# Physics opportunities at $\nu$STORM & ENUBET

**Matheus Hostert**

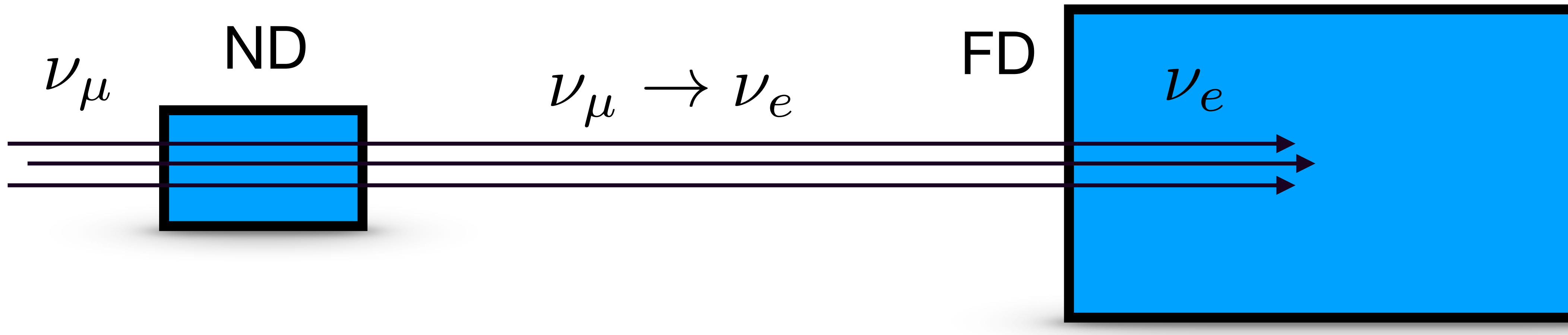
mhostert@perimeterinstitute.ca

University of Minnesota & Perimeter Institute

Neutrino from STORed Muons

nuSTORM meeting 08/08

# Challenges of GeV neutrino beams



- Large scale next-generation accelerator neutrino facilities:
    - Precise measurement of CP violating phase in the leptonic sector.
    - DUNE & Hyper-Kamiokande — both measurements will be systematics dominated

$$R = \Phi_{\nu_\mu}(E_\nu) \times P_{\nu_\mu \to \nu_e} \times \left( \sum_{\nu X \to e X'} \sigma_{\nu_e}(E_\nu) \times \epsilon(E_\nu, E_\nu^r) \right)$$

Neutrino flux
~ 10% uncertainties

The physics

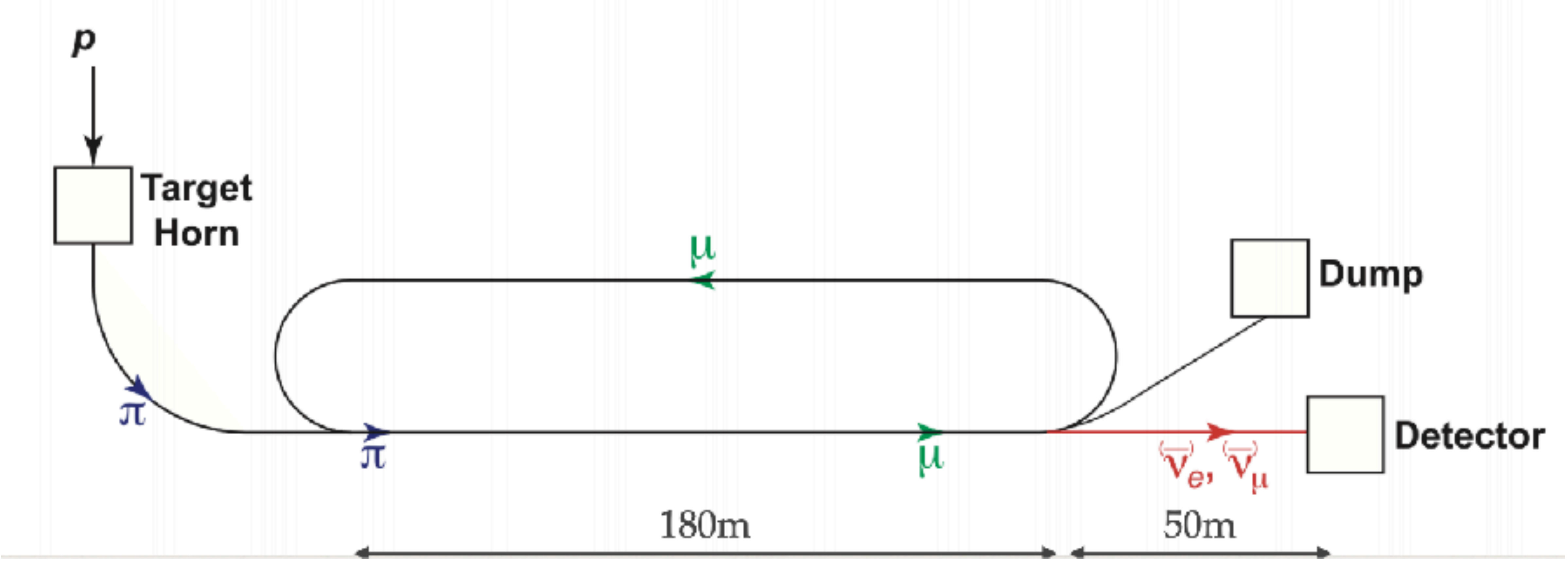
Neutrino-nucleus cross sections

1) **Energy spectrum is not the same between ND and FD (oscillation and geometry).**
2) **Near-to-far detector ratio is not robust against detector systematics.**
3) **Low stats and large bkgs in electron-neutrino (exclusive) measurements at the near detector**

# The $\nu$STORM concept

## Neutrinos from STORed Muons

- A **precision** neutrino facility — 1% flux uncertainties
  1) neutrino-nucleus **cross sections,**
  2) **Muon collider** demonstrator and test-bed.
  3) **new physics** at short-baselines,



Fermilab (2012)

nuSTORM coll., FERMILAB-LOI-2013-02, arXiv:1206.0294

nuSTORM coll., Proposal to the Fermilab PAC, arXiv:1308.6822

Effort redirected to CERN (2013)

nuSTORM coll., Expression of Interest CERN, arXiv:1305.1419

CERN (2019) PBS study

nusSTORM coll. CERN PBC REPORT 2019-003

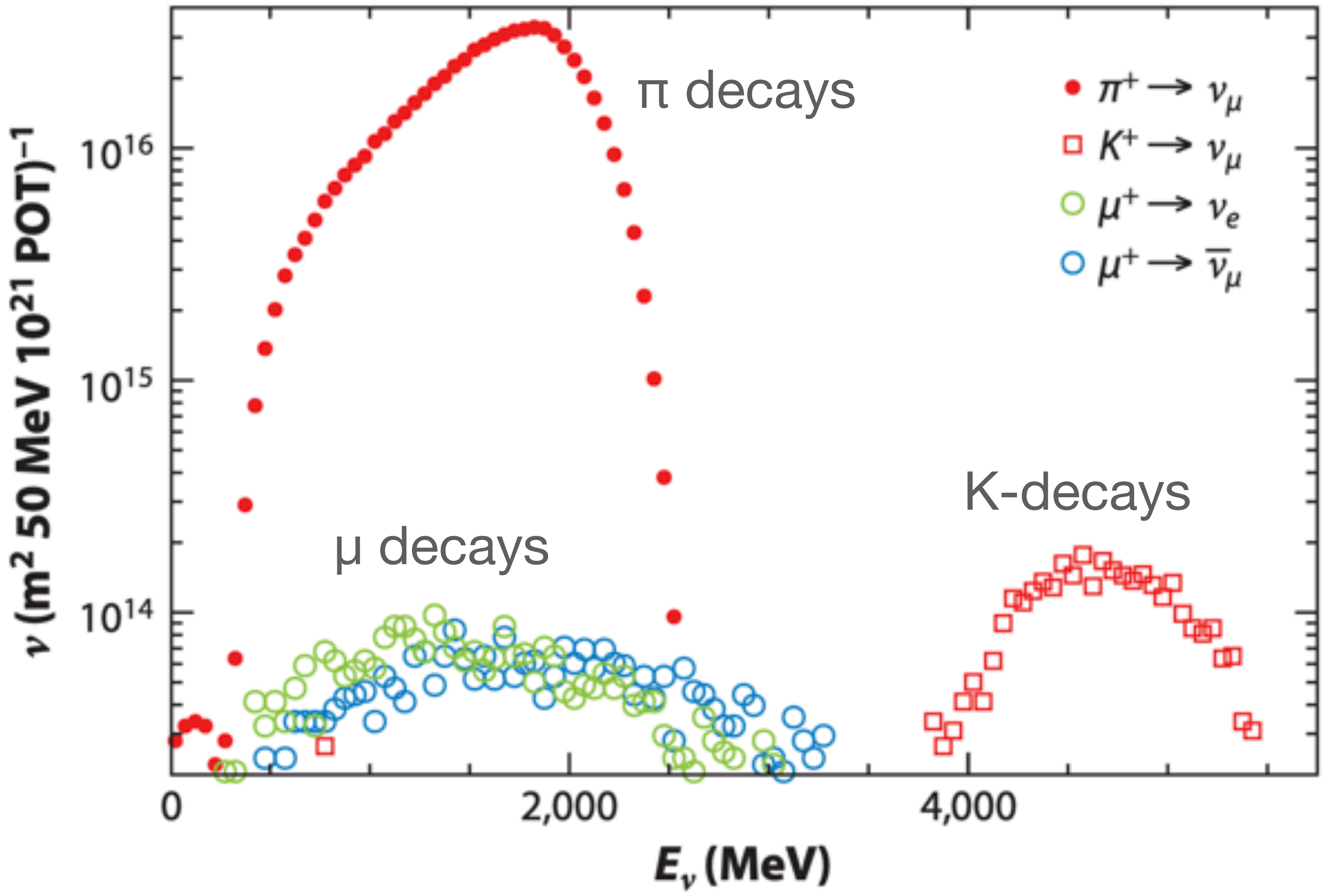
# The νSTORM flux

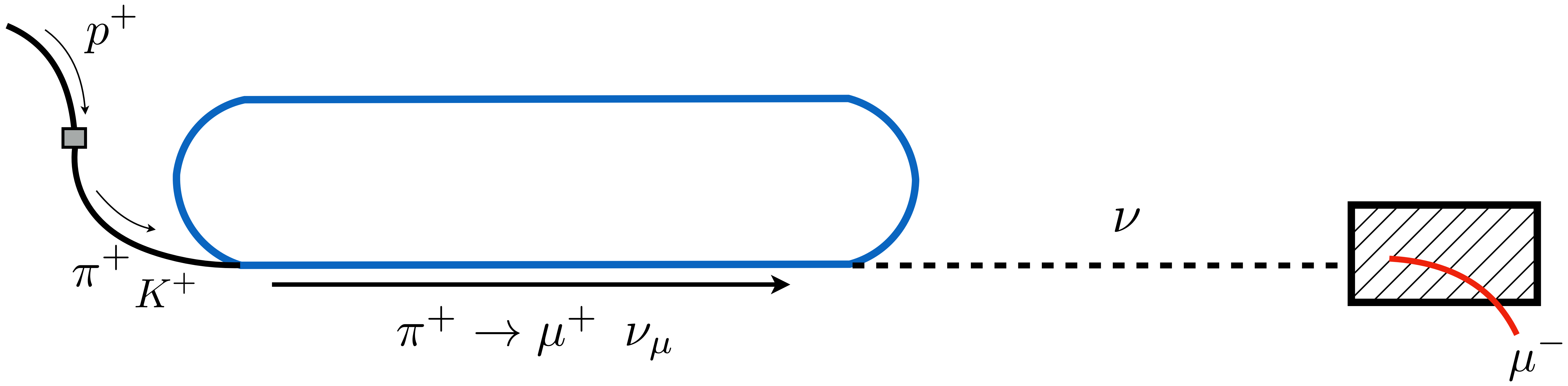
- Usual 5 GeV/c $\pi^\pm$ injection, and 1—6 GeV/c stored $\mu^\pm$

