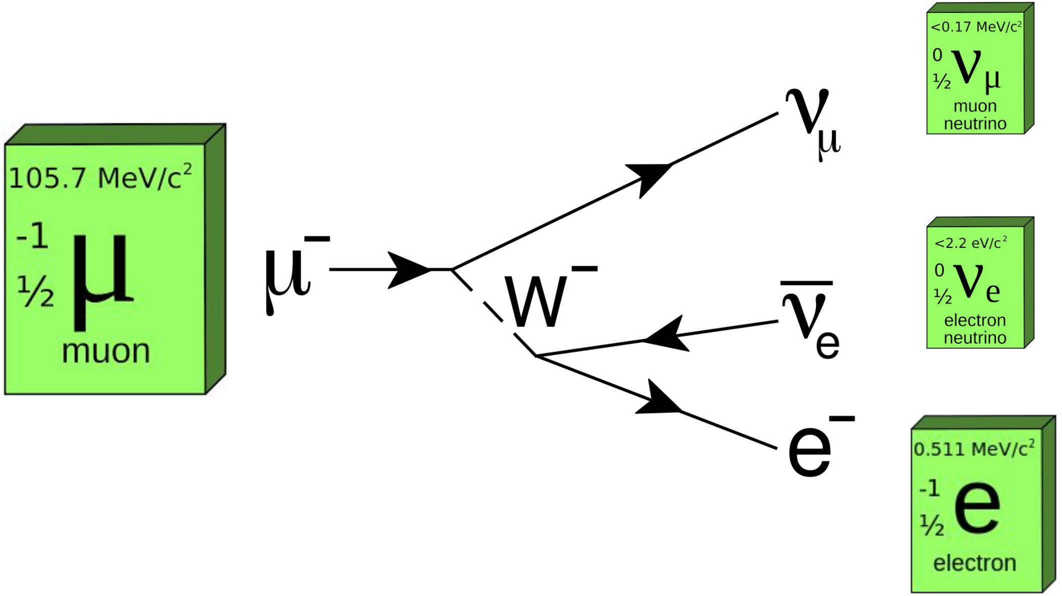
Possible intermediate steps towards a Muon collider

from neutrino neutrino/lepton, electron muon to muon muon collisions?

"Exotica" Particle ➛ 😊 "Exotica" Collider

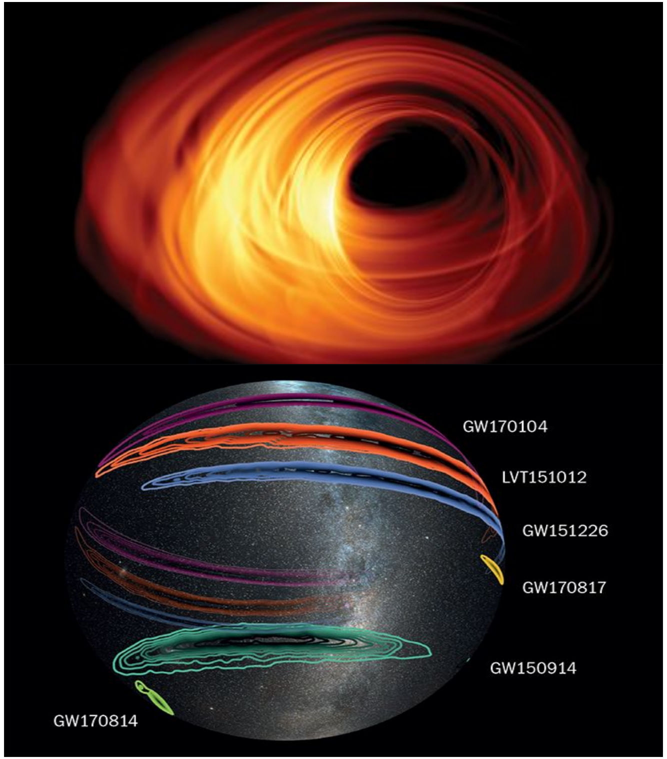


Qiang Li, Peking University 2022/10/12

arXiv:2205.15350, arXiv:2204.11871, arXiv:2201.07808, arXiv:2109.01265, arXiv:2107.13581, arXiv:2010.15144

Richness out of smallness

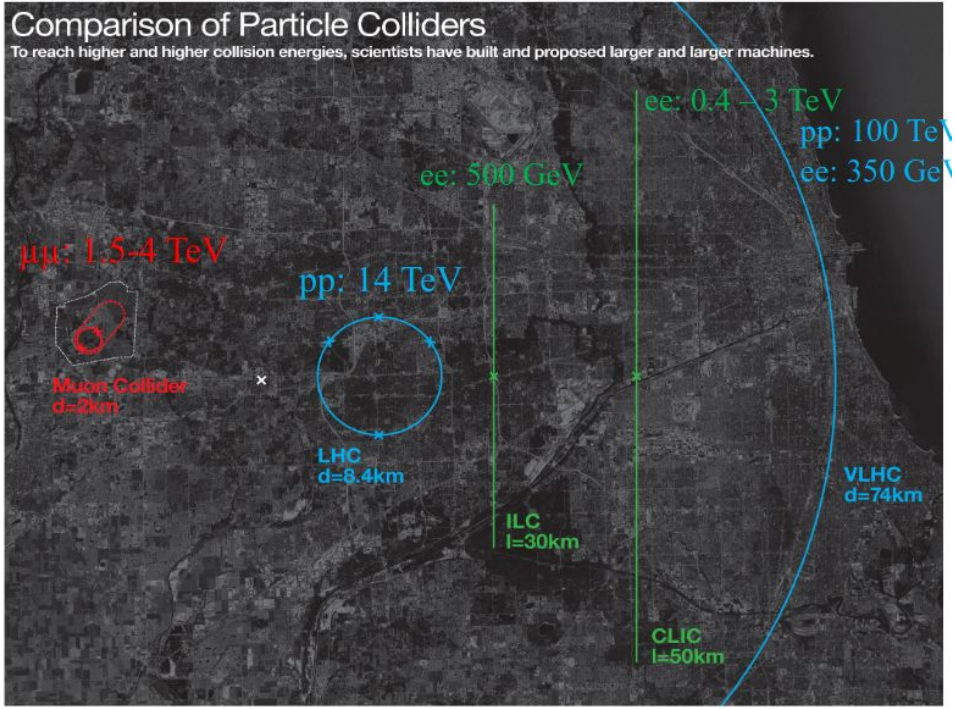
More Is Different



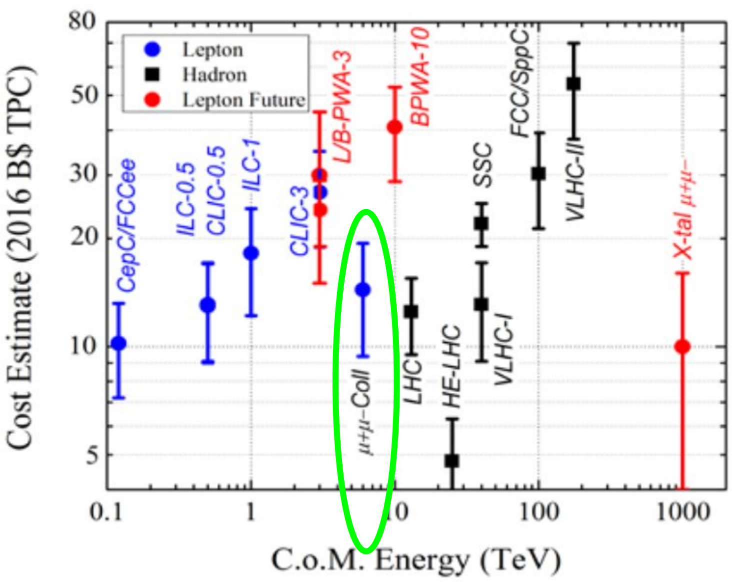
- **Rich** phenomena from colliders?
- **More** at the microscope scale?

Bright future bright Colliders

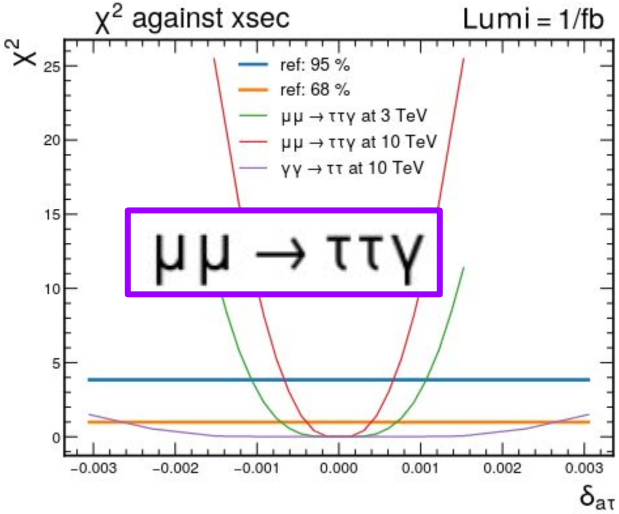
- **An electron-positron Higgs factory** as the highest-priority.
- **O(10) TeV Muon Collider** has also clear advantage
- ……

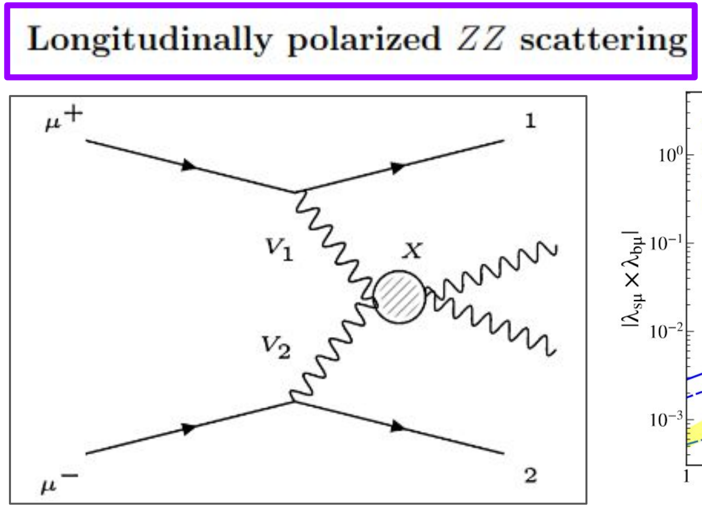


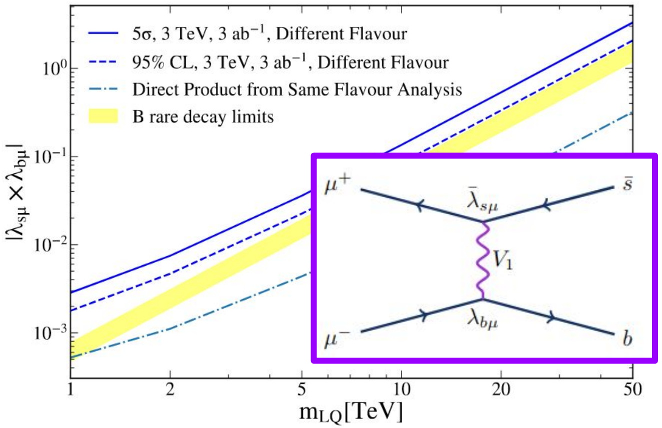
arXiv: 1705.02011



Rich Physics at Muon Collider







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

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

arXiv:2109.01265
Leptoquark searches
B anomaly

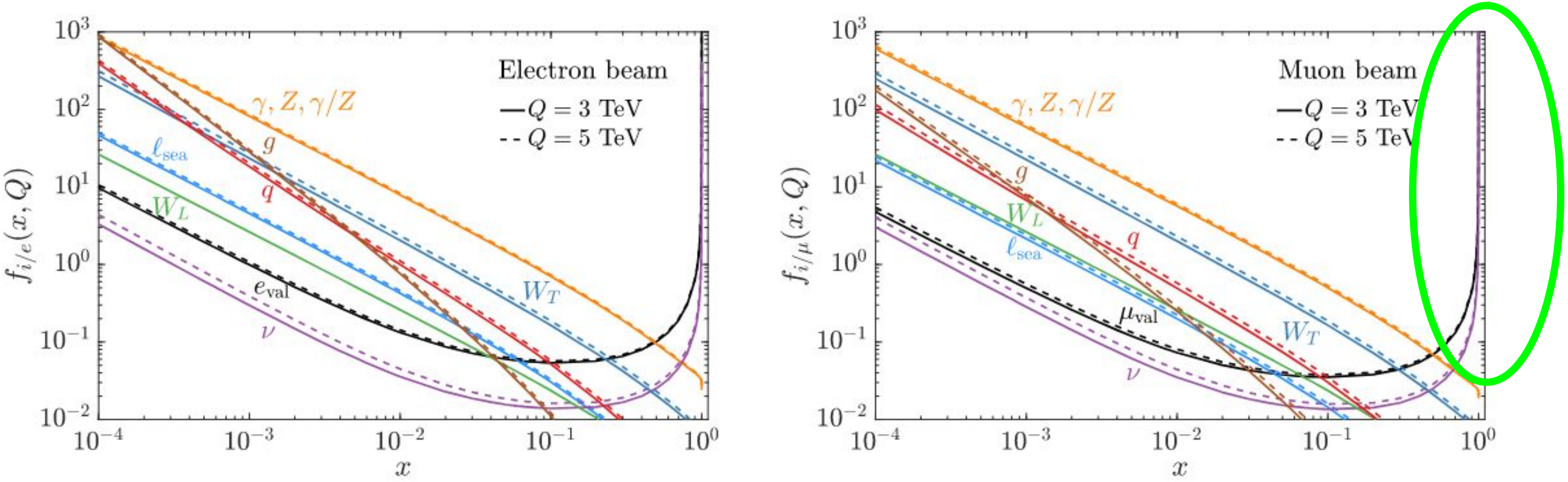
Displaced Tau reconstruction: tracker

Closer Z decay products: finer calorimeter

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 Collider: challenges

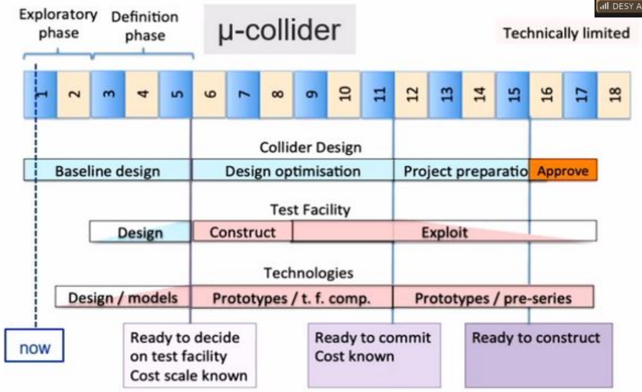
ECFA Workshop on e+e- Higgs/EW/Top Factories October 5-7, 2022, in Hamburg

