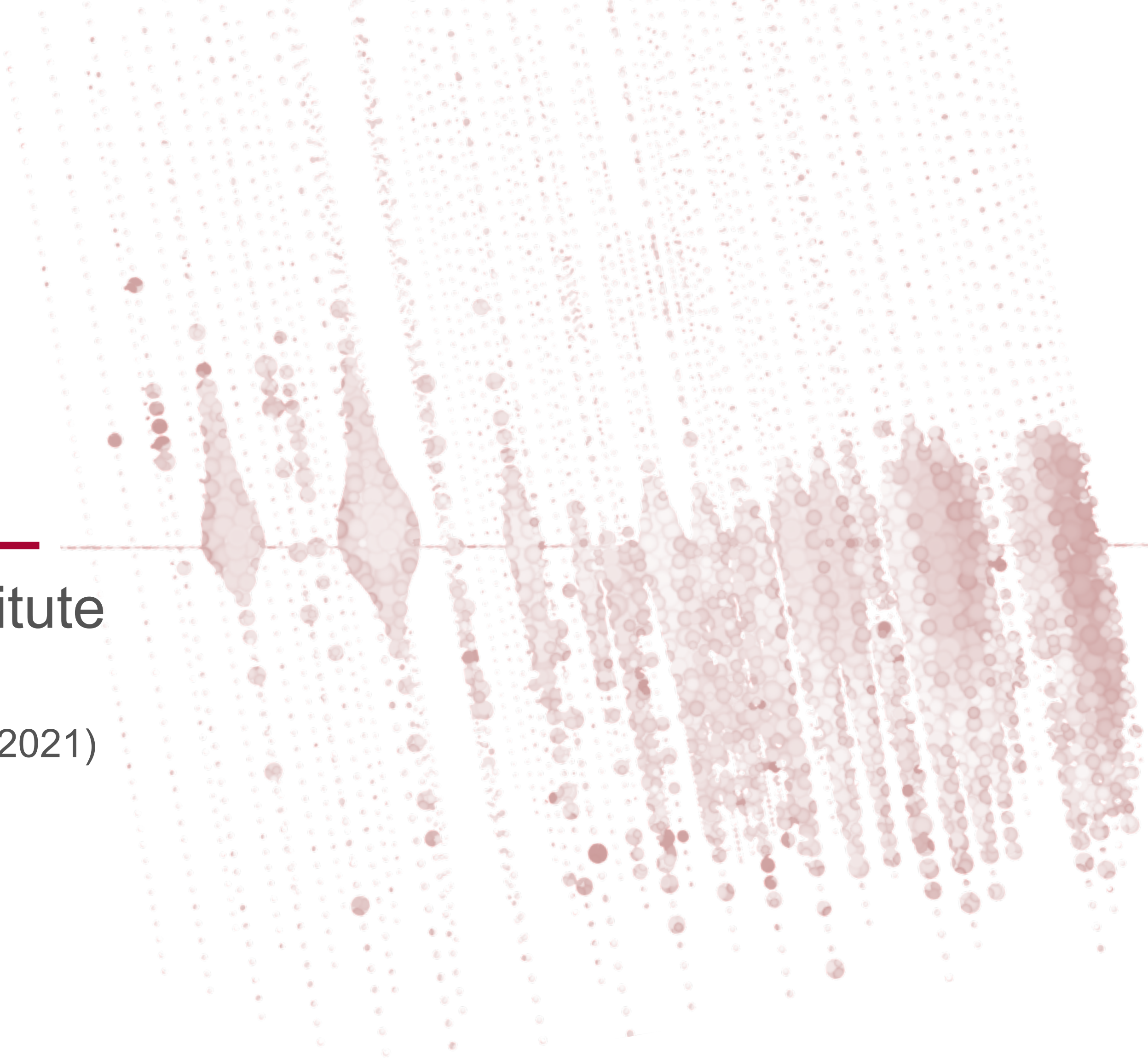
UNIVERSITY OF COPENHAGEN

Tau Neutrino Oscillation & IceCube



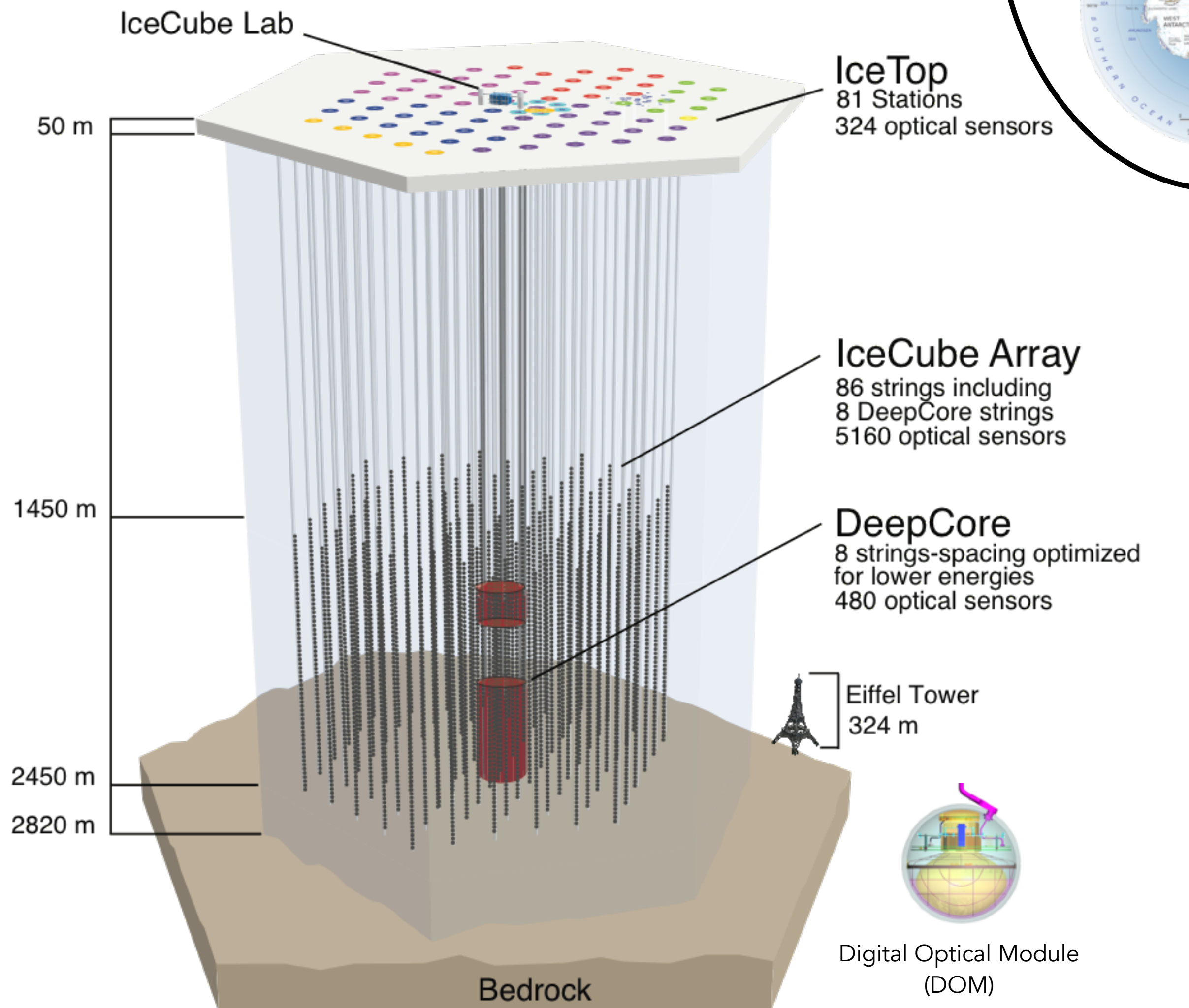
D. Jason Koskinen - Niels Bohr Institute

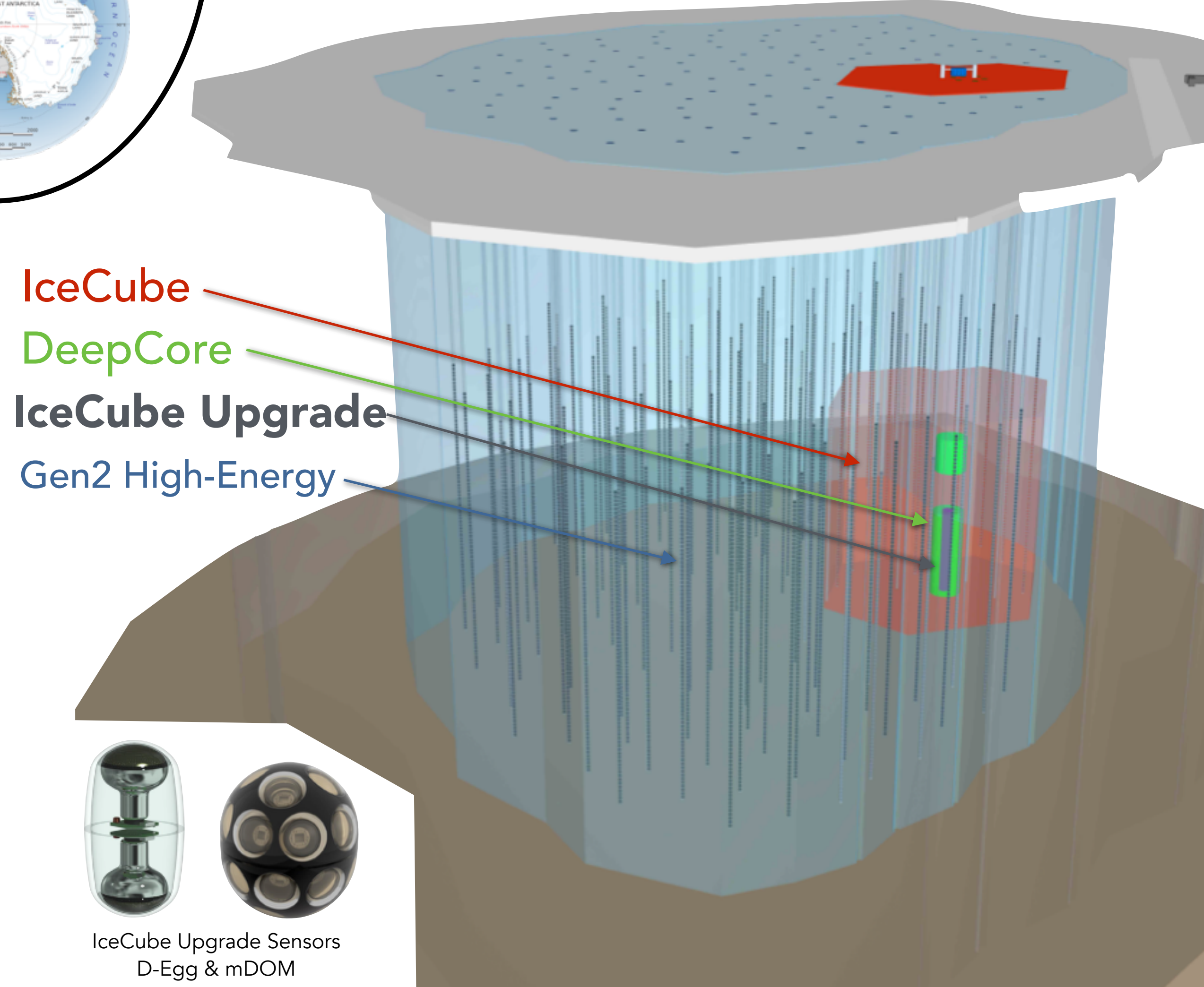
Workshop on Tau Neutrinos from GeV to EeV (NuTau2021)
September 2021

