The physics landscape of Future Colliders

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ROMA TRE UNIVERSITÀ DEGLI STUDI

INFN Roma3

Past, present, and future

We are part of a century-size cooperative effort without boundaries in space and time

How to contribute to this…

As a field

- As a field we need to pursue ambitious projects, driven by science (not politics, not science politics, not money, not careers, not the daily external "push & pull").
- This requires us to explain our own science to ourselves, to the rest of the scientific community, and to the general public.
- Our projects are more expensive than previous ones. We must make an extra effort to motivate our projects and discuss openly their relation with the rest of science.

As an individual

- Being here! You can be part of this if you put in some engagement, activate as researcher and "citizen".
- No better day to start than today, because decisions that impact our field for the next decades are being taken now.

How to contribute to this…

Quand tu veux construire un bateau, ne commence pas par rassembler du bois, couper des planches et distribuer du travail, mais reveille au sein des hommes le désir de la mer grande et large.

Antoine de Saint-Exupéry

We have to deal with unknown

Whoever invented the ship, also invented shipwrecks. [Lao-Tzu]

Study better something I have studied already? something entirely new?

Make room for things we love to pursue

Something Challenging

Something Deep

Something Exciting

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Something
Challenging

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Our job is to find the fundamental laws of Nature

- too many questions for a single collider
- too many questions for just colliders

- deep understanding of the present laws of physics
- formulation of deep and far-reaching questions
- performing experiments that can conclusively answer these questions

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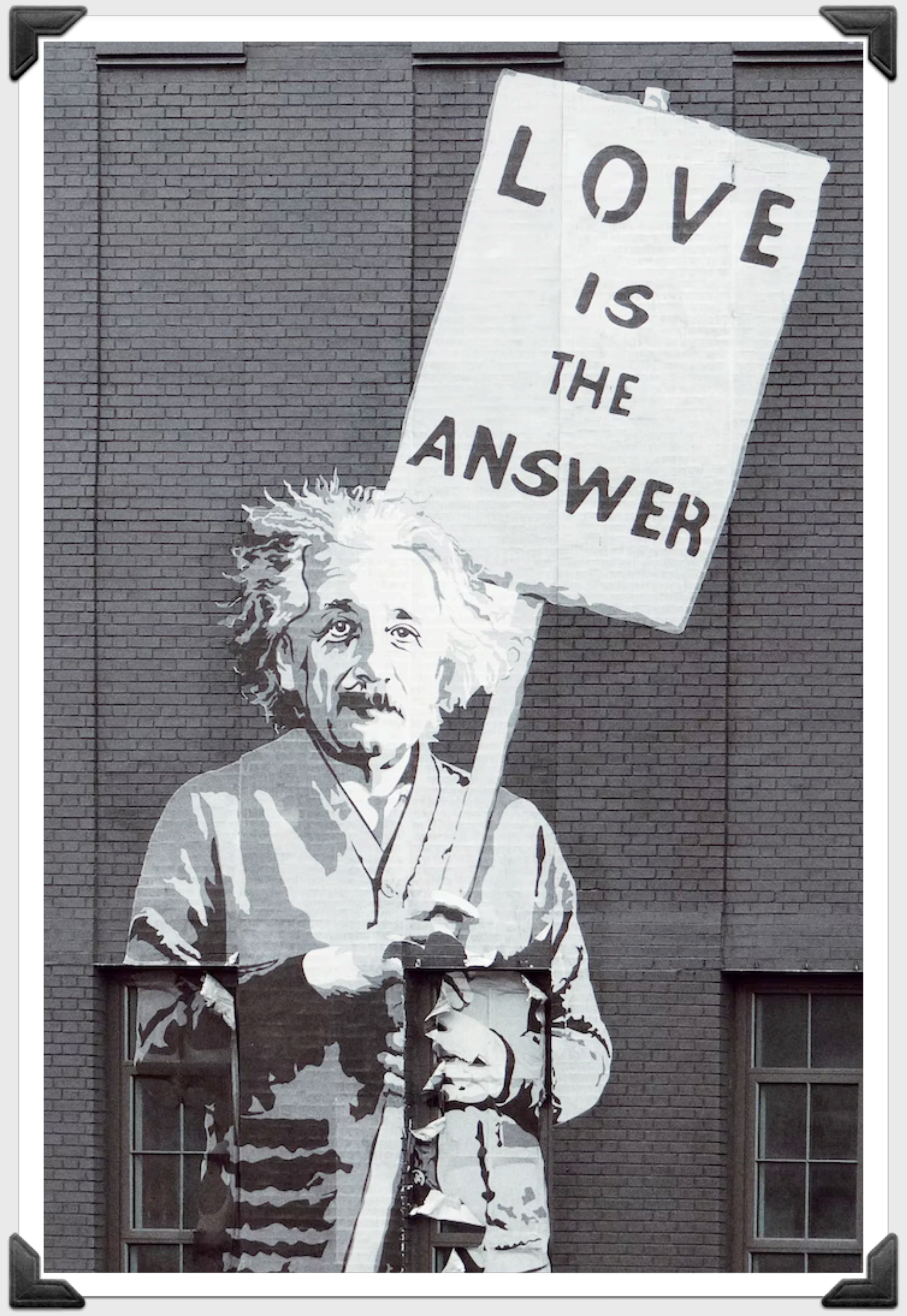

- deep understanding of the present laws of physics
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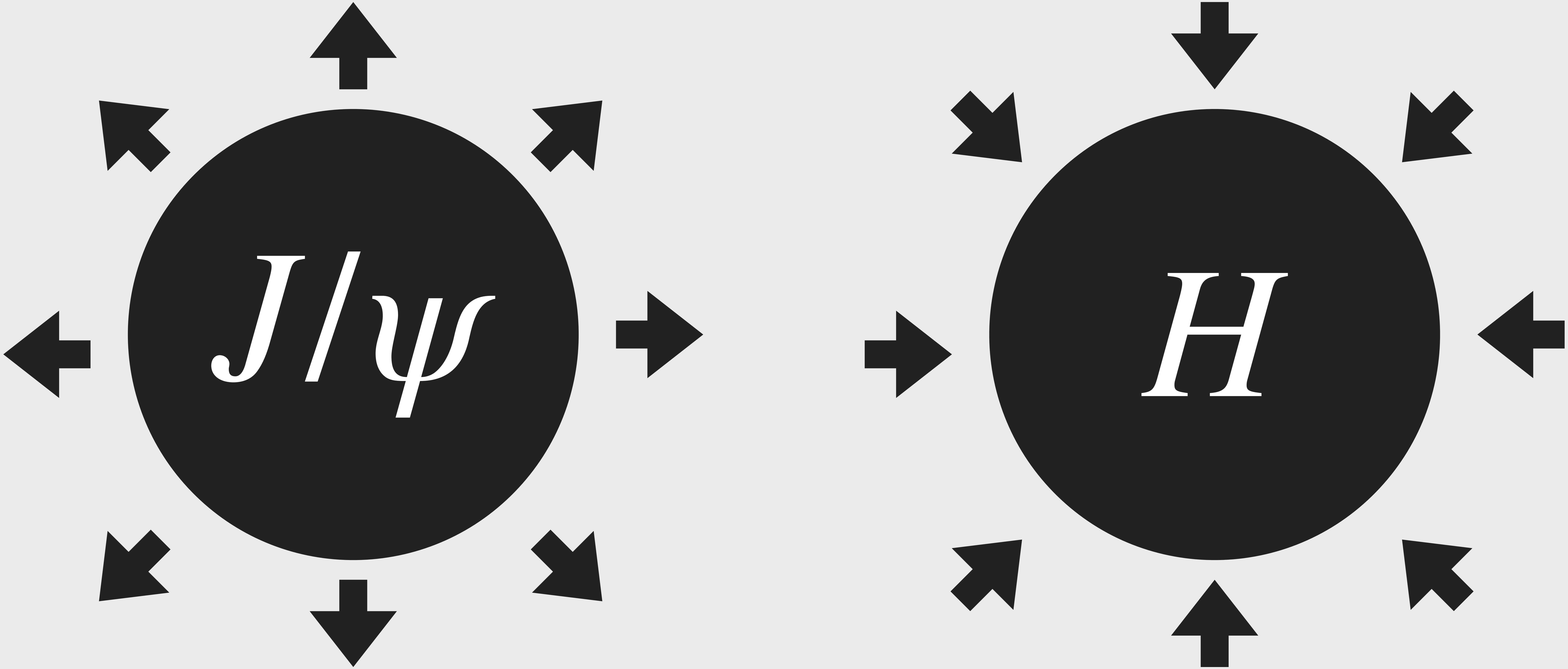
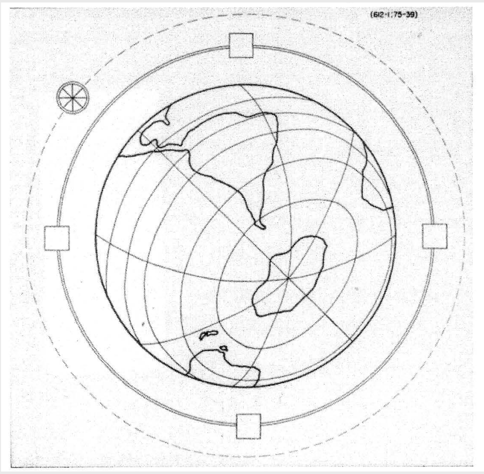
I give this talk as a lover

Driver for Cooperation

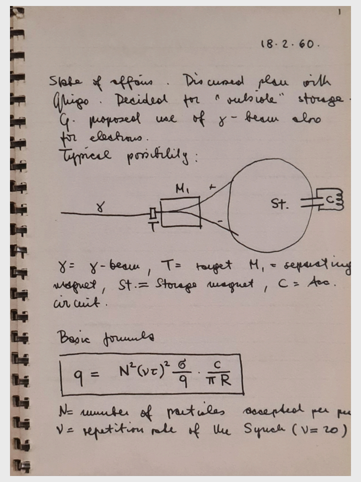


Driver for Cooperation

1954



1960



1968-

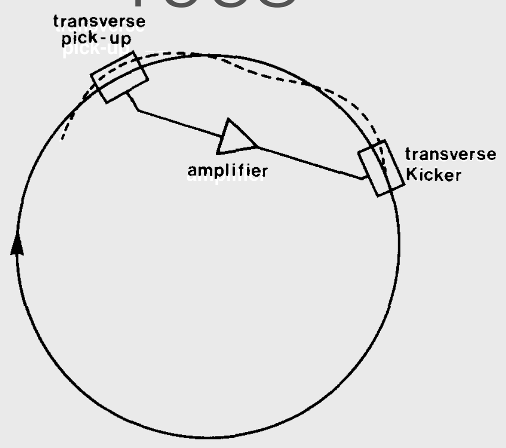


Fig. I.1. Block diagram of a betatron cooling system.

KEYNOTE TALK, ICFA - MEETING, MAY 1984

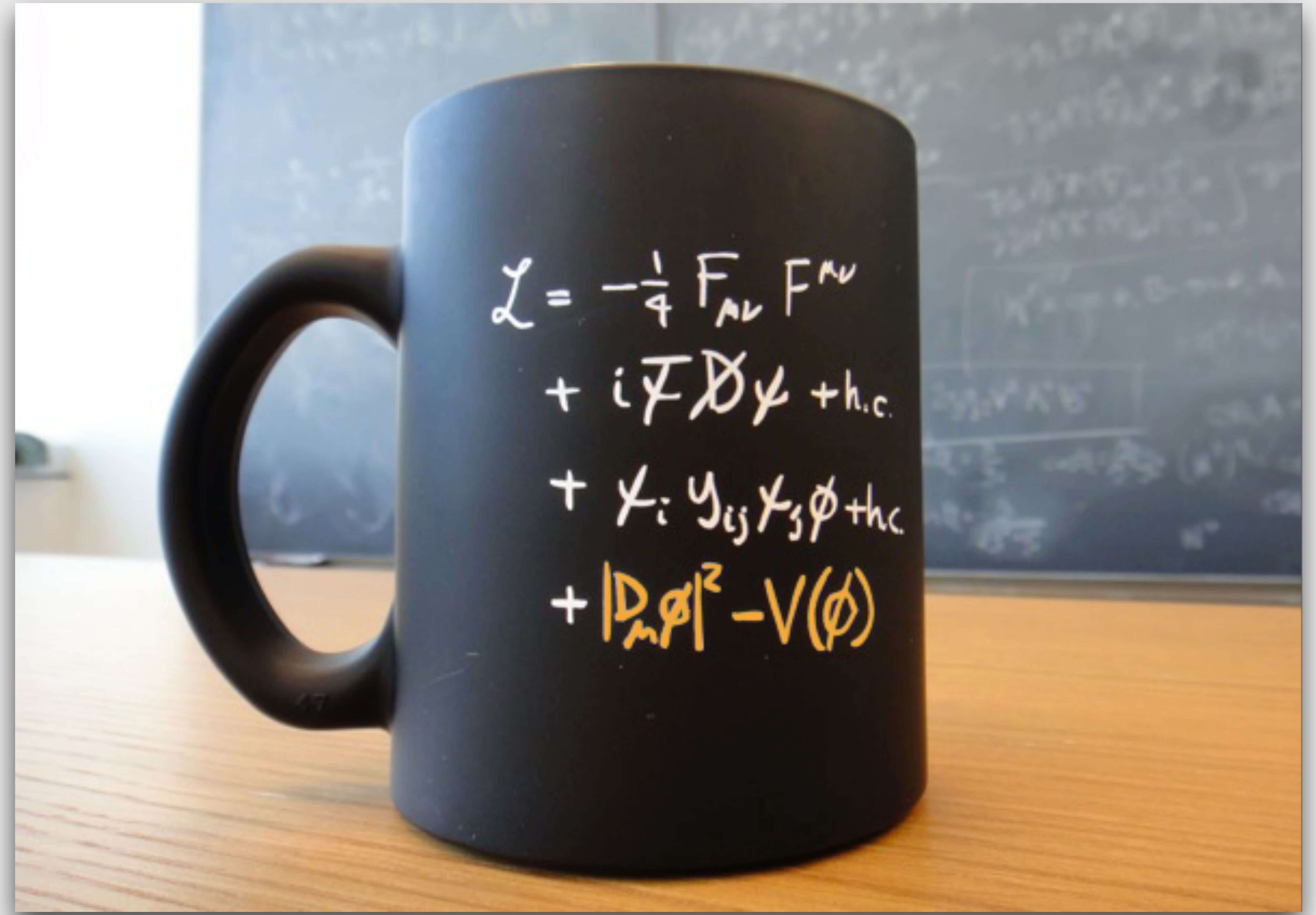
Victor F. Weisskopf

The great tradition of Lawrence, MacMillan, Veksler, Budker, Tuschek, Adams and Livingston is continued by many outstanding pioneers, but they do not get recognition and status they so amply deserve. They do not figure as co-authors in the publications of the discoveries which they have made possible; only a few of them have academic positions; hence, to the detriment of our field this activity does not attract enough young people. After all, in this period they provided us with innovative ideas such as strong focussing, separate magnets, colliding beam devices, stochastic cooling and superconducting magnets. Certainly the intellectual creativity is of the same level as the highly advertised theoretical achievements of that period.

The world community of High Energy Physics must get together in one way or another, and reach a solution of the problem of what should be done where, with the financial, intellectual and technical resources that we expect to be available. It must be the responsibility of the community to find the solution that is best for the progress of our field, best to maintain the enthusiasm of all participants, and best to attract many young people in the field. There is time enough to find a reasonable solution in the coming few years. All these projects are still on the drawing boards only, and we do not know enough today about the technical and political possibilities and about ways of cooperation. In all probability a realization of both projects at the highest energy is excluded within the next decade.

But it is the duty of the community to come to a mutually acceptable solution. It is an issue of scientific responsibility versus scientific greed. But it is also an issue of wise policy towards the governments who pay the bills. We certainly will loose the support that we have received in the past if it appears that different parts of the world community are trying to out-pace each other and are no longer cooperating in the planning and construction of the future accelerators with mutual help and assistance. The danger is all the more acute since even under the best conditions, this support is not assured.

Where do we stand?



We have got "the" formula

… and it is surprisingly short!

And there is more than “just” the Higgs boson

The Standard Model is:

- Observationally “unfit” (misses Gravity, Dark Matter, …)

Open Questions on the "big picture" on fundamental physics as of 2020s

?	Need new matter (or even bigger modifications to the SM)
(dial icon)	Adjusting one SM parameter might do
(gear icon)	Adjusting several SM parameters might do
~~EFT~~	Separation of scales as an organizing principle might fail

- ? — what is the dark matter in the Universe?
- why QCD does not violate CP?
- how have baryons originated in the early Universe?
- what originates flavor mixing and fermions masses?
- what gives mass to neutrinos?
- ~~EFT~~ — why gravity and weak interactions are so different?
- ~~EFT~~ — what fixes the cosmological constant?

EACH of these issues one day will teach us a lesson

Open Questions on the "big picture" on fundamental physics as of 2020s

?

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- EFT what fixes the cosmological constant?

