# ENUBET and SBN@CERN proposal

Budimir Kliček
Ruđer Bošković Institute, Zagreb

On behalf of nuSCOPE

PHOENIX 2025
IIT Hyderabad

10 July 2025

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భారతీయ సాంకేతిక విజ్ఞాన సంస్థ హైదరాబాద్
भारतीय प्रौद्योगिकी संस्थान हैदराबाद
Indian Institute of Technology Hyderabad

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# CP violation in vacuum

$$P_{\nu_\alpha\to\nu_\beta} = \delta_{\alpha\beta} - 4\sum_{i>j}\mathrm{Re}\left(A_{ij}^{\alpha\beta}\right)\sin^2\frac{\Delta m_{ij}^2 L}{4E} \pm 2\sum_{i>j}\mathrm{Im}\left(A_{ij}^{\alpha\beta}\right)\sin\frac{\Delta m_{ij}^2 L}{4E}$$

CP violation
$$P_{\nu_\alpha\to\nu_\beta} \neq P_{\overline{\nu}_\alpha\to\overline{\nu}_\beta}$$

T violation
$$P_{\nu_\alpha\to\nu_\beta} \neq P_{\nu_\beta\to\nu_\alpha}$$

CPT symmetry
$$P_{\nu_\alpha\to\nu_\beta} = P_{\overline{\nu}_\beta\to\overline{\nu}_\alpha}$$

All three equations can be shown using the formula above.

CP violation “amplitude”:

$$P_{\nu_\alpha\to\nu_\beta} - P_{\overline{\nu}_\alpha\to\overline{\nu}_\beta} = 4\sum_{i>j}\mathrm{Im}\left(A_{ij}^{\alpha\beta}\right)\sin\frac{\Delta m_{ij}^2 L}{2E}$$

# CP violation in vacuum

$$P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha\beta} - 4 \sum_{i>j} \mathrm{Re}\left(A_{ij}^{\alpha\beta}\right) \sin^2 \frac{\Delta m_{ij}^2 L}{4E} \pm 2 \sum_{i>j} \mathrm{Im}\left(A_{ij}^{\alpha\beta}\right) \sin \frac{\Delta m_{ij}^2 L}{4E}$$

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CPT symmetry
$$P_{\nu_\alpha \to \nu_\beta} = P_{\overline{\nu}_\beta \to \overline{\nu}_\alpha}$$

This is what
we want to measure.

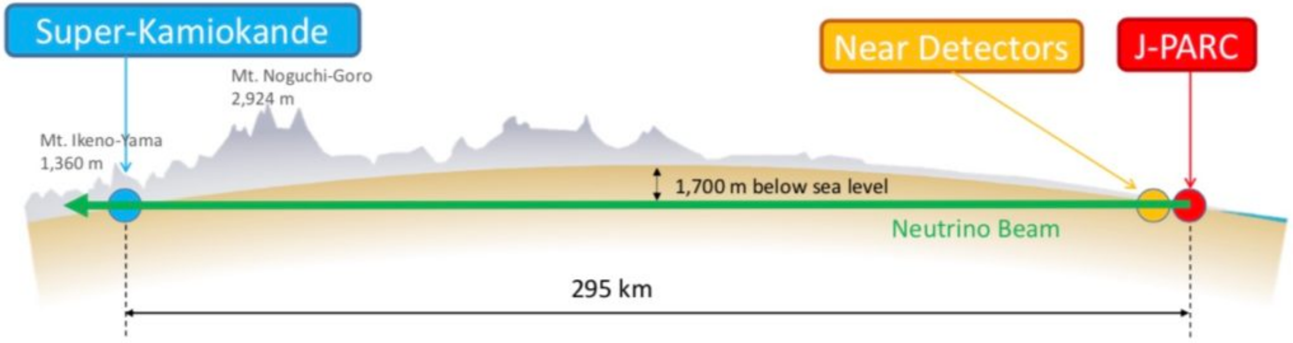
All three equations can be shown using the formula above.

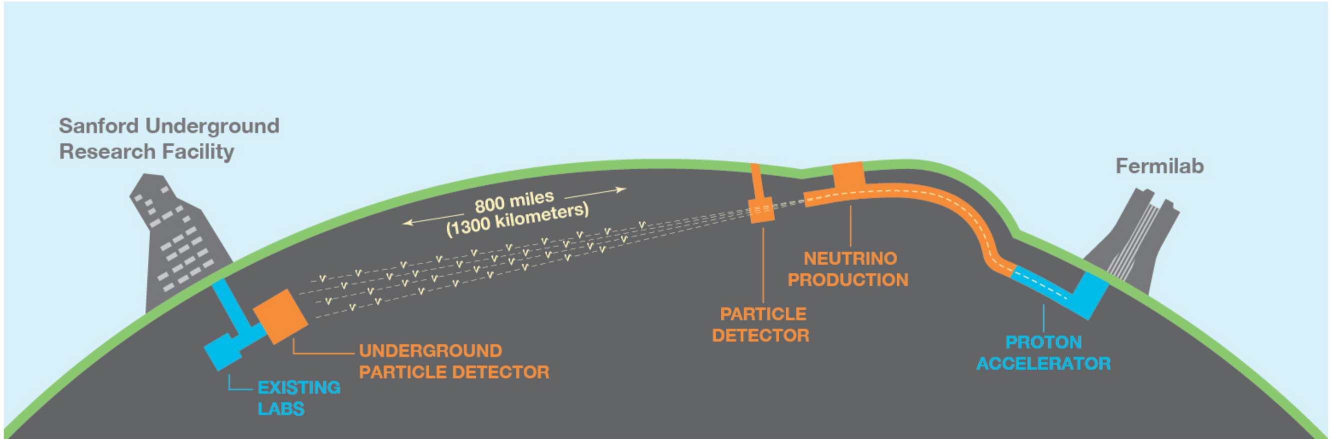
CP violation “amplitude”:

$$P_{\nu_\alpha \to \nu_\beta} - P_{\overline{\nu}_\alpha \to \overline{\nu}_\beta} = 4 \sum_{i>j} \mathrm{Im}\left(A_{ij}^{\alpha\beta}\right) \sin \frac{\Delta m_{ij}^2 L}{2E}$$

# HyperK and DUNE

Hyper Kamiokande
and




Next generation experiments to measure CPV via neutrino osc.

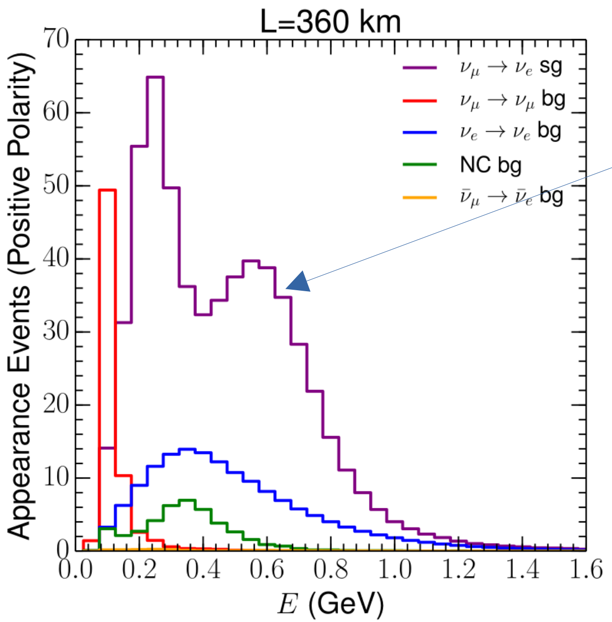
Both use $\nu_e$ appearnace in a $\nu_\mu$ beam

$$P_{\nu_\mu \to \nu_e} \neq P_{\overline{\nu}_\mu \to \overline{\nu}_e}$$

Basis of the CPV measurement:
$\nu_e$ **event rate**

Additionally, huge $\nu_\mu$ rate will be used for precision osc. param. measurement.

# $\nu_e$ oscillated event rate




Example event rate (ESSnuSB)

Flux

Cross-section

$$\frac{dR_{\mathrm{evt}}(E_\nu^{\mathrm{R}})}{dE_\nu} = \int_0^\infty P_{\nu_\mu \to \nu_e}(E_\nu)\Phi(E_\nu)\sigma(E_\nu)R(E_\nu^{\mathrm{R}}, E_\nu)\eta(E_\nu)dE_\nu$$

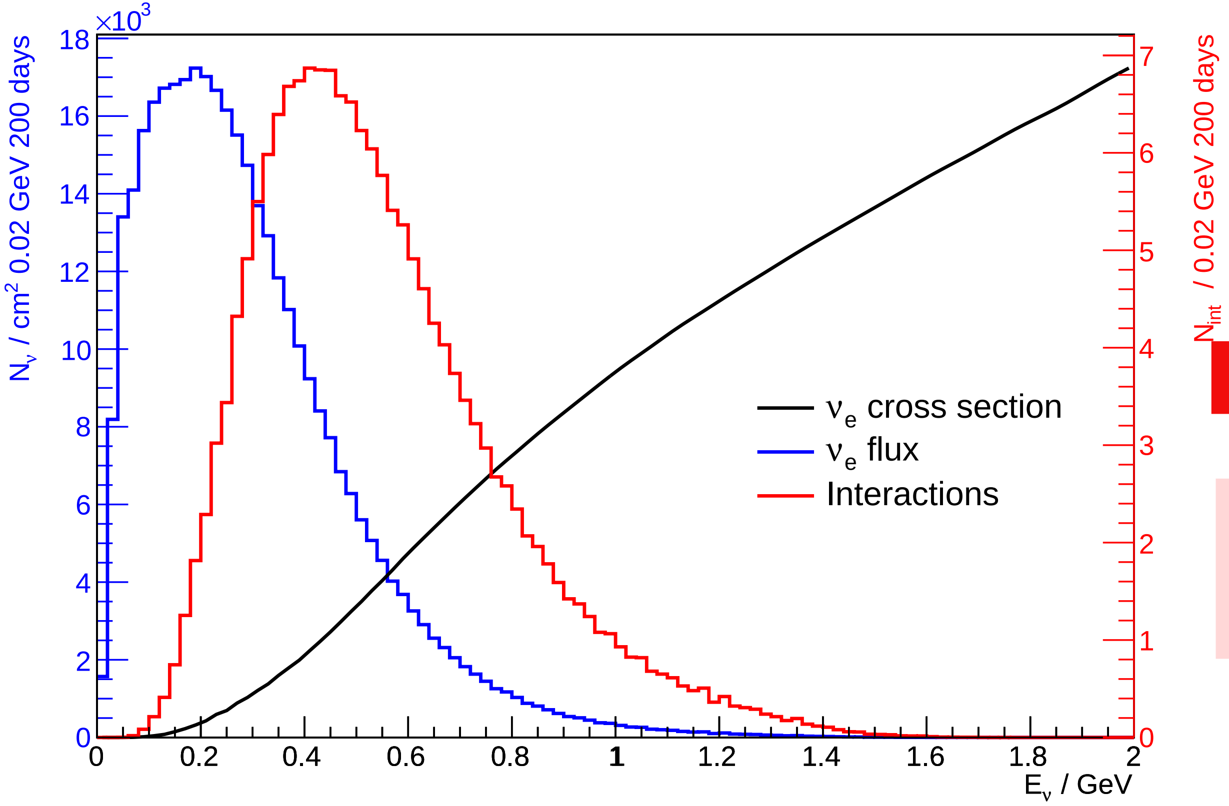
What we want

Detector response

Systematic error in any of the “red” quantities directly translates in CPV measurement systematic.

| | |
|---|---|
| $E_\nu$ | true neutrino energy |
| $E_\nu^{\mathrm{R}}$ | reconstructed neutrino energy |

# Simple $\nu_e$ xsec measurement




$$\frac{dR_{\text{int}}(E_\nu)}{dE_\nu} = \Phi(E_\nu)\sigma(E_\nu)$$

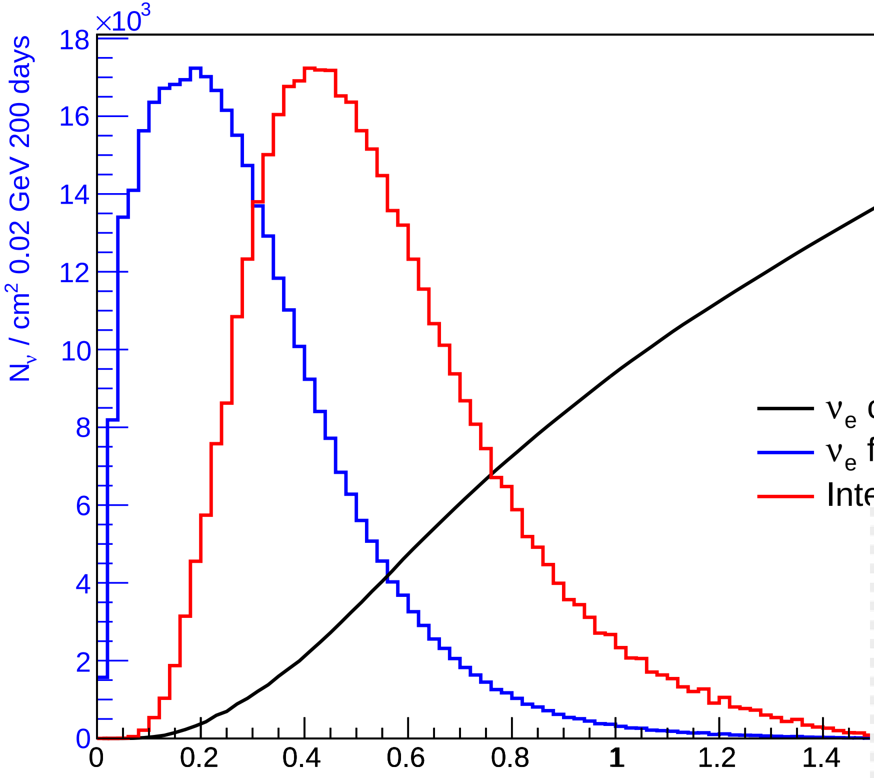
Interaction rate

Flux

Cross-section

Assuming a perfect detector, there is still ambiguity between flux and xsec.

