The Physics Potential of High-Energy Muon Colliders

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Università degli Studi di Padova

CERN

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Why Muons?

Leptons are the ideal probes of short-distance physics:

All the energy is stored in the colliding partons
No energy “waste” due to parton distribution functions
High-energy physics probed with much smaller collider energy

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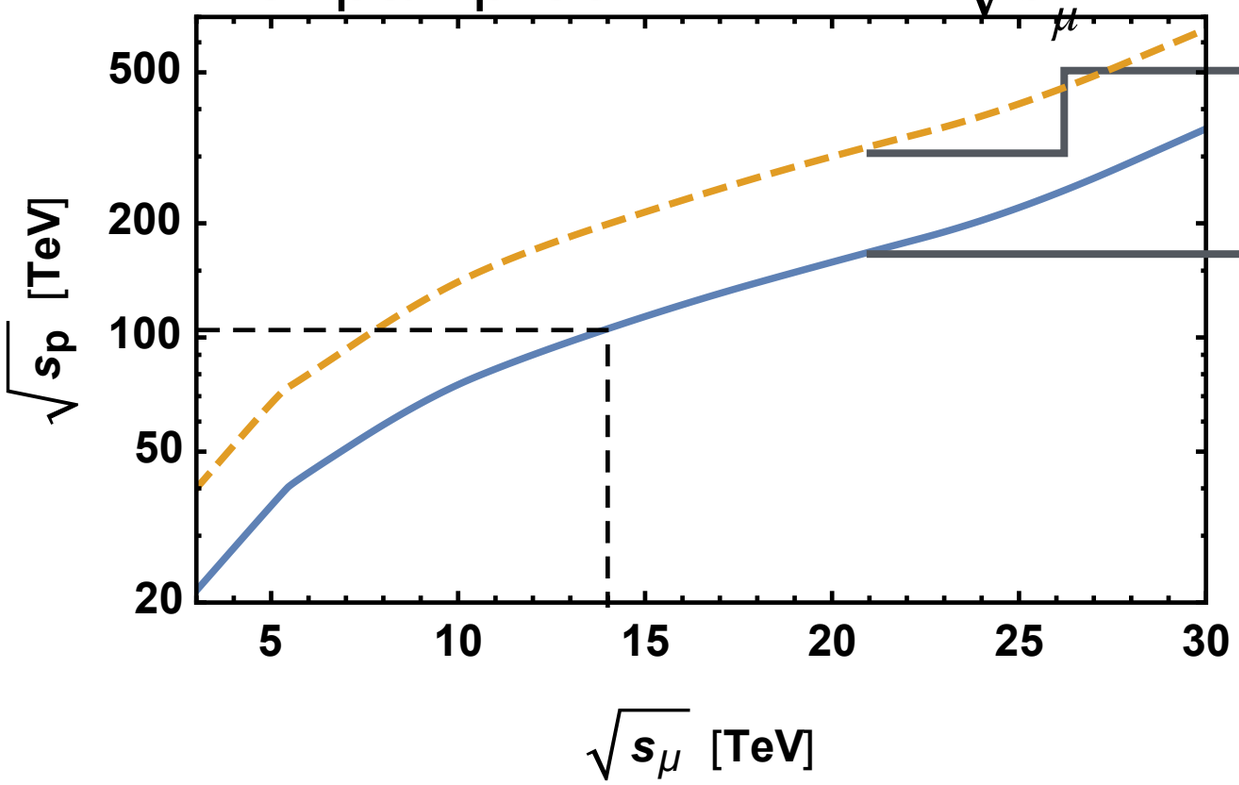

Estimate for EWK-only charged particles

Estimate for EWK+QCD-charged particles

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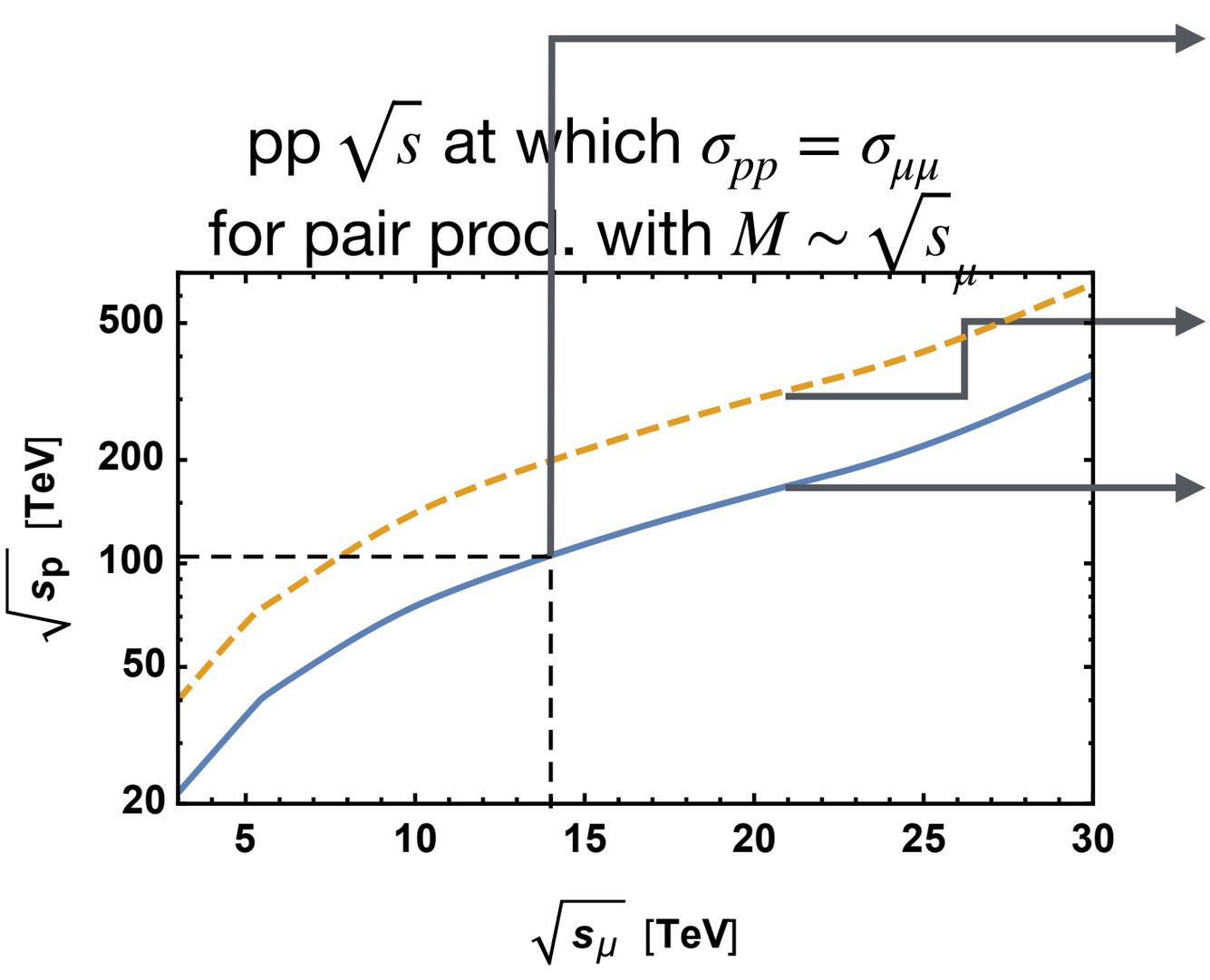

Reference Point:
14 TeV μ-collider ~ FCC@100 TeV

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Muon Colliders **Input to the European Particle Physics Strategy Update**

The Muon Collider Working Group
Jean Pierre Delahaye[1], Marcella Diemoz[2], Ken Long[3], Bruno Mansoulié[4], Nadia Pastrone[5] (chair),
Lenny Rivkin[6], Daniel Schulte[1], Alexander Skrinsky[7], Andrea Wulzer[1,8]

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Deliberation Document
on the 2020 update of the European Strategy for Particle Physics

- an international design study for a muon collider, as it represents a unique opportunity to achieve a multi-TeV energy domain beyond the reach of e+e– colliders, and potentially within a more compact circular tunnel than for a hadron collider. The biggest challenge remains to produce an intense beam of cooled muons, but novel ideas are being explored;

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Letter of Interest: Muon Collider Physics Potential Link

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]

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.

