Opportunities for Neutrino Physics at a Future Muon Collider

Innes Bigaran, University of Tennessee in Knoxville *ibigaran@utk.edu*

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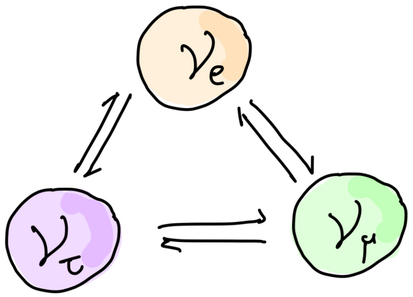
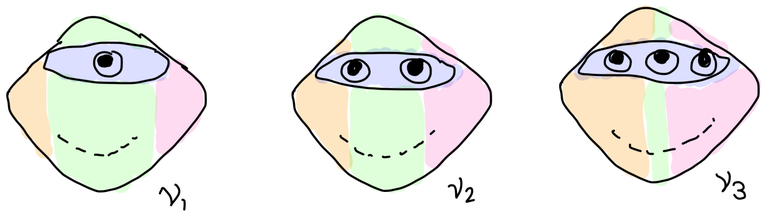
*"A Neutrino Collider within a High-Energy Muon Collider"[**IB**, de Gouvêa, Han, Low, Ma, Tabrizi & Xie] 2610.xxxx*

*"Good nus: Neutrino Physics at a Muon Collider" [**IB** ++ ~30 experimentalists/theorists]- White paper in progress, expected Nov.*

*"Tau Neutrinos at a Neutrino Factory: targeting the silver channel" [**IB**, de Gouvêa, Huber, Mishra, Thompson], In progress*

Why study leptons? Flavour→ BSM





- In the SM, neutrinos are *massless* particles and lepton flavor symmetry is conserved

$$\mathcal{G}_{\rm L} = U(1)_e \otimes U(1)_\mu \otimes U(1)_\tau$$

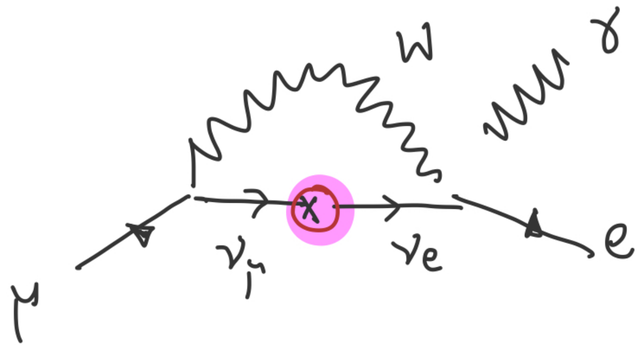
- Flavored lepton number is conserved in SM interactions, thus also total lepton number

$$L = L_\mu + L_e + L_\tau$$

- But neutrinos aren't massless, so at lepton flavor must be broken

Neutrino masses are BSM physics!

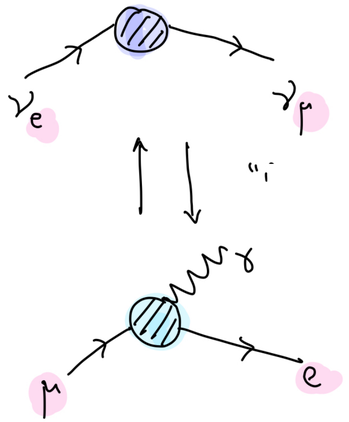
Where else do we look for flavor violation?



$< O(10^{-54})$

Petcov, 1977

Many models for neutrino mass introduce <u>other</u> new sources of LFV.



- Neutrinos and charged-leptons are part of the same SU(2) doublet $L_L \sim \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$
- Flavor-violation in neutrinos should "bleed into" the charged-lepton sector
- Adding just neutrino masses as a parameter for size of flavor-violation, the projected very small effects (projected future reach for $BR(\mu \to e\gamma) \sim \mathcal{O}(10^{-14})$)
- <u>Observing</u> charged-lepton flavor violation (CLFV) is a sign of new physics <u>beyond just neutrino masses</u>

Why collide leptons at high energy?

Precision

Clean signatures with high statistics

e.g. e^+e^- *"Luminosity"*

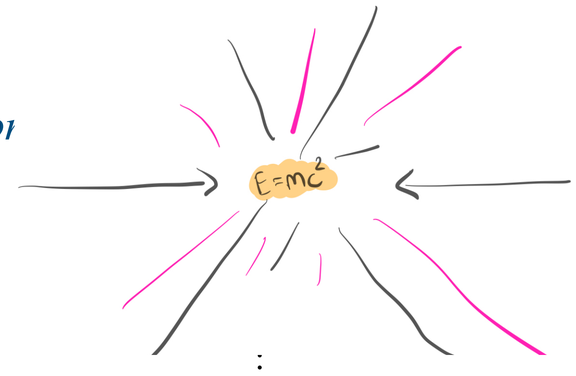
Indirect "hints" of new physics!

Discovery

High energies, on-shell productio

e.g. pp *"COM energy"*

Give the origin of new physics!



- Many open questions remain in the SM and beyond
  - Dark Matter?
  - EW-symmetry breaking?
  - Baryon asymmetry?
  - Neutrino masses?
  - Origin of flavor?

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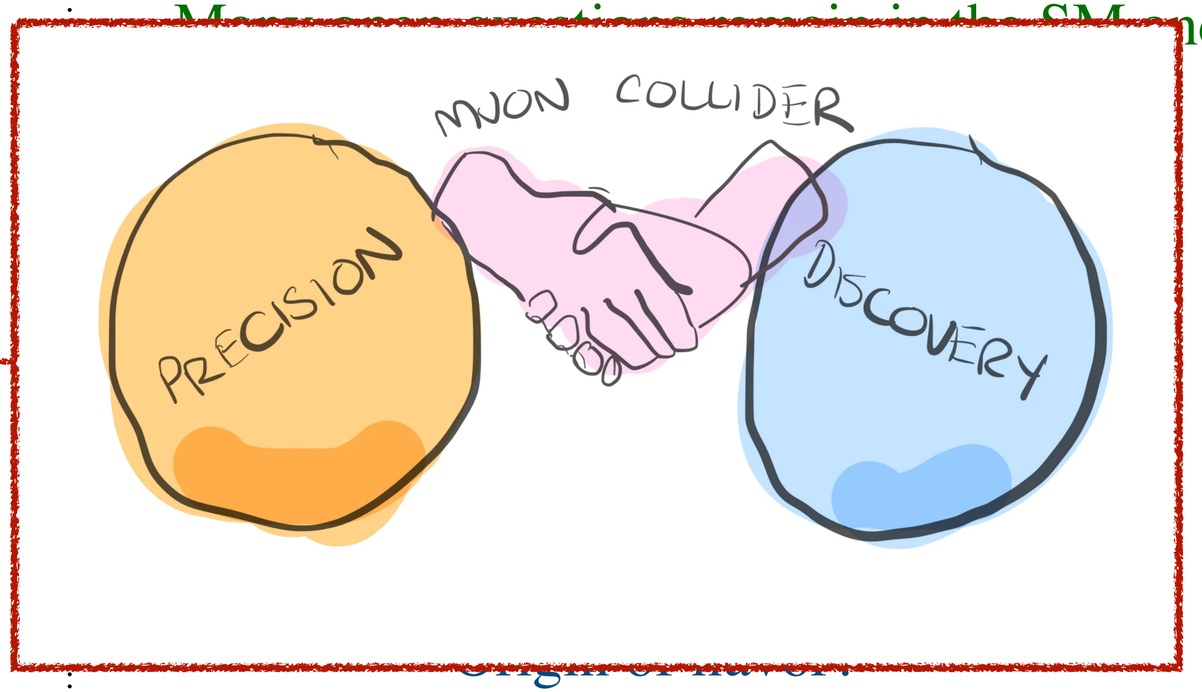
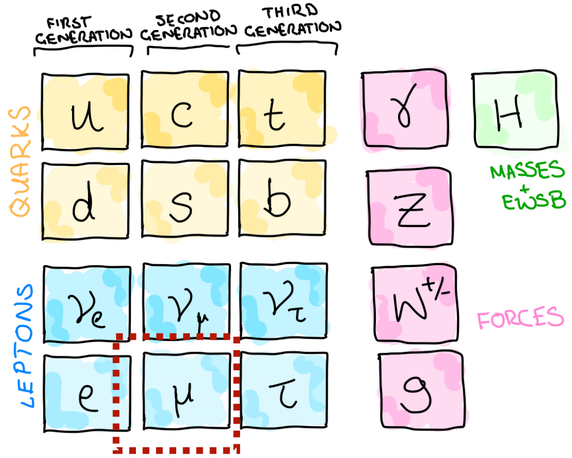
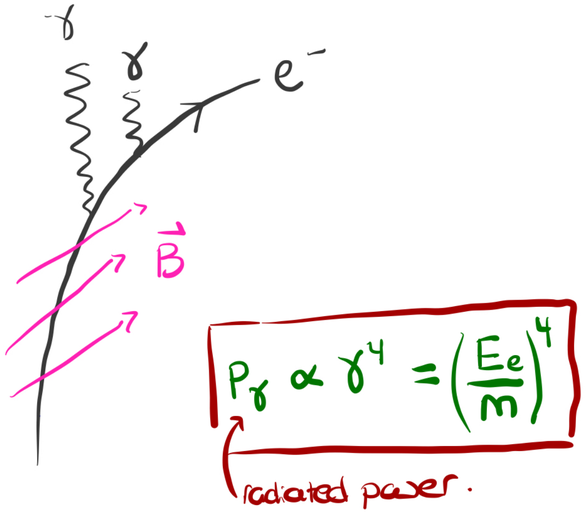


- We need precision and discovery machines!

