Theory and Phenomenology of Fundamental Interactions
UNIVERSITY AND INFN - BOLOGNA

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

UCLouvain

Muon collider physics highlights

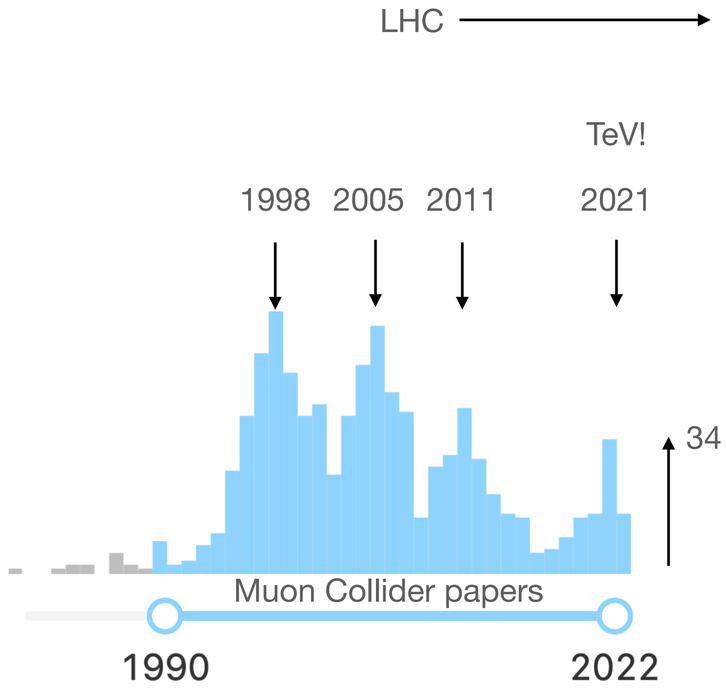
Snowmass muon collider forum conveners

A new interest in a muon collider

Motivations

- Recurrent interest in the HEP community for accelerating muons.
- However, **now a very different context:**
  - New key technologies are becoming available
    => Multi-TeV accelerators being explored
    => Time scale becoming realistic
  - New Physics opportunities
    => 10+ years of LHC: energy gap
    => Higher energy = Higher lumi
    => Direct searches+precision

⇒Timing is right for R&D!



A new interest in a muon collider

White papers and more

1. **Jorge De Blas, et al. ”The physics case of a 3 TeV muon collider stage”, arXiv:2203.07261 [hep-ph] (pdf). (also under EF0)**
2. **Chiara Aimè, et al. ”Muon Collider Physics Summary”, arXiv:2203.07256 [hep-ph] (pdf). (also under EF0)**
3. **L. Bottura, et al., " A Work Proposal for a Collaborative Study of Magnet Technology for a Future Muon Collider", 2203.13998 [physics.acc-ph]**
4. **S. Homiller et al., "Complementary Signals of Lepton Flavor Violation at a High-Energy Muon Collider", 2203.08825 [hep-ph]**
5. Yu. Alexahin et al., "Solving Critical Problems of the Muon Collider Higgs Factory: Optics, Magnets and their Protection, Detector Backgrounds, 2203.09010 [physics.acc-ph]
6. Nazar Bartosiket al. ,"Simulated Detector Performance at the Muon Collider", 2203.07964 [hep-ex]
7. **Brad Abbott et al., "Anomalous quartic gauge couplings at a muon collider", 2203.08135 [hep-ex]**
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12. D. Ally, L. Carpenter, T. Holmes, L. Lee, P. Wagenknecht. ”Strategies for Beam-Induced Background Reduction at Muon Colliders“, **arXiv:2203.06773 [physics.ins-det]** (pdf).
13. Sergo Jindariani, Federico Meloni, Nadia Pastrone, et al. ”Promising Technologies and R&D Directions for the Future Muon Collider Detectors”, **arXiv:2203.07224 [physics.ins-det]** (pdf).
14. D. Stratakis, N. Mokhov, M. Palmer, N. Pastrone, T. Raubenheimer, C. Rogers, D. Schulte, et al. ”A Muon Collider Facility for Physics Discovery“, **arXiv:2203.08033 [physics.acc-ph]** (pdf).
15. Nazar Bartosik, Karol Krizka, Simone Pagan Griso, Chiara Aimè, Aram Apyan, et al. ”Simulated Detector Performance at the Muon Collider”, **arXiv:2203.07964 [hep-ex]** (pdf).
16. K. Black, T. Bose, S. Dasu, H. Jia, S. Lomte, C. Vuosalo. et al. ”Prospects for the Measurement of the Standard Model Higgs Pair Production at the Muon Colliders“, **arXiv:2203.08874 [hep-ex]** (pdf).
17. **Matthew Forslund, Patrick Meade. ”High Precision Higgs from High Energy Muon Colliders”, arXiv:2203.09425 [hep-ph]** (pdf).
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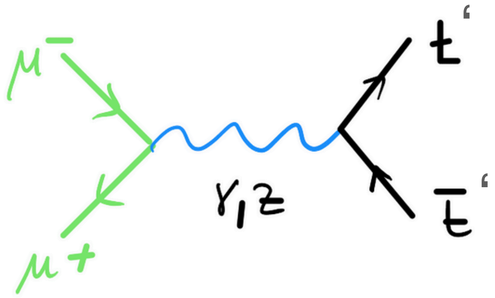
19. **Al Ali, et al. “The muon smasher guide”, 2103.14043 [hep-ph]**

Excitement building up on many innovative aspects from accelerators, to detectors, to exciting physics.
A growing interest in the community has allowed to put efforts in identifying the key technologies that will make a muon collider possible.

