Obvious Physics at the Muon Collider

Andrea Wulzer

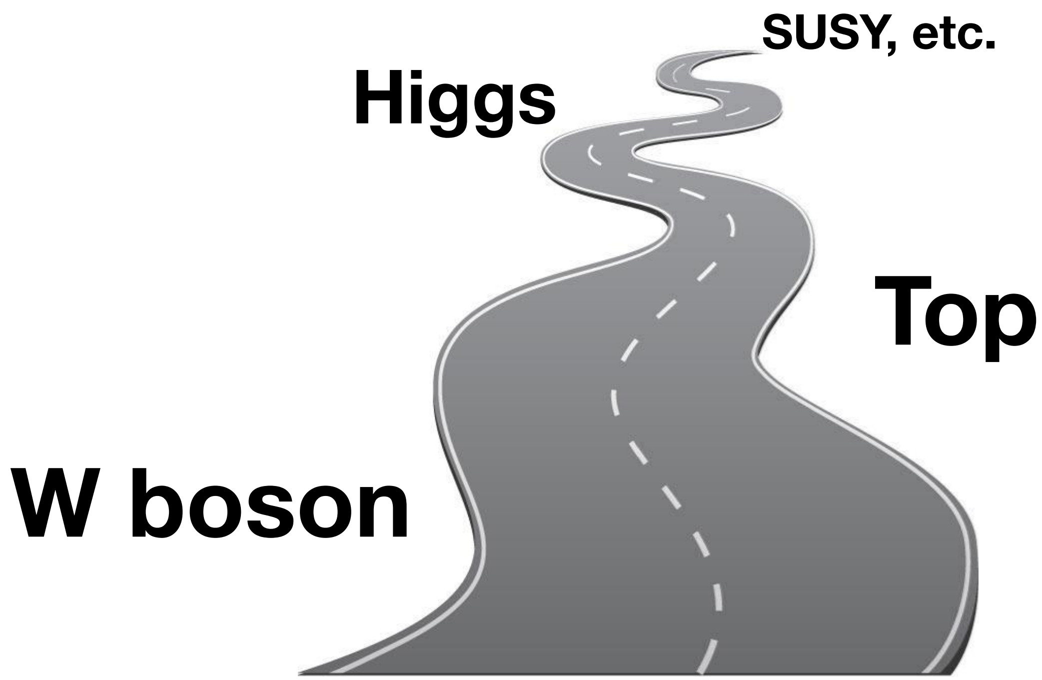
Università degli Studi di Padova

CERN

École Polytechnique Fédérale de Lausanne

Ideology

Particle Physics before the LHC



Particle Physics before the F.C.

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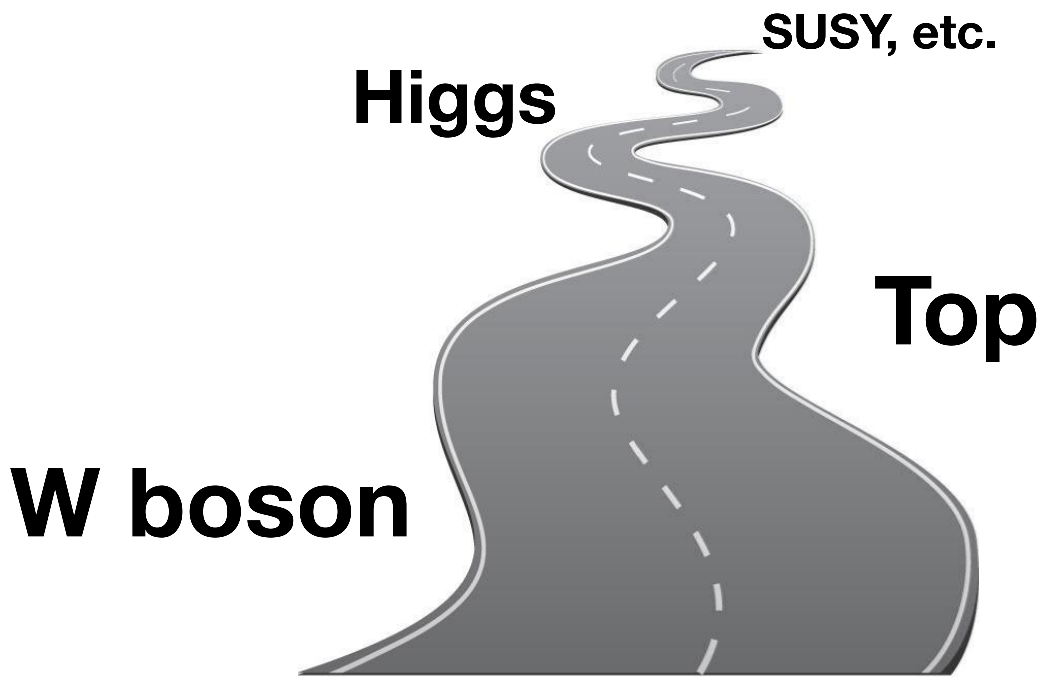

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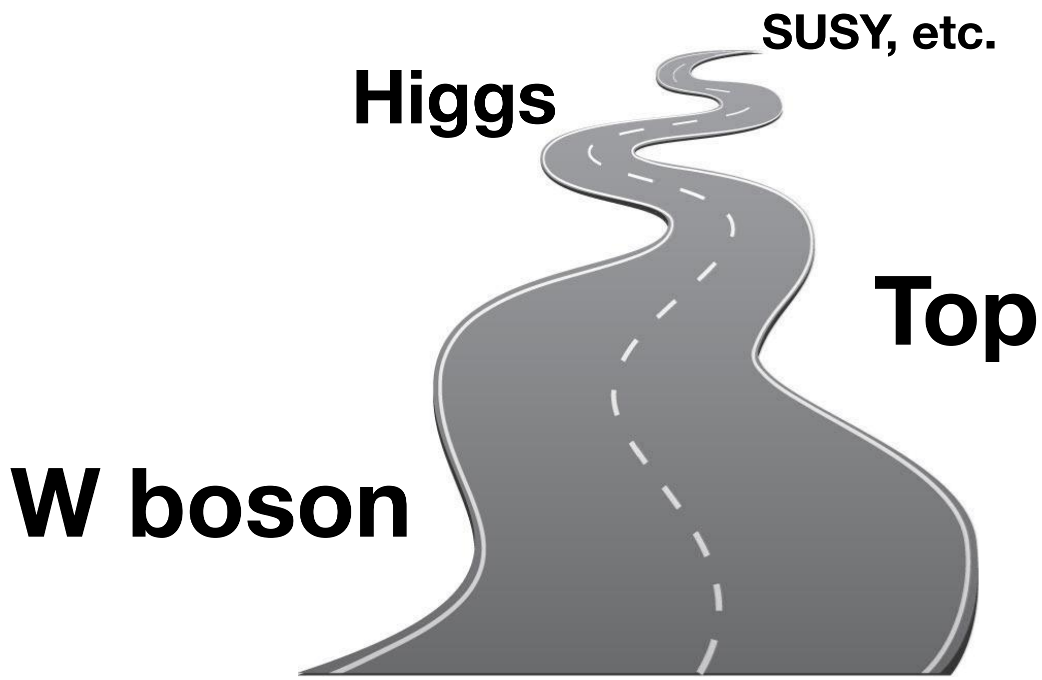

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next discovery will be **revolutionary**

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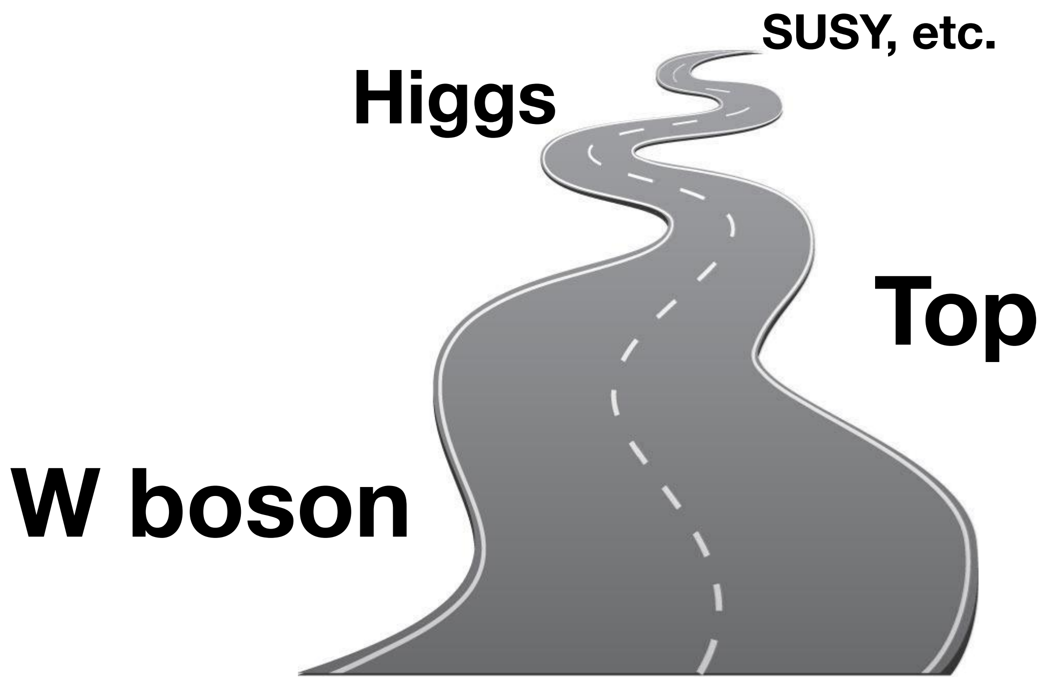

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This is **good:**

next discovery will be **revolutionary**

This is **bad:**

F.C. potential cannot be evaluated on few uniquely identifiable benchmarks (e.g., Higgs for LHC). The **F.C. will exist** if capable of a **big jump** in simultaneous exploration of **many directions**.

