KM3NeT/Super-ORCA:
Measuring the leptonic CP-phase with atmospheric neutrinos – a feasibility study

Jannik Hofestädt
PANE, Trieste, 31.05.2018

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

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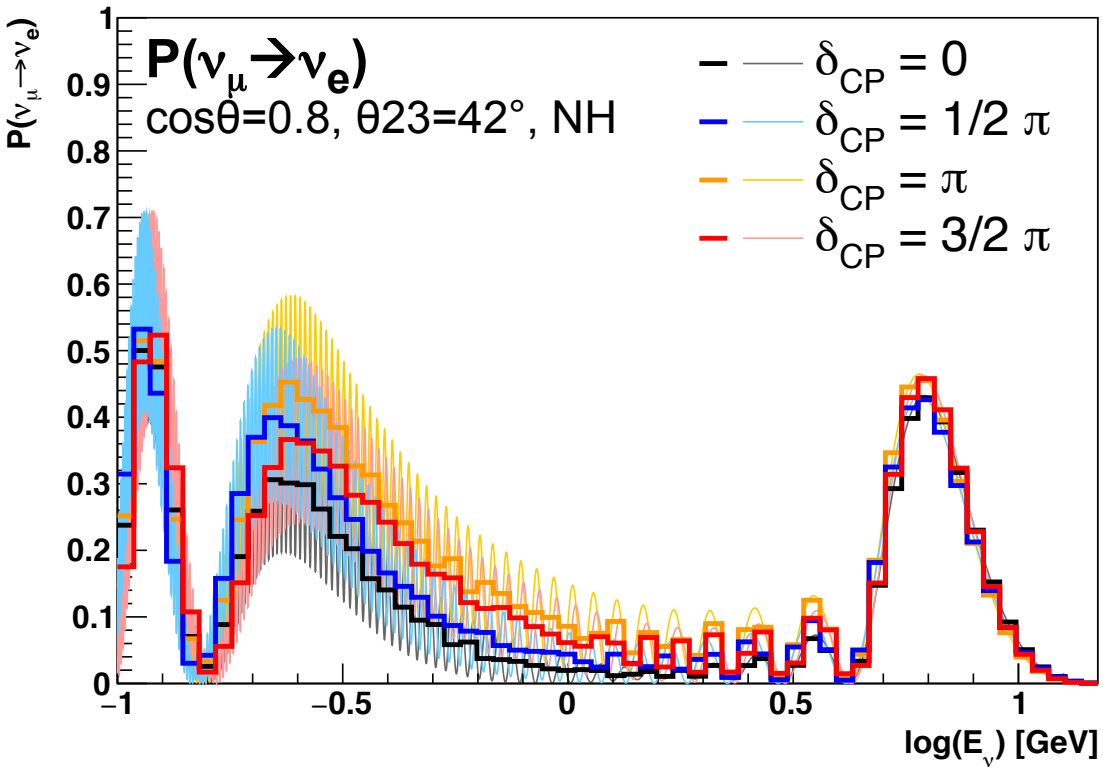
Motivation

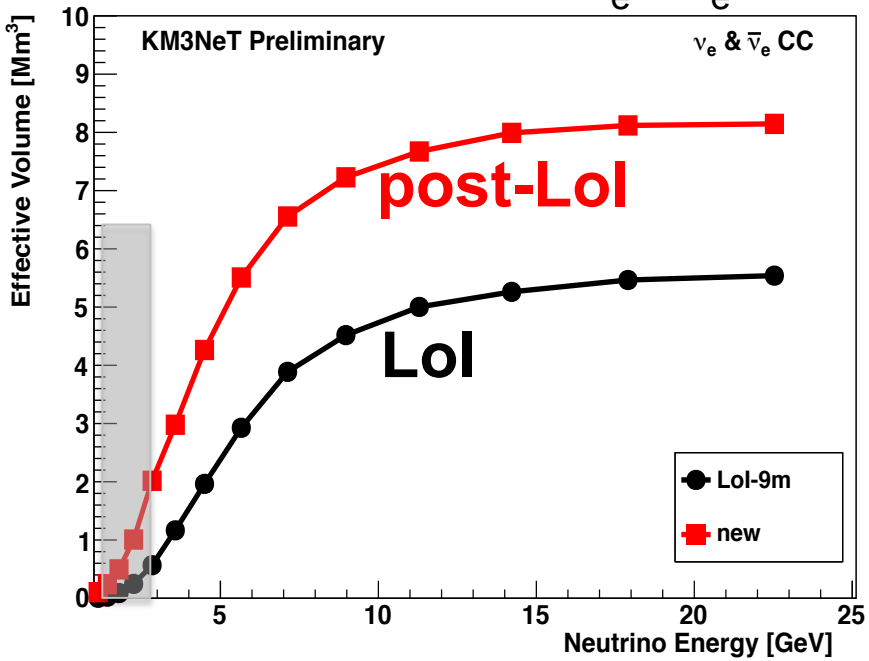
- Use atmospheric neutrinos to measure δ_{CP} phenomenology → previous talk by S. Razzaque
- **δ_{CP} sensitivity <~2GeV**
- **Good ν_e / ν_μ separation crucial !**



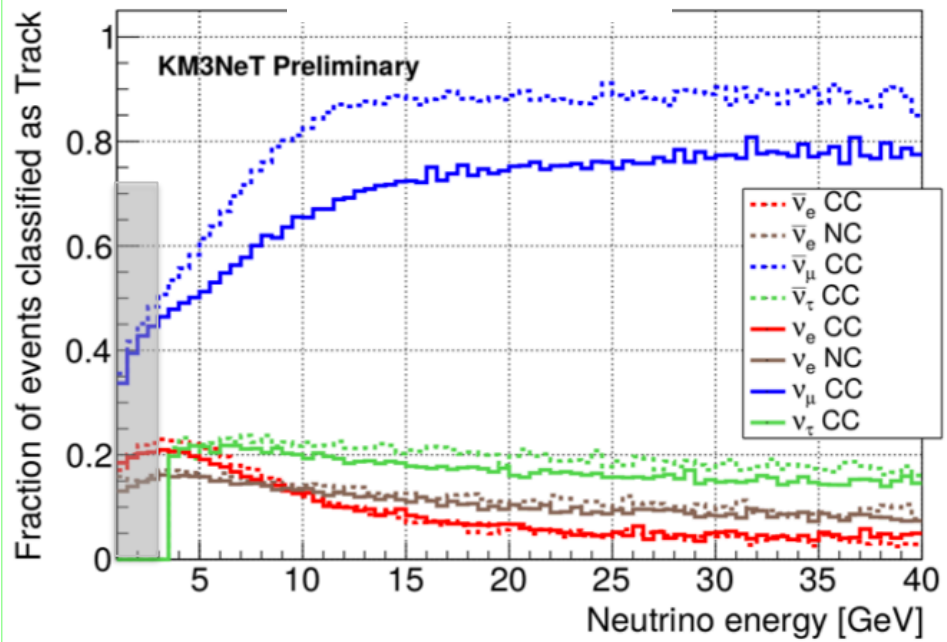
ORCA

- ORCA: detection threshold @ ~2GeV and insufficient PID below ~5GeV

Effective volume for ν_e & $\bar{\nu}_e$ CC



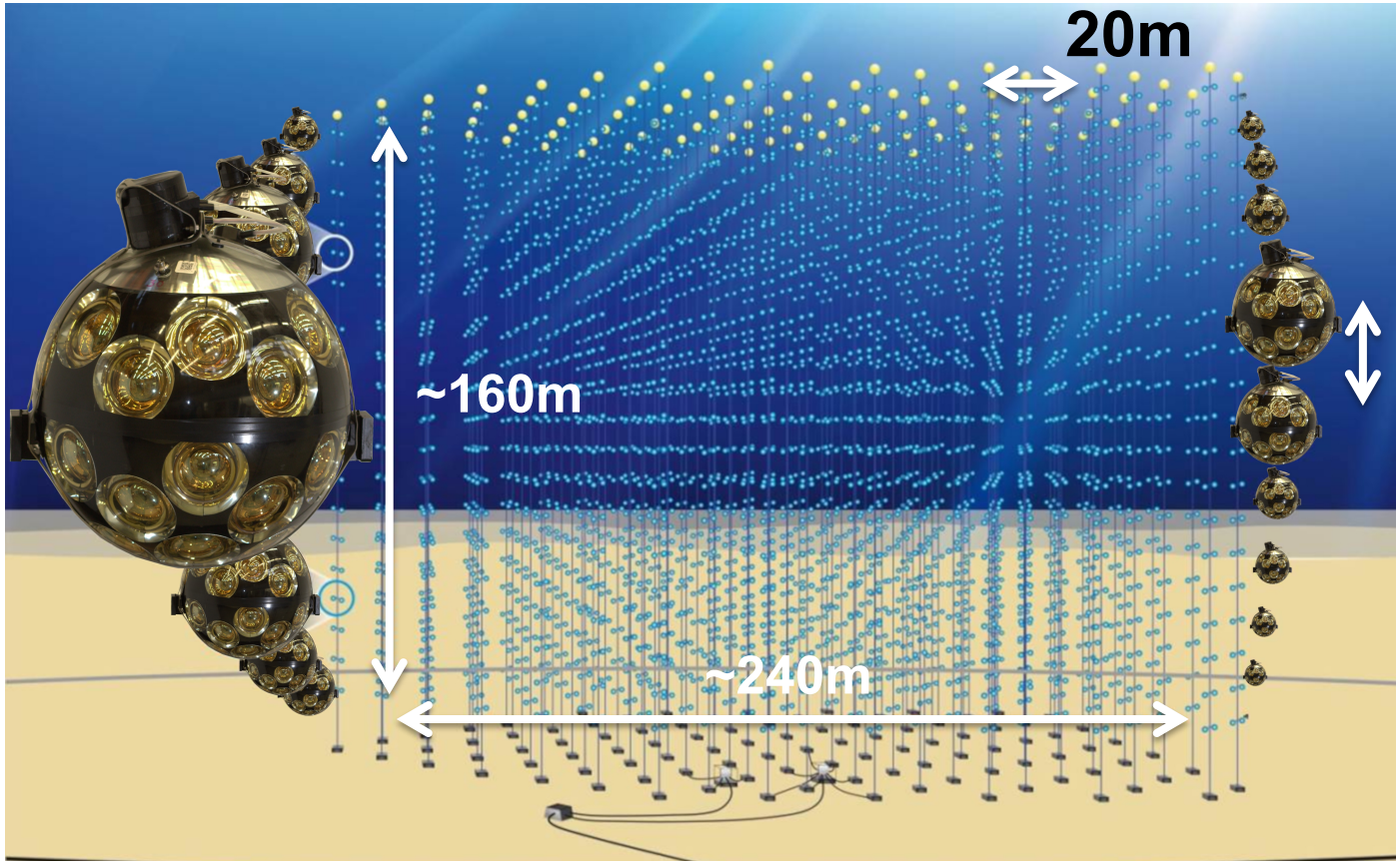
track-shower classification



- δ_{CP} measurement requires lower detection threshold and better ν_e / ν_μ separation capabilities → denser detector
- **Q: Which instrumentation density is required?**