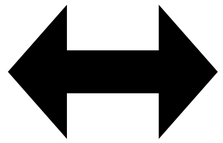
Muon collider physics

The essentials

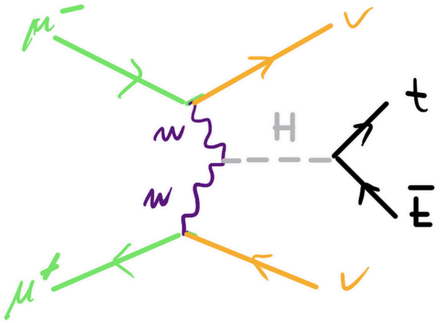
O(10) TeV muon collider energy allows to have two colliders in one:



$$\sigma_s \sim \frac{1}{s}$$



$$\sigma_s \sim \frac{1}{M^2}\log^n \frac{s}{M}$$



Discovery

Measurements

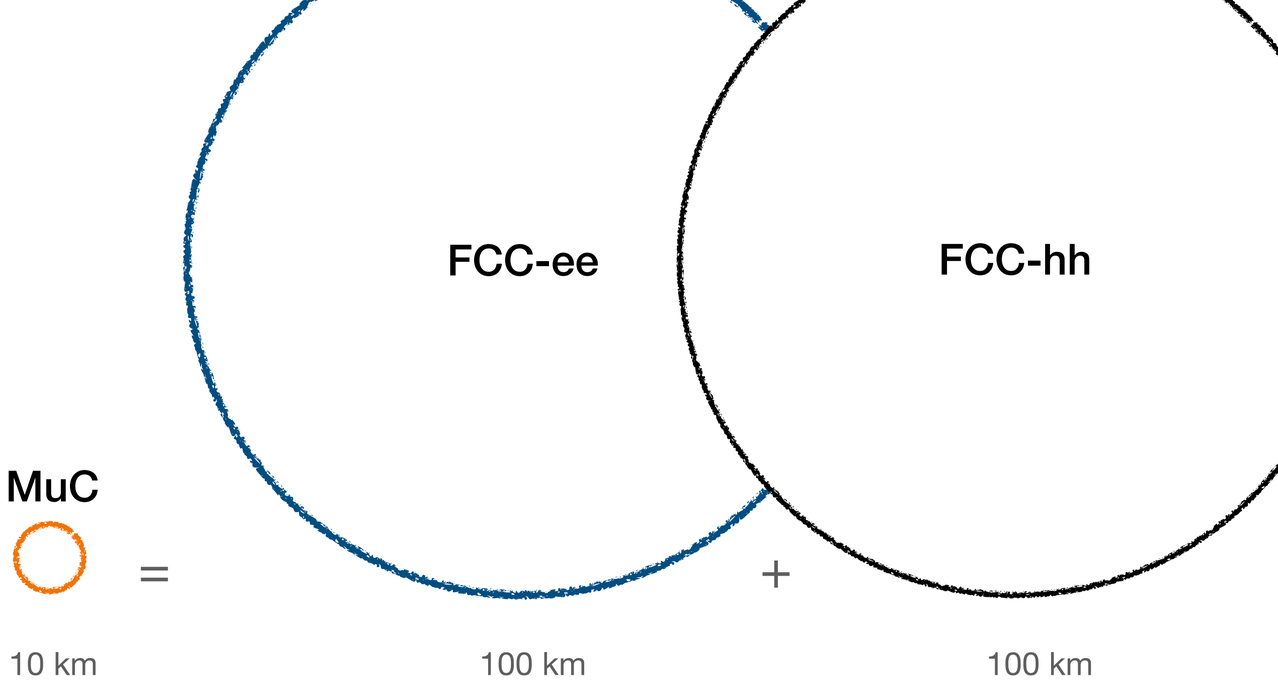
A completely new regime opening for a multi-TeV muon collider

Different physics being probed in the two channels

Muon collider physics

The essentials

1] O(10) TeV Energy small two-in-one collider:



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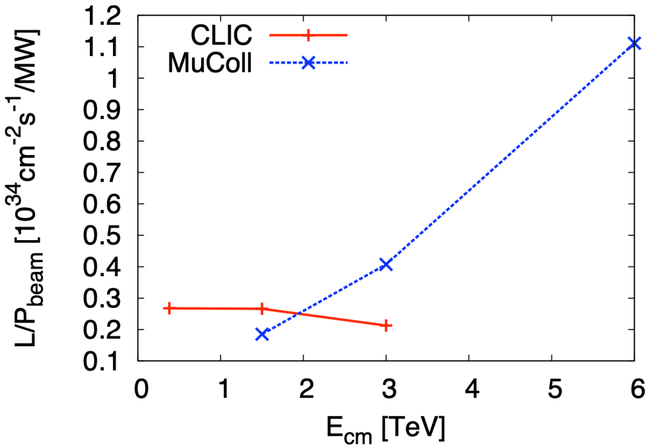
2] Luminosity growing with energy:



⇒MuC is an SSTC = Space-Time Compact Collider

MuC10: 10 TeV, 10 iab, 10 times smaller and 10 times quicker than the FCC

Muon collider physics

The essentials

A O(10 TeV) muC

- will advance the exploration of phenomena at higher scales through both direct access and precision:

