Why building a muon collider

Andrea Wulzer

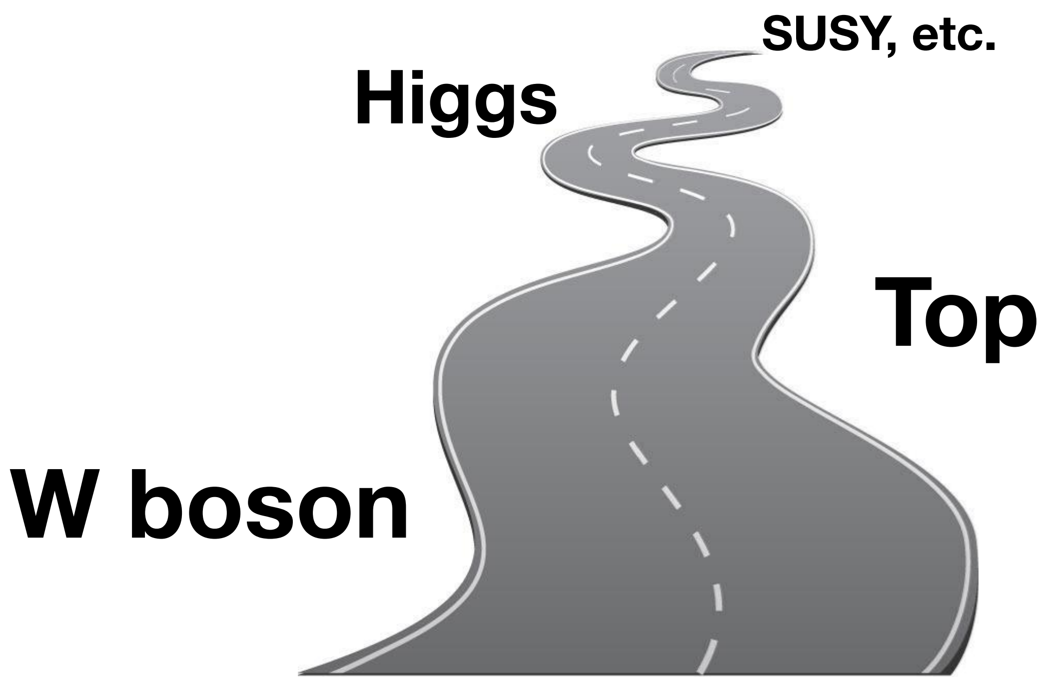
UNIVERSITÀ DEGLI STUDI DI PADOVA

CERN

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Ideology

HEP before the LHC

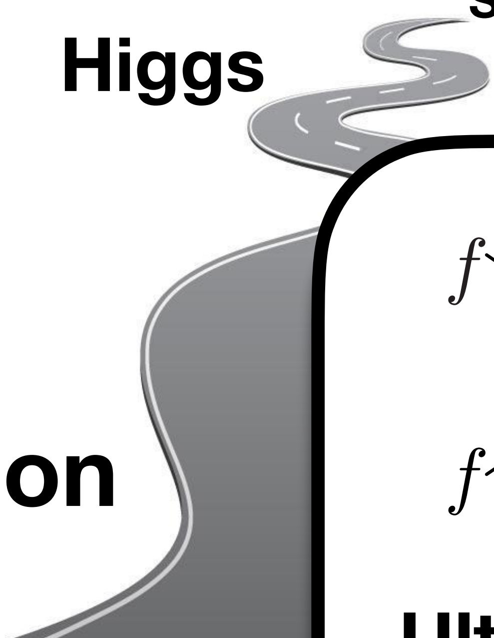


HEP before the F.C.

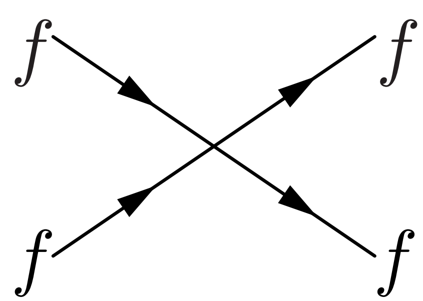
Ideology

HEP before the LHC

HEP before the F.C.



W boson

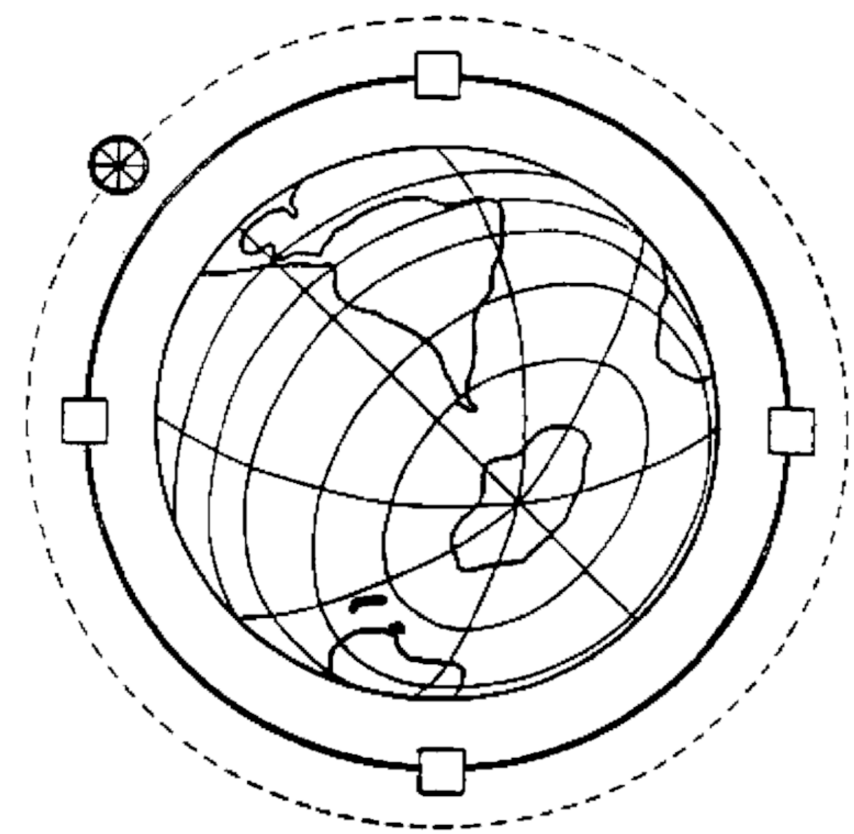


$$\sim G_F E^2 \simeq E^2/v^2 < 16\pi^2 \Rightarrow m_W < 4\pi v$$

Ultimate Accelerator.

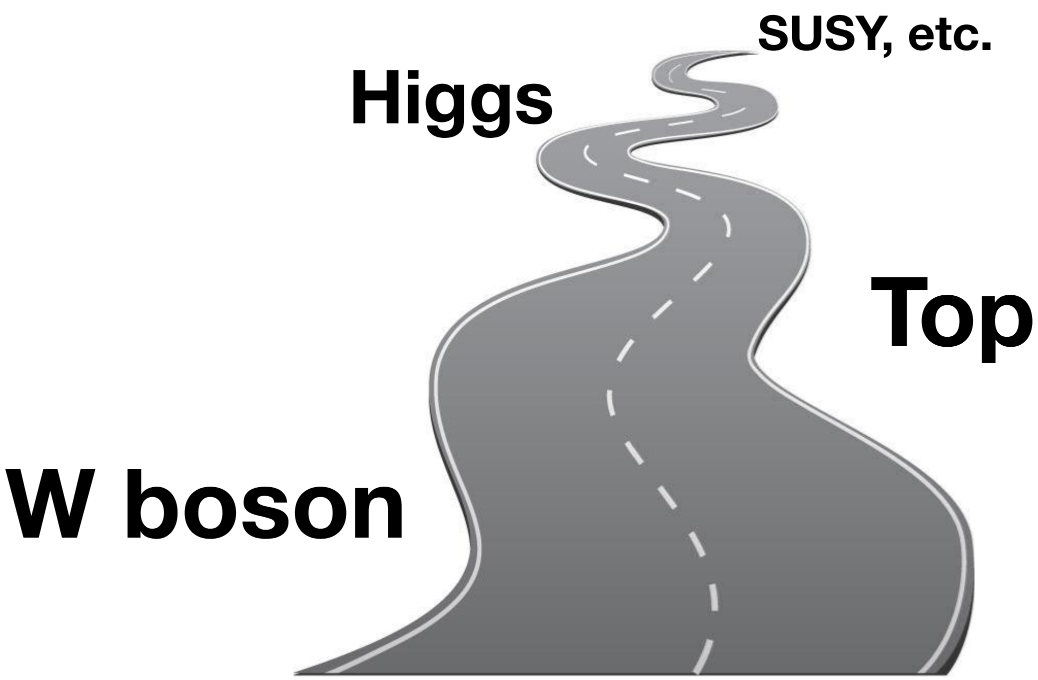
Drawn by Fermi in the ’50 to reach 3 TeV.

The manifesto of HEP!



Ideology

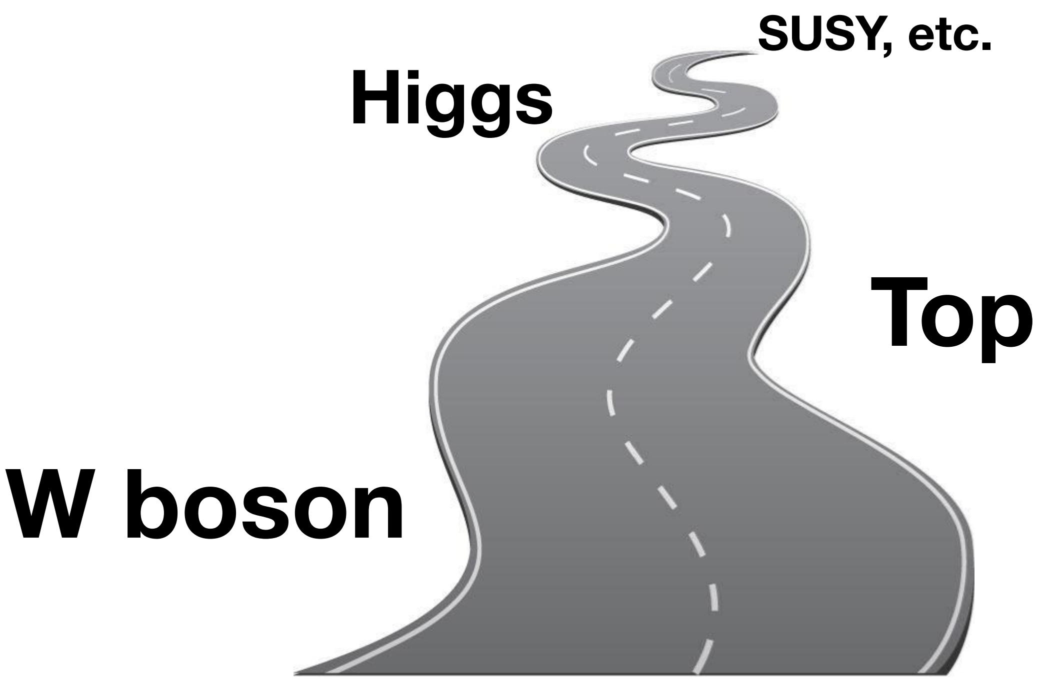
HEP before the LHC



HEP before the F.C.

Ideology

HEP before the LHC



HEP before the F.C.

Particle physics is not **validation** anymore, rather it is **exploration of unknown territories** *

* **Not bad thing.** Columbus left for his trip just because he had no idea of where he was going !!

Ideology

No single experiment can explore all directions at once.

Ideology

No single experiment can explore all directions at once.

None (in heaven or earth) can **guarantee discoveries** of new fundamental laws of nature.

Ideology

No single experiment can explore all directions at once.

None (in heaven or earth) can **guarantee discoveries** of new fundamental laws of nature.

But, HE colliders have guaranteed outcome:

- ✦ SM predictions comparison with data:
  Directly based on QFT principles and techniques.
- ✦ Robust and conclusive exploration of well-posed BSM questions

Ideology

No single experiment can explore all directions at once.

None (in heaven or earth) can **guarantee discoveries** of new fundamental laws of nature.

But, HE colliders have guaranteed outcome:

- ✦ SM predictions comparison with data:
  Directly based on QFT principles and techniques.
- ✦ Robust and conclusive exploration of well-posed BSM questions

Only one drawback: they are **Expensive**.

Next big one **will exist only if** capable of **great jump** in exploration of **multiple directions.**

Ideology

No single experiment can explore all directions at once.

None (in heaven or earth) can **guarantee discoveries** of new fundamental laws of nature.

But, HE colliders have guaranteed outcome:

- ✦ SM predictions comparison with data:
  Directly based on QFT principles and techniques.
- ✦ Robust and conclusive exploration of well-posed BSM questions

Only one drawback: they are **Expensive**.