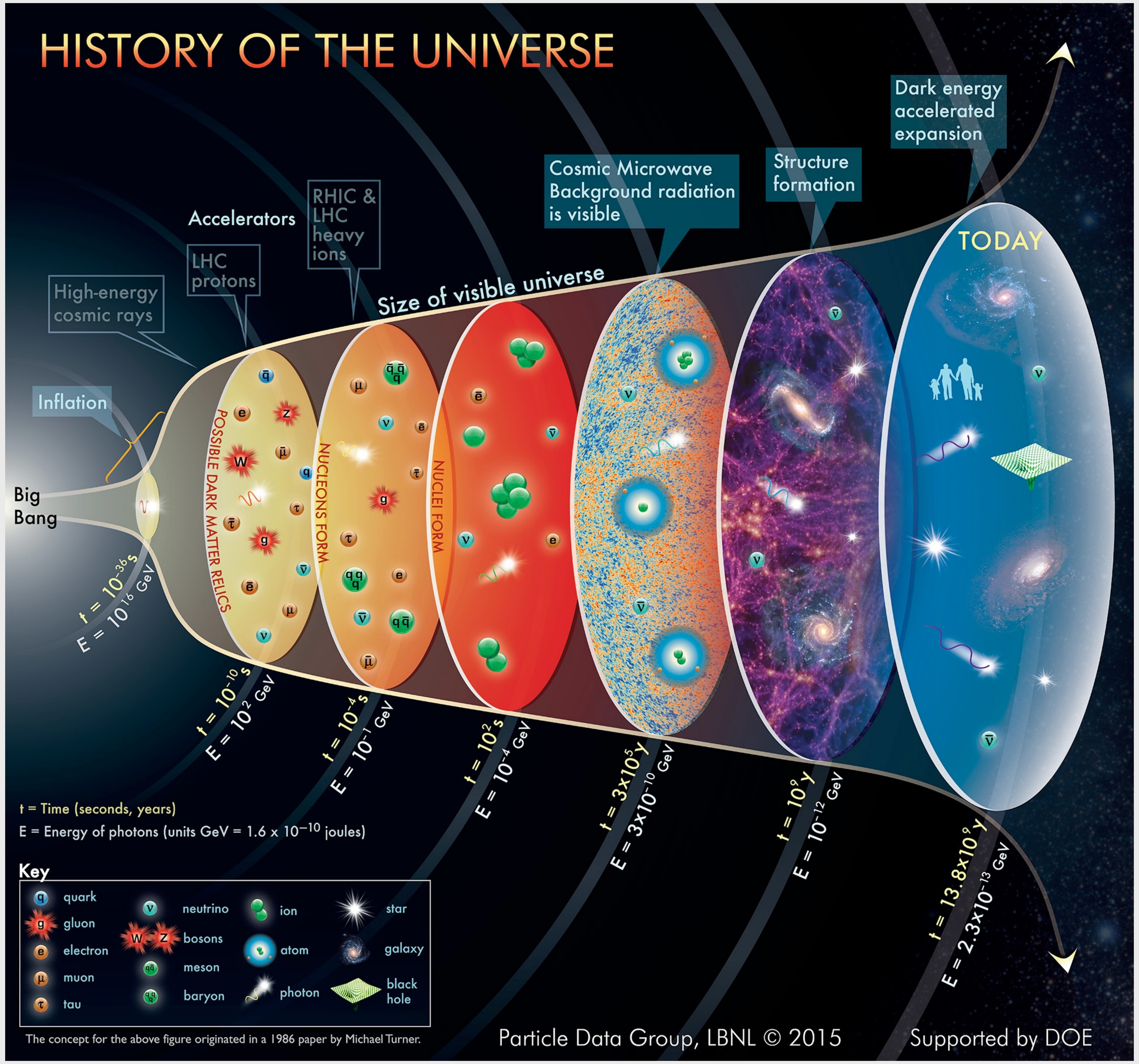
WEAK INTERACTIONS

STRONG INTERACTIONS

NEED SOME COSMOLOGY INPUTS

open questions

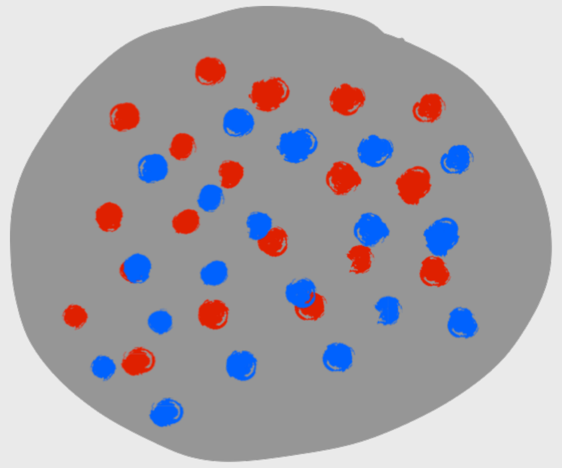
Open Questions on the "big picture" on fundamental physics circa 2020



Nothing we have measured in high energy physics makes so much of a distinction between particles and anti-particles.

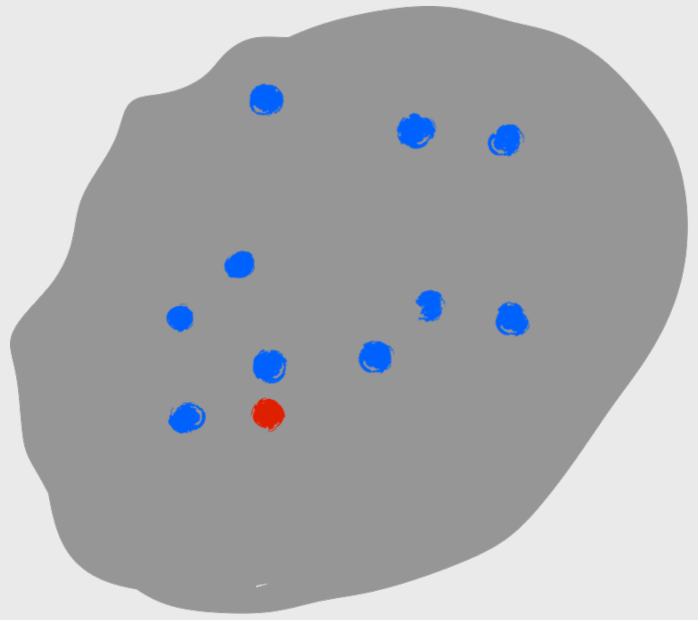
The observable Universe is made of matter, no antimatter

We need to go from this



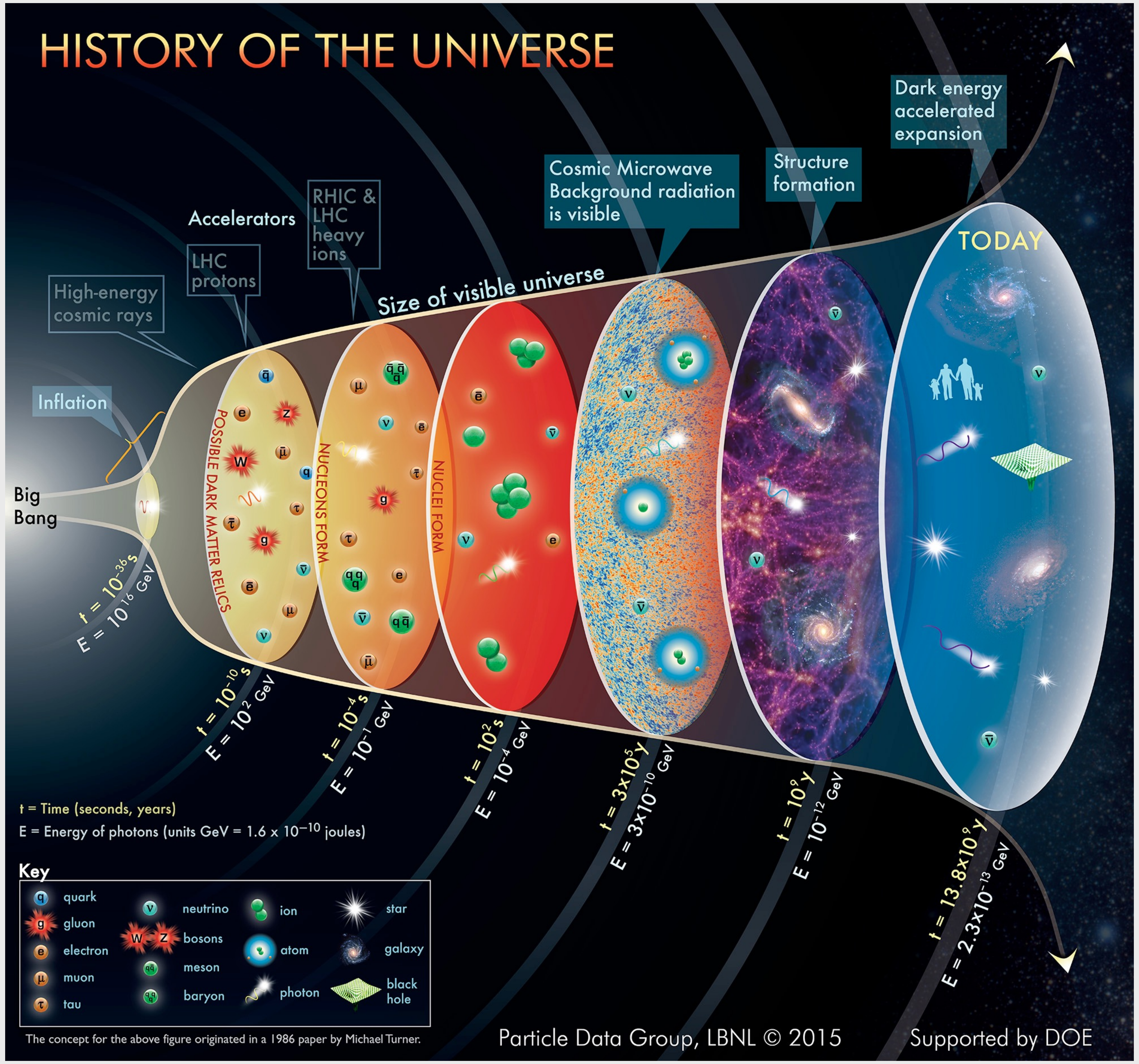
particles
antiparticles

to this



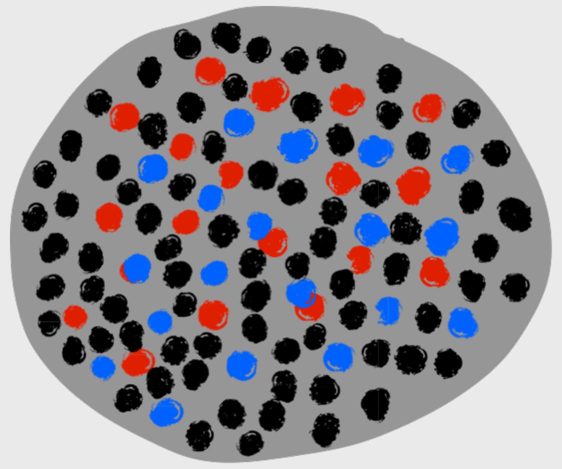
out-of-equilibrium processes are necessary

Open Questions on the "big picture" on fundamental physics circa 2020



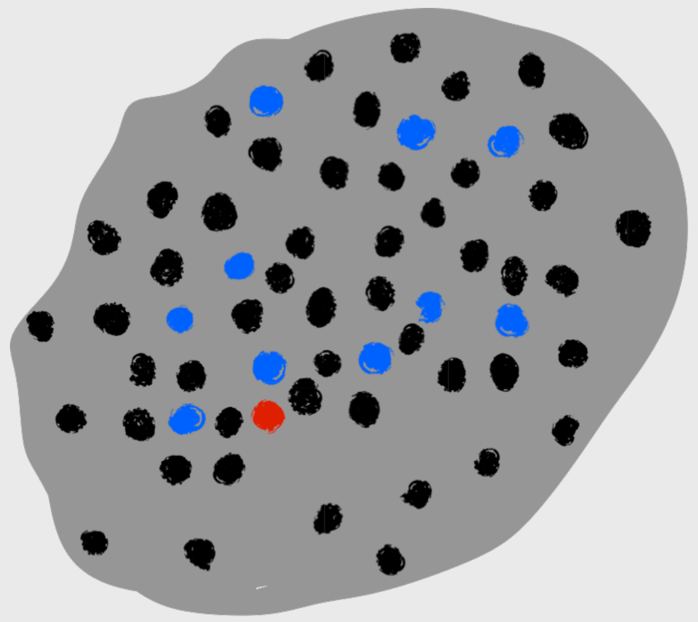
The observable Universe is made of matter, plus about 5 times as much dark matter

We need to go from this



normal particles
dark matter
antiparticles

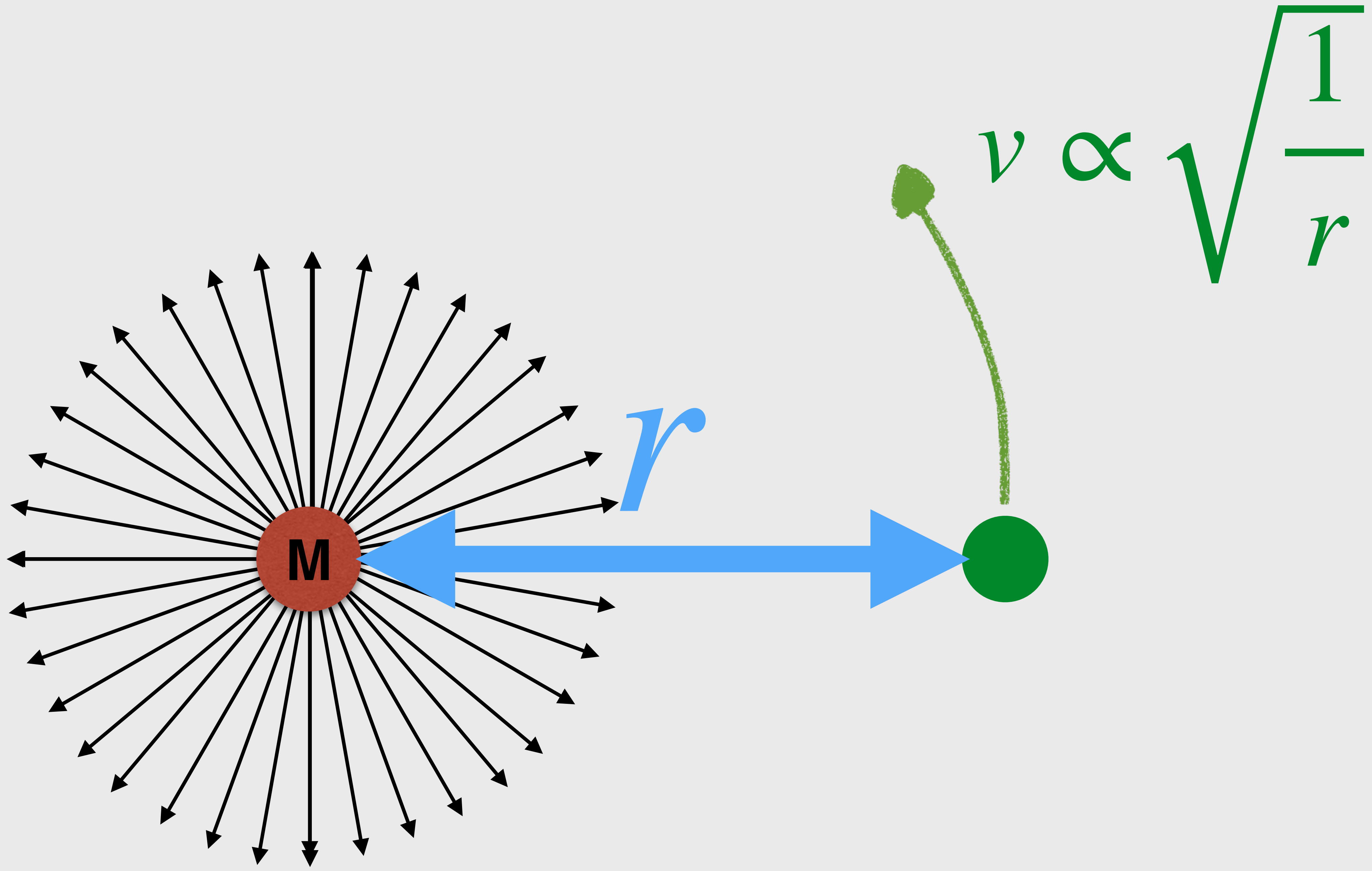
to this



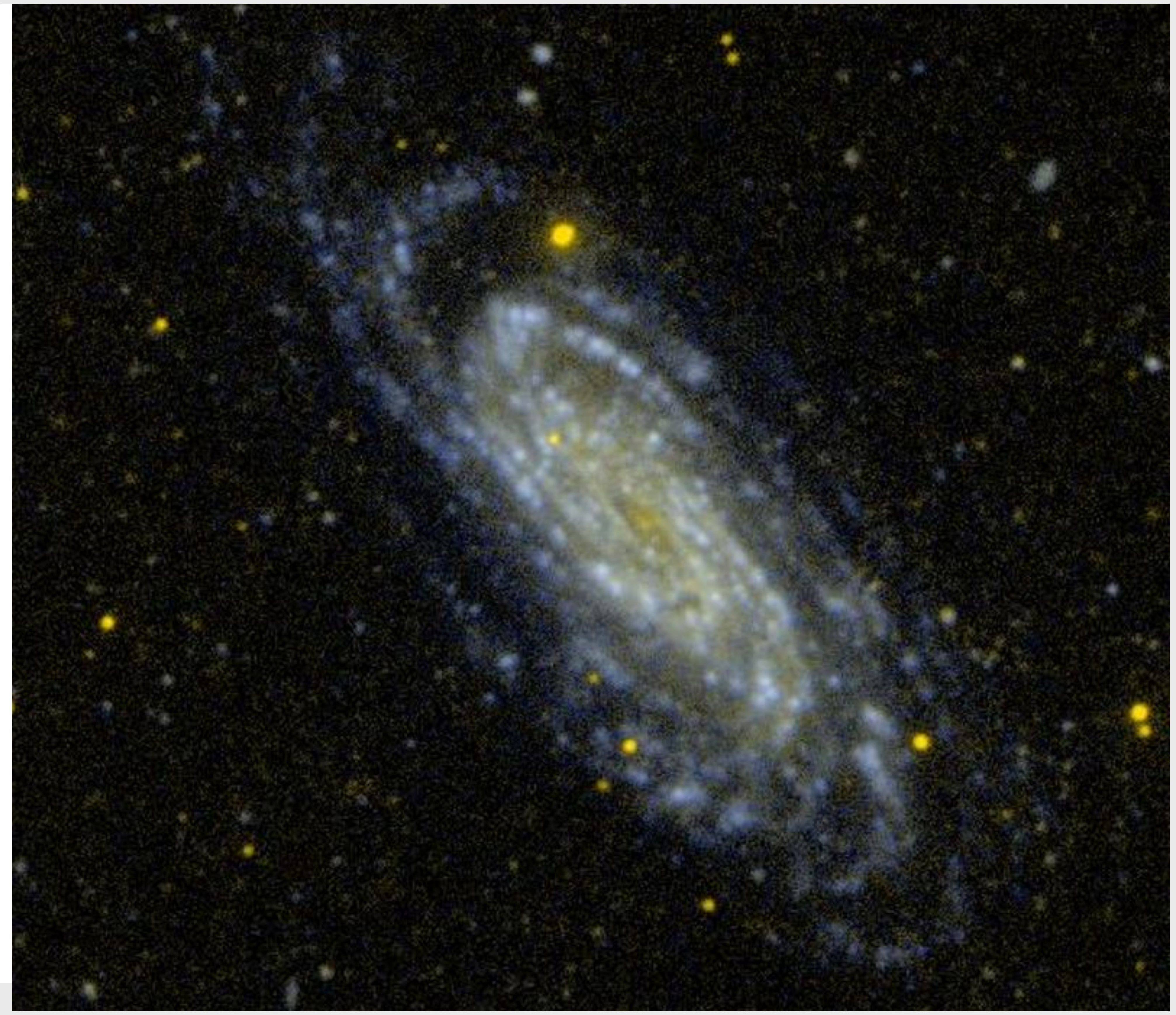
interactions rate from $\sigma = \left(\frac{g_{weak}}{M_{weak}}\right)^2$ are just about right!

