

第三届粒子物理前沿研讨会

Richness out of smallness: from Neutrino Collider to Muon Collider

22 July 2022

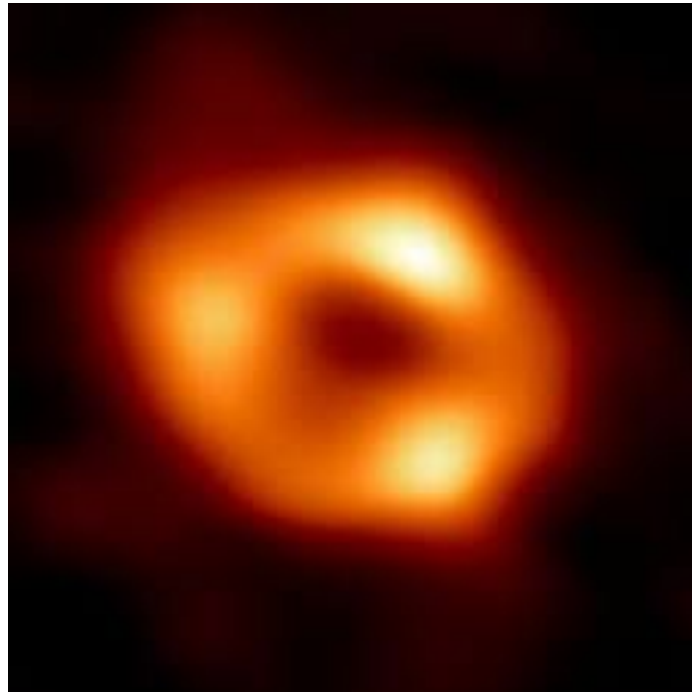
卢梦 中山大学

Outline

- Prelude
- Introduction to HE-Colliders
- Muon Collider
- Neutrino beam
- Neutrino collision
- Electron-Muon Collider
- Summary

Prelude

Gifts from the sky:

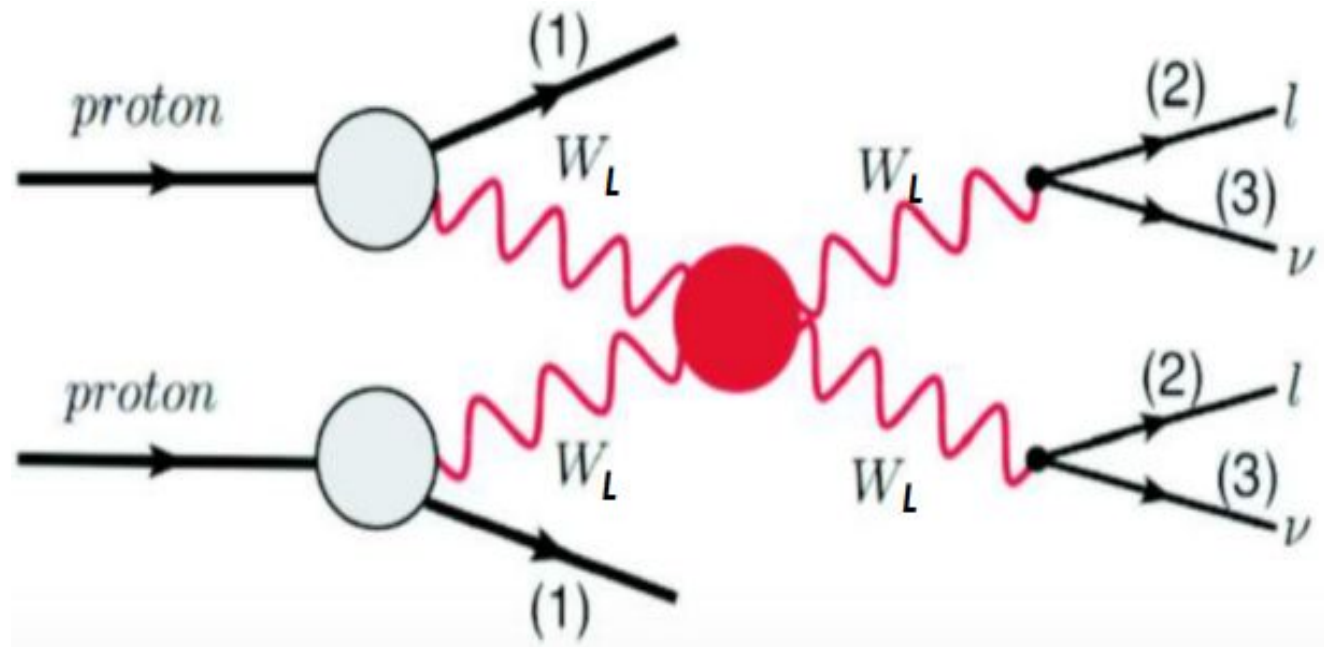


Prelude

Create rich physics from small: Collider

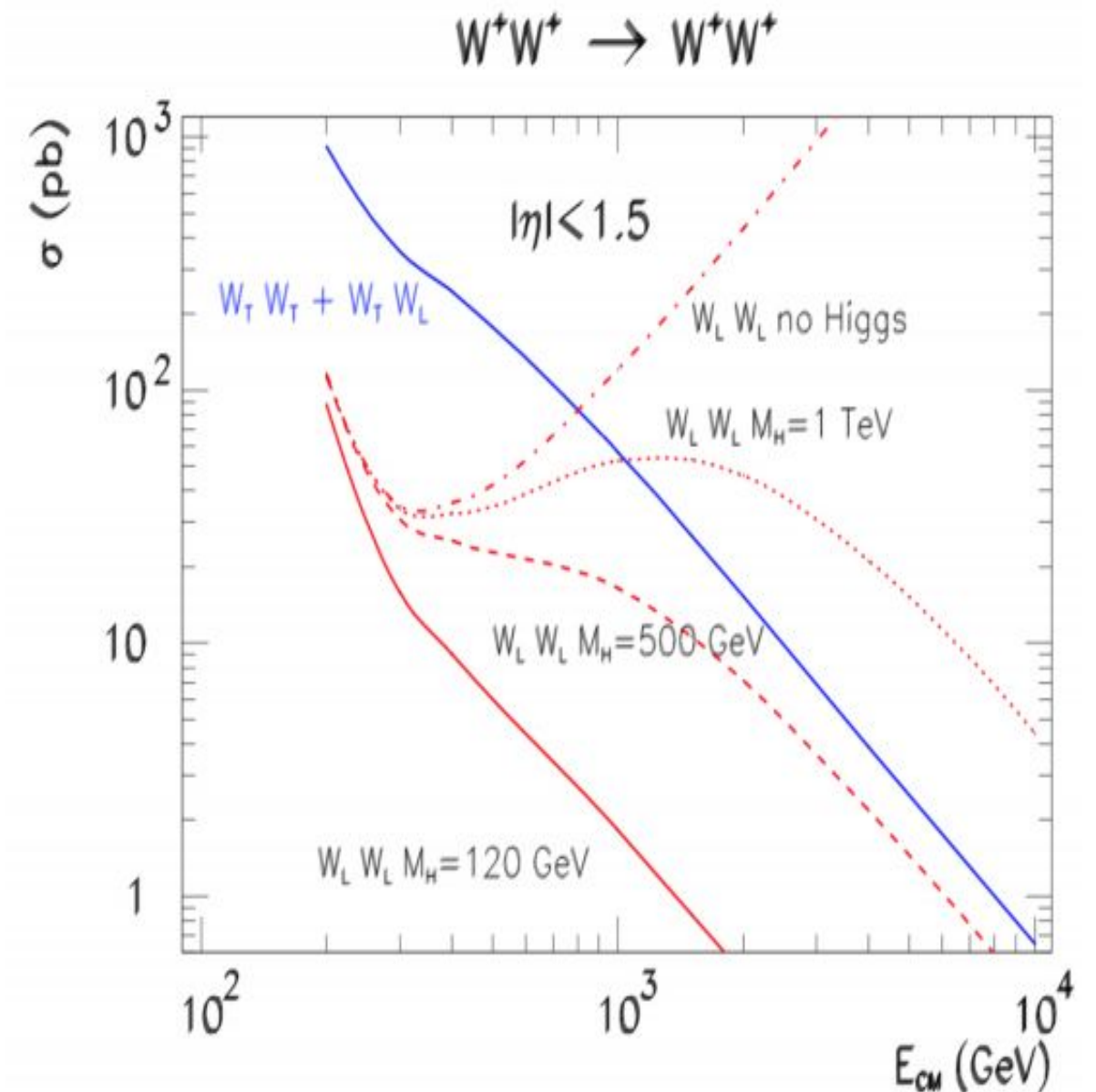


Prelude: Vector Boson Scattering



- 杨米尔斯非阿贝尔相互作用
反常耦合、有效理论EFT
- 电弱对称性破缺
希格斯么正机制
- TeV能级的新物理
Boosted 喷注技术

同电荷W-W玻色子(极化)散射
~ 200(20) 事例 (2016-2018)!



WW- \rightarrow WW behavior on scattering energy

Introduction to HE-Colliders: LHC



The Nobel Prize in Physics 2013



Photo: A. Mahmoud
François Englert
Prize share: 1/2

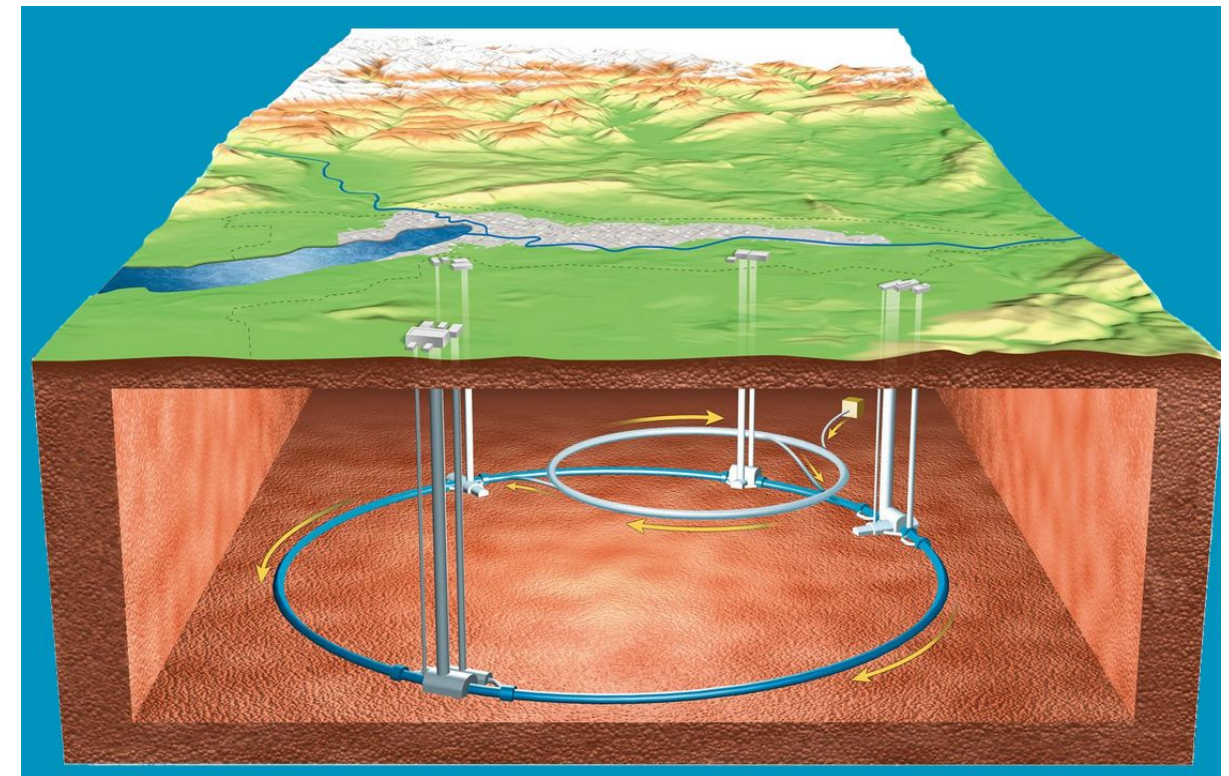


Photo: A. Mahmoud
Peter W. Higgs
Prize share: 1/2



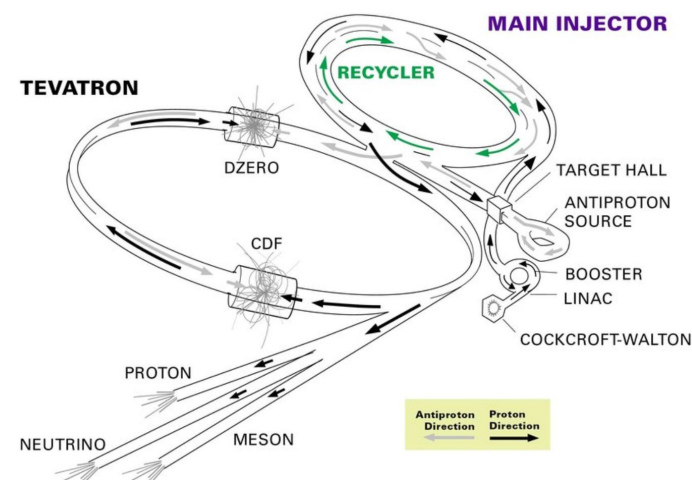
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

Large Hadron Collider: ALICE, ATLAS, CMS, LHCb
O(1000) person experiments

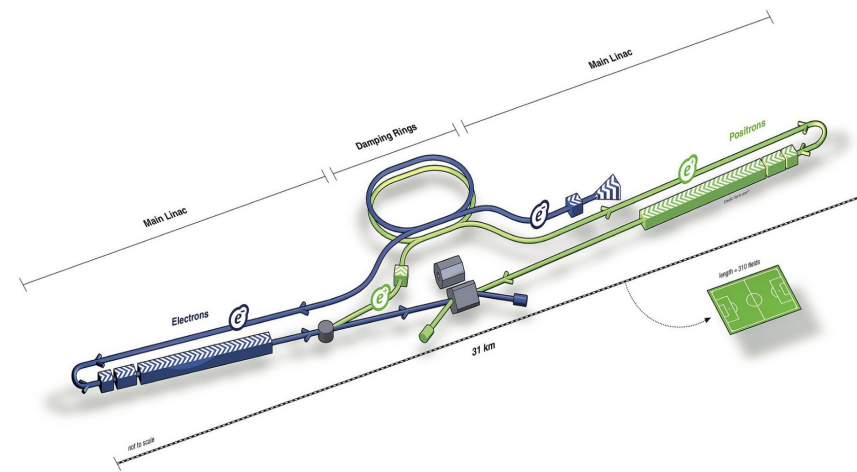


Introduction to HE-Colliders

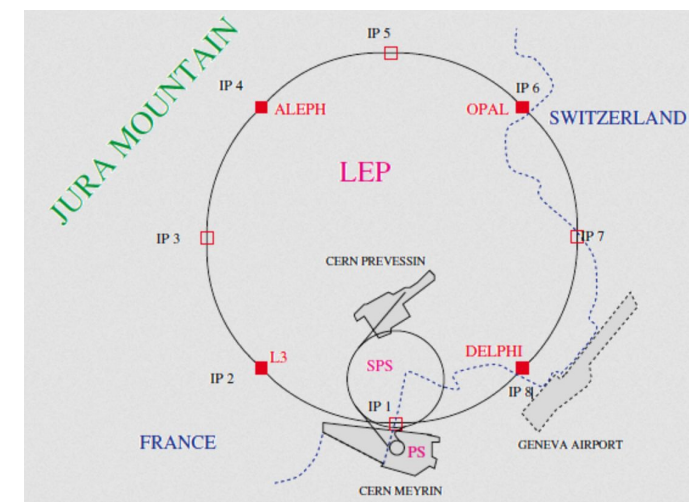
Past
(multiple
colliders 😊)



Tevatron: 1983 ~ 2011

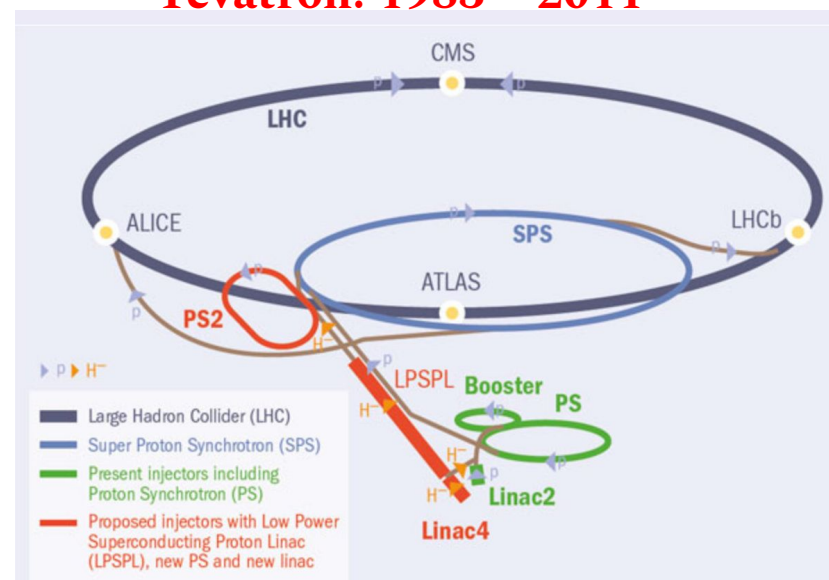


SLC: 1987/9 ~ 1998



LEP: 1989 ~ 2000

Now

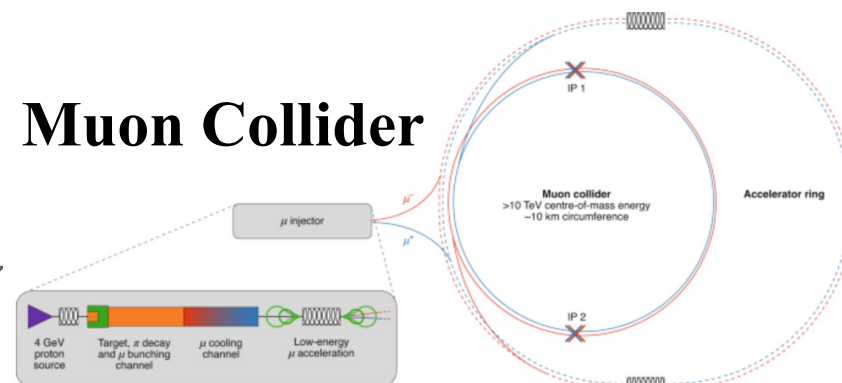


(HL)LHC: 2008 ~

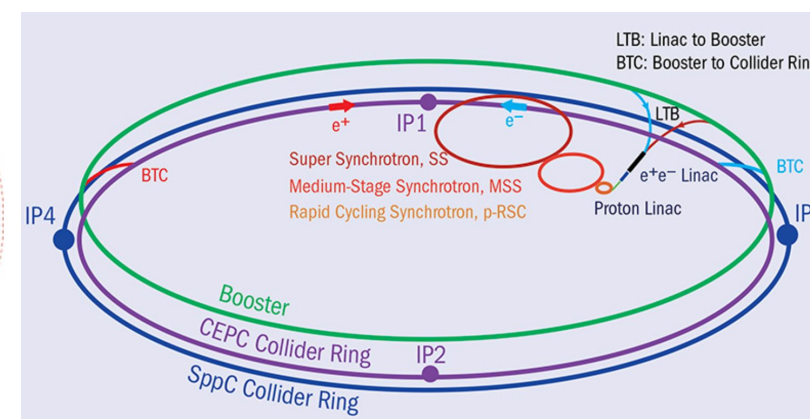
Also ILC, CLIC ...

