Neutrinos at Muon Colliders

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Outline

- Neutrino Slice
- Sterile Neutrinos
- Neutrino collision

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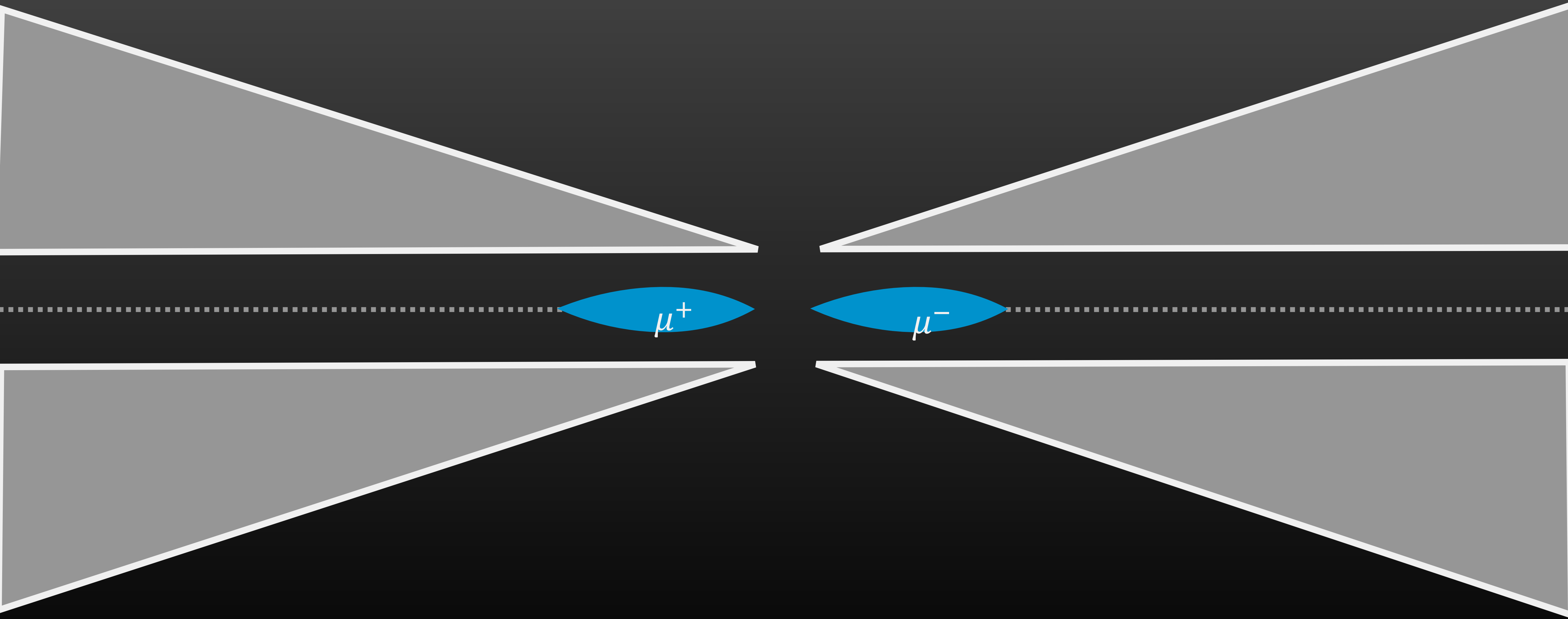
- Sterile Neutrinos
- Neutrino collision

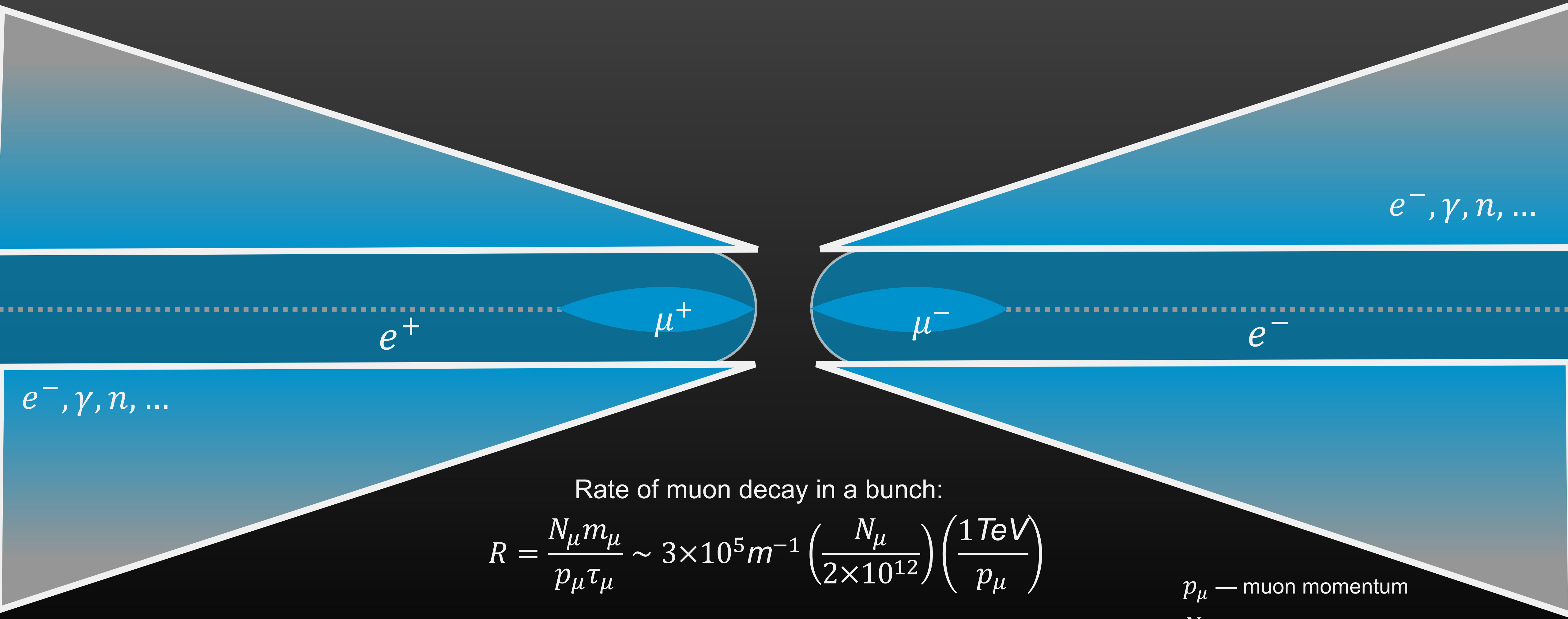
Luc Bojorquez-Lopez, Matheus Hostert, Carlos A. Argüelles, ZL 2412.14115 and ongoing works.

Muon Collider Beam radiation



Muon Collider

Beam radiation — Beam Induced Backgrounds (BIB)



Rate of muon decay in a bunch:

$$R = \frac{N_\mu m_\mu}{p_\mu \tau_\mu} \sim 3\times10^5 m^{-1} \left(\frac{N_\mu}{2\times10^{12}}\right)\left(\frac{1\,TeV}{p_\mu}\right)$$

Bunch rate: 10~30 kHz

p_μ — muon momentum

N_μ — muons in bunch

τ_μ — muon lifetime

Did we forget about Neutrinos?

- Neutrinos cannot be shielded
- Part of the consideration for radiation hazard
- Part of Beam-Induced-Background but “ignored”

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- Part of the consideration for radiation hazard
- Part of Beam-Induced-Background but “ignored”

We show the story is different:

Good or Bad νs:

There exists a unique neutrino flux we need to tackle.

Beam-Induced-Neutrinos (BINs)

The most well-characterized ν beam ever built

- Flux normalization & energy dependence are determined with $< 1\%$ precision
- (muon decay is well-understood, so "*just*" need to measure the muon beam current)
- Compare with $\mathcal{O}(10\%)$ flux uncertainties in traditional accelerators and forward flux at LHC

What are BINs Good for?

MuC BINs would offer a high-Q^2 probe of fundamental matter with Weak interactions.

Beam energies are not necessarily new, but flavor composition, sample size, and precision are.

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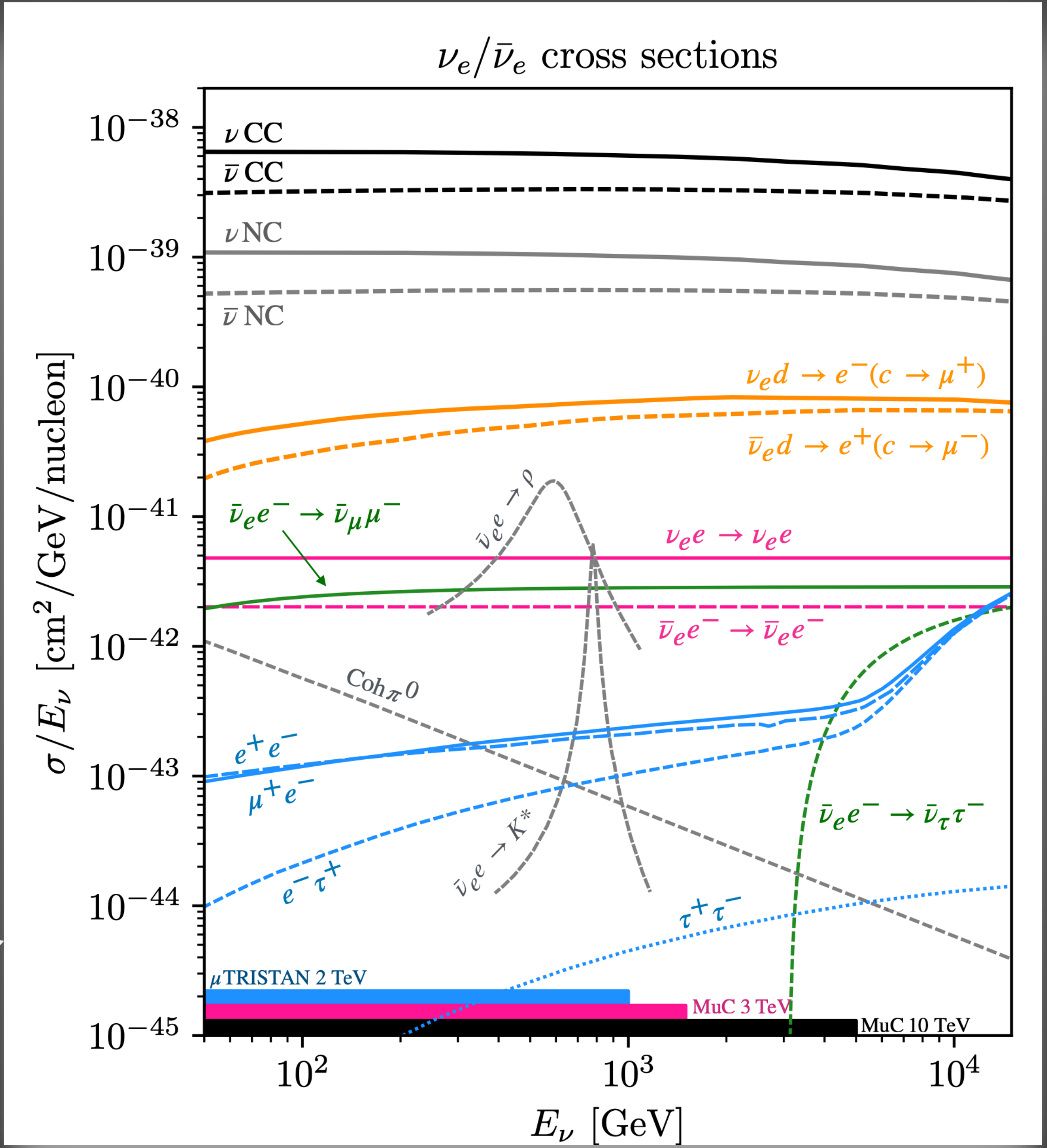
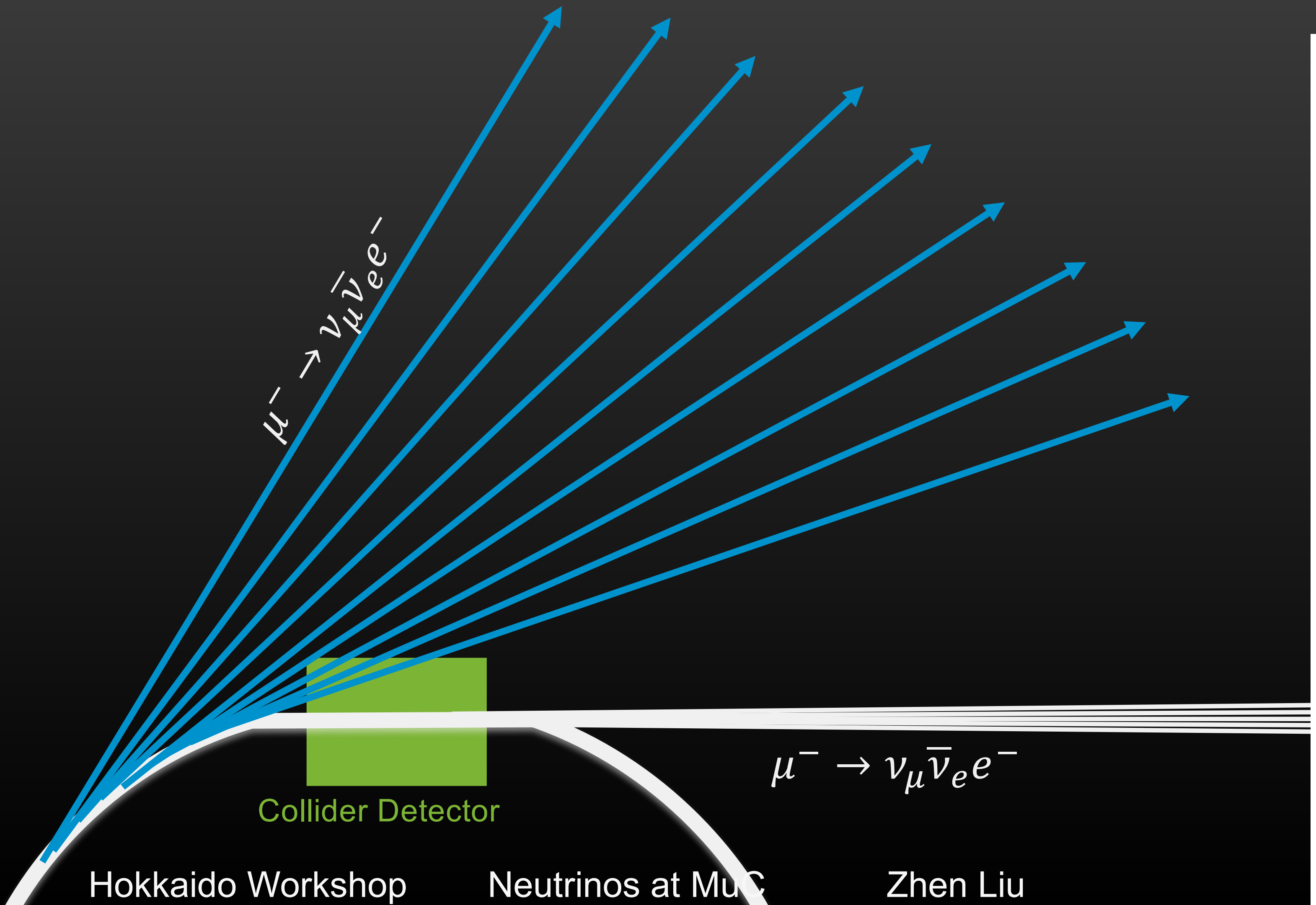
Many exclusive processes

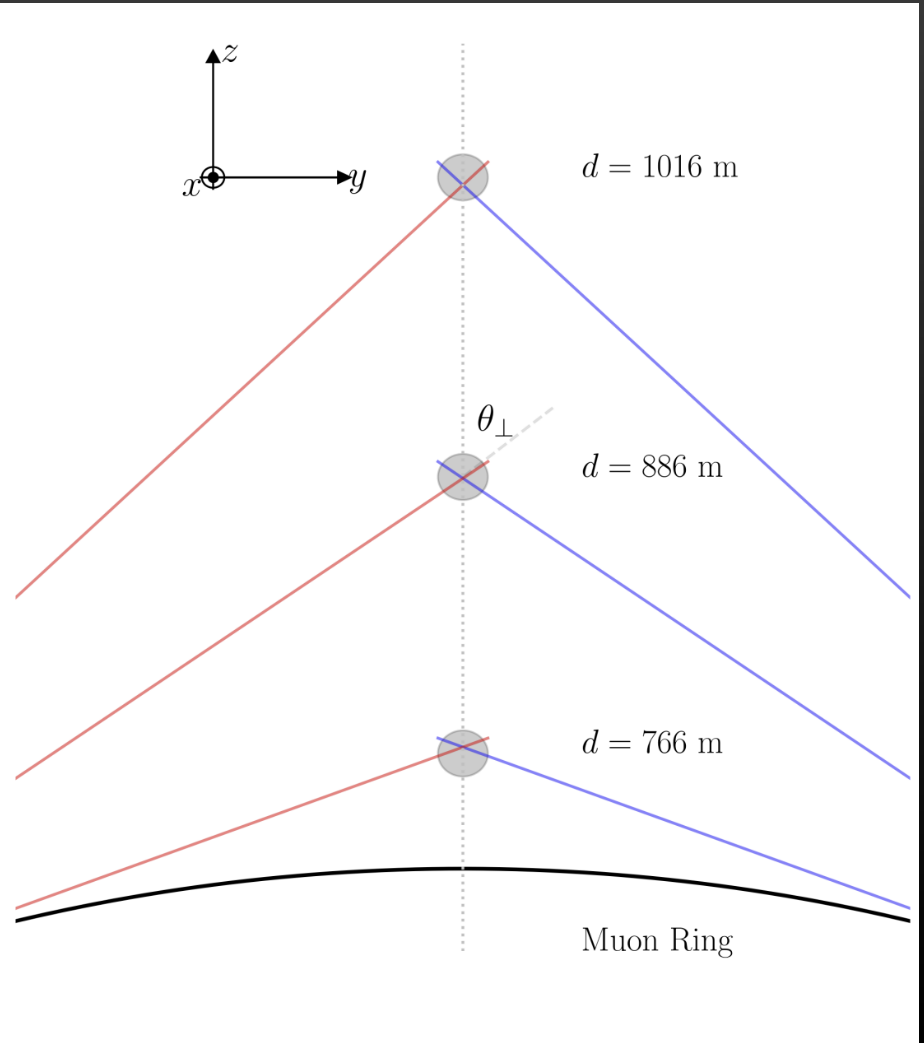
Deep Inelastic Scattering **CC** and NC
Charm production
Inverse muon(tau) decay
Elastic scattering on electrons
Resonant meson production
Neutrino trident production



Detecting BINs: Tangential facilities?

