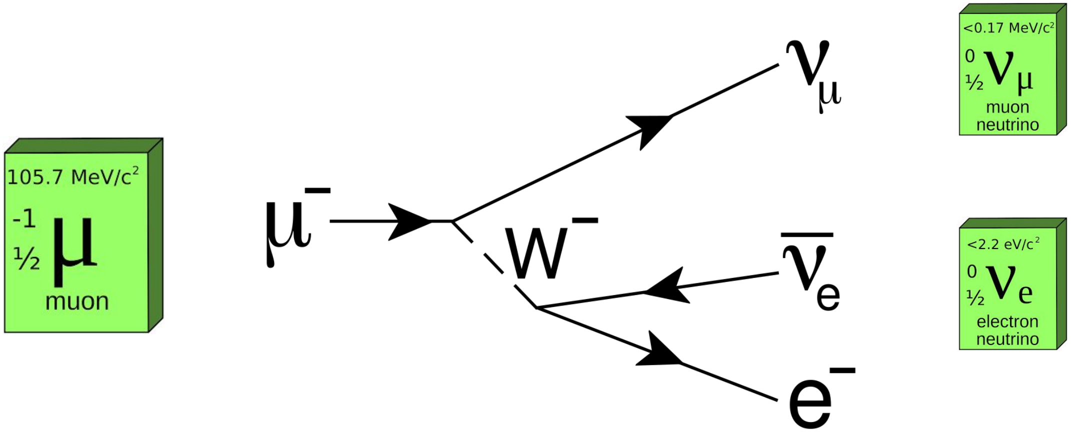
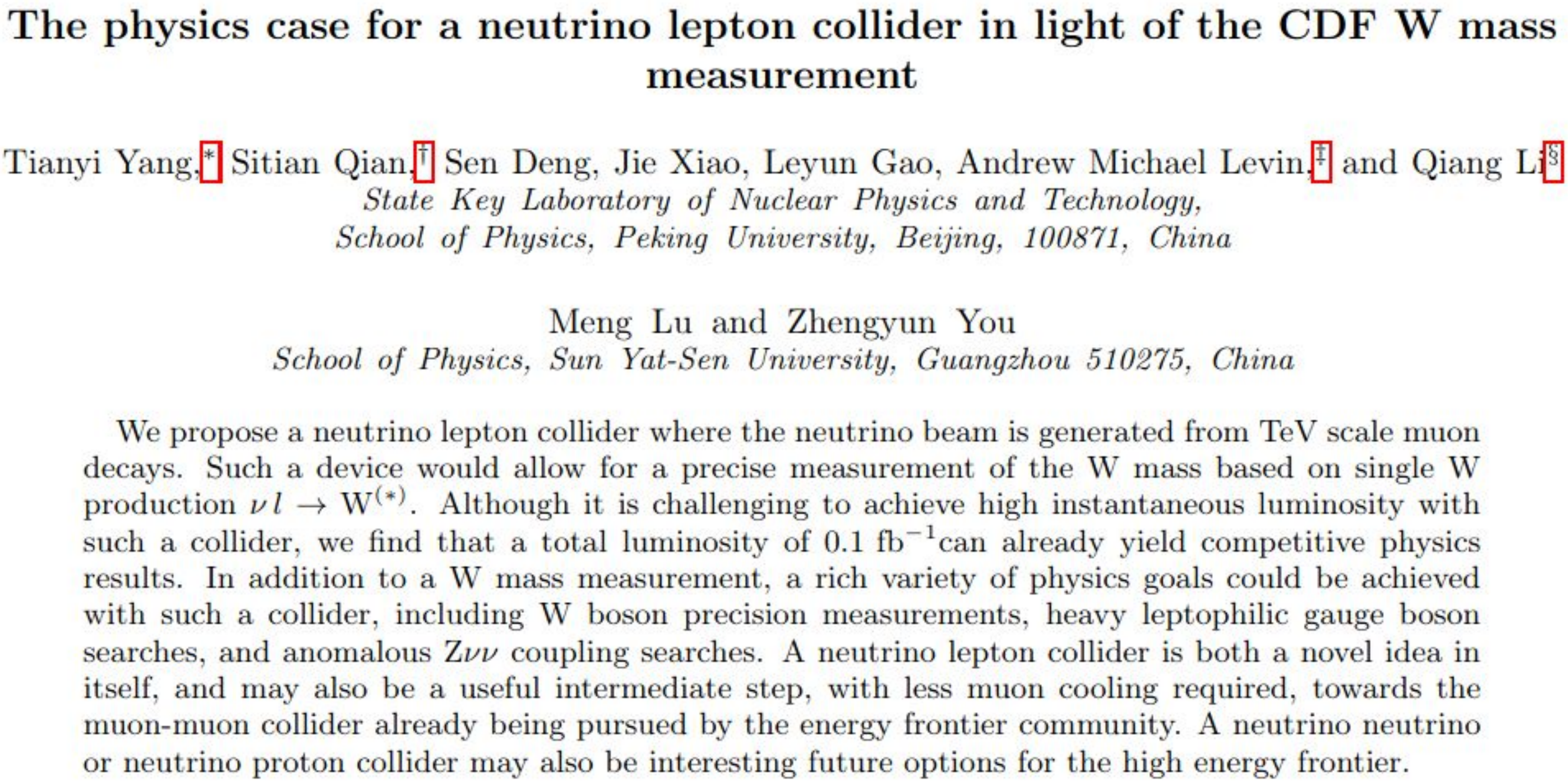
The physics case for a neutrino lepton collider in light of the CDF W mass measurement



Qiang Li, Peking University 2022/05/07

arXiv:2204.11871

W mass : Uncertainties and Opportunities



The physics case for a neutrino lepton collider in light of the CDF W mass measurement

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We propose a neutrino lepton collider where the neutrino beam is generated from TeV scale muon decays. Such a device would allow for a precise measurement of the W mass based on single W production $\nu l \rightarrow W^{(*)}$. Although it is challenging to achieve high instantaneous luminosity with such a collider, we find that a total luminosity of 0.1 fb^{-1}can already yield competitive physics results. In addition to a W mass measurement, a rich variety of physics goals could be achieved with such a collider, including W boson precision measurements, heavy leptophilic gauge boson searches, and anomalous $Z\nu\nu$ coupling searches. A neutrino lepton collider is both a novel idea in itself, and may also be a useful intermediate step, with less muon cooling required, towards the muon-muon collider already being pursued by the energy frontier community. A neutrino neutrino or neutrino proton collider may also be interesting future options for the high energy frontier.

