“One ring to rule them all, one ring to find them” … - J.R.R.Tolkien

Muon collider: physics

Fabio Maltoni
Université catholique de Louvain
Università di Bologna

Frank Simon’s original art work. Adapted

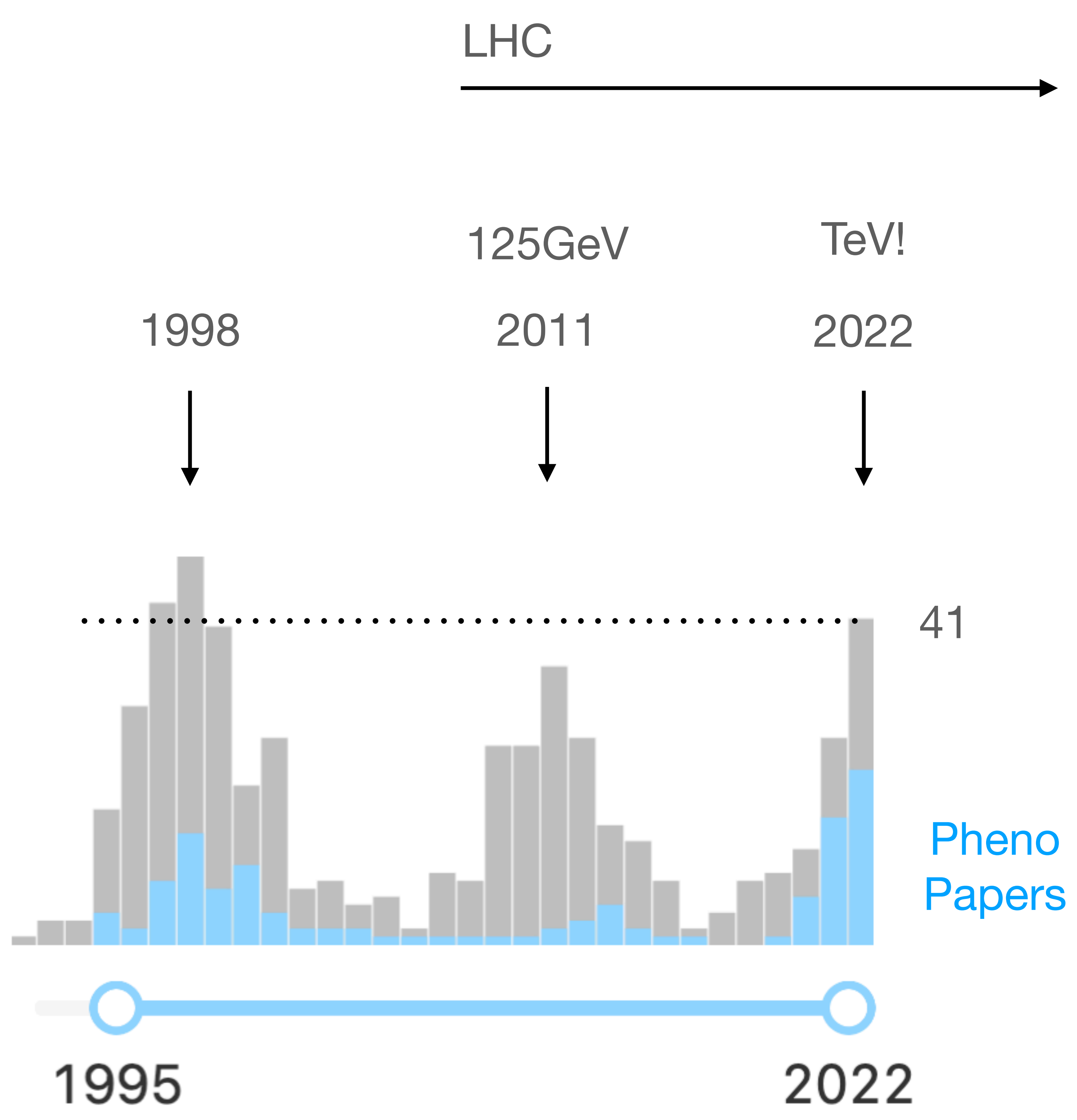
A **new** interest in a muon collider

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
    => After 10+ years of LHC: energy gap
    => Direct searches+precision

⇒Timing is right for R&D!



A new interest in a muon collider

2022 papers (including Snowmass)

1. K.M. Black et al., "Muon Collider Forum Report," : 2209.01318 [hep-ex]
2. Arakawa et al. ,"Probing Muon $g-2$ at a Future Muon Collider et al. " e-Print: 2208.14464 [hep-ph]
3. Brendt et al. ,"NLO Electroweak Corrections to Multi-Boson Processes at a Muon Collider, e-Print: 2208.09438 [hep-ph]
4. Yang et al. ,"Shining light on the electroweak 't Hooft-Polyakov magnetic monopoles: the high-energy muon collider" , e-Print: 2208.02188 [hep-ph]
5. Lu et al.,"Unraveling the Scotogenic Model at Muon Collider", e-Print: 2207.07382 [hep-ph]
6. J. De Blas et al., "The physics case of a 3 TeV muon collider stage", arXiv:2203.07261 [hep-ph] (pdf).
7. Inan et al., "Probe of axion-like particles in vector boson scattering at a muon collider" 2207.03325 [hep-ph]
8. Chakraborty et al. " Searches f
9. Azatov et al., "New Physics in
10. Han et al. " BSM Higgs Produ
11. Senol et al. " Model-independ
12. Ji-Chang Yang et al., "Measur ... hep-ph]
13. Haghighat, Search for lepton-
14. S. Homiller et al. "Complemen
15. Aime et al. , "Muon Collider P
16. W. Altmannshofer et al, Snow
17. Bao et al., "Electroweak ALP
18. De Blas et al. ,"Higgs Precisio
19. L. Bottura, et al., " A Work Pro
20. S. Homiller et al., "Compleme
21. Yu. Alexahin et al., "Solving C ... physics.acc-ph]
22. Nazar Bartosiket al. ,"Simulated Detector Performance at the Muon Collider", 2203.07964 [hep-ex]
23. Brad Abbott et al., "Anomalous quartic gauge couplings at a muon collider", 2203.08135 [hep-ex]
24. Tao Han, Tong Li, Xing Wang. "Axion-Like Particles at High Energy Muon Colliders", arXiv:2203.05484 [hep-ph] (pdf).
25. Tao Han, Zhen Liu, Lian-Tao Wang, Xing Wang. "WIMP Dark Matter at High Energy Muon Colliders", arXiv:2203.07351 [hep-ph] (pdf).
26. 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).
27. 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).
28. 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).
29. 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).
30. 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).
31. Matthew Forslund, Patrick Meade. "High Precision Higgs from High Energy Muon Colliders", arXiv:2203.09425 [hep-ph] (pdf)
32. ……

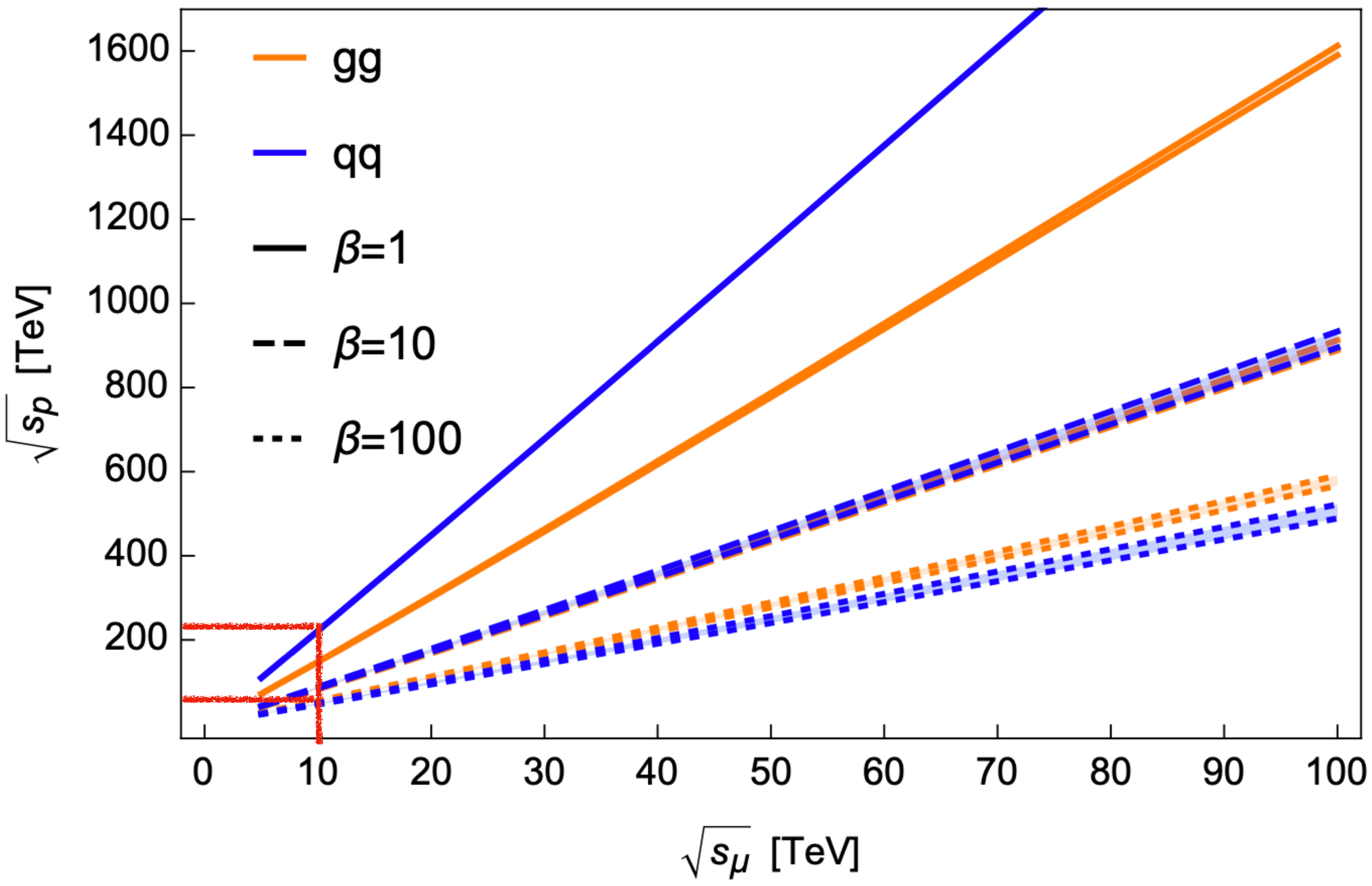
Excitement building up on many innovative aspects from accelerators, to detectors, to an "unexpected" physics reach. A growing interest in the community has allowed to put efforts in identifying the key

1] technologies that make a muon collider possible.

2] physics motivations that make a muon collider worth it

Muon collider physics

The essentials #0 : potential



muC@10 TeV ~ pp@70 TeV

Simple/Naive/Rough estimate based on parton-parton luminosity for a generic $2 \to 2$ scattering.

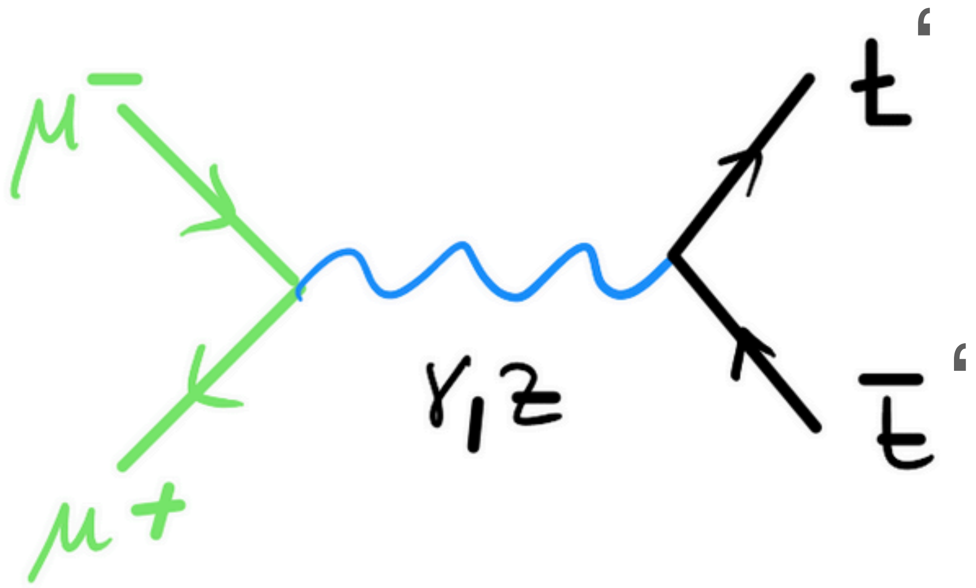
$$EW : \beta \sim 1$$

$$QCD : \beta \sim (\alpha_S/\alpha)^2 \sim 100$$

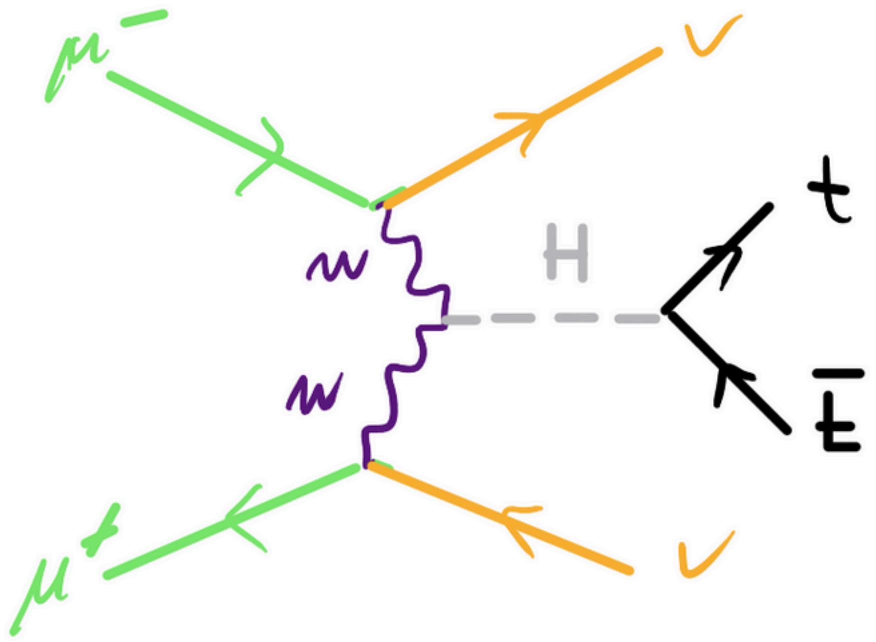
Muon collider physics

The essentials #1 : two colliders in one

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



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



Energetic final states
(either heavy or very boosted)

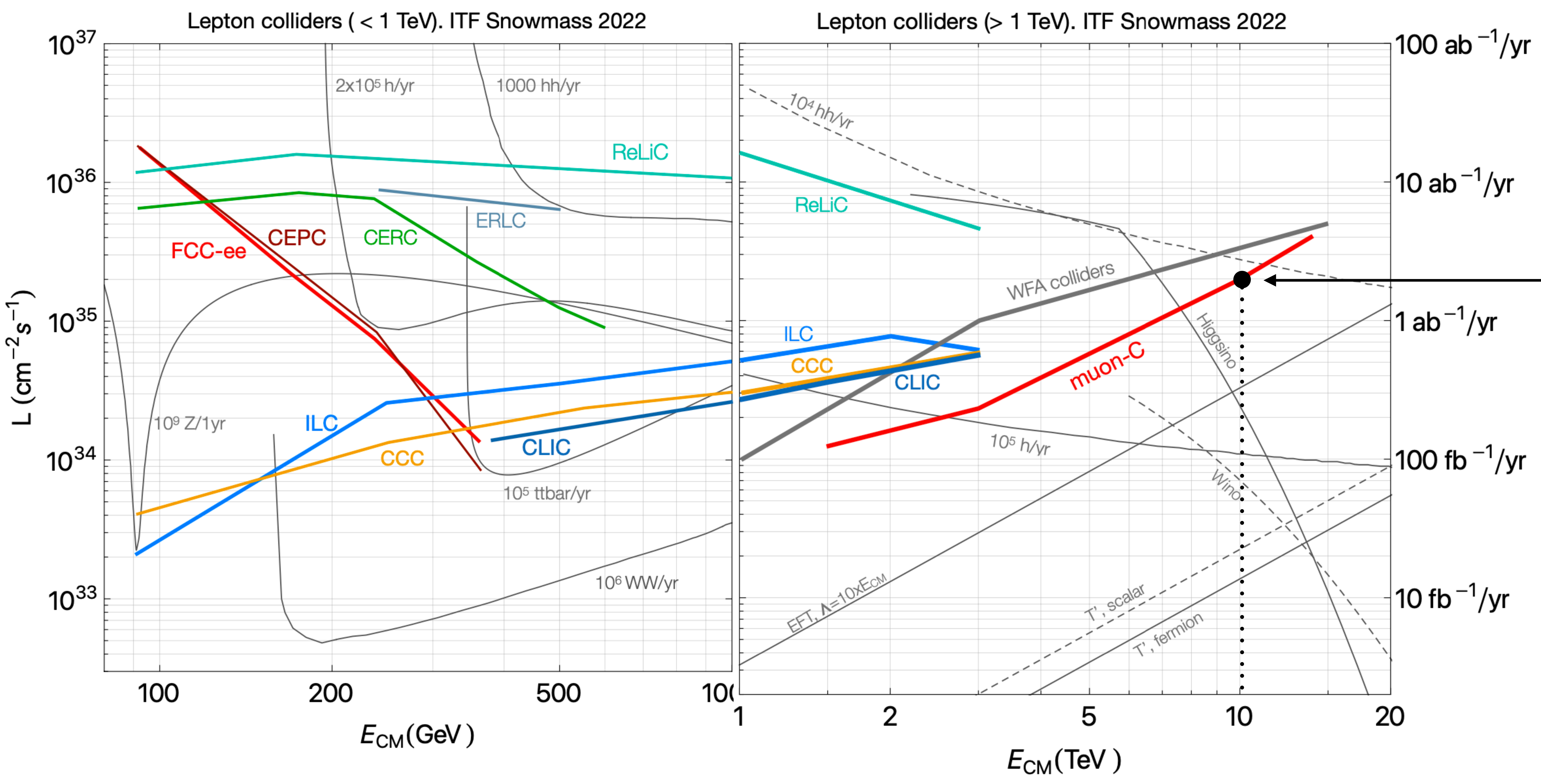
Large production rates,
SM coupling measurements
Discovery light and weakly interacting

