mPMT/NEUT workshop
15/16 July 2016 @ Nikhef

https://indico.nikhef.nl/conferenceDisplay.py?confId=414
pw: hyperkm3net (partly confidential content)

"This workshop aims to bring people from Hyper-K, IceCube and KM3NeT together to enable closer cooperation and to benefit from common developments in technology and software."

HyperK/KM3NeT/IceCube

Organizers:

Tom Feusels, Akira Konaka, Thomas Eberl, Clancy James, Pasquale Migliozzi, Paschal Coyle, Dorothea Samtleben, Darren Grant

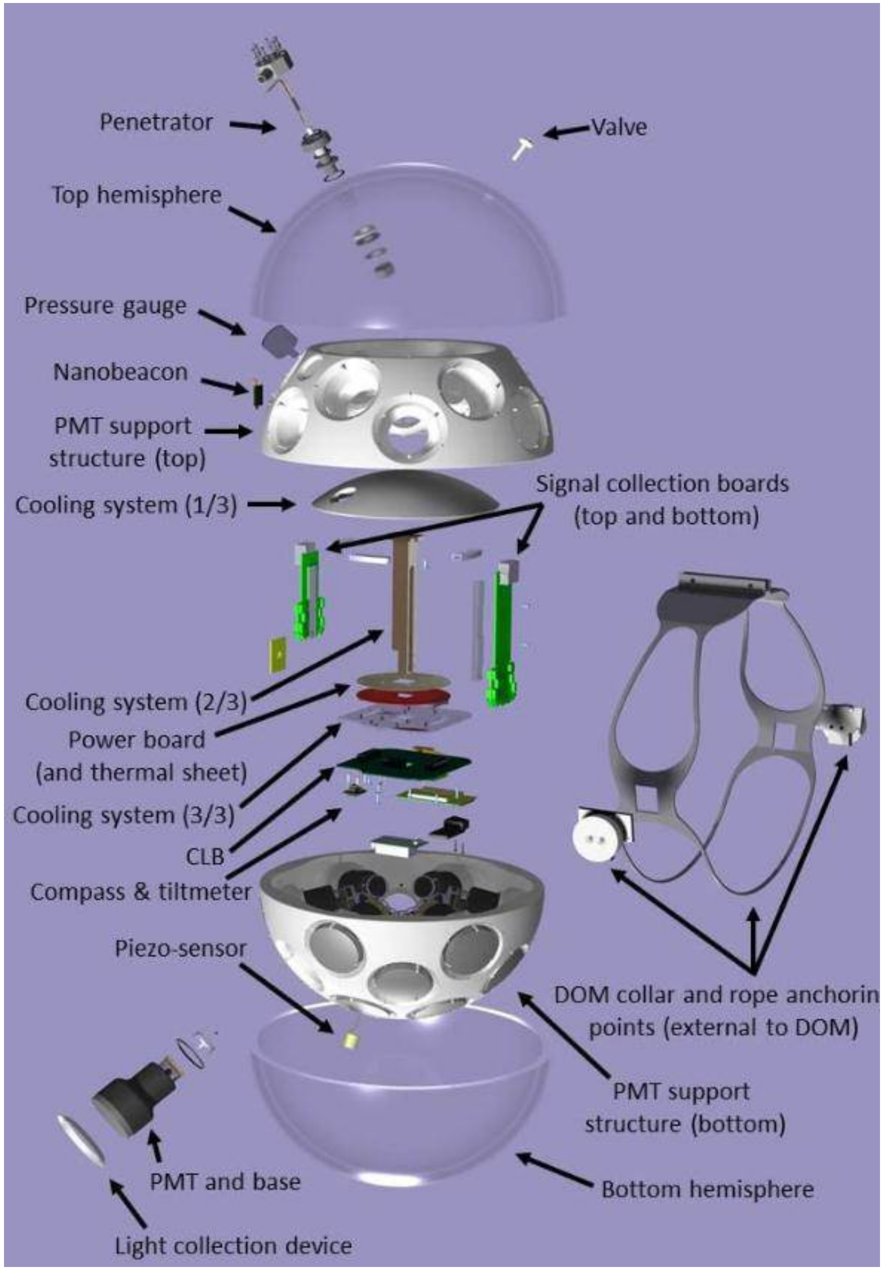
multi PMT hardware

- KM3NeT DOM, IceCube-Gen 2 mDOM, HK/NuPRISM mPMT, PMTs in CHIPS
- PMT options (Hamamatsu/ETEL/HZC) & new photosensors (VSiPMTs)
- PMT dark rates
- Mechanics, pressure vessels
- Electronics
- Mass production & testing
- Calibration & event reconstruction @ KM3NeT

Neutrino generators / Atmospheric neutrinos / Systematics

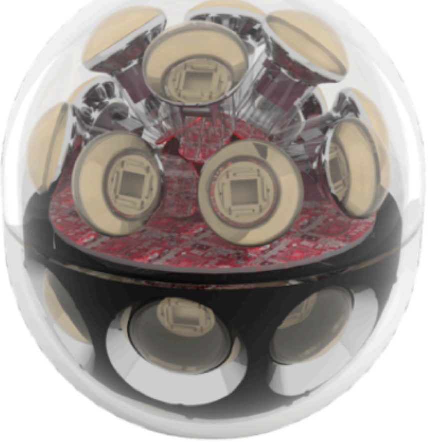
- Neutrino generator overview
- gSeaGen
- NEUT tutorial
- DIS in NEUT/GENIE
- Reweighting of NEUT
- Atmospheric neutrinos/uncertaintites
- Intrinsinc limits in event reconstruction

Multi-PMT design by KM3NeT
31 3” PMTs in one 17inch sphere

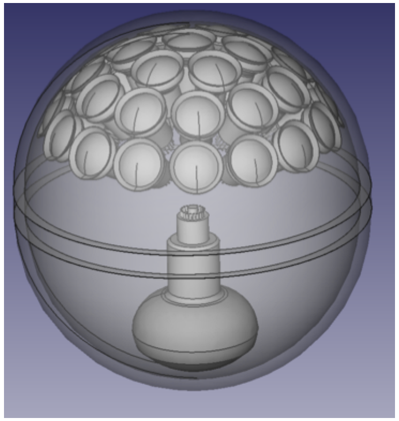


Interest in multi-PMT designs from several experiments:
IceCube, Hyperk, nuPRISM, CHIPS