  A: ~ 5–15x denser than ORCA

ORCA detector layout



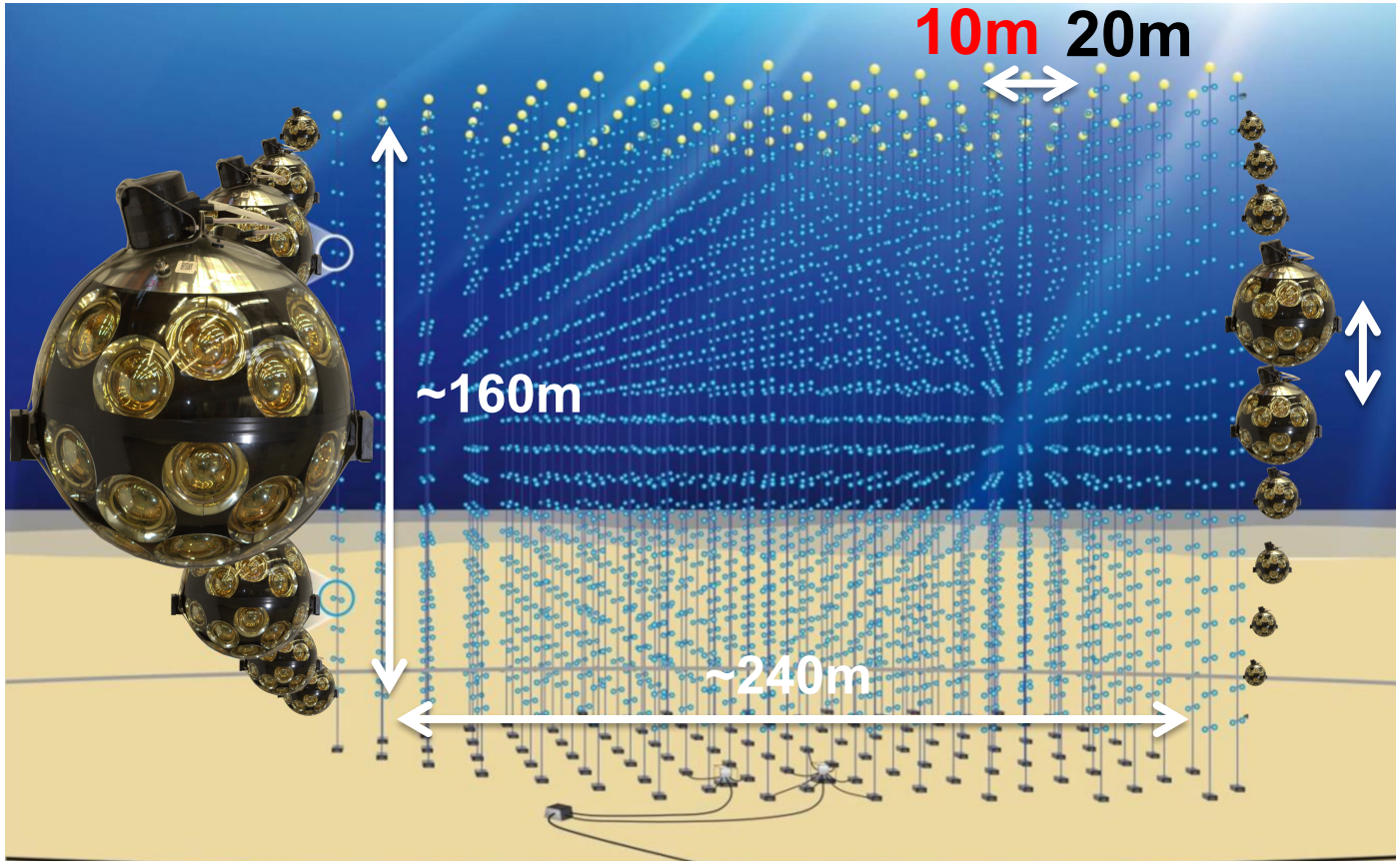
ORCA

9m

115 strings

instrumented volume: ~8Mton

Possible Super-ORCA detector layout



Super-ORCA

ORCA

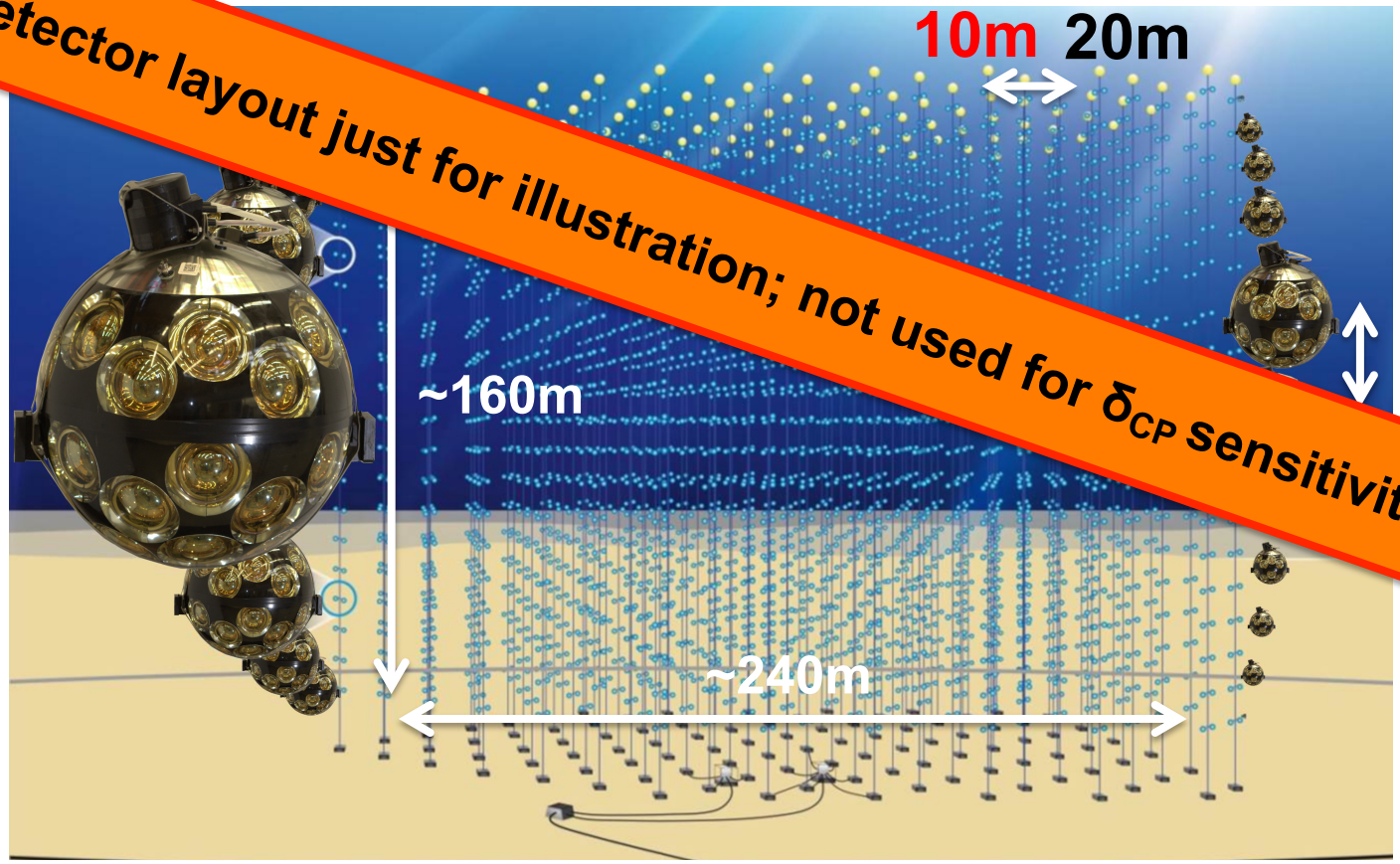
3m
9m

~500 strings
115 strings

instrumented volume: ~8Mton

- Similar detector volume and 10x denser than ORCA: ~100k 3” PMT/Mton
  → **~100 detected photons per GeV**
- For comparison: ~1% of SK’s photo effective area / detector volume

Possible Super-ORCA detector layout



Detector layout just for illustration; not used for δ_{CP} sensitivities in this talk

Super-ORCA

ORCA

3m

9m

trings

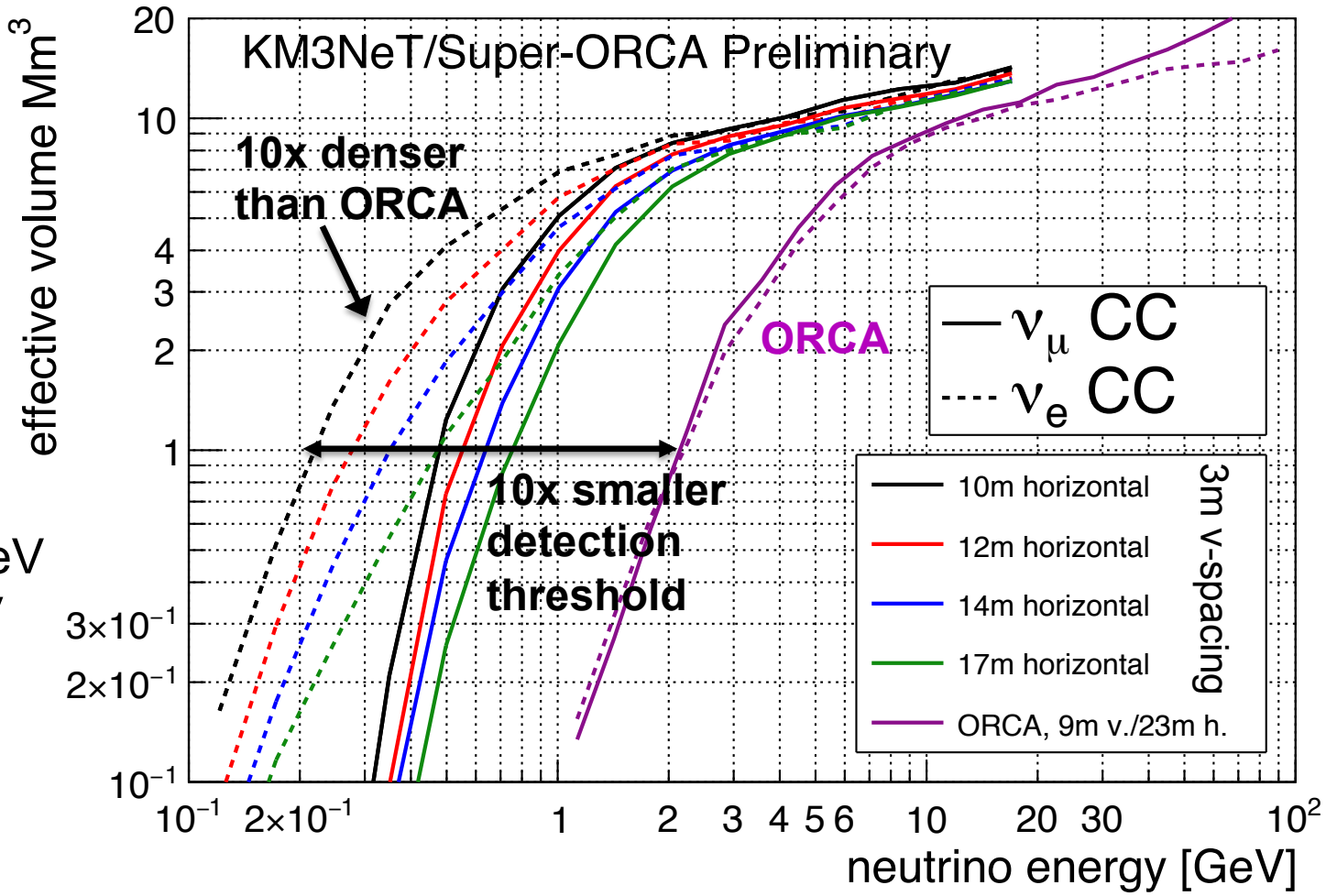
instrumented volume: ~8Mton

- Similar detector volume and 10x denser than ORCA: ~100k 3" PMT/Mton
  → **~100 detected photons per GeV**
- For comparison: ~1% of SK's photo effective area / detector volume

Super-ORCA: effective volume @ trigger level

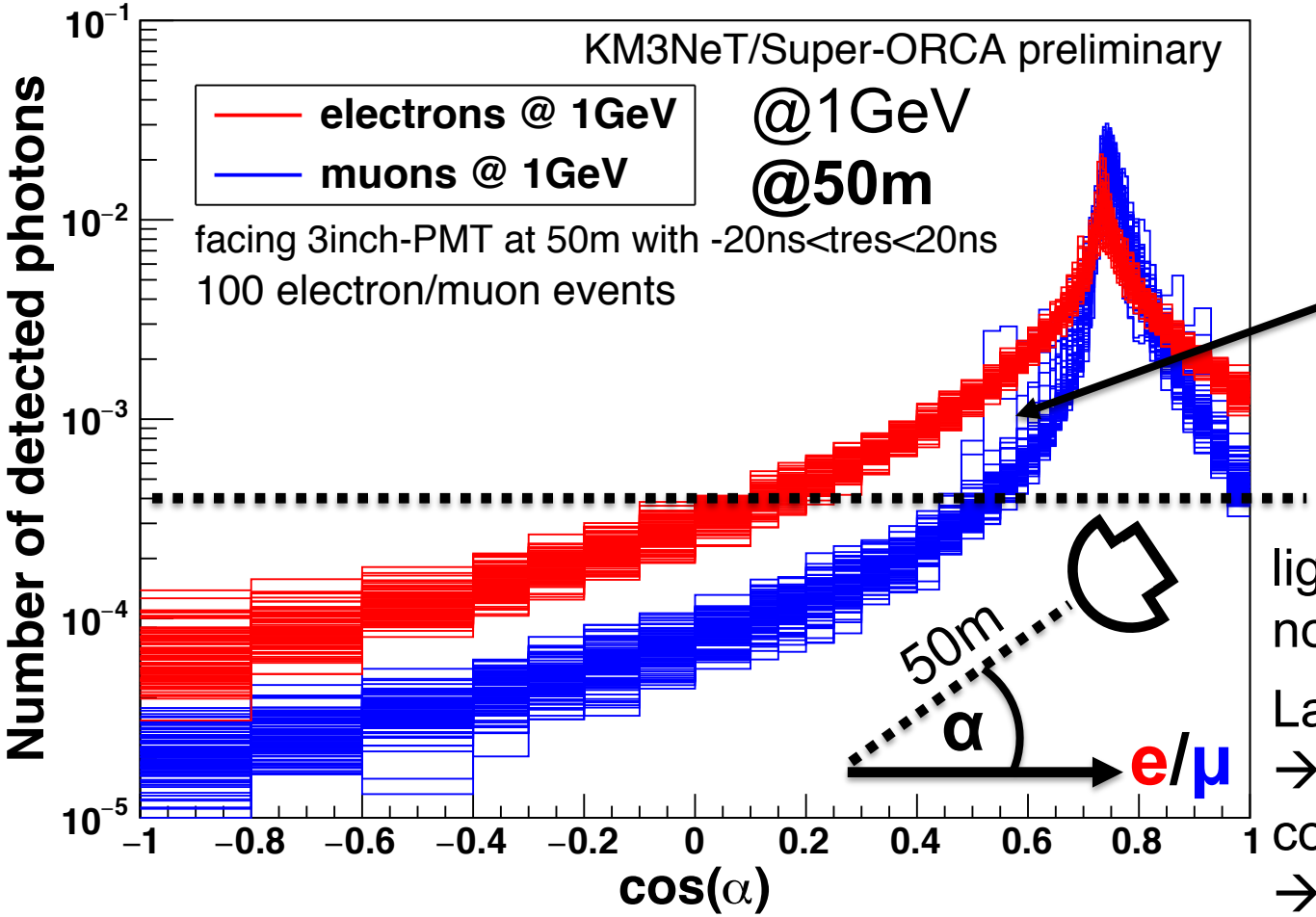
- Simulation of different Super-ORCA detector geometries (4-10x denser)
- 3m vertical inter-DOM spacing and 10/12/14/17m inter-string spacing

for ν_eCC :
4Mton @0.5GeV
7Mton @1GeV



PID: electron vs muon separation

- PID @ ORCA: muon track length → not useful @1GeV (4m track length)
- → strategy a-la Super-K: angular profile of e/μ cone



muon scattering

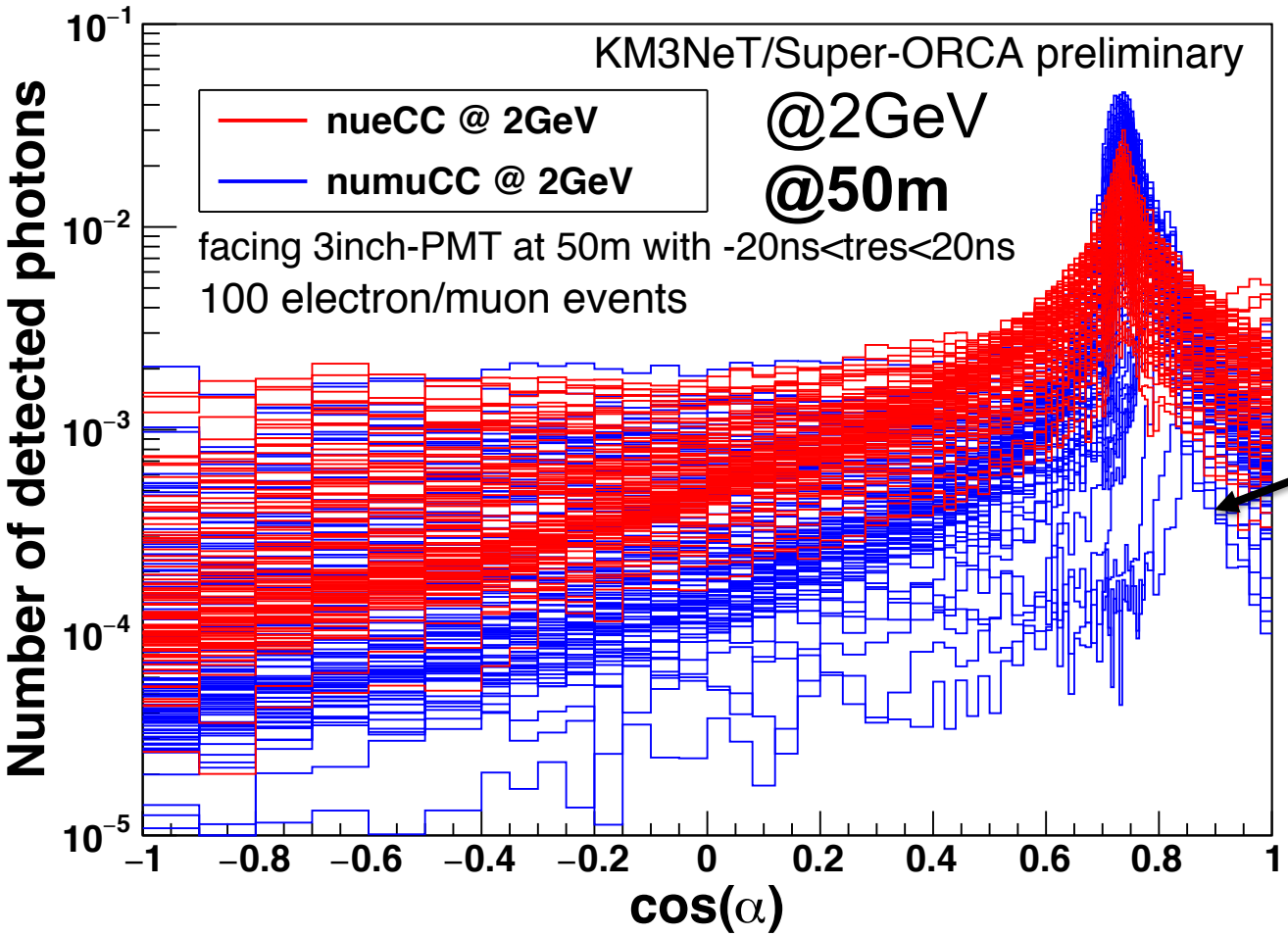
noise level (10kHz/PMT)

light signal above noise up to ~100m

Large scattering length → angular profile conserved → good direction resolution & PID

