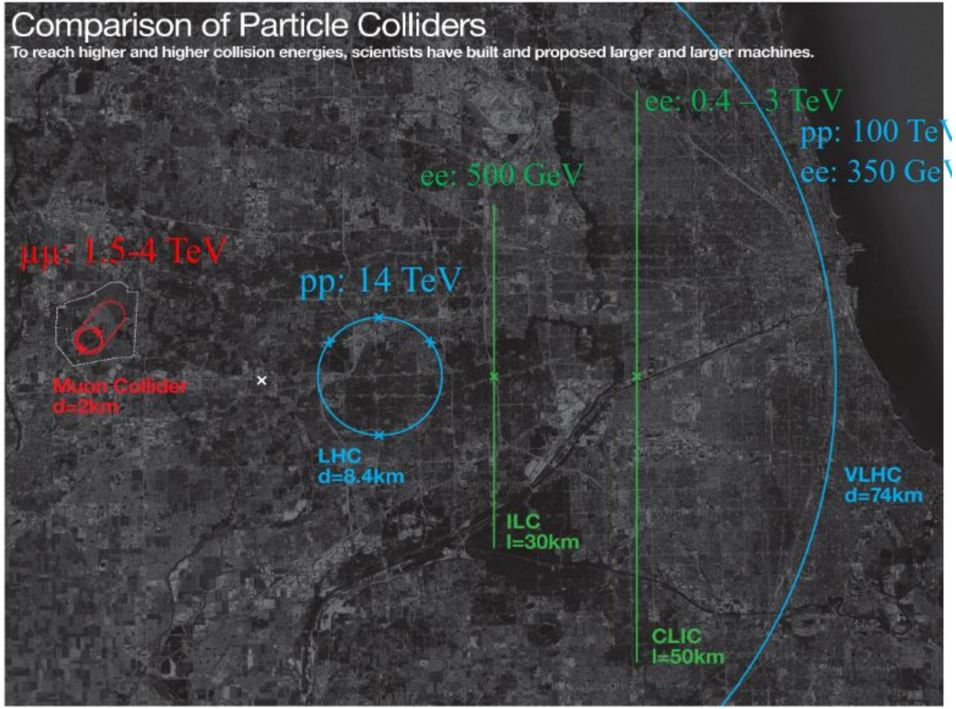
Neutrinos at Energy Frontiers

Qiang Li, Peking University 2023/02/13

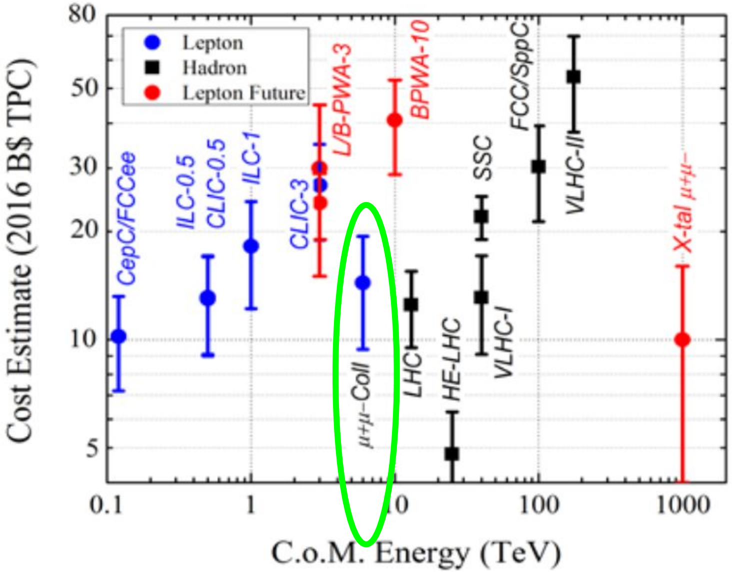
1. VBS Majorana and Weinberg operator
   (CMS Collaboration, accepted by Phys. Rev. Lett. editors' suggestions)
2. Neutrino-Lepton Collider (International Journal of Modern Physics A)
3. Neutrino-neutrino Collisions (under review)
4. Muon beam for Neutrino CP violation (under review)
5. Others

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

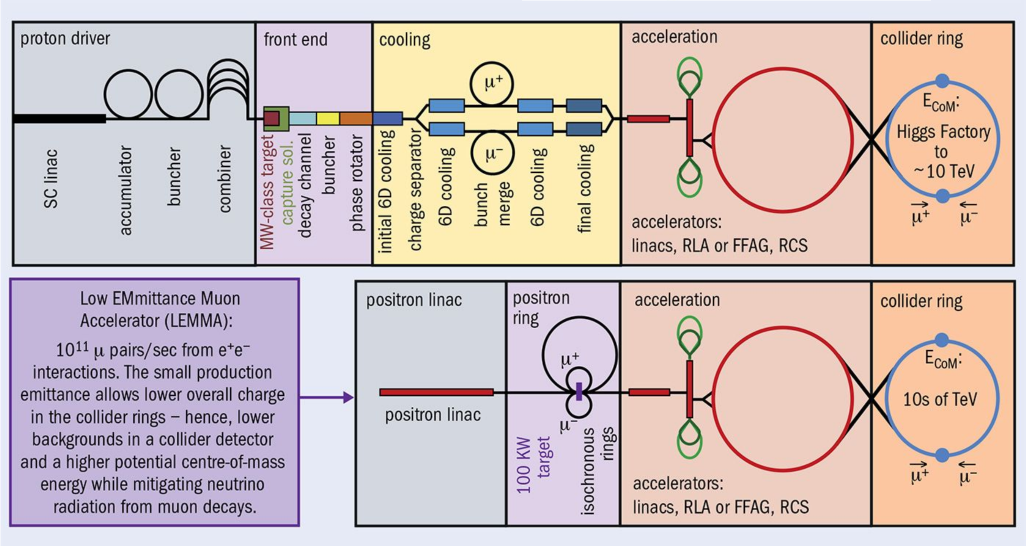


Muon Collider: beam and background

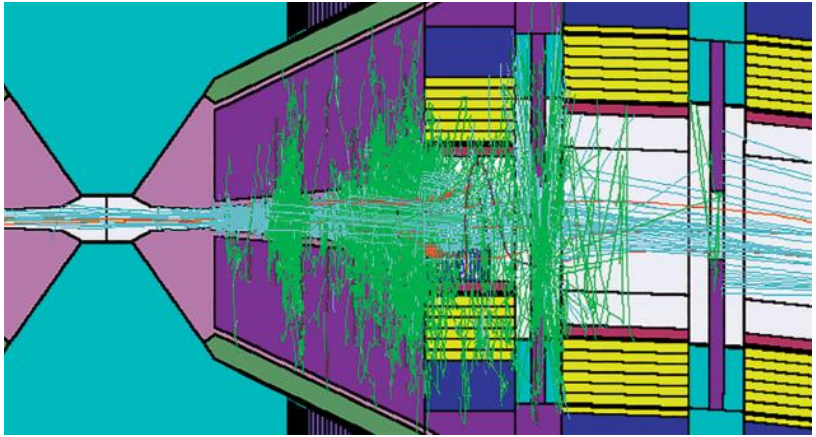
1) Muon Source

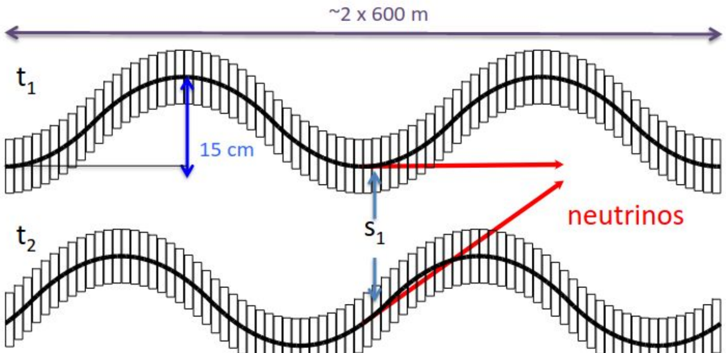
$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon\epsilon_L} f_r N_0 \gamma$$

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.

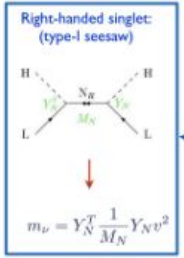
Seattle Snowmass Summer Meeting 2022

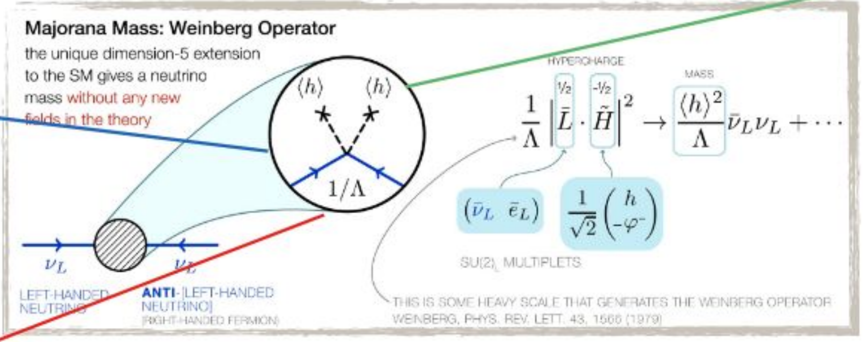
- **"...enough intermediate physics goals (e.g. neutrino beams)"**
- **neutrino mass …"This is certainly the most likely new physics there is…"**

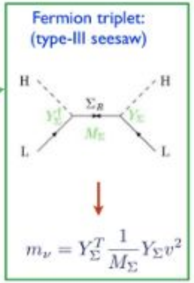
Neutrino **Portal** to BSM

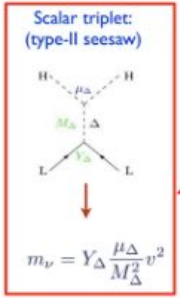
- Neutrino mass:
  - Confirmed by Neutrino Oscillation experiments
  - Beyond the Standard Model (SM) description

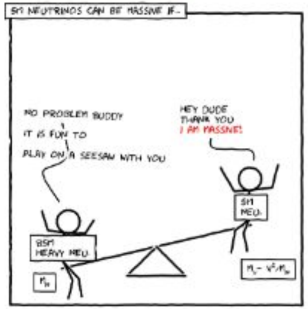
- Neutrino mass can be explained with:
  - Specific Beyond the Standard Model (BSM) theory with UV completeness
    - Example: Seesaw models
      - Tree level realization of the Weinberg Operator











[Sitian Qian]

Weinberg Operator: VVHH interaction!

