Physics at a High Energy Neutrino Collider

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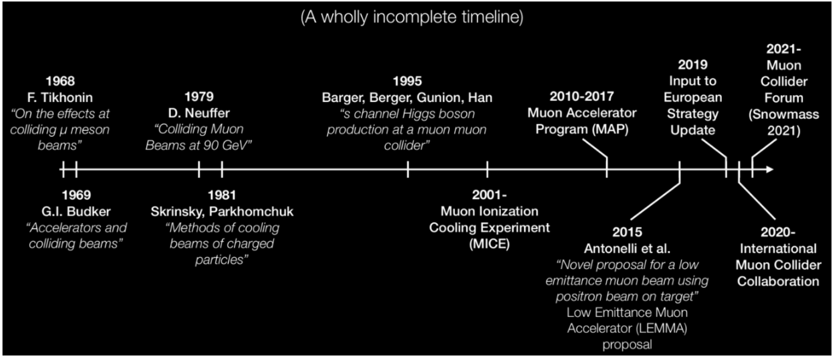
Outline

1. High-energy muon beams
2. Neutrino as a parton
3. Neutrino collisions at muon colliders
4. Conclusion

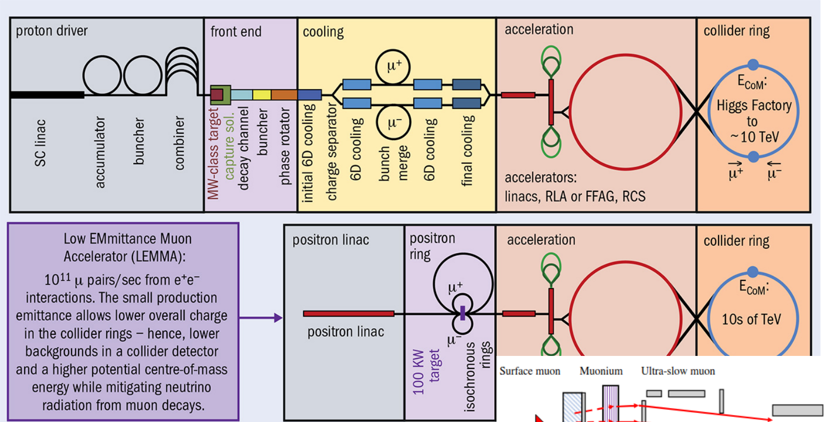
A bit of history

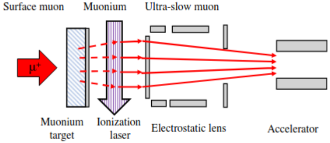
- **1960s**: First literature of Muon Colliders [Tinlot, Green, "A storage ring for 10 Bev muons" (1965)]
- **1990s-2010**: Design studies through US institutional collaborations
- **2010-2017**: Muon Accelerator Program (MAP)
  - Focused on a proton-driver solution
  - Studied 125 GeV and 1.5, 3 and 6 TeV colliders
- **2014** P5: Redirect muon collider R&D and consult with international partners

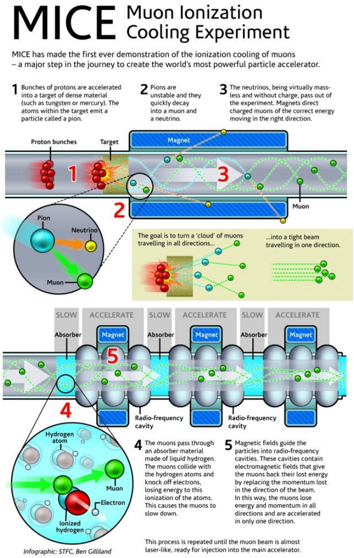


Breakthrough of Muon Cooling

- Muon Ionization Cooling Experiment at Rutherford Lab [Nature 2020]
- LEMMA $e^+e^- \to \mu^+\mu^-$