Next big one **will exist only if** capable of **great jump** in exploration of **multiple directions.**

[even better if constructed with **revolutionary technology**…]

Why Muons?

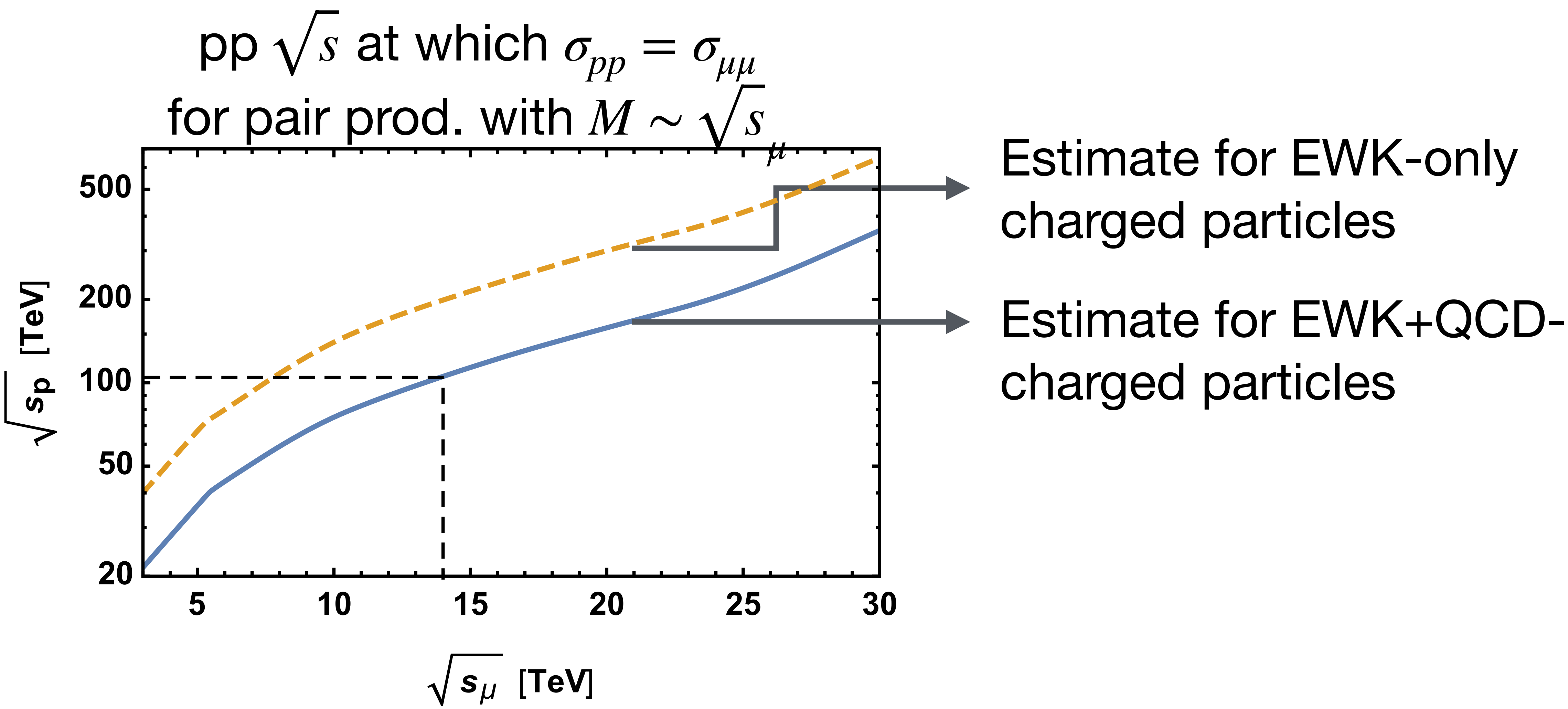
Leptons are the ideal probes of short-distance physics:

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

Why Muons?

Leptons are the ideal probes of short-distance physics:

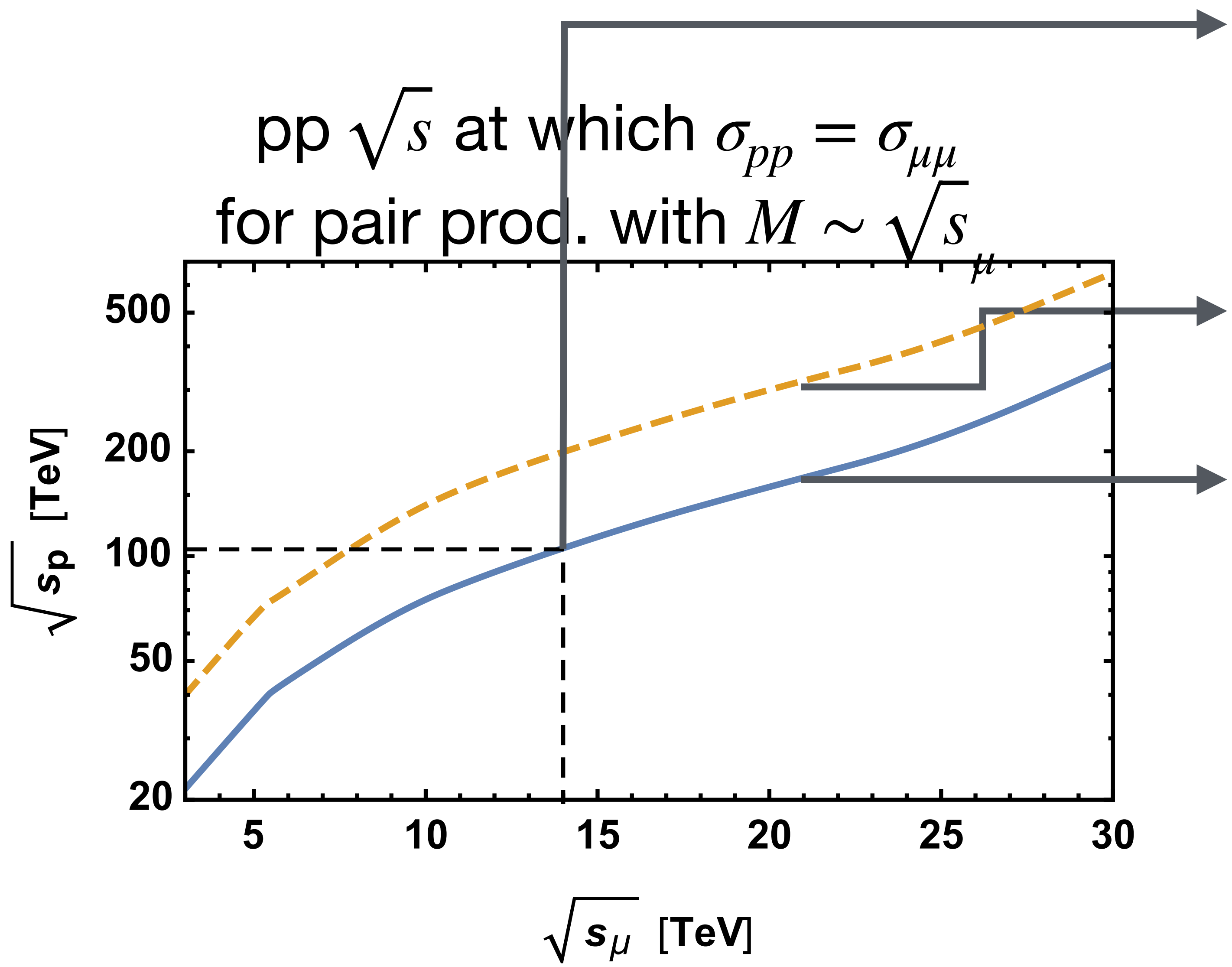
- All the energy is stored in the colliding partons
- No energy "waste" due to parton distribution functions
- High-energy physics probed with much smaller collider energy



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



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

Estimate for EWK-only charged particles

Estimate for EWK+QCD-charged particles

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

Electrons radiate too much

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

Electrons radiate too much

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 $\mathcal{L} = (E_{\rm CM}/10\ \text{TeV})^2 \times 10\,\text{ab}^{-1}$ [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.

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

Electrons radiate too much

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 $\mathcal{L} = (E_{\rm CM}/10\ \text{TeV})^2 \times 10\,\text{ab}^{-1}$ [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.

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

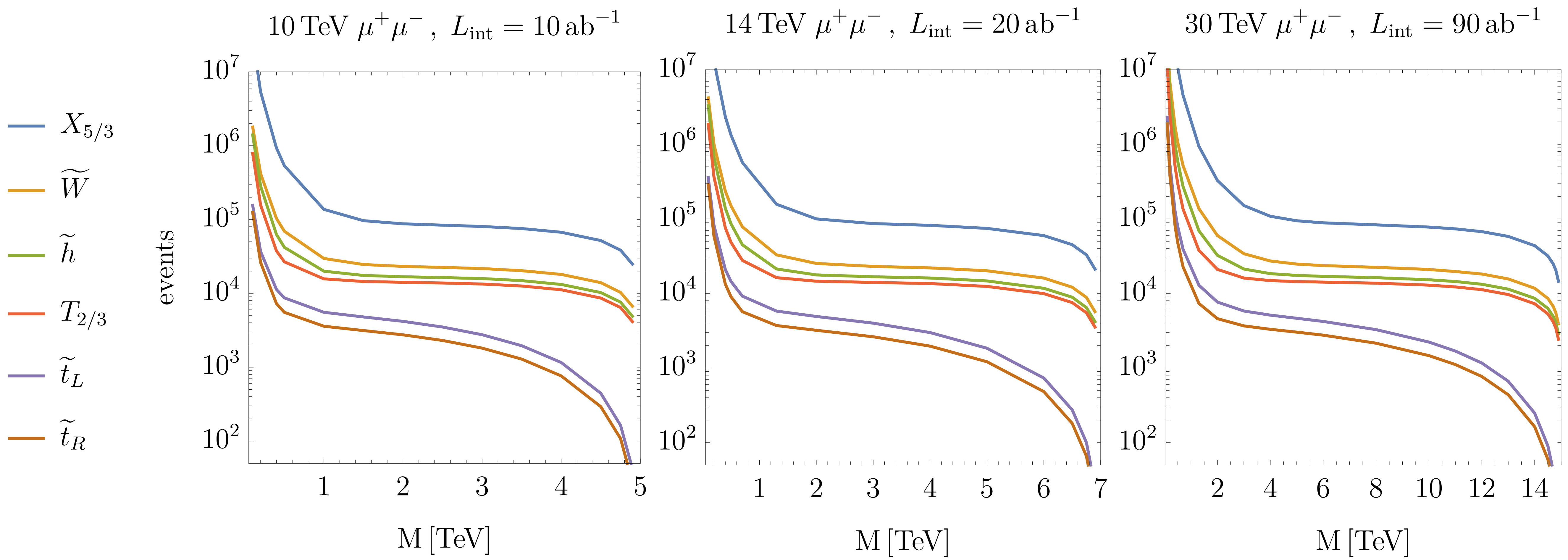
Electrons radiate too much

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



The case for direct searches

EW pair-produced particles up to kinematical threshold

Striking for 10+TeV

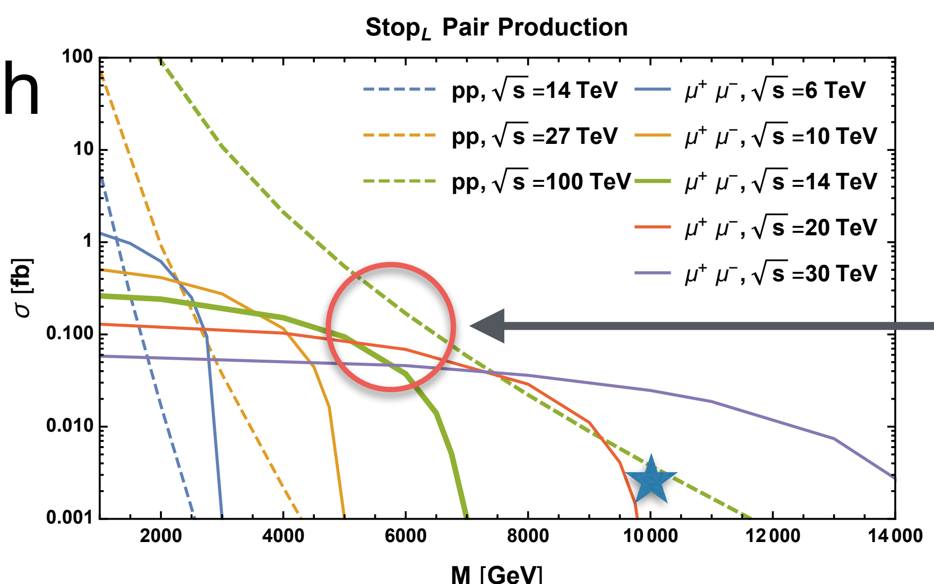
Examples:

