Broad-brush discussion on new physics opportunities at νSTORM

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Neutrino from STORed Muons

nuSTORM meeting 08/08

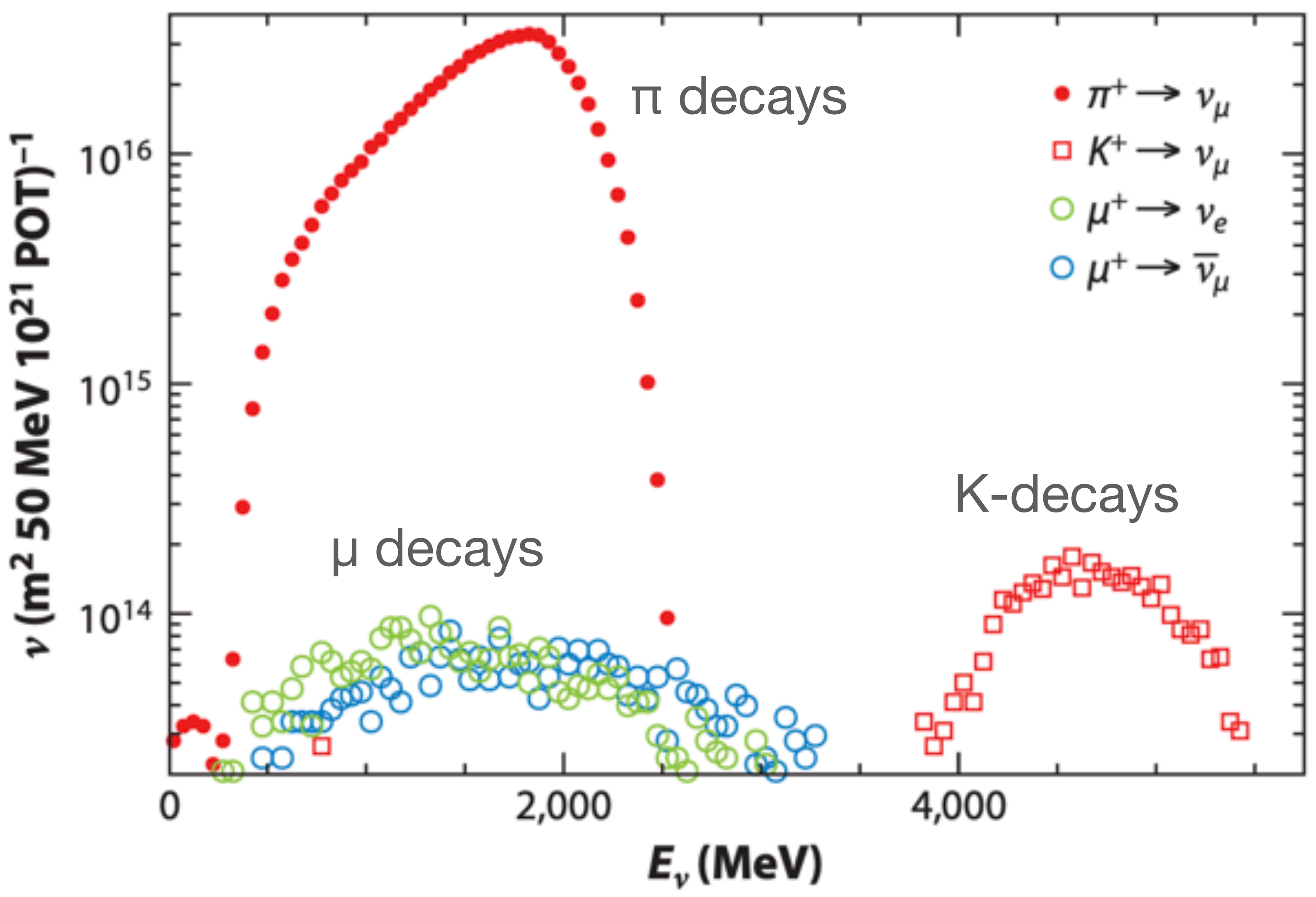
The νSTORM concept

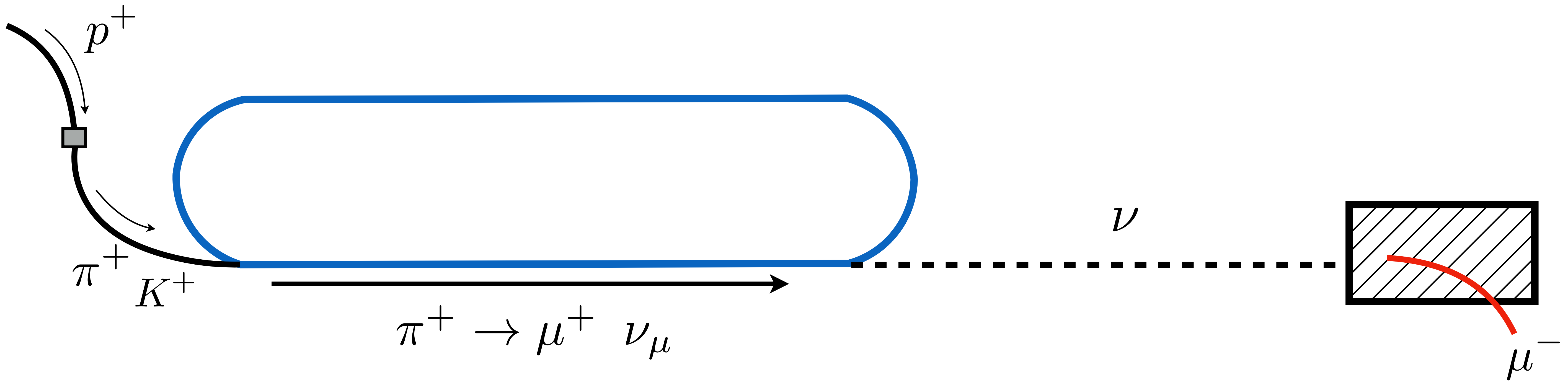
➤ $\pi^{\pm}$ injection, and 1—6 GeV/c stored $\mu^{\pm}$

$\pi^{+} \rightarrow \mu^{+} \; \nu_{\mu}$ Pion-flash

$\mu^{+} \rightarrow e^{+} \nu_{e} \overline{\nu}_{\mu}$ Stored muons

Pion-flash



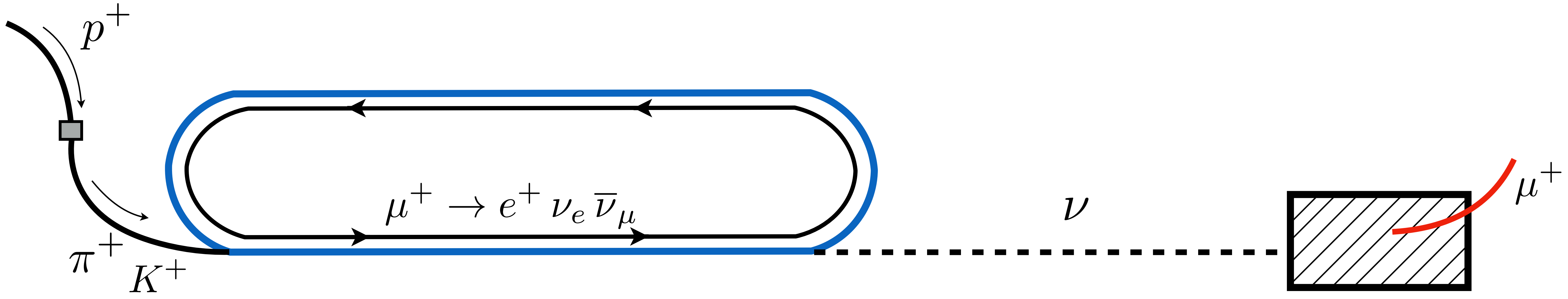


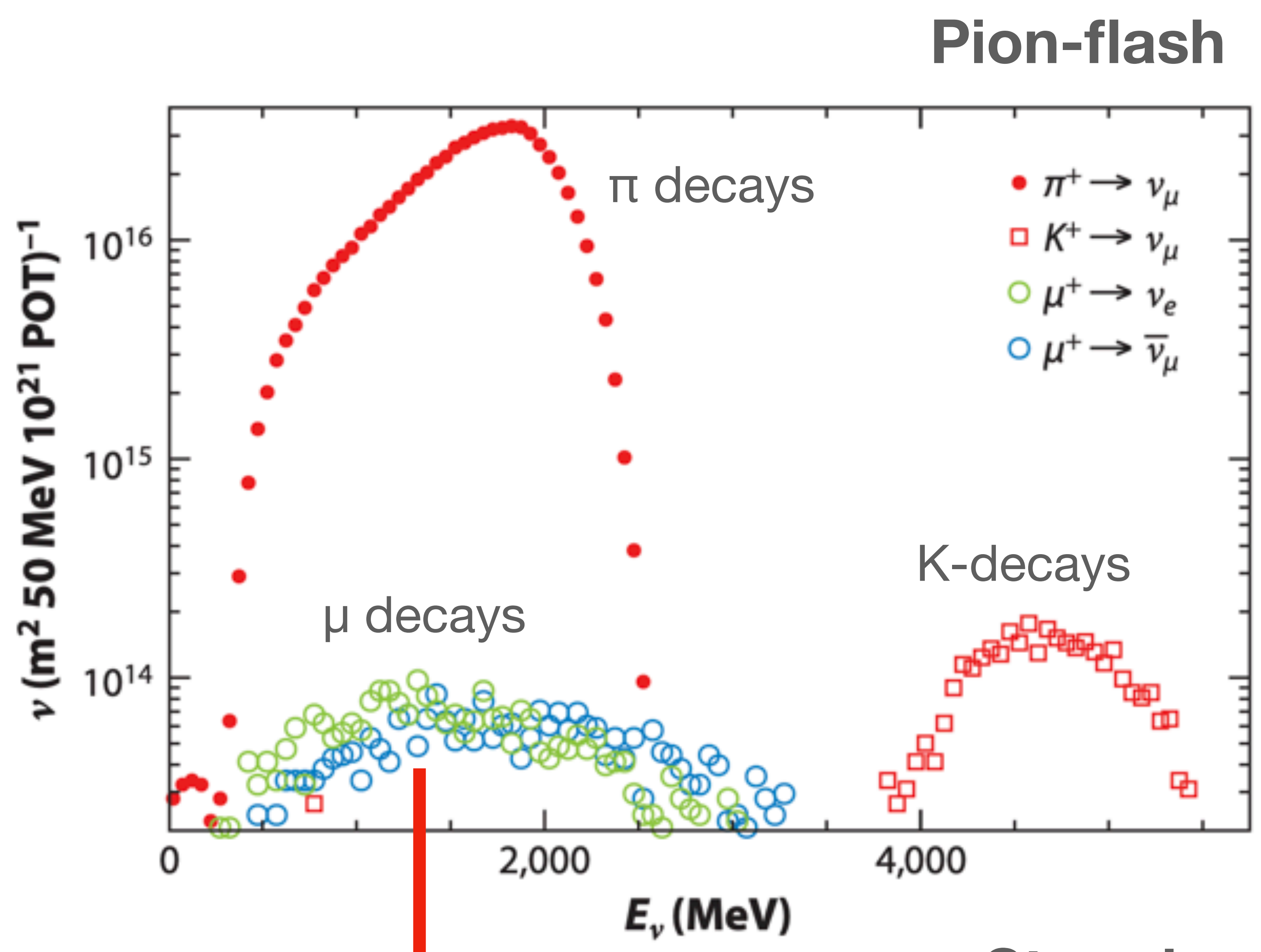
- $\pi^{\pm}$ injection, and 1—6 GeV/c stored $\mu^{\pm}$