      - Why named with "Seesaw"?: **Heavier** BSM particles leads to **lighter** SM neutrinos

CMS: Heavy Majorana seraches via VBS

Jie Xiao, Sitian Qian (PKU PhD students) arXiv:2206.08956 ~ accepted by PRL

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。

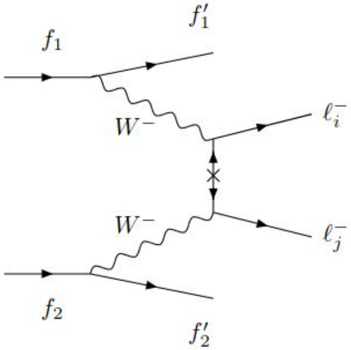
arXiv > hep-ph > arXiv:0901.3589

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

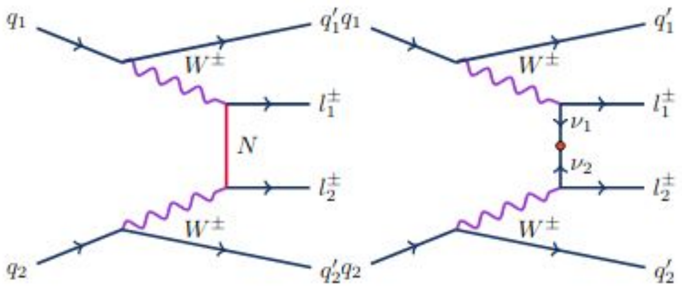
CMS tries out the seesaw 😄

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

CMS: Heavy Majorana and Weinberg Operator



- 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_ν with no new fields

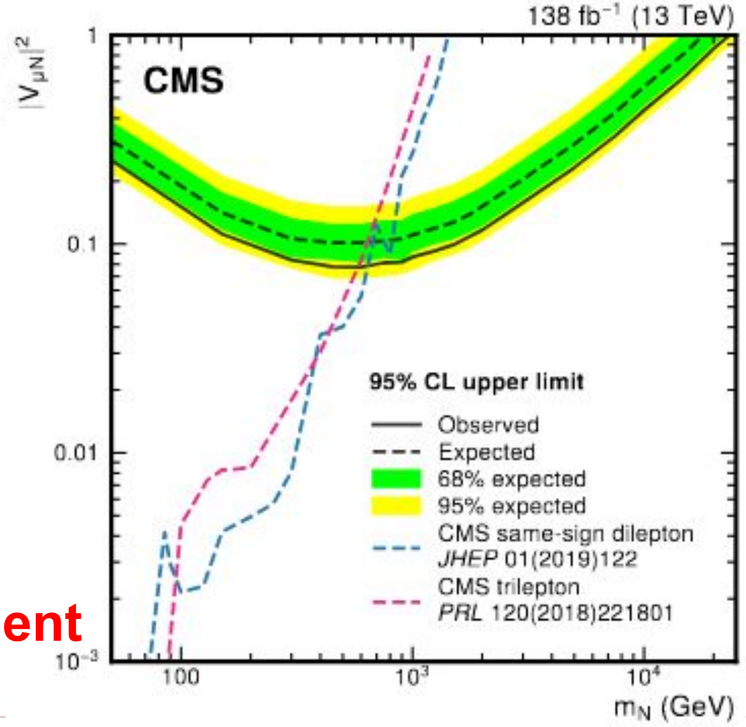
→ Analogous to neutrinoless double β decay, but with μ (instead of e)

~23TeV!

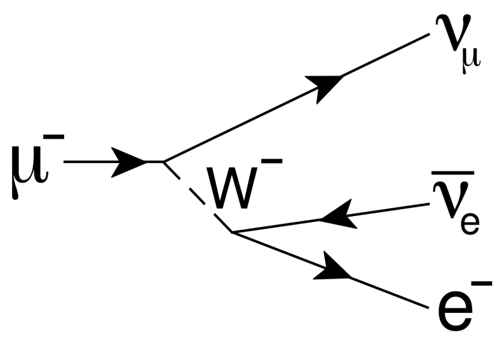
- Final state: two same sign $\mu\mu$ and VBF jets
- Dedicated studies to identify high-p_T μ

0νμμ experiment

- 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!



Neutrino Beam: long ago



B. J. King hep-ex/0005007

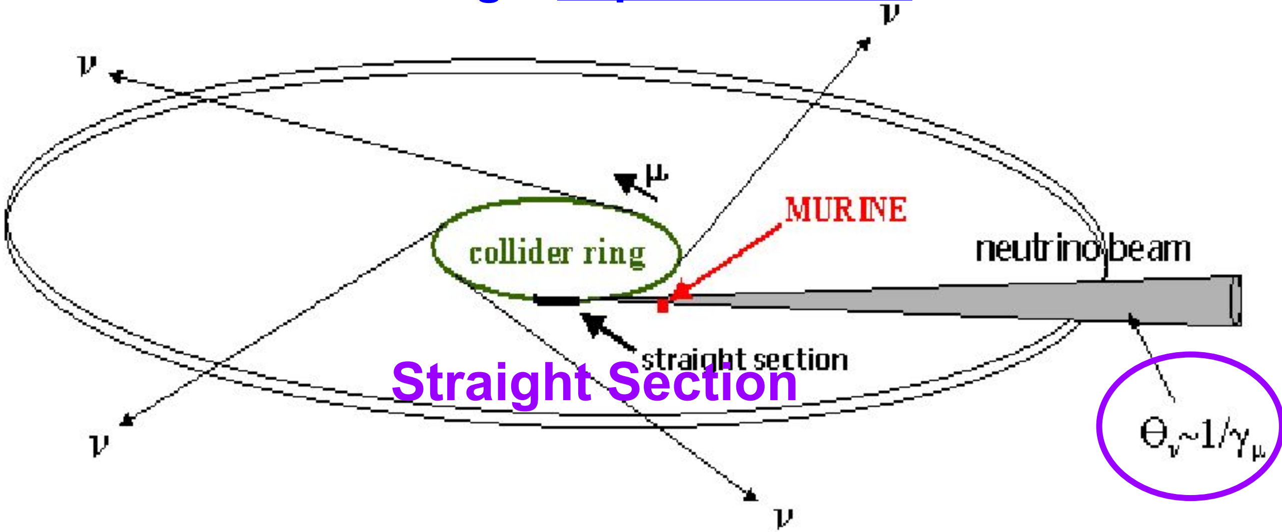
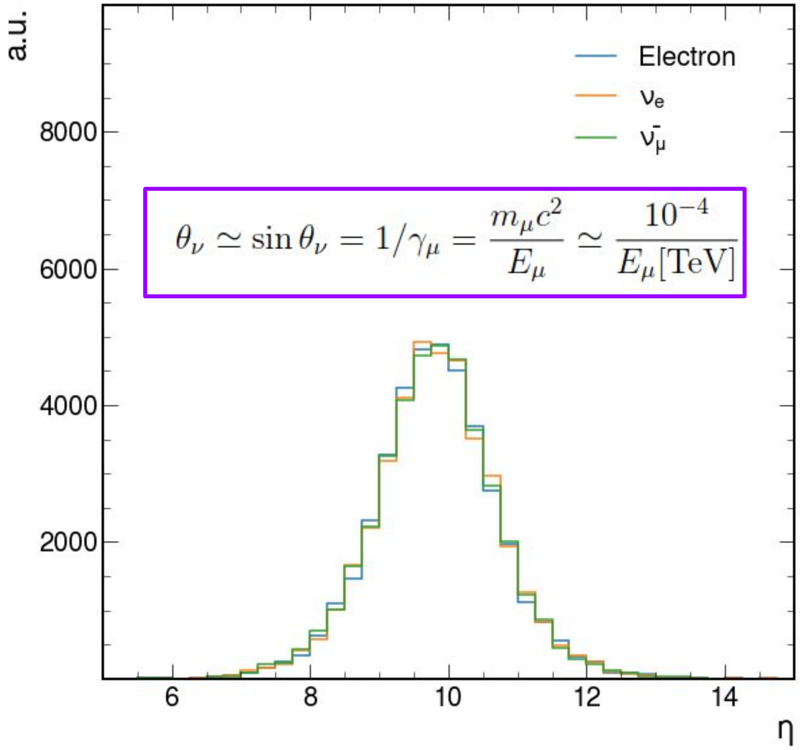


FIGURE 1. The decays of muons in a muon collider will produce a disk of neutrinos emanating out tangentially from the collider ring. The neutrinos from decays in straight sections will line up into beams suitable for experiments. The MURINEs will be sited in the center of the most intense beam and as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

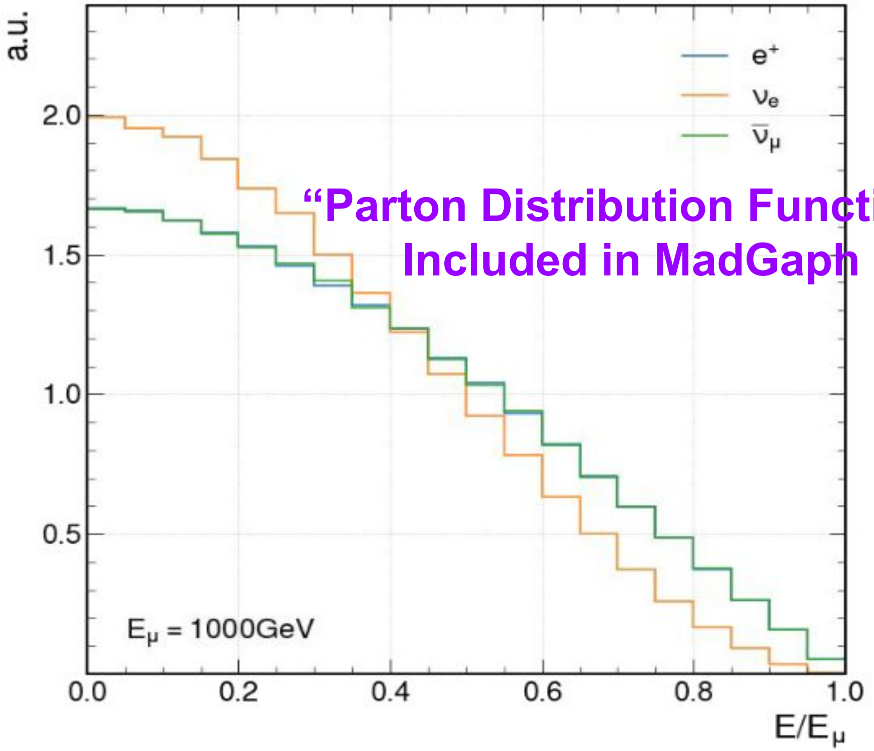
NuTeV
Neutrino-Nucleon Scattering
NuMAX
NuSOnG
Neutrino Scattering on Glass
nuSTORM
"Neutrinos from STORed Muons," …for neutrino oscillation searches

Head-on collisions at TeV scale?