★ = FCC reach

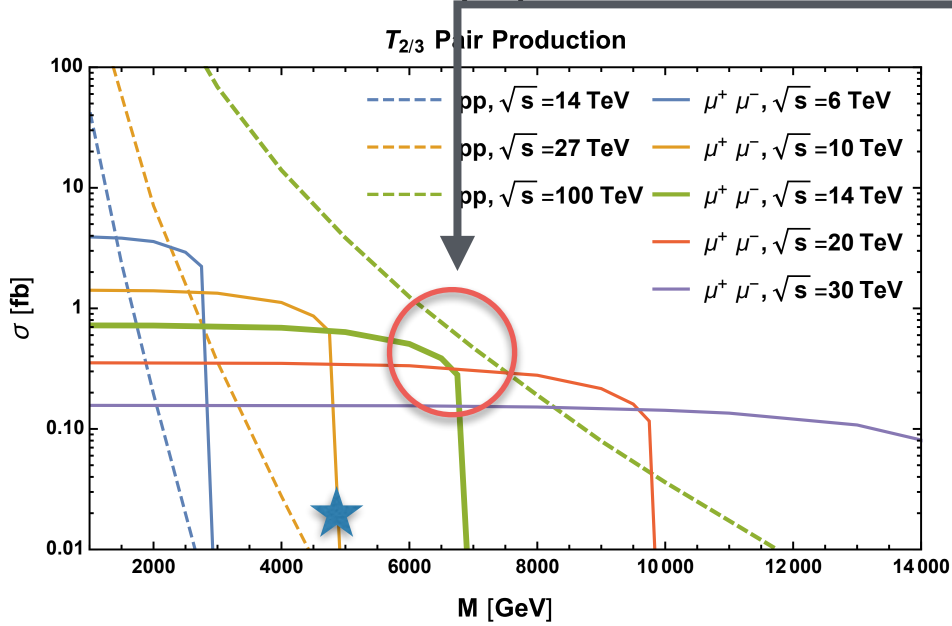
Reference Point:

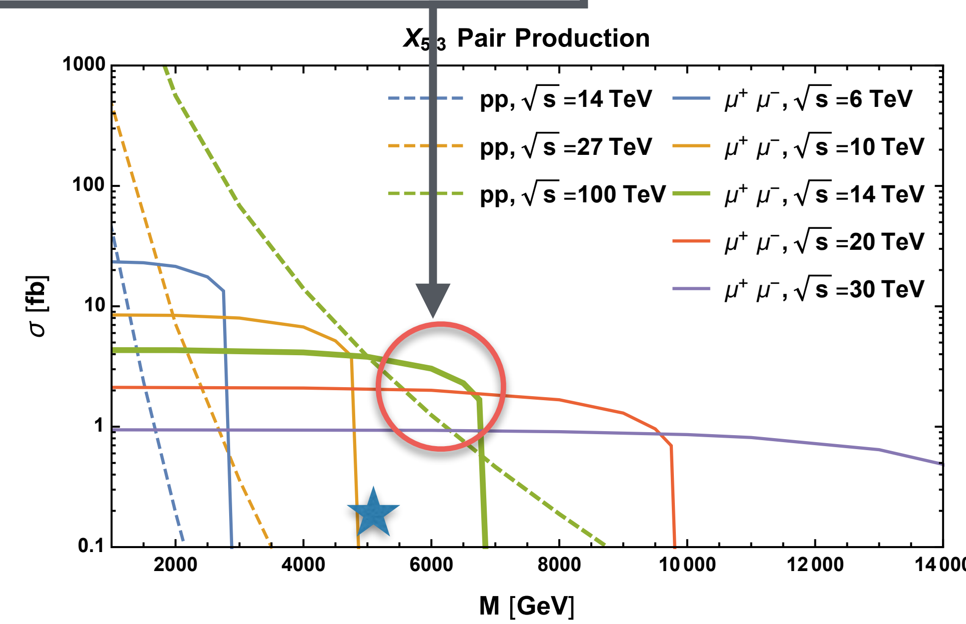
14 TeV μ-collider ~ FCC@100 TeV

Stop



Top-Partners





The case for direct searches

EW pair-produced particles up to kinematical threshold

Striking for 10+TeV

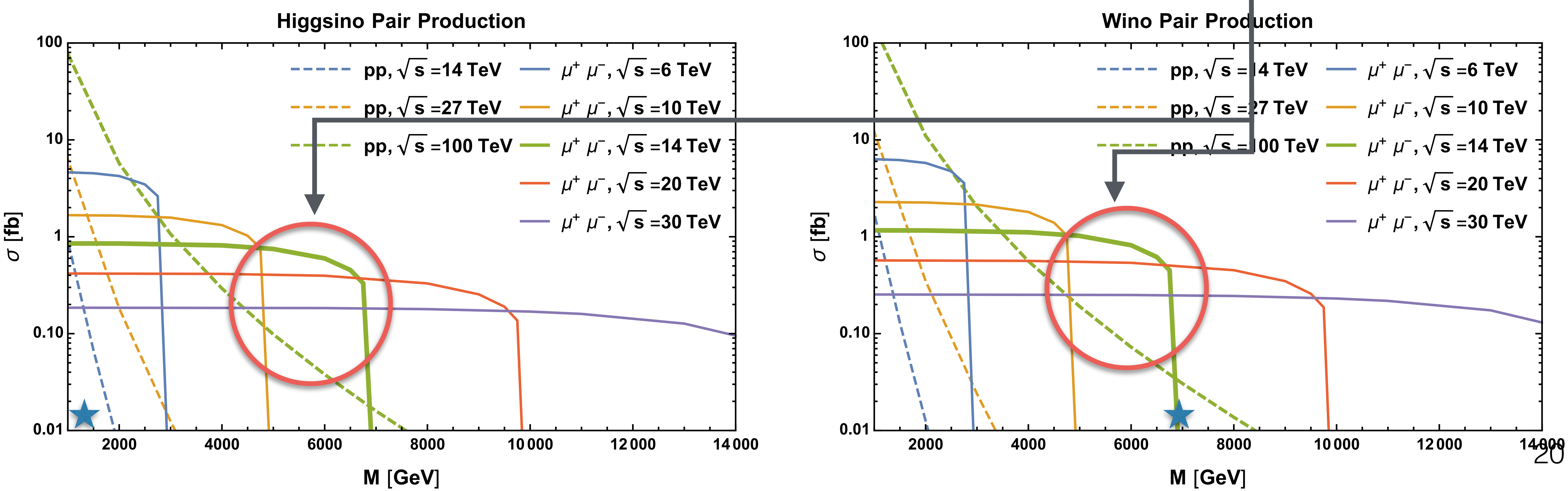
Examples:

★ = FCC reach

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

Reference Point:

14 TeV μ-collider >> FCC@100 TeV



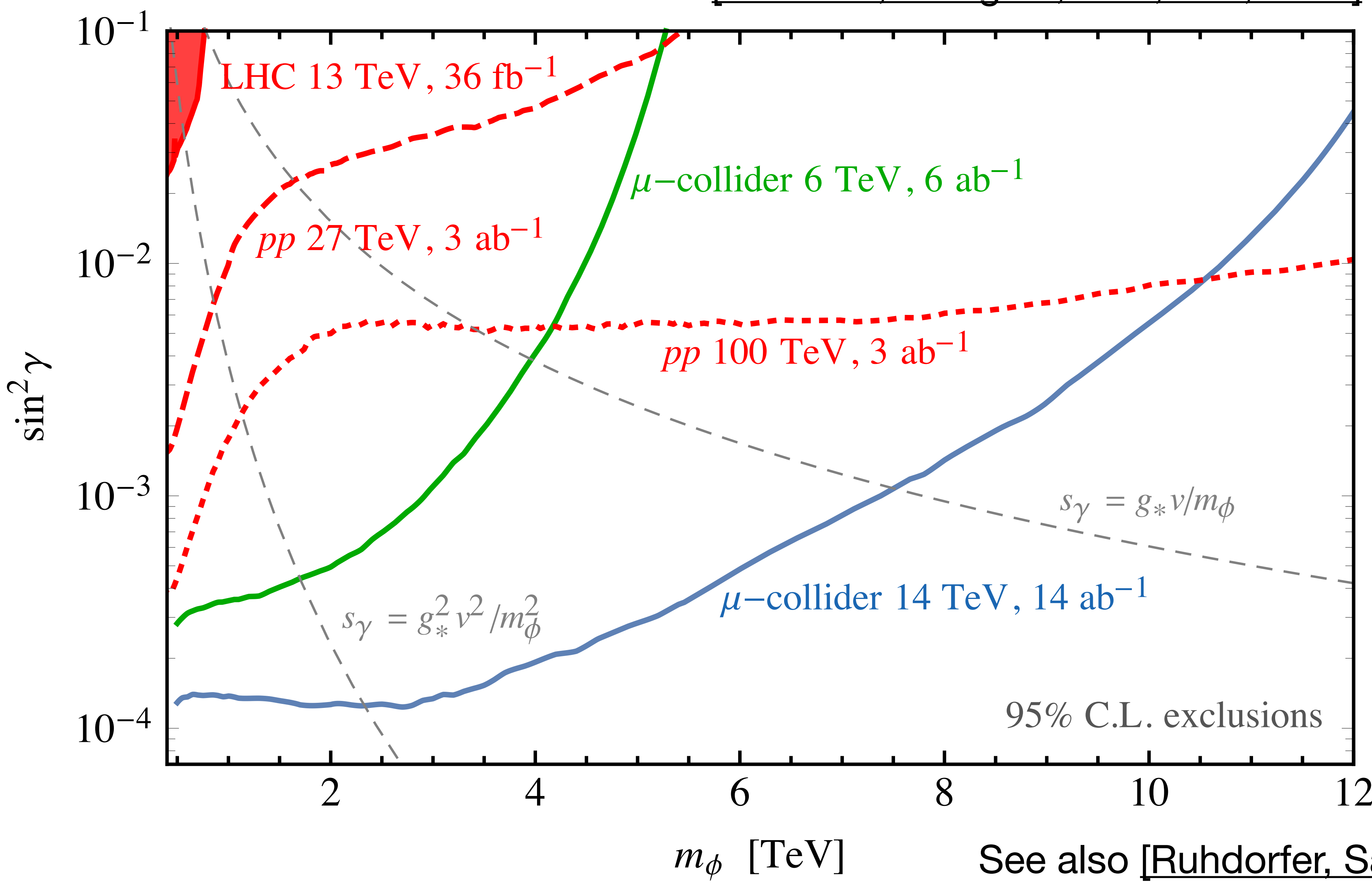
The case for direct searches

EW pair-produced particles up to kinematical threshold

Striking for 10+TeV

Particularly effective for **VBF-produced BSM**

[Buttazzo, Redigolo, Sala, Tesi, 2018]