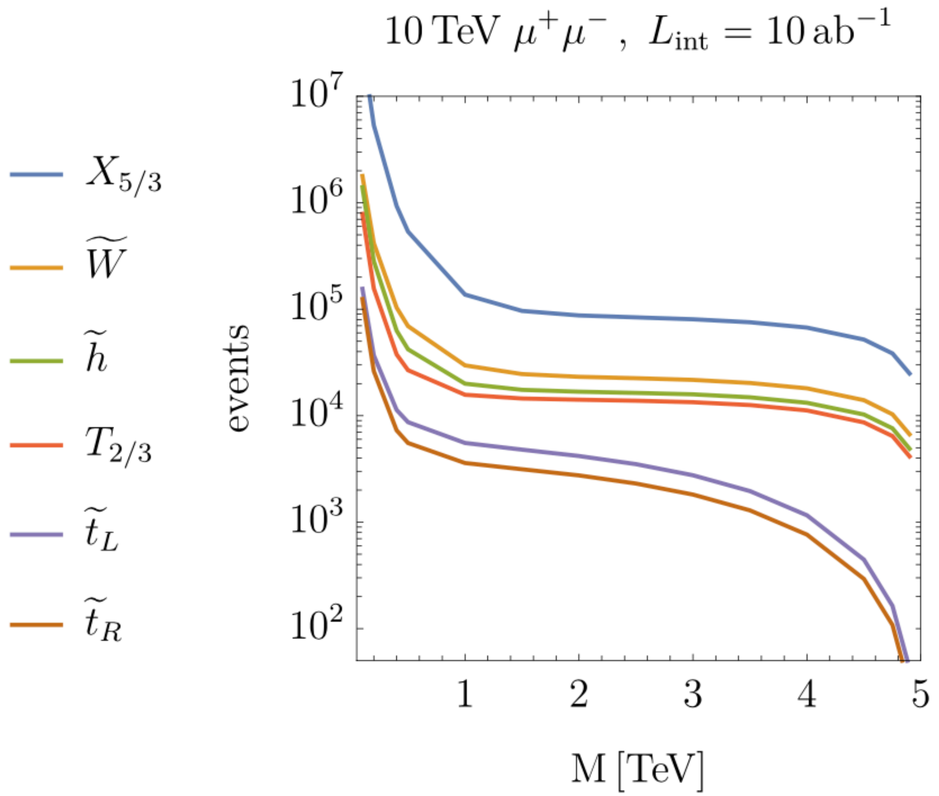
  Given what we know now from the LHC + what will learn from HL-LHC: we can address fundamental open questions in the SM, such as flavour violation and (an extended) Higgs sector and search for heavier states up to M=sqrt(s)/2.

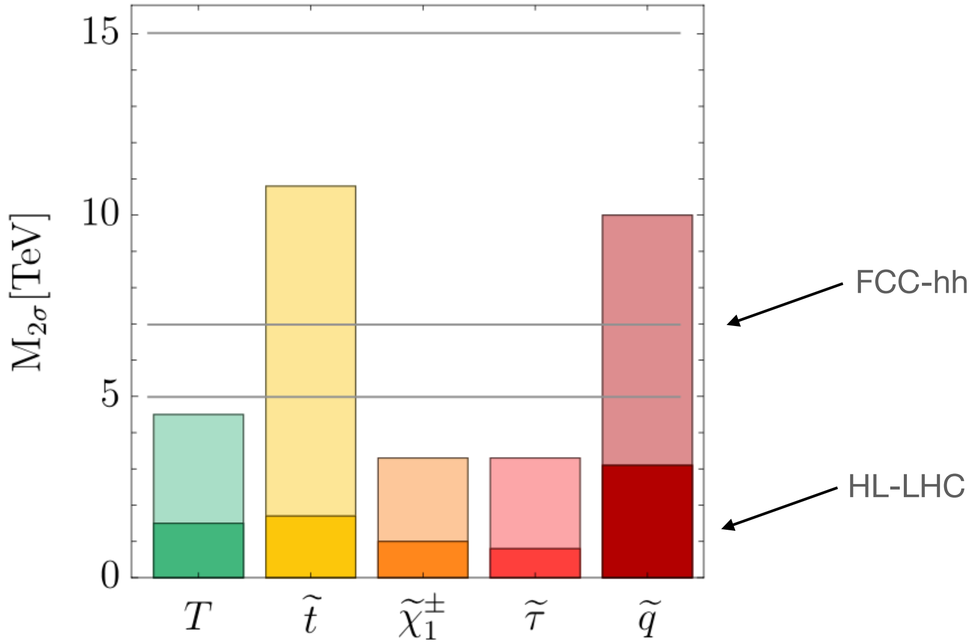
- would be upgradable to higher energy:

  Evidence collected so far indicates luminosity can be expected to increase with energy, so O(10 TeV) collider could be seen as a stepping stone. A showcase for a O(1 TeV) beam with top studies and neutrino applications is motivated.

