Theory motivation: opportunities & challenges

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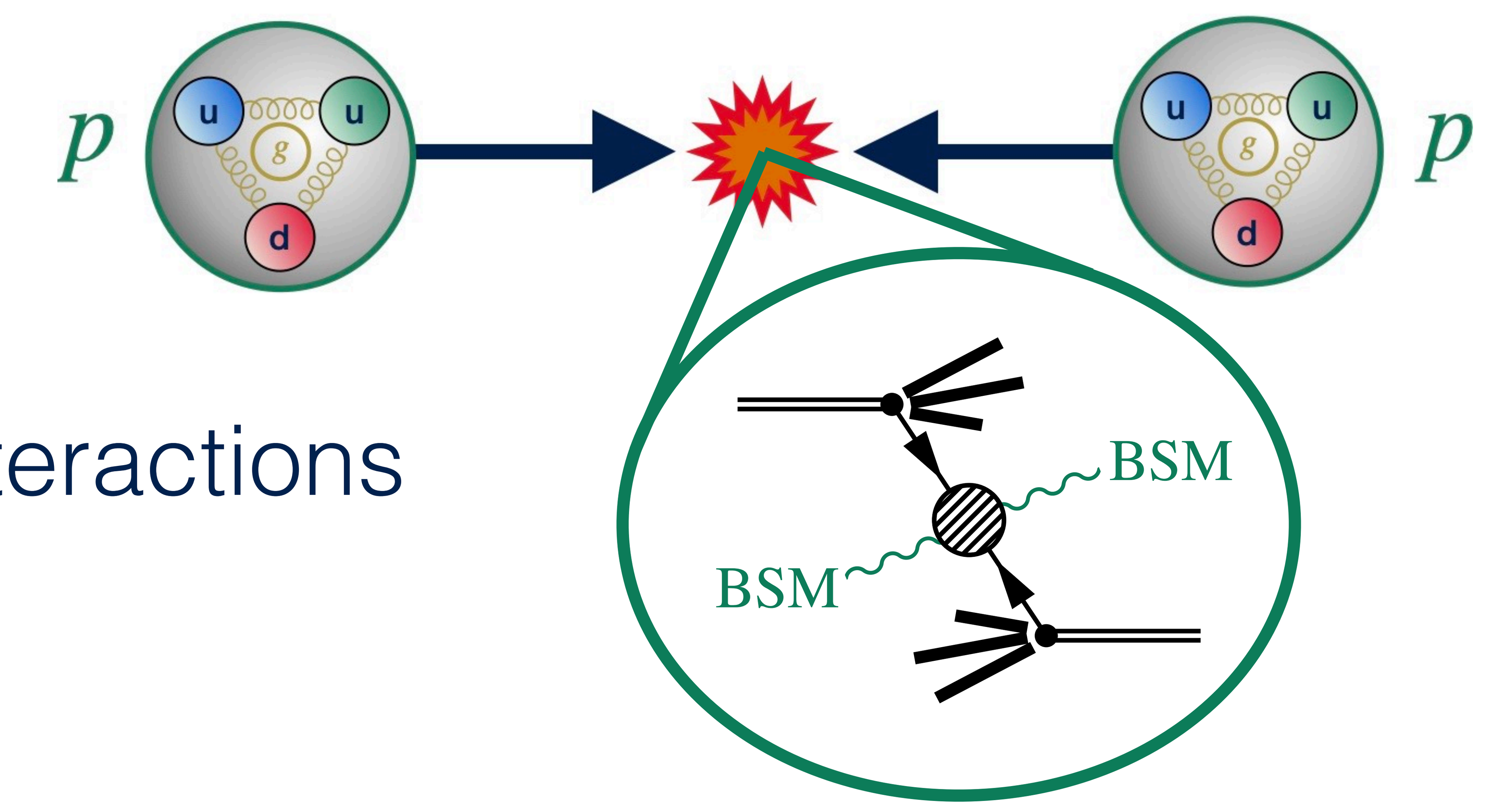
Colliders are explorers

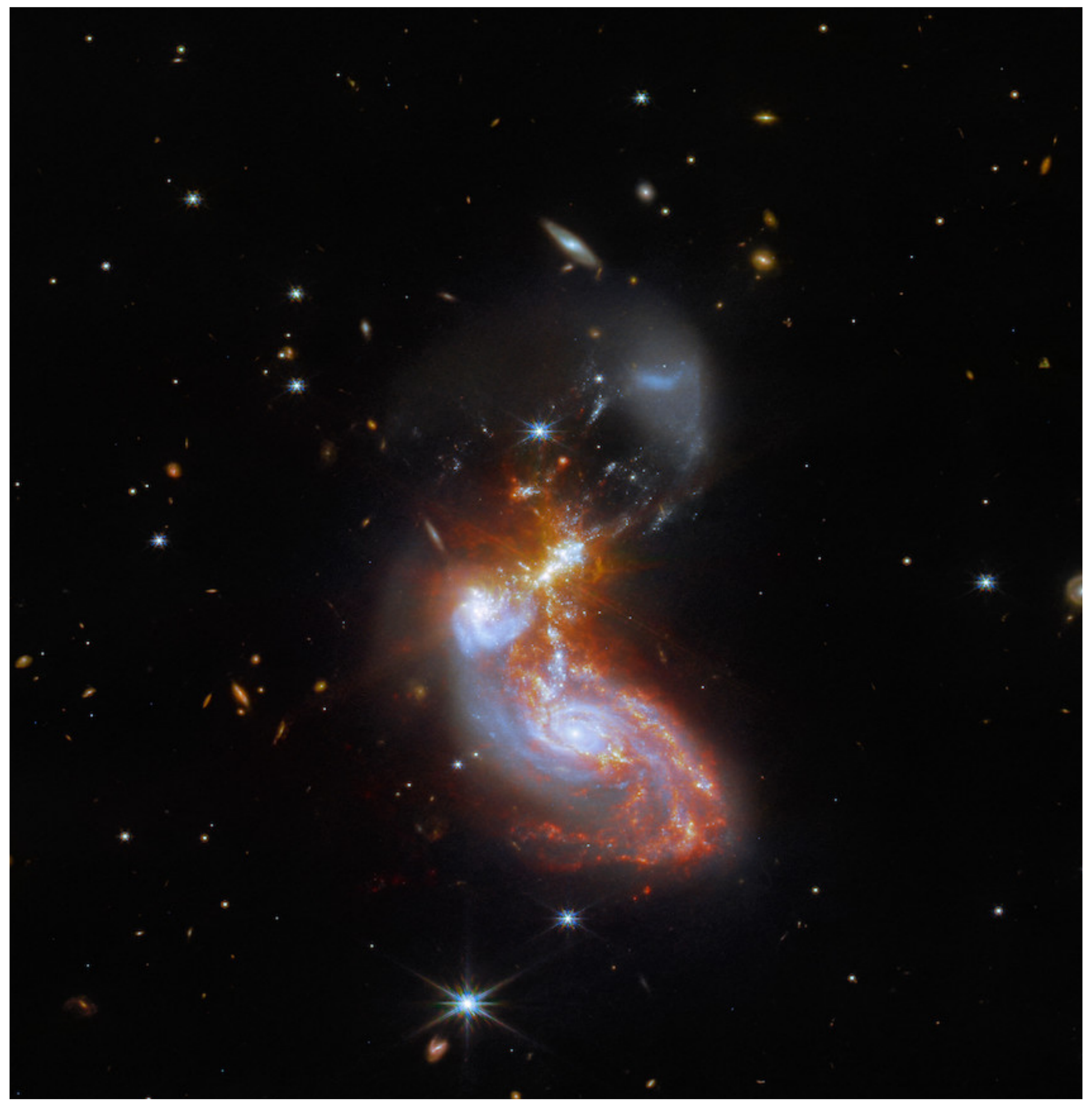
Collider experiments: why do we do it?