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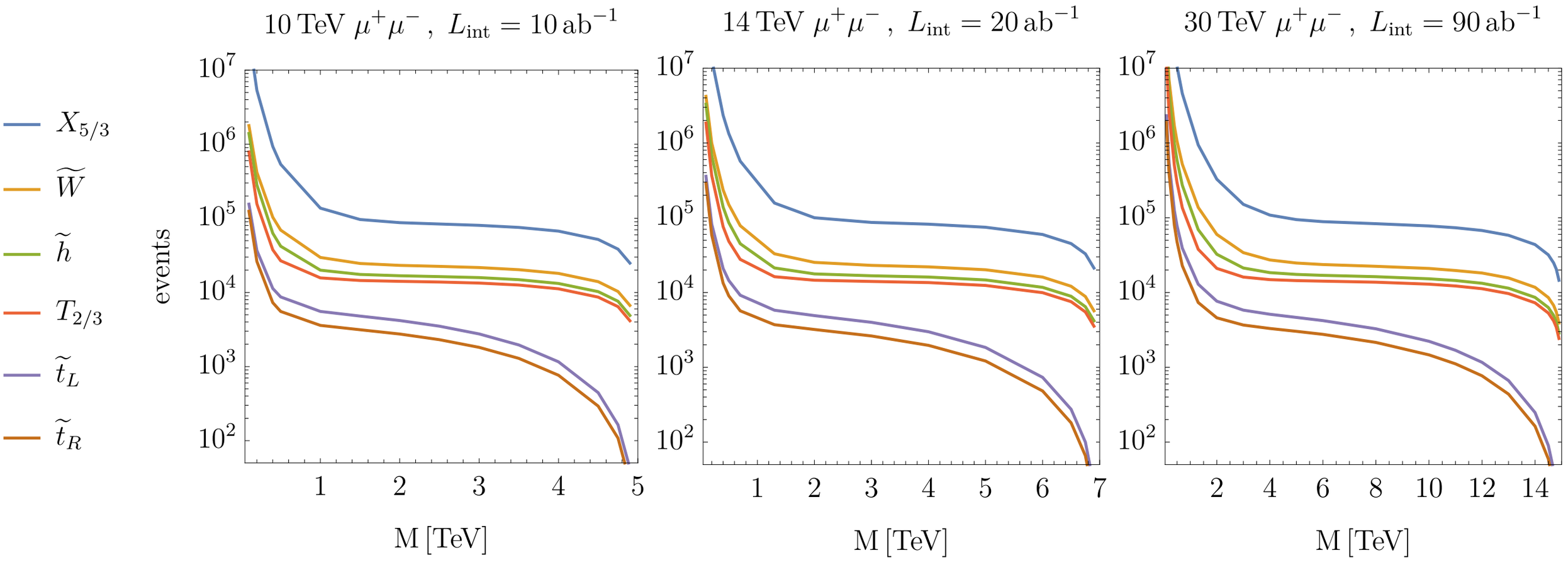
Muon Collider Physics Potential Pillars

Direct search of heavy particles	High rate indirect probes	High energy probes
SUSY-inspired, WIMP, VBF production, 2->1	Higgs single and self-couplings, rare Higgs decays, exotic decays	difermion, diboson, EFT, Higgs compositeness

The case for direct searches

EW pair-produced particles up to kinematical threshold



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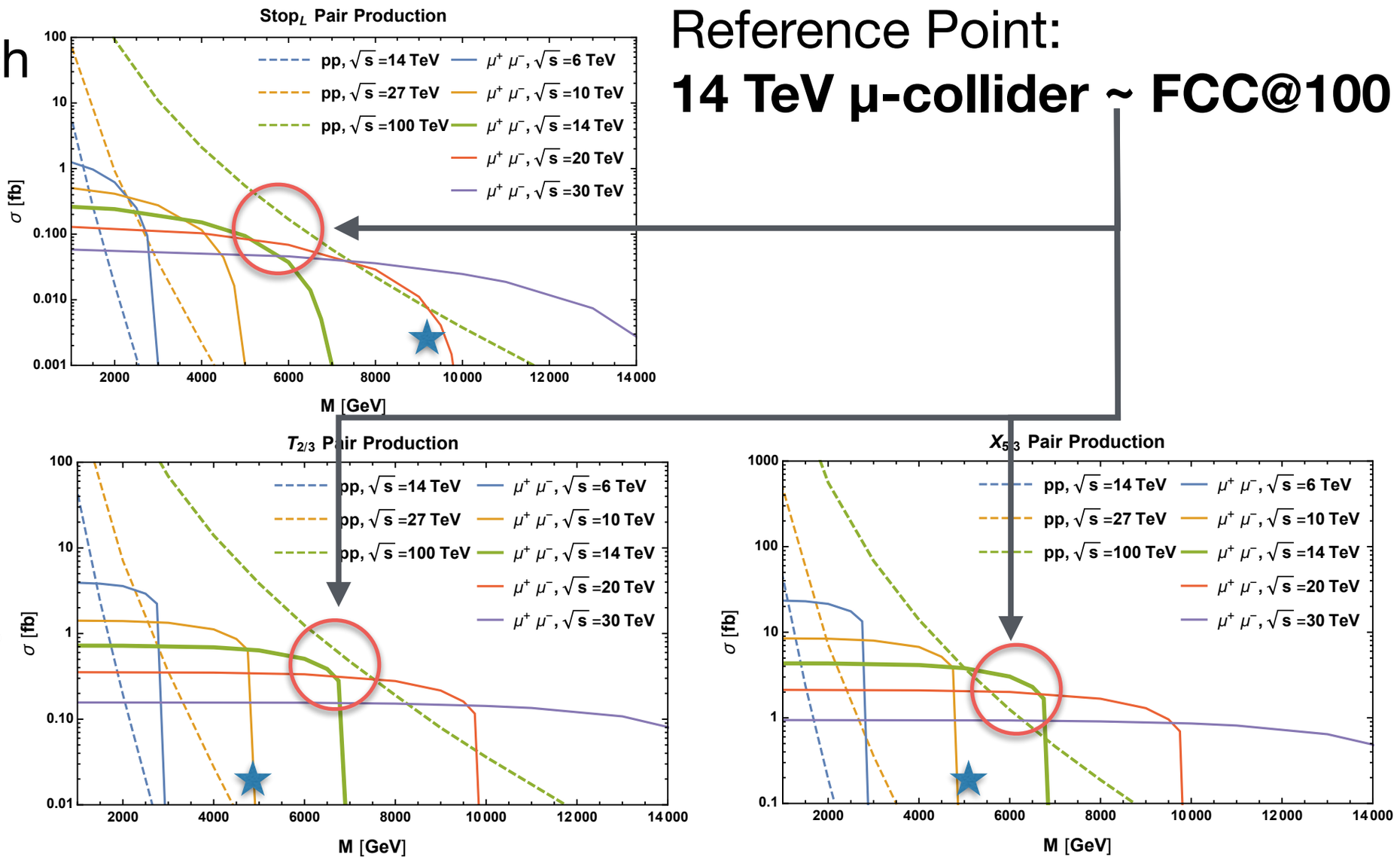
Striking for 10+TeV

Examples:

★ = FCC reach

Stop

Top-Partners



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Comparison even more favourable for EWK-only part. like **Higgsino** and **Wino** (potential **Dark Matter**)

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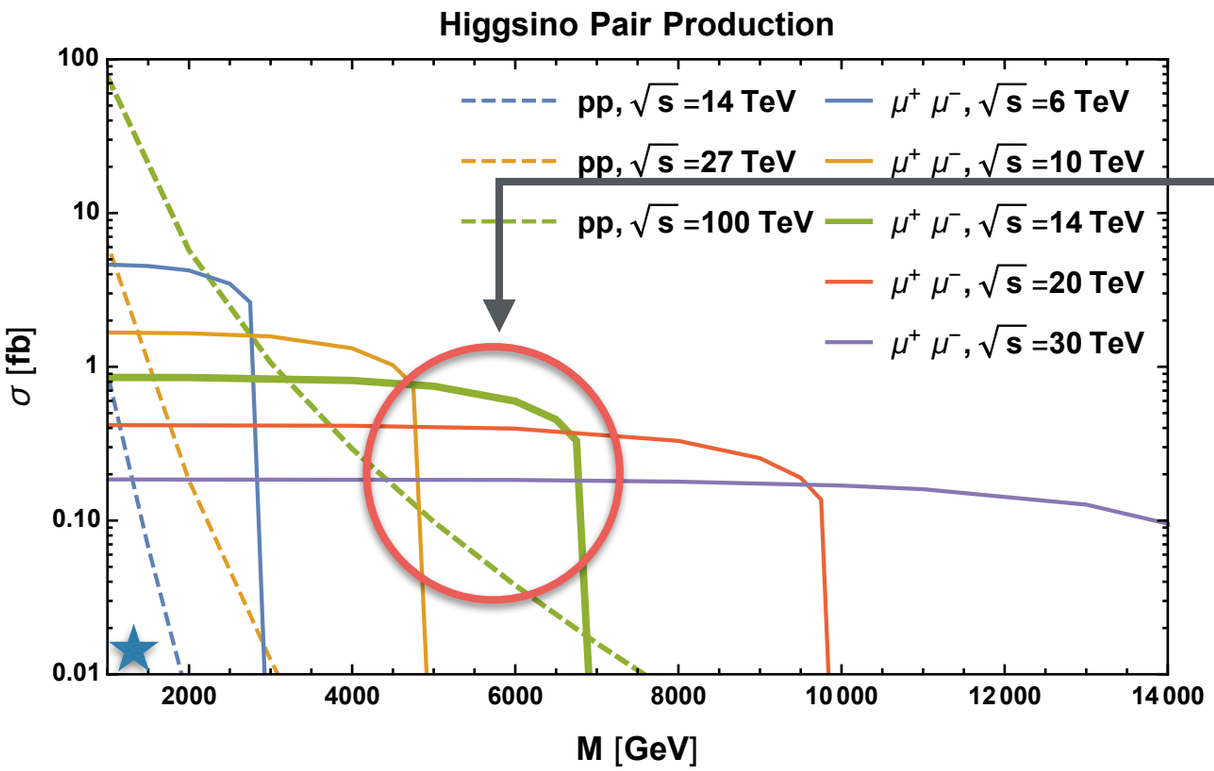