Future?

Muon Collider



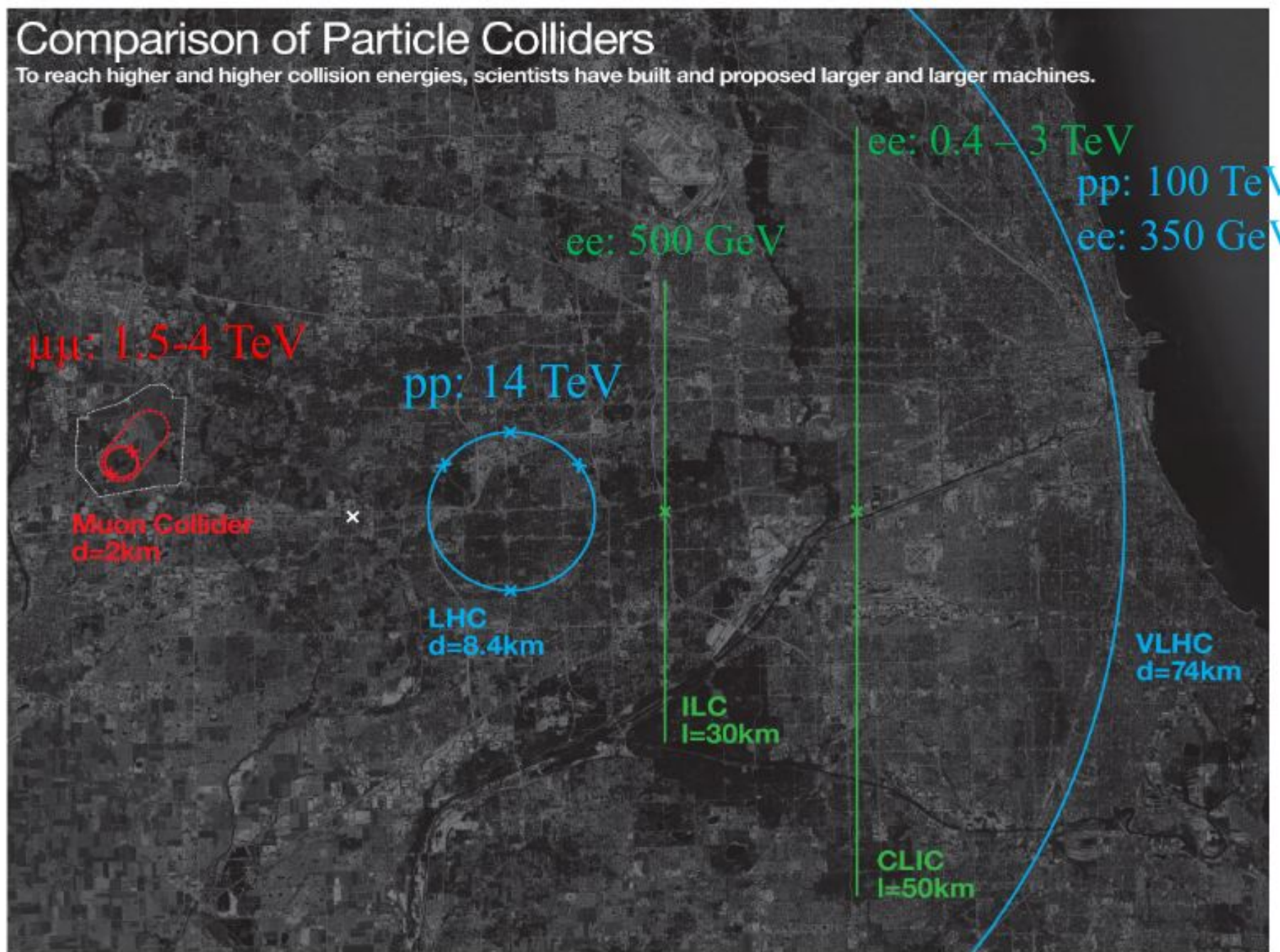
CEPC/SPPC



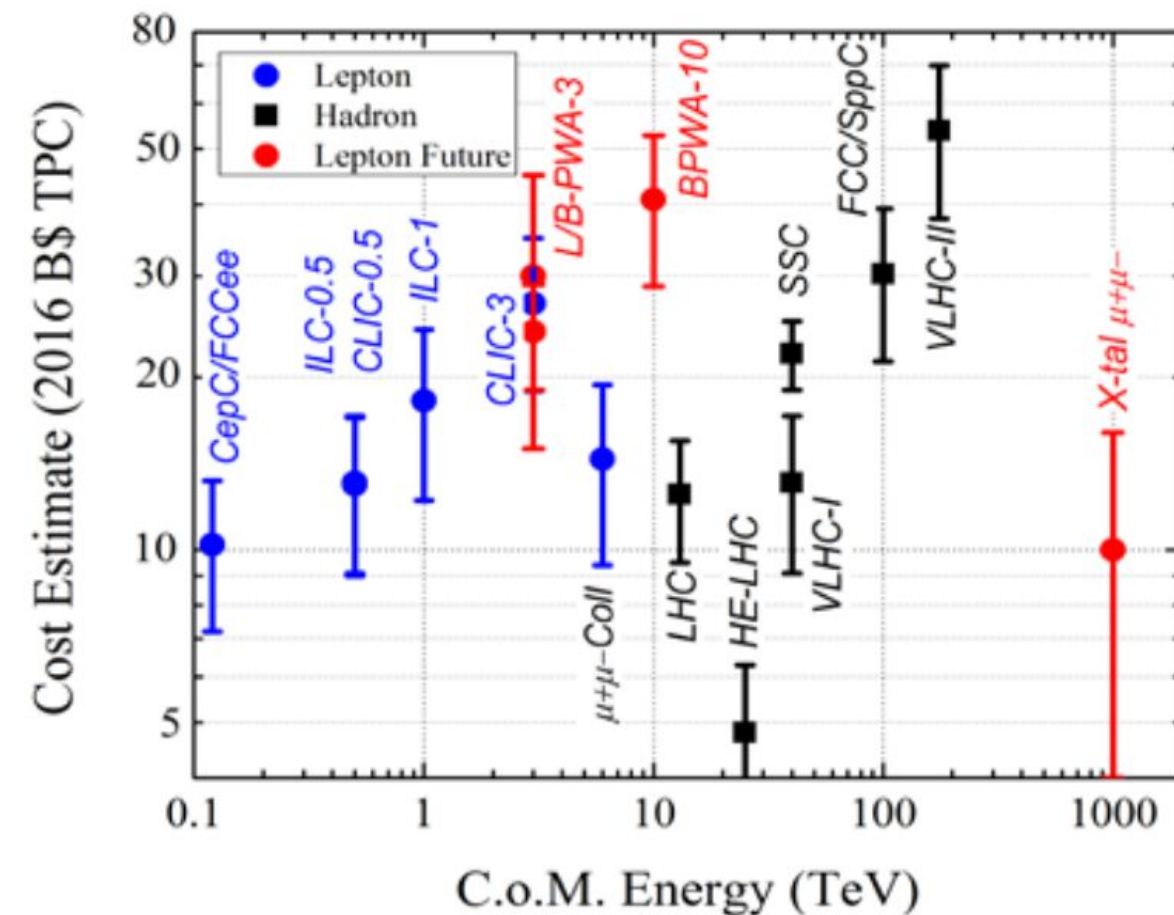
FCC



Introduction to HE-Colliders



arXiv: [1705.02011](https://arxiv.org/abs/1705.02011)



The updated strategy for particle physics in Europe recommends pursuing an electron-positron Higgs factory as the highest-priority.

Muon Collider

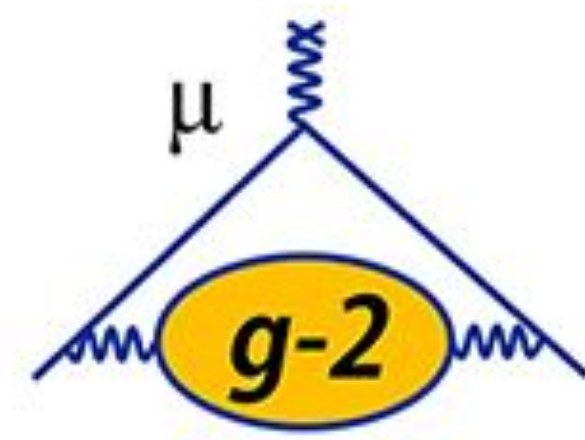
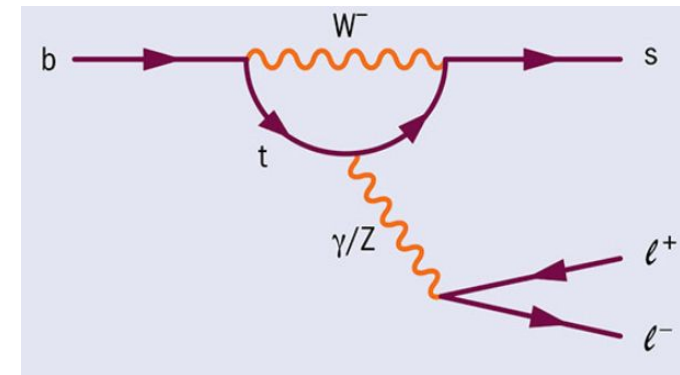
Muon Collider interest Revived upon Muon Anomalies: lepton unitarity, muon $g-2$, w mass.

Pros:

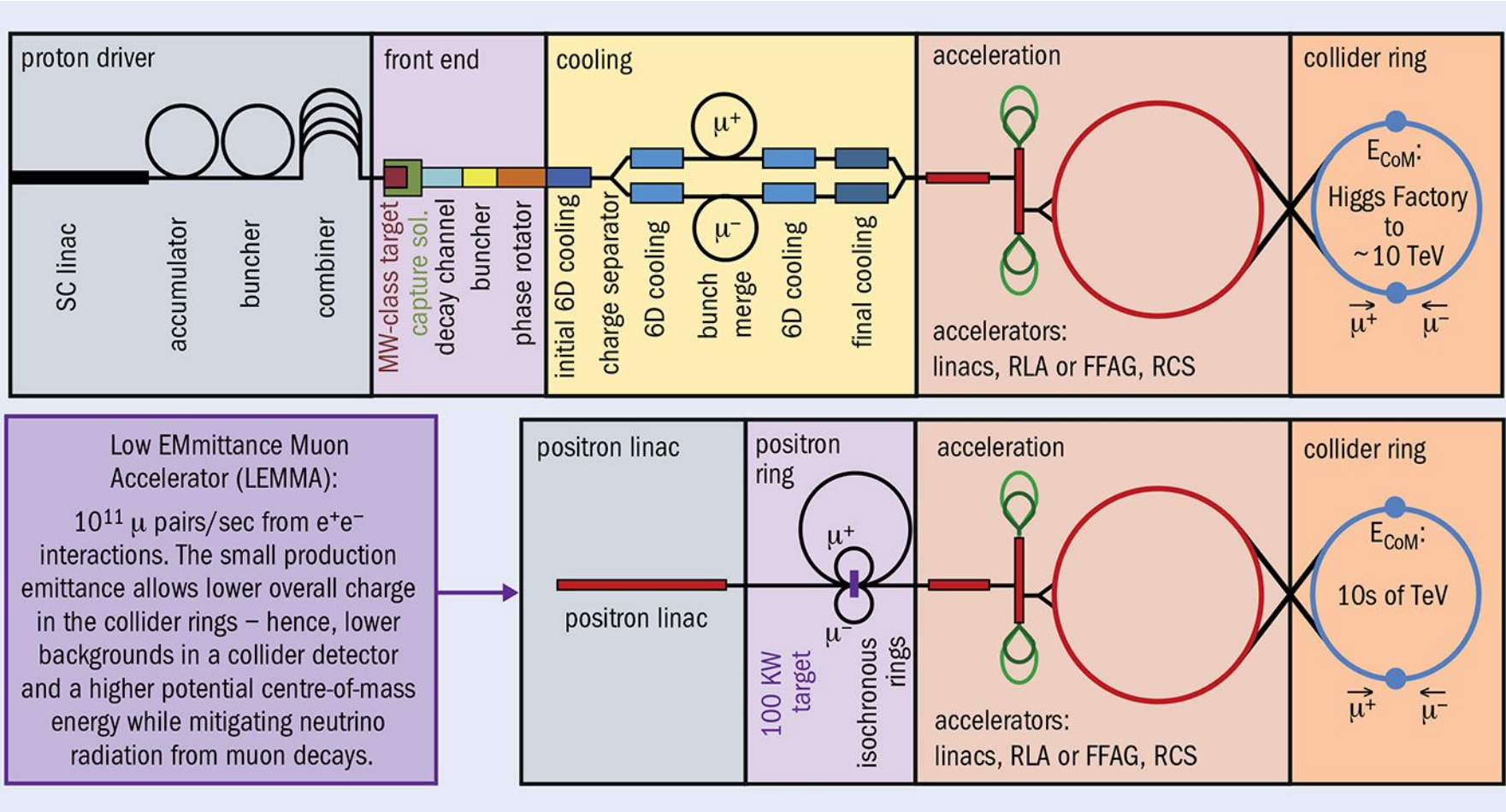
- Clean environment as electron collider
- Synchrotron radiation is smaller than electron $O(10^8)$
- High energy as Hadron collider

Limits:

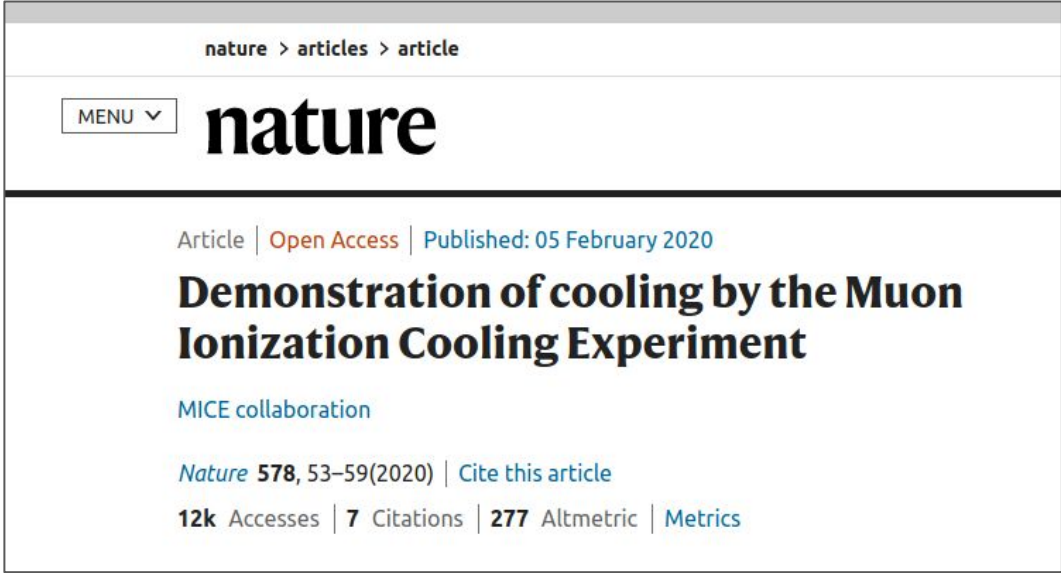
- Muon is unstable particle, lifetime at rest only 2.2 μs , high quality beam source is challenging (both on lumi and emittance)
- Beam-induced background is challenging



Muon Collider: Source



Muon Ionisation Cooling Experiment (MICE)



Tertiary production from protons on target: $p + \text{target} \rightarrow \pi/K \rightarrow \mu$
typically $P_\mu \approx 100 \text{ MeV}/c$ (π , K rest frame)
whatever is the boost P_T will stay in Lab frame
 \rightarrow **very high emittance** at production \rightarrow **cooling needed**
production Rate $> 10^{13} \mu/\text{sec}$ $N_\mu = 2 \cdot 10^{12}/\text{bunch}$ **MAP**

from **direct μ pair production**:
muons produced from $e^+e^- \rightarrow \mu^+\mu^-$ at \sqrt{s} around the $\mu^+\mu^-$ threshold
($\sqrt{s} \approx 0.212 \text{ GeV}$) in asymmetric collisions (to collect μ^+ and μ^-)
 e^+e^- annihilation: e^+ beam on target
 \rightarrow **cooled muon beam with low emittance** at production
Goal: production Rate $\approx 10^{11} \mu/\text{sec}$ $N_\mu \approx 6 \cdot 10^9/\text{bunch}$ **LEMMA**

	LEMMA	Protons on target (MAP)
Physical process	$e^+e^- \rightarrow \mu^+\mu^-$	$p N \rightarrow \pi X, KX \rightarrow \mu X'$
Luminosity [$\text{cm}^{-2}\text{s}^{-1}$]	$\sim 5 \times 10^{34}$	$\geq 10^{35}$
ϵ_N [$\mu\text{m-rad}$]	0.04	25
Rate N_μ/s	0.9×10^{11}	10^{13}
N_μ/bunch	6×10^9	2×10^{12}
$\Delta E/E$ [%]	0.07	0.1

