Physics At The Highest Energies With Colliders

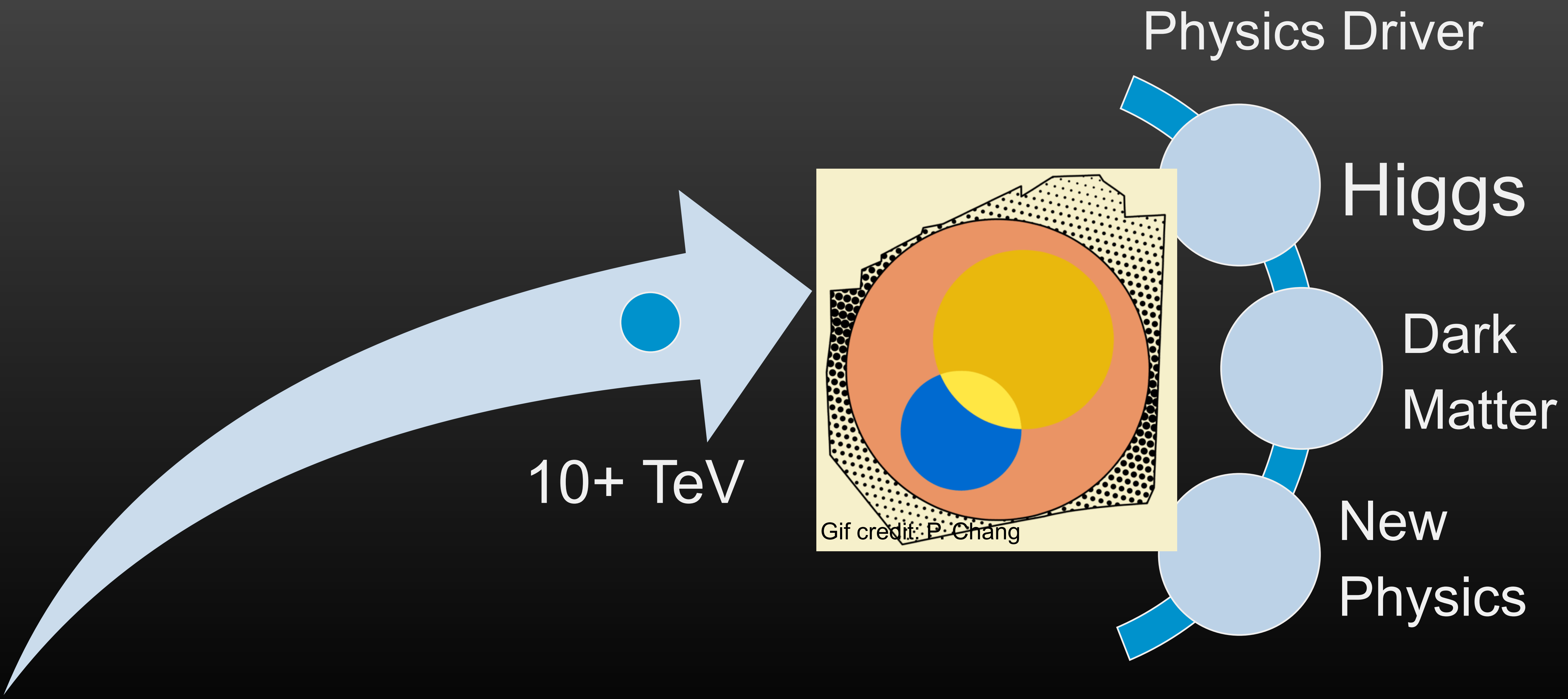
Jul 28 – 31, 2025
GGI

Thinking "Outside the box" about collider experiments

Zhen Liu
University of Minnesota

07/31/2025

The Muon Shot by us



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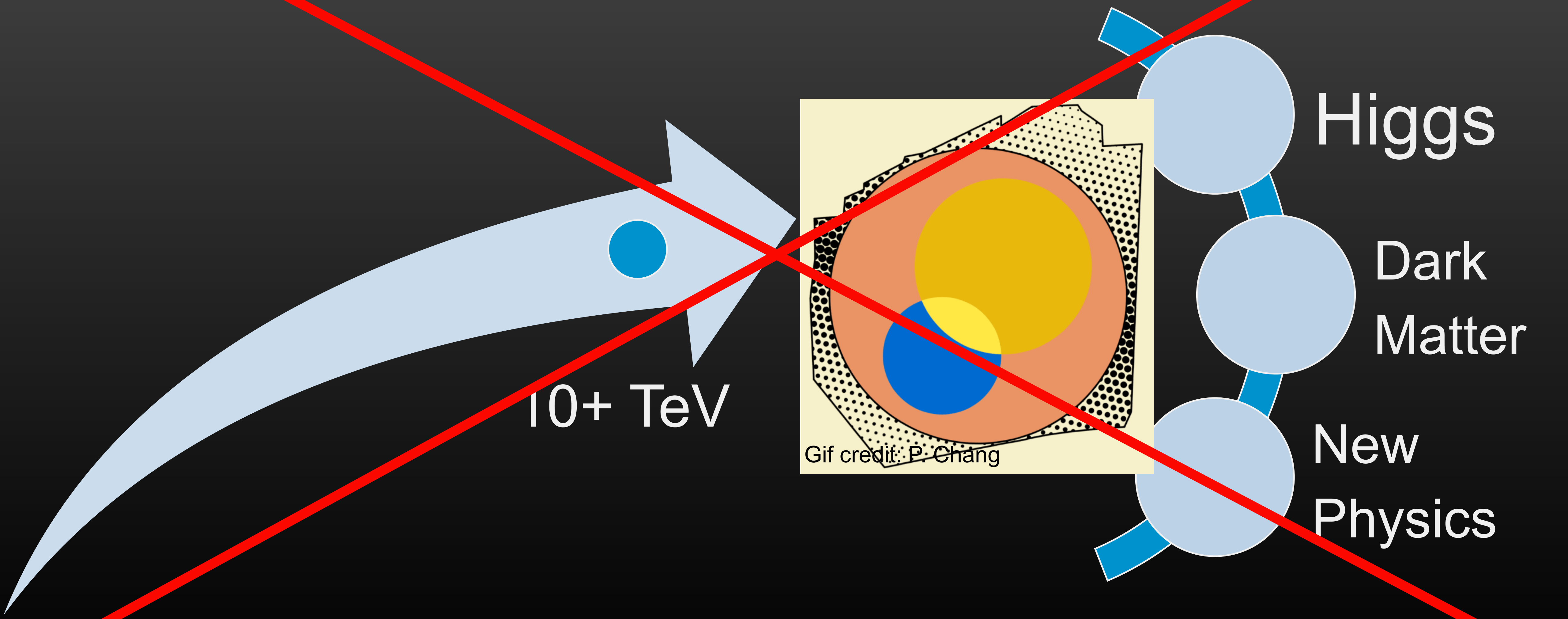


The Muon Collider

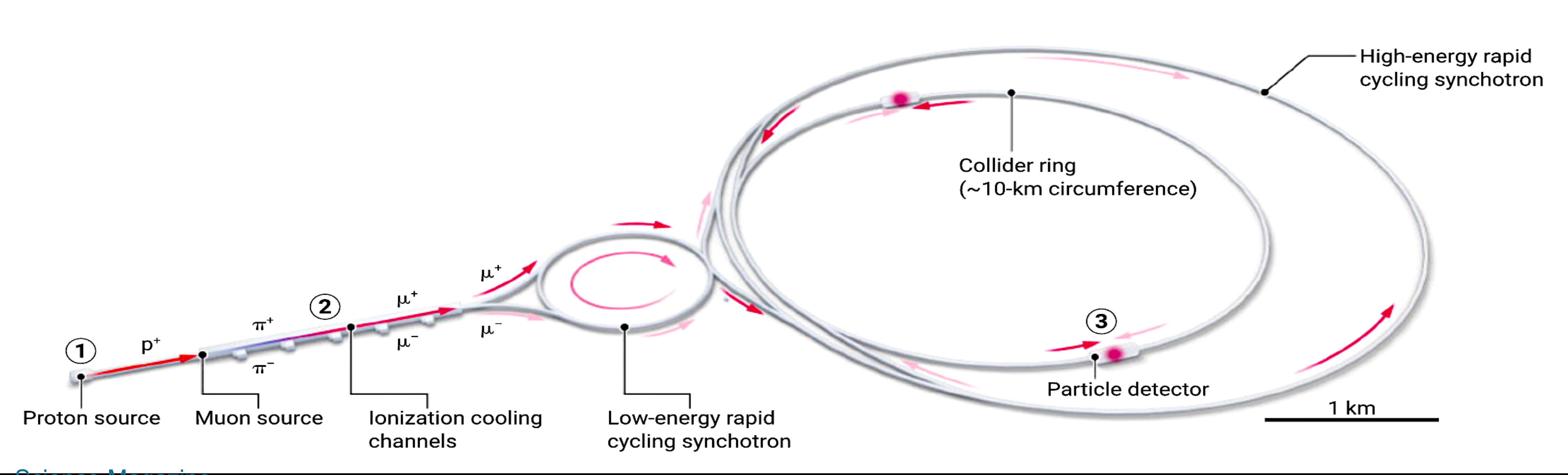
High CM Energy and Low Background

With challenges:

Need to cool and accelerate muons before they decay ($\tau_\mu^0 = 2.2\mu s$)

Need to deal with beam-induced backgrounds

…and need a lot of them! $> 10^{12}$ muons/bunch



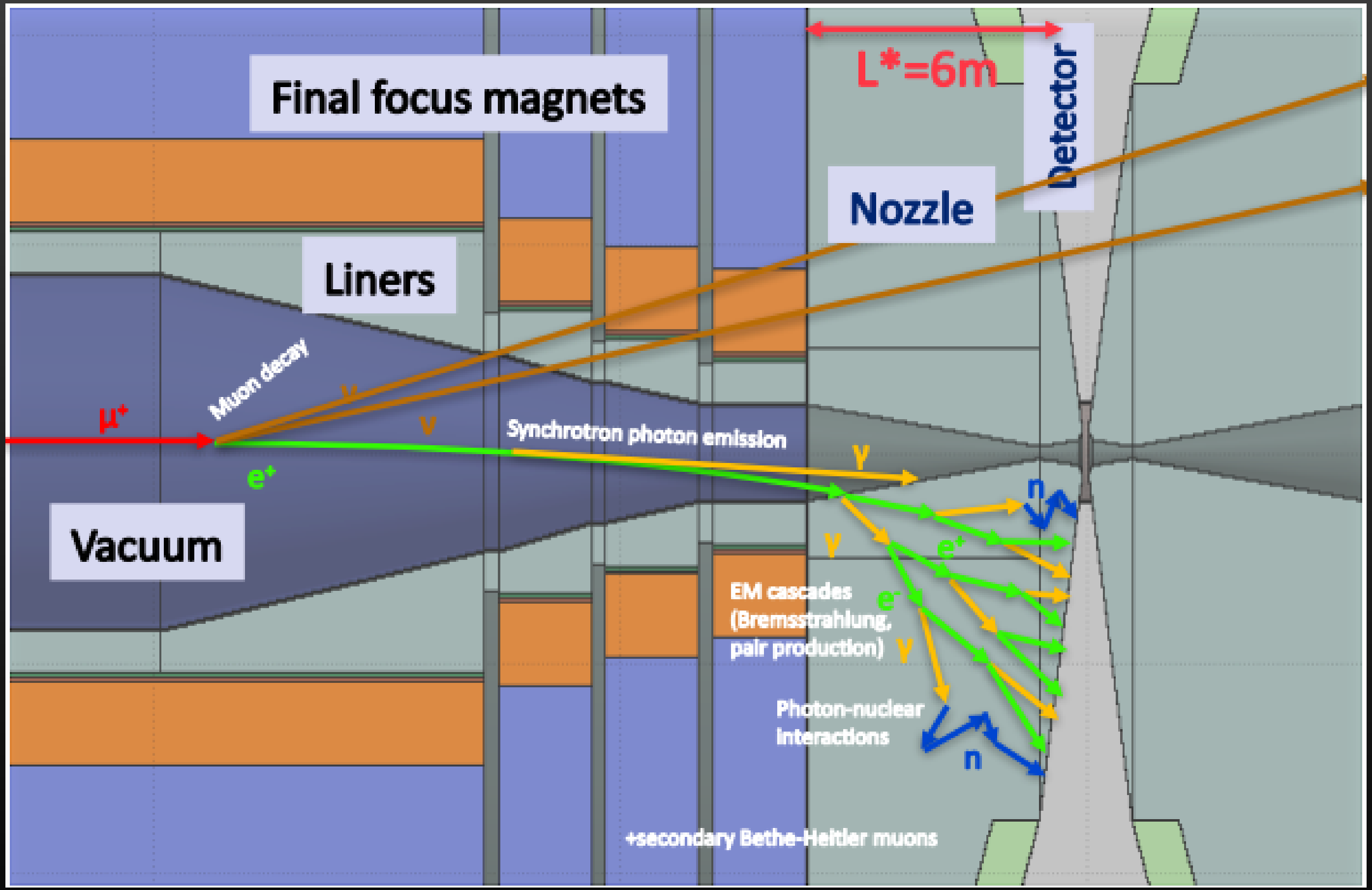
Science Magazine

Outside the Box1

Neutrino Slice

Beam-Induced Background (BIB)

D. Calzolari



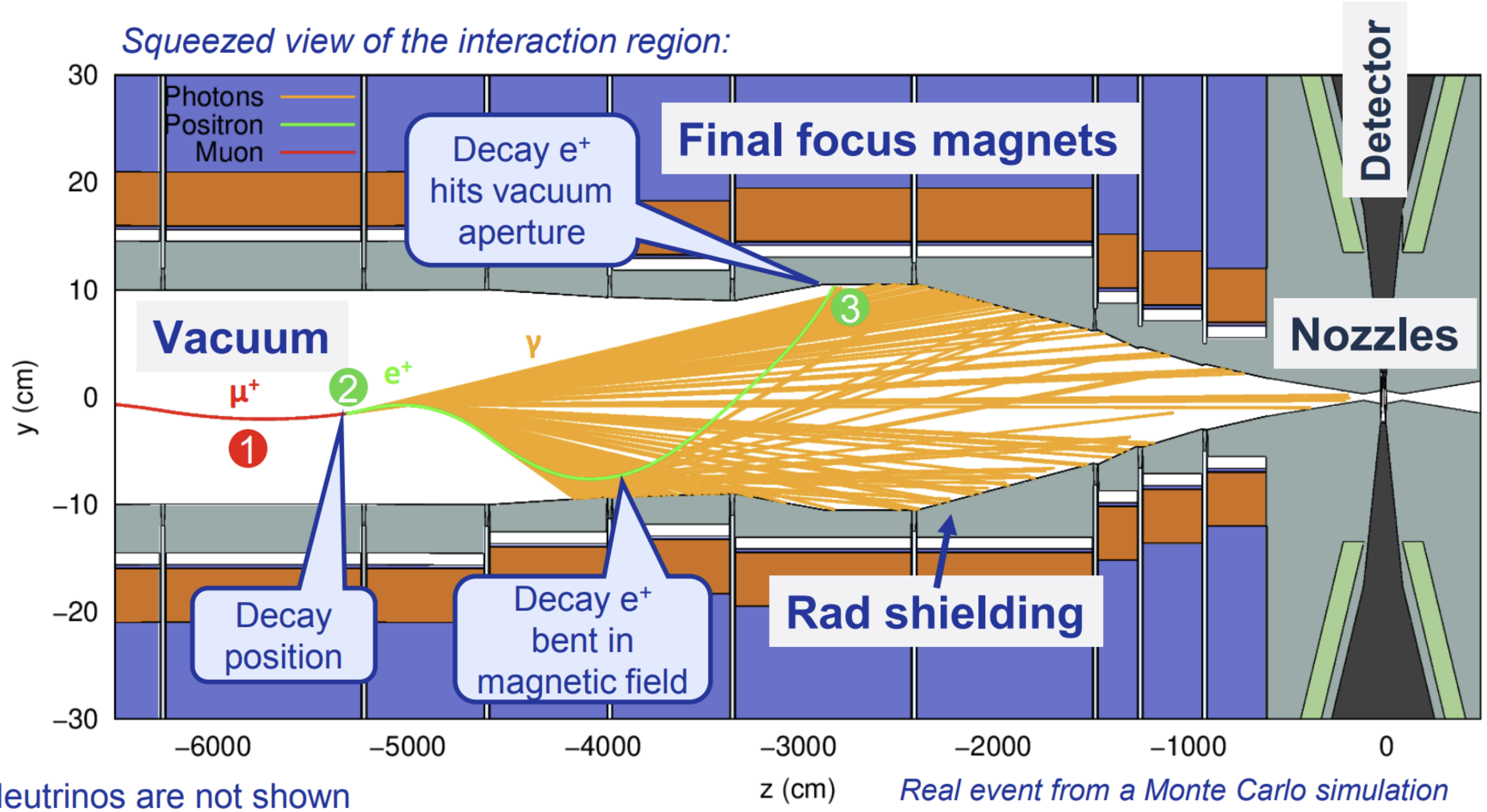
Background particles (from decay) entering detector per bunch crossing (with time cut [-1:15]ns):

- O(10^8) **γ** (>100 keV),
- O(10^7) **n** (>10^{-5} eV)
- O(10^6) **e+ & e-** (>100 keV)

Example of a muon decay in the machine

The lower-energy decay e^-/e^+ are overbent by the strong magnetic fields and emit synchrotron radiation (SR)

Squeezed view of the interaction region:



Neutrinos are not shown

Real event from a Monte Carlo simulation

Here:

1. μ^+ (5 TeV)
2. e^+ (1.20 TeV)
3. e^+ (0.45 TeV)

0.75 TeV emitted as SR photons

Because of the smaller mass, the decay e^+/e^- emit much more SR power than the muons of the beam

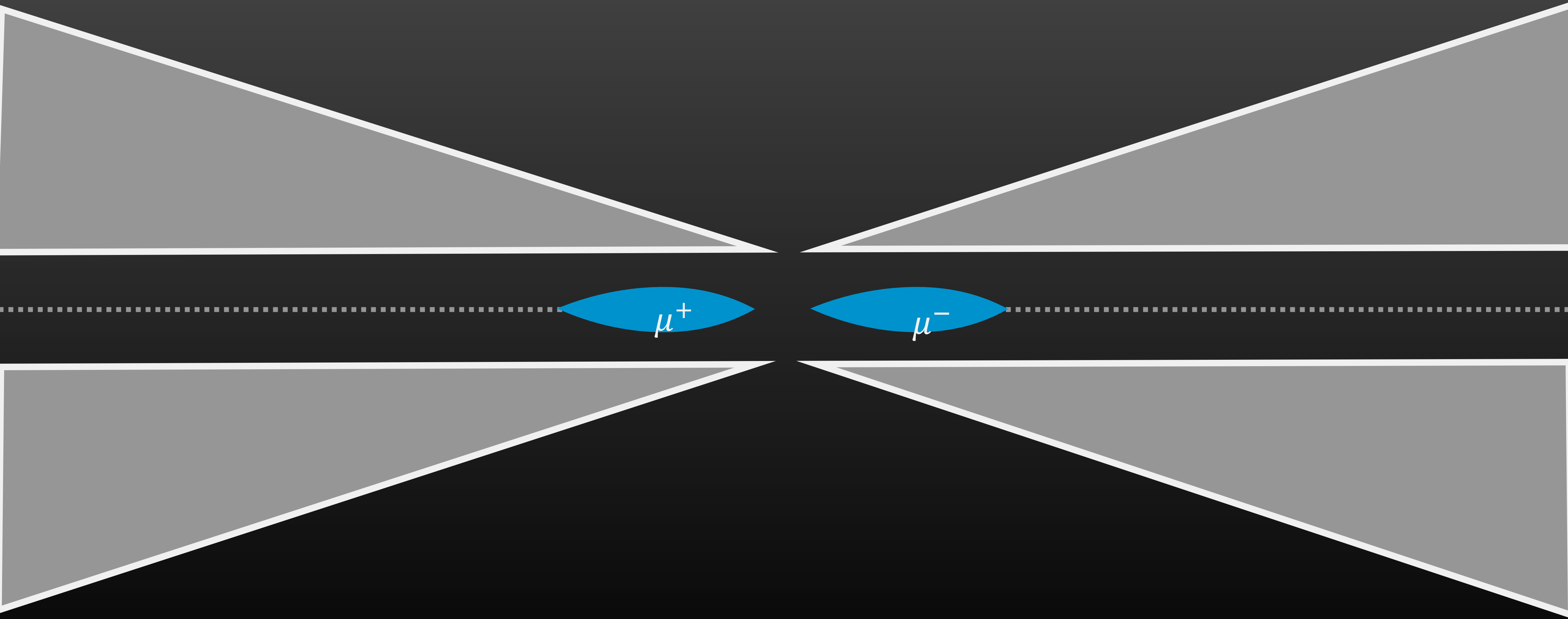
Anton Lechner, first week

Will happen O(10M) times per bunch crossing!


How to Build a
Muon Collider
Lawrence Lee
THE UNIVERSITY OF
TENNESSEE
KNOXVILLE


BUILD A

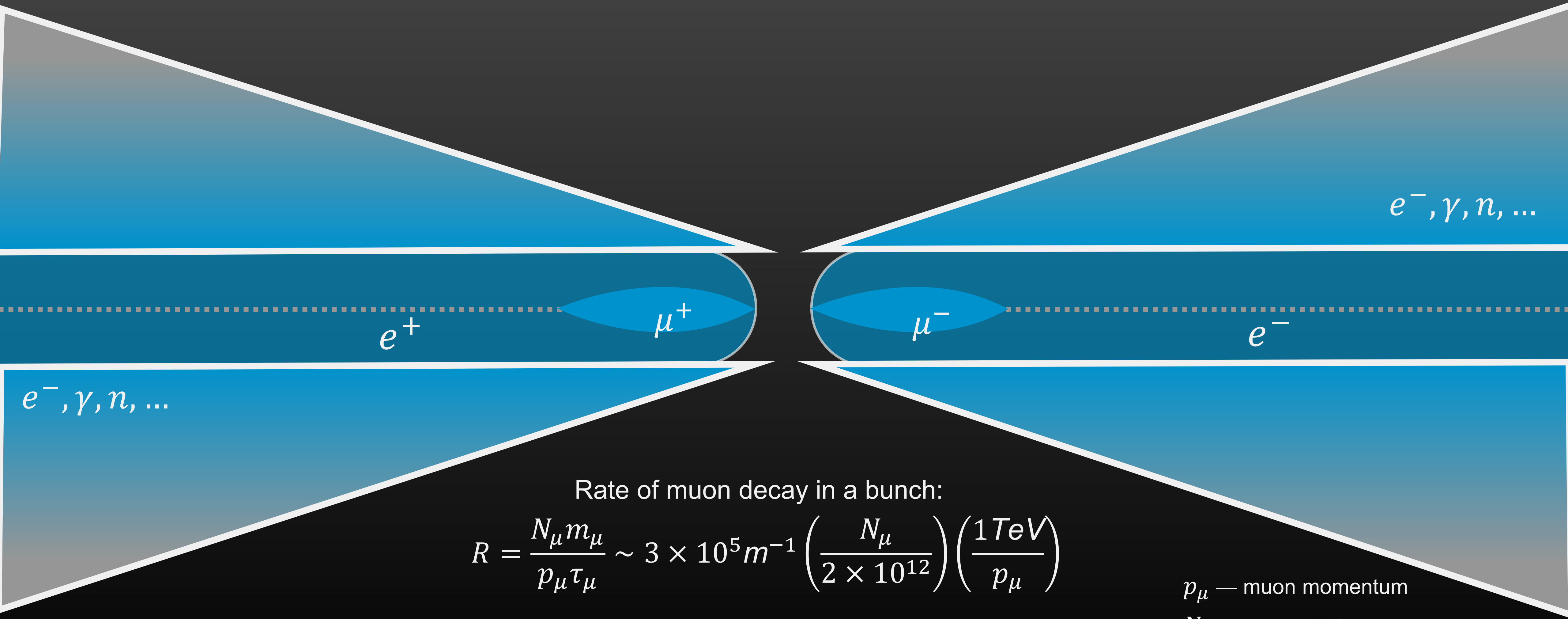
Muon Collider Beam radiation



The first part is mainly based on: Luc Bojorquez-Lopez, Matheus Hostert, Carlos A. Argüelles, Zhen Liu 2412.14115

Muon Collider

Beam radiation — Beam Induced Backgrounds (BIB)



Rate of muon decay in a bunch:

$$R = \frac{N_\mu m_\mu}{p_\mu \tau_\mu} \sim 3 \times 10^5 m^{-1} \left(\frac{N_\mu}{2 \times 10^{12}}\right)\left(\frac{1\,TeV}{p_\mu}\right)$$

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
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We show the story is different:

There exists a unique neutrino flux we need to tackle and utilize.

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

Beam-Induced-Neutrinos (BINs)

The highest-energy and most-collimated neutrino beam ever built:

$$\langle E_\nu^{\mathrm{FASER}} \rangle \lesssim \langle E_\nu^{\boldsymbol{MuC10TeV}} \rangle \lesssim \langle E_\nu^{\boldsymbol{FCC}} \rangle$$

- Neutrinos are unavoidable byproducts of the machine.
- BINs offer a built-in synergy between **energy frontier** and **neutrino/electroweak** physics.

What are BINs good for?

The energies are too large for oscillations:

$$L_{osc} \sim \mathcal{O}(300{,}000)km\left(\frac{E_\nu}{1TeV}\right)\left(\frac{2\times 10^{-3}eV^2}{\Delta m_{31}^2}\right)$$

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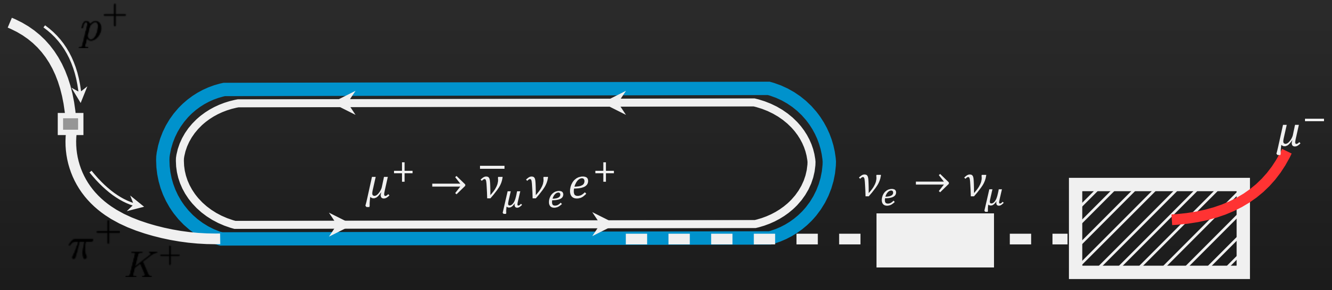
$$L_{osc} \sim \mathcal{O}(300{,}000)km\left(\frac{E_\nu}{1TeV}\right)\left(\frac{2\times10^{-3}eV^2}{\Delta m_{31}^2}\right)$$

A lower-energy "**neutrino factory**" would be more suitable for standard oscillations:



$$E_\nu \sim \mathcal{O}(1-20)GeV$$

- Interesting possibility on its own, but may be even more relevant depending on findings of DUNE & Hyper-K
- Muon Collider Demonstrator Physics?

What are BINs good for?

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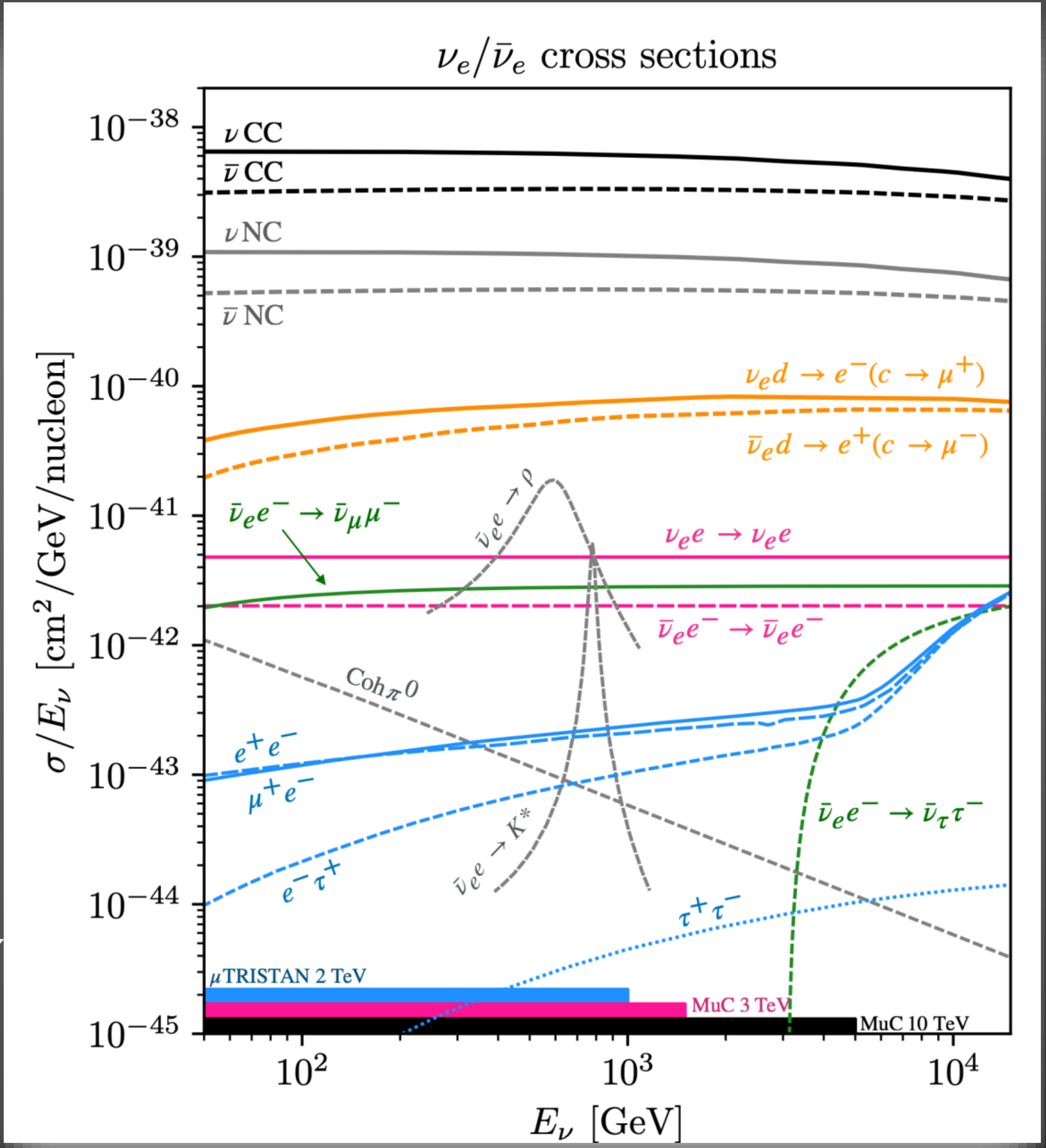
Beam energies are not necessarily new, but flavor composition, sample size, and precision are.

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



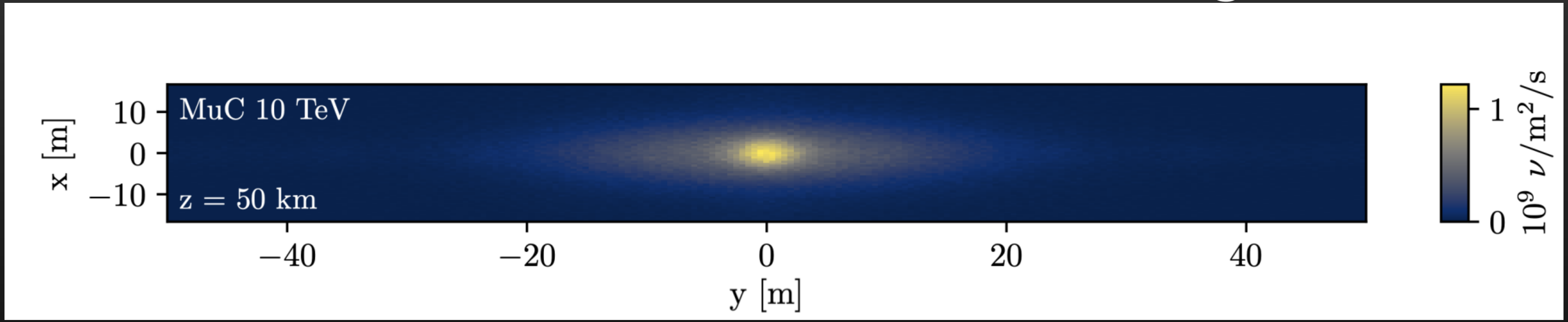
Detecting BINs

Forward facilities?

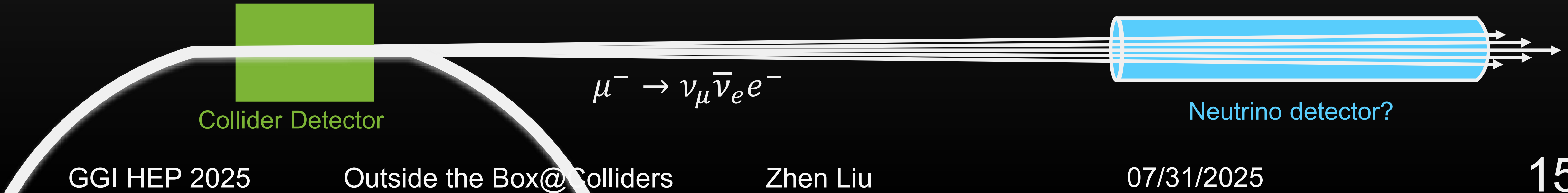
Straight section neutrino flux is extremely collimated. No need for a big detector — event rate is enormous.

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

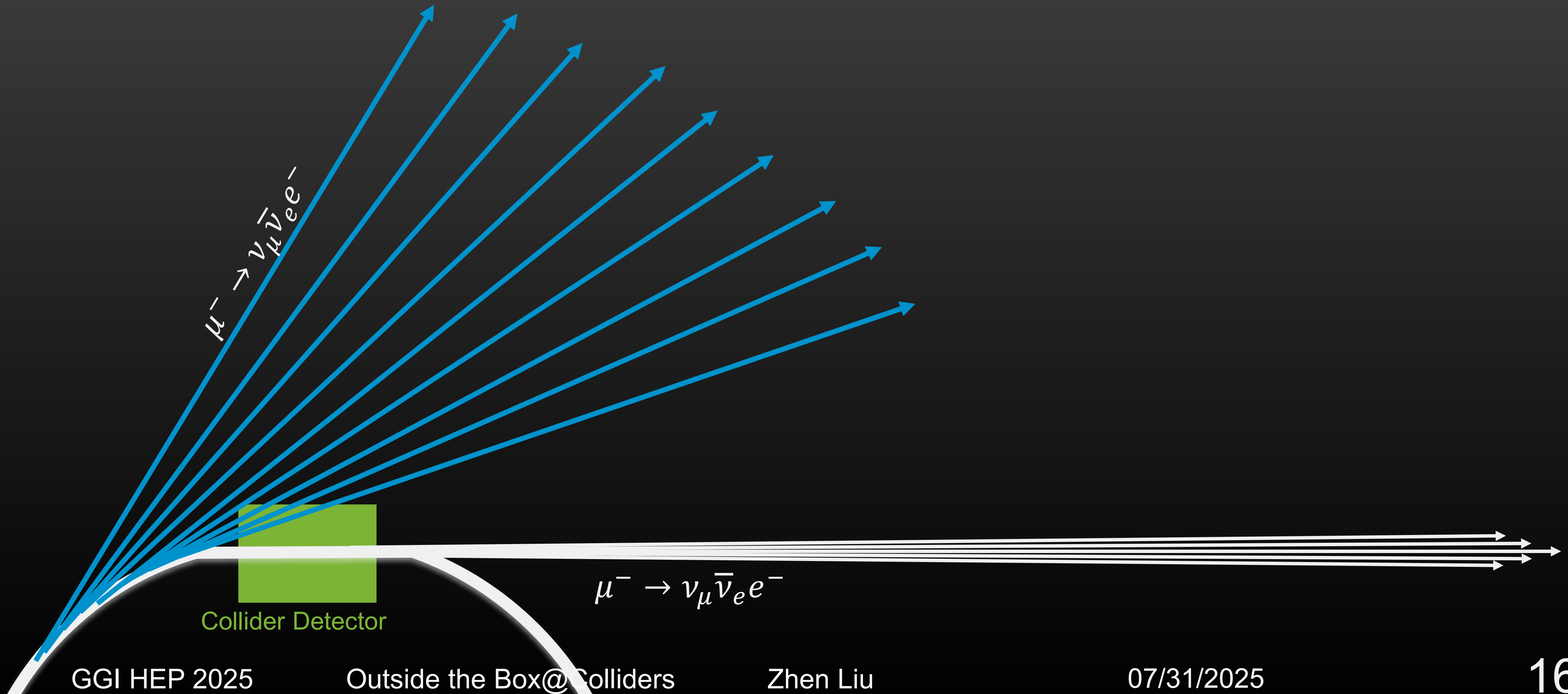
Simulated @ 50 km from IP



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.



Detecting BINs: ~~Forward~~ Tangential facilities?



