# Neutrinos at current/future collider

# through a muon path

**Qiang Li, Peking University 2024/05**

1. Heavy Majorana Neutrino at CMS PRL 2023, editors' suggestions
2. Heavey Majorana Neutrino at Same-Sign MuC PRD2024
3. Neutrino-neutrino Collisions JPG2024

第三届地下和空间粒子物理与宇宙物理前沿问题研讨会

# From current to future colliders: muon path

THIS. IS. OUR. MUON. SHOT!

recent US P5 report

Exploring the Quantum Universe

## 2.3 The Path to a 10 TeV pCM

Realization of a future collider will require resources at a global scale and will be built through a world-wide collaborative effort where decisions will be taken collectively from the outset by the partners. This differs from current and past international projects in particle physics, where individual laboratories started projects that were later joined by other laboratories. The proposed program aligns with **the long-term ambition of hosting a major international collider facility in the US, leading the global effort** to understand the fundamental nature of the universe.

…

In particular, a muon collider presents an attractive option both for technological innovation and for bringing energy frontier colliders back to the US. The footprint of **a 10 TeV pCM muon collider is almost exactly the size of the Fermilab campus**. A muon collider would rely on a powerful multi-megawatt proton driver delivering very intense and short beam pulses to a target, resulting in the production of pions, which in turn decay into muons. This cloud of muons needs to be captured and cooled before the bulk of the muons have decayed. Once cooled into a beam, fast acceleration is required to further suppress decay losses.

…

Although **we do not know if a muon collider is ultimately feasible**, the road toward it leads from current Fermilab strengths and capabilities to **a series of proton beam improvements and neutrino beam facilities**, each producing world-class science while performing critical R&D towards a muon collider. At the end of the path is an unparalleled global facility on US soil. **This is our Muon Shot.**

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**Patrick Meade** @theory_dad · 11h

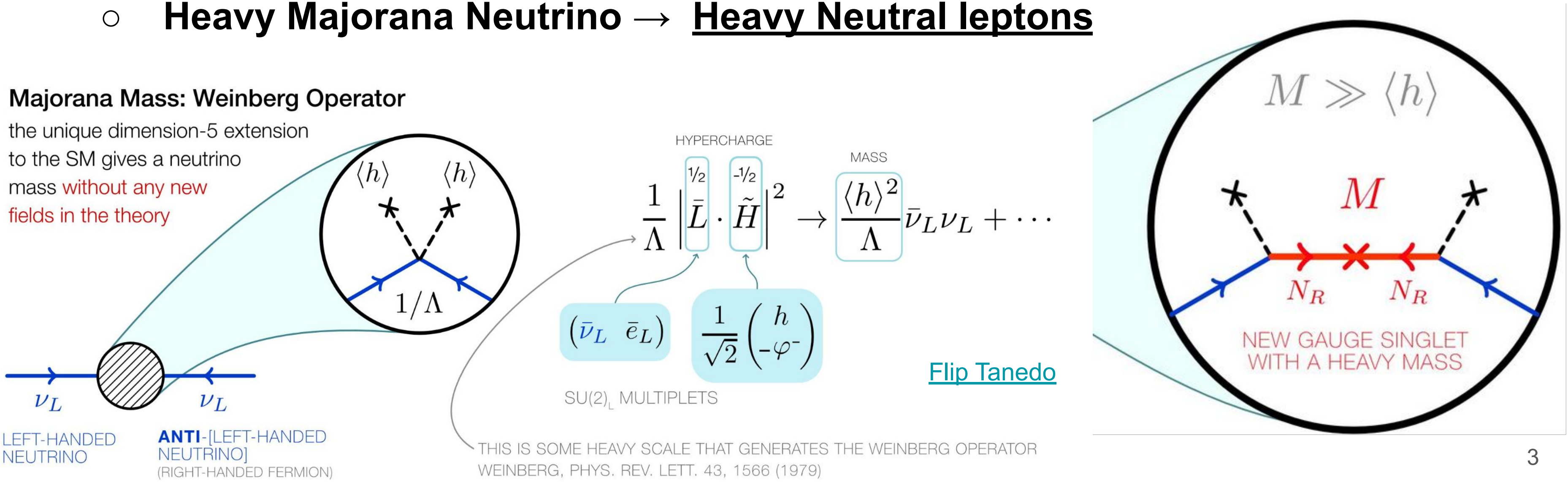
What could end a P5 townhall better than @sleptogenesis and the @Fermilab director cutting a shoot for the @MuonCollider cake? There's a lot of work to be done but it's an exciting future that the #p5report has given us an opportunity to realize!


3 22 733

# Neutrino Portal to BSM

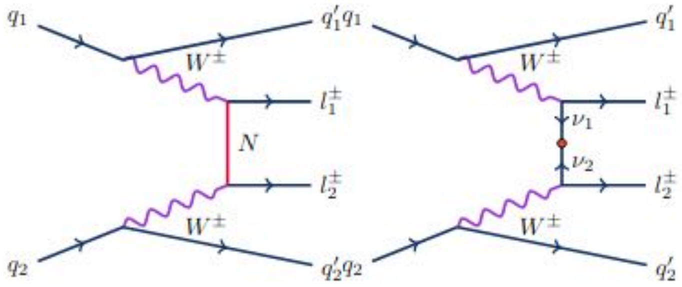
- **Neutrino mass confirmed by Neutrino Oscillation experiments**
  - **Requiring beyond the Standard Model (BSM) description**
    - In the context of SM, neutrinos have to be massless because:
      - Only left handed neutrinos: Dirac mass term is forbidden
      - Only one neutral Higgs doublet: Majorana mass is forbidden
- **Effective field theory and UV completion model**
  - **Dimension-5 Weinberg Operator → See-Saw models**
  - **Heavy Majorana Neutrino → Heavy Neutral leptons**

Sitian Qian



# LHC Searches: Heavy Majorana and Weinberg Operator

**CMS focus on μμ,** **ATLAS results on μμ, ee, eμ**




- Address neutrino mass

✓ Heavy Majorana neutrino HMN (see-saw) → neutrinoless VBF t-channel (high mass sensitivity, new!)

✓ Effective field theory (EFT): dim-5 Weinberg operator (WO) → $m_\nu$ with no new fields

→ Analogous to neutrinoless double $\beta$ decay, but with $\mu$ (instead of $e$)

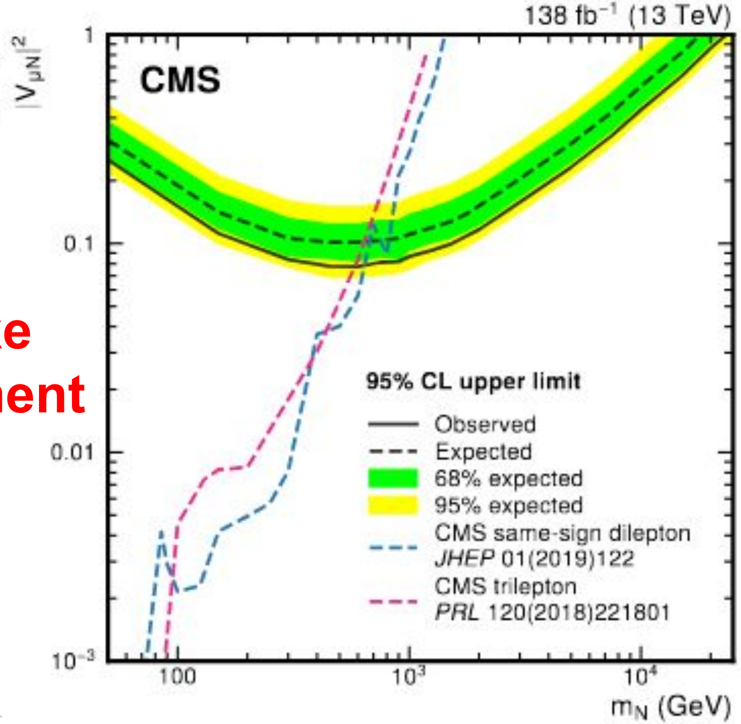
- Final state: two same sign $\mu\mu$ and VBF jets
- Dedicated studies to identify high-$p_T$ $\mu$

- Limits exclude
  - HMN up to $m_N = 23$ TeV
  - Effective Majorana mass up to $m_{\ell\ell} = 10.84$ GeV

  → First constraints for this process!