The Niels Bohr International Academy

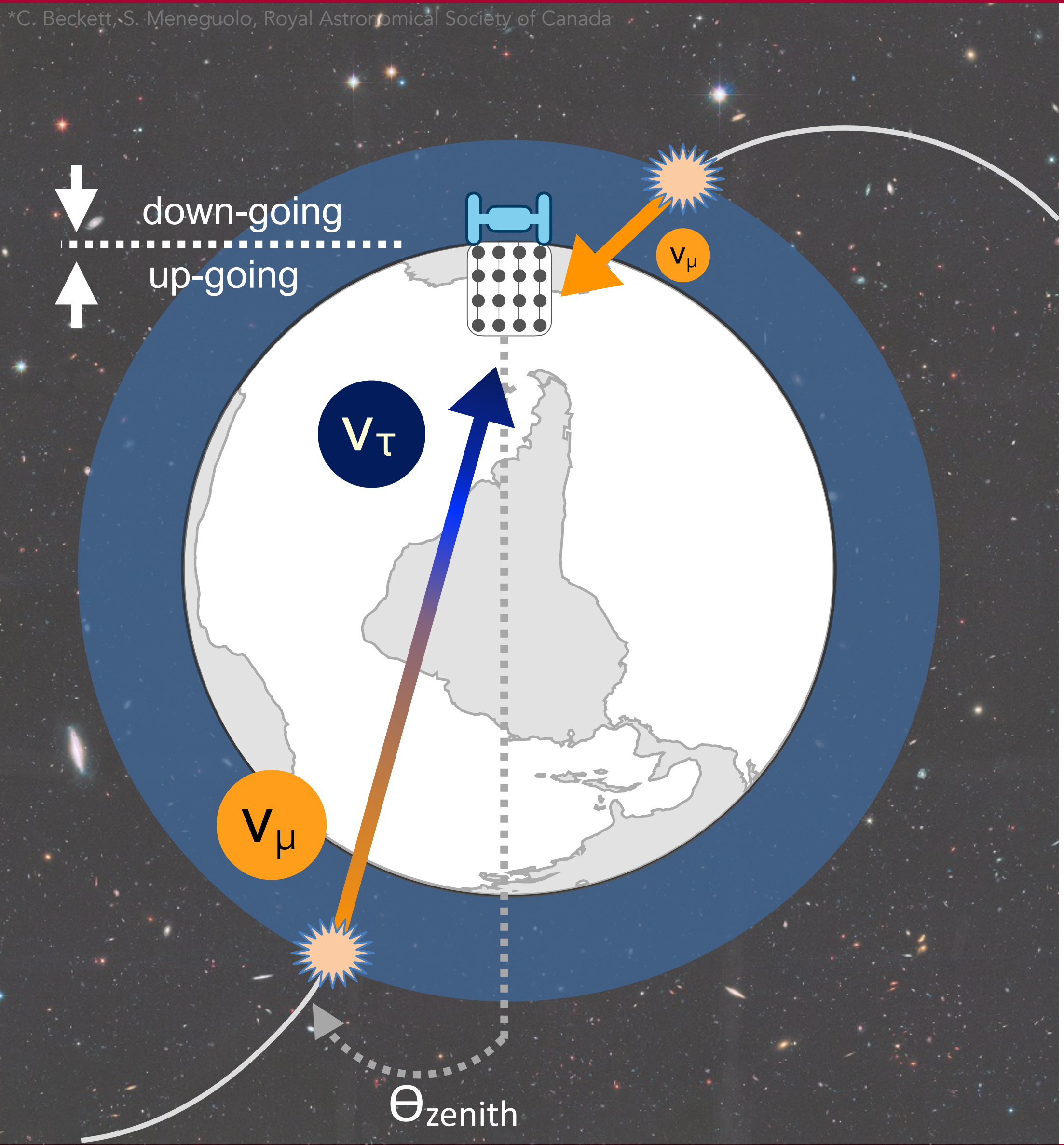
CARLSBERG FONDET

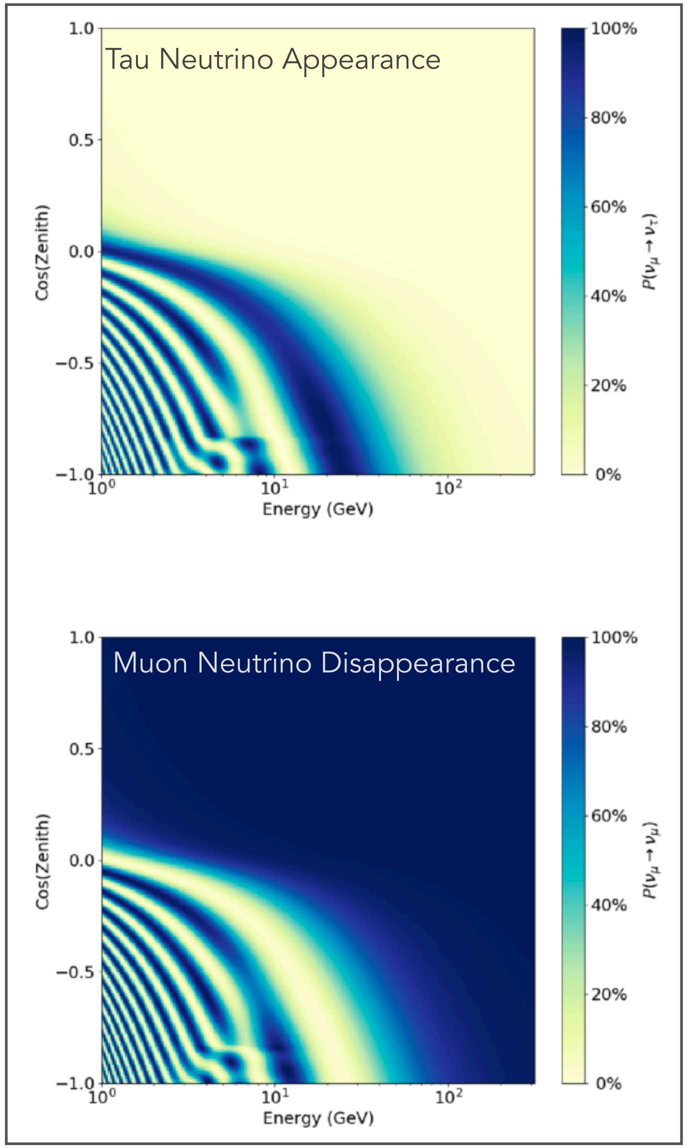
Detectors

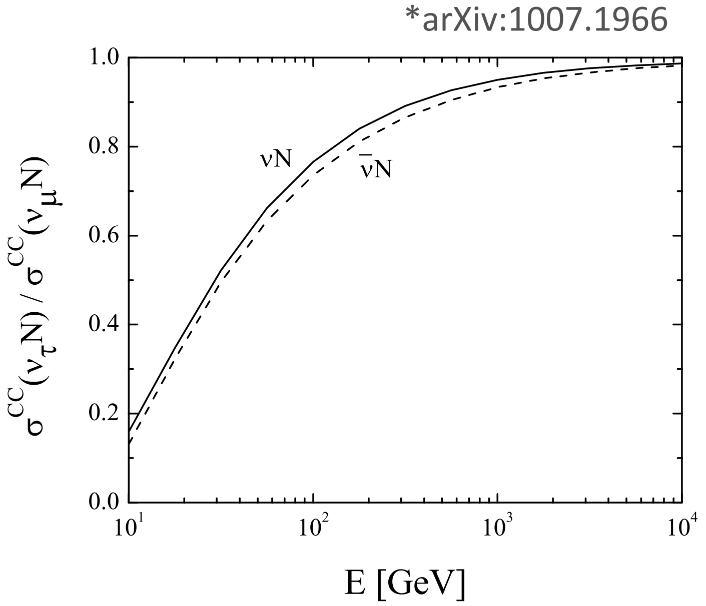

IceCube Lab
IceTop
81 Stations
324 optical sensors
50 m
IceCube Array
86 strings including
8 DeepCore strings
5160 optical sensors
1450 m
DeepCore
8 strings-spacing optimized
for lower energies
480 optical sensors
Eiffel Tower
324 m
2450 m
2820 m
Bedrock
Digital Optical Module
(DOM)


IceCube
DeepCore
IceCube Upgrade
Gen2 High-Energy
IceCube Upgrade Sensors
D-Egg & mDOM

Why IceCube/DeepCore/Upgrade for Atmospheric ν_τ?

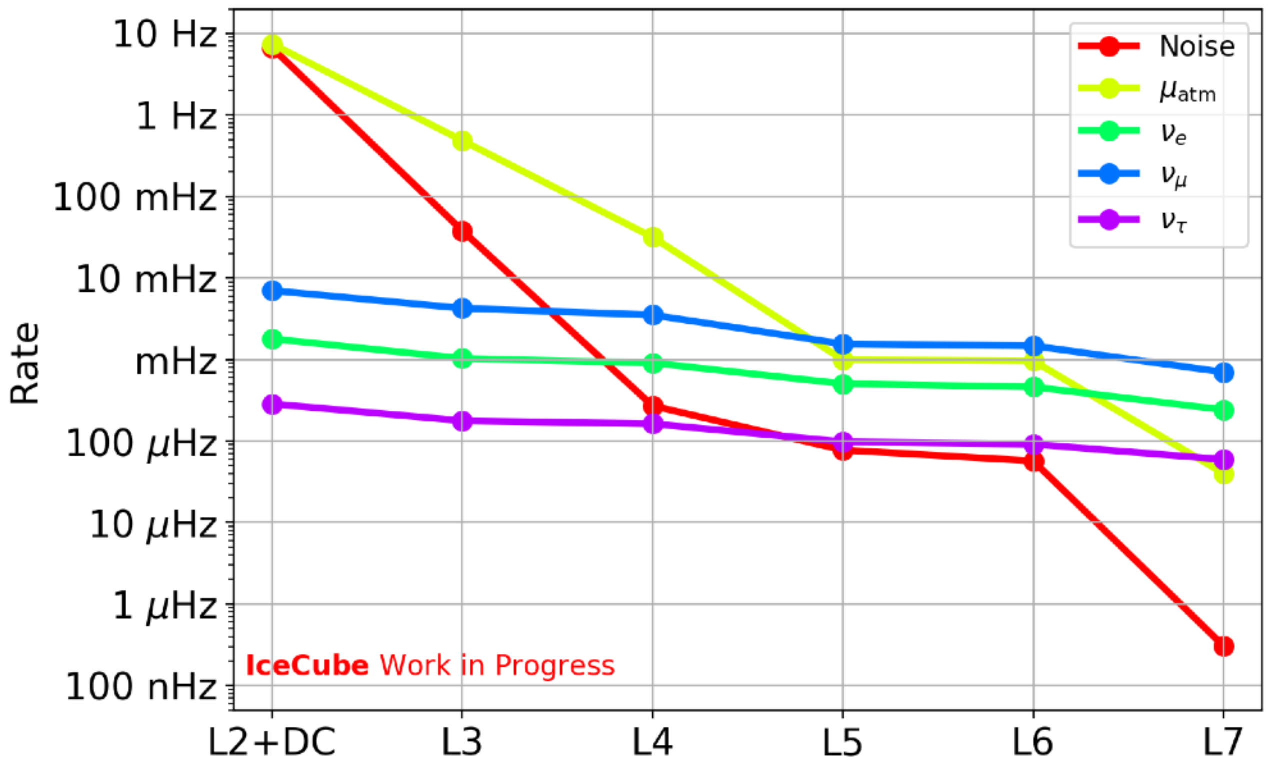






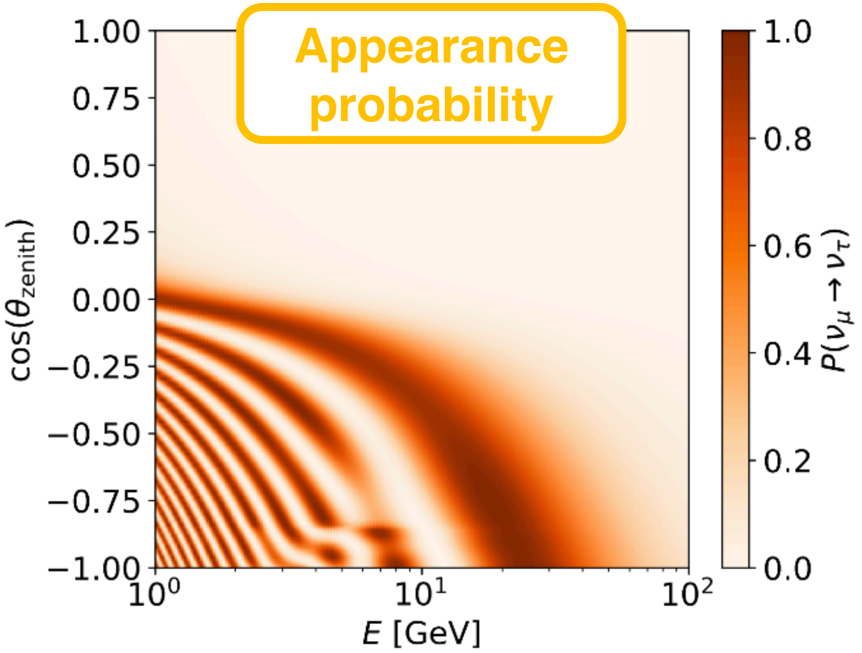
Background & Rates

- Iterative approach to event selection
  - Backgrounds reduced by 5-7 orders of magnitude*
    - Detector/electronics pure-noise
    - Atmospheric muons
  - Combination of straight cuts and boosted decision trees
  - Due to high event rates, the high fidelity reconstructions are introduced near end of the selection chain

