Landscape
Physics Opportunities Ahead

David Marzocca

INFN Trieste

Powering tomorrow's discoveries: INFN Trieste in the European Strategy - 20/11/2024

Why?

The Big Open Questions in Fundamental Physics

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- What is the nature of **dark matter**?
- What is the origin of **neutrino masses**?
- Why does **QCD conserve CP**?
- What is the **origin of fermion masses** and mixings?
- Why the specific assignment of **charges** in the SM?
- Why is the **electroweak scale** smaller than the Planck scale? How is it stable?
- What is the origin of the **baryon asymmetry of the Universe**?
- What iduces the **accellerated expansion** of the Universe?
- What was the mechanism underlying **inflation**?
- How does **gravity behave at the quantum level**?

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Most of these **require physics beyond the Standard Model** to be addressed.

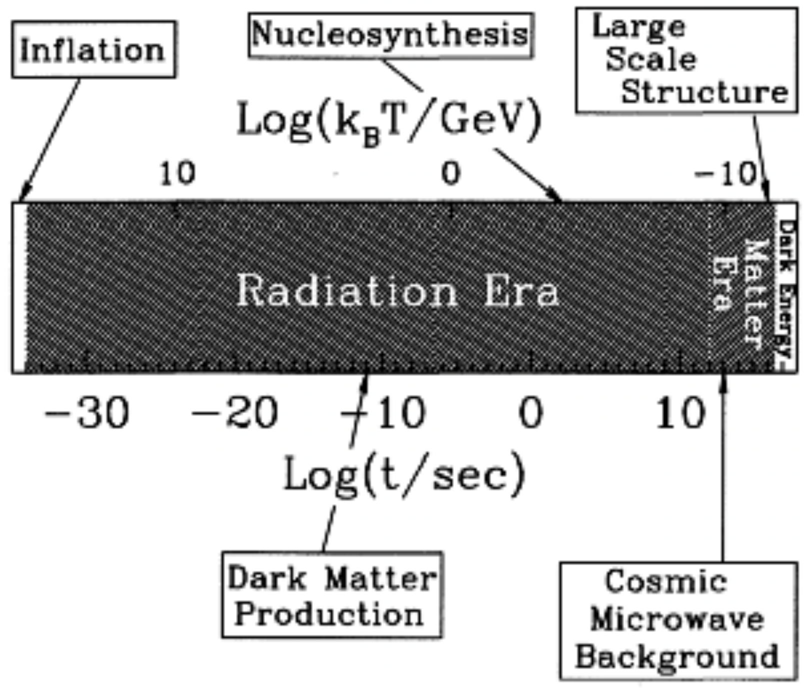
Our **curiosity** motivates **experimental efforts** for finding those answers.

Only the **electroweak hierarchy problem** clearly points to **new dynamics at the TeV scale**.

How?

Looking for answers

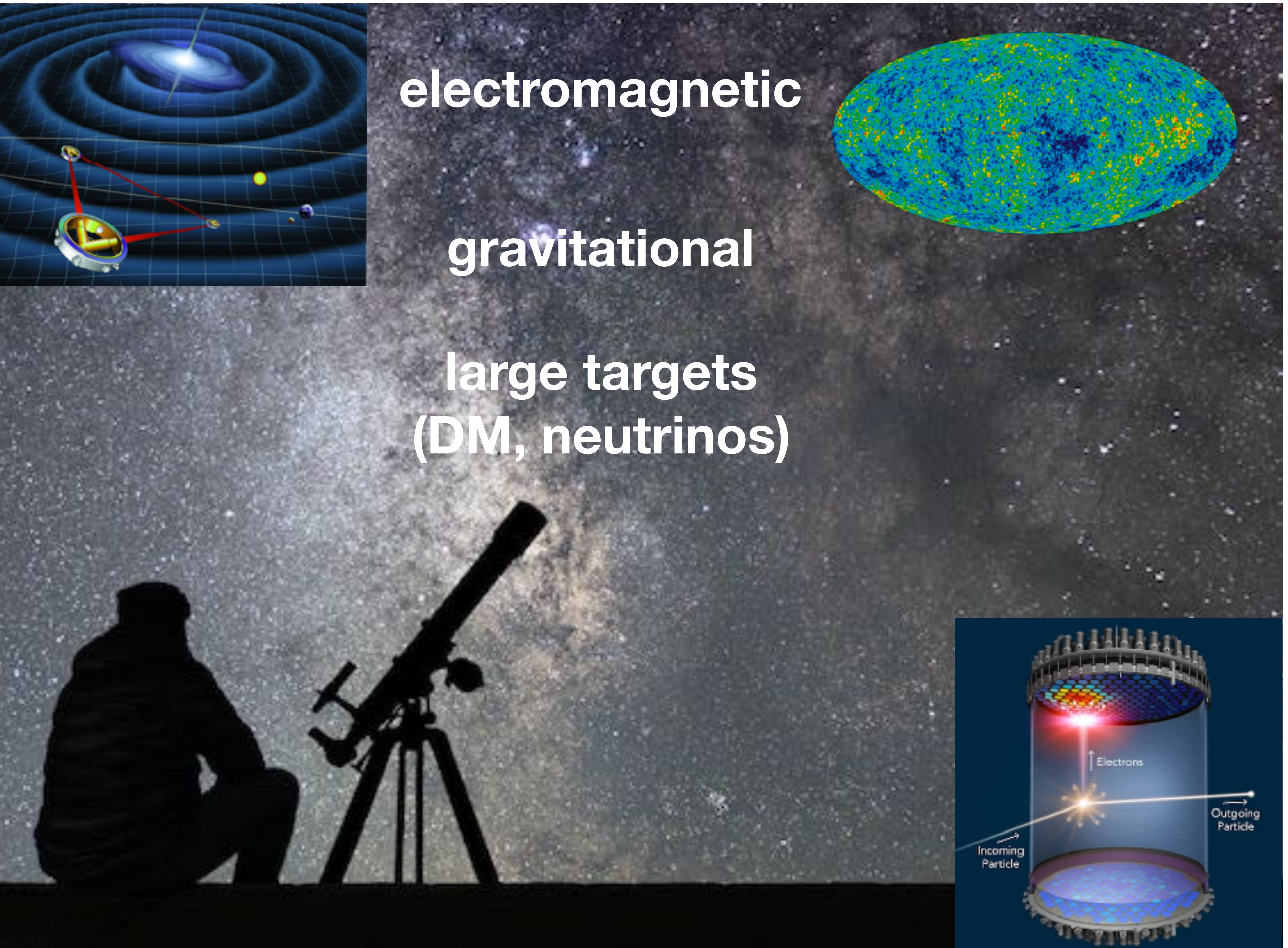
Looking for answers



in the macro …

Telescopes

Cosmological Frontier



electromagnetic

gravitational

large targets
(DM, neutrinos)

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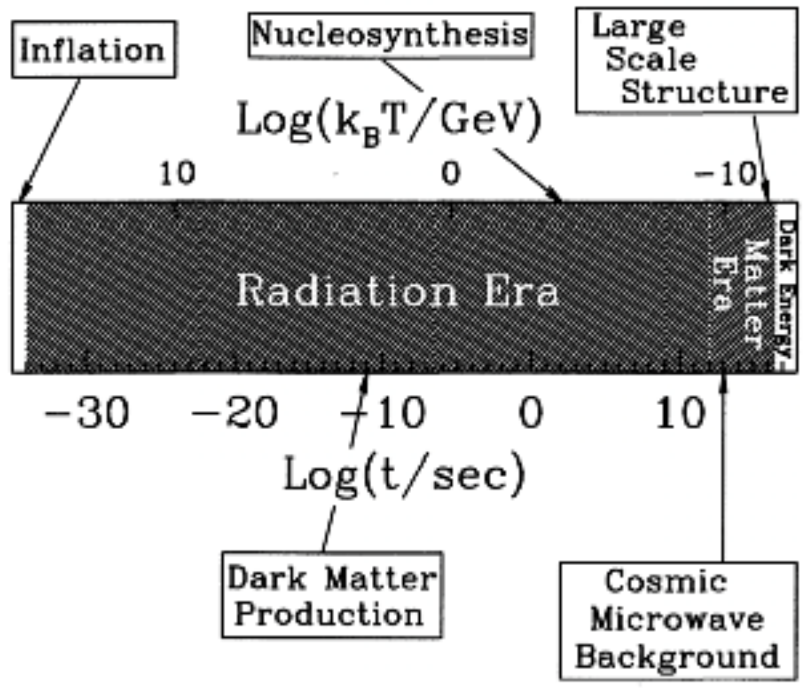


in the macro …

Telescopes

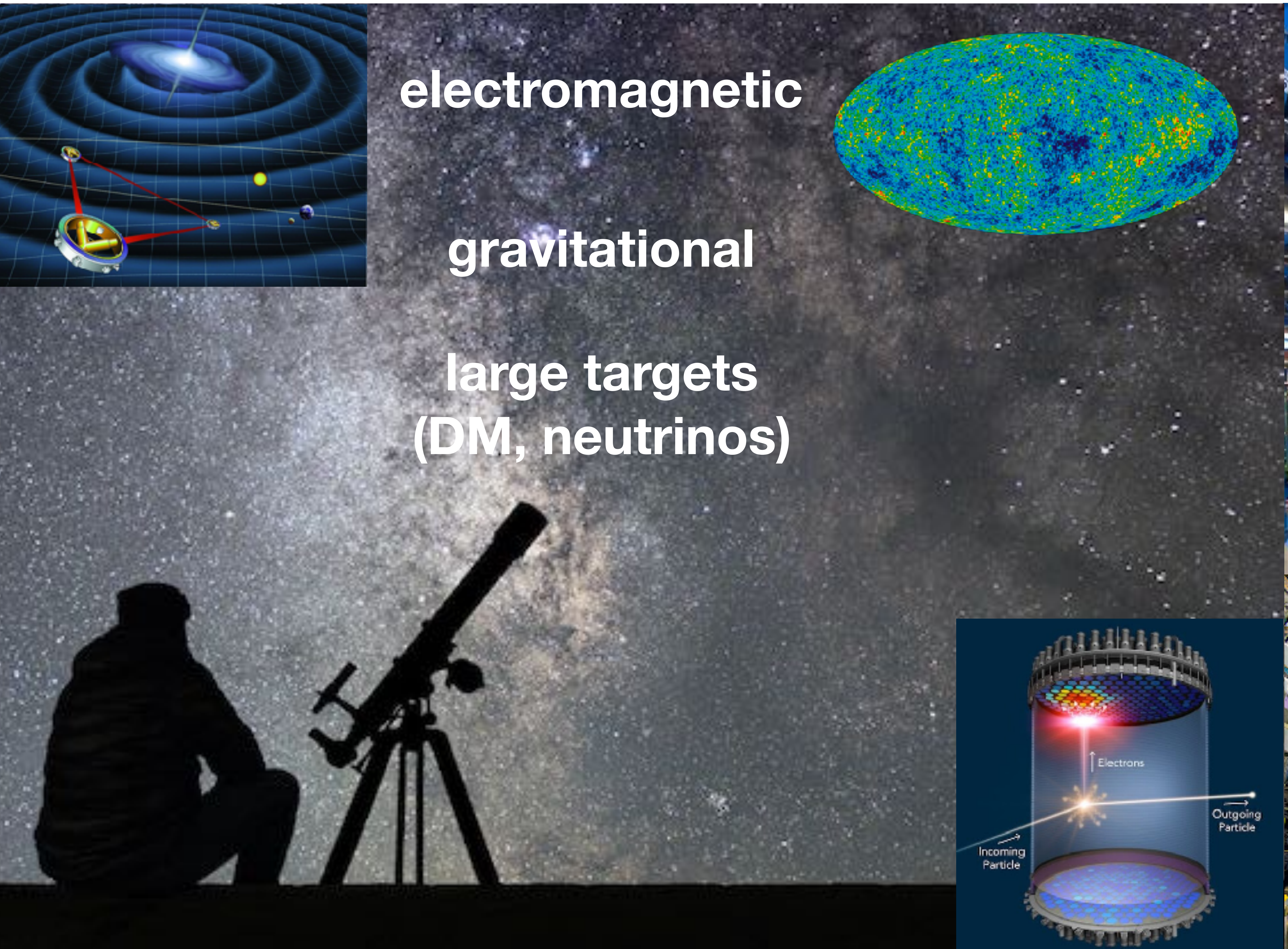
Cosmological Frontier

… and in the micro.

Microscopes: colliders

$$E = \frac{hc}{\lambda}$$

Energy & Intensity Frontiers



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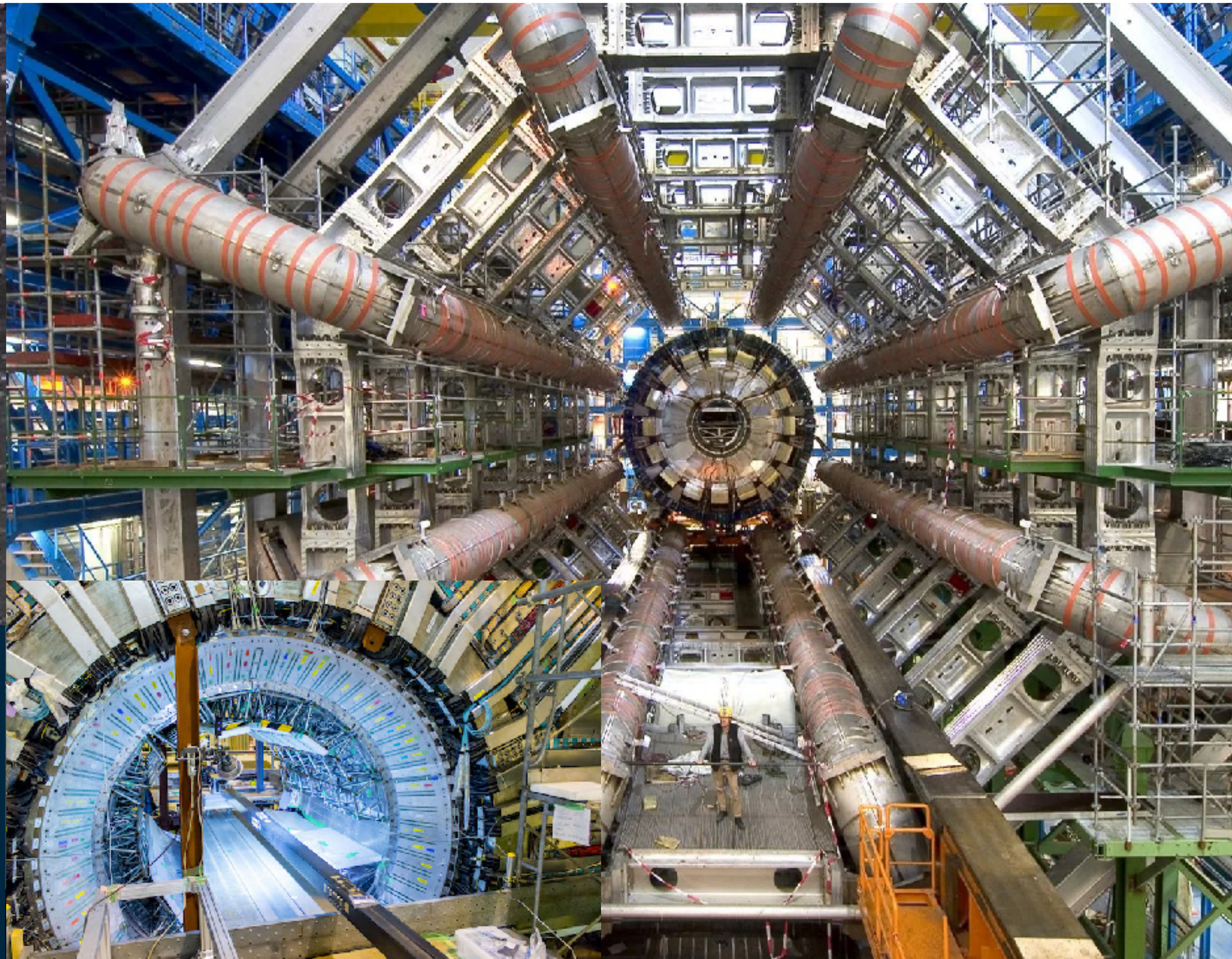
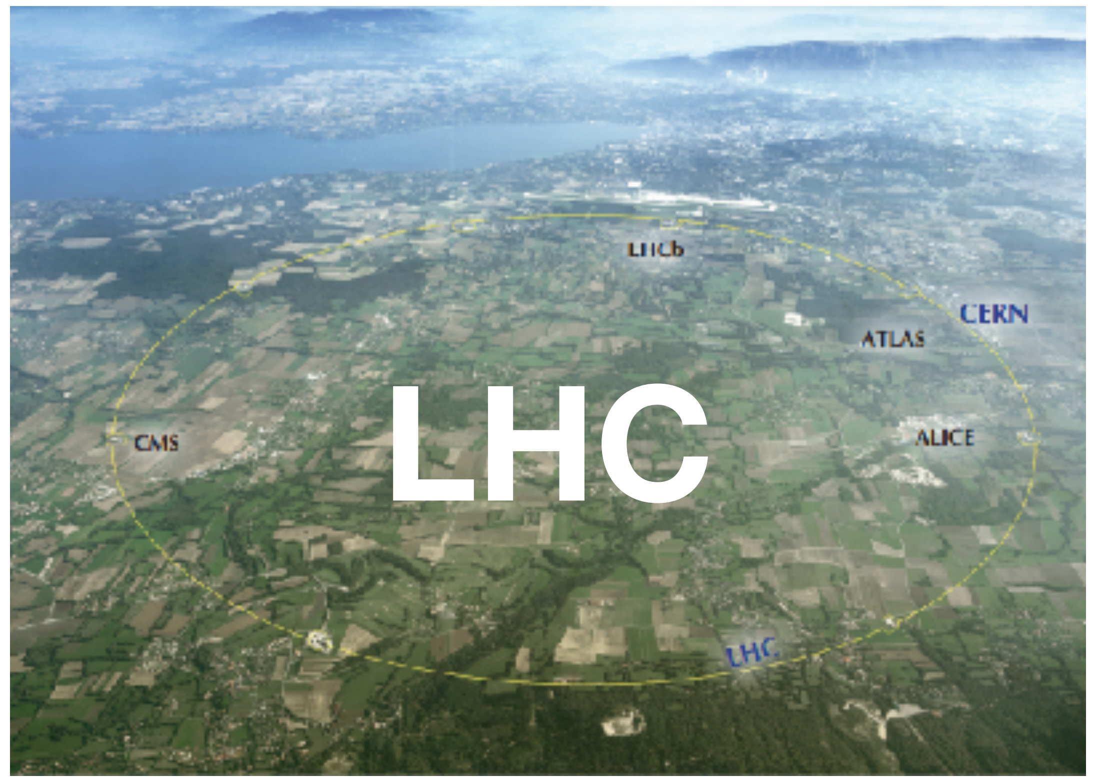


Our Most Powerful Microscope



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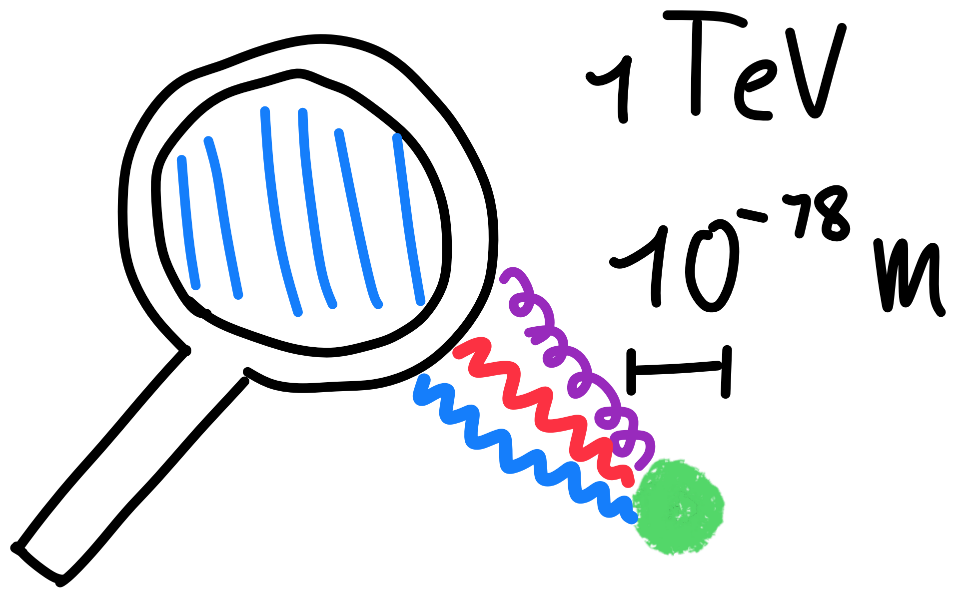

We shine the microcosm with
QCD and EW "light"
in the *atto*-scale.