Exploration Strategies

Direct:

Are there new particles at the **many-TeV scale?**

- Conclusive result on Naturalness or Un-Naturalness [SUSY/CH benchmarks]
- Minimal WIMP DM candidates up to 15 TeV mass

Indirect:

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- Extended Higgs sector, possibly related with EWBG
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High energy precision (i.e., study of **amplified** BSM effects)

- **Needed to overcome accuracy barrier**
- Systematic exploration of heavy BSM by EFT

Simple Things First

It is enough to remember the shape of pdf's !

Lepton coll. operating at energy $\sqrt{s_\mu}$.
Cross section for reaction at $E \sim \sqrt{s_\mu}$
(e.g., production of BSM at M=E)

$$\sigma_\mu(s_\mu) = \frac{1}{s_\mu}[\hat{s}\hat{\sigma}]_\mu$$

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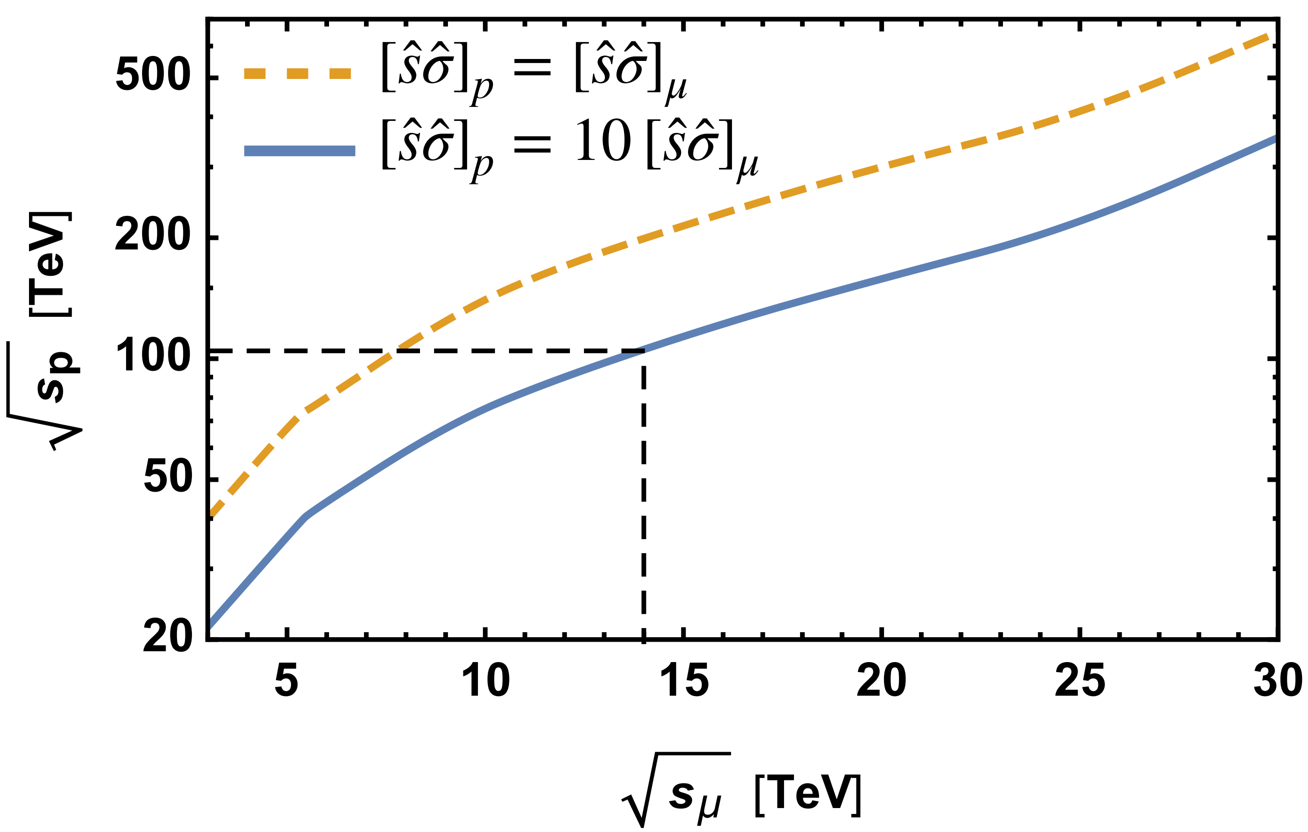

QCD-coloured BSM can easily have much larger partonic XS.

Comparison even more favourable for **QCD-neutral BSM**

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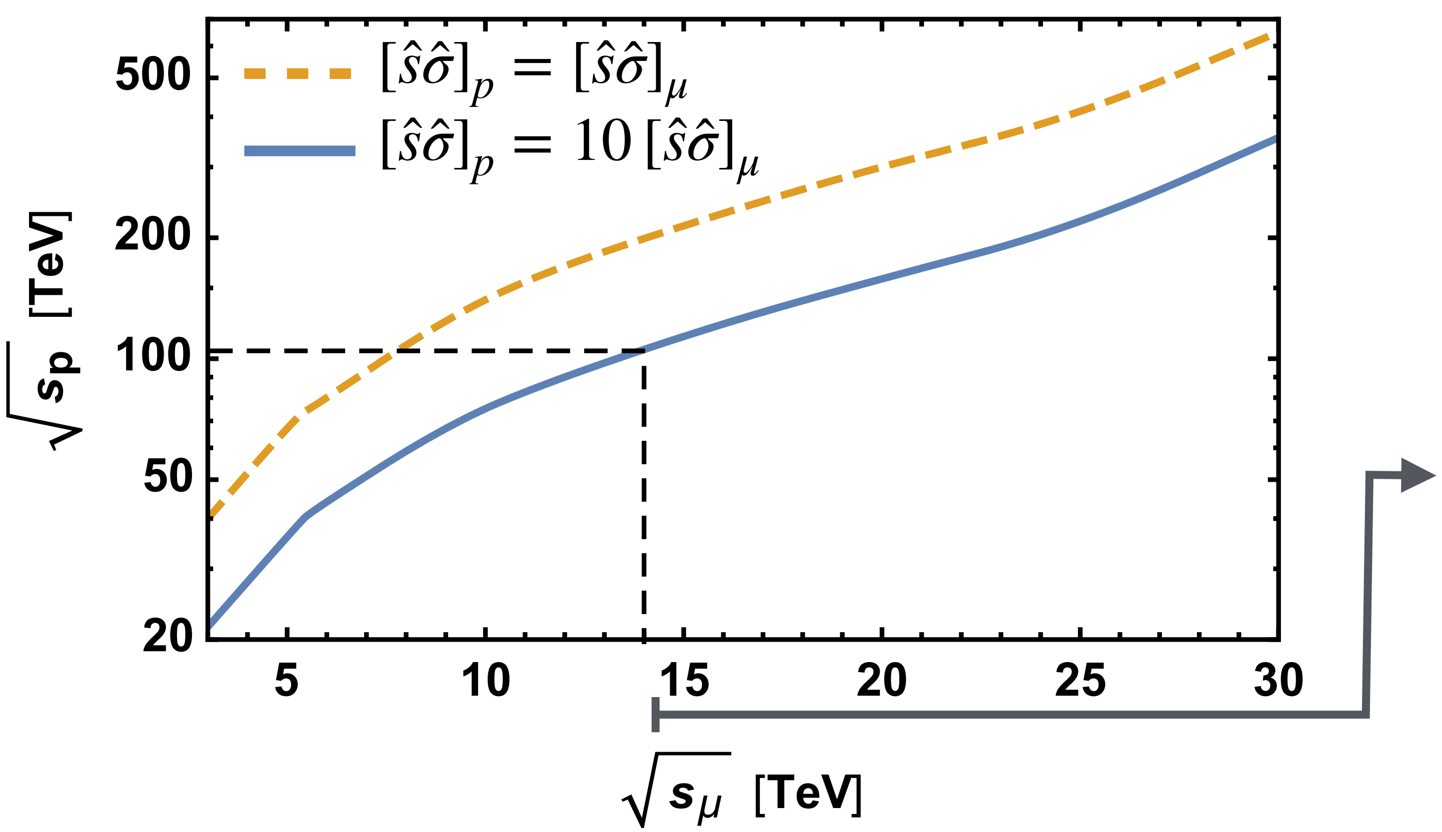

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14 TeV μ-collider nearly as good as the FCC at 100 TeV?