Accelerator R&D at CERN

- ❑ High-field magnet programme (part of FFC study)
- ❑ Continue CLIC study to prepare for next strategy update
  - ❑ Finalize X-band technology towards construction readiness
  - ❑ Improve power efficiency (klystrons)
  - ❑ Project readiness report by end 2025
- ❑ Muon collider
  - ❑ Work on main challenges: muon source, cooling, fast ramping magnets, accelerator, collider ring, neutrino bkgd, civil engineering
  - ❑ For next strategy update: is investment into μ-collider test facility justified?
- ❑ Wakefield acceleration: Infrastructure for the AWAKE experiment

CLIC

Parameter	Unit	Stage 1	Stage 2	Stage 3
√s	GeV	380	1500	3000
Tunnel length	km	11	29	50
Gradient	MV/m	72	72/100	72/100
Pulse length	ns	244	244	244
Luminosity (above 99% of √s)	10^{34} $cm^{-2}s^{-1}$	1.5 0.9	3.7 1.4	5.9 2
Repetition frequency	Hz	50	50	50
Bunches per train		352	312	312
Bunch spacing	ns	0.5	0.5	0.5
Particles/bunch	10^9	5.2	3.7	3.7
Beam size at IP (σ_y/σ_x)	nm	2.9/149	1.5/60	1/40
Annual energy consumption	TWh	0.8	1.7	2.8
Power consumption	MW	170	370	590
Construction cost	BCH	5.9	+5.1	+7.3

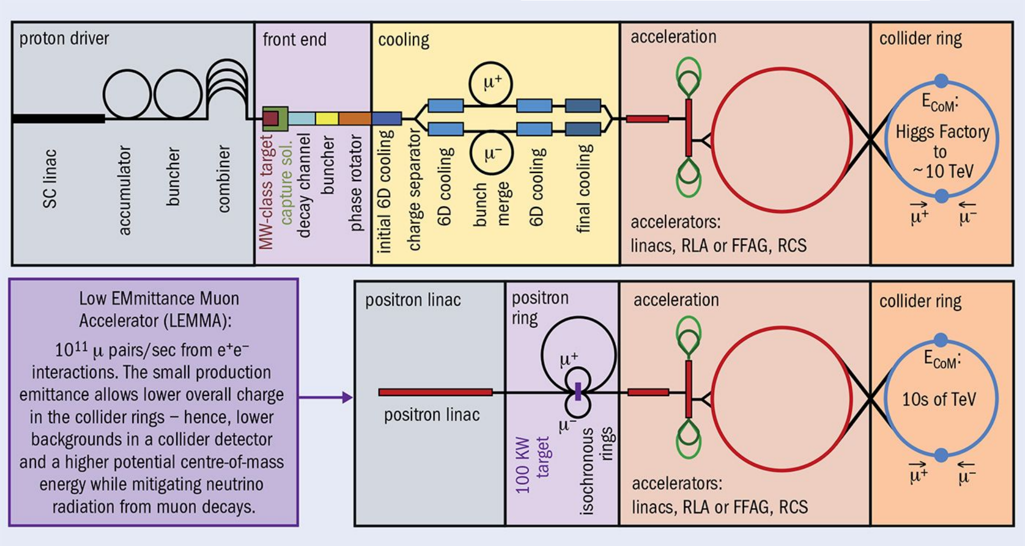


Muon Collider: beam and background

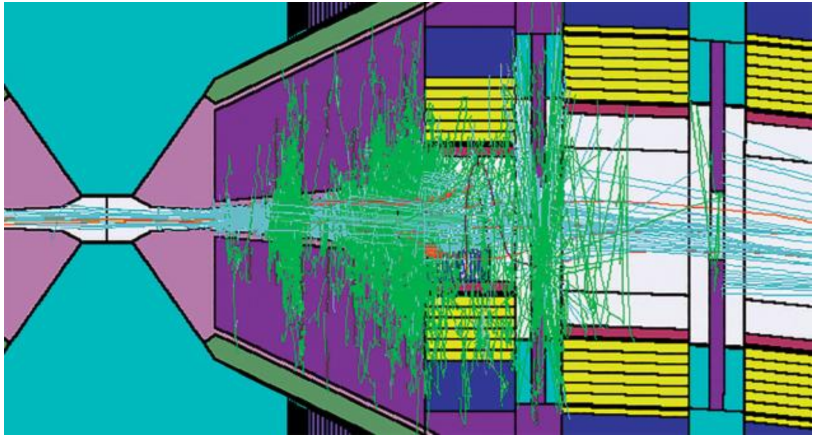
1) Muon Source

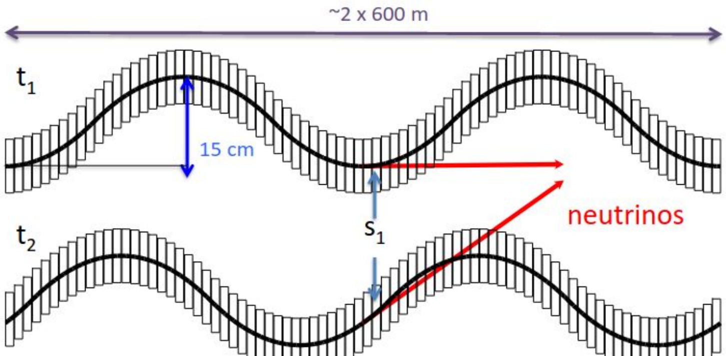
$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon\epsilon_L} f_r N_0 \gamma$$

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…"**

A few final words

ECFA Workshop on e+e- Higgs/EW/Top Factories October 5-7, 2022, in Hamburg

Why do we want a Higgs (and EW) Factory and how we can justify the required resources?

- Particle physics is in competition with other fields (bio sciences, climate, energy, ...)
- They have also very appealing stories to tell, often much easier to understand by the general public and politics than ours

I strongly believe that we have to strengthen and sharpen our physics arguments

- Just higher precision is not enough!
- What are the connections to the really big fundamental questions and miracles of the Universe?
- We have to strengthen our efforts to convince public and politics provide very strong motivation: societal, technological and scientific arguments

Also in: Snowmass Physics Drivers

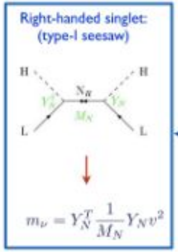
Particle physics still enjoys high interest and strong support from the public

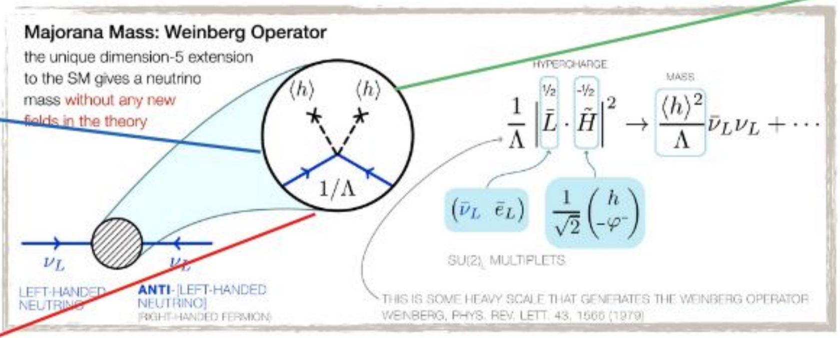
I'm sure that there will be a Higgs (and EW) factory, even if today we are living in very difficult and challenging times

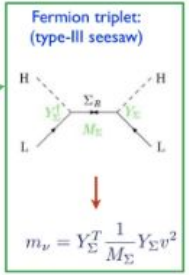
Neutrino **Portal** to BSM

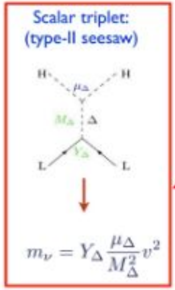
- Neutrino mass:
  - Confirmed by Neutrino Oscillation experiments
  - Beyond the Standard Model (SM) description

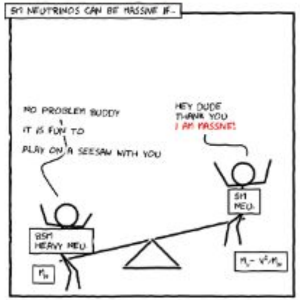
- Neutrino mass can be explained with:
  - Specific Beyond the Standard Model (BSM) theory with UV completeness
    - Example: Seesaw models
      - Tree level realization of the Weinberg Operator









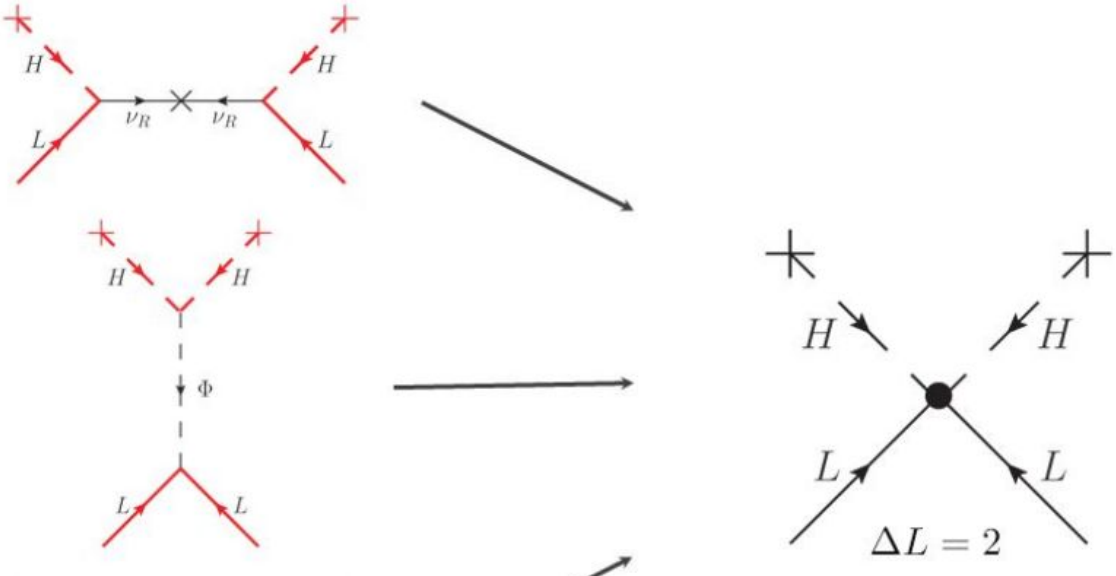


Weinberg Operator: vvHH interaction!

[Sitian Qian](#)

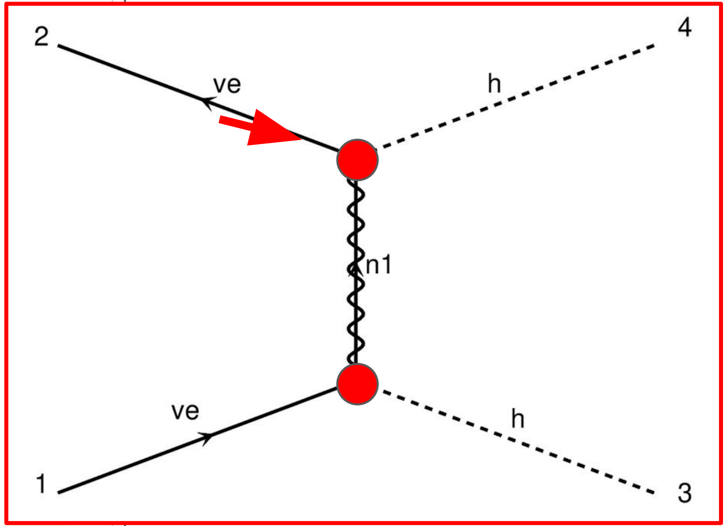
- Why named with "Seesaw"?: **Heavier** BSM particles leads to **lighter** SM neutrinos

Neutrino Portal to BSM



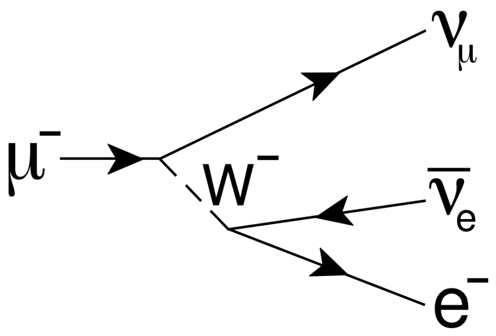
Dimension-5 Weinberg effective operator (1/M)LLHH (shorthand).