- Discover the elementary building blocks of nature
- Establish the fundamental laws that govern their interactions
- Understand the origin and history of our universe

Exploration is our natural instinct

- Colliders are the tool to explore the smallest scales
- Counterparts to telescopes & space programmes
- Each analysis is a new experiment
- New discoveries from the LHC every year

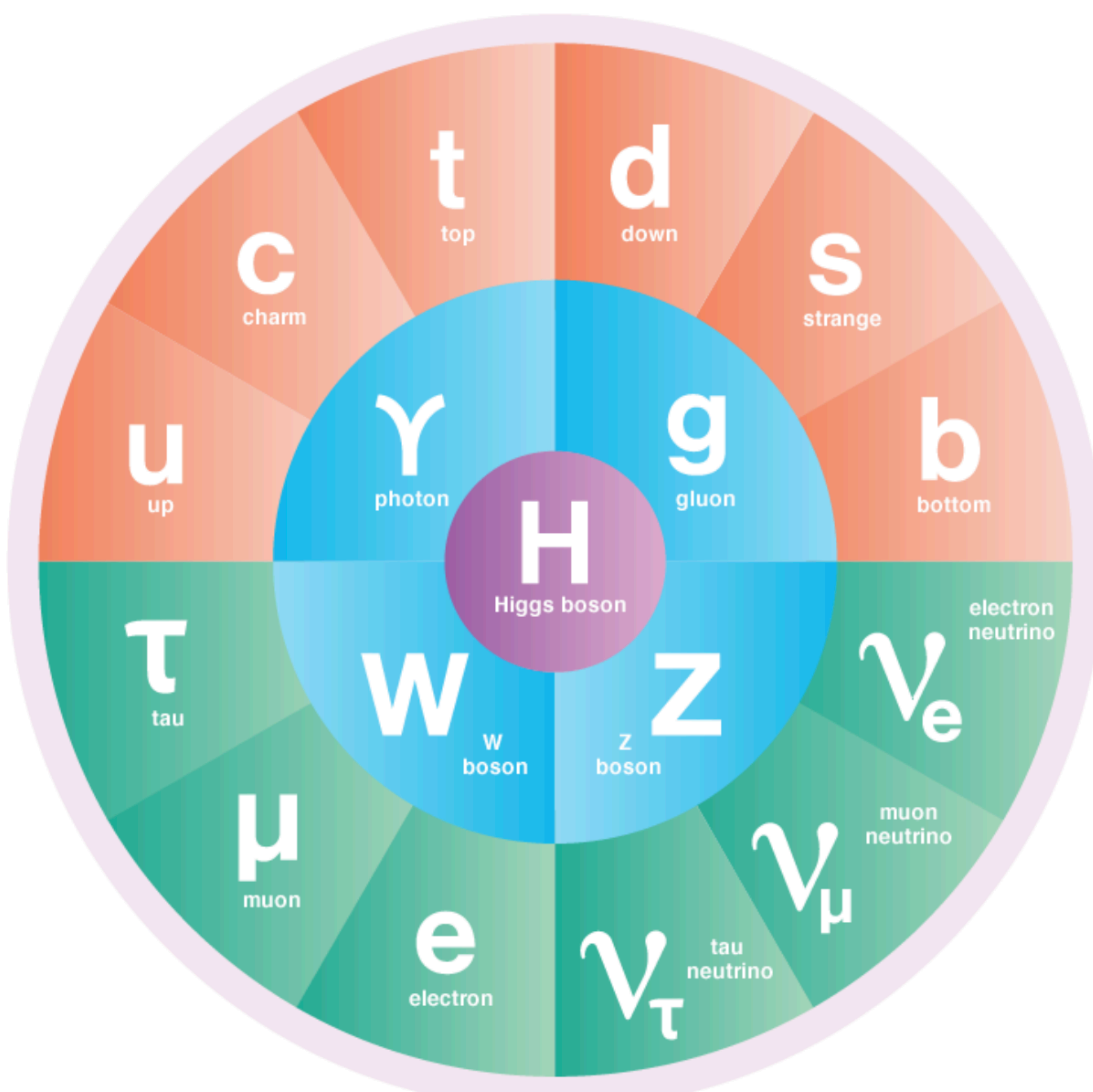


[James Webb Space Telescope]

2023 highlights: 4 top quark production, evidence for $h \to Z\gamma$, LHC neutrinos, new exotic hadrons,…

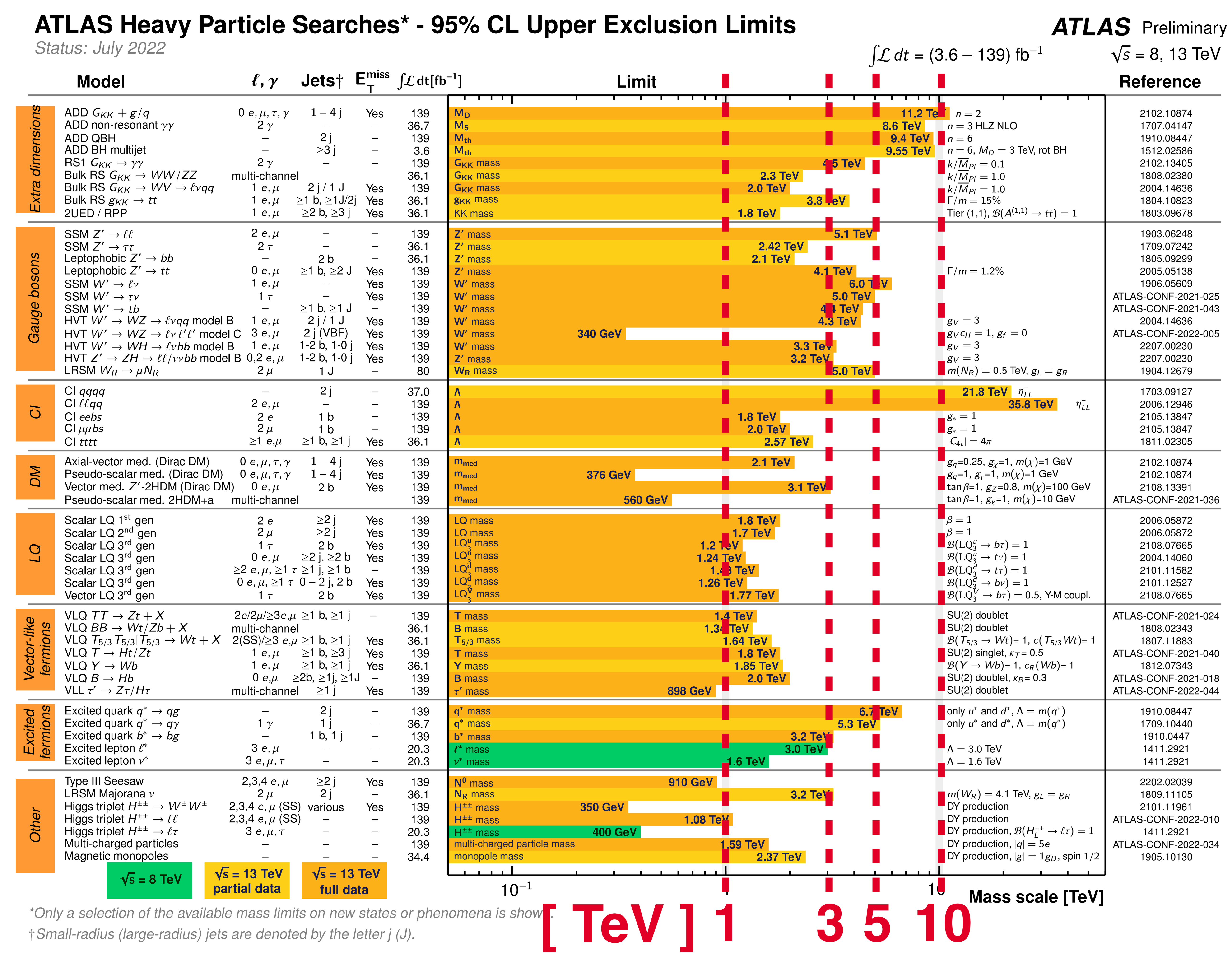
The LHC's success

"Completed" the Standard Model



[Symmetry magazine]

Explored the TeV scale



[ATLAS experiment]

We want more

Dear Santa Claus,

We have been good these past decades. Please could you now bring us

- *a dark matter candidate*
- *an explanation for the fermion masses*
- *an explanation of matter-antimatter asymmetry*
- *an axion, to solve the strong CP problem*
- *a solution to fine tuning the EW scale*
- *a solution to fine tuning the cosmological constant*

Thank you, Particle Physicists

ps: please, no anthropics

[Gavin Salam, FCC Physics Workshop, Krakow, 2023]

Puzzles, problems, naturalness,…

- In many different sectors (EW, flavour, dark,…)

The data is pointing us towards

- Higher scales & weaker couplings
- i.e. more collider energy & better precision