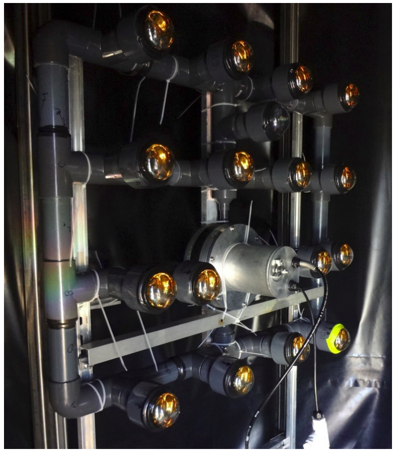
IceCube Gen2 prototype design



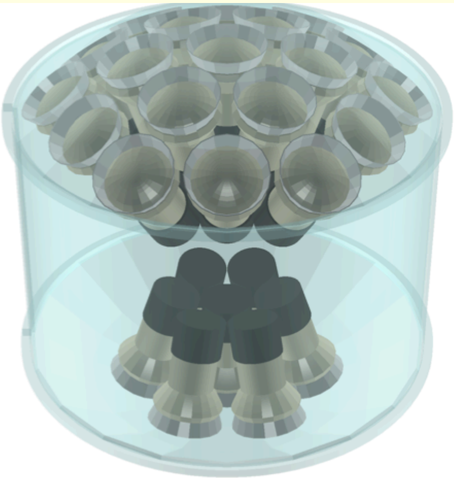
HyperK prototype design



CHIPS test array



νPRISM prototype design



Why Multi-PMTs for Hyper-K/near detector?

Physics:

- **Directionality:** each single PMT sees a different part of the tank. Improves reconstruction and background suppression.
- Neutron tagging in Super-K and Hyper-K: neutron absorption by H/Gd, with prompt γ emission of a few MeV. Reduced random background suppression by using directionality should increase tagging efficiency.
- Reconstruction has additional information from individual 3" PMT acceptance which should help the minimizer.
- **Improved granularity** should help reconstruction and enlarging fiducial volume: Currently fiducial volume cut 2m from the ID/OD wall. Smaller tubes should increase performance (eg. PID) near the wall.

Why Multi-PMTs for Hyper-K/near detector?

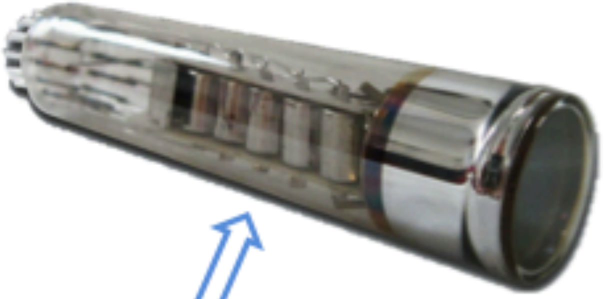
Mechanics:

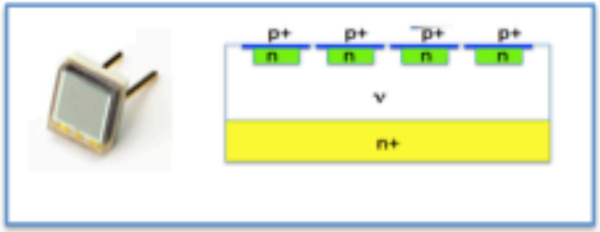
- PMTs encapsulated in pressure vessel, with $\frac{\text{thickness}}{\text{diameter}} > 0.03\text{-}0.04$ for acrylic (15-20mm) $\Rightarrow$ **No depth limitation on Hyper-K tank height.**
- **Natural solution for in-water electronics**: only one water-proof connector to module needed (penetrator). Well known technology.
- Small (3") PMTs do **not need magnetic field shielding**.
- **Containment of radon contamination** from PMT glass inside closed acrylic pressure vessel.
- Natural **integration of OD and ID**. Shorter base of small ID PMTs seriously decreases 60cm ID/OD dead space, hence **increase FV**.

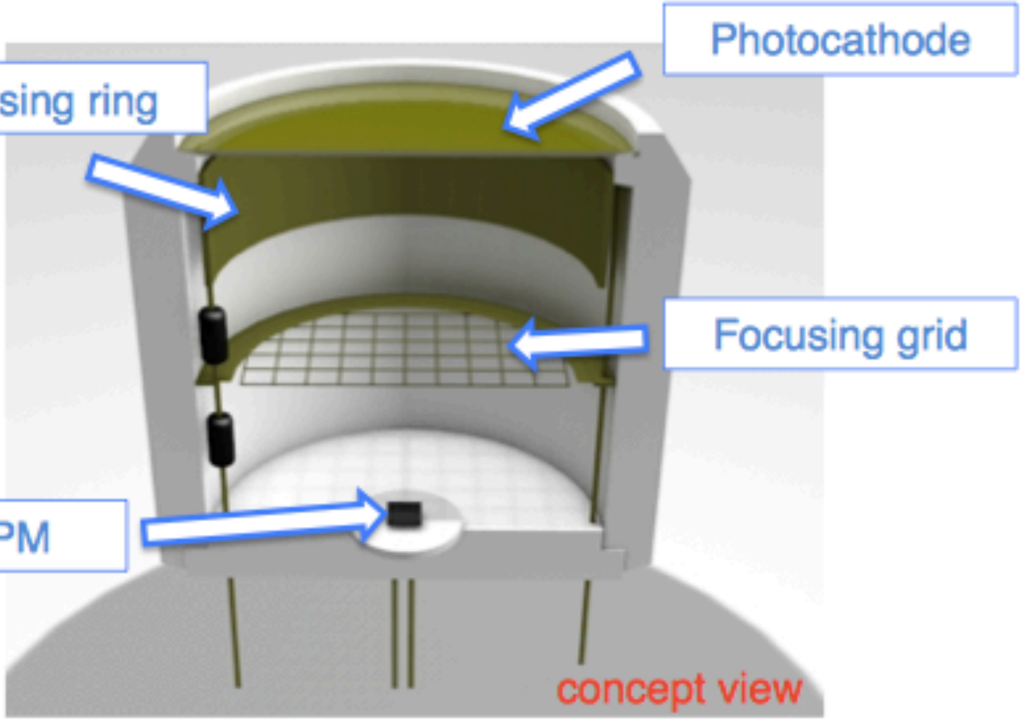
The VSiPMT

Vacuum Silicon PhotoMultiplier Tube (VSiPMT)

An innovative design for a modern hybrid photodetector based on the combination of a Silicon PhotoMultiplier (SiPM) with a Vacuum PMT standard envelope







Photocathode

Focusing ring

Focusing grid

SiPM

concept view

The classical dynode chain of a PMT is replaced with a SiPM, acting as an electron multiplying detector.