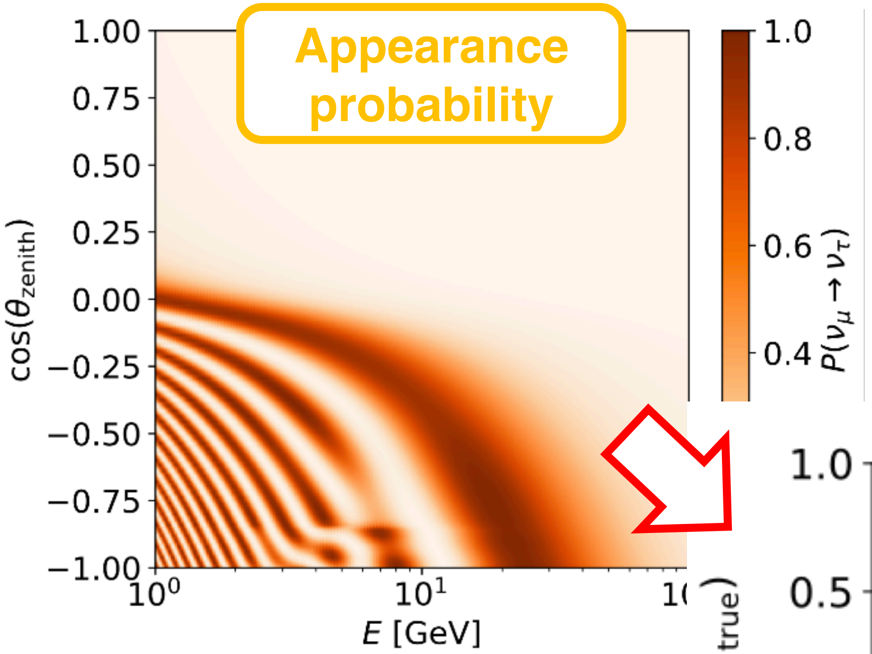


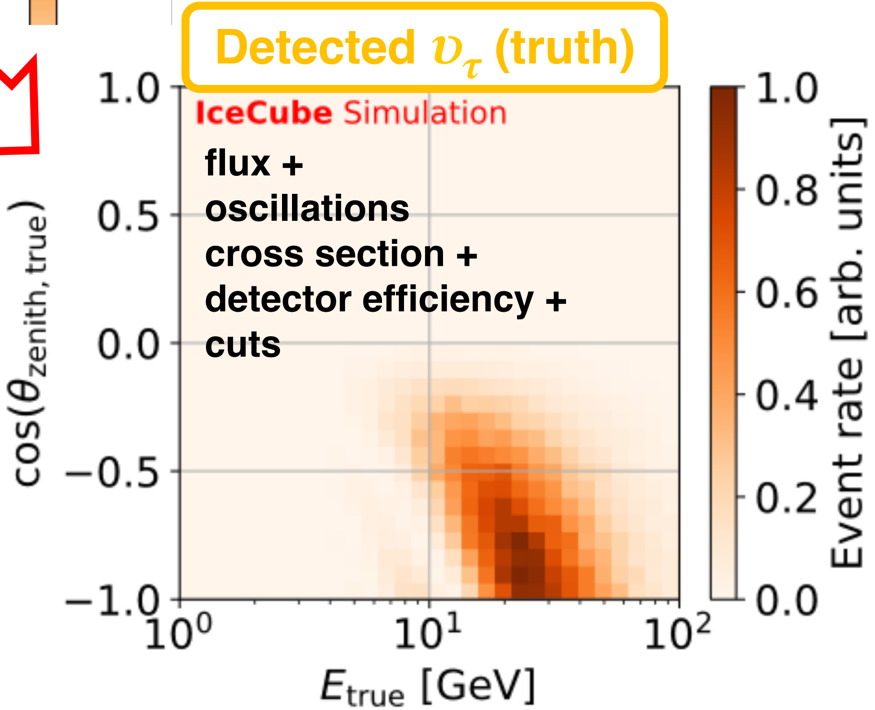
*upcoming 8-year high-statistics event selection

ν_τ appearance @ DeepCore

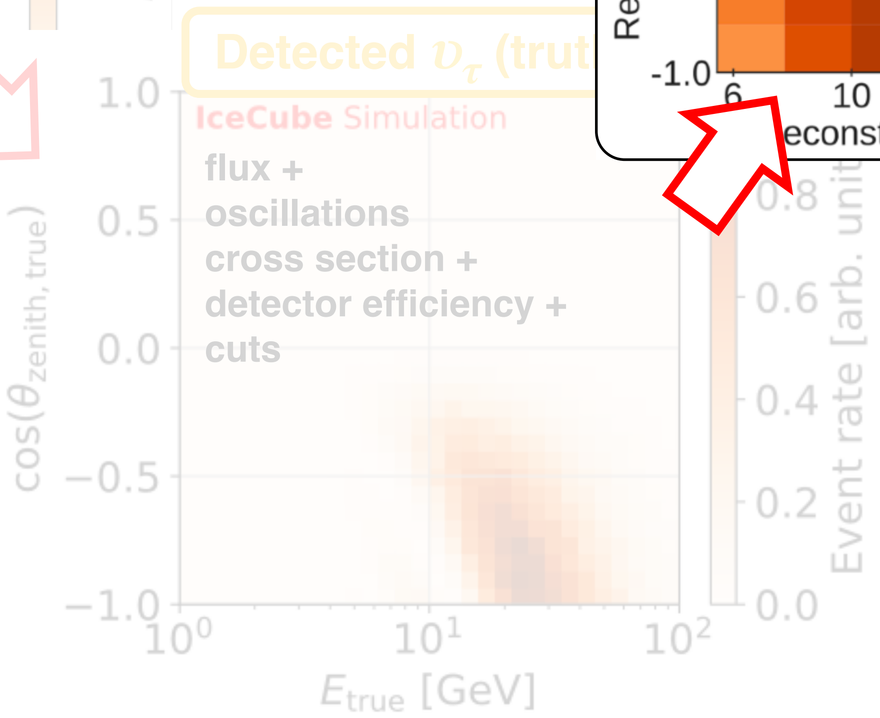


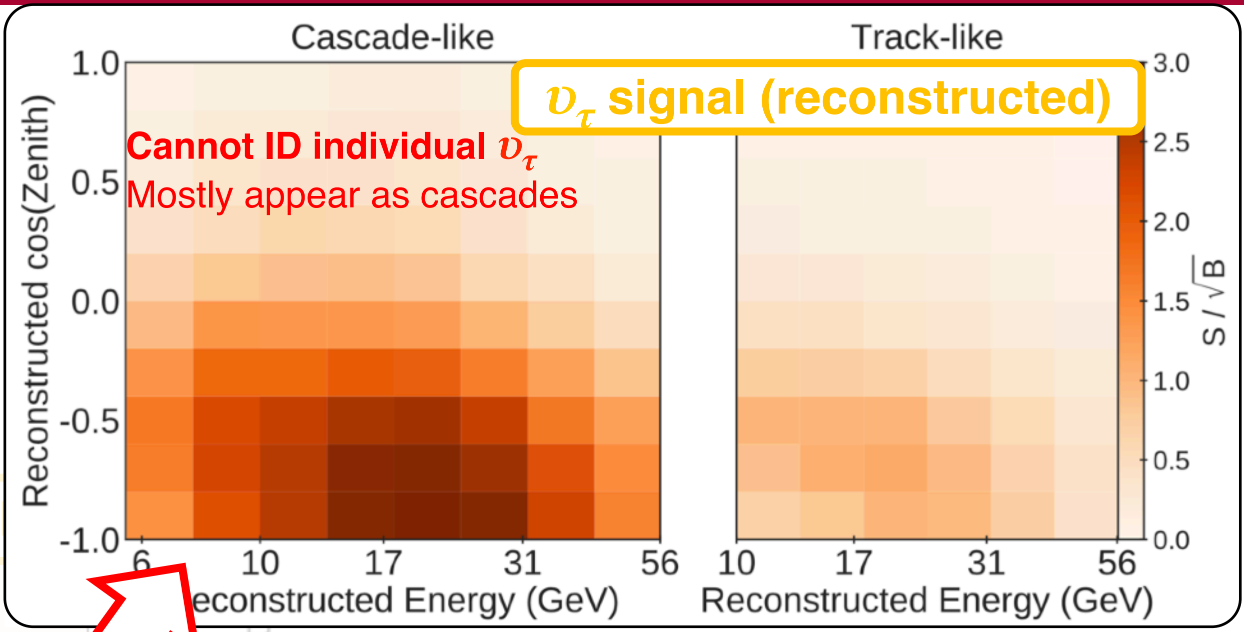
ν_τ appearance @ DeepCore





ν_τ appearance @ DeepCore



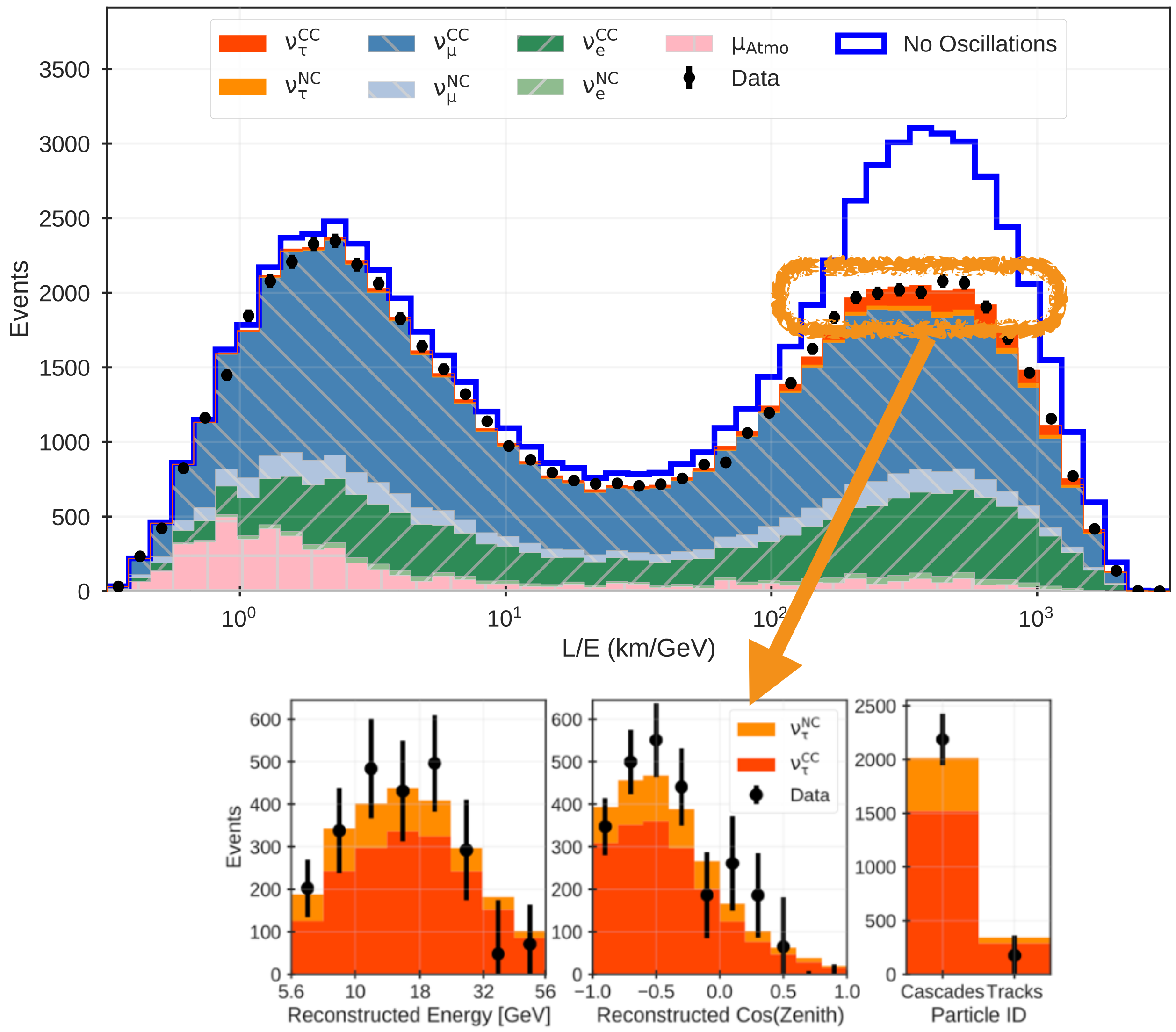


Statistically fit overall ν_τ contribution

- Perform ν_μ disappearance fit
- Allow ν_τ normalisation to vary w.r.t. unitarity