Opportunity for further exploration

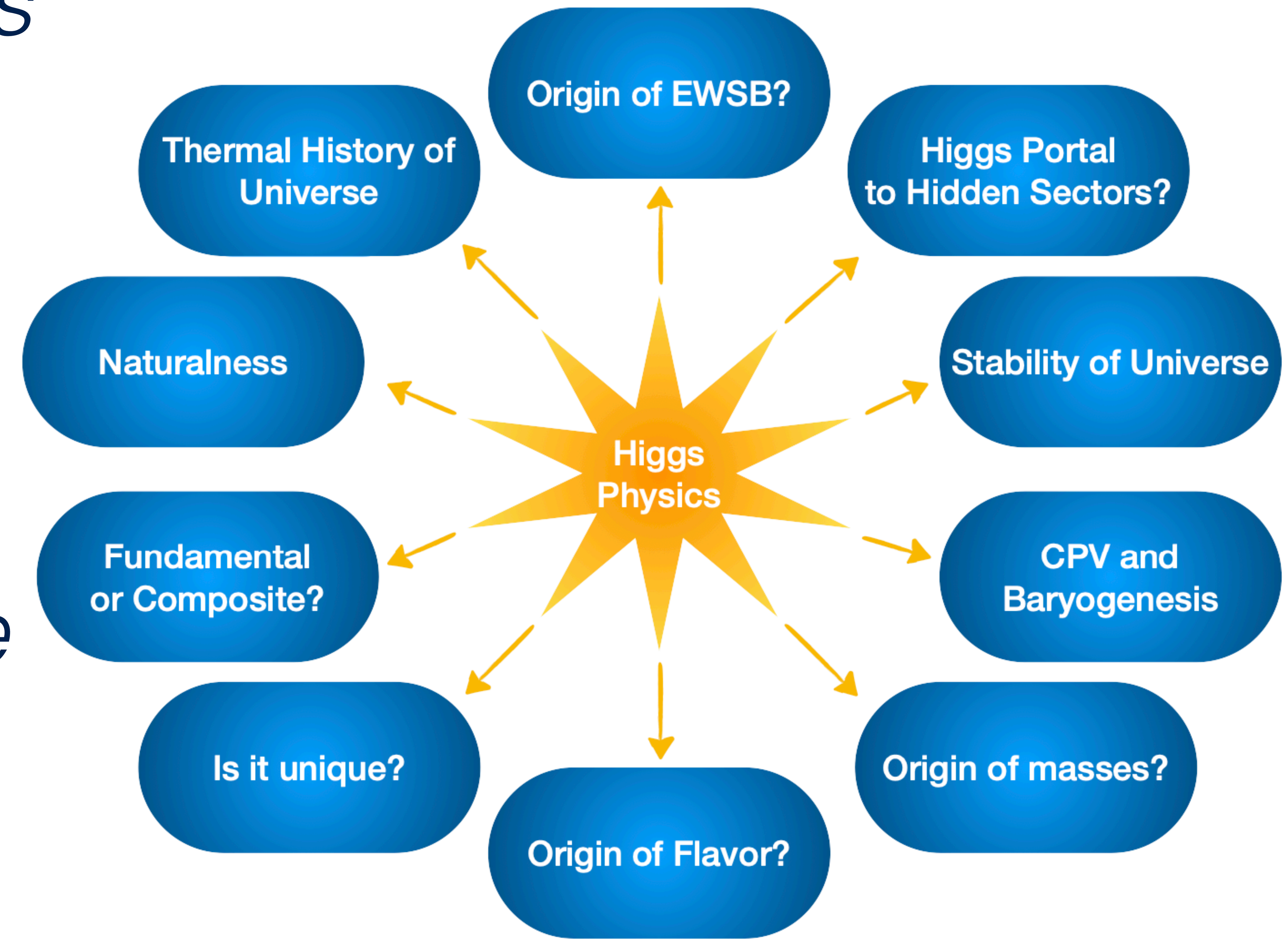
- Testing QFT/SM in the uncharted territory of energy & precision is groundbreaking in & of itself
- Do not know what we will find beyond LHC reach
- Observing **known objects** with **better precision** is reason enough for new experiments in most fields

Higgs: the key player

Involved in many of nature's puzzles

- **Directly:** hierachy/naturalness, flavour/fermion masses, stability of universe,…
- **Potentially:** matter anti-matter asymmetry, portal to dark sector,…

[Snowmass 2021 Higgs report]

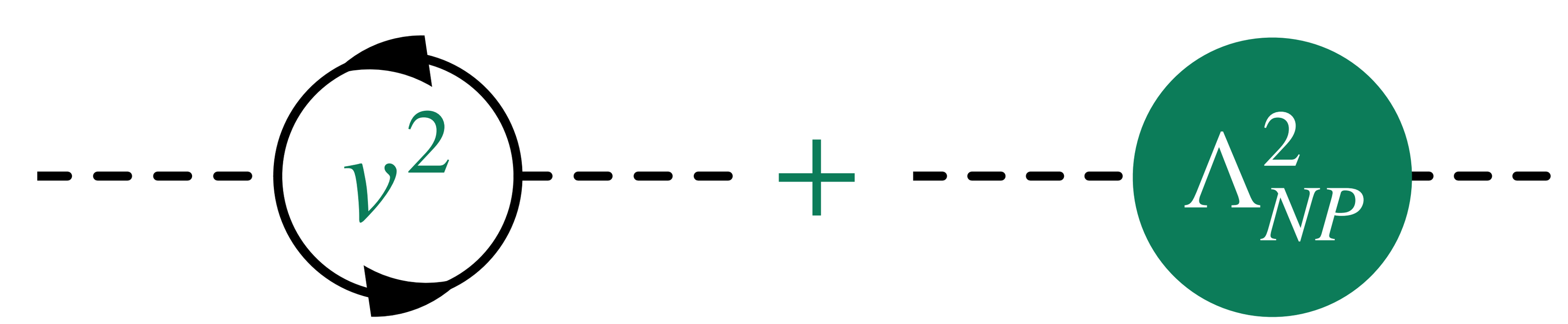


Future colliders must target precise determination of Higgs properties

- HL-LHC: $$\frac{\delta g_h}{g_h} \sim 0.05 = \left(\frac{v}{\Lambda_{NP}}\right)^2$$ $\Rightarrow$ Testing fine-tuning at few % level

$\Rightarrow \quad \Lambda_{NP} \sim 1 \text{ TeV}$

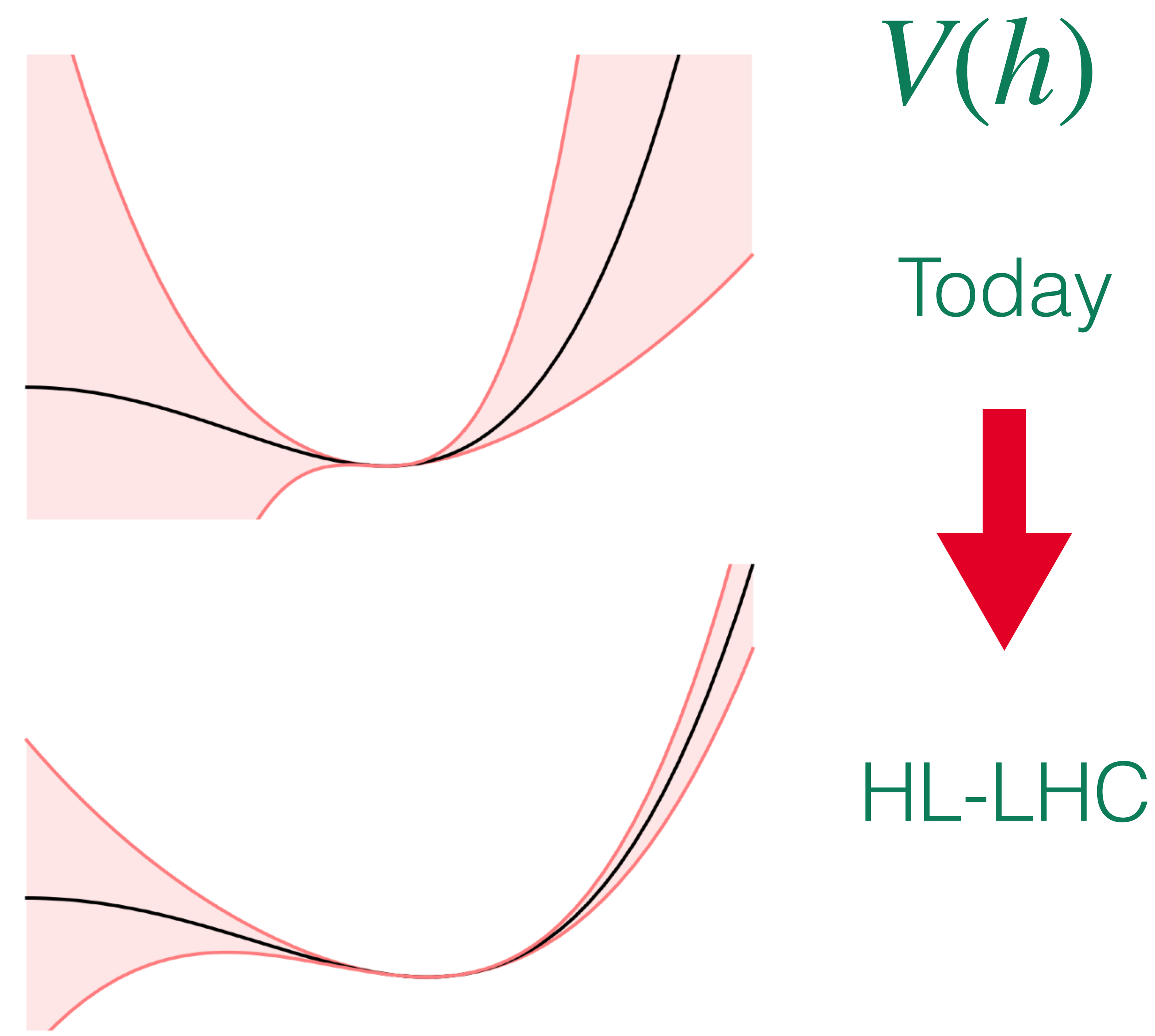
$\delta m_h^2 \sim$



- Covered by LHC reach? (model dependent)

Dynamical origin for the weak scale?

