どれが好き？

Comic © Higgstan

いろいろなニュートリノを見るスーパーカミオカンデちゃん

ニュートリノ大好きスーパーカミオカンデちゃん、大気で作られたニュートリノにJ-PARCさんが作ったニュートリノ、超新星爆発で生まれるニュートリノに昔の超新星爆発のなごりのニュートリノ、他にもたくさん見ています。

大気・加速器ニュートリノ同時解析に向けたπ運動量系統誤差の導入と適合度検定

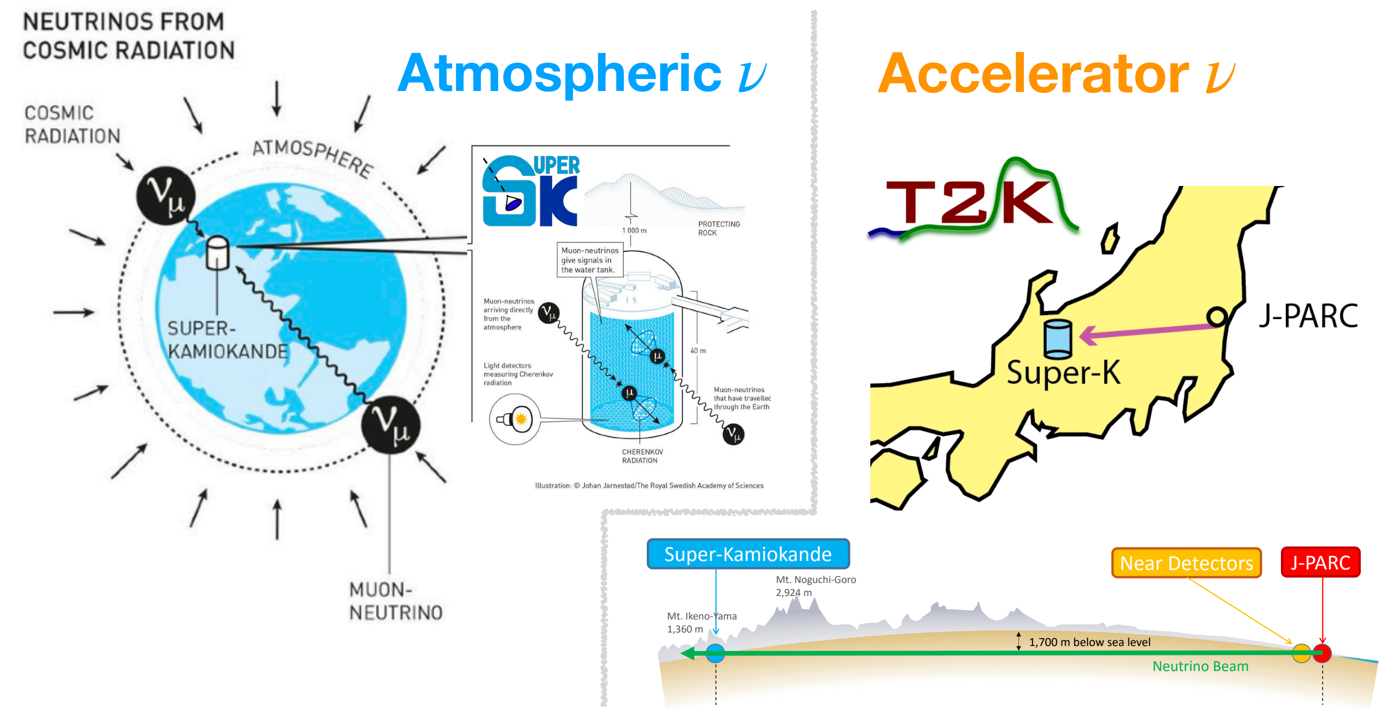
L. Berns, C. Bronner [A], M. Guigue [B], M. Kuze, B. Quilain [C], R. Wendell [D], C. Wret [E], J. Xia [F],
Super-Kamiokande Collaboration, T2K Collaboration

Tokyo Institute of Technology, Kamioka Observatory ICRR [A], LPNHE Paris [B], Laboratoire Leprince-Ringuet [C], Kyoto University [D], University of Rochester [E], ICRR University of Tokyo [F]

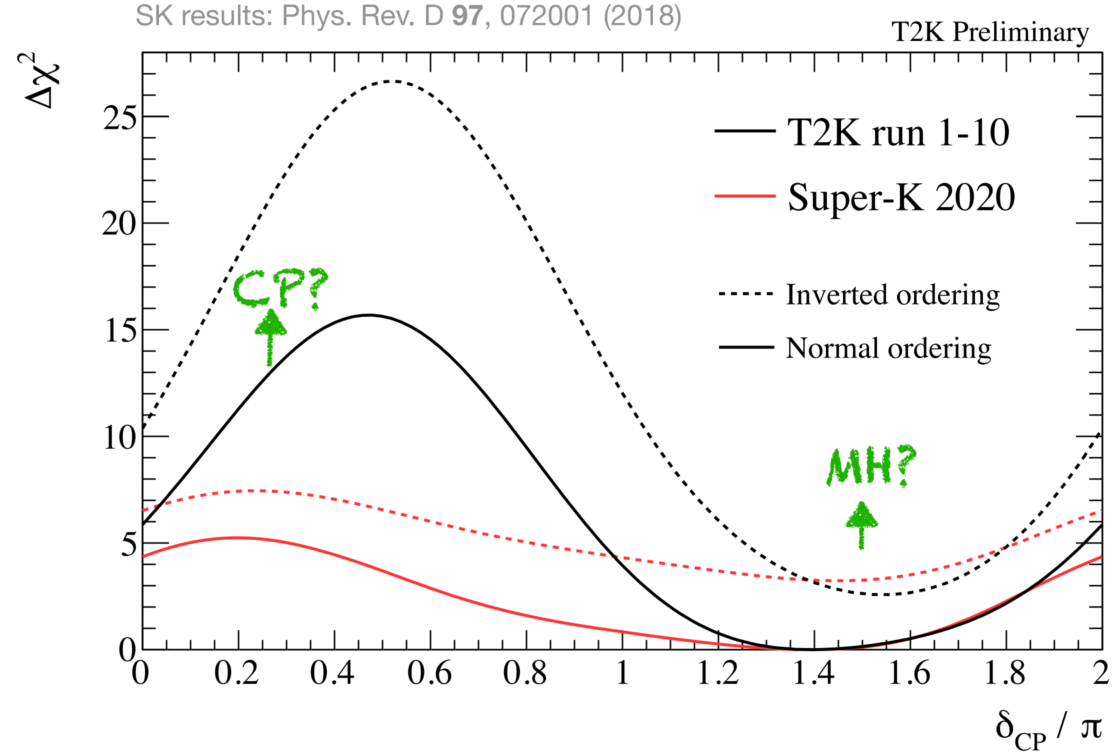
ニュートリノ新学術研究会, 2022-03-08

Background

- Joint fit of atmospheric + accelerator with MOU signed between SK/T2K
- Expect increased sensitivity in δ_{CP}, mass ordering, θ_{23} octant beyond stats increase from resolved degeneracies and syst constraints



Comparison of released contours (not joint fit)
SK results: Phys. Rev. D **97**, 072001 (2018)



For this talk focusing on neutrino cross-section (xsec) model.

1. Overlap in energy range means correlating systematic models is essential for proper analysis
2. SK atm. will benefit from strong xsec constraint by T2K near detector

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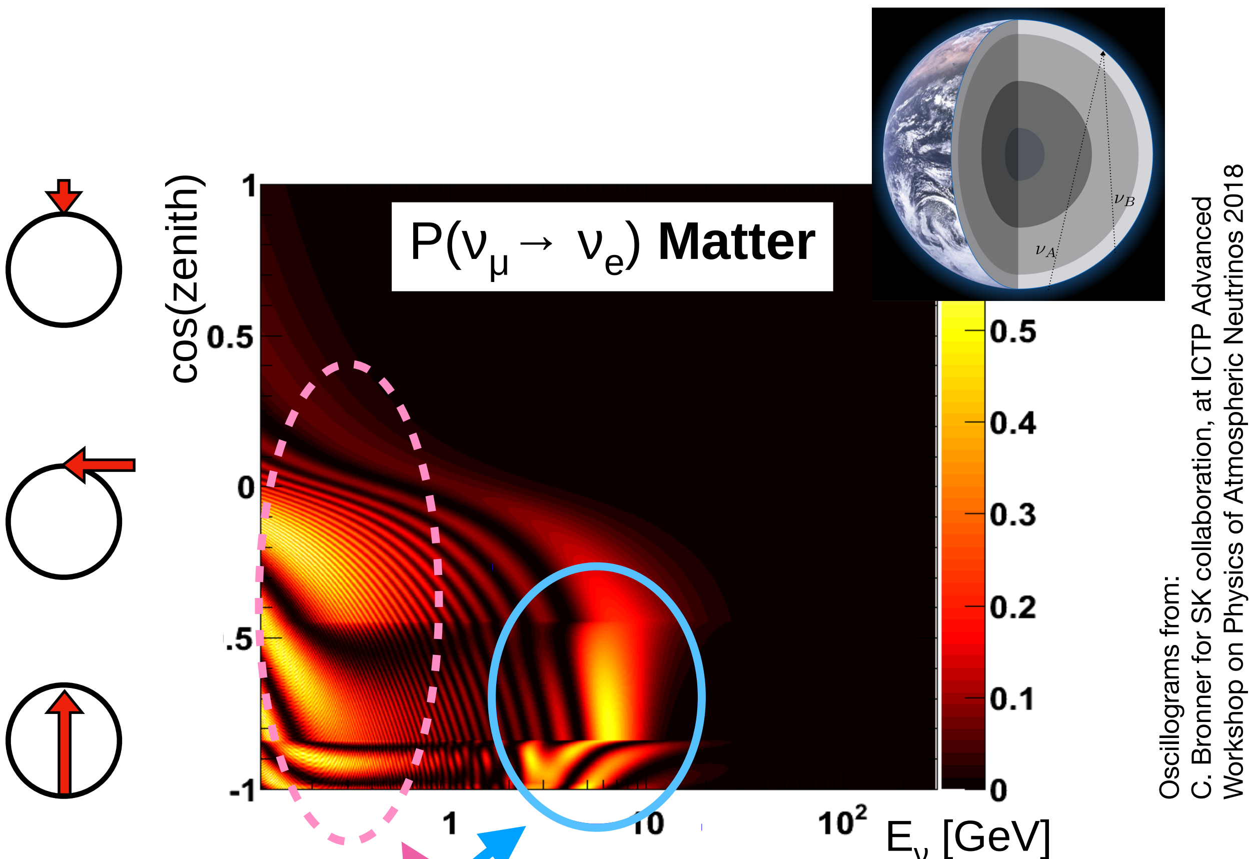
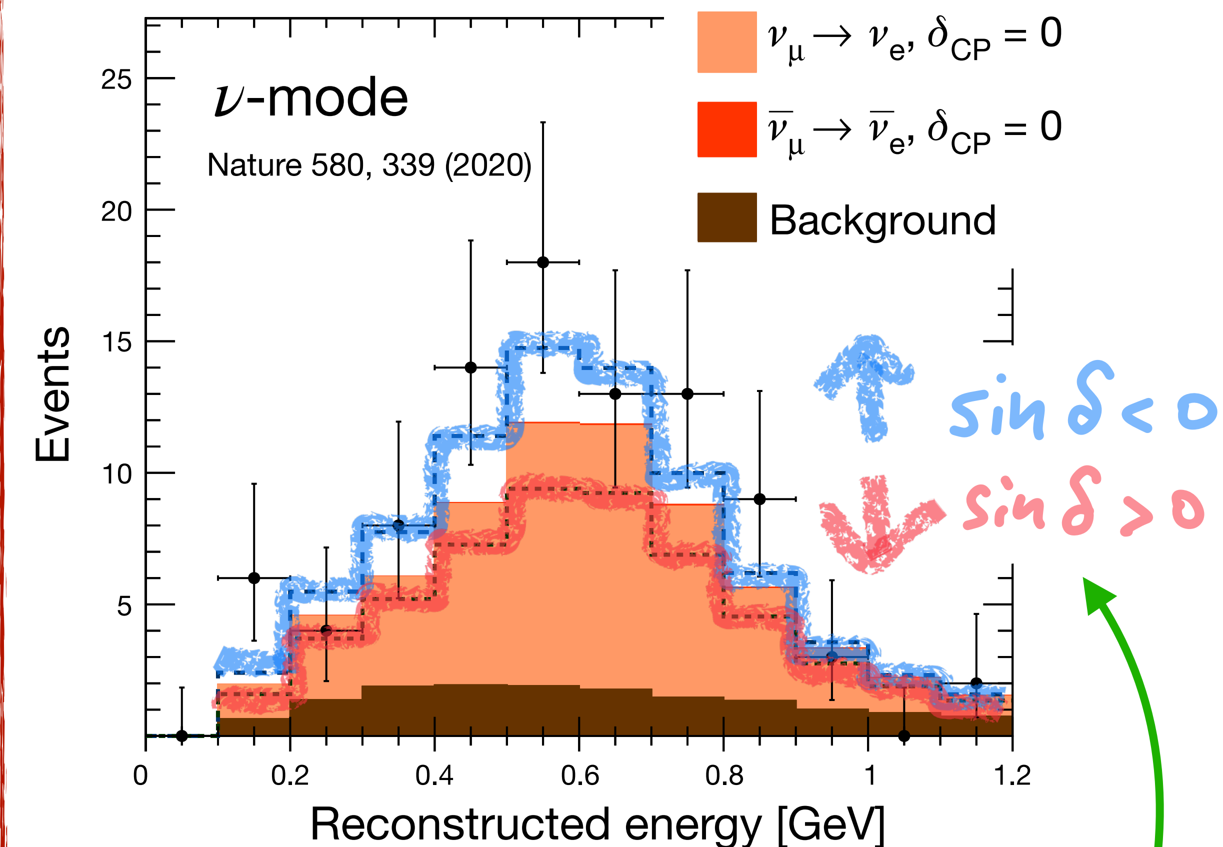
CP and mass ordering sensitivity