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

Different physics being probed in the two channels

Muon collider physics

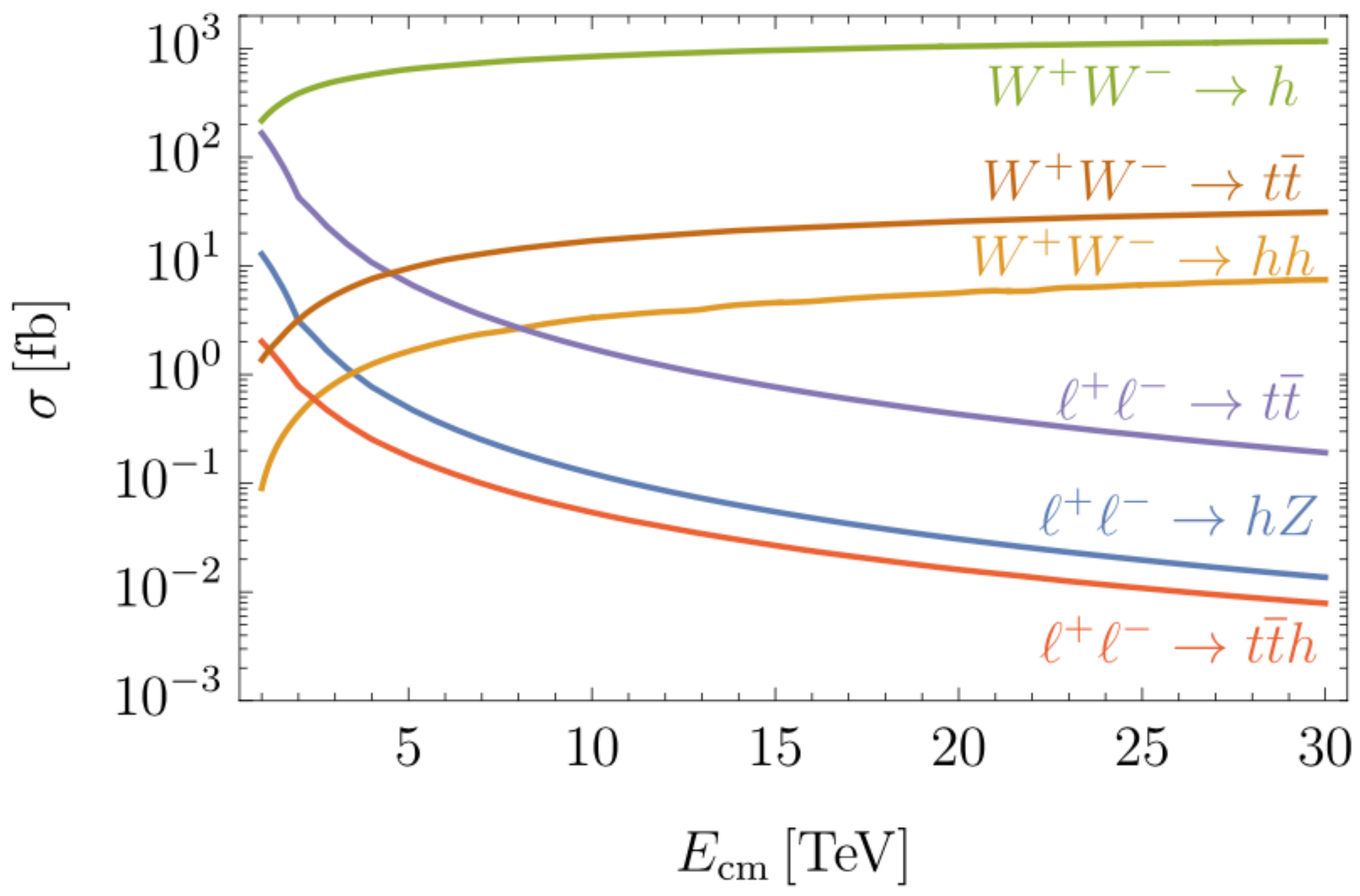
The essentials #2 : luminosity with energy

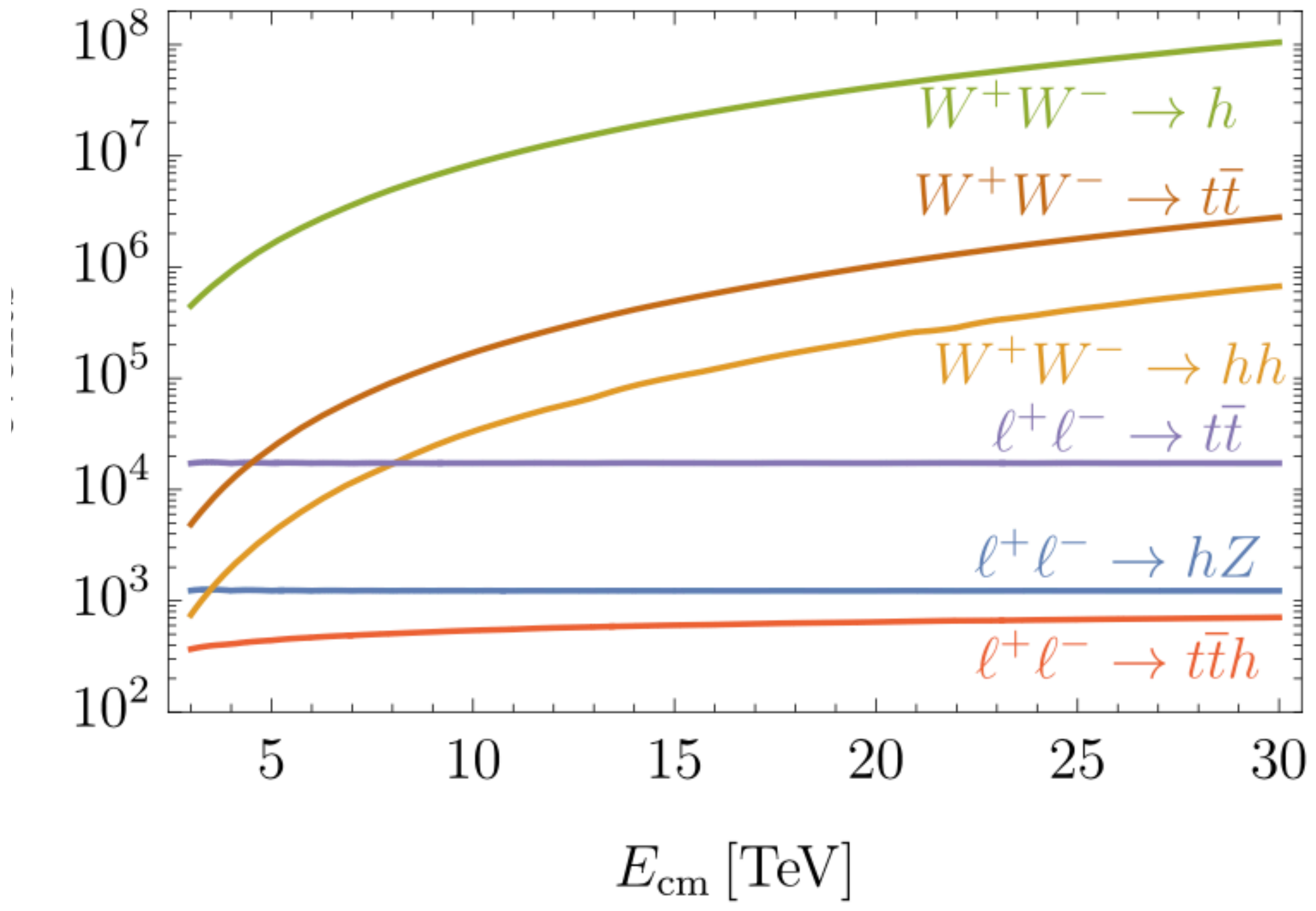


10 ab^{-1} in 5 years

Muon collider physics

The essentials #2 : luminosity with energy



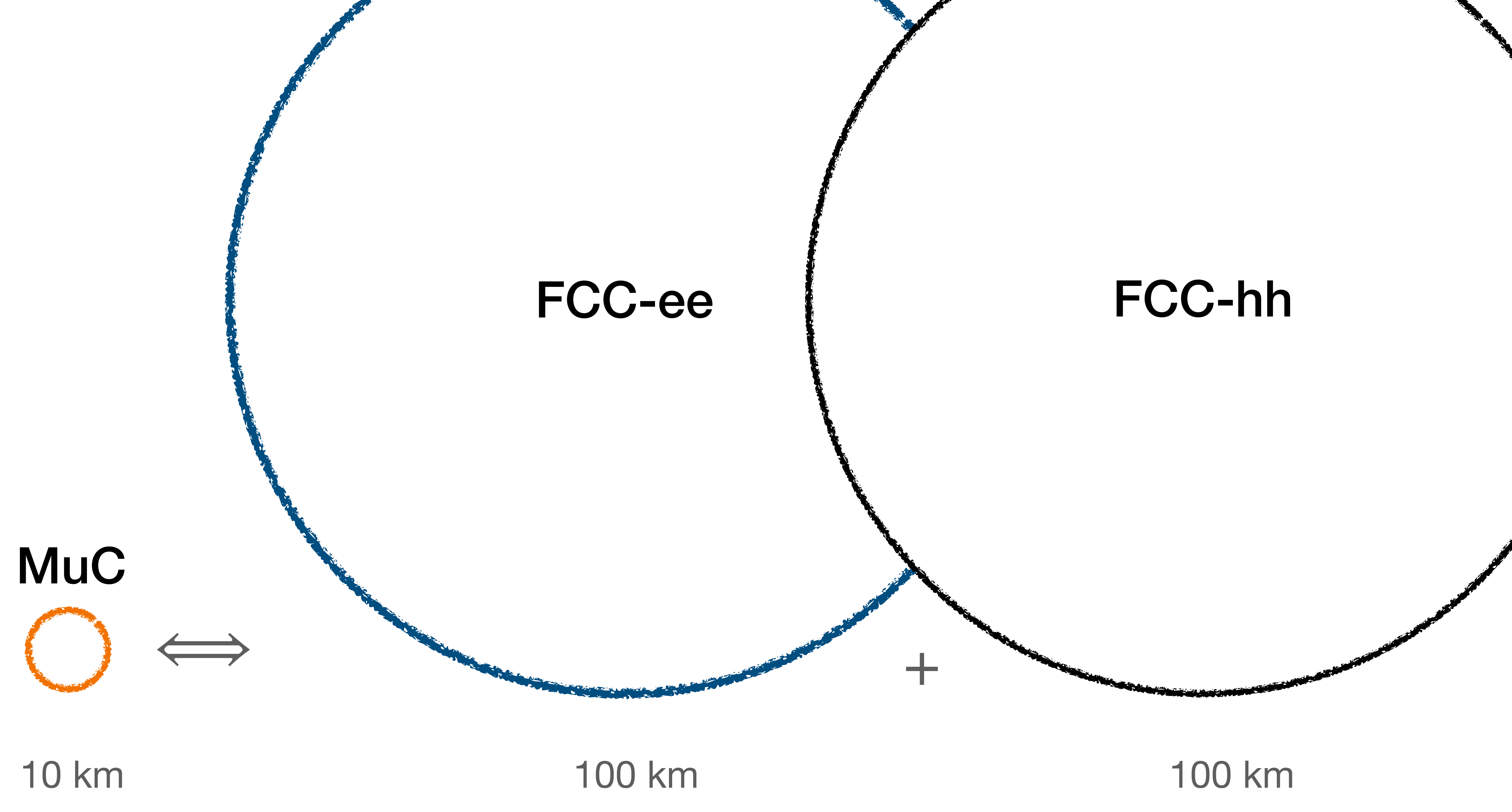


$$\widehat{\mathcal{L}} = 10\,\mathrm{ab}^{-1}\left(\frac{E_{\rm cm}}{10\,\mathrm{TeV}}\right)^2$$

Muon collider physics

The essentials #3: compactness

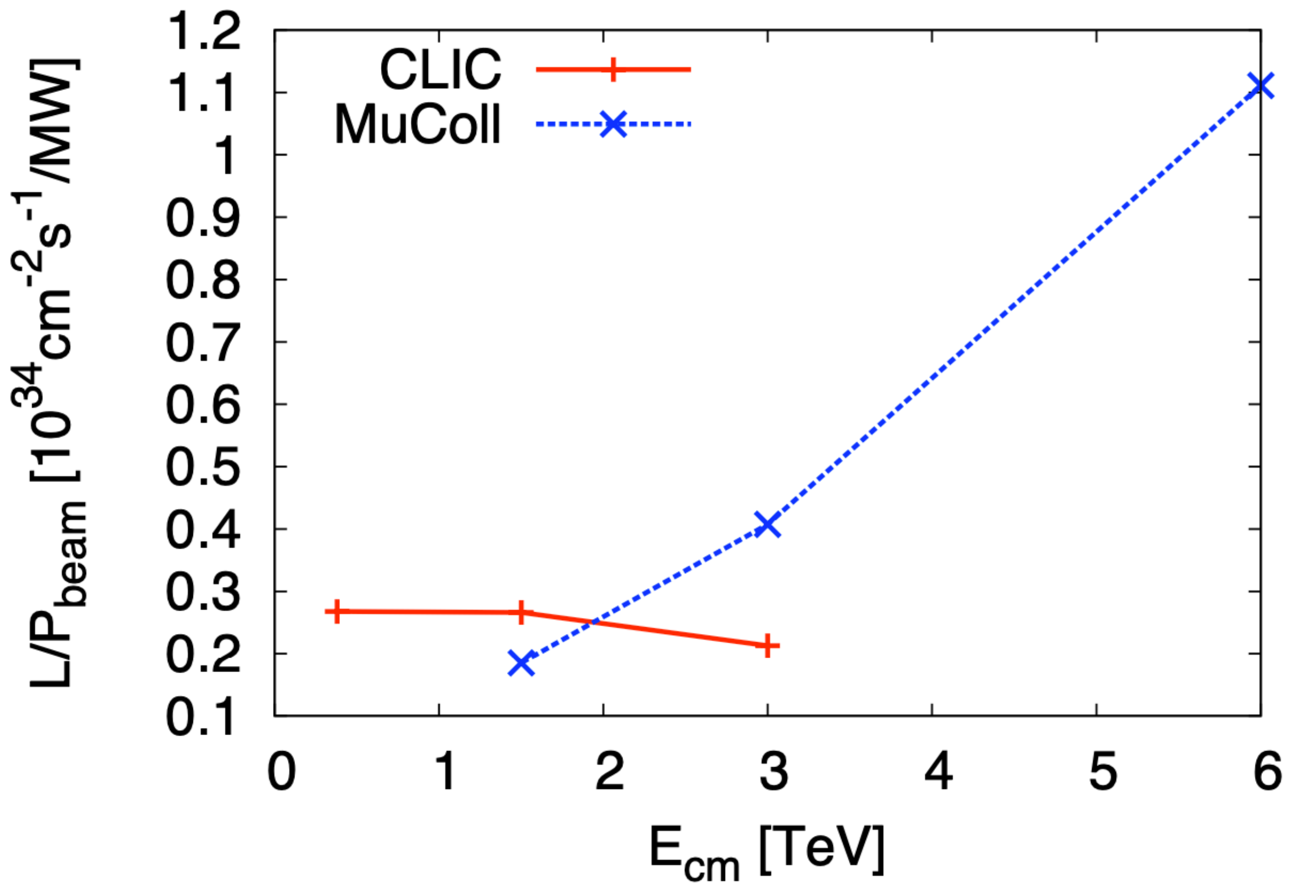
1] O(10) TeV Energy small hybrid collider:



x

t

2] Luminosity growing with energy:



⇒MuC is an STCC = Space-Time-Compact Collider

⇒ Goal of the tens:

