Why building a muon collider

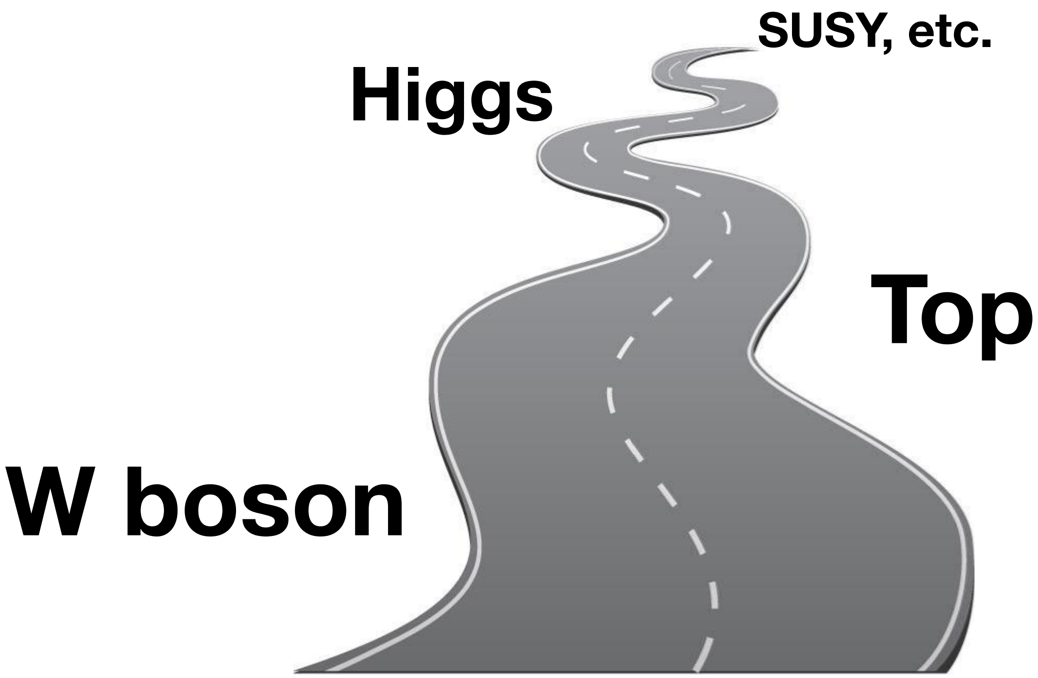
Andrea Wulzer

Università degli Studi di Padova

École Polytechnique Fédérale de Lausanne

The High Energy Physics Landscape

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

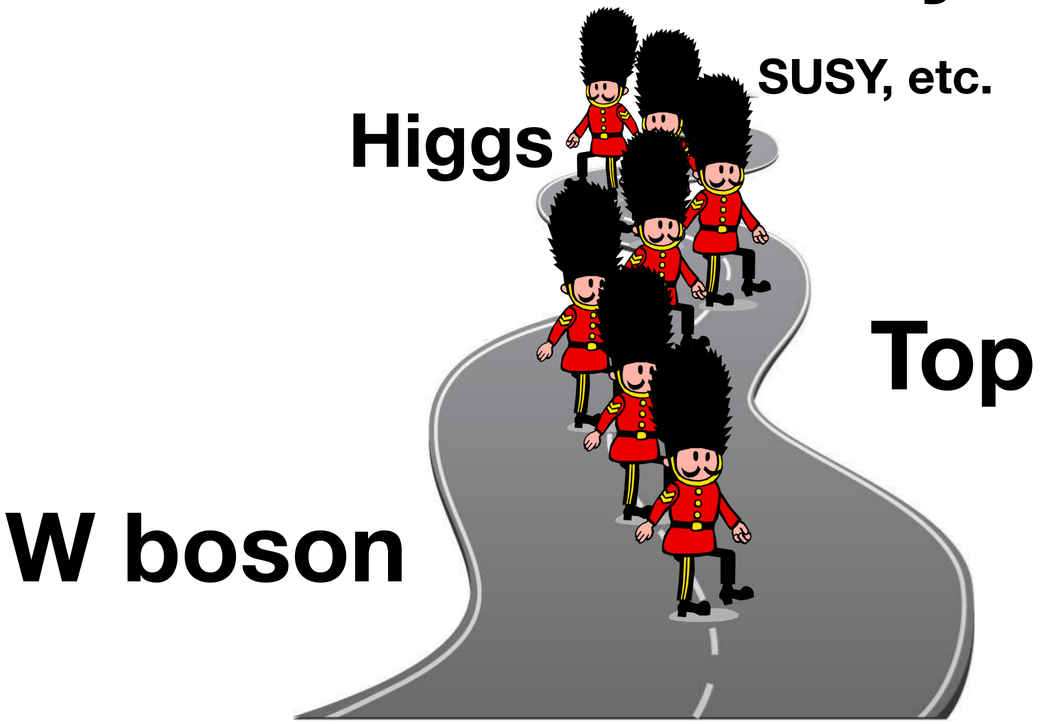


The High Energy Physics Landscape

HEP Yesterday

LHC

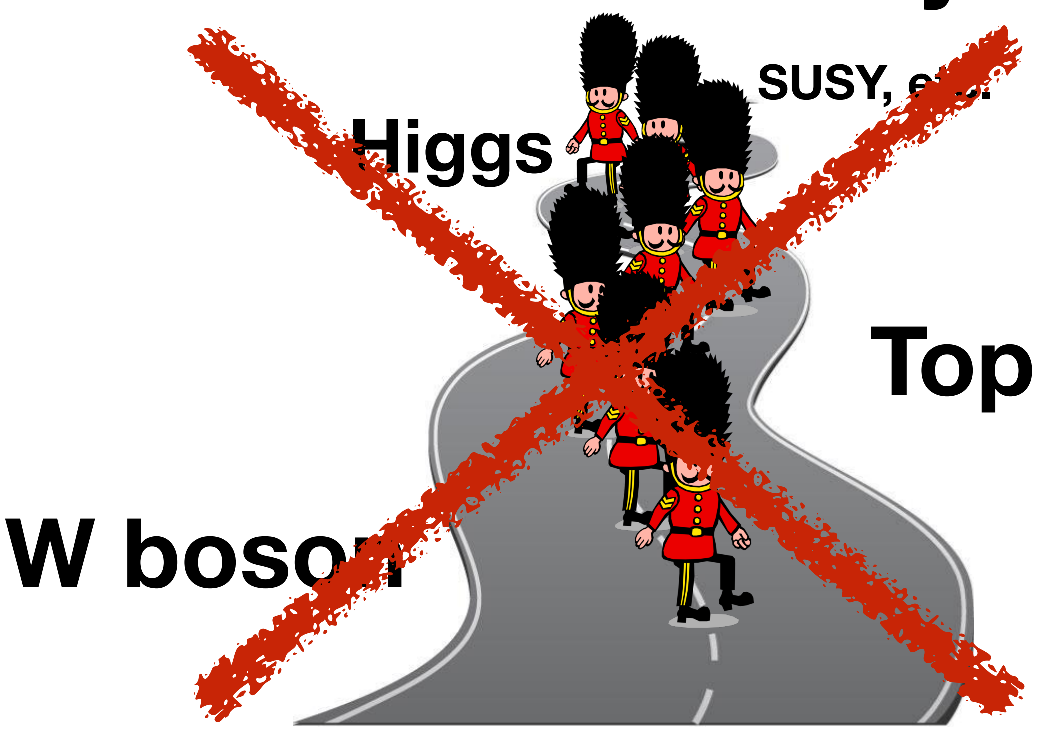
HEP Today

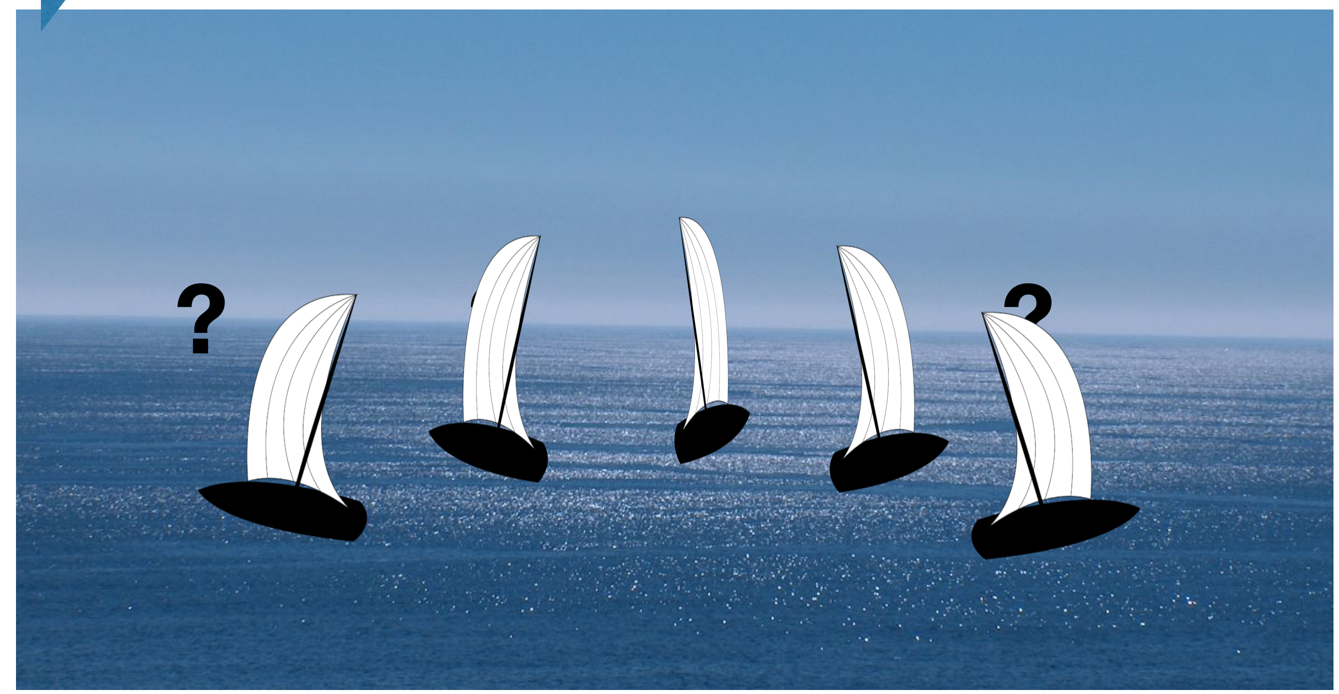


Yesterday, HE-Physicists were used to **follow a road.**

The High Energy Physics Landscape

HEP Yesterday **LHC** → **HEP Today**





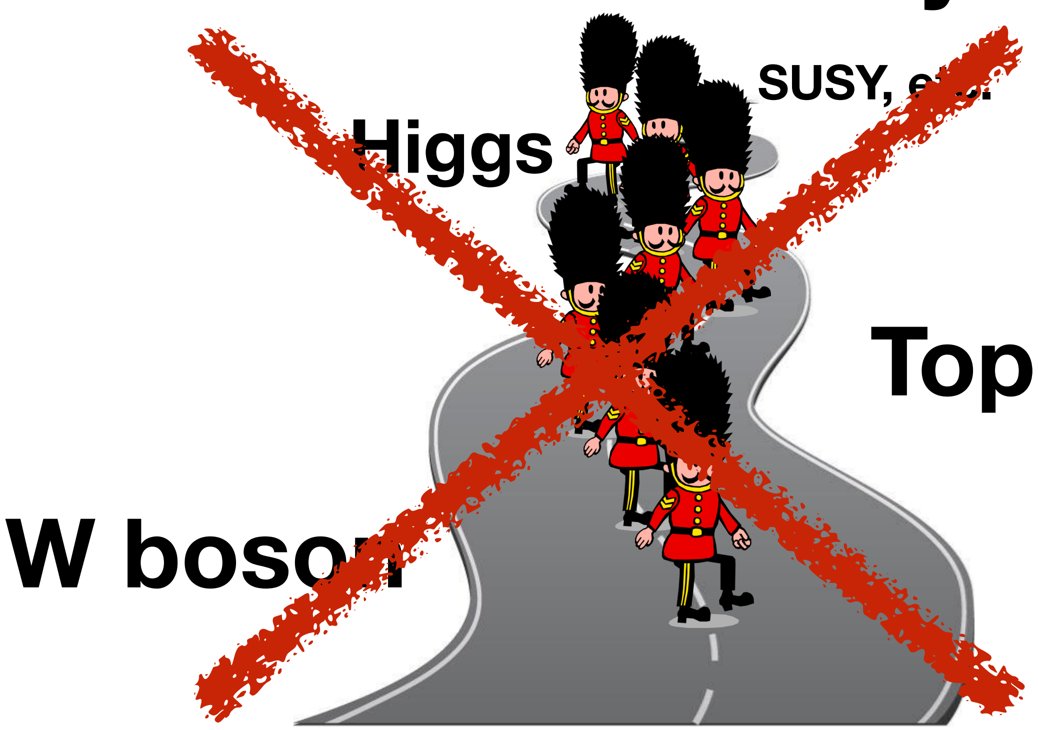
Yesterday, HE-Physicists were used to **follow a road.**

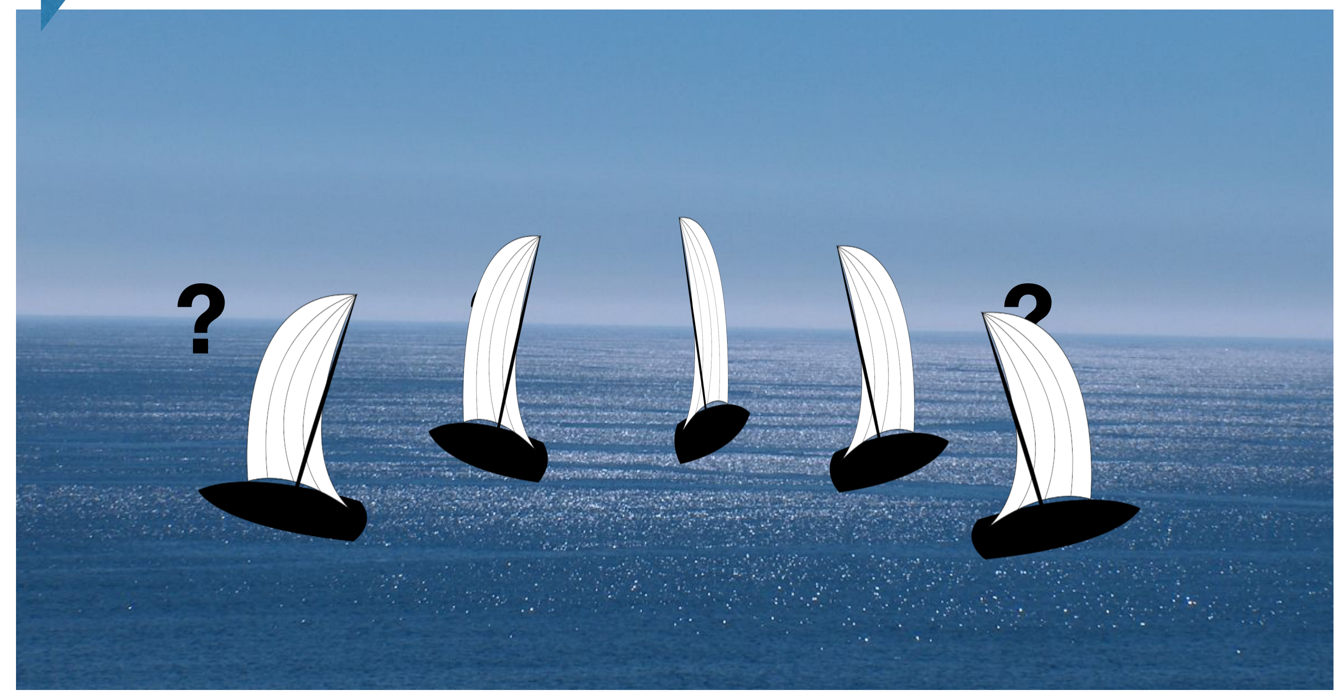
Today, the mission is to **explore uncharted territory***

