The Physics Case For a Short Baseline Beam at CERN

Cross-Section Measurements and BSM Physics

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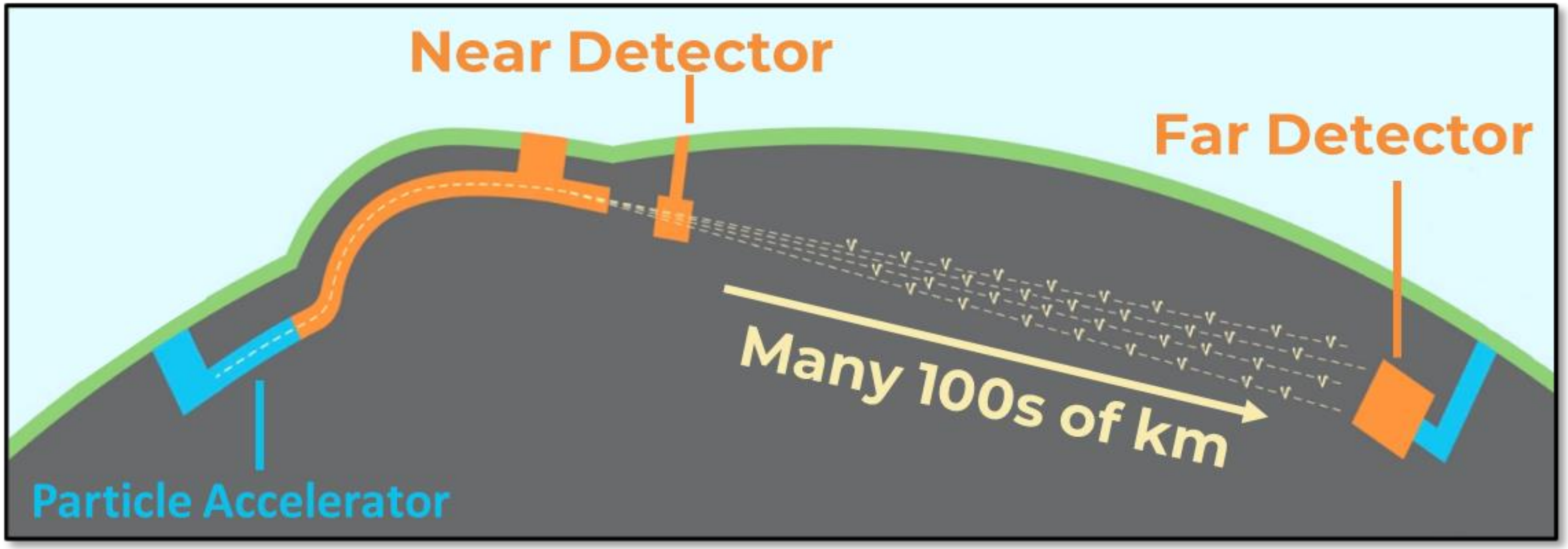
Oscillation experiments



$$N_\ell(E_\nu) \propto P(\nu_\mu \to \nu_\ell)(E_\nu)\, \sigma(E_\nu)\, \Phi_\nu(E_\nu)\, \epsilon(E_\nu)$$

- **Far detector event rate** — $N_\ell(E_\nu)$
- **Oscillation Probability** — $P(\nu_\mu \to \nu_\ell)(E_\nu)$
- **Interaction Cross Section** — $\sigma(E_\nu)$
- **Incoming neutrino flux** — $\Phi_\nu(E_\nu)$
- **Detector Efficiency** — $\epsilon(E_\nu)$

Why do we care about systematics?

Current long-baseline experiments

	T2K	NOvA
Baseline	295 km	800 km
N_{μ}^{rec} (ν-mode)	318	384
N_{e}^{rec} (ν−mode)	94	181

$$N_{\ell}(E_{\nu}) \propto P(\nu_{\mu} \rightarrow \nu_{\ell})(E_{\nu})\, \sigma(E_{\nu})\, \Phi_{\nu}(E_{\nu})\, \epsilon(E_{\nu})$$

Far detector event rate

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NEUTRINO 2024

Current systematic uncertainties

Uncertainty on N_e^{rec}	T2K	NOvA
All Syst.	**~5%**	**~3.5%**

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Far detector event rate

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Incoming neutrino flux

Detector Efficiency

Why do we care about $\sigma(E_\nu)$?

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Current systematic uncertainties

Uncertainty on N_e^{rec}	T2K	NOvA
Cross Sections	**~4%**	**~3.5%**
All Syst.	**~5%**	**~3.5%**

$$N_\ell(E_\nu) \propto P(\nu_\mu \rightarrow \nu_\ell)(E_\nu)\, \boldsymbol{\sigma}(E_\nu)\, \Phi_\nu(E_\nu)\, \epsilon(E_\nu)$$

Far detector event rate

Interaction Cross Section

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Cross Sections	**~4%**	**~3.5%**
All Syst.	**~5%**	**~3.5%**

😱 Large contribution to syst. uncertainties from cross-section modelling

😅 Syst. uncertainties remains small compared to stat. uncertainties

Why do we care about $\sigma(E_\nu)$?

Future long-baseline experiments

	Hyper-K	DUNE
	arXiv:1805.04163	*arXiv:2002.03005*
Baseline	295 km	1300 km
N_μ^{rec} (ν-mode)	~10000	~7000
N_e^{rec} (ν−mode)	~2000	~1500

Current systematic uncertainties

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Cross Sections	**~4%**	**~3.5%**
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Why do we care about $\sigma(E_\nu)$?

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Cross Sections	**~4%**	**~3.5%**
All Syst.	**~5%**	**~3.5%**

😱 Large contribution to syst. uncertainties from cross-section modelling

😱 Current syst. uncertainties are larger than projected stat. uncertainties

➡ Improved understanding of neutrino interactions is necessary to avoid being prematurely limited by syst. uncertainties

Why do we care about $\sigma(E_\nu)$?

Future long-baseline experiments

Current systematic uncertainties

To extract the most physics from DUNE and Hyper-Kamiokande, a complementary programme of experimentation to determine neutrino cross-sections and fluxes is required. Several experiments aimed at determining neutrino fluxes exist worldwide. The possible implementation and impact of a facility to measure neutrino cross-sections at the percent level should continue to be studied. Other important complementary experiments are in preparation .... The design studies for next-generation long-baseline neutrino facilities should continue.

DELIBERATION DOCUMENT
ON THE 2020 UPDATE OF THE EUROPEAN STRATEGY
FOR PARTICLE PHYSICS

Talk by M. Perrin-Terrin

Large contribution to syst. uncertainties from cross-section modelling

A dedicated study should be set-up to evaluate the possible implementation, performance and impact of a percent-level electron and muon neutrino cross-section measurement facility (based on e.g. ENUBET or nSTORM) with conclusion in a few years time.

Improved understanding of neutrino interactions is necessary to avoid being prematurely limitation by syst. uncertainties

What do we need to know about neutrino interactions?

Four things we need to model

(a non exhaustive list)

1. The energy dependence of neutrino cross sections
   - *So we know how to extrapolate from our near to far detectors*

Please find a detailed justification in the backup slides

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How are we doing?

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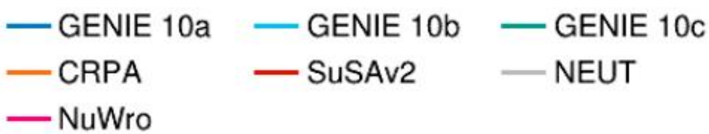
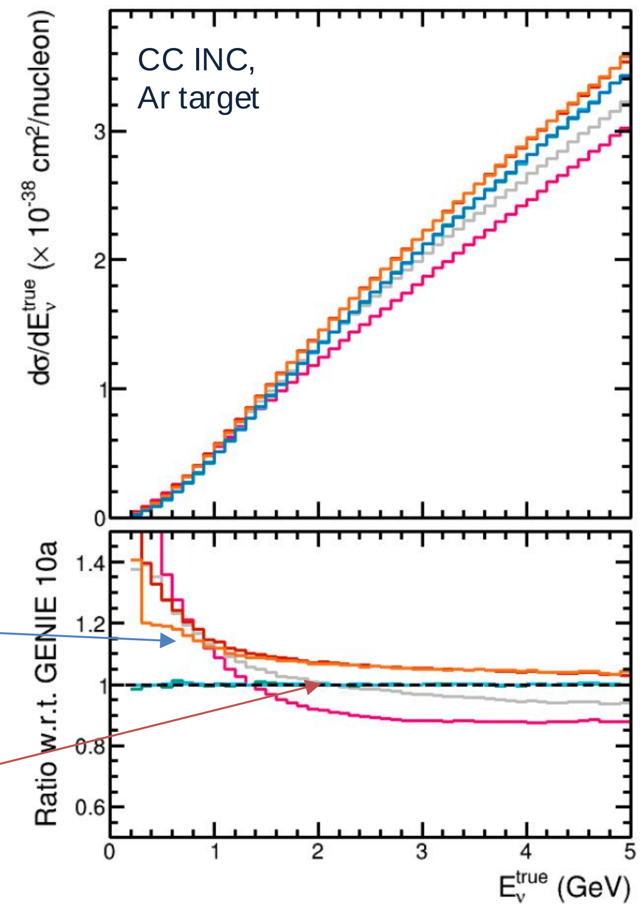


State-of-the-art generators

show **significant (~20%) differences in the cross section** in key regions and on its evolution with E_ν

For Hyper-K

For DUNE



How are we doing?

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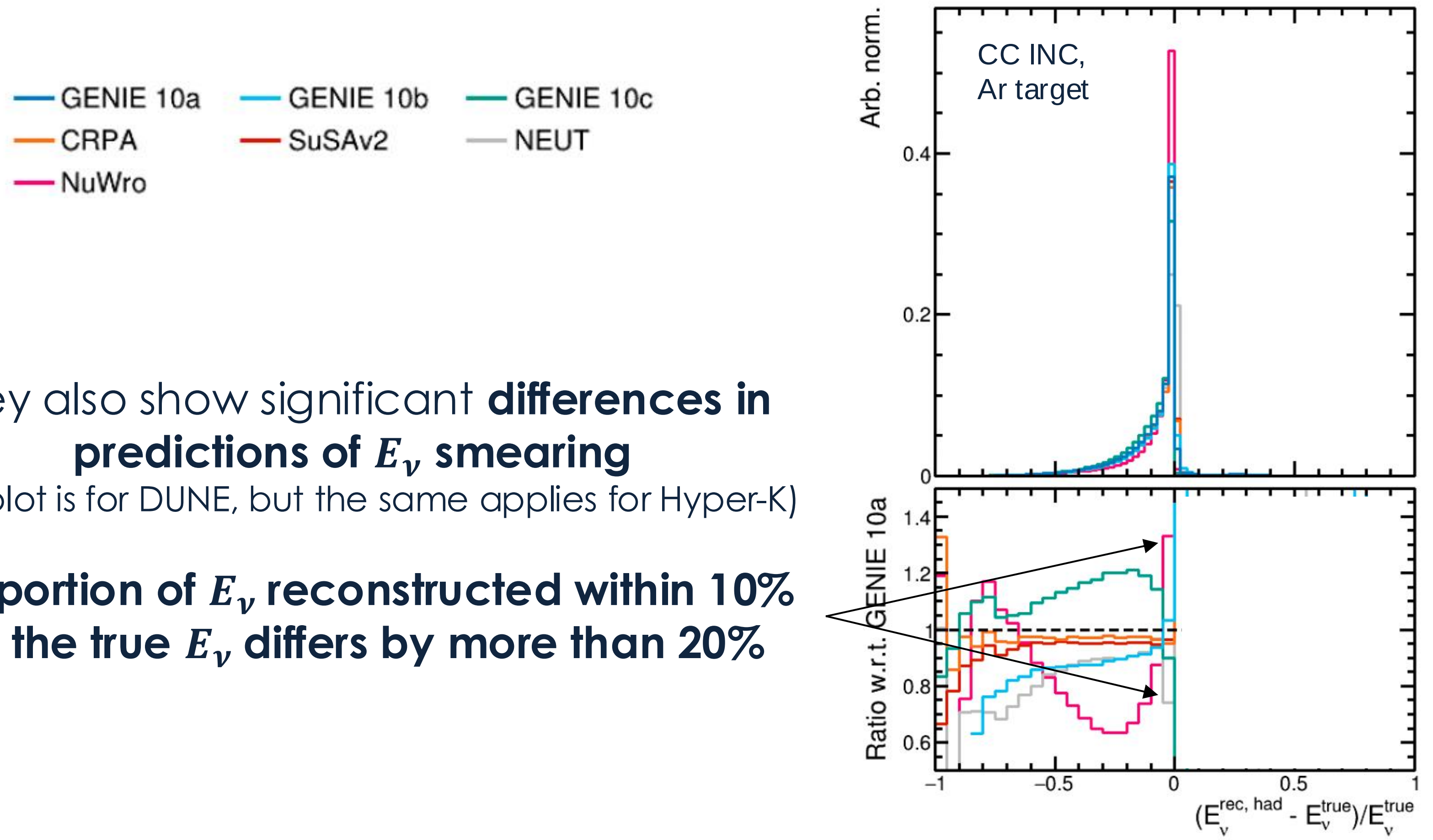
   - *So we can infer the shape of the oscillated spectrum*

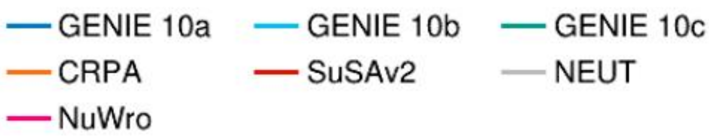


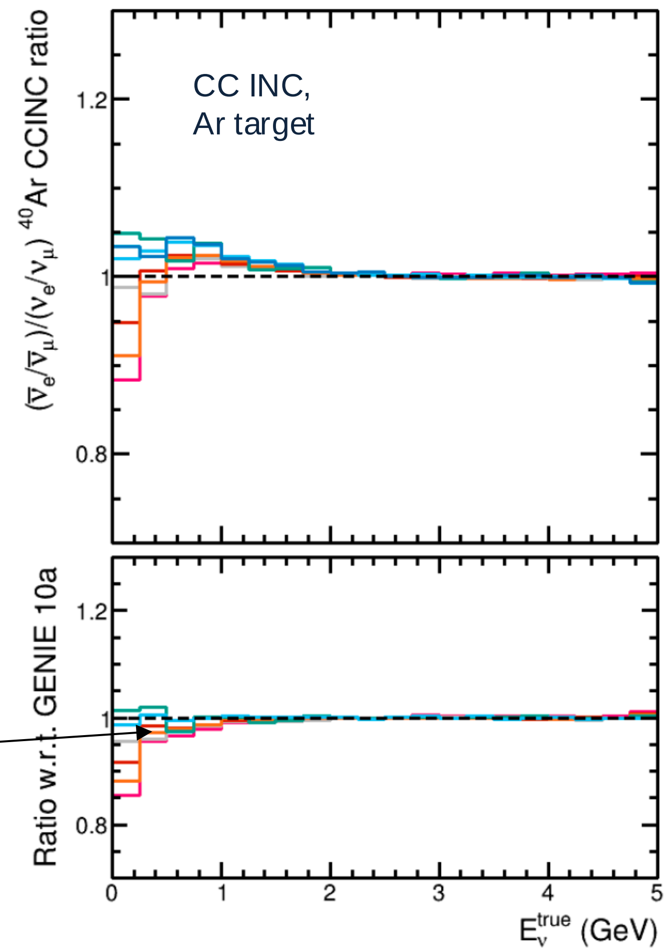
They also show significant **differences in predictions of E_ν smearing**
(This plot is for DUNE, but the same applies for Hyper-K)

Proportion of E_ν reconstructed within 10% of the true E_ν differs by more than 20%

How are we doing?