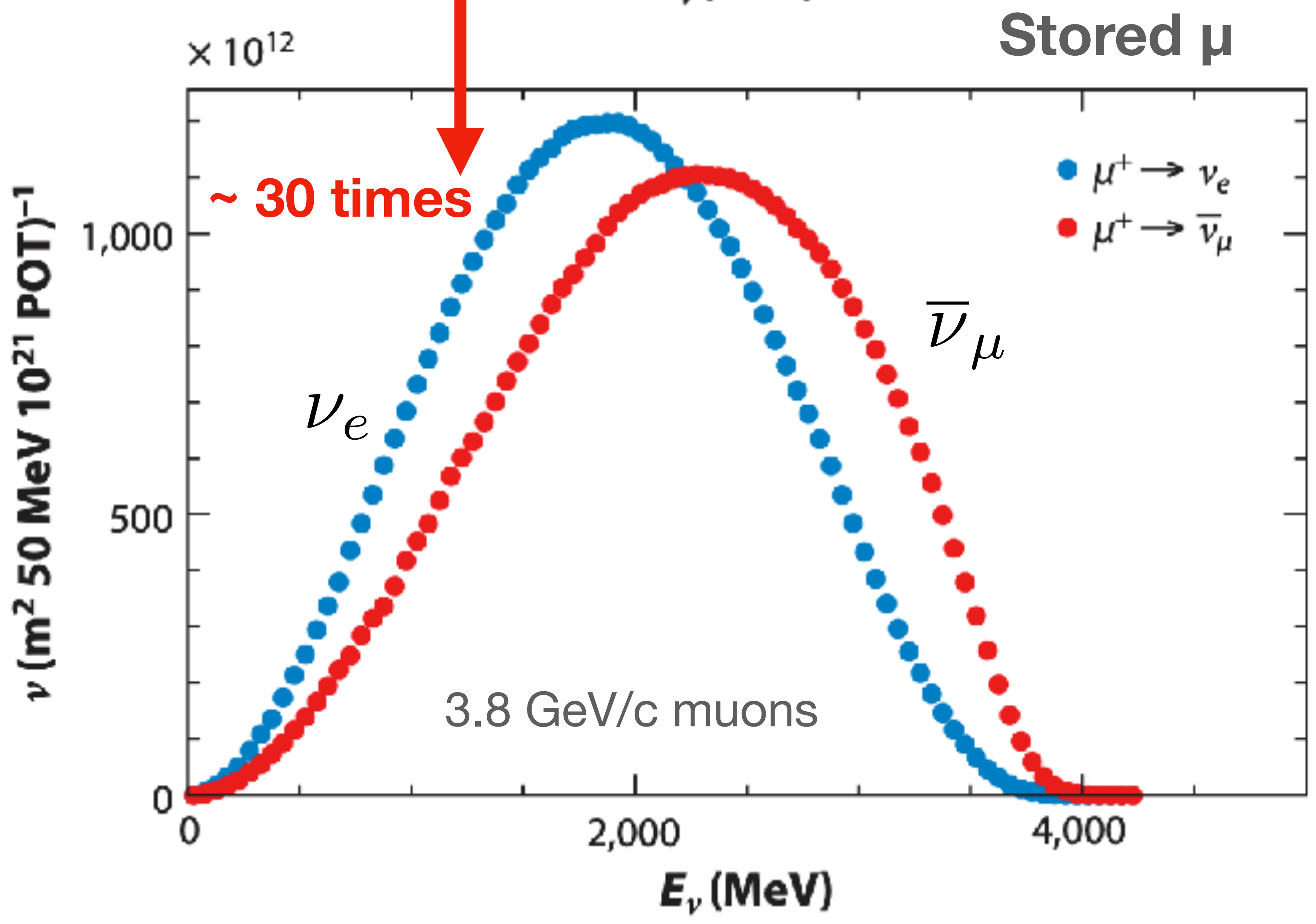
$$\pi^+ \to \mu^+ \; \nu_\mu \qquad \text{Pion-flash}$$

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

- Precision neutrino source:
  - Well-known rate, energy spectrum, and composition
  - unique flavor composition — $(\nu_e : \overline{\nu_\mu}) = (1:1)$
  - Not necessarily in the direction of proton beam.







Direct contributions to new physics searches at νSTORM

- **Precision as an "umbrella strategy":**
  - **Well known flux (✔) + well-known SM xsecs (?)**

Some ideas for new physics strategies at νSTORM

Direct contributions to new physics searches at νSTORM

Summary

- **Precision as an "umbrella strategy":**
  - **Well known flux (✔) + well-known SM xsecs (?)**
- **Rare processes — Statistics (✔):**
  - Neutrino-electron scattering
  - Neutrino trident production
  - Light new particles produced at target/kaon decays/muon decays

Direct contributions to new physics searches at νSTORM

Summary

- **Precision as an "umbrella strategy":**
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- **Short-baseline oscillations/flavor transitions:**
  - **Well-known flux (✔) + Statistics (✔) + Energy reconstruction (?)**
  - Spectral shape distortions or anomalous (dis)appearance signals.

Direct contributions to new physics searches at νSTORM

Summary

- **Precision as an "umbrella strategy":**
  - **Well known flux (✔) + well-known SM xsecs (?)**
- **Rare processes — Statistics (✔):**
  - Neutrino-electron scattering
  - 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.

Indirect contribution to new physics searches elsewhere:

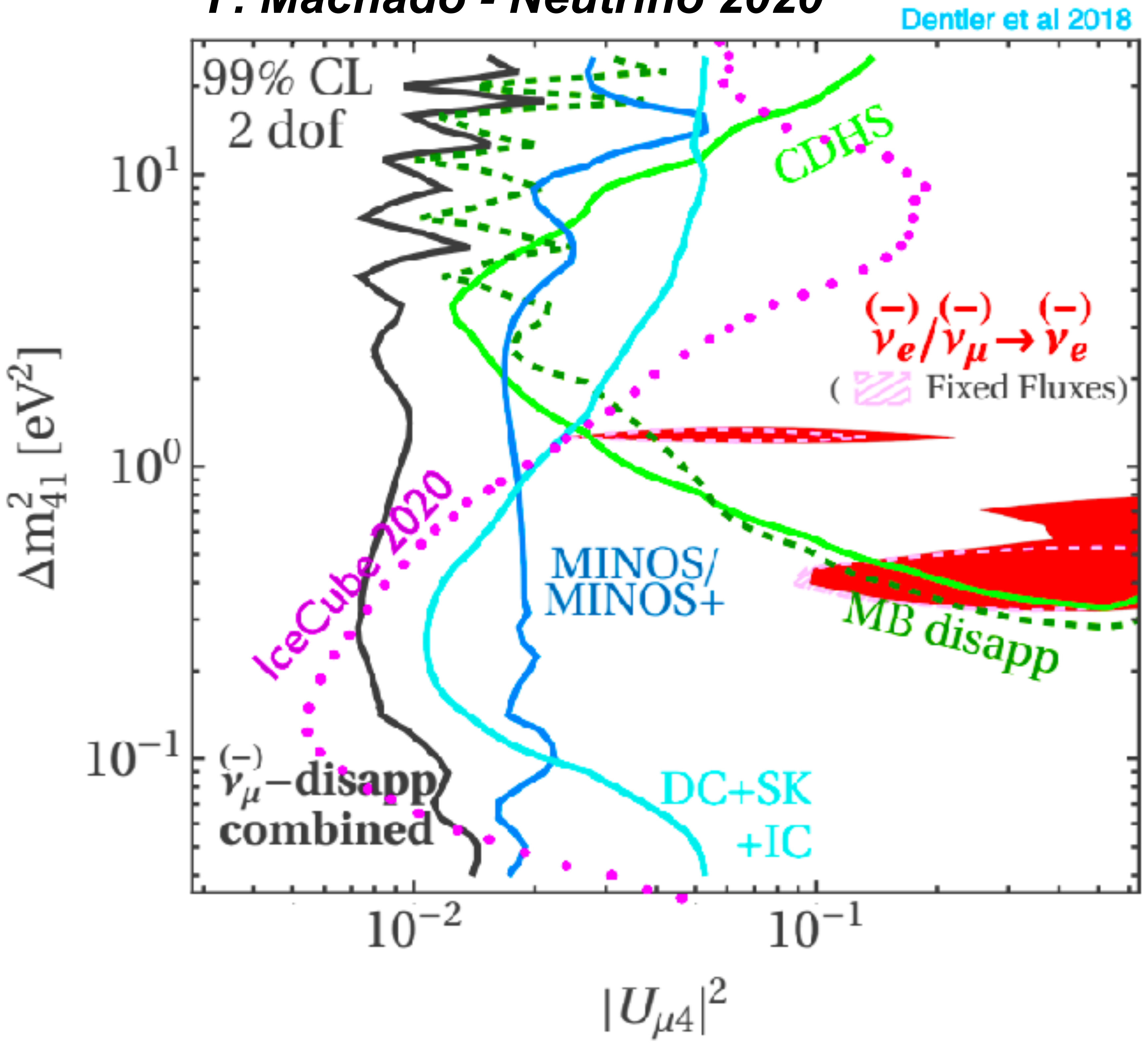
- Clean measurement of **exclusive cross sections** that can be fed to other GeV-scale neutrino exps.
- Precision measurement of "**standard candles**" —
  - could νSTORM help other exps measure their own fluxes? Low-ν? coh-$\pi^{\pm}$ production?

Short-baseline oscillations

Minimal eV sterile oscillations.

Model is in **strong** tension with ν_μ disappearance + cosmology

P. Machado - Neutrino 2020



$$\Delta m^2_{\rm SBL} \sim 1\,{\rm eV}^2$$

$$P^{3+1}_{\nu_\mu \to \nu_e} = 4|U_{\mu 4}|^2 |U_{e4}|^2 \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$P^{3+1}_{\nu_\mu \to \nu_\mu} = 1 - 4\,|U_{\mu 4}|^2 (1 - |U_{\mu 4}|^2)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

A $\nu_\mu \to \nu_e$ **appearance** signal implies **electron- and muon-neutrino disappearance.**

No conclusive evidence to date.

If eV sterile hints persist in short-baseline data (e.g., SBN at FNAL & JSNS2 in Japan), nuSTORM would be a truly unique facility that can provide a (**much overdue!**) definitive test

Sterile neutrino oscillations?

➤ A definitive test of short-baseline oscillations

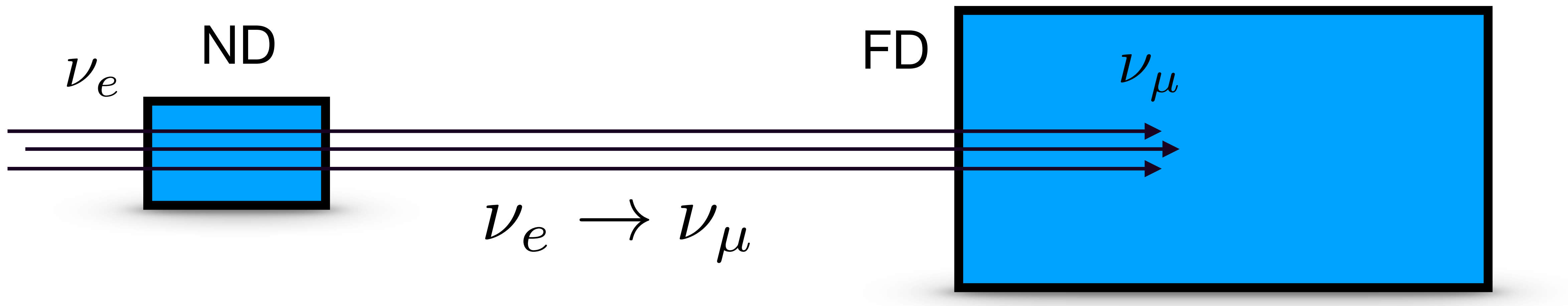
Separated by **timing**.