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

The High Energy Physics Landscape

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





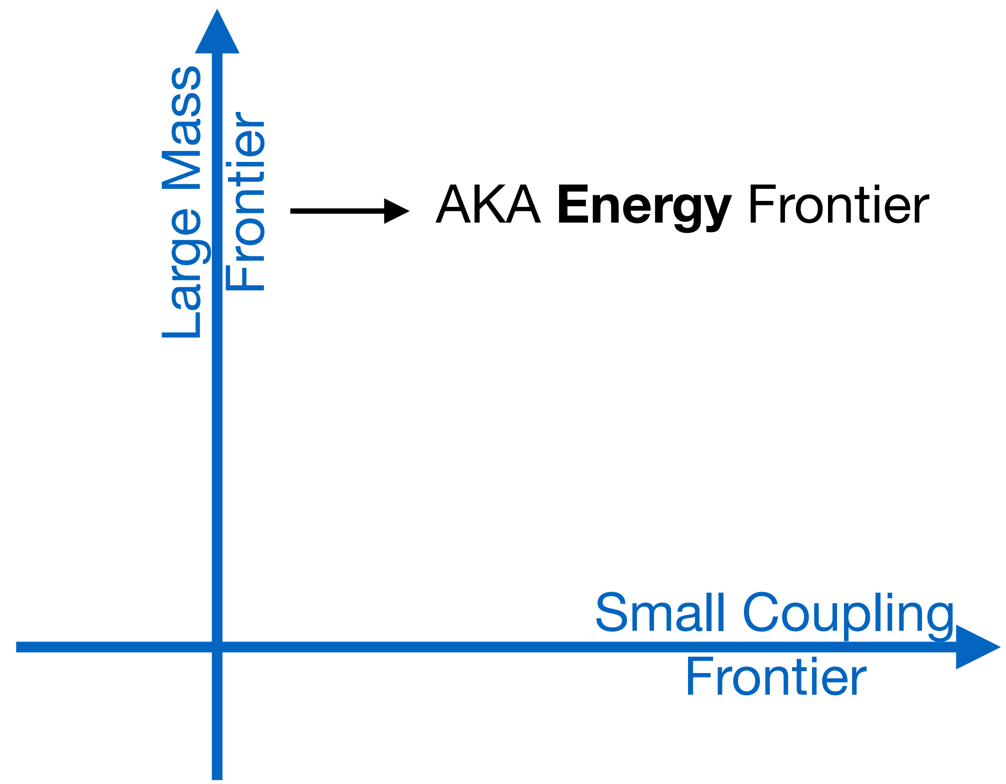
Yesterday, HE-Physicists were used to **follow a road.**

Today, the mission is to **explore uncharted territory***
This is why we started speaking about **Frontiers**

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

The High Energy Physics Landscape

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



W bos

Yest … **oad.**

Today, the mission is to **explore uncharted territory***
This is why we started speaking about **Frontiers**

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

Why Colliders?

No single experiment can explore all directions at once.

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

Why Colliders?

No single experiment can explore all directions at once.

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

But, high energy colliders have **guaranteed outcome:**

Accurate measurements of great variety of observables.

Under precisely known experimental conditions.

+

Accurate predictions within the Standard Model of Particle Physics.

Directly based on microscopic physics laws, principles and techniques.

Why Colliders?

No single experiment can explore all directions at once.

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

But, high energy colliders have **guaranteed outcome:**

Accurate measurements of great variety of observables.

Under precisely known experimental conditions.

+

Accurate predictions within the Standard Model of Particle Physics.

Directly based on microscopic physics laws, principles and techniques.

=

1) Complete and conclusive **exploration** of the Energy Frontier

2) Sharp answers to well-posed **Beyond the SM questions**

Why Colliders?

No single experiment can explore all directions at once.

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

But, high energy colliders have **guaranteed outcome:**

Accurate measurements of great variety of observables.

Under precisely known experimental conditions.

+

Accurate predictions within the Standard Model of Particle Physics.

Directly based on microscopic physics laws, principles and techniques.

=

1) Complete and conclusive **exploration** of the Energy Frontier

2) Sharp answers to well-posed **Beyond the SM questions**

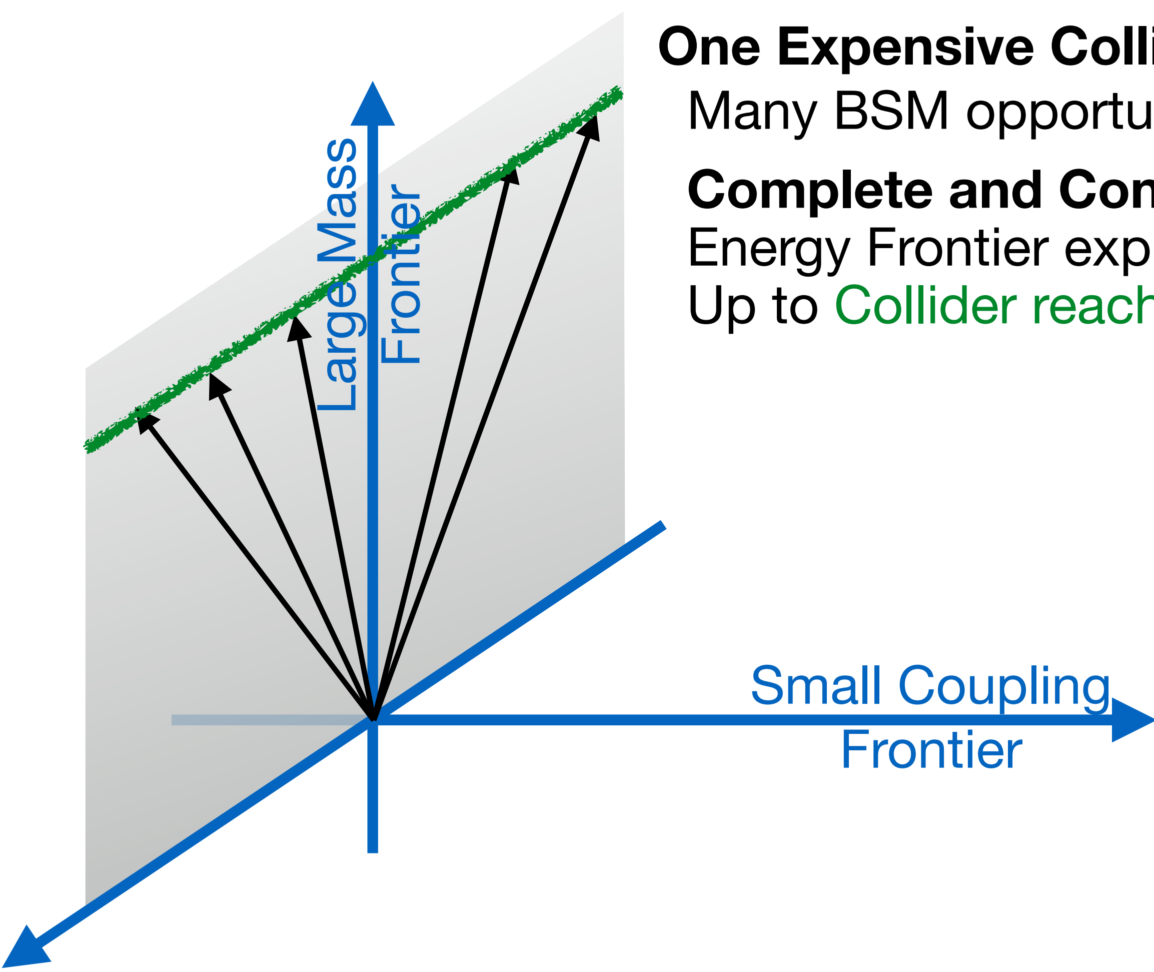
Only one drawback: they are **Expensive**.

Why Colliders?

Expensive? Yes, no doubt, but …

One Expensive Collider
Many BSM opportunities

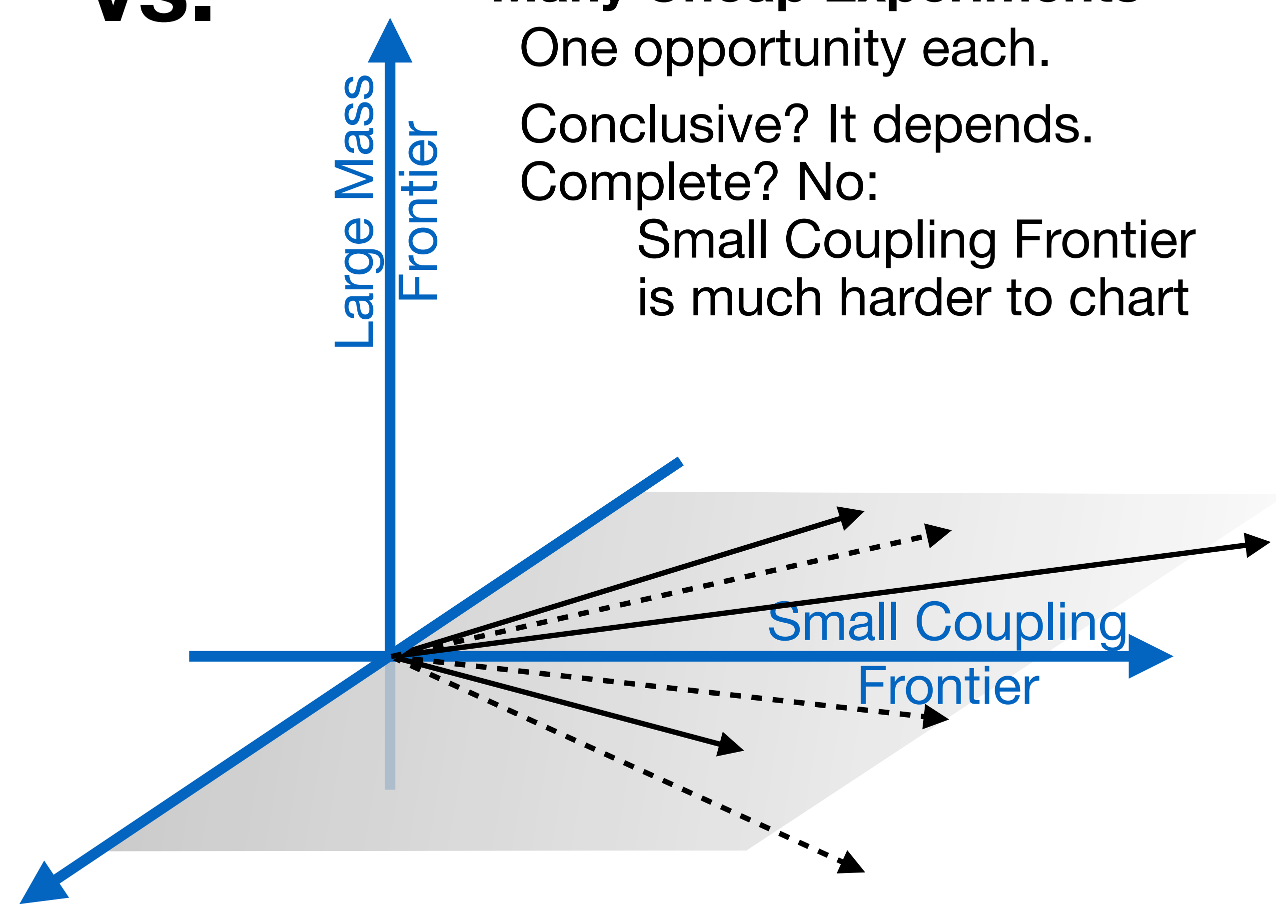
Complete and Conclusive
Energy Frontier exploration.
Up to Collider reach



vs.

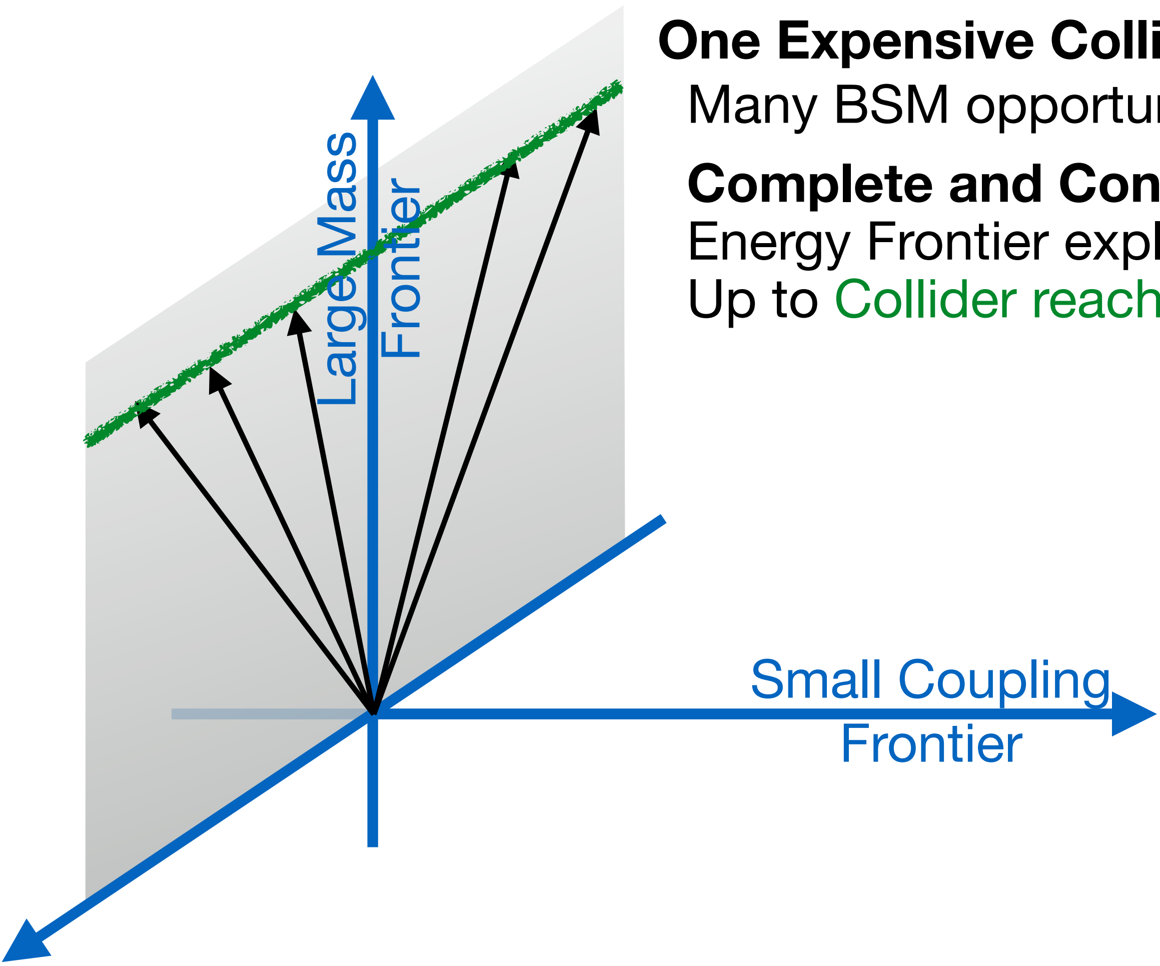
Many Cheap Experiments
One opportunity each.

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



Why Colliders?