VSIPMT VS PMT

	PMT	VSiPMT	comparison
Efficiency	Photocathode x 1st dynode	Photocathode x Fill factor MPPC (→1)	**≈ comparable (slightly worse)**
Gain	10^6 - 10^7	≈ 10^6	**≈ equivalent**
Timing	nsec	fractions of nsec (no spread dynodes)	**+ VSiPMT**
Power Consumption	Divider Dissipation	No dissipation: just amp. G=10-20 (<5mW)	**+VSiPMT**
Stability H.V.	H.V. stabilization for stable gain	No H.V. stability (plateau)	**+VSiPMT**
Dark counts	≈ kHz @ 0.5pe	≈100 kHz/mm^2 @0.5pe	**+PMT**
Photon counting	difficult	excellent	**+VSiPMT**
Linearity	depending on gain	depending on focusing	**≈+PMT**
Peak-to-valley	≈ 3 (typ.)	> 60	**+VSiPMT**
Afterpulse(@0.5 pe)	≈ 10%	Next gen. MPPC <0.3%	**+VSiPMT**
SPE resolution	≈ 30% (typ.)	≈ 17.8%	**+VSiPMT**

D. Vivolo

VSiPMT as a solution for KM3NeT

Dark count rate

Requirement:
< 3kHz at 0.3pe threshold

VSiPMT

Dark count rate unacceptably large
2 orders of magnitude above requirements

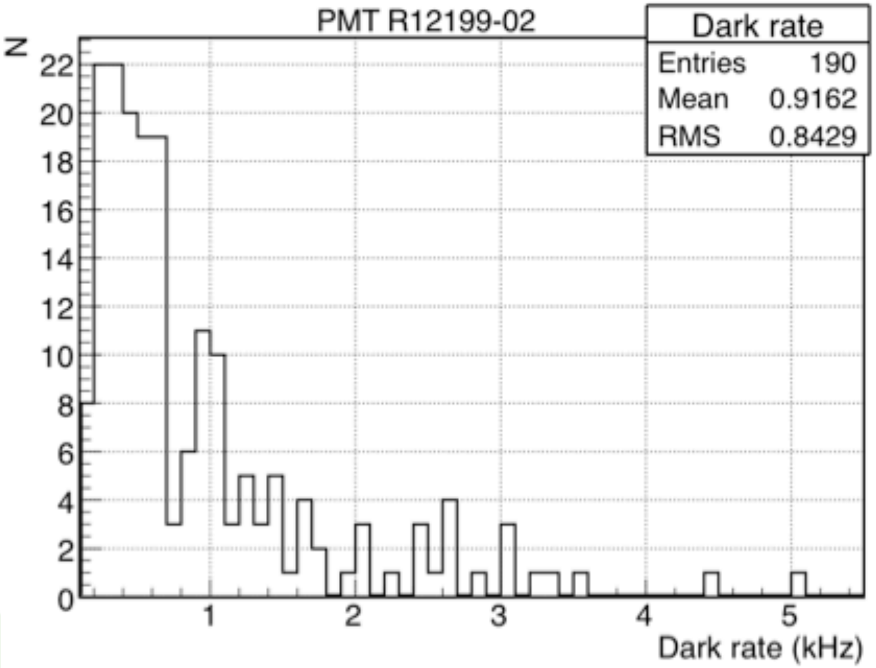
Towards the 3-inch device

Intrinsic limit, two possible approaches:

- high thresholds,
- multiple coincidences.

New generation of Hamamatsu MPPC exhibits a factor 10 improvement (still high)

Hamamatsu R12199-02



Requirement quite satisfactorily fulfilled.
190 PMTs tested:

- ≈ 68% below 1kHz,
- 86% less than 2kHz.

Small fraction out of the allowed range.

Conclusions and Perspectives

VSiPMT is an innovative design for a modern hybrid photodetector based on the combination of a Silicon PhotoMultiplier (SiPM) with a Vacuum PMT standard envelope

It has many **UNPRECEDENTED** features, such as:

- Photon counting capability;
- Low power consumption;
- Large sensitive surface;
- Excellent timing performances (low TTS);
- High stability (not depending on HV).

making it a very attractive solution in many applications

STILL IMPROVABLE!!!

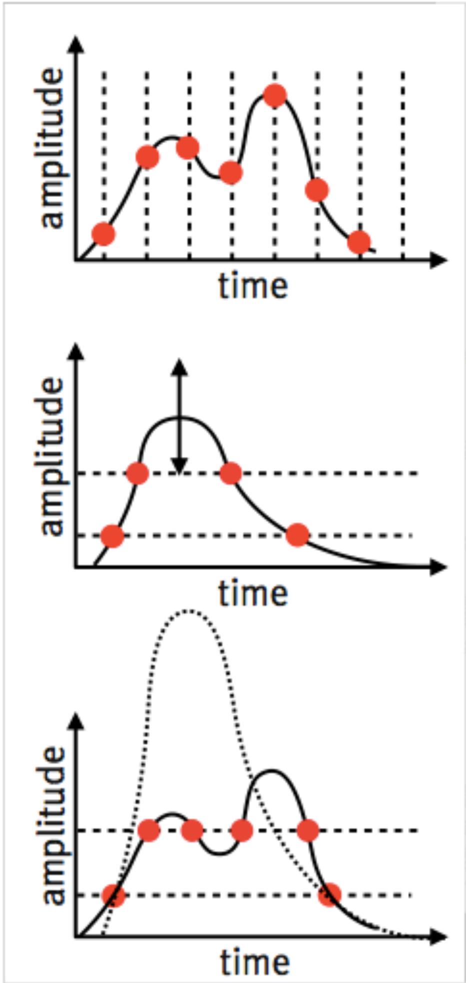
New generation of Hamamatsu MPPCs:

- sensibly lower afterpulse rates;
- lower noise: much reduced dark counts;
- higher gain → no amplification required (persp.);
- focusing optimization required.