10 TeV , 10 iab, 10 x smaller and O(10) x faster than the FCC

Muon collider physics
The essentials

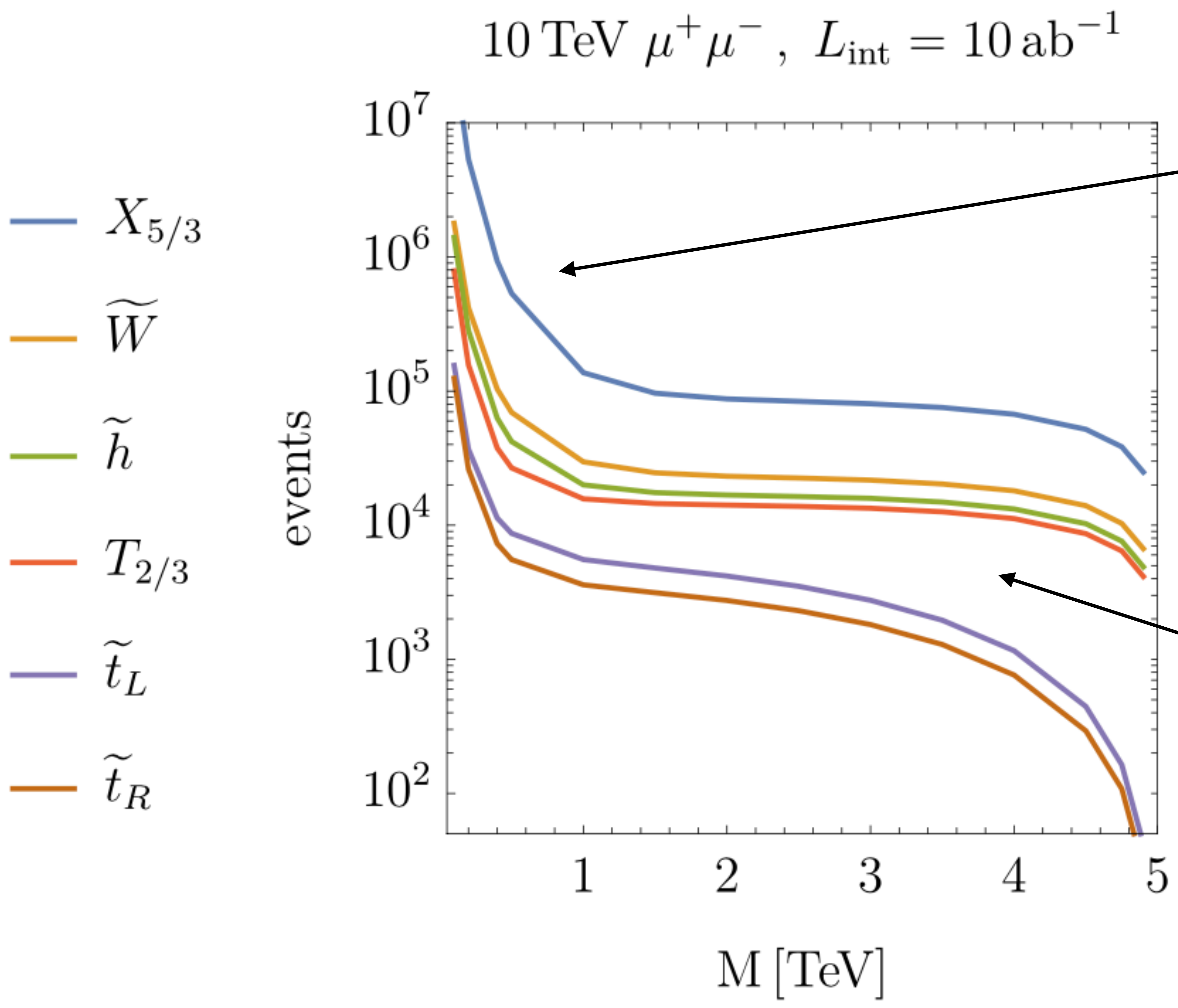
- A O(10 TeV) muC is in the range of what could be technically achievable. R&D is necessary.
- It would radically change the way we do collider physics, opening the exploration of EW phenomena at higher scales through an hybrid direct/indirect approach in a clean environment.
- Given what we know now from the LHC + what will learn from HL-LHC what are the muC physics drivers?

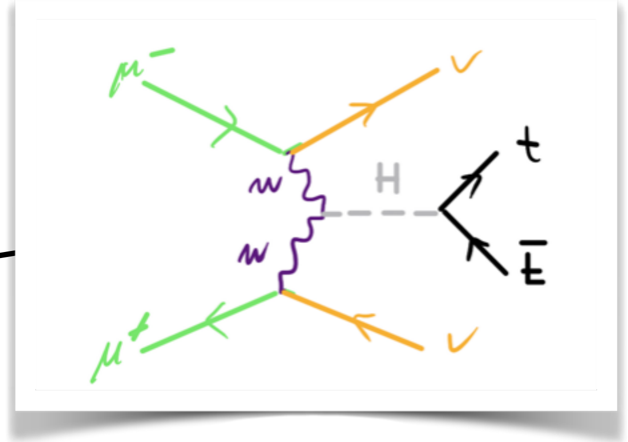
arXiv:2203.07256 Muon Collider Physics Summary

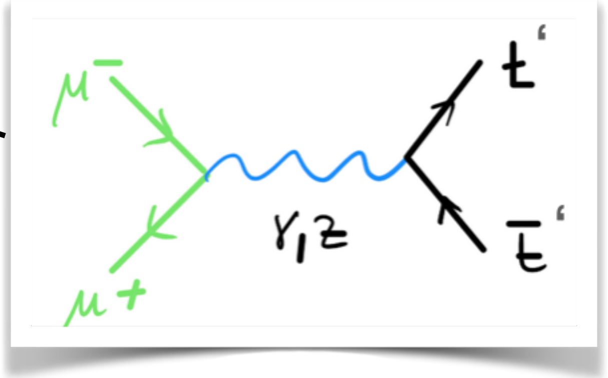
arXiv:2209.01318 Muon Collider Forum Report

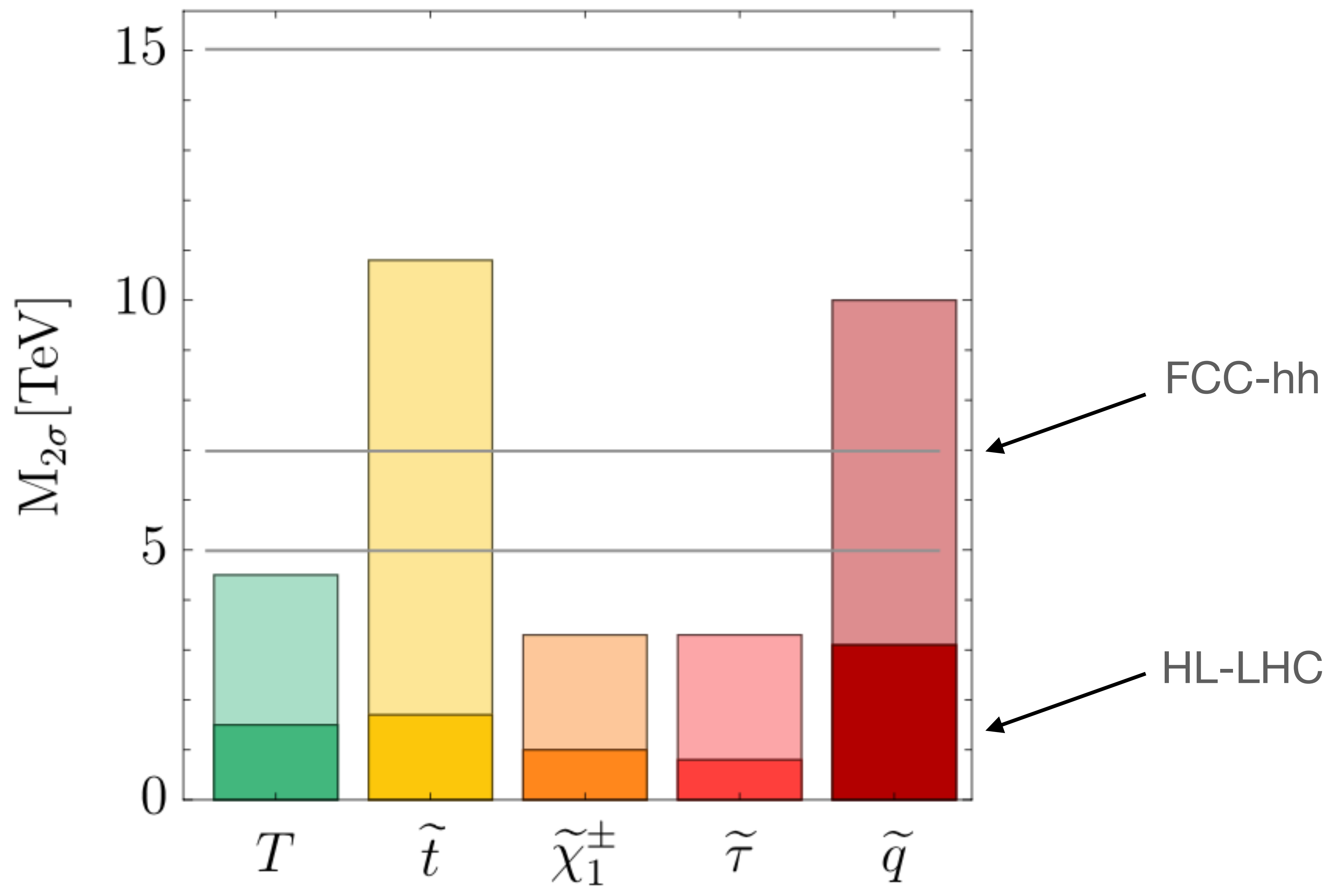
Direct reach

s-channel pair production









$$\delta\kappa_g = \frac{1}{4}\left(\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}^2} - \frac{m_t^2 X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right)$$

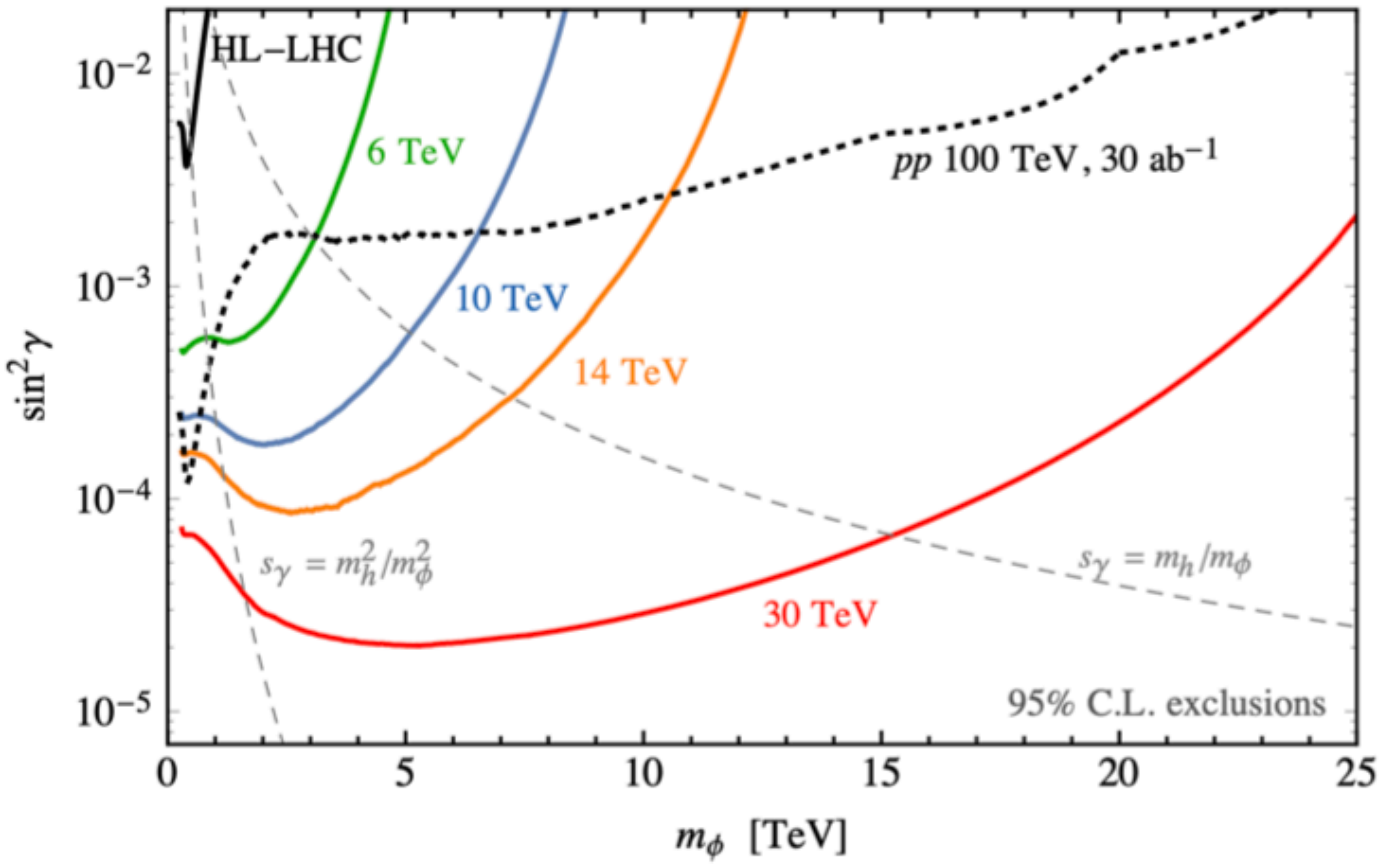
A few months of run could be sufficient for a discovery.

Matching Higgs precision:

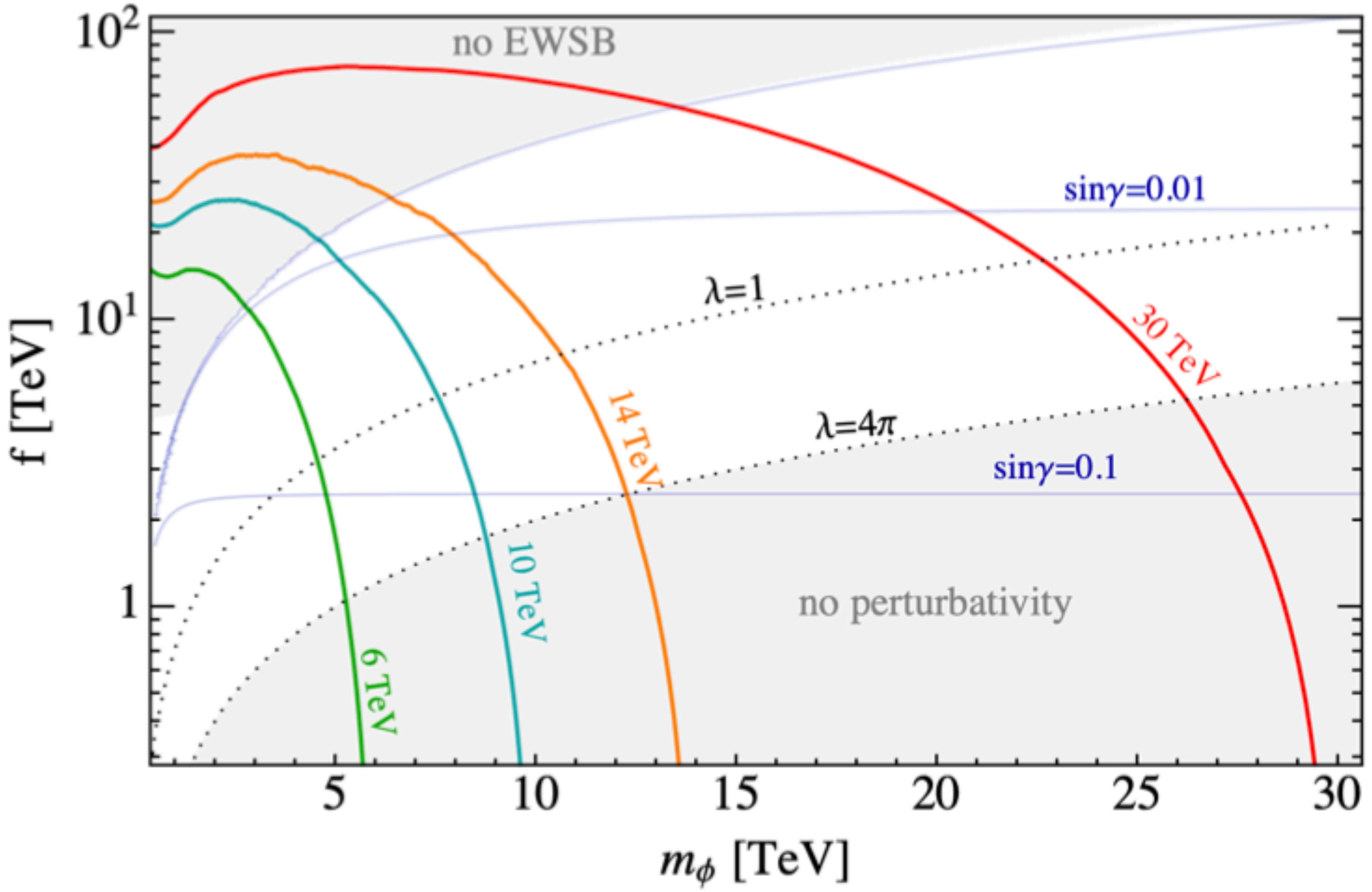
$$m_{\tilde{t}} \gtrsim 1.5\,\mathrm{TeV}\sqrt{\frac{0.67\%}{\delta\kappa_g^{\max}}}.$$

