Bayesian Neutrino Oscillation Analysis at T2K

Henry Israel (University of Sheffield) on behalf of the T2K Collaboration

Lepton Photon 2023

Overview

- Recap of **neutrino oscillation** physics
- Overview of the **T2K** experiment
- Introduction to **Bayesian Markov Chain Monte Carlo (MCMC)**
- Analysis of T2K's **latest results** using MCMC!
- A look into the **future** of Bayesian neutrino oscillation analysis

What are Neutrino Oscillations?

Neutrino Oscillations

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Flavour States — Atmospheric — Reactor — Solar — Mass States

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{cp}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{cp}} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_2\end{pmatrix}$$

$c_{ij} = \cos(\theta_{ij})$

$s_{ij} = \sin(\theta_{ij})$

- Neutrino **mass** and **weak flavour eigenstates** are not the same and related via the **PMNS matrix**
- Results in **neutrino oscillations** i.e. the weak flavour state changes as a function of **propagation distance** and **energy**
- **Interesting physics** still needs to be done! :
  - $\delta_{cp} \neq \{0, \pm\pi\}$ ← Is CP violated in the Lepton Sector?
  - Do the neutrino mass states have a "**normal ordering**" or "**inverted ordering**" ($\Delta m^2_{32} = m^2_3 - m^2_2$>0 or <0)?

Neutrino Oscillations

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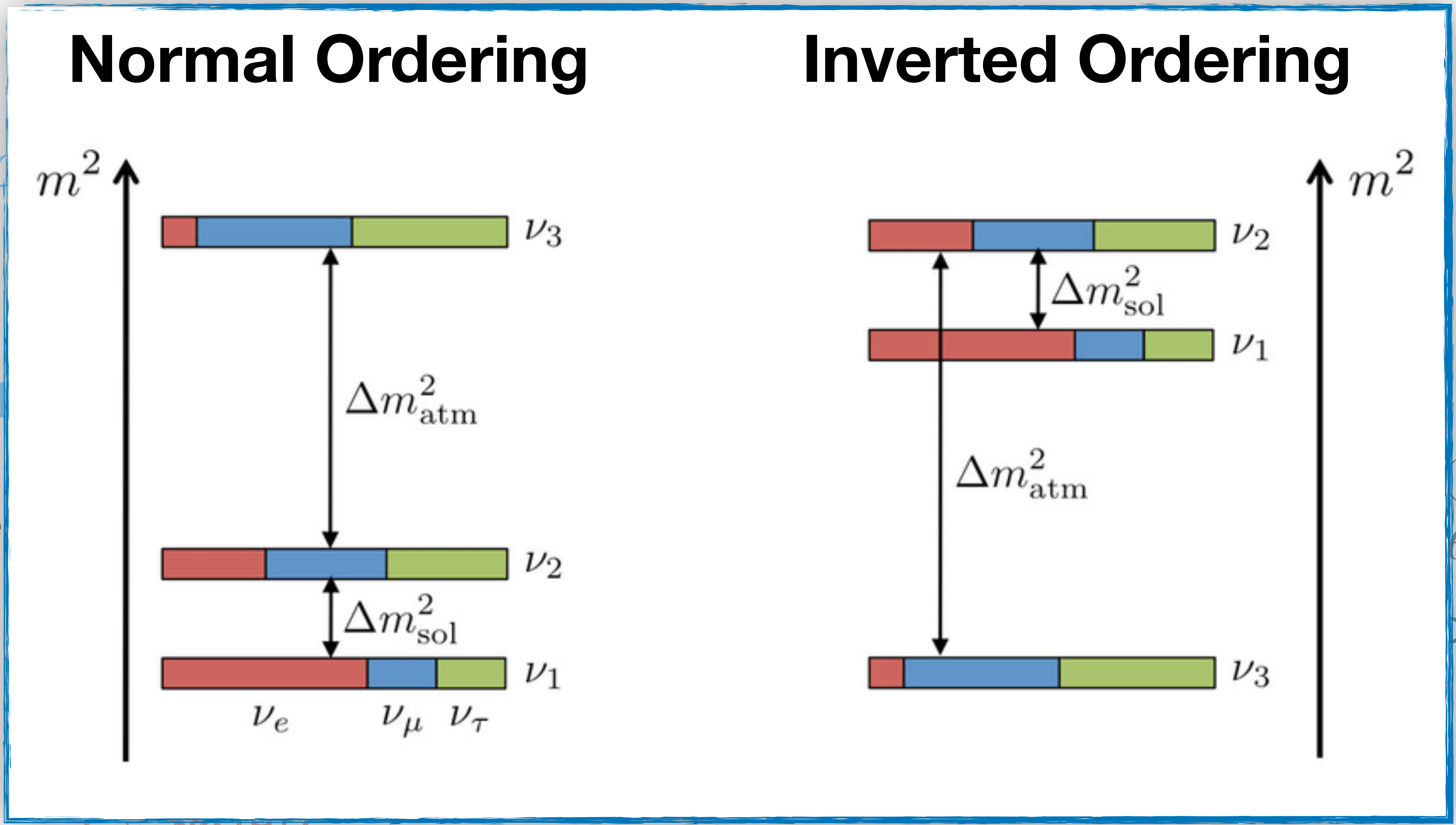
Flavour States Atmospheric

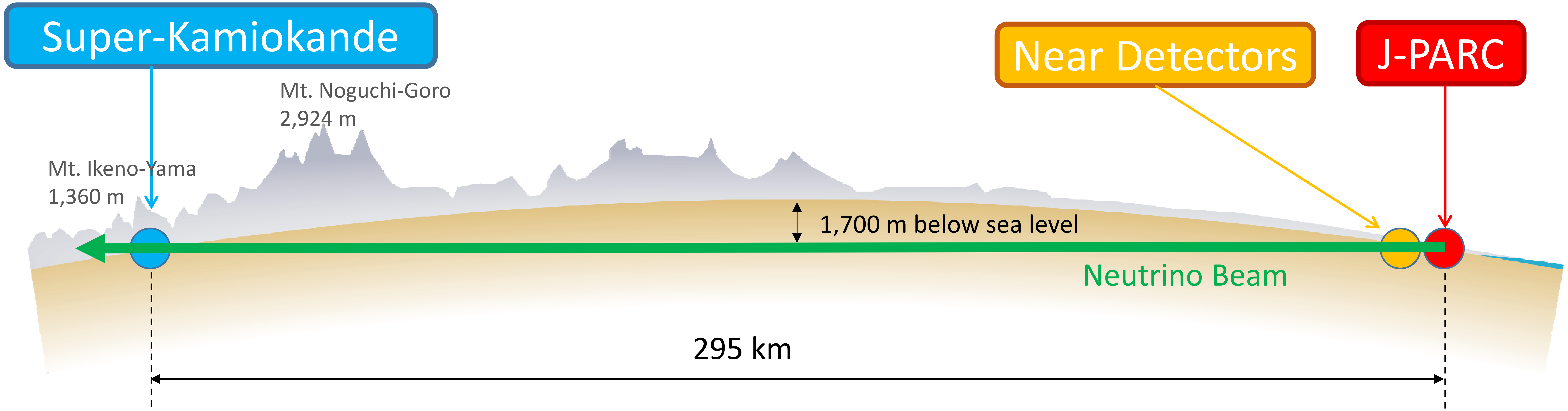
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \ldots$$

- Neutrino **mass** and **weak flavour eigenstate**
- Results in **neutrino oscillations** i.e. the weak ... **energy**
- **Interesting physics** still needs to be done! :
  - $\delta_{cp} \neq \{0, \pm\pi\}$ ← Is CP violated in the Lepton sect
  - Do the neutrino mass states have a "**normal ordering**" or "**inverted ordering**" ($\Delta m^2_{32} = m^2_3 - m^2_2$>0 or <0)?



The T2K Experiment

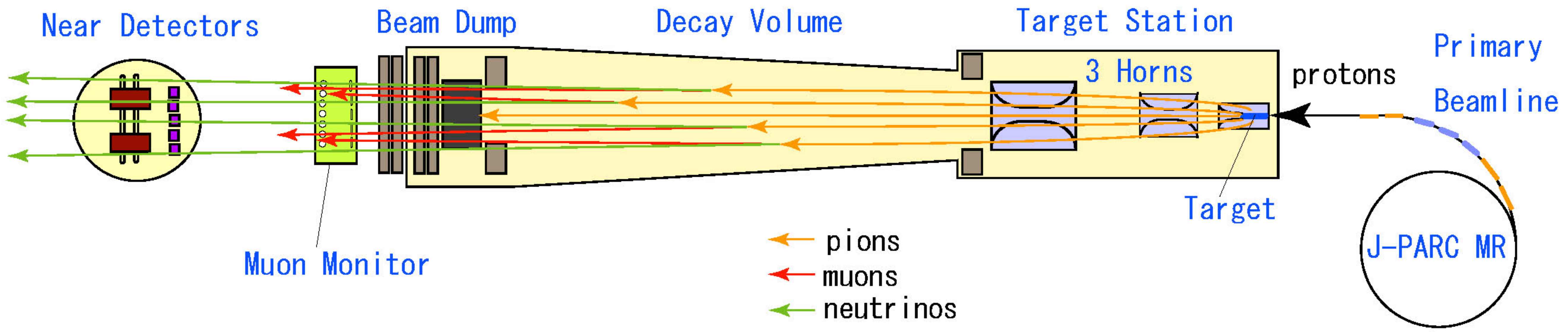
The T2K Experiment



- **Long baseline** and **off-axis** neutrino oscillation experiment
- Two detector complexes:
  - **Far Detector** : Super-Kamiokande (SK) 295km from target
  - **Near Detector** : ND280, INGRID and WAGASCI/BabyMIND 280m from target

J-PARC and T2K Beam

- T2K uses the **J-PARC** proton beam to generate neutrinos
- Protons from the J-PARC beam are fired at a **graphite** target
- The final state contains mostly pions/kaons
- Charged particles can be focused by **magnetic horns** to select for π^+/K^+ and π^-/K^- resulting in a **primarily** $\bar{\nu}_\mu$ or ν_μ beam
- Charged hadrons decay into neutrinos
- The beam hits **bedrock** (sand) absorbing all non-neutrino particles