$$\left(\overline{(\ell_L)^c} H\right)_1 (\ell_L H)_1$$



coupling ∝ heavy neutrino mass

Neutrino Beam: long ago



B. J. King hep-ex/0005007

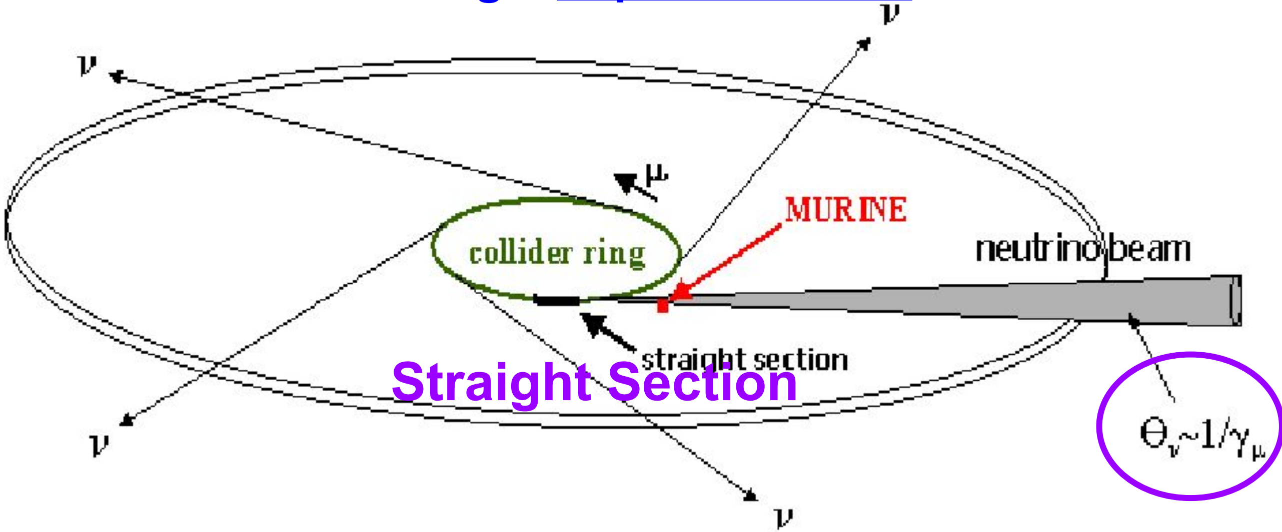
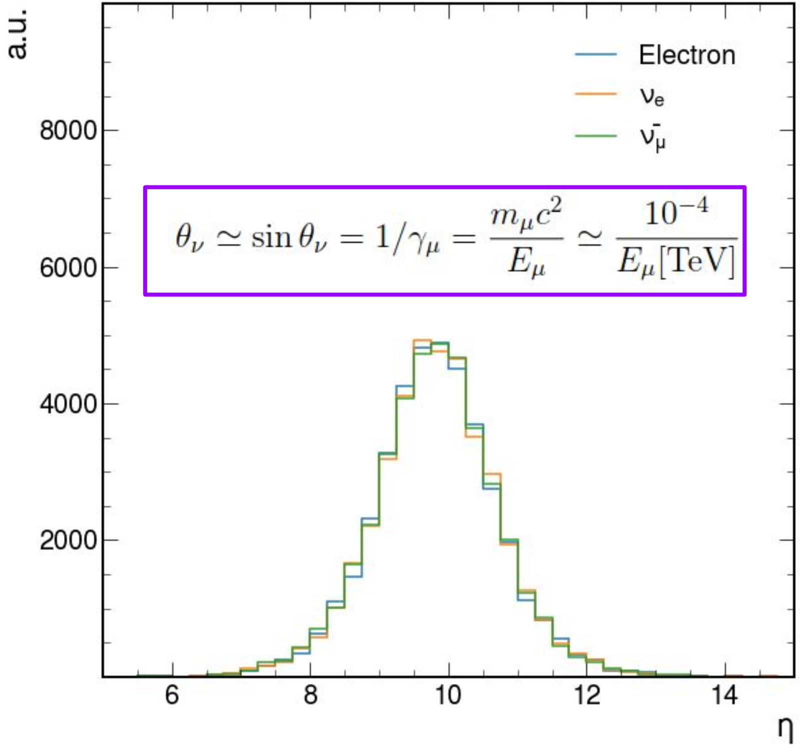


FIGURE 1. The decays of muons in a muon collider will produce a disk of neutrinos emanating out tangentially from the collider ring. The neutrinos from decays in straight sections will line up into beams suitable for experiments. The MURINEs will be sited in the center of the most intense beam and as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

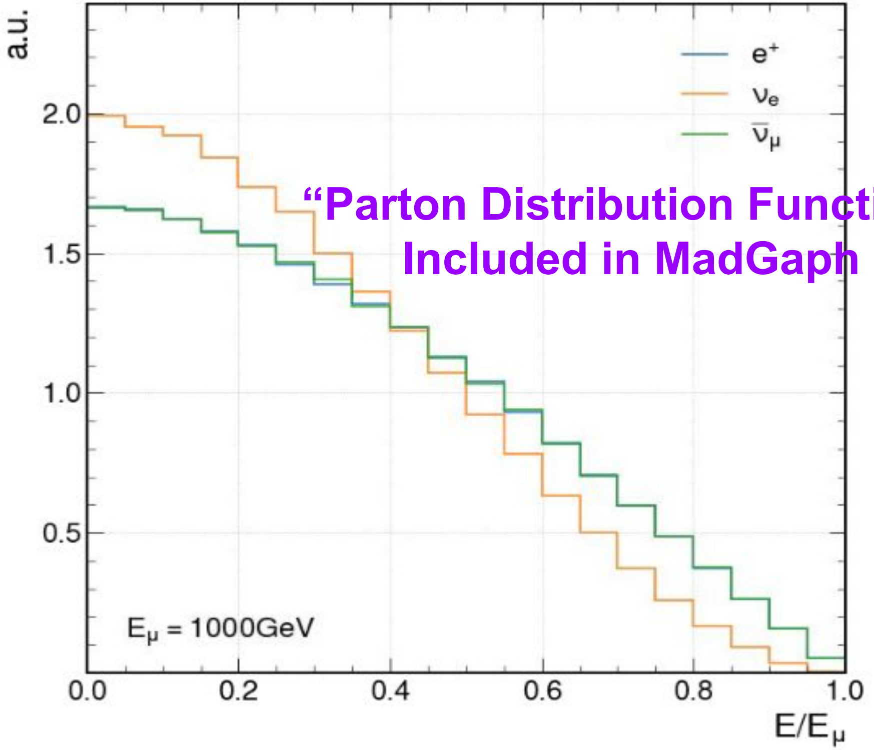
NuTeV
Neutrino-Nucleon Scattering
NuMAX
NuSOnG
Neutrino Scattering on Glass
nuSTORM
"Neutrinos from STORed Muons," …for neutrino oscillation searches

Head-on collisions at TeV scale?

Neutrino Beam from 1TeV Muon beam



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

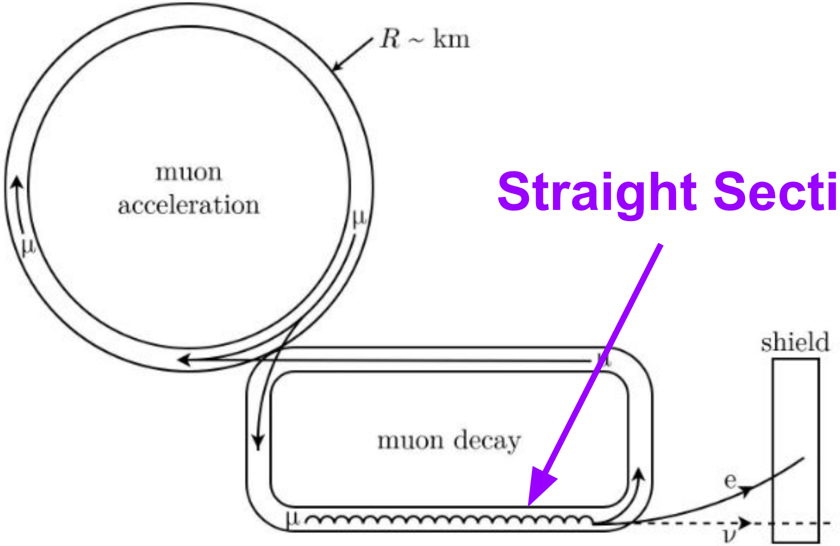


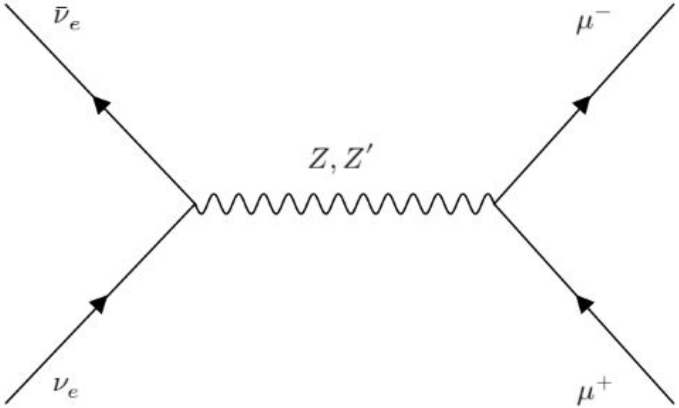
"Parton Distribution Function"
Included in MadGaph

Highly collimated in angle, yet widely distributed in Energy

Neutrino Collider?

Straight Section





Neutrino (anti-)neutrino collisions

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

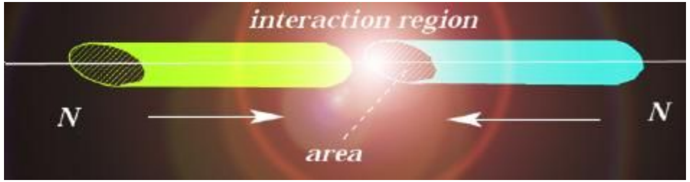
$$\nu_e\nu_e \to HH$$
$$\nu_e\nu_e \to ZZ\,, ZH$$
$$\nu_e\nu_e \to \nu_e\nu_e H,$$
$$\nu_e\nu_e \to \nu_e\nu_e ZZ\,, \nu_e\nu_e WW,$$
$$\nu_e\nu_e \to \nu_e\nu_e ZH\,, \nu_e\nu_e HH,$$
$$\nu_e\nu_e \to e^-e^-W^+W^+,$$

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

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

As for TeV muon colliders, with $f_{\rm rep} = 100\,\text{KHz}$, $\sigma_{x,y} \lesssim 10$ microns, and $N_{\rm beam1,2} = 10^{12}$, 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} 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

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

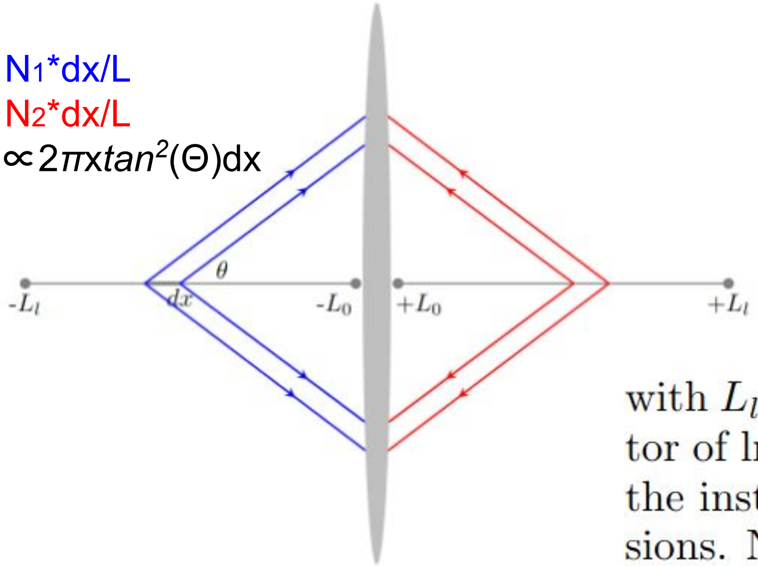
Crude Luminosity Estimation

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

$dN_1 \propto N_1 * dx/L$

$dN_2 \propto N_2 * dx/L$

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



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

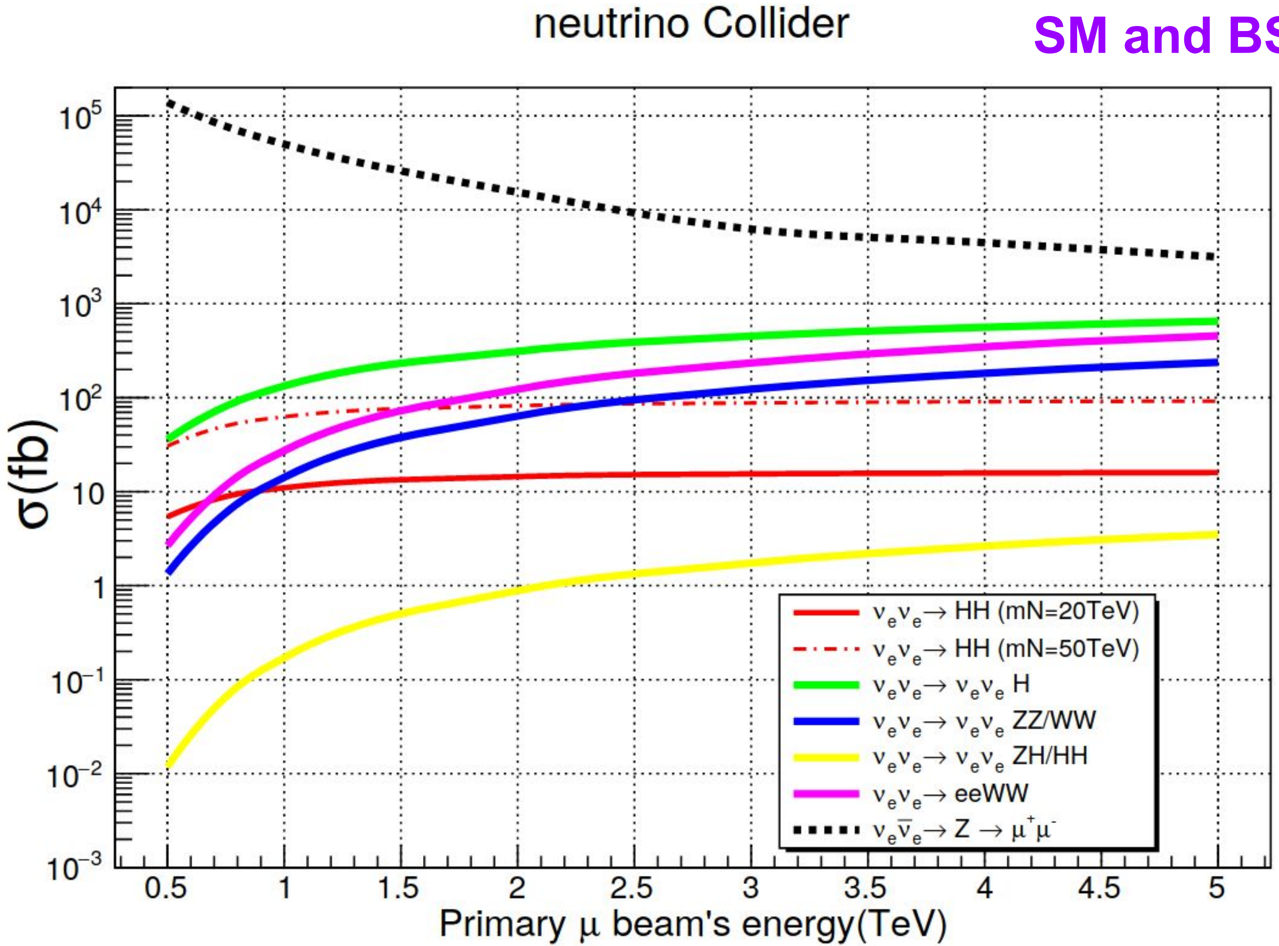
$$= \frac{L_l^2}{L_c^2} \frac{N_{\text{beam1}} N_{\text{beam2}} f_{\text{rep}}}{8\pi L_l^2 \tan^2\theta} \times \ln(L_l/L_0),$$