[Craig, Petrossian-Byrne]



Higgs potential

Today, its shape is basically unknown

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

Precise shape has many implications

- Nature of the EW phase transition: 1st/2nd order? ⇒ Baryogenesis

  How did the Higgs field evolve in the early universe into the EW broken phase?

  Is it responsible for generating the matter-antimatter asymmetry of the universe?

- Potential stochastic gravitational wave background signature at *e.g.* LISA

  [Caprini et al.; JCAP 04 (2016) 001]

- (Meta)stability of the EW vacuum phase

  How do we even exist and could our ground state have a finite lifetime?

- Modifications to $V(h)$ imply new states coupled to the Higgs

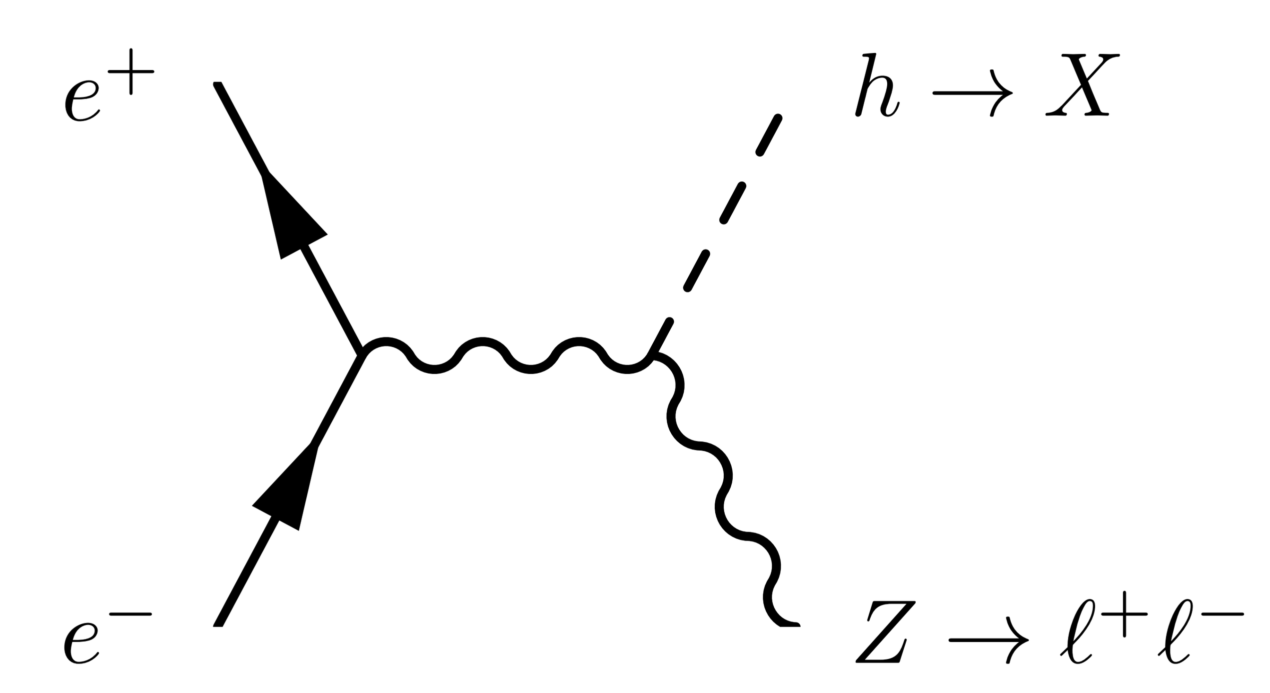
Measuring λ_3 is the no-lose theorem of the FC programme

FCC-ee

Precision programme, lays foundation & targets for FCC-hh

- Like LEP did for the LHC with EWPO ⇒ paved way for Higgs discovery
- Tera Z: **3 million LEPs** worth of Z bosons *[Blondel & Janot; Eur.Phys.J.Plus 137 (2022) 1, 92]*

Unique, precision Higgs/EW/top factory



- Semi-direct measurement of Higgs width with mild assumptions
- Connection to dark sector: invisible Higgs decay channels

Clear feasible pathway to FCC-hh

Challenge & opportunity *[Blondel et al.; Contribution to EPPSU]*

- Precision goals require a **huge leap** in theoretical calculations
- 3/4 loop QCD/EW corrections, beyond current reach
- High priority item to train next generation of theorists (~500 person/years)

FCC-hh

Explore the deep UV ⇒ decaTeV mass reach

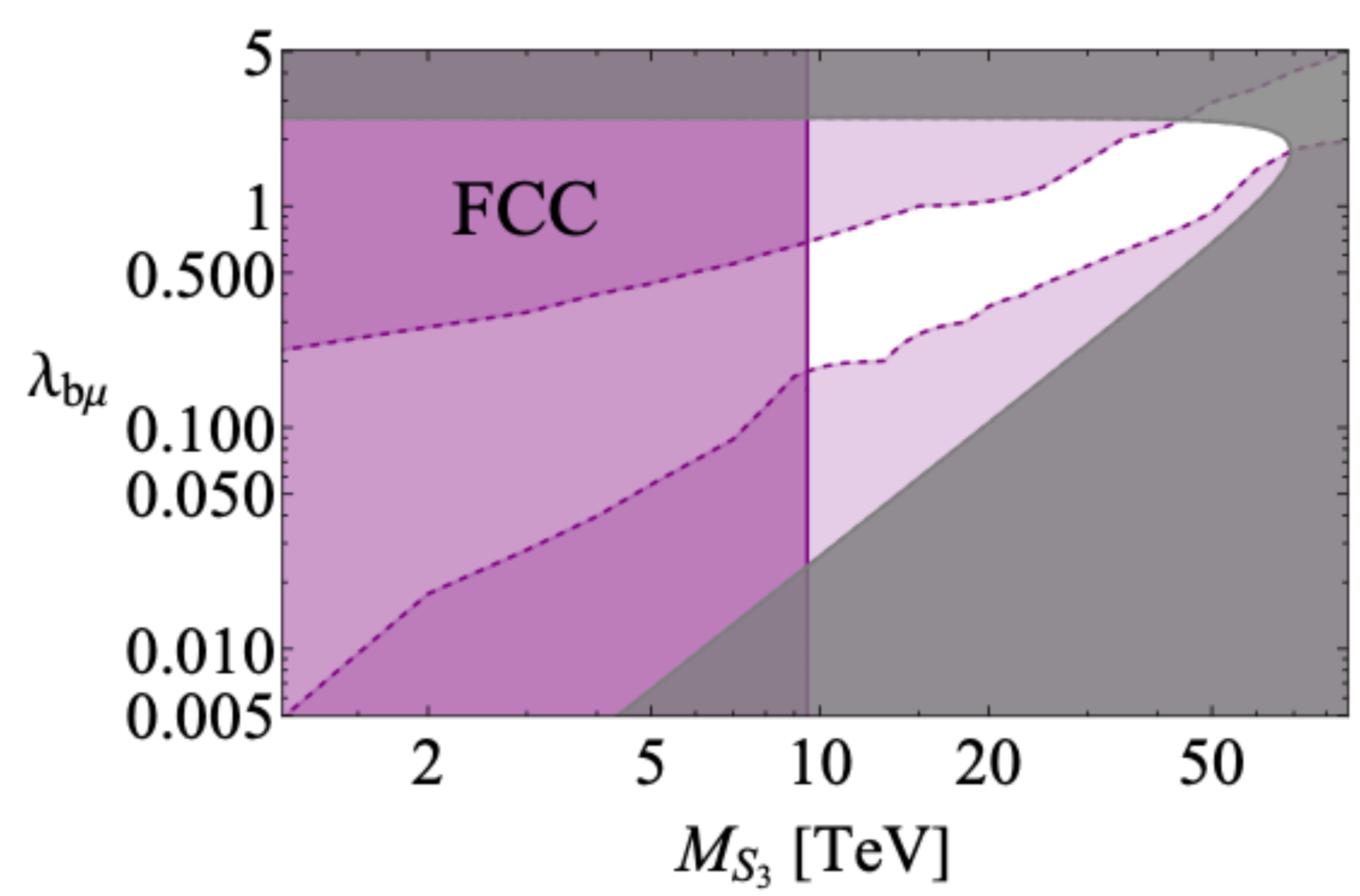
- Follow up on indirect hints from HL-LHC/FCC-ee/…