Muon Collider: BIB

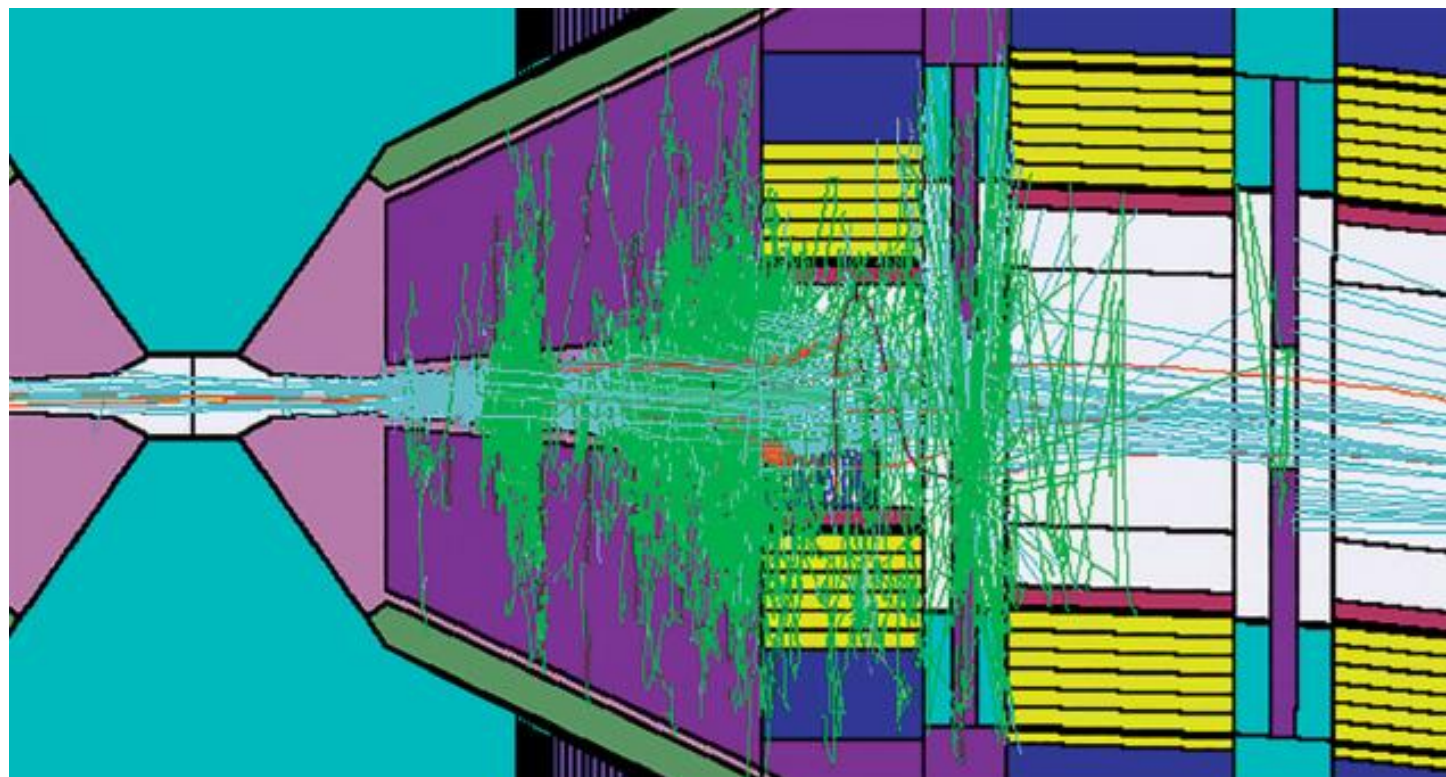
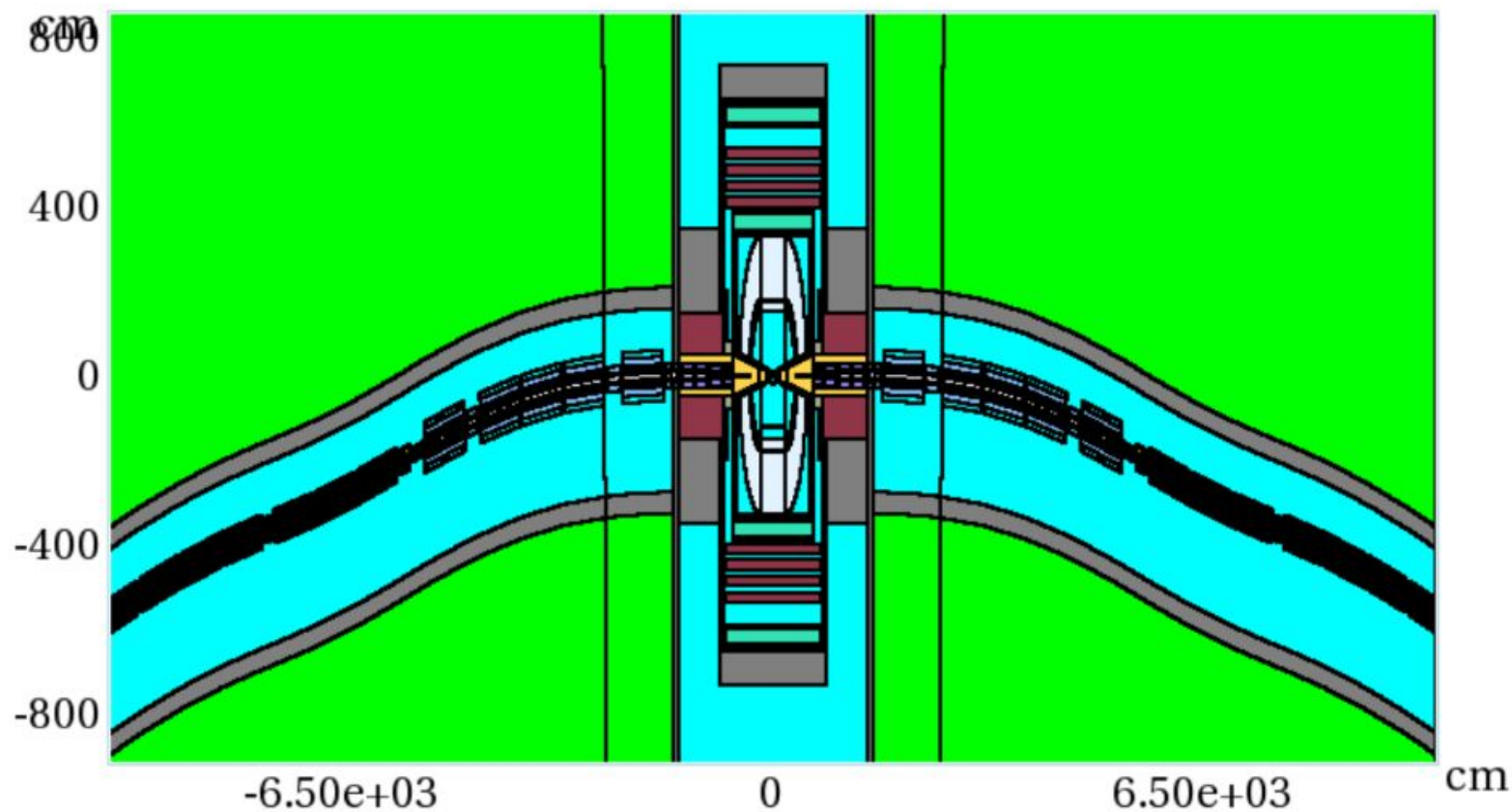


illustration of the model built for the MARS15 simulation in a range of ± 100 m around the interaction point. It includes the machine components in the tunnel and the ILC 4th concept detector with the CMS-type tracker upgraded for the High-Luminosity LHC phase. **The shielding nozzles are represented in yellow inside the detector, which is used to suppress the BIB.** [Link](#)

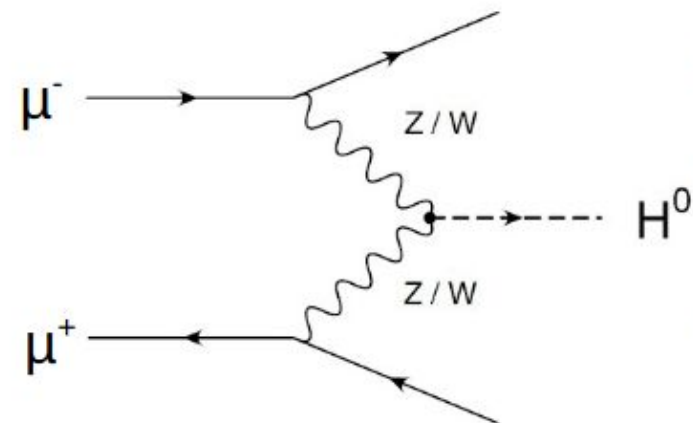
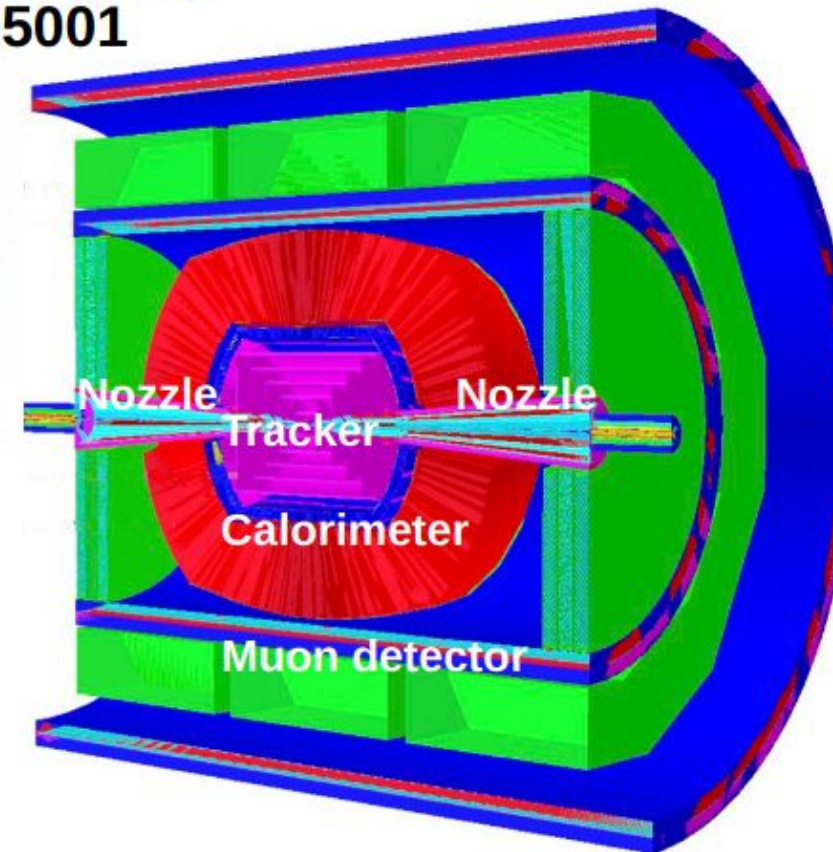
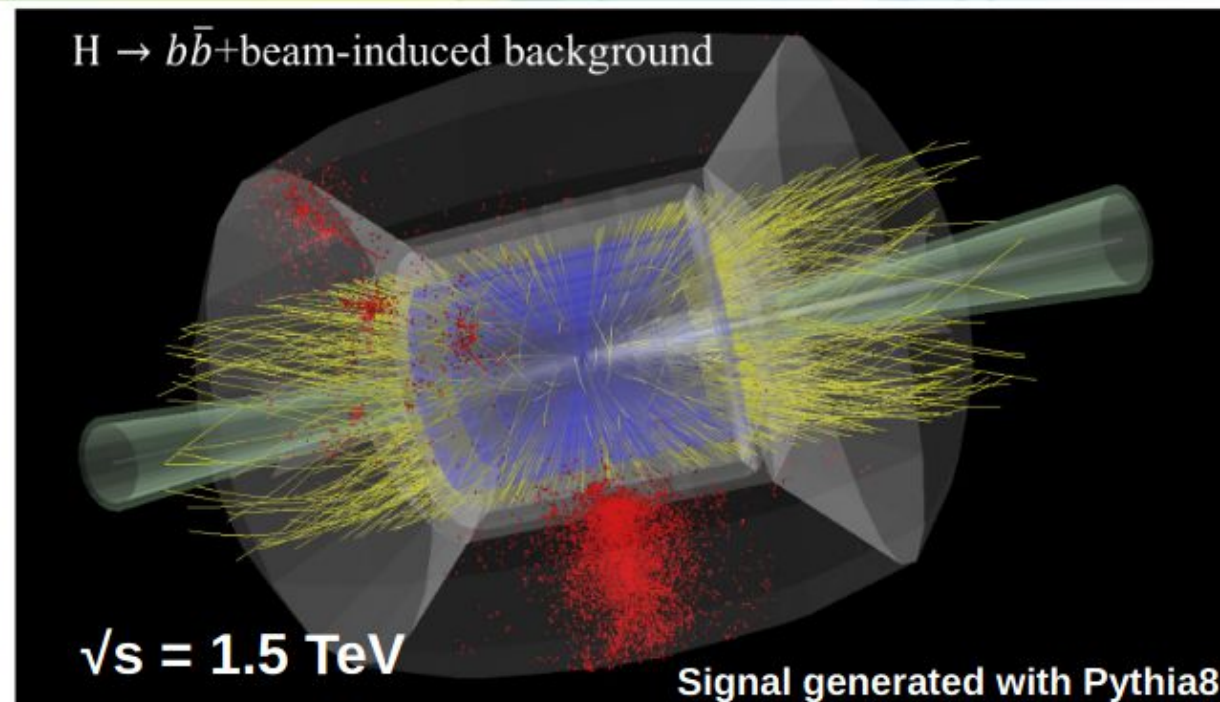
Zoom in the IP region, tracker of charged particle from muon decay.

Muon Collider: Higgs physics



$$\mu^+ \mu^- \rightarrow \nu \bar{\nu} H(\rightarrow b \bar{b})$$

2020 JINST 15 P05001



- We studied the $\mu\mu \rightarrow \nu\nu H(\rightarrow b\bar{b})$ production at a MC
- The goal is to determine the **sensitivity to the cross section measurement and to the Hbb coupling determination**
- In the full simulation (Geant4) we used the detector developed by the MAP collaboration \rightarrow not optimized for the full event reconstruction

7

At multi-TeV, a muon collider is basically a W+W-collider (VBS type): it will be possible to produce high yields of single H, HH and HHH events.

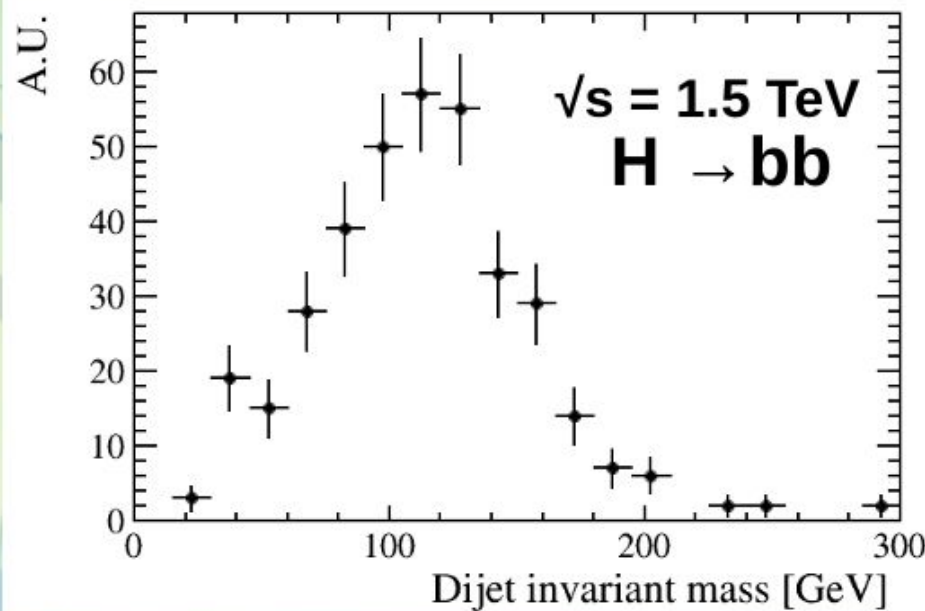
Lorenzo Sestini
@ICHEP2020, [link](#)

Muon Collider: Higgs physics



Cross section and Hbb coupling

2020 JINST 15 P05001



Two b-tagged jets with $p_T > 40 \text{ GeV}$, $|\eta| < 2.5$ are selected

Physics backgrounds

Process
$\mu^+ \mu^- \rightarrow \gamma^*/Z \rightarrow q\bar{q}$
$\mu^+ \mu^- \rightarrow \gamma^*/Z \gamma^*/Z \rightarrow q\bar{q} + X$
$\mu^+ \mu^- \rightarrow \gamma^*/Z \gamma \rightarrow q\bar{q} \gamma$

- As a conservative approach we applied the efficiencies obtained at $\sqrt{s} = 1.5 \text{ TeV}$ to the 3.0 and 10 TeV case → **BUT** the BIB yield is expected to be lower at higher energies.

- We assumed **4 Snowmass years of data taking**, at the luminosities expected by MAP.