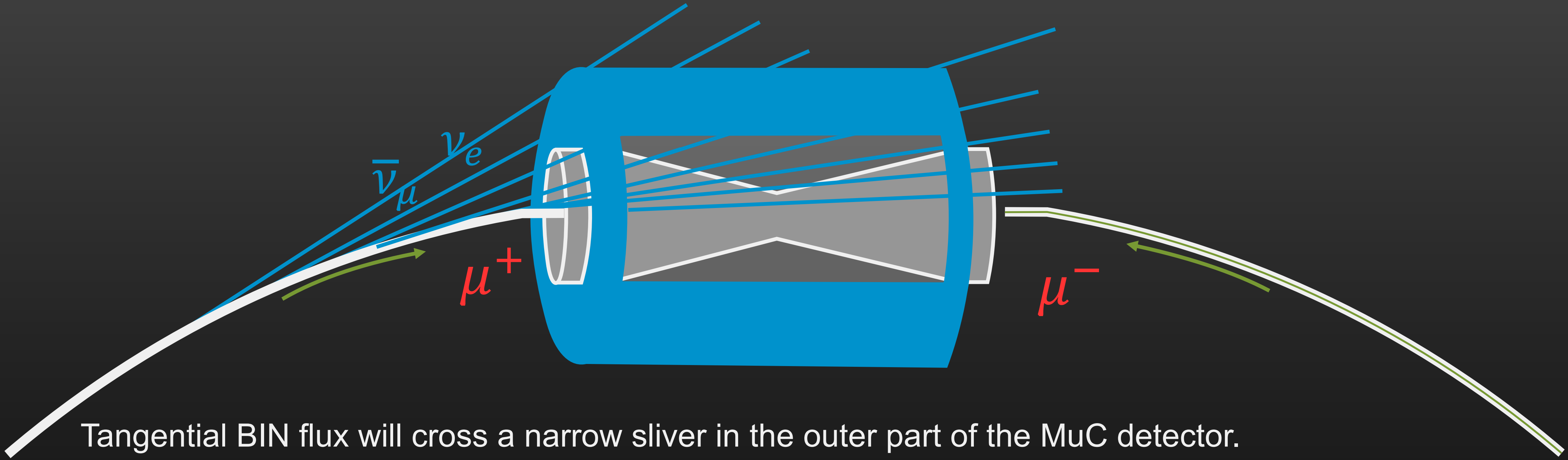
A. de Gouvea, A. Thompson, [2505.00152](2505.00152)





Detecting BINs

Leveraging tangential flux at the main detector



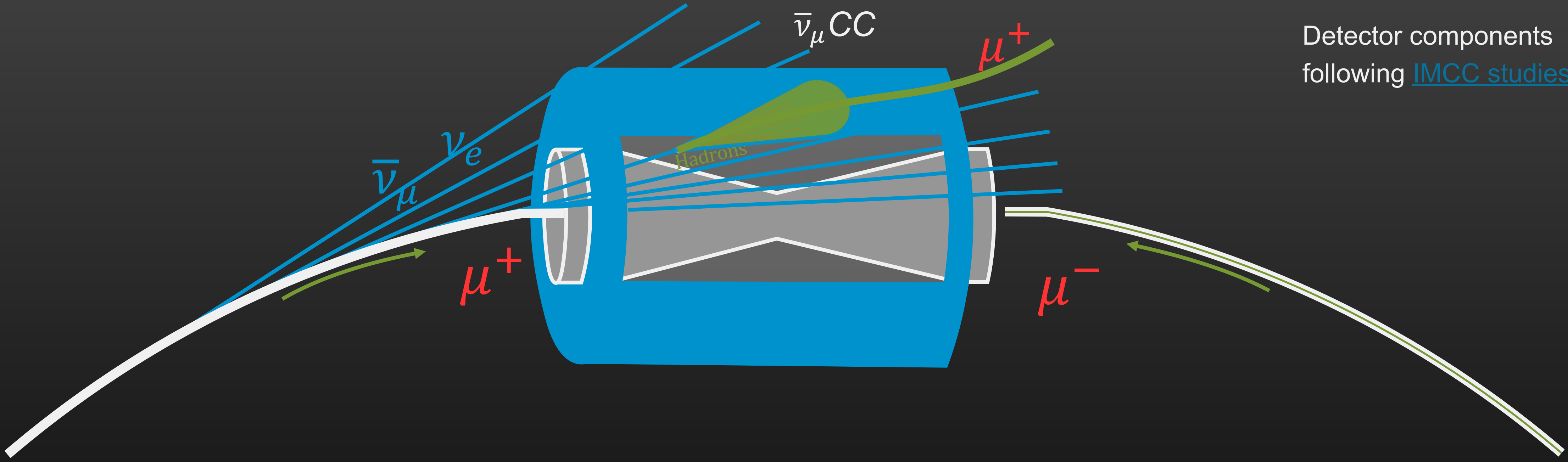
Tangential BIN flux will cross a narrow sliver in the outer part of the MuC detector.

BIN interactions in this “**neutrino slice**” will be abundant and produce high energy particles

$$\sigma_\nu \sim G_F^2 m_p E_\nu$$

Beam-Induced Neutrinos (BINs)

Most frequent events: $\bar{\nu}_\mu$ CC

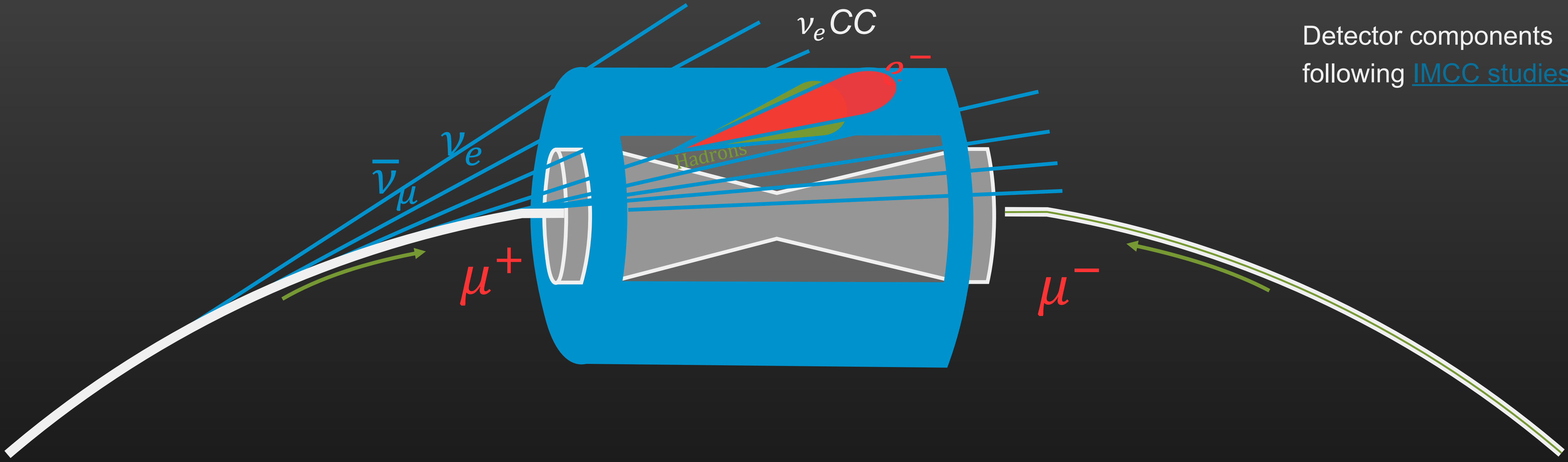


Detector components following IMCC studies

Induce hadronic showers with muons inside the barrel.

Beam-Induced Neutrinos (BINs)

Most frequent events: ν_e CC

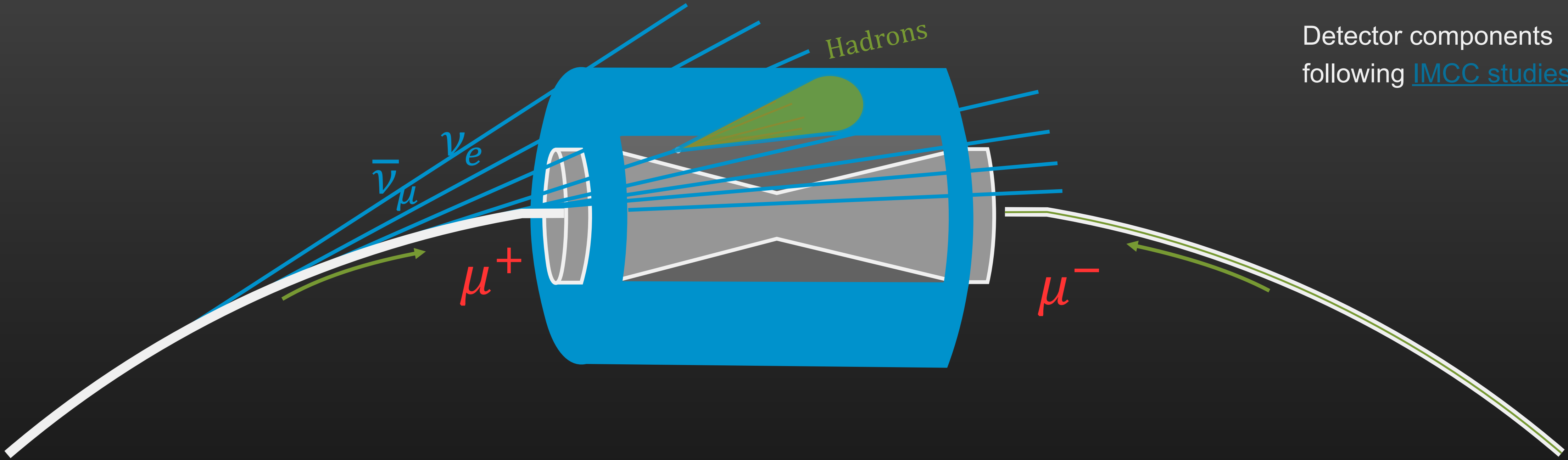


Detector components following IMCC studies

Induce hadronic showers with electrons inside the barrel.

Beam-Induced Neutrinos (BINs)

Most frequent events: ν NC



Detector components following IMCC studies

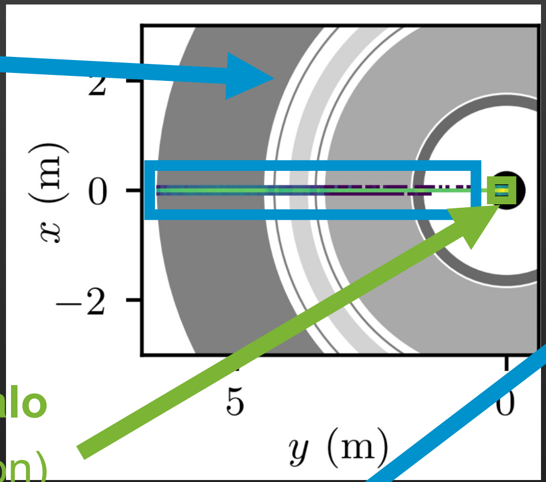
Induce pure hadronic showers inside the barrel.

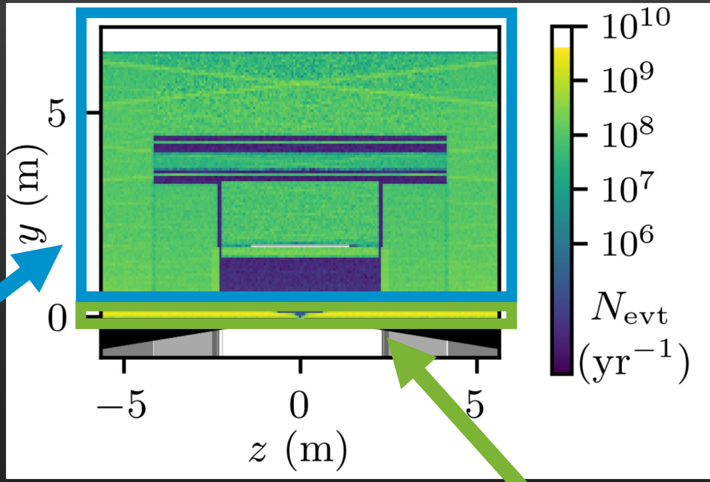
Beam-induced neutrinos

Tangential fluxes

Neutrino Slice

(mostly from main ring)

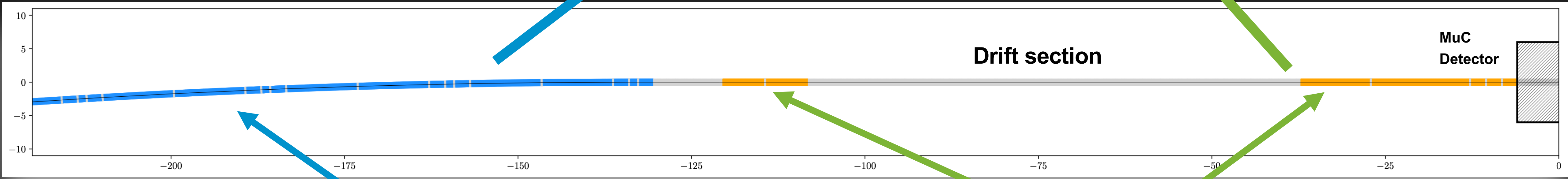




Neutrino Halo

(mostly from straight section)

Vast majority goes down the pipe



Bending magnets

Focusing magnets

Muon Collider

Building toy models of muon collider

More neutrinos than we have ever detected by >3 orders of magnitude.

O(1) events per bunch crossing.

About 0.1 large-R (HCal/ECal) events per bunch crossing.

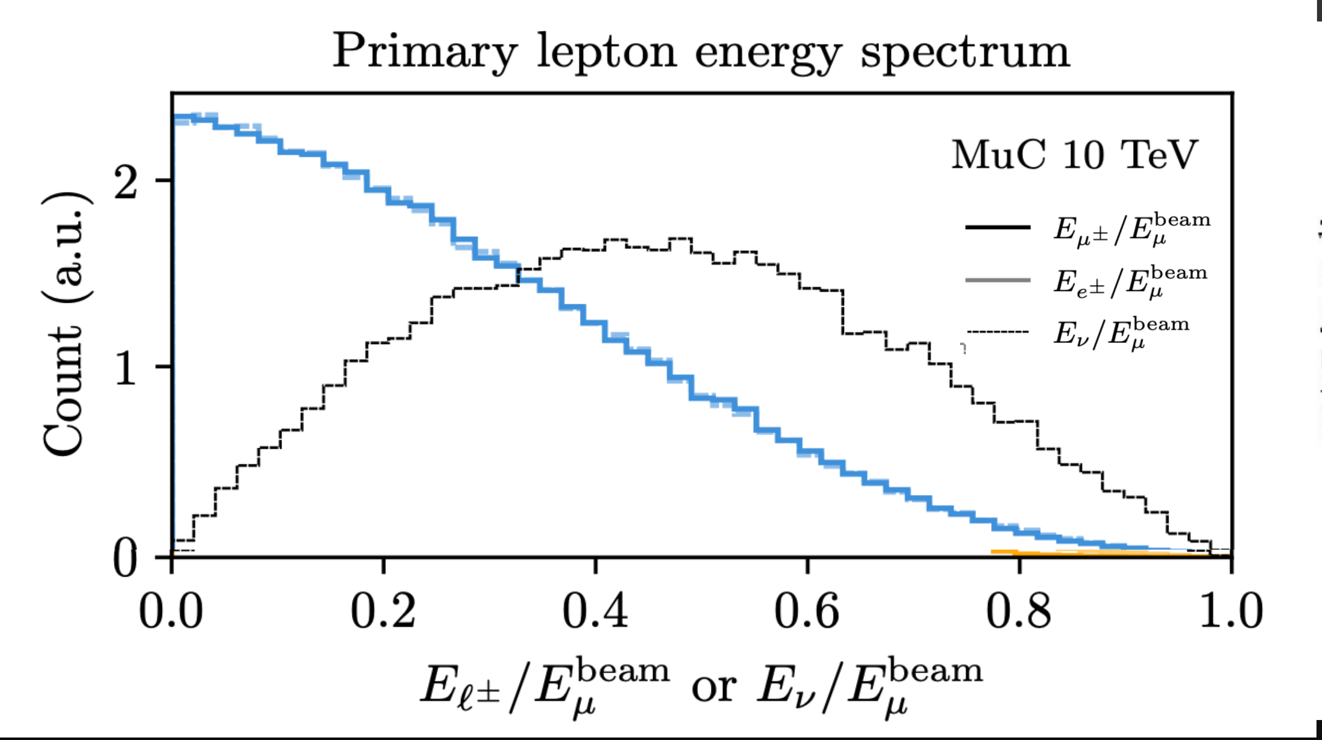
Collider	MuC 10 TeV	MuC 3 TeV	μTRISTAN
Beams	$\mu^+\mu^-$	$\mu^+\mu^-$	$\mu^+\mu^+$
Muons/bunch	1.8×10^{12}	1.8×10^{12}	1.4×10^{10}
bunches/cycle	1	1	40
f_{inj}	5 Hz	5 Hz	50 Hz
C	8.7 km	4.3 km	4.3 km
BIN exclusive reactions in HCAL and ECAL/year			
Total NC	1.5×10^9	4.6×10^8	3.4×10^9
Total ν_e CC	4.7×10^9	1.4×10^9	1.1×10^{10}
Total ν_μ CC	5.4×10^9	1.7×10^9	1.1×10^{10}
ES $\nu_\mu e\to\nu_\mu e$	3.8×10^5	1.1×10^5	0
ES $\bar\nu_e e\to\bar\nu_e e$	8.6×10^5	2.5×10^5	0
ES $\bar\nu_\mu e\to\bar\nu_\mu e$	3.4×10^5	9.9×10^4	1.9×10^6
QE $\nu n\to\ell^-p^+$	2.6×10^6	2.5×10^6	2.8×10^7
QE $\bar\nu p^+\to\ell^+n$	2.7×10^6	2.5×10^6	3.2×10^7
Coh π^0	3.0×10^5	2.9×10^5	3.5×10^6
Res $\bar\nu_e e\to\rho^-$	4.2×10^5	7.7×10^5	0
Res $\bar\nu_e e\to K^{*-}$	2.6×10^4	4.4×10^4	0
IMD $\nu_\mu e\to\nu_e\mu^-$	4.2×10^6	1.2×10^6	0
IMD $\bar\nu_e e\to\bar\nu_\mu\mu^-$	1.2×10^6	3.5×10^5	0
ITD $\bar\nu_e e\to\bar\nu_\tau\tau^-$	9.4×10^3	0	0
Trident e^+e^-	1.2×10^6	2.9×10^5	1.7×10^6
Trident $\mu^\pm e^\mp$	2.9×10^6	6.7×10^5	5.0×10^6
Trident $\mu^+\mu^-$	[illegible]	[illegible]	[illegible]