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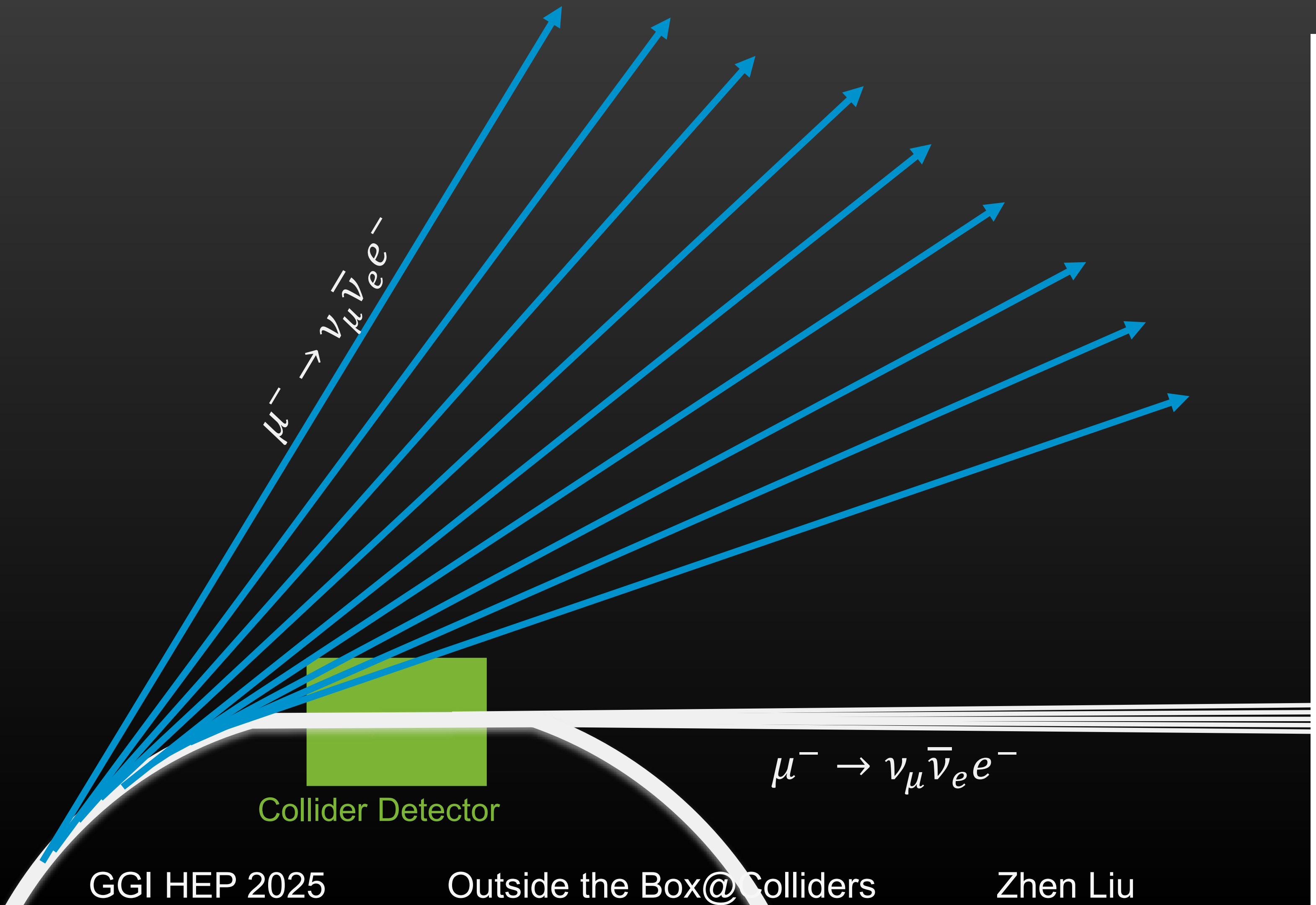
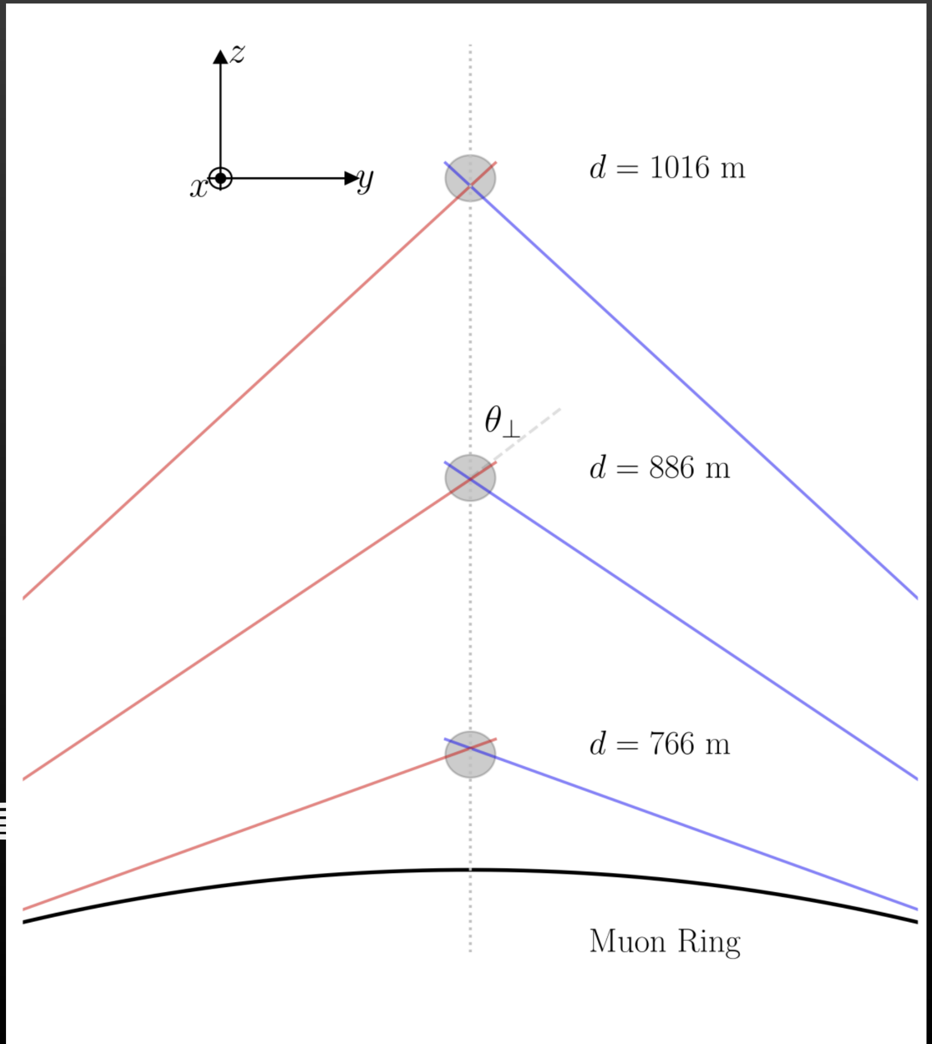
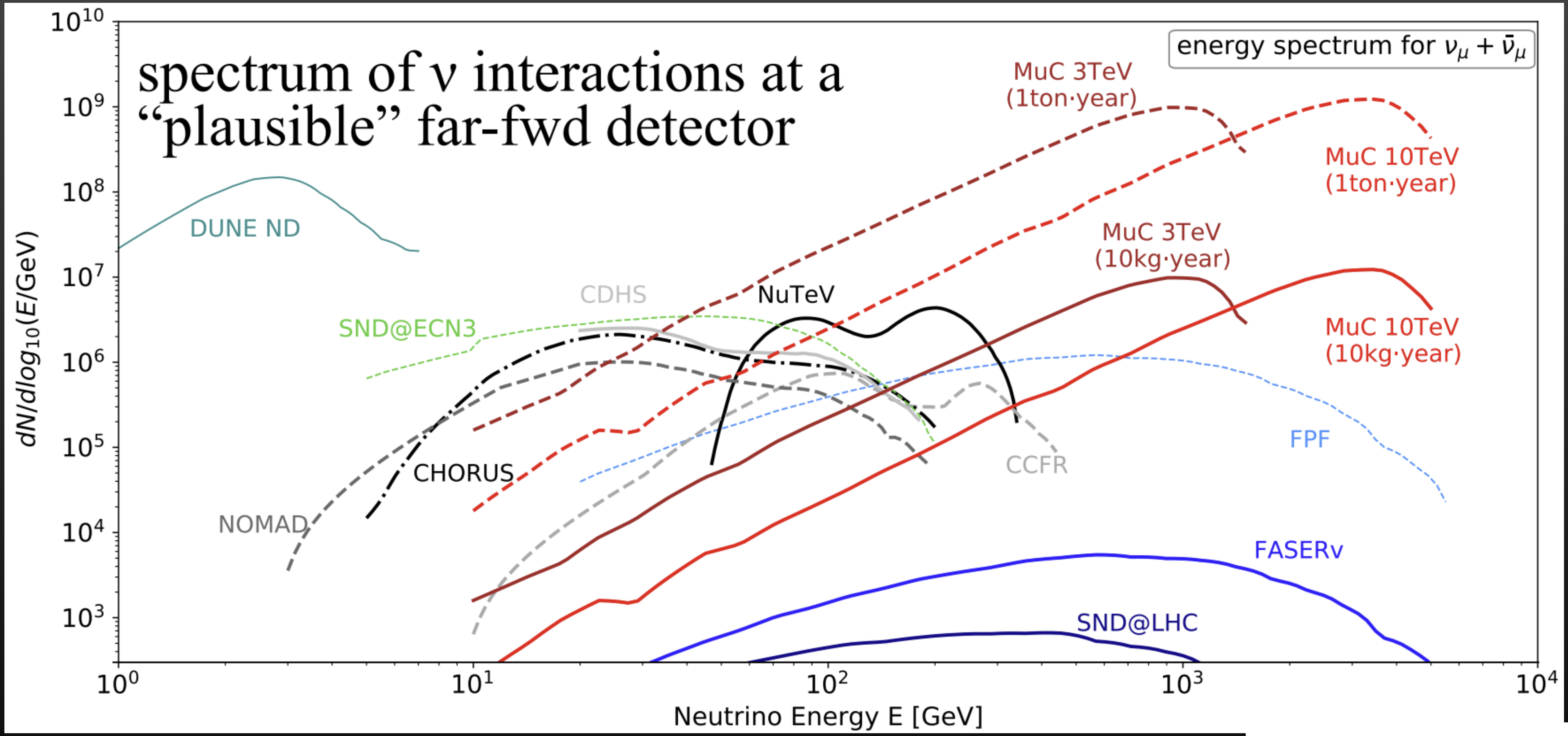
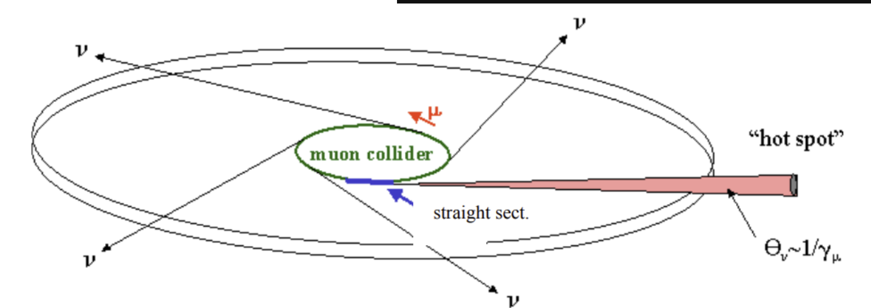


A. de Gouvea, A. Thompson, 2505.00152



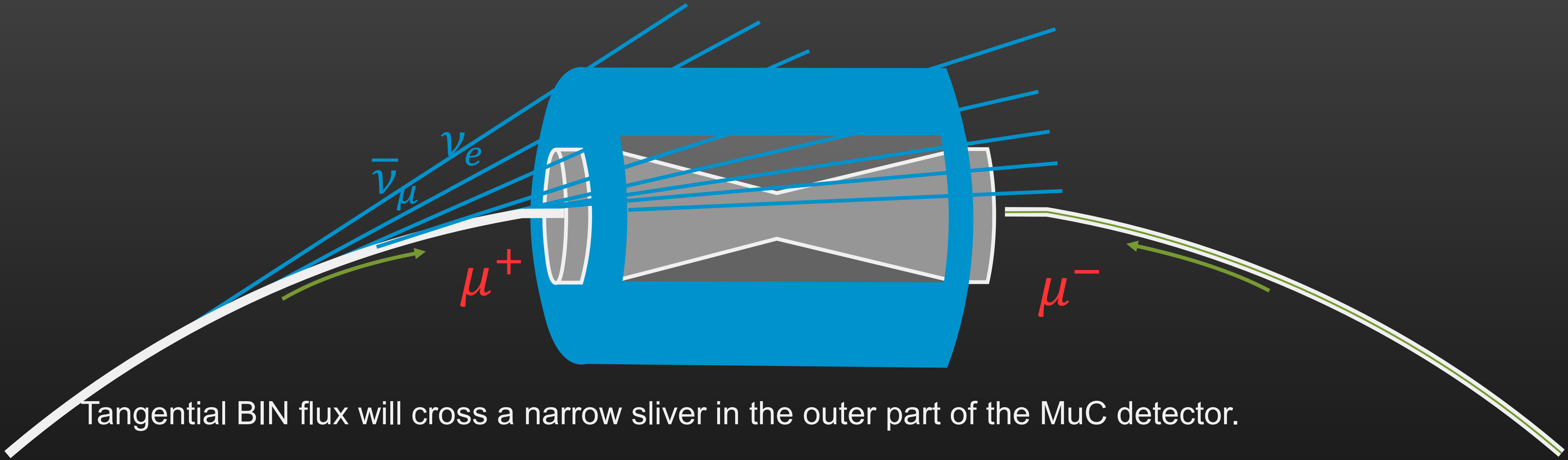
Forward Muon Detector





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.

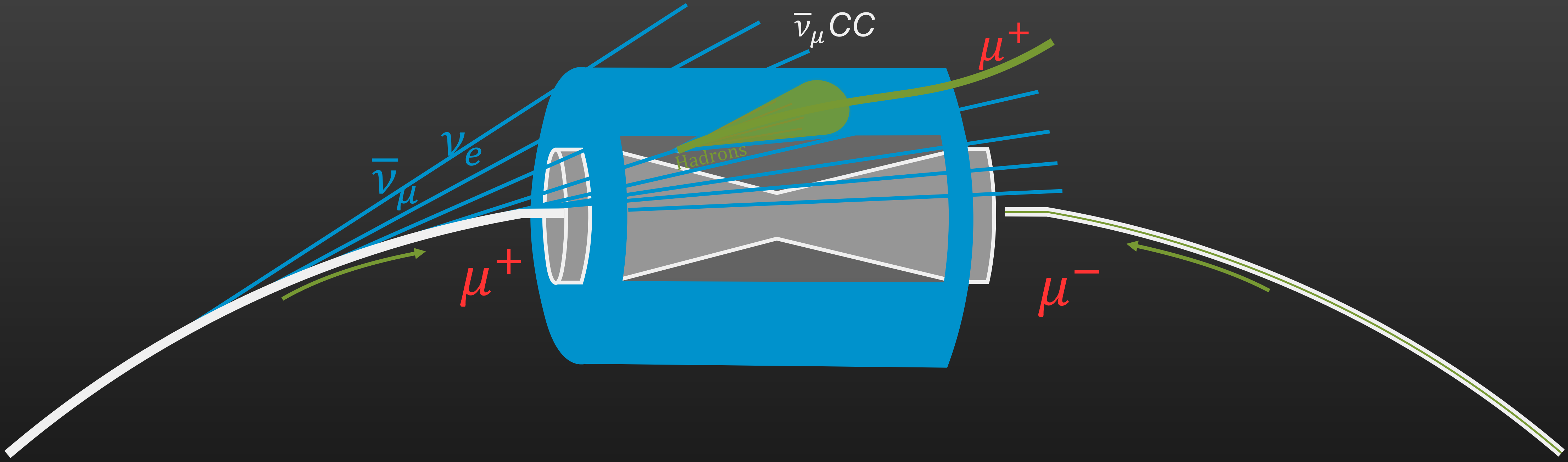
BIN interactions in this “**neutrino slice”** will be abundant and produce high energy particles

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

It turns out interaction rates would be larger than anything we have ever recorded in the lab.

Beam-Induced Neutrinos (BINs)

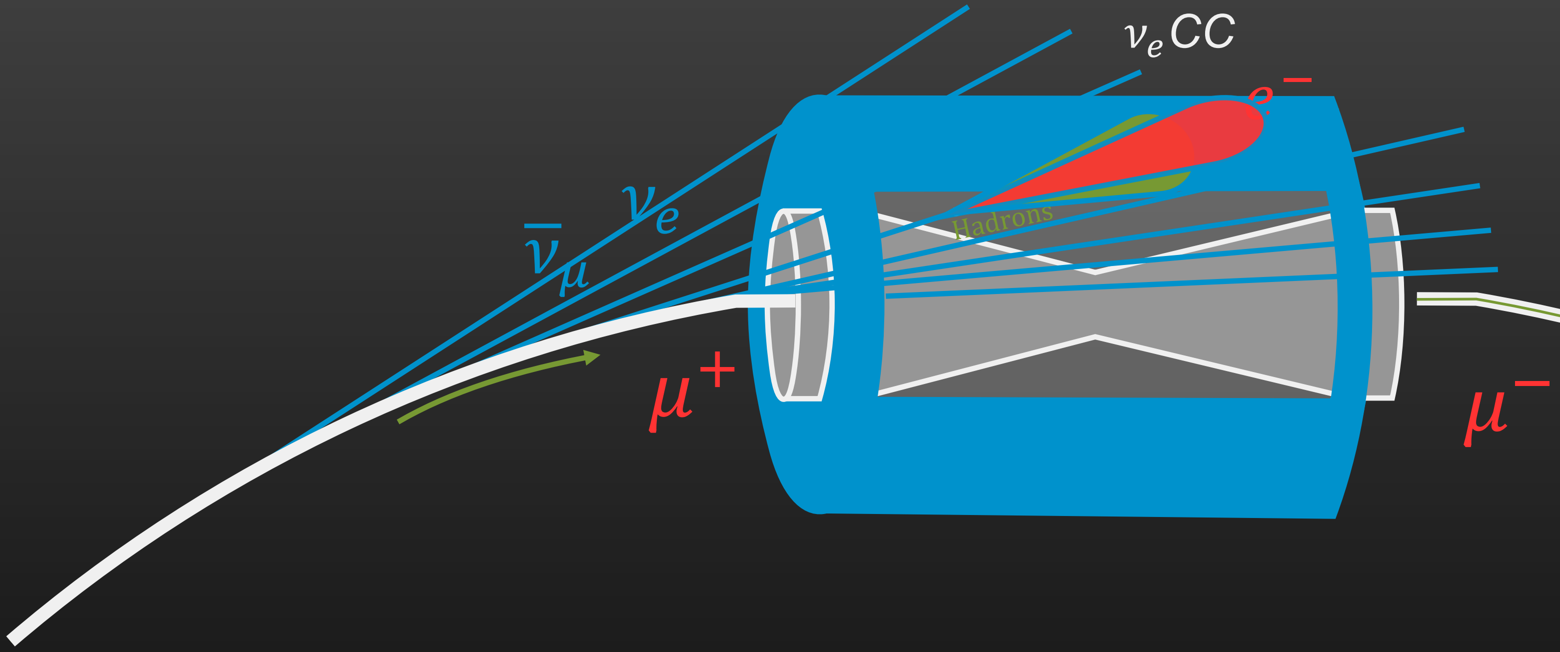
Most frequent events: $\bar{\nu}_\mu$ CC



Induce hadronic showers with muons inside the barrel.

Beam-Induced Neutrinos (BINs)

Most frequent events: ν_e CC

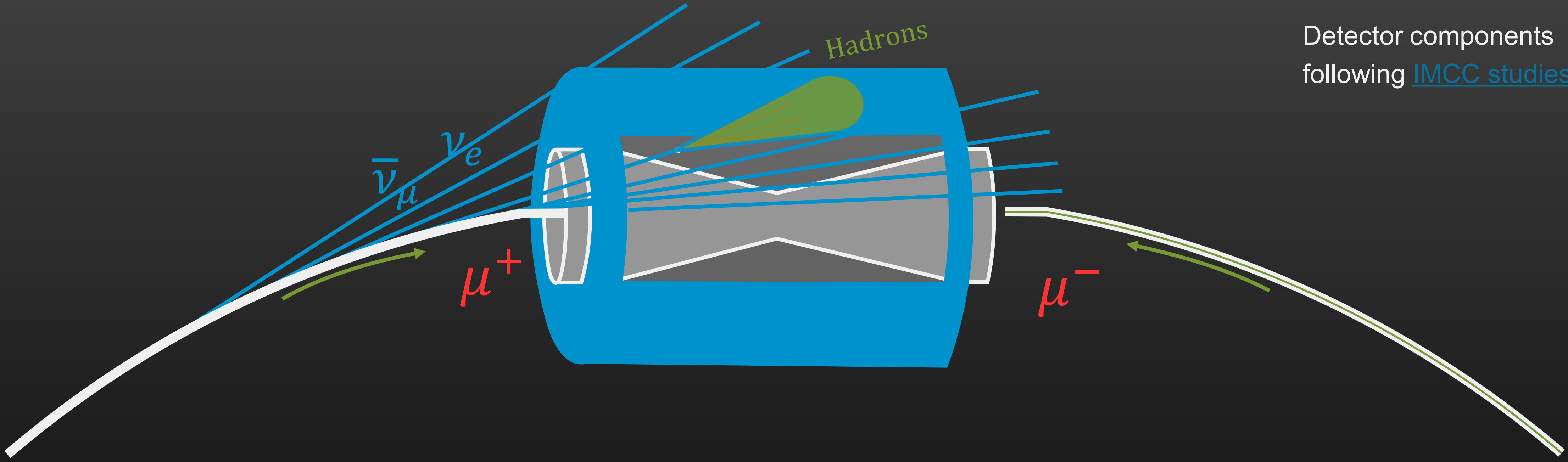


Detector components following IMCC studies

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.

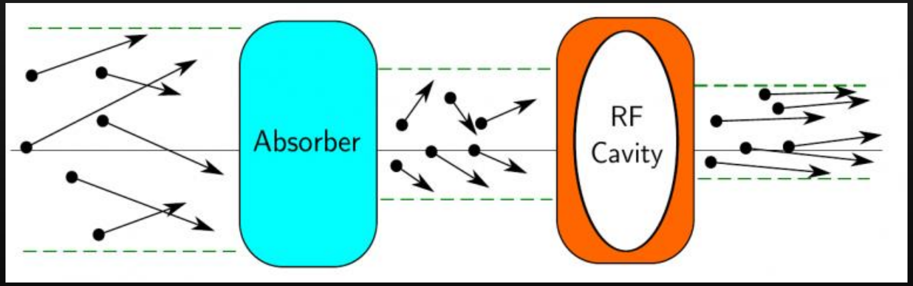
Muon Collider benchmarks

MuC 3 and 10 TeV — $\mu^+\mu^-$ collider

Ionization cooling

Collider magnet lattice from IMCC studies

Assuming the same MAP-like detector

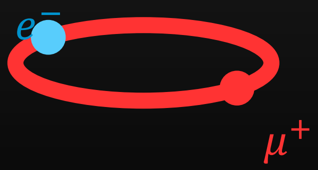


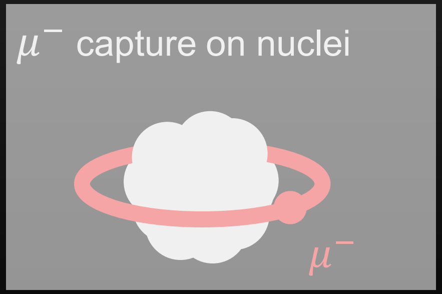
μTRISTAN 2 TeV @ J-PARC — $\mu^+\mu^+$ collider

Cooling: form muonium, strip it of electrons, and boost in z direction. Only works for μ^+

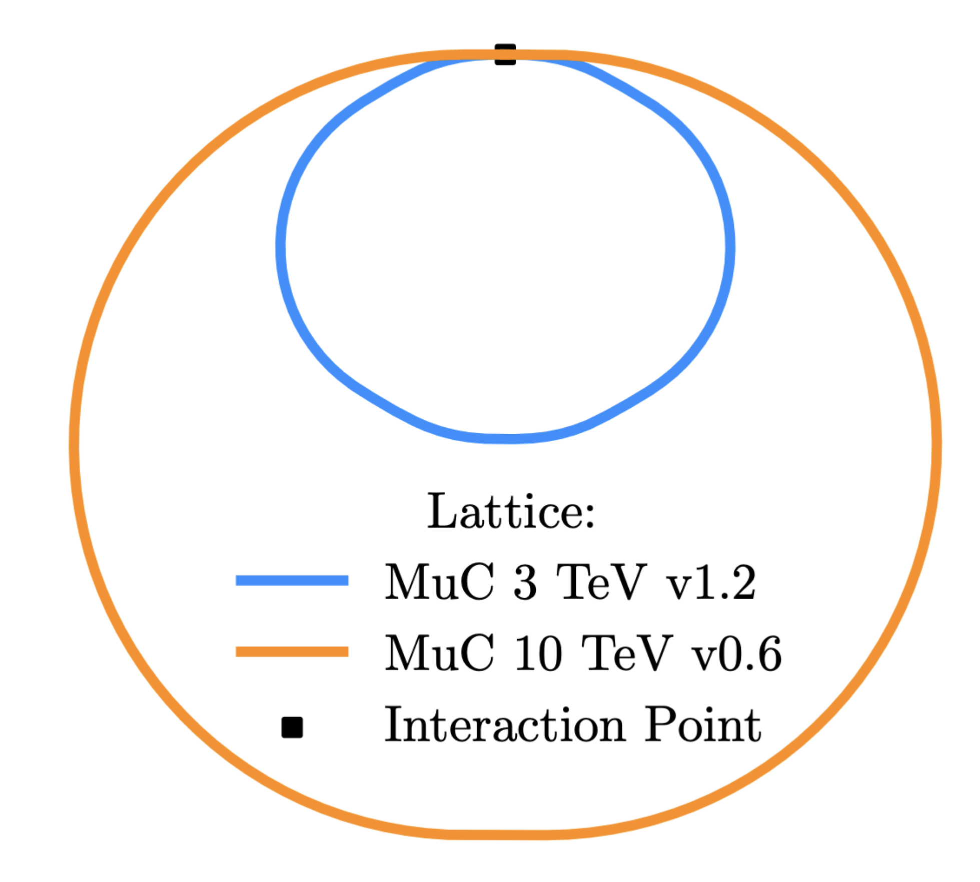
Assuming MuC-3-TeV collider lattice

Same MAP-like detector





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

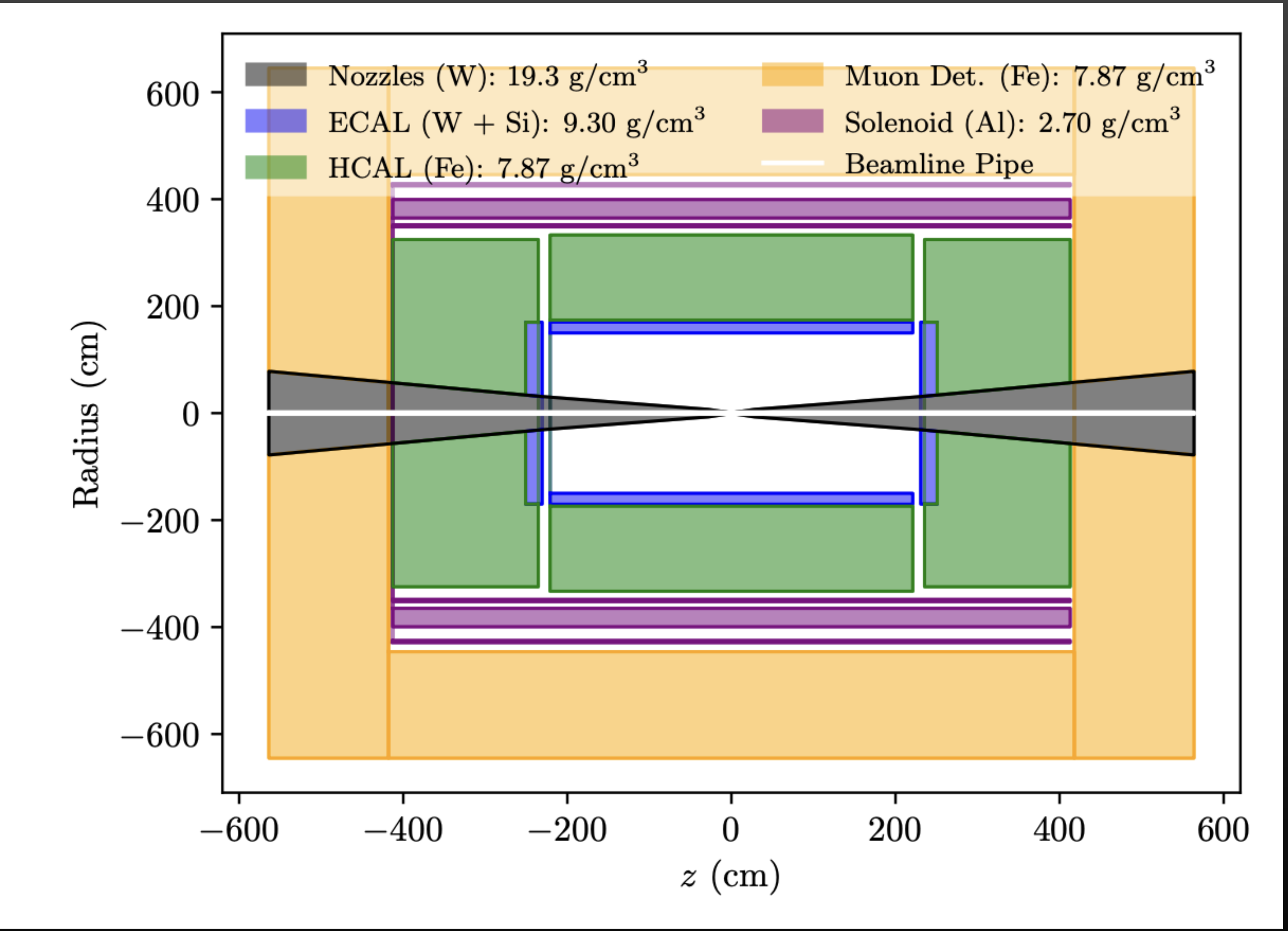
Beam size determined by Twiss parameters $\beta_{x,y}$ and $\gamma_{x,y}$ as a function of distance traveled around the ring (s):

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: $\delta\theta_\nu \sim m_\mu/E_\mu \sim 10^{-4}$

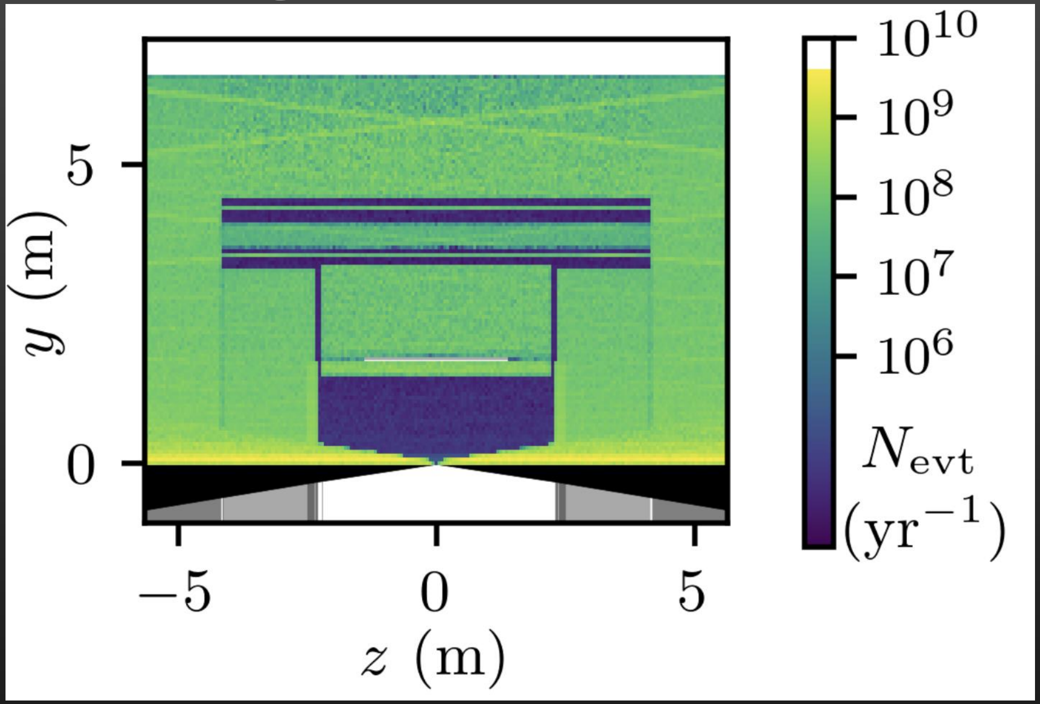
Muon Collider

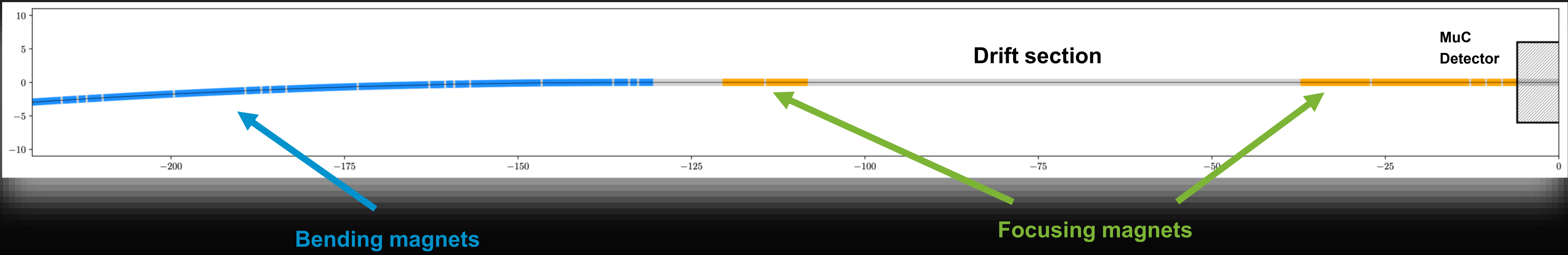
Building toy models of muon collider



Detector components following MAP studies

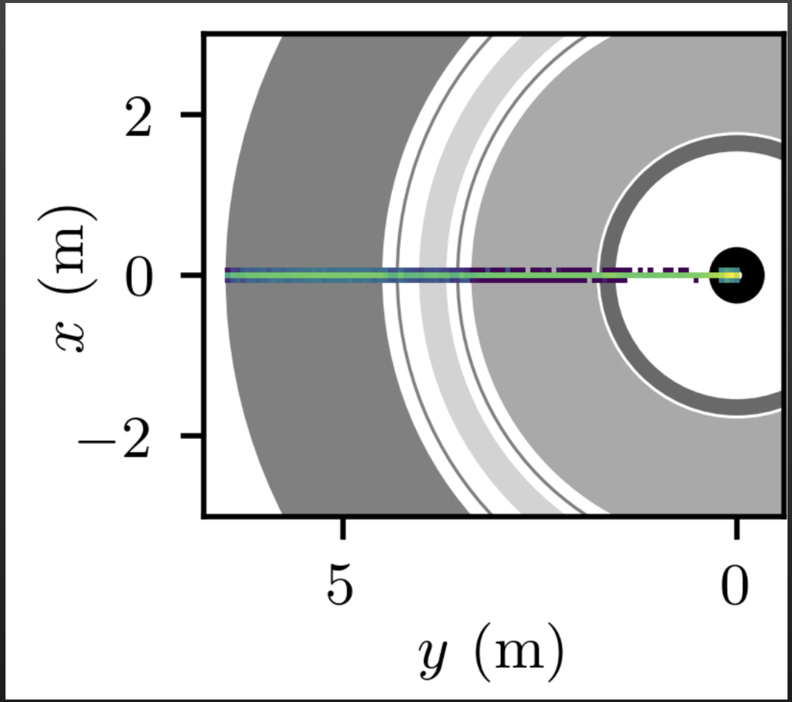
Beam-induced neutrinos: Tangential fluxes

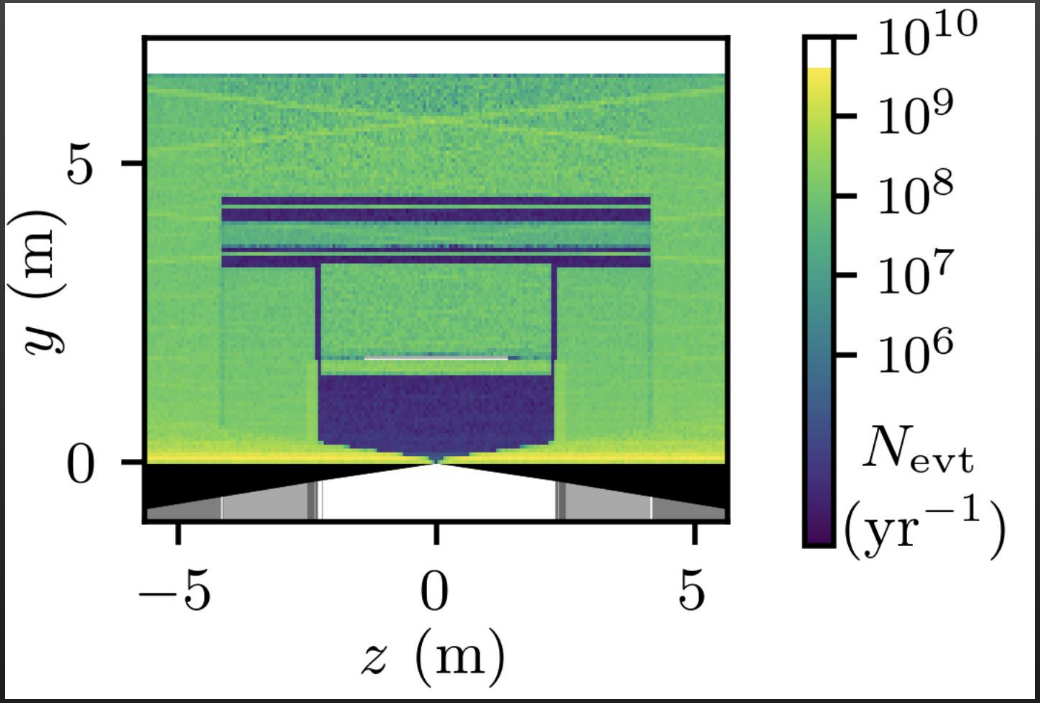


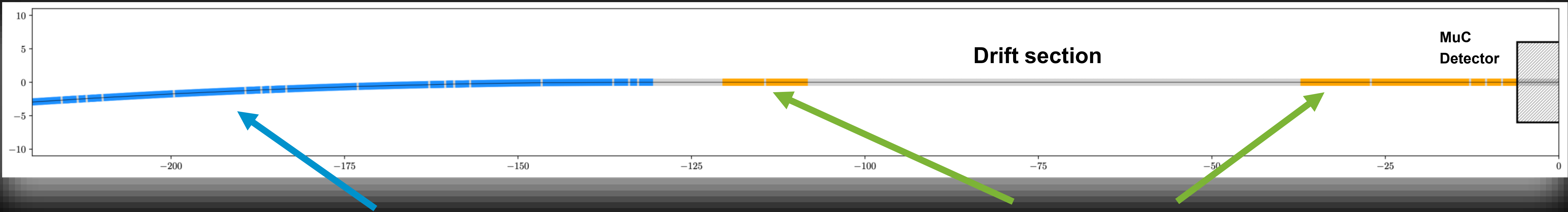


Beam-induced neutrinos: Tangential fluxes

The **Neutrino Slice**!