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

The case for direct searches

EW pair-produced particles up to kinematical threshold

Striking for 10+TeV

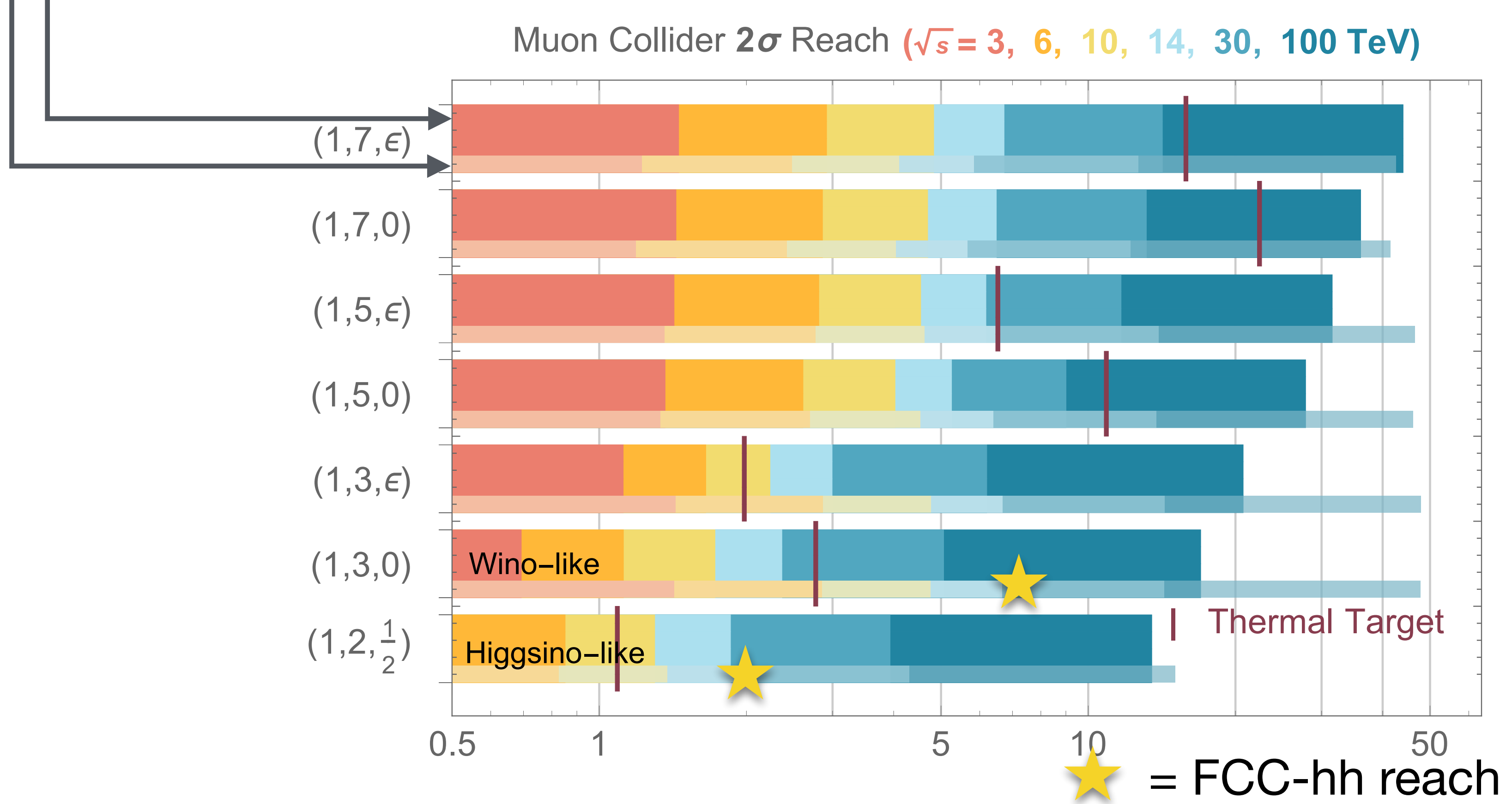
Particularly effective for **VBF-produced BSM**

Need studies for compressed/invisible/difficult decays

WIMP DM:

in mono-X [2009.11287 + Buttazzo, Franceschini et. al. in progress]

disappearing tracks [2009.11287 + Meloni, Zurita et. al. in progress]



The case for direct searches

EW pair-produced particles up to kinematical threshold

Striking for 10+TeV

Particularly effective for **VBF-produced BSM**

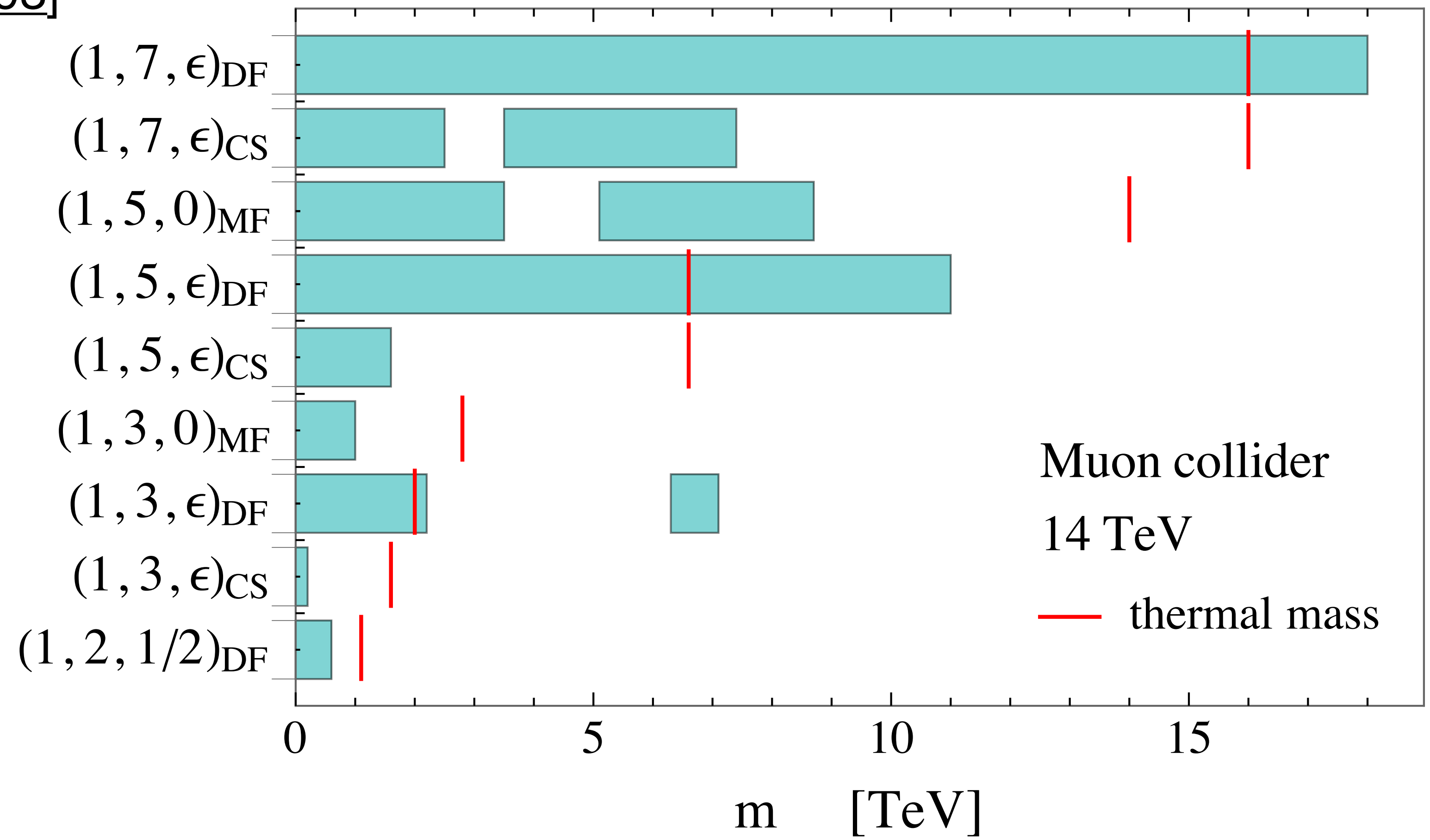
Need studies for compressed/invisible/difficult decays

WIMP DM:

in mono-X [2009.11287 + Buttazzo, Franceschini et. al. in progress]

disappearing tracks [2009.11287 + Meloni, Zurita et. al. in progress]

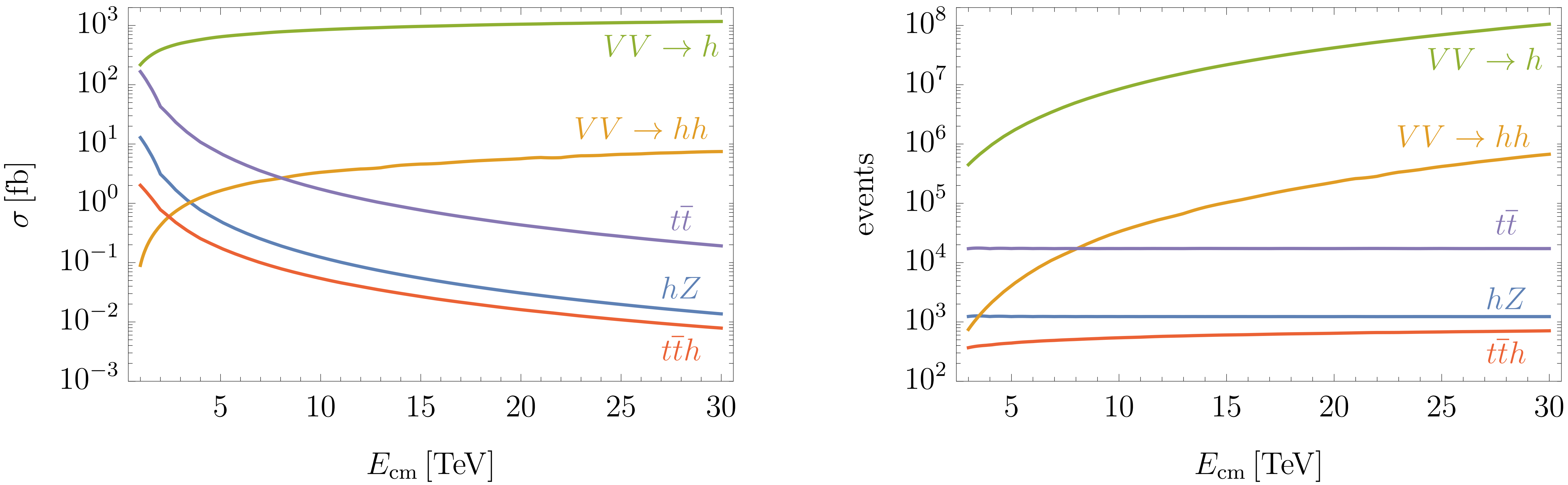
indirectly [1810.10993]



High rate indirect probes

Large single-Higgs VBF rate

- Precision on Higgs couplings driven by systematics. **Could be 1‰**
- Rare/Exotic Higgs decay opportunities ?



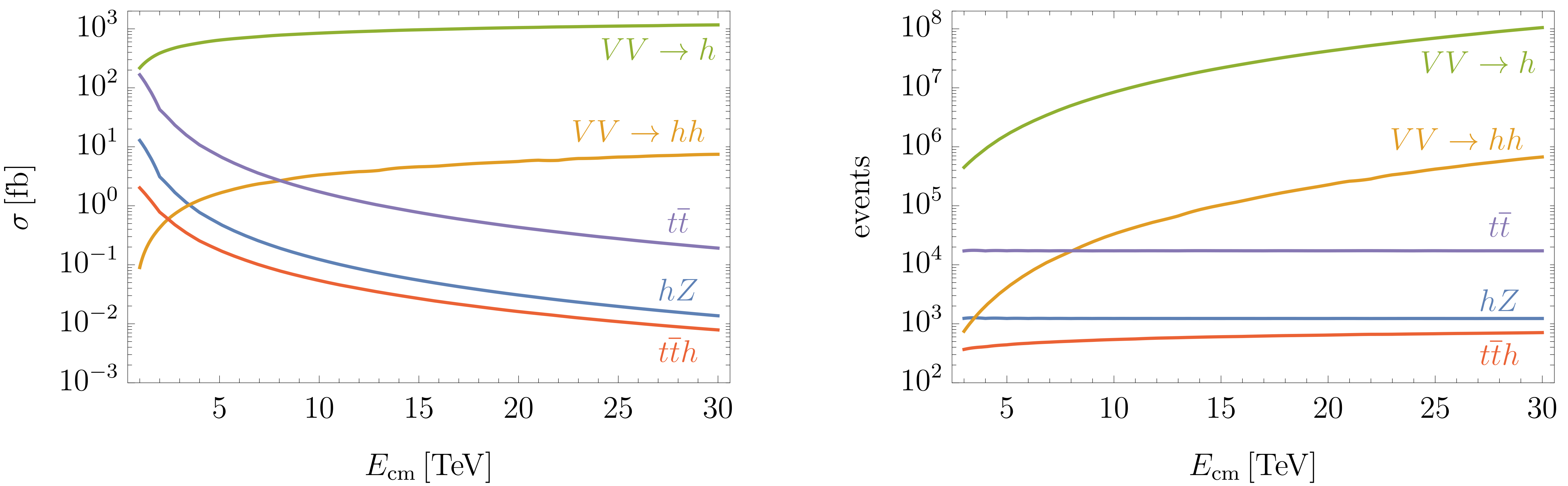
High rate indirect probes

Large single-Higgs VBF rate

- Precision on Higgs couplings driven by systematics. **Could be 1‰**
- Rare/Exotic Higgs decay opportunities ?