3. Differences in the cross section for ν_e/ν_μ (and $\nu/\bar{\nu}$)
    - *So we can use ν_e appearance to probe CP-violation*



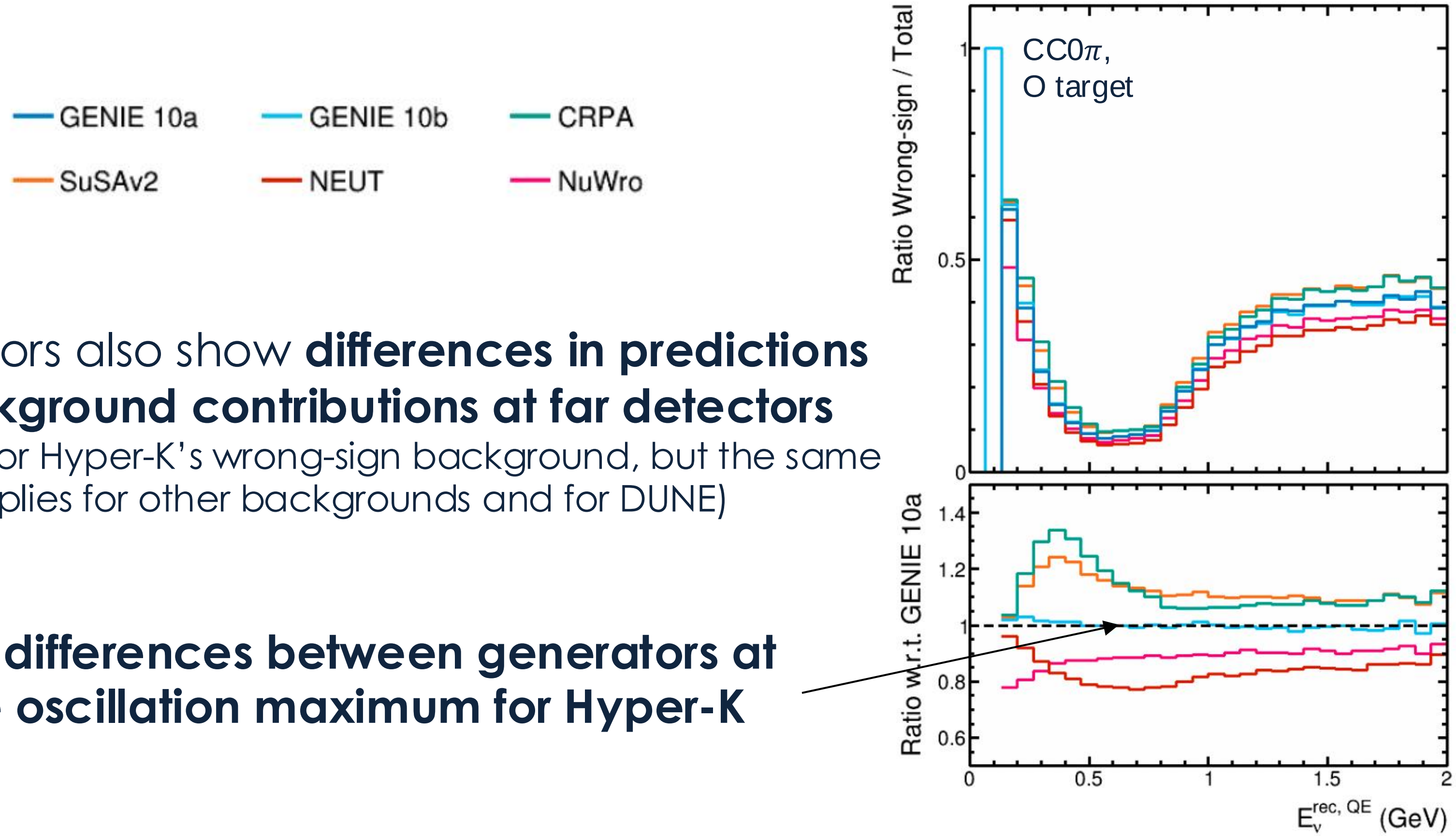


And on ν_e/ν_μ **differences at low E_ν**

Predictions of the double ratio differ by more than 3% at Hyper-K's oscillation maxima

How are we doing?

4. Backgrounds to what we see at the far detector (e.g. NCπ^0)
   - *So we know how to interpret far detector event rates*



Generators also show **differences in predictions of background contributions at far detectors**
(This plot is for Hyper-K's wrong-sign background, but the same applies for other backgrounds and for DUNE)

20% differences between generators at the oscillation maximum for Hyper-K


KEEP CALM
AND
MEASURE dσ/dx

Current cross-section measurements

- Vibrant cross-section measurement program to constrain cross-section uncertainties

- Today's measurements are reaching a very high statistical precision

(many millions of events!)

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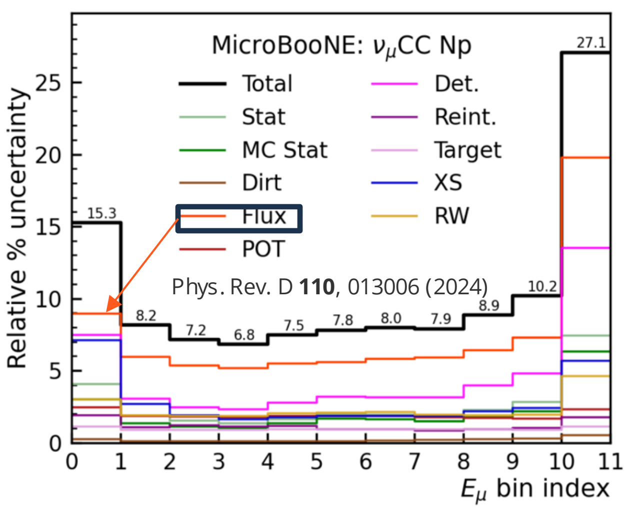
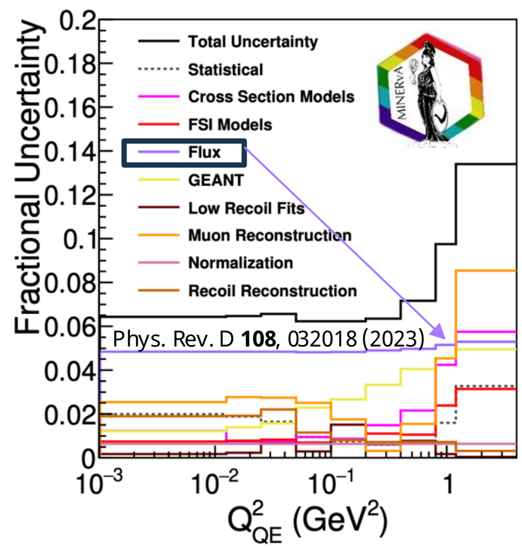
- Vibrant cross-section measurement program to constrain cross-section uncertainties

- Today's measurements are reaching a very high statistical precision (many millions of events!)
- But suffer from systematic uncertainties, often dominated by the flux

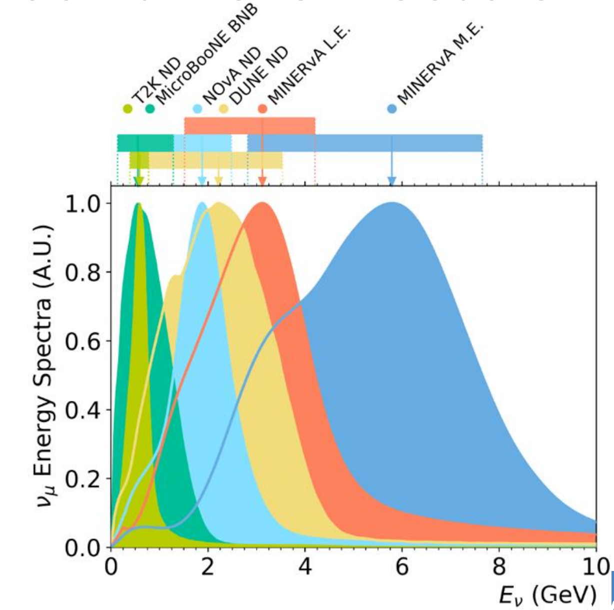




Current cross-section measurements

- Vibrant cross-section measurement program to constrain cross-section uncertainties

- Today's measurements are reaching a very high statistical precision
  (many millions of events!)
- And broad-band beams make measurements hard to interpret



Current cross-section measurements

- Vibrant cross-section measurement program to constrain cross-section uncertainties

T2K

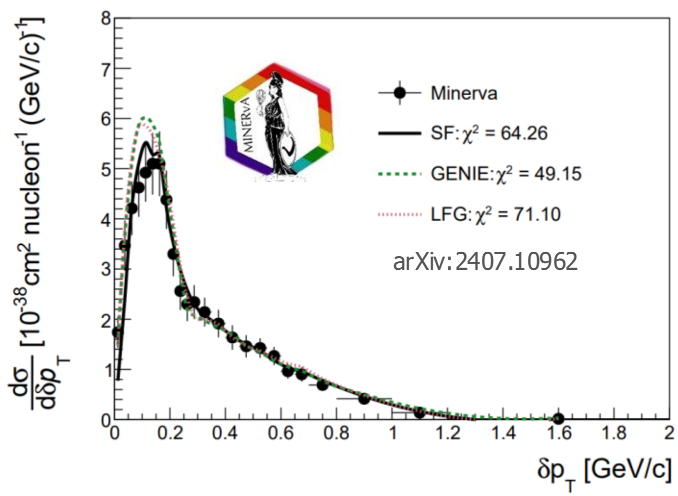
NOvA

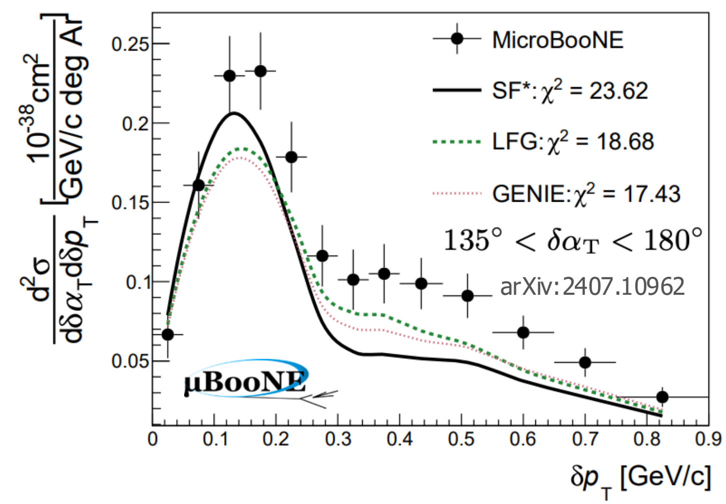
e4v

μBooNE

MINERvA

- Today's measurements are reaching a very high statistical precision (many millions of events!)
- So whilst plenty of measurements show our models are wrong …





Current cross-section measurements

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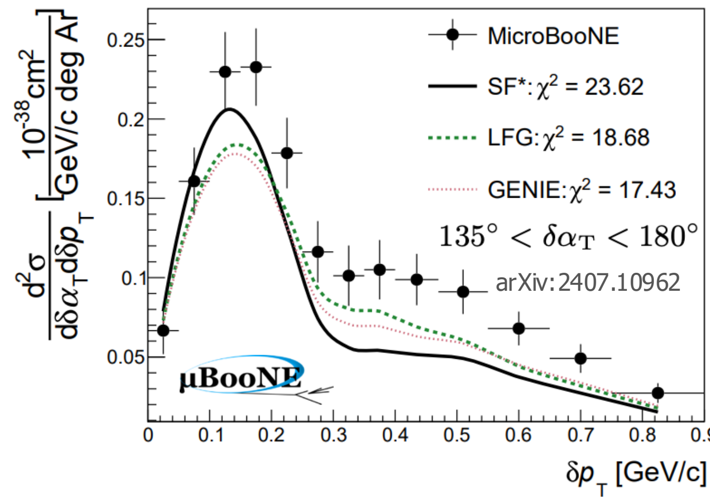
T2K μBooNE NOvA MINERvA e4ν

- Today's measurements are reaching a very high statistical precision (many millions of events!)
- So whilst plenty of measurements show our models are wrong …
- … they don't tell us why …



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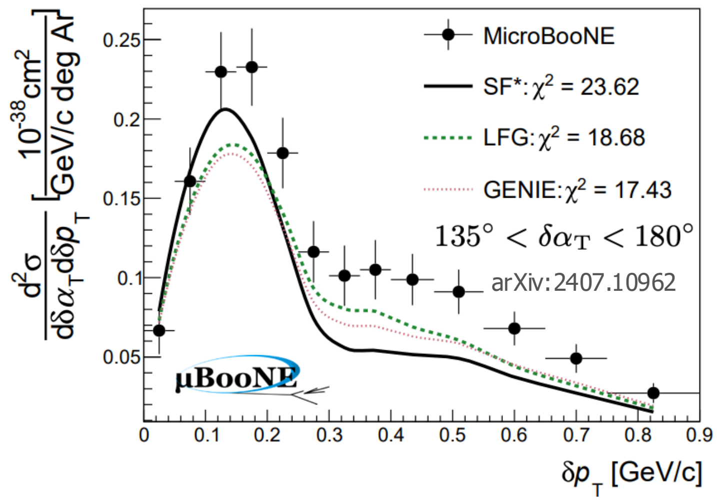
Another crucial gap: no experiment is well positioned to measure cross sections at DUNE energies on Ar



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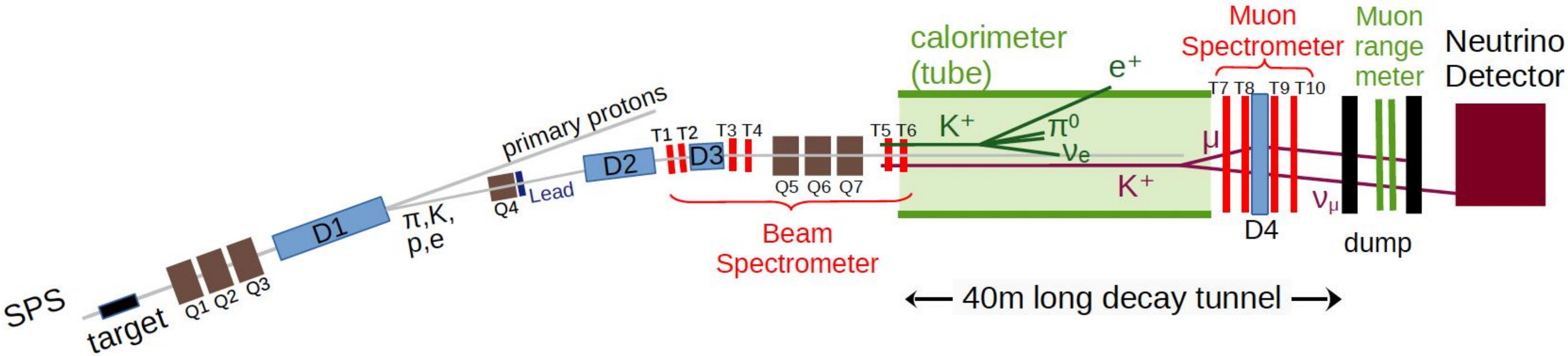
A short baseline experiment with a monitored neutrino beam offers a unique opportunity to tackle this!

