Why building a muon collider

Andrea Wulzer

UNIVERSITÀ DEGLI STUDI DI PADOVA

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If you want to know more, look here:

Muon Collider Physics Summary [2203.07256]
The Muon Smasher's Guide [2103.14043]
The Physics Case of a 3 TeV Muon Collider Stage [2203.07261]

(Emerging) Conclusions

Muon Colliders BSM Physics Pillars:

- **High Energy** available for direct particles production
- **High Rate** available for **Precision** measurements
- **Energy and Precision**

All this, at a single collider with feasible timescale

WIMP Dark Matter

- **Higgsino/Wino "very directly" accessible** (more is coming on WIMP at 10 TeV)

Explaining the origin of the Weak scale

- **Δ=10 ➔ Δ=80** , simply from direct searches
- Probe **Δ=1/ξ=1000**, in CH, in two ways

How much is the Higgs radius?

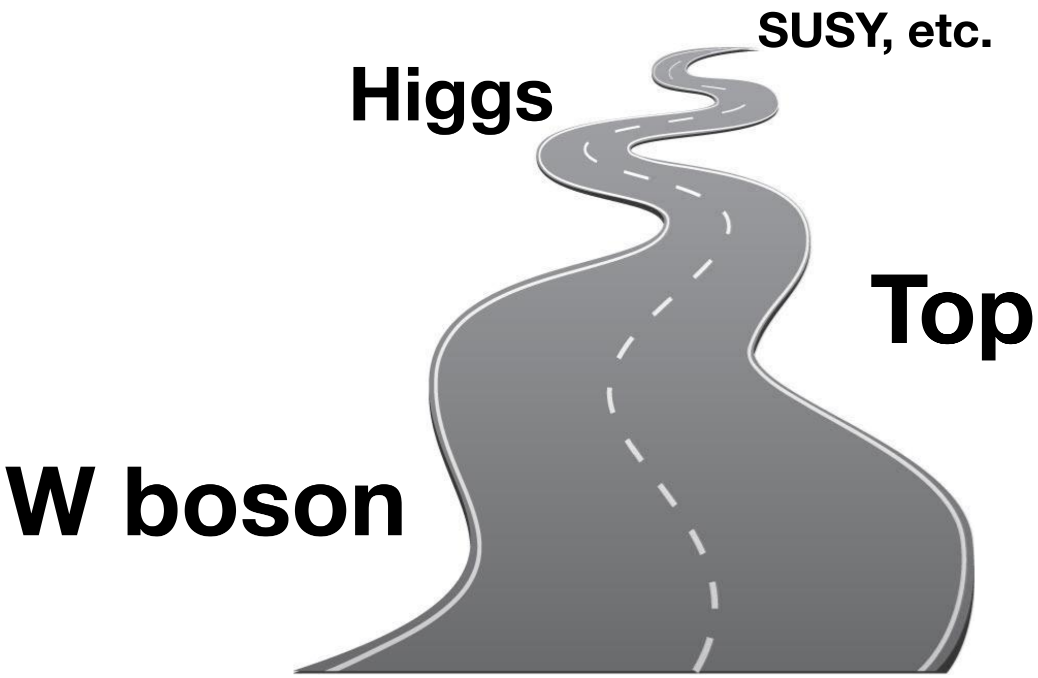
- If as "large" as 1/(50TeV), we can tell

Added value from colliding muons [2203.07261]

- Current anomalies are in muons. If coincidence, a fortunate one: illustrates obvious potential of colliding μ for the first time!

The High Energy Physics Landscape

HEP Yesterday **LHC** **HEP Today**



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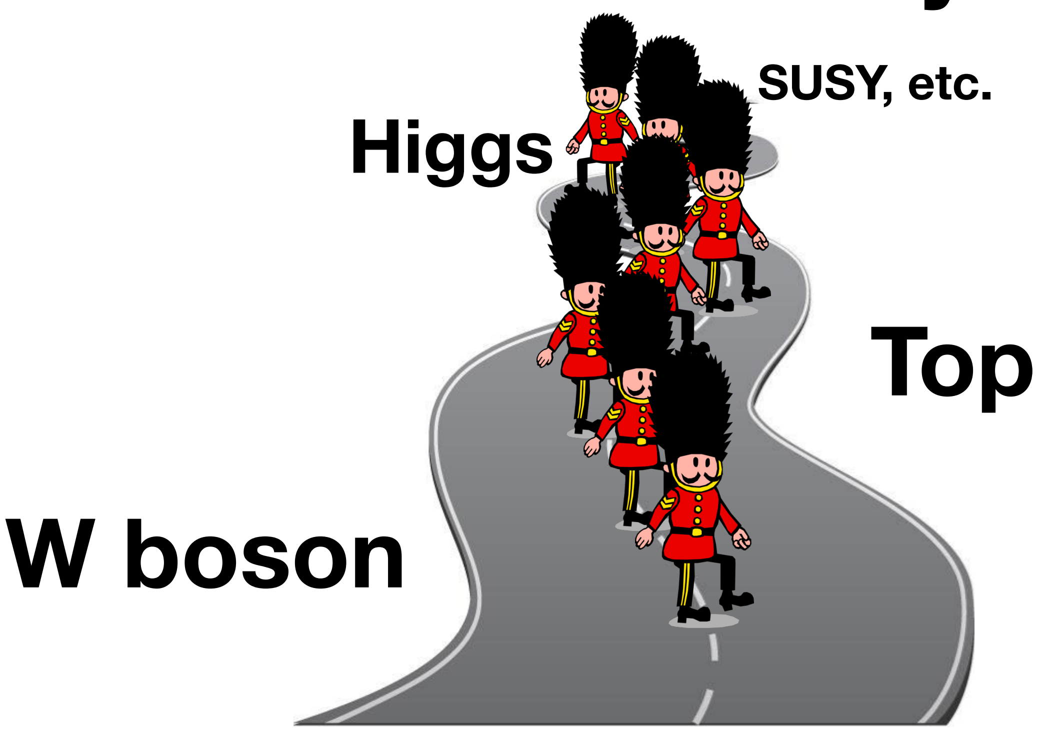

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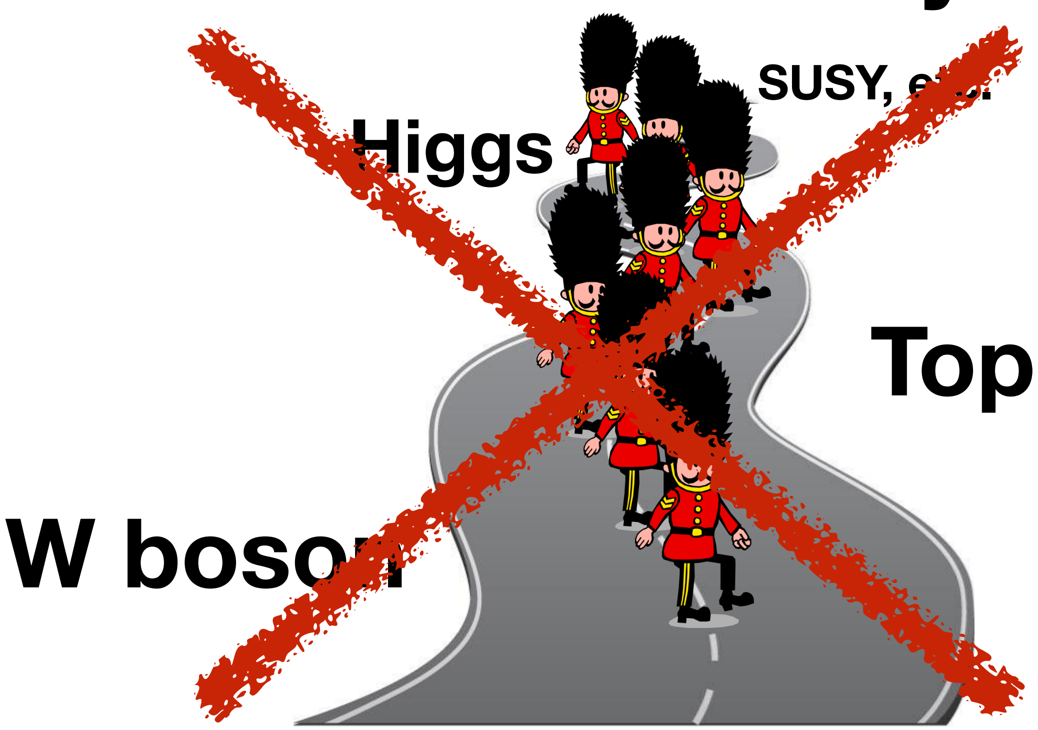

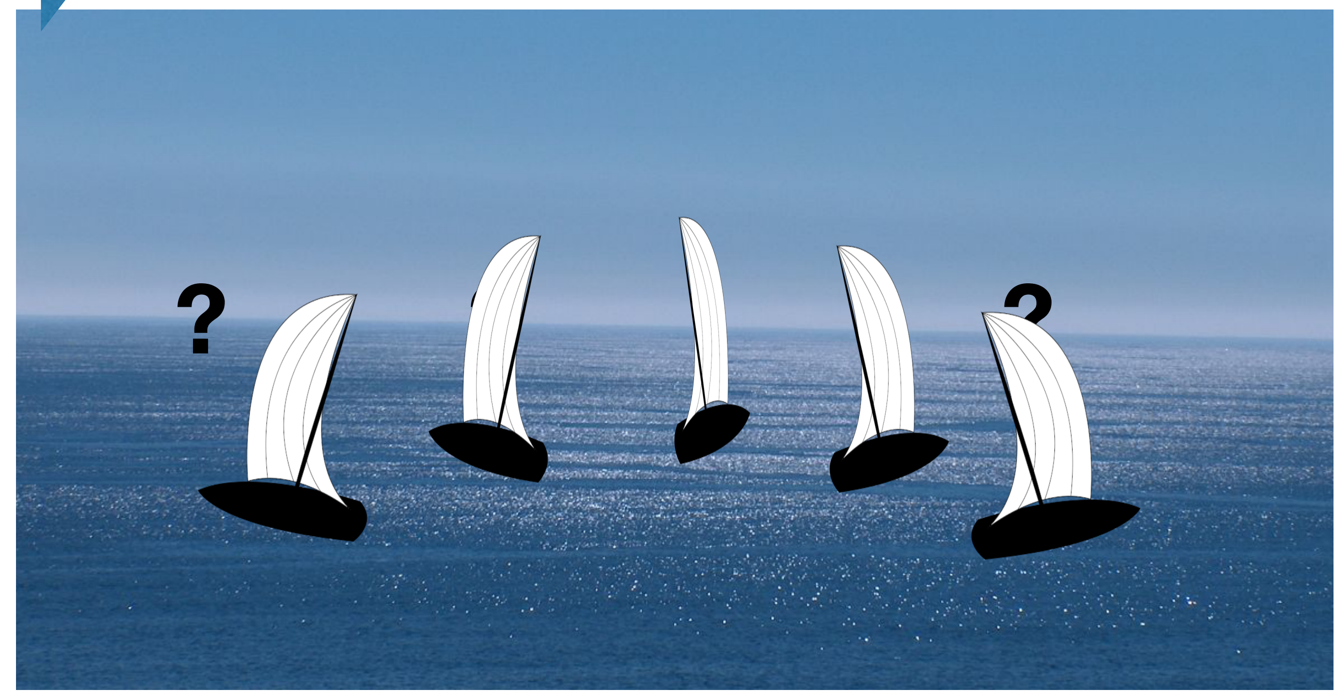

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Today, the mission is to **explore uncharted territory***

*Which is **good!**
It means that the next discovery will be more revolutionary than the Higgs one

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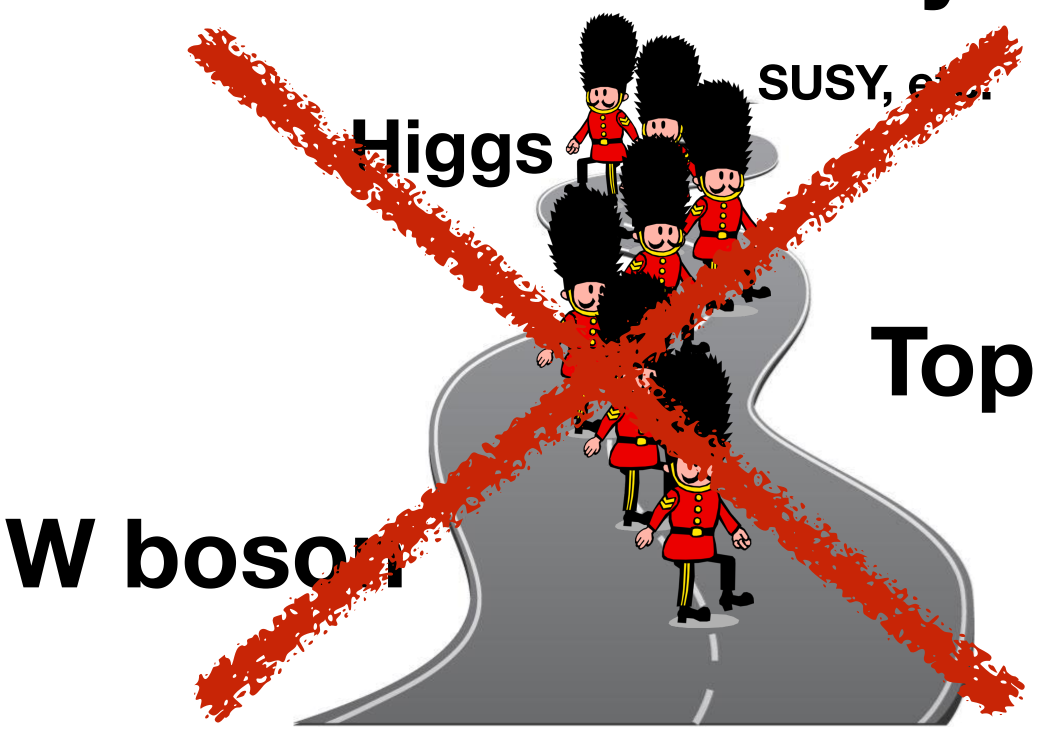

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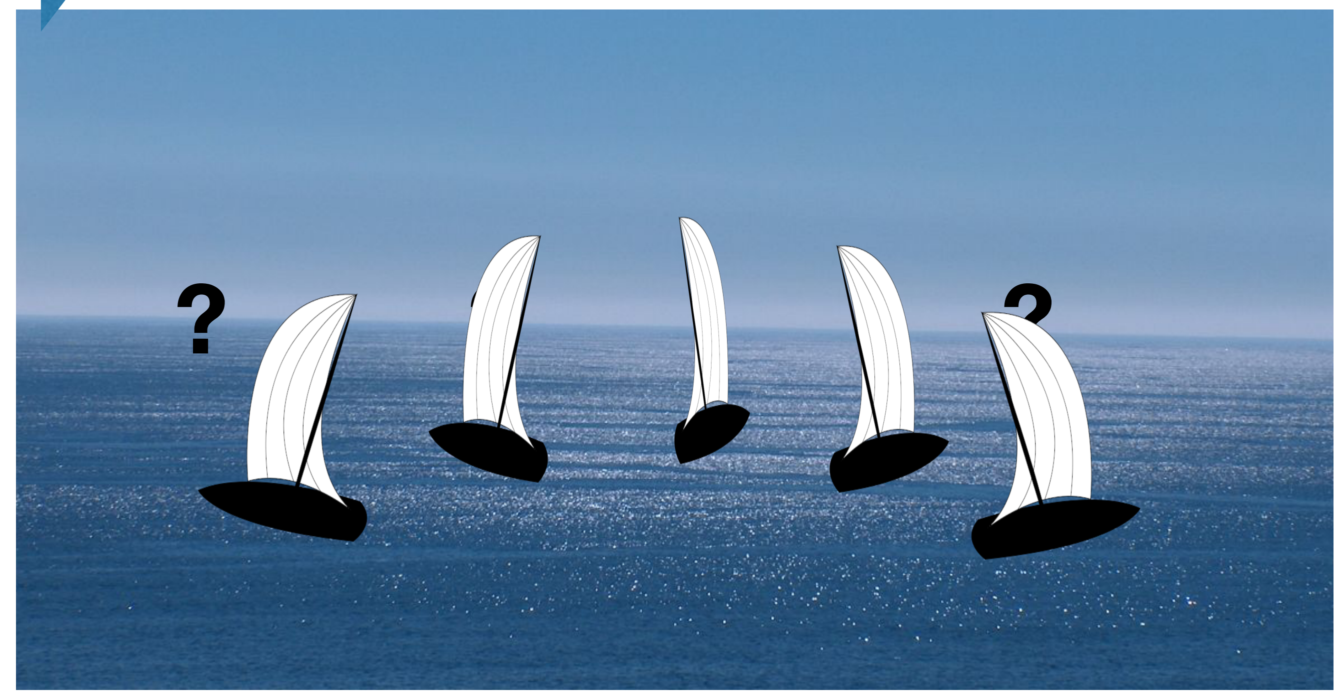

