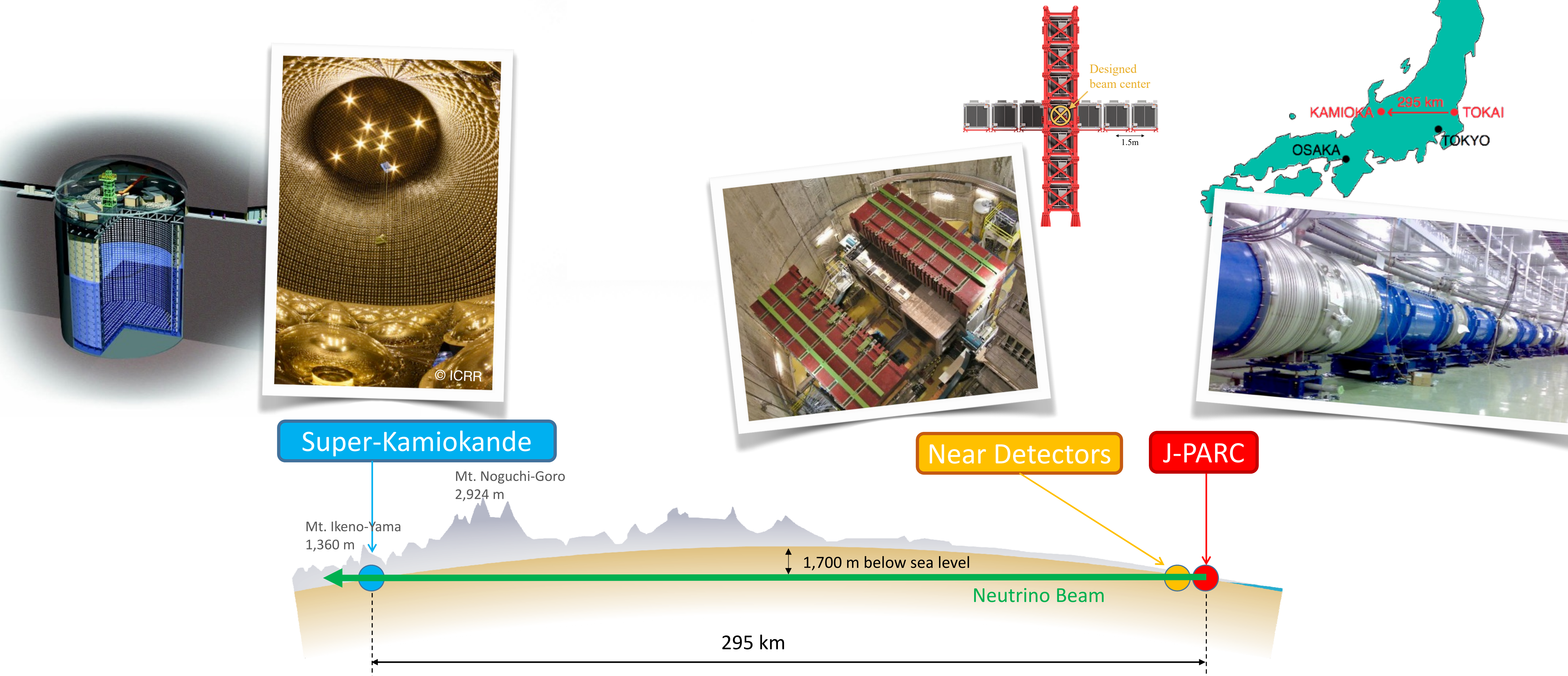
T2K

results on long-baseline oscillations

Neutrino Oscillation Workshop
2022-09-05

Lukas Berns (Tohoku U)
for the T2K Collaboration

T2K experiment



$\nu_\tau, \nu_\tau, \nu_\tau, \nu_\tau, \nu_e, \nu_\mu, \nu_\mu \longleftarrow \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu$

- Study oscillation of neutrino beam from J-PARC accelerator
- ~500 collaborators from institutions in 14 countries

ν-oscillation

(interaction) (propagation)

For neutrinos flavor basis ≠ Hamiltonian basis.

→ Flavor ($\nu_e \mid \nu_\mu \mid \nu_\tau$) oscillates over $L \times \Delta m^2 / E$,

amplitude controlled by (PMNS) mixing matrix U:

atmospheric — reactor — solar

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

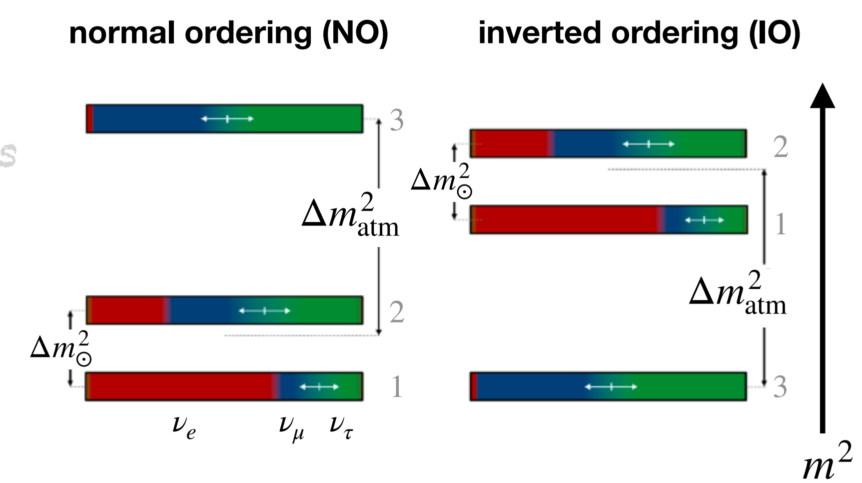
$c_{ij} \equiv \cos\theta_{ij}$
$s_{ij} \equiv \sin\theta_{ij}$

Open questions:

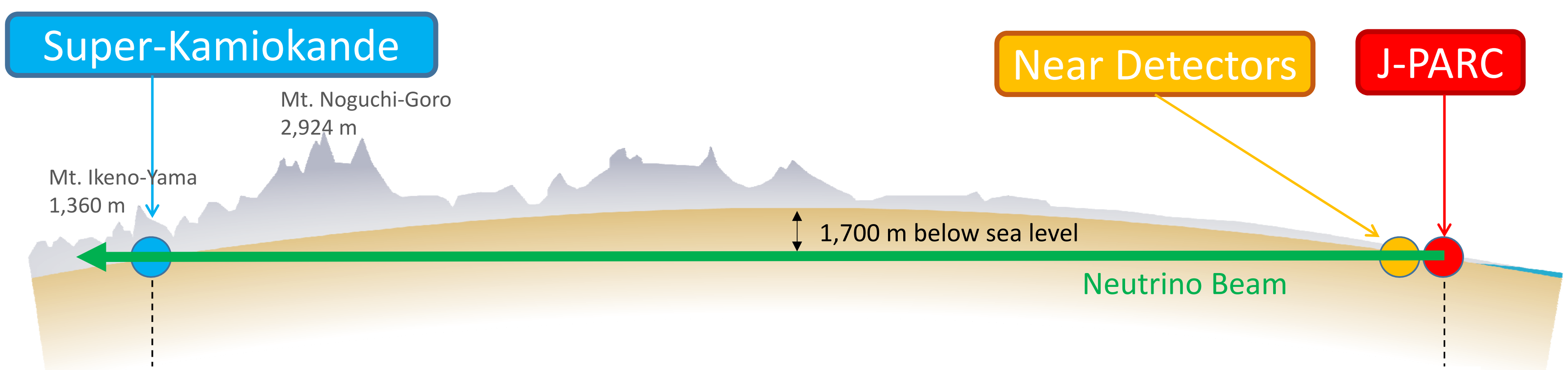
- value of δ_{CP} → if $\sin\delta_{\mathrm{CP}} \neq 0$, CP violation
- sign of Δm^2_{32} (mass ordering)
- is θ_{23} maximal? octant? (i.e. $\theta_{23} < \frac{\pi}{4}$ or $\theta_{23} > \frac{\pi}{4}$)

important params for cosmology (leptogenesis...) and 0ν2β searches

flavor symmetries?



For δ_{CP},MO look for $\nu/\bar{\nu}$ difference of $\nu_\mu \to \nu_e$ appearance



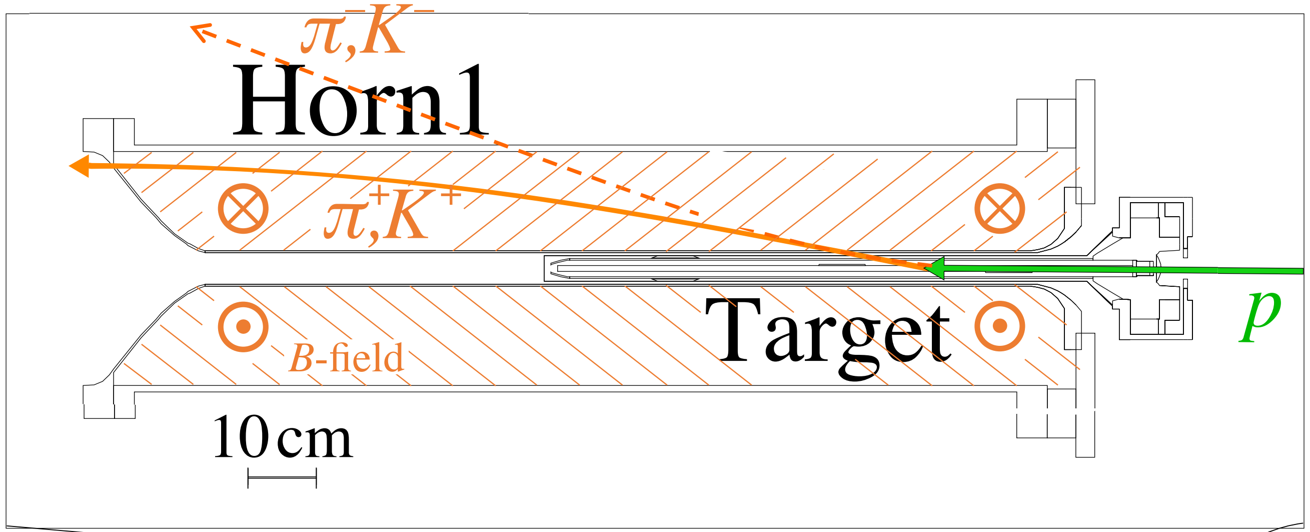
note: wrong-sign ν_μ and intrinsic ν_e backgrounds neglected for illustration

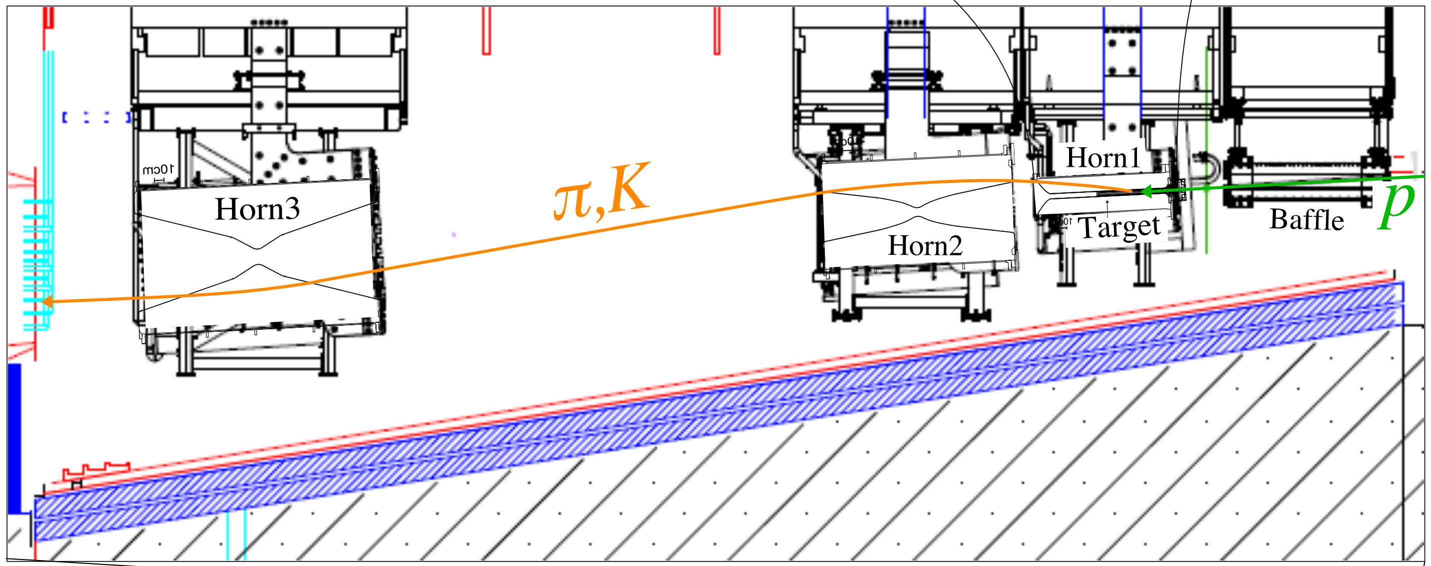
$\nu_\tau, \nu_\tau, \nu_\tau, \boxed{\nu_e,}\ \nu_e, \nu_\mu, \nu_\mu$ ← **Neutrino mode** ← $\nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu$

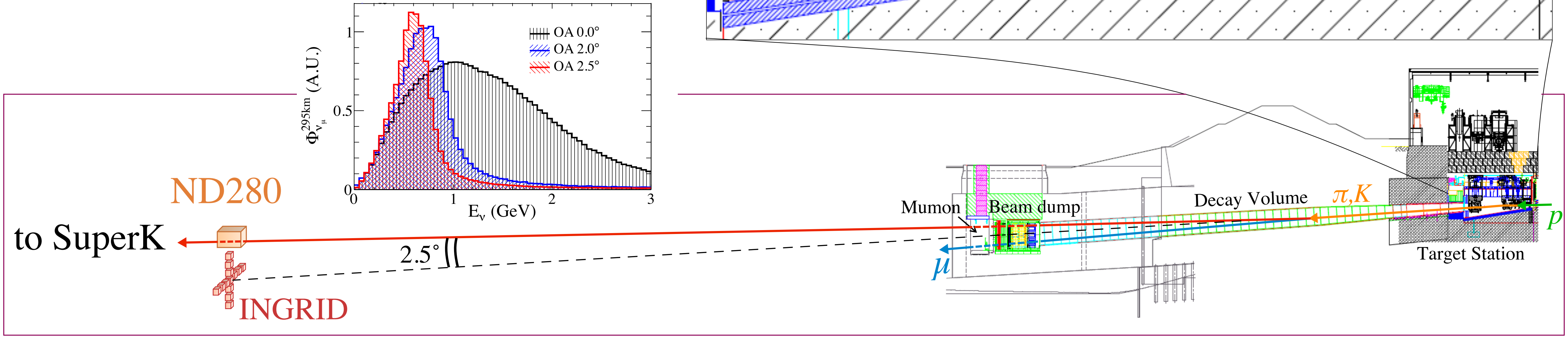
$\bar{\nu}_\tau, \bar{\nu}_\tau, \bar{\nu}_\tau, \boxed{\bar{\nu}_\tau,}\ \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\mu$ ← **Anti-neutrino mode** ← $\bar{\nu}_\mu, \bar{\nu}_\mu, \bar{\nu}_\mu, \bar{\nu}_\mu, \bar{\nu}_\mu, \bar{\nu}_\mu, \bar{\nu}_\mu$

Neutrino beam

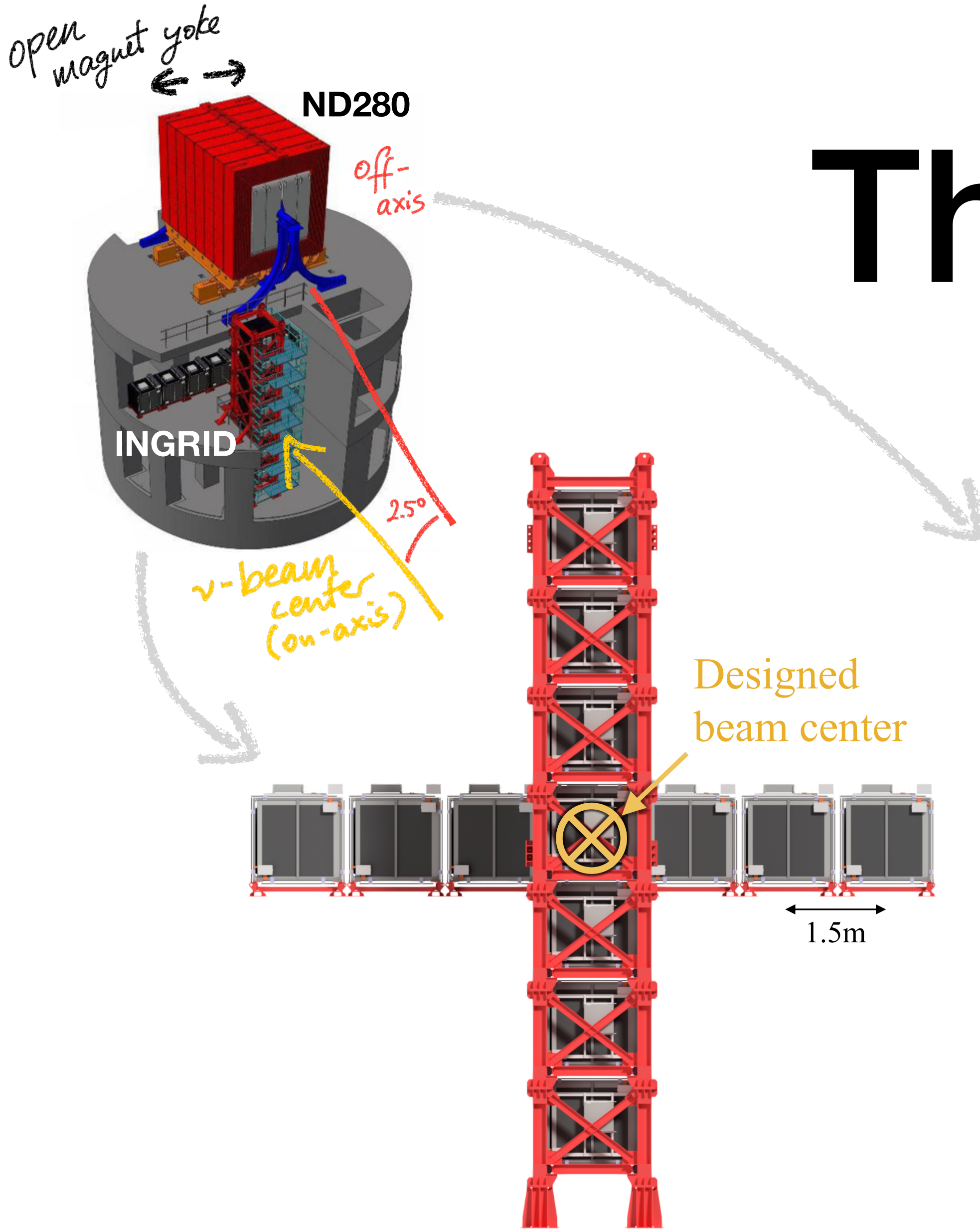
- 30 GeV protons produce π,K in 90 cm graphite target
- Three magnetic horns selectively focus π^+,K^+ or π^-,K^- to produce ν_μ or $\bar{\nu}_\mu$ beam (decay in-flight).
- Narrowband beam thanks to off-axis technique.

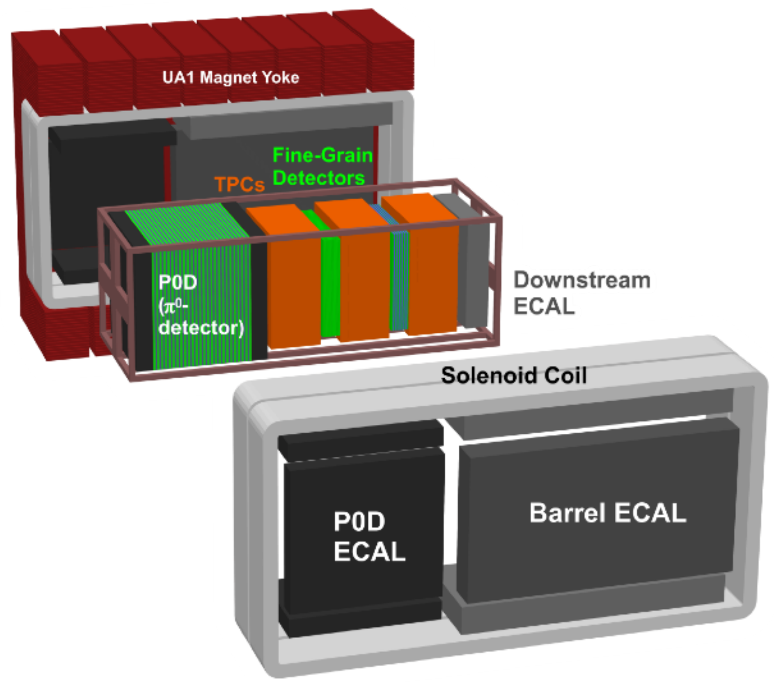


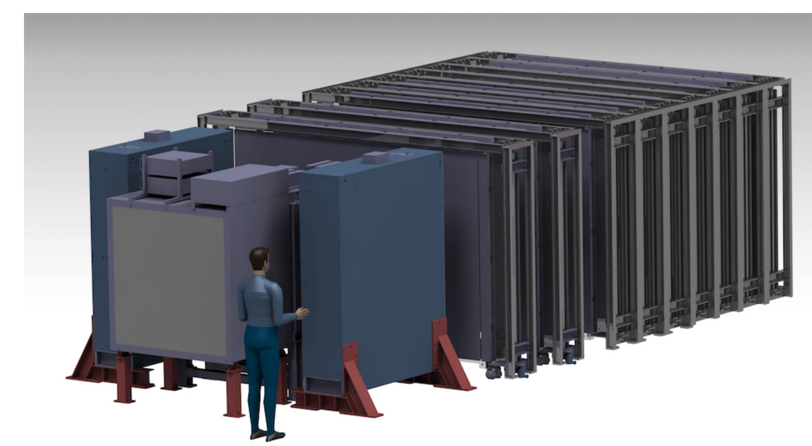




The near detectors







INGRID on-axis detector

- Iron-scintillator sandwich detectors monitor neutrino beam **direction** and intensity

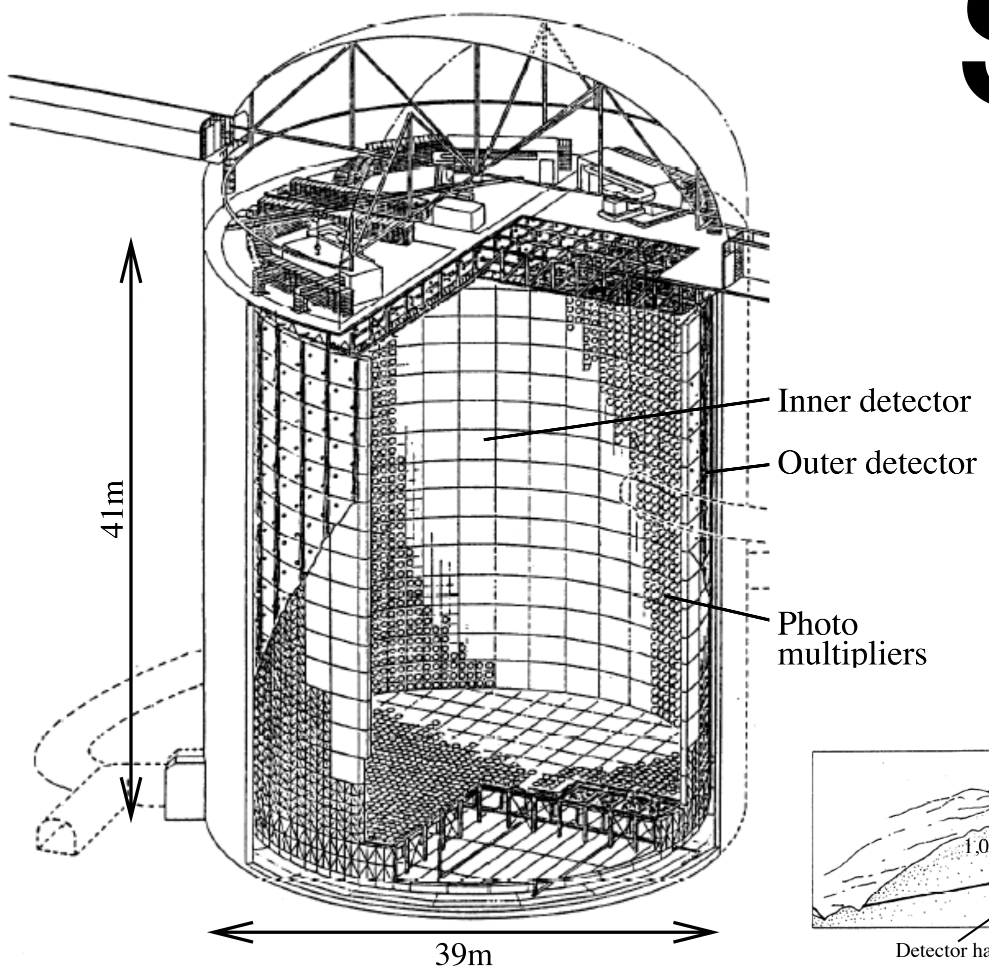
ND280 off-axis detector

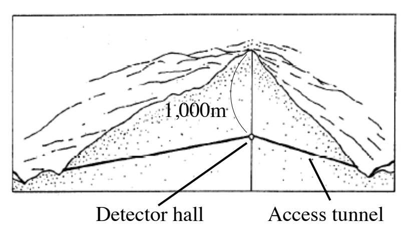
- Active **scintillator** + passive **water** targets
- Tracking with **time projection chambers**
- **Magnetized** for charge and momentum measurement

WAGASCI + BabyMIND

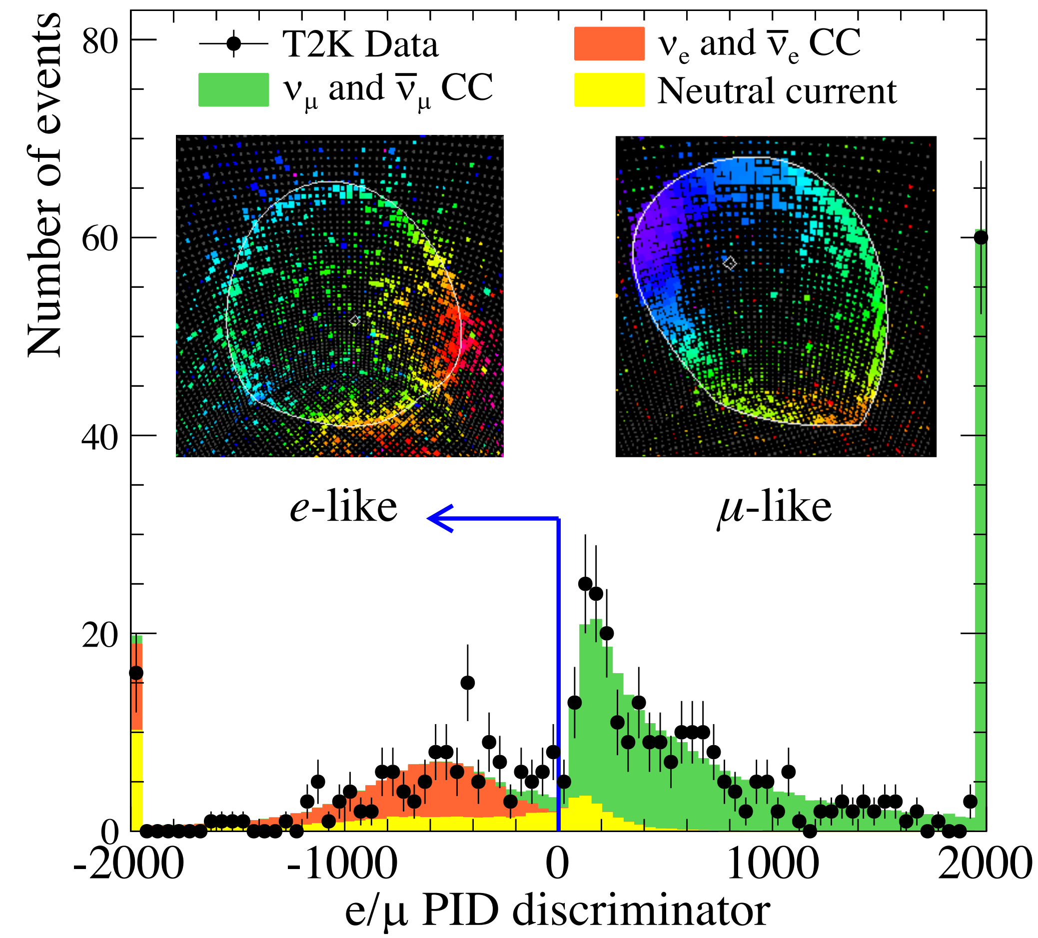
- Latest addition at intermediate **1.5º** off-axis flux
- **Water** target with cuboid lattice scintillators for high angle acceptance
- Compact **magnetized** iron muon range detector
- First xsec meas. published: PTEP, ptab014 (2021)

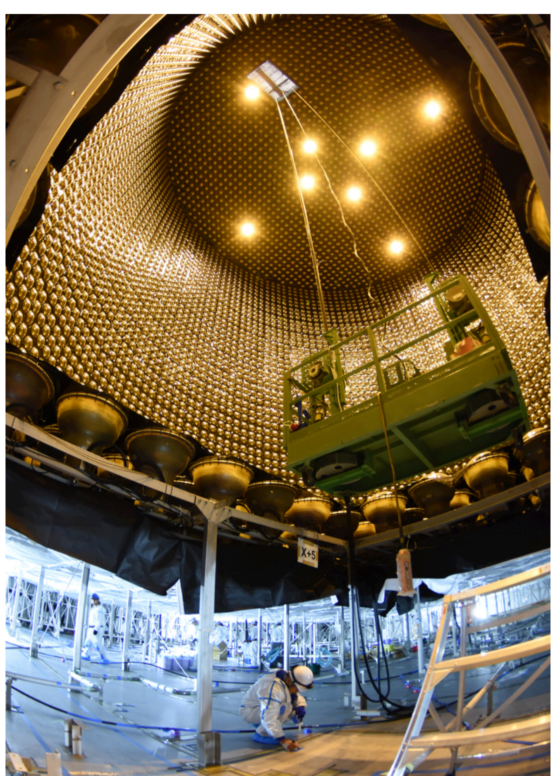
SuperK – the far detector





Adapted from Nature 580, 339-344 (2020)

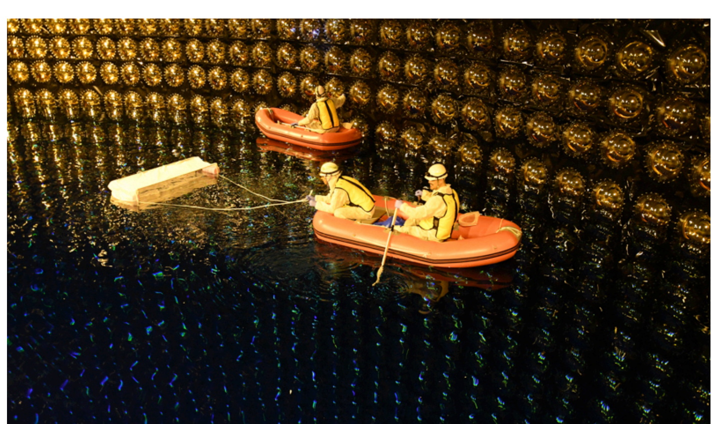




50 kt pure water
~11,000 20 inch PMTs

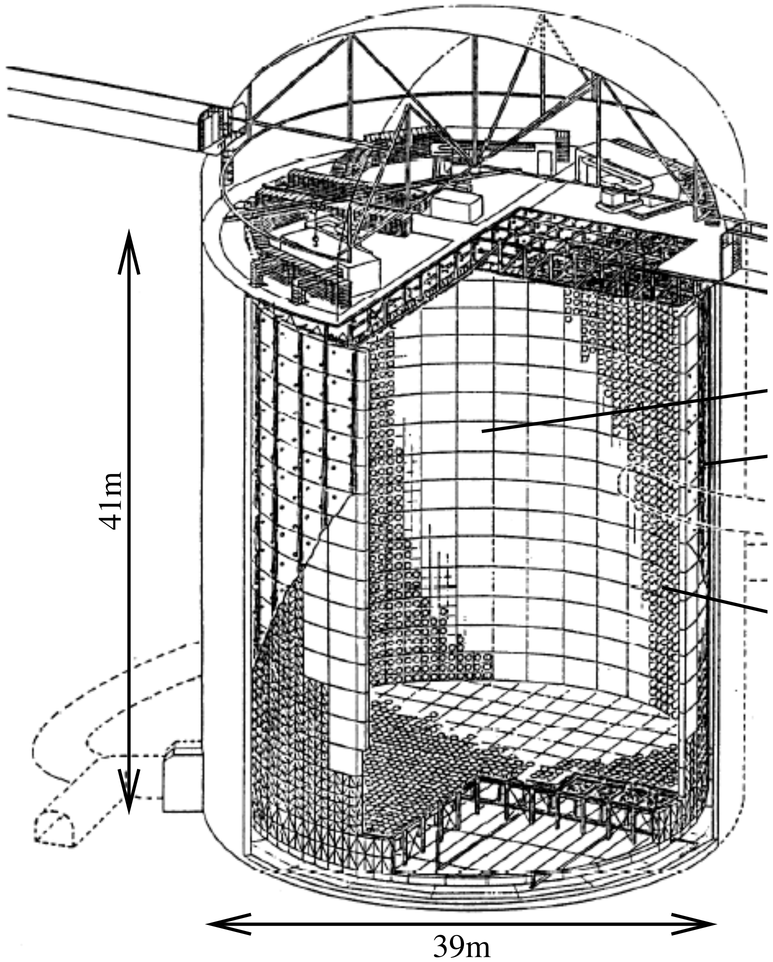
Now loaded with Gadolinium for improved neutron tagging!

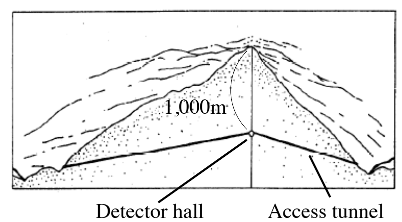
Photos: "Super Kamiokande refurbishment" ICRR (2018)

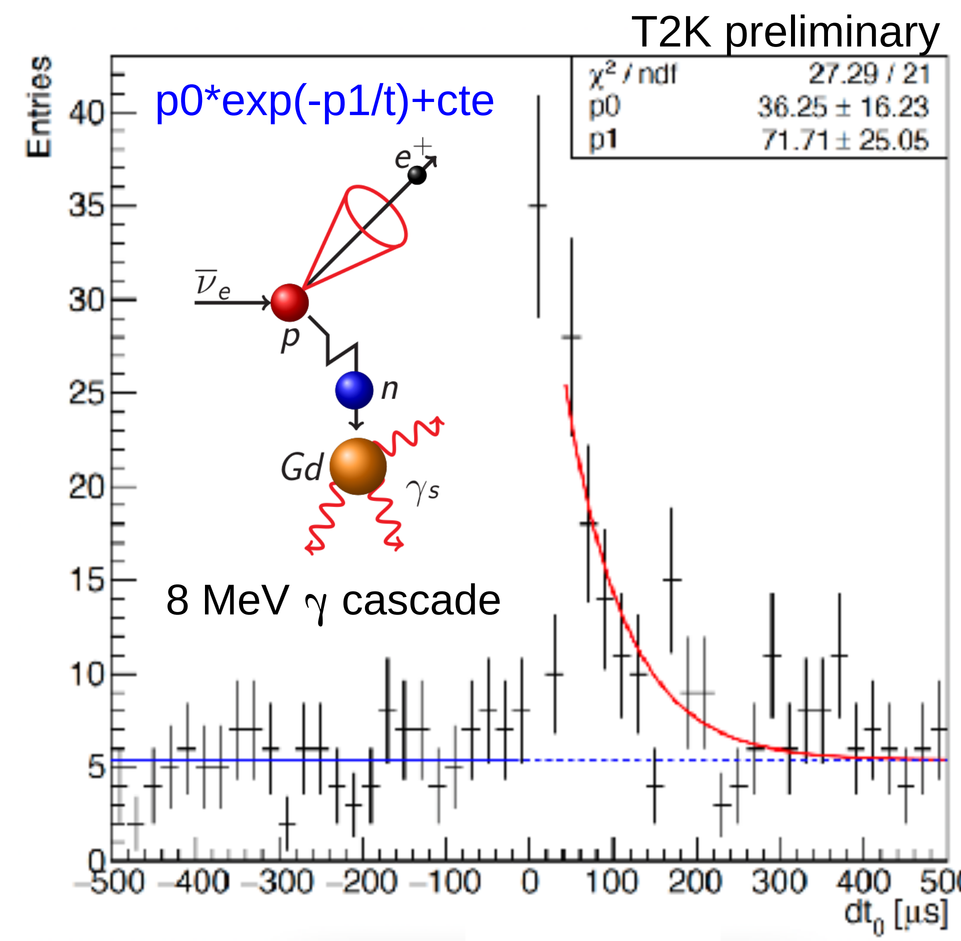


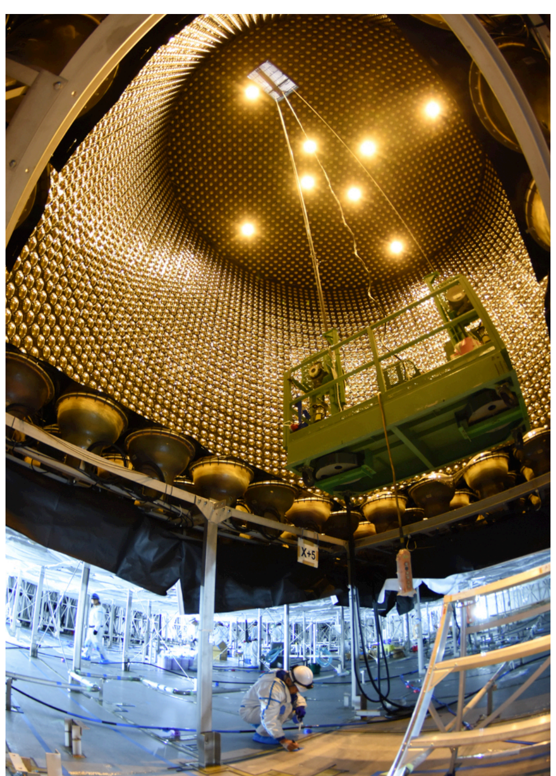
- Good μ/e PID from ring shape
- Reconstruct neutrino energy from lepton momentum and angle w.r.t. neutrino beam
- Not magnetized, so the beam $\nu/\bar{\nu}$-modes are important. ND280 further constrains the wrong-sign background.