Large double-Higgs VBF rate

[2008.12204; 2005.10289; Buttazzo, Franceschini, AW, to appear]



High rate indirect probes

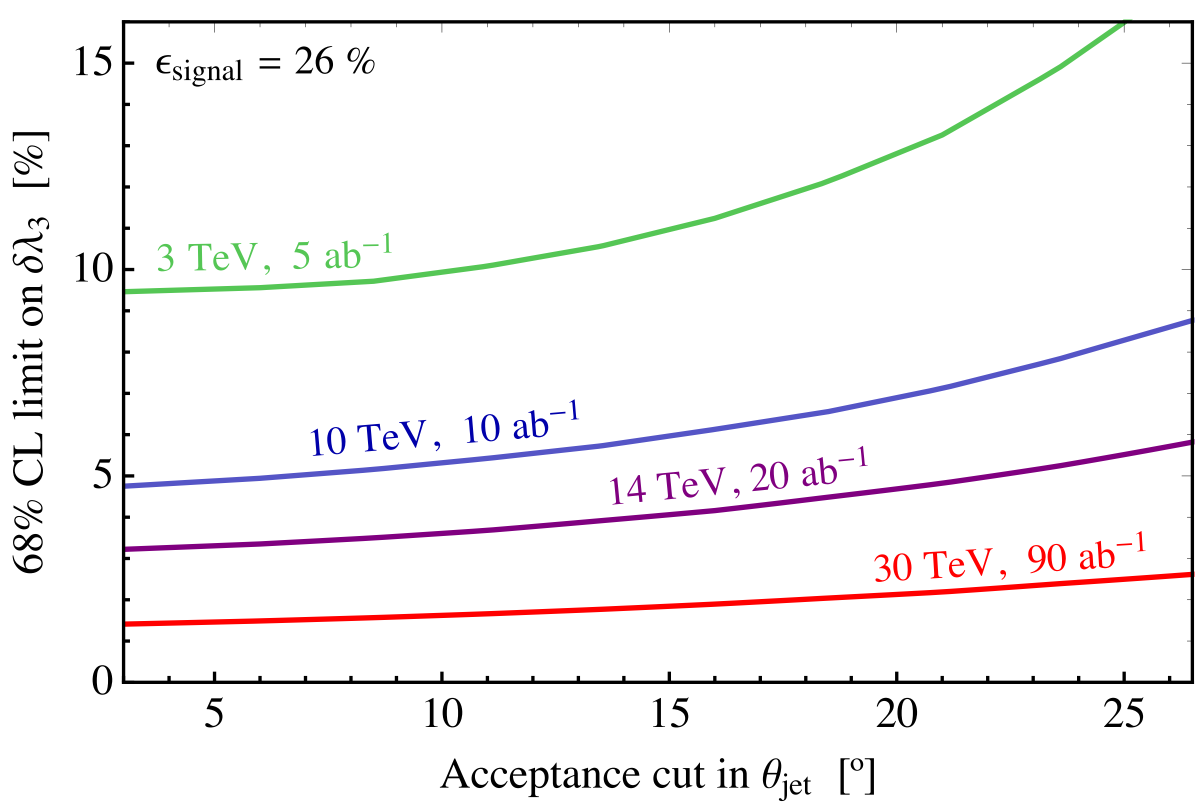
Large single-Higgs VBF rate

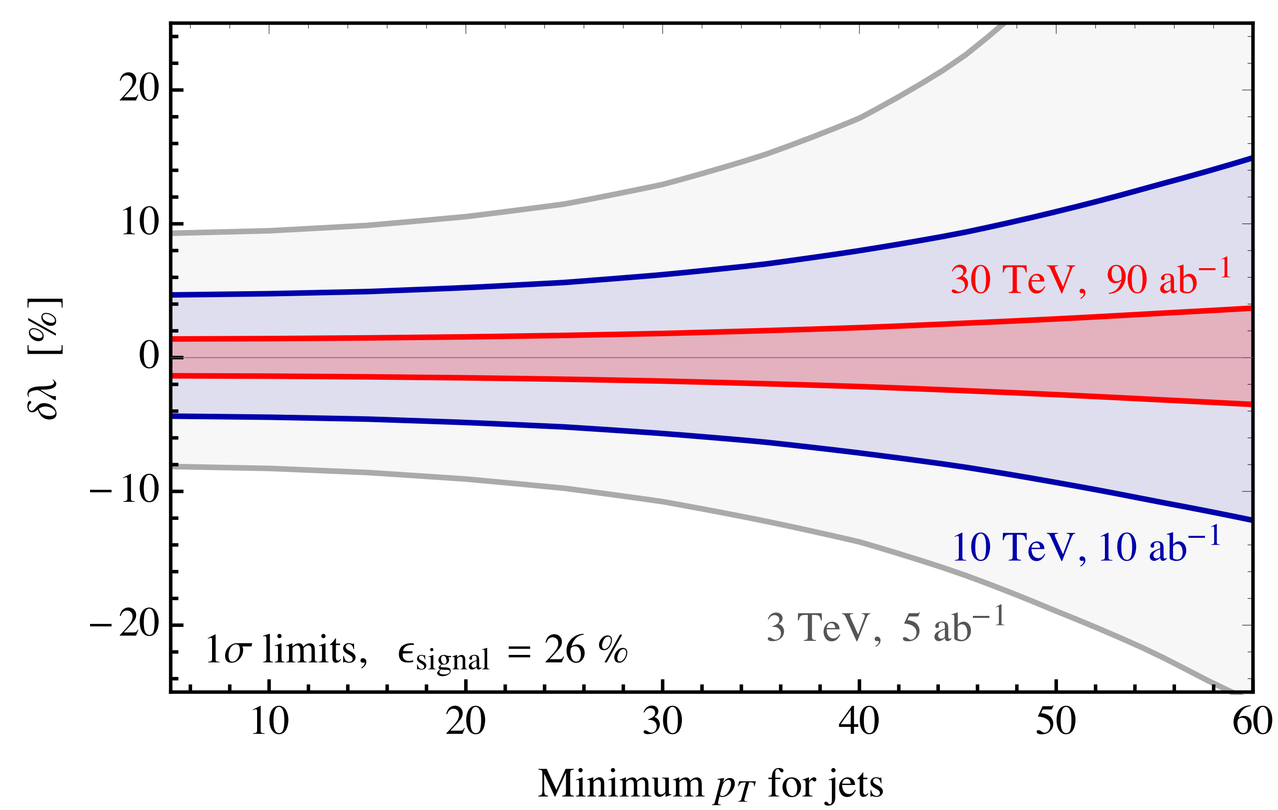
- Precision on Higgs couplings driven by systematics. **Could be 1‰**
- Rare/Exotic Higgs decay opportunities ?

Large double-Higgs VBF rate

[2008.12204; 2005.10289; Buttazzo, Franceschini, AW, to appear]

- 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





High rate indirect probes

Large single-Higgs VBF rate

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

Rare/Exotic Higgs decay opportunities ?

Large double-Higgs VBF rate

[2008.12204; 2005.10289; Buttazzo, Franceschini, AW, to appear]

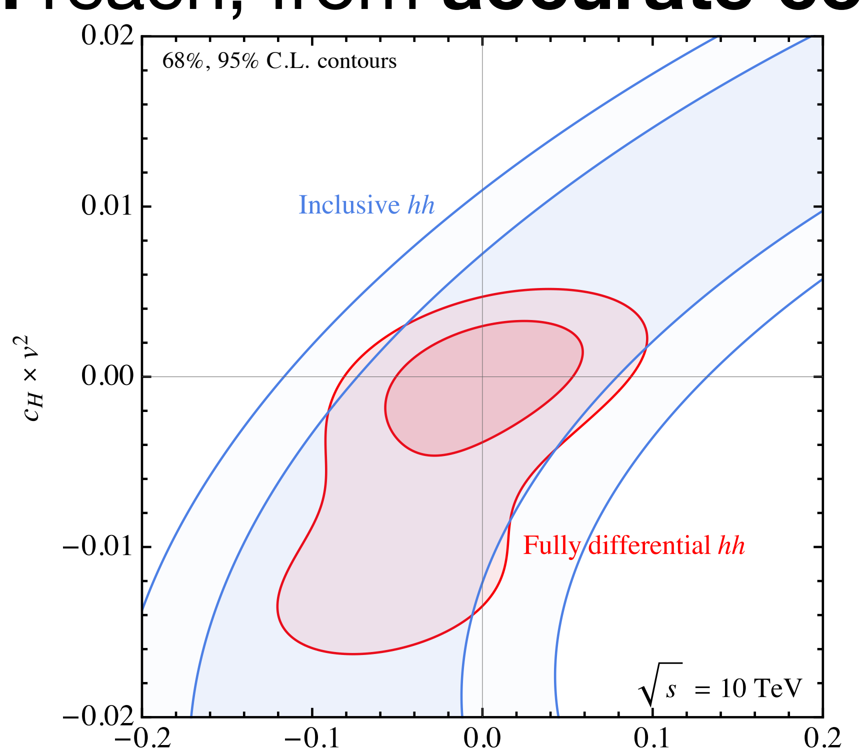
Higgs 3-linear: **$\delta\kappa_\lambda =_{1\sigma}$ (5%, 3.5%,1.6%) for E = (10, 14, 30) TeV**

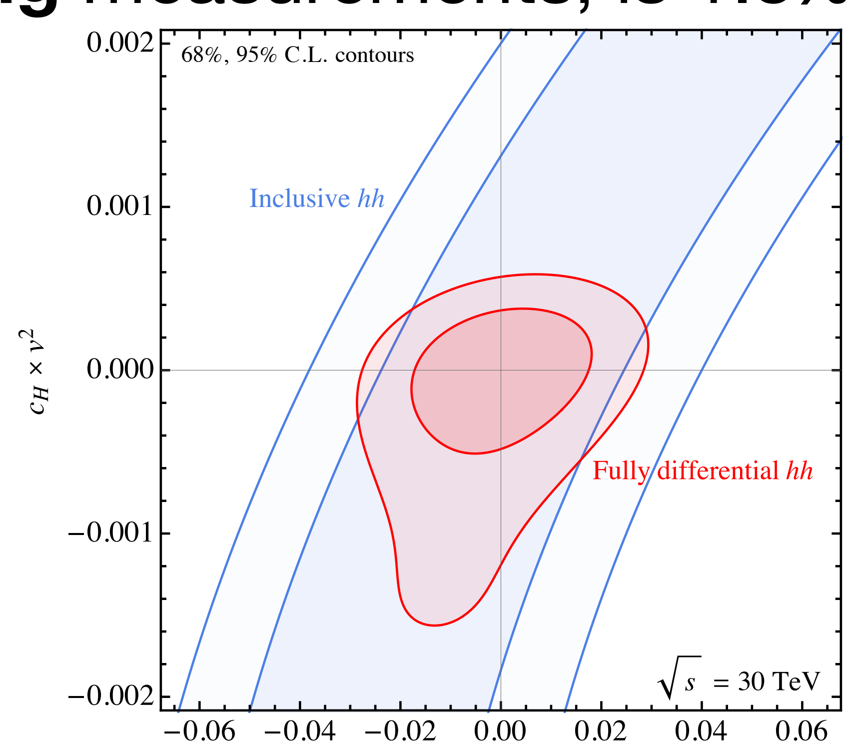
FCC reach is from 3.5 to 8.1%, depending on systematics assumptions

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‰





High energy probes

[Buttazzo, Franceschini, AW, to appear]

As simple as this:

$$\frac{\Delta\sigma(E)}{\sigma_{\rm SM}(E)} \propto \frac{E^2}{\Lambda_{\rm BSM}^2} \quad = \quad \text{[say, } \Lambda_{\rm BSM} = 100\,\text{TeV]}$$

High energy probes

[Buttazzo, Franceschini, AW, to appear]

As simple as this:

$$\frac{\Delta\sigma(E)}{\sigma_{\rm SM}(E)} \propto \frac{E^2}{\Lambda^2_{\rm BSM}}$$

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

- $\mathbf{10^{-6}}$ at EW [FCC-ee] energies
- $\mathbf{10^{-2}}$ at **muon collider** energies

High energy probes

[Buttazzo, Franceschini, AW, to appear]

As simple as this:

$$\frac{\Delta\sigma(E)}{\sigma_{\rm SM}(E)} \propto \frac{E^2}{\Lambda^2_{\rm BSM}} \overset{[\text{say, } \Lambda_{\rm BSM} = 100\,\text{TeV}]}{=}$$

- $\mathbf{10^{-6}}$ at EW [FCC-ee] energies
- $\mathbf{10^{-2}}$ at **muon collider** energies

High-Energy probes are effective at HL-LHC, FCC-hh, CLIC

[Farina, Panico, Pappadopulo, Ruderman, Torre, AW, 2016]
[Franceschini, Panico, Pomarol, Riva, AW, 2018]
[de Blas et., al, 1910.11775; …]

High energy probes

[Buttazzo, Franceschini, AW, to appear]

As simple as this:

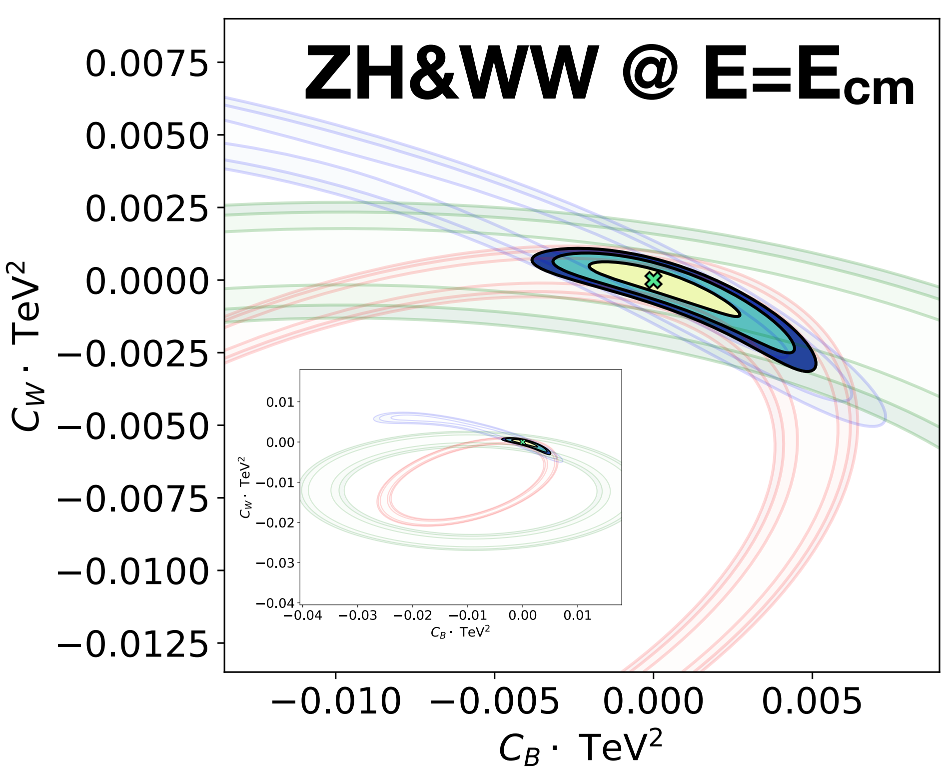
$$\frac{\Delta\sigma(E)}{\sigma_{\rm SM}(E)} \propto \frac{E^2}{\Lambda_{\rm BSM}^2} \overset{\textbf{[say, } \Lambda_{\rm BSM} = 100\,\text{TeV]}}{=}$$

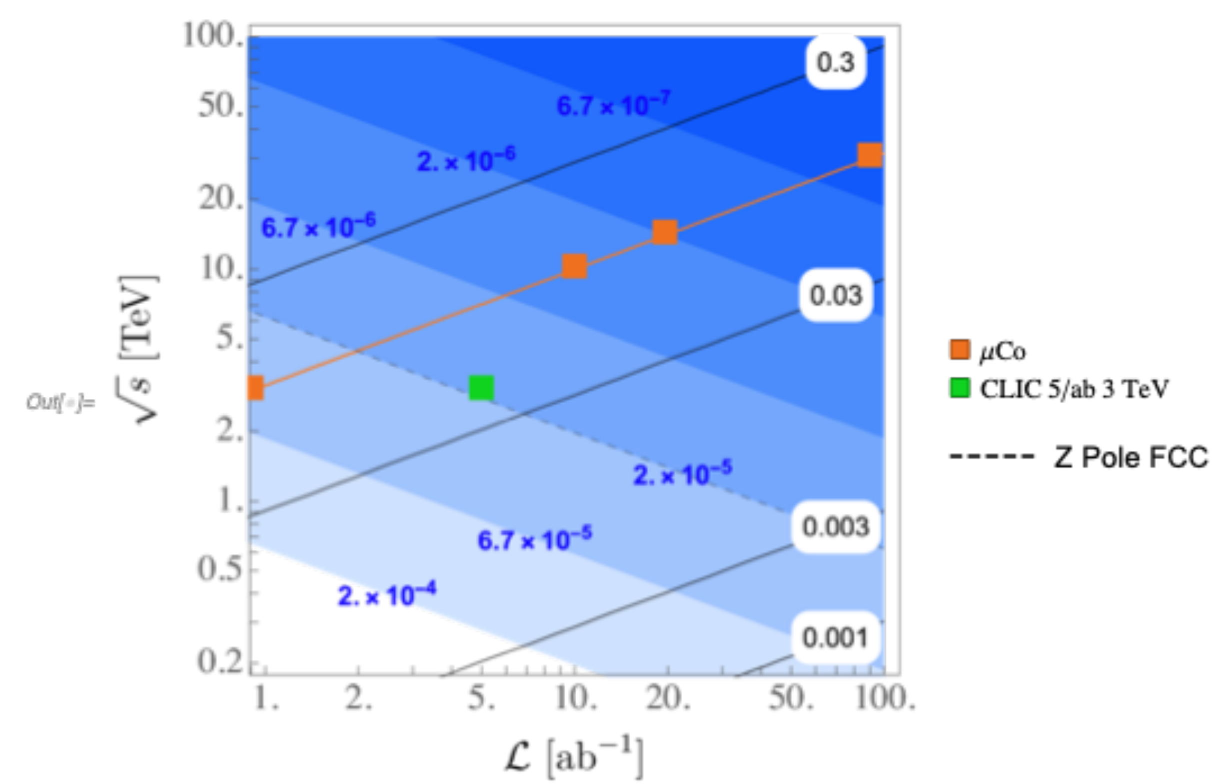
- 10^{-6} at EW [FCC-ee] energies
- 10^{-2} at **muon collider** energies

High-Energy probes are effective at HL-LHC, FCC-hh, CLIC

[Farina, Panico, Pappadopulo, Ruderman, Torre, AW, 2016]
[Franceschini, Panico, Pomarol, Riva, AW, 2018]
[de Blas et., al, 1910.11775; …]

