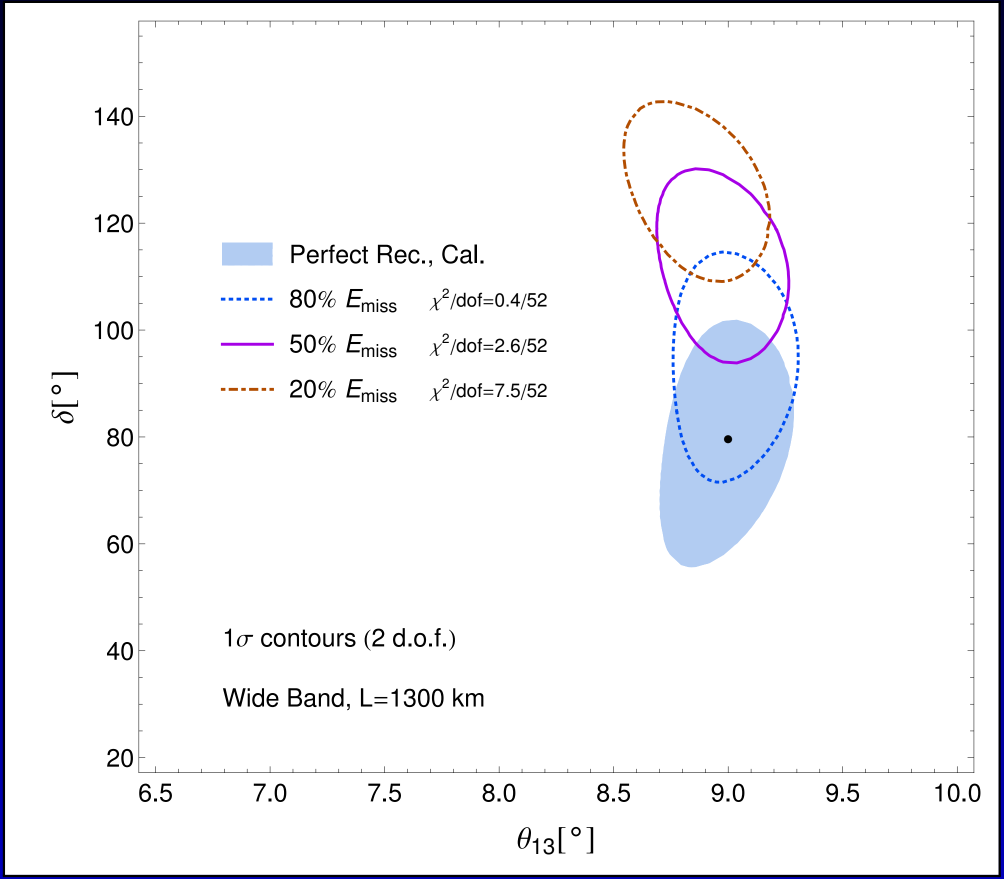
PH, Mezzetto, Schwetz, 2007

Using current cross section uncertainties and a perfect near detector.

Appearance experiments using a (nearly) flavor pure beam can not rely on a near detector to predict the signal at the far site!

Differences between ν_e and ν_μ are significant below 1 GeV, see e.g. Day, McFarland, 2012

Nuclear effects – example



In elastic scattering a certain number of neutrons is made

Neutrons will be largely invisible even in a liquid argon TPC

$\Rightarrow$ missing energy

Ankowski *et al.*, 2015

We can correct for the missing energy IF we know the mean neutron number and energy made in the event. . .