Direct reach

Easy scenarios: pair production

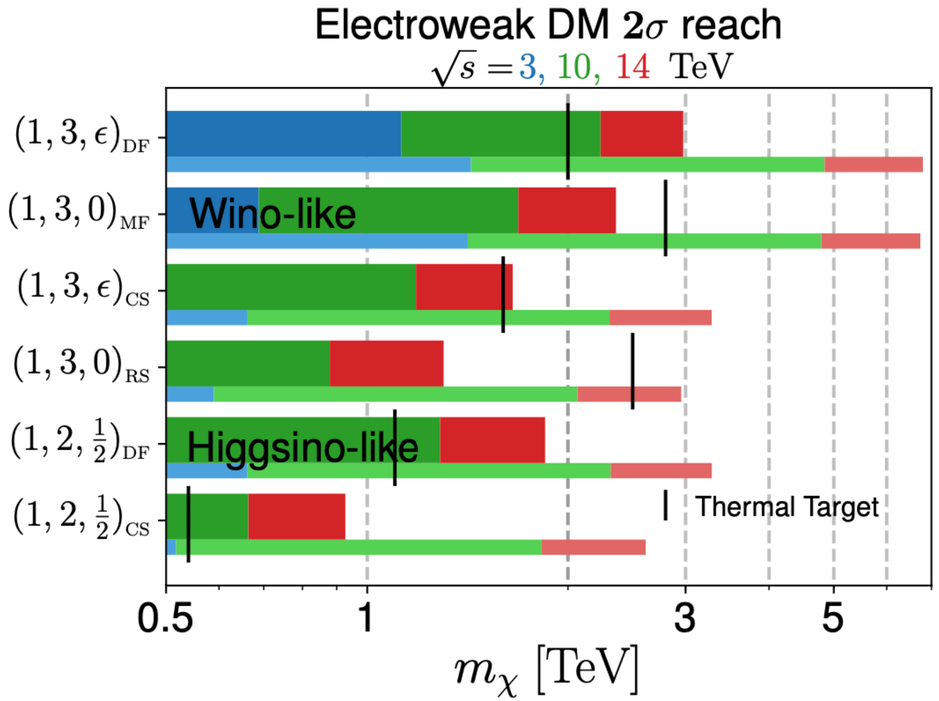




Taking into account that entire target integrated luminosity will be collected in 5 years, a few months of run could be sufficient for a discovery.

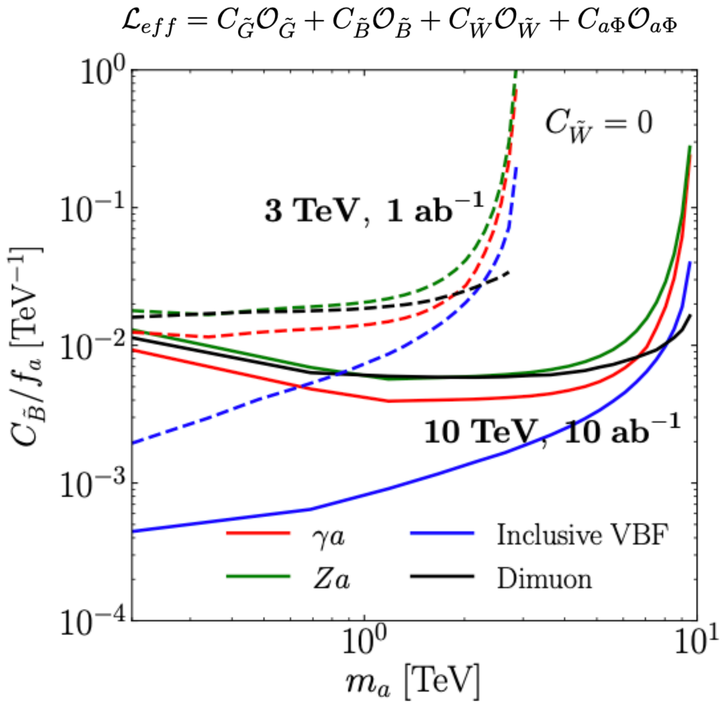
Direct reach

Minimal DM and axions



Tao Han, et al. arXiv:2203.07351 [hep-ph]

2σ exclusion of DM masses with horizontal (thick) bars for combined channels and various muon collider running scenarios by the different color codes. The thin bars are the estimation of the mono-photon plus one disappearing track search. The vertical bars indicate the thermal mass targets for the corresponding WIMP DM.

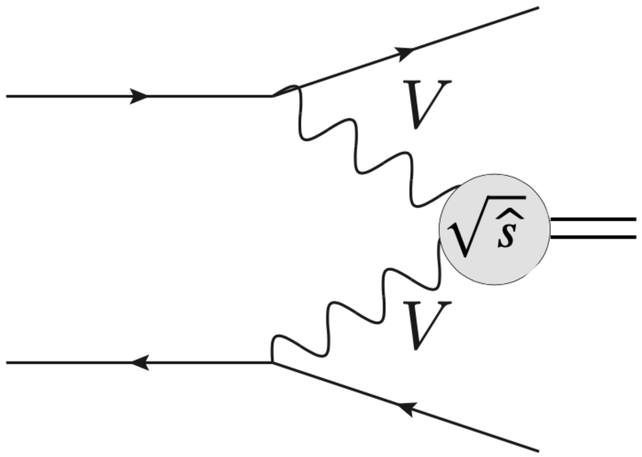


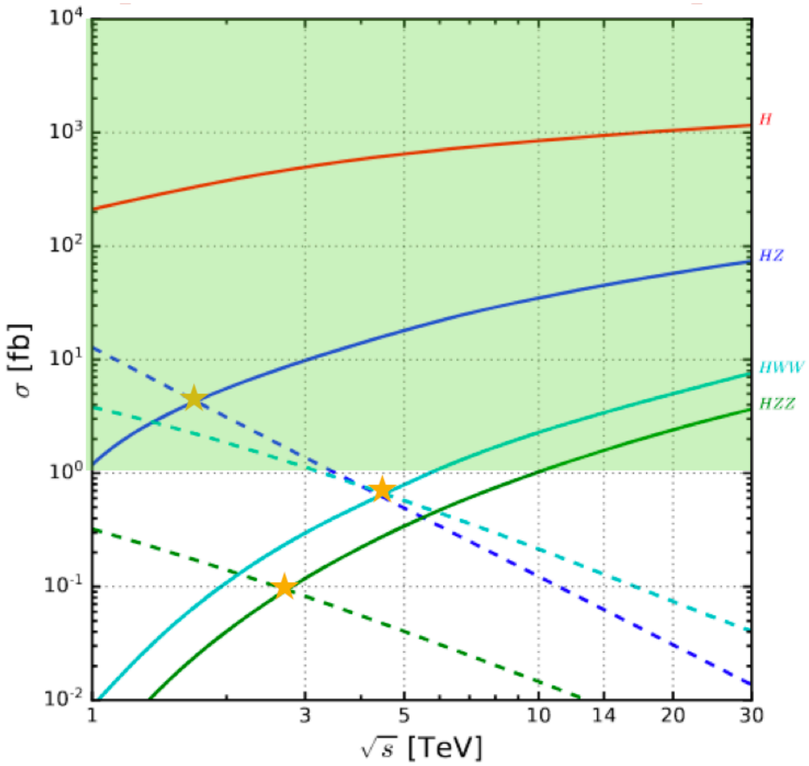
Tao Han et al. arXiv:2203.05484 [hep-ph]