Readout Schemes

- **ADC**
  Measure amplitude at fixed times
  - Conventional approach used in many experiments, incl. IceCube
  - Power consumption too high for mDOM

- **Leading edge time and time-over-threshold**
  Measure time at fixed amplitude
  - Can be implemented at low power
    No current flow between PMT base and mainboard while signal below threshold
  - Potential ambiguities with one (few) thresholds

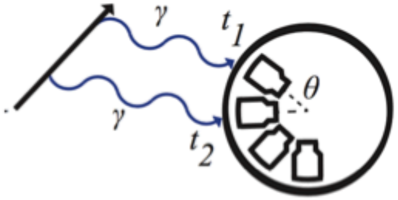


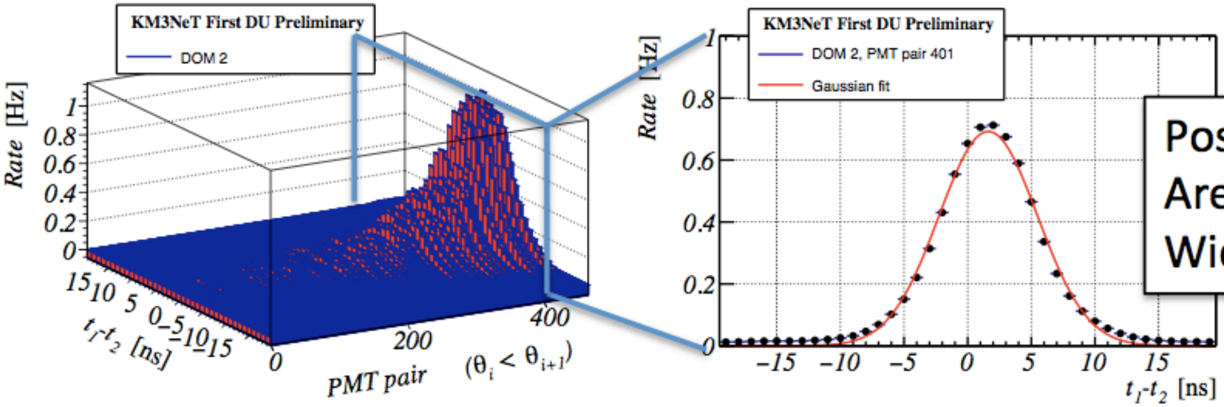
Summary & Outlook

- mDOM readout scheme
  - leading and trailing edge time at multiple thresholds for all 24 PMTs
  - either 4 comparators in discrete design or 63-comparator ASIC
  - discrete design: 1.2 GHz sampling for lowest threshold; 600 MHz sampling for the others
- Half-mDOM evaluation system has been developed
  - front-end, data transmission to MB, mainboard
  - capability to externally inject and monitor analog signals
  - system currently in commissioning
- Expect design studies with evaluation system until end of 2016; full mDOM mainboard by end of 2017

Inter-PMT Calibration: Principle

- Coincident light from ^{40}K decays
- 465 PMT-pairs, 93 fit parameters





Position	➔	Time offset
Area	➔	Efficiency
Width	➔	Time spread

Neutrino generators

Reweighting

Intrinsic resolutions

Updated FSI model tune, uncertainties

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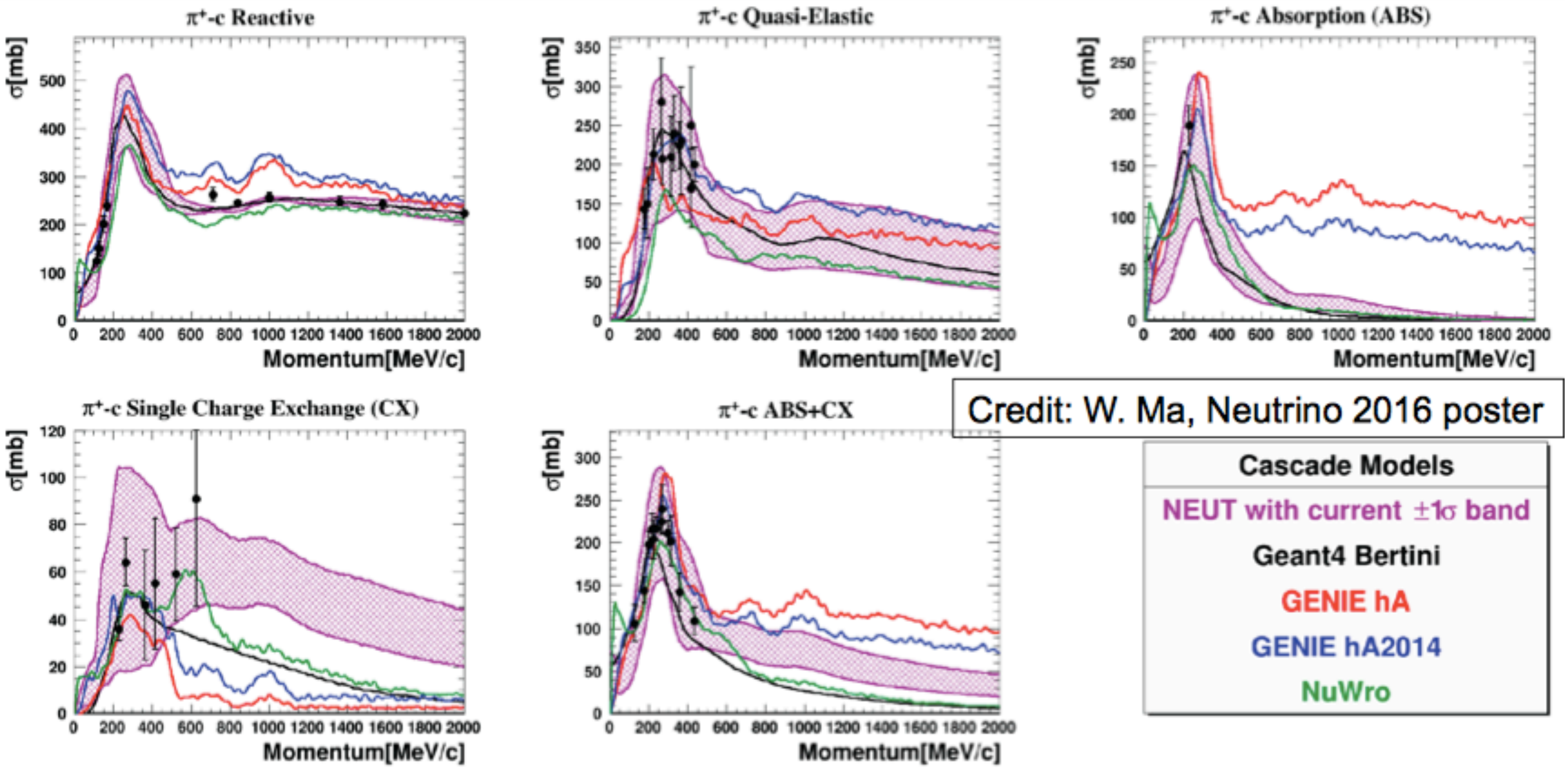