A short baseline monitored & tagged neutrino beam at CERN

SBN@CERN: a monitored & tagged beam



- **Instrument decay tube** to measure charged leptons from neutrino parent-meson decays → in-situ flux measurement → **%-level uncertainties**

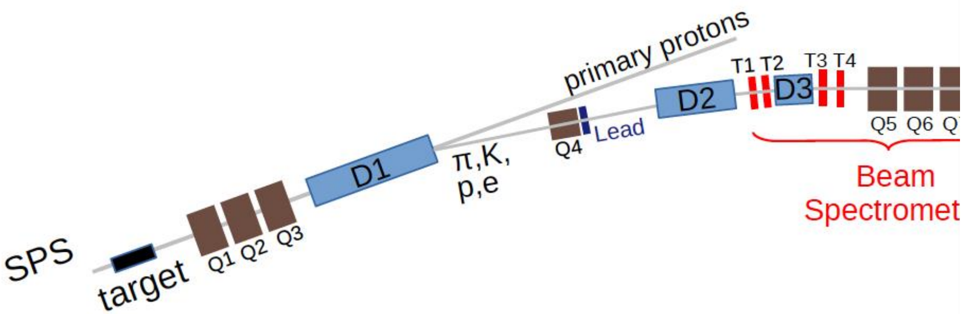
See talk from A. Longhin
Eur. Phys. J. C 83 (2023) 10, 964

- Also **tag neutrino interactions** in the detector to their parent's decay products → **know neutrino energy event-by-event**

See talk from M. Perrin-Terrin *Eur. Phys. J. C* 84 (2024) 10, 1024

- A merge of ***ENUBET*** and ***NuTag*** proposals
  - Employ pixel detectors & calorimeter in the decay tube

SBN@CERN: a monitored & tagged beam



Parameter	Value
Primary proton energy	400 GeV/c
Beamline momentum (mesons)	up to 8.5 GeV/c
Extraction type	Slow: 4.8s or 9.6s from the SPS
Spill intensity	1.0E13 protons/spill
Event rate	1 – 2 THz
Instantaneous power	170 – 340 W
K^+ / π^+ per proton	1.3E-3 / 1.9E-2
K^+ / π^+ rate	up to 2.7 GHz / 40 GHz
Annualized proton requirement	2E18 – 3E18 protons/year
Total proton requirement (1% stat. error on ν_e x-section)	1.4E19 PoT
Beamline length to decay tube	23 m
Bending magnet strength	1.8 T

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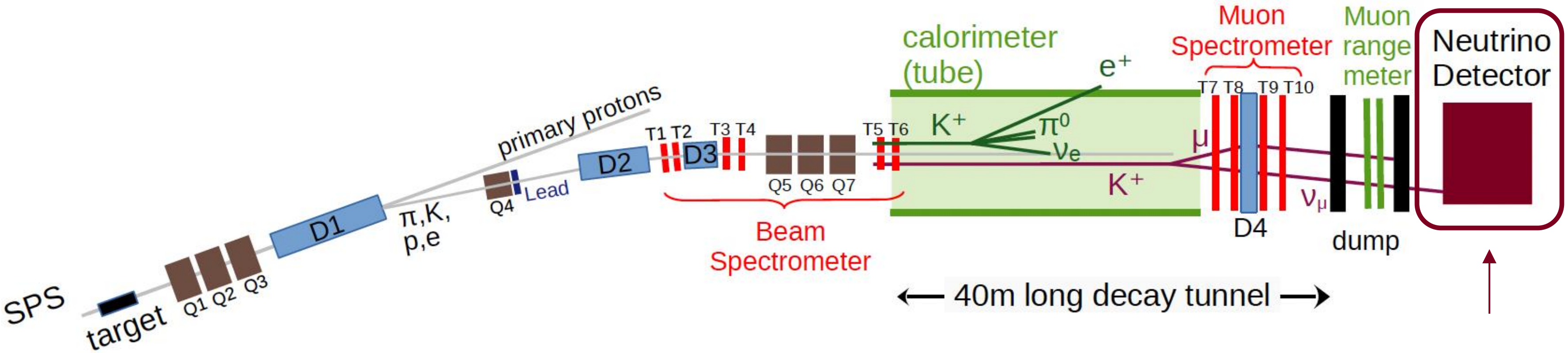
- Also **tag neutrino intera** decay products → **kno**

See talk from M. Perrin-Terrin *Eur.*

- A merge of ***ENUBET*** and ***NuTag*** proposals
  - Employ pixel detectors & calorimeter in the decay tube
- **The SPS beam** as the driver of the beamline has been identified **as the only feasible option at CERN** (see M. Jebramcik's talk)
  - Highly optimized beamline design for 400 GeV/c protons
- The beamline's meson production is maximized and the event rate is adjusted to meet the pile-up constraints of the NuTAG pixel detectors

SBN@CERN: a monitored & tagged beam



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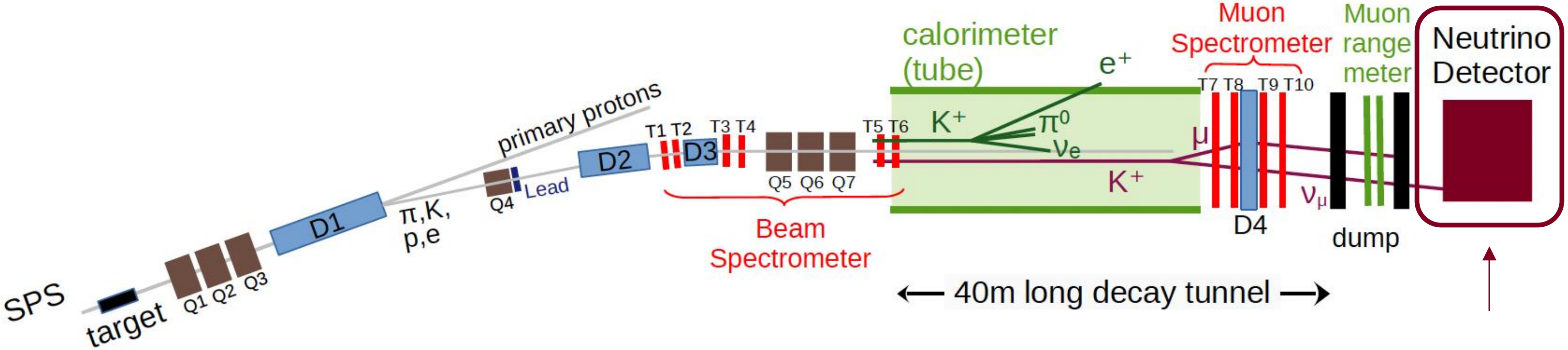
- A merge of ***ENUBET*** and ***NuTag*** proposals
  - Employ pixel detectors & calorimeter in the decay tube

- **The detector**: large, O or Ar based, very close to the decay tube (<50 m)
  - High statistics, relevant energies, relevant targets
  - Spans a very wide range of off-axis angles (3-6°): sample different ν-fluxes

SBN@CERN: a monitored & tagged beam



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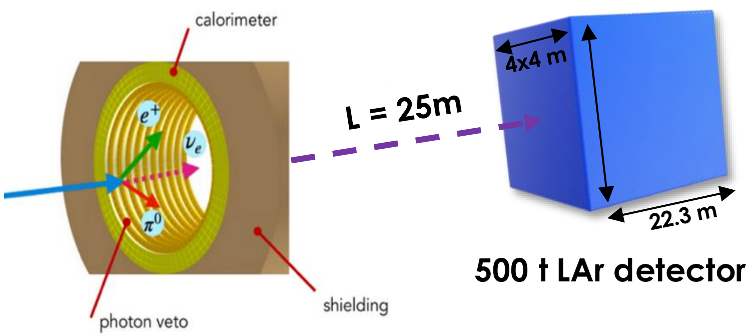
-

SBN@CERN combines a monitored & tagged beam!

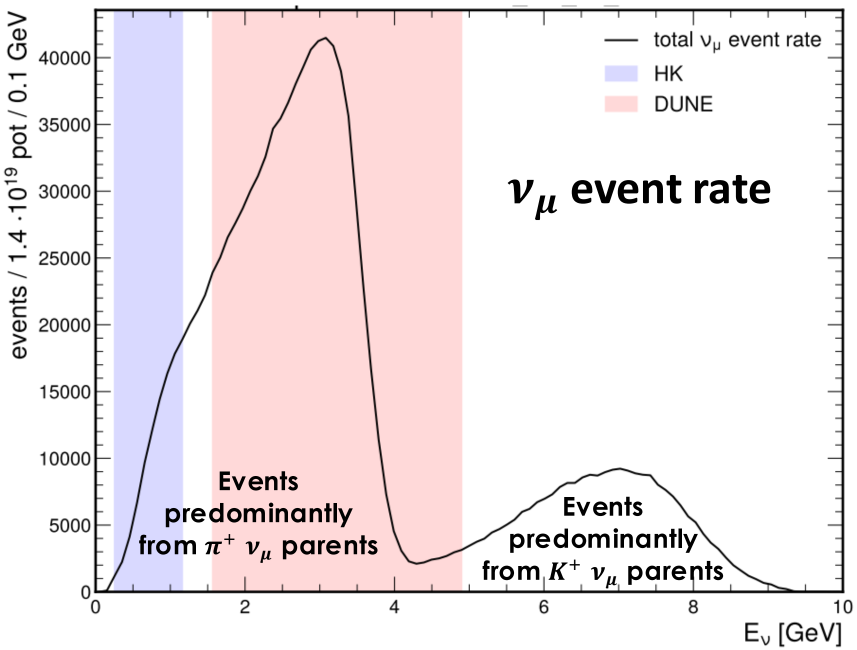
In the following slides we show performance studies, which focus on the physics reach of the monitored beam, before discussing what we gain from tagging

Reference set up

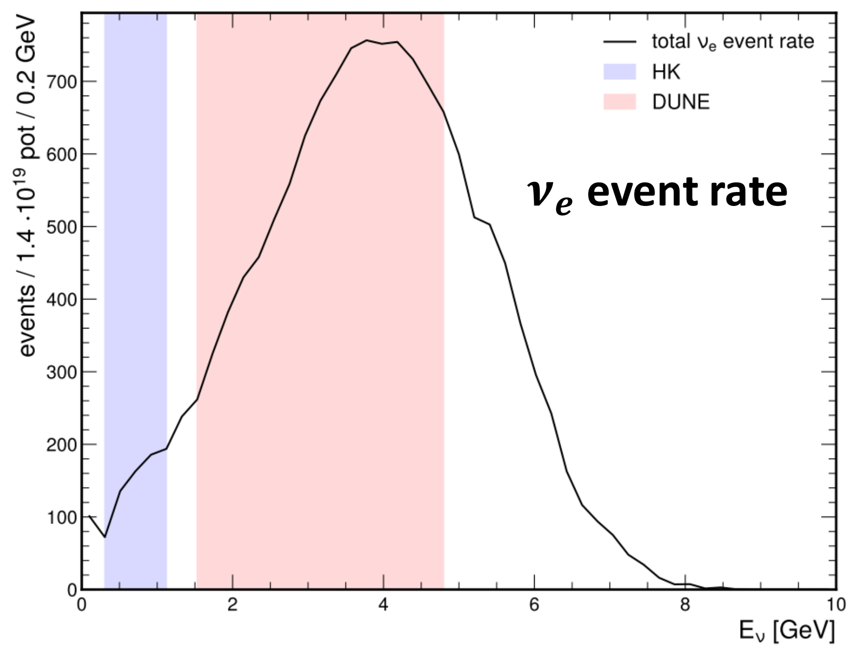
See talk from M. Andre Jebramcik for details



500 t LAr detector



- 8.5 GeV/c meson selection
- 500 ton LAr detector; 4x4 m^2 face; 22.3 m length; 25 m from tube
- Collect 1.4×10^{19} PoT in ~5 years:
  - ~1.2M ν_μ interactions
  - ~15k ν_e interactions
- Projected event spectra estimated using GENIE
- **Event spectra overlap well with Hyper-K and DUNE regions of interest**



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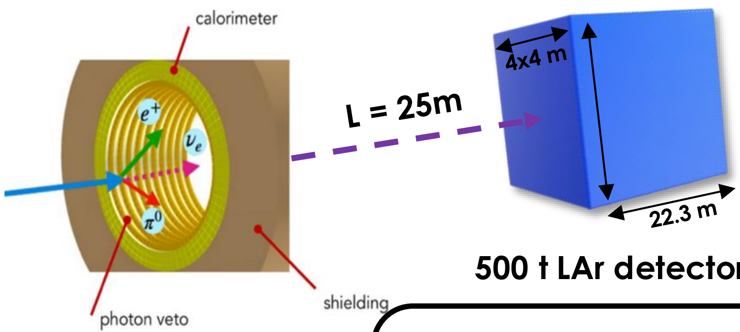

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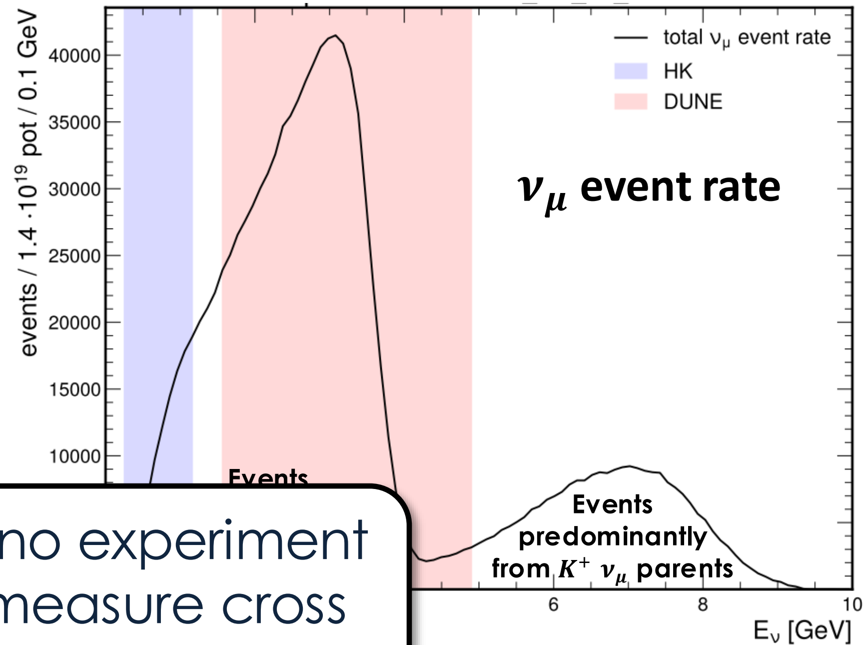