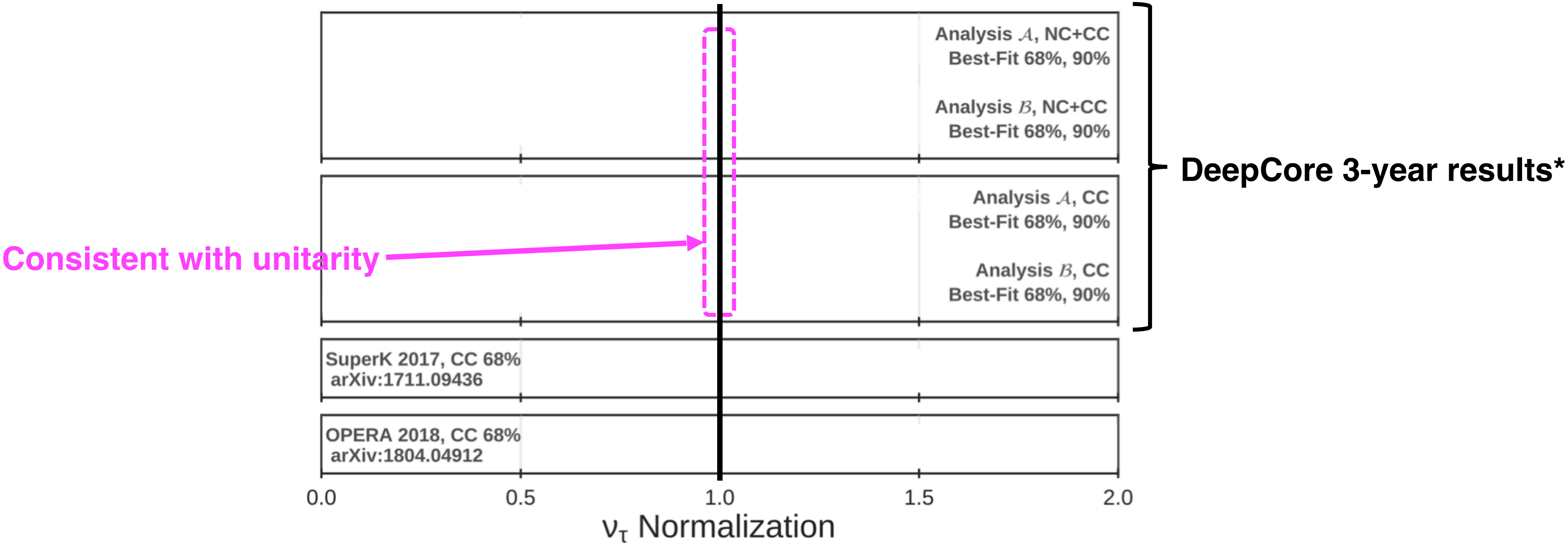
L/E ‘Signal’

- ν_τ appearance is inclusive/ statistical analysis
  - 3-year dataset (2018*)
    - ~60k events, ~1.8k nutau CC
    - April 2012 - May 2015
    - 5.6 GeV - 56 GeV
  - 8-year dataset (soon)
    - ~250k events, ~10.8k nutau CC [prediction]
    - 5 GeV - 300 GeV
- Analyzed in 3 dimensions
  - Particle identification bins
    - 3-year used cascades & tracks
    - 8-year uses cascades, mixed, & tracks
  - Energy
  - Zenith (for baseline)



*arXiv:1901.05366

Results

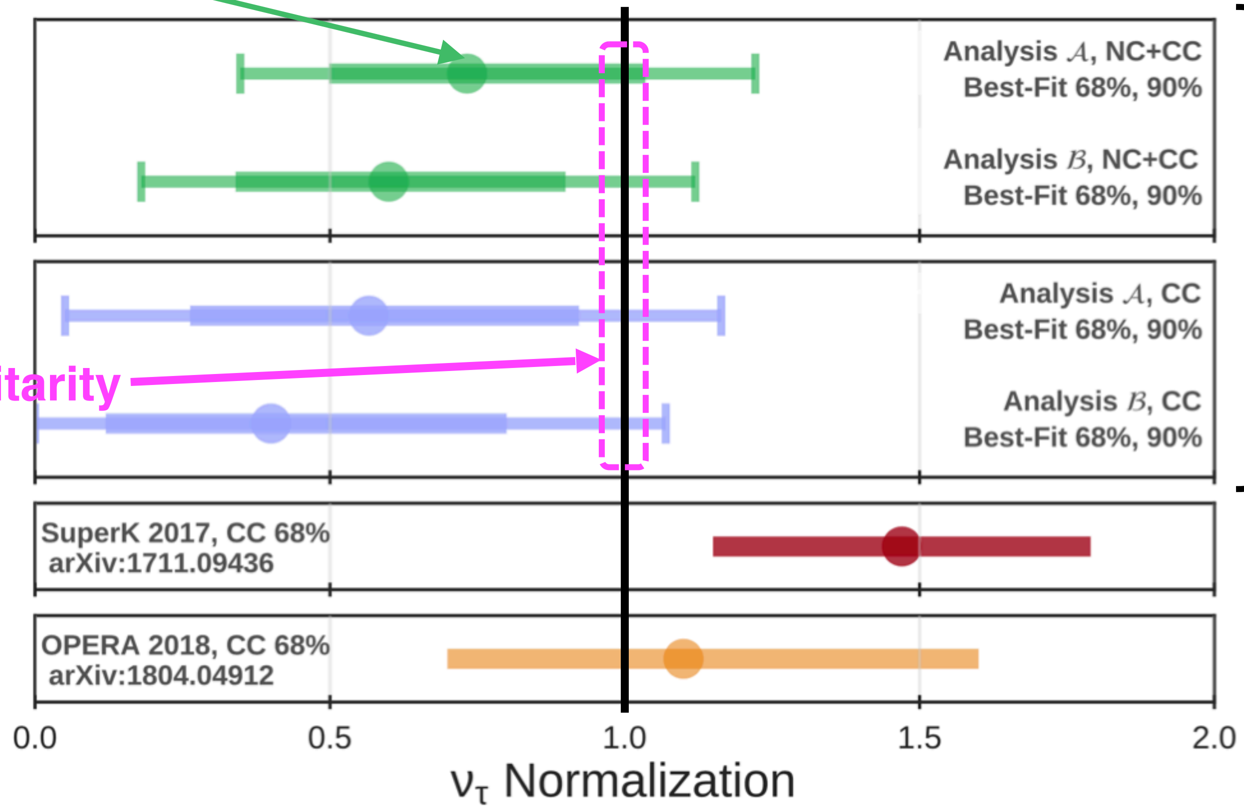


*arXiv:1901.05366

Results

$$N_{\nu_\tau} = 0.73^{+0.30}_{-0.24}$$

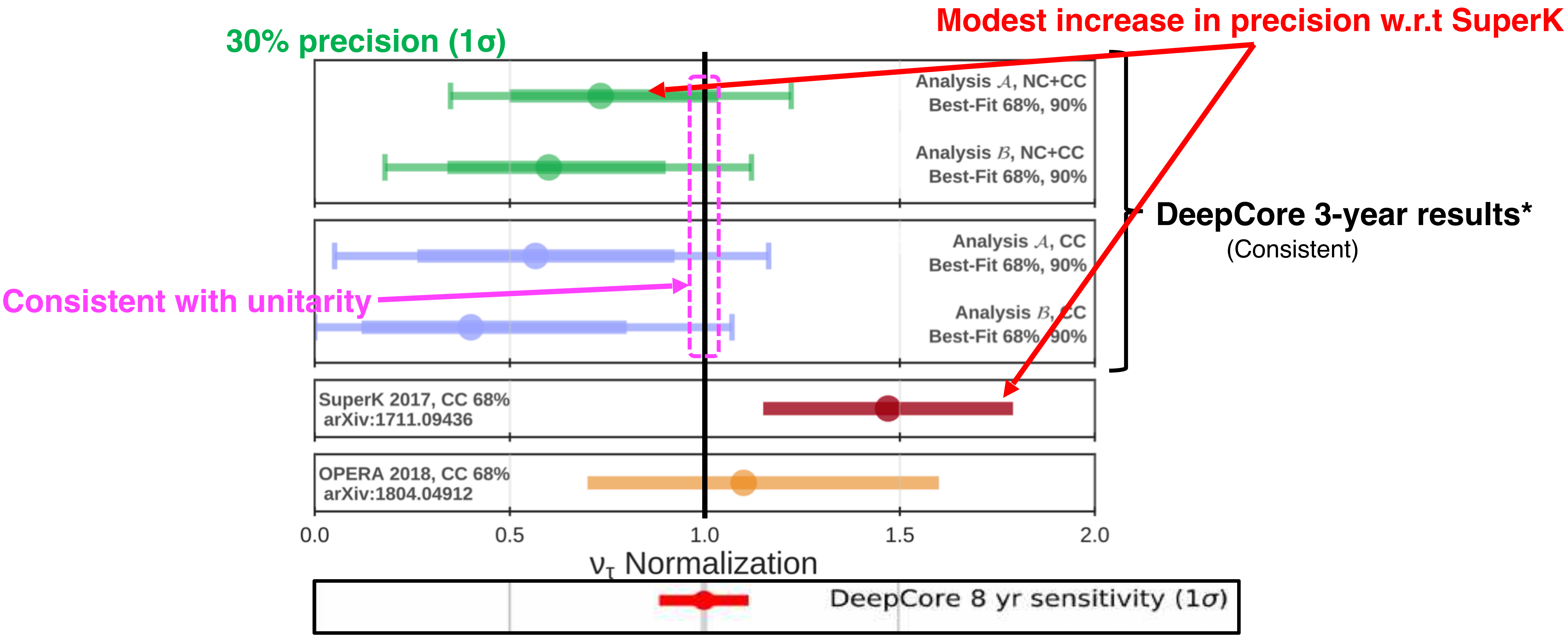
Consistent with unitarity



DeepCore 3-year results*
(Consistent)