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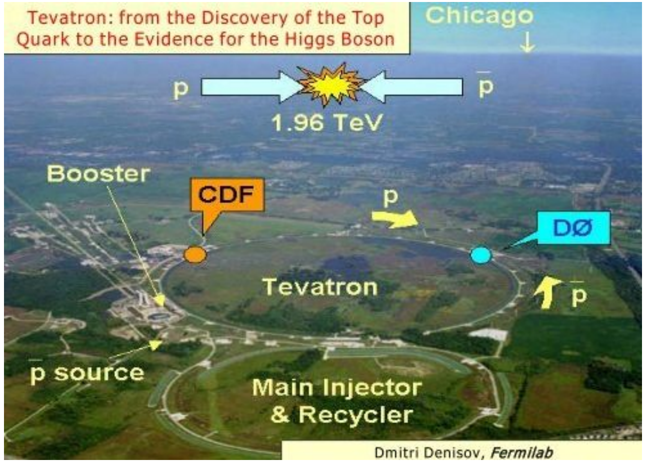
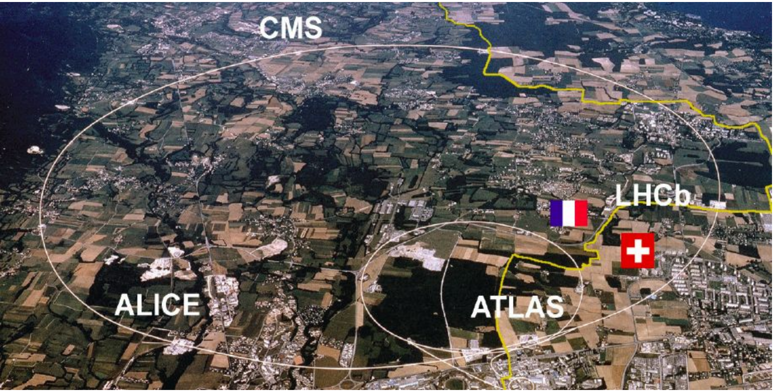
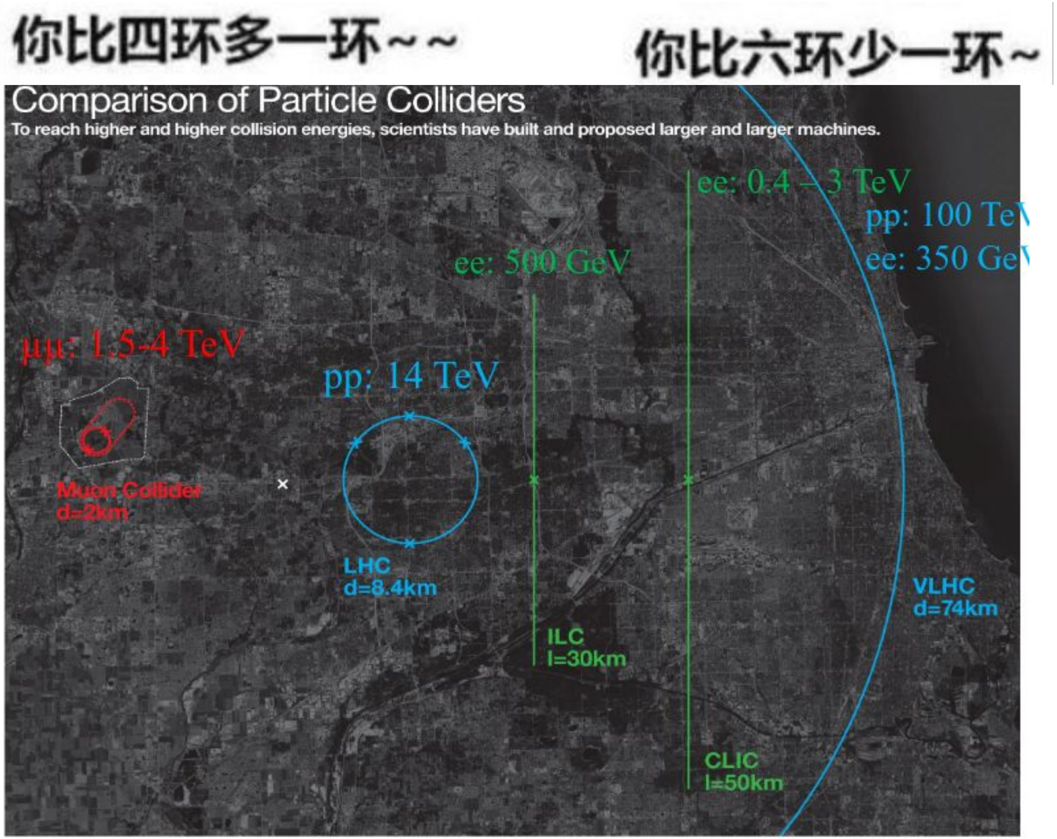
Colliders：ee, pp, ep,...HL-LHC, CEPC, muon…





未来对撞机



Comparison of Particle Colliders

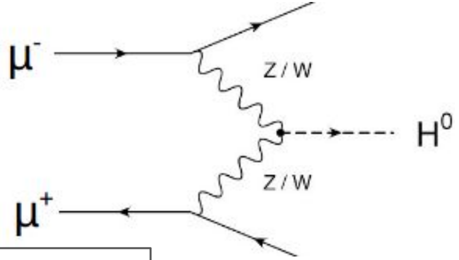
To reach higher and higher collision energies, scientists have built and proposed larger and larger machines.