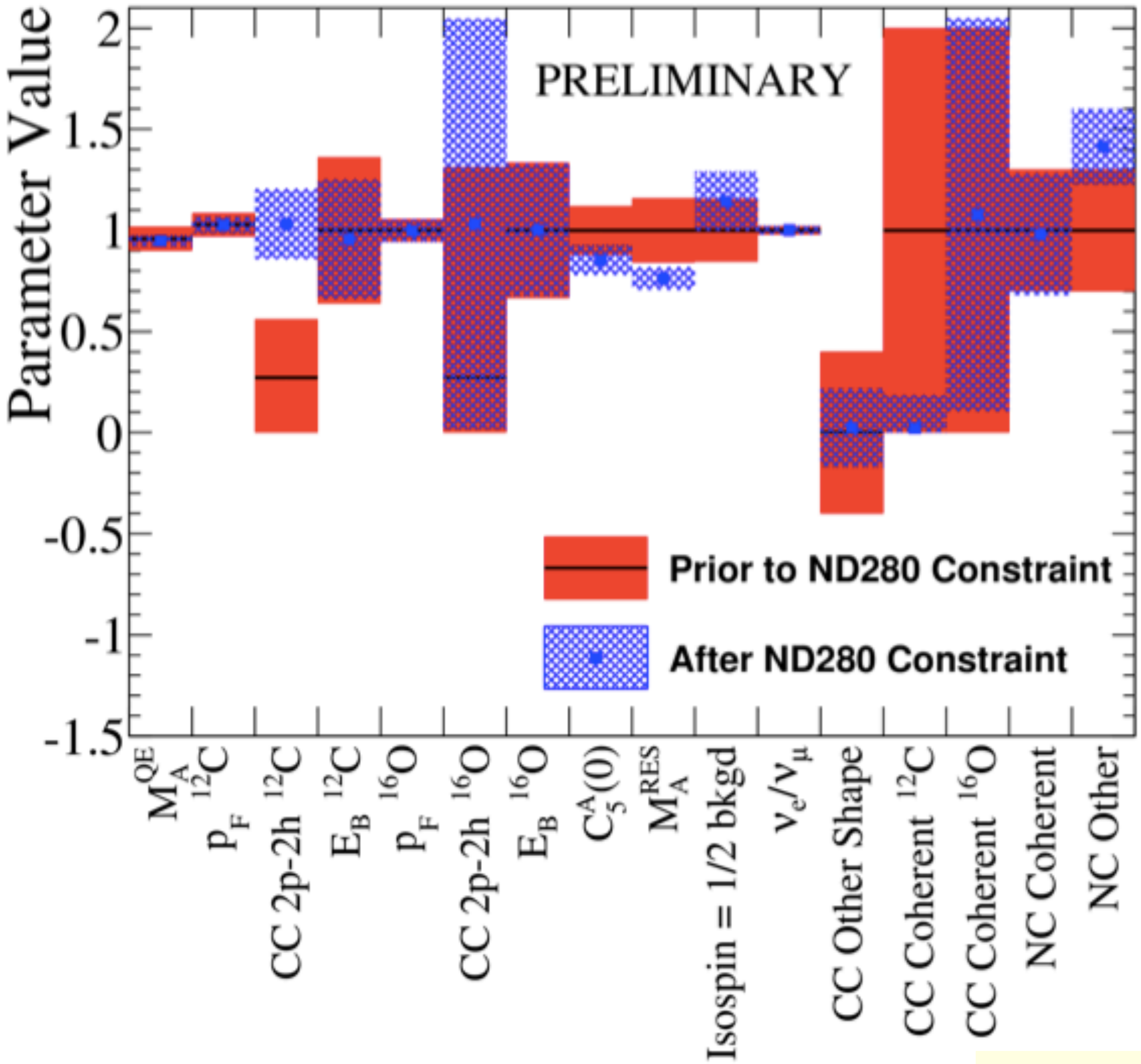
Credit: W. Ma, Neutrino 2016 poster

Work ongoing on T2K (Tom Feusels is the expert!) to include:

- New data sets (DUET experiment)
- Comparisons to other generators
- Updated fit machinery, parameterization

Kendall Mahn

Parameterization Summary



Slightly outdated error table:

- Less significant processes (e.g. CC coherent) get a simple normalization uncertainty
- CC Other Shape is a ~normalization uncertainty to allow for large uncertainties at low energy and small at higher energy, set from a lack of pion data
- Hadronization uncertainty under development

Kendall Mahn

Summary

On T2K, extensive program to determine appropriate uncertainties on the underlying cross section models within NEUT generator

- KM3NeT may be interested in neutrino/antineutrino cross section measurements on water made with T2K near detectors

Model development effort is a challenging task currently on 3rd iteration:

- Have implemented new models on NEUT to better represent data
- Propagate uncertainties through weighting techniques ("reweighting") or by re-running the MC in a limited fashion (FSI)
- No perfect model yet, and outstanding questions remain, but uncertainties inflated or theoretical uncertainties added.