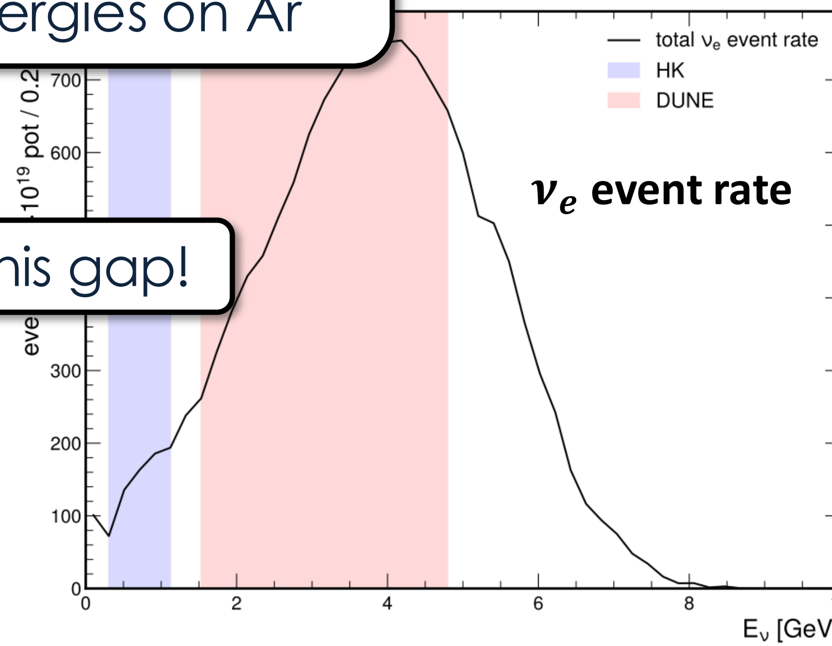

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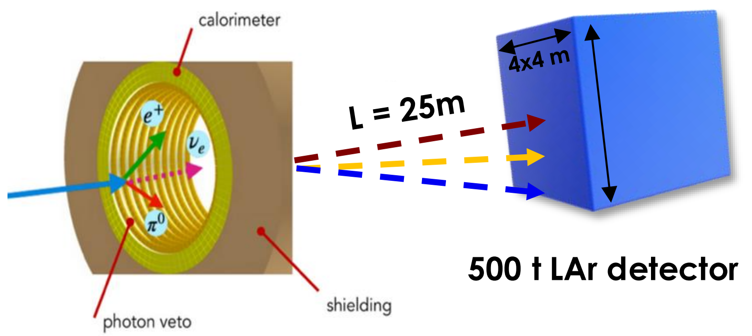
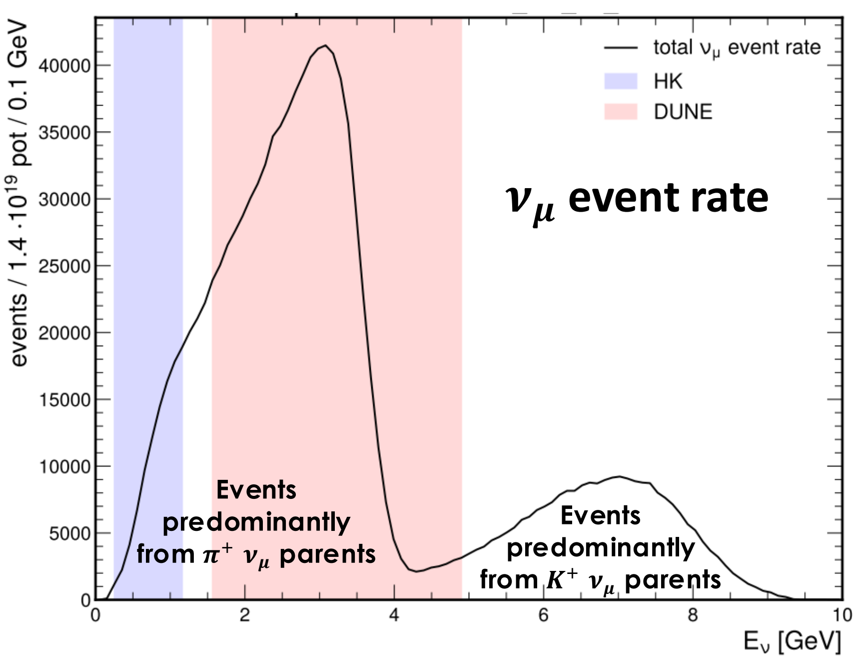
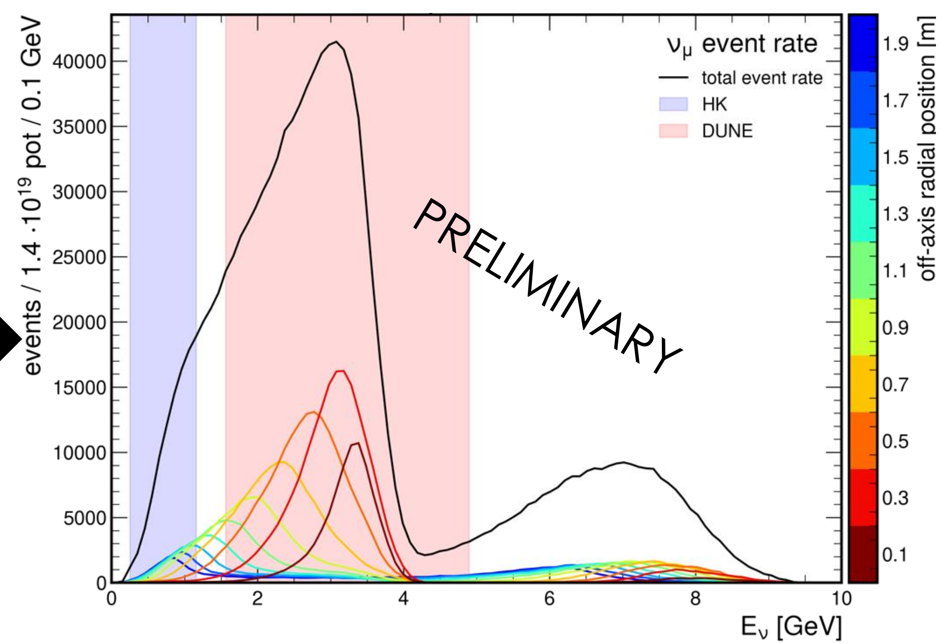
Narrow-band off-axis fluxes

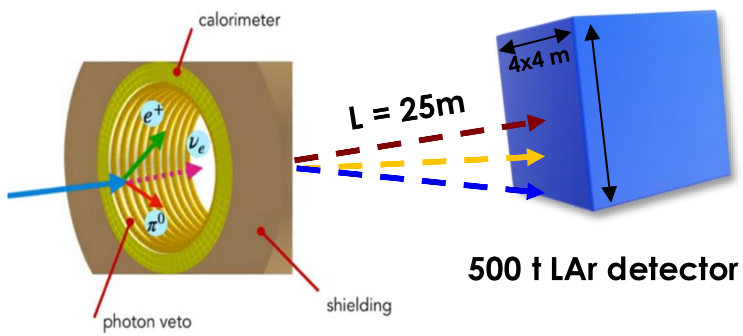


- Measure the ν_μ event rate in different 20 cm radial slides
- Probes different off-axis angles (0-4.5°)
- Accesses different energy spectra





Constraining energy dependence



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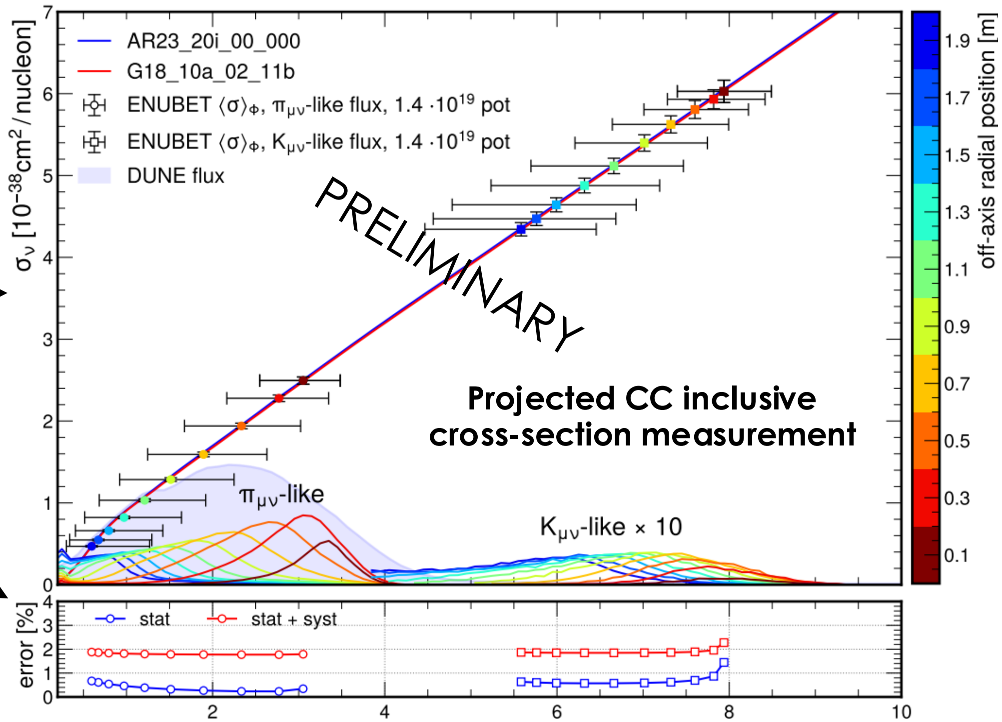
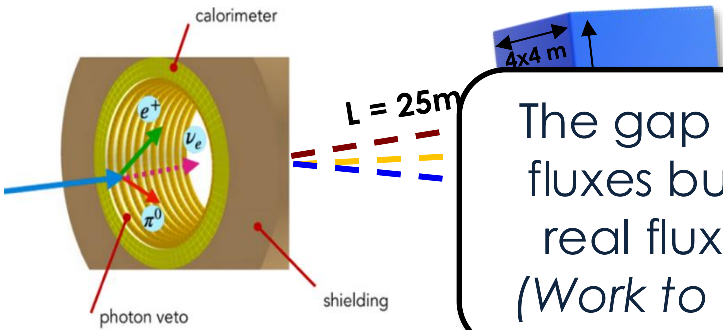
- Measure cross-section at each different off-axis angle
- **Directly measure the energy dependence of cross sections**
  - From ~0.6 - 8 GeV
- Project %-level uncertainties thanks to beam monitoring
- Crucial model validation for DUNE (and Hyper-K)



Bin width represents flux width (as 68% quartiles from flux mean)

Constraining energy dependence



- Measure the ν_μ event rate in different 20 cm radial slides

angles (0-4.5°)

ectra

The gap here may be filled in by virtual fluxes built from linear combinations of real fluxes using the PRISM technique
(Work to demonstrate this is in progress)

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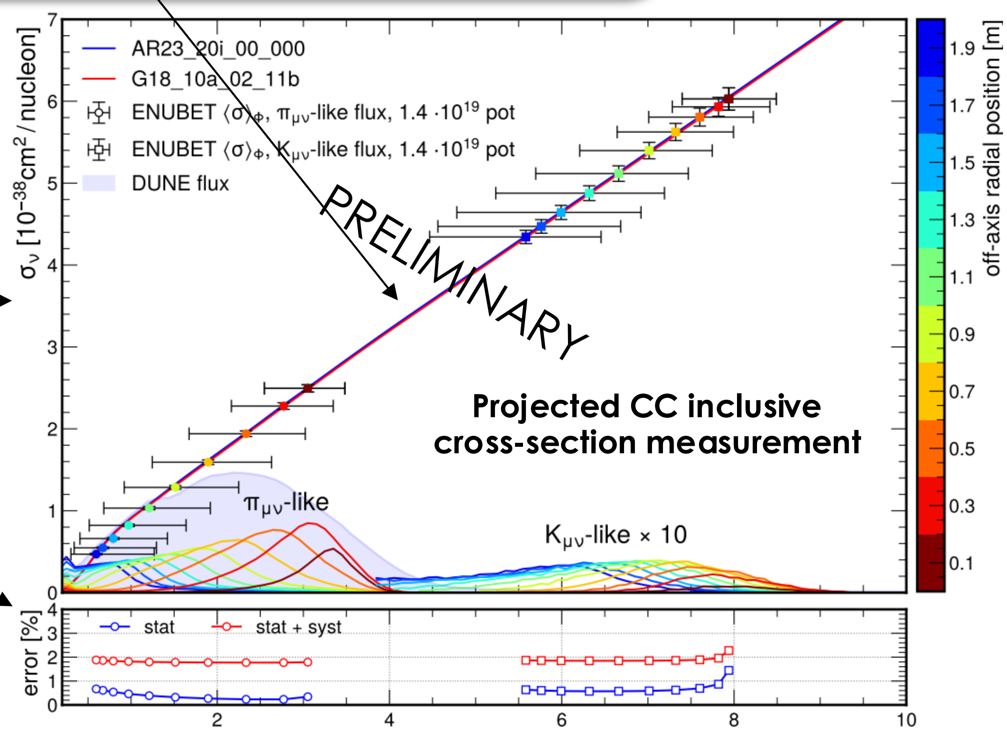
  - From ~0.6 - 8 GeV
- Project %-level uncertainties thanks to beam monitoring
- Crucial model validation for DUNE (and Hyper-K)



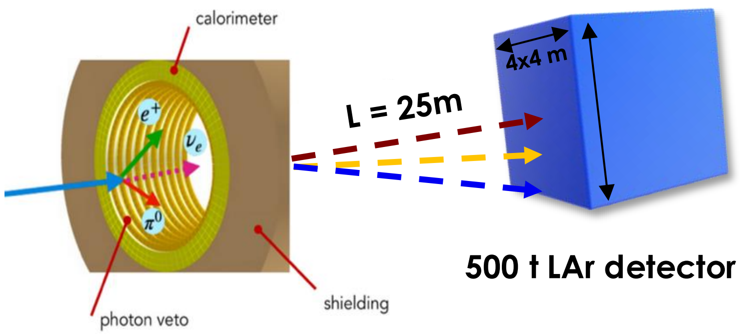
Bin width represents flux width (as 68% quartiles from flux mean)

Four things we need to model

(a non exhaustive list)

1. The energy dependence of neutrino cross sections
   - *So we know how to extrapolate from our near to far detectors*
2. The smearing of our neutrino energy reconstruction
   - *So we can infer the shape of the oscillated spectrum*
3. Differences in the cross section for ν_e/ν_μ (and $\nu/\bar{\nu}$)
   - *So we can use ν_e appearance to probe CP-violation*
4. Backgrounds to what we see at the far detector (e.g. NCπ^0)
   - *So we know how to interpret far detector event rates*

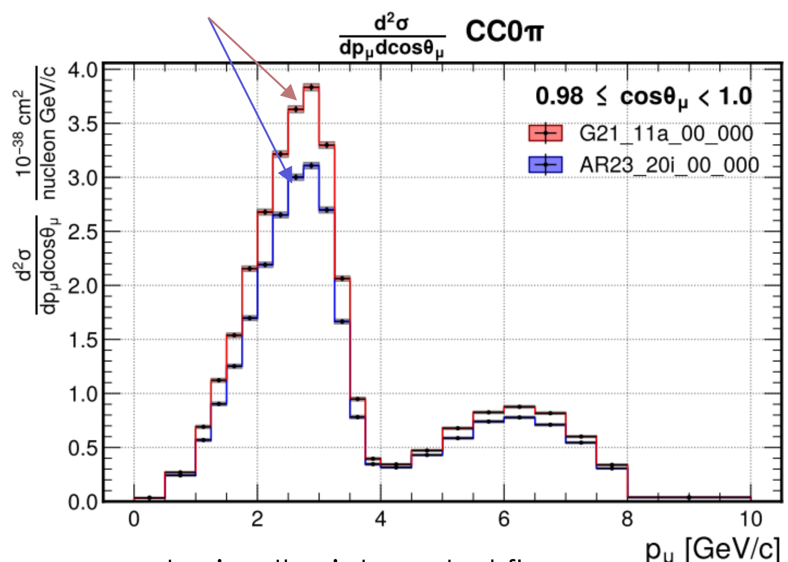
Constraining energy smearing

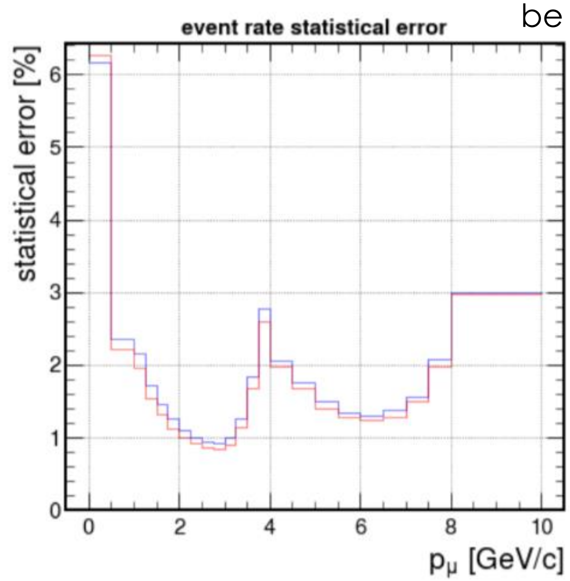


- Can make differential cross-section measurements at different off-axis angles
- Allows a profound exploration of cross-section modelling, can get at the physics responsible for neutrino energy smearing
- Expect %-level statistical uncertainties
- The monitored beam prevents syst uncertainties dominating