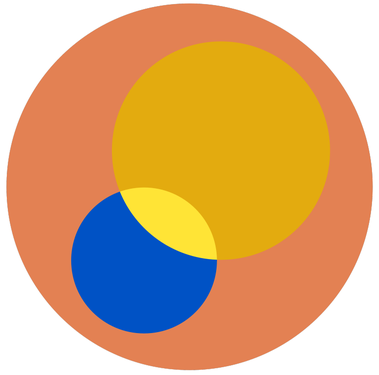
Why collide Muons?





- A high-energy muon collider has the capacity to be a precision and discovery machine
- Lepton collisions: “cleaner” than composite particle collisions, precision.
- If we accelerate electrons too high energy, high radiation E loss. This radiation loss from acceleration is suppressed for heavier particles. Muons have a higher accessible energy.
- Caveats on cooling and accelerator technology (= opportunities)!

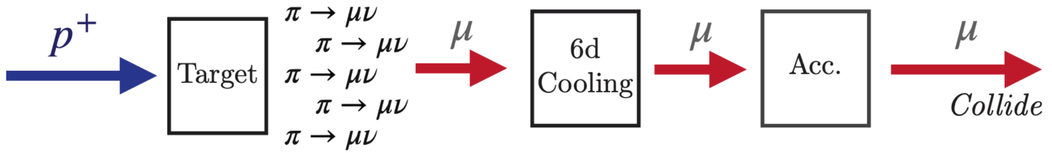




US Muon Collider Collaboration

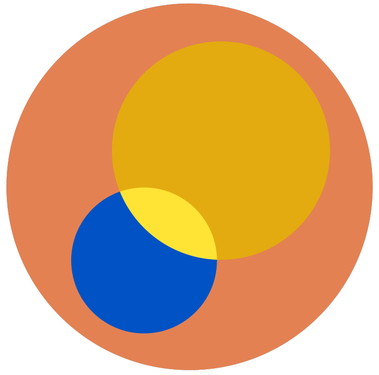
Muon acceleration and cooling

- One of the largest challenges: Muons decay! $\tau_\mu \sim 2.2 \times 10^{-6}$s



- We need to get through these steps before the muons disappear: we need the boost!
- To collimate a beam, muons need to be cooled.
- Nevertheless, we will have
  - Beam induced neutrinos: $\mu \to e\nu\bar{\nu}$
  - Unprecedented environment for electroweak radiation





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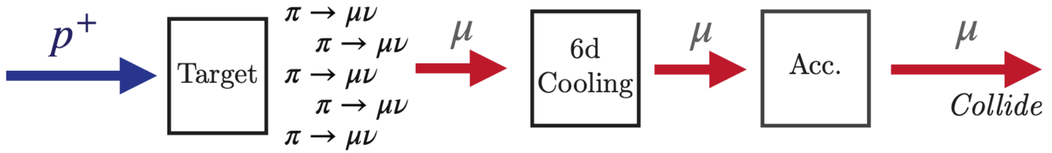

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Focus of the the remainder of this talk: Neutrino Opportunities

1. Beam induced neutrino fluxes
2. Electroweak radiation at a Muon Collider

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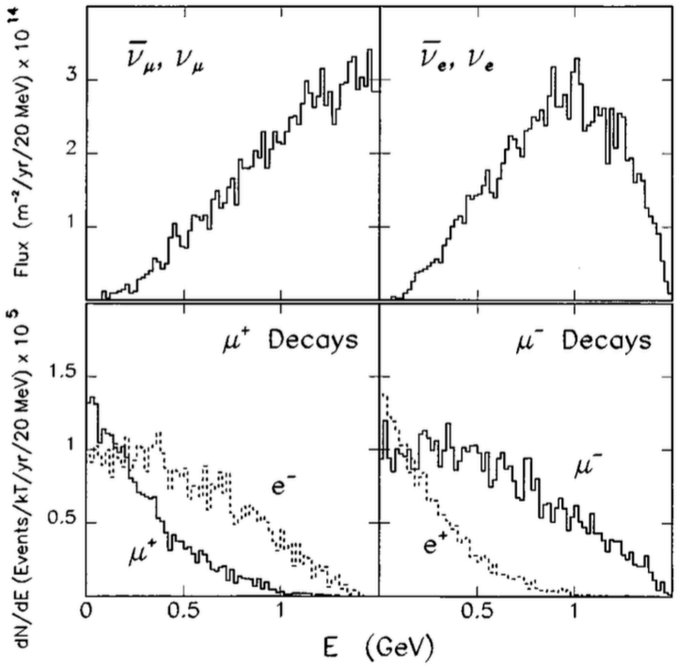
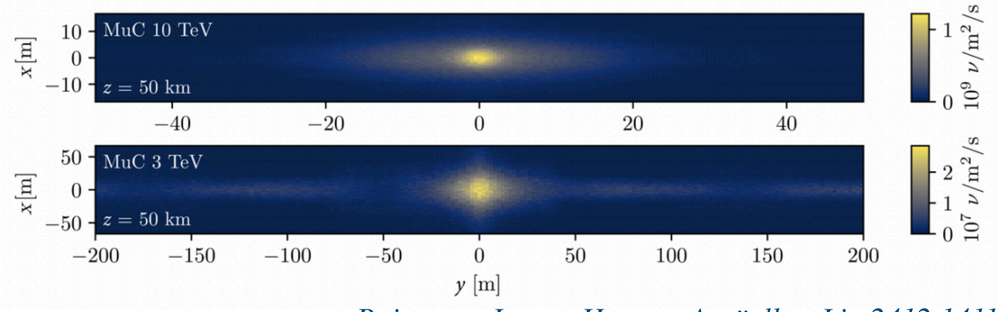
Decay neutrinos at a muon collider



1.5 GeV unpolarized muon source, 1kn downstream detector
Geer, hep-ph/9712290



Bojorquez-Lopez, Hostert, Argüelles, Liu 2412.14115

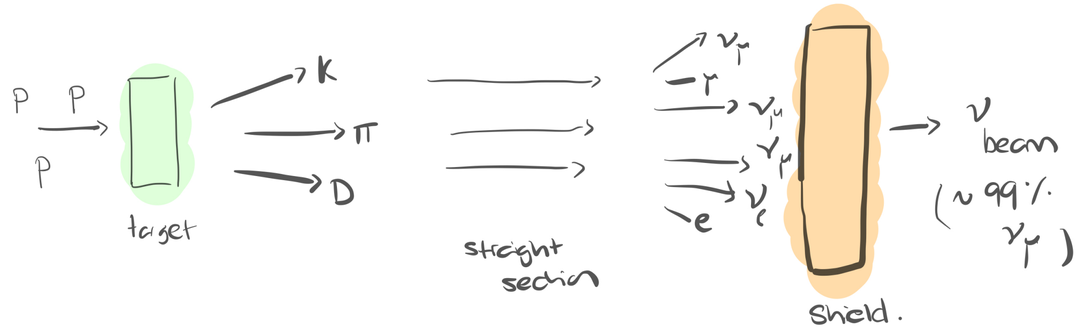
- Muons in the beam will decay primarily as $\mu^- \to e^- \bar{\nu}_e \nu_\mu$
- The neutrino flux from muon decay will be boosted into a narrow cone around the beam direction in the lab frame, with characteristic angle

$$\theta_\nu \sim \frac{m_\mu}{E_\mu} \sim \frac{10^{-4}\ \text{TeV}}{E_\mu}$$

Very Narrow Beam !

- Michel spectrum is well-known, neutrino fluxes from high-energy muon beams: equally both electron and muon flavors.

Neutrinos from Accelerators: Meson sources



- Standard accelerator neutrino fluxes rely on the decay of mesons.
- Preferential decays to muon final states for two-body meson decay, small $\mathcal{O}(1\%)$ electron neutrino content from three-body kaon decays and tau from D_s if high energy

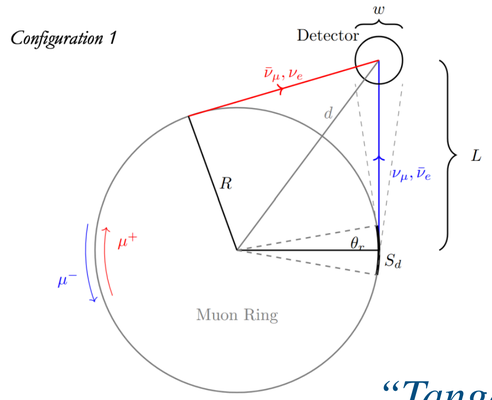
- Challenges: *Geer, hep-ph/9712290*
  - Small deviation from pure ν_μ is difficult for oscillation measurements $\nu_\mu \to \nu_x$
  - Cannot look for $\nu_e \to \nu_x$ or $\nu_\tau \to \nu_x$ oscillation
  - Uncertainty in flux for near-detector scattering