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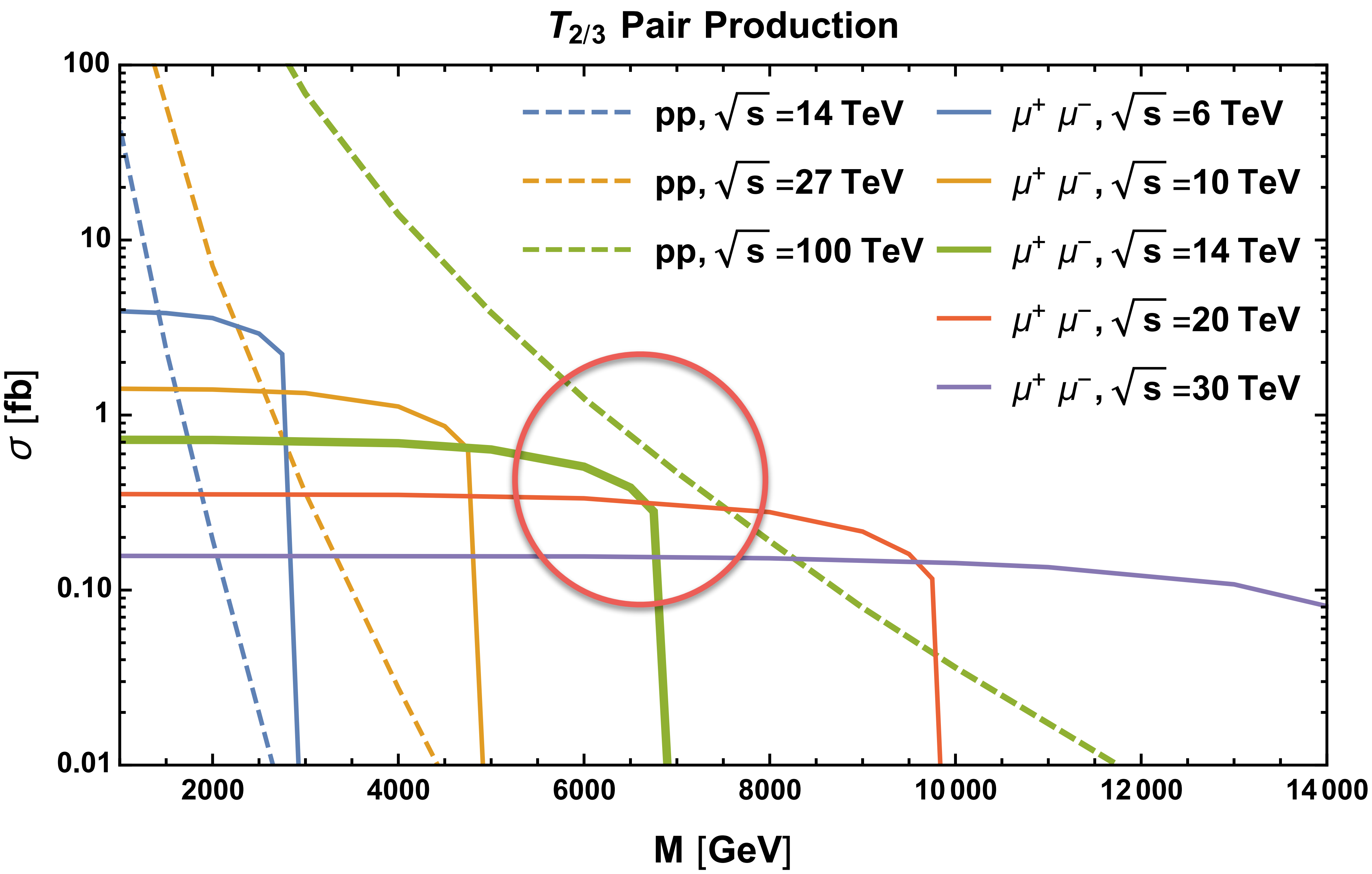
Protons vs Muons Cross-Sections



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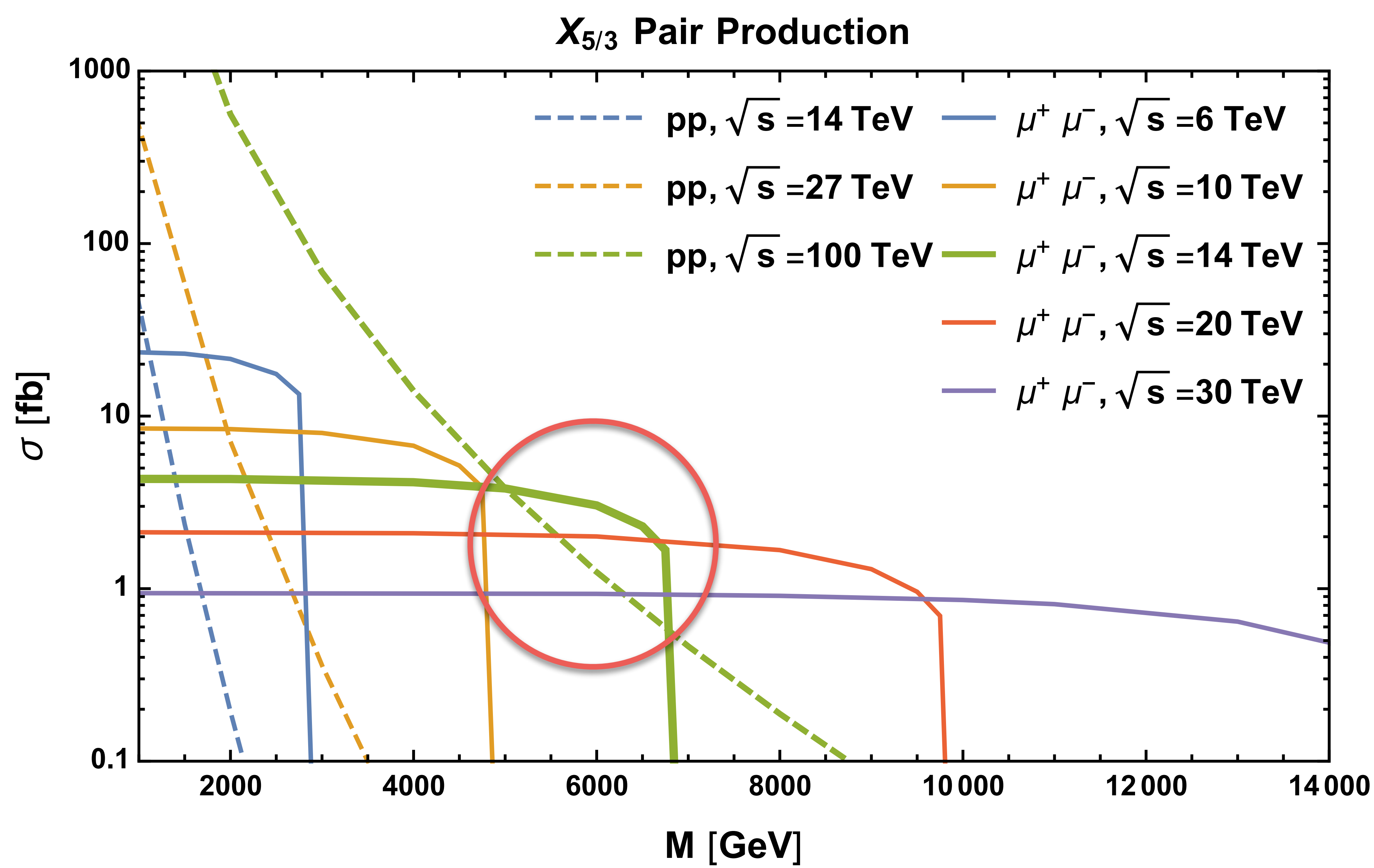

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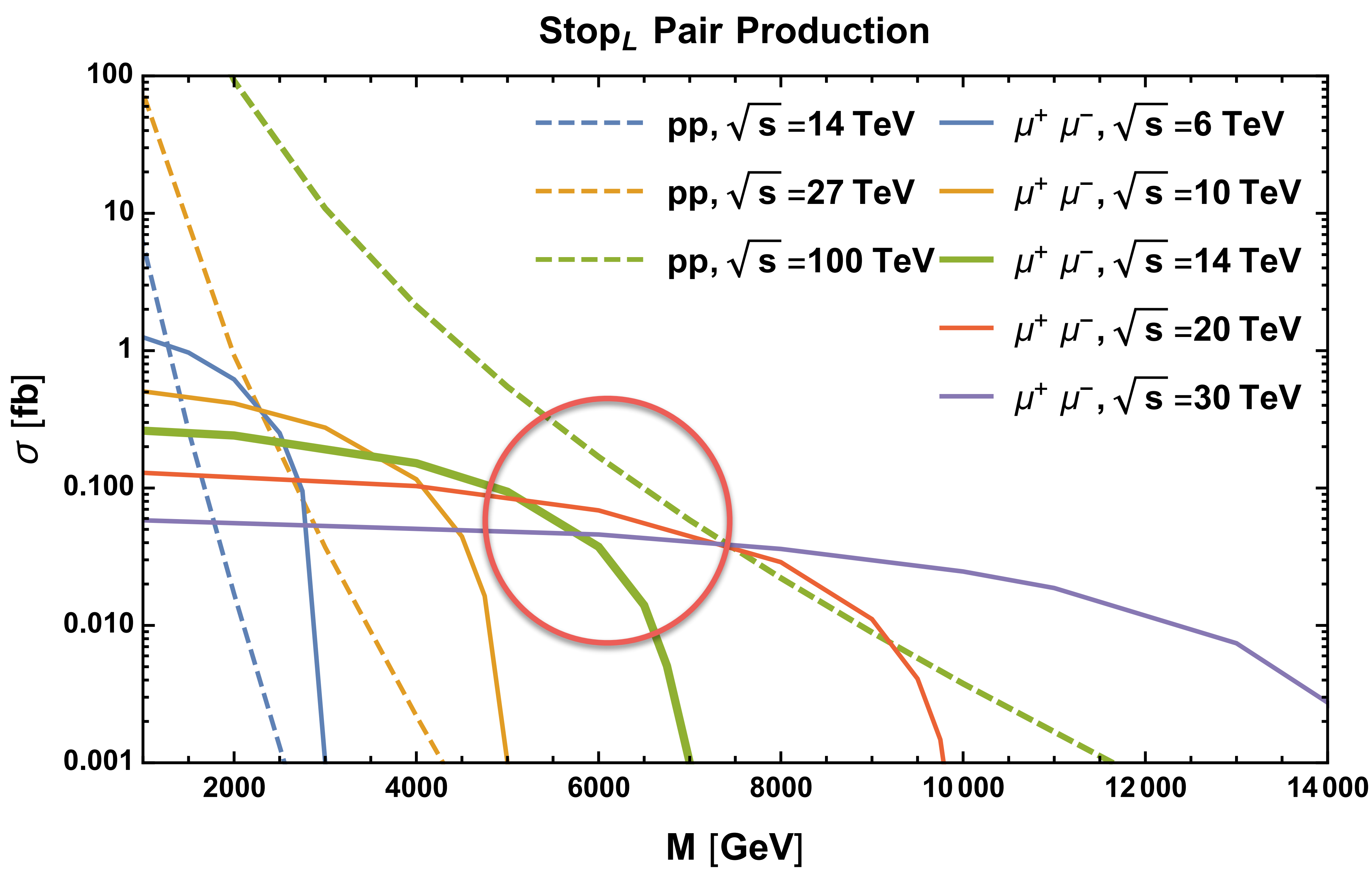