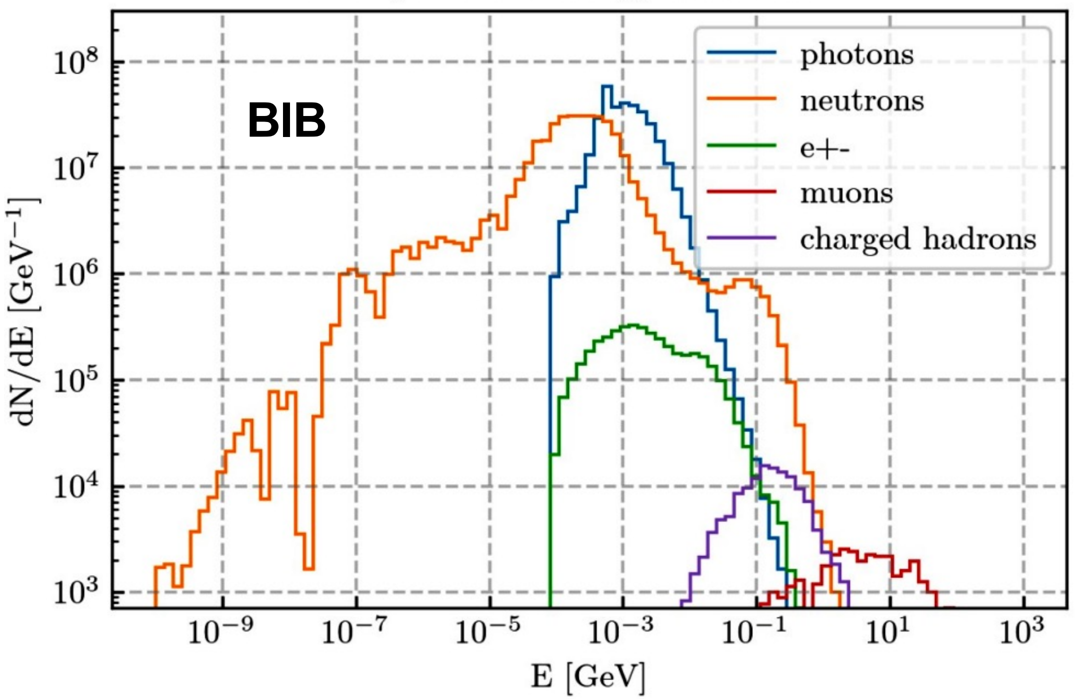
BIN Interaction properties

1) TeV amounts of energy

Bad ν_s?

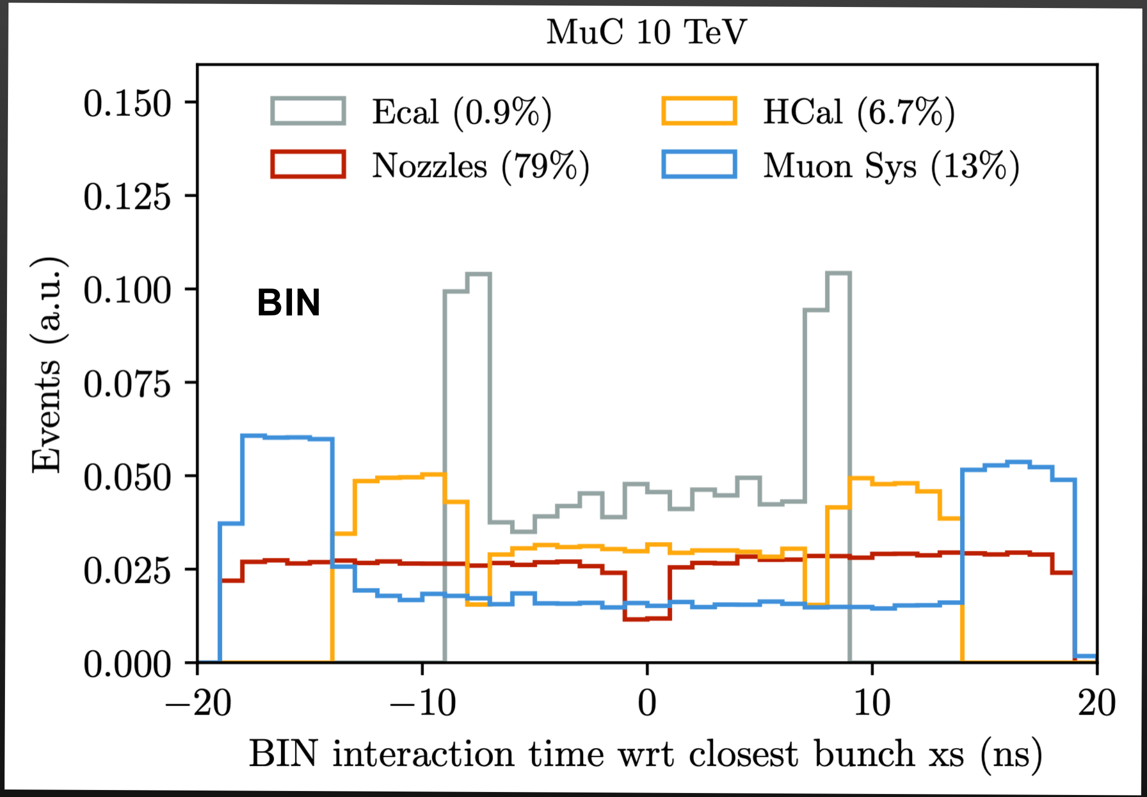
TeV Energy Deposit in ~every collision! And in large R in very 10% of the collisions.





D. Calzolari US Inaugural Muon Collider meeting 2024

BIN Interactions
2) Temporal profile



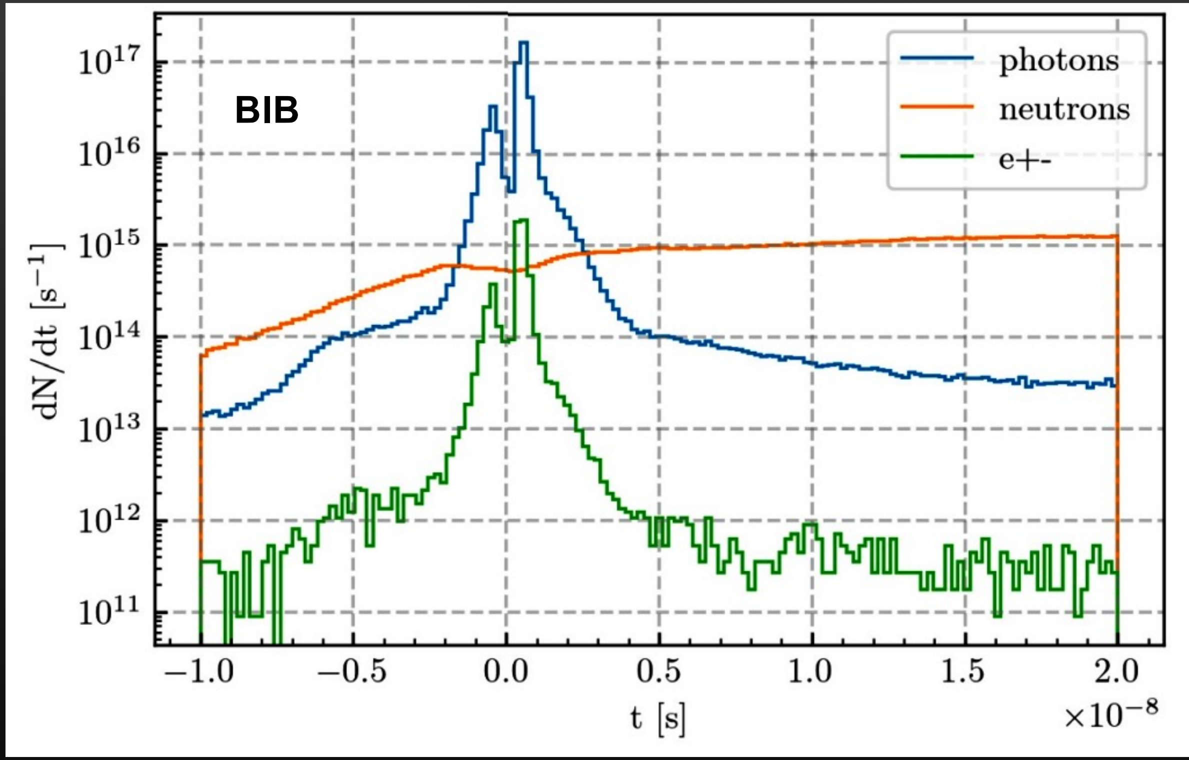
Early events will be better as there will be less BIB and charged particles will cross more detector material on the way out

O(ns) resolution is already enough to see substructure.

Not so bad ν_s?

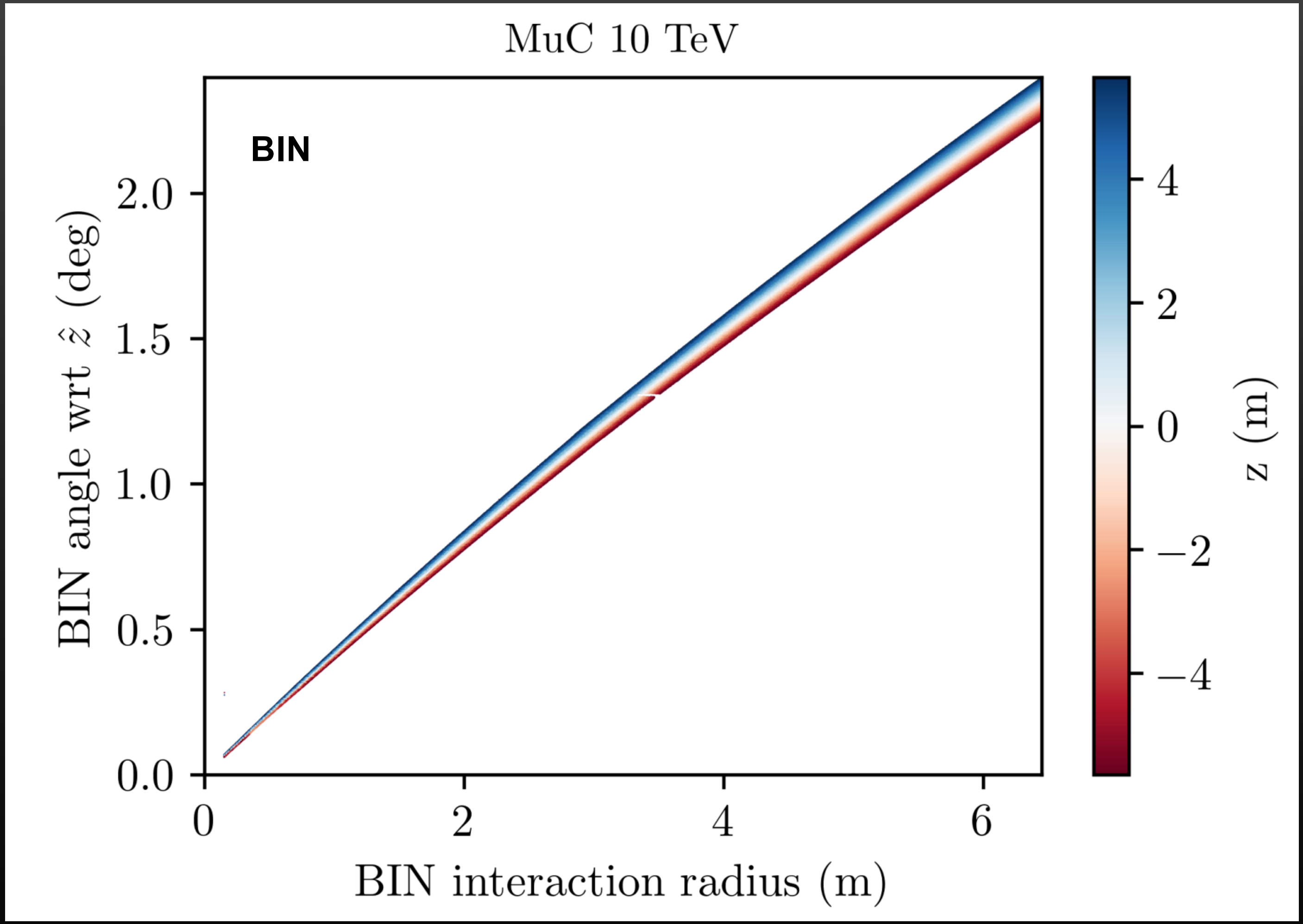
TeV Energy Deposit in large R in ~every collision!
The good news is that they are "localized" in a space-time slice.

D. Calzolari US Inaugural Muon Collider meeting 2024



BIN Interactions
3) Spatial profile

Good ν_s!



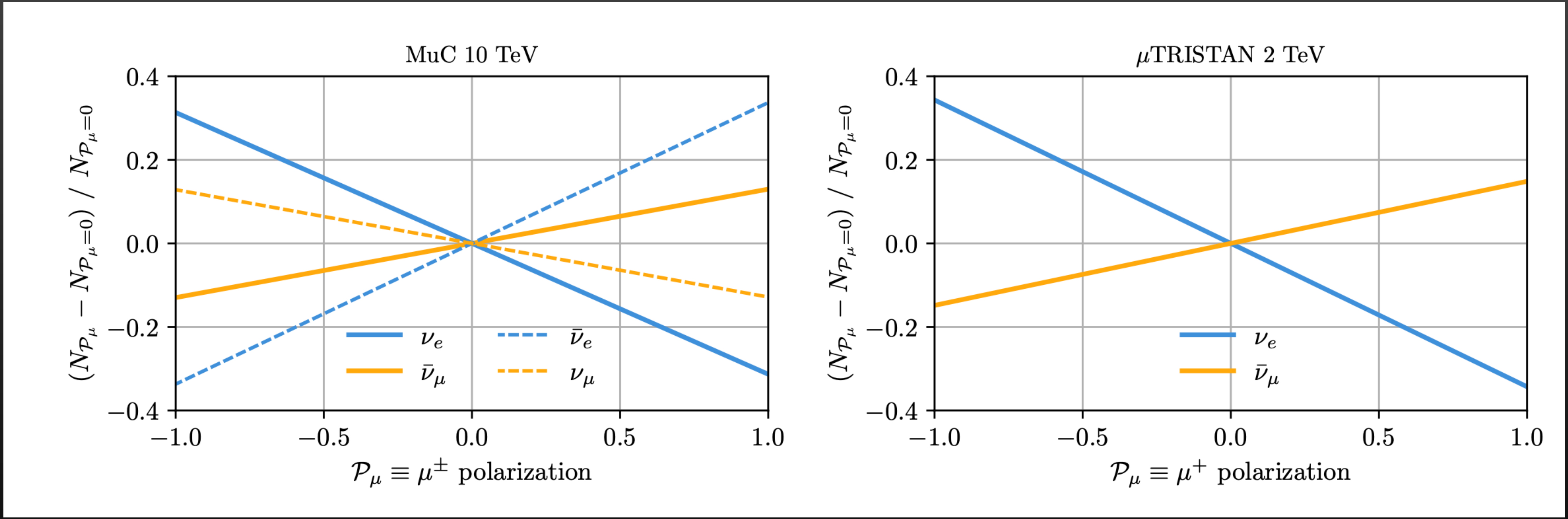
Neutrino scattering is forward (low-Q^2) so CC charged leptons is a good tracer of direction, which is also correlated with where the neutrino came from.

$\langle p_T^\ell \rangle \simeq 37$ GeV for MuC-3-TeV
$\langle p_T^\ell \rangle \simeq 32$ GeV for MuC-10-TeV
$\langle p_T^\ell \rangle \simeq 21$ GeV for μTRISTAN

BIN Interactions

Good νs!