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

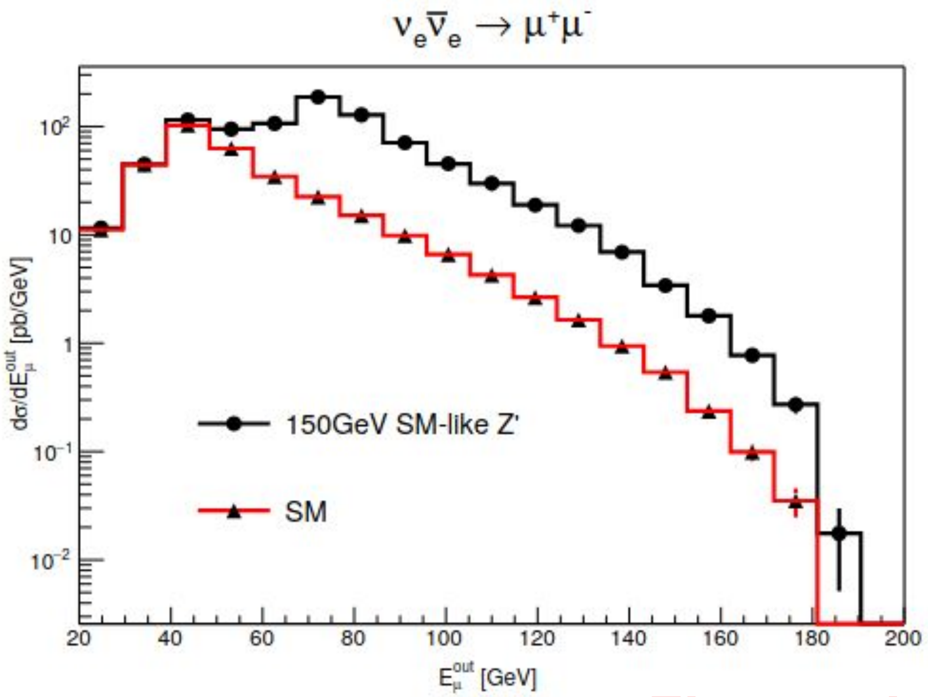


SM and BSM (Heavy Majorana)

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

Neutrino antineutrino Annihilation

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



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

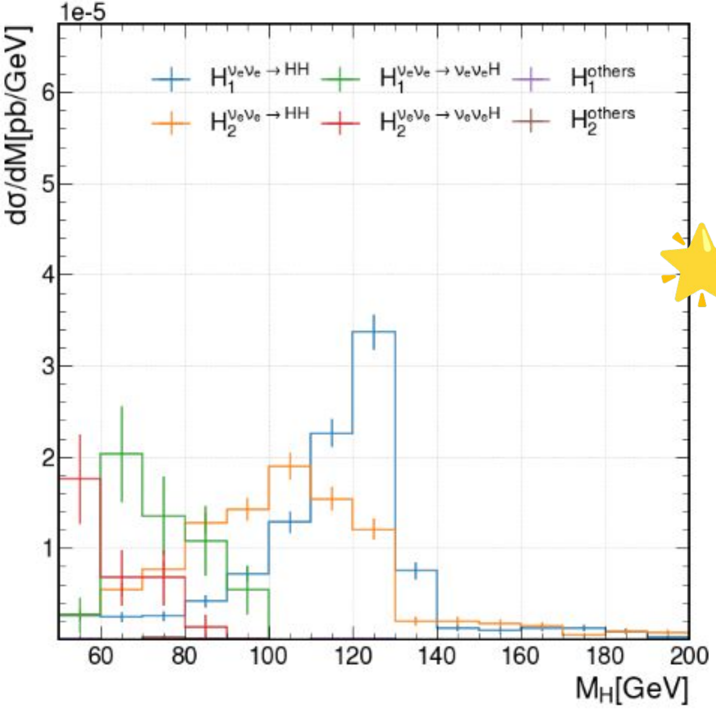
Outgoing muon energy distributions for neutrino antineutrino annihilation into Z and SM-like Z' bosons, with Z' mass set as 150 GeV with narrow width.

First probe on di-neutrino resonances!

Heavy Majorana Neutrino

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

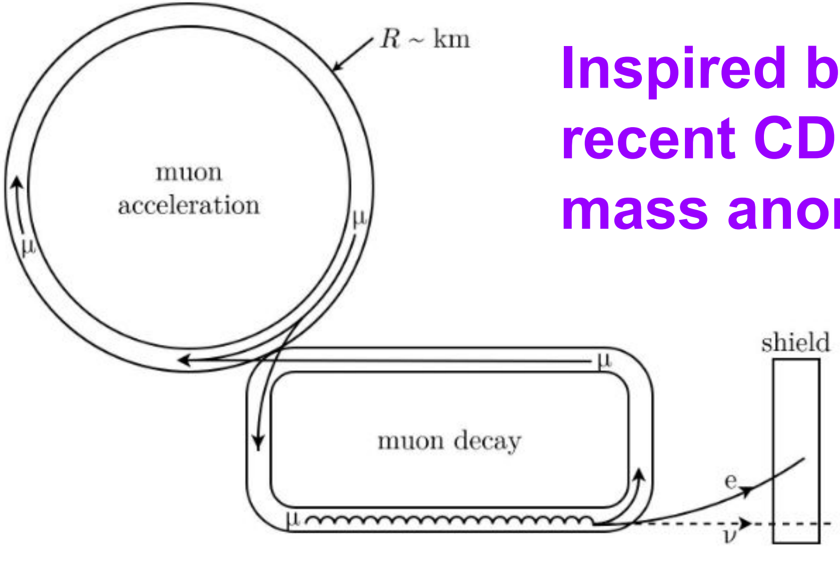
Weinberg Operator, UV completion with See-Saw models



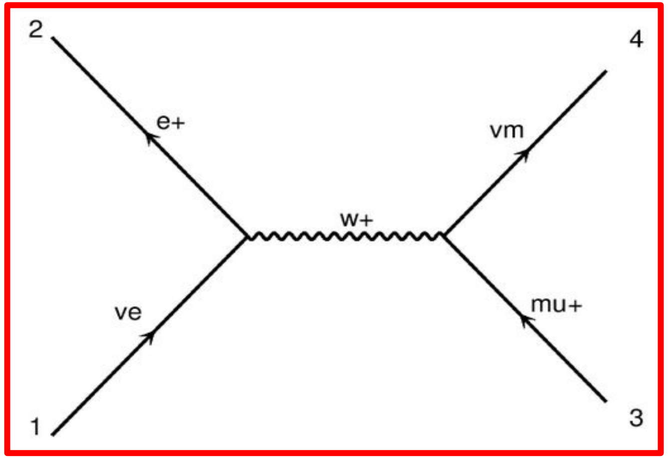
With 1 $\mathrm{fb}^{-1}$of data, by cutting on reconstructed $\mathrm{M_H}$, we are close to exclude $V_{eN1} \gtrsim 0.01$ at $\mathrm{M_N} = 20\,\mathrm{TeV}$, at 95% C.L., which surpasses already current best limits from the CMS experiment [25] by two orders of magnitude. An interesting fact is that cross sections of $\nu_e\nu_e \to \mathrm{HH}$ scale as $\mathrm{M_N^2}$, 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 $\mathrm{fb}^{-1}$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

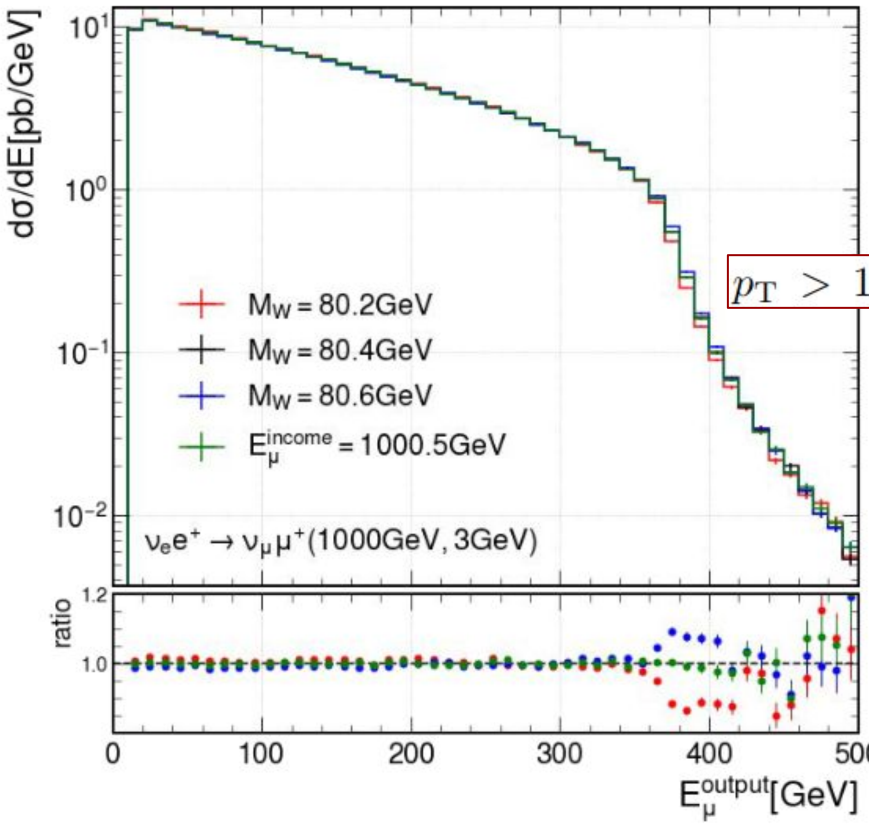


The instantaneous luminosity of a neutrino lepton collider would be limited by two main factors: 1) the intensity of the neutrino beam compared with the incoming muon beam is suppressed by roughly $L_l/L_c \sim 0.1$, i.e., the fraction of the collider ring circumference occupied by the production straight 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].

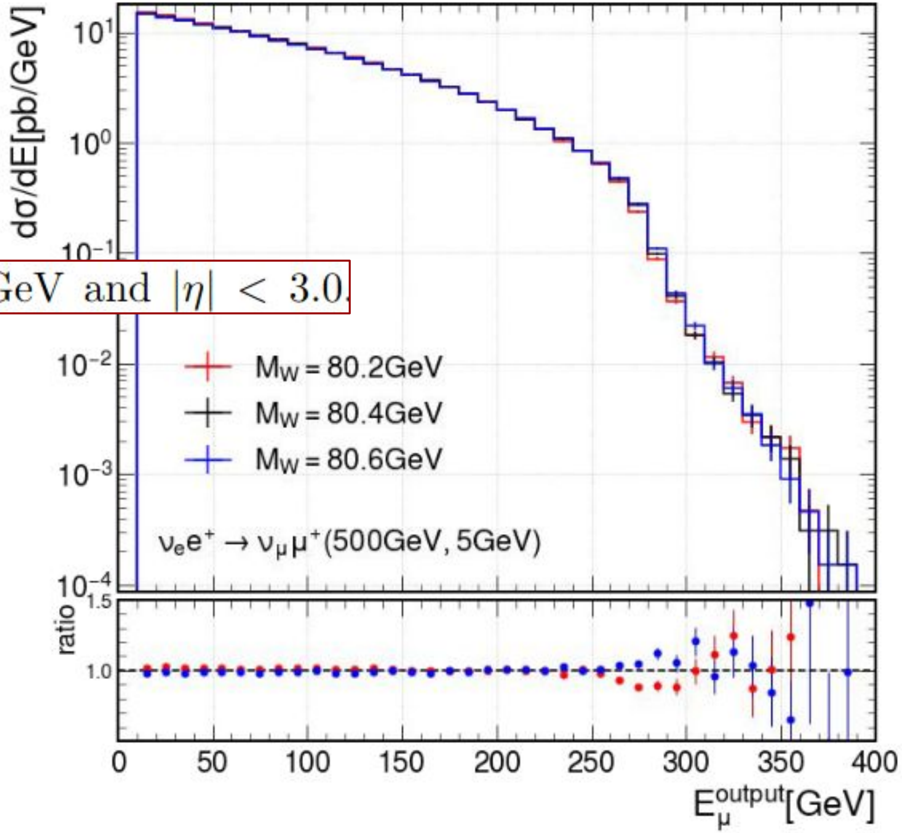
Similar design, but with only one sided neutrino beam, 0.1-1/fb in 10 years?