Atmospheric



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

Accelerator



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

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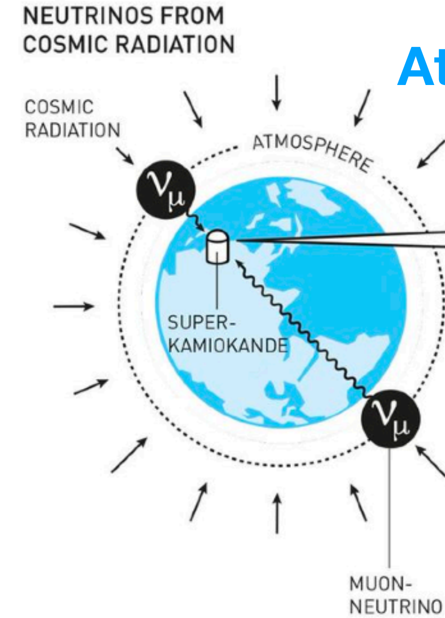

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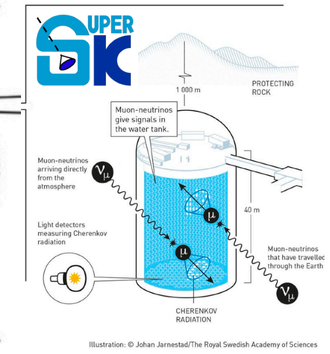
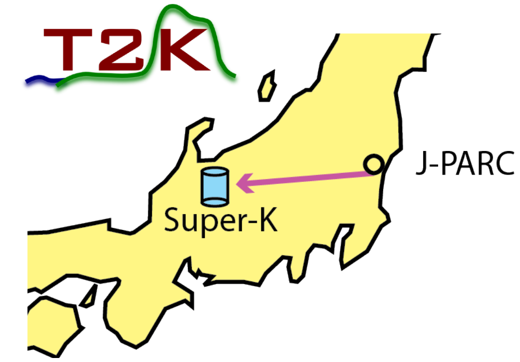
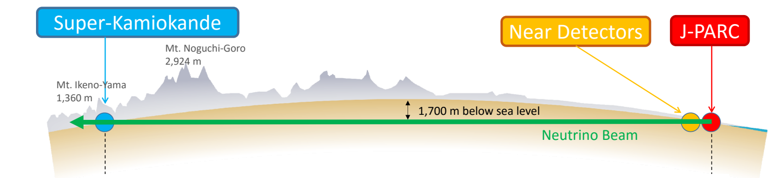


Accelerator ν





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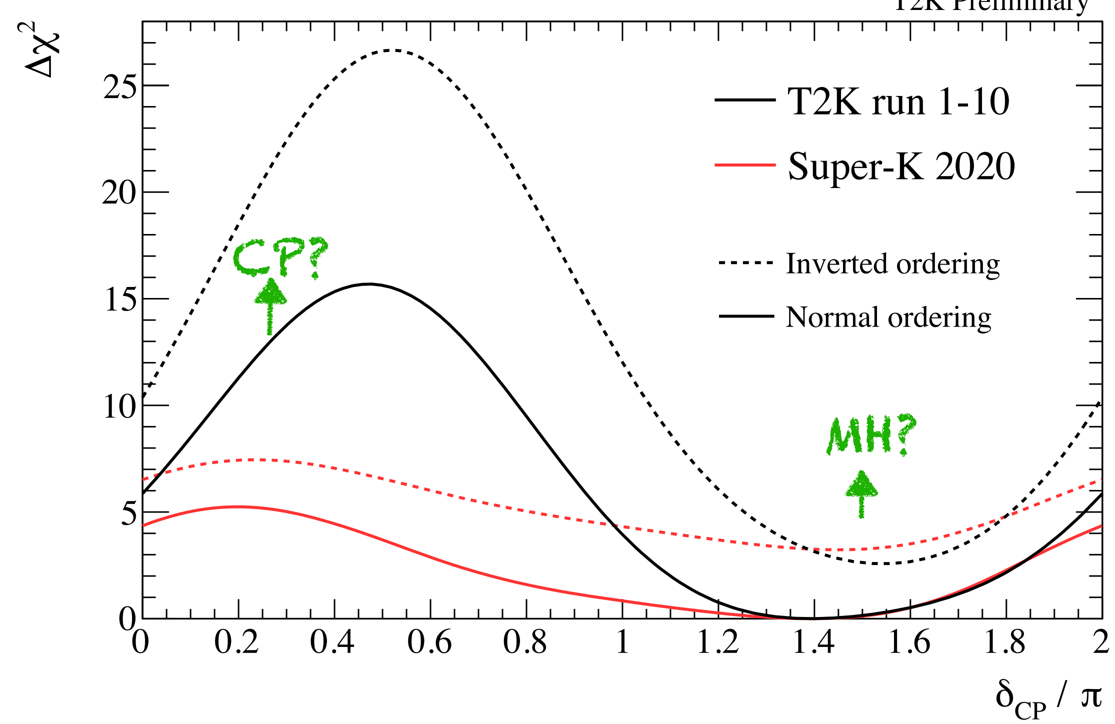

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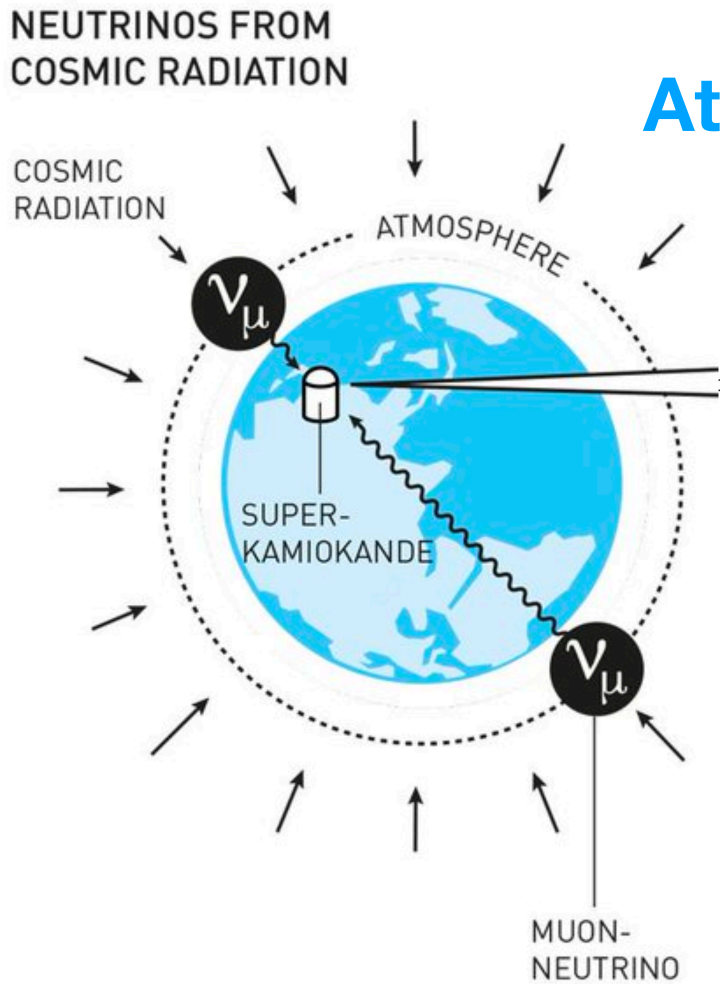

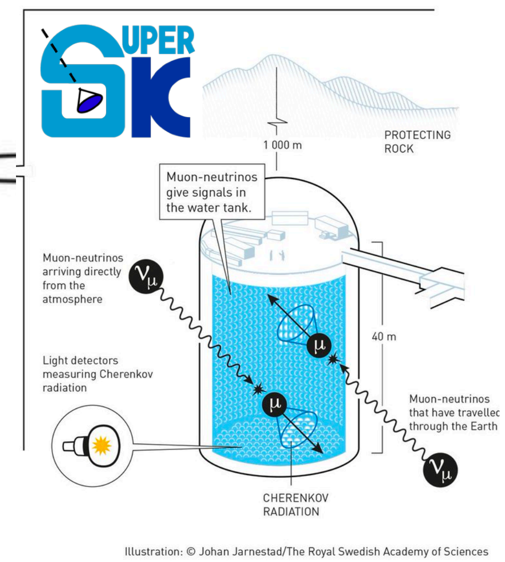

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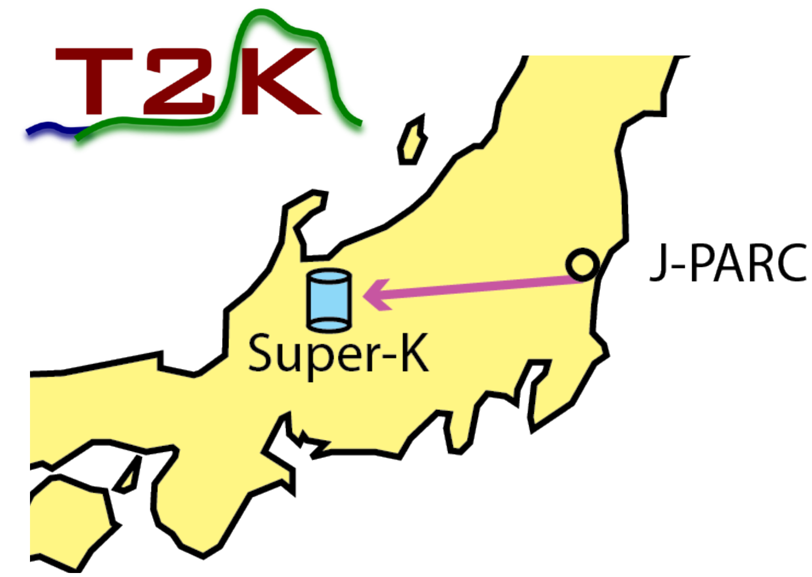

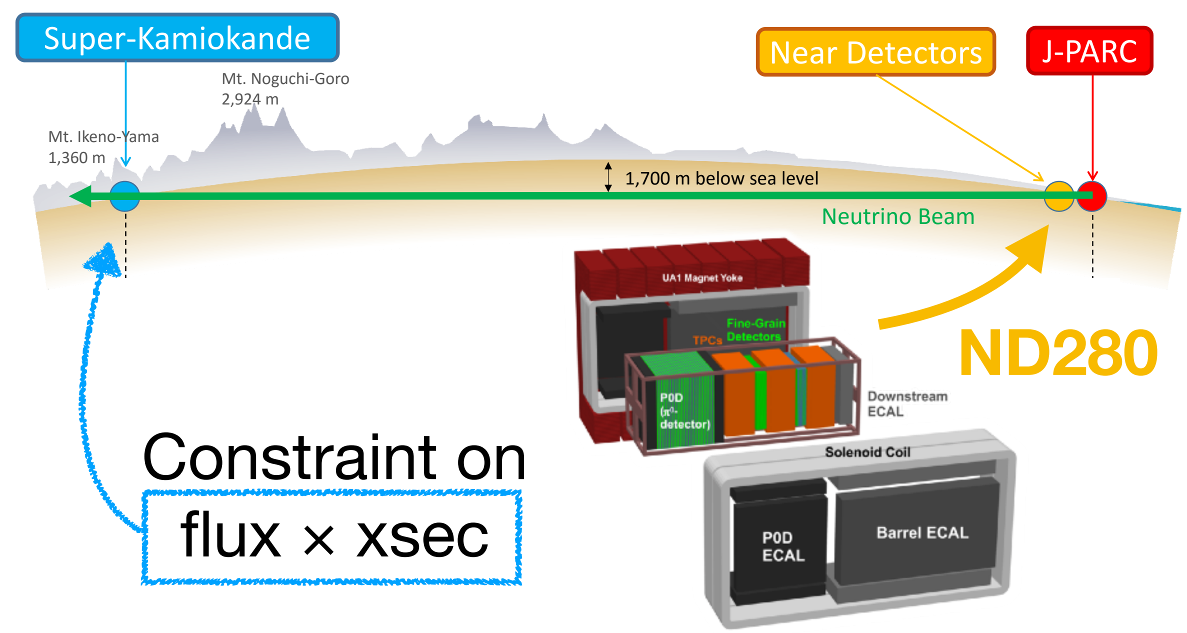

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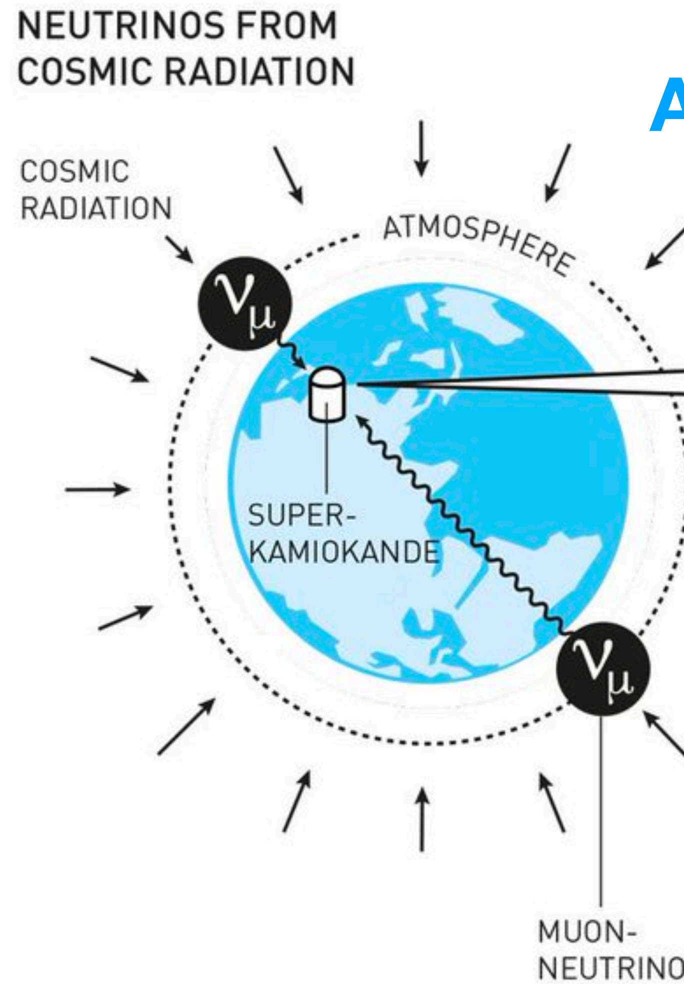

