Why building a muon collider

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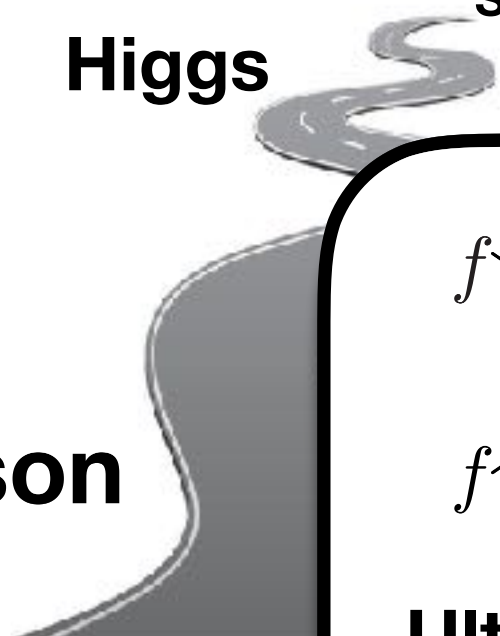
Ideology

HEP before the LHC

HEP before the F.C.

Ideology

HEP before the LHC



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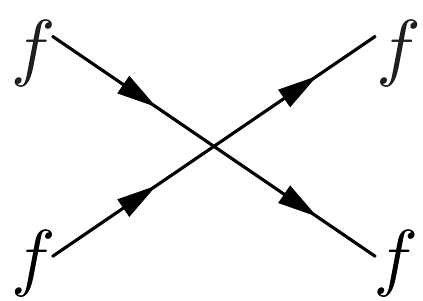
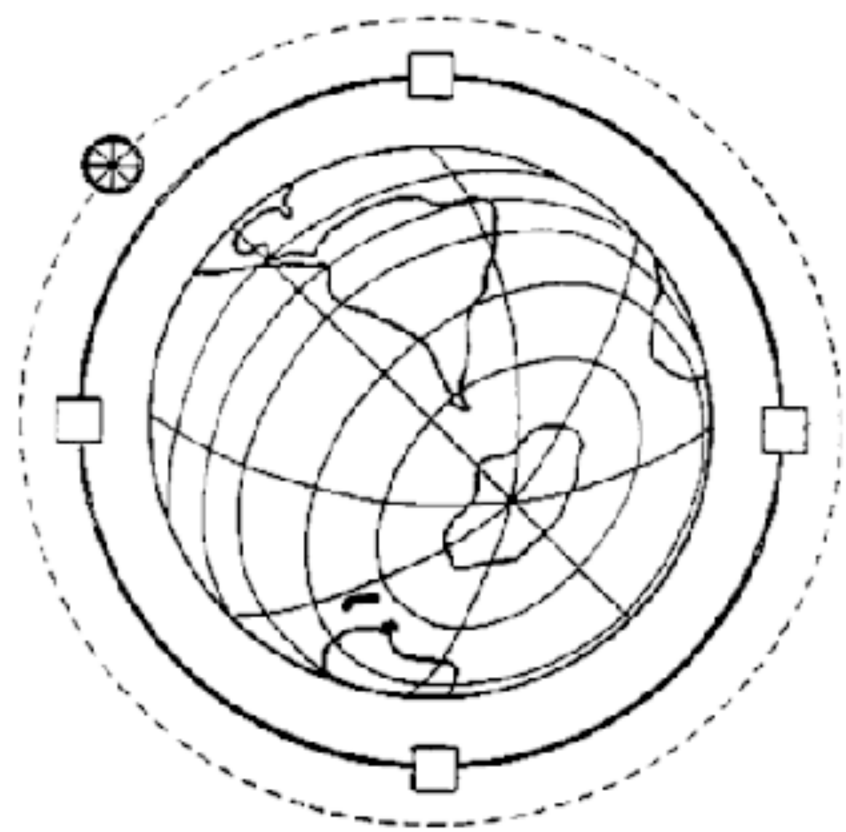


$$\sim G_F E^2 \simeq E^2/v^2 < 16\pi^2 \rightarrow m_W < 4\pi v$$

Ultimate Accelerator.

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

The manifesto of HEP!



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

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

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No single experiment can explore all directions at once.

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The next big FC **will exist only if** capable to **explore many directions**, and be **conclusive** on some of those

Naturalness

"Is m_H Unnatural?" $=$ "Is m_H Unpredictable?"

$$\left(m_H^2\right)_{Phys.} = \int_0^\infty F_{true}(E;\, g_{true})$$

UV Contribution

$$c\,{\Lambda_{\rm SM}}^2$$

$$= \int_0^{\Lambda_{\rm SM}} (\ldots) + \int_{\Lambda_{\rm SM}}^\infty (\ldots)$$

SM Contribution

$$\delta m_H^2 = \frac{3y_t^2}{8\pi^2}{\Lambda_{\rm SM}}^2$$

Fine Tuning: $\Delta \geq \frac{\delta m_H^2}{m_H^2} \simeq \left(\frac{126\,\text{GeV}}{m_H}\right)^2 \left(\frac{\Lambda_{\rm SM}}{500\,\text{GeV}}\right)^2$

Measures how much Unpredictable m_H is.

Unnaturalness is a challenge to **Reductionism**

Dramatic paradigm shift. E.g. Anthropic or Dynamical

[more in backup]

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LHC may push conventional Natural models to

$$\Lambda_{\mathrm{SM}} \gtrsim 2 \text{ TeV} \longrightarrow \Delta \gtrsim 10$$

Still Naturalness might be there in the form of:

Partial Unnaturalness

$$\Delta \sim 100$$

$$\downarrow$$

$$\Lambda_{\mathrm{SM}} \sim 5 \text{ TeV}$$

Neutral Naturalness

$$\Delta \sim \text{few} \longrightarrow \Lambda_{\mathrm{SM}}^{\mathrm{col.}} \sim 5 \text{ TeV}$$

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$$\Lambda_{\mathrm{SM}}^{\mathrm{neut.}} \lesssim 1 \text{ TeV}$$

Need **5 TeV** reach on ordinary Top Partners

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Still, the higher the reach, the better

Dark Matter

[For recent lectures, see e.g. arXiv:1603.03797]

Thermal Freeze-Out is the simplest explanation of DM.
All you need is:

- A nearly **stable BSM** particle ($\tau > \tau_U \sim 10^{10}$yrs)

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No new force required, annihilation through Weak Force:

$$\sigma \sim \left(\frac{g^2}{4\pi}\right)^2 \frac{1}{M^2} \sim 1\,\mathrm{pb}\left(\frac{650\,\mathrm{GeV}}{M}\right)^2$$

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Range **barely probed** by LHC, naively **excluded by Direct Detection**
[even if there are caveats, e.g. Higgsino DM @ 1TeV still OK]

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Minimal Dark Matter

[arXiv:hep-ph/0512090, arXiv:1512.05353]

However, WIMP can have **tens of TeV** mass:

$$\sigma \sim \left(\frac{g^2}{4\pi}\right)^2 \frac{1}{M^2} \sim 1\,\mathrm{pb}\left(\frac{650\,\mathrm{GeV}}{M}\right)^2$$

Large n-plet of SU(2)

$$\langle \sigma_A v \rangle \simeq \frac{g_2^4\ (3 - 4n^2 + n^4) + 16\ Y^4 g_Y^4 + 8 g_2^2 g_Y^2 Y^2 (n^2 - 1)}{64\pi\ M^2\ g_{\mathcal{X}}} \qquad \text{if } \mathcal{X} \text{ is a scalar}$$

$$\langle \sigma_A v \rangle \simeq \frac{g_2^4\ (2n^4 + 17n^2 - 19) + 4Y^2 g_Y^4 (41 + 8Y^2) + 16 g_2^2 g_Y^2 Y^2 (n^2 - 1)}{128\pi\ M^2\ g_{\mathcal{X}}} \qquad \text{if } \mathcal{X} \text{ is a fermion.}$$

Larger charge requires larger mass to keep σ right.
Subtle effects like Sommerfeld further raise M

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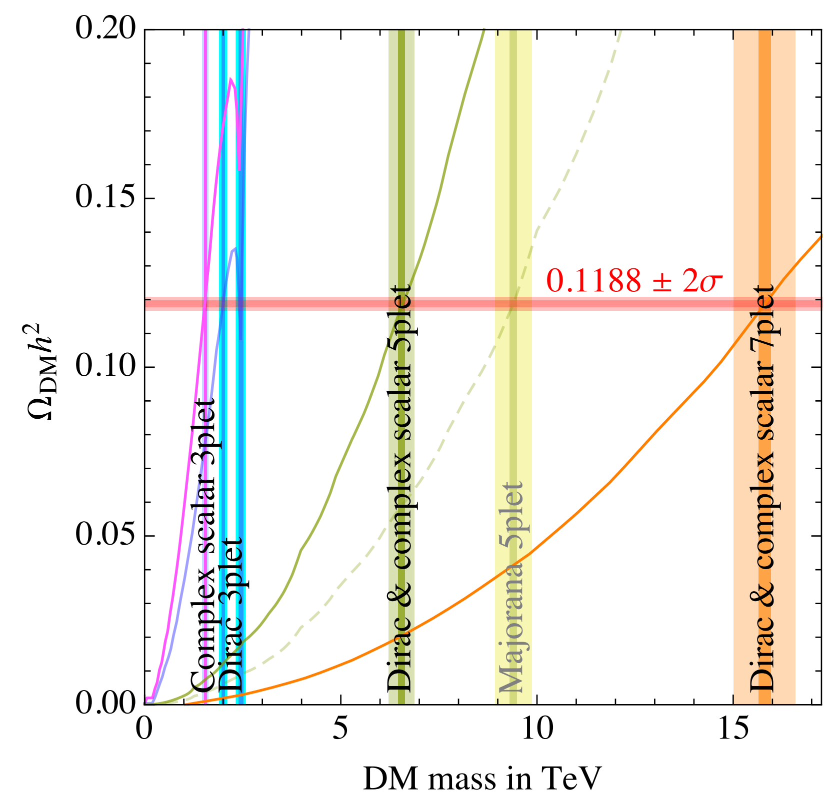
Minimal DM is a very appealing possibility:

- Large multiplets make DM **Accidentally Stable** (no decay at ren. level)
- Large multiplets preserve **SM Accidental Symmetries** (e.g., stable prot.)
- Easily **evades DD** because of **inelastic scattering** (automatic if Q=Y=0)

χ	$M_\chi^{(\mathrm{DM})}$ [TeV]
$(1,3,\epsilon)_{\mathrm{CS}}$	1.5
$(1,3,\epsilon)_{\mathrm{DF}}$	2.0
$(1,3,0)_{\mathrm{MF}}$ *	3.0
$(1,5,\epsilon)_{\mathrm{CS,\,DF}}$	6.6
$(1,5,0)_{\mathrm{MF}}$ **	9.6
$(1,7,\epsilon)_{\mathrm{CS,\,DF}}$	16



EW-produced @colliders. Seen in mono-V or stub-tracks

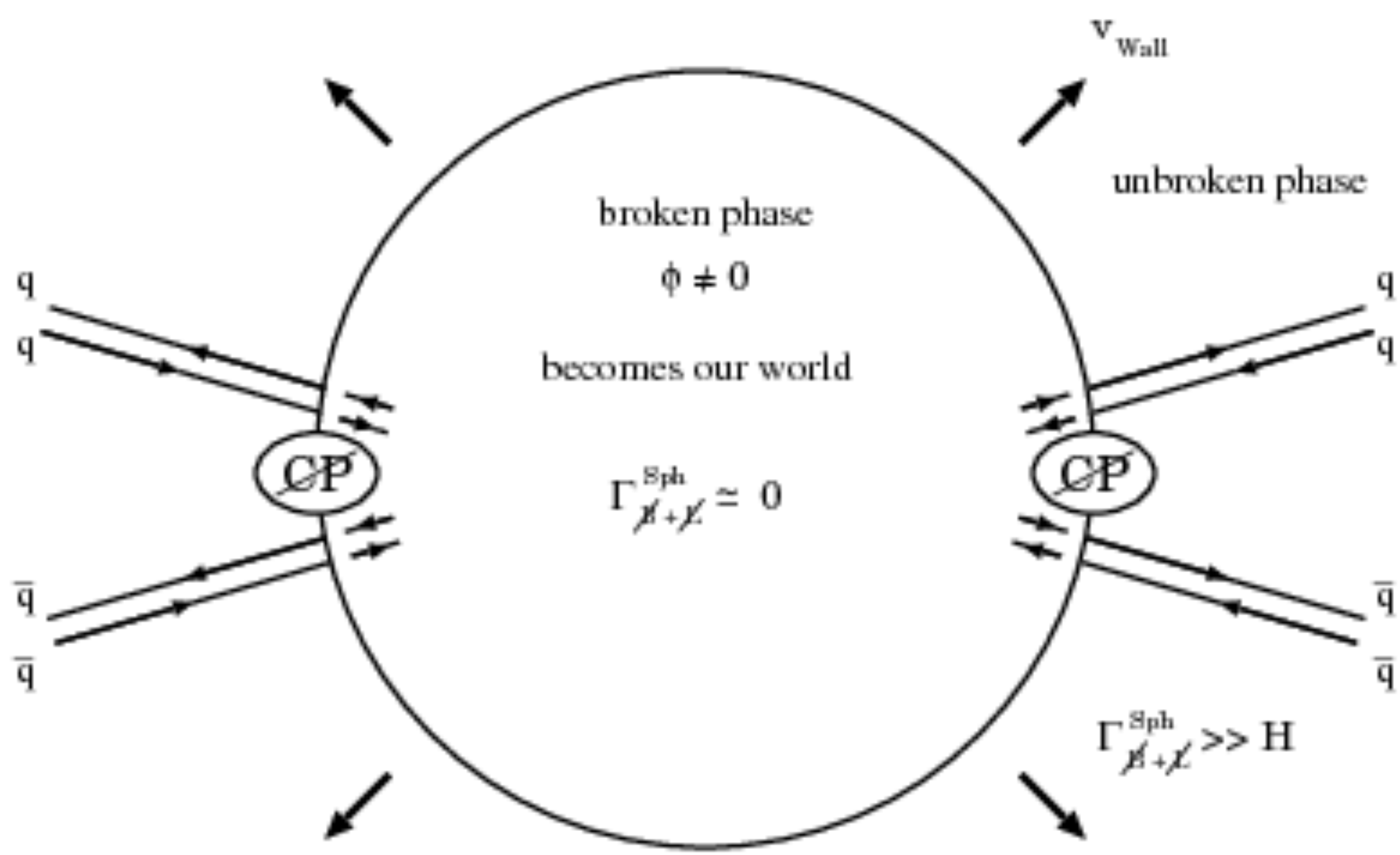
EW Baryogenesis

[see e.g., arXiv:hep-ph/9901312]

Why there are more baryons than anti-baryons?