# Simple $\nu_e$ xsec measurement

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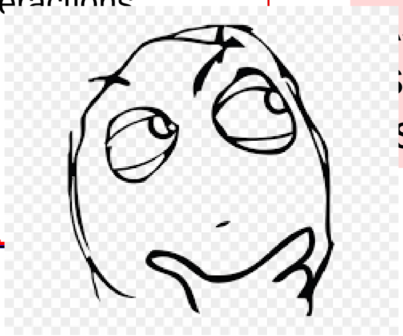
Interaction rate | Flux | Cross-section



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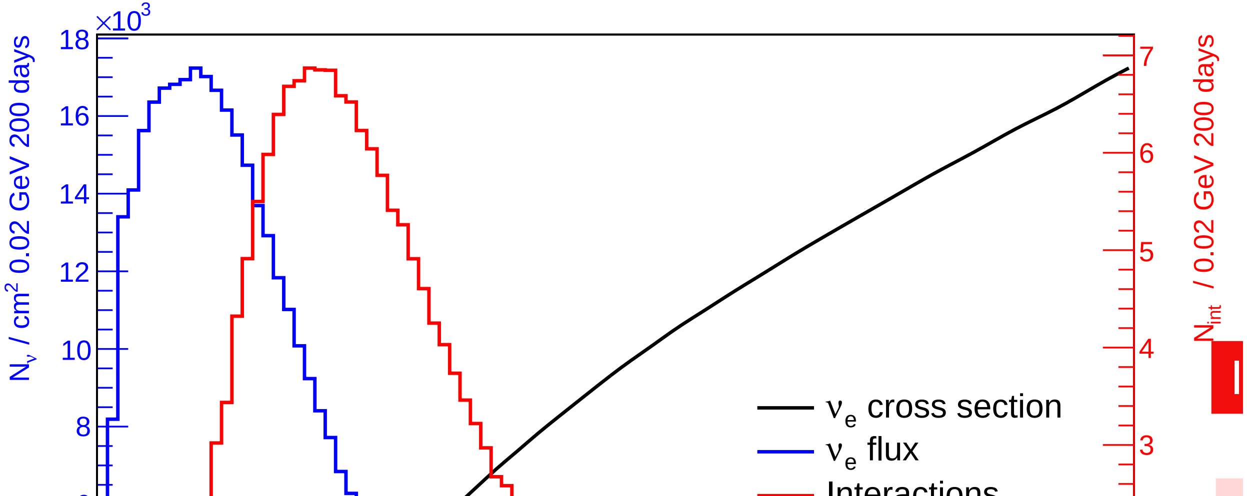
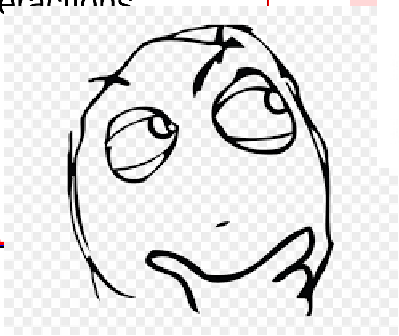
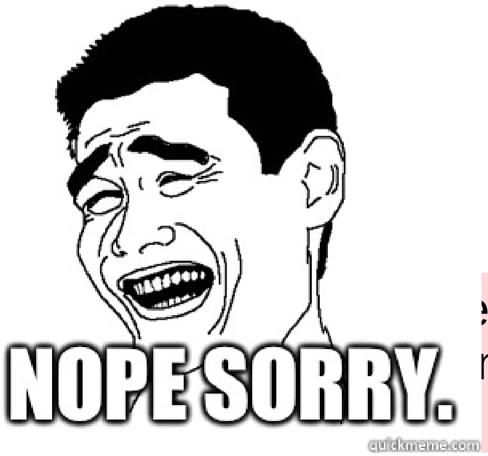
But we know the flux, don't we?

# Simple $\nu_e$ xsec measurement





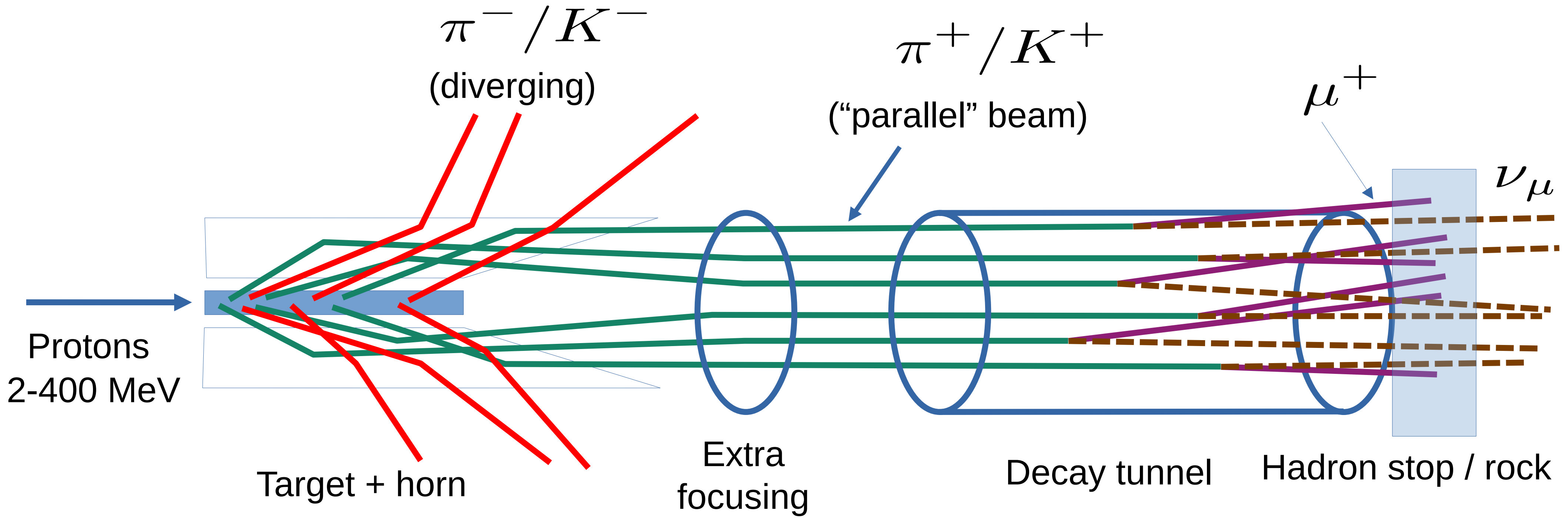

$$\frac{dR_{\text{int}}(E_\nu)}{dE} = \Phi(E_\nu)\sigma(E_\nu)$$

Cross-section

ector, there
n flux and

But we know the flux, don't we?

# Conventional neutrino beam production

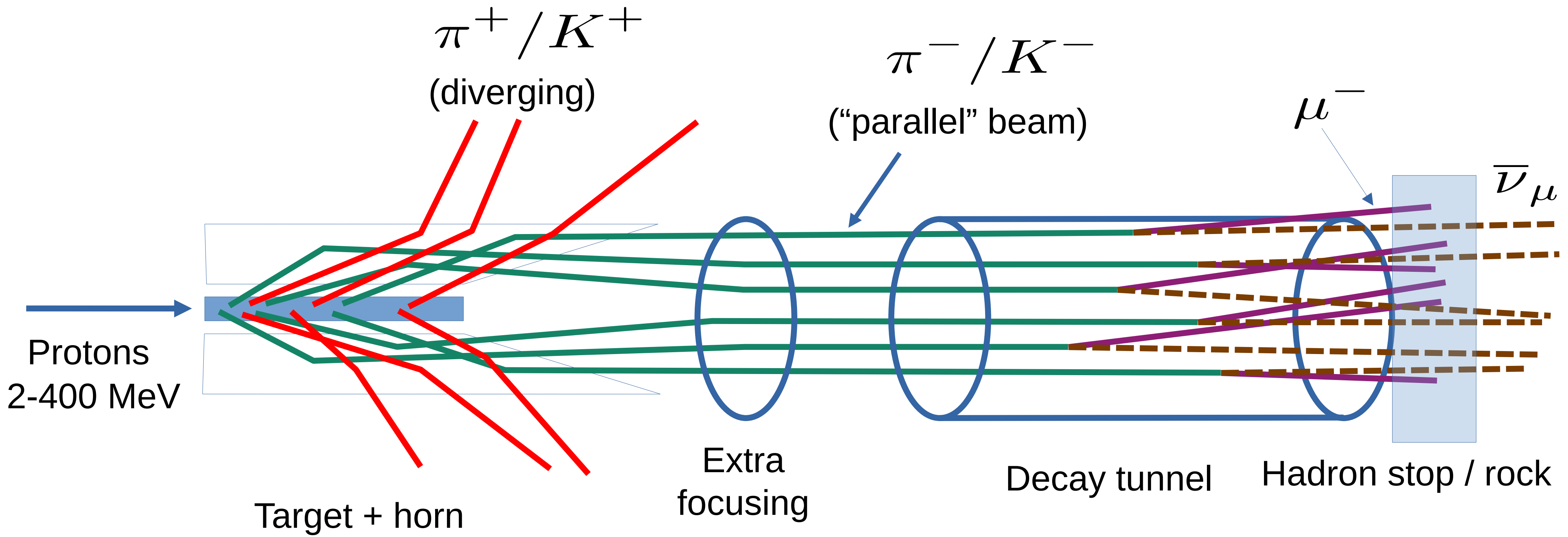



$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad \pi^- \rightarrow \mu^- + \overline{\nu}_\mu$$

ESSnuSB – 2.5 GeV kinetic (ESS)
T2K – 30 GeV (J-Parc)
NUMI – 120 GeV (Fermilab)
CNGS – 400 GeV (SPS)