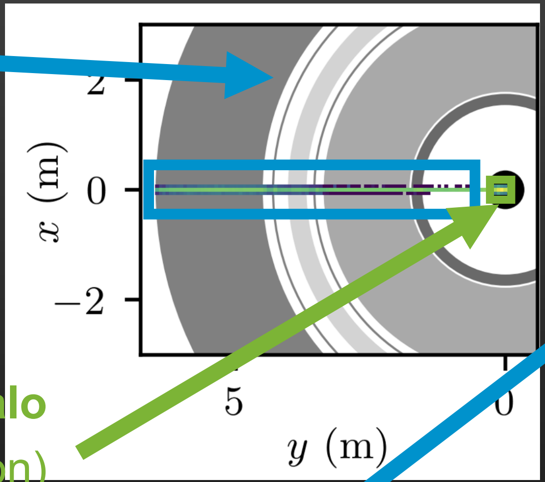
Bending magnets

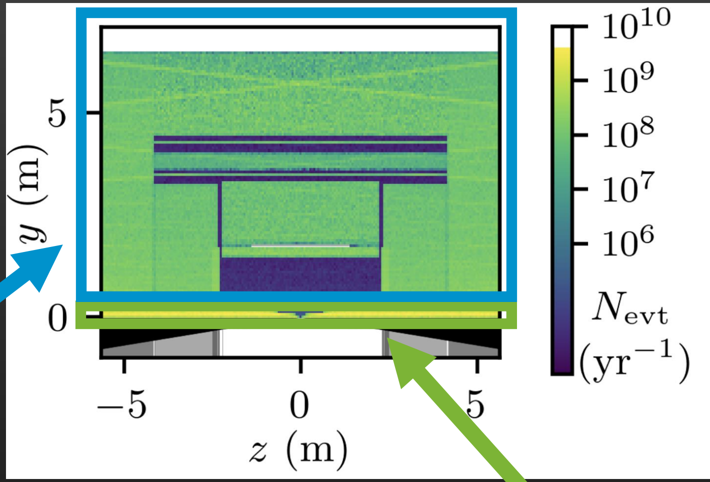
Focusing magnets

Beam-induced neutrinos

Tangential fluxes

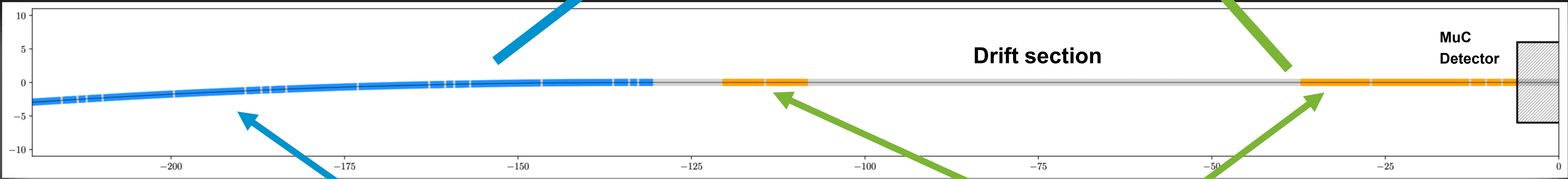
Neutrino Slice
(mostly from main ring)





Neutrino Halo
(mostly from straight section)
Vast majority goes down the pipe

Very interesting main Interaction point physics and regulating t-channel singularities. A unique problem for unstable particle collisions (Melnikov, Serbo, hep-ph/9601221).



Bending magnets

Focusing magnets

Muon Collider

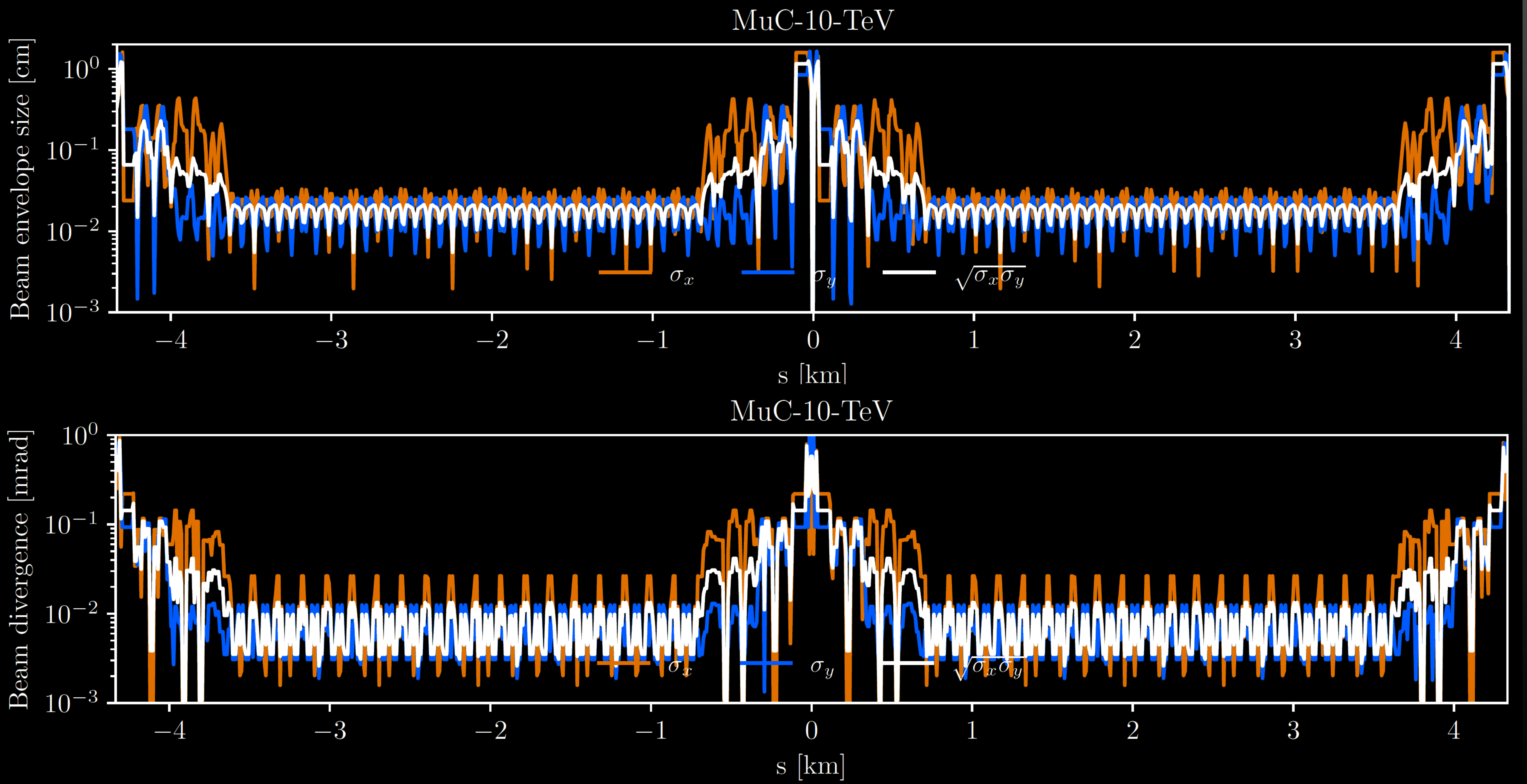
Building toy models of muon collider

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

About 0.5 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 $\overline{\nu}_e e \to \overline{\nu}_e e$	8.6×10^5	2.5×10^5	0
ES $\overline{\nu}_\mu e \to \overline{\nu}_\mu e$	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 $\overline{\nu} p^+ \to \ell^+ n$	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 $\overline{\nu}_e e \to \rho^-$	4.2×10^5	7.7×10^5	0
Res $\overline{\nu}_e e \to K^{*-}$	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 $\overline{\nu}_e e \to \overline{\nu}_\mu \mu^-$	1.2×10^6	3.5×10^5	0
ITD $\overline{\nu}_e e \to \overline{\nu}_\tau \tau^-$	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 $\mu^+\mu^-$	7.5×10^5	1.6×10^5	1.3×10^6

Beam Simulation



Beam Wobbling

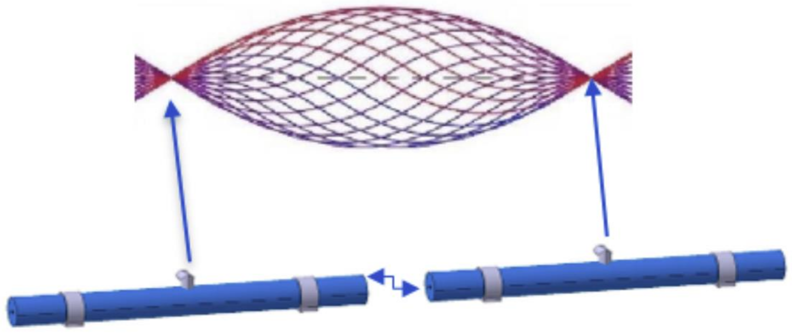
It changes the spread size by (using black lines) 15cm/600m, which at 50km location, spread the neutrino beam out by 15m (in 2D), comparable to the BINs spread.
Instead, at the main detector, it broadens the BINs by O(cm) (with a rms smaller)

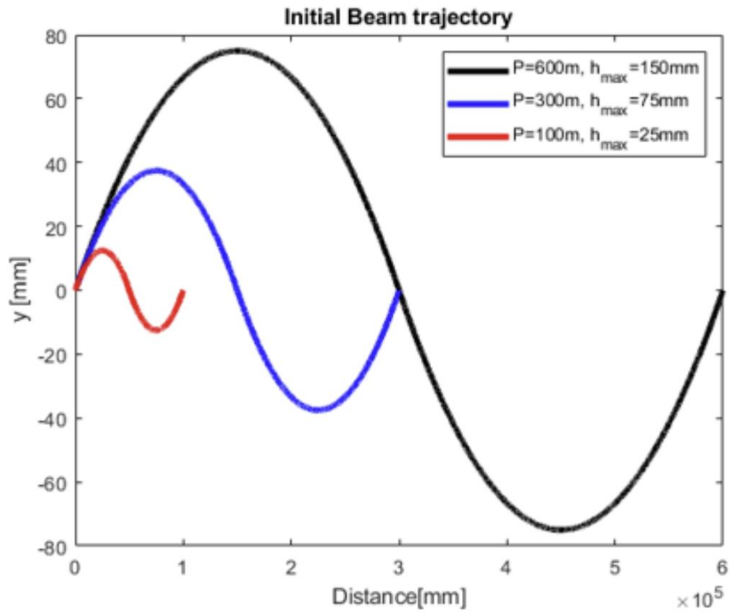
International MUON Collider Collaboration

He supply

CERN

- **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)

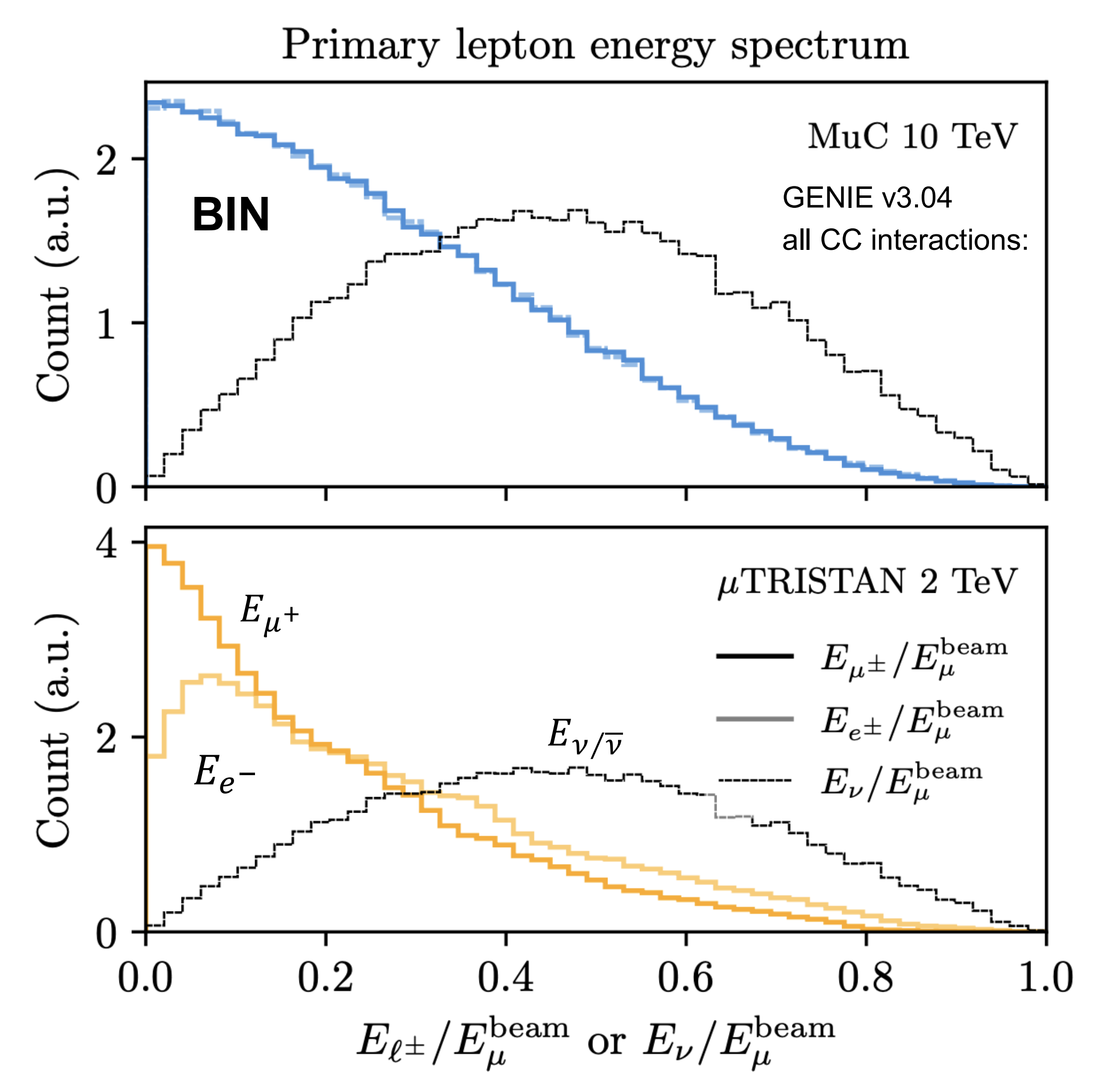




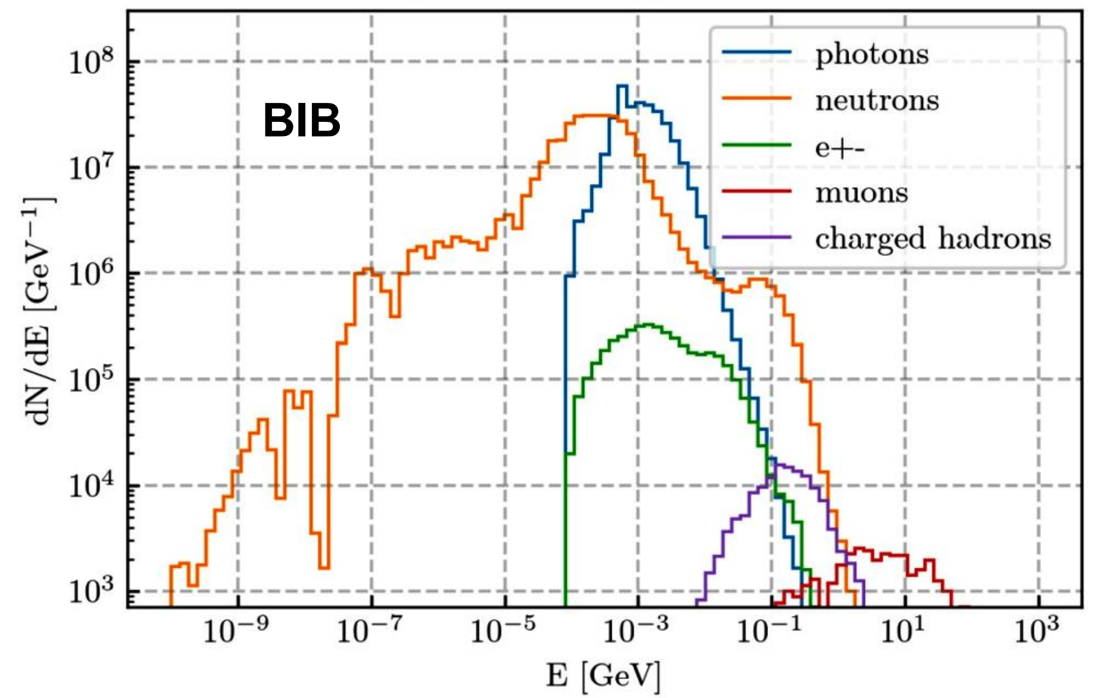
A magnet movement system is investigated allowing for a machine deformation resulting in ±1 mrad* variations of the slope of the tangent of the beam trajectory
C. Carli, "Neutrino Radiation for a realistic Collider", IMCC Annual Meeting 2022

BIN Interaction properties

1) TeV amounts of energy

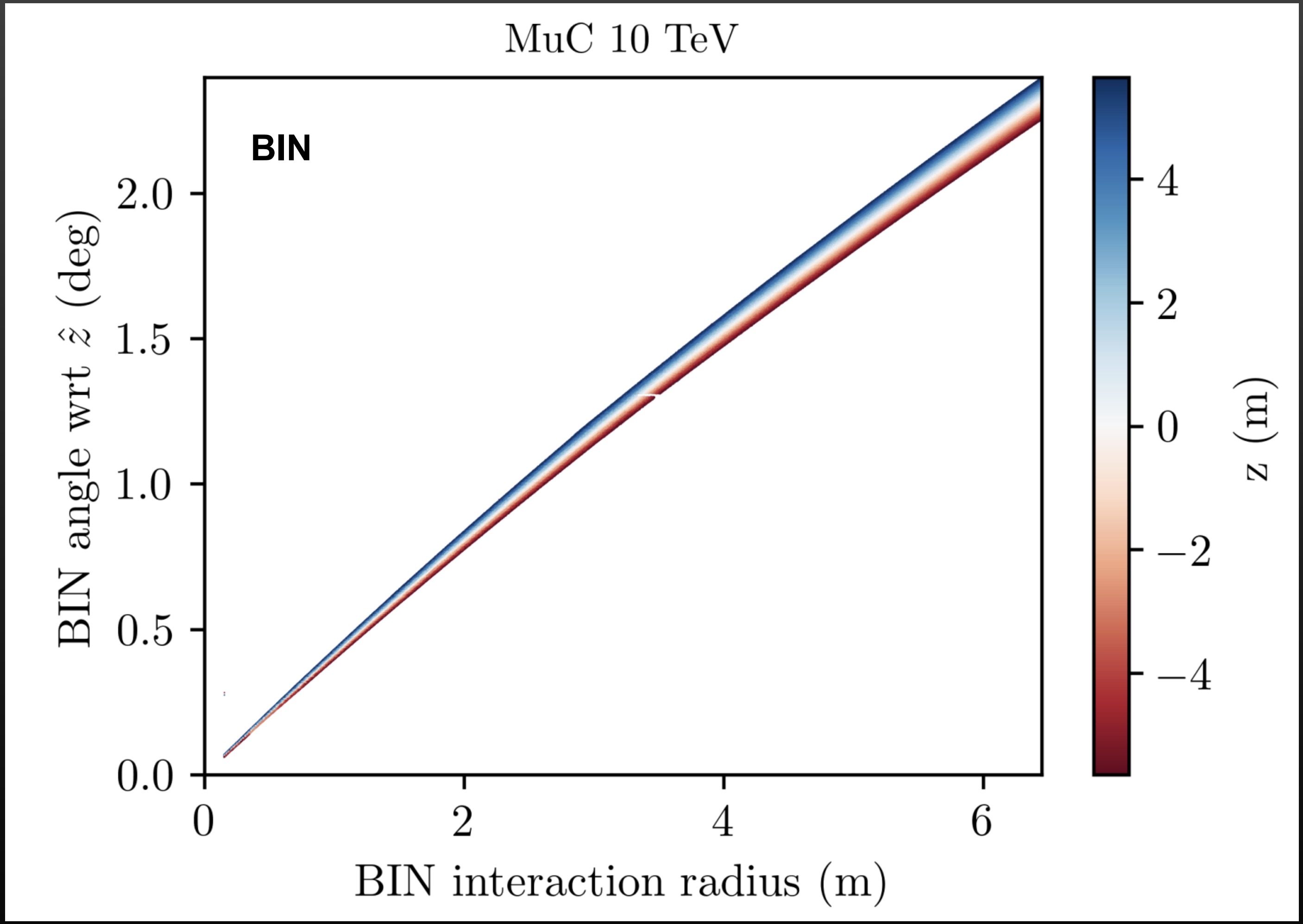


D. Calzolari US Inaugural Muon Collider meeting 2024



BIN Interactions

2) Angles and radial dependence of events



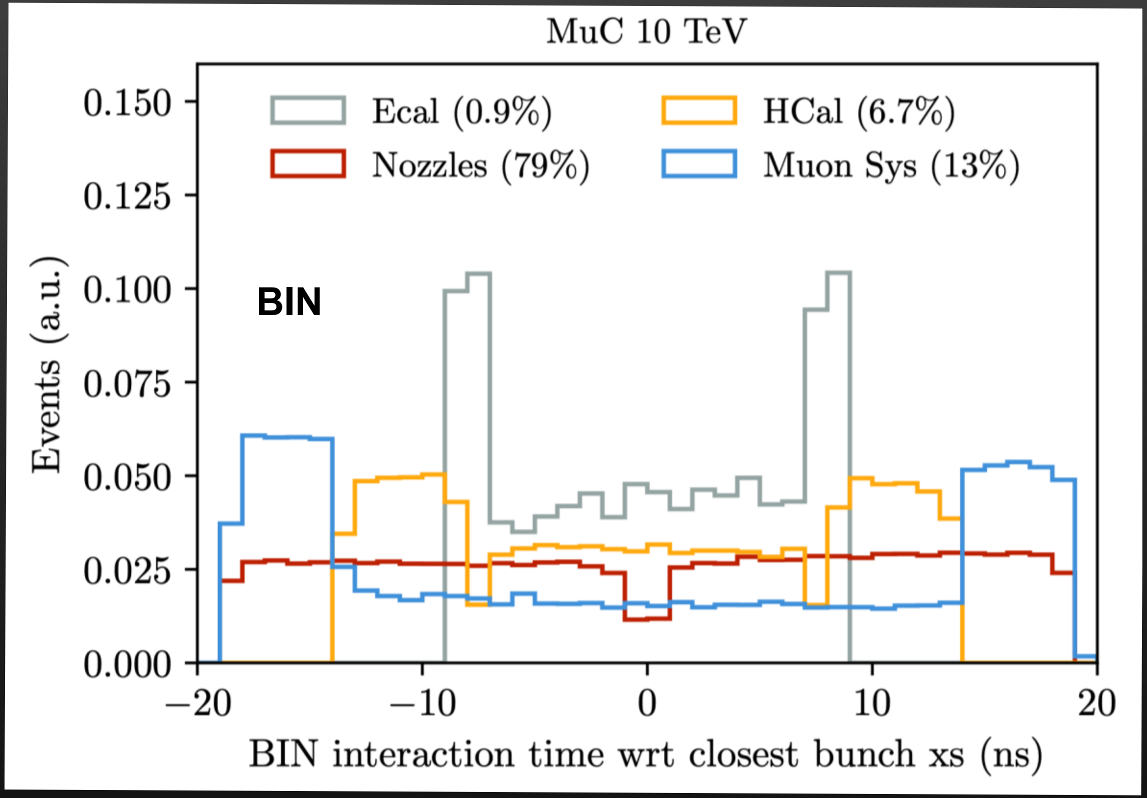
Neutrino scattering is forward (low-Q^2) so CC charged leptons is a good tracer of direction, which is also correlated with where the neutrino came from.

$\langle p_T^\ell \rangle \simeq 37$ 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
3) Timing profile



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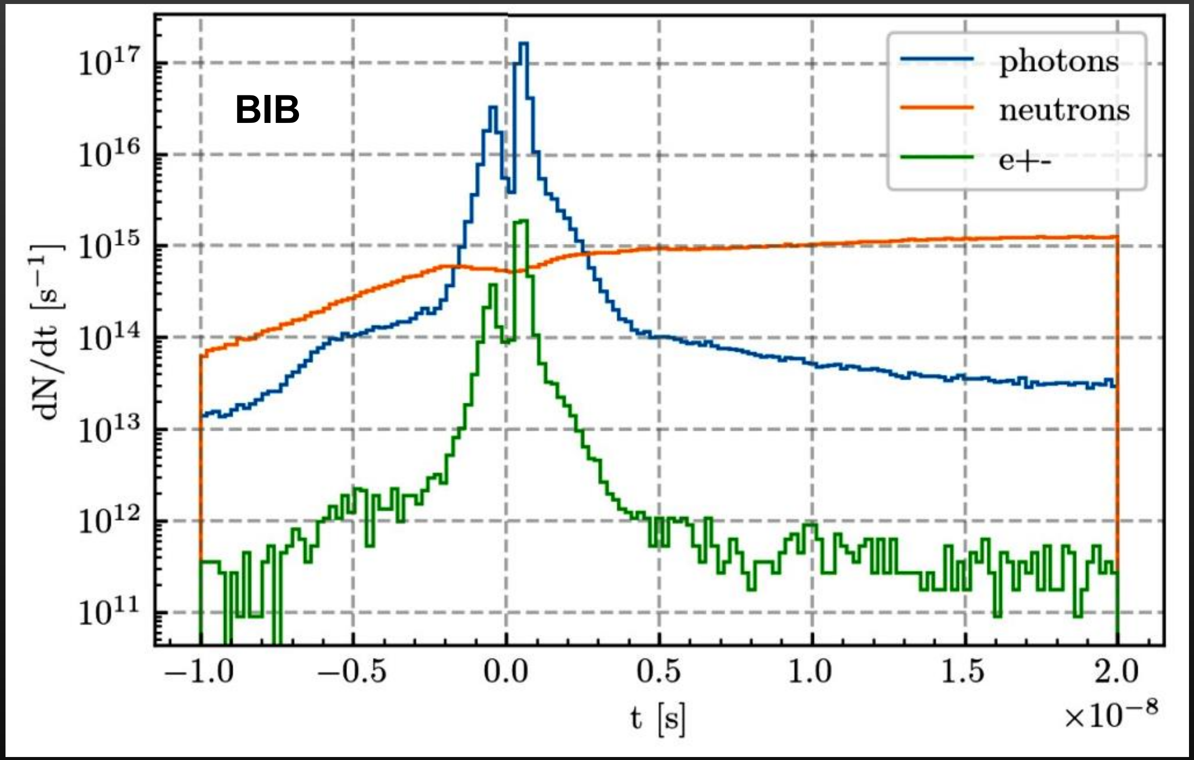
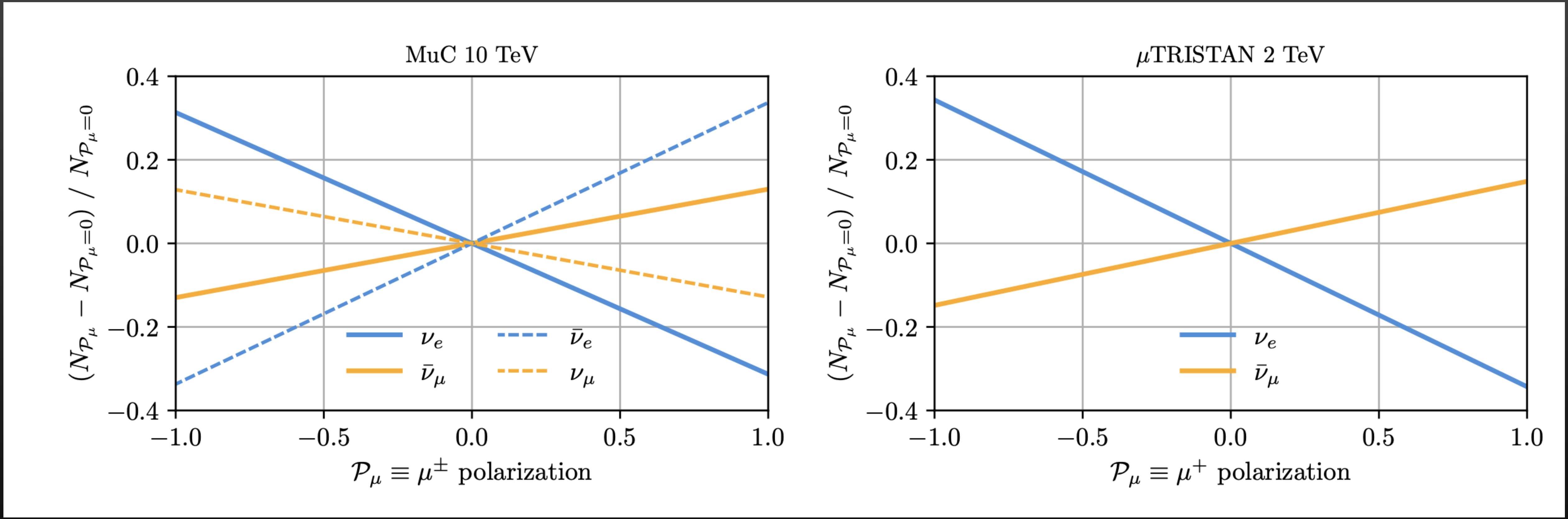


Early events will be better as there will be less BIB and charged particles will cross more detector material on the way out

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

BIN Interactions

4) Dependence on muon beam polarization



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

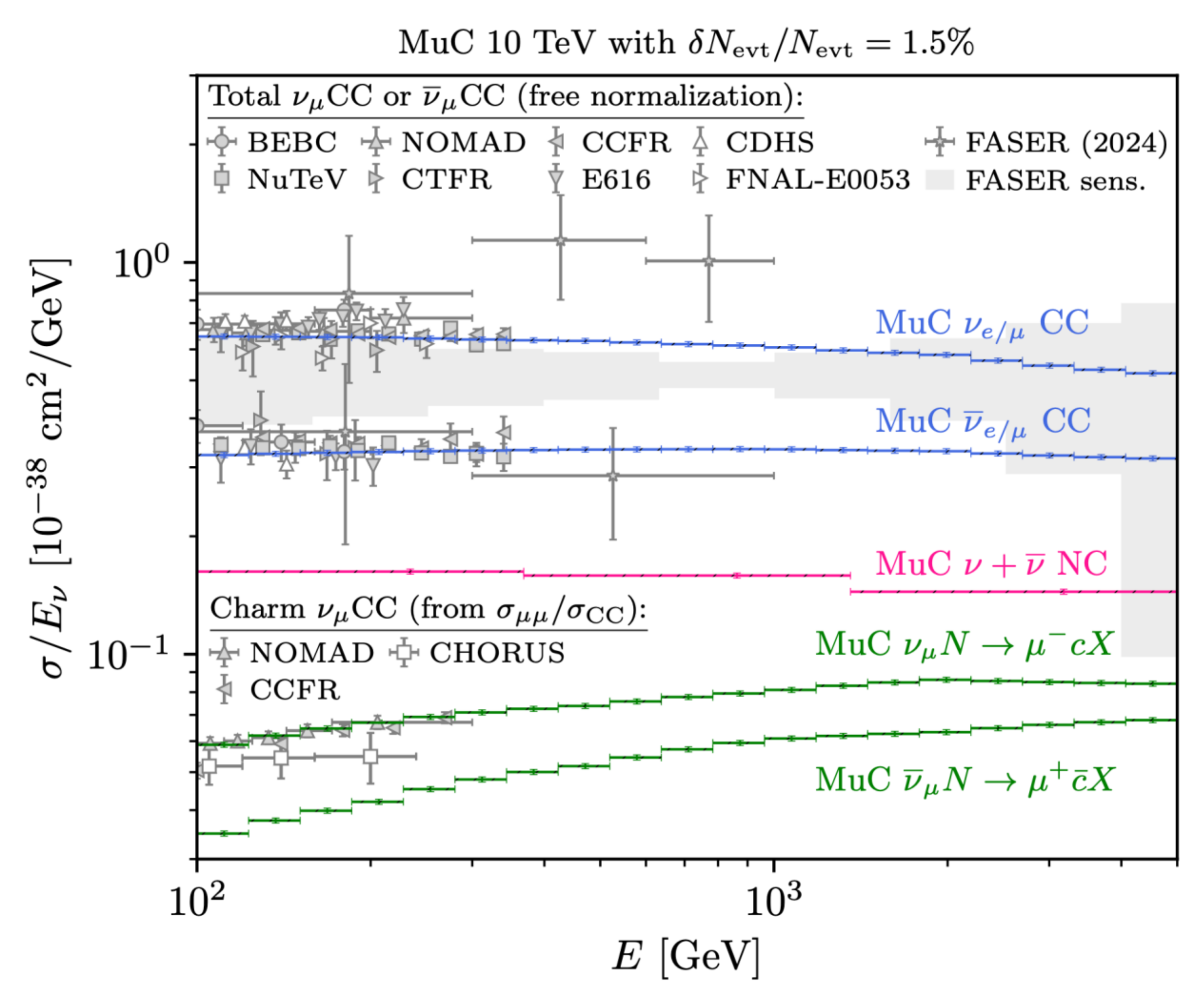
Total rate and differential spectra are very sensitive to the beam polarization.

BIN interactions

Neutrino-nucleus scattering measurement

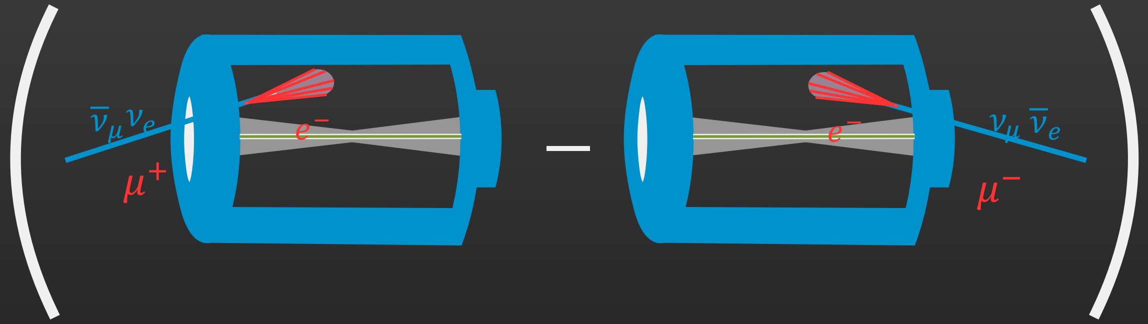
This is what a 1.5% uncertainty on TeV neutrino cross sections would look like:

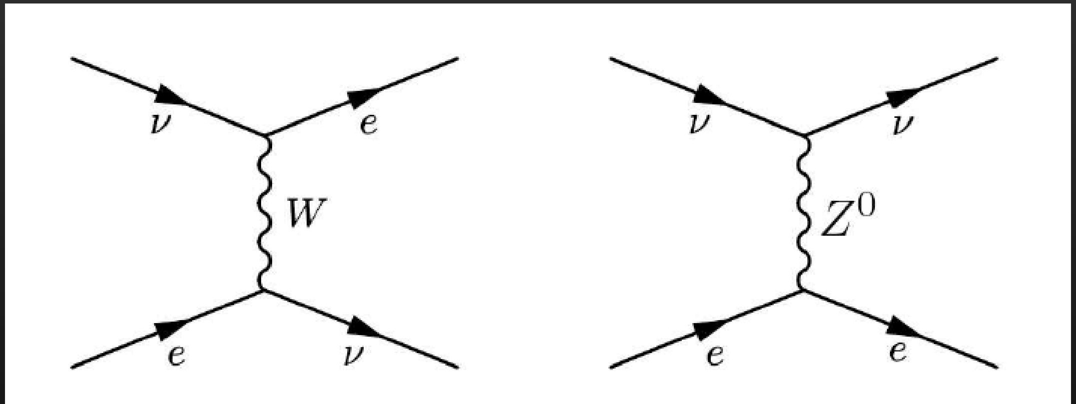
Clearly more works required to understand if feasible at the neutrino slice, but such precision can undoubtedly be achieved with a forward detector if needed.



BIN as precision probes of electroweak sector

Neutrino-electron scattering





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

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

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.