**~23TeV!**

**0νμμ-like experiment**



# CMS Searches: Heavy Majorana and Weinberg Operator

**Jie Xiao, Sitian Qian (PKU PhD students)** Phys. Rev. Lett. 131 (2023) 011803

| Code | Name | Status |
| --- | --- | --- |
| EXO-21-003 » \| ▲show \| ▼CDS \| ▼PRL | Search for VBF production of same-sign muons through Majorana neu ... | CWR-ended |

EXO-21-003 (Fri, 8 Apr 2022 08:42:36)

| | | | |
| --- | --- | --- | --- |
| Name | Search for VBF production of same-sign muons through Majorana neutrinos or the Weinberg operator | Description | Search for VBF production of sar neutrinos or the Weinberg operat |
| Status | CWR-ended | Contact Person | Jie Xiao (PEKING-UNIV) |
| Twiki | EXO-21-003 | HN | EXO-21-003 |

作者：韩扬眉 来源：中国科学报 发布时间：2022/5/10 21:54:35 选择字号：小 中 大

## 测试“跷跷板模型”，揭示中微子质量之谜

**北大CMS合作组对中微子质量的“跷跷板模型”进行了新的测试**

中国科学家关于中微子质量模型探测的研究，近日得到了世界上最大型的粒子物理学实验室——欧洲核子中心的特别关注。

大型强子对撞机中国合作组之一、北京大学高能物理CMS组李强团队对解释中微子小质量来源的“跷跷板模型”进行了新的检验，结果为大型强子对撞机的数据挖掘打开了新的窗口。

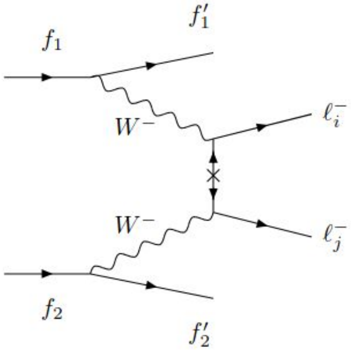
arXiv > hep-ph > arXiv:0901.3589

**High Energy Physics - Phenomenology**

*[Submitted on 23 Jan 2009 (v1), last revised 7 May 2009 (this version, v2)]*

**The Search for Heavy Majorana Neutrinos**

Anupama Atre, Tao Han, Silvia Pascoli, Bin Zhang




**0νμμ-like**

arXiv:2203.12169 [pdf, other]

hep-ph hep-ex hep-lat nucl-ex nucl-th

**Neutrinoless Double-Beta Decay: A Roadmap for Matching Theory to Experiment**

**CERN** @CERN

CMS tries out the seesaw 😄

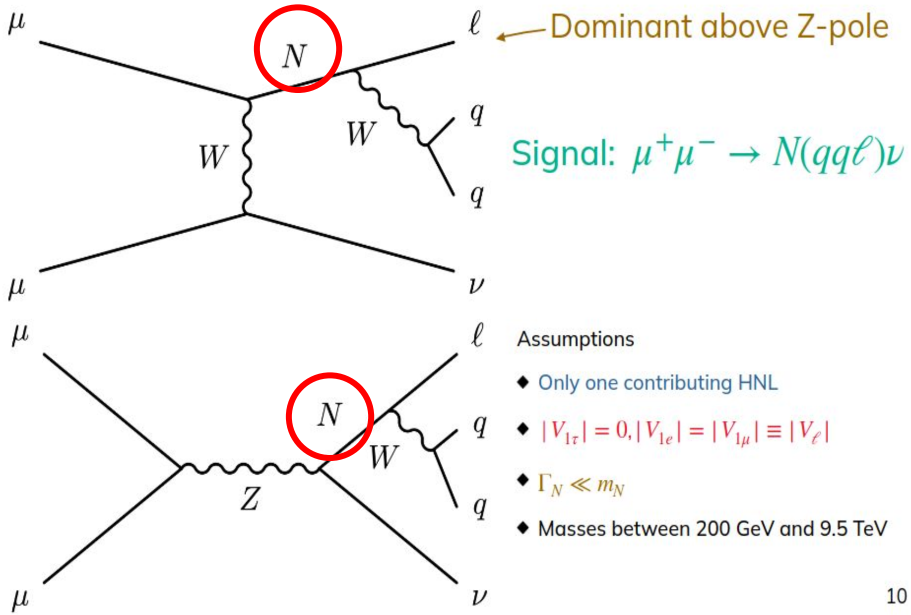
The CMS collaboration has put the seesaw model of neutrino mass to a new test.

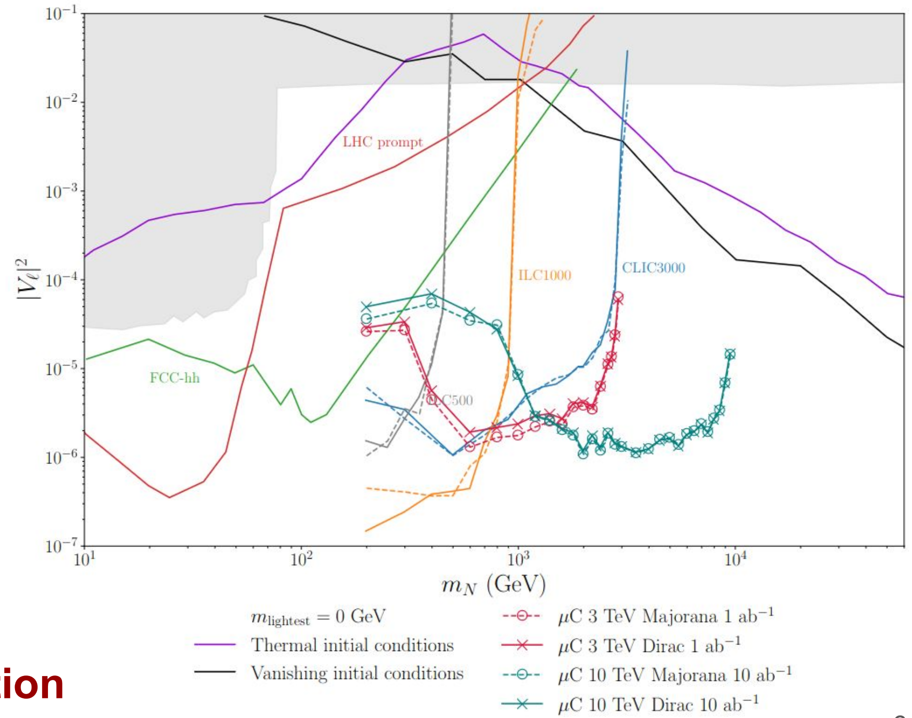
Find out why this model is named “seesaw” and what result @CMSExperiment achieved: home.cern/news/news/phys...

Cartoon by Sitian Qian

# Heavy Majorana at Muon Colliders

**Tsz Hong Kwok, Lingfeng Li, Tao Liu, Ariel Rock** arXiv:2301.05177
**Peiran Li, Zhen Liu, Kun-Feng Lyu** JHEP03(2023)231

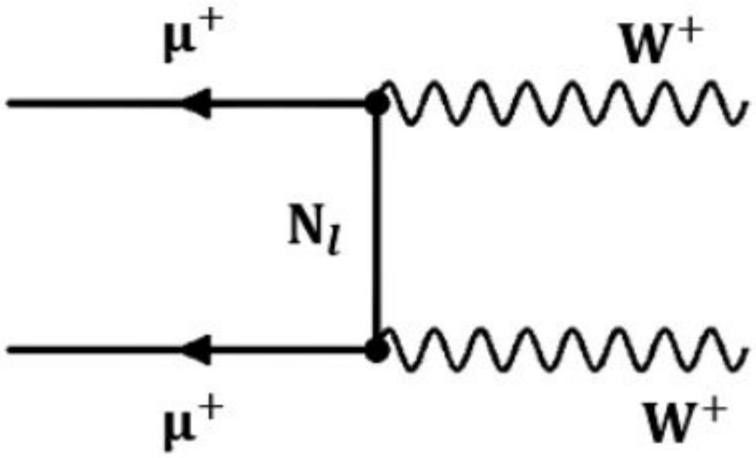



**Signal Background Analysis with Fast Simulation**

# Same-Sign Muon Colliders

**Jin-Lei Yang, Chao-Hsi Chang, Tai-Fu Feng** [CPC 48, no.4,043101 (2024)]
**Ruobing jiang, QL, et.al.** [PRD 109 (2024) 3, 035020]

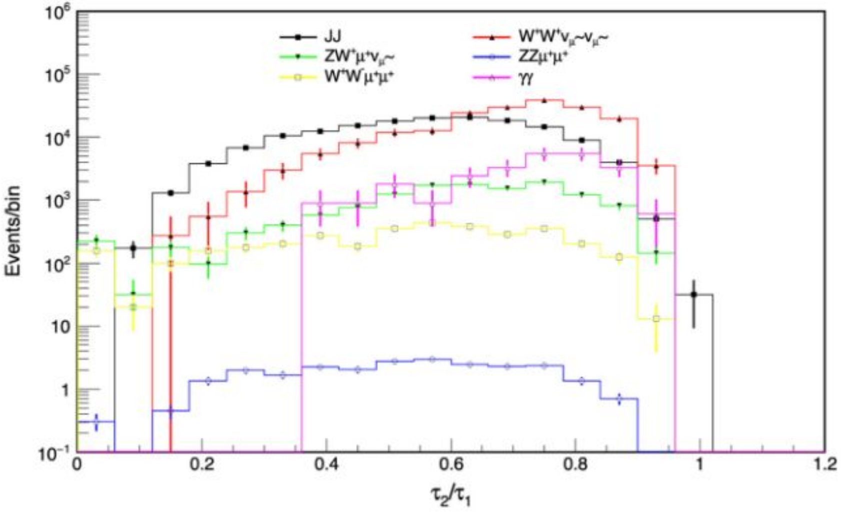



- Pure-leptonic channel
- Semi-leptonic channel
- Hadronic resolved channel
- Hadronic merged channel