PID: nueCC vs numuCC

- Full ν_e / ν_μ events; some events with energetic hadrons

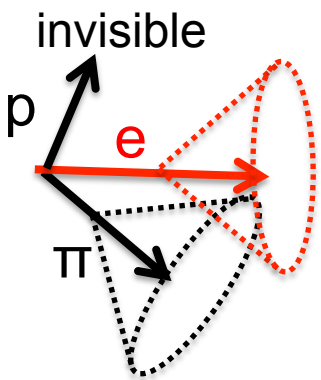


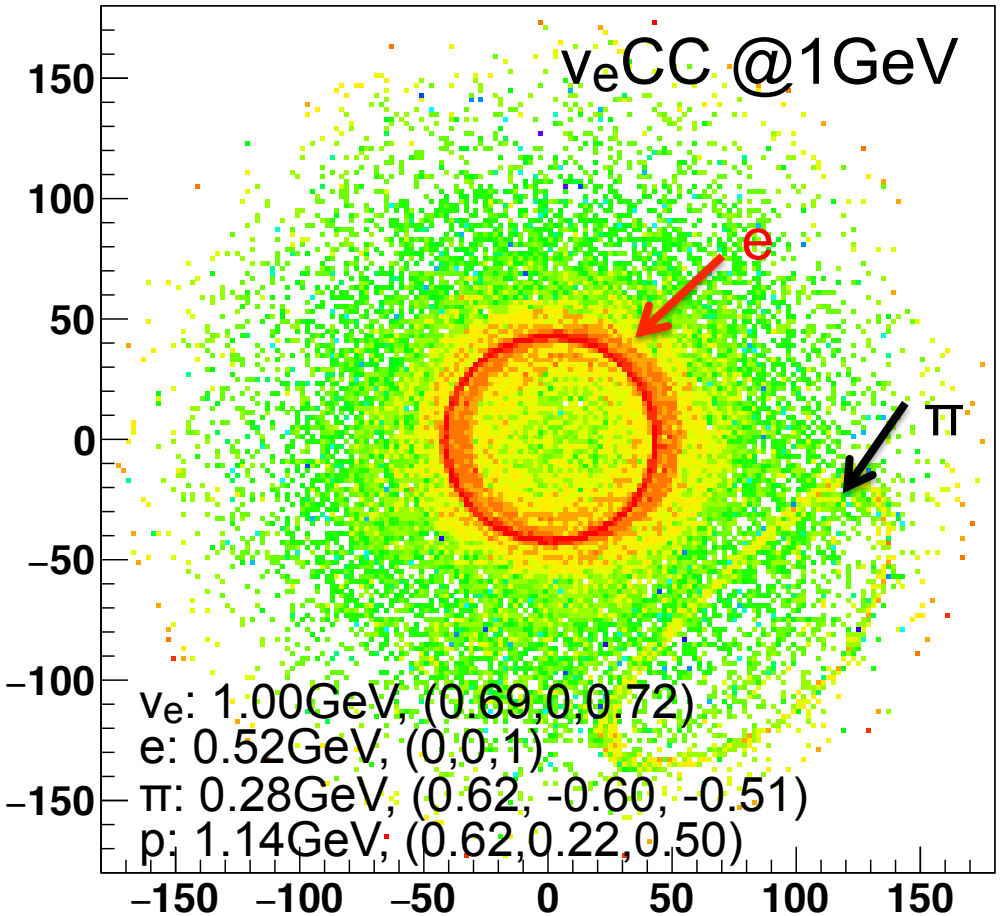
low-E muons from high Bjorken-y events

angle α w.r.t. e/μ direction

Cherenkov light signature

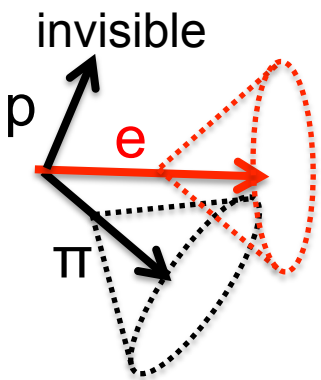
- Note: 3D event signature in detector → cone



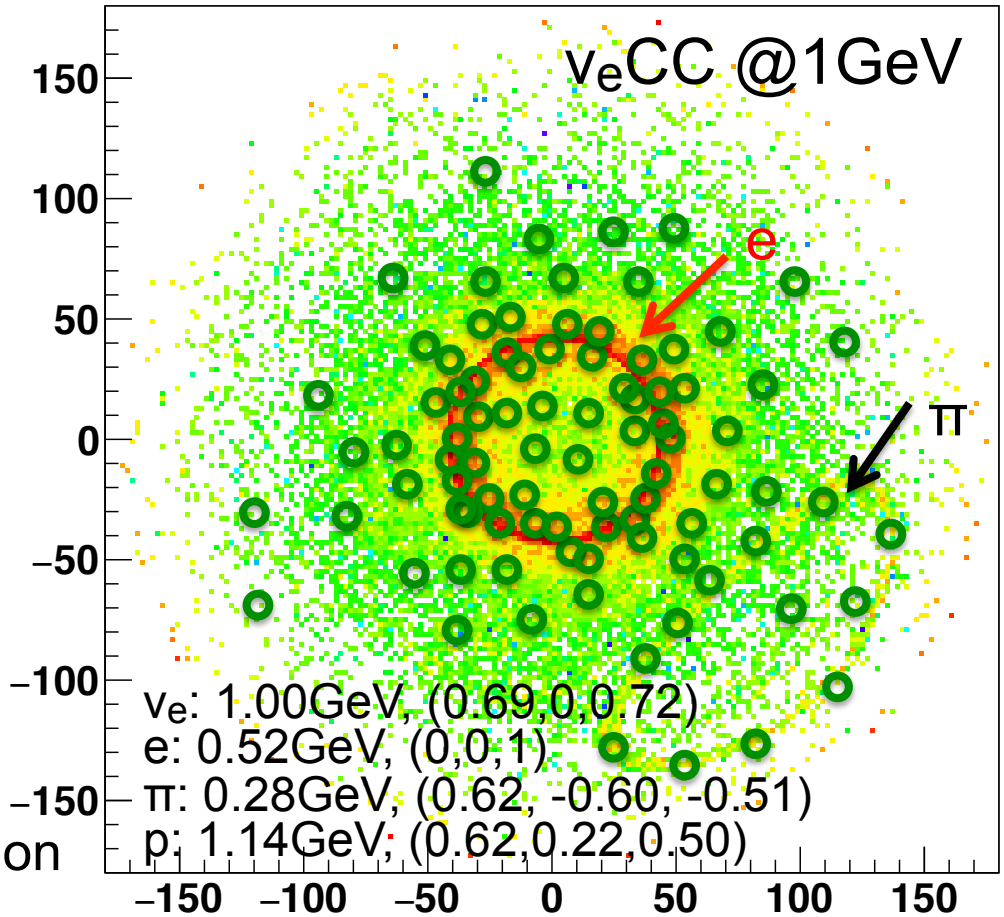


Cherenkov light signature

- Note: 3D event signature in detector → cone



- 'faint' particles might not be identified as individual cones
- → challenging for reconstruction
- → source for systematics



detected photon (~100/GeV)

Simplified detector response

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- **No** full detector simulation used for sensitivity calculations in this talk
- **Idealised detector response:**
  assume **homogeneous** detector with infinitely small PMTs with **isotropic** orientations, i.e. no 'clumpiness' of PMTs in DOMs, and
  infinitely large detector → fully contained events, i.e. no edge effects

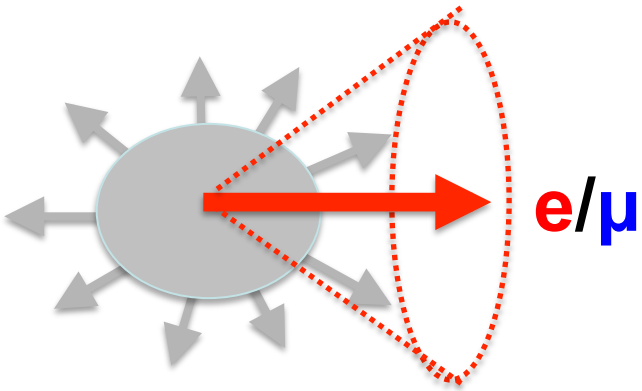
→ Detector response only depends on assumed instrumentation density

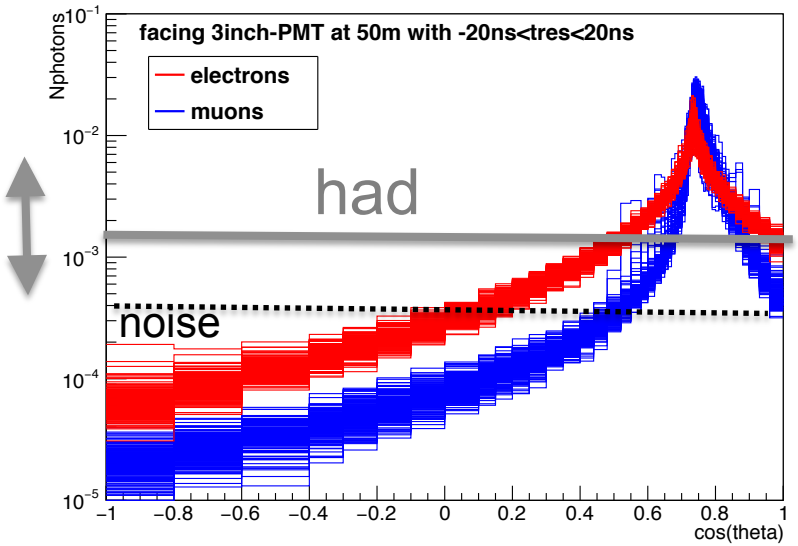
In the following: **10x denser than ORCA & 4Mton fiducial volume**
(8Mton instrumented & 50% fiducializing)

- Neutrino event generation: GENIE 2.10.2
- Particle tracking: Geant
- Photon tracking with up-to-date model of optical water properties
- Realistic optical background in the deep sea (10kHz/PMT)

Reconstruction

- Full likelihood reconstruction for idealised detector
  strategy: cone from e/μ + isotropic light from hadronic shower



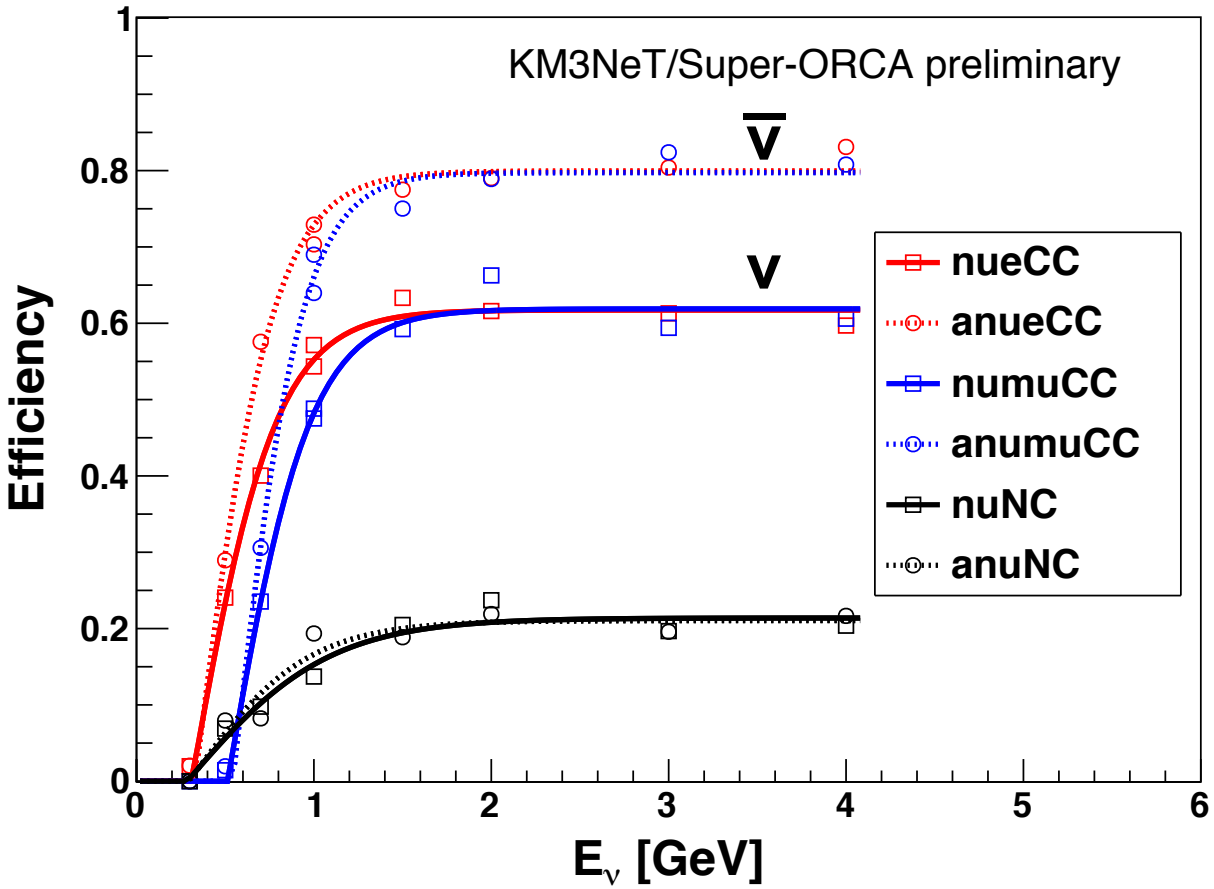


- Simple event selection based on reco variables
- Main e/μ separation power from: LLH(e) – LLH(μ)

Efficiency

- Efficiency and not effective volume, as infinitely large detector assumed
- Efficiency ~0.8/0.6/0.2 for anuCC/nuCC/NC → Meff= 0.8/0.6/0.2*4Mton
- Nearly plateau reached @ 1GeV