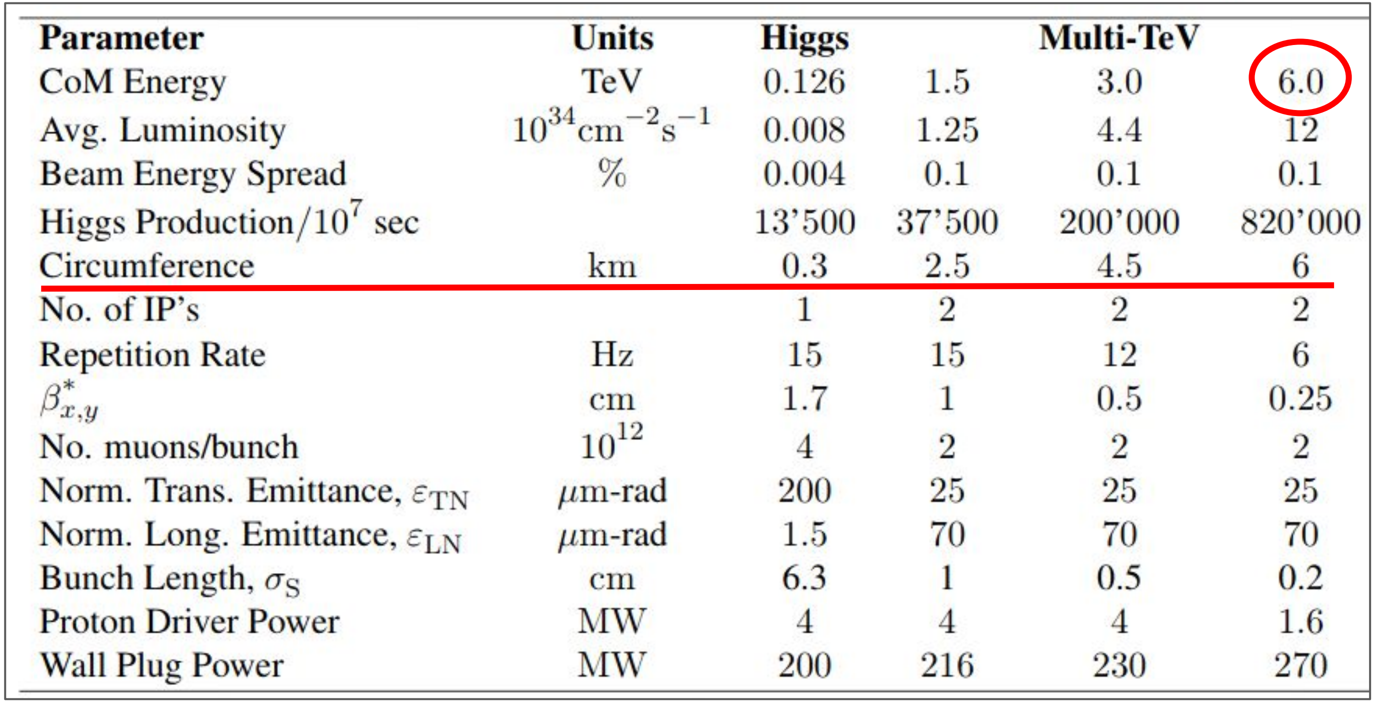
Muon Collider interest Revived upon Muon Anomalies

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.



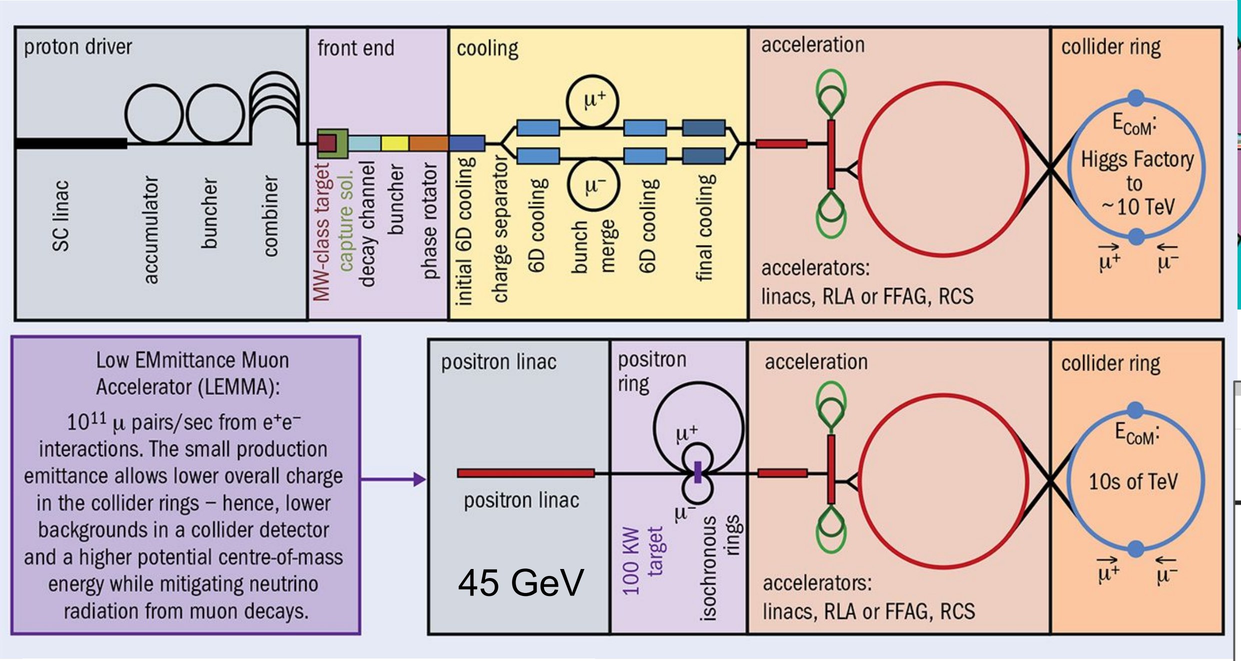


Parameter	Units	Higgs		Multi-TeV	
CoM Energy	TeV	0.126	1.5	3.0	6.0
Avg. Luminosity	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^7 sec		13'500	37'500	200'000	820'000
Circumference	km	0.3	2.5	4.5	6
No. of IP's		1	2	2	2
Repetition 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, $\varepsilon_{\mathrm{TN}}$	μm-rad	200	25	25	25
Norm. Long. Emittance, $\varepsilon_{\mathrm{LN}}$	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 Collider: beam and background

Muon Source



Low EMmittance Muon Accelerator (LEMMA):

10^{11} μ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential centre-of-mass energy while mitigating neutrino radiation from muon decays.

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

High energy

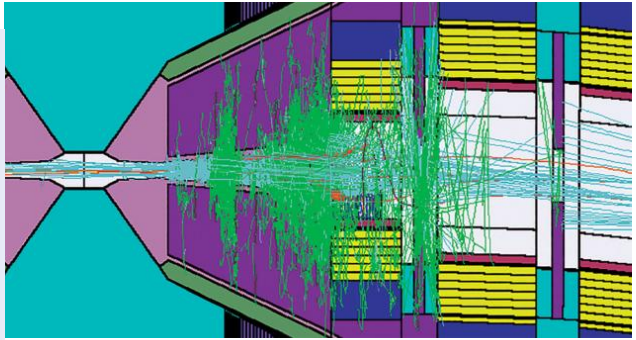
High field in collider ring

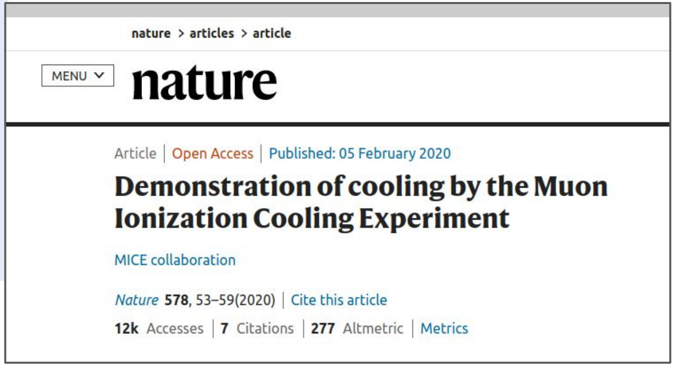
Large energy acceptance

Dense beam

High beam power

Muon Beam Induced background





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Demonstration of cooling by the Muon Ionization Cooling Experiment