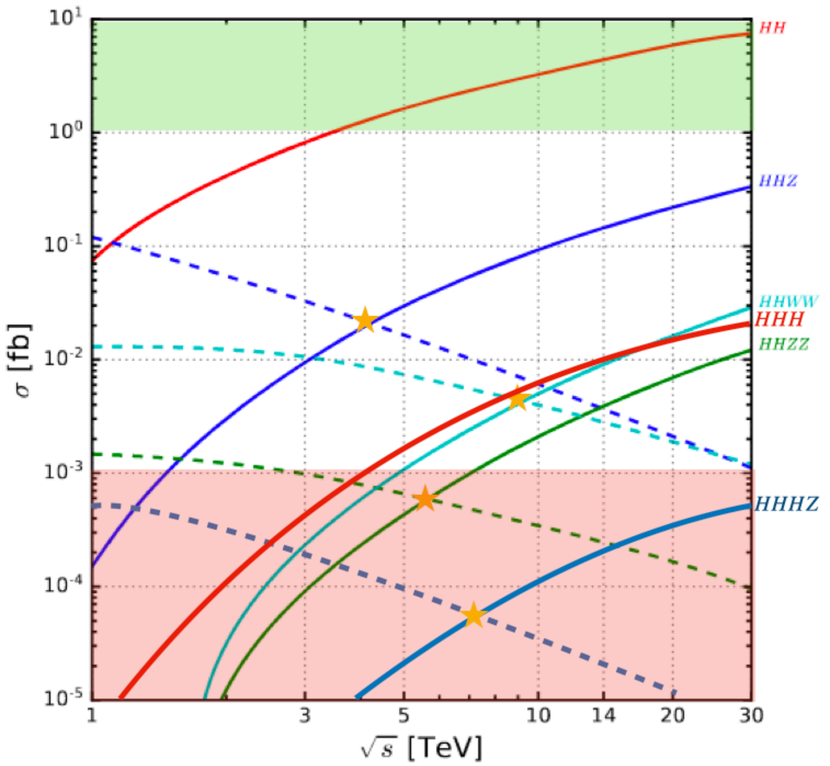
Projected 5σ sensitivity of C_B/f_a versus C_W/f_a. Selection cuts include Eq. (3.16), $|m_{\gamma\gamma} - m_a|/m_a < 5\%$, and $m_{\mu^+\mu^-} > 200$ GeV. The leading backgrounds considered for γa, Za, inclusive VBF, and Dimuon channels are $\mu^+\mu^- \to \gamma\gamma\gamma$, $\mu^+\mu^- \to Z\gamma\gamma$, $\mu^+\mu^- \to \gamma\gamma$ with ISR, and $\mu^+\mu^- \to \mu^+\mu^-\gamma\gamma$, respectively

Precision physics

Weakedron collider

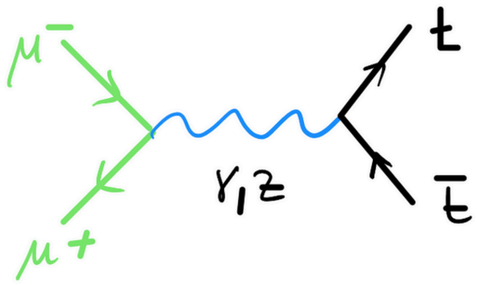






Precision physics

Weakedron collider



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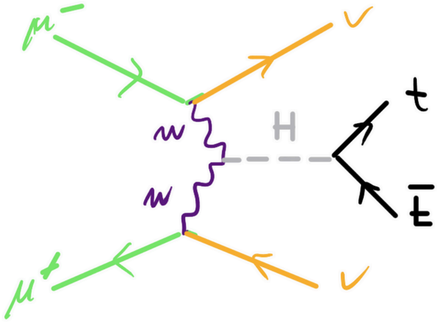
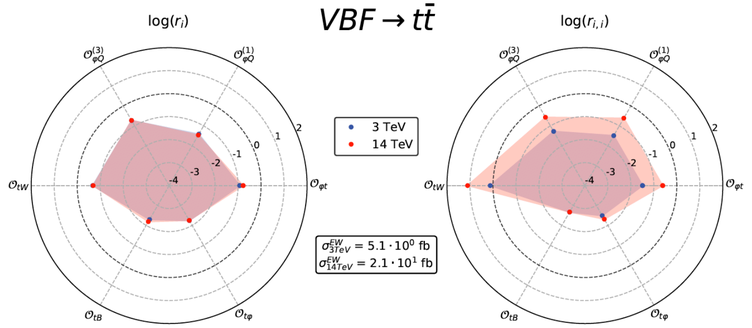


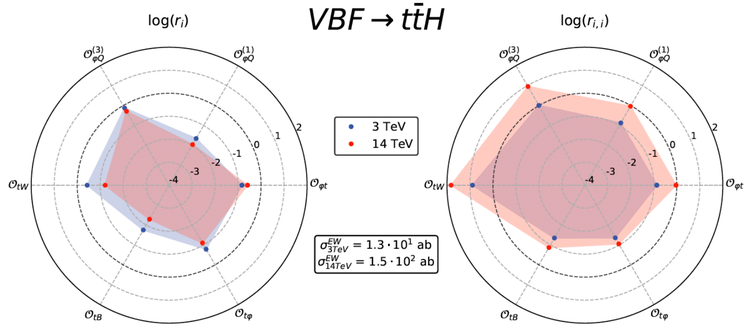
Annihilation can probe $t\bar{t}\gamma, t\bar{t}Z$ couplings at very high energy with a large statistics.