**Fast Simulation: MadGraph+Pythia8+Delphes**
**Full Simulation: Muon software toolkit**

# Same-Sign Muon Colliders

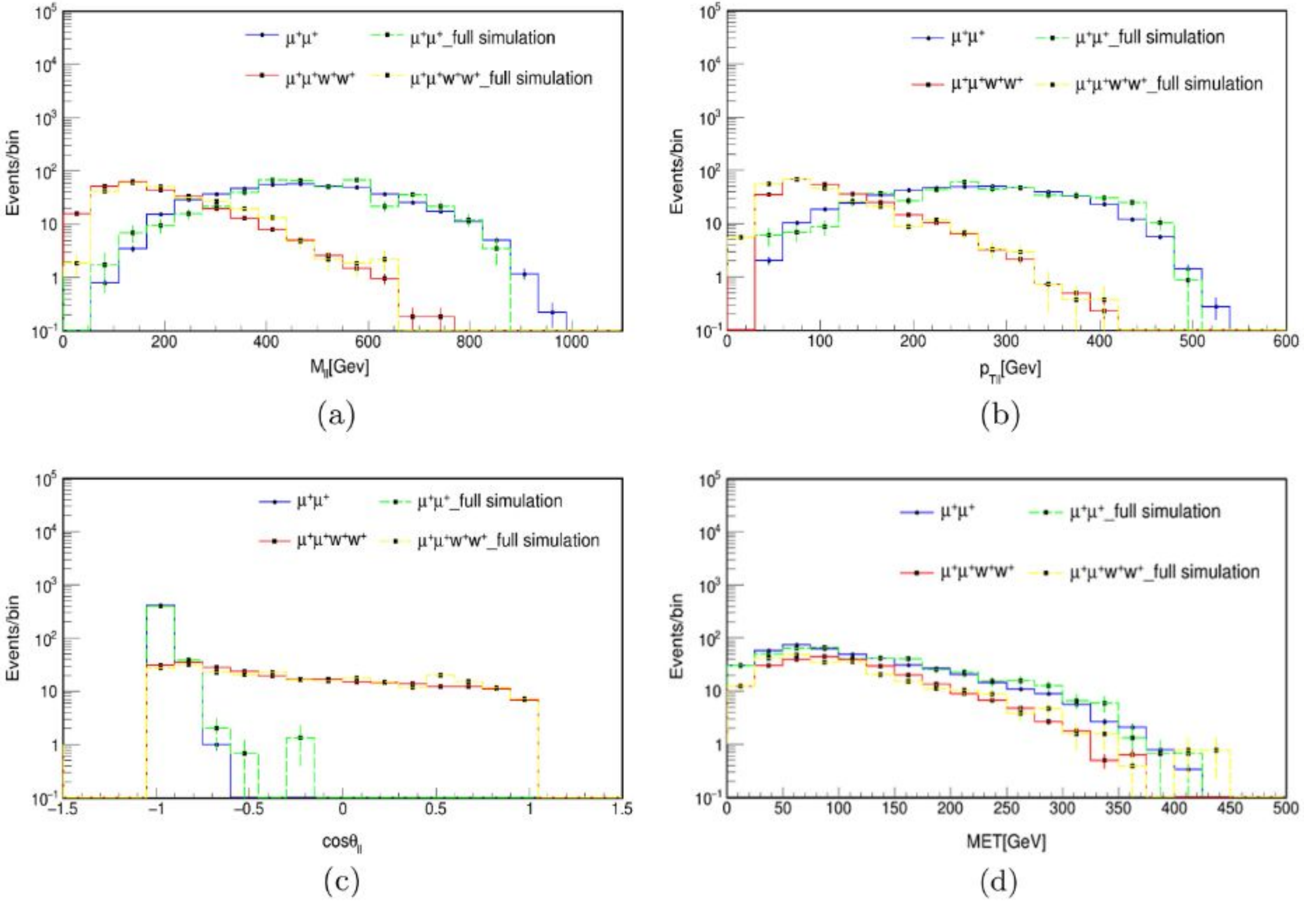
| Variables | Limits |
|---|---|
| Energy | [2000.0 GeV, 6000.0 GeV] |
| $E_t$ | [100 GeV, 6000 GeV] |
| $p_{\mathrm{T}}$ | [100 GeV, 6000 GeV] |
| $p_{\mathrm{T},\ell}$ | $>$ 5.0 GeV |
| $\tau_2/\tau_1$ | [0.05, 0.95] |
| $M_{JJ}$ | [3000 GeV, 11000 GeV] |
| $\lvert\eta_\ell\rvert$ | $<$ 7.0 |
| $\lvert\eta_{\mathrm{FatJet}}\rvert$ | $<$ 5.0 |
| Lepton veto | 0 |

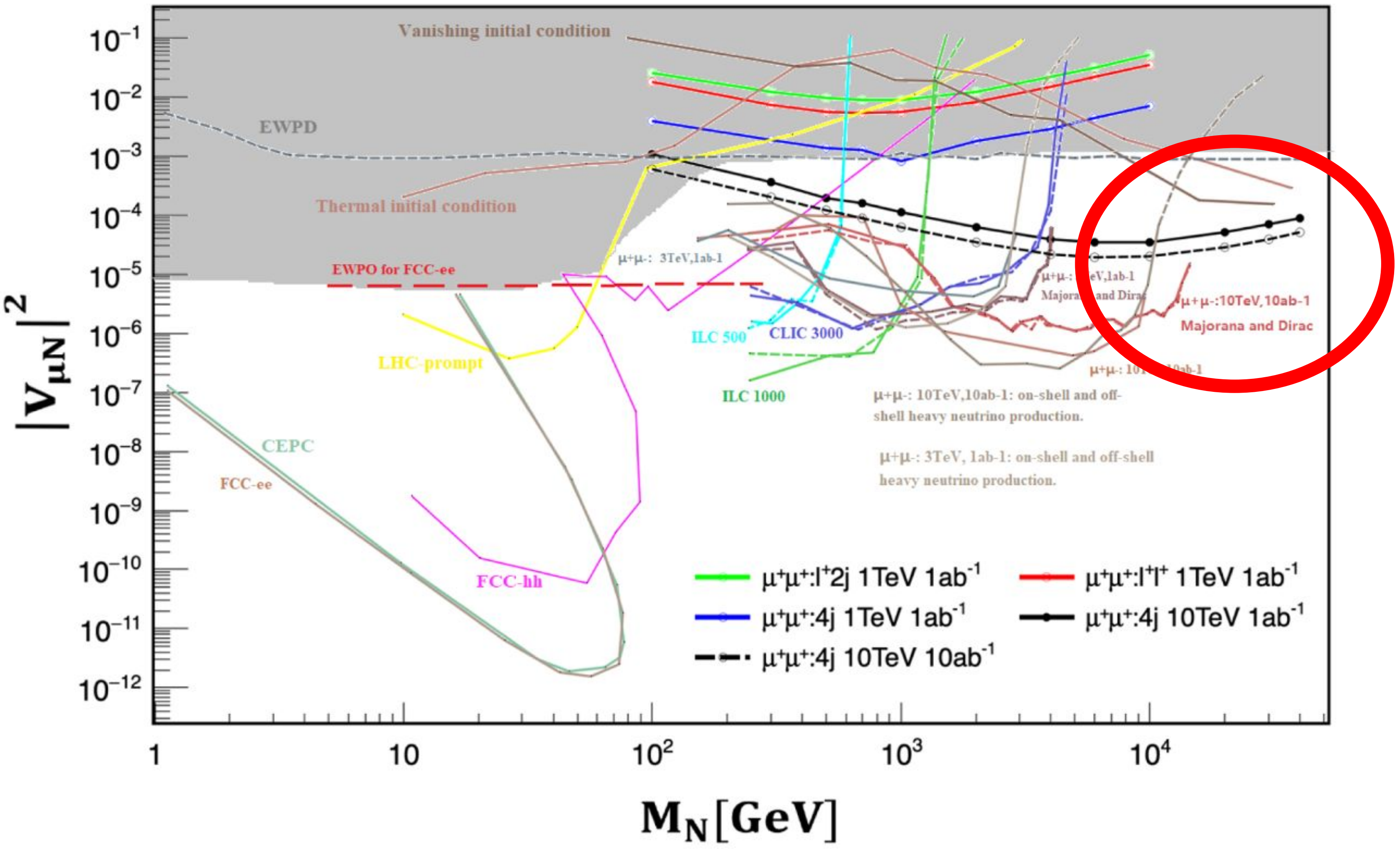



## Hadronic merged channel

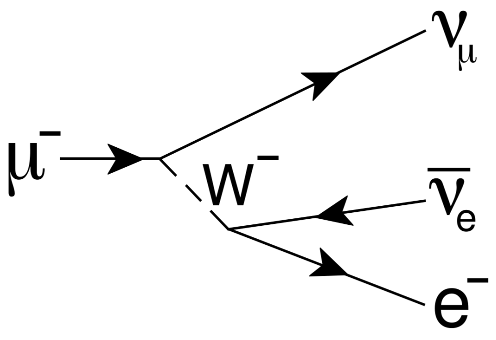
- $\mu^+\mu^+ \to W^+W^+\tilde{\nu_\mu}\tilde{\nu_\mu}$,
- $\mu^+\mu^+ \to ZW^+\mu^+\tilde{\nu_\mu}$,
- $\mu^+\mu^+ \to W^+\mu^+\nu_\mu\nu_\mu$,
- $\mu^+\mu^+ \to Z\mu^+\mu^+$,
- $\mu^+\mu^+ \to ZZ\mu^+\mu^+$,
- $\mu^+\mu^+ \to W^+W^-\mu^+\mu^+$,
- $\gamma\gamma \to W^+W^-$.