  e.g. flavour anomalies

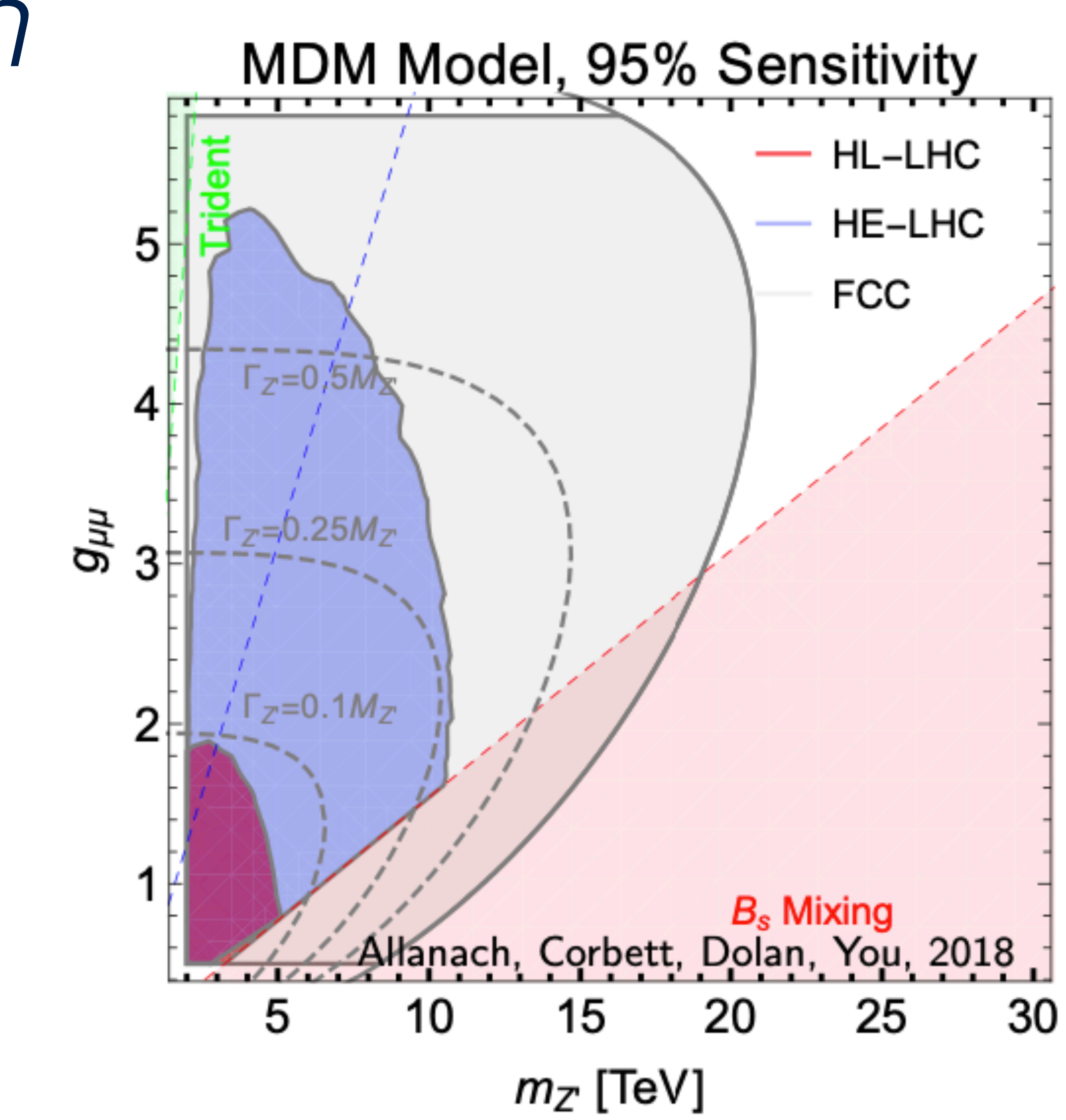
- "Complete coverage" for canonical BSM scenarios

  e.g. WIMP dark matter

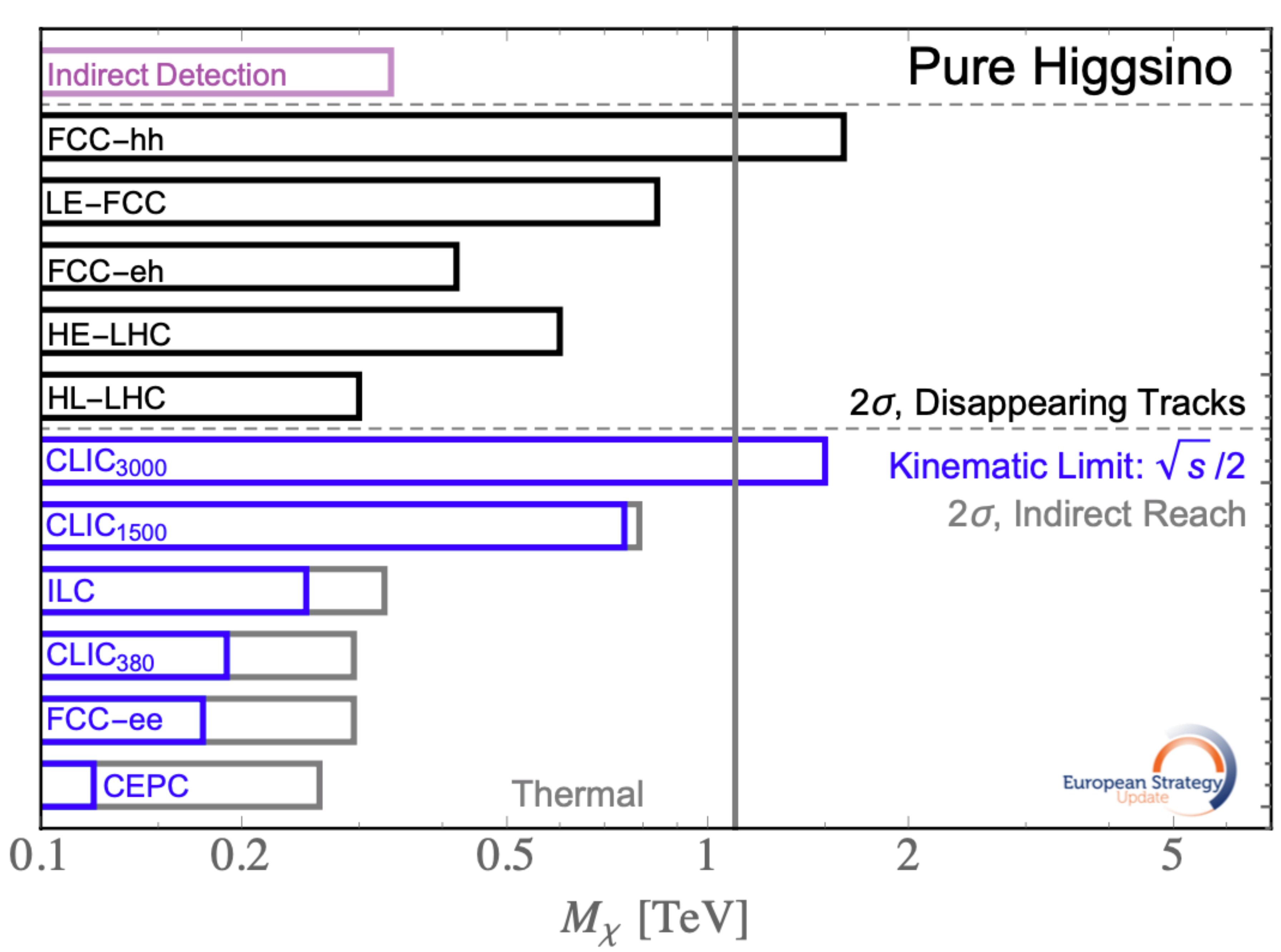
[Azatov et al.; JHEP 10 (2022) 149]



[Allanach et al.; JHEP 03 (2019) 137]