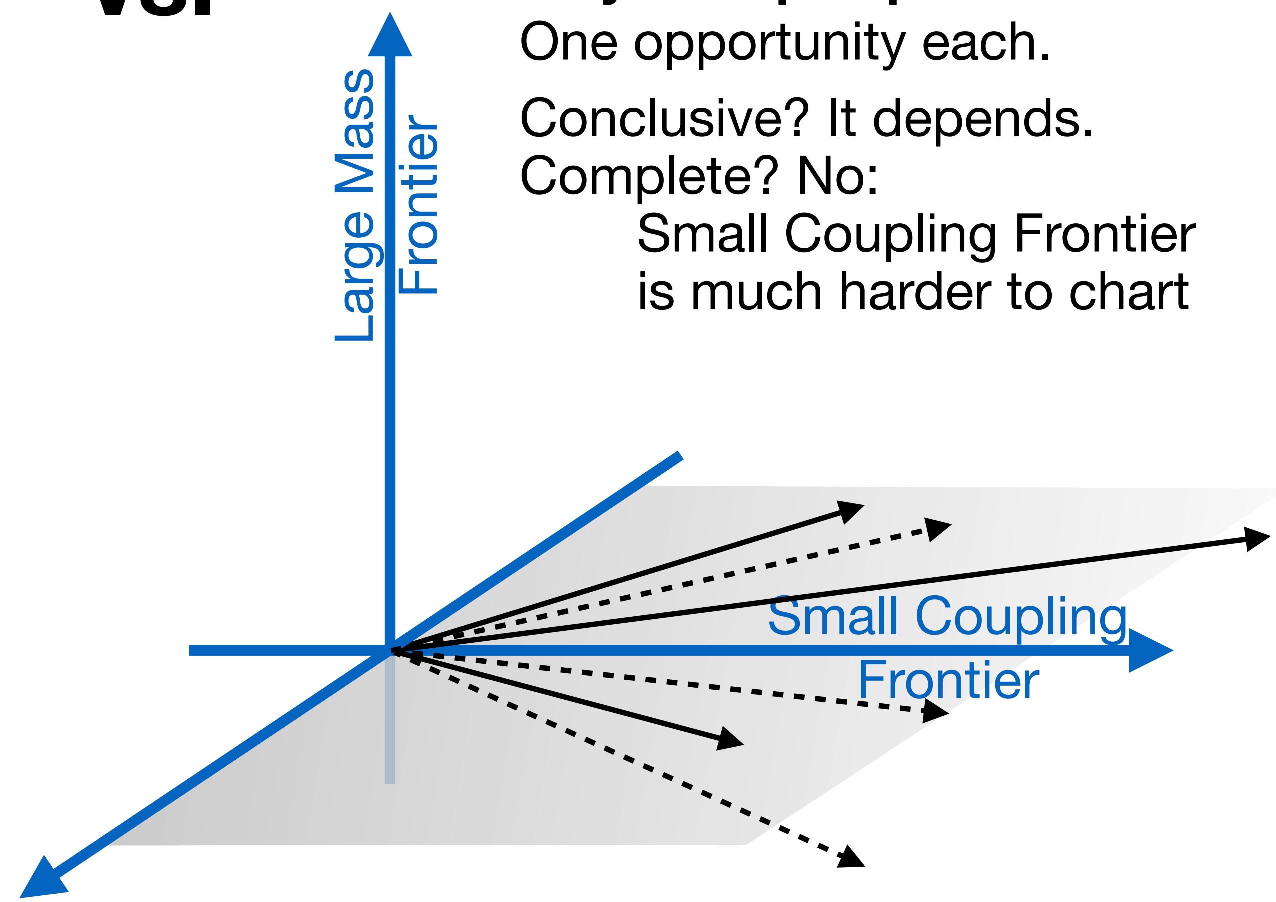
Expensive? Yes, no doubt, but …



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

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:

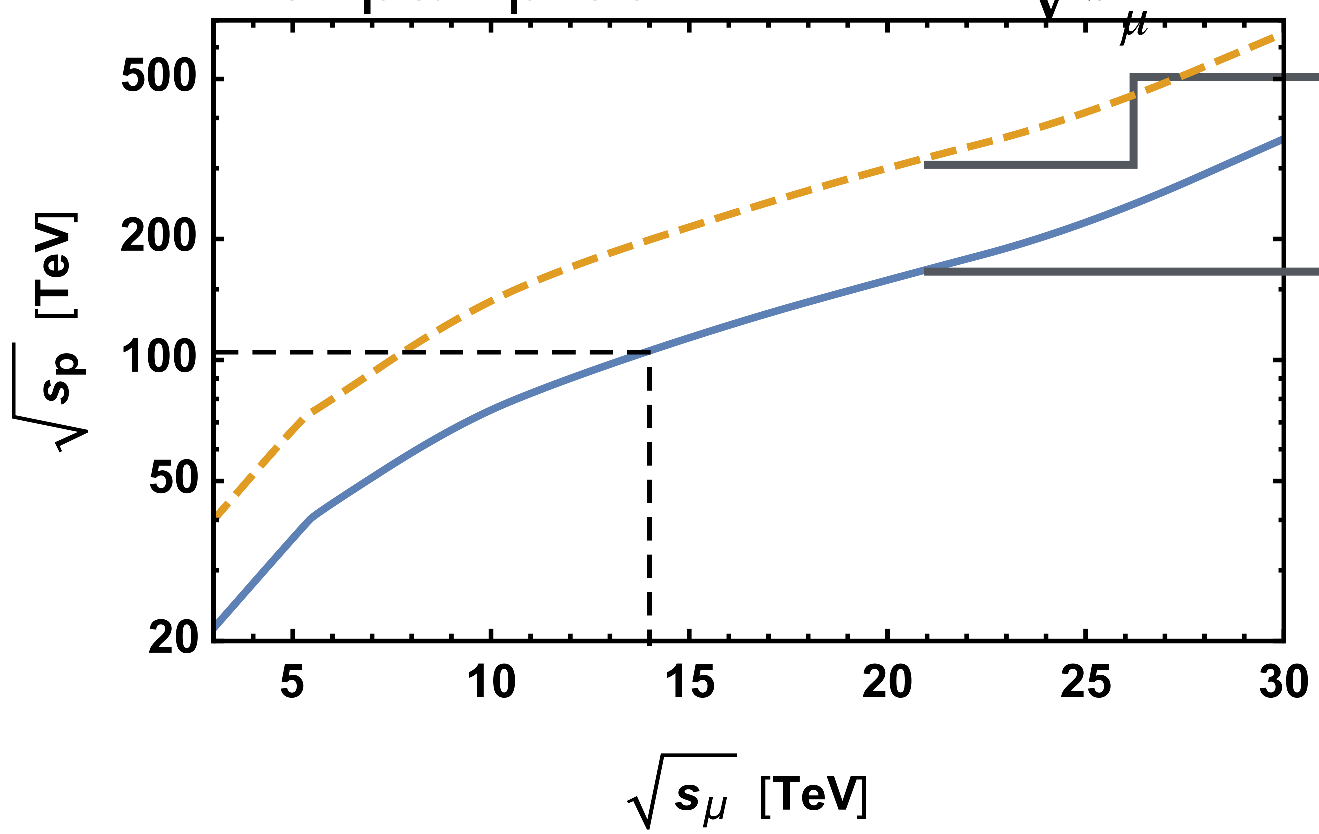
All the energy is stored in the colliding partons
No energy “waste” due to parton distribution functions
High-energy physics probed with much smaller collider energy

Why Muons?

Leptons are the ideal probes of short-distance physics:

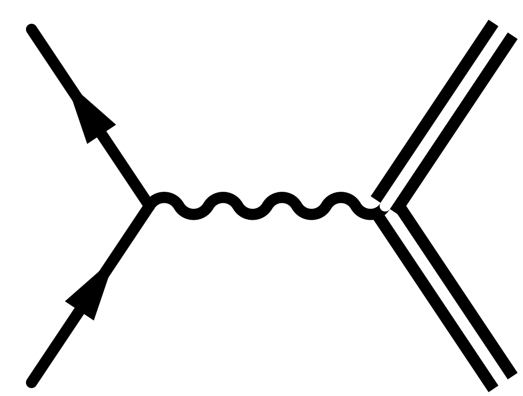
All the energy is stored in the colliding partons
No energy "waste" due to parton distribution functions
High-energy physics probed with much smaller collider energy

pp $\sqrt{s}$ at which $\sigma_{pp} = \sigma_{\mu\mu}$
for pair prod. with $M \sim \sqrt{s_\mu}$



Estimate for EWK-only charged particles

Estimate for EWK+QCD-charged particles



Why Muons?

Leptons are the ideal probes of short-distance physics:

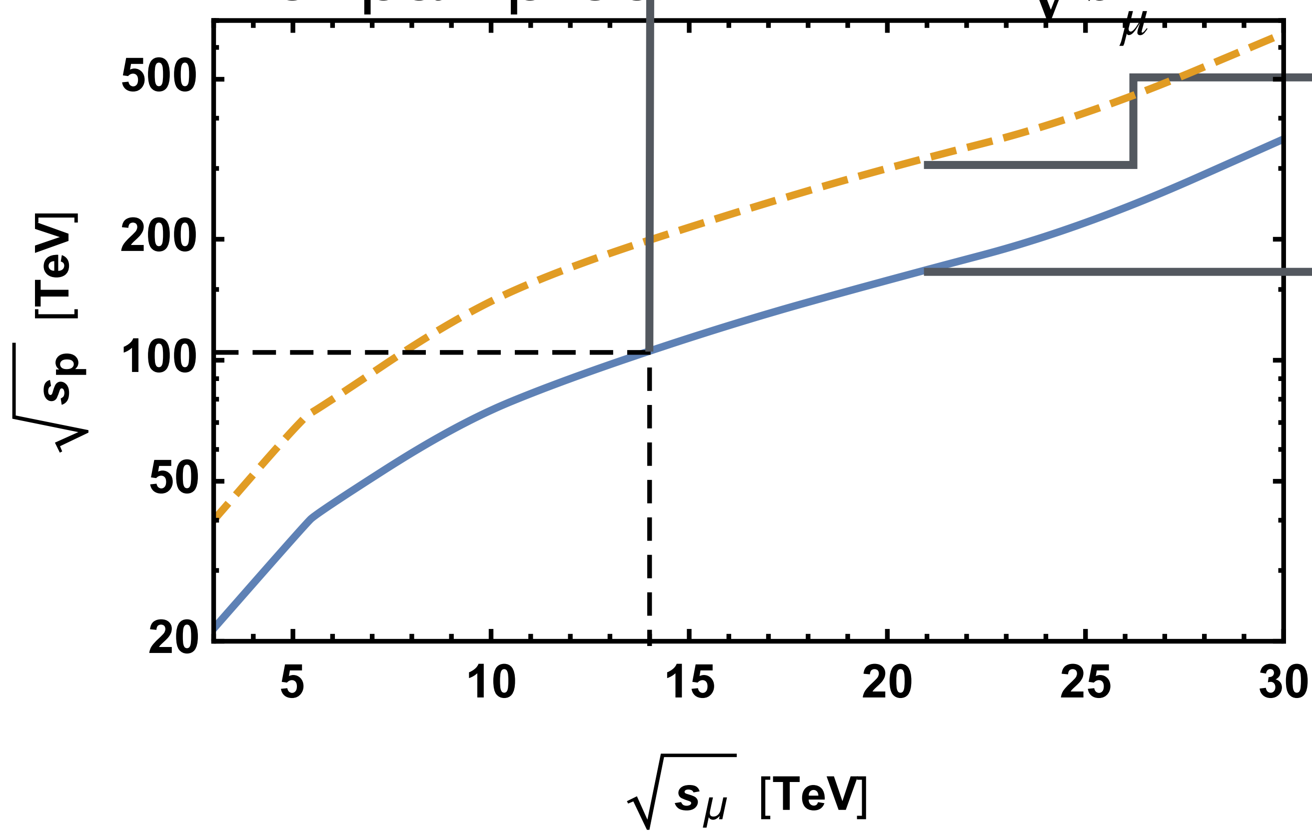
All the energy is stored in the colliding partons

No energy "waste" due to parton distribution functions

High-energy physics probed with much smaller collider energy

pp $\sqrt{s}$ at which $\sigma_{pp} = \sigma_{\mu\mu}$

for pair prod. with $M \sim \sqrt{s_\mu}$

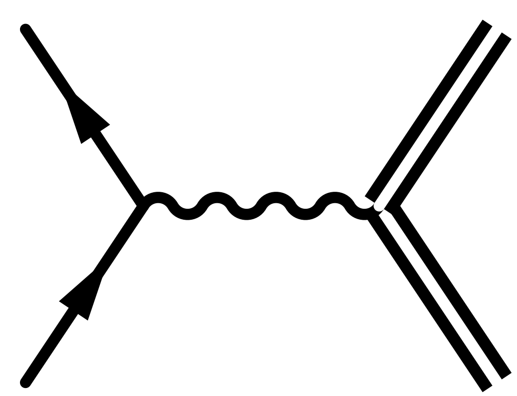


Reference Point:

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

[cannot accelerate them in rings above few 100 GeV]

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

[cannot accelerate them in rings above few 100 GeV]

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;

Why Muons?

Leptons … sics:

All the e…
No ene…
High-er…

Electro…

…GeV]

International
MUON Collider
Collaboration

muoncollider.web.cern.ch

- 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;

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
[cannot accelerate them in rings above few 100 GeV]

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 $E_{\text{CM}} = 3, 10, 14$ and the more speculative $E_{\text{CM}} = 30$ TeV, with reference integrated luminosities $\mathcal{L} = (E_{\text{CM}}/10\ \text{TeV})^2 \times 10\,\text{ab}^{-1}$ [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?

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?
- …

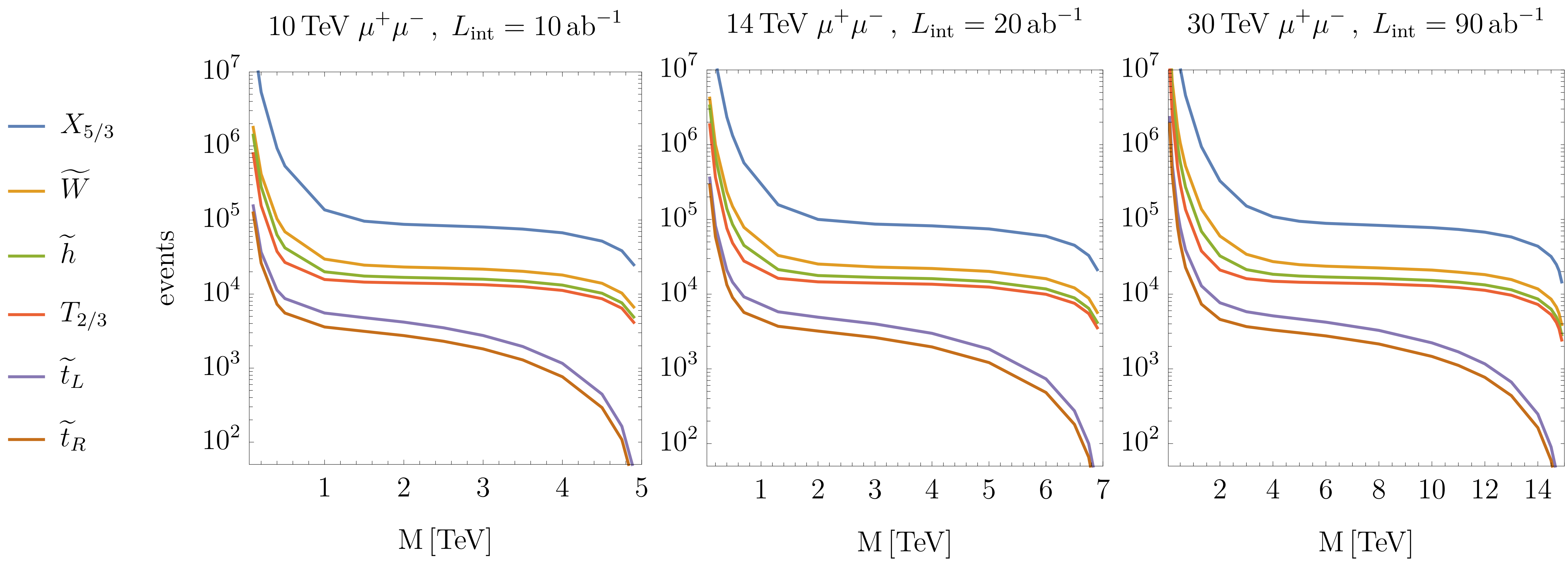
Specific BSM Questions

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 pair-produced particles up to kinematical threshold



The case for direct searches

EW pair-produced particles up to kinematical threshold

Striking for 10+TeV

“Postponed Naturalness” Probes

Note that scale here is logarithmic, but tuning is quadratic!