Neutrinos from Accelerators: muon sources

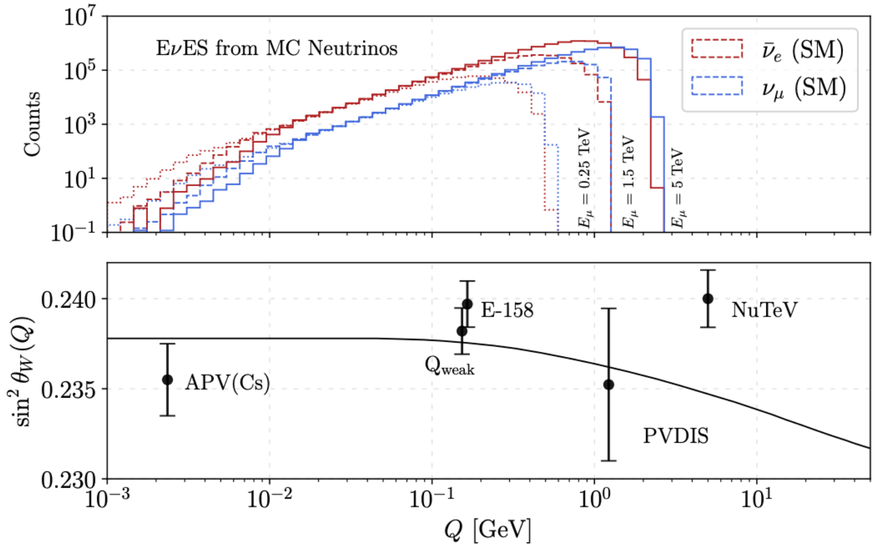


- Muon storage rings offer a unique opportunity for high well-known fluxes, including of electron neutrinos : electron neutrino scattering experiments and electron neutrino oscillations.
- Understanding electron neutrino scattering is esp. important for neutrino oscillation experiments. Reduction of key uncertainties.
- Staged collider R&D program provides opportunities for complementarity with neutrino experiments (e.g. DUNE)

Opportunities for near detection: Electron Neutrinos



"Tangential facilities"



de Gouvea, Thompson 2505.00152

- Elastic neutrino-electron scattering: pure weak at tree-level, no photon-neutrino interaction

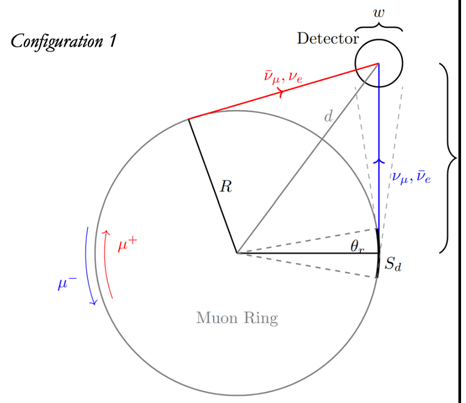
$$\nu_\alpha\, e^- \to \nu_\alpha\, e^-$$
$$\bar{\nu}_\alpha\, e^- \to \bar{\nu}_\alpha\, e^-$$

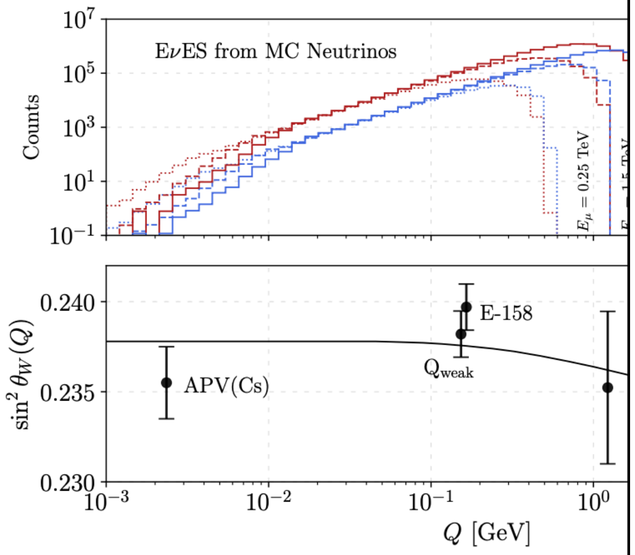
Bardin, Bilenky, Pontecorvo `70
't Hooft `71
Chen, Lee `72
Sehgal `74

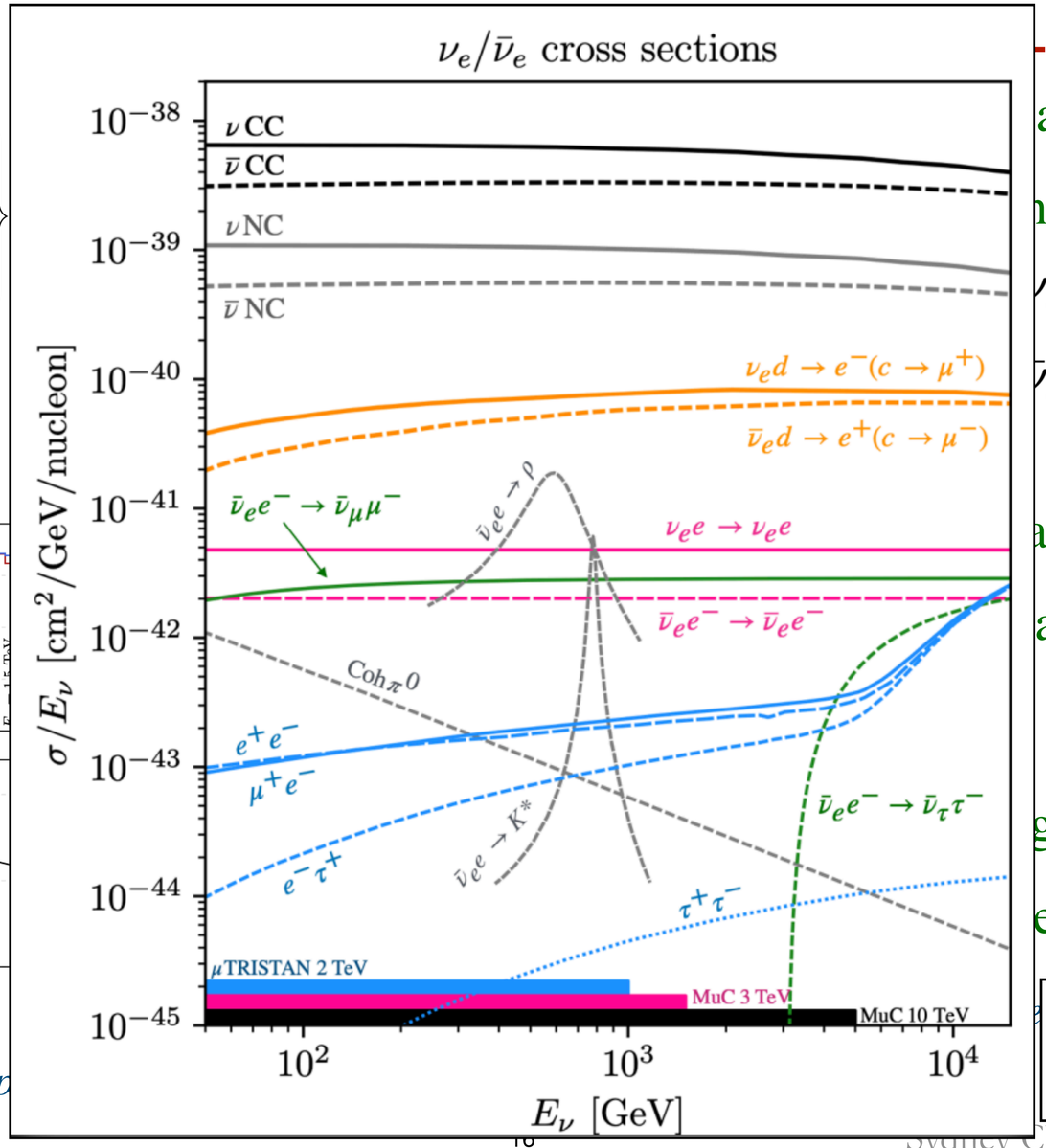
- Dependent only on SM weak charges, and the weak mixing angle: precision measurement of the weak mixing angle
- We can think about utilizing the electron-neutrino source for other novel scattering measurements.

Bojorquez-Lopez, Hostert, Argüelles, Liu 2412.14115

Opportunities for near detection: Electron Neutrinos







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Bojorquez-Lopez, Hostert, Argüelles, Liu 2412.14115

