LoIs on Muon Collider Physics

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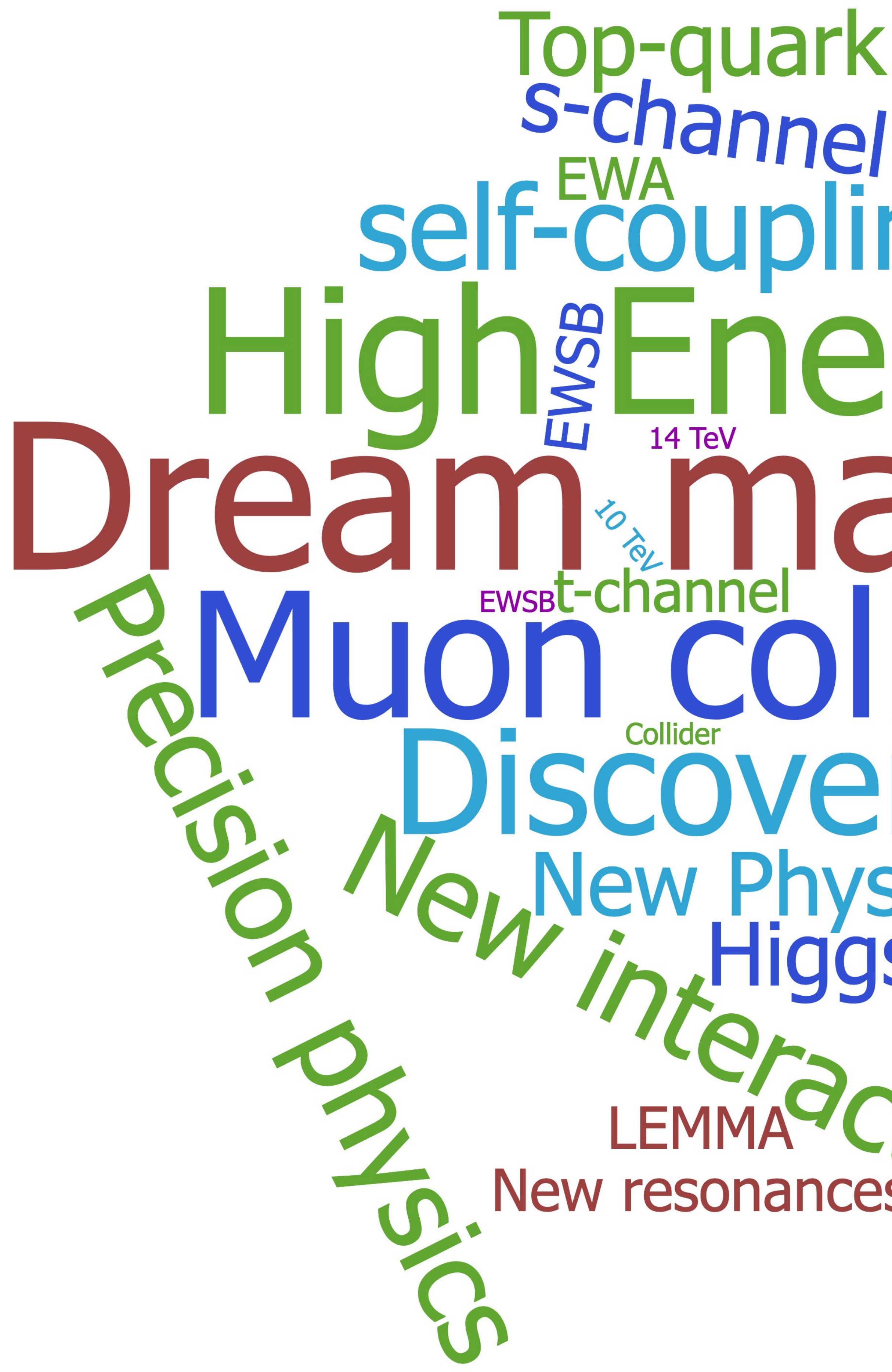
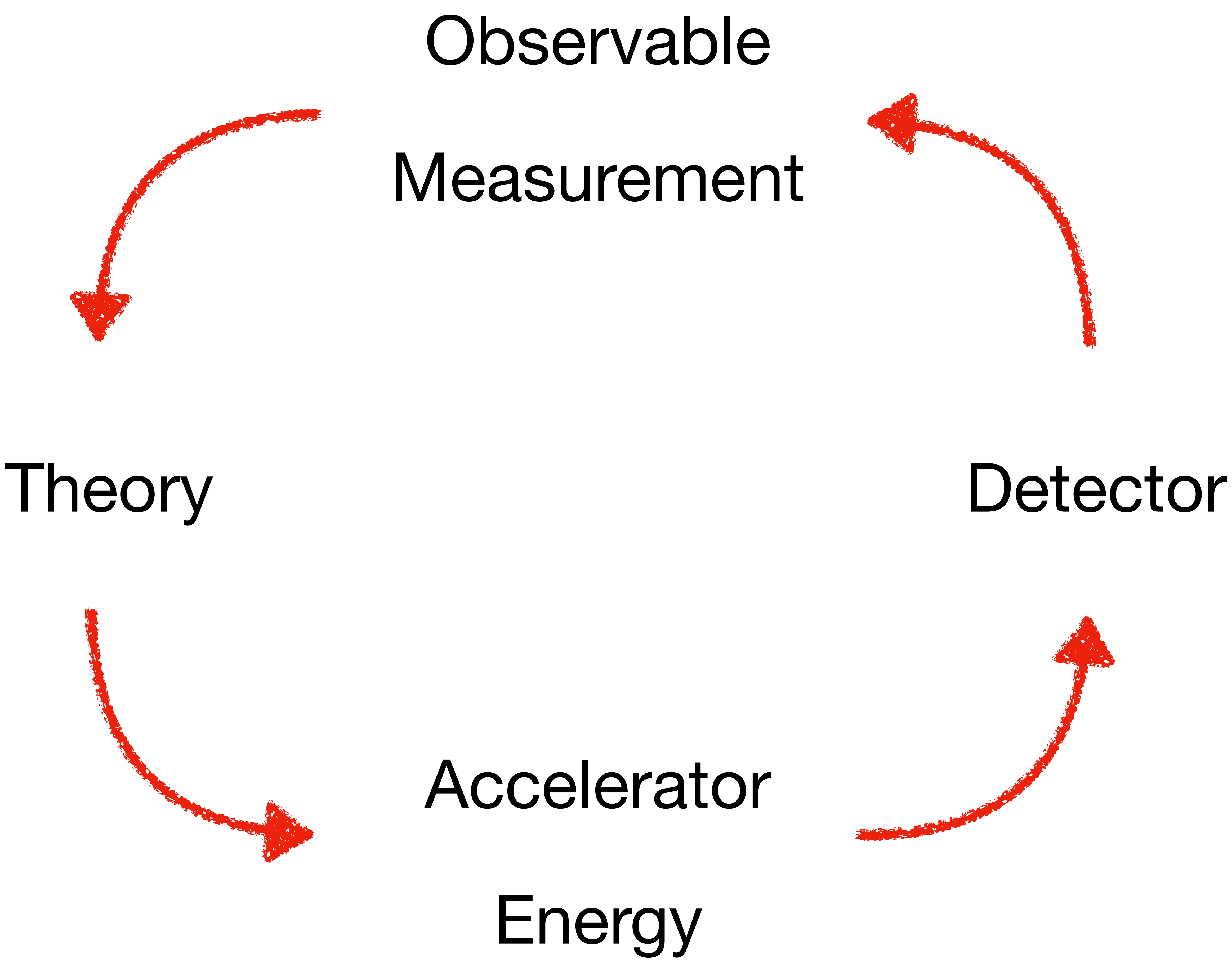
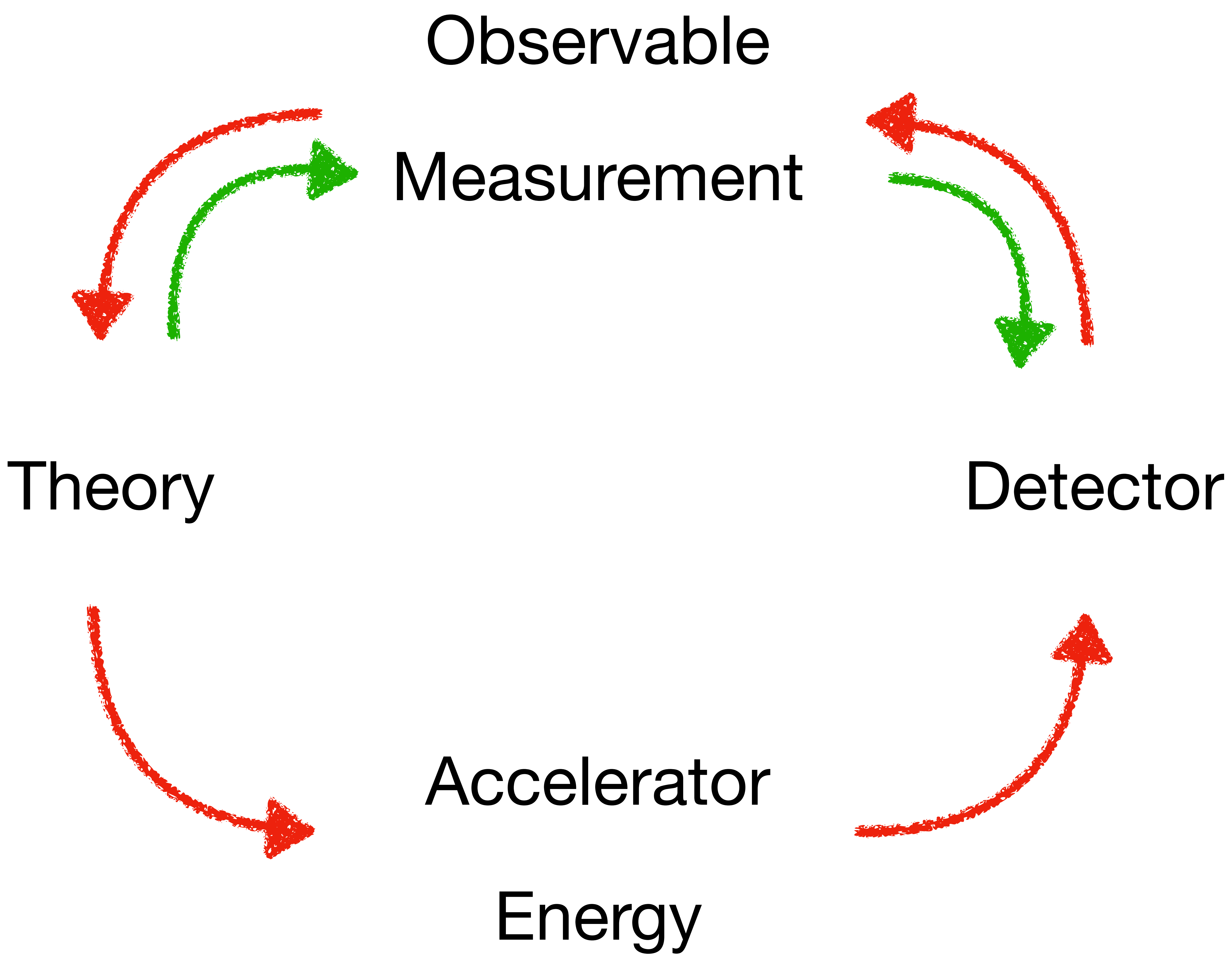