$\pi^+ \to \mu^+ \ \nu_\mu$ Pion-flash

$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$ Stored muons

**Pion-flash**





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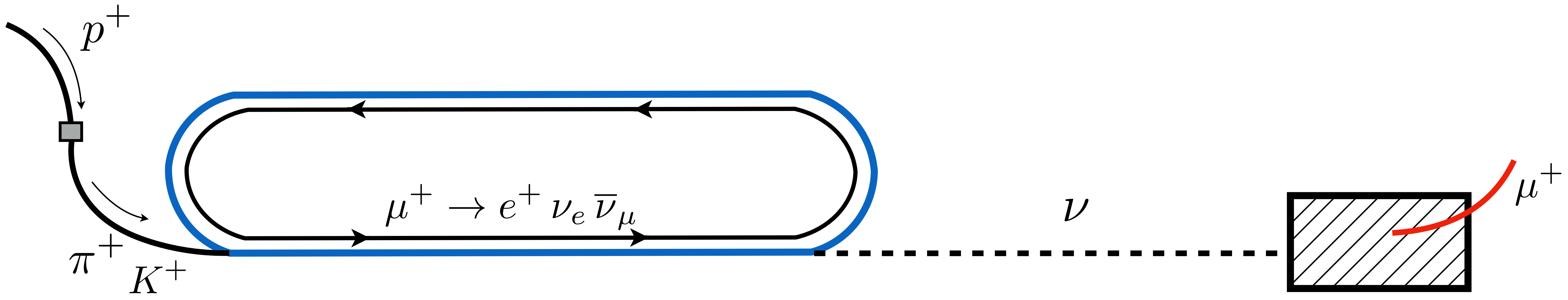
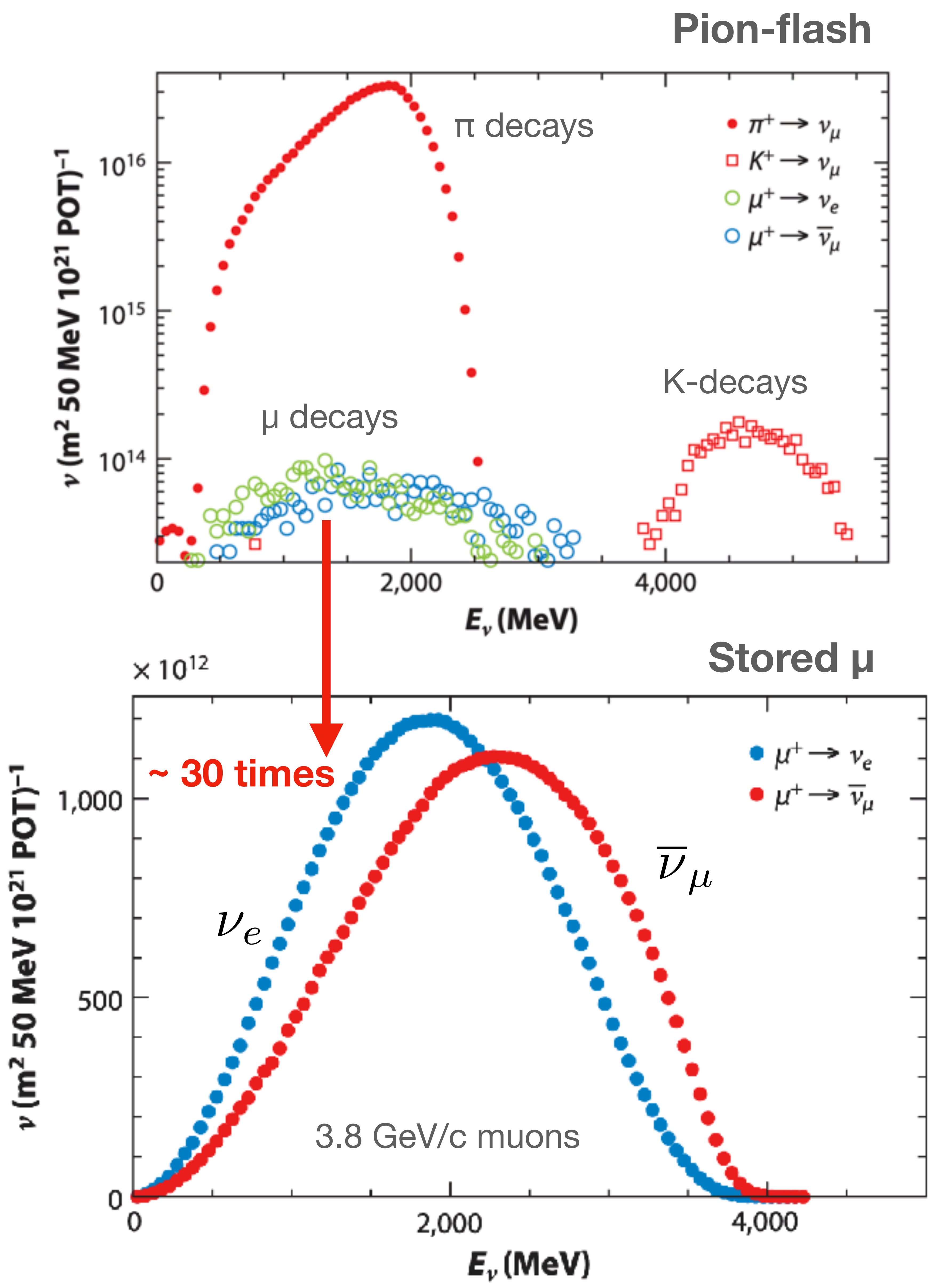
- Precision neutrino source:
  - Well-known rate, energy spectrum, and composition
  - unique flavor composition — $(\nu_e : \overline{\nu_\mu}) = (1:1)$
  - monitored beam line

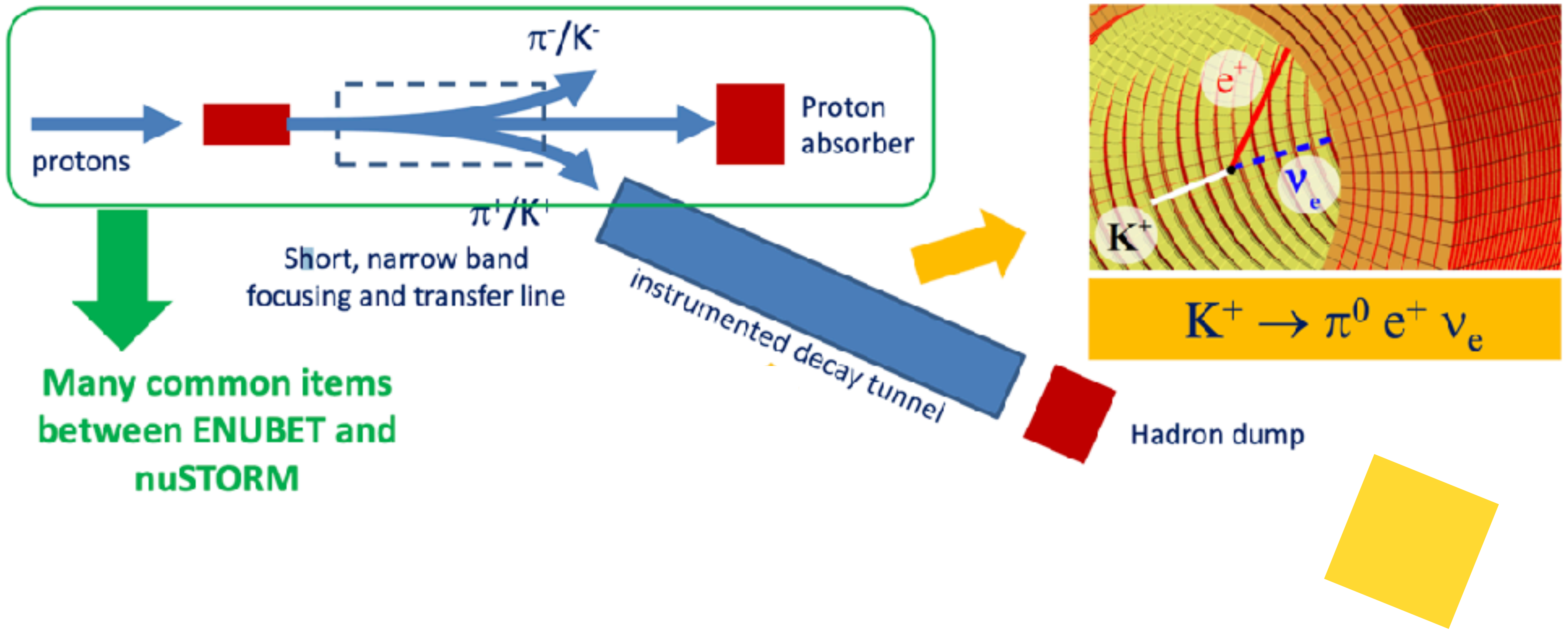




# The ENUBET concept

## Enhanced NeUtrino BEams from kaon Tagging

A. Longhin, L. Ludovici, F. Terranova, EPJ C75 (2015) 155



**Many common items between ENUBET and nuSTORM**

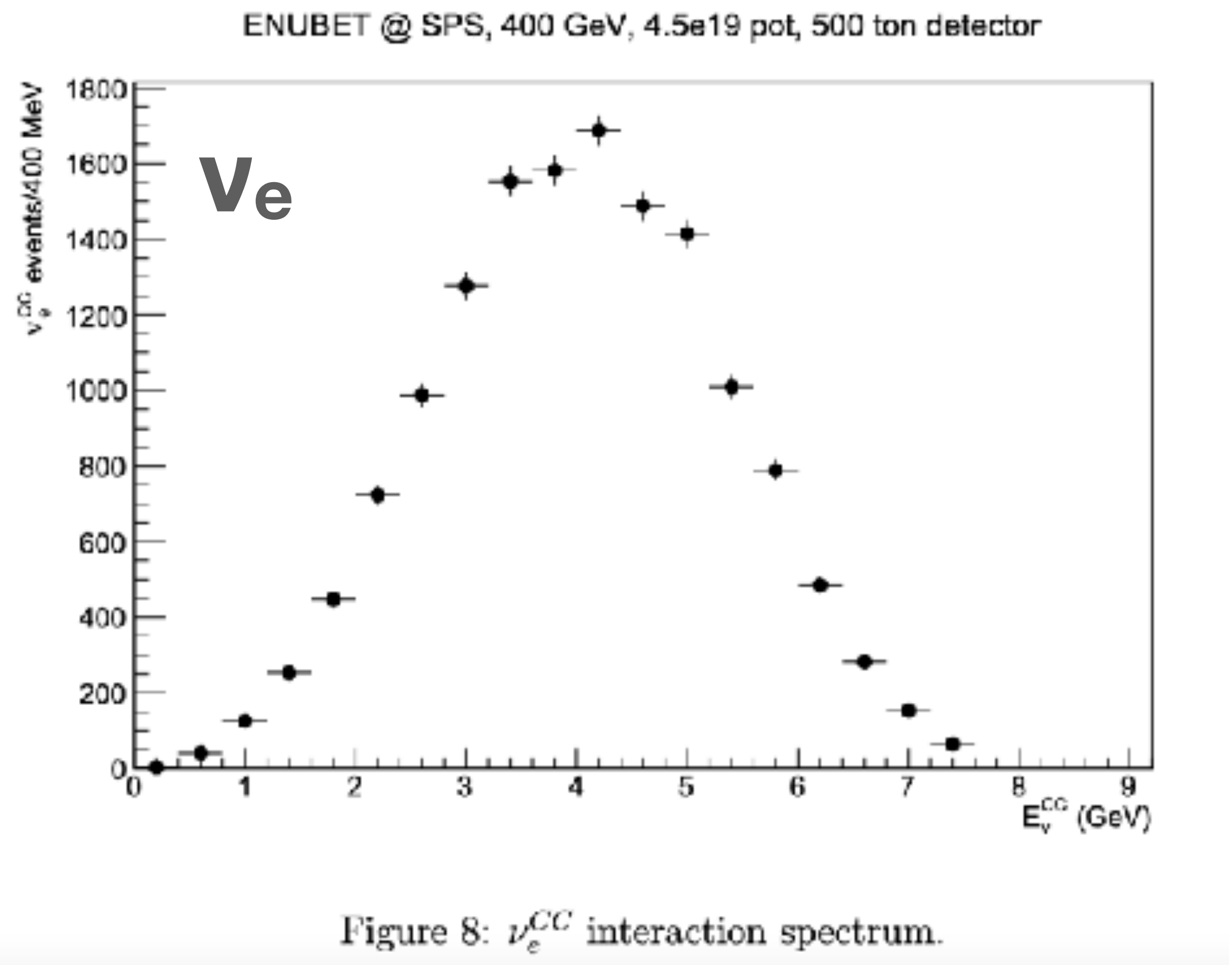
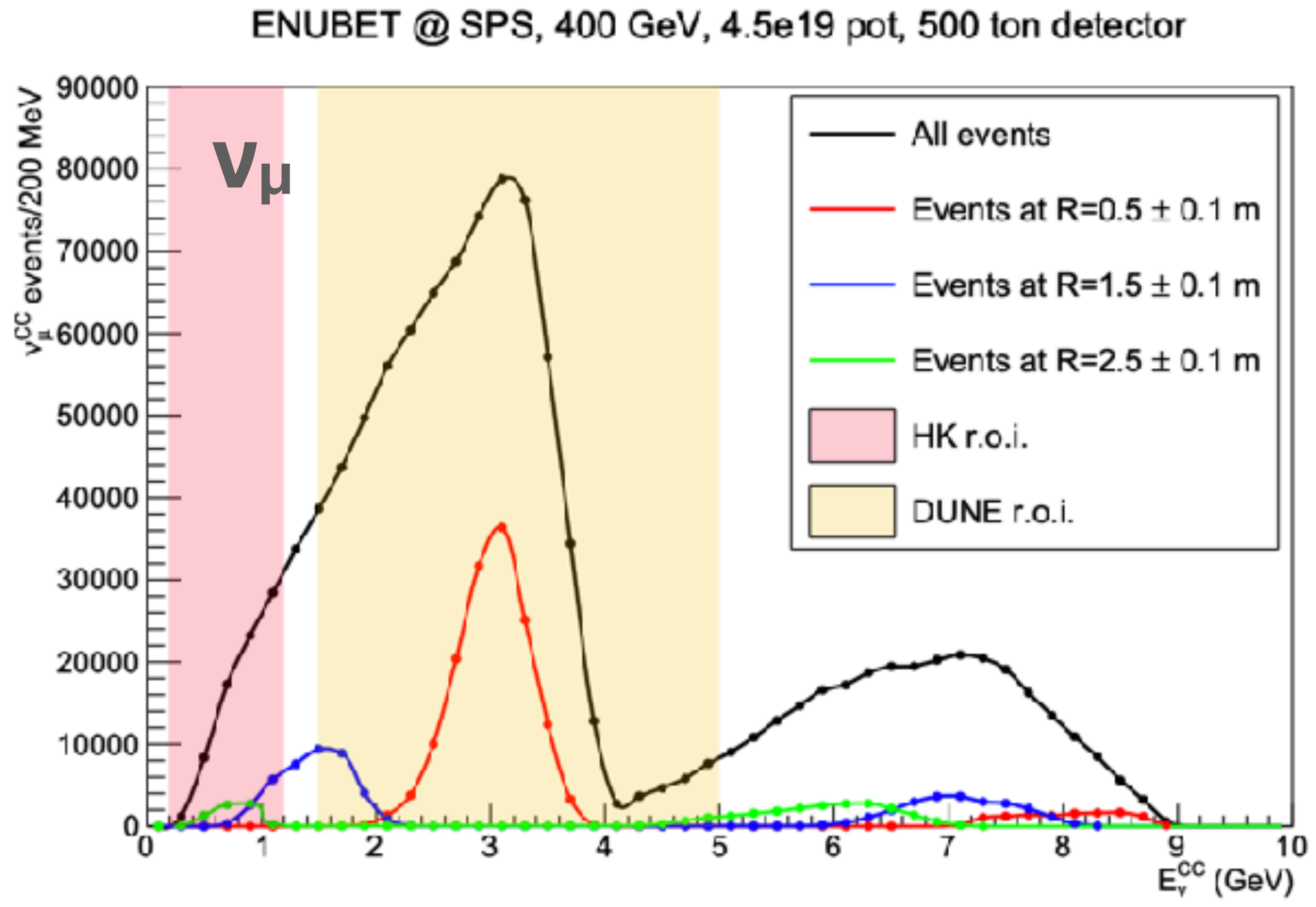


Figure 8: $\nu_e^{CC}$ interaction spectrum.