A puzzle we have no idea how to solve

NEWTONIAN MECHANICS FAILS?



Perfect in our "neighborhood"



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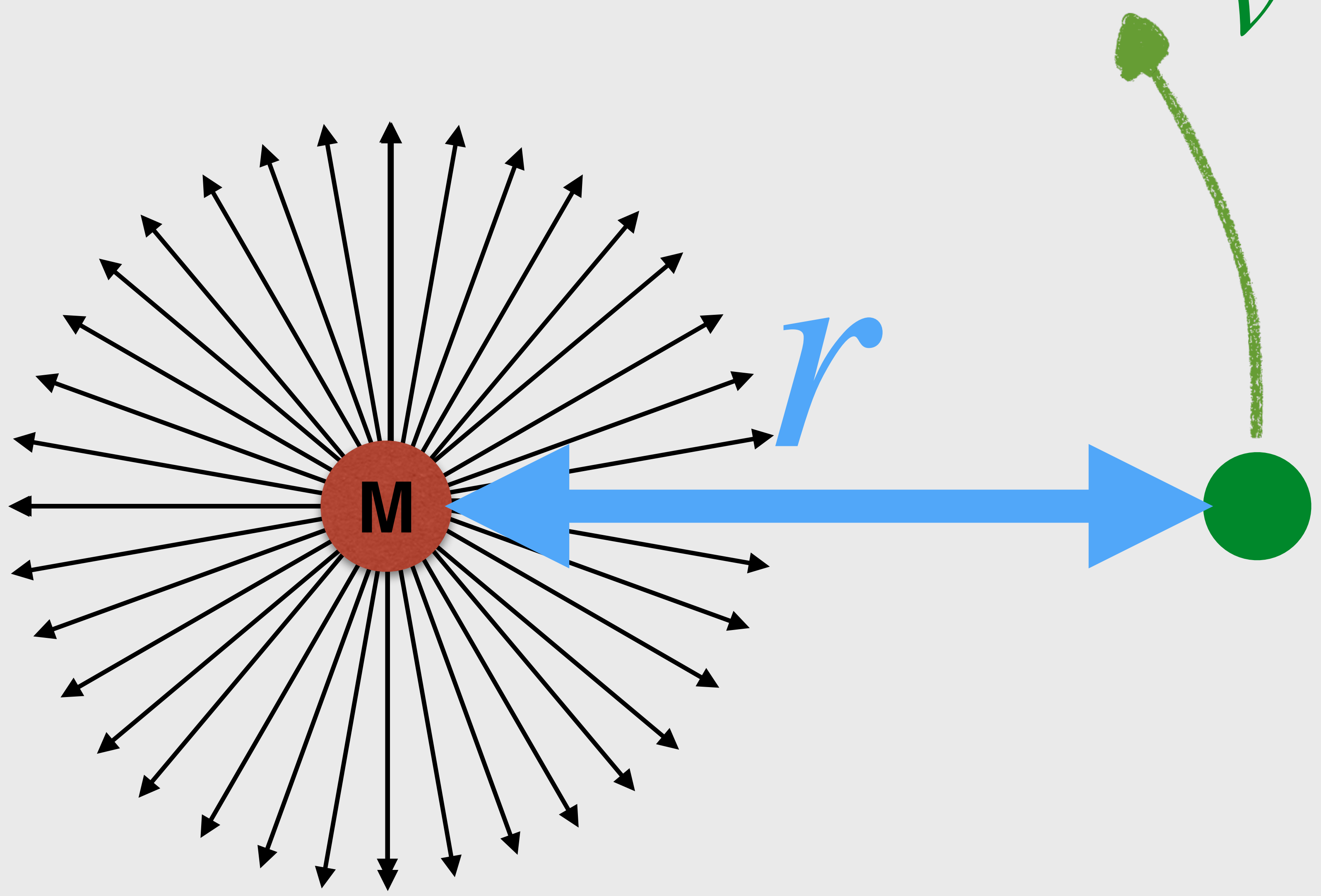

$$v \propto \sqrt{\frac{1}{r}}$$

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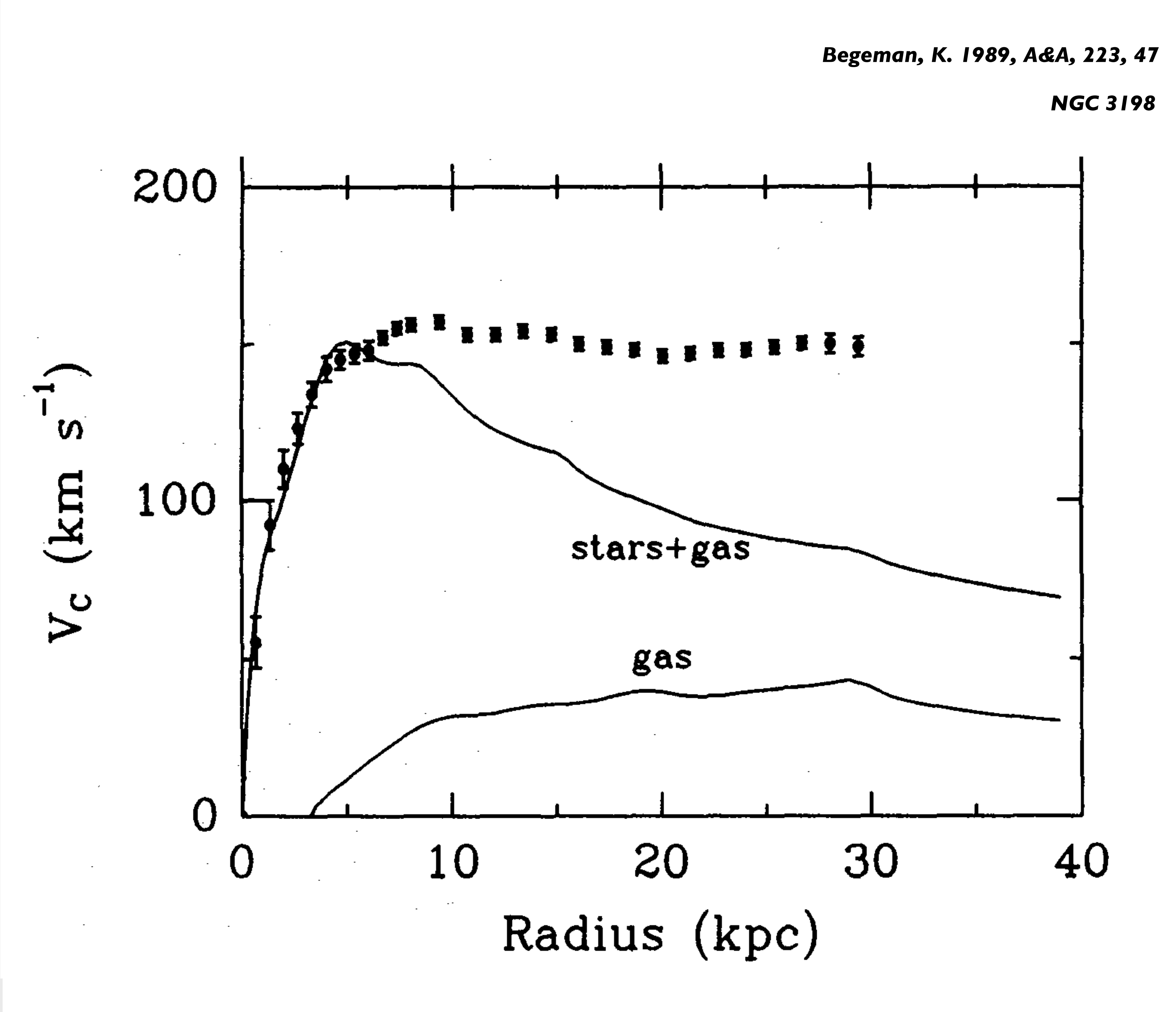

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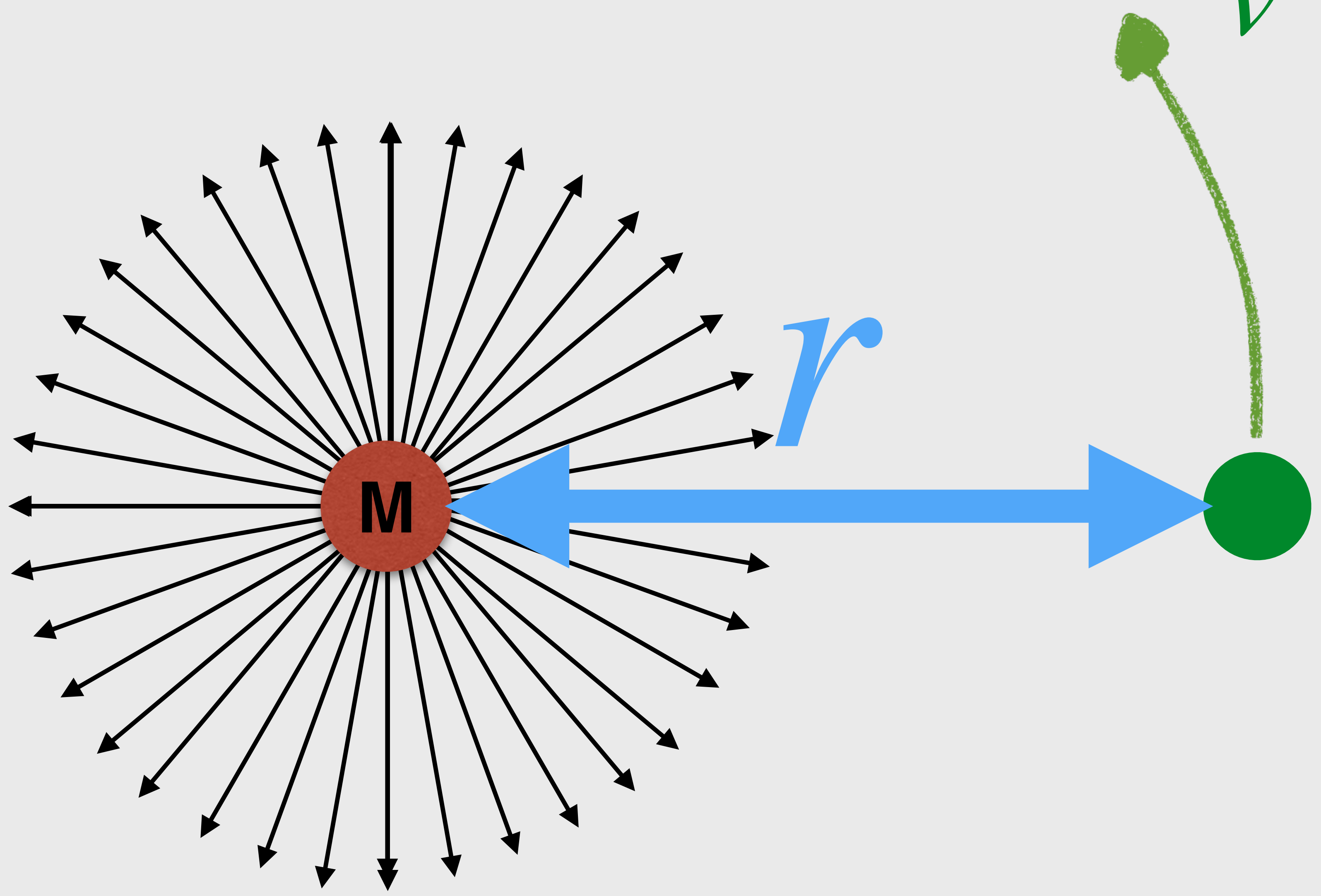

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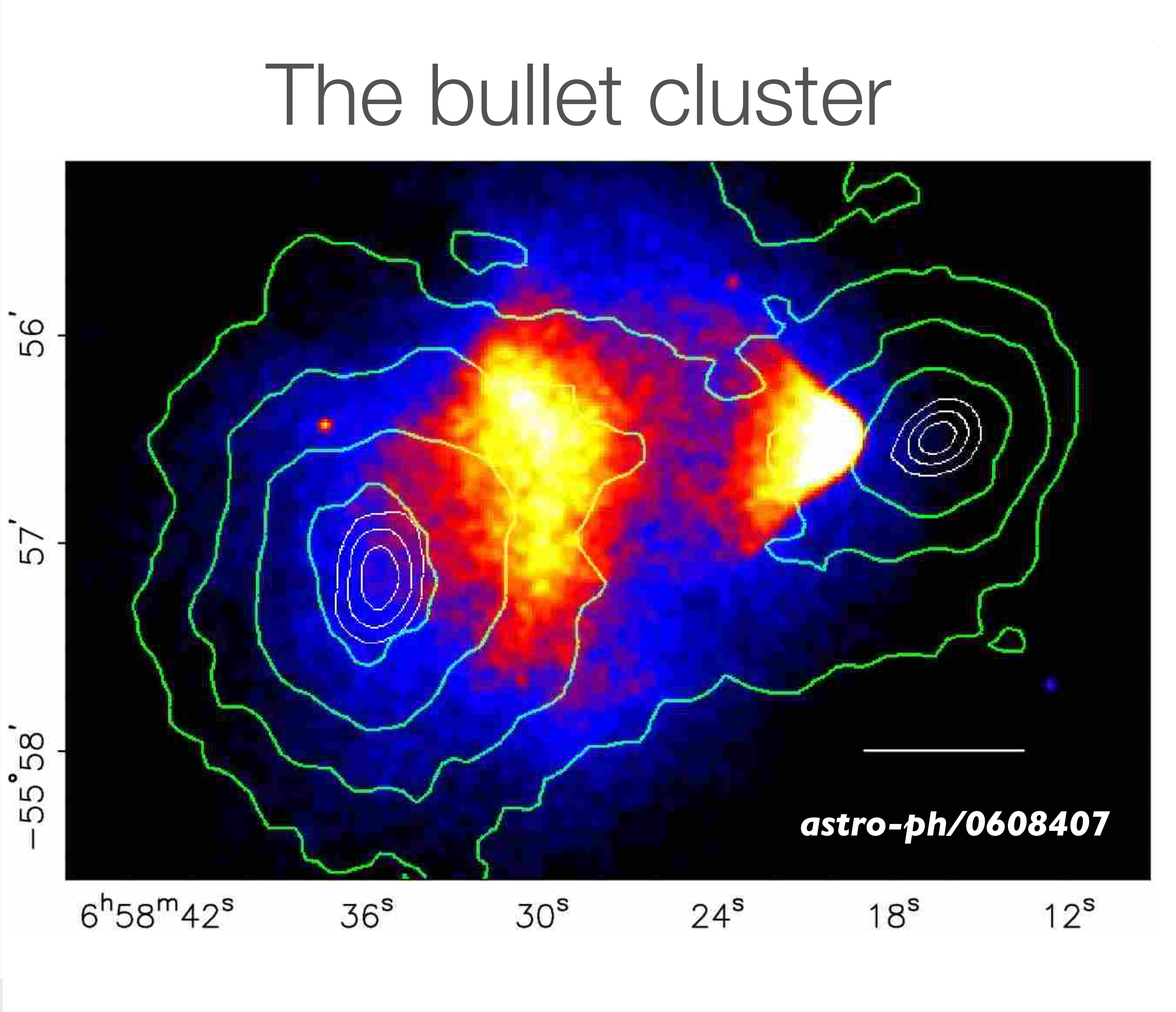

A puzzle we have no idea how to solve

A number of observations (including CMB from early Universe) suggest

a new form of matter must exist

It may well be not of the kind we are used to:

- **It may have only weak interactions (even possible it feels only gravity)**
- **There are candidates "particles" with Compton length 1/M ranging from the size of a Galaxy down to High Energy Physics scales (GeV-TeV) and even beyond**

It is not necessarily material for particle physics and accelerators

A puzzle we have no idea how to solve

A number of observations (including CMB from early Universe) suggest

- We know the scope of the search for Dark Matter is huge
- In principle, it can be very elusive (to all experiments)
- The simplest history of the early Universe suggests the "TeV" mass range
- Accelerators are the only way to go see it and study it in detail

Open Questions on the "big picture" on fundamental physics circa 2020

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• why QCD does not violate CP?

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~~EFT~~ • why gravity and weak interactions are so different?