Triggering the virtuous circle



Triggering the virtuous circle



Letter of Interest: Muon Collider Physics Potential

D. Buttazzo, R. Capedevilla, M. Chiesa, A. Costantini, D. Curtin, R. Franceschini, T. Han, B. Heinemann, C. Helsens, Y. Kahn, G. Krnjaic, I. Low, Z. Liu, F. Maltoni, B. Mele, F. Meloni, M. Moretti, G. Ortona, F. Piccinini, M. Pierini, R. Rattazzi, M. Selvaggi, M. Vos, L.T. Wang, A. Wulzer *, M. Zanetti, J. Zurita

On behalf of the forming muon collider international collaboration [1]. * **wulzer@cern.ch**

We describe the plan for muon collider physics studies in order to provide inputs to the Snowmass process. The goal is a first assessment of the muon collider physics potential. The target accelerator design center of mass energies are 3 and 10 TeV or more [2]. Our study will consider energies $E_{\rm CM} = 3, 10, 14$, and the more speculative $E_{\rm CM} = 30$ TeV, with reference integrated luminosities $\mathcal{L} = (E_{\rm CM}/10\ {\rm TeV})^2 \times 10\,{\rm ab}^{-1}$ [3]. Variations around the reference values are encouraged, aiming at an assessment of the required luminosity of the project based on physics performances. Recently, the physics potentials of several future collider options have been studied systematically [4], which provide reference points for comparison for our studies.

Submitted by Andrea Wulzer as LoI to the EF/TF/AF

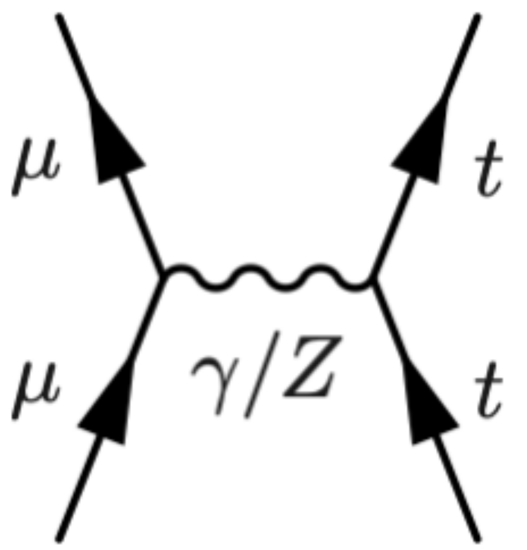
Reach of direct searches

Reach of the direct search for heavy new physics particles. This will be a main strength of the muon collider running at multi-TeV energies. Selected study topics include:
1) SUSY. The reaches for the stop, other sfermions, and EW-inos will be estimated, possibly including R-parity-violating signatures. Scenarios with well separated to compressed particle spectra will be considered, which will require significantly different strategies and challenge the detector performances (see below). The lessons learned from SUSY benchmarks will be also useful for the study of other new physics scenarios.
2) Minimal WIMP dark matter scenarios. Many of the simplest WIMP dark matter scenarios put its mass in the multi-TeV range, within the reach of a high energy muon collider. They often feature a highly compressed spectrum. Direct reach can be based on stub-tracks, as well as more inclusive search channels, such as the mono-X. Indirect searches can also be sensitive [5]. Possible benchmarks include the Minimal DM [6] in which the dark matter resides in an electroweak multiplet, as well as the Coannihilation [7] and well-tempered [8] scenarios. See also [9, 10]
3) Heavy particle production in Vector Boson Fusion (VBF), including $\gamma\gamma$ initial state. VBF is instrumental at a high energy muon collider. Its potential in the singlet searches has been demonstrated [11,12]. An assessment of the VBF opportunities for direct new physics searches, by extending and refining Ref. [13], will be performed. This might impact the studies in “1” and ”2”.