4) Dependence on muon beam polarization



Polarization with ionization cooling (MuC benchmarks) seems very challenging, but μTRISTAN aims for $\mathcal{P}_\mu \sim 0.8$

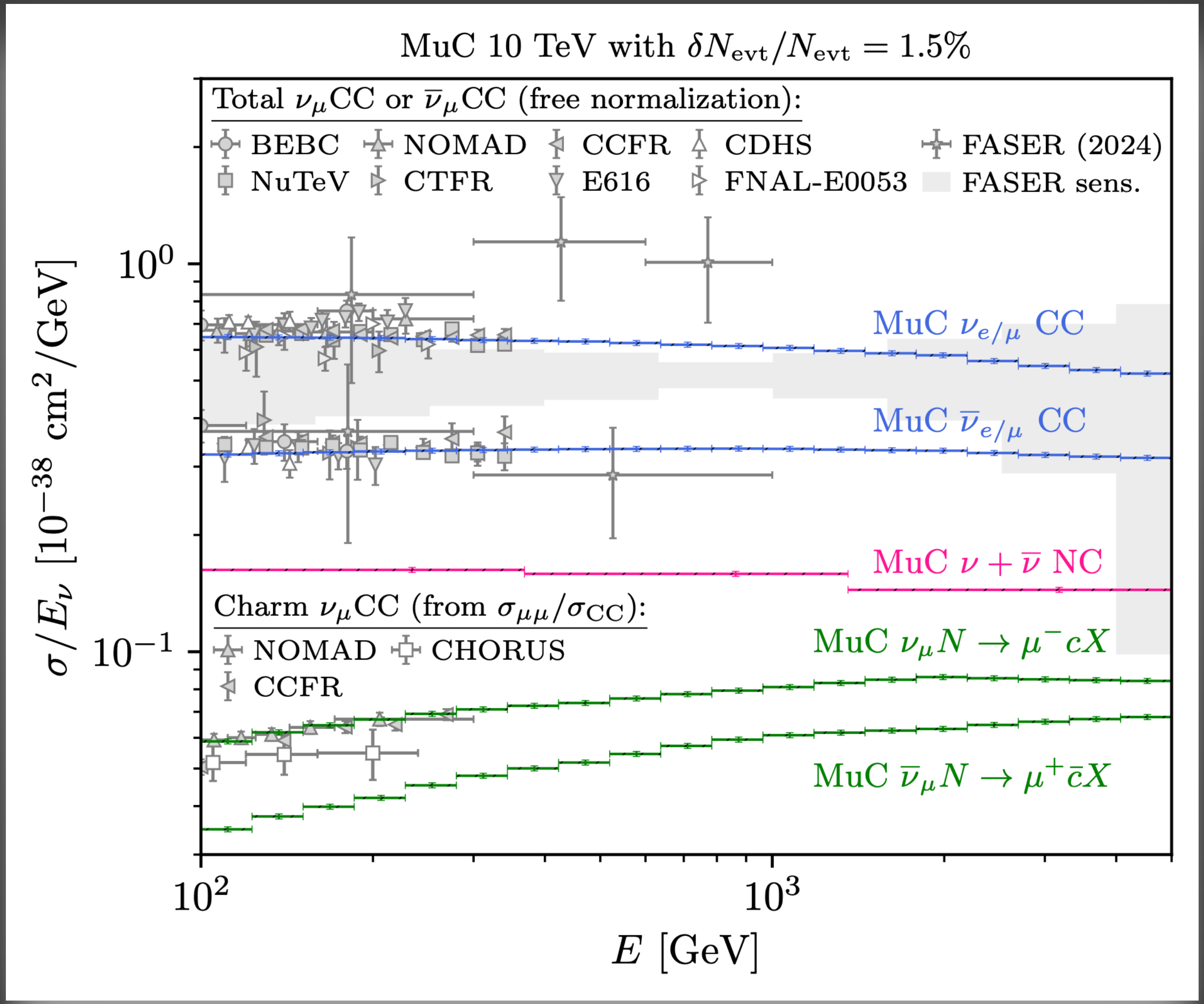
Total rate and differential spectra are very sensitive to the beam polarization.

BIN interactions

Neutrino-nucleus scattering measurement

Good νs!

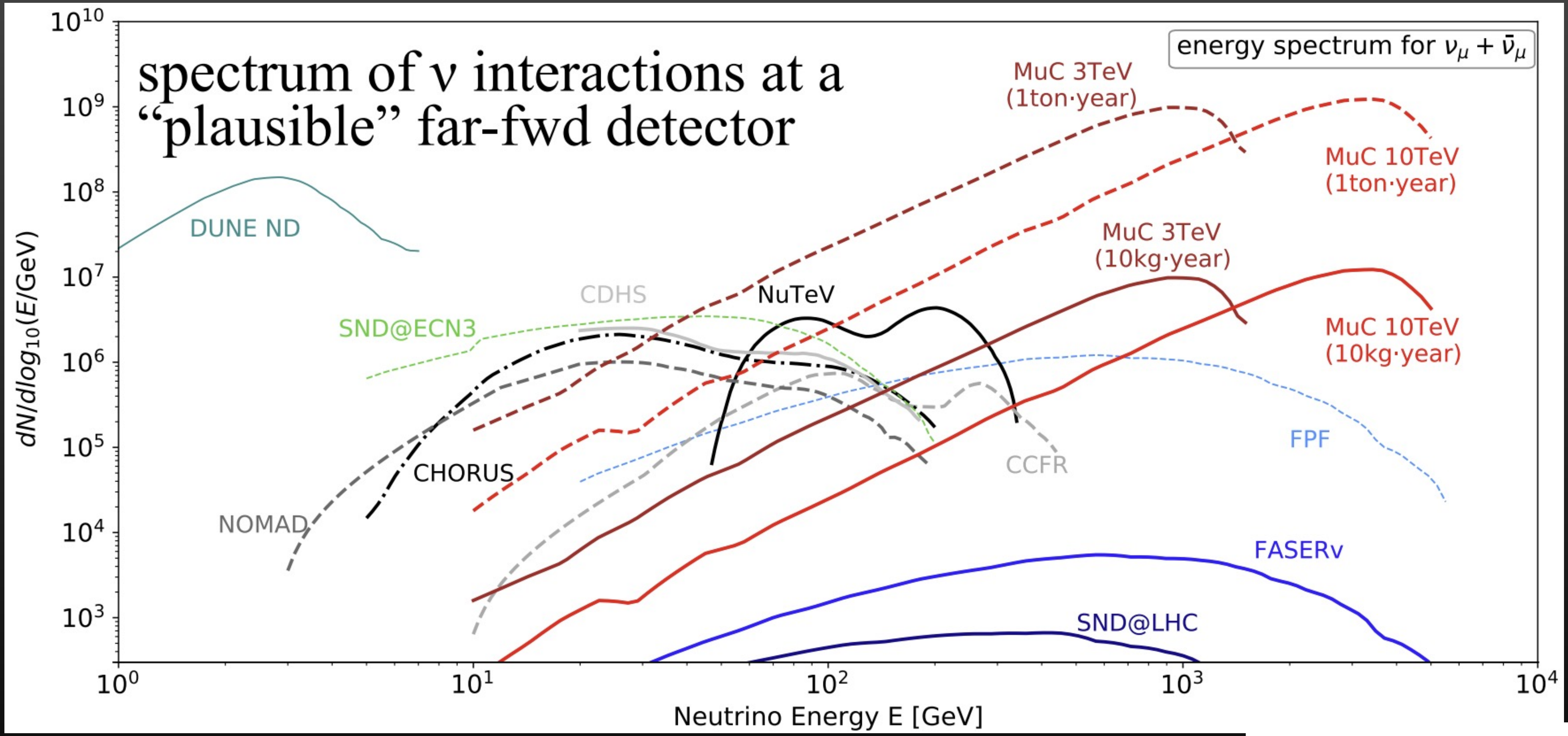
This is what a 1.5% uncertainty on TeV neutrino cross sections would look like:



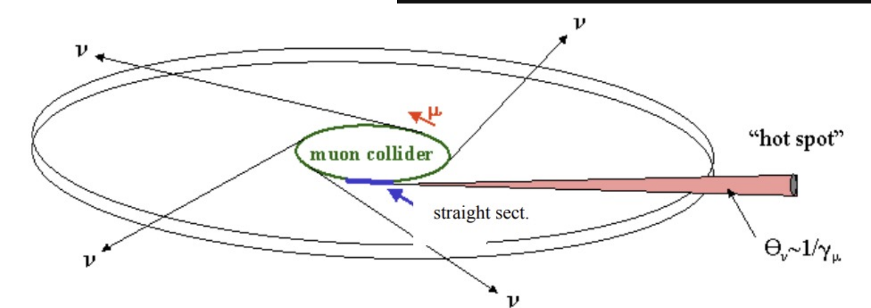
Clearly more works required to understand if feasible at the neutrino slice. (Ongoing collaboration with T. Holmes, L. Lee et al)

Many other physics, such as beam polarization monitoring, Weinberg angle from neutrino sector, rare neutrino-nucleus process, neutrino effective interactions, etc.

Muon Beamdump? Muon+Neutrino Beamdump



It seems we need to **dump the beam anyway at 5-50Hz rate…**



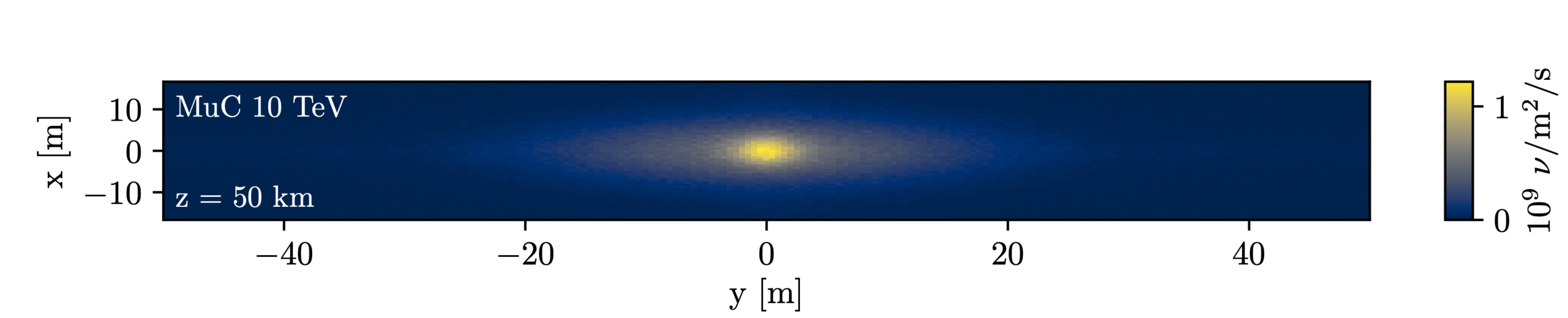
Adhikary, Kelly, Kling, Trojanowski, 2412.10315
Kling, Ma, Mękała, Reuter, Tabrizi, 2508.00761

Forward Detection of BINs

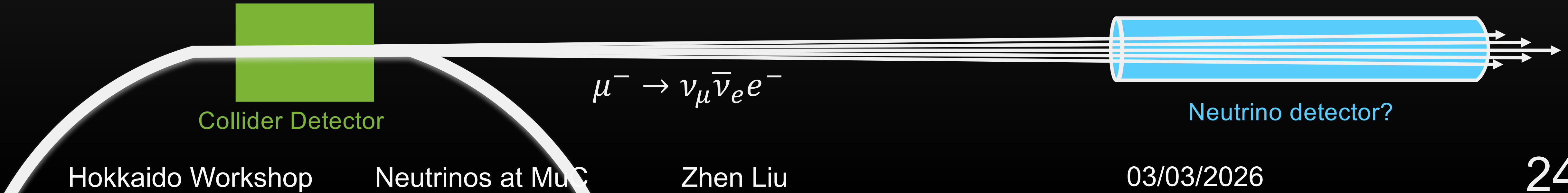
Straight section neutrino flux is extremely collimated. No need for a big detector — event rate is enormous.

The far-forward region will have no beam-induced background but will keep most of the neutrino flux.

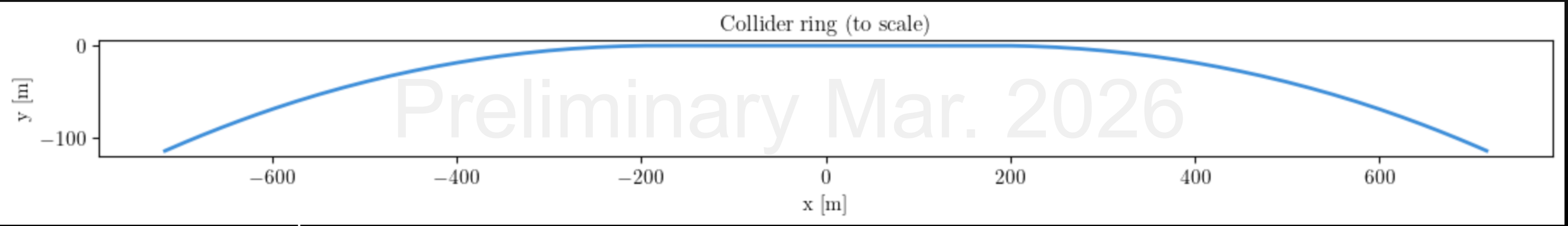
Simulated @ 50 km from IP



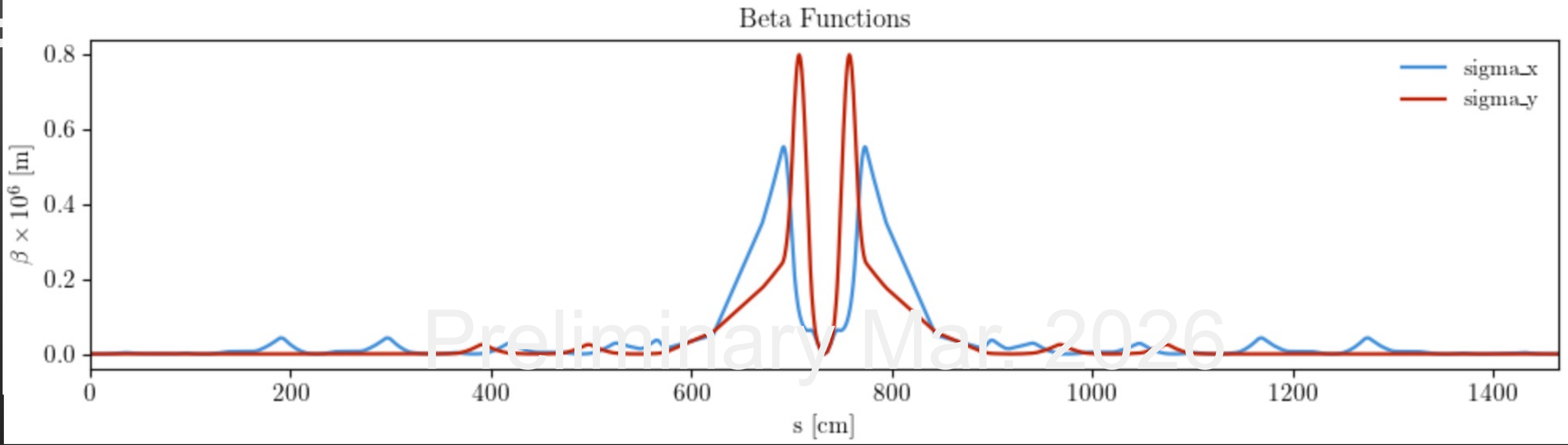
This is to demonstrate the high colimation of the BINs; detailed beam dynamics, including beam wobbling to mitigate radiation hazard would change such. In fact, we don't need such a long forward location to shield background. One can do a much closer forward neutrino facility.

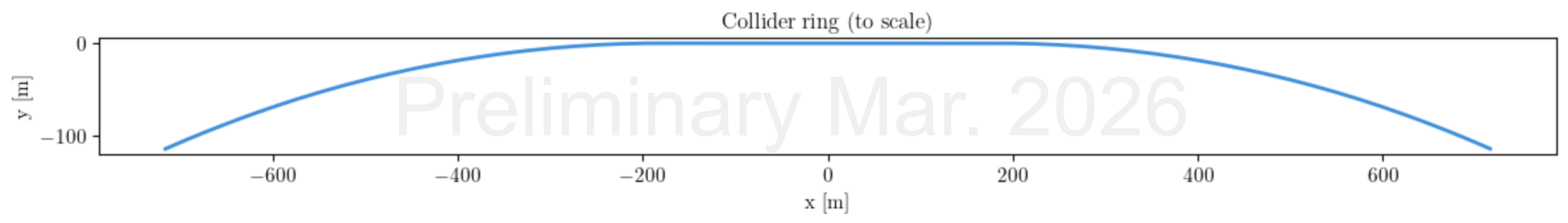


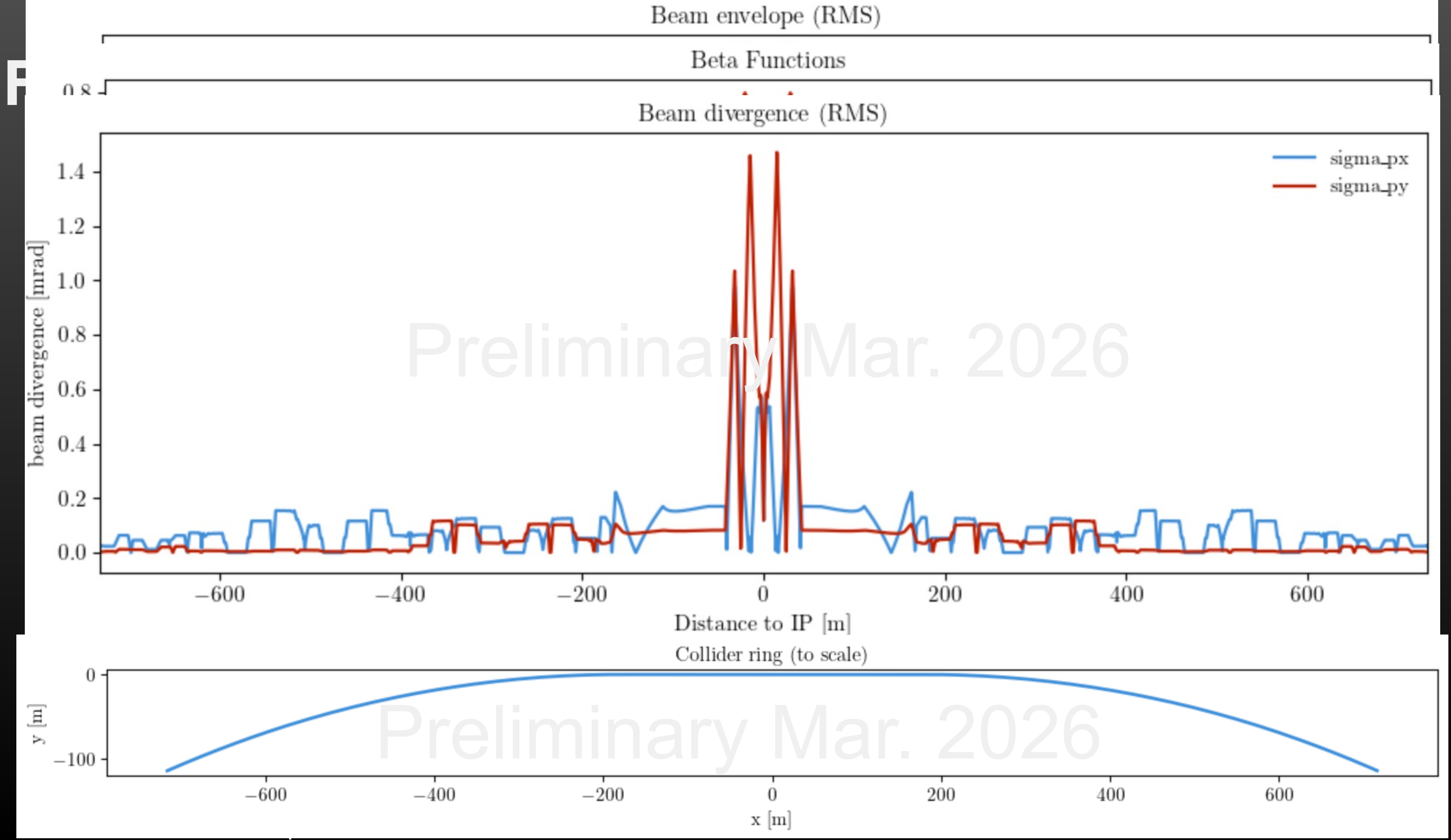
Forward Detection of BINs: Dynamics Matter