Without this, the measurement would be systematics limited

Measurement projection offers clear separation between these two different GENIE simulations





Plots show a measurement using the integrated flux

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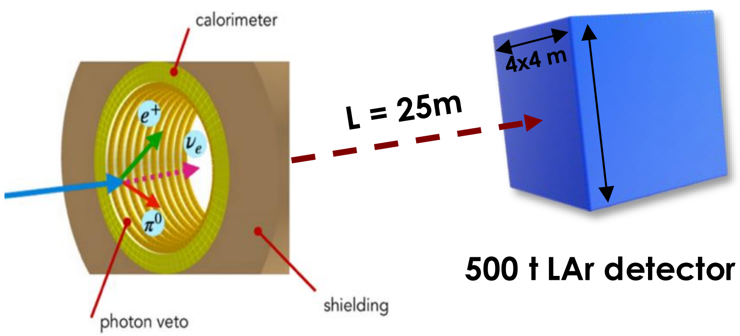
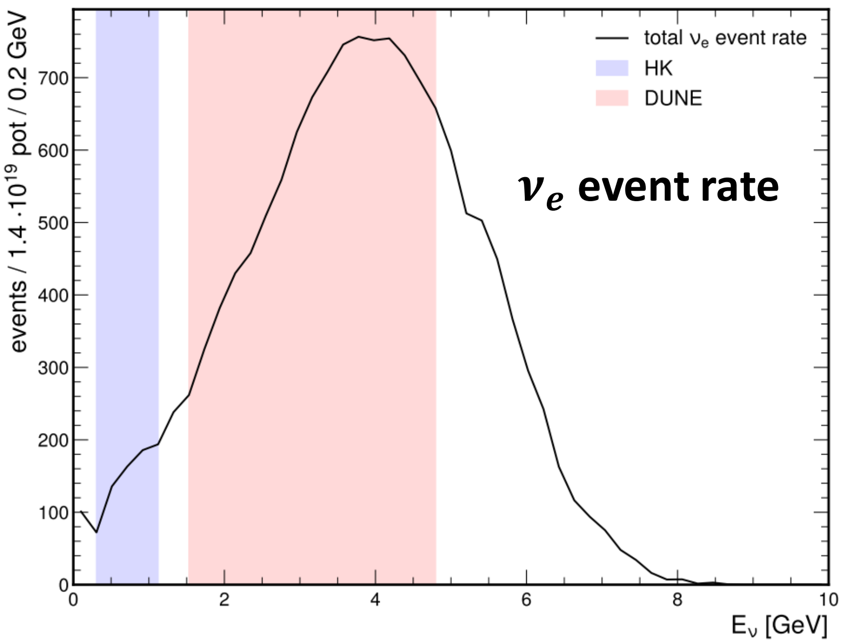
Constraining ν_e/ν_μ



- ~15k ν_e interactions is sufficient for a %-level cross-section measurement
  - Monitored beam is essential to control systematics



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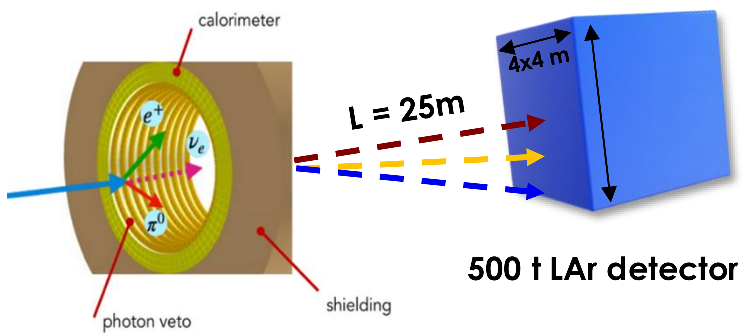

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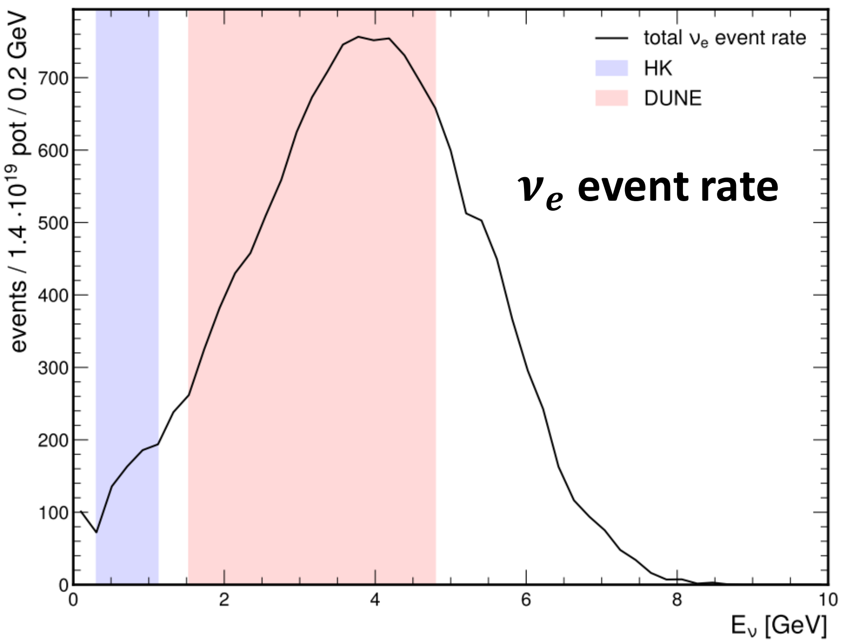

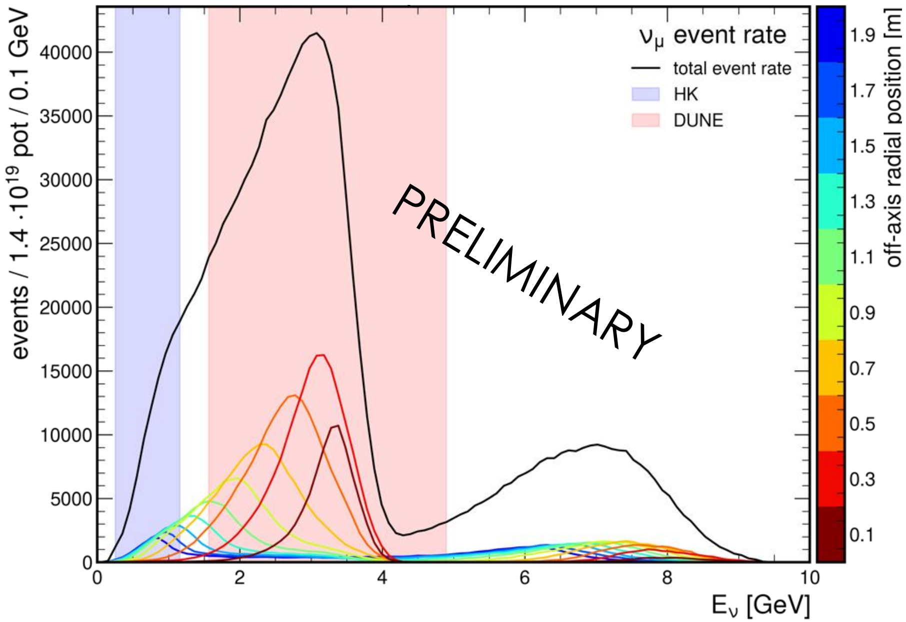

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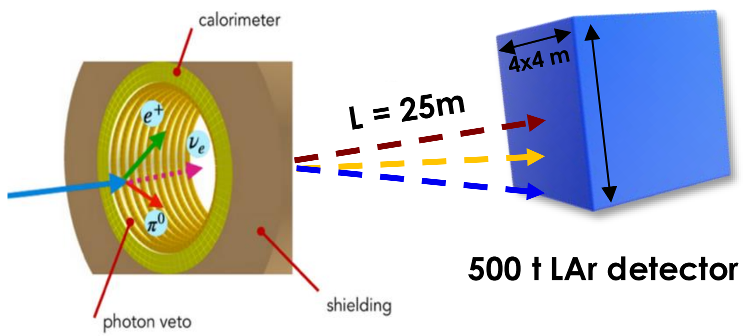

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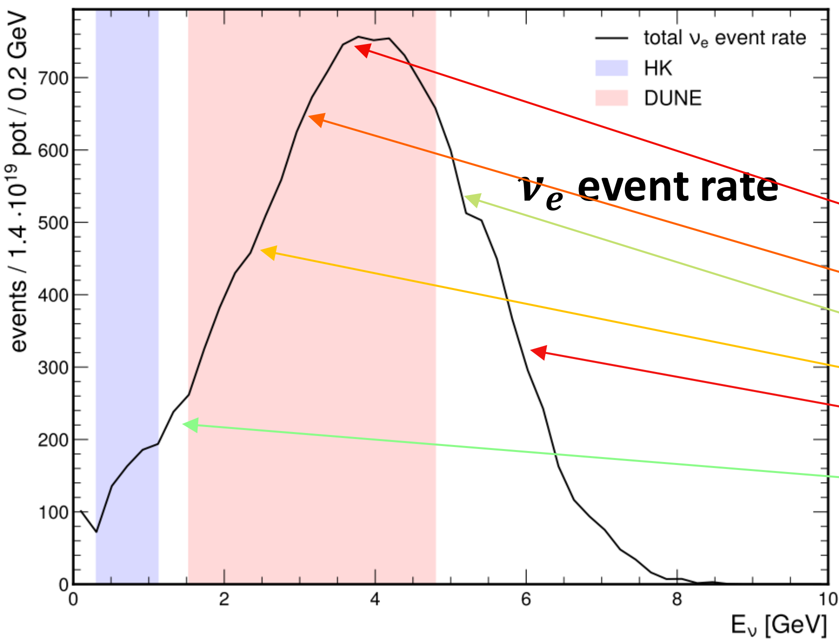

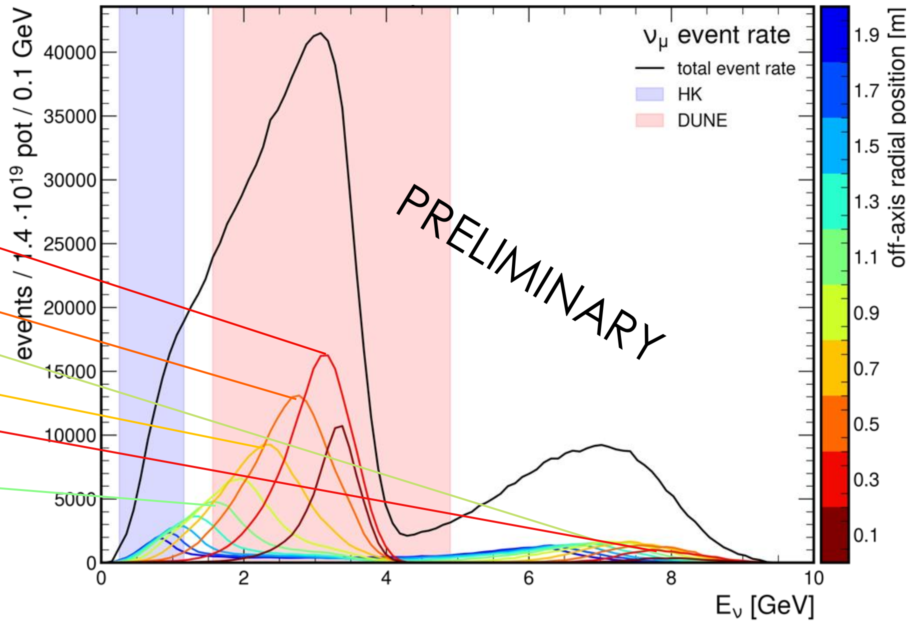

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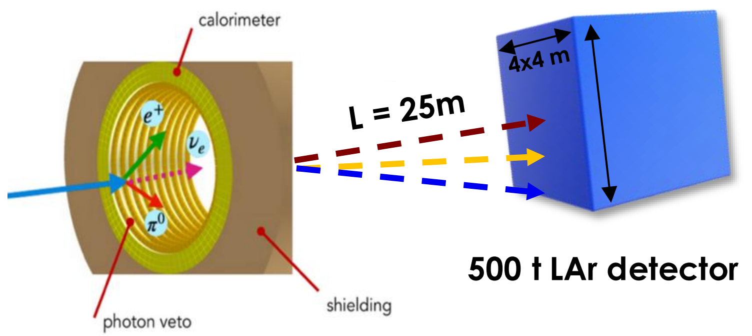

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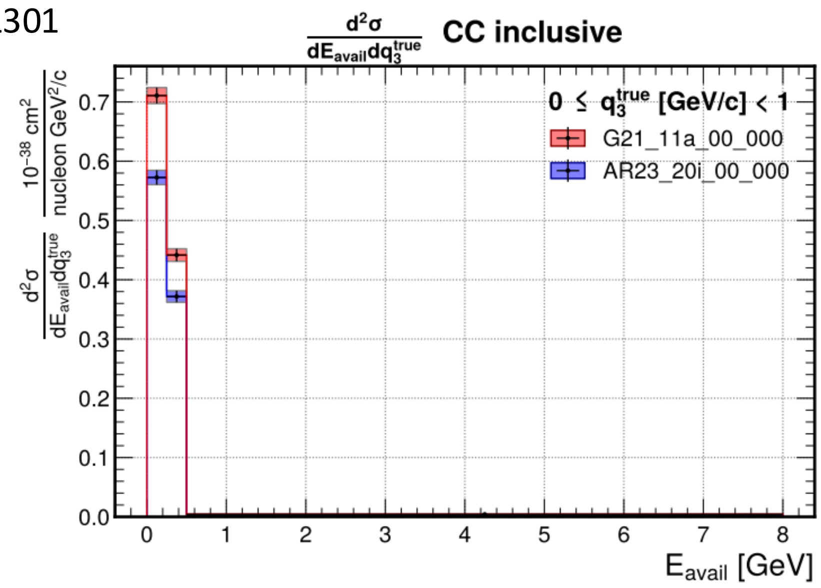
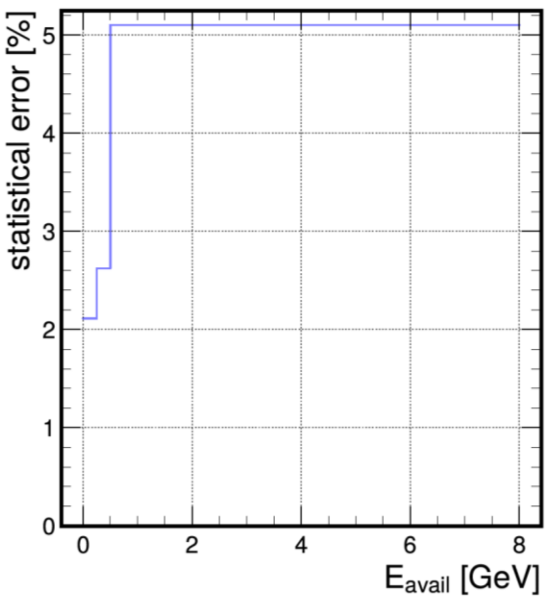
- Going even further, can measure ν_e cross-section in kinematic regions that matter for ν_e/ν_μ ratio