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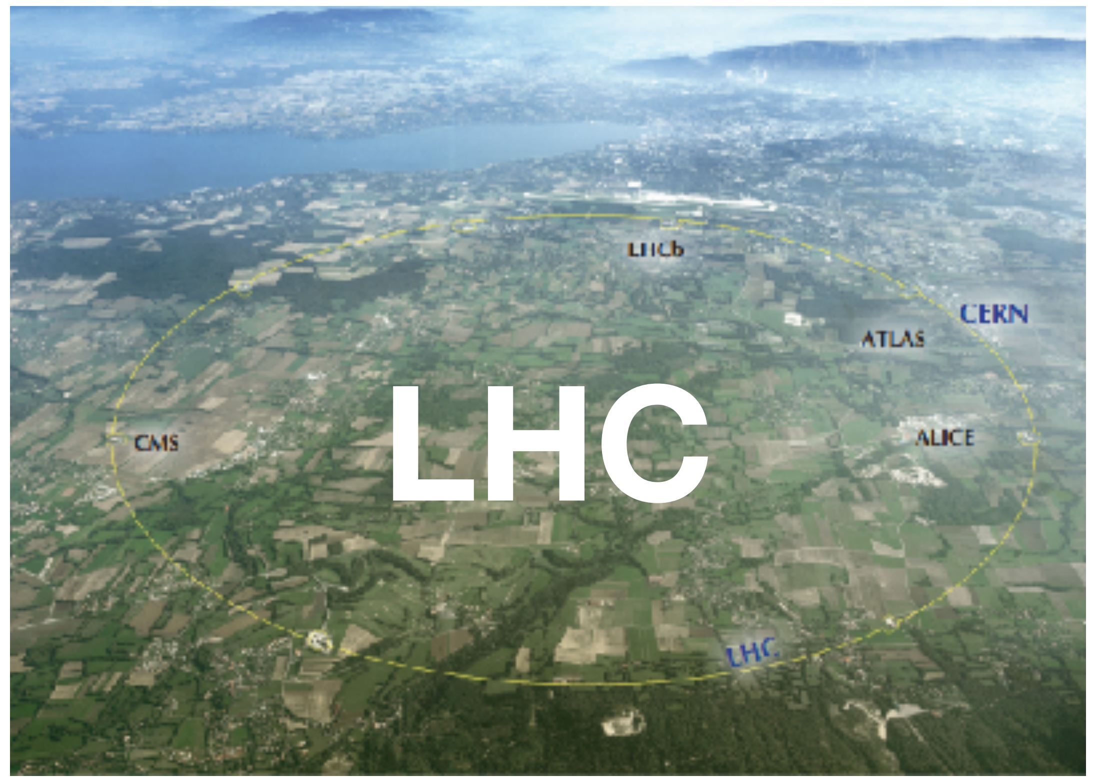

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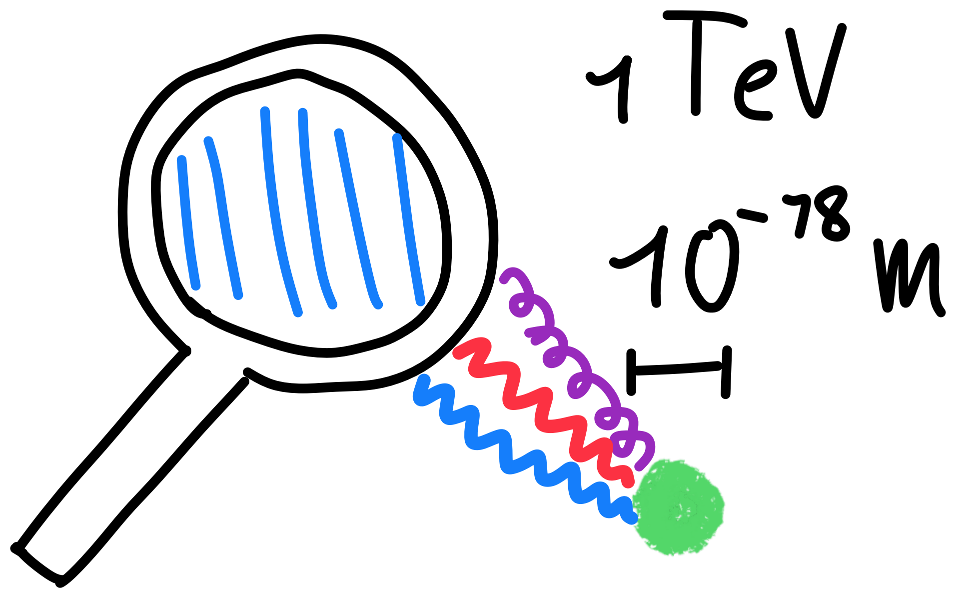

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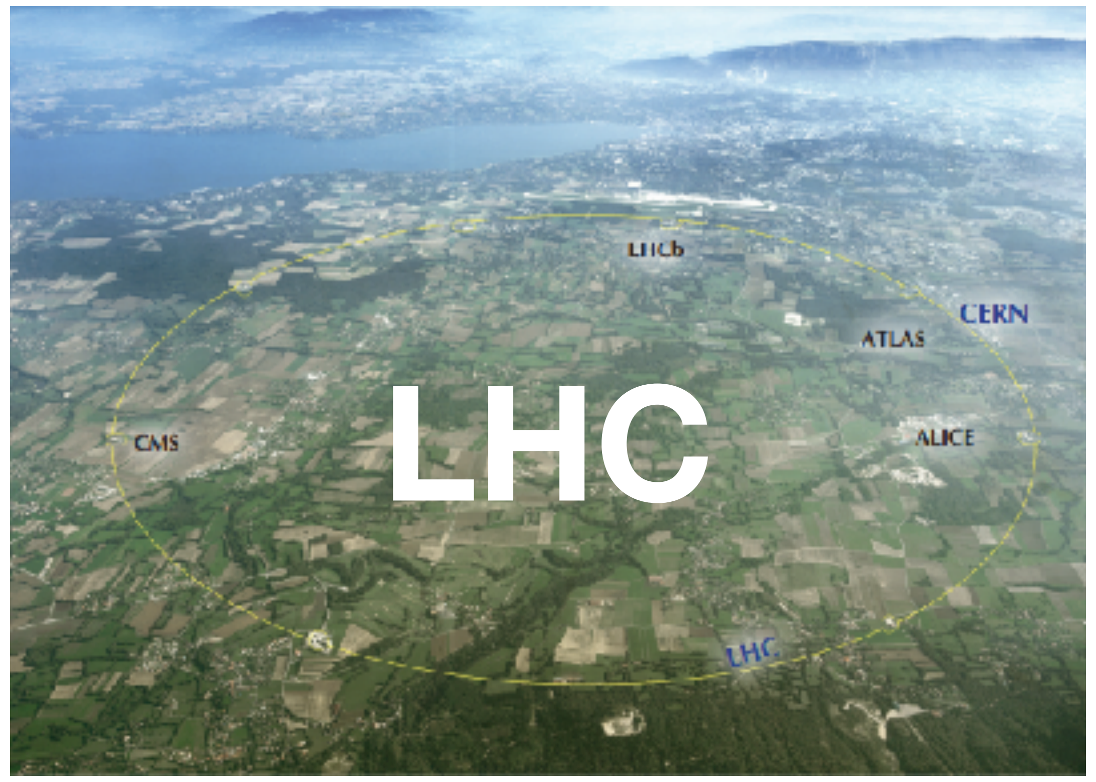

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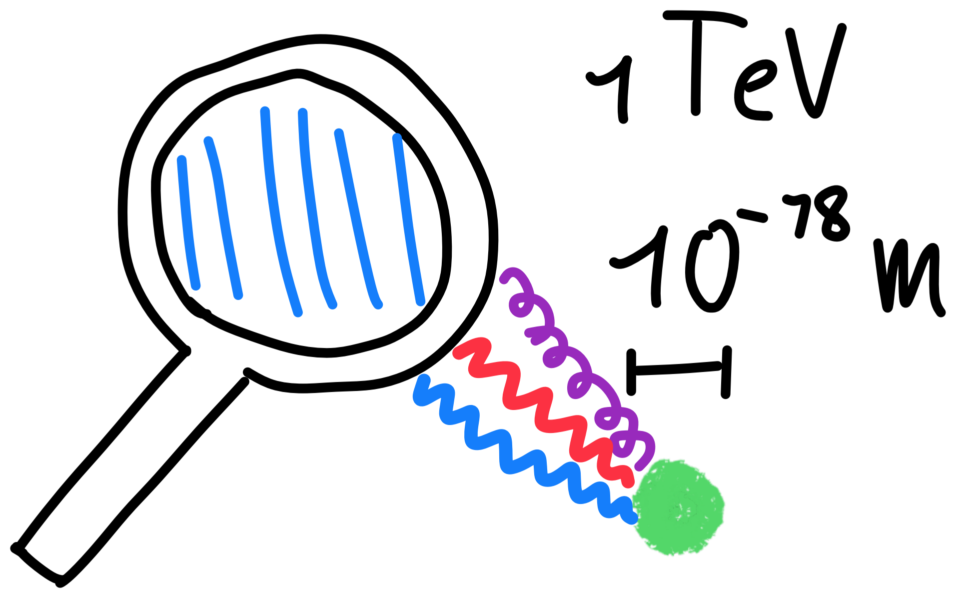

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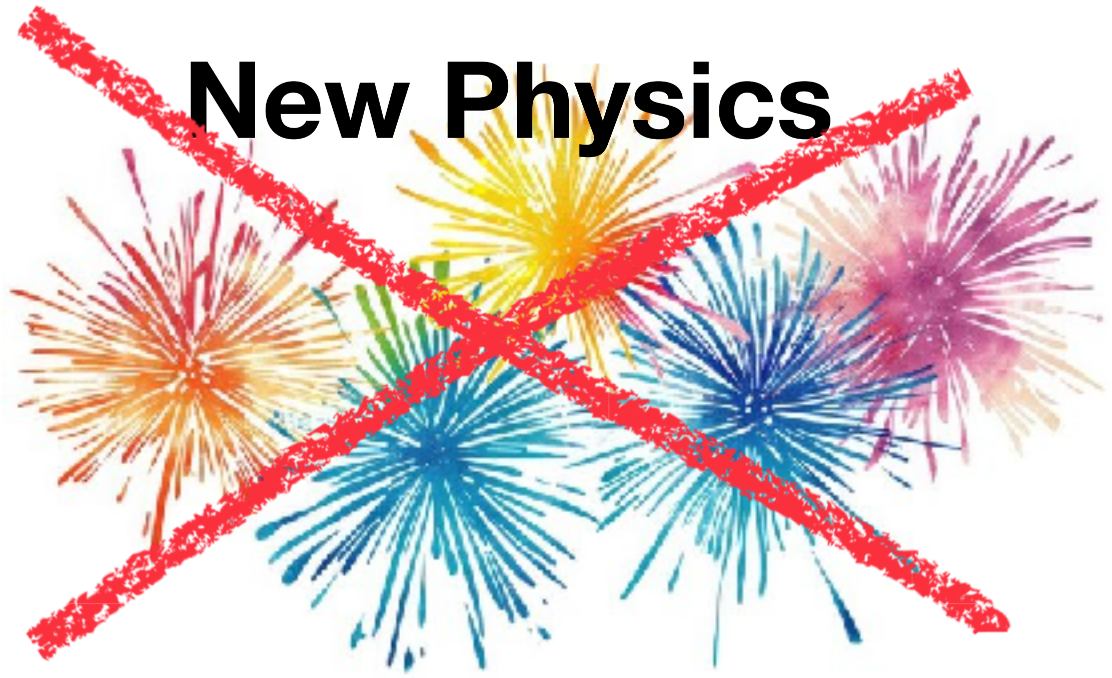

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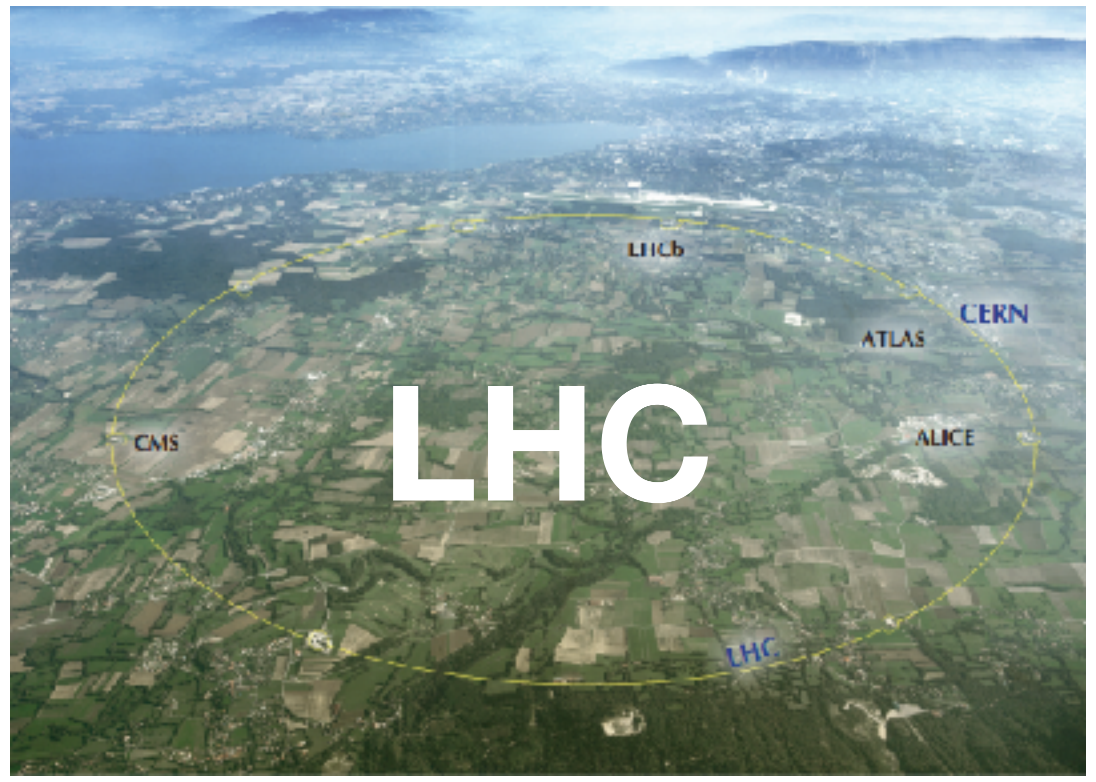

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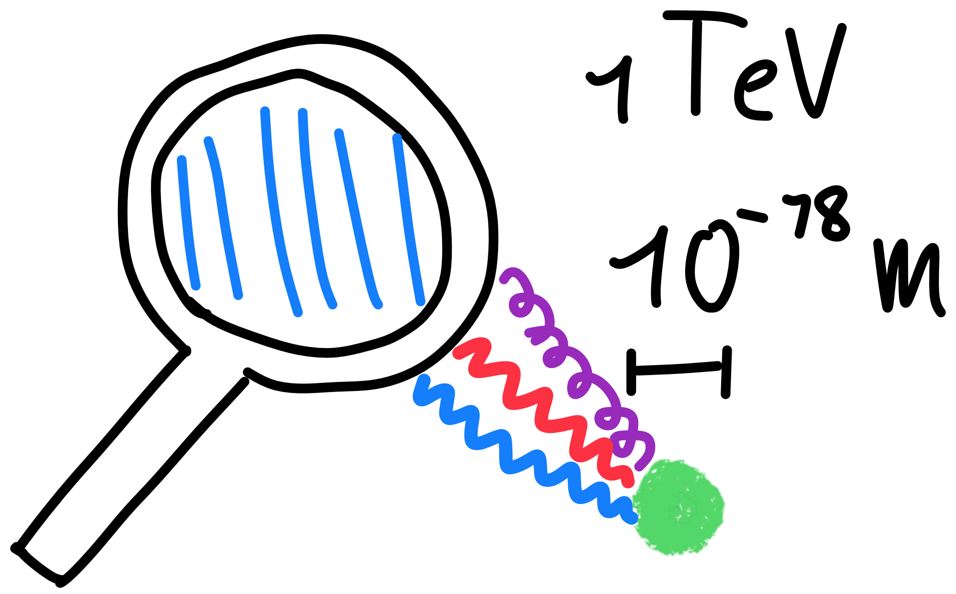

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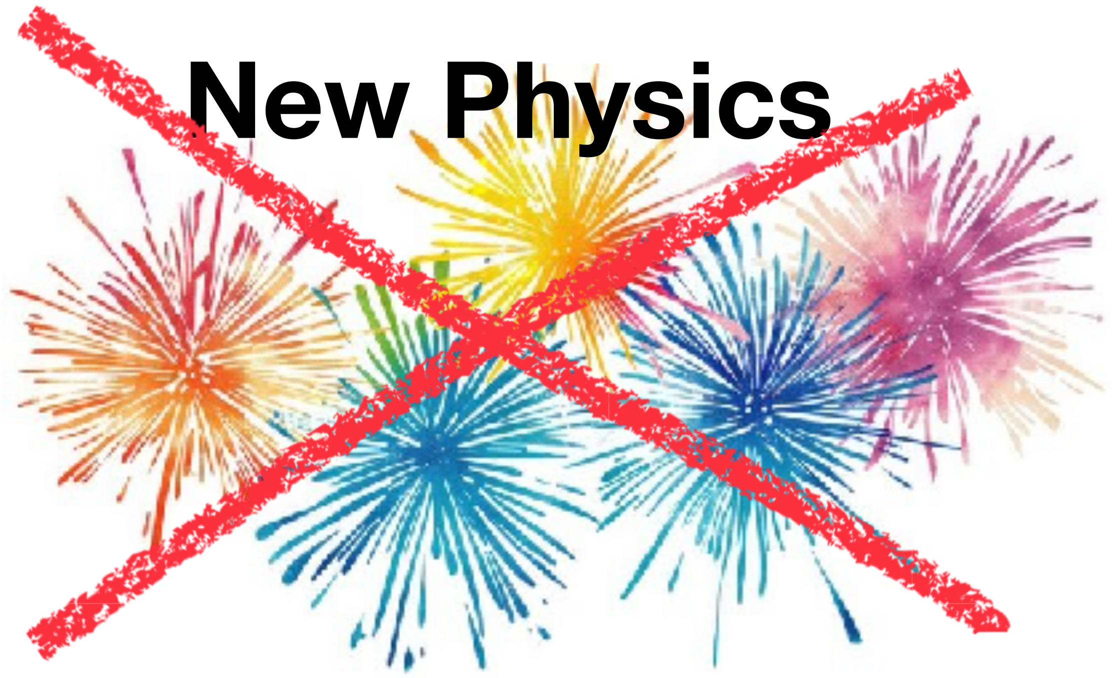

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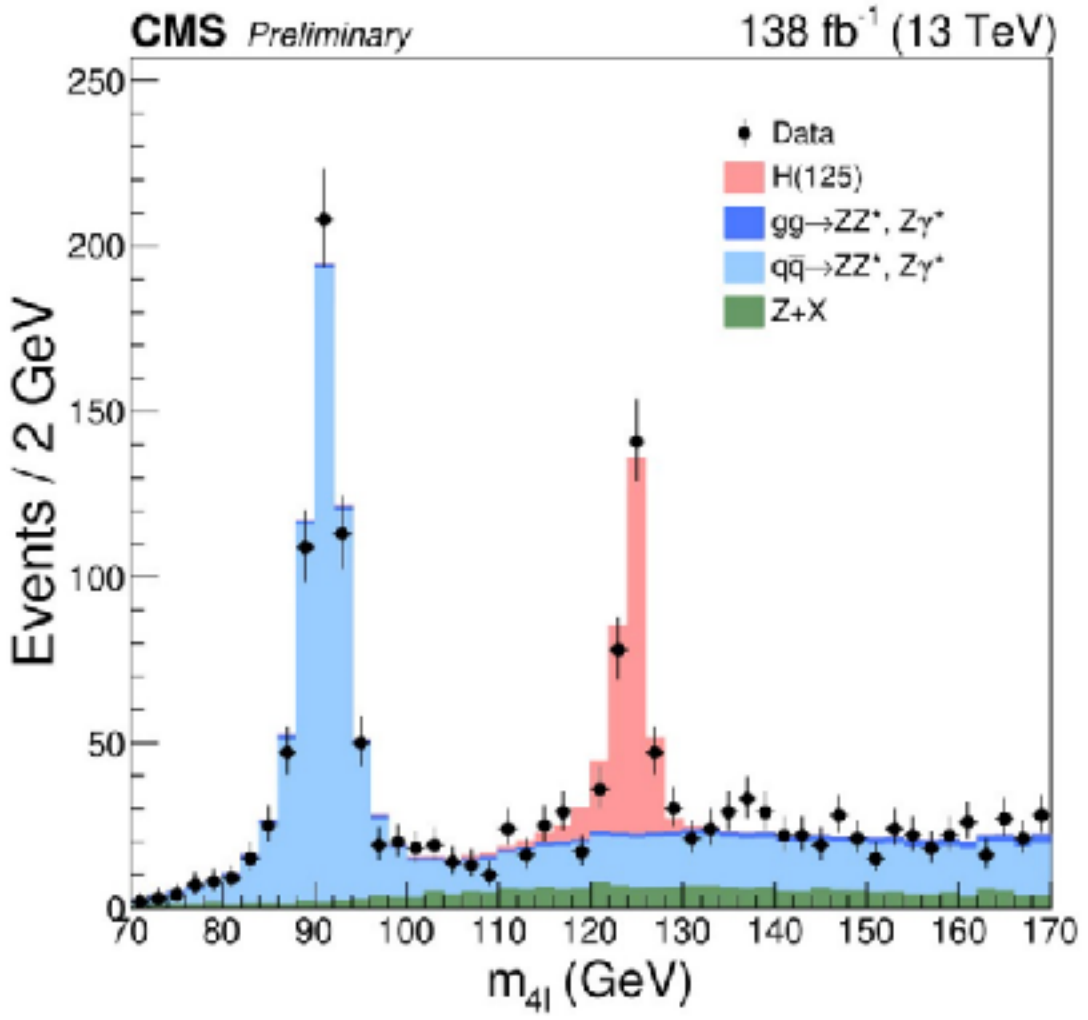
Should we go **deeper**?
The only way to learn how Nature works at even smaller scales, is to test it there!

What?

The Higgs boson and its mysteries



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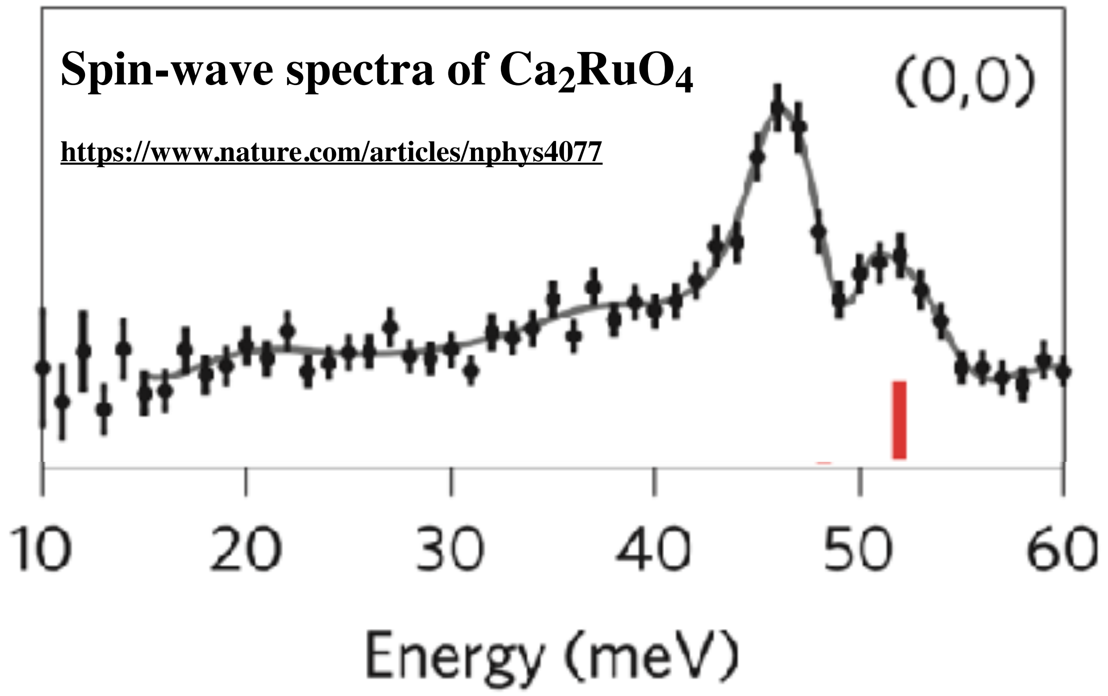
“Our Universe is not a piece of crappy metal”
Nima Arkani Hamed


Spin-wave spectra of Ca$_2$RuO$_4$

https://www.nature.com/articles/nphys4077

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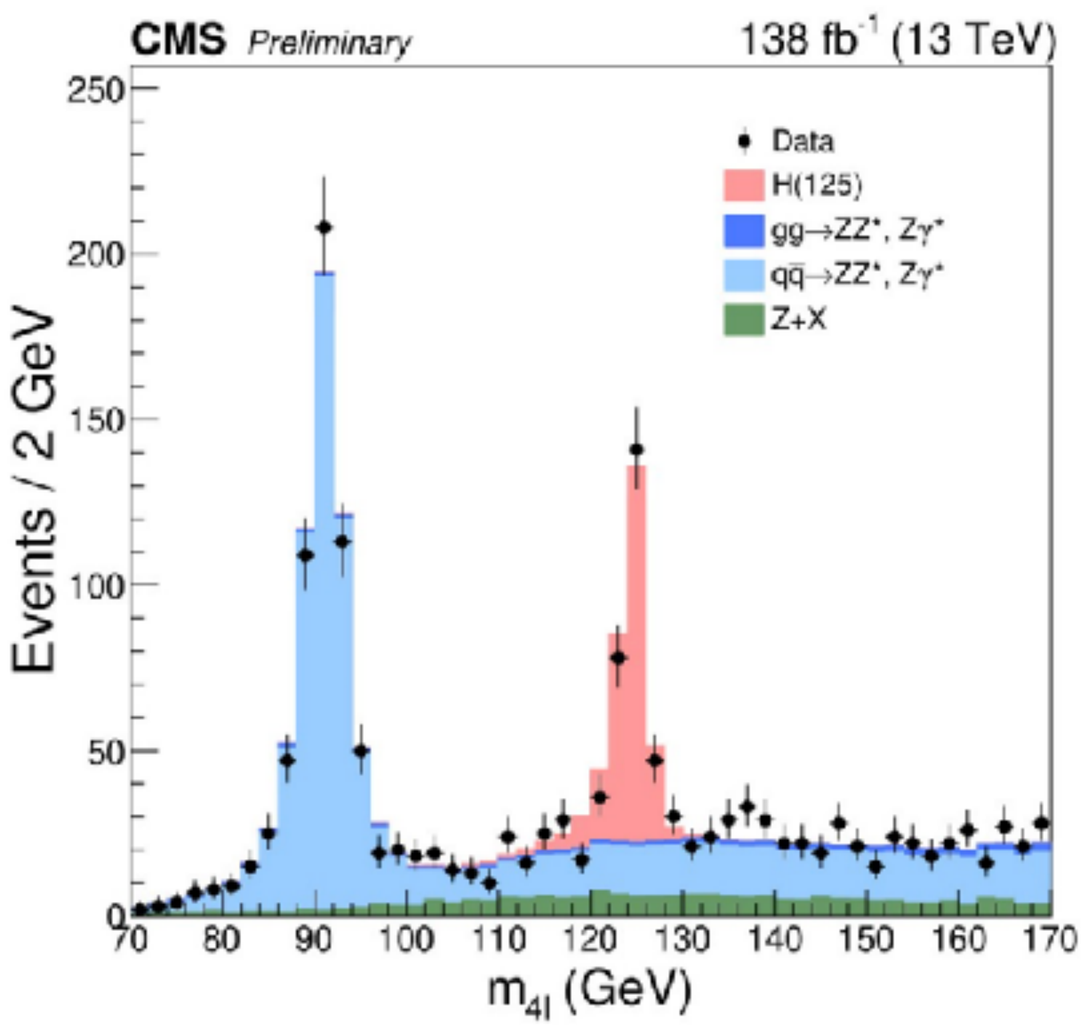

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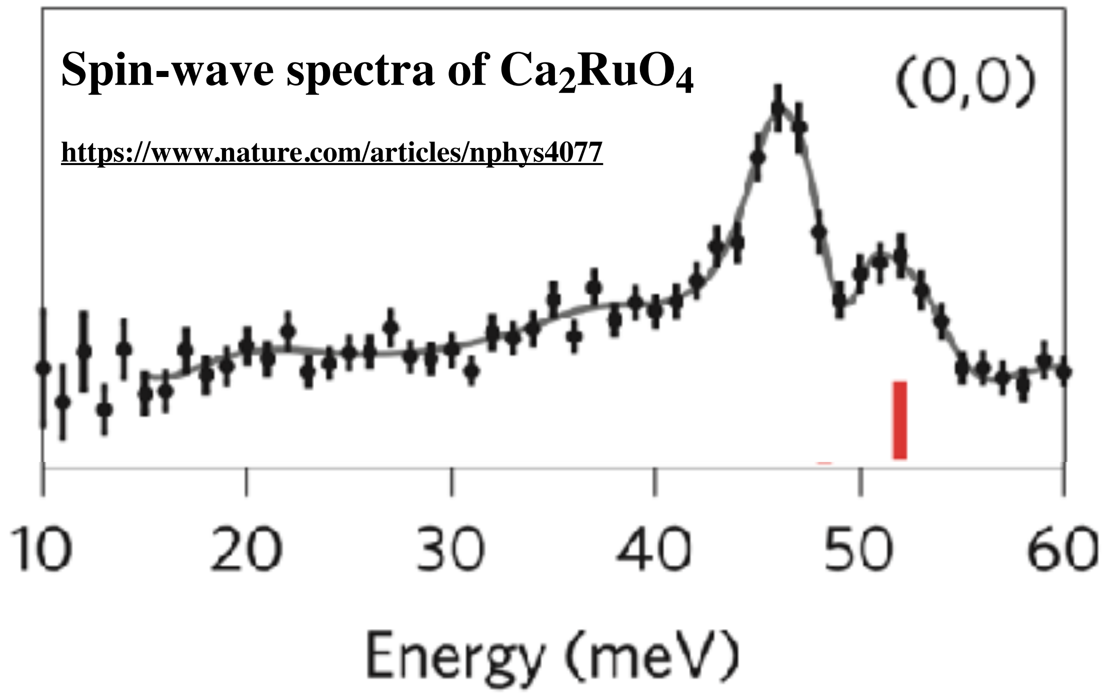
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How <u>elementary</u> is it, given our knowledge?