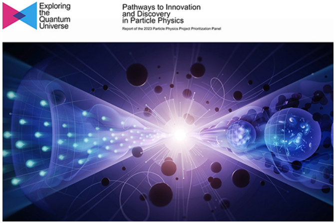


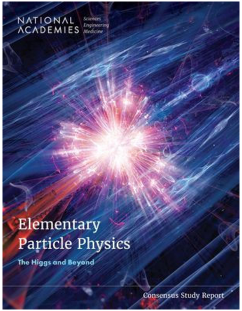


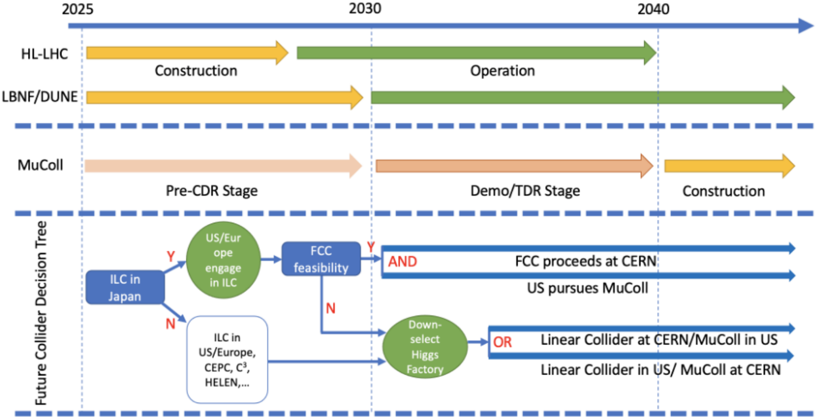
- μTRISTAN: muonium μ^+e^- [2201.06664]

Revival of muon colliders

- Snowmass 2020-2022: Muon Collider Forum
- 2023 P5 Report [2407.19176]: 10 TeV pCM collider
- IMCC and USMCC
- NAS recommendation for next 40 years (2025)

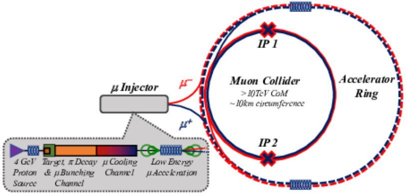


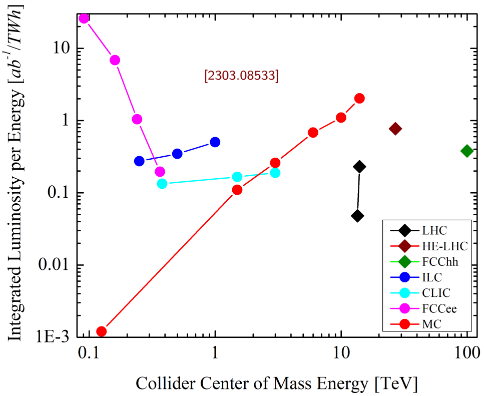




International MUON Collider Collaboration

Energy and Luminosity





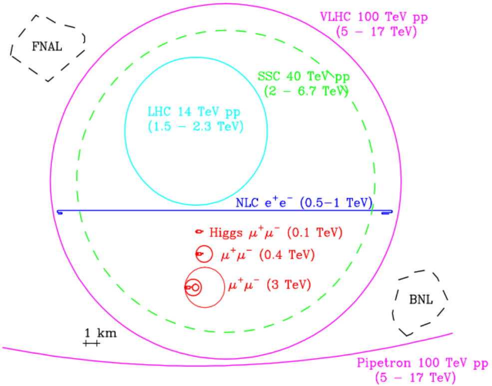
Luminosity scaling

$$\mathcal{L}_{\text{int}} = 10\ \text{ab}^{-1} \left(\frac{\sqrt{s}}{10\ \text{TeV}} \right)^2$$

$$\mathcal{L} = \frac{5\ \text{year}}{\text{Time}} \left(\frac{\sqrt{s}}{10\ \text{TeV}} \right)^2 2 \cdot 10^{35} \text{cm}^{-2}\text{s}^{-1}$$

Parameter	Unit	Target	
CM energy $\sqrt{s}$	TeV	3	10
Luminosity	$10^{34}\text{cm}^{-2}\text{s}^{-1}$	2	20
Collider circumference	km	4.5	10
Muons/bunch	10^{12}	2.2	1.8
Beta function at IP	mm	5	1.5

Physics potentials at muon colliders



Size and Benchmarks [Ankenbrandt+, arXiv:physics/9901022]

- A s-channel Higgs factory
- Multi-TeV muon colliders
  - Center of mass energy 3 – 15 TeV
  - New particle mass coverage $M \sim (0.5 - 1)E_{\rm cm}$
  - High precision for WWH, $WWHH$, H^3, H^4.
  - $\cdots$

Muon Collider Physics Potential Pillars

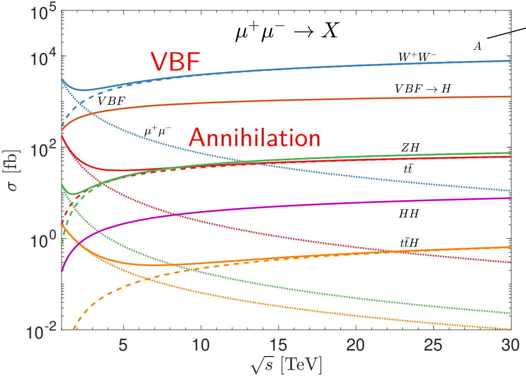
Direct search of heavy particles
SUSY-inspired, WIMP, VBF production, 2->1