SuperK – the far detector









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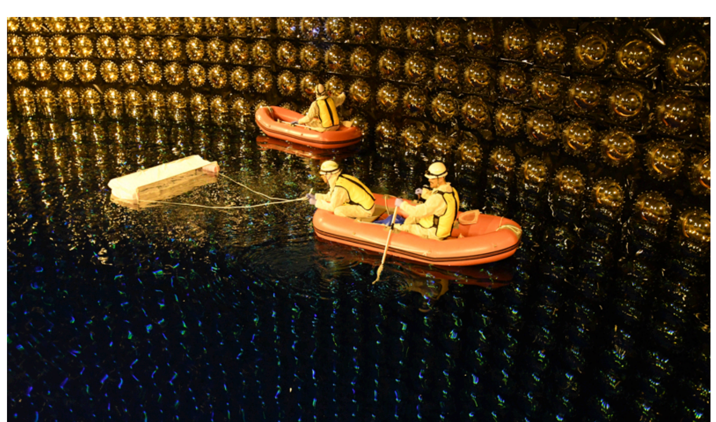


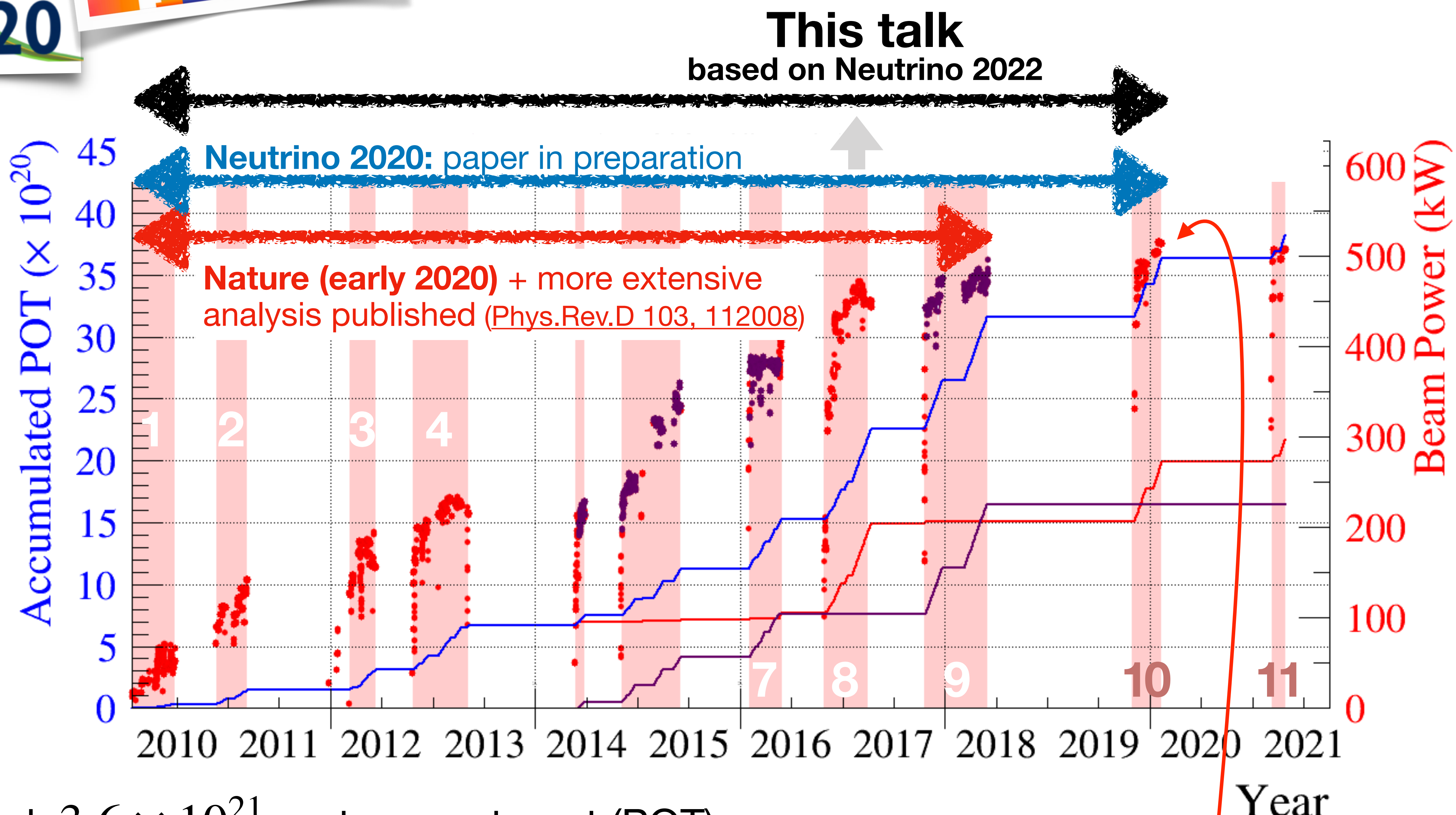
After addition of Gd…

Exponential decrease of #events *after* beam timing consistent with Gd capture time constant (115 μs)

Monday morning, Session I plenary,
Yasuo Takeuchi,
"SK oscillation physics (atmospheric, solar, Gd)"

Dataset

same data,
many analysis improvements!



Analyzed: 3.6×10^{21} protons on target (POT)

ν-mode : $\bar{\nu}$-mode $\sim 6:5$

Total Accumulated POT for Physics
ν-Mode Accumulated POT for Physics
ν̄-Mode Accumulated POT for Physics
ν-Mode Beam Power
ν̄-Mode Beam Power

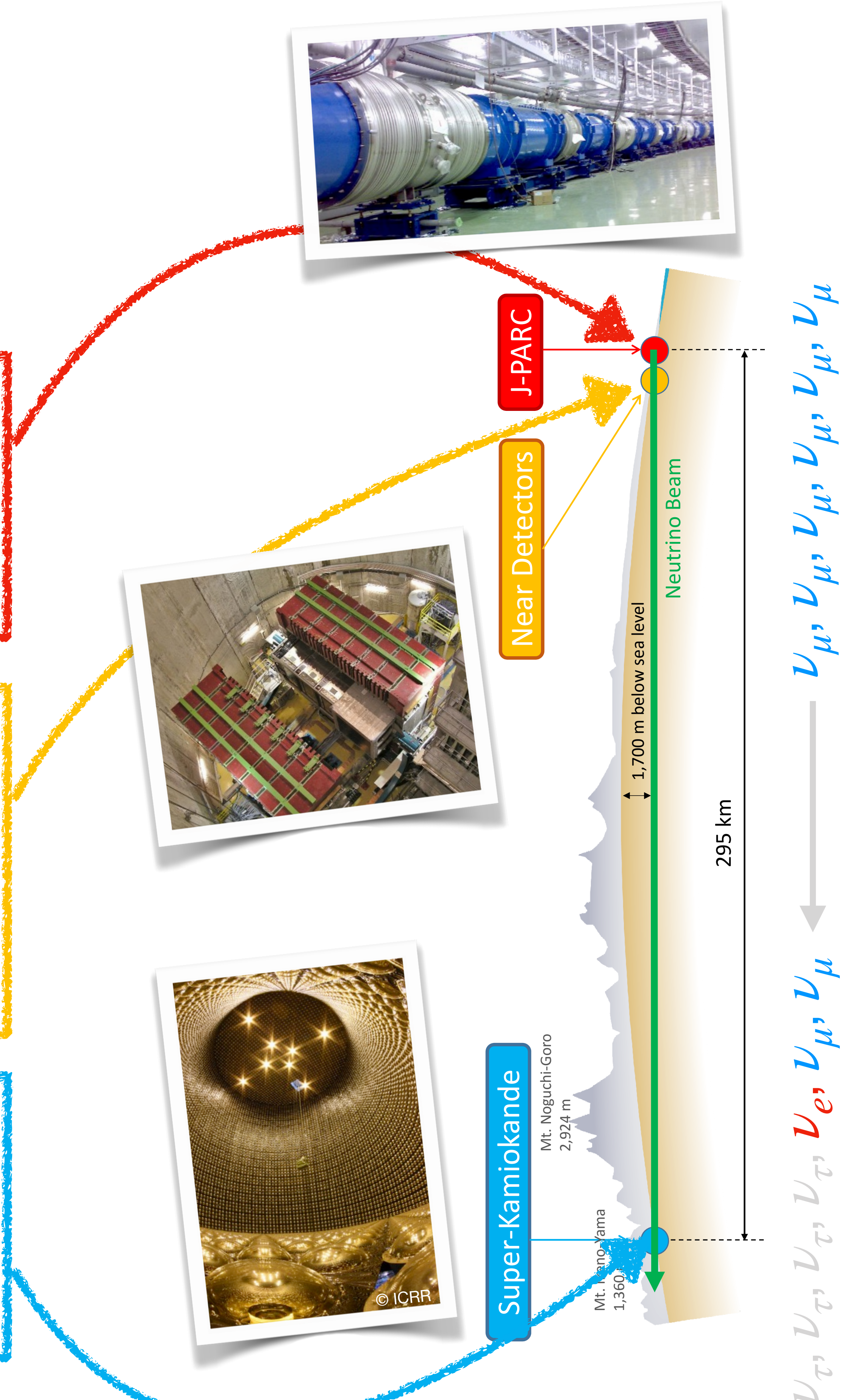
515 kW operation!
Additional run 11 data taken early 2021 (with Gd at SK), not used in this analysis

Analysis strategy

- Beam monitors + hadron production experiments
  → **neutrino flux**

- ND280 measurements
  + interaction model
  + external constraints
  → **unoscillated flux × xsec**

- 6 samples at SK
  → ν_μ **disappearance +**
  ν_e **appearance**



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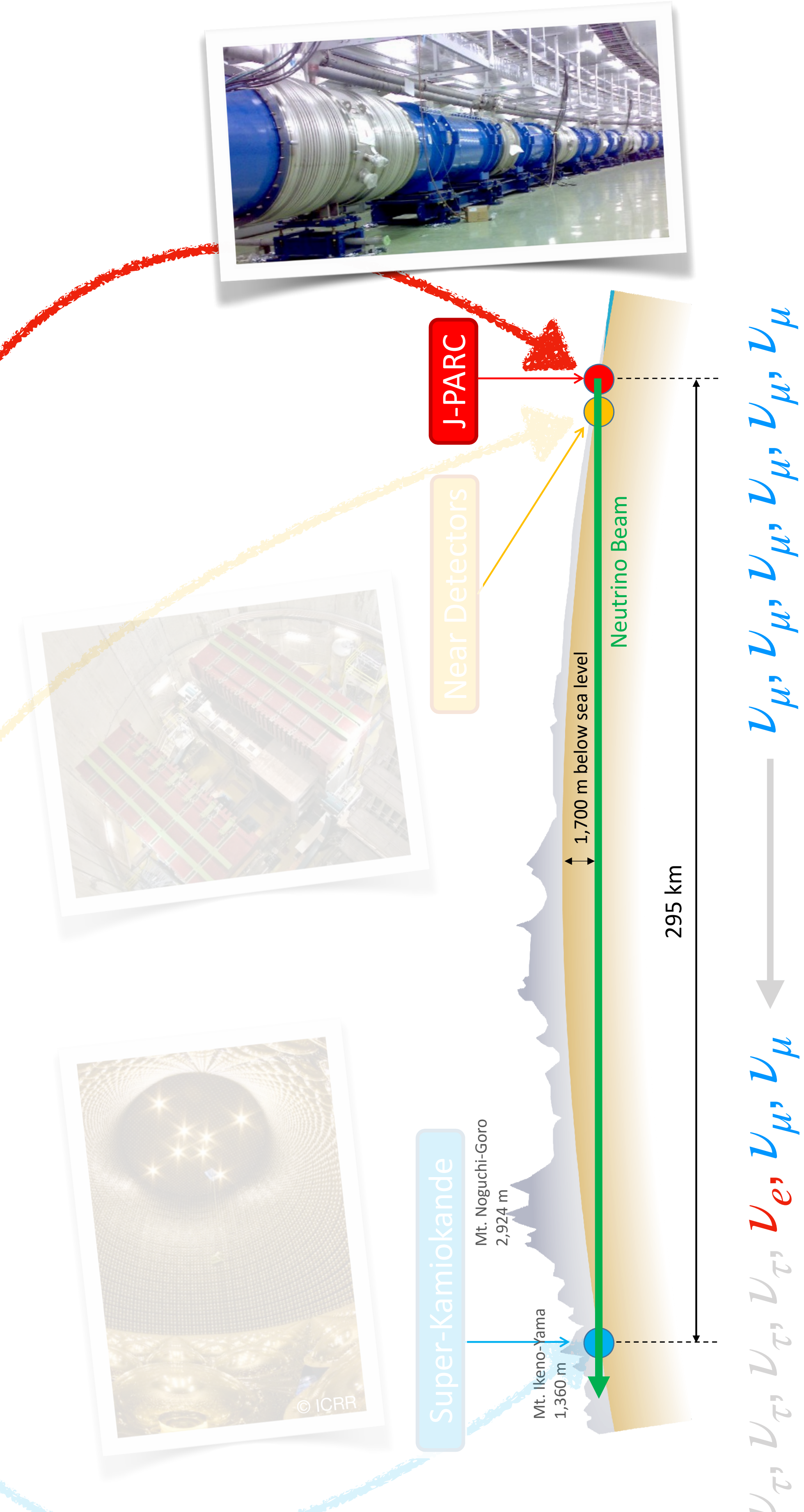

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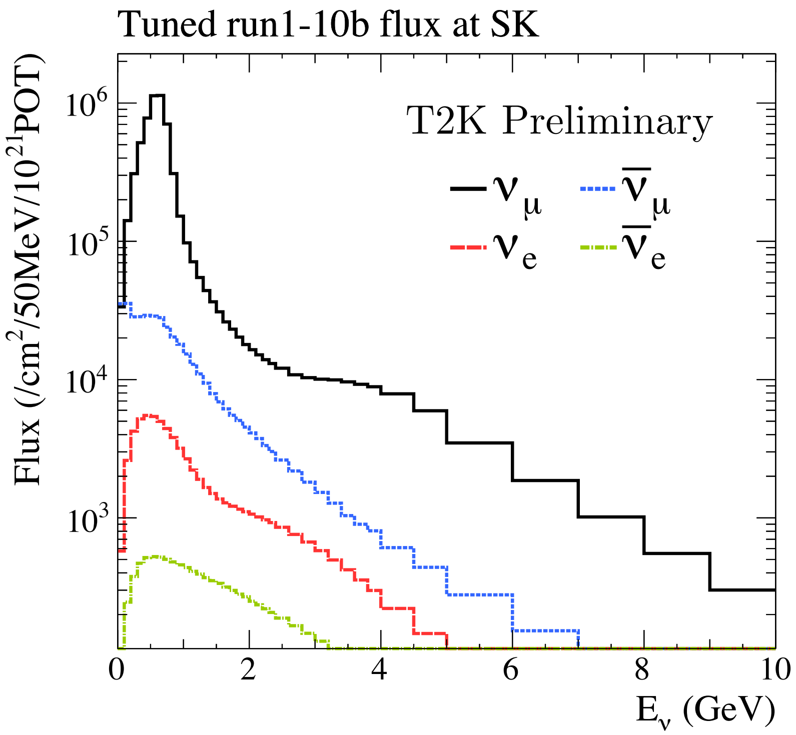
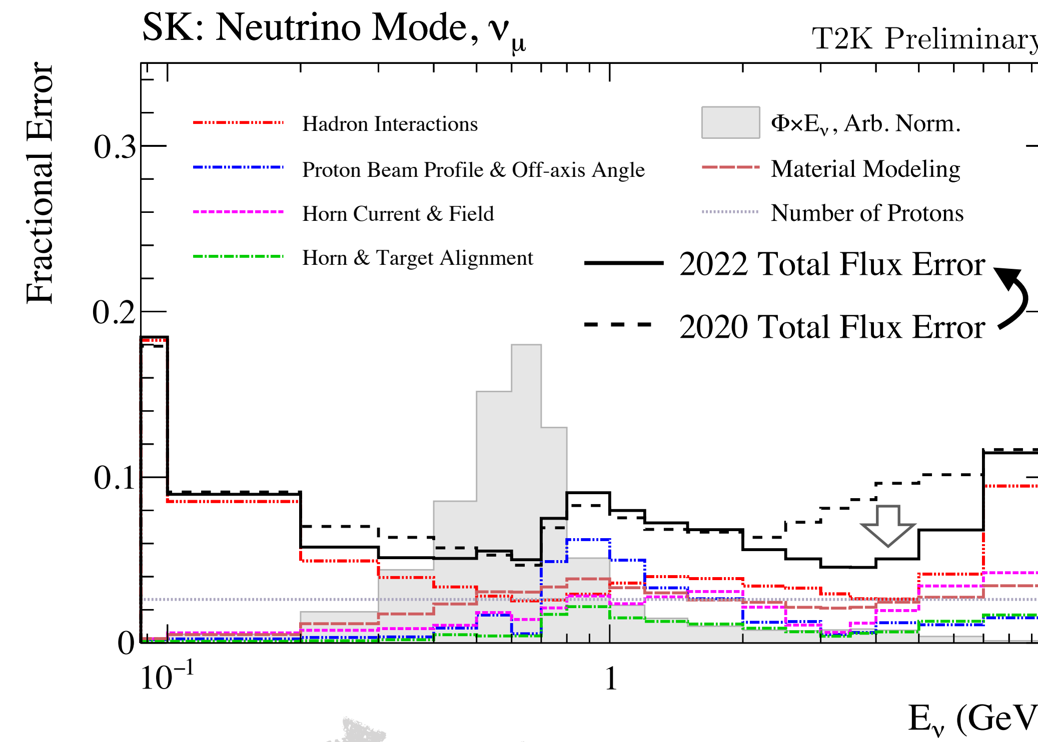
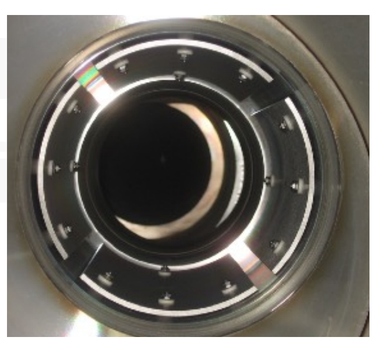




Beam line modeling



← Beam monitors

More realistic modeling of cooling water in horns slightly increased uncertainty at flux peak

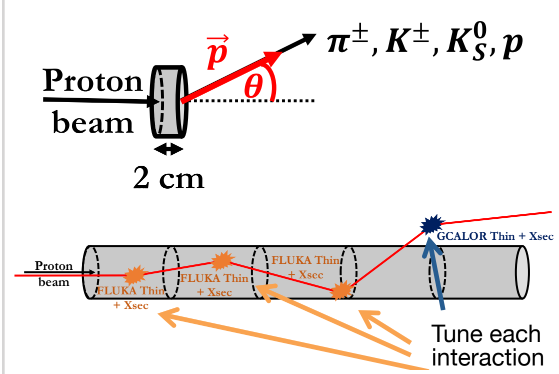
Hadron production experiments

Hadron interaction uncertainty at high-E reduced thanks to higher-statistics **NA61** measurement that includes **kaon** yields from **replica** of T2K target.

K,p in previous analysis

Thin target data

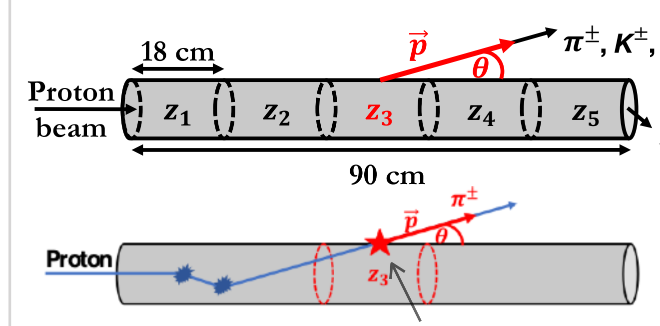
Mainly Eur. Phys. J. C (2016) 76:84



K,p in this analysis

Replica target data

Eur. Phys. J. C (2019) 79:100



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- Beam m
  productio
  → neutri

- ND280 m
  + interac
  + externa
  → unosc

- 6 sample
  → ν_μ dis
  ν_e app

New NA61 measurements are being performed for further reduction in the future!

Photos from this summer
(by Y. Nagai, Eric D. Zimmerman, NA61/SHINE)

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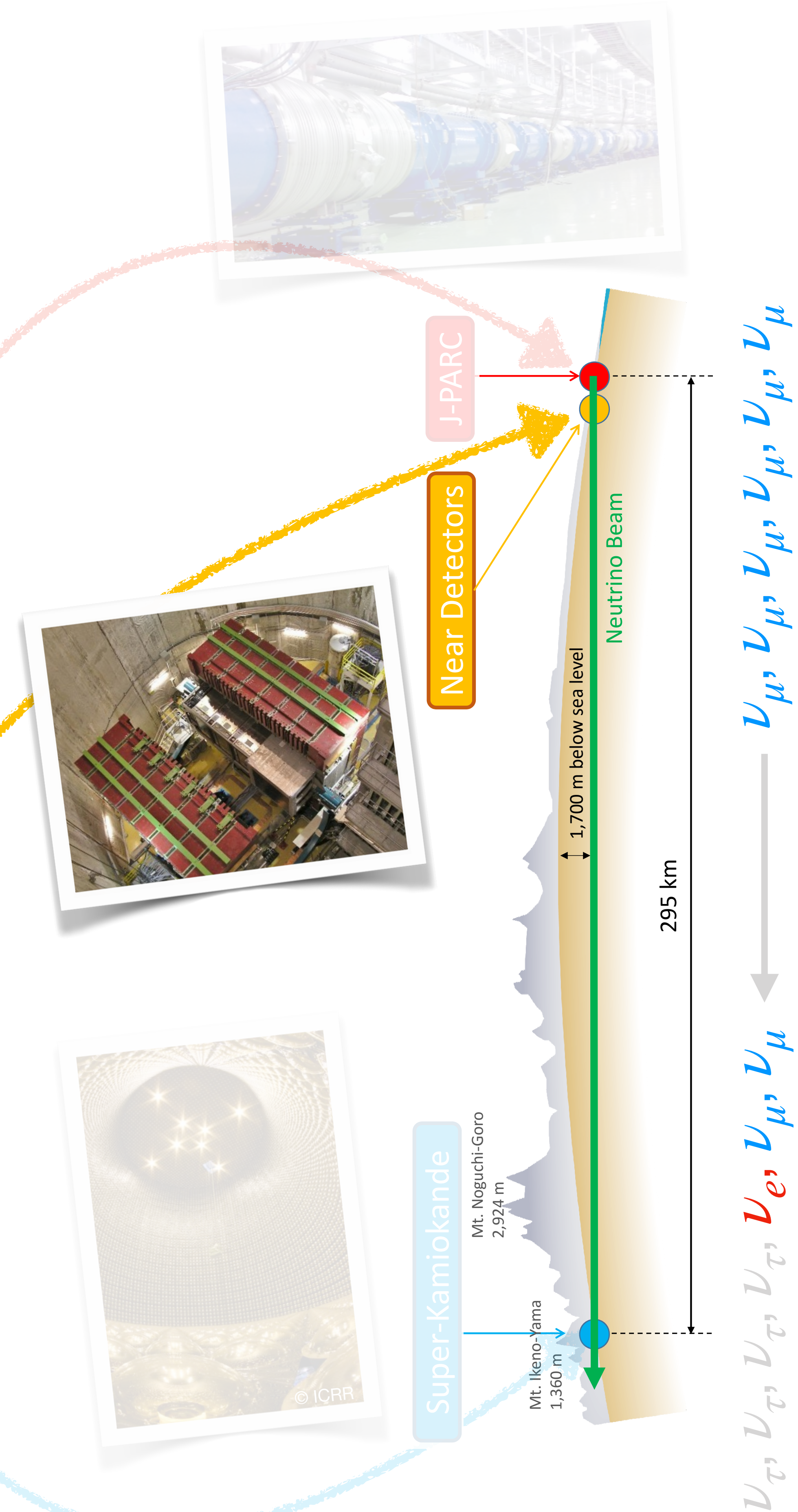
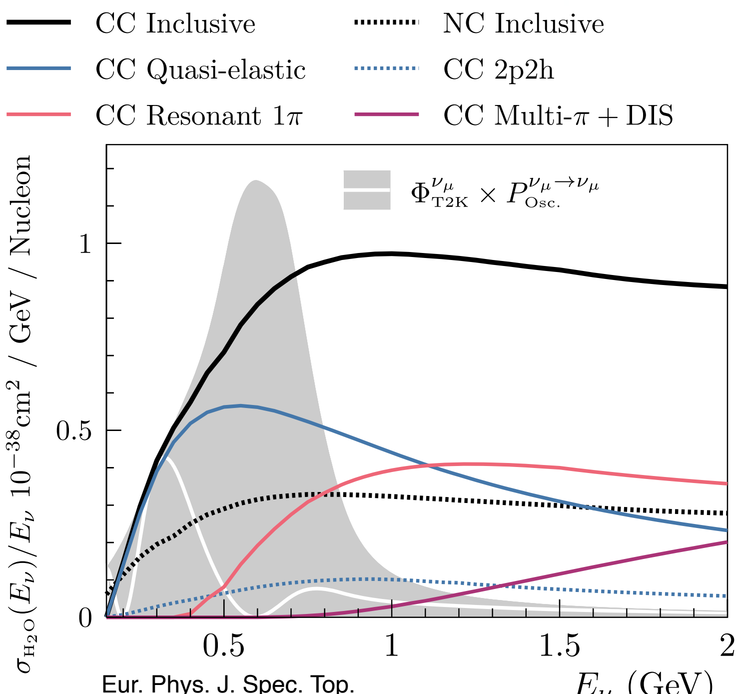




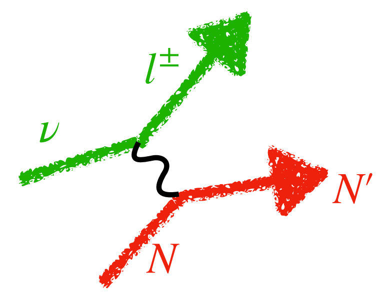
Eur. Phys. J. Spec. Top. (2021) 230:4469–4481

→ neutrin

- ND280 me
+ interactic
+ external
→ unoscil

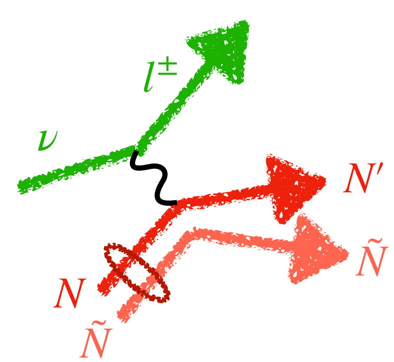
Good E_ν reconstruction

Charged current quasi-elastic (CCQE)

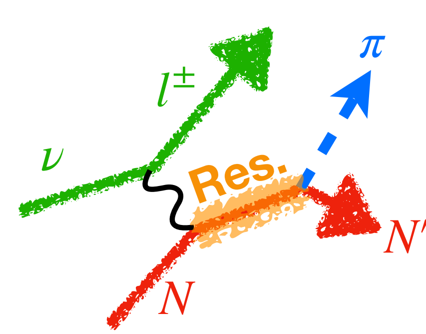


Mis-reconstruction of E_ν (~25% of events)

CC multi-nucleon knock-out (2p2h)



CC Resonant



Significant updates to interaction model

CCQE based on Spectral Function model tuned to e-A scattering data.

- uncertainty on nucl. shell structure
- $|\mathbf{q}|^2$-dependence of removal energy

Replace empirical freedom by physics-motivated low-Q^2 modeling:

- optical potential
- Pauli blocking

Uncertainties for tagging protons

- **2p2h** separation in pp and pn
- nucleon FSI

Resonant based on Rein-Sehgal model with RFG nuclear model.

New tune to bubble chamber data

New uncertainties including effective binding energy.

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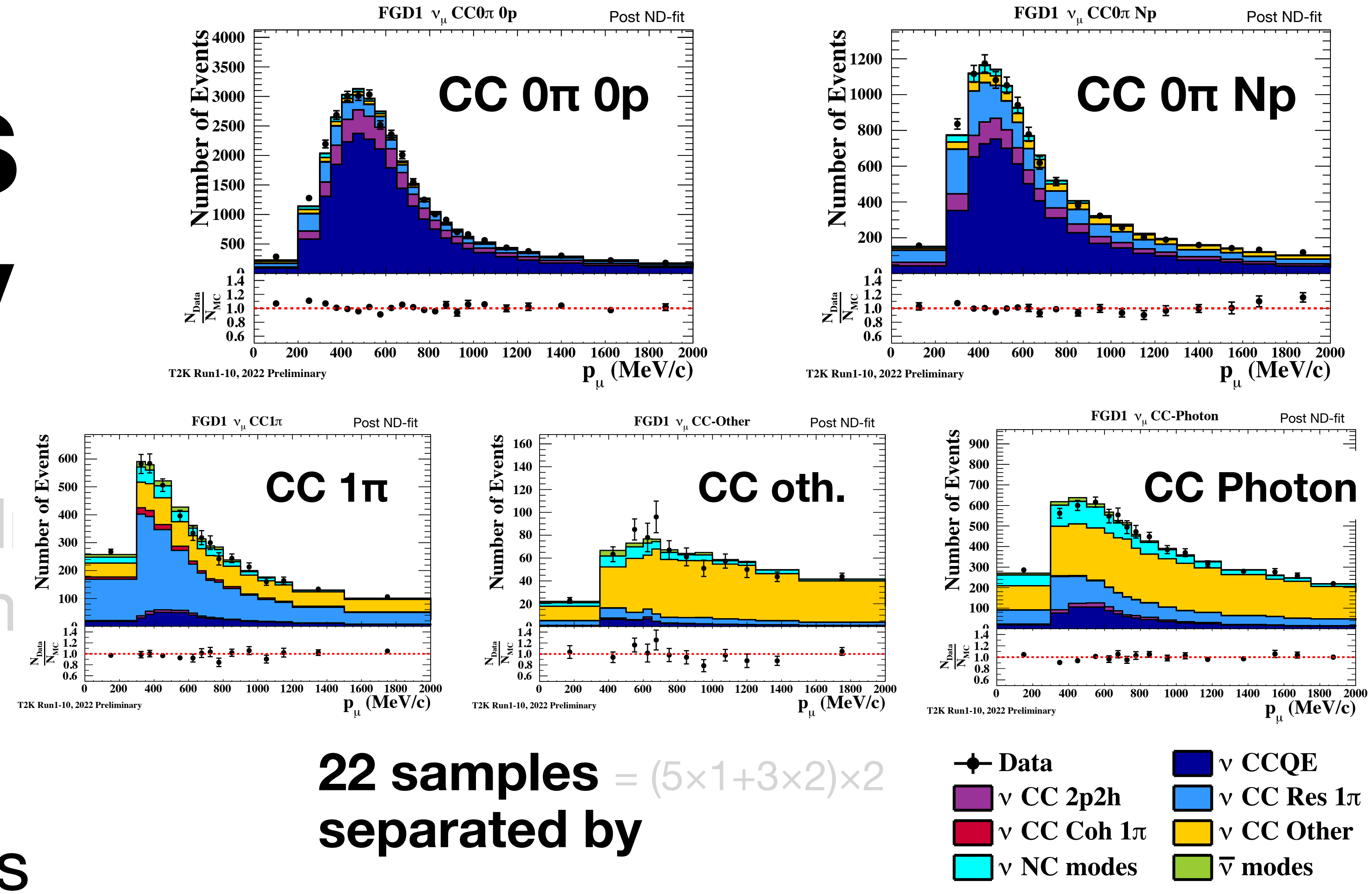
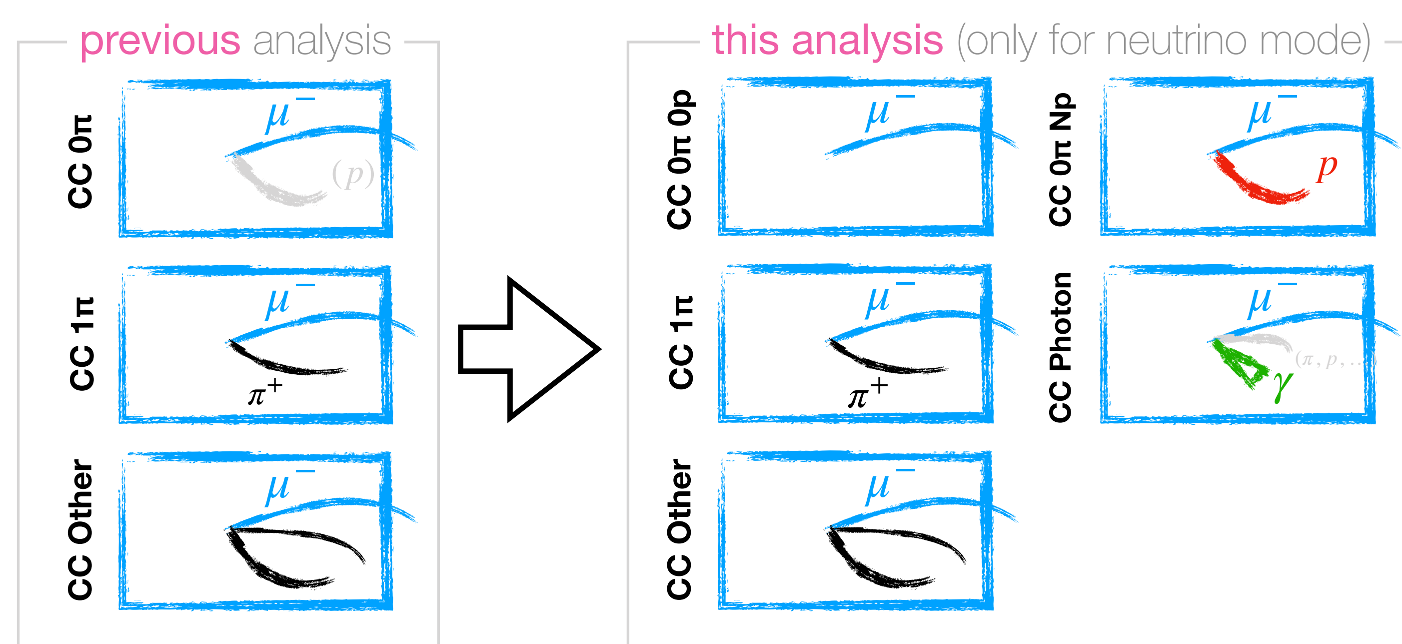


22 samples = (5×1+3×2)×2
separated by

1. π,p,γ multiplicity
   → interaction mode

Finer sample separation in this analysis!



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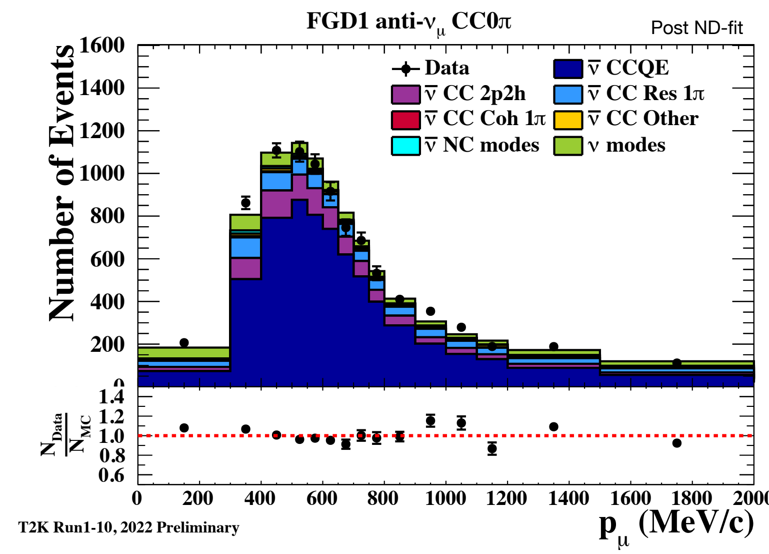
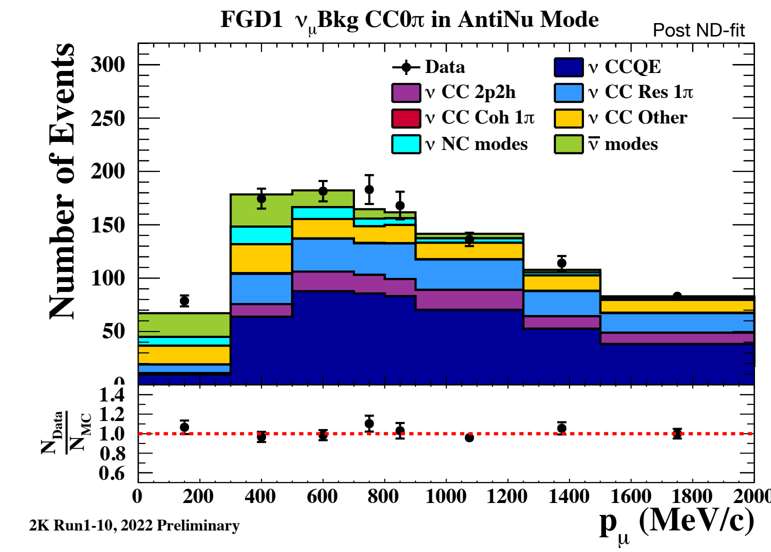
Right-sign



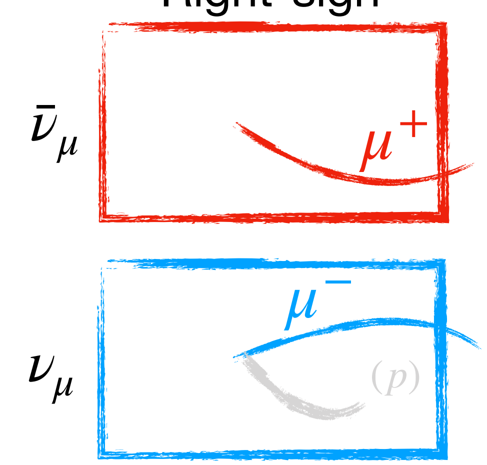
Wrong-sign bkg.