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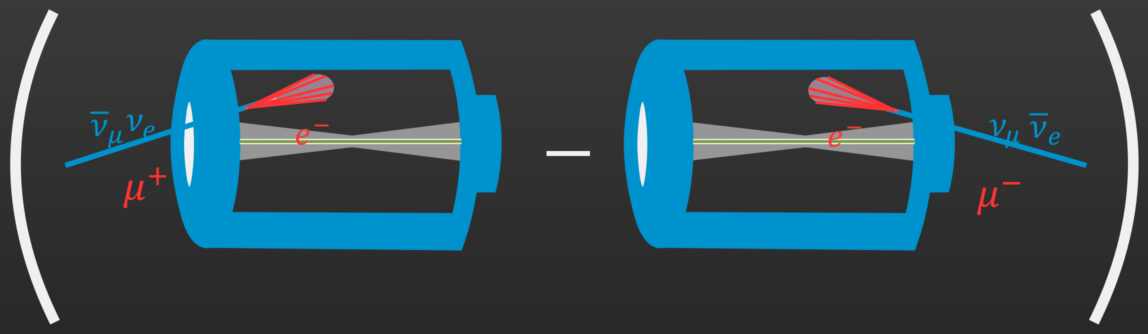

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N^{μ^+}: the sum of $\bar{\nu}_\mu$ and ν_e electron scattering rate from μ^+ beam.

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

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:

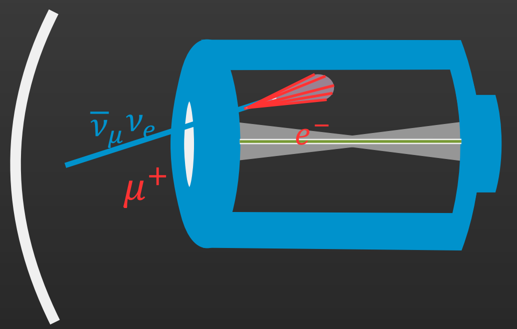
$$\delta R^{\theta_W}_{\nu-e}/R^{\theta_W}_{\nu-e} < 0.20\%$$

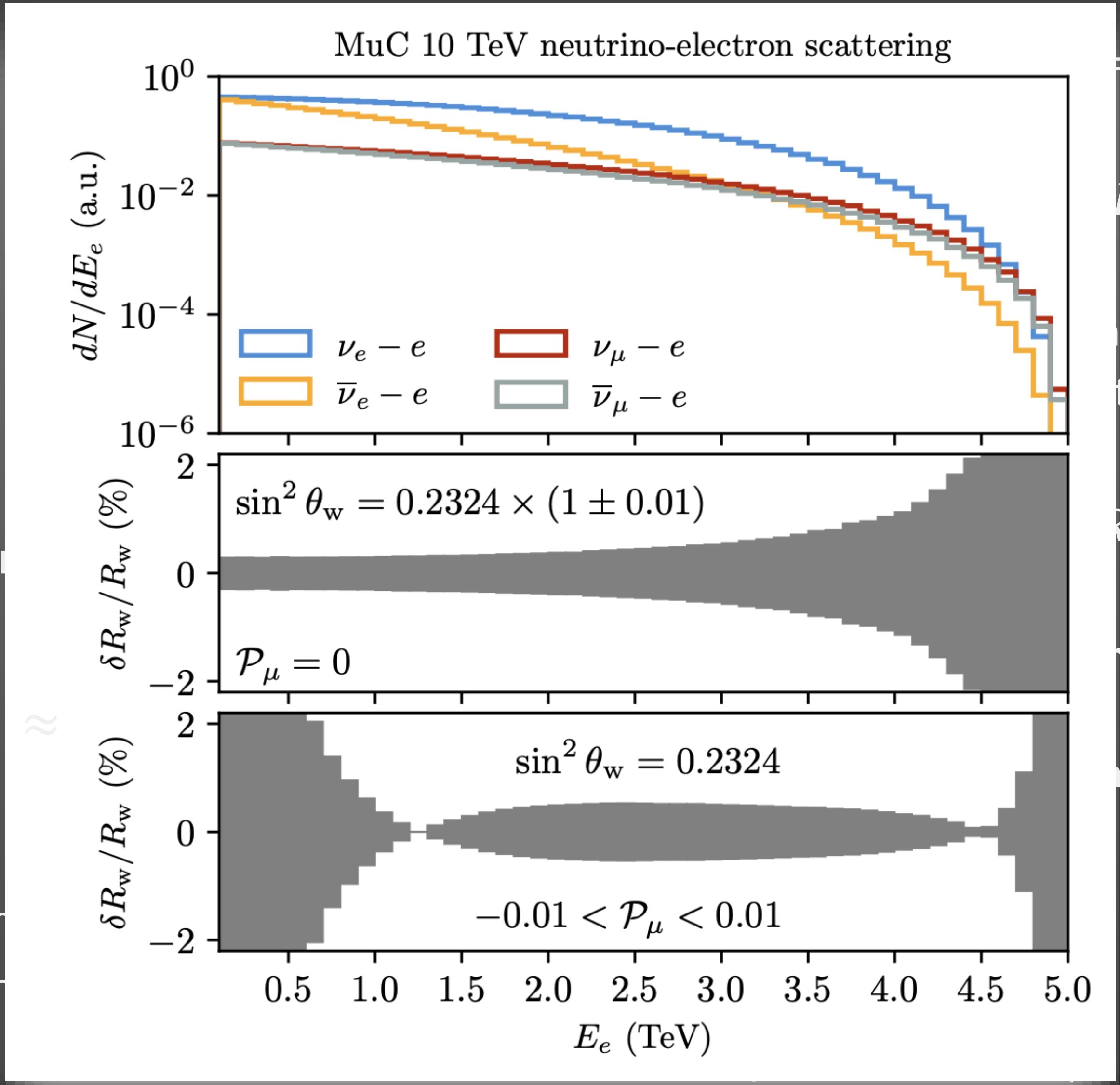
- **May also probe the running of θ_W in the same experiment.**
- **Sub-percent measurement would also measure the neutrino charge radius!**

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

BIN as precision probes of electroweak sector

Neutrino-electron scattering





= 0.2324 ± 0.0083), need:

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

ts:

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

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

$\nu - e$ scattering (A. de Gouvea,

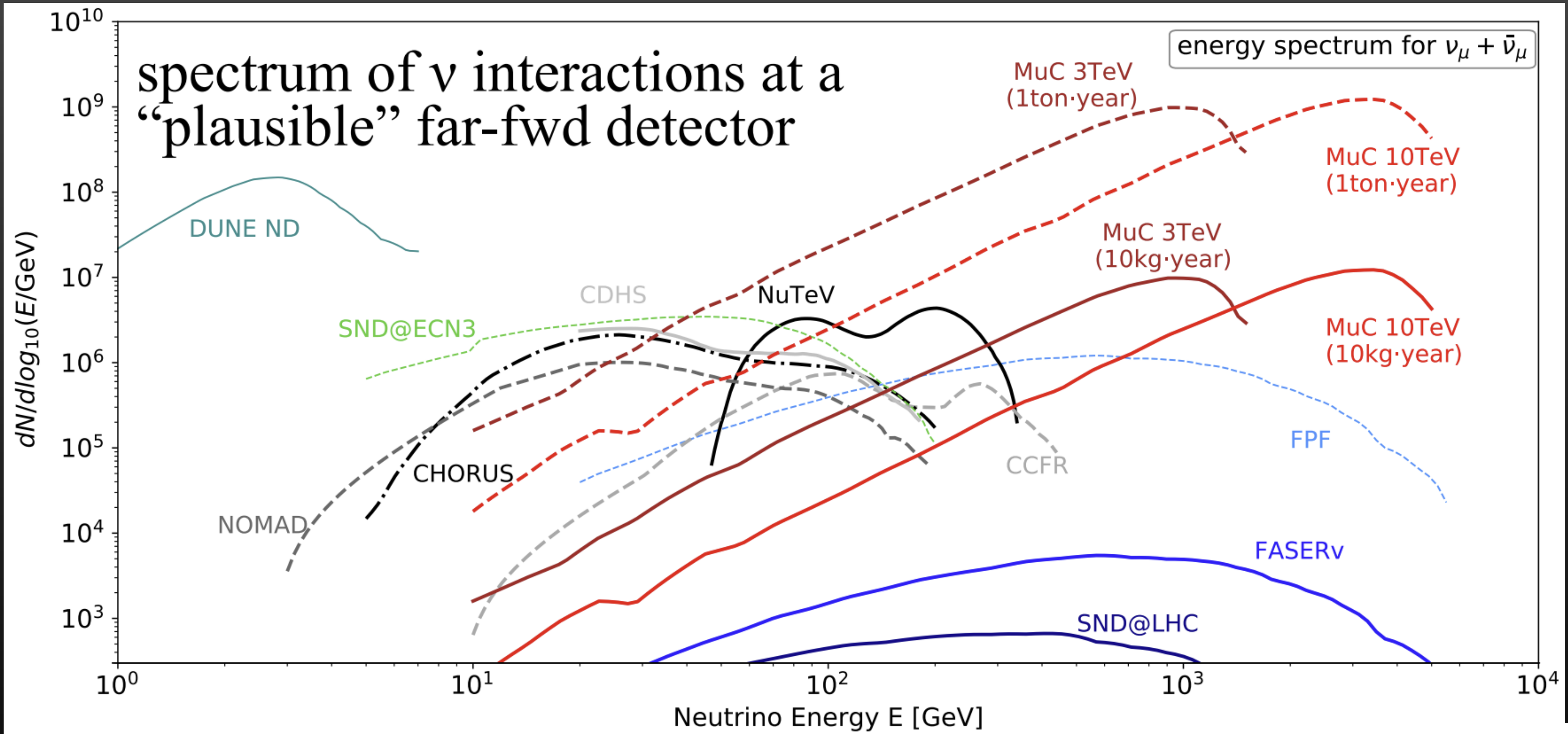
Neutrino Slice Summary

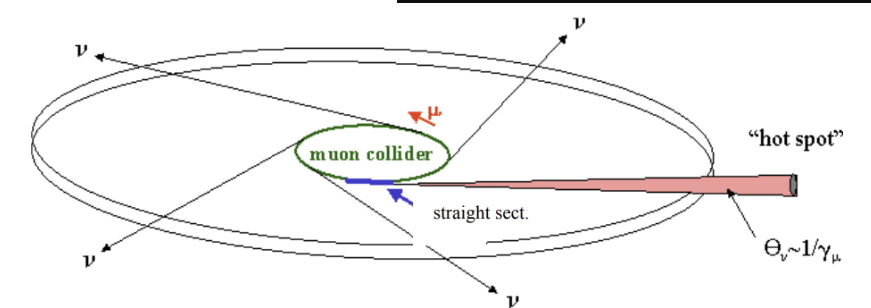
The **neutrino slice from BINs** provides a **new program** at a muon collider detector

- Large rates from a unique neutrino sources:
  - O(1) per collision
  - Help characterize the beam (flux, polarization, radiation monitoring?)
  - Affects energy resolution? How to mitigate it?
- Ultimately, a new way to leverage muon colliders to do:
  - weak scattering precision physics
  - DIS at low-x
  - rare leptonic process
  - new physics searches
- **We need take BINs into account.**

This was a first look into these events, but there is a lot of physics that can be explored.

Muon Beamdump? Muon+Neutrino Beamdump





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

Outside the Box2

Inclusive Higgs with Special Request

Basics:

pp

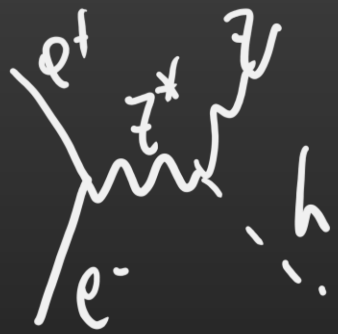
LHC 14 TeV

50 pb

3 ab^{-1}

150 million Higgs

e^+e^-



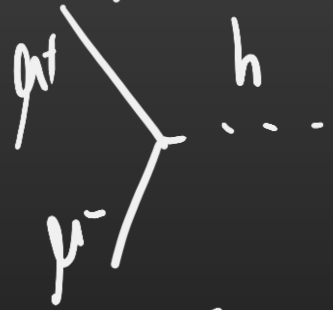
e^+e^- 240~250 GeV

200 fb

5 ab^{-1}

1 million Higgs

$\mu^+\mu^-$



$\mu^+\mu^-$ 125 GeV

22 pb × 65%

5~20 fb^{-1}

0.07 ~0.28 million Higgs

$\mu^+\mu^-$

$\mu^+\mu^-$ 10 TeV

~ 1 pb

10 ab^{-1}

~10 million Higgs

Basics: VBF Higgs

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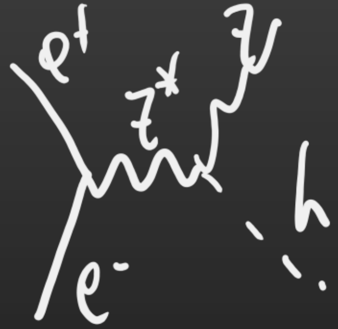

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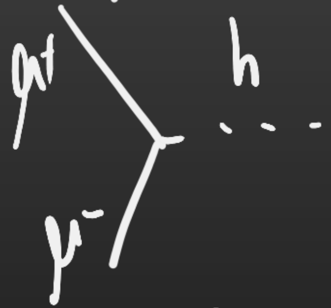

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Measurements to be interpreted

Observables at the colliders are the cross sections, a convolution of PDF, hard scattering, parton shower, detector response …

$$\kappa_i = \frac{g_i}{g_i^{SM}}, \kappa_\Gamma = \frac{\Gamma_{tot}}{\Gamma_{tot}^{SM}}$$

For the hard scattering*:

$$\sigma(i \to H \to j) \propto \frac{\Gamma_i \Gamma_j}{\Gamma_{tot}} \propto \frac{\kappa_i^2 \kappa_j^2}{\kappa_\Gamma}$$

All exclusive channels can be parametrized this way, simple extension possible for more channels/observables.

*zero-width approximation, Higgs width 10^{-5} of its mass, in general valid. Violations (% level correction) see Campbell, Carena, Harnik, ZL, PRL 18'

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For the hard scattering:

$$\sigma(i \to H \to j) \propto \frac{\Gamma_i \Gamma_j}{\Gamma_{tot}} \propto \frac{\kappa_i^2 \kappa_j^2}{\kappa_\Gamma}$$

If $\kappa_\Gamma = \kappa_i^2 \kappa_j^2$, the observed rates do not change.

We **cannot** measure Higgs couplings strength, without some inputs to break this flat direction!

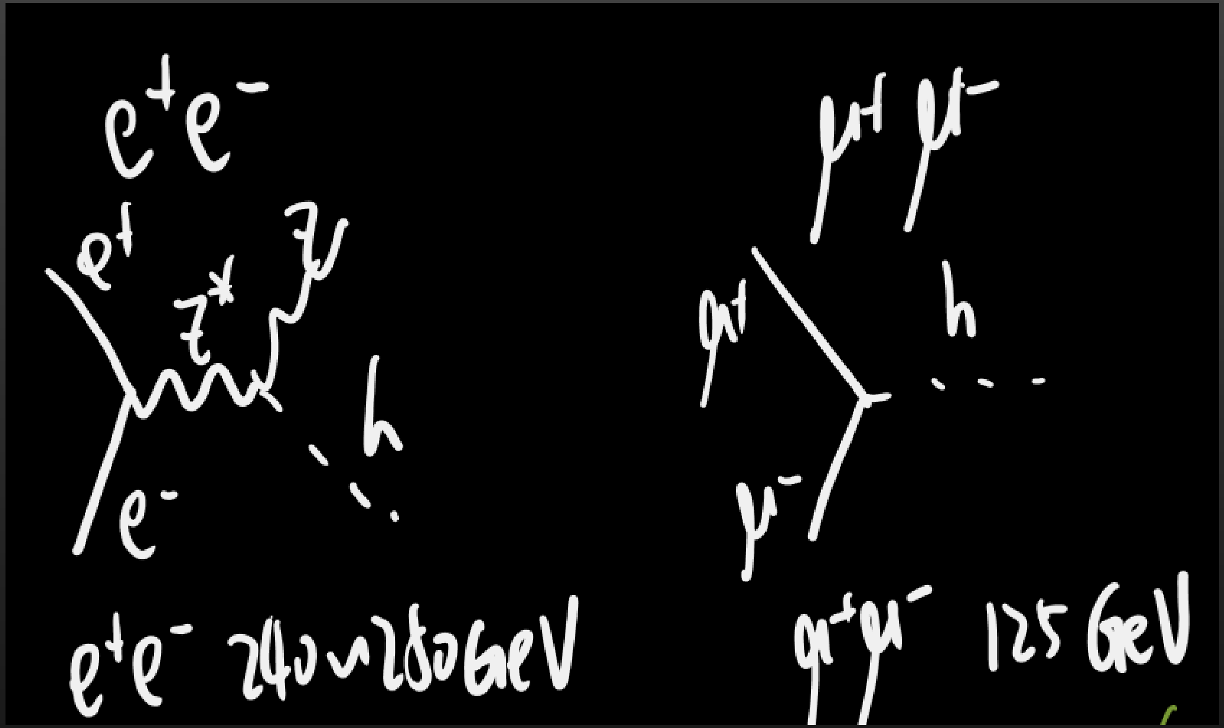
- All Kappas are positively correlated with the total width (from the point of cross sections);
- The naïve scaling of $\kappa_{tot} \propto \kappa_{i,f}^2$, does not reflect this flat direction, one needs additional particle width to enter;
- In principle, a given specific BSM model might have more constraints to all stronger constraints, but generally, this direction is unconstrained that leads to a bad projection of sensitivity (without the correlation matrix).

Is the Higgs fundamental?

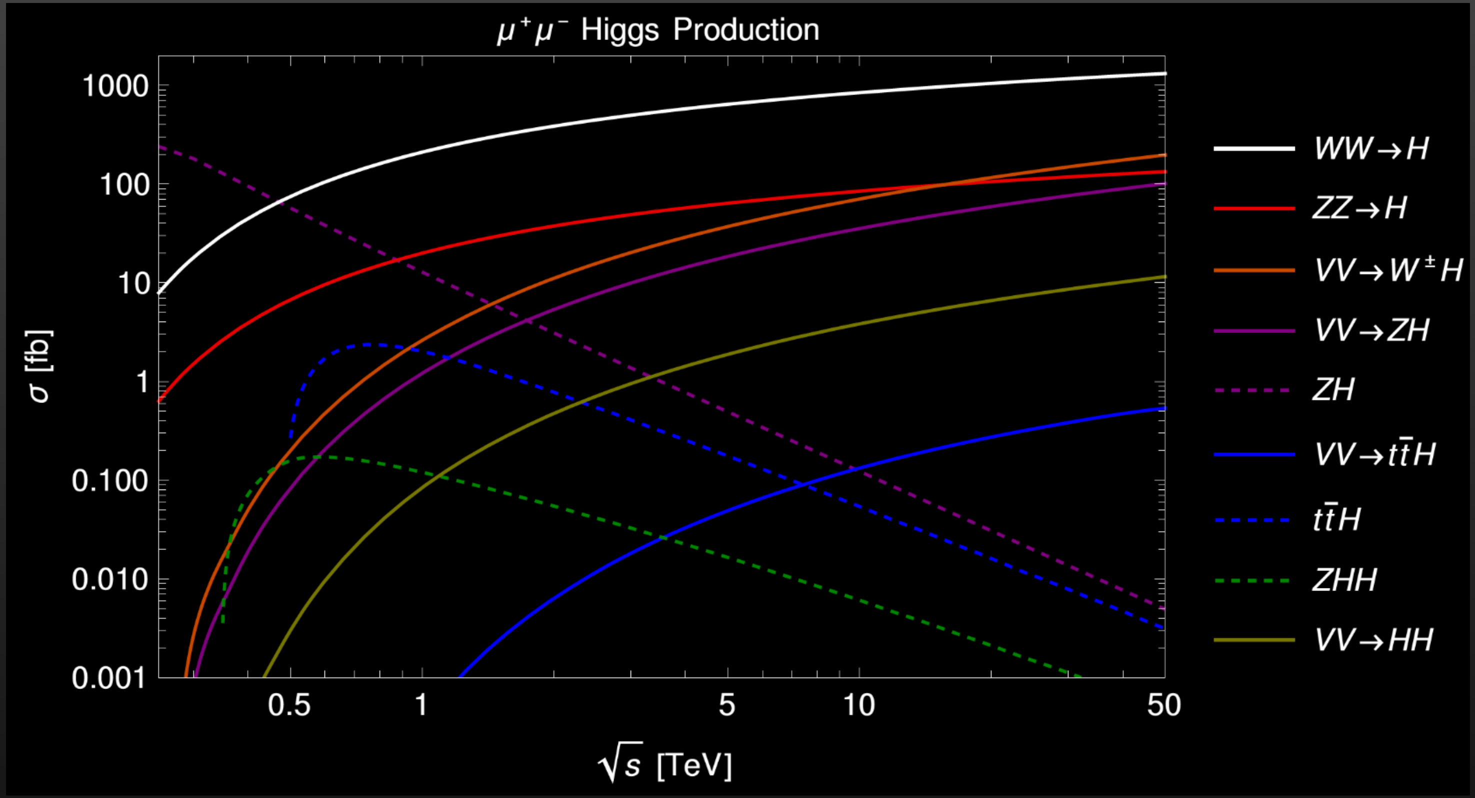
Measurements to be interpreted

Future Higgs factories, e.g., can solve this issue by inclusive Higgs measurement or lineshape scan.

- Inclusive rate: $\sigma(i \to H) = \sum_j \sigma(i \to H \to j) \propto \sum_j \frac{\Gamma_i \Gamma_j}{\Gamma_{tot}} = \Gamma_i$
- Lineshape scan: break the parameterization $\sigma(i \to H \to j) \propto \frac{\Gamma_i \Gamma_j}{\Gamma_{tot}^2}$

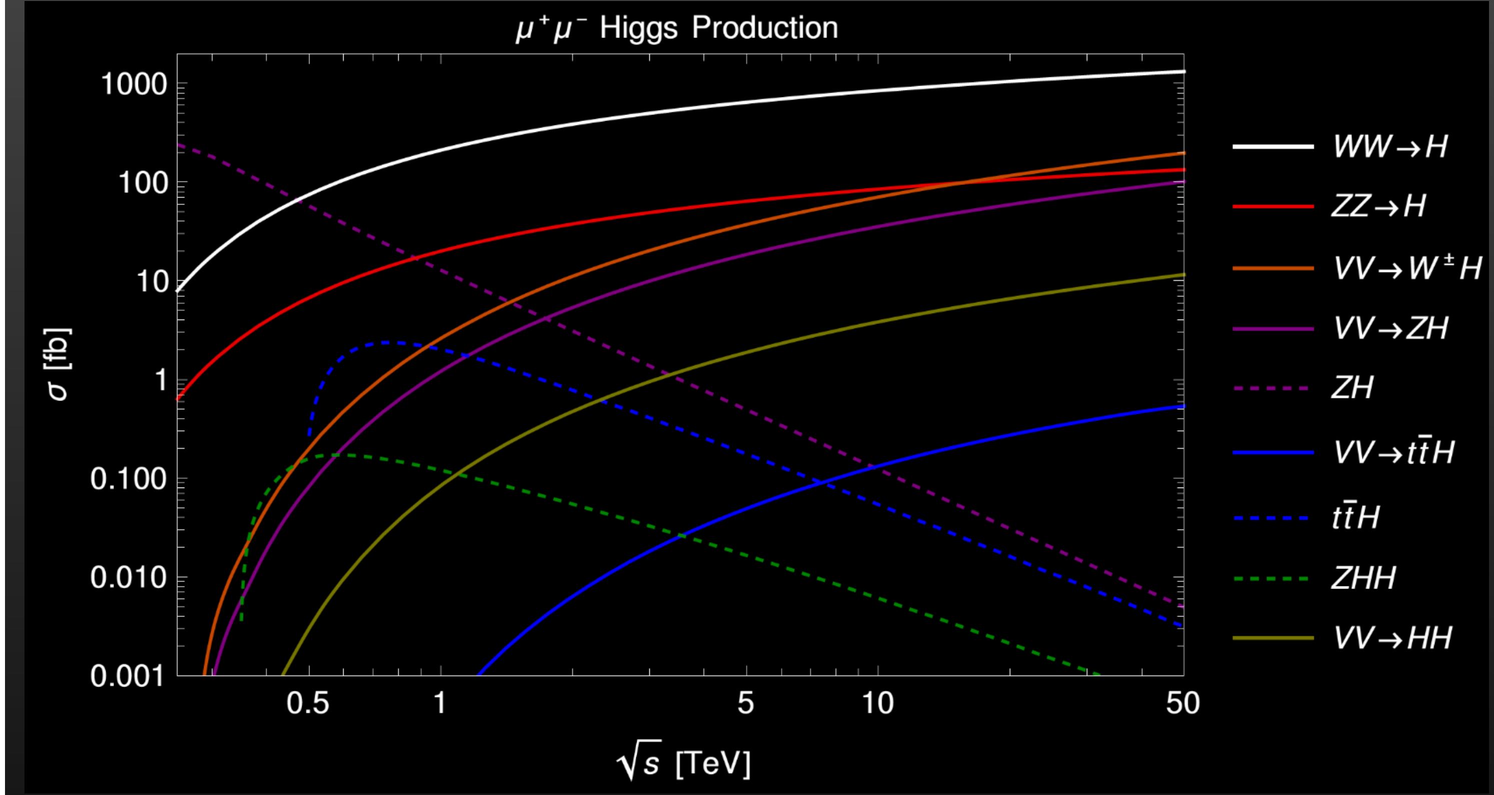


Baseline Higgs Measurements



Baseline Higgs Measurements

Production	Decay	$\Delta\sigma/\sigma$ (%) 3 TeV	10 TeV
WW-fusion	bb	0.84	0.24
	cc	14	4.4
	gg	4.2	1.2
	$\tau^+\tau^-$	4.5	1.3
	$WW^*(jj\ell\nu)$	1.8	0.50
	$WW^*(4j)$	5.7	1.4
	$ZZ^*(4\ell)$	48	13
	$ZZ^*(jj\ell\ell)$	12	3.5
	$ZZ^*(4j)$	67	16
	$\gamma\gamma$	7.7	2.1
	$Z(jj)\gamma$	73	20
	$\mu^+\mu^-$	43	11
ZZ-fusion	bb	7.9	2.2
	bb, $(N_\mu \geq 2)$	2.6	0.77
	$WW^*(4j)$	49	12
	$WW^*(4j)$, $(N_\mu \geq 2)$	17	4.3
tth	bb	61	53

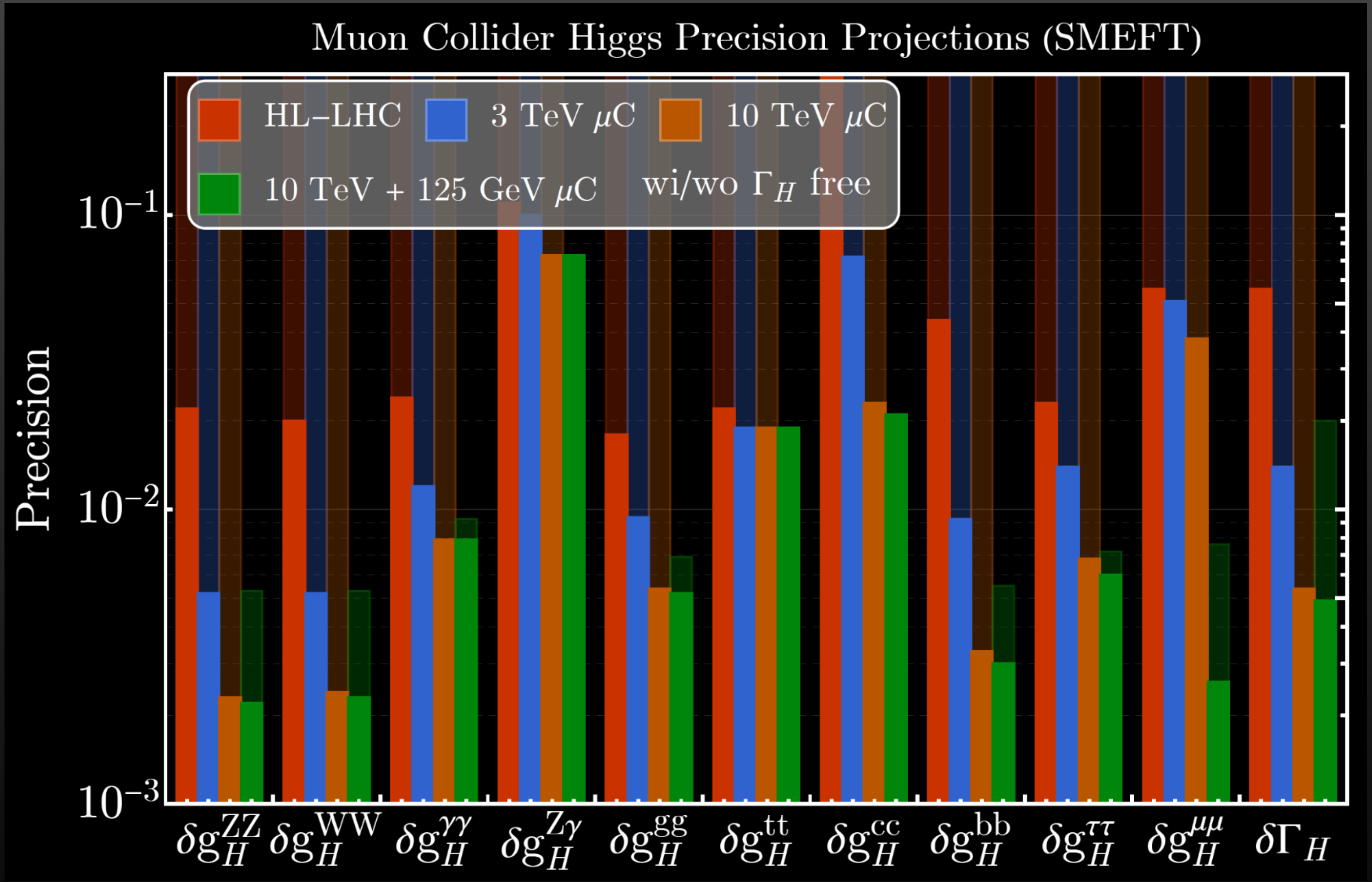


M. Forslund, P. Meade, 2203.09425

See also discussion in
Muon Smasher's Guide, 2103.14043
T. Han, Y. Ma, K.-P. Xie, 2007.14300;
Costanini, De Lillo, Maltoni, Mantani, Mattelaer, 2005.10289

How well in Higgs precision?

- Without absolute coupling measurement (equivalently, a width determination), we cannot pin down the overall size of the Higgs coupling.



The conclusion in this paper holds on any basis (kappa, SMEFT+exotic, etc.) with width as an effective free parameter.

[2209.01318] Muon Collider Forum Report

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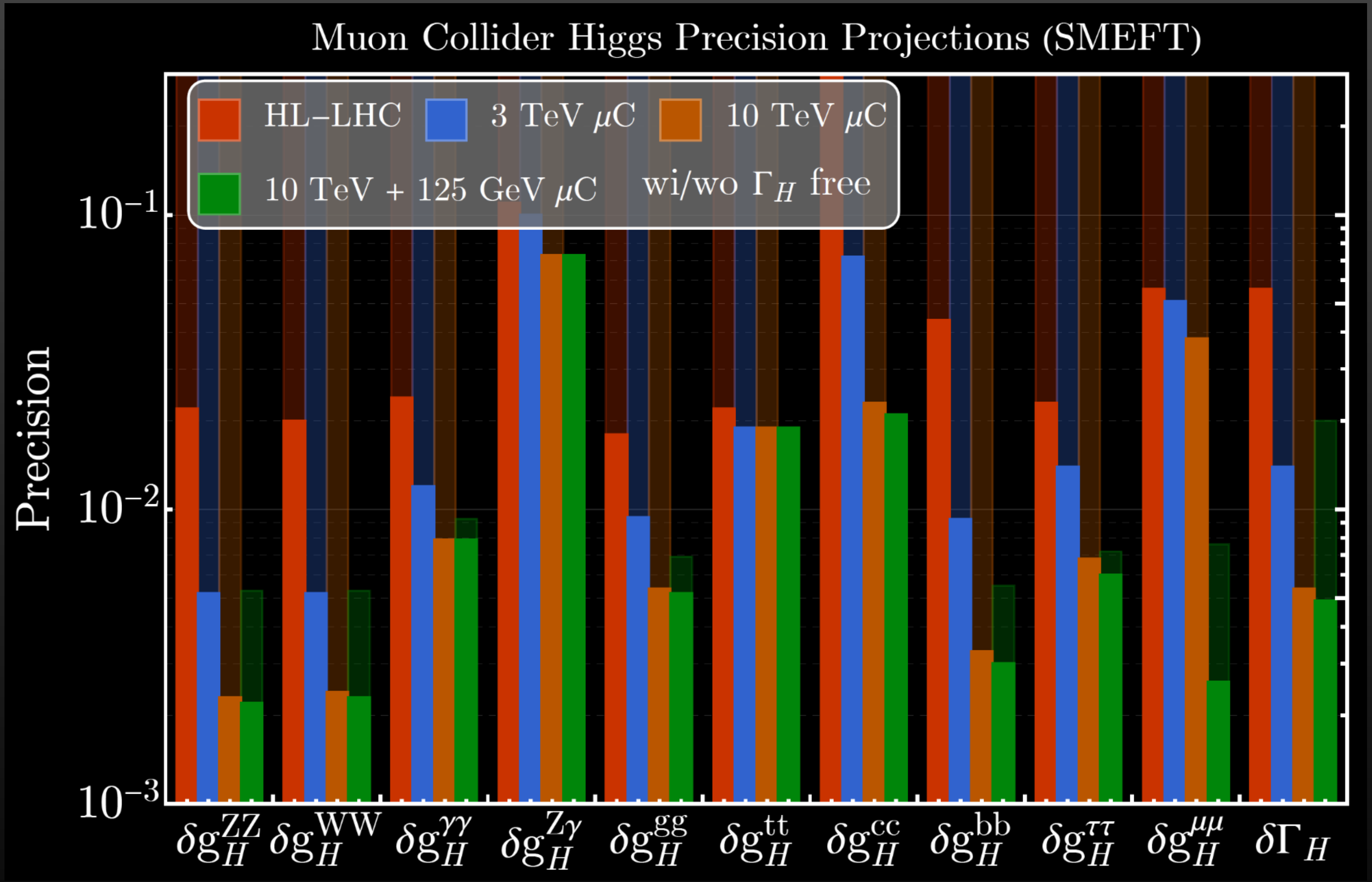
    - Look at the light shaded results with width being a free parameter



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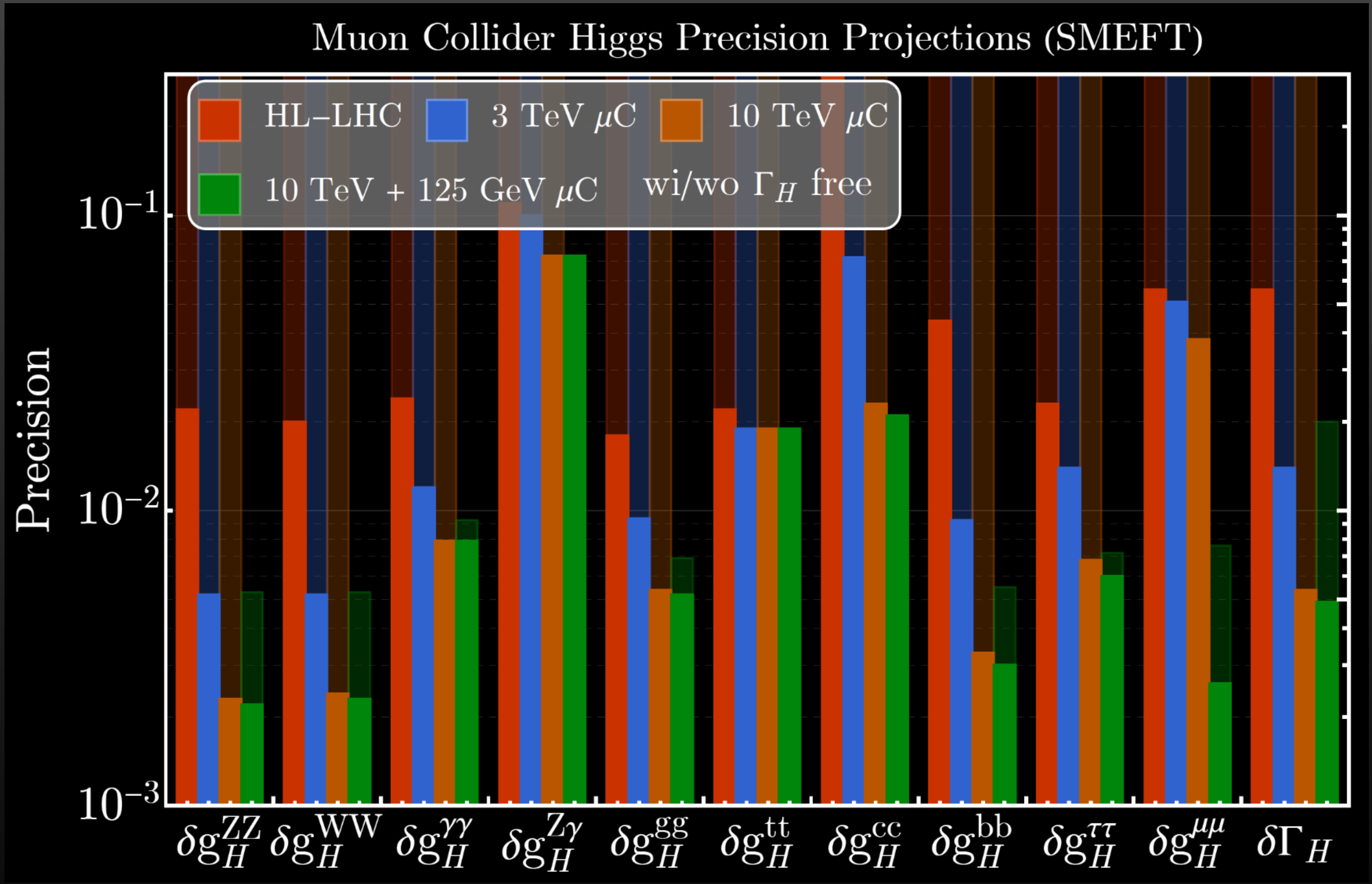
- High Energy Muon Collider seems to be handicapped in Higgs measurements (similar to hadron colliders).