This could have happened at the EW phase transition if:

- The transition was **strong first order** (unlike in SM)
- There is **more CP violation** that in SM



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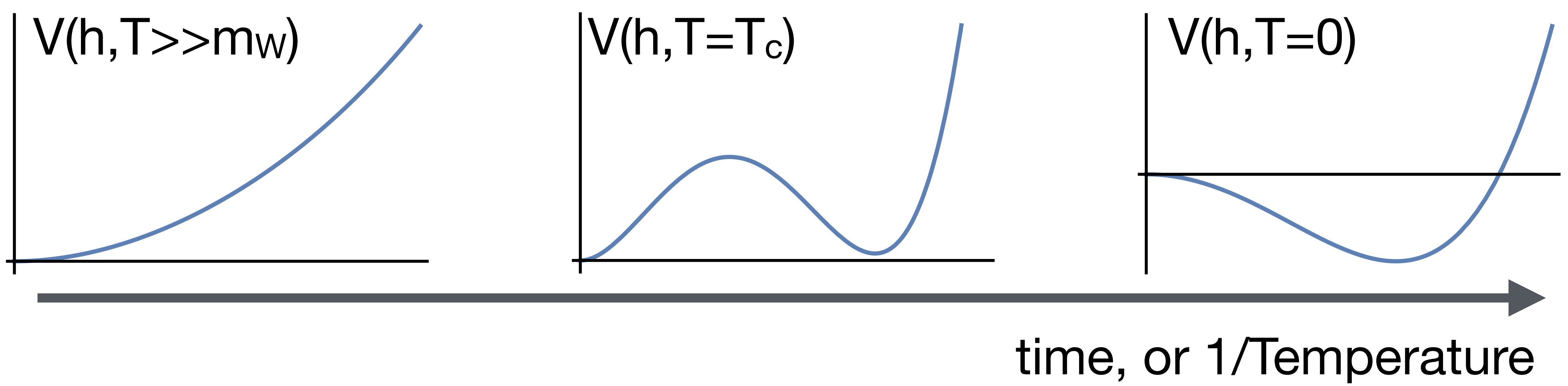

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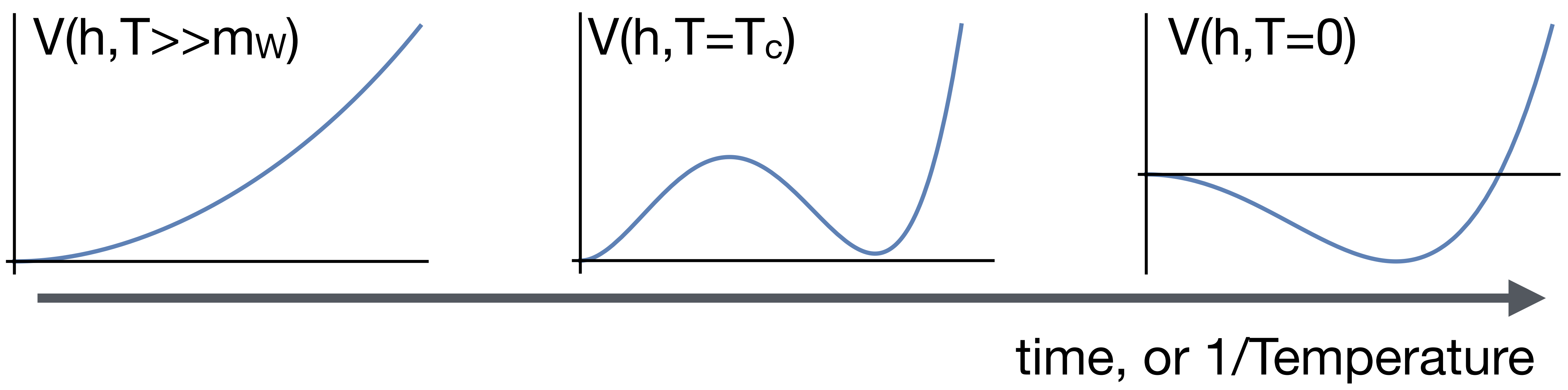

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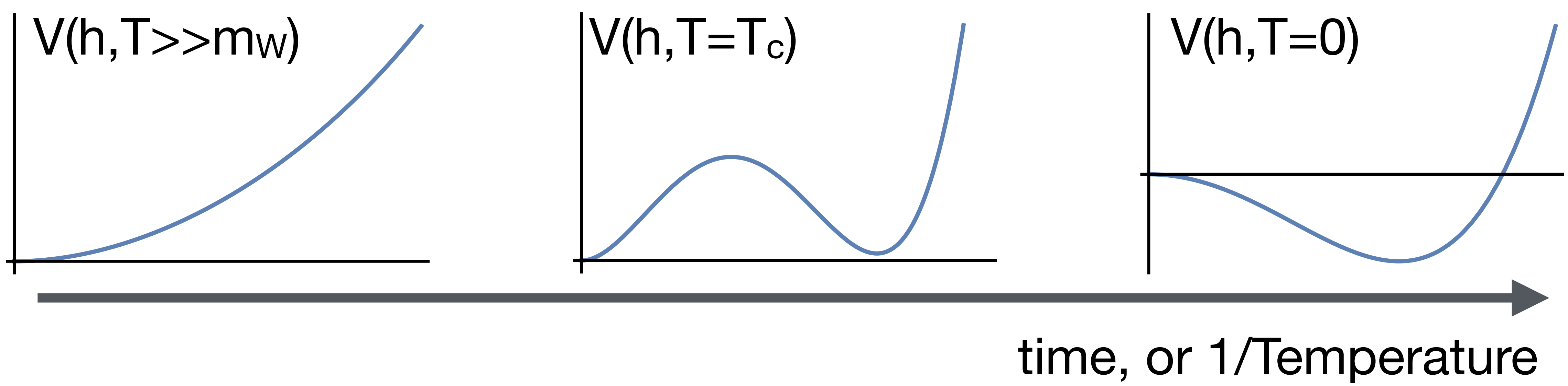

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SM quartic λ=0.13 more than 2 times larger.

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Needs BSM states coupled to Higgs. Since Higgs potential modified, connection with **trilinear Higgs**.

EW Baryogenesis

A benchmark scenario is the scalar singlet: [arXiv:1606.09408 + ref.s]

$$V(H,S) = -\mu^2\left(H^\dagger H\right) + \lambda\left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right)S + \frac{a_2}{2}\left(H^\dagger H\right)S^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4 \quad .$$

Also benchmark for other BSM [see arXiv:1807.04743 + ref.s]

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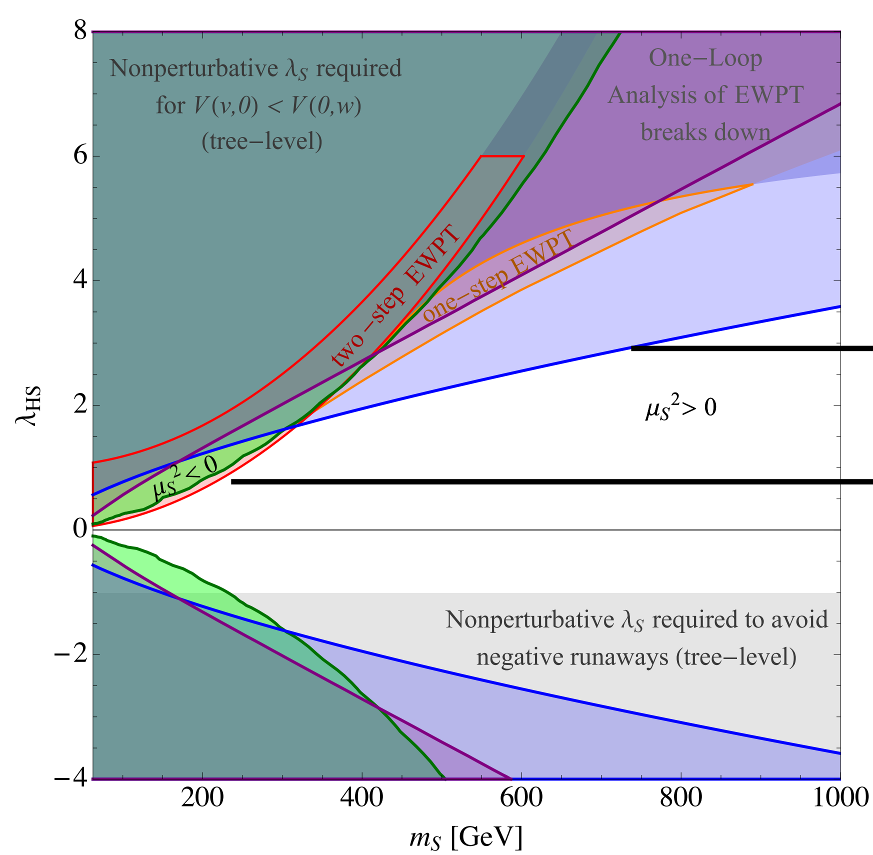
Signatures are WW>SS (or S) and modified couplings.



Modified H 3-linear (FCC reach)

SS production (FCC reach)

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The FC must allow for extensive measurements program:

- **Guaranteed outcome**
- **Indirect BSM** (reach above collider threshold)
- **Characterise discoveries**

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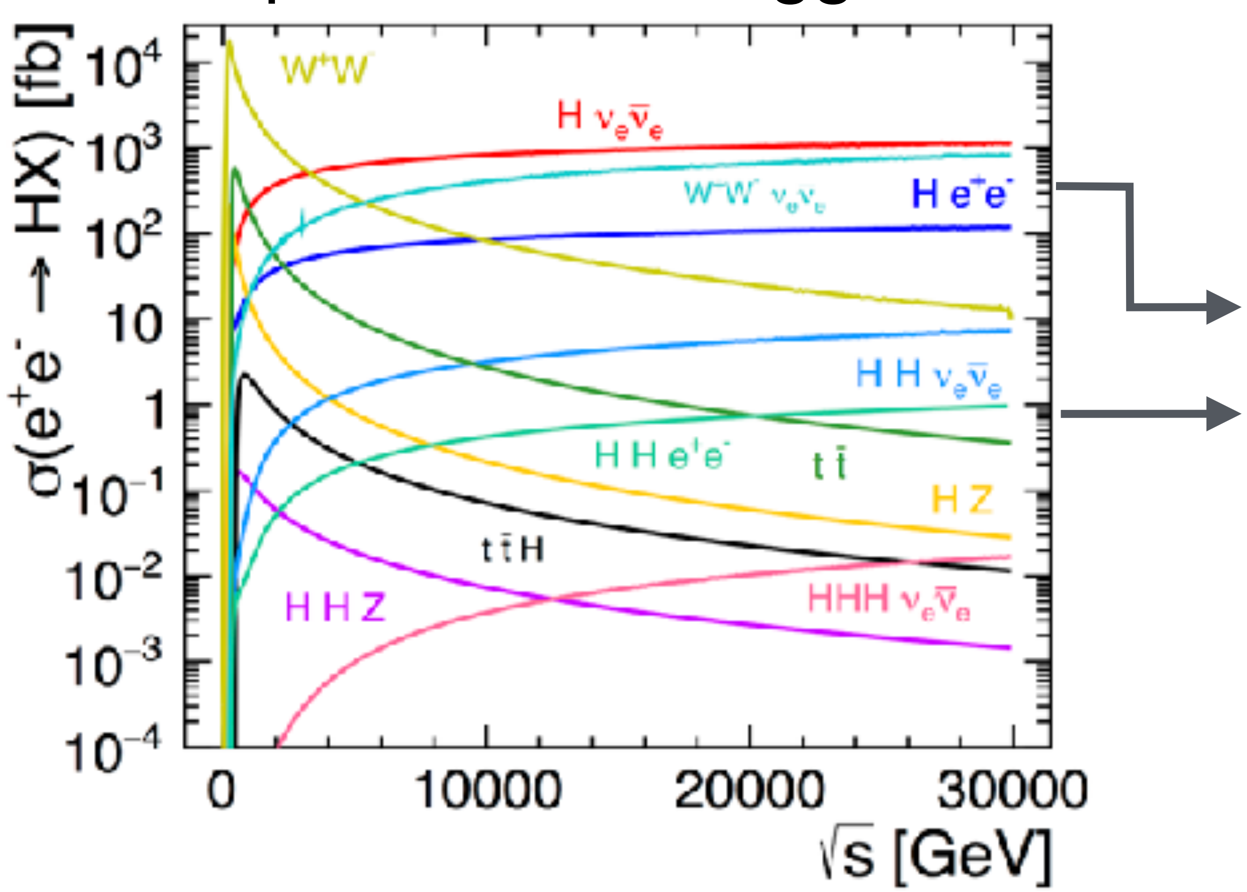
Higgs couplings are **central**

lepton collider Higgs XS



VV-fusion single and double Higgs channels are huge!