Beam envelope (RMS)





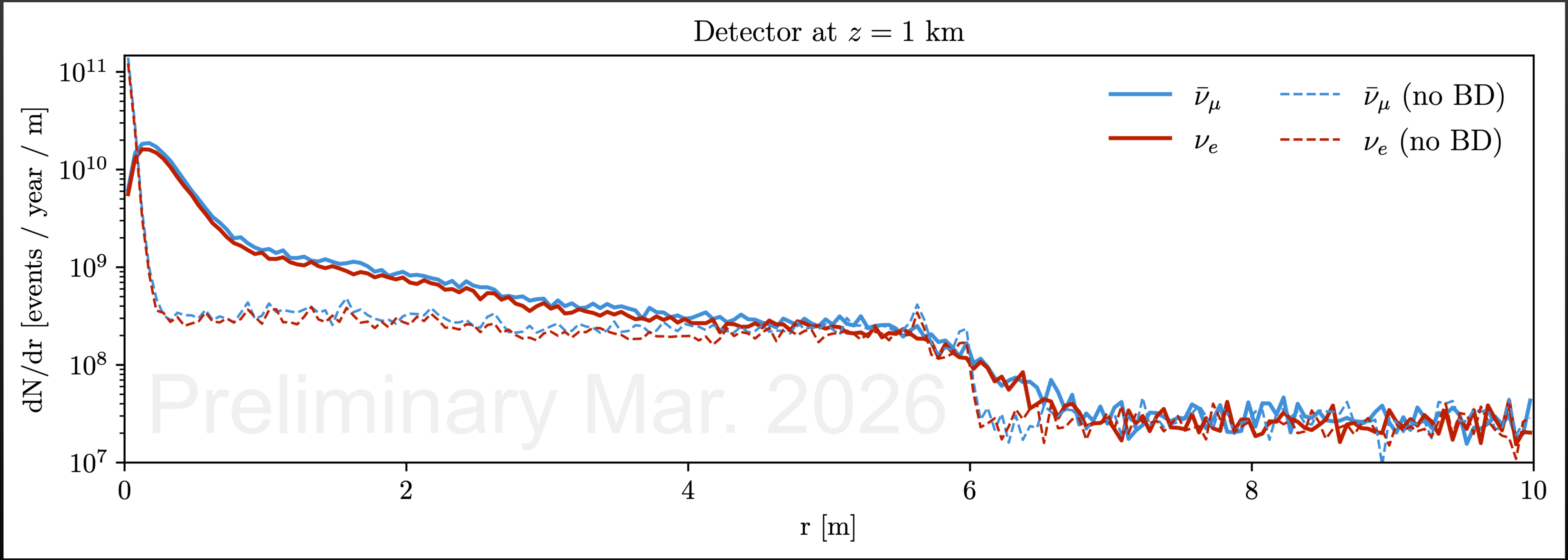


Beam envelope (RMS)
Beta Functions
Beam divergence (RMS)
sigma_px
sigma_py
beam divergence [mrad]
Distance to IP [m]
Preliminary Mar. 2026
Collider ring (to scale)
y [m]
x [m]
Preliminary Mar. 2026

Beam Dynamics Matters

Ongoing study with **Joel Choi**, Matheus Hostert, Peiran Li

Muon Inducted Neutrino Tool (MINT)



Outline

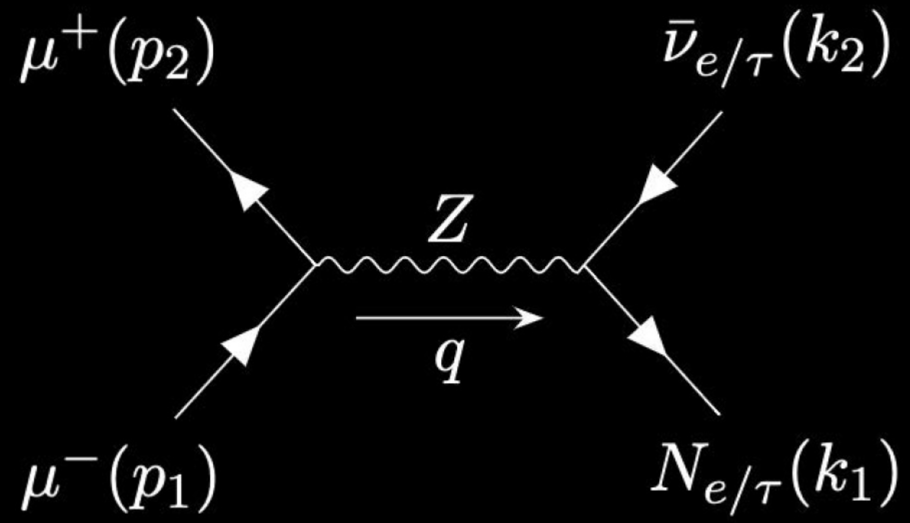
- Neutrino Slice
- Sterile Neutrinos
- Neutrino collision

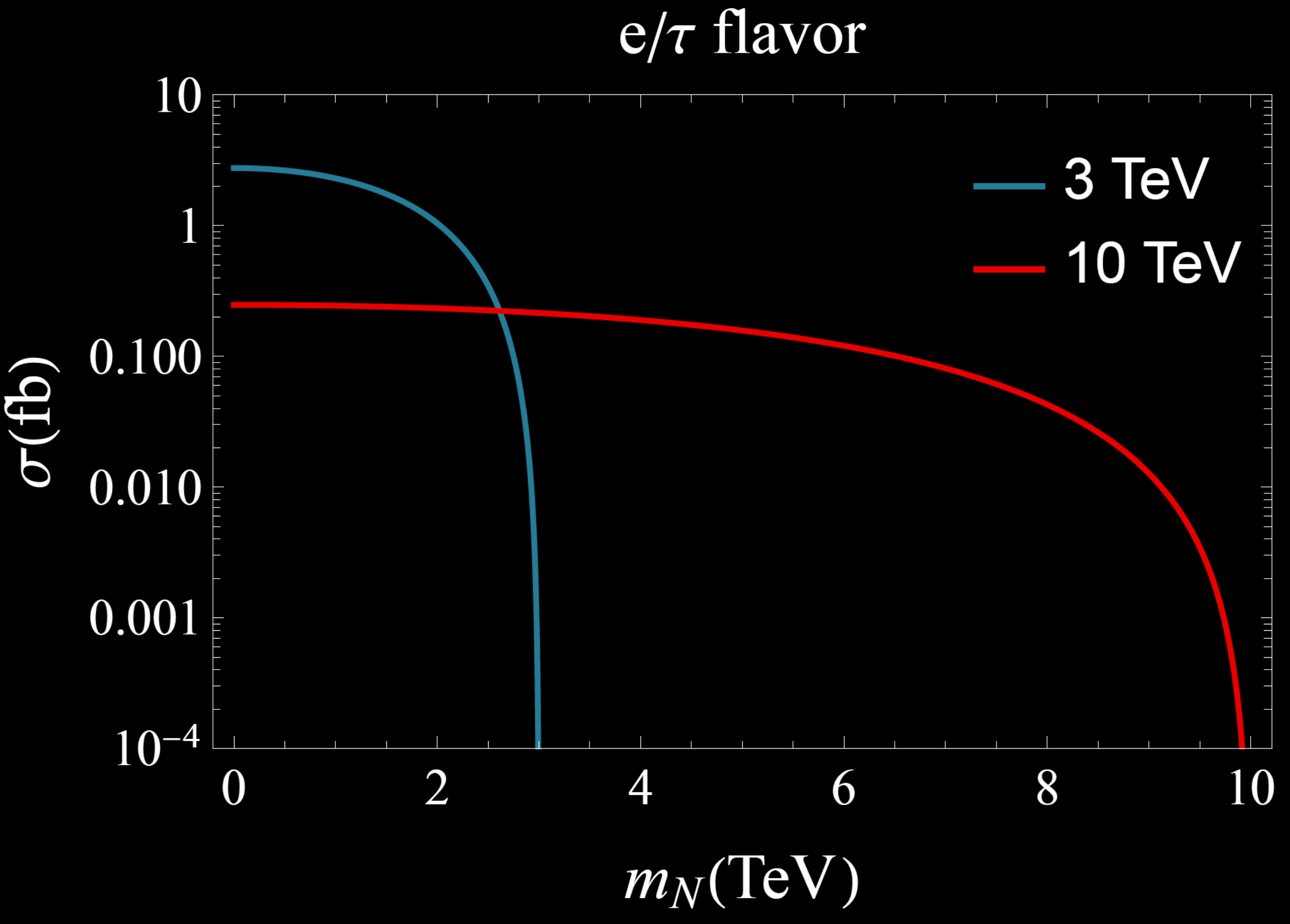
Peiran Li, ZL, Kun-Feng Lyu, 2301.07117

Neutrino is a puzzling sector: More ν_s

- In SM, neutrino is massless. While the experiments have confirmed its tiny mass <0.1 eV.
- Seesaw mechanism
- Suppose there is a heavy neutral lepton. We can parametrize its mass m_N and mixing angle with SM neutrino $U_\ell = sin\theta_\ell$. This is generic all variations of Type-I seesaws.

s-channel production ($e/\ \mu\ /\tau$ flavored)

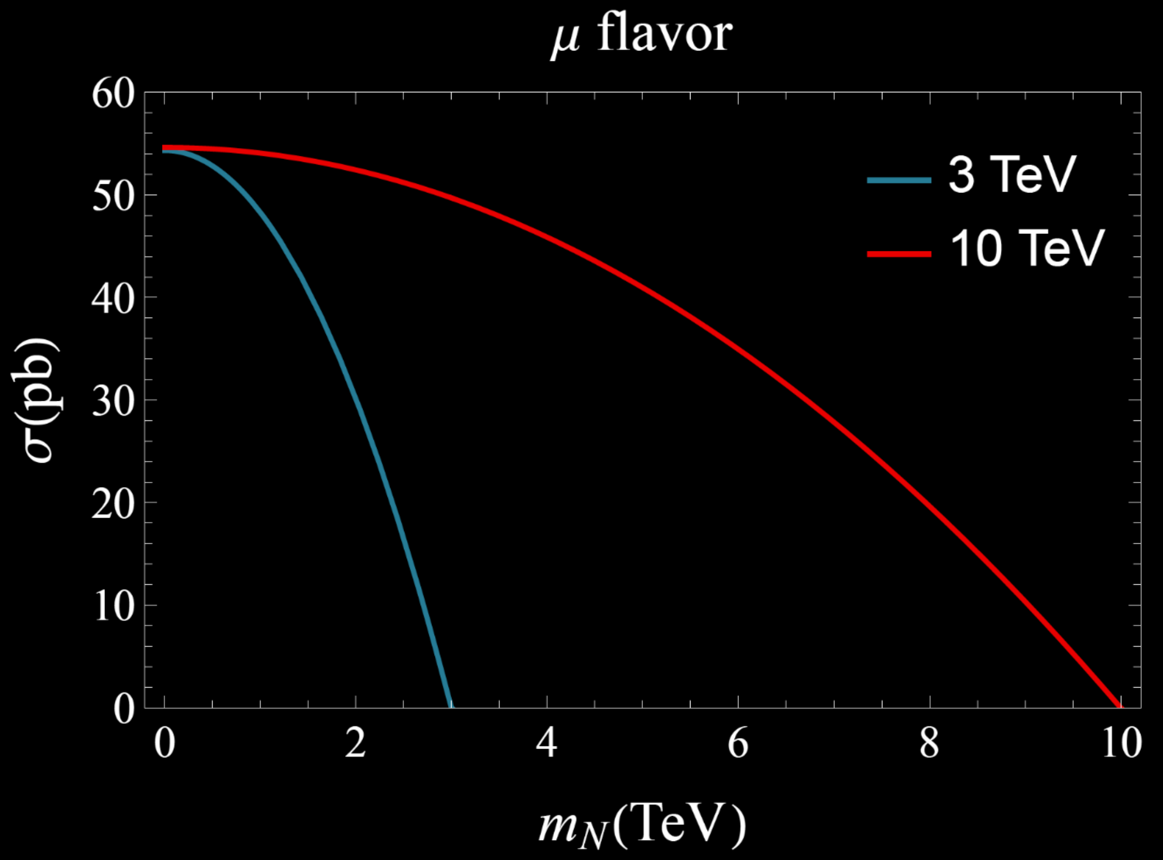


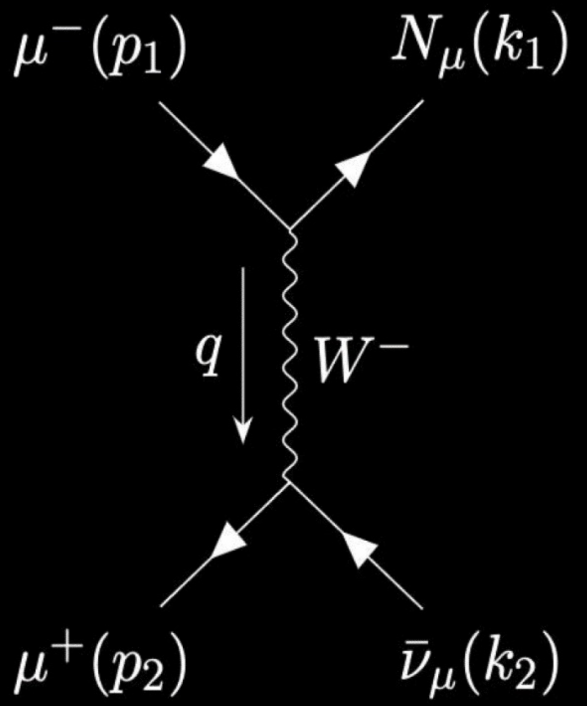


- 1/s suppressed;
- Flat rate until near the threshold s/2
- $O(fb)$ cross section;

Muon Flavor

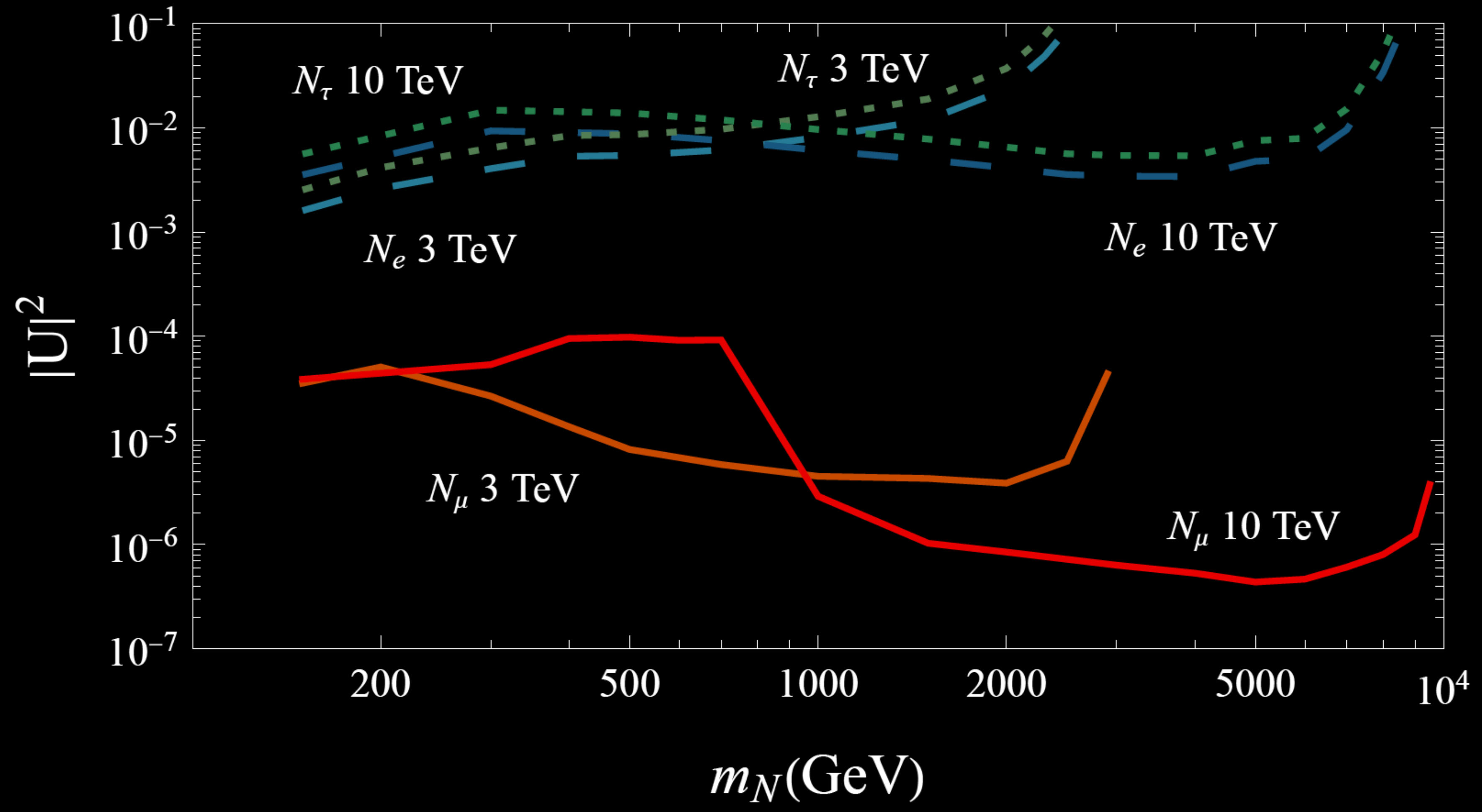
Production dominated by t-channel (equivalently μW-fusion)