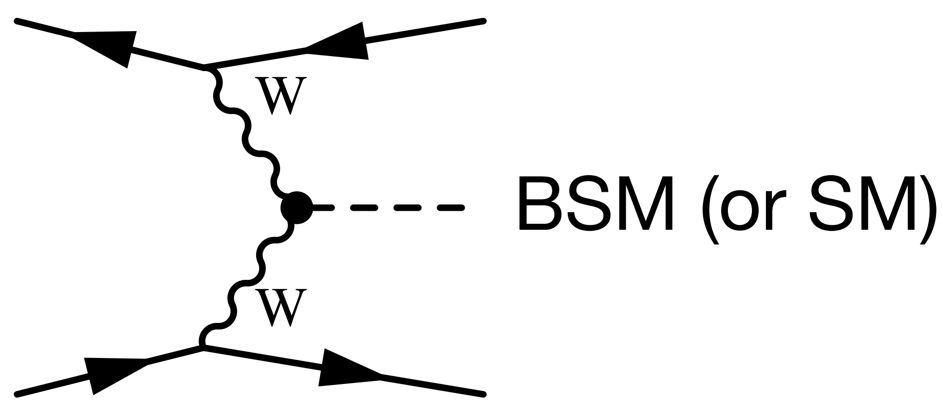
The case for direct searches

EW pair-produced particles up to kinematical threshold

Striking for 10+TeV

Great reach on “Higgs-Portal-Coupled” BSM

Thanks to huge **VBF rate**



The case for direct searches

EW pair-produced particles up to kinematical threshold

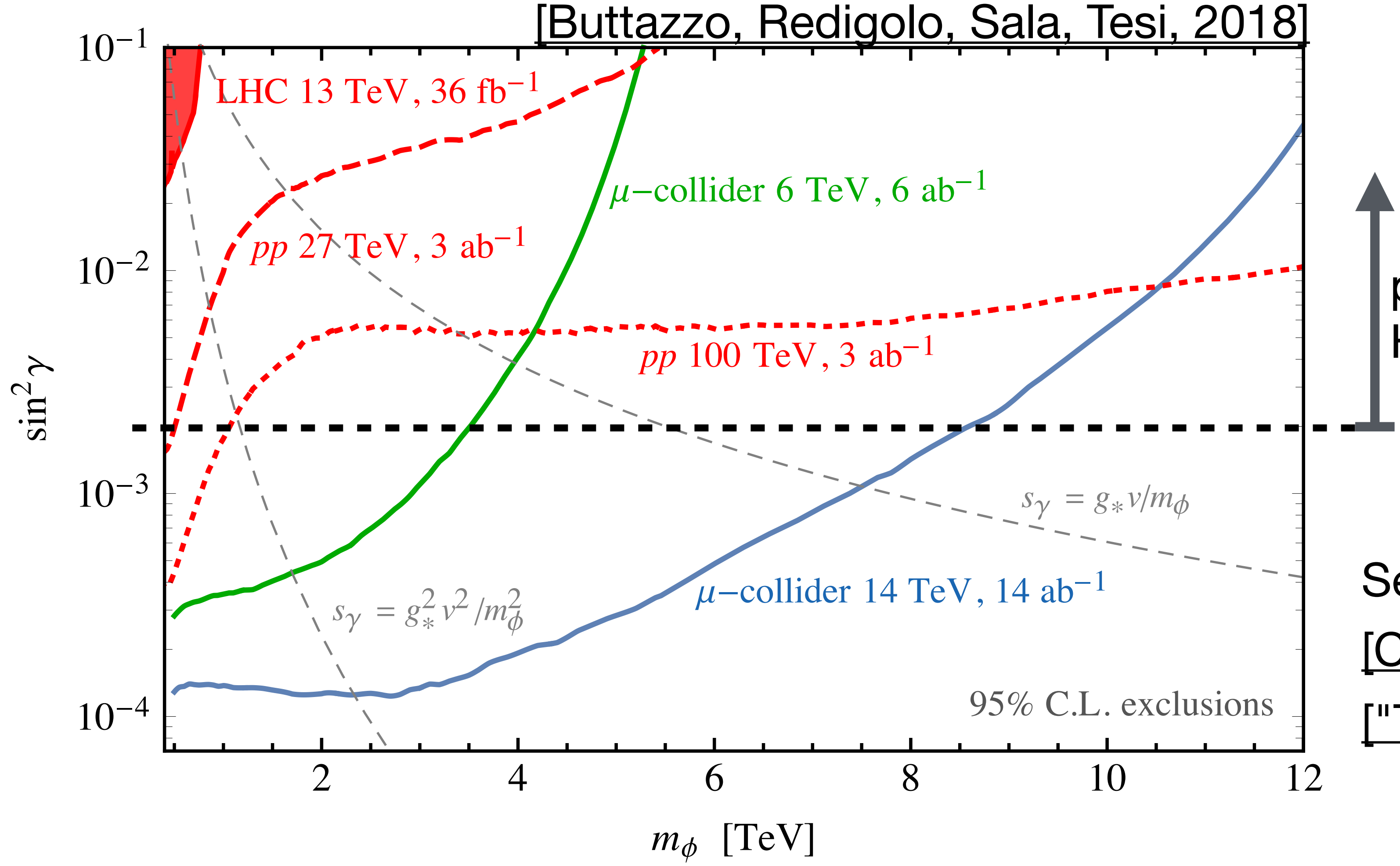
Striking for 10+TeV

Great reach on “Higgs-Portal-Coupled” BSM

Thanks to huge **VBF rate**

Scalar Singlet Simplified Model

[Buttazzo, Redigolo, Sala, Tesi, 2018]



See also [Ruhdorfer, Salvioni, Weiler, 2019]

[Costantini, De Lillo, Maltoni et. al., 2020]

["The muon's smashers guide", 2021]

The case for direct searches

EW pair-produced particles up to kinematical threshold

Striking for 10+TeV

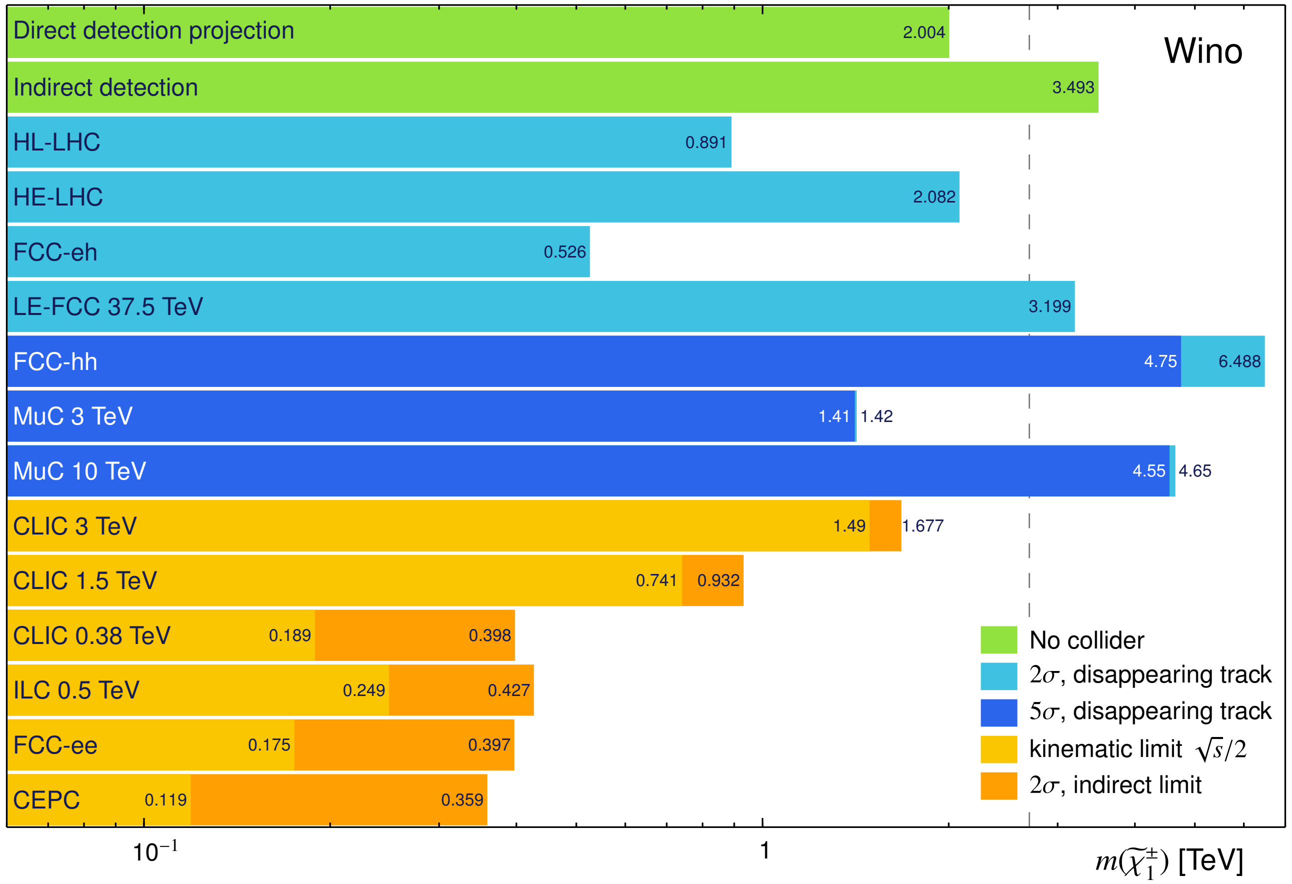
Great reach on “Higgs-Portal-Coupled” BSM

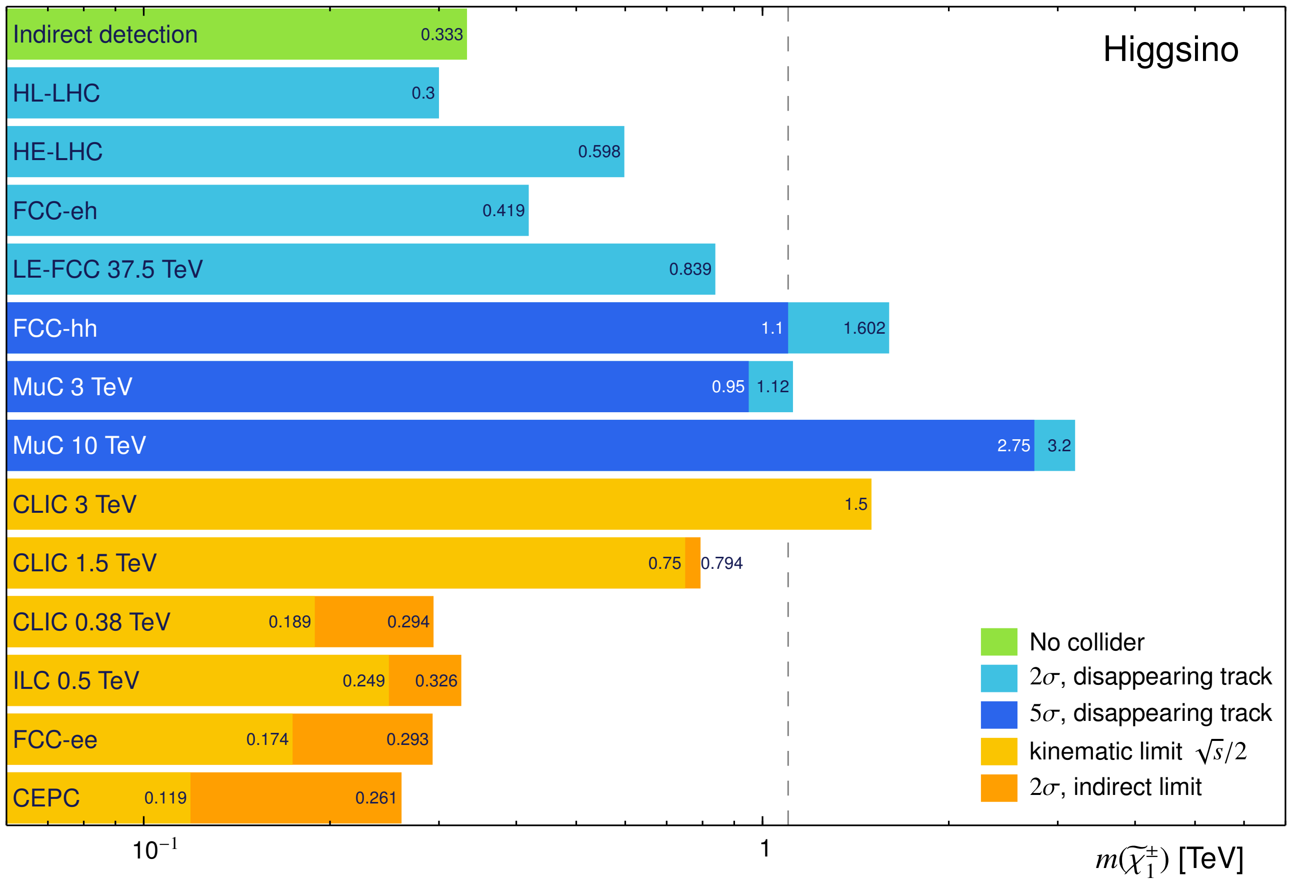
Thanks to huge **VBF rate**

Thermal Higgsino/Wino WIMP Dark Matter

[Han, Liu, Wang and Wang, 2020], [Di Luzio, Gröber, Panico, 2018]

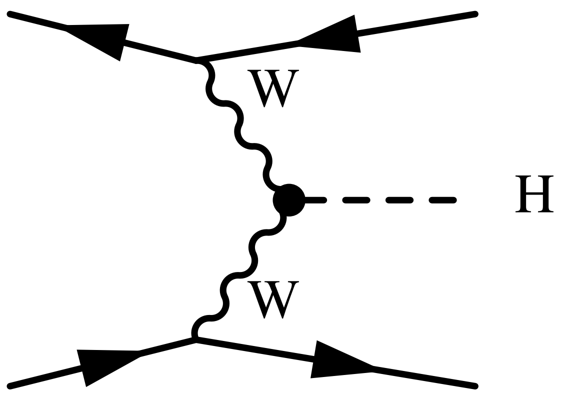
By **Disappearing Tracks:** [Capdevilla, Meloni, Simoniello, Zurita, 2021]