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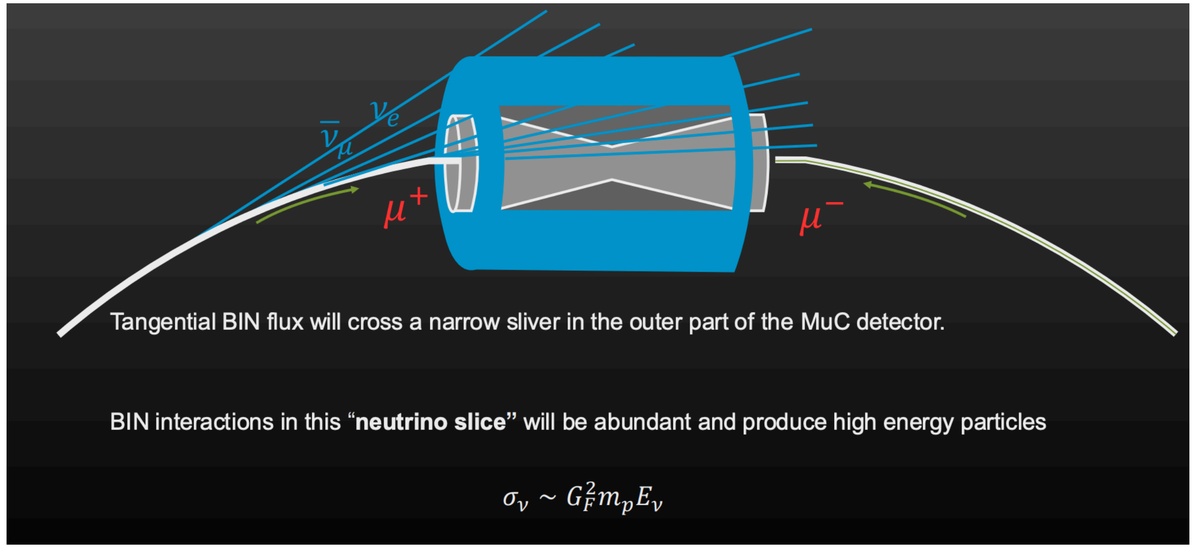
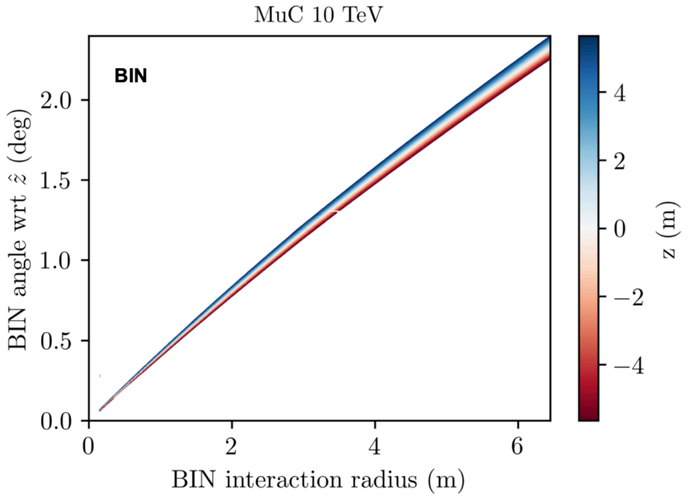
Opportunities for near detection: The Neutrino "Slice"



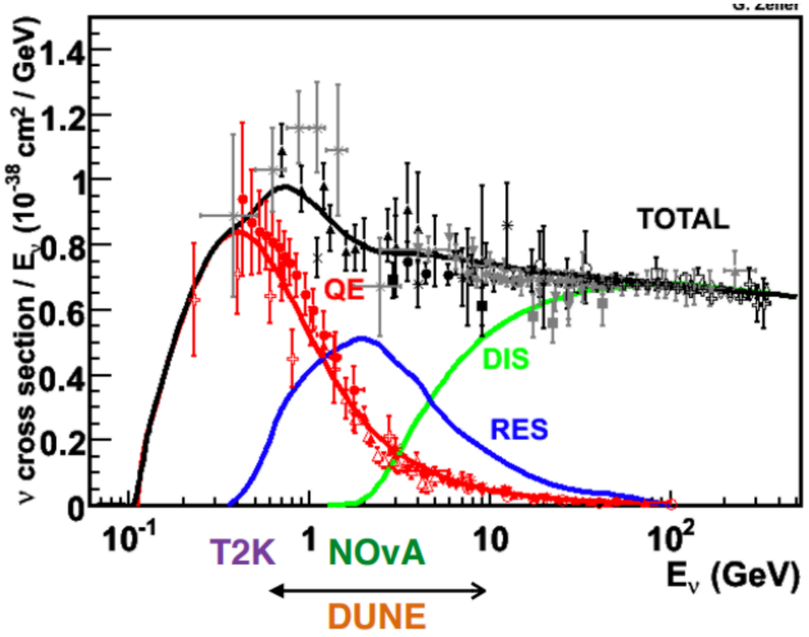
From slides by Hostert + Liu



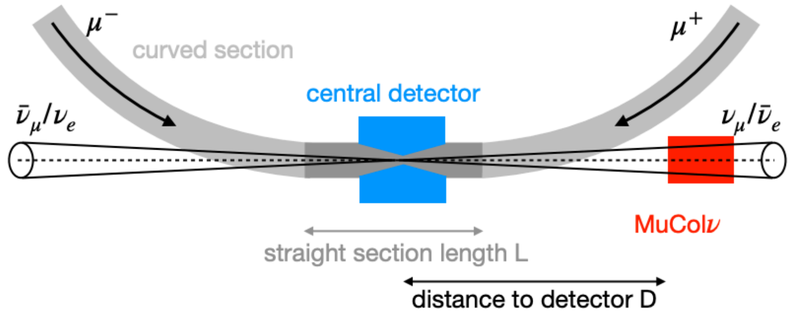
Bojorquez-Lopez, Hostert, Argüelles, Liu 2412.14115

- Rather than building an adjacent detector, could the beam induced neutrinos be detected inside the main MuC detector
- A "Slice" of these will interact with the detector and provide an opportunity for, in particular, neutrino electron scattering.
- Filtering these out of other collision products is challenging, but they have very localized interaction region. Significant dependence on beam polarization: tracer for degree of polarized muon in collision.

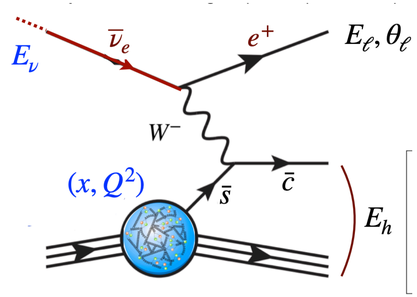
Opportunities for near detection: A Forward Facility



J.A. Formaggio, G. Zeller, Reviews of Modern Physics, 84 (2012)



- Above ~ 10 TeV neutrino-nuclear scattering is primarily Deep Inelastic Scattering off parton-content
- Utilize neutrinos from the collision point in a forward adjacent facility. *Kling, Ma, Mekala, Reuter, Tabrizi* [2508.00761]
- Neutrino DIS probes different quark contents of the hadrons.
  - EFT studies *Kling, Ma, Mekala, Reuter, Tabrizi* [2508.00761]
  - PDF studies
  - CKM measurements



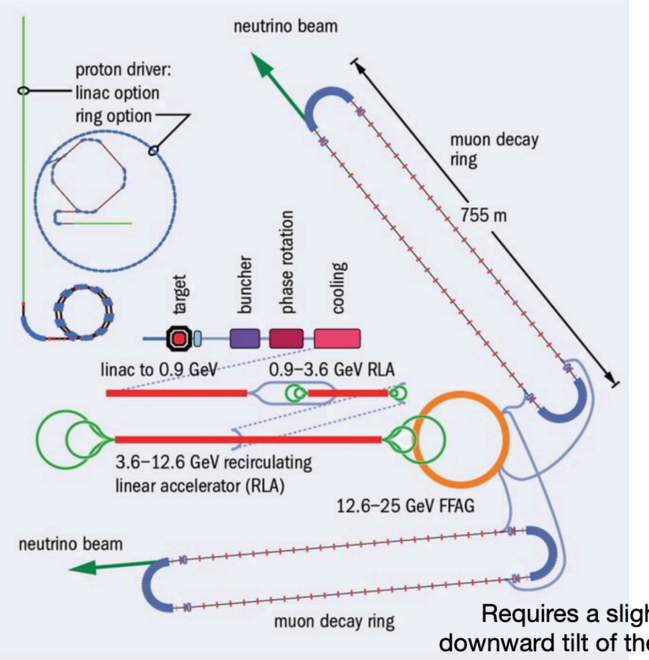
See e.g.

Bai, Xie, Zhao 2510.13948

Marzocca, Morales-Alvadaro, Montagno, Wulzer [2511.23288]

Krack, Montagno, Rojo, Wulzer, [To appear]

Opportunities for "far" detection



- **Neutrino Factory concept**: neutrinos from a straight region of muon storage ring, pointed in the direction of a detector at some distance. Target: oscillation physics.

Considered esp. in late 90s, early 2000s for measuring θ_{13} [Many refs]

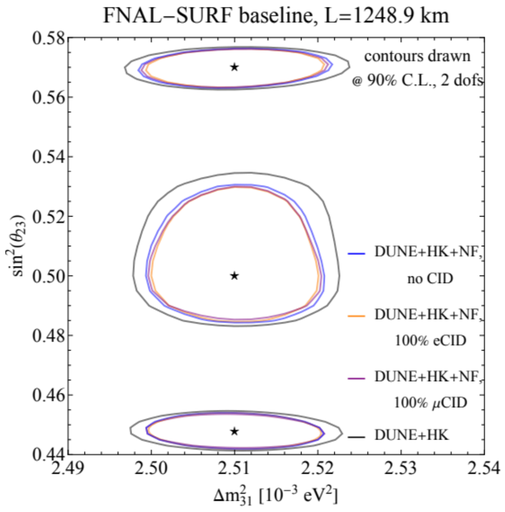
NUFACT conference series est. 1999

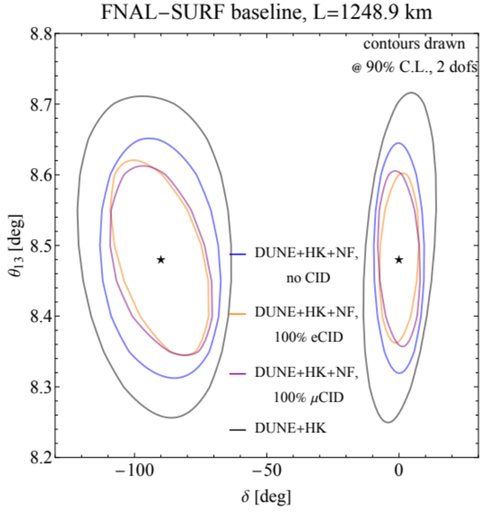
Revisited in Denton, Gehrlein 2407.02572

- ν_e, ν_μ disappearance, and ν_e, ν_μ, ν_τ appearance
- At least six new parameters in SM+ massive neutrinos, require [and are rapidly developing] precision measurements.
- See also: "Kaleidoscope" concept, directed at other large neutrino detectors elsewhere in the world.