Due to **Effective W emission.**

Refs:

S. Dawson Nucl.Phys. B249 (1985) 42-60

refs in arXiv:1807.04743 [application to μ-coll.]

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

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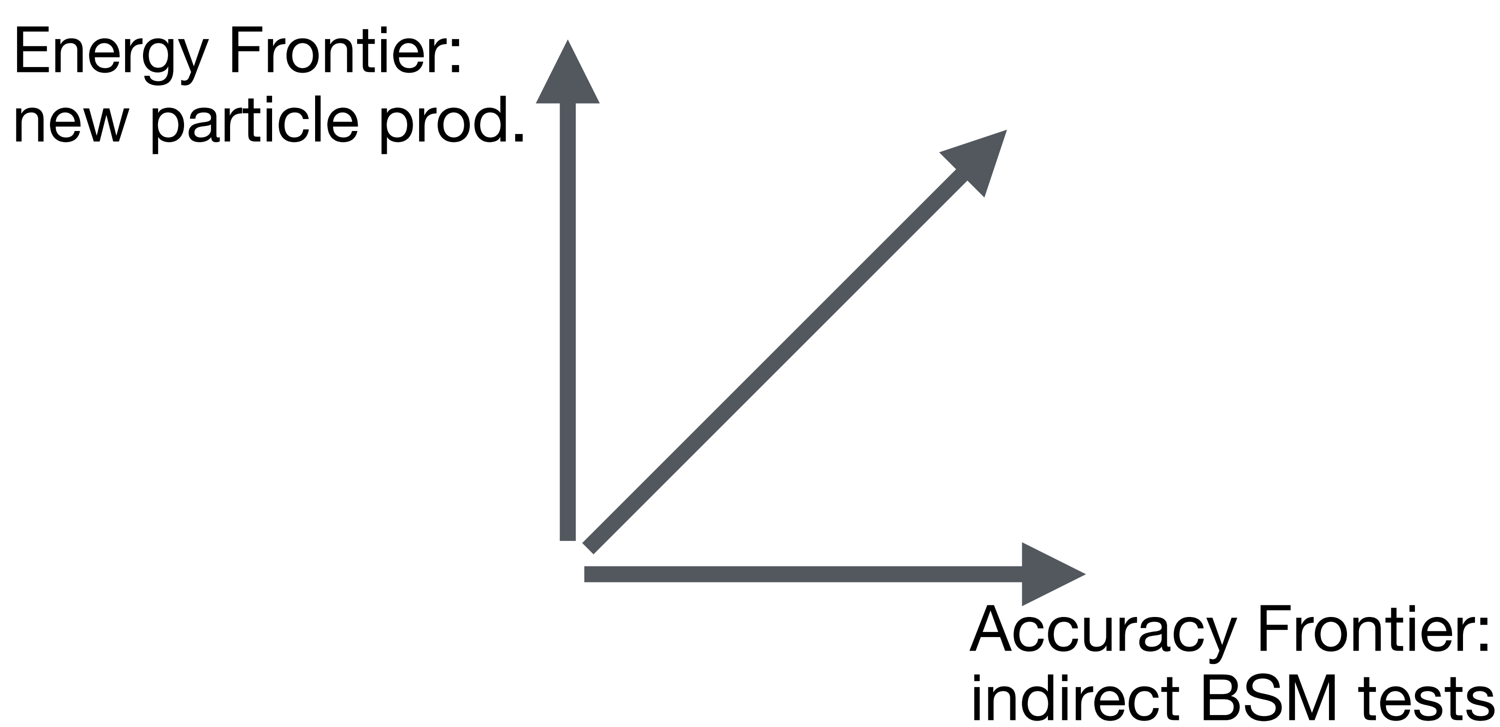
The Energy and Accuracy Frontier



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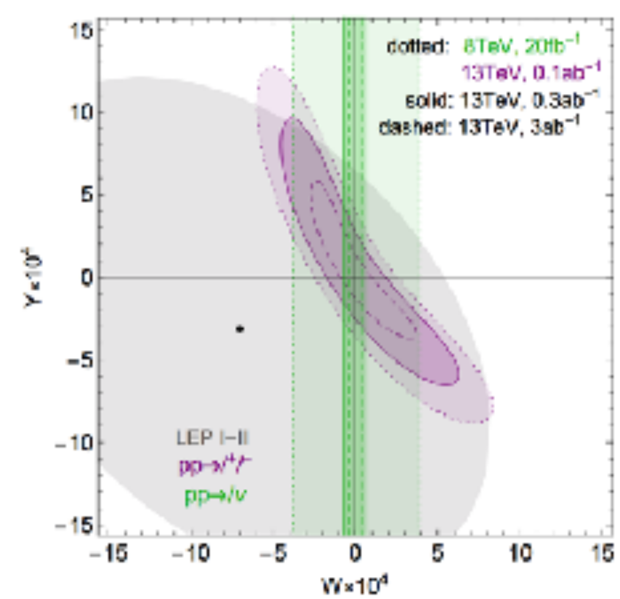
This is why LHC can beat LEP EWPT: [arXiv:1609.08157]



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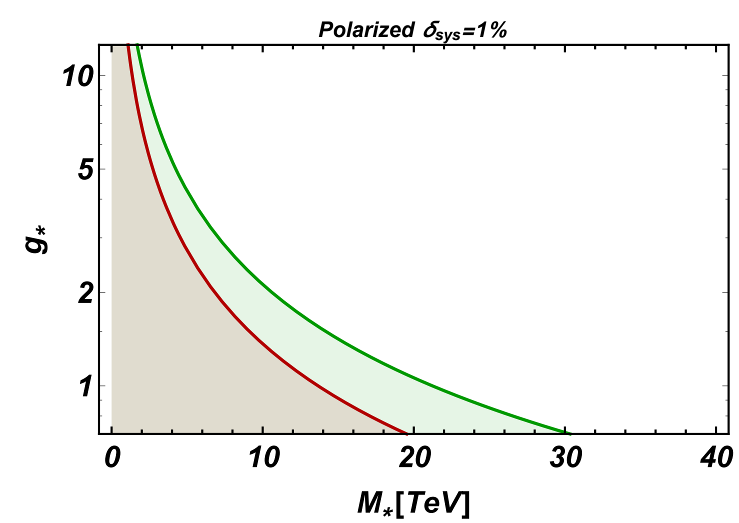
And why **CLIC@3TeV** can probe **30 TeV** scale!



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

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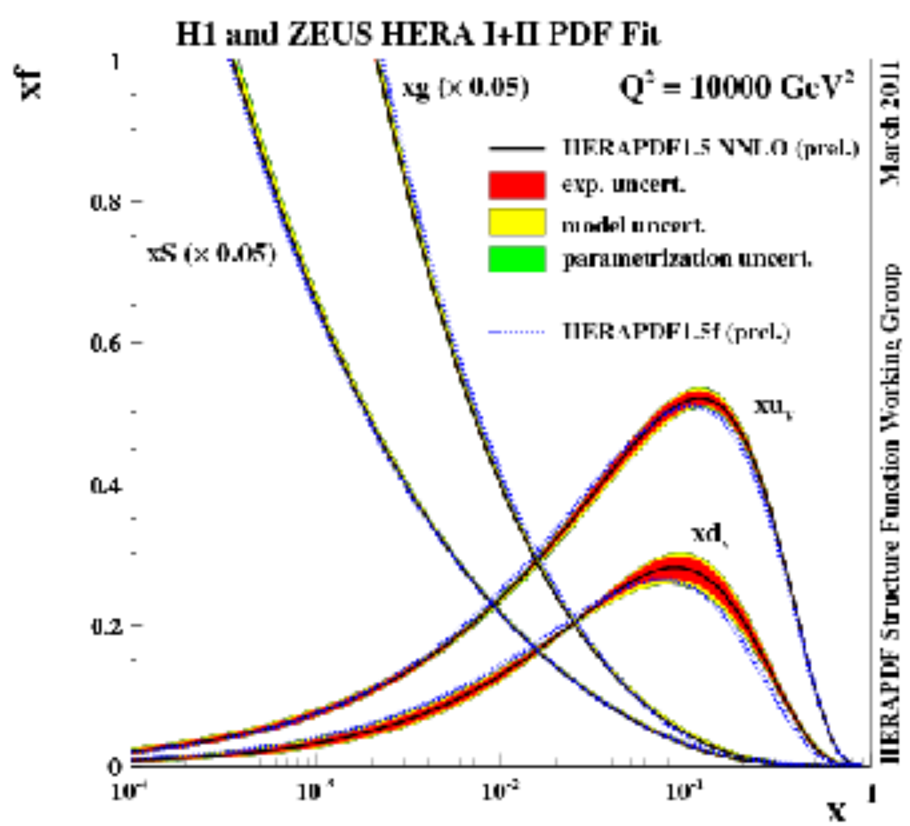