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

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

Charge separation with Magnetic field

$\nu_e \to \nu_\mu$



1) T or CPT conjugate of usual appearance channels
2) **muon identification** much easier than electrons

Already studied for FNAL design

D. Adey et al, 10.1103/PhysRevD.89.071301

Sample	Channel	Sensitivity
π^+ flash	$\nu_\mu \to \nu_\mu$	$\|U_{\mu 4}\|^2$
	$\nu_\mu \to \nu_e$	$\|U_{e4}U_{\mu 4}\|^2$
Stored μ^+	$\nu_e \to \nu_e$	$\|U_{e4}\|^2$
	$\overline{\nu}_\mu \to \overline{\nu}_\mu$	$\|U_{\mu 4}\|^2$
	$\nu_e \to \nu_\mu$	$\|U_{e4}U_{\mu 4}\|^2$

On the detector side, can one hit all the target the channels Above in a single experiment??

- **Near detector** sensitive to large mass splittings (10 eV^2) but it would see averaged-out flavor transitions (**flat in energy** — not an oscillation per se)

- **With** 50 m **baseline and** Enu ~ 2 GeV**, nuSTORM would not be sensitive to a** 1 eV **sterile neutrino, unless a far detector is built at** *O(1)* **km away.**

  - Anomalous **energy modulated disappearance** on top of the (well-known) muon decay flux. Great exp to measure oscillation wave.

  - Anomalous **appearance of wrong-sign muons**. Background limited**.**

Exotics at short-baselines

Open the floodgates to *exotica*

Modified from P. Machado - Neutrino 2020

New signatures:

Gninenko 1107.0279 *No LSND*
Heavy neutrino O(MeV), magnetic moment, decay

Bertuzzo et al 1807.09877, Ballett et al 1808.02916, Arguelles et al 1812.08768
Heavy neutrino O(1-100MeV), light Z', decay
W. Abdallah et al 2010.06159 ~~No LSND~~

Oscillations+:

Asaadi et al 1712.08019
Resonant matter effect *UV challenge*

Doring et al 1808.07460, Barenboim et al 1911.02329
eV steriles and extra dimensional shortcuts *not clear*

Liao et al 1810.01000
Steriles + NCNSI + CCNSI *Baroque*

Decay:

O. Fischer et al 1909.09561 *Delayed signal?*
Long lived HNL O(MeV) mag moment

Bai et al 1512.05357, Dentler et al 1911.01427, de Gouvêa et al 1911.01447
Heavy sterile O(keV-MeV) decay to ν_e *May work...*

Even though this list is specific for MiniBooNE/LSND explanations it is still **a good proxy for what kind of new physics a facility like nuSTORM would be sensitive to.**

New exotic hypothesis to explain MiniBooNE

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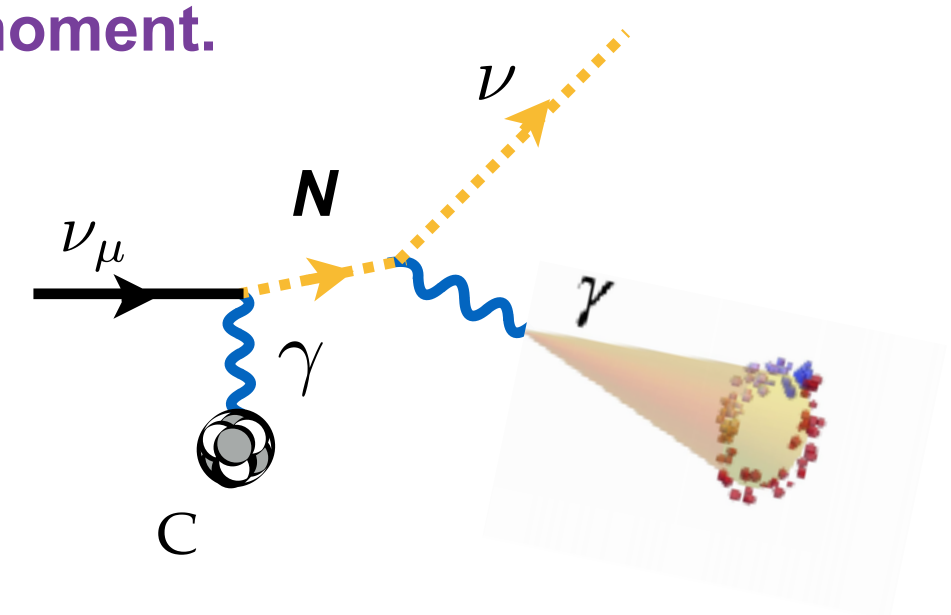
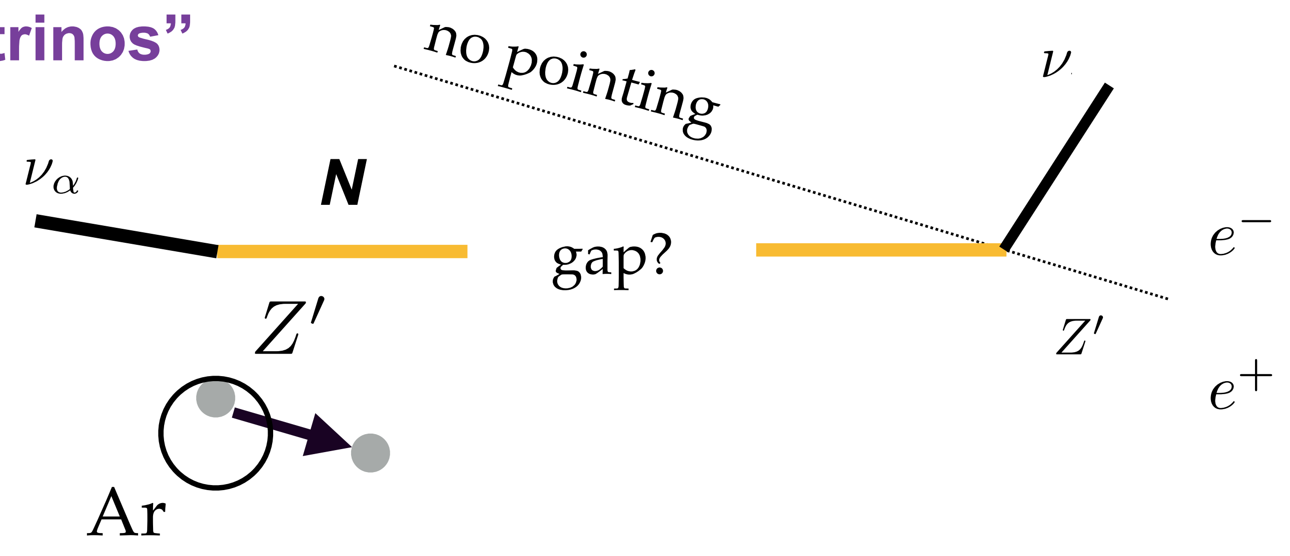
New physics
In scattering

Transition magnetic moment.



"Dark sector neutrinos"



νSTORM

- **No need for a far detector**
- Near detector will require good γ **and e± reconstruction** (would like to distinguish e± / γ / e+ e- pairs if possible)
- **Energy dependence** (can only test these models with few GeV neutrinos)

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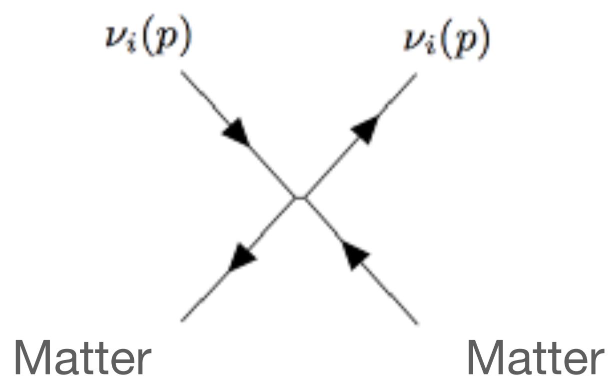
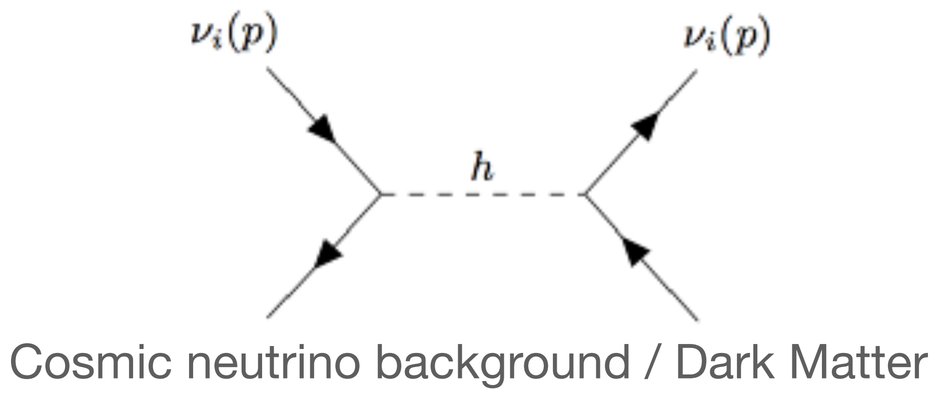
New physics
In propagation

Additional interactions to enlarge the matter potential



Neutrinos scattering on some new invisible background



νSTORM

- **Needs far detector** to integrate more matter effects
- Similar to oscillation signatures — still looking for anomalous flavor transitions at the end of the day — **wrong sign muons still great signature.**
- **Would like the same L/E as MiniBooNE/LSND.**

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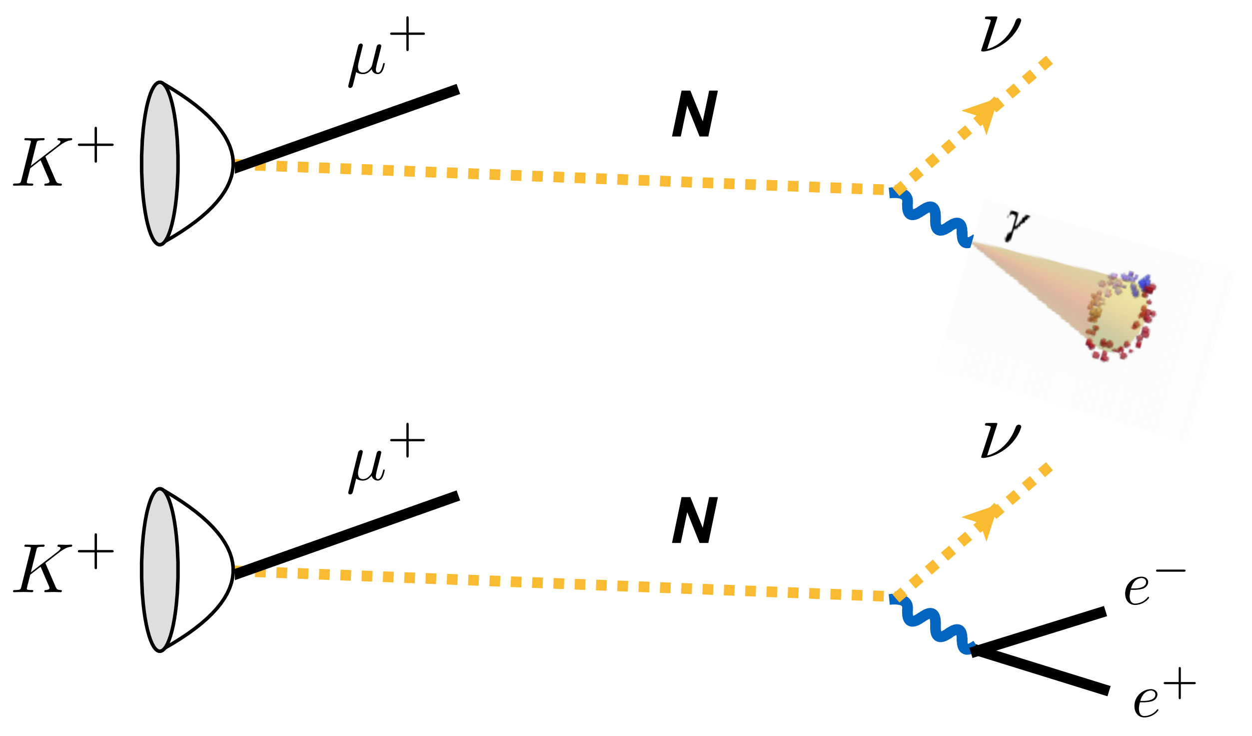
Heavy sterile O(keV-MeV) decay to ν_e — May work