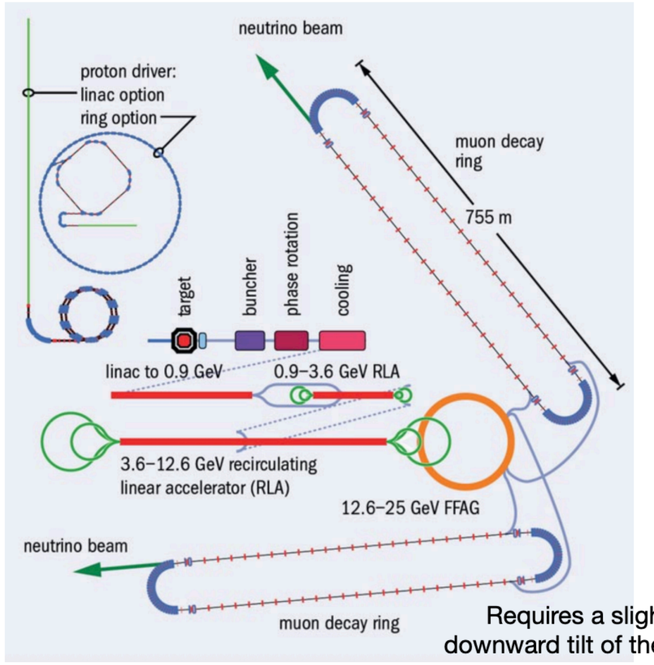
Kamp, Putnam 2508.09249

Denton, Gehrlein 2407.02572





Opportunities for "far" detection



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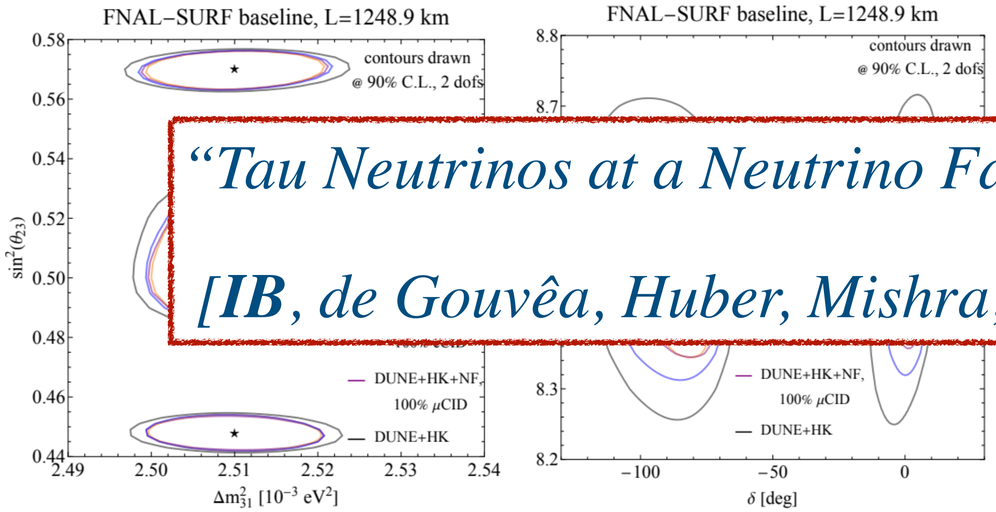

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"Tau Neutrinos at a Neutrino Factory: targeting the silver channel"

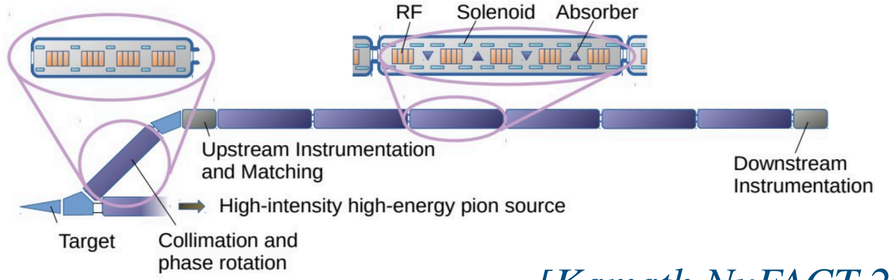
*[**IB**, de Gouvêa, Huber, Mishra, Thompson], In progress*

- See also: "Kaleidoscope" concept, directed at other large neutrino detectors elsewhere in the world.

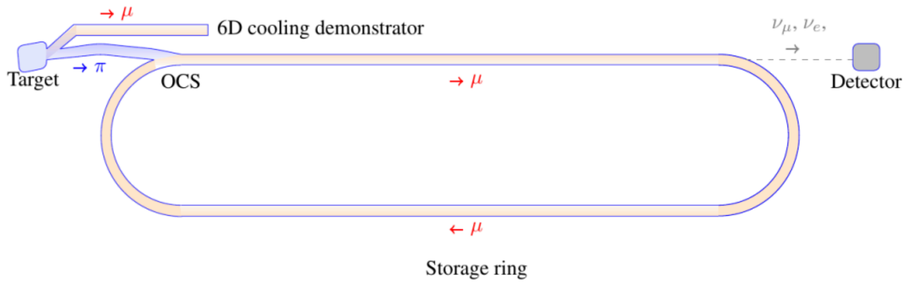
Kamp, Putnam 2508.09249

Staged program and intermediate fluxes

Cooling demonstrator proposal @ FNAL



[Kamath NuFACT 2024]



nuSTORM proposal [1206.0294, LOI]

"Neutrinos from stored muons"

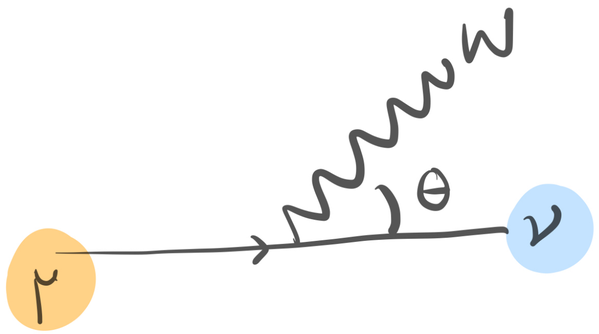
- Smaller scale high-E muon beam facility: Muon Demonstrator (~ hundreds of GeV to TeV)
- Necessary for R&D for (accelerator and) cooling, useful to also develop a supporting physics case
- Projected ~ 10^{15} useful muons on target per year, after cooling losses *USMCC+IMCC + Private communication*
- Useful for neutrino flux studies: use neutrino detector target, neutrino scattering? Enhance the utility of intermediate stages of collider development!

Focus of the the remainder of this talk: Neutrino Opportunities

1. Beam induced neutrino fluxes

2. Electroweak radiation at a Muon Collider

Electroweak radiation at a muon collider



$$L_L \sim \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

- Recall the existence of the SM neutrino in a SU(2) doublet
- A high-energy muon can radiate a massive charged vector boson with a rate

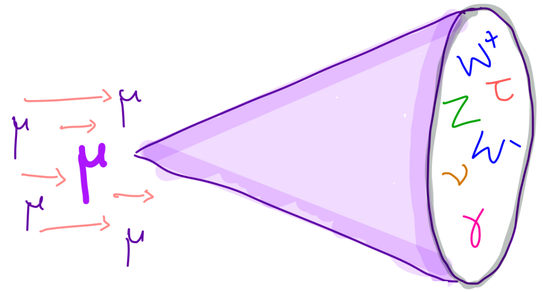
$$f_L \propto \log\left(s/M_V^2\right)$$

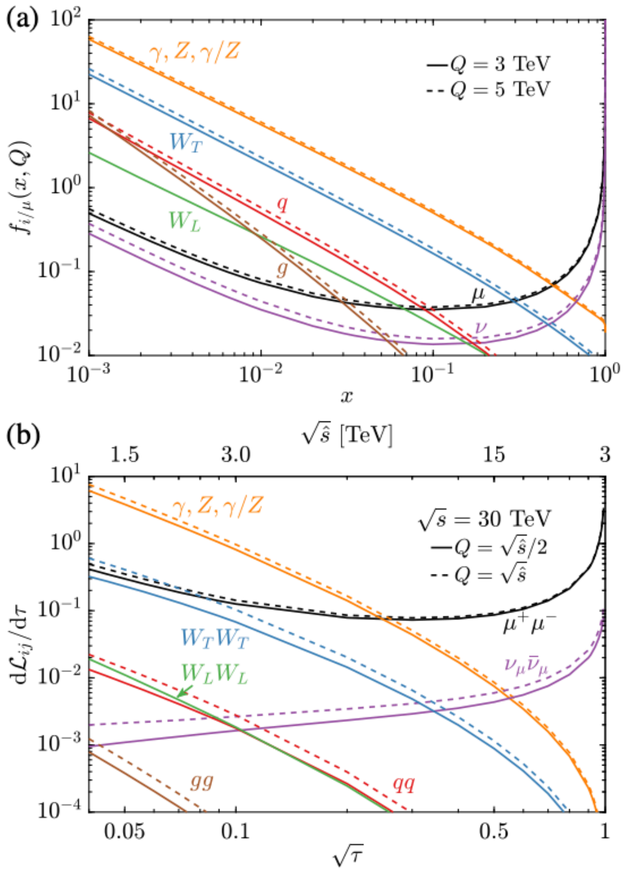
- Here we have assumed the factorization scale is roughly the COM of the collider, s, for demonstration.
- Once we reach s~ 10 TeV, this leading log is *very large* and electroweak radiation becomes very important

Chen, Gliotti, Ratazzi, Ricci, Wulzer 2202.10509
Wulzer, Glioti, Marzocca, Wulzer 2509.08132

- Distinct from QCD and QED radiation well-studied in colliders, because this emission is charge-changing. Flips a muon to a neutrino!