# Fast vs Full Simulations **Pure leptonic channel**




Vanishing initial condition
EWPD
Thermal initial condition
EWPO for FCC-ee
μ+μ-: 3TeV,1ab-1
ILC 500
CLIC 3000
ILC 1000
LHC-prompt
μ+μ-:10TeV,10ab-1
Majorana and Dirac
μ+μ-: 10TeV,10ab-1: on-shell and off-shell heavy neutrino production.
μ+μ-: 3TeV, 1ab-1: on-shell and off-shell heavy neutrino production.
CEPC
FCC-ee
FCC-hh
$\mu^+\mu^+$:$l^+$2j 1TeV 1ab$^{-1}$
$\mu^+\mu^+$:$l^+l^+$ 1TeV 1ab$^{-1}$
$\mu^+\mu^+$:4j 1TeV 1ab$^{-1}$
$\mu^+\mu^+$:4j 10TeV 1ab$^{-1}$
$\mu^+\mu^+$:4j 10TeV 10ab$^{-1}$
$|V_{\mu N}|^2$
$M_N$[GeV]

# Neutrino Beam: long ago




[NuTeV](#)
Neutrino-Nucleon Scattering
[NuMAX](#)
[NuSOnG](#)
Neutrino Scattering on Glass
[nuSTORM](#)
"Neutrinos from STORed Muons," …for neutrino oscillation searches

**B. J. King** [hep-ex/0005007](#)

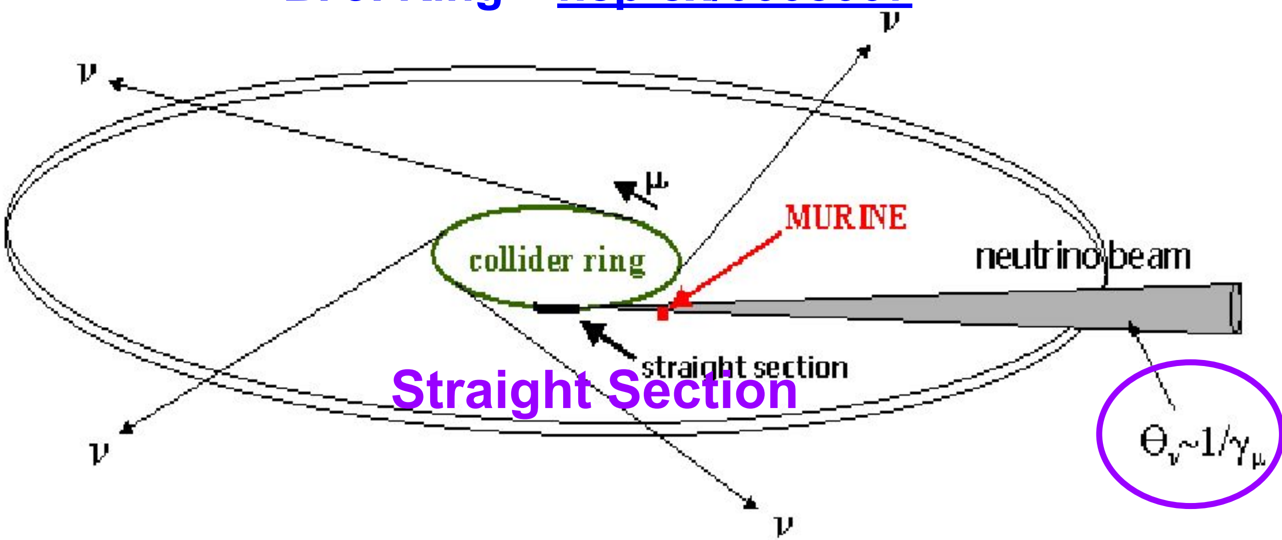
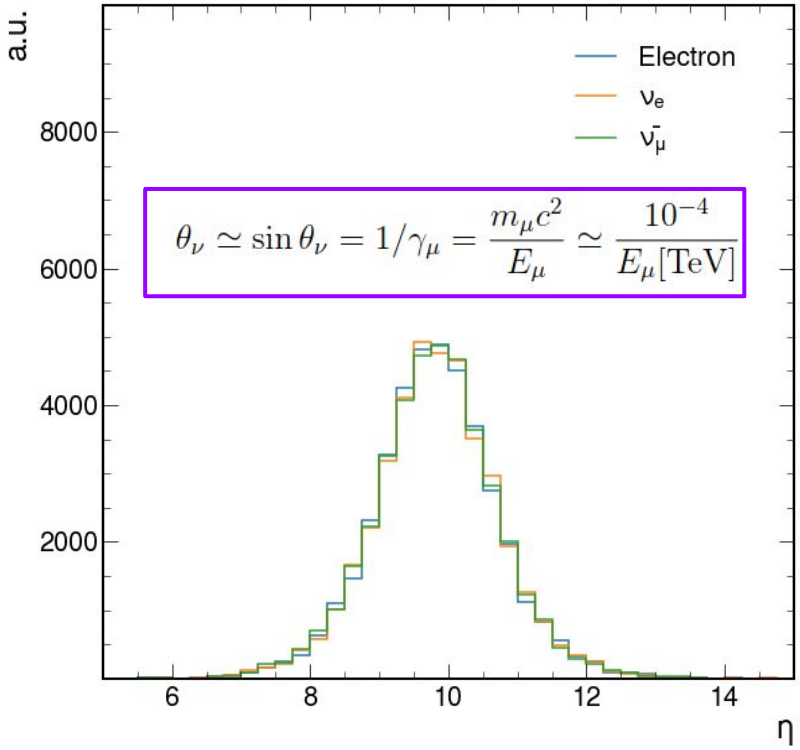


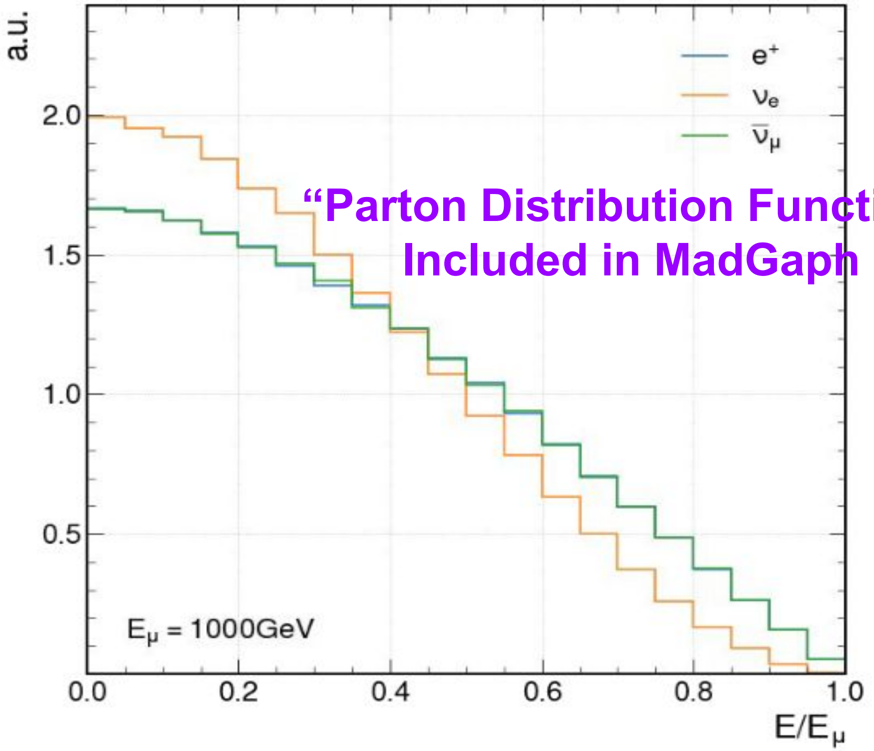

**FIGURE 1.** The decays of muons in a muon collider will produce a disk of neutrinos emanating out tangentially from the collider ring. The neutrinos from decays in straight sections will line up into beams suitable for experiments. The MURINEs will be sited in the center of the most intense beam and as close as is feasible to the production straight section.

**Head-on collisions at TeV scale?**

# Neutrino Beam from 1TeV Muon beam



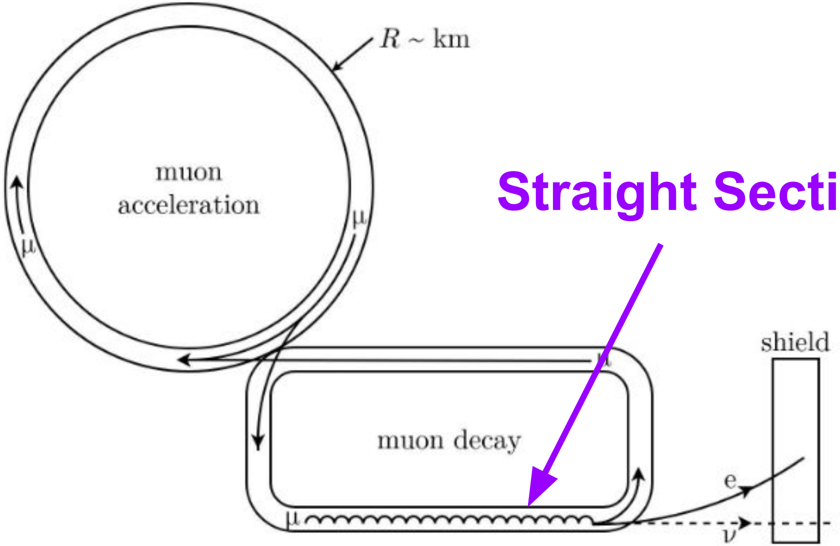

$$\theta_\nu \simeq \sin\theta_\nu = 1/\gamma_\mu = \frac{m_\mu c^2}{E_\mu} \simeq \frac{10^{-4}}{E_\mu[\mathrm{TeV}]}$$



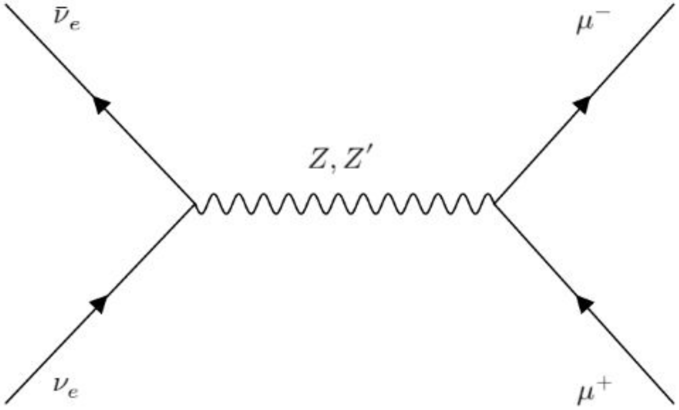

**"Parton Distribution Function" Included in MadGaph**

**Highly collimated in angle, yet widely distributed in Energy**

# Neutrino Collider?




**Straight Section**




**Neutrino (anti-)neutrino collisions**

A small modulation of the muon decay angle through vertical bending, symbolized by the squiggly line, may be used to focus the neutrino beam.