Neutrino Beam from 1TeV Muon beam



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

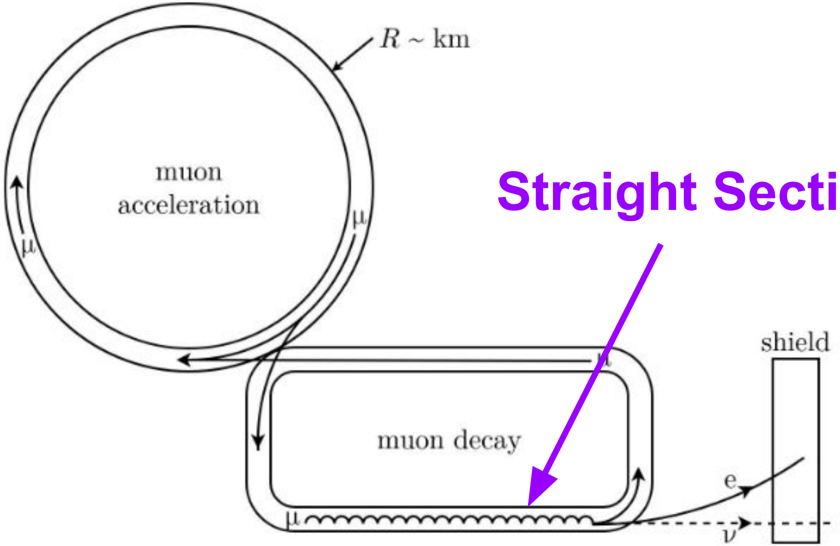


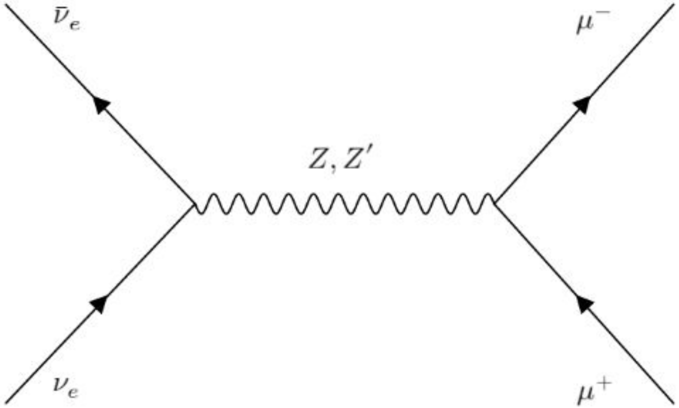
"Parton Distribution Function"
Included in MadGaph

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.

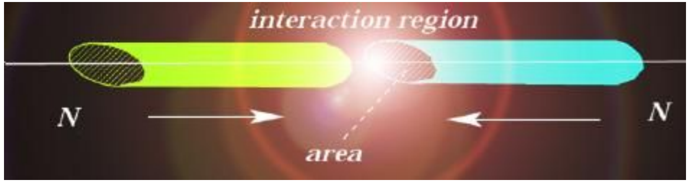
$$\nu_e \bar{\nu}_e \to Z \to \mu^+ \mu^- .$$

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

Question: ?/fb in 1-10 years

Very Crude Luminosity Estimation

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



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

As for TeV muon colliders, with $f_{\rm rep} = 100\,{\rm KHz}$, $\sigma_{x,y} \lesssim 10$ microns, and $N_{\rm beam1,2} = 10^{12}$, then $\mathcal{L} = 10^{33}$–10^{34} cm^{-2}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 $\mathcal{L} = 10^{28}$ cm^{-2}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} 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

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

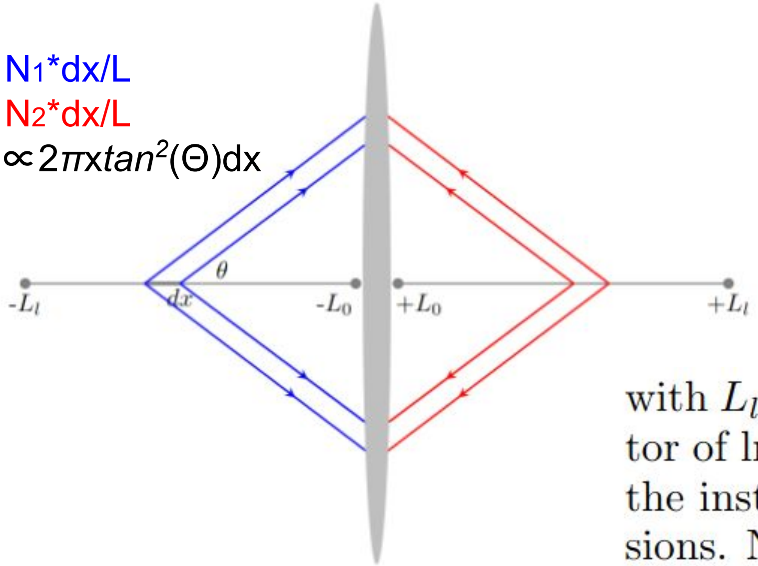
Crude Luminosity Estimation

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[area]$\propto 2\pi x \tan^2(\Theta)dx$



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

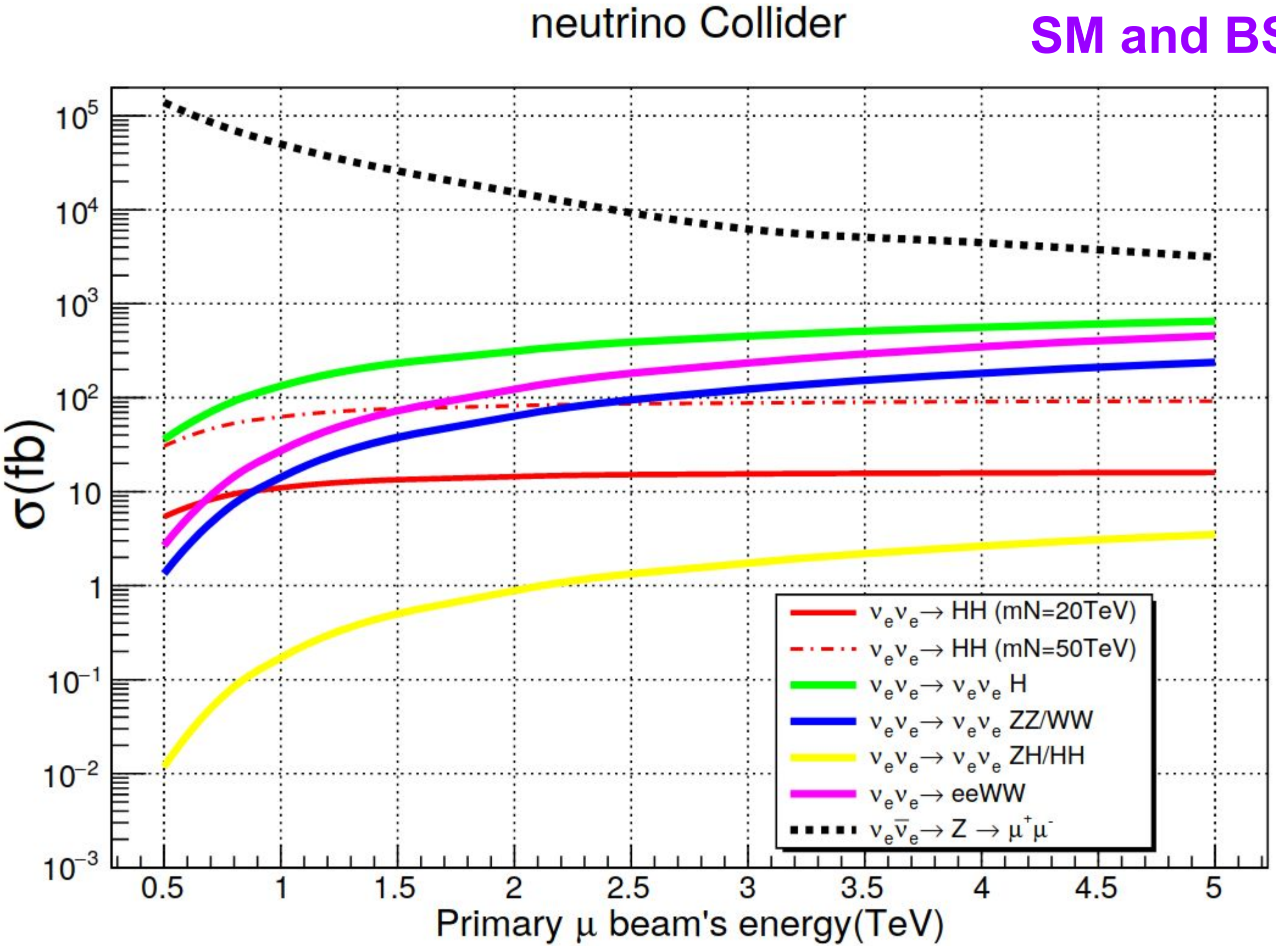
$$= \frac{L_l^2}{L_c^2}\frac{N_{\rm beam1}N_{\rm beam2}f_{\rm rep}}{8\pi L_l^2 \tan^2\theta} \times \ln(L_l/L_0),$$

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.

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

Neutrino Collision Processes

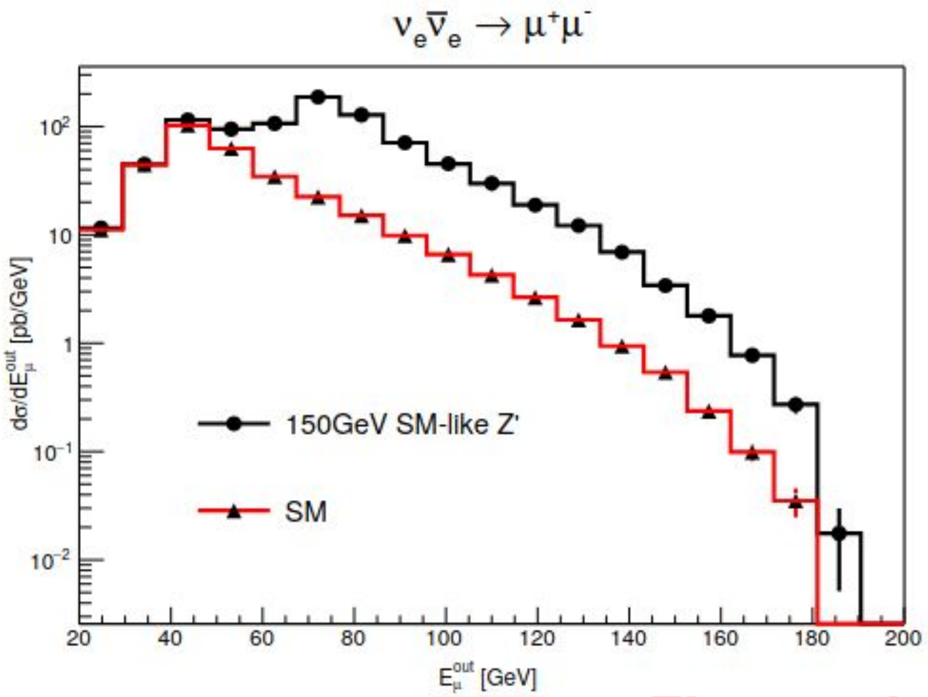


SM and BSM (Heavy Majorana)

- **vvbar->Z:**
  large cross section
  >100pb
  can be observed in short time!
  ~days to weeks
- **May loosen requirement on beam quality!**

Neutrino antineutrino Annihilation

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



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

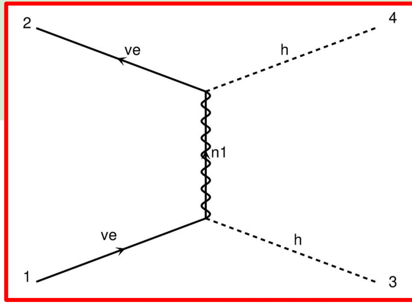
Outgoing muon energy distributions for neutrino antineutrino annihilation into Z and SM-like Z' bosons, with Z' mass set as 150 GeV with narrow width.