Theory and cross sections

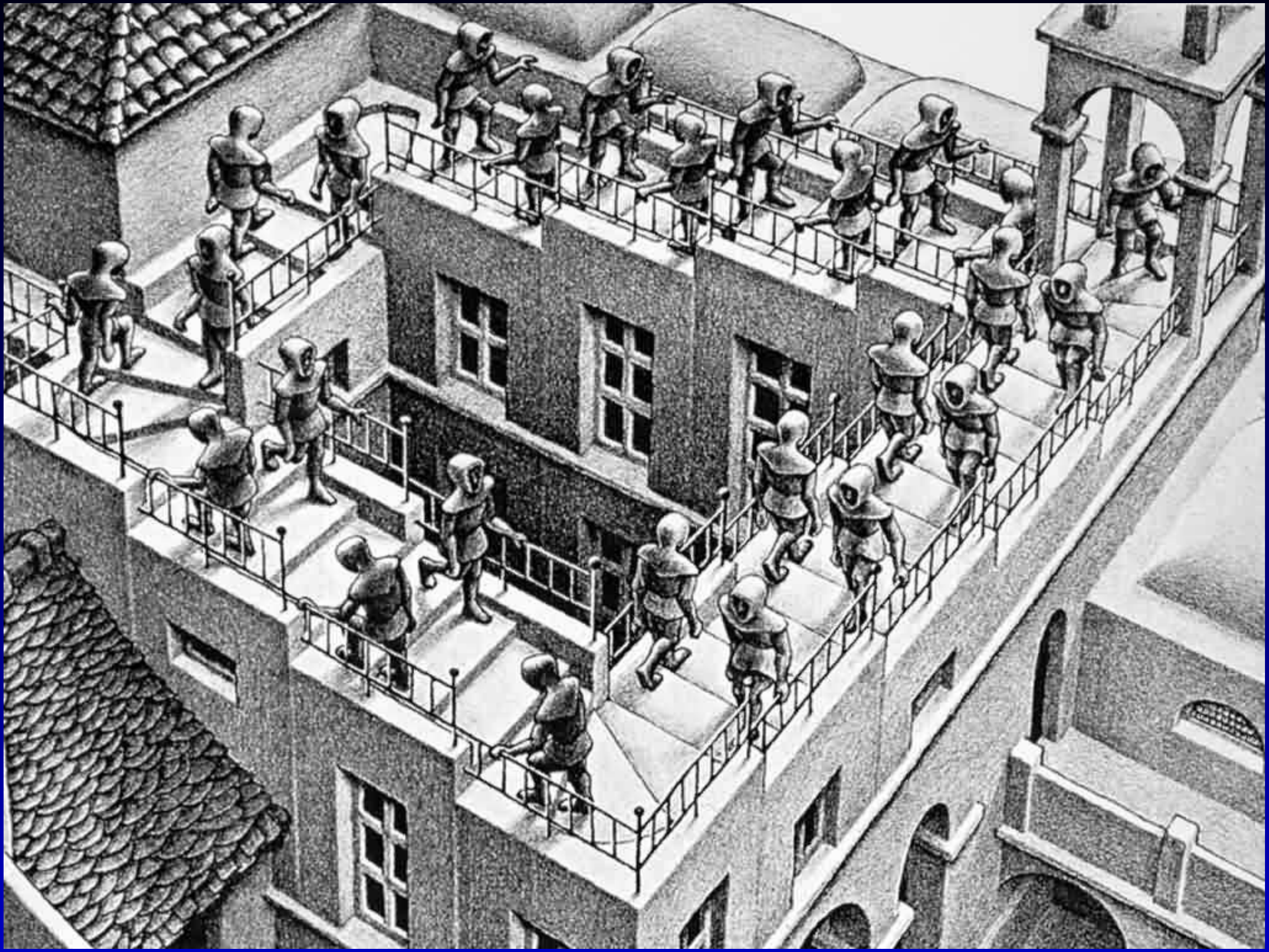
Theory is cheap, but multi-nucleon systems and their dynamic response are a hard problem and there is not a huge number of people with expertise working on this. . .

Any result will contain assumptions, which are not based on controlled approximations.

Generators

Many talks on this topic, key issues

- Tremendous progress in the past years
- Most of them implement very similar physics (exception GiBUU)
- Tuning is a central part in this game
- Once tuned, different physics models often yield same result
- Tuning has to be repeated with each new data set



Corollary:

Without data generators are not reliable, ever.

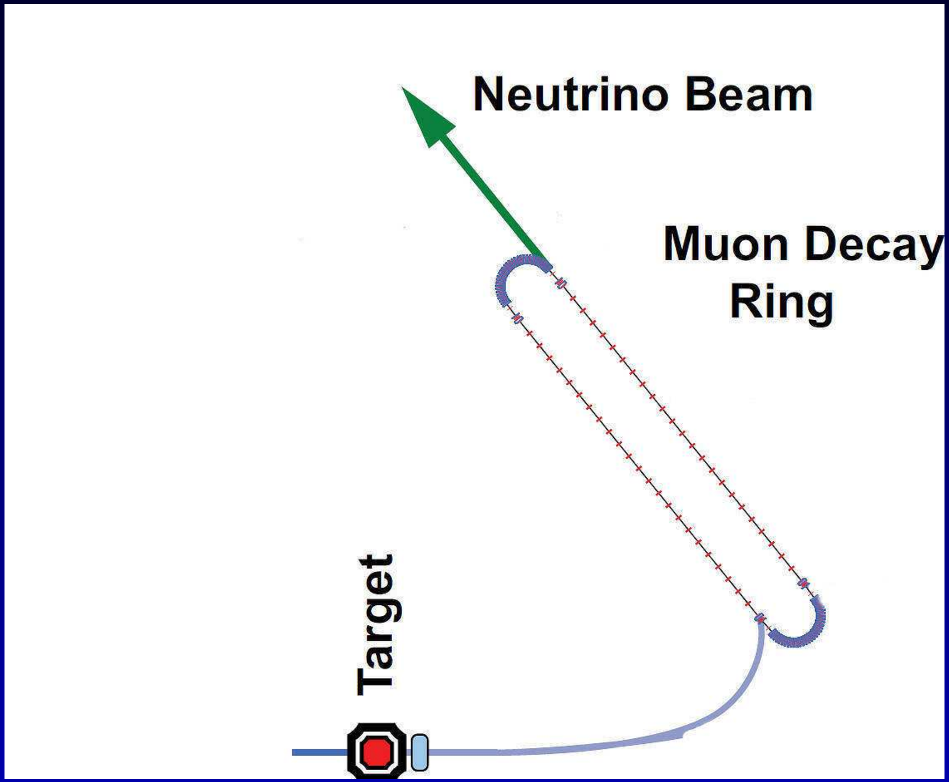
Give me a lever long enough and a fulcrum on which to place it, and I shall move the world.