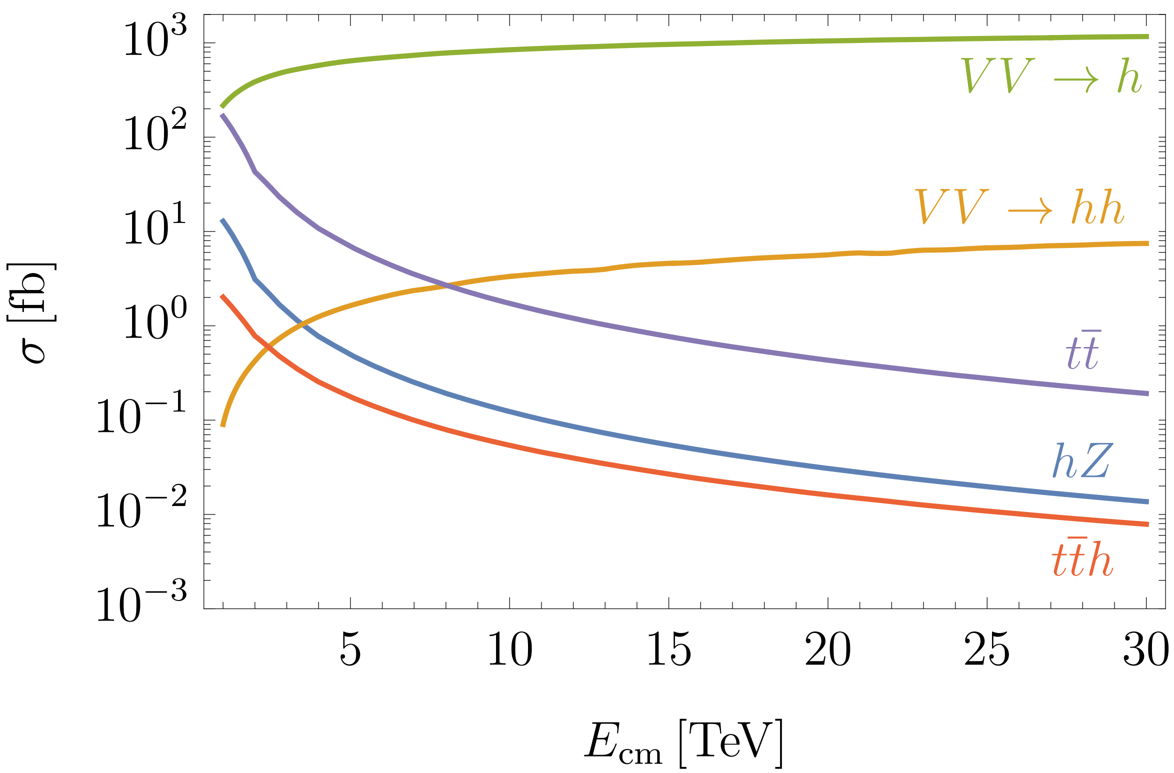


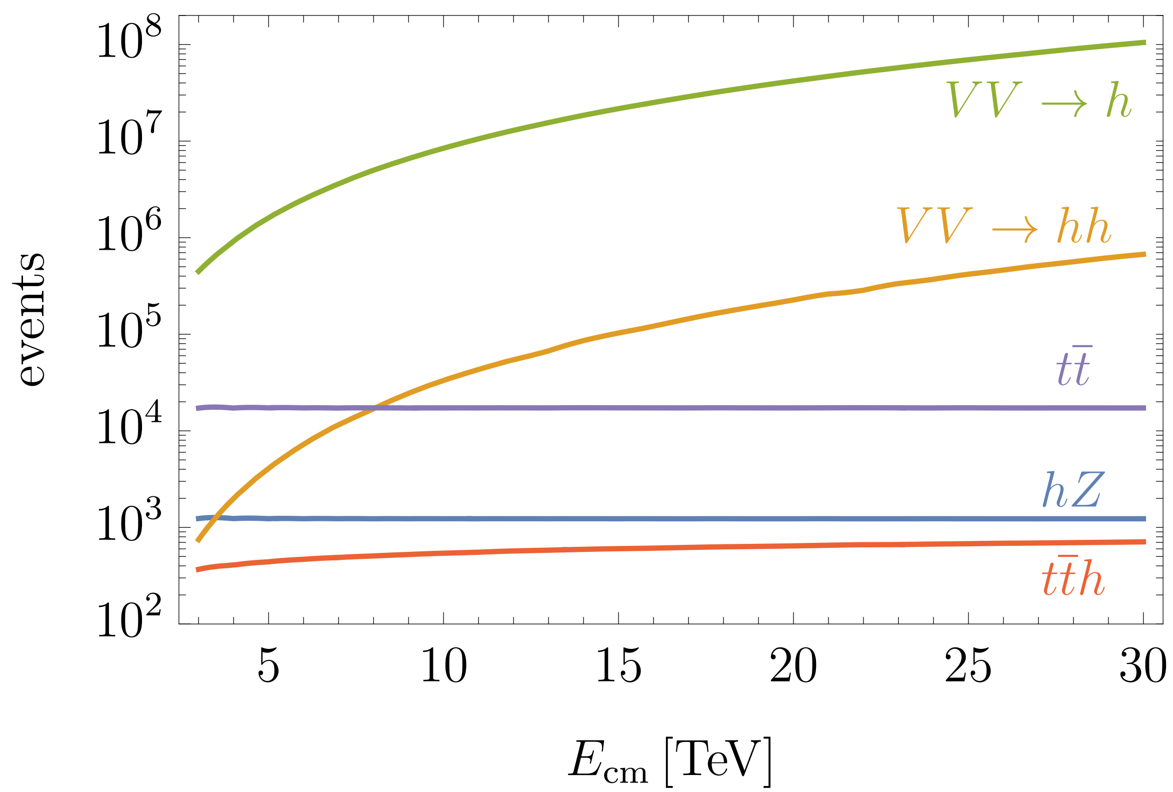


High rate indirect probes

Large single-Higgs VBF rate







High rate indirect probes

Large single-Higgs VBF rate

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

[Han, Liu, Low and Wang, 2020], ["The muon's smashers guide", 2021]

Fit Result [%]

	10 TeV Muon Collider	with HL-LHC	with HL-LHC + 250 GeV e^+e^-
κ_W	0.06	0.06	0.06
κ_Z	0.23	0.22	0.10
κ_g	0.15	0.15	0.15
κ_γ	0.64	0.57	0.57
$\kappa_{Z\gamma}$	1.0	1.0	0.97
κ_c	0.89	0.89	0.79
κ_t	6.0	2.8	2.8
κ_b	0.16	0.16	0.15
κ_μ	2.0	1.8	1.8
κ_τ	0.31	0.30	0.27

["The muon's smashers guide", 2021]

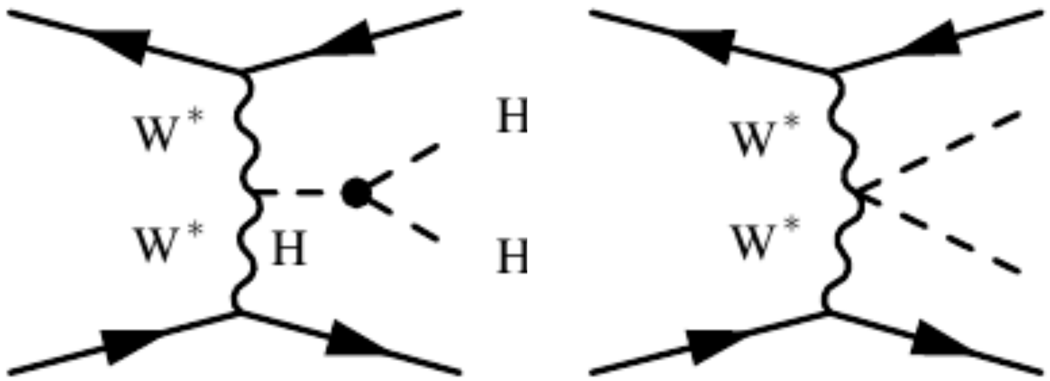
High rate indirect probes

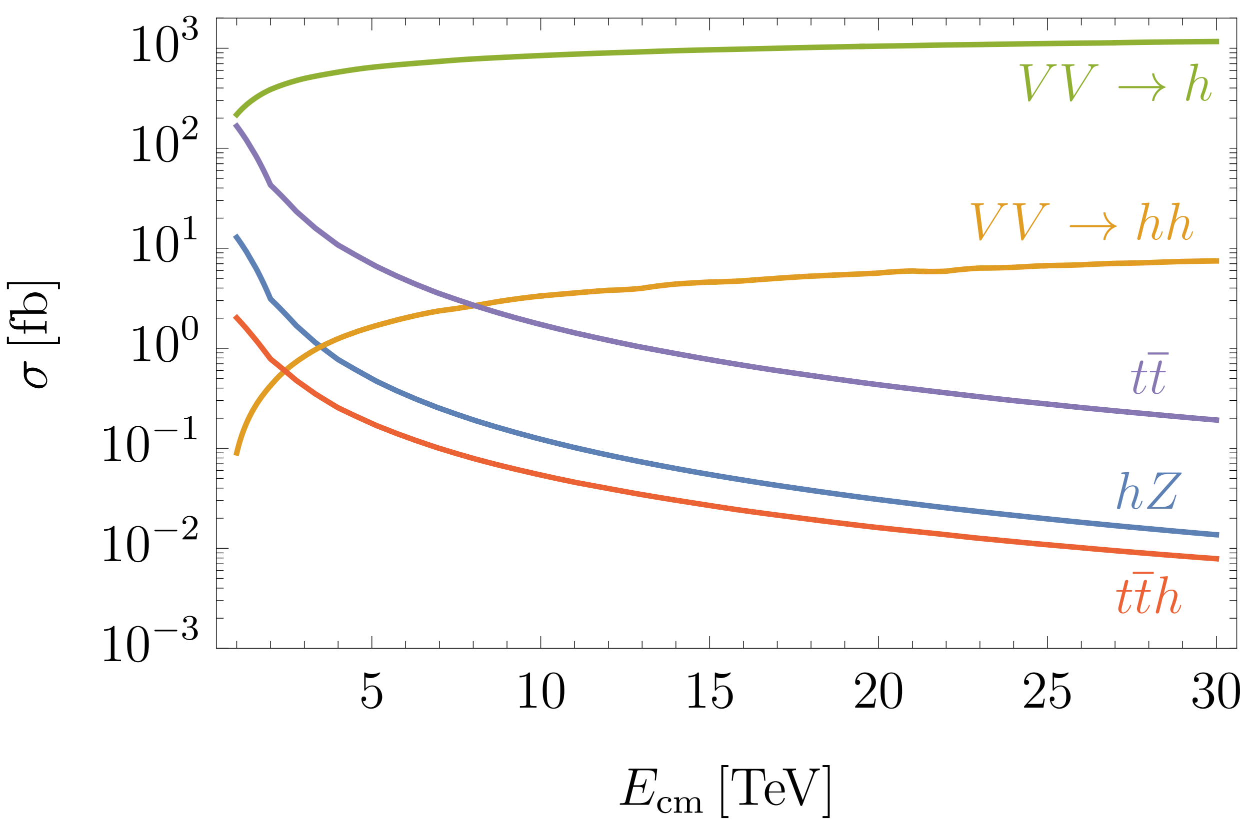
Large single-Higgs VBF rate

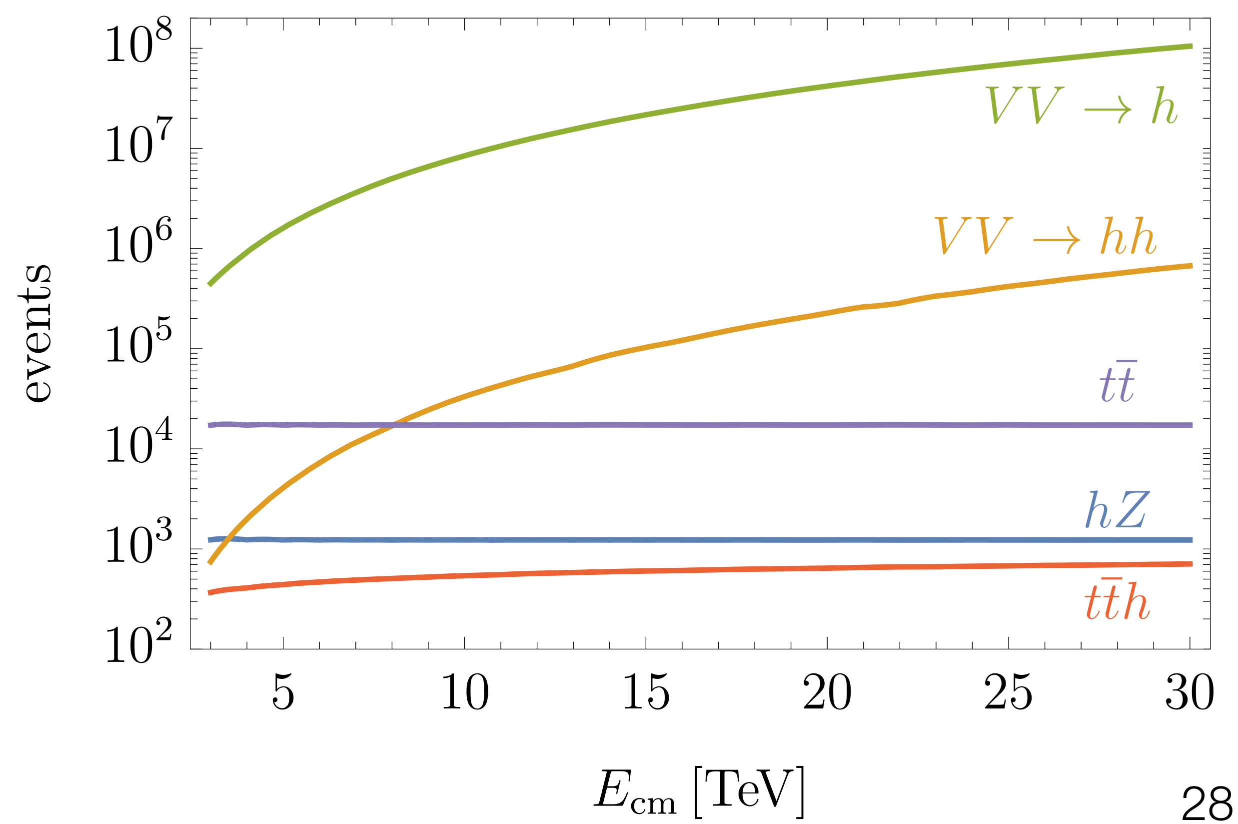
Precision on Higgs couplings driven by systematics. **Could be 1‰**

[Han, Liu, Low and Wang, 2020], ["The muon's smashers guide", 2021]

Large double-Higgs VBF rate







High rate indirect probes

Large single-Higgs VBF rate

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

[Han, Liu, Low and Wang, 2020], ["The muon's smashers guide", 2021]

Large double-Higgs VBF rate

[Buttazzo, Franceschini and AW, 2020], also 2008.12204, 2005.10289;]

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

[FCC reach is from 3.5 to 8.1%, depending on detector assumptions]

High rate indirect probes

Large single-Higgs VBF rate

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

[Han, Liu, Low and Wang, 2020], ["The muon's smashers guide", 2021]

Large double-Higgs VBF rate

[Buttazzo, Franceschini and AW, 2020], also 2008.12204, 2005.10289;]

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

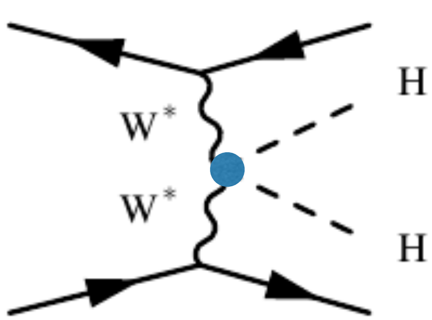
[FCC reach is from 3.5 to 8.1%, depending on detector assumptions]