Single W production

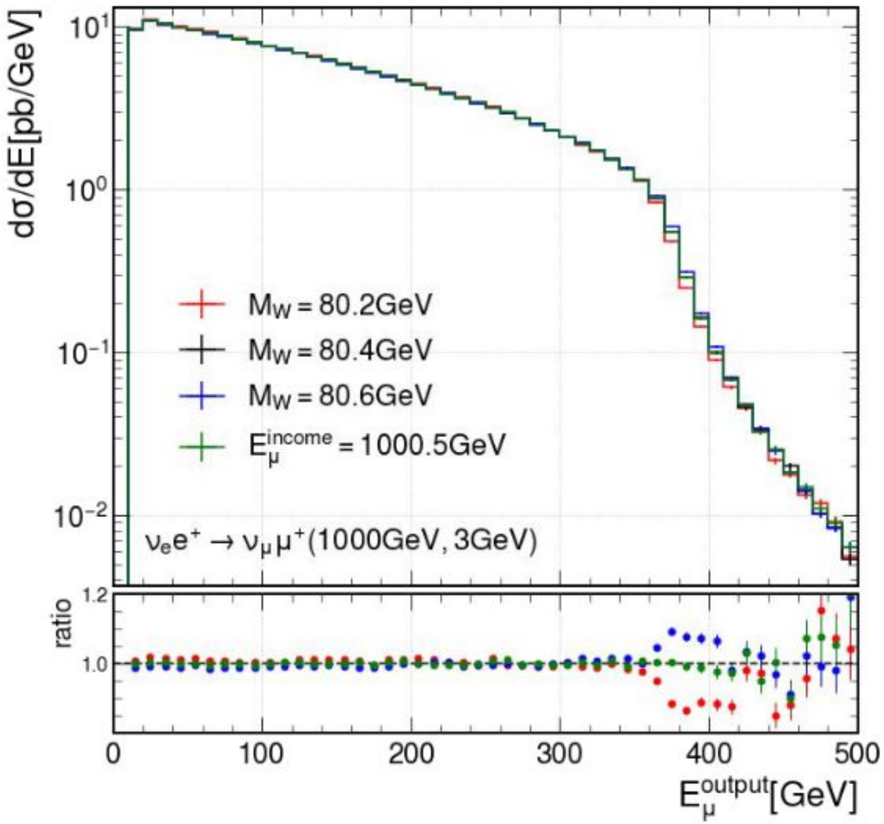
Kink Structure from W threshold in convolution with Beam PDF



$p_T > 10\,\text{GeV and } |\eta| < 3.0$



Single W production



Larger MW →

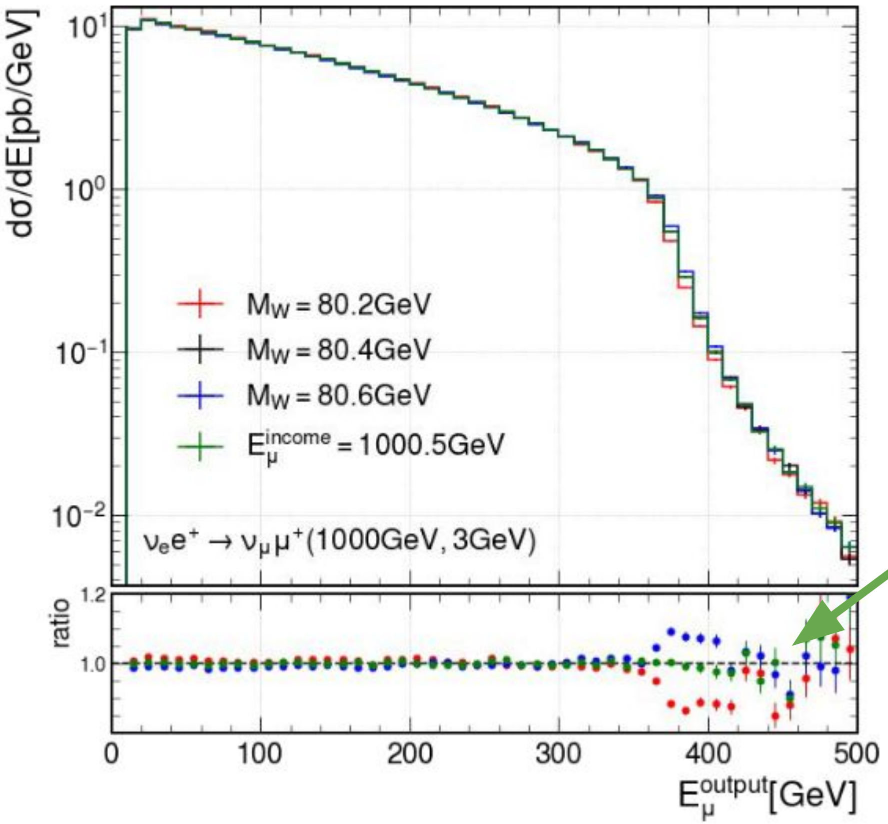
Higher incoming neutrino Energy →

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



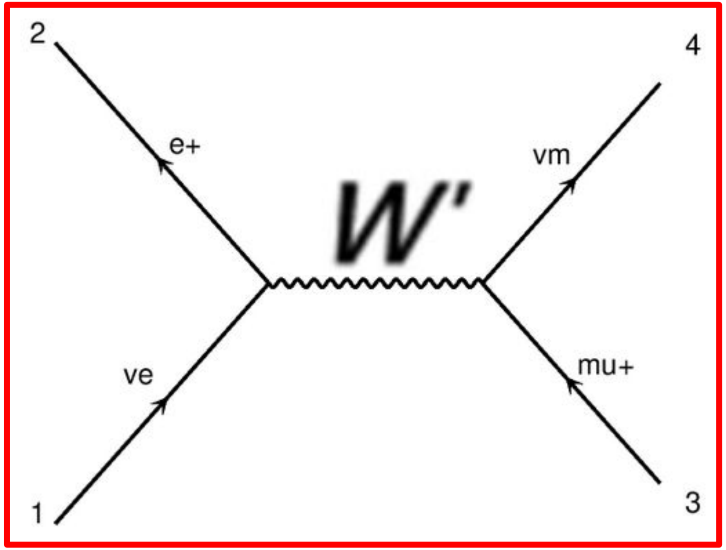
We varied the incoming muon and electron beam energy by 0.5 GeV and 10 MeV, respectively, which are quite conservative following previous refs.

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

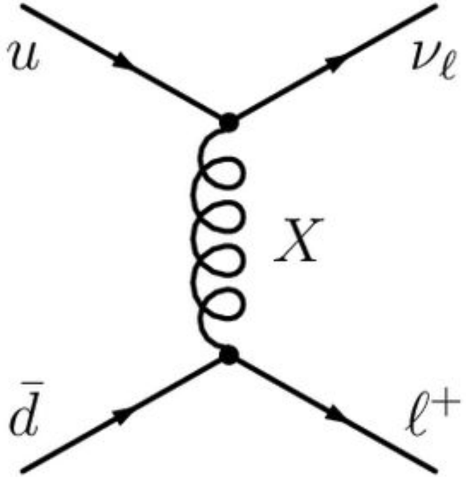
This uncertainty could be **mitigated by using the shape of the outgoing muon energy**, by scanning different incoming beam energies, or by calibrating
the incoming muon beam energy with the electron decay products.

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**

electron-muon collider

- A novel kind of collider from 0 -> 1
  - low to high collision energy
  - linear/circular/hybrid
  - various beam combinations:
    $e^-\mu^+$, $e^+\mu^-$, $e^+\mu^+$, $e^-\mu^-$, polarization
- An important intermediate step
  - between e-e and mu-mu
  - Robust under muon beam induced background
- Rich physics with economical budget
  - Charged Lepton Flavor violation
  - Higgs precision measurement
  - majorana neutrino, heavy lepton
  - ~ 1-2 billion $ in total

Flexibility to extend to various options!

CERNCOURIER
March/April 2021 cerncourier.com Reporting on international high-energy physics

Novel collider concept

Peking University physicists urge the community to consider the merits of a novel electron–muon collider (arXiv:2010.15144). Collisions between different species of lepton could reduce physics backgrounds for studies of charged-lepton flavour violation and Higgs-boson properties, and the asymmetric nature of the collisions could be used to control troublesome backgrounds caused by muon decays inside the accelerator, argue the authors. The preprint proposes 10 GeV electron and muon beams initially, and upgrades culminating in a TeV-scale muon–muon collider.

electron-muon collider: ~26 years ago

Possible Resonances in $\mu^+ e^- \to \mu^- e^+$ Collisions

George Wei-Shu Hou (National Taiwan University) hep-ph/9605204

We study the possibility of discovering resonances in $\mu^+ e^- \to \mu^- e^+$ and $e^- e^- \to \mu^- \mu^-$ collisions. We
antimuonium transitions, where the experimental limit has just been improved by one order of magnitude. We
Yukawa coupling domain for neutral scalar bosons. The stringent $\mu \to e\gamma$ decay is evaded by invoking some
scalar bosons give rise to distinguishable effects in muonium transitions. Alternatively, they could show up as
$\mu^+ e^- \to \mu^- e^+$ and $e^- e^- \to \mu^- \mu^-$ collisions, respectively. This could occur independent of whether, but
experimentally observed.

> The question for this meeting is, therefore, whether there are any fundamental difficulties in colliding μ^+ on e^-. Can such studies be an end in itself? Afterall, we should collide together all possible fundamental constituents of Nature in an effort to reveal its secrets.

Comments: 10 pages plus separate cover page, latex, 5 embedded eps figures. Talk presented at 3rd International Conference on $\mu^+ \mu^-$ Colliders, December 1995, San Francisco, USA
Subjects: **High Energy Physics - Phenomenology (hep-ph)**
Journal reference: Nucl.Phys.Proc.Suppl. 51A (1996) 40-49

We found these papers after we submitted ours to arXiv. These focused mostly on LFV though.
We here for the first time connect low energy collision with high energy collision for both LFV and Higgs.

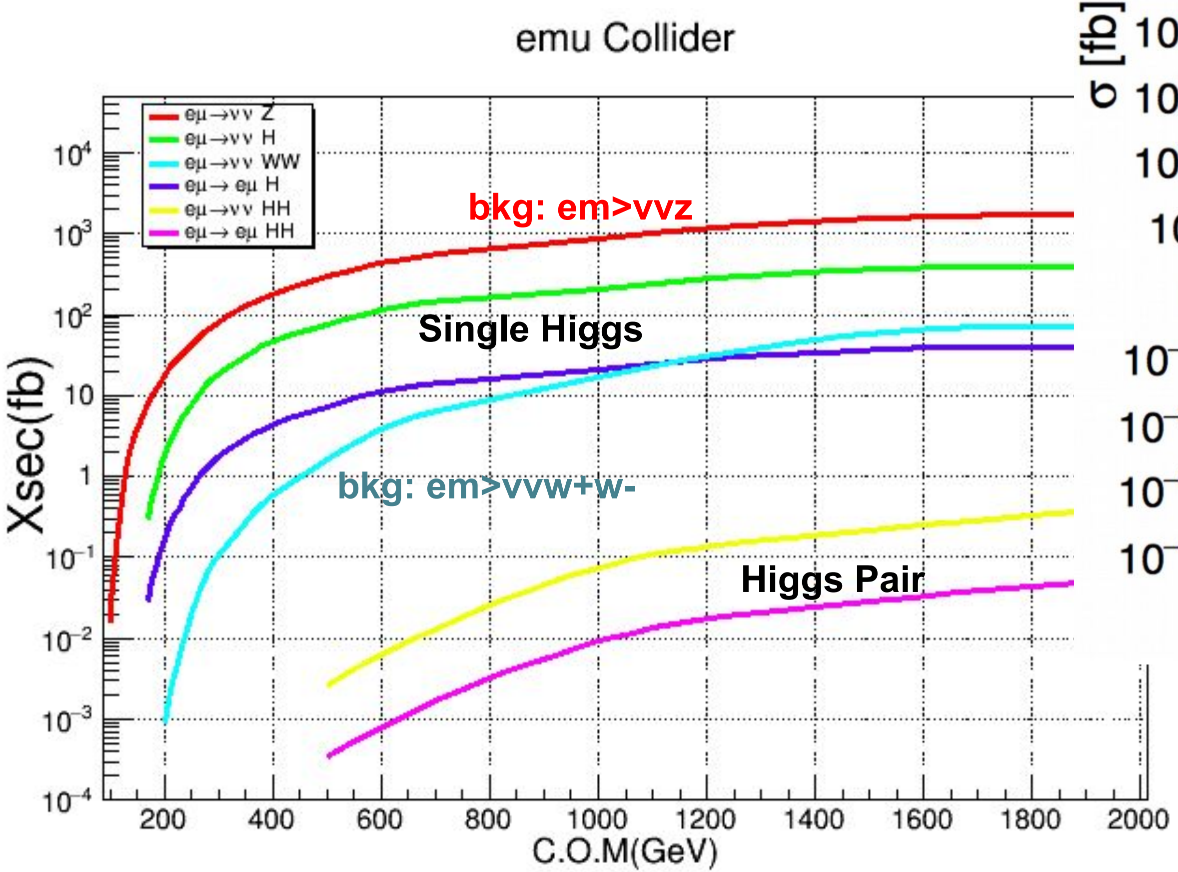
Are $e\mu$ colliders interesting?