Archimedes, ca. 250BC

Towards precise data

Needs better neutrino sources

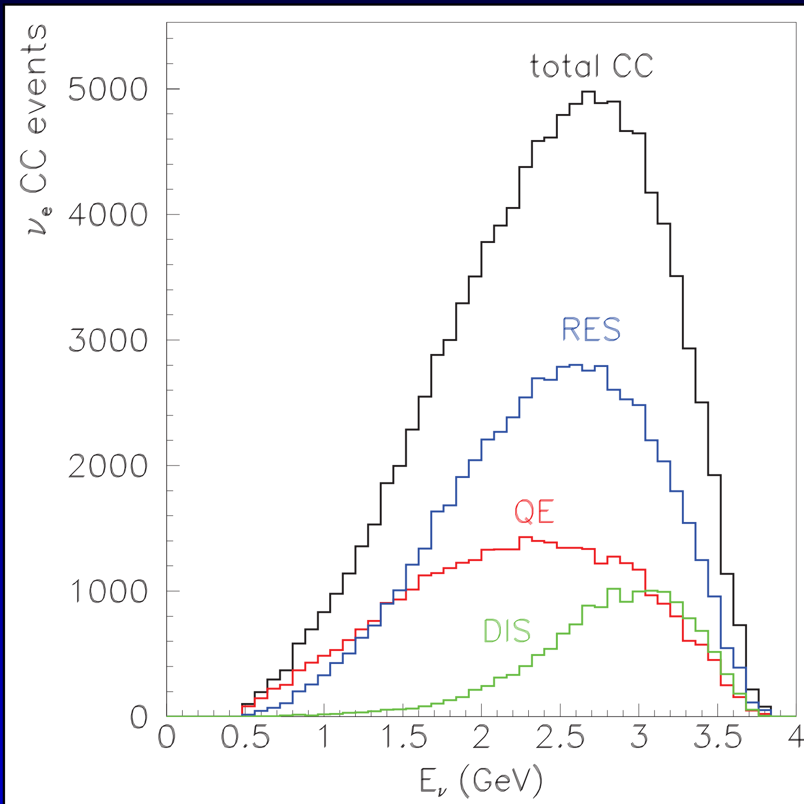
- Sub-percent beam flux normalization
- Very high statistics needed to map phase space
- Neutrinos and antineutrinos
- ν_μ and ν_e



One (the only?) source which can deliver all that is a muon storage ring, aka nuSTORM.

nuSTORM in numbers

Beam flux known to better than 1%



μ^+		μ^-	
Channel	N_{evts}	Channel	N_{evts}
$\bar{\nu}_\mu$ NC	1,174,710	$\bar{\nu}_e$ NC	1,002,240
ν_e NC	1,817,810	ν_μ NC	2,074,930
$\bar{\nu}_\mu$ CC	3,030,510	$\bar{\nu}_e$ CC	2,519,840
ν_e CC	5,188,050	ν_μ CC	6,060,580
π^+		π^-	
ν_μ NC	14,384,192	$\bar{\nu}_\mu$ NC	6,986,343
ν_μ CC	41,053,300	$\bar{\nu}_\mu$ CC	19,939,704

nuSTORM collab. 2013

Approximately 3-5 years running for each polarity with a 100 t near detector at 50 m from the storage ring

Outlook

Neutrino oscillation is solid evidence for new physics

- Precision measurements have the best potential to uncover even “newer” physics – either by finding discrepancies or correlations among results
- This will require unprecedented levels of accuracy in our understanding of neutrino-nucleus interactions.

Are near detectors alone enough?