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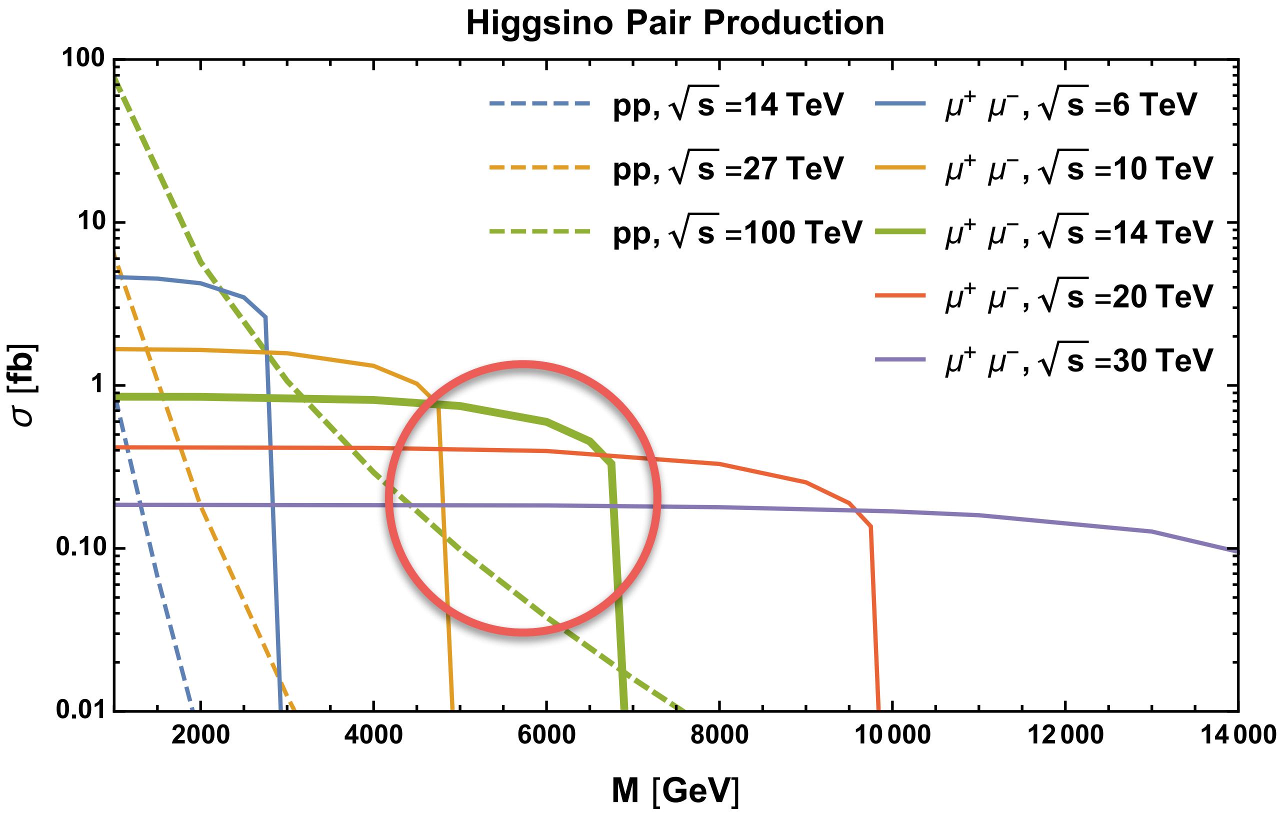
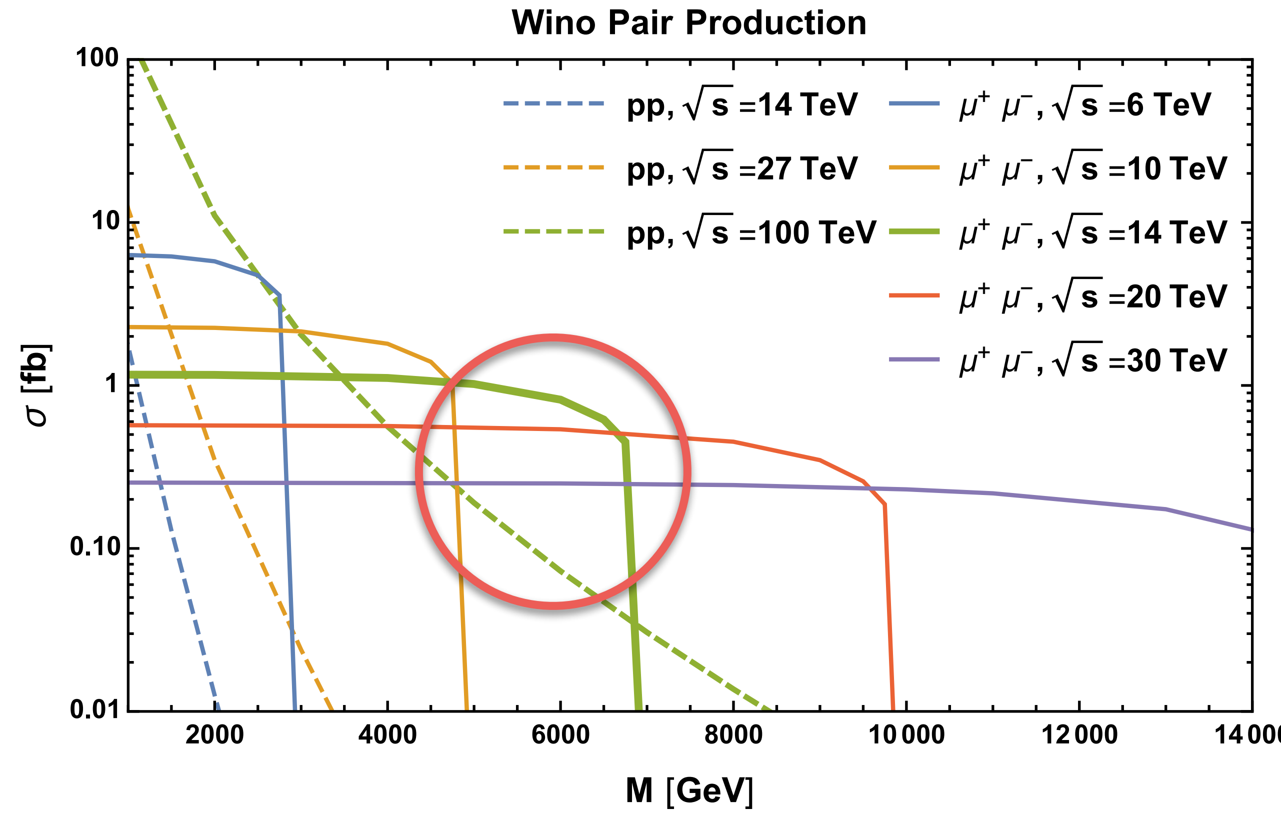