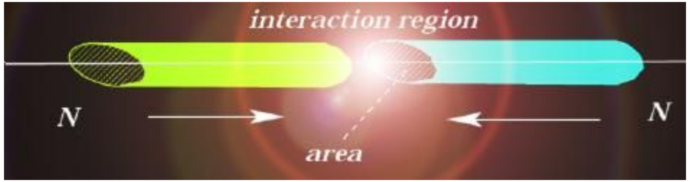
$$\nu_e \bar{\nu}_e \to Z \to \mu^+ \mu^- .$$

$$\nu_e \nu_e \to HH$$
$$\nu_e \nu_e \to ZZ\,, ZH$$
$$\nu_e \nu_e \to \nu_e \nu_e H,$$
$$\nu_e \nu_e \to \nu_e \nu_e ZZ\,, \nu_e \nu_e WW,$$
$$\nu_e \nu_e \to \nu_e \nu_e ZH\,, \nu_e \nu_e HH,$$
$$\nu_e \nu_e \to e^- e^- W^+ W^+,$$

**Question: ?/fb in 1-10 years**

# Very Crude Luminosity Estimation

$$\mathcal{L} = \frac{N_{\text{beam1}} N_{\text{beam2}}}{4\pi\sigma_x\sigma_y} f_{\text{rep}},$$




Take the LHC as an example, with $f_{\text{rep}} = 40\,\text{MHz}$, $\sigma_{x,y} = 16$ microns, and $N_{\text{beam1,2}} = 10^{11}$, one can get $\mathcal{L} = 10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$.

As for TeV muon colliders, with $f_{\text{rep}} = 100\,\text{KHz}$, $\sigma_{x,y} \lesssim 10$ microns, and $N_{\text{beam1,2}} = 10^{12}$, then $\mathcal{L} = 10^{33}$–$10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$.

As for the neutrino neutrino collisions discussed above, there are further suppression factors from linear over arc ratio ($L_l^2/L_c^2 \sim 1/100$) with the exact value depending on the realistic design, and the neutrino beam spread which can be around 1000 microns for $L_l \sim 10$ to 100 meters. Taking all these into account, a realistic instantaneous luminosity for neutrino neutrino collisions can reach around $\mathcal{L} = 10^{28}$ $\text{cm}^{-2}\text{s}^{-1}$ level. Although it is a small number, however, to reach the discovery threshold of neutrino antineutrino annihilation process $\nu_e\tilde{\nu}_e \to Z$, a tiny integrated luminosity of about $10^{-5}$ $\text{fb}^{-1}$ is needed, i.e., several days of data taking.

**On top of muon collider luminosity projection, suppressed by:**

1. (Flat over ARC)^2 ~ ( 1/10)^2~1/100
2. Wide Beam, e.g. 1000 microns ~ (1/100)^2~1/10^4

$$\mathcal{L} = 10^{28}\ \text{cm}^{-2}\text{s}^{-1}\ \text{level}$$

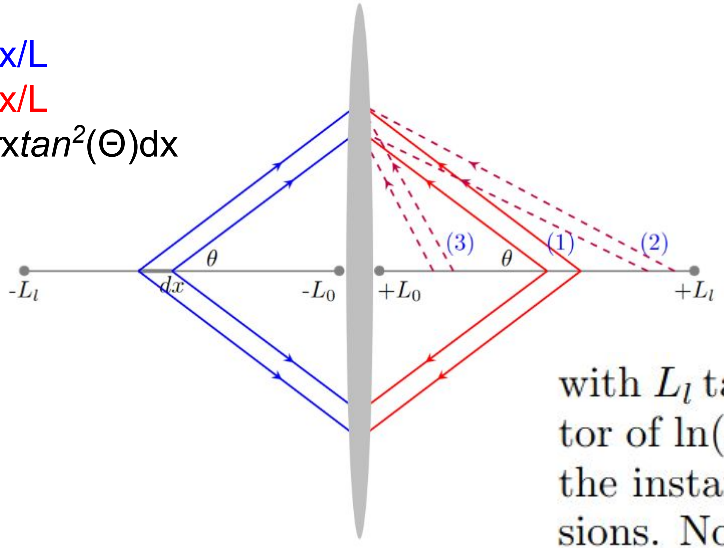
# Crude Luminosity Estimation

## Approximating neutrino emitted along muon beam lines with a fixed cone angle

$dN_1 \propto N_1 * dx/L$

$dN_2 \propto N_2 * dx/L$

$d[\text{area}] \propto 2\pi x \tan^2(\Theta) dx$




$$\mathcal{L} = \frac{L_l^2}{L_c^2} \int_{L_0}^{L_l} \frac{N_{\text{beam1}} N_{\text{beam2}} f_{\text{rep}}}{L_l^2 \times (4 \times 2\pi x \tan^2\theta)} \times dx$$

$$= \frac{L_l^2}{L_c^2} \frac{N_{\text{beam1}} N_{\text{beam2}} f_{\text{rep}}}{8\pi L_l^2 \tan^2\theta} \times \ln(L_l/L_0),$$

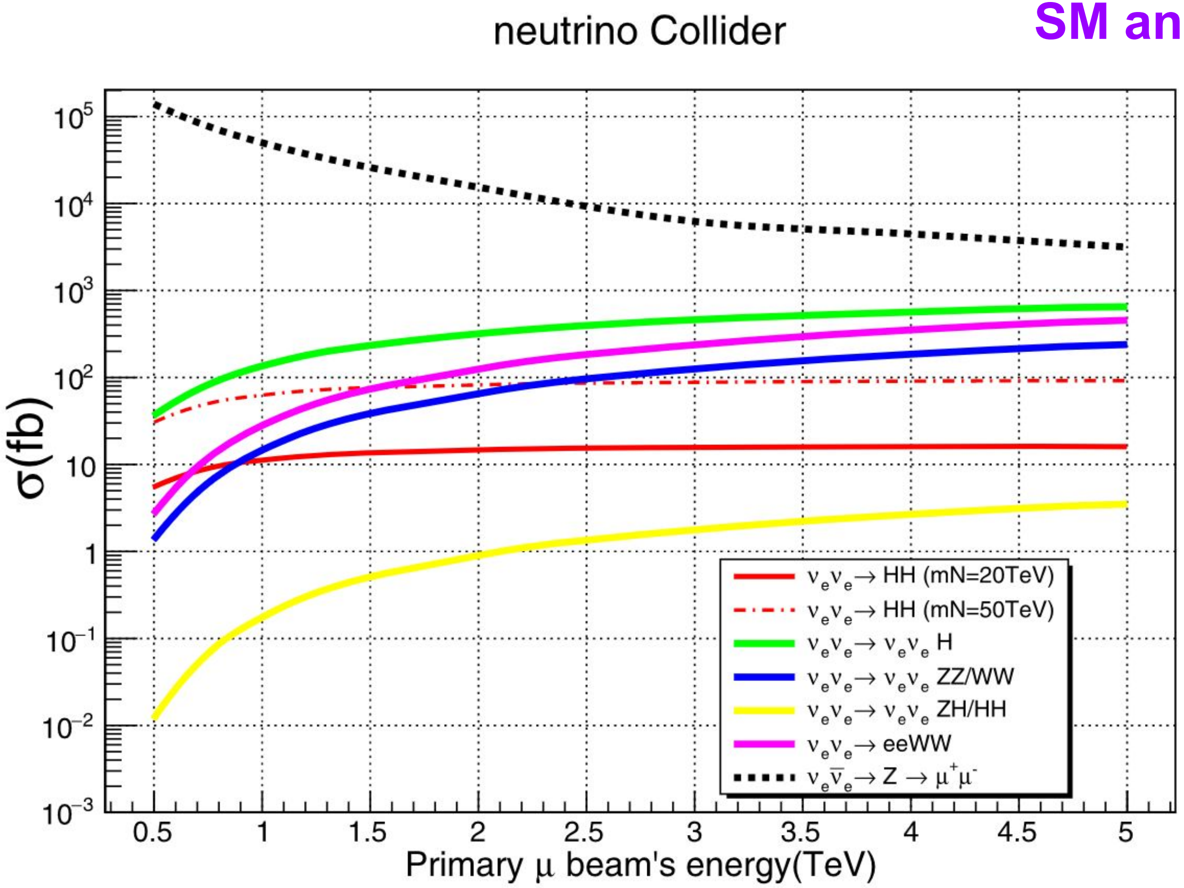
with $L_l \tan\theta \sim r_s$, and there appears as an enhanced factor of $\ln(L_l/L_0)/2 \sim 2-5$, and thus can further increase the instantaneous luminosity for neutrino neutrino collisions. Note $L_0$ is a cut-off parameter in above integration formula and defined by the muon beam size, which can be at the order of 1-10 cm and thus may relax the stringent requirement on beam cooling of the nominal muon collider being pursued.

**Can confirm result in previous slide.**

$$\mathcal{L} = 10^{28}\ \text{cm}^{-2}\text{s}^{-1}\ \text{level}$$

# Neutrino Collision Processes

**SM and BSM (Heavy Majorana)**




- **vvbar->Z:**
  **large cross section**
  **>100pb**
  **can be observed in short time!**
  **~days to weeks**

- **May loosen requirement on beam quality!**

# Committee on Elementary Particle Physics: Progress and Promise - Meeting No. 6

André de Gouvêa April 3-4, 2023



- We still **know very little** about the new physics uncovered by neutrino oscillations. I have no idea how much this will change in 20 years. It could, but it doesn't have to.
- **neutrino masses are very small** – we don't know why, but we think it means something important. **neutrino mixing is "weird"** – we don't know why, but we think it means something important.
- We **need more experimental input** (neutrinoless double-beta decay, precision neutrino oscillations, UHE neutrinos, charged-lepton precision measurements, colliders, etc). This is unlikely (?) to change in 20 years.
- **Precision measurements of neutrino oscillations** are sensitive to several new phenomena. **There is at least one clear option – muon storage rings – for what to do after DUNE and Hyper-K.** And a lot of work to do to find out how much more interesting things could get.
- There is plenty of **room for surprises**, as neutrinos are potentially very deep probes of all sorts of physical phenomena. Remember that neutrino oscillations are "quantum interference devices."