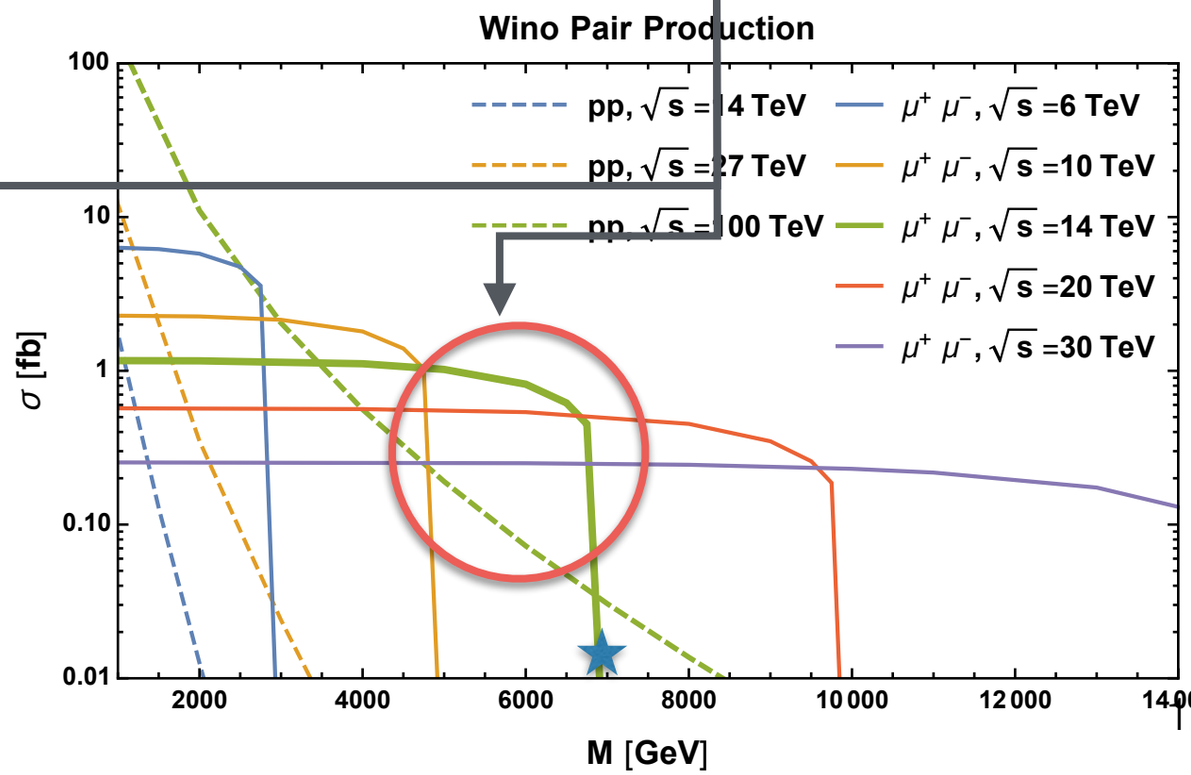

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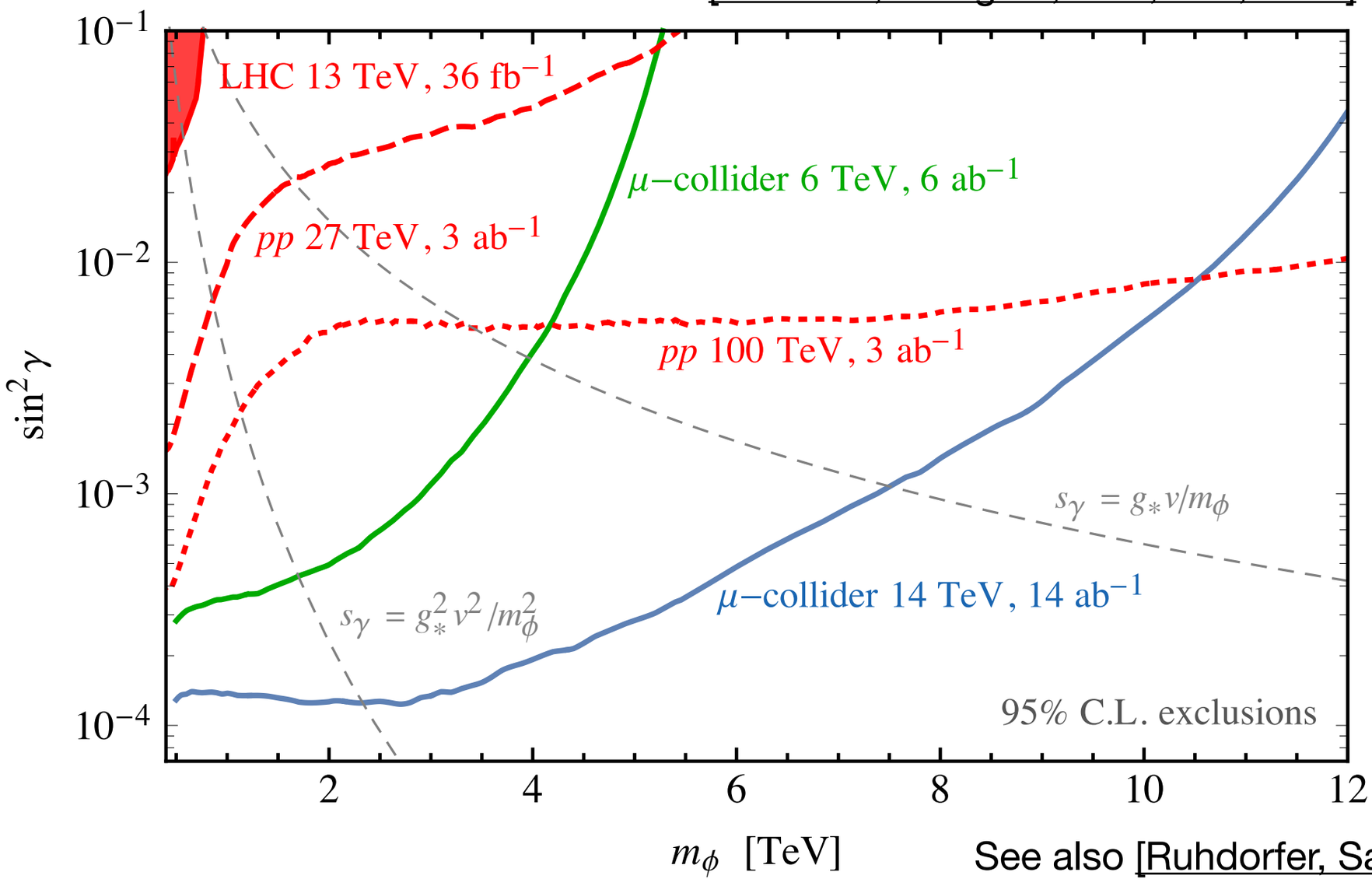
Particularly effective for **VBF-produced BSM**

[Buttazzo, Redigolo, Sala, Tesi, 2018]



See also [Ruhdorfer, Salvioni, Weiler, 2019]
[Costantini, De Lillo, Maltoni et. al., 2020]

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Need studies for compressed/invisible/difficult decays

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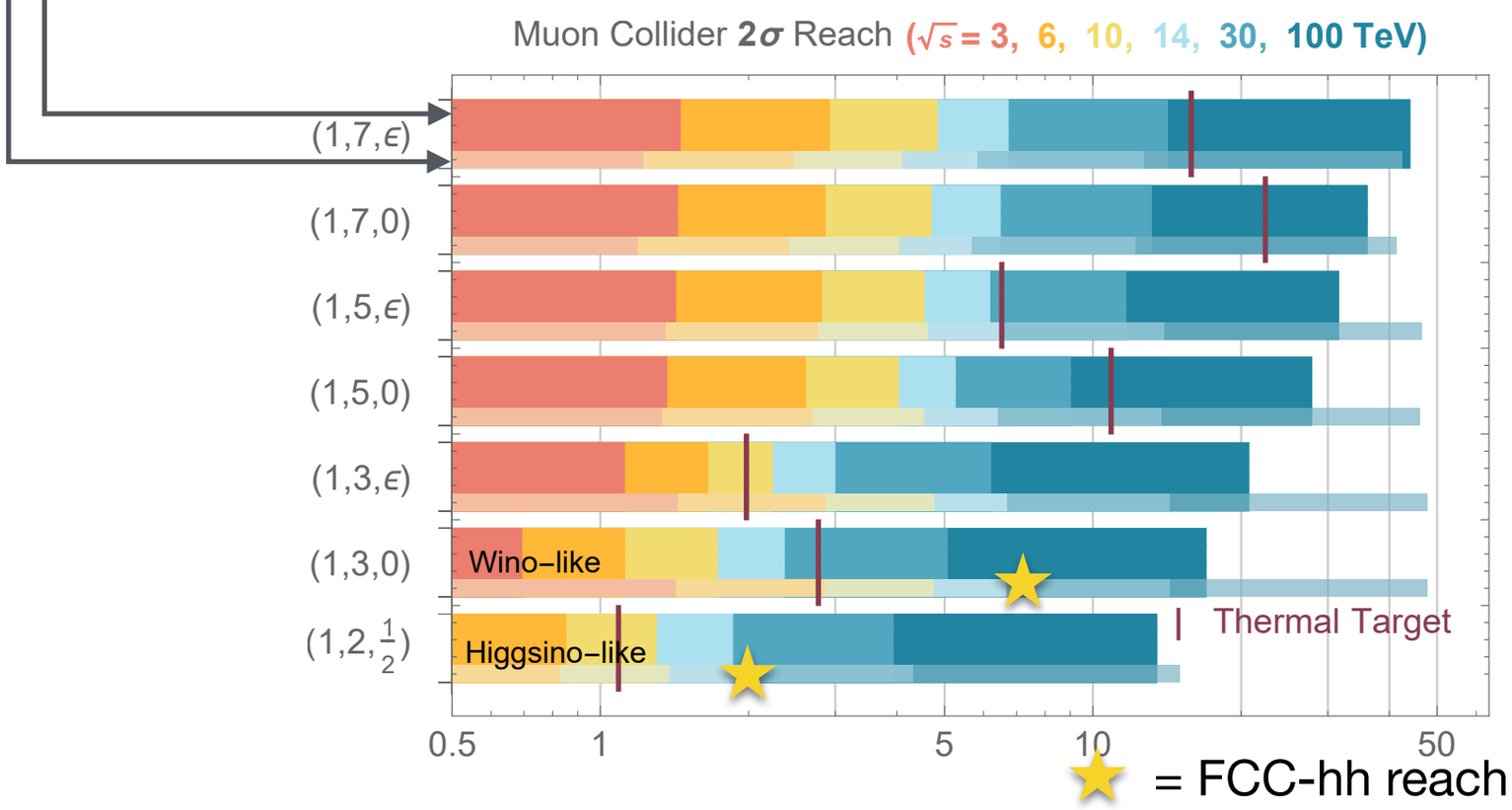