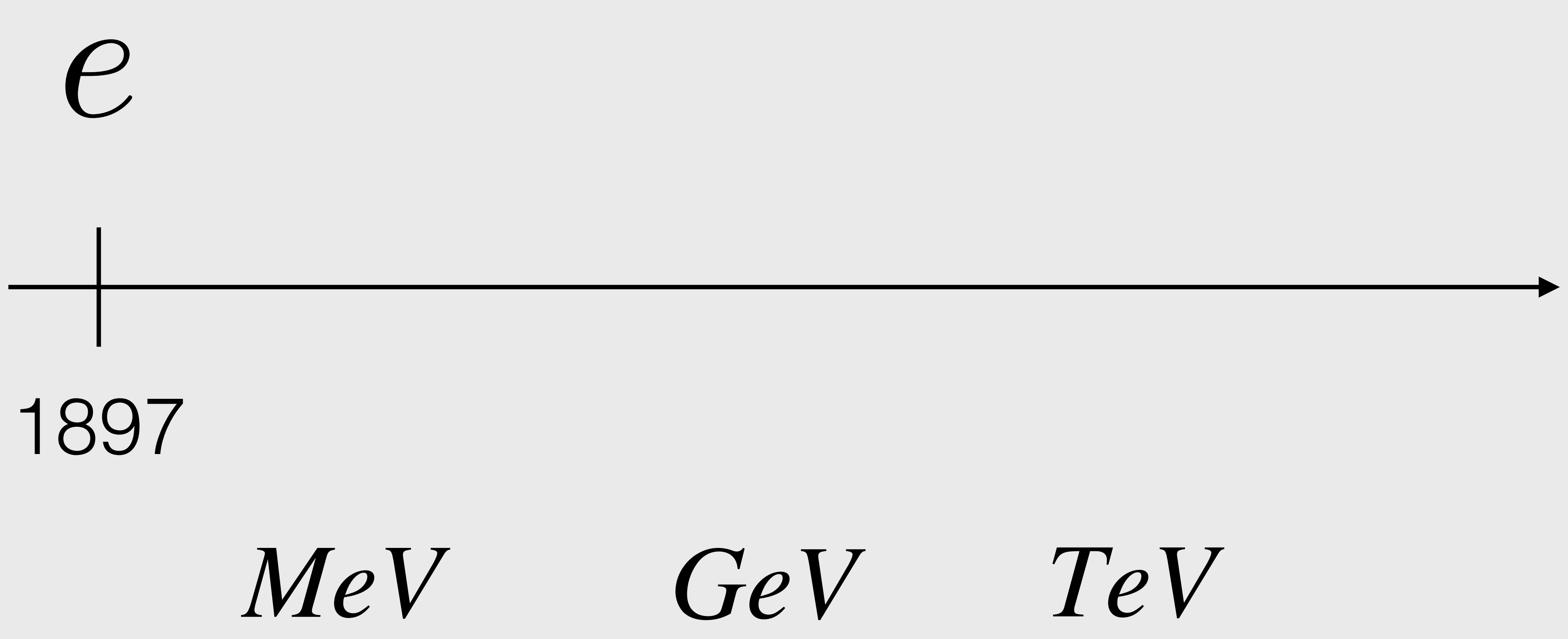
~~EFT~~ • what fixes the cosmological constant?

EACH of these issues one day will teach us a lesson

The march of symmetry

SYMMETRY AS A FUNDAMENTAL CHARACTER OF NATURE

Symmetries and particles



The march of symmetry

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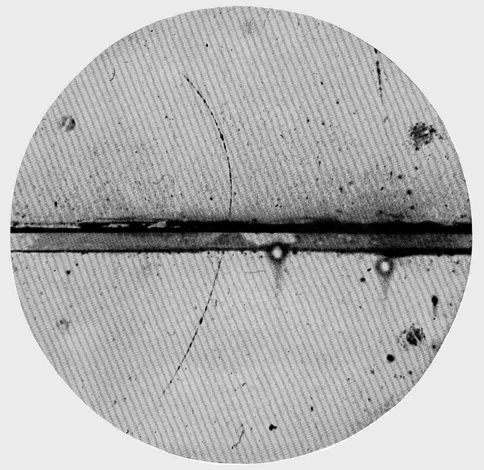

$B = 1.5$ T

e — 1897

e^-, e^+ — 1928-1933

MeV *GeV* *TeV*

The march of symmetry

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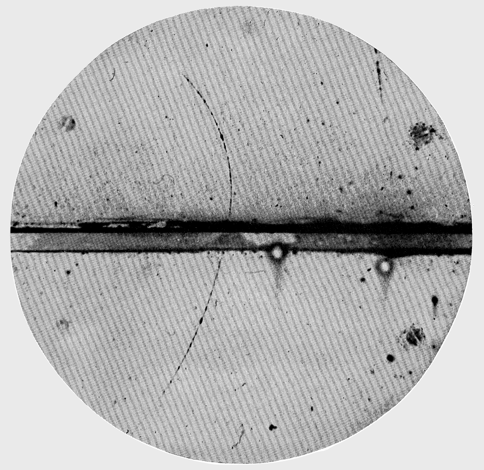
Symmetries and particles



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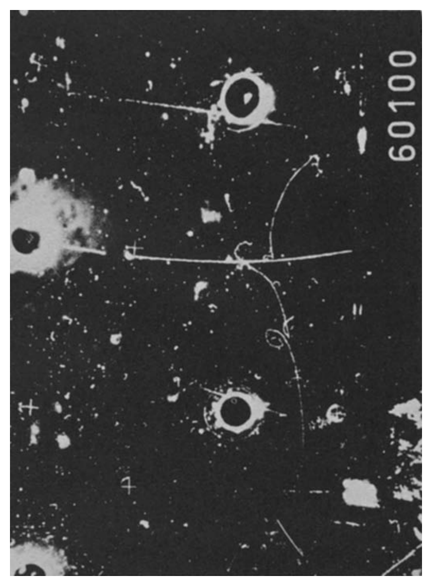

Fig. 1. Possible event of the type $\bar{\nu}_\mu + e^- \to \bar{\nu}_\mu + e^-$.

$B = 2$ T

1897	1928-1933	196x-1973
	e^+	ν_e
e	e^-	e

MeV *GeV* *TeV*

The march of symmetry

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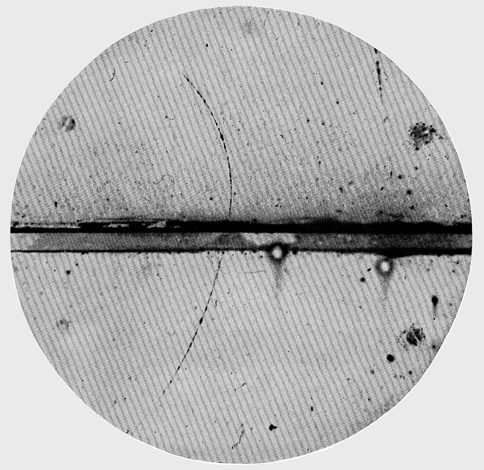

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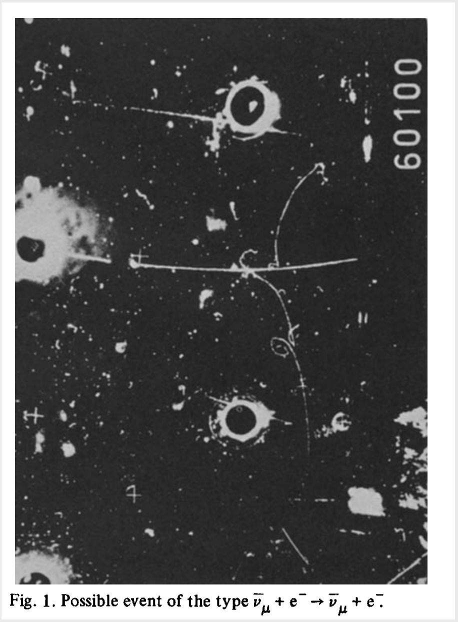

$B = 2$ T

1897	1928-1933	196x-1973	2020s
e	e^+, e^-	ν_e, e	⋮

MeV GeV TeV

The march of symmetry

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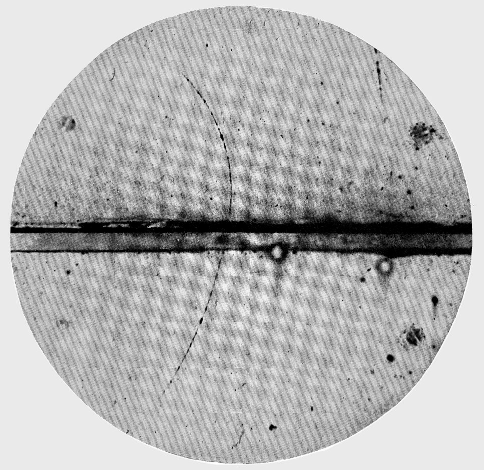

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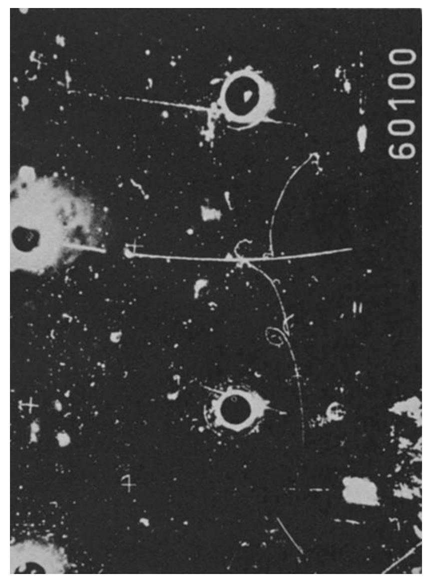

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e — 1897

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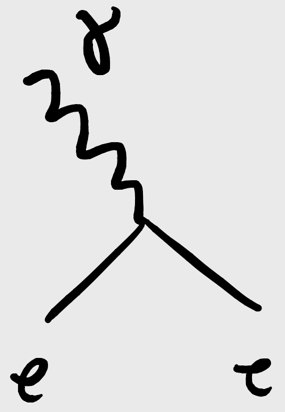
ν_e, e — 196x-1973

? — 2020s

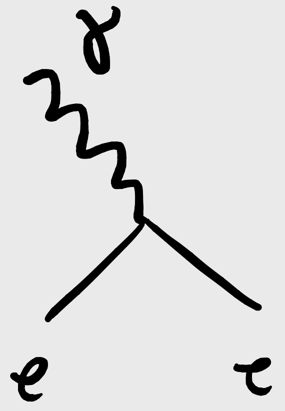
MeV *GeV* *TeV*

Where do we stand?

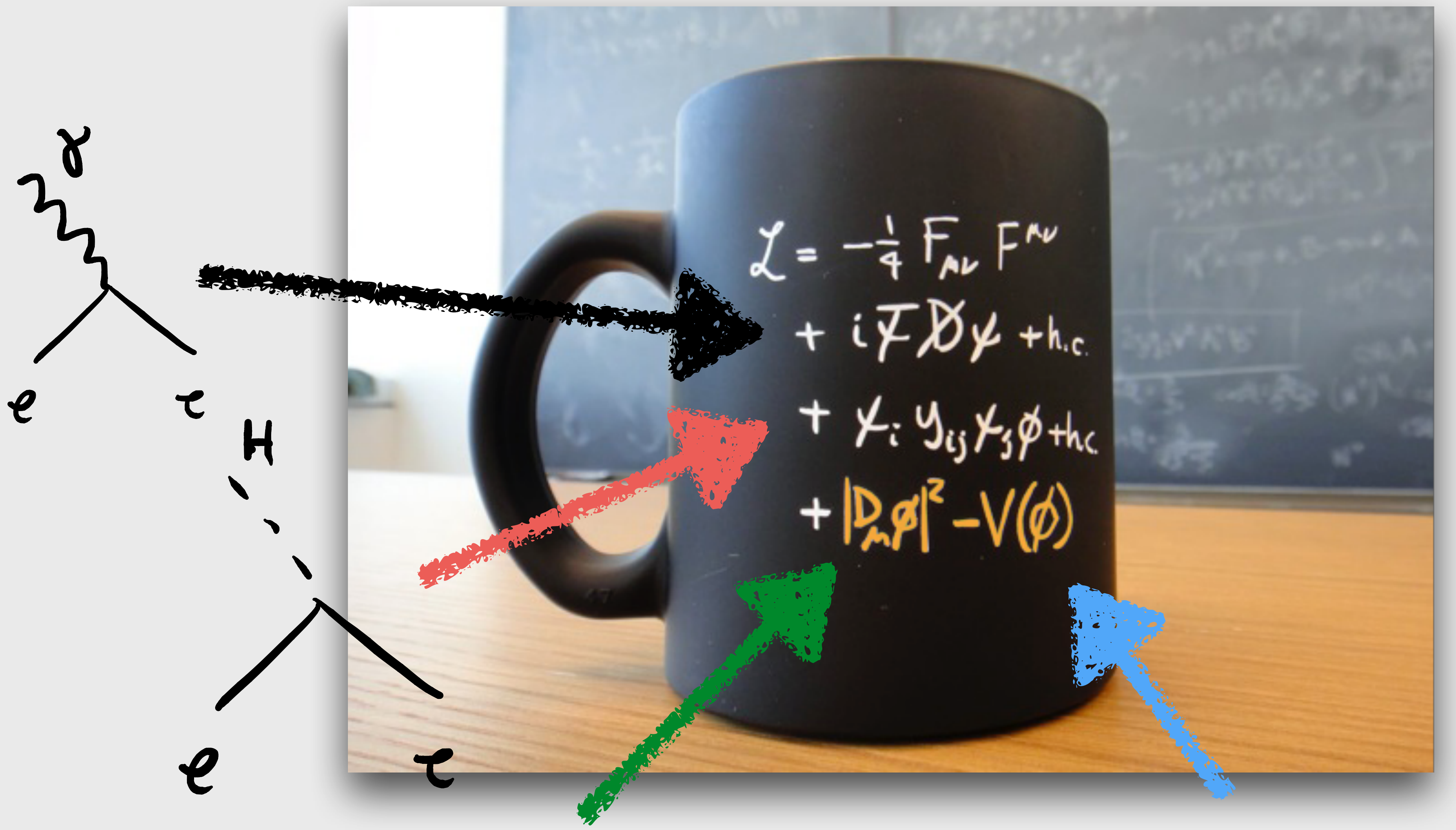
SYMMETRY | AS A FUNDAMENTAL CHARACTER OF NATURE | ?????