Muon collider physics 101

s-channel vs t-channel

$\sqrt{s} \lesssim$ 1-5 TeV

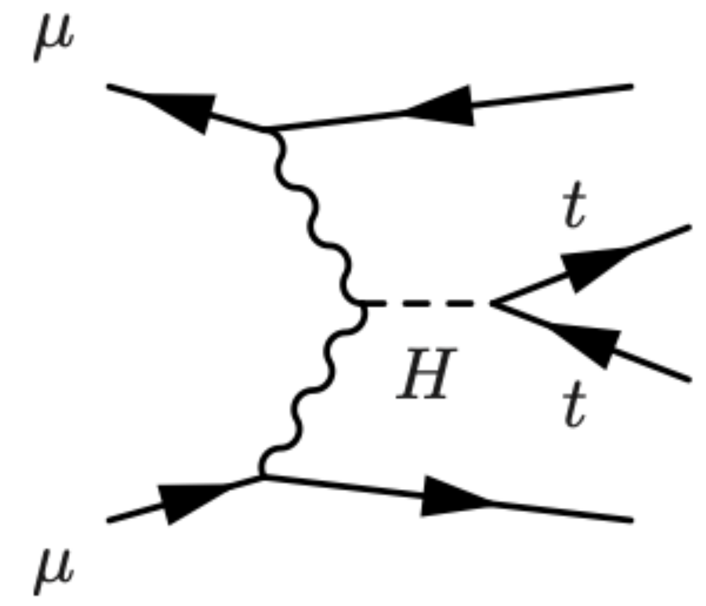


$$\sigma_s \sim \frac{1}{s}$$

⟷

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

$\sqrt{s} \gtrsim$ 1-5 TeV

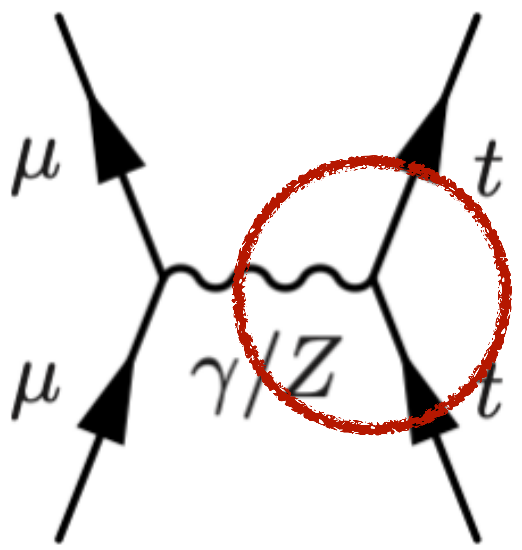


[Costantini et al. 2005.10289]

Muon collider physics 101

s-channel vs t-channel

$\sqrt{s} \lesssim$ 1-5 TeV



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

↔

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

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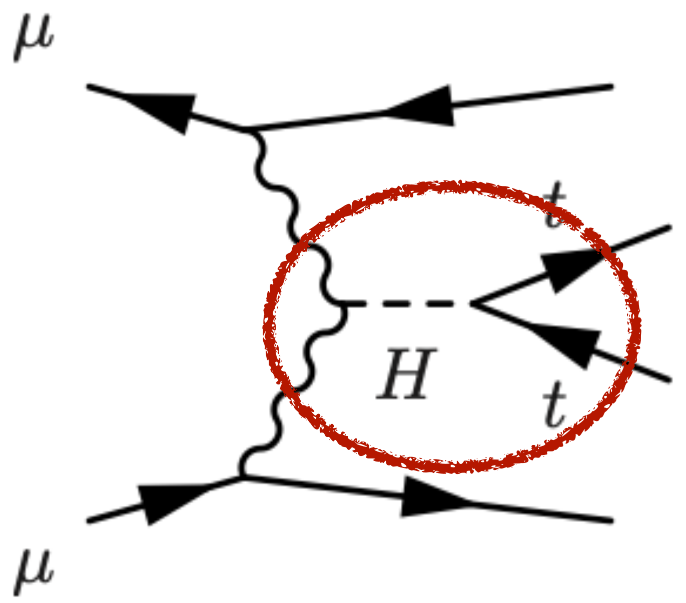