Direct reach

VBF scalar singlet production



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

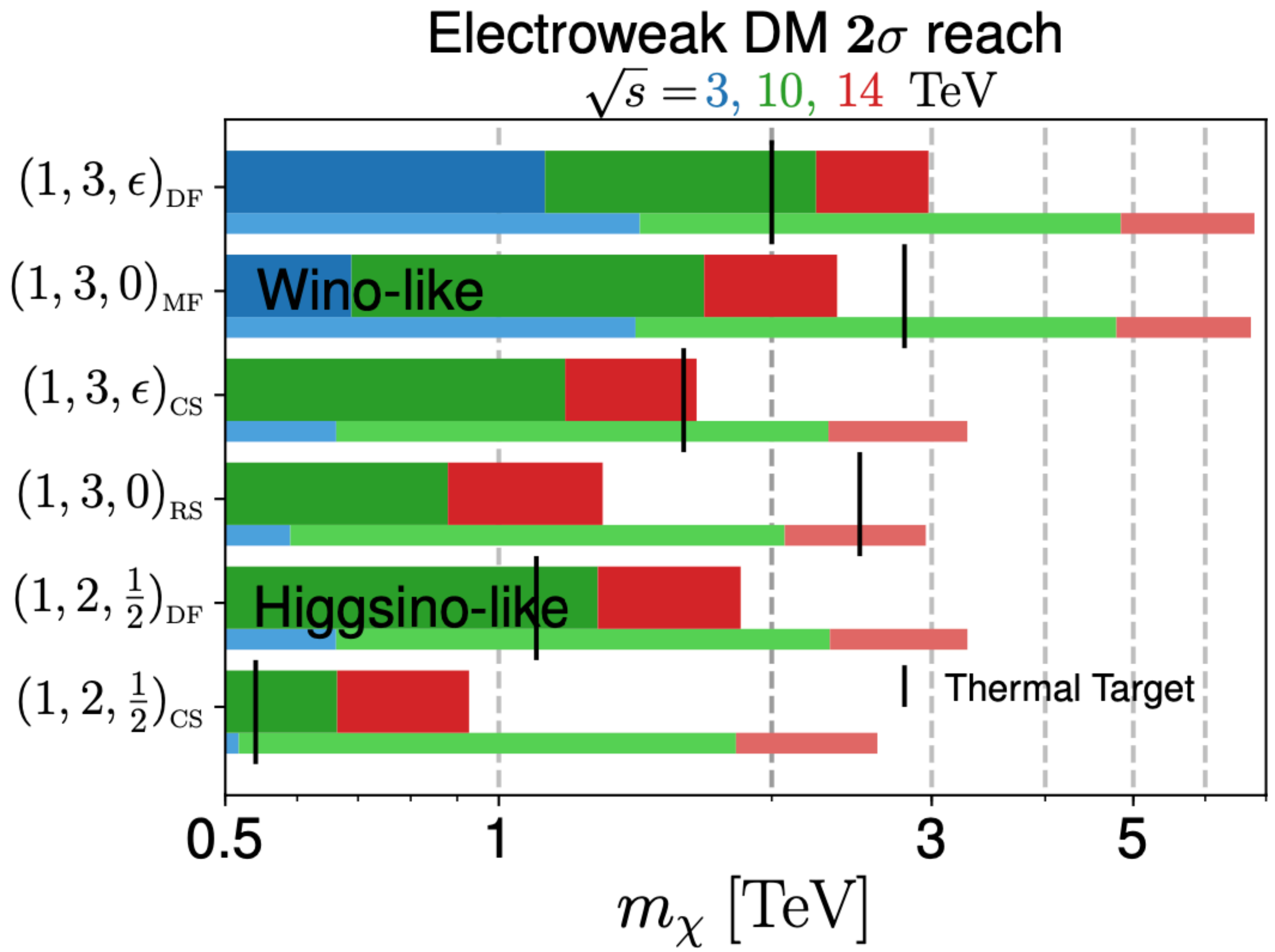


[Buttazzo et al. 1807.04743]

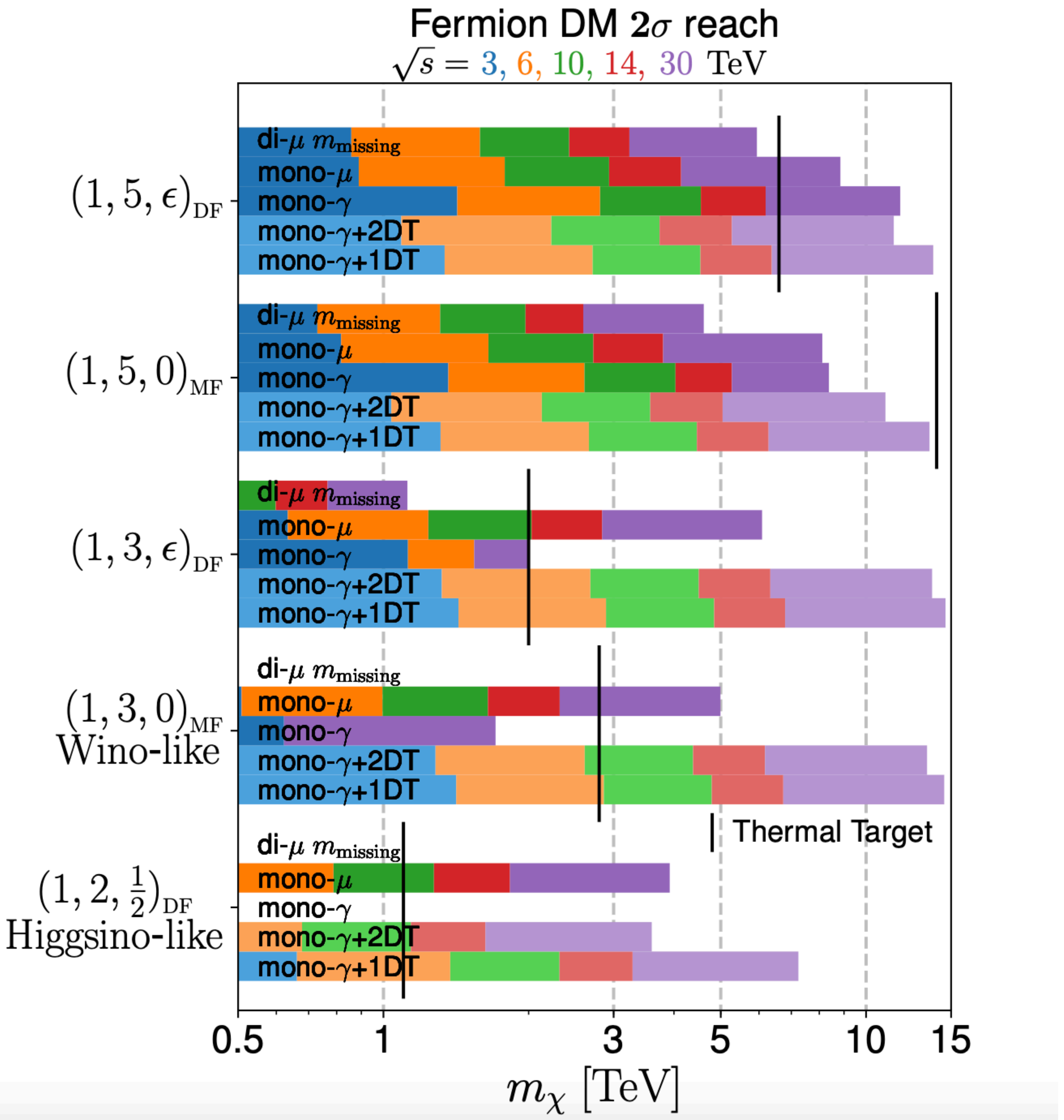
Reach in terms of the scale f in the Twin Higgs model

Direct reach

Minimal DM



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.

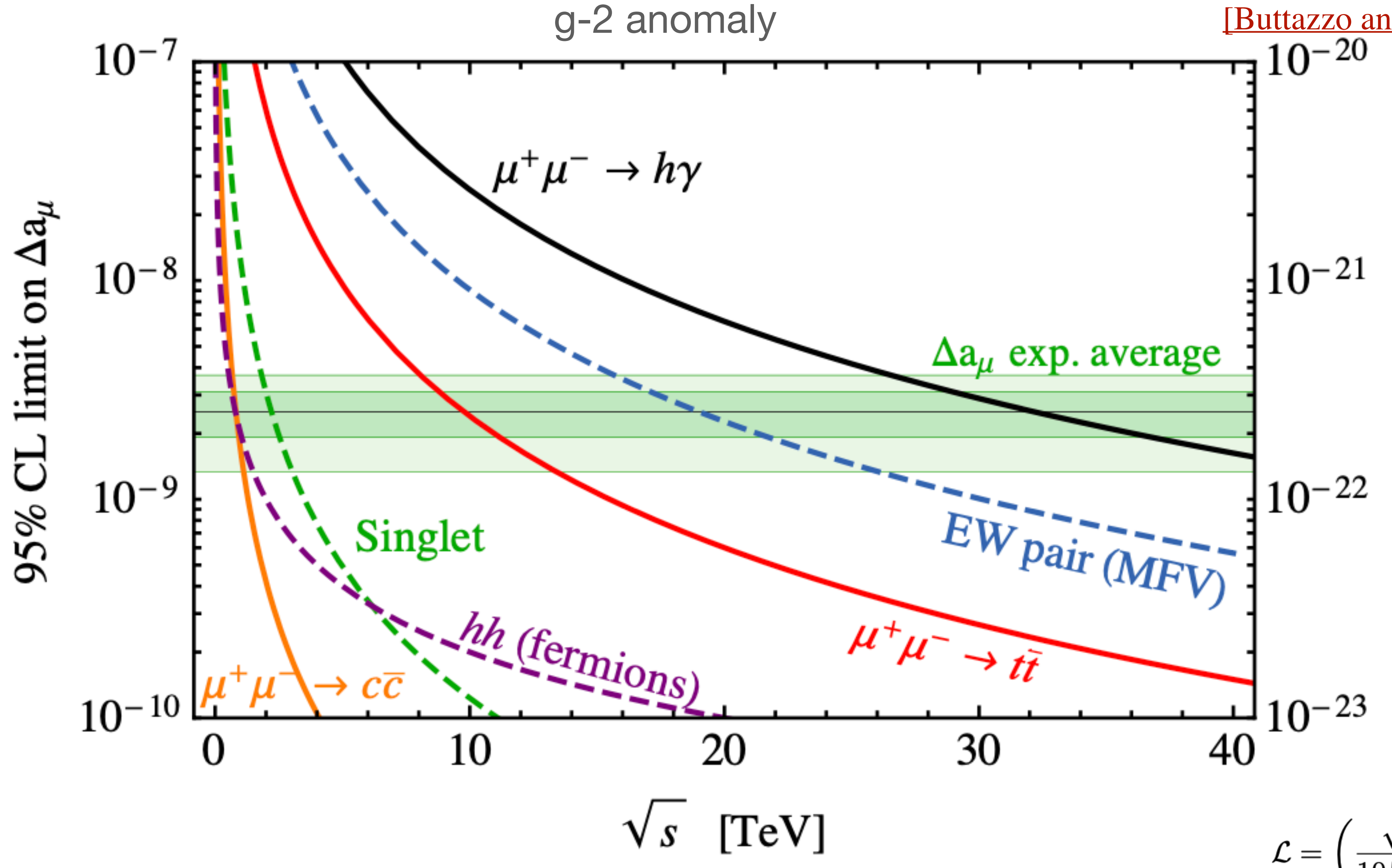


2σ exclusion of fermion DM masses with horizontal bars for individual search channels and muon collider energies by the different colors. The vertical bars indicate the thermal mass targets

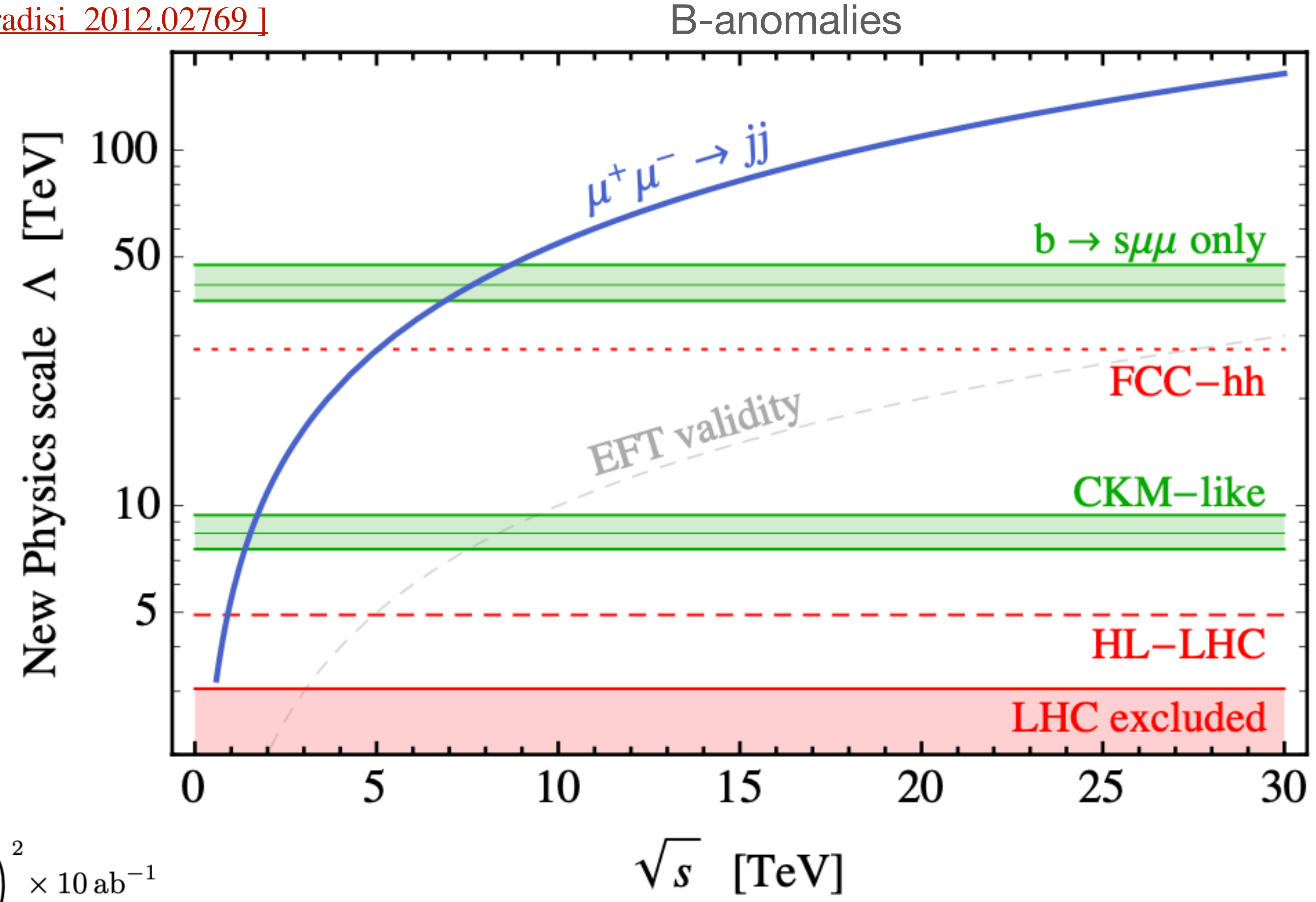
Anomalies

g-2 and B-anomalies: EFT scenarios

[Buttazzo and Paradisi 2012.02769]



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



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

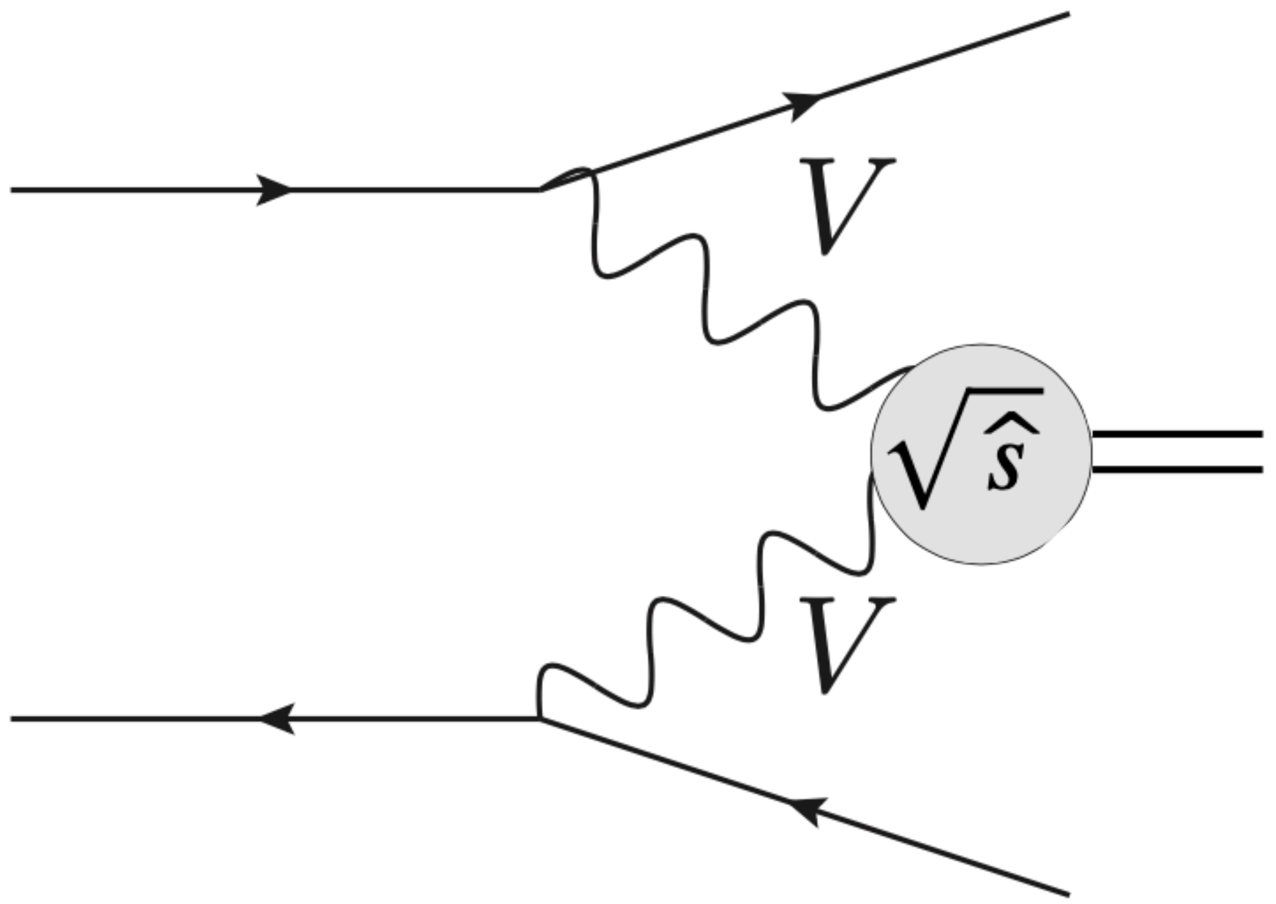
Reach from μμ → jj (solid line) on the scale Λ of semi-leptonic interactions that can account for the B-anomalies.