Near Detectors

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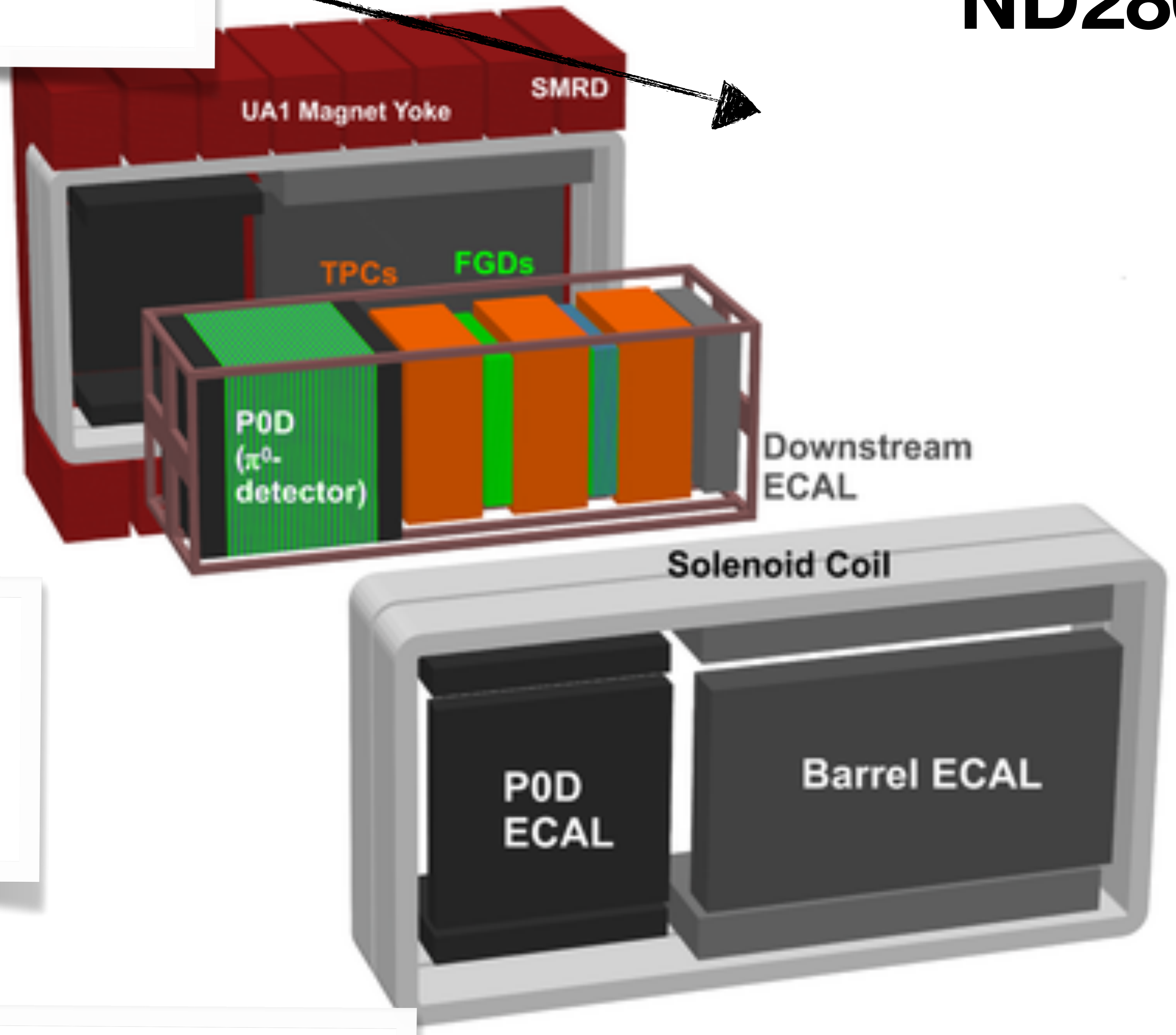
Located at same off axis angle as SK (2.5°)

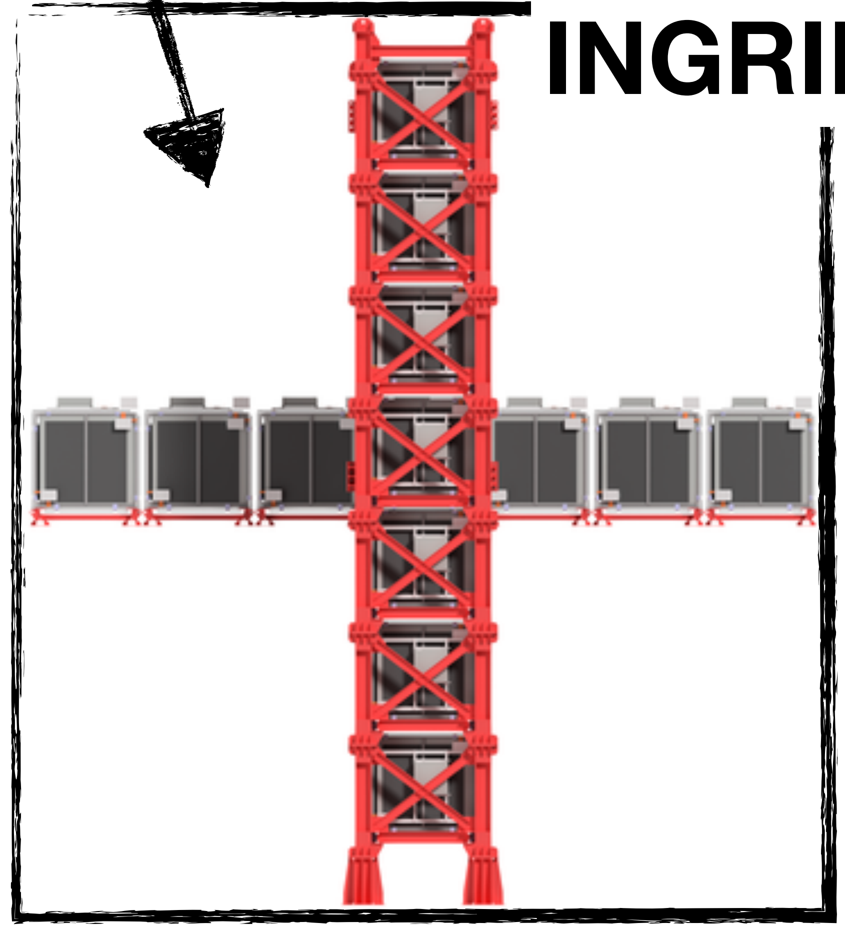
Only ND280 data used in OA

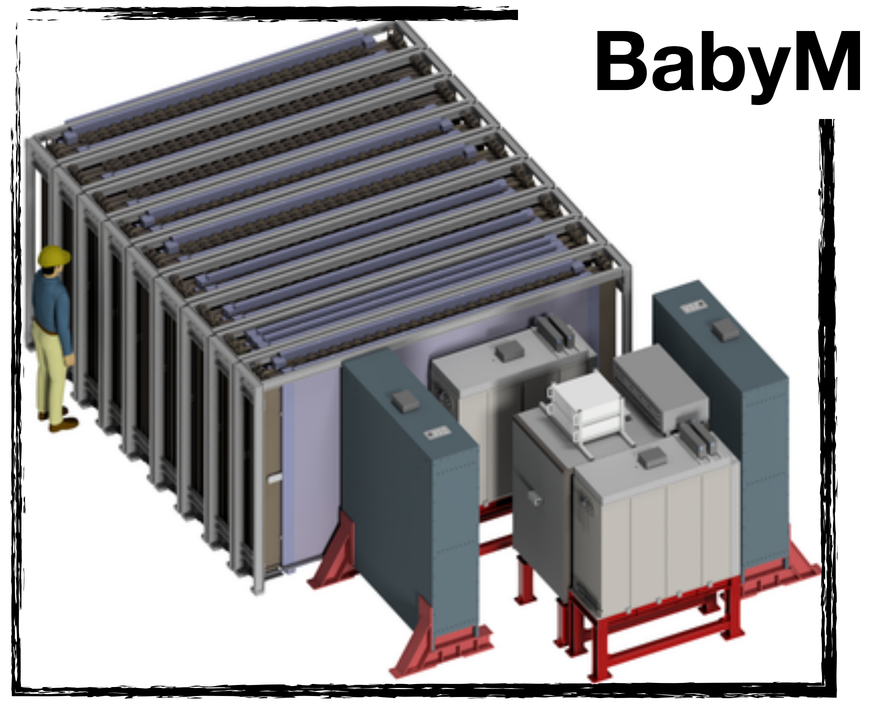
INGRID and ND280 used to provide constraints on beam flux parameters

Provides world leading neutrino cross-section measurements!