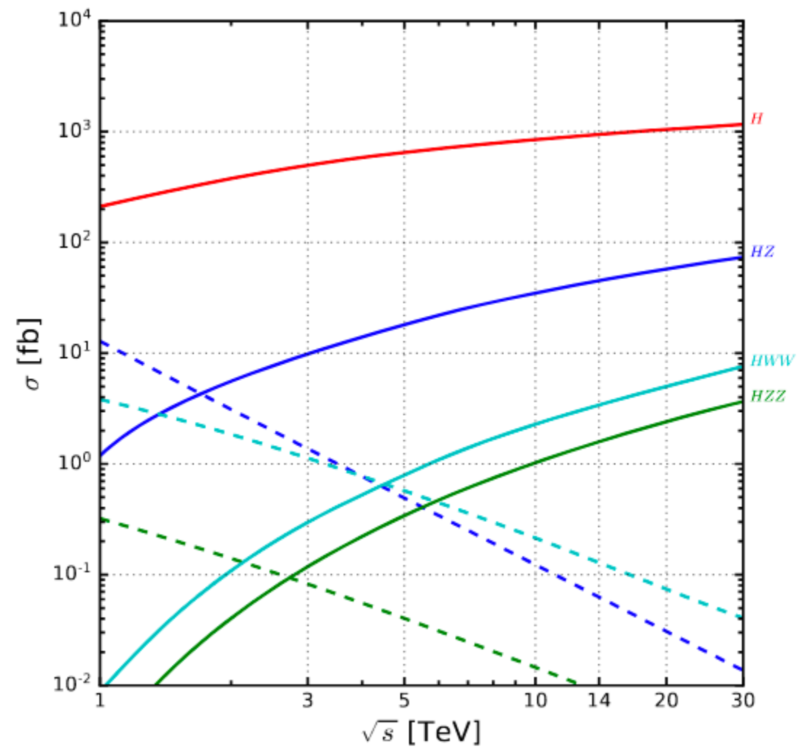

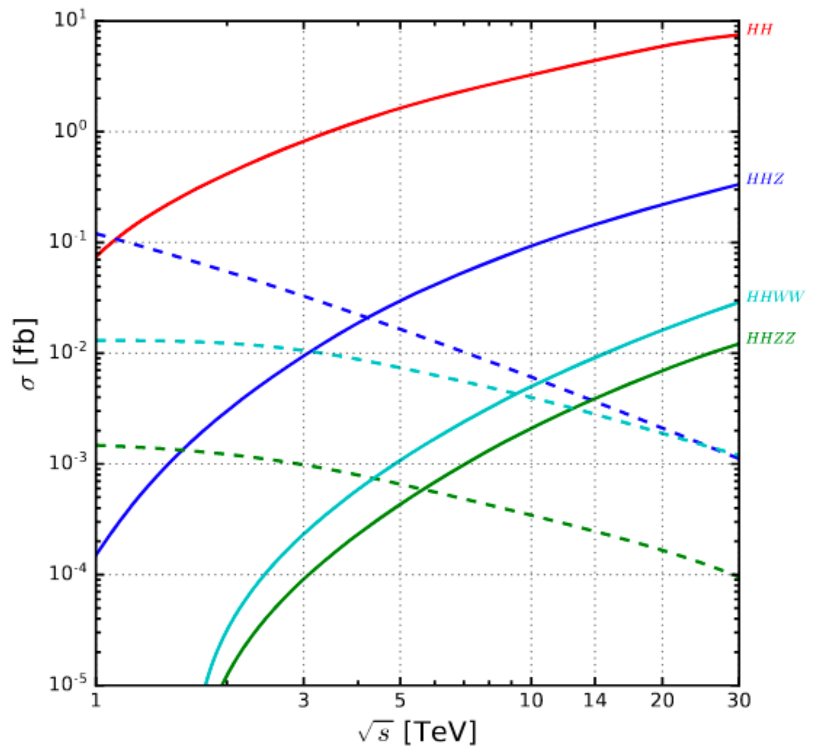

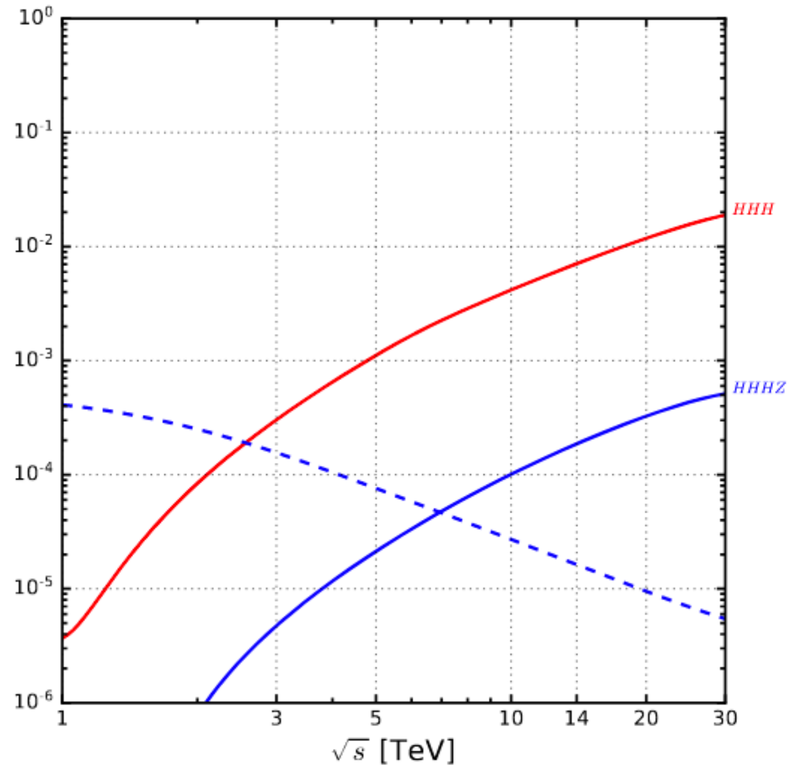

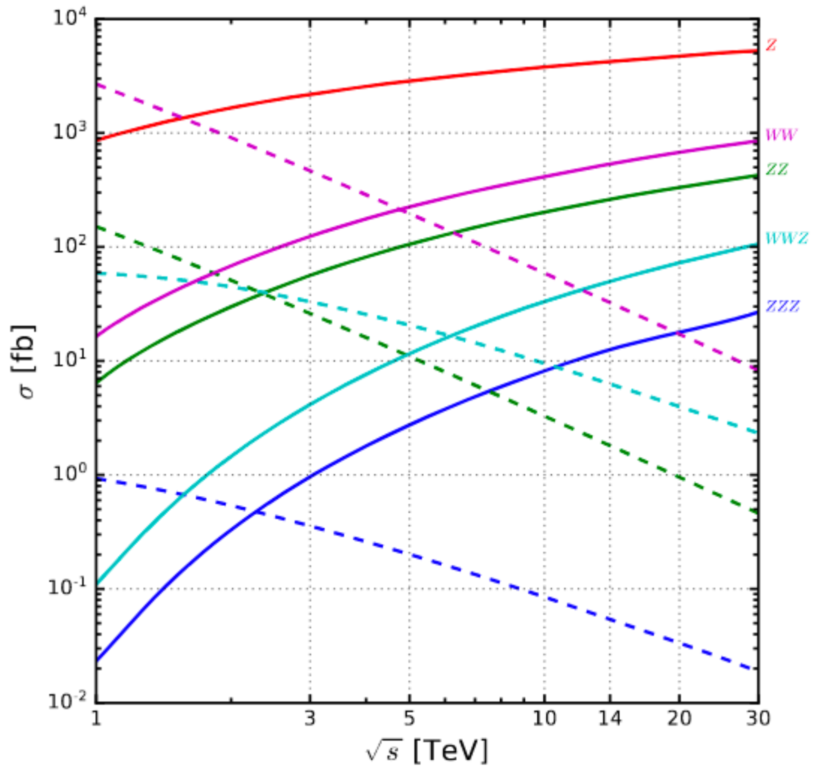

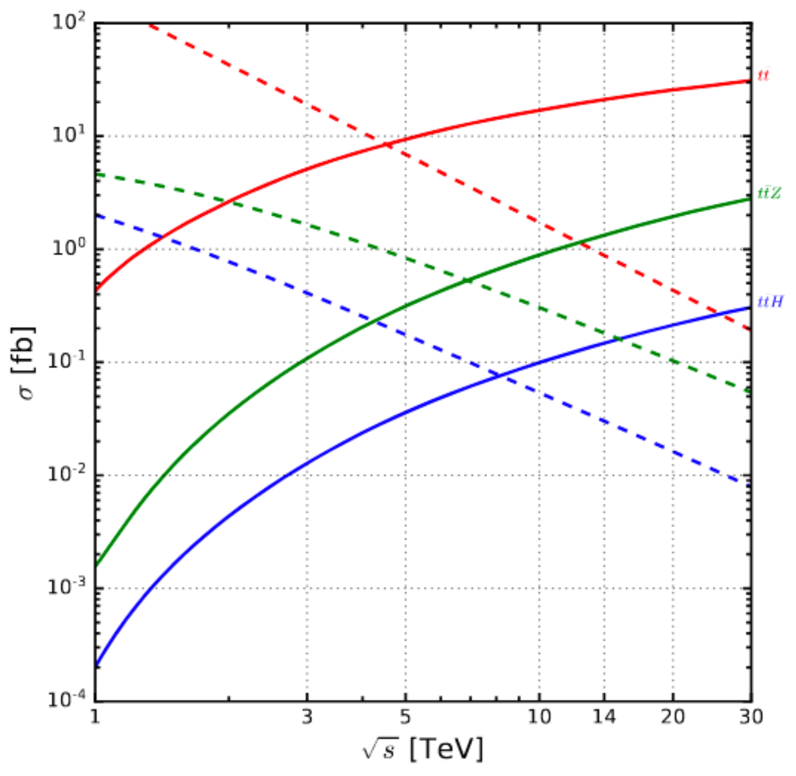

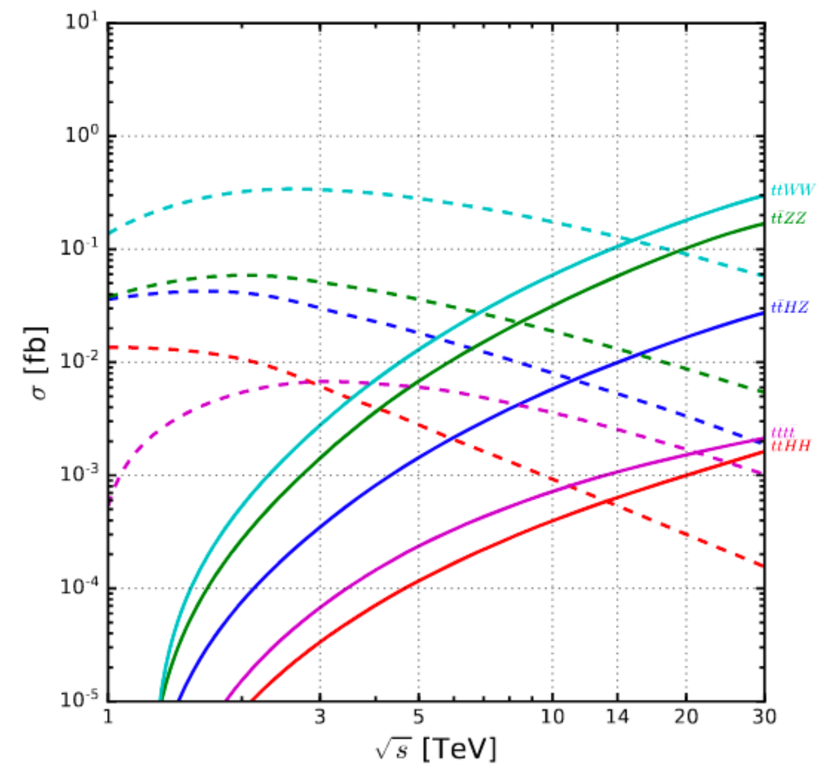

[Costantini et al. 2005.10289]