EW PDFs at a high-energy Muon Collider





Han, Ma, Xie, 2007.14300

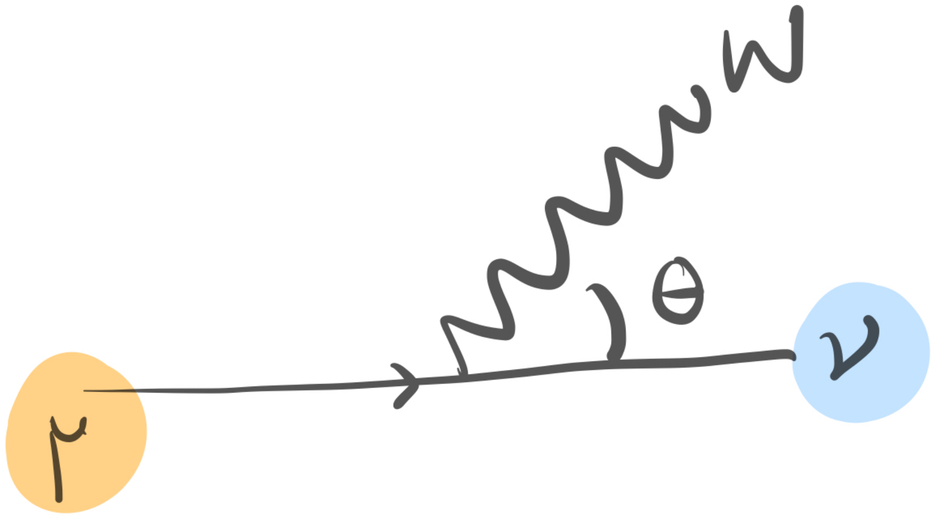
- The emissions and corrections from EW radiation at a muon collider thus require detailed study and consideration. Active undertaking by many groups worldwide [I can't possibly cite everyone]
- " A Muon Collider is an electroweak boson collider" -Petcov in LEP era
- Effective Vector-boson Approximation: factorize initial-state emissions and hard scattering, paving a way to electroweak PDF description of the muon

  Dawson '85 , Kane '85

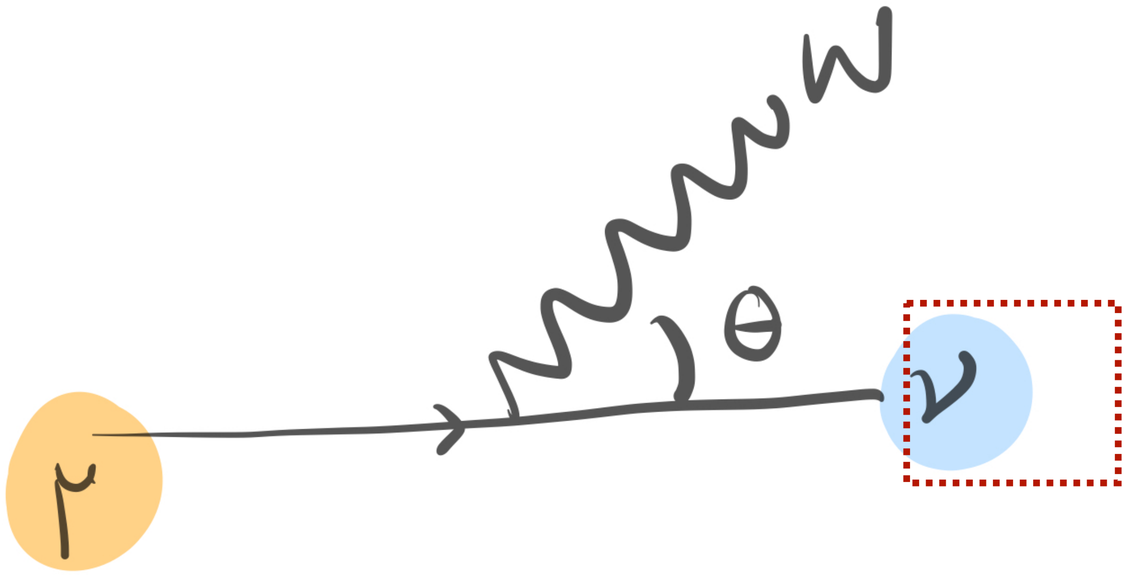
  *Revisited and implemented in MG5 (most recently **IB**, Ruiz 2502.07878)*
- Present day: Electroweak PDF description based on LLA of EVA with electroweak radiation effects included at increasing accuracy.

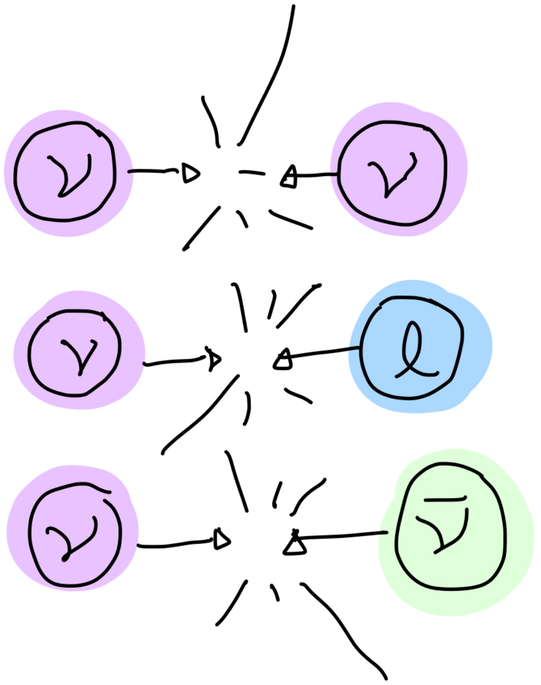
See Han, Ma, Xie, 2007.14300 and Garosi, Marzocca, Trifinopoulos 2303.16964

I don’t want to focus on EW bosons here…

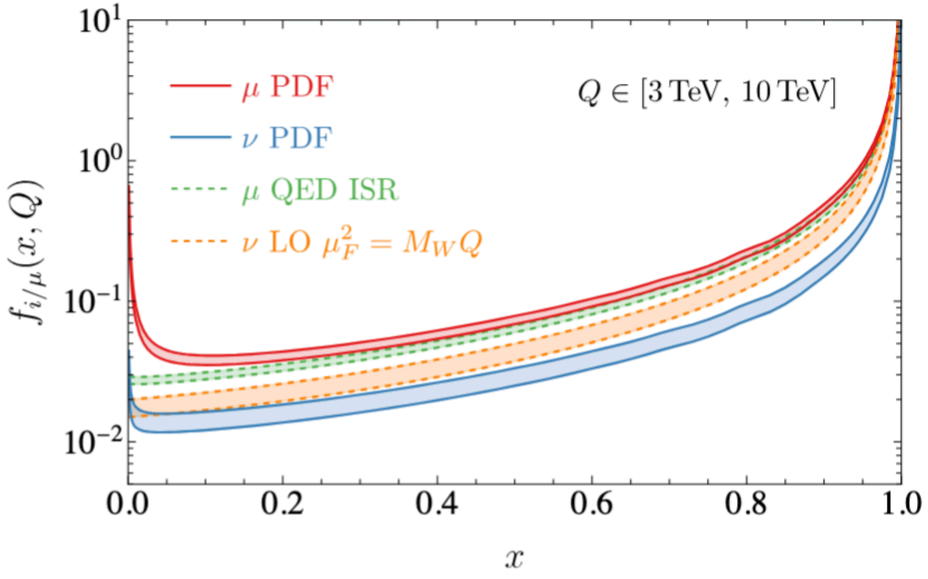


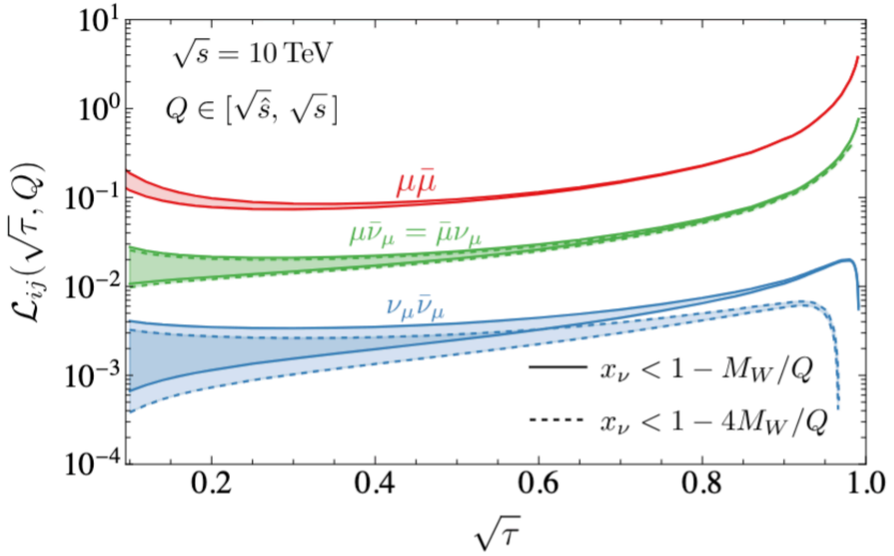
What about neutrinos in collisions?