MICE collaboration

Nature **578**, 53–59(2020) | Cite this article

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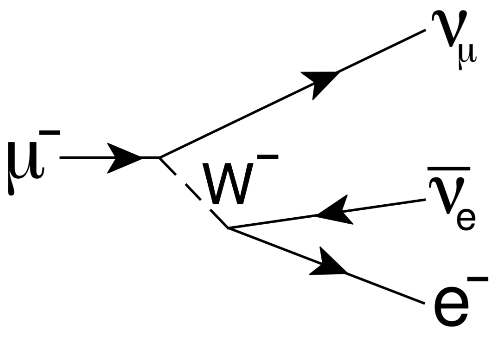
Muon Ionisation Cooling Experiment (MICE)

Neutrino Beam



B. J. King hep-ex/0005007

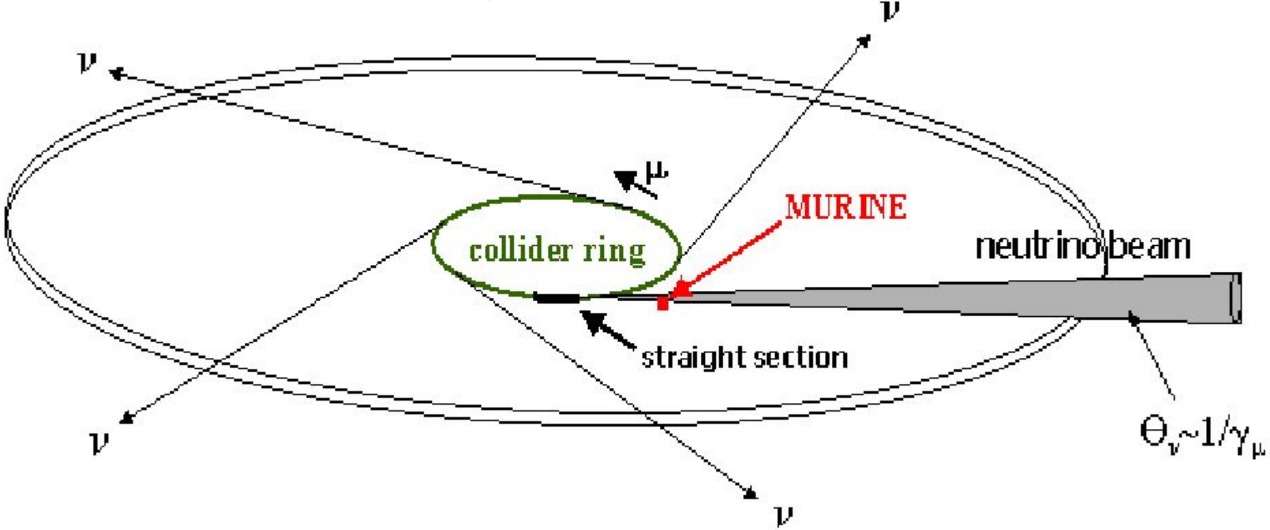
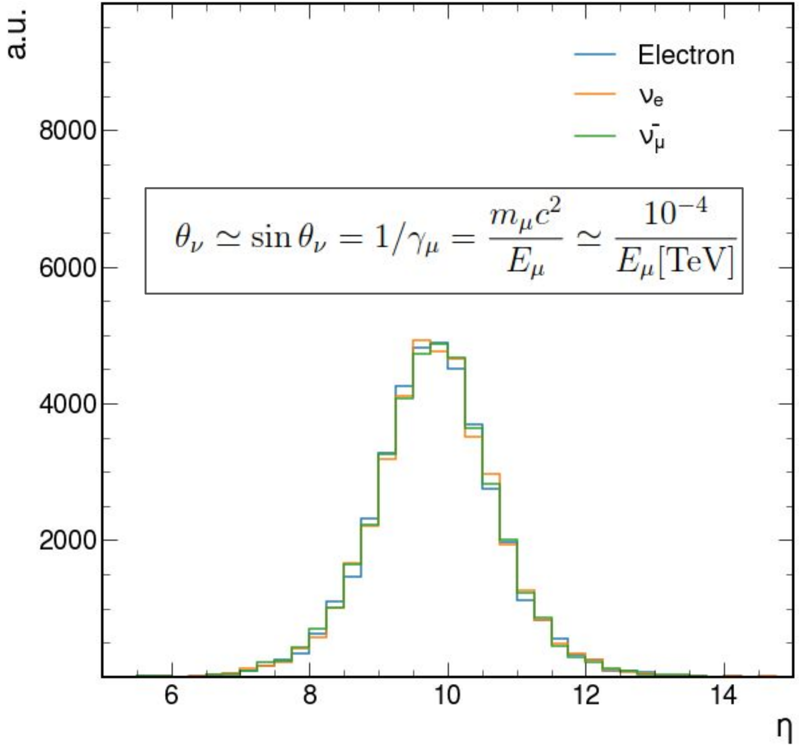


FIGURE 1. The decays of muons in a muon collider will produce a disk of neutrinos emanating out tangentially from the collider ring. The neutrinos from decays in straight sections will line up into beams suitable for experiments. The MURINEs will be sited in the center of the most intense beam and as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