*arXiv:1901.05366

Results

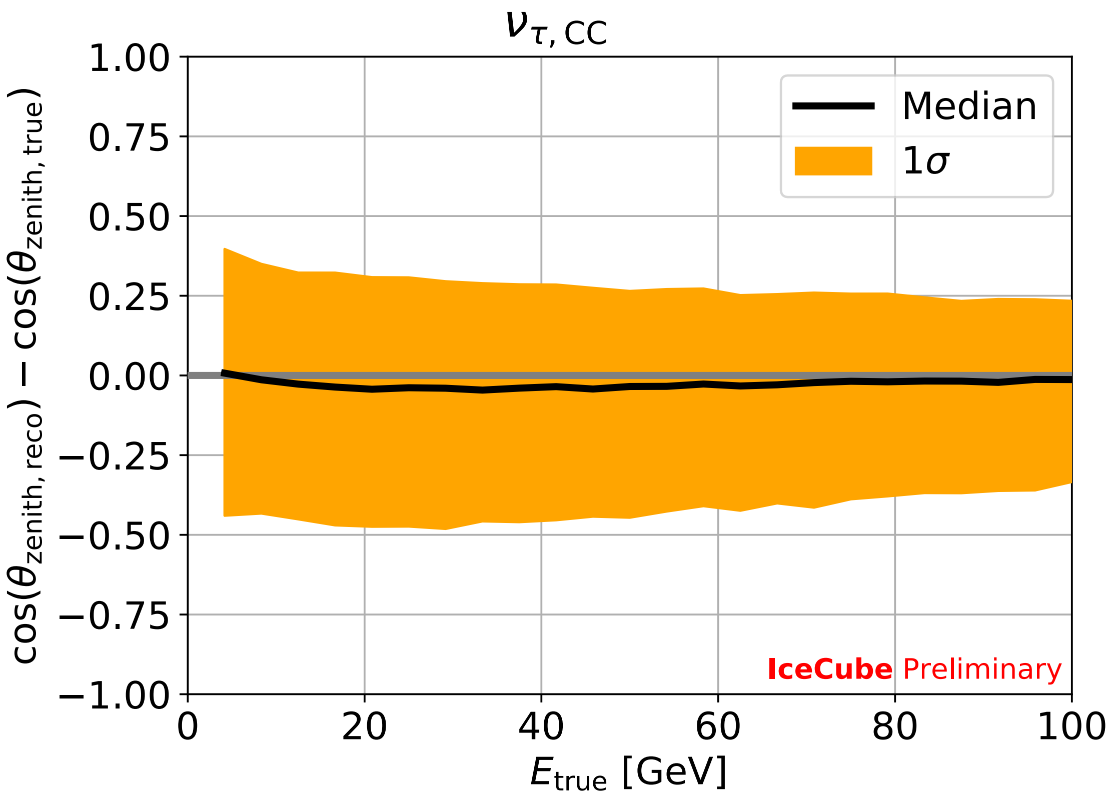


*arXiv:1901.05366

EXPERIMENTAL TECHNIQUES & FEATURES

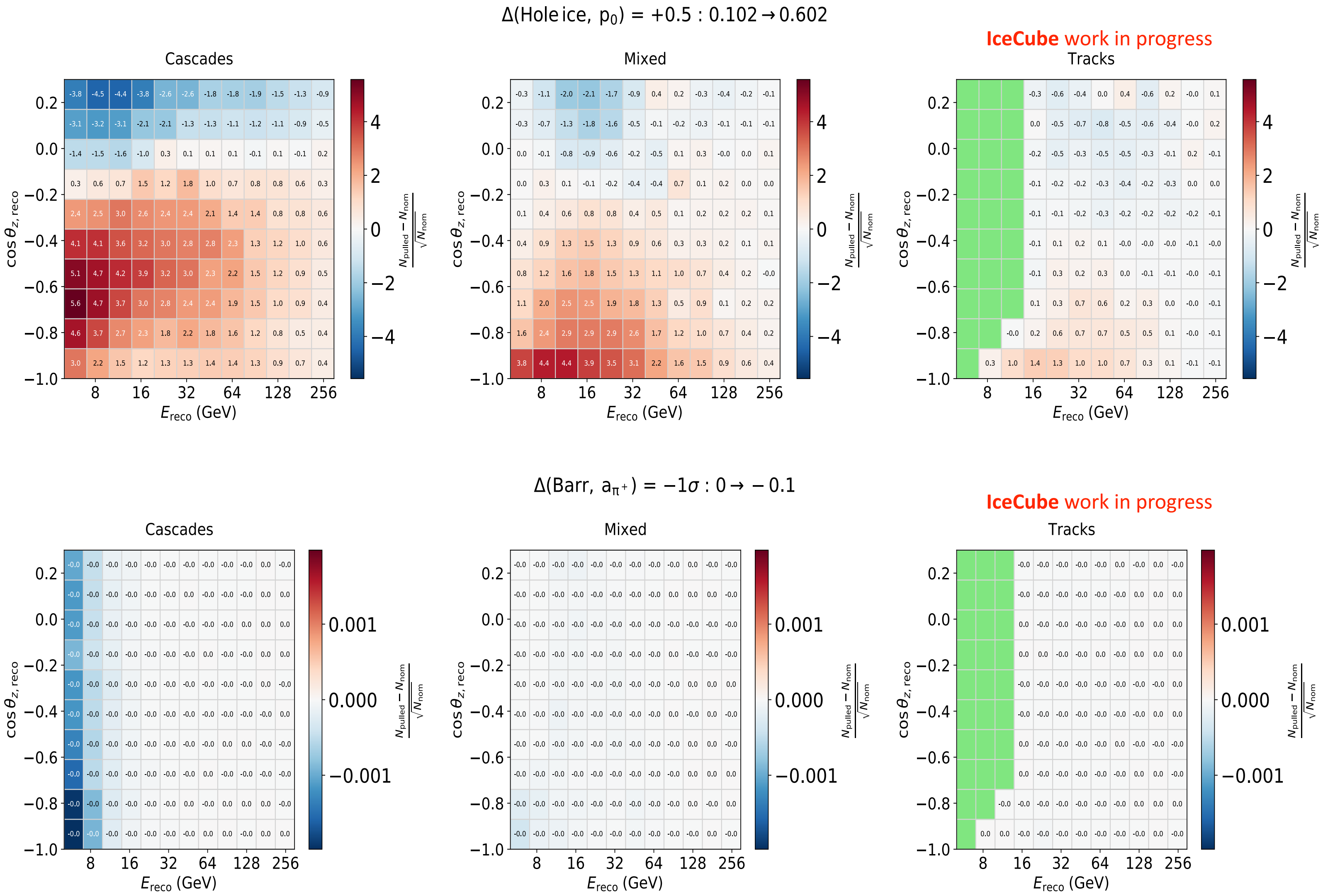
Cascade Reconstructions (ν_τ)

- Previous analyses - forward light propagation
- Upcoming analysis - backwards light propagation
- Future analysis & IceCube Upgrade - likelihood free inference, convolution neural network, graph neural network
  - Faster reconstructions will provide better event selections… positive feedback loop
  - Better reconstruction resolutions are always better



Systematics

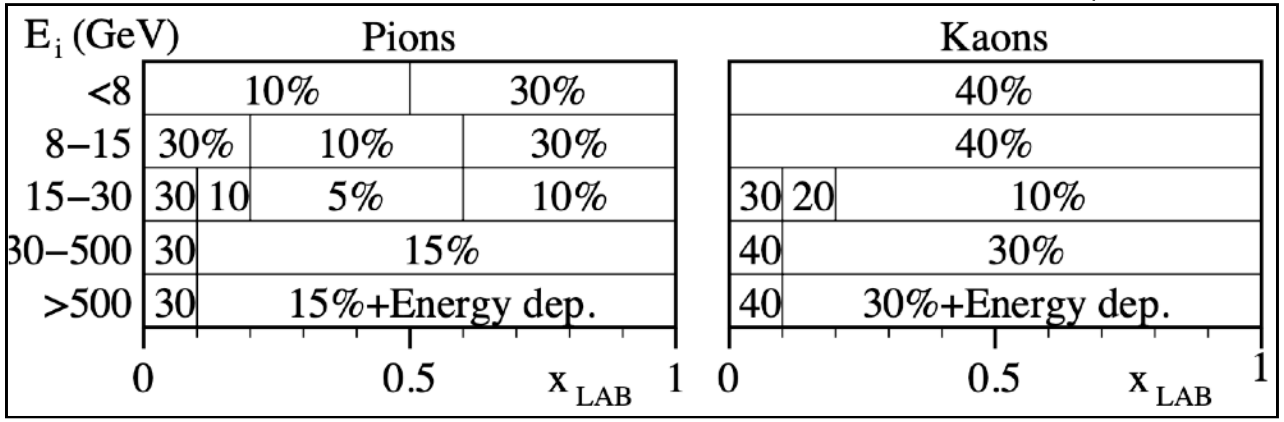
- 30+ systematic uncertainties evaluated for upcoming analysis
  - Many have a negligible impact on oscillation measurements and are dropped
  - The non-negligible systematics can be **very** non-negligible
    - e.g. DOM efficiency, hole ice photon scattering, spectral index
  - Subset of systematics checked for ν_τ appearance are in backup



Flux Uncertainties

- Using ‘Barr blocks’* for hadroproduction flux-related uncertainties
  - ~18 total
- Matrix Cascade Equation (MCEq)** for flux
  - Fast and amenable to different cosmic ray spectra & hadronic interaction models
  - Correlated treatment of evolving flux particle interactions & decays

*arXiv:astro-ph/0611266



$$\frac{d\Phi}{dX} = [\hat{\Lambda}_{int} + \hat{\Lambda}_{dec}\rho^{-1}]\Phi$$

**arXiv:1503.00544

cross section uncertainty

- Relevant cross section uncertainties are included in analyses (DIS, RES, QE). Do we need an additional uncertainty for ν_τ specifically?
  - Independent of kinematic considerations (x, Q^2, W) or parton distribution functions, is a relative—or absolute—systematic uncertainty necessary for CC-DIS ν_τ, e.g. $r_{\tau/\mu} \equiv \sigma^{\mathrm{CC}}(\nu_\tau N)/\sigma^{\mathrm{CC}}(\nu_\mu N)$?

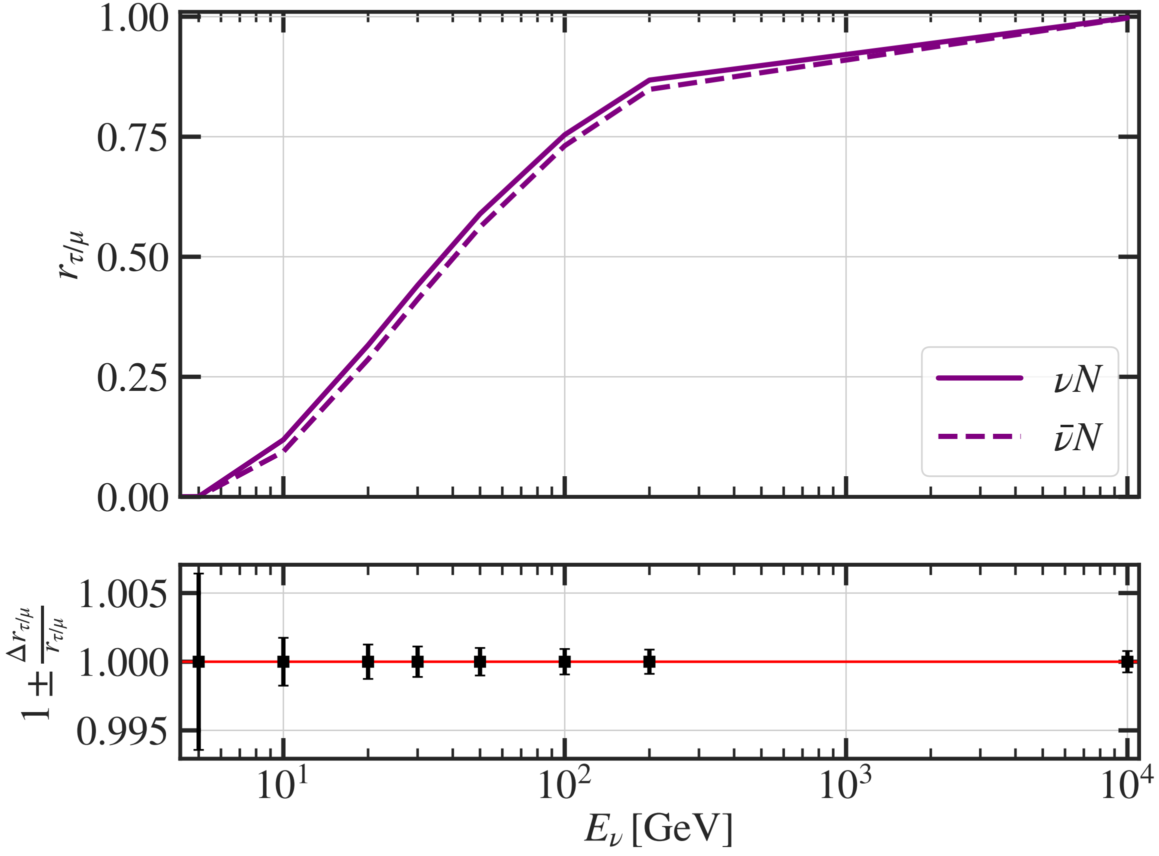
DIS cross section

$$\frac{\mathrm{d}^2\sigma^{\nu/\bar{\nu}}}{\mathrm{d}x\mathrm{d}y} = \frac{G_F^2 M_N E_\nu}{\pi(1+Q^2/M_W^2)^2}\Bigg\{(y^2 x + \frac{m_l^2 y}{2E_\nu M_N})F_1(x,Q^2) + \left[(1-\frac{m_l^2}{4E_\nu^2}) - (1+\frac{M_N x}{2E_\nu})y\right]F_2(x,Q^2)$$
$$\pm\left[xy(1-\frac{y}{2}) - \frac{m_l^2 y}{4E_\nu M_N}\right]F_3(x,Q^2) + \frac{m_l^2(m_l^2+Q^2)}{4E_\nu^2 M_N^2 x}F_4(x,Q^2) - \frac{m_l^2}{E_\nu M_N}F_5(x,Q^2)\Bigg\}$$

The cross section ratio + uncertainties

$$r_{\tau/\mu} \equiv \sigma^{\mathrm{CC}}(\nu_\tau N)/\sigma^{\mathrm{CC}}(\nu_\mu N)$$