Kendall Mahn

Remaining differences between GENIE and NEUT

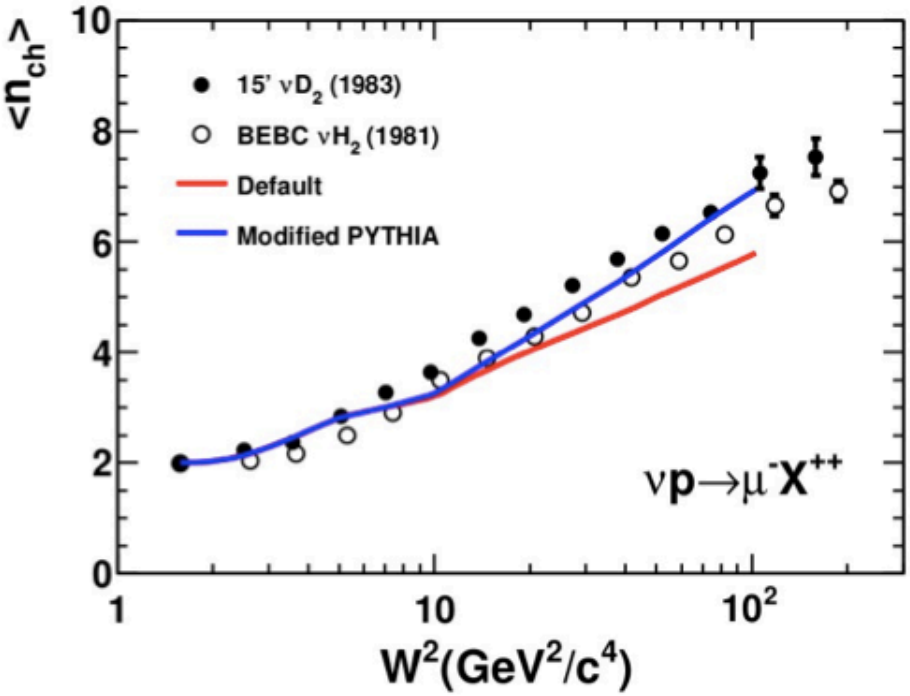
Outside of the position of the transition between resonant and DIS, there are other differences between GENIE and NEUT for deep inelastic interactions:

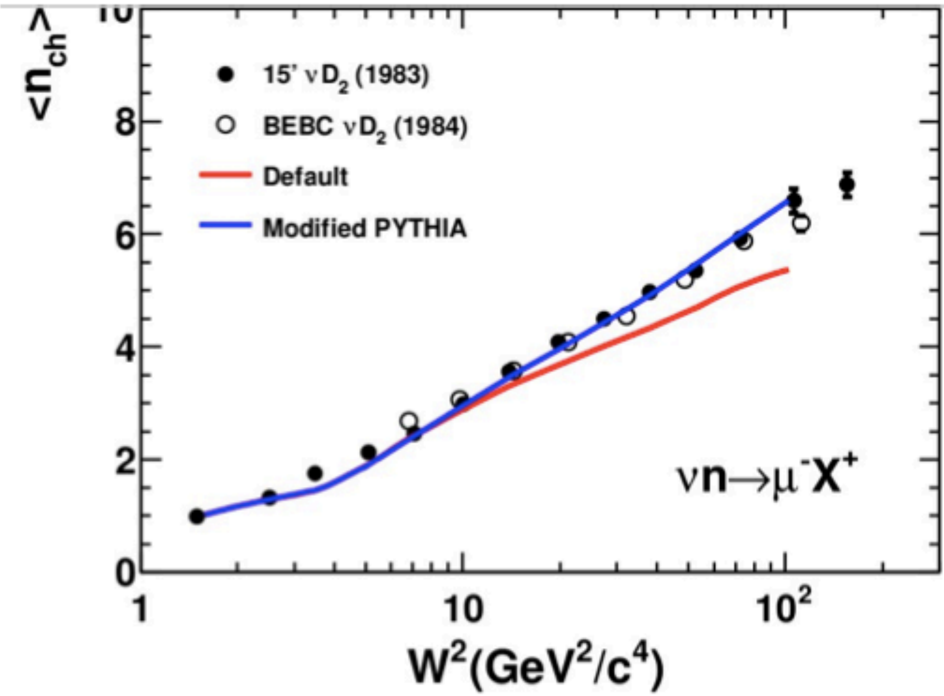
- For the low-W DIS modes, NEUT only produces nucleons and pions, while GENIE allows strange particle production (kaons and hyperons)
- The scheme to avoid double counting of events between resonant and deep-inelastic modes in the low W region is quite different
- For the high W DIS events, NEUT uses PYTHIA 5.72 and GENIE PYTHIA 6. Looking at putting PYTHIA 6 in NEUT
- Modification of the PDF due to nuclear effects (shadowing/anti-shadowing) implemented in GENIE but not in NEUT
- Model for the Fermi momentum is different in the two generators, GENIE uses the Bodek-Ritchie model which gives an high momentum tail

Christophe Bronner

Tuning of charged hadron multiplicities in PYTHIA

Tuned PYTHIA parameters using expertise from members of the HERMES collaboration
Allows to properly reproduce average charged hadron multiplicities when tested in GENIE:





Also found some difficulties:
- ➔ dispersion of the charged hadron multiplicities
- ➔ neutral hadron multiplicities
  "Further tuning is ongoing"

T. Katori, S. Mandalia
arxiv: 1412.4301v3

Summary

- Modeling of the deep-inelastic interactions in GENIE and NEUT differ in the way they deal with the transition region between resonant and DIS models
- At low W, the generators use custom models, and PYTHIA at higher W
- Update of NEUT code (and a fix in GENIE) ongoing, after that the generators should agree for the global kinematic variables W and Q^2 <u>for free nucleons</u>
- Discussed some possible sources of systematic uncertainties:
  - Corrections by Bodek and Yang for low Q^2 region
  - relation between the structure functions
  - multiplicities of the charged hadrons