Possibility to tag:

**$K \longrightarrow \pi 0\ e+\ \nu_e$**

and

**$K \longrightarrow \mu\ \nu_\mu$**

**$\pi \longrightarrow \mu\ \nu_\mu$**

➤ A **precision** neutrino facility — 1% flux uncertainties

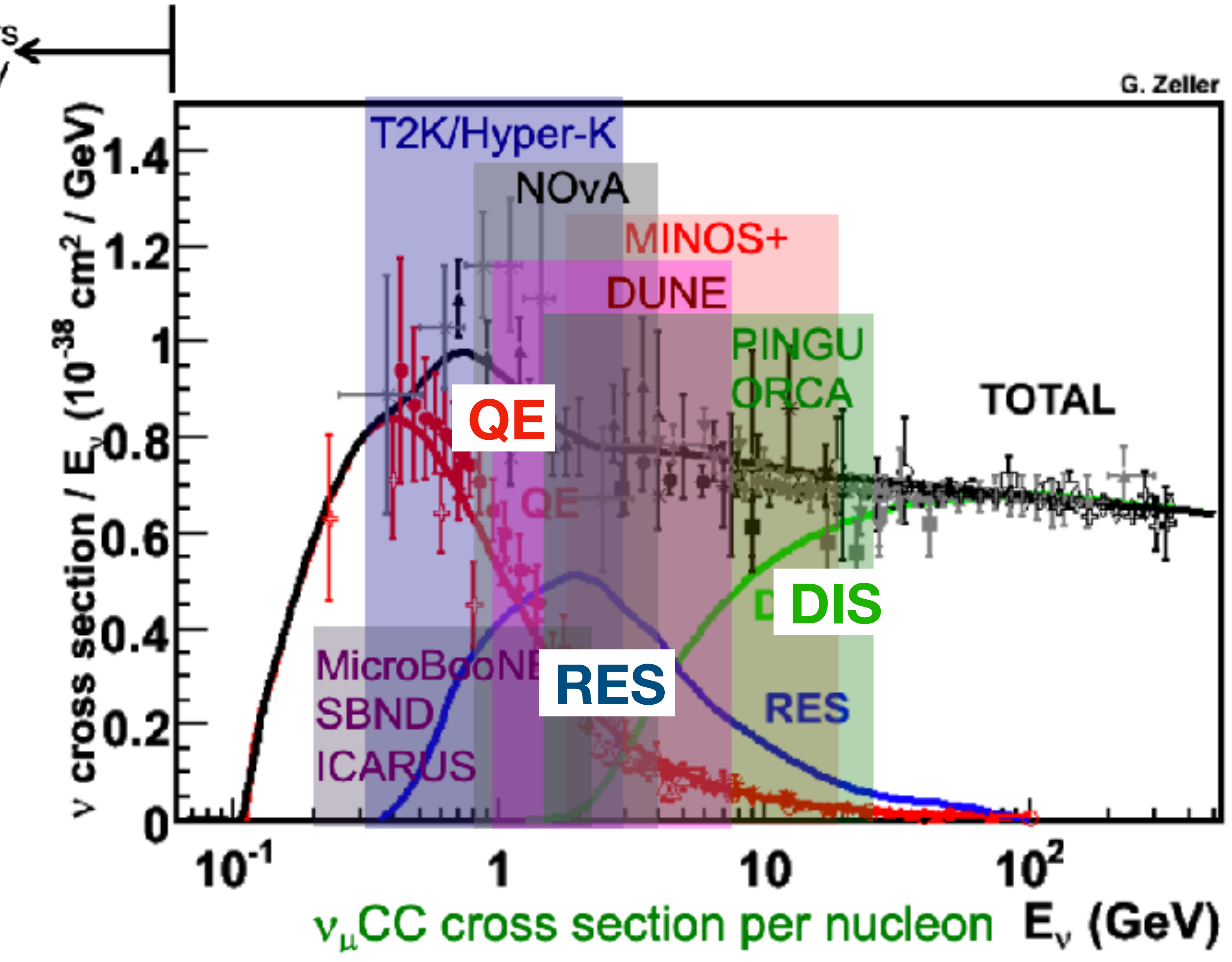
1) **electron-neutrino scattering on nuclei,**

2) new physics at **short-baselines**

3) first **tagged neutrino beam**

# The GeV neutrino energy region — cross sections

Accelerator neutrino fluxes span a challenging region:
**Poorly measured cross sections** and several **overlapping regimes** in **nuclear medium.**



See NuSTEC white paper — 10.1016/j.ppnp.2018.01.006.

By L. Alvarez

- **Neutrino QE scattering**
  - Axial form factor of the nucleon
- **Inelastic scattering**
  - Dominated by Δ(1232) resonance — single pion and photon production
  - Several other overlapping resonances + interference effects
- **Shallow inelastic scattering**
  - Low $Q^2$ and W region — transition region: quark-hadron duality
- **Deep inelastic scattering**
  - Better understood, but also subject to in-nuclear-medium effects.

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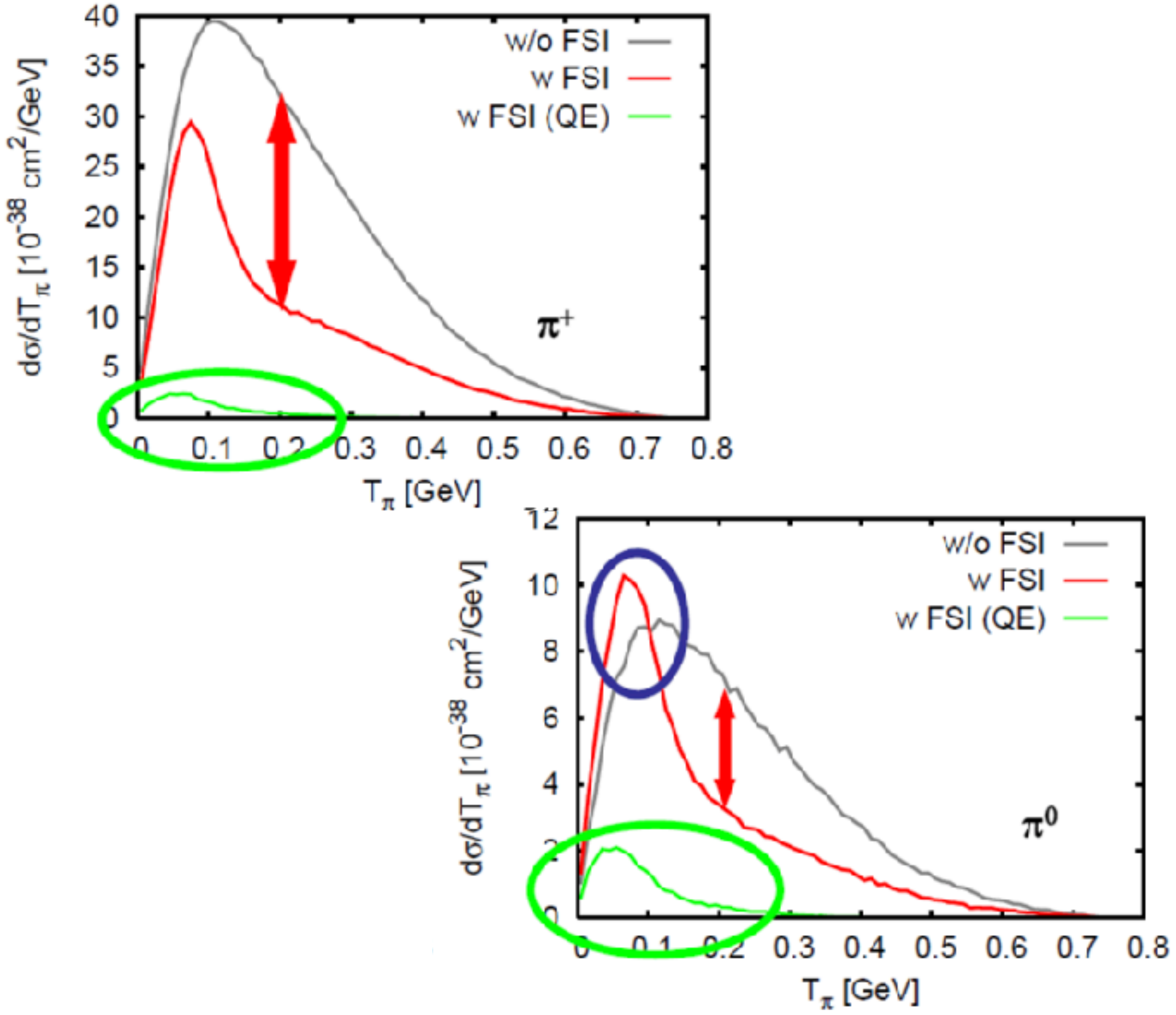
Leitner, LAR, Mosel, PRC 73 (2006)



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Measuring these contributions requires **well known flux** and **ability to measure exclusive final states**

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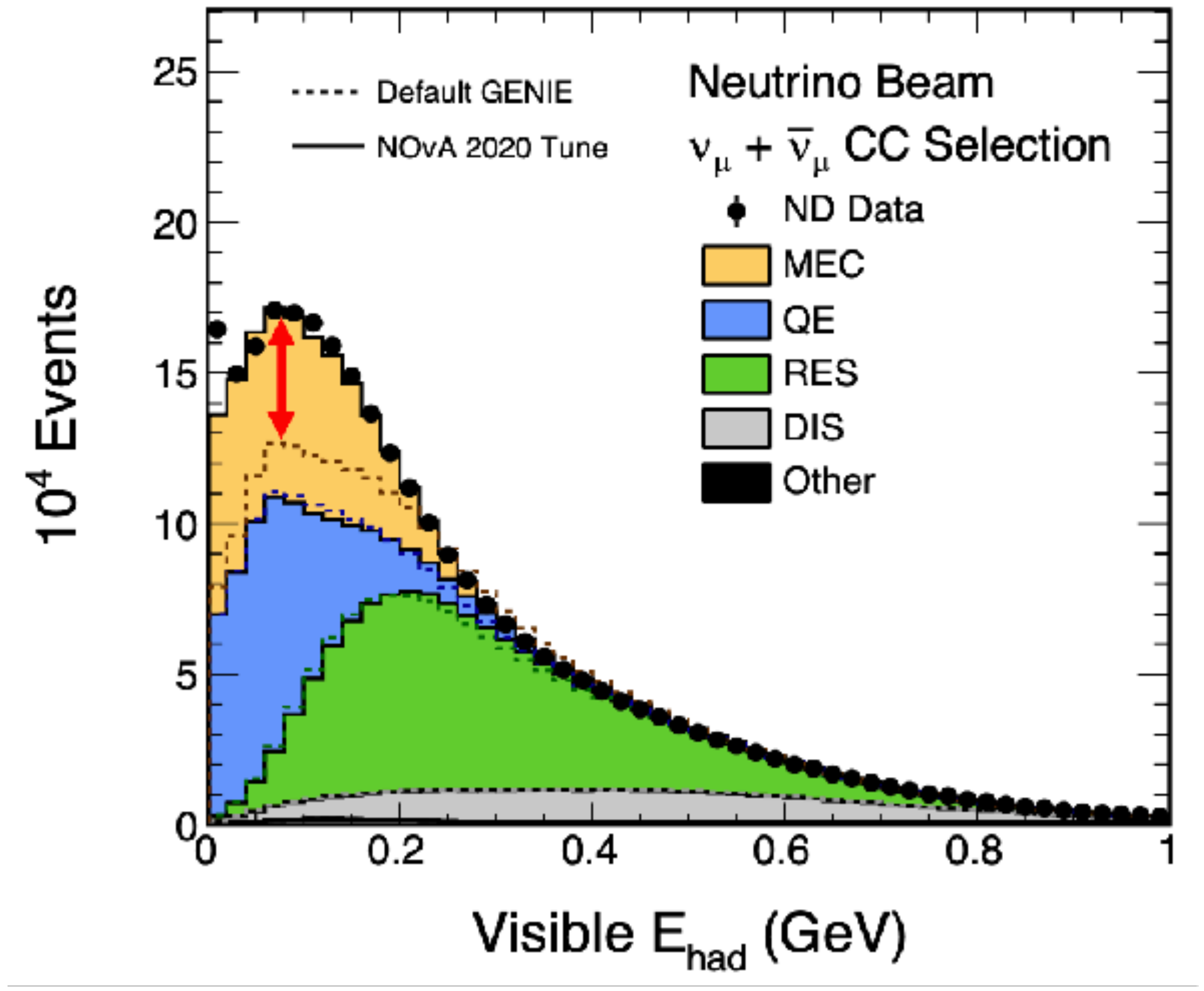
NOvA coll., *Eur.Phys.J.C* 80 (2020) 12, 1119

A. Himmel. For NOvA (NEUTRINO2020)



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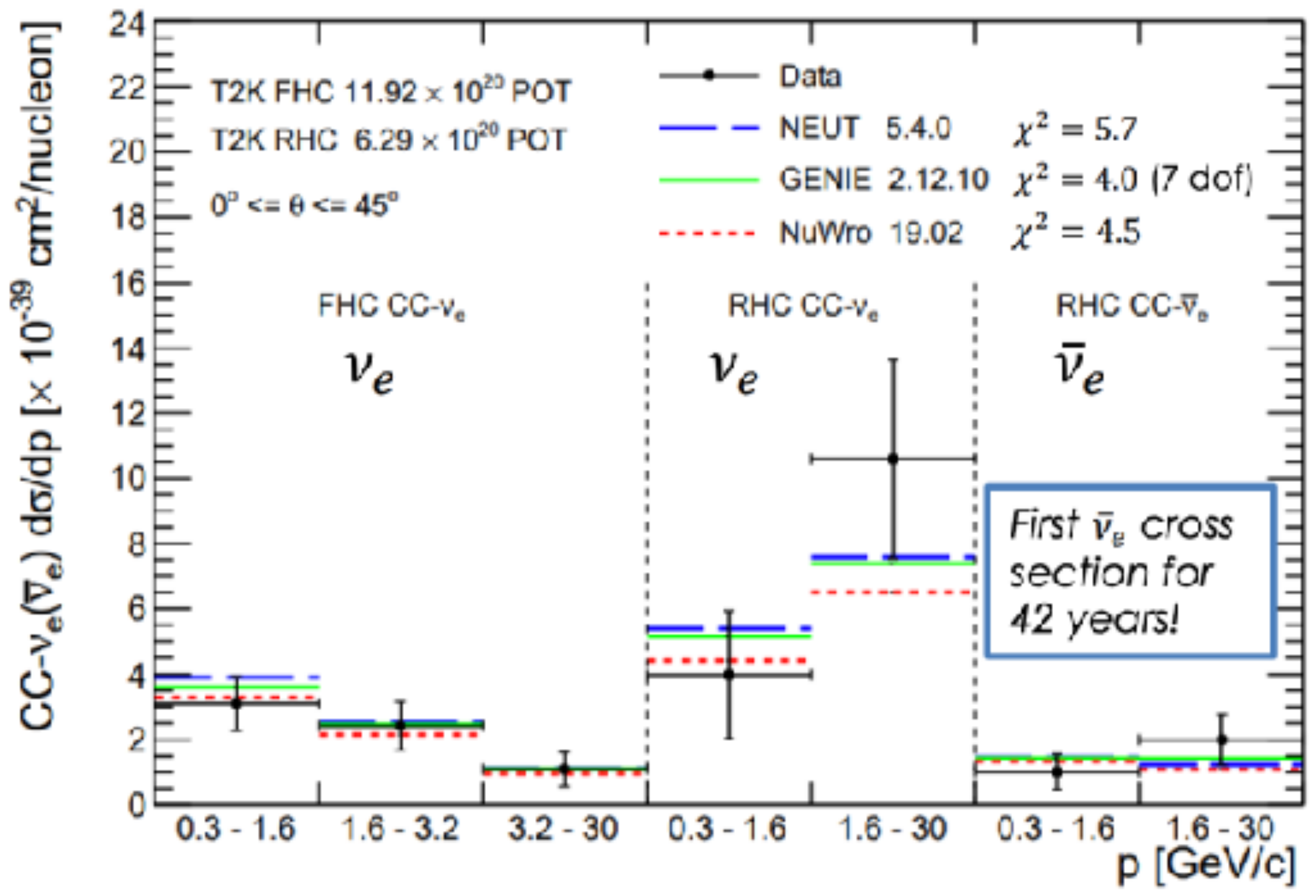
Monte Carlo tuning is not physical — we do not learn how to make general predictions.