Type	Signal process	$\sigma/\vert U_\mu\vert^2$ (w. conj. channel) $m_N = 1$ TeV
t-channel	$\mu^+\mu^- \longrightarrow N_\mu \bar{\nu}_\mu$	20.28 pb
VBF	$\mu^+\mu^- \longrightarrow \mu^+\mu^- N_\mu \bar{\nu}_\mu$	~ 1 pb
VBF	$\mu^+\mu^- \longrightarrow \bar{\nu}_\mu \nu_\mu N_\mu \bar{\nu}_\mu$	~ 0.1 pb

Projected sensitivity



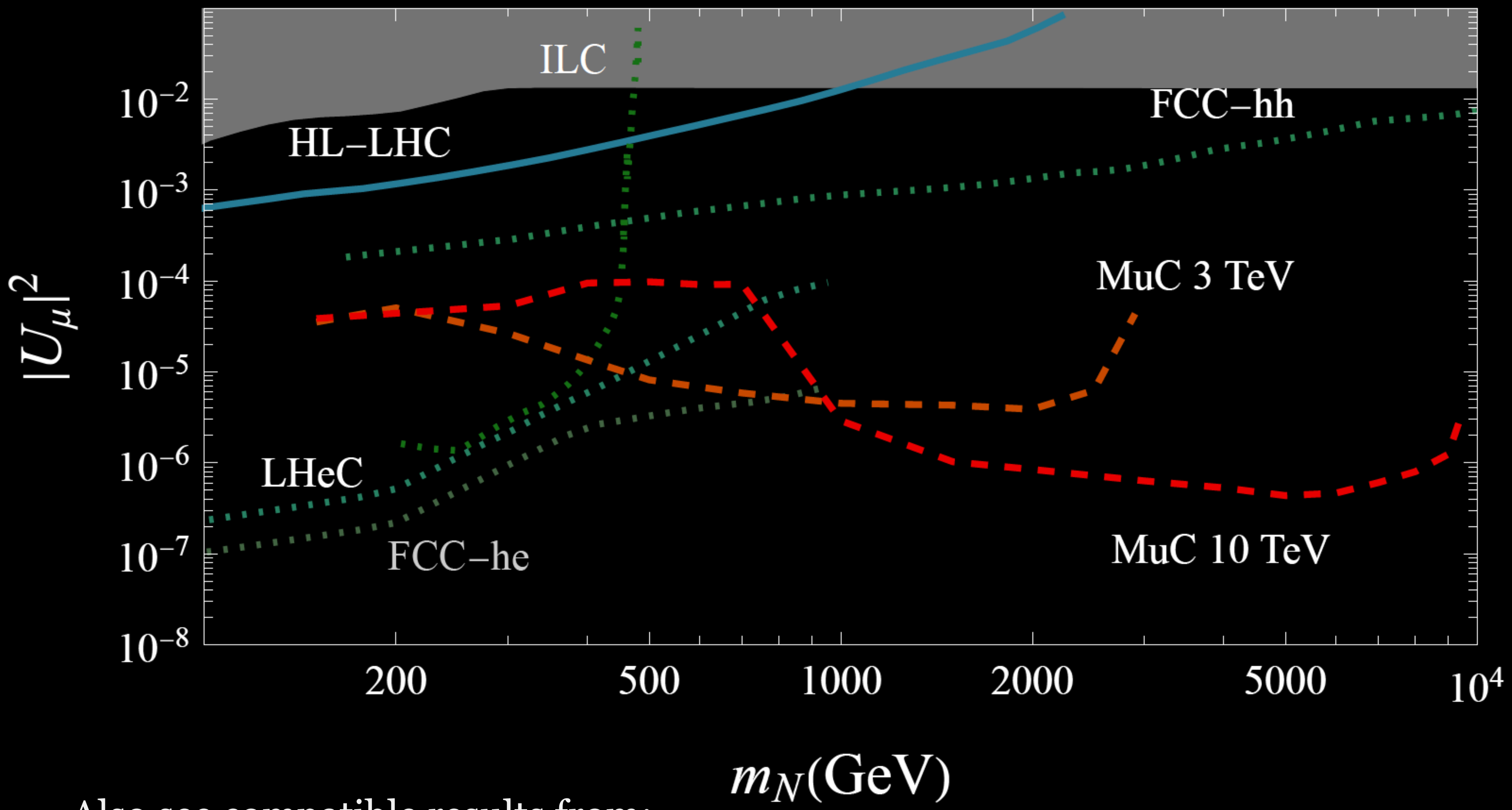
Sensitivity to e and τ flavor is moderate

Muon Collider features the strong direct probe of the μ flavored HNL

10 TeV muon collider can probe the $|U_\mu|^2$ to a few 10^{-7} for TeV scale HNLs.

The VBF background increases for high energy muon colliders and renders the 3 TeV muon collider competitive in sub TeV scale.

Projections w. others



Focusing on the muon-flavored case:

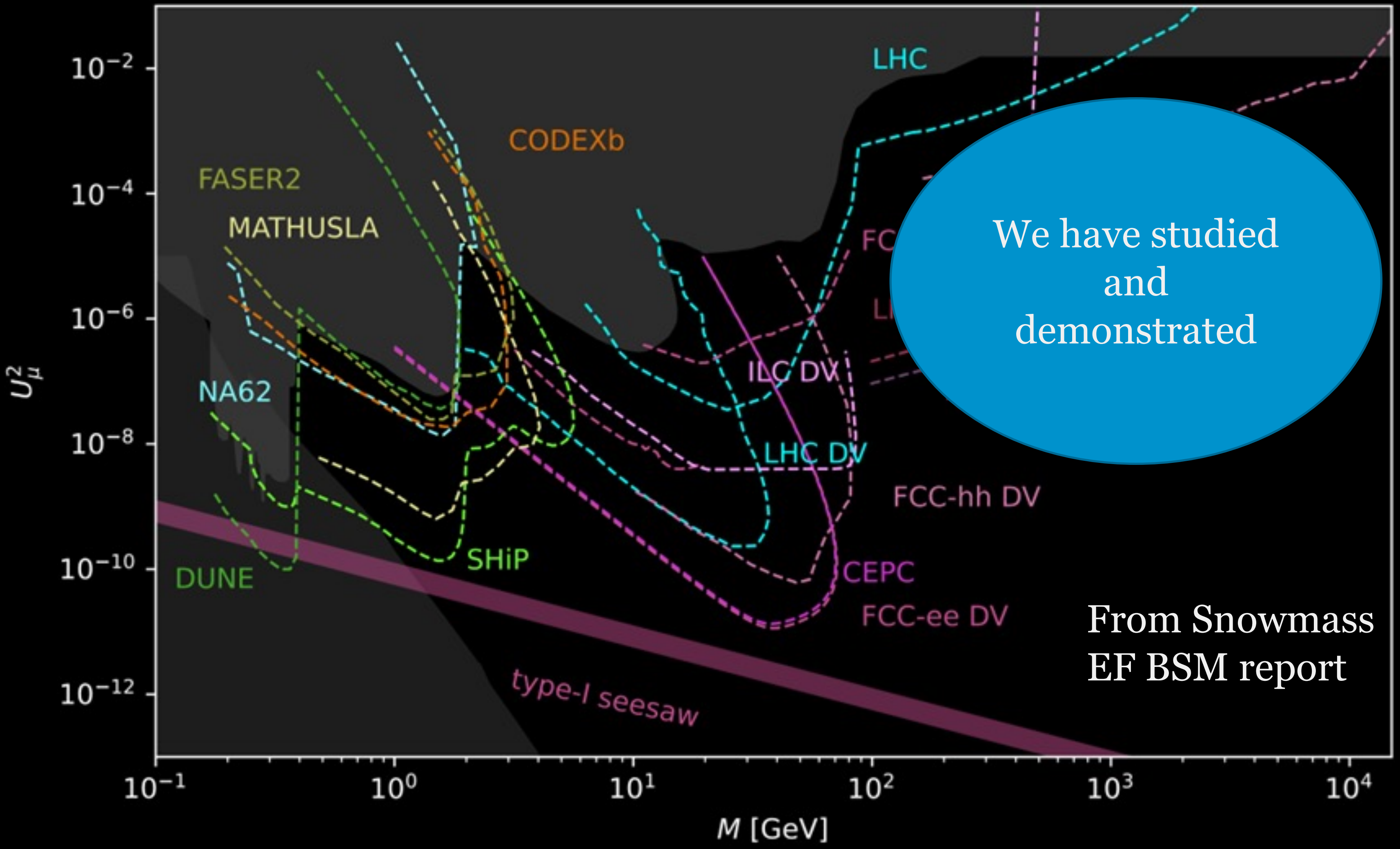
LHC and EWPD probe $O(10^{-3})$

Muon Collider has unique roles in probing the parameter space (thanks to the t-channel enhancement).

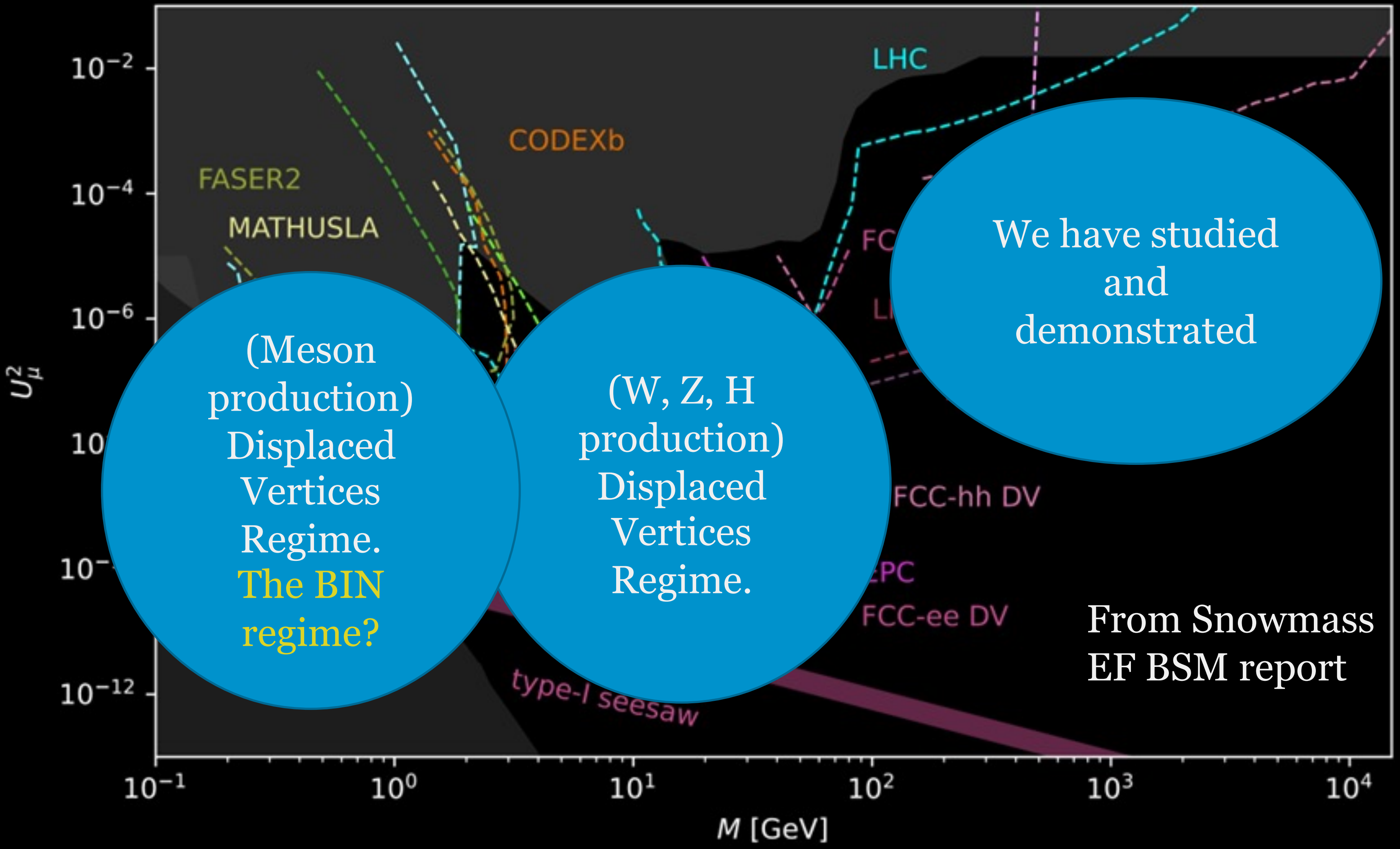
In the inverse seesaw setup, $|U_\ell|^2 = \left(\frac{\lambda v}{m_N}\right)^2$, and hence a unitarity limit exist on the upper right corner, overlapping very little with the region of our interests.

Also see compatible results from:
T.H. Kwok, L. Li, T. Liu and A. Rock, arXiv:2301.05177
K. Mekała, J. Reuter and A.F. Zarnecki, arXiv:2301.02602

New studies for other regions



New studies for other regions



(Meson production) Displaced Vertices Regime. The BIN regime?

(W, Z, H production) Displaced Vertices Regime.

We have studied and demonstrated

From Snowmass EF BSM report

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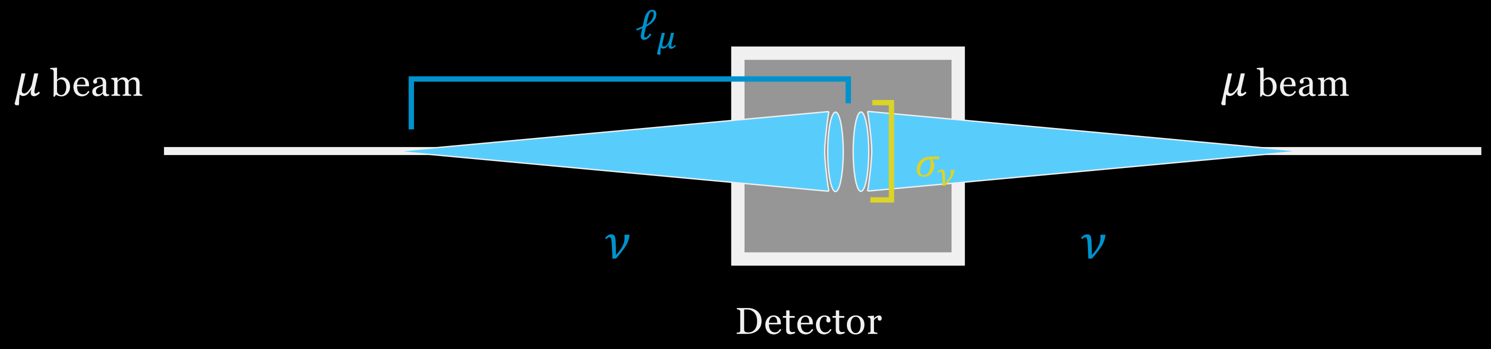


Ongoing study with B. Dev, I. Lewis, G. Sedhein, and ZL ongoing study.

Muon Collision → Neutrino Collisions*

One has to separate these two sources

- Virtual neutrino collisions

- Real neutrino collisions

*Including neutrino (anti-neutrino) collisions and neutrino (antineutrino) muon (and muon PDF) collisions.

Muon Collision → Neutrino Collisions*

One has to separate these two sources

- Virtual neutrino collisions
  - Colinearly enhanced (regulated by W boson mass)
  - Can be taken using hard matrix element calculation
  - Can be taken (in large Q^2 limit) via EW PDF
- Real neutrino collisions

*Including neutrino (anti-neutrino) collisions and neutrino (antineutrino) muon (and muon PDF) collisions.

Muon Collision → Neutrino Collisions*

One has to separate these two sources

- Virtual neutrino collisions
  - Colinearly enhanced (regulated by W boson mass)
  - Can be taken using hard matrix element calculation
  - Can be taken (in large Q^2 limit) via EW PDF
- Real neutrino collisions
  - Unique for unstable particle collisions
  - Unique t-channel singularity being regularized by muon width, beam size
  - Responsive to beam dynamics (beyond leading order)

*Including neutrino (anti-neutrino) collisions and neutrino (antineutrino) muon (and muon PDF) collisions.