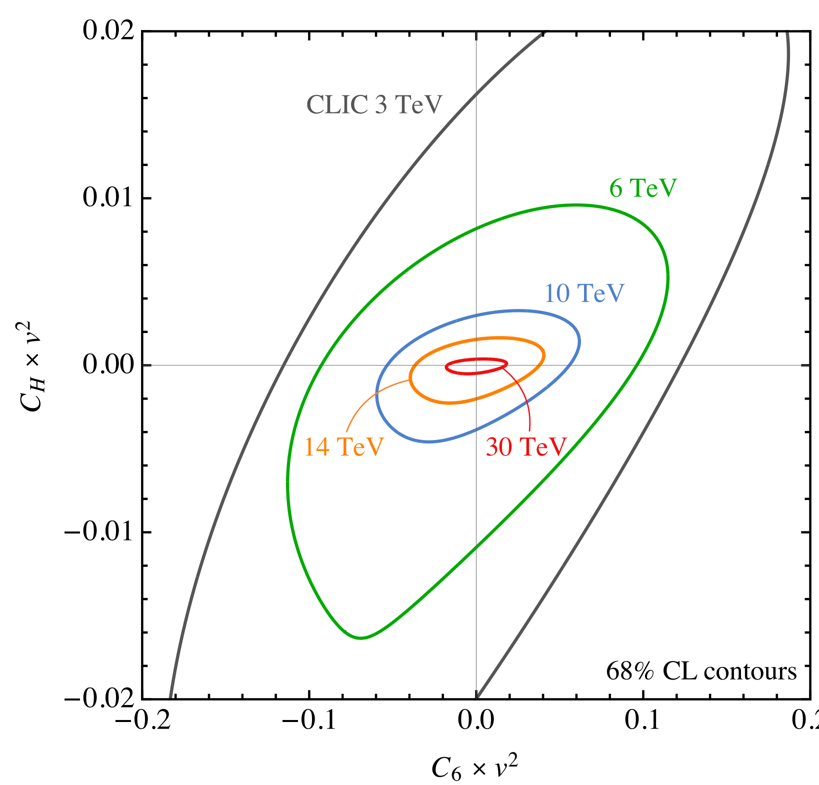
Composite Higgs ξ: $\boldsymbol{\xi =_{1\sigma}}$ **(2.5‰, 1.2‰, 0.3‰) for E = (10, 14, 30) TeV**

[FCC-all reach, from Higgs couplings, is 1.8‰]

From **no-so-accurate measurements of high mass Higgs pair**

Trick is that ξ is a d=6 operators, O_H, and its effect grows with WW>HH energy





High energy probes

[Buttazzo, Franceschini, AW, 2020]

As simple as this:

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

High energy probes

[Buttazzo, Franceschini, AW, 2020]

As simple as this:

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

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

High energy probes

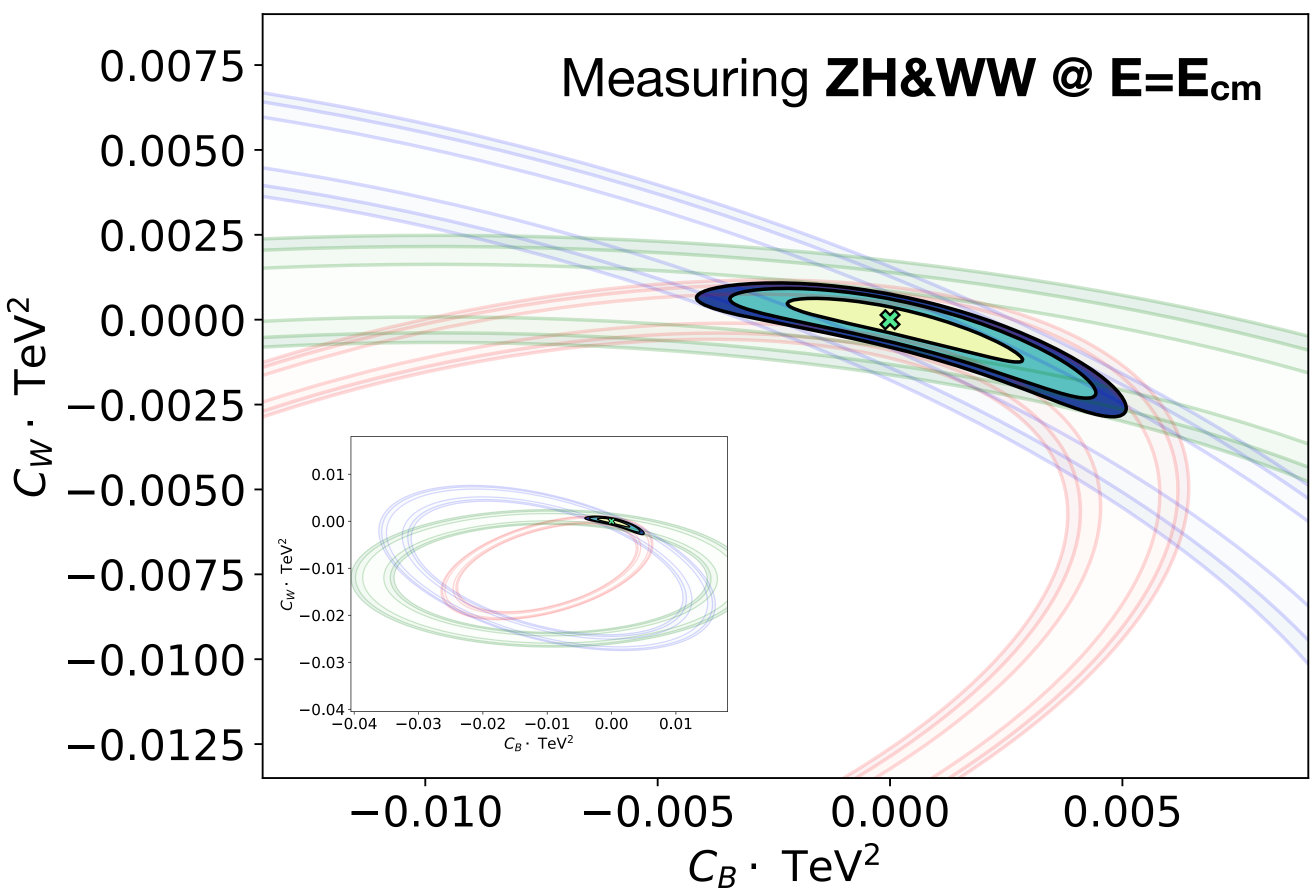
[Buttazzo, Franceschini, AW, 2020]

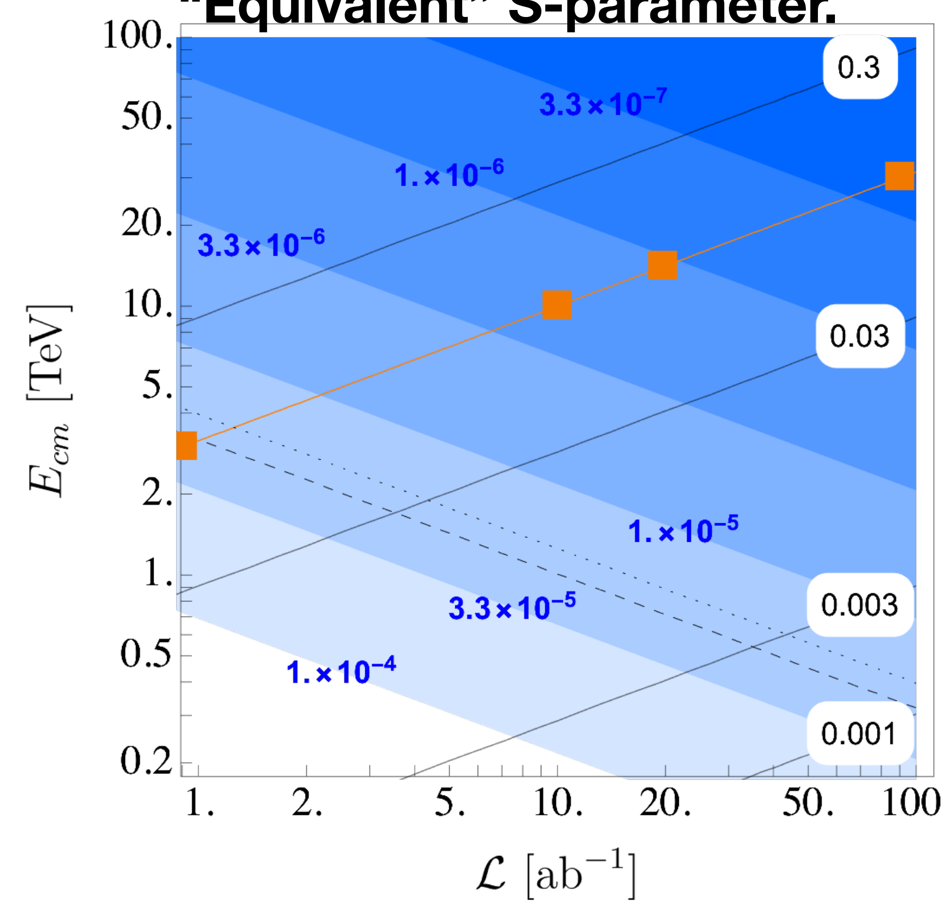
As simple as this:

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

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

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





Today:

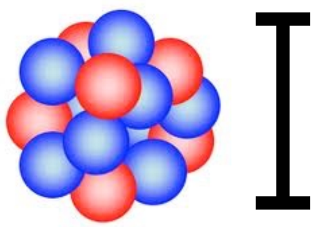
10^{-3}

MUC14

10^{-6}

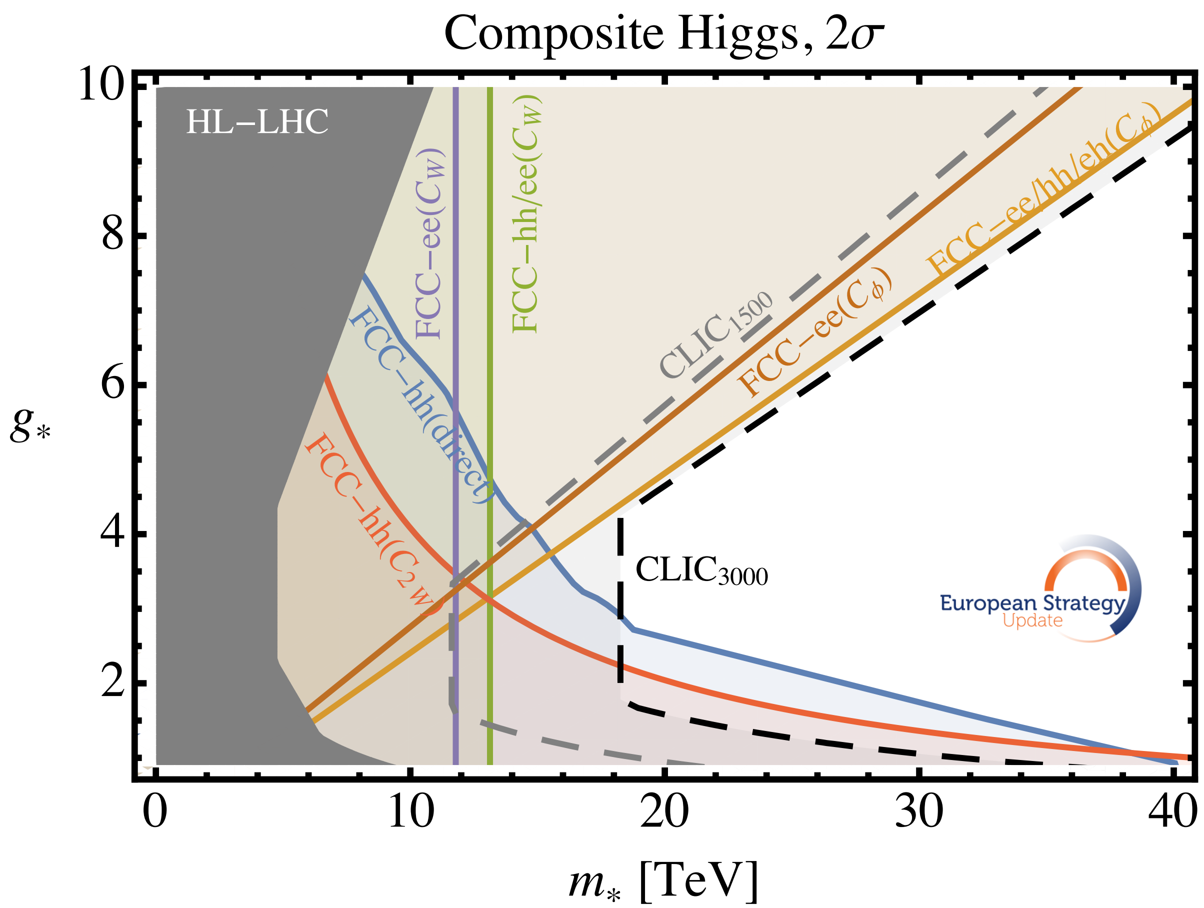
Probing Higgs compositeness

[Buttazzo, Franceschini, AW, 2020]



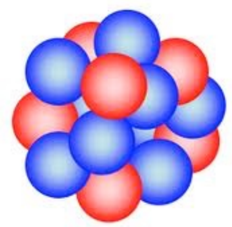
$l_H = 1/m_*$

"Standard" Future Colliders



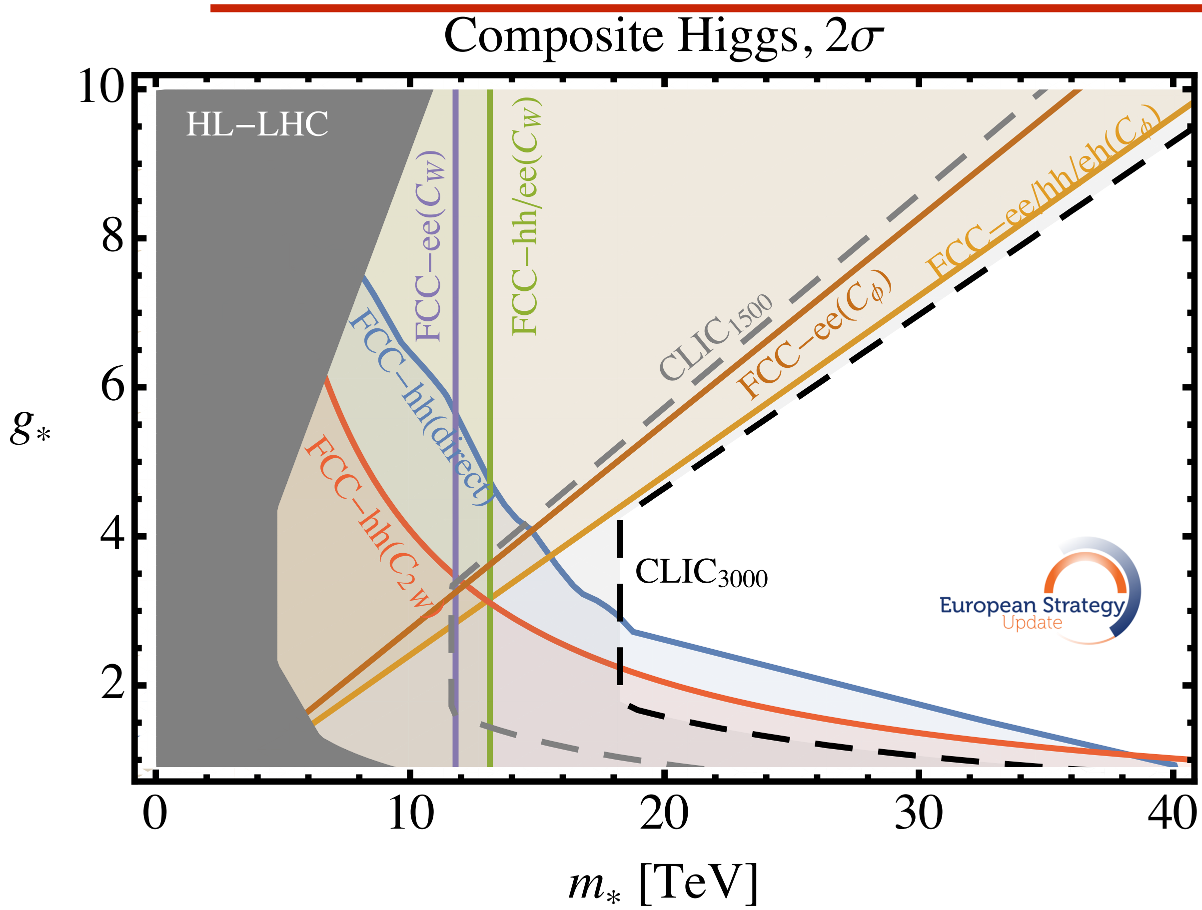
Probing Higgs compositeness

[Buttazzo, Franceschini, AW, 2020]