NATIONAL ACADEMIES Sciences Engineering Medicine

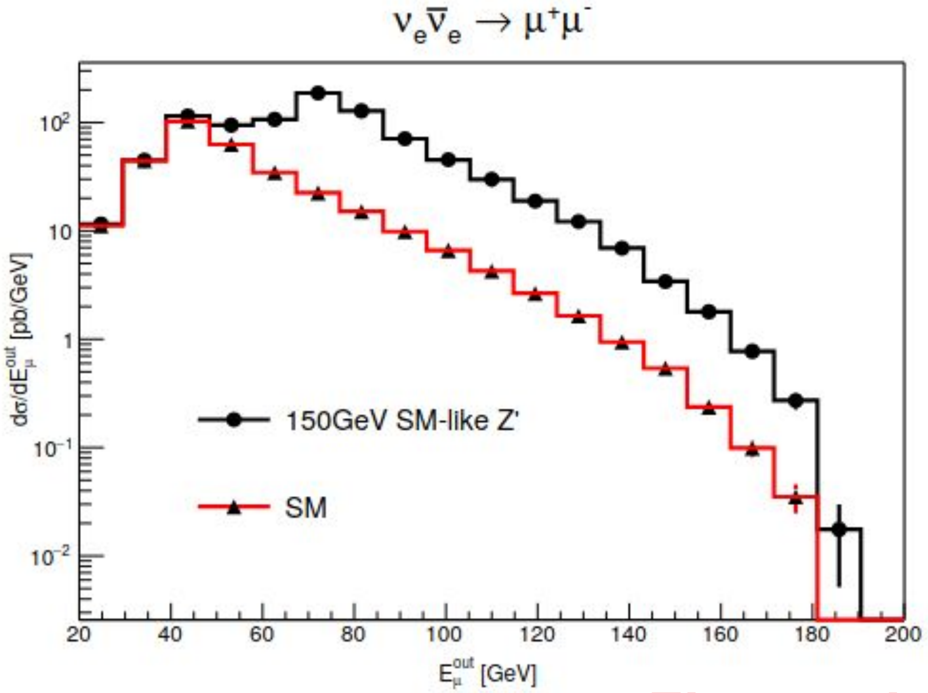
The muon collider is also a neutrino

So imagine you could do new new bar scattering.

We've never done that right? That's that we totally craz

# Neutrino antineutrino Annihilation

**Neutrino antineutrino annihilation has large cross section, can be observed in short time!**

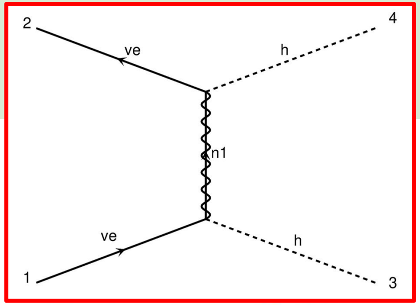



$$\nu_e\bar{\nu}_e \rightarrow Z \rightarrow \mu^+\mu^-$$

Outgoing muon energy distributions for neutrino antineutrino annihilation into Z and SM-like Z' bosons, with Z' mass set as 150 GeV with narrow width.

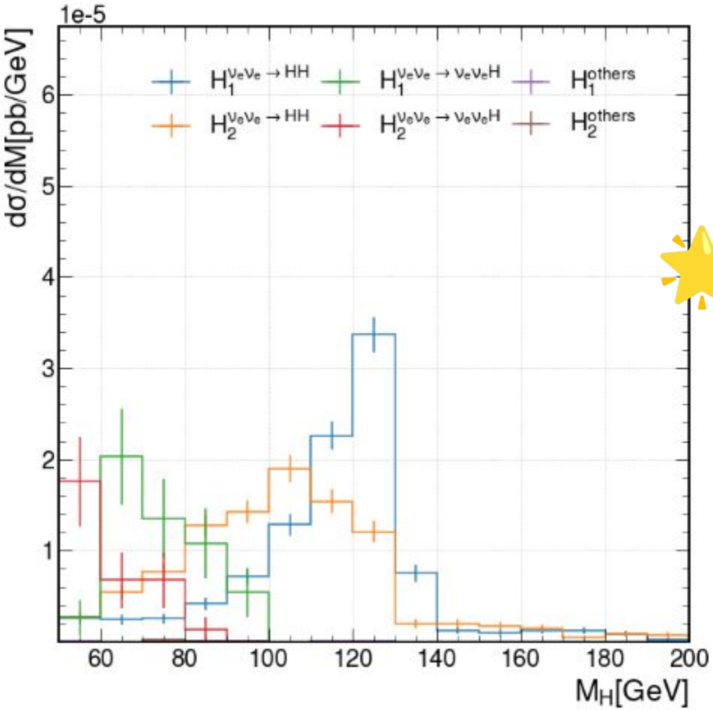
**First probe on di-neutrino resonances!**

# Heavy Majorana Neutrino




$$\mathcal{L}_5 = \left( C_5^{\ell\ell'}/\Lambda \right) [\Phi \cdot \overline{L}_\ell^c][L_{\ell'} \cdot \Phi],$$

**Weinberg Operator,**
**UV completion with See-Saw models**




With 1 $fb^{-1}$ of data, by cutting on reconstructed $M_H$, we are close to exclude $V_{eN1} \gtrsim 0.01$ at $M_N = 20$ TeV, at 95% C.L., which surpasses already current best limits from the CMS experiment [25] by two orders of magnitude. An interesting fact is that cross sections of $\nu_e\nu_e \to HH$ scale as $M_N^2$, thus this proposal can touch super heavy HMN region which is not possible in other experiments. For example, for 1000 TeV HMN, the 95% C.L exclusion limit can reach $V_{eN1} \gtrsim 0.001$ with 1 $fb^{-1}$ of data, based on the same simulation study as described above.

**With 1/fb of data, the sensitivity on mixing elements for a 10 TeV scale Heavy Majorana can already surpass LHC by 2 orders of magnitudes!**

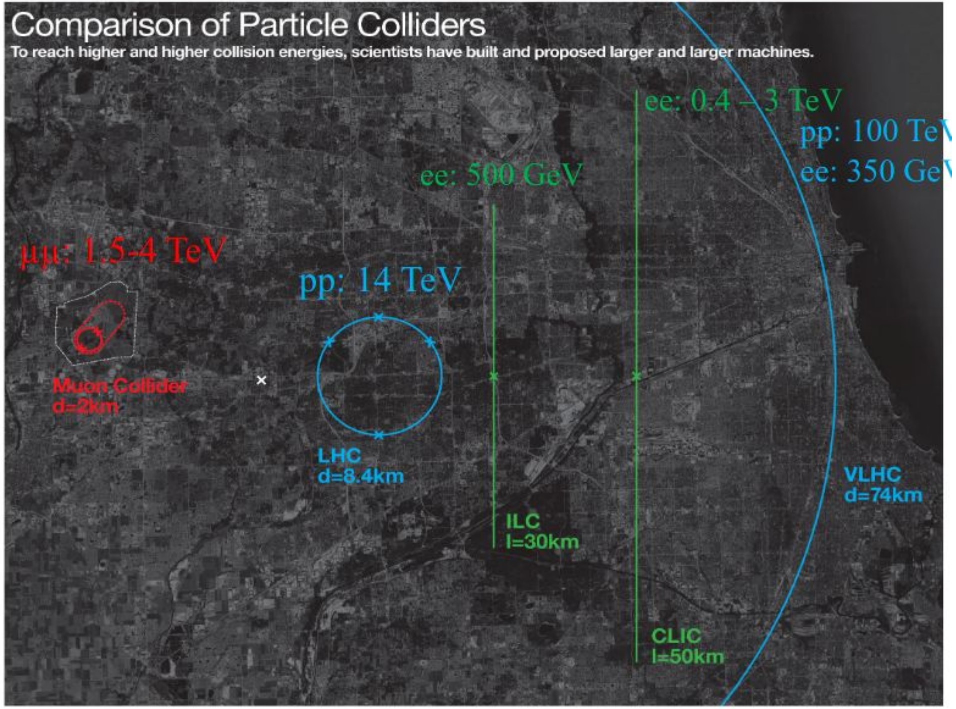
# Summary

- **Large Hadron Collider and Future Muon Colliders**
  - Searches for Heavy neutral leptons
  - $0\nu\mu\mu$-like experiment
- **Neutrino beam for collisions**
  - **Neutrino-neutrino collider**
  - **Neutrino-lepton collider**