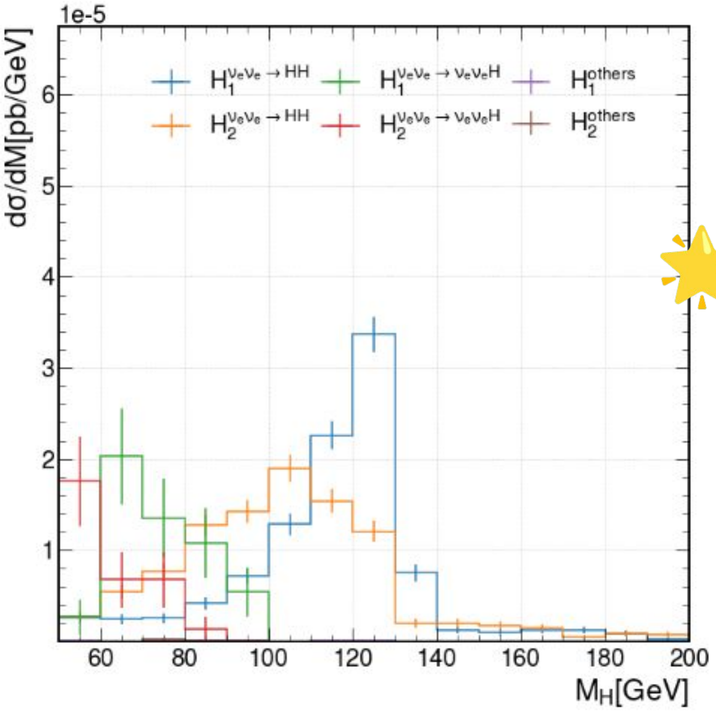
First probe on di-neutrino resonances!

Heavy Majorana Neutrino

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

Weinberg Operator,
UV completion with See-Saw models

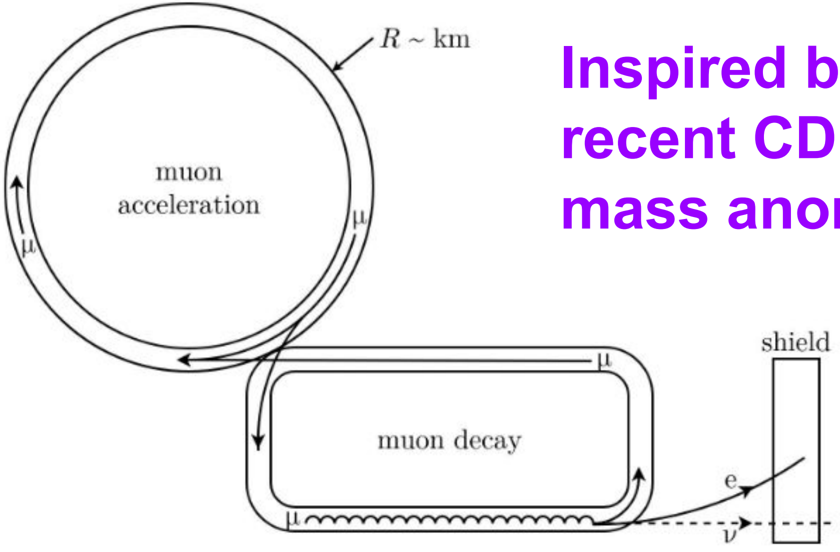




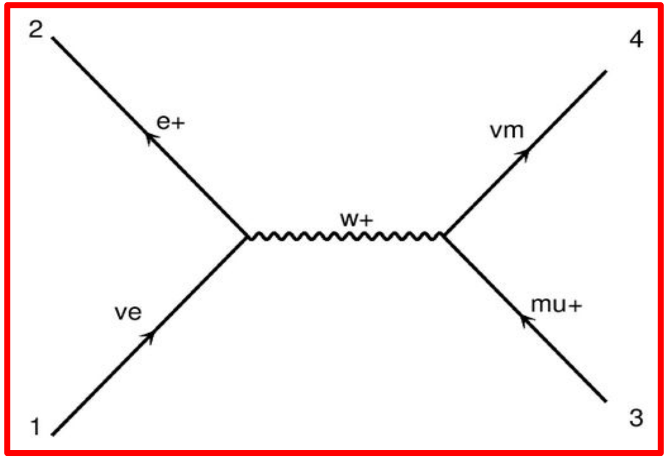
With 1 $\text{fb}^{-1}$of data, by cutting on reconstructed M_H, we are close to exclude $V_{eN1} \gtrsim 0.01$ at $M_N = 20$ TeV, at 95% C.L., which surpasses already current best limits from the CMS experiment [25] by two orders of magnitude. An interesting fact is that cross sections of $\nu_e\nu_e \to HH$ 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 $\text{fb}^{-1}$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!

Neutrino lepton Collider



Inspired by recent CDF W mass anomaly

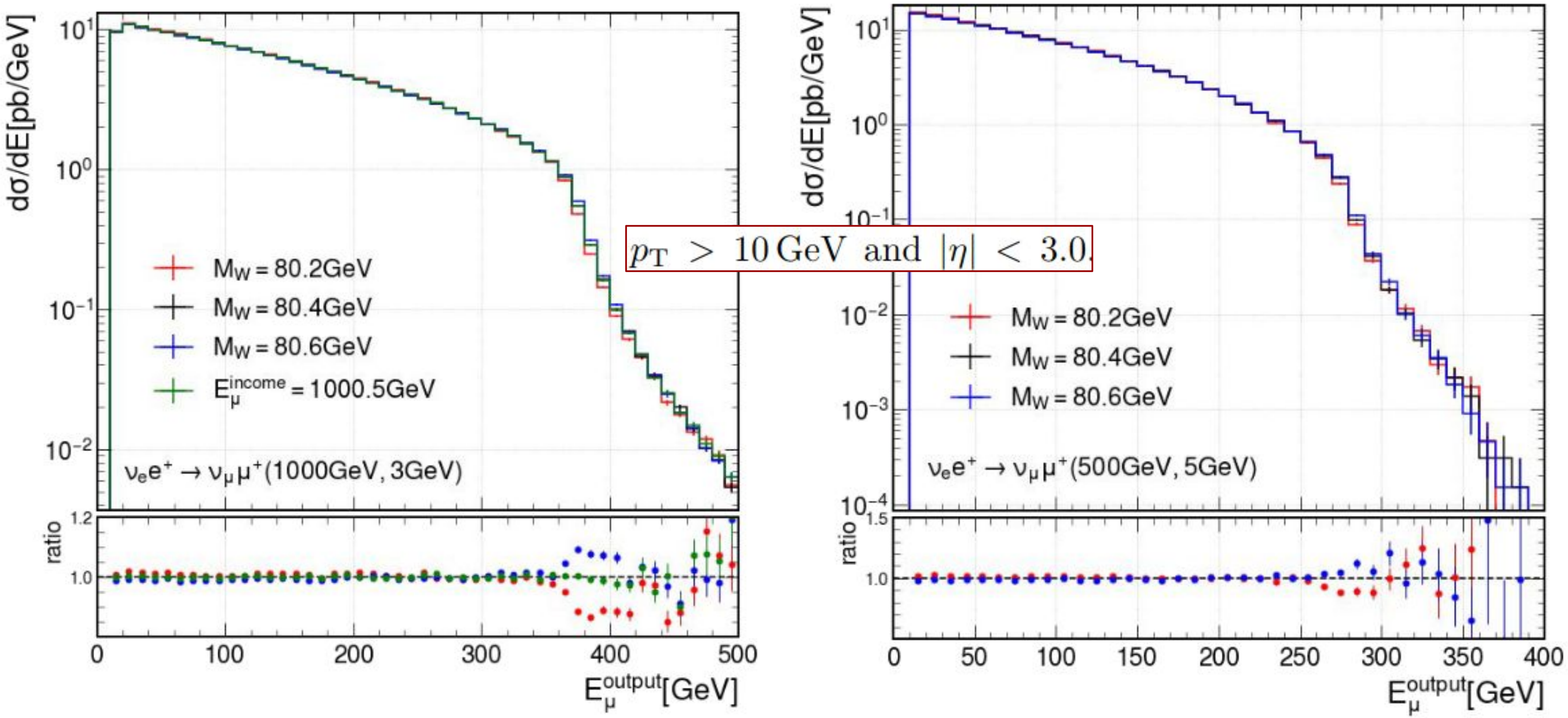


The instantaneous luminosity of a neutrino lepton collider would be limited by two main factors: 1) the intensity of the neutrino beam compared with the incoming muon beam is suppressed by roughly $L_l/L_c \sim 0.1$, i.e., the fraction of the collider ring circumference occupied by the production straight section [22], 2) the neutrino beam spread, which may still be kept at 10 to 100 microns at the interaction point, by applying a small modulation on muon decay angle through vertical bending to achieve more focused neutrino beam [24].

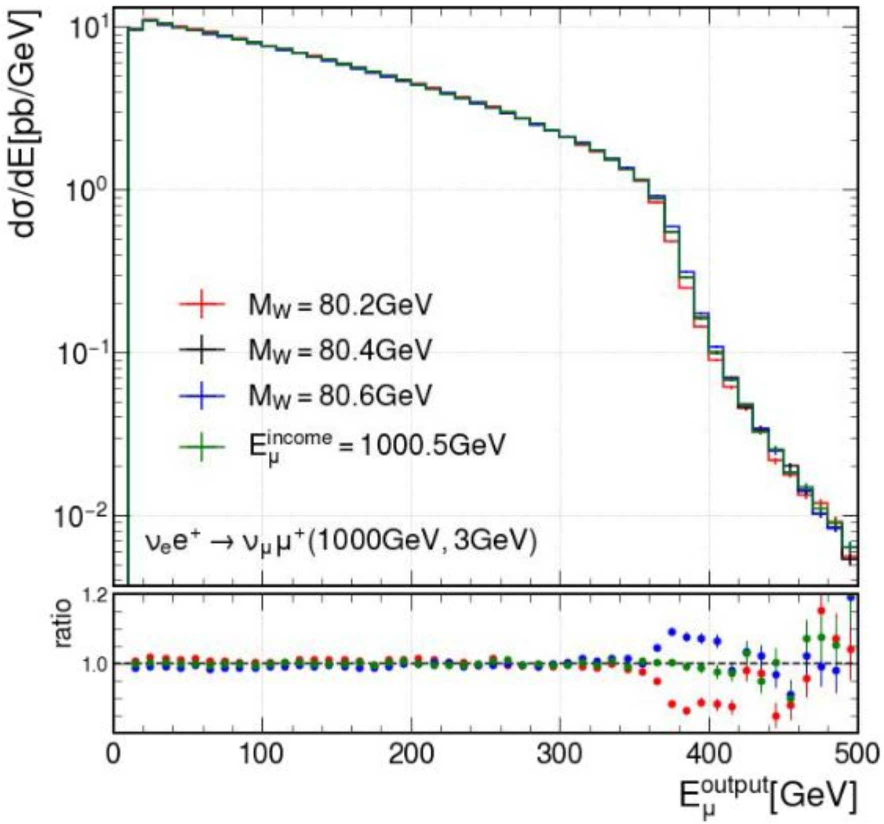
Similar design, but with only one sided neutrino beam, 0.1-1/fb in 10 years?