# Direct measurement of the $\nu_e$ cross section

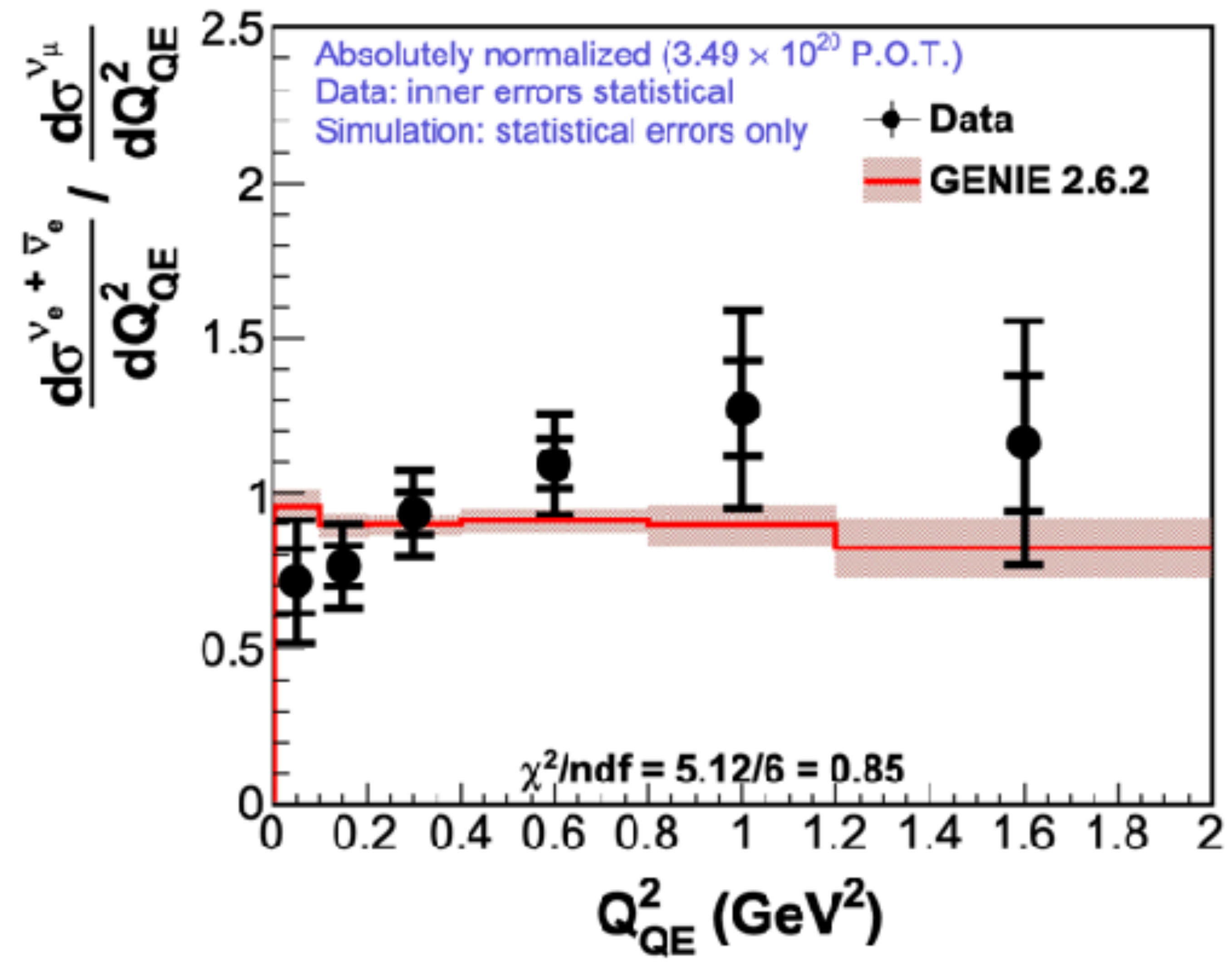
T2K. JHEP10(2020)114



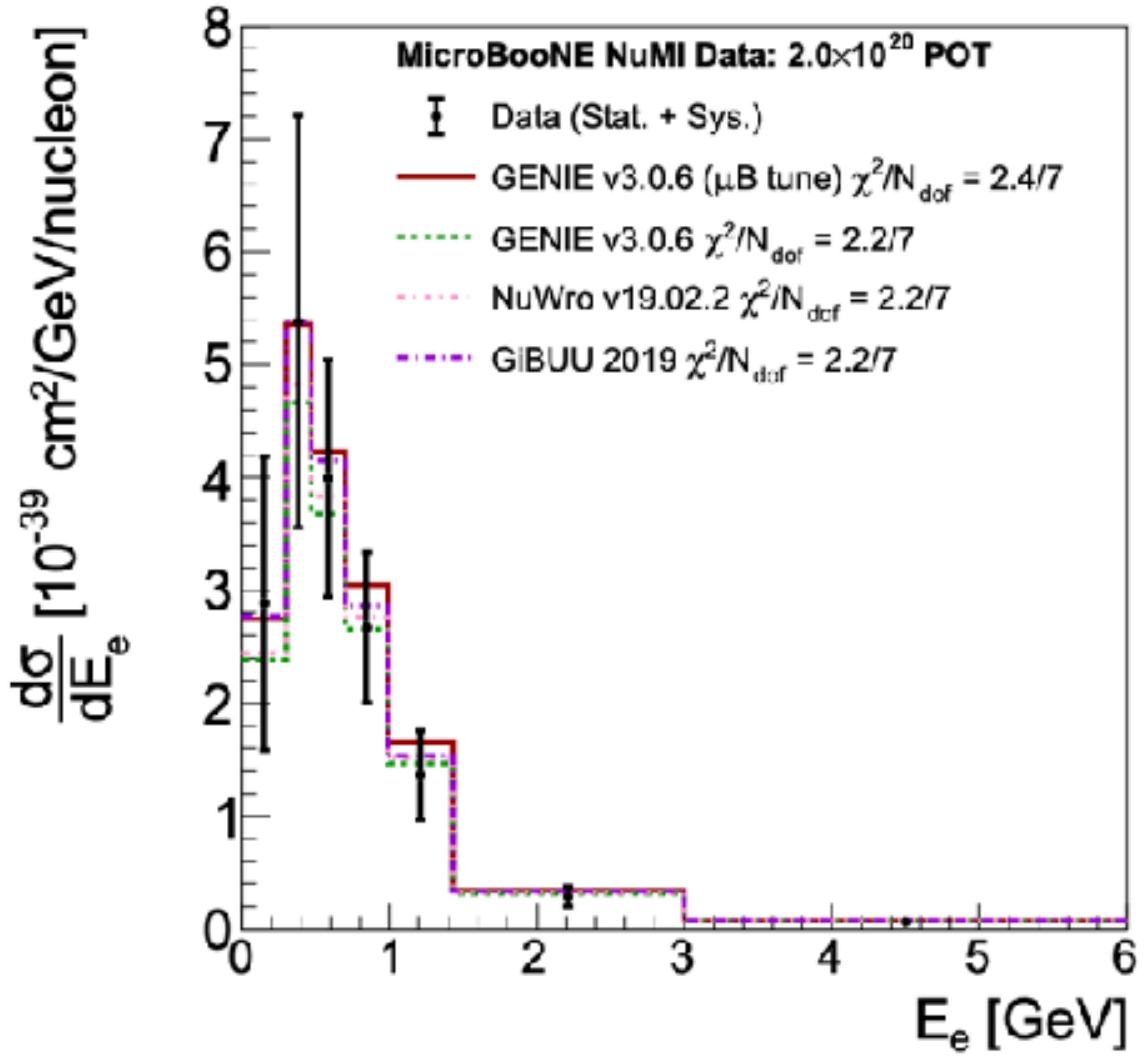
First $\bar{\nu}_e$ cross section for 42 years!

Oscillation studies assume a theoretical uncertainty of 2.8% for $\sigma_{\nu e} / \sigma_{\nu\mu}$

MINERvA, PRL 116, 081802 (2016)



MicroBooNE, arXiv:2109.06832



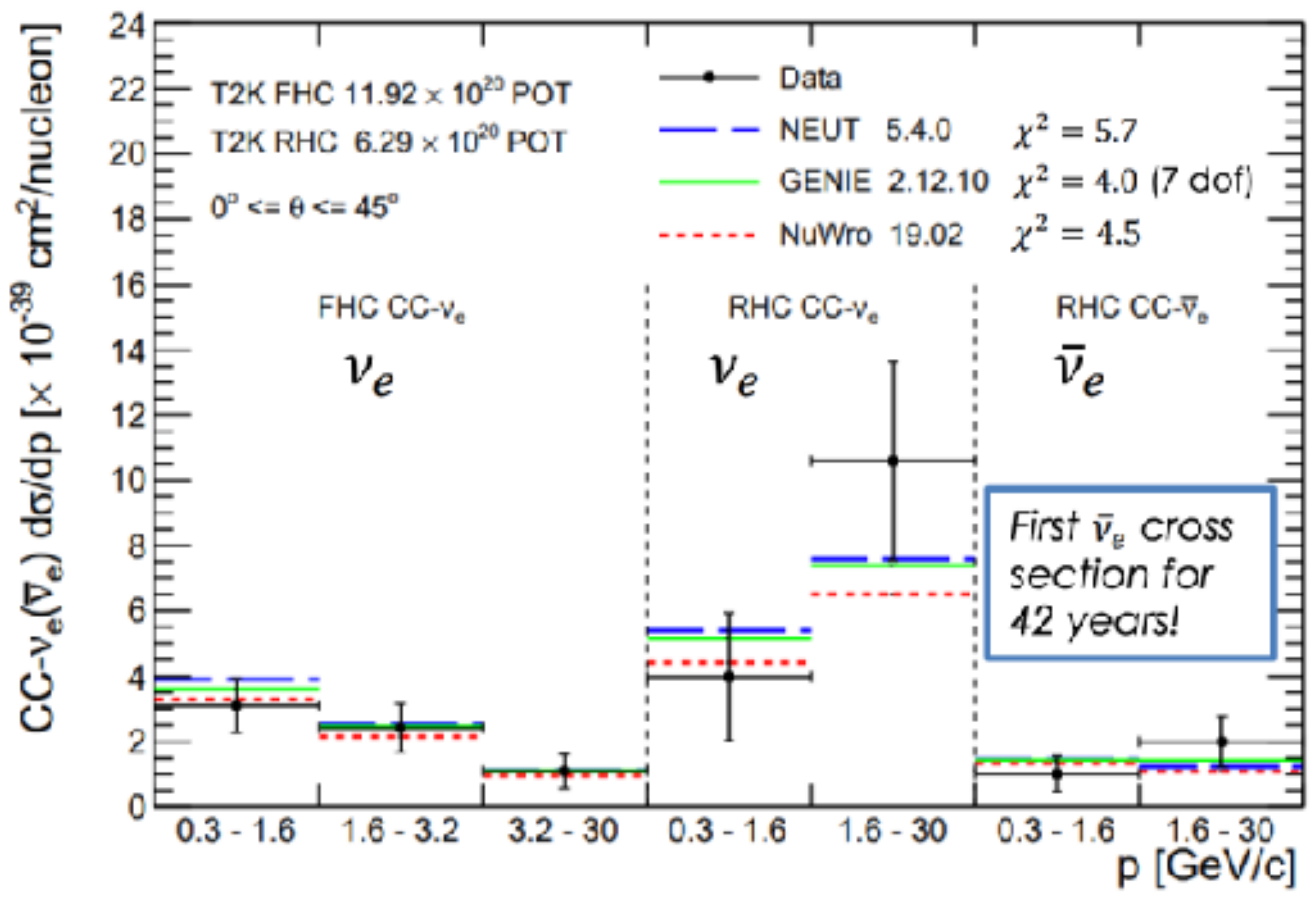
Uncertainties are large, always subject to flux normalization and detector systematics.

Statistics still low — increasing exposure may not help due to large backgrounds from muon-neutrinos.