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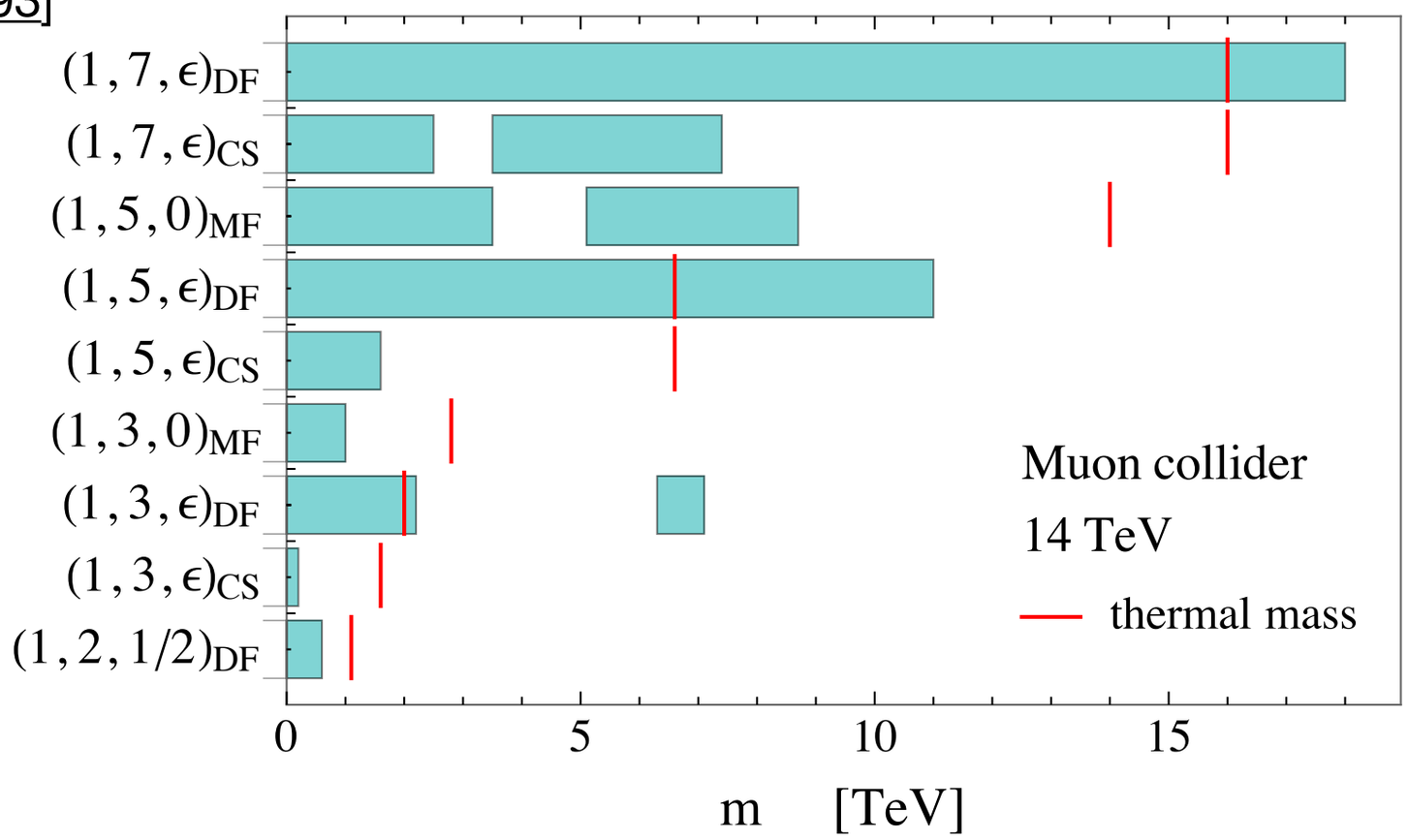
indirectly [1810.10993]

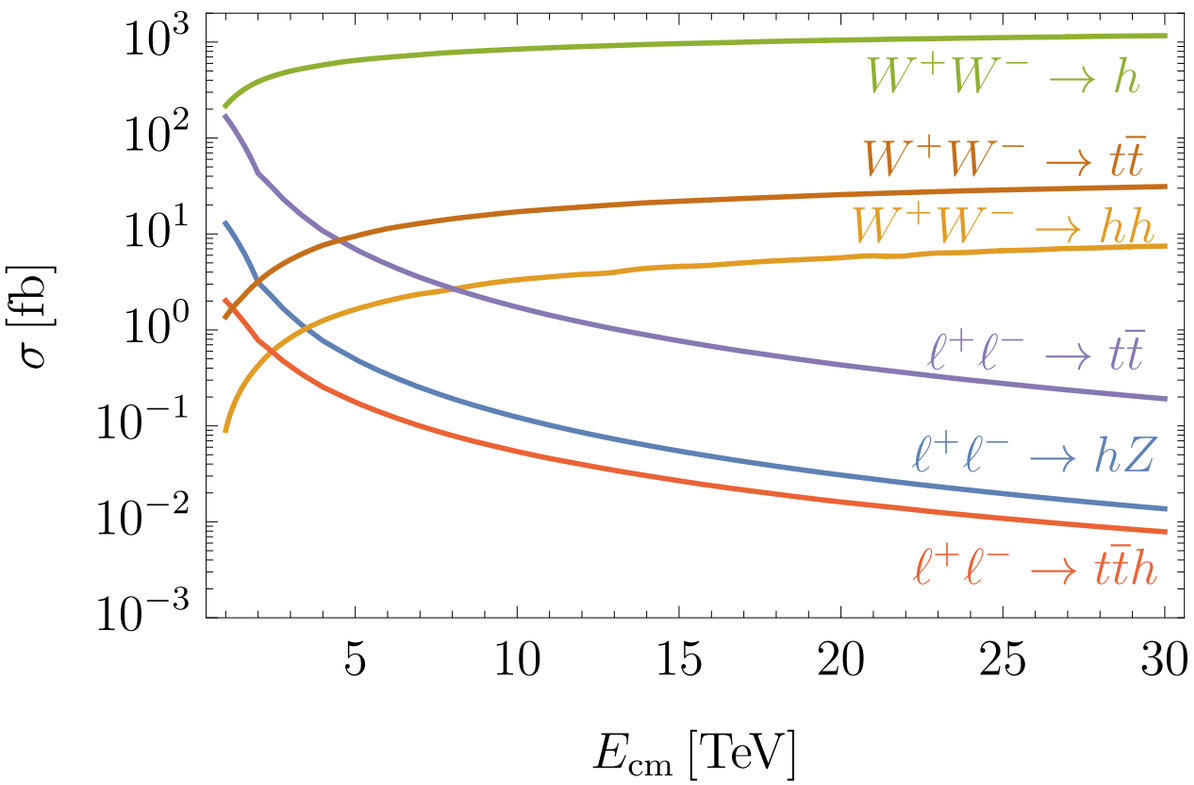


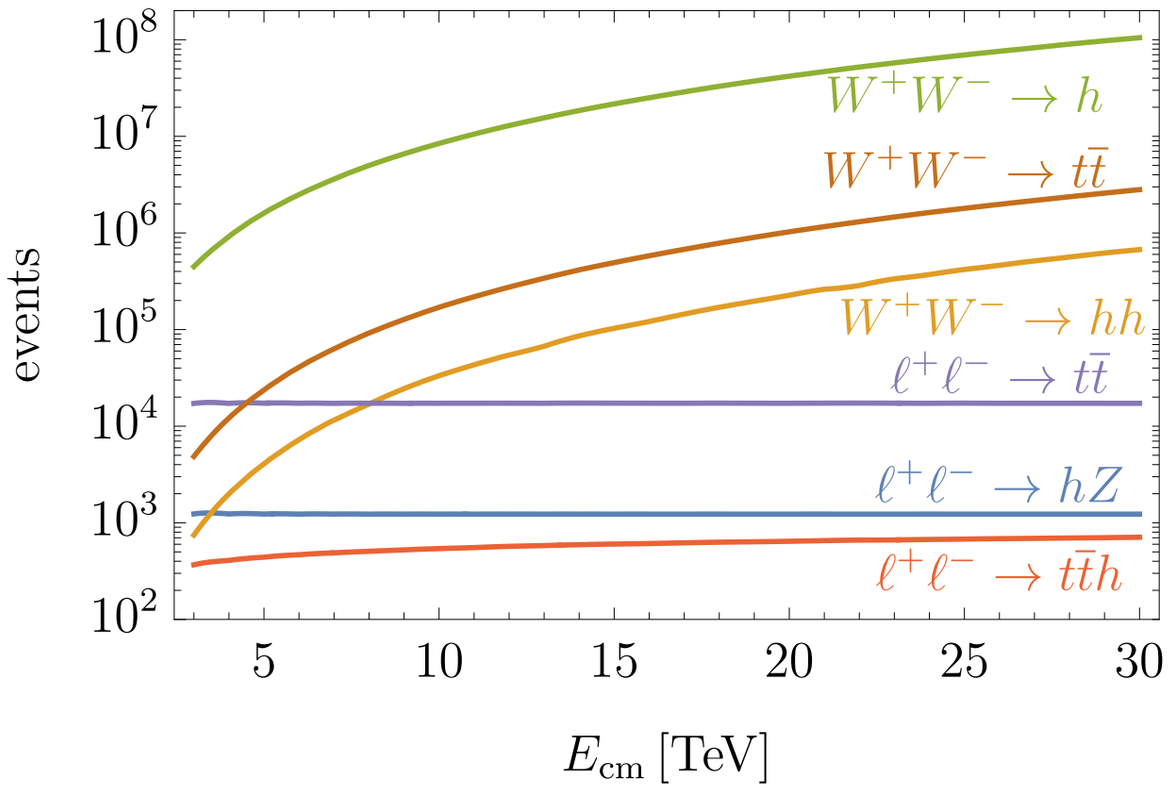
High rate indirect probes

Large single-Higgs VBF rate

Precision on Higgs couplings driven by systematics. **Could be 1‰**

Rare/Exotic Higgs decay opportunities ?