Single W production

Kink Structure from W threshold in convolution with Beam PDF



Single W production



Larger MW →

Higher incoming neutrino Energy →

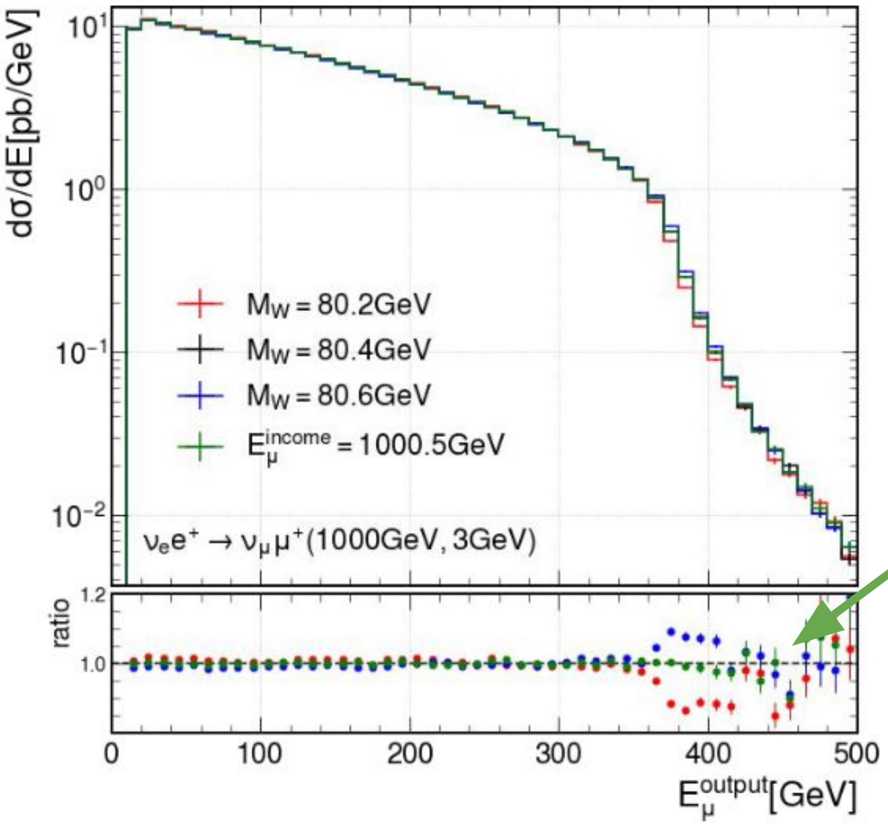
Larger outgoing Muon Energy (More boosted)

If pT(outgoing muon) > 40 GeV

the cross sections with **MW = 80.4 (80.41) are 166.2 (167.6) pb.**

Based on a simple counting experiment, **a 10 MeV accuracy on MW** can be achieved with an integrated luminosity of **only 0.1 fb−1.**

Robustness on W mass precision



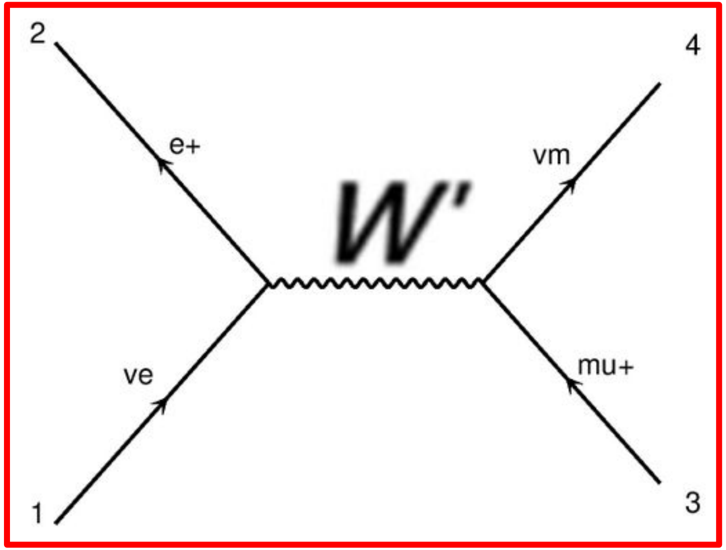
We varied the incoming muon and electron beam energy by 0.5 GeV and 10 MeV, respectively, which are quite conservative following previous refs.

We found that the **cross sections changed by about 0.6 pb for both variations.**

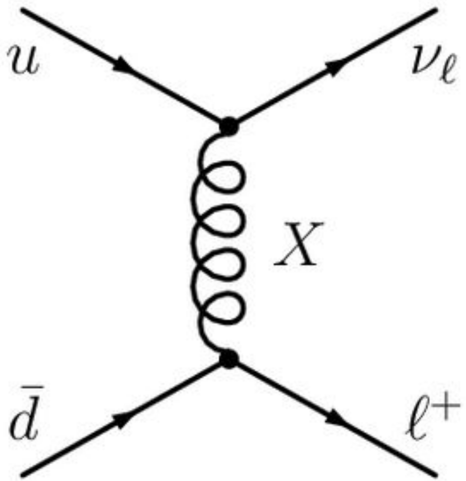
This uncertainty could be **mitigated by using the shape of the outgoing muon energy**, by scanning different incoming beam energies, or by calibrating the incoming muon beam energy with the electron decay products.

More Physics from neutrino-lepton collisions

$$e^+e^- \to Z^{0(*)},\ \nu_e e^- \to \nu_e e^-,\ \tilde{\nu}_\mu e^- \to \tilde{\nu}_\mu e^-,$$
$$\nu_e e^+ \to W^{+(*)},\ \tilde{\nu}_\mu e^+ \to \tilde{\nu}_\mu e^+,\ \tilde{\nu}_\mu e^+ \to \tilde{\nu}_e \mu^+,$$
$$\tilde{\nu}_\mu \mu^- \to W^{-(*)},\ \nu_e \mu^- \to \nu_e \mu^-,\ \nu_e \mu^- \to e^- \nu_\mu.$$