22 samples = (5×1+3×2)×2
separated by

1. π,p,γ multiplicity
   → interaction mode
2. lepton charge
   → wrong-sign bkg
   (in antineutrino mode)
3. C / C+O target
   → ν+O xsec

Right-sign



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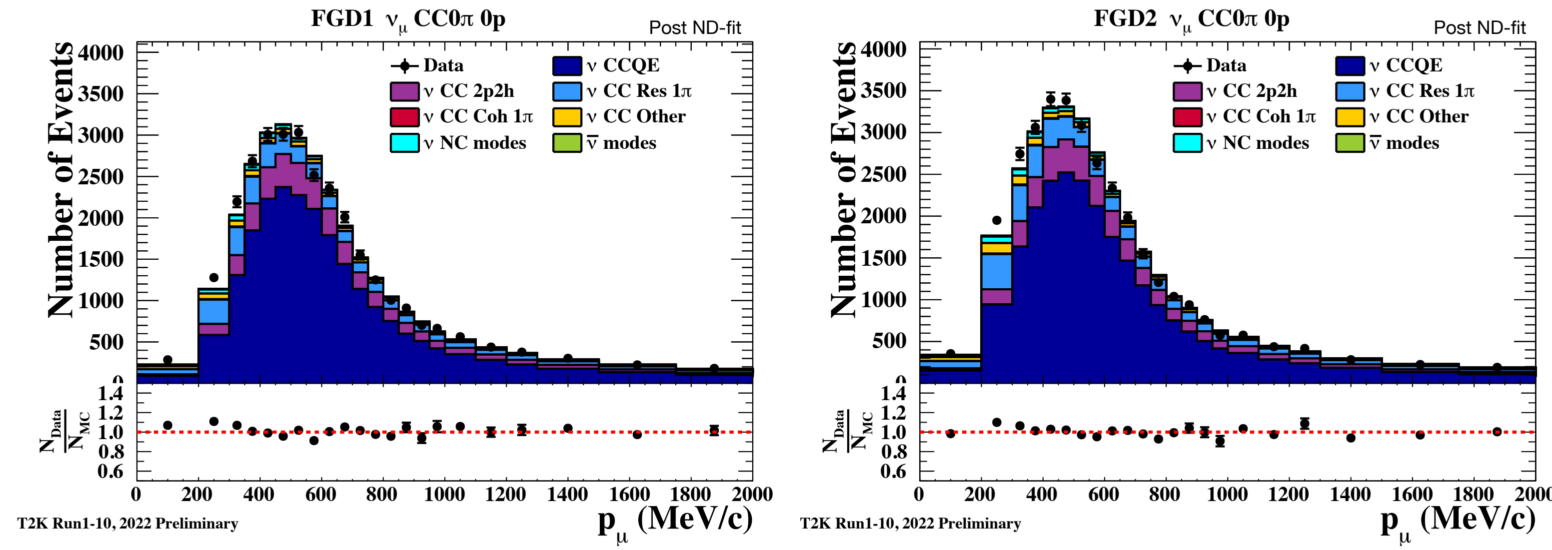
C target **C+O target**



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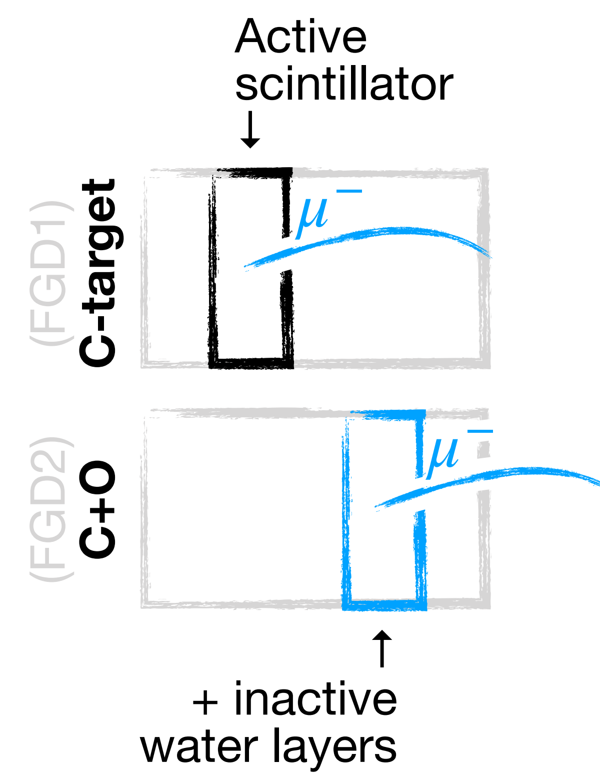

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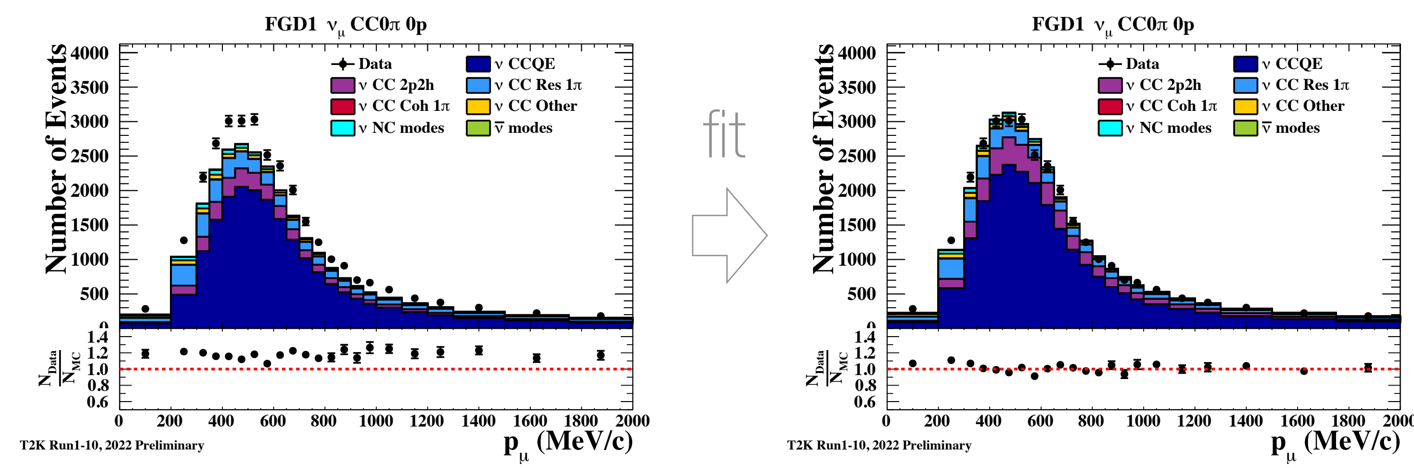
Fit result with correlated flux × xsec propagated to far detector analysis via covariance matrix or joint ND+FD fit.

Both methods give consistent results.

Pre-ND **Post-ND**



ND fit p-value: **10.9%** (> 5% threshold)

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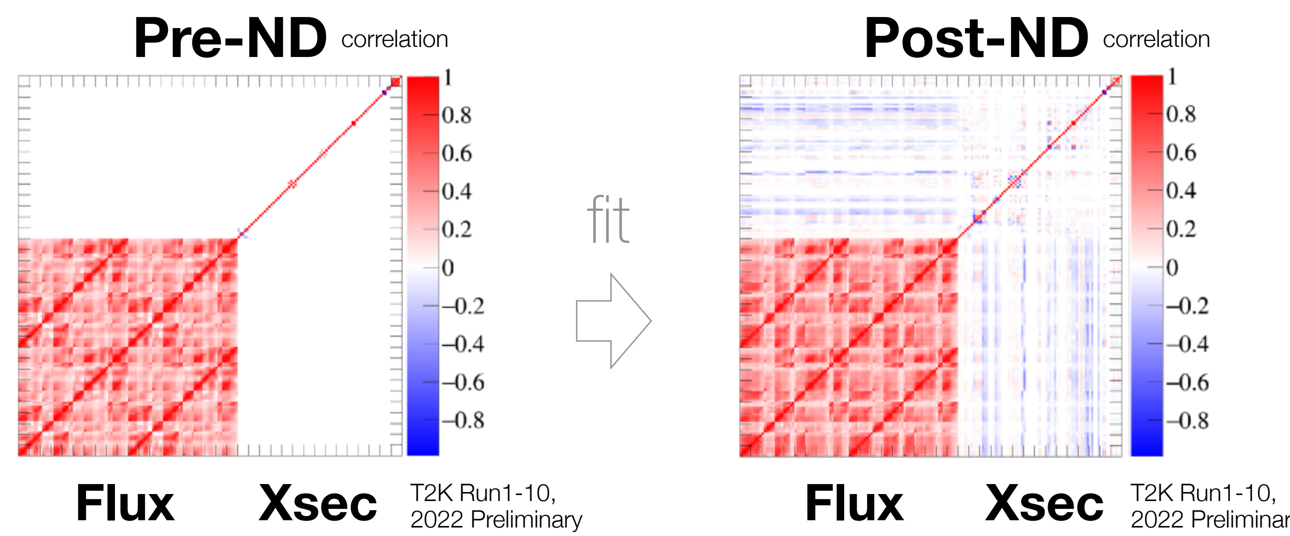

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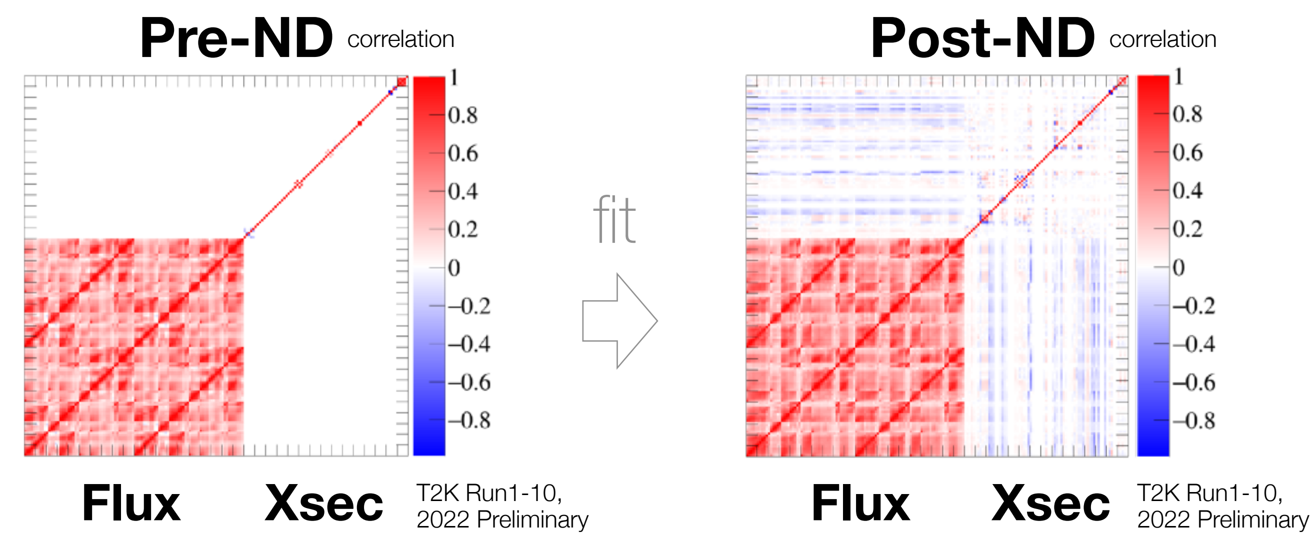

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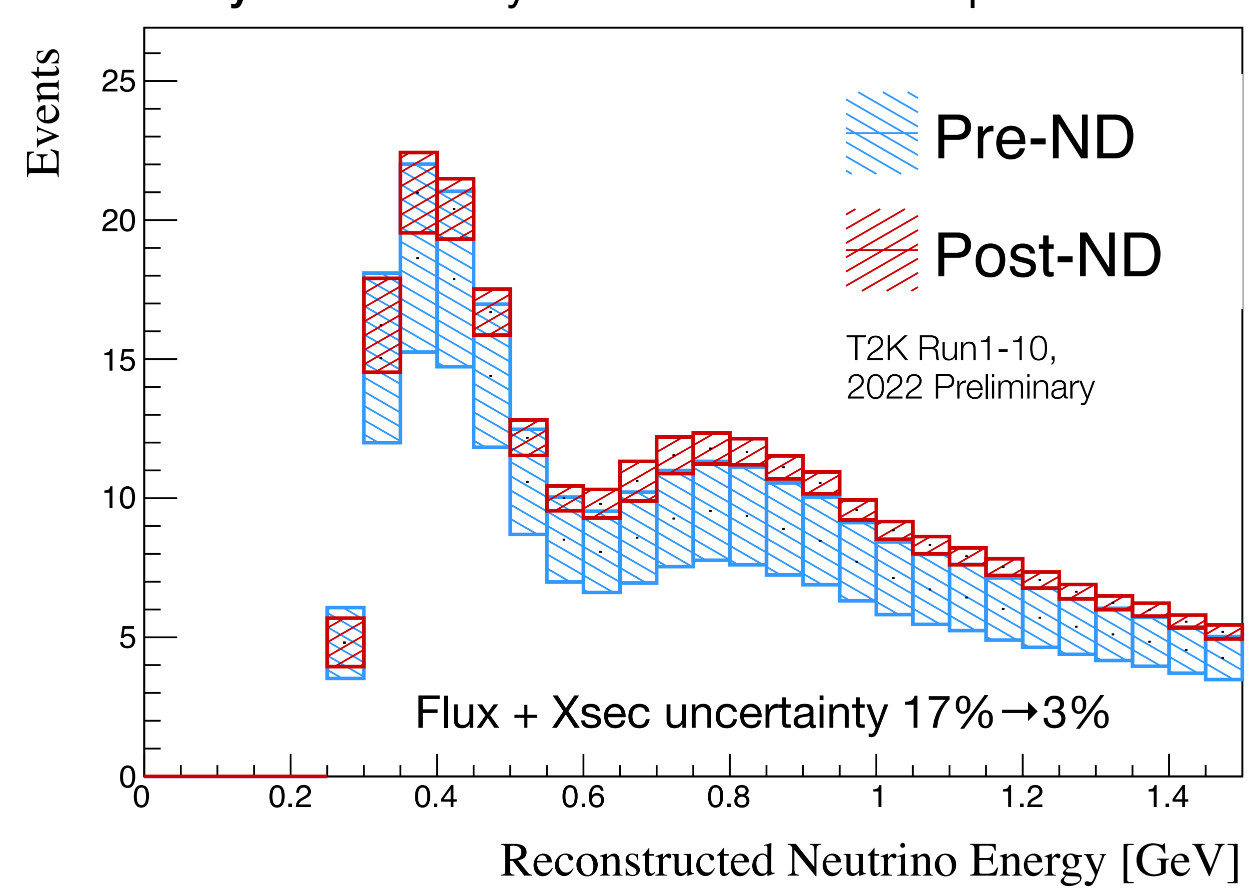
Total syst uncertainty on neutrino mode 1Rμ events at SK



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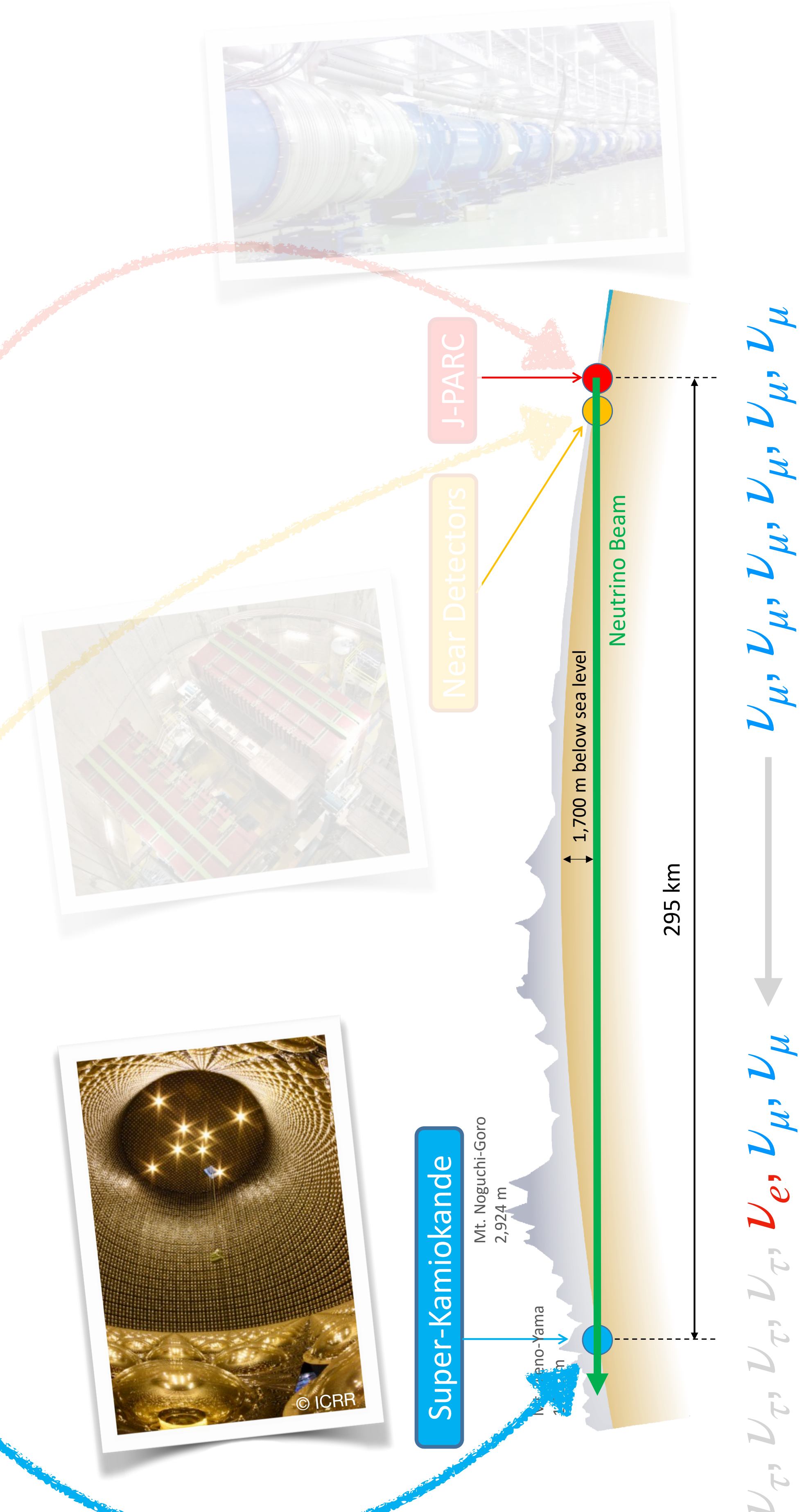

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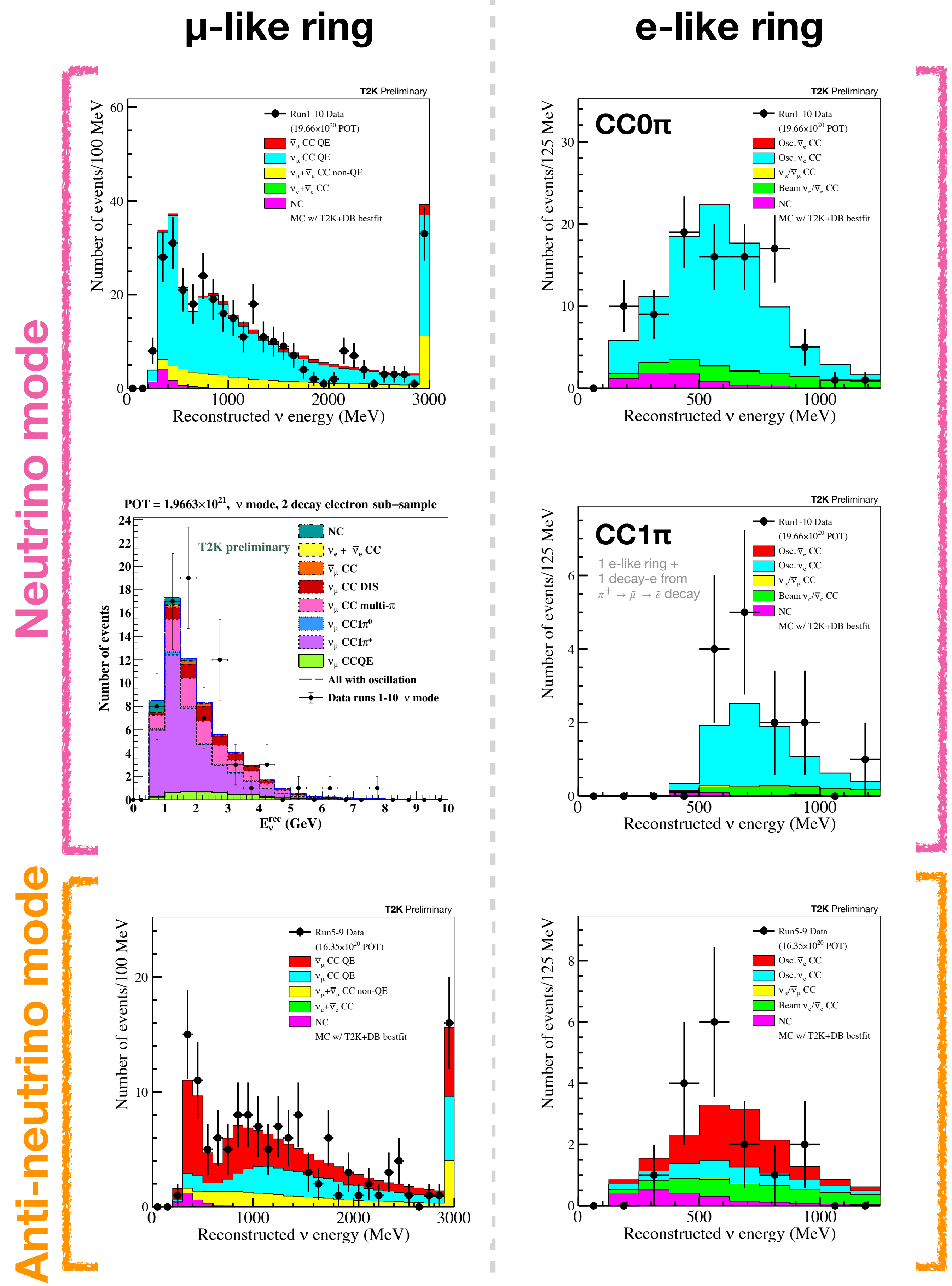
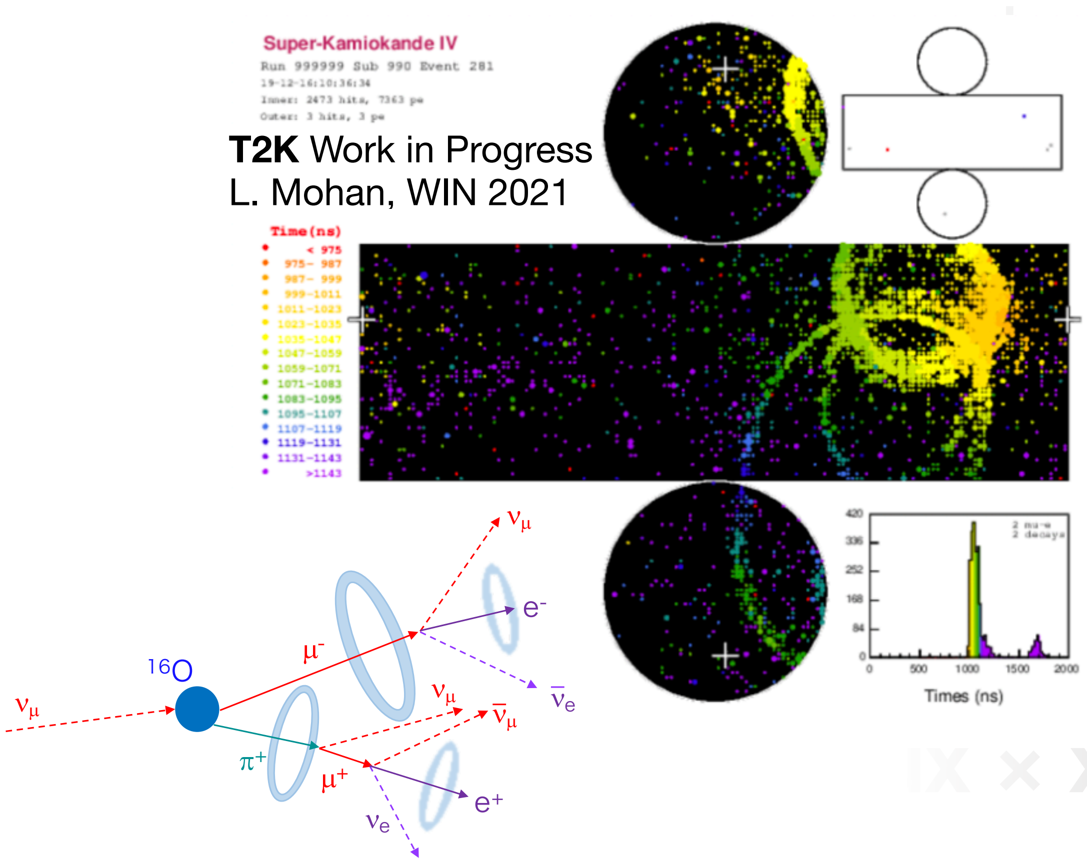
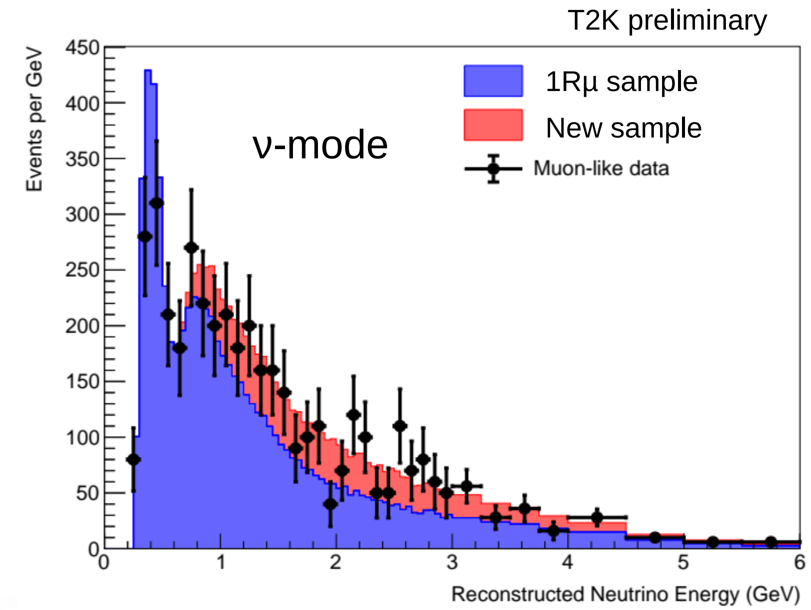
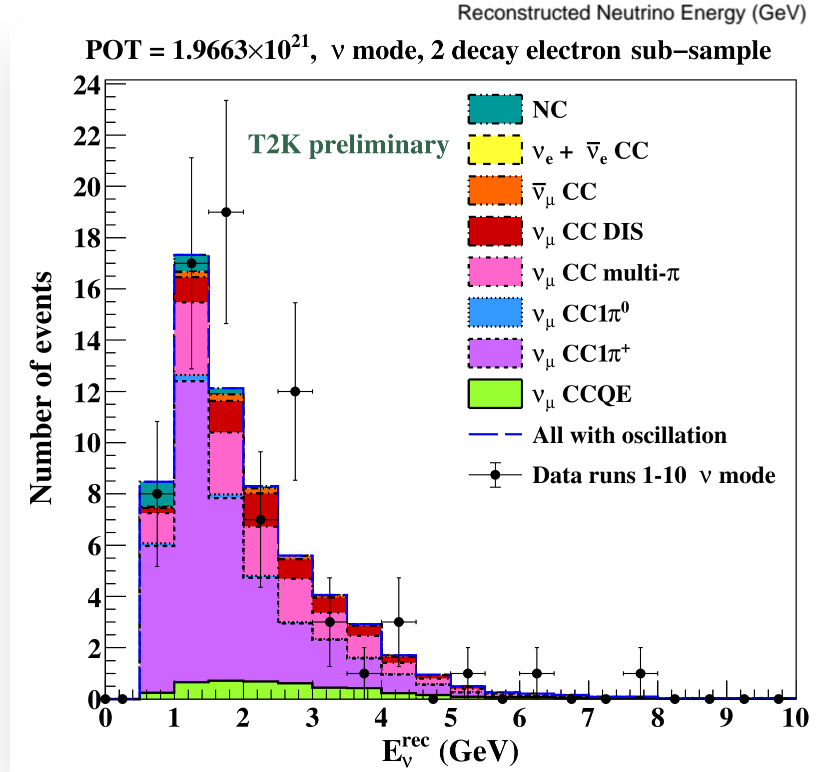


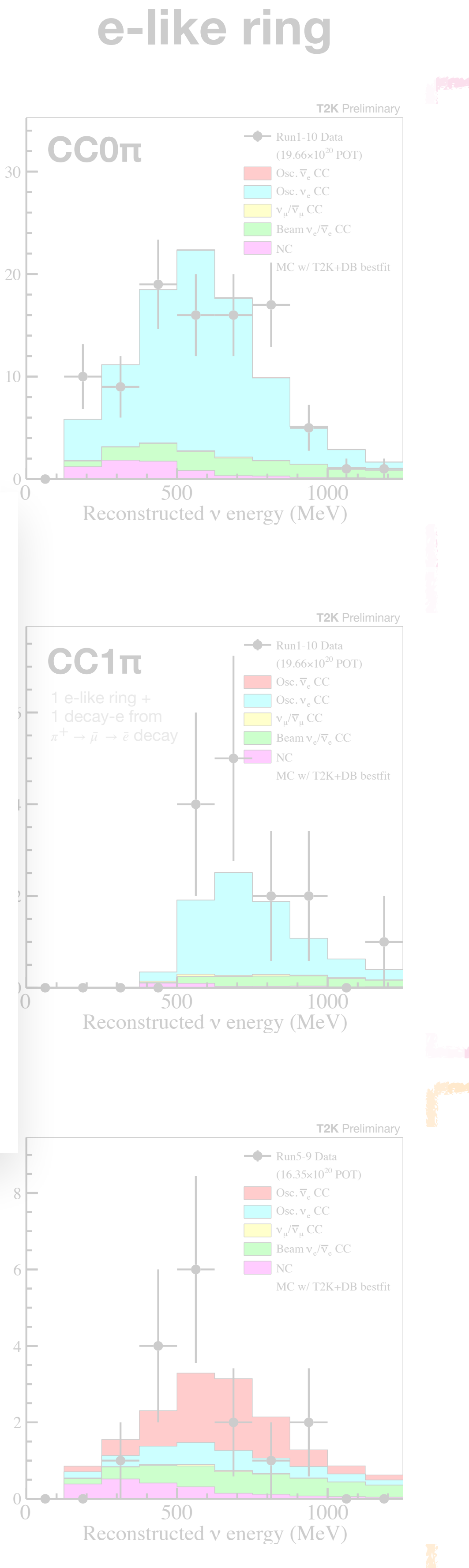
Multi-ring sample added for the first time

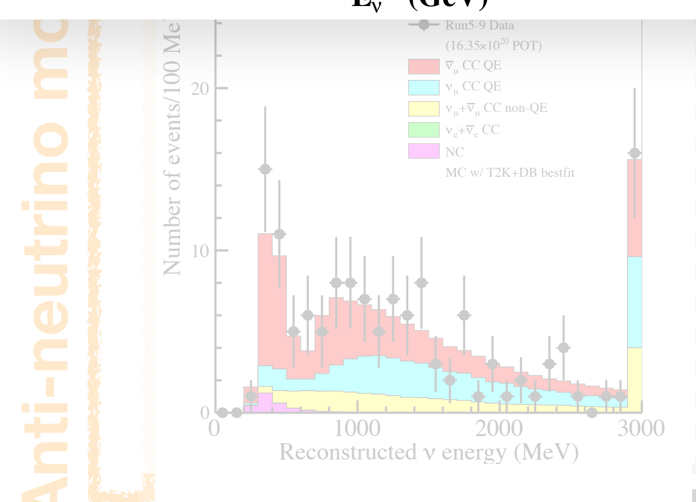
Analysis strategy











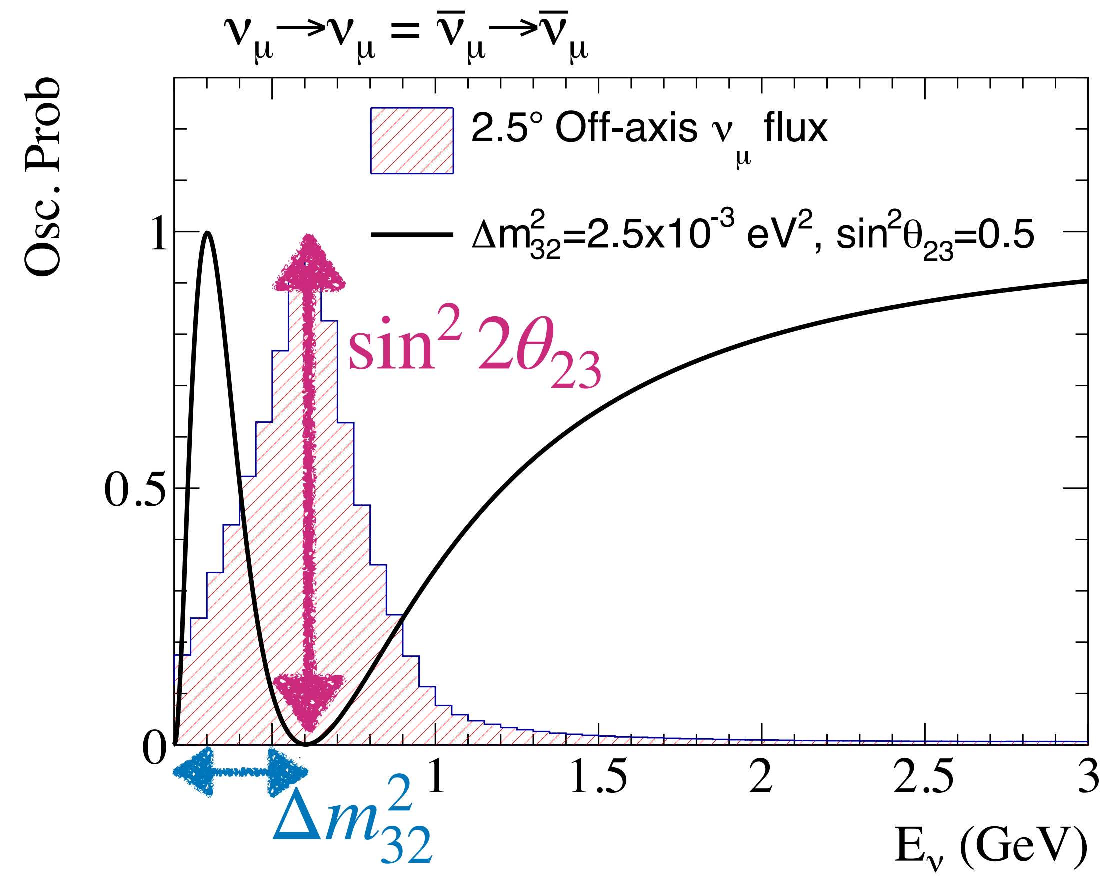
- 6 samples at SK
  → ν_μ **disappearance +**
  ν_e **appearance**

Multi-ring sample added for the first time

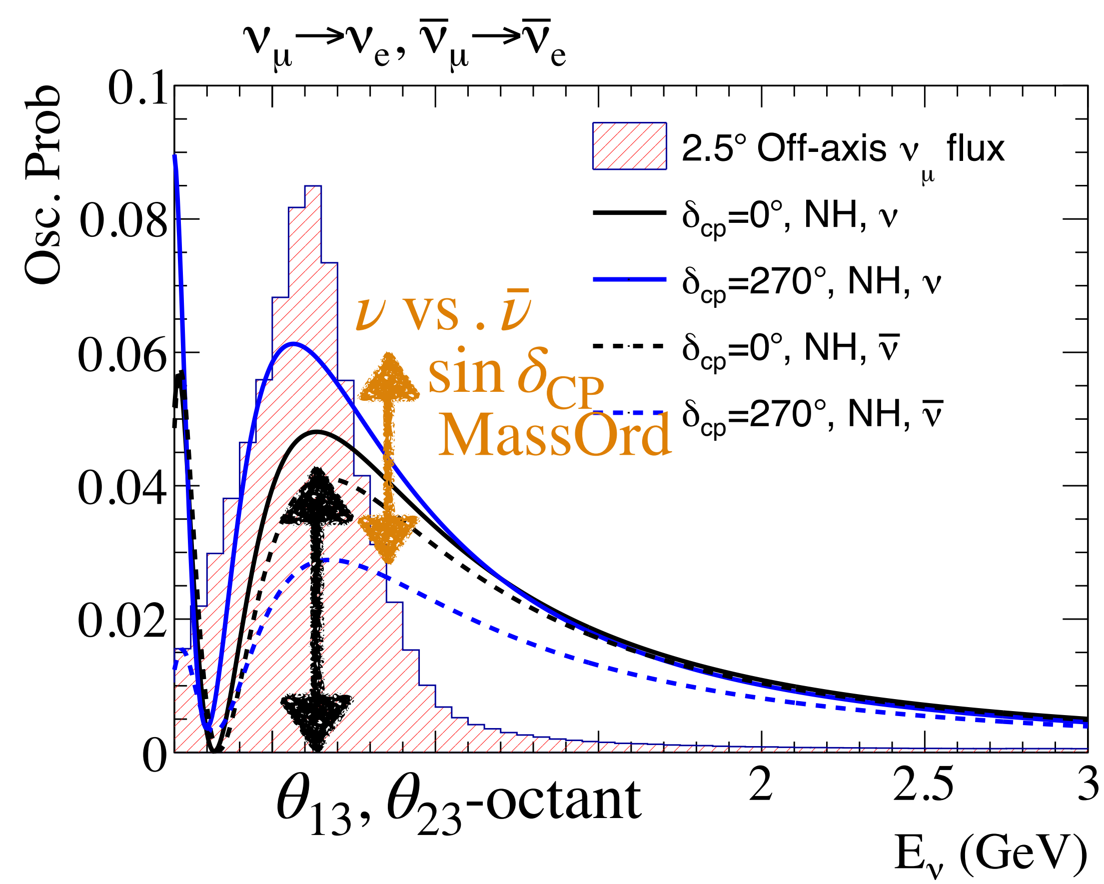
Analysis strategy

- Beam monitors + hadron production experiments → **neutrino flux**
- ND280 measurements + interaction model + external constraints → **unoscillated flux × xsec**
- 6 samples at SK → ν_μ **disappearance +** ν_e **appearance**