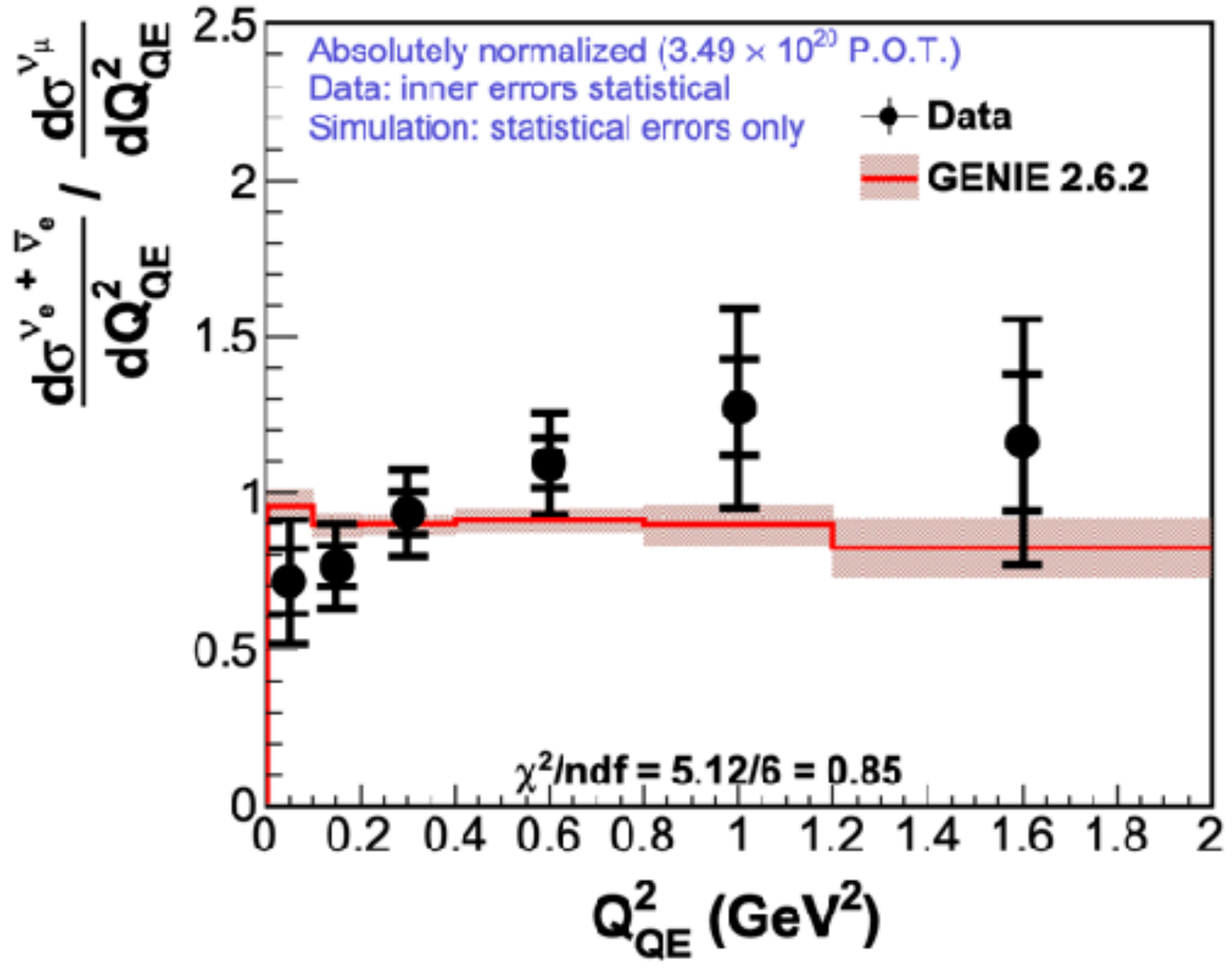
**Tuning with electron-neutrinos is much harder than muon-neutrinos — does it still cover “unknown unknowns”?**

# Direct measurement of the $\nu_e$ cross section

T2K. JHEP10(2020)114



MINERvA, PRL 116, 081802 (2016)



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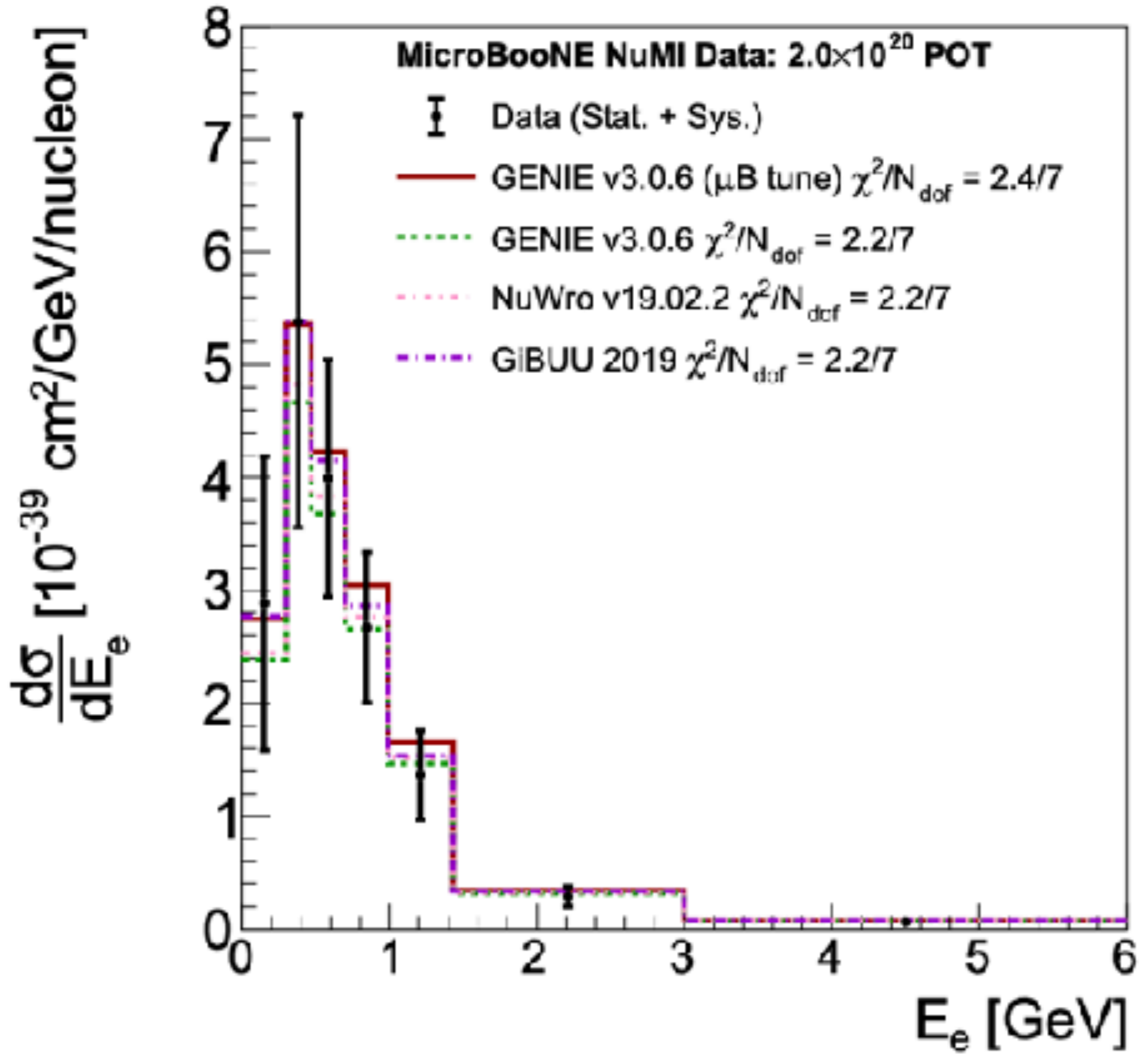


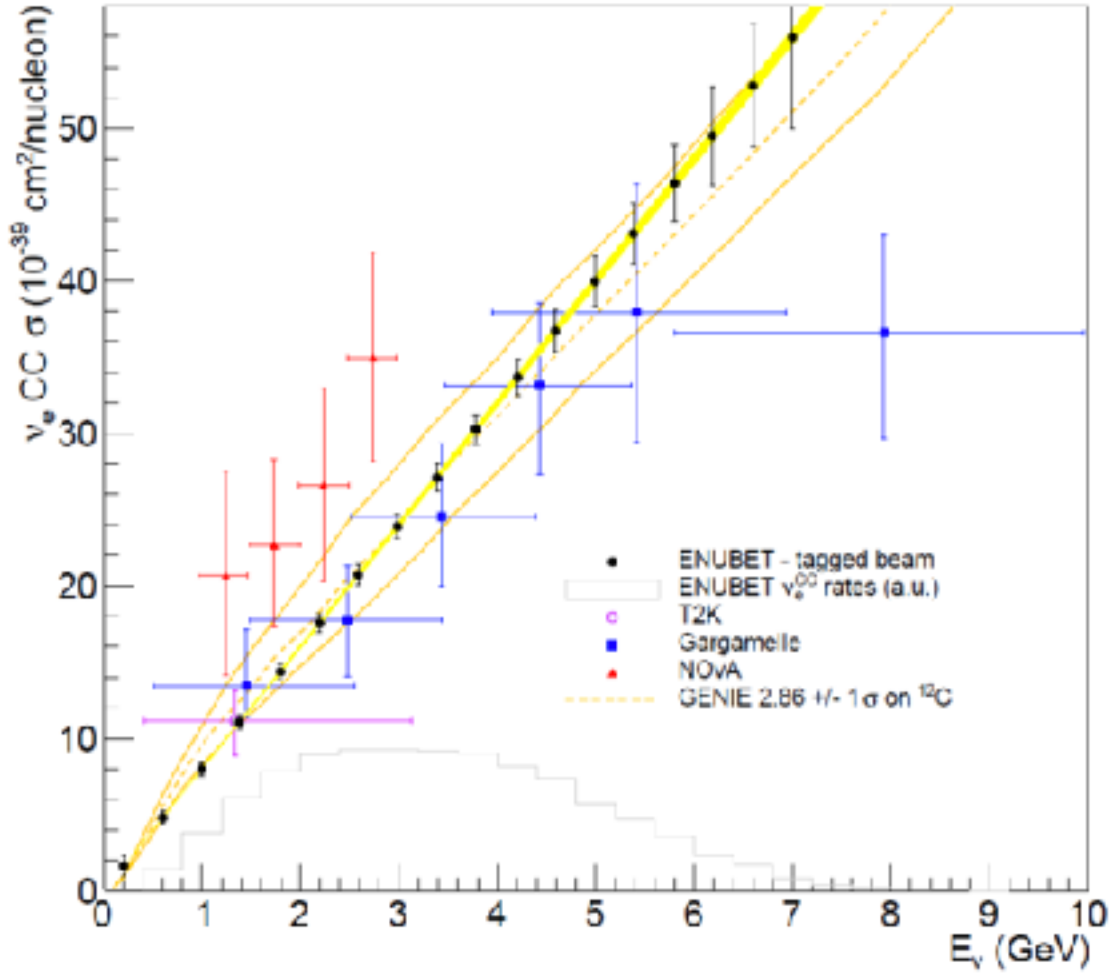
$10^{21}$ POT on 100 ton LAr detector at 50 m

| Channel | $\mu^+$ $N_{evts}$ | Channel | $\mu^-$ $N_{evts}$ |
|---|---|---|---|
| $\bar{\nu}_\mu$ NC | 1,174,710 | $\bar{\nu}_e$ NC | 1,002,240 |
| $\nu_e$ NC | 1,817,810 | $\nu_\mu$ NC | 2,074,930 |
| $\bar{\nu}_\mu$ CC | 3,030,510 | $\bar{\nu}_e$ CC | 2,519,840 |
| $\nu_e$ CC | 5,188,050 | $\nu_\mu$ CC | 6,060,580 |
|  | $\pi^+$ |  | $\pi^-$ |
| $\nu_\mu$ NC | 14,384,192 | $\bar{\nu}_\mu$ NC | 6,986,343 |
| $\nu_\mu$ CC | 41,053,300 | $\bar{\nu}_\mu$ CC | 19,939,704 |

D. Adey, R. Bayes, A. Bross and P. Snopok, Ann.Rev.Nucl.Part.Sci 2015, 65:145-175

## $\nu$STORM

Enough rates for detailed exclusive final state studies
+
differential cross sections



## ENUBET

>10k events in 0.5 kt detector

Assuming 1% flux uncertainty

Energy range optimized for DUNE's flux

# Some ideas for new physics strategies at $\nu$STORM

**Direct contributions to new physics searches at $\nu$STORM**

**Summary**

- **Precision as an “umbrella strategy”:**
  - **Well known flux (✓) + well-known SM xsecs ( ? )**

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- **Precision as an "umbrella strategy":**
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- **Rare processes — Statistics (✓):**

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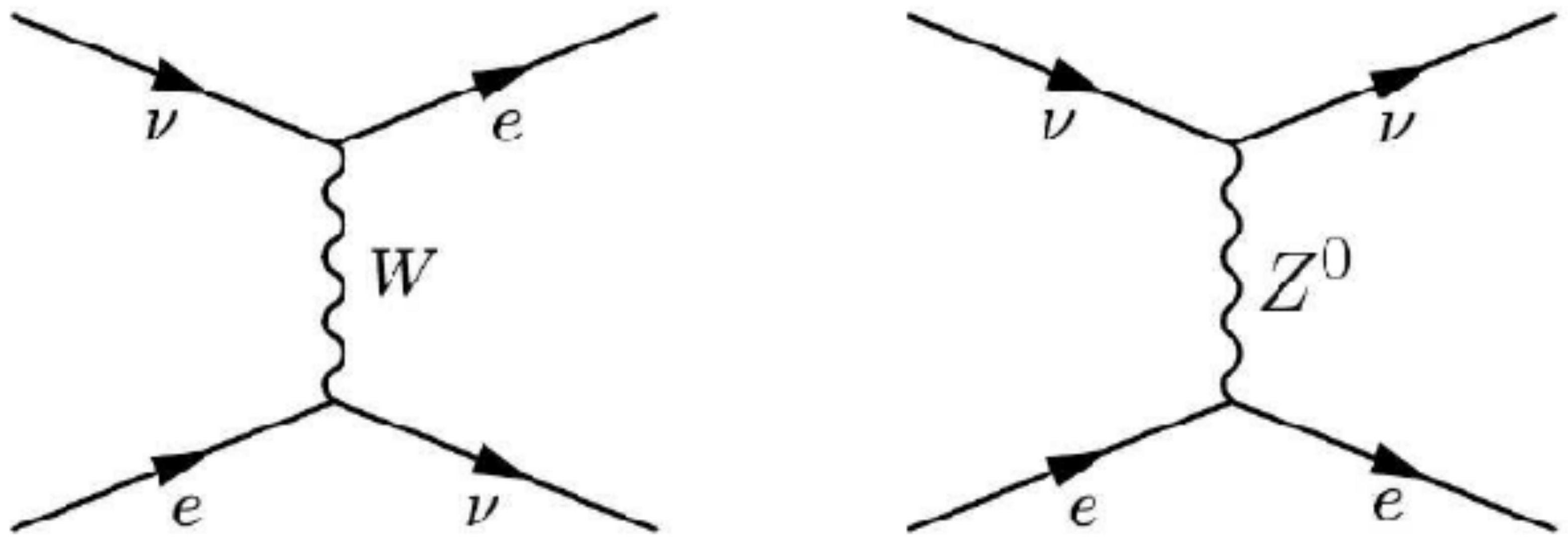
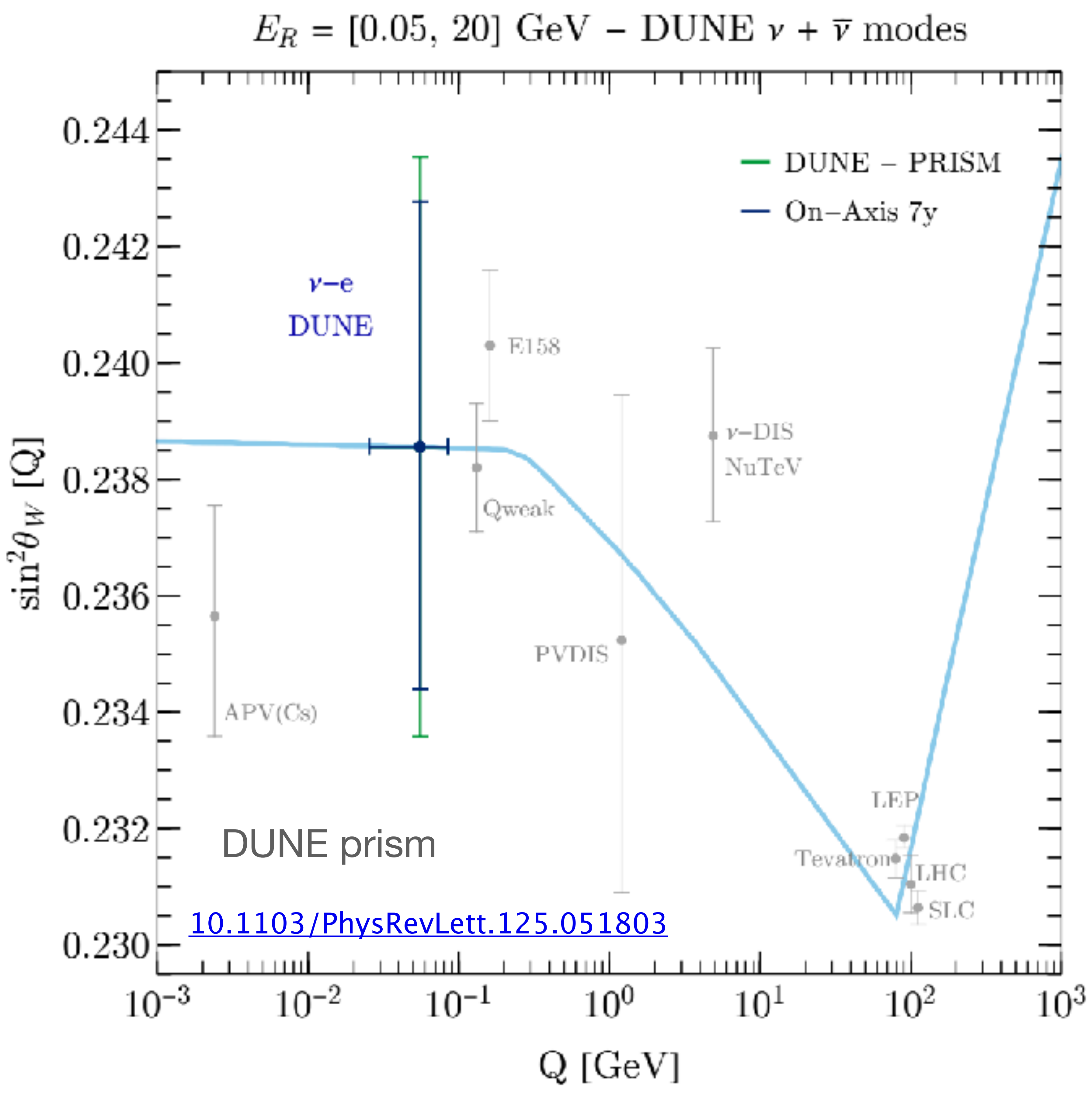
  - Neutrino-electron scattering