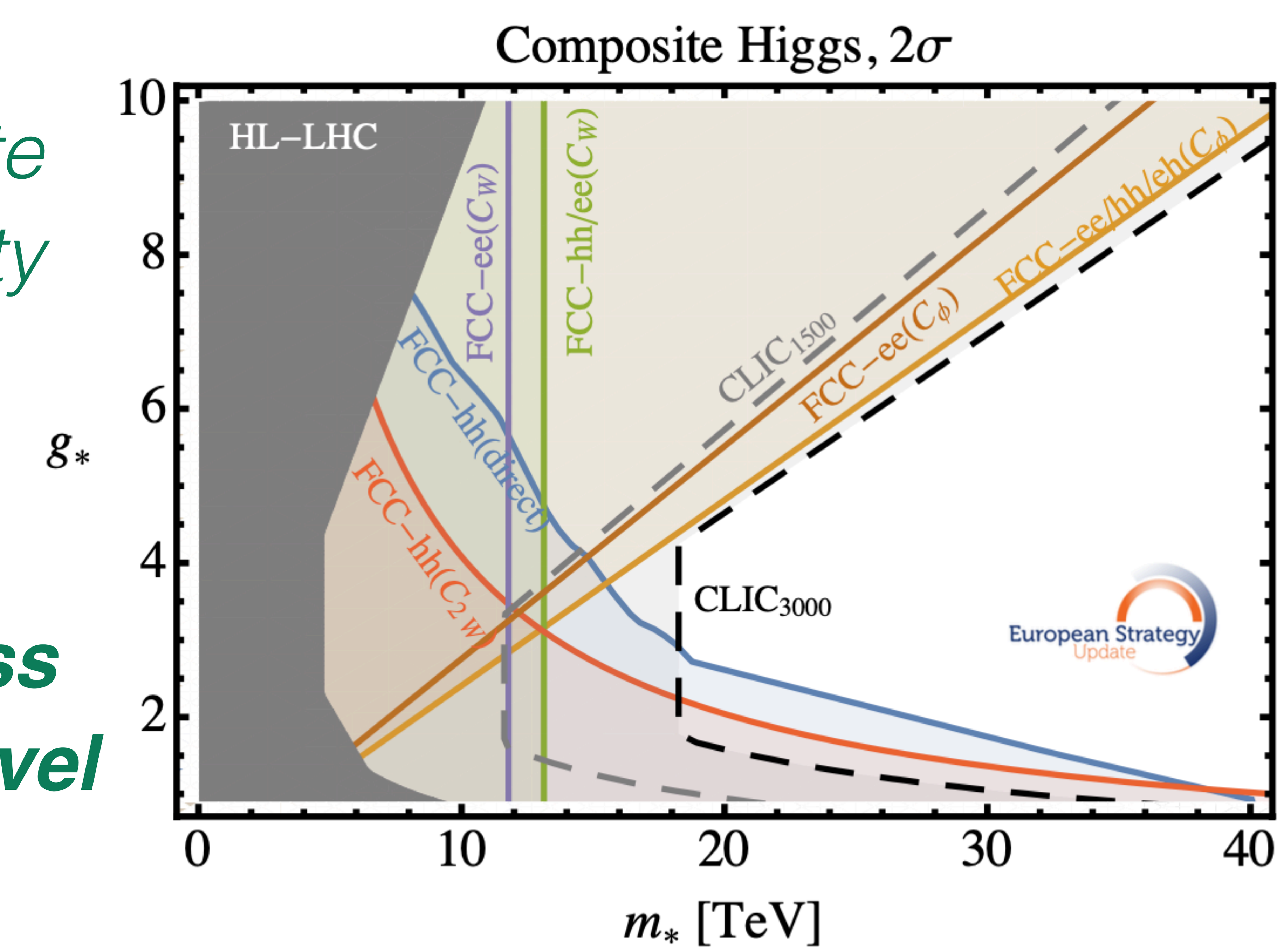


[Ellis et al.; Physics briefing book for ESU]



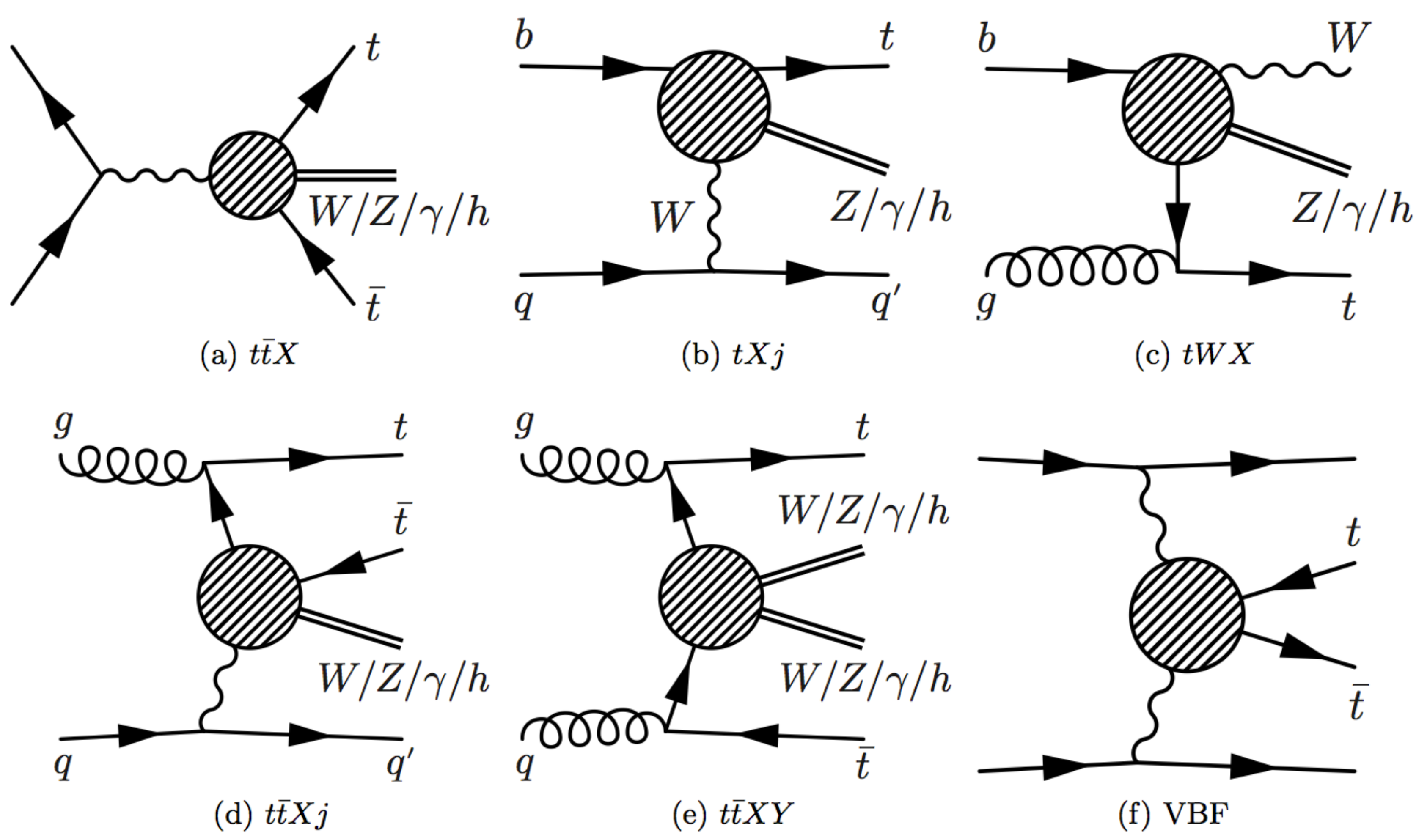
Extend composite Higgs sensitivity

Probe naturalness below per-mille level



FCC-hh

[Maltoni, Mantani, KM; JHEP 10 (2019) 004]