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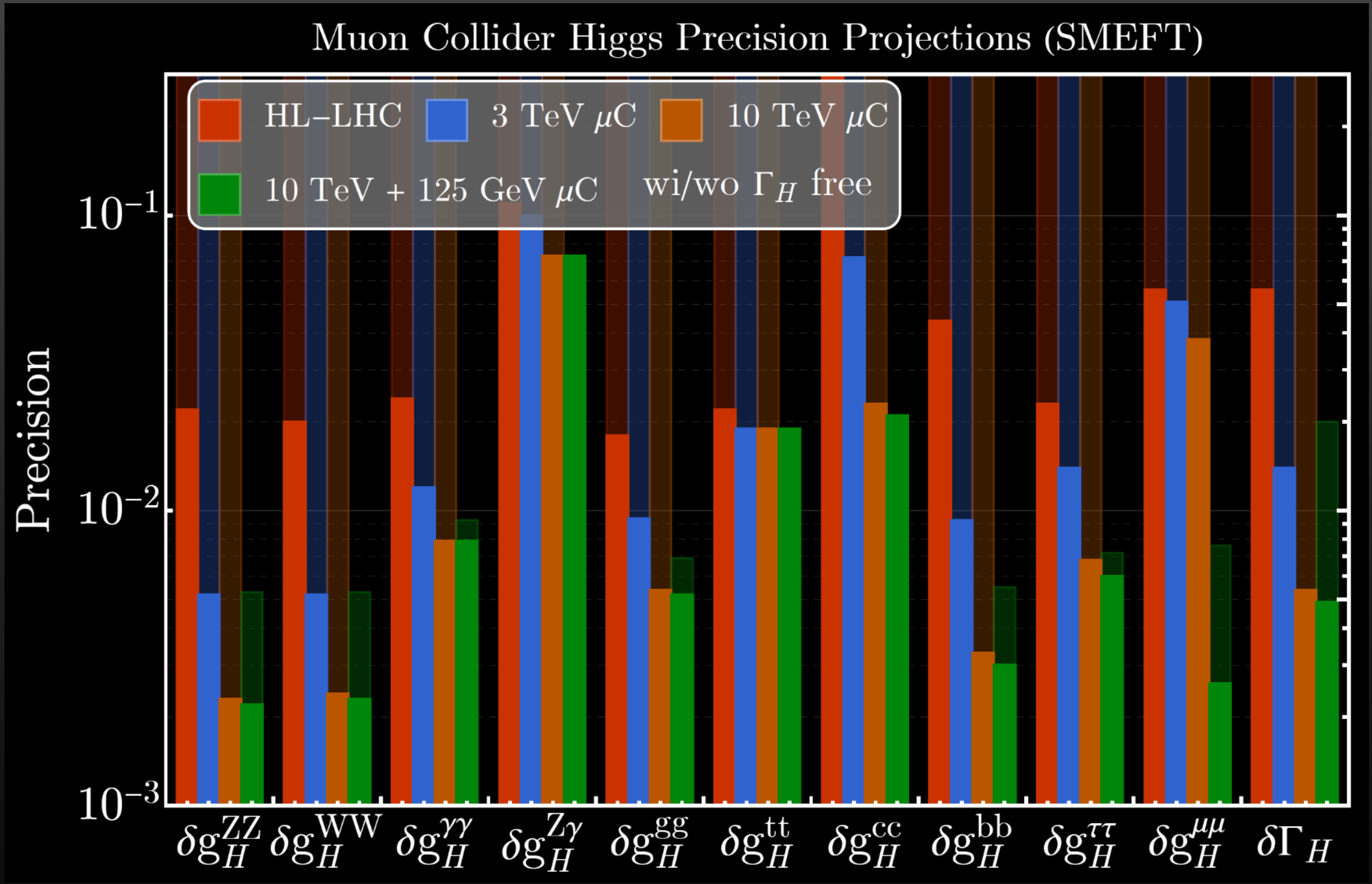
- High Energy Muon Collider seems to be handicapped in Higgs measurements (similar to hadron colliders).

- We propose a new search using forward muons.



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[2209.01318] Muon Collider Forum Report

Inclusive Higgs rate from ZZ fusion

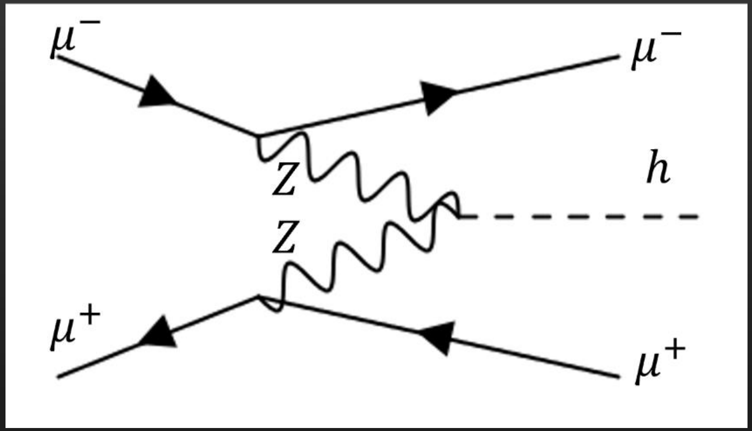
Forward muon coverage: $2.5 < \eta(\mu) < 4, 6, 8$

P.R. Li, ZL, K.F. Lyu, 2401.08756

$$p_h = (\sqrt{s}, 0,0,0) - p_{\mu^+} - p_{\mu^-}$$

$$m_h^2 = \left[(\sqrt{s}, 0,0,0) - p_{\mu^+} - p_{\mu^-}\right]^2$$

Recoil mass of dimuon

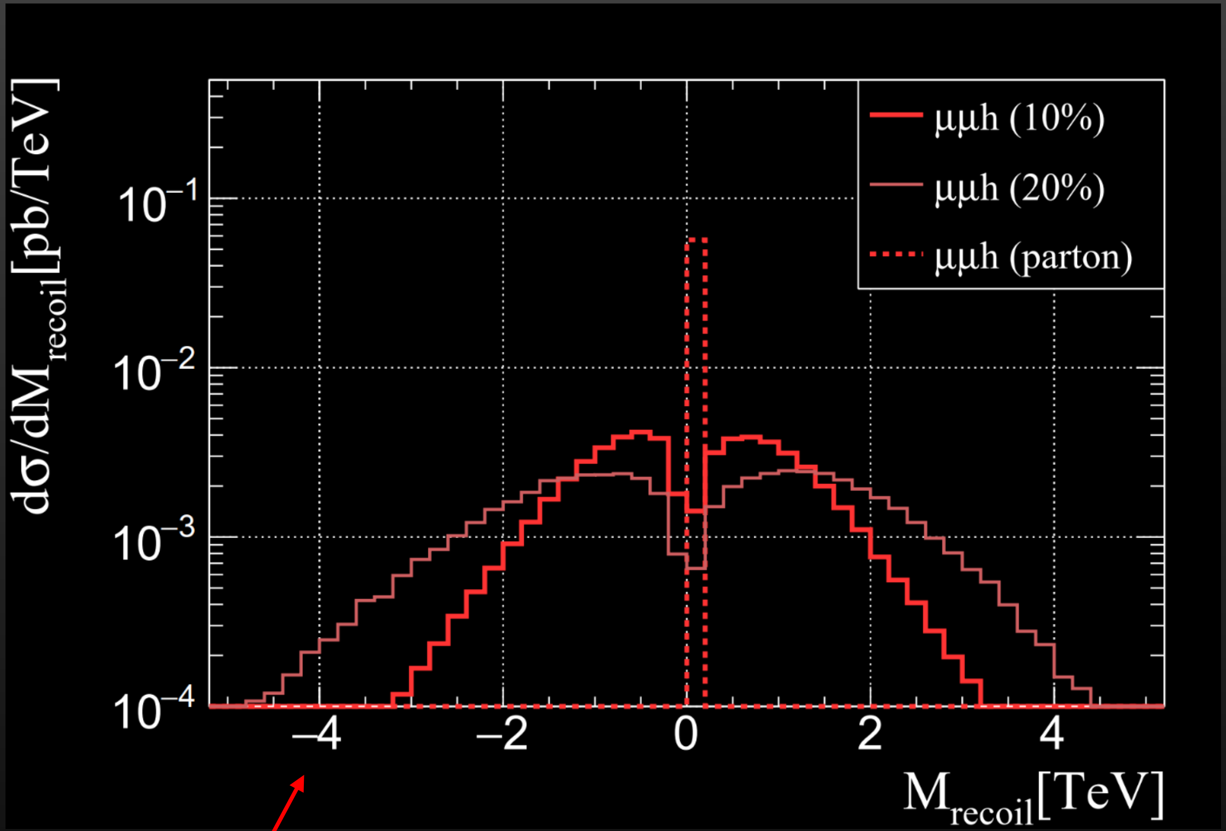


This subleading Higgs production channel, once tagged, does not rely on the detection of Higgs decay channel.

Inclusive rate: $\sigma(i \to H) = \sum_j \sigma(i \to H \to j) \propto \sum_j \frac{\Gamma_i \Gamma_j}{\Gamma_{tot}} = \Gamma_i$

Inclusive Higgs rate from ZZ fusion

Due to the uncertainty of high energy measurement, the smearing effect dominate the recoil mass distribution.

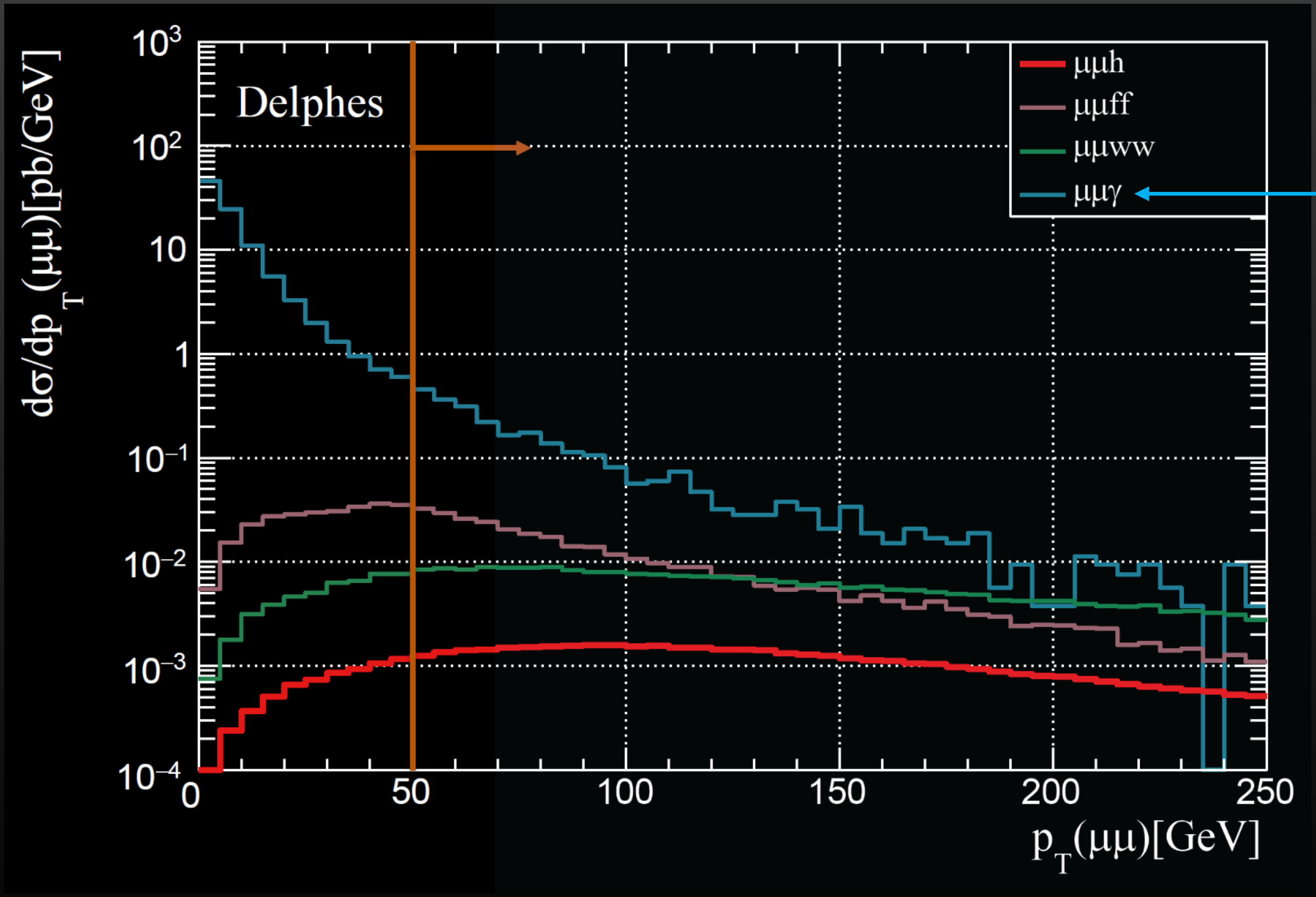


Fast detector simulation using Delphes.

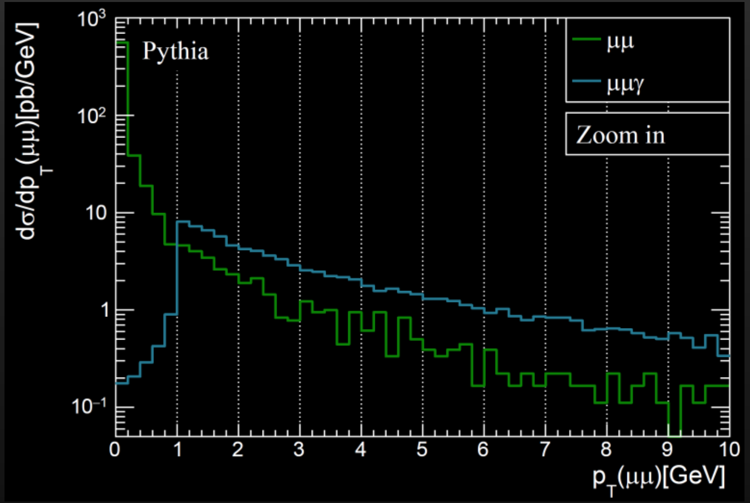
$\left[\left(\sqrt{s},0,0,0\right)-p_{\mu^+}-p_{\mu^-}\right]^2<0$

Signal vs. Background $(\sqrt{s} = 10\ \mathrm{TeV})$

Require $p_T(\mu\mu) > 50\ \mathrm{GeV}$

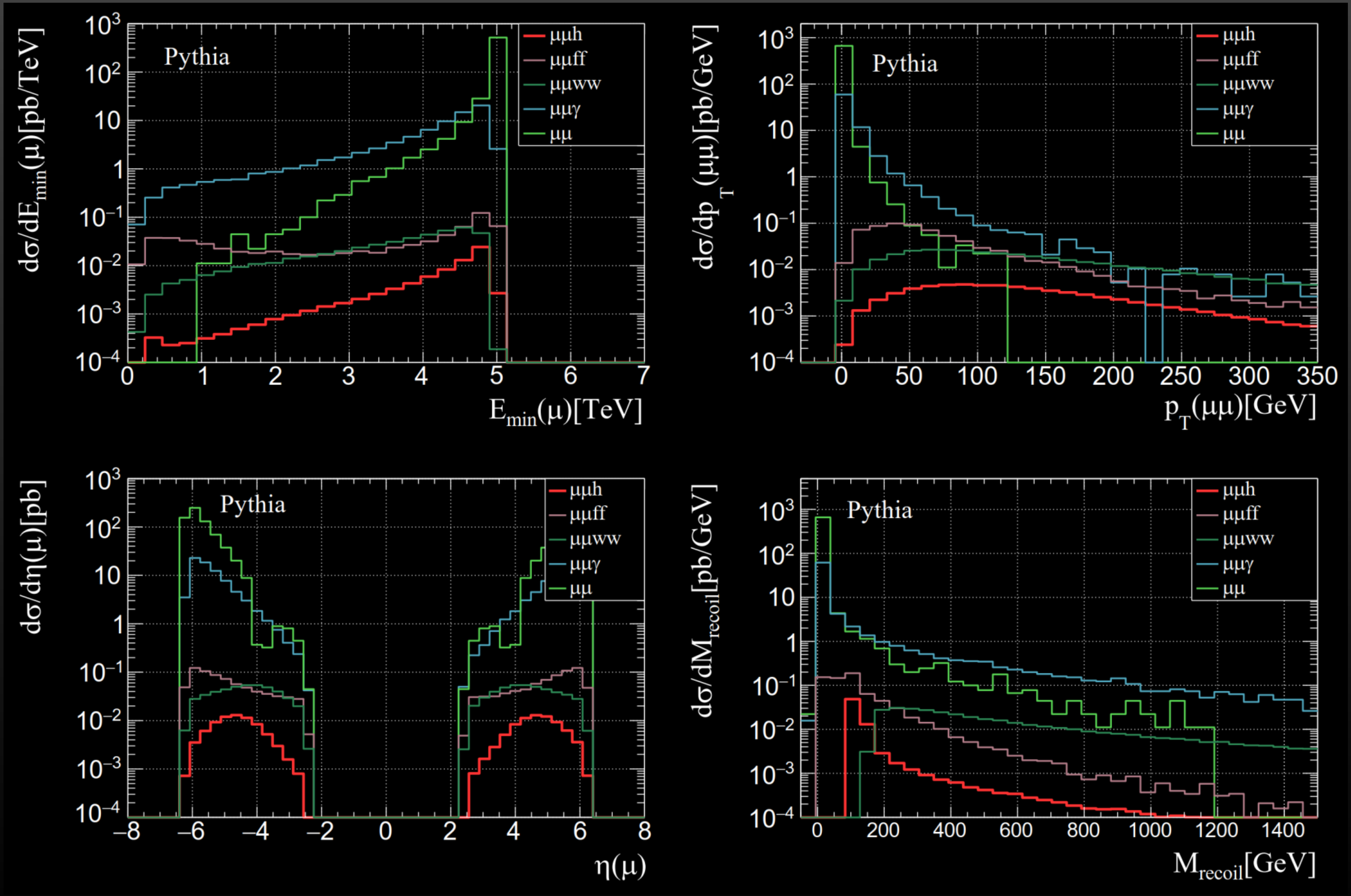


Merging $\mu\mu \to \mu\mu$ and $\mu\mu \to \mu\mu\gamma$



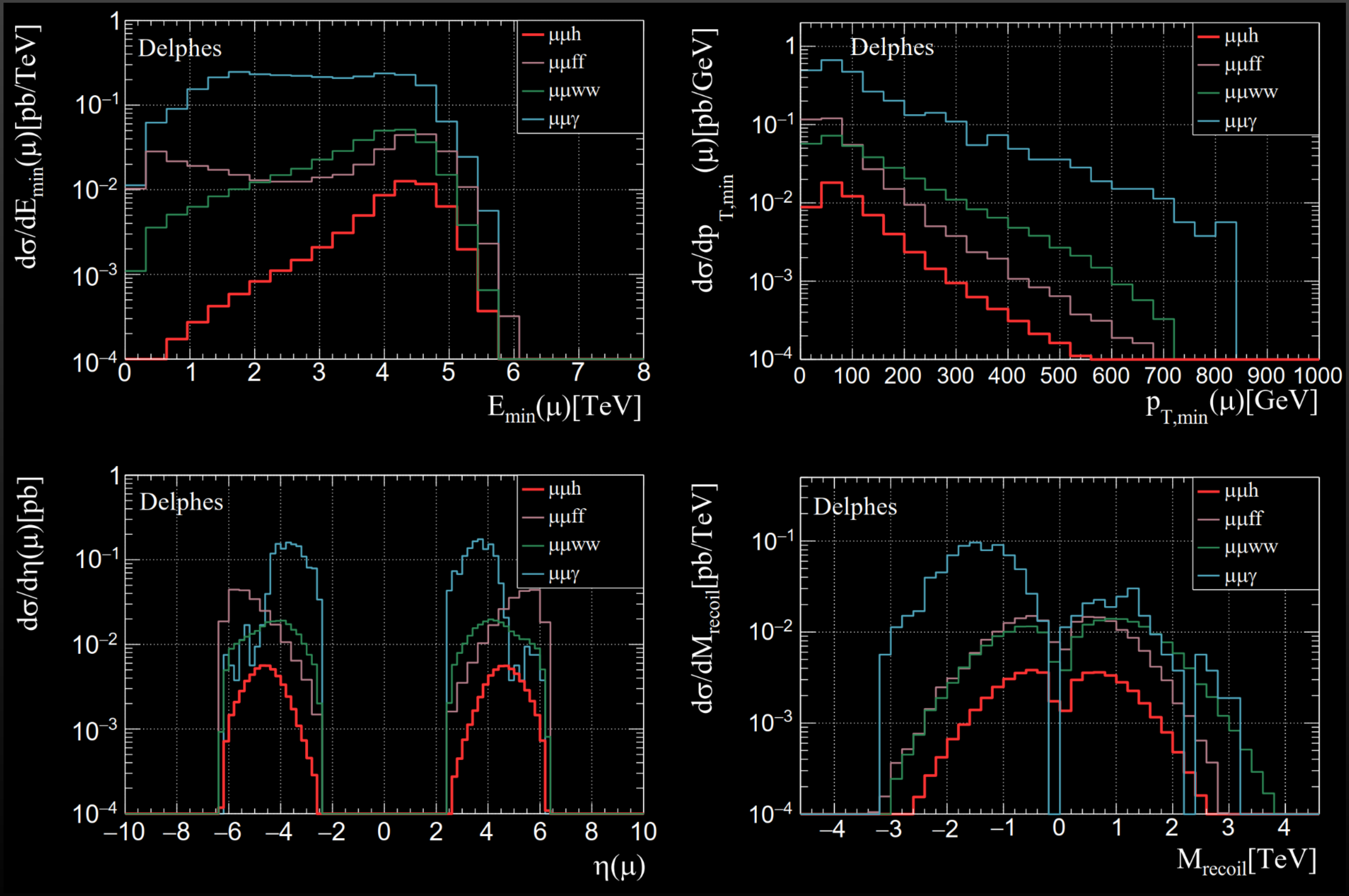
Also see a similar treatment in Higgs invisible study, Ruhdorfer, Salvioni, Wulzer, 2303.14202

Other relevant distributions



For the signal muons, the typical eta is around 5. Dominant background is more forward.

Other relevant distributions (reconstruction)



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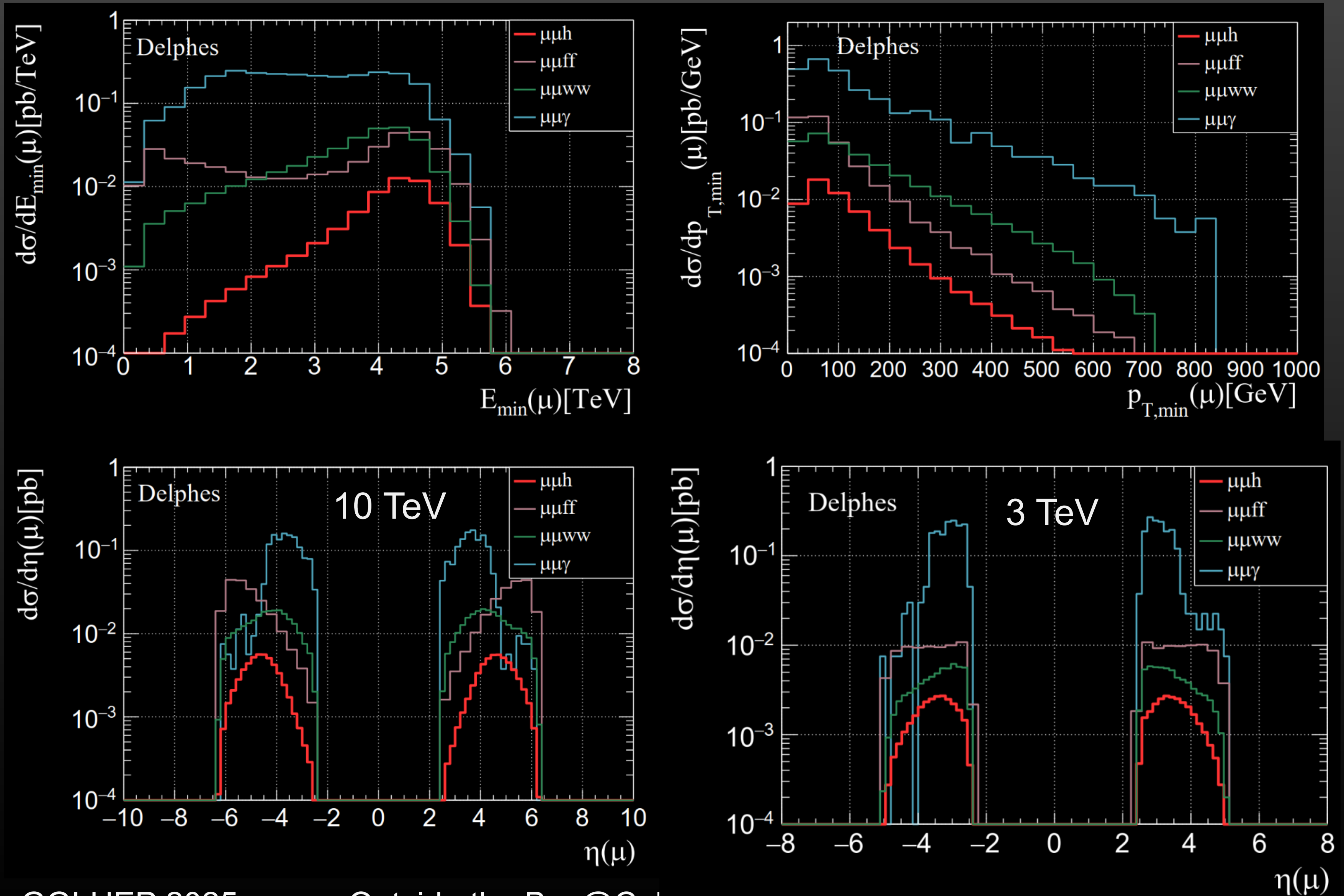

For the signal muons, the typical eta is around 5. Dominant background is more forward.

Sensitivity

Process	Pre-selection	$p_T(\mu\mu) > 50$ GeV	$E(\mu) > 3000$ GeV & $p_{T,\min}(\mu) < 300$ GeV
$\mu^+\mu^- \to \mu^+\mu^- h$	73.3%	65.7%	56.4% (0.0489 pb)
$\mu^+\mu^- \to \mu^+\mu^- \gamma$	13.1%	0.38%	0.12% (0.906 pb)
$\mu^+\mu^- \to \mu^+\mu^- f\bar{f}$	8.13%	4.69%	2.58% (0.199 pb)
$\mu^+\mu^- \to \mu^+\mu^- W^+W^-$	40.0%	34.9%	22.0% (0.207 pb)

10 TeV

Benchmark	$\lvert\eta(\mu)\rvert < 4$	$\lvert\eta(\mu)\rvert < 6$	$\lvert\eta(\mu)\rvert < 8$
$\Delta\sigma/\sigma$	15%	0.75%	0.74%

Sensitivity

3 TeV

Benchmark	$\lvert\eta(\mu)\rvert < 4$	$\lvert\eta(\mu)\rvert < 6$	$\lvert\eta(\mu)\rvert < 8$
$\Delta\sigma/\sigma$	6.2%	3.9%	3.9%

Covering up to eta of 6 is critical for 10 TeV.

10 TeV

Benchmark	$\lvert\eta(\mu)\rvert < 4$	$\lvert\eta(\mu)\rvert < 6$	$\lvert\eta(\mu)\rvert < 8$
$\Delta\sigma/\sigma$	15%	0.75%	0.74%

Now High Energy Muon Collider is a full-fledged Higgs factory

$\eta(\mu) < 6$

$\mu_{\text{production}}^{\text{decay}}$	μ_{VV}^{tt}	μ_{WW}^{bb}	μ_{WW}^{cc}	μ_{WW}^{gg}	$\mu_{WW}^{\tau\tau}$	μ_{WW}^{WW}	μ_{WW}^{ZZ}	$\mu_{WW}^{\gamma\gamma}$	$\mu_{WW}^{\mu\mu}$
$\Delta\sigma/\sigma(\%)$	2.8	0.22	3.6	0.79	1.1	0.40	3.2	1.7	5.7
$\mu_{\text{production}}^{\text{decay}}$	μ_{ZZ}^{bb}	μ_{ZZ}^{cc}	μ_{ZZ}^{gg}	$\mu_{ZZ}^{\tau\tau}$	μ_{ZZ}^{WW}	μ_{ZZ}^{ZZ}	$\mu_{ZZ}^{\gamma\gamma}$	μ_{ZZ}^{inv}	μ_{ZZ}^{H}
$\Delta\sigma/\sigma(\%)$	0.77	17	3.3	4.8	1.8	11	4.8	0.05	0.75

Other inputs used in this study.

- (Exclusive Higgs) M. Forslund and P. Meade. [2203.09425]
- (Invisible Higgs) M. Ruhdorfer, E. Salvioni, A. Wulzer. [2303.14202]
- (Top Yukawa) Z. Liu, K.F. Lyu, I. Mahbub, L.T. Wang. [2308.06323]
- (off-shell Higgs; not used but relevant) M. Forslund and P. Meade [2308.02633]

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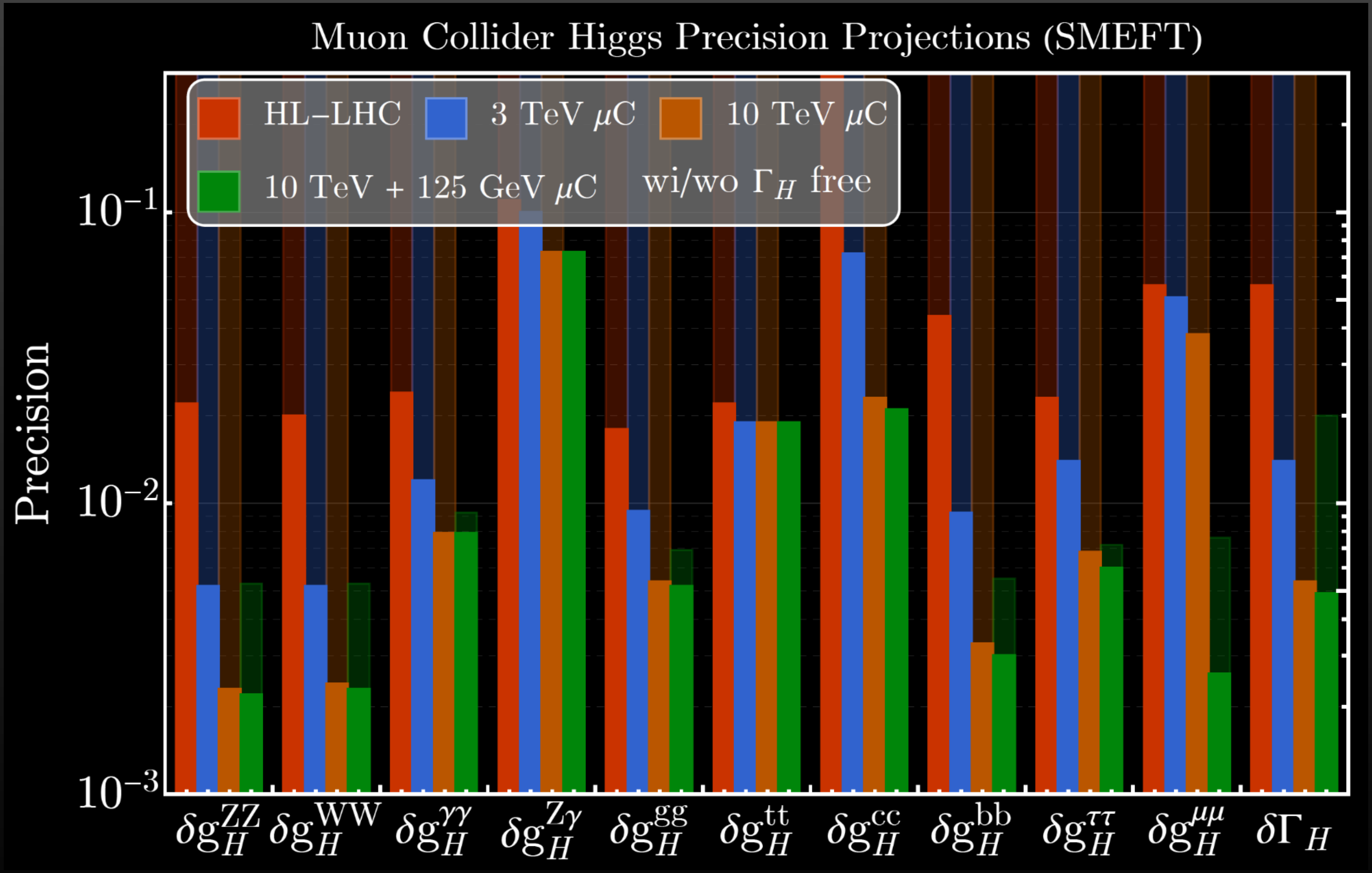

New inclusive Higgs rate result enables a full-fledges Higgs precision.

- With forwarded detection $2.5<\eta(\mu)<6$, the cross-section precision is ~0.75%
- Combining with other studies, we can constraint on Γ_H~2% and Higgs couplings in 0.5% level.