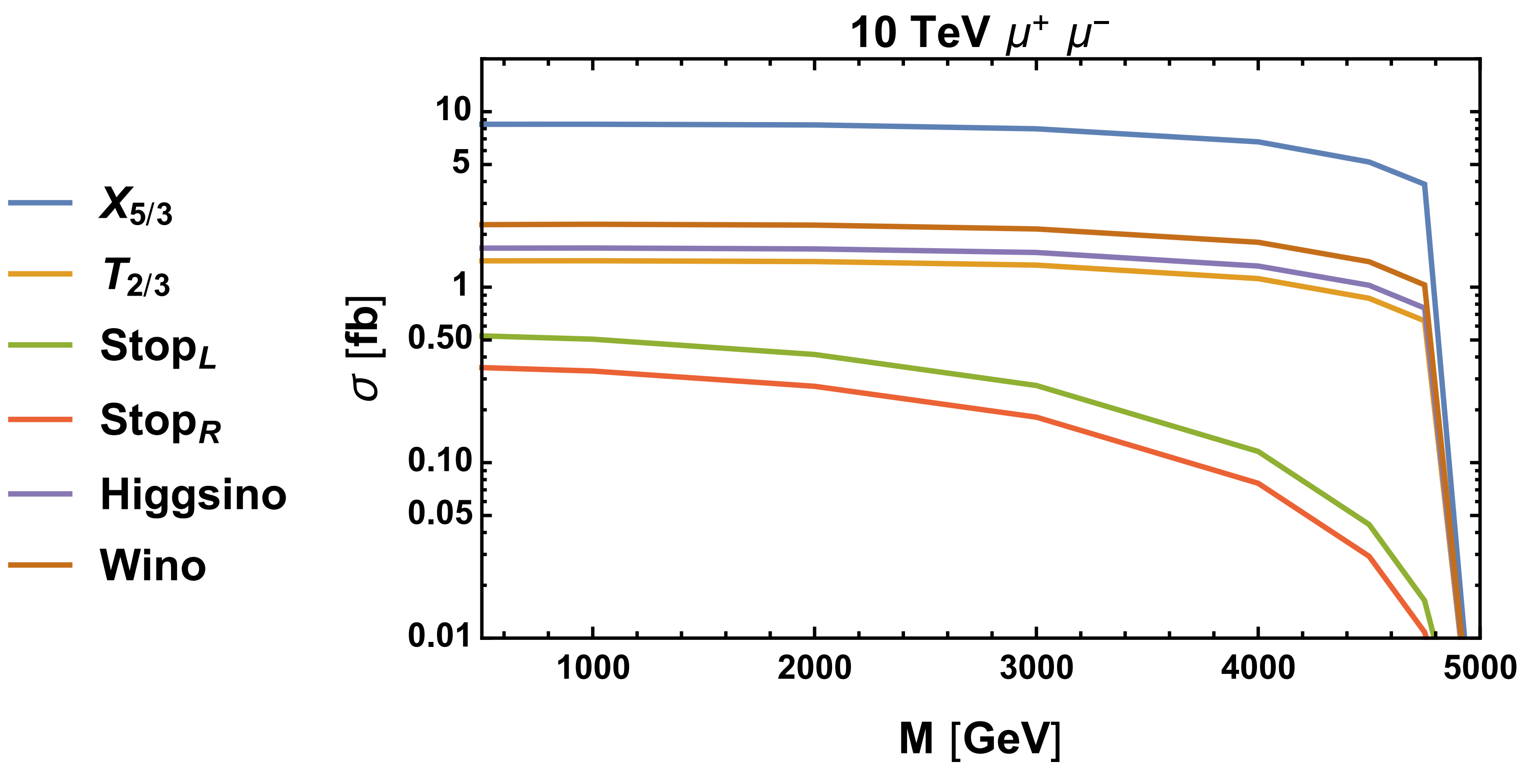
Much much better than proton collider for EW-only particles like Higgsino/EWKino/Sleptons …

Simple Things First

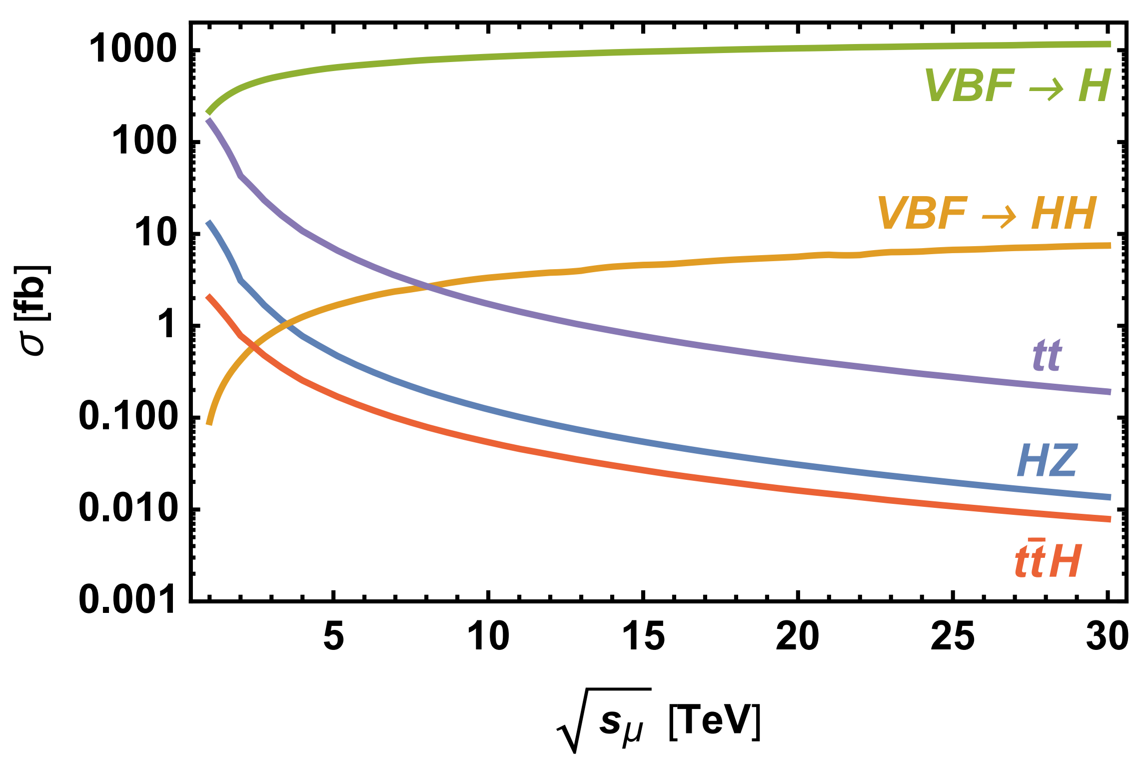
Typical Muon Collider Cross-Section:

$$\sigma_\mu = \left(\frac{10\,\text{TeV}}{\sqrt{s}}\right)^2 \cdot 1\text{fb}$$

For **Hard** EW BSM or SM production: (VBF is Soft, see later)



Heavy BSM



High-Energy SM

Muon Colliders Requirements Specification

The muon collider must:

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   10 TeV >> LHC; 14 TeV ~ FCC-hh; 30 TeV = amazing

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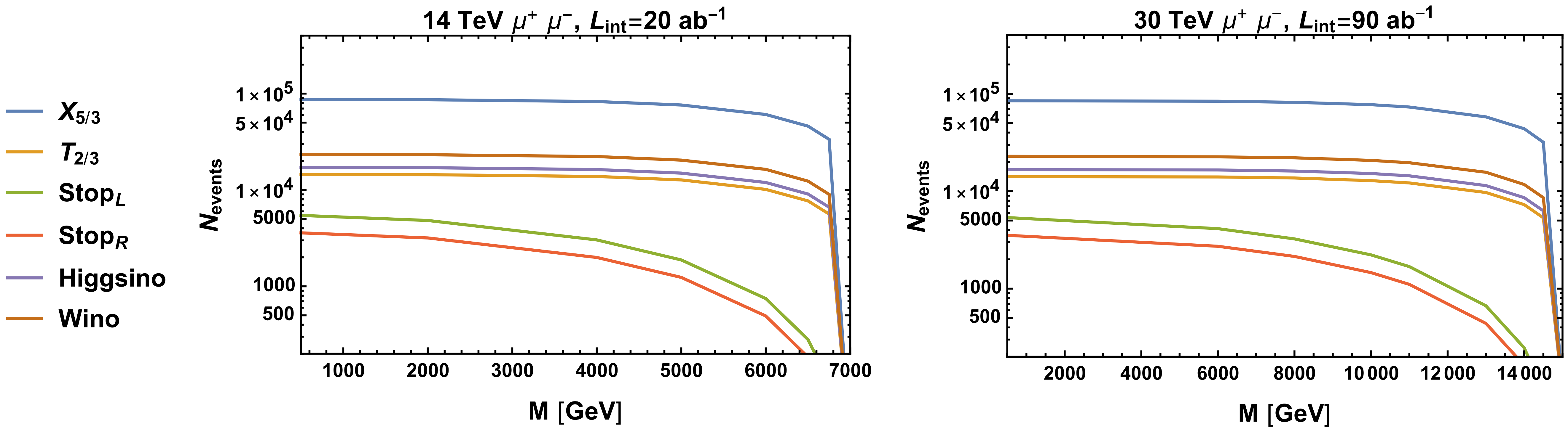
Luminosity Target

$$L \gtrsim \frac{5\ \text{years}}{\text{time}} \left(\frac{\sqrt{s_\mu}}{10\ \text{TeV}} \right)^2 2 \cdot 10^{35} \text{cm}^{-2}\text{s}^{-1}$$

Direct Reach

Discover **Generic EW** particles **up to mass threshold**

exotic (e.g., displaced) **or difficult** (e.g., compressed) decays to be studied