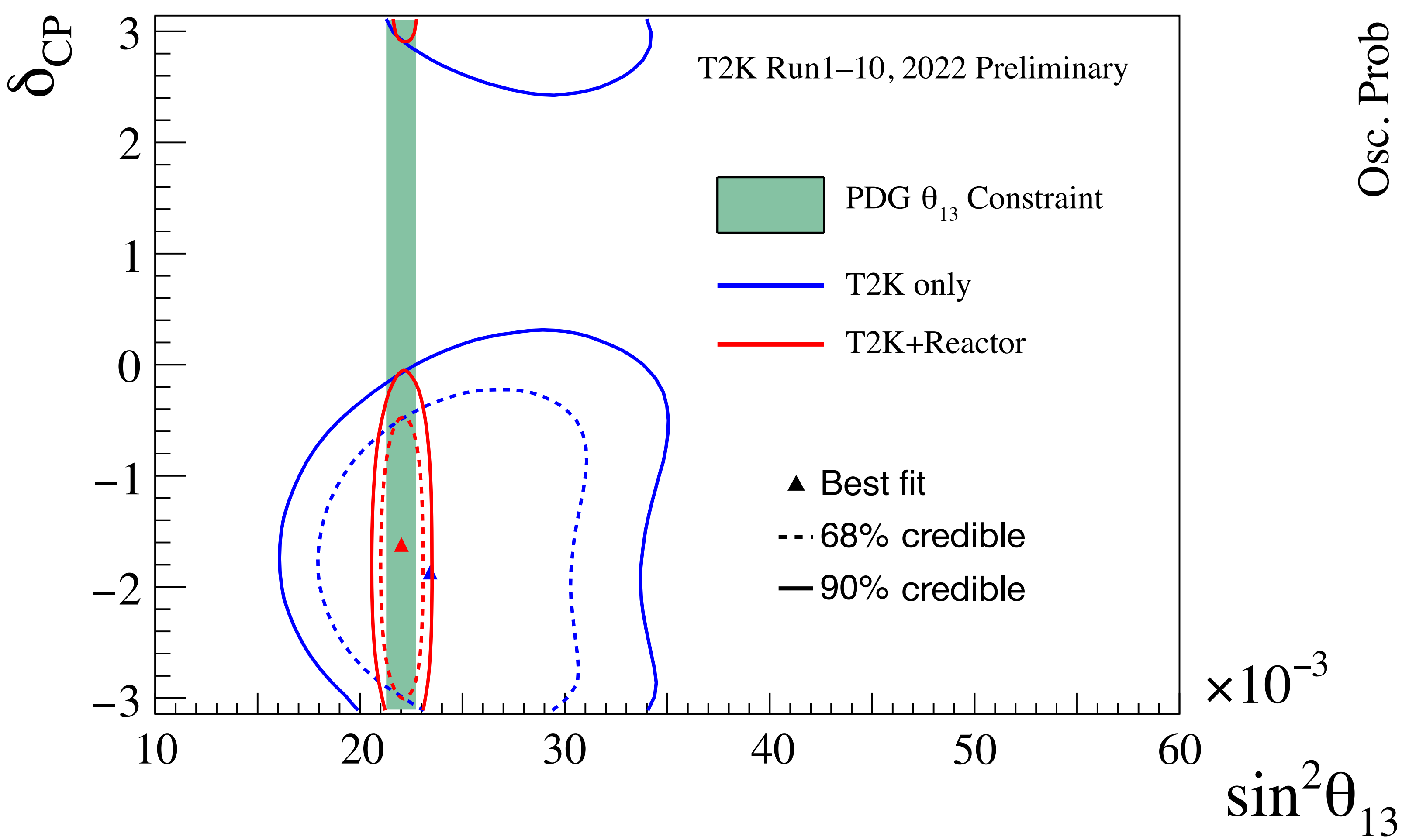
μ-like ring

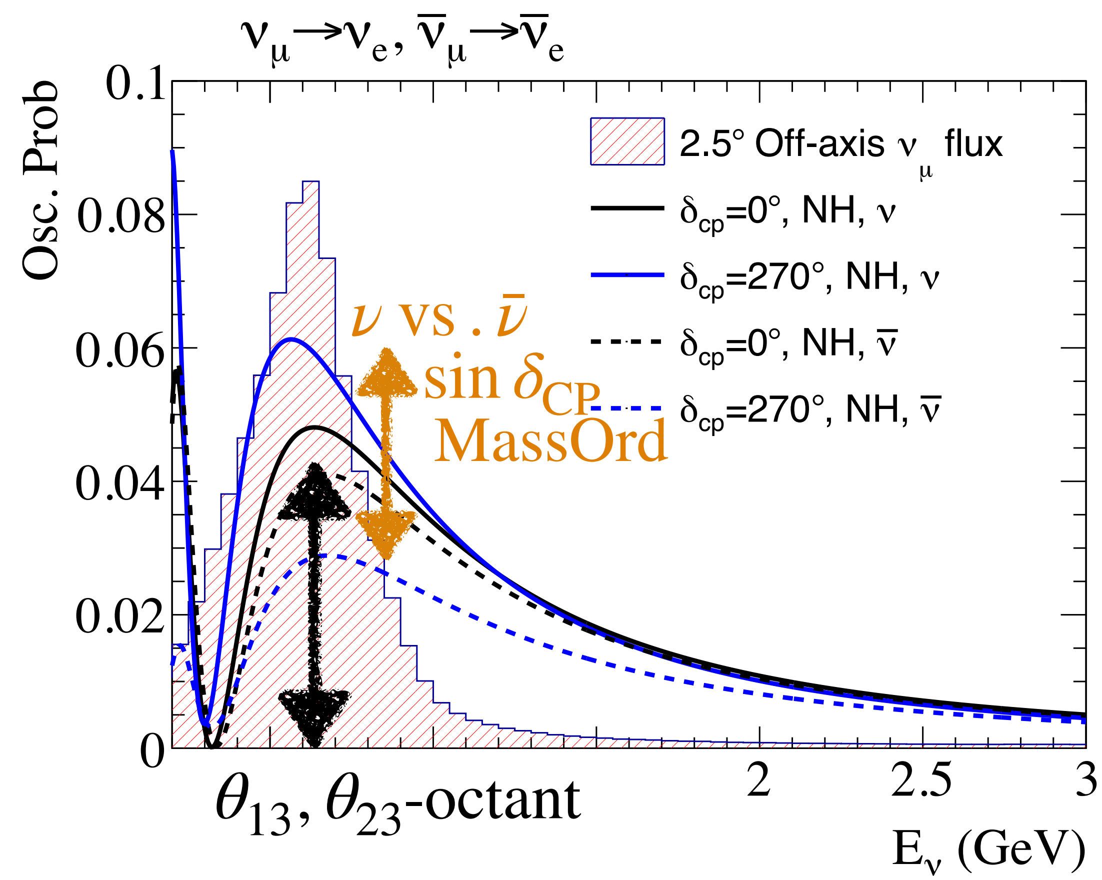


e-like ring



Constraints on θ_{13}



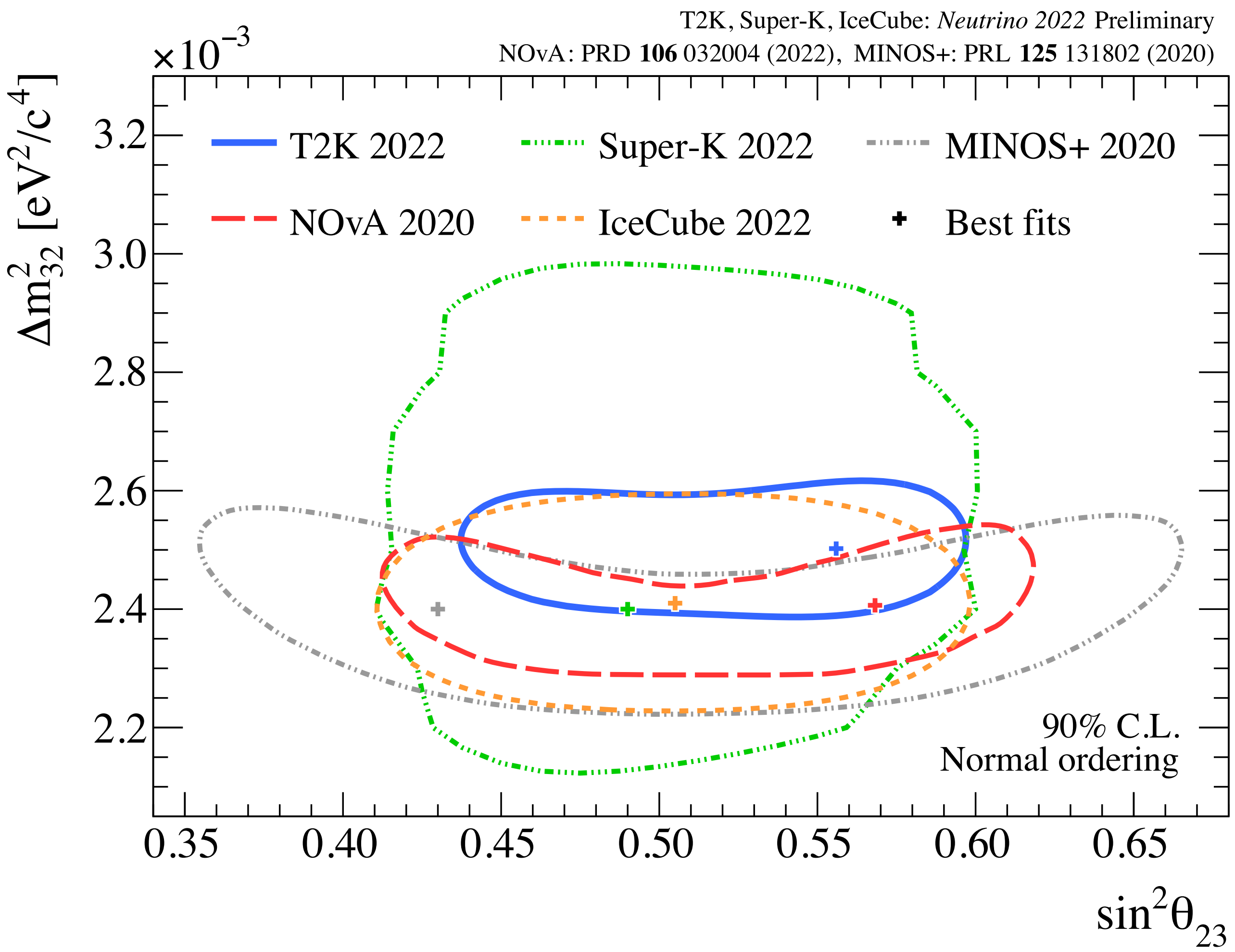


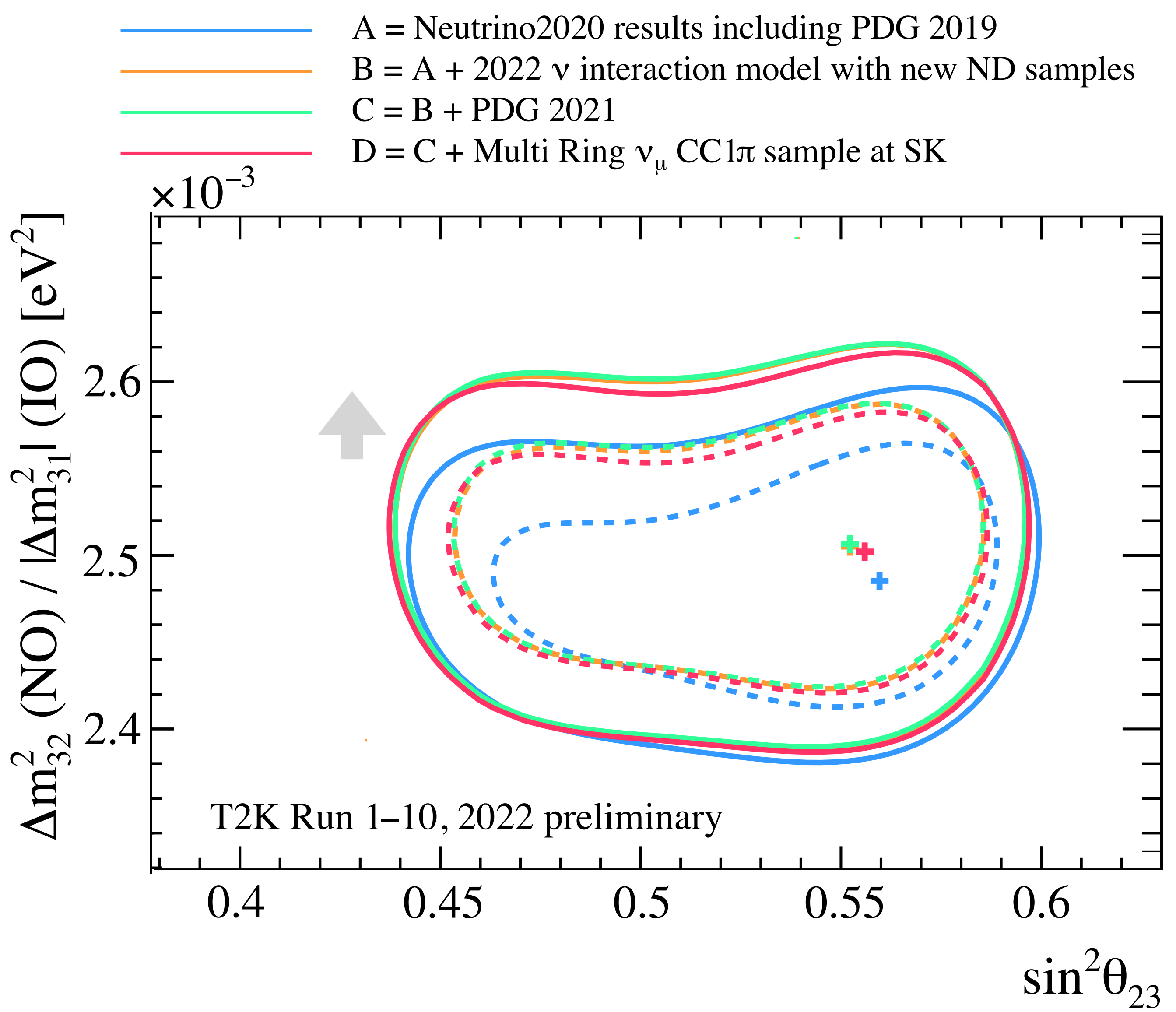
- T2K's θ_{13} constraint ($\nu_\mu \to \nu_e$ appearance) consistent with the much stronger constraint from reactor experiments ($\bar{\nu}_e \to \bar{\nu}_e$ disappearance)

- Unless otherwise noted, reporting the T2K+Reactor constraints on the other oscillation parameters, especially important for δ_{CP}, and θ_{23} octant

Δm^2_{32} vs. θ_{23}

Atmospheric mixing parameters

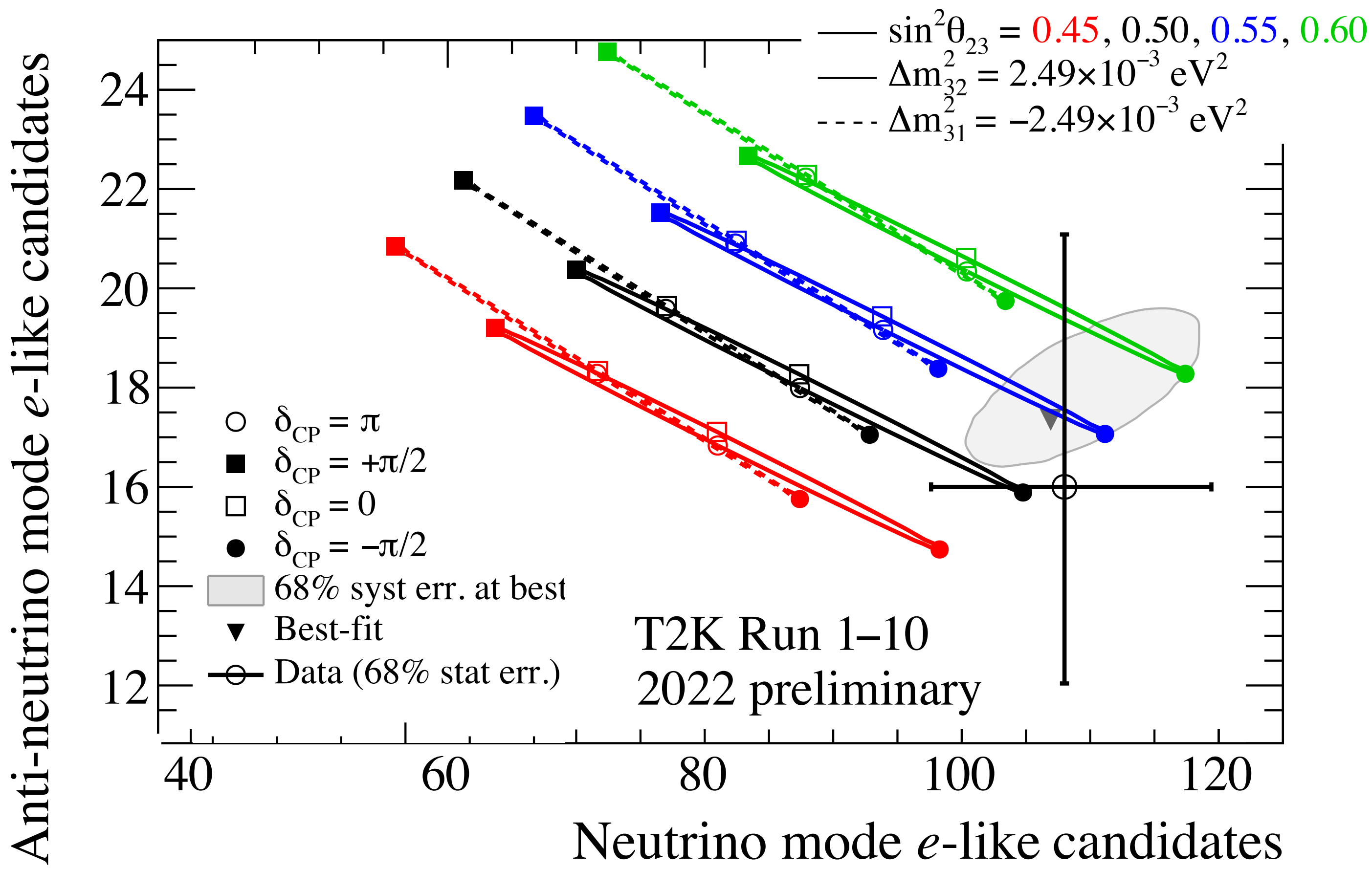




World-leading measurement of atmospheric params still compatible with both octants, very weakly preferring upper

- **New** interaction model and ND samples cause largest change compared to **2020**
- Multi-ring ν_μCC1π sample only gives small contribution due to being above oscillation maximum

ν_e vs. $\bar{\nu}_e$ appearance

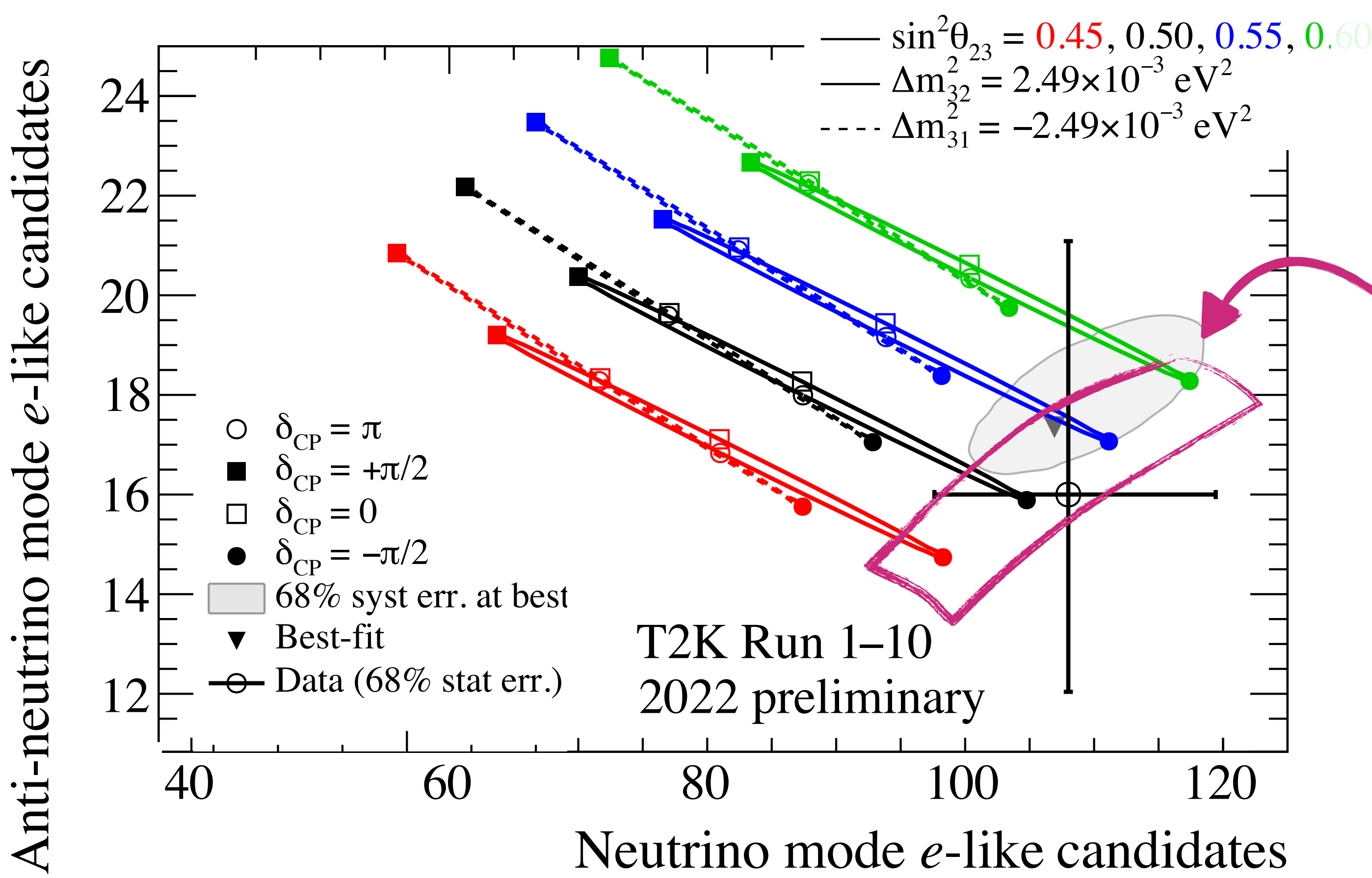


- Bi-event plot illustrates origin of data constraints.
- Best-fit $\delta_{\rm CP}$ around **maximal CP-violation** $-\frac{\pi}{2}$
- Weak preference for **Normal ordering** with Bayes factor 2.8 $= P_{\rm NO}/P_{\rm IO}$
- Weak preference for **upper octant** with Bayes factor 3.0 $= P_{\rm upper}/P_{\rm lower}$

Octant / **Mass ordering**

Posterior prob.	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NO ($\Delta m^2_{32} > 0$)	0.20	0.54	0.74
IO ($\Delta m^2_{32} < 0$)	0.05	0.21	0.26
Sum	0.25	0.75	1.00

ν_e vs. $\bar{\nu}_e$ appearance



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Octant

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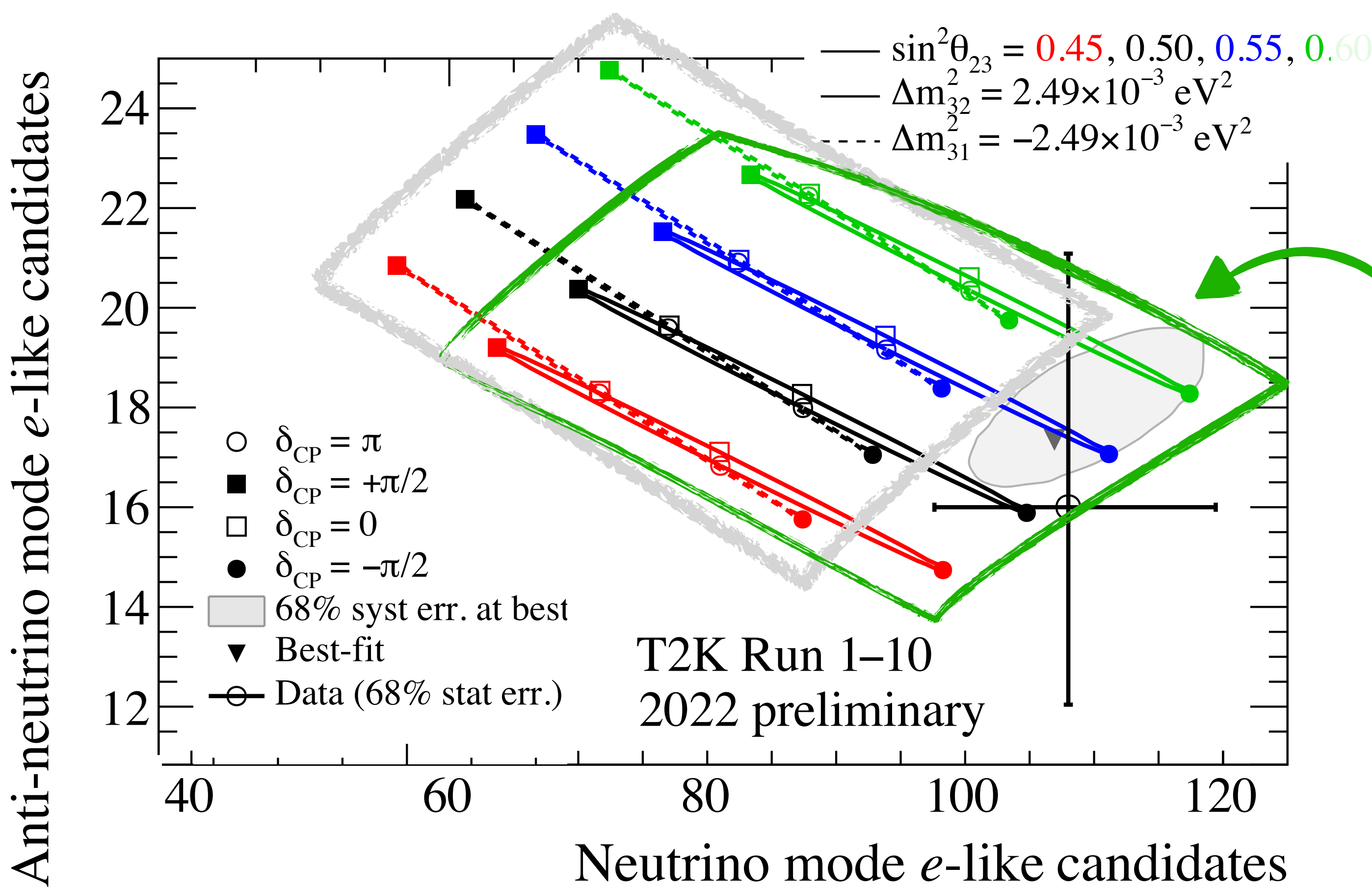

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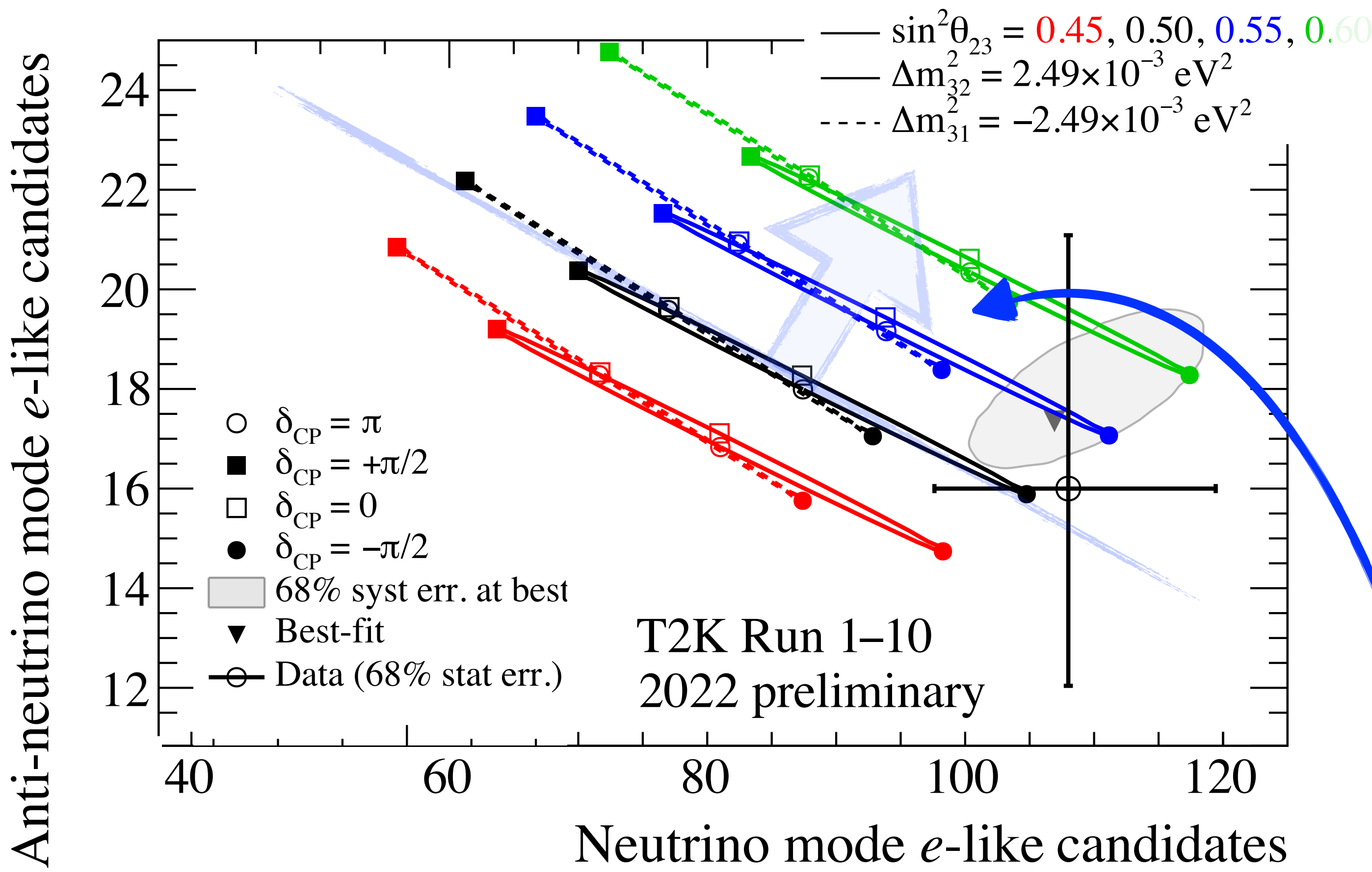

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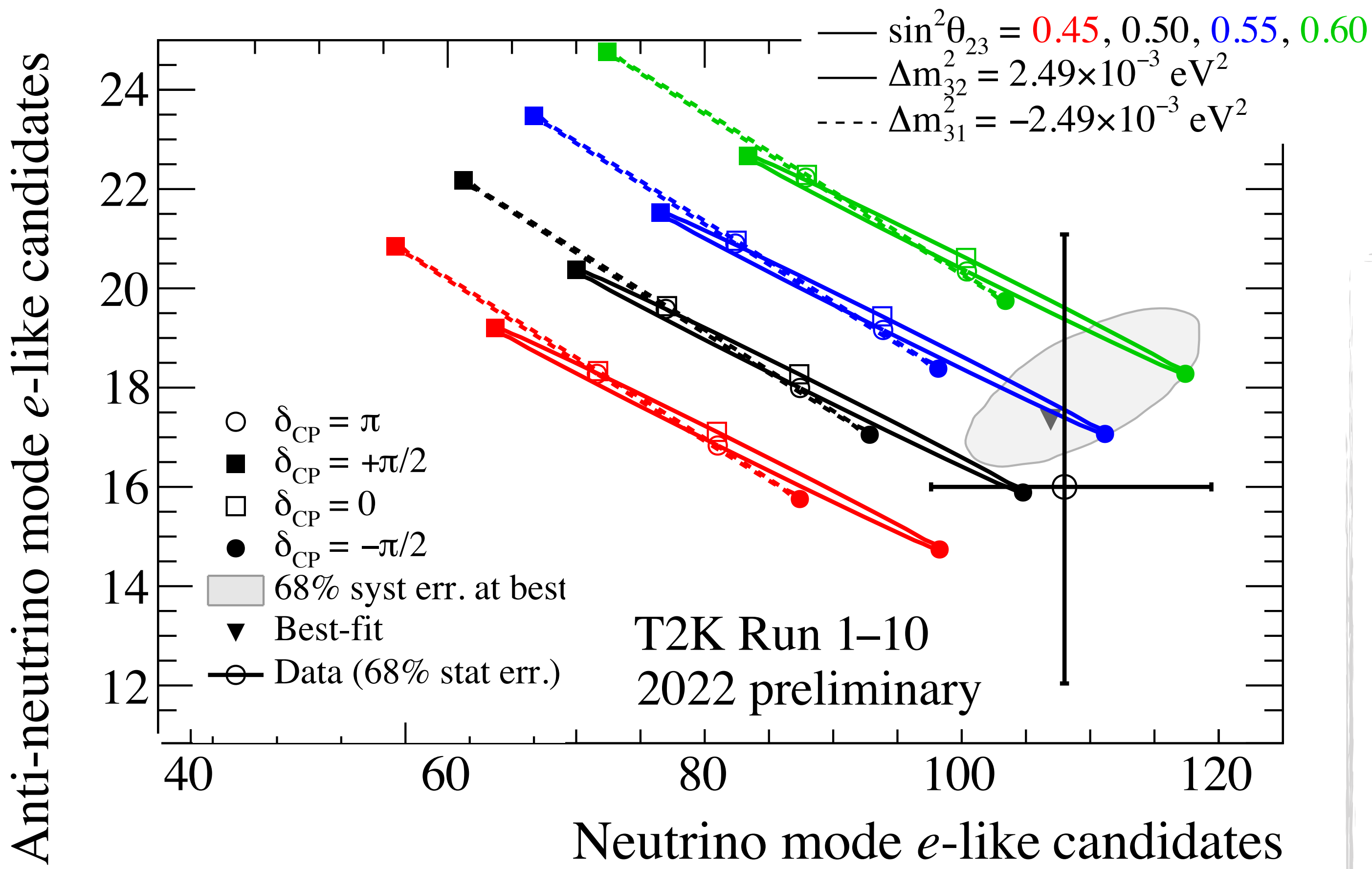
ν_e vs. $\bar{\nu}_e$ appearance



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Overall less prominent than in previous analysis

Octant (columns) / **Mass ordering** (rows)

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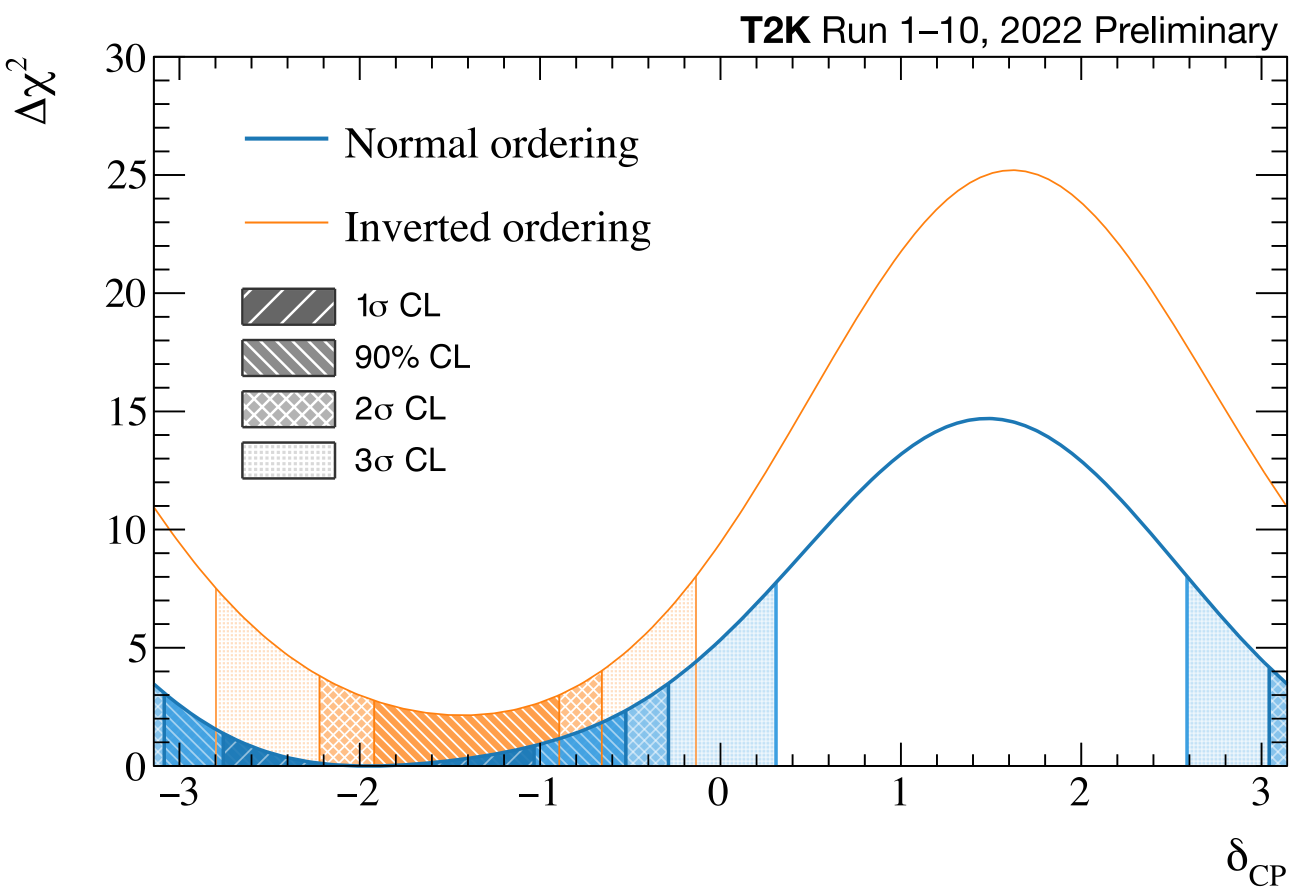
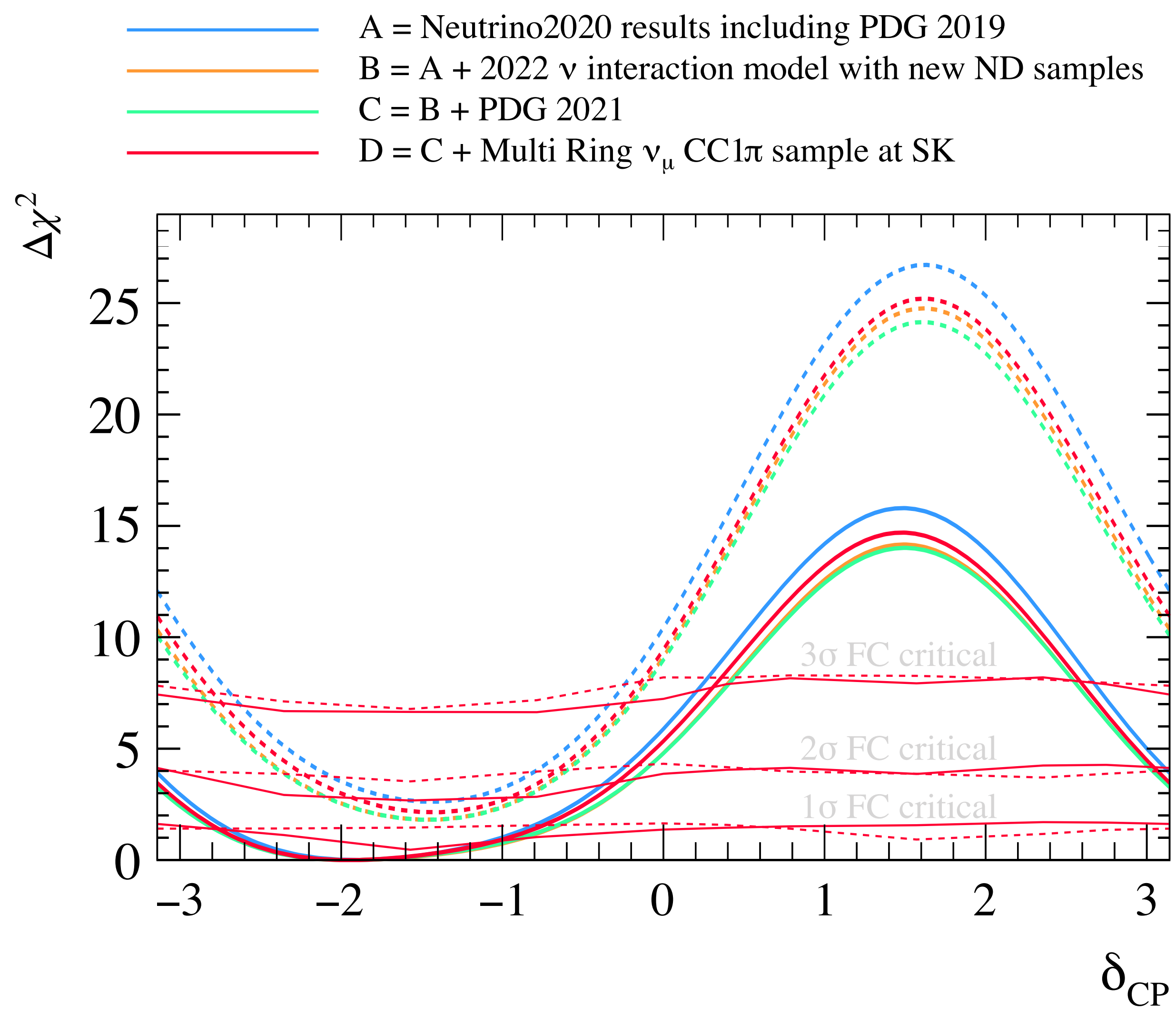
Constraints on δ_{CP} and mass ordering