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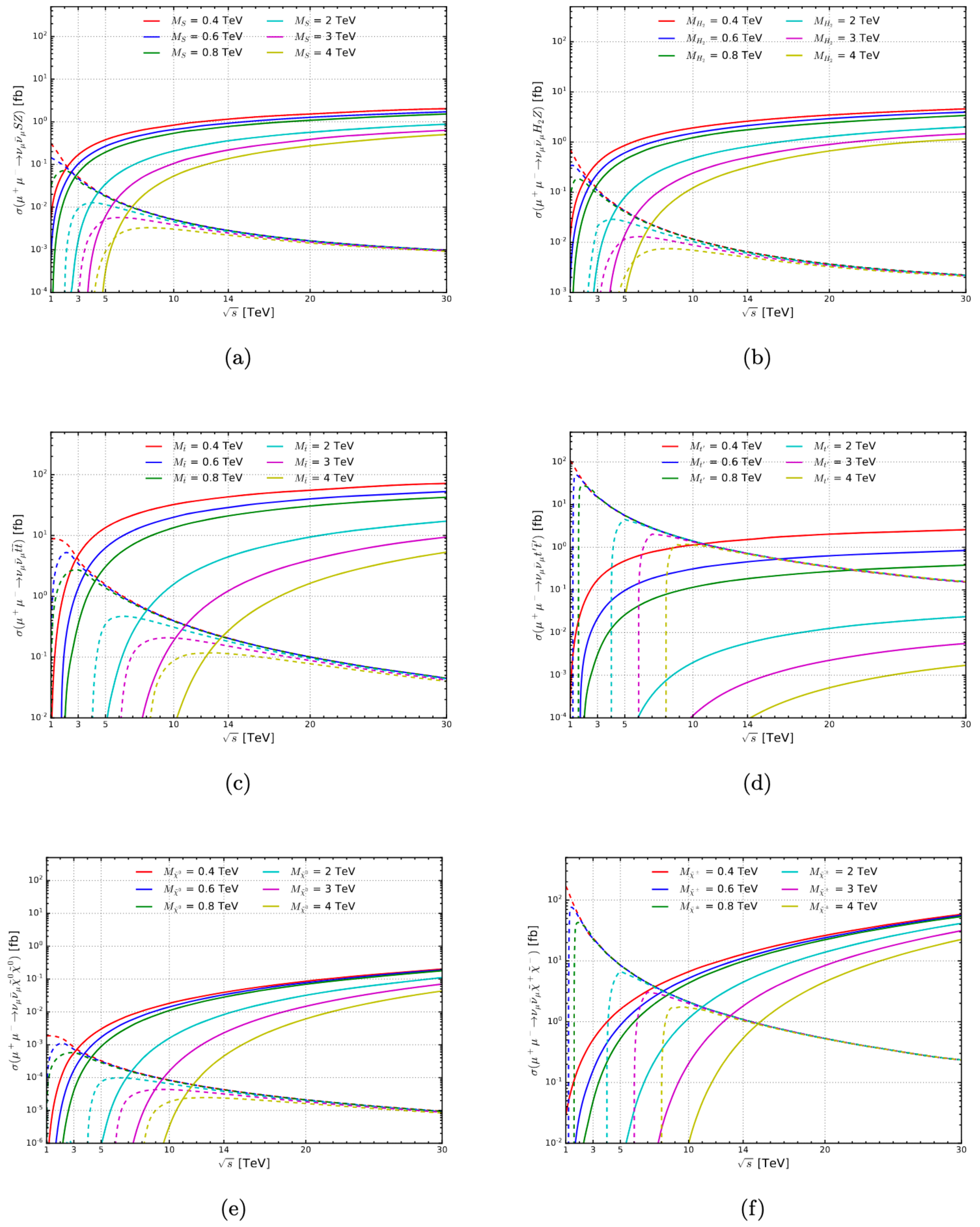
BSM exploration



(a) Singlet production

(b) HZ in 2HDM

(c) $\tilde{t}\tilde{t}*$

(d) $t'\bar{t}'$

(e) $\tilde{\chi}^0\tilde{\chi}^0$

(f) $\chi^+\chi^-$

Sample of BSM processes explored s-channel vs t-channel. Just scratched the surface. Proof of principle: no technical problems encountered.

Opens the way for more studies from the BSM community and prepare representative BSM scenarios to be identified and used as “official” benchmarks.

High energy measurements

High energy measurements. Cross-sections at the highest available energies offer tremendous indirect sensitivity to very heavy new physics. This will be substantiated by the following study. **4)** Effective Field Theory (EFT) sensitivity of high energy di-boson/di-fermion production cross-section, with interpretation in Composite Higgs (and Top) and simple Z' models. The interplay with direct searches will also be explored. Low-energy (e.g., Higgs couplings) and intermediate-energy (e.g., VBF double-Higgs at TeV energies [14]) probes will be also exploited.

Precision Higgs

The precision measurement of the Higgs couplings. The muon collider with the baseline energies and luminosities will produce a large number of Higgs bosons, from 10^5 at 3 TeV to more than 10^7 at 10 TeV and above. We will study how to fully take advantage of this opportunity.The main targets of the study are:

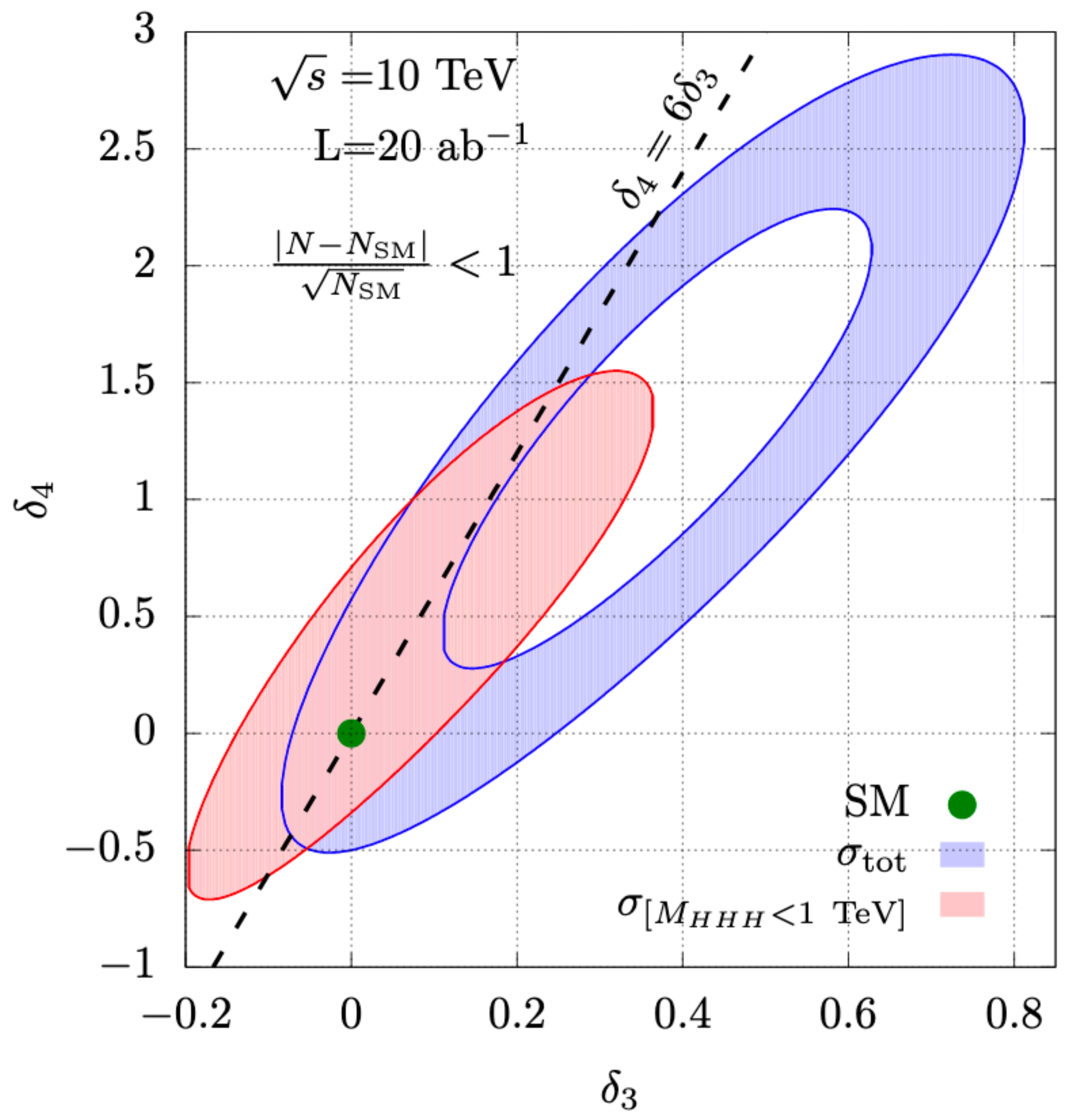
5) Projections of the precision of single Higgs coupling measurements, with EFT interpretation for a comparison of the sensitivity with other probes such as those at point "4". Unlike the other proposed (e^+e^-) Higgs factories running at lower energies, the main Higgs production mode would be vector boson fusion instead of higgsstrahlung. The implications of this difference will be carefully investigated. The possible complementarity with low-energy Higgs factories, probably constructed before the muon collider, will be investigated.

6) Higgs self-coupling measurements. The muon collider at 10 TeV would produce 3×10^4 double Higgs events, which offers a golden opportunity for Higgs trilinear coupling measurements [16]. The quadrilinear Higgs coupling could also be measured in triple-Higgs events [15]. We aim at realistic sensitivity projections including differential analysis, Higgs decays and backgrounds. We will interpret the findings in concrete new physics scenarios. We will also assess the interplay with direct searches for the degrees of freedom responsible for the self-coupling modifications, which are very effective at the muon collider due to the high mass-reach.