A neutrino collision picture





***IB**, de Gouvêa, Han, Low, Ma, Tabrizi & Xie, 2610.xxxx*

- A consequence of EW splitting is that we can also define neutrino content of the muon
- Access to neutrino scattering at the collision point, and previously inaccessible energies, and in an environment not subject to nuclear effects.
- We pay a price for parton luminosity, but given the high luminosity of MuC this still leaves many events.
- Aside τ can be thought of as a measure of the fraction of energy carried by the parton. $\tau = \hat{s}/s$

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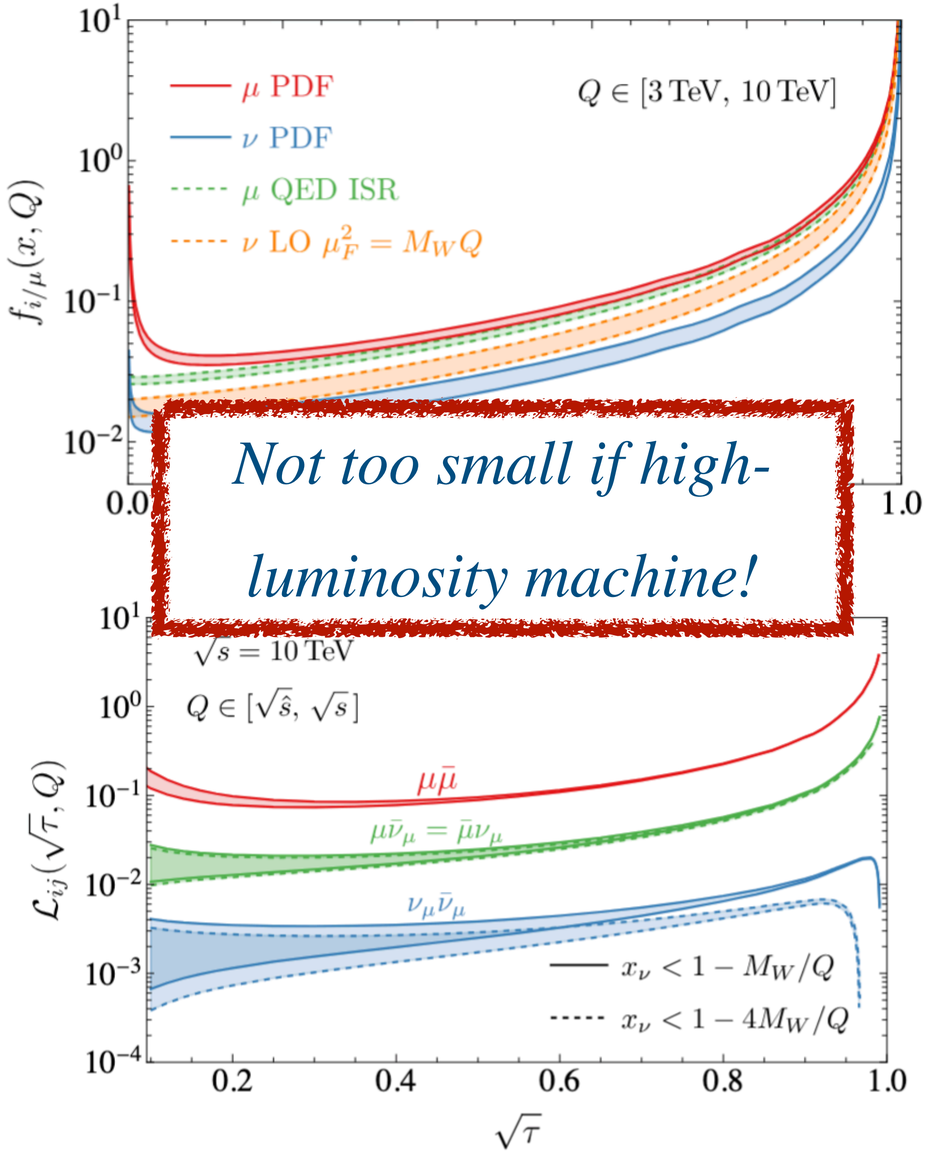

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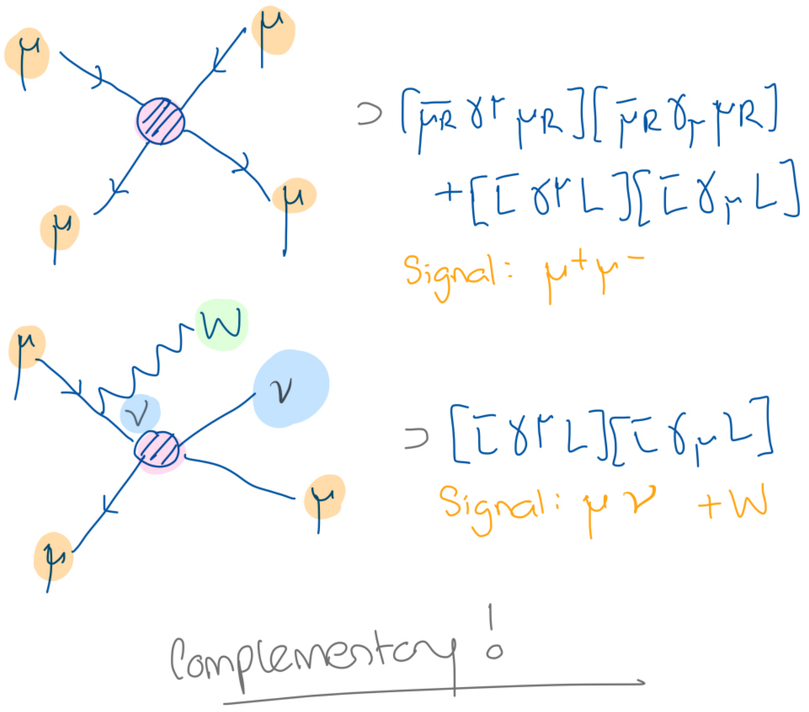
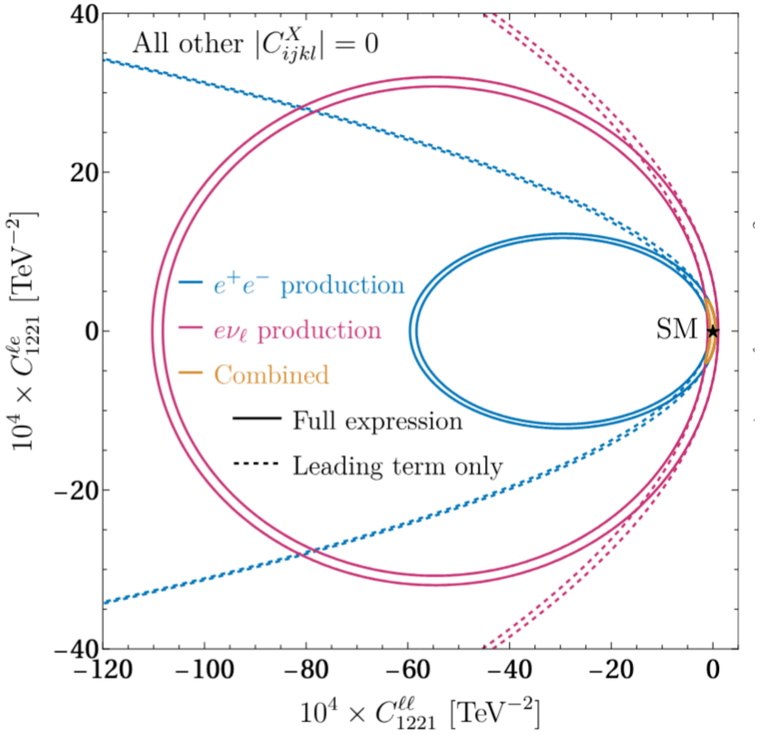
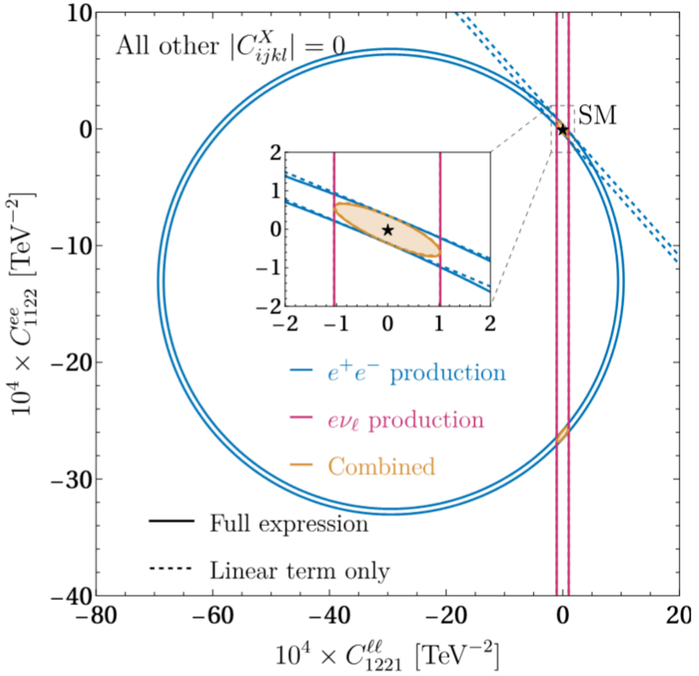
A neutrino PDF picture with EFT



- Consider for example, contact interactions with and without EW radiation
  - With EW boson emissions, you are probing different set of contact interaction at high energy in the hard scattering process. This “EW Parton” cross-sections are convolved with the EW PDFs
  - Reduce flat-directions in parameter space.
  - Measurements in a regime where EW symmetry is approximately restored.