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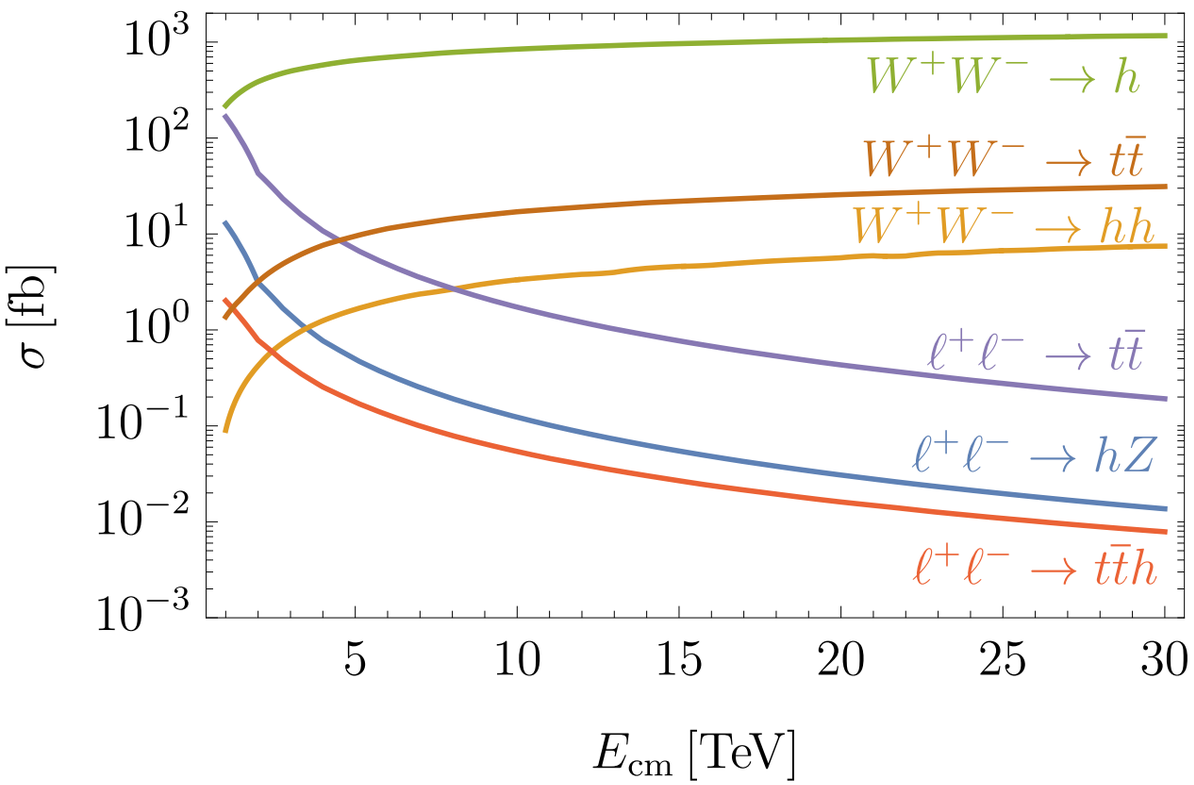