Precision physics



**Forward electrons — hard background due to large electron-neutrino flux.**



DUNE prism

10.1103/PhysRevLett.125.051803

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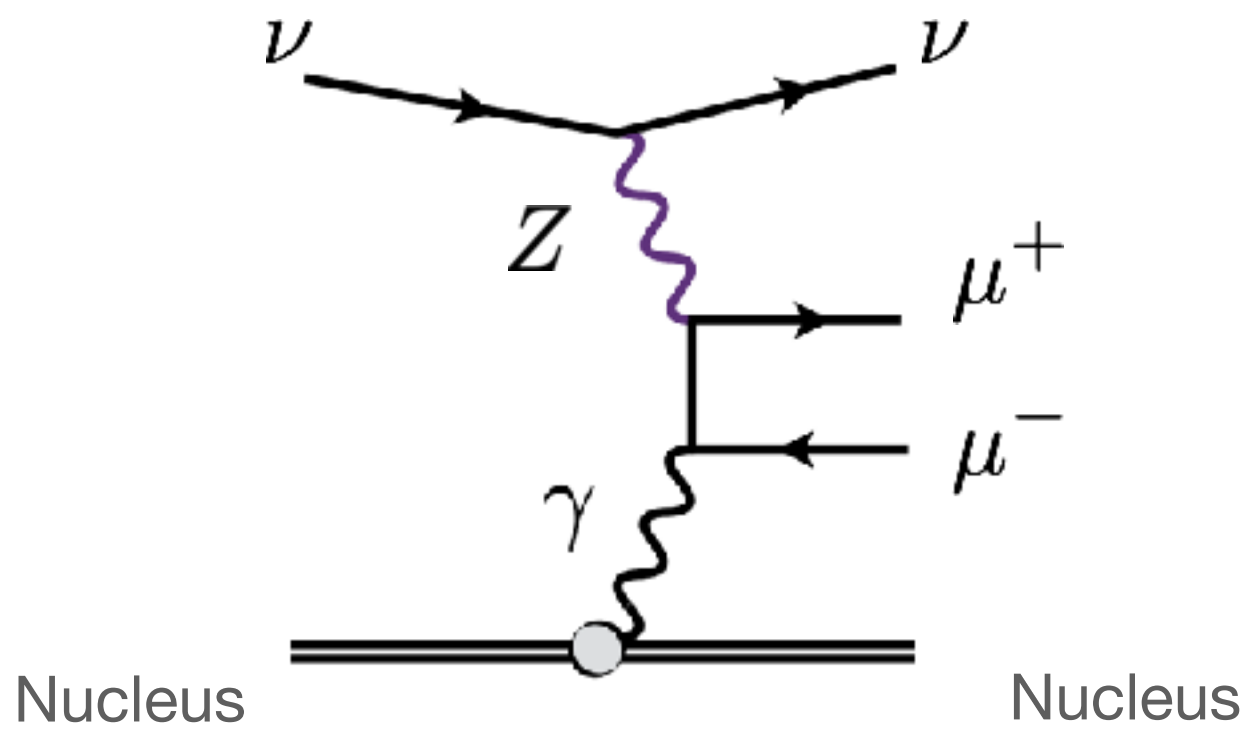
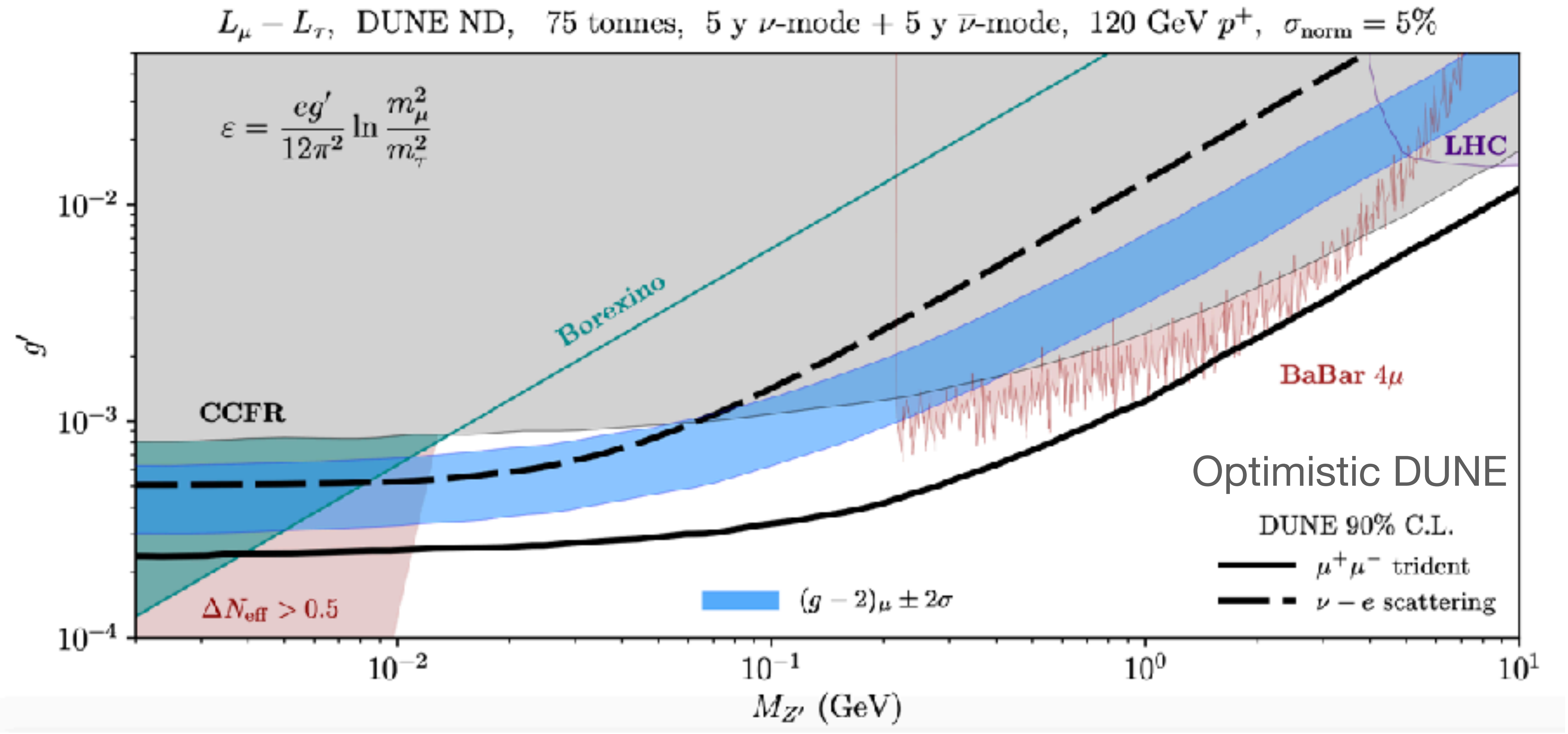
  - Neutrino trident production



P. Ballet et al, PRD 100 (2019) 5, 055012



Cross section at the level of $10^{-6}$ of CCQE at 2 GeV

**Magnetized detector with large Z nuclei is ideal.**

Test of new physics explanations to (g-2)μ

# Some ideas for new physics strategies at νSTORM

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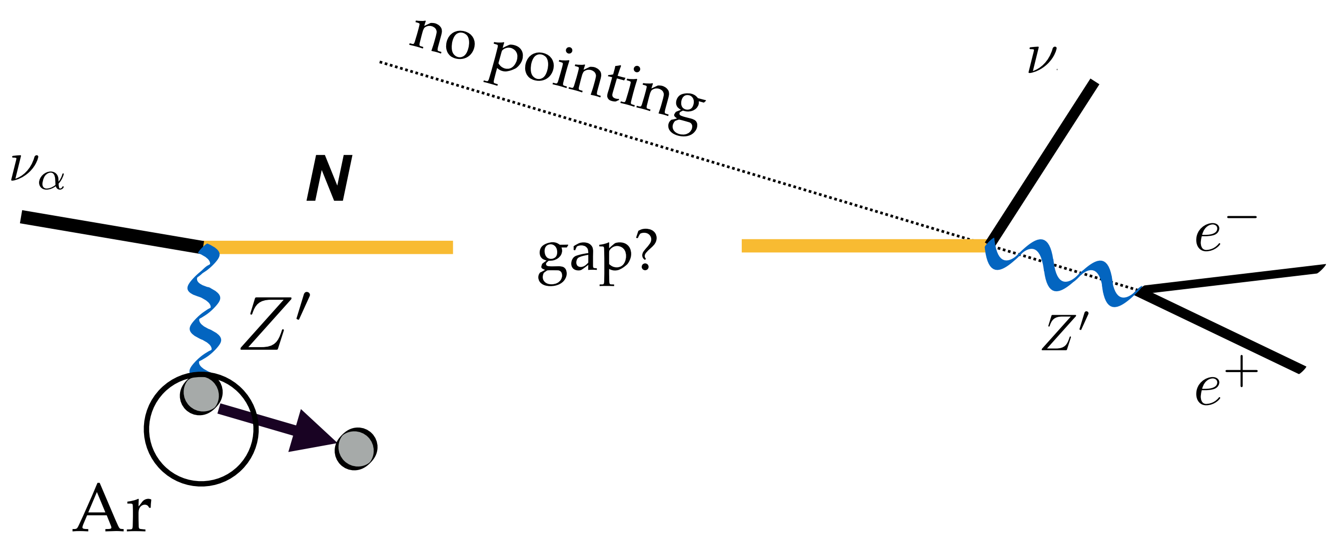
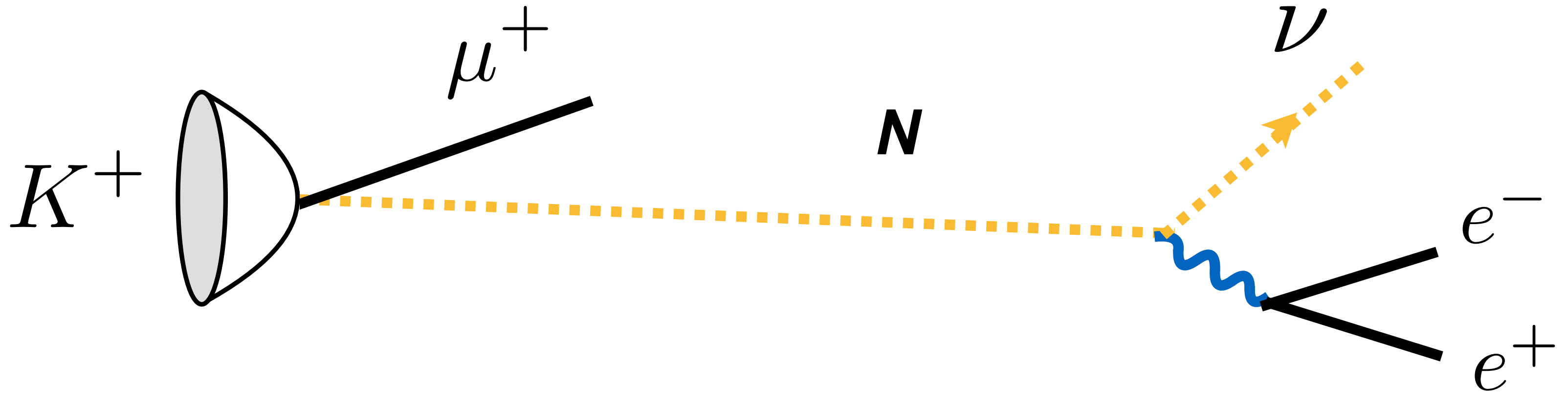


Production in neutrino scattering



Production in K/π/μ decays and decay in flight

Alternative explanations to the MiniBooNE excess with dark sectors

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  - Neutrino trident production
  - Light new particles produced at target/kaon decays/muon decays

- **Short-baseline oscillations/flavor transitions:**
  - **Well-known flux (✔) + Statistics (✔) + Energy reconstruction ( ? )**
  - Spectral shape distortions or anomalous (dis)appearance signals.
  - Zero-baseline effects: non-unitarity/non standard interactions