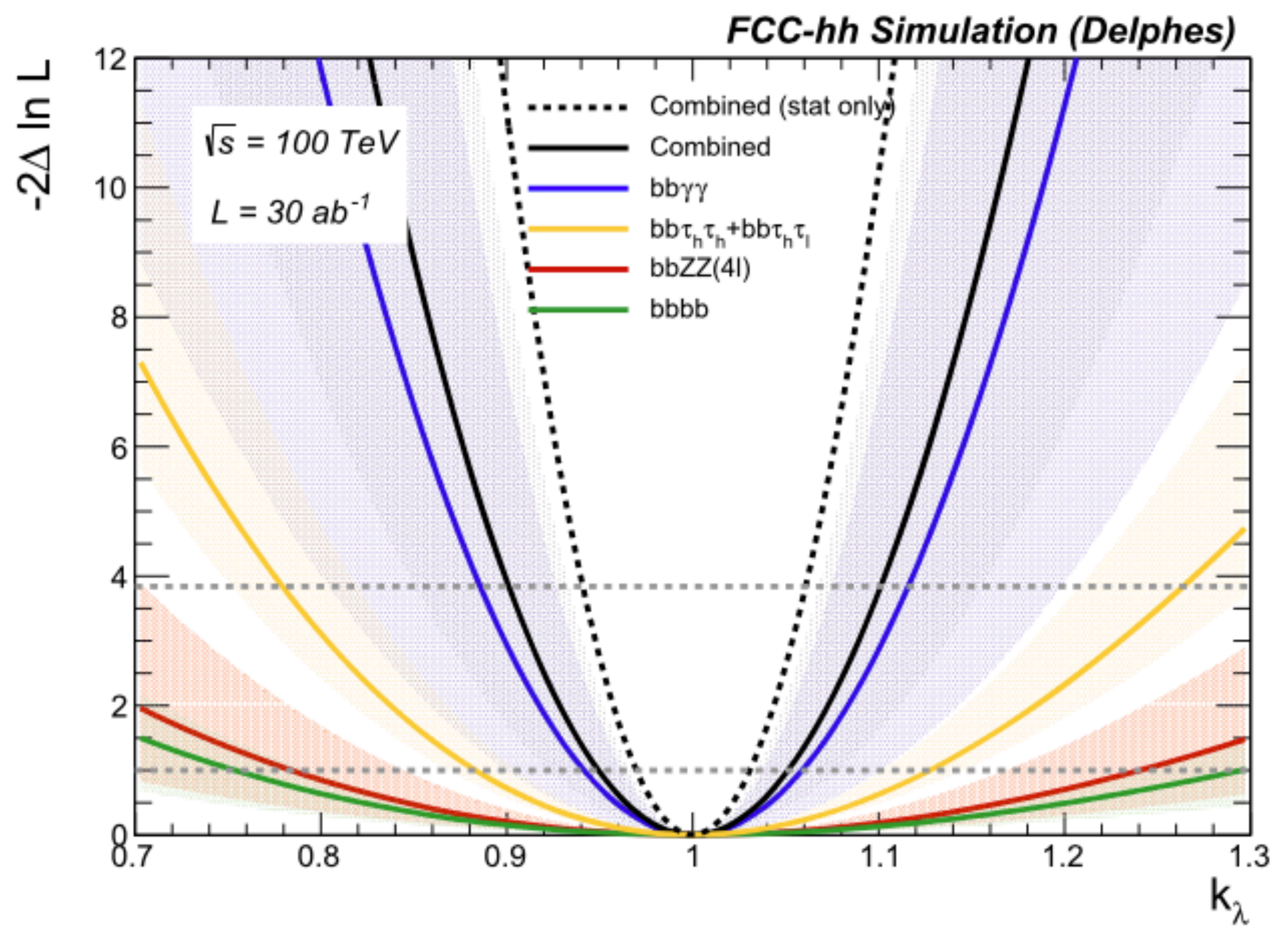


Discover & test rare processes

- High-energy & high-multiplicity
- Precision measurements of multi top quark production
- High-multiplicity production of Higgs/Top/EW bosons

Directly/indirectly measure new interactions

[Mangano, Selvaggi, Ortona; EPJC 80 (2020) 11, 1030]

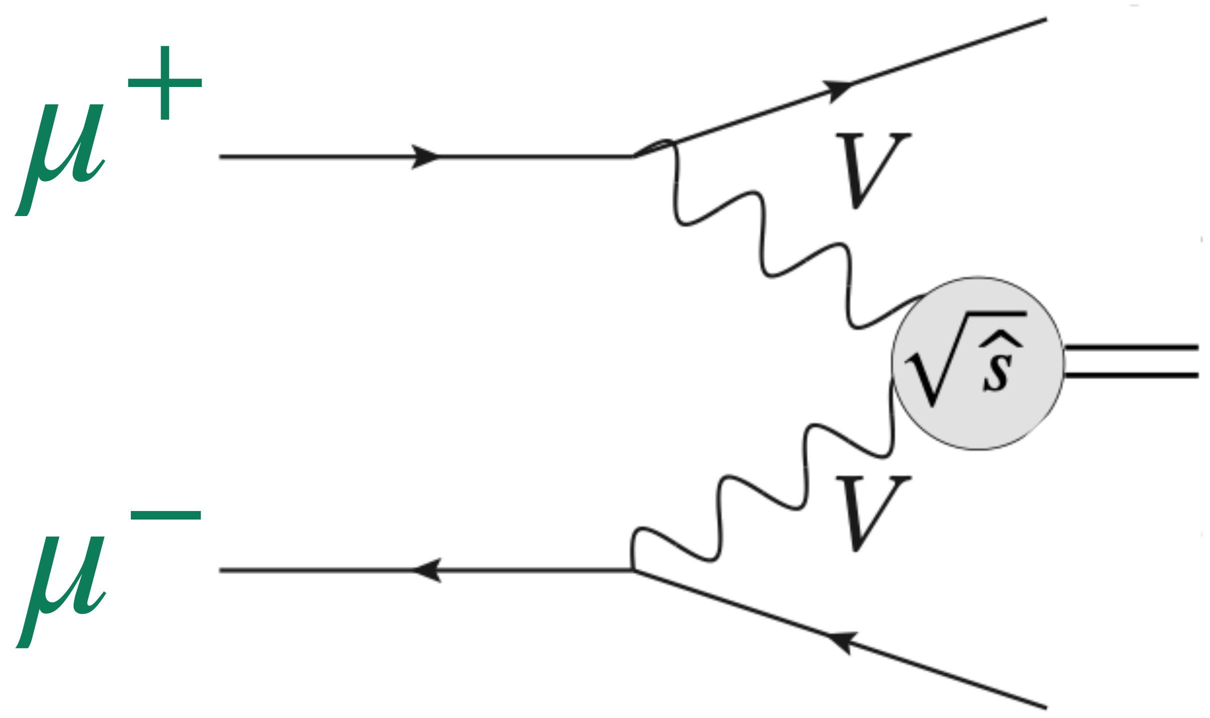


- **Prime target:** λ_3 from di-Higgs production
- Quartic Higgs coupling from triple-Higgs production
- EW top quark couplings, $t\bar{t}hh$ interaction,…

Exploring terra incognita

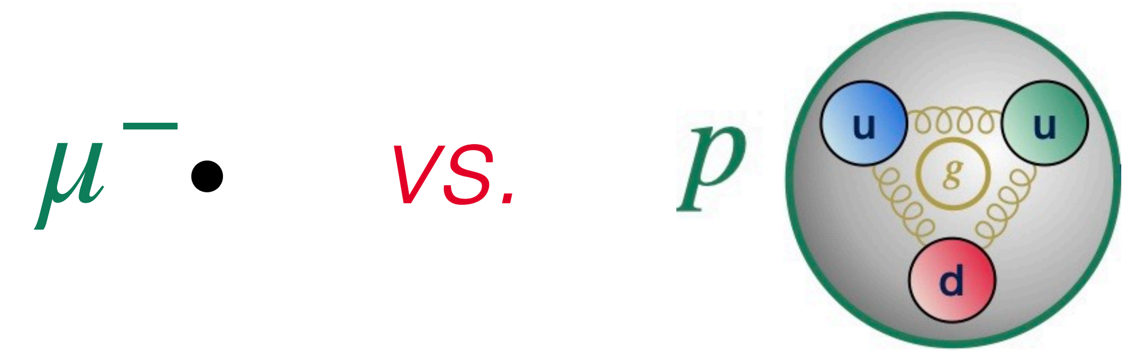
- Cannot know what lies around the corner, our luck might change…
- Keep an open mind and build the collider!