However, VBF can access a much larger set of dim=6 operators with very interesting energy-growth behaviors (yet with lower statistics).

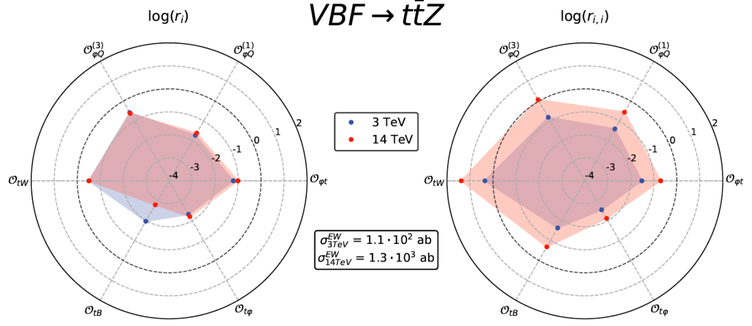
[Costantini et al. 2005.10289]



(a)



(b)



(c)

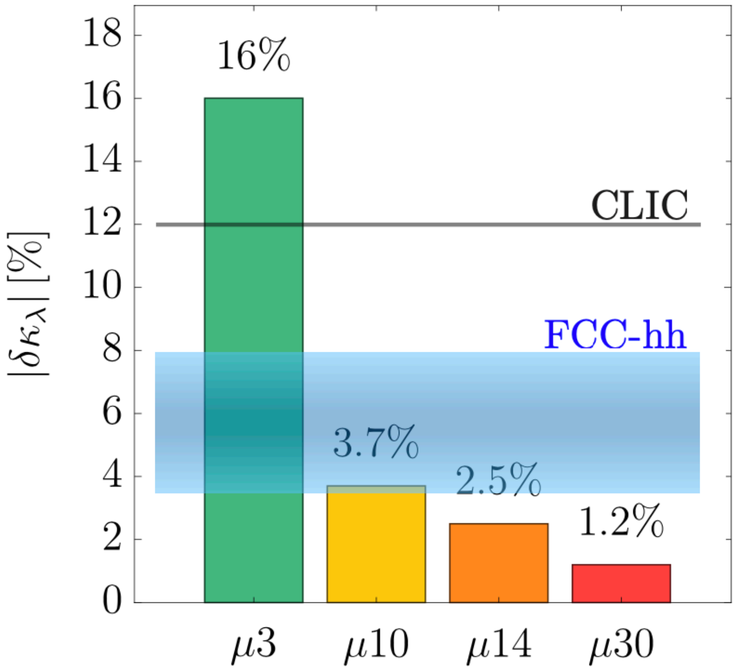
Precision physics

Higgs coupling sensitivities k-framework

	HL-LHC	HL-LHC +10 TeV	HL-LHC +10 TeV + ee
κ_W	1.7	0.1	0.1
κ_Z	1.5	0.4	0.1
κ_g	2.3	0.7	0.6
κ_γ	1.9	0.8	0.8
κ_c	-	2.3	1.1
κ_b	3.6	0.4	0.4
κ_μ	4.6	3.4	3.2
κ_τ	1.9	0.6	0.4
$\kappa^*_{Z\gamma}$	10	10	10
κ^*_t	3.3	3.1	3.1

* No input used for μ collider

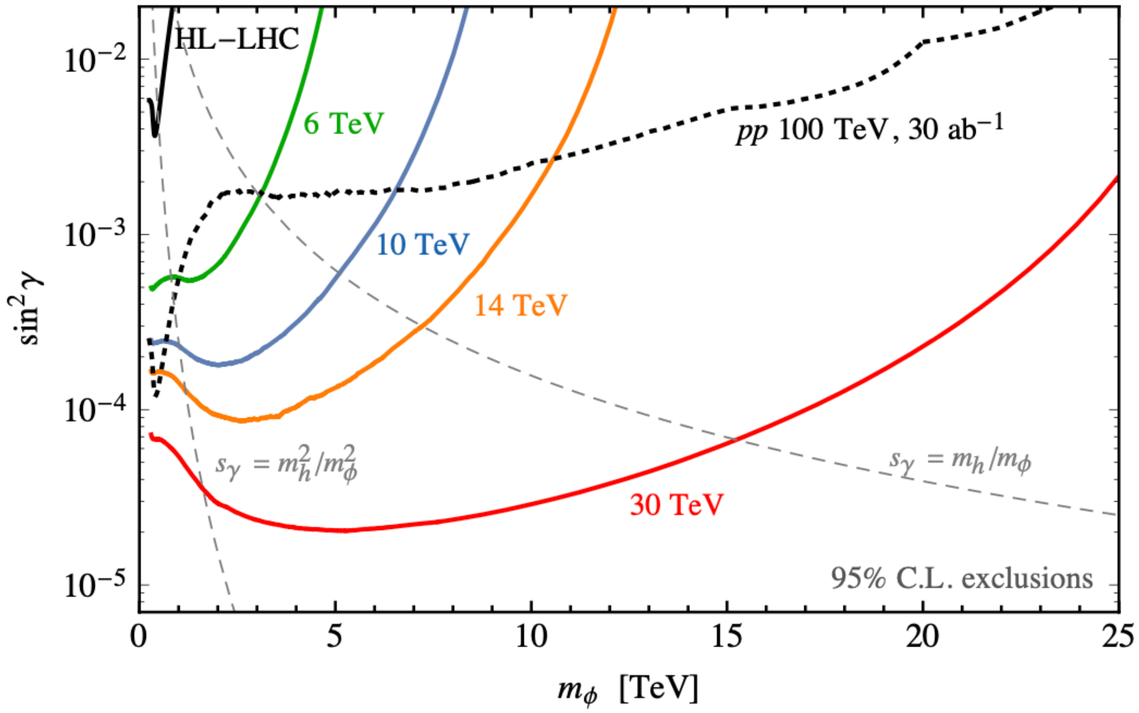
1σ sensitivities (in %) from a 10-parameter fit in the k-framework at a 10 TeV muon collider with 10 ab^{-1} , compared with HL-LHC. The effect of measurements from a 250 GeV e^+e^- Higgs factory is also reported.