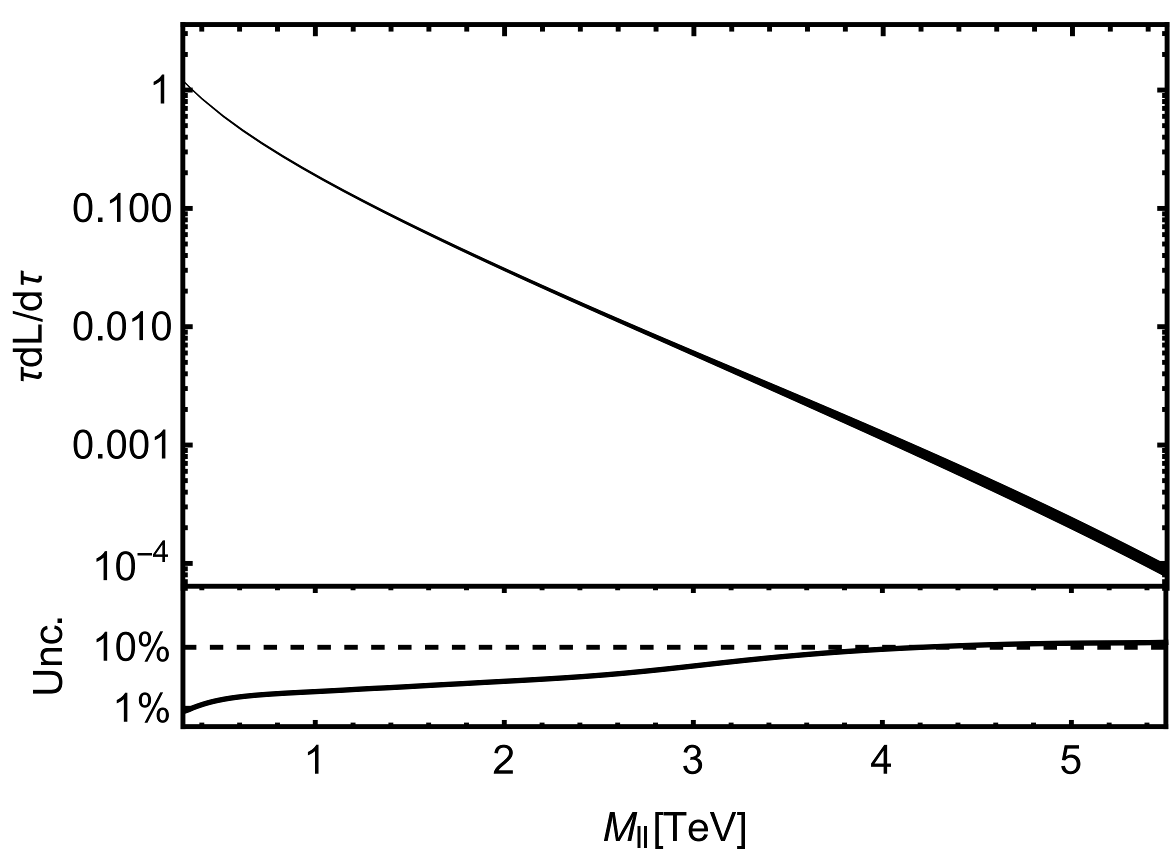

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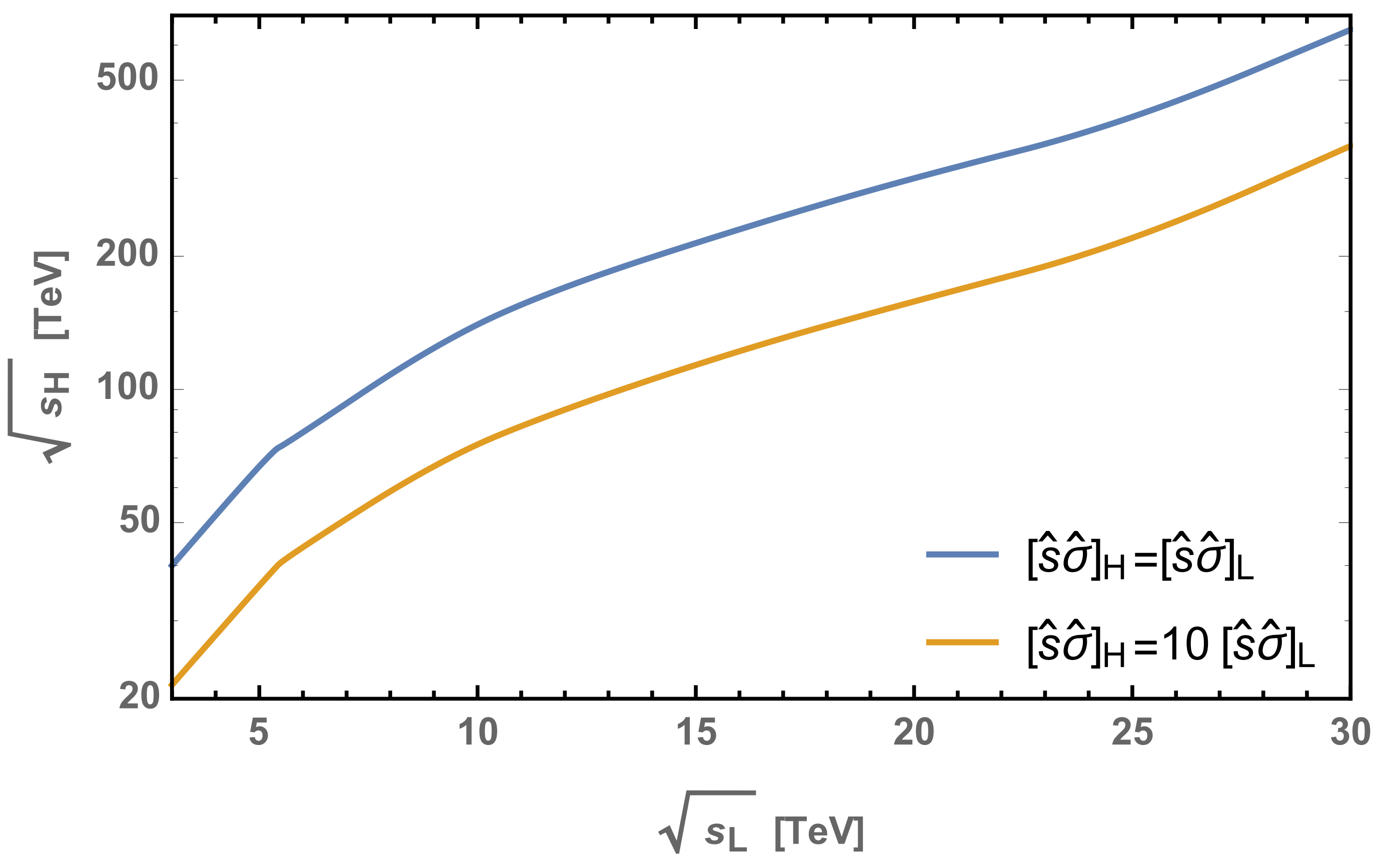

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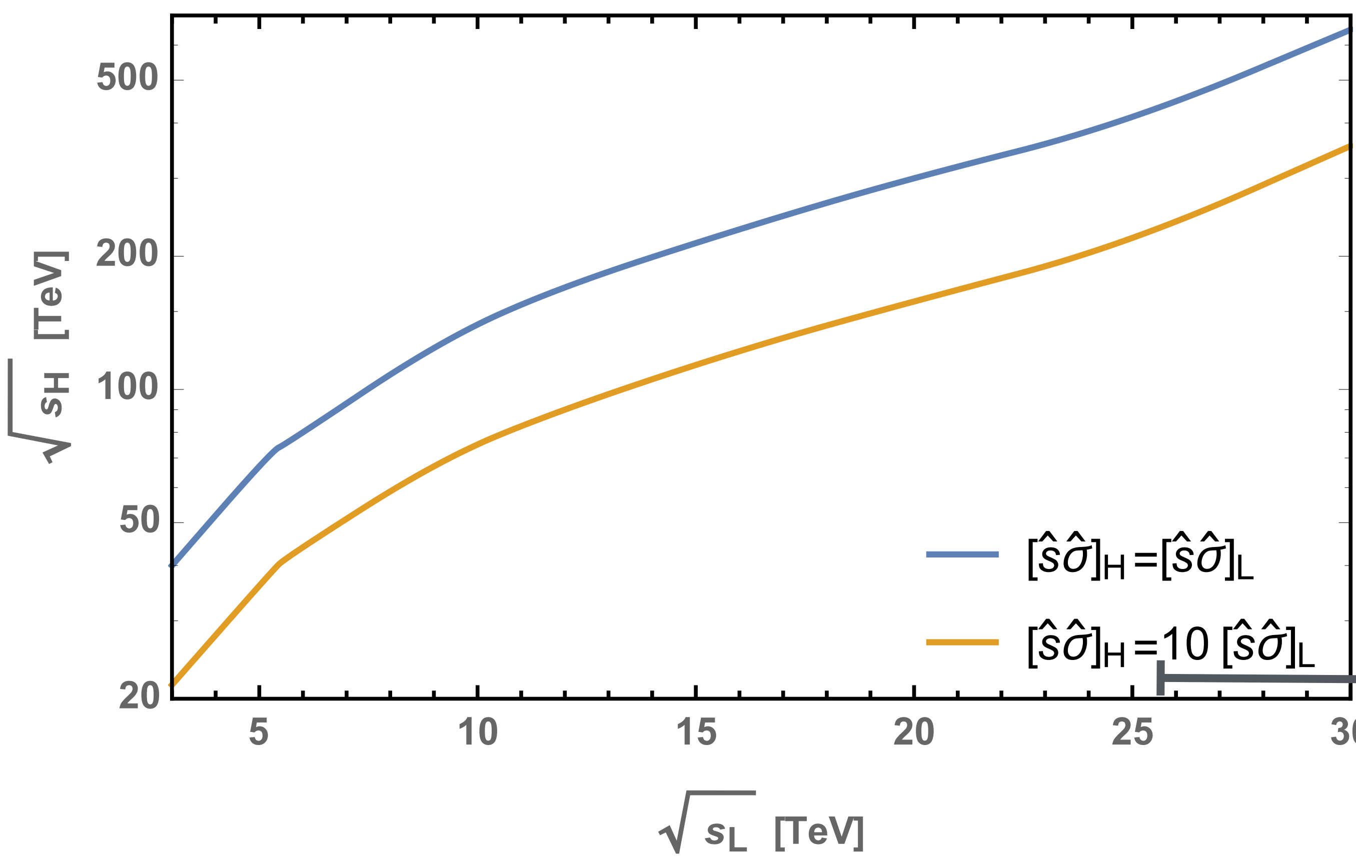

QCD-coloured BSM can easily have much larger partonic XS.

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

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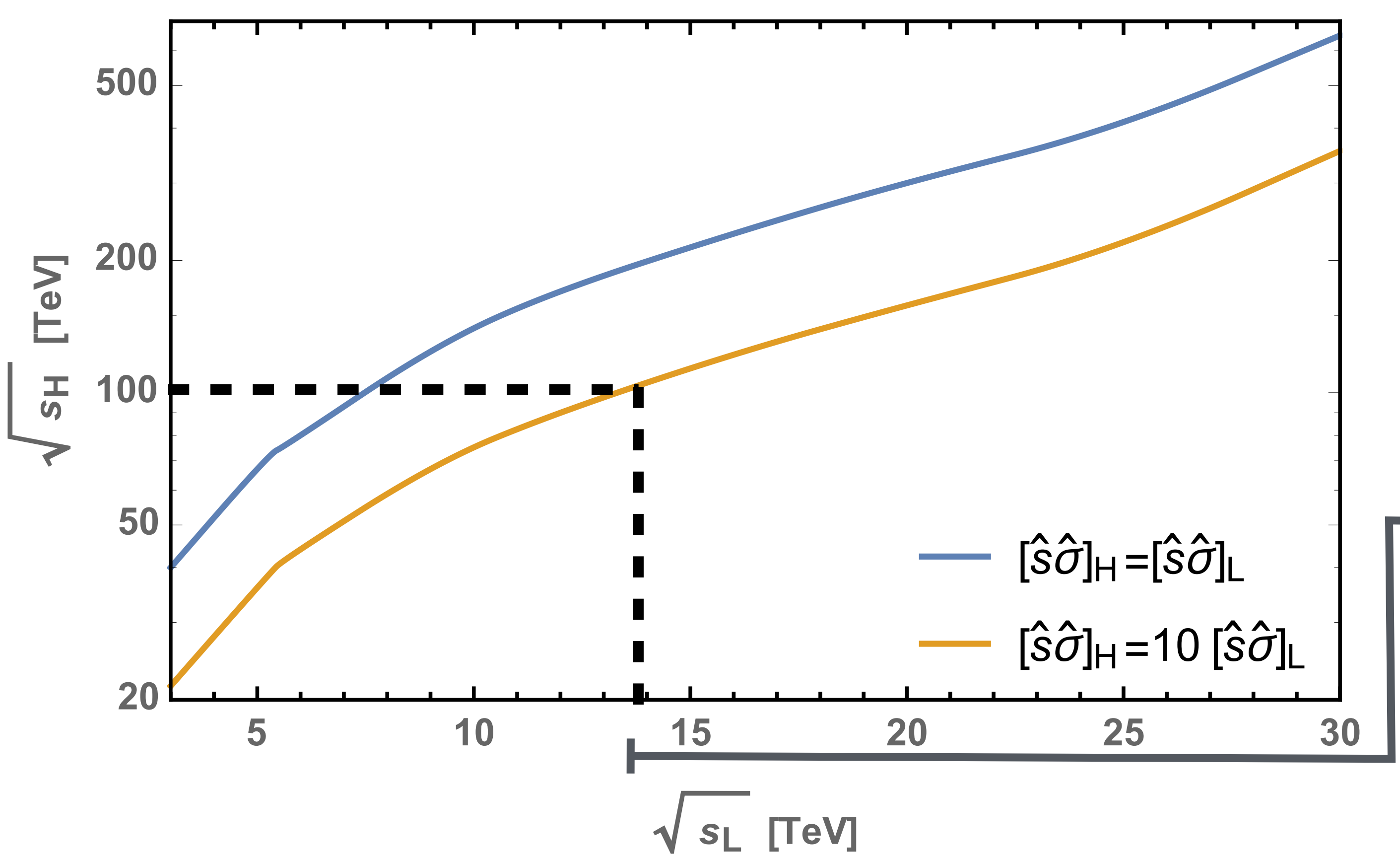


QCD-coloured BSM can easily have much larger partonic XS.

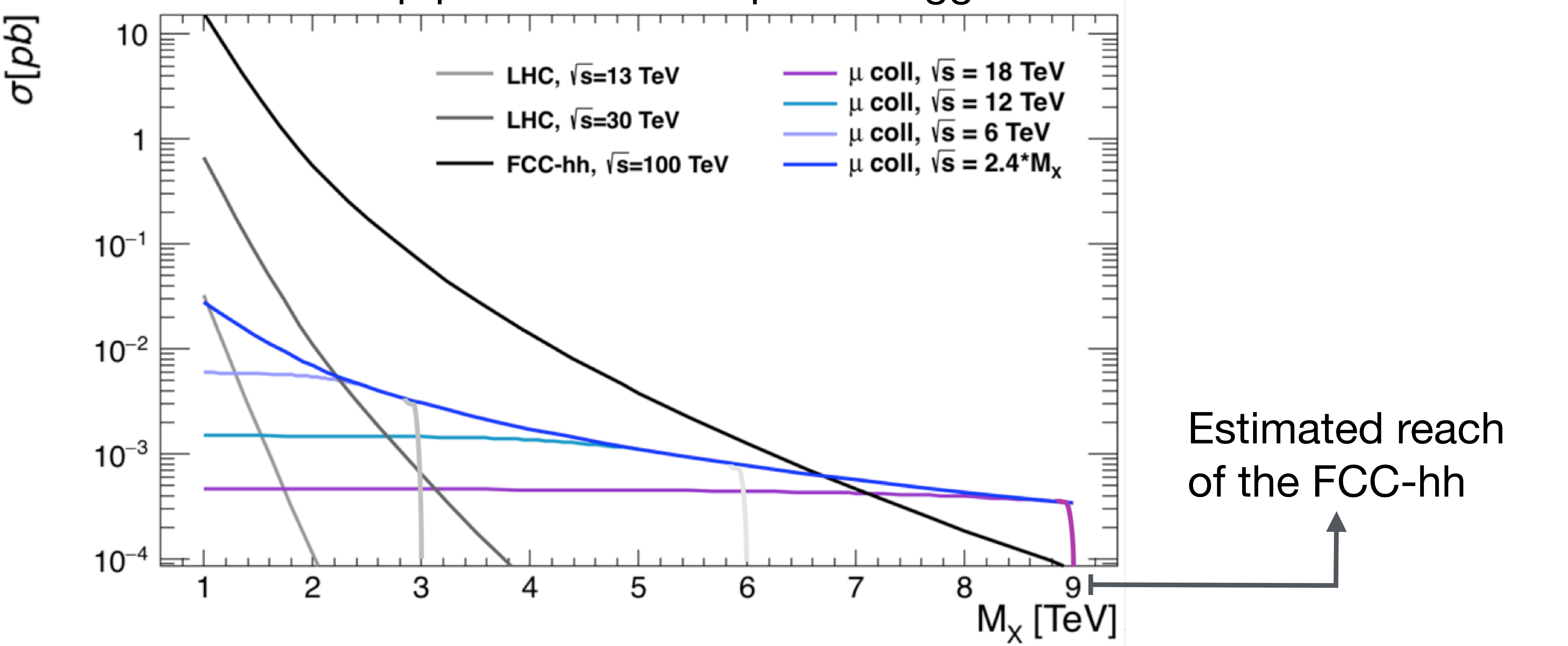
Comparison even more favourable for **QCD-neutral BSM**