On Axis

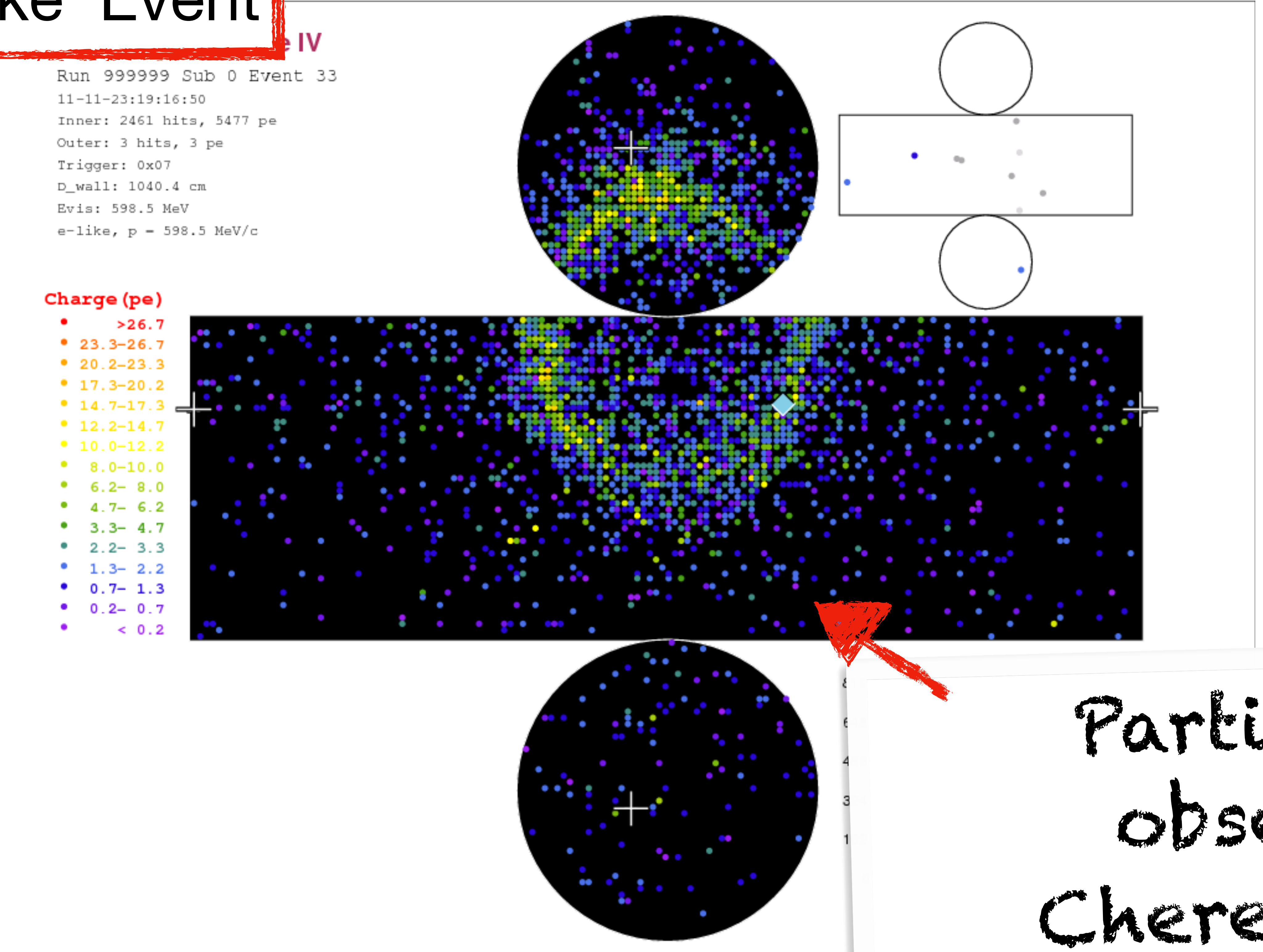




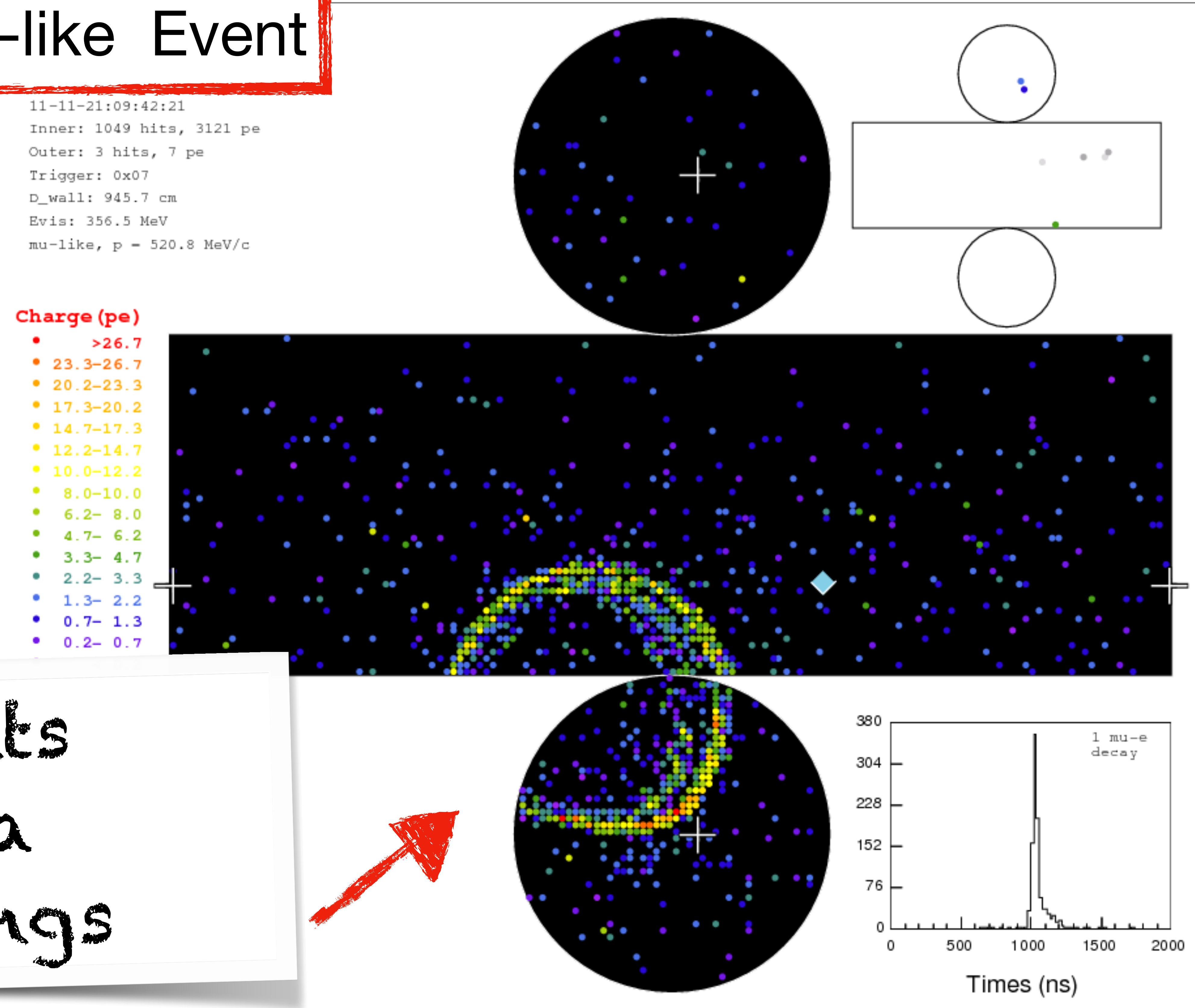


Super-Kamiokande

e-like Event



μ-like Event



Particle events observed via Cherenkov rings

50 kt water Cherenkov detector!

Located at "oscillation maximum" (probability of $\nu_\mu \to \nu_e$ is highest)

Bayesian Fits

Bayesian Approach

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- T2K's **Bayesian fitter** is known as MaCh3
- Use **Bayesian Markov Chain Monte Carlo (MCMC)** for T2K analysis
- Can think of Metropolis-Hastings as a **"directed random walk"** around the parameter space where direction is determined by the likelihood
- The **number of steps** in a given region is proportional to the posterior likelihood
- **Marginalisation** used to get 1D and 2D **posteriors**

Want to evaluate this

$$P(\theta|D) \propto P(D|\theta)\, P(\theta)$$

Posterior Likelihood Prior

Use MC and Data to make likelihood space

Use current knowledge

Markov Chain Monte Carlo

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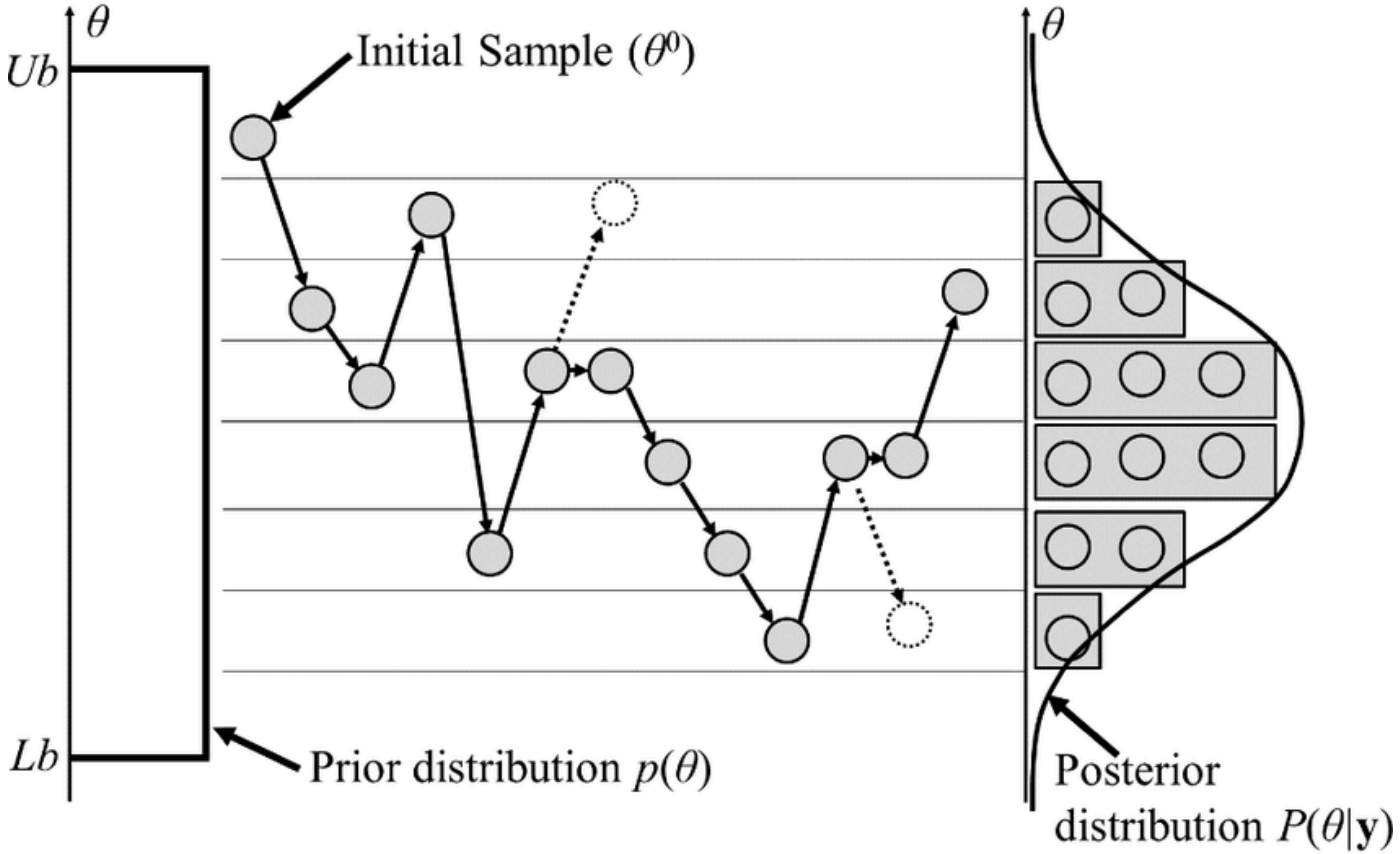

Figure : Lee, Jaewook & Sung, Woosuk & Choi, Joo-Ho. (2015). *Metamodel for Efficient Estimation of Capacity-Fade Uncertainty in Li-Ion Batteries for Electric Vehicles,* Energies