- **No need for a far detector.**
- Would also like to tell $e^\pm$ / γ / $e^+ e^-$ pairs apart —
- **benefits from low density.**
- Kaons are usually more interesting for producing new particles:
  - **If proton beam is not aligned w/ detector, can still exploit stopped kaons at the absorber**
  - Not optimized for new particles produced in neutral meson decays (π^0, etas, J/psi)
- New particle production from mu-decay is still possible, but more constrained

νSTORM

Decay-in-flight of light particles In the beam

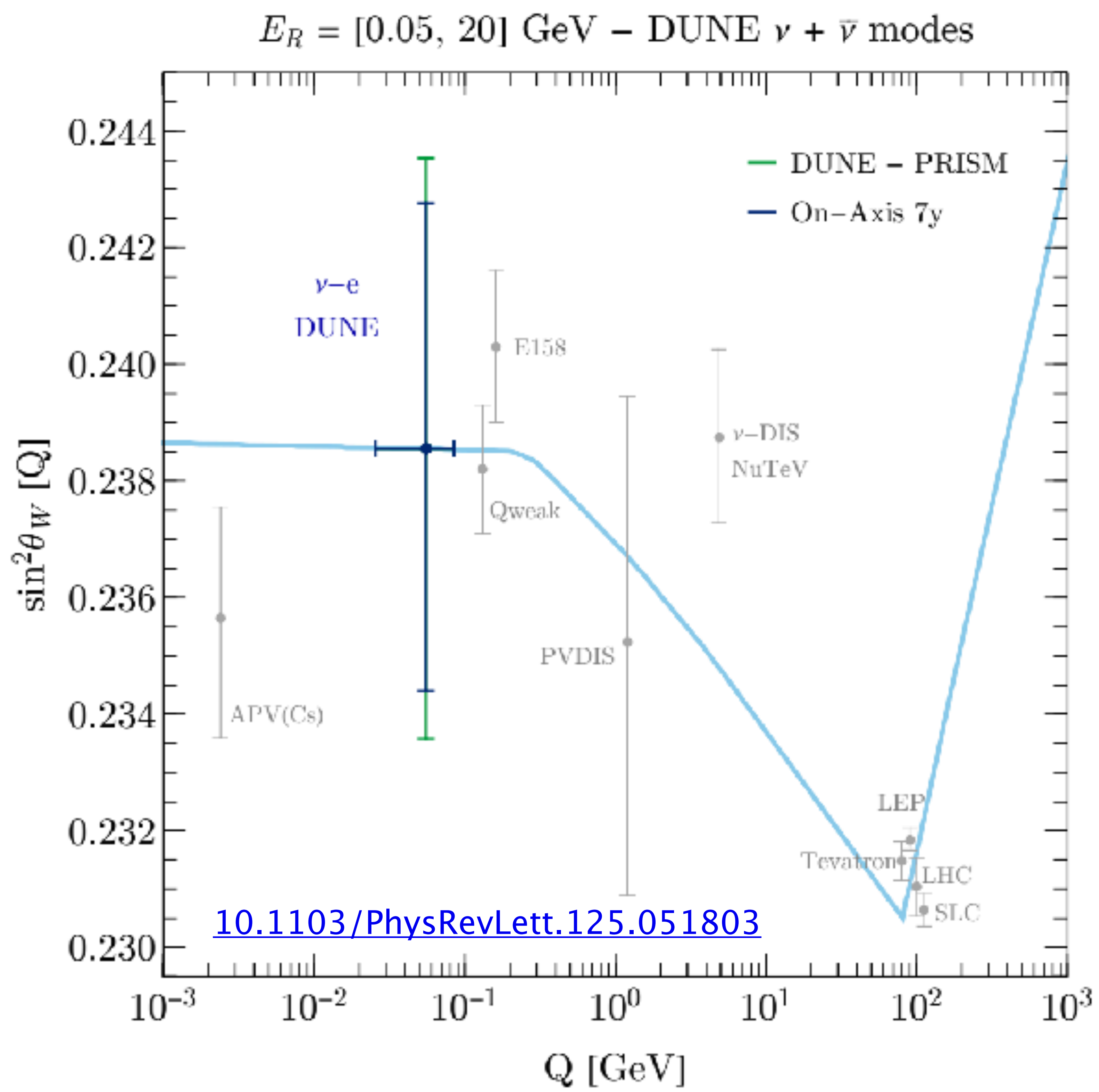
Heavy neutrino decay-in-flight



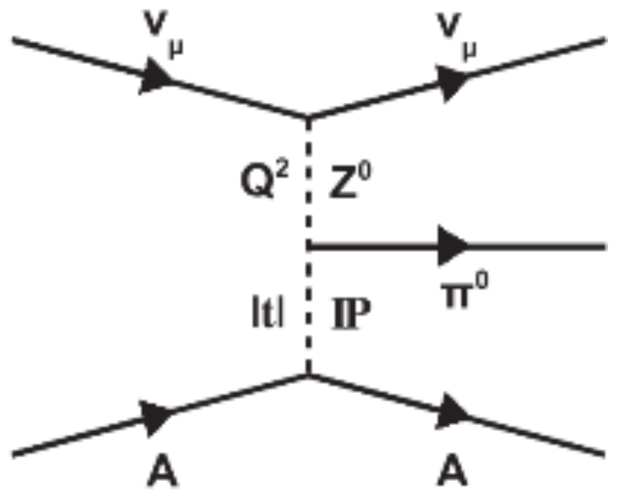
Rare scattering processes

Neutrino-electron scattering

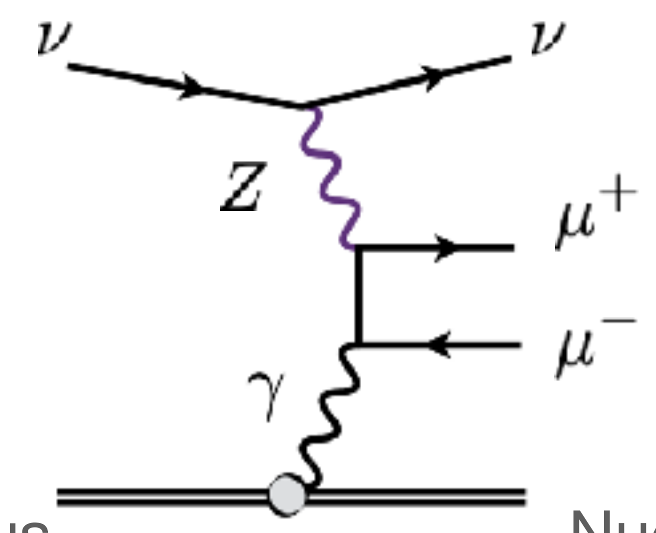
- Precision measurement of a well-known cross section.
  - Weak scattering sensitive to the Weak angle.
- Other scattering channels sensitive to the Weak angle at difference Q^2 values.
  - Neutrino trident scattering (scattering on virtual muons)
  - Coherent meson production
  - DIS scattering a la NuTeV (hard at low-E)



10.1103/PhysRevLett.125.051803

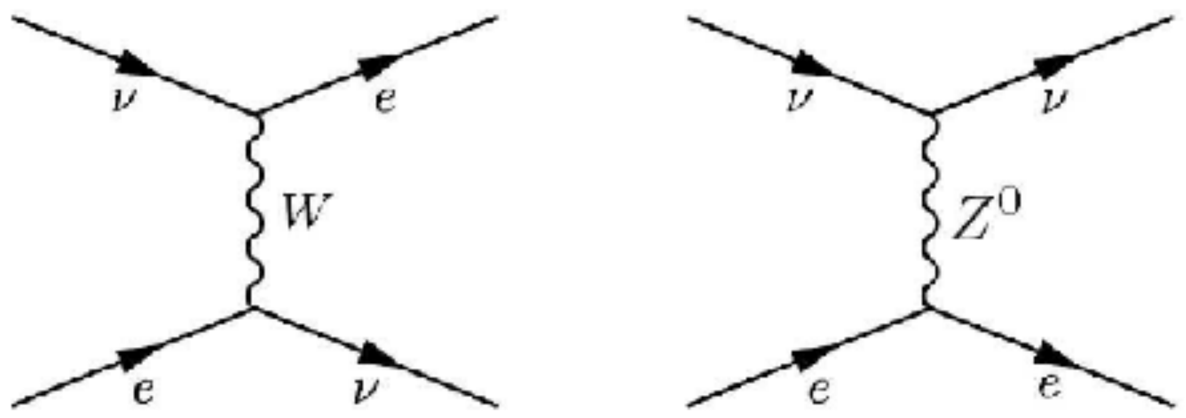


Rho production may be more promising. Also useful for pointing.



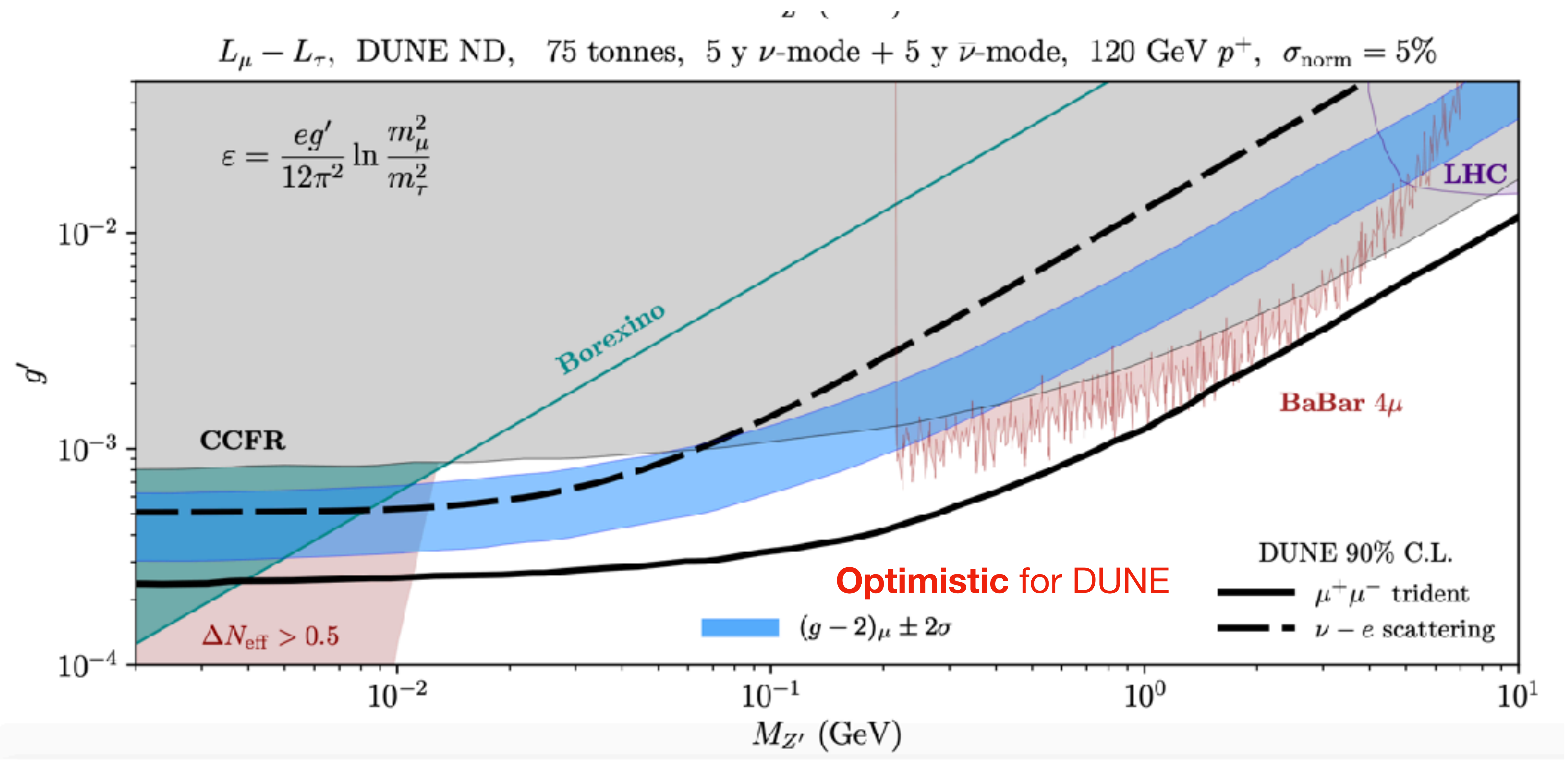
Cross section at the level of 10^{-6} of CCQE at 2 GeV