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

Muon Colliders

Plenty of examples can be made to refine the claim

Fermionic top partners in Composite Higgs:



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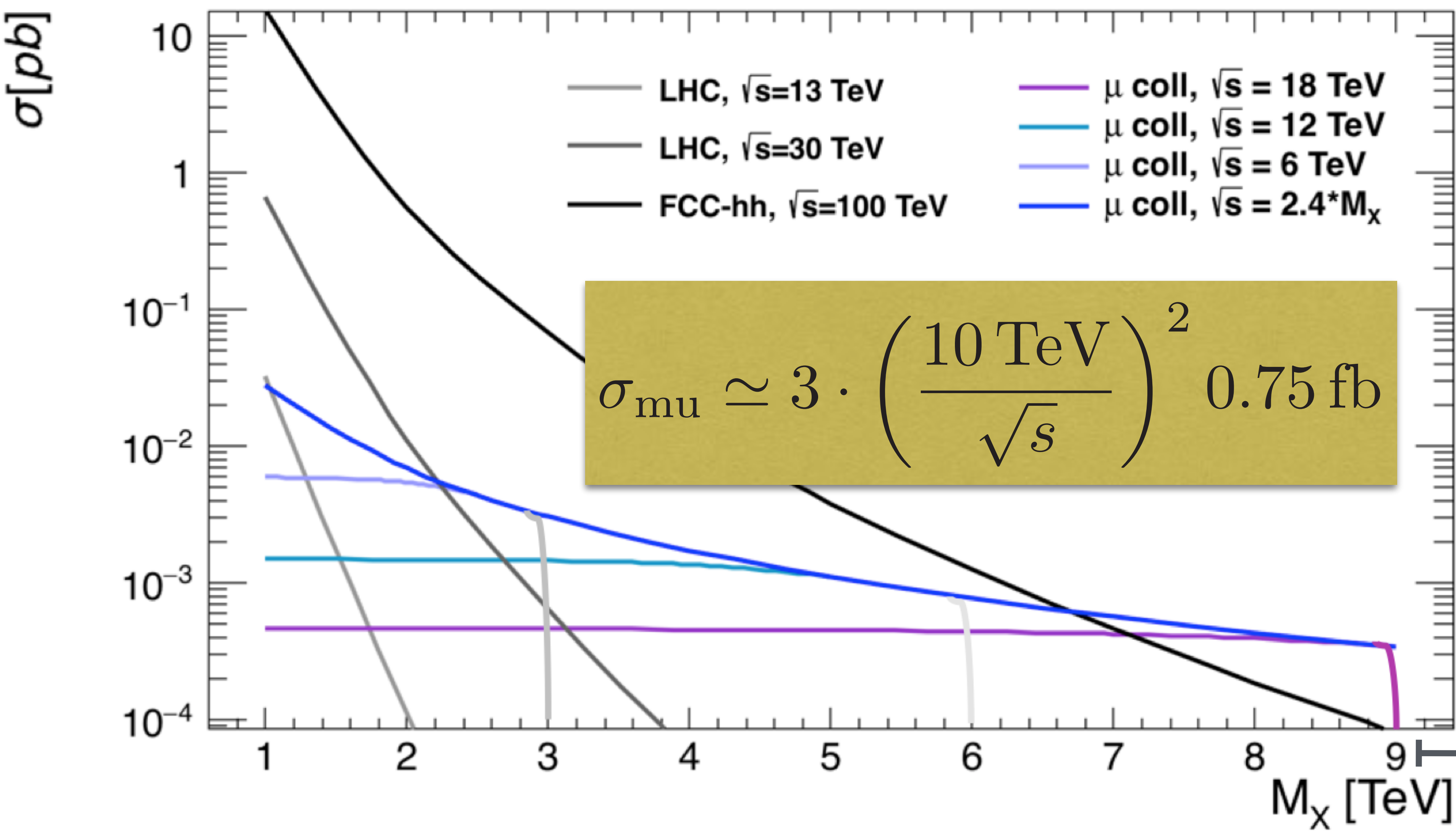

$$\sigma_{\rm mu} \simeq 3 \cdot \left(\frac{10\,\mathrm{TeV}}{\sqrt{s}}\right)^2 0.75\,\mathrm{fb}$$

Estimated reach of the FCC-hh

Analogous results for **SUSY Stops/Squarks.**

Muon Colliders Requirements Specification

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0) Reach interesting energies:
   10 TeV >> LHC; 14 TeV ~ FCC-hh; 30 TeV = amazing

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   10 TeV >> LHC; 14 TeV ~ FCC-hh; 30 TeV = amazing
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   simple estimate for 2 → 2, but what about WW scattering, HH prod?

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Muon Colliders Requirements Specification

The muo

0) Reac … 10 Te

1) Run … ^{1}/(5yrs)

“reaso … cts!

2) Pair … suffici … s/stops)

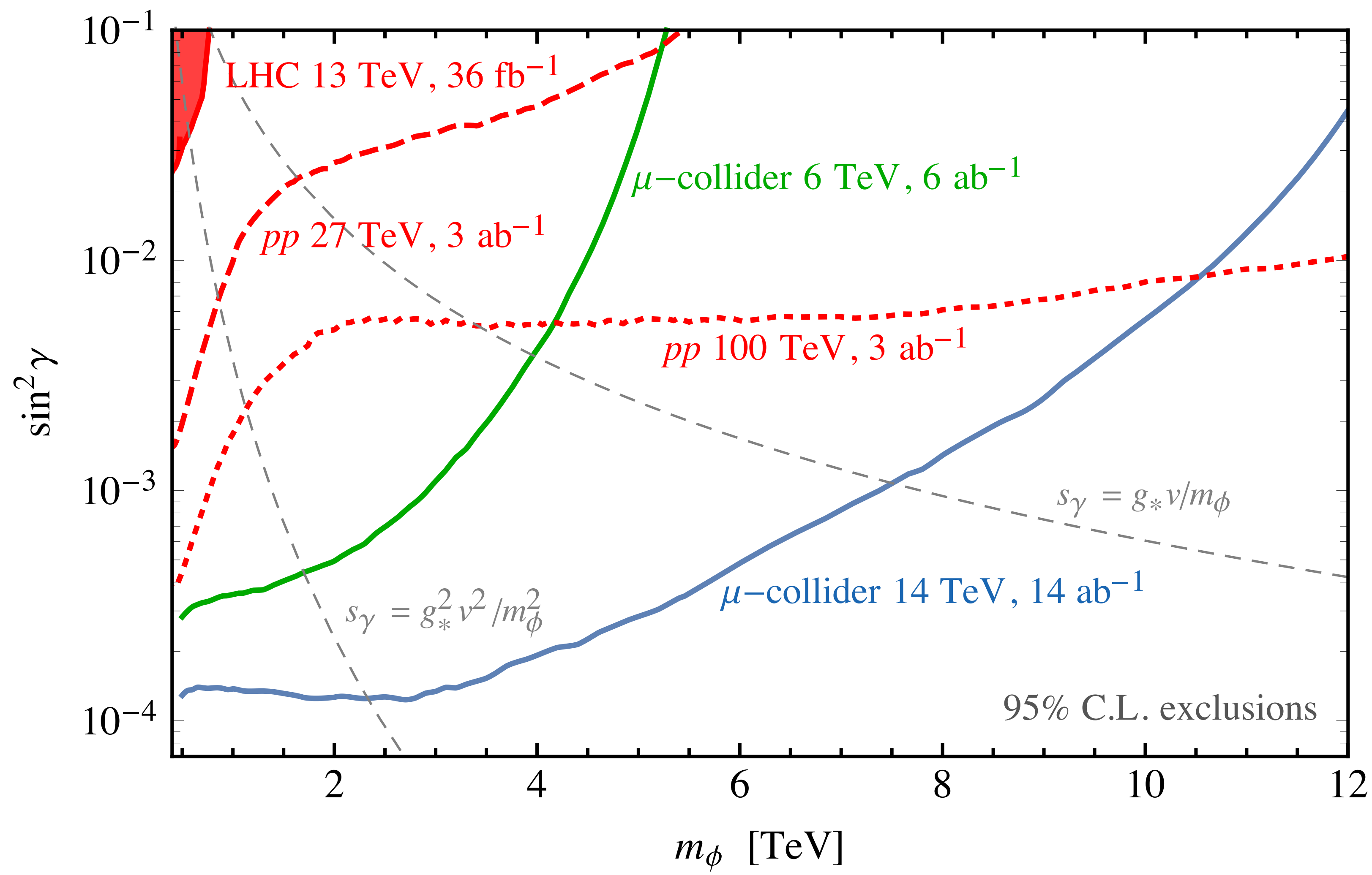
$N = 400$ … $10^{34}\mathrm{cm}^{-2}s^{-1}$

3) Meas … 00

simple … H prod?

The first “New μ-coll.” reach projection:

[arXiv:1807.04743]



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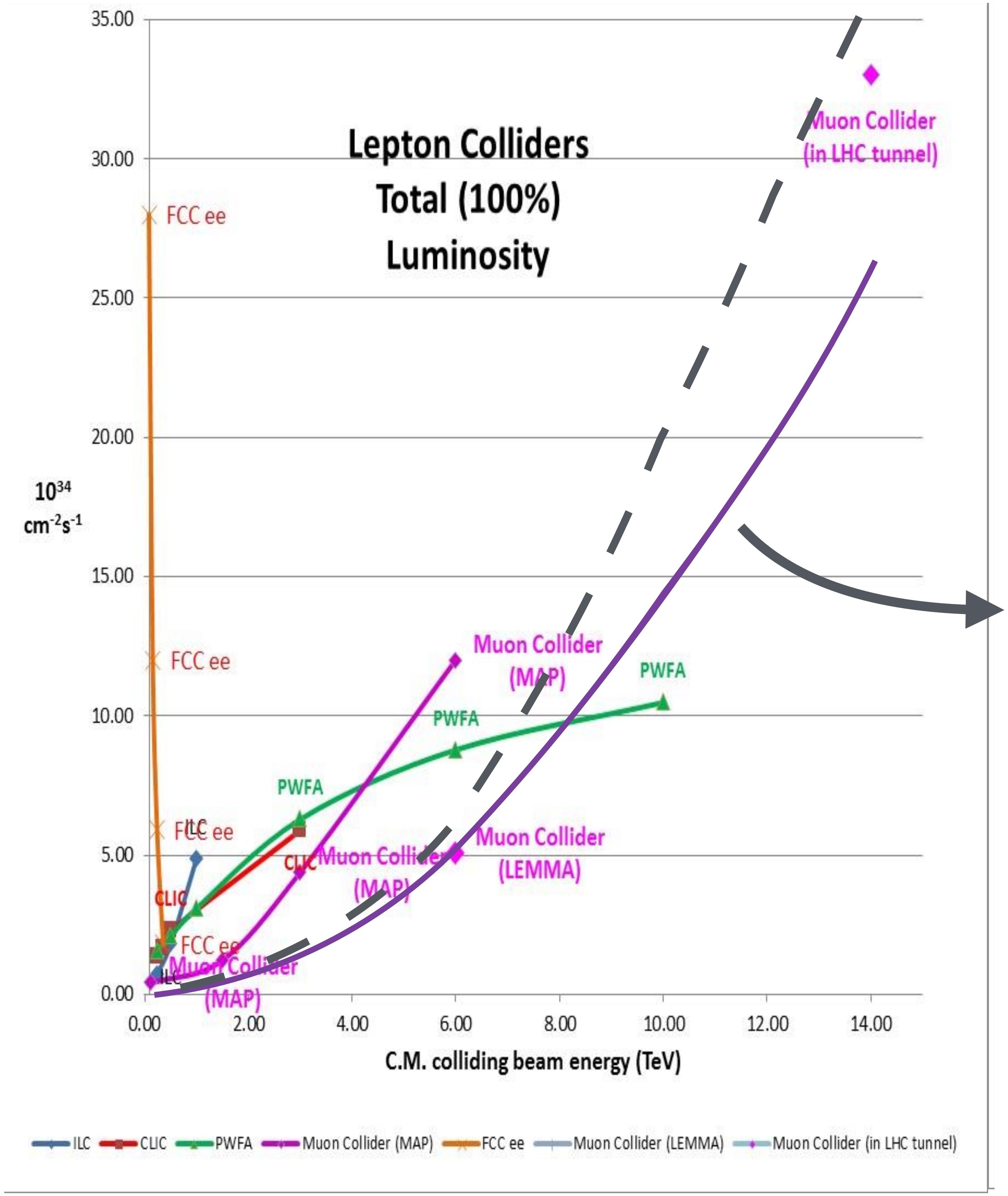

Both MAP and LEMMA claim they can make it

Low
Emittance
Muon
Muon
Accelerator

Muon Colliders Requirements Specification

But also:

5) Comply with radiation limit from neutrino flux

   lower emittance = less ν = less radiation

   not quite enough. **Rolandi's pipe**? [CERN-TIS-RP-IR-98-34]

6) Produce low enough background level

   again pointing towards low emittance

Conclusions

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1. Decent physics case only if no other lepton collider is built before
2. Poses significant extra challenges
3. Impossible with LEMMA. On the other hand, LEMMA requires ~45GeV=$m_Z/2$ high intensity positron beam …

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Can we dream of it? If we can, **long ToDo list:**

- Reach on pair-produced EW particles with "easy" decay mode
- EW particles with "invisible" (or long-lived) products: Minimal DM
- WW>whatever (eg., SS)
- Higgs couplings (beam background assessment crucial)
- Energy and Accuracy in SM measurements (ff, VV, **VBS**)
- … new ideas!