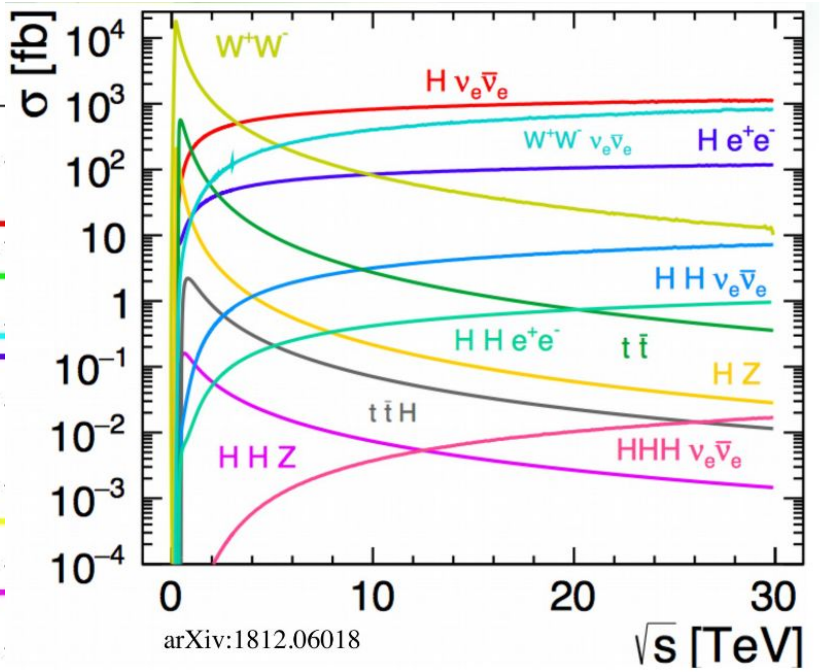
V. Barger, S. Pakvasa, X. Tata

We show that current experimental constraints already severely restrict what might be observable at $e\mu$ colliders. We identify some cases where it may be possible to probe physics beyond what might be possible at other facilities and make some remarks about physics capability of high energy $e\mu$ colliders.

hep-ph/9709265

emu collider processes





mu-mu collider

A vector boson scattering/fusion machine

Benchmark collision energy

(Benchmark\GeV)	e-	mu+	COM	Comments
A	10	10	20	Lepton Flavor Violation
B	50	50	100	Lepton Flavor Violation
C	20	200	126.5	H->emu
D	50	1000	447.21	LFV, Higgs, Top **H ~60fb**
E	100	1000	632.46	LFV, Higgs, Top **H ~115fb**
F	100	3000	1095.4	Higgs Top **H ~300fb**

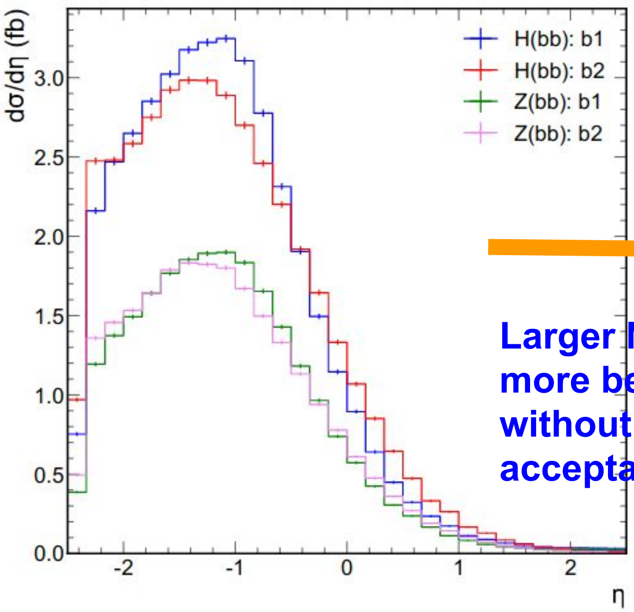
Mostly background free, or at most from VBS processes, e.g. e mu > v v Z.

Higgs xsec~210fb at CEPC@250GeV.

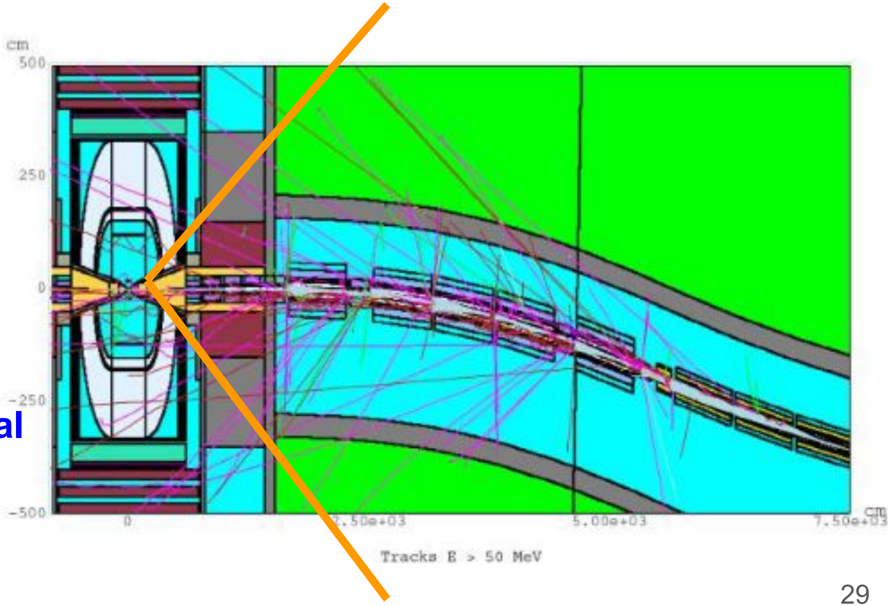
Higgs property measurement

- Take 50-1000/100-3000 GeV benchmark as examples
- Higgs produced through VBS, ~60fb
- Main background is VBS Z production
- Using MG+Pythia+Delphes (Muon Collider Card)

require the leading and sub-leading b-tagged jets with $p_T > 40$ GeV and $-2.5 < \eta < 1$ (corresponding to a 40.4° shielding nozzle in muon beam side, compared with a commonly taken value at muon collider studies as around 10–20° [11]). Fig. 4 shows the invariant mass distribution



Larger Nozzle to suppress more beam background, without much loss on signal acceptance.



Higgs property measurement

$$\sigma = \sigma(\nu\nu\mathrm{H}) \cdot BR(\mathrm{H} \to \mathrm{b}\bar{\mathrm{b}}) = \frac{g^2_{\mathrm{HWW}} g^2_{\mathrm{Hbb}}}{\Gamma_{\mathrm{H}}}$$

$$\frac{\Delta g_{\mathrm{Hbb}}}{g_{\mathrm{Hbb}}} = \frac{1}{2}\sqrt{\left(\frac{\Delta\sigma}{\sigma}\right)^2 + \left(\frac{\Delta \frac{g^2_{\mathrm{HWW}}}{\Gamma_{\mathrm{H}}}}{\frac{g^2_{\mathrm{HWW}}}{\Gamma_{\mathrm{H}}}}\right)^2}.$$

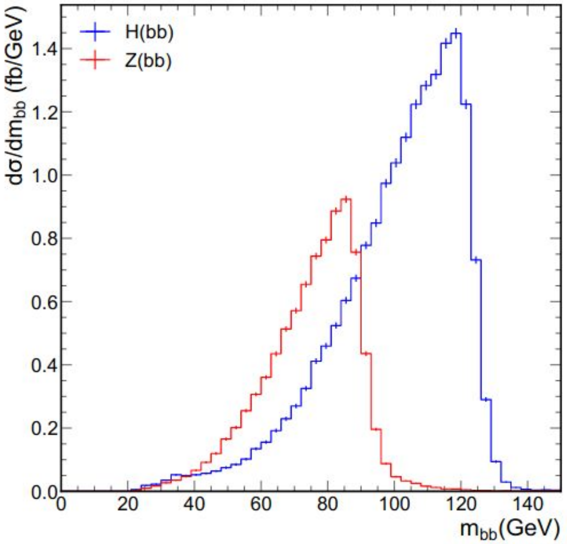
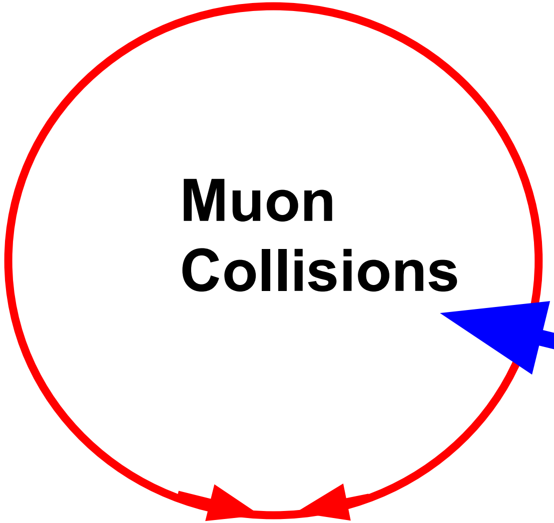


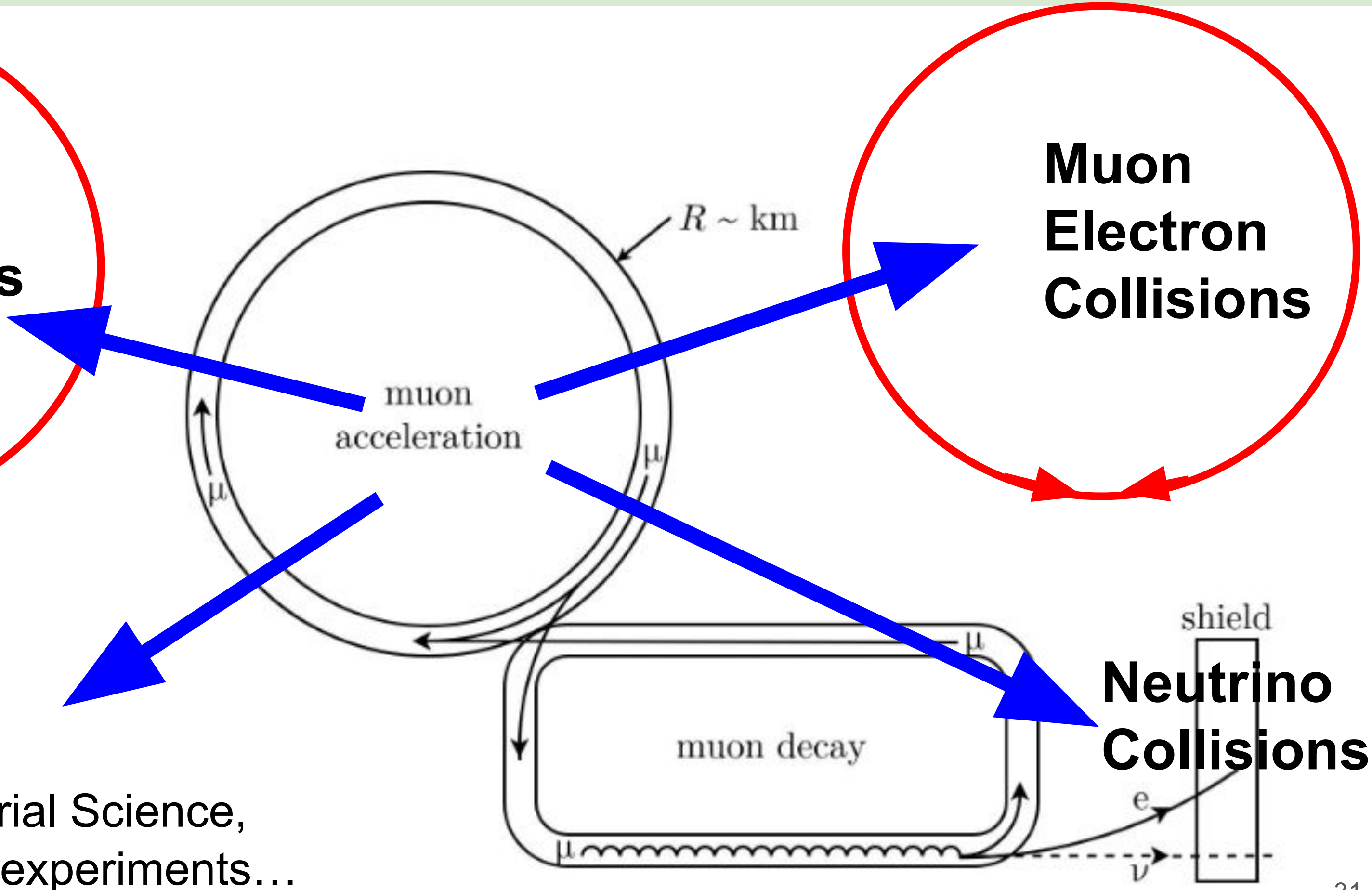
TABLE I: Summary of the parameters used in the estimation of the Higgs boson coupling to b-quarks in different collision schemes. The uncertainty on $g^2_{\mathrm{HWW}}/\Gamma_{\mathrm{H}}$ is set to 3% in all collision schemes. $\sqrt{s} = 447.2(1095.3)$ GeV corresponds to a 50(100) GeV electron beam and a 1(3) TeV muon beam. The ISR effect is not included as its effect is validated to be small.

$\mathcal{L}_{\mathrm{int}}[ab^{-1}]$	$\sqrt{s}$[GeV]	$\frac{\Delta\sigma}{\sigma}$[%]	$\frac{\Delta \frac{g^2_{\mathrm{HWW}}}{\Gamma_{\mathrm{H}}}}{\frac{g^2_{\mathrm{HWW}}}{\Gamma_{\mathrm{H}}}}$[%]	$\frac{\Delta g_{\mathrm{Hbb}}}{g_{\mathrm{Hbb}}}$[%]
0.5	447.2	2.5	3	2.0
	1095.4	1.4		1.7
1.5	447.2	1.4	3	1.7
	1095.4	0.8		1.6
2.0	447.2	1.2	3	1.6
	1095.4	0.7		1.6

The measured precision of gHbb in the electron-muon collider can reach to a few percent level with order ab−1 of data and is dominated by the uncertainty on gHWW.