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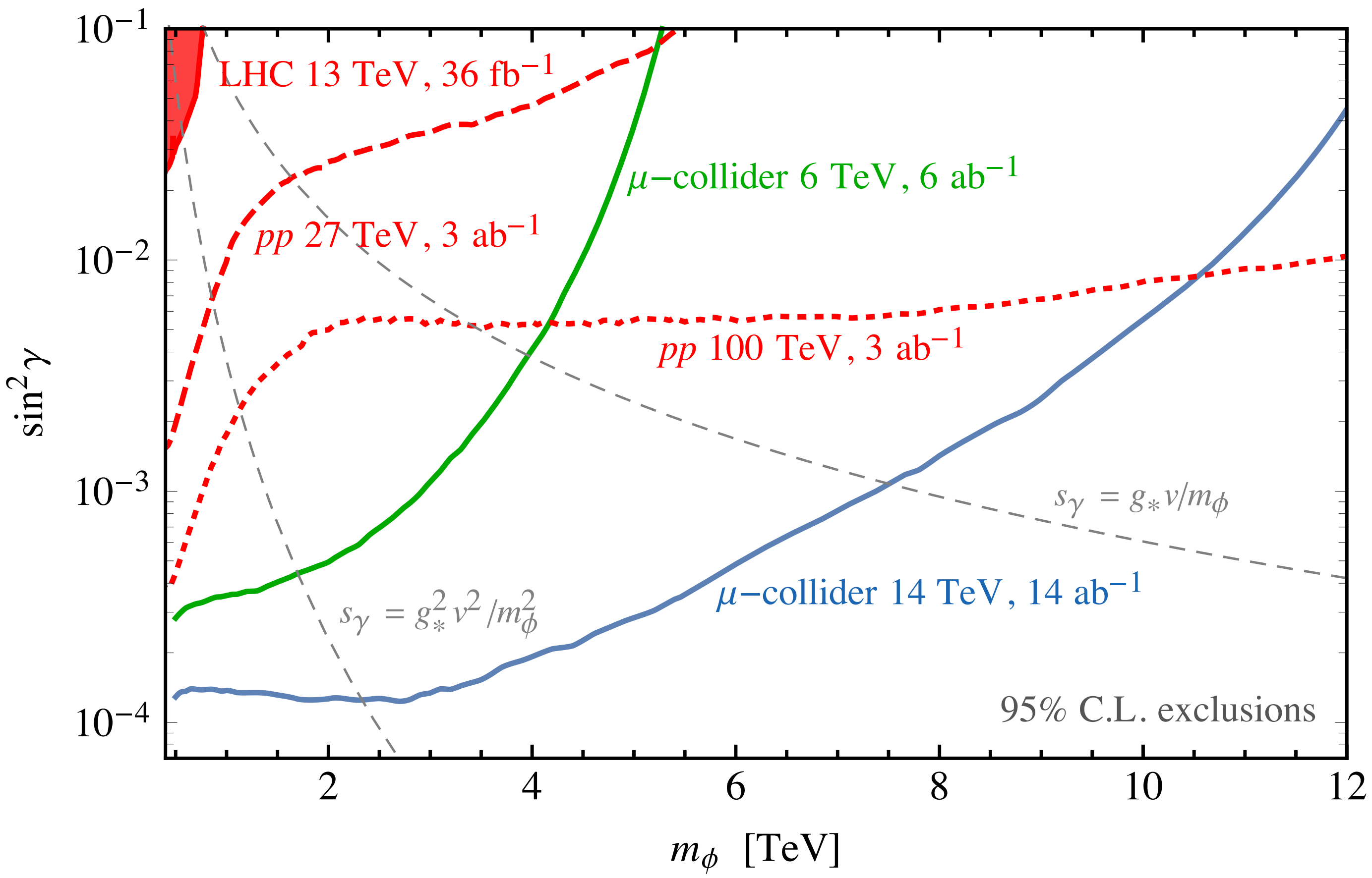
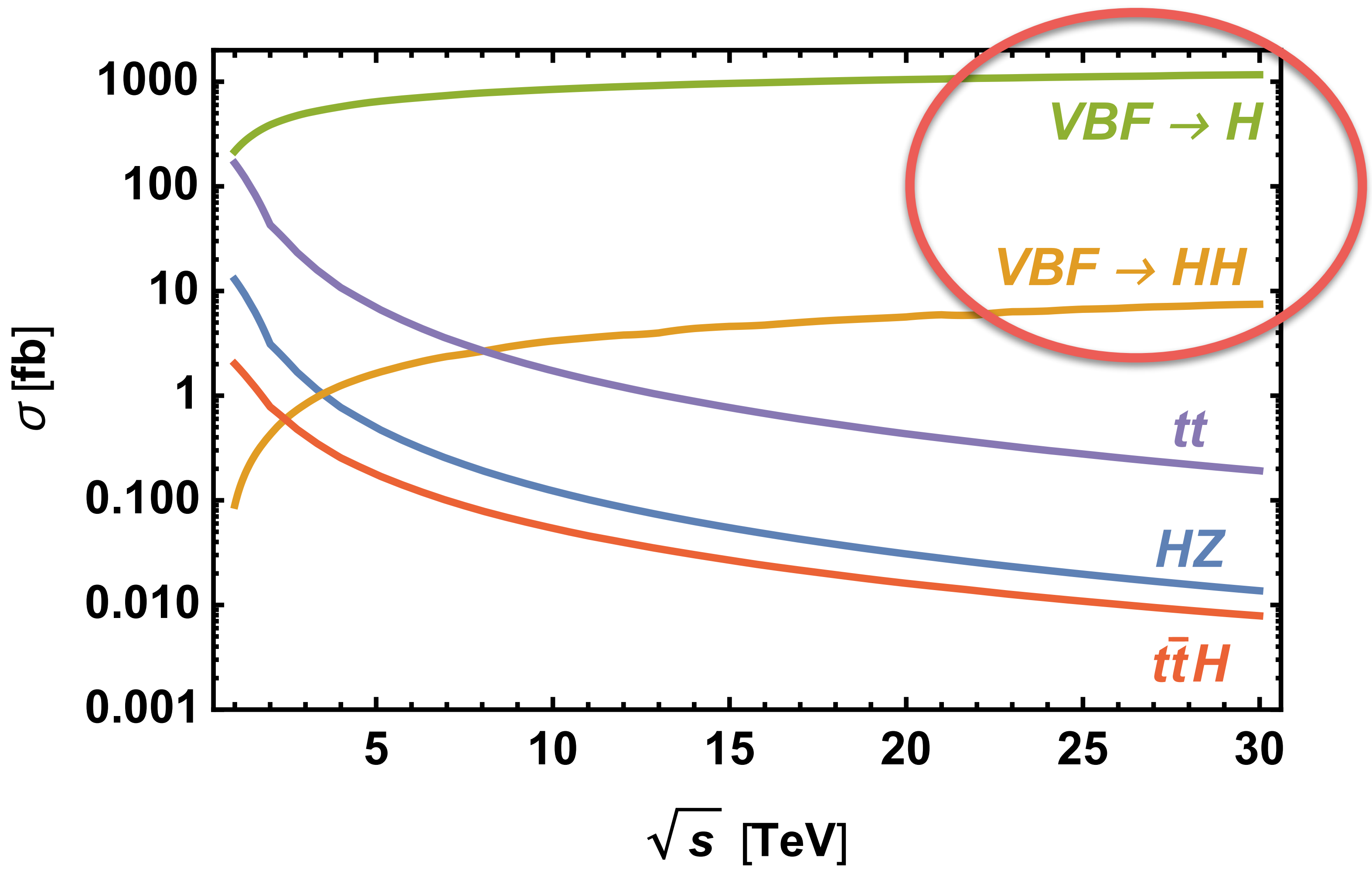
Exploit large VBF for extra scalars

e.g., **singlet Higgs-Portal singlet** (see Dario's talk)



High Rate (but Low-Energy) Precision

Huge VBF Higgs: ~ 10^7 Higgses, 30’000 Higgs pairs [at 10 TeV]



Rate large because process soft: $\sigma \propto 1/E_W^2$

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10 TeV	Sens. Degradation	N_{SM} [10 ab^{-1}]	$\frac{\text{Degradation}}{\sqrt{N_{SM}}}$ [10 ab^{-1}]
Total HH	2.44826	10 476.8 ϵ_b	$\frac{0.023919}{\sqrt{\epsilon_b}}$
After θ>5°	1.79402	5386.76 ϵ_b	$\frac{0.0333575}{\sqrt{\epsilon_b}}$
PT>30 GeV on top	1.81422	3346.09 ϵ_b	$\frac{0.0313633}{\sqrt{\epsilon_b}}$
PT>50 GeV on top	2.42269	1291.06 ϵ_b	$\frac{0.0674256}{\sqrt{\epsilon_b}}$
PT>80 GeV on top	1.35534	328.448 ϵ_b	$\frac{0.0747853}{\sqrt{\epsilon_b}}$

30 TeV	Sens. Degradation	N_{SM} [90 ab^{-1}]	$\frac{\text{Degradation}}{\sqrt{N_{SM}}}$ [90 ab^{-1}]
Total HH	3.8792	216 726. ϵ_b	$\frac{0.00833272}{\sqrt{\epsilon_b}}$
After θ>5°	2.03452	64 812. ϵ_b	$\frac{0.0152375}{\sqrt{\epsilon_b}}$
PT>30 GeV on top	2.08392	41 492.2 ϵ_b	$\frac{0.0102305}{\sqrt{\epsilon_b}}$
PT>50 GeV on top	1.88029	17 637.2 ϵ_b	$\frac{0.0141583}{\sqrt{\epsilon_b}}$
PT>80 GeV on top	1.24629	5513.52 ϵ_b	$\frac{0.0167844}{\sqrt{\epsilon_b}}$

10 TeV:
$\delta\lambda_3$= 3%

If **reasonable detector performances**. First detector benchmark.