Conclusions

Muon collider: Dream or Reality?

Backup

Result of the coupling (a.k.a. κ) fit

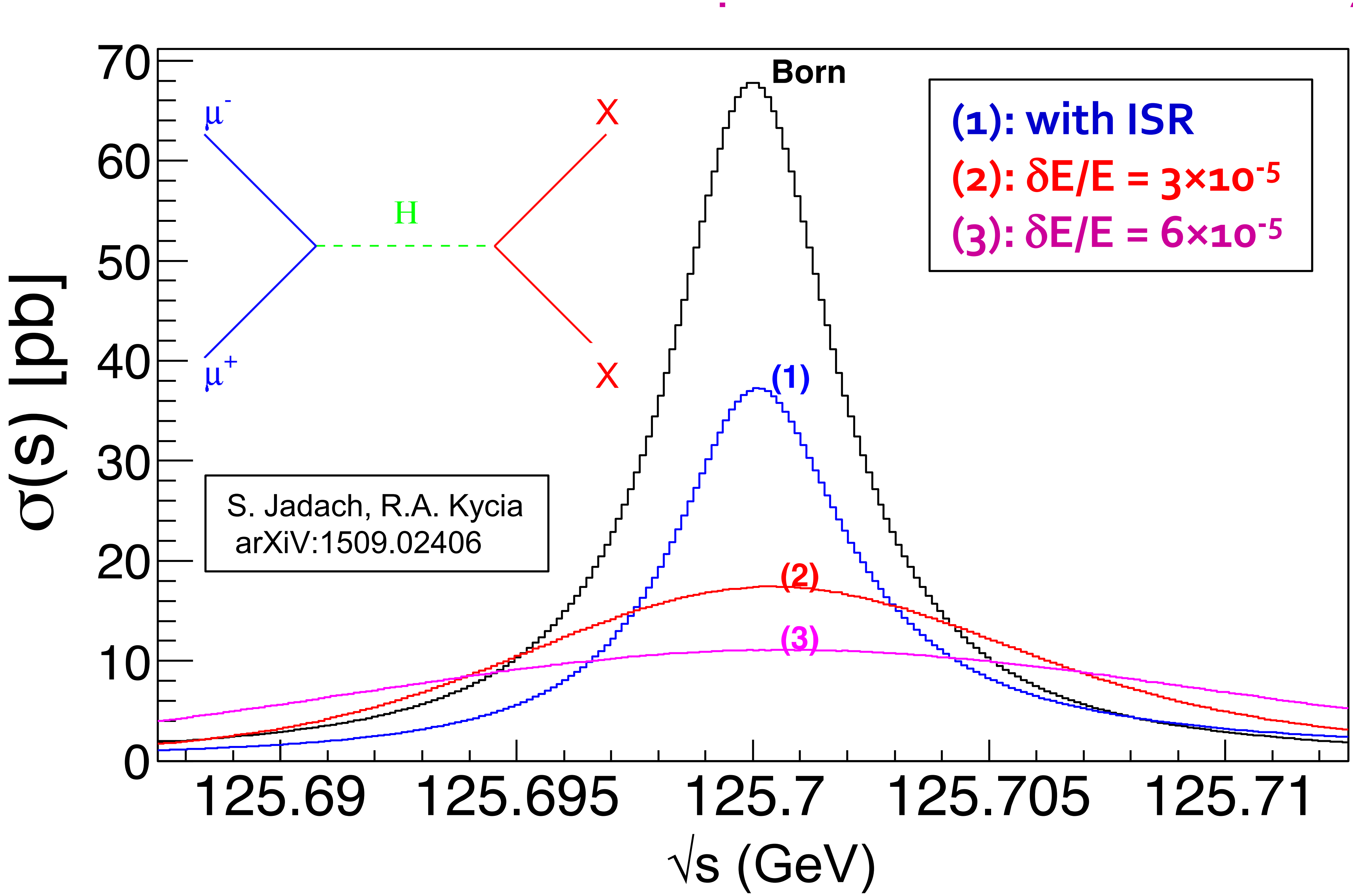
- Comparison(*) with other lepton colliders at the EW scale (up to 380 GeV)

13	μ $Coll_{125}$	ILC_{250}	$CLIC_{380}$	$LEP3_{240}$	$CEPC_{250}$	$FCC\text{-}ee_{240}$	$FCC\text{-}ee_{365}$
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

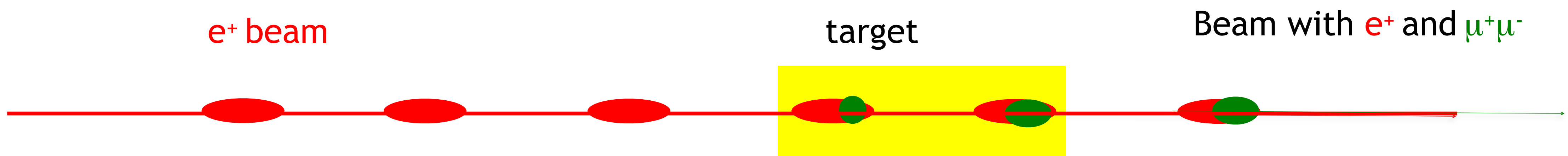
(*) Green = best
Red = worst

Backup

μ-coll s-channel Higgs: arXiv:hep-ph/9504330



Backup



Ideally muons will *copy* the positron beam

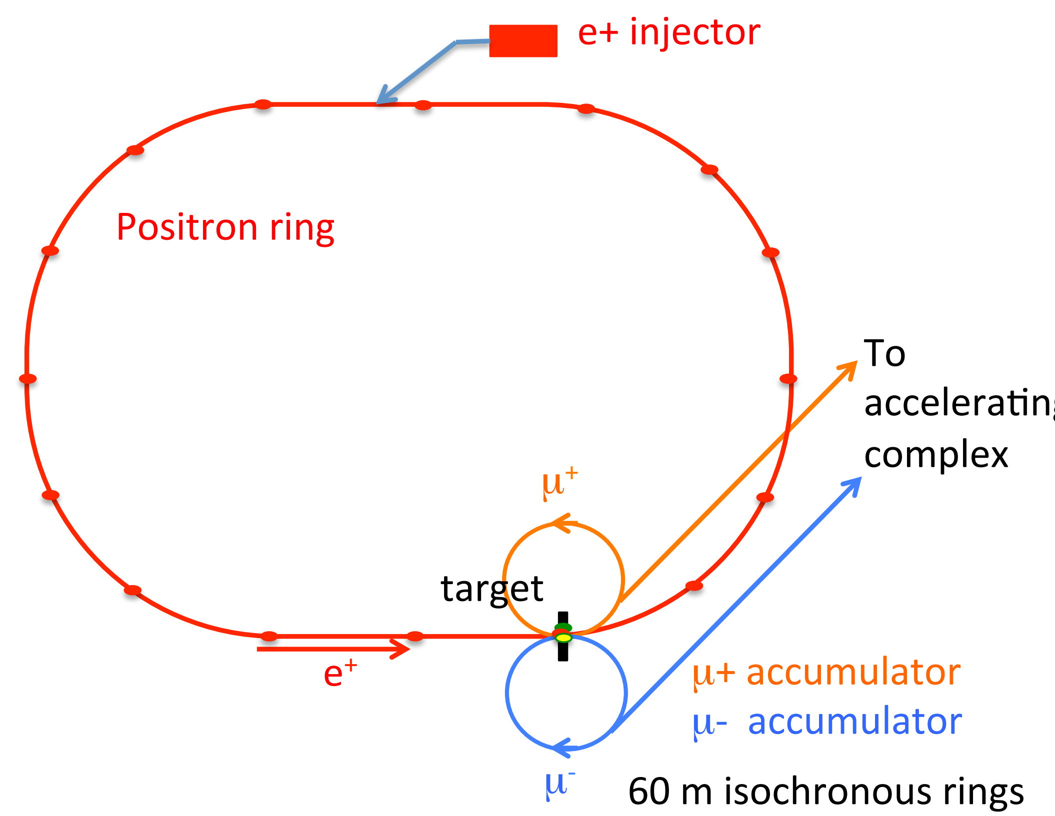
Low emittance μ from e^+ on target

[Antonelli, Boscolo, di Nardo, Raimondi, 2016]

- avoids cooling
- few circulating μ ➡ little radiological hazard and machine bckg.

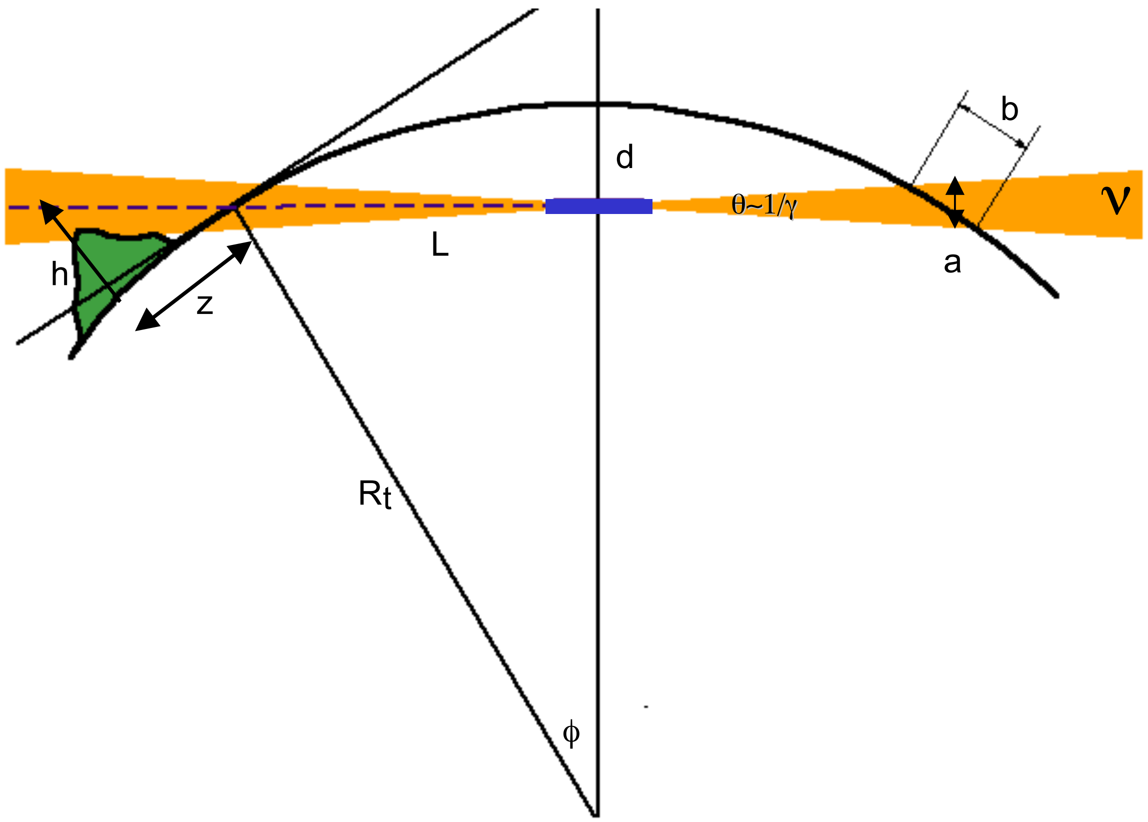
Challenges:

- e^+ source (embedded?)
- target breakdown
- top up muons?