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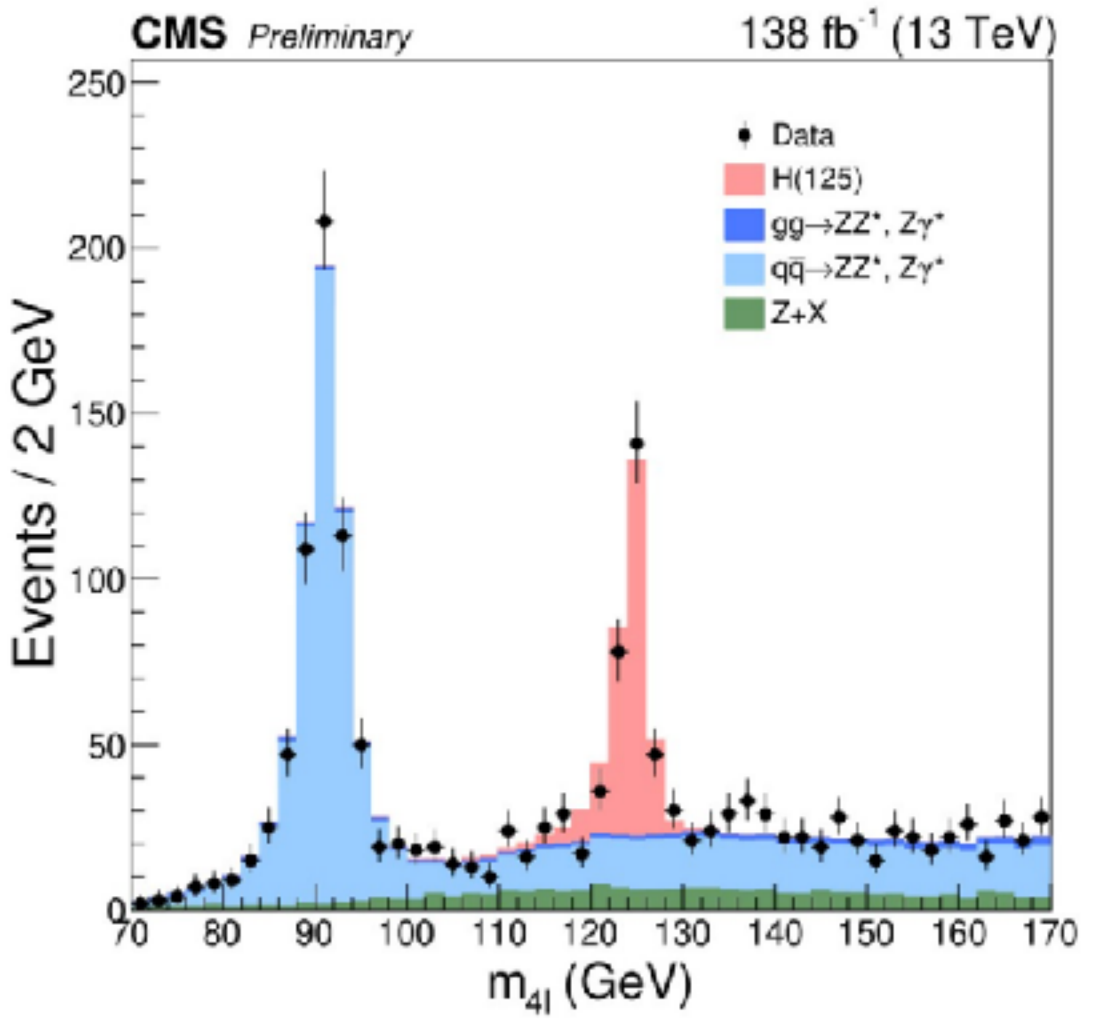

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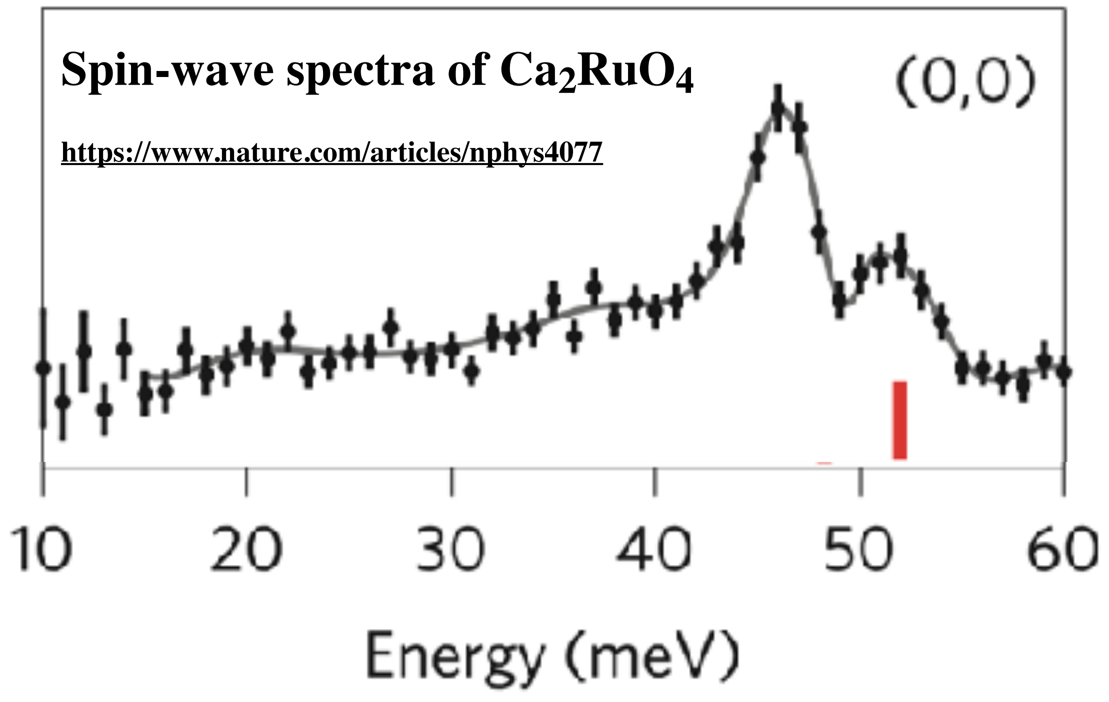

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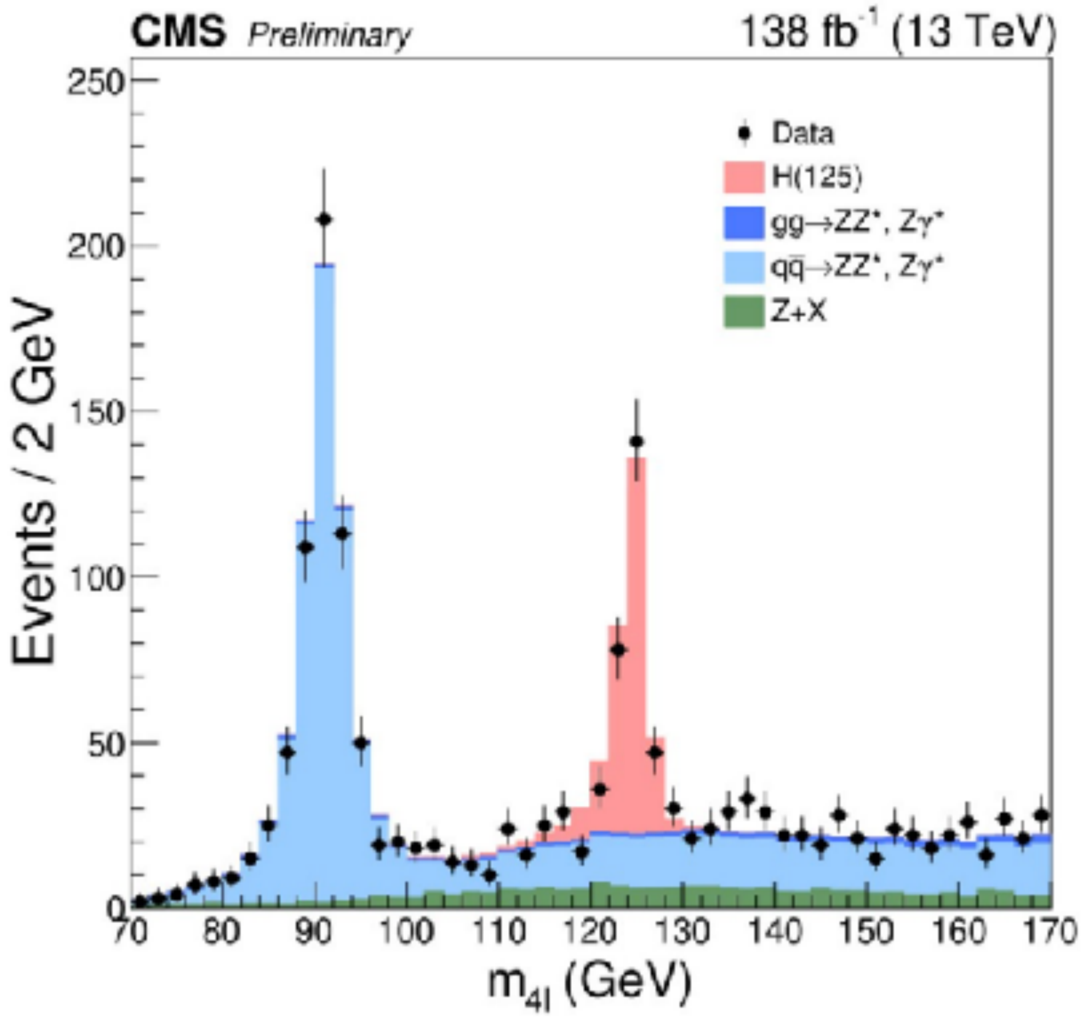

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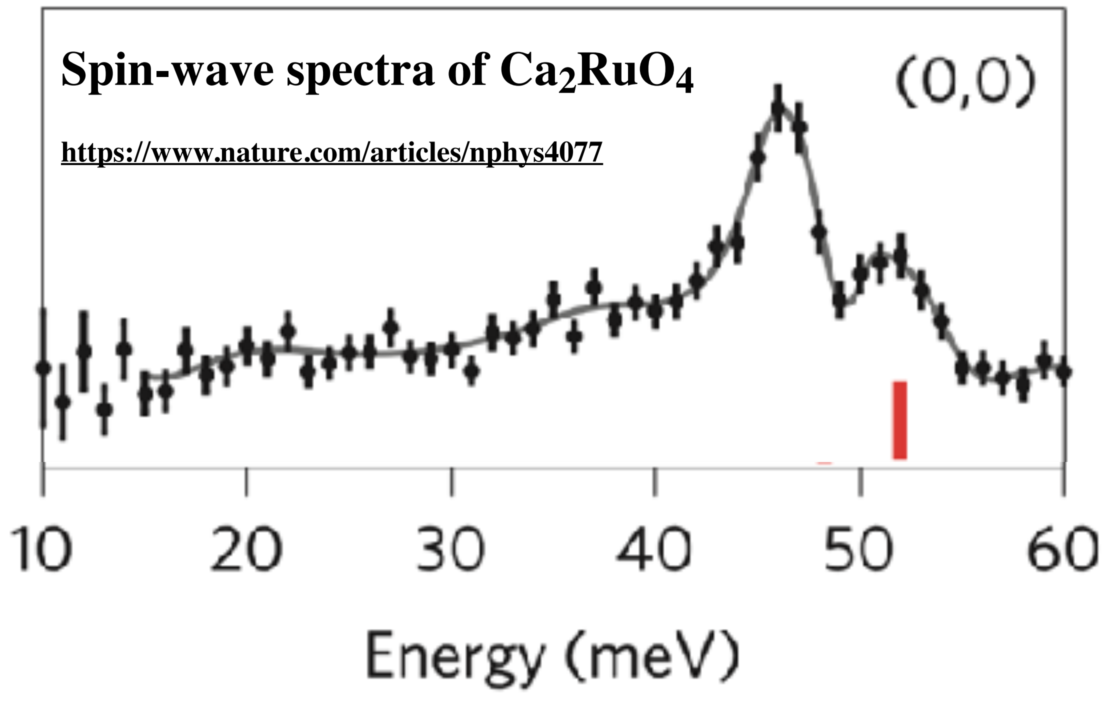

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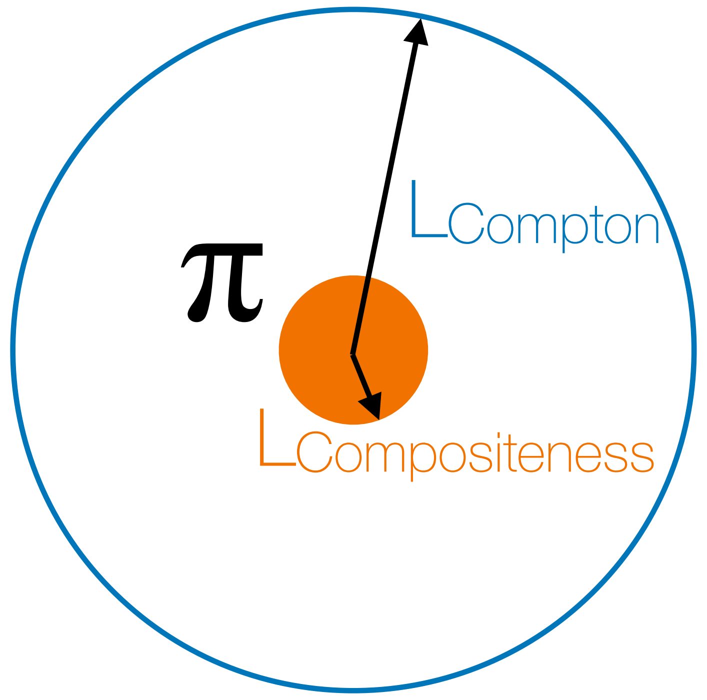
How elementary is it, given our knowledge?

Pion

$L_{\text{Compton}} \sim 1/m_\pi$
$\sim 1/135$ MeV

$L_{\text{Compositeness}} \sim 1/m_\rho$
$\sim 1/770$ MeV



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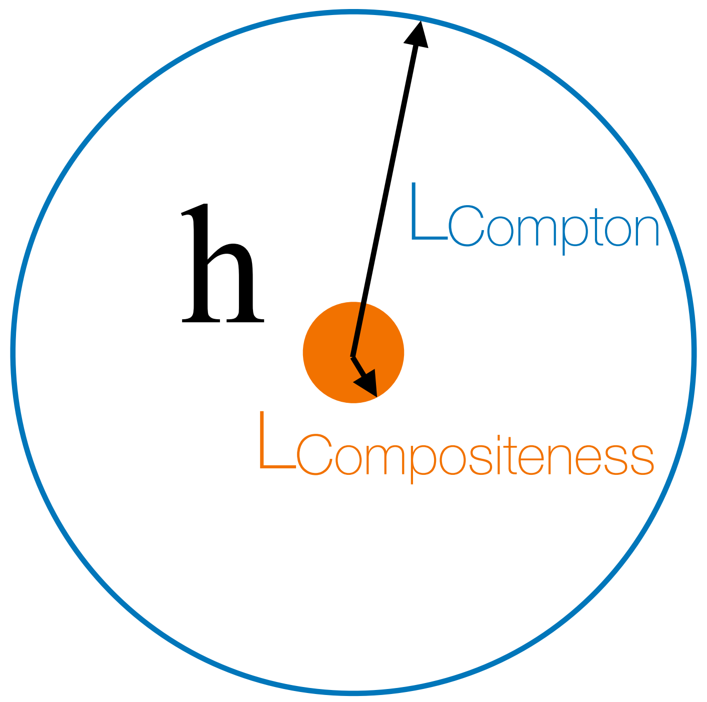

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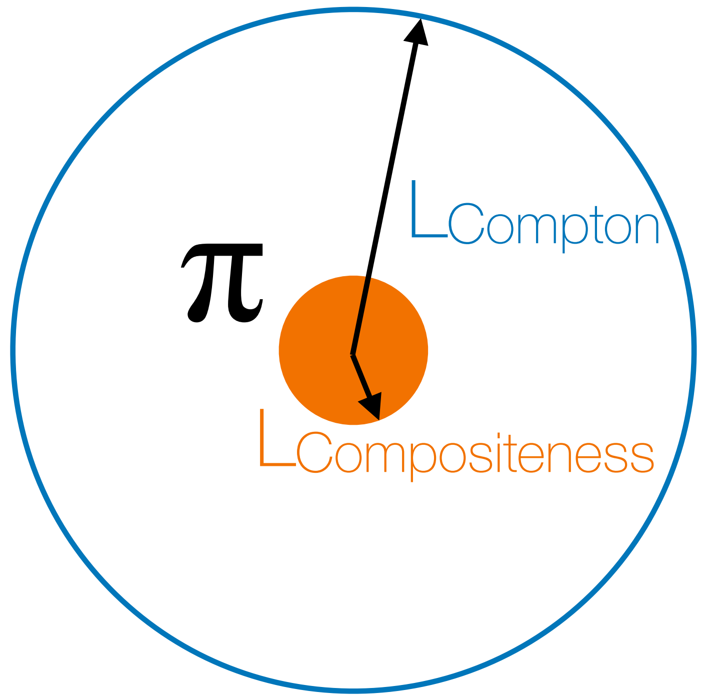

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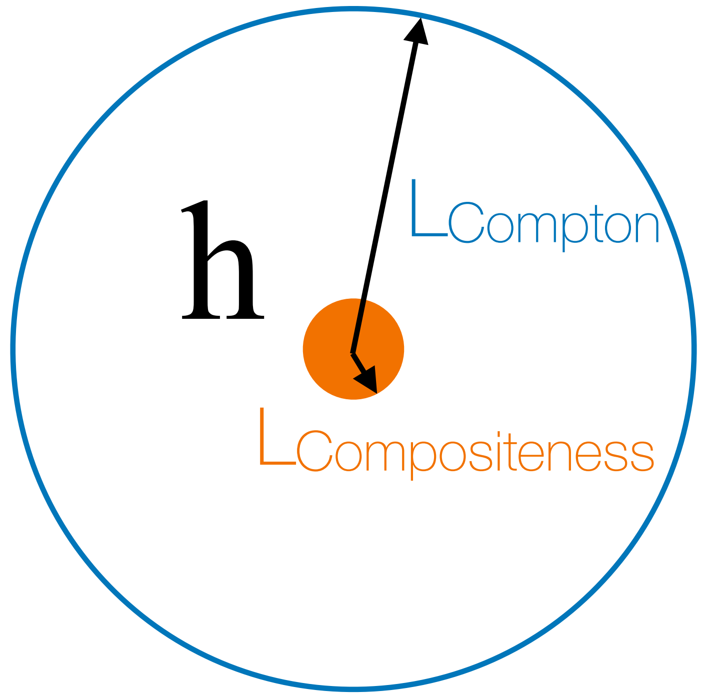
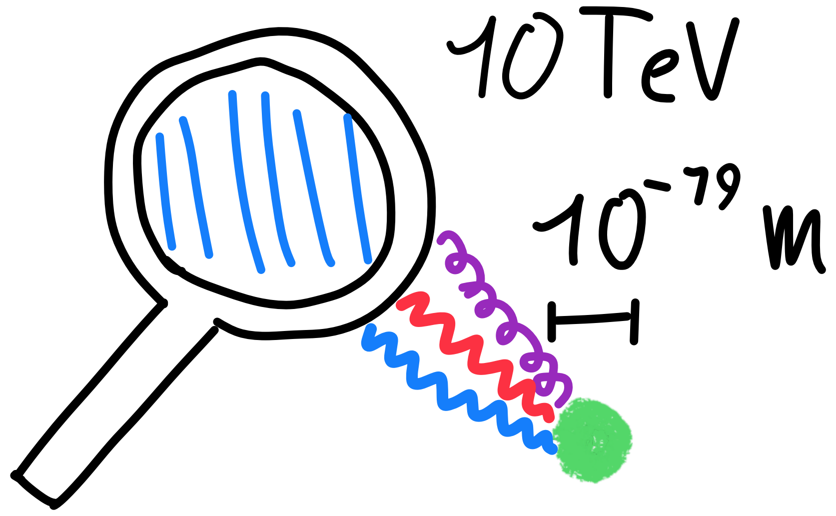


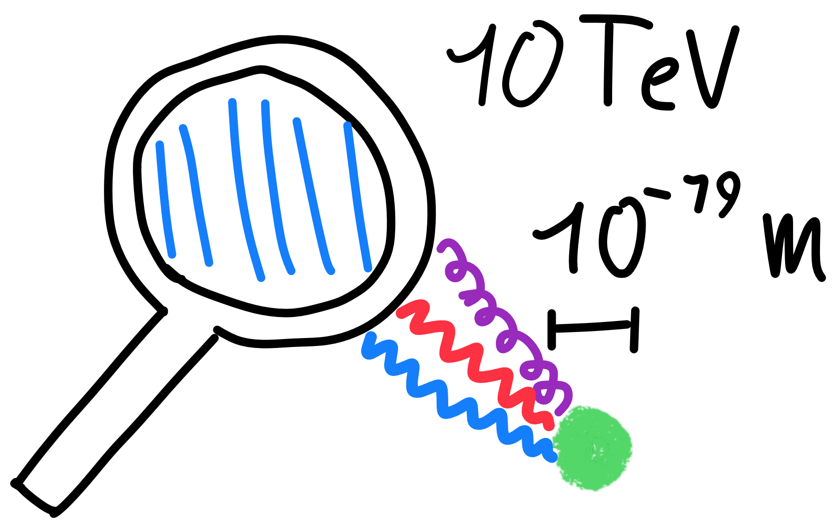
About as elementary as a pion.