- Cross section sensitivity obtained with $\frac{\Delta\sigma}{\sigma} \simeq \frac{\sqrt{N+B}}{N}$,

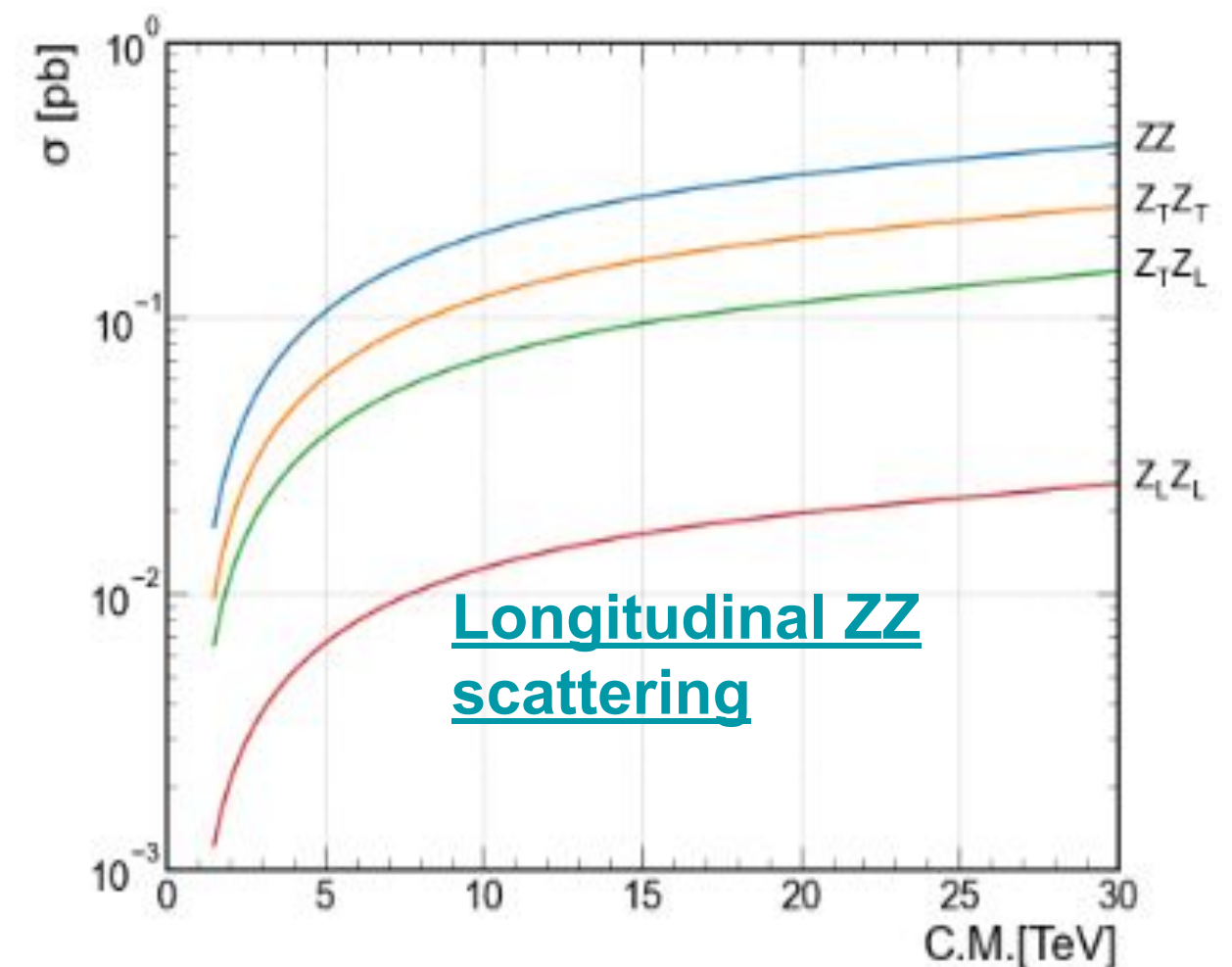
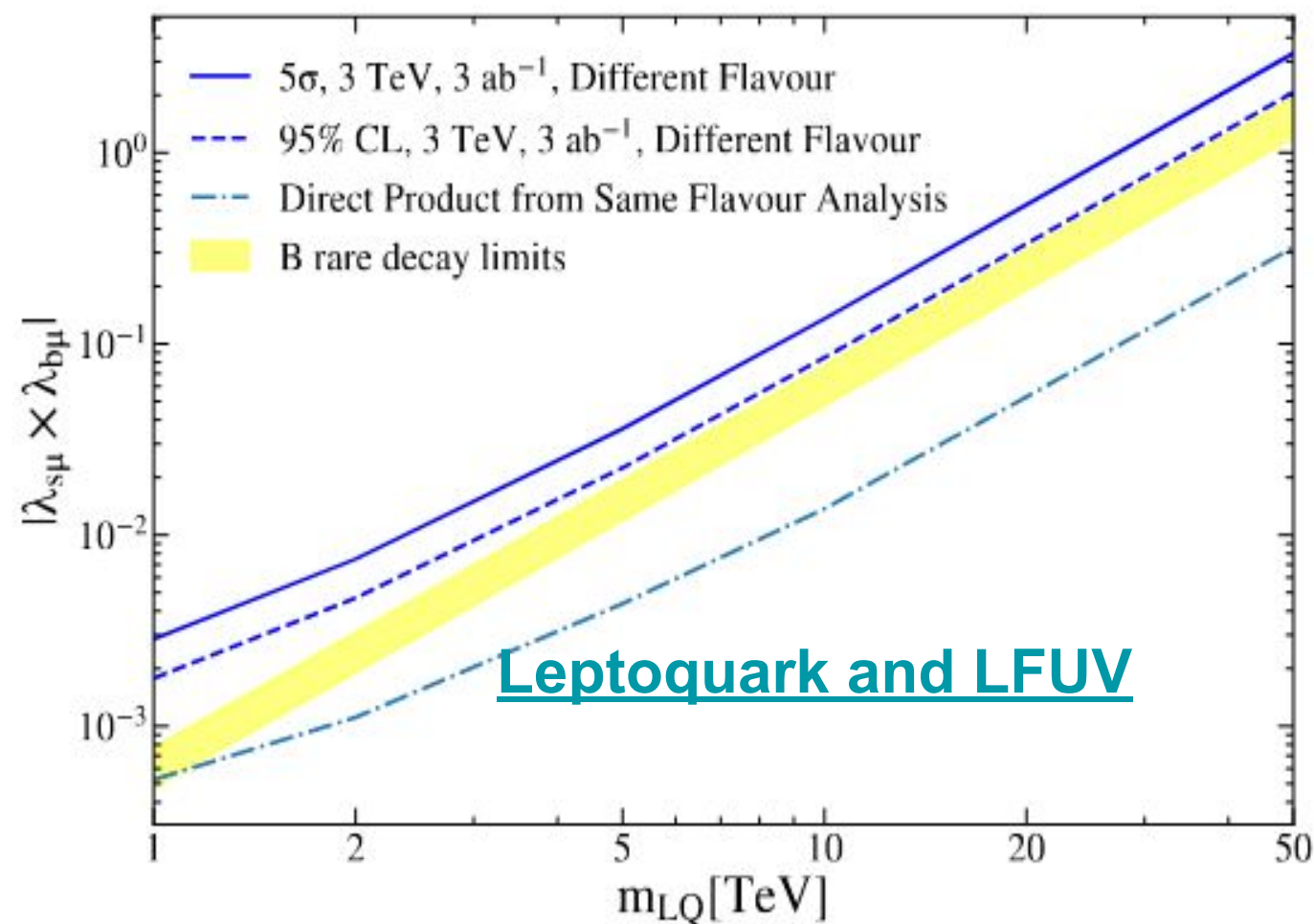
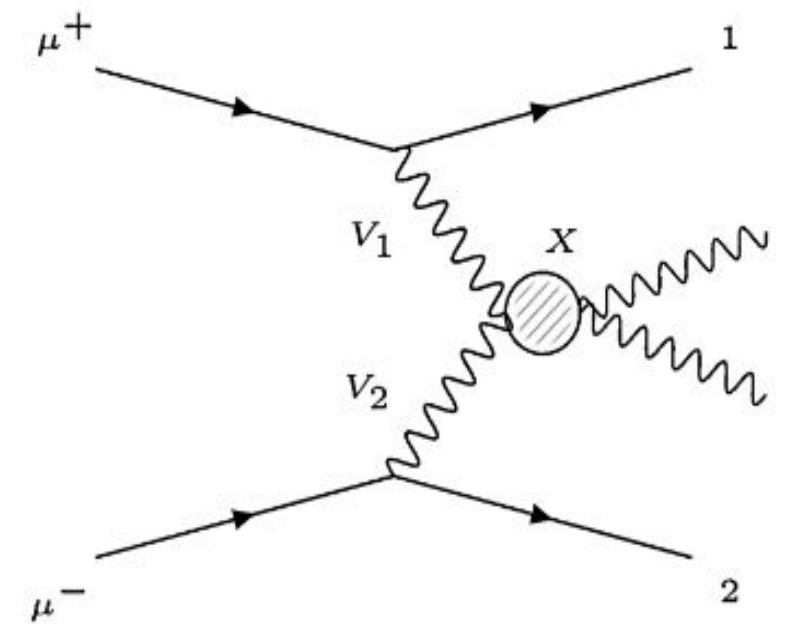
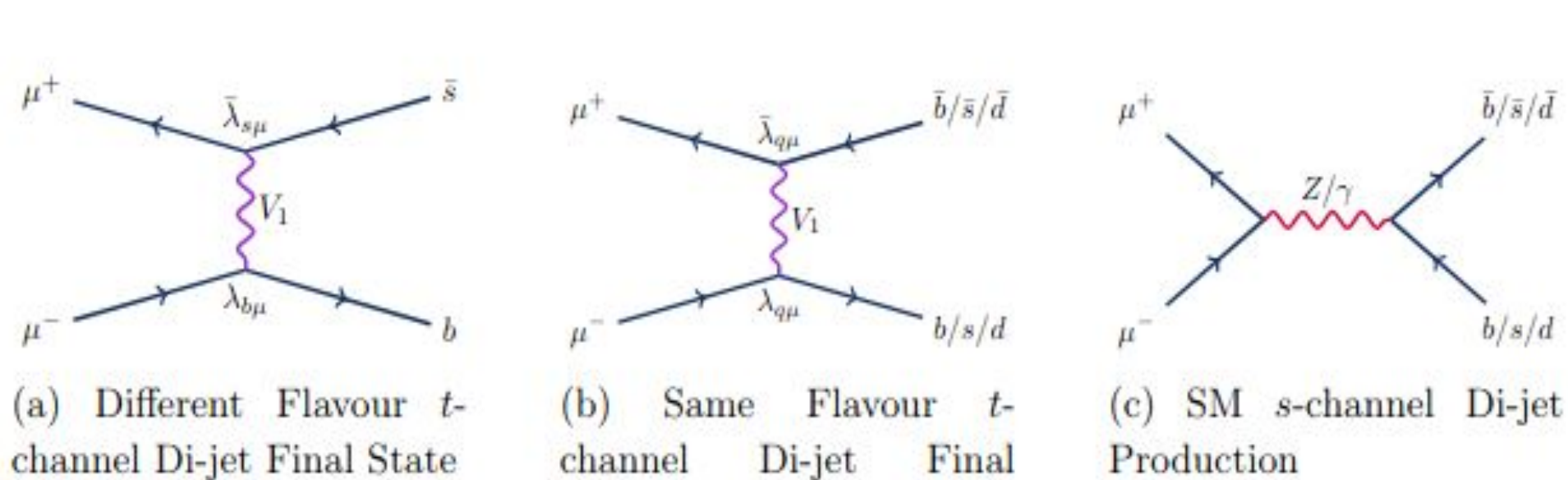
- Hbb coupling sensitivity $\frac{\Delta g_{Hbb}}{g_{Hbb}} = \frac{1}{2} \sqrt{\left(\frac{\Delta\sigma}{\sigma}\right)^2 + \left(\frac{\Delta \frac{g_{HWW}^2}{\Gamma_H}}{\frac{g_{HWW}^2}{\Gamma_H}}\right)^2}$ → Taken from CLIC expectation

\sqrt{s} [TeV]	A [%]	ϵ [%]	\mathcal{L} [cm ⁻² s ⁻¹]	\mathcal{L}_{int} [ab ⁻¹]	σ [fb]	N	B	$\frac{\Delta\sigma}{\sigma}$ [%]	$\frac{\Delta g_{Hbb}}{g_{Hbb}}$ [%]
1.5	35	15	$1.25 \cdot 10^{34}$	0.5	203	5500	6700	2.0	1.9
3.0	37	15	$4.4 \cdot 10^{34}$	1.3	324	33000	7700	0.60	1.0
10	39	16	$2 \cdot 10^{35}$	8.0	549	270000	4400	0.20	0.91

At 3 TeV the Hbb coupling sensitivity is compatible with the one expected by CLIC, but very conservative assumptions have been done!

Lorenzo Sestini
@ICHEP2020,
[link](#)

More on Muon Collider

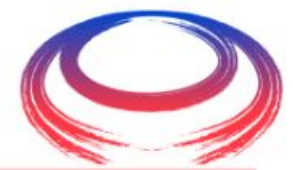


International Muon Collider Collaboration

https://ipac2022.vrws.de/talks/tuizsp2_talk.pdf



MoC and Design Study Partners



IEIO	CERN
FR	CEA
	CNRS-LNCMI
DE	DESY
	Technical University of Darmstadt
	University of Rostock
	KIT
IT	INFN
	University of Milano
	University of Padova
	University of Pavia
	University of Bologna
	ENEA
CH	PSI
	University of Geneva

D. Schulte

UK	STFC-RAL
	UK Research and Innovation
	University of Lancaster
	University of Southampton
	University of Strathclyde
	University of Sussex
	Imperial College
	Royal Holloway
	University of Huddersfield
	University of London
	JAI
	University of Oxford
	University of Warwick
SE	ESS
	University of Uppsala

Muon Collider, IPAC, June 2022

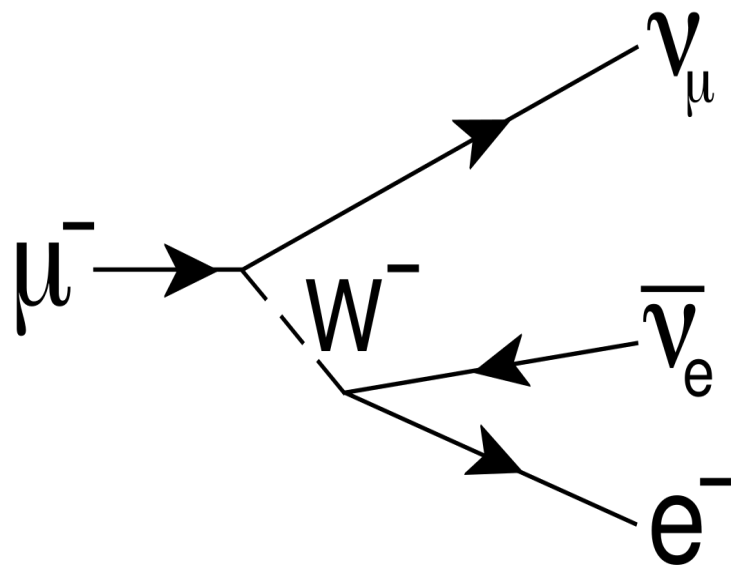
PT	LIP
NL	University of Twente
FI	Tampere University
US	Iowa State University
	BNL
China	Sun Yat-sen University
	IHEP
	Peking University
EST	Tartu University
LAT	Riga Technical Univers.
AU	HEPHY
ES	I3M

CHART is contributing (and EPFL)
Informal contributions (US, Japan)

Note: some MoC still being processed

Neutrino beam

B. J. King hep-ex/0005007



[NuTeV](#)

Neutrino-Nucleon Scattering

[NuMAX](#)

[NuSOnG](#)

Neutrino Scattering on Glass

[nuSTORM](#)