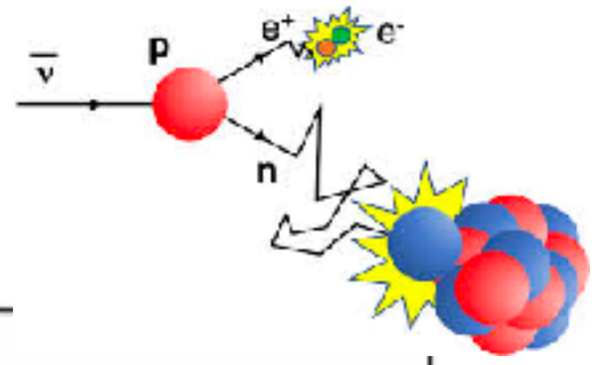
# Short-baseline anomalies

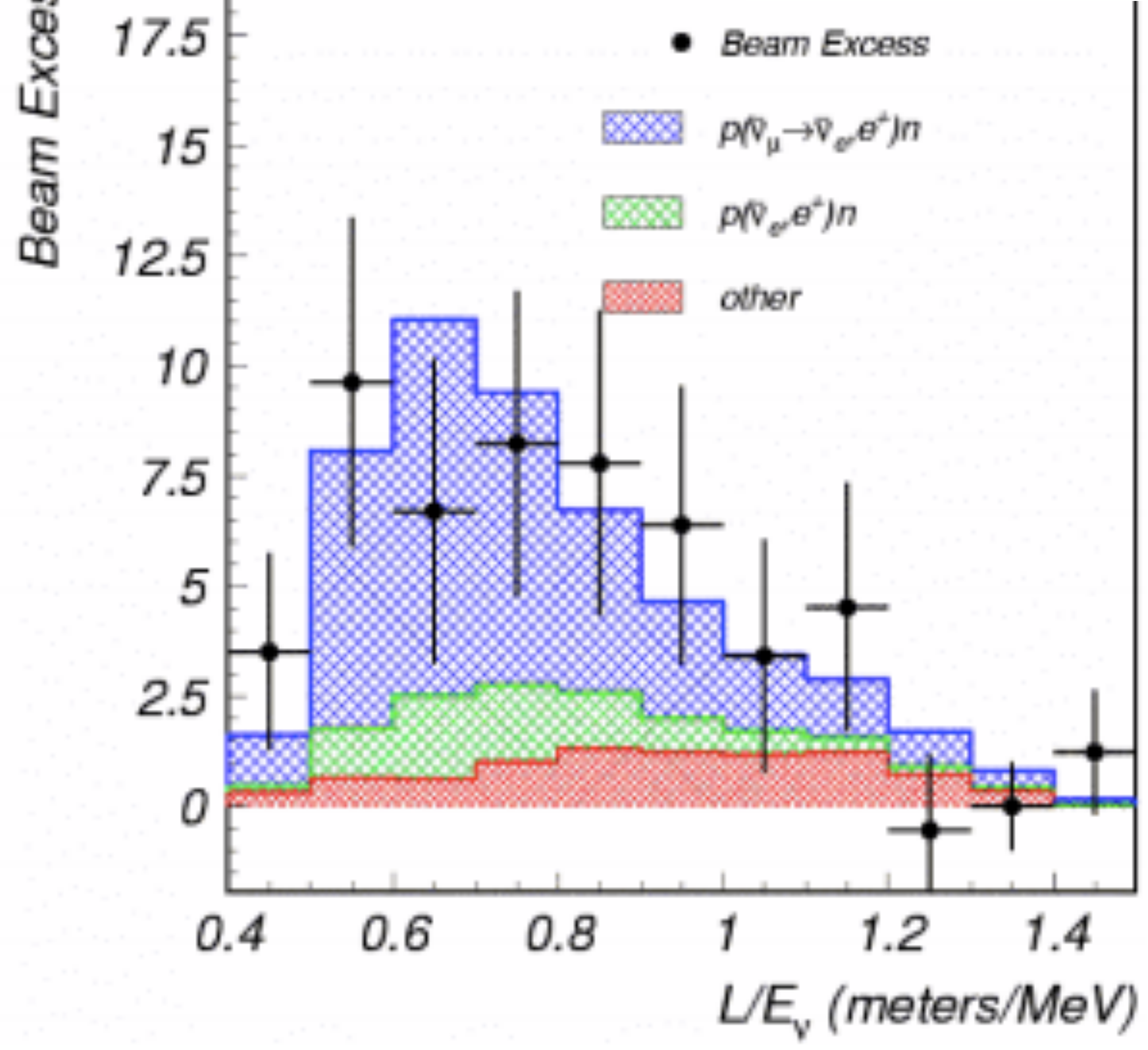
**@ LSND:** $\pi^+ \to \mu^+ \nu_\mu$

arXiv:0104049

$\mu^+ \to e^+ \nu_e \overline{\nu_\mu}$

$\overline{\nu}_\mu \to \overline{\nu}_e$





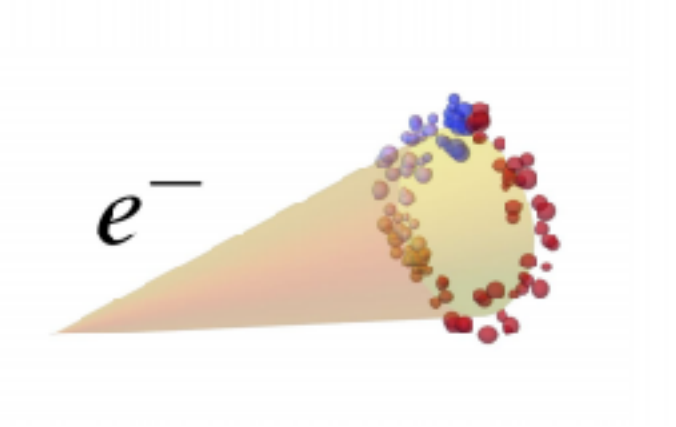
EXCESS: 87.9 ± 22.4 ± 6 EVENTS

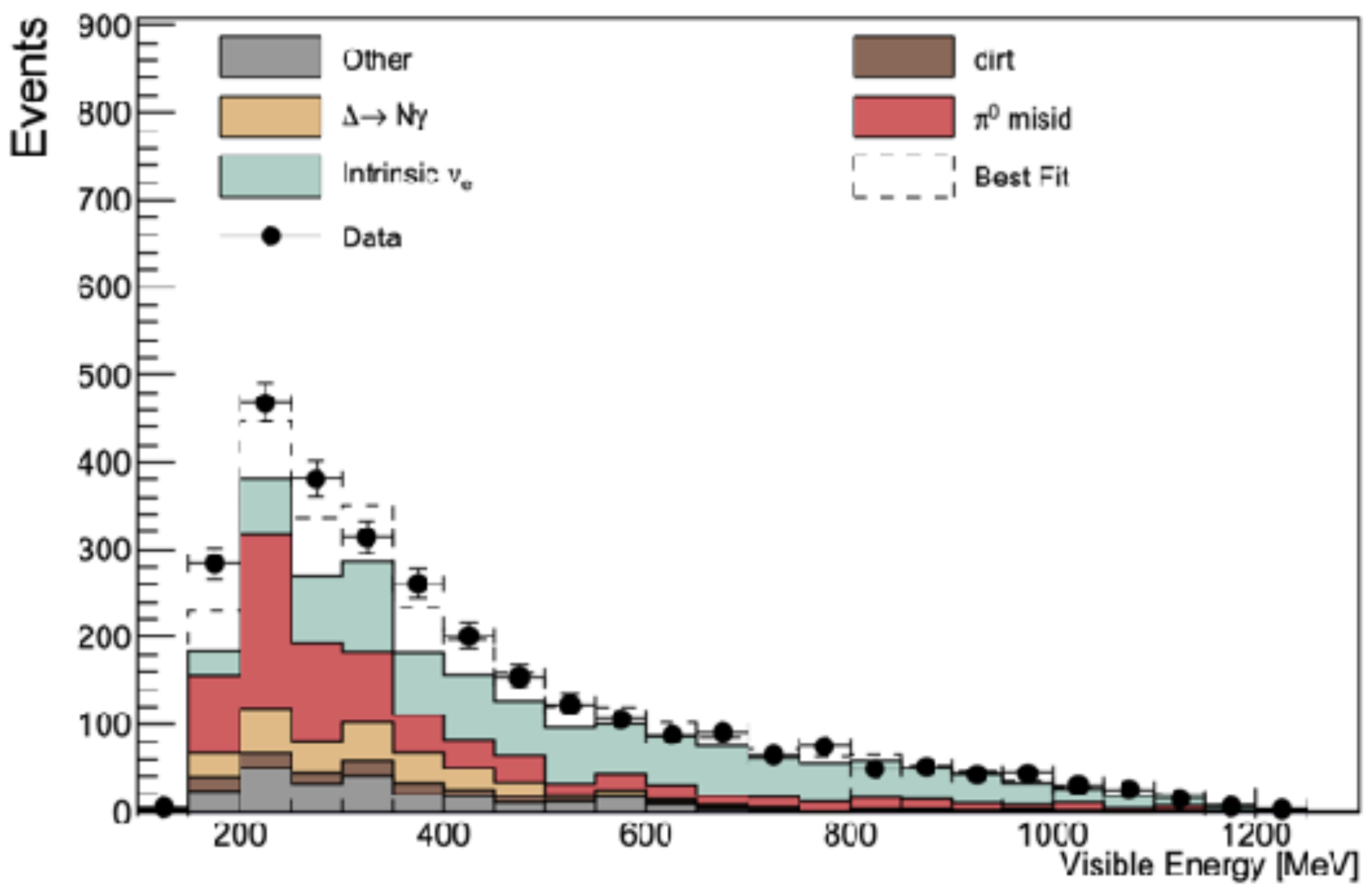
**3.8 sigma**

**@ MiniBooNE:** $\pi^+ \to \mu^+ \nu_\mu$

arXiv:2006.16883

$\nu_\mu \to \nu_e$





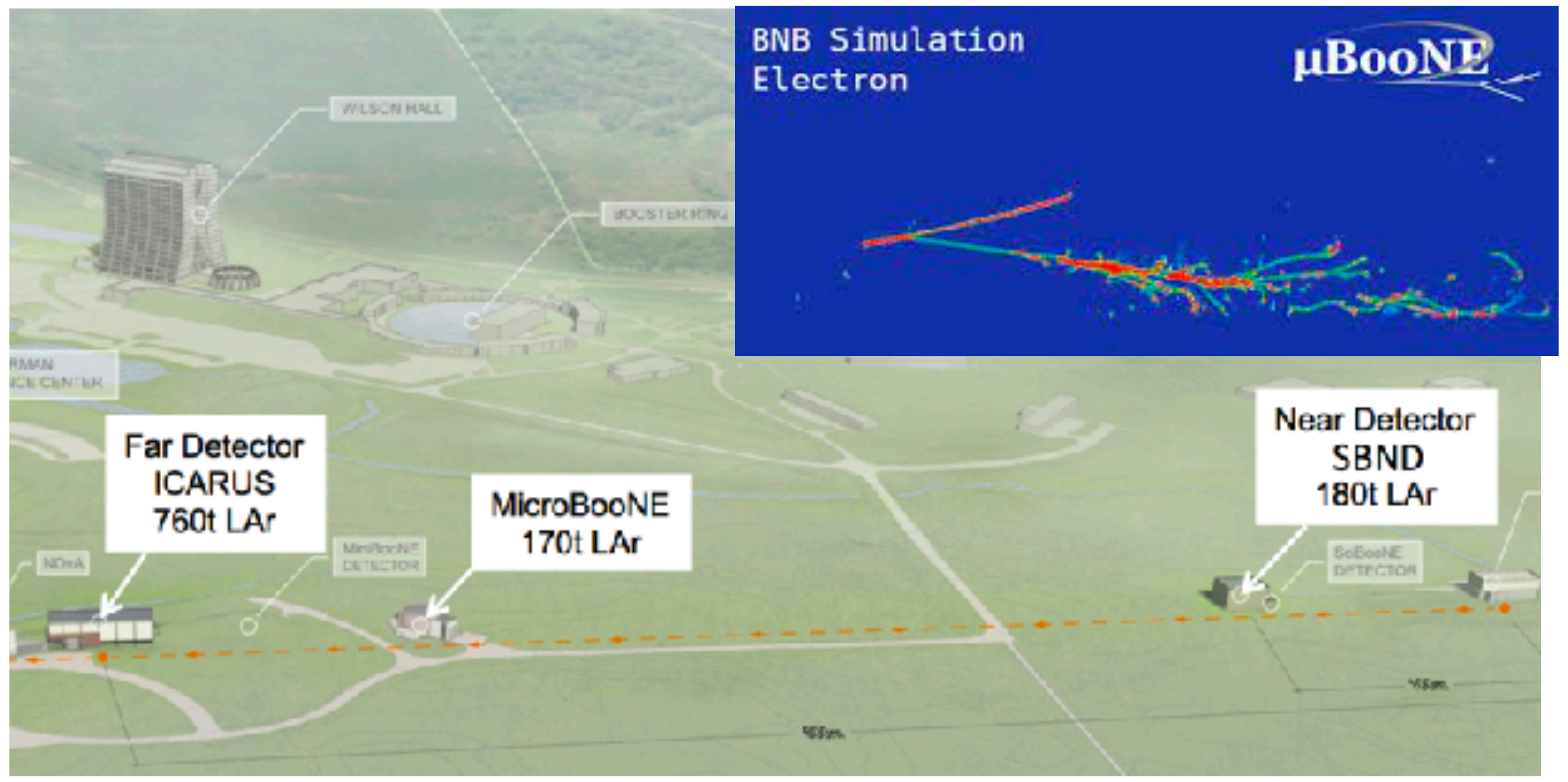
EXCESS: 560± 119.6 EVENTS only in nu mode

**4.8 sigma significance**

- Short-baseline oscillation at

$$L/E \sim \left(\frac{1\mathrm{eV}^2}{\Delta m^2}\right)$$

SBN program @ FNAL may confirm or constrain it.



In case of a positive signal,
we will need dedicated facilities to study it
**and definitive tests.**

# New Physics searches

- A definitive test of short-baseline oscillations

Separated by timing.