Improving this by a **factor of 10** will qualitatively change the picture.

>> This requires **probing for new states** above the **10 TeV scale** <<



The Microscopes of the Future



The Microscopes of the Future

Repeating the successful LEP+LHC story:

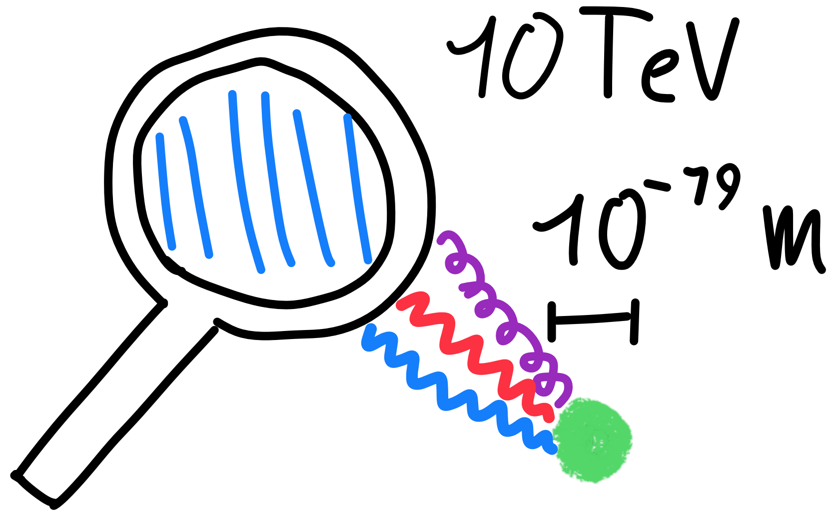
FCCee
CEPC

e^+e^- Z, Higgs, W factory to study the Higgs at 0.1% level and Z at 0.01% level.
10^{12} Z bosons, 10^6 Higgses, 10^8 WW pairs, in a clean and precise environment

90.7 km ring

FCChh
SppC

84 TeV pp collider (14T magnets), typical **partonic energy** available of about **15TeV**.
https://indico.cern.ch/event/1439072



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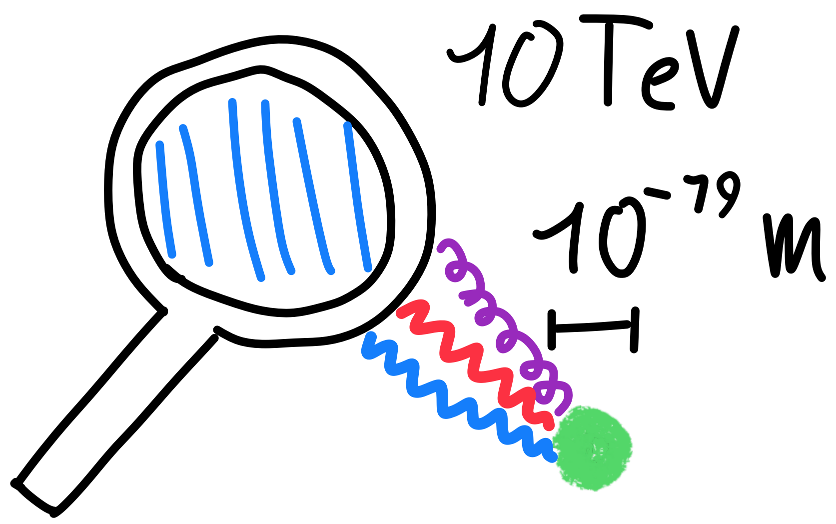
The linear e^+e^- option

ILC
(CLIC)

Linear e^+e^- Higgs, W, top factory to study the Higgs at <1% level + top mass.
Energy from 250GeV (Zh) up to **1 TeV** (3TeV for CLIC).

20-50 km



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20-50 km

The revolutionary technology

Muon Collider

$\mu^+\mu^-$ collider at 10 TeV. All energy available for hard scattering.
10^7 Higgses, copious amounts of EW states, relatively clean environment.
[2407.12450]

10km ring

The Microscopes of the Future

Different Energy and Luminosity potential for each collider: **different**, and often **complementary**, **physics programs**.

The Age of the Cathedrals

2020 2030 2040 2050 2060 2070 2080 2090 2100

LHC & HL-LHC

Belle II

FCC-ee 15y

FCC-hh 20y

CEPC [link]

SppC

MuC-stage1 5y

MuC-10 5y [link]

The Age of the Cathedrals

https://phdcomics.com/comics/archive.php?comicid=1436

The Age of the Cathedrals

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[link]

[link]

Notre-Dame: started in 1163, completed in 1345.
Sagrada Familia: started in 1882, still going on (2024).

The direct and the indirect ways

New Physics can be searched for **looking directly for the new particles**,
or **looking for the effects of new particles in SM processes**.

The direct and the indirect ways

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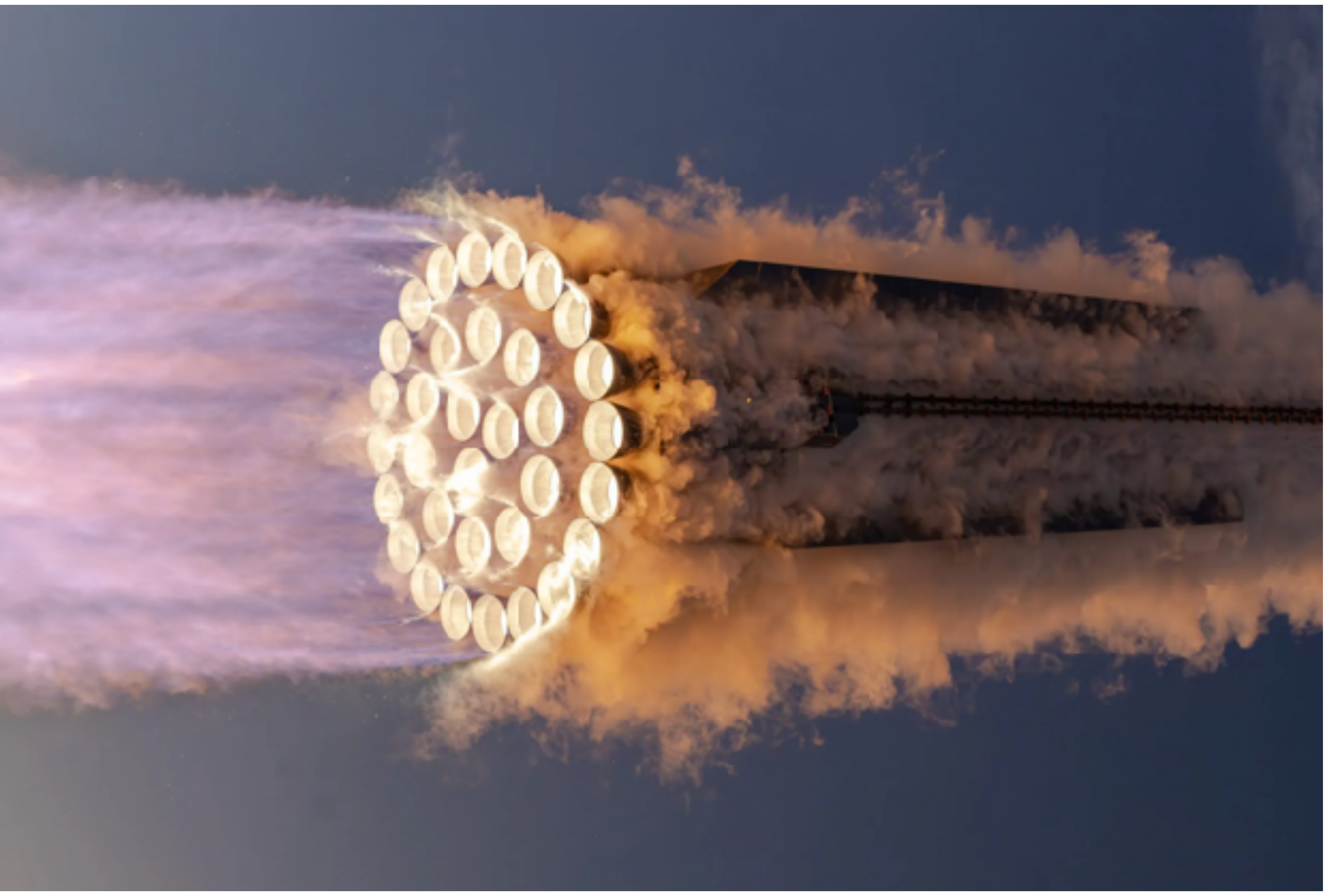
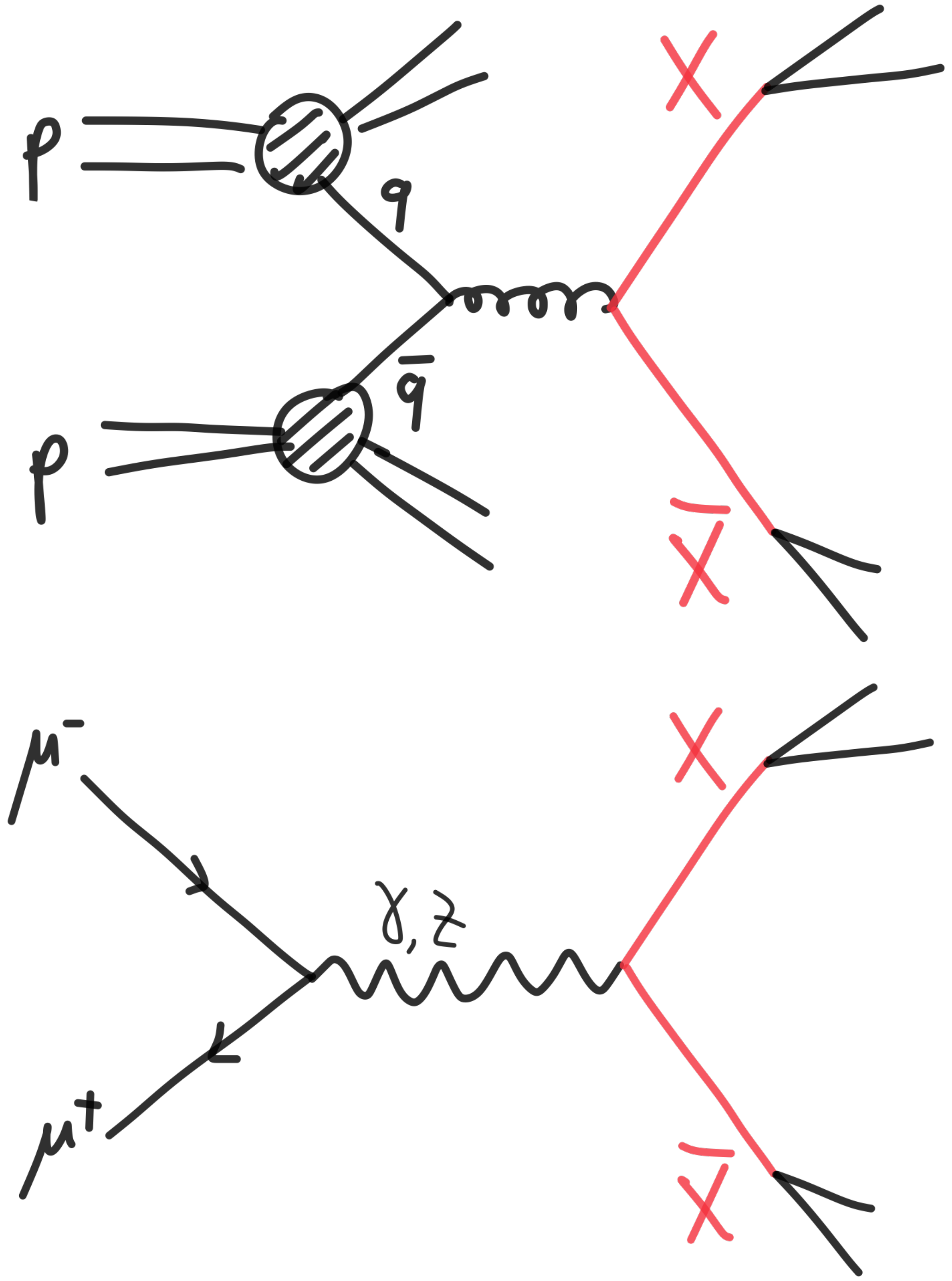
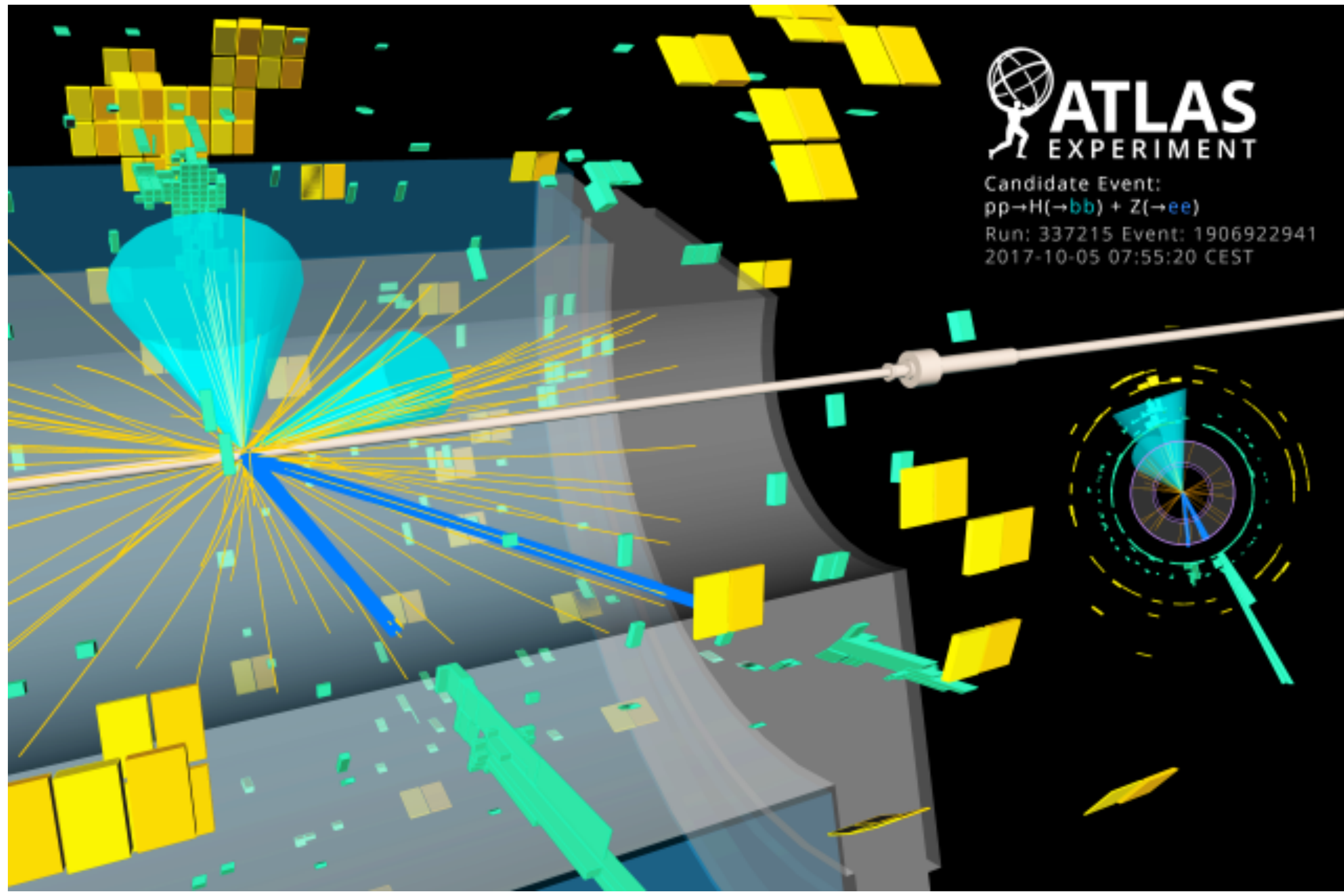
If $\mathbf{E > \Lambda_{NP}}$ we can **produce the new states** and look for the signatures of their decays in detectors.







Direct searches of heavy NP

In **proton-proton** collisions the available partonic energy is suppressed by PDFs.

$$M_X \sim \frac{\sqrt{s_{pp}}}{10}$$

Anything colored.
Much **smaller if not colored**

Mass reach in pair-pruduction
(assuming QCD & EW couplings)

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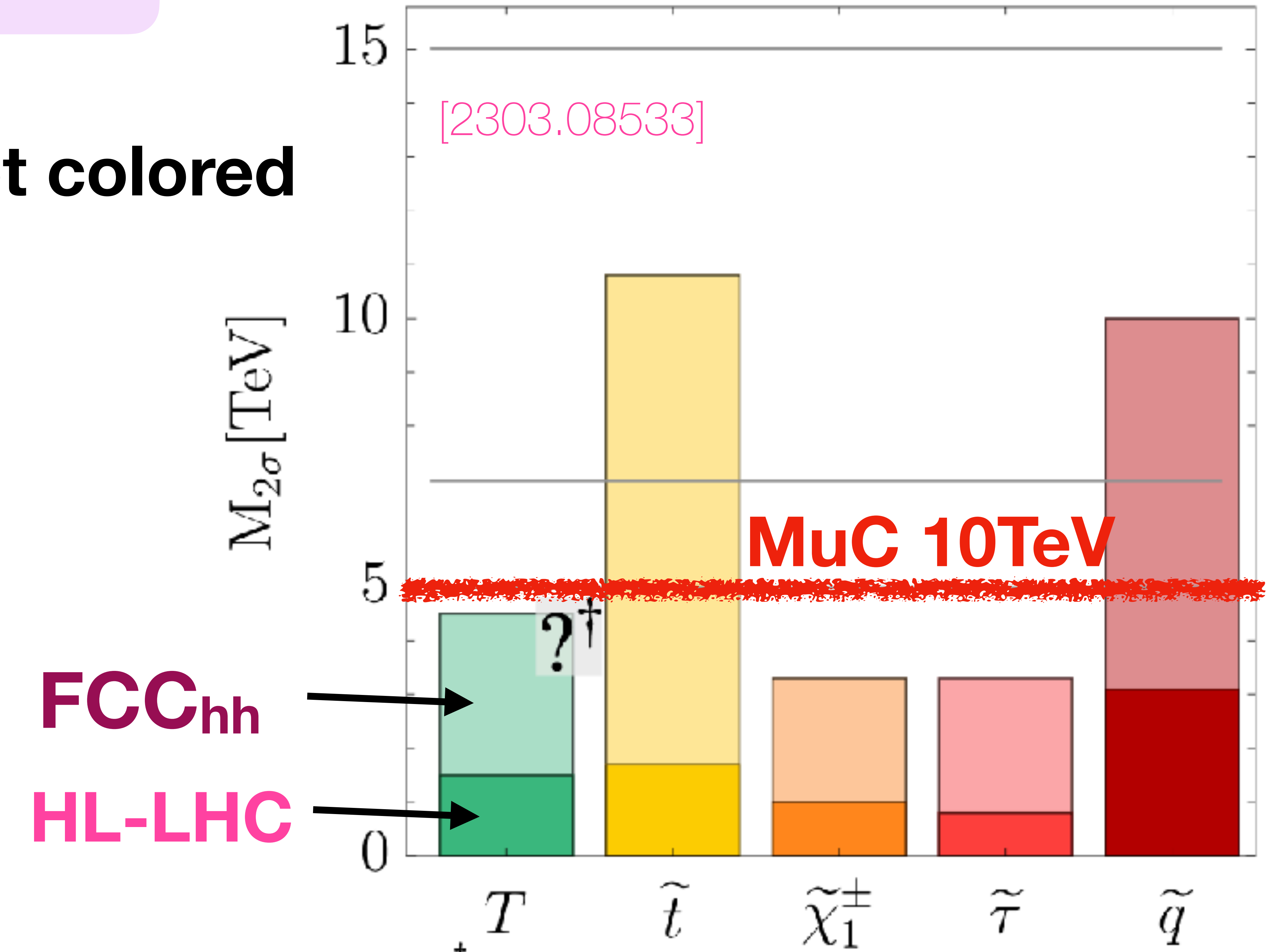

† The low FCC-hh mass reach on Top Partners could be due to a non-optimal analysis

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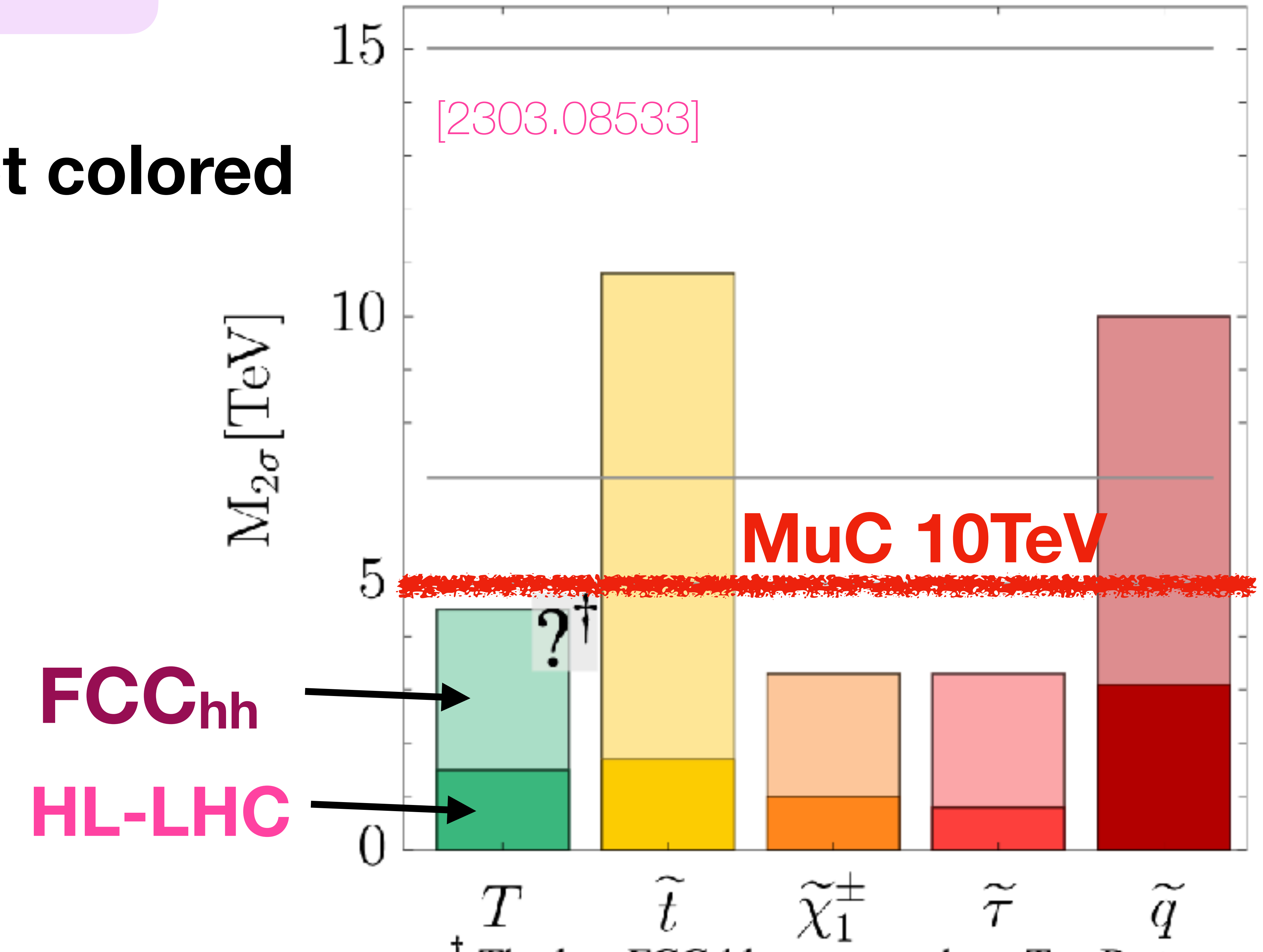