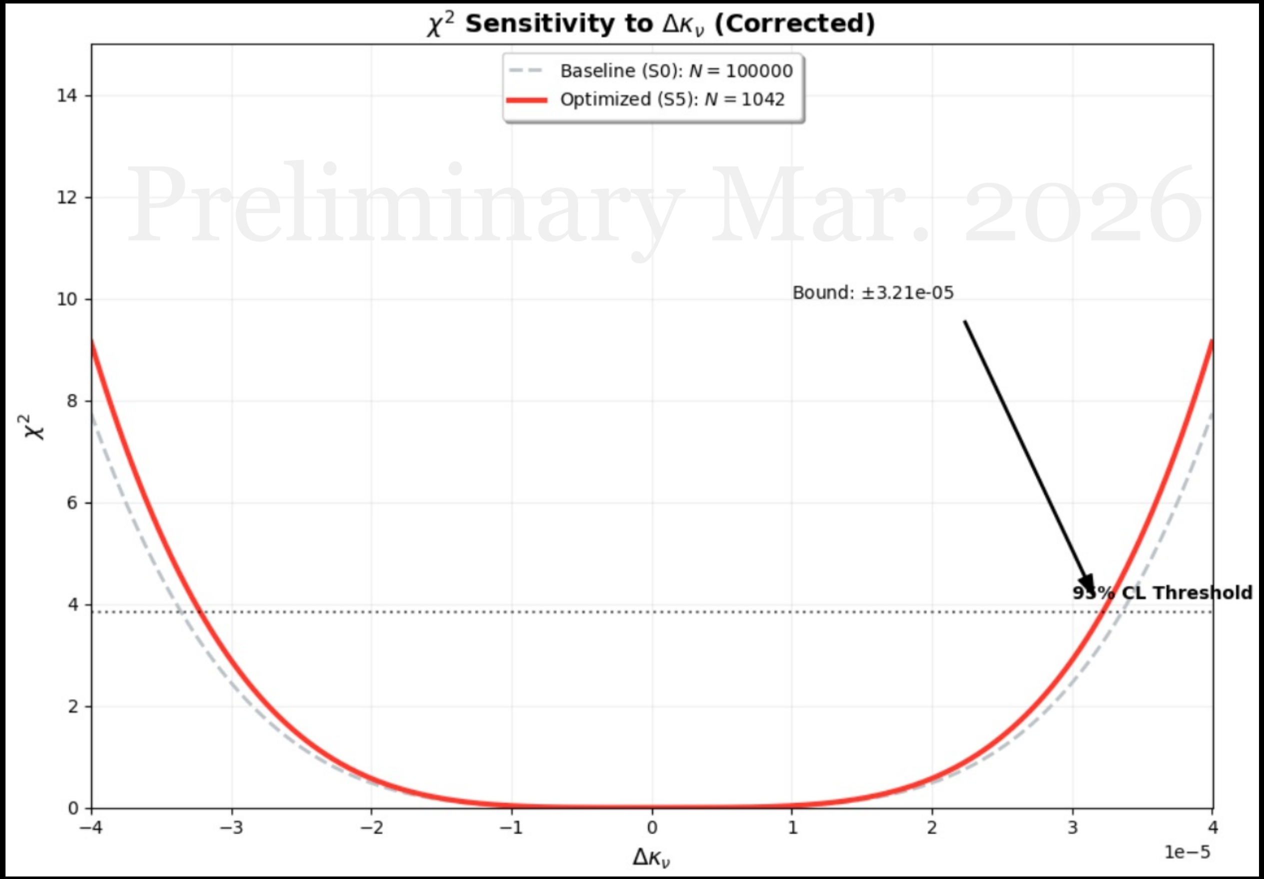
Muon Collision → Neutrino Collisions*

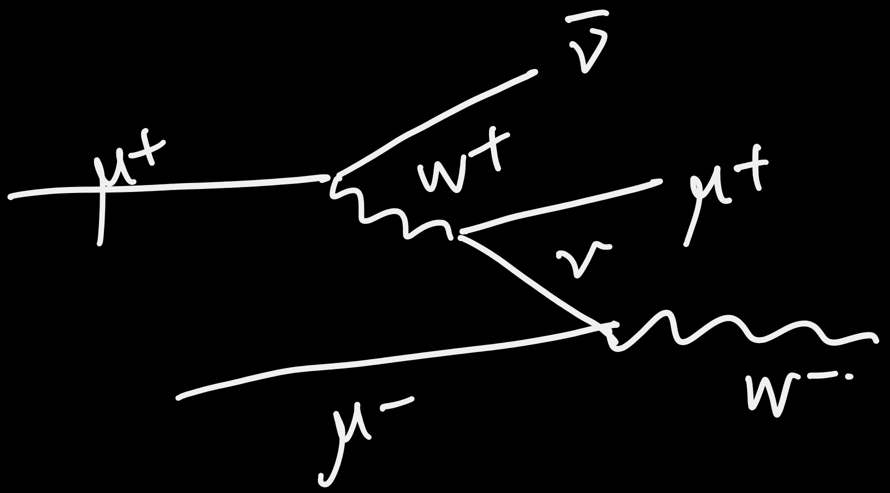
One has to separate these two sources

- Virtual neutrino collisions

Let's explore how can we measure neutrino-fusion rate to Z, and probe Z to neutrino couplings:

(One immediately realize this is only true under PDF picture and there are actually many diagrams contributing; and one shall be careful as real neutrino collisions contribute.)

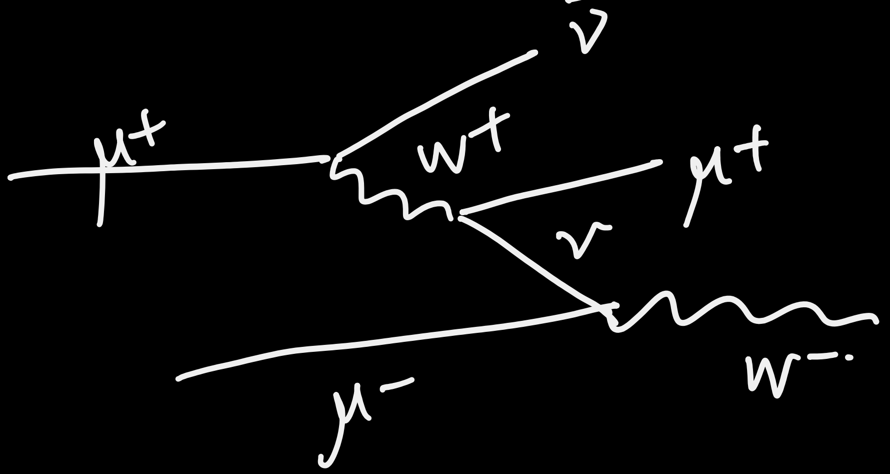




$$\mu^+\mu^- \to W^- \mu^+ \bar{\nu}$$

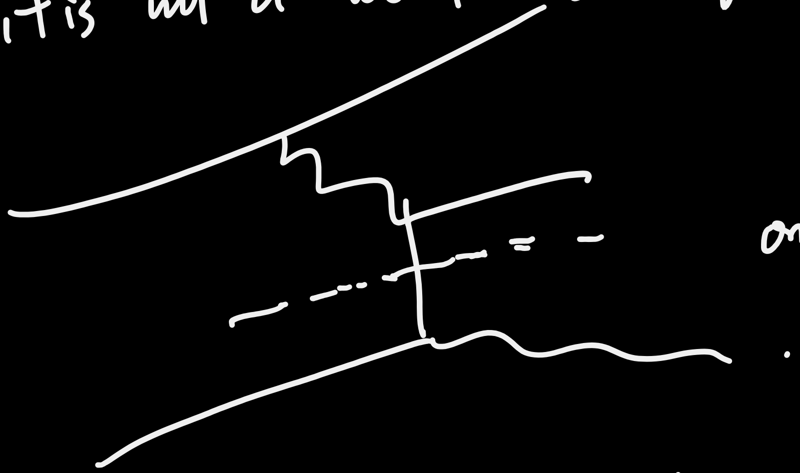
If you calculate it, analytically or any honest generator, you will get ∞.

Physical Poles from Unstable Particle Scattering



$\mu^+\mu^- \to W^- \mu^+ \bar{\nu}$

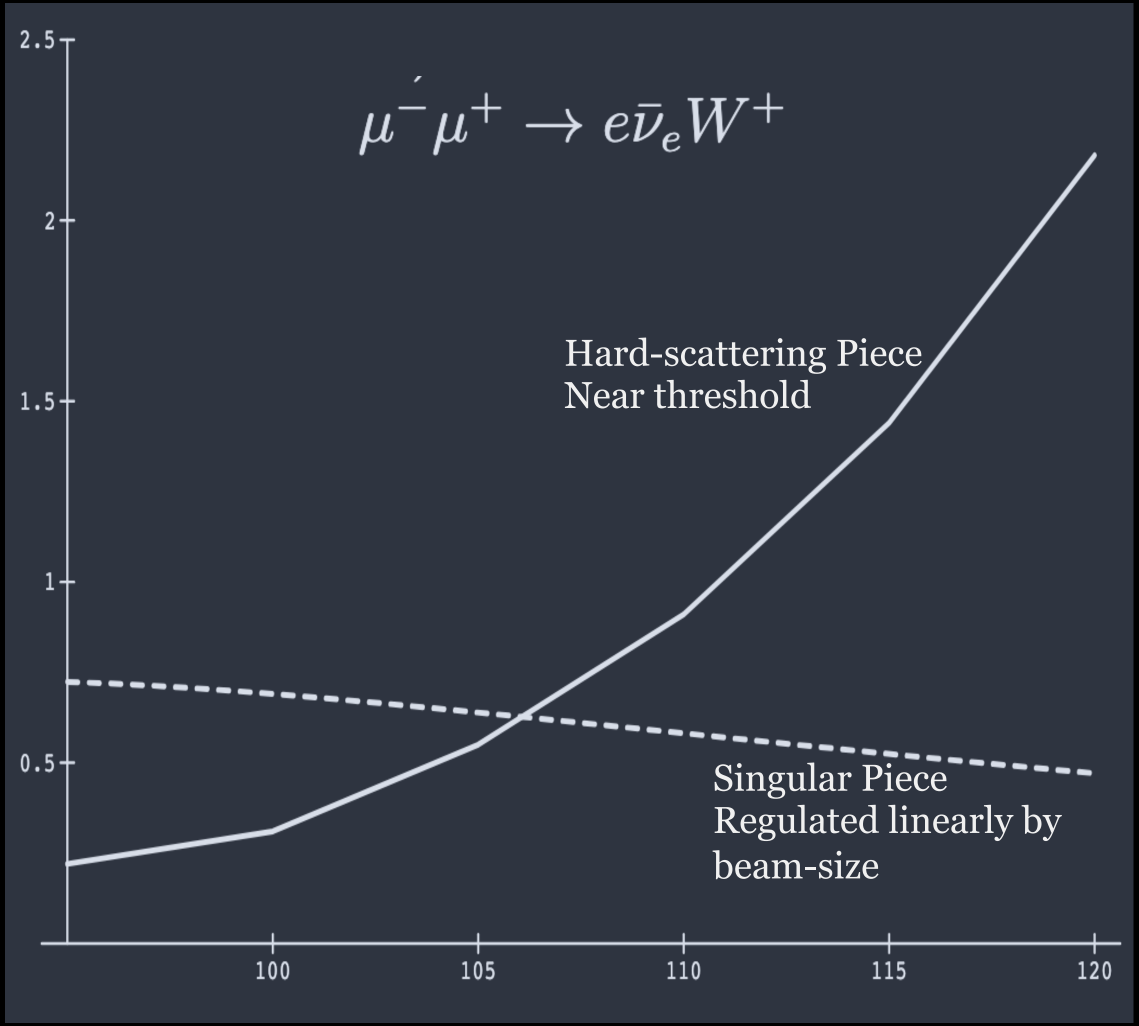
But this is not normal QFT divergences. it is not a "local" divergence, it comes from



on-shell neutrino.

If you calculate it, analytically or any honest generator, you will get ∞. And this is not a part of the ν-PDF neither., as muon decays

Beam size regulate on-shell singularity



Most neutrino participated processes contain this singular piece, which contribute to the measurable cross section.

This is singularity physically is smaller than the typical/traditional hard scattering, but it is a new piece we need to tackle as well.

$$\sigma(\mu^- \mu^+ \to e\bar{\nu}_e W^+) = \sigma_0 \frac{\pi a}{2c\tau}\, x_0 f(x_0), \quad x_0 = \frac{M^2}{s}$$

$$a = \sqrt{\frac{\pi}{2}}\, \frac{a_x\ a_y}{\sqrt{a_y^2 \cos^2\varphi + a_x^2 \sin^2\varphi}}.$$

Peierls 60' and Ginzburg 95' postulated muon width as regulator; (IMO,)correctly regulated by Melnikov, Serbov, Kotkin in 96 via finite wave-packaging treatment on top of traditional planewave calculation.

ZL ongoing study.

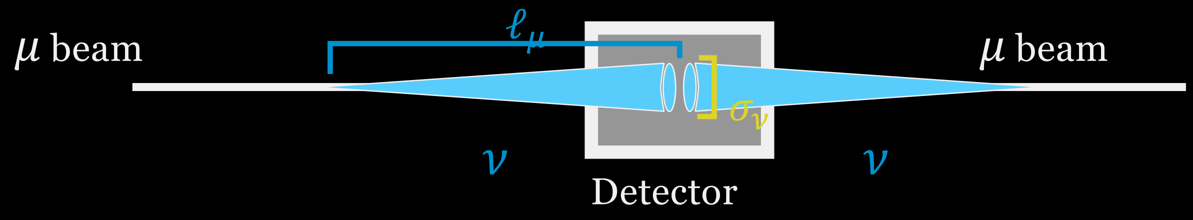
From a decay point of view:

BIN collisions are extremely rare — boils down to the large size of the beam spot — cannot focus neutrinos to better than $\frac{1}{\gamma_\mu}$

"Neutrino beam" size: $\sigma_\nu^2 \sim (1mm)^2 \times \left(\frac{10^4}{\gamma_\mu}\frac{l_\mu}{10m}\right)^2$ should be compared to $\sigma_\mu^2 \lesssim (1\mu\text{m})^2$

$$\mathcal{L}^{\nu\nu}_{per\ bunch} \sim \frac{N_\nu^2}{4\pi\sigma_\nu^2} f_{\text{rep}} \sim \left(2\times N_\mu \frac{\ell_\mu}{c\tau_\mu\gamma_\mu}\right)^2 \frac{1}{4\pi}\left(\frac{\ell_\mu}{\gamma_\mu}\right)^{-2}\left(\frac{c\tau_\mu\gamma_\mu}{C_{\text{ring}}}\times f_{\text{inj}}\right) \sim \frac{2\times10^{-7}}{barn}\left(\frac{N_\mu}{2\times10^{12}}\right)^2\left(\frac{10km}{C_{\text{ring}}}\right)\left(\frac{\gamma_\mu}{10^4}\right)$$

$$\mathcal{L}^{\nu\nu}_{\text{tot}} \sim \mathcal{O}(0.1)barn^{-1}\times\left(\frac{f_{\text{rep}}}{5Hz\times10^3}\right)\left(\frac{T}{10years}\right)$$



This non-standard piece of cross section is a direct probe of beam dynamics.

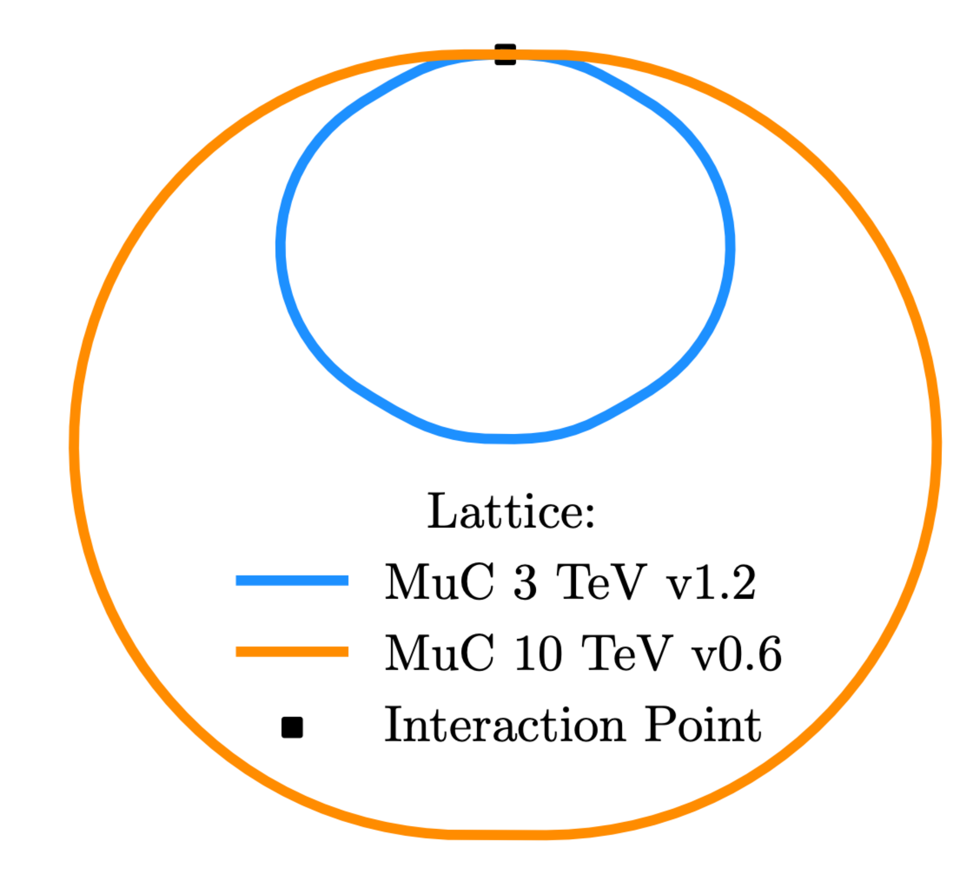
ZL ongoing study.

Neutrinos at High Energy Muon Colliders have Very Rich Physics

We are at the cross road of particle physics:
Muon collider is not just a high CM collider, not just a higher energy version of e+e- collider; it is not a standard physics we just turn the cranks.

It is new technology we also yet to understand all its implications. There are much more to explore!