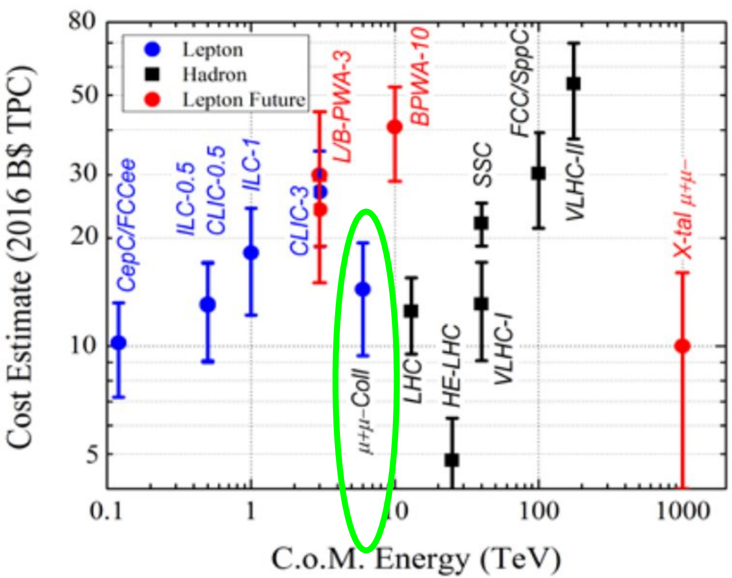
# Backup

# Bright future bright Colliders

- **Fruits produced from LHC and HL-LHC**
- **An electron-positron Higgs factory** as the highest-priority.
- **O(10) TeV Muon Collider** has also clear advantage




**arXiv: 1705.02011**

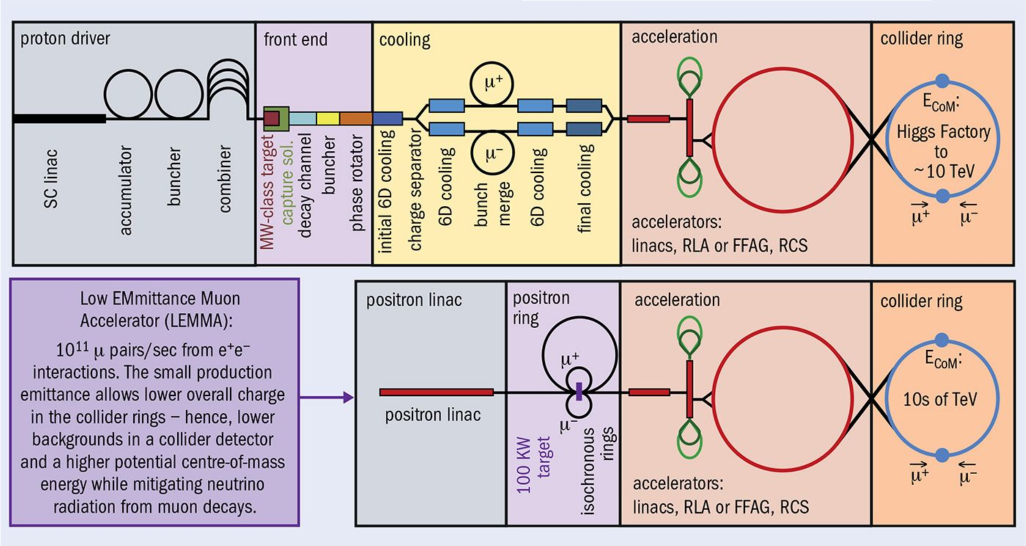


# Muon Collider: beam and background

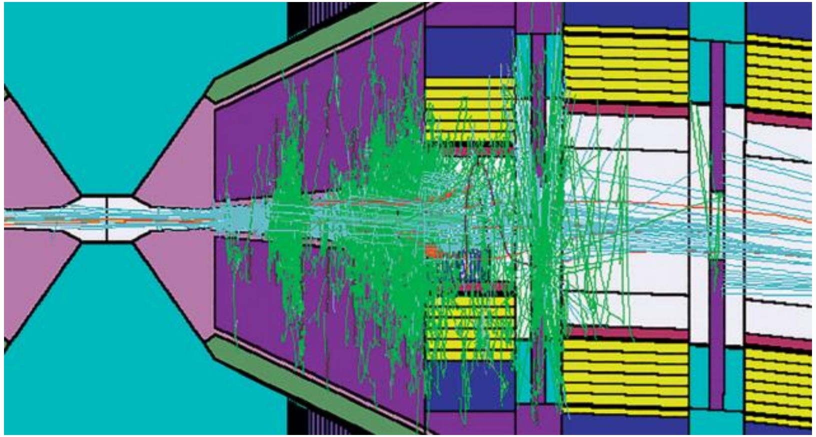
## 1) Muon Source

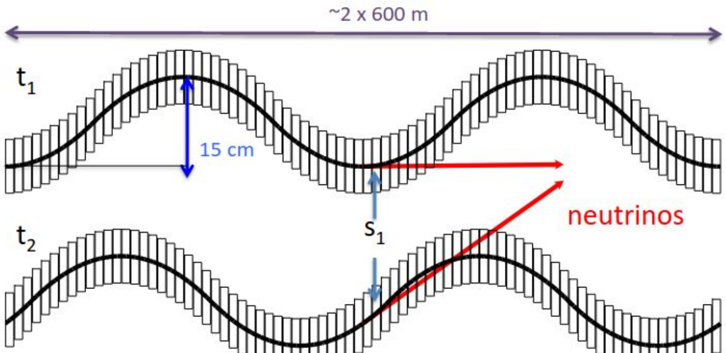
$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon_L} f_r N_0 \gamma$$

High energy
High field in collider ring
Large energy acceptance
Dense beam
High beam power




## 2) Muon Beam Induced background






## 3) Neutrino Flux Mitigation:

move collider ring components, e.g. vertical bending with 1% of main field

# Muon Collider: intermediate steps?

link

**Matt Strassler** | June 10, 2022 at 6:22 PM | Reply

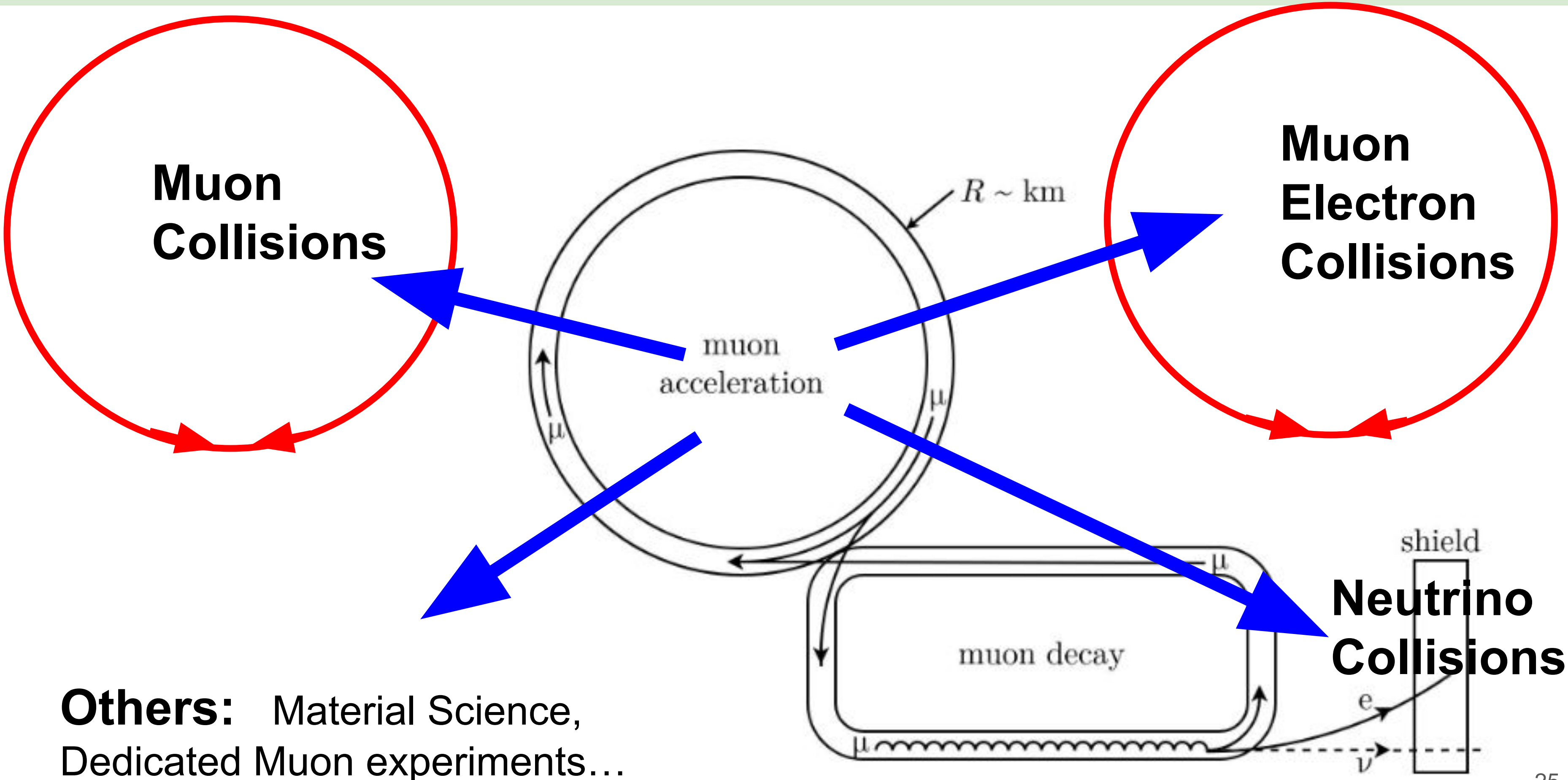
Andrew, these are very serious concerns too. But one cannot move before one has funding, and one cannot get funding without a clear argument as to why funding should be provided. At higher energy, the only clear arguments, right now, are for a Higgs/top factory. That will be an electron positron machine of some type, unless the ambitious muon collider project can demonstrate enough likelihood of success and enough intermediate physics goals (e.g. neutrino beams) that it can be justified as well. (Meanwhile other colliders at lower energy but very high luminosity might be pursued.)