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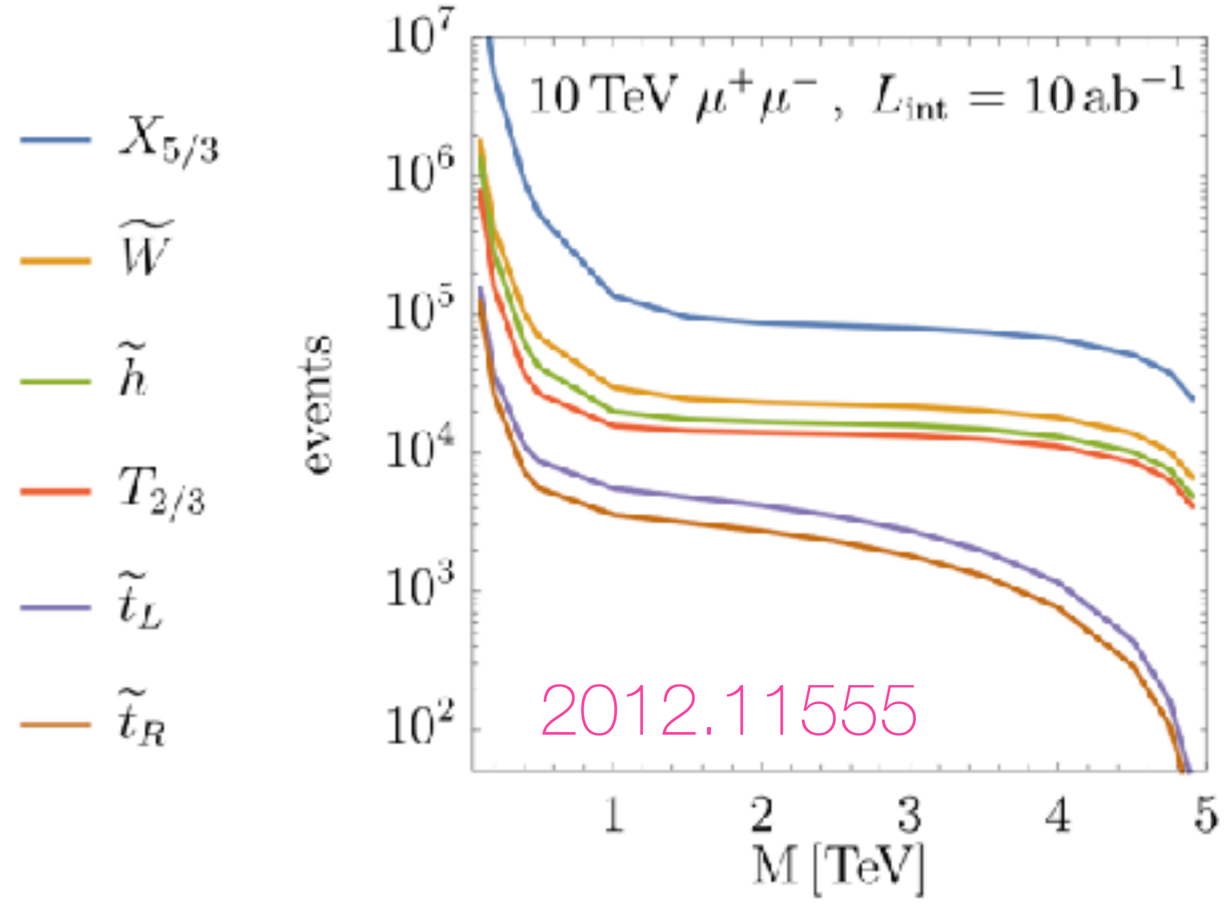
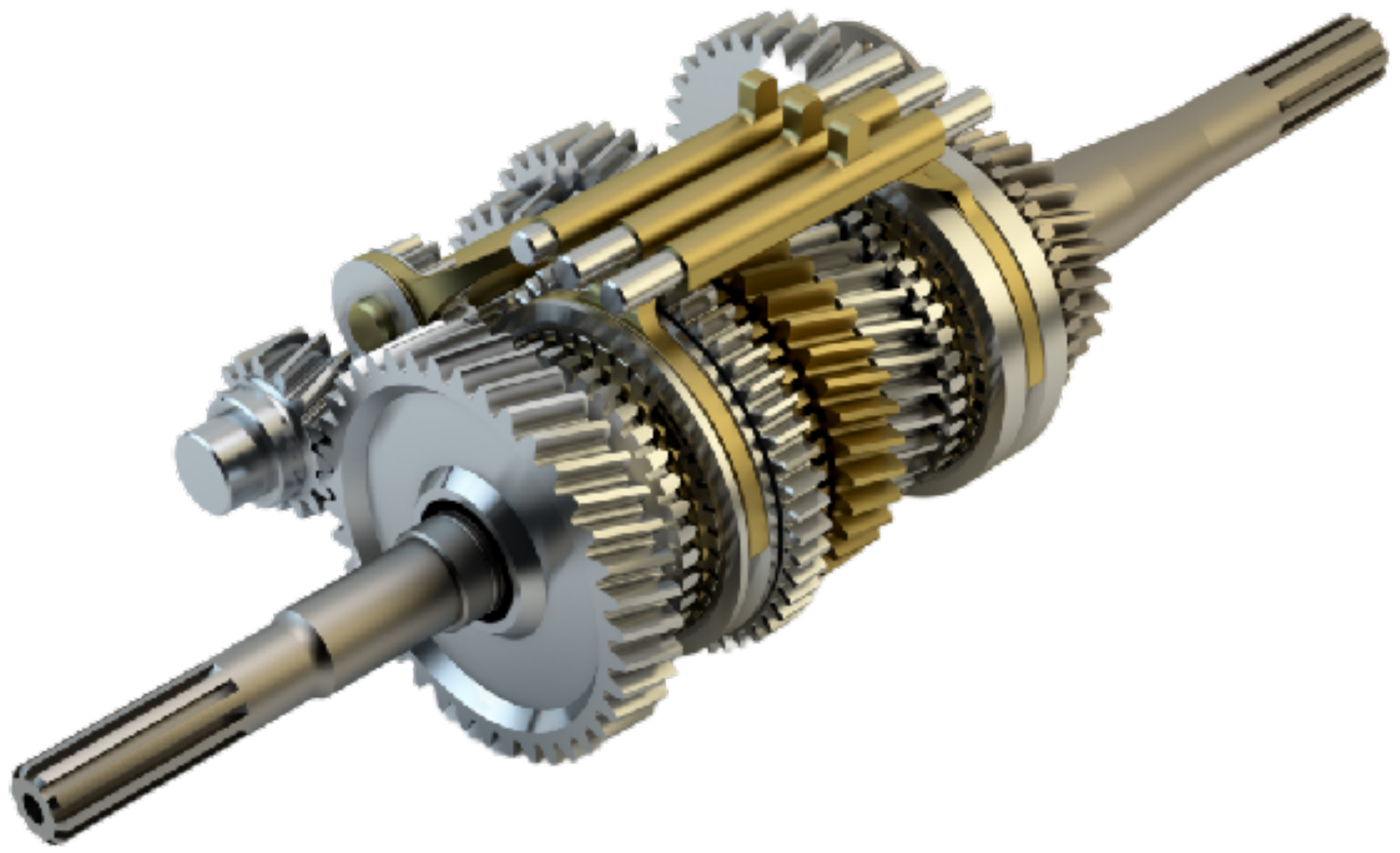


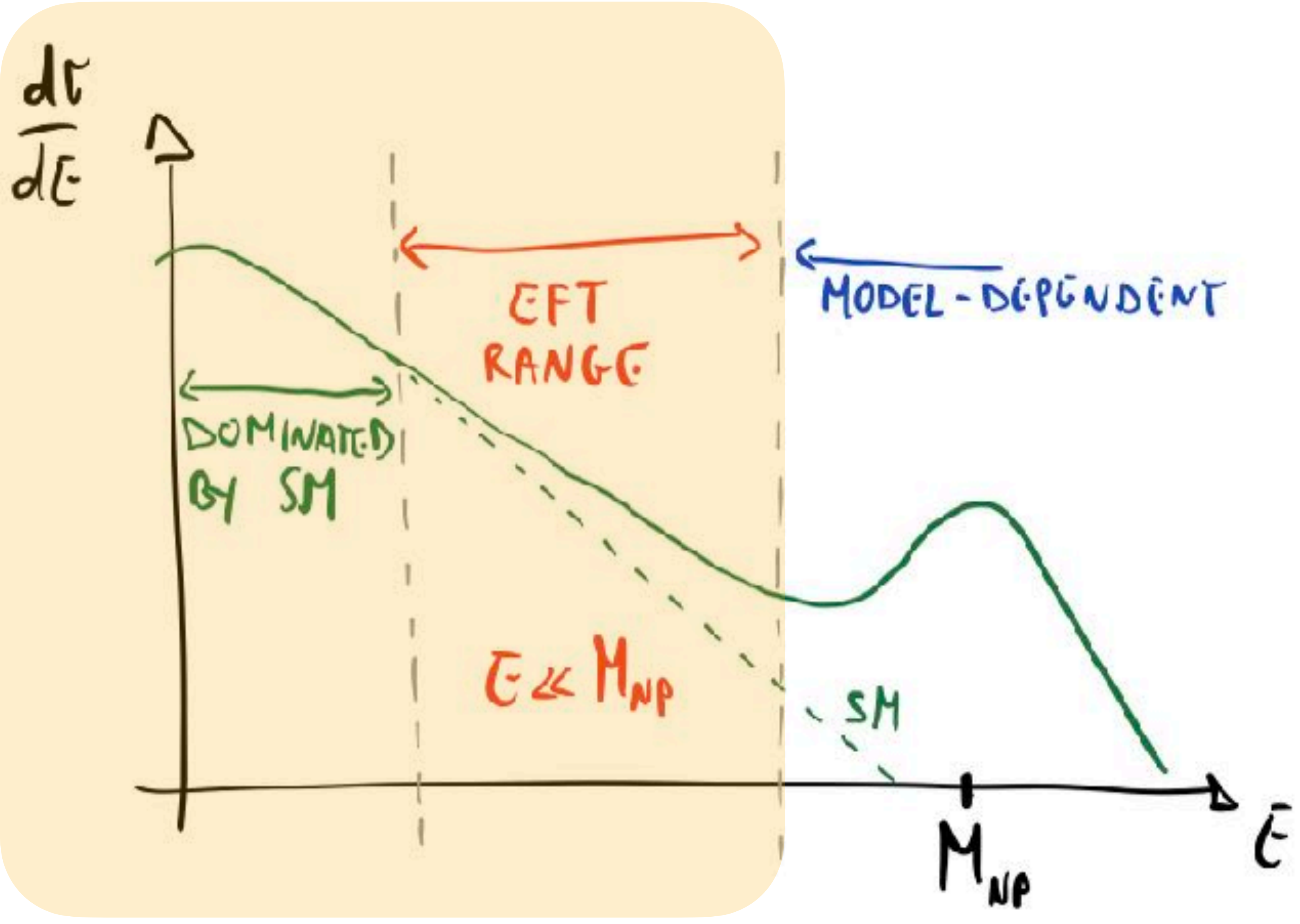
The huge number of events would allow for a precise characterization of the new state.

The direct and the indirect ways

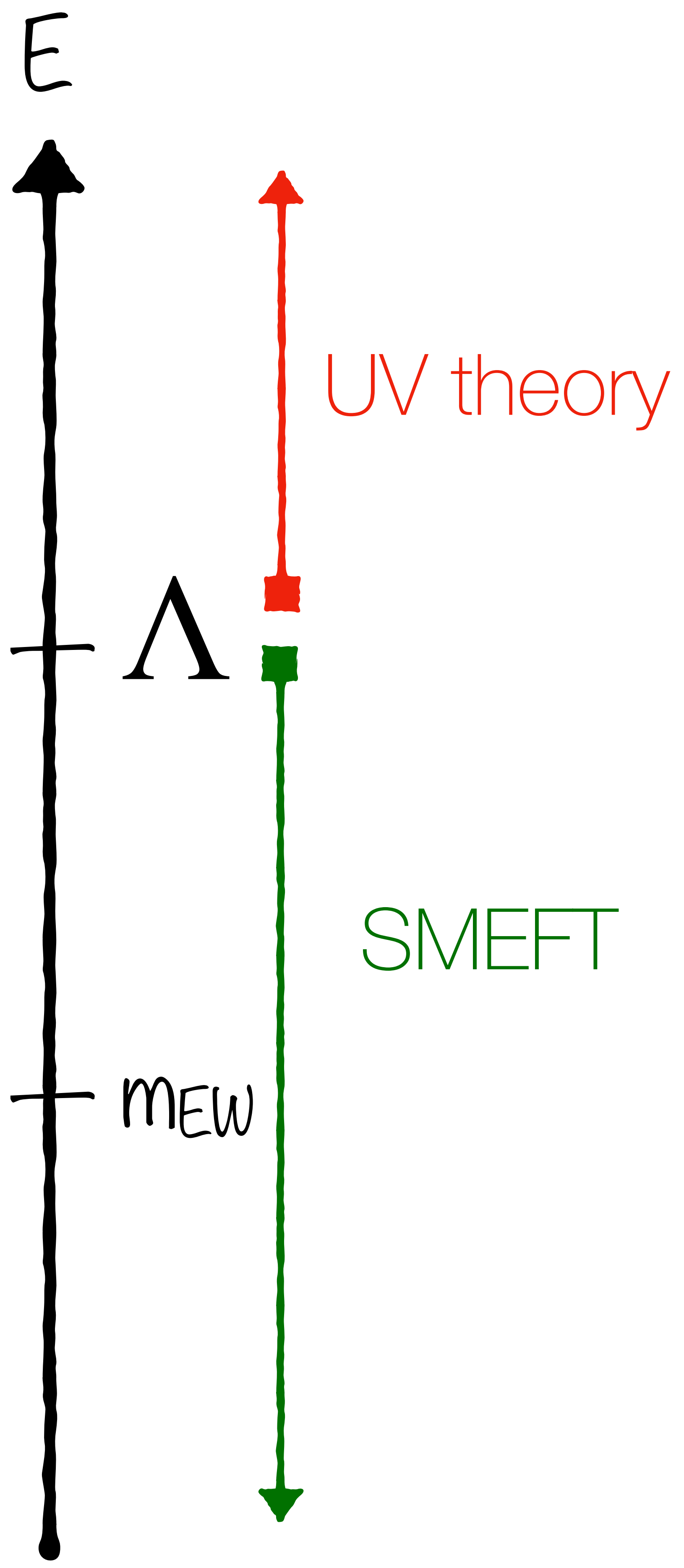
New Physics can be searched for **looking directly for the new particles**, or **looking for the effects of new particles in SM processes**.

If instead $\mathbf{E} \ll \Lambda_{\mathrm{NP}}$ we can **use the EFT approach** and look for **deviations in SM processes**.





Heavy New Physics and the EFT paradigm



If instead $E \ll \Lambda_{NP}$ we can **use Effective Field Theories** to describe all the **deviations from the SM** consistent with gauge symmetries.

$$\mathcal{L}^{NP}_{SMEFT} \supset \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \mathcal{O}(\Lambda^{-4})^{*}$$

Standard Model Effective Field Theory

At **low energies**, their effects are **suppressed** by powers of

$$\frac{E^2}{\Lambda^2}, \frac{v^2}{\Lambda^2} \ll 1$$

---

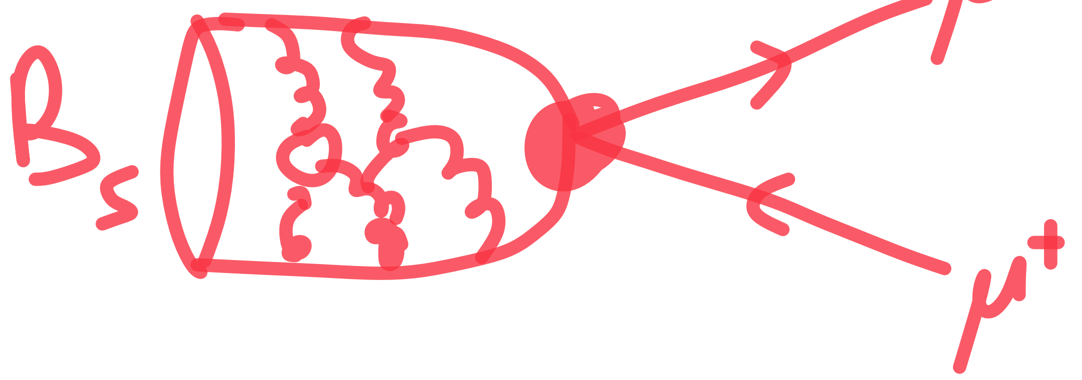
* I neglect the d=5 Weinberg operator since its effects in colliders are very suppressed by the small neutrino masses.

Heavy New Physics and the EFT paradigm

$$\mathcal{L}_{SMEFT} \supset \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)}$$

Low-energy
(e.g. FCNC rare decays)

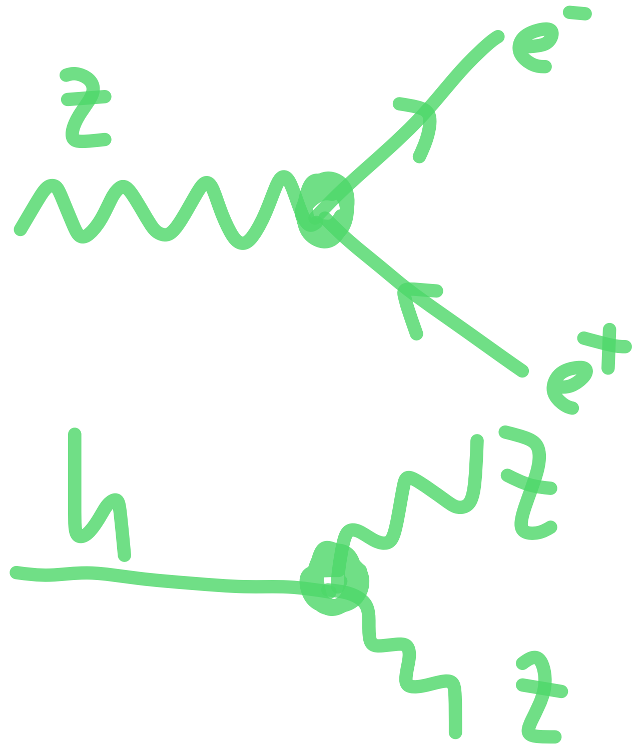
$$\frac{\delta C^{\mathrm{NP}}_{\mathrm{EFT}}}{C^{\mathrm{SM}}_{\mathrm{EFT}}} \sim \frac{c}{G_F c_{\mathrm{SM}} \Lambda^2}$$



Leverage the **rarity** of the SM process, **small c_{SM}**. **More in backup slides.**

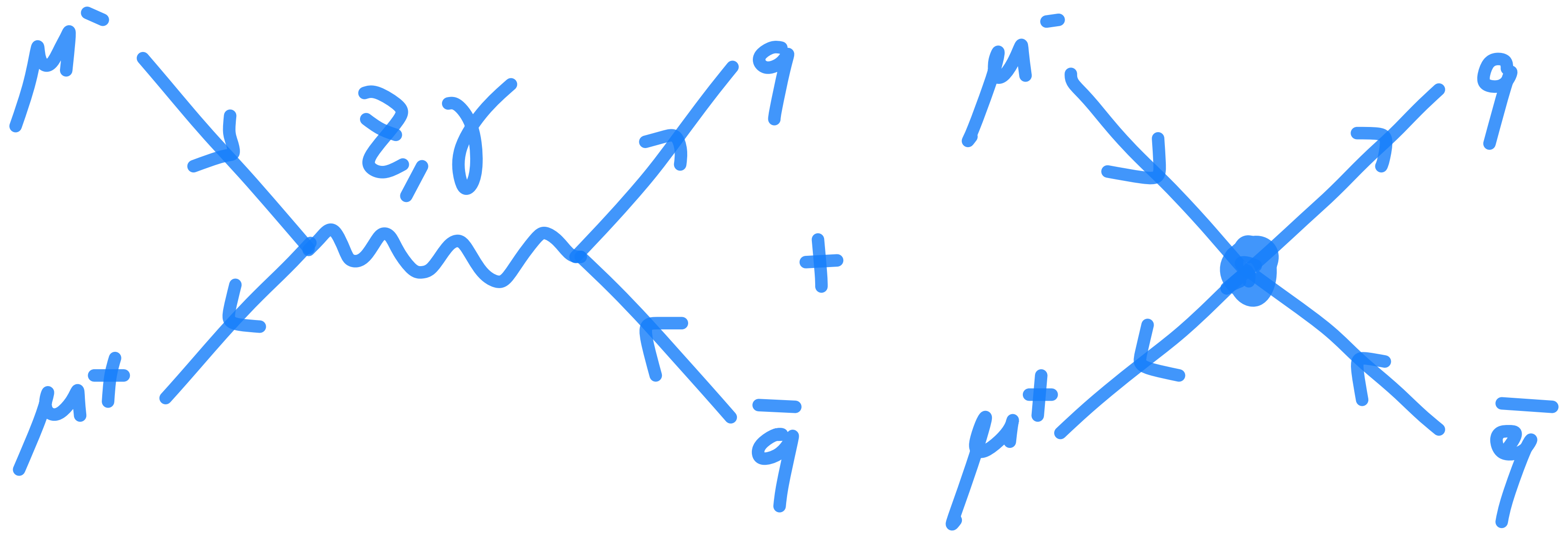
EW and Higgs

$$\frac{\delta g_{EW}}{g^{\mathrm{SM}}_{EM}} \sim \frac{v^2 c}{\Lambda^2}$$



Energy + Accuracy

$$\frac{\delta \mathcal{A}^{\mathrm{NP}}_{\mathrm{EFT}}}{\mathcal{A}_{\mathrm{SM}}} \sim \frac{E^2 c}{g^2_{\mathrm{SM}} \Lambda^2}$$

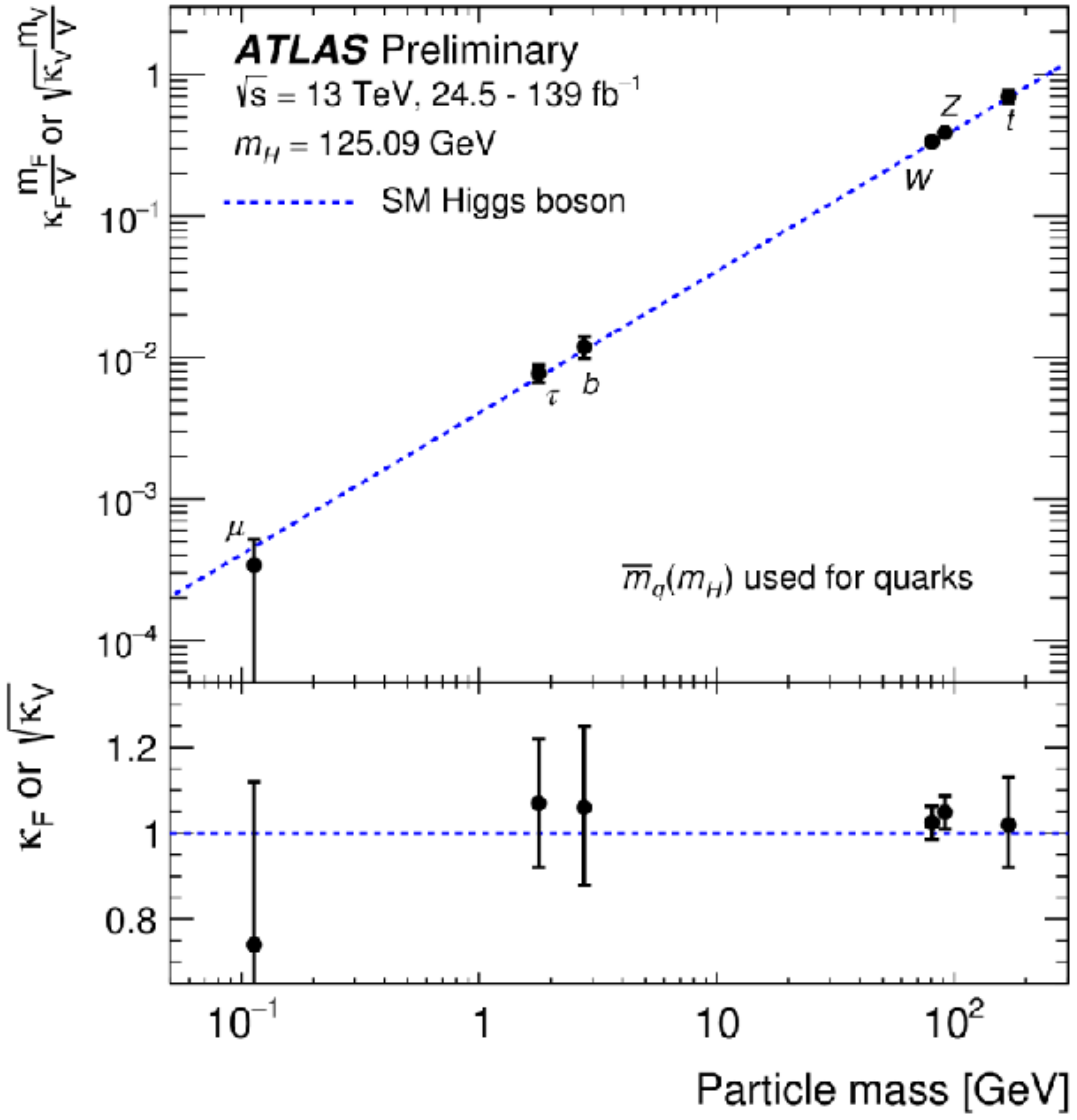


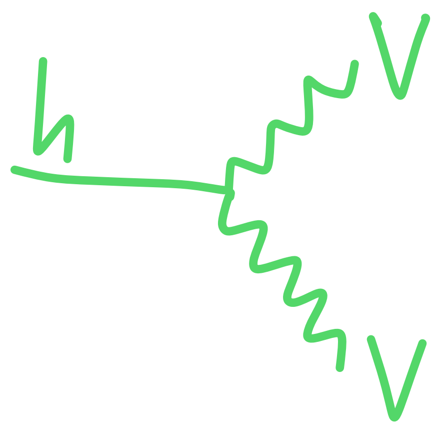
Leverage the **energy² enhancement** of the EFT contribution.