**All long baseline beams are $\nu_\mu$ beams.**

# Conventional neutrino beam production

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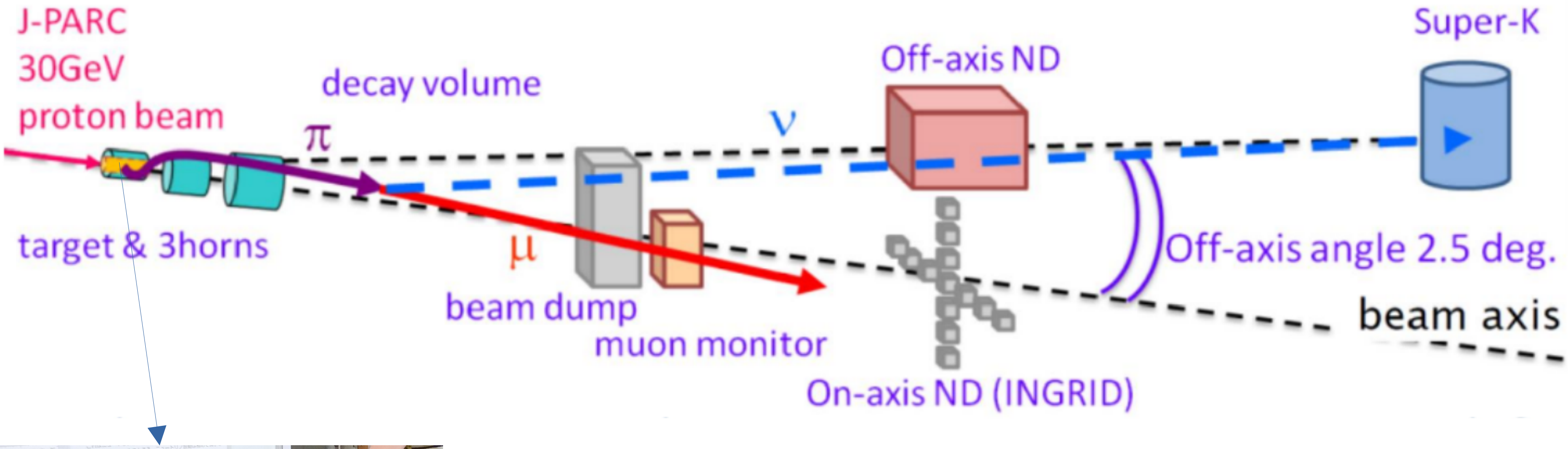
**All long baseline beams are $\nu_\mu$ beams.**

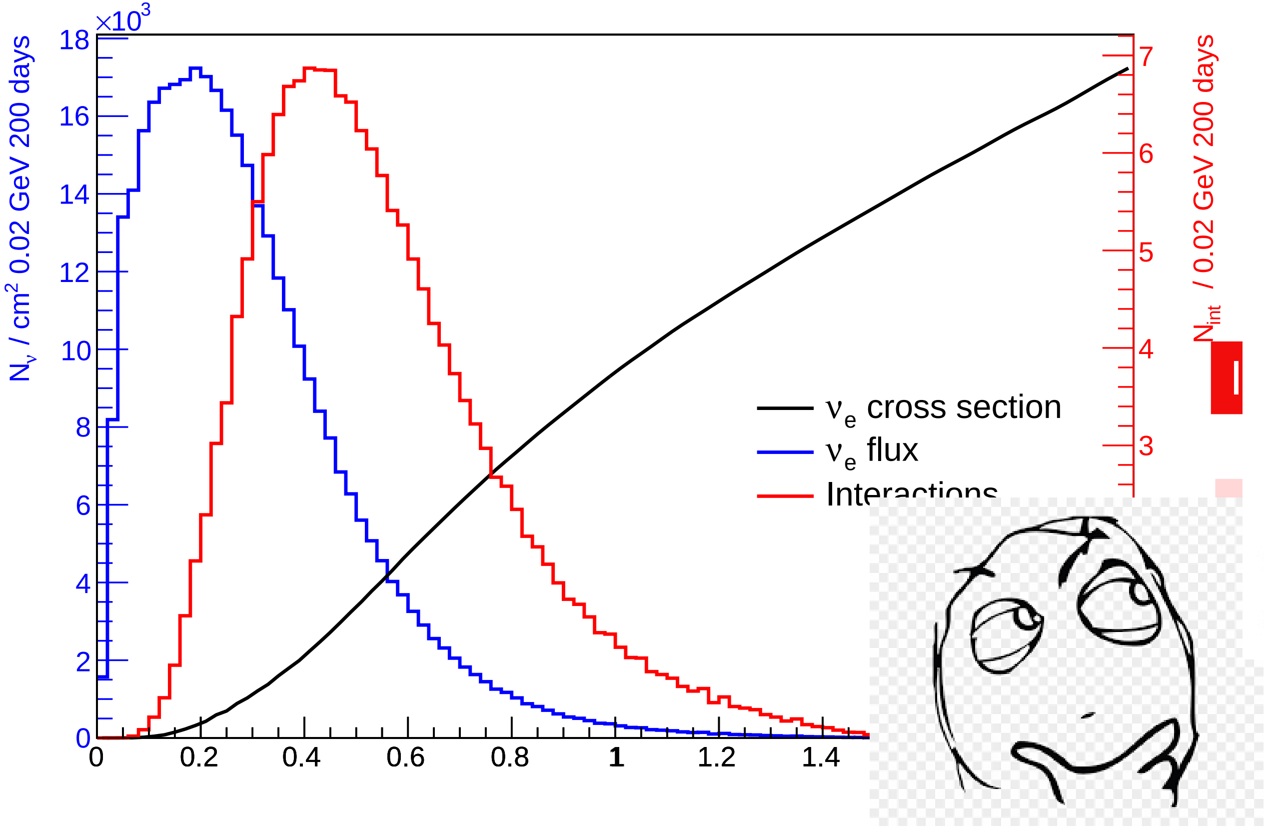
# Conventional neutrino beam (T2K)




Difficult to model the meson flux: a very “dirty” QCD process.
Simulations alone have uncertainty ~ 15 %

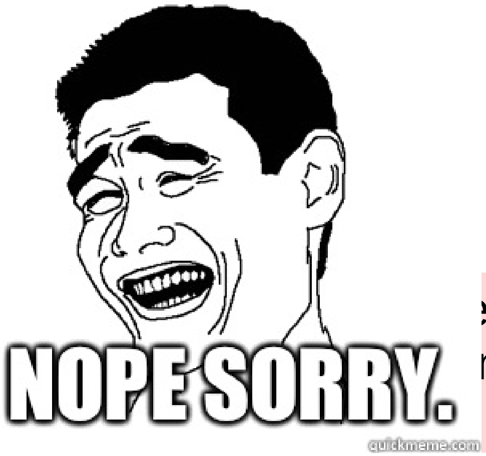
Dedicated experiments, like NA61/SHINE reduce systematics of the neutrino beam to ~ 6%

# Simple $\nu_e$ xsec measurement




$$\frac{dR_{\text{int}}(E_\nu)}{dE} = \Phi(E_\nu)\sigma(E_\nu)$$

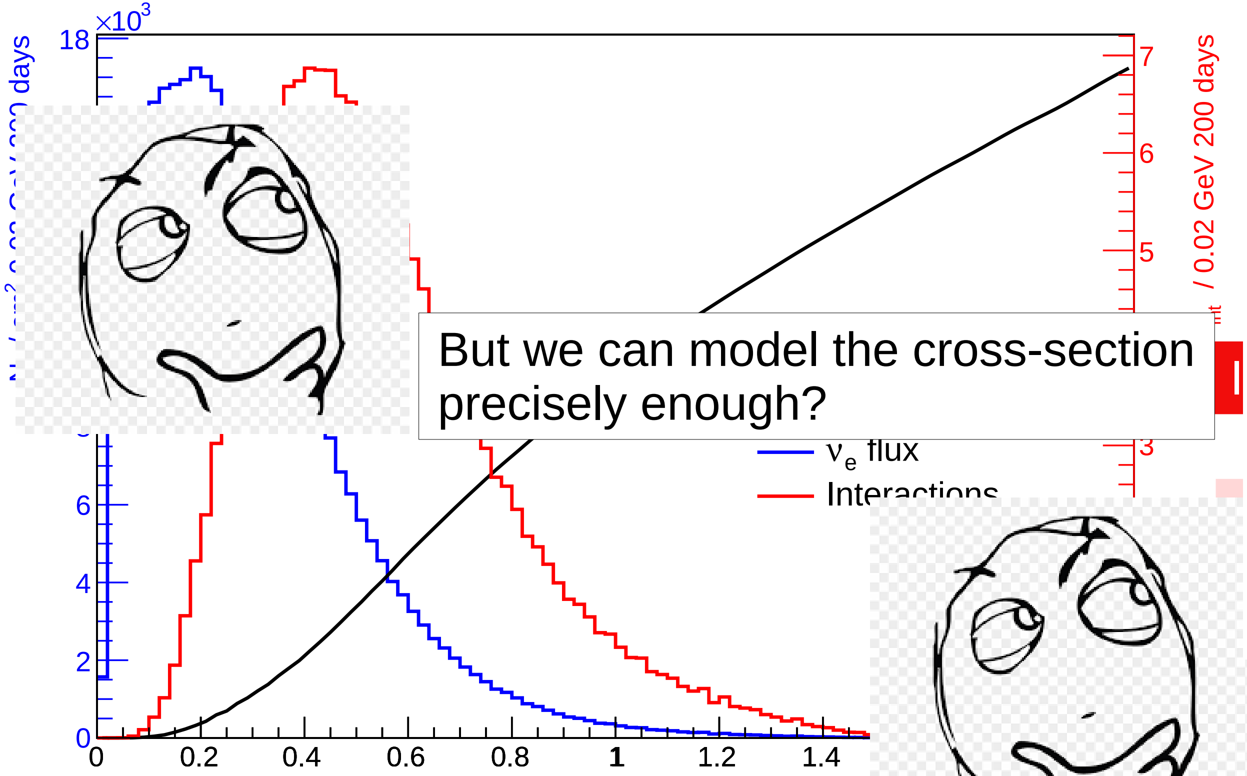
Cross-section




ector, there
n flux and

But we know the flux, don't we?

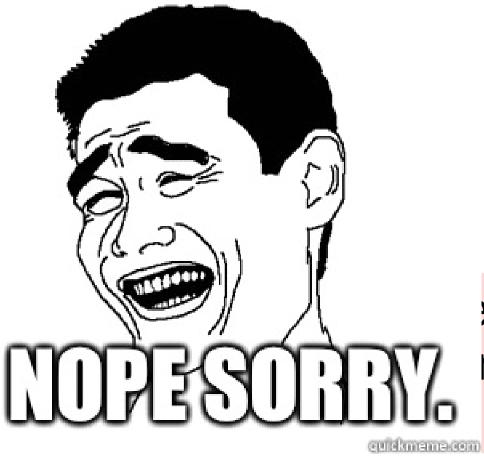
# Simple $\nu_e$ xsec measurement




But we can model the cross-section precisely enough?

$$\frac{dR_{\text{int}}(E_\nu)}{dE} = \Phi(E_\nu)\sigma(E_\nu)$$

Cross-section




ector, there
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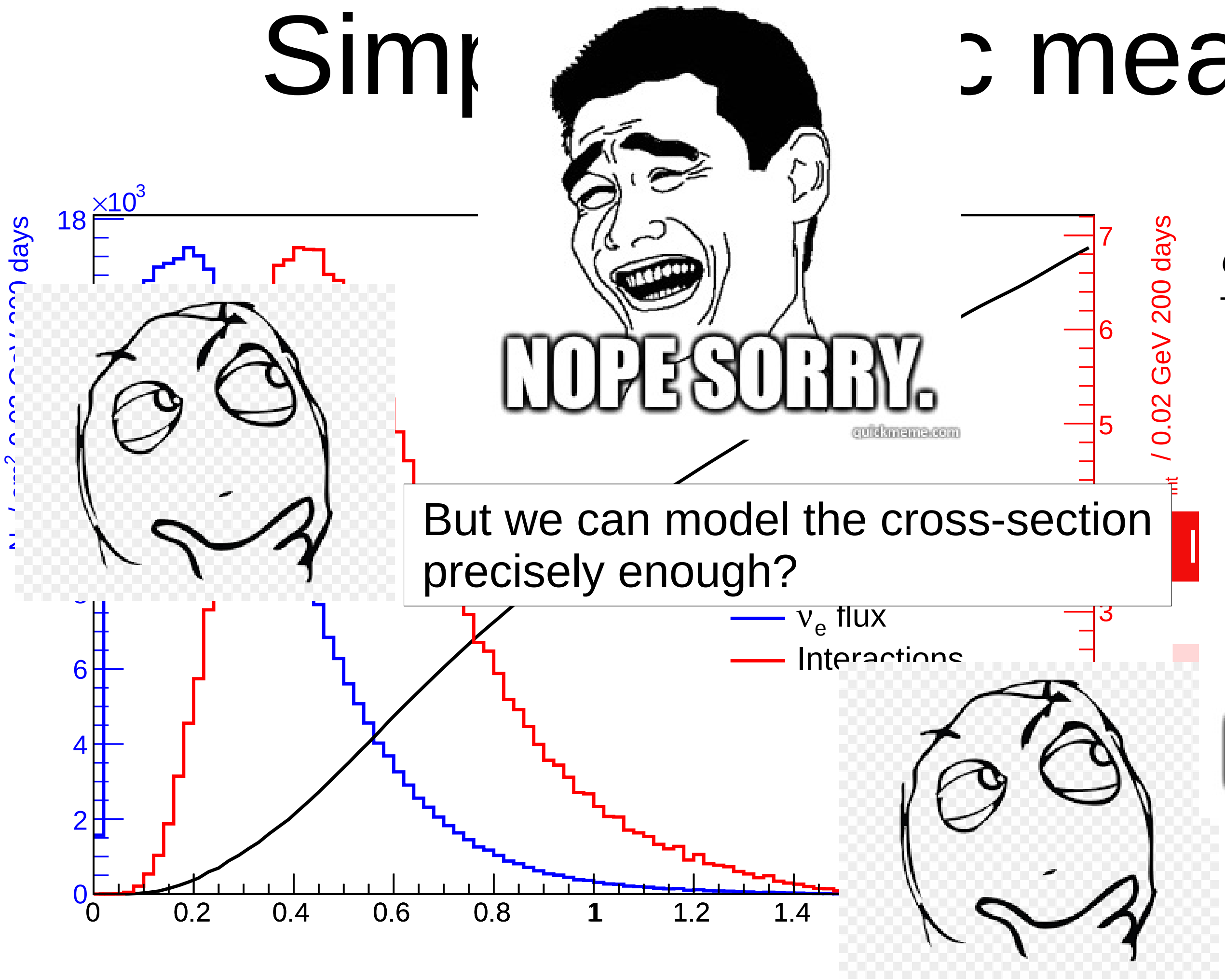
# Simp c measurement