Recent T2K Results

T2K 2022 Systematics Model

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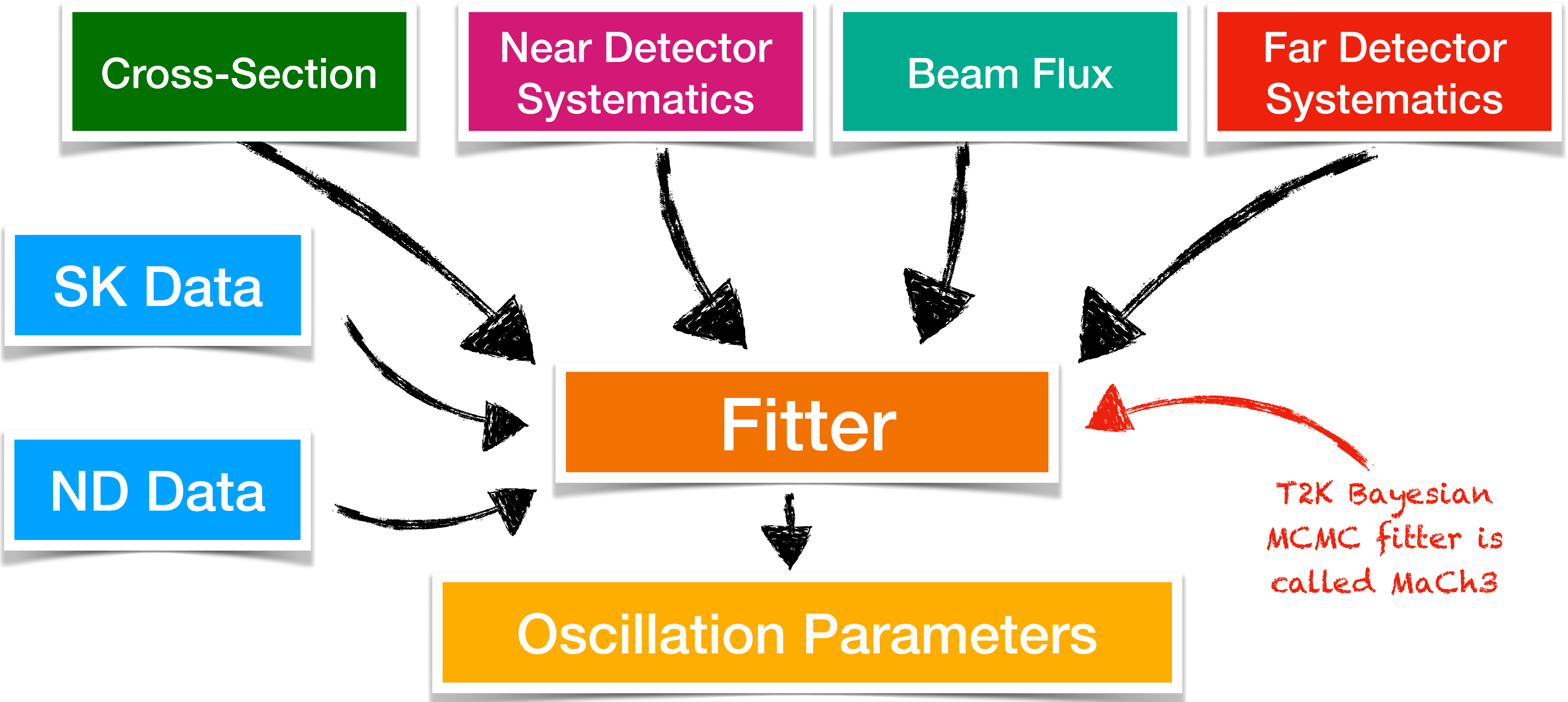
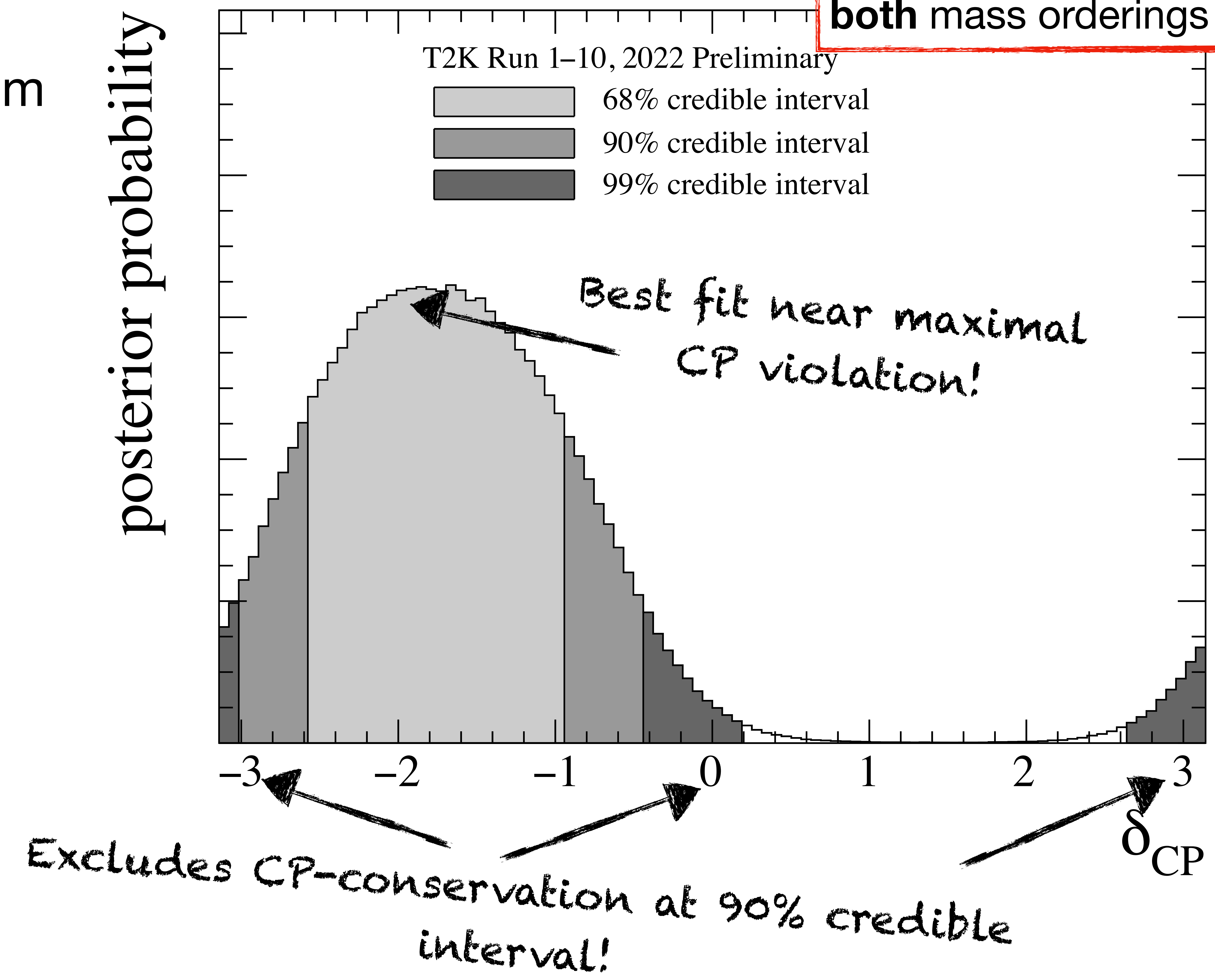


δ_{cp} Result

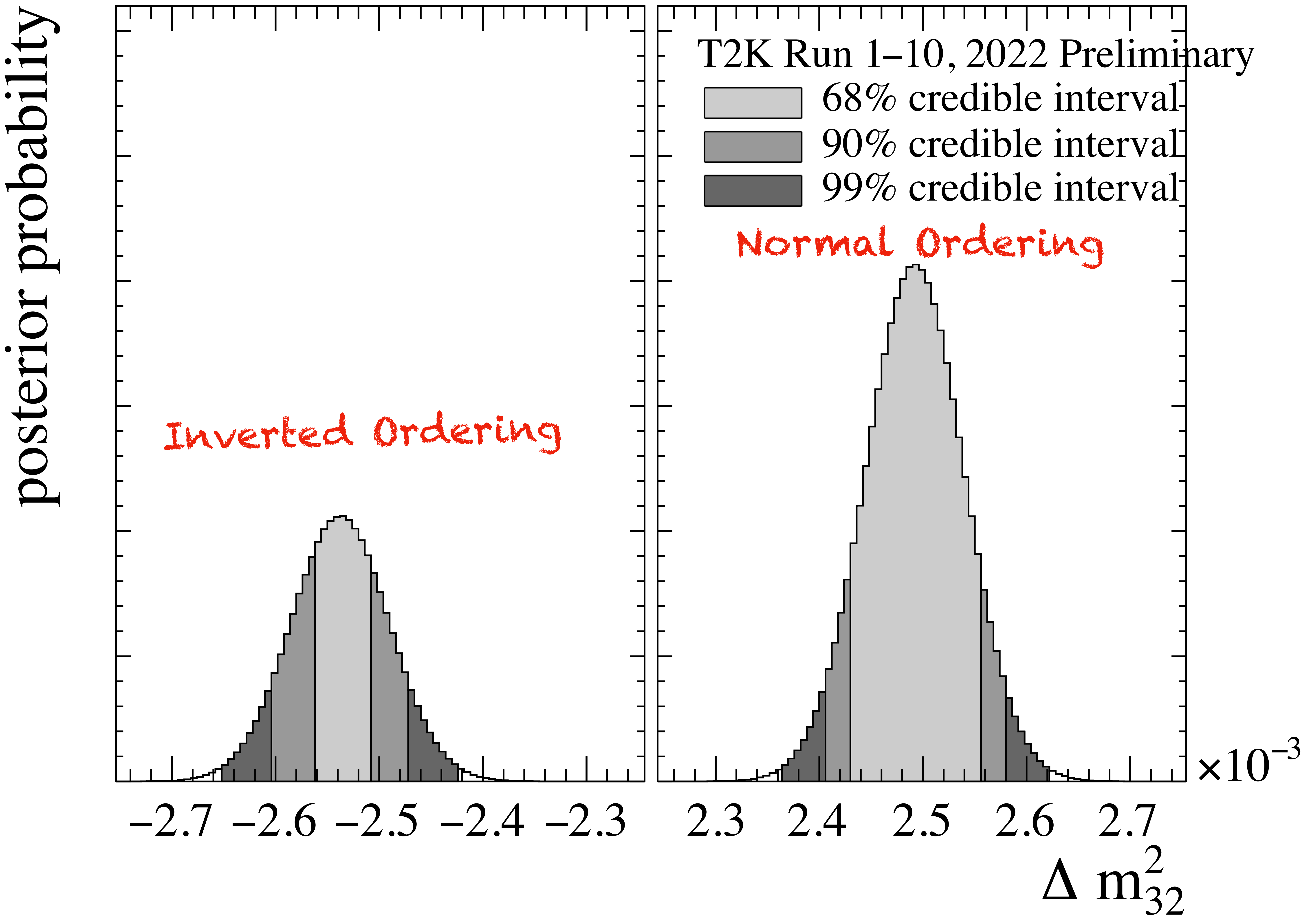
- Fit here uses constraint $\sin^2(\theta_{13})$ on taken from **reactor** experiments
- **CP conserving** values lie outside the 90% credible interval
- Large region now outside the **99% credible interval**
- Best fit region near **maximal CP violation** $(-\pi/2)$