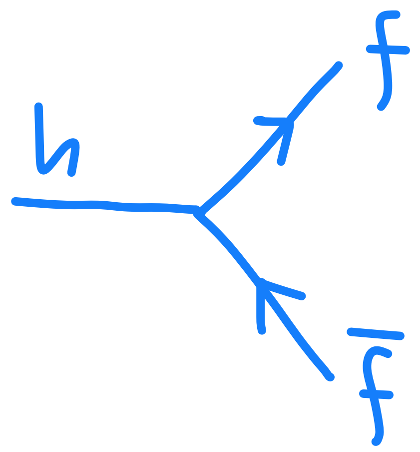
Higgs Physics

Higgs SM couplings are predicted from masses.

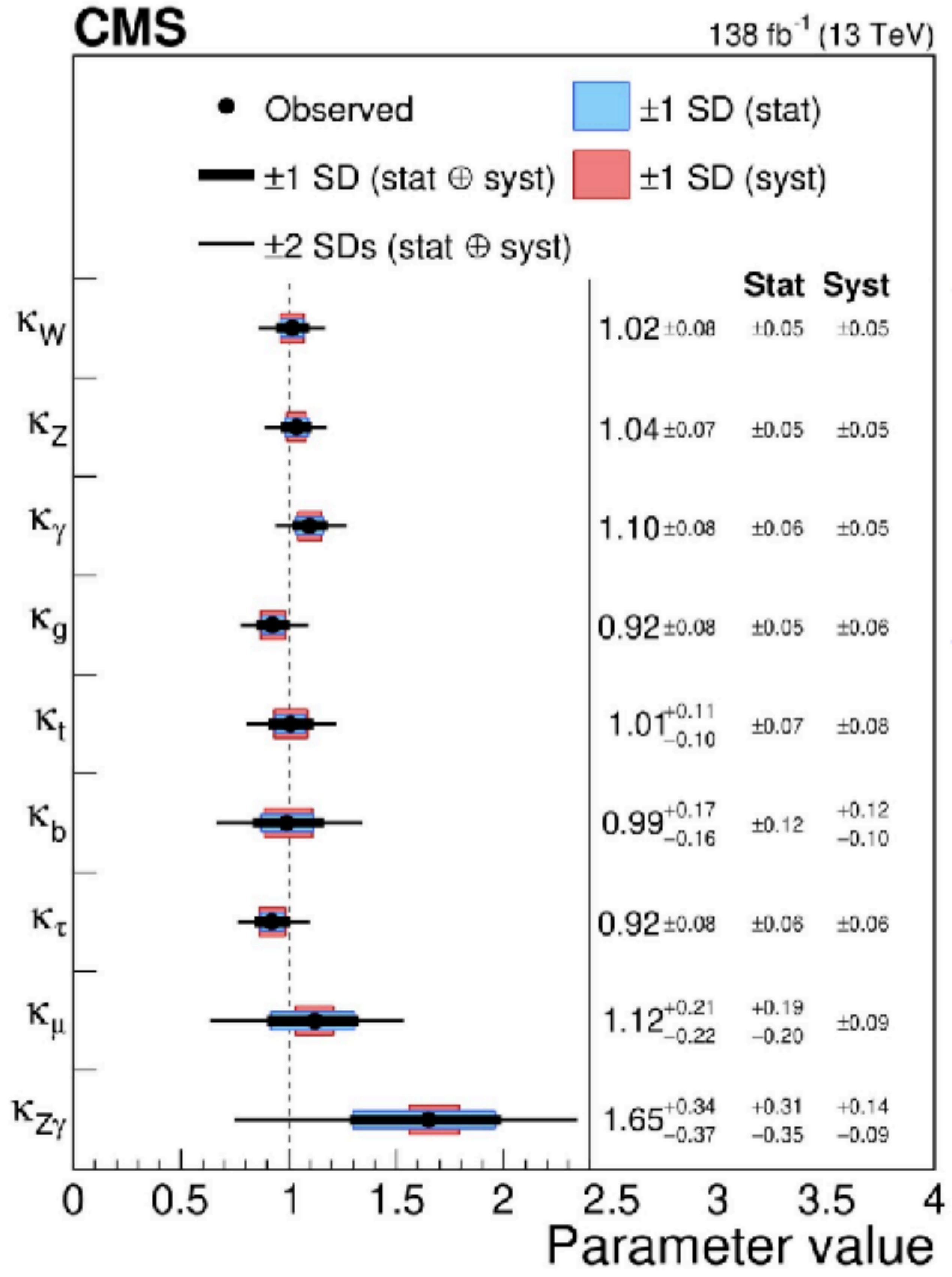
Testing for **deviations in Higgs couplings** gives us access to **new physics coupled to the Higgs**.







Where do we stand?



$$\kappa = \frac{g}{g_{SM}}$$

~7-8%

~10%

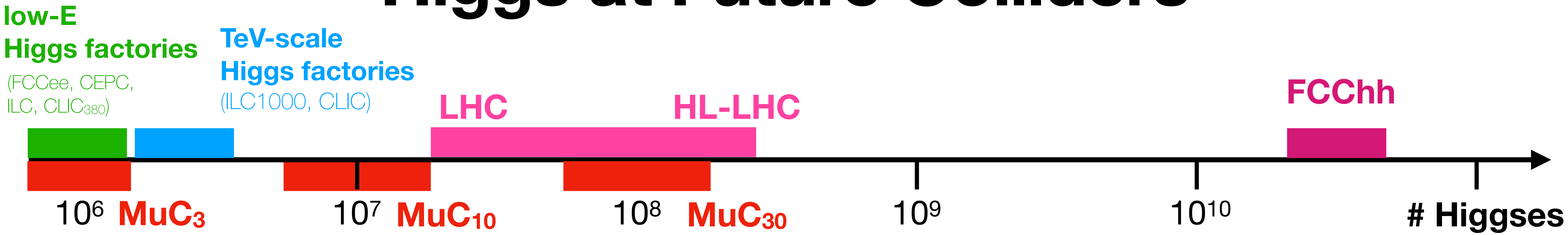
~15%

~ 8%

~20%

~35%

Higgs at Future Colliders



Higgs at Future Colliders

low-E
Higgs factories
(FCCee, CEPC,
ILC, CLIC$_{380}$)

TeV-scale
Higgs factories
(ILC1000, CLIC)

LHC

HL-LHC

FCChh

10^6 **MuC$_3$**

10^7 **MuC$_{10}$**

10^8 **MuC$_{30}$**

10^9

10^{10}

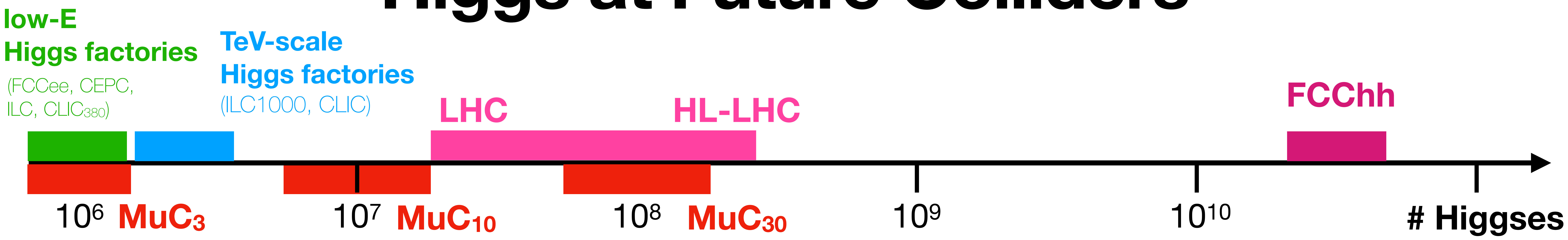
 # Higgses

[1905.03764, 2103.14043]

Coupling	HL-LHC	HL-LHC + 125 GeV μ-coll. 5 / 20 fb^{-1}	HL-LHC + 3 TeV μ-coll. 1 ab^{-1}	**HL-LHC + MuC10 10 ab^{-1}**	HL-LHC + 10 TeV μ-coll. + e^+e^- H fact (240/365 GeV)	**FCC-ee 240+365**	**FCC-ee/eh/hh**
κ_W [%]	1.7	1.3 / 0.9	0.4	**0.1**	0.1	**0.4**	**0.1**
κ_Z [%]	1.5	1.3 / 1.0	0.9	**0.4**	0.1	**0.2**	**0.1**
κ_g [%]	2.3	1.7 / 1.4	1.4	**0.7**	0.6	**1.0**	**0.5**
κ_γ [%]	1.9	1.6 / 1.5	1.3	**0.8**	0.8	**3.9**	**0.3**
$\kappa_{Z\gamma}$ [%]	10	10 / 10	9.9	**7.2**	7.1	**75**	**0.7**
κ_c [%]	-	12 / 5.9	7.4	**2.3**	1.1	**1.3**	**1.0**
κ_b [%]	3.6	1.6 / 1.0	0.9	**0.4**	0.4	**0.7**	**0.4**
κ_μ [%]	4.6	0.6 / 0.3	4.3	**3.4**	3.2	**8.9**	**0.4**
κ_τ [%]	1.9	1.4 / 1.2	1.2	**0.6**	0.4	**0.7**	**0.4**
$\kappa_t^\dagger$ [%]	3.3	3.2 / 3.1	3.1	**3.1**	3.1	**—**	**1.0**
$\Gamma_H^\ddagger$ [%]	5.3	2.7 / 1.7	1.5	**0.5**	0.4		

~2% **~0.3%** **~0.3%** **~0.1%**

Higgs at Future Colliders



low-E Higgs factories
(FCCee, CEPC, ILC, CLIC_{380})

TeV-scale Higgs factories
(ILC1000, CLIC)

LHC

HL-LHC

FCChh

10^6 **MuC_3**

10^7 **MuC_{10}**

10^8 **MuC_{30}**

10^9

10^{10}

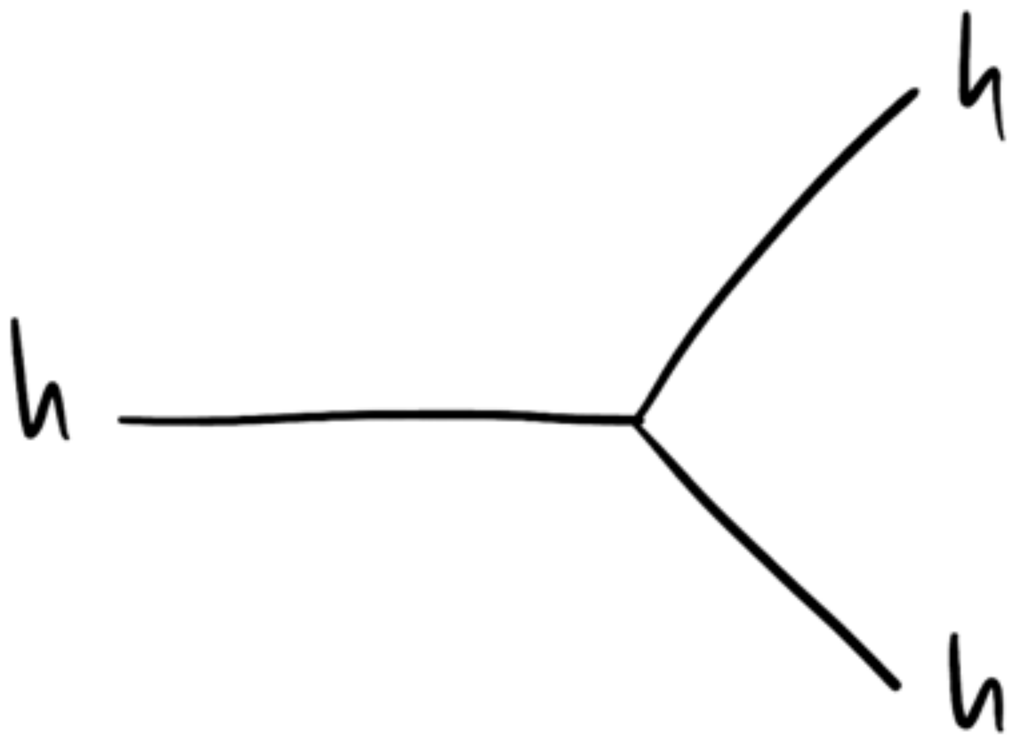
 # Higgses

Which mass scale does it probe?

$$\frac{\delta g_{hXX}}{g_{hXX}^{SM}} \sim \frac{v^2 c}{\Lambda^2} \sim \begin{cases} 10^{-1} & \text{today} \\ 10^{-2} & \\ 10^{-3} & \text{future} \end{cases} \longrightarrow \quad \frac{\Lambda}{\sqrt{c}} \gtrsim \begin{cases} 0.8\,\text{TeV} \\ 2\,\text{TeV} \\ 8\,\text{TeV} \end{cases}$$

Higgs potential

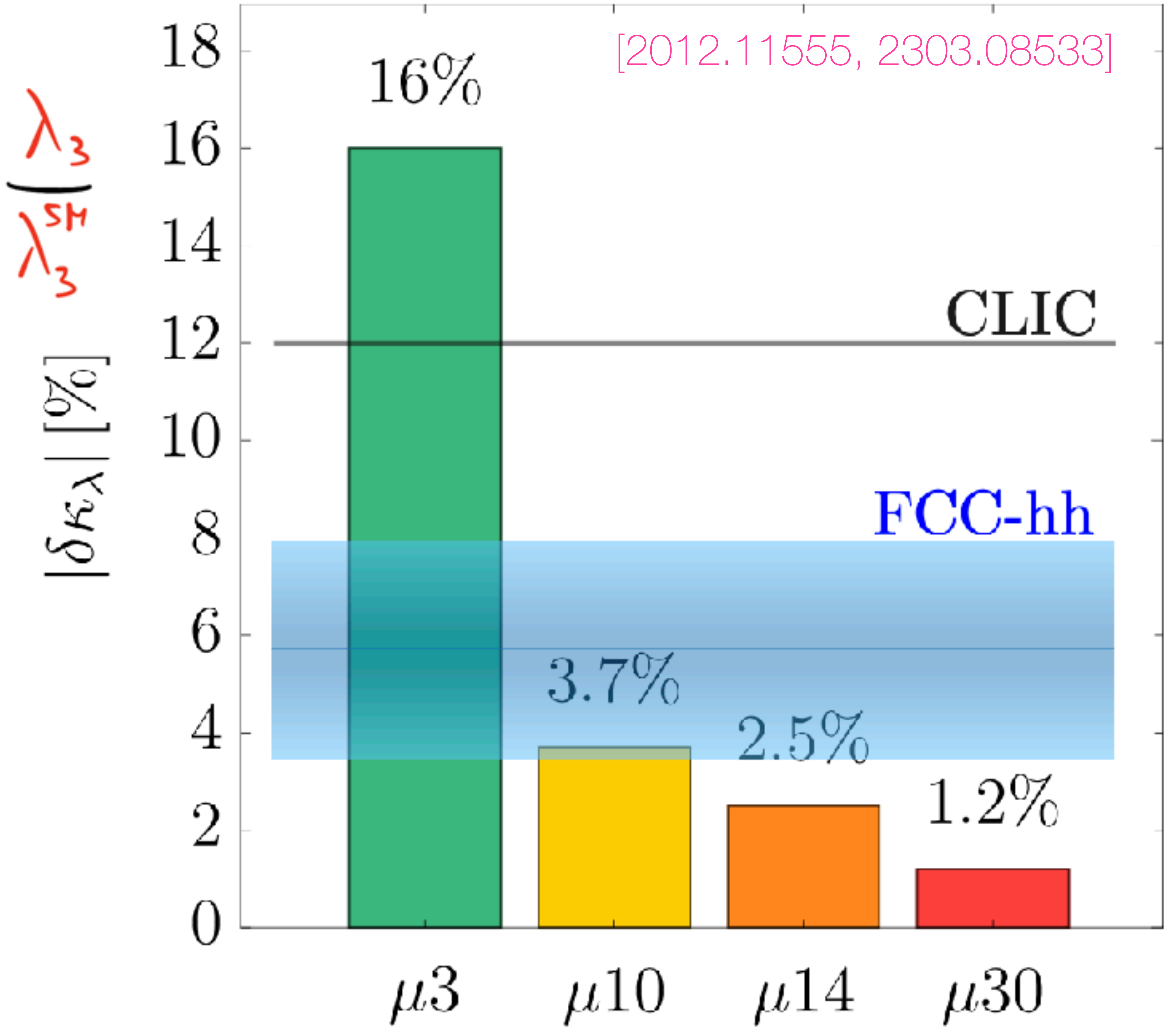
$$V(h) = \frac{1}{2} m_H^2 h^2 + \lambda_3 v h^3 + \frac{1}{4} \lambda_4 h^4$$



$$\lambda_3^{SM} = \lambda_4^{SM} = \frac{m_H^2}{2v^2}$$

$$\kappa_\lambda \equiv \frac{\lambda_3}{\lambda_3^{SM}}$$

Measuring the **Higgs trilinear coupling** is important to confirm the SM picture in the Higgs potential and test for many BSM scenarios with important implications: **EW phase transition**, **Higgs stability**, **additional neutral scalars**, etc..



few % precision tests new physics at the 1 TeV scale

FCC-hh and a 10 TeV MuC have similar capability.

Electroweak physics

FCCee will deliver **6 x 10^{12} Z bosons**: 2 x 10^5 times the number of Z bosons produced at LEP-1.

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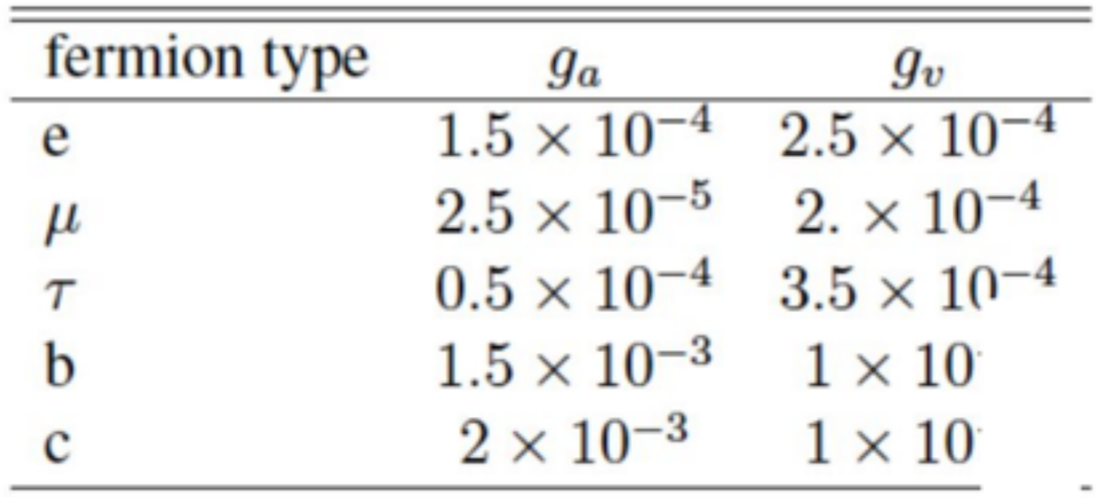
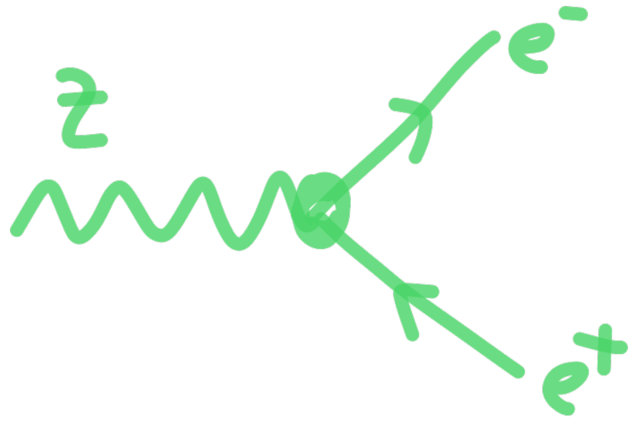
Z couplings at FCCee



fermion type	g_a	g_v
e	1.5×10^{-4}	2.5×10^{-4}
μ	2.5×10^{-5}	$2. \times 10^{-4}$
τ	0.5×10^{-4}	3.5×10^{-4}
b	1.5×10^{-3}	1×10
c	2×10^{-3}	1×10



$$\frac{\delta g_{Z\ell}}{g_{Z\ell}^{SM}} \sim \frac{v^2 c}{\Lambda^2} \sim \begin{cases} \text{few } 10^{-3} \\ 10^{-4} \div \text{few } 10^{-5} \end{cases} \longrightarrow \frac{\Lambda}{\sqrt{c}} \gtrsim \begin{cases} 5\,\text{TeV} \\ 25 \div 50\,\text{TeV} \end{cases}$$

LEP-1

FCCee

+ 10^8 W bosons and precision studies of $e^-e^+ \to f\bar{f}$ at WW and ttbar thresholds.