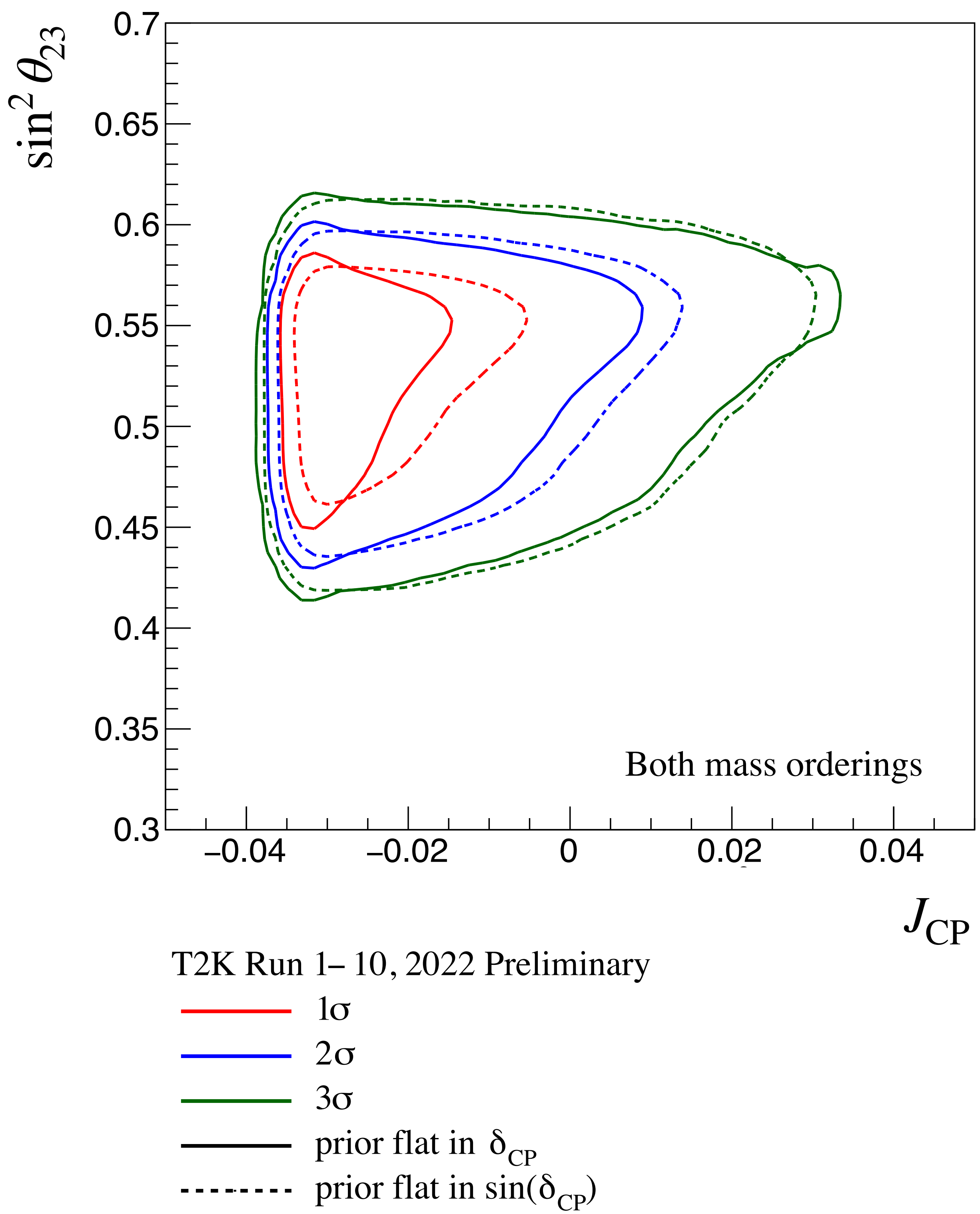




- Large region **excluded at 3σ**
- CP-conservation $\{0, \pi\}$ **excluded at 90%**, π is within 2σ
- In checks for biases caused by xsec model choices, left (right) 90% CI edge moves at most by 0.06 (0.05)
- Weak preference of **normal ordering**

- Slightly weaker constraint compared to 2020 analysis, mainly due to updated model with new ND samples

Jarlskog invariant



- $J_{CP} = s_{13}c_{13}^2 s_{12}c_{12}s_{23}c_{23}\sin\delta_{CP}$
  parameterization*-invariant measure of CP violation

- Constraint depends on δ_{CP} prior and $\sin^2\theta_{23}$,
  CP conservation ($J_{CP} = 0$) currently inside of 2σ credible region
  (and 1D credible interval)

* of PMNS matrix

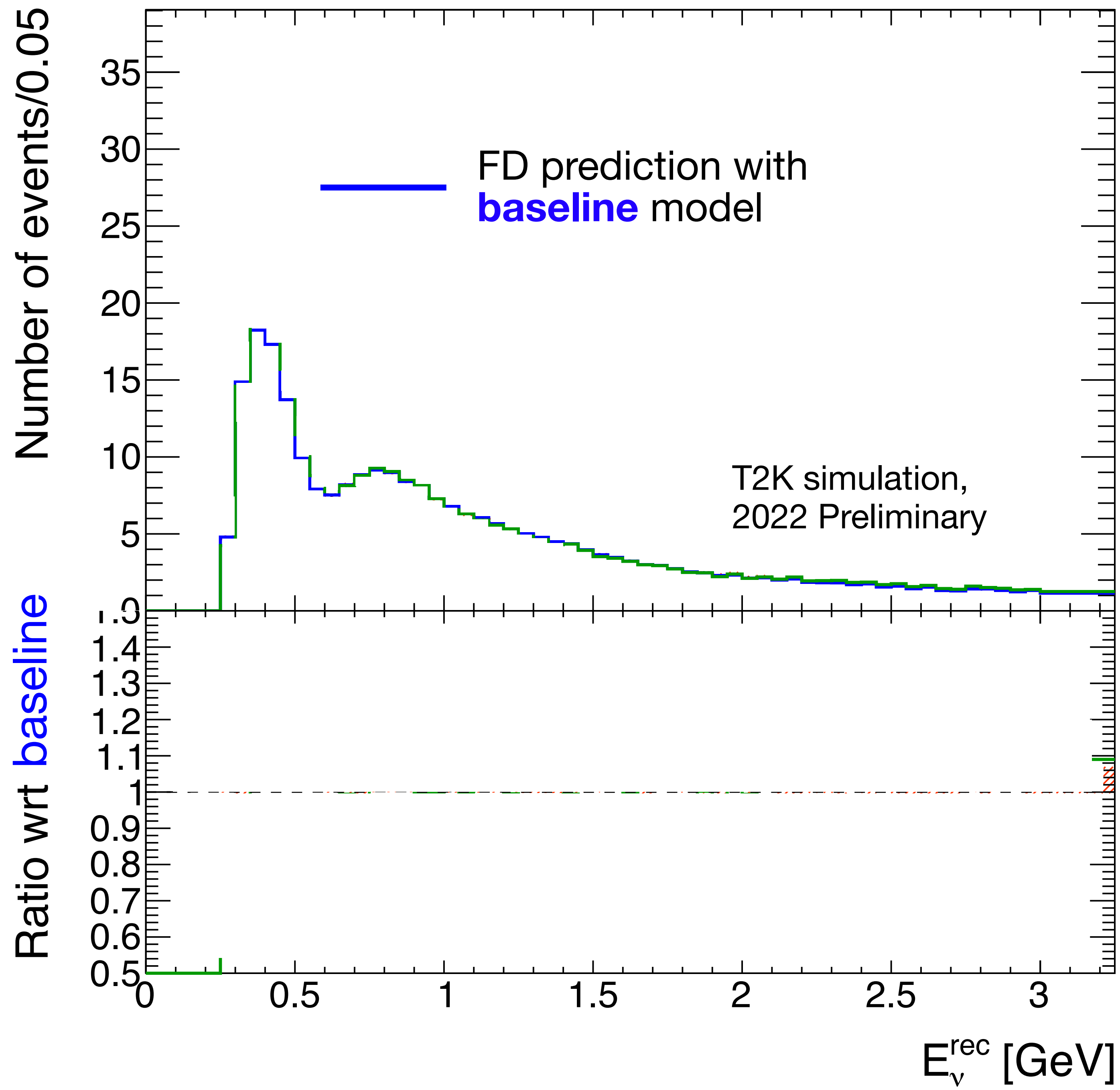
Robustness studies

- Test interaction model for biases using fits to “simulated data” from theory- or data-driven **alternative interaction models**

- For θ_{23} no significant biases observed

- For Δm^2_{32} **small bias** observed
  ↓
  additional gaussian uncertainty with $\sigma = 2.7 \times 10^{-5}\,\mathrm{eV}^2$ is added to compensate

- For δ_{CP} we report effect on confidence intervals, but **no change** of main conclusions



Continuum Random-Phase Approximation
- Phys. Rev. C, 65:025501, 2002,
- Phys. Rev. C, 92(2):024606, 2015

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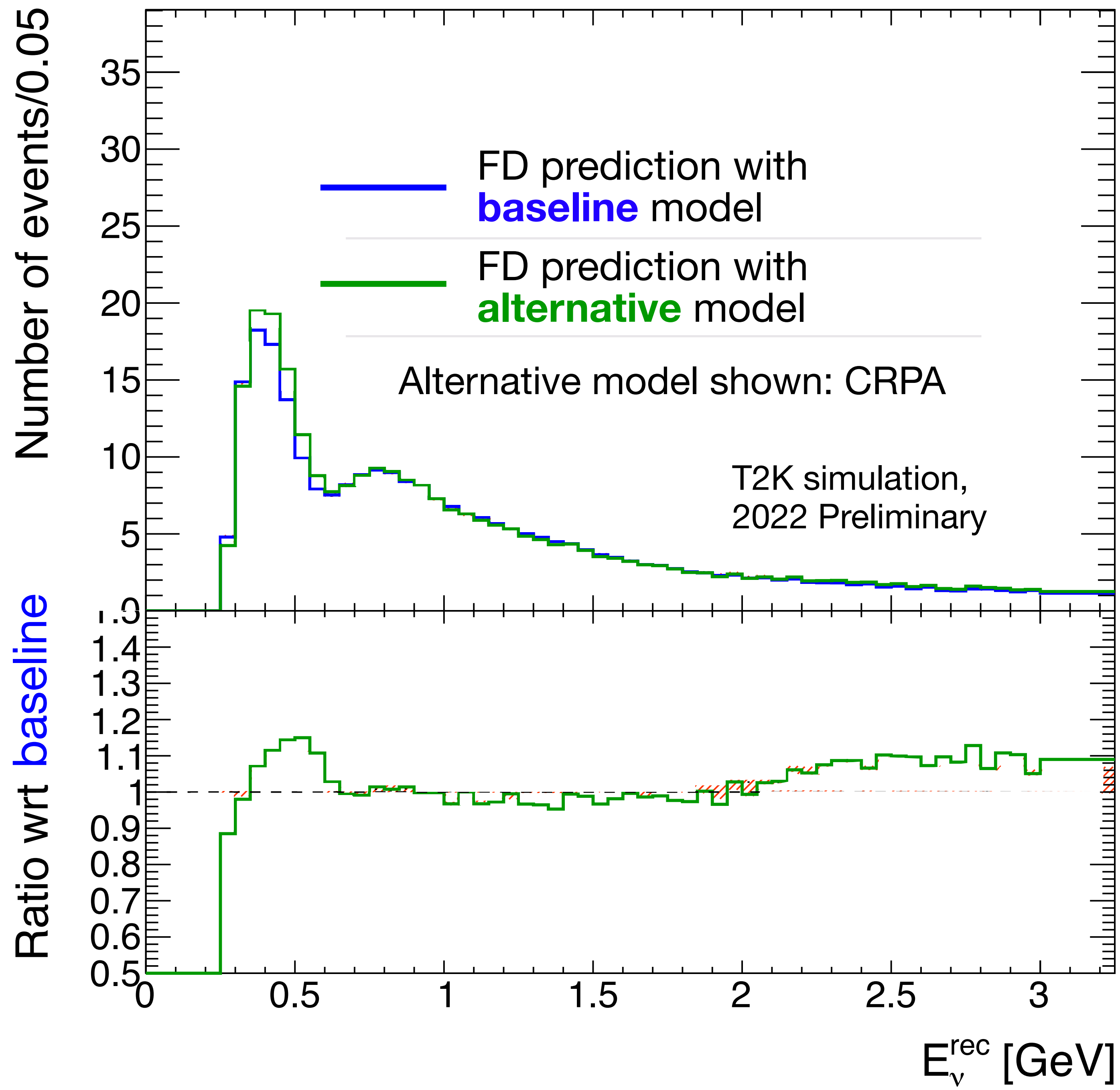

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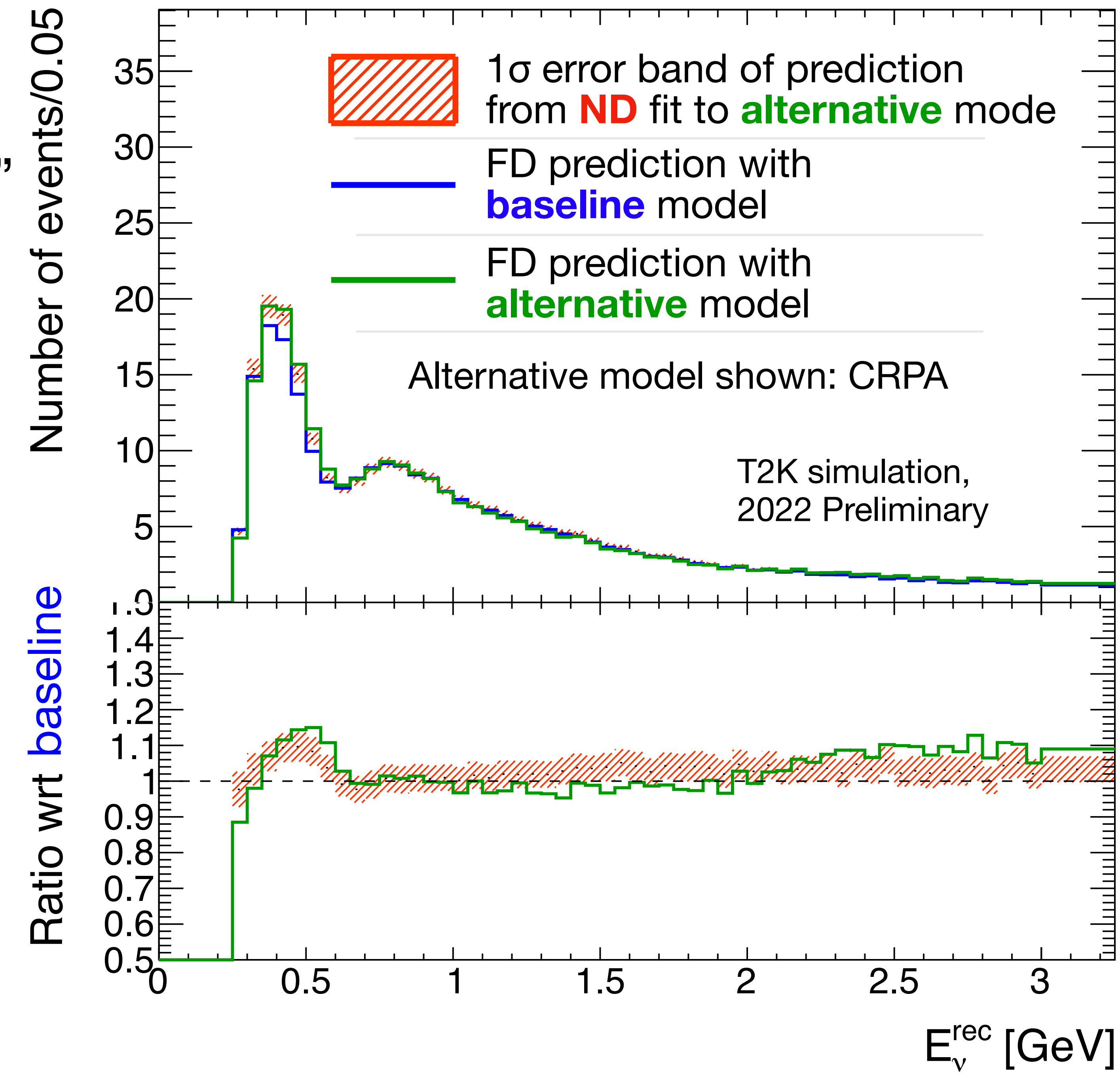

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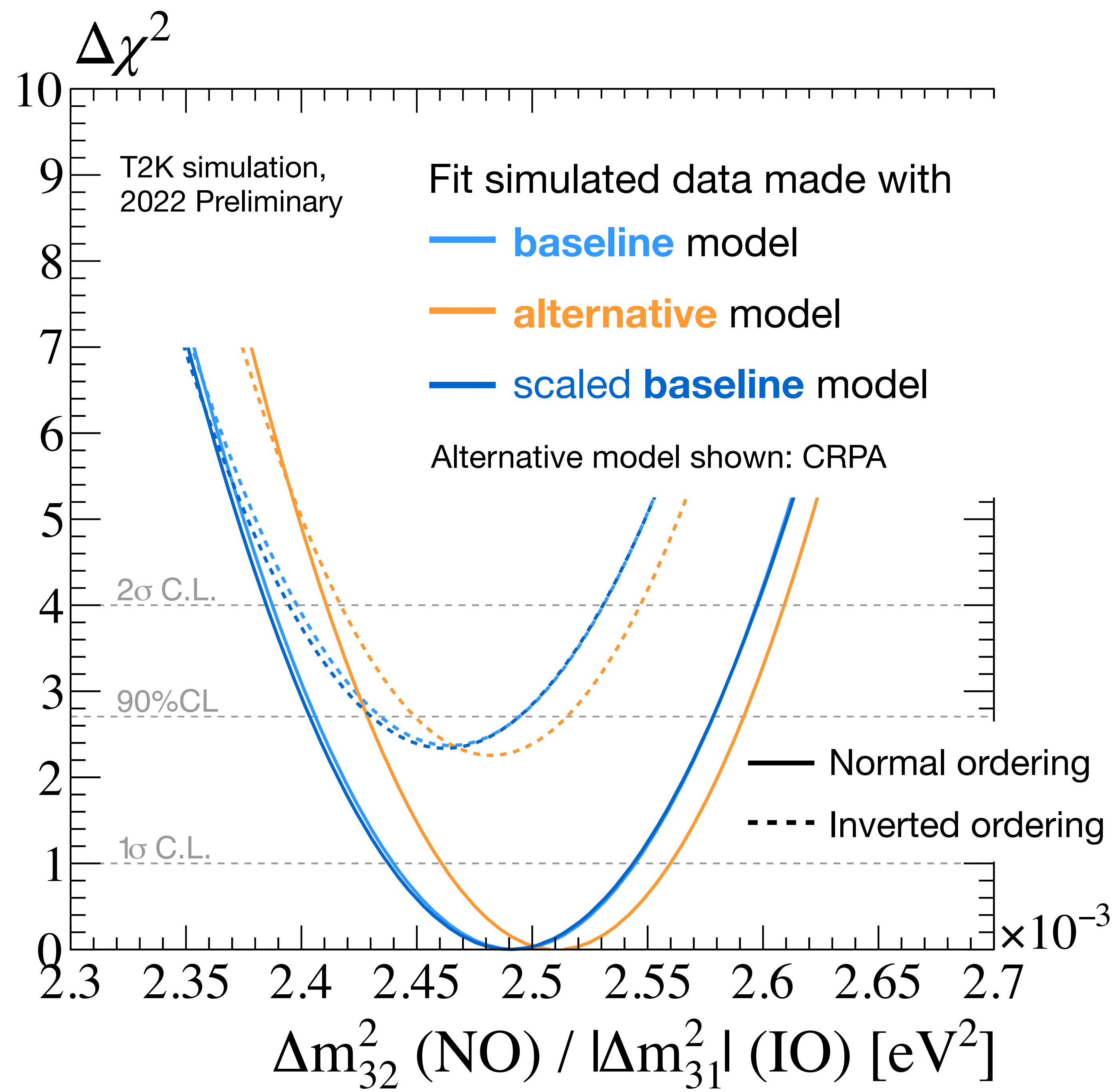


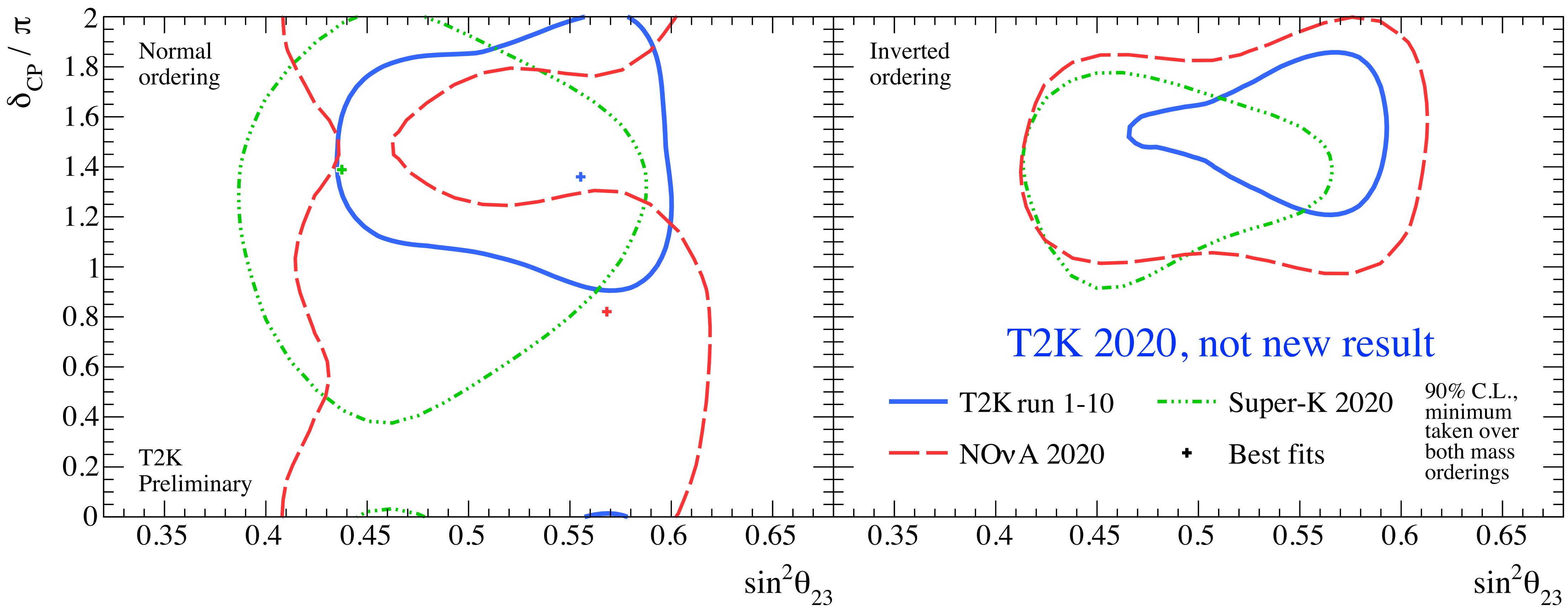
NOvA + T2K
810 km / 295 km

Ongoing joint fits

SK + T2K
atmospheric + accelerator

Comparison of released contours (not joint fit)

NOvA results: A. Himmel (2020) Zenodo, (preliminary)
SK results: Y. Nakajima (2020) Zenodo, (preliminary)
NOvA and T2K use Feldman-Cousins, SK use fixed $\Delta\chi^2$



- Joint fits between experiments with different oscillation baselines/energies and detector technologies

→ expect increased sensitivity in δ_{CP}, mass ordering, θ_{23} octant
beyond stats increase from resolved degeneracies and syst constraints

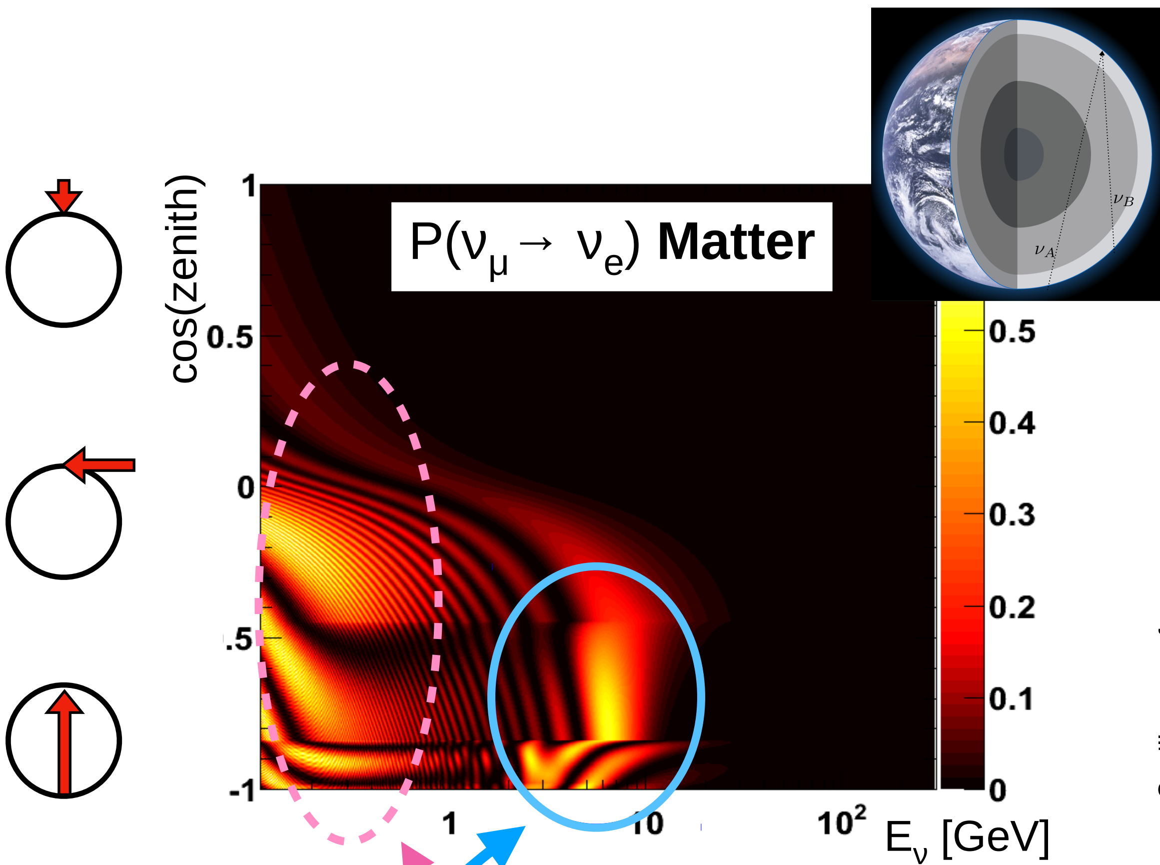
- important to understand potentially non-trivial syst. **correlations** between experiments

First results expected soon!

SK + T2K Joint fit

CP and mass ordering sensitivity

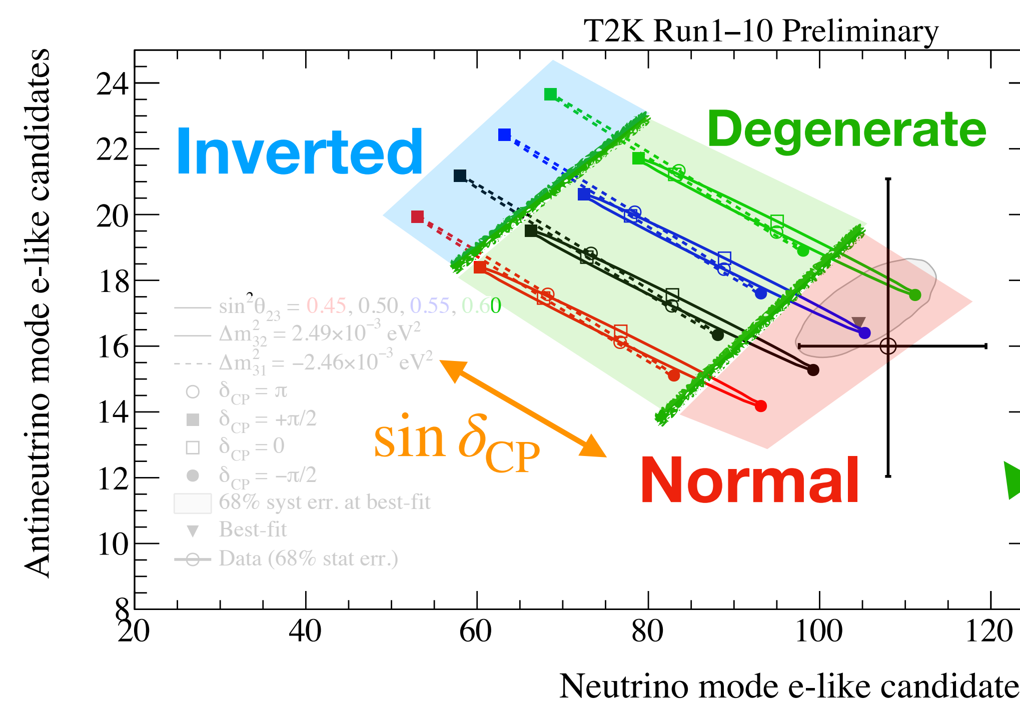
SK Atmospheric



Oscillograms from:
C. Bronner for SK collaboration, at ICTP Advanced Workshop on Physics of Atmospheric Neutrinos 2018

- Resonance in Earth mantle & core sensitive to mass ordering
- Weakly sensitive to δ_{CP} via normalization of sub-GeV e-like

T2K Accelerator



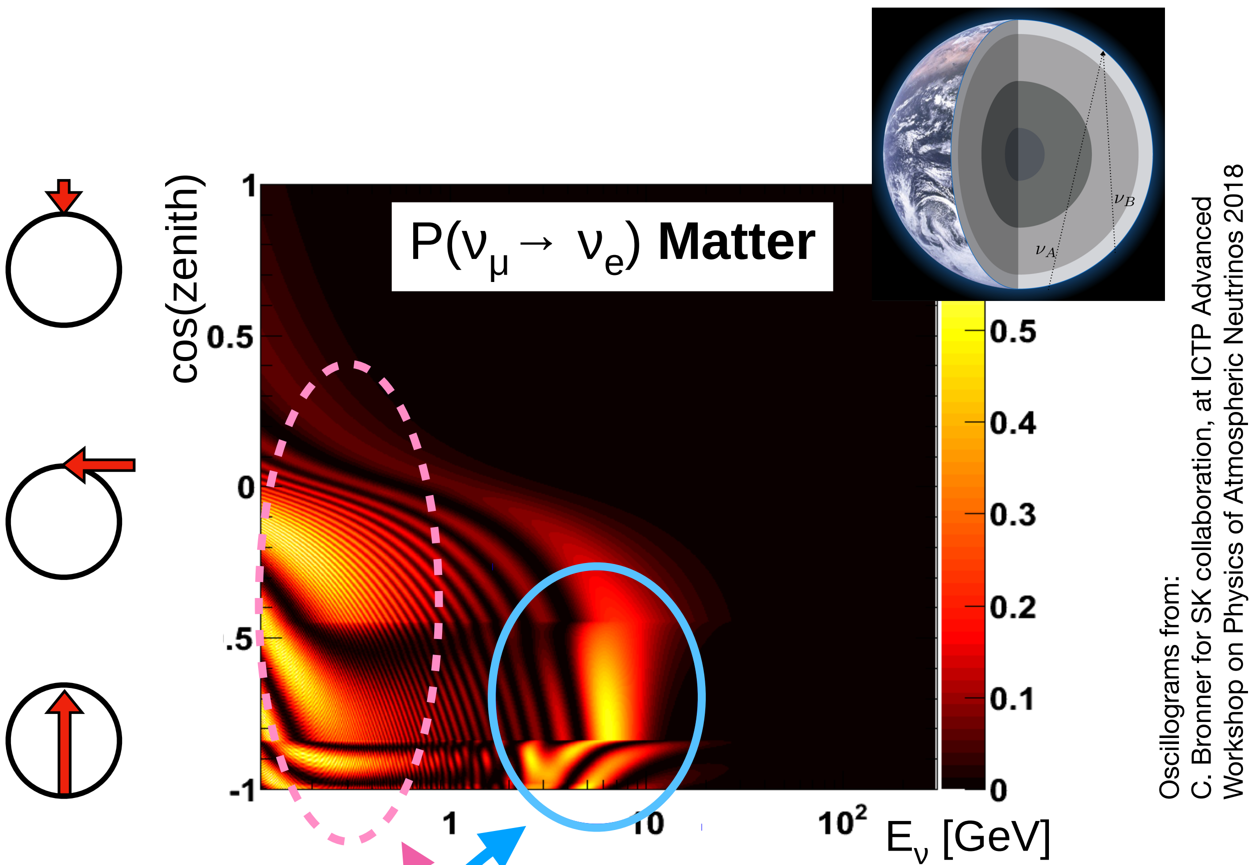
- Anti-correlated change of $\nu_e, \bar{\nu}_e$ appearance probability → δ_{CP}
- For large changes also weakly sensitive to mass ordering

degenerate

When combined, can resolve degeneracy and have better CP violation sensitivity!