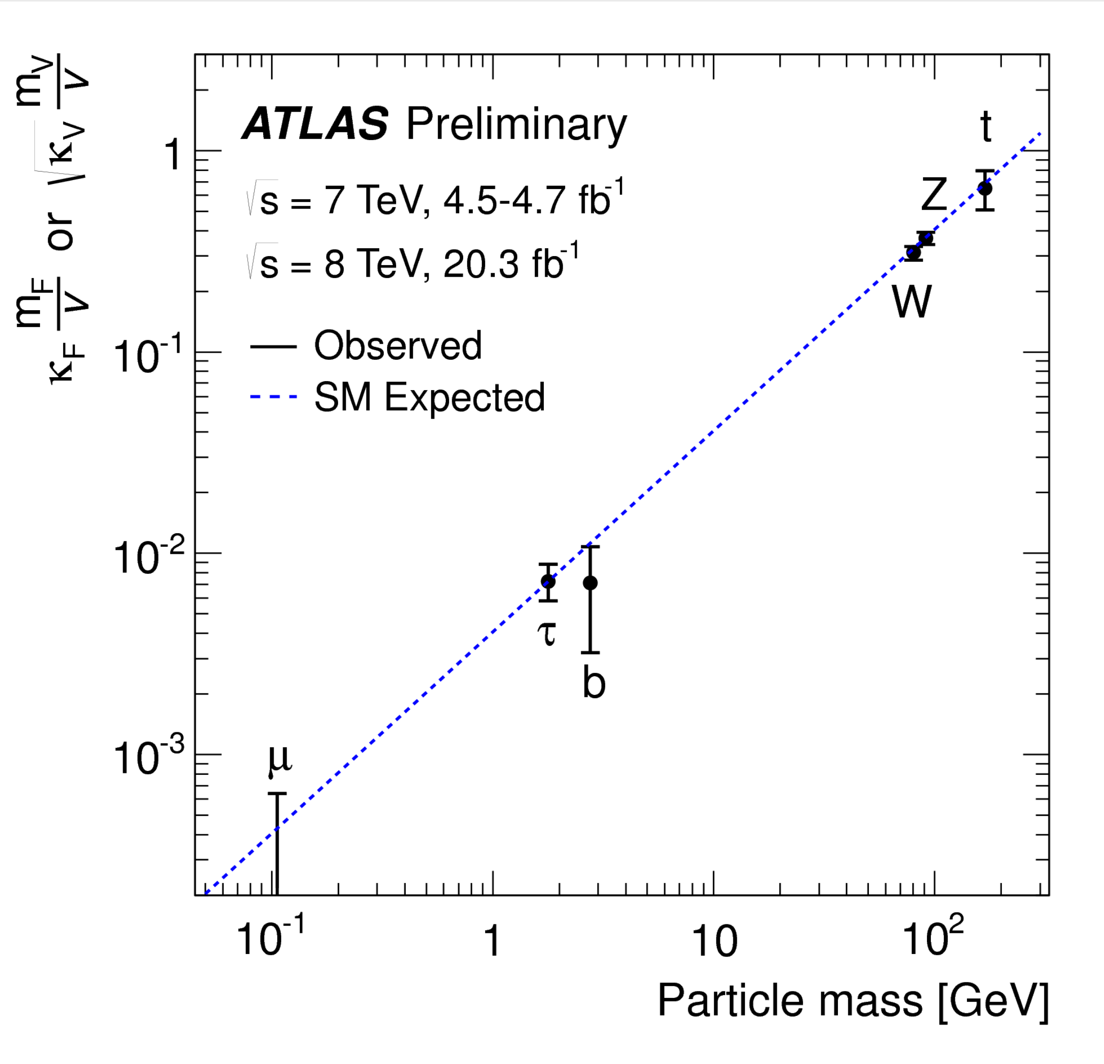


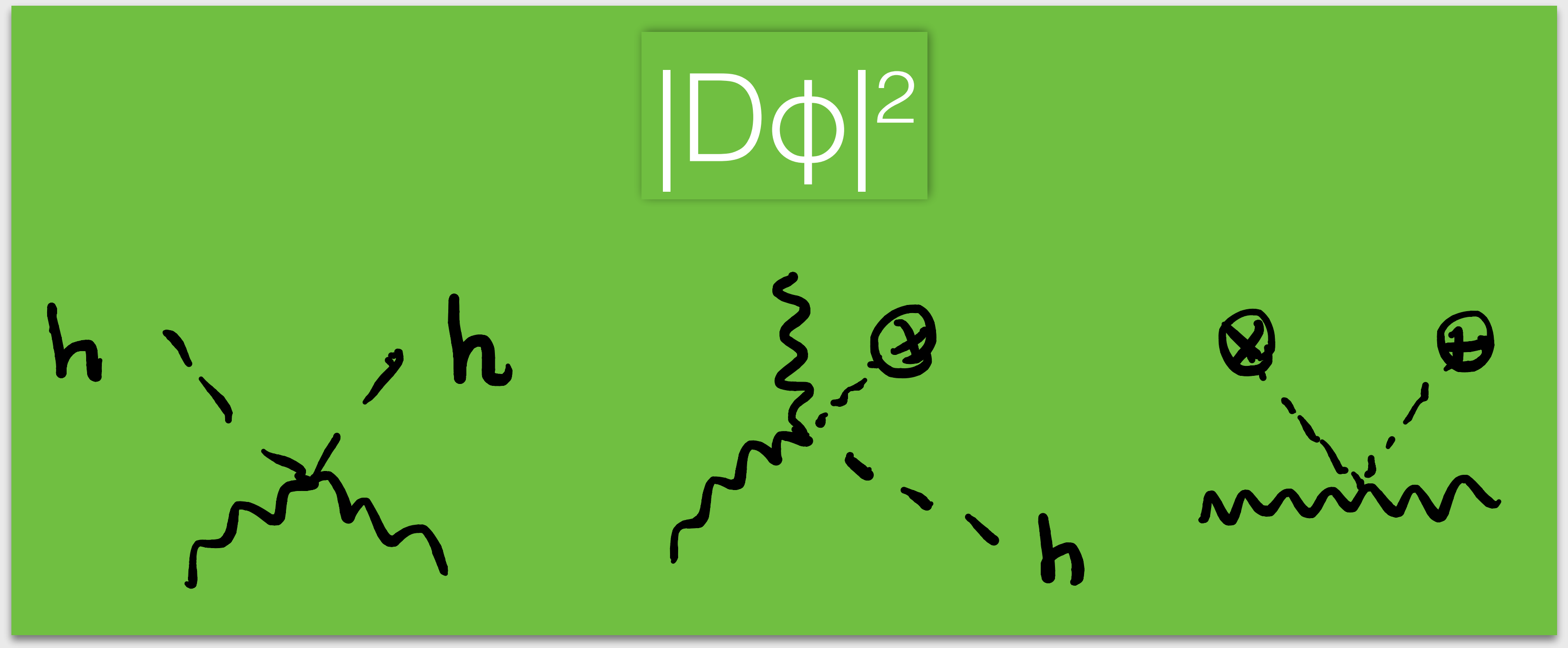
electro-weak interactions

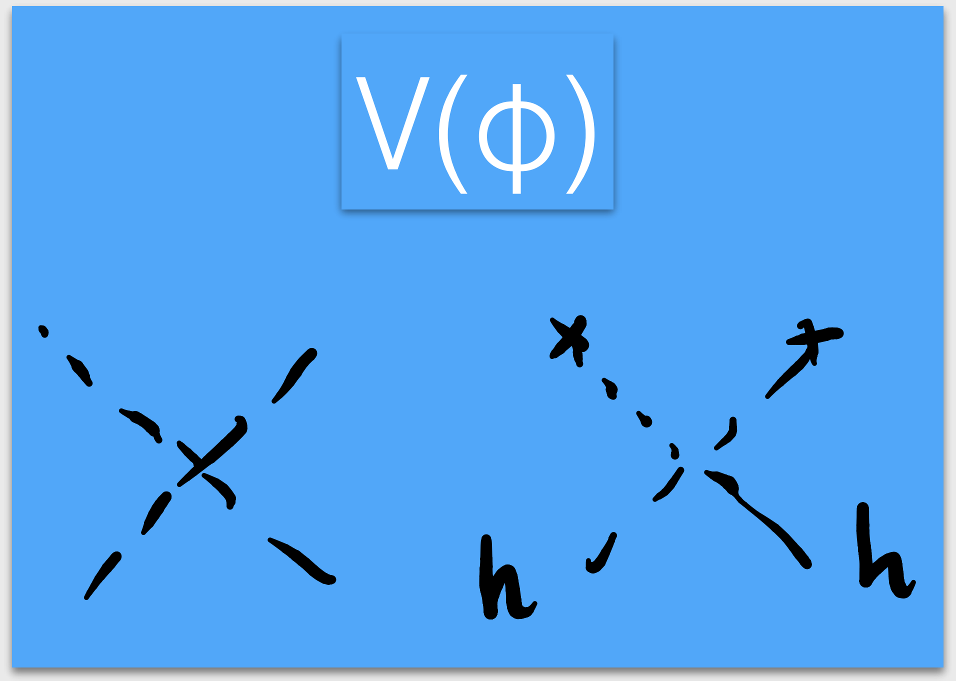


strong interactions







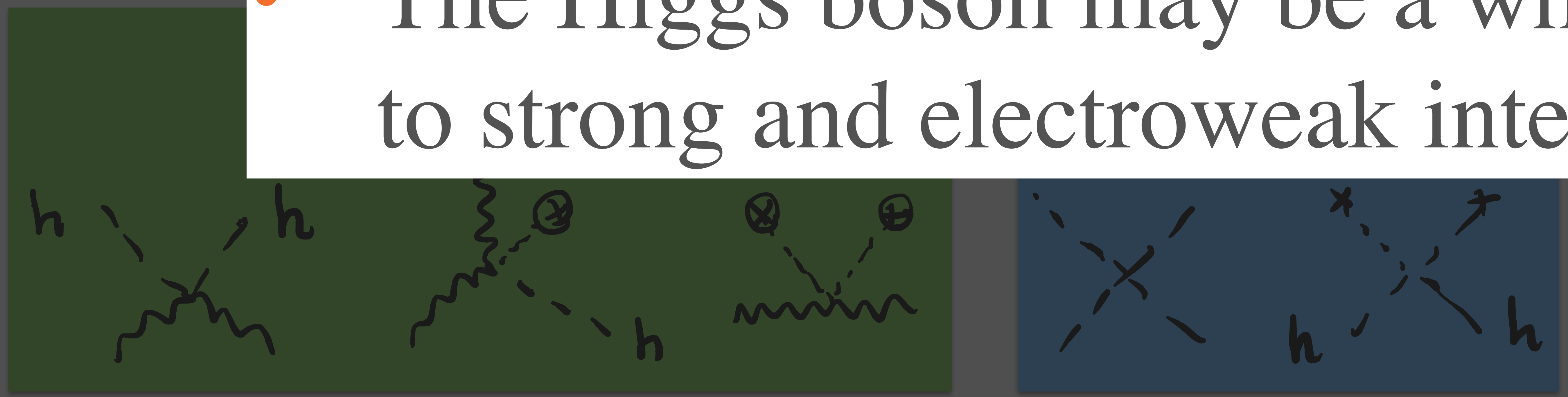


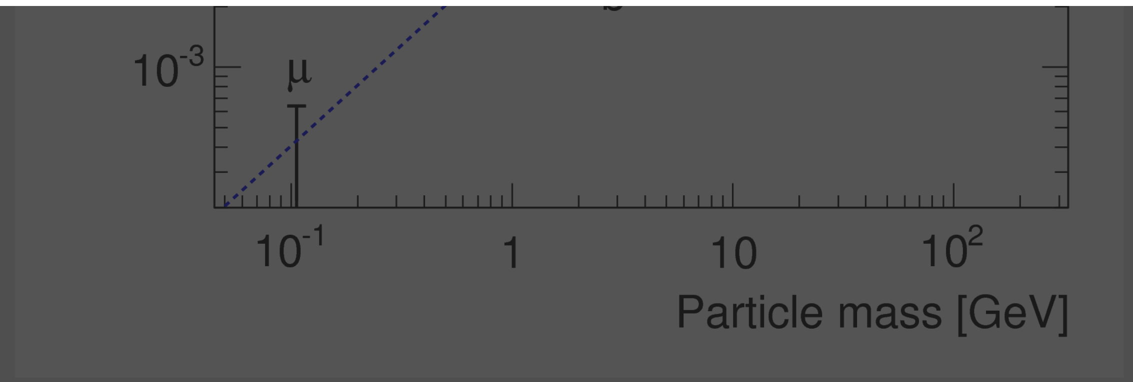
Where do we stand?

SYMMETRY | AS A FUNDAMENTAL CHARACTER OF NATURE | ?????

electro-weak interactions

- We established the principles behind electroweak and strong interaction very well
- We measured the Higgs boson only very “broad brush”
- The Higgs boson may be a whole new thing compared to strong and electroweak interactions





• Outlook

SYMMETRY | AS A FUNDAMENTAL CHARACTER OF NATURE | ?????

Coincidences ?

$$\mathcal{L} = \mathrm{c} + \mu^2 H^2 + \lambda H^4$$

Fermi constant
(periodic table)

Higgs boson mass
(meta-)stability of the Universe

Cosmological Constant
(galaxy formation)

Steven Weinberg Phys. Rev. Lett. 59, 2607 - If $c > 200\, c_{\mathrm{measured}}$ galaxies would ne be able to form (matter-domination phase too short)

arXiv:hep-ph/9707380 Agrawal et al. - If $\mu > 5 \cdot \mu_{SM}$ periodic table disappears! (neutron decay too fast)

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Rev. Mod. Phys. 68, 951 - Cahn, Robert N. - The eighteen arbitrary parameters of the standard model in your everyday life

Phys.Rept. 807 (2019) 1-111 - Adams, F.~C. - The Degree of Fine-Tuning in our Universe - and Others

• Outlook

SYMMETRY | AS A FUNDAMENTAL CHARACTER OF NATURE | ?????

Coincidences ?

$$\mathcal{L} = c + \mu^2 H^2 + \lambda H^4$$

- Symmetry, the very idea at the basis of “the” formula, is challenged by a number of phenomena, which may, at best, be described in this language

Cosmological Constant
(galaxy formation)

(meta-)stability of the Universe

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Open Questions on the "big picture" on fundamental physics circa 2020

weak interactions

	?	• what is the dark matter in the Universe?	✓	
		• why QCD does not violate CP?	✓	✓
		• how have baryons originated in the early Universe?	✓	
		• what originates flavor mixing and fermions masses?	✓	
		• what gives mass to neutrinos?	✓	
~~EFT~~		• why gravity and weak interactions are so different?	✓	
~~EFT~~		• what fixes the cosmological constant?	✓	

WEAK INTERACTIONS

STRONG INTERACTIONS

Accelerators are excellent probes

Open Questions on the "big picture" on fundamental physics circa 2020

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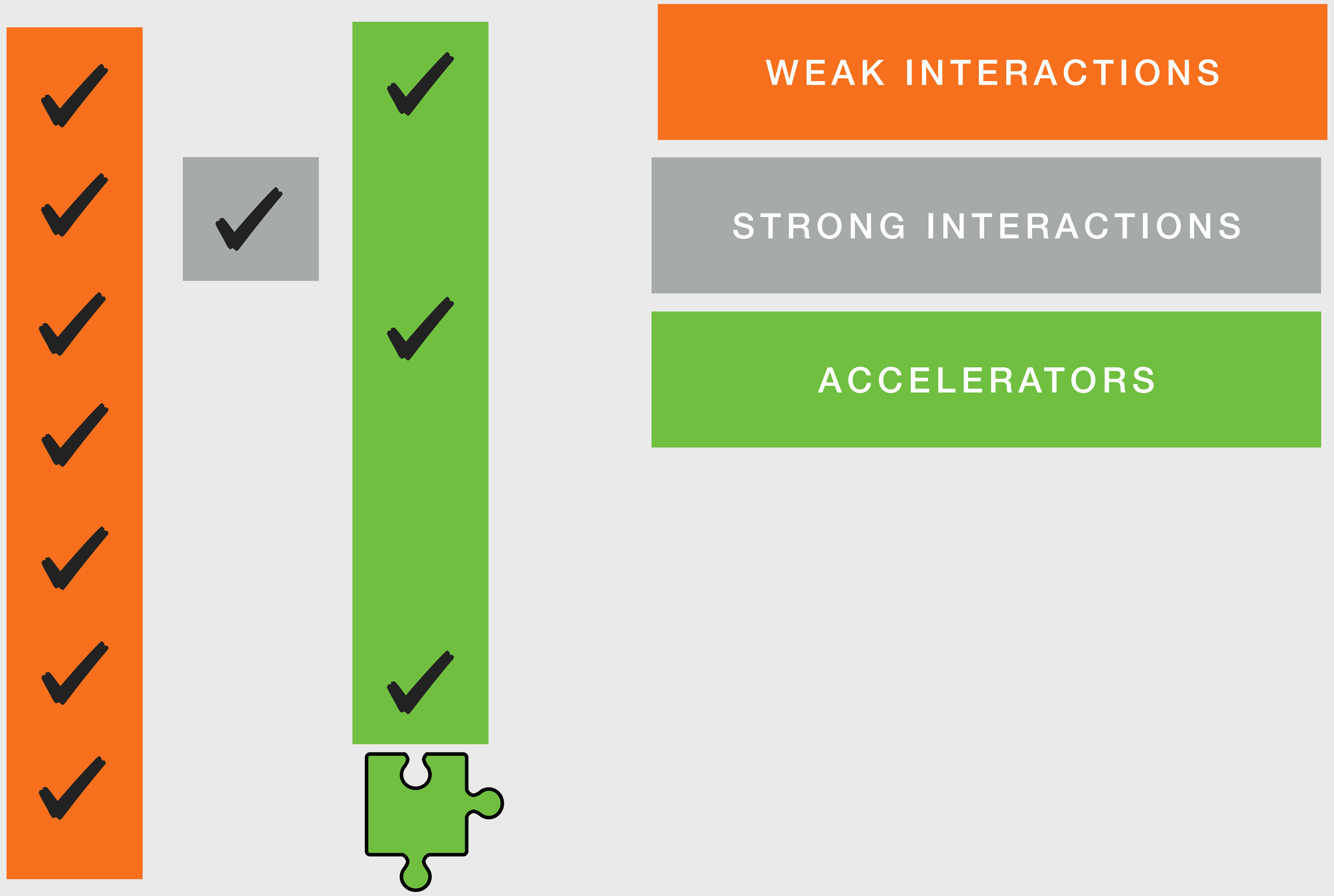

Accelerators are excellent probes

Open Questions on the "big picture" on fundamental physics circa 2020

weak interactions

WEAK INTERACTIONS

STRONG INTERACTIONS

- ? what is the dark matter in the Universe?
- why QCD does not violate CP?
- how have baryons originated in the early Universe?

- Today I left most of the material on these "technical" results in the backup, please ask me(!)

- EFT why gravity and weak interactions are so different?
- EFT what fixes the cosmological constant?

Accelerators are excellent probes

A gauge of the progress made so far

- The **depth of the questions** that can be asked based on the progress made so far witnesses the maturity of the investigation on fundamental interactions

A gauge of the progress we can make with any future collider

- The **breadth of the physics** program is very important. Had the Higgs boson not been observed at the LHC, the experiments were ready to catch the experimental signals from alternatives to the Higgs boson of the SM.

- The <u>guaranteed discovery</u> of the Higgs or its substitute at the LHC is a very enviable position under which ambitious projects could be envisioned and implemented.

- None of the future colliders currently under study enjoy this enviable position … back to regular science exploration

TARGETS

What energy/length scale do I need to explore to answer this question? Is this a finite range?

TOOLS

What do you need to explore the energy/length range you are interested in?

COSTS

How long and how much money does it take to answer this question?

TARGETS

What energy/length scale do I need to explore to answer this question? Is this a finite range?

TOOLS

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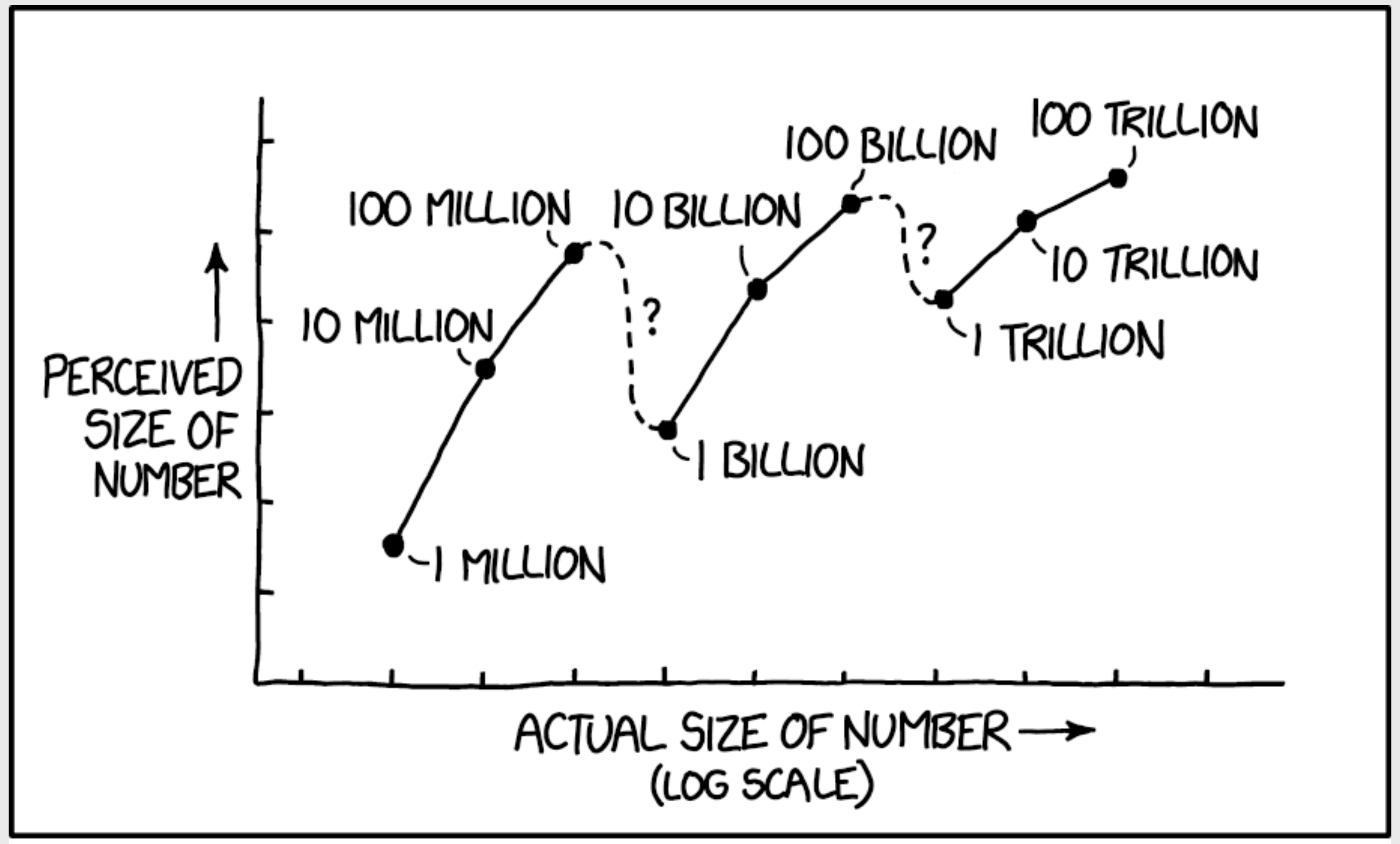
How long and how much money does it take to answer this question?