4Mton fiducial volume



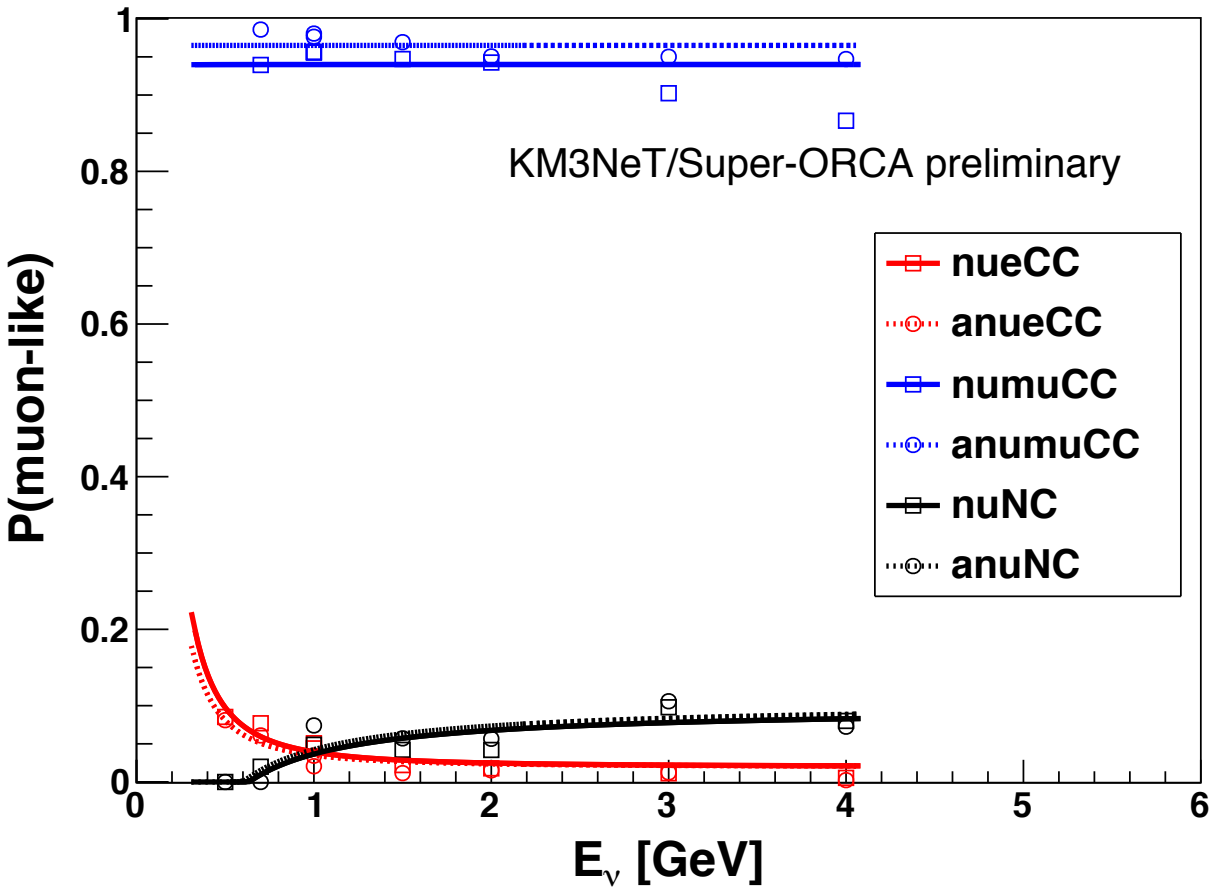
ν_eCC

ν_μCC

NC

Particle identification

- ~95% purity @ E_ν=1GeV, because:
  → many QE events without 'confusion' with light from hadrons
  → event selection favours clean e/μ events



Energy and direction resolution

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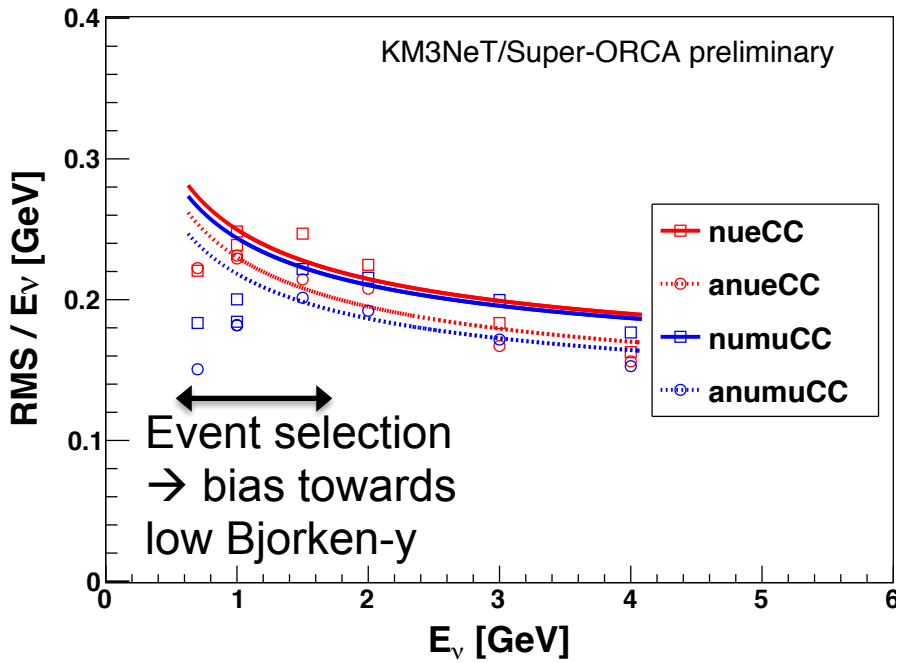
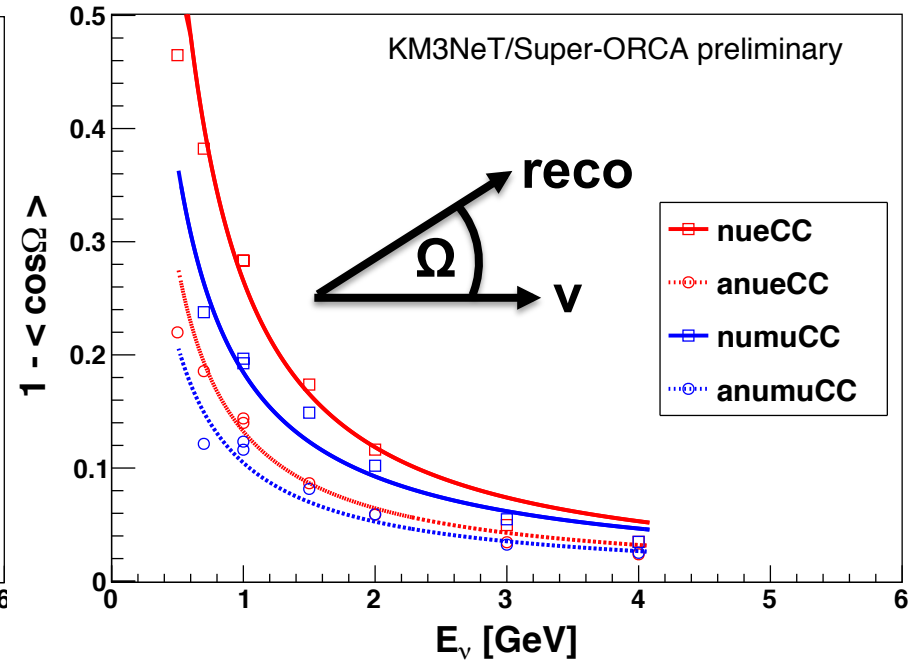
Energy resolution



- RMS/E_ν ~ 20–25% @ 1GeV
- dominated by intrinsic light yield fluctuations
  📖 JHEP 05, 008 (2017)

Direction resolution

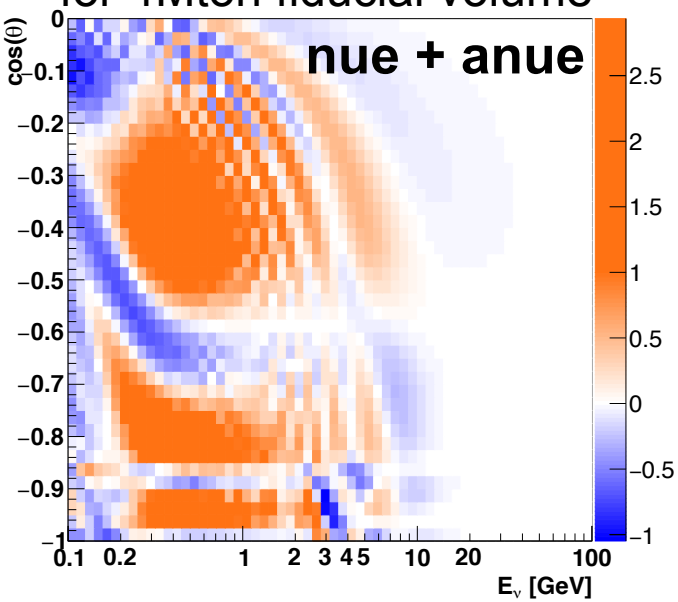


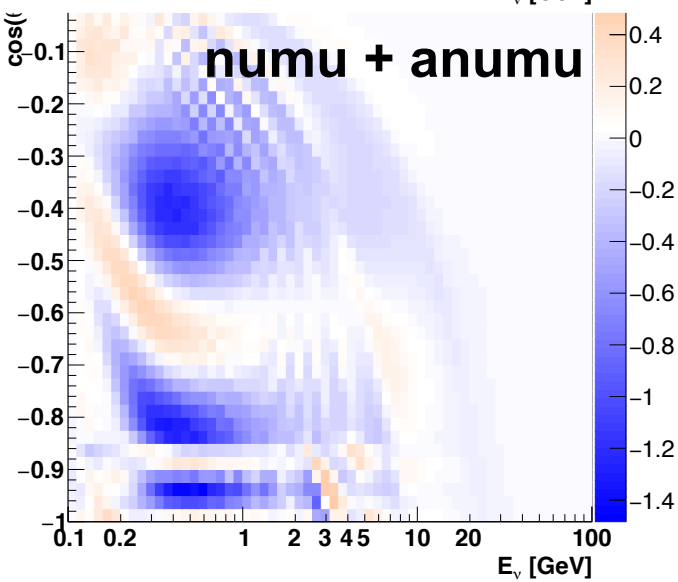
- <cosΩ> ~ 0.8–0.9 @ 1GeV
  → Ω ~ 30°@ 1GeV
- dominated by intrinsic ν-lepton scattering angle
- resolution on lepton direction: few degree