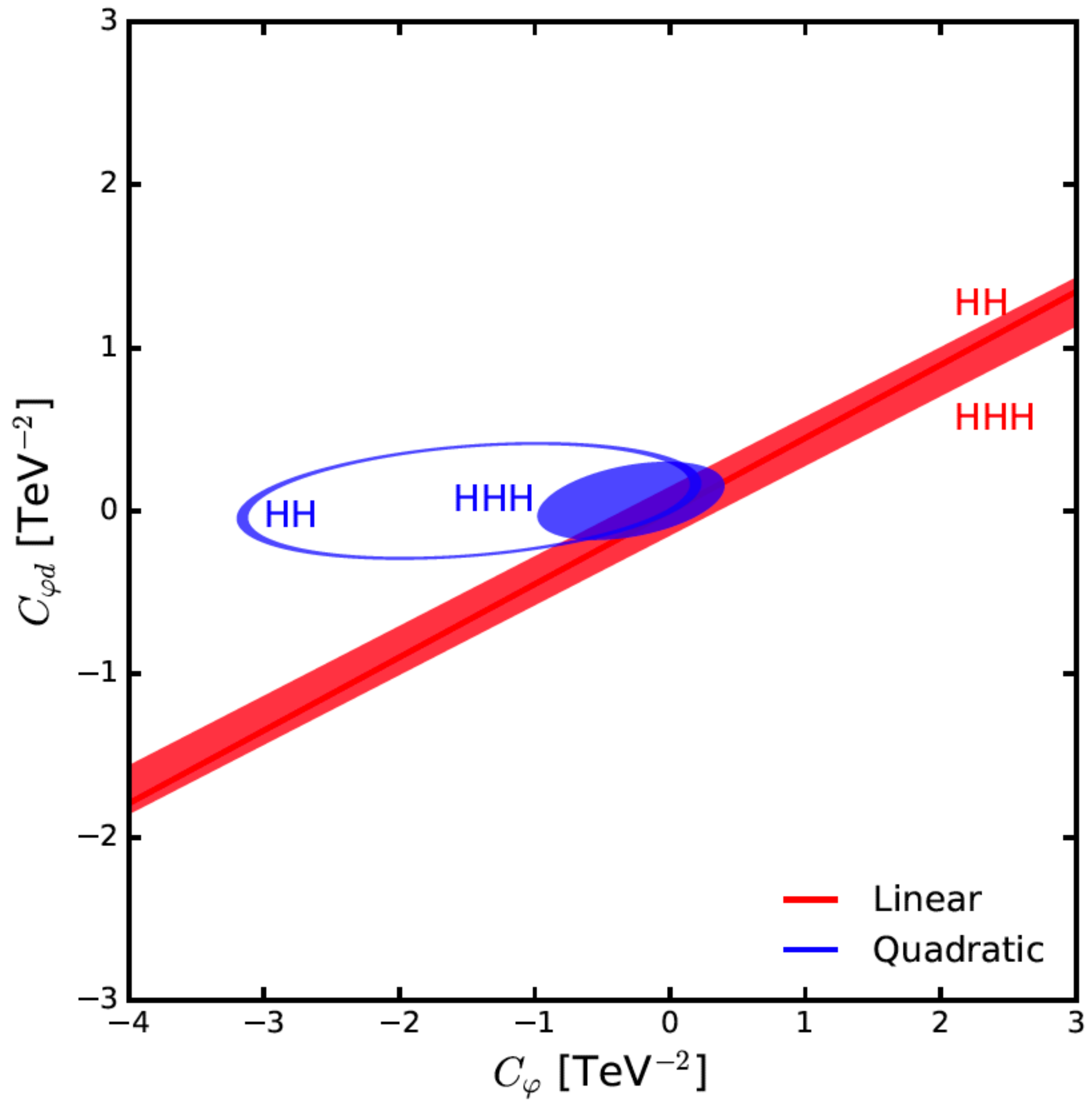
Higgs couplings

Example: Sensitivity to the Higgs self-interactions

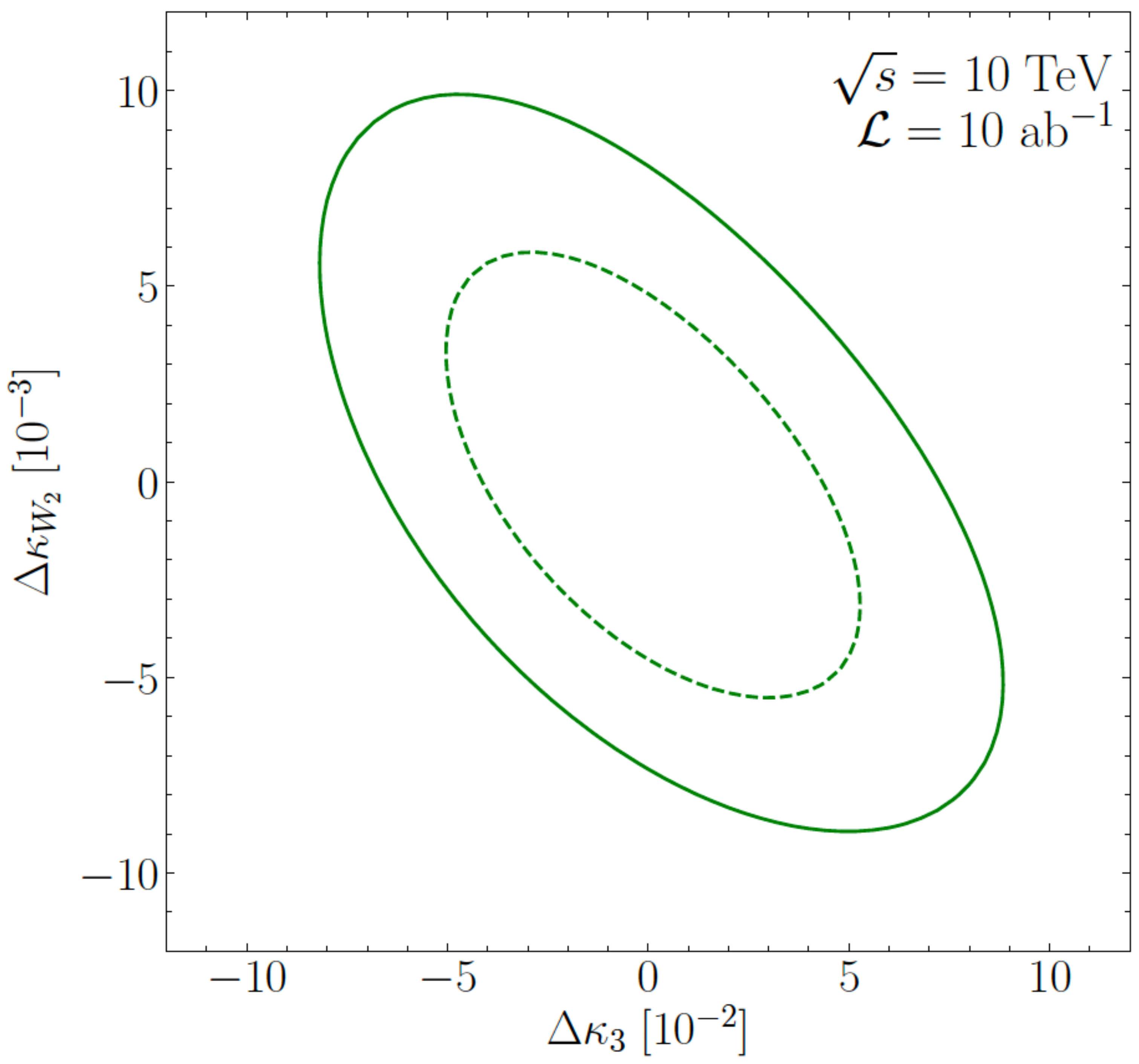
[Chiesa et al. 2003.13628]



[Costantini et al. 2005.10289]



[Han et al. 2008.12204]



(c)

Exotica

More exotic possibilities. We will study several scenarios of new physics with unique signals. The goal here is to showcase the rich physics program we could have at a muon collider, and to offer additional targets for detector studies.