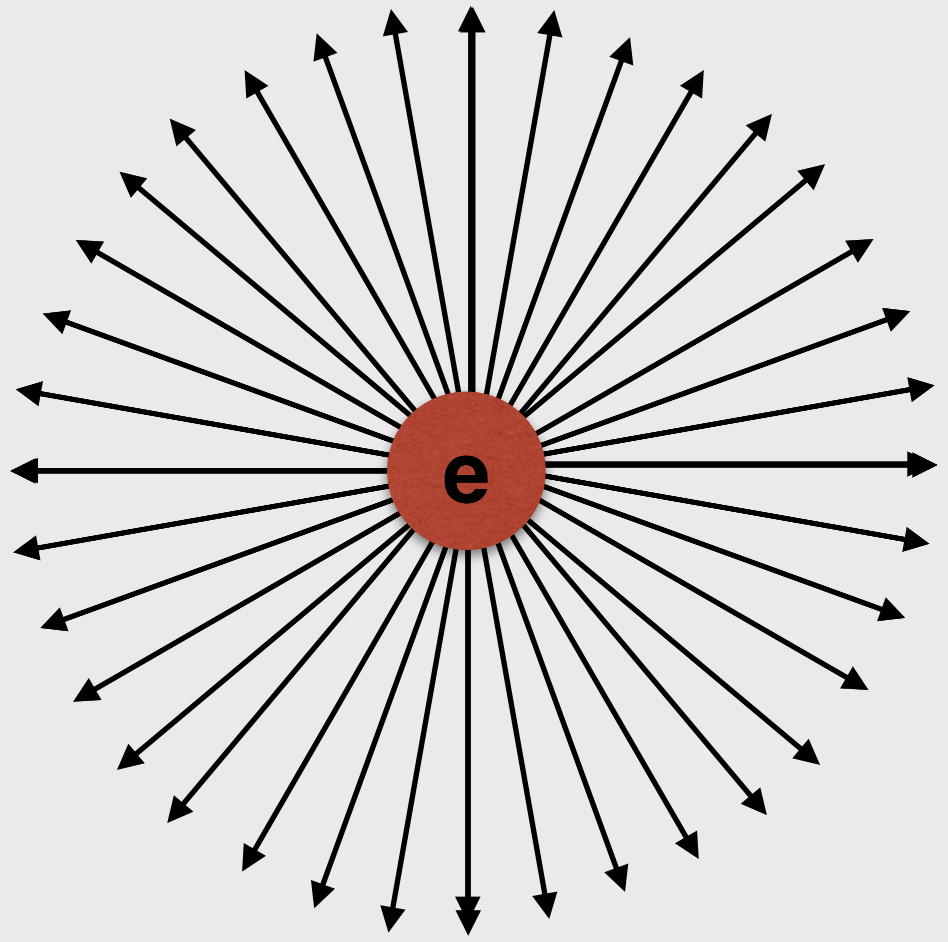
TALKING ABOUT LARGE NUMBERS IS HARD

The mystery of

the size of the Higgs boson

A puzzle (today) we know how to solve

AFTER RELATIVITY



$$m_e = m_e^{(0)} + \int_{r_e}^{\infty} \mathcal{E}$$

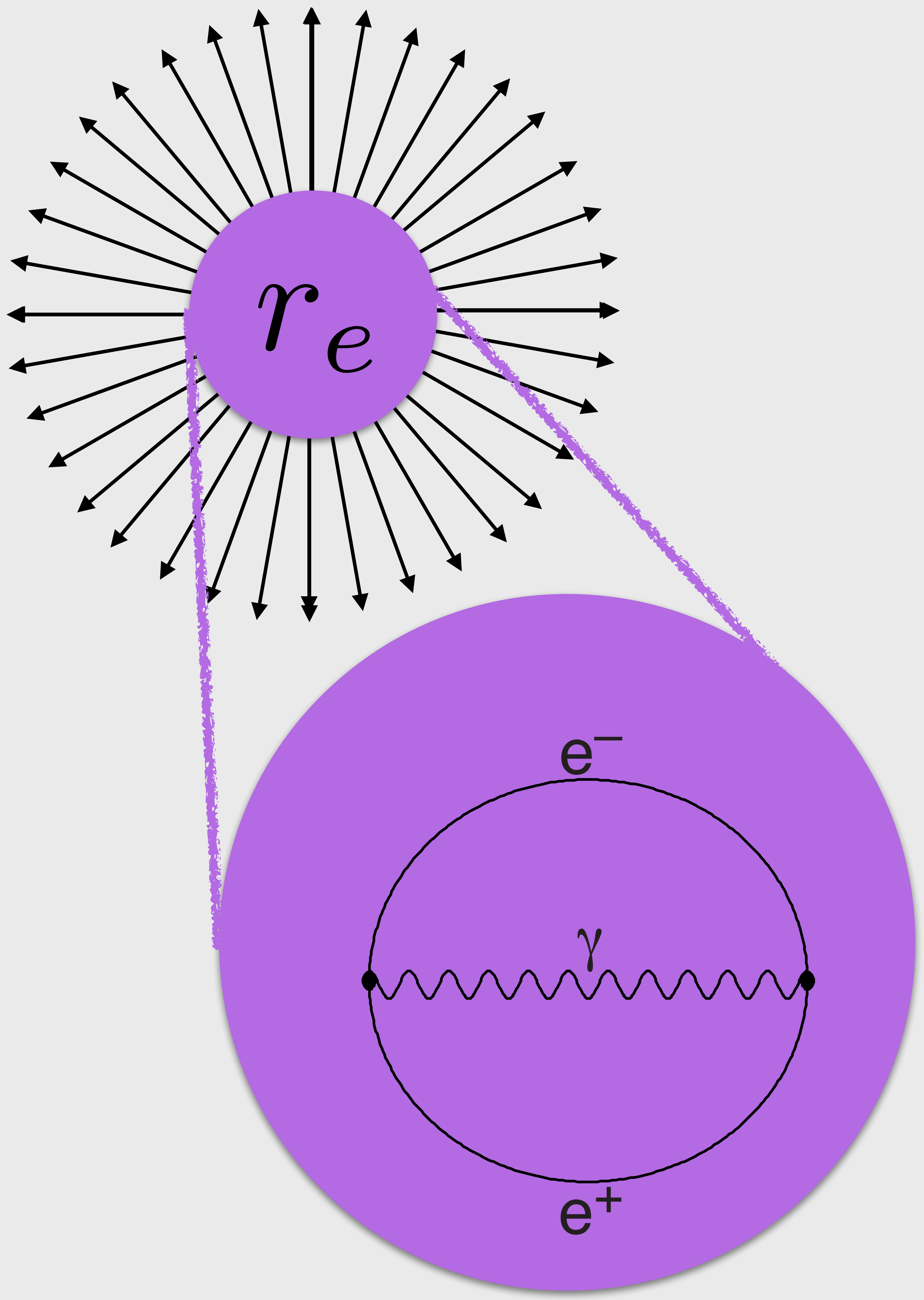
$$\int_{r_e}^{\infty} \mathcal{E} = \frac{1}{4\pi\epsilon_0}\frac{e^2}{r_e}$$

$$\delta m_e \simeq \frac{\alpha_{em}}{r_e} \xrightarrow{r_e \to 0} \infty$$

A puzzle (today) we know how to solve

AFTER

RELATIVITY & QUANTUM MECHANICS



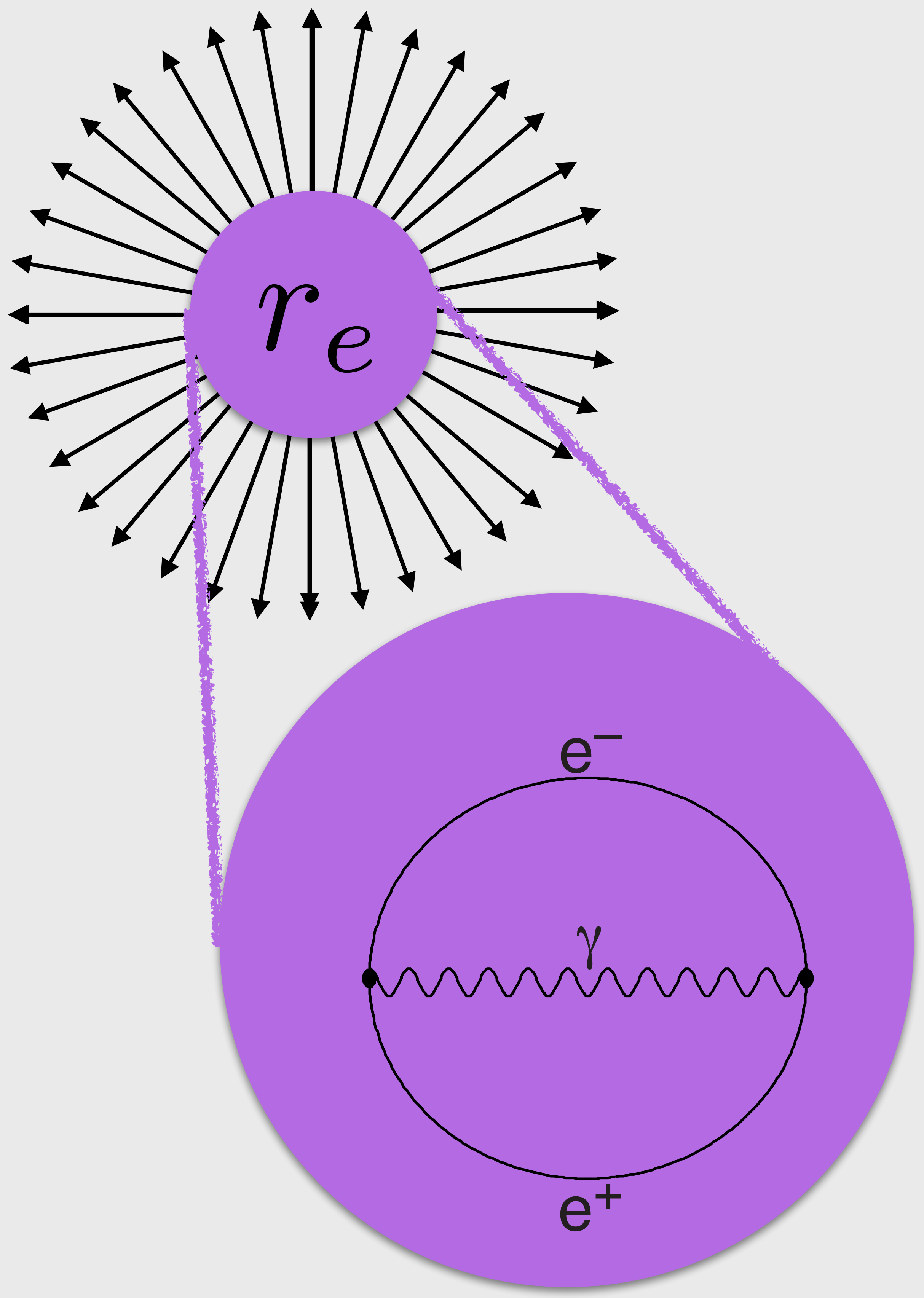
$$m_e = m_e^{(0)} + \int_{r_e}^{\infty} \mathcal{E}$$

$$\int_{r_e}^{\infty} \mathcal{E} = \frac{1}{4\pi\epsilon_0}\frac{e^2}{r_e}$$

$$\delta m_e \simeq \frac{\alpha_{em}}{r_e} \xrightarrow{r_e \to 0} \infty$$

A puzzle (today) we know how to solve

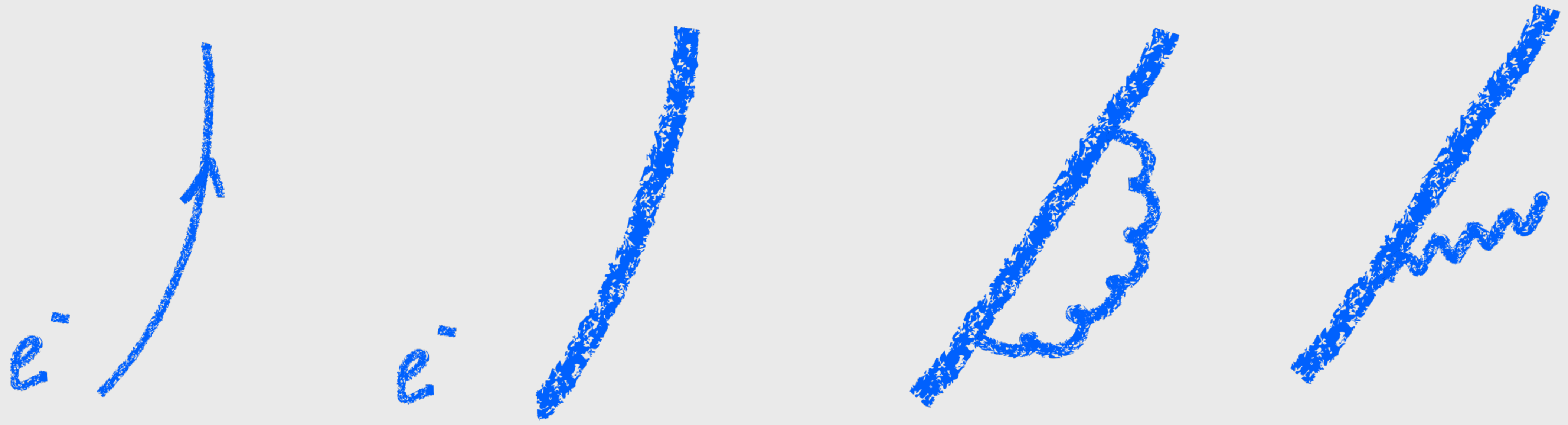
AFTER RELATIVITY & QUANTUM MECHANICS



The electron is a **point-like particle**, surrounded by it “quantum cloud”.