Backup

Radiological Hazard



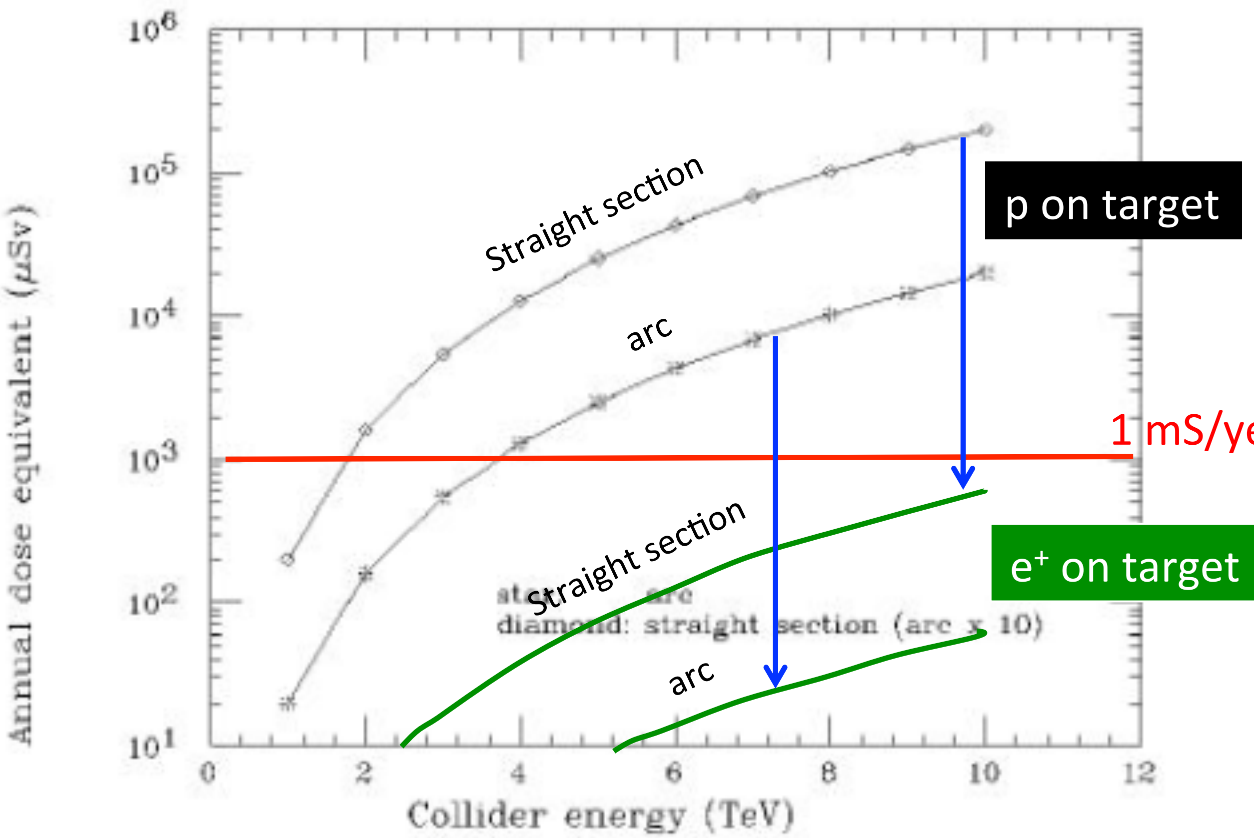


Fig. 1. Dose equivalent due to neutrino radiation at 36 km distance (collider at 100 m depth)

Helicoidal Orbits??
Rolandi's pipe??

What if Un-Natural?

(Un-)Naturalness **discovery** has **profound implications**

- **Crucial** to make our best with LHC phenomenology and model building.
- Any **loophole?** [Twin Higgs, Folded SUSY, compressed spectra …]

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If Un-Natural, m_H has no **microscopic** origin (e.g. $\neq G_F$).

It could:

- be a fundamental input par. of the Final Theory
- have **environmental anthropic** origin
- have **dynamical** (set by time evolution) origin

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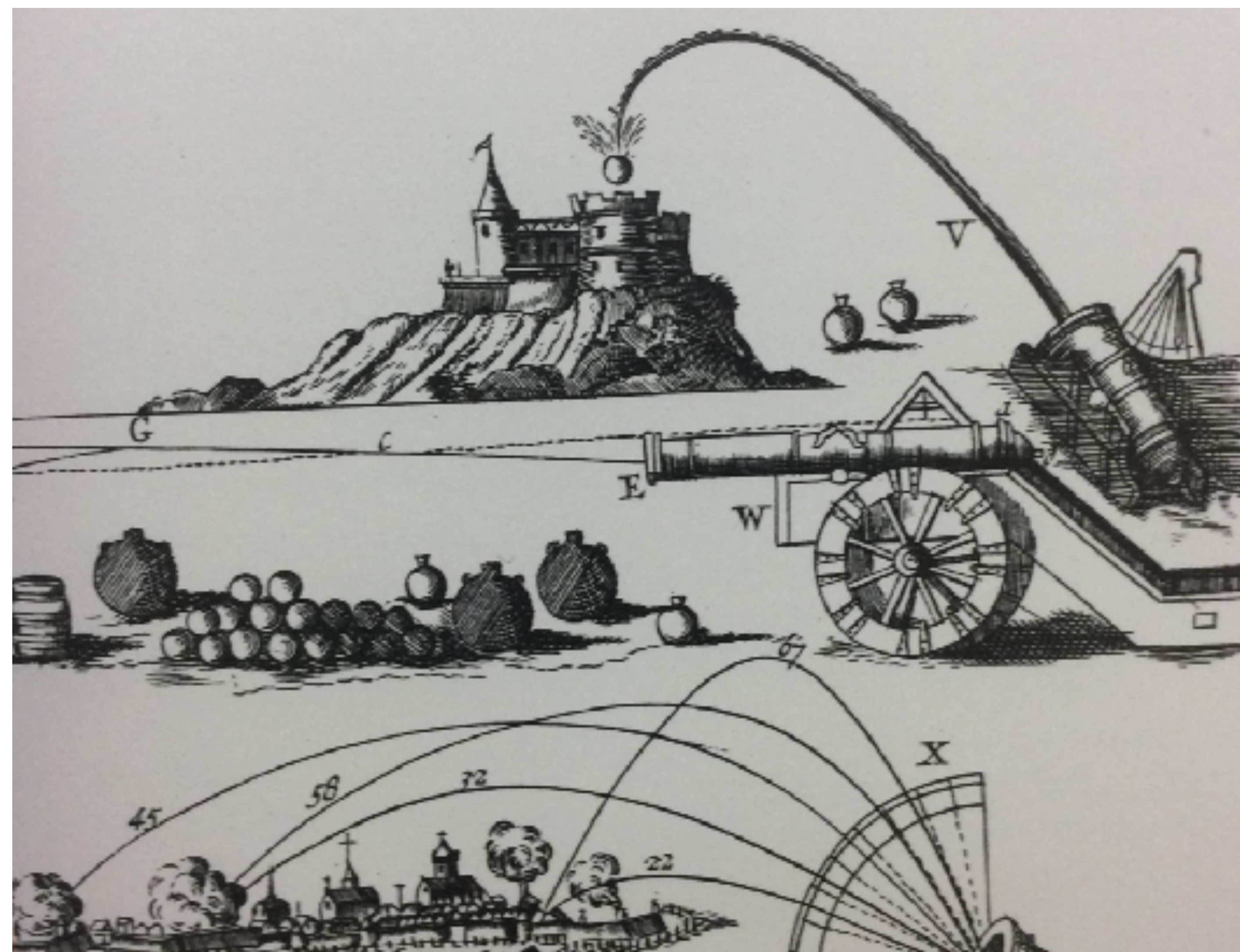
Example is gravity of Earth $\mathbf{g} = 9.81\mathrm{m}/\mathrm{s}^2$. Fundamental input parameter of the theory of **Ballistics**.



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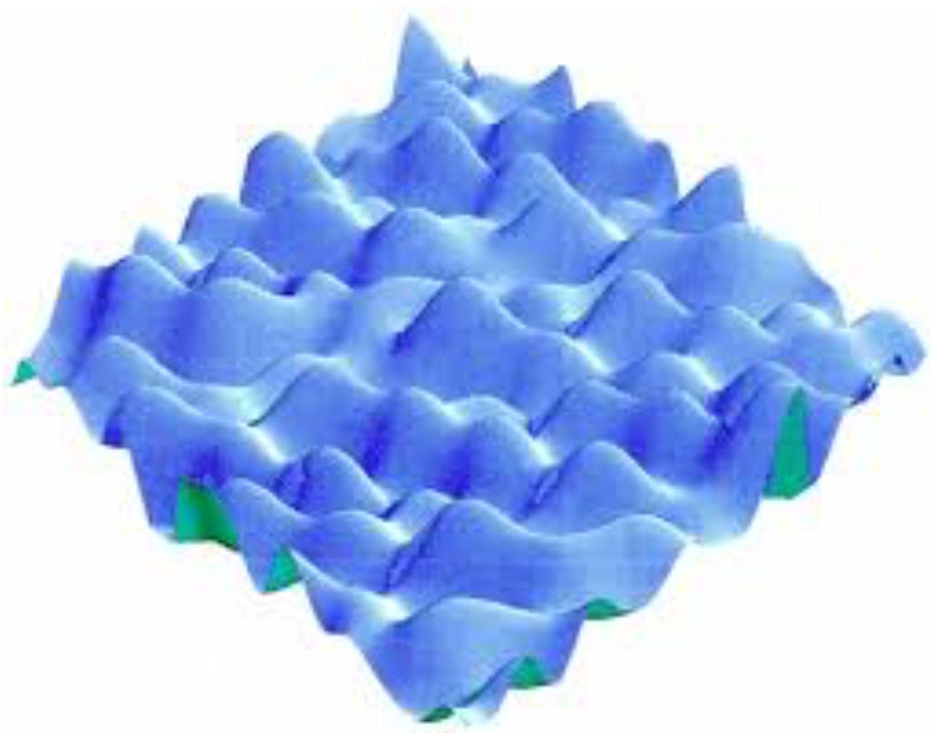

Landscape of vacua

Higgs mass depends on the vacuum where we live.

Not quite like g. Vacua are **causally disconnected**. Cannot go there and check.

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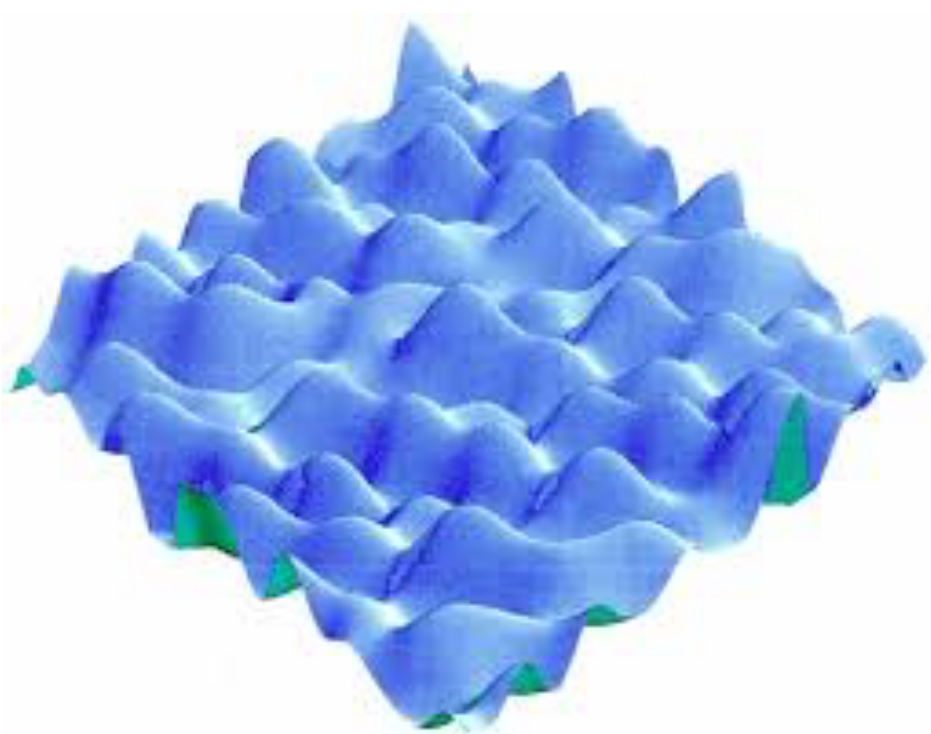

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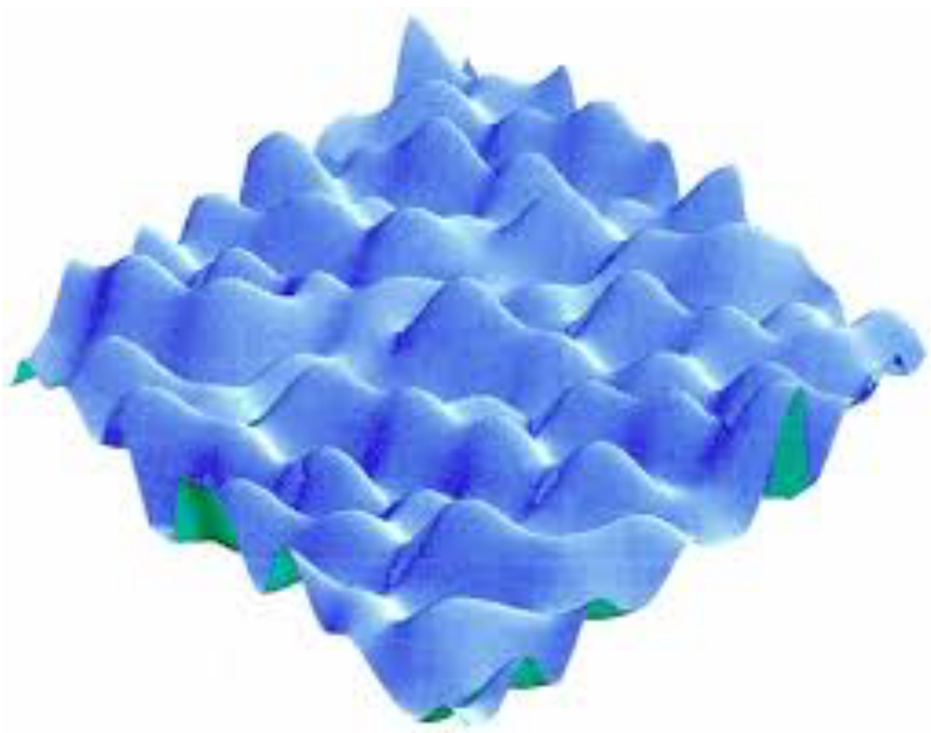