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This is why we started speaking about **Frontiers**

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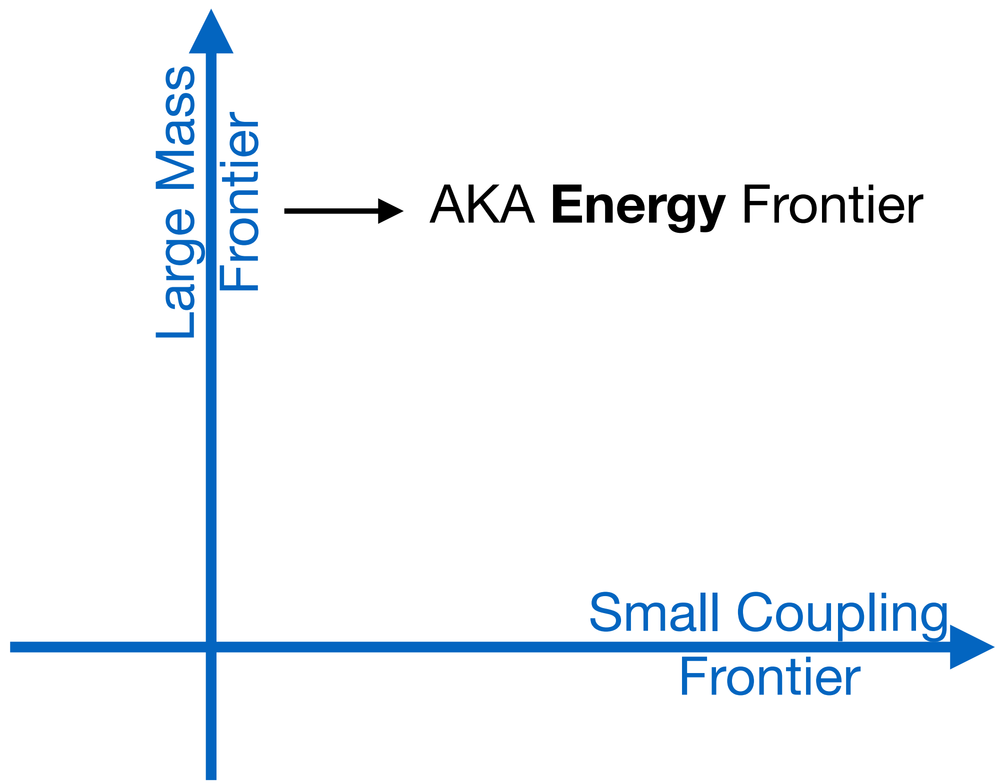
The High Energy Physics Landscape

Our **Frontiers are the directions** in which (i.e., reasons why) New Physics might hide



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

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Accurate measurements of great variety of observables.

Under precisely known experimental conditions.

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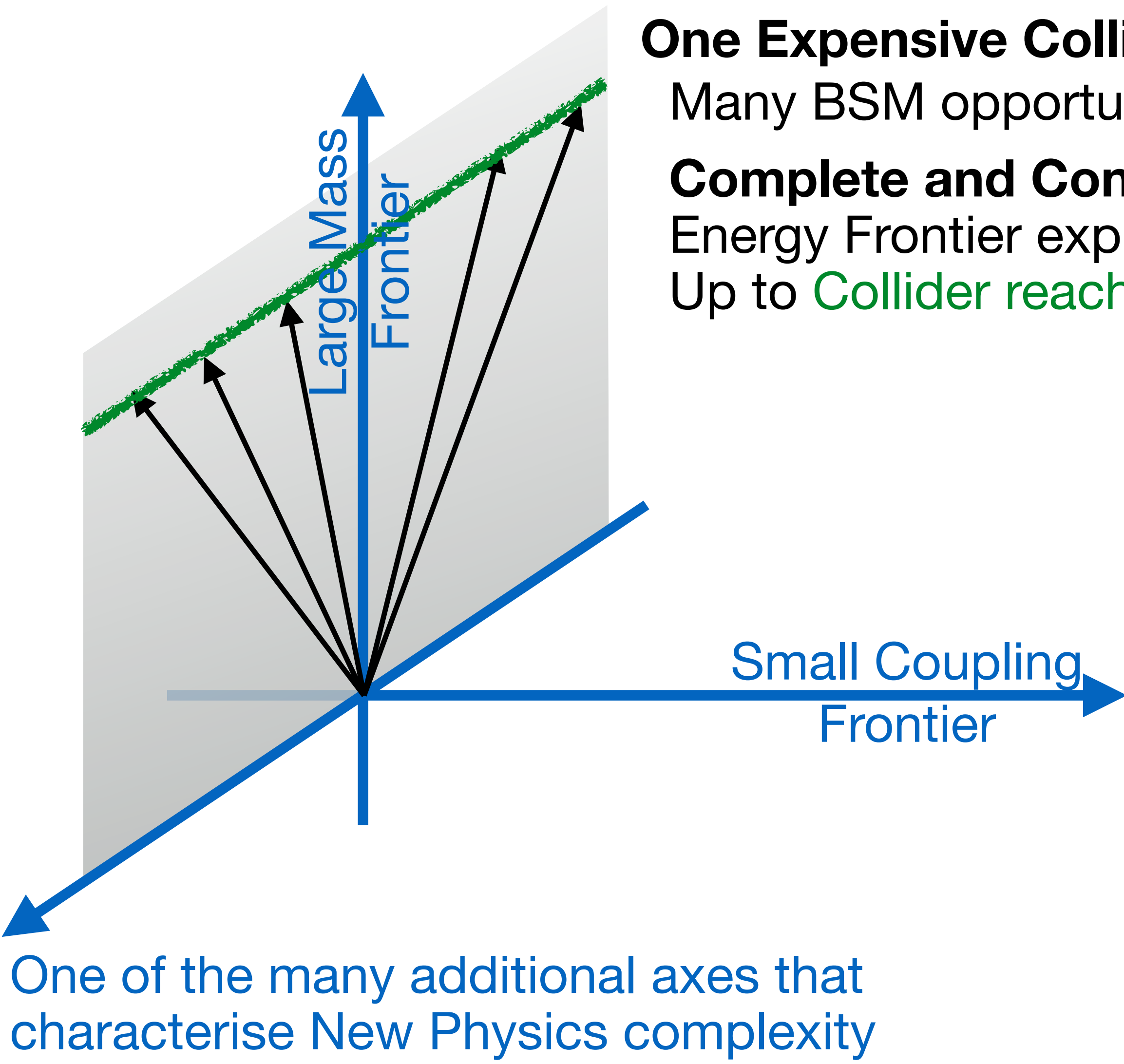
Only one drawback: they are **Expensive**.

Why Colliders?

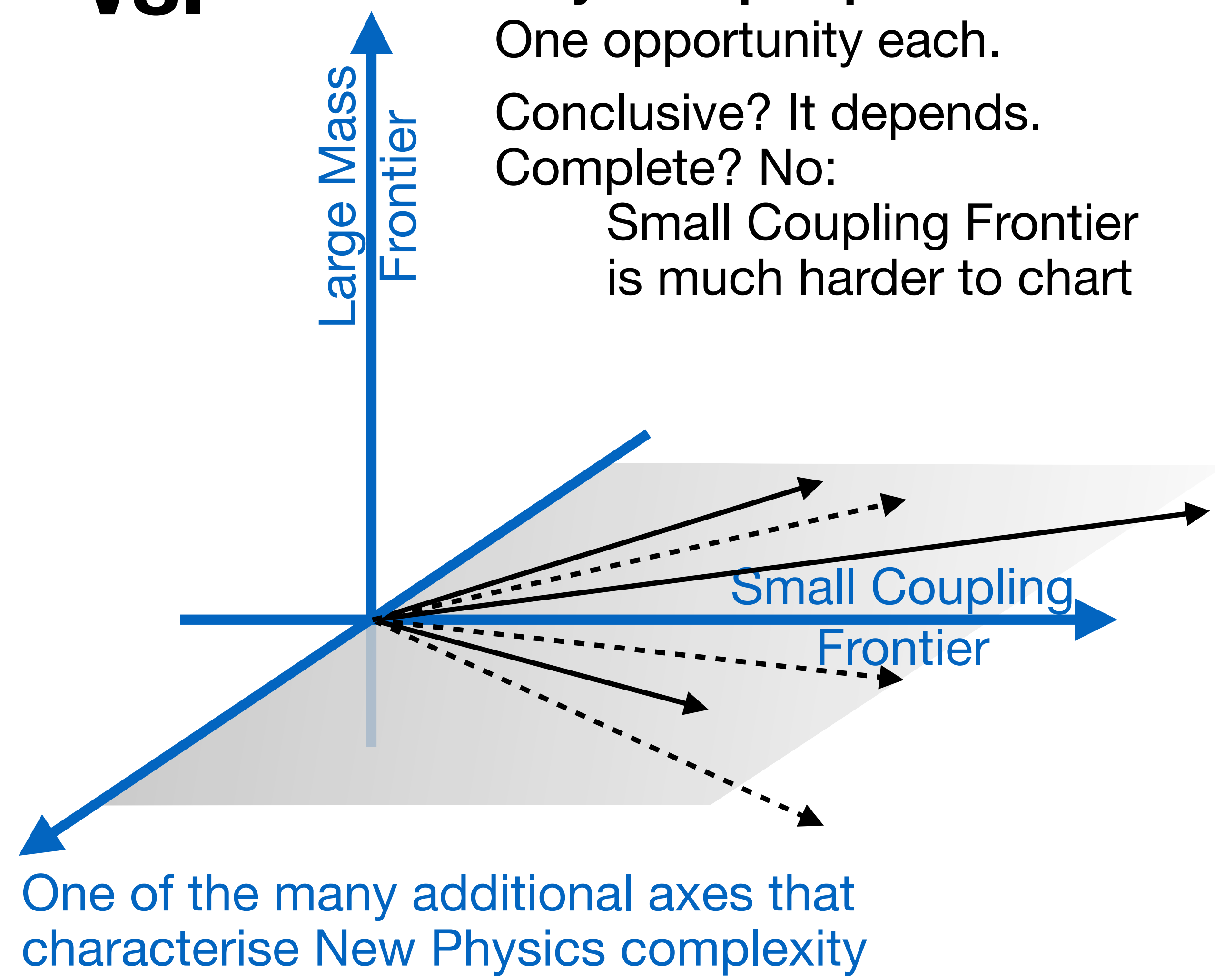
Expensive? Yes, no doubt, but …



One Expensive Collider
Many BSM opportunities

Complete and Conclusive
Energy Frontier exploration.
Up to Collider reach

vs.



Many Cheap Experiments
One opportunity each.

Conclusive? It depends.
Complete? No:
Small Coupling Frontier is much harder to chart

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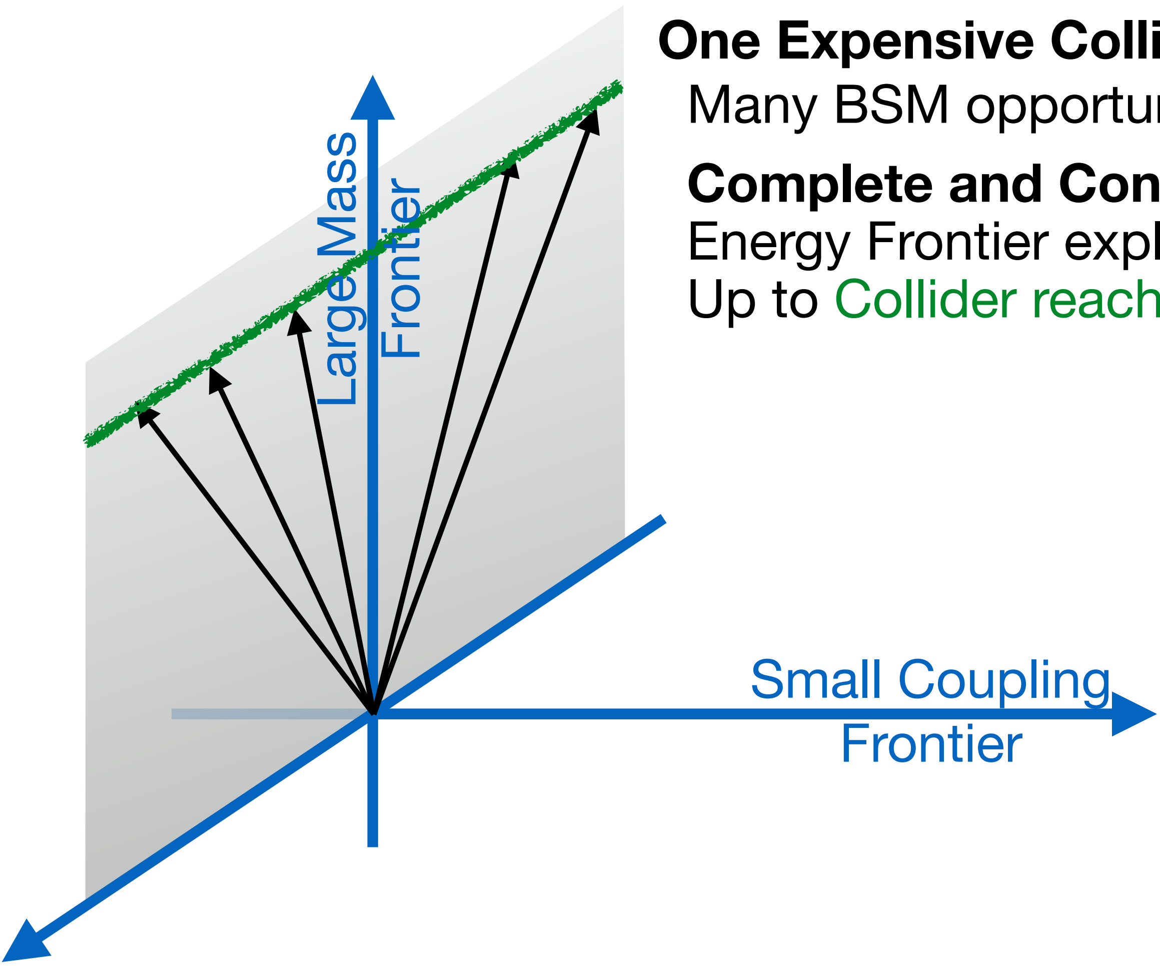