Marginalised over **both** mass orderings



Mass Ordering

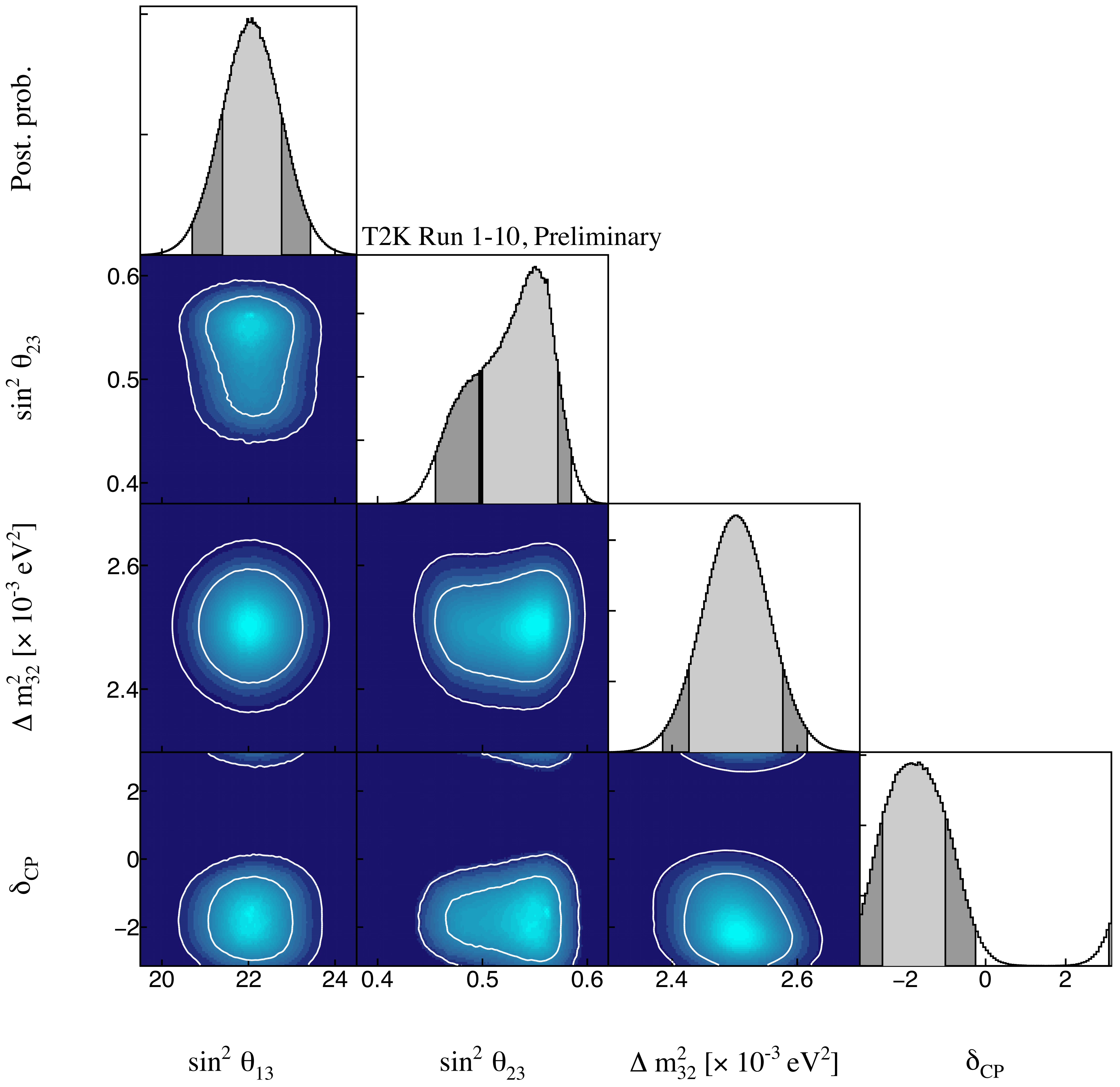
- We also have sensitivity to **neutrino mass ordering**
- We prefer NO over IO by a factor of 1.7×
- MCMC fitter can fit to **both** orderings!



Triangle Plot

- Really nice way to visualise all **correlations**

- Shows every combination of **pairs** of **oscillation parameters**



The Future!

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- The **MaCh3 fitter** is now active on **multiple experiments** both **current** and **future**!
- Combined analysis using **Super-Kamiokande Atmospherics** + **T2K data** to provide even better constraints on oscillation parameters
- **Joint analysis** of **T2K/NOνA** data is ongoing
- Thinking about the future, there's a huge amount of work towards getting the fitter ready for **HK** and **DUNE**!
- The **core MaCh3 code** is being **overhauled** and is now **publicly** available in a **pre-alpha** state https://github.com/mach3-software/MaCh3

Coming Soon!

Fitter should be ready from day 1 for these experiments!

Multiple experiments will be able to use the same core code and share expertise!

Summary

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- T2K is producing **world leading** neutrino oscillation analysis measurements
- World leading δ_{cp} constraint on **CP-conservation** of 2σ
- **Bayesian MCMC** is an incredibly powerful tool for these analyses!
- Helping to pave the way for **future** oscillation analyses!

The T2K Collaboration!

Backups

What's New for T2K?

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- Results are from **2022 oscillation** analysis
- Improved **flux prediction** based on a replica target at NA61/SHINE. This brings down flux uncertainties by **6%**
- This analysis uses a new **cross-section systematics model**
- Primary changes are new **CCQE**, **MEC**, **resonant π production** and **final state interaction (FSI)** affecting systematics
- New treatment of **binding energy** (E_b) based on electron scattering data
- Additional **Super-Kamiokande** selection accounting for muon-ring events with **multiple Cherenkov rings** in the final state
- New **ND280 selections** with improved **proton** and **photon** tagging!

CCQE Improvements :

- More theory driven uncertainties!
- Improvements to Spectral Function parametrisation
- Improved normalisation of nuclear shell model, short range correlations and Pauli blocking

MEC Improvements:

- Model now includes 2p2h for proton/neutron vs proton/

Resonant π Improvements:

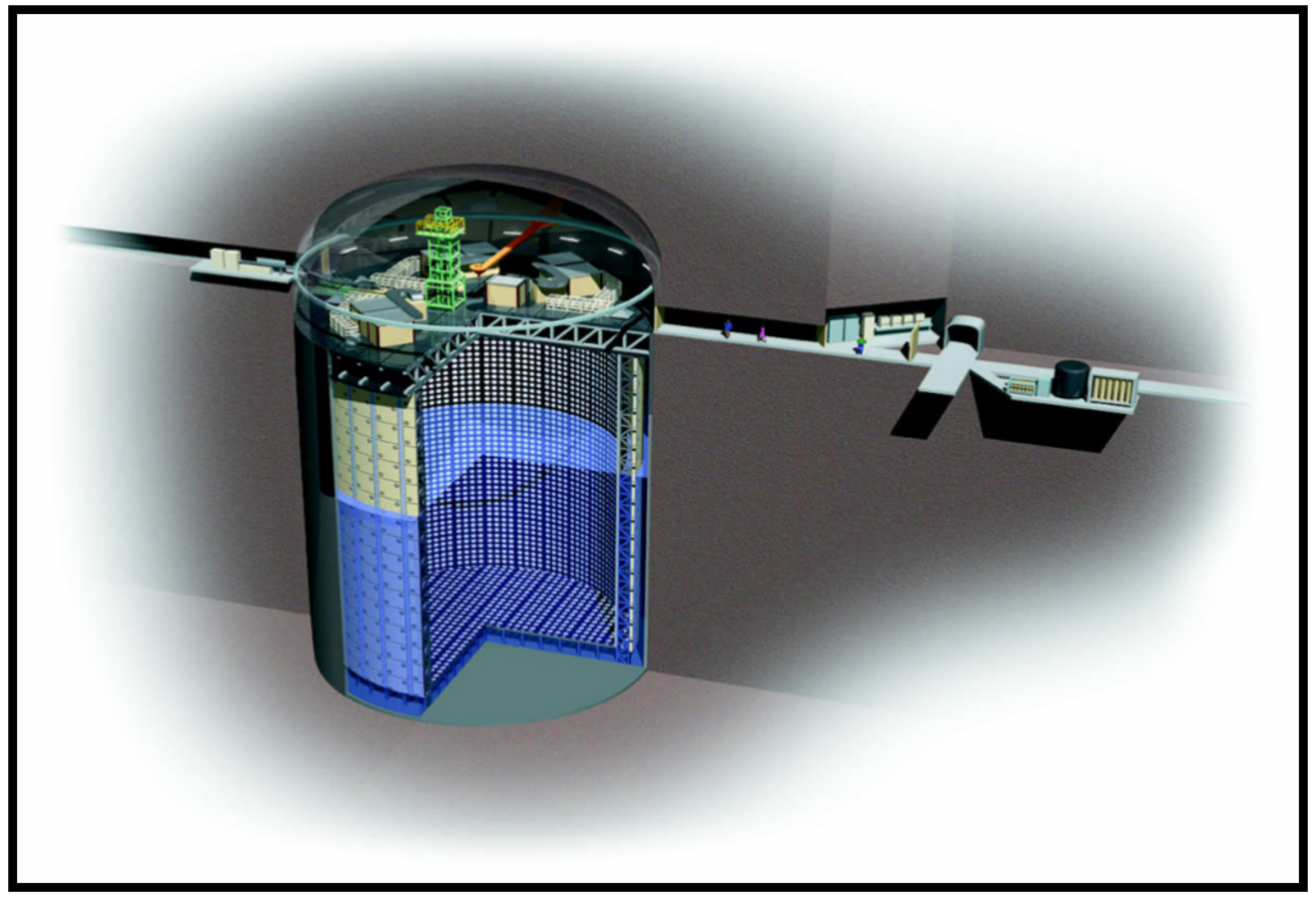
- Improved uncertainty of $\pi^{\pm}$ vs π^{0} production
- New parameters for resonant pion decay