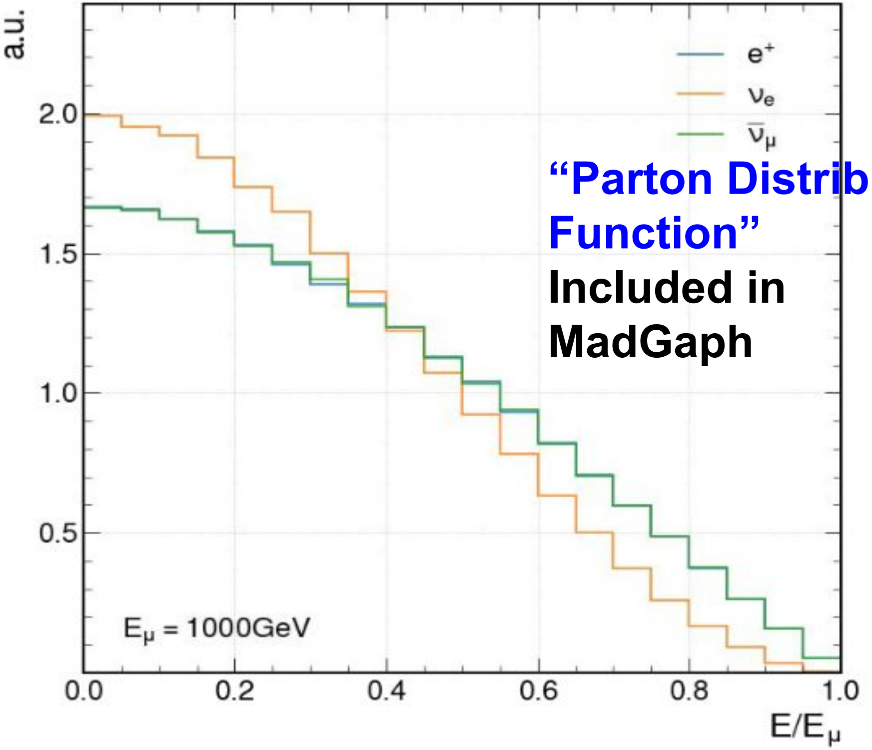
NuTeV
Neutrino-Nucleon Scattering
NuMAX
NuSOnG
Neutrino Scattering on Glass
nuSTORM
"Neutrinos from STORed Muons," …for neutrino oscillation searches

很多中微子打靶实验，但是没有head-on对撞构想

Neutrino Beam from 1TeV Muon beam



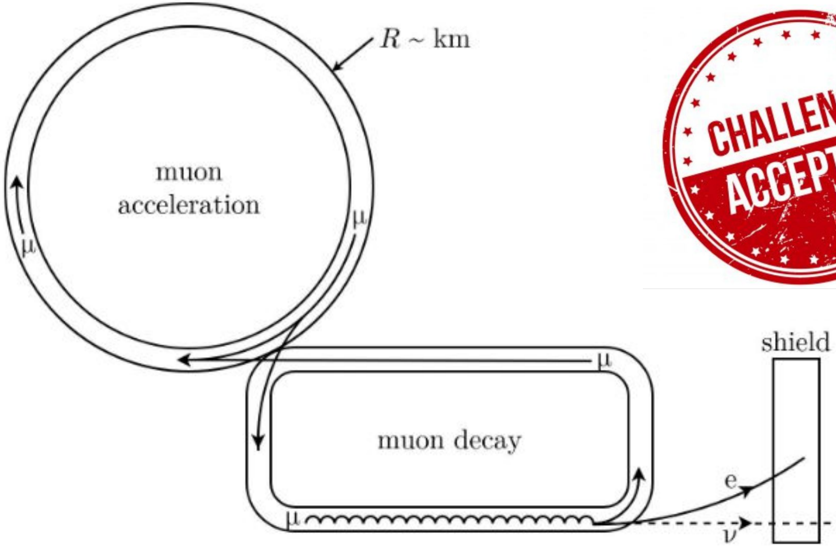
$$\theta_\nu \simeq \sin\theta_\nu = 1/\gamma_\mu = \frac{m_\mu c^2}{E_\mu} \simeq \frac{10^{-4}}{E_\mu[\mathrm{TeV}]}$$



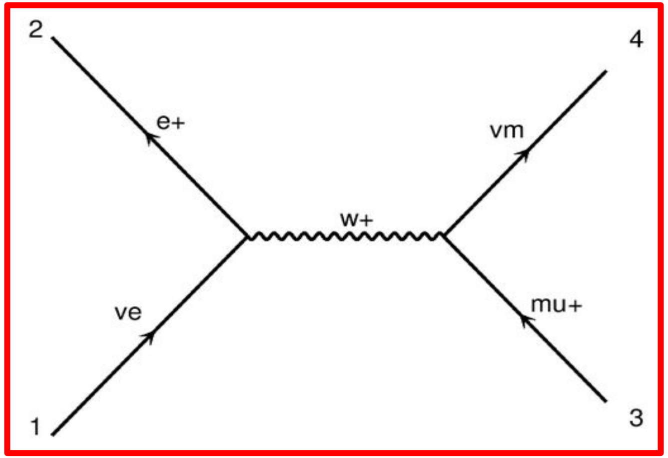
"Parton Distribution Function"
Included in MadGaph

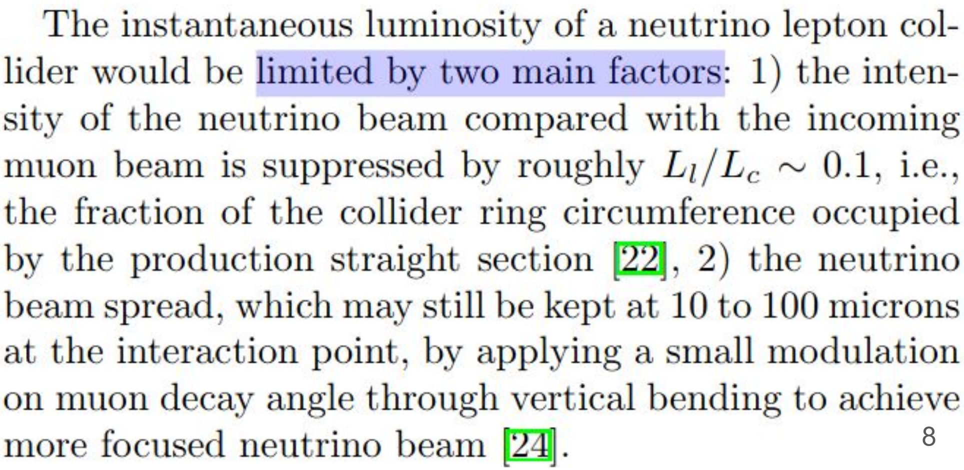
Highly collimated in angle, yet widely distributed in Energy