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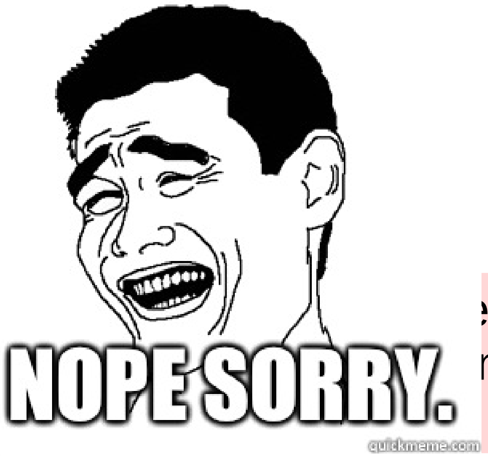
$$\frac{dR_{\text{int}}(E_\nu)}{dE} = \Phi(E_\nu)\sigma(E_\nu)$$

Cross-section



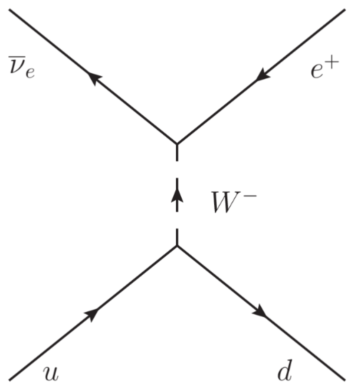

ector, there
n flux and

But we know the flux, don't we?

# Xsec modelling problem

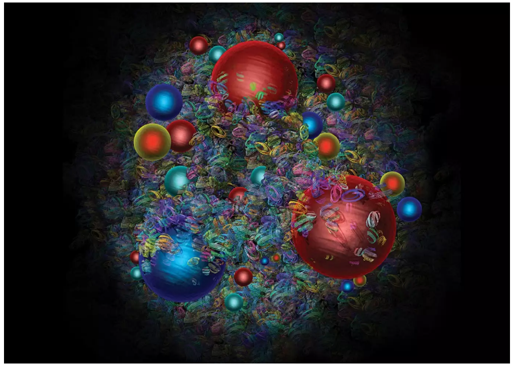
At $E_\nu$ >~ 100 MeV, almost all CC interactions are between the neutrino and a nucleus.

Basic interaction:
**Neutrino interacts with a quark**




- Easy enough to solve for invariant amplitude
- Hadronization not trivial

**But quarks are bound in a nucleon.**



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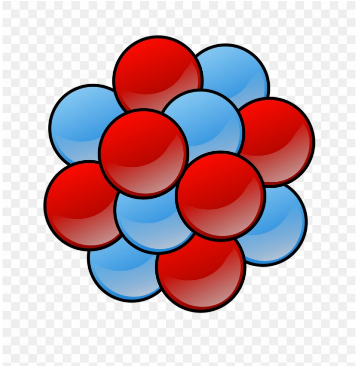
**Already many problems:**
- form factors, esp. axial coupling
- resonances
- quark seas
- ...

**And nucleons are bound in nuclei.**



**World of pain:**
- nuclear model
- final state interactions (FSI)
- nucleon clustering (e.g. 2p2h)
- coherent pi0 production
- …..

State-of-the-art theoretical xsec models sometimes differ by factor 2 in total xsec.

# Neutrino data anomalies are (mostly) by Strong interaction


Courtesy of T. Katori

# Flux is the main uncertainty for measuring neutrino xsec.

Can we determine the flux a-priori?

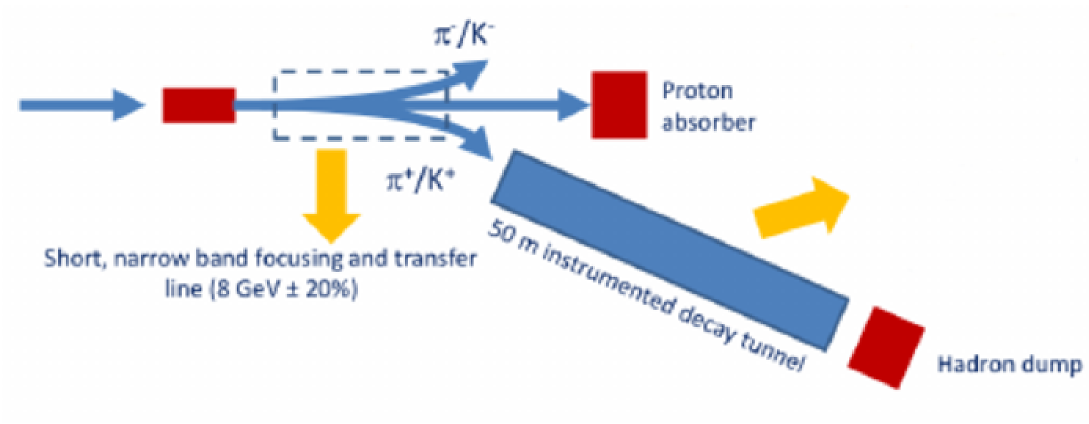
# Original ENUBET idea

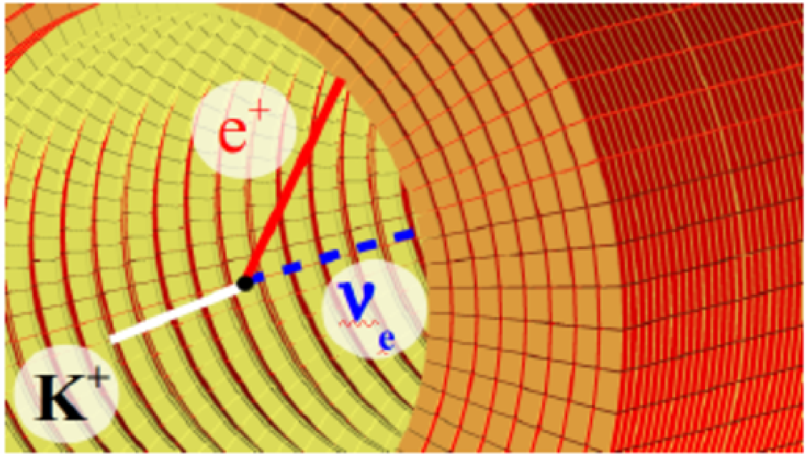
**Instrumentize the decay tunnel** to precisely measure the neutrino flux

- In particular, measure $\nu_e$ flux component from charged kaon decays
- Use this to measure $\nu_e$ interaction cross-section for CPV measurement and more

$$K^+ \to \pi^0 + e^+ + \nu_e$$

BR ~ 5 %



# ENUBET evolved

- **A breakthrough:** static focusing system replacing the pulsed horn design
  - made possible by the continuous proton extraction mode (~4s spills as opposed to ~ms spills)
- **Monitoring of the $\pi \rightarrow \nu_\mu + \mu$ decays** by instrumenting the hadron dump
  - also due to continuous extraction
  - makes it possible get an a-priori estimation of $\nu_\mu$ energy (NBOA technique)
- NP06/ENUBET, ERC

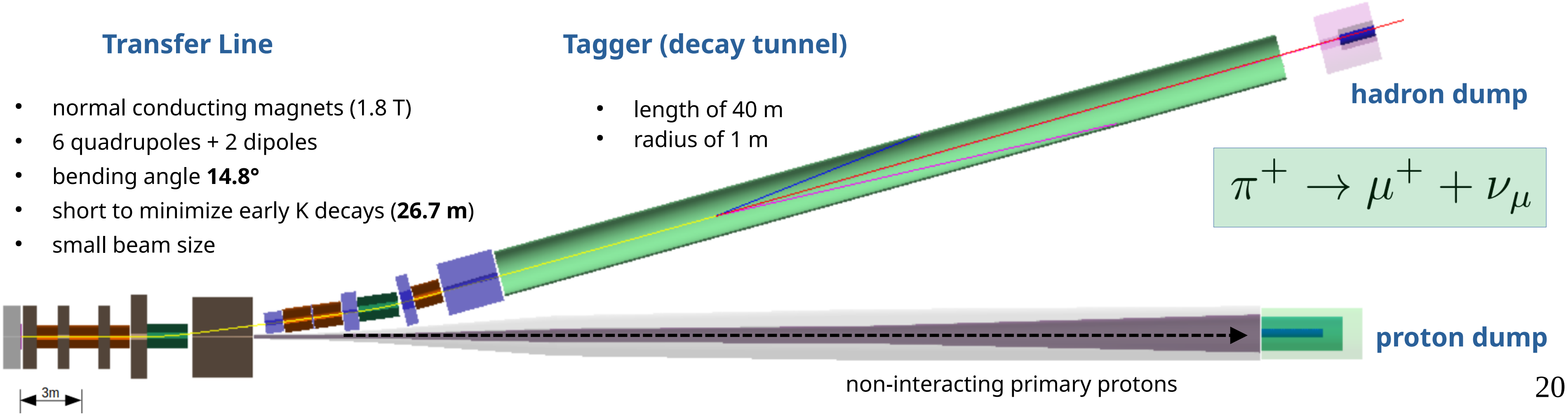
**Transfer Line**

- normal conducting magnets (1.8 T)
- 6 quadrupoles + 2 dipoles
- bending angle **14.8°**
- short to minimize early K decays (**26.7 m**)
- small beam size