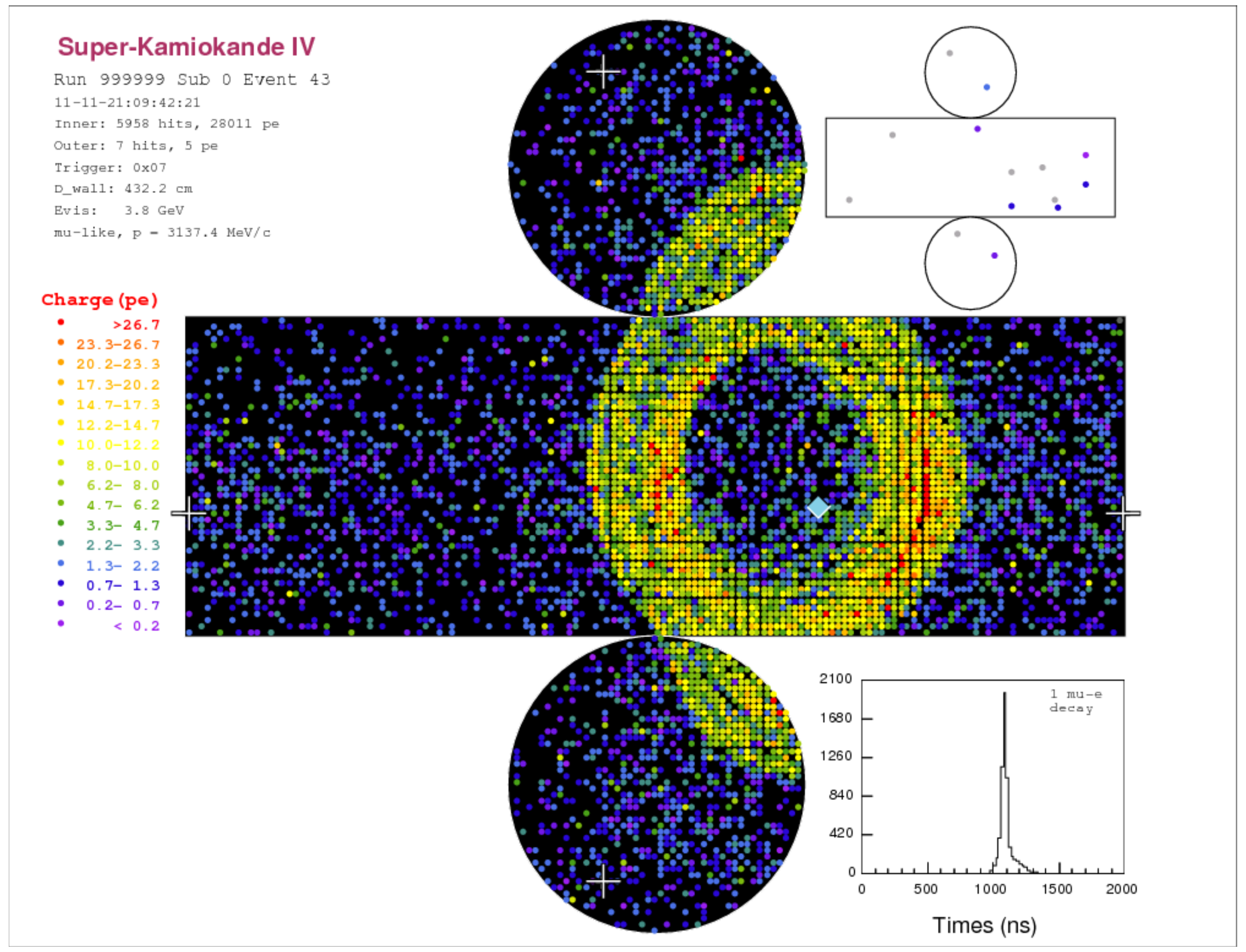
FSI Improvements:

- New nucleon FSI parameter

Far Detector

- Located **295 km** from the proton target
- SK uses **Cherenkov radiation** to detect particles created during neutrino interactions
- SK selections are created using characteristic **rings** left behind by the **Cherenkov cone**
- Cherenkov radiation can be detected by **Photomultiplier Tubes** (PMTs) located around the edge of the detector
- Selections are split broadly in **"μ-like"** and **"e-like"** and by **beam production mode** (ν and $\bar{\nu}$ mode)
- Recently **gadolinium** has been added for increased $\nu/\bar{\nu}$ discrimination!



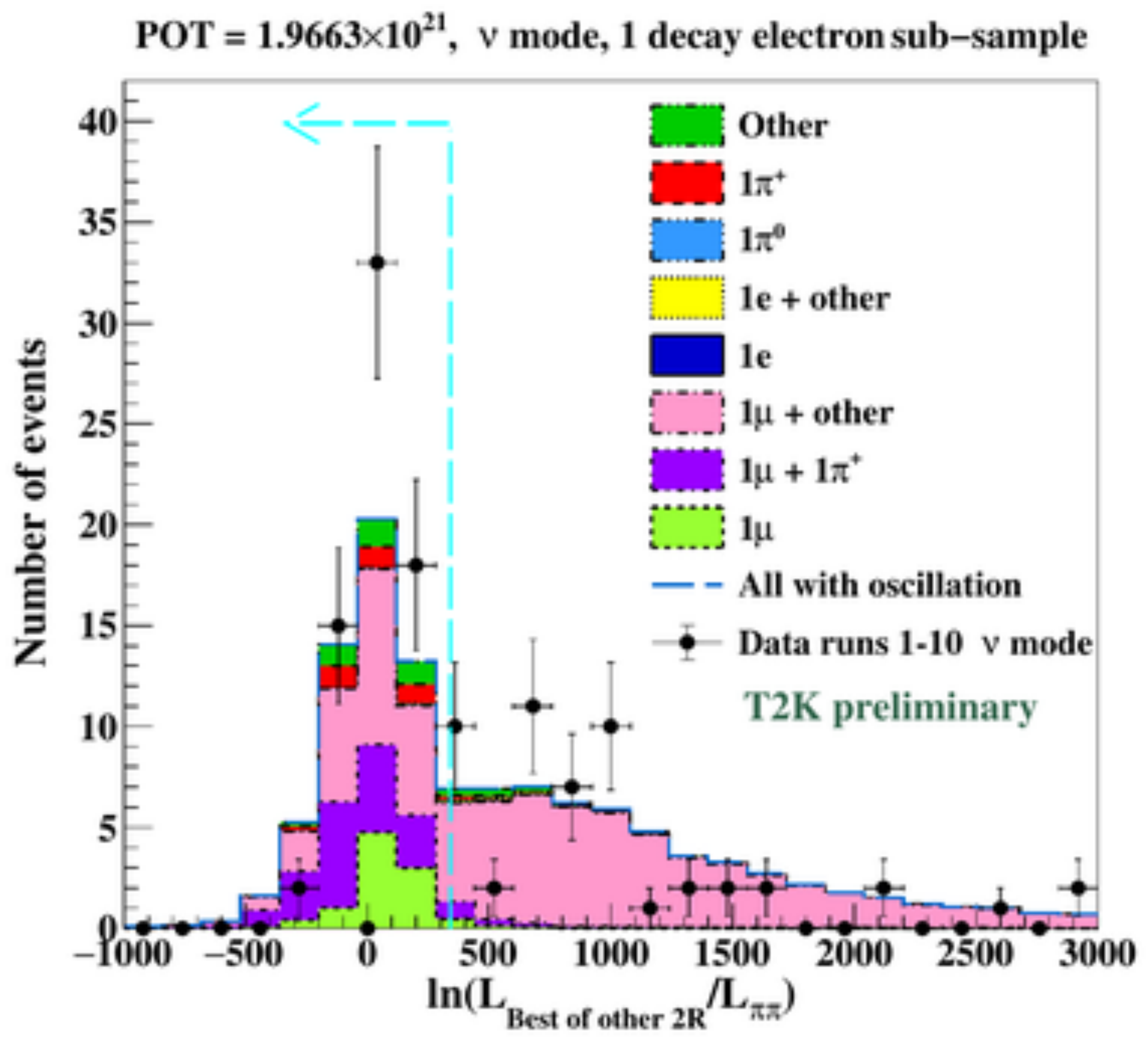


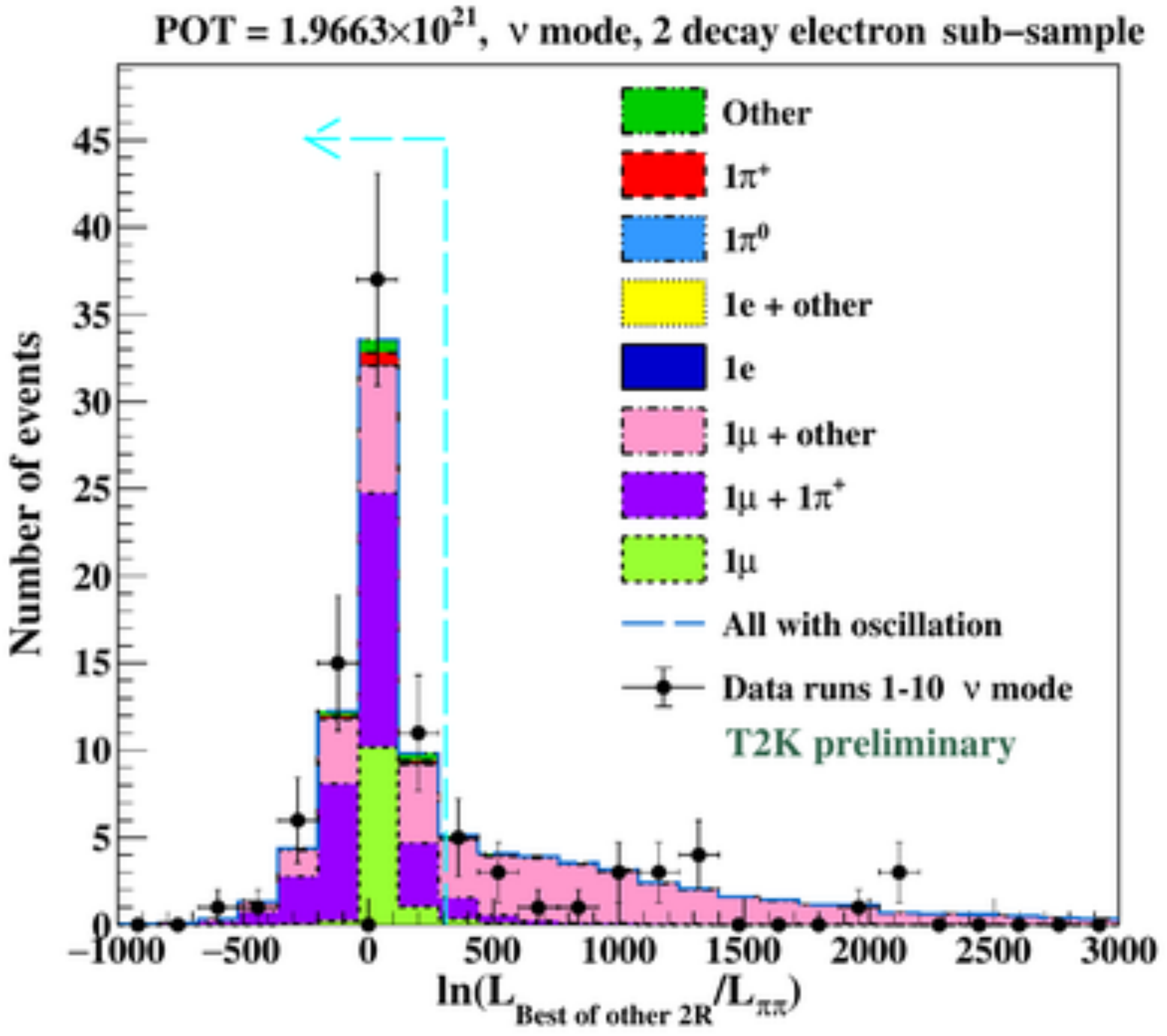
Far Detector Selections

- 6 selections are now used:
  - ν and $\bar{\nu}$ mode events with **1 e-like ring** in the final state
  - ν and $\bar{\nu}$ mode events with **1 μ-like ring** in the final state
  - ν mode events with 1 **e-like ring** and **1 Michel electron** in final state