CP and mass ordering sensitivity

SK Atmospheric



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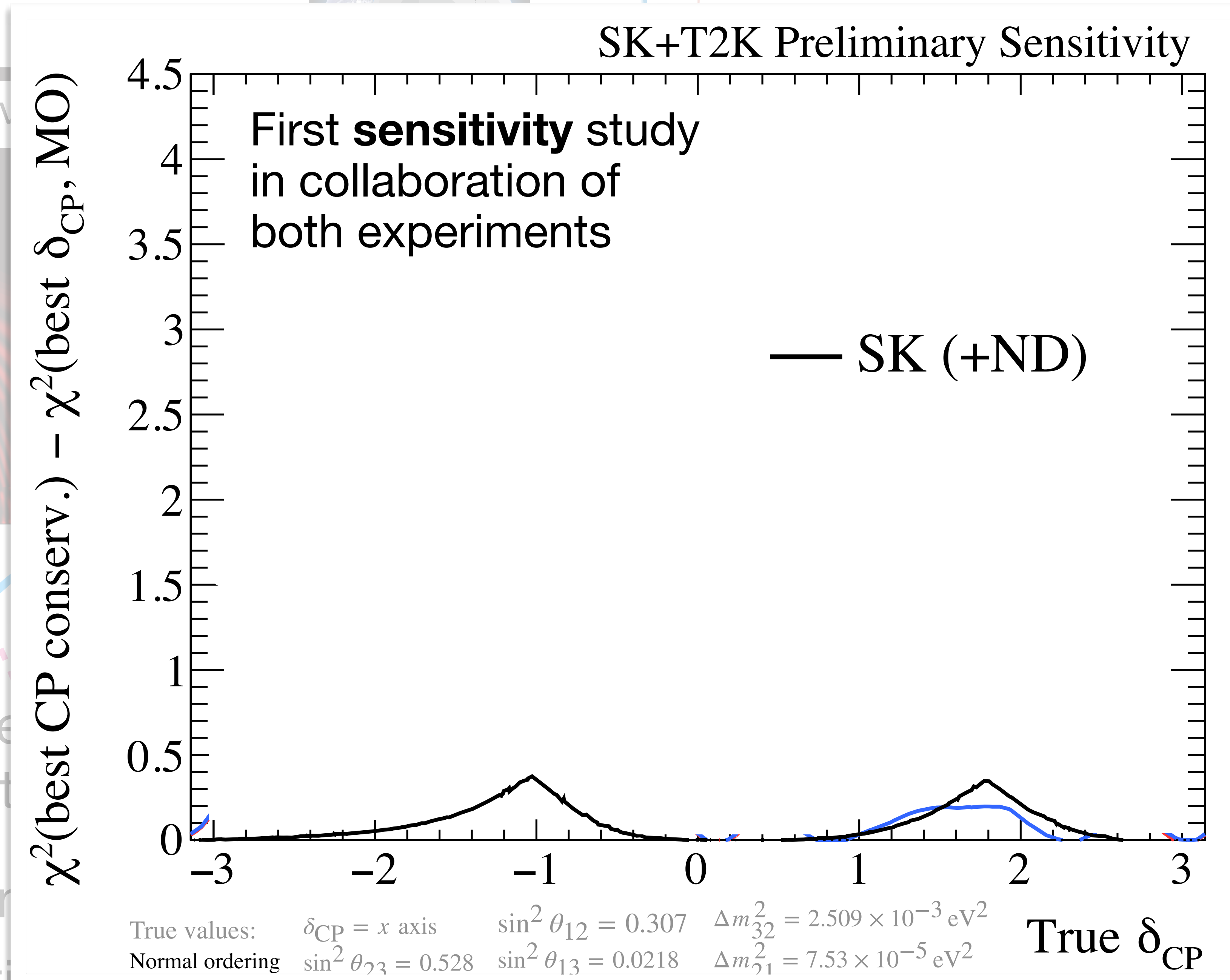

- Resonance ... core sensit...
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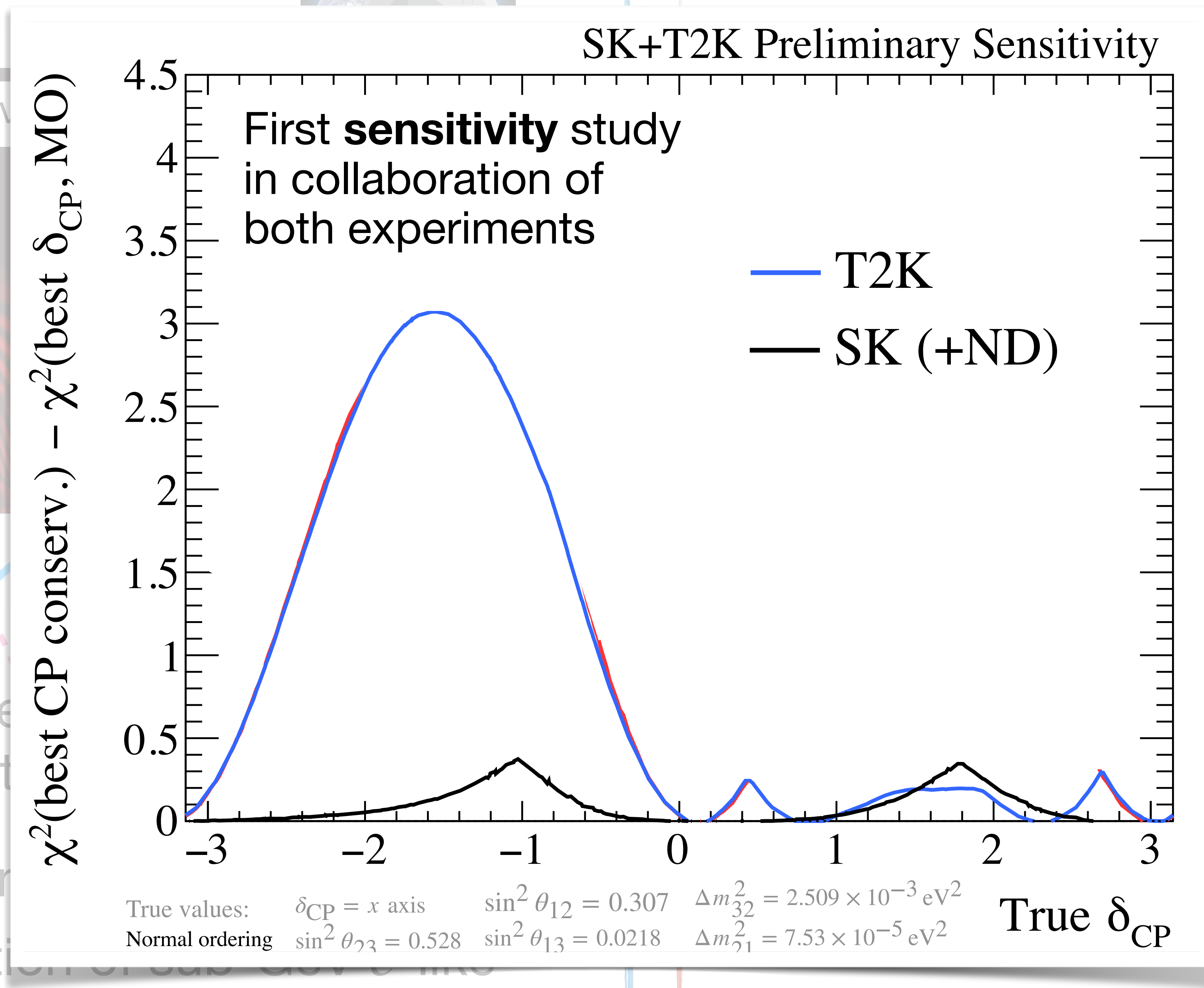

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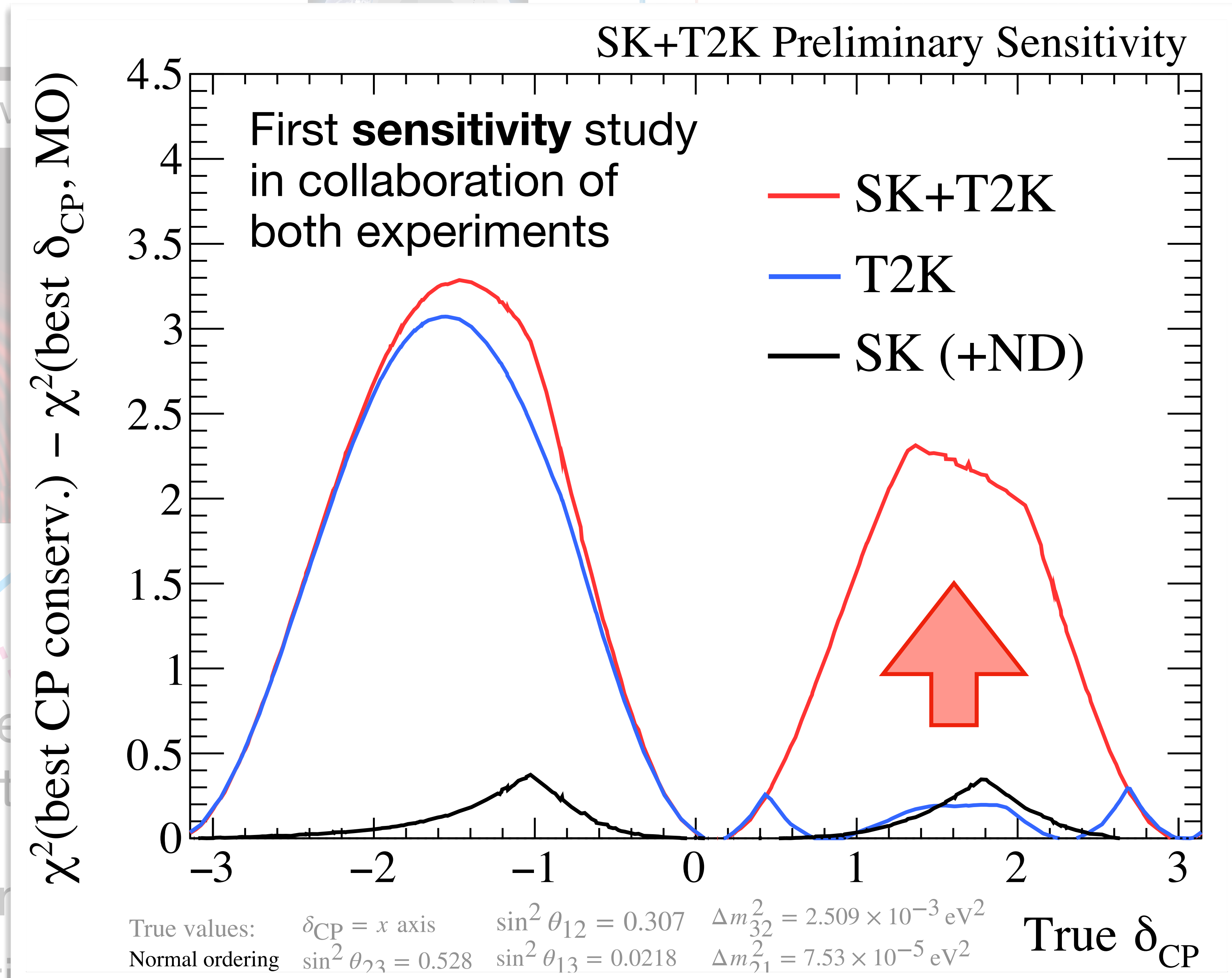

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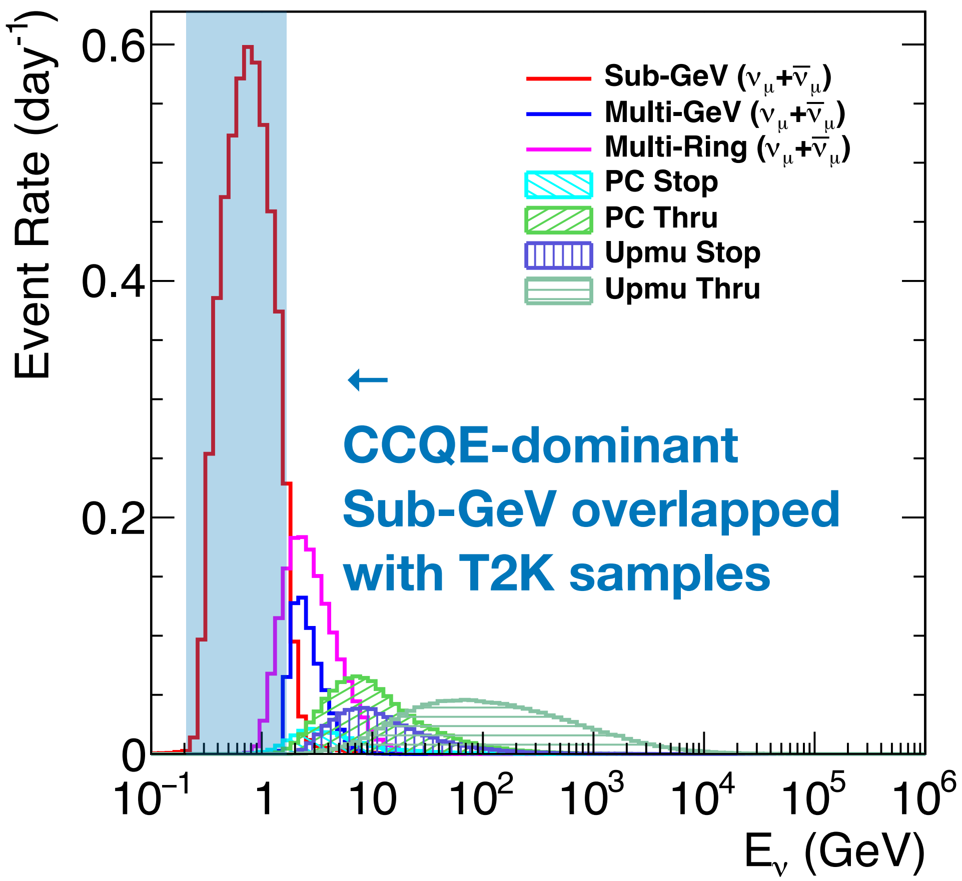
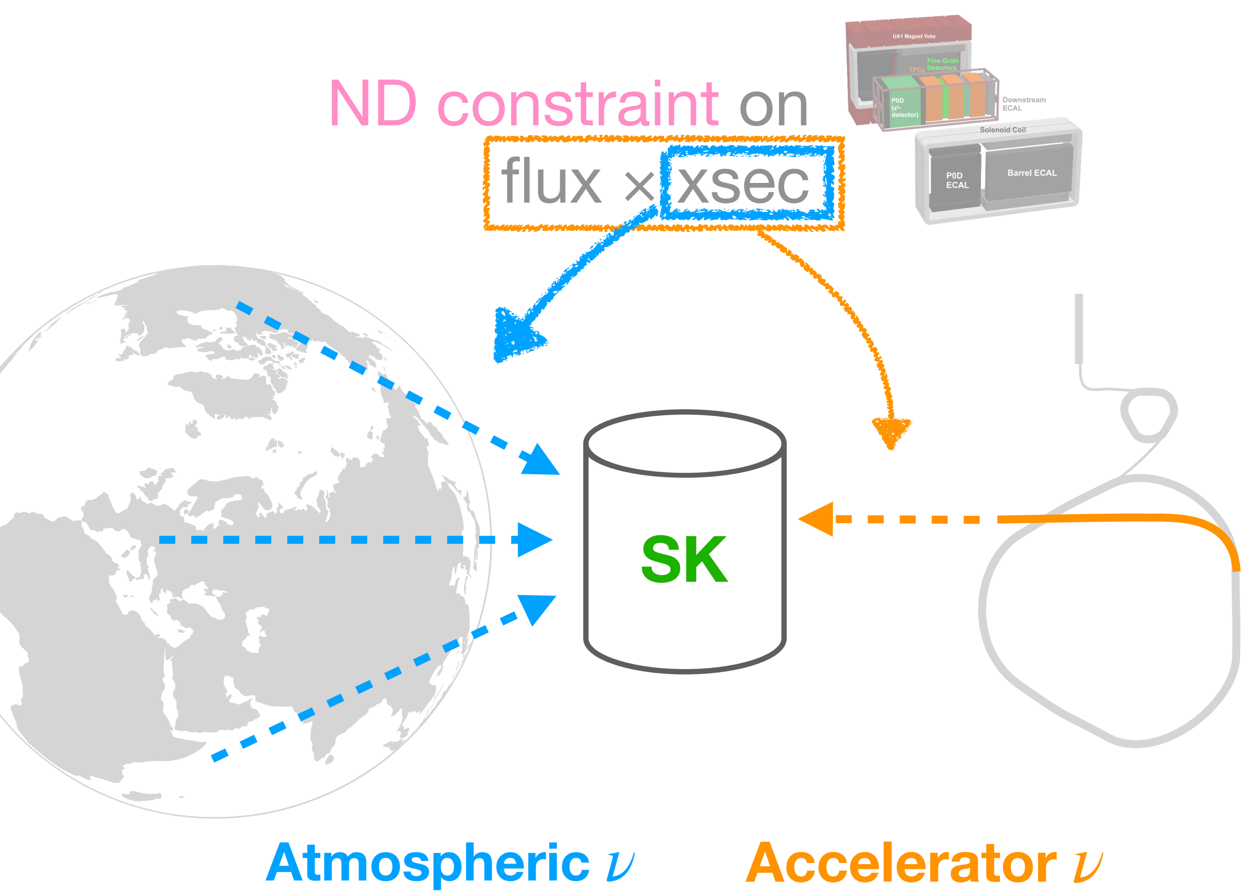
Atmospheric μ-like samples



Systematic correlations

- Overlapping true energy region
  → shared **interaction model** to capture correlations
  → Bonus: **ND constraint** for atmospherics!

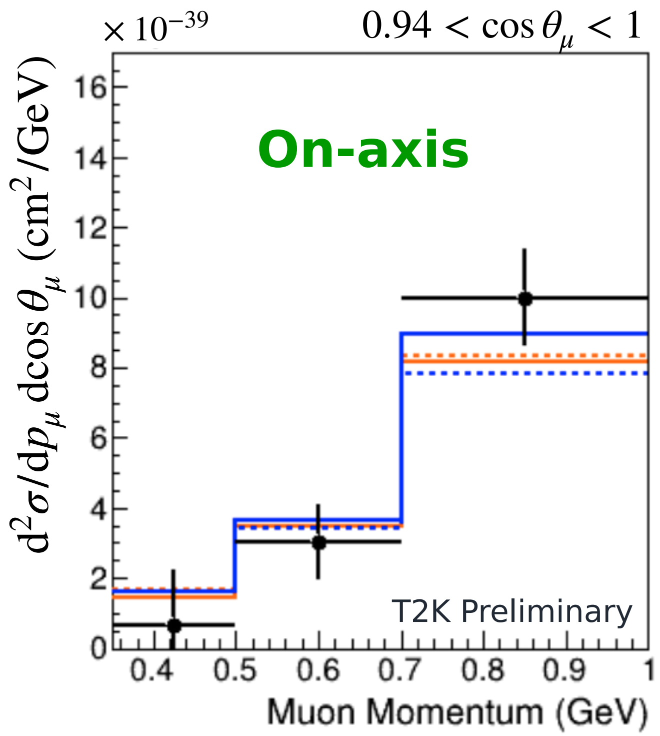


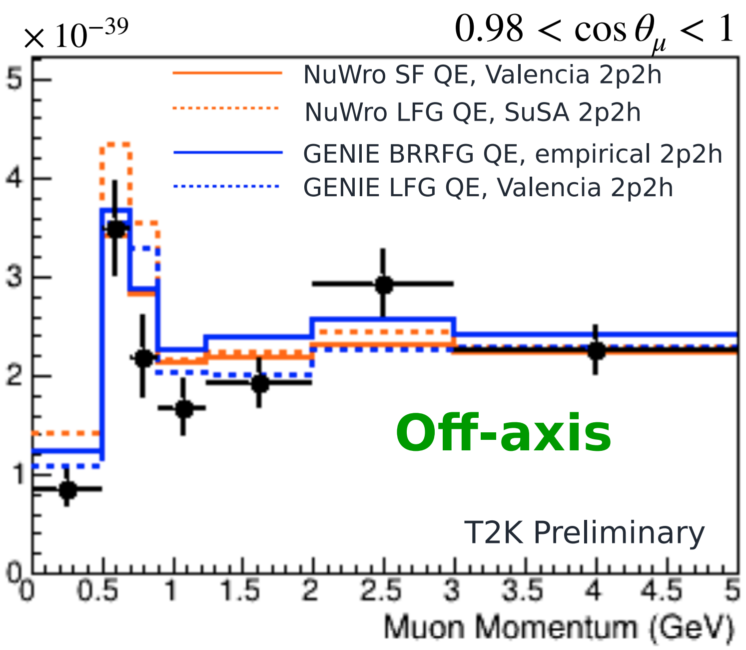
- Same Super-K detector used by both experiments
  → estimate contribution from **detector syst.** correlations

Monday afternoon, **Session I parallel,**
Junjie Xia,
"T2K-SK joint ν oscillation sensitivity"

Measurements of

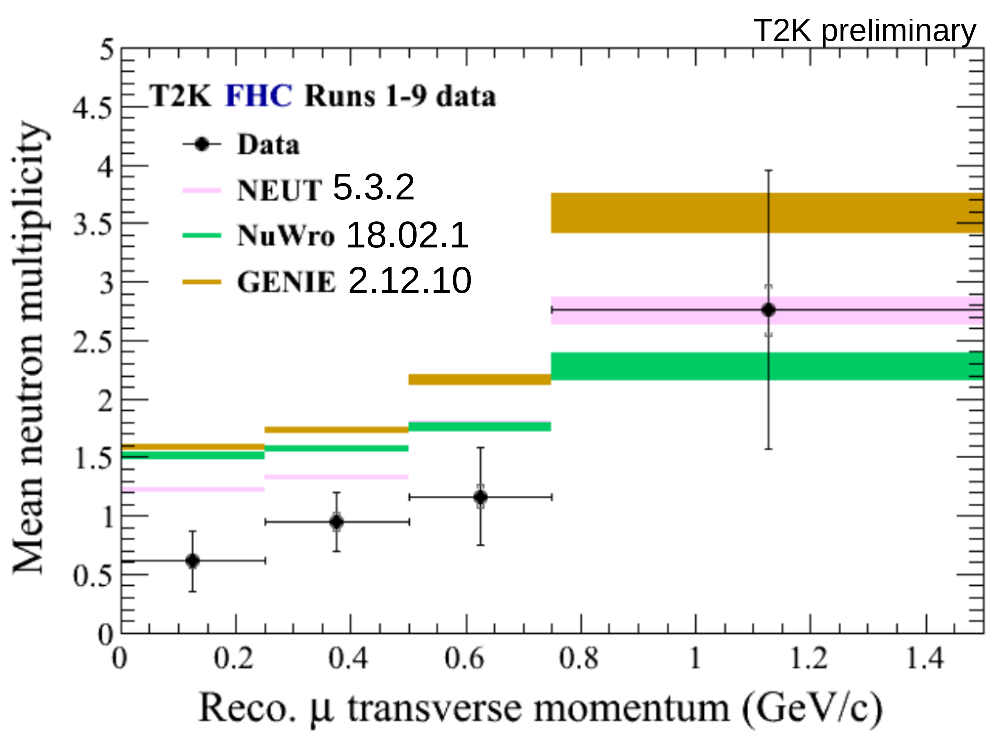
ν cross-section at ND





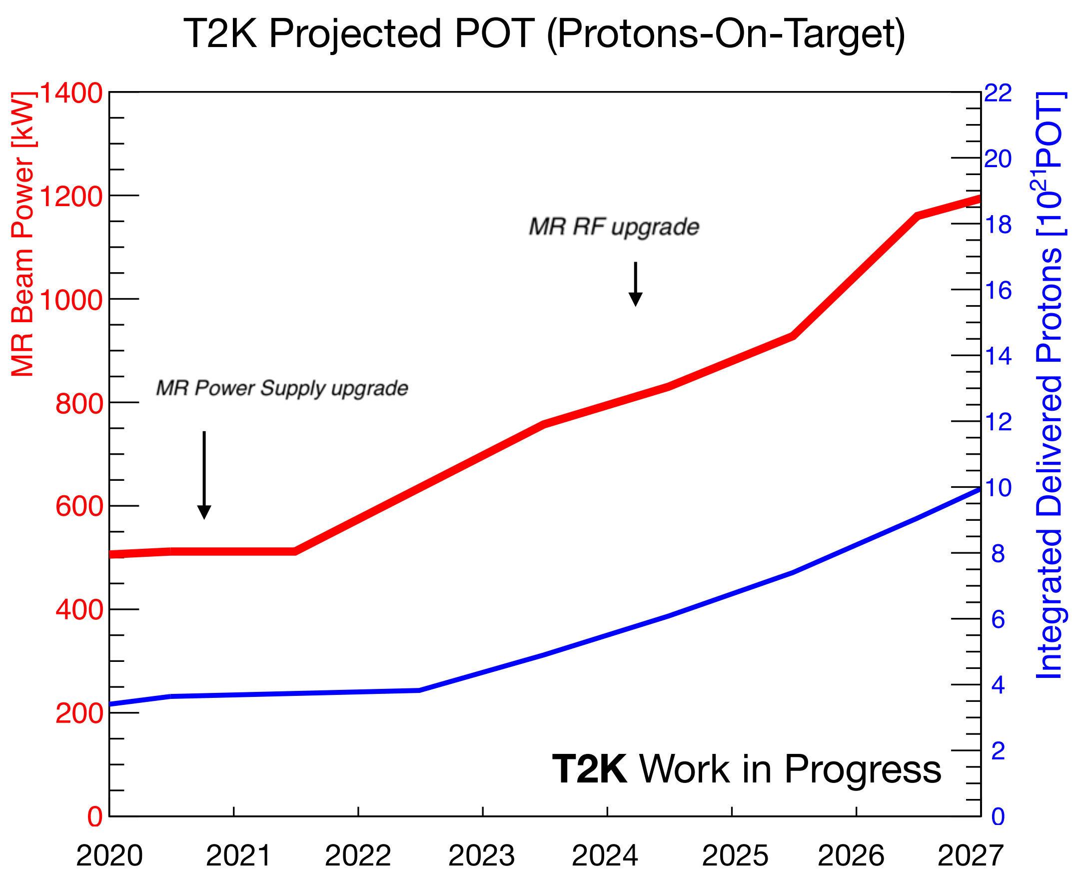
- First joint measurement using different fluxes ↑
- Many other joint measurements ongoing
  - C/O
  - $\nu_\mu/\overline{\nu}_\mu$
- Also challenging low-rate measurements

Neutron multiplicity at SK



- Neutron tagging at SK very interesting for $\nu/\overline{\nu}$ and CC/NC separation, requires good prediction of multiplicity
- Measured multiplicity using T2K beam, all generators over-predict
- Note: measurement uses data before adding Gd

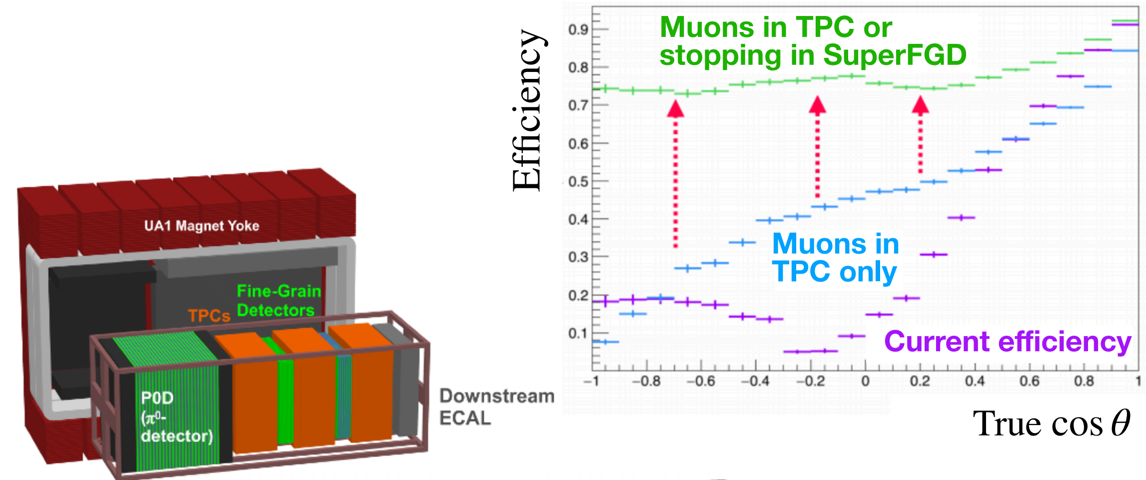
Beam line upgrade

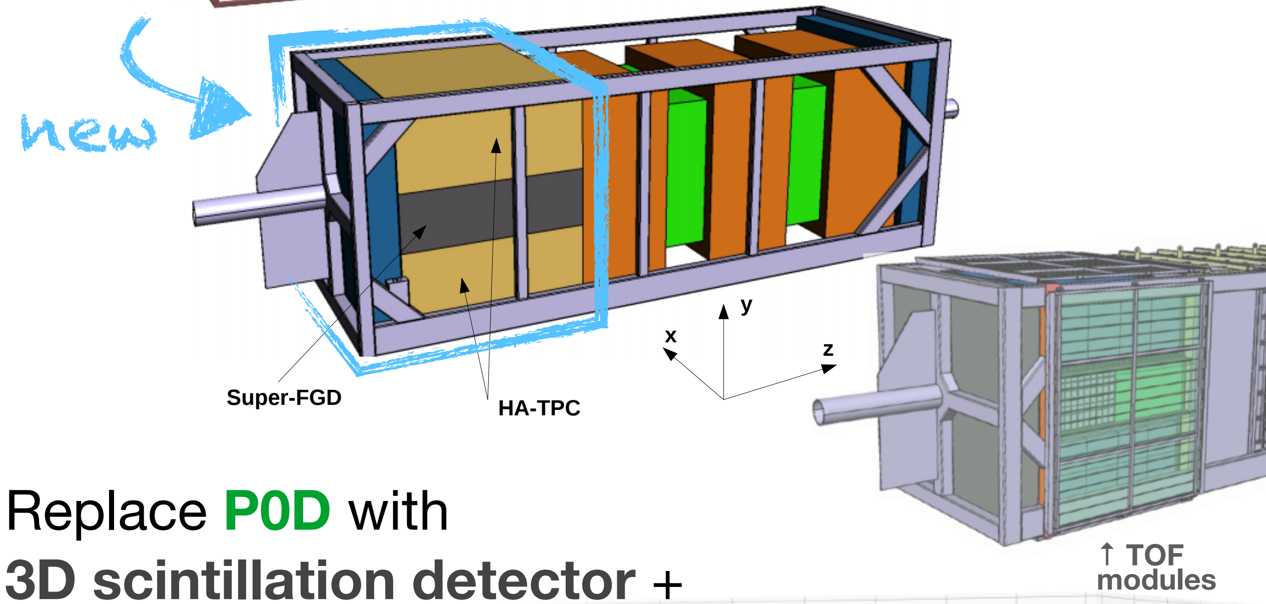


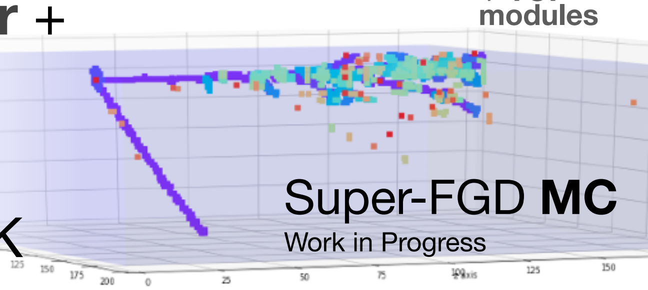
- Increase **beam power** from ~500 kW to 1.3 MW via upgrades to main ring power supply and RF (mostly increased rep rate)
- Many upgrades to neutrino beam line (target, beam monitors, …) ongoing to accept 1.3 MW beam
- Increase **horn current** 250 kA → 320 kA for ~10% more neutrinos/beam-power and reduced wrong-sign background
  Aiming for 320 kA operation in next run!

TDR: arXiv:1908.05141 [physics.ins-det]

ND280 upgrade







Replace **P0D** with
3D scintillation detector +
high-angle TPCs +
TOF enclosure

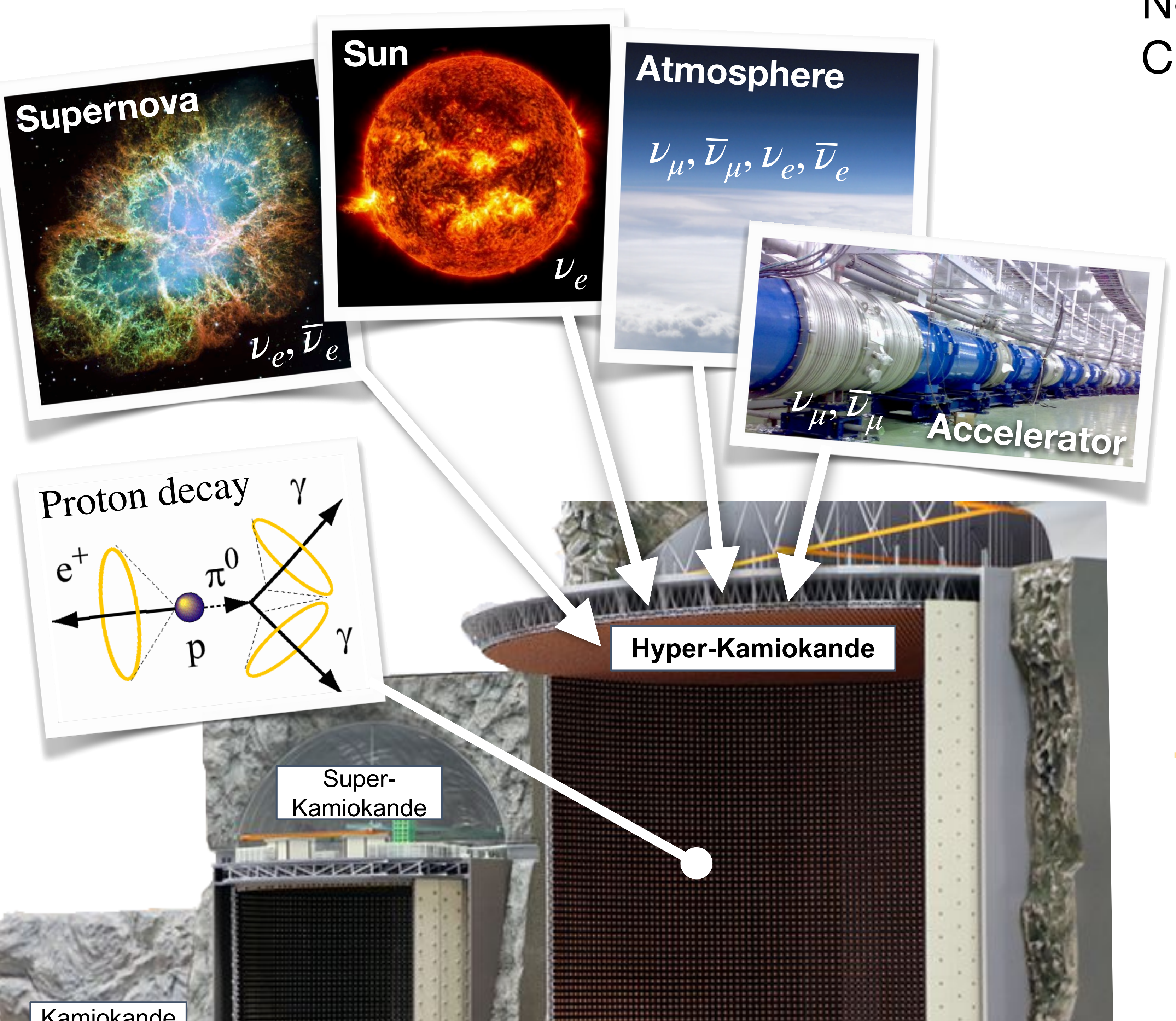
→ 4π acceptance like SK

→ lower (proton) mom. threshold

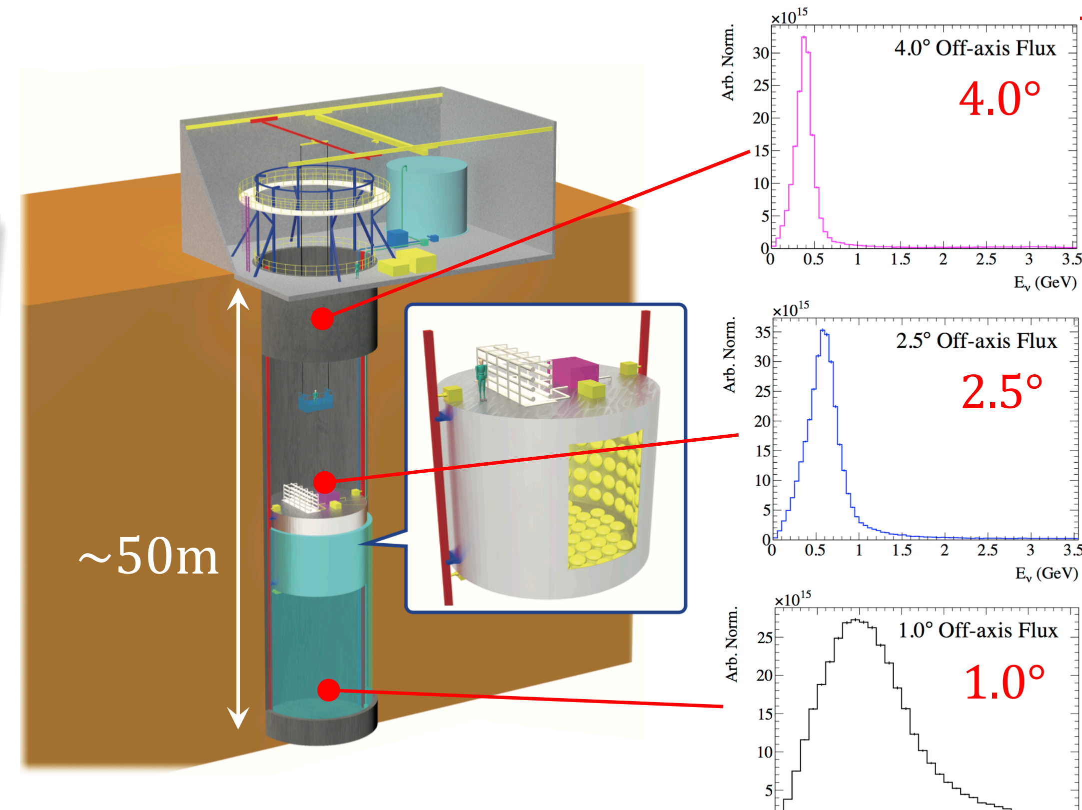
Reduce **xsec systematics** and better understanding of nuclear effects. CERN-SPSC-2019-001 arXiv:1901.03750 [physics.ins-det]

Tuesday afternoon, Session II parallel,
Jaafar Chakrani,
"The T2K near detector Upgrade"

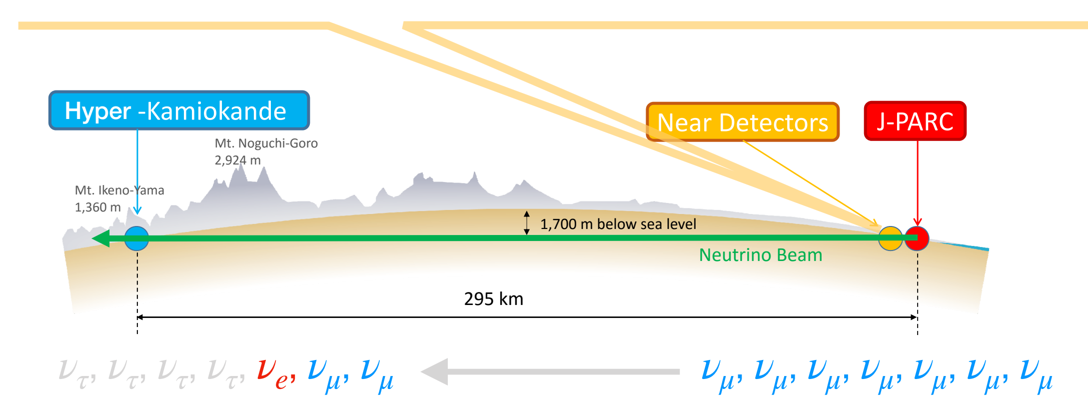
Hyper-Kamiokande / IWCD



New 1 kt scale "intermediate water-Cherenkov detector" planned



Vertically movable



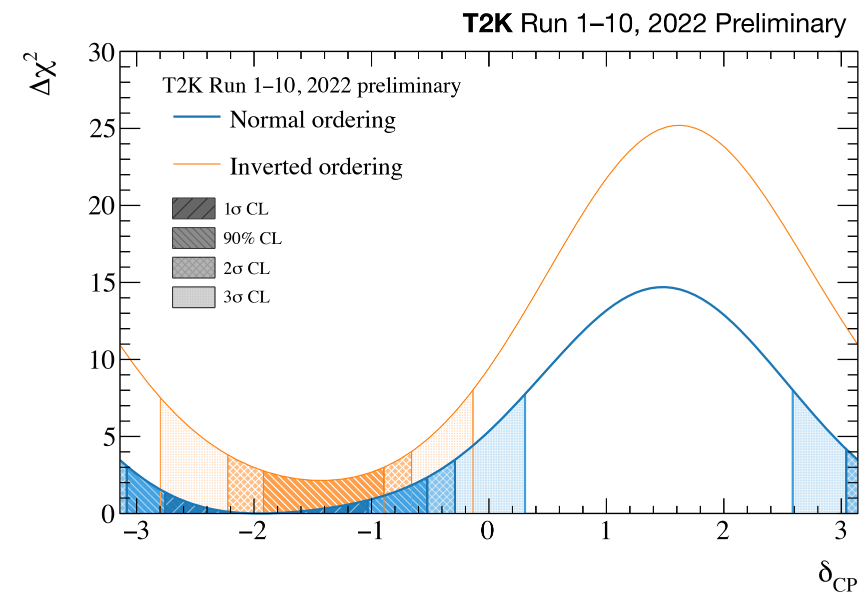
Tuesday morning, Session II plenary,
Zhenxiong Xie,
"Oscillation physics with Hyper-Kamiokande"