A neutrino PDF picture with EFT





***IB**, de Gouvêa, Han, Low, Ma, Tabrizi & Xie, 2610.xxxx*

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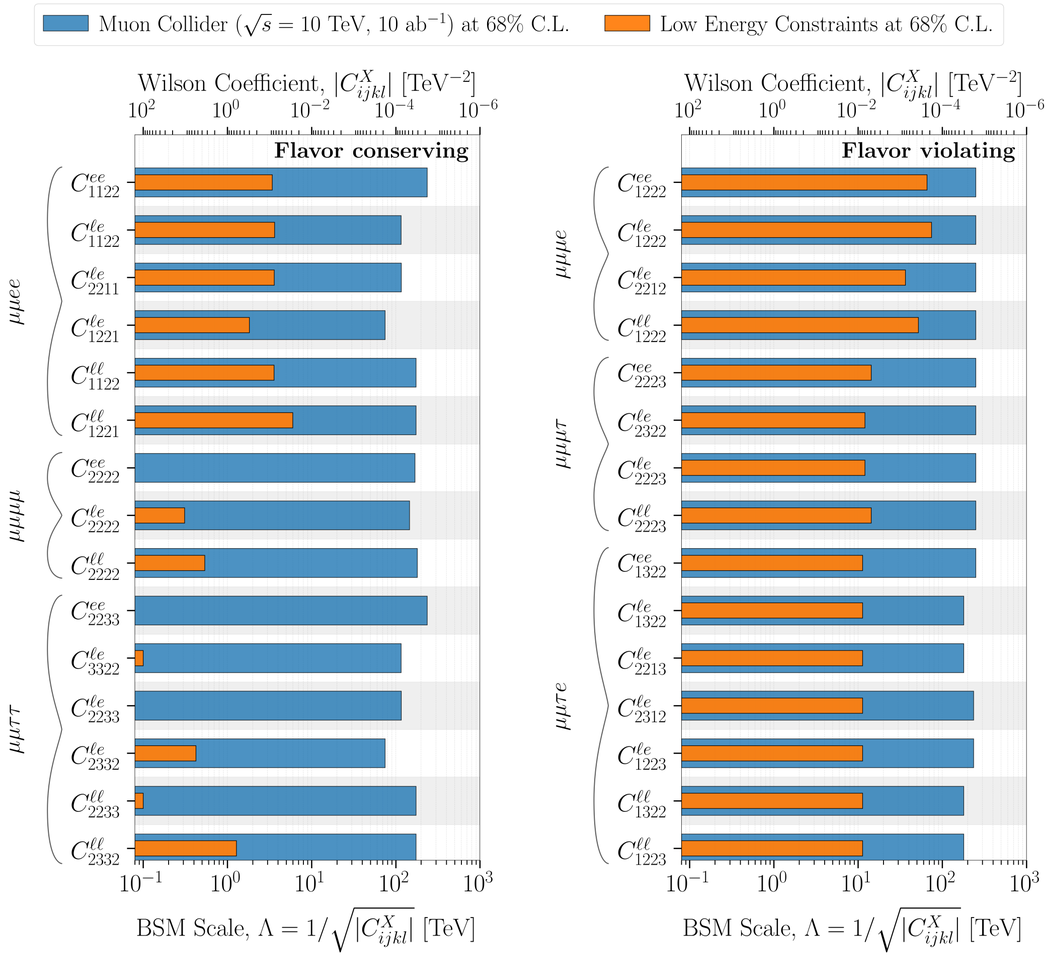
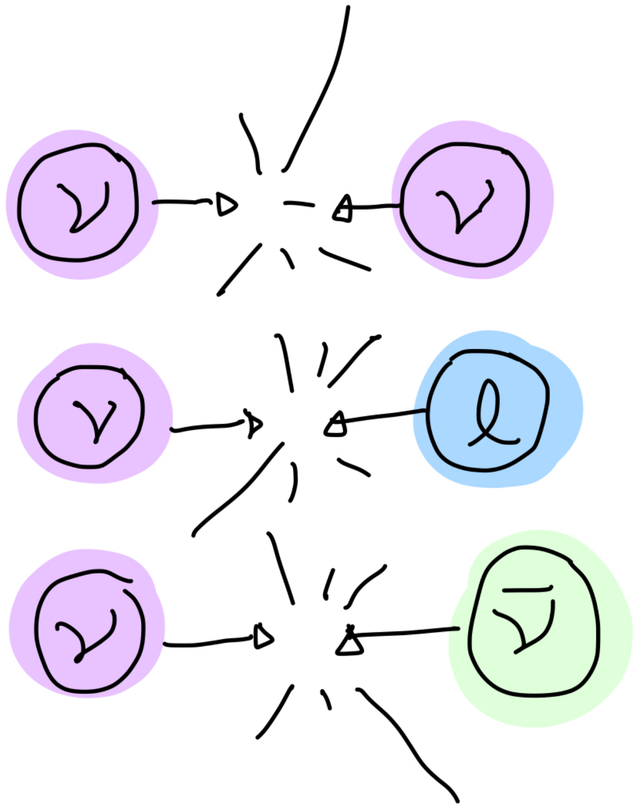
New best-constraints on EFT?



- For muon-flavor only contact interactions: present constraints from muon tridents. From, the MuC orders of magnitude improvement!
- For tau-containing contact interactions: presently there are no low-energy muon-tau constraints from neutrino physics, because of lack of tau scattering
- Constrain contact interactions which we have not had precision access to before.

See also Asadi, Bagherian, Fraser, Homiller, Lu 2509.22771 for LFV

Opportunities from neutrino PDF



- Many probes from neutrino content of the muon:

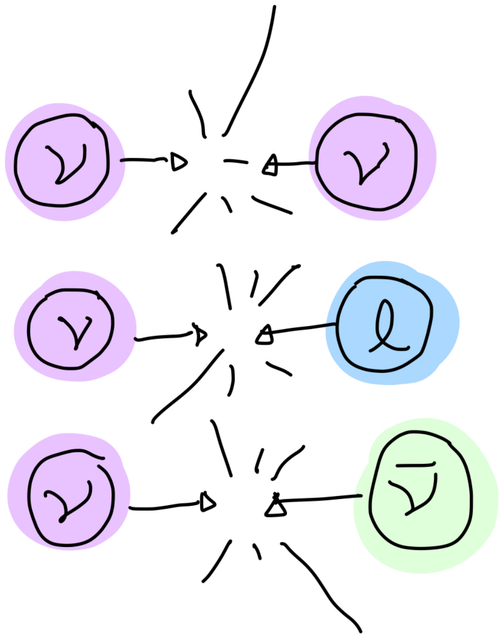
  lepton flavor violation, lepton number violation,

  neutrino-VB scattering…

  - *Capdevilla, Garosi, Marzocca, Stechauner,2410.21383*
  - *Glioti, Marzocca, Wultzer, 2509.08132*
  - ***IB**, de Gouvêa, Han, Low, Ma, Tabrizi & Xie, 2610.xxxx*

We are utilizing the PDF picture to enable easier folding-in of higher order EW radiation effects, as the work in this space develops.

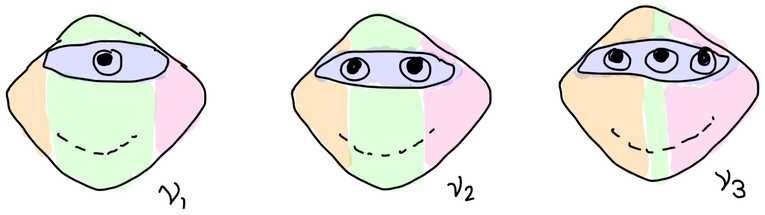
Conclusions: Good νs!



*"A Neutrino Collider within a High-Energy Muon Collider" [**IB**, de Gouvêa, Han, Low, Ma, Tabrizi & Xie] 2610.xxxx*

- A high energy lepton collider is a neutrino factory: not only in the "high baseline oscillation" sense
- We have exciting opportunities for probing SM and BSM physics in scattering, oscillation, and in collisions
- Second wave of excitement in MuC neutrinos. I didn't even get to chat about probes from regular collider searches, e.g HNLs.
- "Good nus: Neutrino Physics at a Muon Collider" White Paper in progress, should appear soon.
- Theorists and experimentalists have an exciting opportunity to work together to maximize complementarity and science output as we work towards a future Muon Collider.

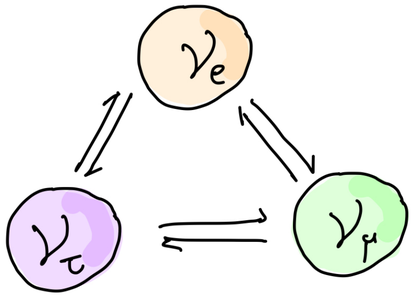
Thank ν



ibigaran@utk.edu

Backup Slides

A selection from the First wave of neutrinos at a MuC



- MURINE (Muon Ring Neutrino Experiment) [e.g. B.J. King, hep-ex/9907033] ~ 250 GeV muons storage ring.
  - Charm physics, EW precision, CKM…
- 1999 Neutrino Factory studies, decay from straight section of muon storage ring. [see also: start of NUFACT workshop series 1999] for oscillation studies, especially theta-13
- US MAP 2010 onwards: Muon Accelerator Program.
- NuSOnG (Neutrino Scattering on Glass) [0803.0354] Tevatron-based neutrino beam.
  - Precision EW, DIS QCD

- NuSTORM (Neutrinos from Stored Muons) [~1-6 GeV] , [1206.0294 LOI]

  - Neutrino scattering