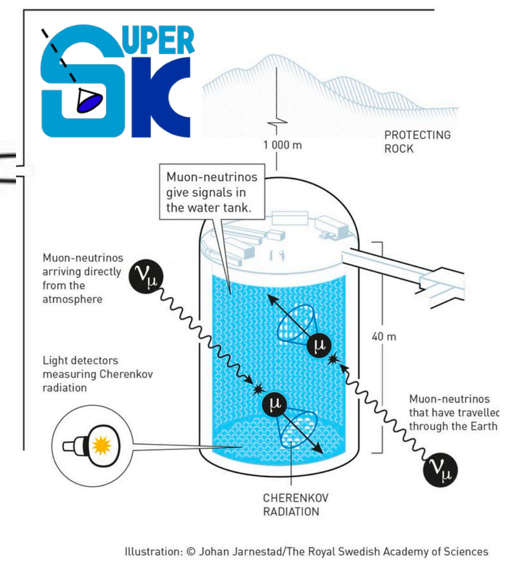

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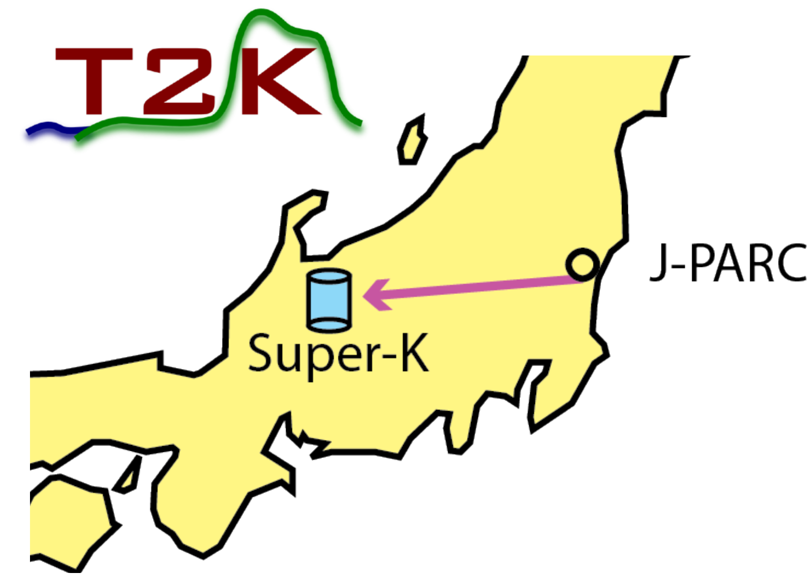

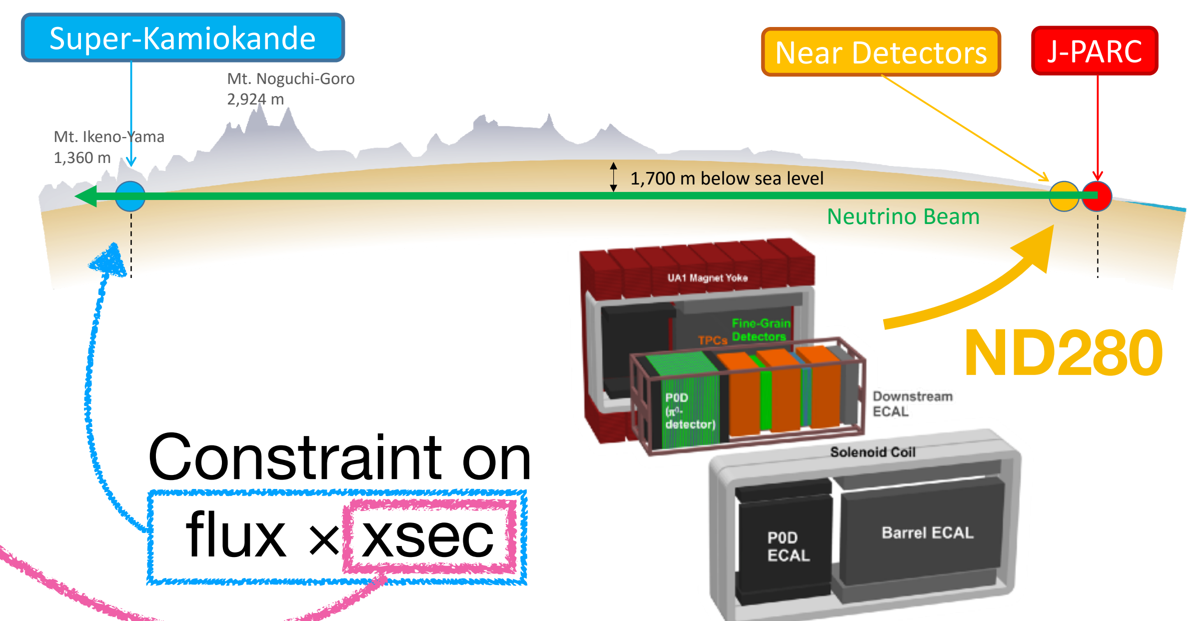

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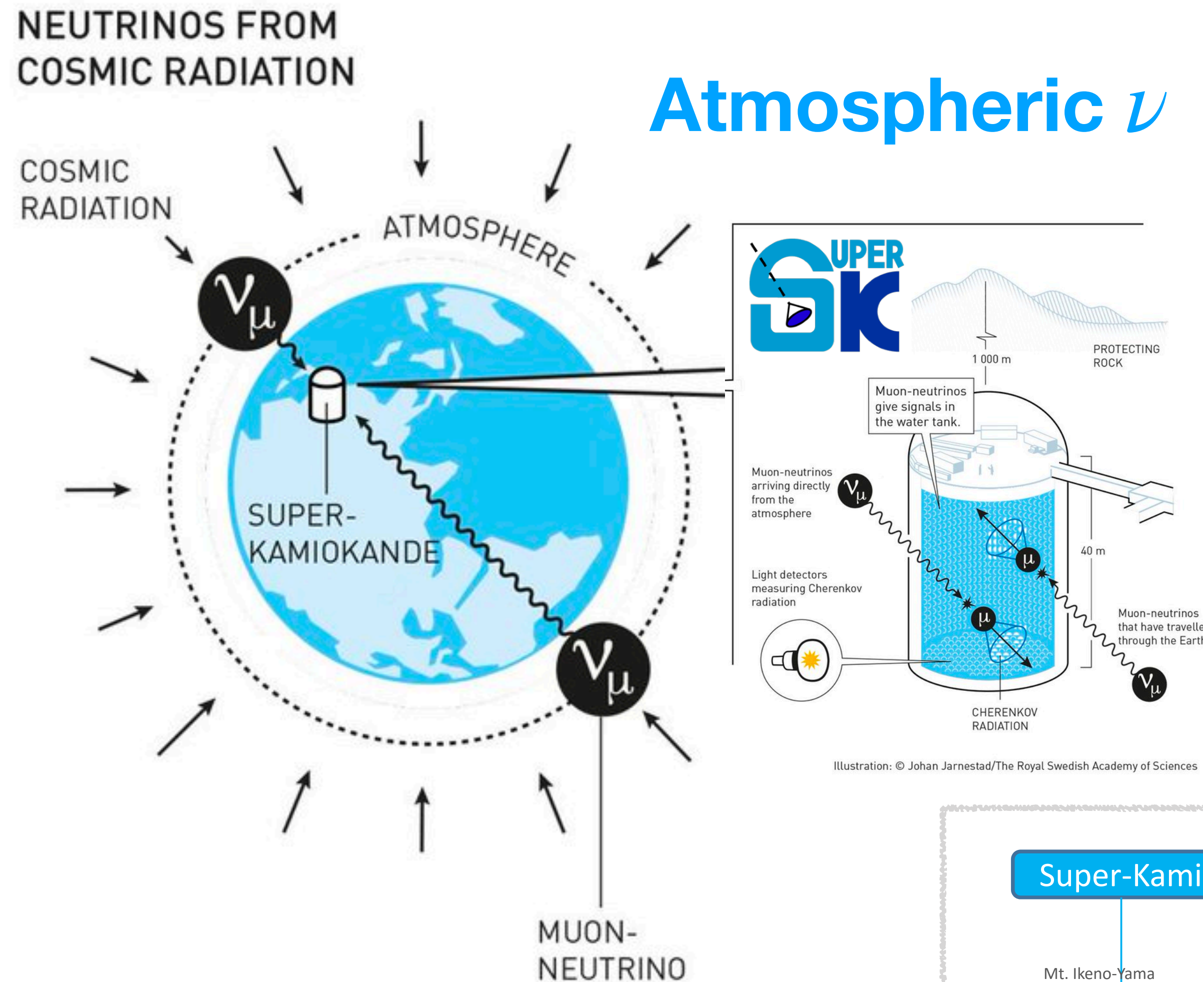

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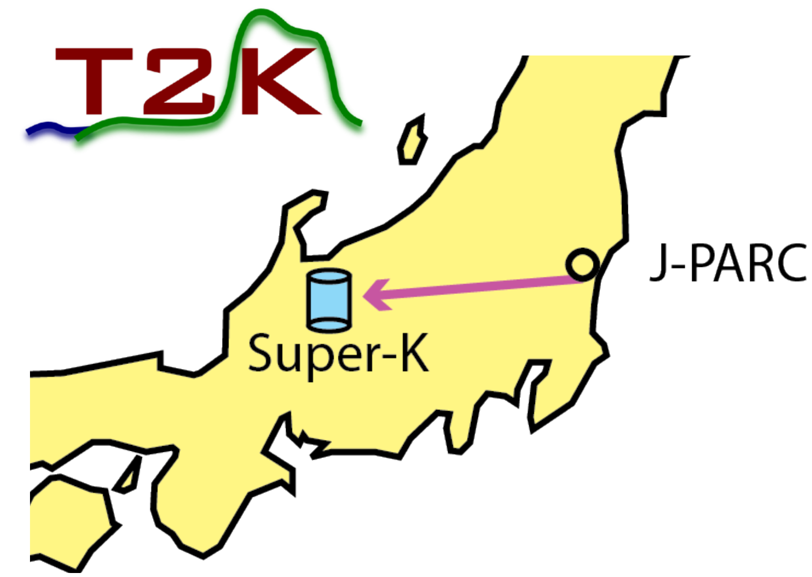

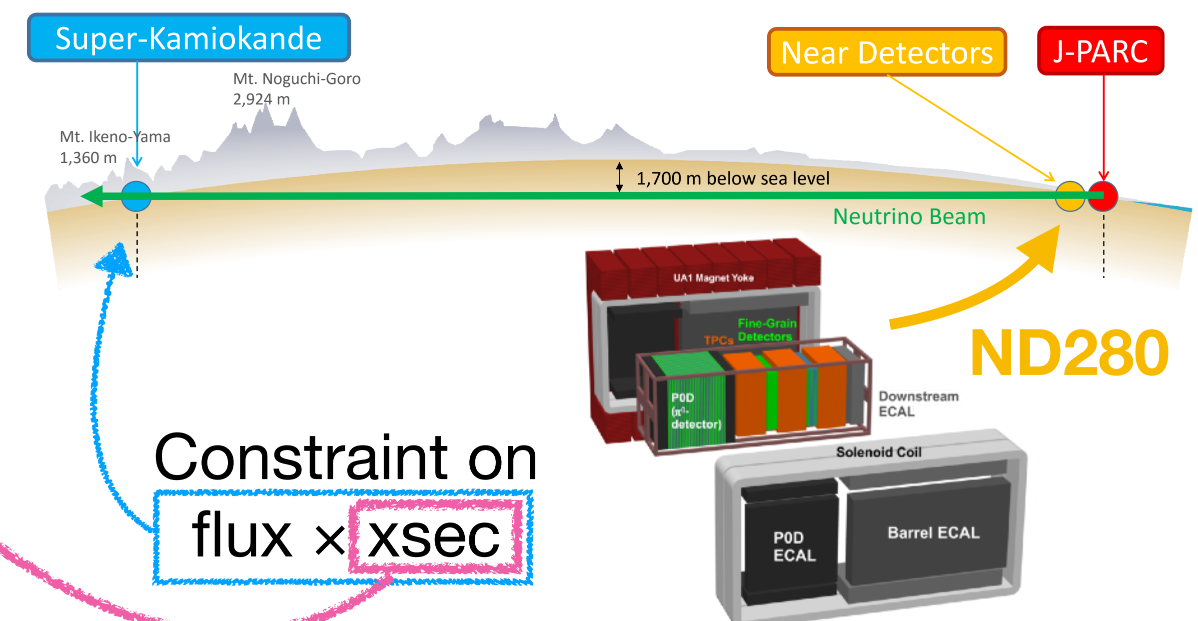

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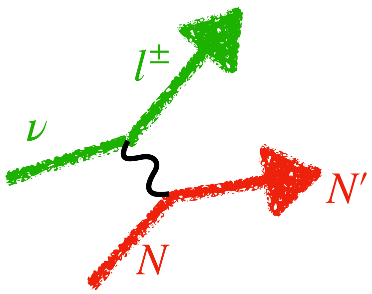
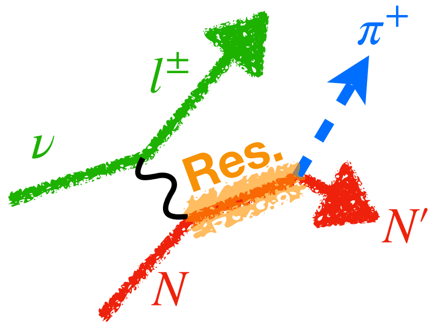