Challenging level for theory and experimental uncertainties

Electroweak physics

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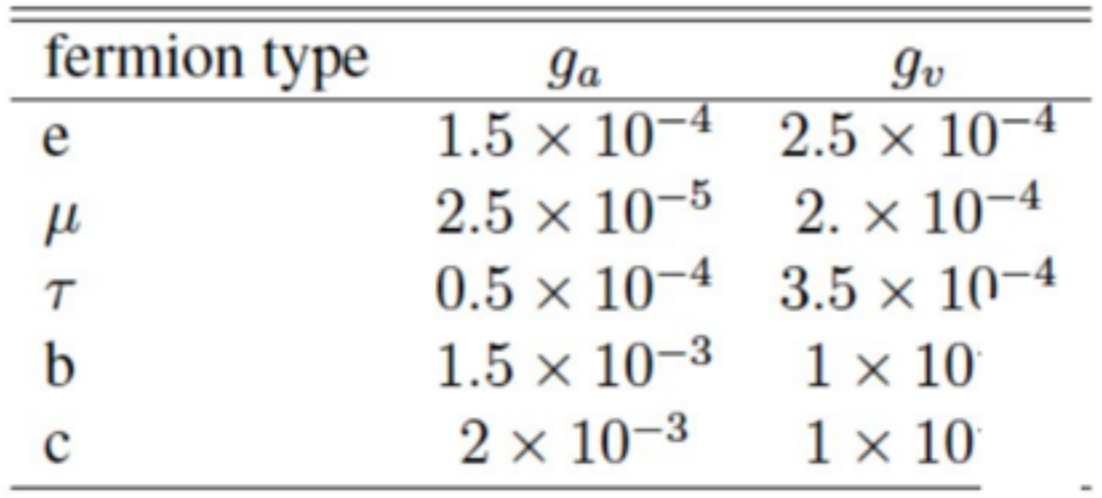
Z couplings at FCCee



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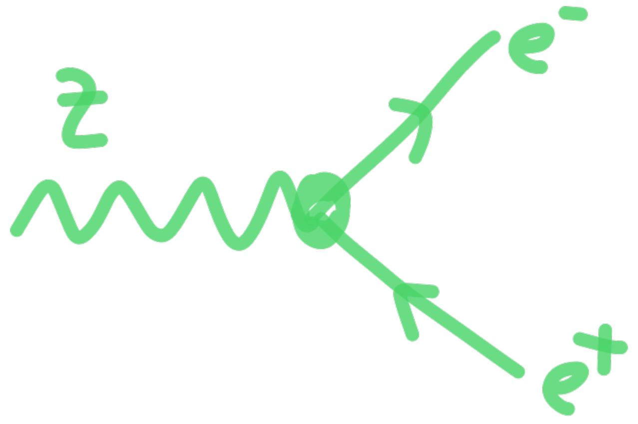

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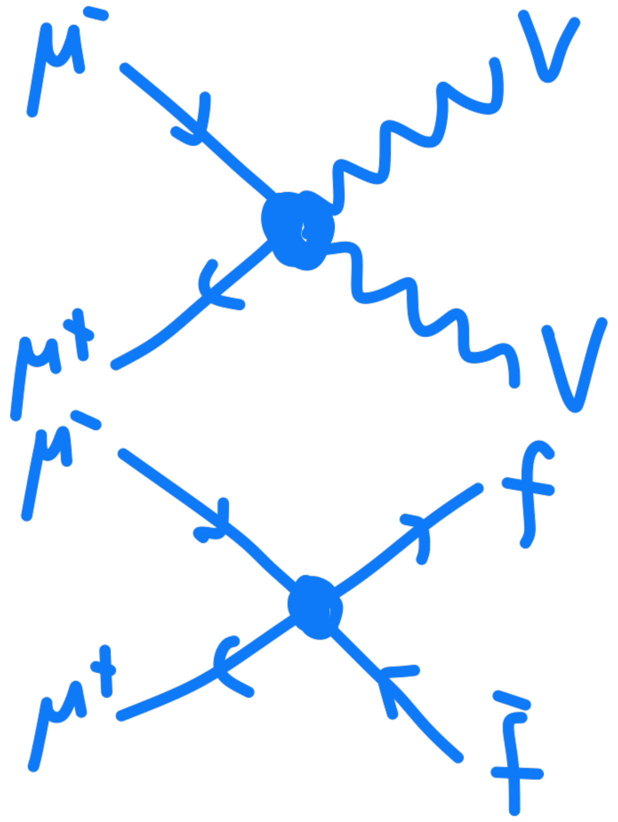
LEP-1

FCCee

+ 10^8 W bosons and precision studies of $e^- e^+ \to f\bar{f}$ at WW and ttbar thresholds.

Challenging level for theory and experimental uncertainties

The **Muon Collider** instead **probes the same effective operators in high-energy scattering** with 1% precision.



$$\frac{\delta\sigma}{\sigma_{SM}} \sim \frac{E^2 c}{g_{SM}^2 \Lambda^2} \lesssim 1\,\%$$

10TeV MuC

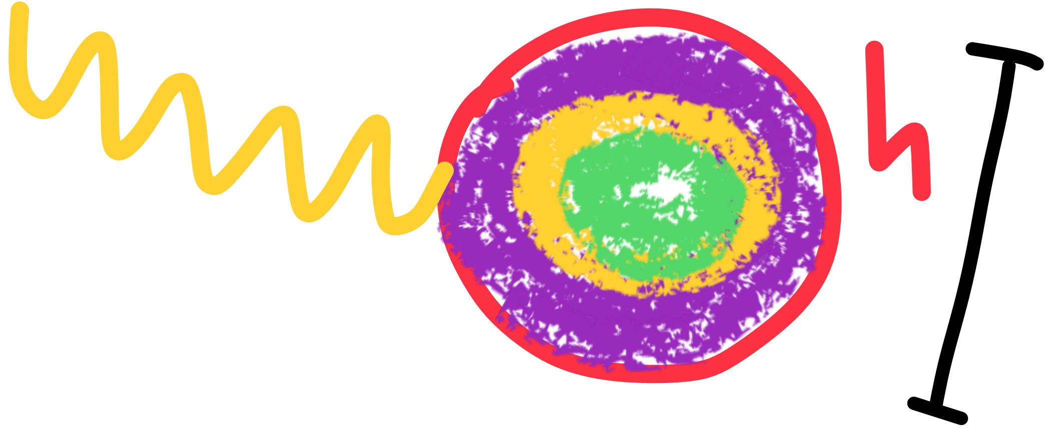
$$\frac{\Lambda}{\sqrt{c}} \gtrsim 150\,\text{TeV}$$

We will need to learn how to deal with EW radiation

Higgs compositeness

2 parameters:

[review: 1506.01961]



Compositeness scale

$\ell_h \simeq \frac{1}{m_*}$

Strong coupling

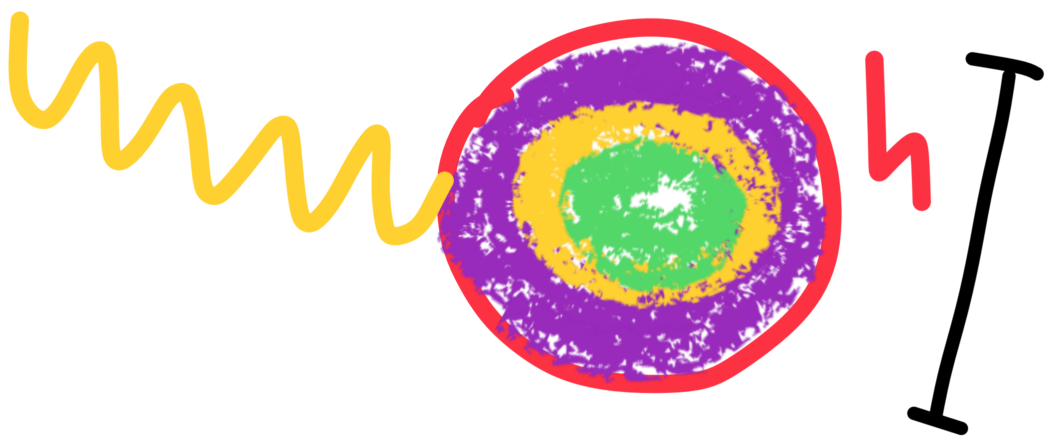
$1 \lesssim g_* \lesssim 4\pi$

Higgs compositeness

2 parameters:

[review: 1506.01961]

Compositeness scale



$\ell_h \approx \frac{1}{m_*}$

Strong coupling

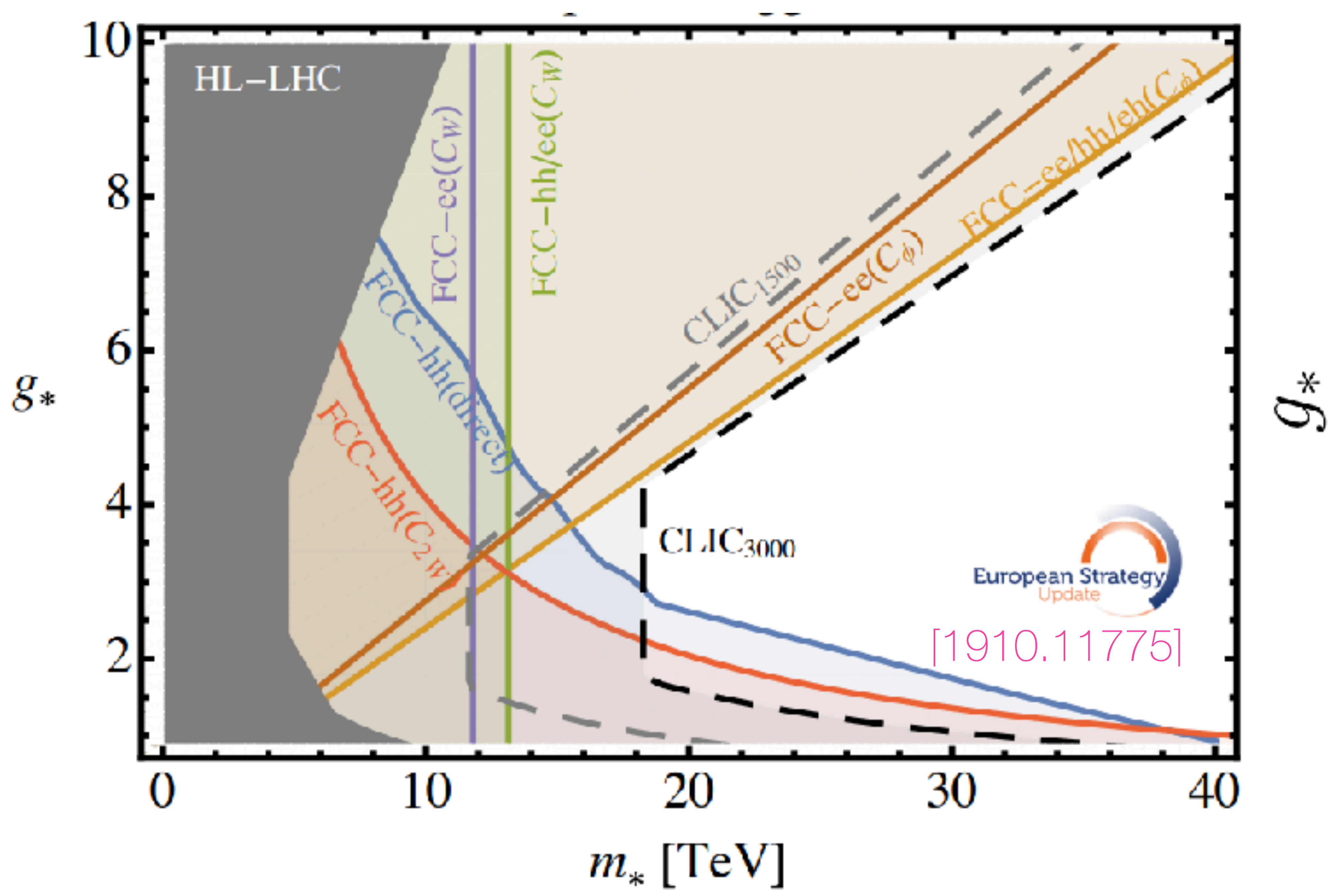
$1 \lesssim g_* \lesssim 4\pi$

Reach of different colliders from **Higgs couplings** and high-energy **di-lepton**, $t\bar{t}$, $b\bar{b}$, and **diboson** production.

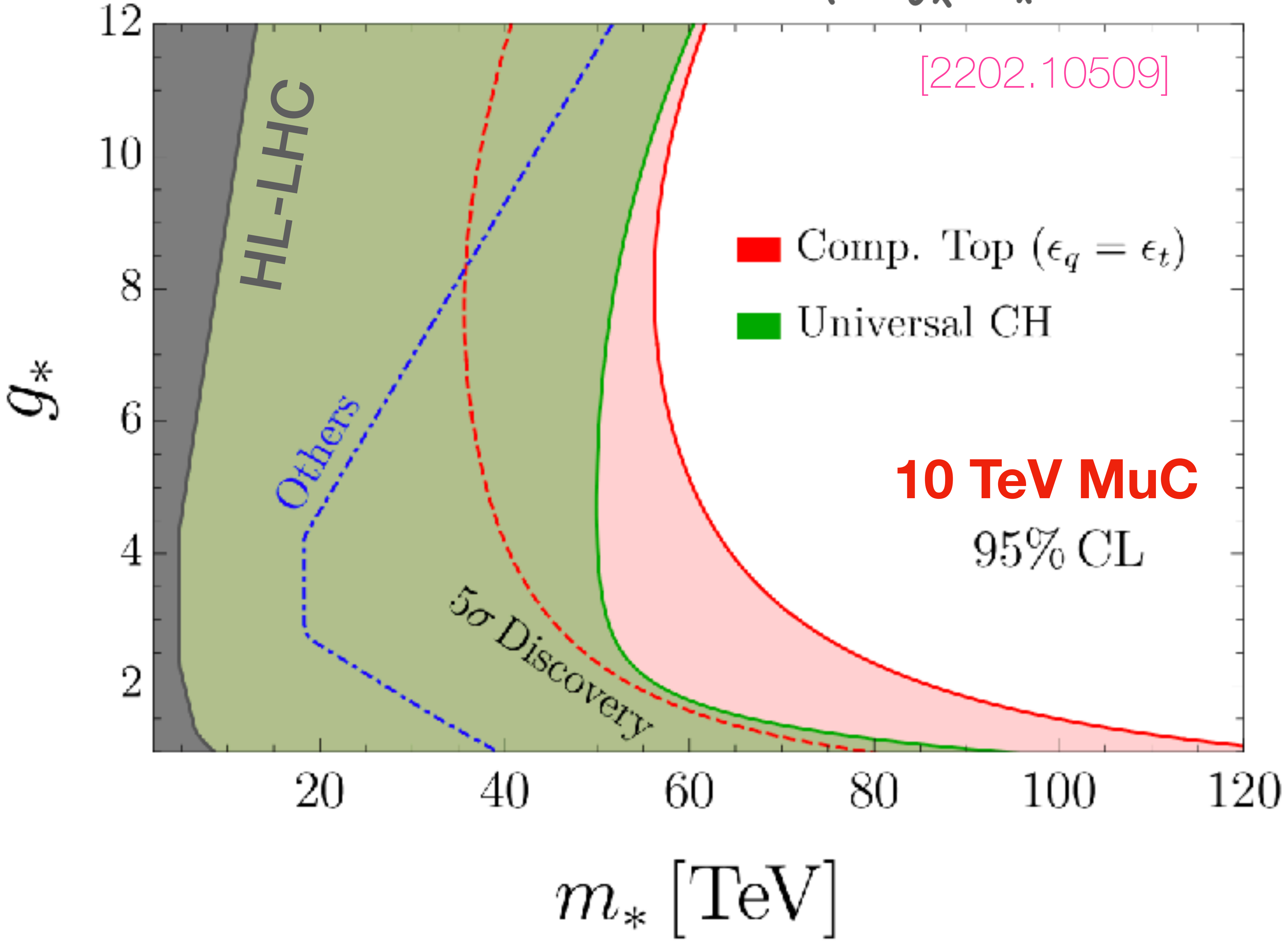
$\frac{C_W}{\Lambda^2} \sim \frac{1}{m_*^2}$

$C_\phi/\Lambda^2 \sim g_*^2/m_*^2$

$\frac{C_{2W}}{\Lambda^2} \sim \frac{1}{g_*^2 m_*^2}$



[1910.11775]



[2202.10509]

HL-LHC

$m_* \gtrsim 5$ TeV

FCCee+hh

$m_* \gtrsim 16$ TeV

CLIC 3TeV

$m_* \gtrsim 18$ TeV

MuC 10TeV

$m_* \gtrsim 50$ TeV

Conclusions

LHC was a machine built with a **precise primary goal: discovering the Higgs**.
It delivered this, and so much more. We have been able to push it beyond all expectations.

The **next collider will be an exploration machine**, allowing us to probe the microcosm well **below the atto-scale**. The only way to know what's there is to **go and look!**

The **indirect** and the **direct** ways give us **complementary** and crucial information, this mixed goal can be achieved:

- with **FCCee + FCChh**, giving a perspective for particle physics **until the end of the century**,
- with a **revolutionary** **muon collider**, paving the way for the next-to-next generation of experiments.

These collider projects are **modern cathedrals of science and human ingenuity**,

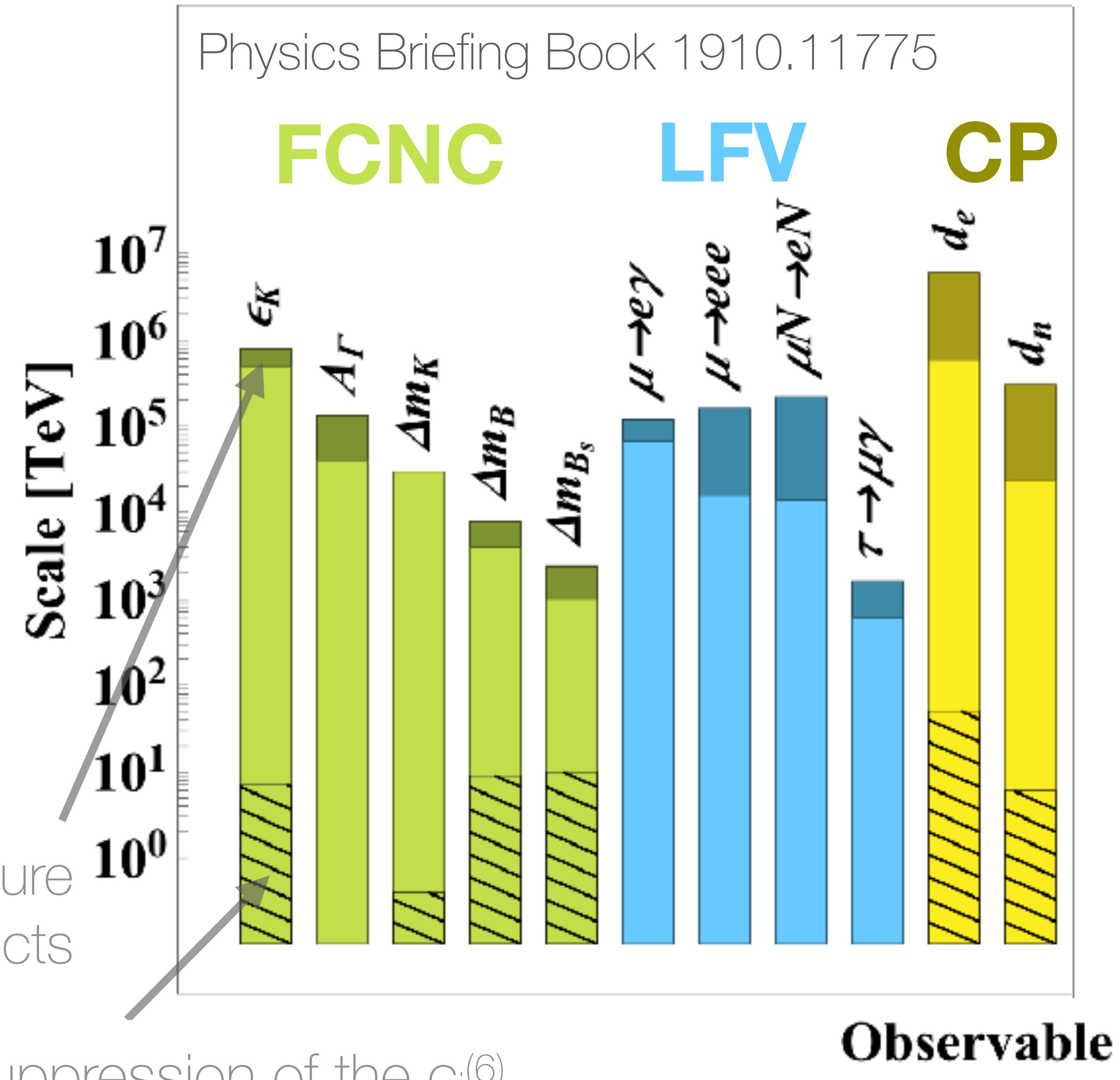
it is a privilege to live at a time and place where we have the chance to work on such projects.

Backup

Flavour

Processes rare or forbidden by the accidental SM symmetries and properties allow to probe indirectly very large New Physics scales.

Bounds on Λ (taking $c_i^{(6)} = 1$) from various processes



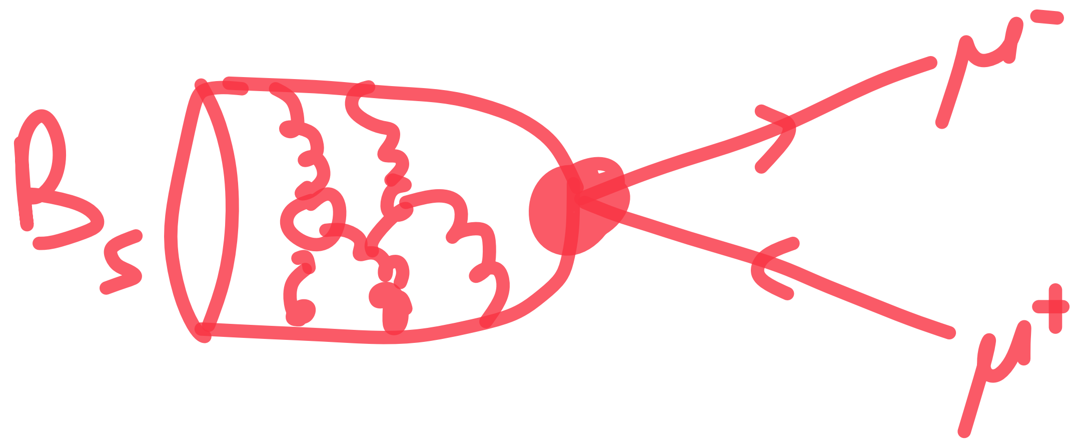
Physics Briefing Book 1910.11775

Near-future prospects

CKM suppression of the $c_i^{(6)}$

$$\mathcal{L}^{(d=6)}_{\mathrm{SMEFT}} = \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)}[\varphi_{\mathrm{SM}}]$$

$$\frac{\delta C^{\mathrm{NP}}_{\mathrm{EFT}}}{C^{\mathrm{SM}}_{\mathrm{EFT}}} \sim \frac{c}{G_F c_{\mathrm{SM}} \Lambda^2}$$

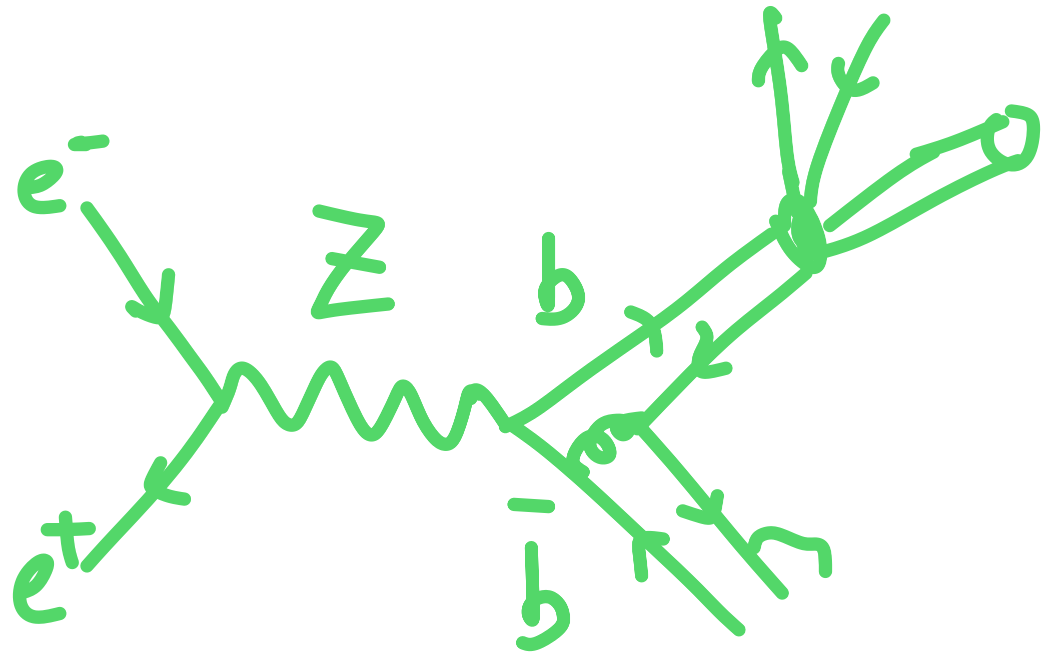


If New Physics is present **at the TeV scale**, **its flavour structure should be constrained**: **the BSM Flavour Problem**.