High-energy muon colliders open the way to direct measurements of the Higgs trilinear self-coupling, λ_3, and at above 10 TeV, even the potential observation of multi-Higgs production, which is sensitive to the quartic self-coupling. We find that the precision in the determination of λ_3 of the 3 TeV muon collider would substantially benefit from an increase in the total luminosity by a factor~ 2 with respect to the proposed benchmark of 0.9 ab^{-1}, suppressing a second mode in the likelihood for λ_3 and allowing a determination at the 15% level. Percent level uncertainties will be achieved at the higher energy stages.

Direct reach

Higgs singlet extension

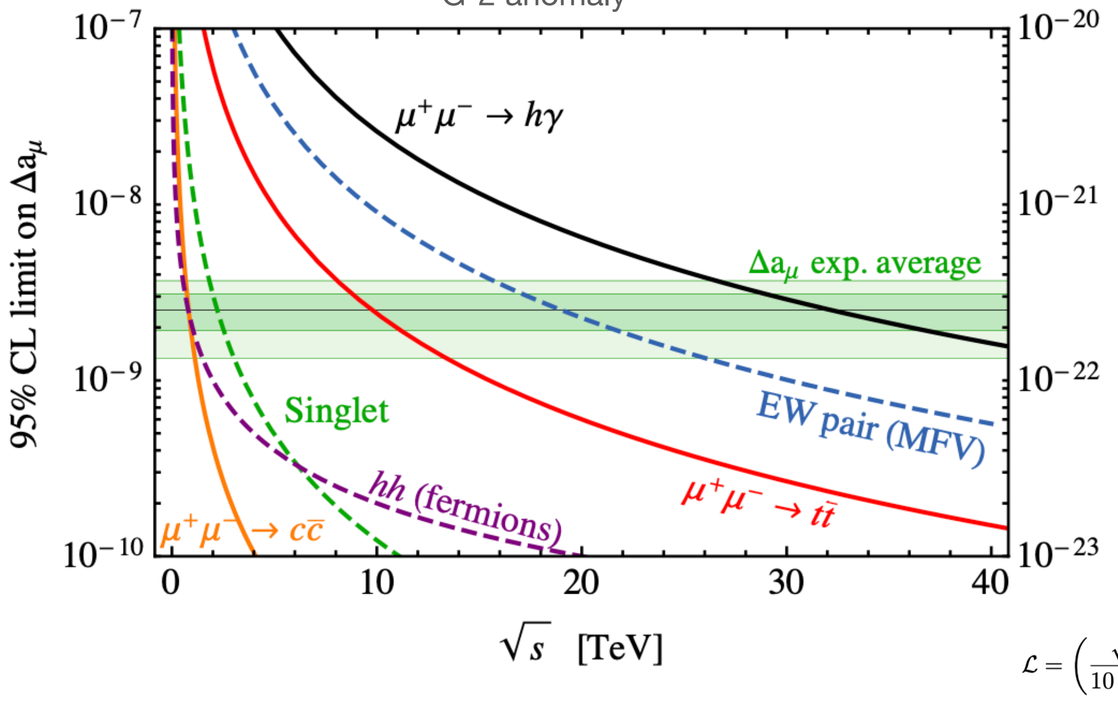


Exclusion contour for a scalar singlet of mass mϕ mixed with the Higgs boson with strength sin γ.

Precision

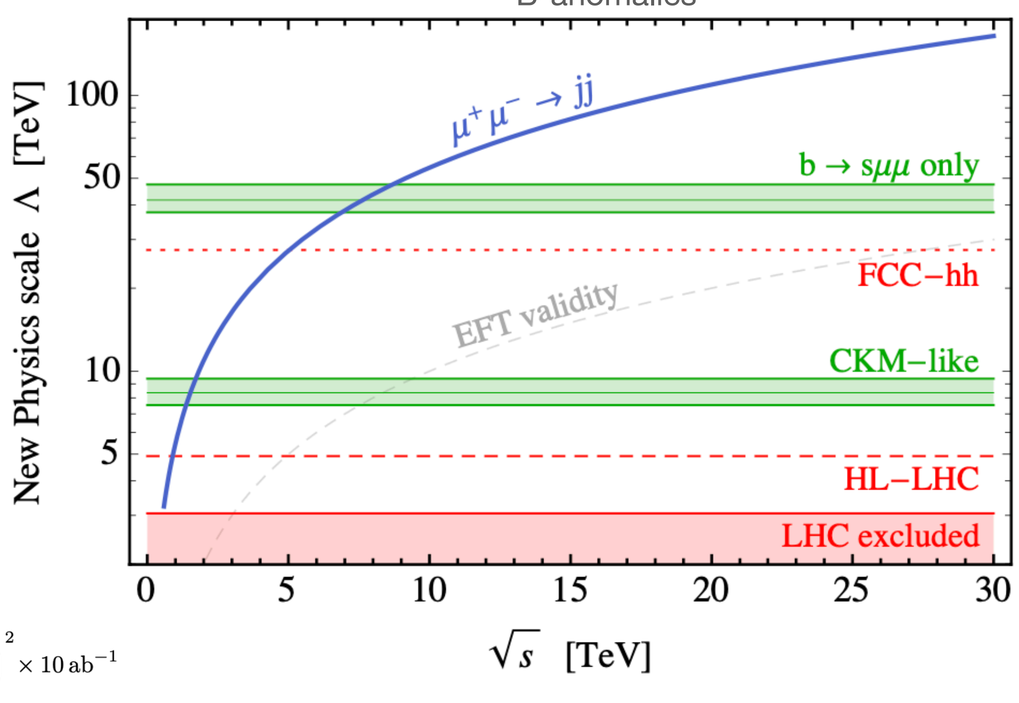
G-2 and B-anomalies: EFT scenarios

G-2 anomaly



Reach on the muon g-2 from high-energy measurements (solid lines), and from direct searches for new particles in explicit models (dashed lines).