Christophe Bronner

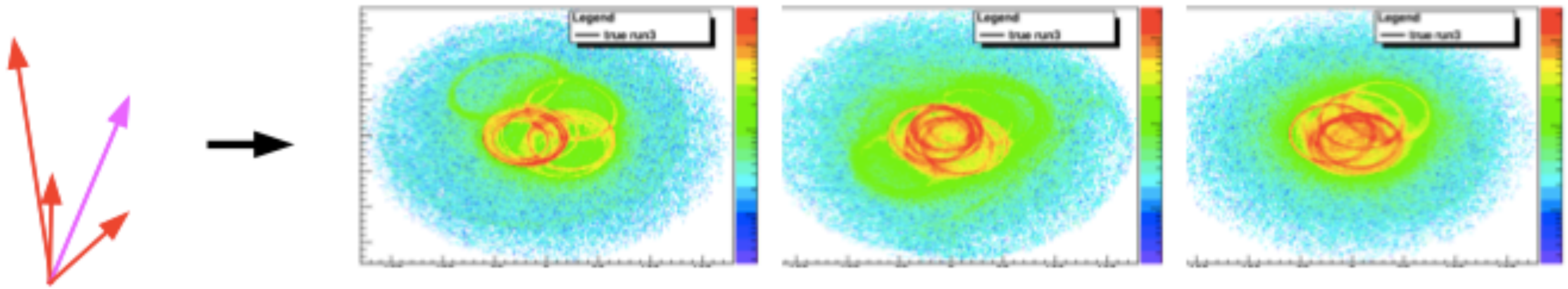
Sources of Fluctuations

Jannik Hofestädt

- **'hadronic state'** = composition of particle type and momenta

composition 1 composition 2 composition 3

- **'propagation'** = cascade evolution (= random number seed)



propagation 1 propagation 2 propagation 3

- Simulating many different 'hadronic state' with many different random seeds ('propagation') → separate effects

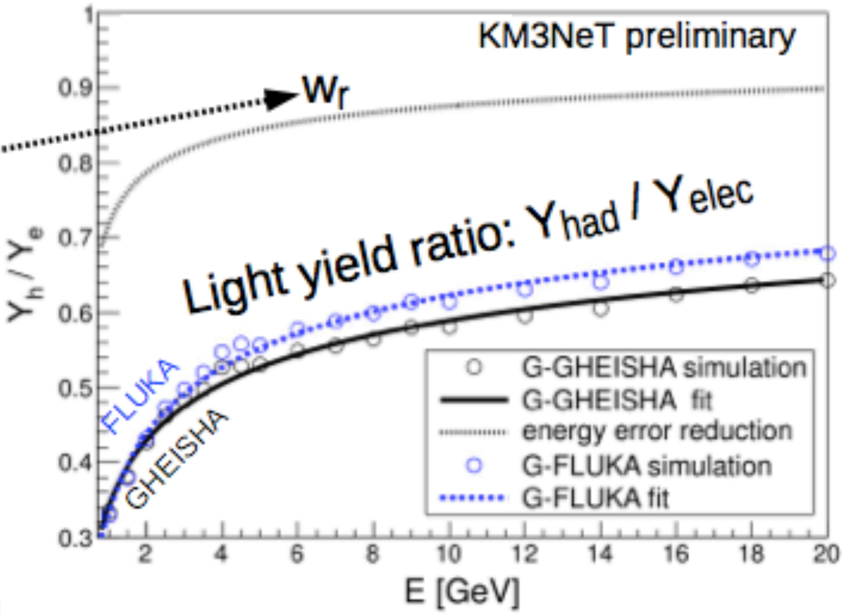
- **'photon sampling'** = number N_γ of detected photons → $\sigma_N \propto \sqrt{N}$