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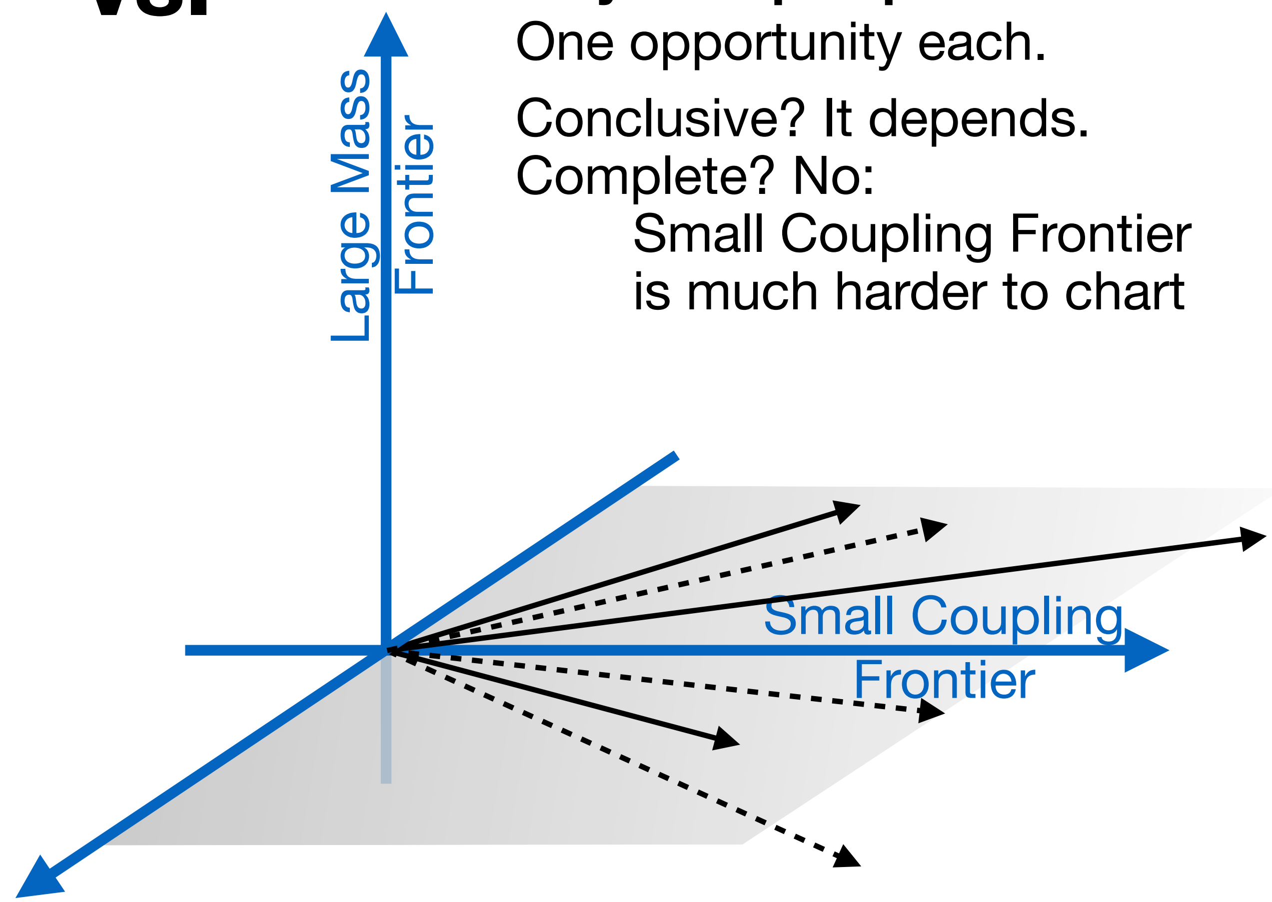

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Still, no doubt that next big project, to have a chance, must be ambitious enough to make **great jump ahead** in exploration of **multiple directions** [even better if constructed with **revolutionary technology**]

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

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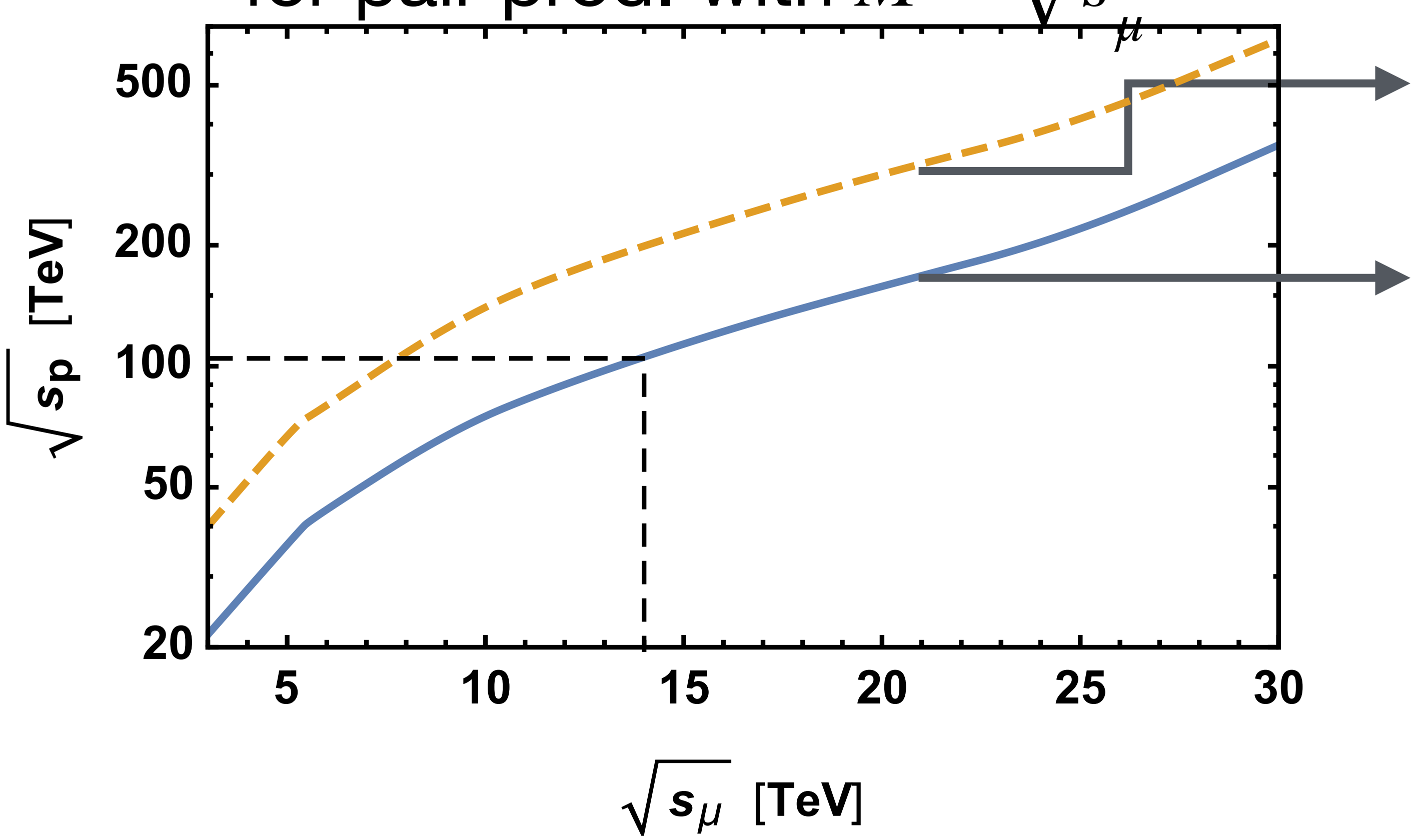
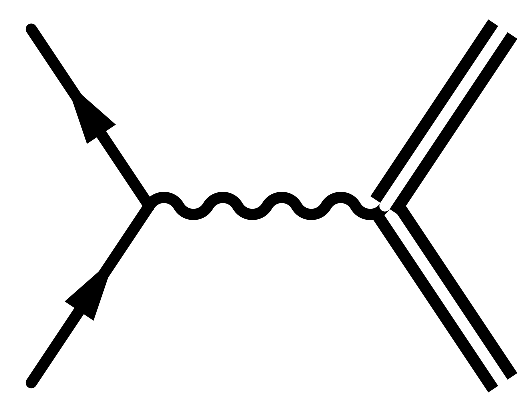


Estimate for EWK-only charged particles

Estimate for EWK+QCD-charged particles



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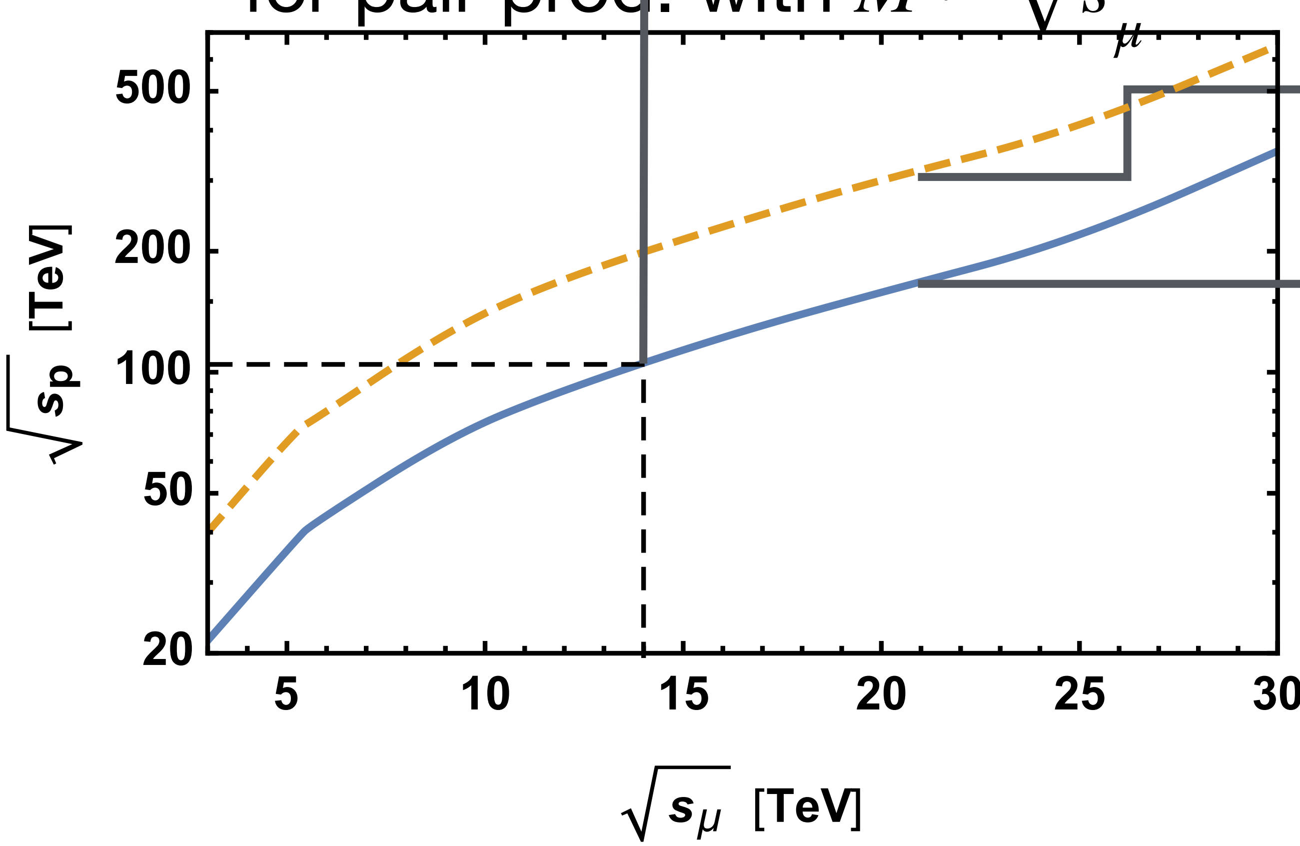

Reference Point:
14 TeV μ-collider ~ FCC@100 TeV

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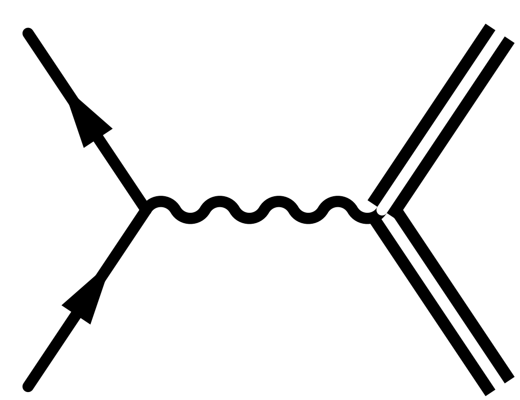

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[cannot accelerate them in rings above few 100 GeV]

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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]

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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MUON Collider
Collaboration

muoncollider.web.cern.ch

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IMCC Design Targets:

- **~3 TeV MuC with ~1/ab**, in 5 yrs for 1 IP
- **10 TeV MuC with 10/ab**, in 5 yrs for 1 IP
- **Emax MuC = ?**, to be assessed

Most focus on 10 TeV and 10/ab in what follows

Why Muons?

Muon Collider Physics Potential Pillars

Generic Exploration
Strategies

Direct search of heavy particles

Answering **questions** like:

“Postponed“ Naturalness?
Extended Higgs Sector?
WIMP Dark Matter?
…

High rate indirect probes

Answering **questions** like:

Higgs potential shape?
BSM Higgs couplings?
What about the Top?
…

High energy probes

Answering **questions** like:

A Composite Higgs?
A new gauge force?
EW matter in loops?
…

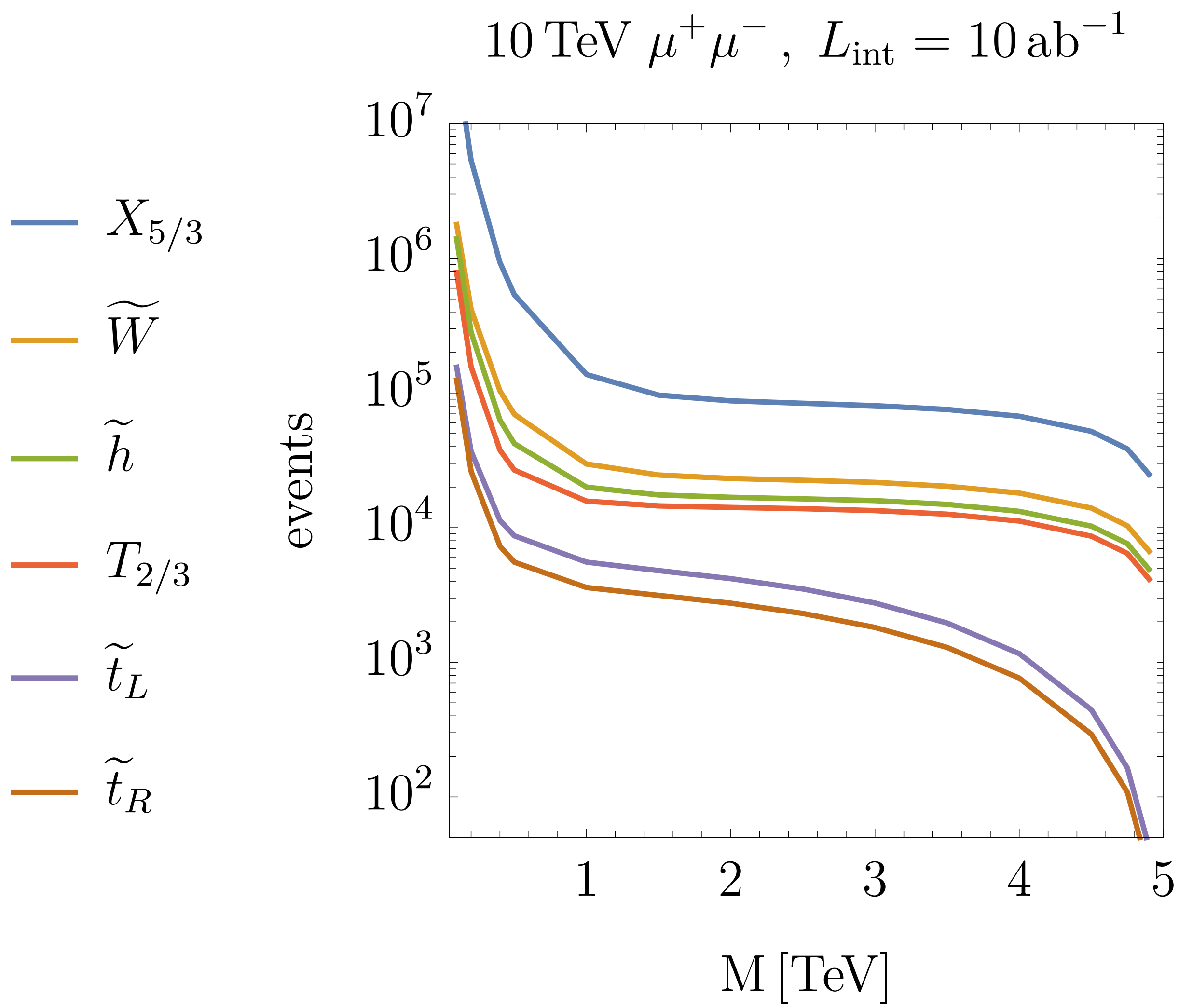
Specific BSM
Questions

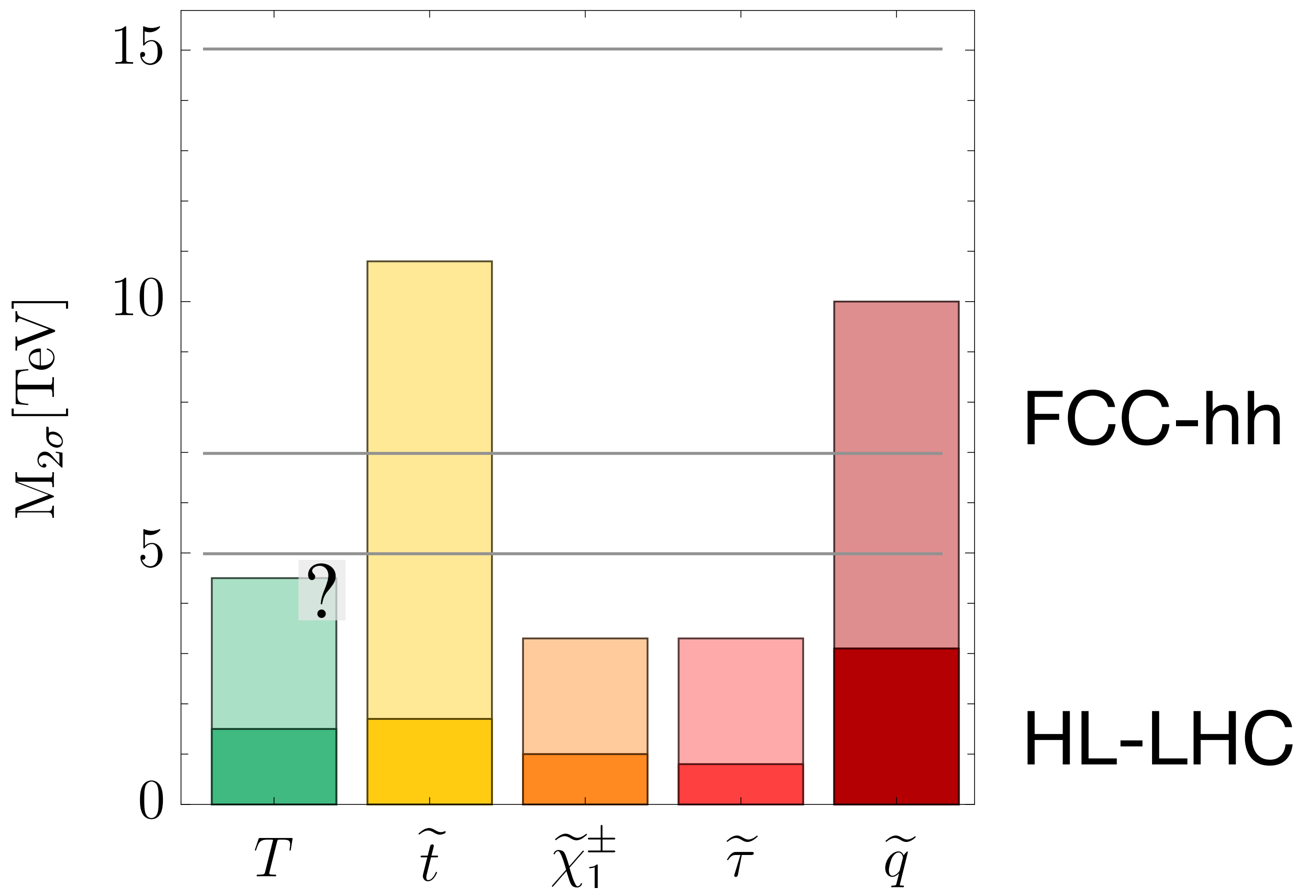
1) Complete and conclusive **exploration** of the Energy Frontier
2) Sharp answers to well-posed **Beyond the SM questions**

The case for direct searches

EW particles discovered up to kinematical threshold

say, 0.9 Ecm/2=4.5 TeV





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Naturalness implications*: (“minimal tuning” scenario: Δ=10 today)

- **Δ=80**, from Stops (SUSY) and from Top Partners (CH)
- **Δ=2500**, from generic Higgsinos (tree-level tuning)

*though less popular today than in the past, the question on the origin of the EW scale will keep being asked until when solution found!

The case for direct searches

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… but only if decay final states not "difficult" to see.

Relevant "difficult" cases:

Compressed spectra:

Not studied yet. Perspectives to cover LHC "holes" already at 3 TeV

Minimal WIMP Dark Matter:

Possibly Higgsino, but more general.

"Very direct" signatures from disapp. tracks [realistic BIB included! 2009.11287]

Probed in mono-X [2009.11287, 2107.09688, 2203.07351]

"Indirect" probes **above mass-reach** [1810.10993]

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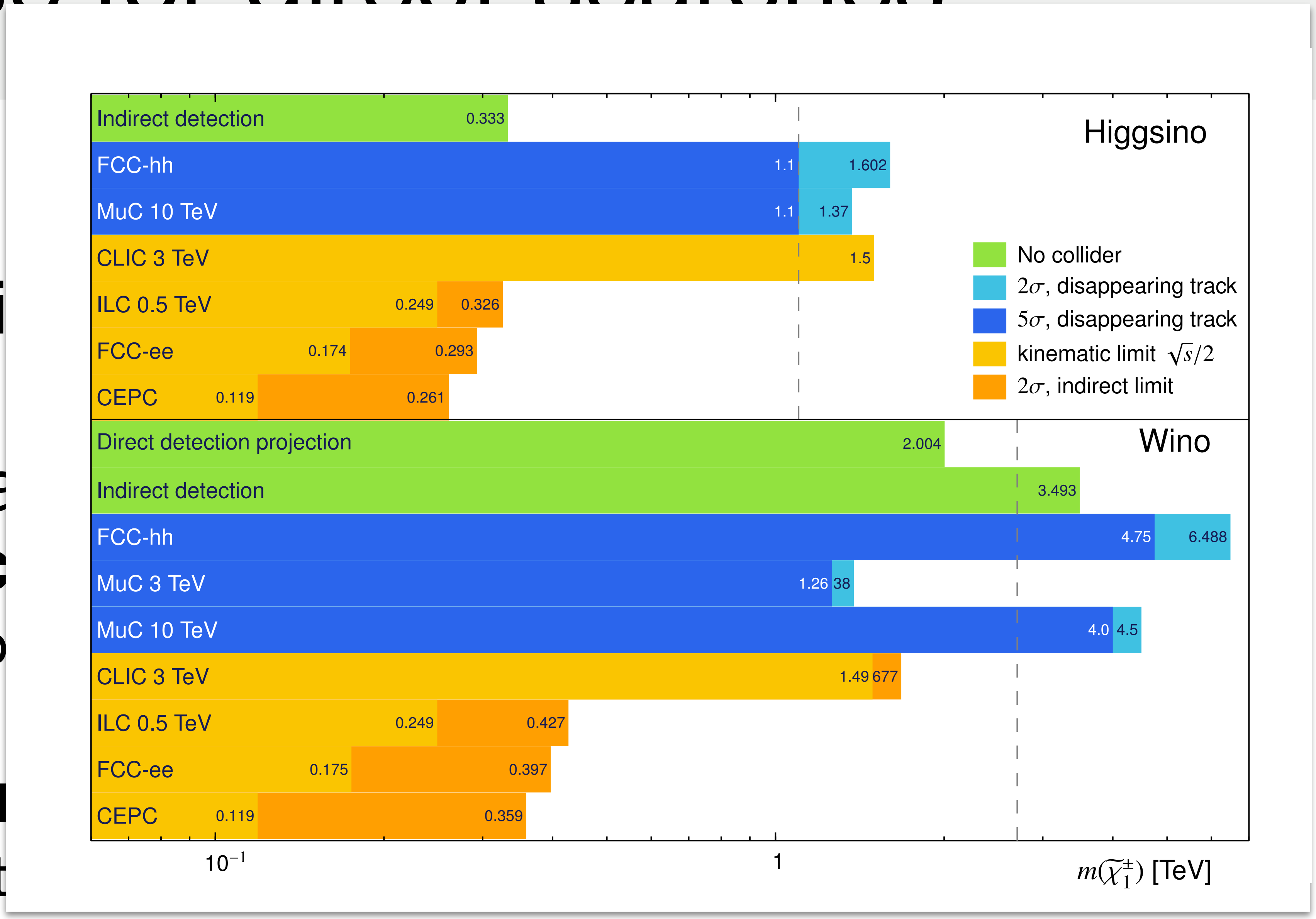

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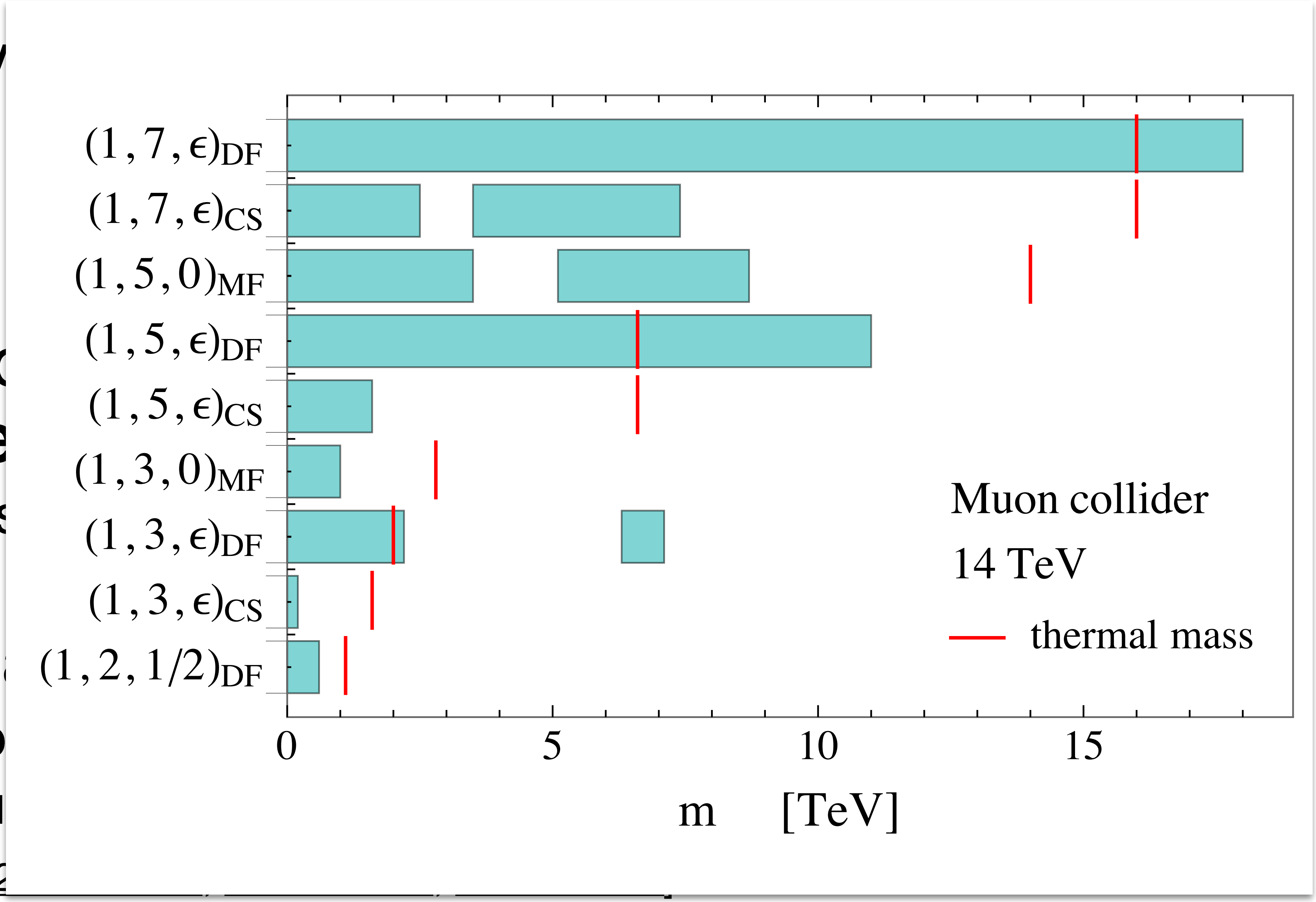
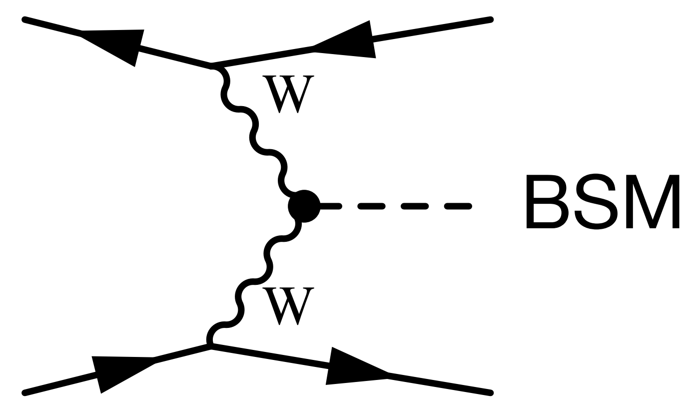


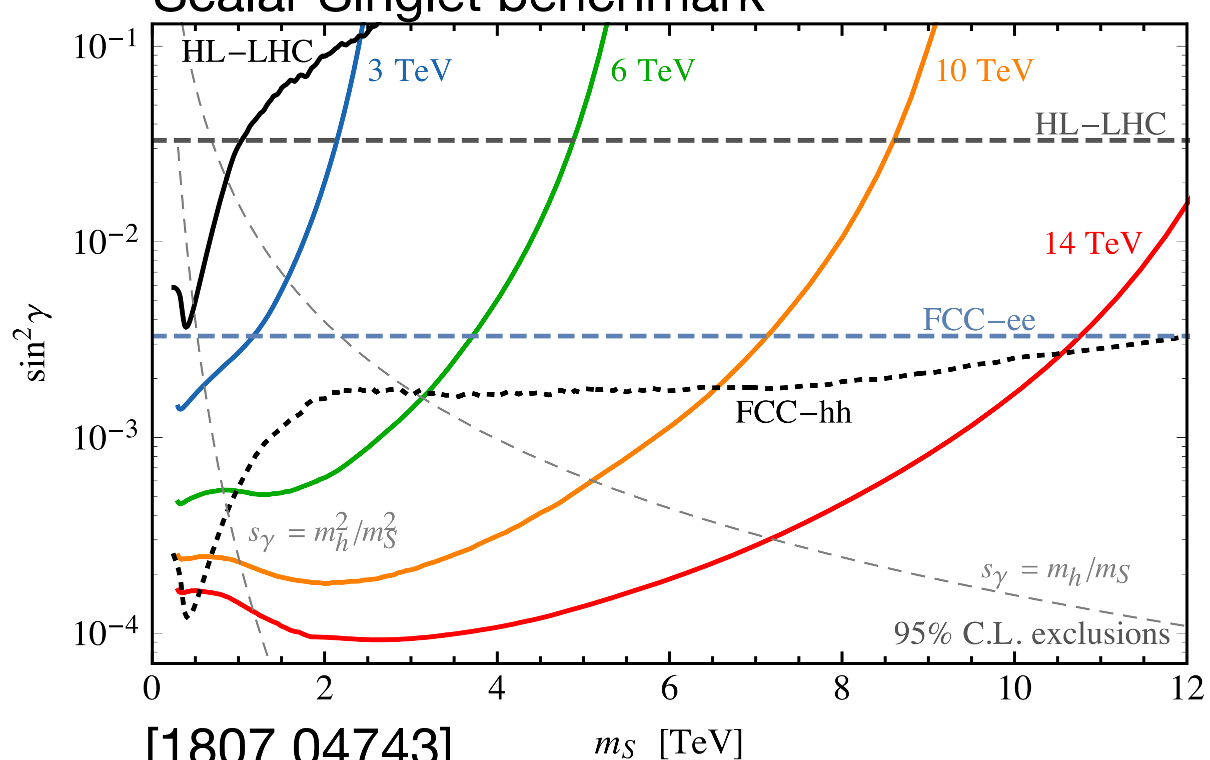
The case for direct searches

EW-Neutral, **Higgs portal-coupled** particles:

Great Reach, from VBF:

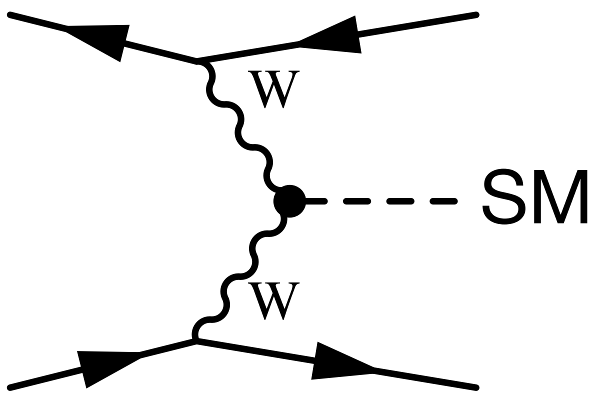


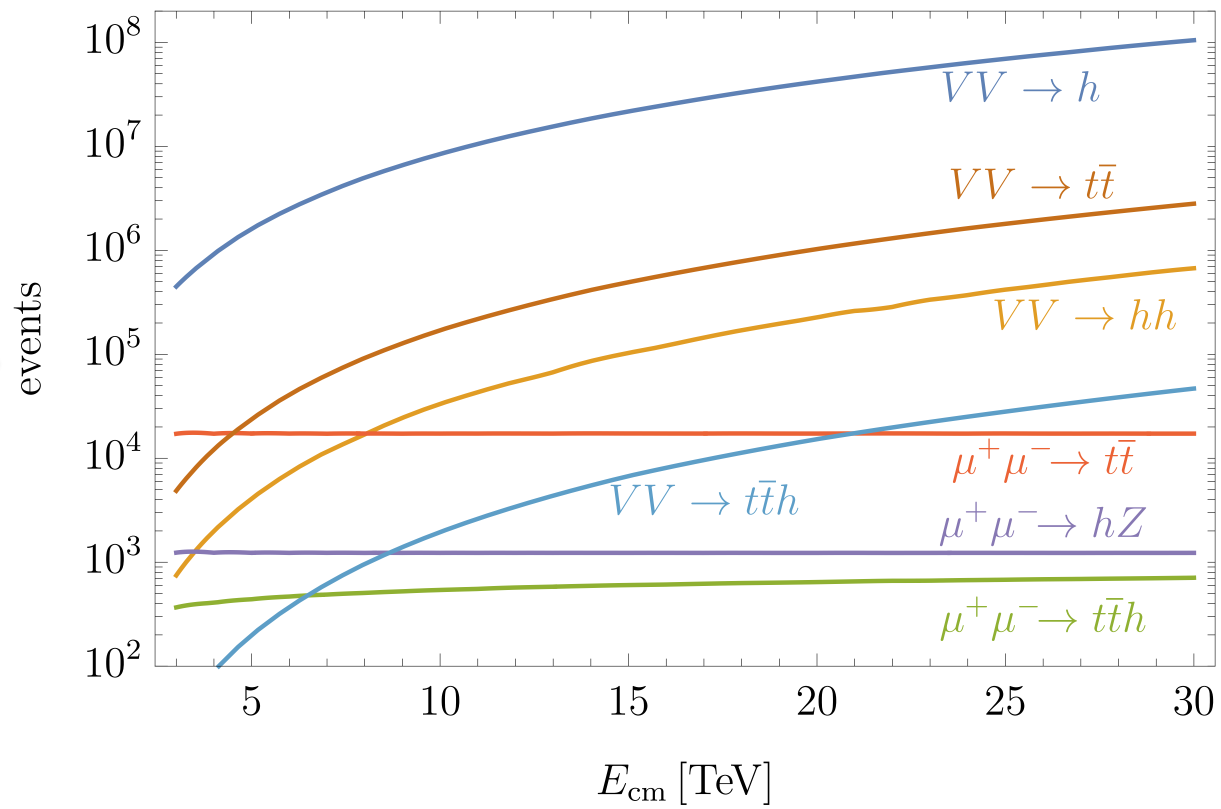
Scalar Singlet benchmark



[1807.04743]

A vector bosons collider

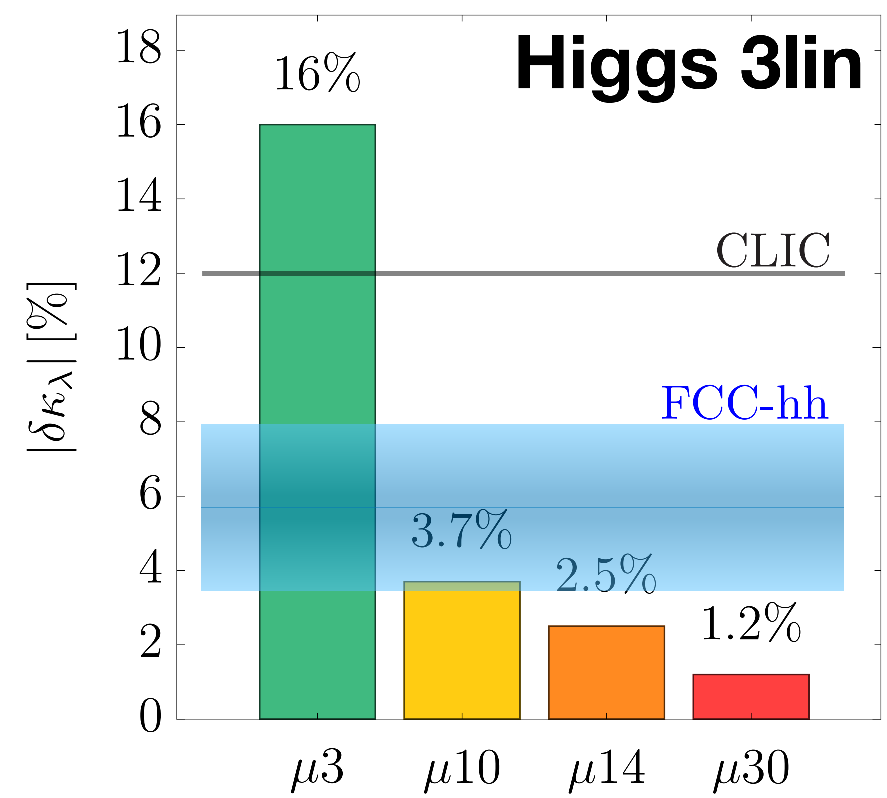




Single Higgs couplings

	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



High energy probes

[Buttazzo, Franceschini, AW, 2020]

As simple as this:

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

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

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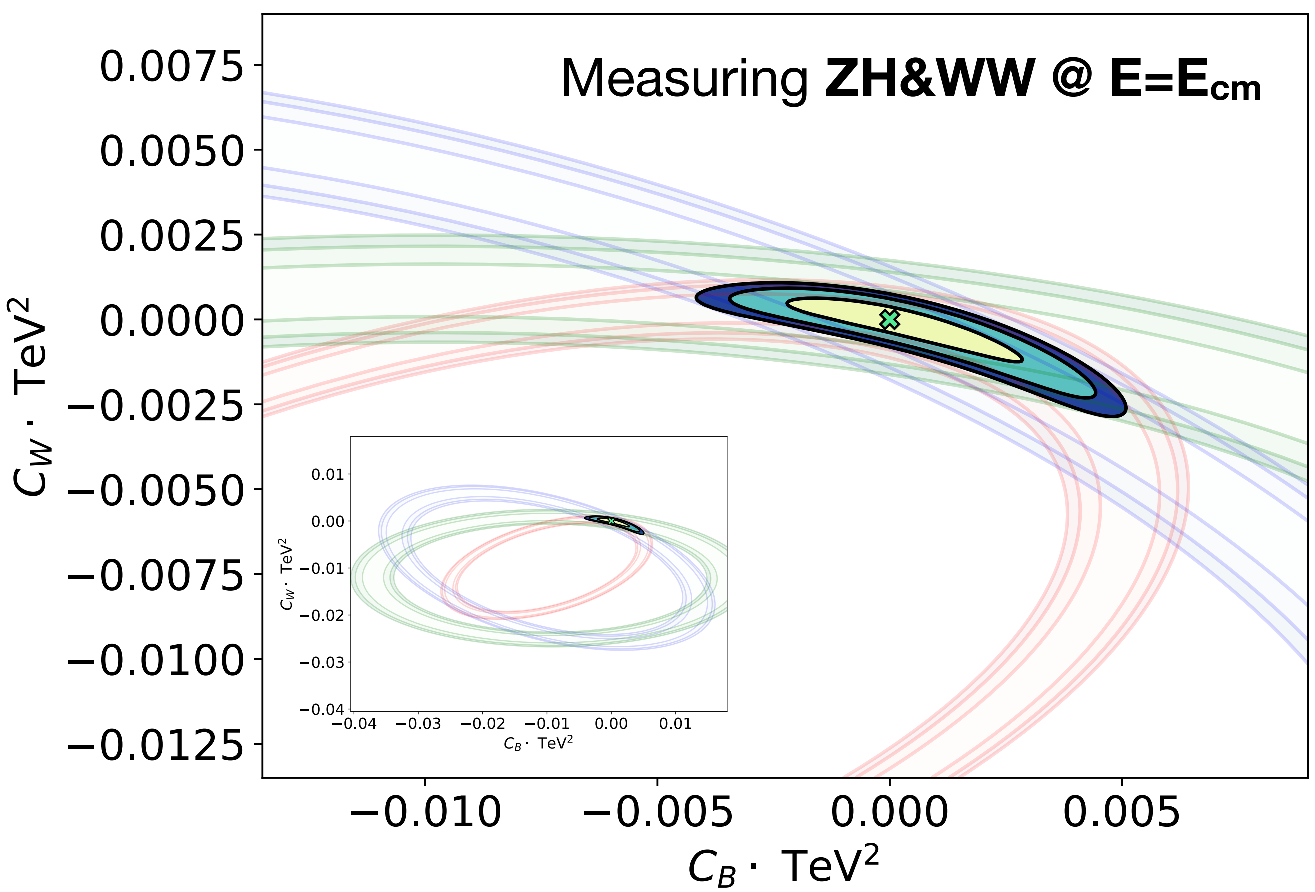
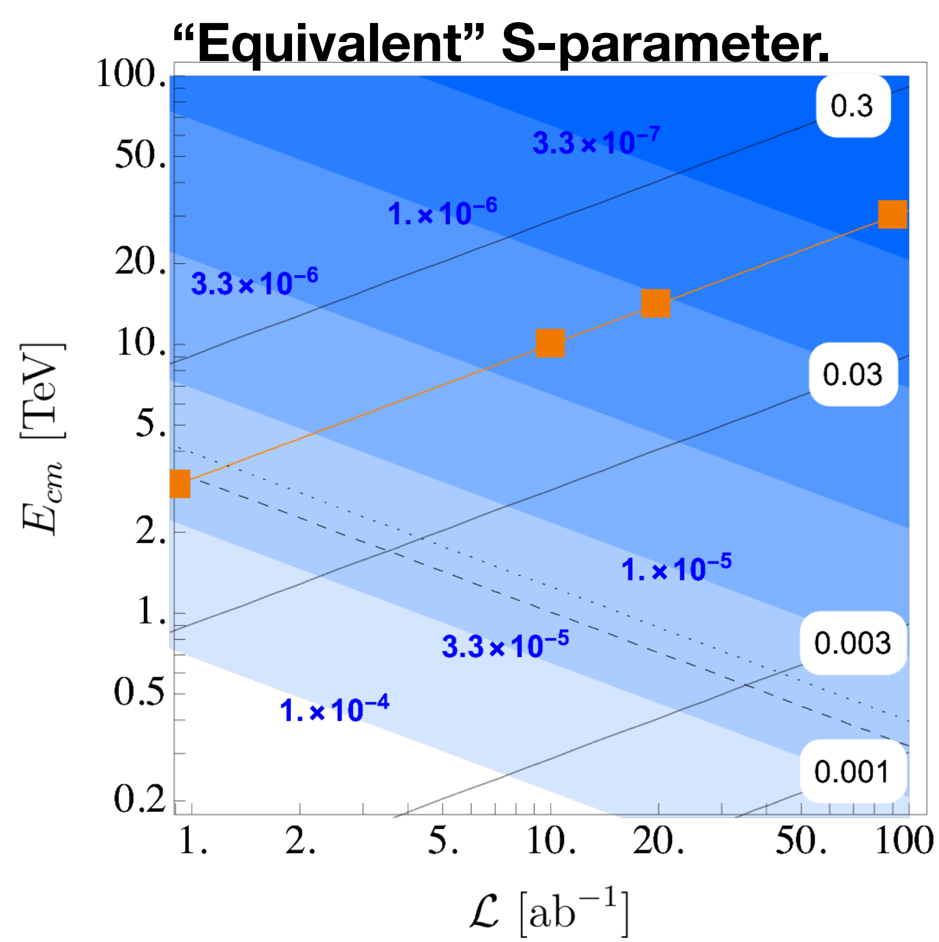




Today:

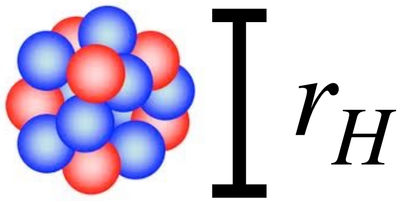
10^{-3}

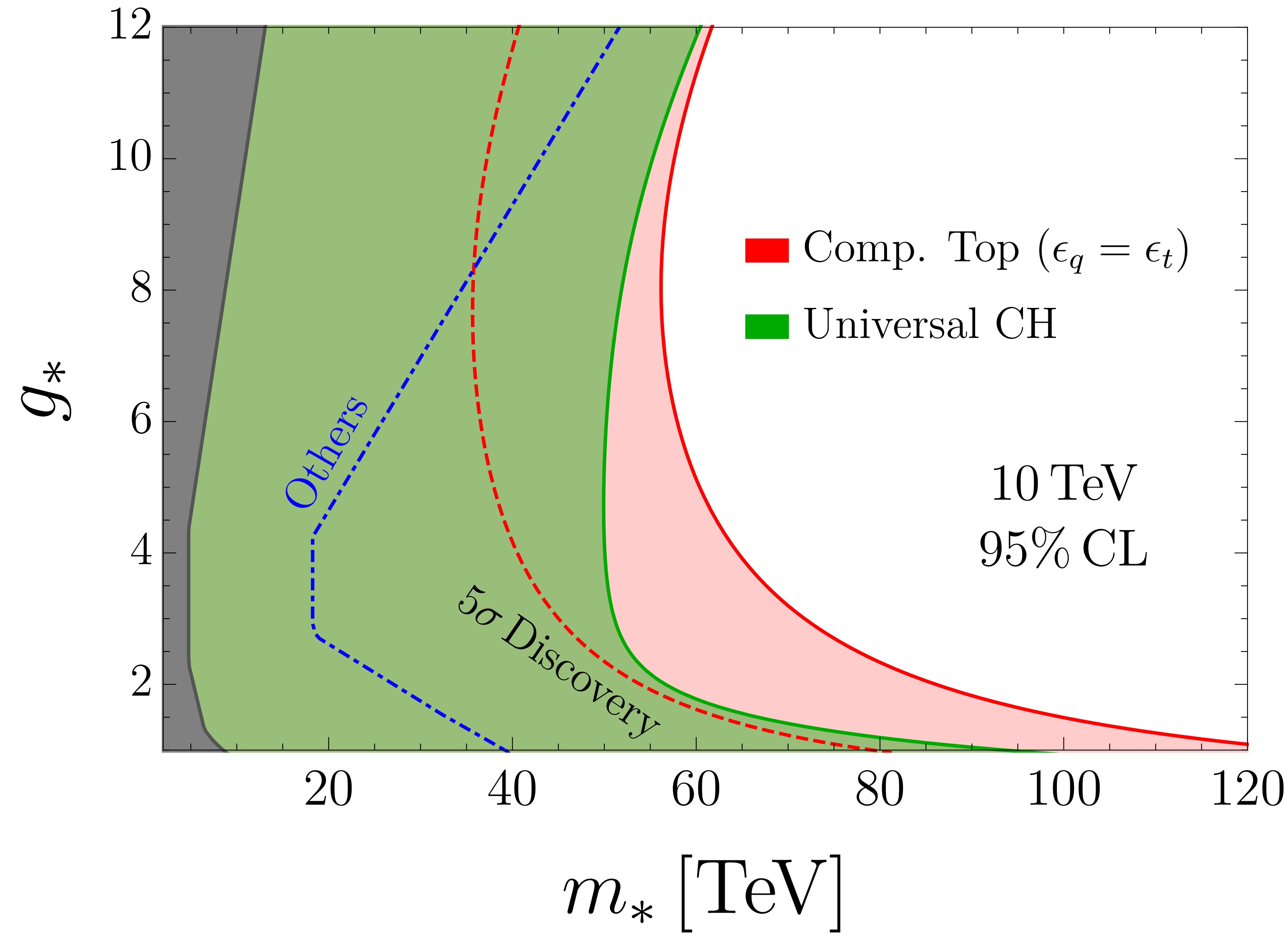
MUC14

10^{-6}

Composite Higgs, indirect

[Chen, Glioti, Rattazzi, Ricci, AW]





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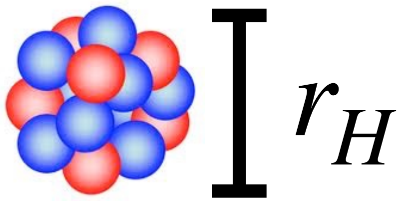
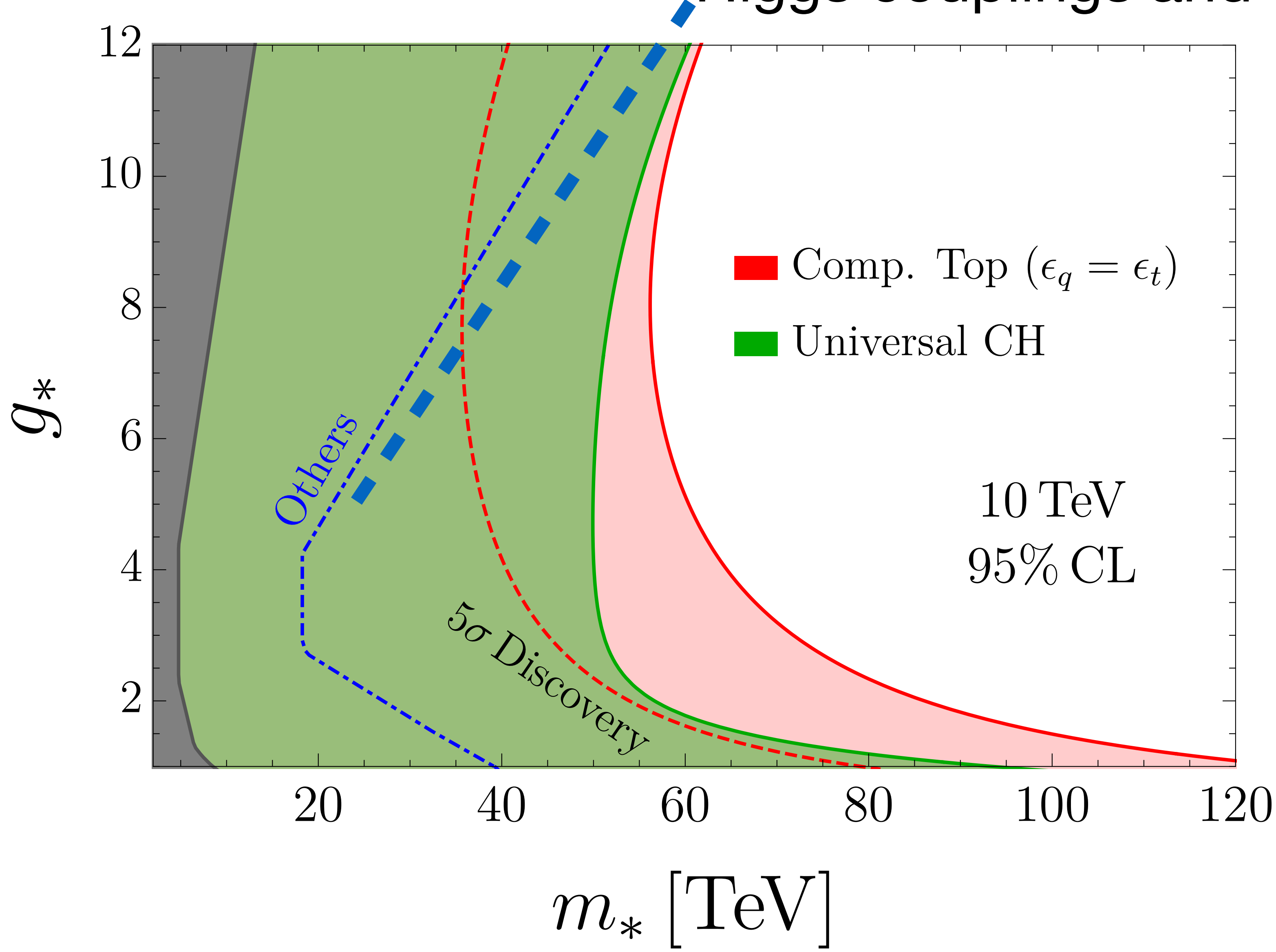


Probed “twice”:
Higgs couplings and VV > HH



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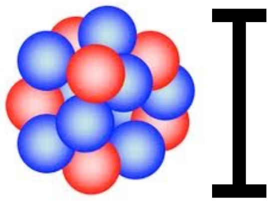

r_H

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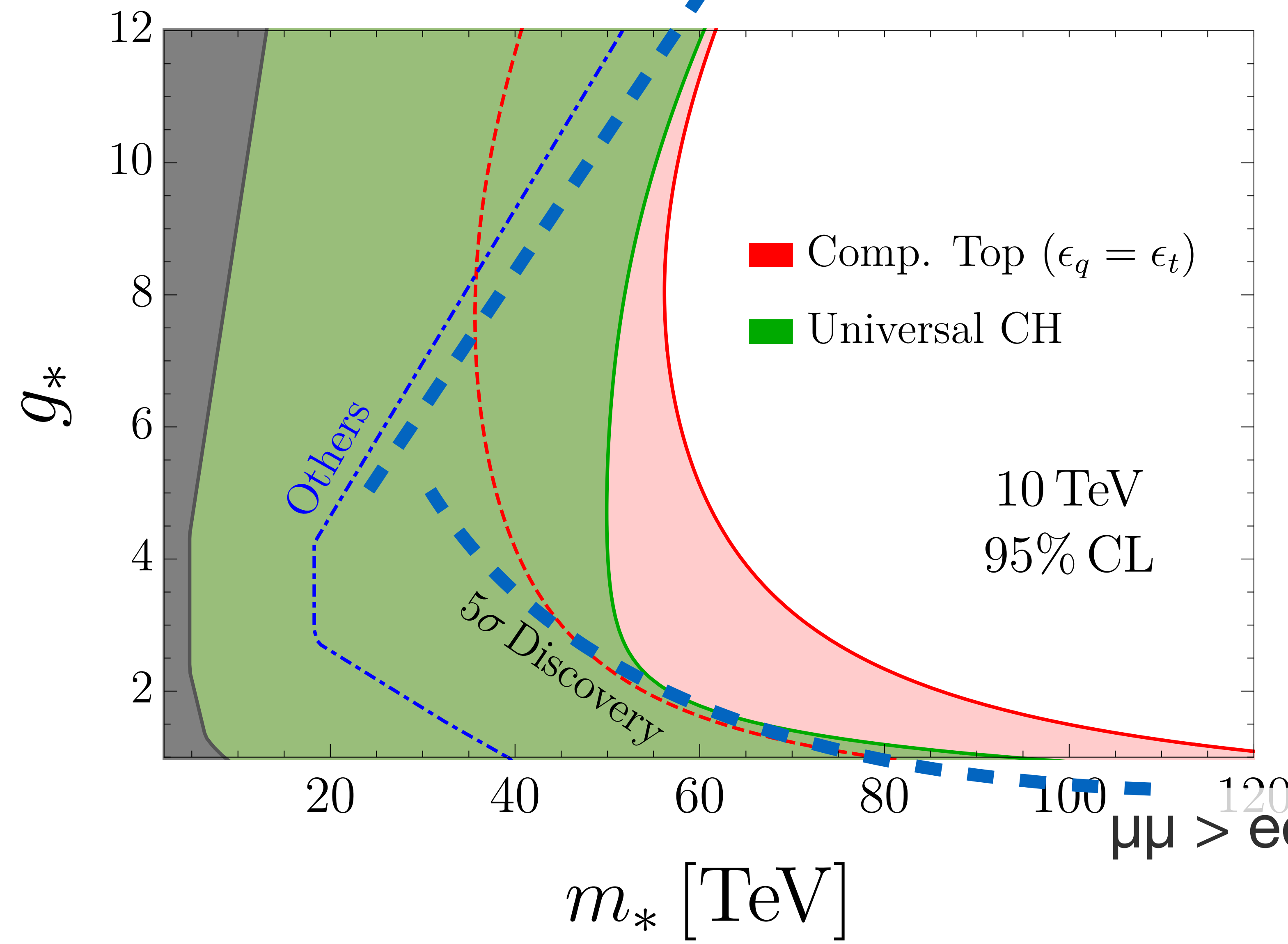

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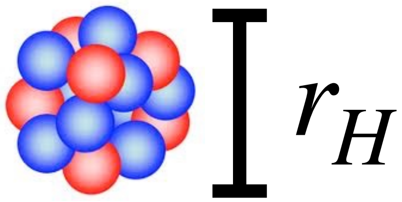

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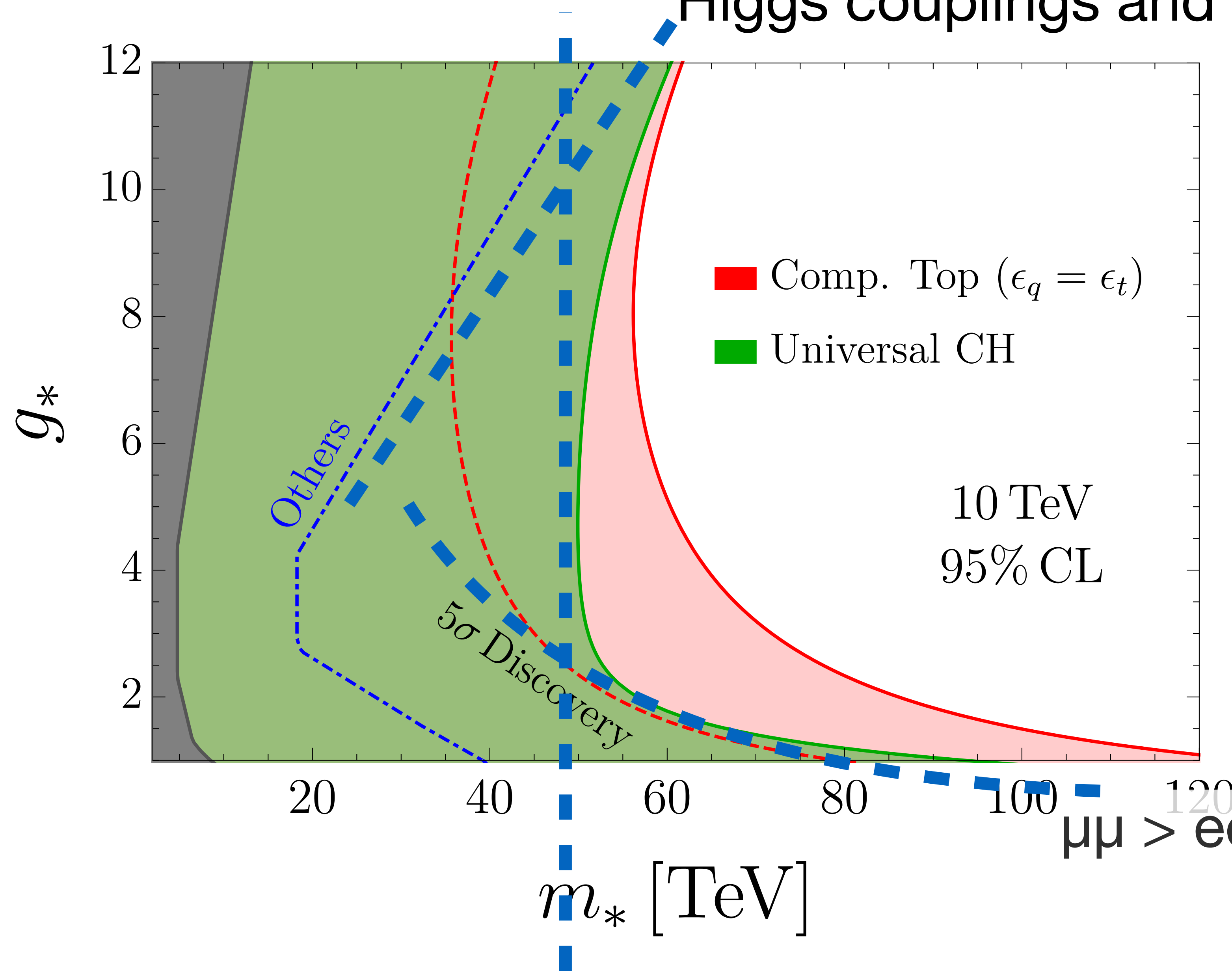

μμ > ee, qq, tt, …

μμ > ZH, WW, WZ, ..