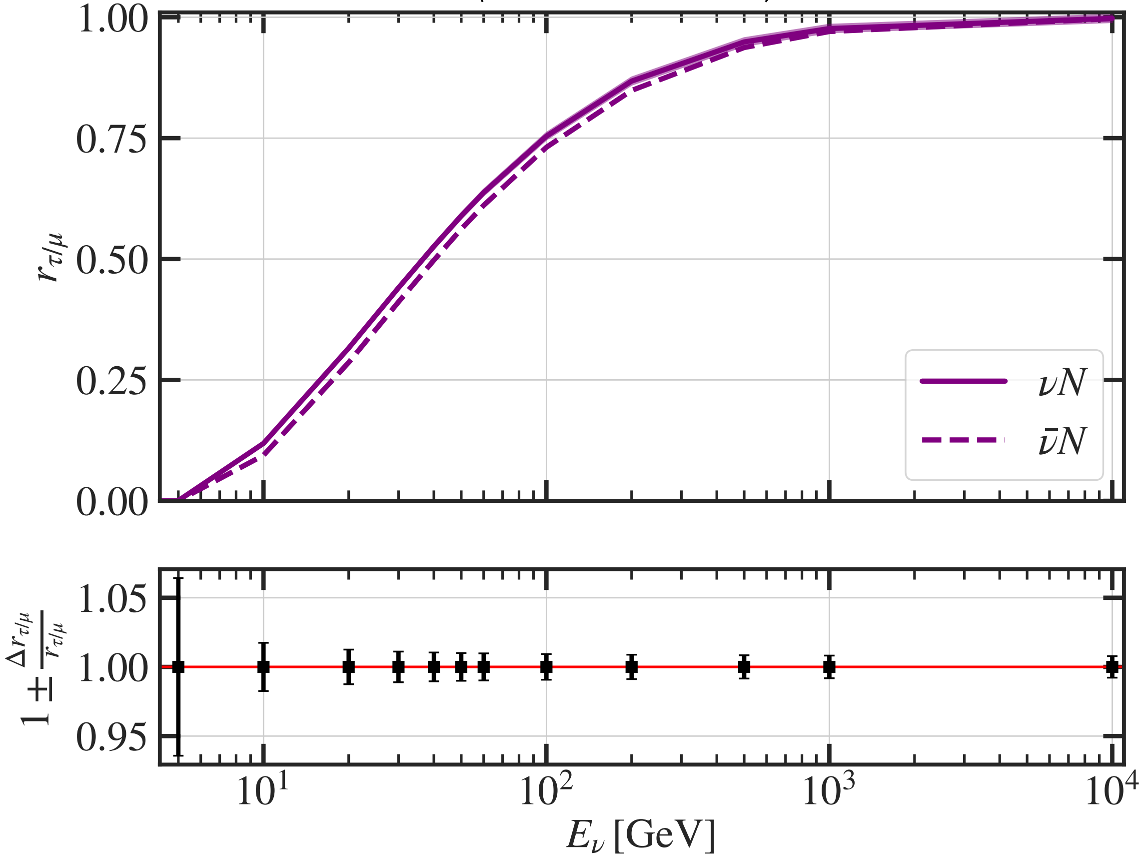
propagating 1 × the F_i uncertainties



~0.5% relative uncertainty at 5 GeV → *small!*

propagating 10 × the F_i uncertainties

(unrealistic scenario)

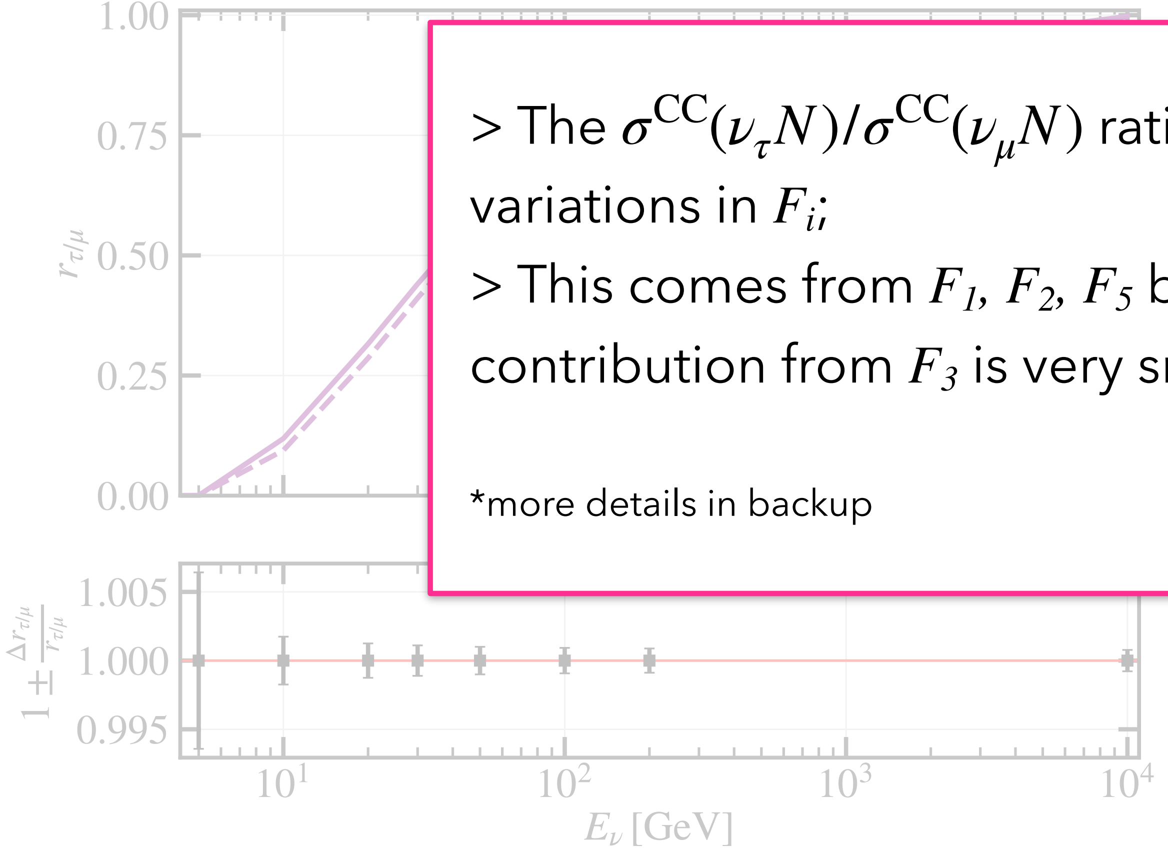


~5% relative uncertainty at 5 GeV

The cross section ratio + uncertainties

$$r_{\tau/\mu} \equiv \sigma^{\mathrm{CC}}(\nu_\tau N)/\sigma^{\mathrm{CC}}(\nu_\mu N)$$

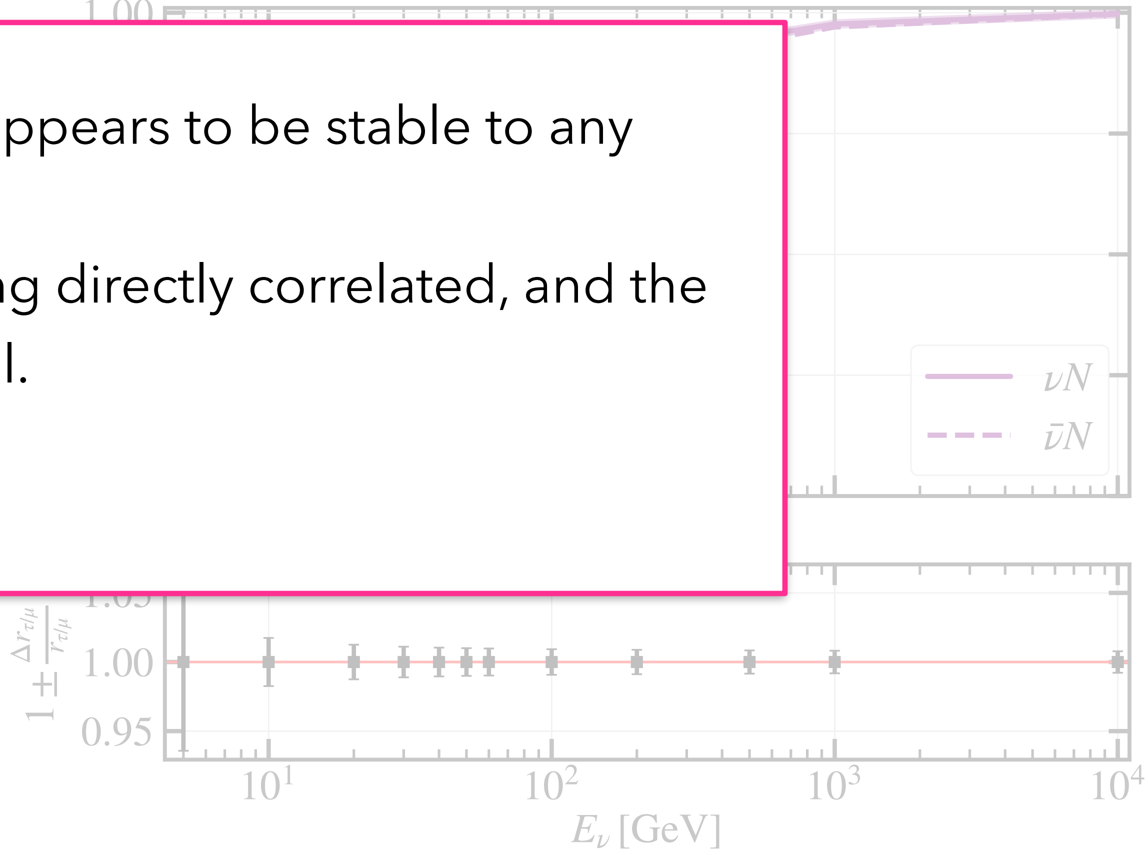
propagating 1 × the F_i uncertainties



~0.5% relative uncertainty at 5 GeV → *small!*

propagating 10 × the F_i uncertainties

(unrealistic scenario)



~5% relative uncertainty at 5 GeV

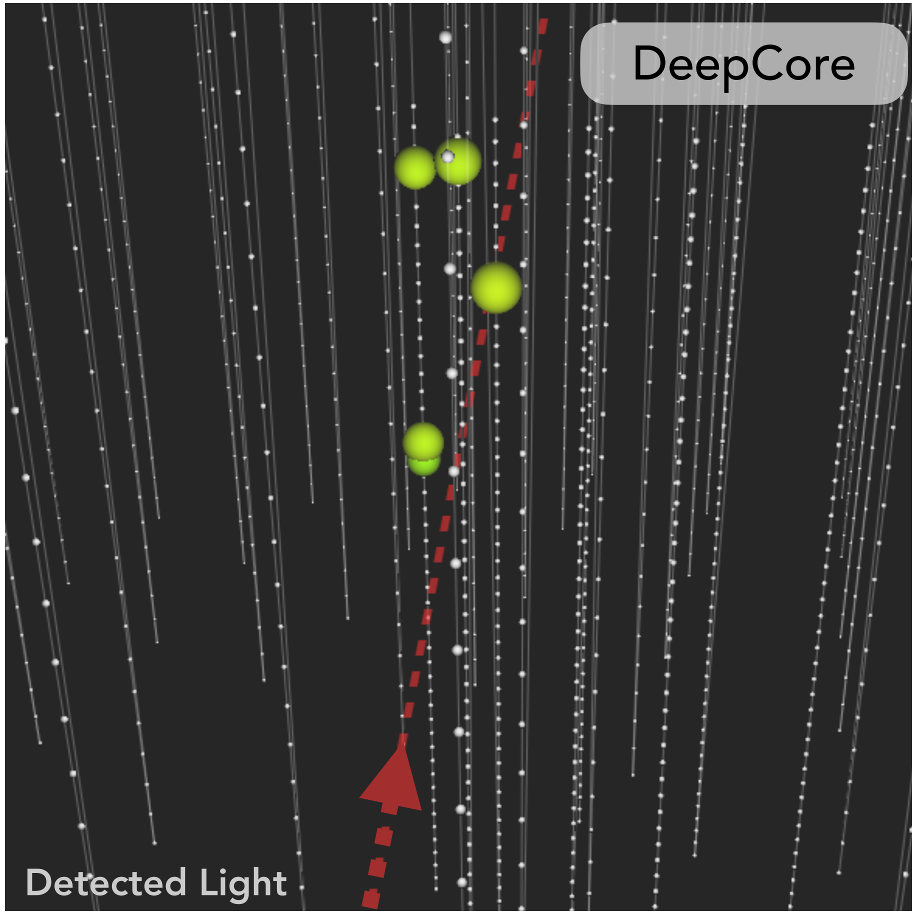
> The $\sigma^{\mathrm{CC}}(\nu_\tau N)/\sigma^{\mathrm{CC}}(\nu_\mu N)$ ratio appears to be stable to any variations in F_i;
> This comes from F_1, F_2, F_5 being directly correlated, and the contribution from F_3 is very small.