Distinguishability

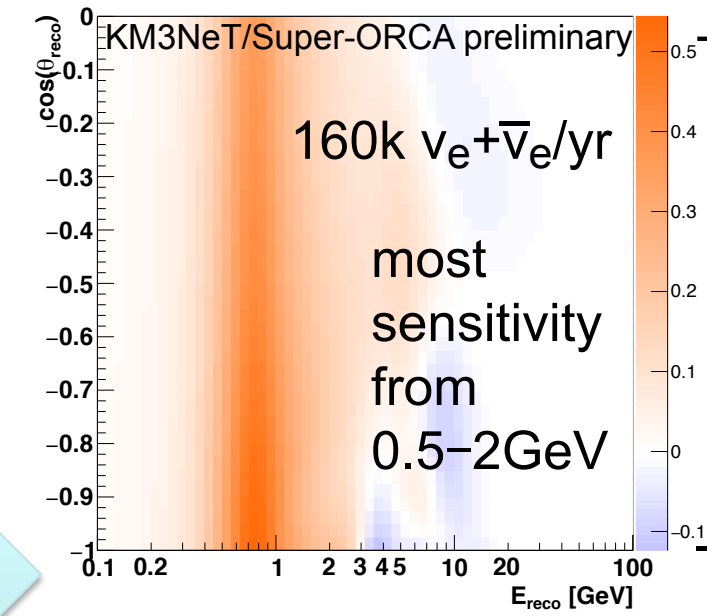
for 4Mton fiducial volume

$(N_{\delta=\pi} - N_{\delta=0}) / \mathrm{sqrt}(N_{\delta=0})$



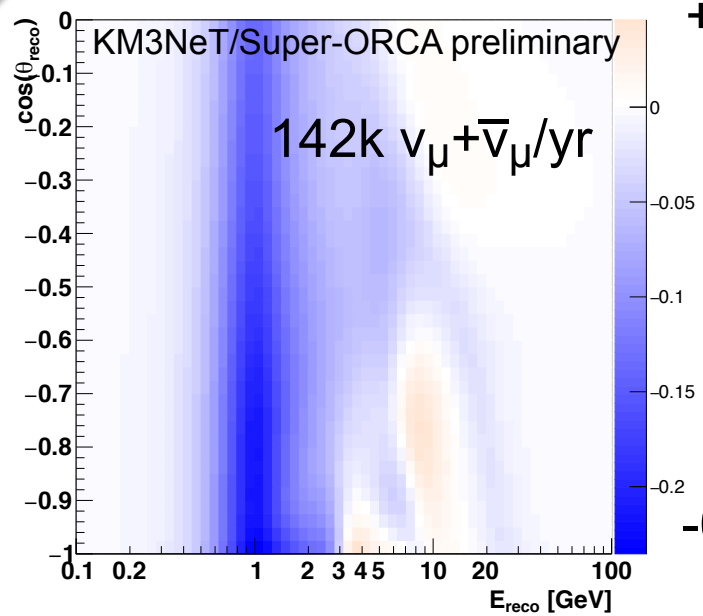


detector response



+0.50

-0.1

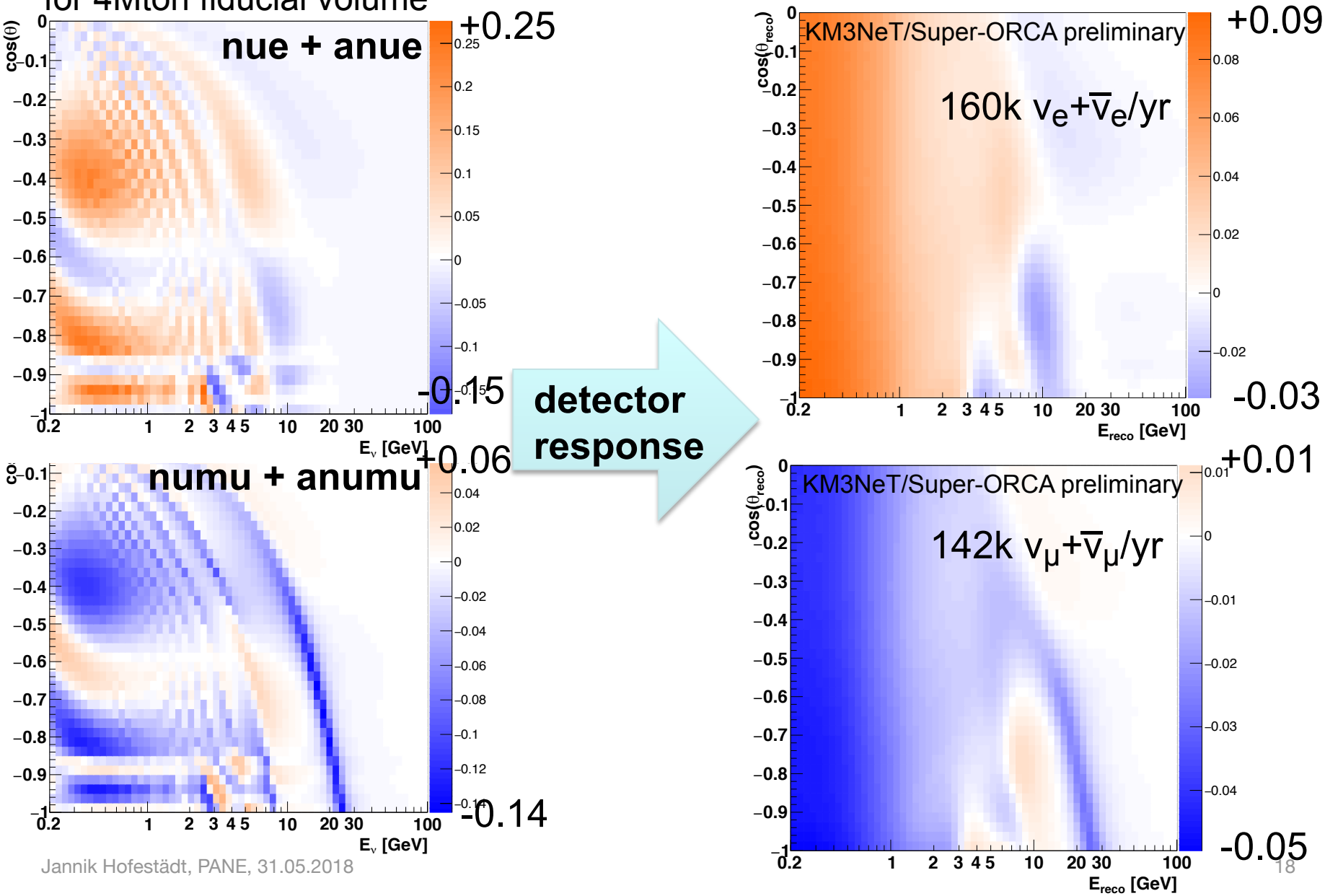


+0.05

-0.20

Relative differences $(N_{\delta=\pi} - N_{\delta=0}) / N_{\delta=0}$

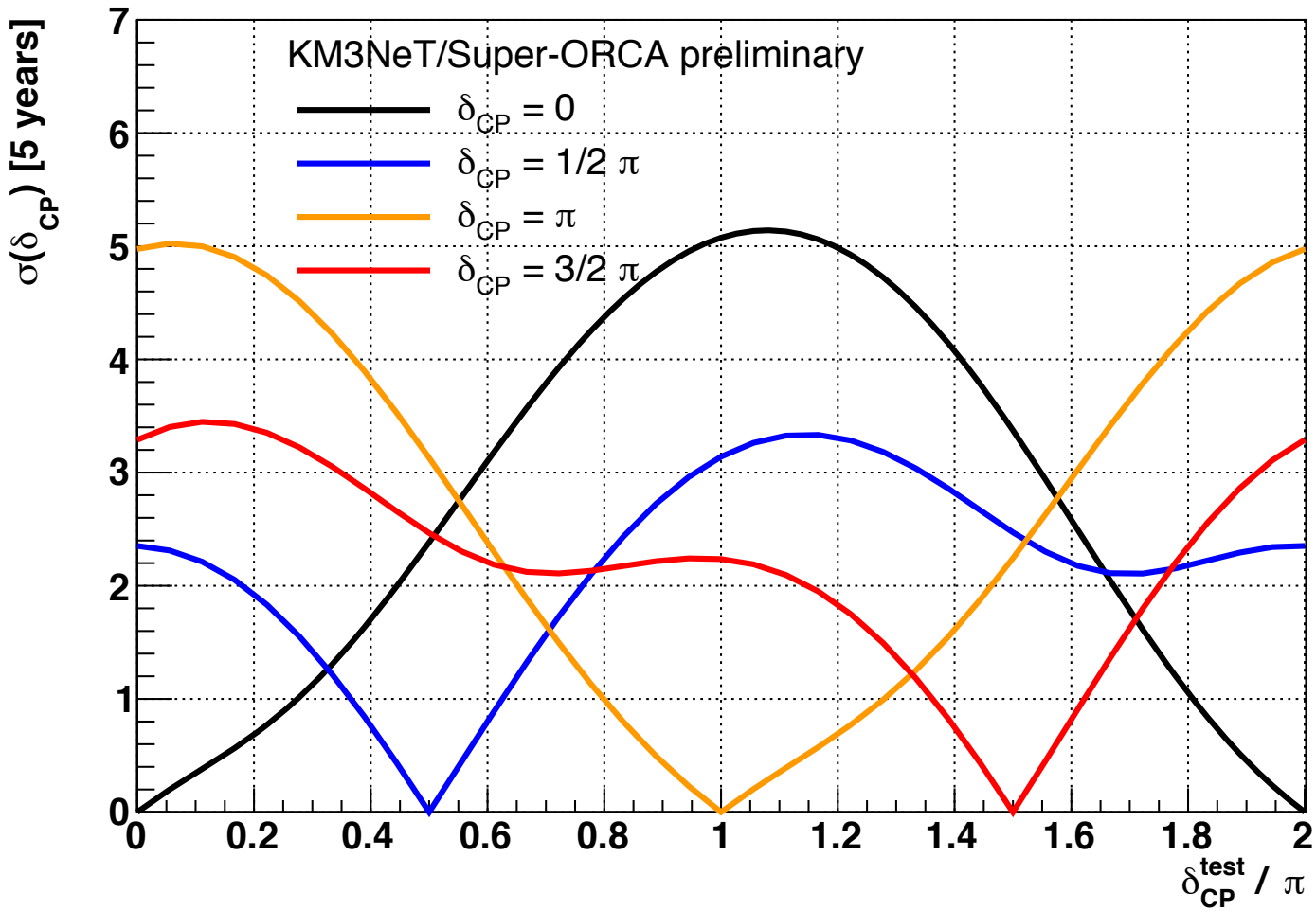
for 4Mton fiducial volume



δ_{CP} sensitivity

10x denser than ORCA
NH known
θ_{23}=42°
4Mton*5yr

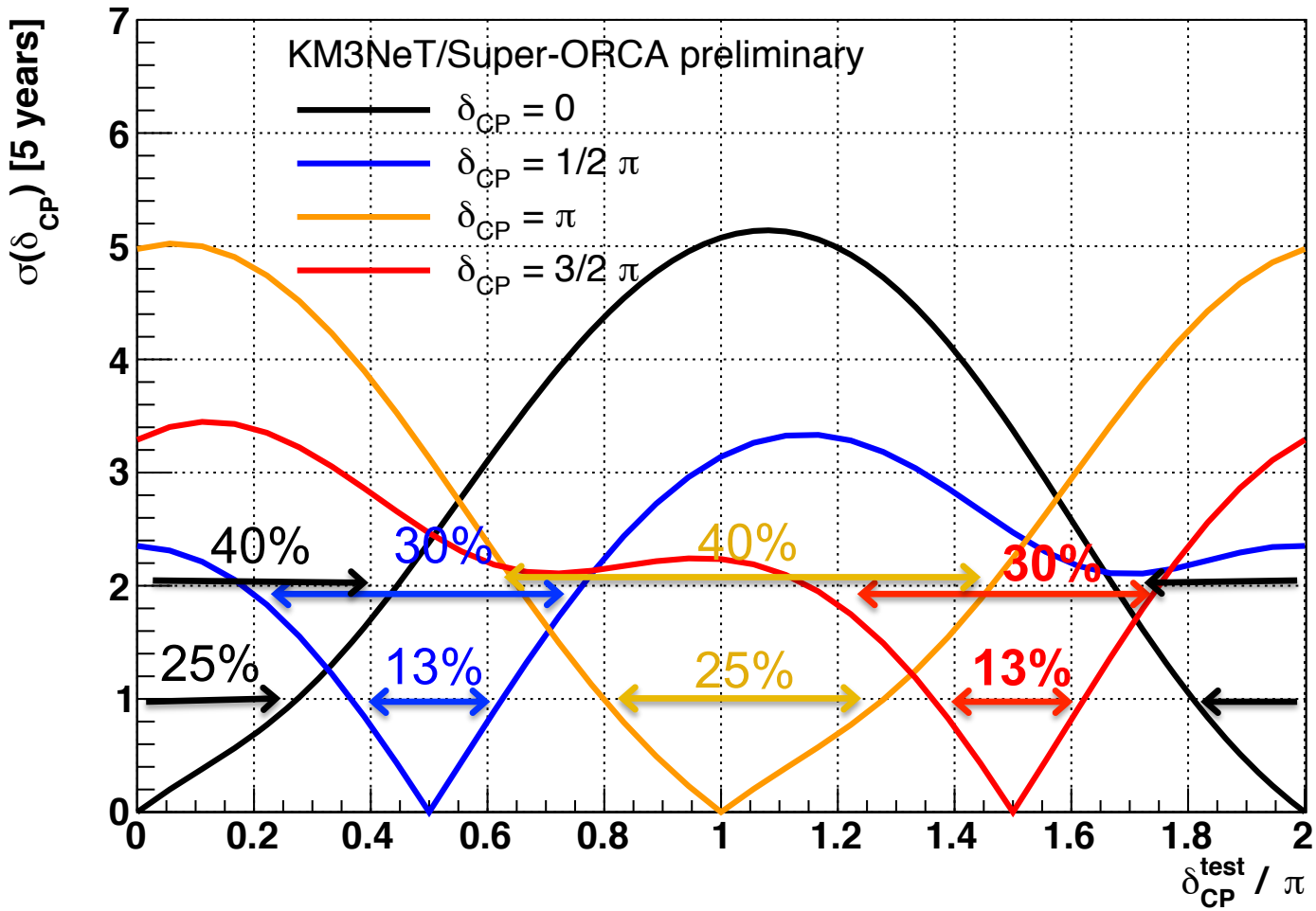
- Method: χ^2 minimisation assuming a test δ_{CP} value and simultaneously fitting oscillation and nuisance parameters



δ_{CP} sensitivity

10x denser than ORCA
NH known
θ_{23}=42°
4Mton*5yr

- Maximal distinguishability between δ_{CP}=0 and δ_{CP}=π with 5σ
- 60% (70%) disfavoured with ≥2σ for δ_{CP}=0, π (δ_{CP}=π/2, 3/2π)

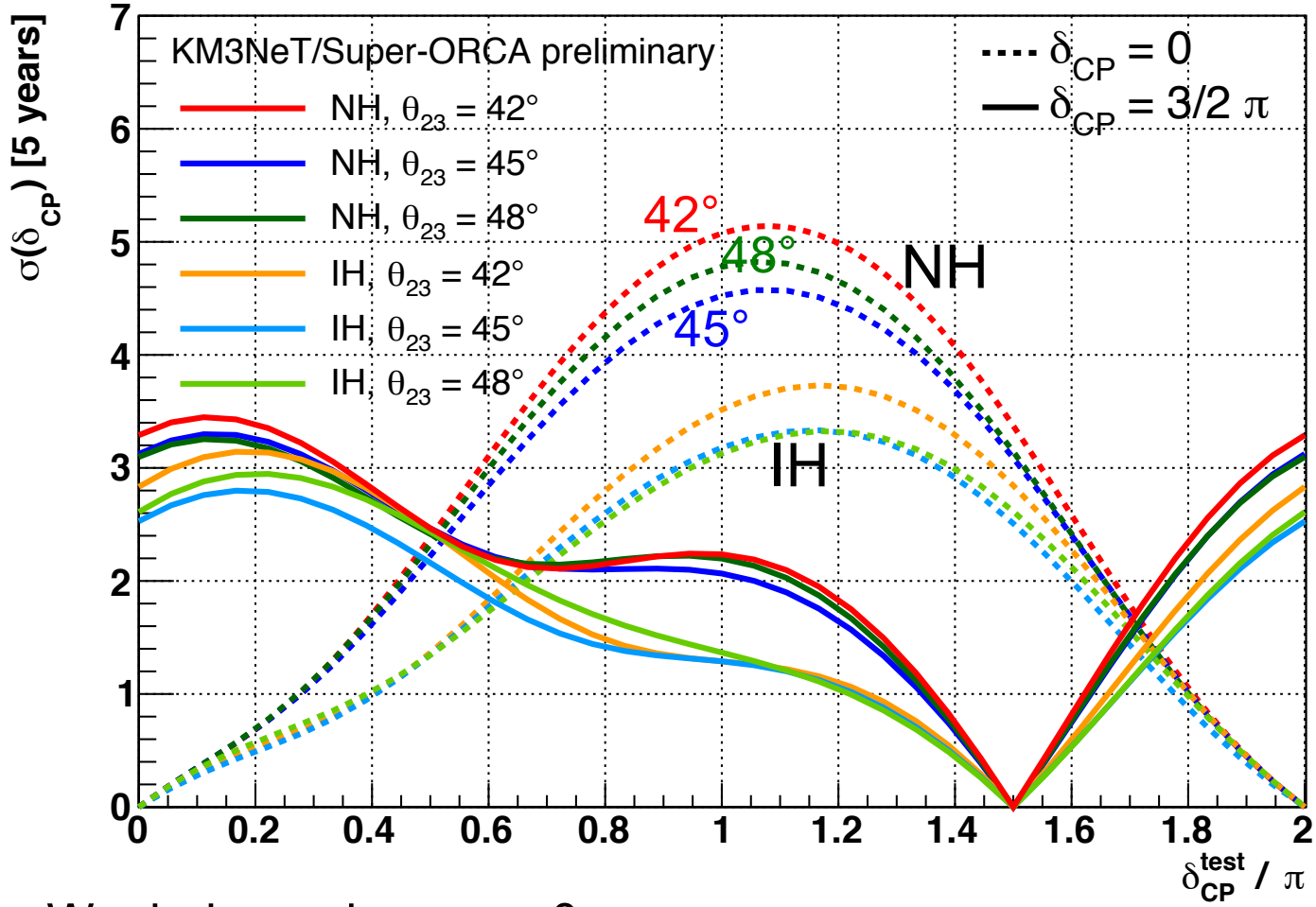


2σ range

1σ range
23° – 45°

IH vs NH and different θ23

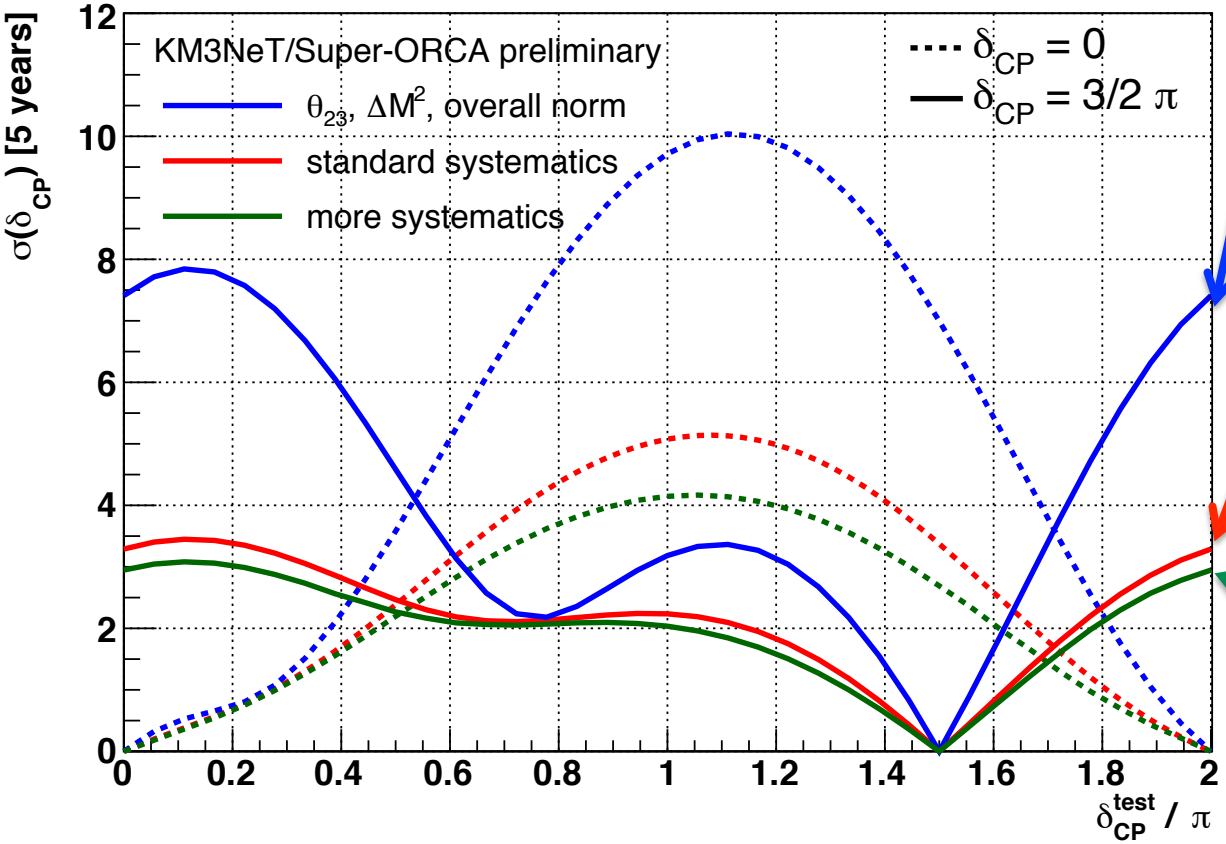
10x denser than ORCA
4Mton*5yr



- Weak dependence on θ_{23}
- IH needs larger exposure than NH for comparable significance