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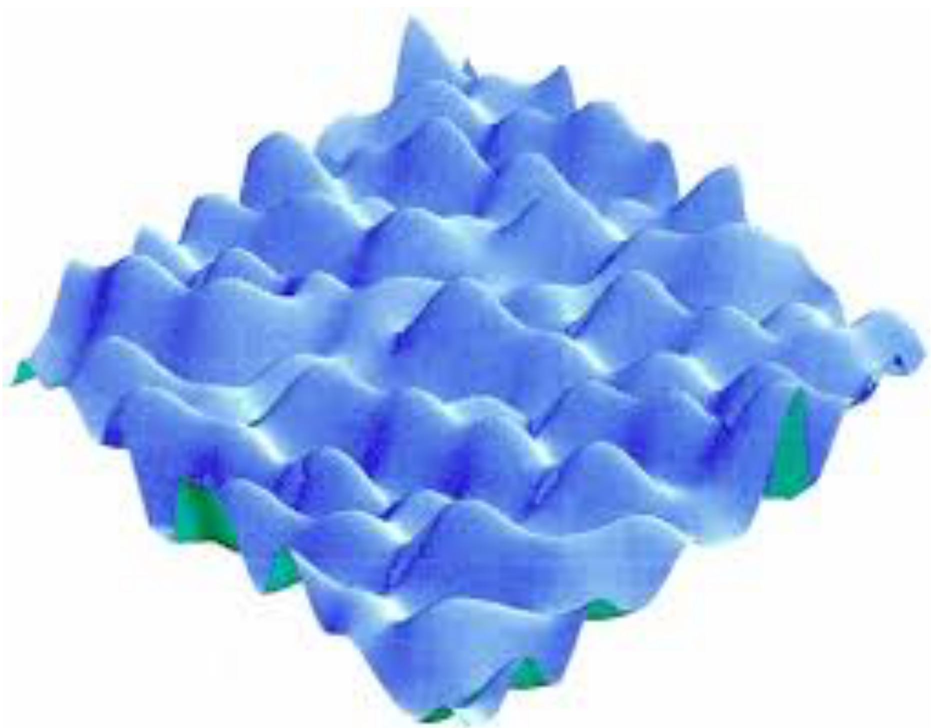

Landscape of vacua

We live where we can. There might be **upper bound** on m_H for us to exist.

Landscape distribution peaks at Λ_{SM}, but has a tail. Likely to live **close to the upper bound**.

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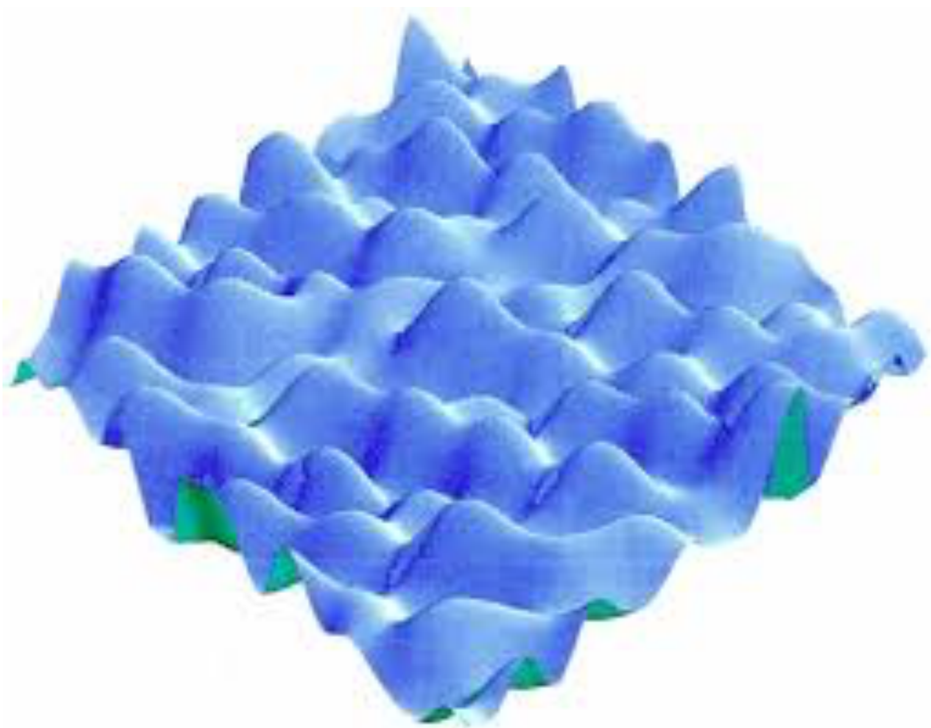

Landscape of vacua

Successful Weinberg prediction of the Cosmological Constant:

For galaxies to form, it must be:

$$\Lambda_{\rm c.c.} \lesssim ({\rm few} \cdot 10^{-3}{\rm eV})^4 \sim 10^{-120} M_P^4$$

Observed value:

$$\Lambda_{\rm c.c.} \simeq (2 \cdot 10^{-3}{\rm eV})^4$$

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[Graham, Kaplan, Rajendran, 2015]

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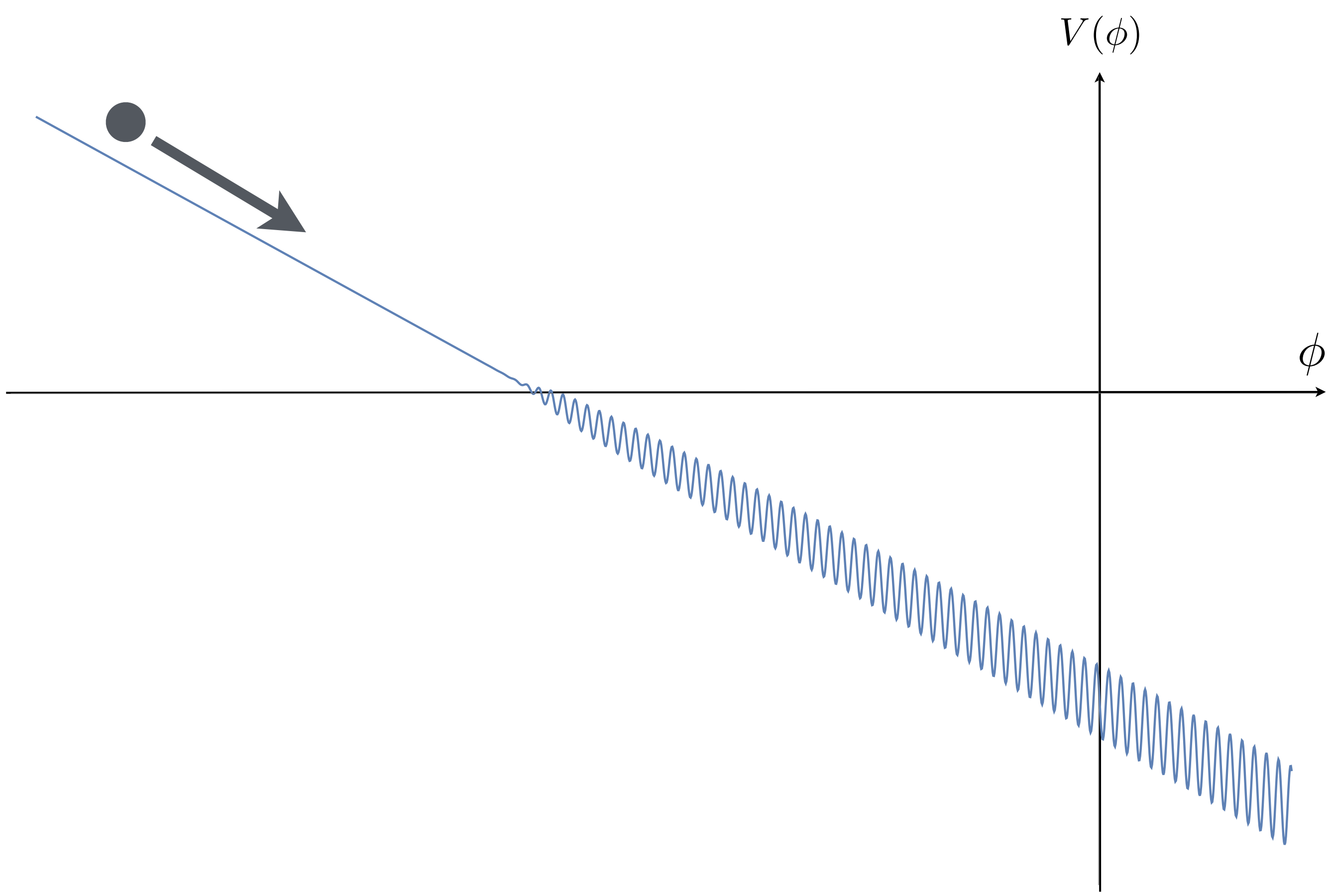
Field-dependent Higgs mass **Proportional to Higgs VEV**

$$(-M^2 + g\phi)|h|^2 + \left(gM^2\phi + g^2\phi^2 + \cdots\right) + \Lambda^4\cos(\phi/f)$$



Field rolls during Inflation.

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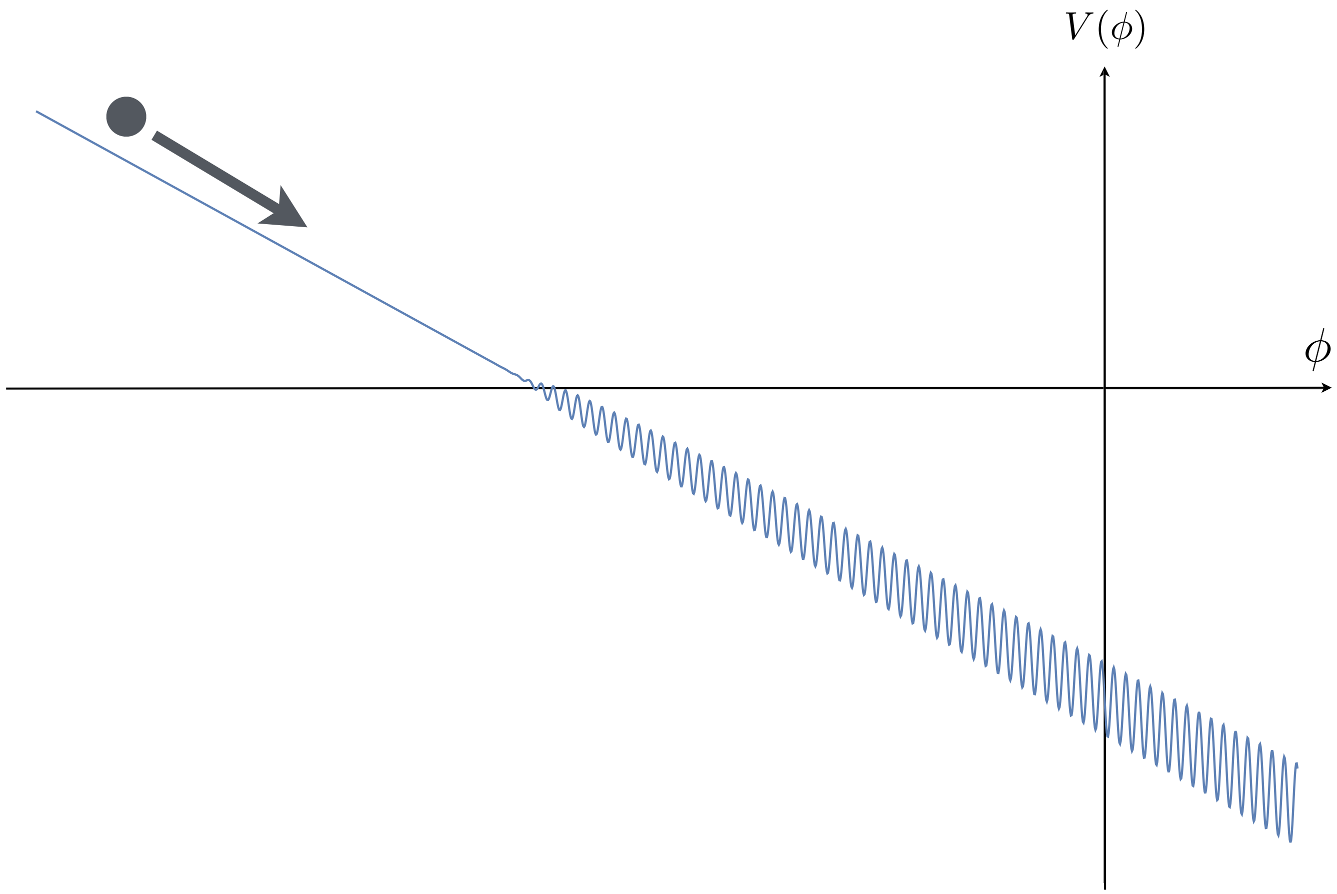

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Viability of large field excursion requires ad hoc mechanism like **Clockwork** [Kaplan, Rattazzi & Choi, Kim, Yun]

What if Un-Natural?

One can like/believe these radical speculations or not.

One can argue that they involve too much complexity to produce a concrete BSM scenario.

One can hope in UV physics “obeying different rules”, nullifying Naturalness problem, but concretely what?

All this shows the **dramatic impact** Un-Naturalness discovery is having on our field.