*more details in backup

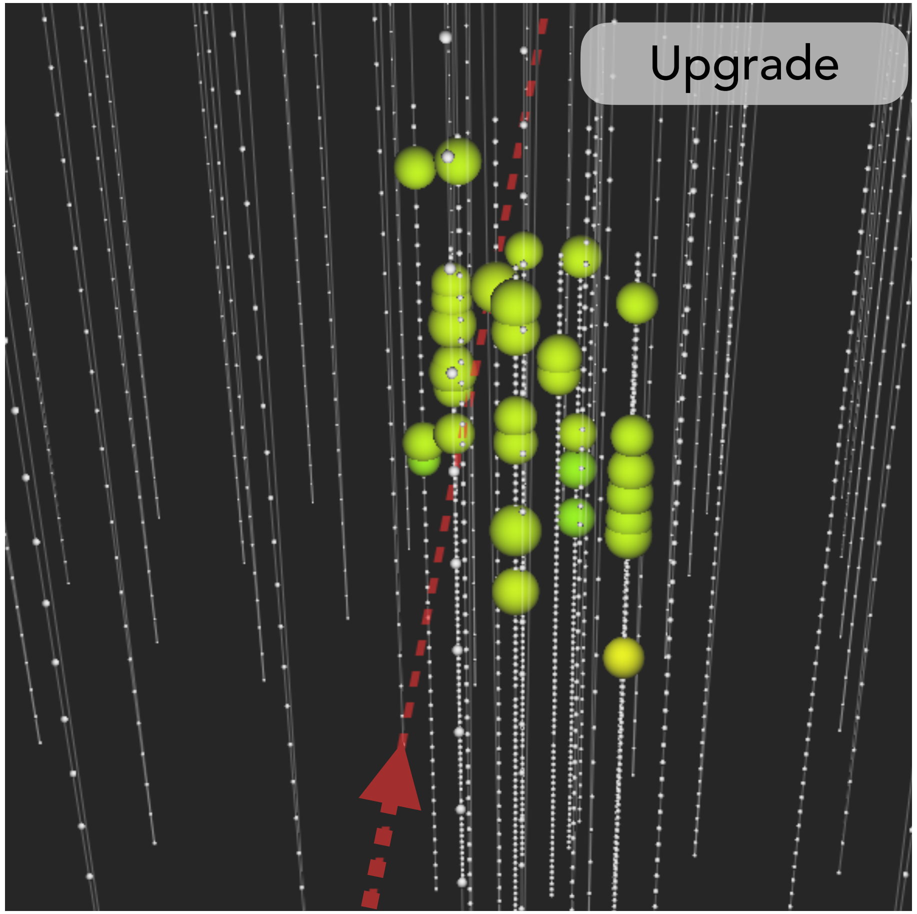
THE FUTURE

IceCube Upgrade

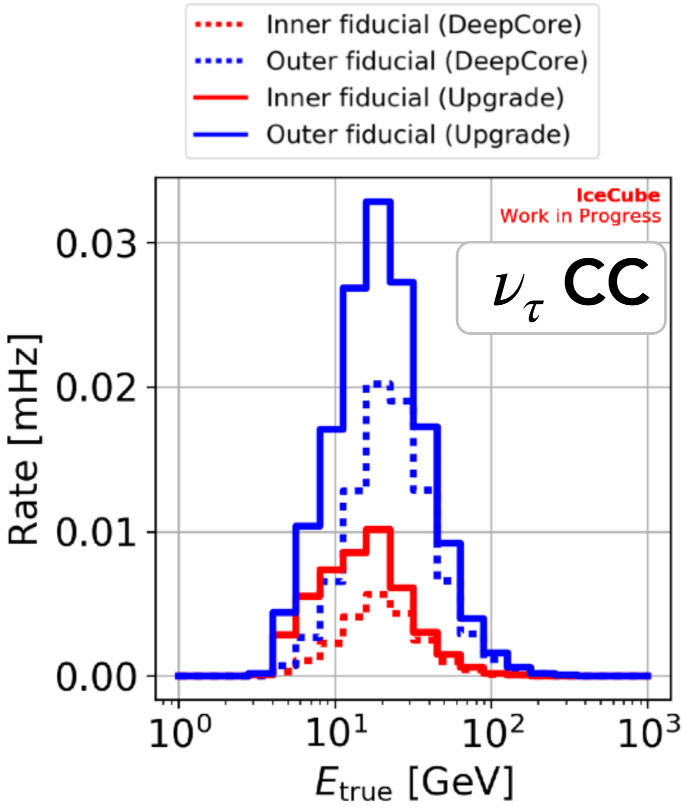
- Dense instrumentation within inner core

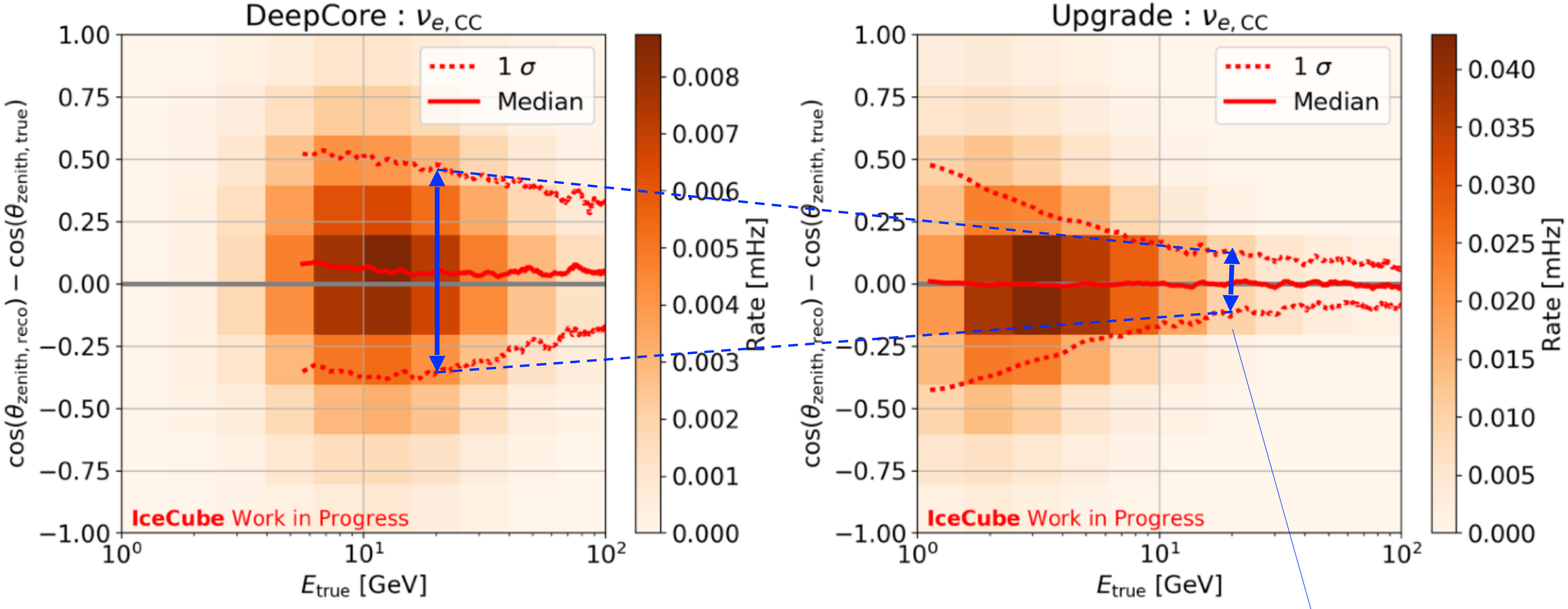


29 GeV ν_τ
(up-going)



IceCube Upgrade



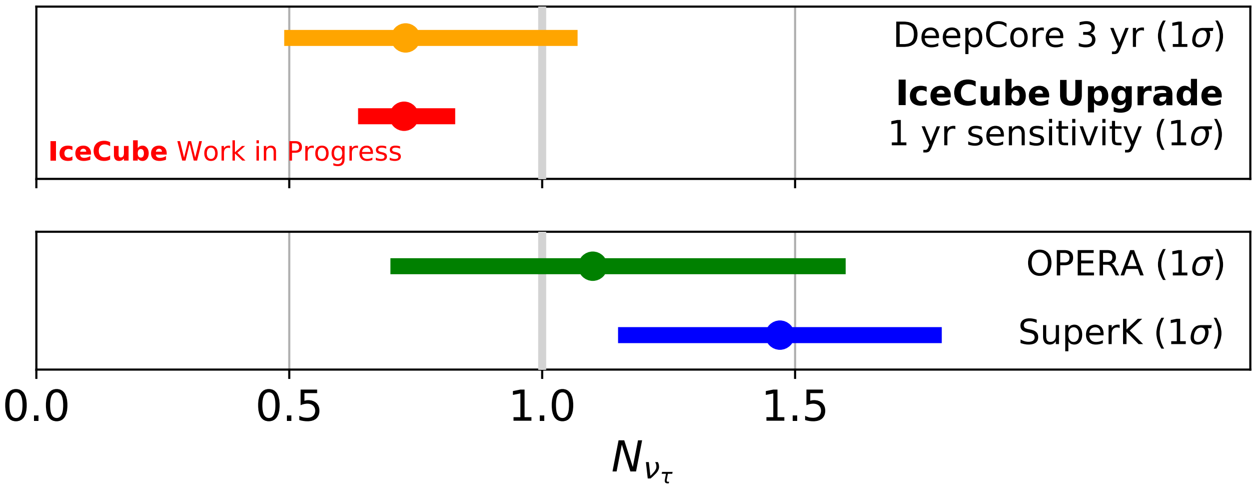


3x improvement in cascade resolution @ ν_τ appearance energies

*ν_e CC and ν_τ CC both appear as cascades. ν_e are an easier proxy for cascade reconstruction development.

IceCube Upgrade

- Conservative experimental choices still illustrate potential of IceCube Upgrade for physics
  - ~10% N_{ν_τ} resolution with 1-year of data
  - Excludes improvements from new reconstructions, better detector systematics, better flux treatment, and no combination of 10+ years of DeepCore data



Conclusion

- Leading ν_τ appearance measurement(s) & constraints for (non)unitarity through N_{ν_τ}

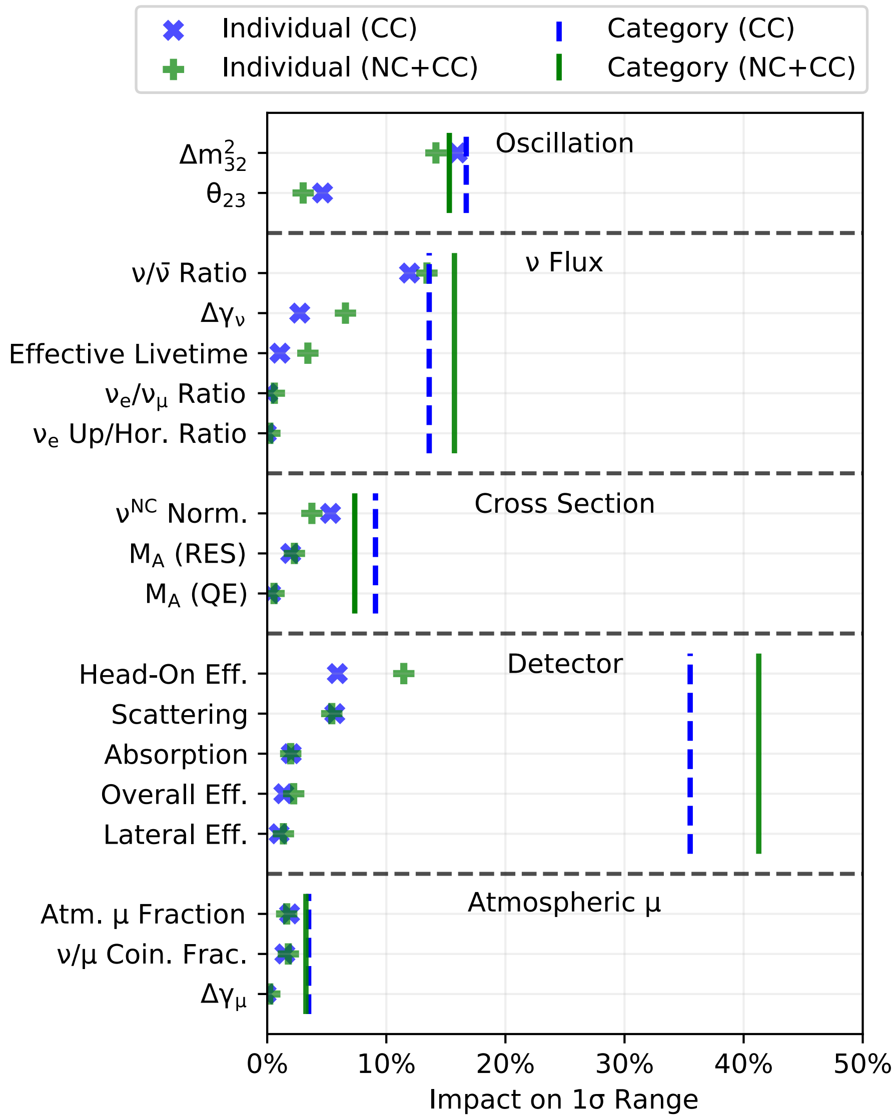
- IceCube Upgrade provides incredible future for oscillation results, notably ν_τ