Dream Bigger: muon complex





Others: Material Science,
Dedicated Muon experiments…

Summary

- **An neutrino-neutrino collider is quite sensitive to neutrino physics**
  - Several days of run to observe neutrino annihilation
- **An neutrino-lepton collider is quite sensitive to W mass**
  - 10MeV accuracy with 0.1/fb!
- **An electron-muon collider is sensitive to CLFV and Higgs Physics**

- **These colliders are both novel ideas in themselves, and may also be useful intermediate steps, with less muon cooling required, towards the final muon-muon collider.**

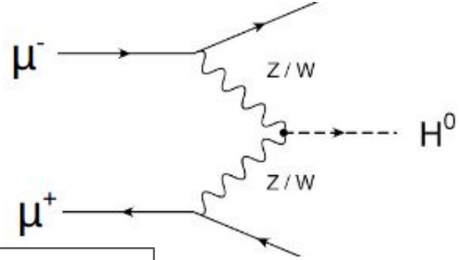
Backup

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

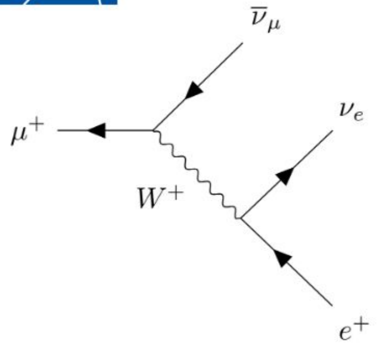
But lifetime at rest only 2.2 μs.



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

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

ICHEP

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

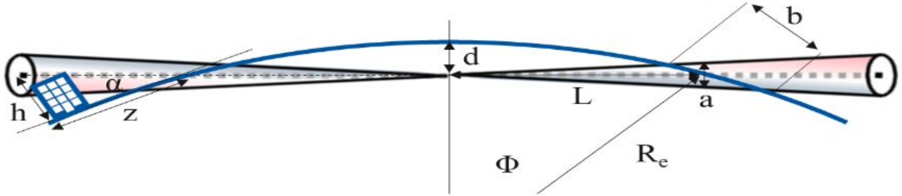
Neutrino flux to have negligible impact on environment

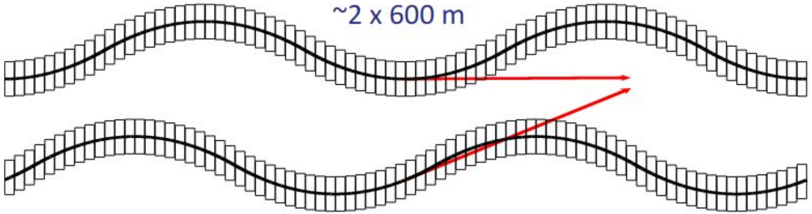
- want to be **negligible** (same level as LHC)
- opening cone decreases, cross section and shower energy increase with energy

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





B. J. King   hep-ex/0005007

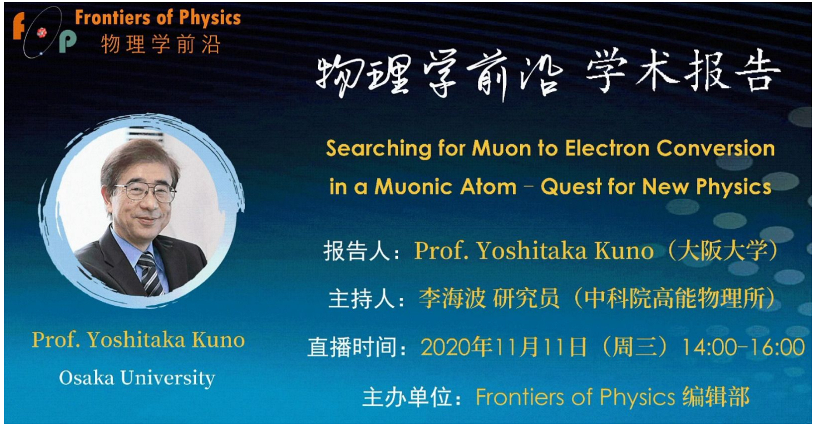
B Luminosities at Neutrino Experiments

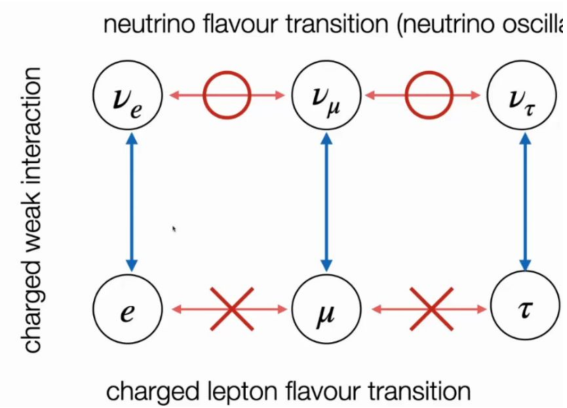
For a cylindrical experimental target extending out from the beam center to an angle $\theta_\mu = 1/\gamma_\mu$, the luminosity, $\mathcal{L}$, is proportional to the product of the mass depth of the target, l, and the number of muon decays per second in the beam production straight section, according to:

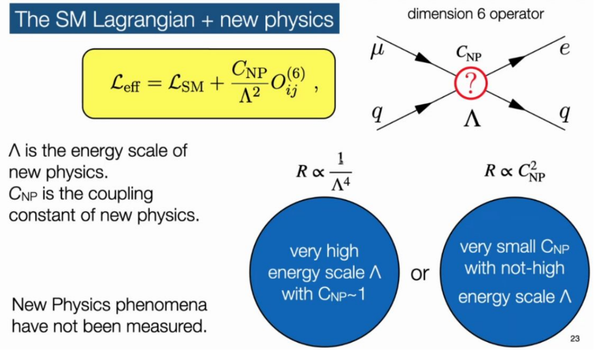
$$\mathcal{L}[\mathrm{cm}^{-2}.\mathrm{s}^{-1}] = \mathrm{N}_{\mathrm{Avo}} \times \mathrm{f}_{\mathrm{ss}} \times \mathrm{n}_\mu\,[\mathrm{s}^{-1}] \times l[\mathrm{g.cm}^{-2}], \tag{3}$$

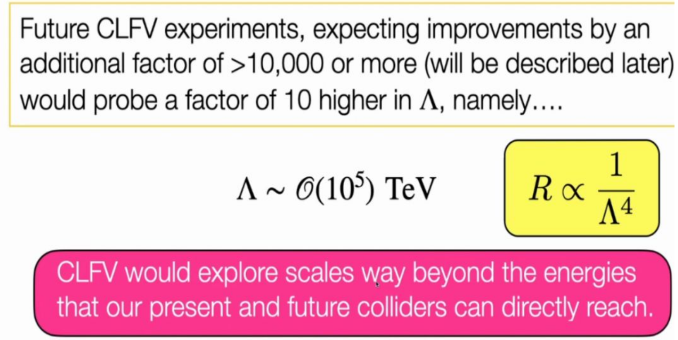
where f_{ss} is the fraction of the collider ring circumference occupied by the production straight section, n_μ is the rate at which each sign of muons is injected into the collider ring (assuming they all circulate until decay rather than being eventually extracted and dumped) and the appropriate units are given in square brackets in this equation and all later equations in this paper. The proportionality constant is Avagadro's number, $\mathrm{N}_{\mathrm{Avo}} = 6.022 \times 10^{23}$, since exactly one neutrino per muon is emitted on average into the boosted forward hemisphere, i.e. each muon decay produces two neutrinos and half of them travel forwards in the muon rest frame.

Lepton Flavor Violation



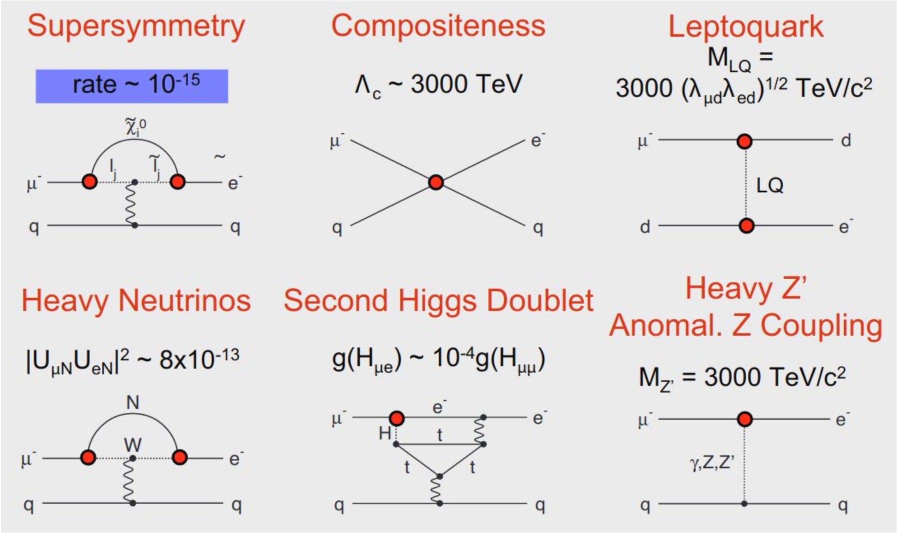


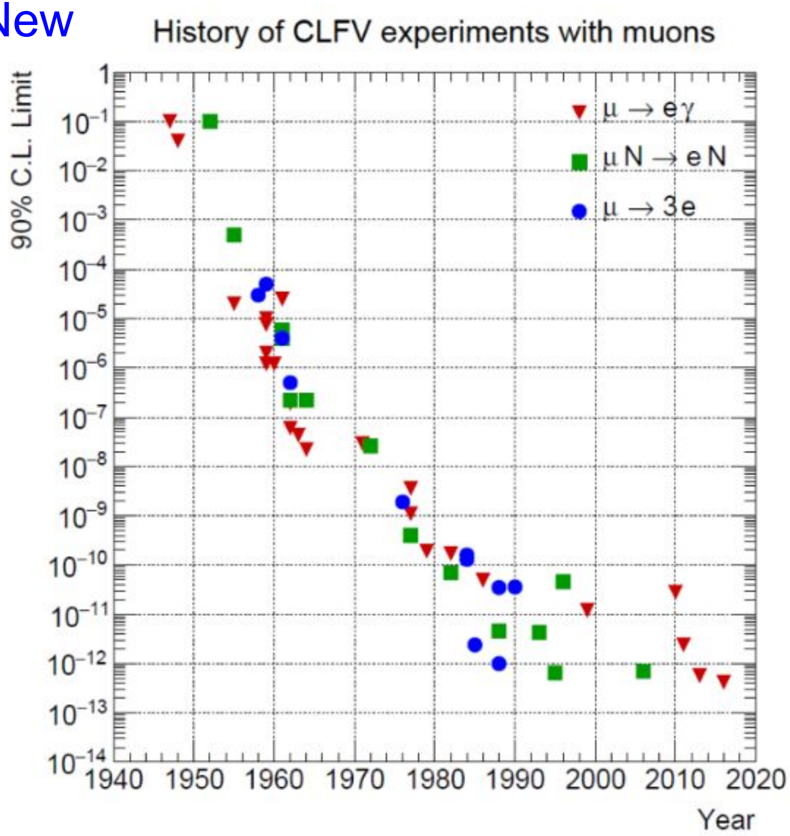




Lepton Flavor Violation

Discovery of Charged Lepton Flavor Violation is New Physics! violation of a (so-far) conservation law.