Muon Collider benchmarks Modeling BIN flux



Using CERN public models for the magnet lattice:
https://gitlab.cern.ch/acc-models/acc-models-mc

Uniformly distribute muons around the ring

Beam size determined by Twiss parameters $\beta_{x,y}$ and $\gamma_{x,y}$ as a function of distance traveled around the ring (s):

1. Fixed geometric emittance: $\epsilon = 0.5$ nm
2. Transverse beam size: $\sigma_{x,y}(s) = \sqrt{\epsilon\beta_{x,y}(s)}$
3. Angular divergence of the beam: $\delta\theta_{x,y}(s) = \sqrt{\epsilon\gamma_{x,y}(s)}$

Turns out beam divergence is of similar size to the intrinsic muon decay neutrino angles of: $\delta\theta_\nu \sim m_\mu/E_\mu \sim 10^{-4}$

Beam Wobbling

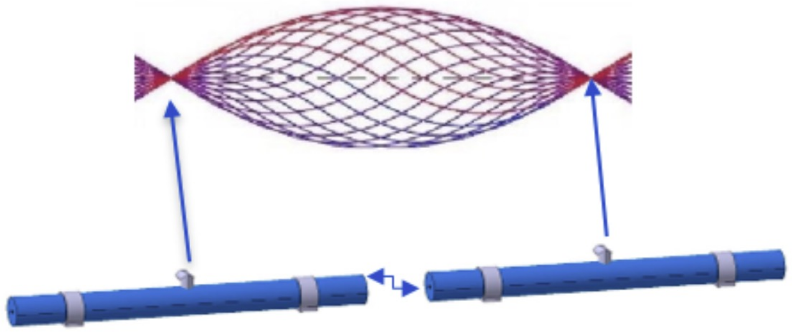
It changes the spread size by (using black lines) 15cm/600m, which at 50km location, spread the neutrino beam out by 15m (in 2D), comparable to the BINs spread.
Instead, at the main detector, it broadens the BINs by O(cm) (with a rms smaller)

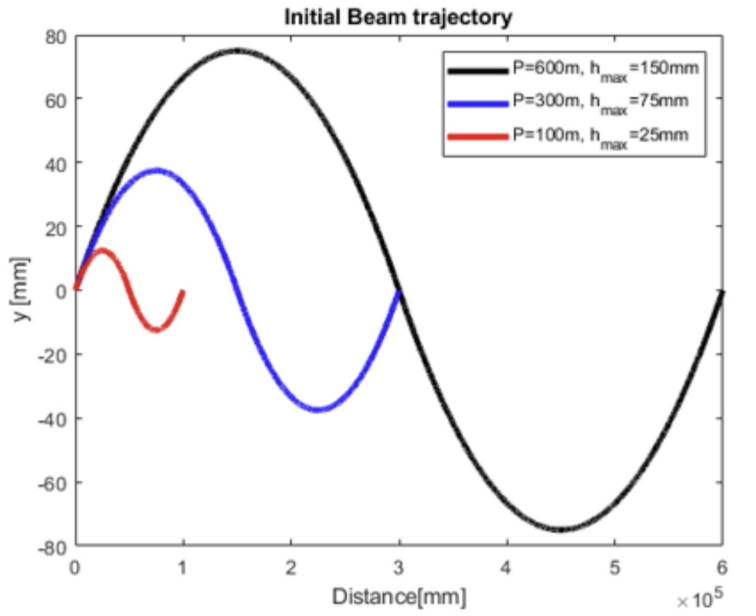
International MUON Collider Collaboration

CERN

He supply

- **MUON COLLIDER TUNNEL**
  - First estimation: He supply at the ~LHC distance→ ~100m
  - Reduction of period
  - Reduction of maximum vertical displacement→ ±25 mm
  - Stronger vertical kick (horizontal field)





A magnet movement system is investigated allowing for a machine deformation resulting in ±1 mrad* variations of the slope of the tangent of the beam trajectory
C. Carli, "Neutrino Radiation for a realistic Collider", IMCC Annual Meeting 2022

Muon Collider Beam-induced neutrinos (BINs)

Back of the envelope

Probability for neutrino to interact:

$$P_{\rm int}^{\nu} \sim 1 - \exp(-n\sigma\ell) \sim n\sigma\ell \sim 10^{-8}\times\left(\frac{n}{10^{24}/\mathrm{cm}^3}\right)\left(\frac{\sigma}{10^{-35}\mathrm{cm}^2\times(E_\nu/\mathrm{TeV})}\right)\left(\frac{\ell}{10m}\right)$$

$$R = \frac{N_\mu m_\mu}{p_\mu \tau_\mu} \sim 3\times10^5 m^{-1}\left(\frac{N_\mu}{2\times10^{12}}\right)\left(\frac{1\,TeV}{p_\mu}\right)$$

We have O(1) acceptance for the muons in the last L_{eff}~O(100) meter or so.

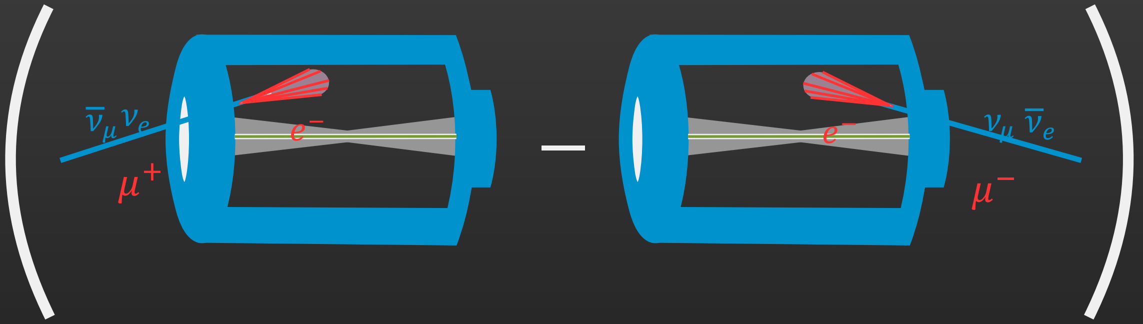
The detection rate at the main detector is then $P_{\rm int}^{\nu}\times R\times L_{eff}\sim 0.3$ per collision

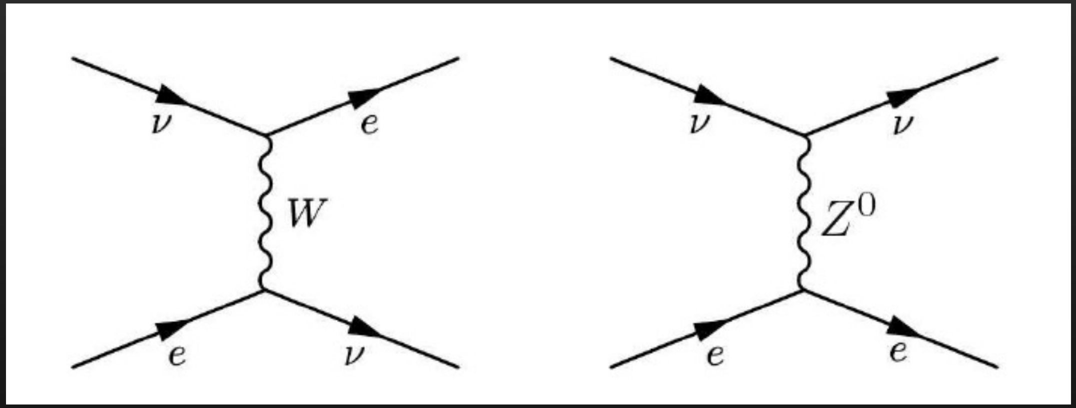
With at 10kHz collision rate (determined by the collision ring size), we get $\sim 10^{10}$ events per year.

BIN as precision probes of electroweak sector

Neutrino-electron scattering

Good νs!





You can isolate Weinberg's angle at a muon source with:

$$R^{\theta_\mathrm{w}}_{\nu-e} = \frac{N^{\mu^+} - N^{\mu^-}}{N^{\mu^+} + N^{\mu^-}} \approx \frac{2\sin^2\theta_\mathrm{w}}{1 + 8\sin^4\theta_\mathrm{w}}$$

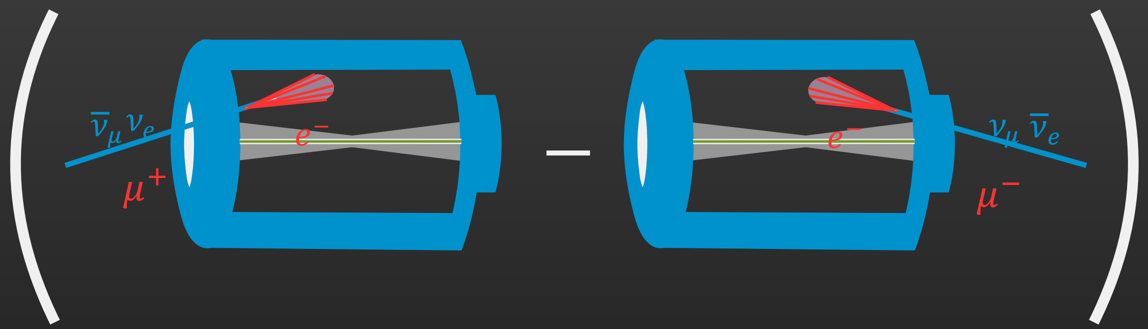
N^{μ^+}: the sum of $\bar{\nu}_\mu$ and ν_e electron scattering rate from μ^+ beam.

N^{μ^-}: the sum of ν_μ and $\bar{\nu}_e$ electron scattering rate from μ^- beam.

BIN as precision probes of electroweak sector

Neutrino-electron scattering

Good νs!



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N^{μ^+}: the sum of $\overline{\nu}_\mu$ and ν_e electron scattering rate from μ^+ beam.

N^{μ^-}: the sum of ν_μ and $\overline{\nu}_e$ electron scattering rate from μ^- beam.

To beat CHARM-II ($\sin^2\theta_W = 0.2324 \pm 0.0083$), need:

$$\delta R^{\theta_W}_{\nu-e}/R^{\theta_W}_{\nu-e} < 1.4\%$$

To beat the best measurement ($\sin^2\theta_W = 0.2383 \pm 0.0011$) by Qweak APV measurements:

$$\delta R^{\theta_W}_{\nu-e}/R^{\theta_W}_{\nu-e} < 0.20\%$$

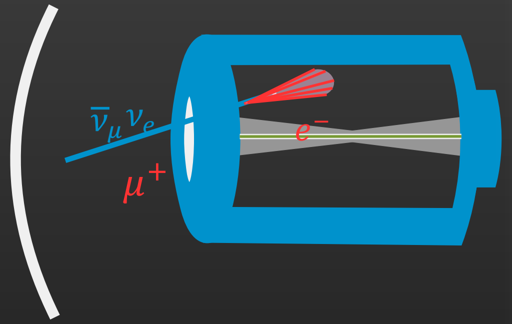
- **May also probe the running of θ_W in the same experiment.**
- **Sub-percent measurement would also measure the neutrino charge radius!**

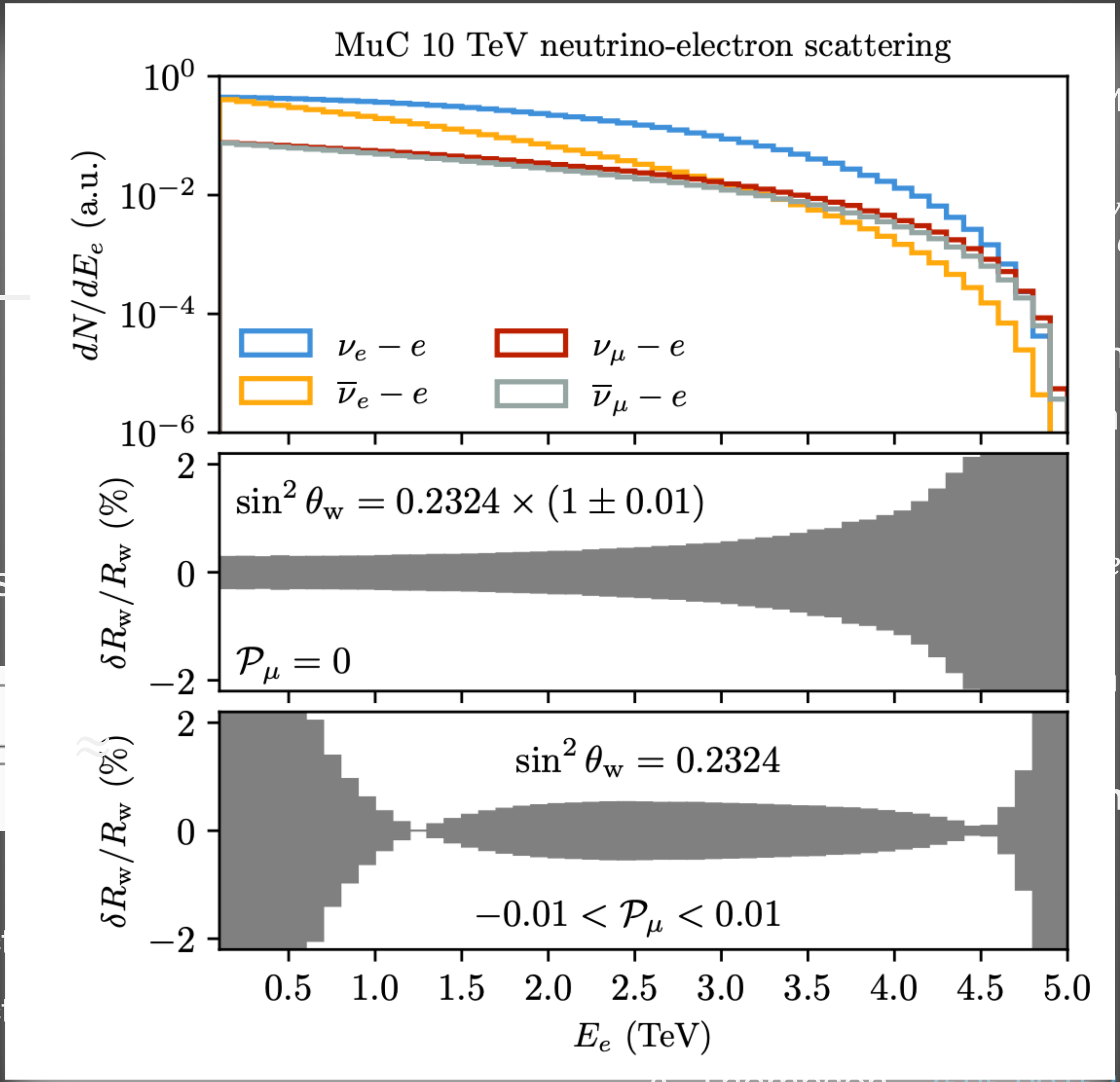
More quantitative studies of $\nu - e$ scattering (A. de Gouvea, A. Thompson, 2505.00152)

BIN as precision probes of electroweak sector

Neutrino-electron scattering

Good νs!





$_W = 0.2324 \pm 0.0083$), need:

$_e/R^{\theta_W}_{\nu-e} < 1.4\%$

nent ($\sin^2\theta_W = 0.2383 \pm 0.0011$)

nents:

$/R^{\theta_W}_{\nu-e} < 0.20\%$

You can isolate Weinberg's

nning of θ_W in the same experiment.

$$R^{\theta_w}_{\nu-e} = \frac{N^{\mu^+} - N^{\mu^-}}{N^{\mu^+} + N^{\mu^-}}$$

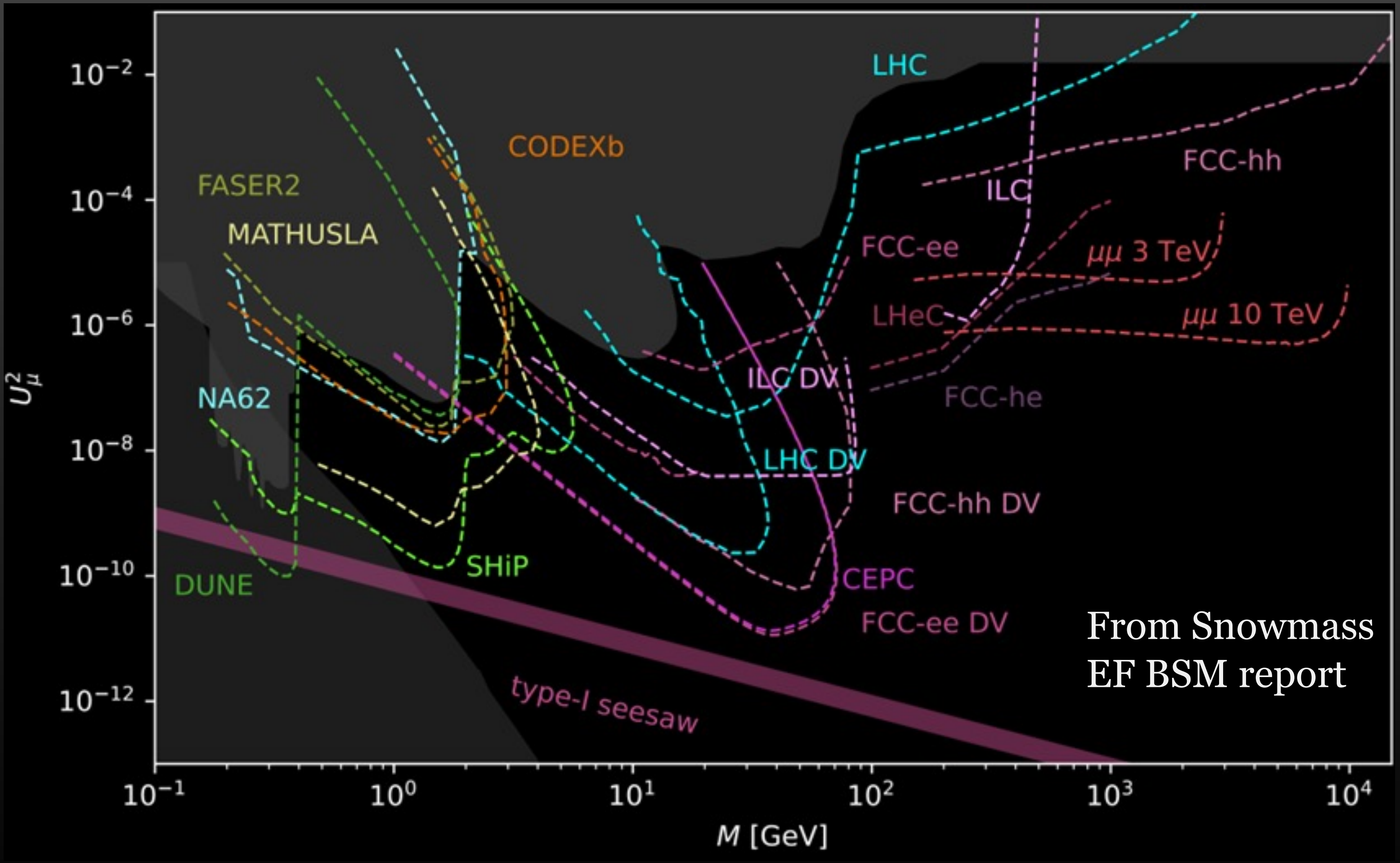
nent would also measure the

N^{μ^+}: the sum of $\bar{\nu}_\mu$ and ν_e elec

N^{μ^-}: the sum of ν_μ and $\bar{\nu}_e$ elec

of $\nu - e$ scattering (A. de Gouvea, A. Thompson, 2505.00152)

New studies for other regions



From Snowmass EF BSM report

The bottom left "type-I seesaw" represents the most pessimistic seesaw benchmarks. In general multi-generation seesaw, the motivated parameter regions spans over the space above that line, very much like the inverse seesaw spectra.