See e.g. *Phys. Rev. D* **108** L031301





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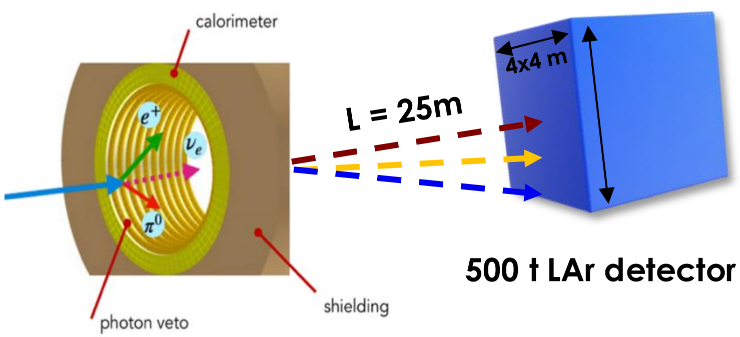
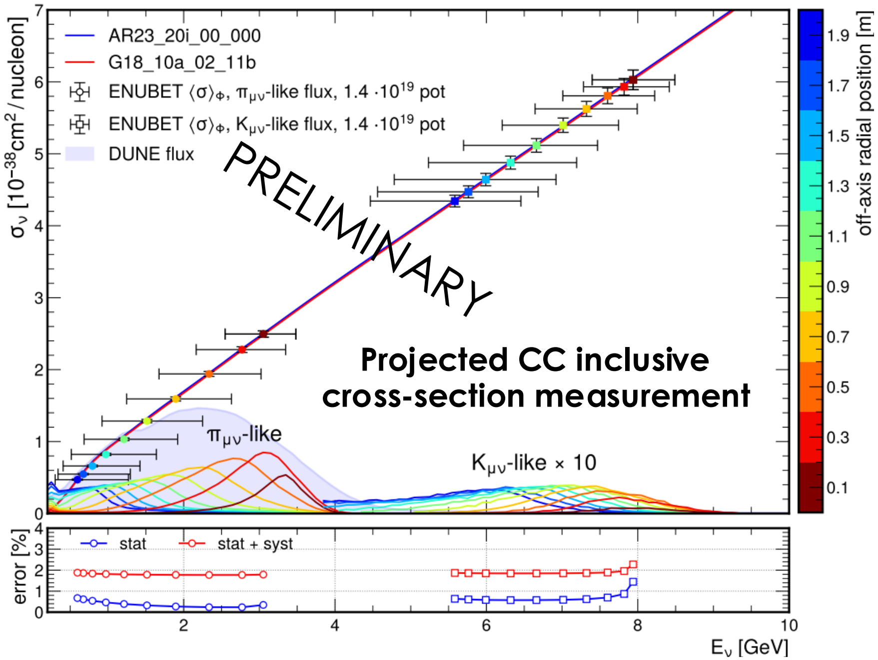
Constraining far det. background



- Make the same measurements, but for topologies that are backgrounds to oscillation analyses



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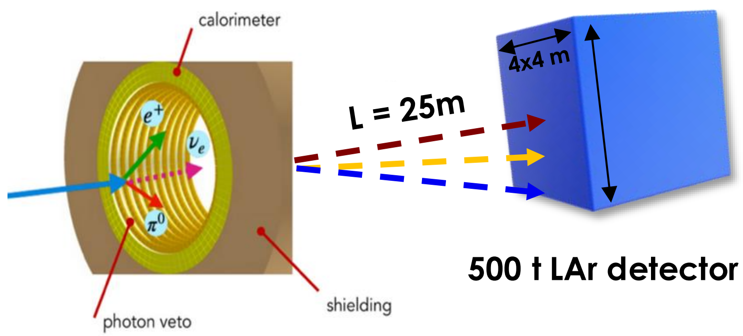
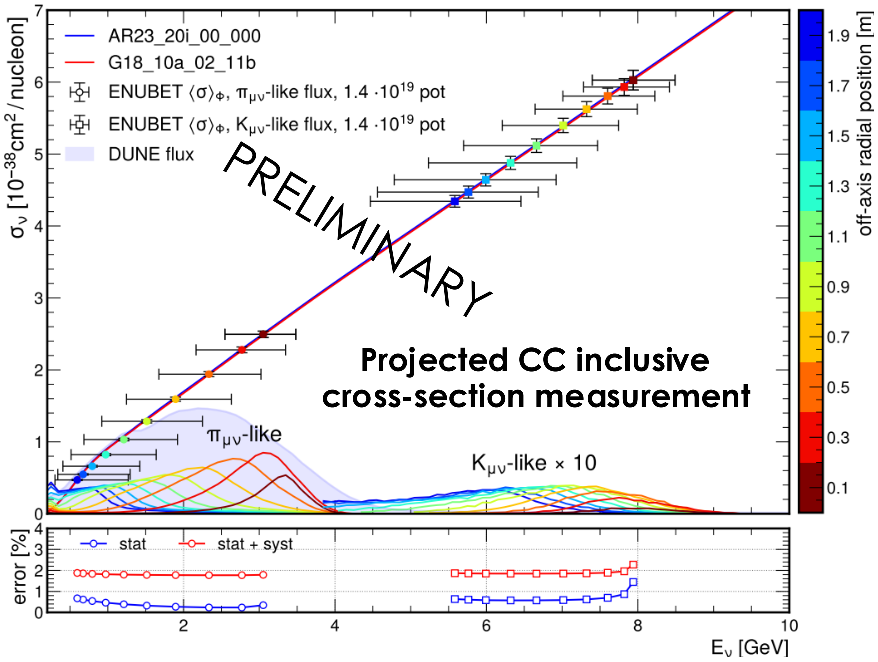
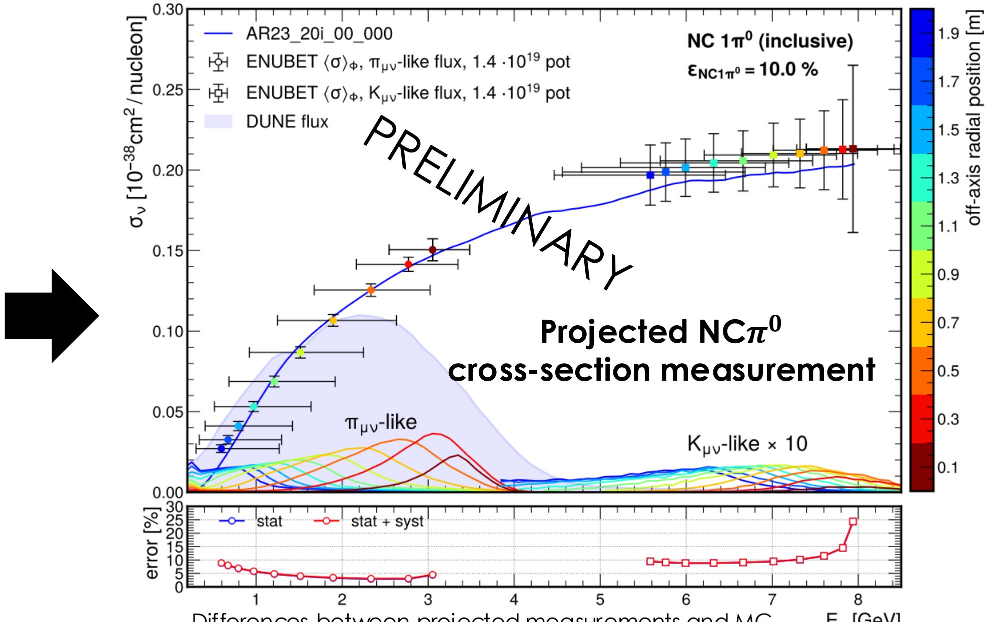


- Make the same measurements, but for topologies that are backgrounds to oscillation analyses

- E.g. expect sub-5% measurements of NCπ^0 cross section
  - c.f. current T2K uncertainty is 30%





Differences between projected measurements and MC are related to limited MC stats and interpolations

Eur. Phys. J. C 84 (2024) 10, 1024

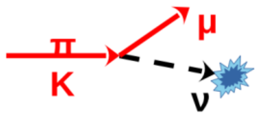
Tagging features of SBN@CERN employing the NuTAG technique

See talk from M. Perrin-Terrin

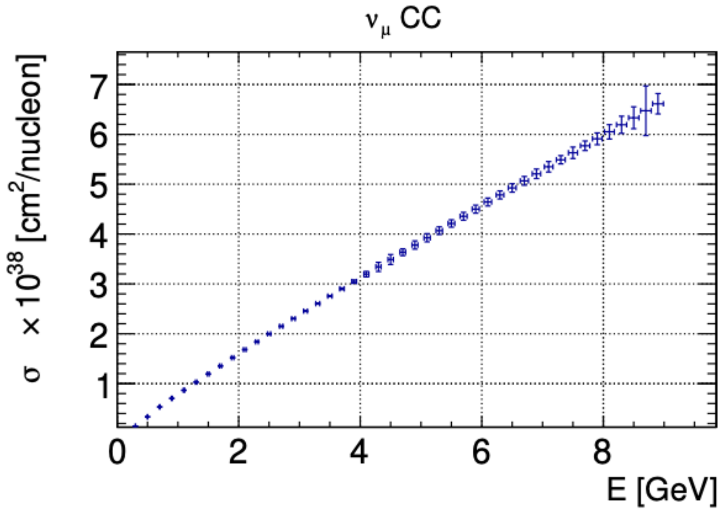
Eur. Phys. J. C 84 (2024) 10, 1024

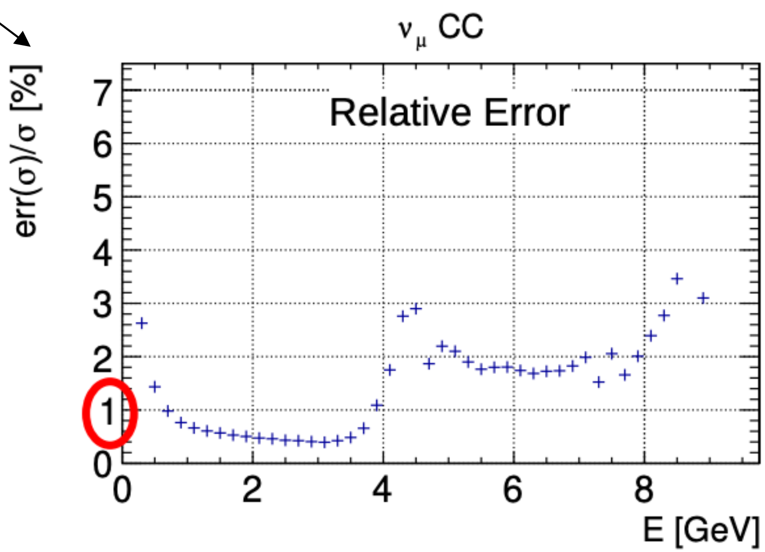
Tagging with SBN@CERN?

See talk from M. Perrin-Terrin



- In a tagged neutrino beam we know E_ν independently from the interaction
  - Expect a sub-% resolution!
- Can directly measure:
  - The cross-section as a function of E_ν





Tagging with SBN@CERN?

Eur. Phys. J. C 84 (2024) 10, 1024

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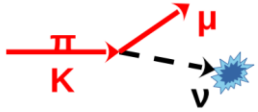

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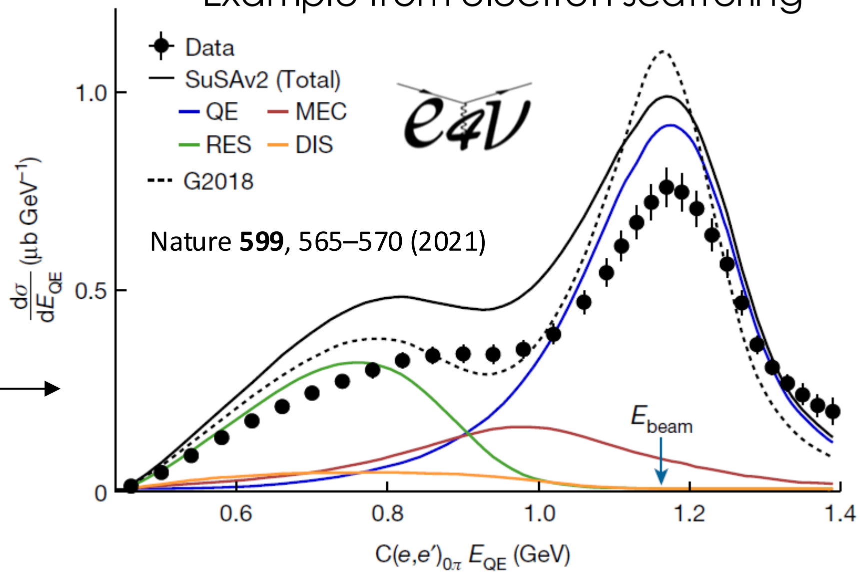
  - The neutrino energy smearing function (compare reconstructed energy to true)
- Allows electron-scattering-like measurements with neutrinos!