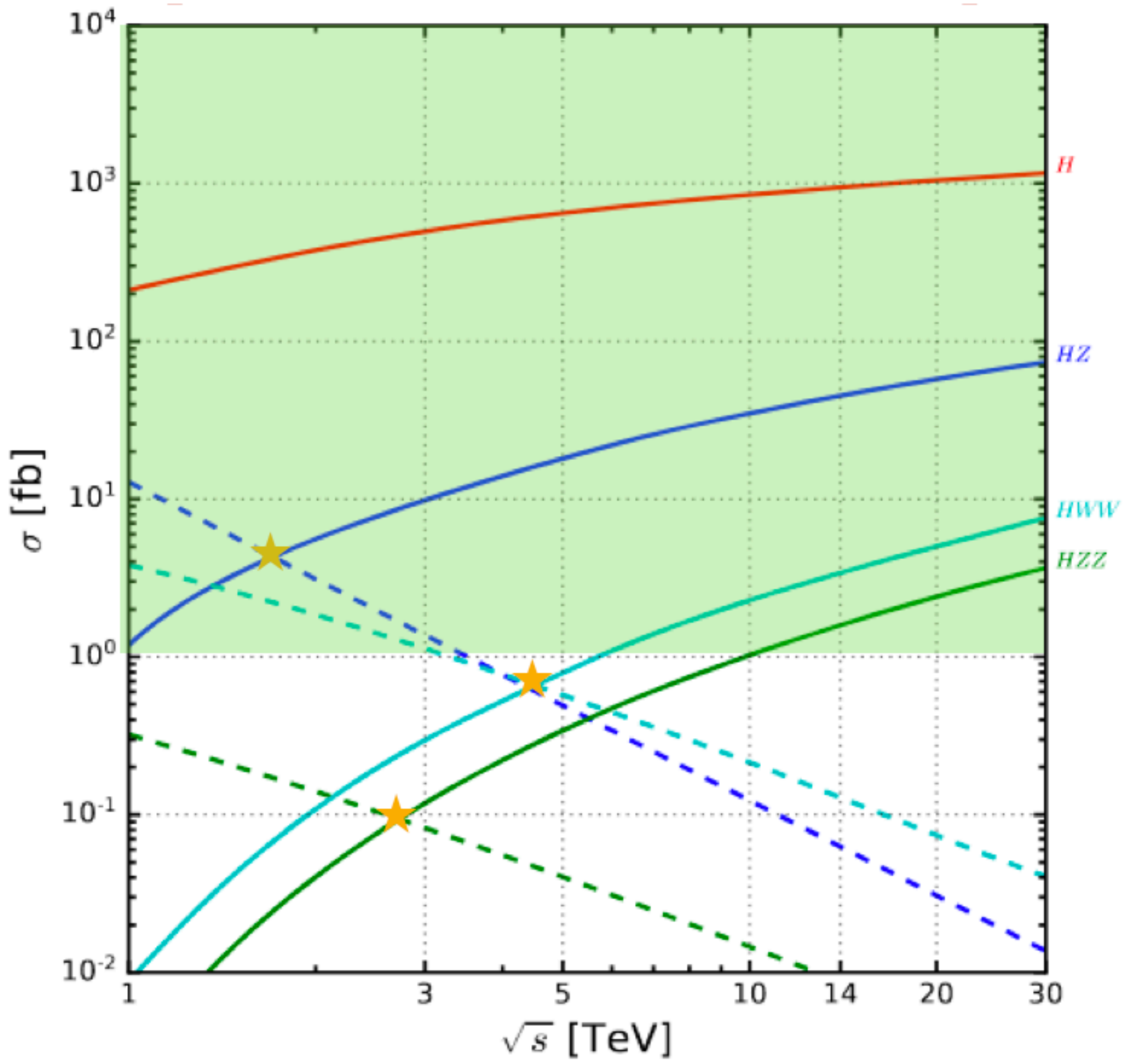
See also [Arakawa et al. 2208.14464]

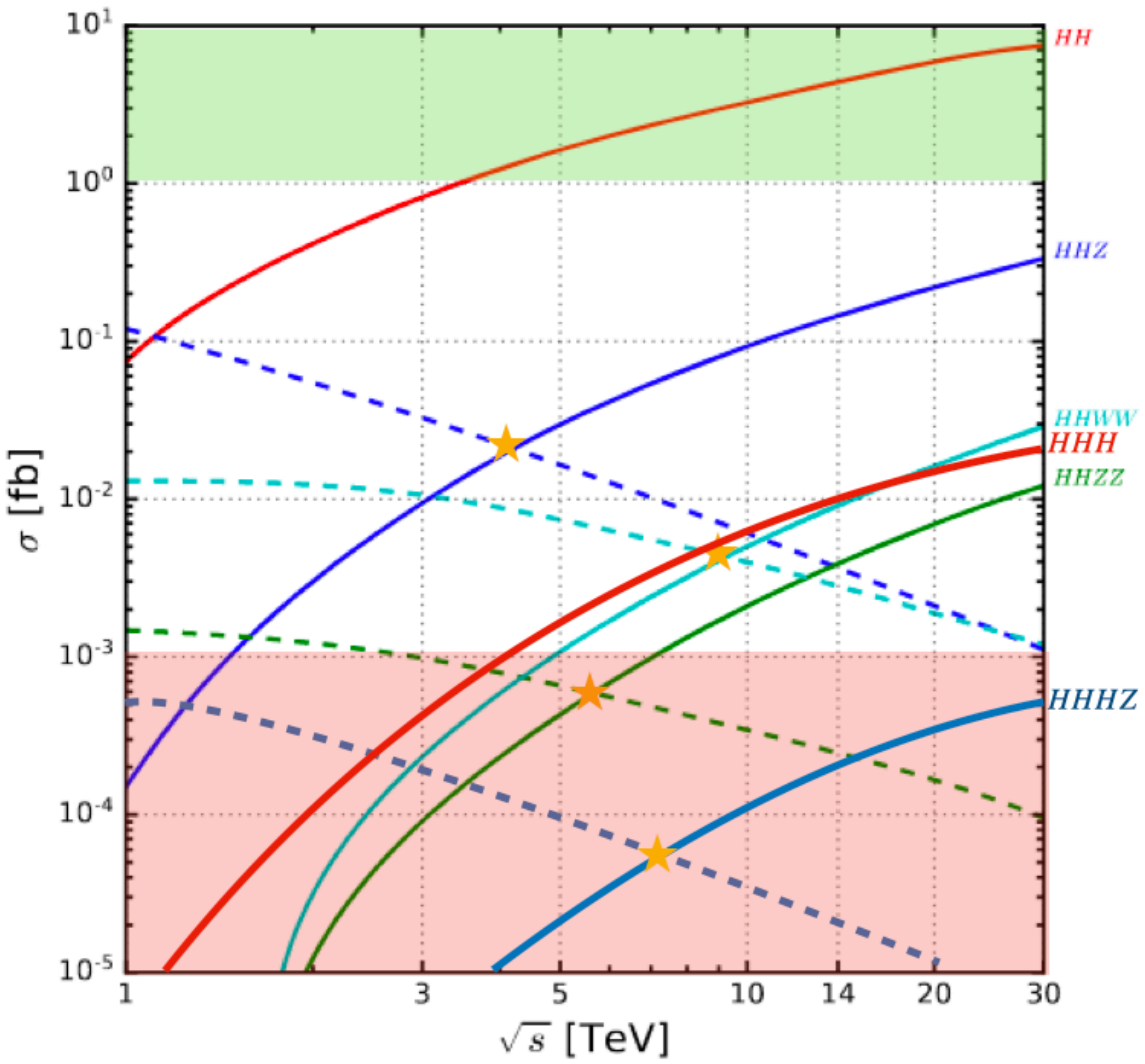
See also: [Azatov et al. 2205.13552]

Precision physics

Weak boson collider







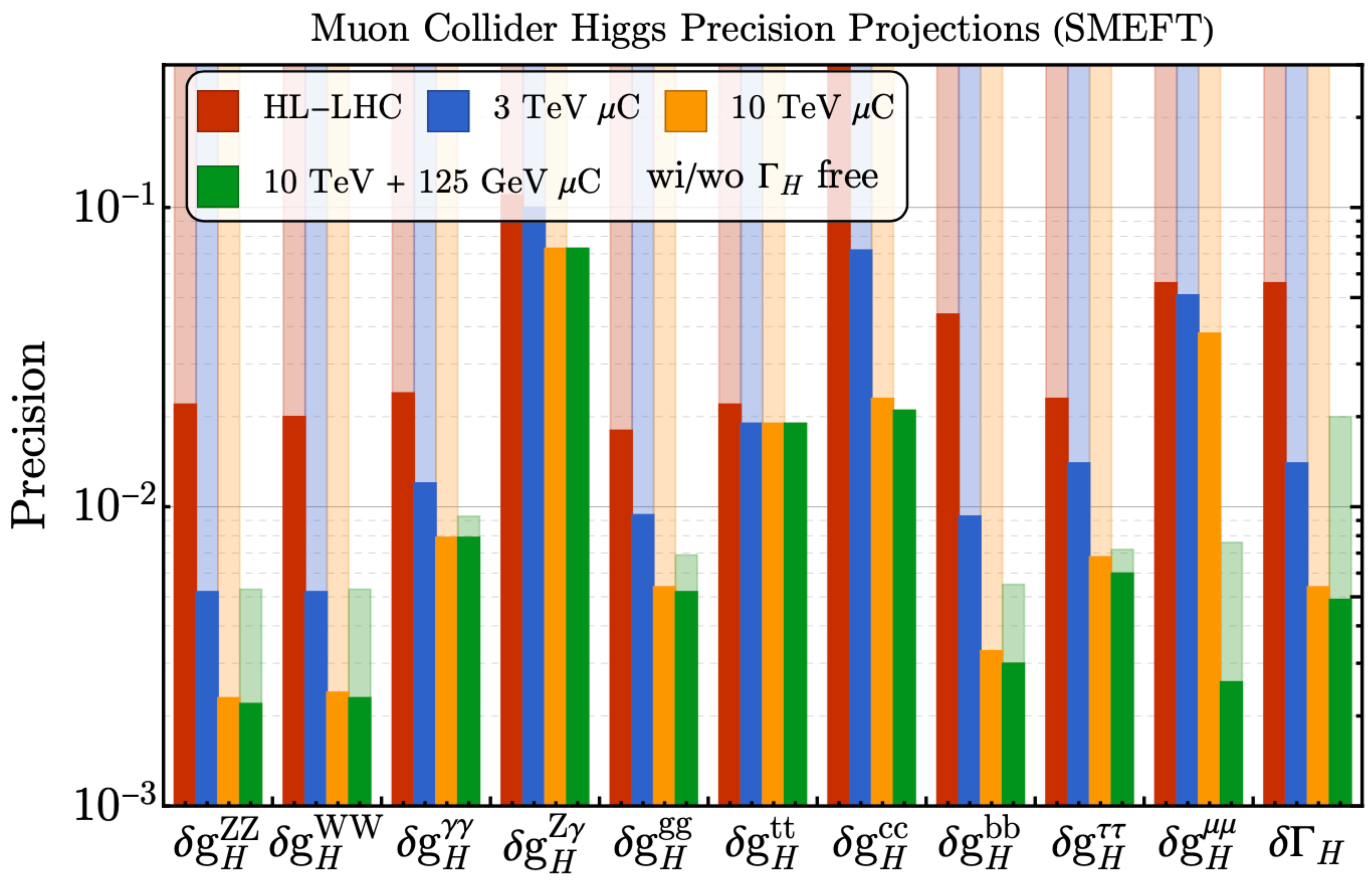
Higgs precision physics

Higgs coupling sensitivities

%	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

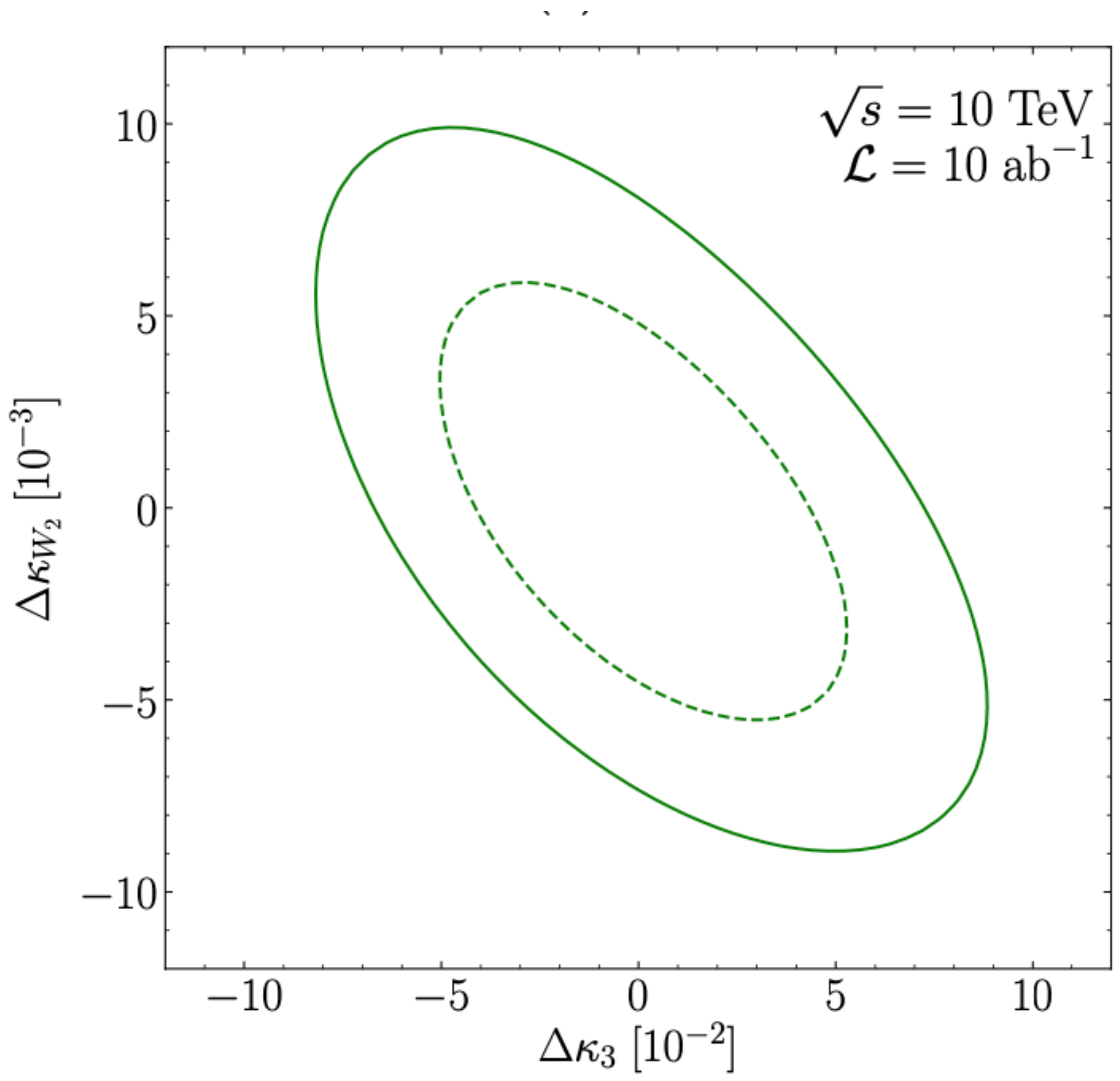
* No input used for μ collider

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.