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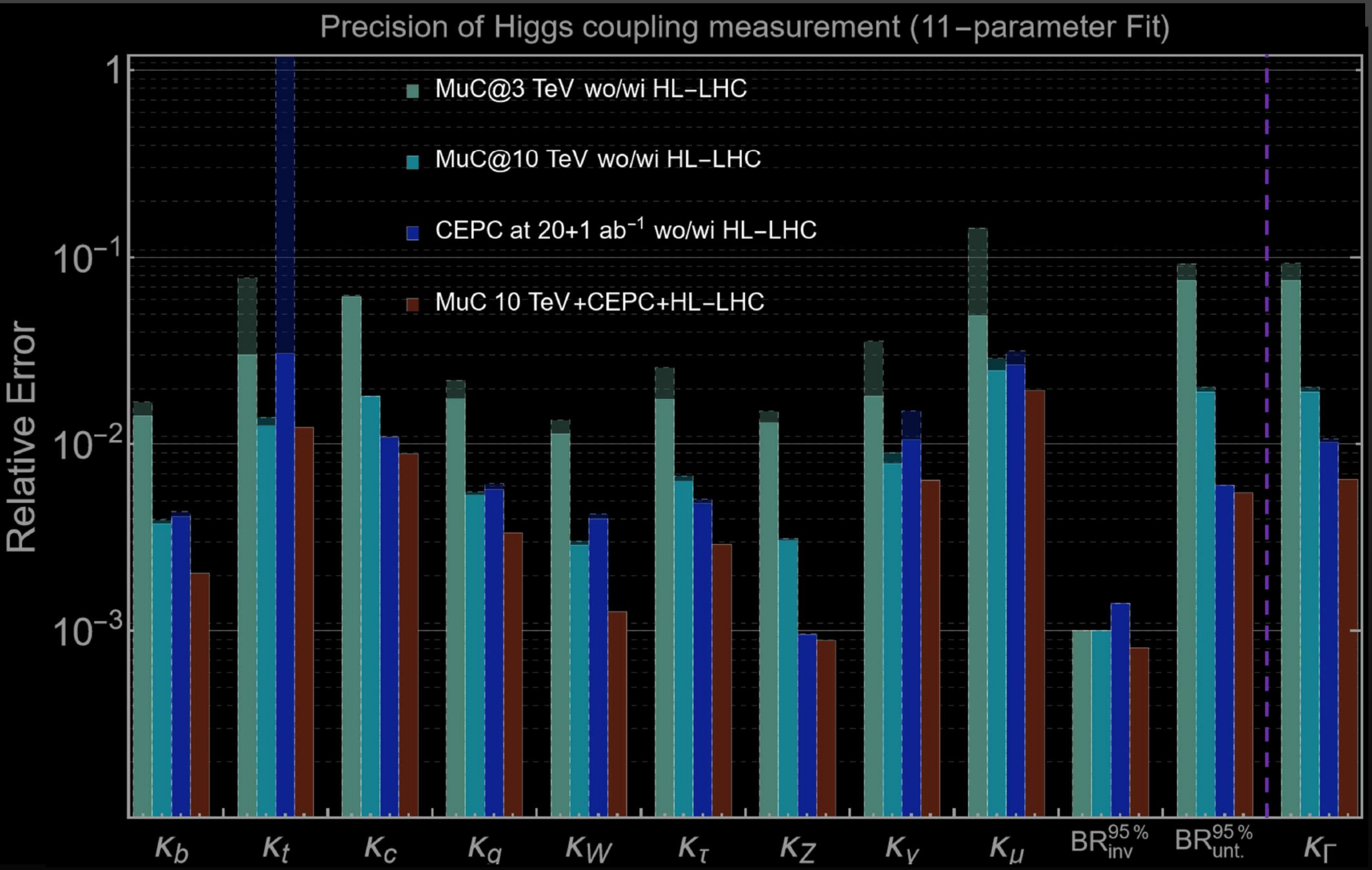

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Results and approximate analytics

$$\kappa_\Gamma = \frac{\left(\mu^{H}_{ZZ}\right)^2}{\mu^{WW}_{WW}} \left(\frac{\mu^{bb}_{WW}}{\mu^{bb}_{ZZ}}\right)^2$$

$$\Delta\kappa_\Gamma = \left[4\left(\Delta\mu^{H}_{ZZ}\right)^2 + \left(\Delta\mu^{WW}_{WW}\right)^2 + 4(\Delta\mu^{bb}_{WW})^2 + 4(\Delta\mu^{bb}_{ZZ})\right]^{1/2} = 2.2\%$$

	$\lvert\eta(\mu)\rvert < 4$			$\lvert\eta(\mu)\rvert < 6$		
	MuC@10TeV	+HL-LHC	$+e^+e^-$	MuC@10TeV	+HL-LHC	$+e^+e^-$
$\kappa_b(\%)$	$^{+7.5}_{-0.25}$	$^{+1.7}_{-0.24}$	$^{+0.25}_{-0.18}$	$^{+0.56}_{-0.23}$	$^{+0.53}_{-0.23}$	$^{+0.24}_{-0.17}$
$\kappa_t(\%)$	$^{+1.4}_{-7.1}$	$^{+1.3}_{-1.6}$	$^{+1.3}_{-1.2}$	$^{+1.4}_{-1.4}$	$^{+1.3}_{-1.2}$	$^{+1.3}_{-1.2}$
$\kappa_c(\%)$	$^{+7.8}_{-2.1}$	$^{+2.6}_{-2.1}$	$^{+0.91}_{-0.91}$	$^{+1.8}_{-1.8}$	$^{+1.8}_{-1.8}$	$^{+0.89}_{-0.89}$
$\kappa_g(\%)$	$^{+7.5}_{-0.52}$	$^{+1.7}_{-0.50}$	$^{+0.38}_{-0.35}$	$^{+0.67}_{-0.45}$	$^{+0.63}_{-0.44}$	$^{+0.35}_{-0.32}$
$\kappa_W(\%)$	$^{+7.5}_{-0.15}$	$^{+1.7}_{-0.13}$	$^{+0.17}_{-0.099}$	$^{+0.51}_{-0.10}$	$^{+0.48}_{-0.10}$	$^{+0.16}_{-0.090}$
$\kappa_\tau(\%)$	$^{+7.5}_{-0.62}$	$^{+1.8}_{-0.57}$	$^{+0.33}_{-0.27}$	$^{+0.76}_{-0.56}$	$^{+0.71}_{-0.55}$	$^{+0.32}_{-0.27}$
$\kappa_Z(\%)$	$^{+7.3}_{-1.4}$	$^{+1.9}_{-0.93}$	$^{+0.13}_{-0.058}$	$^{+0.37}_{-0.25}$	$^{+0.37}_{-0.25}$	$^{+0.12}_{-0.056}$
$\kappa_\gamma(\%)$	$^{+7.6}_{-0.83}$	$^{+1.8}_{-0.71}$	$^{+0.66}_{-0.64}$	$^{+0.97}_{-0.82}$	$^{+0.86}_{-0.71}$	$^{+0.65}_{-0.64}$
$\kappa_\mu(\%)$	$^{+9.1}_{-5.0}$	$^{+3.8}_{-3.6}$	$^{+2.3}_{-2.4}$	$^{+2.9}_{-2.9}$	$^{+2.5}_{-2.5}$	$^{+1.9}_{-2.0}$
$\mathrm{Br}^{95\%}_{\mathrm{inv}}(\%)$	$^{+0.64}_{0}$	$^{+0.63}_{0}$	$^{+0.13}_{0}$	$^{+0.10}_{0}$	$^{+0.10}_{0}$	$^{+0.080}_{0}$
$\mathrm{Br}^{95\%}_{\mathrm{unt}}(\%)$	$^{+27}_{0}$	$^{+6.6}_{0}$	$^{+0.57}_{0}$	$^{+2.0}_{0}$	$^{+1.9}_{0}$	$^{+0.54}_{0}$
$\kappa_\Gamma(\%)$	$^{+34}_{-0.45}$	$^{+6.9}_{-0.43}$	$^{+0.69}_{-0.31}$	$^{+2.1}_{-0.41}$	$^{+1.9}_{-0.40}$	$^{+0.65}_{-0.29}$

Results and approximate analytics

$$\kappa_\Gamma = \frac{(\mu^H_{ZZ})^2}{\mu^{WW}_{WW}} \left(\frac{\mu^{bb}_{WW}}{\mu^{bb}_{ZZ}}\right)^2$$

s

$$\Delta\kappa_\Gamma = \left[4\left(\Delta\mu^H_{ZZ}\right)^2 + \left(\Delta\mu^{WW}_{WW}\right)^2 + 4(\Delta\mu^{bb}_{WW})^2 + 4(\Delta\mu^{bb}_{ZZ})\right]^{1/2} = 2.2\%$$

$$\kappa_W^4 = (\mu^{WW}_{WW})\kappa_\Gamma = (\mu^H_{ZZ})^2 \left(\frac{\mu^{bb}_{WW}}{\mu^{bb}_{ZZ}}\right)^2,$$

$$\Delta\kappa_W = \frac{1}{4}\left[4\left(\Delta\mu^H_{ZZ}\right)^2 + 4(\Delta\mu^{bb}_{WW})^2 + 4(\Delta\mu^{bb}_{ZZ})^2\right]^{1/2} = 0.55\%.$$

$$\kappa_b^2 = \frac{\mu^{bb}_{WW}\kappa_W^2}{\mu^{WW}_{WW}} = \frac{\mu^H_{ZZ}(\mu^{bb}_{WW})^2}{\mu^{bb}_{ZZ}\mu^{WW}_{WW}},$$

$$\Delta\kappa_b = \frac{1}{2}\left[\left(\Delta\mu^H_{ZZ}\right)^2 + 4(\Delta\mu^{bb}_{WW})^2 + (\Delta\mu^{bb}_{ZZ})^2 + \left(\Delta\mu^{WW}_{WW}\right)\right]^{1/2} = 0.61\%$$

	$\lvert\eta(\mu)\rvert < 4$			$\lvert\eta(\mu)\rvert < 6$		
	MuC@10TeV	+HL-LHC	$+e^+e^-$	MuC@10TeV	+HL-LHC	$+e^+e^-$
$\kappa_b(\%)$	+7.5 / −0.25	+1.7 / −0.24	+0.25 / −0.18	+0.56 / −0.23	+0.53 / −0.23	+0.24 / −0.17
$\kappa_t(\%)$	+1.4 / −7.1	+1.3 / −1.6	+1.3 / −1.2	+1.4 / −1.4	+1.3 / −1.2	+1.3 / −1.2
$\kappa_c(\%)$	+7.8 / −2.1	+2.6 / −2.1	+0.91 / −0.91	+1.8 / −1.8	+1.8 / −1.8	+0.89 / −0.89
$\kappa_g(\%)$	+7.5 / −0.52	+1.7 / −0.50	+0.38 / −0.35	+0.67 / −0.45	+0.63 / −0.44	+0.35 / −0.32
$\kappa_W(\%)$	+7.5 / −0.15	+1.7 / −0.13	+0.17 / −0.099	+0.51 / −0.10	+0.48 / −0.10	+0.16 / −0.090
$\kappa_\tau(\%)$	+7.5 / −0.62	+1.8 / −0.57	+0.33 / −0.27	+0.76 / −0.56	+0.71 / −0.55	+0.32 / −0.27
$\kappa_Z(\%)$	+7.3 / −1.4	+1.9 / −0.93	+0.13 / −0.058	+0.37 / −0.25	+0.37 / −0.25	+0.12 / −0.056
$\kappa_\gamma(\%)$	+7.6 / −0.83	+1.8 / −0.71	+0.66 / −0.64	+0.97 / −0.82	+0.86 / −0.71	+0.65 / −0.64
$\kappa_\mu(\%)$	+9.1 / −5.0	+3.8 / −3.6	+2.3 / −2.4	+2.9 / −2.9	+2.5 / −2.5	+1.9 / −2.0
$\mathrm{Br}^{95\%}_{\mathrm{inv}}(\%)$	+0.64 / 0	+0.63 / 0	+0.13 / 0	+0.10 / 0	+0.10 / 0	+0.080 / 0
$\mathrm{Br}^{95\%}_{\mathrm{unt}}(\%)$	+27 / 0	+6.6 / 0	+0.57 / 0	+2.0 / 0	+1.9 / 0	+0.54 / 0
$\kappa_\Gamma(\%)$	+34 / −0.45	+6.9 / −0.43	+0.69 / −0.31	+2.1 / −0.41	+1.9 / −0.40	+0.65 / −0.29

Results and approximate analytics

$$\kappa_\Gamma = \frac{(\mu^H_{ZZ})^2}{\mu^{WW}_{WW}}\left(\frac{\mu^{bb}_{WW}}{\mu^{bb}_{ZZ}}\right)^2$$

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$$\kappa_b^2 = \frac{\mu^{bb}_{WW}\kappa_W^2}{\mu^{WW}_{WW}} = \frac{\mu^H_{ZZ}(\mu^{bb}_{WW})^2}{\mu^{bb}_{ZZ}\mu^{WW}_{WW}},$$

$$\Delta\kappa_b = \frac{1}{2}\left[\left(\Delta\mu^H_{ZZ}\right)^2 + 4(\Delta\mu^{bb}_{WW})^2 + (\Delta\mu^{bb}_{ZZ})^2 + (\Delta\mu^{WW}_{WW})\right]^{1/2} = 0.61\%$$

The diverse production and decay measurements at MuC de-correlate many coupling precision, which leads to a good projection in the coupling basis.

	$\lvert\eta(\mu)\rvert < 4$			$\lvert\eta(\mu)\rvert < 6$		
	MuC@10TeV	+HL-LHC	$+e^+e^-$	MuC@10TeV	+HL-LHC	$+e^+e^-$
$\kappa_b(\%)$	$^{+7.5}_{-0.25}$	$^{+1.7}_{-0.24}$	$^{+0.25}_{-0.18}$	$^{+0.56}_{-0.23}$	$^{+0.53}_{-0.23}$	$^{+0.24}_{-0.17}$
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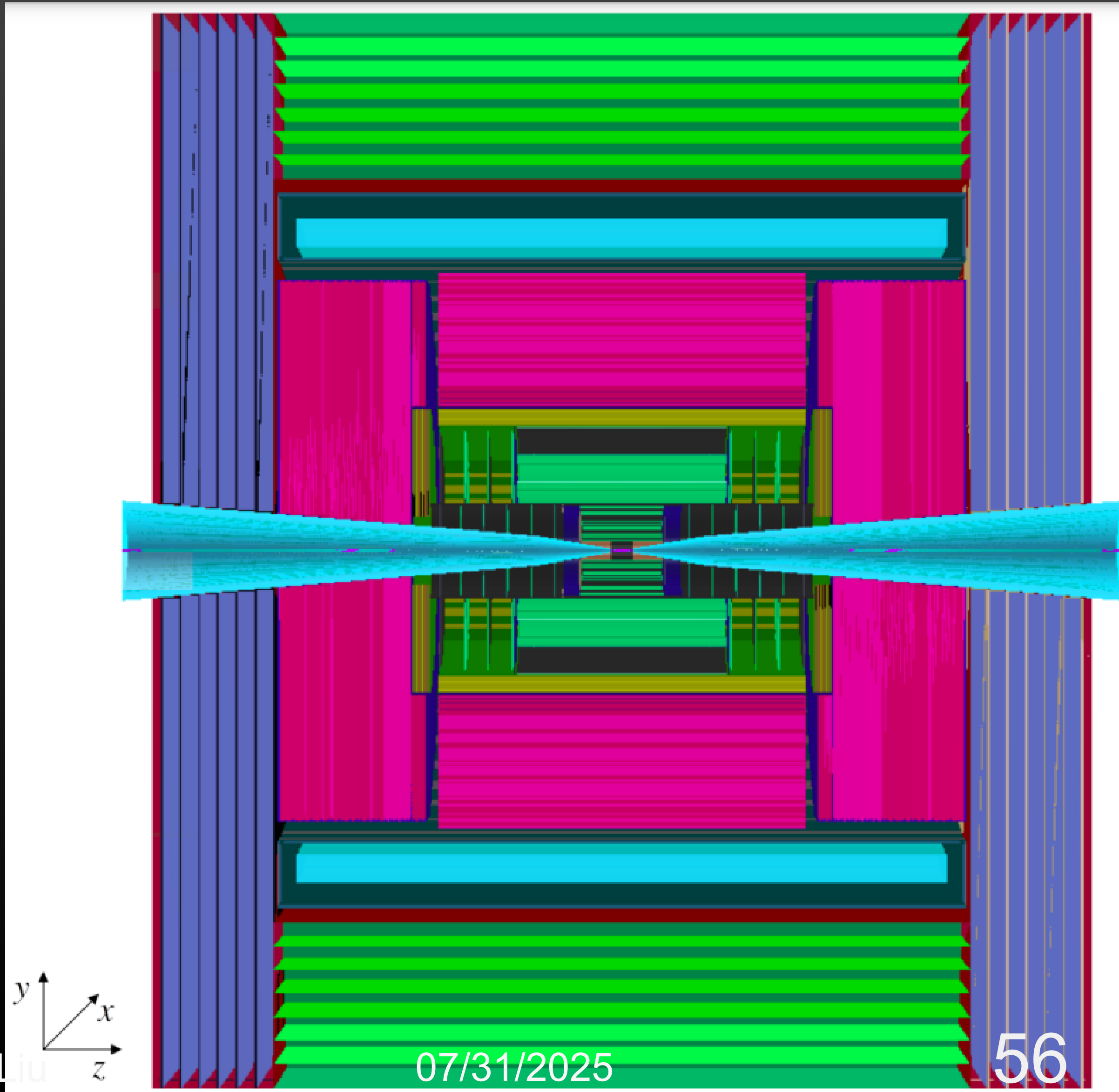
$\mathrm{Br}^{95\%}_{\mathrm{unt}}(\%)$	$^{+27}_{0}$	$^{+6.6}_{0}$	$^{+0.57}_{0}$	$^{+2.0}_{0}$	$^{+1.9}_{0}$	$^{+0.54}_{0}$
$\kappa_\Gamma(\%)$	$^{+34}_{-0.45}$	$^{+6.9}_{-0.43}$	$^{+0.69}_{-0.31}$	$^{+2.1}_{-0.41}$	$^{+1.9}_{-0.40}$	$^{+0.65}_{-0.29}$

Forward Muon Detector Required!

- Is it feasible?
- We only require to tag Energetic Muons.
- Muons pass through the nozzle regions
- Energy resolution is not important (basically need to separate TeV scale energetic muons from soft muons)
- Angular resolution is not important (~50mrad should be good enough;)
- This is a very strong case for a forward muon detector
- Also important for general physics
  - VBF tagging and disentangling
  - Invisible Higgs (Ruhdorfer, Salvioni, Wulzer, 2411.00096, 2303.14202)
  - …



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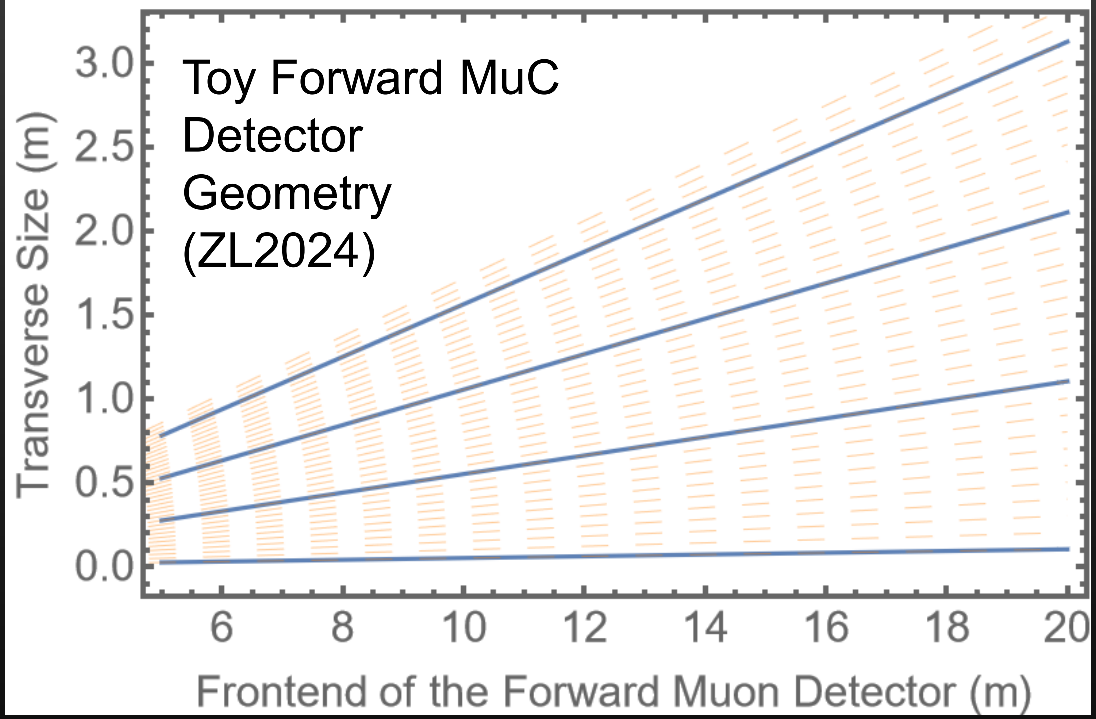
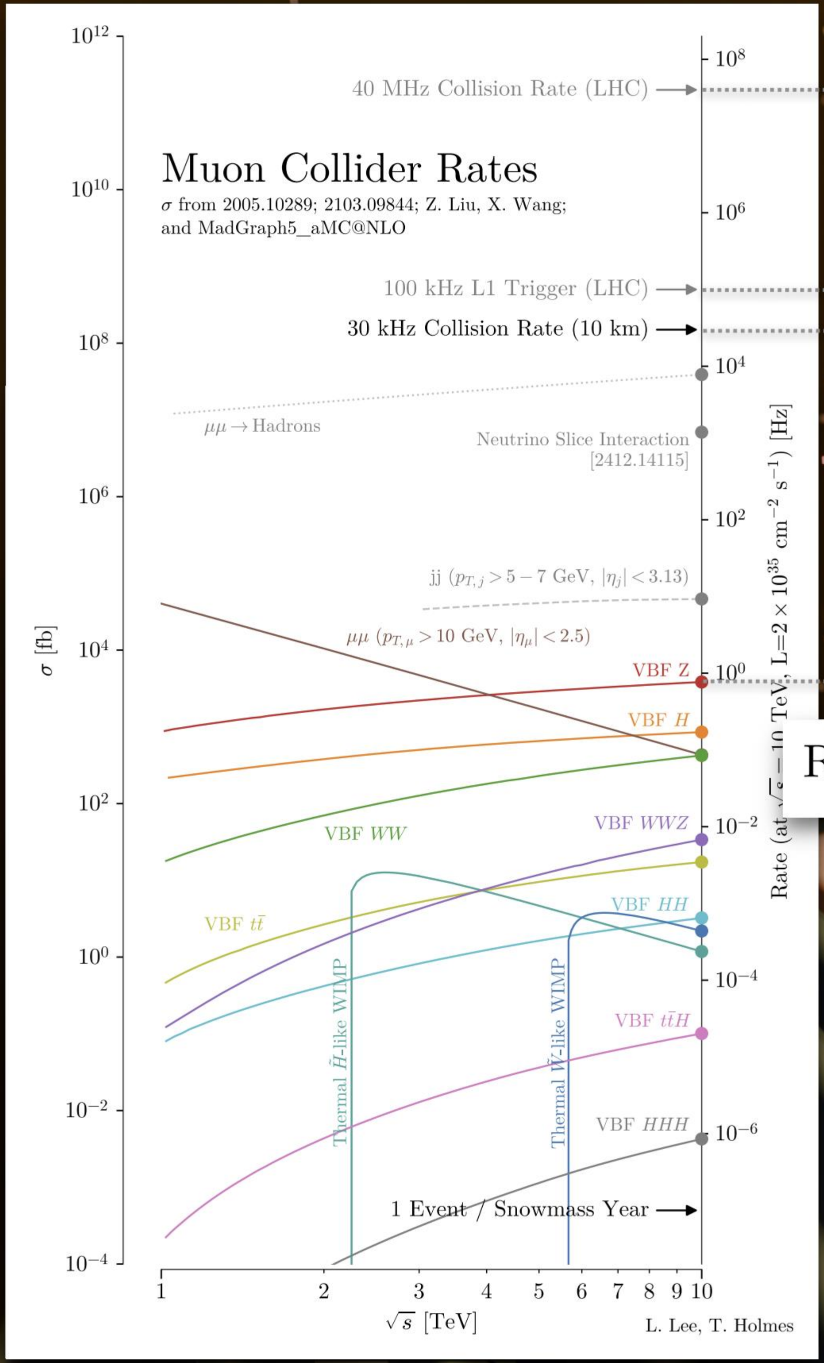


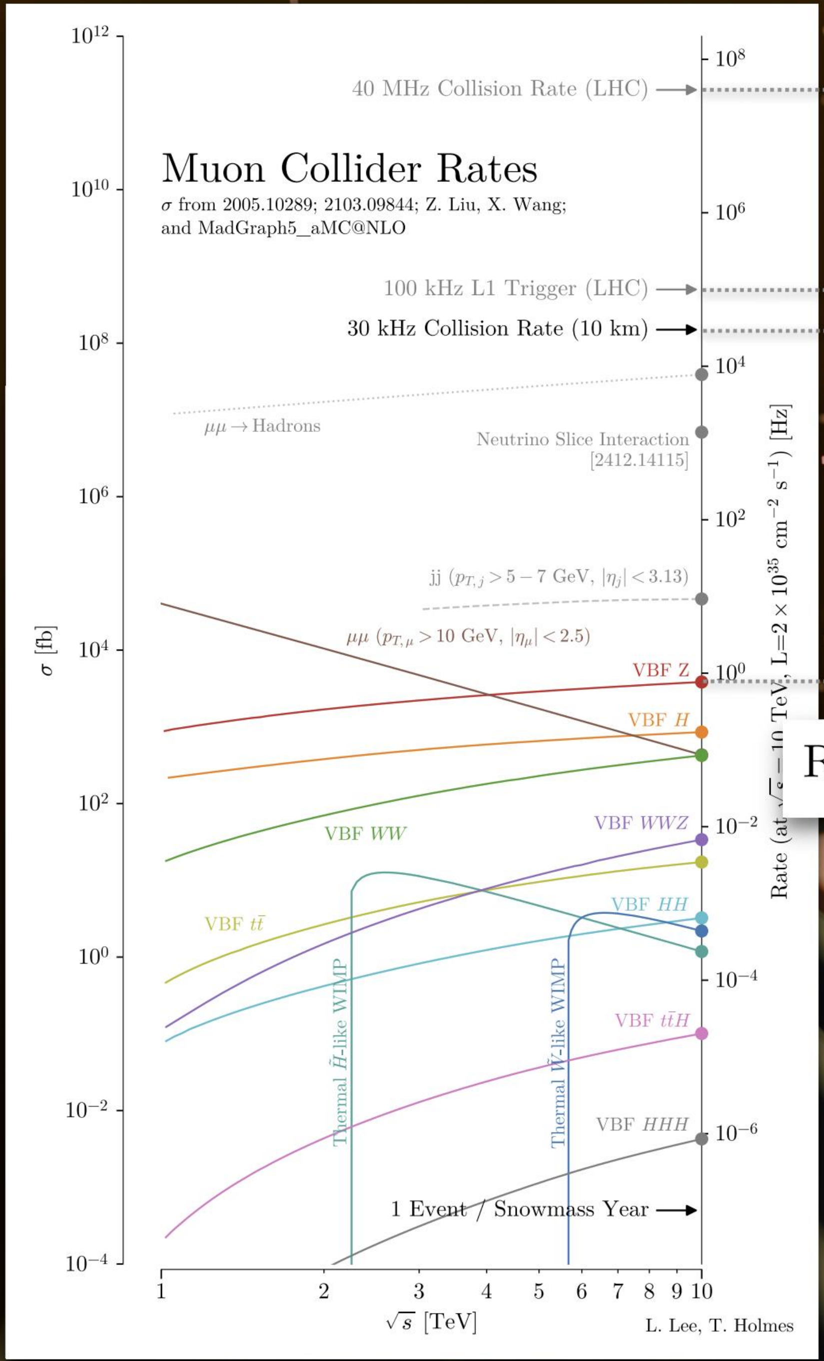


Larger fraction than LHC throws away at L1!

Swamped by uninteresting stuff

Rate (at $\sqrt{s} = 10$ TeV, L=2×10^{35} cm^{-2} s^{-1}) [Hz]

- Muon Smasher's Guide's σ_{tot} (VBF Z/W) is < 10^{-4} × collision rate!
- We've been thinking about this wrong…
- Huge implications for detector design in trigger and DAQ



Larger fraction than LHC throws away at L1!

Unrealized Opportunities

Rate (at $\sqrt{s} = 10$ TeV, L=2×10^{35} cm^{-2} s^{-1}) [Hz]

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Muon Collider is Specially Interesting

Challenges and Surprises

When thinking outside the box of the Standard SM and BSM physics, we can come up with many interesting research tasks. I gave two examples:

- Neutrino Slice
- Forward Muon

There are much more to explore!

Disclaimer page:

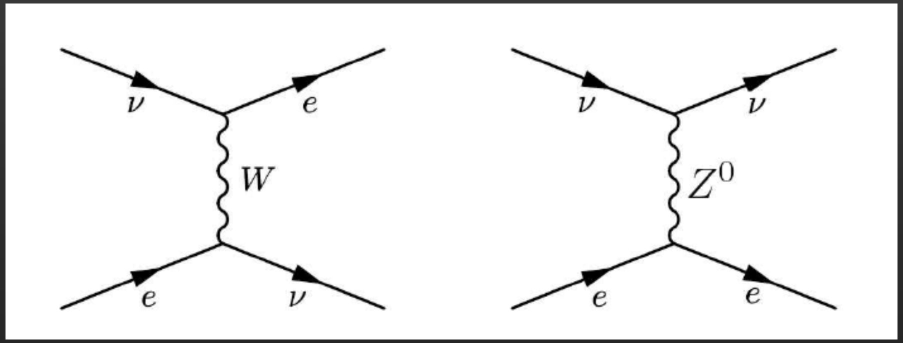
Note that (I want to avoid oversell):

- This flat direction is not mysterious or called upon by some special arrangement of UV theory. It represent a ‘loose’ direction in our global fit where couplings could vary AROUND a specific way.
- One can make assumptions (in fact, one has to do it for the LHC), e.g.,
  - No (unprobed) exotic decays
  - $\kappa_V \leq 1$
  - Specifying the underlying model
  - Off-shell on-shell Higgs rate comparison (other assumptions needed)
- Measurement information is encoded in all the differential rates, but it is natural to ask for Higgs precision that is projected onto the coupling precision axis;
- This framework and assumption set is commonly adapted by all future colliders, by ESG, and by Snowmass. It is meaningful to address this flat direction.

Rare BIN interactions

Neutrino-electron elastic scattering

Neutrino-electron scattering

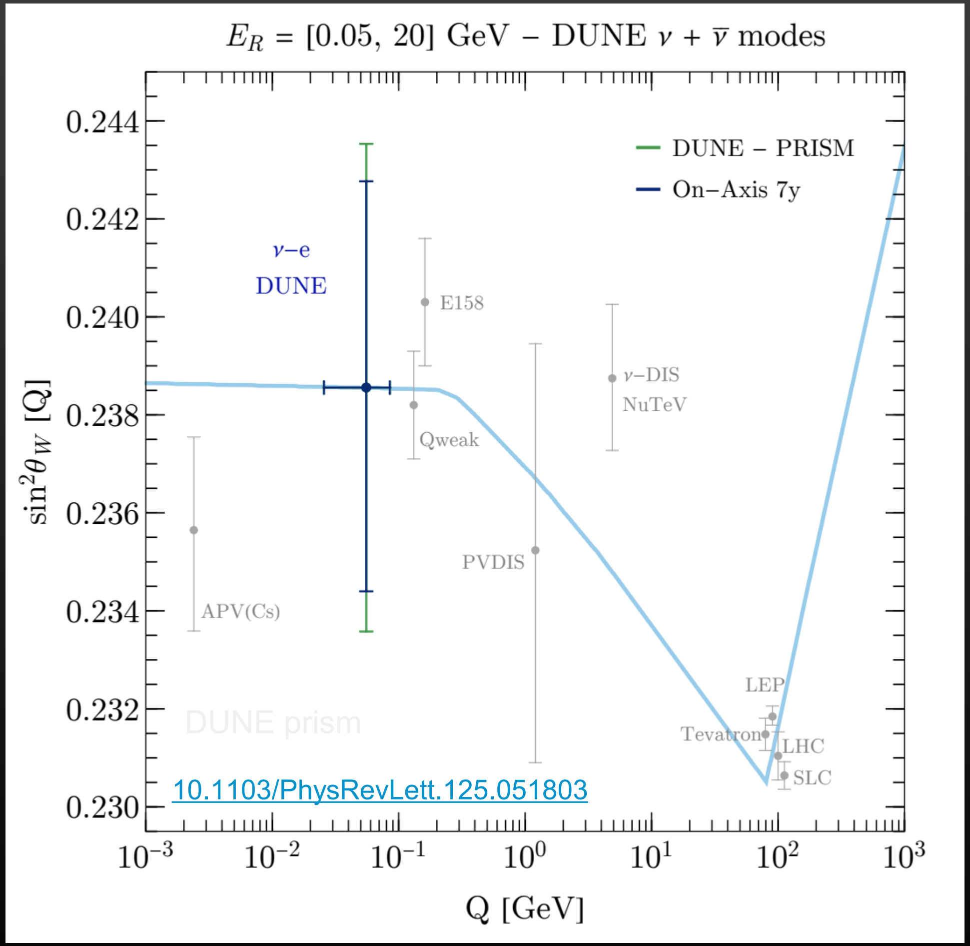


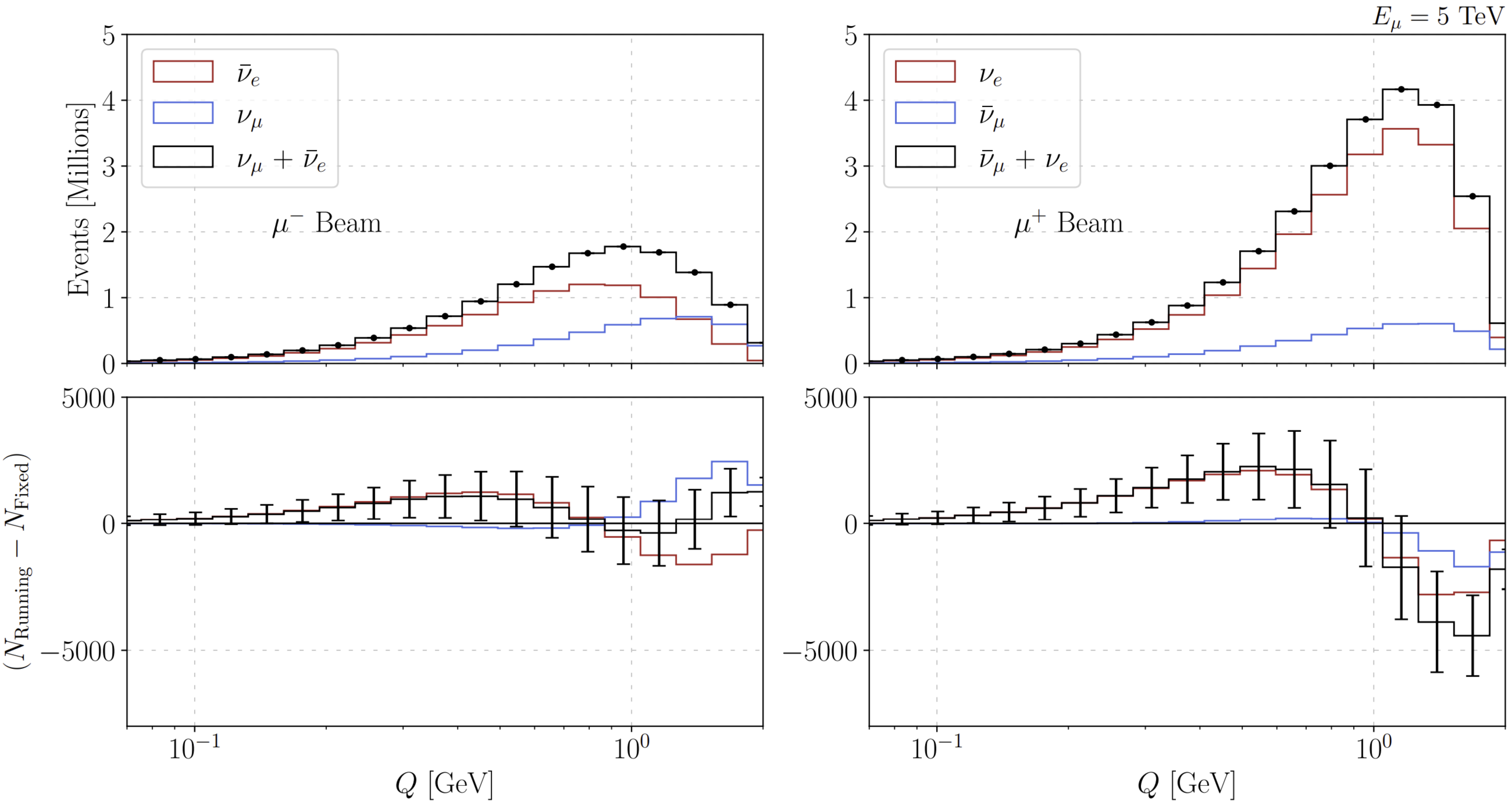
Clean channel and sensitive to fundamental Weak interaction parameters.

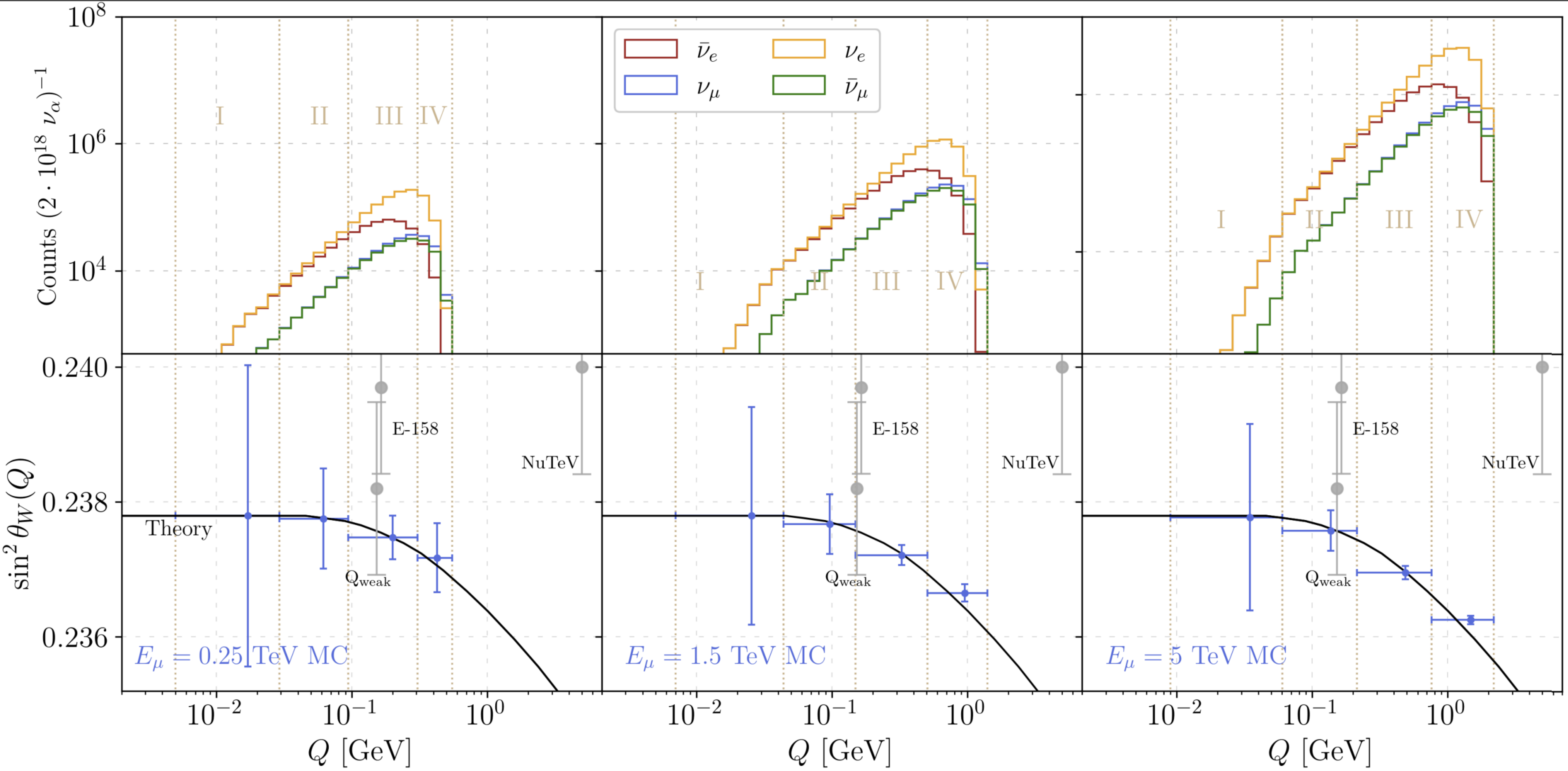
$$\frac{d\sigma}{dT} = \frac{2G_F^2 m}{\pi}\left\{g_L^2(T)\left[1+\frac{\alpha}{\pi}f_-(z)\right] + g_R^2(T)(1-z)^2\left[1+\frac{\alpha}{\pi}f_+(z)\right] - g_R(T)g_L(T)\frac{m}{q}z\left[1+\frac{\alpha}{\pi}f_{+-}(z)\right]\right\}$$

T is the electron recoil energy, z the inelasticity, and q the neutrino energy.