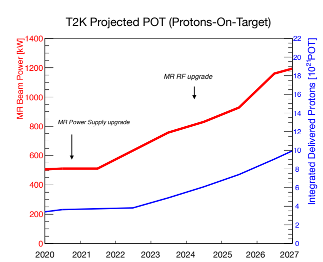
Tuesday afternoon, Session II parallel,
Tailin Zhu,
"HK and the Intermediate Water Cherenkov Detector"

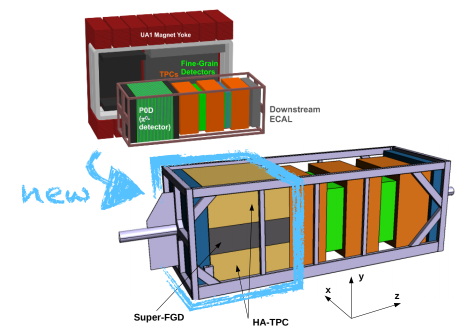
Summary

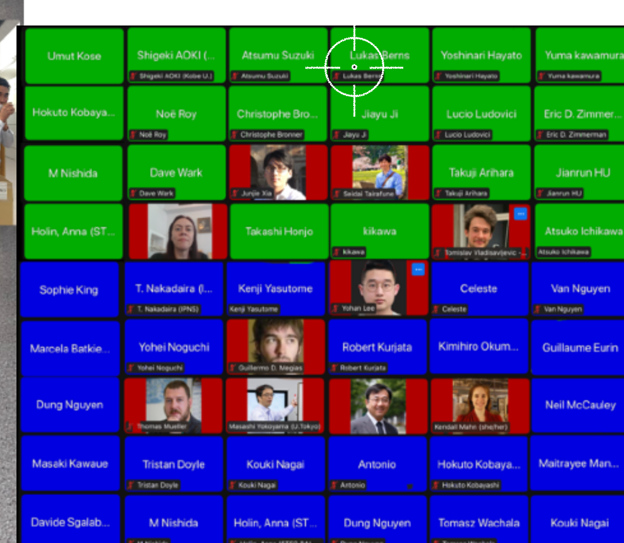
- Latest **T2K** neutrino oscillation results using 3.6×10^{21} protons on target, with **many improvements** at each level of analysis.
- **CP** conserving values of δ_{CP} excluded at 90%, **large range** excluded at 3σ.
- Weak preference for normal **ordering** and upper **octant**.
- Ongoing **joint** analyses with SK / NOvA, xsec and neutron multiplicity measurements
- Exciting perspective for **future**: new detectors, stronger beam, …

stay tuned!









backup

Systematic uncertainties

Before ND fit T2K Run 1-10, 2022 Preliminary

	1R		MR	1Re			
Error source (units: %)	FHC	RHC	FHC CC1π^+	FHC	RHC	FHC CC1π^+	FHC/RHC
Flux	5.0	4.6	5.2	4.9	4.6	5.1	4.5
Cross-section (all)	15.8	13.6	10.6	16.3	13.1	14.7	10.5
SK+SI+PN	2.6	2.2	4.0	3.1	3.9	13.6	1.3
Total All	16.7	14.6	12.5	17.3	14.4	20.9	11.6

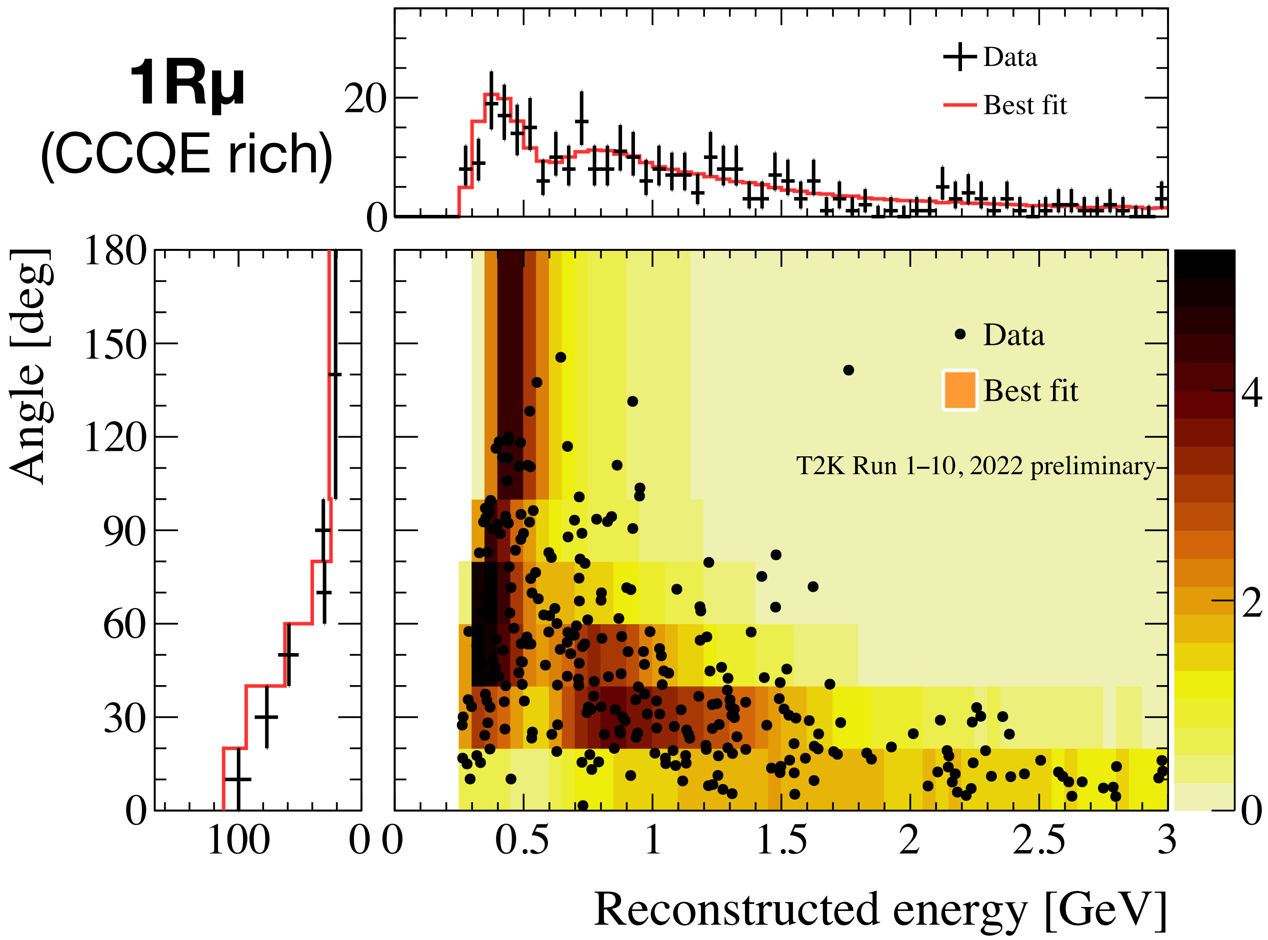
After ND fit T2K Run 1-10, 2022 Preliminary

	1R		MR	1Re			
Error source (units: %)	FHC	RHC	FHC CC1π^+	FHC	RHC	FHC CC1π^+	FHC/RHC
Flux	2.8	2.9	2.8	2.8	3.0	2.8	2.2
Xsec (ND constr)	3.7	3.5	3.0	3.8	3.5	4.1	2.4
Flux+Xsec (ND constr)	2.7	2.6	2.2	2.8	2.7	3.4	2.3
Xsec (ND unconstr)	0.7	2.4	1.4	2.9	3.3	2.8	3.7
SK+SI+PN	2.0	1.7	4.1	3.1	3.8	13.6	1.2
Total All	3.4	3.9	4.9	5.2	5.8	14.3	4.5

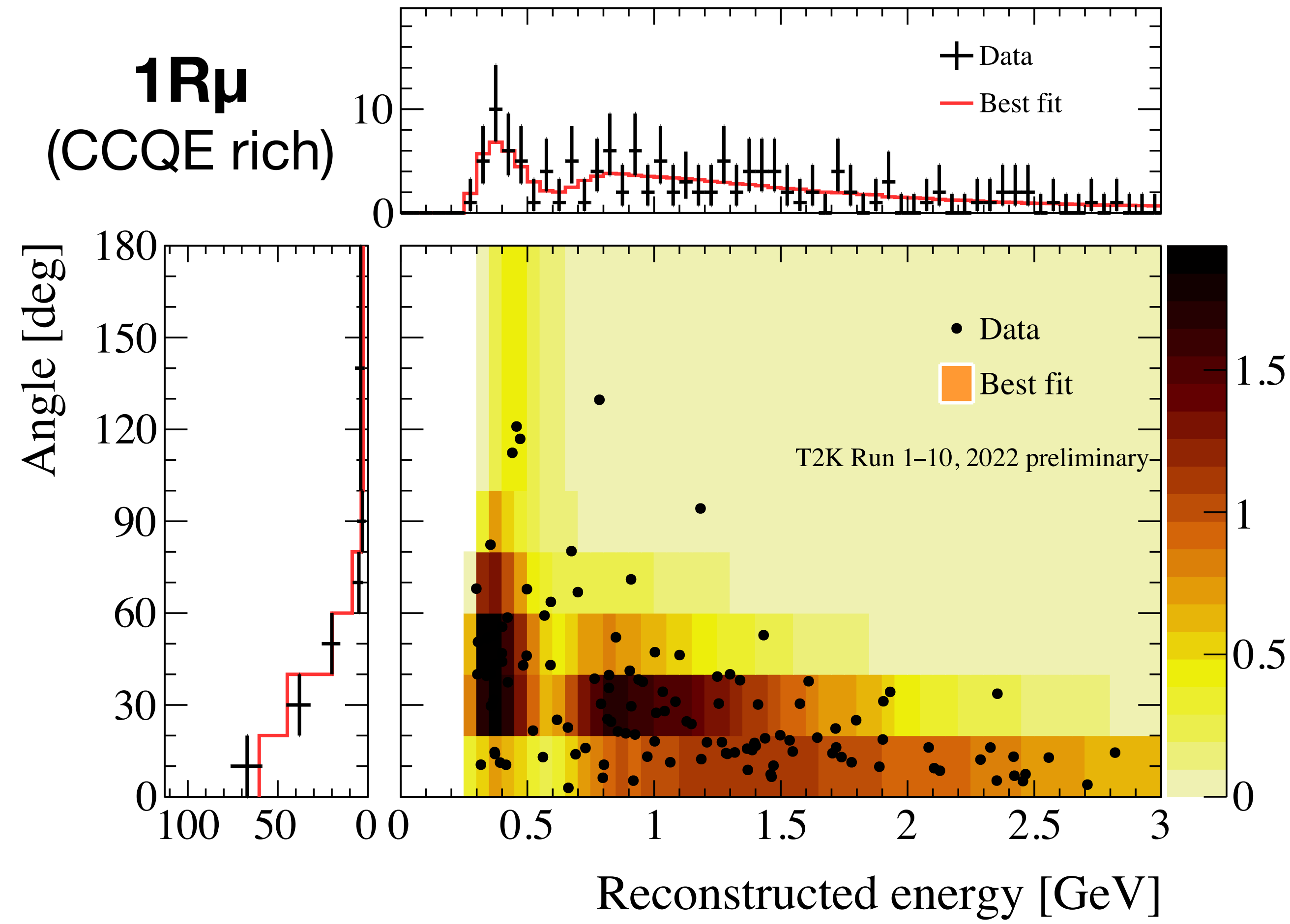
Neutrino mode

Antineutrino mode

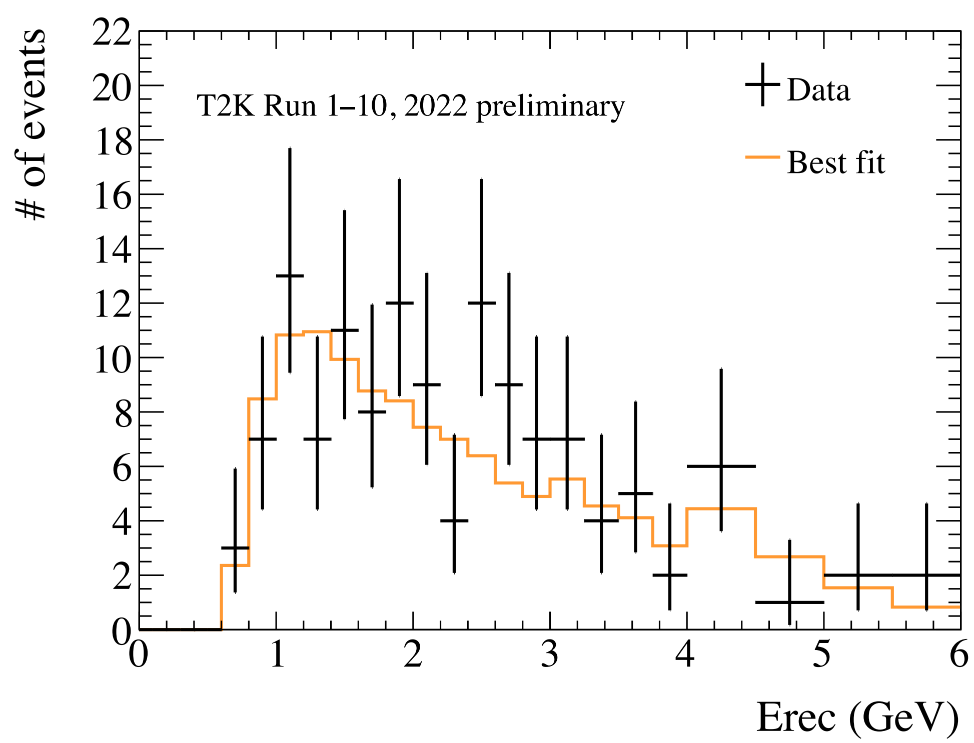
1Rμ
(CCQE rich)



1Rμ
(CCQE rich)



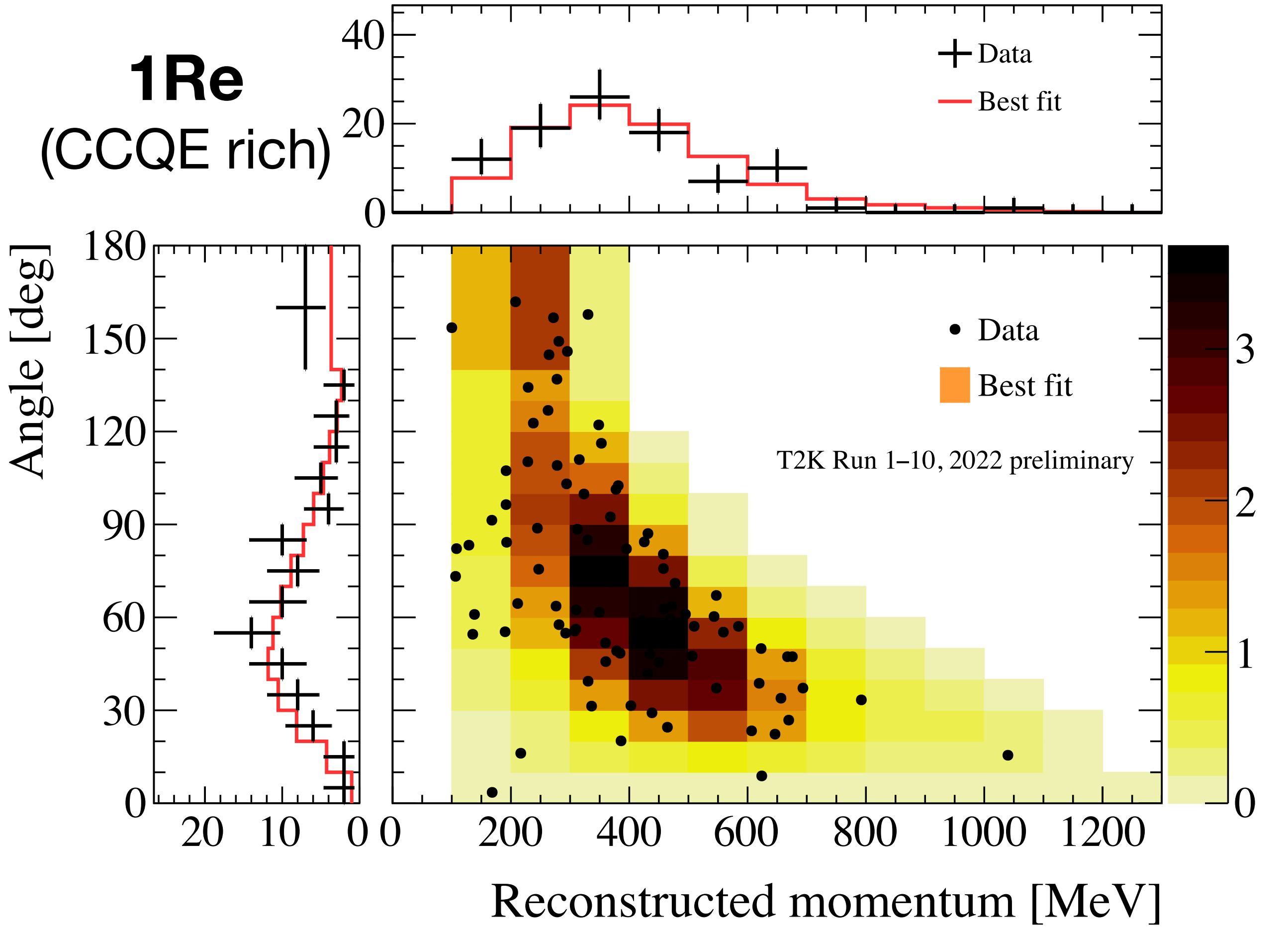
1+2R μ+π
(CC1π rich)



μ-like event distributions

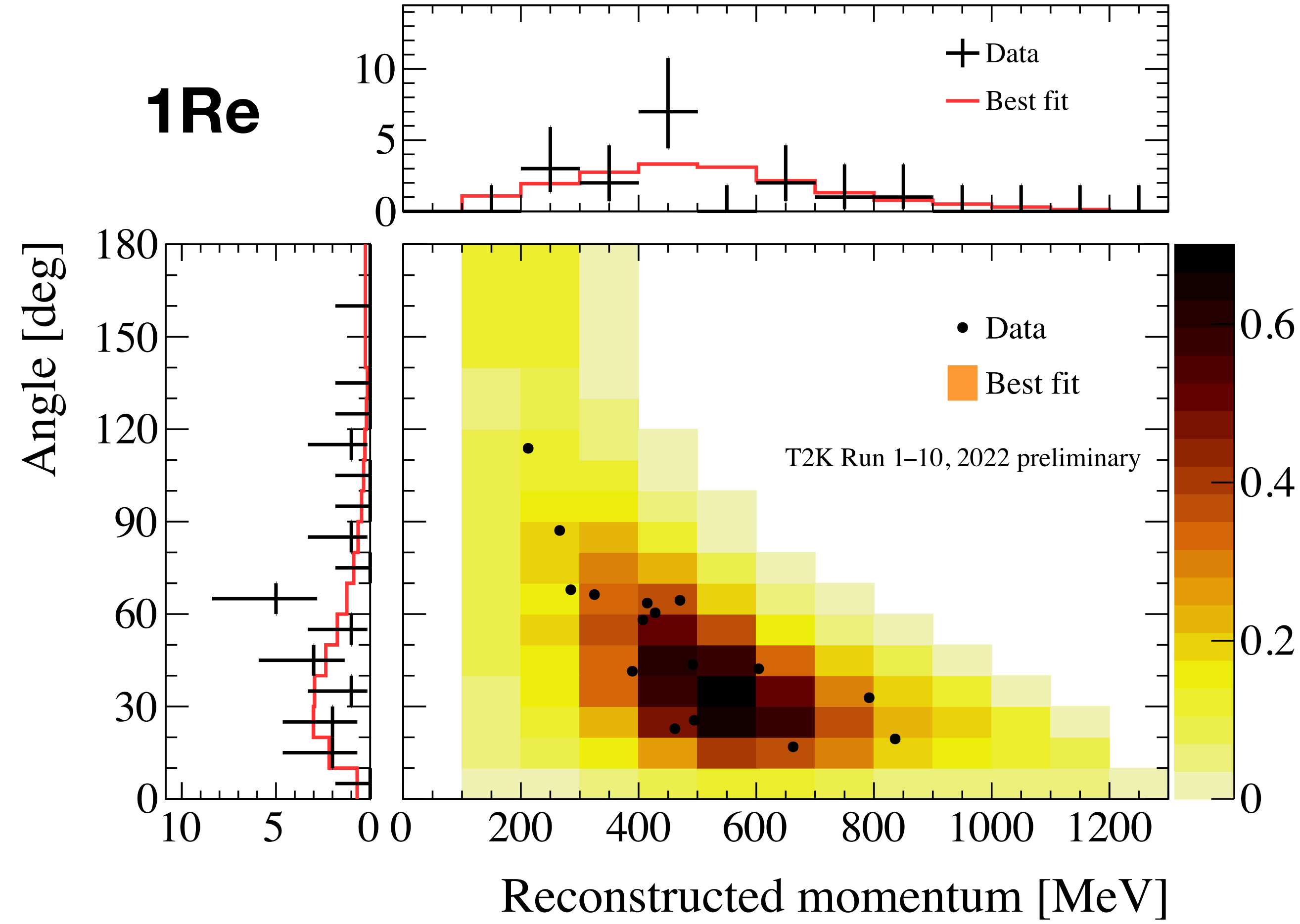
Neutrino mode

1Re
(CCQE rich)

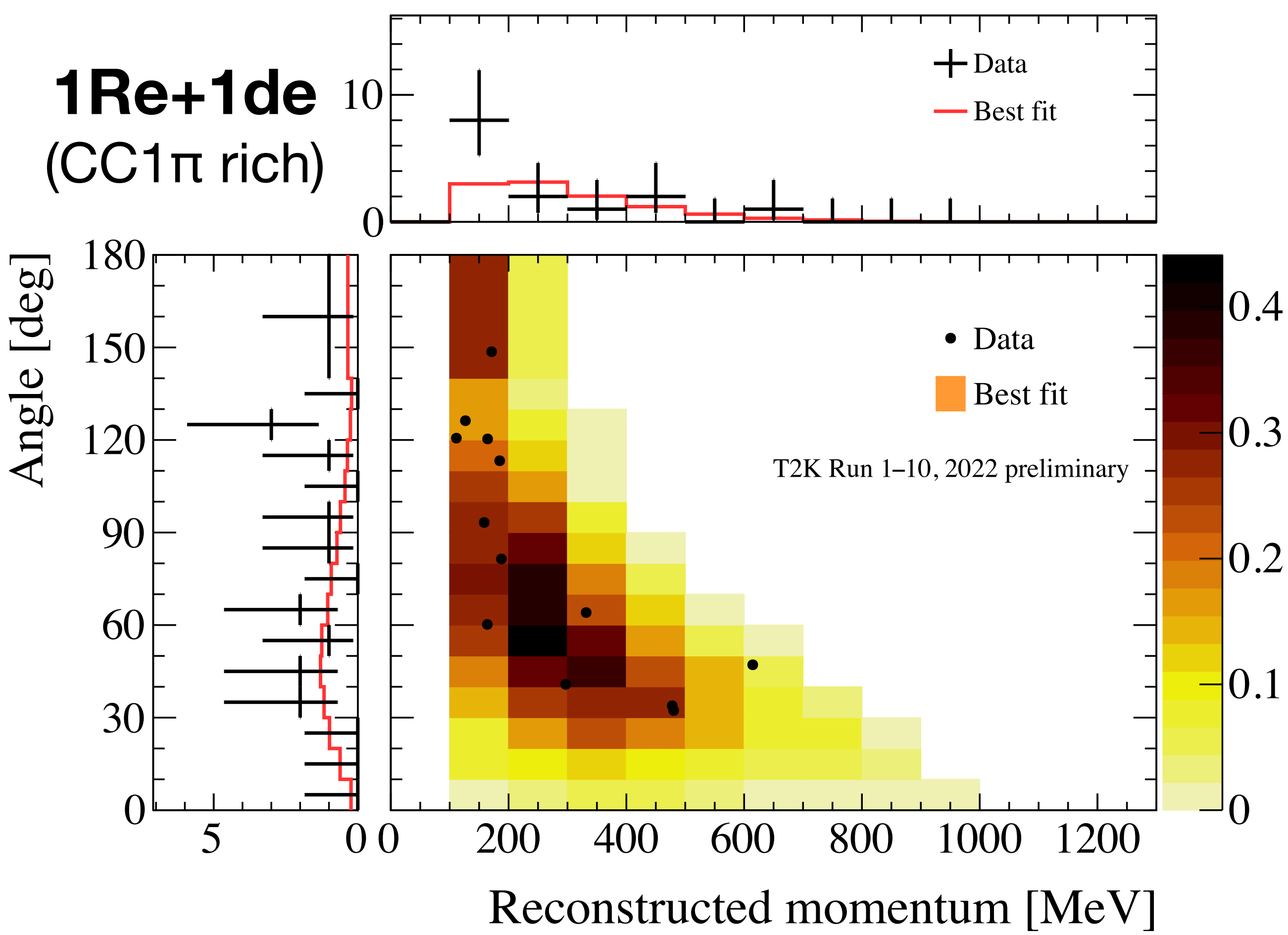


Antineutrino mode

1Re



1Re+1de
(CC1π rich)



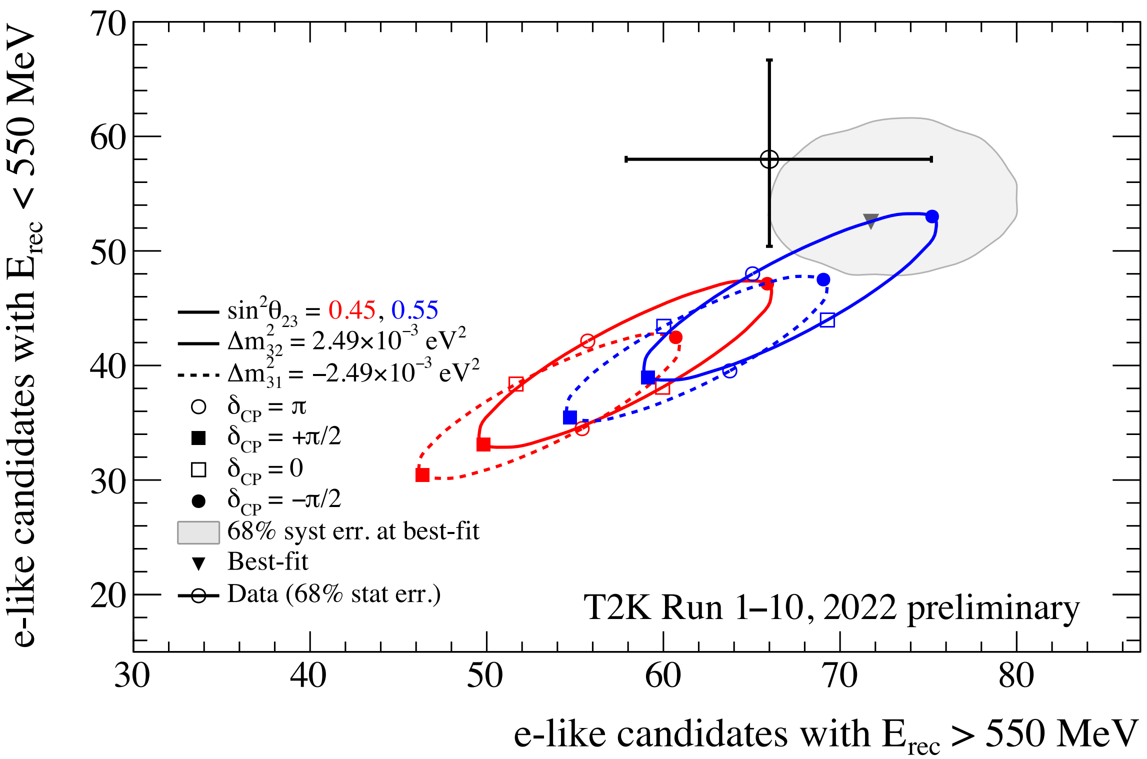
e-like event distributions

Best-fit values

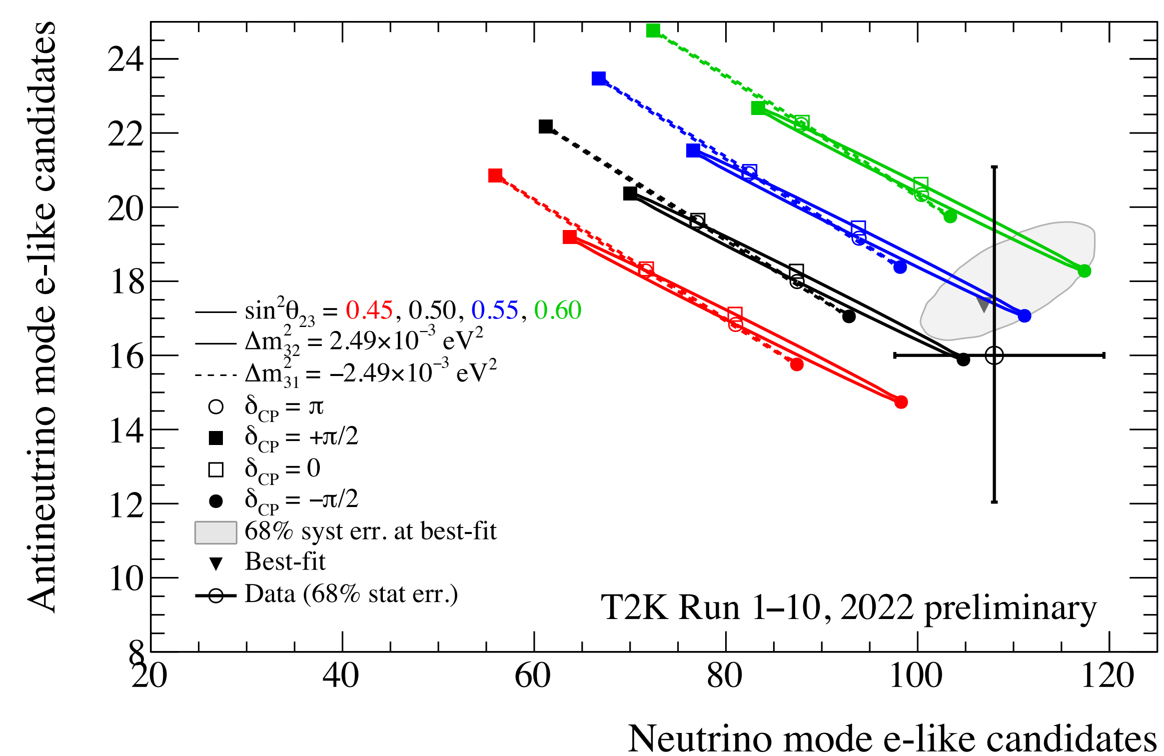
Parameter	Best fit			
Data	T2K only		T2K + reactor	
Hierarchy	Normal	Inverted	Normal	Inverted
$\sin^2(2\theta_{13})$	0.103	0.114	0.0861	0.0865
$\sin^2(\theta_{13})/10^{-3}$	$26.6^{+2.8}_{-5.8}$	$29.3^{+3.1}_{-6.1}$	$22.0^{+0.76}_{-0.6}$	$22.1^{+0.74}_{-0.63}$
δ_{CP}	$-2.25^{+1.39}_{-0.75}$	$-1.25^{+0.69}_{-0.91}$	$-2.18^{+1.22}_{-0.47}$	$-1.37^{+0.52}_{-0.68}$
Δm^2_{32} (NH)/$\lvert\Delta m^2_{31}\rvert$ (IH) $[10^{-3}\ \mathrm{eV}^2/\mathrm{c}^4]$	$2.506^{+0.048}_{-0.058}$	$2.474^{+0.049}_{-0.056}$	$2.506^{+0.047}_{-0.059}$	$2.473^{+0.051}_{-0.054}$
$\sin^2(\theta_{23})$	$0.466^{+0.106}_{-0.015}$	$0.465^{+0.103}_{-0.015}$	$0.559^{+0.018}_{-0.078}$	$0.560^{+0.019}_{-0.041}$
$-2\ln L$	651.433	652.254	651.584	653.222
$-2\Delta\ln L$	0	0.821	0	1.638

T2K Run 1-10, preliminary

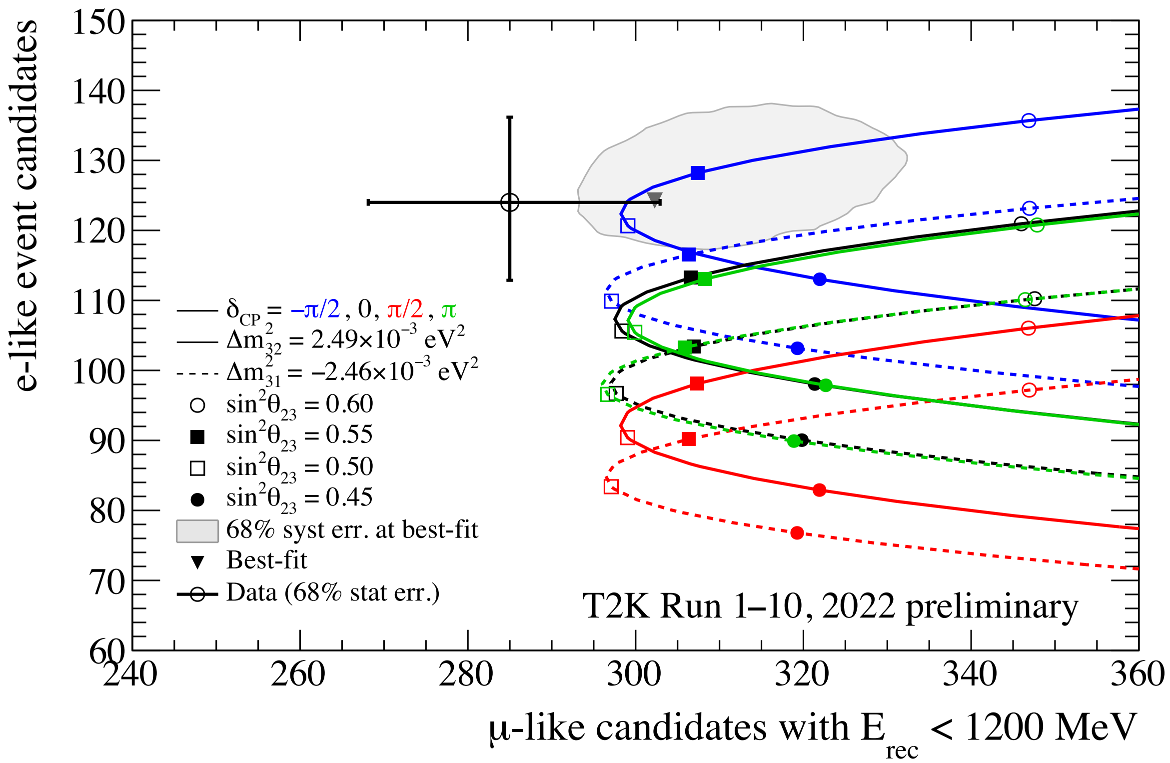
Understanding $\cos\delta$ sensitivity



Understanding $\sin\delta$, MO sensitivity



Understanding θ_{23} sensitivity

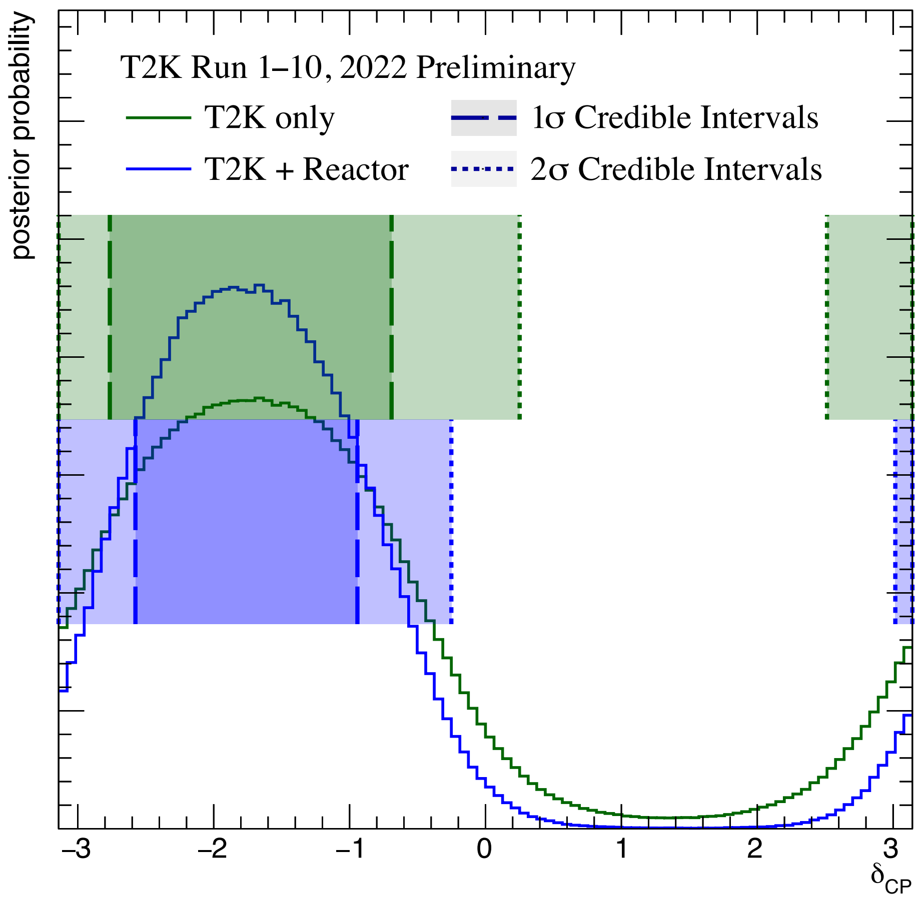


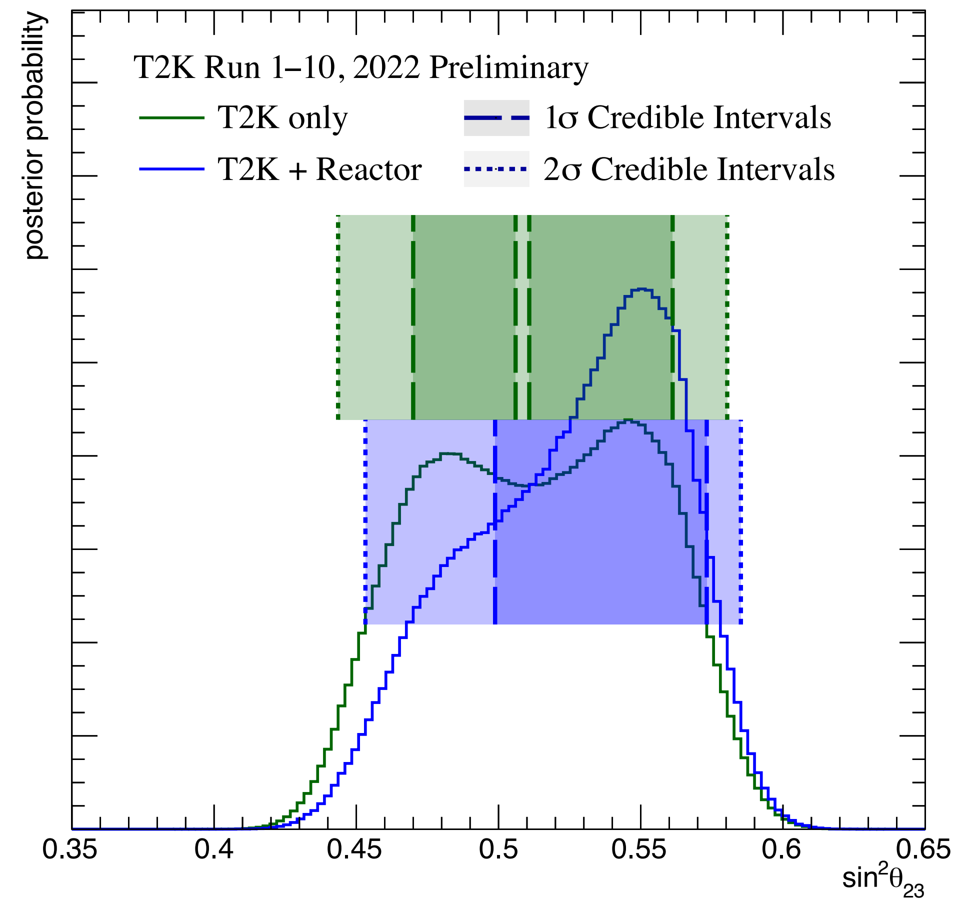
Bi-event plots to illustrate constraints

- Note: especially for μ-like samples the number of events only shows a partial picture

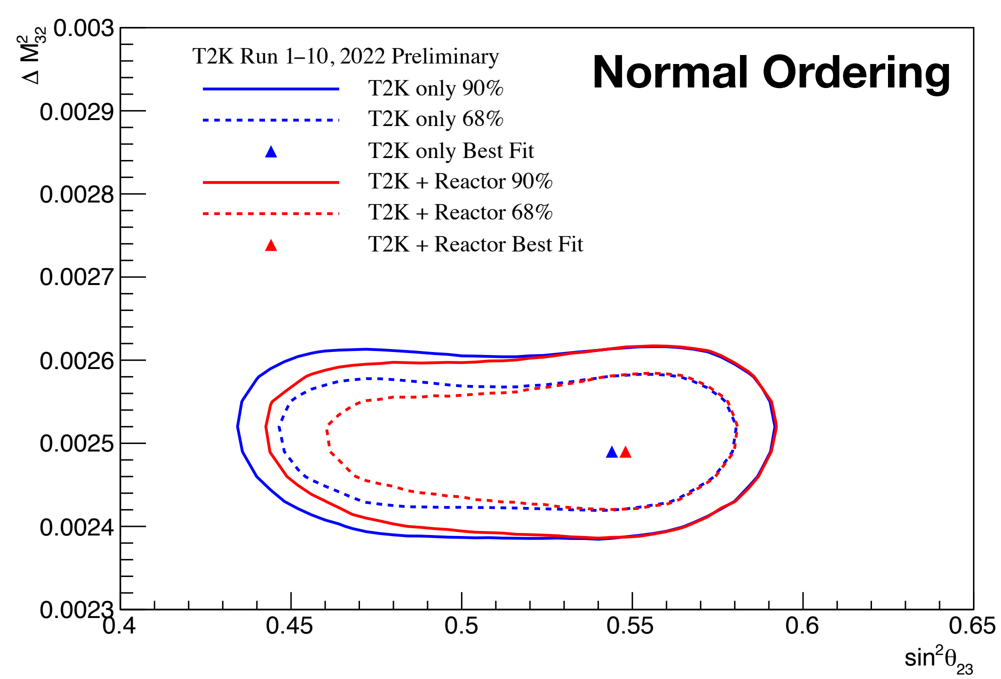
68% syst err. at best-fit
▼ Best-fit
Data (68% stat err.)