NEW FOR THIS ANALYSIS

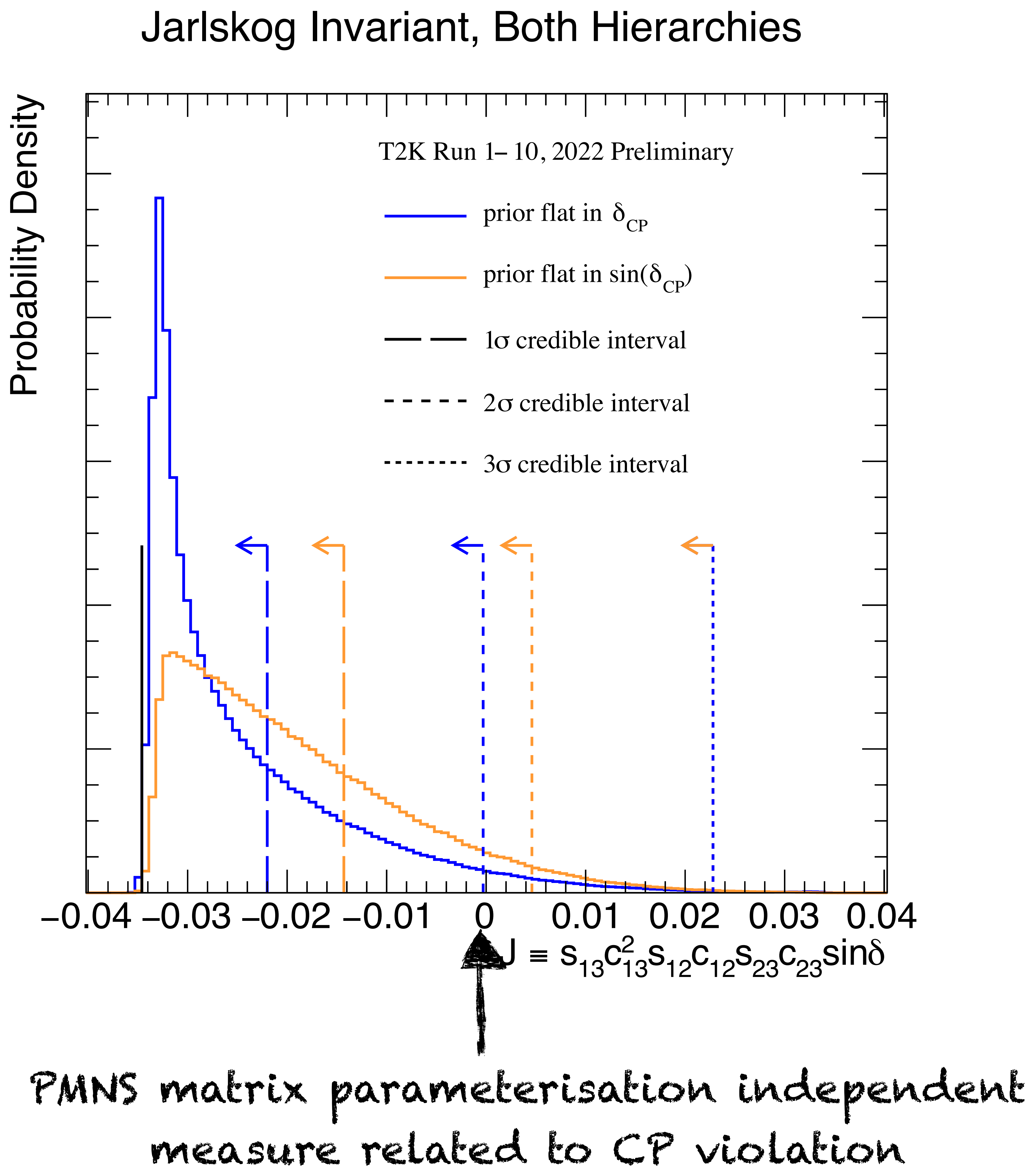
  - ν mode events with 1 **μ-like ring** and either **2 Michel electrons** or **1 Michel electron** and $1\pi^+$ in the final state





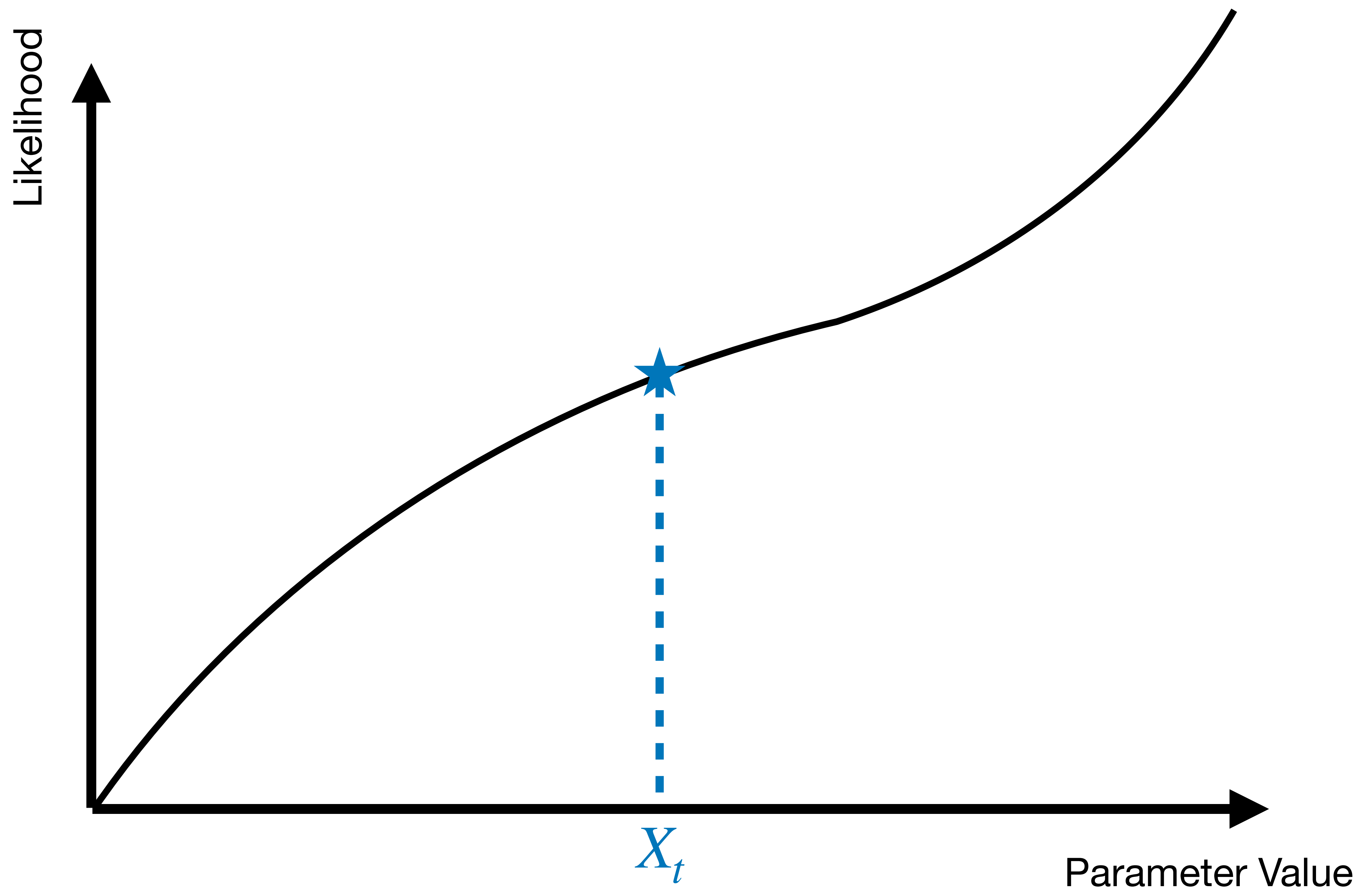
Jarlskog Invariant

- Another useful metric for measuring CP violation is the **Jarlskog invariant**
- This is the actual term in the $\nu_\mu \rightarrow \nu_e$ oscillation probability that differs between ν and $\bar{\nu}$ for non-0/$k\pi$ values of δ_{cp}
- As it's proportional to $\sin(\delta_{cp})$ $J_{cp} = 0 \Rightarrow$ CP violation



Demonstration of MCMC

Start position for each step



1. At step t location in parameter space is given by X_t
2. Pick a new point, Y, from a Gaussian centred on X_t
3. Evaluate the ratio of likelihoods $\alpha = \min\left[1, \mathscr{L}(Y)/\mathscr{L}(X)\right]$
4. Generate a random number, $u \sim U(0,1)$
5. If $\alpha > u : X_{t+1} = Y$
   else : $X_{t+1} = X_t$

Demonstration of MCMC

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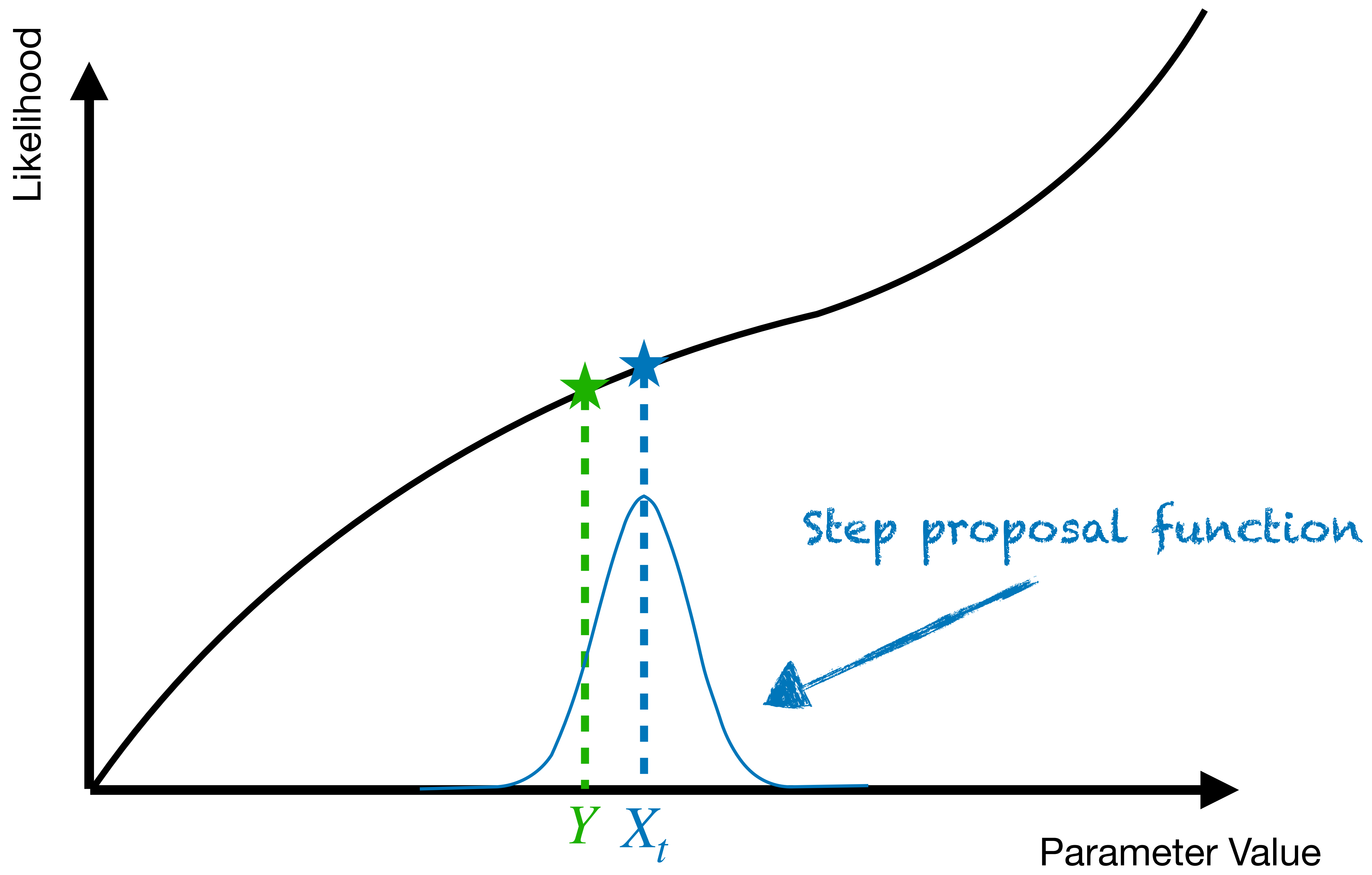
Step Proposal