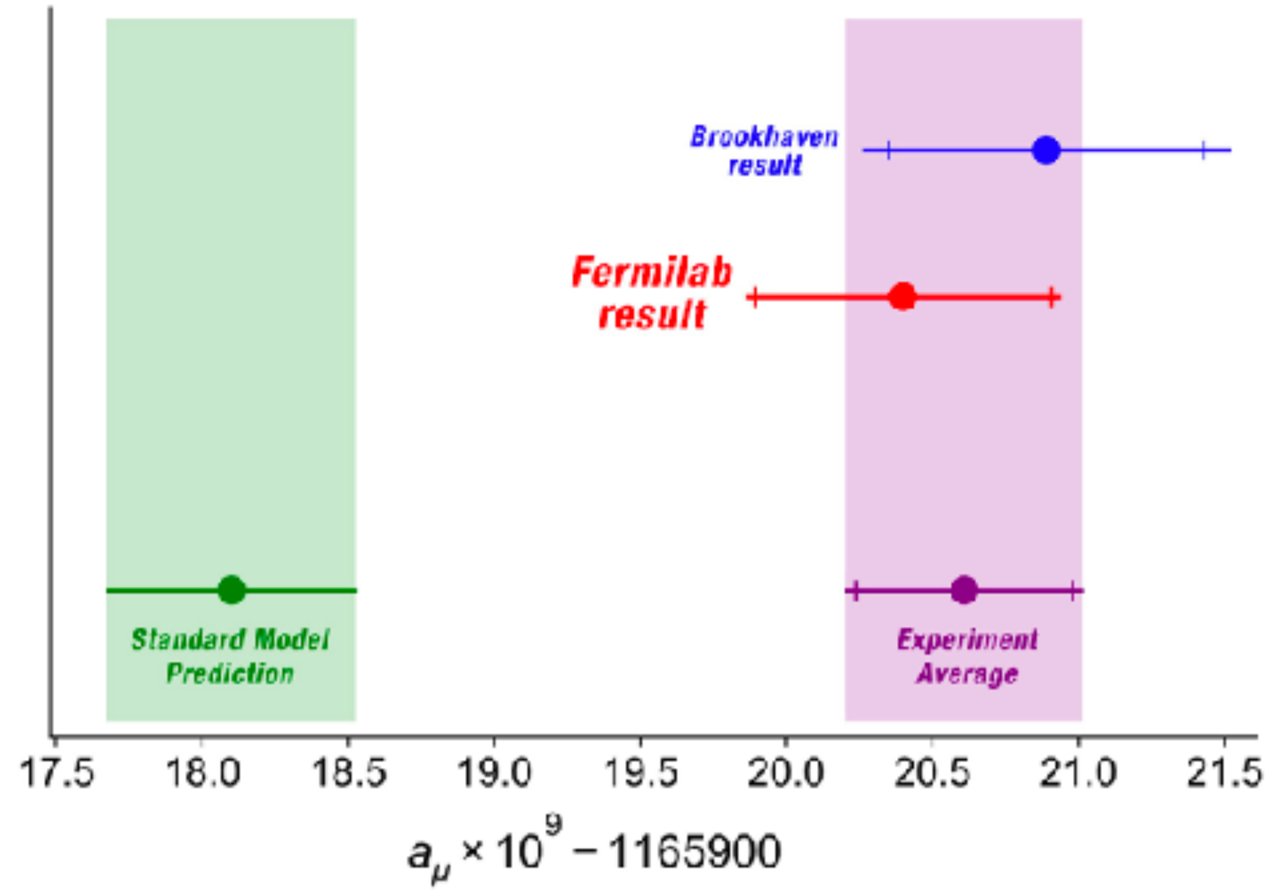
Magnetized detector with large Z nuclei is ideal.



Forward electrons.
Access to more flavors than DUNE.

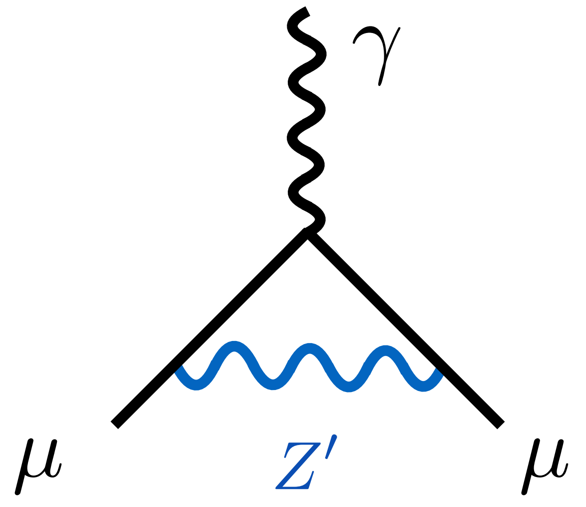
Dark forces contributing neutrino trident production

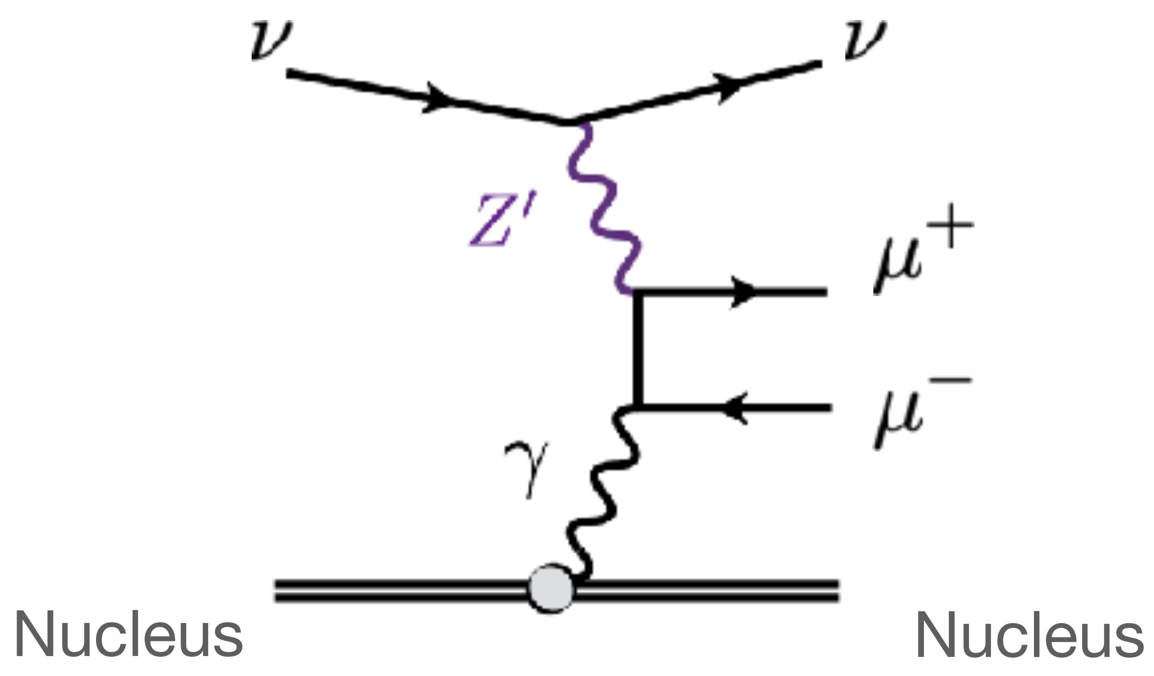


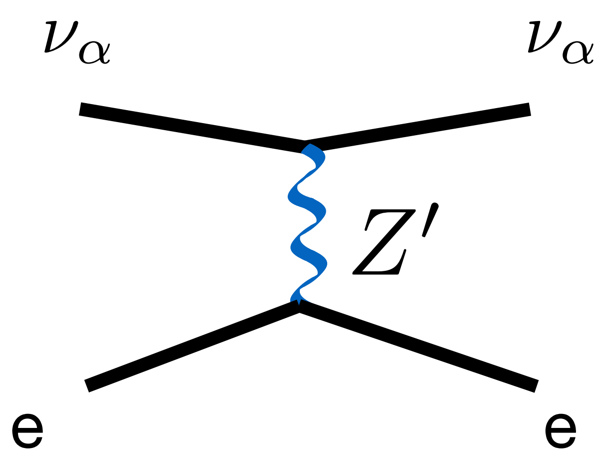


Muon (g-2) explanations
With light **Z'**

Pospelov, PRD80:095002,2009







This field may see many new developments in near futures, but no guarantee of discovery in neutrino facilities.

But one can try.

Conclusions

- nuSTORM would open a door to precision neutrino physics (<1% flux uncertainties) in both $\boldsymbol{\nu}_e$ and $\boldsymbol{\nu}_\mu$ sectors with GeV neutrinos. Good for an "umbrella strategy" for new physics that is weakly coupled to neutrinos.
- **Definitive** test of short-baseline neutrino oscillations

  T and CPT conjugate channels of MiniBooNE and LSND (muons are much easier final states — provided one can separate μ+ from μ-).
- Light particle production by neutrino scattering —> test of exotic short-baseline models.
- Light particle production by meson decay —> stopped kaons?
- Matter effects and oscillation —> would like a far detector.