"Neutrinos from STORed Muons," ...for neutrino oscillation searches

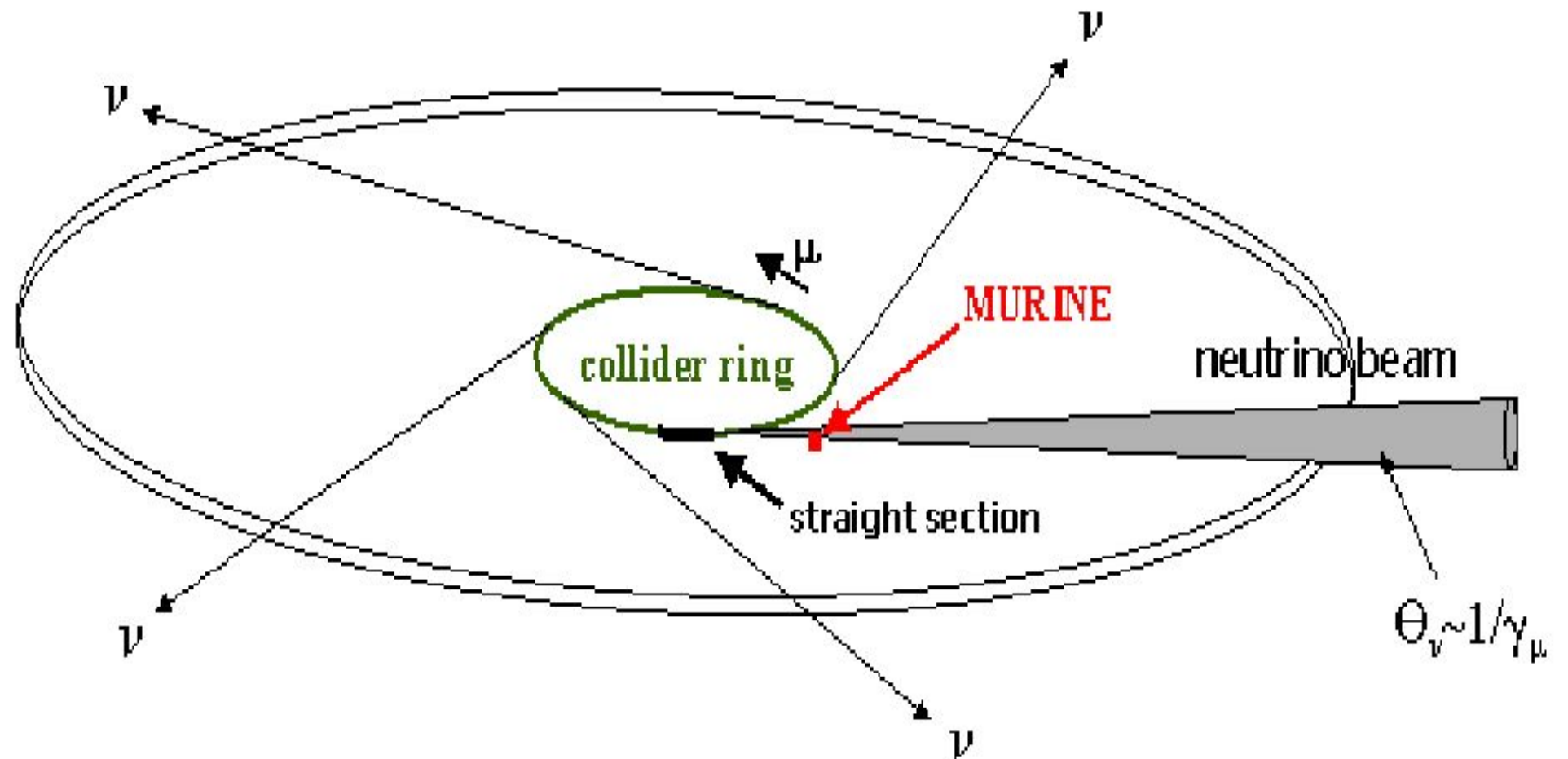
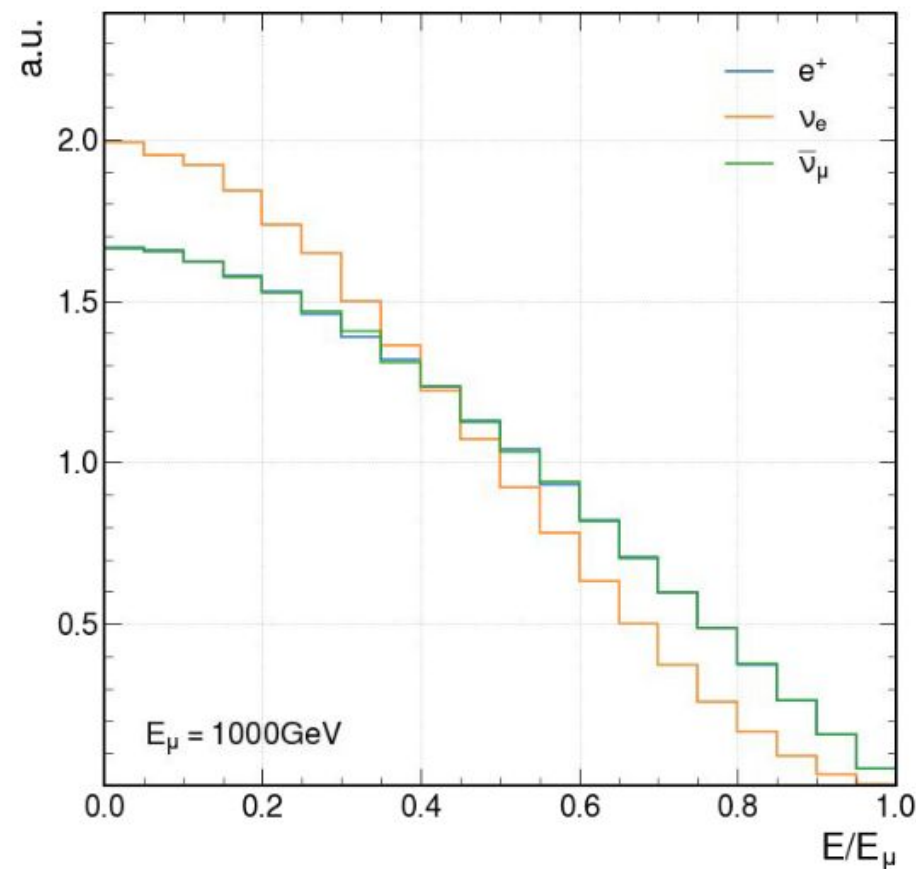
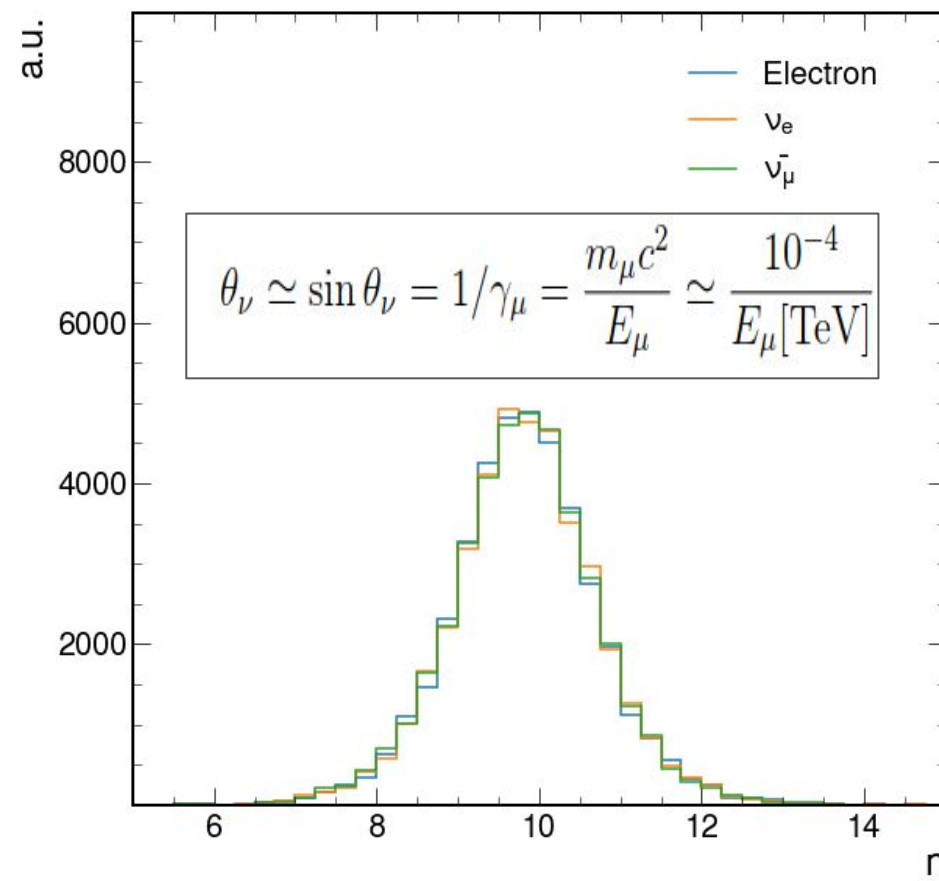


FIGURE 1. The decays of muons in a muon collider will produce a disk of neutrinos emanating out tangentially from the collider ring. The neutrinos from decays in straight sections will line up into beams suitable for experiments. The MURINEs will be sited in the center of the most intense beam and as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

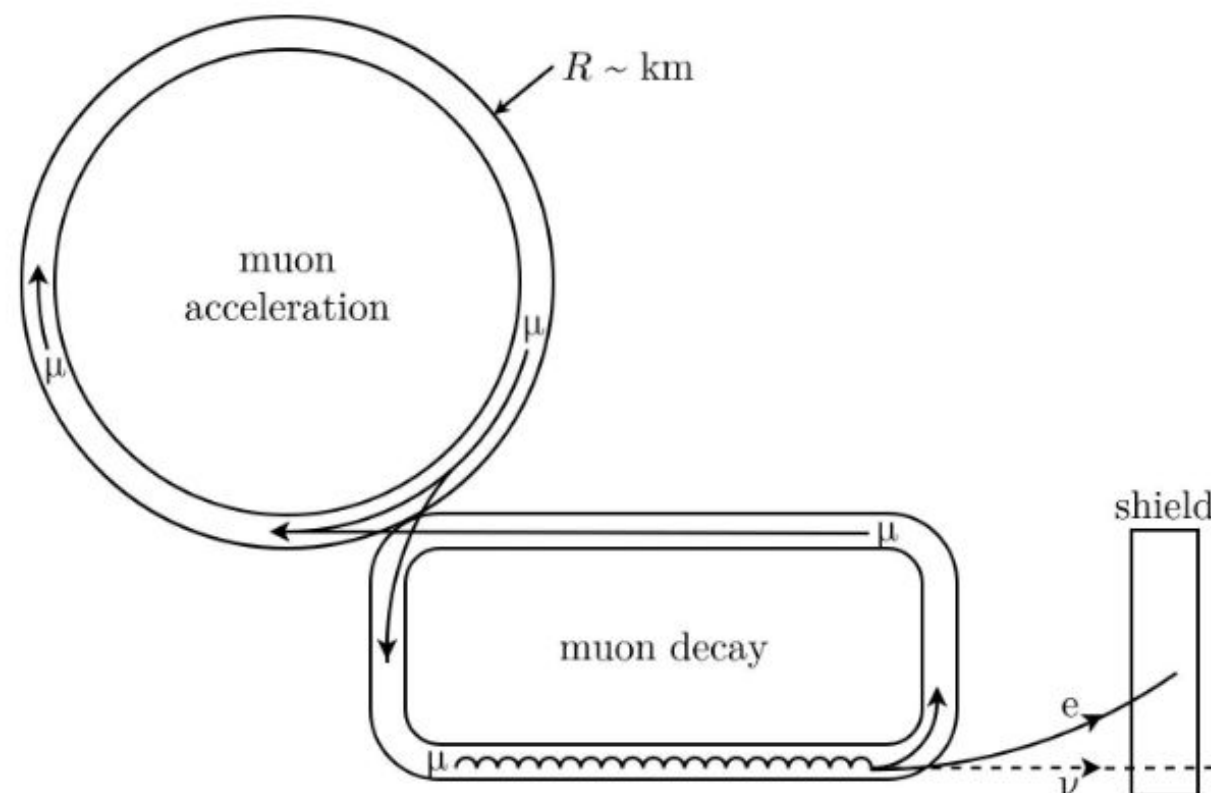
很多中微子打靶实验, 但是没有head-on对撞构想

Neutrino Beam from 1 TeV Muon beam



“Parton Distribution Function”
Included in MadGaph

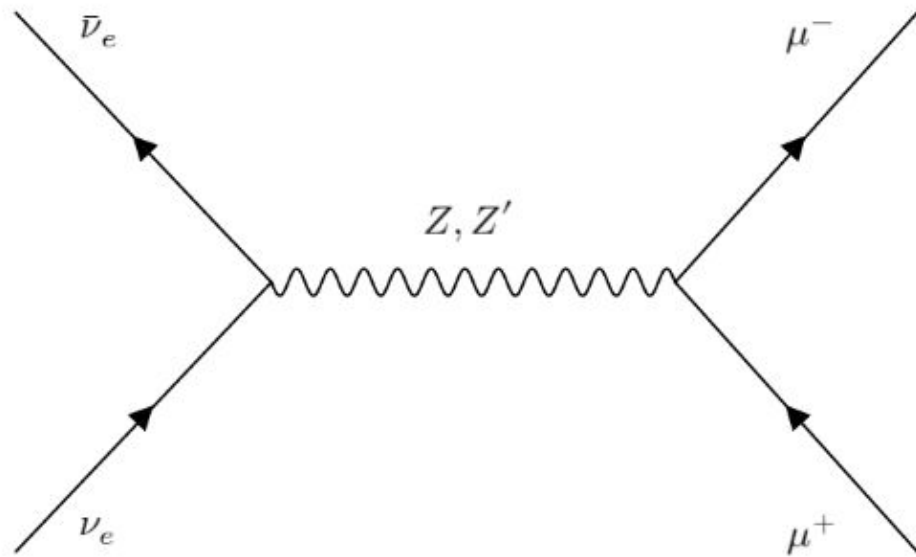
Highly **collimated** in angle,
yet widely distributed in
Energy



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

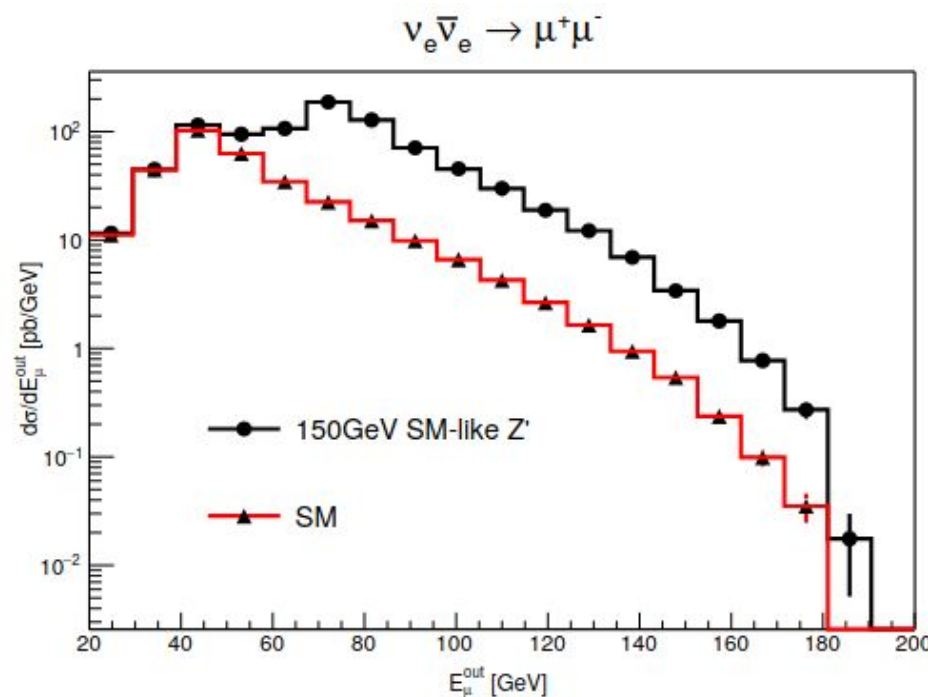
[Link](#)

Neutrino collision: neutrino annihilation



Neutrino annihilation could be served as a vector boson collider.

$$\begin{aligned} \nu_e \bar{\nu}_e &\rightarrow HH \\ \nu_e \bar{\nu}_e &\rightarrow ZZ, ZH \\ \nu_e \bar{\nu}_e &\rightarrow \nu_e \bar{\nu}_e H, \\ \nu_e \bar{\nu}_e &\rightarrow \nu_e \bar{\nu}_e ZZ, \nu_e \bar{\nu}_e WW, \\ \nu_e \bar{\nu}_e &\rightarrow \nu_e \bar{\nu}_e ZH, \nu_e \bar{\nu}_e HH, \\ \nu_e \bar{\nu}_e &\rightarrow e^- e^- W^+ W^+, \end{aligned}$$

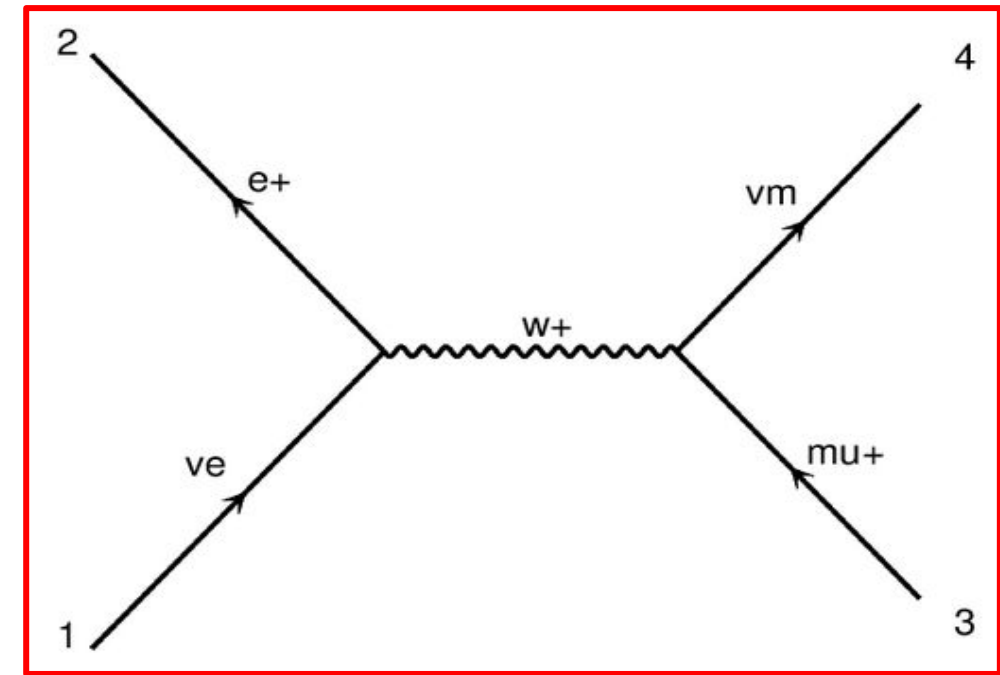
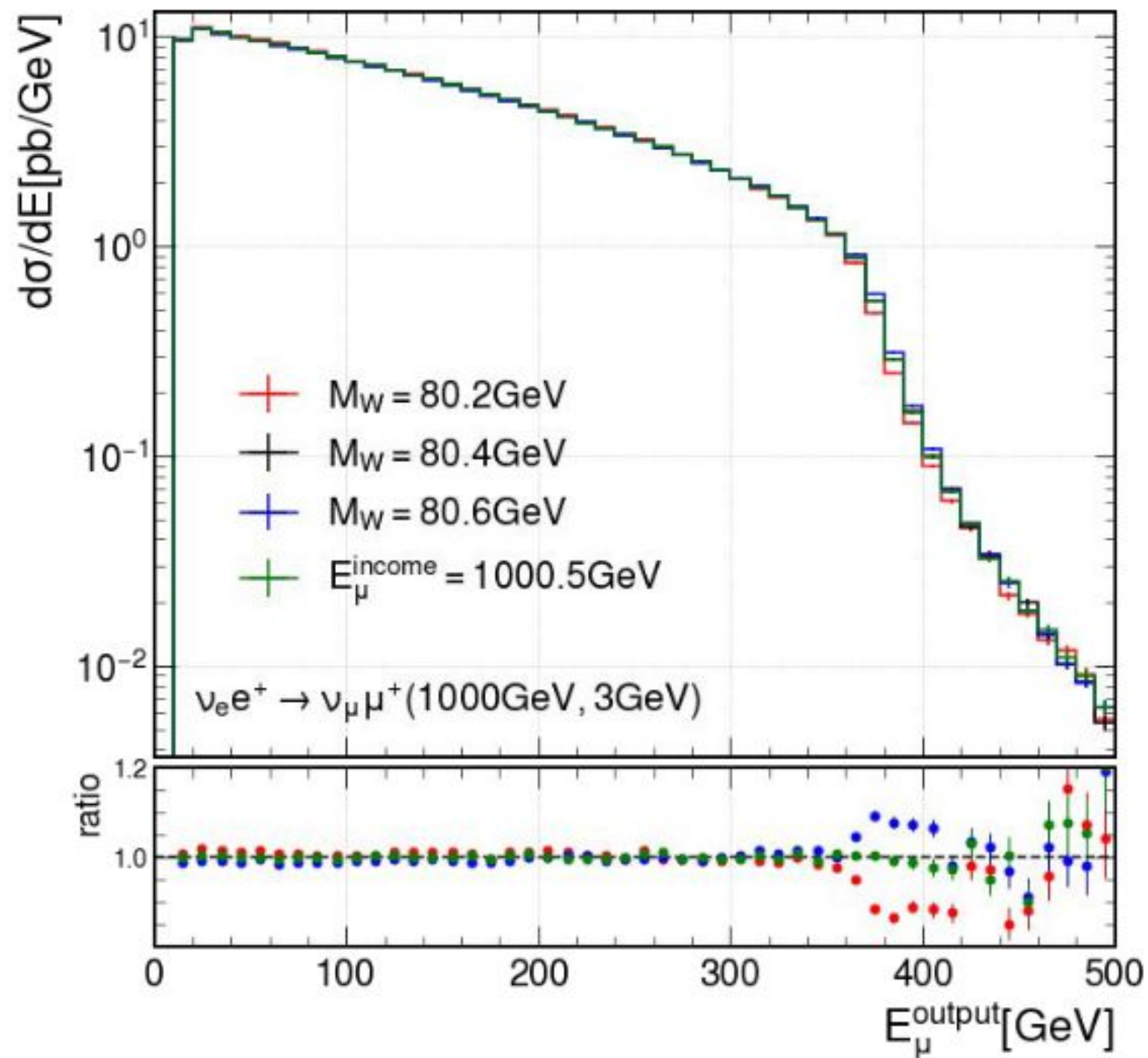


Simplest neutrino mass origination: dimension-5 Weinberg operator, which lead Majorana neutrino masses and introduce lepton number violation. So we can use $\nu\nu HH$ (t-channel Majorana neutrino) to study the BSM.