quasi-elastic



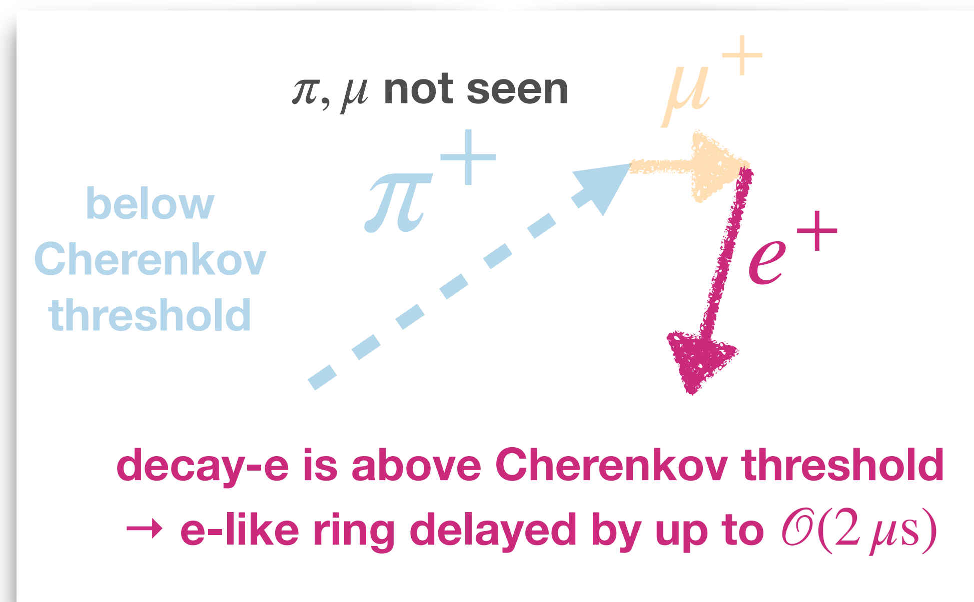
resonant

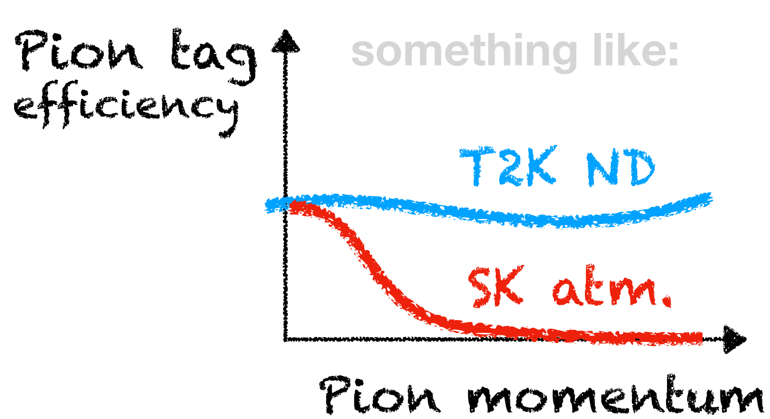
T2K ND → atm?

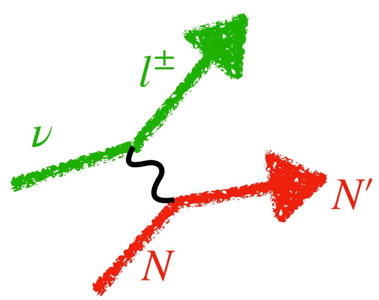
- Would like to apply xsec constraint from T2K ND to Sub-GeV atmospheric samples. Dominant interaction: quasi-elastic, next is resonant single pion production.

- Both T2K ND and SK atmospheric samples only fit in **lepton** kinematics (momentum and direction) and do not directly use pion kinematics.

- However, samples are separated by number of pions, with
  - T2K ND: combines multiple pion tags → insensitive to p_π
  - SK atm: only uses decay-e tag for "invisible" pions → selects low-p_π pions







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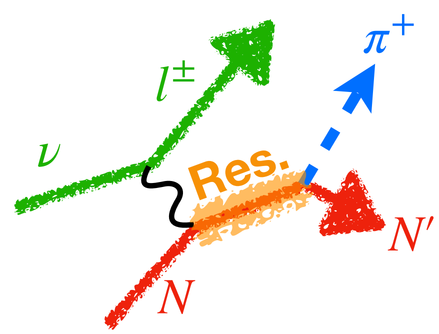

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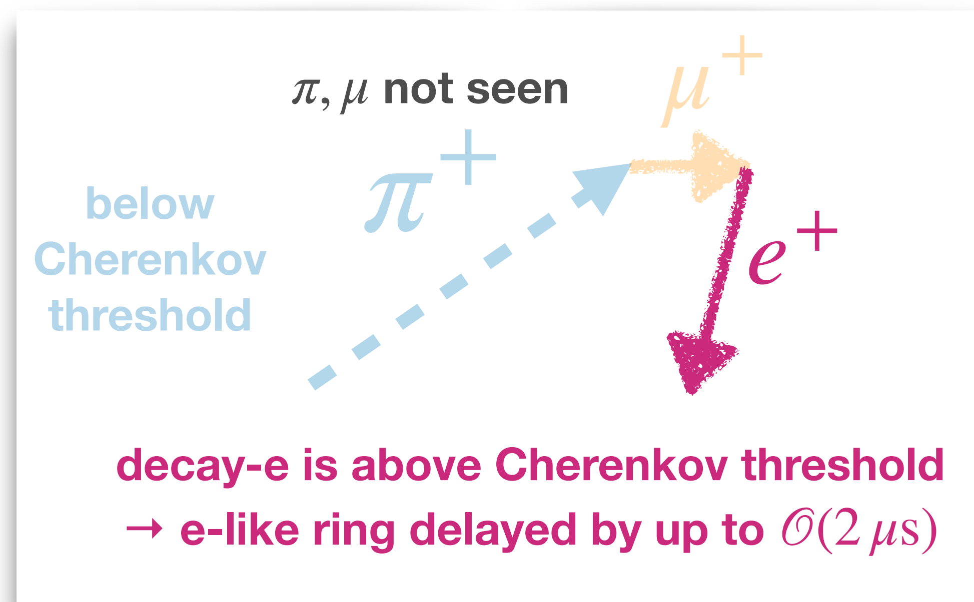

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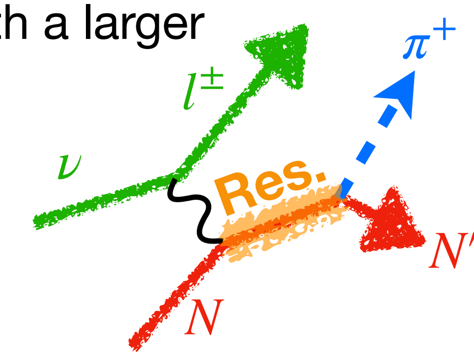
- The cross section model used in ND280 fits does **not** have systematics affecting the **pion momentum** distribution, and we do not believe the MC has this distribution correct (e.g. nuclear effects)

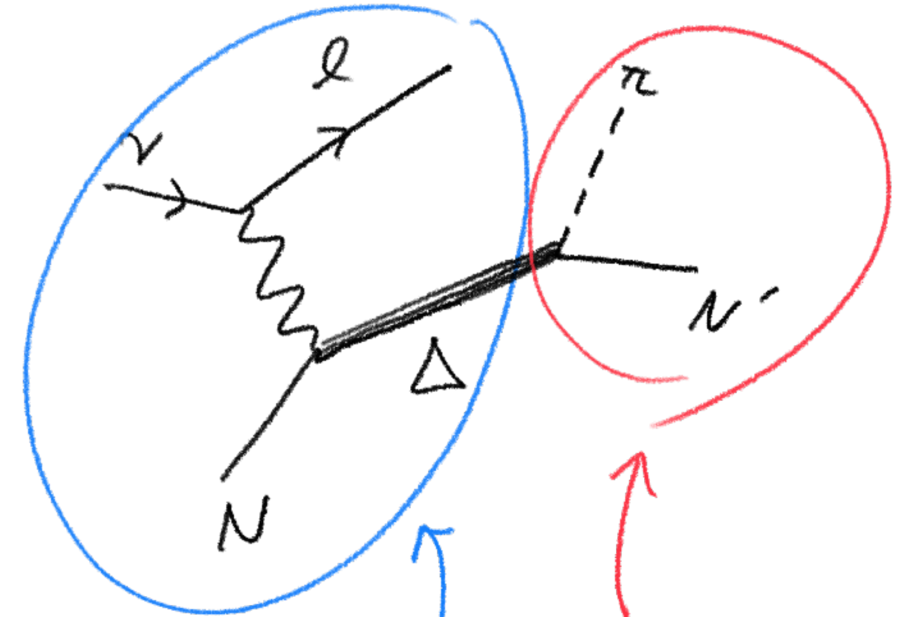
- In order to apply existing T2K ND constraint to SK atmospheric, want to develop a systematic uncertainty to **change** the **pion** momentum distribution while **keeping** the **lepton** kinematics the same, since these are well measured.

Adler angle distortion

Trick to achieve goal: (idea by C. Wret)

1. lepton kinematics only depends on the kinematics of the resonance
2. so in the resonance rest frame, we can change the angular distribution of pion emission (“Adler angle”) without affecting the lepton kinematics
3. since the resonance is boosted, a pion emitted along the boost direction will end up with a larger momentum etc.



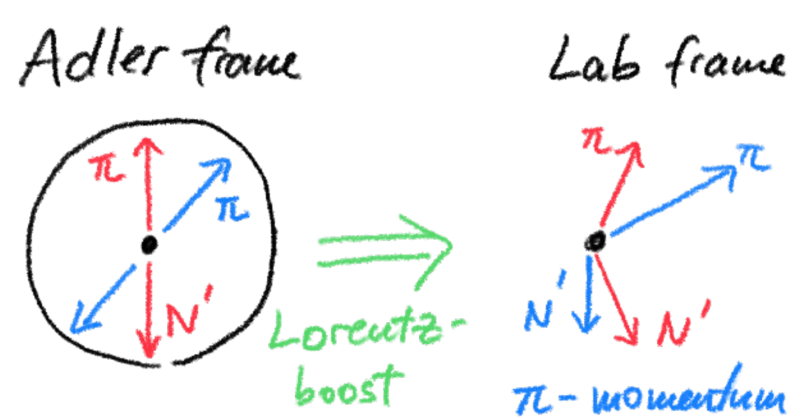


lepton kinematics fully described by this part (at least in MC)

2-body "decay", back-to-back in Adler frame

⇓

Can change angular distribution of π-emission in Adler frame without affecting the lepton kinematics



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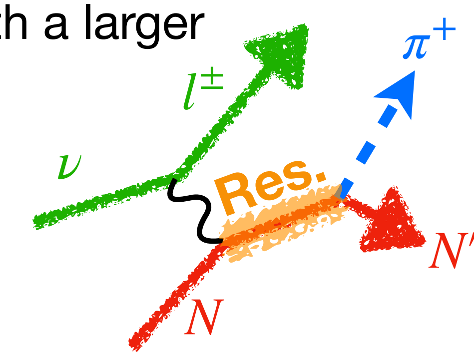
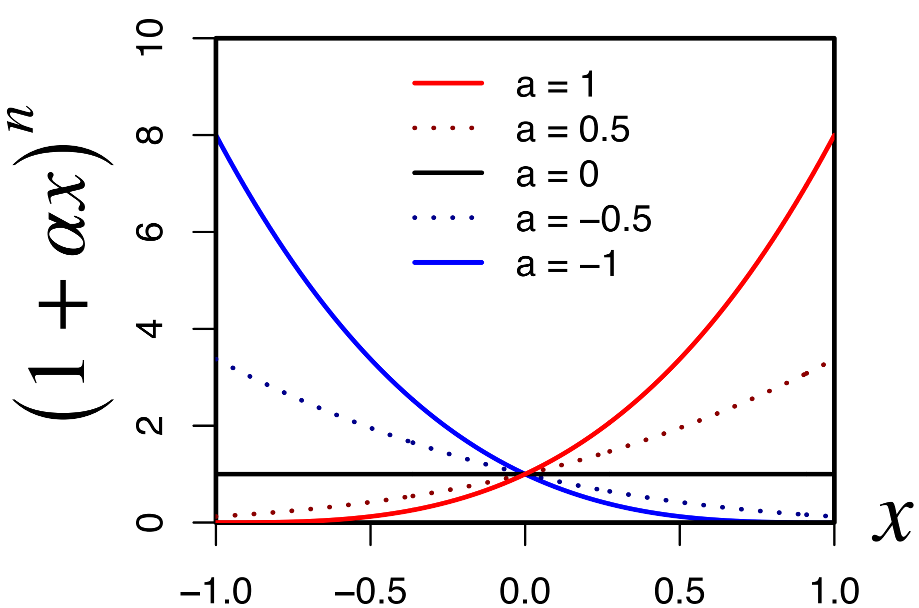
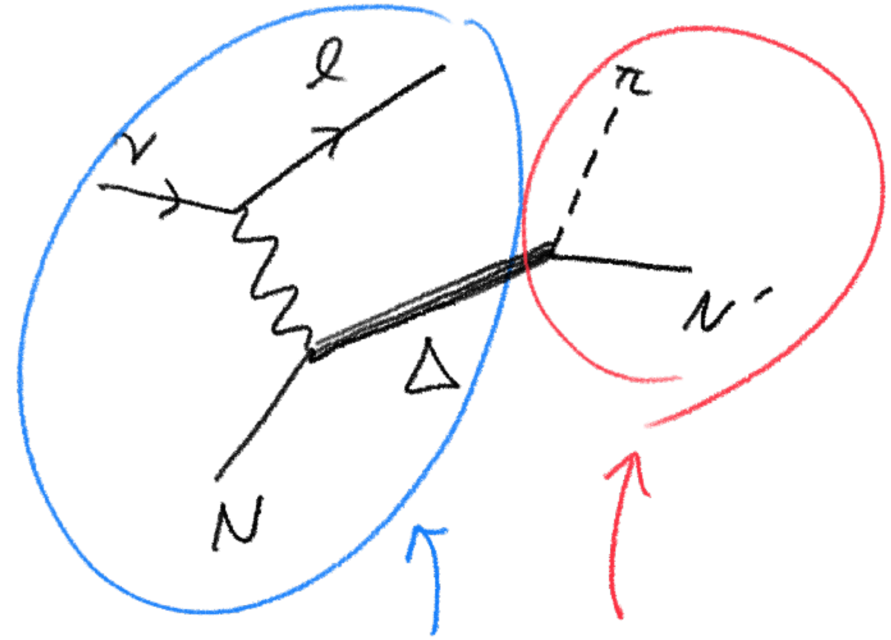