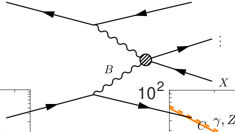
High rate indirect probes
Higgs single and self-couplings, rare Higgs decays, exotic decays

High energy probes
difermion, diboson, EFT, Higgs compositeness

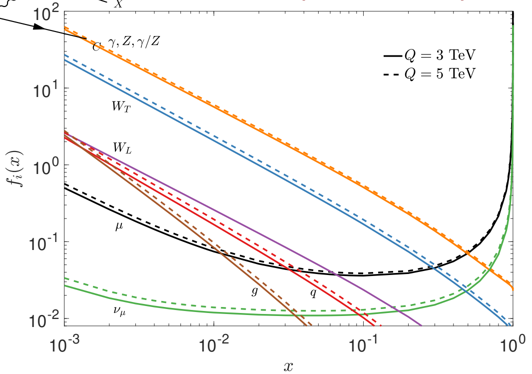
Vector Boson Fusion

[Han, Ma, KX, 2007.14300]

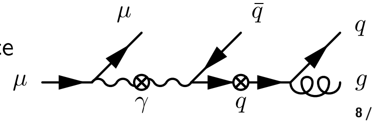




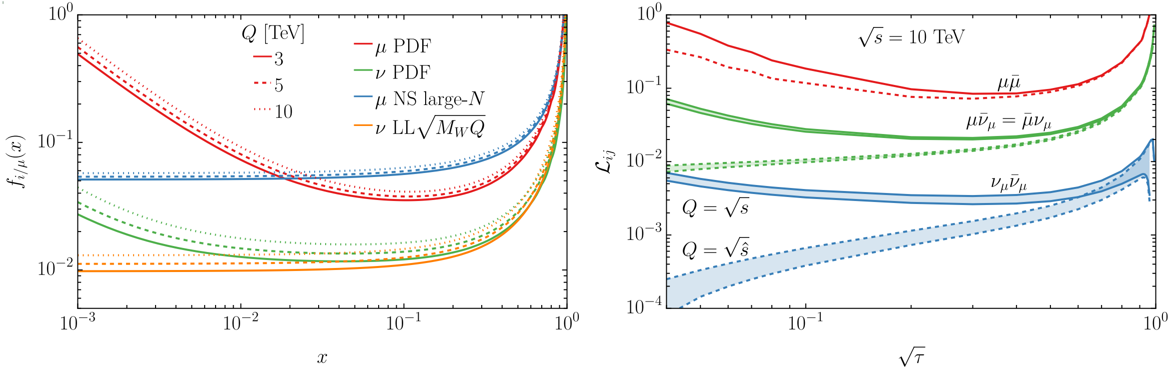
[Han, Ma, KX, 2103.09844]



- A multi-TeV muon collider is a gauge-boson collider (**Vector Boson Fusion**)
- All SM particles (Electroweak bosons, quark, gluons, neutrinos) becomes partons (**EW PDFs**)
- 10^7 Higgs (more than Higgs Factory) and 10^4 di-Higgs
- QCD di-jet production (quark-gluon initiated) make a big difference



Neutrino Parton Distribution Function



- Lepton beam PDF in the large-x limit, can be resummed to all orders with large-N approximation
- But the large-N μ PDF loses its reliability very soon, e.g., when $x < 0.9$
- The ν PDF can be obtained through the W boson radiation in the leading-logarithm approximation
- Similarly, at low x, we have a sizable higher-order resummation effect

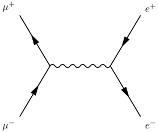
The luminosity can be determined correspondingly, with a sizable scale variation

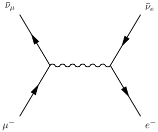
Application to the SMEFT operators

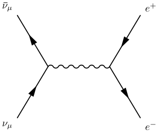
4-fermion interactions

$$\mathcal{L} = \frac{1}{2} C^{\ell\ell}_{ijkl} (\overline{L_i}\gamma^\mu L_j)(\overline{L_k}\gamma_\mu L_l) + \frac{1}{2} C^{ee}_{ijkl} (\overline{e_i}\gamma^\mu e_j)(\overline{e_k}\gamma_\mu e_l) + C^{\ell e}_{ijkl} (\overline{L_i}\gamma^\mu L_j)(\overline{e_k}\gamma_\mu e_l),$$

Hermitian implies $C^X_{ijkl} = C^{X,*}_{jilk}$ for $X = \ell\ell, ee, \ell e$.