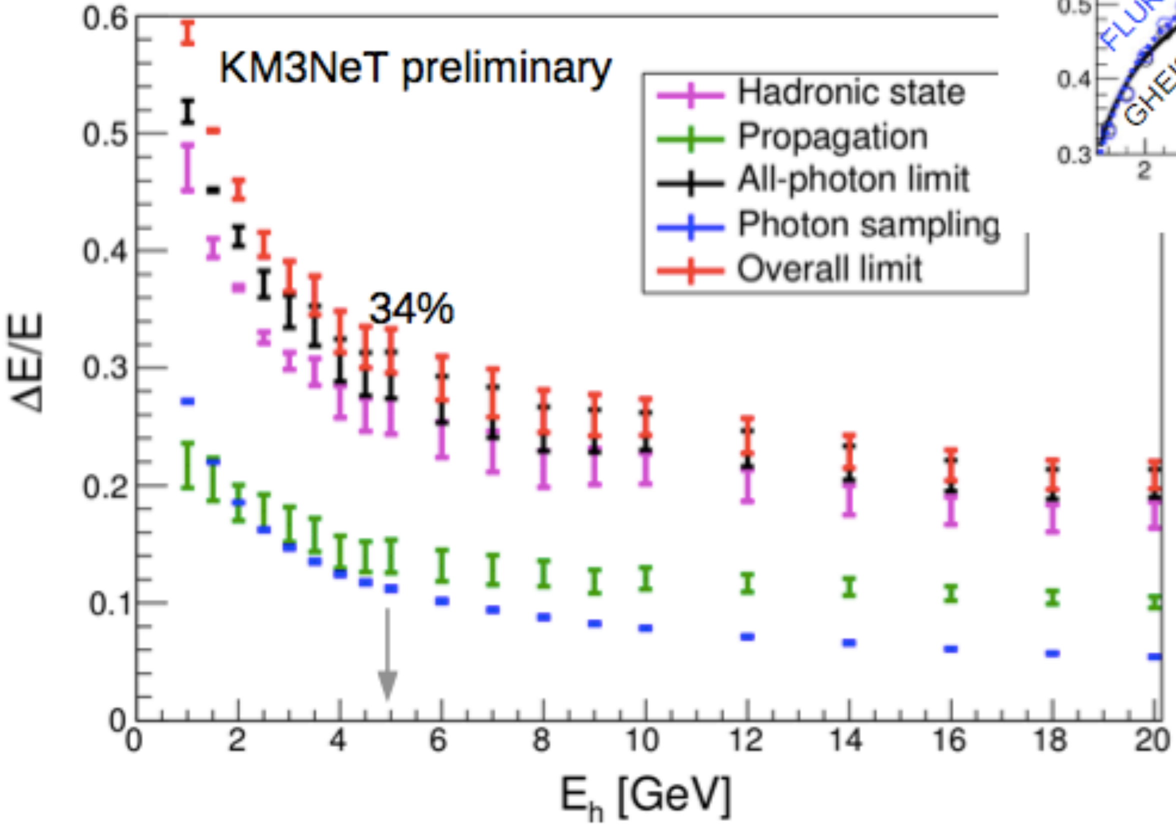
Hadronic Cascade: Energy Resolution

- N_γ scales faster than linear with E_h
  → relative error reduction factor w_r

$$\frac{\Delta E}{E} = \frac{\Delta N_\gamma}{N_\gamma} * w_r$$

- Here: ΔE = RMS





- **Light yield fluctuations dominated by hadronic sate**
  → event generator

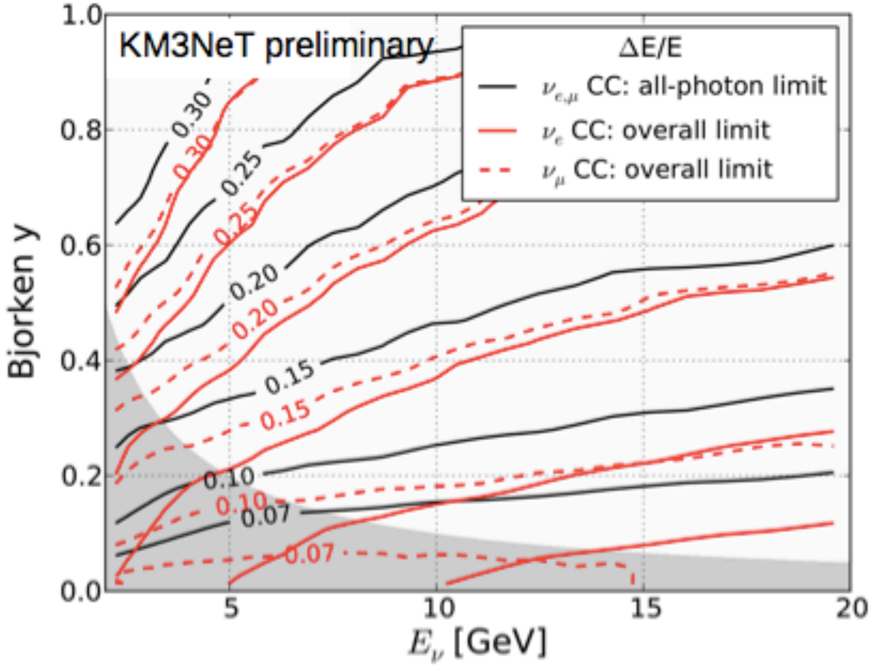
Jannik Hofestädt

ν_e & ν_e CC Resolutions (E, y)

$$y = 1 - E_l / E_\nu$$

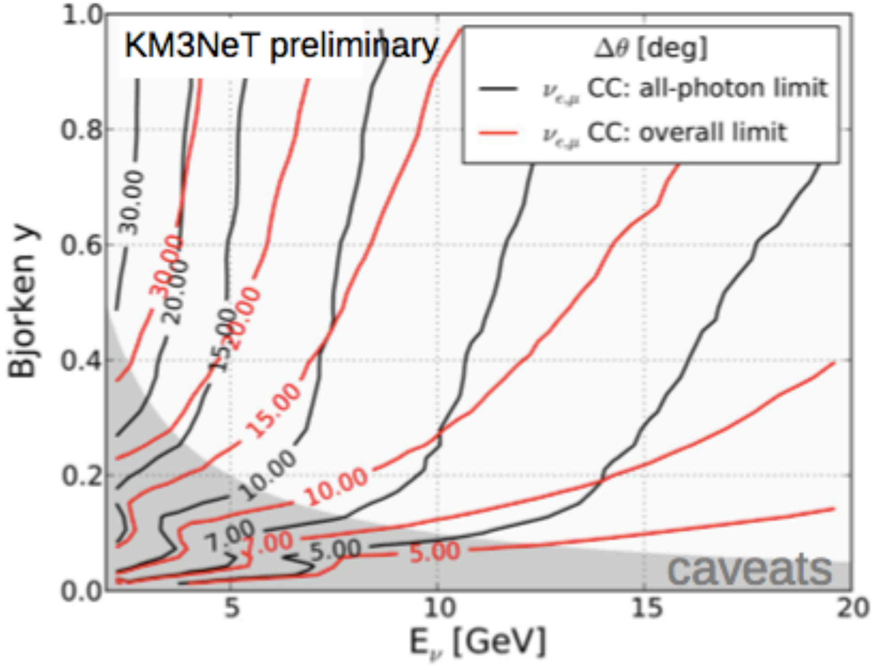
$$\frac{\Delta E}{E}$$

$$E_\nu^{reco} = E_l^{reco} + E_h^{reco}$$



$$\Delta\theta$$

$$\vec{u}_\nu^{reco} = E_l^{reco}\,\vec{u}_l^{reco} + E_h^{reco}\,\vec{u}_h^{reco}$$



- nearly identical for ν_e & ν_μ, as dominated by had. cascade fluctuation
- ΔE limited by intrinsic fluctuations, Δθ limited by detected photon statitsics
- ΔE ↔ Δθ strongly correlated via Bjorken y (= interaction inelasticity)

Jannik Hofestädt

Summary

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

- Derived limiting energy & direction resolutions
  for (isolated) hadronic cascades / muons / electrons
  and combined these to $\nu_{e,\mu}$ CC events

- Neutrino resolutions dominated by large intrinsic errors in had. cascade
  - direction resolution dominated by detected photon statistics
  - energy resolution dictated by fluctuations due to different 'hadronic states'
  - similar interaction physics in ice → expect very similar effects for PINGU
    (but different direction reco effects)
- ORCA resolutions relatively close to these intrinsic limits
  → **'neutrino generator physics' matters !!!**

- Outlook:
  - Paper in preparation
  - Study effect of different neutrino generators
  - What is PMT density 'threshold' for identifying had. cascade substructure?
    → gain in resolution?

Jannik Hofestädt

Many areas of common interest also with HyperK

Fruitful discussions and new connections

Follow-up encouraged!