- Using the Adler angle $x = \cos\theta$, simply weight events with

$$\frac{1}{\mathrm{norm}(\alpha)}(1+\alpha x)^n \quad (-1 \le \alpha \le +1),$$

we pick $n = 3$ (up to sextupole weights)





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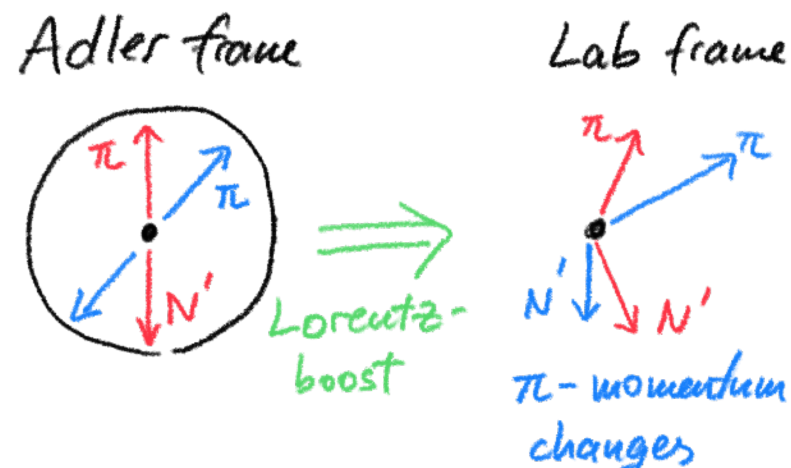

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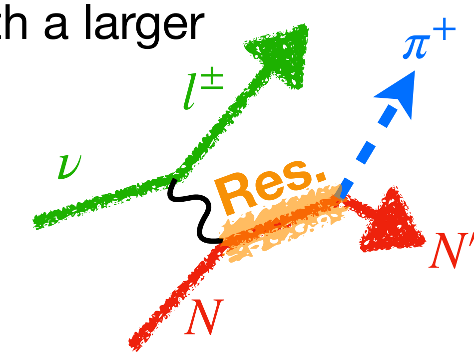

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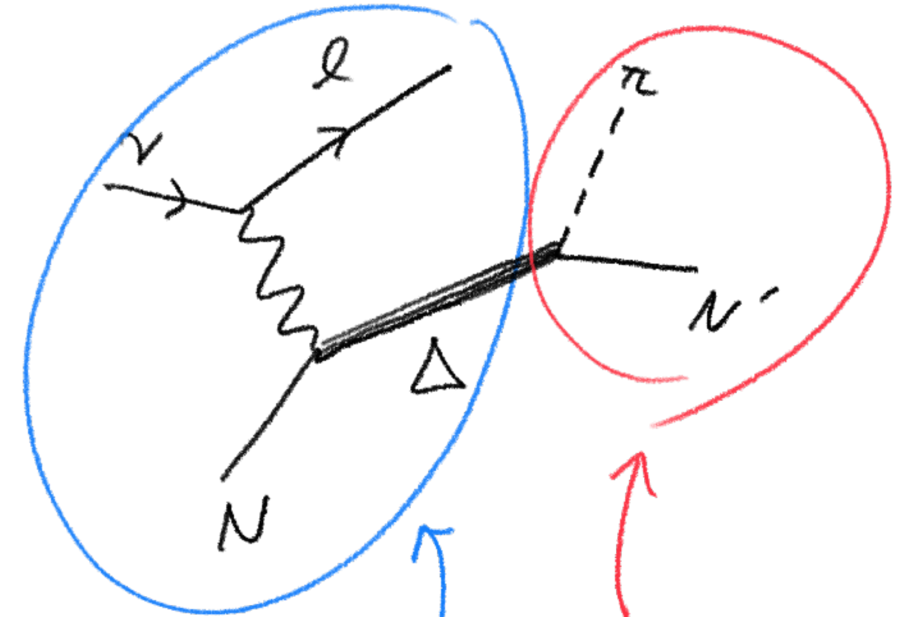
(Will try to explore more physically motivated uncertainty in future.)



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Lab frame

Lorentz-boost

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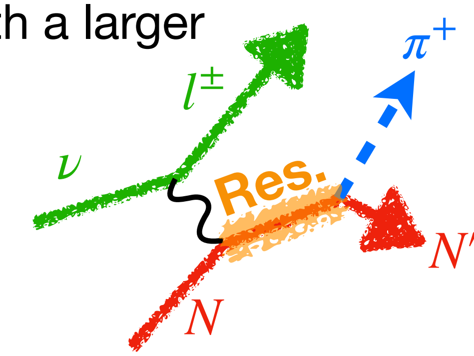

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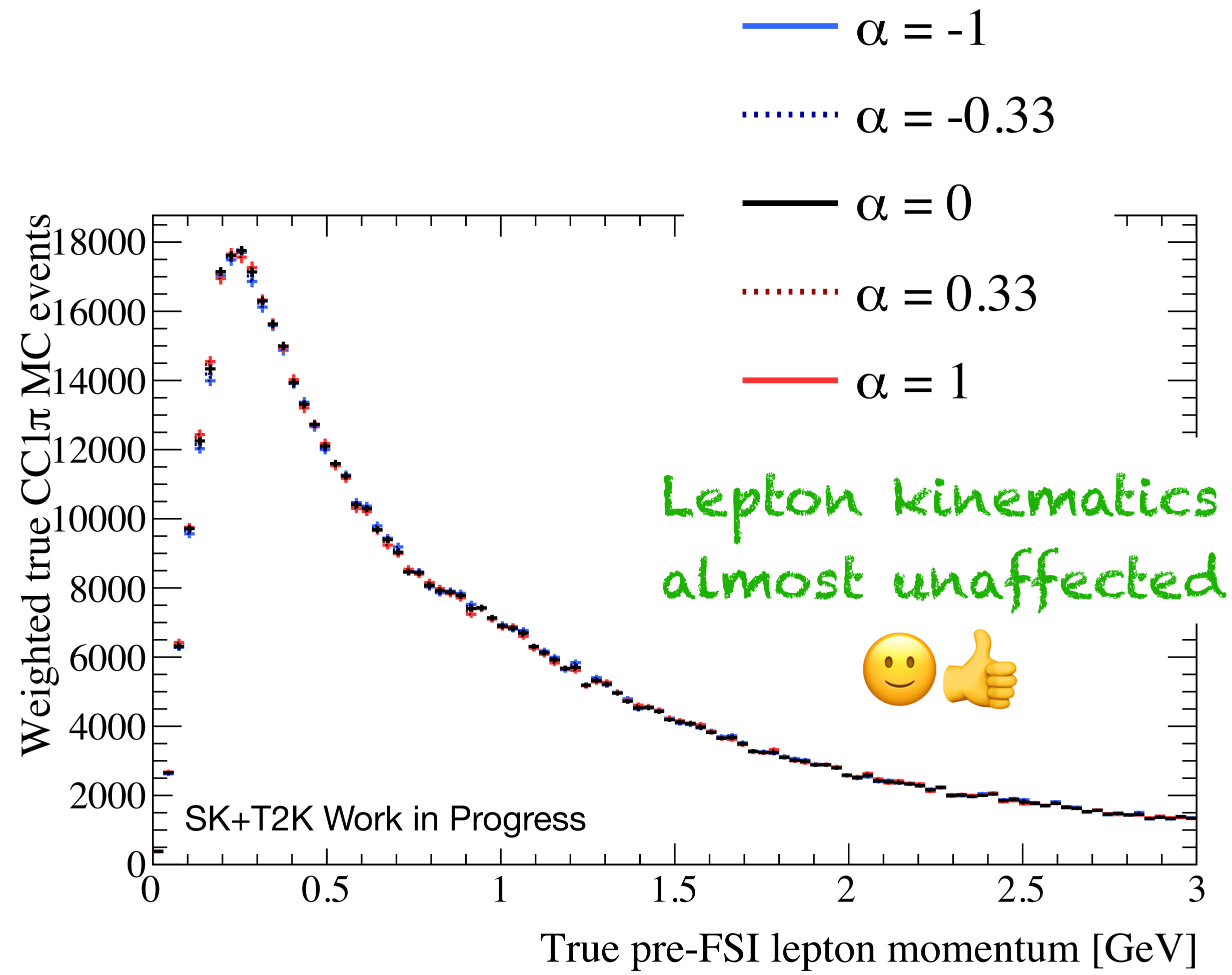
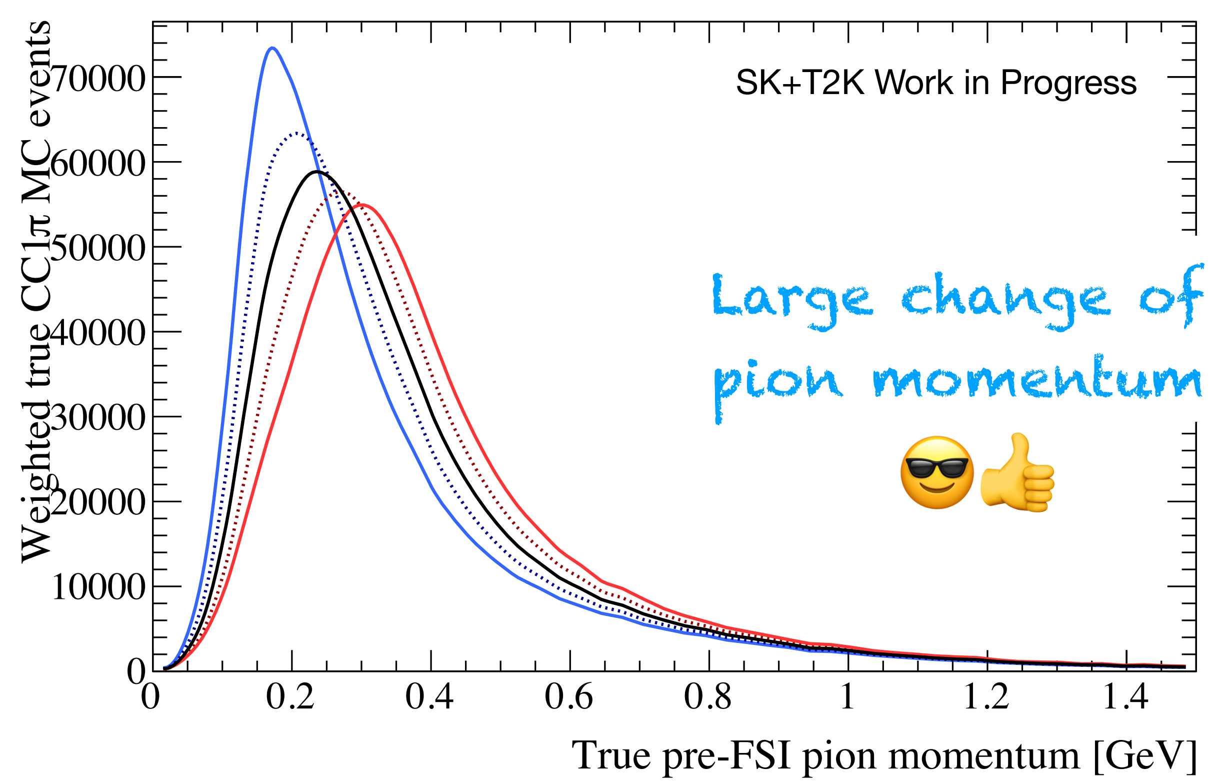
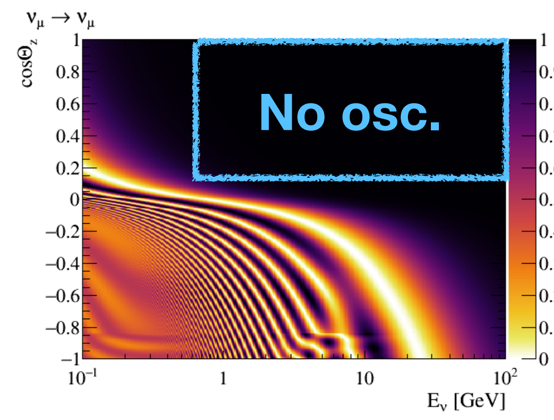




Does pion momentum distribution matter?

- Use **maximum distortion** of new pion momentum systematic and **fit *without*** it to see potential impact
- Here, using down-going atm. samples to study systematic model without “unblinding” effect on oscillation parameters (this is still MC, not data)
- Metric: goodness-of-fit (GOF)
Good GOF is essential for reliable oscillation parameter constraints.

Note: impact on osc. params also estimated, hopefully can share in near future.



Without ND constraint, other parameters can absorb effect

SK+T2K Work in Progress	**Pearson GOF CC1π**	**Parameter GOF CC1π vs. other**	**Combined p-value**
w/o ND	+0.2σ	+0.6σ	**0.11**
With ND	+1.6σ	+2.0σ	**0.001**

With ND constraint, pion momentum shift cannot be absorbed by other parameters → poor GOF

- In this case, fitting with new pion momentum systematic will perfectly absorb the effect, because that's how it was generated
- In practice, dependence of pion momentum distribution on neutrino energy / flavor etc. may be different from this systematic. Similar GOF on actual data should help in deciding whether systematic necessary / good enough or not.
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For fit of SK atm. *with* ND, having this kind of pion momentum systematic may be essential for good fit.

- Expected increase in value of statistic estimated using Asimov fits
- These are converted to p-values using statistic distribution estimated by fitting toy experiments
- The individual statistic p-values were converted to a +Xσ value using the standard normal quantile function

Does pion momentum distribution matter?

- Use **maximum distortion** of new pion momentum systematic and **fit *without*** it to see potential impact

- Here, using down-going atm. samples to study systematic model without “unblinding” effect on oscillation parameters (this is still MC, not data)

- Metric: goodness-of-fit (GOF) Good GOF is essential for reliable oscillation parameter constraints.

Note: impact on osc. params also estimated, hopefully can share in near future.