- Search for new physics in precision measurements of rare scattering (nu-e scattering, tridents, coherent meson production) will rely on how well you can reject backgrounds. Can only assess this potential with a detector design

Appendix

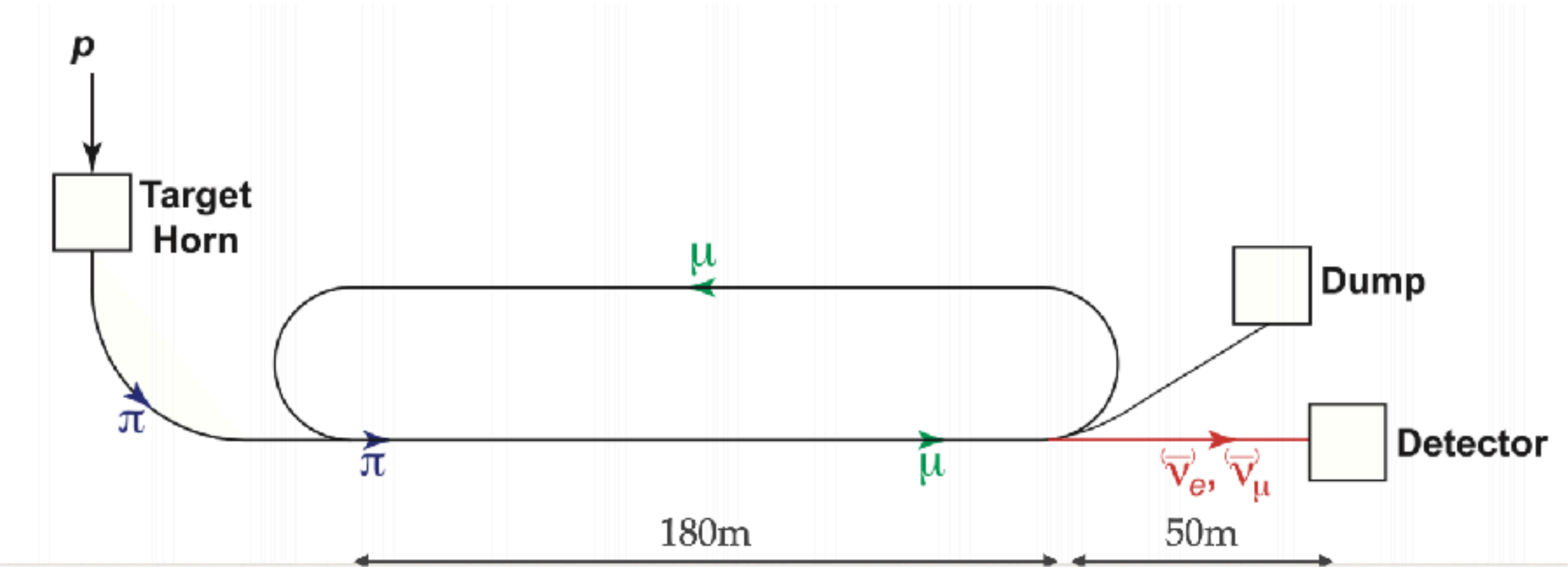
Neutrinos from STORed Muons

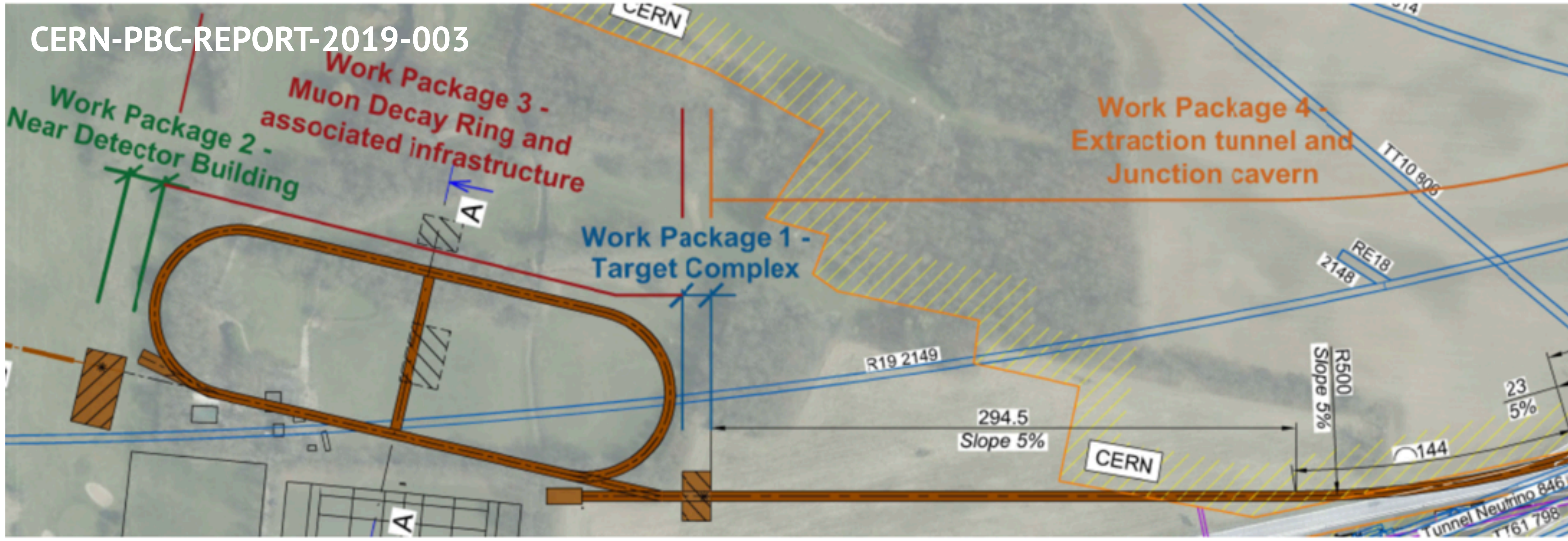
➤ A **precision** neutrino facility — 1% flux uncertainties

1) neutrino-nucleus **cross sections,**

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

3) **Muon collider** demonstrator and test-bed (see talk B08.00007 in Muon Collider Symposium I)





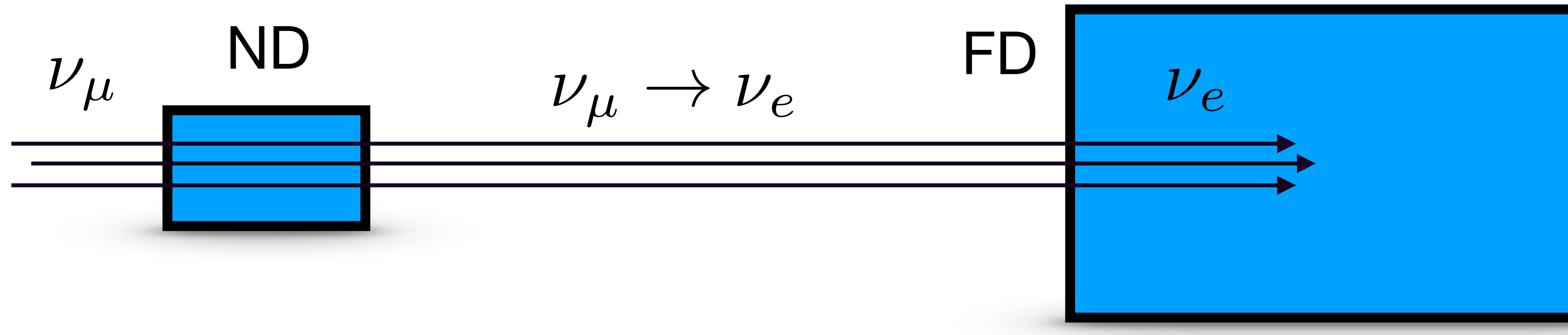
Physics Beyond Colliders study at CERN

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

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

Challenge 1) Flux, cross sections, and efficiencies are never measured separately

a) near-to-far detector ratio is not robust against detector systematics.

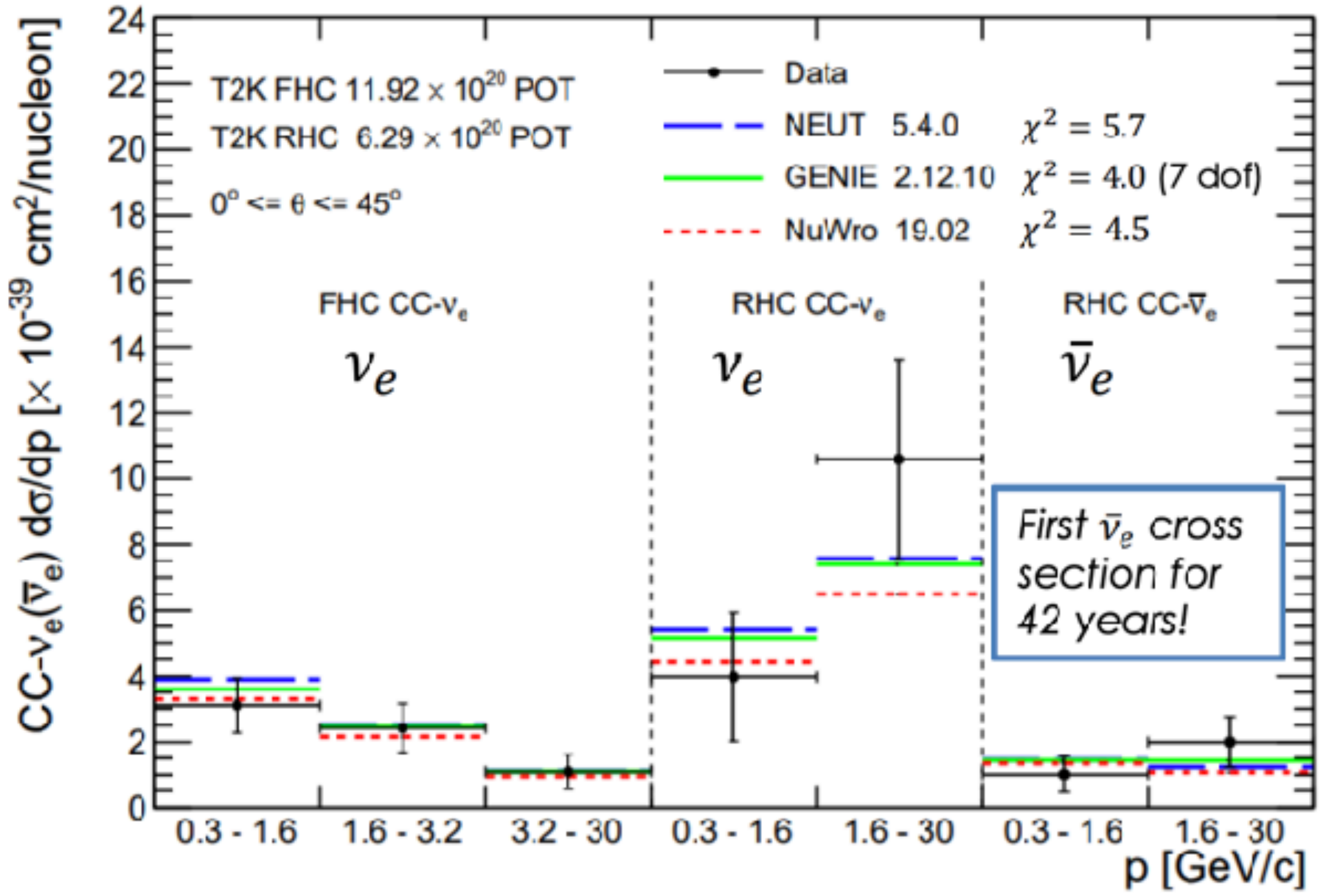
b) energy spectrum is not the same between ND and FD (oscillation and geometry).