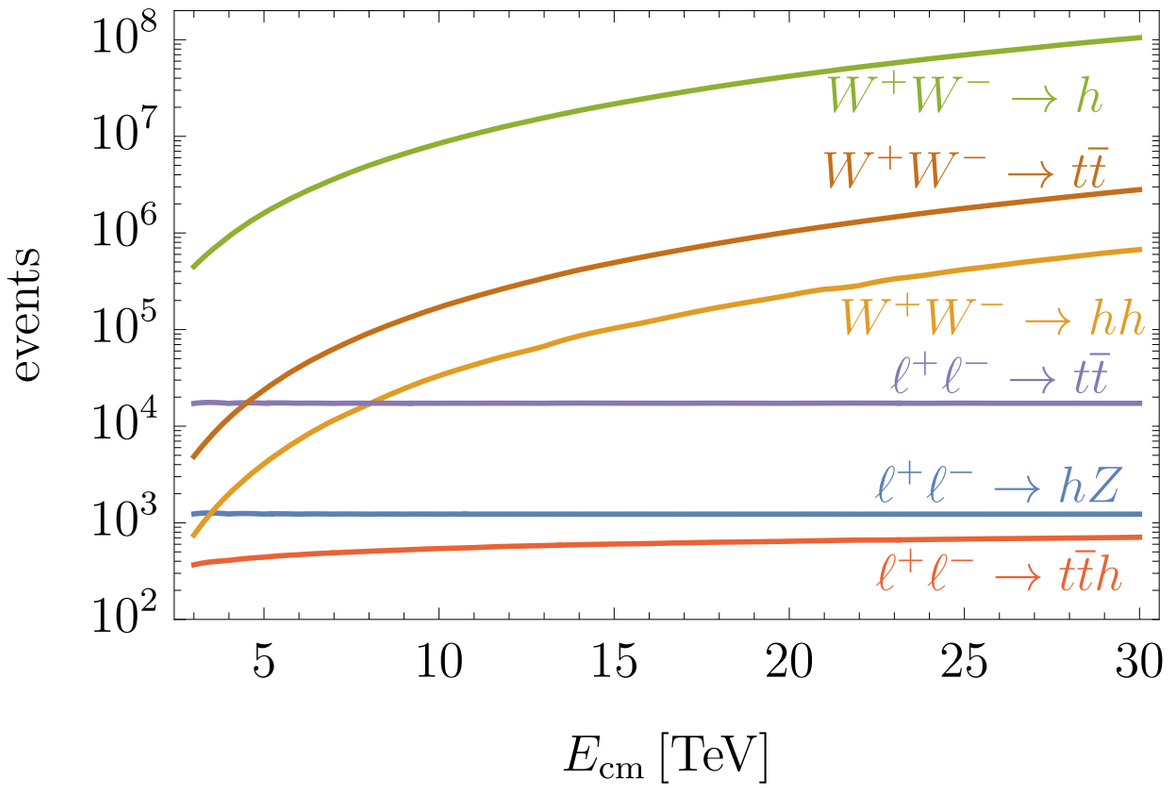

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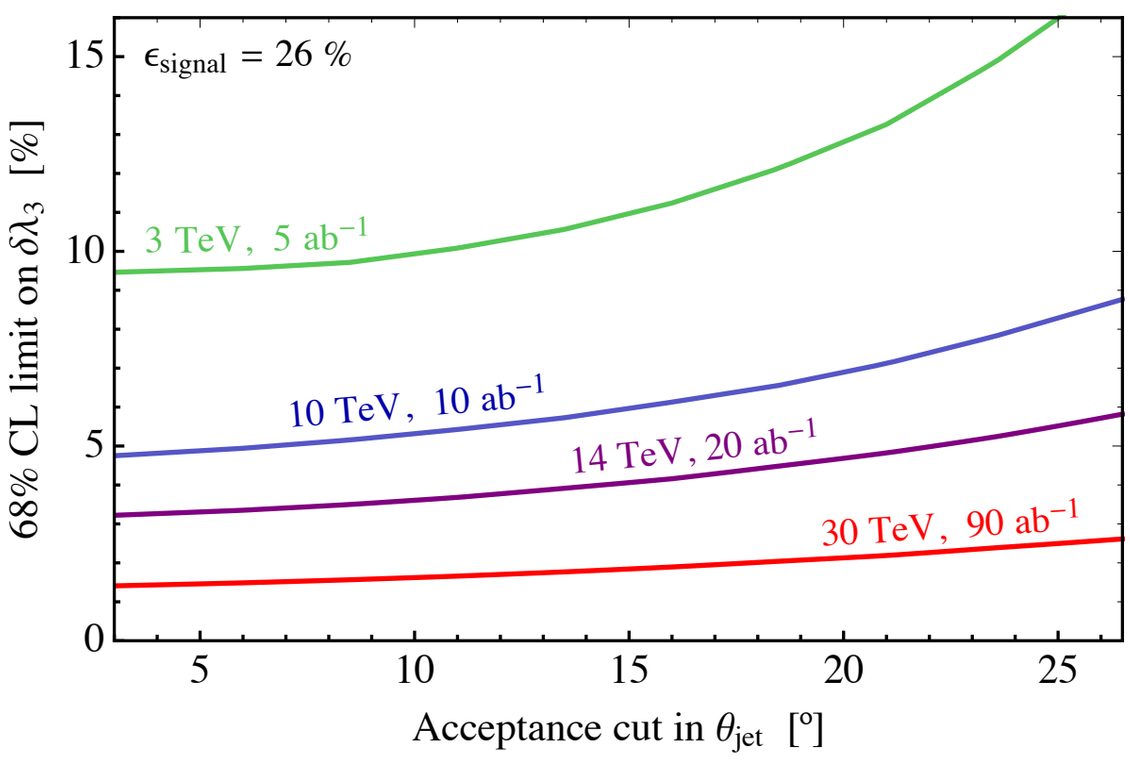
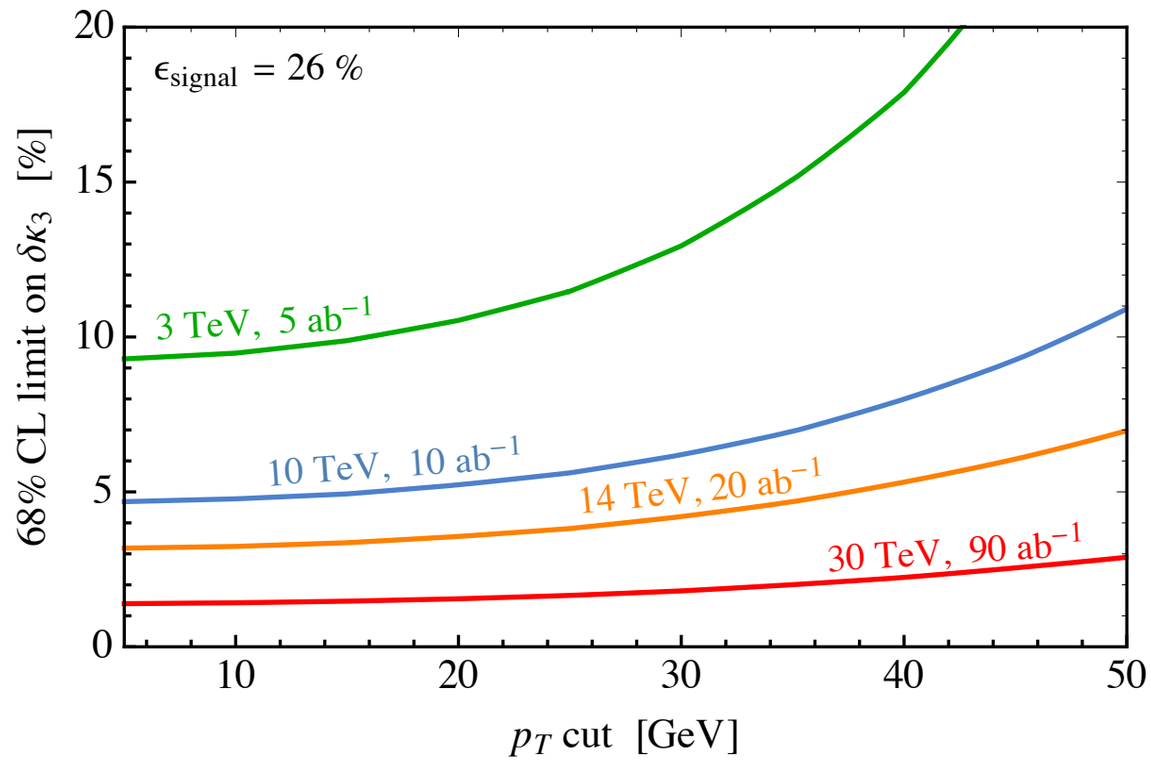
Higgs 3-linear: $\delta\kappa_\lambda =_{1\sigma}$ **(5%, 3.5%,1.6%) for E = (10, 14, 30) TeV**

FCC reach is from 3.5 to 8.1%, depending on systematics assumptions





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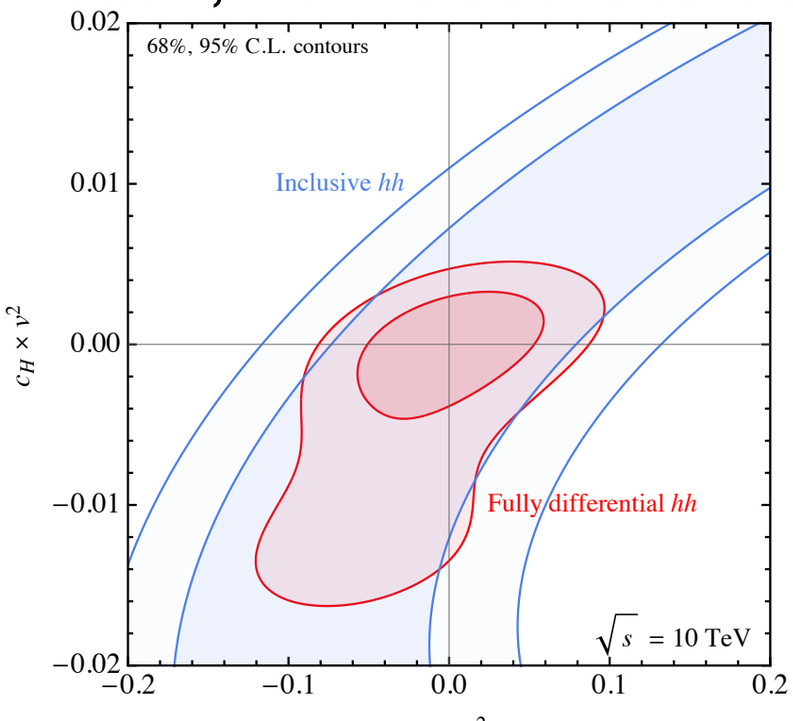
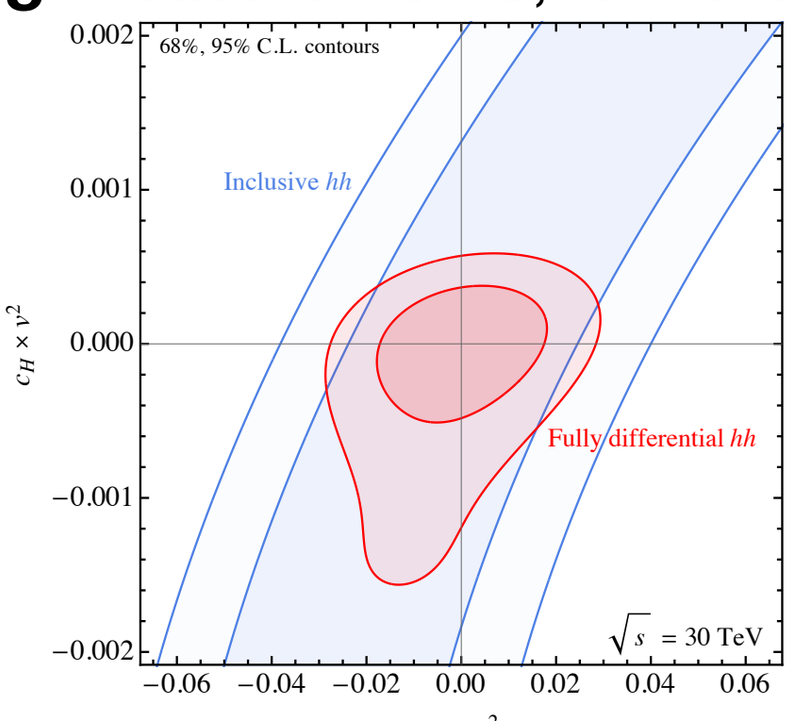
Composite Higgs ξ: **$\xi =_{1\sigma}$ (2.5‰, 1.2‰, 0.3‰) for E = (10, 14, 30) TeV**

From **no-so-accurate measurements in high mass tail** [O_H energy growth]

FCC-all reach, from **accurate coupling** measurements, is 1.8‰





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[Buttazzo, Franceschini, AW, 2012.11555]

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[say, $\Lambda_{\rm BSM} = 100\,\text{TeV}$]