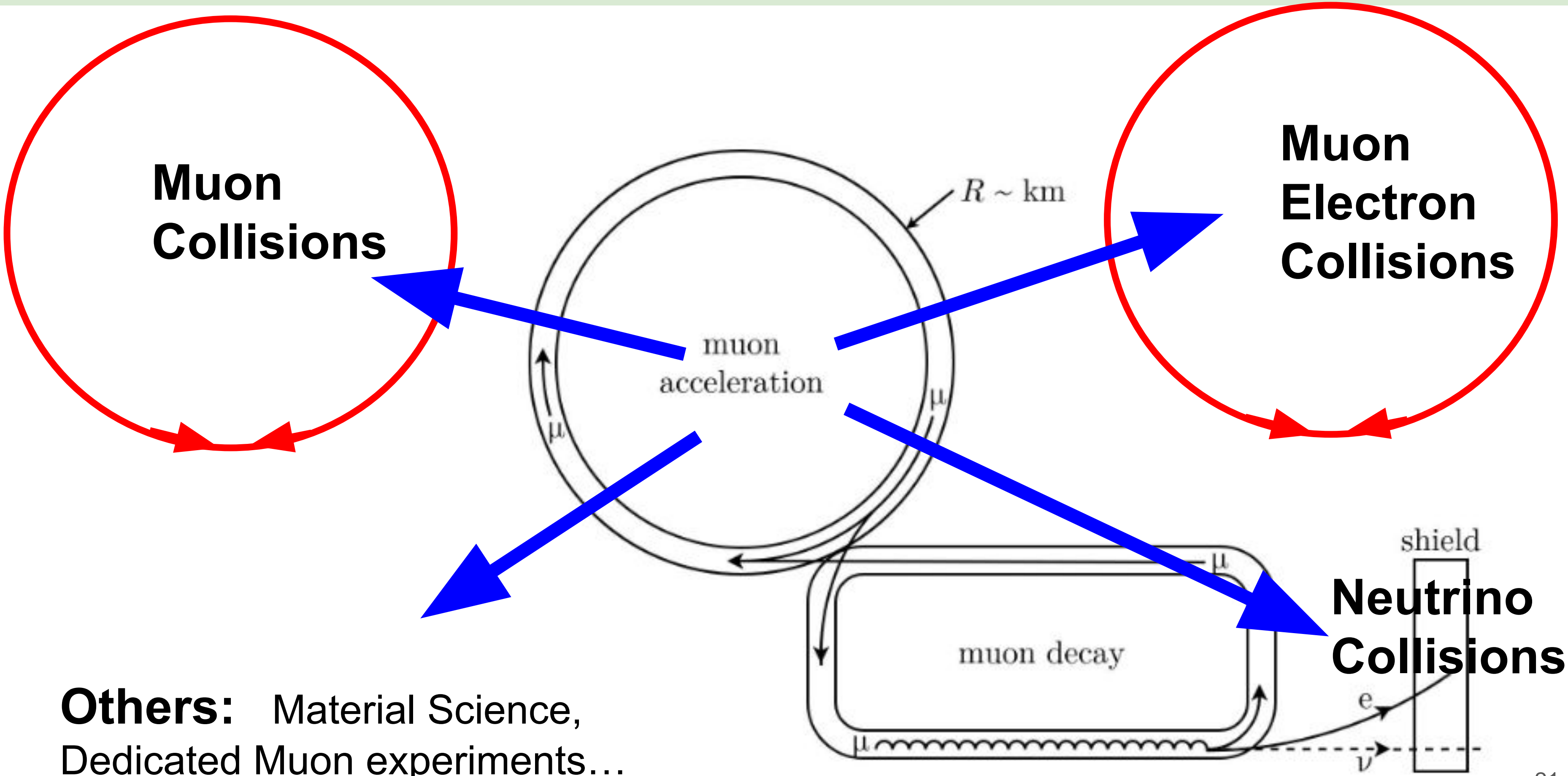


Anomalous Zvv couplings



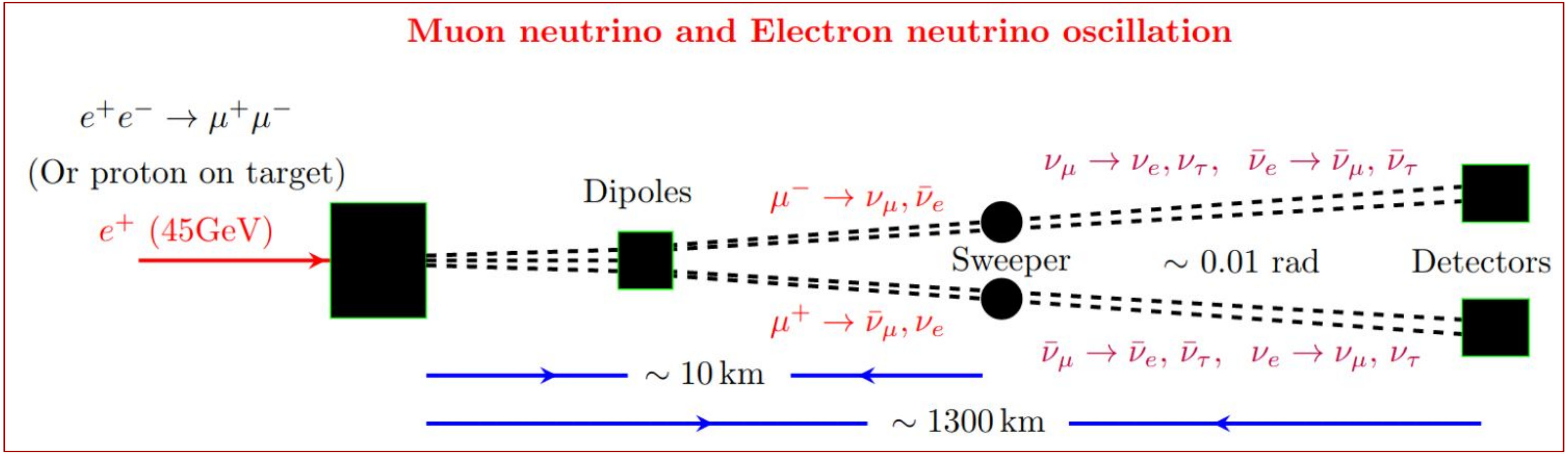
⇚ **leptoquark**

Dream Bigger: muon complex



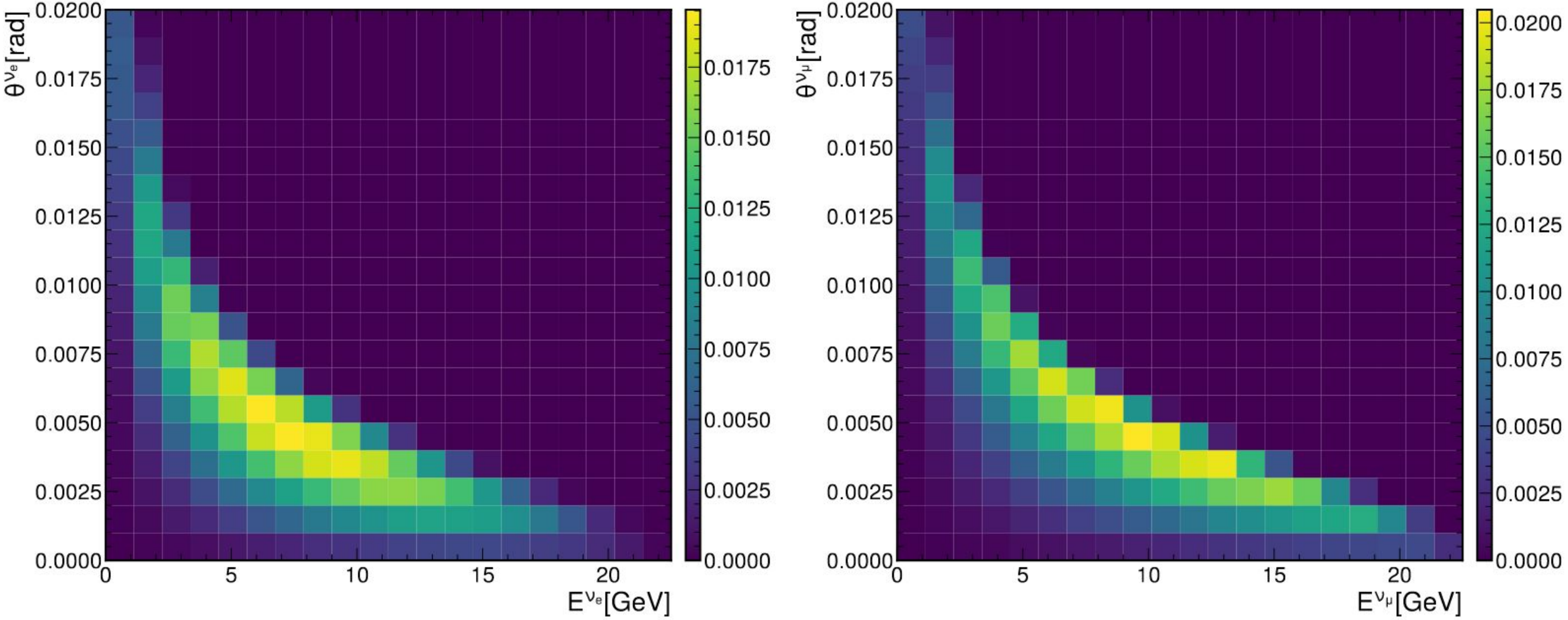
Others: Material Science,
Dedicated Muon experiments…

Muon Beam for Neutrino CP Violation



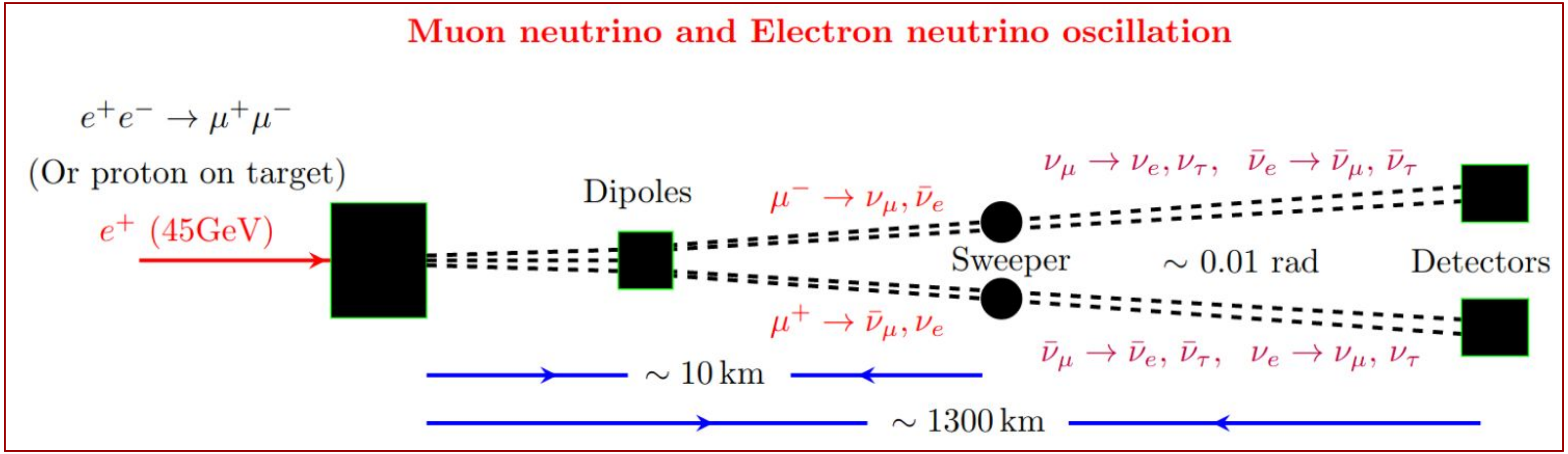
- **Collimated and manipulable** muon beams, which lead to a larger acceptance of neutrino sources in the far detector side.
- **Symmetric μ+ and μ− beams,** and thus symmetric neutrino and antineutrino sources, ideally useful for measuring neutrino CP violation.

Neutrino Profile from Muon Decay



5-7 GeV In average

Neutrino Event Rates at Far Detector



Muon production rates $n(\mu^+\mu^-)_{max} \approx n^+ \times 10^{-5}$ [10]. Assuming positron bunch density as 10^{12}/bunch and bunch crossing frequency as 10^5/sec, we get **muon production rates** $dN_\mu/dt \sim 10^{12}$**/sec (or** 10^{19}**/year)**.

$$N^{cc}_{\nu_{\mu,e}} \sim 10^{19} \times 10^{-1} \times 10^{-4} \times 10^{-9} = 10^5/\text{year},$$

LEMMA Muon source — *Usually thought not intense yet for a muon collider*

Decay Fraction

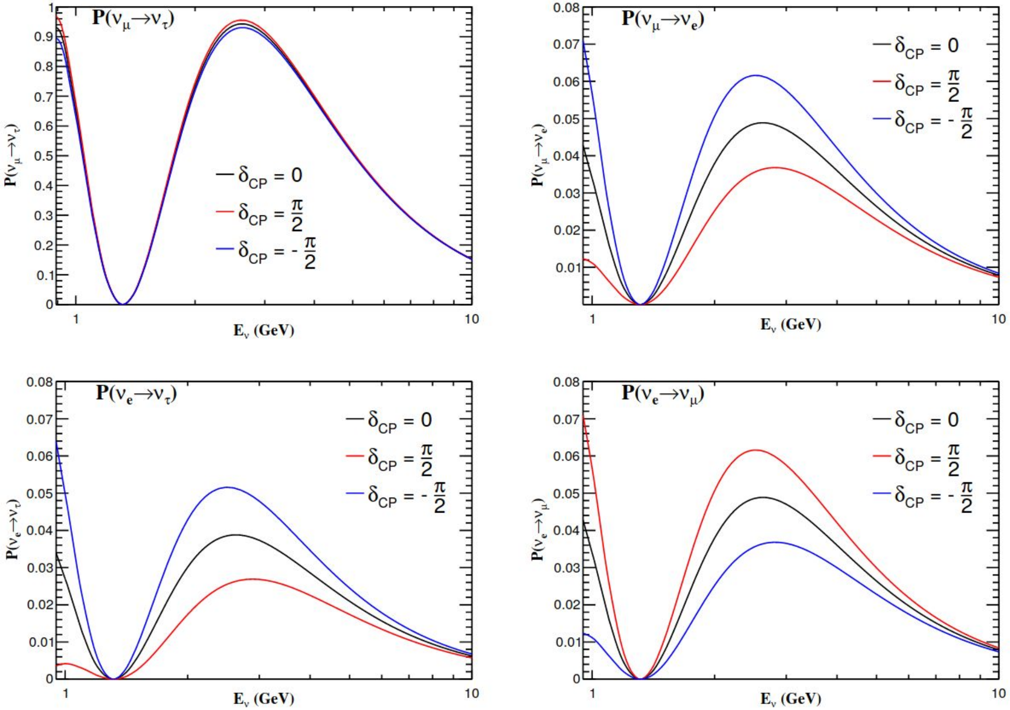
Acceptance

CC event in DUNE like detector

Long Base Line Neutrino Mixing

$$\mu^+ \to e^+ \bar{\nu}_{\mu 1} \nu_{e1} \implies \bar{\nu}_{\mu 1} \to \bar{\nu}_{\tau 1}, \; \nu_{e1} \to \nu_{\tau 1},$$

$$\mu^- \to e^- \nu_{\mu 2} \bar{\nu}_{e2} \implies \nu_{\mu 2} \to \nu_{\tau 2}, \; \bar{\nu}_{e2} \to \bar{\nu}_{\tau 2},$$



$$P(\nu_\mu \to \nu_\tau) \simeq \sin^2(2\theta_{23}) \cos^4(\theta_{13}) \sin^2\left(1.27 \frac{\Delta m^2_{32} L}{E_\nu}\right)$$
$$\pm 1.27 \Delta m^2_{21} \frac{L}{E_\nu} \sin^2\left(1.27 \frac{\Delta m^2_{32} L}{E_\nu}\right) \times 8 J_{CP}$$

$$N^{cc}_{\nu_\tau} \sim [(3 \times 10^4) \pm (2.6 \times 10^2)]/\text{year},$$

$$P(\nu_e \to \nu_\tau) \simeq \sin^2(2\theta_{13}) \cos^2(\theta_{23}) \sin^2\left(1.27 \Delta m^2_{32} \frac{L}{E_\nu}\right)$$
$$\mp 1.27 \Delta m^2_{21} \frac{L}{E_\nu} \sin^2\left(1.27 \Delta m^2_{32} \frac{L}{E_\nu}\right) \times 8 J_{CP}$$

CP Violations from tau (anti) neutrinos

- **1)** Firstly, we consider the tau (anti-) neutrino appearance from muon and electron neutrino oscillations:

$$\mu^+ \to e^+ \bar{\nu}_{\mu 1} \nu_{e1} \implies \bar{\nu}_{\mu 1} \to \bar{\nu}_{\tau 1}, \; \nu_{e1} \to \nu_{\tau 1}, \tag{14}$$

$$\mu^- \to e^- \nu_{\mu 2} \bar{\nu}_{e2} \implies \nu_{\mu 2} \to \nu_{\tau 2}, \; \bar{\nu}_{e2} \to \bar{\nu}_{\tau 2}, \tag{15}$$

where '1' and '2' symbol the two far detectors as shown in Fig. 1.