Example from electron scattering



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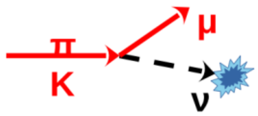

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- Beyond neutrino energy smearing, neutrino tagging would be paradigm changing for nuclear physics measurements

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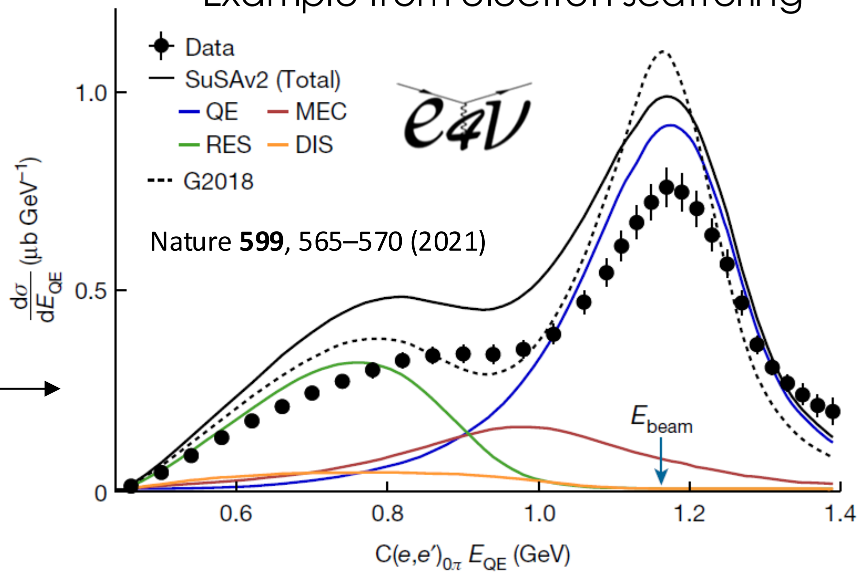

BSM physics with SBN@CERN

- Beyond cross-section physics SBN@CERN would offer unique opportunities for BSM searches thanks to:
  - The extremely well controlled flux
  - For a tagged beam: event-by-event energy + flavour measurement and ν parent decay position

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Crucial for SBL NSI searches

Phys. Rev. D 103, 035018 (2021)

Low systematic HNL-searches

Allows novel ways to eliminate backgrounds in rare process measurements

Unique possibilities for SBL oscillation searches

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Unique possibilities for SBL oscillation searches

- Work to quantitatively assess sensitivity remains, but there are certainly promising prospects

Summary

- A detailed understanding of neutrino-nucleus interactions is **crucial for current and future experiments** to realise their extraordinary goals
  - As a community, if we do not take this problem seriously, **we will be prematurely limited by systematic uncertainties**
- The latest cross-section measurements have allowed us to make enormous progress, but **beam width and flux uncertainties hinder their interpretation**

→ A dedicated program at CERN offers an opportunity for Europe to **take the lead on confronting the challenges that will enable groundbreaking oscillation measurements** in the US and Japan

Summary

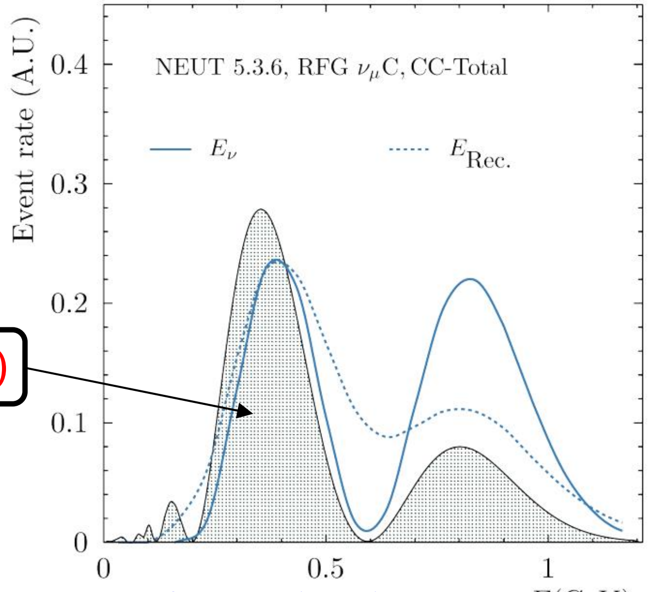
- A detailed understanding of neutrino-nucleus interactions is **crucial for current and future experiments** to realise their extraordinary goals
  - As a community, if we do not take this problem seriously, **we will be prematurely limited by systematic uncertainties**
- The latest cross-section measurements have allowed us to make enormous progress, but **beam width and flux uncertainties hinder their interpretation**
- **SBN@CERN** offers **a unique possibility to constrain and cross-check crucial cross-sections** for Hyper-K and DUNE
- Allows measurements **tailored to confronting the key challenges**:
  - Energy dependence of cross sections
  - Neutrino energy smearing
  - ν_e/ν_μ cross-section ratio
  - Constraints on far-detector backgrounds
- The **tagged neutrino beam** further opens the door to a range of game-changing measurements: **electron-scattering physics w/ neutrinos**!

Backups

Event rates to oscillation parameters

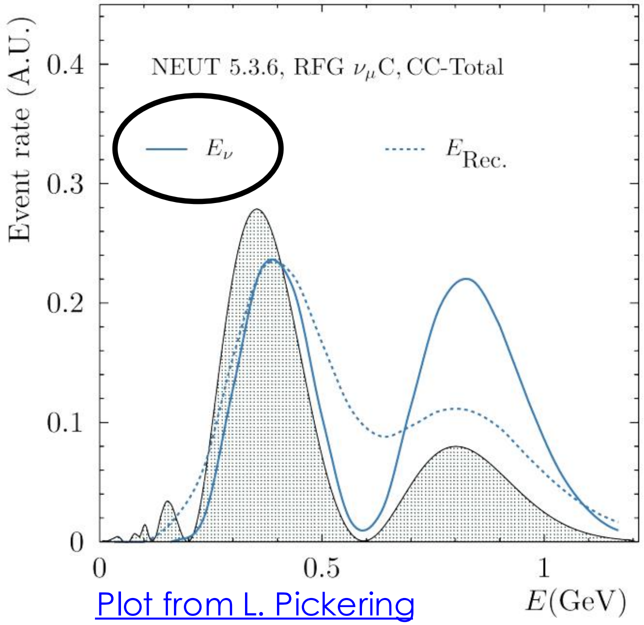
Our physics of interest

$P(\nu_\mu \to \nu_\ell)(E_\nu)\ \Phi_\nu(E_\nu)$



Plot from L. Pickering

Event rates to oscillation parameters

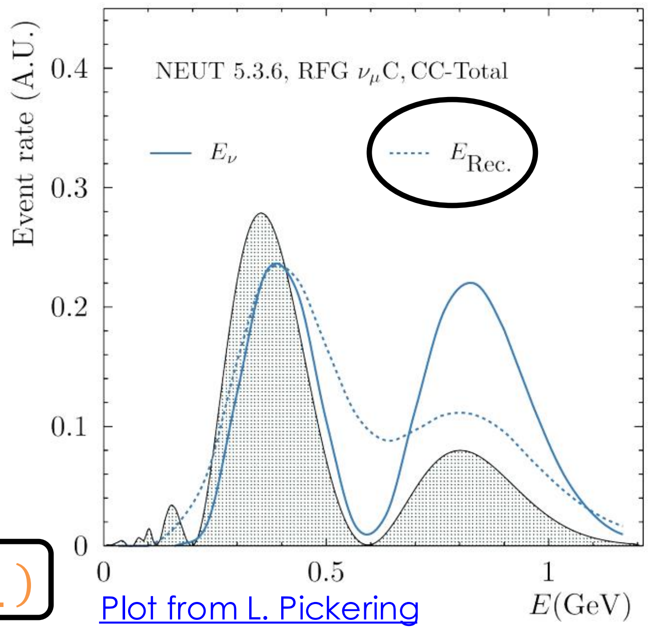


[Plot from L. Pickering](#)

What we would like to measure

$$N_\ell(E_\nu) = P(\nu_\mu \rightarrow \nu_\ell)(E_\nu)\ \sigma(E_\nu)\ \Phi_\nu(E_\nu)\ \epsilon(E_\nu)$$

Event rates to oscillation parameters



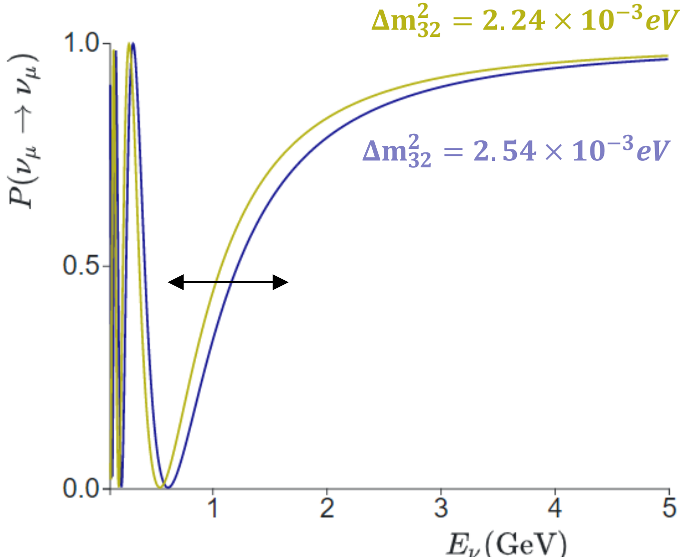
Plot from L. Pickering

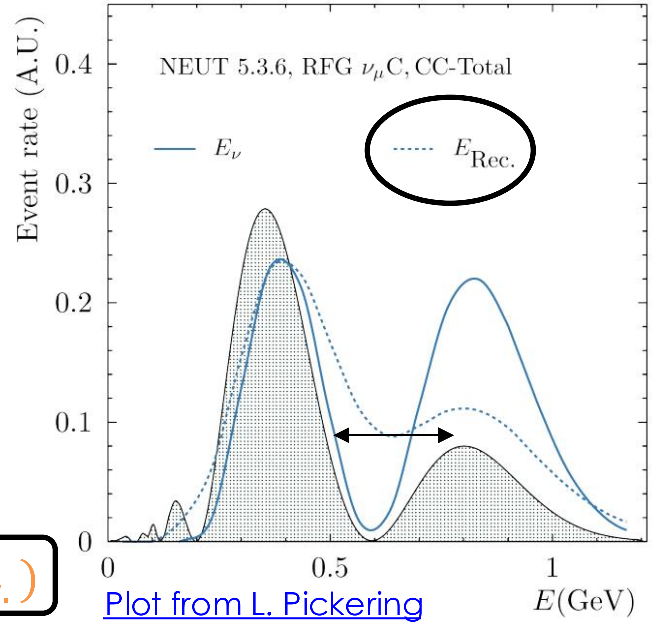
What we can actually measure

$$N_\ell(E_{Rec.}) = P(\nu_\mu \rightarrow \nu_\ell)(E_\nu)\ \sigma(E_\nu)\ \Phi_\nu(E_\nu)\ \epsilon(E_\nu)\ S(E_\nu, E_{Rec.})$$

Event rates to oscillation parameters

- For a precision probe of oscillation parameters, reconstructing the shape of the oscillated spectrum is crucial





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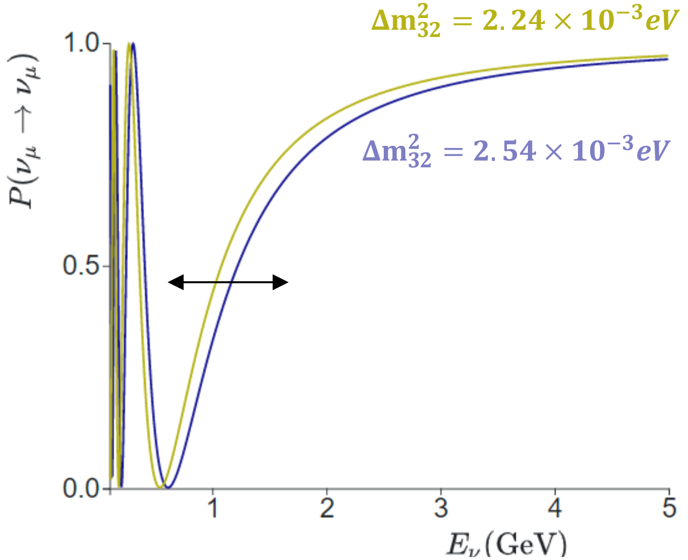
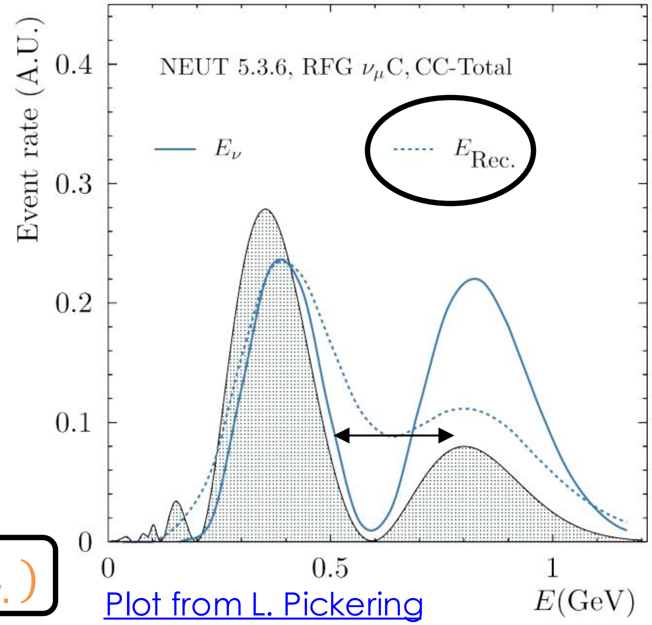
Plot from L. Pickering

Event rates to oscillation parameters

- For a precision probe of oscillation parameters, reconstructing the shape of the oscillated spectrum is crucial
- **Require a good control over cross section energy dependence and energy reconstruction!**





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Event rates to oscillation parameters

- For a precision probe of oscillation parameters, reconstructing the shape of the oscillated spectrum is crucial
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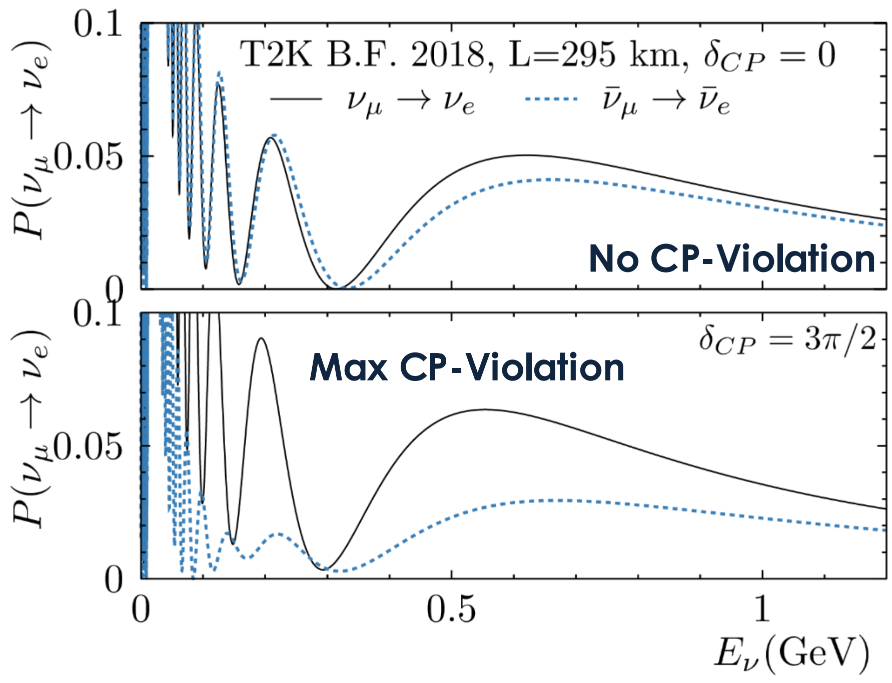
- Constraints on δ_{CP} rely on differences between **electron neutrino and anti-neutrino appearance**



Event rates to oscillation parameters

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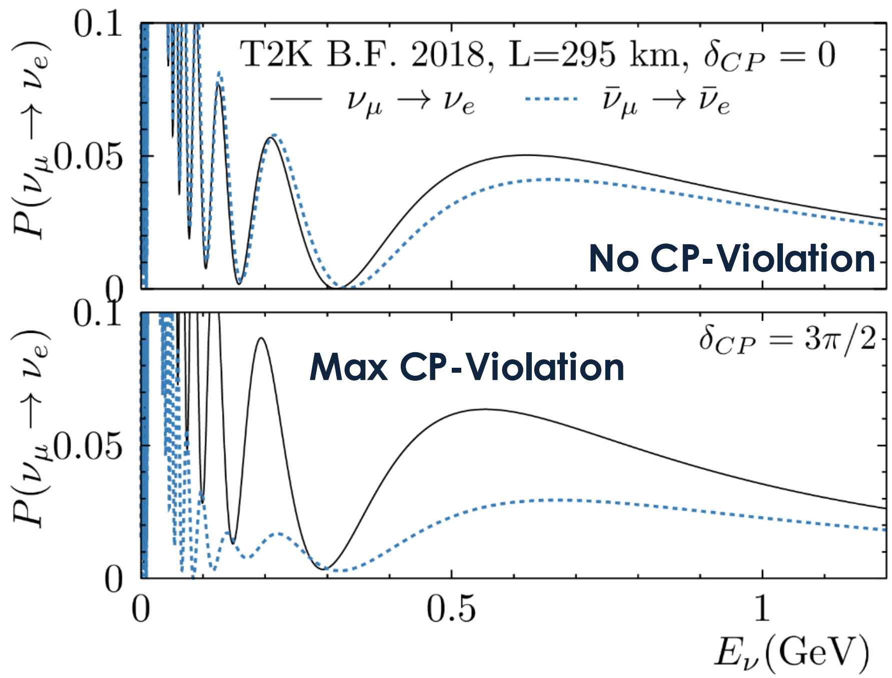
- **A good modelling of ν_e/ν_μ cross section ratio is essential**