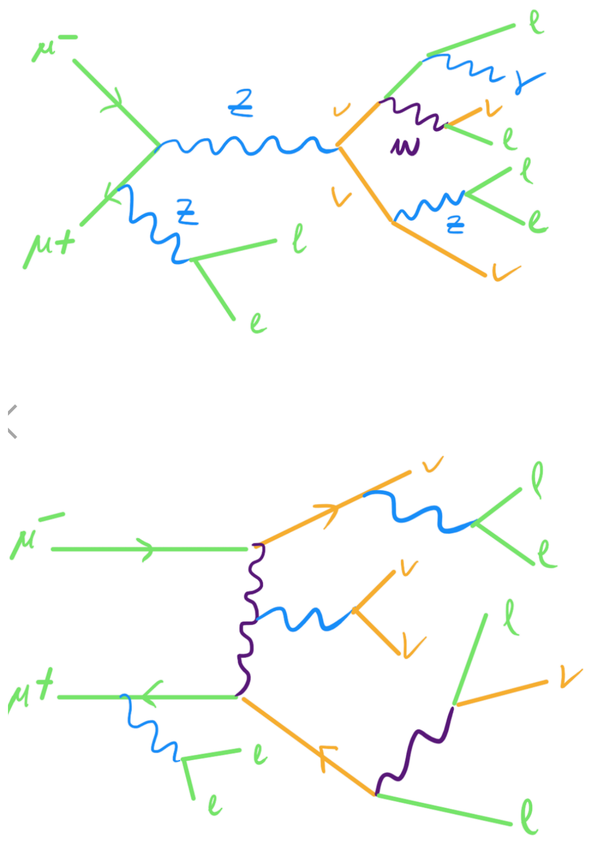
B-anomalies



Reach from μμ → jj (solid line) on the scale Λ of semi-leptonic interactions that can account for the B-anomalies.

New SM Physics

EW radiation



Various approaches available in the literature:

Using SCET:
[Chiu, Golf, Kelley, Manhoar, 0709.2377, 0712.0396,0806.1240, 0909.0012, 0909.0947]

Using DGLAP:
[Bauer, Webber et al. 1703.08562, 1712.07147, 1806.10157, 1808.08831, 2007.15001]

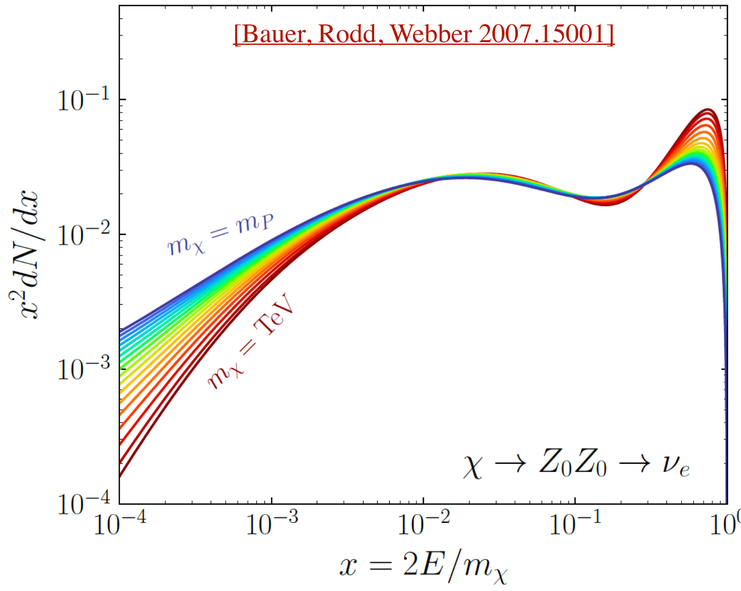
Parton showers:
[Christiansen and Sjostrand 1401.5238
[Kleiss and Verheyen, 2002.09248]

EW splitting functions
[Chen, Han, Tweedie, 1611.00788]

New gauge formulation
[Cuomo, Vecchi, Wulzer, 1911.12366]

EW PDF at muon collider
[Han, Ma, Xie, 2007.14300]

EW Soft effects
[Cen, Glioti, Rattazzi, Ricci, Wulzer, 2202.10509]



arXiv:2203.07256v1 Muon Collider Physics Summary

Detectors

Handling a new environment

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19. Al Ali, et al. “The muon smasher guide”, 2103.14043 [hep-ph]

Detailed studies about BIB mitigation at 1.5 and 3 TeV available as well as in physical studies (HH).
Concrete proposal for detector design and technologies for R&D is now available.

Final considerations

Muon Collider

- Enthusiastic return from the theory community on the opportunities that a muon collider will open up to explore the energy frontier after what we have learnt from the HL-LHC.
- **A Multi-TeV MuC is a space-time compact collider**, **energy upgradable**, with the unique ability to act as a lepton collider as well as a VV collider.
- In the last two years a wealth of phenomenological explorations have clearly indicated how rich the physics program of a 10 TeV/10 iab machine will be.
- Advances in detector and accelerator pair with the opportunities of the physics case