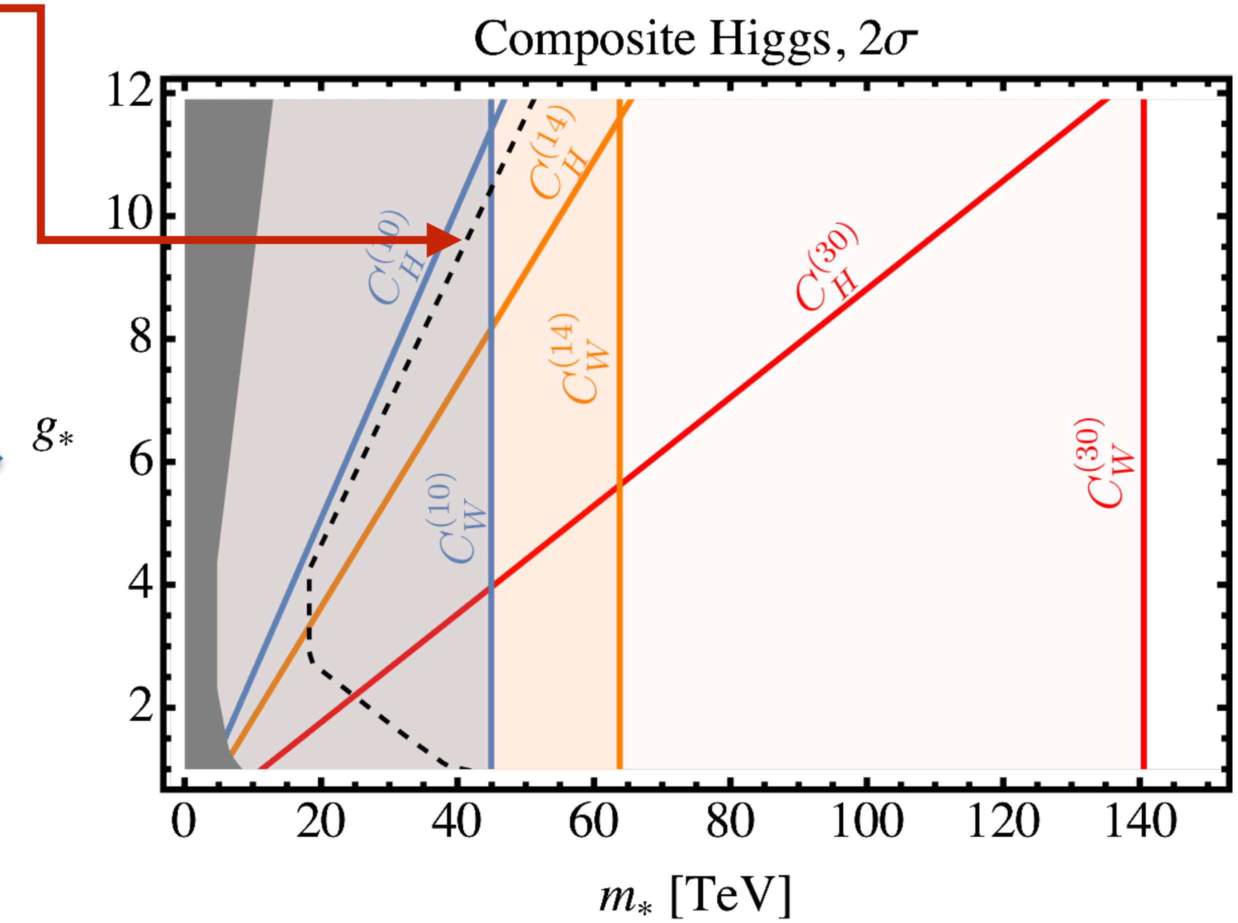


$$l_H = 1/m_*$$

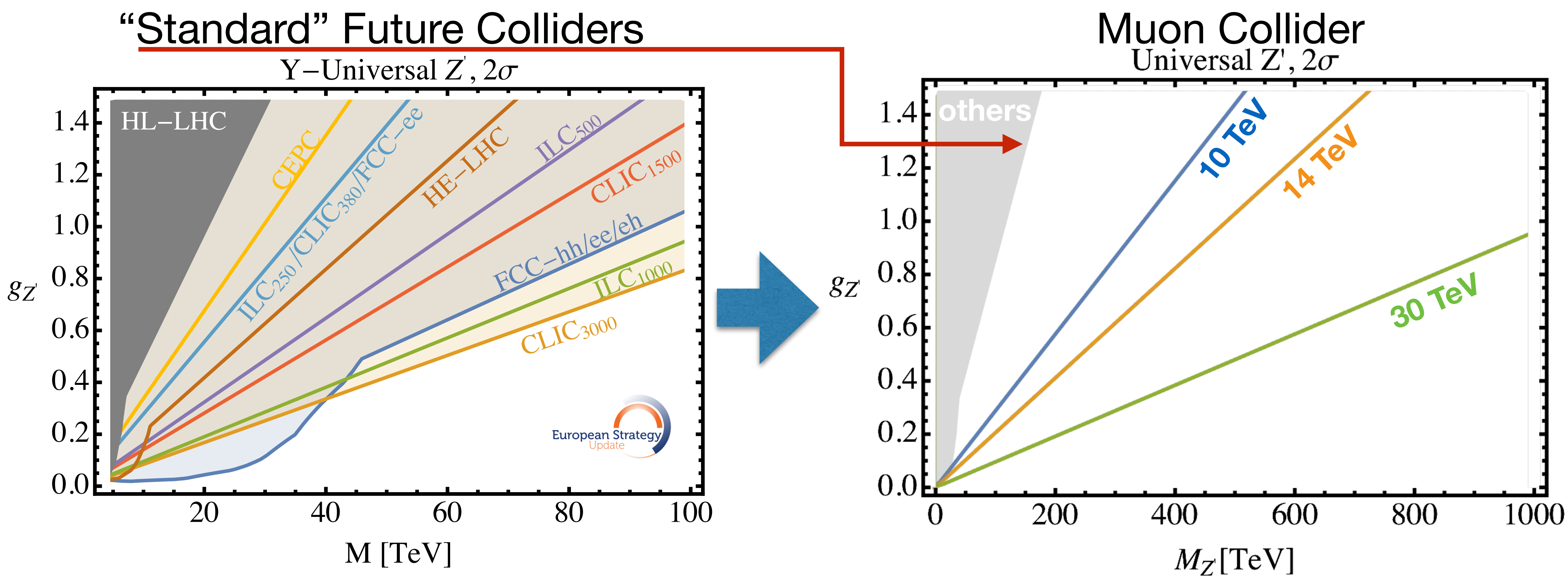
“Standard” Future Colliders



Muon Collider



Even Simpler: Minimal Z's



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

Is this potential **real?**

Remember what we expect from colliders:

Accurate measurements of great variety of observables.

Under precisely known experimental conditions.

+

Accurate predictions within the Standard Model of Particle Physics.

Directly based on microscopic physics laws, principles and techniques.

Is this potential **real?**

Remember what we expect from colliders:

Accurate measurements of great variety of observables.

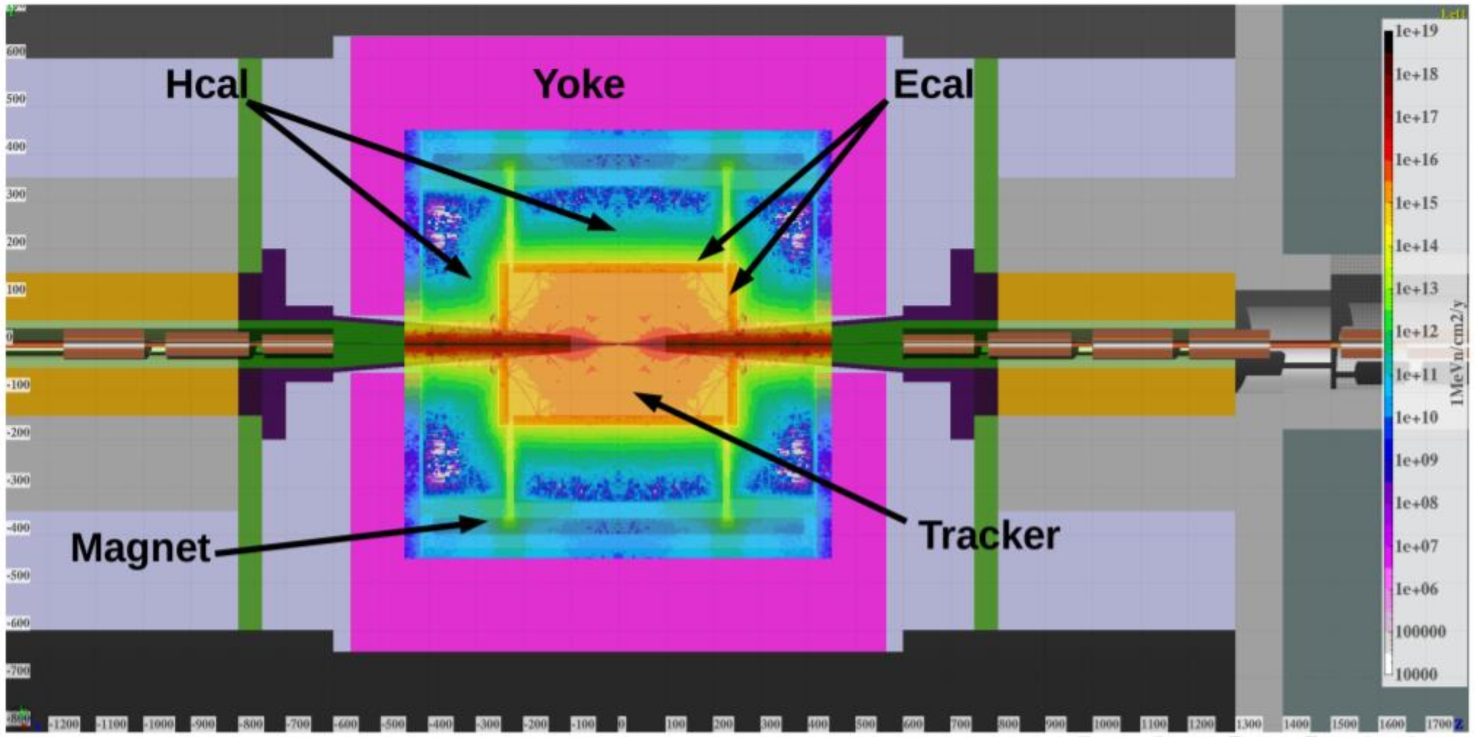
Under precisely known experimental conditions.

+

Accurate predictions within the Standard Model of Particle Physics.

Directly based on microscopic physics laws, principles and techniques.

Background from decaying muons (BIB)



FLUKA @ 1.5 TeV

New Challenge for Detector@Analysis design

For info, you can browse the slides of the last Muon Community Meeting

Is this potential **real?**

Remember what we expect from colliders:

Accurate measurements of great variety of observables.

Under precisely known experimental conditions.

+

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

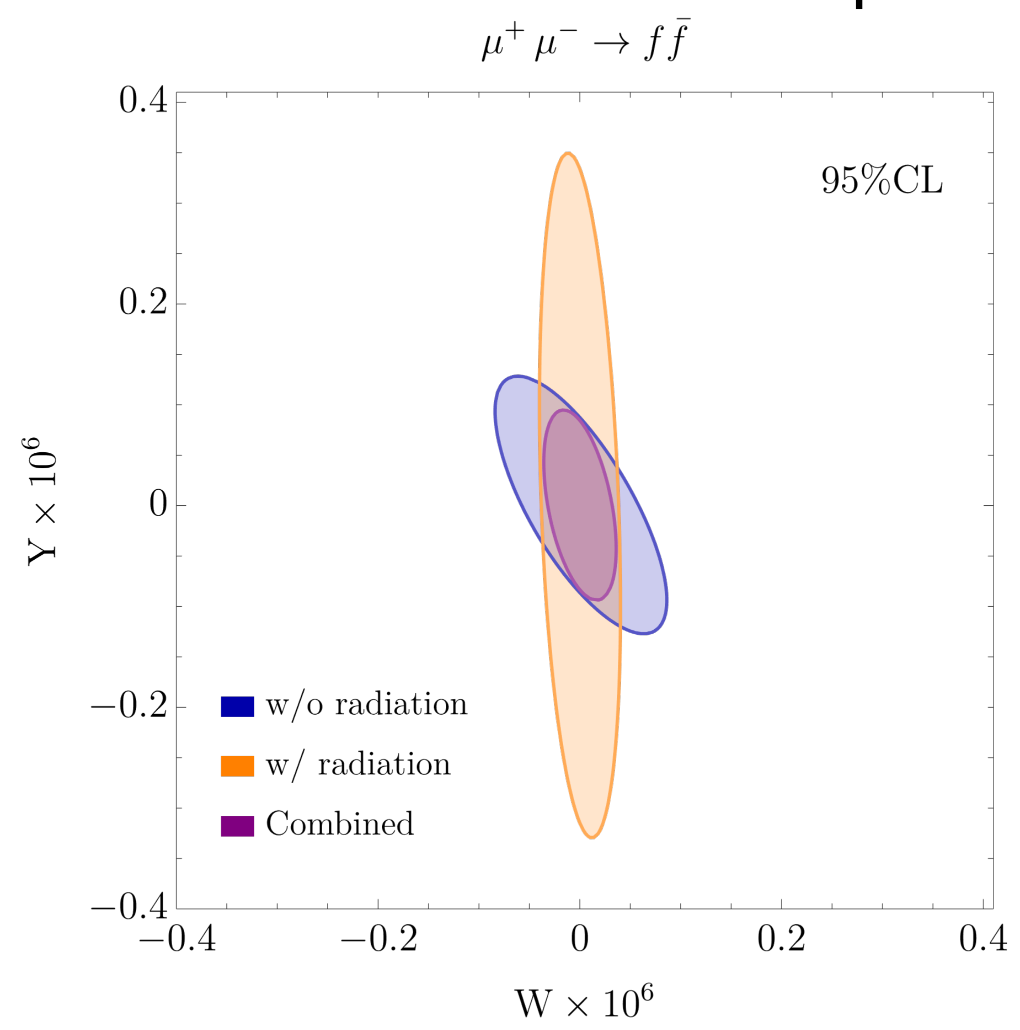
Because of the accuracy we need

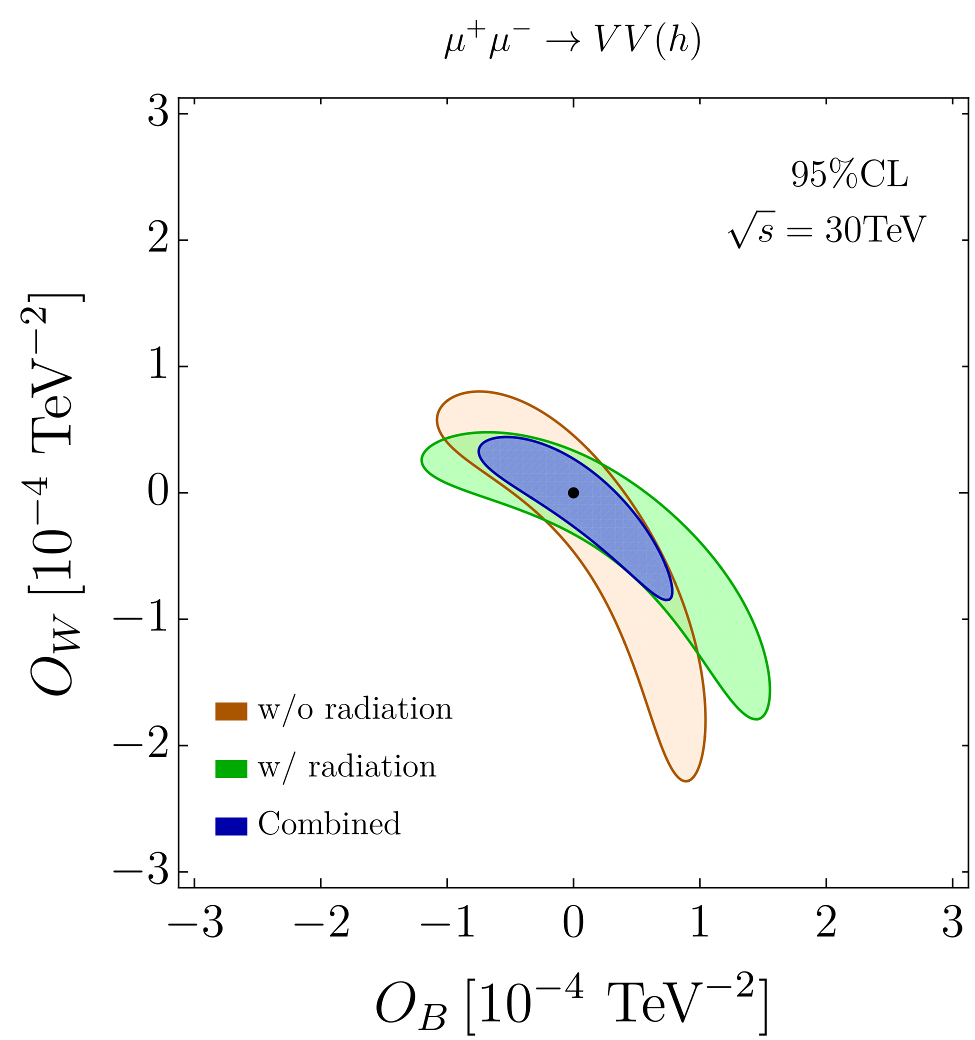
Because from radiation structure we can learn about New Physics!