Without ND constraint, other parameters can absorb effect

SK+T2K Work in Progress	**Pearson GOF CC1π**	**Parameter GOF CC1π vs. other**	**Combined p-value**
w/o ND	+0.2σ	+0.6σ	**0.11**
With ND	+1.6σ	+2.0σ	**0.001**

With ND constraint, pion momentum shift cannot be absorbed by other parameters → poor GOF

- In this case, fitting with new pion momentum systematic will perfectly absorb the effect, because that's how it was generated

- In practice, dependence of pion momentum distribution on neutrino energy / flavor etc. may be different from this systematic. Similar GOF on actual data should help in deciding whether systematic necessary / good enough or not.

- This was only using down-going part, for full atm. samples expect even stronger impact

- Expected increase in value of statistic estimated using Asimov fits
- These are converted to p-values using statistic distribution estimated by fitting toy experiments
- The individual statistic p-values were converted to a +Xσ value using the standard normal quantile function

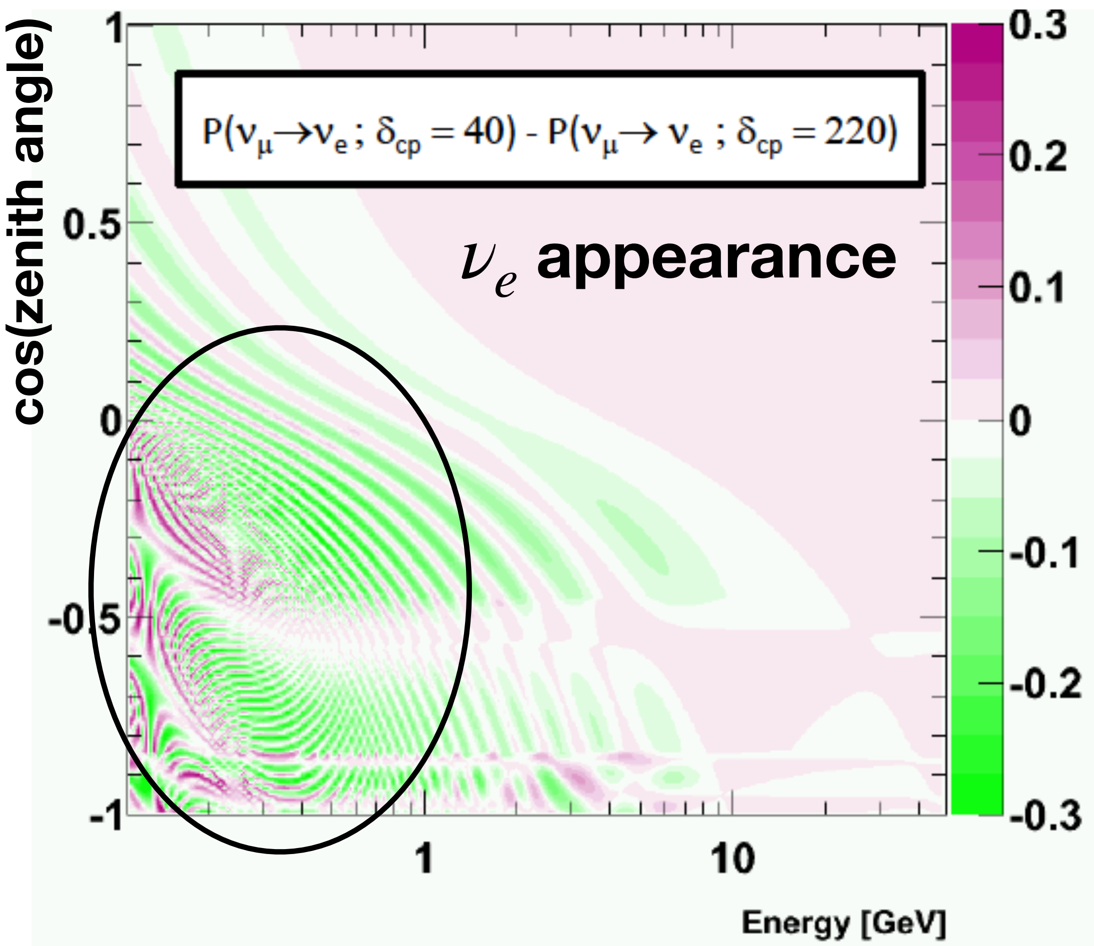
Summary

- Joint fit of **atm**ospheric and **acc**elerator neutrinos from SK+T2K ongoing
- Presented one of the ongoing works toward a coherent systematics model: an uncertainty to vary **pion** momentum distribution
  - By reweighting angular distribution in resonance rest-frame, was able to shifts pion momentum distribution *without* altering **lepton** kinematics
  - Confirmed to be an **essential addition** for correlating Sub-GeV interaction models of SK and T2K due to different pion momentum dependence of pion selection efficiency at T2K ND and SK atm.
  - Down-going events already sensitive to these kinds of mis-modeling effects with various **goodness-of-fit** metrics
- Various other studies of cross section and detector systematics ongoing, expect first oscillation parameter sensitivity studies **soon**.

backup

CP violation sensitivity

Atmospheric

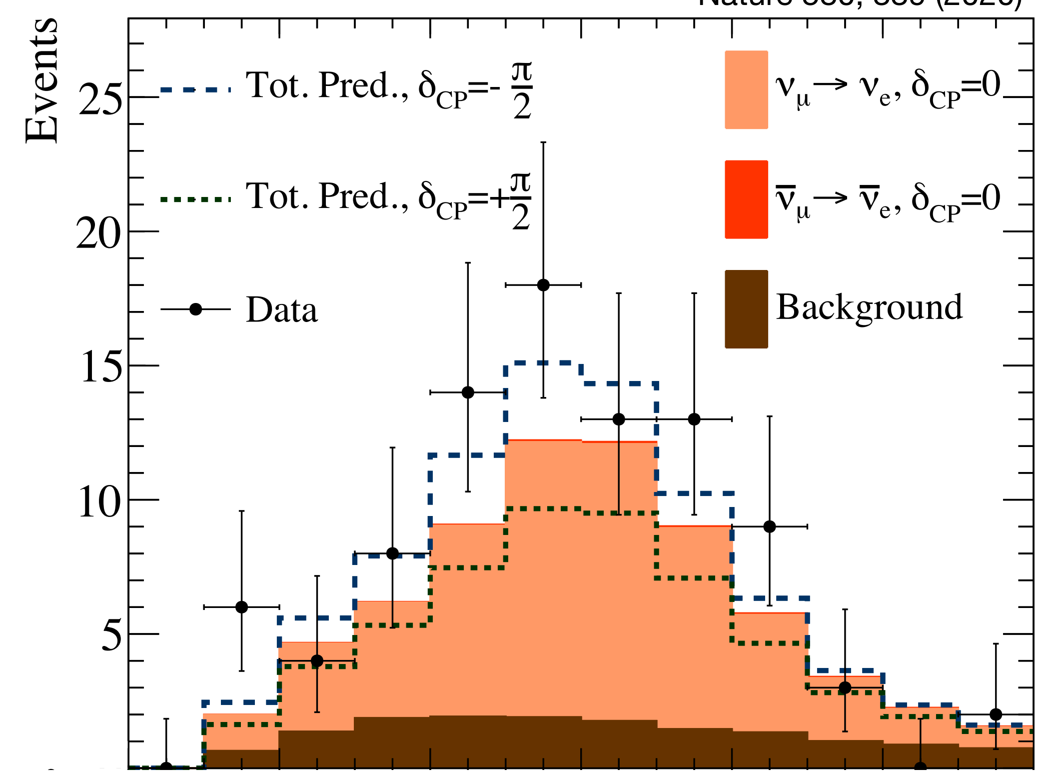


Oscillogram from:
C. Bronner for SK collaboration, at ICTP Advanced
Workshop on Physics of Atmospheric Neutrinos 2018

- Complicated pattern in appearance prob.
- Due to detector resolution, sensitivity mostly from #events in sub-GeV region.
  → $\cos(\delta_{\mathrm{CP}} - \phi_0)$ sensitivity with different phase offset ϕ_0 than accelerator
- $\nu, \bar{\nu}$ separation difficult but ν has larger flux and xsec.

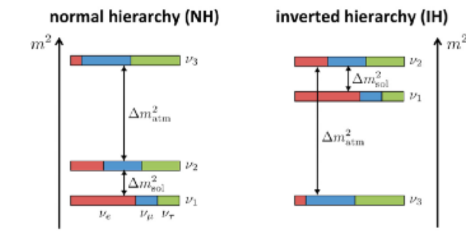
Accelerator

Nature 580, 339 (2020)



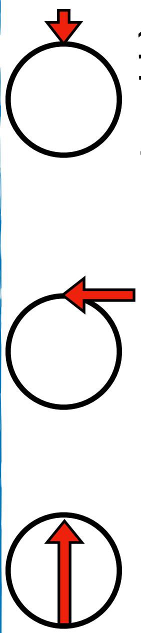
- Anti-correlated change of $\nu_e, \bar{\nu}_e$ appearance probability
- Since T2K only sees first oscillation maximum, mostly a change in # of e-like events
  → sensitive to $\sin(\delta_{\mathrm{CP}})$

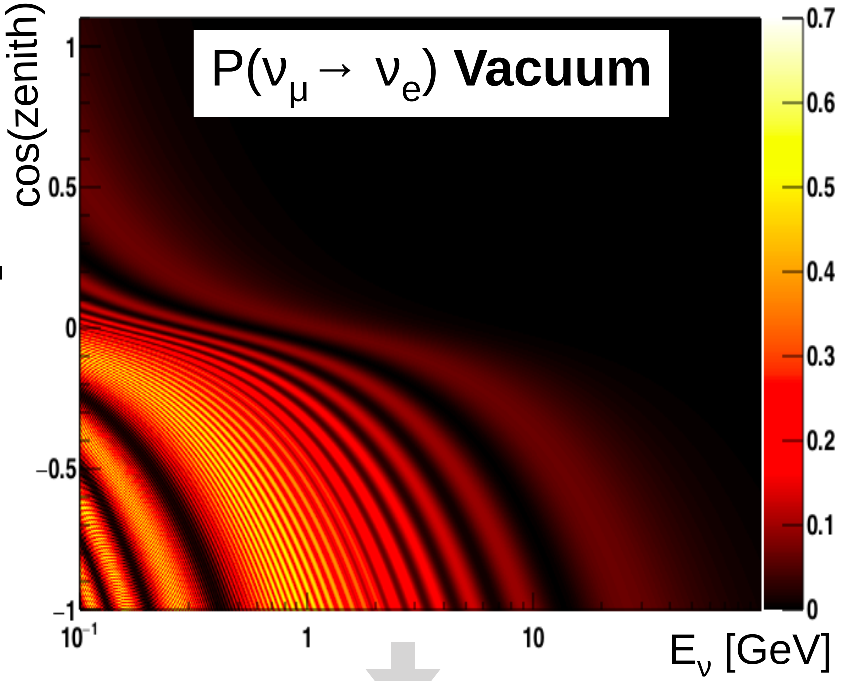
Mass ordering sensitivity (MO)

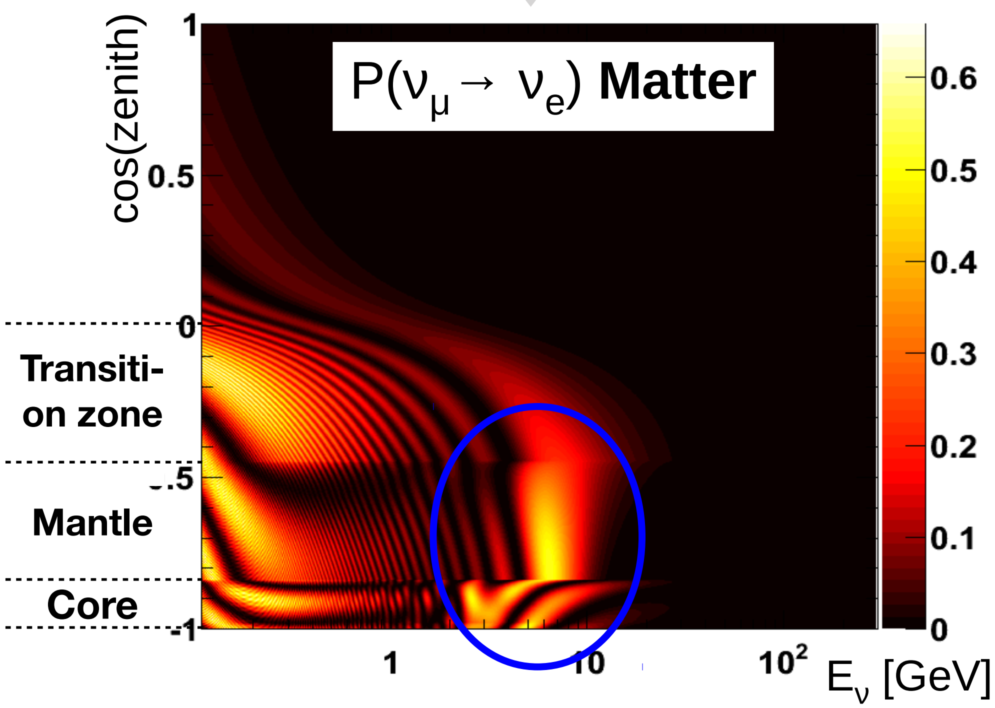


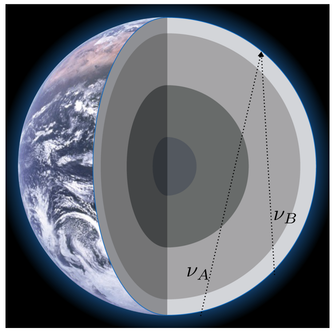
Credit: JUNO Collaboration / JGU-Mainz

Atmospheric





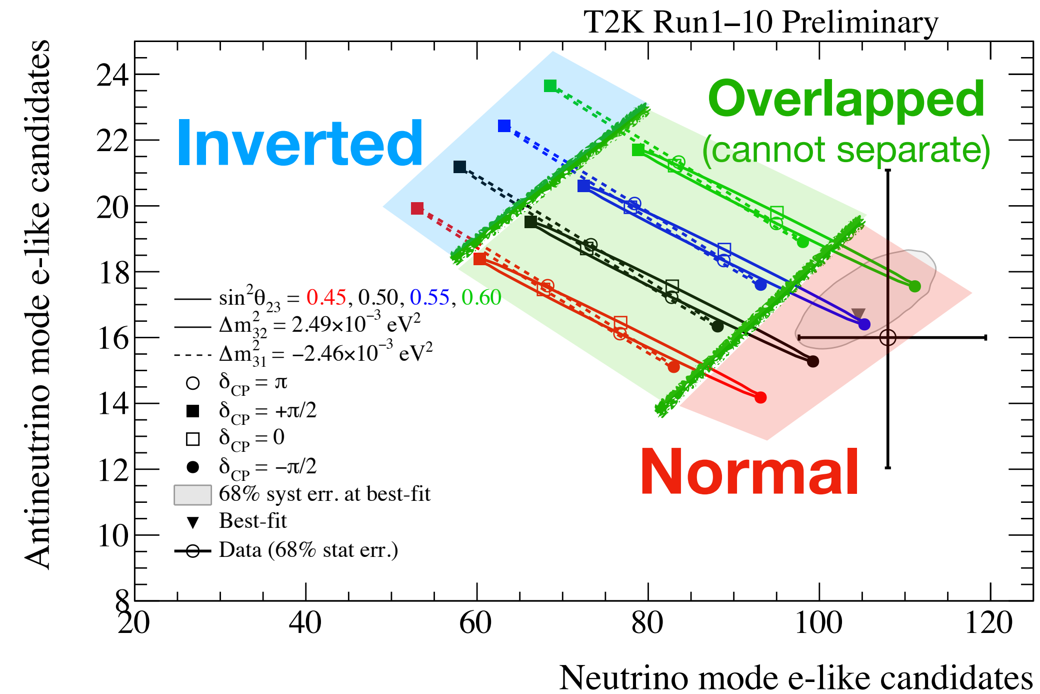




Oscillograms from:
C. Bronner for SK collaboration, at ICTP Advanced
Workshop on Physics of Atmospheric Neutrinos 2018