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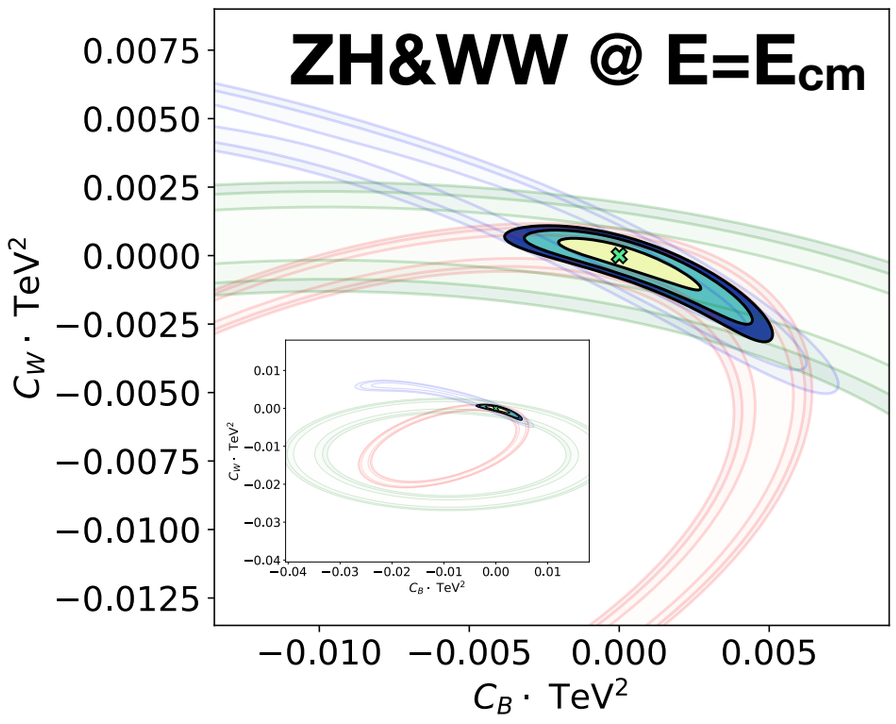
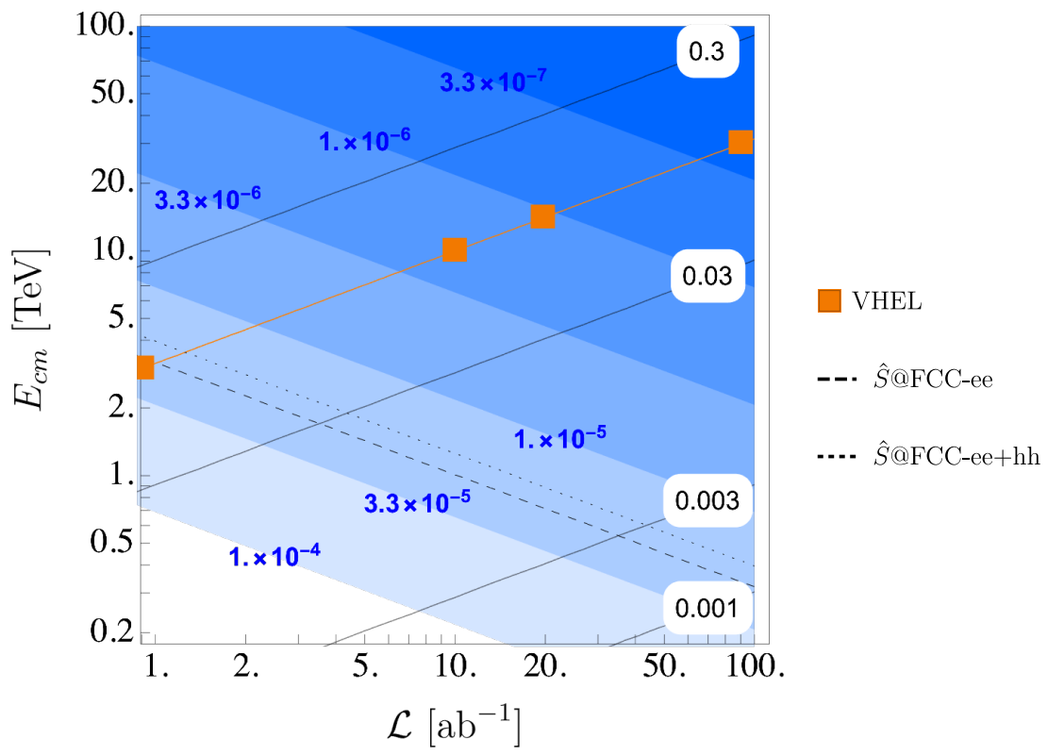
But they are **much more effective** at the **muon collider!**





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Important technical remark:

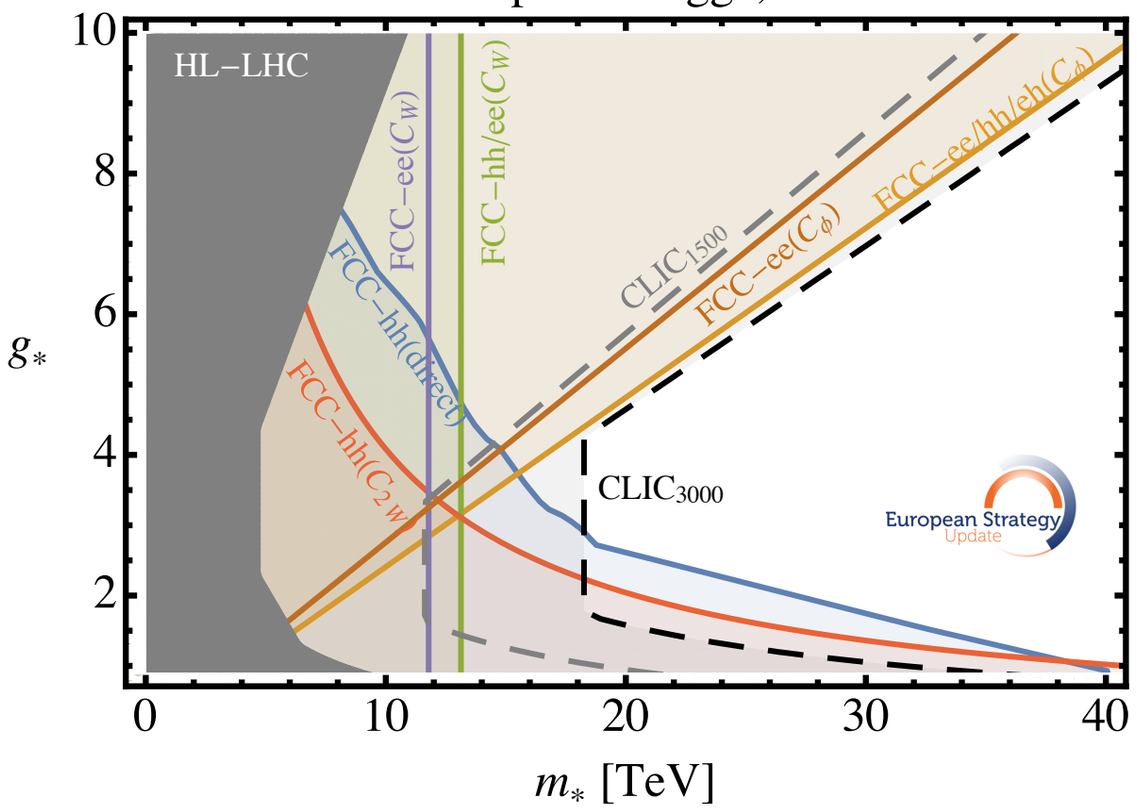
- **EW logs** ($\alpha \log^{(2)}[E/m_{\rm W}]$, virtual or real) are **order one**
- Do **not cancel**, not even in **inclusive** observables …
- … and in any case, inclusive (IR-safe) observables are **not enough**

Progress needed in calculations/simulations/obs.definition!

Probing Higgs compositeness

[Chen, Glioti, Ricci, Rattazzi, AW, in progress]

"Standard" Future Colliders



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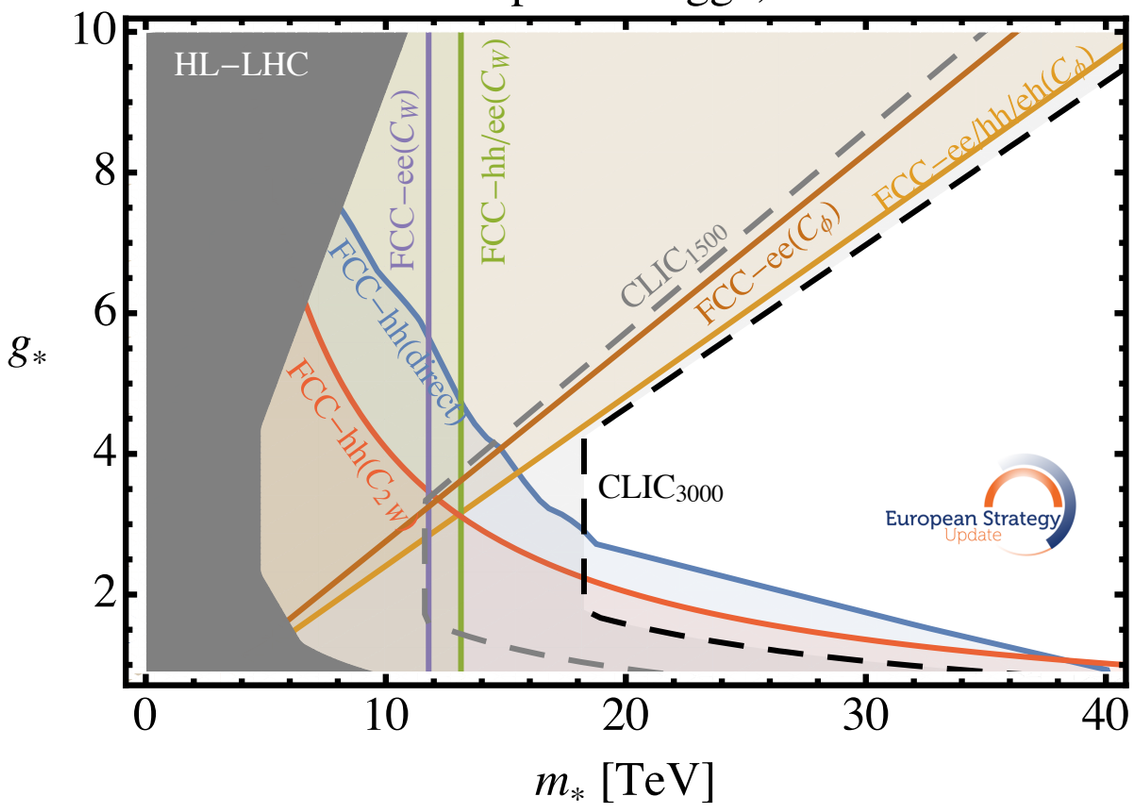