Notice that the CP dependence of $P(\nu_e \to \nu_\tau)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_\tau)$ as shown in Eq. 10 vary in the same direction. If we count on tau-related events in the far detector inclusively, this means our signal doubles. The sensitivity can be estimated then as

$$\frac{\bar{\nu}_{\tau 2} + \nu_{\tau 2} - \bar{\nu}_{\tau 1} - \nu_{\tau 1}}{\sqrt{\bar{\nu}_{\tau 2} + \nu_{\tau 2} + \bar{\nu}_{\tau 1} + \nu_{\tau 1}}} \tag{16}$$

which is around $4 \times 260/\sqrt{60000} \sim 4.2$ standard deviations (σ) in one year, and can reach near 13.4σ in 10 years. Although only statistics are taken into account here, systematics should be able to be reduced efficiently due to the symmetric property of the proposed device. Furthermore, it is possible to exchange μ^+ and μ^- flying routes, thus further reducing possible bias or systematic.

Can use directly DUNE/T2K detector.
Needs high efficiency to detect tau neutrinos.

CP Violations from e/mu neutrinos

- **2)** Secondly, if the far detector can distinguish tau neutrino from antineutrino such as the CERN SHiP experiment [36], then with only $P(\nu_e \to \nu_\tau)$, we can already have higher CP sensitivity. The sensitivity can be estimated then as

$$\frac{\bar{\nu}_{\tau 2} - \nu_{\tau 1}}{\sqrt{\bar{\nu}_{\tau 2} + \nu_{\tau 1}}} \tag{17}$$

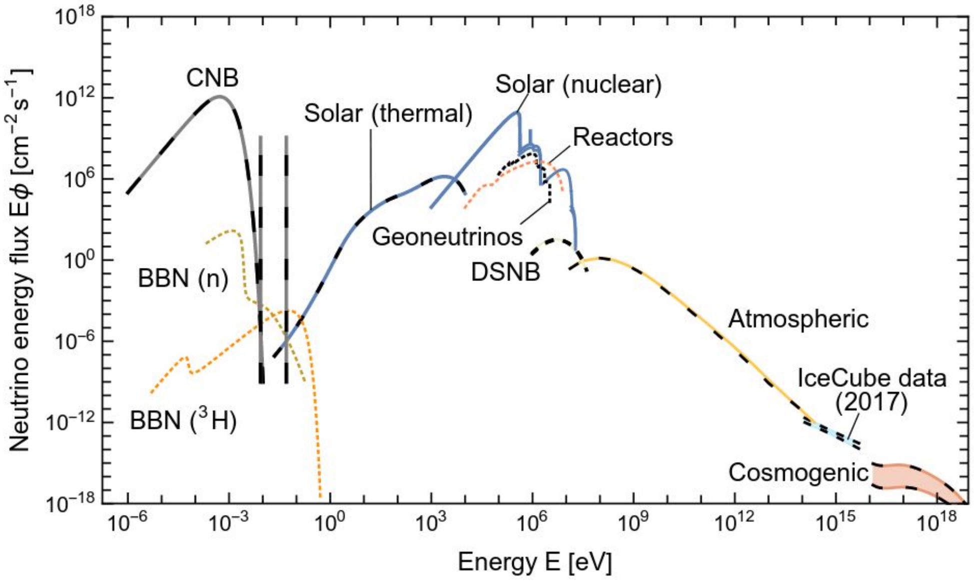
which is around $2 \times 260/\sqrt{2200} \sim 11\ \sigma$ in one year.

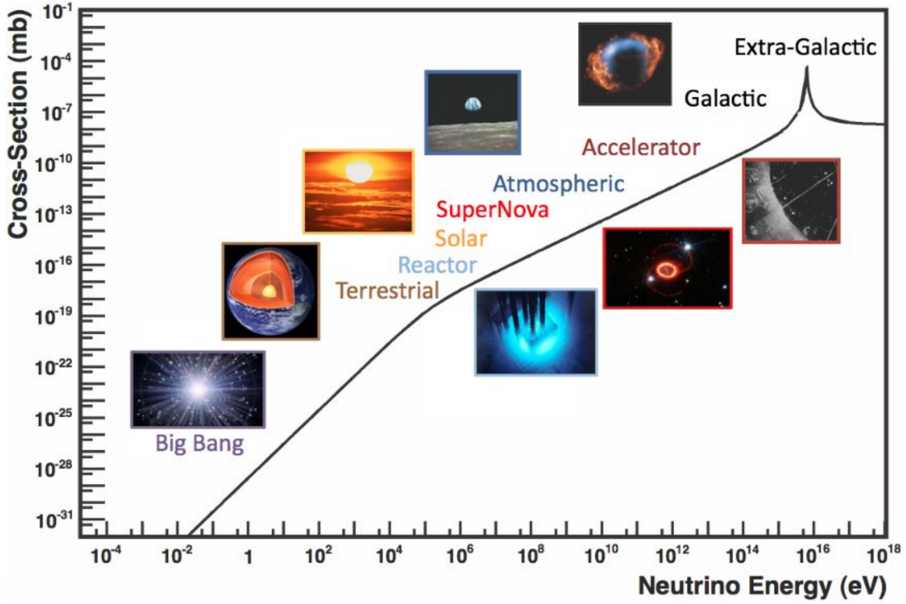
- **3)** Finally, one can also exploit electron to muon oscillation which has also clear sensitivity on neutrino CP phase, if the far detector can distinguish muon neutrino from antineutrino, possibly can be achieved with moderate magnets. The sensitivity can be estimated then as $2 \times 260/\sqrt{3000} \sim 9.5\ \sigma$ in one year.

Much Higher sensitivity. However, needs to distinguish neutrino from anti-neutrino, thus putting requirements (e.g. magnetism field) on experiments.

Bonus: Low Energy/Mass Neutrino and Dark Matter Detection Using Freely Falling Atoms

Rev. Mod. Phys. 84, 1307 (2012)





Rev. Mod. Phys. 92, 45006 (2020)

FIG. 1 Representative example of various neutrino sources across decades of energy. The electroweak cross-section for $\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$ scattering on free electrons as a function of neutrino energy (for a massless neutrino) is shown for comparison. The peak at 10^{16} eV is due to the W^- resonance, which we will discuss in greater detail in Section VII.

https://aip.scitation.org/doi/pdf/10.1063/1.4915587

How difficult it would be to detect Cosmic Neutrino Background?

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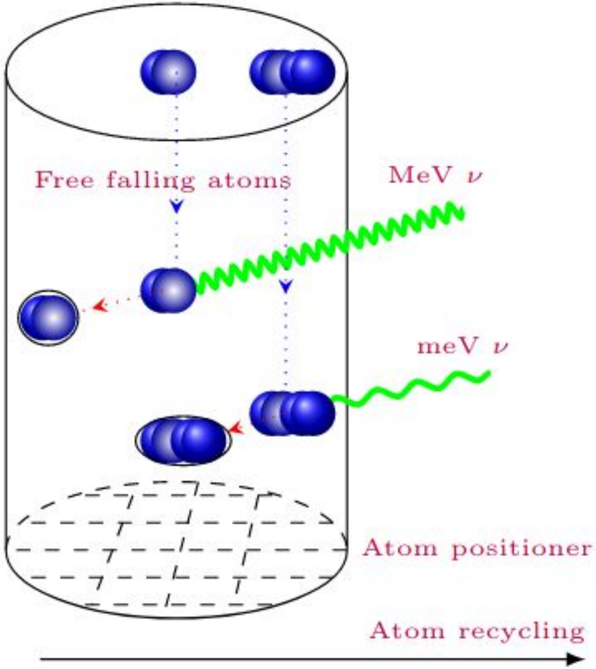
Abstract. Possible ways of detecting the cosmic neutrino background are described and their difficulties discussed. Among them, the capture on the radioactive tritium nuclei is challenging, but perhaps doable. The principal difficulty is the need for the combination of a very strong source and very good detector resolution. It is argued that if it turns out that the neutrino masses follow the degenerate scenario, i.e. if $m_\nu \geq 0.1$ eV for all three massive neutrinos, then it is important to devote a substantial effort to develop a realistic detection experiment.

Keywords: Cosmology, relic neutrinos
PACS: 95.30.Cq, 14.60.Lm, 14.60.Pq

For 10^7 heavy atoms of a mass number around 100 with a small recoil energy as 1 meV, the velocity will be

$$v \sim \sqrt{2 \times 1.6 \times 10^{-22}/(1.7 \times 10^{-18})} \sim 0.01\,\mathrm{m/s}, \qquad (1)$$

which will produce significant kinematic shift to be detected, while almost impossible with conventional method.



Summary

- **Boson-Boson collisions to search for Majorana neutrino at CMS**
- **Revived interests in Muon Colliders**
  - **connection to neutrino Frontiers**
  - **Neutrino-neutrino collider sensitive to neutrino physics**
    - Several days of run to observe neutrino annihilation
  - **An neutrino-lepton collider to measure W mass**
    - 10MeV accuracy with 0.1/fb!
  - **Muon beams to generate symmetric ν and anti-ν source**
    - CP violation

Happy Mu Nu Year!

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The goal of this Special Issue, entitled "Symmetry on Multiboson Physics", is to report on the latest advances on all these multiboson-related topics. We kindly invite all researchers working in the area to contribute to this Special Issue.