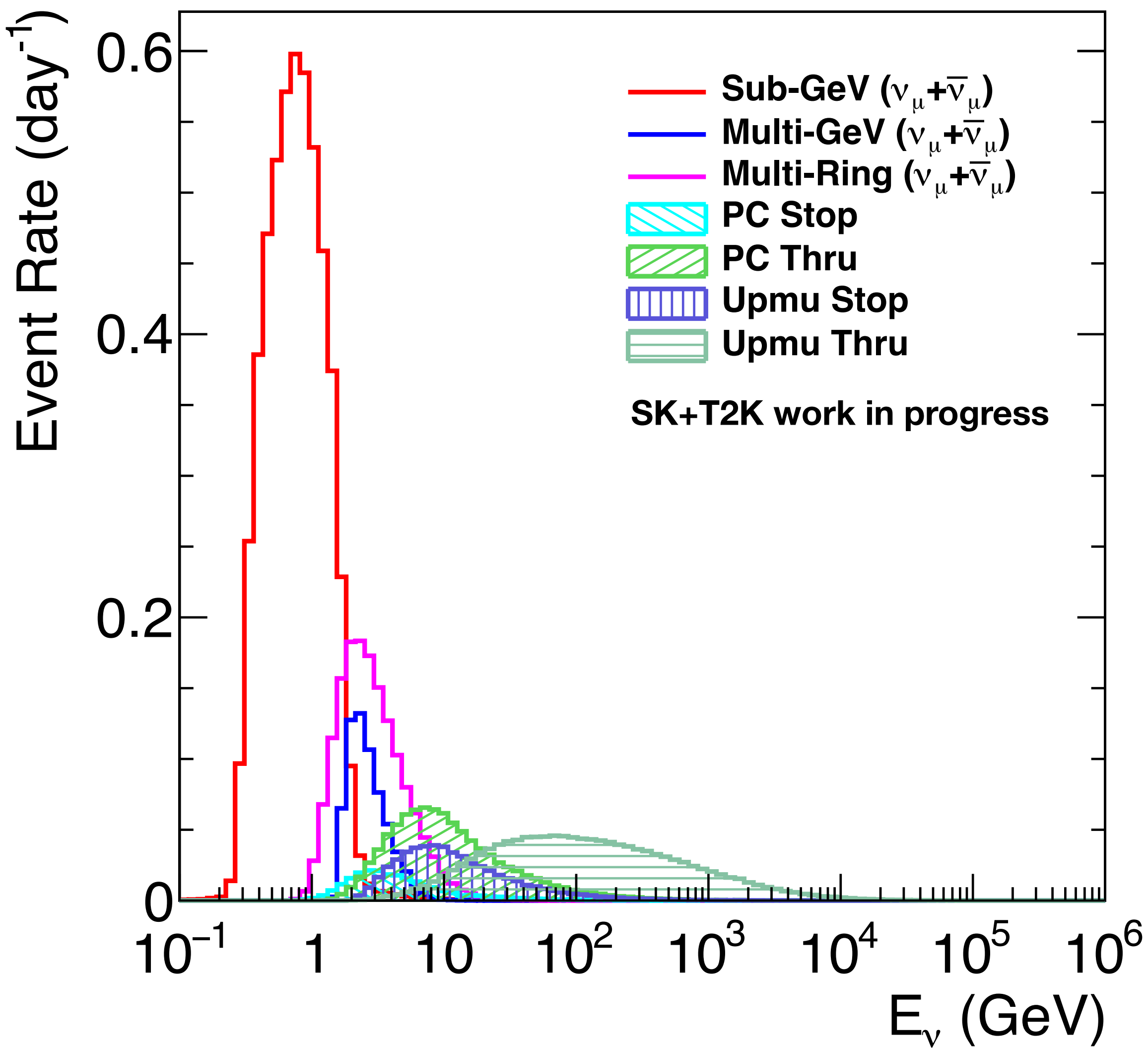
- Resonance in Earth mantle and core in few-GeV region
- Only for ν in normal, and $\bar{\nu}$ in inverted ordering → MO sensitivity
- Effect size depends on θ_{23} octant

Accelerator

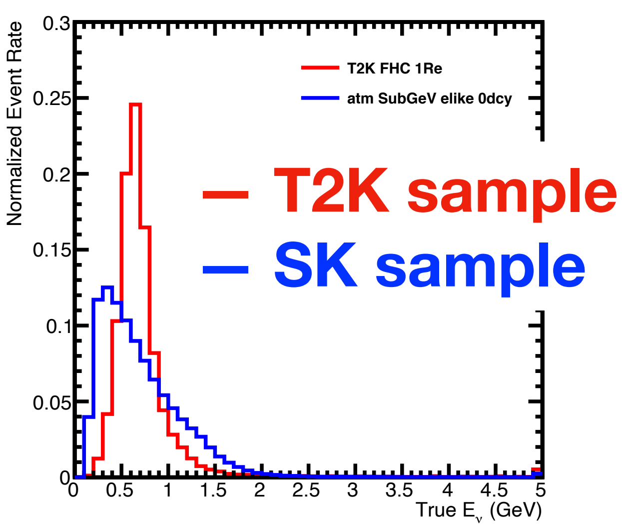


- Small matter effect due to short baseline
- For some values of δ_{CP} the MO degeneracy in number of e-like events is resolved, → MO sensitivity

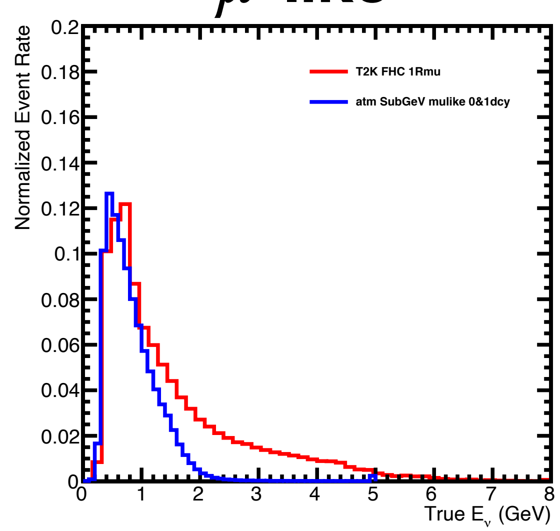
True neutrino energies of various μ-like atm. samples



e-like

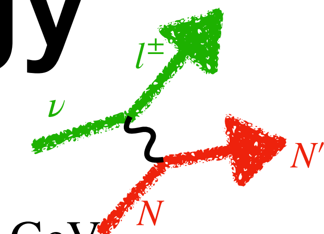


μ-like



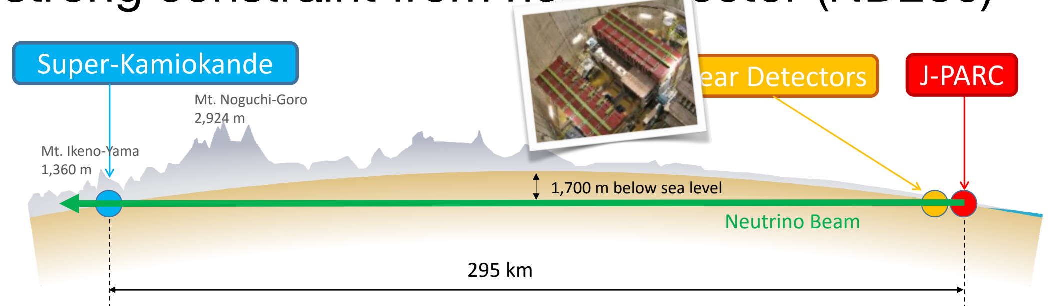
SK+T2K work in progress

Cross section model strategy



quasi-elastic

- T2K beam samples (3 types of samples)
  - precision study of a narrow flux at $E_\nu \lesssim 1\,\mathrm{GeV}$
  - dominated by simple quasi-elastic scattering
  - strong constraint from near detector (ND280)



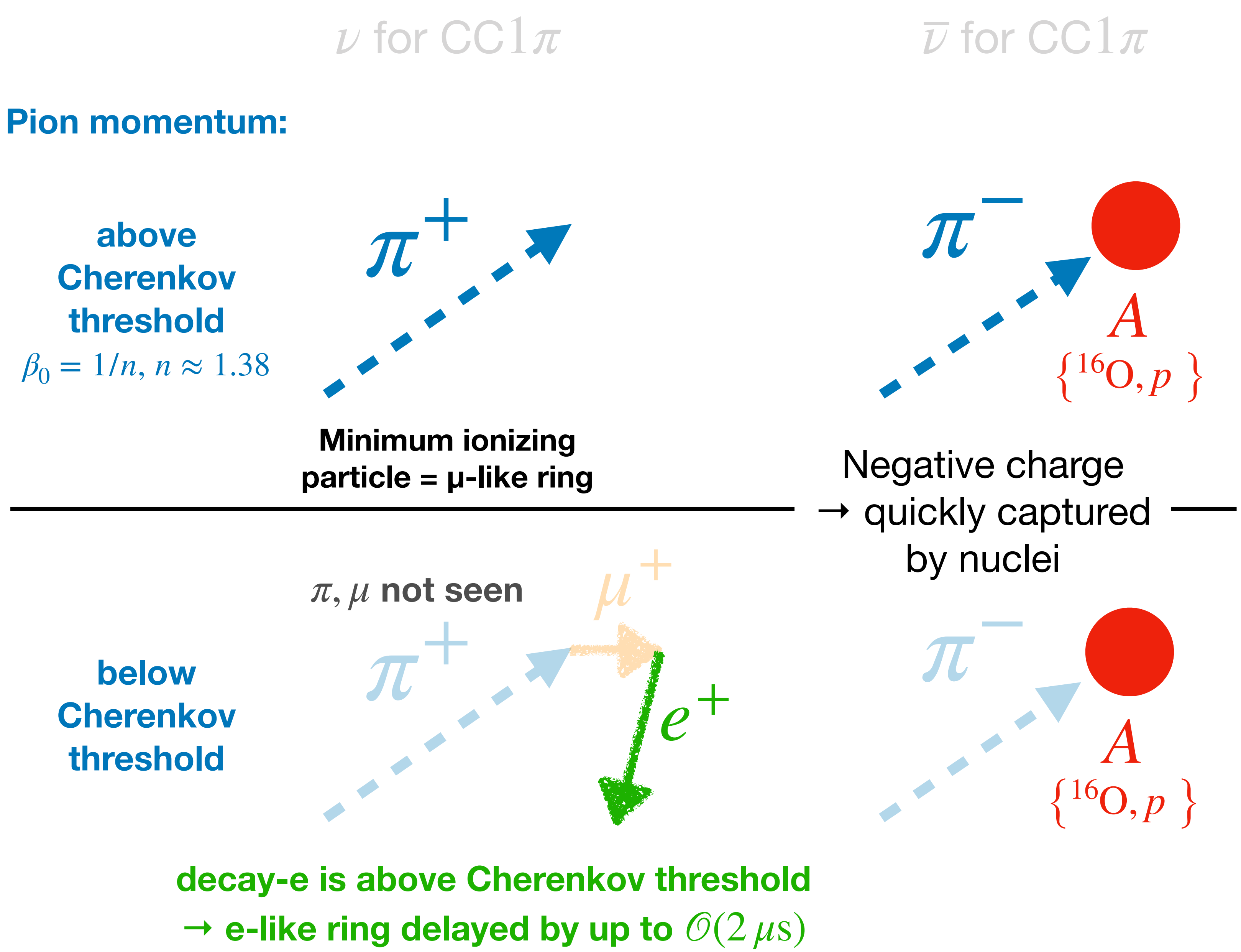
- SK atmospheric samples (18 samples)
  - many types of samples including ones with tagged pions which ND280 constraint is not targeted for
  - some range up to very high energies with very inelastic interactions (many pions)