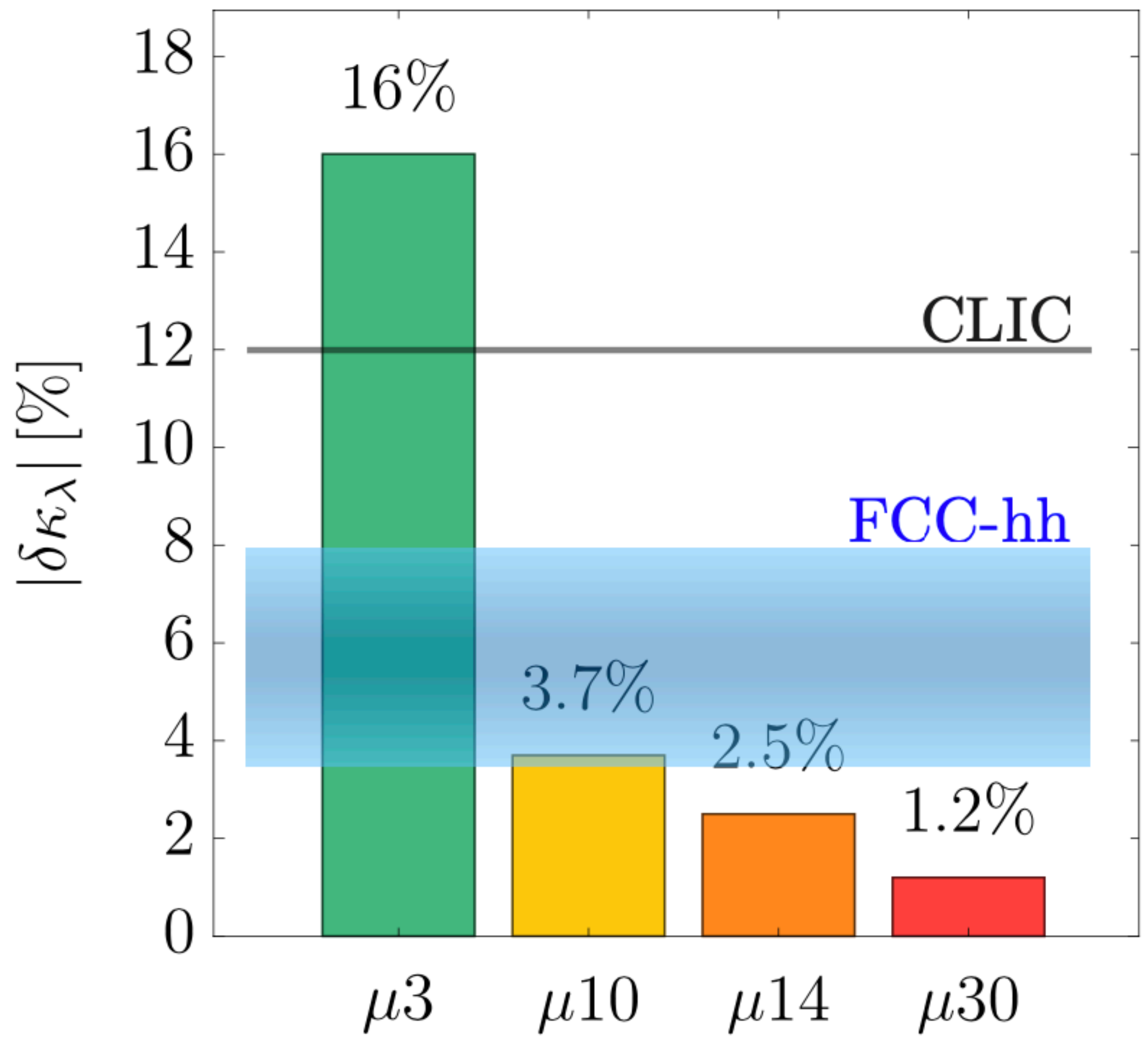


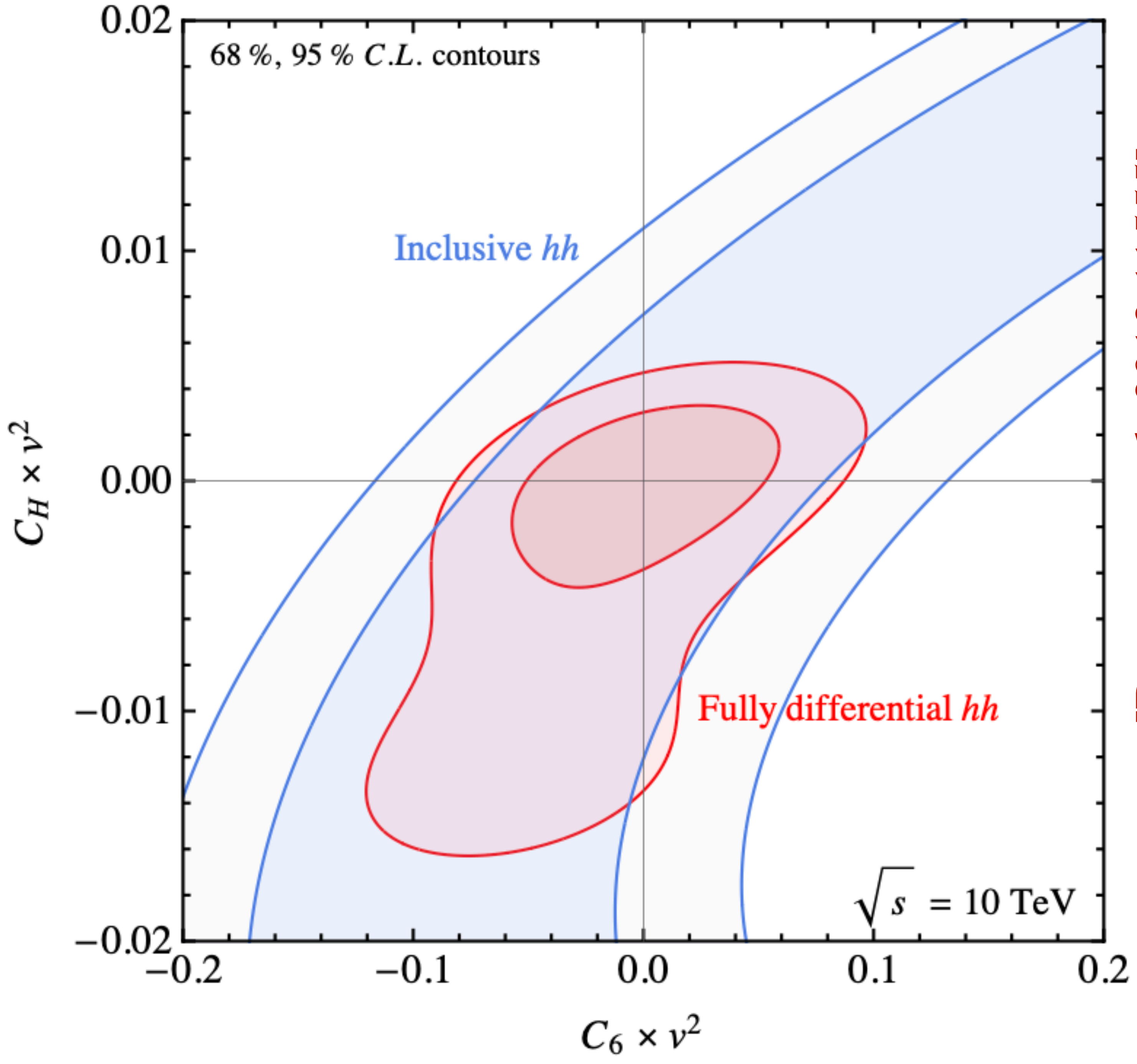
Higgs precision physics

The shape of the H potential: HH production



[Han et al. 2008.12204]





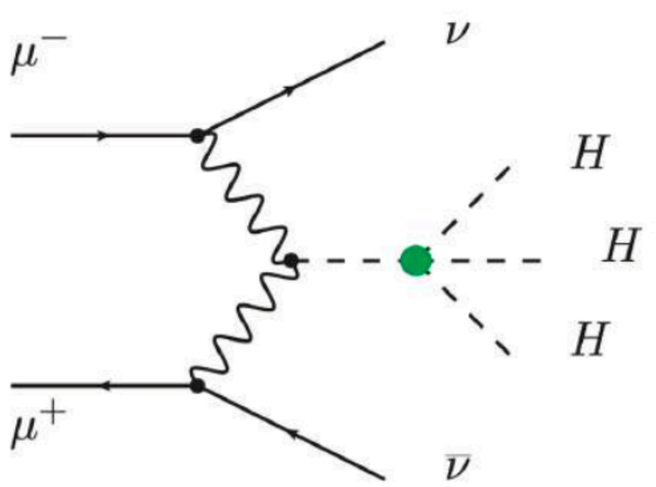
[Buttazzo et al. 2012.11555]

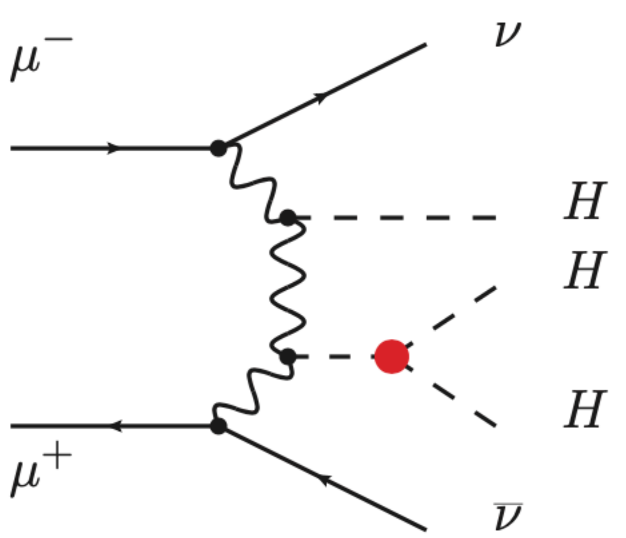
Reach on the trilinear coupling (and more) extremely competitive.

Higgs precision physics

The shape of the H potential : HHH production

3 Higgs final state

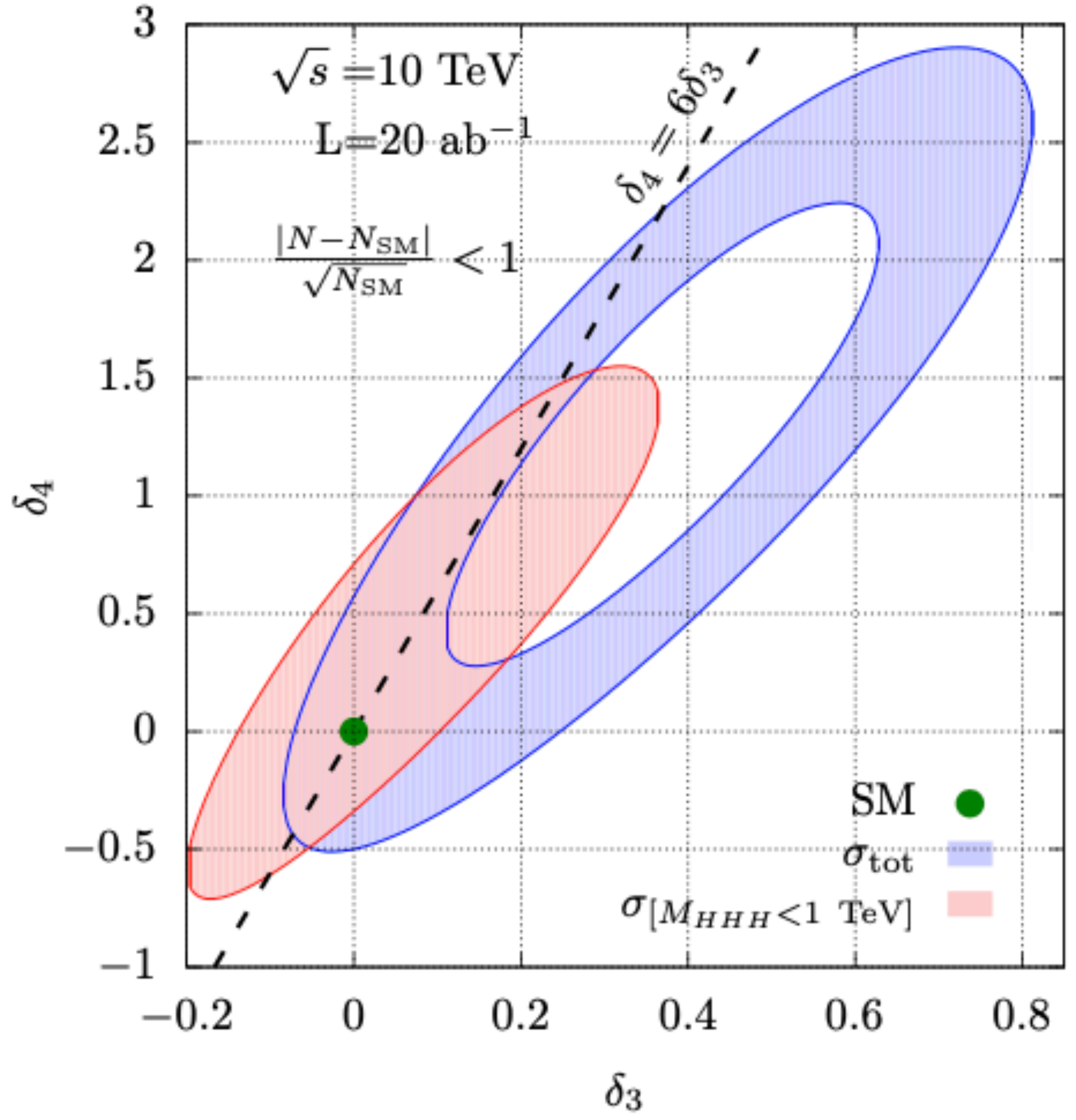




Quadrilinear determination extremely challenging at any collider, due to limited sensitivity.

$$\text{ILC} \sim [-10, 10]$$
$$\text{CLIC} \sim [-5, 5]$$
$$\text{FCC} \sim [-2, 4]$$

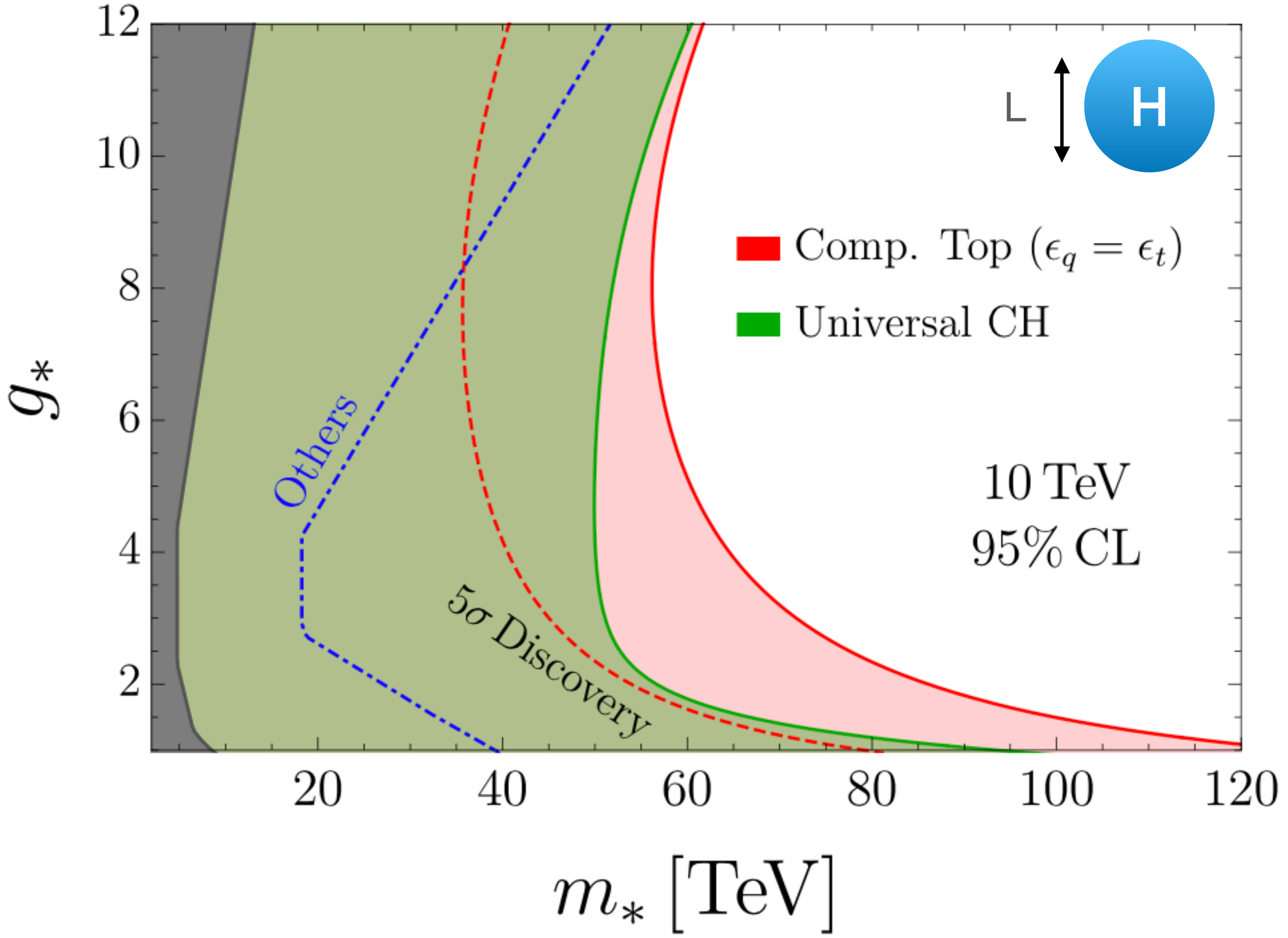
Very preliminary study points to the possibility of setting competitive bounds at a muon collider.