Systematics

10x denser than ORCA
NH known & θ_{23}=42°
4Mton*5yr



parameter	
θ_{23} [°]	
θ_{13} [°]	fixed
θ_{12} [°]	fixed
ΔM^2 [10^{-3} eV^2]	
Δm^2 [10^{-5} eV^2]	fixed
mass ordering	fixed
overall norm	
CC/NC skew	
$\bar{\nu}/\nu$ skew	
μ/e skew	
spectral index tilt	
up/hor skew $\propto \cos\theta$	
up/hor skew $\propto \cos^2\theta$	
energy scale overall	
Escale $\nu/\bar{\nu}$ skew	
Escale $\overset{(-)}{\nu}_e/\overset{(-)}{\nu}_\mu$ skew	
Escale $\overset{(-)}{\nu}_{e,\mu}/\overset{(-)}{\nu}_\tau$ skew	
Escale CC/NC skew	
Escale up/hor skew	

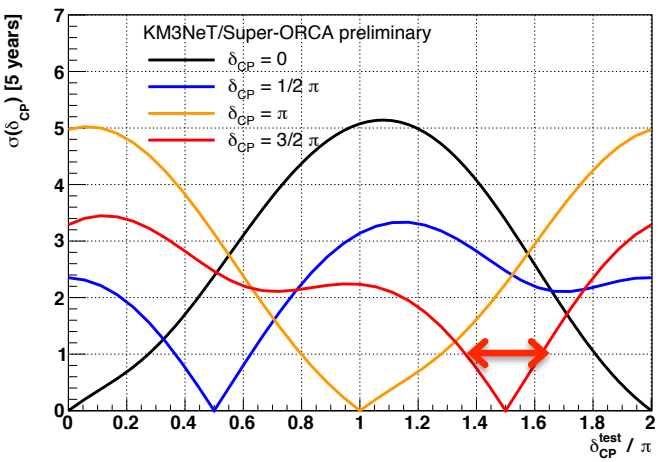
Remark: uncertainties in PID due to interaction
uncertainties in x-sec & kinematics not included

Summary & Outlook

- Super-ORCA: ~10x more densely instrumented version of ORCA to measure δ_{CP} with atmospheric neutrinos

- δ_{CP} sensitivity estimate based on idealised detector response assumptions:

  @1σ: 23° for δ_{CP}=270° after 5years



- Outlook:
  - 'full' detector simulation & reconstruction
  - PID uncertainties due to interaction xsec & kinematics uncertainties
    → comparison : GENIE vs GiGUU vs NEUT vs NUWRO
  - improvements: multi-particle reconstruction (instead of e/mu + had)
    Michel electron tagging (first indications not very promising)
  - other possible physics: Earth tomography, proton decay?, ???

BACKUP

Systematics

[5] Phys. Rev. D89, 093018

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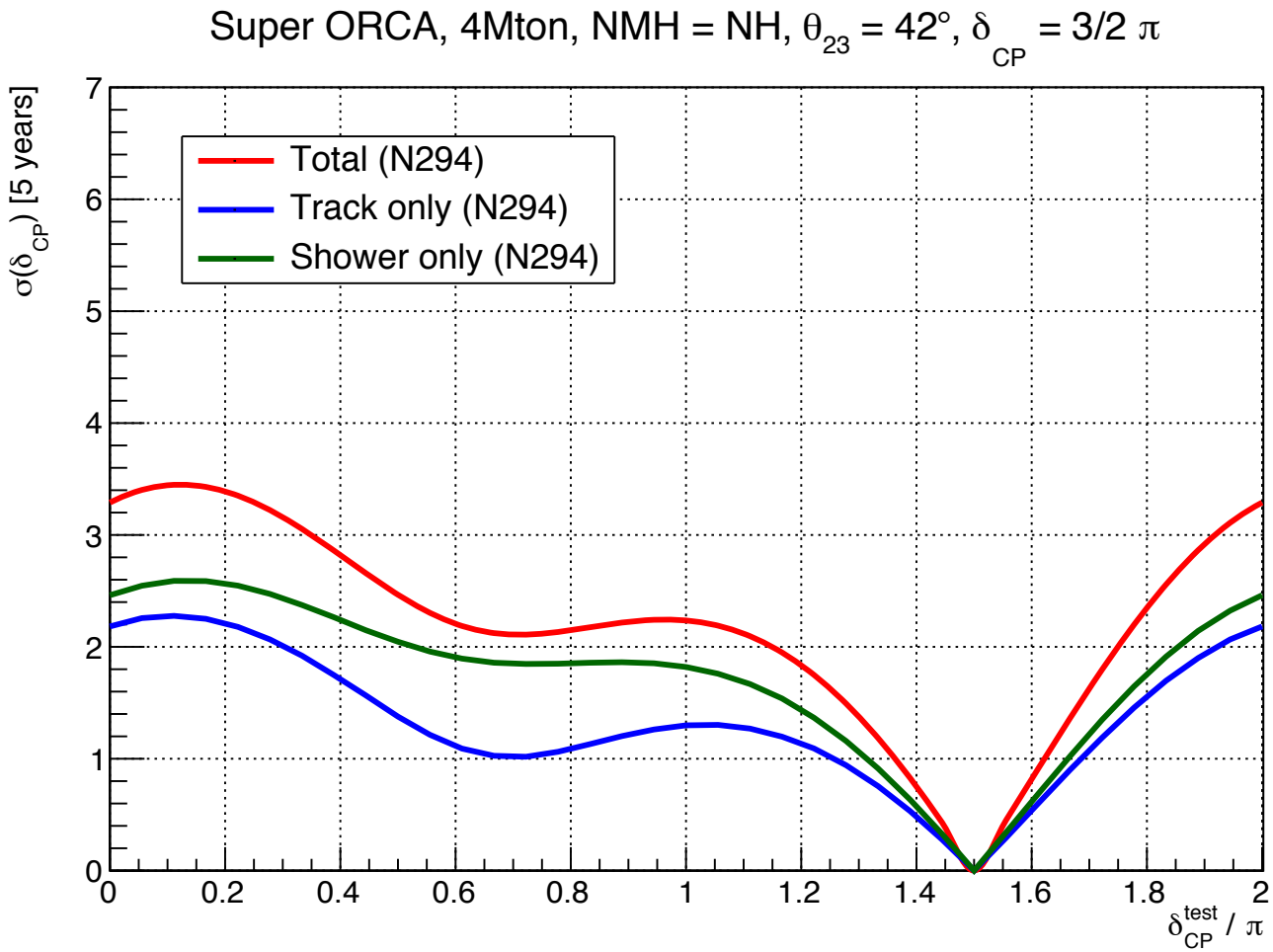
parameter	*true* [5]	*prior*
θ_{23} [°]	42	-
θ_{13} [°]	8.8	fixed
θ_{12} [°]	33.7	fixed
ΔM^2 [10^{-3} eV^2]	2.43	-
Δm^2 [10^{-5} eV^2]	7.54	fixed
mass ordering	NO	fixed
overall norm	1	-
CC/NC skew	1	-
$\bar{\nu}/\nu$ skew	0	-
μ/e skew	0	-
spectral index tilt	0	-
up/hor skew $\propto \cos\theta$	0	-
up/hor skew $\propto \cos^2\theta$	0	-
energy scale overall	1	0.03
Escale $\nu/\bar{\nu}$ skew	0	0.03
Escale $\overset{(-)}{\nu}_e/\overset{(-)}{\nu}_\mu$ skew	0	0.03
Escale $\overset{(-)}{\nu}_{e,\mu}/\overset{(-)}{\nu}_\tau$ skew	0	0.05
Escale CC/NC skew	0	0.05
Escale up/hor skew	0	0.03

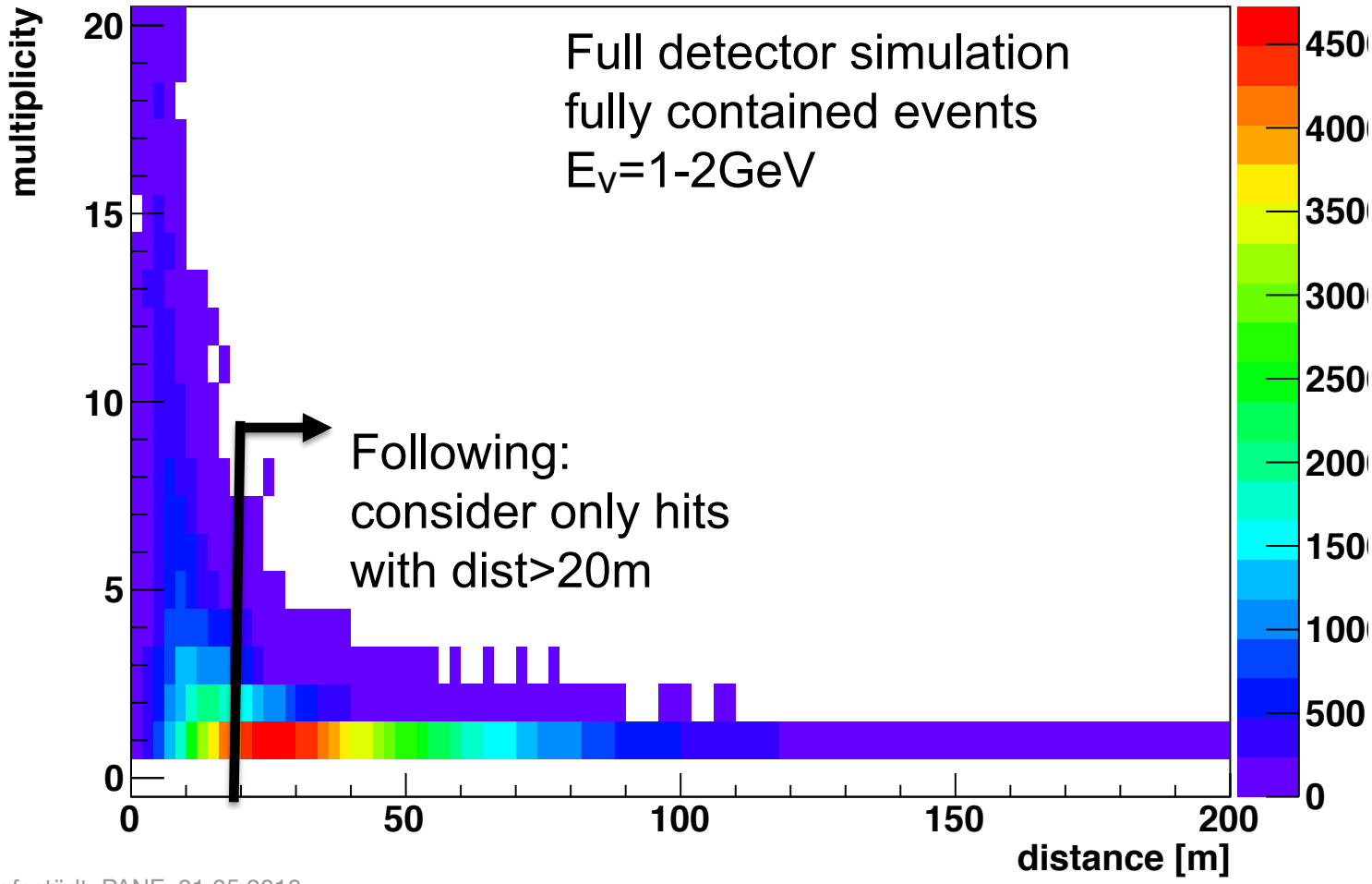
Importance of muon-like and electron-like events

- Electron-like events are more important
- ‘tracks’ = muon-like events & ‘shower’ = electron-like events



Hit multiplicity vs distance (full simulation)

- Realism of assumed idealised detector response?
  → ignoring 'clumpiness' of PMTs in DOMs



Reconstruction considerations

- Likelihood calculation

$$LLH = \sum_{allPMTs} P^i = \sum_{hitPMTs} P^i_{hit} + \sum_{no-hitPMTs} P^i_{no-hit}$$

$$= \underbrace{\sum_{allPMTs} P^i_{no-hit}} - \sum_{hitPMTs} P^j_{no-hit} + \sum_{hitPMTs} P^i_{hit}$$

Can be **pre-calculated once** for idealised detector, because P^i_{no-hit} independent of event hypothesis, assuming linear scaling of light yield with energy