Bayesian credible intervals





- Priors flat in plotted variables are assumed
- Top two plots marginalized over mass ordering with uniform prior
- Qualitatively similar results to frequentist fits.
- Application of reactor constraint on θ_{13} results in preference of upper octant.



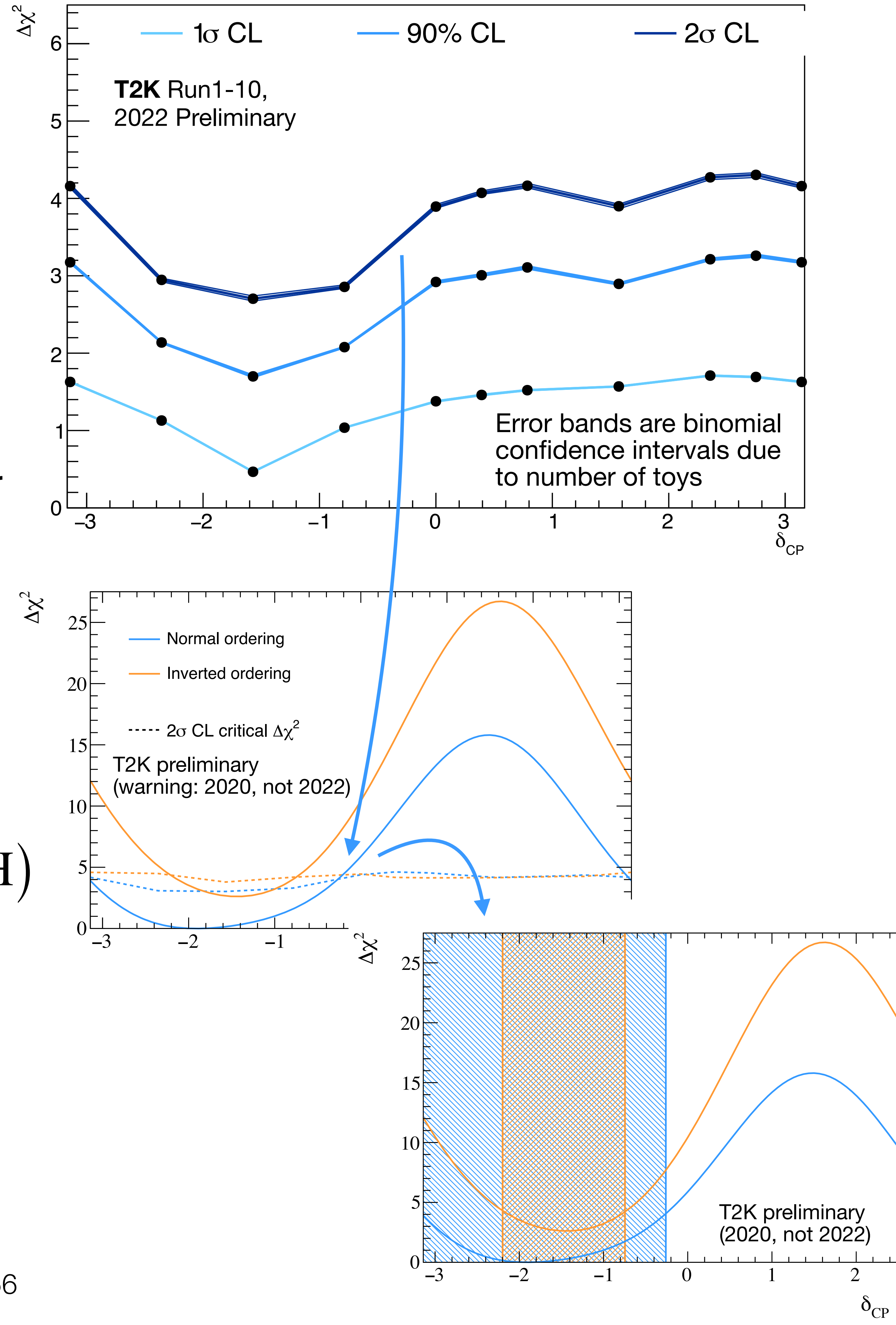
Feldman Cousins implementation

- For proper estimation of δ_{CP}, θ_{23} confidence intervals, we use Feldman Cousins method:

- At couple true δ_{CP}+MH values, generate 50k toy experiments. θ_{13} is sampled from reactor prior. θ_{23}, Δm^2_{32} are sampled from an Asimov contour with true params set to data-best-fit point.

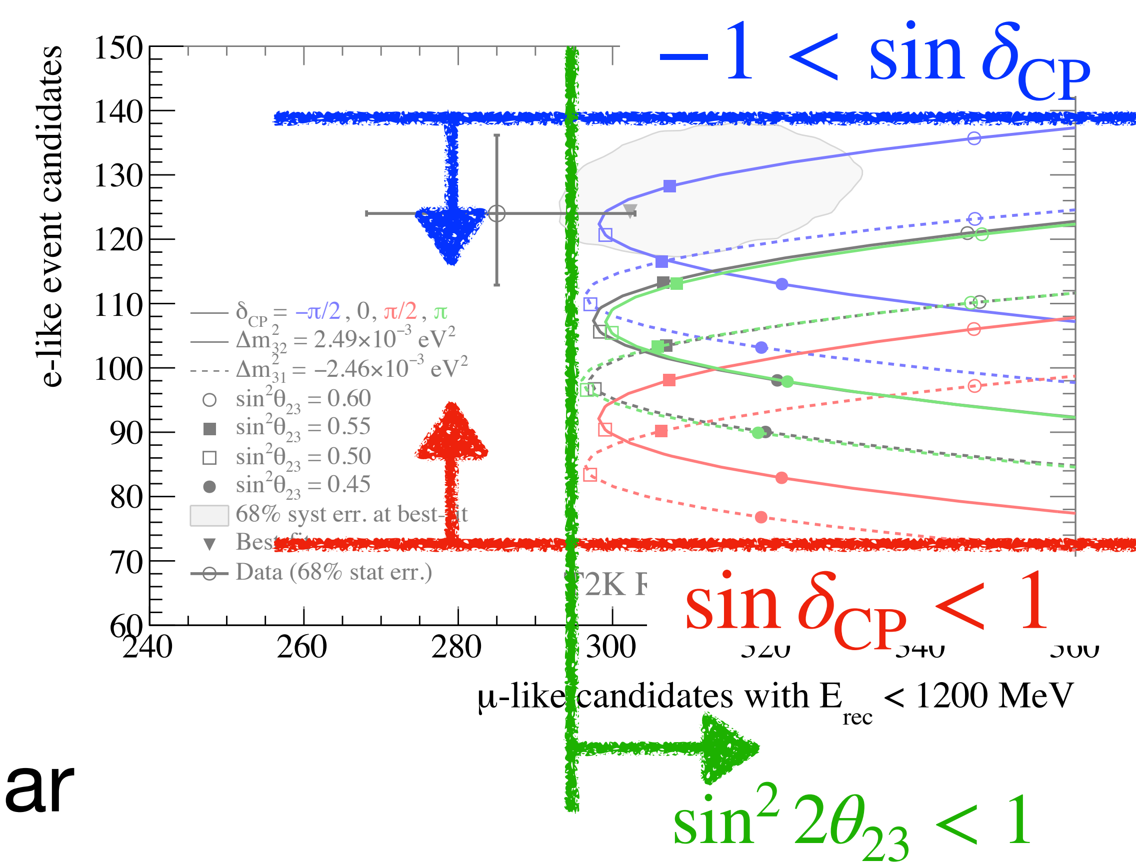
- Fit each toy to calculate $\chi^2(\delta_{CP}, \mathrm{MH})$ curves, and order toys according to $\Delta\chi^2_{\mathrm{true}} = \chi^2\left(\delta_{\mathrm{true}}, \mathrm{MH}_{\mathrm{true}}\right) - \min_{\delta,\mathrm{MH}} \chi^2\left(\delta, \mathrm{MH}\right)$
Define lower 68.3%, 90%, … quantiles as critical values $\Delta\chi^2_c$

- Connect critical values for all true δ_{CP} values (linear interpolation) and define confidence interval by intersection with data-$\Delta\chi^2$ curve.



Causes of coverage issues

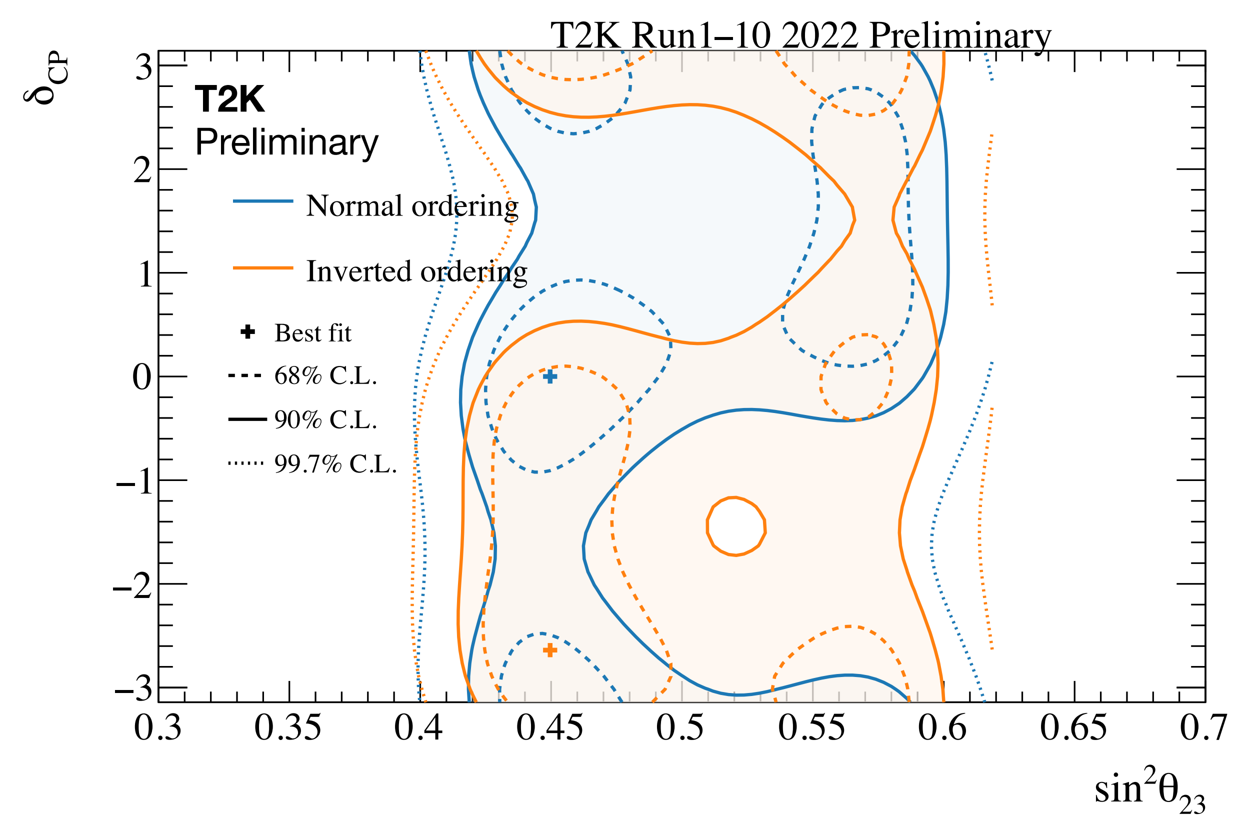
- Physical boundaries decrease $\Delta\chi^2_c$:
  $-1 < \sin\delta_{\rm CP} < 1$ and $\sin^2 2\theta_{23} < 1$



- Discrete degrees of freedom, in particular degeneracies increase $\Delta\chi^2_c$:

  8-fold degeneracy of
  (θ_{23} octant) × (sign of $\cos\delta$) × (MO)

8-fold degeneracy seen for Asimov sensitivity at true NO, lower octant, $\delta = 0$ ↓

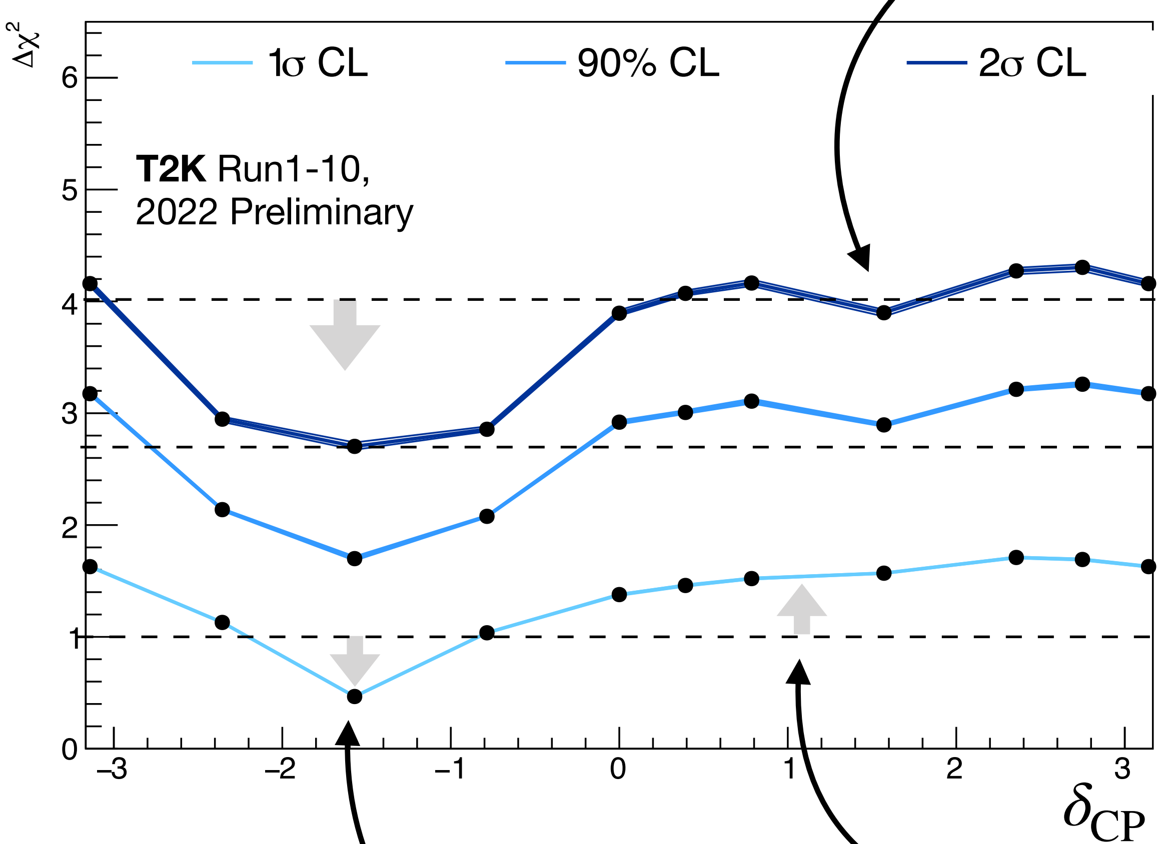


- Non-trivial effect due to prior distribution of nuisance params in the toys

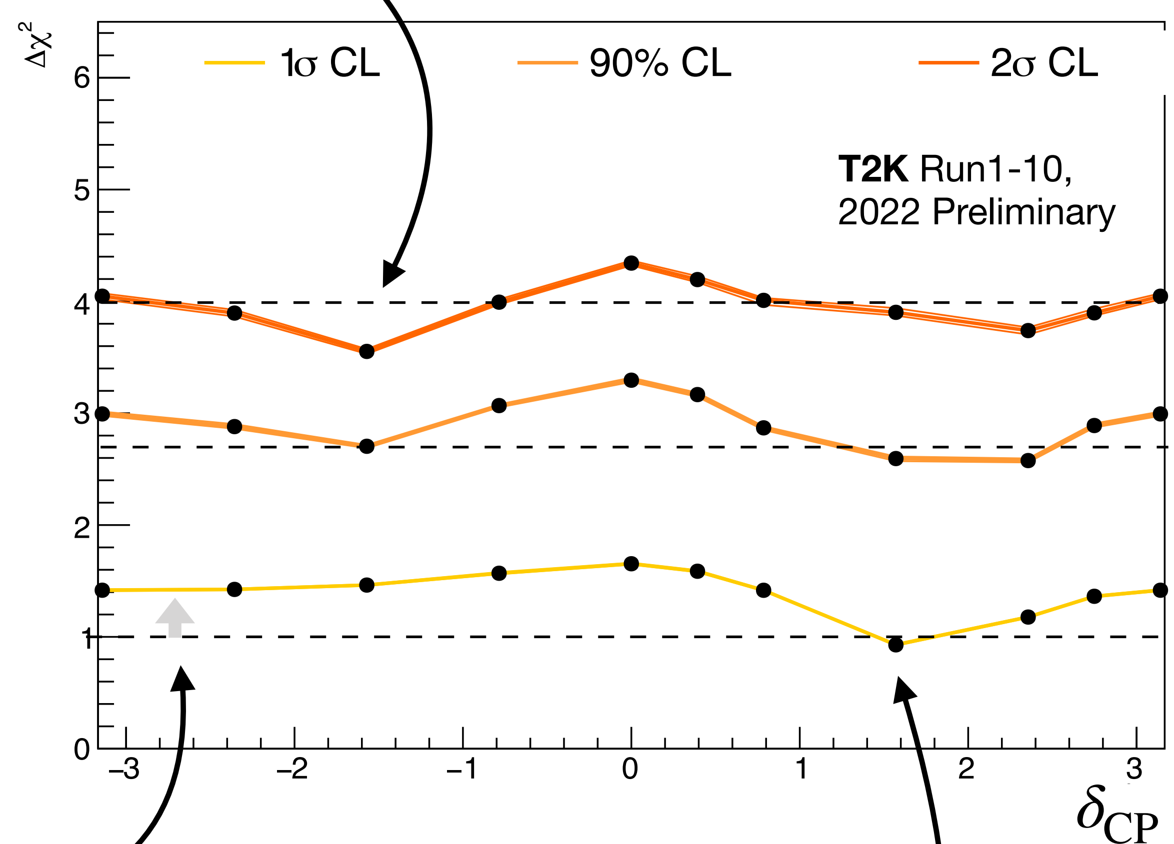
Critical values for δ_{CP}

At high CL start to see the $\sin\delta$ boundary in other mass ordering

Normal ordering



Inverted ordering

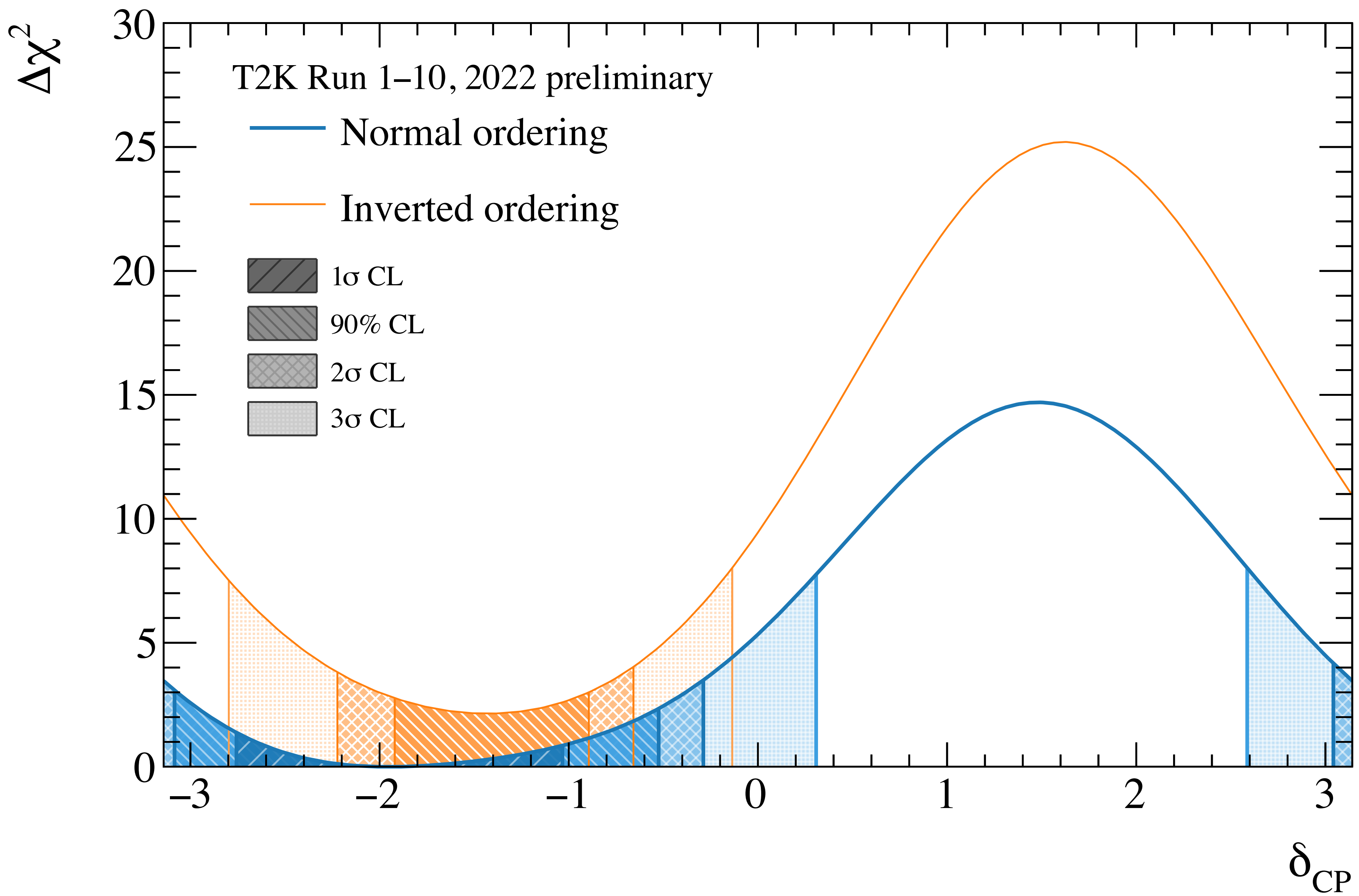


MO and $\operatorname{sgn}\cos\delta$ degeneracies

$\sin\delta = -1$ boundary

$\sin\delta = +1$ boundary

Evaluation of confidence intervals with Feldman-Cousins method

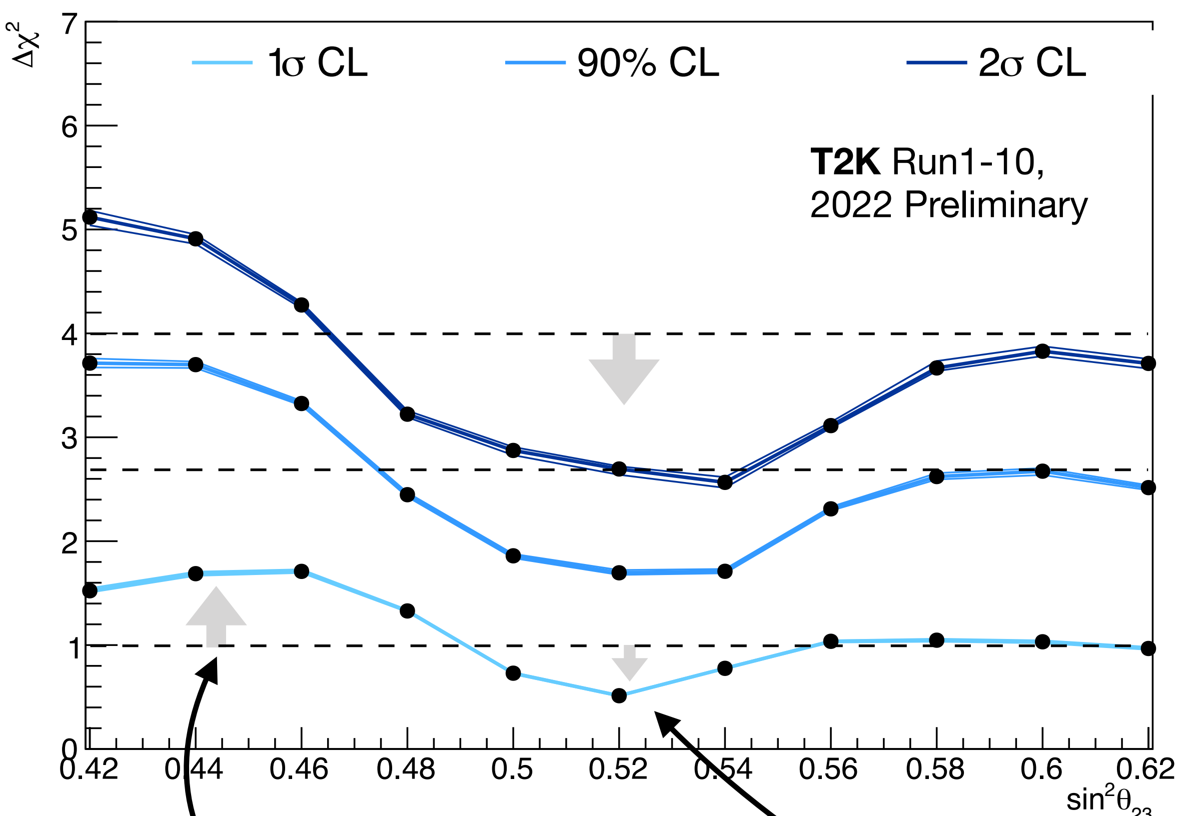


Confidence level	Interval (NH)	Interval (IH)
1σ	$[0.460, 0.491] \cup [0.526, 0.578]$	
90%	$[0.444, 0.589]$	$[0.525, 0.582]$
2σ	$[0.437, 0.594]$	$[0.459, 0.588]$

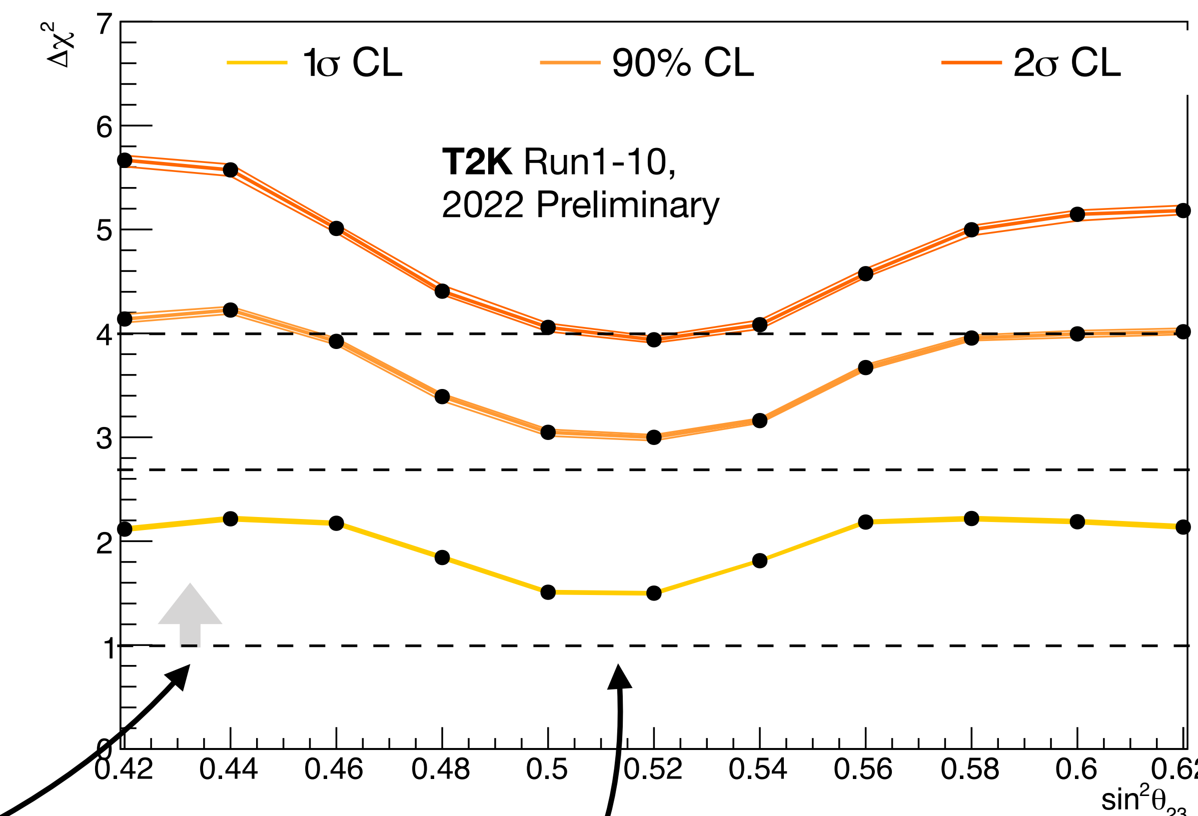
T2K Run 1-10, preliminary

Critical values for $\sin^2\theta_{23}$

Normal ordering



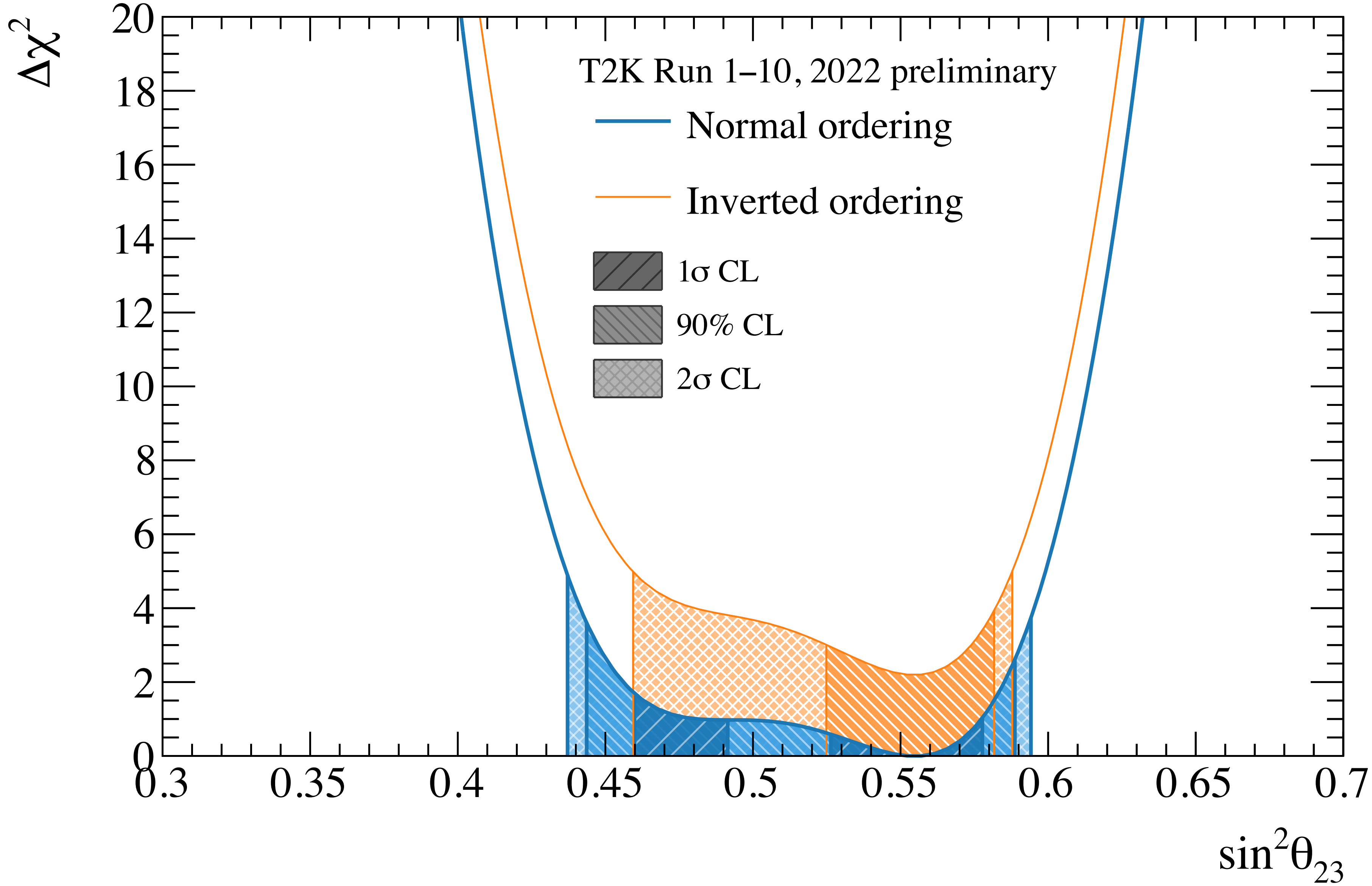
Inverted ordering



Octant, MO degeneracy and marginalization effects caused by δ_{CP} toy distribution prior favoring $\sin\delta_{CP} = -1$

$\sin^2 2\theta_{\mu\mu} = 1$ boundary ($\sin^2\theta_{23} \approx 0.51$)

Evaluation of confidence intervals with Feldman-Cousins method



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T2K Run 1-10, preliminary