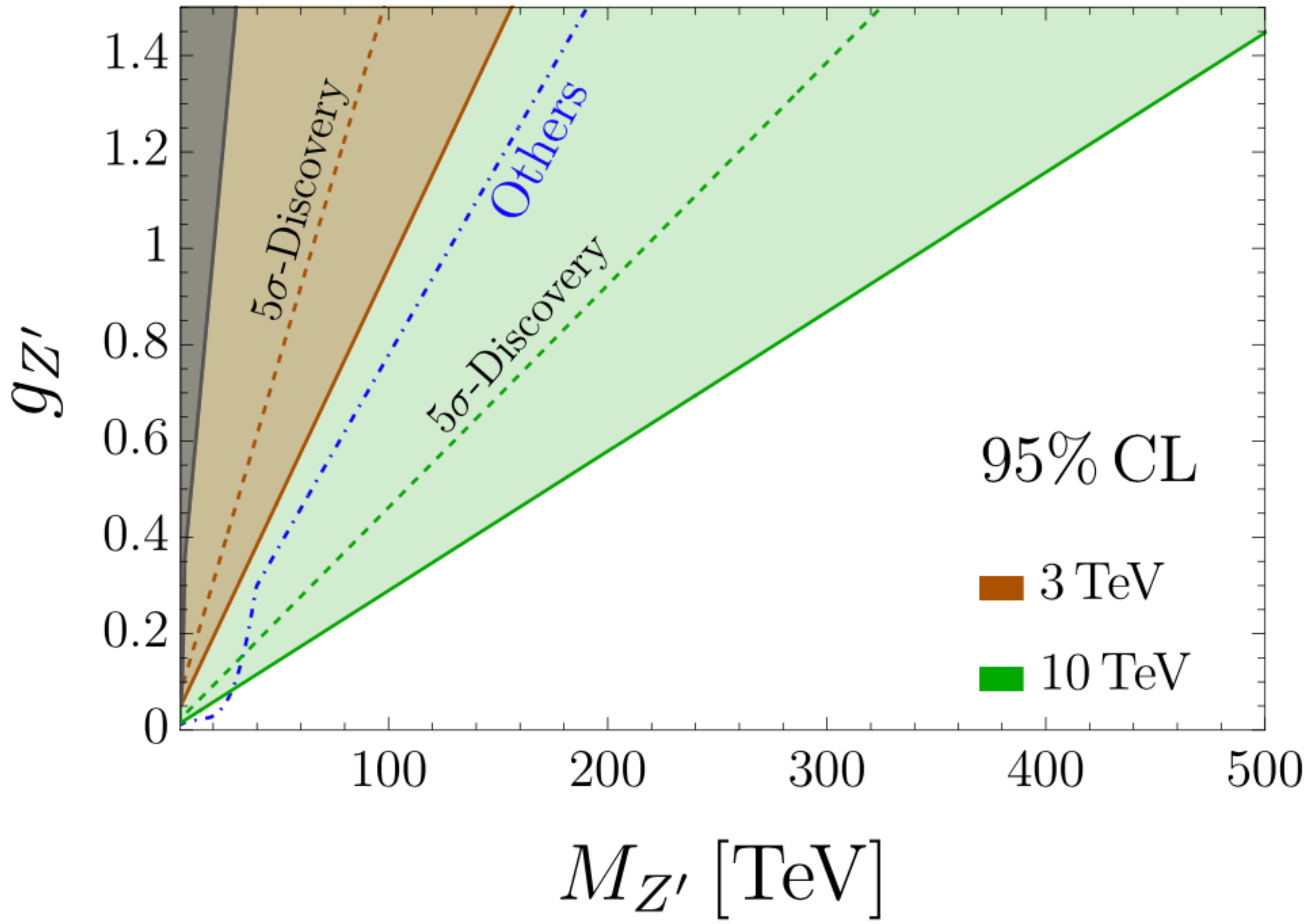
$$10\ \text{TeV} \quad \delta_4 \sim [-0.4, 0.7]$$

Precision physics

BSM interpretation: Higgs compositeness

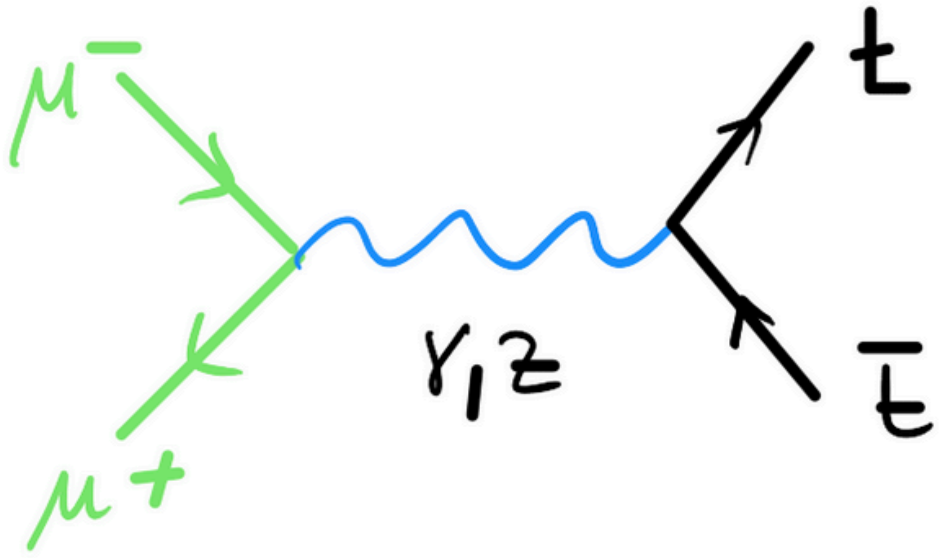


95% reach on the Composite Higgs scenario from high-energy, measurements in di- boson and di-fermion final states. The green contour display the sensitivity from "Universal" effects related with the composite nature of the Higgs boson and not of the top quark. The red contour includes the effects of top compositeness.

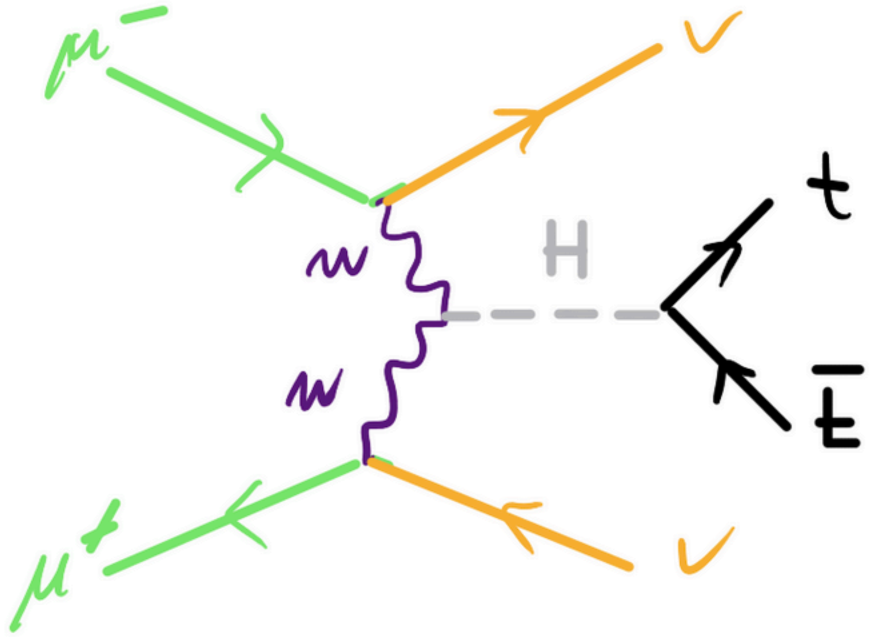


Sensitivity to a minimal Z′

Precision physics
SMEFT analysis

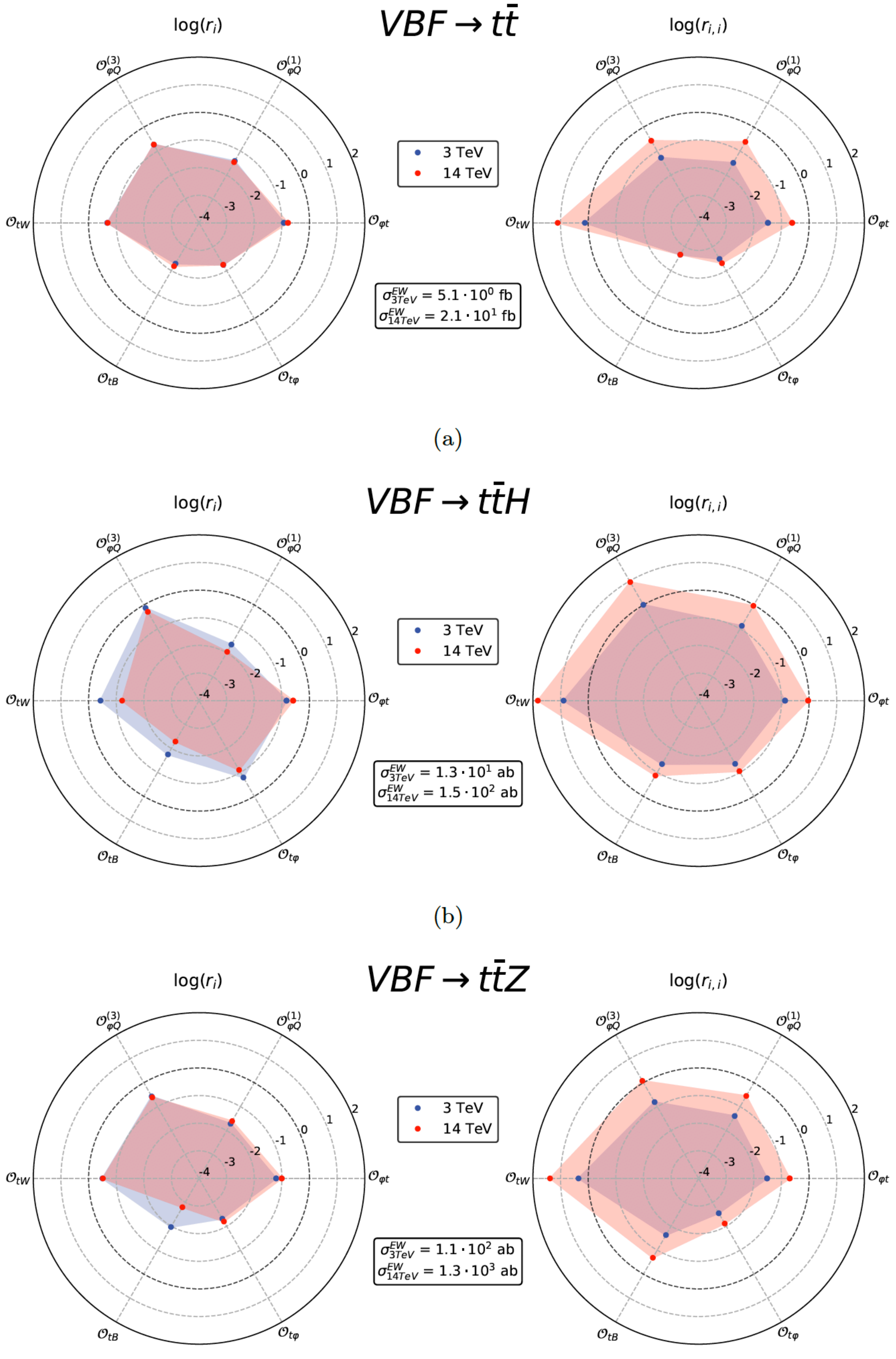


VS



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).



(a)

(b)

(c)