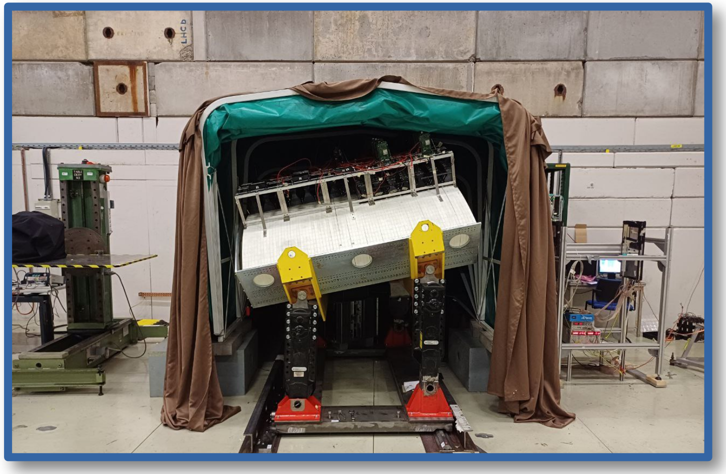
**Tagger (decay tunnel)**

- length of 40 m
- radius of 1 m

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

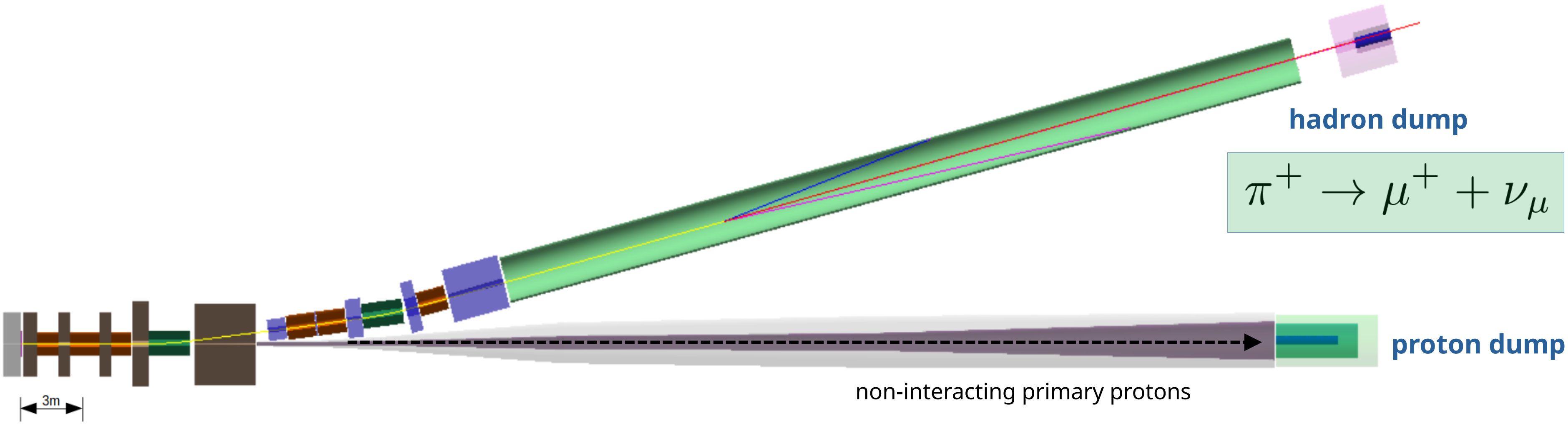


# The ENUBET demonstrator



Assembled in INFN-Legnaro, charged beam tested at CERN several times under NP06/ENUBET experiment

# A neutrino detector in the monitored beam



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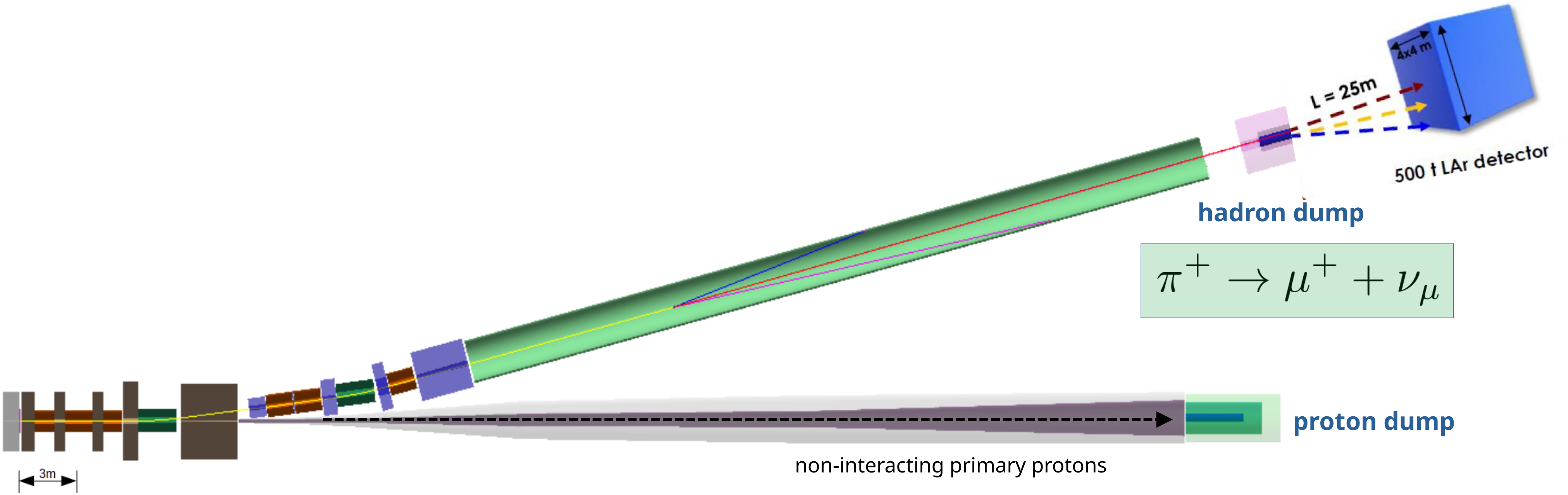



$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

Say, ProtoDUNE? That is already at CERN? Or maybe WCTE?

# The narrow-band off-axis technique

**Narrow-band off-axis technique**

narrow momentum beam O(10%)

↓

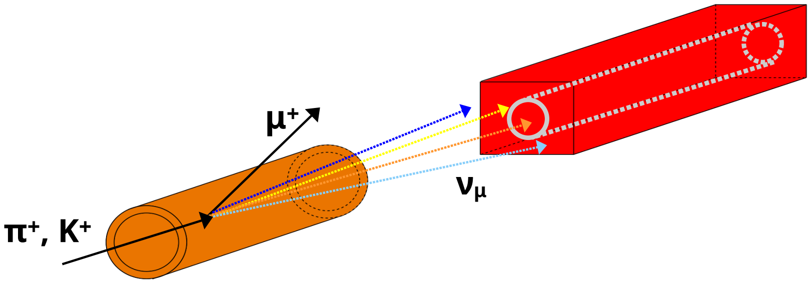
**($E_\nu$, r) are strongly correlated**

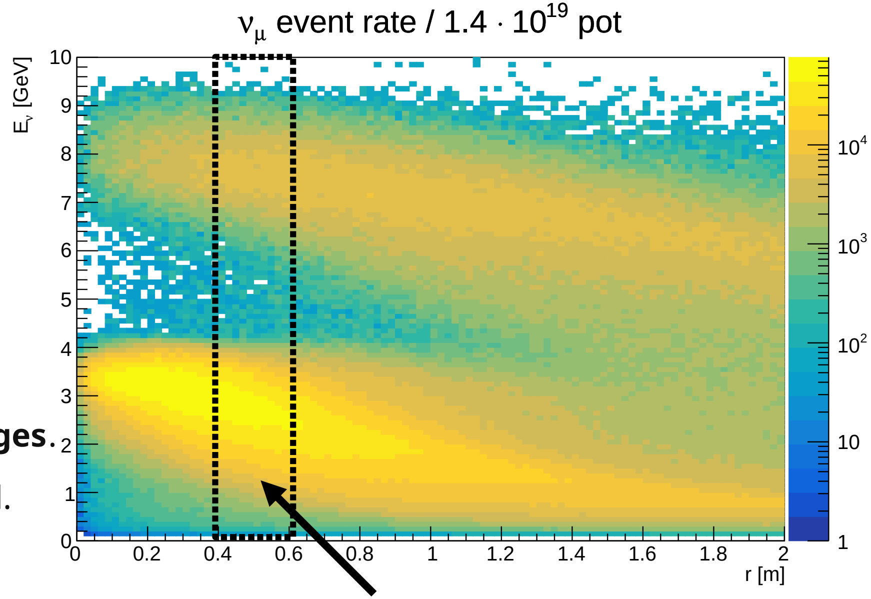
- **$E_\nu$** = neutrino energy
- **r** = radial distance of interaction vertex from beam axis

⬇

**precise determination of $E_\nu$ :**

**w/o relying on reconstruction of final state particles from $\nu_\mu$ interactions**




- **$\nu_\mu$ interacting at different off-axis angles span different energy ranges.**
- selecting a radial slice, a flux narrower than the total flux can be probed.
- **10 radial slices**, each spanning a **20 cm window**.
  - access to different energy spectra probing many off-axis angles (0 - 4.5°)

select $\nu_\mu$ with given energy with a radial cut



Courtesy of F. Bramati

# The narrow-band off-axis technique

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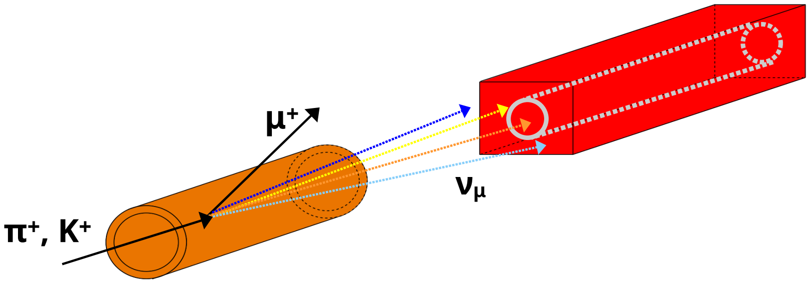


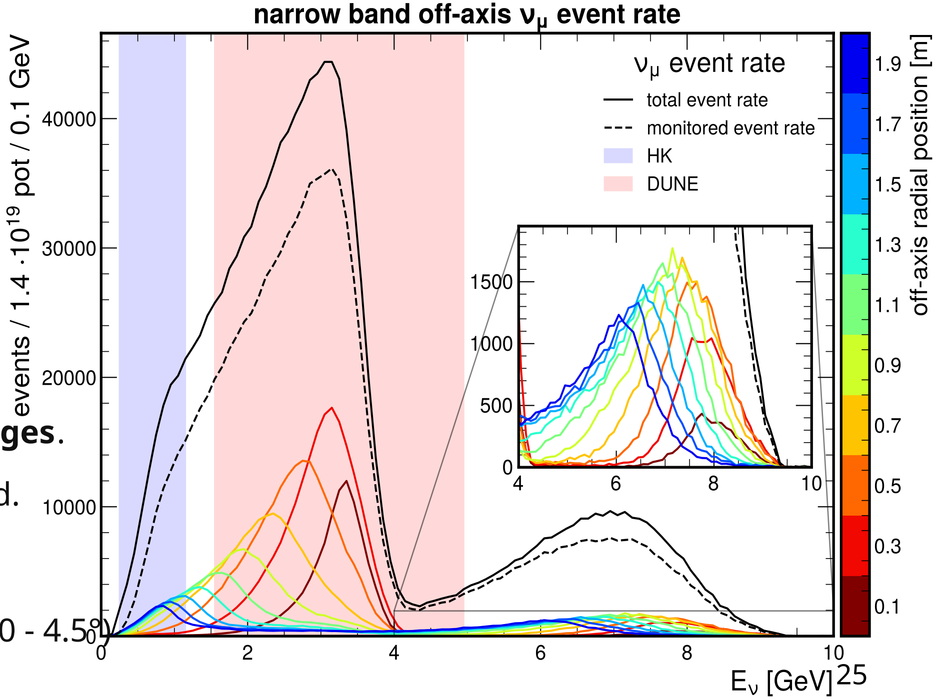


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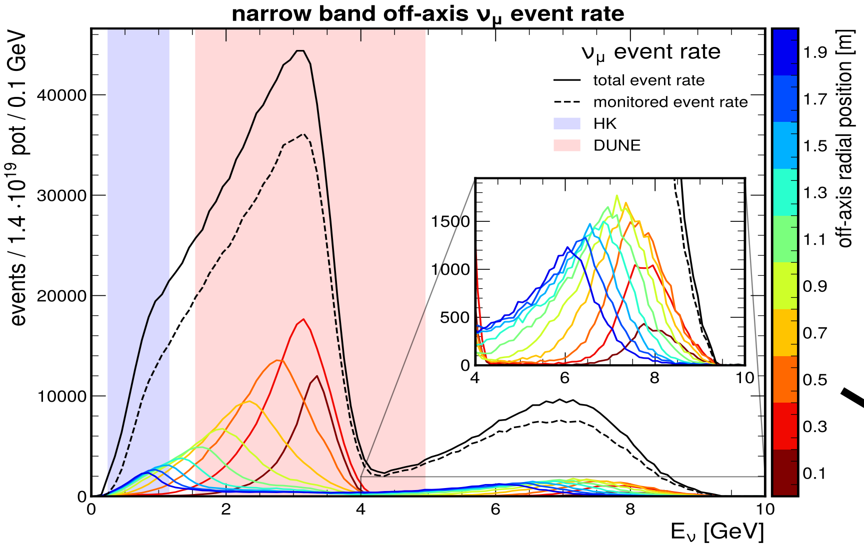
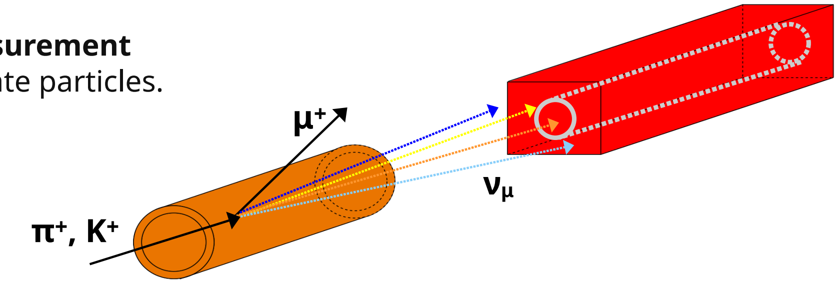
Courtesy of F. Bramati