7) Higgs exotic decay. Lepton colliders such as the e^+e^- Higgs factories can have good sensitive to a variety of Higgs exotic decay channels [16]. A muon collider running at high energies will produce one to two orders of magnitude more Higgs bosons. It has the potential of significantly enhancing the sensitivity. Higgs decays to Long-lived particles, which are ubiquitous in dark sector models, will be also considered. A common benchmark is the Higgs portal decay $h \to XX$ with X being long lived. With 10^7 to 10^8 Higgs bosons, the muon collider could be competitive with other projects.

MC simulations

Standard tools such as WHIZARD [17] and MadGraph5_aMC@NLO [18] are already available for signal and (physics) background simulations at the muon collider. Work is ongoing to include in MadGraph5_aMC@NLO the generation of Initial State Radiation and (when available) the Beam Energy Spectrum. Notice that both effects are reduced in comparison with high-energy e^+e^- colliders, with potential advantages on some aspects of the physics reach. ISR-based (i.e., from radiative return) $2 \to 1$ BSM production should be also studied [19].

On the other hand, computation of cross sections and simulations of VBF processes at such high energies pose new challenges. Potentially large electroweak logarithms $\log(s/m_W^2)$ (and QED $\log(s/m_\mu^2)$ logs) may be generated, making on the one hand the fixed order simulations hard to converge, and on the other hand possibly affecting the accuracy of the predictions at fixed order. The implementation of the equivalent W, Z, γ approximations are available both in WHIZARD and MadGraph5_aMC@NLO. A systematic comparison of the reliability of these approximations is planned. In addition, the effects of the resummation of the large logarithms at high energy have started to be explored [20], and their impact on the accuracy of the total cross section will be studied.

MonteCarlos

- Event generation at LO based on matrix elements available (e.g. MadGraph and Whizard) for s-channel

  - $\mu^+\mu^- \to X$

  and t-channel (MadGraph and Whizard)

  - $\mu^+\mu^- \to X + \nu_\mu \bar{\nu}_\mu$ W·W fusion
  - $\mu^+\mu^- \to X + \nu_\mu \mu$ W·Z/γ* fusion
  - $\mu^+\mu^- \to X + \mu \bar{\mu}$ Z/γ*·Z/γ* fusion

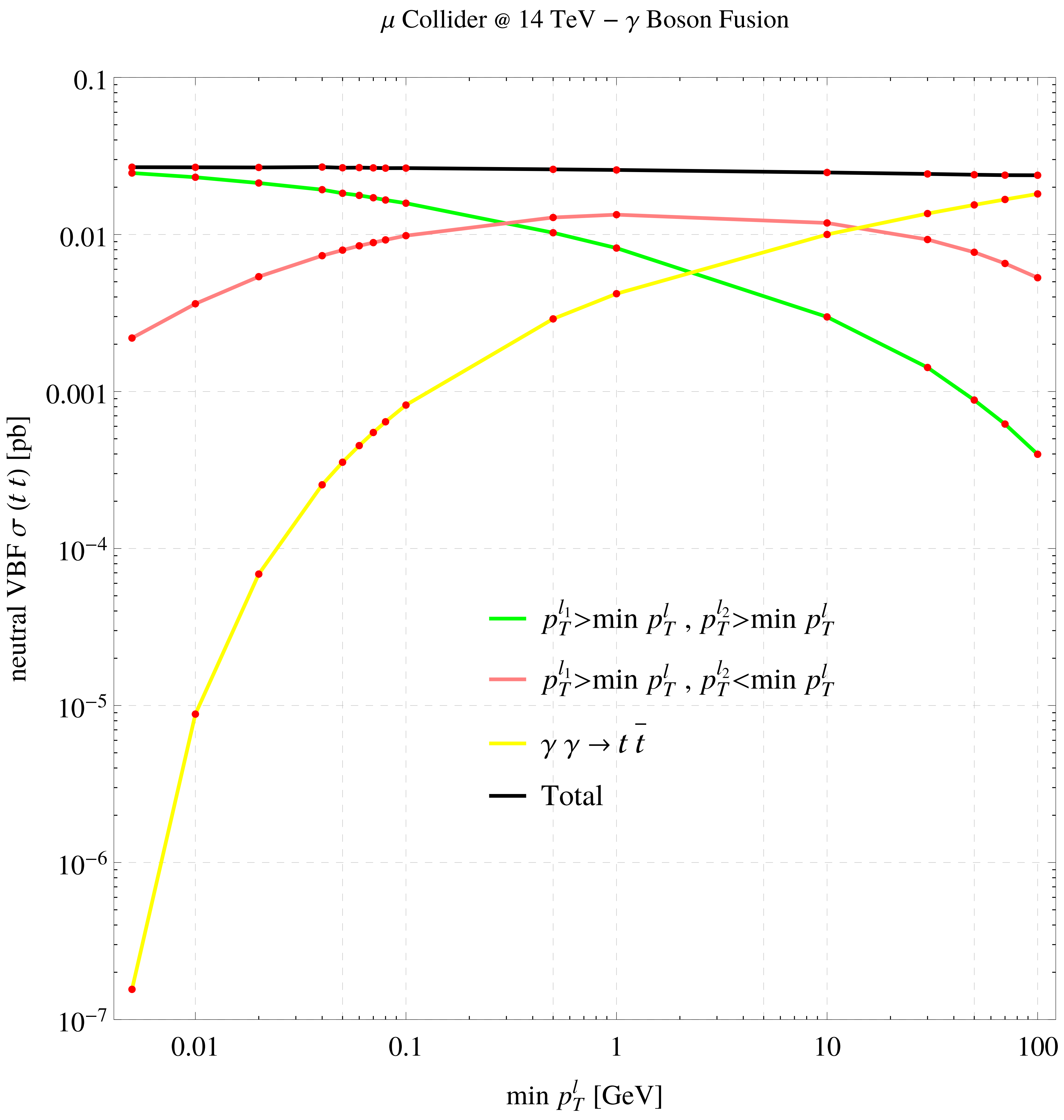
Recent Examples:

- 2006.16277 * Capdevilla et al. (MadGraph)
- 2005.10289 * Costantini et al. (MadGraph)
- 2003.13628 * Chiesa et al (MadGraph and Whizard)
- 2002.12218 * Kumar et al. (MadGraph)
- 2001.04431 * Bartosik et al. (Pythia8)
- 1810.10993 * Di Luzio et al. (by hand)
- 1807.04743 * Buttazzo et al. (MadGraph)
- more…

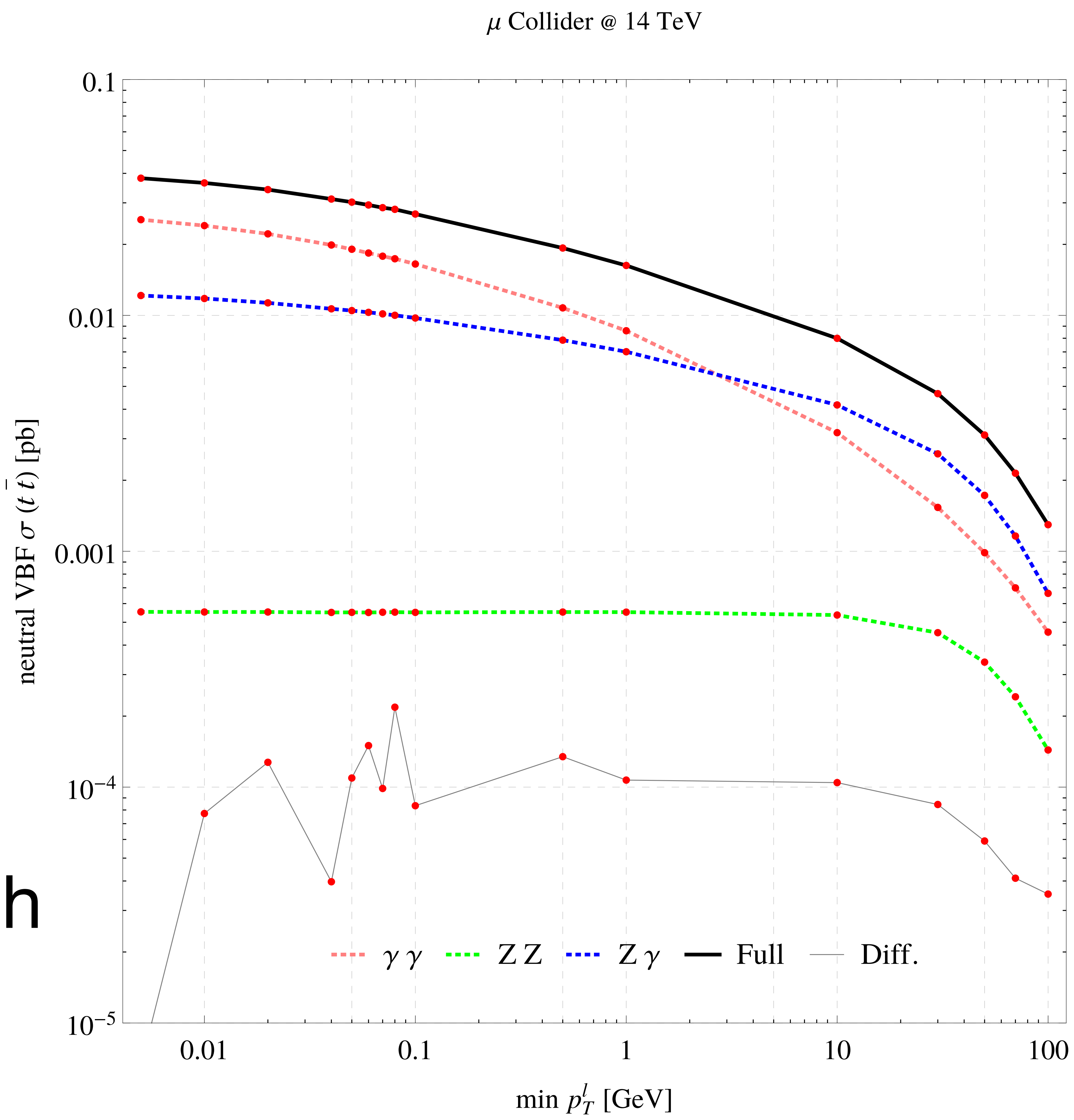
- EWA/EZA(/EPA) LL implementations being validated in MadGraph to be compared with available resummed results [Han, Ma, Xie, to appear].