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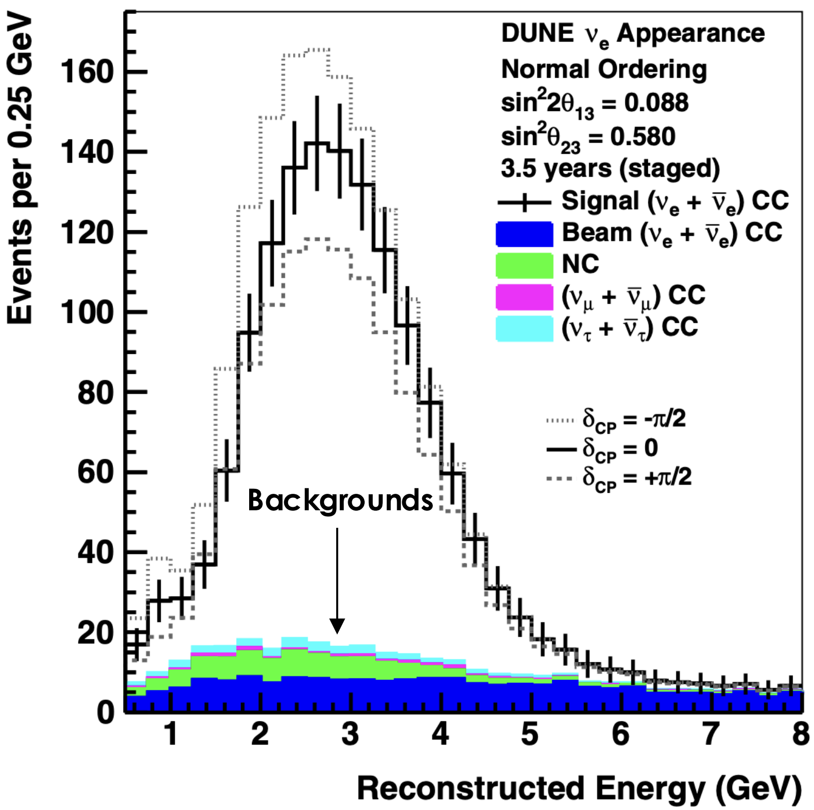
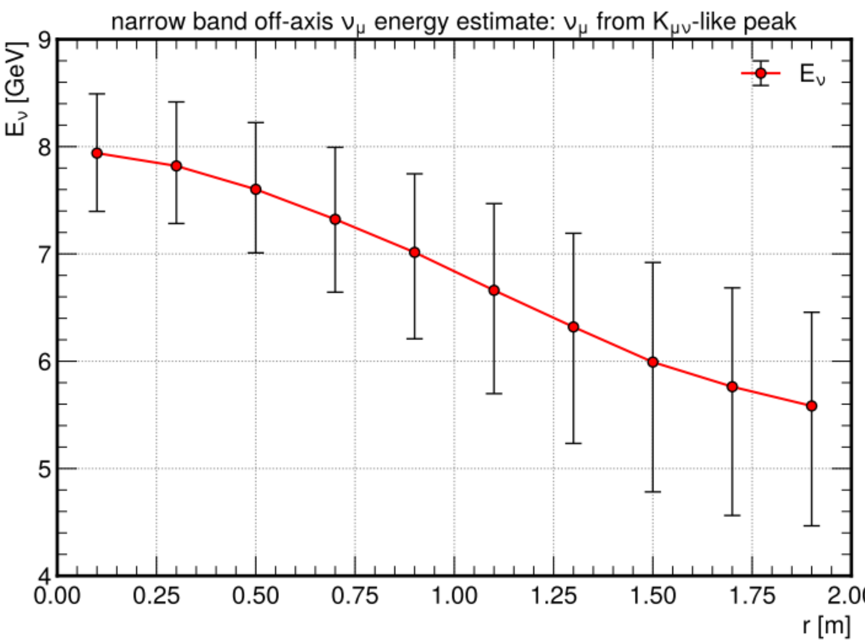
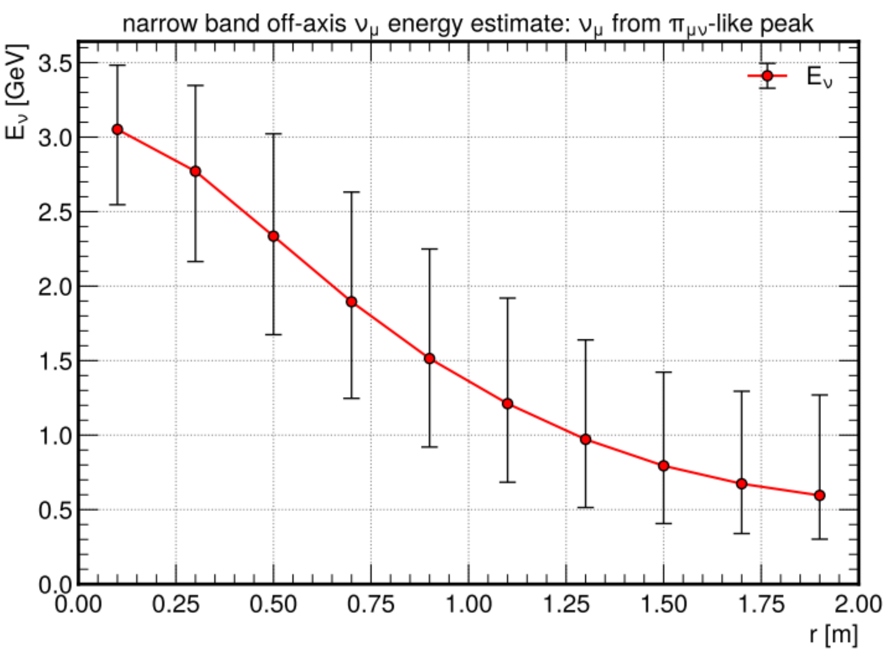
- Background contributions are not-negligible (e.g. NCπ^0 looking like ν_e)
- **A good modelling of non-oscillation backgrounds is needed**



NBOA performance details

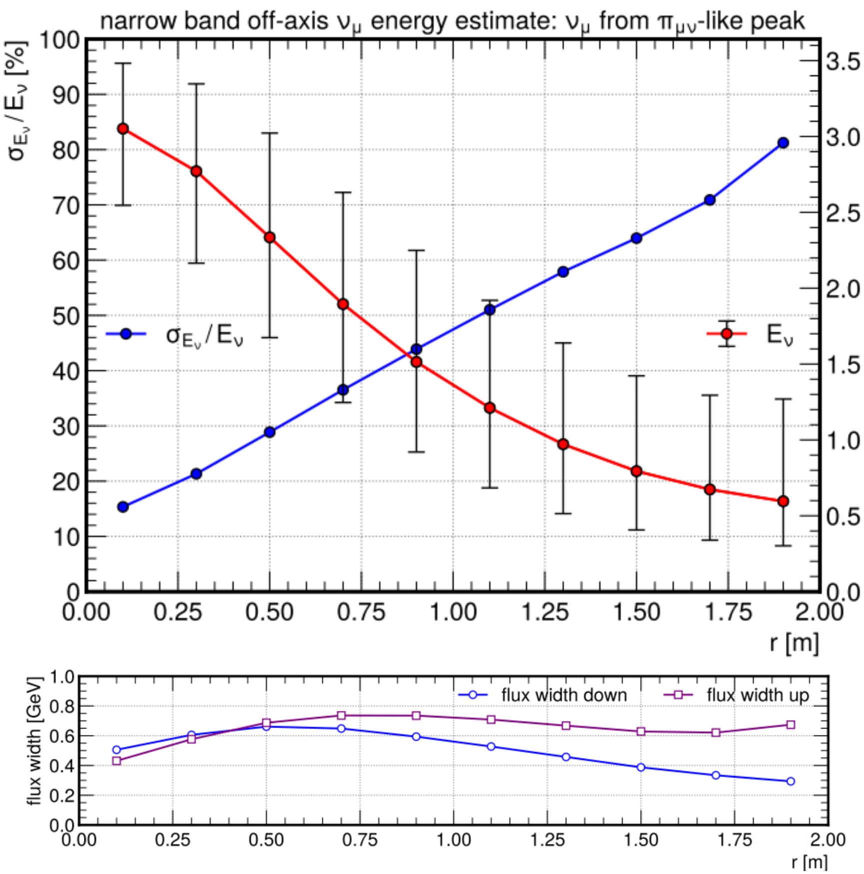
- Flux mean and 68% quartiles as a function of slice radius

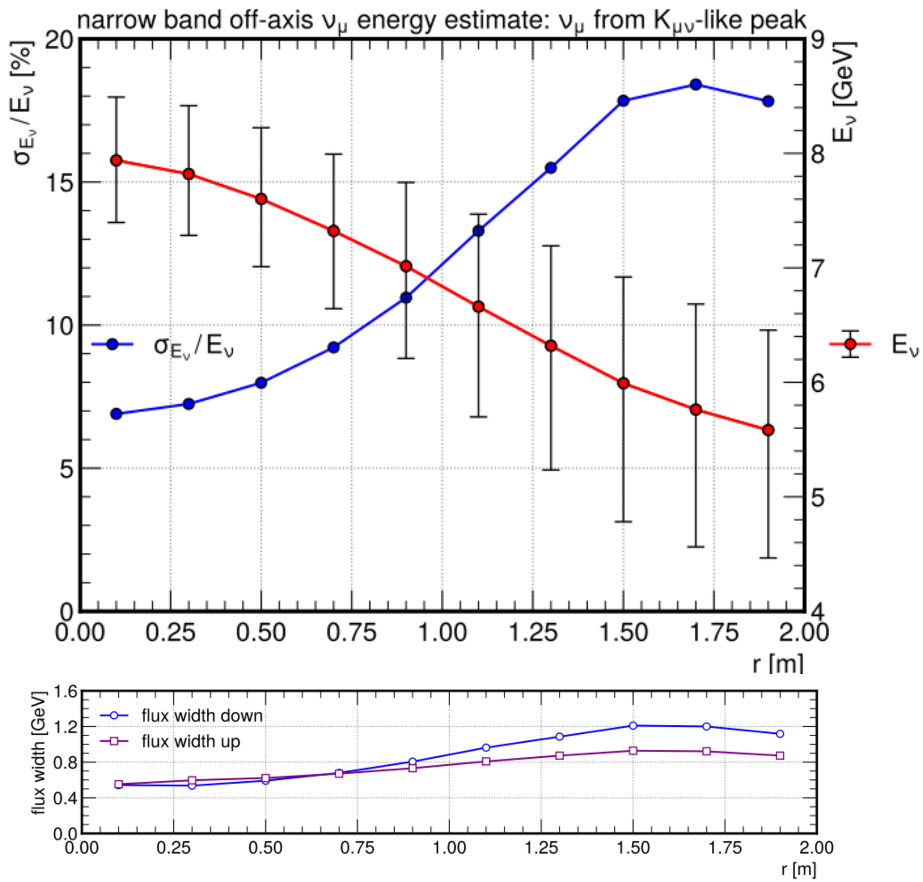




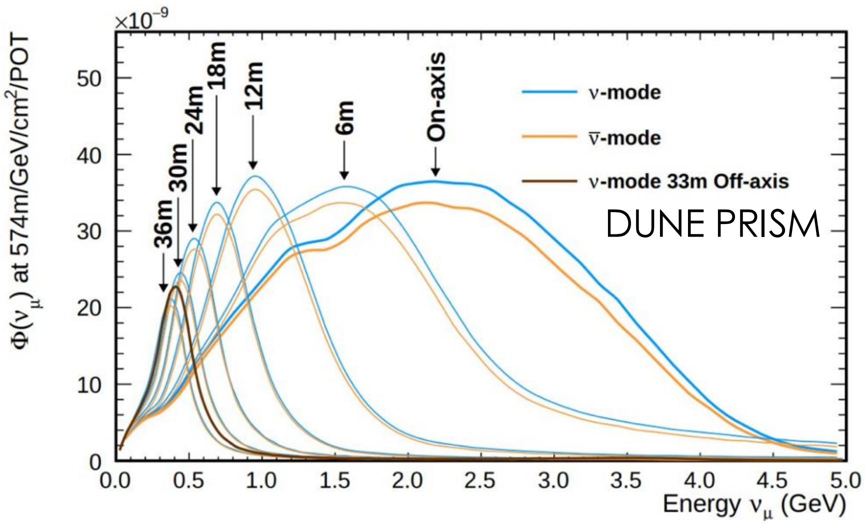
NBOA performance details

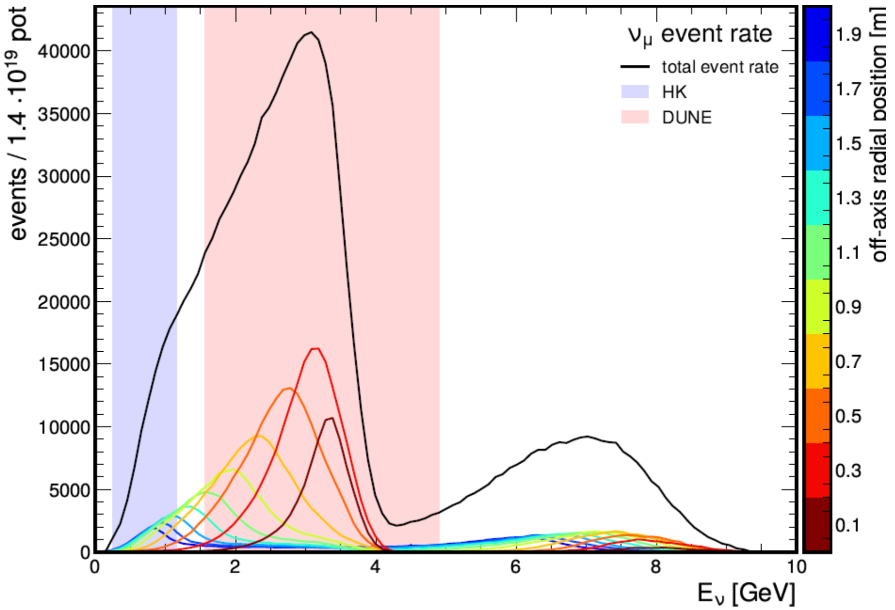
- The plots show the flux mean and 68% quartiles as a function of slice radius
- The energy resolution from the flux width is also shown





NBOA and DUNE PRISM





- DUNE PRISM fluxes are typically wider than for SBN@CERN

The PRISM technique

- The idea: build virtual fluxes of a desired shape from linear combinations of real fluxes available at different off-axis angles

Ingredients:

Flux matrix F - an estimation of what flux distribution we will get for each off-axis angle

Target flux $\vec{T}$ – a flux distribution we would like to approximate

Directions:

Solve $\boldsymbol{F\vec{c}} = \boldsymbol{\vec{T}}$ - find a solution that will give an approximation of our target as a linear combination of fluxes