# flux averaged $\nu_\mu$ CC inclusive cross section measurement

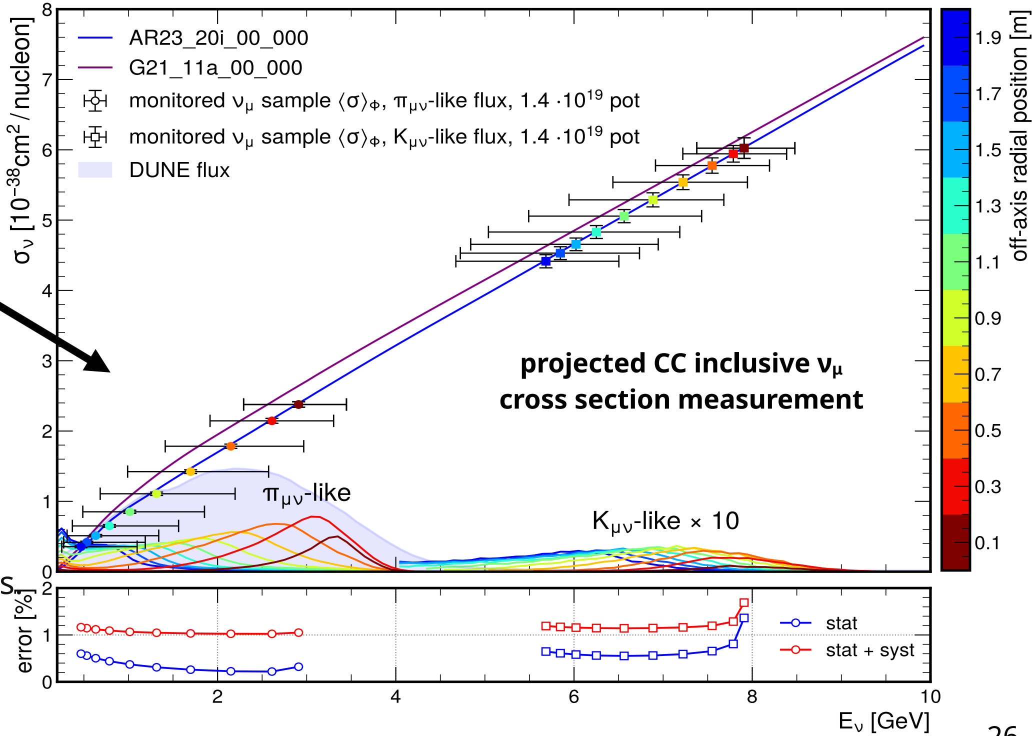
- The narrow band off-axis technique can provide an **“a priori” measurement of neutrino energy** for $\boldsymbol{\nu_\mu}$ w/o relying on reconstruction of final-state particles.




- The **$\pi_{\mu\nu}$- and $K_{\mu\nu}$-like** peaks in the narrow band off-axis fluxes can be separated using an energy cut at ~ 4 GeV.
- Since **$\pi_{\mu\nu}$** and **$K_{\mu\nu}$** peaks are well separated, **flux averaged neutrino cross section** can be measured using both peaks.

$$\langle \sigma \rangle_\Phi = \frac{N_{\text{events}}}{\Phi N_{\text{tgt}} N_{\text{PoT}}}$$




horizontal error bars encase the flux width (68% percentiles wrt mean energy)

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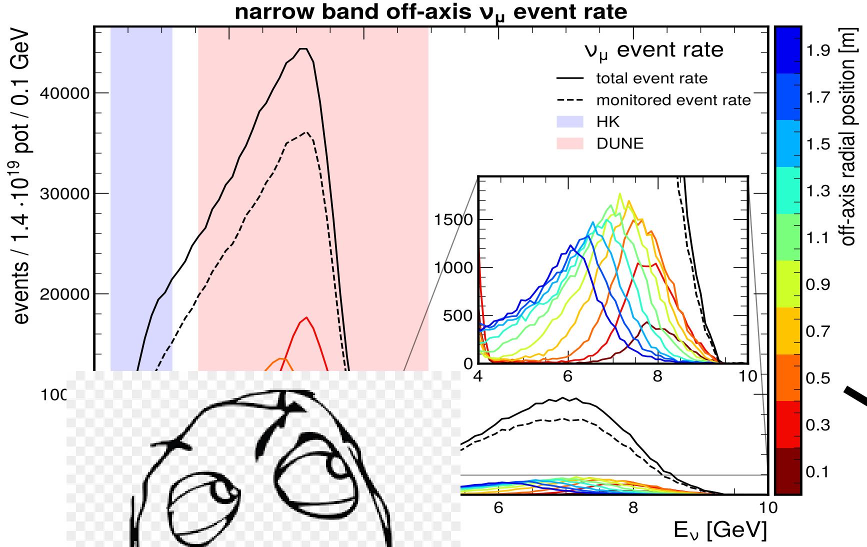


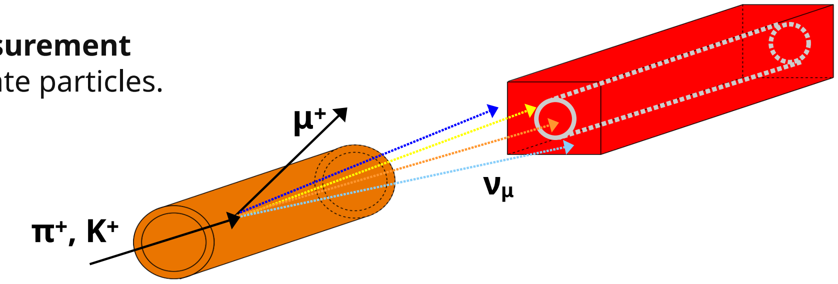


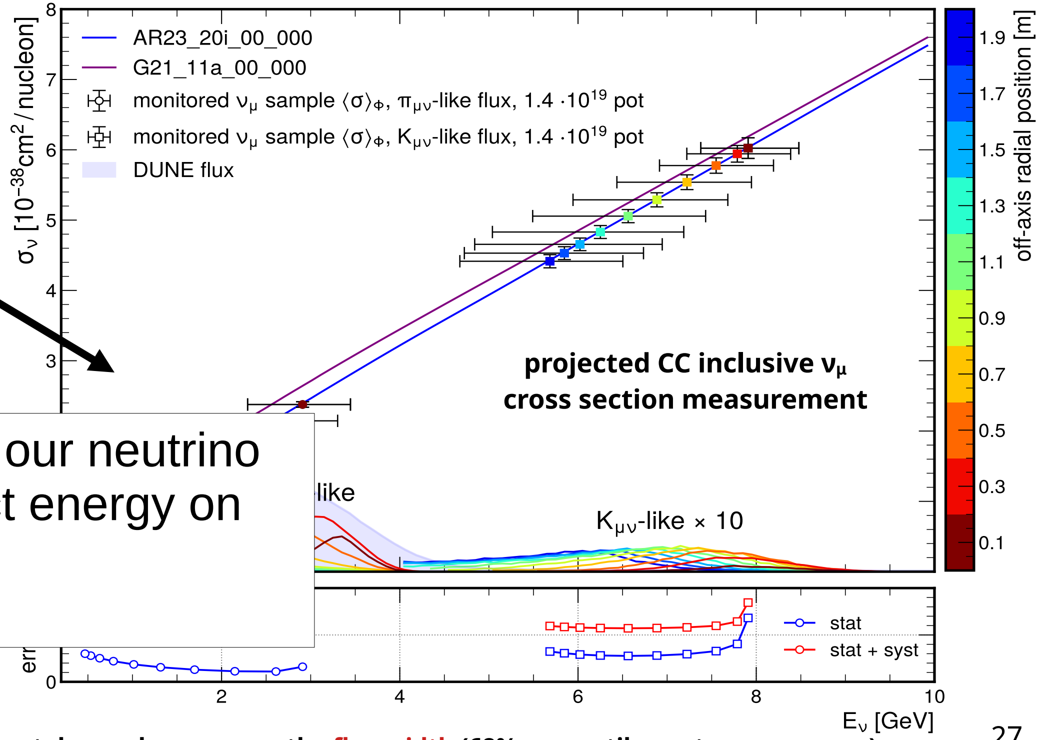


- k…
- u…
- Since … peaks ar… **neutrino cross section** ca…

But, can’t we just use our neutrino detector to reconstruct energy on event-by-event basis?

$$\langle\sigma\rangle_\Phi = \frac{N_{\text{events}}}{\Phi N_{\text{tgt}} N_{\text{PoT}}}$$

**horizontal error bars encase the flux width (68% percentiles wrt mean energy)**

Courtesy of F. Bramati

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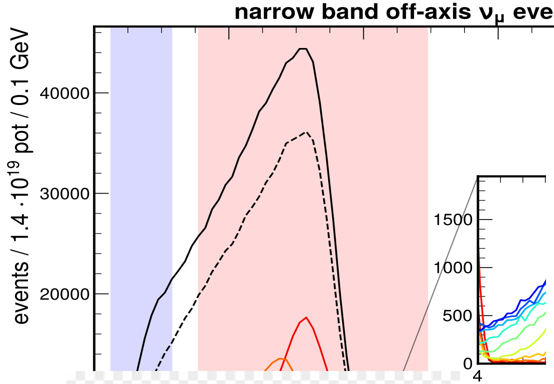


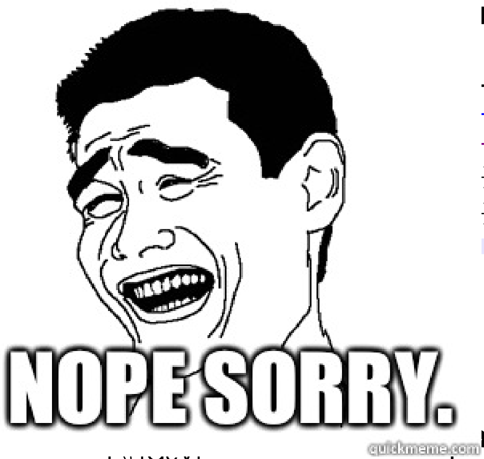


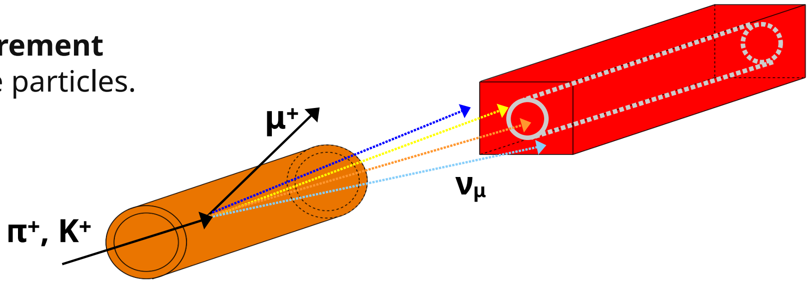


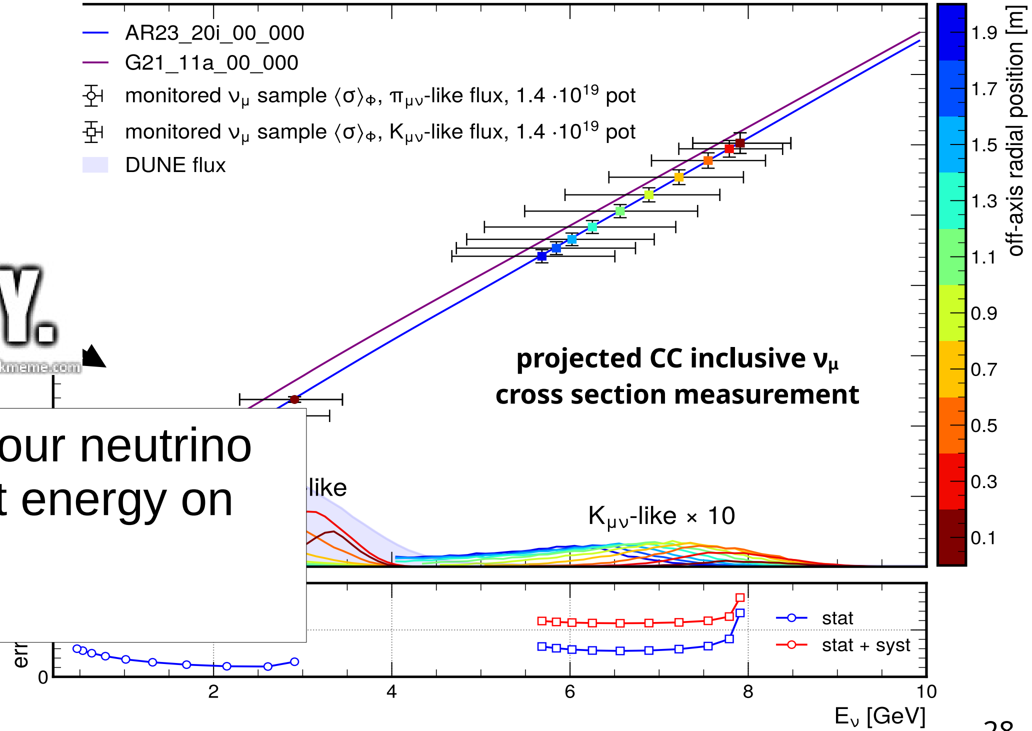


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But, can’t we just use our neutrino detector to reconstruct energy on event-by-event basis?