Neutrino Collider



CHALLENGE ACCEPTED





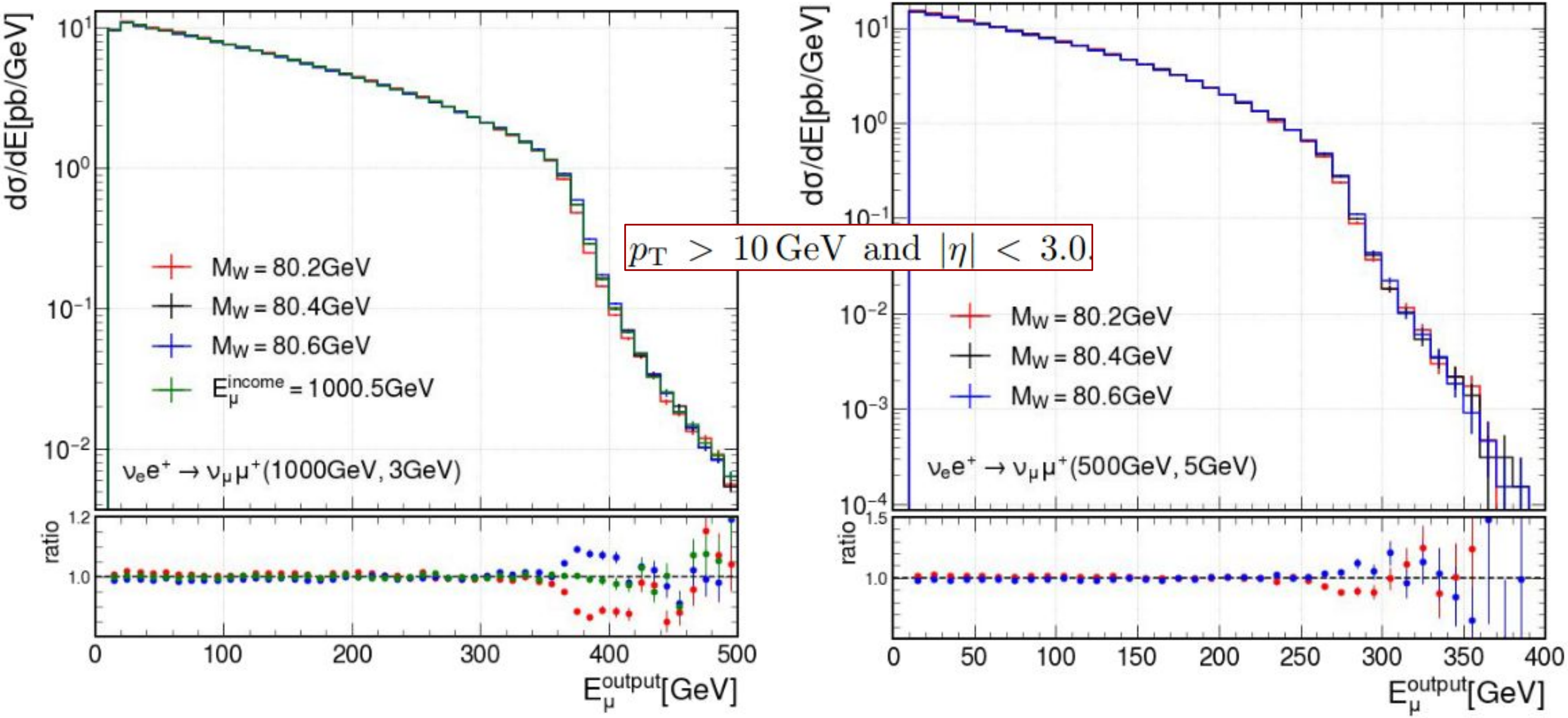
The instantaneous luminosity of a neutrino lepton collider would be limited by two main factors: 1) the intensity of the neutrino beam compared with the incoming muon beam is suppressed by roughly $L_l/L_c \sim 0.1$, i.e., the fraction of the collider ring circumference occupied by the production straight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