Challenge 2) Final state neutrino-flavor is not abundant at the near detector

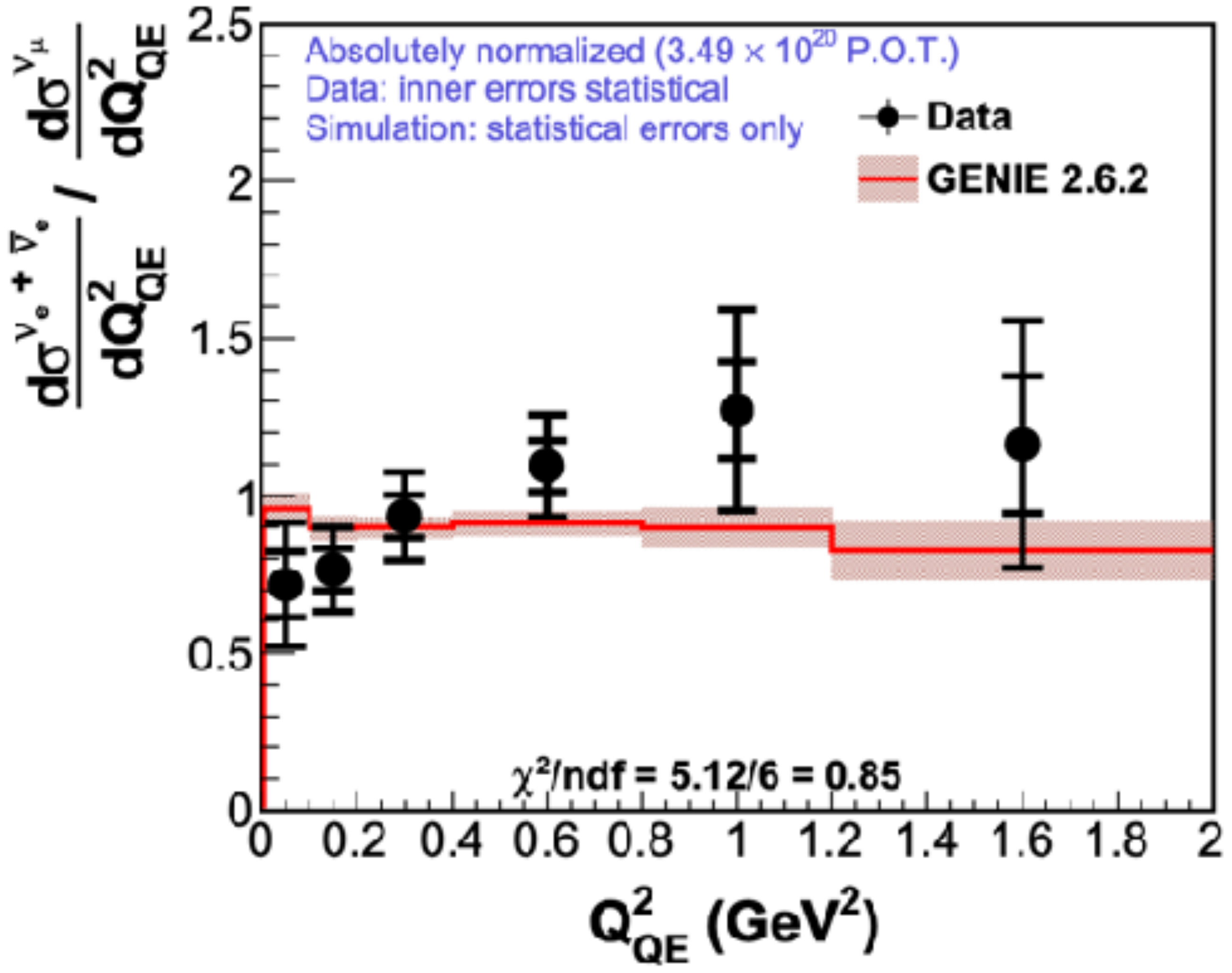
a) cross sections x efficiency are not exactly the same.

- With few % uncertainties in flux — we will need a **detector with improved PID capabilities (under study)**.
  - Clean measurement of **exclusive cross section**, which can be fed to other LBL experiments.
  - Precise measurement of "**standard candles**" for LBL experiments (low-ν, ν-e elastic, coh π production) — can help other exps measure their own fluxes.
  - Direct contribution to **nuclear physics,** including the structure of nuclei.
- Scarce data on **ν_e cross section**

T2K coll., JHEP10(2020)114



MINERvA, PRL 116, 081802 (2016)



νSTORM

Would be worlds largest sample of ν_e scattering events.

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

μ^+ Channel	N_{evts}	μ^- Channel	N_{evts}
$\bar{\nu}_\mu$ NC	1,174,710	$\bar{\nu}_e$ NC	1,002,240
ν_e NC	1,817,810	ν_μ NC	2,074,930
$\bar{\nu}_\mu$ CC	3,030,510	$\bar{\nu}_e$ CC	2,519,840
ν_e CC	5,188,050	ν_μ CC	6,060,580
π^+		π^-	
ν_μ NC	14,384,192	$\bar{\nu}_\mu$ NC	6,986,343
ν_μ 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