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

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?**

International
UON Collider
Collaboration

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.**

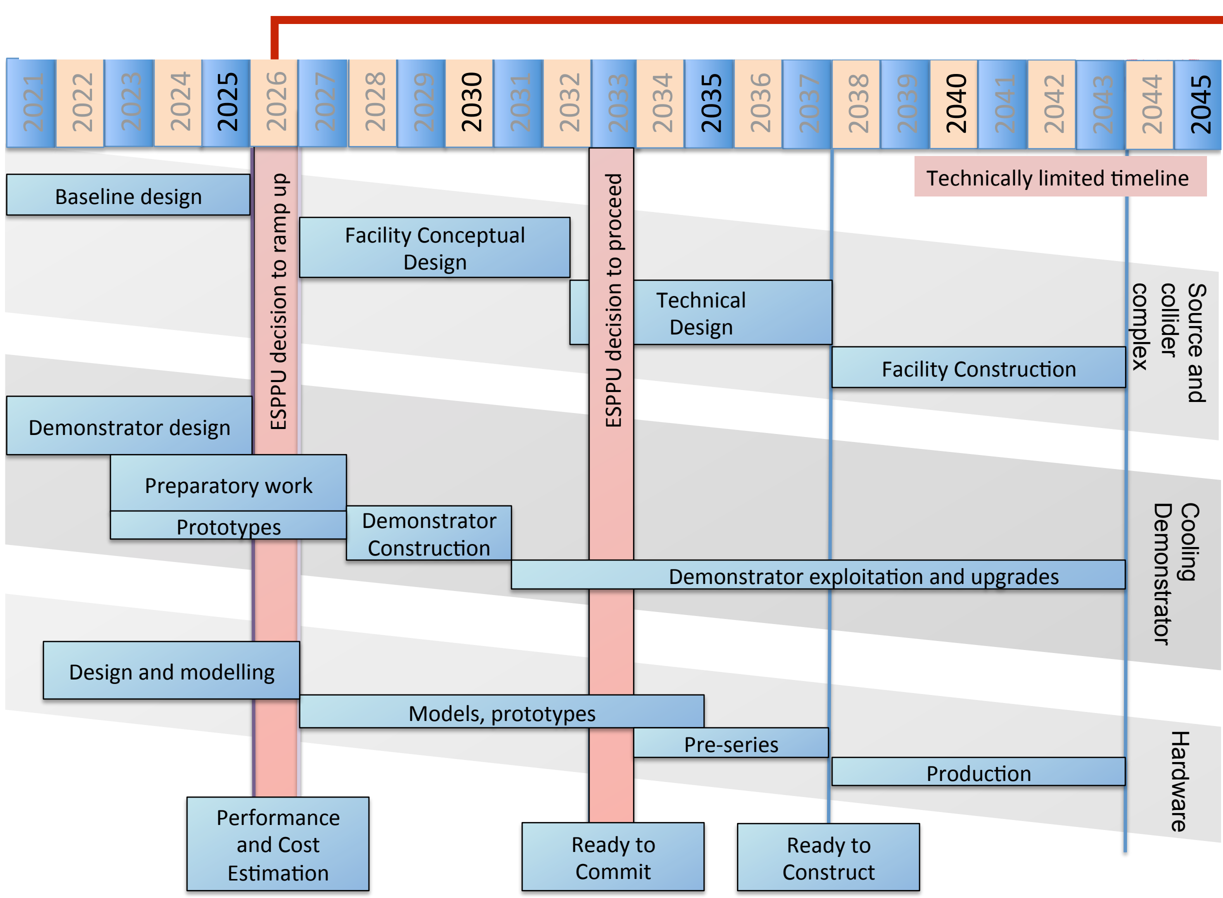
[Daniel Schulte, IMCC head. link]

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

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**.

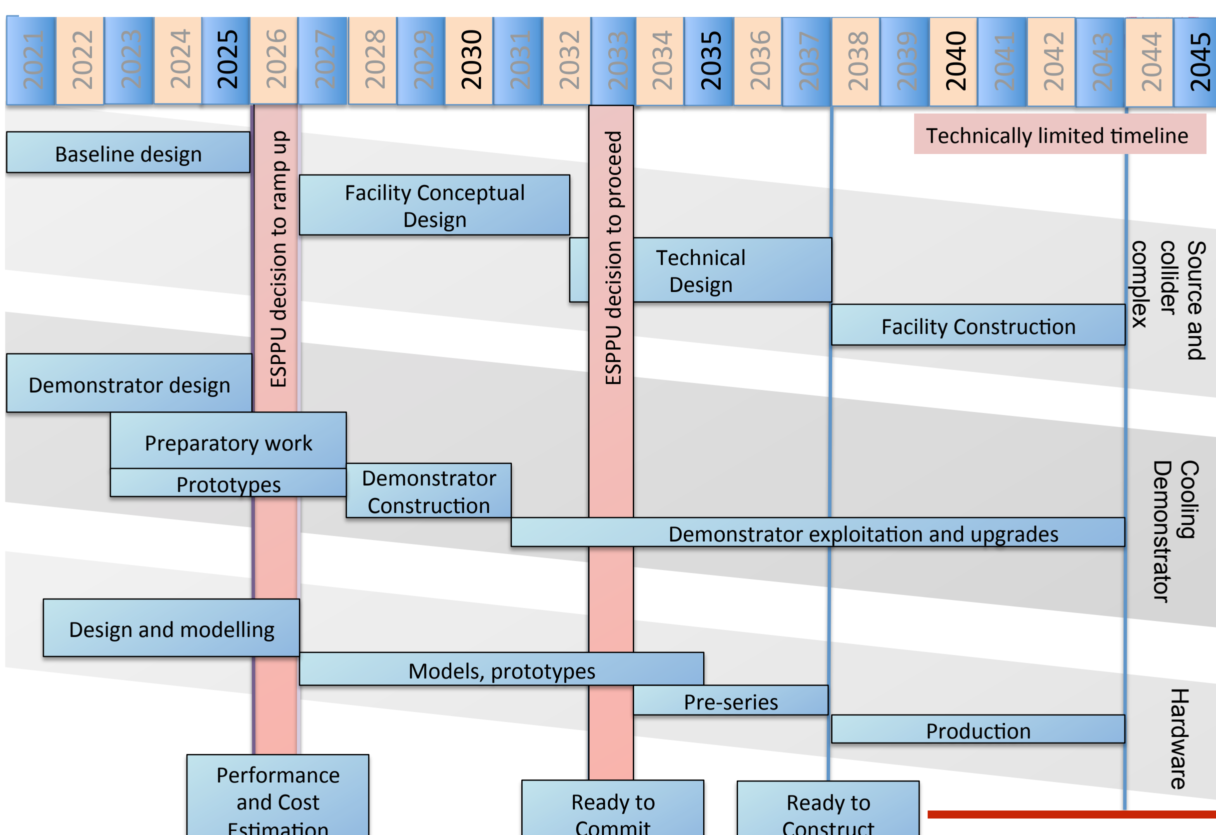
[Daniel Schulte, IMCC head. link]

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



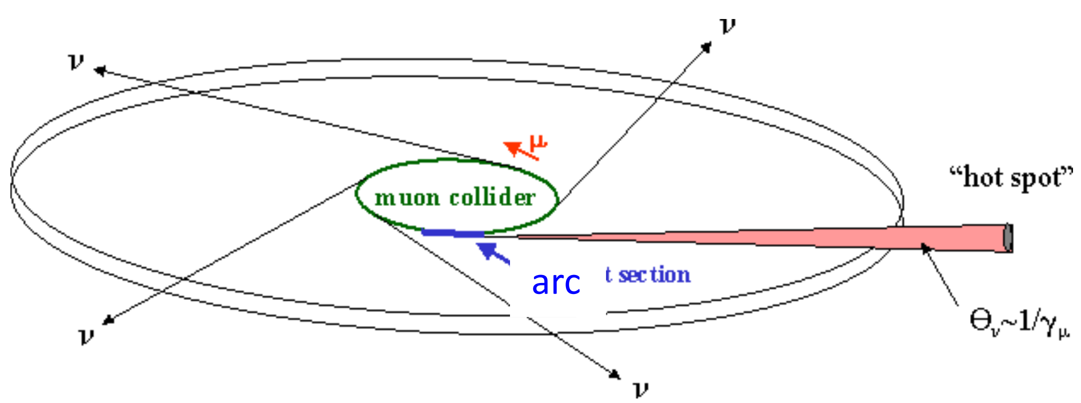
We might know the answer in few years

A first MUC, 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

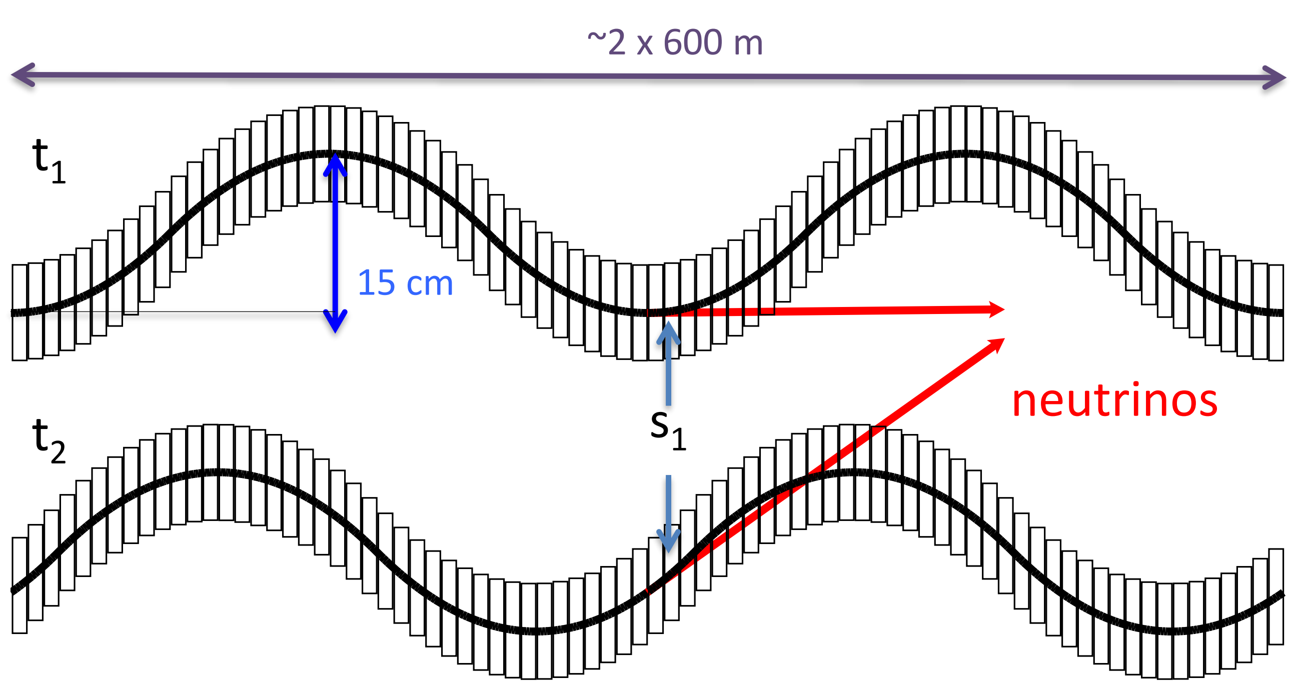


Concentrate neutrino cone from arcs can approach legal limits for 14 TeV

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

Conclusions

The muon collider is potentially a **first-class option** for the continuation of the high energy physics journey

- Could be **compact** enough (even 30 TeV in LHC-sized tunnel with FCC-hh magnets)
- **Not in competition** with other projects: **we do not know if feasible!**

Conclusions

The muon collider is potentially a **first-class option** for the continuation of the high energy physics journey

- Could be **compact** enough (even 30 TeV in LHC-sized tunnel with FCC-hh magnets)
- **Not in competition** with other projects: **we do not know if feasible!**

Its physics potential relies on three pillars

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?
...

Conclusions

The muon collider is potentially a **first-class option** for the continuation of the high energy physics journey

- Could be **compact** enough (even 30 TeV in LHC-sized tunnel with FCC-hh magnets)
- **Not in competition** with other projects: **we do not know if feasible!**

Its physics potential relies on three pillars, **plus**

- **Muon-specific opportunities** (intriguing muon-related **anomalies**)

Muon-specific opportunities

Direct probes of B-Anomalies models [2101.04956, 2103.01617, 2104.05720]

Direct/Indirect probes of g-2 anomaly [2006.16277, 2012.02769, 2101.10334, 2102.05619, 2012.03928]

Conclusions

The muon collider is potentially a **first-class option** for the continuation of the high energy physics journey

- Could be **compact** enough (even 30 TeV in LHC-sized tunnel with FCC-hh magnets)
- **Not in competition** with other projects: **we do not know if feasible!**

Its physics potential relies on three pillars, **plus**

- **Muon-specific opportunities** (intriguing muon-related **anomalies**)
- **Neutrino opportunities** (in MUC operation, or demonstration stages)

Conclusions

The muon collider is potentially a **first-class option** for the continuation of the high energy physics journey

- Could be **compact** enough (even 30 TeV in LHC-sized tunnel with FCC-hh magnets)
- **Not in competition** with other projects: **we do not know if feasible!**

Its physics potential relies on three pillars, **plus**

- **Muon-specific opportunities** (intriguing muon-related **anomalies**)
- **Neutrino opportunities** (in MUC operation, or demonstration stages)

Why working on muon colliders physics?

- It is **Important:** we must **consolidate** the potential, define **new targets**, **motivate** and **inform** Accelerator design.
- It is **Fun:** novel BSM possibilities wait to be explored, as well as novel challenges for predictions, object reconstruction, BIB mitigation, etc.

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 !