BACKUP

Systematic Uncertainties

- Figure is relative impact from 3-year ν_τ appearance analysis for the non-negligible uncertainties

- Updated list for upcoming 8-year analysis nearing finalization



Outline of the ν_τ xsec relative uncertainty study

1. Take the good old Reno & Kretzer (2002) expression for the DIS cross section:

$$\frac{d^2\sigma^{\nu/\bar{\nu}}}{dx\,dy} = \frac{G_F^2 M_N E_\nu}{\pi(1+Q^2/M_W^2)^2}\left\{ \left(y^2 x + \frac{m_l^2 y}{2E_\nu M_N}\right) F_1(x,Q^2) + \left[\left(1 - \frac{m_l^2}{4E_\nu^2}\right) - \left(1 + \frac{M_N x}{2E_\nu}\right) y\right] F_2(x,Q^2) \right.$$
$$\left. \pm \left[xy\left(1 - \frac{y}{2}\right) - \frac{m_l^2 y}{4E_\nu M_N}\right] F_3(x,Q^2) + \frac{m_l^2(m_l^2+Q^2)}{4E_\nu^2 M_N^2 x} F_4(x,Q^2) - \frac{m_l^2}{E_\nu M_N} F_5(x,Q^2) \right\}$$

2. Compute the structure functions $F_i(x,Q^2)$:

   2.1. Express $F_i(x,Q^2)$ in terms of the parton distribution functions (PDFs) for individual quarks, $q(x,Q^2)$;

   2.2. Choose a PDF set and extract the respective $q(x,Q^2)$ ± uncertainty.

3. $\boxed{q(x,Q^2) \pm \Delta q(x,Q^2)} \rightarrow \boxed{F_i(x,Q^2) \pm \Delta F_i(x,Q^2)} \rightarrow \boxed{\sigma_l(E) \pm \Delta\sigma_l(E)} \rightarrow \boxed{\frac{\sigma_{\nu_\tau}}{\sigma_{\nu_\mu}}(E) \pm \Delta\left(\frac{\sigma_{\nu_\tau}}{\sigma_{\nu_\mu}}(E)\right)}$

*T. Kozynets, NBI

2.1. Computing the structure functions

$u(x)$, $c(x)$… etc. are PDF-specific

proton target	$F_{2p}^{\nu}(x) = 2x[d(x) + s(x) + \bar{u}(x) + \bar{c}(x)]$ $xF_{3p}^{\nu}(x) = 2x[d(x) + s(x) - \bar{u}(x) - \bar{c}(x)]$	$F_{2p}^{\bar{\nu}}(x) = 2x[u(x) + c(x) + \bar{d}(x) + \bar{s}(x)]$ $xF_{3p}^{\bar{\nu}}(x) = 2x[u(x) + c(x) - \bar{d}(x) - \bar{s}(x)]$
neutron target	$F_{2n}^{\nu}(x) = 2x[u(x) + s(x) + \bar{d}(x) + \bar{c}(x)]$ $xF_{3n}^{\nu}(x) = 2x[u(x) + s(x) - \bar{d}(x) - \bar{c}(x)]$	$F_{2n}^{\bar{\nu}}(x) = 2x[d(x) + c(x) + \bar{u}(x) + \bar{s}(x)]$ $xF_{3n}^{\bar{\nu}}(x) = 2x[d(x) + c(x) - \bar{u}(x) - \bar{s}(x)]$
isoscalar target	$F_{iN} = \frac{F_{ip} + F_{in}}{2}$ ← assumed in this work	
leading order relations	$F_1(x) = F_5(x) = \frac{F_2(x)}{2x}; F_4(x) = 0.$	

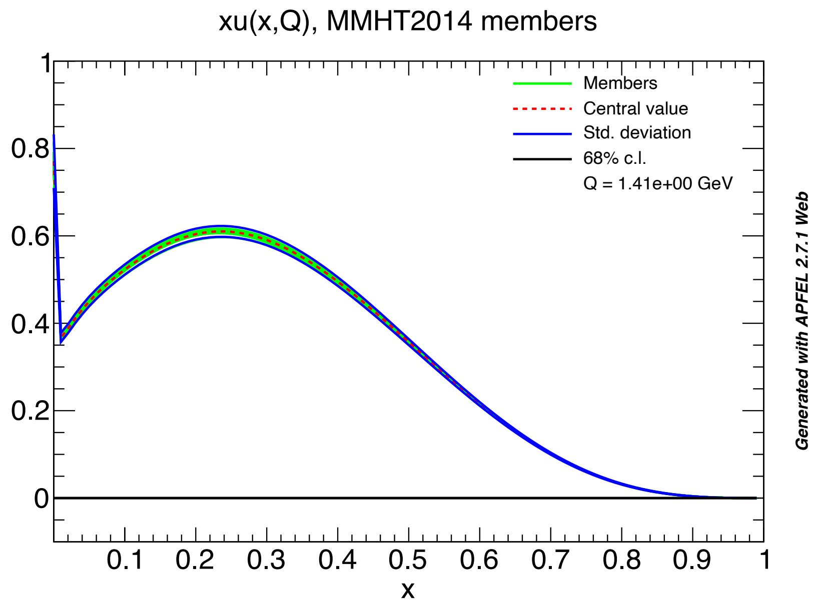
Albright-Jarlskog; Callan-Gross

Ansari et al. 2020

*T. Kozynets, NBI

2.2. Accessing the individual quark PDFs

> The LHAPDF database provides the PDF sets with measurements & fits from different groups, for example:



LHAPDF 6.3.0

Main page | PDF sets | Class hierarchy | Functions | Examples | More...

PDF sets

Official LHAPDF 6.3 PDF sets: currently 1045 available, of which 1044 are validated.

LHAPDF ID	Set name and links		Number of set members	Latest data version	Notes
251	GRVPI0	(tarball) (info file)	1	1	alpha_s was broken in LHAPDF5. This version uses approximate 1st order running from reported Lambda4,5 values.
252	GRVPI1	(tarball) (info file)	1	1	
270	xFitterPI_NLO_EIG	(tarball) (info file)	8	1	
280	xFitterPI_NLO_VAR	(tarball) (info file)	6	1	
10000	cteq6	(tarball) (info file)	41	-1	Corresponds to LHAPDF5's cteq6 or cteq6mE; central member equivalent to cteq6m.
10042	cteq6l1	(tarball) (info file)	1	4	
10150	cteq61	(tarball) (info file)	41	1	
10550	cteq66	(tarball) (info file)	45	1	

> Several Python libraries (such as parton or pdfflow) can process these files directly and extract the PDFs for a needed flavor;
> The central value is normally “member 0”;
> The confidence limits (68 or 90%, stated in the info file) are given in the other “members” of the PDF set.

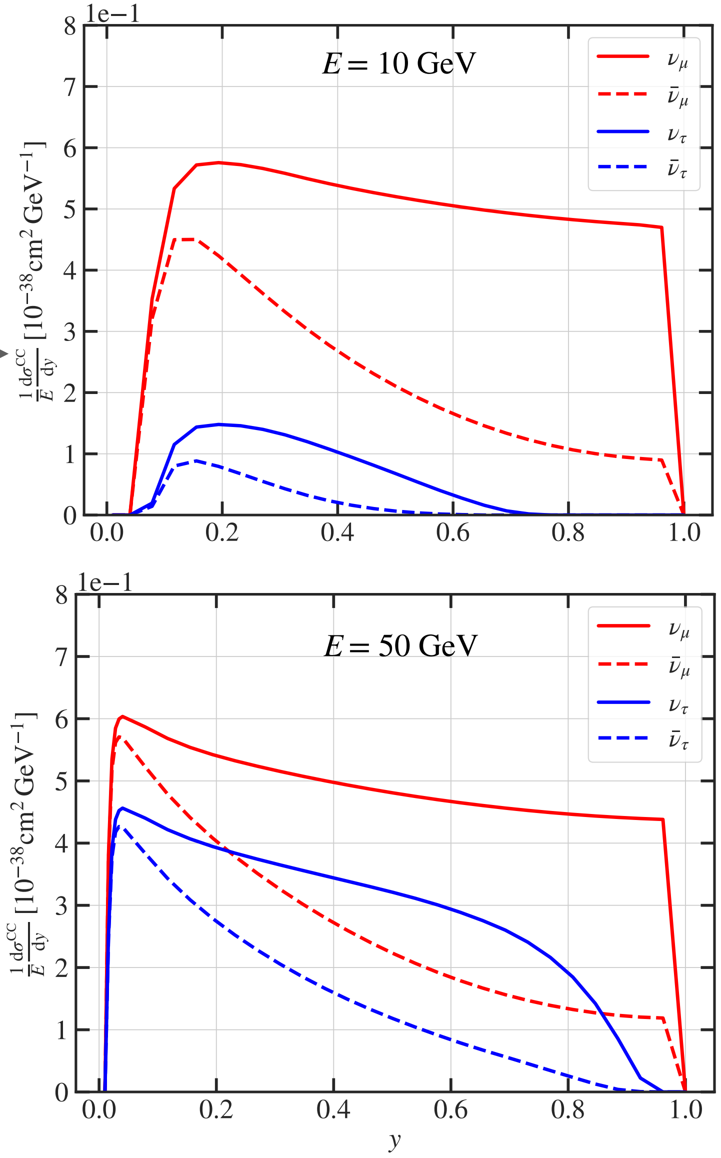
*T. Kozynets, NBI

3. Building up the cross sections: $d\sigma/dy$

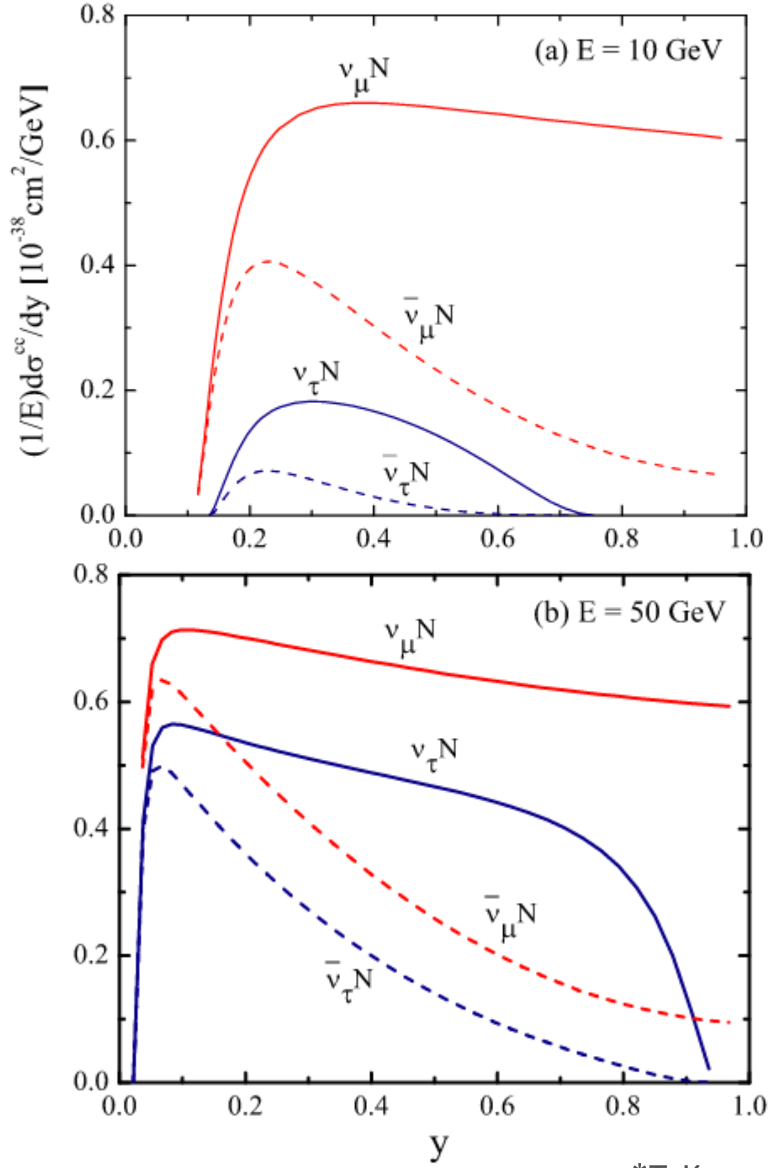
> Plugging the F_i into the DIS cross section formula, we get the following differential cross sections:

> The shapes and the relative scaling between the flavours are ~in agreement with those from Reno (right panel).

This work (LO)



Reno & Jeong (NLO)



*T. Kozynets, NBI