At step t location in parameter space is given by X_t

Pick a new point, Y, from a Gaussian centred on X_t

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$\alpha = \min\left[1,\ \mathscr{L}(Y)/\mathscr{L}(X)\right]$

Generate a random number, $u \sim U(0,1)$

If $\alpha > u : X_{t+1} = Y$
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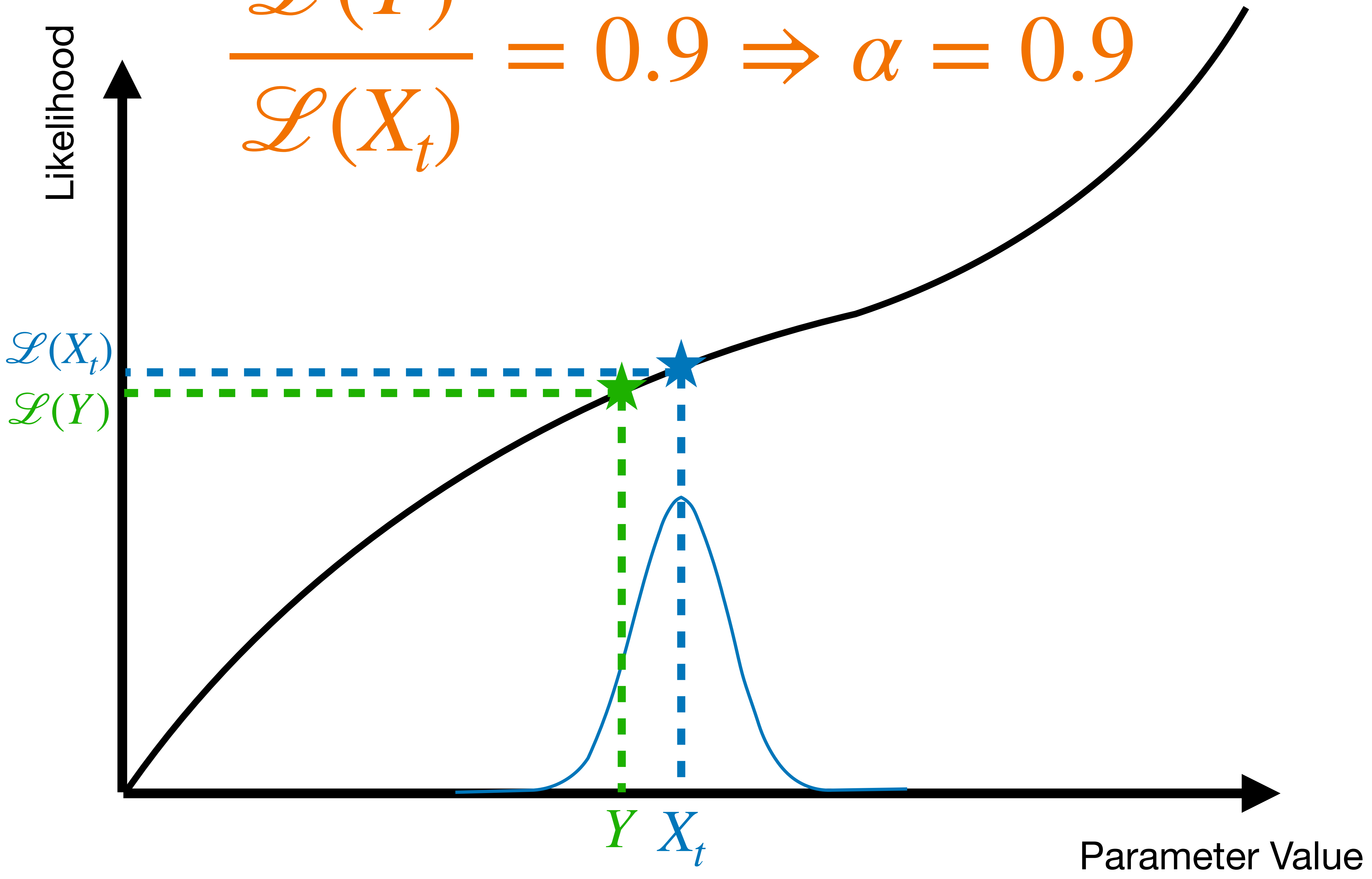
Demonstration of MCMC

Evaluate Likelihoods

$$\frac{\mathcal{L}(Y)}{\mathcal{L}(X_t)} = 0.9 \Rightarrow \alpha = 0.9$$



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If $\alpha > u : X_{t+1} = Y$
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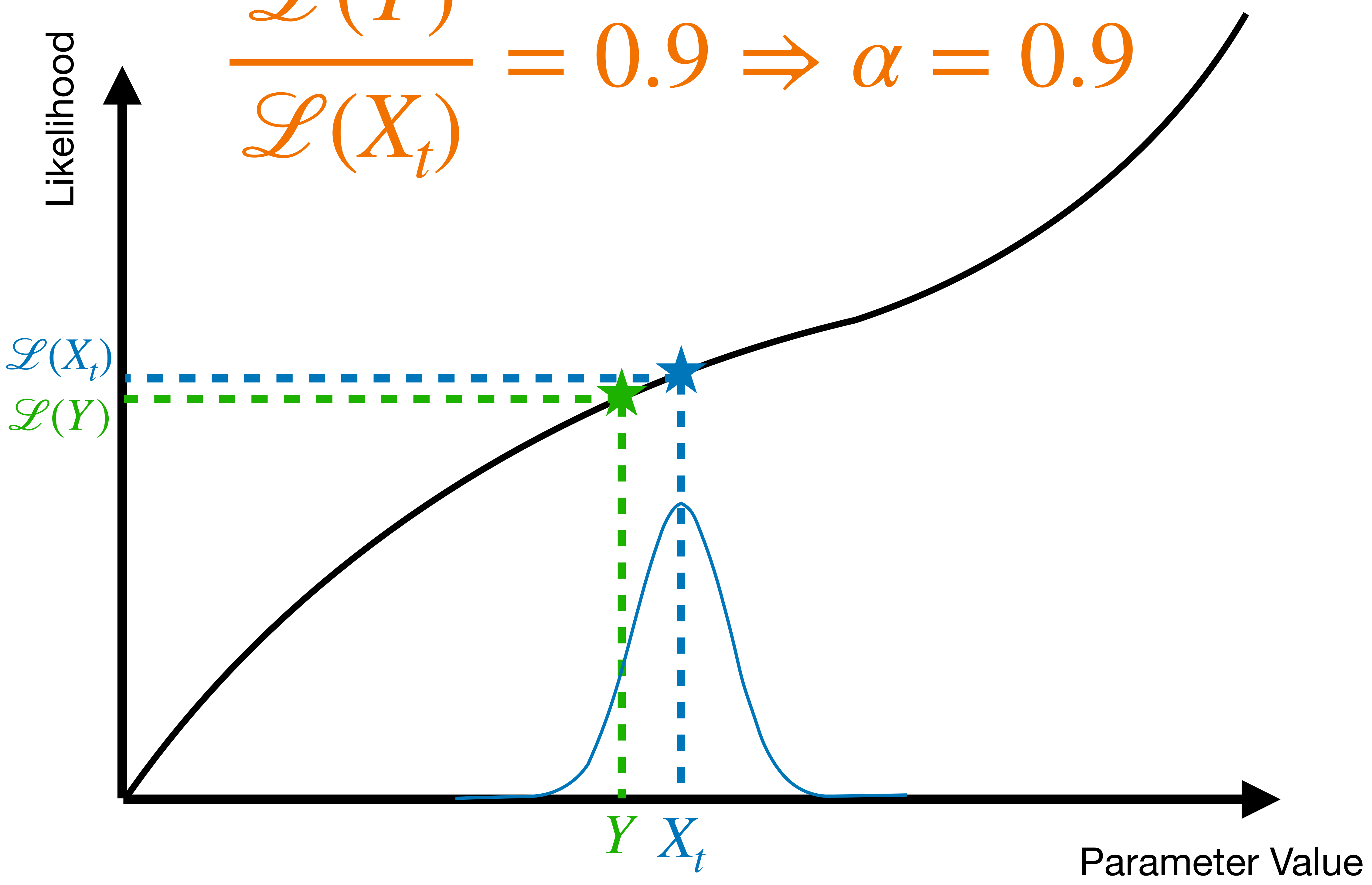
Demonstration of MCMC

Generate Acceptance Probability

$$\frac{\mathscr{L}(Y)}{\mathscr{L}(X_t)} = 0.9 \Rightarrow \alpha = 0.9$$



$$u = 0.4 \Rightarrow u < \alpha$$

At step t location in parameter space is given by X_t

Pick a new point, Y, from a Gaussian centred on X_t

Evaluate the ratio of likelihoods
$\alpha = \min\left[1, \mathscr{L}(Y)/\mathscr{L}(X)\right]$

Generate a random number, $u \sim U(0,1)$

If $\alpha > u : X_{t+1} = Y$
else : $X_{t+1} = X_t$

Demonstration of MCMC

Accept/Reject Step and Repeat!