30 TeV:
$\delta\lambda_3$= 1%

High Energy Precision

EFT

$\mathcal{L}^{d=6}$

Low-Energy: $\Delta\mathcal{O}/\mathcal{O} \sim m_{\rm EW}^2/\Lambda^2$

- require **accuracy:** large lumi, low syst. and th. err

High-Energy: $\Delta\mathcal{O}/\mathcal{O} \sim E^2/\Lambda^2$

- benefit from high **energy and** high **accuracy**

If high-energy, we **can learn already from 1% measur.**

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Example:

O_W

$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overset{\leftrightarrow}{D}{}^\mu H\right) D^\nu W^a_{\mu\nu}$$

On Z-pole: $\Delta\mathcal{O}/\mathcal{O}\,|_Z \sim C_W m_Z^2 = \hat{S}$

On H.E. ZH: $\Delta\mathcal{O}/\mathcal{O}\,|_E \sim C_W E^2$

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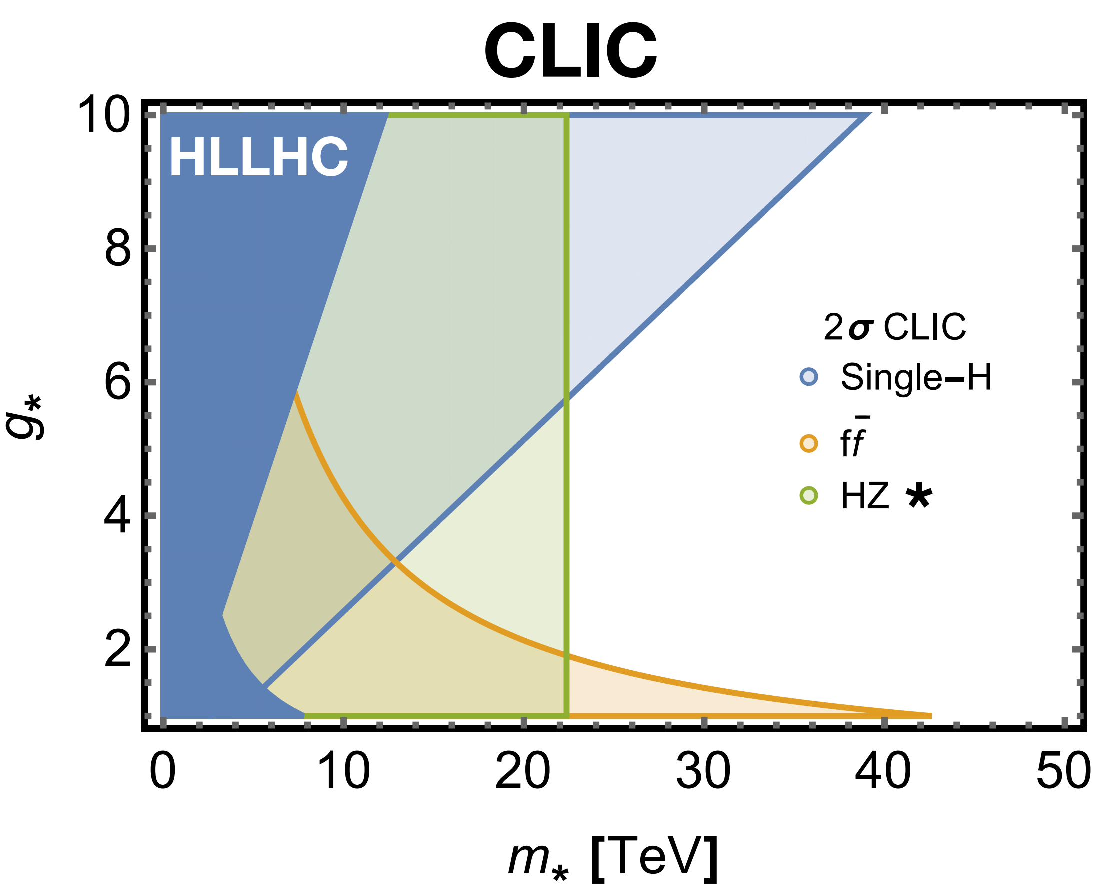
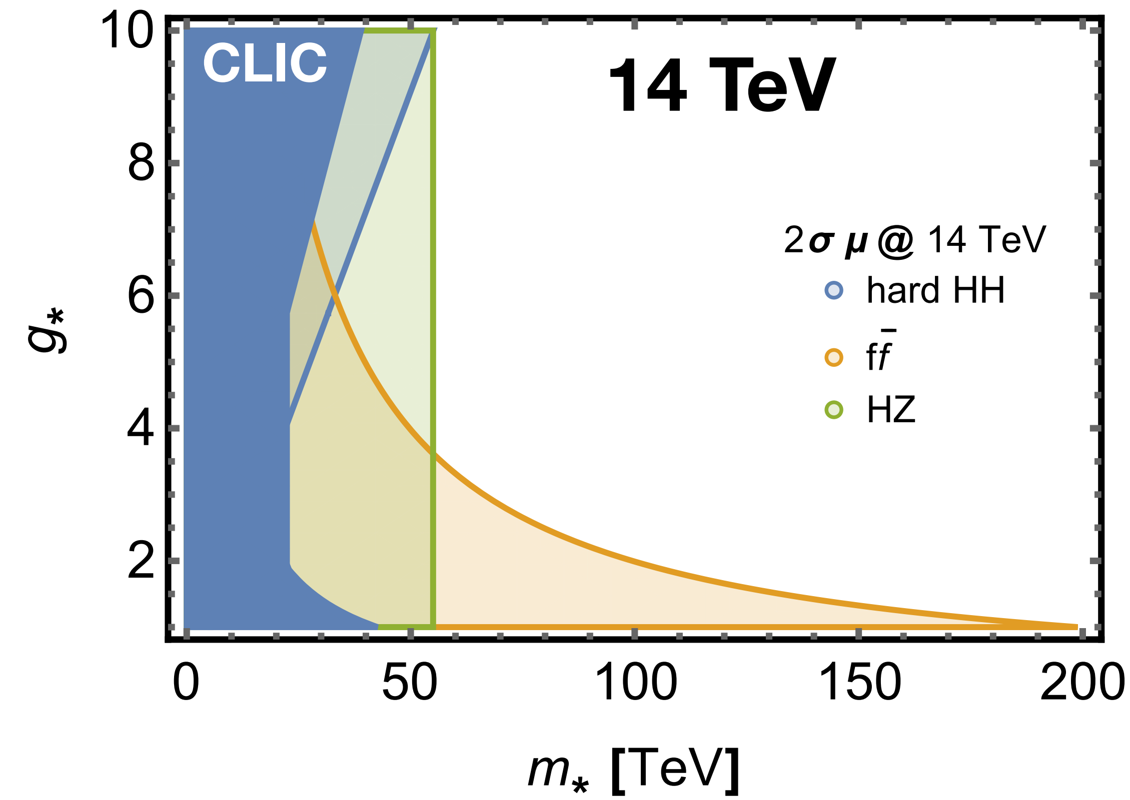
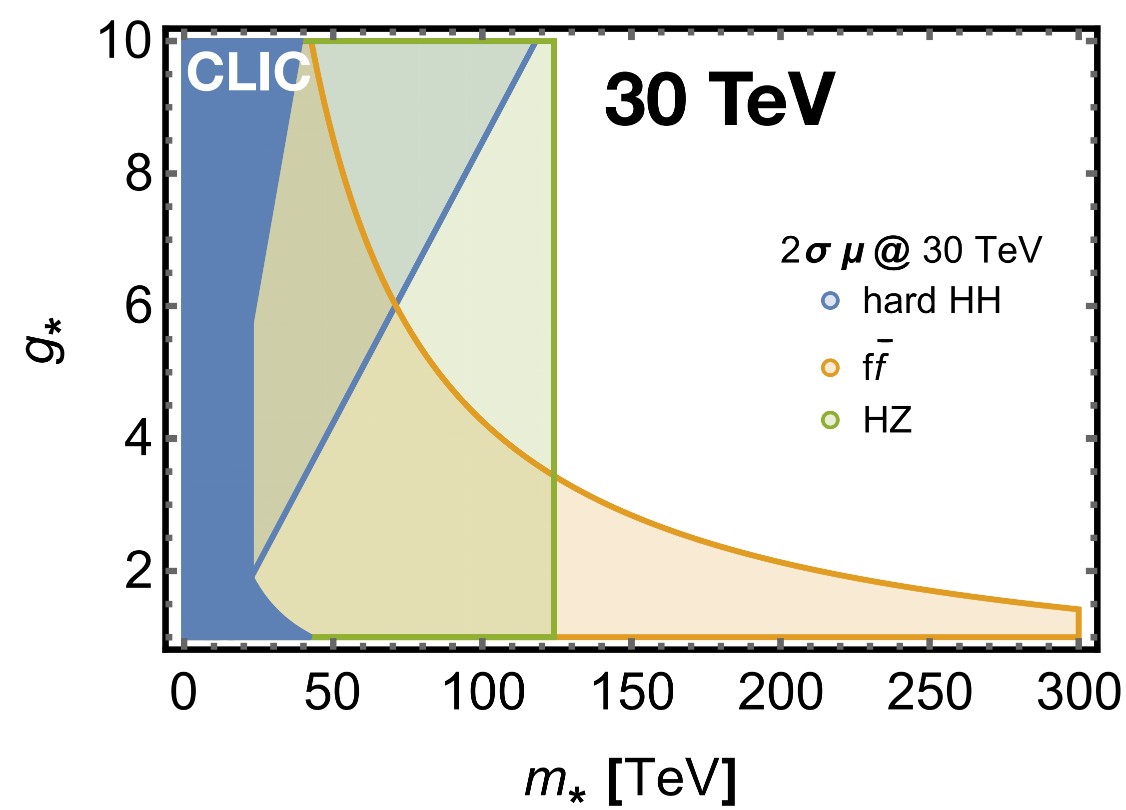
From 1% ZH, equivalent Z-pole accuracy $\hat{S}_{\rm equiv} \sim 10^{-6}\left(10\,\text{TeV}/E\right)^2$