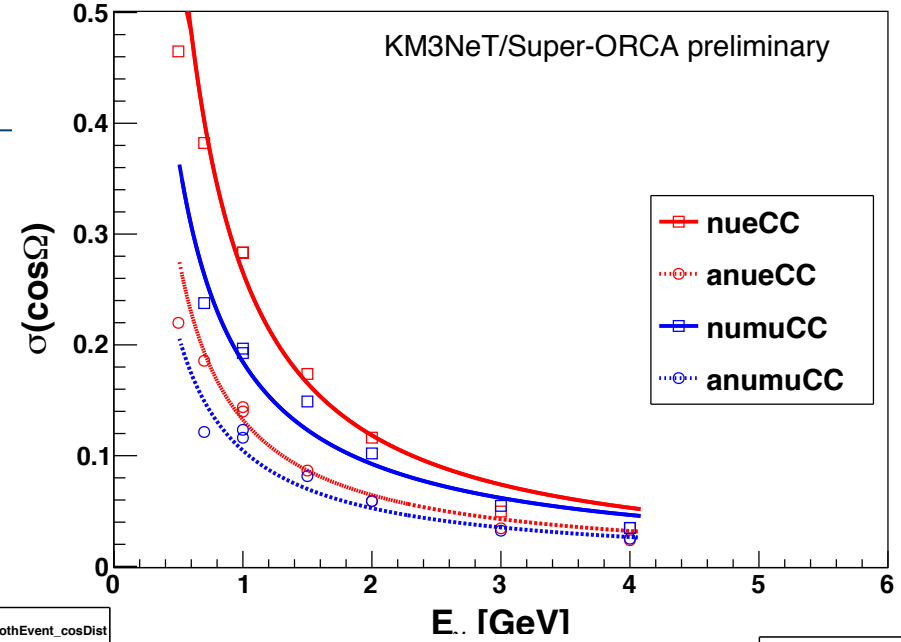
$$\sum_{allPMTs} = O(1000'000)$$

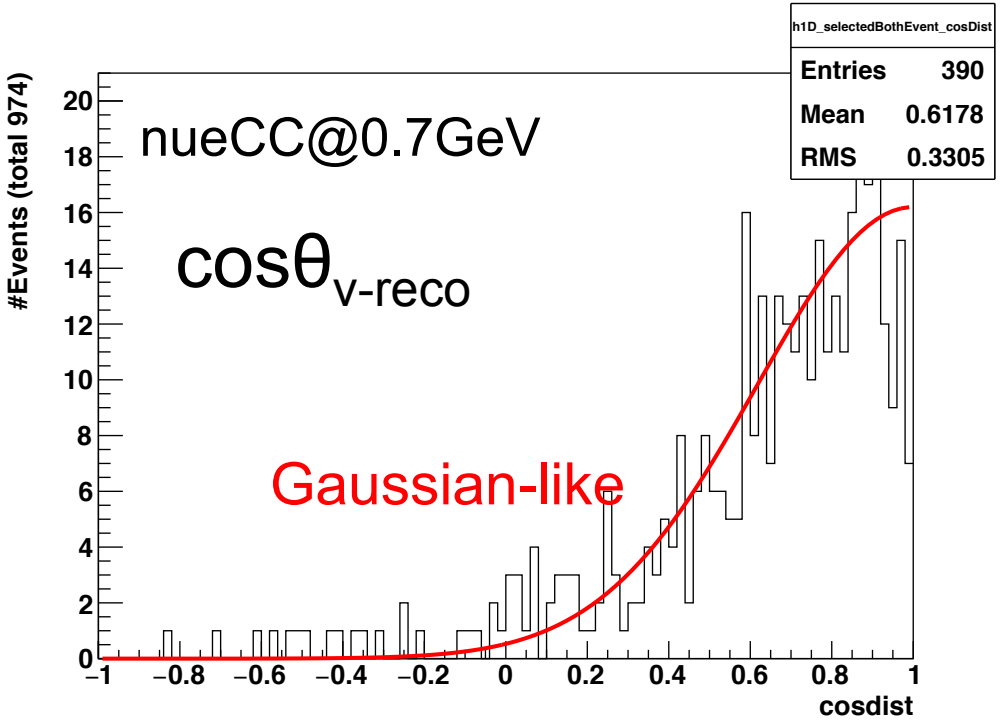
$$\sum_{hitPMTs} = O(100)$$

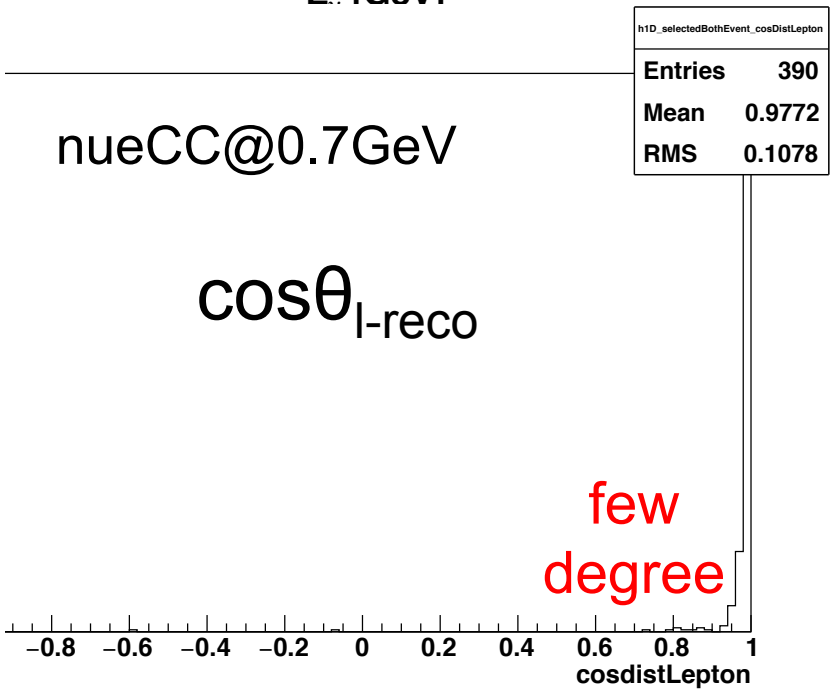
Compared to ARCA/ORCA reco's:
O(10) more PMTs
O(10) more seeds
O(10) more complex muon hypothesis
→ 1000 larger runtime (than AAshower)

Direction resolution

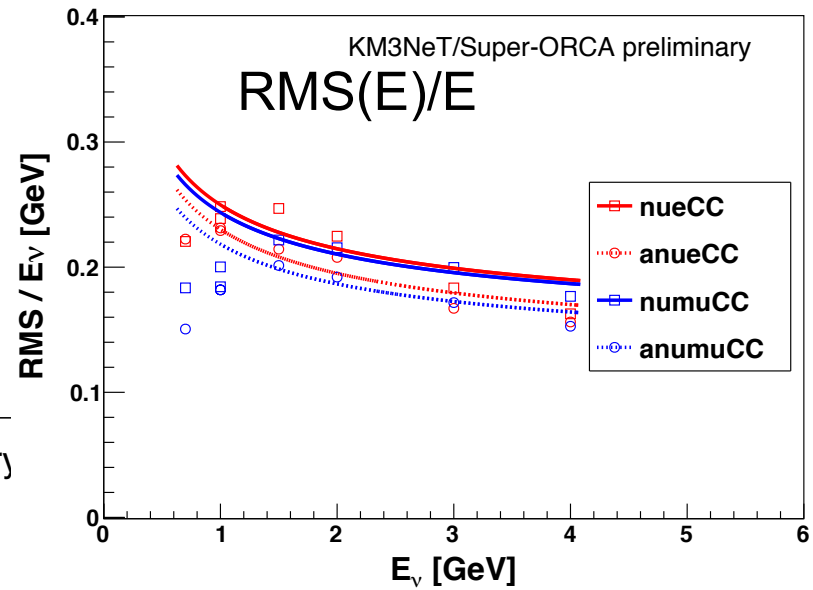
- Few degree resolution on lepton direction ($\cos\theta_{l\text{-reco}}$)
- Neutrino direction resolution ($\cos\theta_{\nu\text{-reco}}$) dominated by ν-lep scattering angle

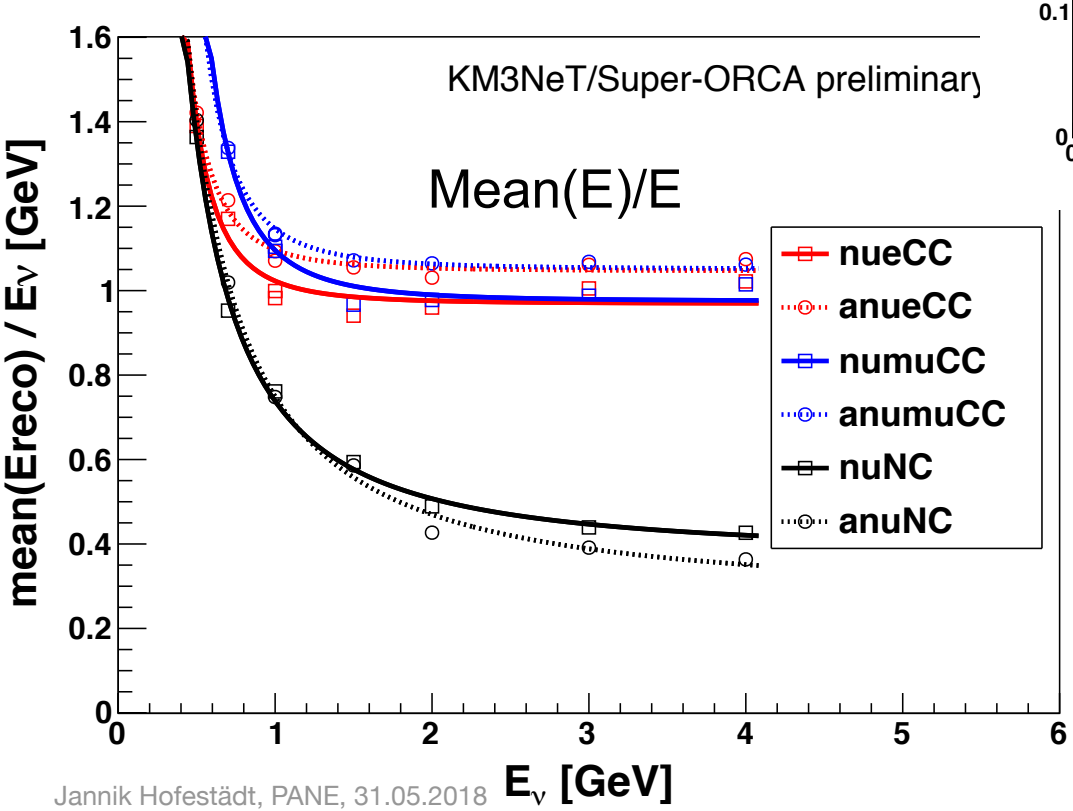




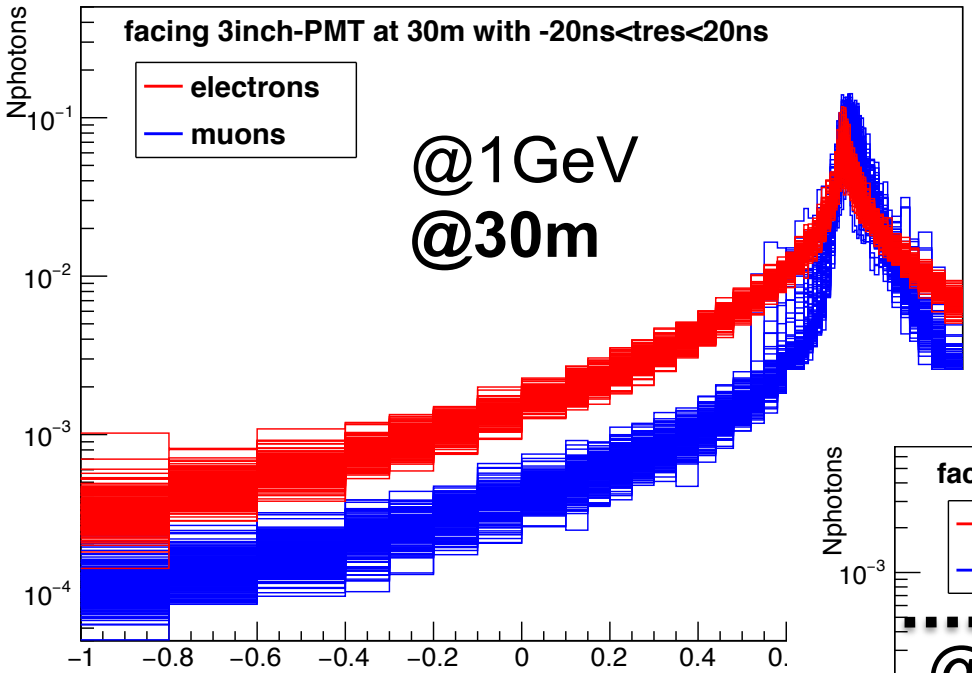


Energy resolution

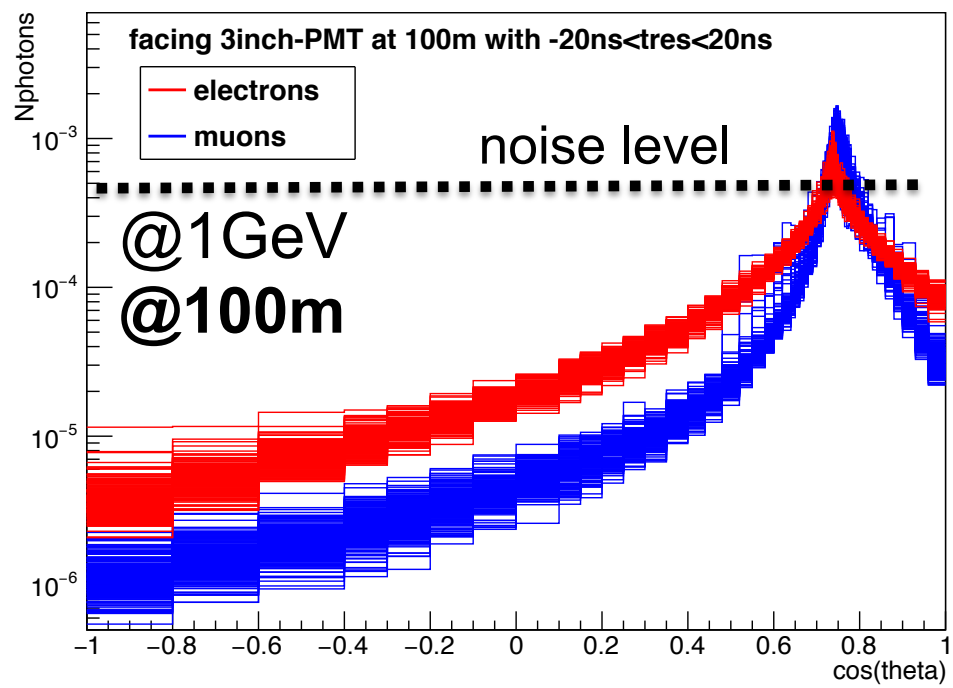




PID: elec vs muon separation

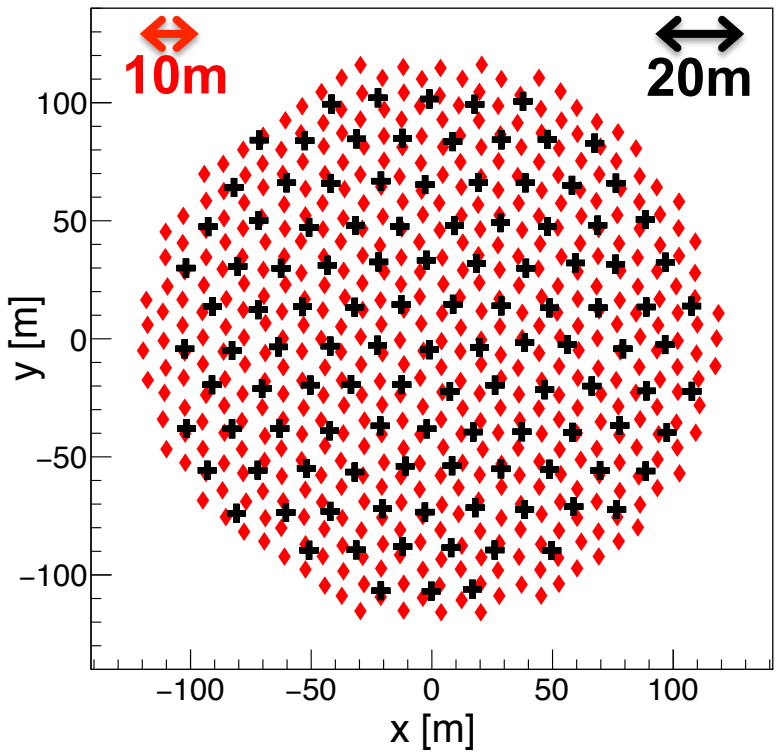


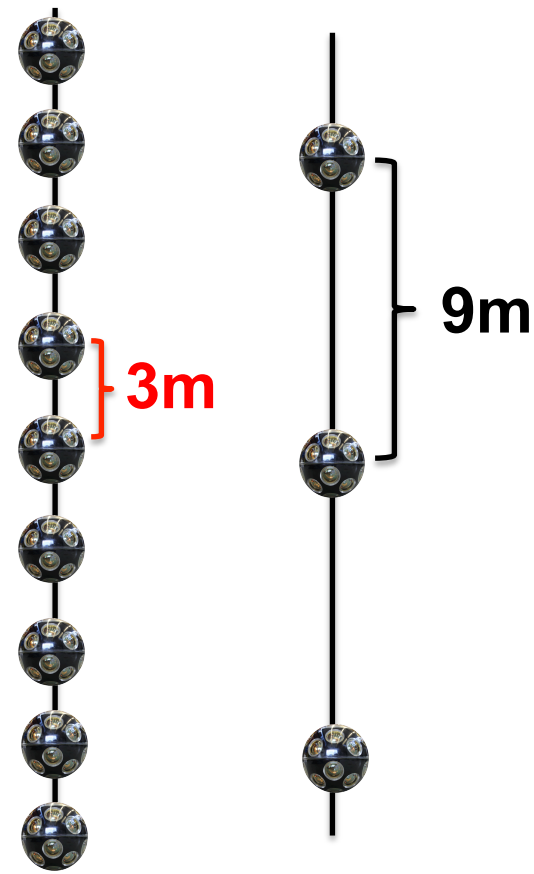
- Cherenkov peak above noise for ~100m
  - → large level arm
  - → good angular resolution



Possible Super-ORCA detector layout

- String layout: 159m height with 54 DOMs → 3m vertical spacing
- Footprint: cylinder with R=120m & 500 strings → 10m inter-string spacing
  → ~10x denser than LoI-9m