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

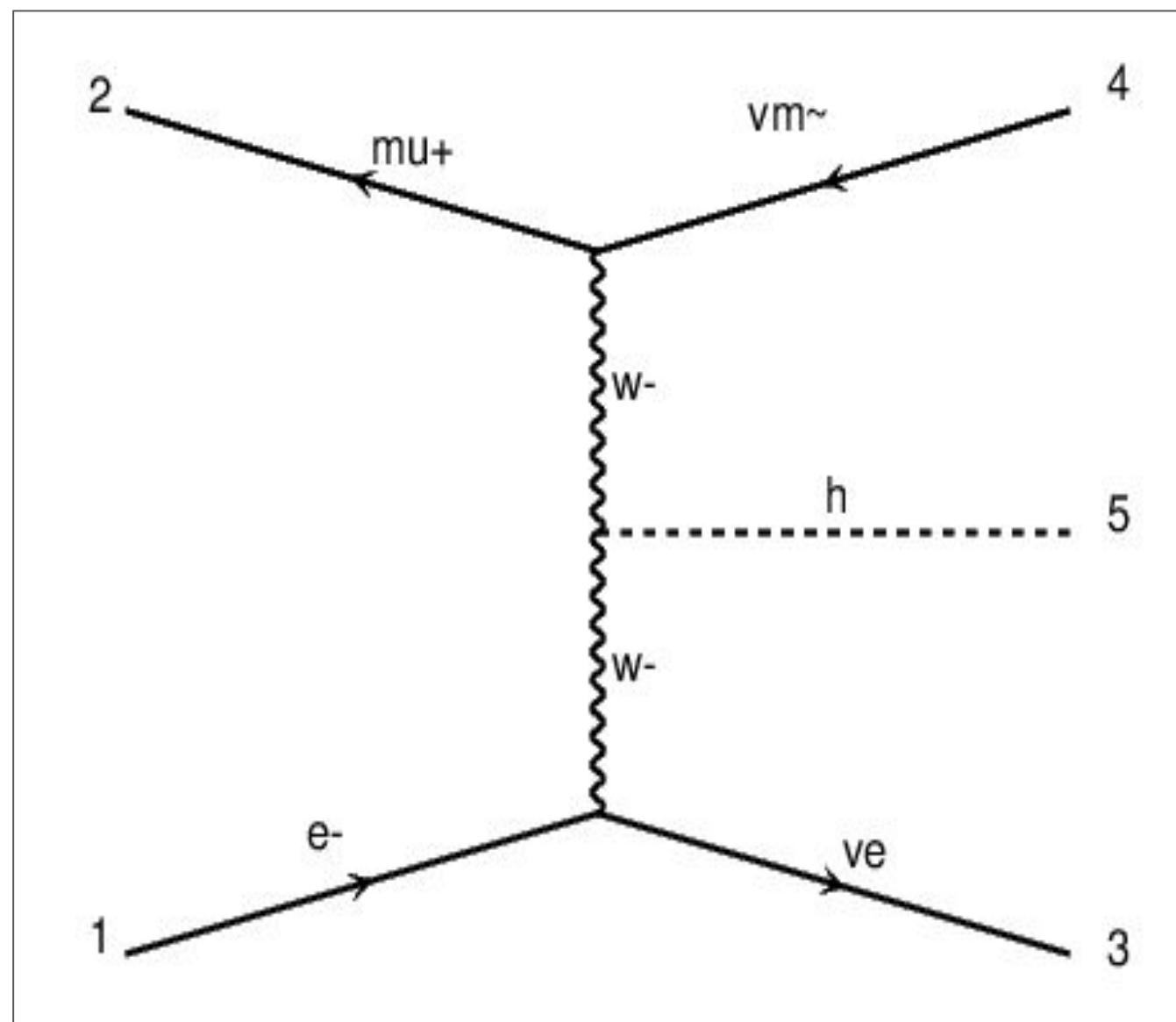
$$m_{\ell\ell} = C_5^{\ell\ell} v^2 / \Lambda$$

Neutrino collision: neutrino-lepton collision



If $p_T(\text{outgoing muon}) > 40 \text{ GeV}$
the cross sections with **$M_W = 80.4$ (80.41)**
are 166.2 (167.6) pb.

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



- 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!



《欧洲核子研究中心快报》创刊于1959年，是欧洲核子研究中心报道全球高能物理重要进展的期刊。

NEWS DIGEST



BASE's Jack Devlin alongside the experiment's superconducting magnet.

Unorthodox ALP antenna

The Baryon Antibaryon Symmetry Experiment (BASE) collaboration at CERN's Antiproton Decelerator has demonstrated an ingenious new way to search for axion-like particles (ALPs, see p25). The team looked for unexpected electrical signals in doughnut-shaped superconducting coils that are usually used to precisely measure the oscillation frequencies of individual trapped antiprotons. Faint signals, which might easily be mistaken for noise, could in fact be caused by ALPs interacting with the strong magnetic field of the Penning trap. The collaboration set a new upper laboratory limit for the coupling between photons and ALPs within a narrow mass range around 2.79 neV, demonstrating the feasibility of using Penning traps to search for cold dark matter (Phys. Rev. Lett. **126** 041301).

Dark-age detectors

Valerie Domcke (CERN) and Camilo Garcia-Cely (DESY) have proposed using radio telescopes to detect high-frequency gravitational waves (GWs) from the "dark ages" – the period in the early universe between atoms forming and stars igniting (Phys. Rev. Lett. **126** 021104). As a result of embedding classical electrodynamics in general relativistic spacetime, it is expected that GWs can be converted into photons in the presence of magnetic fields, leading to a distortion of the

cosmic microwave background. Data from the Square Kilometer Array, which may begin construction in South Africa and Australia as early as this year, could allow the detection of GWs with frequencies in the MHz and GHz regime, far beyond the reach of LIGO, VIRGO or KAGRA, write the pair.

Industrial innovation

DESY virtually kicked-off a new "innovation factory" late last year, allowing detailed planning for the building's infrastructure to begin. The facility will offer laboratories and spaces for start-ups, scientists and established corporations, in the hope of building strong ties between research and industry. Construction is proposed to begin in 2023, with completion aimed for 2025. Science City Bahrenfeld, a new district in Hamburg, Germany, where the facility will be built, is also home to DESY's PETRA III synchrotron X-ray source.

Cosmic rays get weirder

Results from the Alpha Magnetic Spectrometer (AMS-02) on the International Space Station have thrown up another surprise that may shed light on the processes that create and accelerate cosmic rays. Last year, the collaboration reported unexpected differences in the rigidity (momentum

of the spectrum of iron – the rarest and heaviest cosmic ray to be characterised so far – unexpectedly resembles the light elements more than the heavier ones (Phys. Rev. Lett. **126** 041904). "Iron is an atomic-number frontier that won't be crossed for years to come," said AMS-02 spokesperson Sam Ting.

Snowmass postponed

The summer study of the 2021 Snowmass exercise has been postponed one year to July 2022, due to the ongoing COVID-19 pandemic. The community exercise, which will plot a course for US particle physics over the coming decade, was originally planned for this summer. First convened in 1982 in the Colorado mountain resort of the same name, Snowmass studies have been produced on numerous occasions throughout the years, most recently in 2013. More than 1500 letters of intent – an unusually large number – have already been submitted across 10 "Snowmass frontiers", from the energy frontier to community engagement.

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.

32 is not a magic number

A study at CERN's ISOLDE facility has exposed shortcomings in the best nuclear models,

which cannot reconcile recent measurements of neutron-rich nuclei. 32 had been thought to be a "magic" number of neutrons that completes a nuclear shell and results in a slimmer nucleus with a greater binding energy than its neighbours. However, researchers using the Collinear Resonance Ionisation Spectroscopy apparatus found that potassium-52, which has 33 neutrons, was not observably fatter than the supposedly magic potassium-51, which boasts 39 protons and 32 neutrons (Nat. Phys. doi:10.1038/s41567-020-01136-5).

Rival probes approach Mars

As the Courier went to press, probes from the United Arab Emirates (UAE), China and the



The first image of Mars sent by China's Tianwen-1 probe.

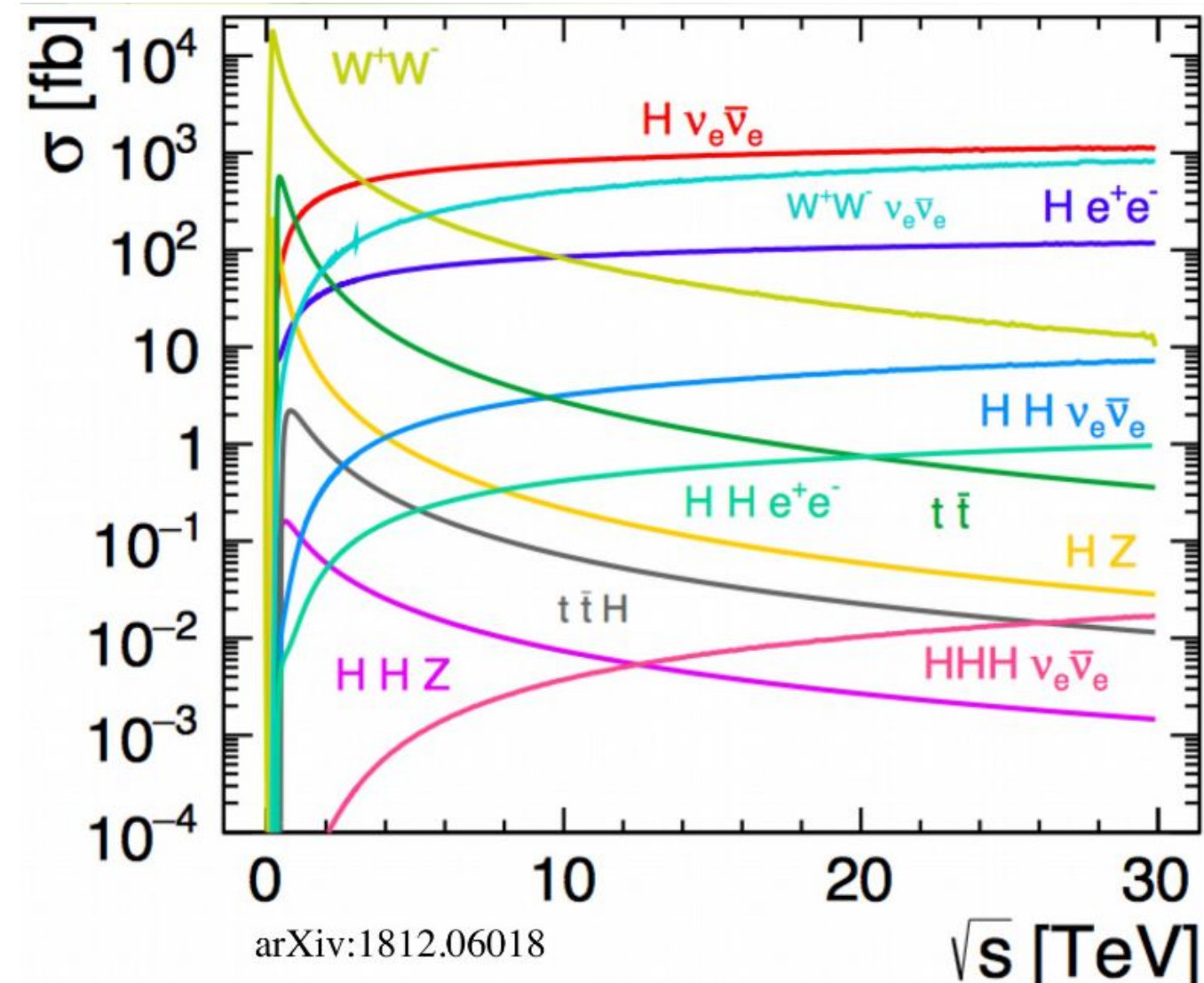
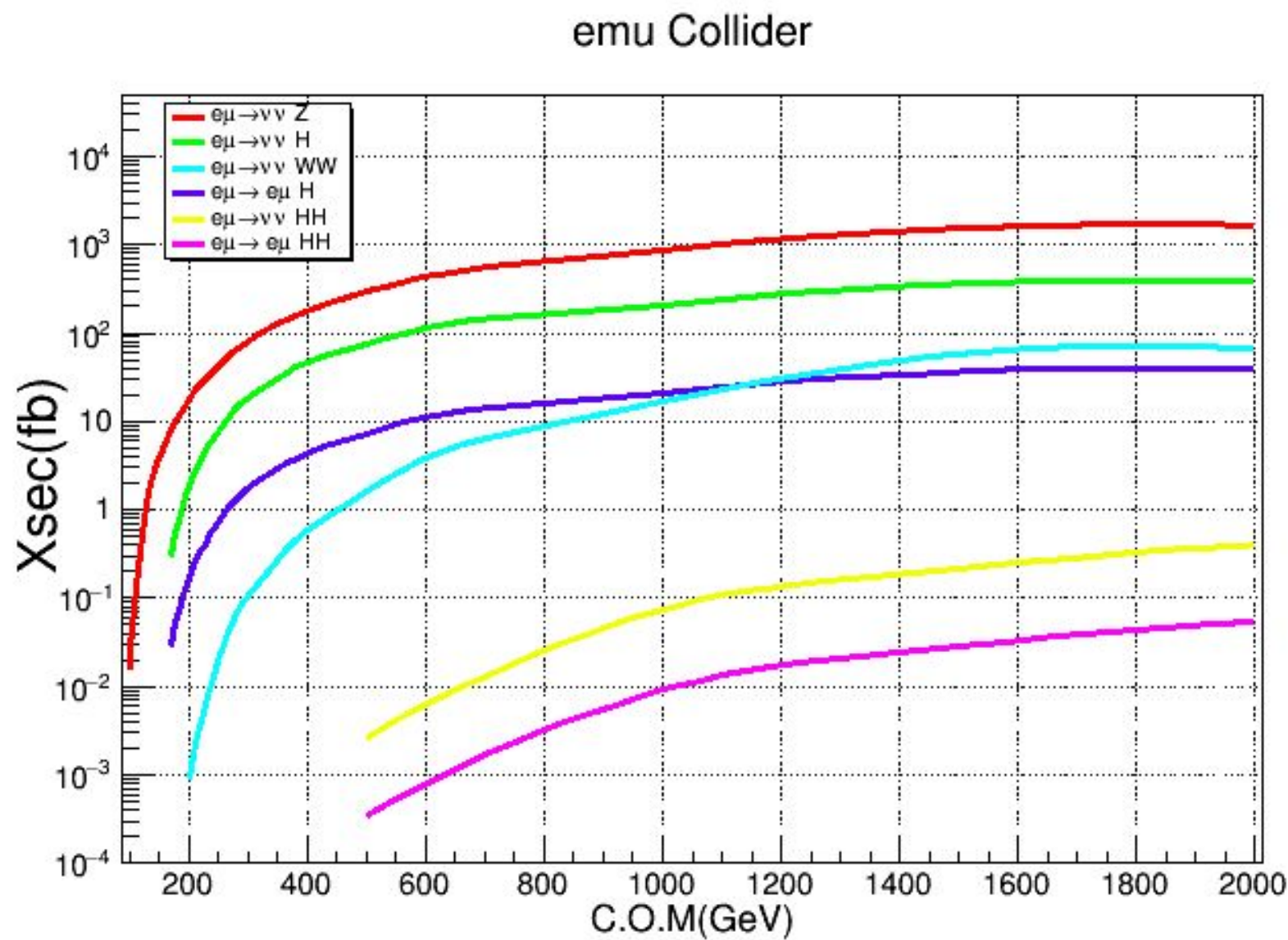
were approaching the Red Planet – a testament to the growing desire of many nations to develop space technology and explore the solar system. The UAE's Hope – the Arab world's first interplanetary spacecraft – will remain in orbit and make the first map of Mars' surprisingly sparse atmosphere. China's Tianwen-1 will study the planet for several months before dropping a lander, potentially making China only the second nation in the world to successfully land a robot vehicle on another world, after the US. The US rover Perseverance will descend to the planet's surface in search of signs of habitability and evidence of microbial life.

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“北京大学物理学家呼吁学界考虑一种新型的电子缪子对撞机及其带来的好处 (arXiv:2010.15144)。不同种类轻子的对撞，可压低物理本底，从而可以(更好地)研究带电轻子味道破坏以及希格斯玻色子的性质。作者认为，不对称的对撞能量构型，可控制加速器中缪子衰变带来的讨厌的本底。该预印本提议可从10GeV能级的电子和缪子束流开始，最终升级直至TeV能级的缪子—缪子对撞机。”

electron-muon collider: physics



- A vector boson scattering/fusion machine
- No s-channel SM background

mu-mu collider

electron-muon collider: Energy benchmark

(Benchmark\G eV)	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. $e\mu \rightarrow \nu\nu Z$.