- BSM scenarios including EFT available in FeynRules/MadGraph

W,Z,γ as partons



MadGraph



Fast detector simulation with DELPHES

A parametric modeling of the detector response, in terms of high-level objects efficiencies and reconstruction performances, is needed for a realistic assessment of the physics potential including physics backgrounds (as opposite to Beam-Induced Backgrounds (BIB)). This will be provided by a DELPHES [21] card, which we will prepare and maintain. The first version of the card will incorporate "target" performances of high level objects (tracking, lepton and photon identification, jet reconstruction and heavy flavour tagging), that are comparable with those of present detectors and of future projects, and supposedly sufficient to achieve the physics goals.

The "target" detector is expected to provide realistic results for the majority of the studies described in Section 1. However, the BIB might pose significant challenges on the reconstruction and identification (heavy-flavour tagging for example) of low pT objects produced in the compressed decay regime of item "1" and the Higgs decay products (e.g., the bottom quarks, for which BIB-aware studies exist [22], see also [23]) in items "5" and "6". Forward- or backward-produced particles could be also difficult to see because of the reduced angular acceptance of the detector due to the radiation-absorbing nozzles in the current designs. Finally, BIB is definitely crucial for certain aspects of the physics potential, such as the study of disappearing tracks in item "2", and of long-lived particles in item "7". The impact on the physics reach of these aspects will be monitored, also by progressively updating the DELPHES card as the detector studies proceed [24], in order to link the design of the machine and the detectors to the physics goals.

Letter of Interest: Tau-neutrino Production at a multi-TeV Lepton Collider

GaetanoMarco Dallavalle, Fabio Maltoni, Silvia Pascoli, Antonio Sidoti

to be submitted to

the Accelerator Frontier (AF04), Energy Frontier (EF03), and Neutrino Frontier (NF06)

TeV-neutrino interactions in the laboratory are uncharted physics [1]: muon neutrinos have been studied up to about 350 GeV, electron neutrino measurements only exist at lower energies, Experiments being planned at LHC have the potential to fill in the energy gap between 350 GeV and a few TeV, and test different neutrino flavours [7–9]. Their detectors will intercept the flux of neutrinos from b and c decays, and those from pion and kaon decays. However the sample of observed tau-neutrino interactions in the LHC Run 3 (2022-2024) is expected to be marginal for precision measurements. Extension of those experiments in the High Luminosity LHC era beyond 2028 is unlikely, because the LHC environmental background will become prohibitive, ten times worse than at the LHC.

We would like to propose a Snowmass activity on the opportunities for neutrino tau flavour studies at present and future colliders. More specifically, here we express our interest in investigating tau neutrino production in the process W^+W^- at future high-energy lepton colliders, such as a muon collider.

SNOWMASS21-AFF4_AFF0-EFF3_EF0-NF6_NF10-081

Muon Collider: Study of Higgs couplings and self-couplings precision

C. Aimè[a], F. Balli[b], N. Bartosik[c], L. Buonincontri[d], M. Casarsa[e], M. Chiesa[f], F. Collamati[g], C. Curatolo[d], D.Lucchesi[d], B. Mele[g], F. Maltoni[h], B. Mansouliè[b], A. Nisati[g], N. Pastrone[c], F. Piccinini[i], C. Riccardi[a], P. Sala[l], P. Salvini[i], L. Sestini[m], I. Vai[a], D. Zuliani[d]

Abstract

The Higgs boson can be considered as a portal to new physics. The determination of its couplings to fermions and bosons and of its self-couplings constitute one of the fundamental tests of the mechanism at the basis of the Electroweak Symmetry Breaking. While the formers are expected to be measured with the necessary precision at any future collider, the latter, i.e. the full determination of the Higgs potential will be extremely challenging. In this letter we propose to determine the accuracy that could be reached at a muon collider on the Higgs couplings to b-quarks, W and Z bosons and to demonstrate that it will be possible to determine the Higgs potential by using the full simulation of the detector and taking into account the beam-induced background at $\sqrt{s}$ = 1.5 TeV, $\sqrt{s}$ = 3.0 TeV, and $\sqrt{s}$ = 10 TeV.

SNOWMASS21-EF2_EF1-TF7_TF6-139

Muon Collider: Study of methods for the luminosity measurement

C. Aimè[a], N. Bartosik[b], L. Buonincontri[c], M. Casarsa[d], M. Chiesa[e], C.M. Carloni Calame[a], F. Collamati[f], C. Curatolo[c], U. Dosselli[g], A. Ferrari[h], S. Giovannella[i], C. Giraldin[c], F. Happacher[i], G. Krintiras[l], D.Lucchesi[c], A. Mereghetti[m], S. Miscetti[i], G. Montagna[a], O. Nicrosini[n], N. Pastrone[b], F. Piccinini[n], C. Riccardi[a], P. Sala[o], P. Salvini[n], I. Sarra[i], L. Sestini[g], I. Vai[a], D. Zuliani[c]

Abstract

The renewed interest for the muon collider, in particular in the multi-TeV energy range is posing several unprecedented challenges to the HEP community. Among them there are the interaction region and the detector designs that have to cope with the very high fluxes of particles coming from the muon beams decays. In order to mitigate the effect of the beam-induced background on the detector performance an ad-hoc shielding structure has been designed whose side effect is to limits the detector acceptance in the forward regions and makes difficult to determine the integrated luminosity with the standard methods adopted by the LHC experiments [1].
In this letter we propose to study an alternative way to determine such a fundamental parameter, which **is** mandatory for almost all physics measurements.

SNOWMASS21-TF7_TF0-EF4_EF0-AF4_AF0-046

Letter of Interest: EW effects in very high-energy phenomena

C. Arina, G. Cuomo, T. Han, Y.Ma, F. Maltoni, A. Manohar, S. Prestel, R. Ruiz,
L. Vecchi, R. Verheyen, B. Webber, W. Waalewijn, A. Wulzer, K. Xie

to be submitted to the Theory Frontier (TF07) and Energy Frontier (EF04)

The purpose of this LoI is to undertake a critical assessment of recent progress towards studying EW effects in multi-TeV processes and to set goals for the coming years by identifying the hurdles and open questions. In this quest, it is important to stress the broad scope of this task, which ranges from the need for field-theoretic constructions such as factorization theorems to efficient Monte Carlo techniques. Such a broad-based approach is necessary for a precise description of EW interactions at high energies.

SNOWMASS21-TF7_TF0-EF4_EF0-AF4_AF0-046

Additional material