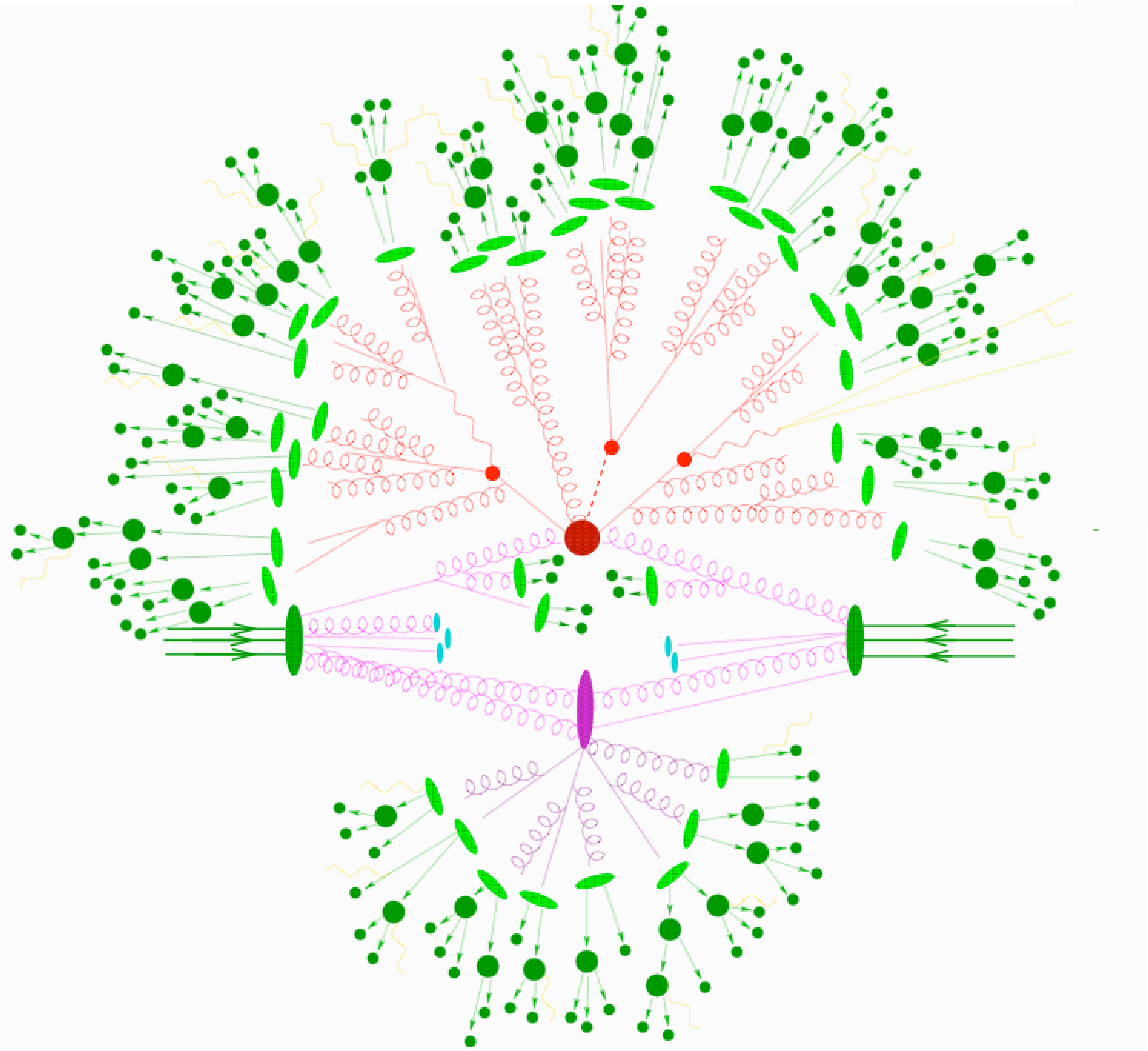
New SM physics

EW interactions at high energy

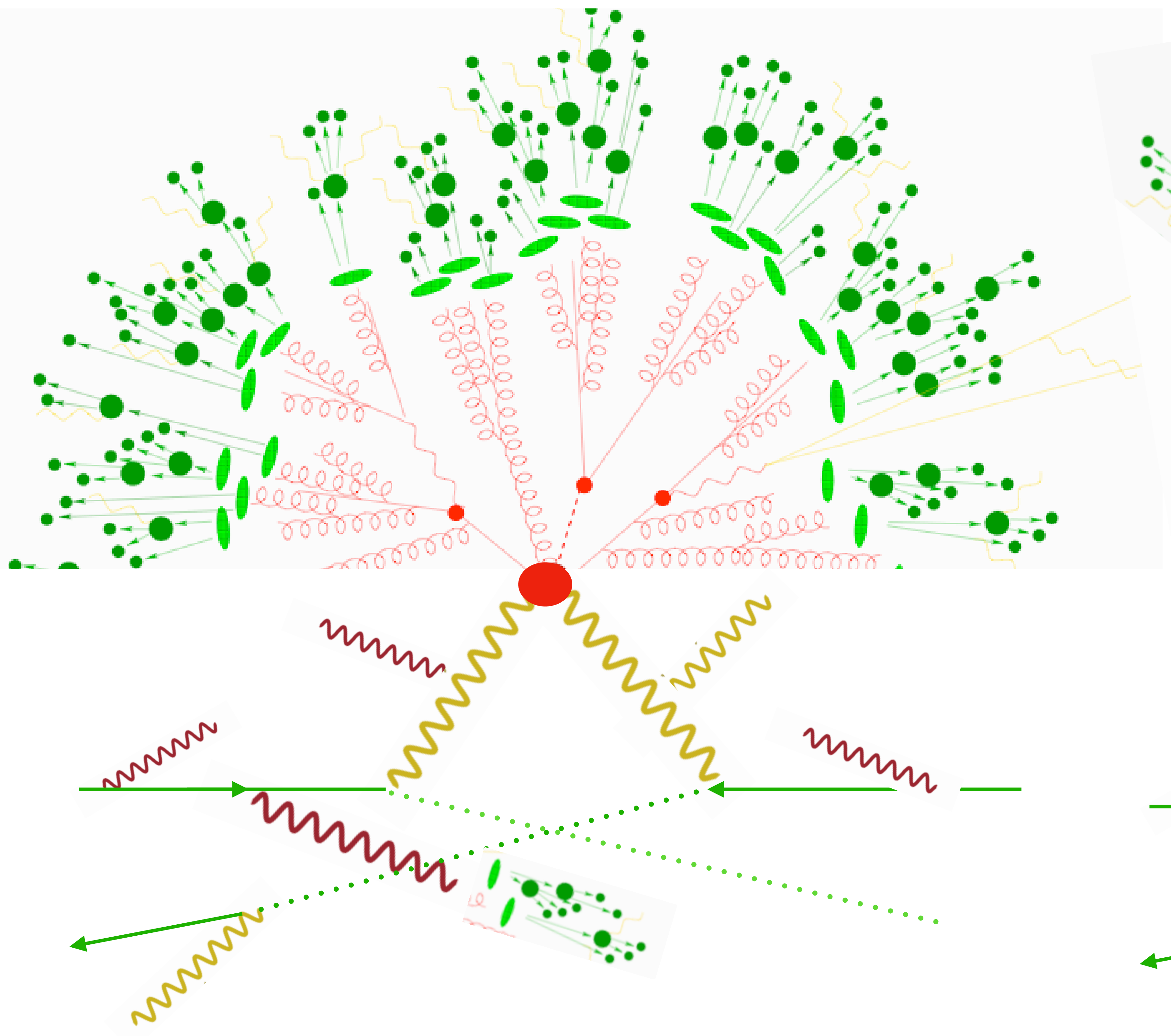
- Our ability to make accurate measurement and to constrain/discover new physics will depend on how accurate will be our SM predictions.
- At a muon collider EW interactions will be probed at tens of TeV in a very clear environment for the first time.
- Not only QED but more in general EW virtual and real radiation will play an important role.
- A new regime of the SM to be explored…

How events will look at a multi-TeV muon collider?

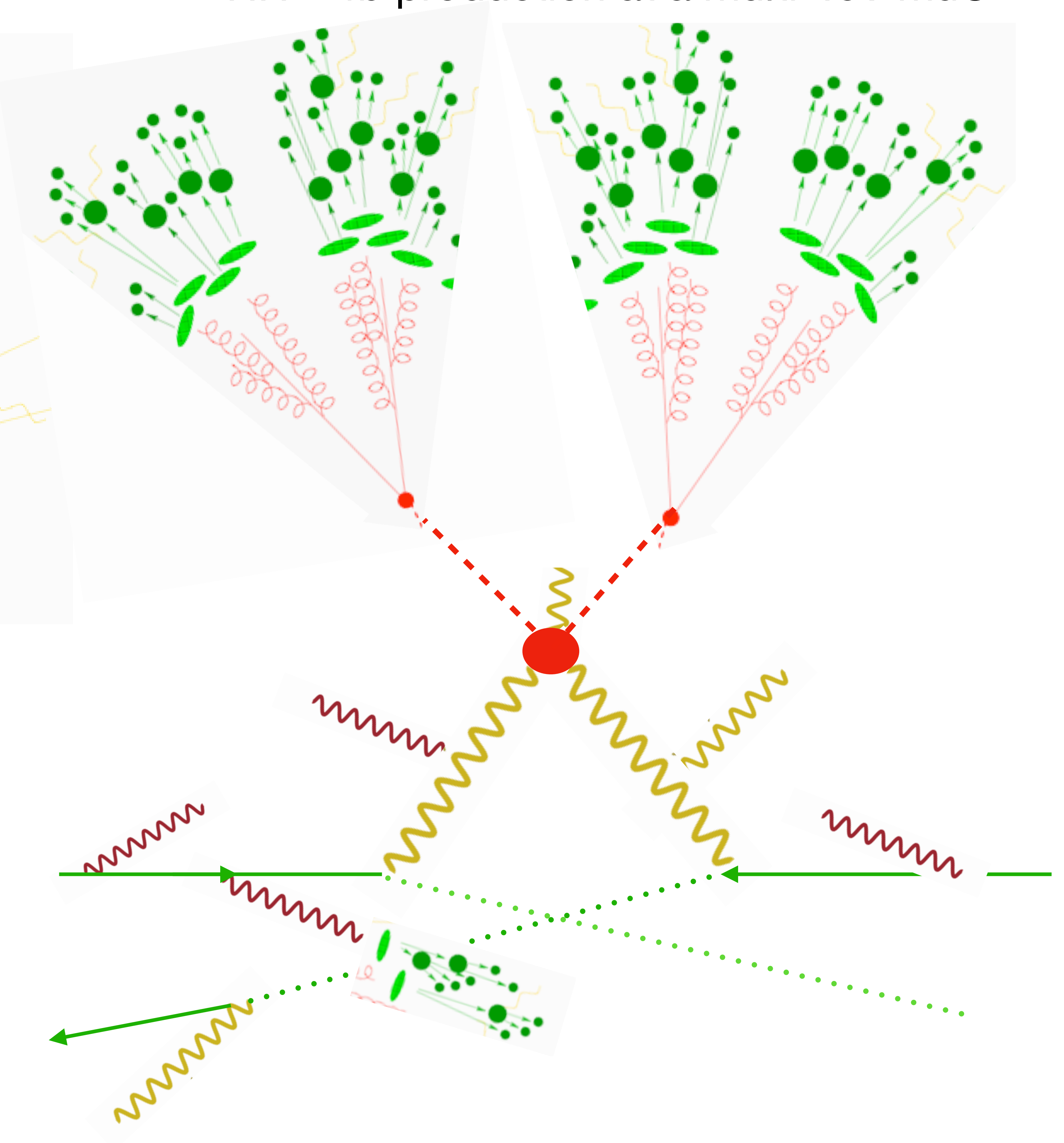
tth production at the LHC (Fully hadronic)



tth production at the muC 100 TeV



HH→4b production at a multi-TeV muC

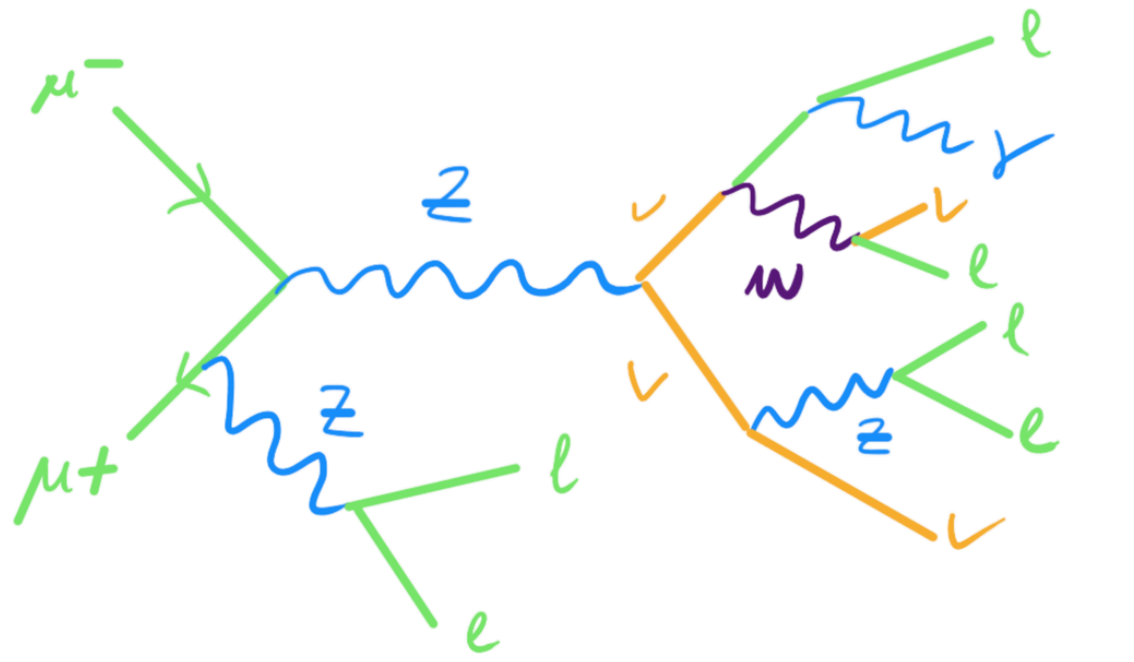


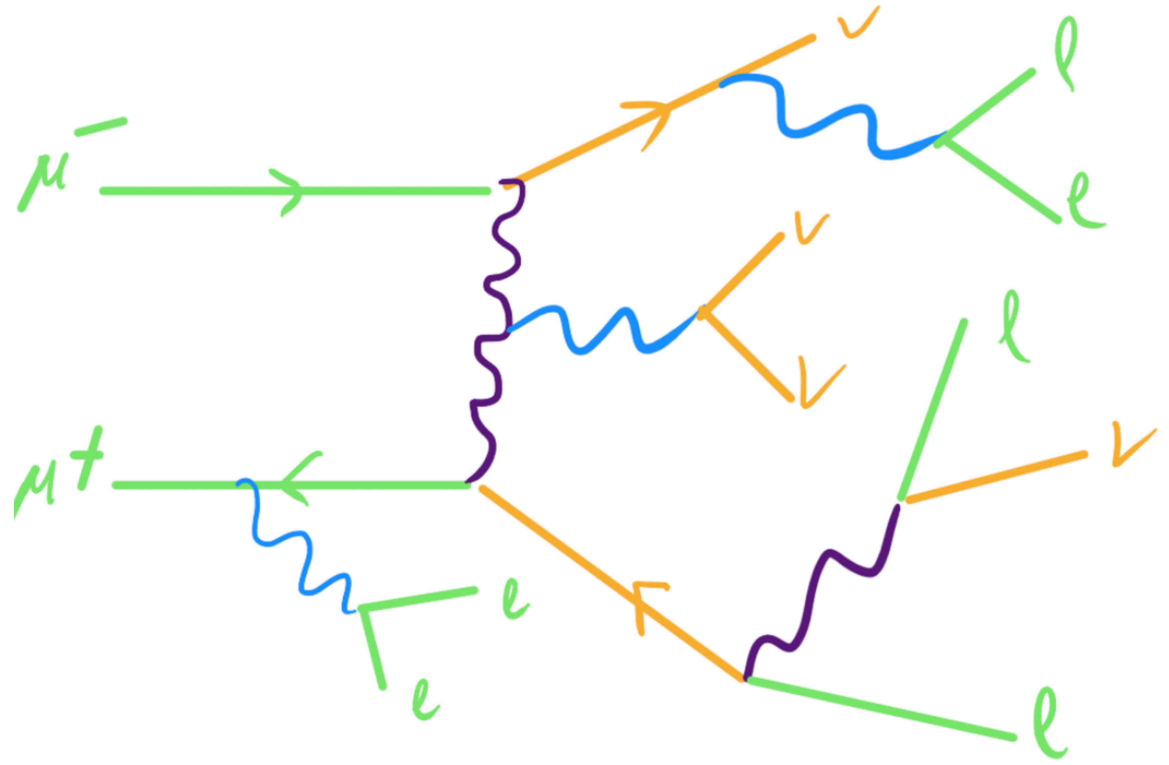
In a muon collider gluons and quarks first appear at scales of order 100 GeV in the decays of W,Z,H (from either initial state or final state radiation) or from photon splitting.

Multijet final states are of EW origin.

New SM Physics

EW real and virtual 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]

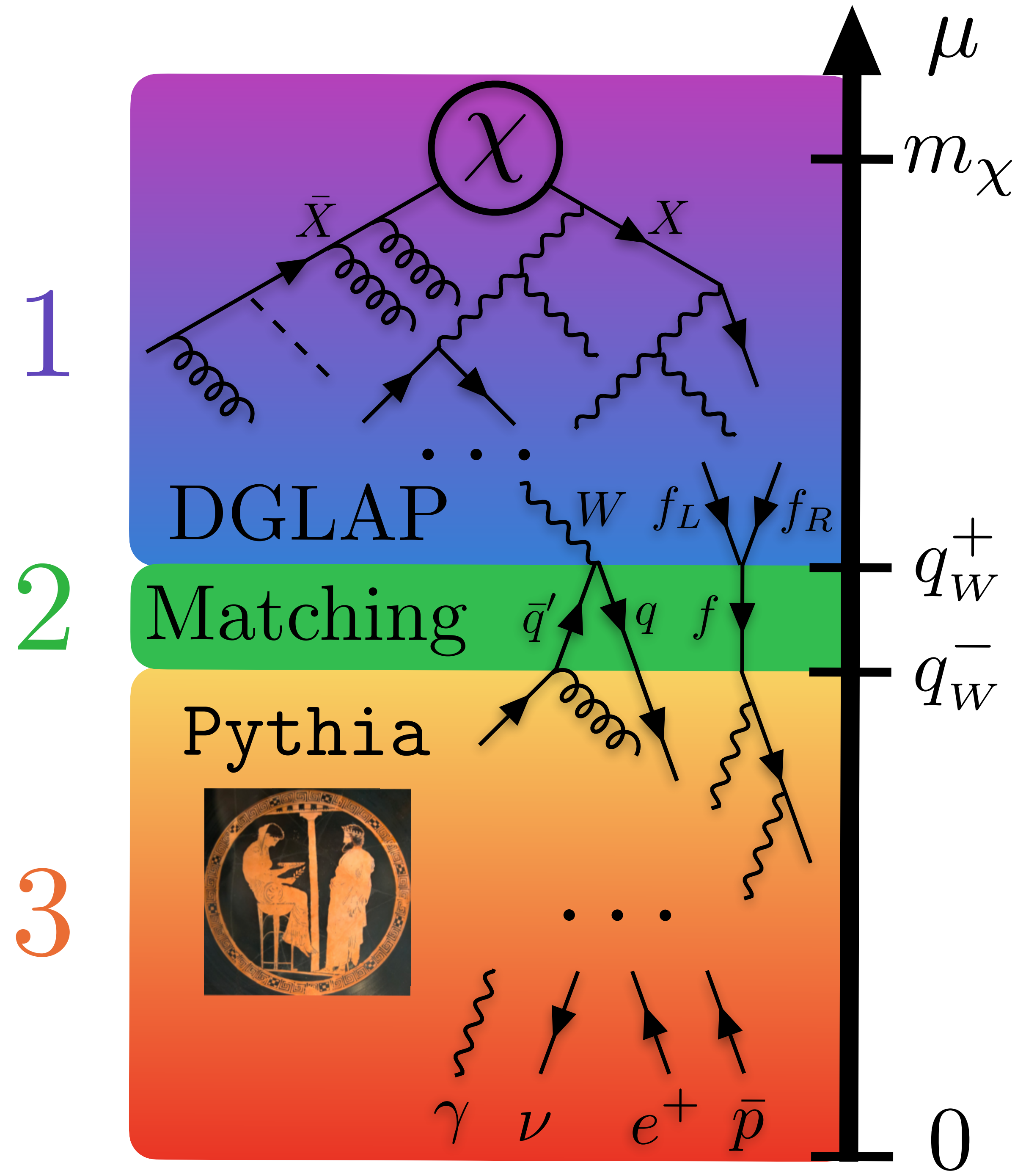
New gauge formulation
[Cuomo, Vecchi, Wulzer, 1911.12366]

[J. Chen et al.2203.10440]

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

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

EW NLO
[P. Bredt et al. 2208.09438]



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** 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.
- A broad and convincing physics case has been layed out, together with the identification of open directions for more detailed studies.