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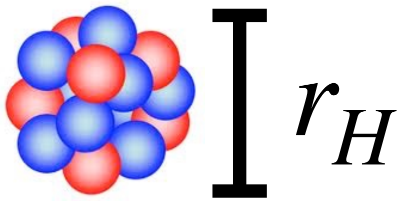
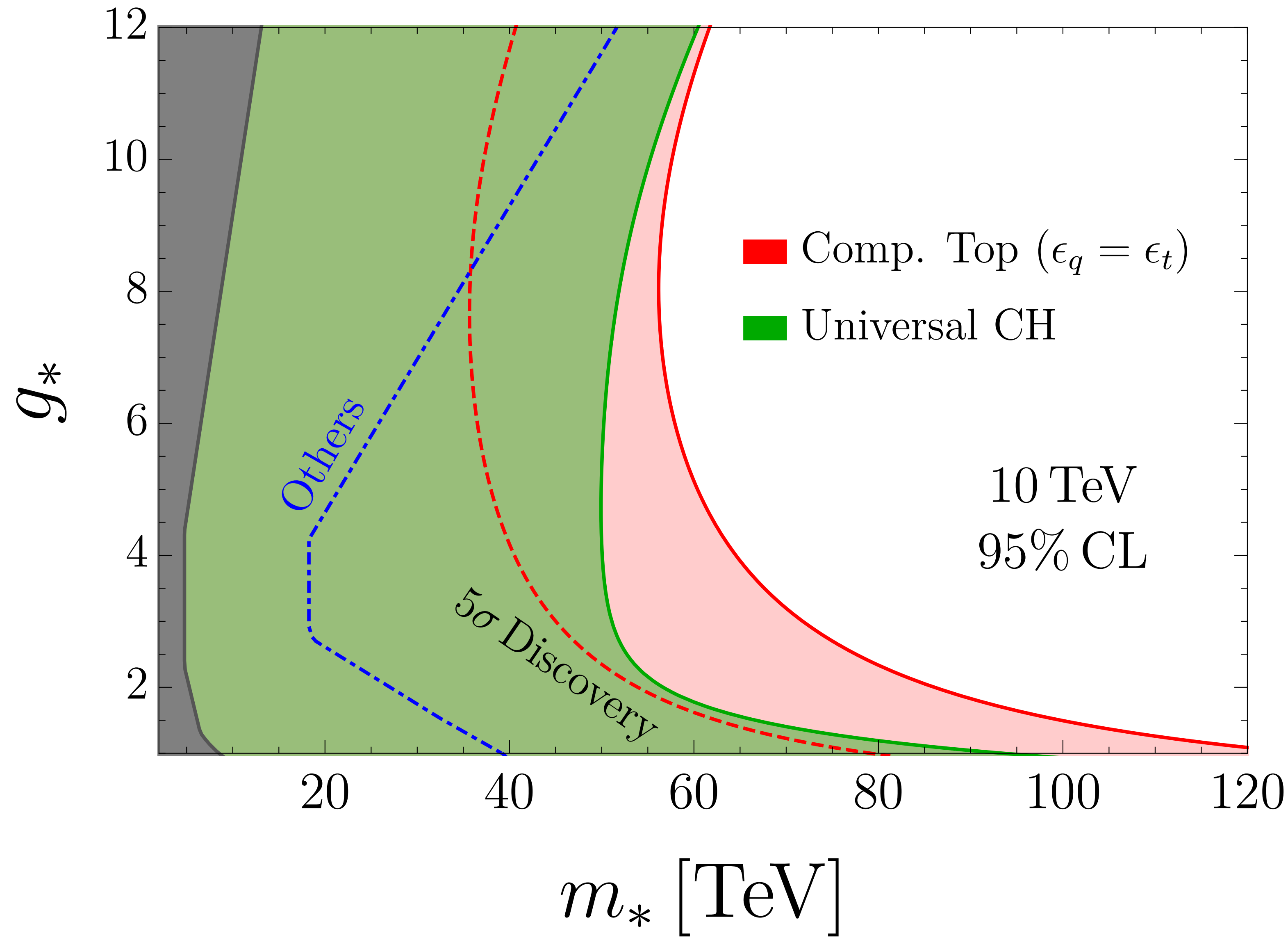




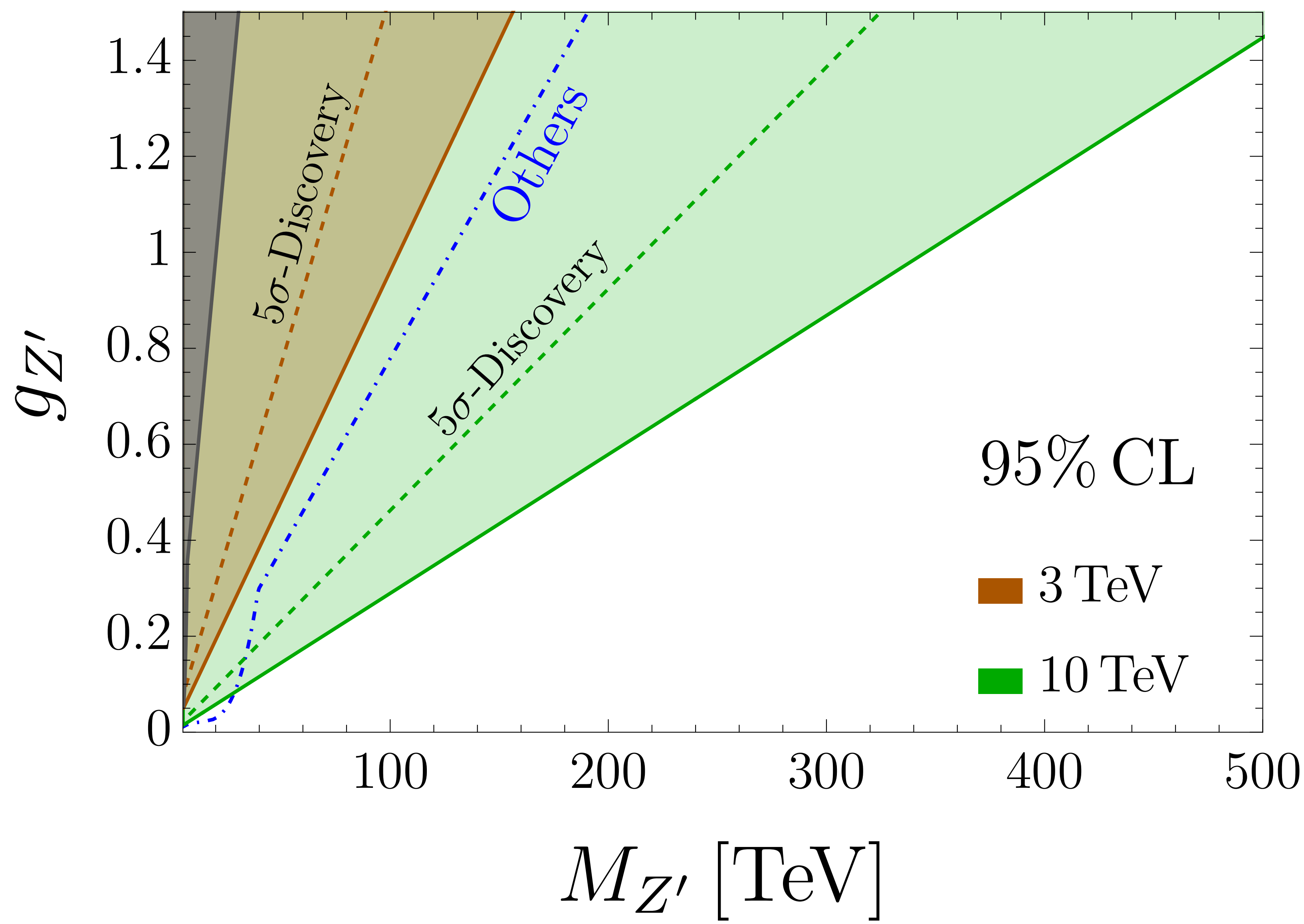
Superior reach on Higgs radius from measurements at the high collider energy, where Higgs size effects are enhanced.

Proton size discovered this way: raising energy until close enough to r_P^{-1}
We might be lucky again!

Same mechanism, simpler model

[Chen, Glioti, Rattazzi, Ricci, AW]

Minimal Z’



Generically, we can test EW interactions at > 100 TeV scale.

Is this potential **real?**

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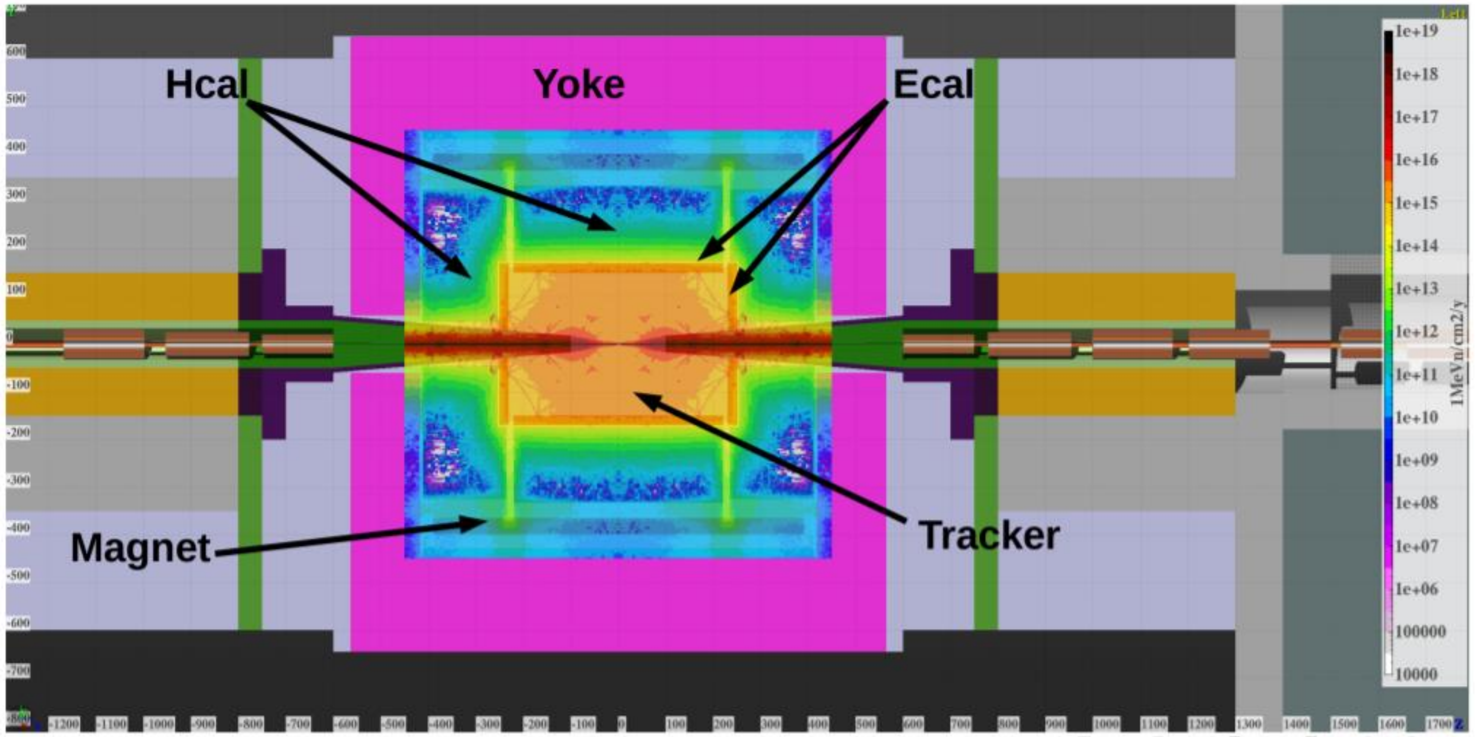
Directly based on microscopic physics laws, principles and techniques.

Background from decaying muons (BIB)



FLUKA @ 1.5 TeV

New Challenge for Detector@Analysis design

Is this potential **real?**

Remember what we expect from colliders:

Accurate measurements of great variety of observables.

Under precisely known experimental conditions.

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Accurate predictions within the Standard Model of Particle Physics.

Directly based on microscopic physics laws, principles and techniques.

EW Infrared logarithms are **order one** at MUC energies

Accurate **resummation** is needed.

[Manohar and Waalewijn, 2018, …]

As well as accurate **EW showering.**

[Chen, Han, Tweedie, 2016; Han, Ma and Xie, 2021, …]

NOT an easy extension of QED/QCD radiation treatment

Because of the peculiarities of broken gauge theories

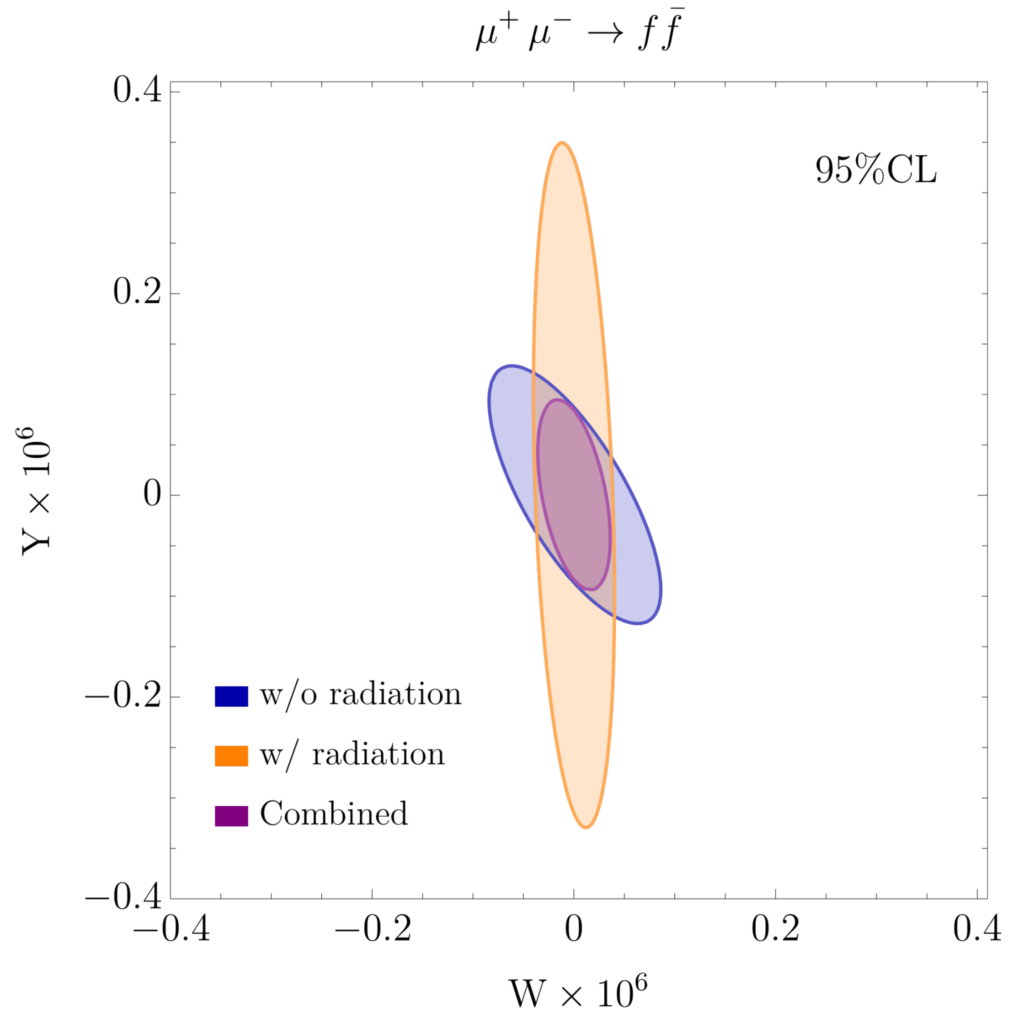
Because of the accuracy we need

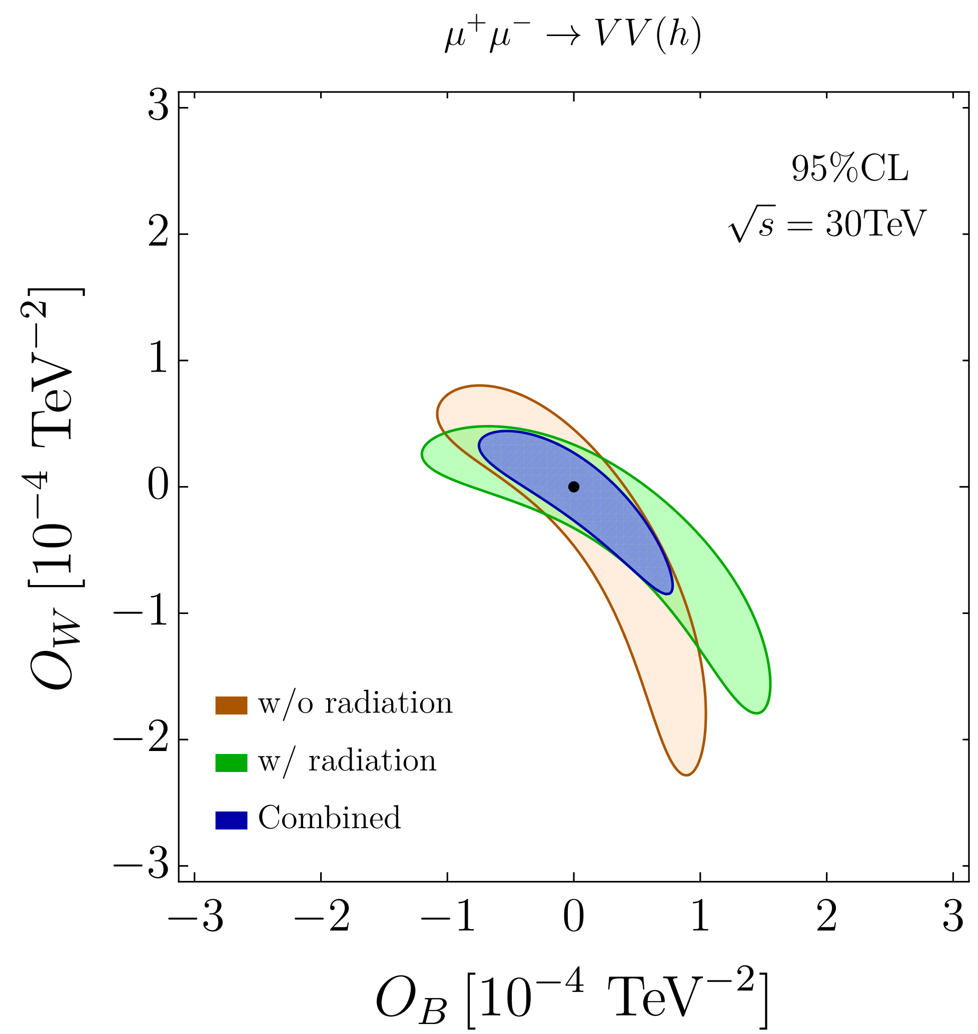
Because from radiation structure we can learn about New Physics!