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

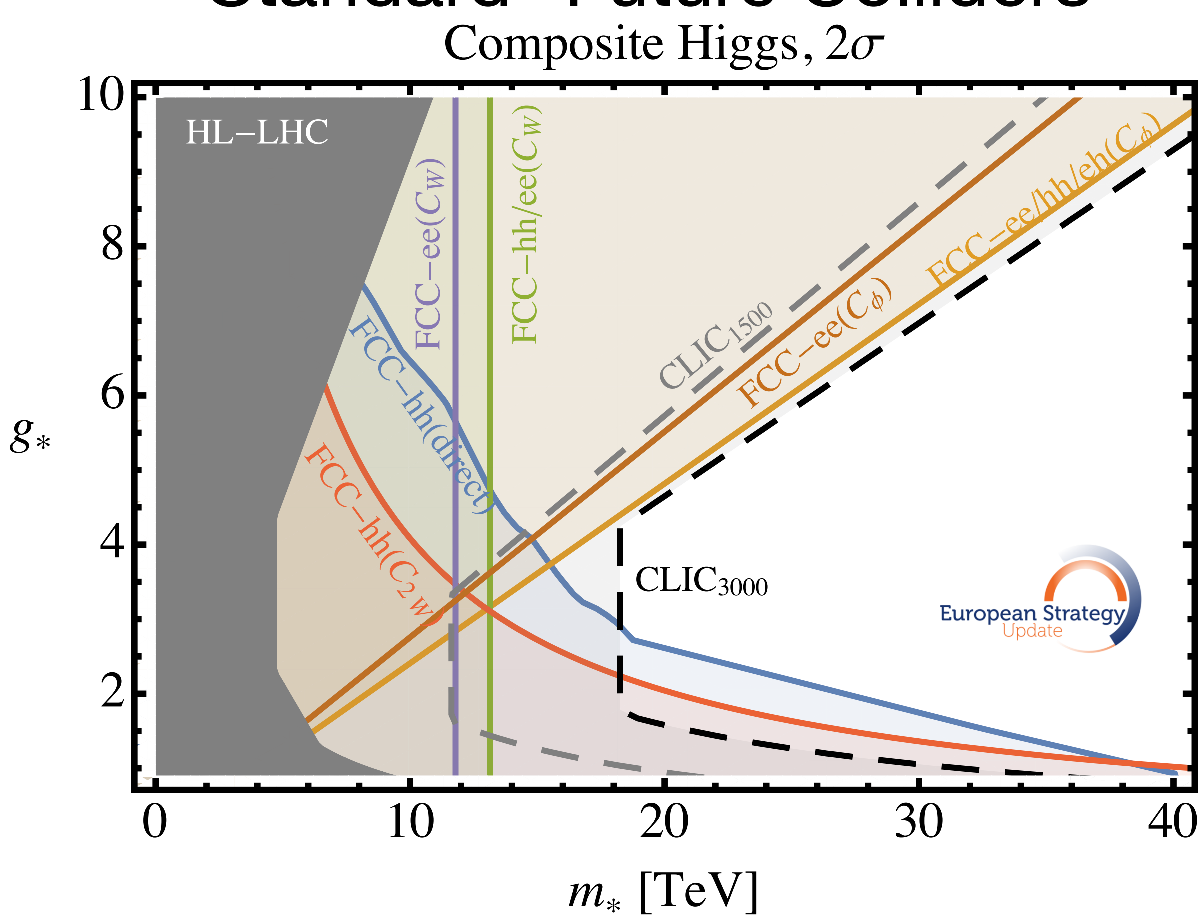




Probing Higgs compositeness

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

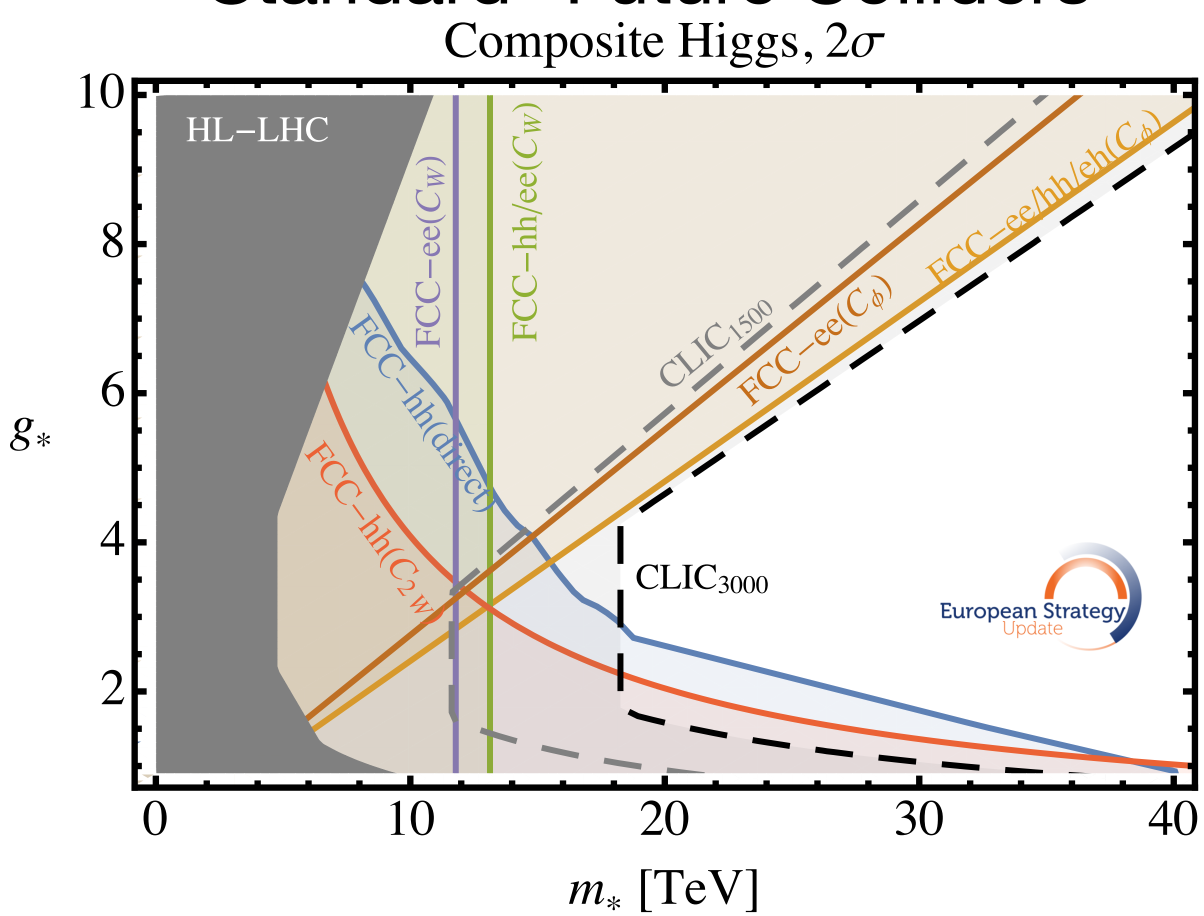
"Standard" Future Colliders



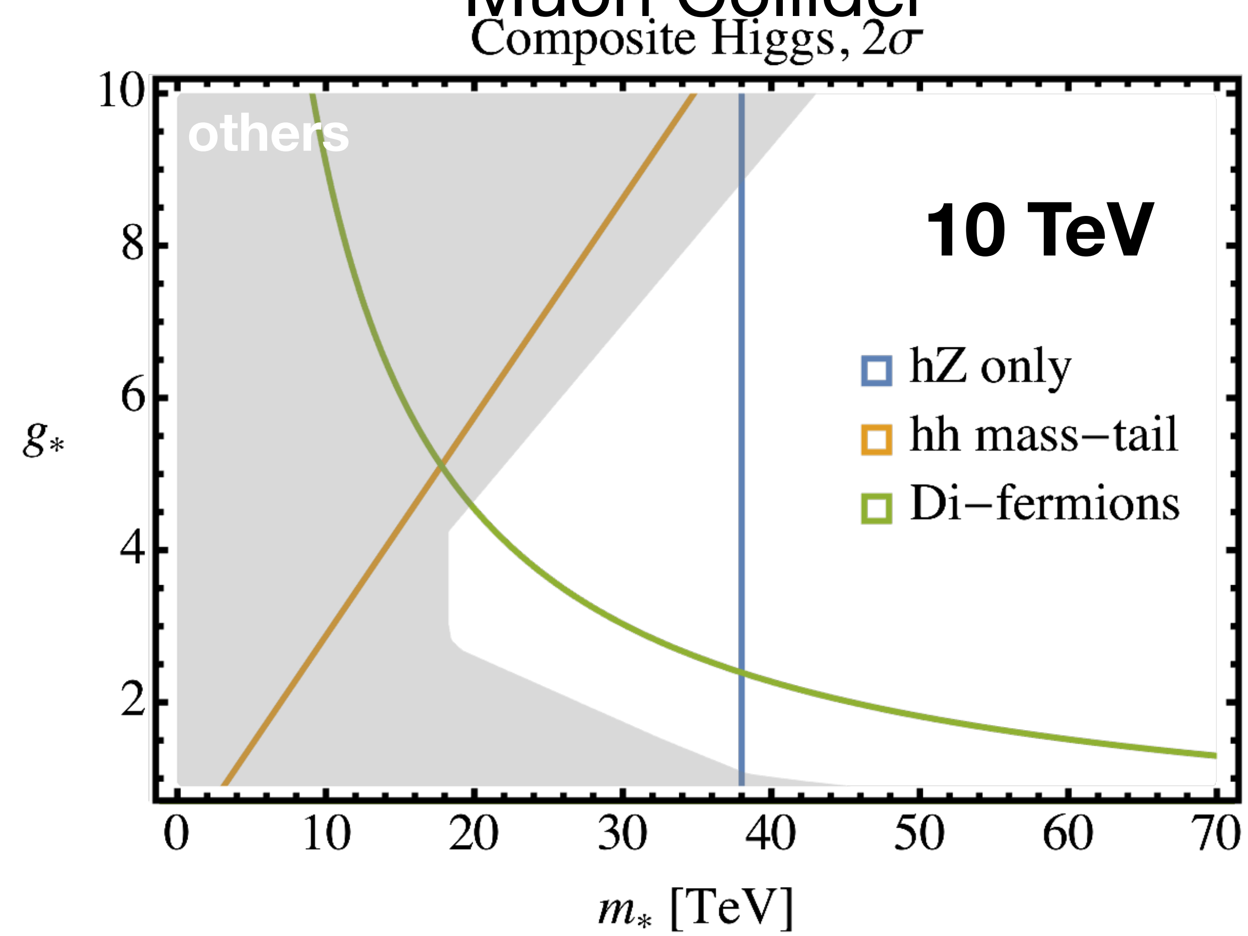
Probing Higgs compositeness

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

“Standard” Future Colliders



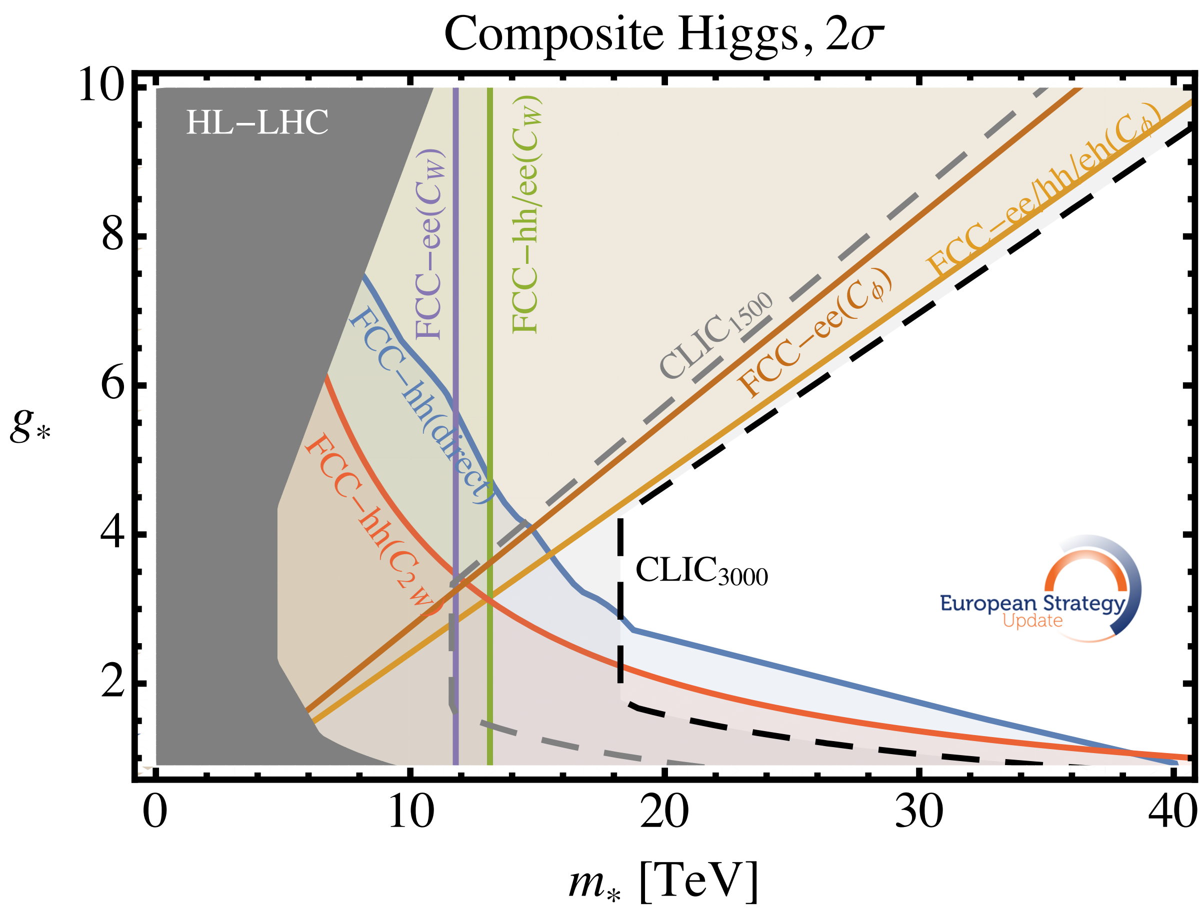
Muon Collider



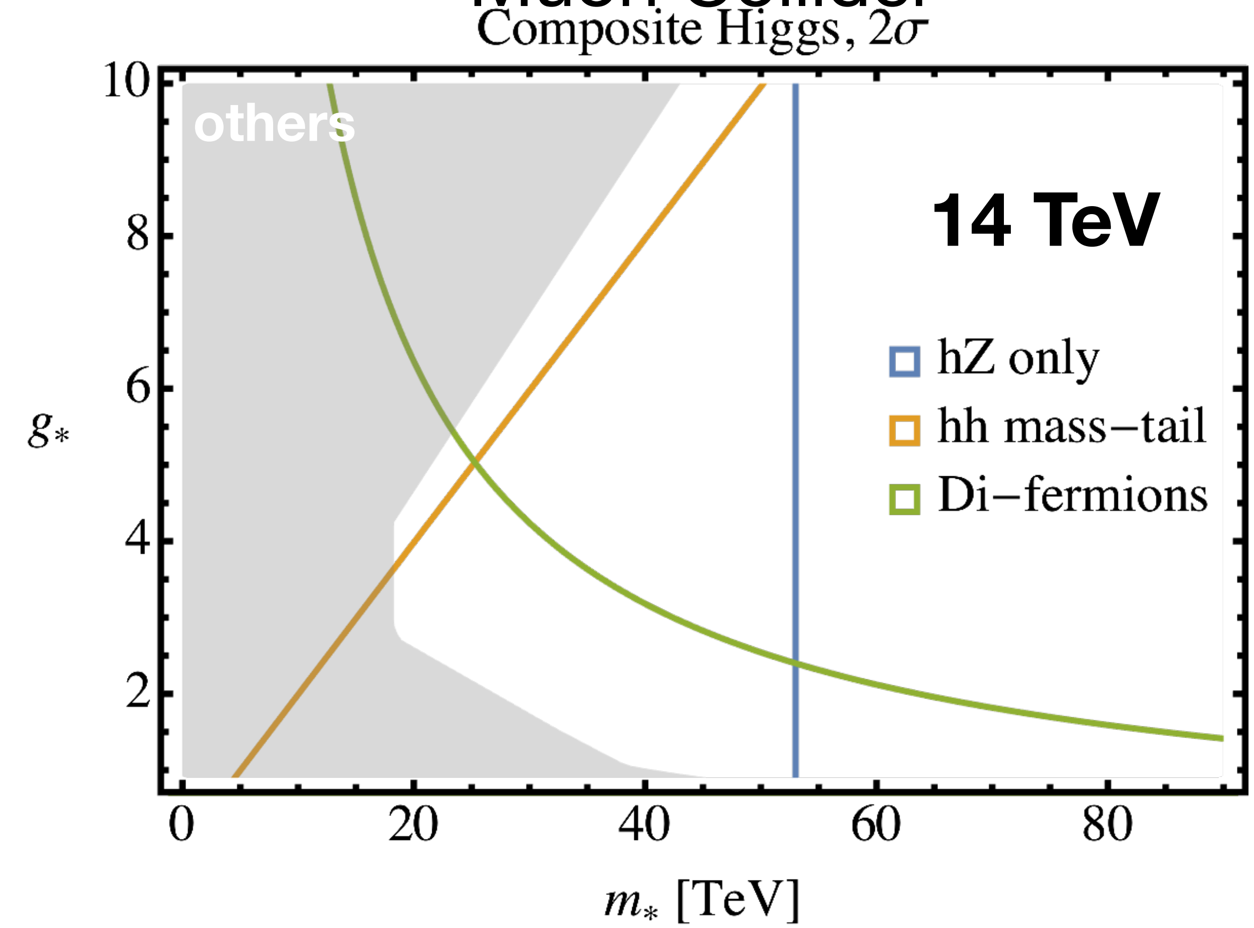
Probing Higgs compositeness

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

“Standard” Future Colliders



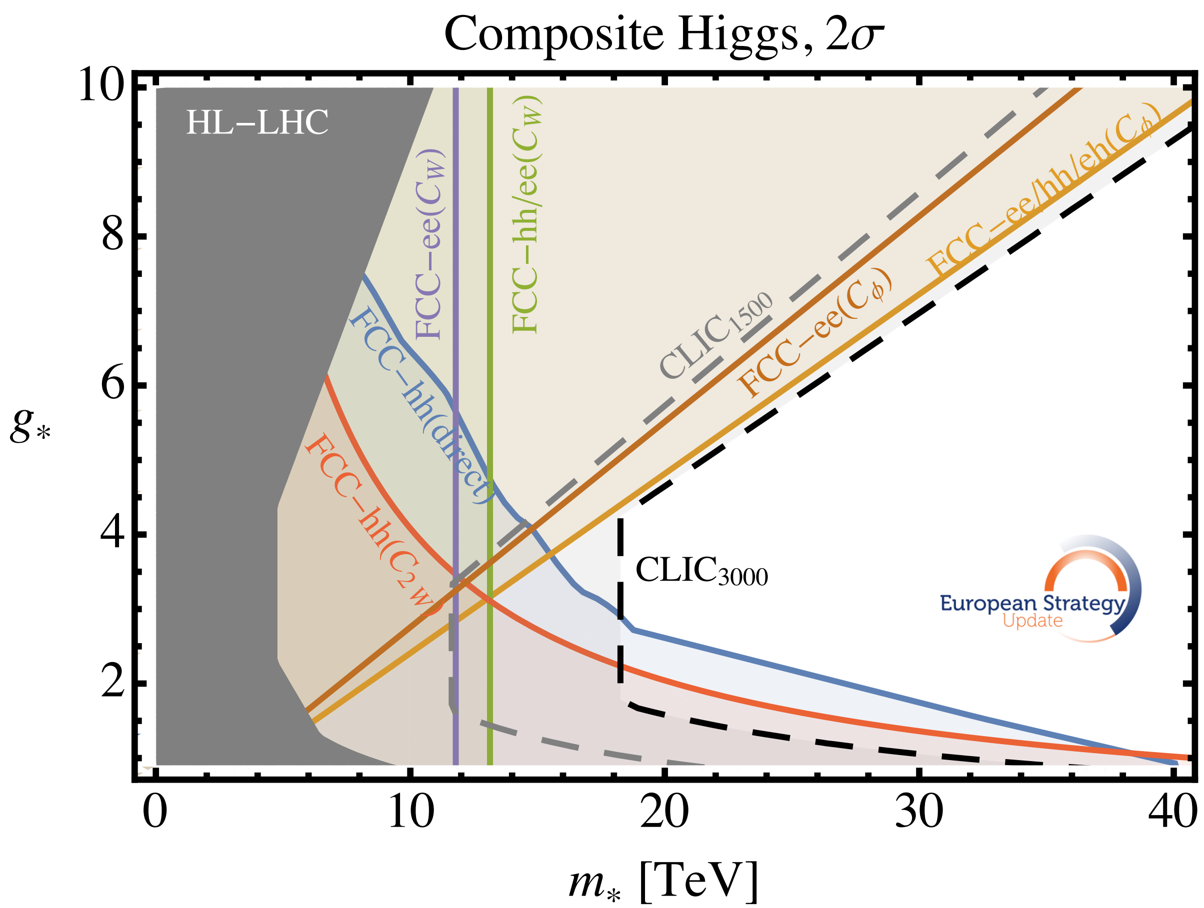
Muon Collider



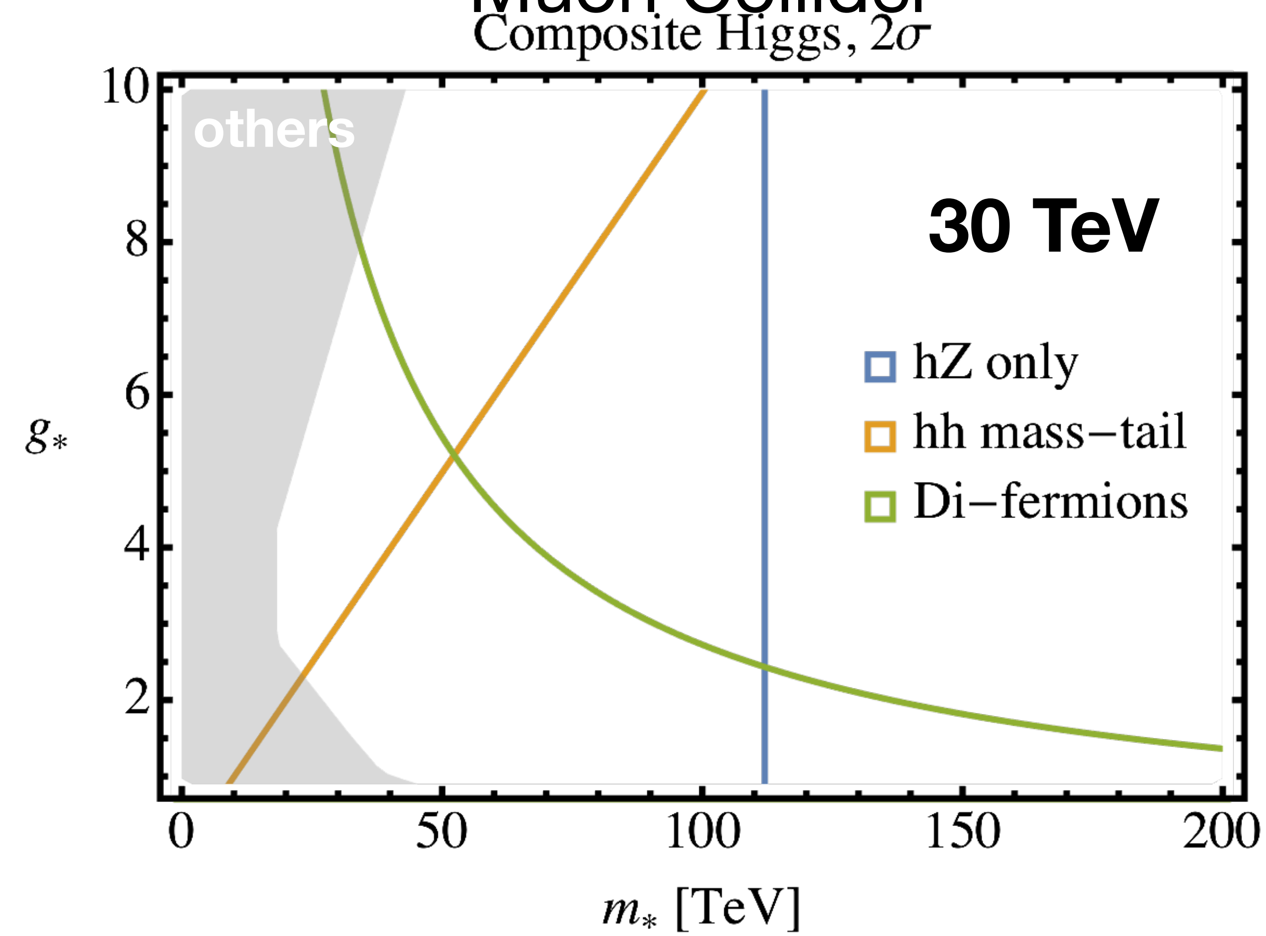
Probing Higgs compositeness