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

10-100/fb in 10 years

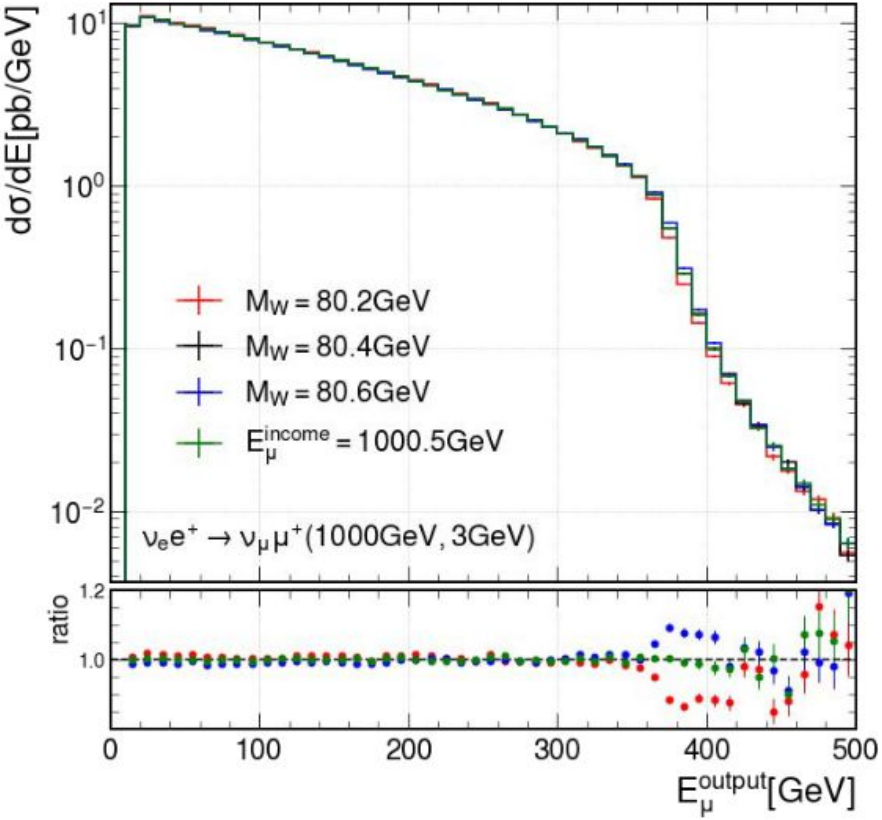
Single W production

Kink Structure from W threshold in convolution with Beam PDF



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

Single W production



Larger MW →

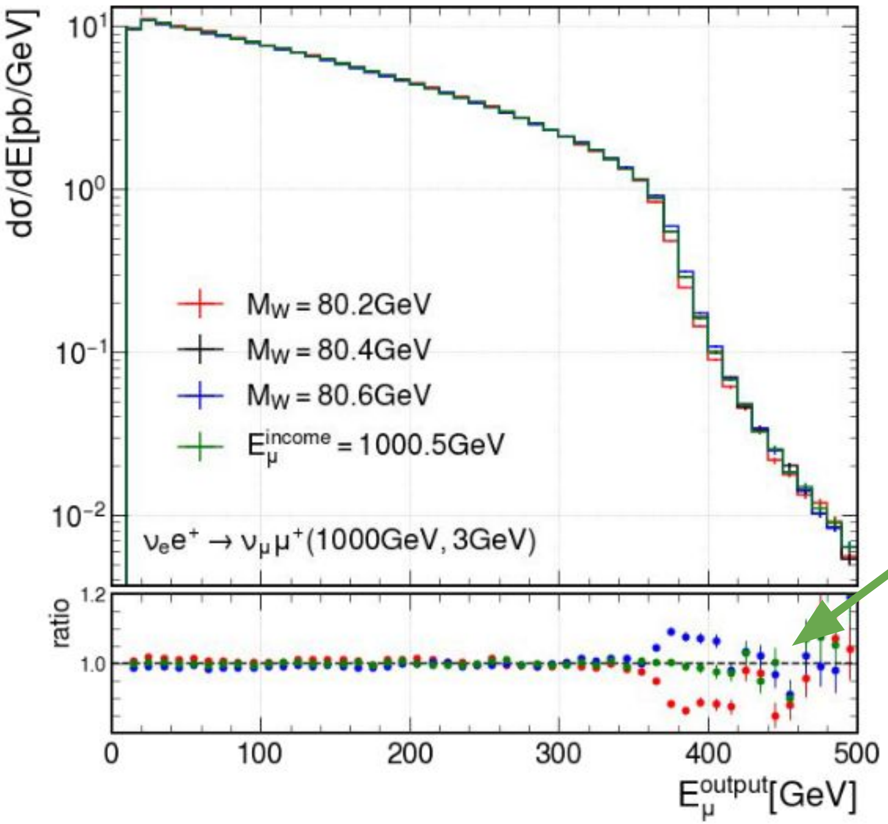
Higher incoming neutrino Energy →

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



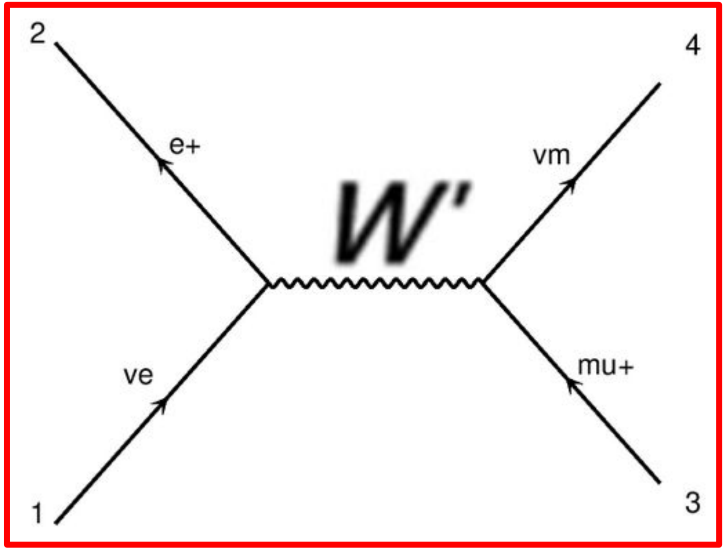
We varied the incoming muon and electron beam energy by 0.5 GeV and 10 MeV, respectively, which are quite conservative following previous refs.

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

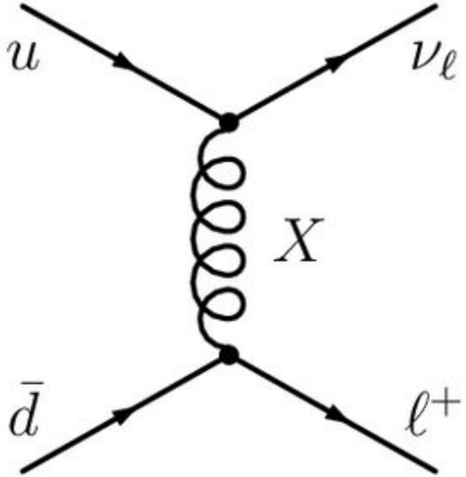
This uncertainty could be **mitigated by using the shape of the outgoing muon energy**, by scanning different incoming beam energies, or by calibrating
the incoming muon beam energy with the electron decay products.

More Physics

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



Anomalous Zvv couplings



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leptoquark

Summary

- **An neutrino-lepton collider is quite sensitive to W mass**
  - **10MeV accuracy with 0.1/fb!**
  - Many options for various Physics
    - Electron Neutrino + Electron/Muon
    - Muon Neutrino + Muon/Electron

- **A neutrino lepton collider is both a novel idea in itself, and may also be a useful intermediate step, with less muon cooling required, towards the muon-muon collider.**