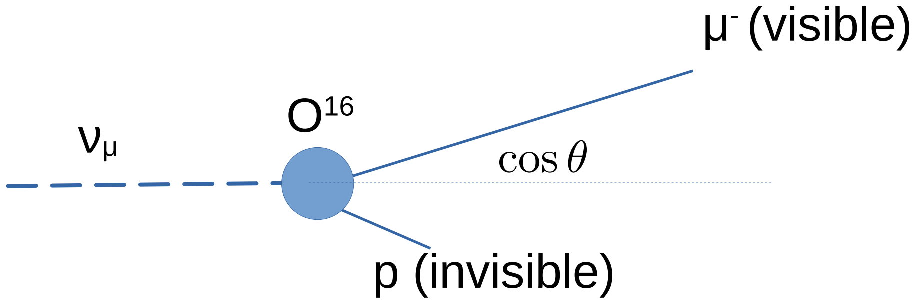
- …
- … **neutrino cross section** ca…

$$\langle\sigma\rangle_\Phi = \frac{N_{\text{events}}}{\Phi N_{\text{tgt}} N_{\text{PoT}}}$$

Courtesy of F. Bramati

# Energy reco problem

**Water Cherenkov detector**

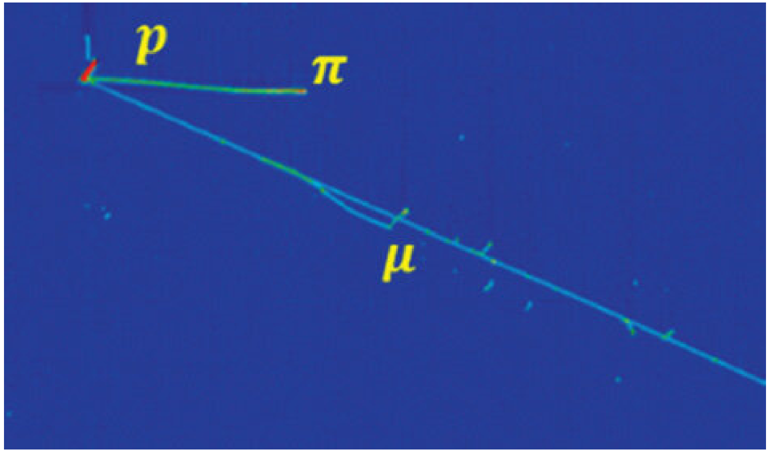



Example: $\nu_\mu$ CC QES interaction

Assume:
1. Basic reaction: $\nu_\mu + n \rightarrow \mu^- + p$ (CCQES)
2. Neutron free and at rest

Calculate:
$E_\nu$ from $\mu^-$ momentum and $\cos\theta$
→ Uncertainty and **bias** (use model to compensate)

**LArTPC**




Most FS charged particles visible.
Neutral ones problematic: use model
→ uncertainty and **bias**

Both examples use neutrino interaction model (differential xsec) to measure energy which is then used to measure total xsec as function of energy.

ENUBET is a **monitored** neutrino beam: we know the flux a-priori, but have limited knowledge of nu energy on event-by-event basis

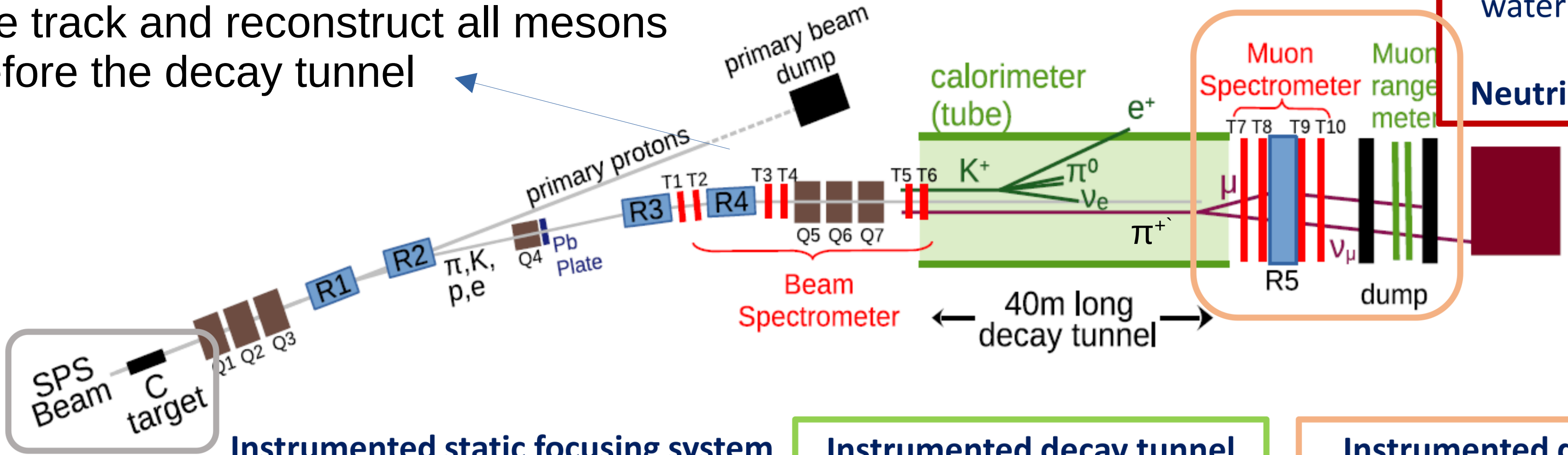
**Can we go further?**

# Tagged neutrino beam

- Connect each neutrino interaction with its parent particle and corresponding parent meson
  - kinematically closed system for two-body decay: a-priori knowledge of the neutrino energy at <1% level
  - requires tracking of all primary mesons and secondary leptons
- No detector bias/uncertainty on netrino energy: **“perfect” measurement of the (differential) cross-section**
  - proposed with modern techniques in 2022, R&D from the **NP06** and **NuTAG** Collaboration (paper here)
- **nuSCOPE: merge of NuTAG and ENUBET techniques**

# The nuSCOPE implementation

We track and reconstruct all mesons before the decay tunnel




Liquid argon and water Cherenkov/ WBLS
**Neutrino detectors**

**Proton accelerator:**
CERN SPS (400 GeV/c)
Carbon target

**Instrumented static focusing system**
Two quadrupole triplet, four dipoles, six silicon trackers for momentum measurement and tagging

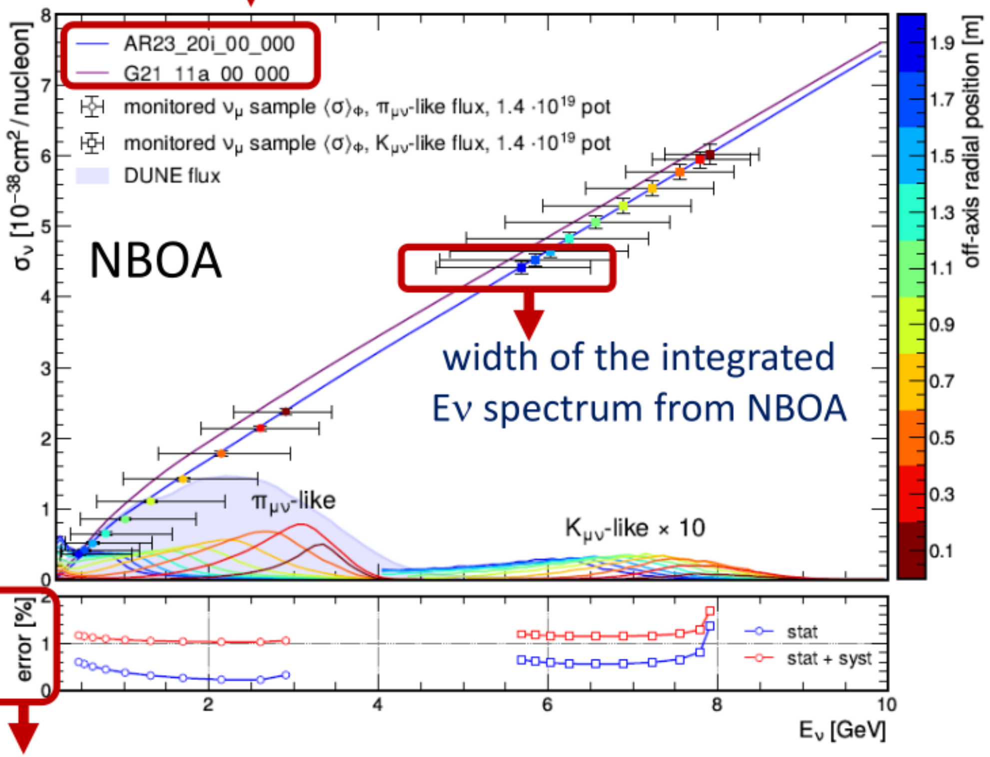
**Instrumented decay tunnel**
Segmented Fe-scint calorimeter for lepton monitoring in the tunnel wall

**Instrumented dump**
Muon spectrometer and muon range-meter

Event-by-event energy reconstruction from neutrino parent particle kinematics!