19. Alain Blondel: alain.blondel@cern.ch question general but triggered by Steve Ritz. Establish the list of questions that are of great importance and should be answered across frontiers/experiments/facilities. Here is **a** question that I think if of key importance and is addressed in many 'frontiers' without being sufficiently asked as a unique question for which the various groups would gain to reflect in common:
**– given that neutrinos have masses, the question of existence and masses of right handed neutrinos (or their alternatives) should have a common discussion, formalism, expectations, visible consequences and what other problems they might solve, while understanding the possibilities, from the minimal one to those more complicated.** This is certainly the most likely new physics there is, and it seems to naturally result from the present discoveries. It was evident from the presentations today that this question appears in the neutrino frontier, rare processes, cosmic and energy frontier as well as instrumentation, and in Hitoshi's presentation, and yet there is not a uniform language or momentum to look for it in all possible ways – so it remains somewhat confidential.

Seattle Snowmass Summer Meeting 2022

- **"...enough intermediate physics goals (e.g. neutrino beams)"**
- **neutrino mass …"This is certainly the most likely new physics there is…"**

# Dream Bigger: muon complex



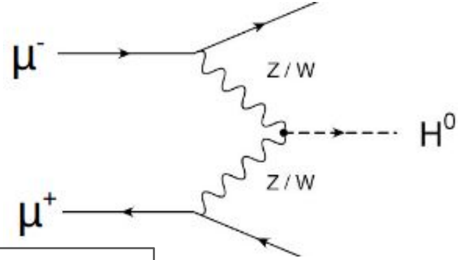

**Others:** Material Science, Dedicated Muon experiments…

# Muon Collider interest Revived upon Muon Anomalies

**Muon colliders have suppressed synchrotron radiation.**

- Clean events as in e+e- colliders
- High collision energy as in hadron colliders

**But lifetime at rest only 2.2 μs.**

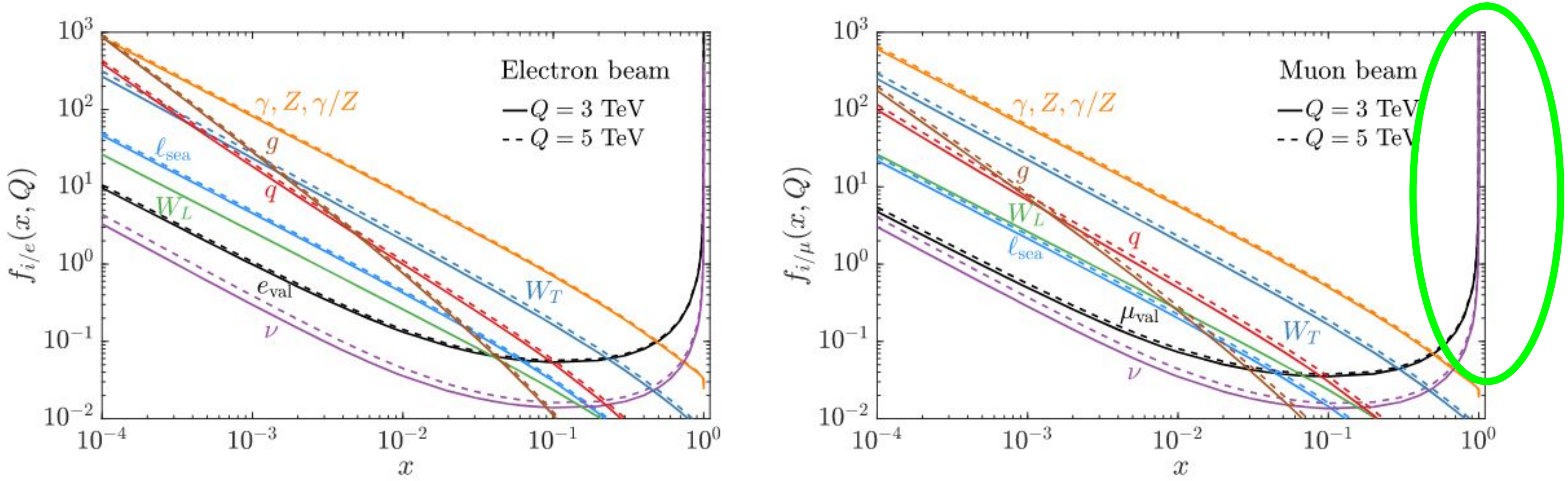



| Parameter | Units | Higgs | Multi-TeV | | |
|---|---|---|---|---|---|
| CoM Energy | TeV | 0.126 | 1.5 | 3.0 | 6.0 |
| Avg. Luminosity | $10^{34}\text{cm}^{-2}\text{s}^{-1}$ | 0.008 | 1.25 | 4.4 | 12 |
| Beam Energy Spread | % | 0.004 | 0.1 | 0.1 | 0.1 |
| Higgs Production/$10^7$ sec | | 13'500 | 37'500 | 200'000 | 820'000 |
| Circumference | km | 0.3 | 2.5 | 4.5 | 6 |
| No. of IP's | | 1 | 2 | 2 | 2 |
| Repetition Rate | Hz | 15 | 15 | 12 | 6 |
| $\beta^*_{x,y}$ | cm | 1.7 | 1 | 0.5 | 0.25 |
| No. muons/bunch | $10^{12}$ | 4 | 2 | 2 | 2 |
| Norm. Trans. Emittance, $\varepsilon_{\text{TN}}$ | $\mu$m-rad | 200 | 25 | 25 | 25 |
| Norm. Long. Emittance, $\varepsilon_{\text{LN}}$ | $\mu$m-rad | 1.5 | 70 | 70 | 70 |
| Bunch Length, $\sigma_S$ | cm | 6.3 | 1 | 0.5 | 0.2 |
| Proton Driver Power | MW | 4 | 4 | 4 | 1.6 |
| Wall Plug Power | MW | 200 | 216 | 230 | 270 |

link

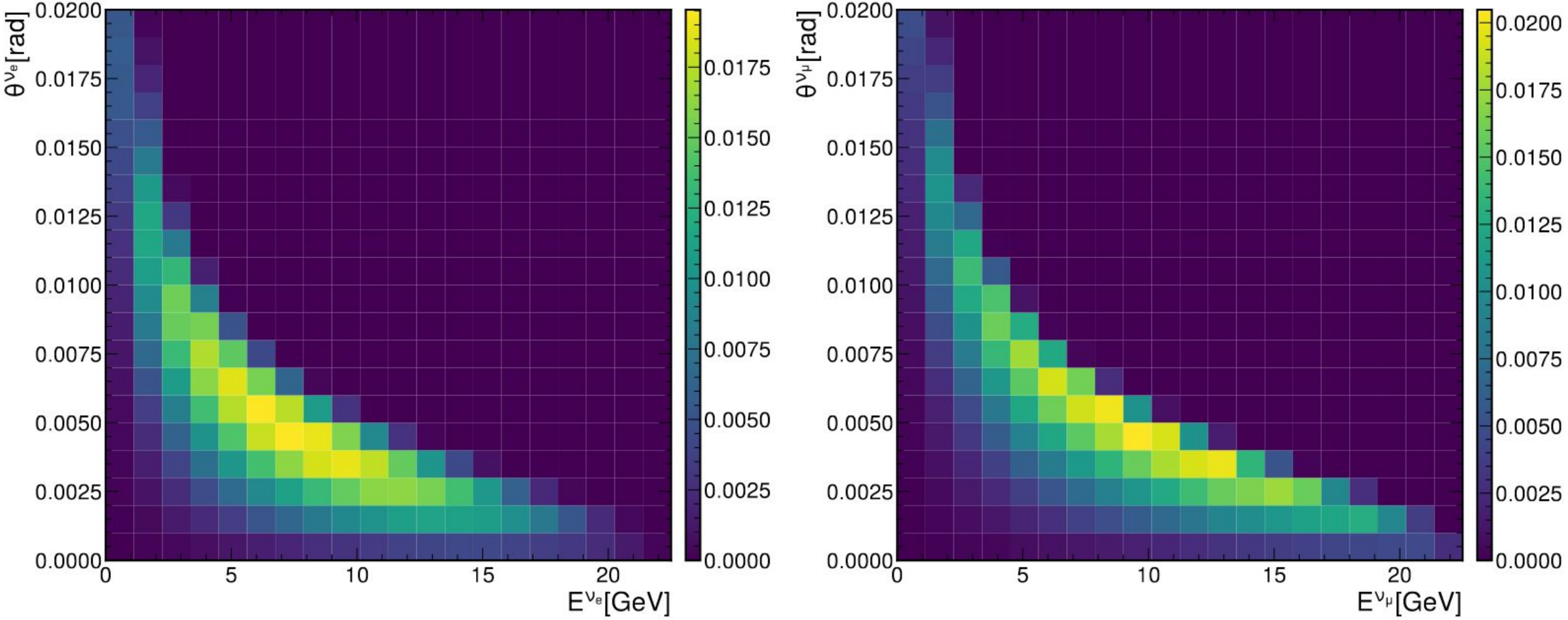
# and more funs

**See e.g. recent talk from Dr. Keping Xie, and many talks at the workshop**




- **All SM particles are partons** [Han, Ma, KX, 2007.14300]
- $W_L(Z_L)$ does not evolve: **Bjorken-scaling restoration**: $f_{W_L}(x) = \frac{\alpha_2}{4\pi}\frac{1-x}{x}$.
- The EW correction can be large: $\sim 50\%$ $(100\%)$ for $f_{d/e}$ $(f_{d/\mu})$ due to the relatively **large SU(2) gauge coupling**. [Han, Ma, KX et. al, 2106.01393]
- Scale uncertainty: $\sim 15\%$ $(20\%)$ between $Q = 3$ TeV and $Q = 5$ TeV

# Neutrino Profile from Muon Decay




**5-7 GeV In average**