on long time scale

on short time scale



New symmetry (particle-antiparticle) which brought a new particle: the positron

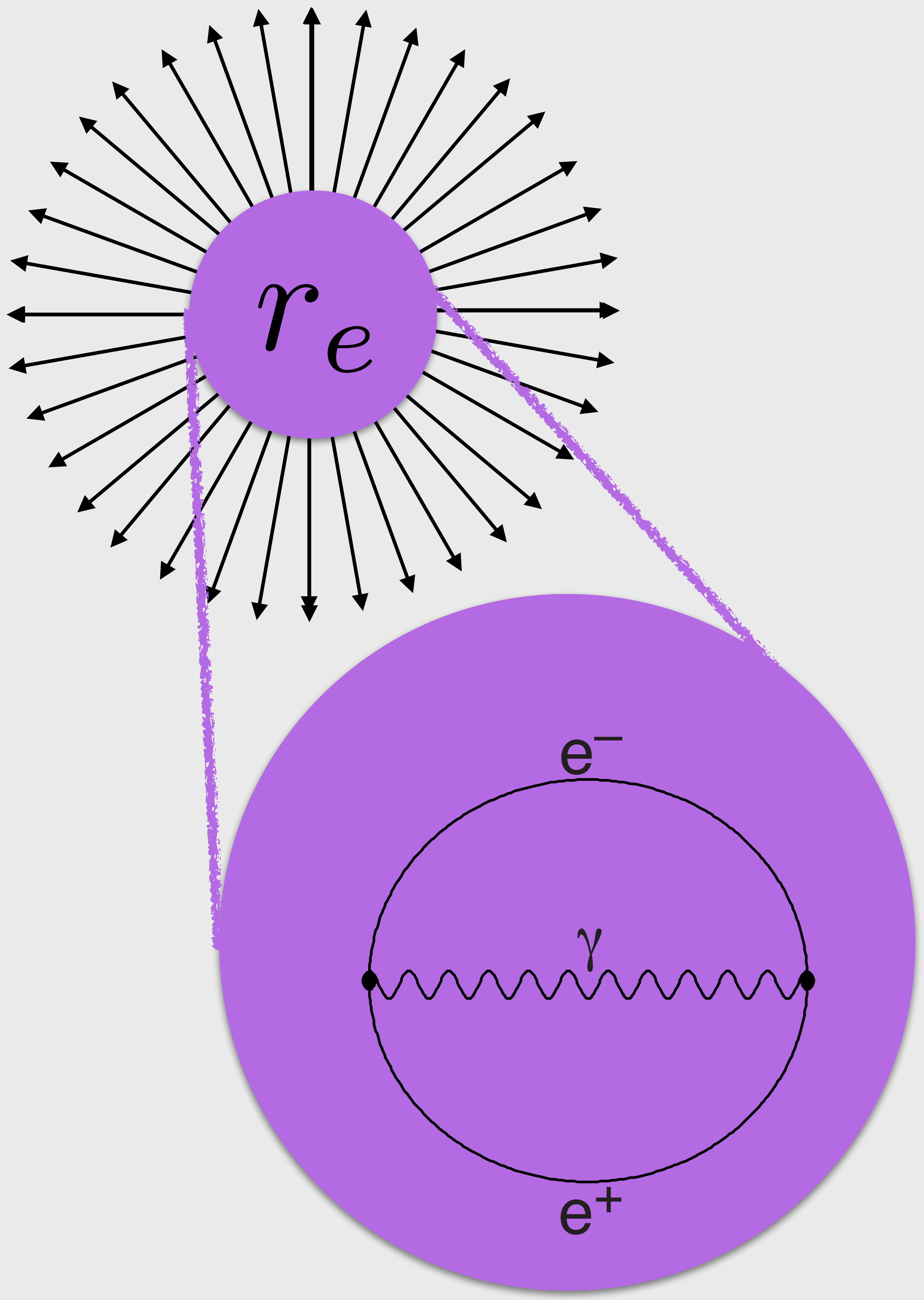
We learned a lesson on physics **at the same mass scale** as where the puzzle arises:

$$m_{positron} = m_{electron} \ll m_{electron}/\alpha_{em}$$

A puzzle (today) we know how to solve

AFTER

RELATIVITY & QUANTUM MECHANICS



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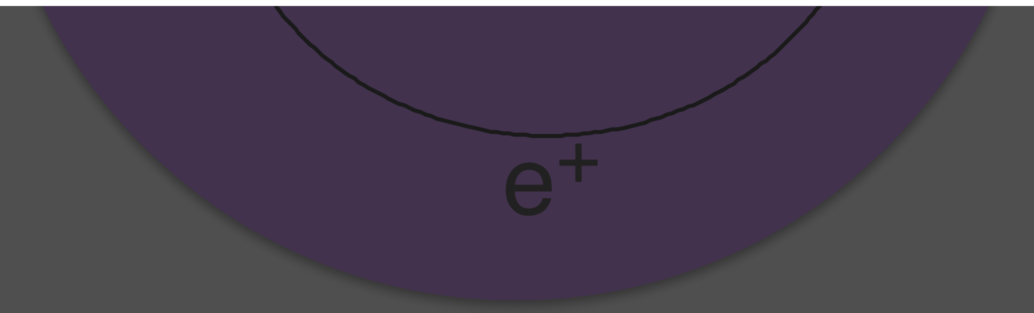
A puzzle (today) we know how to solve

AFTER

RELATIVITY & QUANTUM MECHANICS

- Similar arguments would require a contribution of the electric filed to the mass of the charged pion
- In that case the solution is not an antiparticle, but a “heavy photon”, the ρ meson, somewhat heavier than the pion
- In the grand picture, both the positron and the ρ meson appear at the same scale where the problem arises.



The size of the Higgs boson

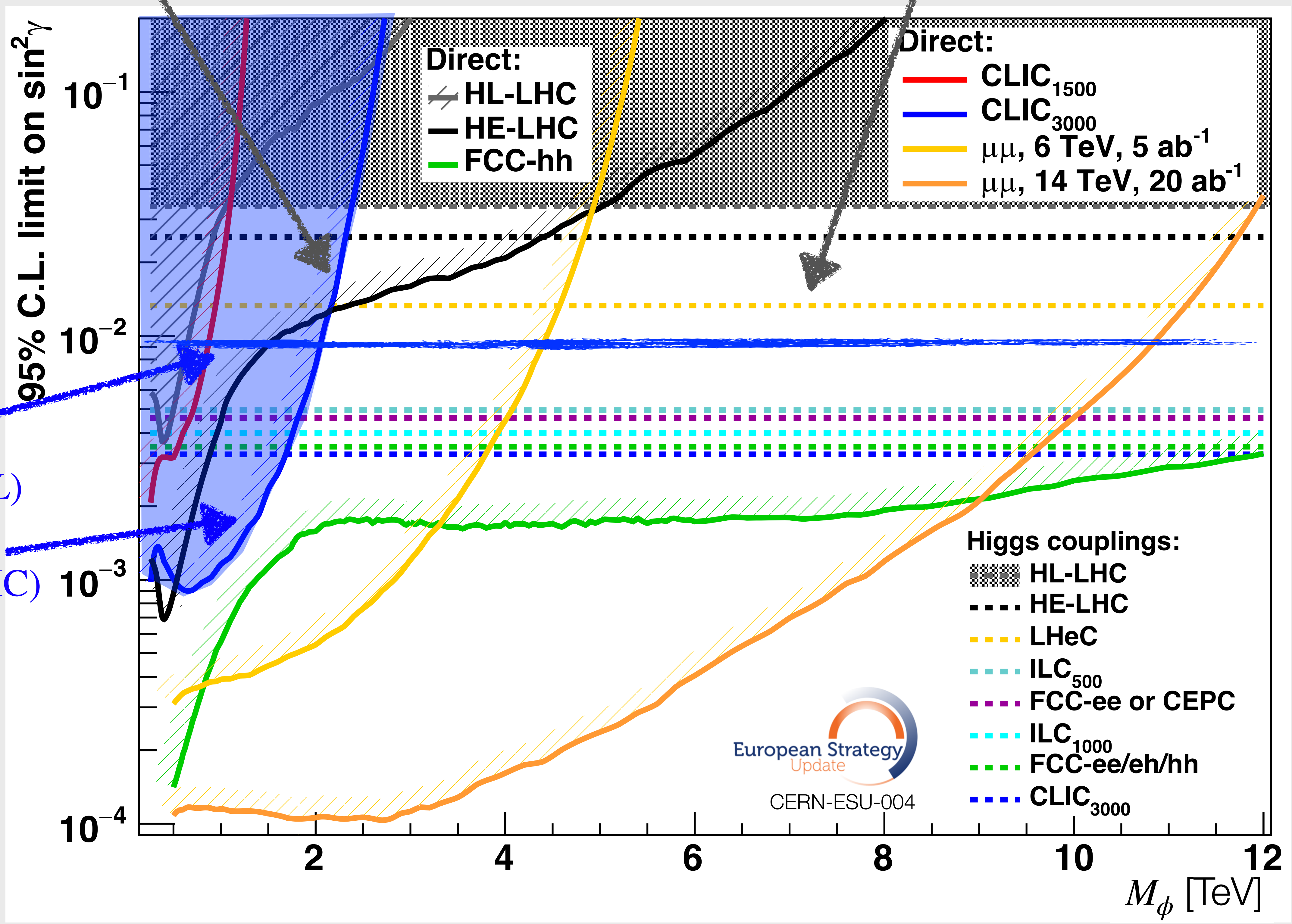
The size of the Higgs boson

- Is the Higgs boson like the electron? waiting for “partner” states (other Higgs-like states) to be found ?
- Is the Higgs boson like the pion? waiting for us to discover its constituents (quarks)?

The size of the Higgs boson

curves
direct search of ϕ

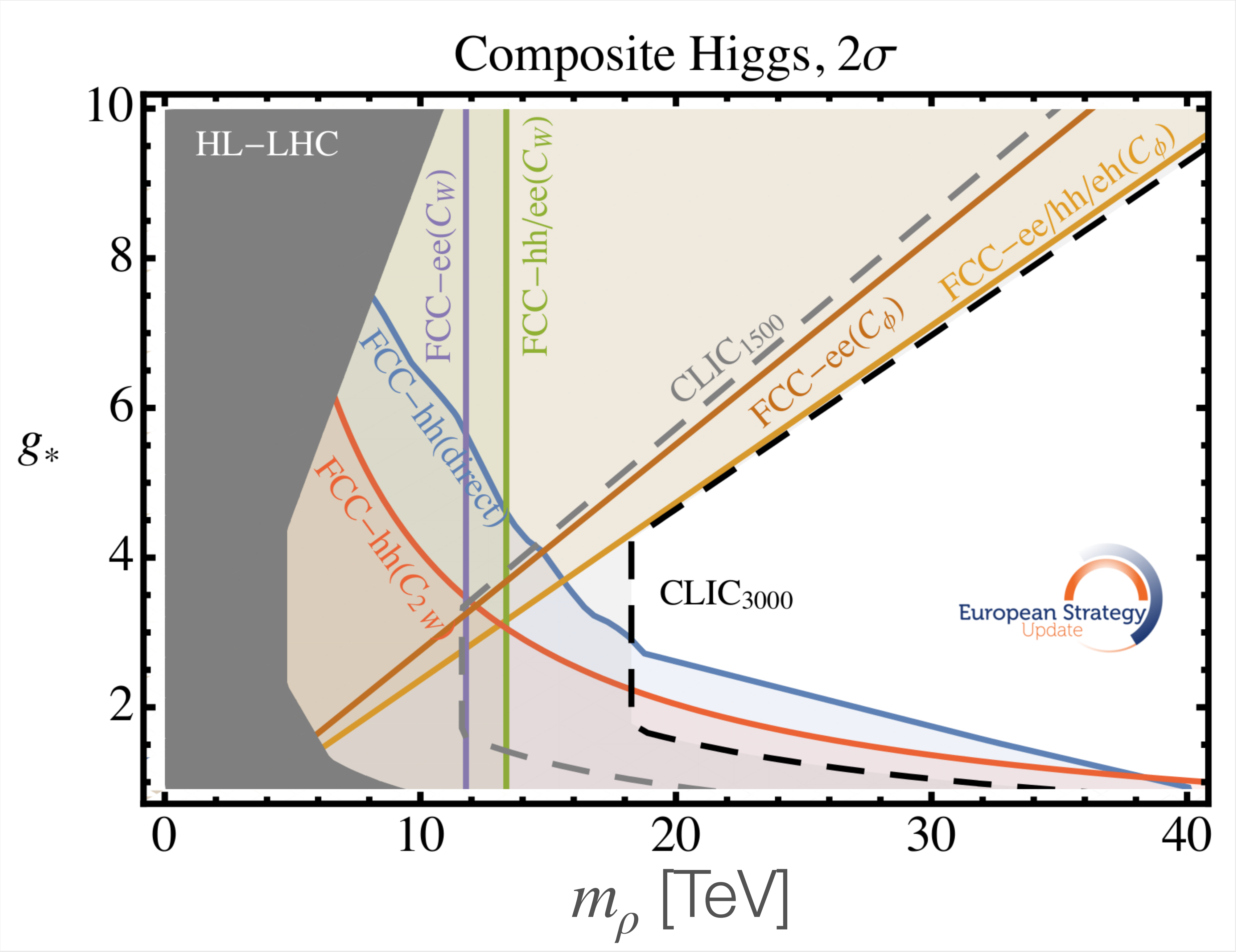
H precision couplings



3 TeV

$\sigma_h \cdot BR_{bb} @ 1\,\%$ (95 % CL)

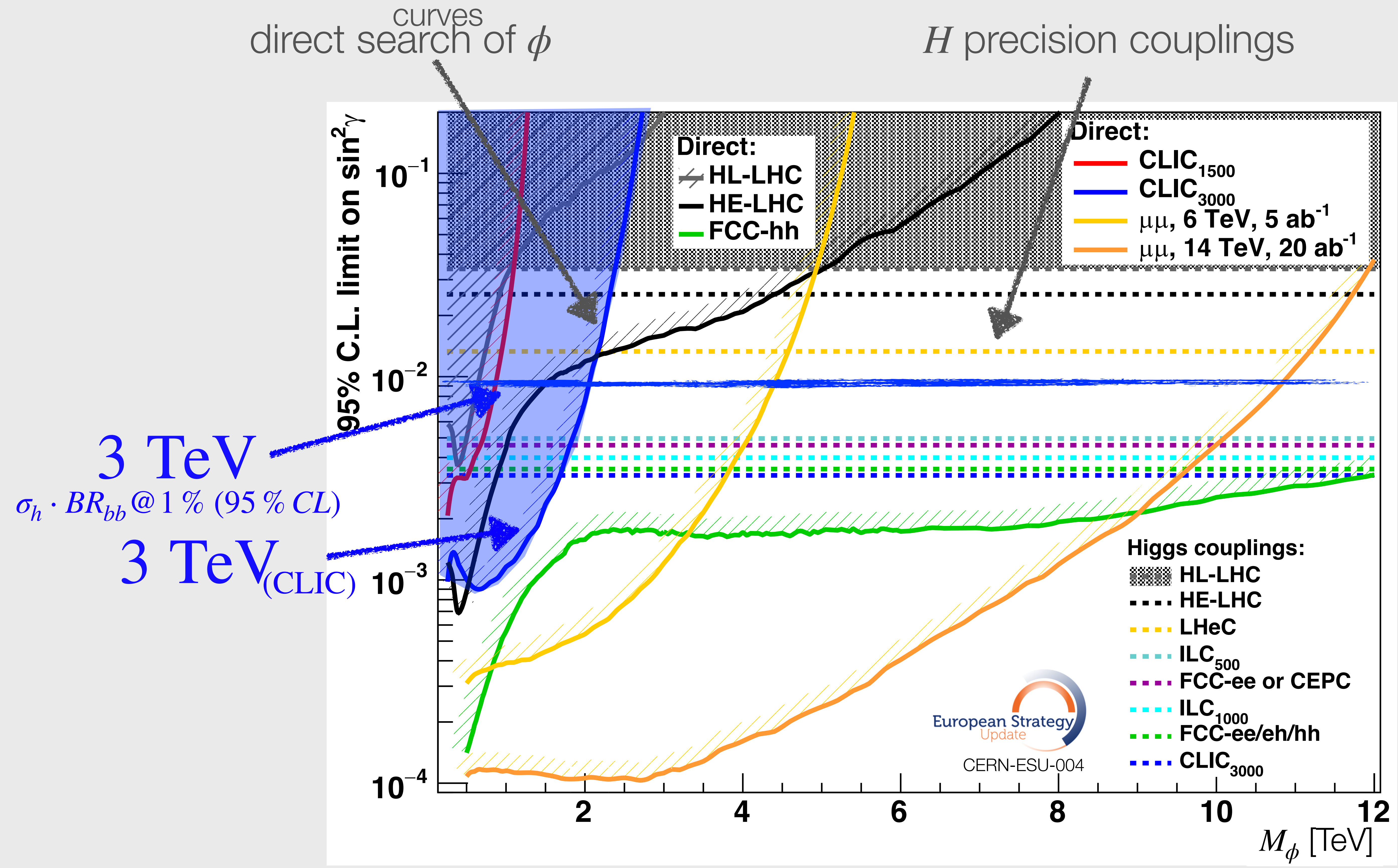
3 $TeV_{(CLIC)}$

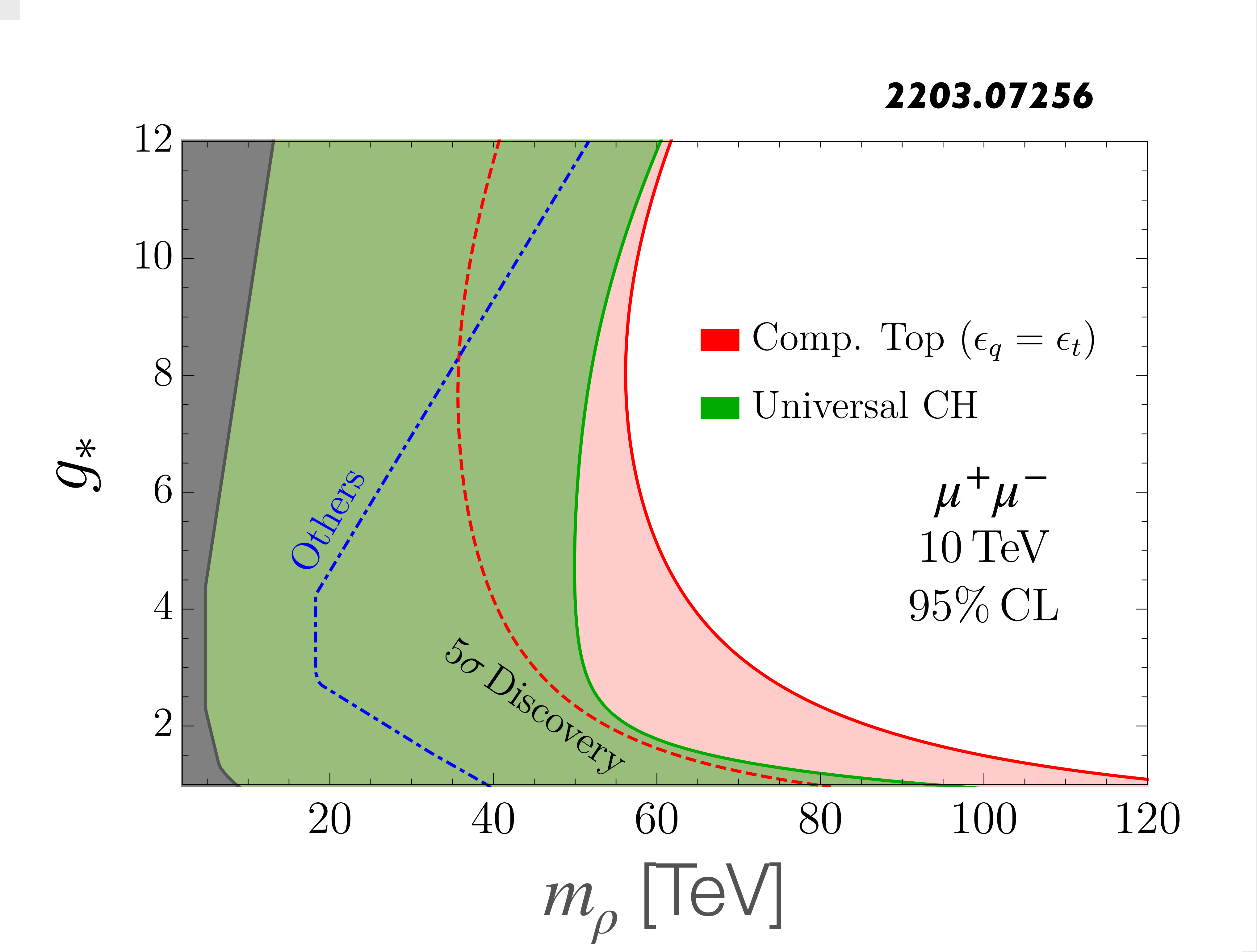


compositeness at few TeV @ HL-LHC

Higgs as composite as QCD pion

The size of the Higgs boson





compositeness at 100 TeV

Higgs 100x more point-like than QCD pion

What is the Higgs boson potential like?