High Energy Precision

Reach on Higgs Compositeness:
(very) tentative (more in Dario's talk)



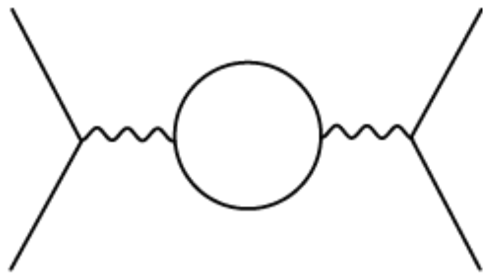


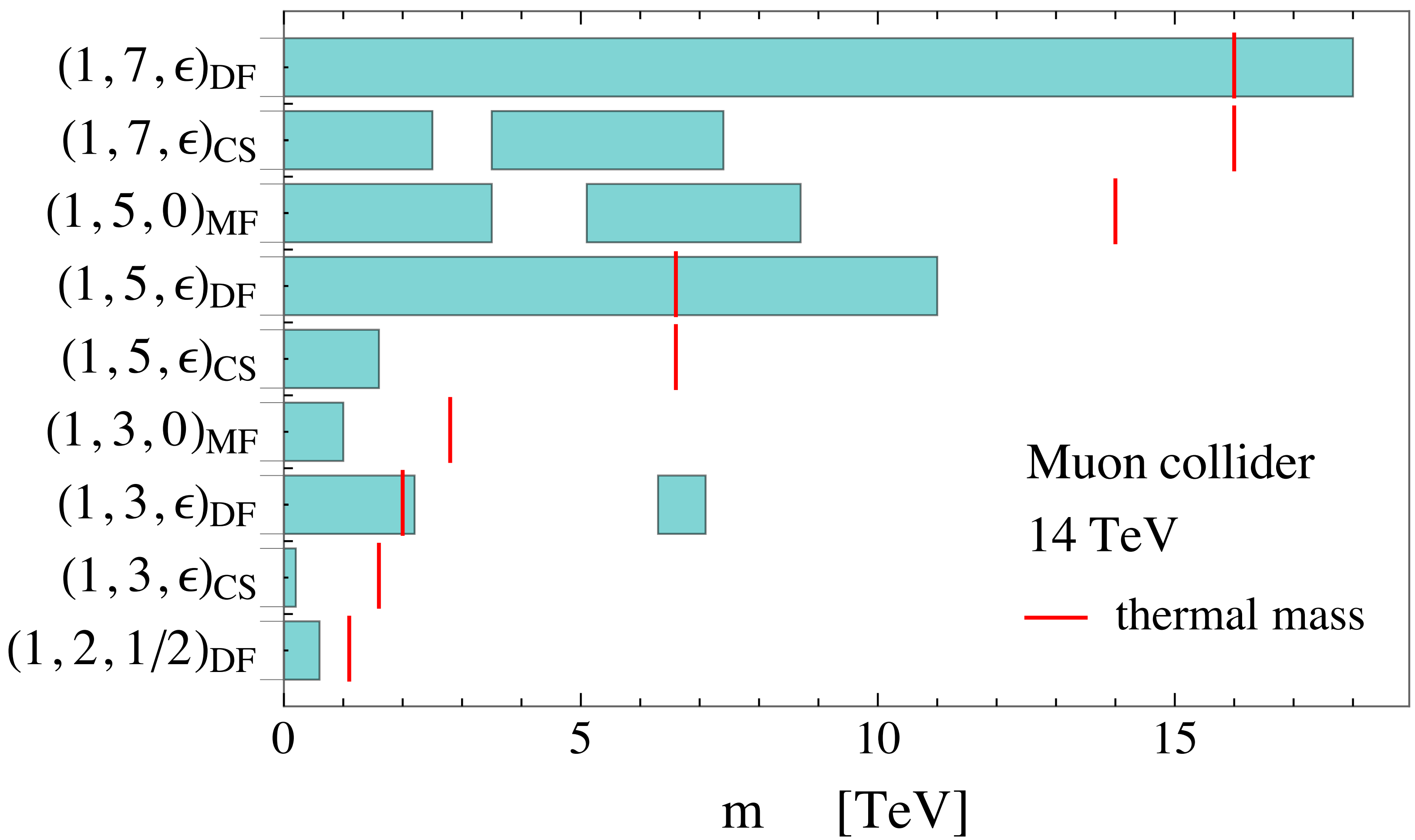


* refined analysis

High Energy Precision

Minimal (Dark) Matter in Loops:





Reach extends well above threshold for high representations

Conclusions

A 10-or-more TeV muon collider has **immense self-evident physic potential**, covering **all** exploration strategies

- **Directly** discover **many-TeV** particles, and **LHC-elusive below-TeV ones**
- **Indirect high-rate** (e.g., $\delta\lambda_3$= 1-3%) and **high-energy** (100 TeV CH) probes

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Could it become Reality ??

Backup

Result of the coupling (a.k.a. κ) fit

- Comparison(*) with other lepton colliders at the EW scale (up to 380 GeV)

13	μ Coll$_{125}$	ILC$_{250}$	CLIC$_{380}$	LEP3$_{240}$	CEPC$_{250}$	FCC-ee$_{240}$	FCC-ee$_{365}$
Years	6	15	5	6	7	3	+4
Lumi (ab^{-1})	0.005	2	0.5	3	5	5	+1.5
δm_H (MeV)	0.1	t.b.a.	110	10	5	7	6
$\delta\Gamma_H / \Gamma_H$(%)	6.1	3.8	6.3	3.7	2.6	2.8	1.6
$\delta g_{Hb} / g_{Hb}$ (%)	3.8	1.8	2.8	1.8	1.3	1.4	0.70
$\delta g_{HW} / g_{HW}$ (%)	3.9	1.7	1.3	1.7	1.2	1.3	0.47
$\delta g_{H\tau} / g_{H\tau}$(%)	6.2	1.9	4.2	1.9	1.4	1.4	0.82
$\delta g_{H\gamma} / g_{H\gamma}$ (%)	n.a.	6.4	n.a.	6.1	4.7	4.7	4.2
$\delta g_{H\mu} / g_{H\mu}$ (%)	3.6	13	n.a.	12	6.2	9.6	8.6
$\delta g_{HZ} / g_{HZ}$ (%)	n.a.	0.35	0.80	0.32	0.25	0.25	0.22
$\delta g_{Hc} / g_{Hc}$ (%)	n.a.	2.3	6.8	2.3	1.8	1.8	1.2
$\delta g_{Hg} / g_{Hg}$ (%)	n.a.	2.2	3.8	2.1	1.4	1.7	1.0
Br_{invis} (%)$_{95\%CL}$	SM	<0.3	<0.6	<0.5	<0.15	<0.3	<0.25
BR_{EXO} (%)$_{95\%CL}$	–	<1.8	<3.0	<1.6	<1.2	<1.2	<1.1

(*) Green = best
Red = worst

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13	μ Coll$_{125}$	HL-LHC S2 (S1)
Years	6	
Lumi (ab^{-1})	0.005	
δm_H (MeV)	0.1	← Not competitive, but what for?
$\delta\Gamma_H / \Gamma_H$(%)	6.1	← ~50
$\delta g_{Hb} / g_{Hb}$ (%)	3.8	← 2.9(4.3)
$\delta g_{HW} / g_{HW}$ (%)	3.9	← 1.4(2.0)
$\delta g_{H\tau} / g_{H\tau}$(%)	6.2	← 1.7(2.3)
$\delta g_{H\gamma} / g_{H\gamma}$ (%)	n.a.	
$\delta g_{H\mu} / g_{H\mu}$ (%)	3.6	← 4.4(5.5)
$\delta g_{HZ} / g_{HZ}$ (%)	n.a.	
$\delta g_{Hc} / g_{Hc}$ (%)	n.a.	
$\delta g_{Hg} / g_{Hg}$ (%)	n.a.	
Br_{invis} (%)$_{95\%CL}$	SM	
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Patrick Janot — Higgs properties @ Circular Lepton Colliders, 1 June 2018 — 12

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