Higgs $\sigma_{\text{sec}} \sim 210\text{fb}$ at CEPC@250GeV.

electron-muon collider: Higgs property

$$\sigma = \sigma(\nu\nu H) \cdot BR(H \rightarrow b\bar{b}) = \frac{g_{HWW}^2 g_{Hbb}^2}{\Gamma_H}$$

$$\frac{\Delta g_{Hbb}}{g_{Hbb}} = \frac{1}{2} \sqrt{\left(\frac{\Delta\sigma}{\sigma}\right)^2 + \left(\frac{\Delta \frac{g_{HWW}^2}{\Gamma_H}}{\frac{g_{HWW}^2}{\Gamma_H}}\right)^2} \quad \frac{\Delta\sigma}{\sigma} \simeq \frac{\sqrt{N+B}}{N},$$

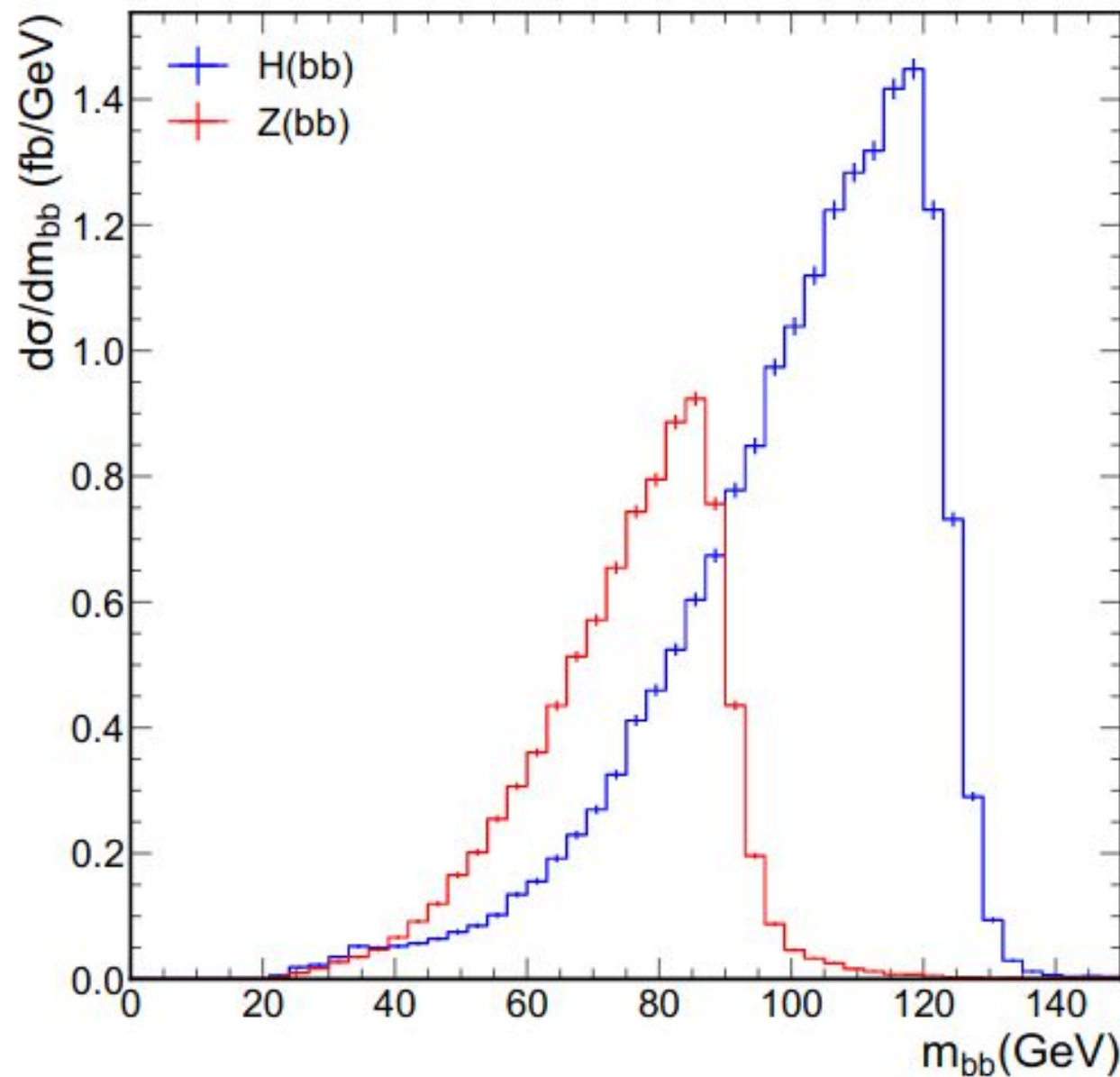
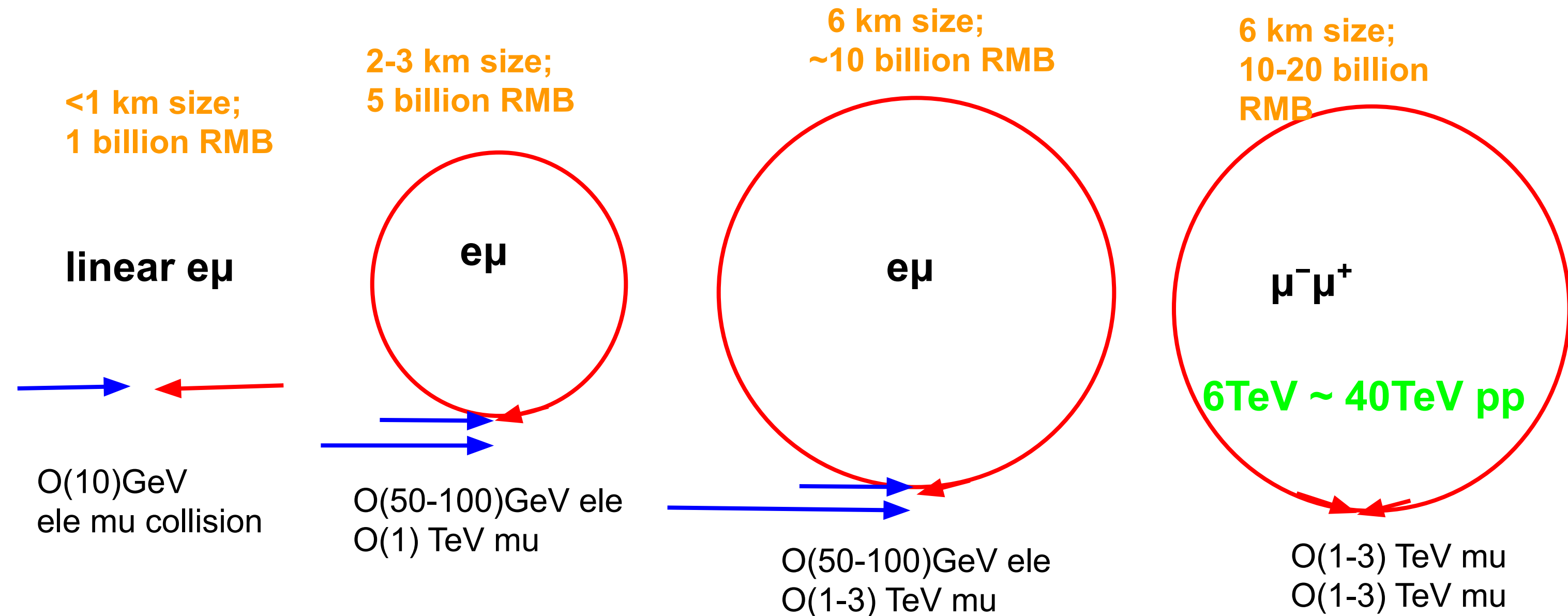


TABLE I: Summary of the parameters used in the estimation of the Higgs boson coupling to b-quarks in different collision schemes. The uncertainty on g_{HWW}^2/Γ_H is set to 3% in all collision schemes. $\sqrt{s} = 447.2(1095.3)$ GeV corresponds to a 50(100) GeV electron beam and a 1(3) TeV muon beam.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

$\mathcal{L}_{\text{int}}[ab^{-1}]$	$\sqrt{s}[\text{GeV}]$	$\frac{\Delta\sigma}{\sigma}[\%]$	$\frac{\Delta \frac{g_{HWW}^2}{\Gamma_H}}{\frac{g_{HWW}^2}{\Gamma_H}}[\%]$	$\frac{\Delta g_{Hbb}}{g_{Hbb}}[\%]$
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 g_{Hbb} 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 g_{HWW} .

electron-muon collider: Facility and cost



LFV, Higgs, majorana neutrino

$\sim 10-20$ billion RMB in total to reach physics hopefully \sim CEPC + half-SPPC

Summary

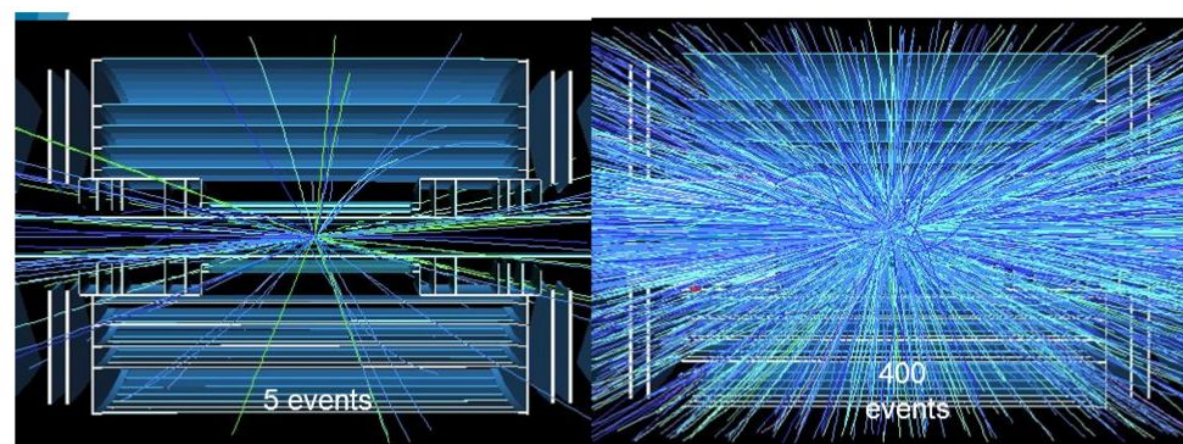
- **An neutrino-neutron collider is quite sensitive to neutrino physics**
 - Several days of run to observe neutrino annihilation
- **An neutrino-lepton collider is quite sensitive to W mass**
 - 10MeV accuracy with 0.1/fb!
- **An electron-muon collider is sensitive to CLFV and Higgs Physics**



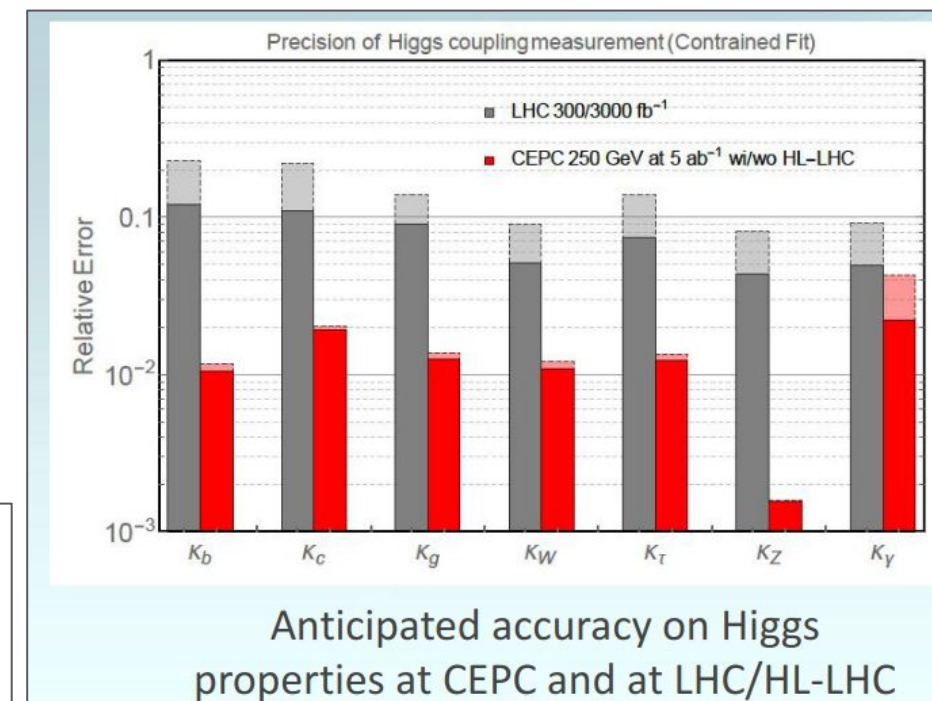
- **These colliders are both novel ideas in themselves, and may also be useful intermediate steps, with less muon cooling required, towards the muon-muon collider.**

Additional slides

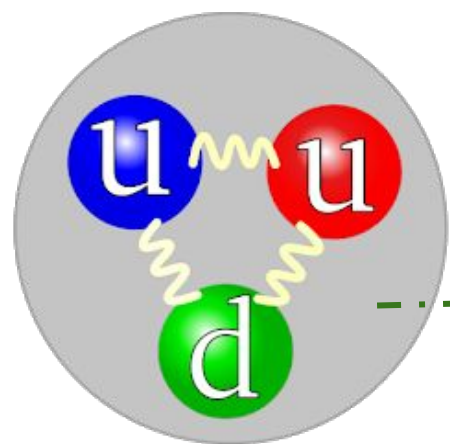
(HL-)LHC: busy environment



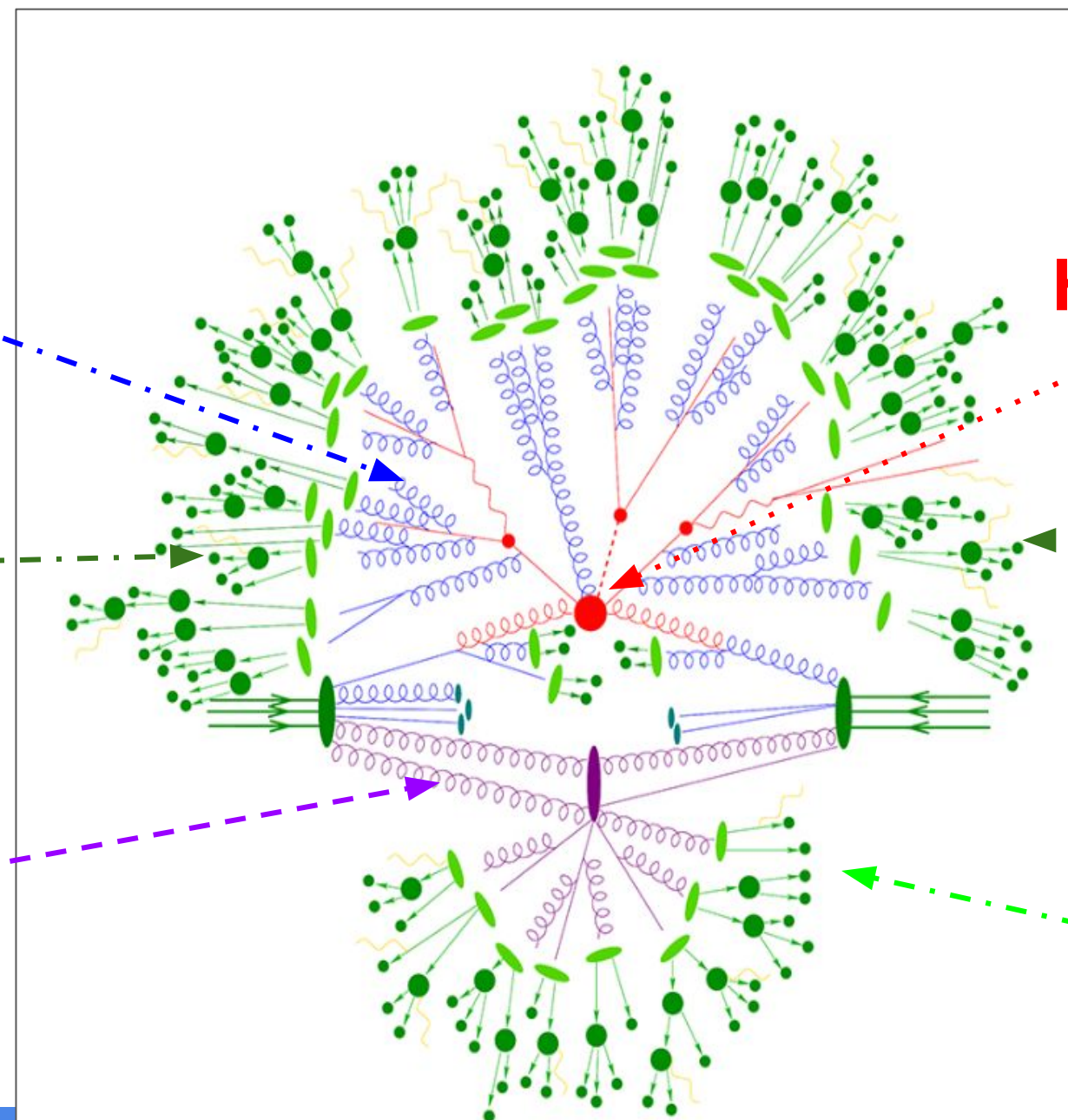
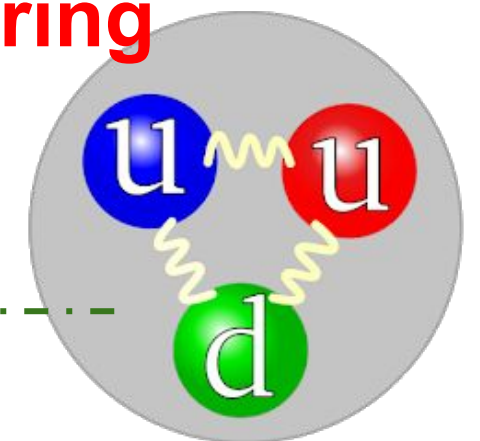
Challenging yet exciting tasks on Detector, Computing, Analysis.....



Parton Shower



Hard Scattering



Multiple-Interaction

Hadronization, decay

Luminosity Estimation

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

where f_{rep} is the rate of collisions and is typically 100 kHz (40 MHz) for lepton colliders (hadron colliders), and $N_{\text{beam1,2}}$ are the number of particles in each bunch which can be taken as $\sim 10^{11}$ – 10^{12} , σ_x and σ_y are the beam sizes.