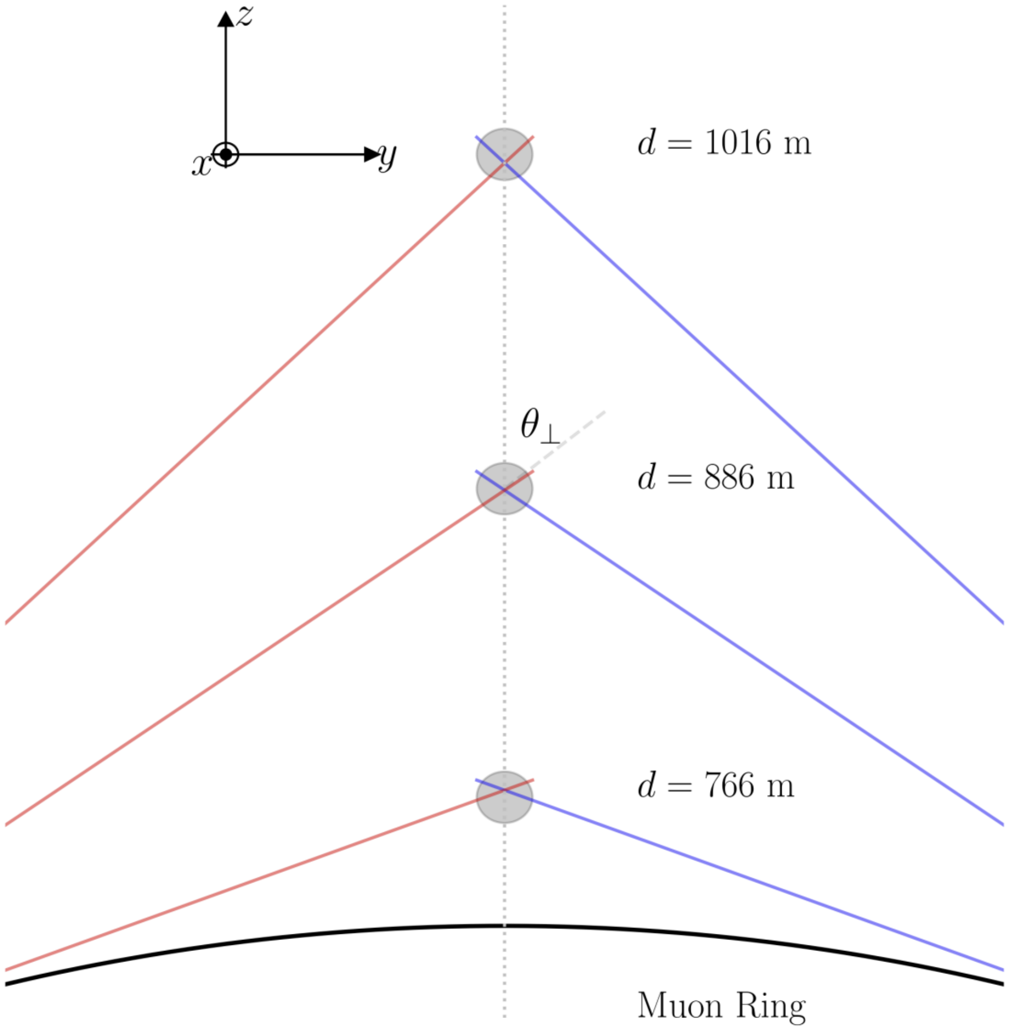
Note the running of Weak parameters.



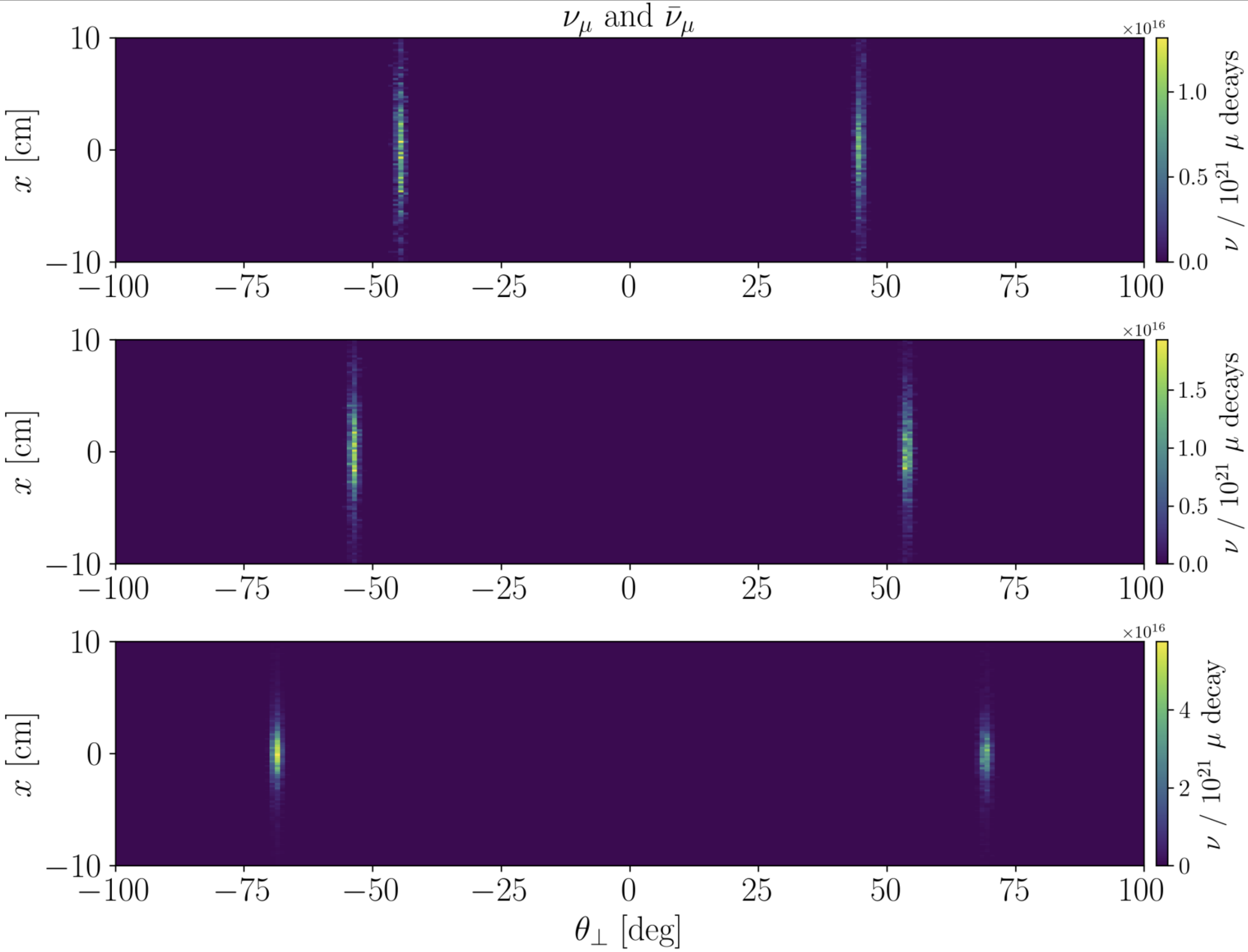

$E_\mu = 5$ TeV
$\bar{\nu}_e$
ν_μ
$\nu_\mu + \bar{\nu}_e$
μ^- Beam
ν_e
$\bar{\nu}_\mu$
$\bar{\nu}_\mu + \nu_e$
μ^+ Beam
Events [Millions]
$(N_{\text{Running}} - N_{\text{Fixed}})$
Q [GeV]



10^8
10^6
10^4
Counts $(2 \cdot 10^{18}\ \nu_\alpha)^{-1}$
I
II
III
IV
$\bar{\nu}_e$
ν_e
ν_μ
$\bar{\nu}_\mu$
0.240
0.238
0.236
$\sin^2\theta_W(Q)$
E-158
NuTeV
Theory
Q_{weak}
$E_\mu = 0.25$ TeV MC
$E_\mu = 1.5$ TeV MC
$E_\mu = 5$ TeV MC
10^{-2}
10^{-1}
10^0
Q [GeV]



z
x
y
$\theta_\perp$
$d = 1016$ m
$d = 886$ m
$d = 766$ m
Muon Ring



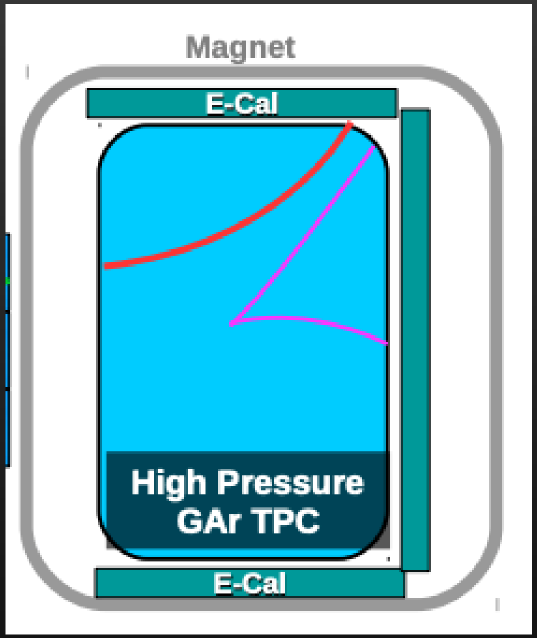
ν_μ and $\bar{\nu}_\mu$
x [cm]
$\theta_\perp$ [deg]
ν / 10^{21} μ decays
ν / 10^{21} μ decay
$\times 10^{16}$

Utilizing the straight section

“Forward neutrino facility”

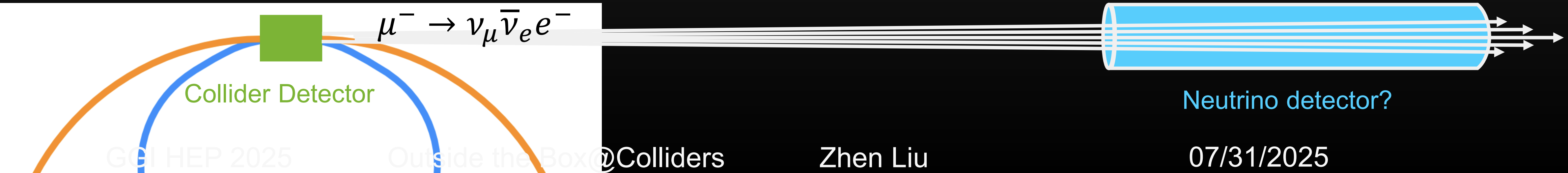
Ultimate $\nu - e$ scattering measurement @ a long, magnetized, and low-density detector:

In the $\mu^- \to \nu_\mu \bar{\nu}_e e^-$ beam, there should be no neutrino-induced backgrounds to $\nu + e^- \to \nu + e^-$ signal:



* $\bar{\nu}_e$CC produces a positron (charge ID in magnet).
* Coherent NCπ^0 gammas do not convert in gas.

Extremely clean measurement — magnetize 10 meters of material?



Beam halo losses

The “muon slice”?

μ+μ− Collider: Feasibility Study (Snowmass 1996)

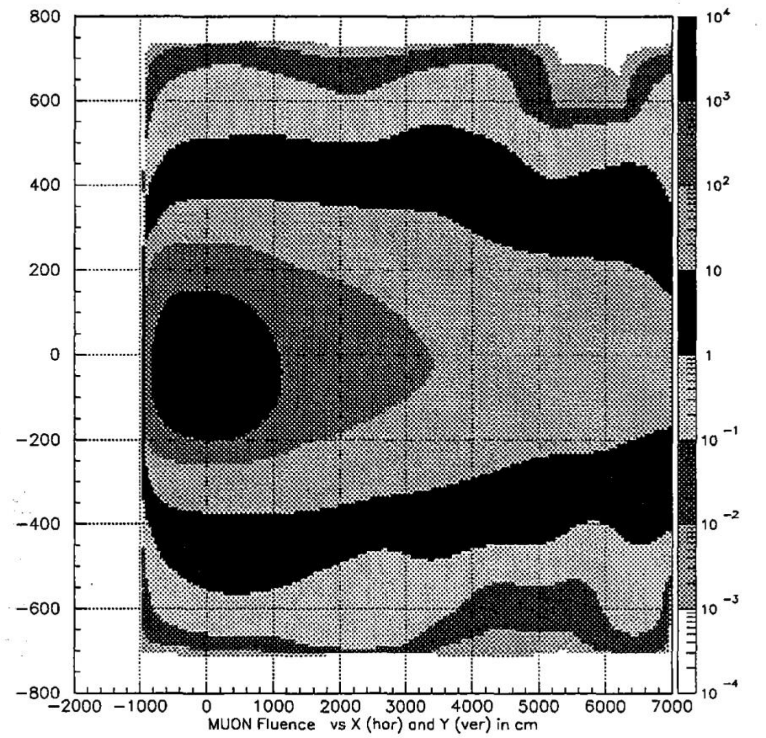
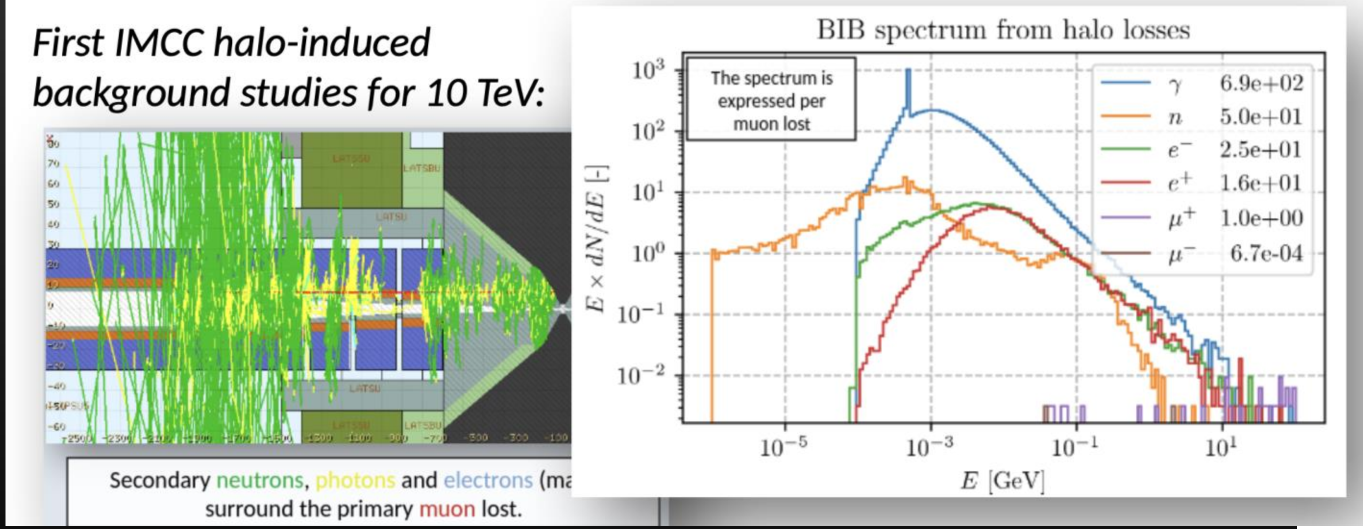


Figure 9.36: Muon flux contours ($cm^{-2}s^{-1}$) in a vertical plane of the collider tunnel and surrounding soil/rock at the entrance to the interaction region for 2 TeV muon beam decays as calculated with MARS. Beam axis is at x=y=0.

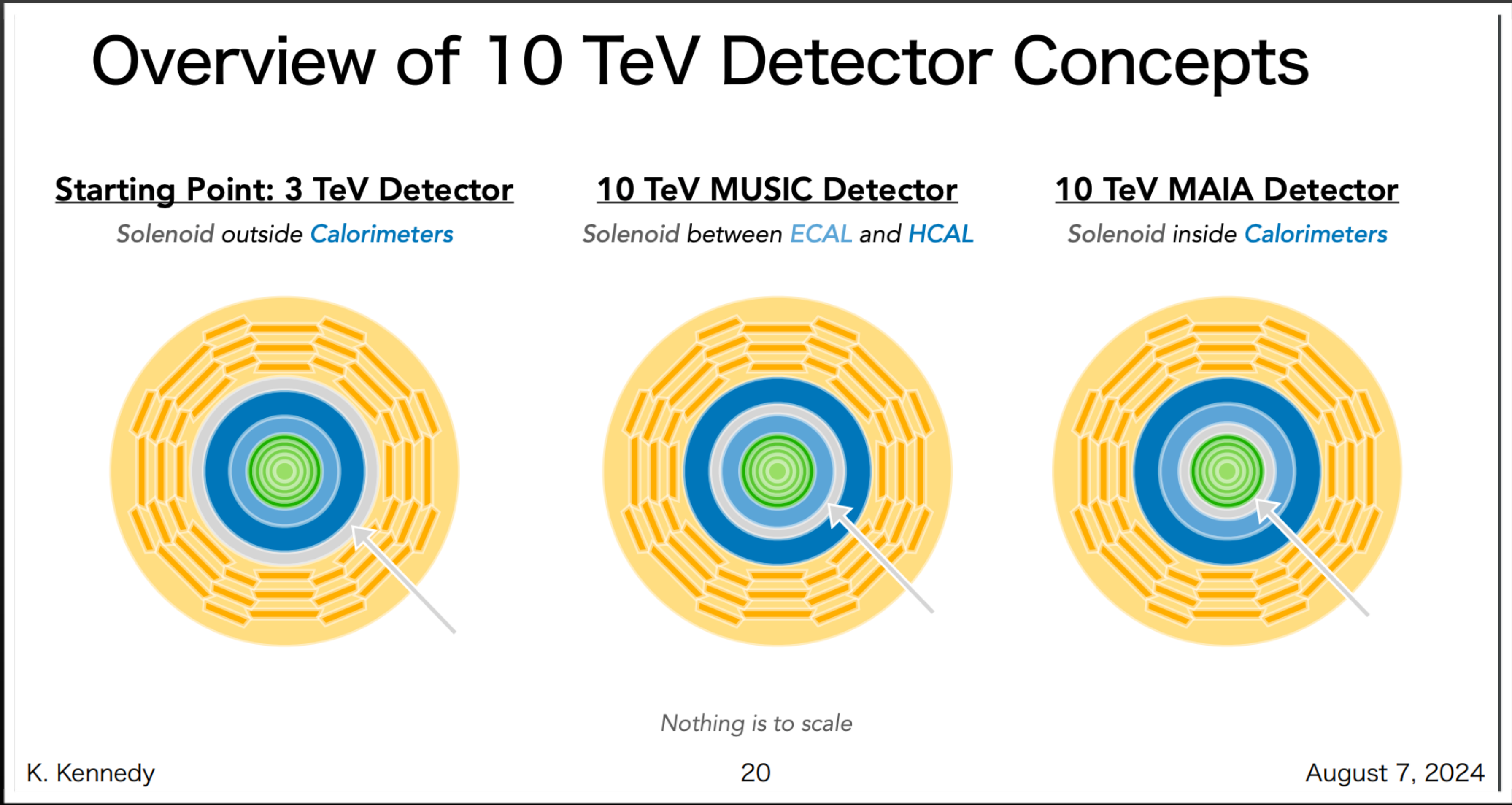
D. Calzolari, ICHEP 2024



New detector ideas
BINs in detector R&D

Moving the solenoid inwards is in a sense advantageous for BINs.

The BIB occupancy goes down, so reconstruction of BIN events is probably better



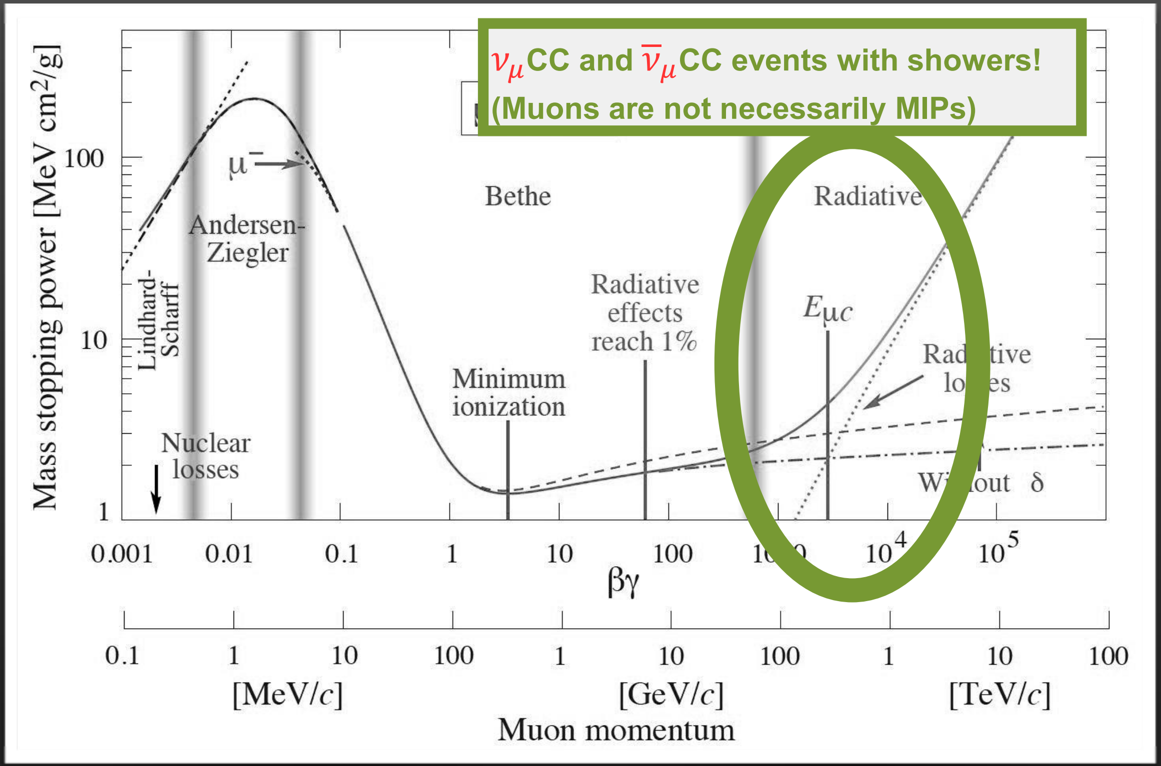
New detector ideas

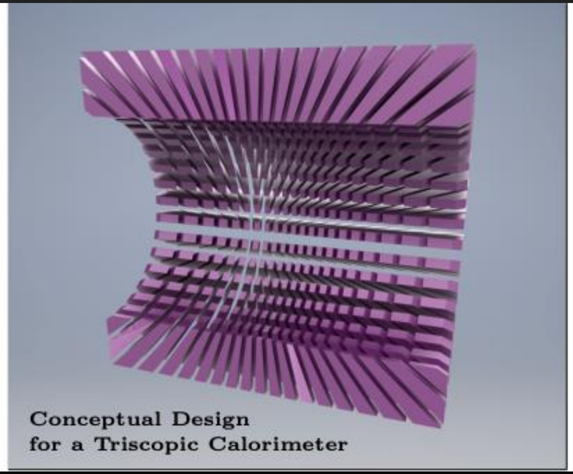
Reco of BINs in detector R&D

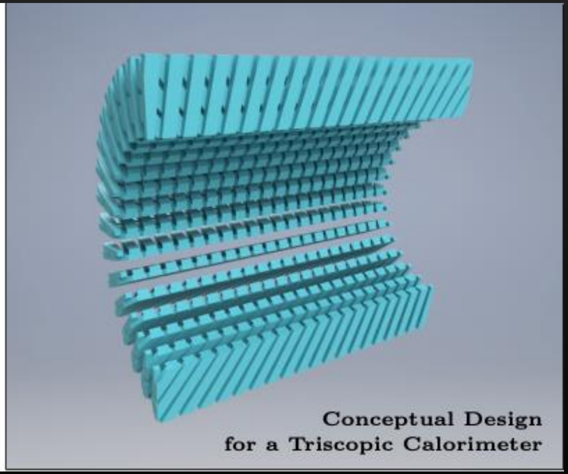
Orientation of cells in calorimeters is also crucial to reconstruct these events.

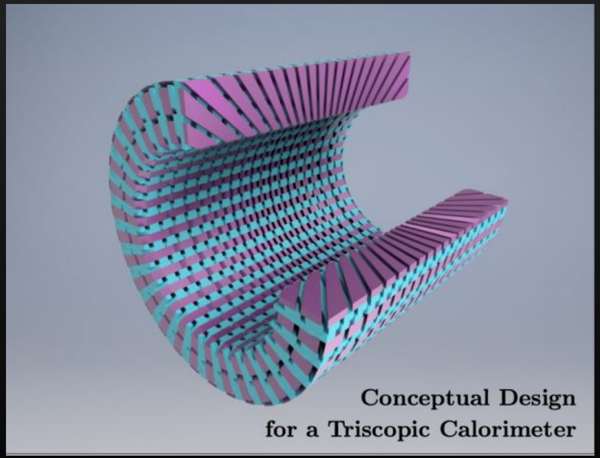
Many of the muon events will contain significant hadronic and EM shower. Reconstruction work needed.

For example: "Triscopic" calorimeter to improve BIB rejection (D. Ally, L. Carpenter, T. Holmes, L. Lee, P. Wagenknecht)









Characterizing neutrino events

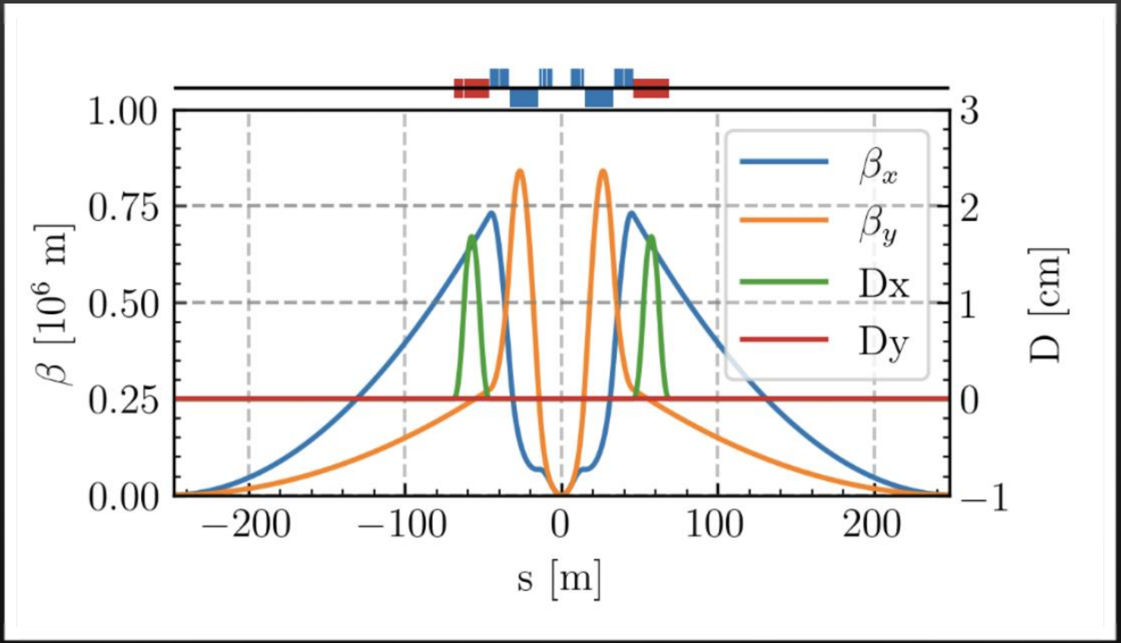
Toy MC of a muon collider

Detector components following IMCC studies

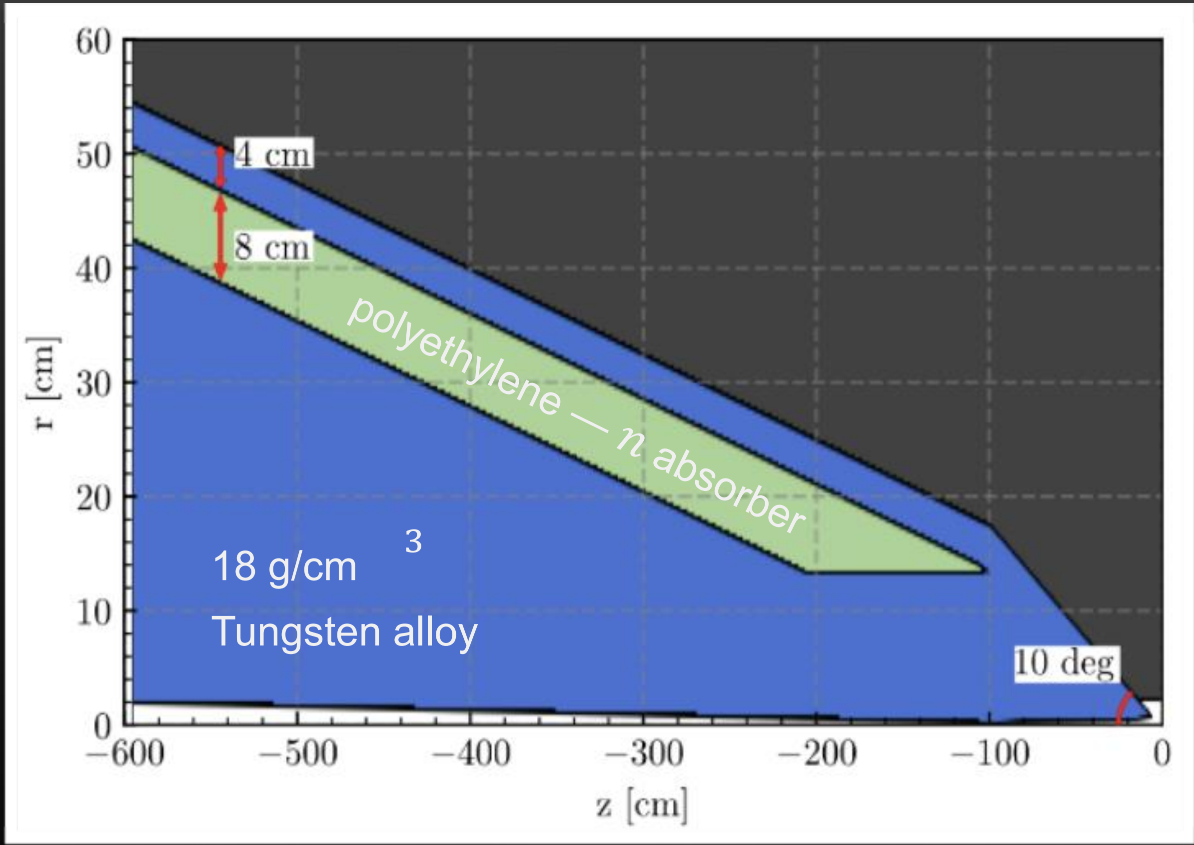
Detector Parts	$\|Z\|$ (cm)	R (cm)	Material	N_{targets} $(10^{24}/\text{cm}^{-3})$
Beampipe	$0-563.8$	$0-2.2$	Vacuum	0
Nozzles 1	$6.5-230.7$	$2.2, 2.2-31$	W	11.63
Nozzles 2	$230.7-563.8$	$2.2-31, 2.2-78.2$	W	11.63
ECal (Barrel)	$0-221$	$150-170.2$	0.38W +0.46Cu +0.1Si	6.99
ECal (Endcap)	$230.7-250.9$	$31-170, 33.9-170$	0.38W +0.46Cu +0.1Si	6.99
HCal (Barrel)	$0-221$	$174-333$	0.75Fe +0.03Al +0.11PS	3.72
HCal (Endcap 1)	$235.4-250.9$	$170-324.6$	0.75Fe +0.03Al +0.11PS	3.72
HCal (Endcap 2)	$250.9-412.9$	$33.9-324.6$, $56.8-324.6$	0.75Fe+0.03Al+0.11PS	3.72
Solenoid (Inner)	$0-412.9$	$348.3-352.3$	Fe	4.75
Solenoid (Middle)	$0-412.9$	$364.9-399.3$	Al	1.63
Solenoid (Outer)	$0-412.9$	$425-429$	Fe	4.75
Muon Detector (Barrel)	$0-417.9$	$446.1-645$	Fe	4.75
Muon Detector (Endcap)	$417.9-563.8$	$57.5-645$, $78.2-645$	Fe	4.75

Muon collider
Preliminary Parameters

https://zenodo.org/records/14000854



Twiss parameters around the interaction region



The nozzle around the interaction region

Muon collider

Preliminary Parameters

https://zenodo.org/records/14000854

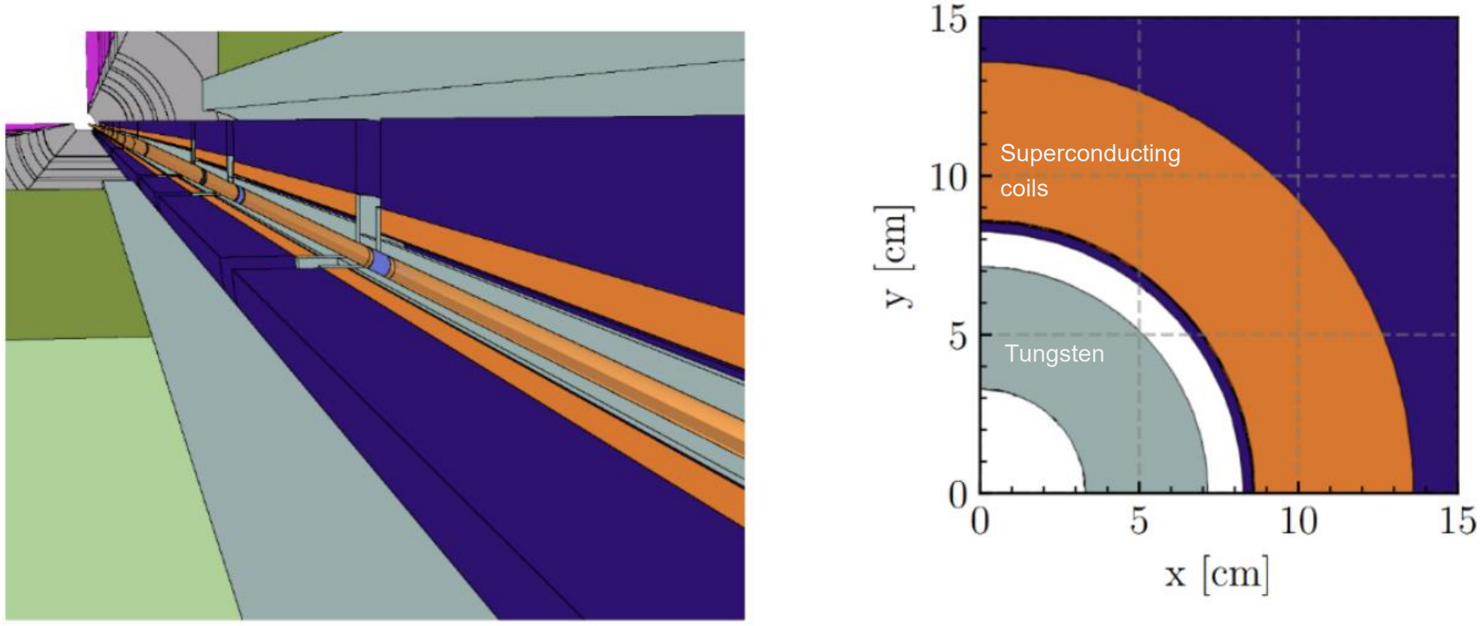


Figure 3 FLUKA beamline geometry (left) and the radial build of quadrupoles (right). The point of view in the left figure is from a muon leaving the interaction region and heading towards the arcs. The main components are the tungsten shielding (grey) and the superconducting coils (orange).

Muon collider
Preliminary Parameters

https://zenodo.org/records/13970100

Center of mass energy	Unit	3 TeV	10 TeV
Luminosity for target parameters	10^{34} cm^{-2} s^{-1}	2	20
Transverse emittance	µm	25	
Proton beam power	MW	2 - 4*	
Number of μ^+ muons per bunch	10^{12}	2.2	1.8
Number of μ^- muons per bunch	10^{12}	2.2	1.8
Target integrated luminosity	ab^{-1}	1	10
Luminosity lifetime	Turns	1039	1158
Collider peak field	T	11	16
Repetition rate	Hz	5	
Beam power	MW	5.3	14.4
Longitudinal emittance	eV s	0.025	
IP bunch length	mm	5	1.5

Subsystem	Energy GeV	Length m	Achieved Transm. %	Achieved μ^-/bunch 10^{12}	Target μ^-/bunch 10^{12}
Proton Driver	5 (p^+)	1500	–	500 (p^+)	
Front End	0.17	150	9	45.0	
Charge Sep.	0.17	12	95	42.8	
Rectilinear A	0.14	363	50	21.4	
Bunch Merge	0.12	134	78	16.7	
Rectilinear B	0.14	424	32	5.3	
Final Cooling	0.005	100	60	3.2	
Pre-Acc.	0.25	140	86	2.8	4.0
Low-Energy Acc.	5	–	*90**	2.5	
RLA2	62.5	∘2430	90	2.3	
RCS1	314	∘5990	90	2.1	
RCS2	750	∘5990	90	1.9	
RCS3	1500	∘10700	90	1.7	
3 TeV Collider	1500	∘4500	–	1.7	2.2
RCS4	5000	∘35000	90	1.5	
10 TeV Collider	5000	∘10000	–	1.5	1.8

Muon collider

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Longitudinal emittance	eV s	0.025	
IP bunch length	mm	5	1.5

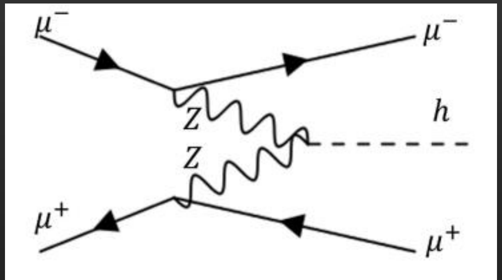
Parameter	Unit	version relaxed	version target
Center of mass energy	TeV	10	
Geometric Luminosity[1]	$10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	5.77	19.2
Beam energy	TeV	5	
Relativistic Lorentz factor		47322	
Circumference	km	≈ 10	
Dist. of last magnet to IP	m	6	
Repetition rate	Hz	5	
Bunch intensity (one bunch per beam)	10^{12}	1.80	
Injected beam power per beam	MW	7.2	
Normalized transverse rms emittance	µm	25	
Longitudinal norm. rms emittance	eVs	0.025	
Relative rms momentum spread	10^{-3}	0.3	1
RMS bunch length in space	mm	5	1.5
RMS bunch length in time domain	ns	.017	0.005
Twiss betatron function at the IP	mm	5	1.5
Energy loss per turn[2]	MeV	≈ 27.2	
Integrated RF gradient[3]	MV	30	

BINs as backgrounds?