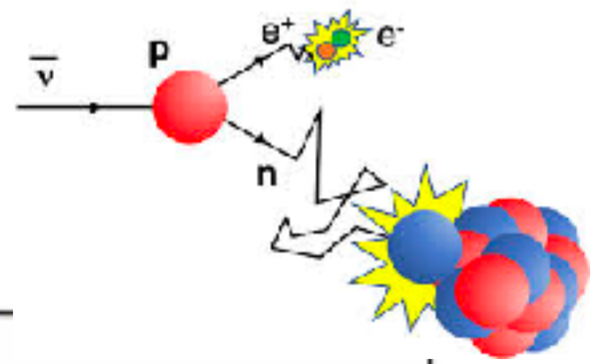
Short-baseline anomalies

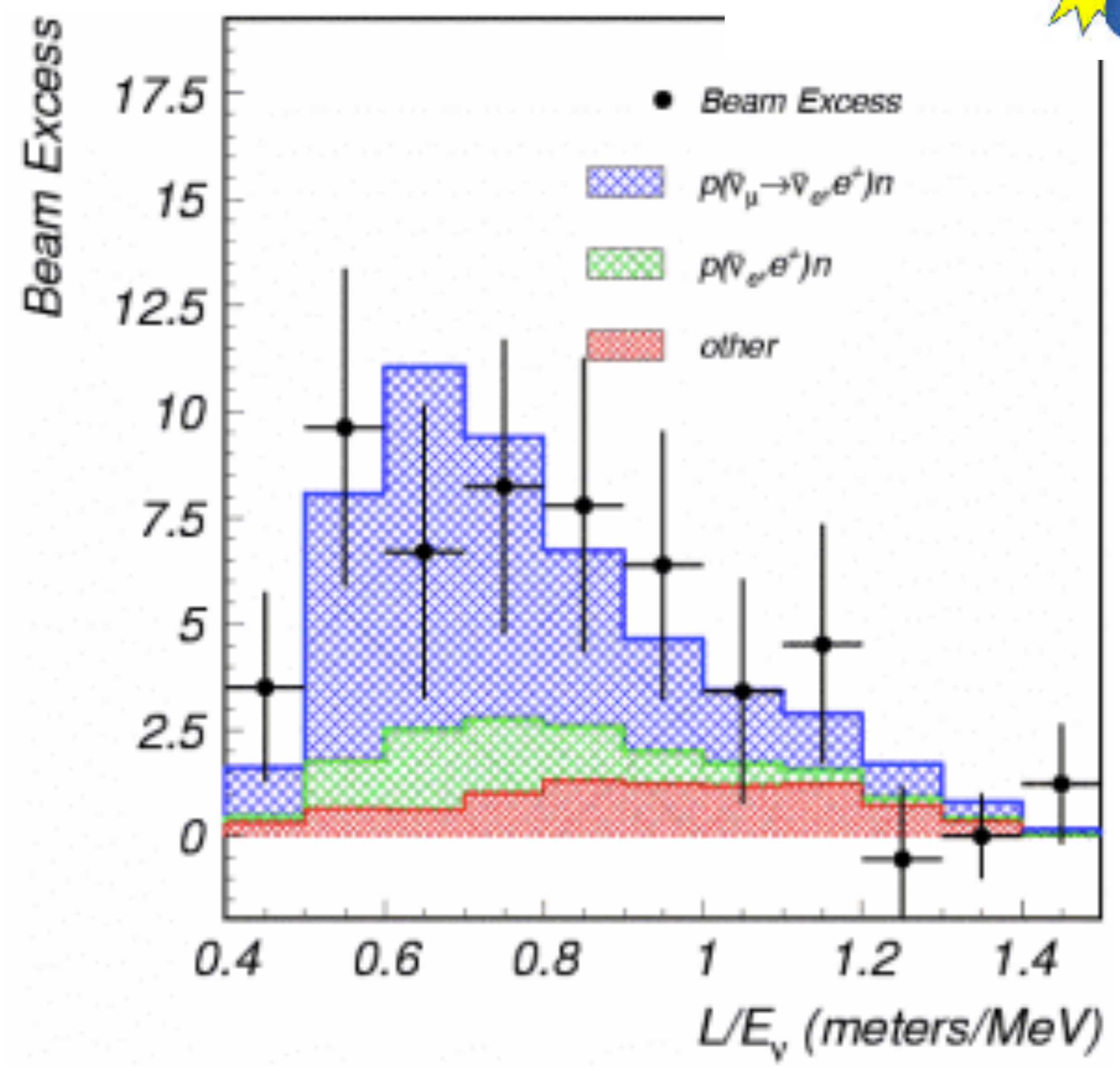
@ LSND: $\pi^+ \to \mu^+ \nu_\mu$

arXiv:0104049

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

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





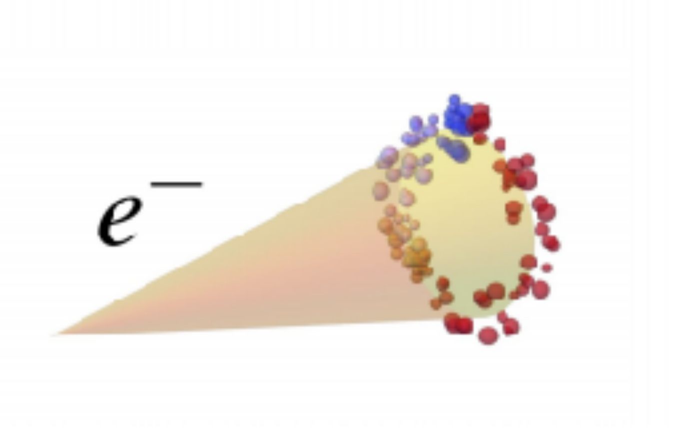
EXCESS: 87.9 ± 22.4 ± 6 EVENTS

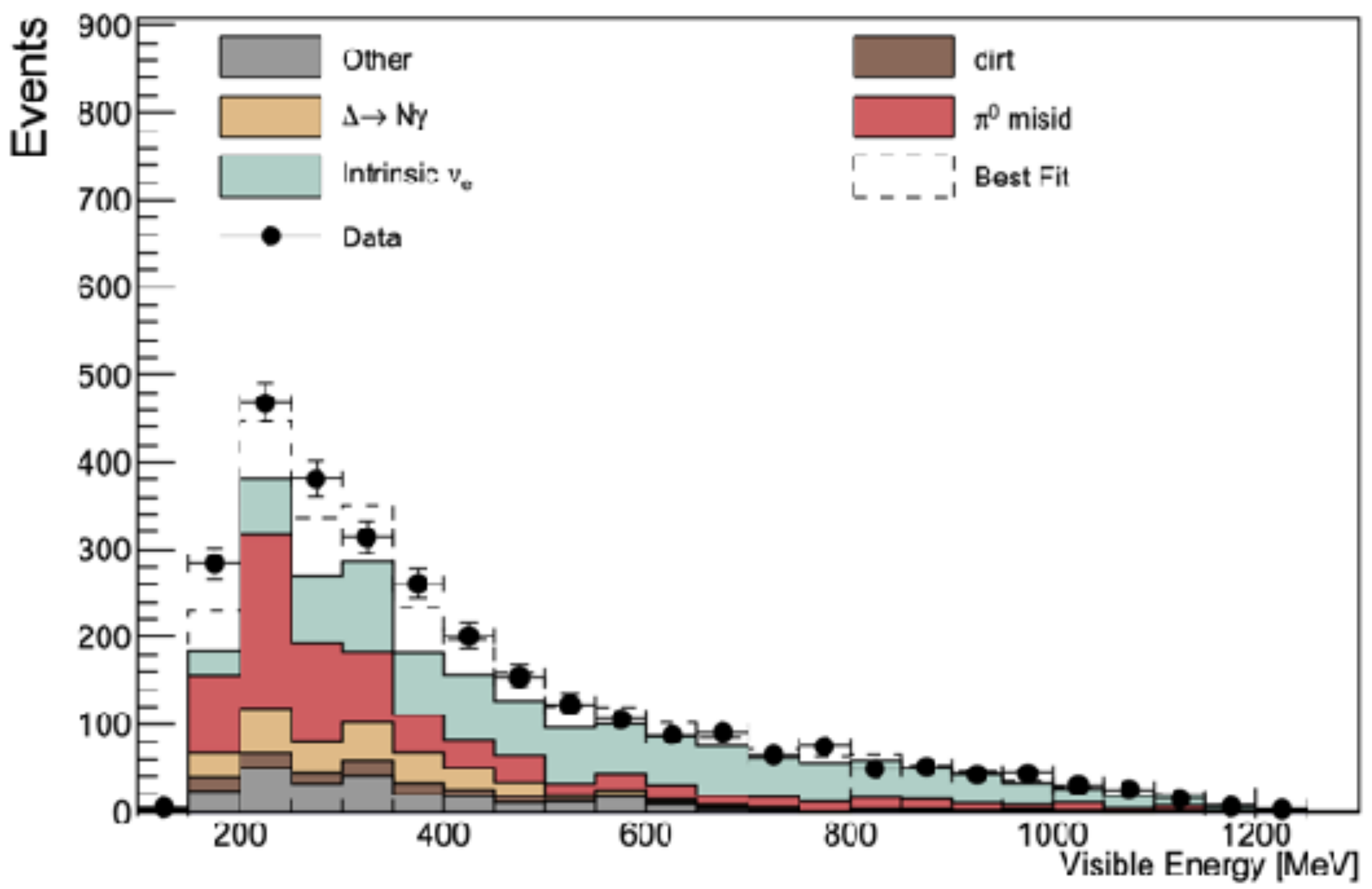
3.8 sigma

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

arXiv:2006.16883

$\nu_\mu \to \nu_e$





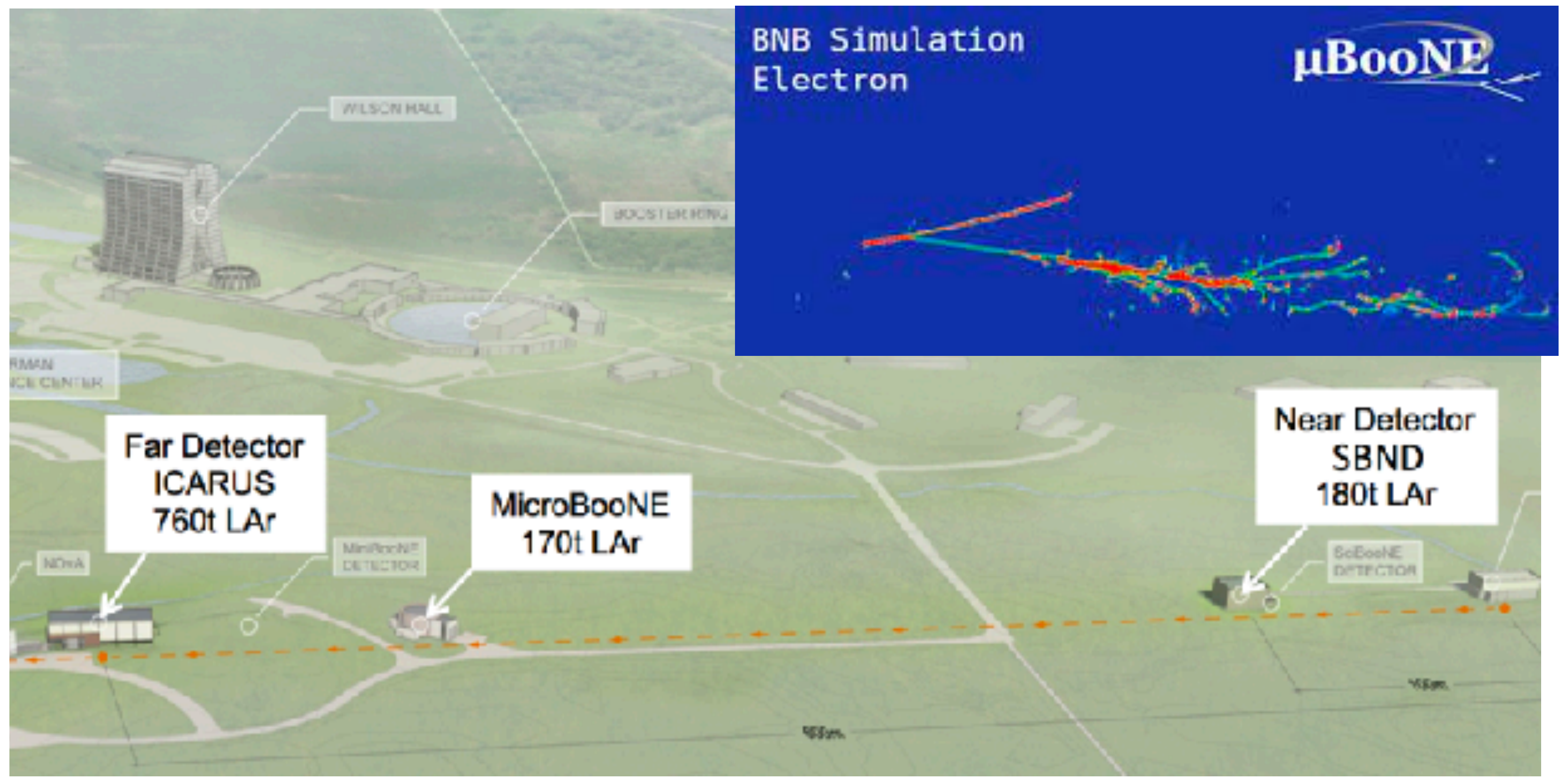
EXCESS: 560± 119.6 EVENTS only in nu mode

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.

New Physics searches

➤ A definitive test of short-baseline oscillations

Separated by **timing**.

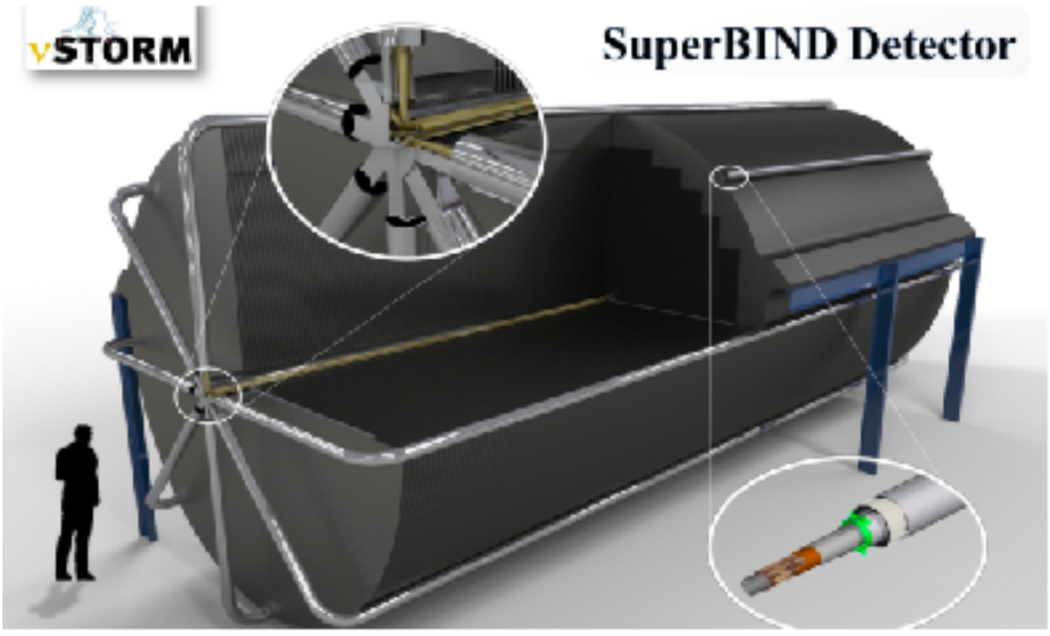
$\nu_\mu \to \nu_\mu$

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

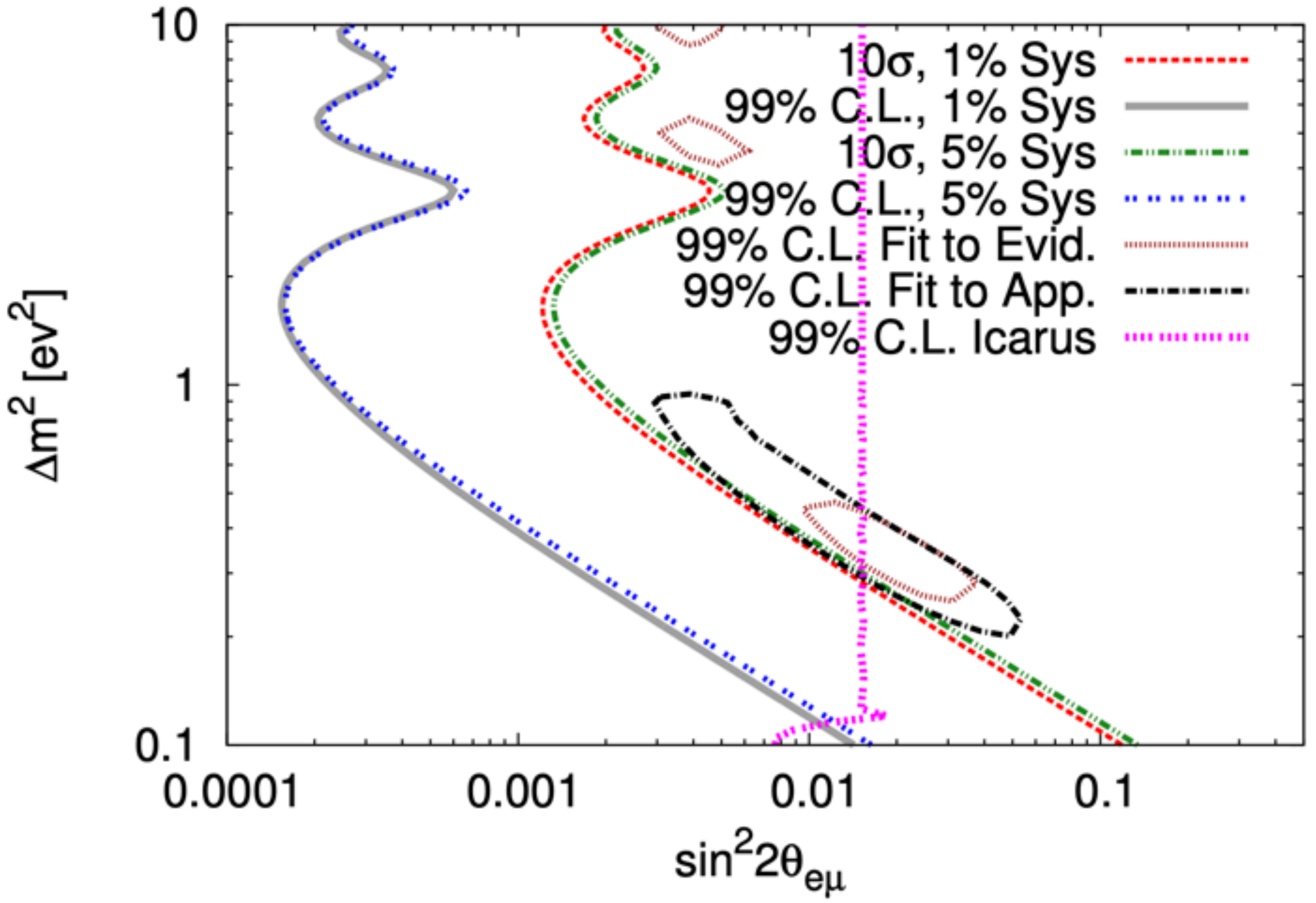
Charge separation with Magnetic field

$\nu_e \to \nu_\mu$

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



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



D. Adey et al, 10.1103/PhysRevD.89.071301

➤ Also sensitive to zero-distance effects:

e.g. non-unitarity of PMNS matrix.

Oscillation data

$$|U_{e1}U^*_{\mu 1} + U_{e2}U^*_{\mu 2} + U_{e3}U^*_{\mu 3}| \leq 0.07 \text{ at } 3\sigma$$

[S. Parke, M. Ross-Lonergan, 2015]

νSTORM

$$|U_{e1}U^*_{\mu 1} + U_{e2}U^*_{\mu 2} + U_{e3}U^*_{\mu 3}| \leq 0.008 \text{ at } 3\sigma$$

[MH, PhD thesis]