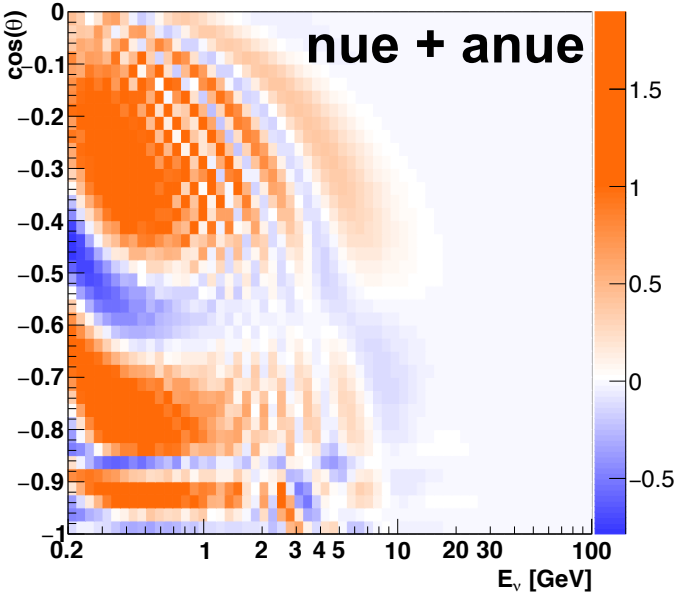


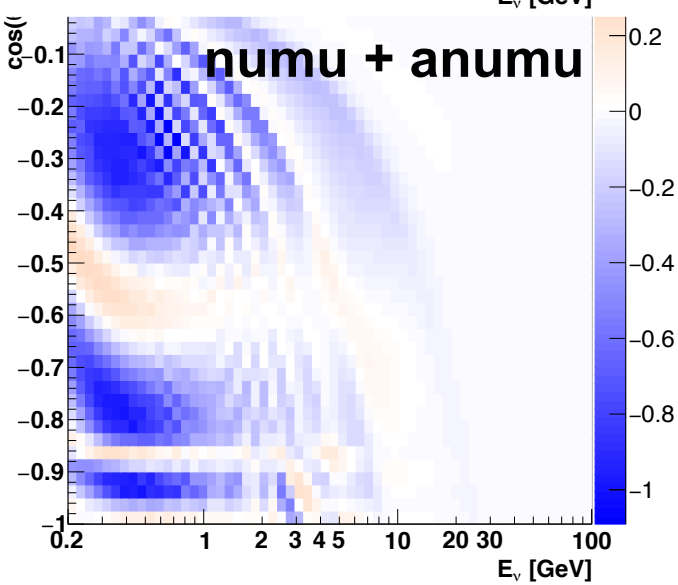
Caveat:
This geometry <u>not</u> used for sensitivity calculations in this talk; just for illustration purpose

Distinguishability

for 4Mton fiducial volume

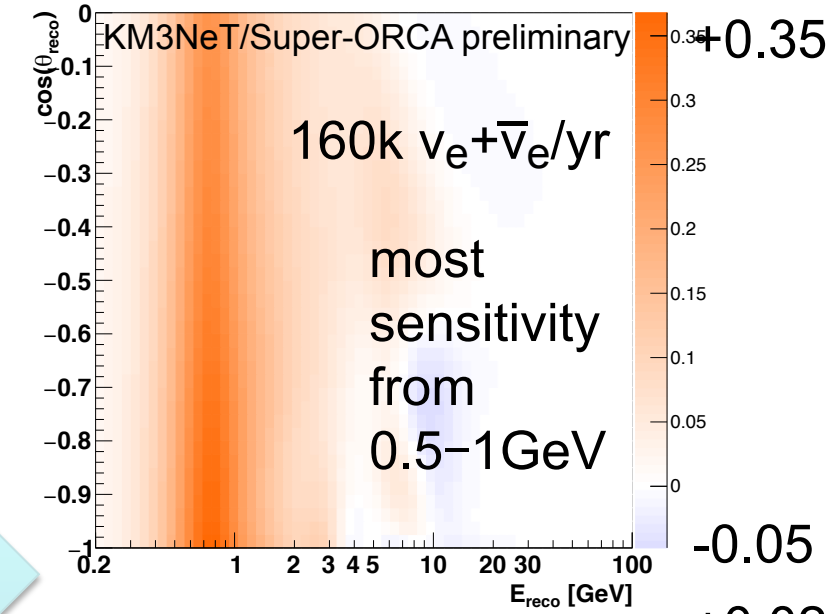
$(N_{\delta=3/2\pi} - N_{\delta=0}) / \mathrm{sqrt}(N_{\delta=0})$

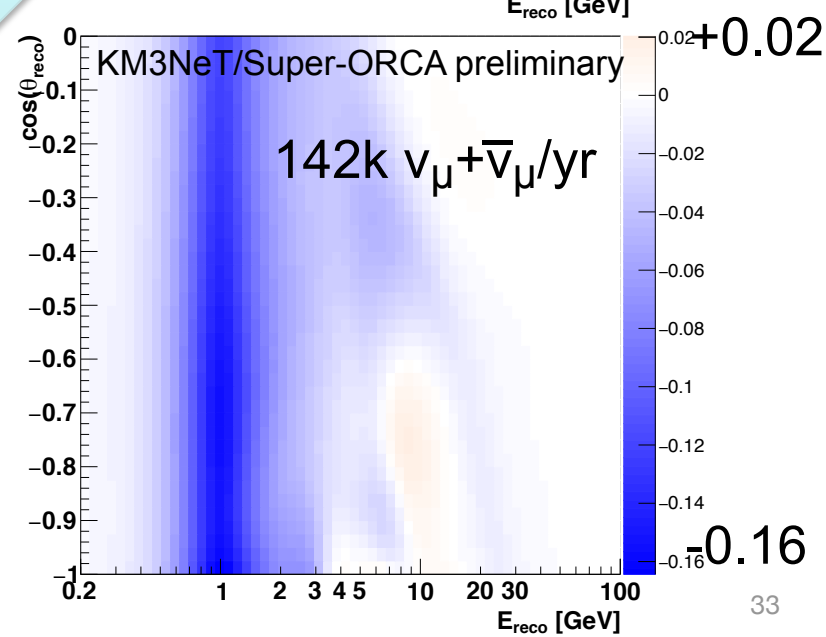




4Mton

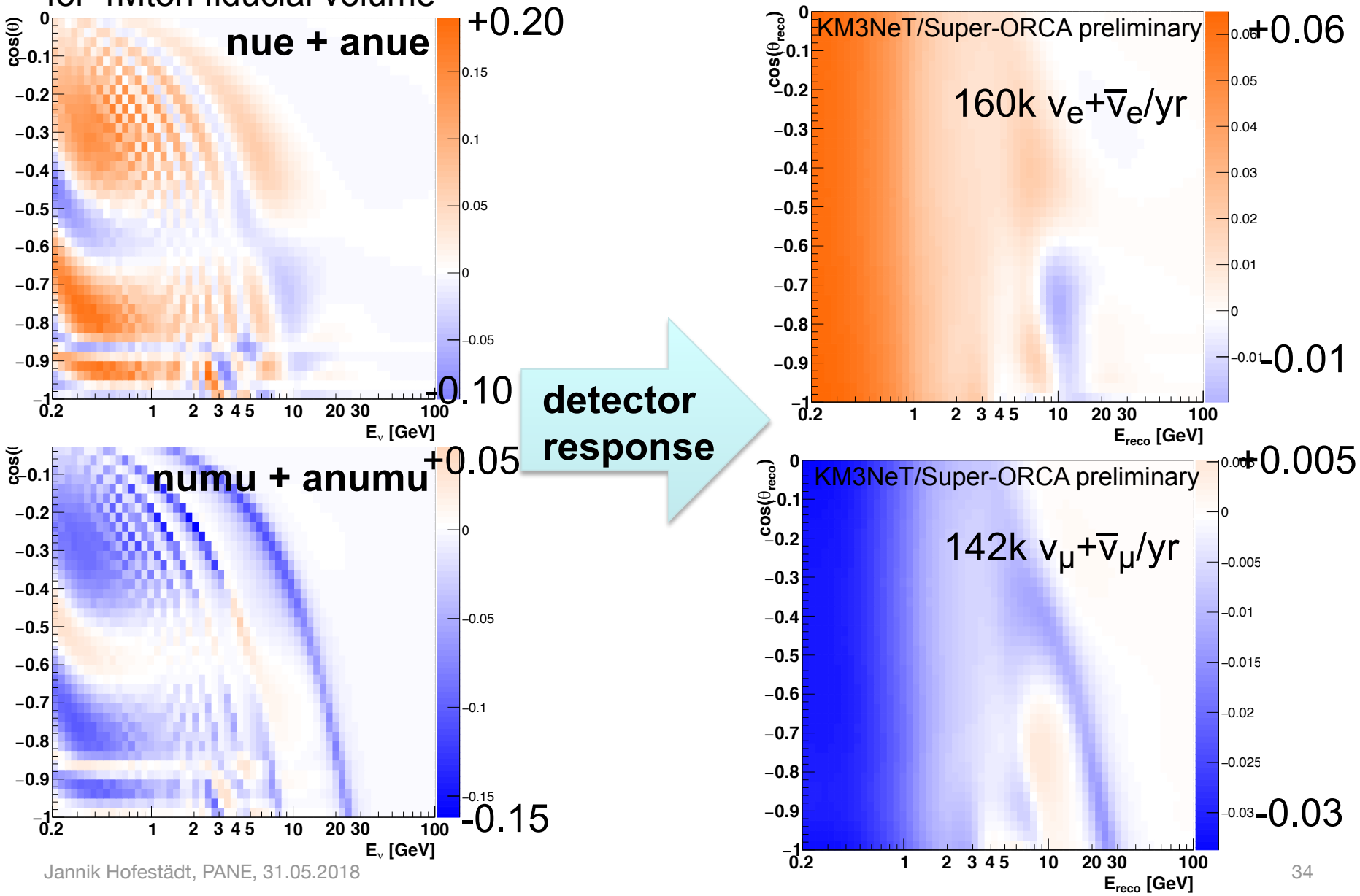
detector response





Relative differences $(N_{\delta=3/2\pi} - N_{\delta=0}) / N_{\delta=0}$

for 4Mton fiducial volume

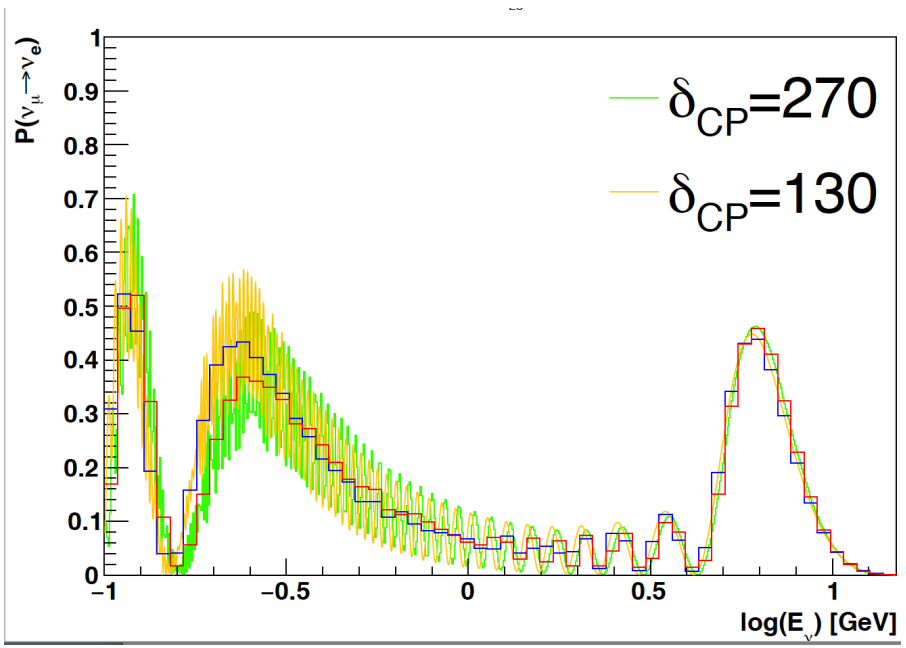


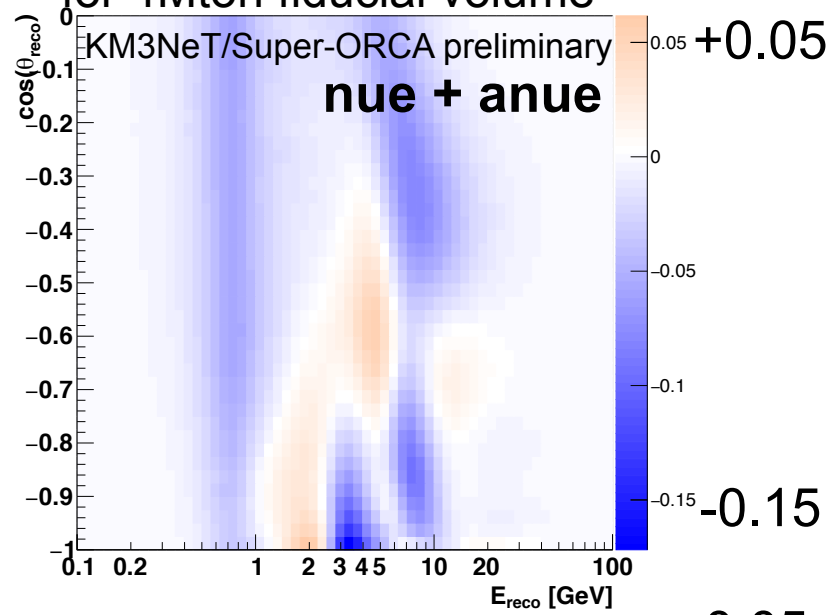
Degeneracy

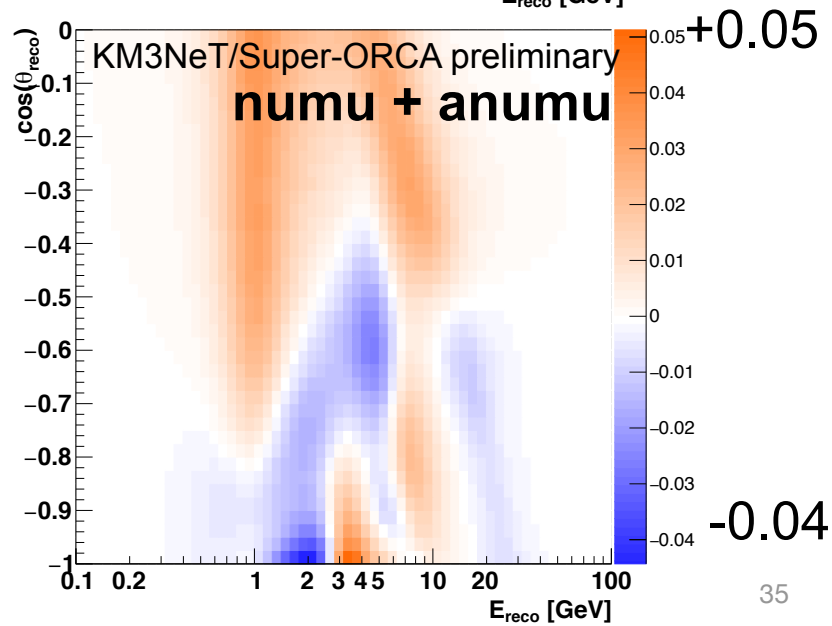
$(N_{\delta=0.72\pi} - N_{\delta=3/2\pi}) / N_{\delta=3/2\pi}$

for 4Mton fiducial volume

- Nearly degeneracy for 270° vs 130°
- Low-E differences not accessible for Super-ORCA
- Some sensitivity from higher energy range







Event rate differences

- Reconstructed energy distribution, after PID