Forward tagging of muons

M. Forslund, P. Meade, arxiv:2203.09425
M. Ruhdorfer, E. Salvioni, A. Wulzer, arXiv:2303.14202
P. Li, Z. Liu, and KF Lyu, arXiv:2401.08756

Proposals to measure the Higgs width with forward muon tagging in ZZ fusion:



With an optimistic luminosity benchmark of 1 ab^{-1}/year at the IMCC and $\sigma(\mu^+\mu^- \to \mu^+\mu^- h) = 8.7 \times 10^{-2}$ pb, we expect about 8.7×10^5 ZZ-fusion Higgses per year

Benchmark	$\lvert\eta(\mu)\rvert < 4$	$\lvert\eta(\mu)\rvert < 6$	$\lvert\eta(\mu)\rvert < 8$
$\Delta\sigma/\sigma$	15%	0.75%	0.74%

P. Li, Z. Liu, and KF Lyu, arXiv:2401.08756

The probability of getting two BINs events in the same bunch crossing in the nozzles is about

$$P(\mu^+\mu^-) = 0.0045$$

For a singe BIN rate of $\lambda = 0.1$ BIN/bunch crossing.

So, the rate for "double-BIN" events is sizeable, $\gtrsim 10^8$ per year.

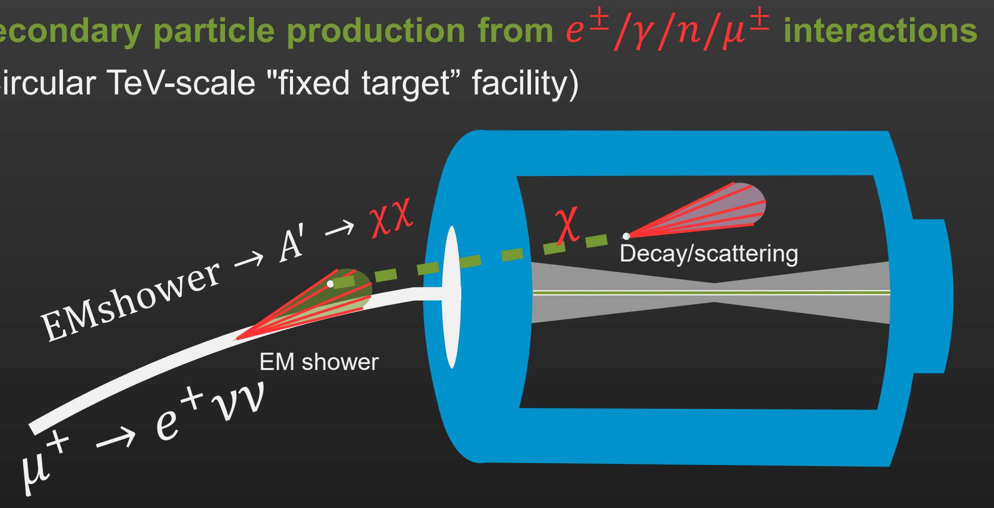
But rapidity of halo BINs is too large $\langle|\eta|\rangle \sim 8$.

Not to mention pointing, tracking, and pT cuts.

It appears not to be an issue for VBF physics with muon tagging.

More than neutrinos

Beam-induced dark particles (secondary $\mu \to e \to X$)



Electrons/positrons hit the magnets/walls/absorbers.

A MuC is essentially a high energy beam dump experiment.

The EM showers can lead to production of intermediate mass dark particles.

Around $\sqrt{s} \sim (10-40)$ GeV CoM energy in $e^{\pm}A \to Xe^{\pm}A$, bremsstrahlunging a new X particle for $E_e \sim (0.1-1)$ TeV.

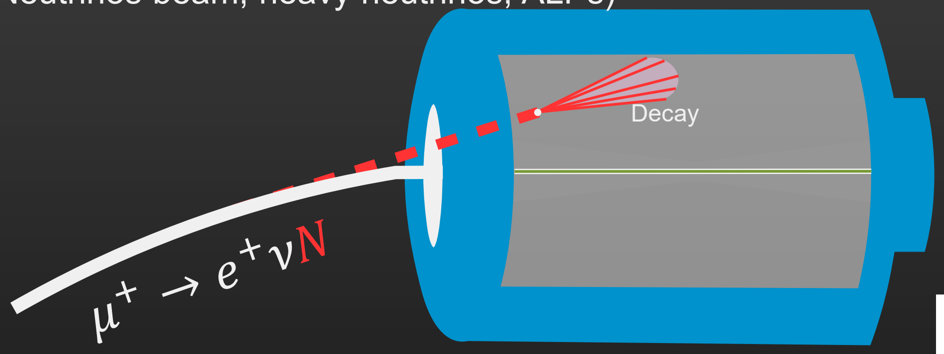
Secondary shower can also be initiated by muon beam halo (muon beam dump).

All of this still needs to be quantified for simple benchmarks. Still in discussions…

More than neutrinos

Beam-induced dark particles (primary $\mu \to X$)

Primary particle production from muon decay
(Neutrinos beam, heavy neutrinos, ALPs)

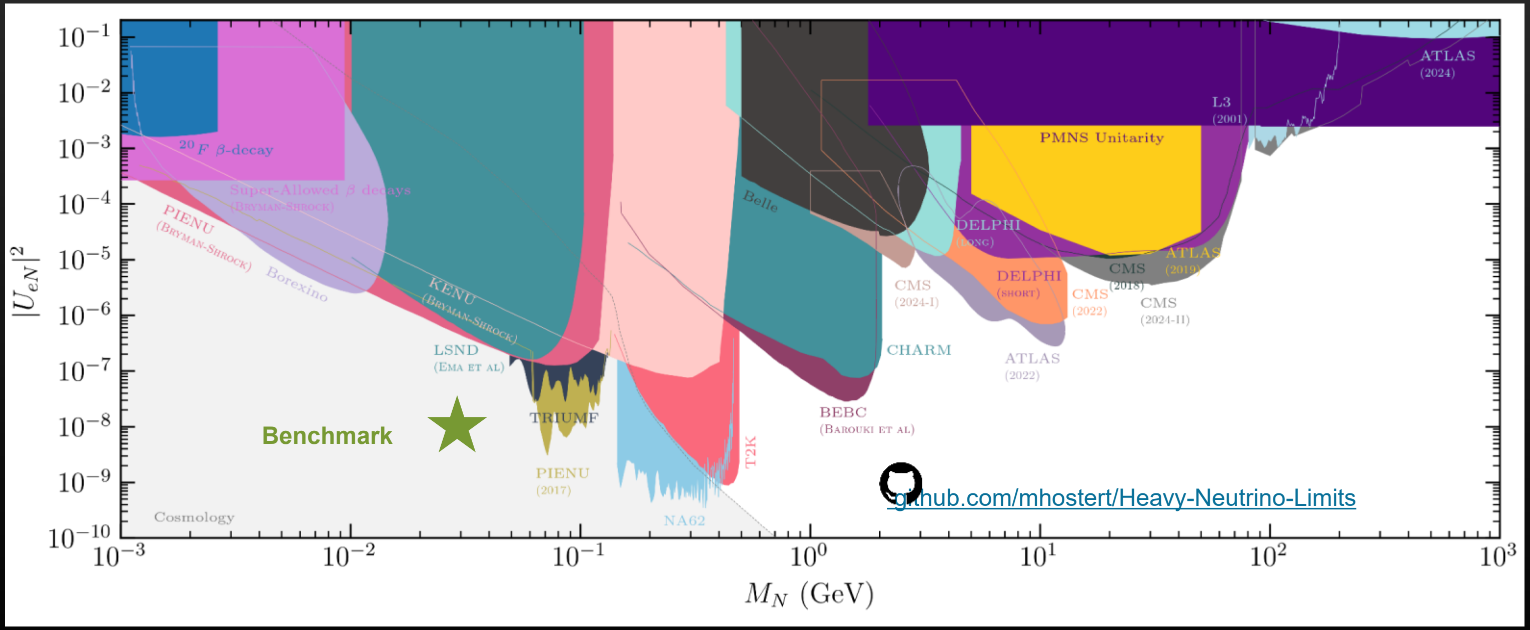


Even though statistics is really good, the boost of the new particles is bad for decay-in-flight signatures. For example:

$$N_{N\to\nu e^+e^-} \simeq \textit{(geom accep)} \times P_{\rm decay} \times \mathcal{B}(\mu \to N\nu e) \simeq 100 \times \left(\frac{|U_{\mu 4}|^2}{10^{-8}}\right)^2 \left(\frac{m_N}{30MeV}\right)$$

100 signal events may seem like a lot, but recall that $N_\nu \sim 10^{10} - 10^{11}$.

More useful for short-lived particles
(e.g., dark photons with $\varepsilon \sim 10^{-4}$)



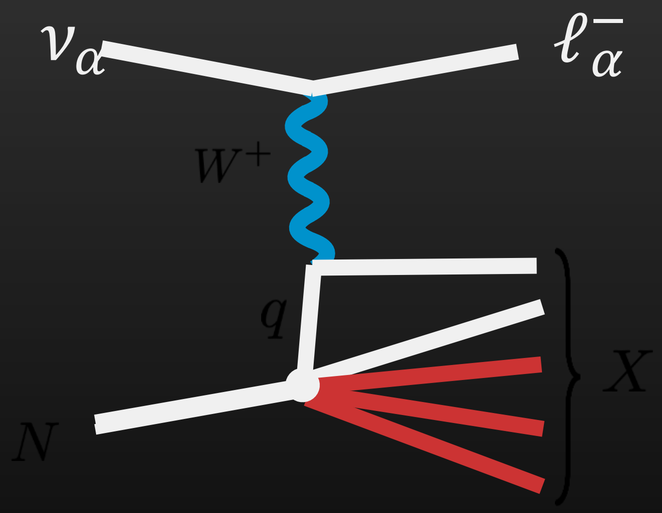
Can also consider forward region.

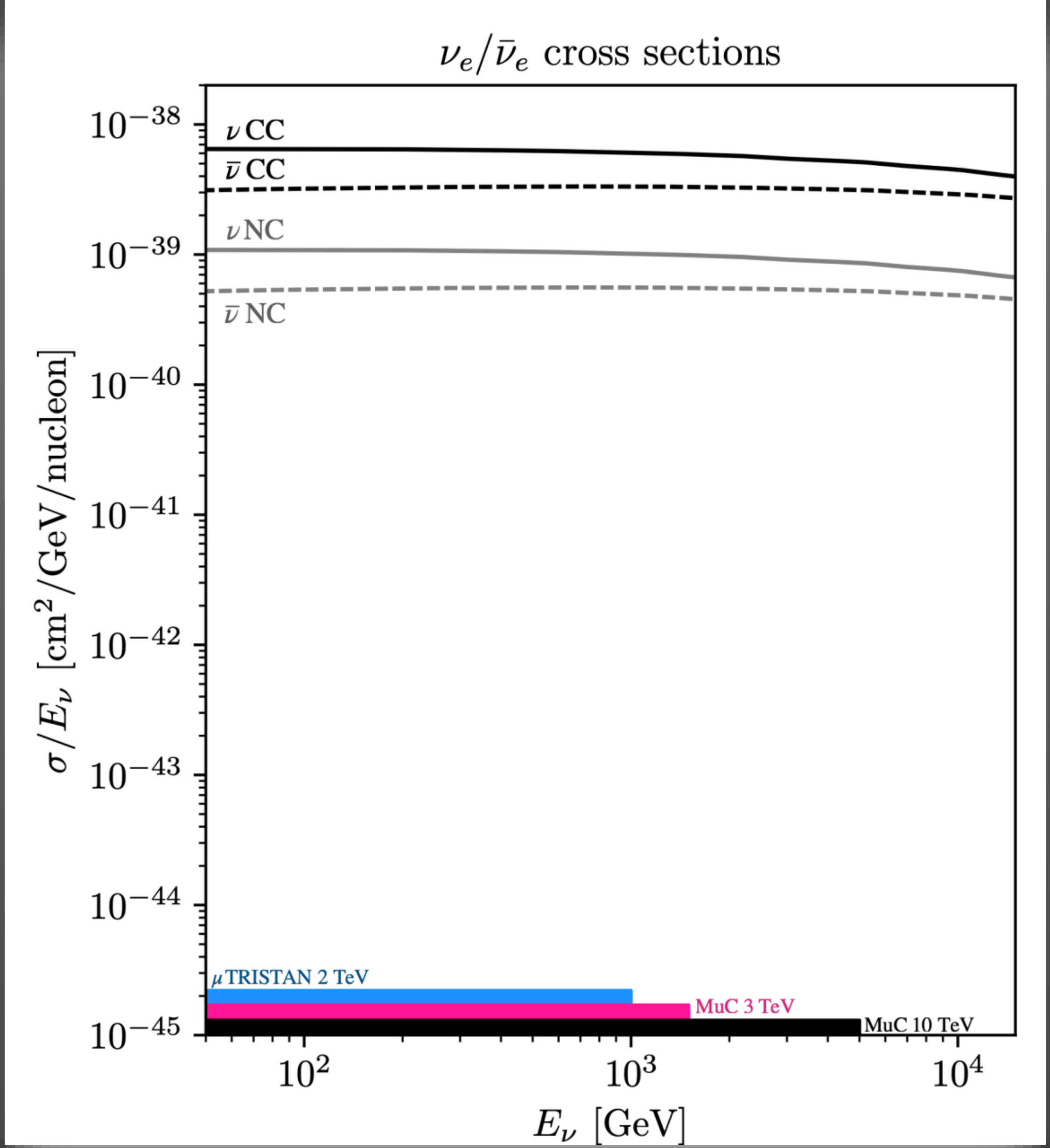
One can build very long and empty detectors to maximize $P_{\rm dec}$

Rare BIN interactions

Leptonic processes

Deep Inelastic Scattering:

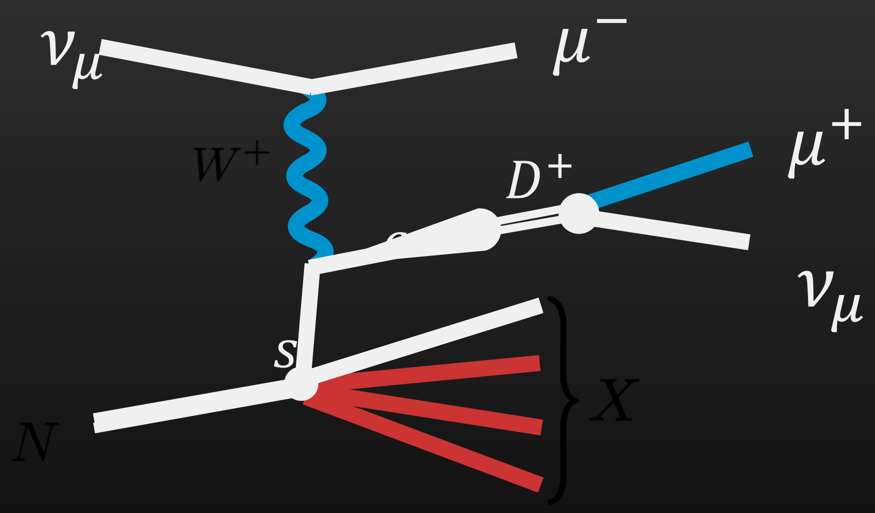


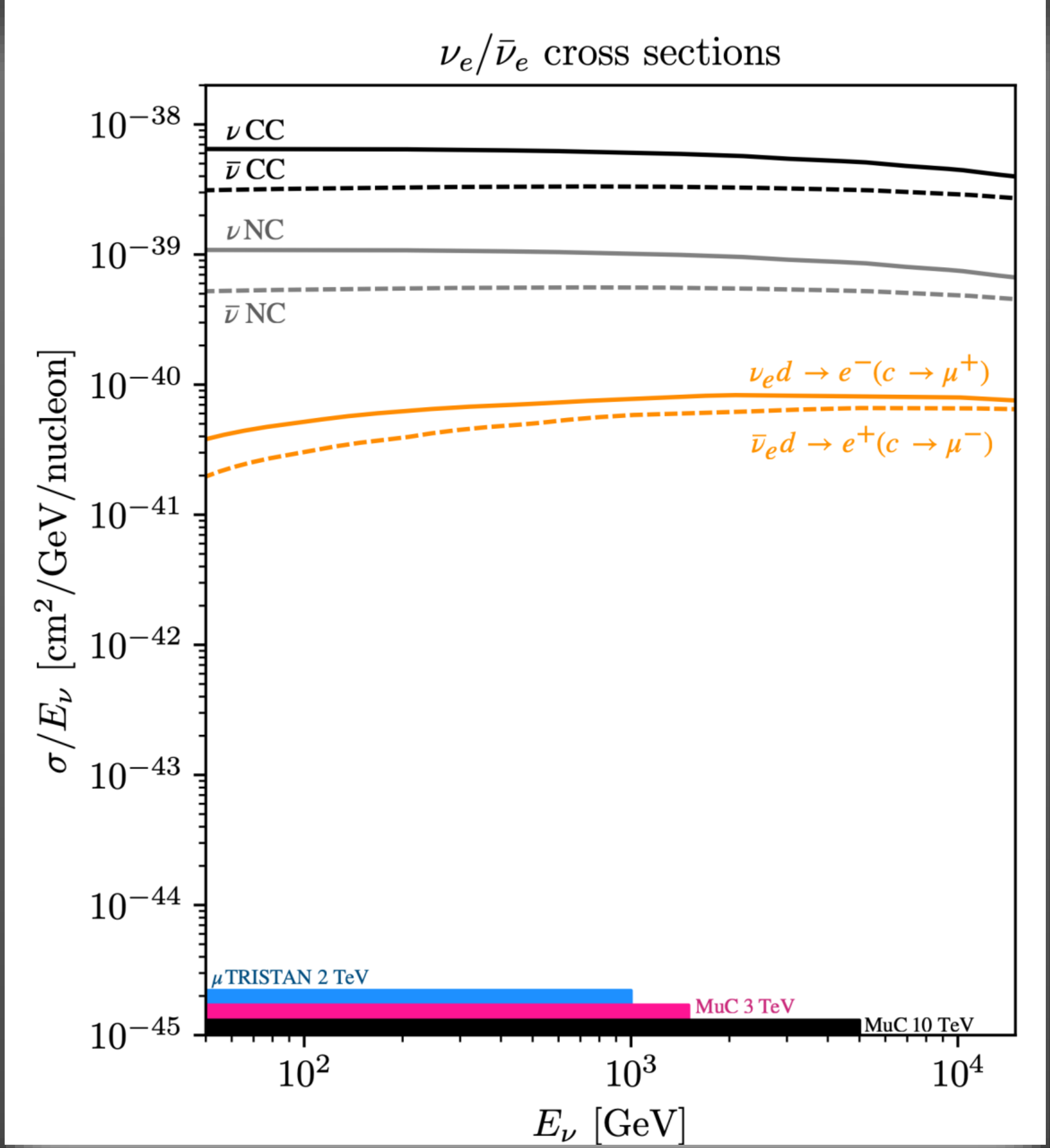


Rare BIN interactions

Leptonic processes

Di-muons from charm production:

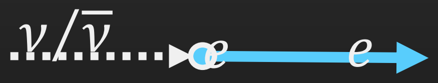




Rare BIN interactions

Leptonic processes

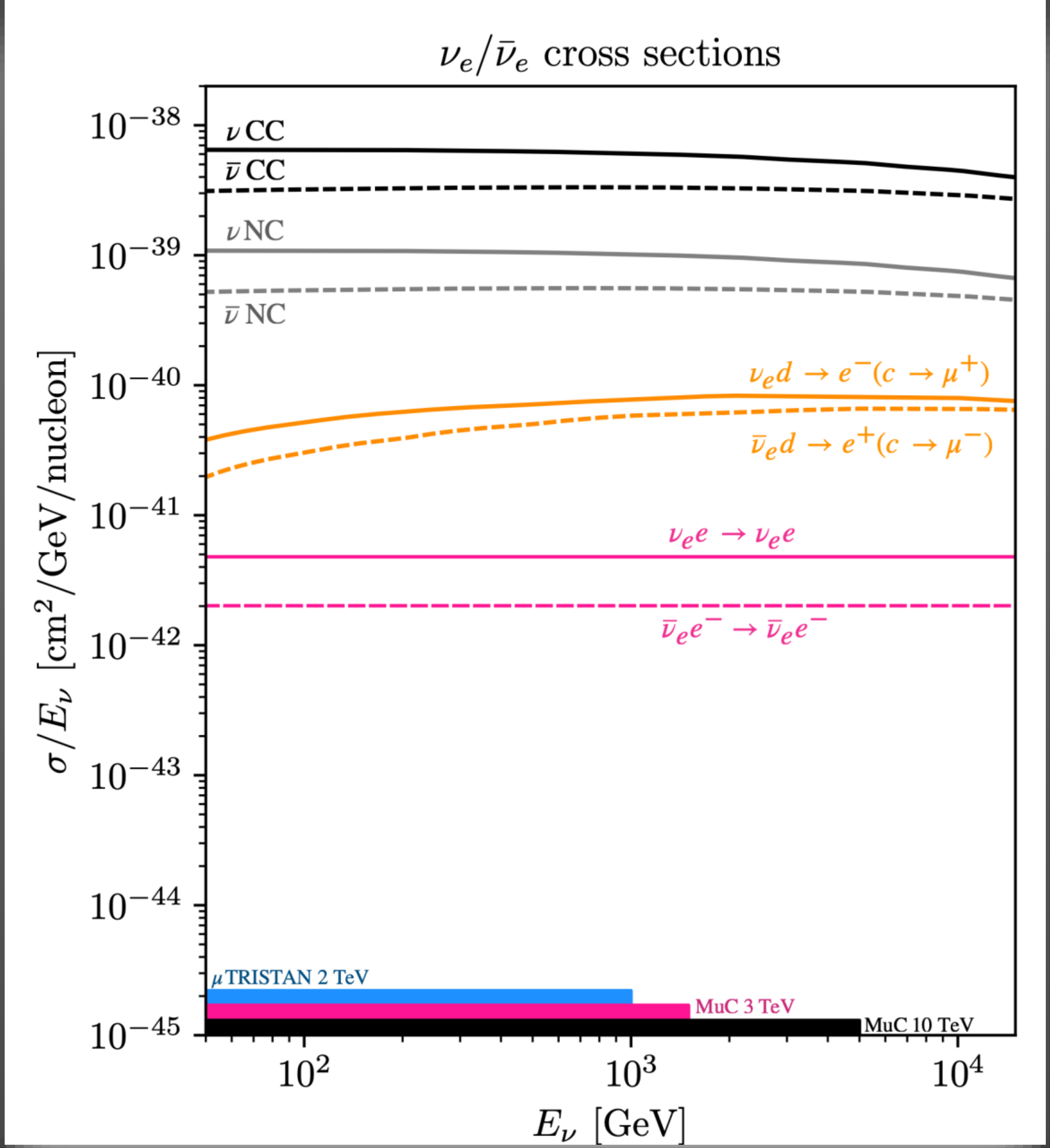
Elastic Neutrino-Electron
(CC, NC, or NC+CC)



$$\sigma/E_\nu \sim 10^{-41} cm^2/GeV$$

No hadronic activity + extremely forward lepton.

Theoretically clean probe of Weak interactions.



Rare BIN interactions

Leptonic processes

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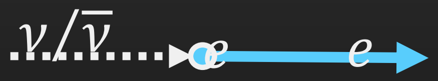
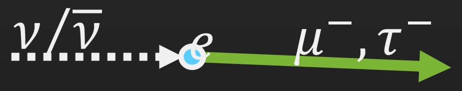


Inverse muon/tau decay (always CC)



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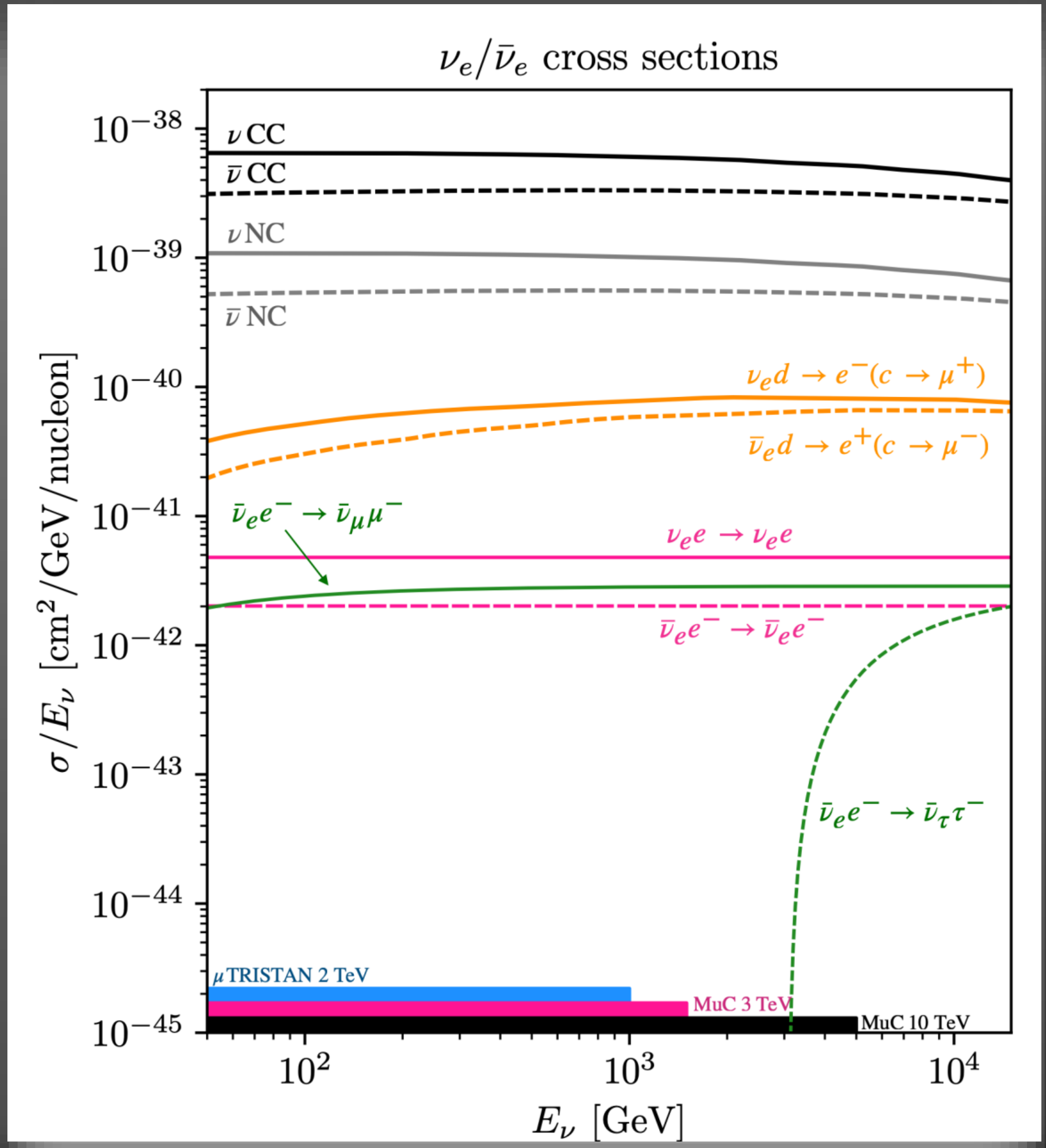
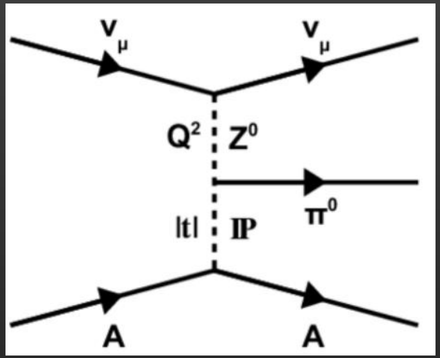


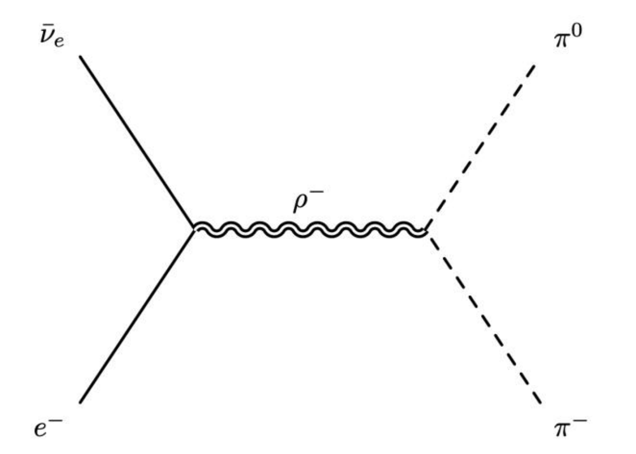
Rare BIN interactions

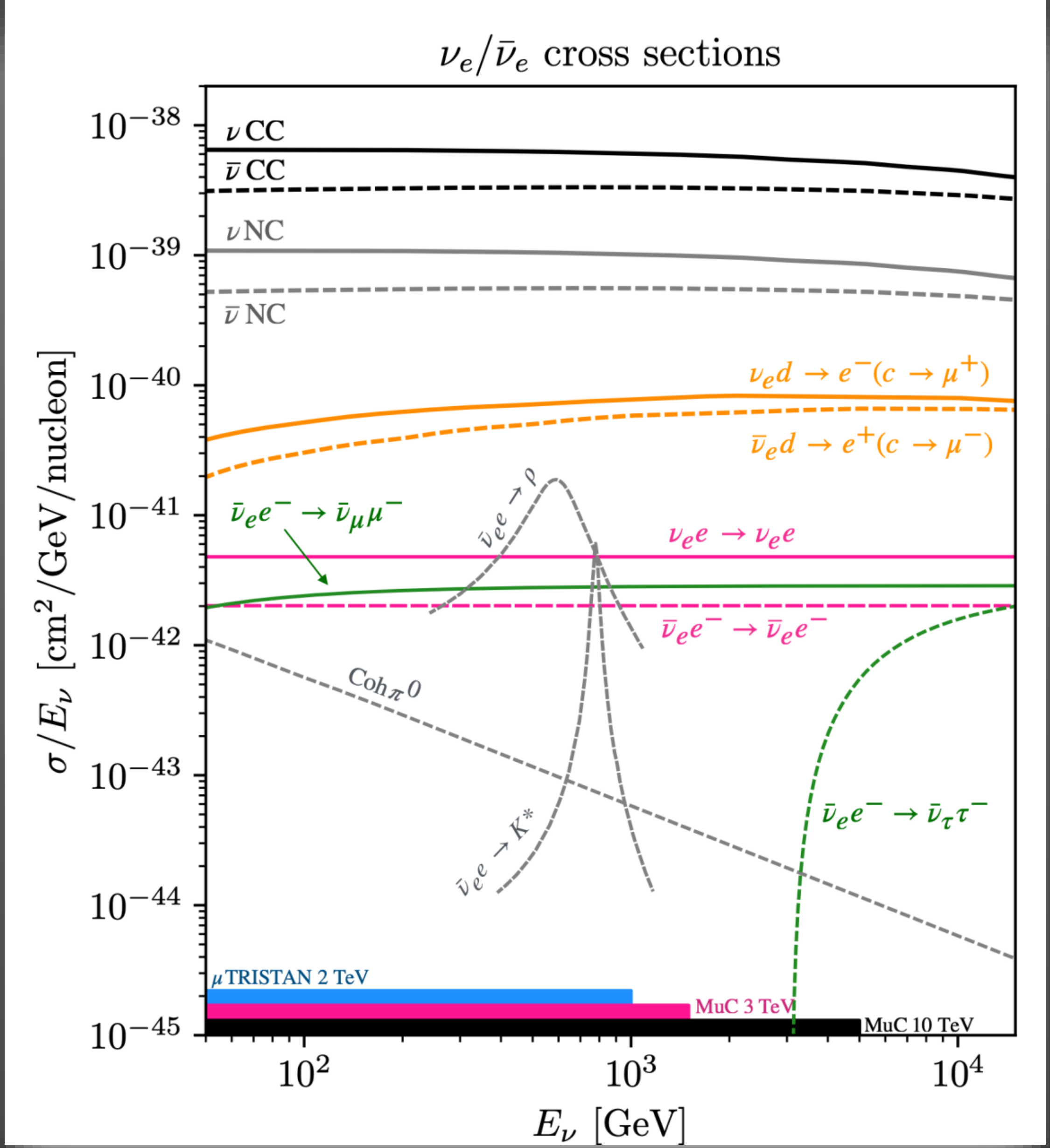
Leptonic processes

Coherent pion production:



Resonant meson production:



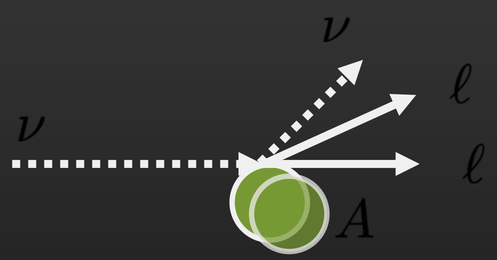


V. Brdar, A. De Gouvea, P. A. N. Machado, R. Plestid,
Resonances in $\bar{\nu}_e - e^-$ scattering below a TeV, arXiv:2112.03283

Rare BIN interactions

Leptonic processes

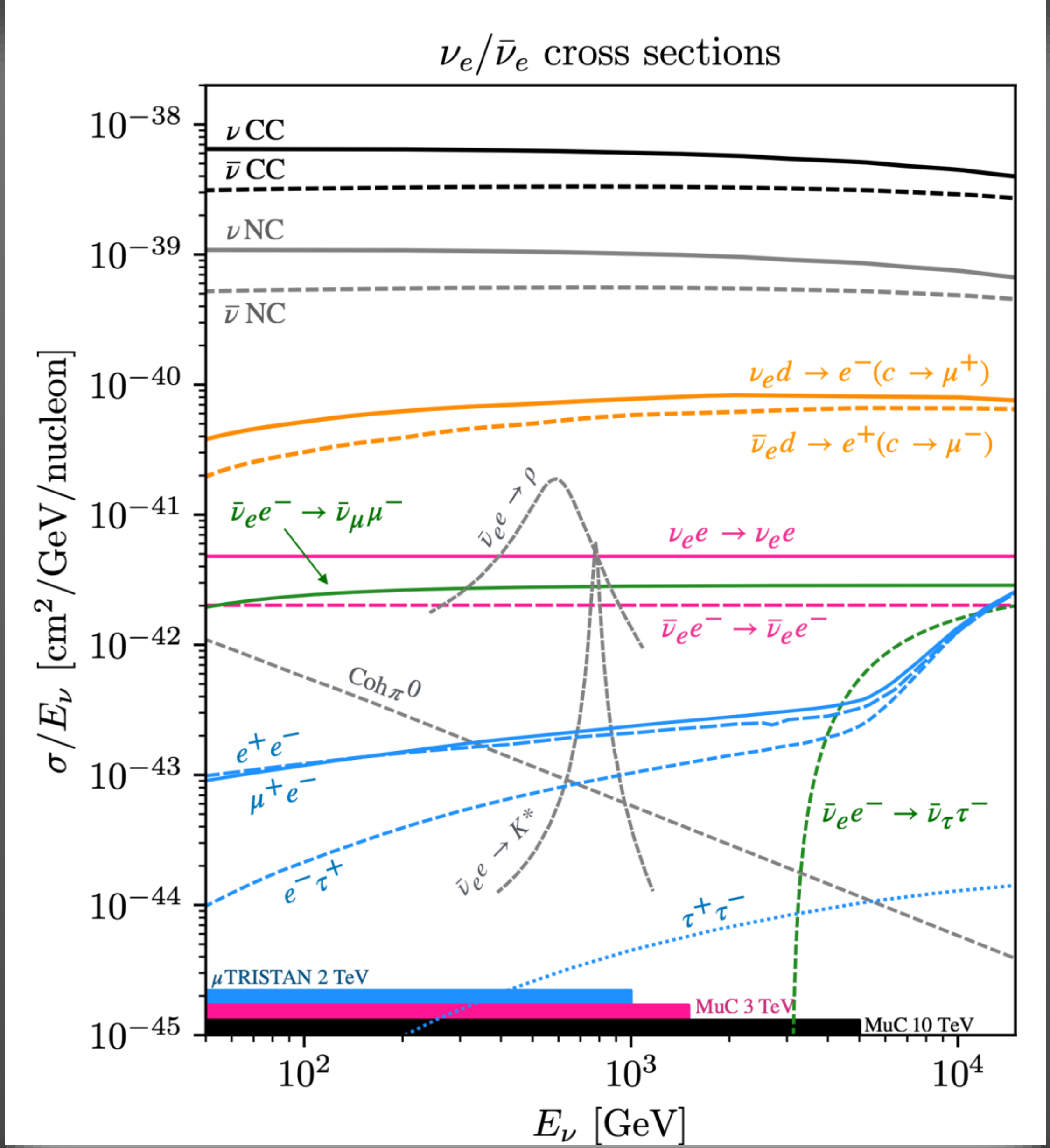
Neutrino trident scattering



$\sigma/E_\nu \sim 10^{-43} cm^2/GeV$

Clean, **very rare** process with a rich **flavour structure**.

No hadronic activity for the largest (coherent) piece.



Neutrino collider?

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 $\sigma_\mu^2 \lesssim (1\mu\mathrm{m})^2$

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

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