- **Keywords**

W/Z boson; photon; Higgs boson; standard model measurements; vector boson fusion/scattering; di/tri-boson; boosted jet; deep learning

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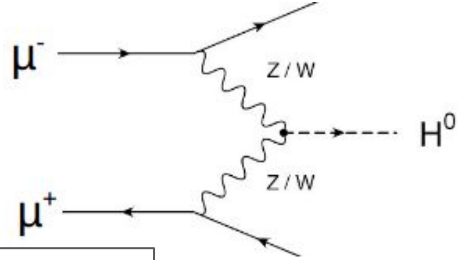
Backup

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

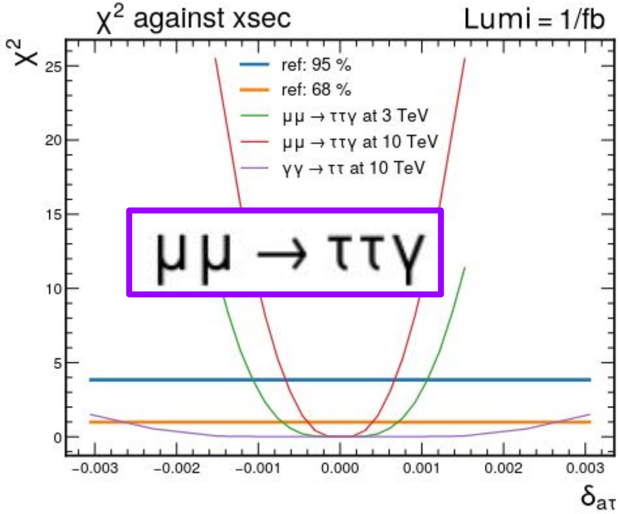
But lifetime at rest only 2.2 μs.

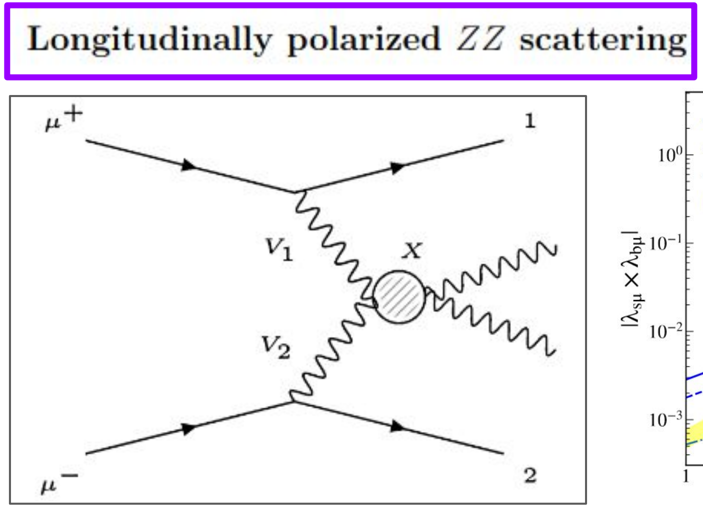


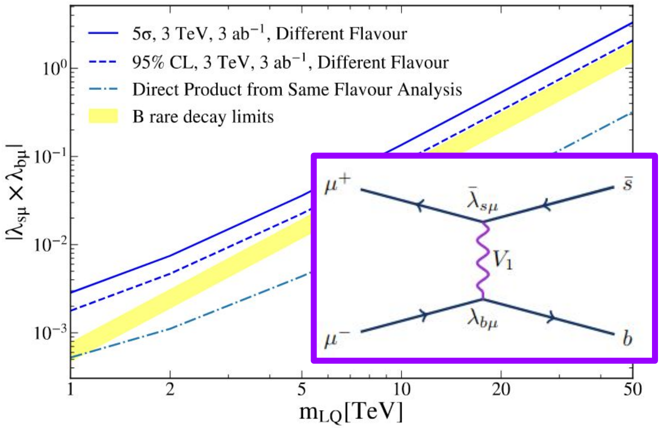
Parameter	Units	Higgs		Multi-TeV	
CoM Energy	TeV	0.126	1.5	3.0	6.0
Avg. Luminosity	10^{34}cm^{-2}s^{-1}	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^7 sec		13'500	37'500	200'000	820'000
Circumference	km	0.3	2.5	4.5	6
No. of IP's		1	2	2	2
Repetition Rate	Hz	15	15	12	6
$\beta^*_{x,y}$	cm	1.7	1	0.5	0.25
No. muons/bunch	10^{12}	4	2	2	2
Norm. Trans. Emittance, ε_{TN}	μm-rad	200	25	25	25
Norm. Long. Emittance, ε_{LN}	μm-rad	1.5	70	70	70
Bunch Length, σ_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

Rich Physics at Muon Collider







arXiv:2201.07808
Tau at TeV scale, flying several cms, sensitive to tau g-2

Displaced Tau reconstruction: tracker

arXiv:2107.13581
LL Polarized ZZ scattering
>5σ with 3/ab at 14 TeV MC

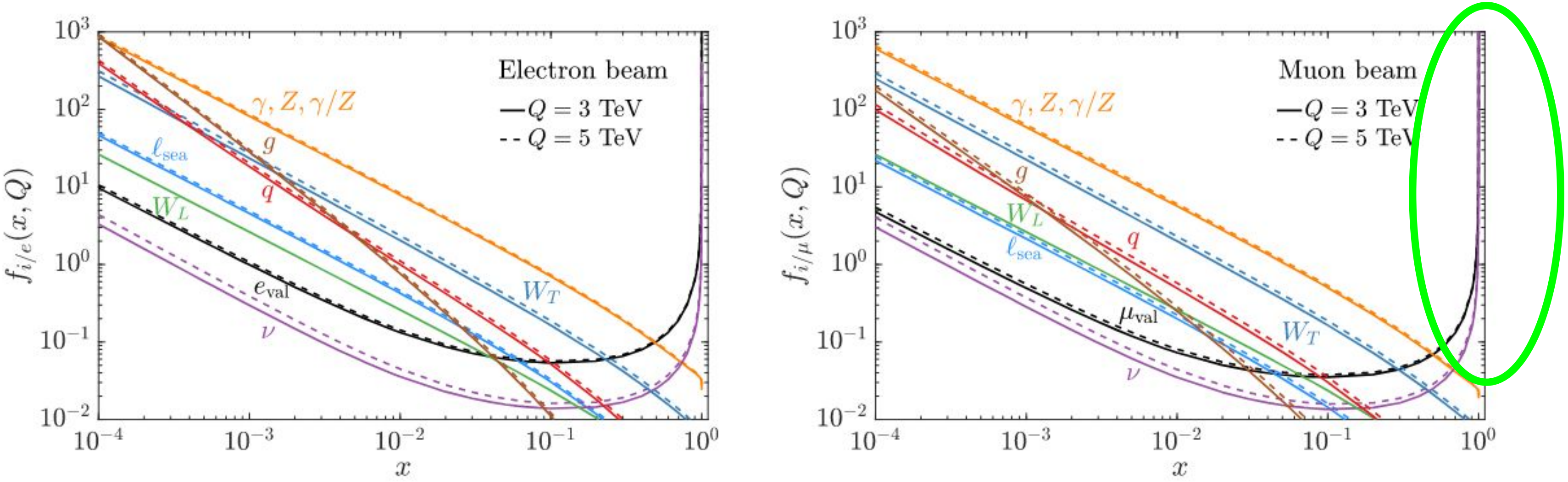
Closer Z decay products: finer calorimeter

arXiv:2109.01265
Leptoquark searches
B anomaly

Flavor tagging: Tracker, vertex

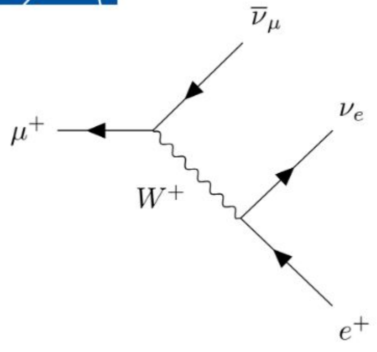
and more funs

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

Muon Decay



About 1/3 of energy in electrons and positrons:

Experiments needs to be protected from **background** by masks

- simulations of 1.5, 3 and 10 TeV
- optimisation of masks and lattice design started
- first results look encouraging
- will be discussed at ICHEP

Collider ring magnets need to be shielded from losses

Losses elsewhere will also need to be considered but are less severe

International MUON Collider Collaboration

ICHEP

D. Lucchesi, A. Lechner, C Carli et al.

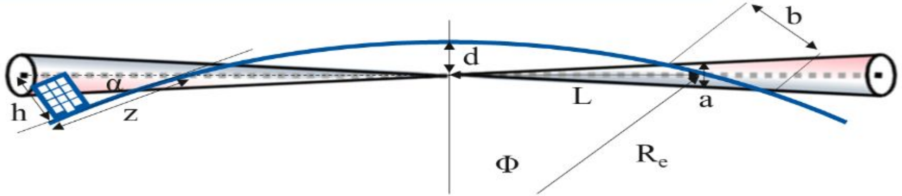
Neutrino flux to have negligible impact on environment

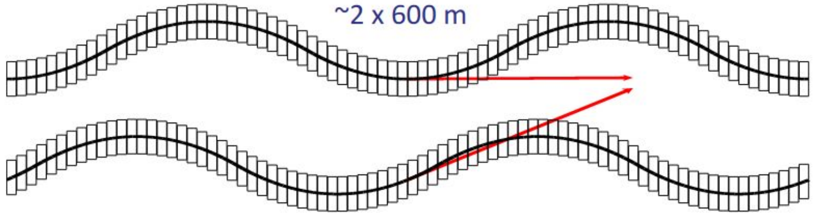
- want to be **negligible** (same level as LHC)
- opening cone decreases, cross section and shower energy increase with energy

Above about 3 TeV need to make beam point in different vertical directions

Mechanical system with 15cm stroke, 1% vertical bending

Length of pattern to be optimised for minimal impact on beam





for the neutrino oscillations at Ev = 7 (5) GeV

$$P(\nu_\mu \to \nu_\tau) = 0.2916 \pm 0.0026 \sin\delta_{\rm CP}\ (0.5093 \pm 0.0048 \sin\delta_{\rm CP}),$$
$$P(\nu_\mu \to \nu_e) = 0.0151 \mp 0.0026 \sin\delta_{\rm CP}\ (0.0264 \mp 0.0048 \sin\delta_{\rm CP}),$$
$$P(\nu_e \to \nu_\mu) = 0.0151 \pm 0.0026 \sin\delta_{\rm CP}\ (0.0264 \pm 0.0048 \sin\delta_{\rm CP}),$$
$$P(\nu_e \to \nu_\tau) = 0.0119 \mp 0.0026 \sin\delta_{\rm CP}\ (0.0209 \mp 0.0048 \sin\delta_{\rm CP}).$$

- The opening angles between muons and decay products are around 0.005 rad. as shown in Fig. 3 and may be kept smaller with quadrupoles. For neutrinos traveling 1300 Km to reach far detectors, the spread size can be around 1-5 Km. For a DUNE-like detector with a cubic size of about 20 m [29], **the neutrino acceptance is then** 10^{-4}.

- Muon/electron neutrinos and antineutrinos interacting with detectors. With a $L = 20$ m long detector (DUNE far detector indeed has a length around 50m [29]), **the expected event yield rate can be roughly estimated with:** $dN_\mu/dt \times L \times \sigma_{n\nu} \times \rho N_A \cdot dE \sim 10^{-9} \times dN_\mu/dt$, where N_A is the Avogadro constant, $\rho \sim 2$ g/cm^3, $\sigma_{n\nu}$ symbols the neutrino nucleon cross sections and is around 10^{-37}cm^2 for a 10 GeV neutrino [31, 32].