Muon Collider

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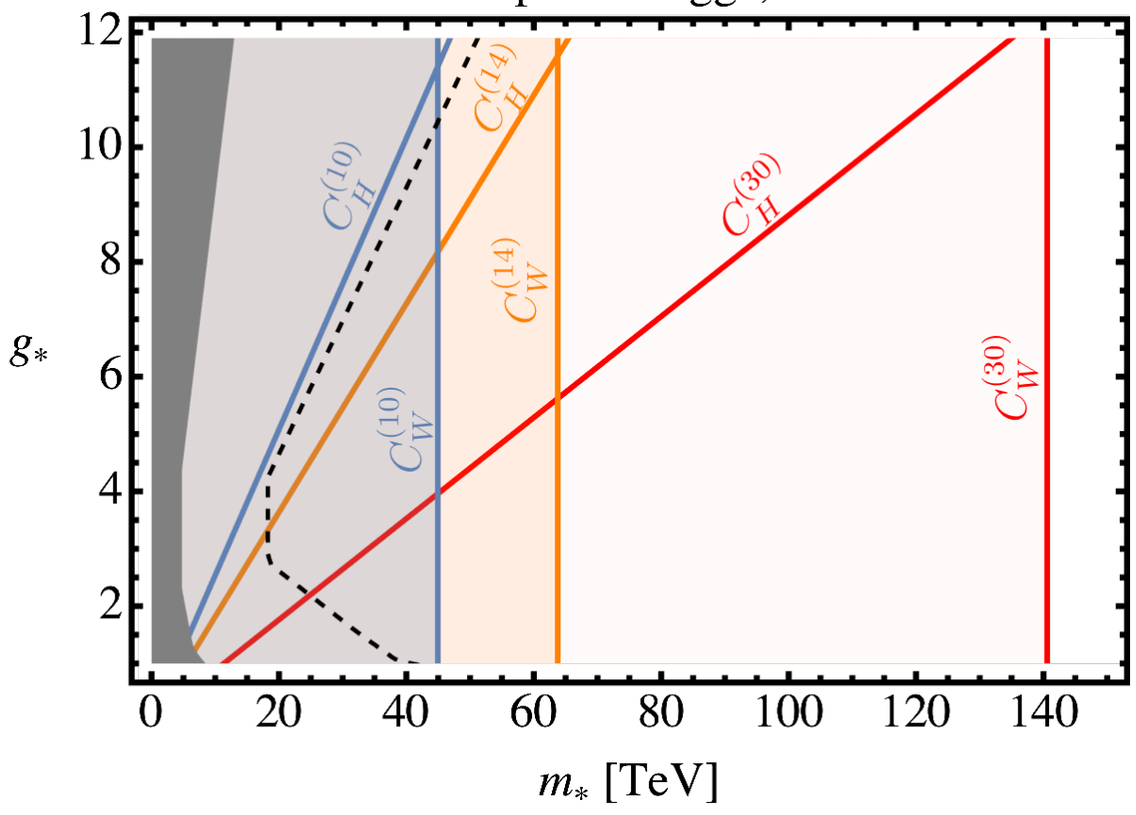

Even Simpler: Minimal Z's

[Chen, Glioti, Ricci, Rattazzi, AW, in progress]

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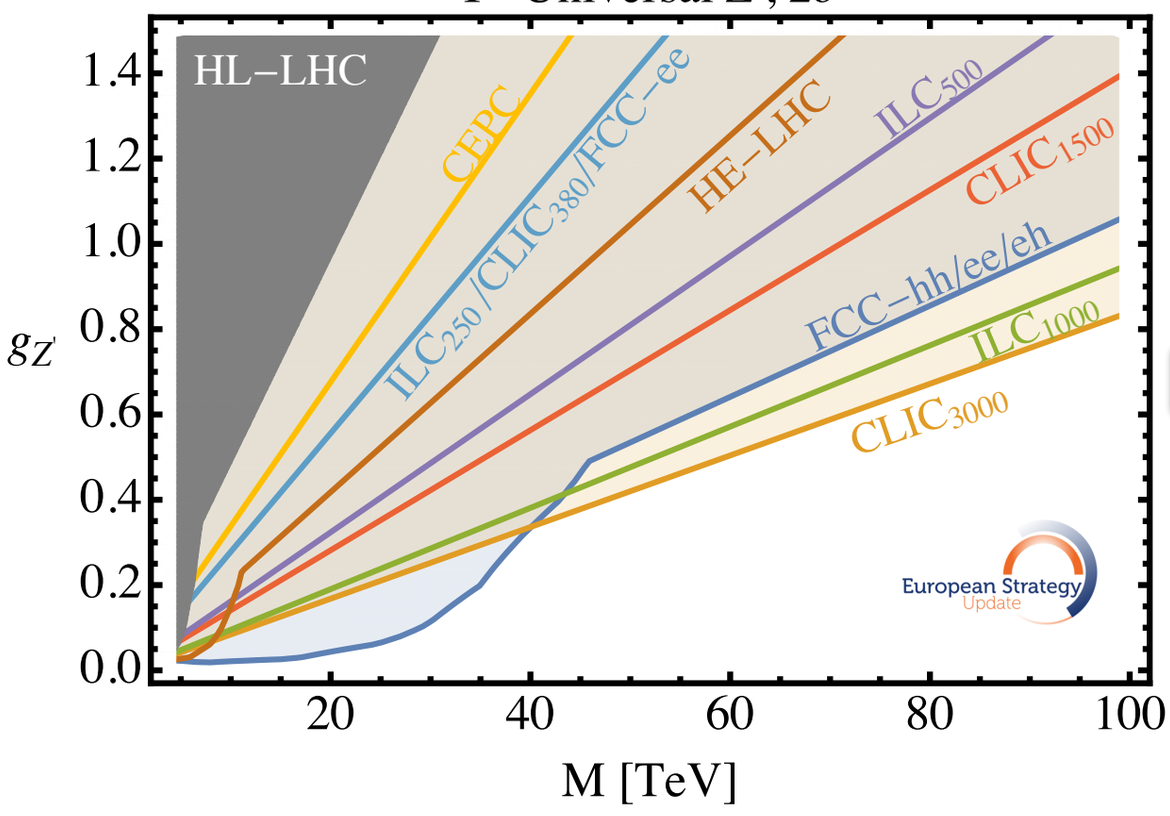

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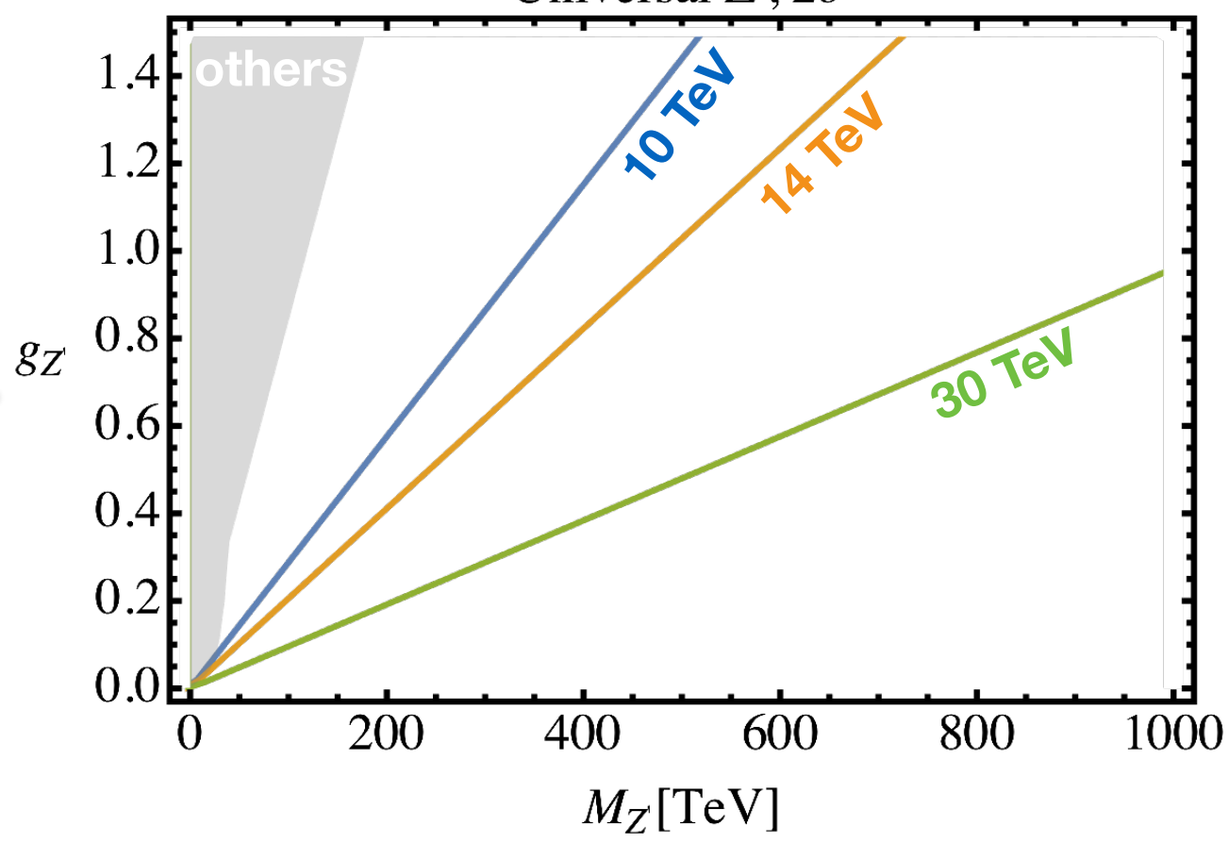

Outlook

Why working on muon colliders?

- It is **Important:** we might end up outlining a new possible direction for the continuation of the High Energy Physics journey
- It is **Fun:** novel BSM possibilities wait to be explored, as well as novel QFT challenges for predictions [HE EW physics, see Tao's talk]

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Prominent role of **poorly understood** but **fully understandable** new "IR Problem"

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Goals of the Physics Potential group:

- Collect as many reach plots as possible; make them as realistic as possible
- Contribute and encourage work for **Snowmass**
- Inform Detector design of Physics needs, and get feedback
- Join us! Write me, if you want to contribute to our regular meetings

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The Very High Energy Muon Collider is a Dream

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And, often, Dreams DO become Reality!

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Thank You !