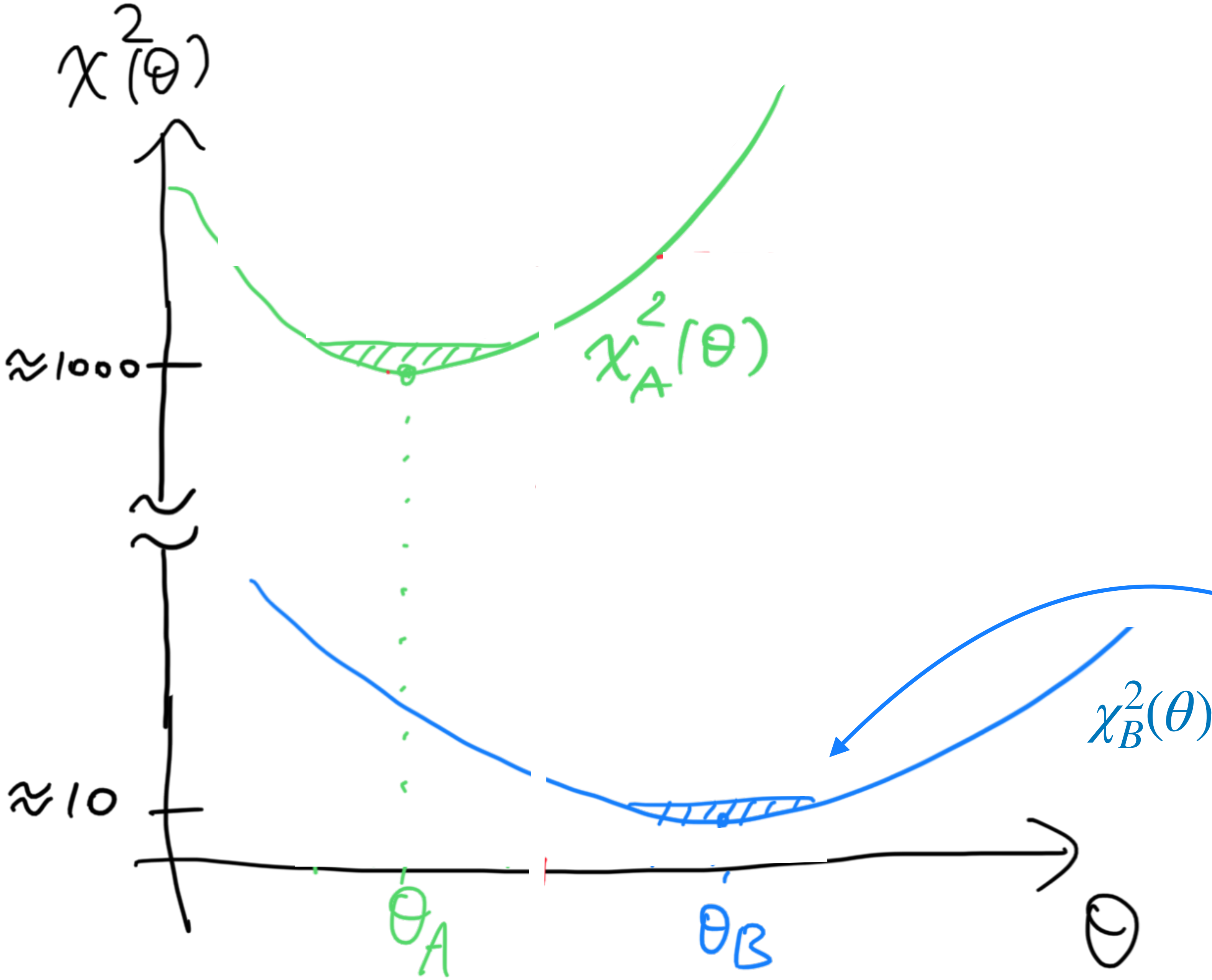
1. For beam and atm-SubGeV samples: (overlapping in energy region ←)
   - use T2K model + ND280 constraint
   - develop additional systematics to cover degrees of freedom not measured by ND280

2. For atm-MultiGeV samples:
   - use SK model without ND280 constraint

Charged pions

what is visible in water Cherenkov detectors





Goodness of fit

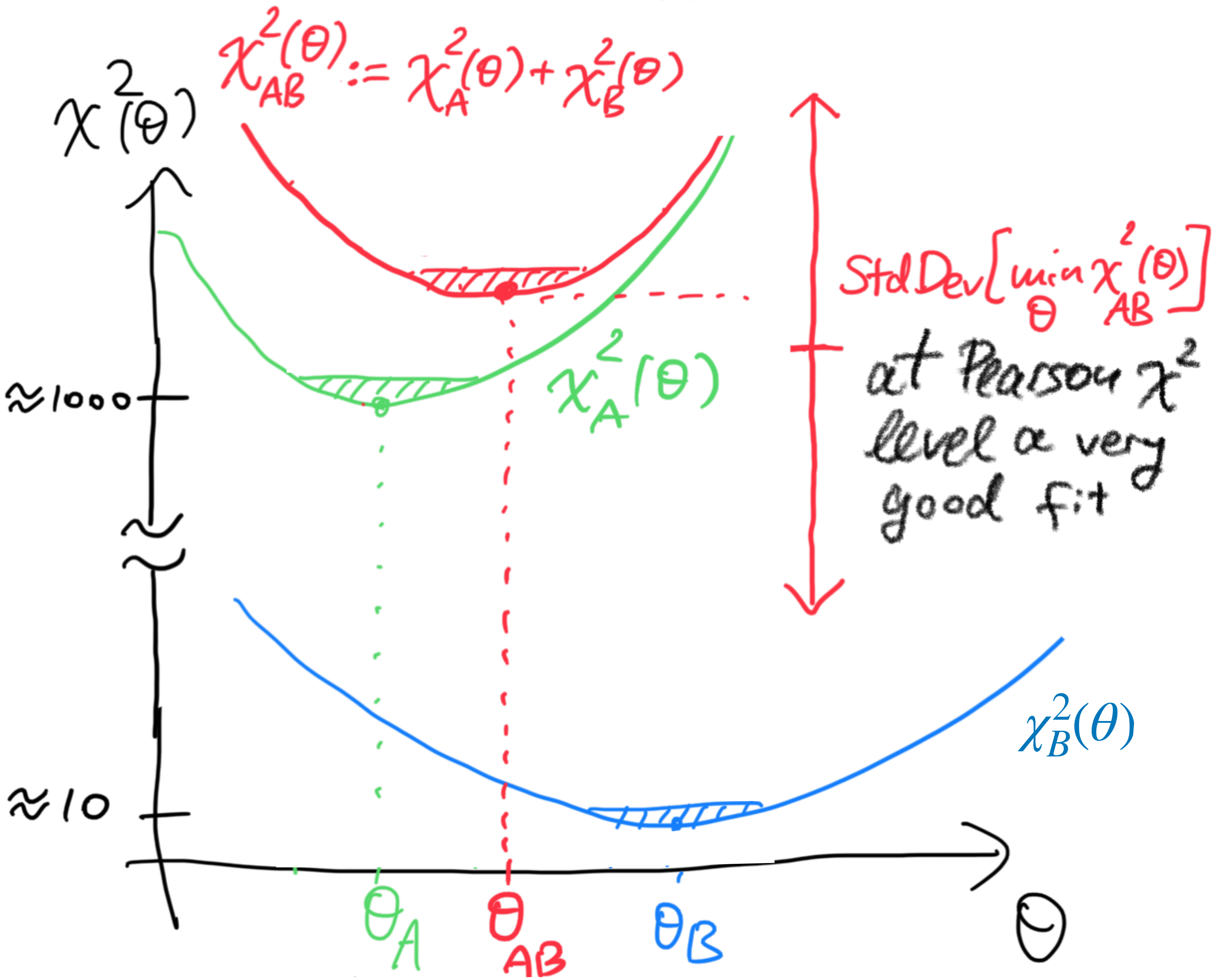
- **Pearson GOF**, i.e.
  $\chi^2_{\text{Pearson}} := \min_\theta \chi^2(\theta)$
  Simple, but good Pearson GOF can still be a poor fit because
  $\chi^2_{\text{Pearson}} \sim \chi^2_k$ with $k = N_{\text{bins}} - N_{\text{free}}$
  and N_{free} the number of unconstrained parameters.

  If e.g. we mis-model a sub-dominant interaction mode for which the **control sample** has small number of bins, the large variation of χ^2_k can hide this poor fit

- **Parameter GOF** [1], check the agreement of two independent data sets A,B:
  $\chi^2_{\text{PGOF}} := \min_\theta \left[\chi^2_A(\theta) + \chi^2_B(\theta)\right] - \min_{\theta'} \chi^2_A(\theta') - \min_{\theta''} \chi^2_B(\theta'')$
  asymptotically related to the number of **common parameters** (not bins) and independent from A-only and B-only χ^2_{Pearson}.

- We extended the PGOF formalism to work with data sets that are correlated through common prior constraints.

[1] Phys. Rev. D, 68:033020, 2003. doi: 10.1103/PhysRevD.68.033020.



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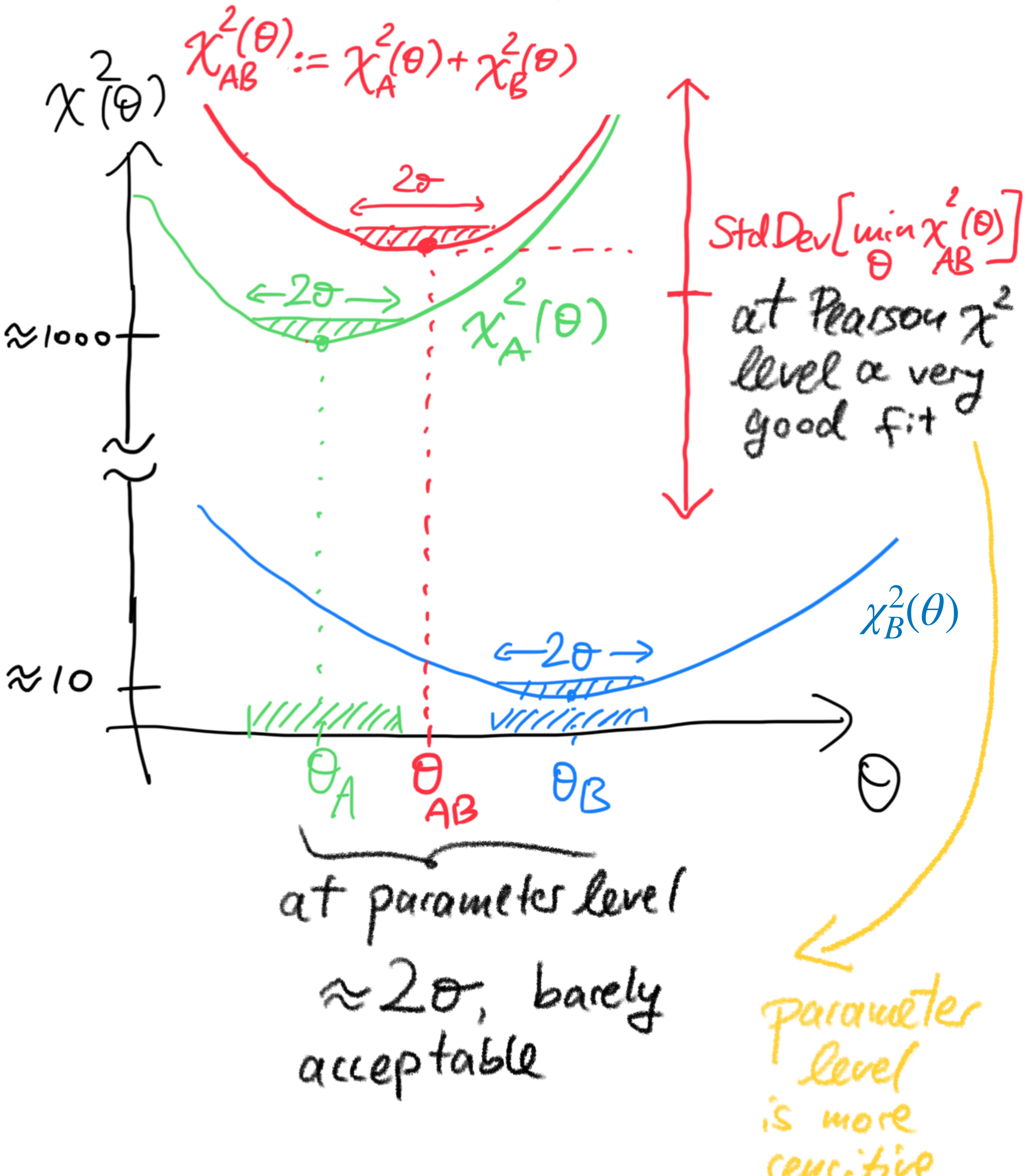

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Goodness-of-fit

Under null hypothesis (nominal MC)

Prior	Adler syst	DG $\mathbb{E}[\chi^2_{\text{min}}]$	DG not CC1π^+ $\mathbb{E}[\chi^2_{\text{min}}]$	DG CC1π^+ $\mathbb{E}[\chi^2_{\text{min}}]$	DG CC1π^+ vs. other $\mathbb{E}[\chi^2_{\text{PGOF}}]$	DG CC1π^+ vs. other $\text{SD}[\chi^2_{\text{PGOF}}]$
Pre-ND	✓	83.7	77.4	4.5	14.4	4.5
Pre-ND		86.4	77.7	7.0	15.7	5.0
Post-ND	✓	85.1	78.9	5.1	12.6	5.1
Post-ND		86.7	79.7	5.9	13.0	4.1

Under maximal distortion of Adler angle distribution $(\alpha = -1)$

Prior	Adler syst	DG $\Delta\mathbb{E}[\chi^2_{\text{min}}]$	DG p	DG not CC1π^+ $\Delta\mathbb{E}[\chi^2_{\text{min}}]$	DG not CC1π^+ p	DG CC1π^+ $\Delta\mathbb{E}[\chi^2_{\text{min}}]$	DG CC1π^+ p	DG CC1π^+ vs. other $\Delta\mathbb{E}[\chi^2_{\text{PGOF}}]$	DG CC1π^+ vs. other p
Pre-ND	✓	0	0.48	0	0.48	0	0.48	0	0.46
Pre-ND		0.7	0.46	0	0.48	0.2	0.41	1.0	0.28
Post-ND	✓	0	0.48	0	0.48	0	0.42	0	0.62
Post-ND		13.8	0.15	0.04	0.48	6.3	0.055	11.8	0.022

DG: SK down-going