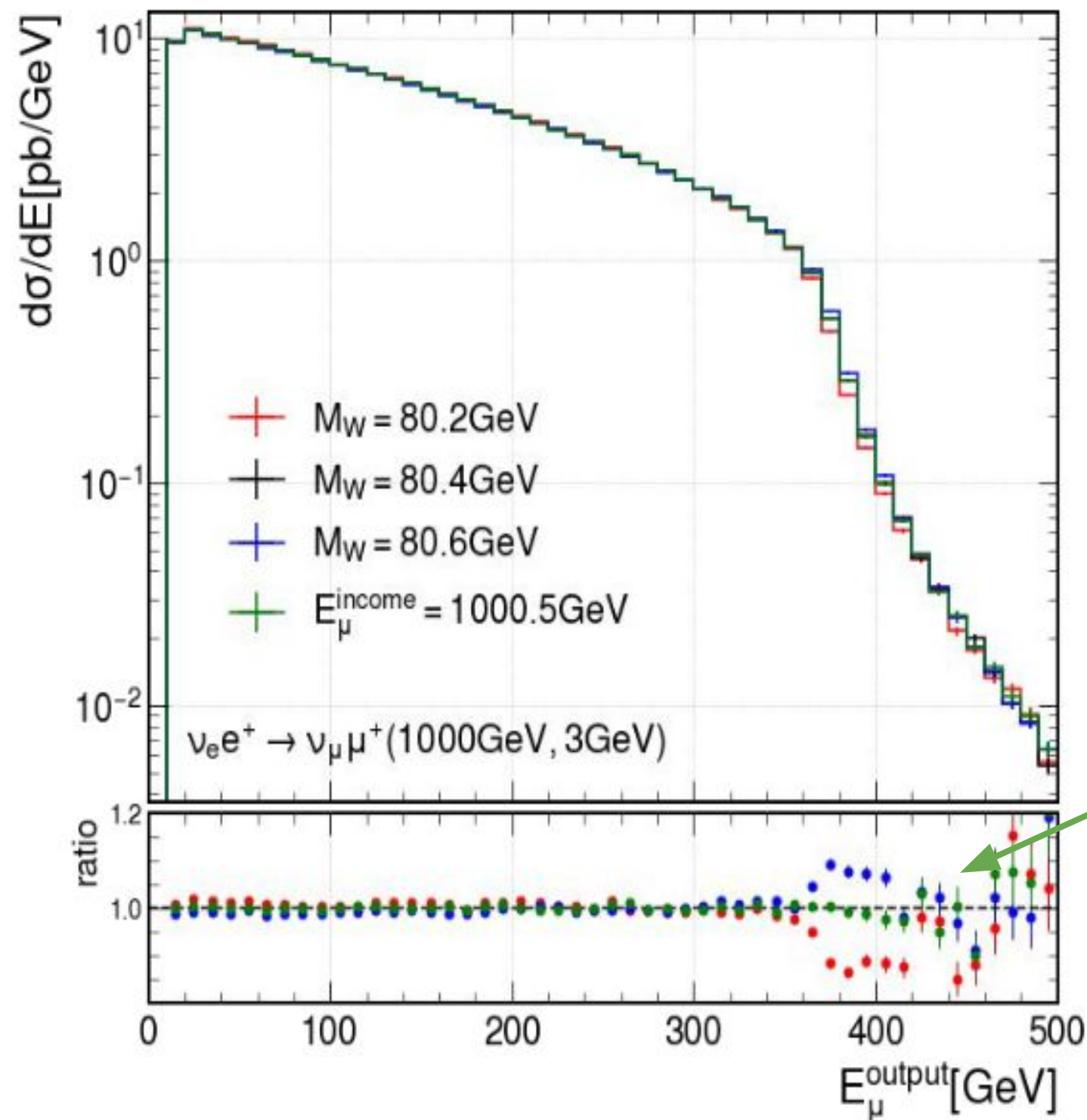
Take the LHC as an example, with $f_{\text{rep}} = 40$ MHz, $\sigma_{x,y} = 16$ microns, and $N_{\text{beam1,2}} = 10^{11}$, one can get $\mathcal{L} = 10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$.

As for TeV muon colliders, with $f_{\text{rep}} = 100$ 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 $\nu_e \bar{\nu}_e \rightarrow Z$, a tiny integrated luminosity of about 10^{-5} fb^{-1} is needed, i.e., several days of data taking.

正反中微子湮灭可以较快地被观测到！对束流质量要求可以放松。

Neutrino collision: neutrino-lepton collision



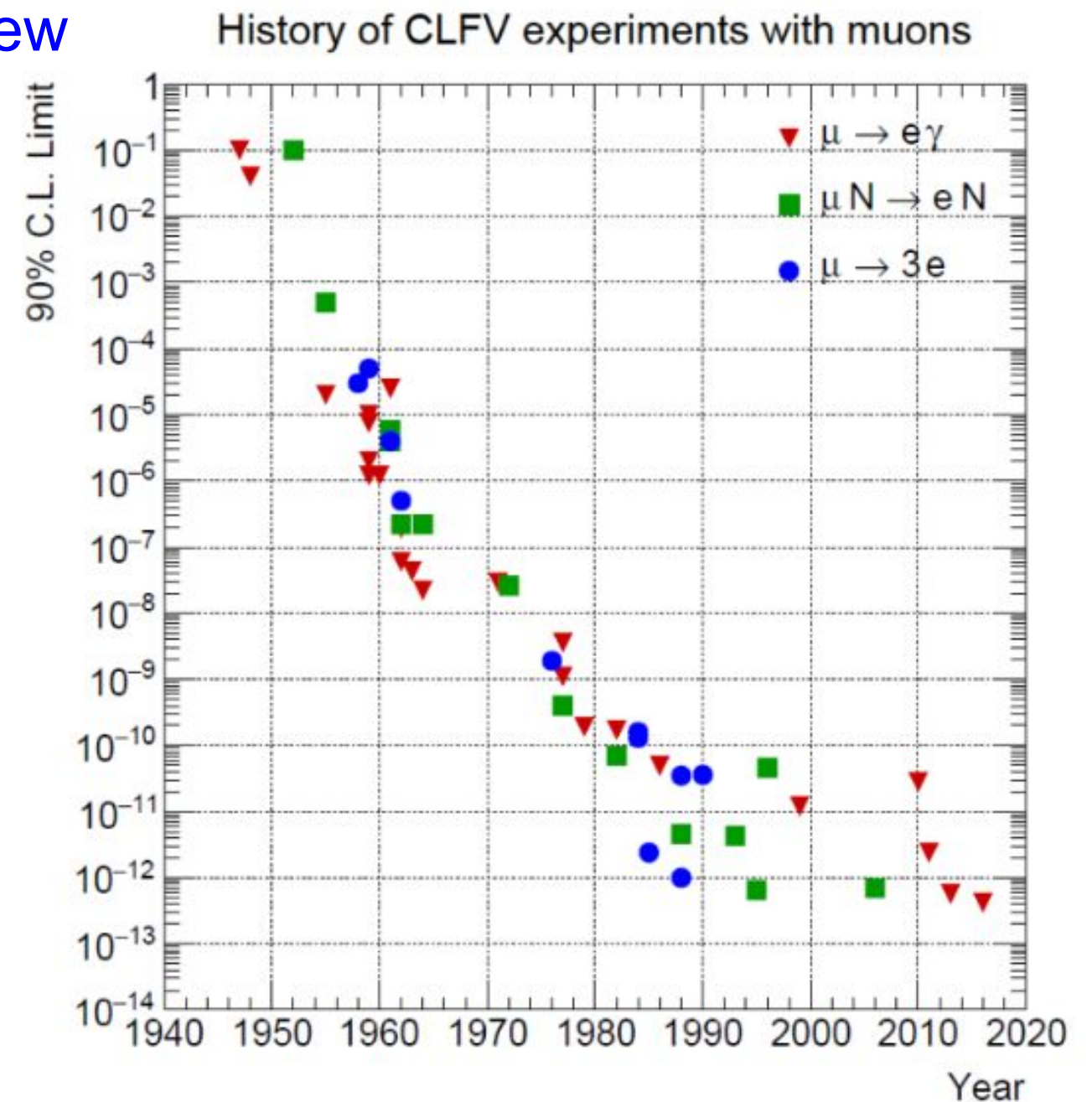
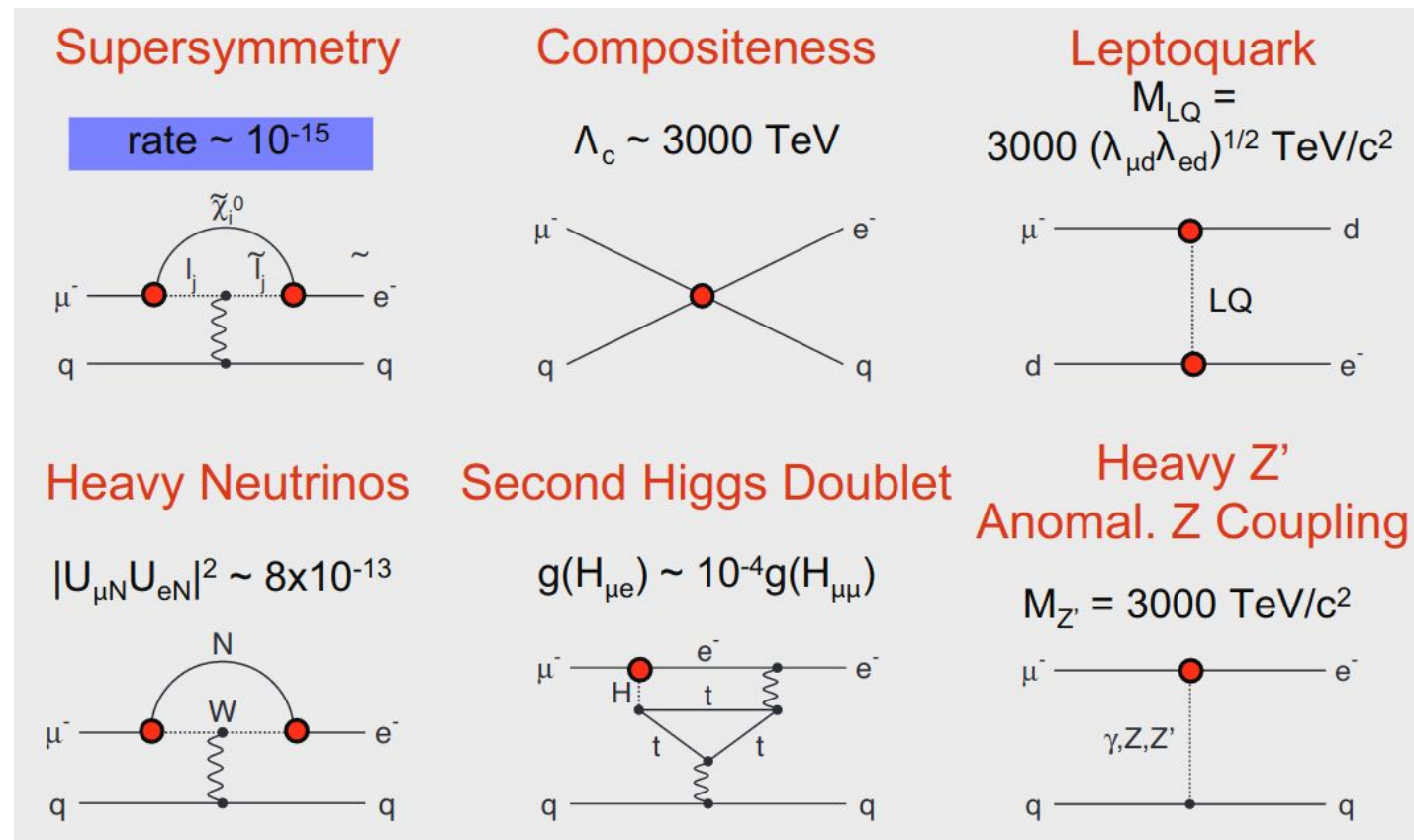
We varied the incoming muon and electron beam energy by 0.5 GeV and 10 MeV, respectively, which are quite conservative following previous refs.

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.

Lepton Flavor Violation

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

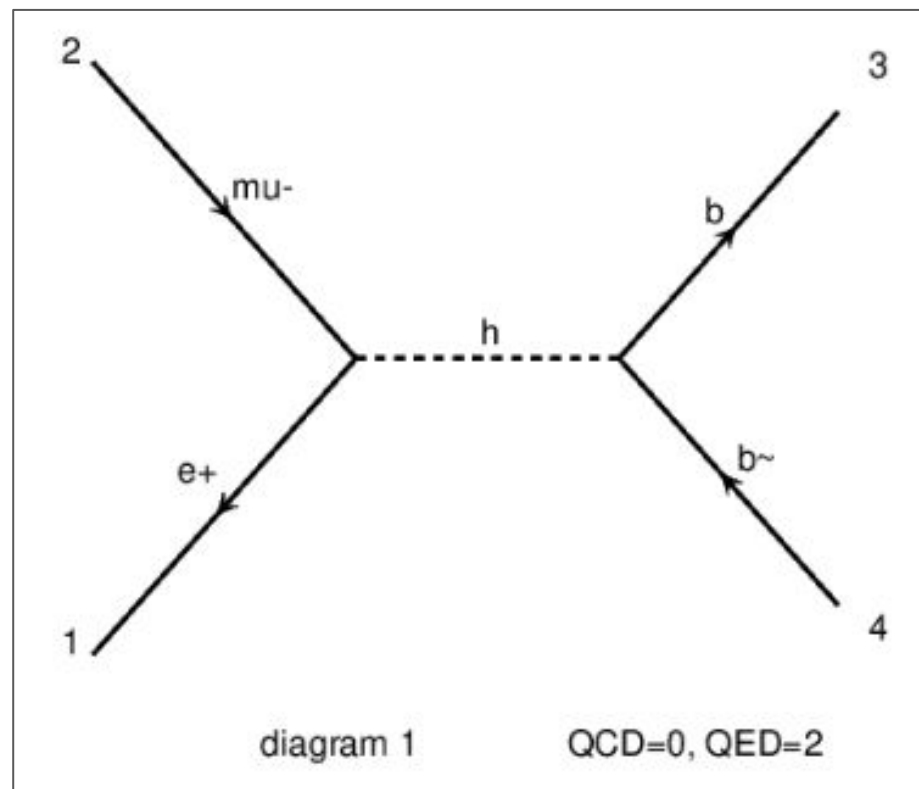


CLFV2019

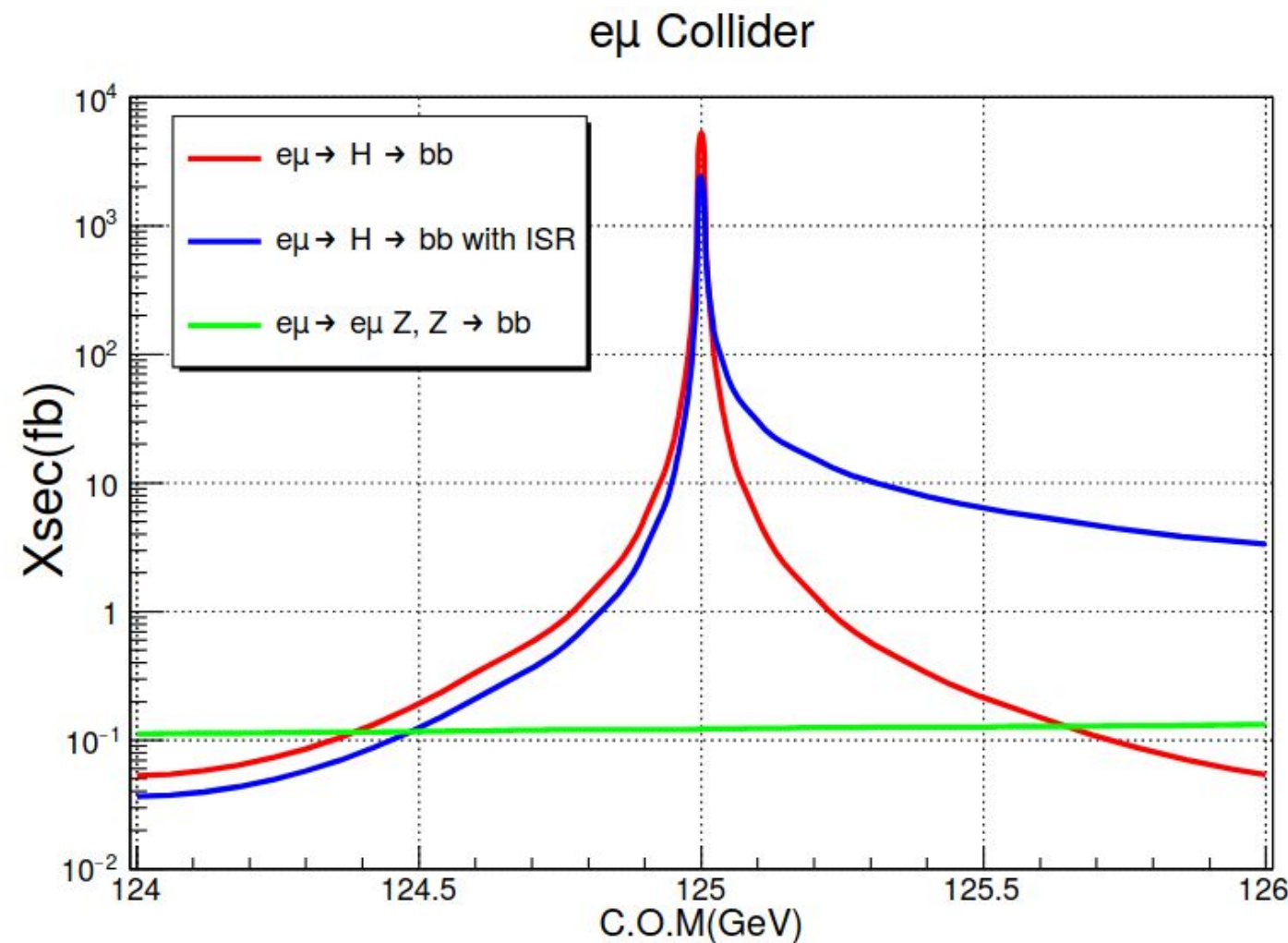
<https://arxiv.org/abs/1801.04688>

Emu: Lepton Flavor Violation arXiv:2010.15144

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



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



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.

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

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

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”

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

1TeV Muon beam:

$$2\text{B\$} \times (4\text{km}/10\text{km})^{0.5} + 2\text{B\$} \times (2)^{0.5} + 2\text{B\$} \times (100\text{MW}/100\text{MW})^{0.5} \\ \sim 6\text{B\$}$$

(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

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

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

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 Tel'nov 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."

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:

$$\mathcal{L}[\text{cm}^{-2}.\text{s}^{-1}] = N_{\text{AvO}} \times f_{\text{ss}} \times n_\mu [\text{s}^{-1}] \times l[\text{g.cm}^{-2}], \quad (3)$$

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, $N_{\text{AvO}} = 6.022 \times 10^{23}$, 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.