CLFV2019 : The 3rd International Conference on Charged Lepton Flavor Violation

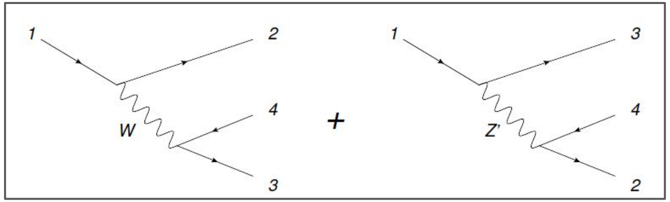
CLFV2019

https://arxiv.org/abs/1801.04688

Lepton Flavor Violation arXiv:2003.03997

- **Many specific and well motivated BSM models including LFV can be found in literature.**
- A simple model where LFV transitions are mediated by a generic heavy neutral boson (Z’)
  - Z’ as a gauge singlet, SU(2)L invariance
  - No assumption on the couplings of the Z’ with quarks

$$g_{ij}^{eL}\bar{e}_i Z' P_L e_j + g_{ij}^{eR}\bar{e}_i Z' P_R e_j + g_{ij}^{\nu L}\bar{\nu}_i Z' P_L \nu_j + g_{ij}^{\nu R}\bar{\nu}_i Z' P_R \nu_j$$



Low energy bounds on Z’ couplings

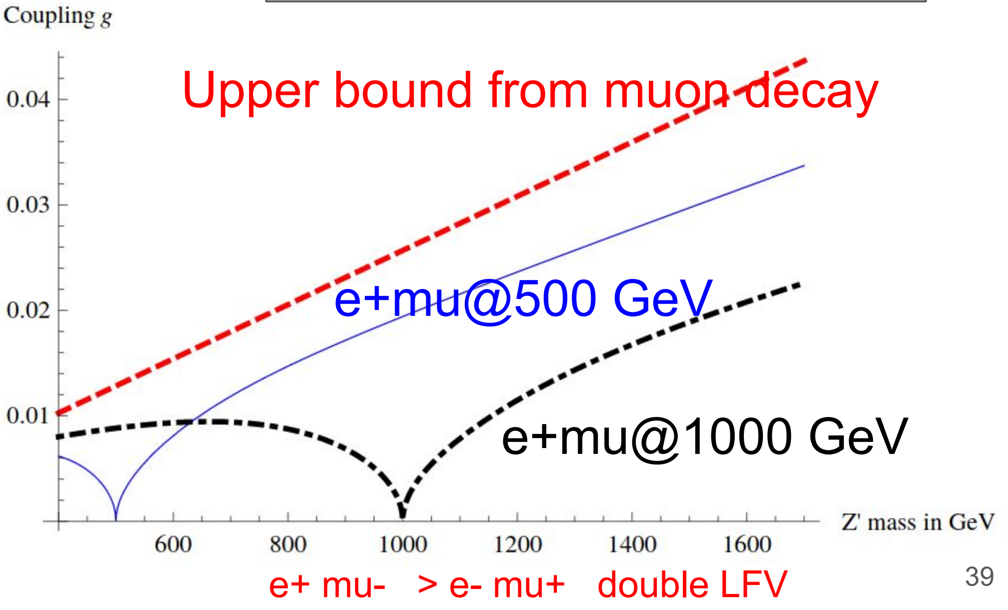
$$\frac{\Gamma_\mu}{m_\mu^5} = \frac{G_F^2}{192\pi^3} - \frac{4\sqrt{2}}{1536\pi^3}\frac{G_F (g_{\mu e}^L)^2}{M_{Z'}^2} + \frac{[(g_{\mu e}^L)^2 + (g_{\mu e}^R)^2][(g_{\mu e}^L)^2 + (g_{\nu_\mu \nu_e}^R)^2]}{1536\pi^3 M_{Z'}^4}$$

$$|BR(\mu^- \to e^-\bar{\nu}_e\nu_\mu) - BR(\mu^- \to e^-\bar{\nu}_e\nu_\mu)_{SM}| \leq 4\times 10^{-5}$$

$$\Gamma(\mu^- \to e^- e^+ e^-) = m_\mu^5 \frac{(g_{ee}g_{\mu e})^2}{384\pi^3 M_{Z'}^4}$$

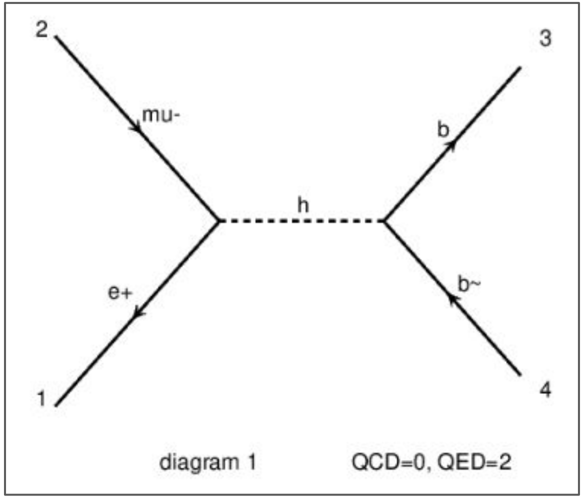
$$\mathrm{Br}(\mu \to eee) < 1.0\cdot 10^{-12}, \quad 90\%\mathrm{CL}.$$

SINDRUM Collaboration



Lepton Flavor Violation arXiv:2010.15144

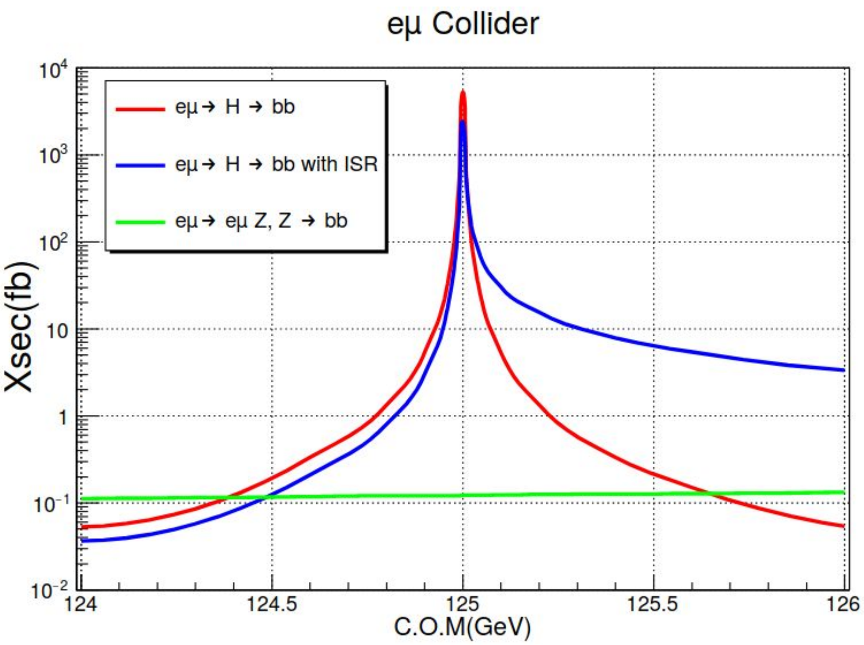
$$L_V \equiv -Y_{e\mu}\bar{e}_L\mu_R H - Y_{\mu e}\bar{\mu}_L e_R H - Y_{e\tau}\bar{e}_L\tau_R H - Y_{\tau e}\bar{\tau}_L e_R H - Y_{\mu\tau}\bar{\mu}_L\tau_R H - Y_{\tau\mu}\bar{\tau}_L\mu_R H$$



$$\Gamma(H \to \ell^\alpha \ell^\beta) = \frac{M_H}{8\pi}(|Y_{\ell^\beta\ell^\alpha}|^2 + |Y_{\ell^\alpha\ell^\beta}|^2)$$

$$\mathcal{B}(H \to \ell^\alpha \ell^\beta) = \frac{\Gamma(H \to \ell^\alpha\ell^\beta)}{\Gamma(H \to \ell^\alpha\ell^\beta) + \Gamma_{SM}}$$

Current best limit from ATLAS: $\mathrm{Br}(H \to e\mu) < 6.2 \times 10^{-5}$
CEPC Projection: $\mathrm{Br}(H \to e\mu) < 1.2 \times 10^{-5}$



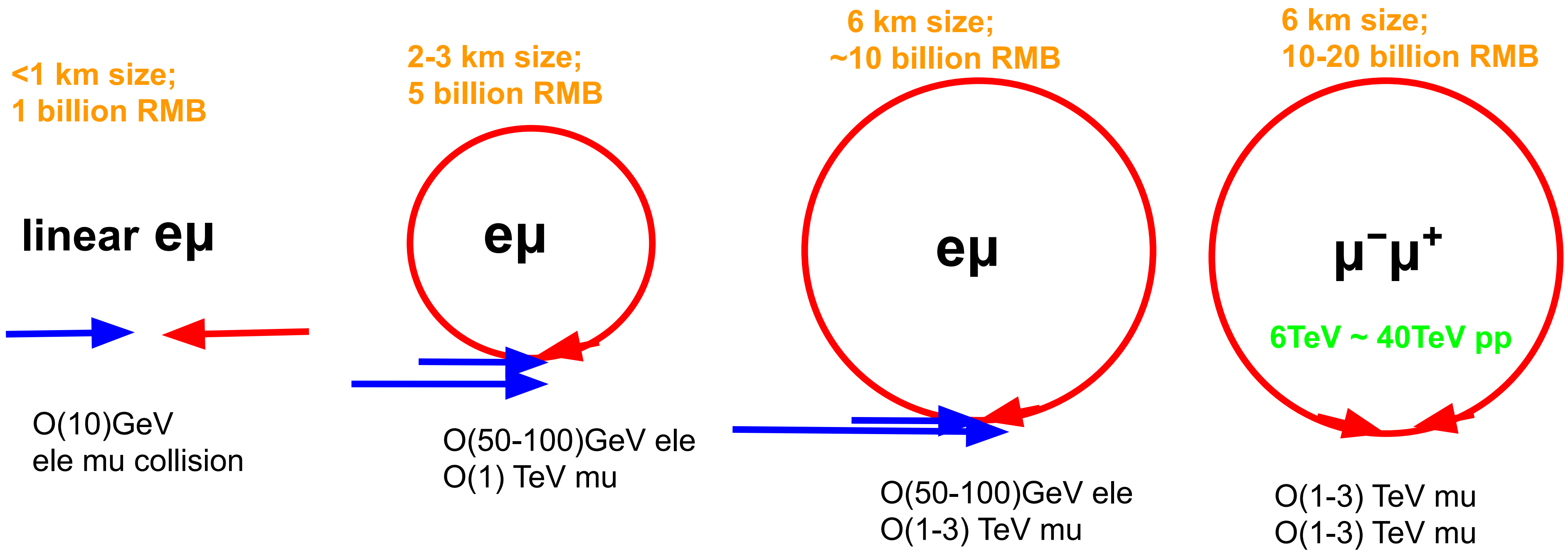
Model implemented in MG, w or wo ISR;

Signal at peak ~ 5.3pb, while bkg ~0.1fb

A simple estimation gives 100 times better limit than ATLAS, with only 1/fb.

Crude cost estimation

New World/Virgin land from the low energy collision



LFV, Higgs, majorana neutrino ....
~10-20 billion RMB in total to reach physics hopefully ~ CEPC + half-SPPC

Facility and cost estimation

Total Project Cost (TPC) model in US accounting (EU accounting might be 2-3 times lower):

"civil construction", "accelerator components", "site power infrastructure"

$$TPC \approx \alpha \times (Length/10km)^{1/2} + \beta \times (Energy/TeV)^{1/2} + \gamma \times (Power/100MW)^{1/2} \quad , \quad (1)$$

1TeV Muon beam:

2B$*(4km/10km)^0.5+2B$*(2)^0.5+2B$*(100MW/100MW)^0.5~6B$

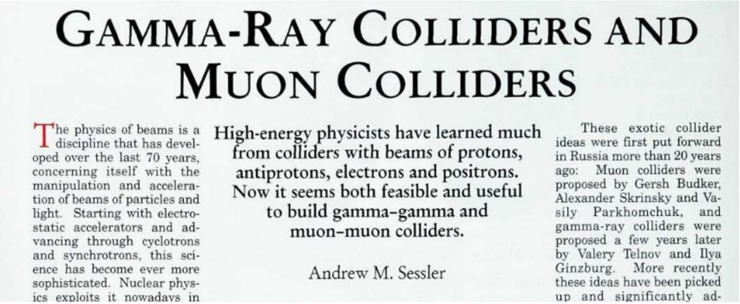
(3TeV Muon ~8B $)

If 3 times larger

2B$ in total

Note:

- **electron part cost is relatively small**
- **O(100)GeV e-mu collider cost much less**



GAMMA-RAY COLLIDERS AND MUON COLLIDERS

High-energy physicists have learned much from colliders with beams of protons, antiprotons, electrons and positrons. Now it seems both feasible and useful to build gamma-gamma and muon-muon colliders.

Andrew M. Sessler

The physics of beams is a discipline that has developed over the last 70 years, concerning itself with the manipulation and acceleration of beams of particles and light. Starting with electrostatic accelerators and advancing through cyclotrons and synchrotrons, this science has become ever more sophisticated. Nuclear physics exploits it nowadays in

These exotic collider ideas were first put forward in Russia more than 20 years ago: Muon colliders were proposed by Gersh Budker, Alexander Skrinsky and Vasily Parkhomchuk, and gamma-ray colliders were proposed a few years later by Valery Telnov and Ilya Ginzburg. More recently these ideas have been picked up and significantly ad-

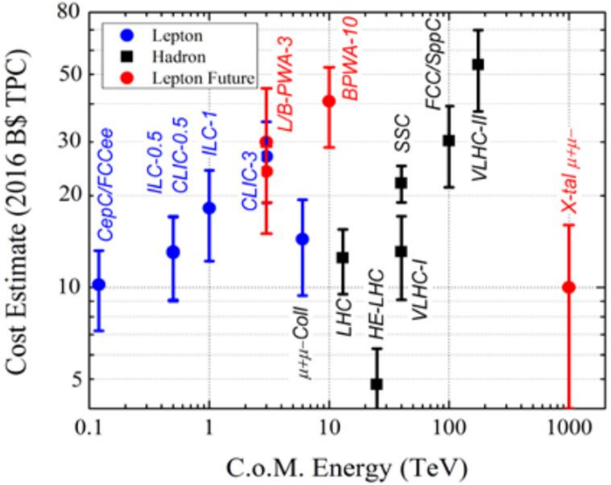
Physics Today 51, 3, 48 (1998)

"But the result might well be a machine that is less expensive than an ee linear collider with the same final energy, though a TeV muon collider would still be a **billion-dollar** undertaking."

Facility and cost estimation

Total Project Cost (TPC) model in US accounting (EU accounting might be 2-3 times lower):
"civil construction", "accelerator components", "site power infrastructure"

$$TPC \approx \alpha \times (Length/10km)^{1/2} + \beta \times (Energy/TeV)^{1/2} + \gamma \times (Power/100MW)^{1/2} \quad , \quad (1)$$



CEPC:
2B\$*(50km/10km)^0.5+2B\$*(0.25)^0.5+2B\$*(500MW/100MW)^0.5~10B\$
or
2B\$*(**100**km/10km)^0.5+2B\$*(0.25)^0.5+2B\$*(500MW/100MW)^0.5~12B\$

3 times larger

The ambitious 30-billion-yuan (US$4.3-billion) facility, known as the Circular Electron–Positron Collider (CEPC), is the brainchild of IHEP's director, Wang Yifang. He has spearheaded the project since the discovery of the elementary particle called the Higgs boson at the LHC in 2012.

https://www.nature.com/articles/d41586-018-07492-w