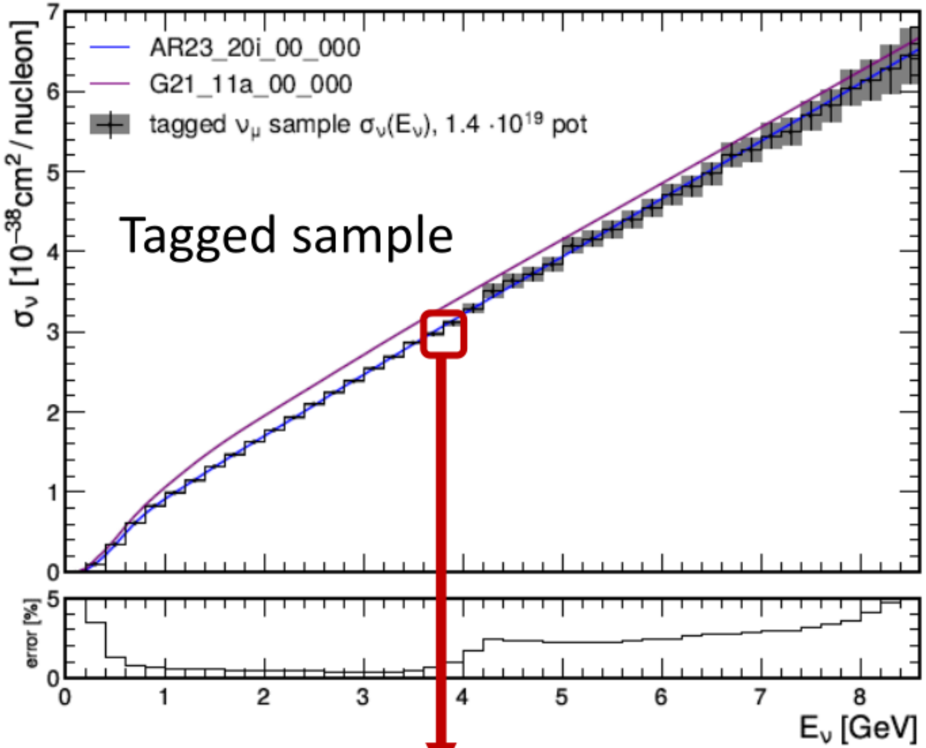
# The energy dependence of $\nu_\mu$ cross section

it illustrates sensitivity to theory models




width of the integrated Eν spectrum from NBOA

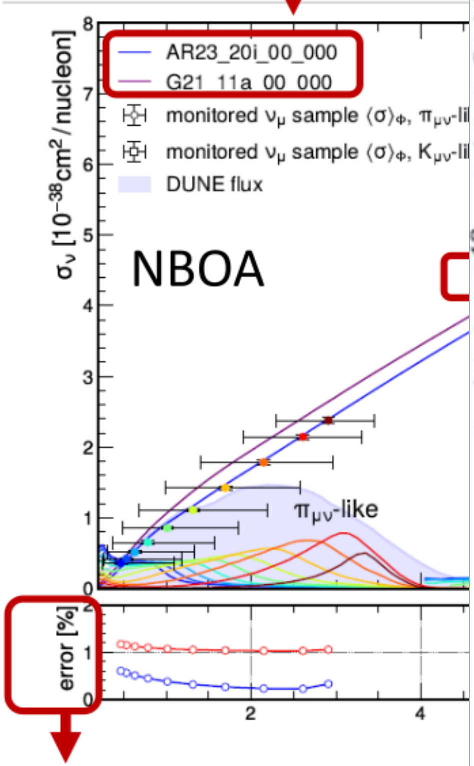
stat.+sys. error




in the golden tagged sample, the integration width is no more driven by the energy uncertainty (<1% !!) but just by statistics

# The energy dependence of $\nu_\mu$ cross section

it illustrates sensitivity to theory models

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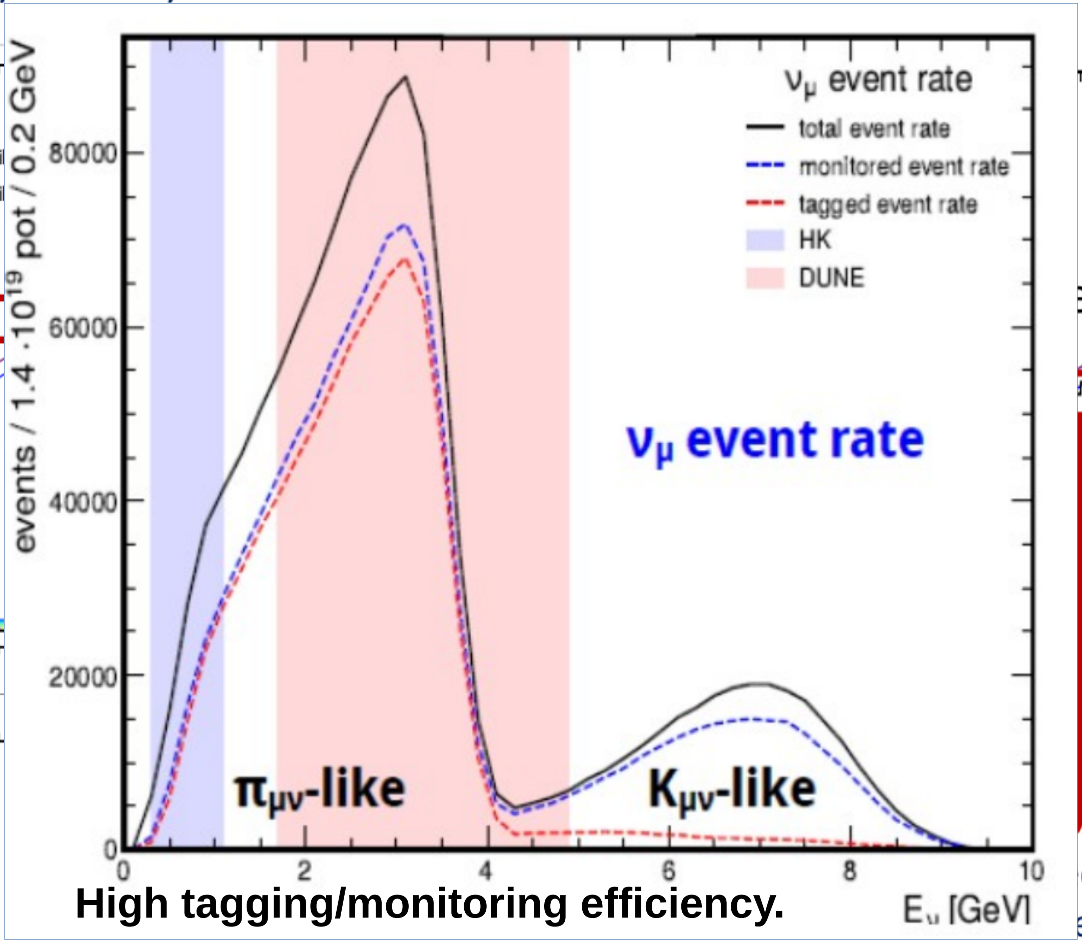


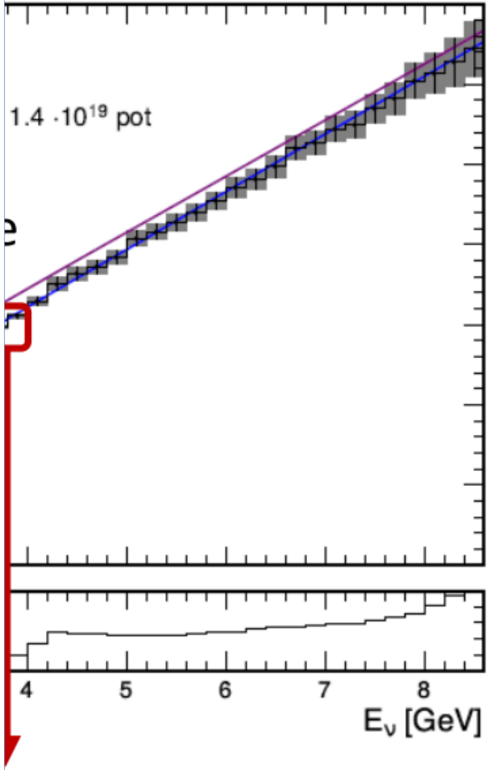


d sample, the integration

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uncertainty (<1% !!) but just by statistics

# Measurements "menu"

**1) Energy dependence of the neutrino cross section** → know how to extrapolate from near to far detectors in oscillation experiments

**2) Smearing of neutrino energy reconstruction** → infer the shape of the oscillated spectrum in DUNE/HyperKamiokande

**3) differences in the cross section for $\nu_e$ and $\nu_\mu$** → reliably use $\nu_e$ appearance to probe CP violation

**4) Interaction channels that constitute backgrounds**
(e.g. NC-$\pi^0$ production)
→ how to interpret far detector event Rates in DUNE/HyperKamiokande

**5) $\nu$-N elastic scattering with tagged $\nu_\mu$**
The axial counterpart of e-N elastic scattering

Many **other channels** not covered because they are work in progress exclusive channels, non-standard interactions, dark sector probes, sterile neutrinos, etc.

# References

## Documents


- ENUBET proposal: https://link.springer.com/article/10.1140/epjc/s10052-015-3378-9
- ENUBET design: https://link.springer.com/article/10.1140/epjc/s10052-023-12116-3
- NuTAG paper: https://link.springer.com/article/10.1140/epjc/s10052-022-10397-8
- nuSCOPE paper: https://arxiv.org/abs/2503.21589


## Talks


- https://indico.cern.ch/event/1558536/contributions/6564236/attachments/3085203/5473427/bramati_nuSCOPE_v1.pdf
- https://www.hep.ph.ic.ac.uk/seminars/slides/2025/FTerranova.pdf
- https://indico.in2p3.fr/event/36107/contributions/153939/attachments/93151/142490/nuSCOPE_12June2025_Longhin_v4.pdf

# Conclusions

- Neutrino xsec is a leading uncertainty of the future leptonic CPV measuring experiments
  - experimental measurements of xsec needed
- ENUBET is a **monitored** neutrino beam
- nuSCOPE is a **tagged** neutrino beam, merge of ENUBET and NuTag collaborations
  - a-priori knowledge of neutrino energy at sub-percent level allows an unprecedented precision of xsec measurement
- Proposal of the new facility at CERN to perform these measurements

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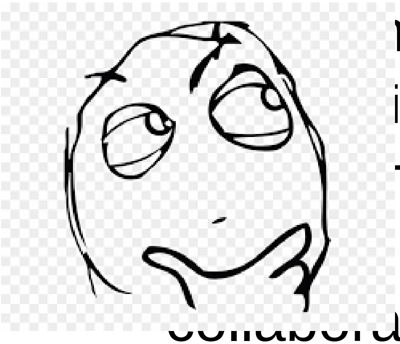

We've been successfully doing experimental neutrino physics for 70 years now, why are xsecs suddenly such a problem?

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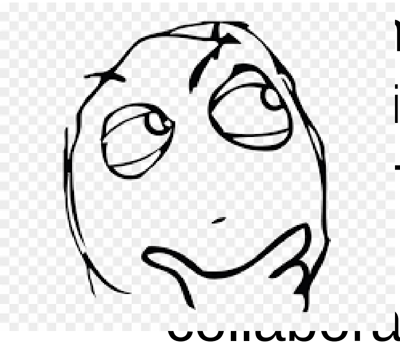
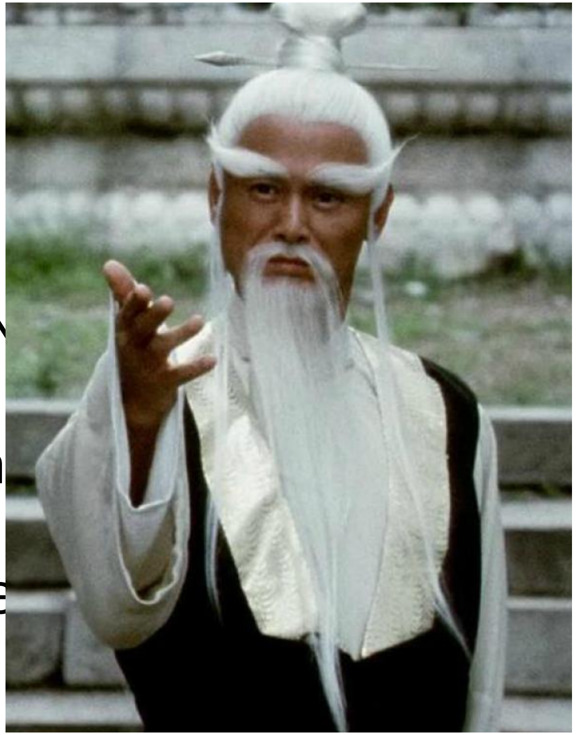


Experiments didn't have enough statistics.

We've been successfully doing experimental neutrino physics for 70 years now, why are xsecs suddenly such a problem?



# BACKUP

# Technical readiness of nuSCOPE

Is nuSCOPE "ready for construction"? While most of the facility relies on validated technologies, there are still areas that require full confirmation. In particular,

| Beamline | | |
|---|---|---|
| Design | OK | Still room for improvement in reduction of non-monitored ν |
| Components | OK | Standard and existing (at CERN) components |
| Slow extraction | in progress | Depends on final implementation |
| Infrastructure | in progress | Depends on final implementation |

| Diagnostics for lepton monitoring/tagging | | |
|---|---|---|
| Decay tunnel instrumentation | OK | ENUBET R&D (2016-2022) |
| Hadron dump | in progress | ENUBET+PIMENT R&D (2021-ongoing) |
| Silicon tracking planes | R&D | The technologies are identified within HL-LHC R&D but not yet fully validated |
| Outer tracking planes and muon spectrometer | in progress | Technologies are identified but design and validation in progress |

| Neutrino detectors | | |
|---|---|---|
| Liquid argon | in progress | Based on ProtoDUNE's technologies with enhanced light detection (ProtoDUNE Run III) |
| Water Cherenkov - WBLS | OK | Based on WCTE's technology or Water Based Liquid Scintillators (WBLS) |
| Muon catcher and cosmic ray veto | in progress | Depends on final implementation |