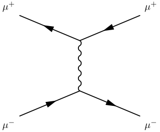


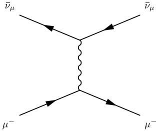


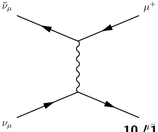


EW-parton level processes	WCs
$\mu^+\mu^- \to e^+e^-$	C^{ee}_{1122}, $C^{\ell e}_{1122}$, $C^{\ell e}_{2211}$, $C^{\ell e}_{1221}$, $C^{\ell\ell}_{1122}$ $C^{\ell\ell}_{1221}$
$\bar{\nu}_\mu\mu^- \to \bar{\nu}_e e^-$	$C^{\ell e}_{1221}$, $C^{\ell\ell}_{1221}$
$\bar{\nu}_\mu\nu_\mu \to e^+e^-$	$C^{\ell e}_{2211}$, $C^{\ell\ell}_{1122}$

EW-parton level processes	WCs
$\mu^+\mu^- \to \mu^+\mu^-$	C^{ee}_{2222}, $C^{\ell e}_{2222}$, $C^{\ell\ell}_{2222}$
$\bar{\nu}_\mu\mu^- \to \bar{\nu}_\mu\mu^-$	$C^{\ell e}_{2222}$, $C^{\ell\ell}_{2222}$
$\bar{\nu}_\mu\nu_\mu \to \mu^+\mu^-$	$C^{\ell e}_{2222}$, $C^{\ell\ell}_{2222}$