Muon collider

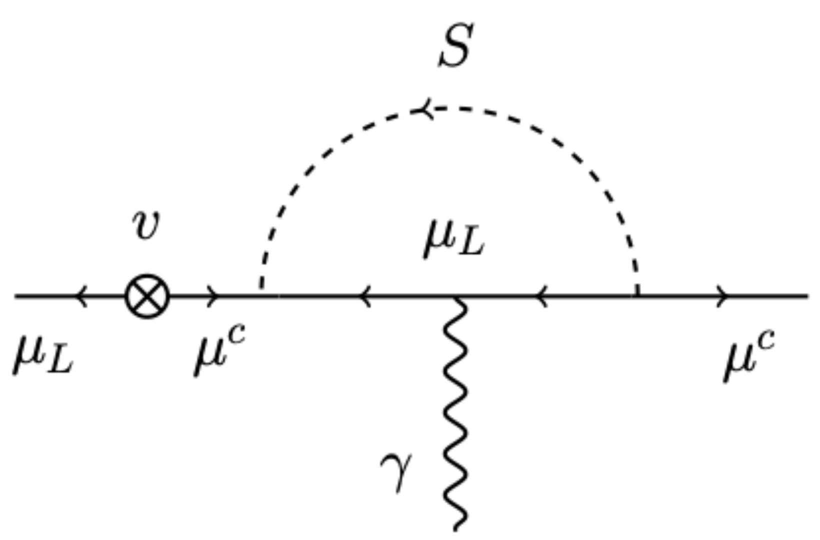


Radically new collider technology

- Combines clean final state with high energy : $\sqrt{s} \sim 10$ TeV

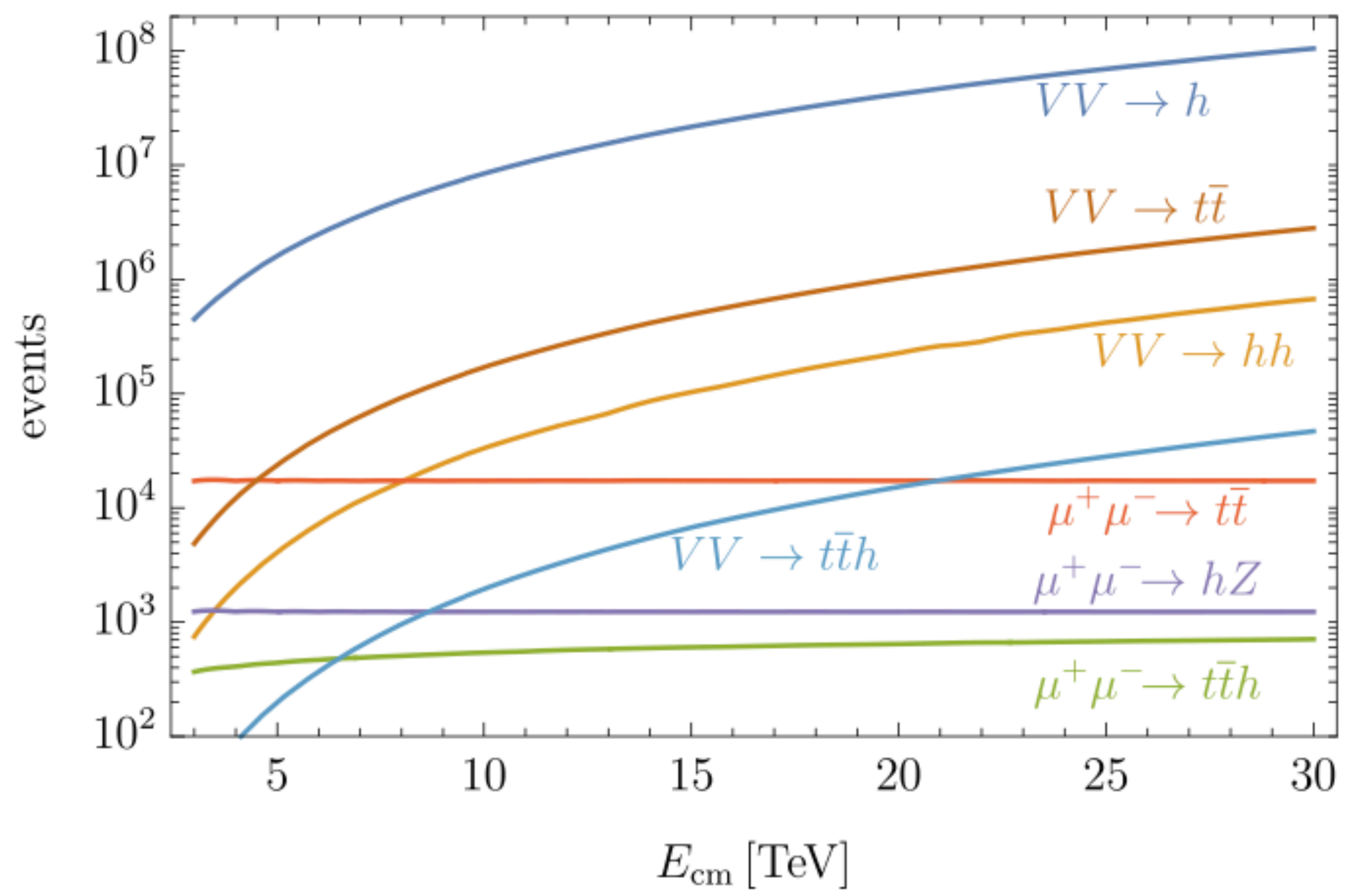


Comparable physics case to FCC-ee/hh



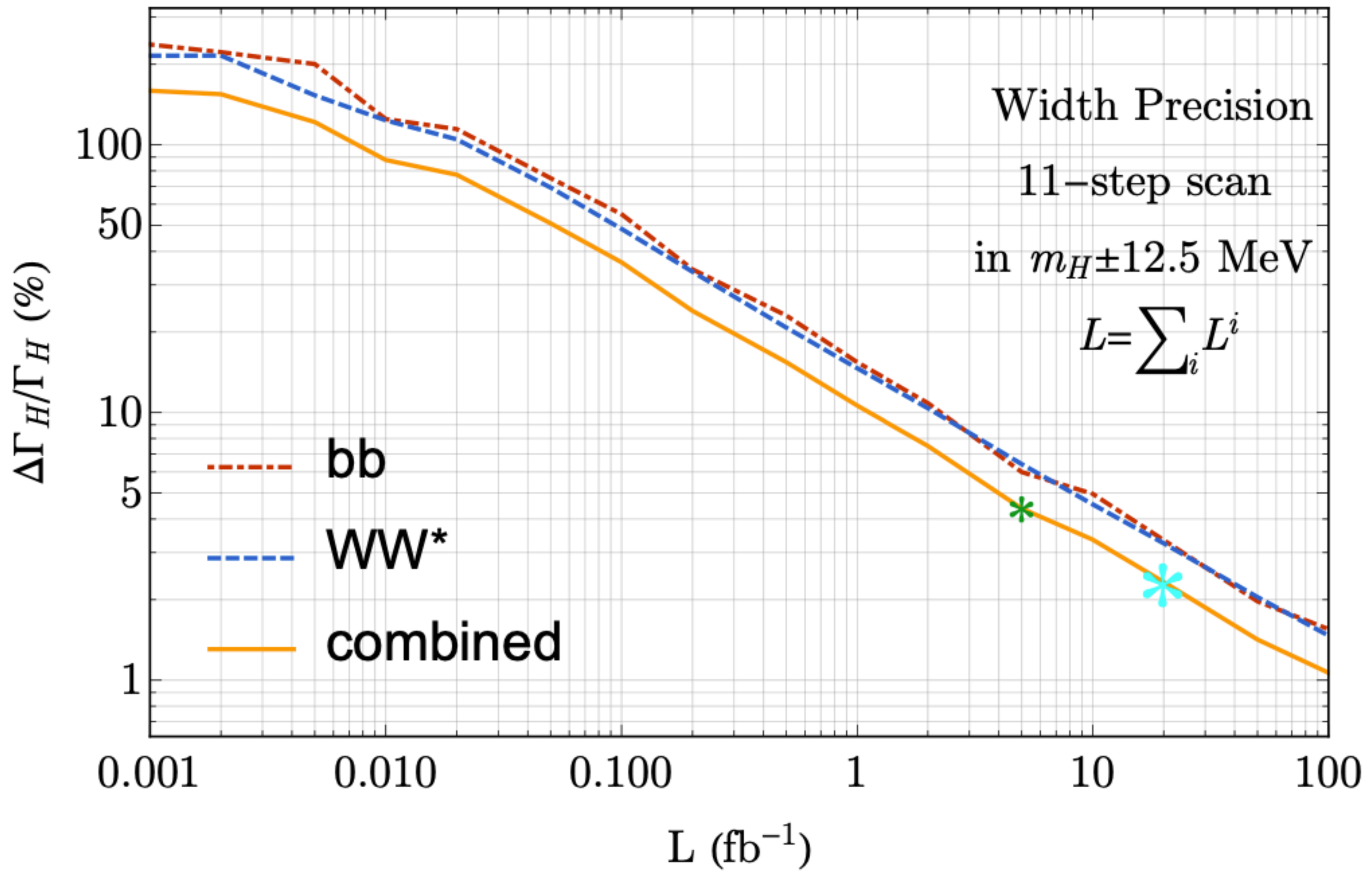
"vector boson collider"

[Delahaye et al.; input to ESU]



$\mu^+\mu^- \to h$ @ 125 GeV

[de Blas, Gu & Liu.; PRD 106 (2022) 7, 073007]



See also: "no-lose theorem" for new physics scenarios associated to muon g-2 anomaly

[Capdevilla et al.; PRD 105 (2022) 1, 015028]

Significant R & D required to determine feasibility

- Long timescale ⇔ possibly high rewards in offshoot technologies

Search for new physics in at the decaTeV scale

Quantum leap in experimental & theoretical precision

Explore uncharted territory precision & energy

Revolutionise accelerator technology

Thanks for your attention

Measure the Higgs boson self coupling

Probing naturalness

Origin of mass

Origin of flavour

EW phase transition

Nature of the dark sector

References, further reading

Public lecture: Does the world need a future collider and why? (YouTube)

European strategy for particle physics homepage

European Comittee for Future Accelerators (ECFA) homepage

FCC-ee: your questions answered

FCC-ee overview

SM theory for FCC-ee: Tera Z stage

FCC-hh conceptual design report

Snowmass FCC study

FCC week 2023 conference webpage

FCC physics workshop 2023 webpage

"Muon colliders" input to the ESU

"Towards a muon collider"

Muon collider forum report (Snowmass)

"The muon smasher's guide"