[Chen, Glioti, Rattazzi, Ricci, AW]

Is this potential **real?**

We can, e.g., access charged current int. from W in.state radiation.
Exclusive/semi-inclusive complementarity in EFT interactions sensitivity.





Because from radiation structure we can learn about New Physics!

[Chen, Glioti, Ricci, Rattazzi, AW, to appear]

Is the collider **feasible?**

Objective:

In time for the next European Strategy for Particle Physics Update, the study aims to **establish whether the investment into a full CDR and a demonstrator is scientifically justified**.

[Daniel Schulte, IMCC head. link]

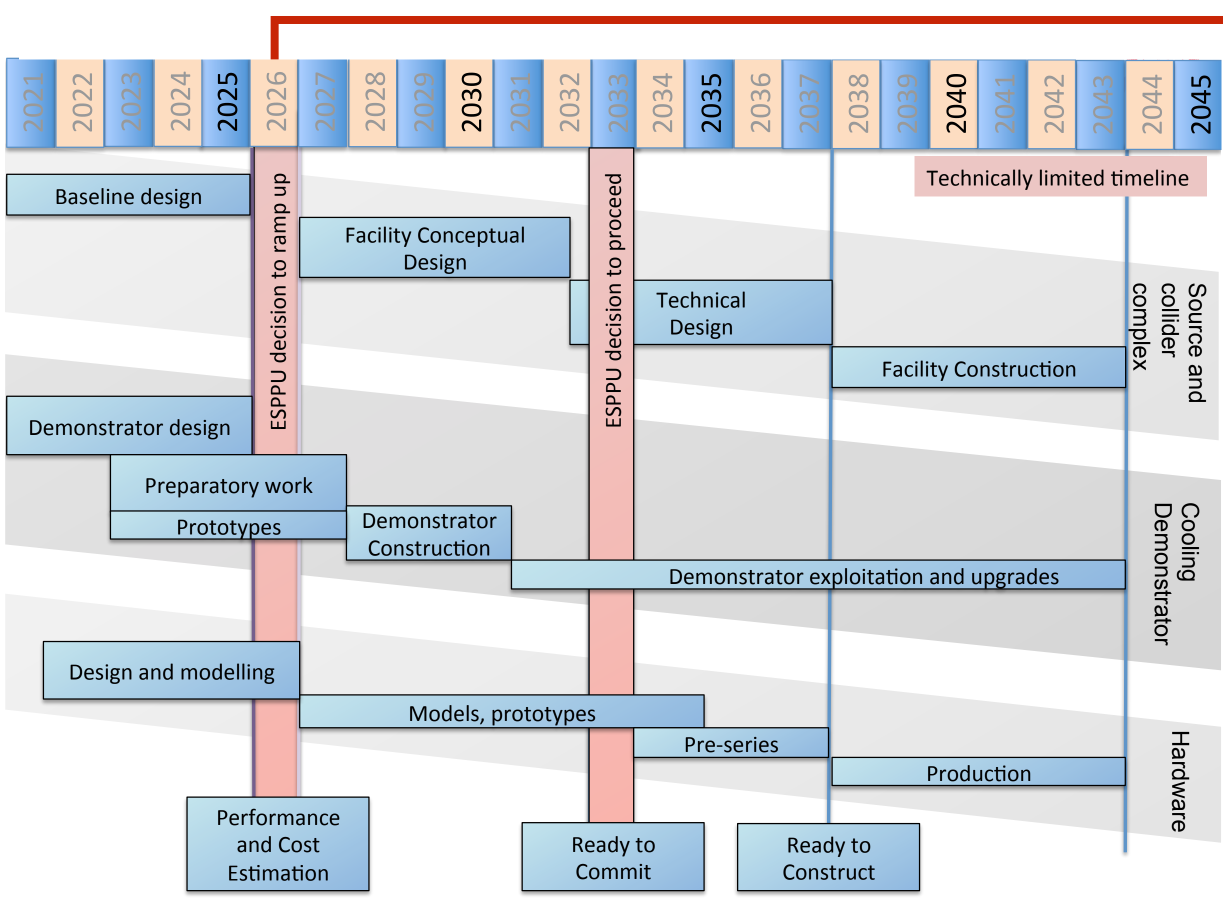
International UON Collider Collaboration

Scope:

- Focus on two energy ranges:
  - **3 TeV**, if possible with technology ready for construction in 10-20 years
  - **10+ TeV**, with more advanced technology, **the reason to chose muon colliders**

[Daniel Schulte, IMCC head. link]

Tentative Target for Aggressive Timeline



We might know the answer in few years

A summary, and a work plan, available here

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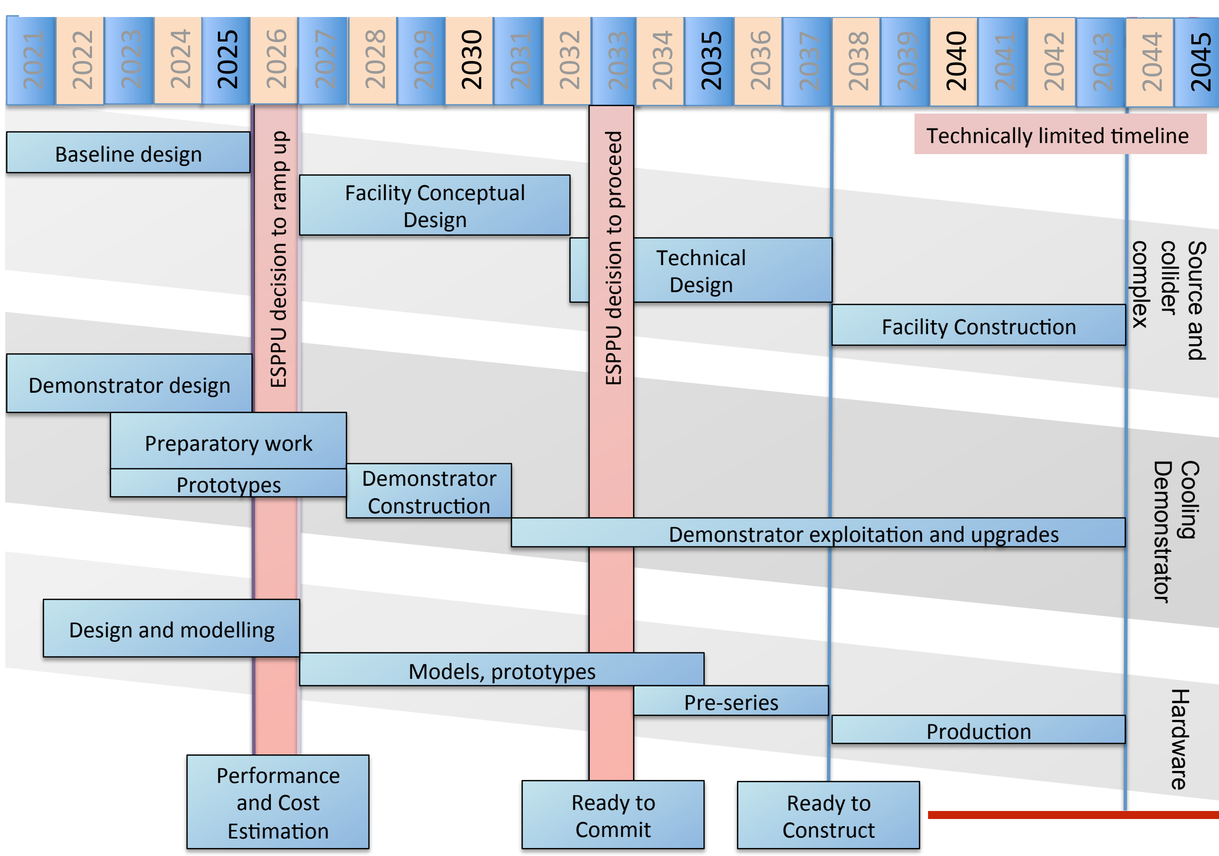

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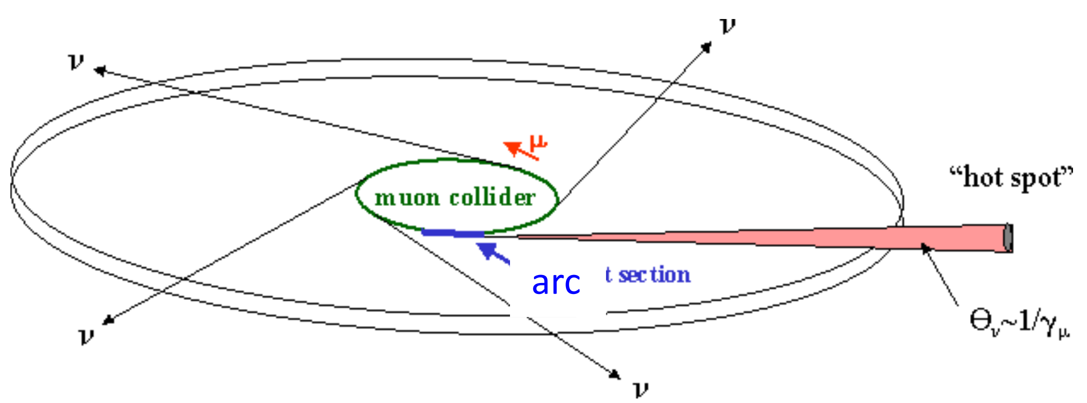
A first MUC, maybe at 3 TeV, could start being built as early as 2038!

Is the collider **feasible?**

One famous possible issue is radiation from h.e. neutrinos

Neutrino Flux Mitigation

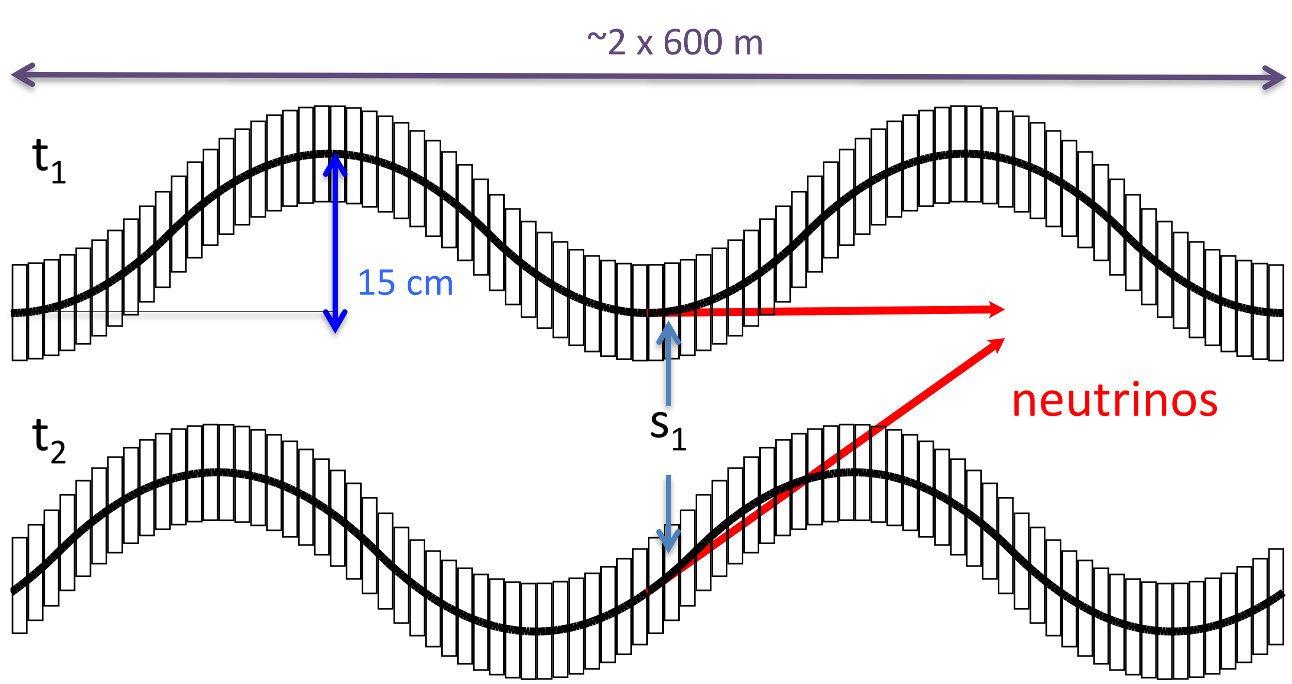


Concentrate neutrino cone from arcs can approach legal limits for 14 TeV

Goal is to reduce to level similar to LHC

3 TeV, 200 m deep tunnel is about OK

Need mitigation of arcs at 10+ TeV: idea of Mokhov, Ginneken to move beam in aperture
Our approach: move collider ring components, e.g. vertical bending with 1% of main field



Opening angle ± 1 mradian

14 TeV, in 200 m deep tunnel comparable to LHC case

Need to study mover system, magnet, connections and impact on beam

Working on different approaches for experimental insertion

(Emerging) Conclusions

For 10 TeV MuC! Much better if higher Energy!

Muon Colliders BSM Physics Pillars:

- **High Energy** available for direct particles production
- **High Rate** available for **Precision** measurements
- **Energy and Precision ➔ probing EW in 100 TeV ballpark**

All this, at a single collider with feasible timescale

WIMP Dark Matter

- **Higgsino/Wino "very directly" accessible** (more is coming on WIMP at 10 TeV)

Explaining the origin of the Weak scale

- **Δ=10 ➔ Δ=80** , simply from direct searches
- Probe **Δ=1/ξ=1000**, in CH, in two ways

How much is the Higgs radius?

- If as "large" as 1/(50TeV), we can tell

Added value from colliding muons [2203.07261]

- Current anomalies are in muons. If coincidence, a fortunate one: illustrates obvious potential of colliding μ for the first time!

Thank You