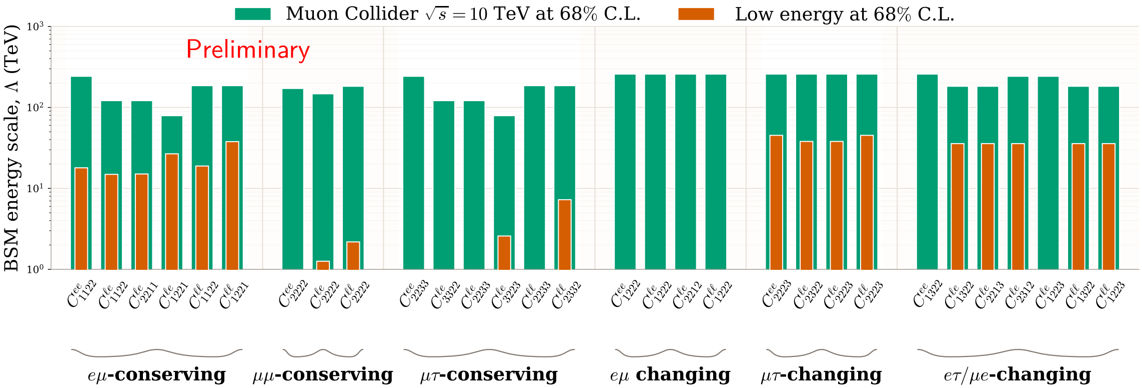




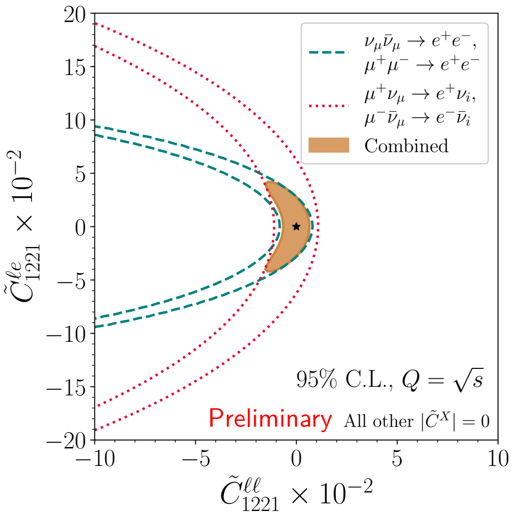


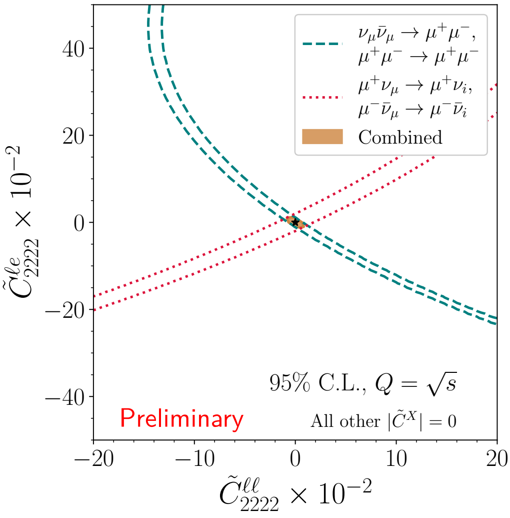
Mun collider constraints

With respect to low-energy observables

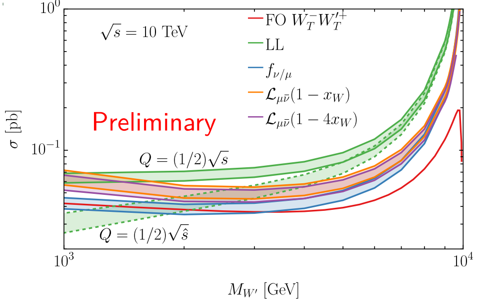


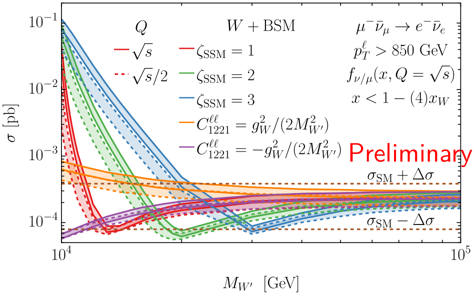
Remove flat directions

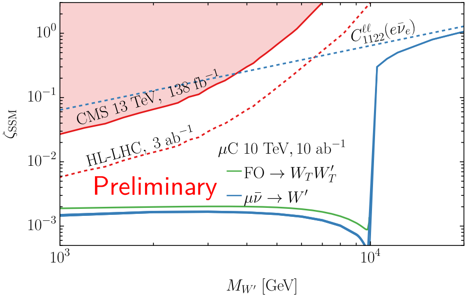




Heavy W' production

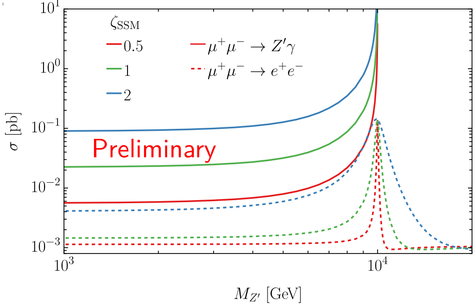


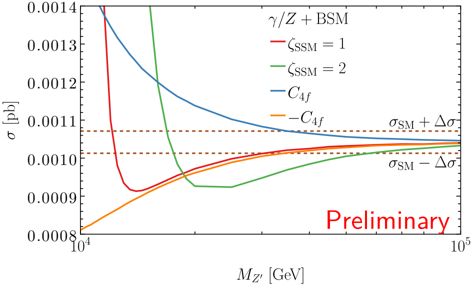


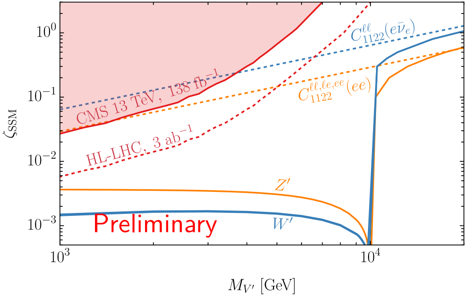


- Heavy W' can be initiated through $\nu\bar{\mu} \to W'$.
- Sizable uncertainty from the scale $Q = \sqrt{s}$ or $\sqrt{\hat{s}}$ and the W mass effect
- On-shell W' embraces a big advantage through the resonance enhancement
- Off-shell W' production returns back to SMEFT bounds

Heavy Z' production







- Z' is mainly initiated through $\mu\bar{\mu} \to Z'$
- In the off-shell region $M_{Z'} > \sqrt{s}$, we mainly relies on the electron channel
- On-shell Z' is weaker than W', due to the smaller cross section
- Off-shell Z' is stronger than W', as no missing

Summary

- A lot of enthusiasm and activities about high-energy muons in last a few years
- A lot of physics potential: SM precision and new physics, neutrinos, proton/nuclear structure, etc
- Many reviews and reports about muon colliders: Snowmass [2209.01318] and ESPPU [2504.21417]
- Endorsements from US P5, NAS, and ESPP and a clear timeline
- Chance for Muon-Ion Scattering in China?