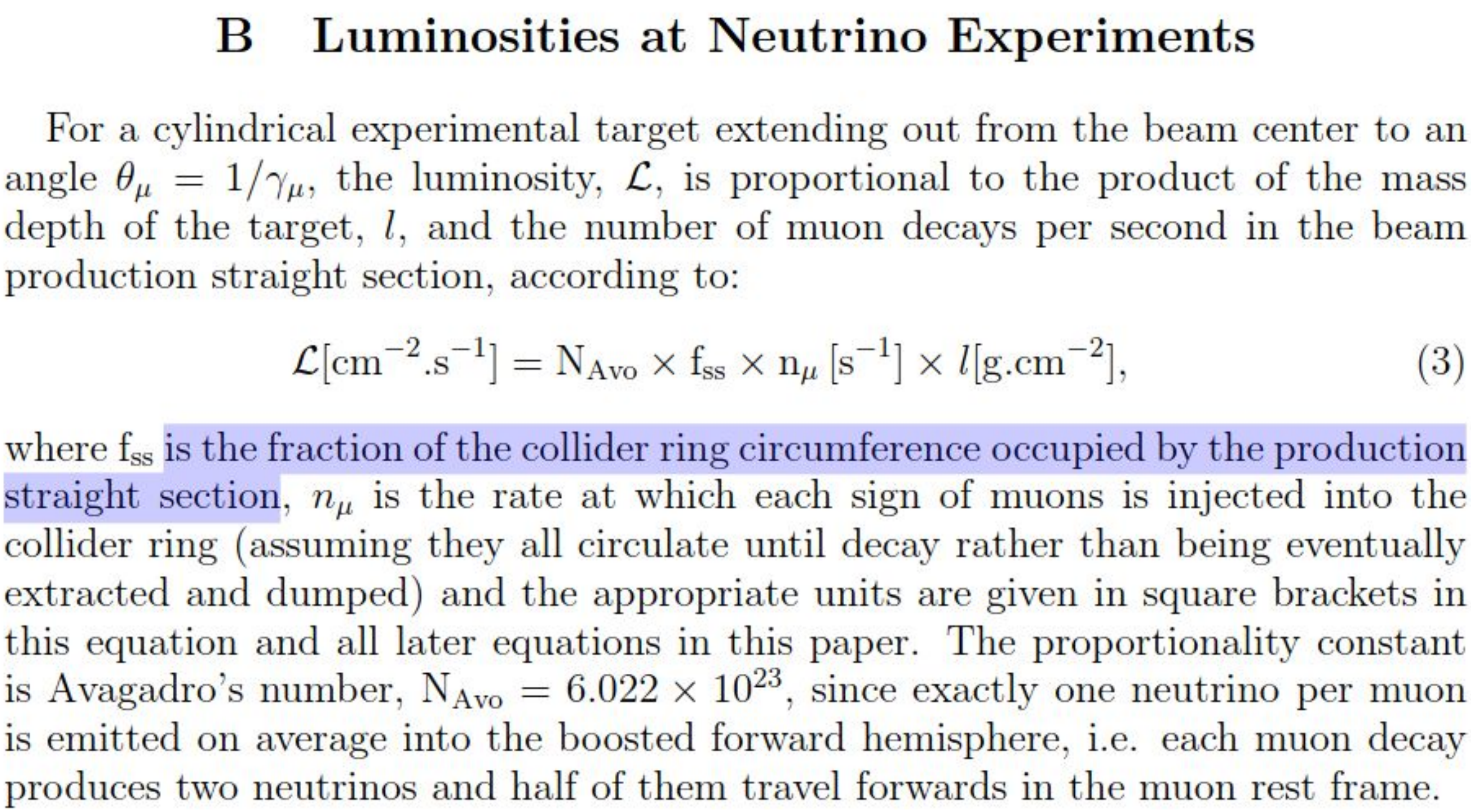
$$\boxed{\nu_e e^+ \to W^{+(*)}}$$

νν?

- **We urge the community to consider this new option seriously.**

Backup

B. J. King **hep-ex/0005007**

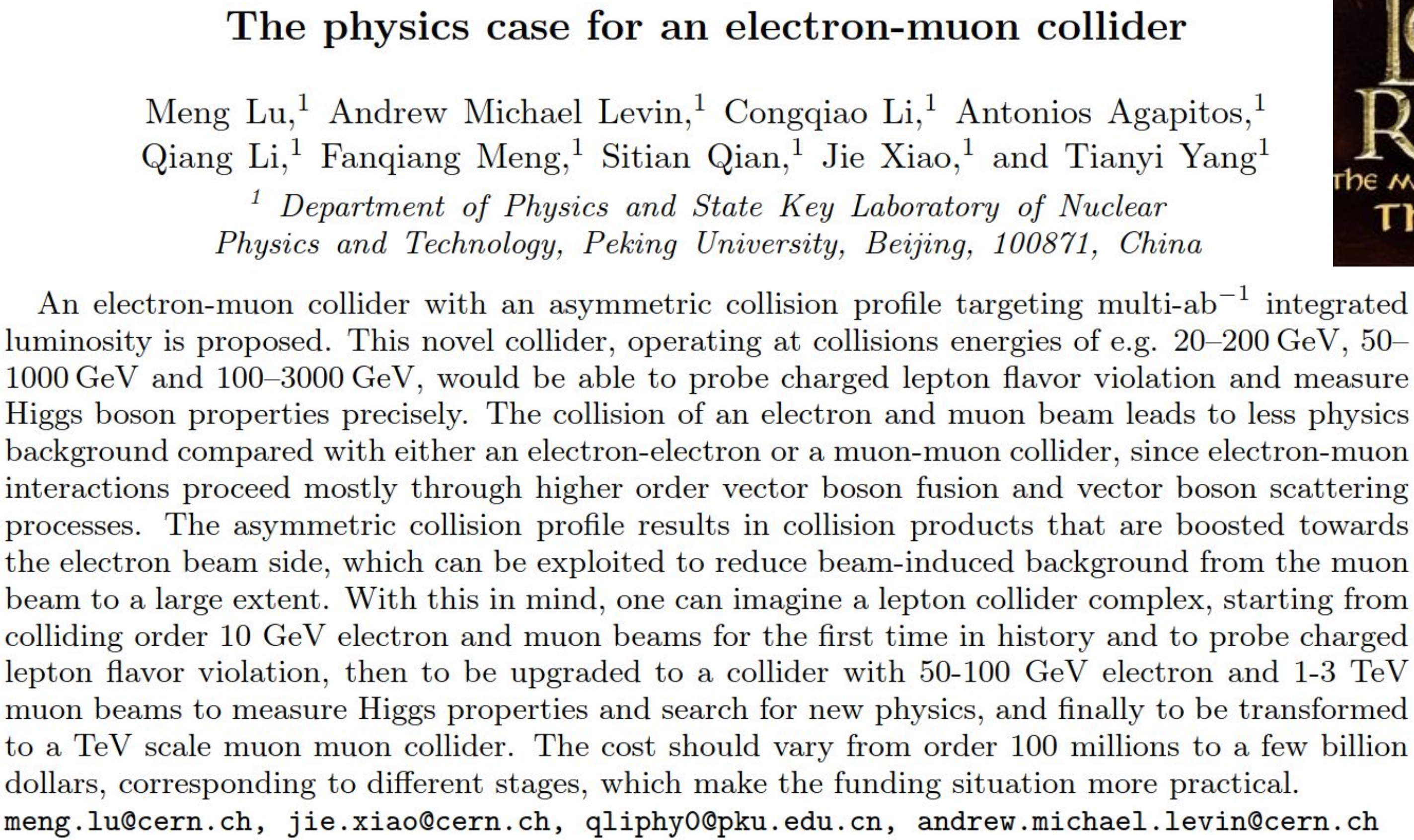


B Luminosities at Neutrino Experiments

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.



The physics case for an electron-muon collider

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Qiang Li,[1] Fanqiang Meng,[1] Sitian Qian,[1] Jie Xiao,[1] and Tianyi Yang[1]
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An electron-muon collider with an asymmetric collision profile targeting multi-ab^{-1} integrated luminosity is proposed. This novel collider, operating at collisions energies of e.g. 20–200 GeV, 50–1000 GeV and 100–3000 GeV, would be able to probe charged lepton flavor violation and measure Higgs boson properties precisely. The collision of an electron and muon beam leads to less physics background compared with either an electron-electron or a muon-muon collider, since electron-muon interactions proceed mostly through higher order vector boson fusion and vector boson scattering processes. The asymmetric collision profile results in collision products that are boosted towards the electron beam side, which can be exploited to reduce beam-induced background from the muon beam to a large extent. With this in mind, one can imagine a lepton collider complex, starting from colliding order 10 GeV electron and muon beams for the first time in history and to probe charged lepton flavor violation, then to be upgraded to a collider with 50-100 GeV electron and 1-3 TeV muon beams to measure Higgs properties and search for new physics, and finally to be transformed to a TeV scale muon muon collider. The cost should vary from order 100 millions to a few billion dollars, corresponding to different stages, which make the funding situation more practical.

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https://arxiv.org/pdf/2010.15144.pdf