The $c^{(6)}$ coefficients that violate flavour or CP should be suppressed: MFV, U(2), etc.

Flavour at FCC-ee

6 x 10^{12} Z bosons provide a very large number of all **b and c mesons and τ leptons**, allowing to study their rare or forbidden decays in a clean environment.

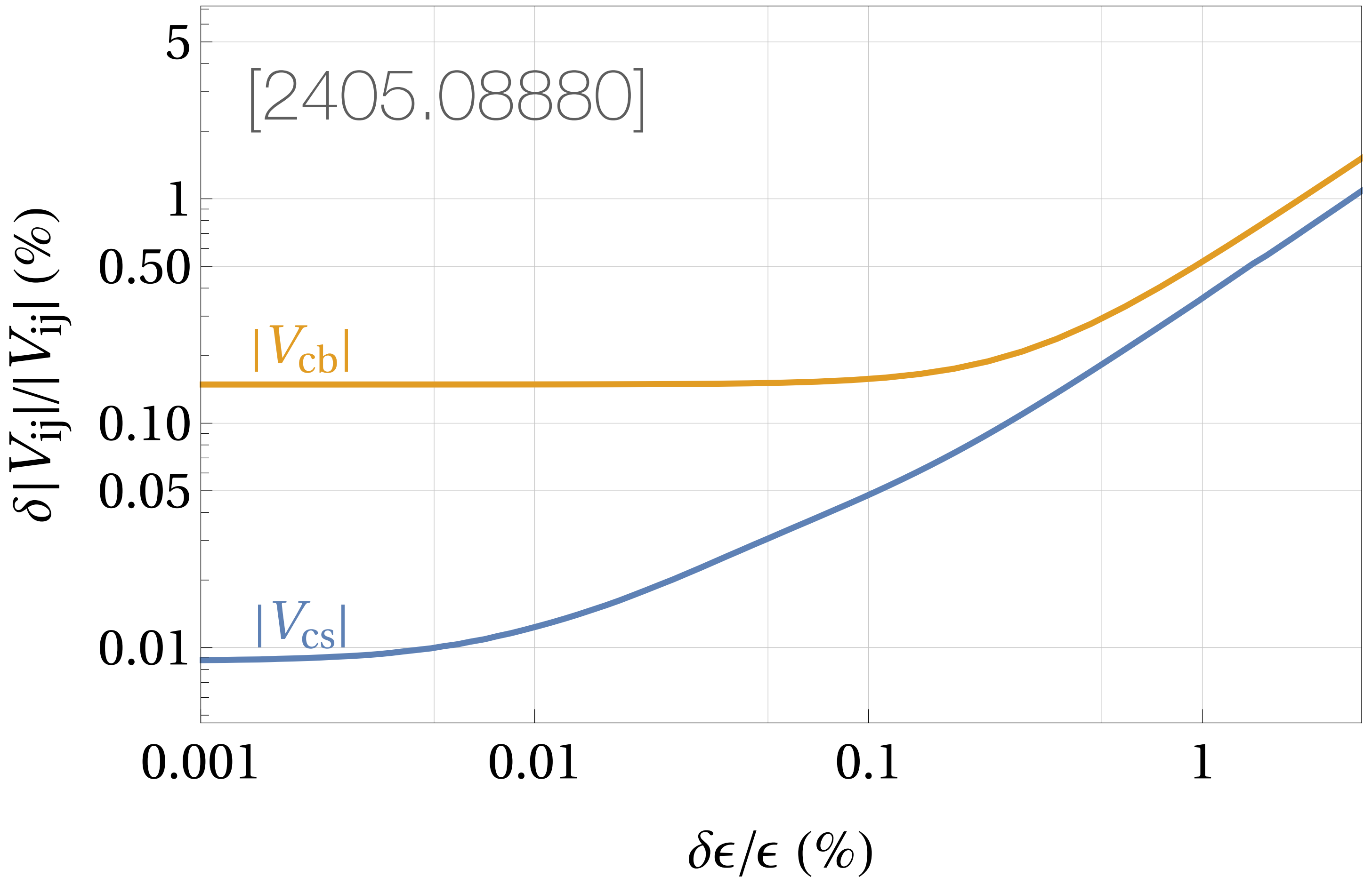


Particle production (10^9)	$B^0/\overline{B}^0$	B^+/B^-	$B^0_s/\overline{B}^0_s$	$B^+_c/\overline{B}^-_c$	$\Lambda_b/\overline{\Lambda}_b$	$c\bar{c}$	$\tau^+\tau^-$
Belle II	27.5	27.5	n/a	n/a	n/a	65	45
FCC-ee	620	620	150	4	130	600	170

Attribute	$\Upsilon(4S)$	pp	Z
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

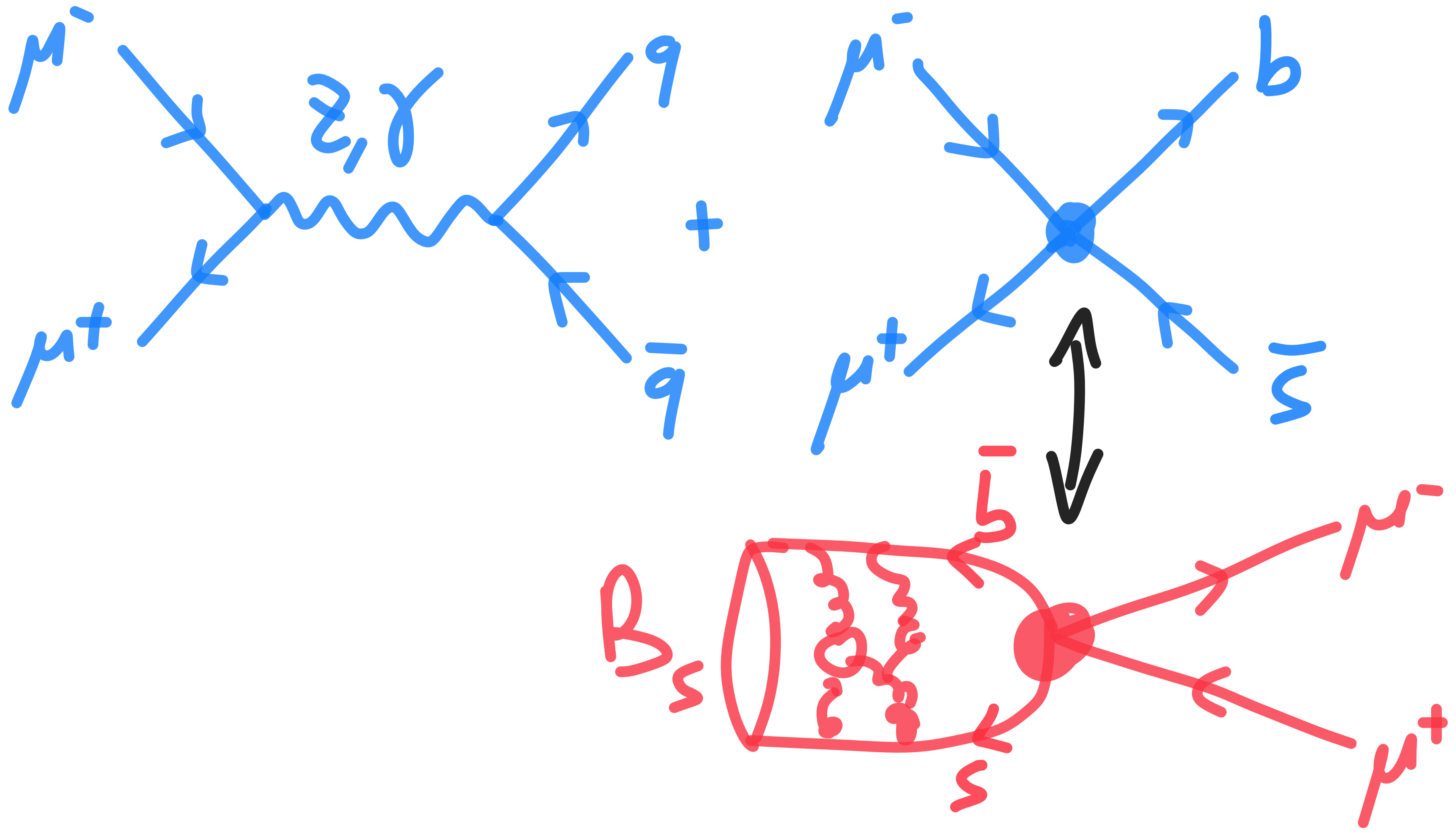
[2203.06520 + ECFA, FCC studies]

- few % level in $B_{(c)} > \tau\, \nu$,
- O(30)% level in $B > K^* \tau\, \tau$,
- <1% level in $B > K^{(*)} \nu\, \nu$,
- 10^{-11} sensitivity on the BR of LFV τ decays.
- 0.1% (0.05%) precision on $|V_{cb}|$ ($|V_{cs}|$) from W decays
- . . .



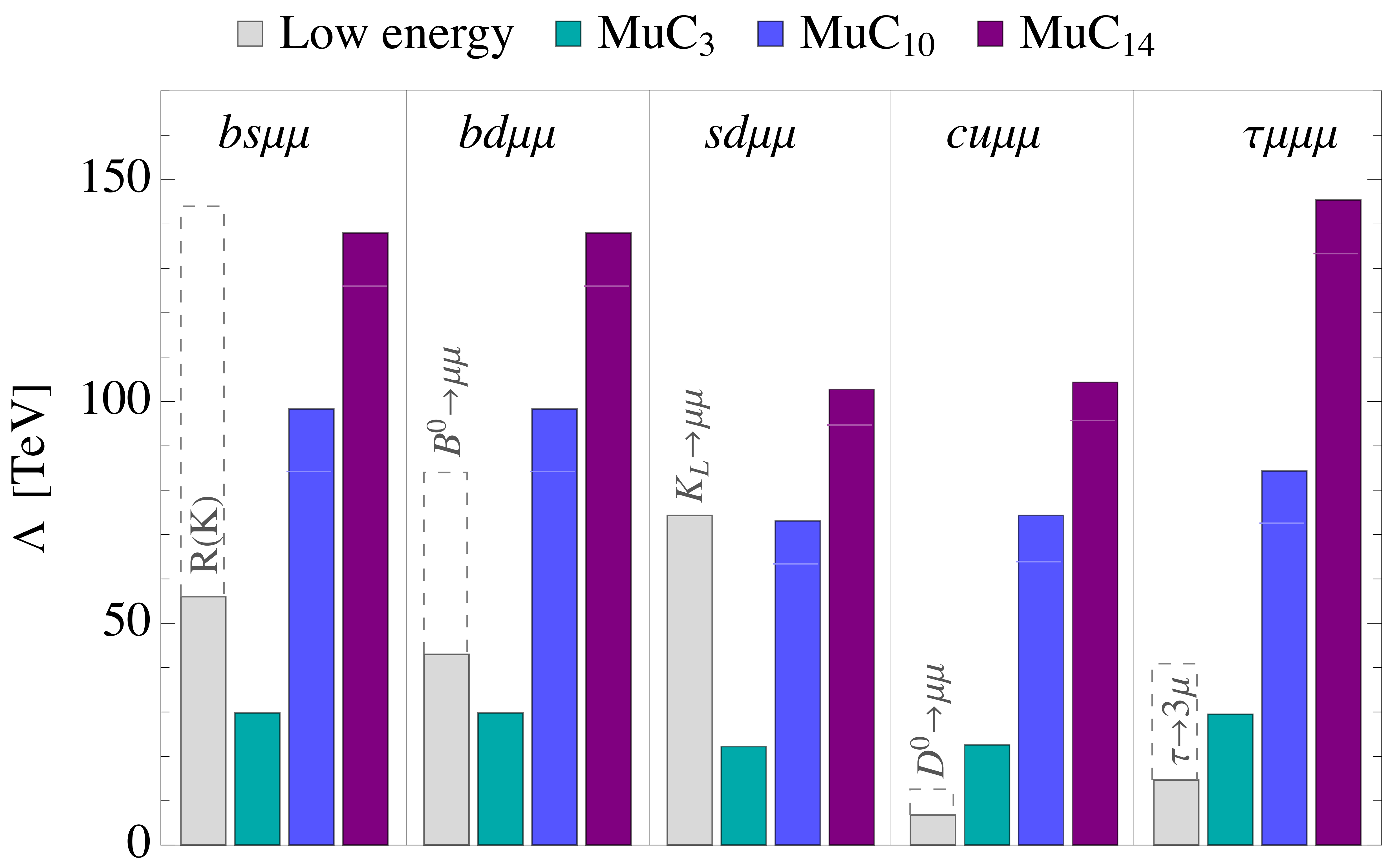
Flavour at Muon Colliders

$$\frac{\delta\mathcal{A}^{\rm NP}_{\rm EFT}}{\mathcal{A}_{\rm SM}} \sim \frac{E^2 c}{g^2_{\rm SM}\Lambda^2}$$



Test **same flavour-violating interaction** in **rare meson decays** or in **high-energy processes**.

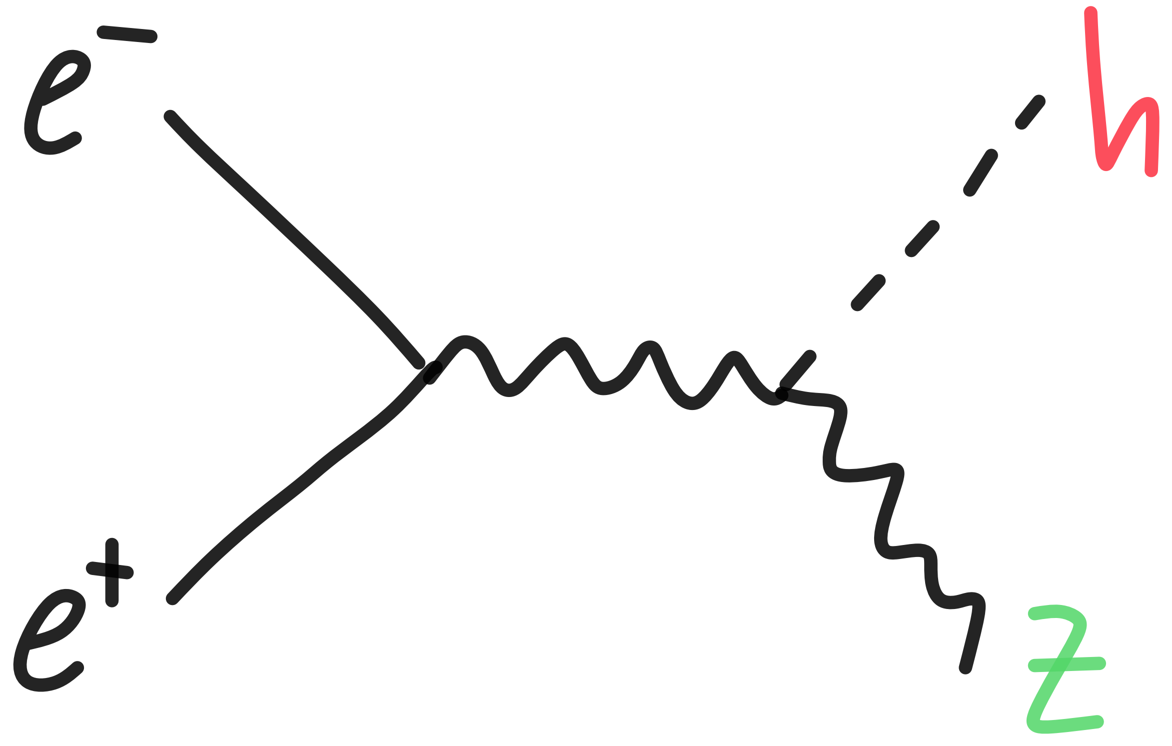
One can leverage the **E^2 enhancement** of the new physics scattering amplitude.



A 10 TeV MuC is sensitive to scales of about 100 TeV.

Higgs production at lepton colliders

Higgs production → At an e+e- machine the main process is $e^+e^- \to Z\,h$



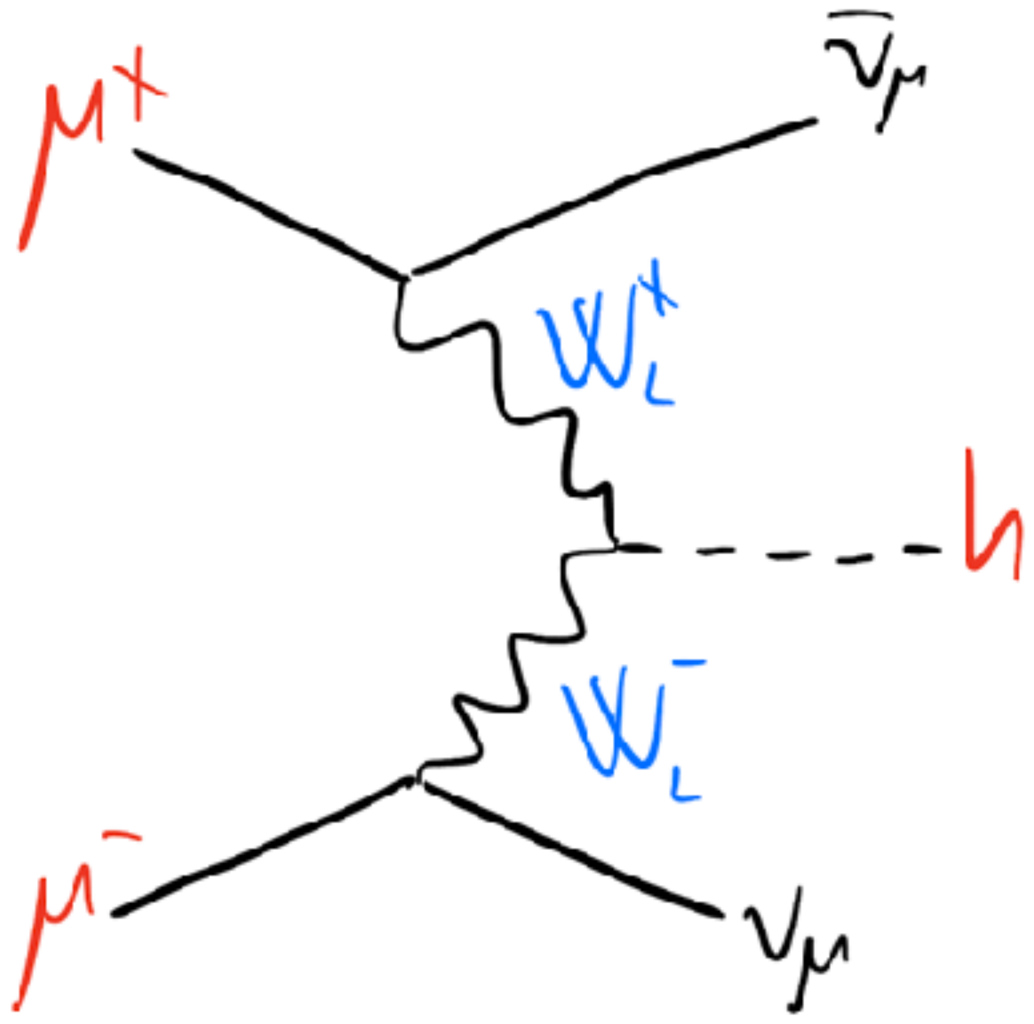
$$\sigma_{ann} \propto \frac{\alpha^2}{s}$$

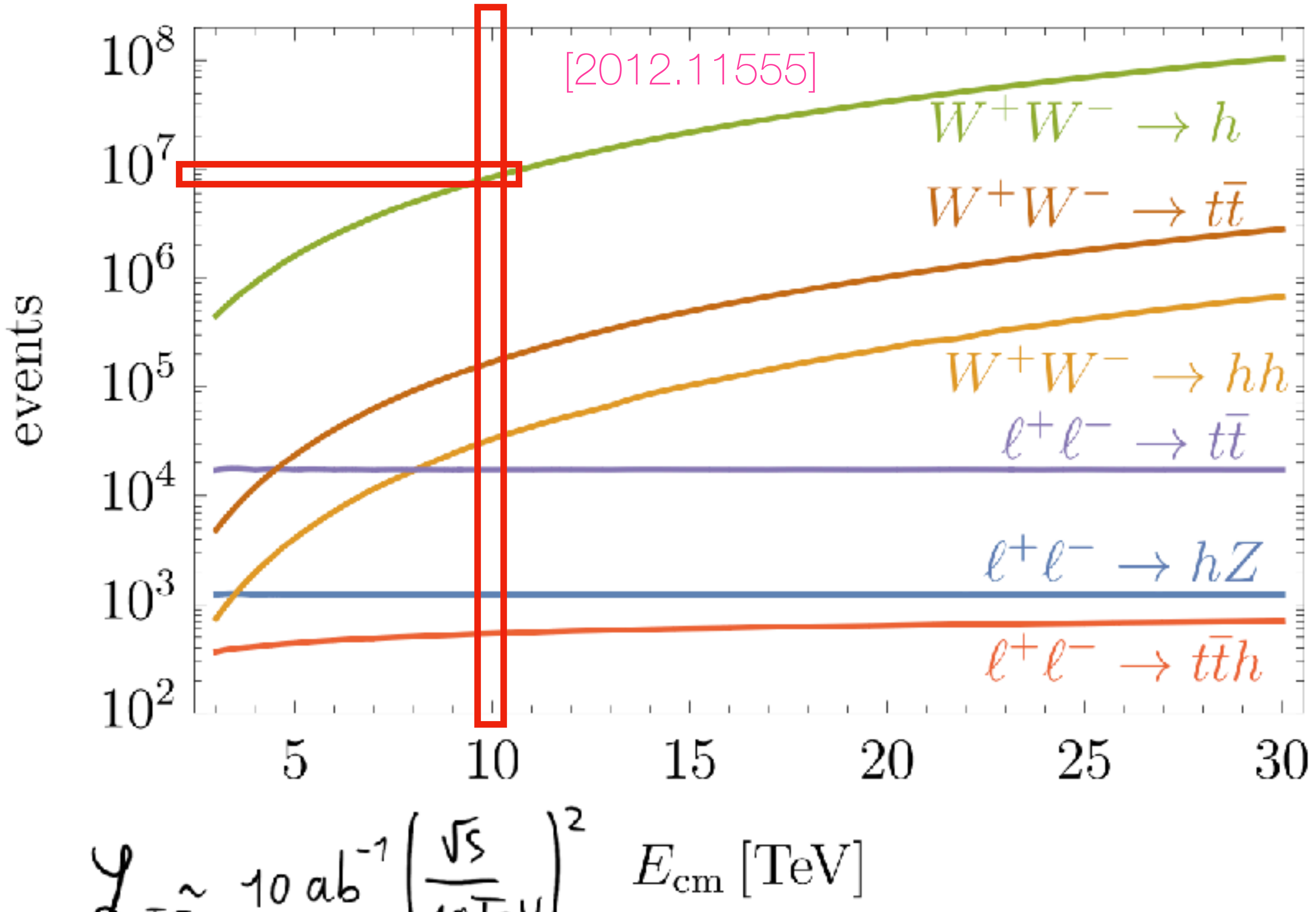
This annihilation process has small cross section at large collider energies.

Max σ at ~240 GeV: e+e- Higgs factories.

Another possibility is via **Vector Boson Fusion** (**VBF**):

A **10 TeV MuC** has **10^7 Higgs boson** events (~ # Z's at LEP)




[2012.11555]

$$\mathcal{L}_{TOT} \sim 10\,ab^{-1}\left(\frac{\sqrt{s}}{10\,TeV}\right)^2$$

Muon Colliders

We want to probe EW-size cross sections with % precision:

$$\sigma_{EW} \sim \frac{\alpha^2}{s} \sim 1\,\text{fb}\left(\frac{10\,\text{TeV}}{\sqrt{s}}\right)^2$$

To have % precision,
need 10k events:

Integrated luminosity

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

[1901.06150, 2303.08533]

Assuming 10^7 s/year operation, the **instantaneous luminosity** required is:

$$L \sim \frac{5\,\text{y}}{\text{time}}\left(\frac{\sqrt{s}}{10\,\text{TeV}}\right)^2 10^{35}\ \text{cm}^{-2}\,\text{s}^{-1}$$

The MuC is a short experiment: about **5 years** needed to collect the required integrated luminosity.