$\nu_\mu \to \nu_\mu$

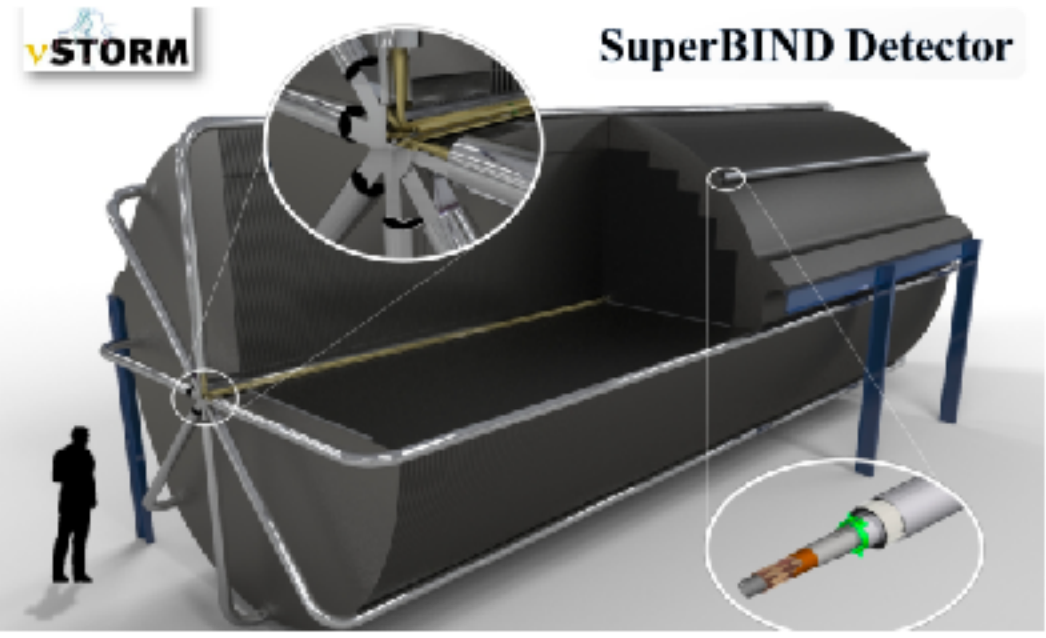
$\overline{\nu}_\mu \to \overline{\nu}_\mu$

$\nu_e \to \nu_\mu$

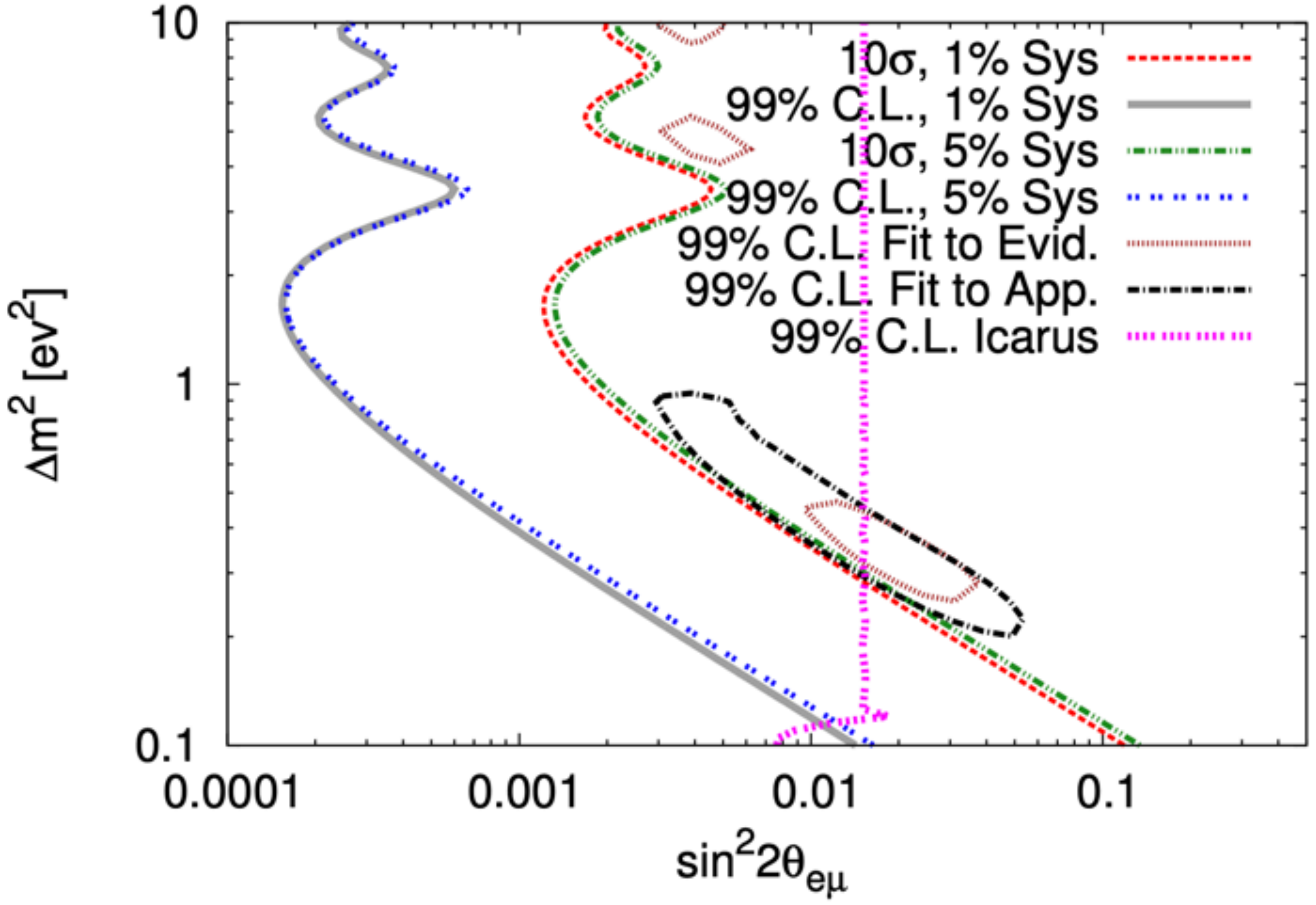
Charge separation with Magnetic field

1) **T or CPT conjugate** of usual appearance channels
2) **muon identification** much easier than electrons
3) **no photon backgrounds.**

| Sample | Channel | Sensitivity |
|---|---|---|
| $\pi^+$ flash | $\nu_\mu \to \nu_\mu$ | $\lvert U_{\mu 4}\rvert^2$ |
| | $\nu_\mu \to \nu_e$ | $\lvert U_{e4}U_{\mu 4}\rvert^2$ |
| Stored $\mu^+$ | $\nu_e \to \nu_e$ | $\lvert U_{e4}\rvert^2$ |
| | $\overline{\nu}_\mu \to \overline{\nu}_\mu$ | $\lvert U_{\mu 4}\rvert^2$ |
| | $\nu_e \to \nu_\mu$ | $\lvert U_{e4}U_{\mu 4}\rvert^2$ |



Magnetized far detector
@ 2 km
1.6 x $10^{18}$ useful muon decays



D. Adey et al, 10.1103/PhysRevD.89.071301

# New Physics searches

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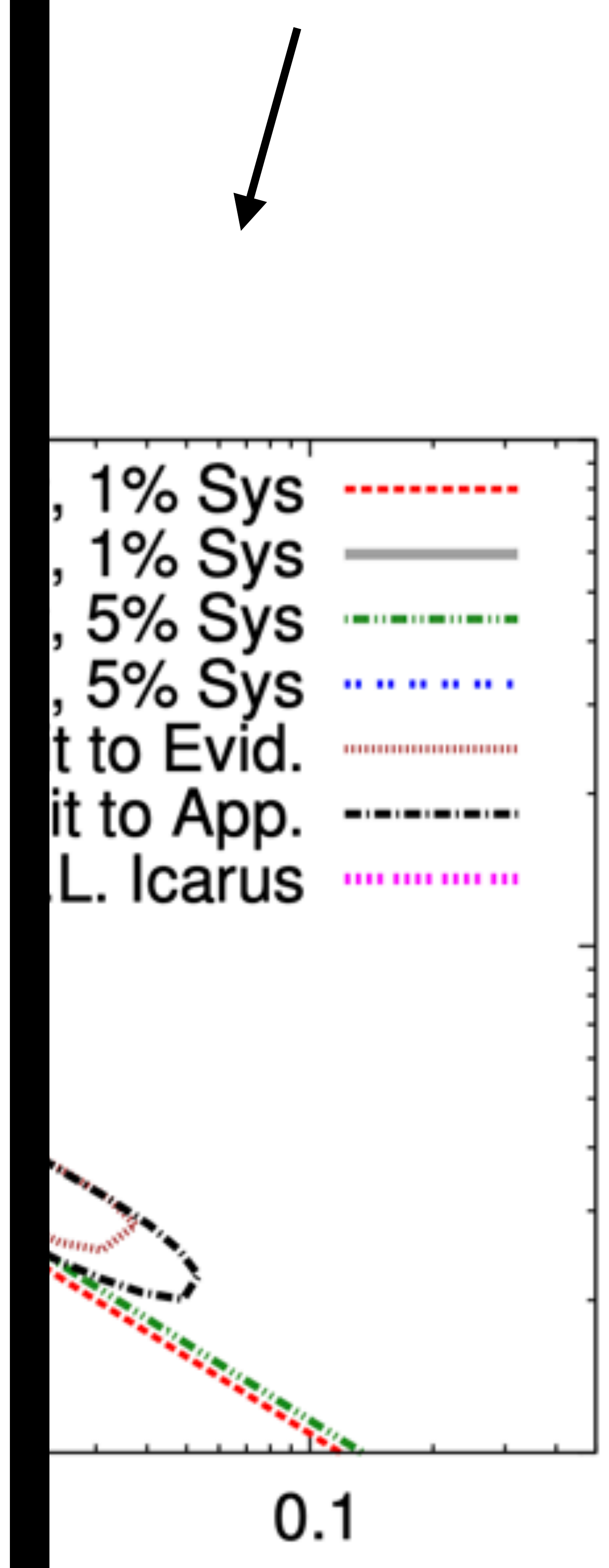
2) muc
3) no p

etized far detector
@ 2 km
$^{8}$ useful muon decays



evD.89.071301

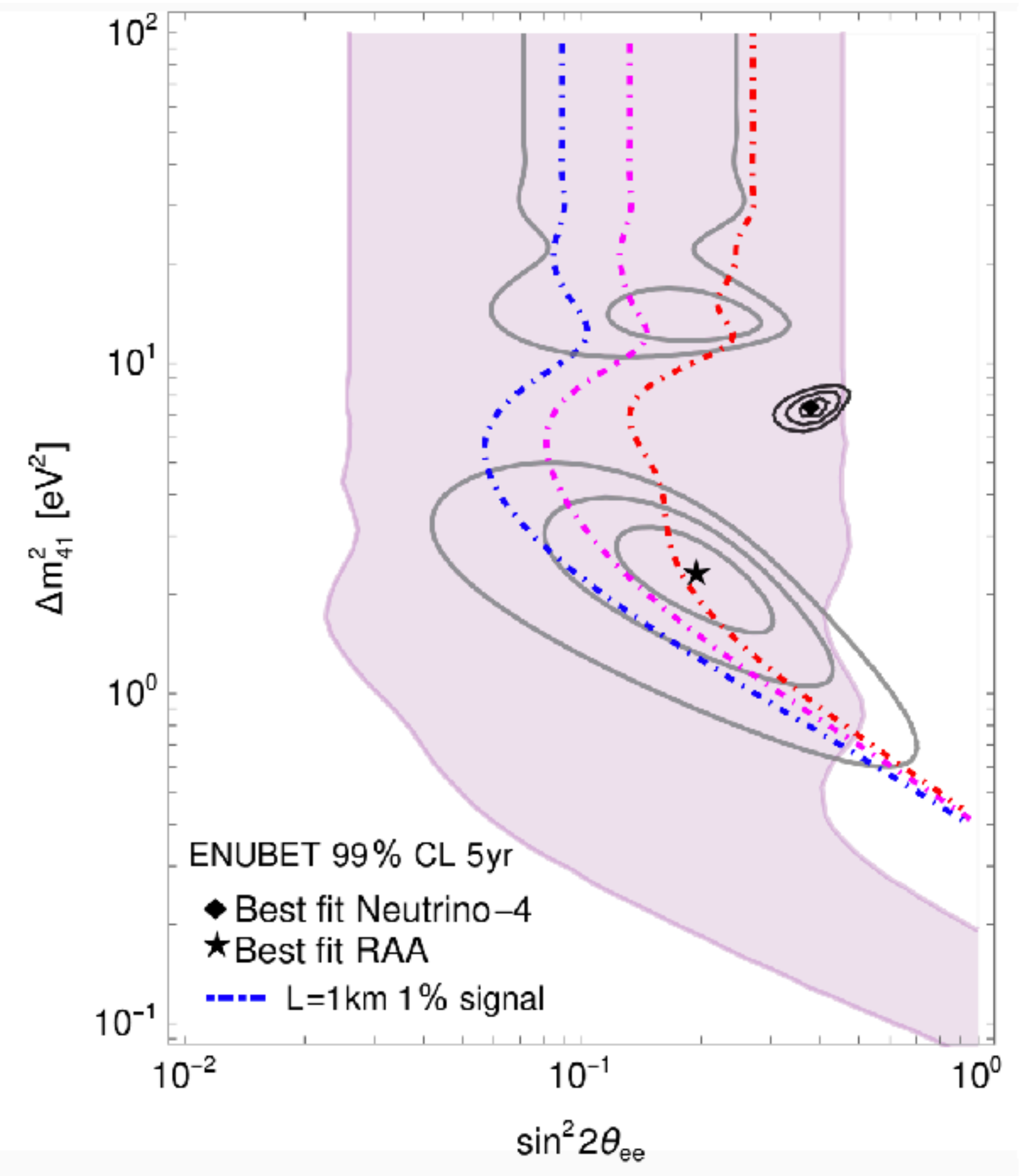
## ENUBET is also an electron-neutrino disappearance experiment:

1 kt LAr detector at 1 km
w/ (1%, 2%, 5%) flux uncertainty.

**Performs a direct check of anomalies in electron-neutrino disappearance**

$$\nu_e \to \nu_e$$

Test of eV-sterile neutrino hypothesis



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**Indirect contribution to new physics searches elsewhere:**

- Clean measurement of **exclusive cross sections** that can be fed to other GeV-scale neutrino exps.
- Precision measurement of "**standard candles**" — Low-ν? coh-$\pi^{\pm}$ production?

# Conclusions

- nuSTORM and ENUBET would open a door to precision neutrino physics (<1% flux uncertainties) in both $\nu_e$ and $\nu_\mu$ sectors.
- Cross section measurements would provide invaluable input to LBL program
  - Would like **precise measurements of exclusive channels, preferrably in differential format.**
- **Definitive** test of short-baseline neutrino oscillations

  T and CPT analogues of MiniBooNE and LSND.
- Search for new physics at zero-distances (eg. non-unitarity) or neutrino scattering.

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**See also synergies between nuSTORM and ENUBET**

**Monitored K decays for a precise $\nu_e$ beam**

Andrea Longhin @ Neutrino 2020: 10.5281/zenodo.4139739