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

"Standard" Future Colliders



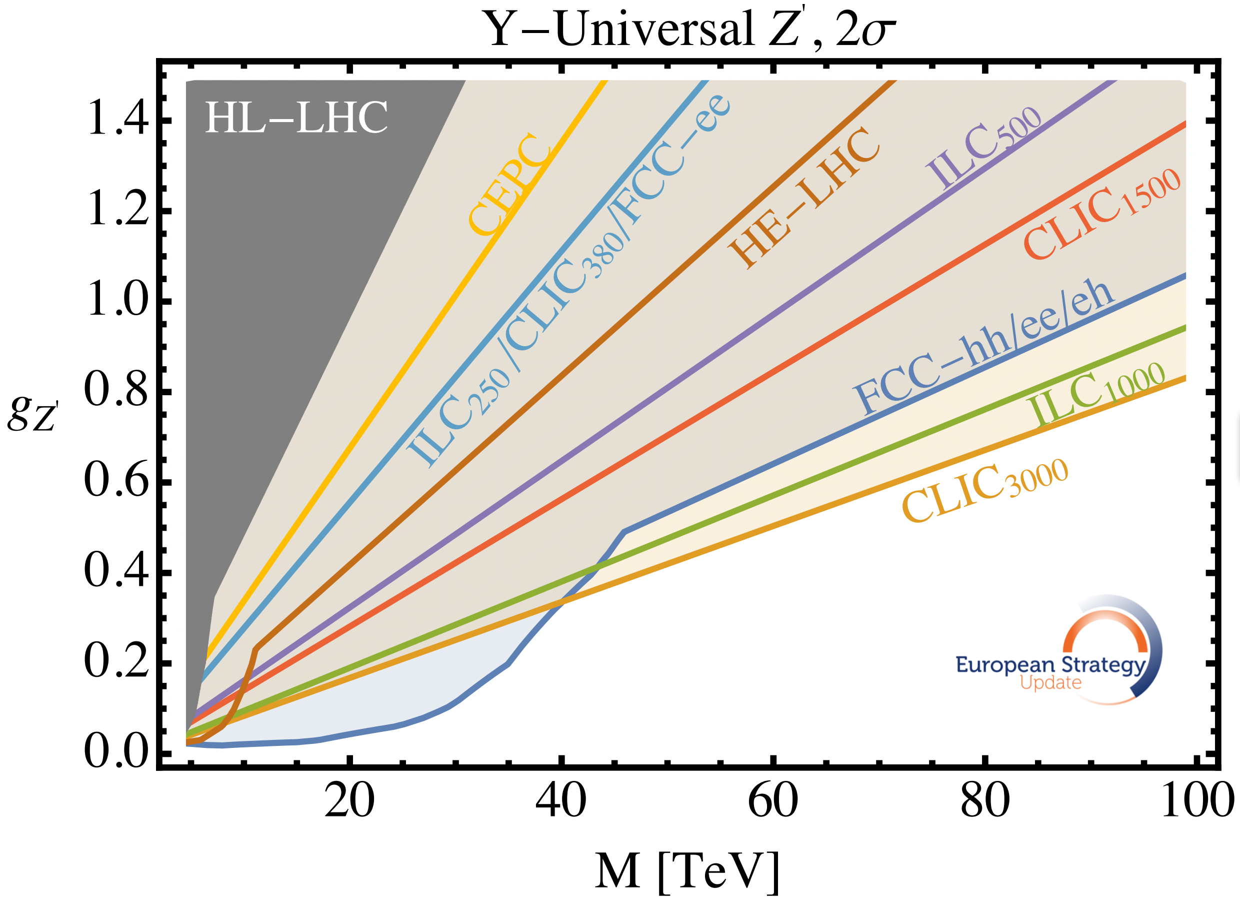
Muon Collider



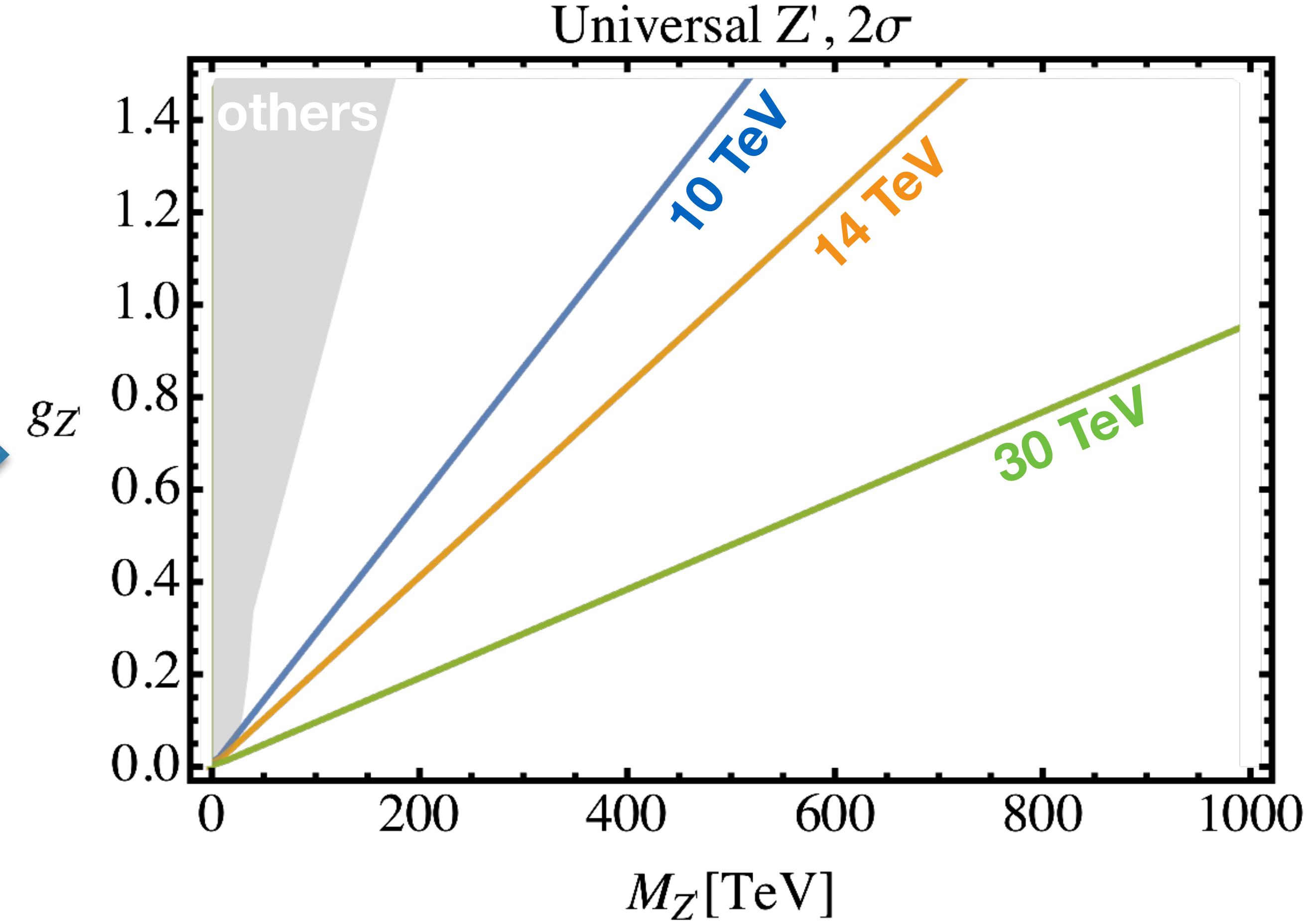
Even Simpler: Minimal Z's

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

"Standard" Future Colliders



Muon Collider



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 Fabio’s talk]

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 Fabio’s talk]

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

Outlook

The Very High Energy Muon Collider is a Dream

Outlook

The Very High Energy Muon Collider is a Dream

And, often, Dreams DO become Reality!

Outlook

The Very High Energy Muon Collider is a Dream

And, often, Dreams DO become Reality!

Thank You !