ORIGIN OF ELECTROWEAK SYMMETRY BREAKING (AND OF THE MATTER OF THE UNIVERSE)

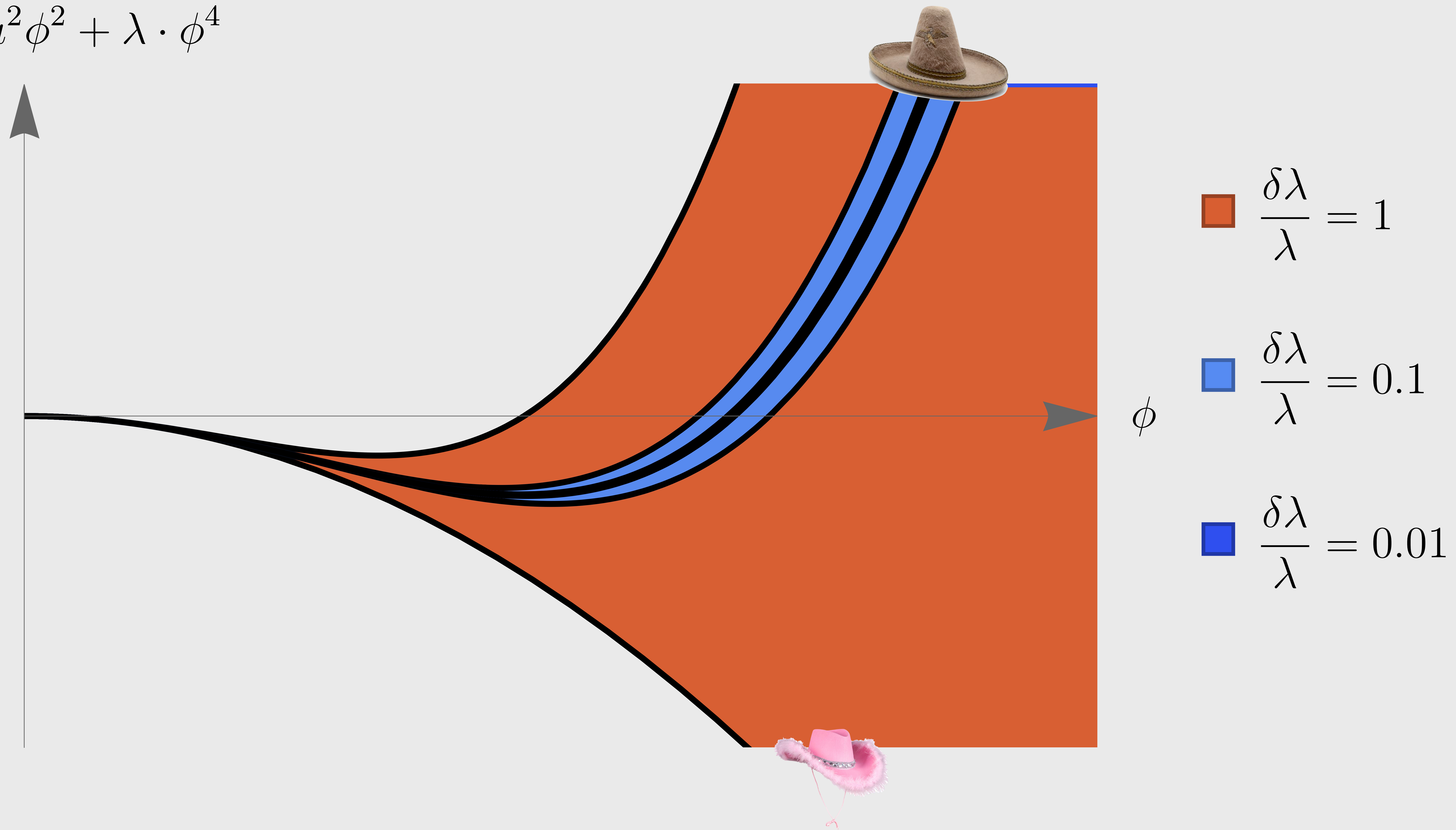
local minimum ⇒ false ground state

global minimum ⇒ ground state

What is the Higgs boson potential like?

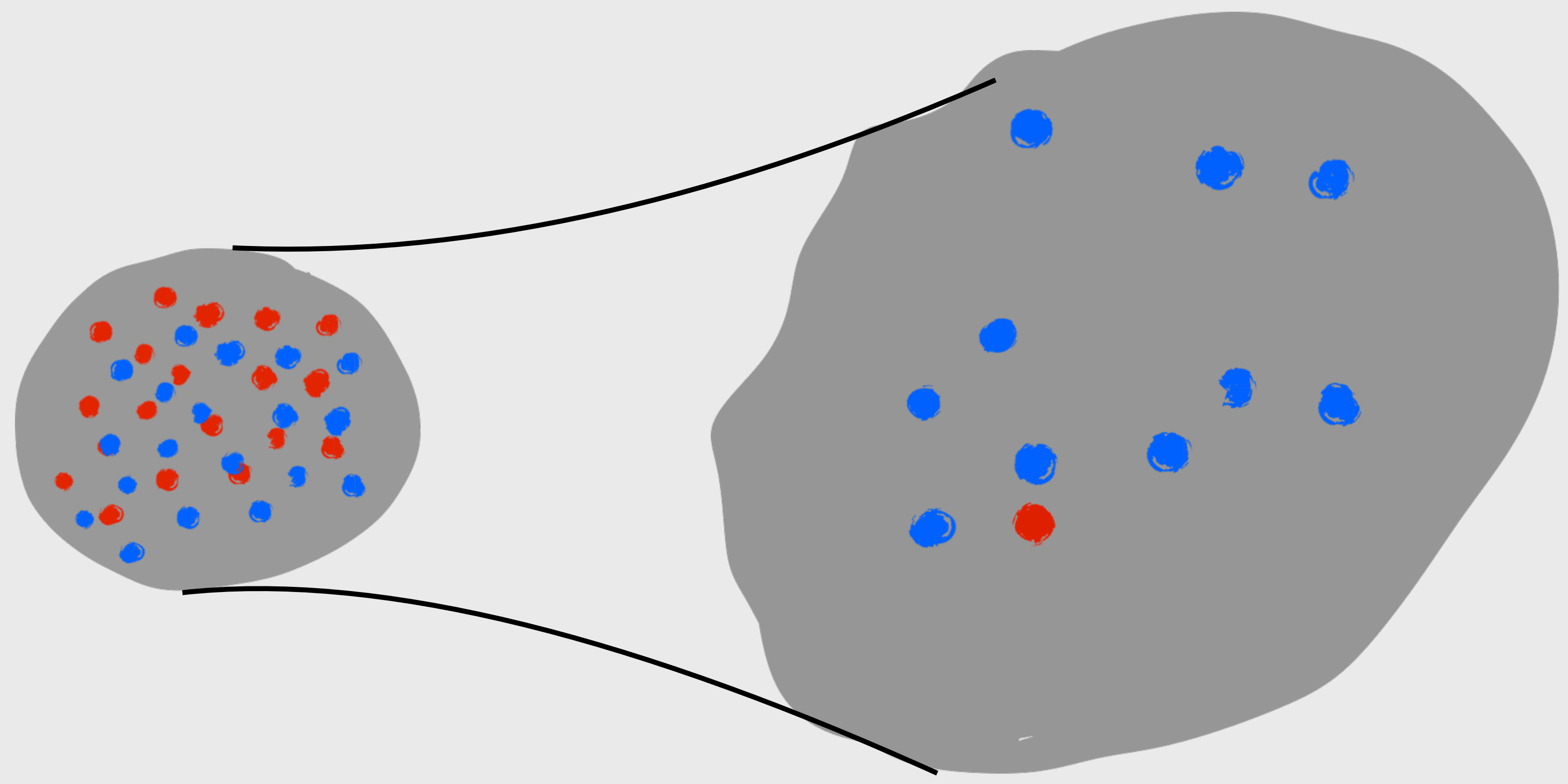
ORIGIN OF ELECTROWEAK SYMMETRY BREAKING (AND OF THE MATTER OF THE UNIVERSE)

$$V(\phi) = \mu^2\phi^2 + \lambda \cdot \phi^4$$

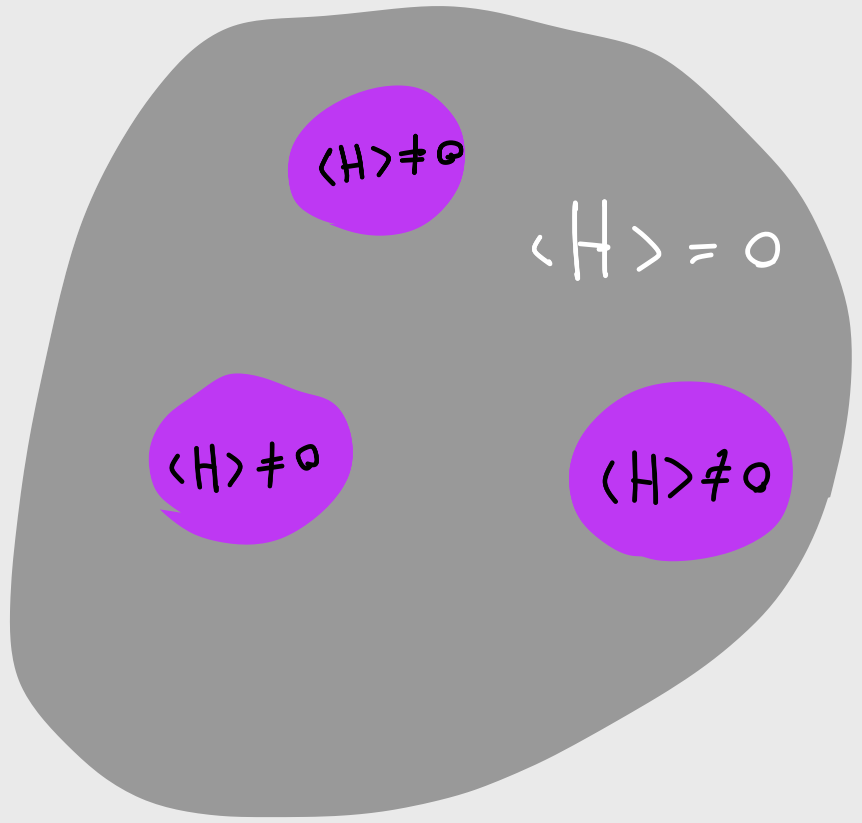


The mystery of

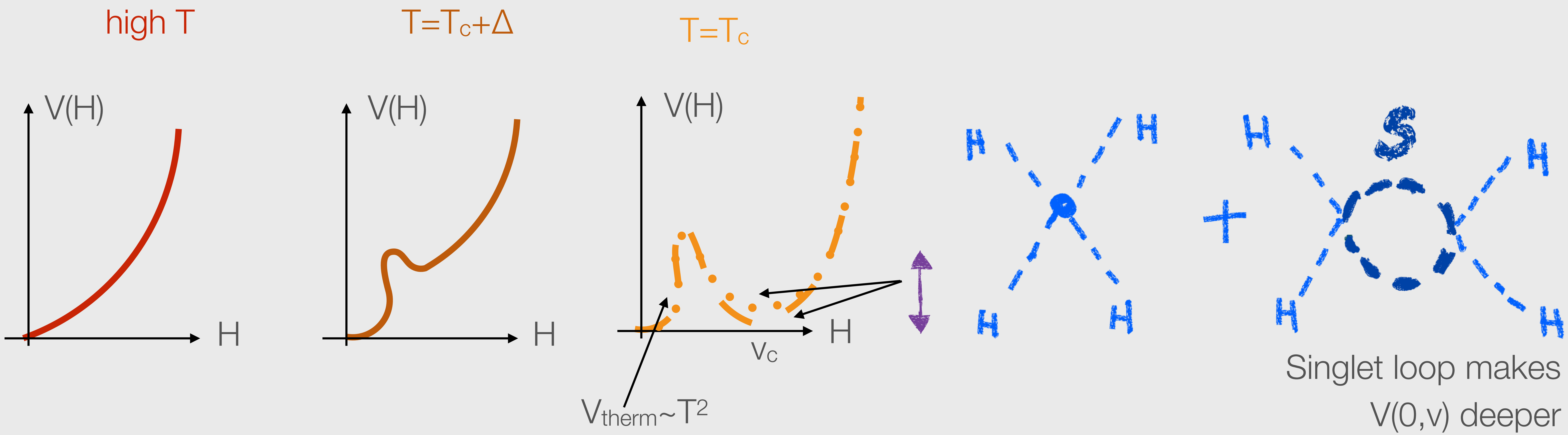
EW phase transition



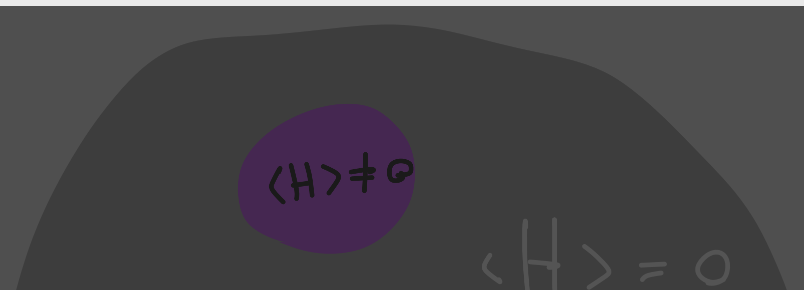
Electroweak phase transition



- Modifications of the Higgs potential ⇒ Out of Equilibrium transition from one vacuum to a new energetically favorable one



Electroweak phase transition



- We need to study all possible new states that induce a change in the Higgs boson potential.

- For these new state to have sizable effects in the early Universe they must be light, around 1 TeV at most.

- All searches for new Higgs bosons (or general electroweak particles) probe such fundamental issue of the origin of matter in the early Universe!

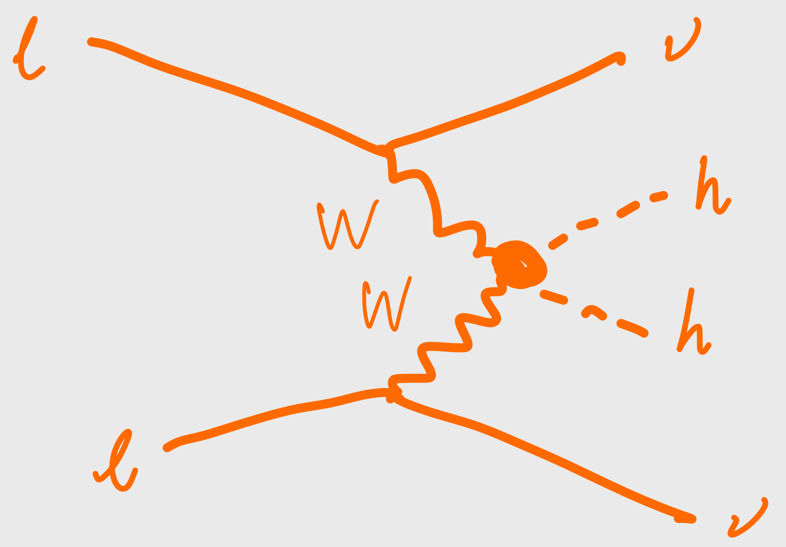
$V_{therm} \sim T^2$

V(0,v) deeper

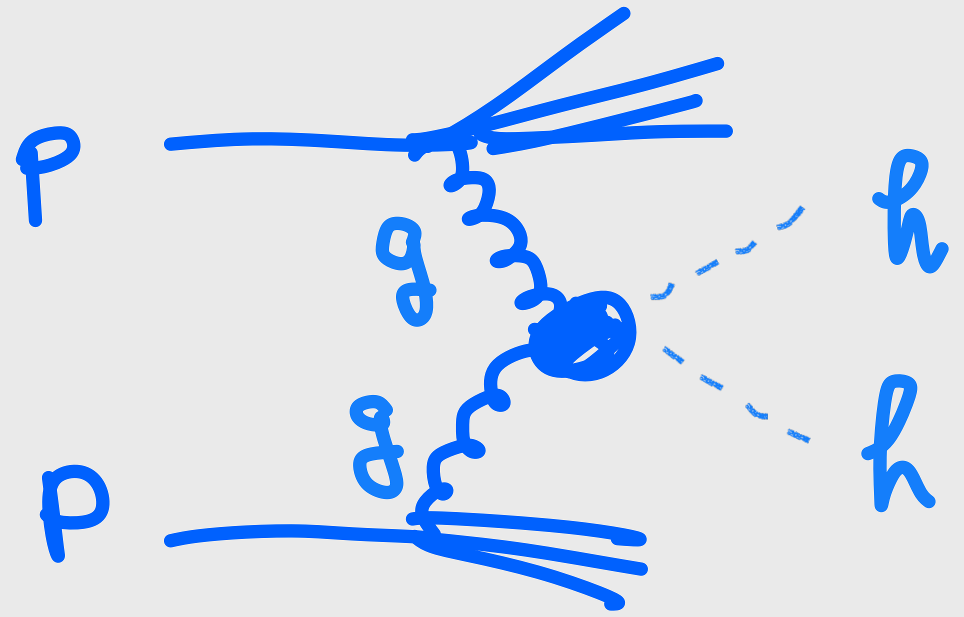
pp or $\ell^+\ell^- \to hh$

W BOSON **COLLIDER**

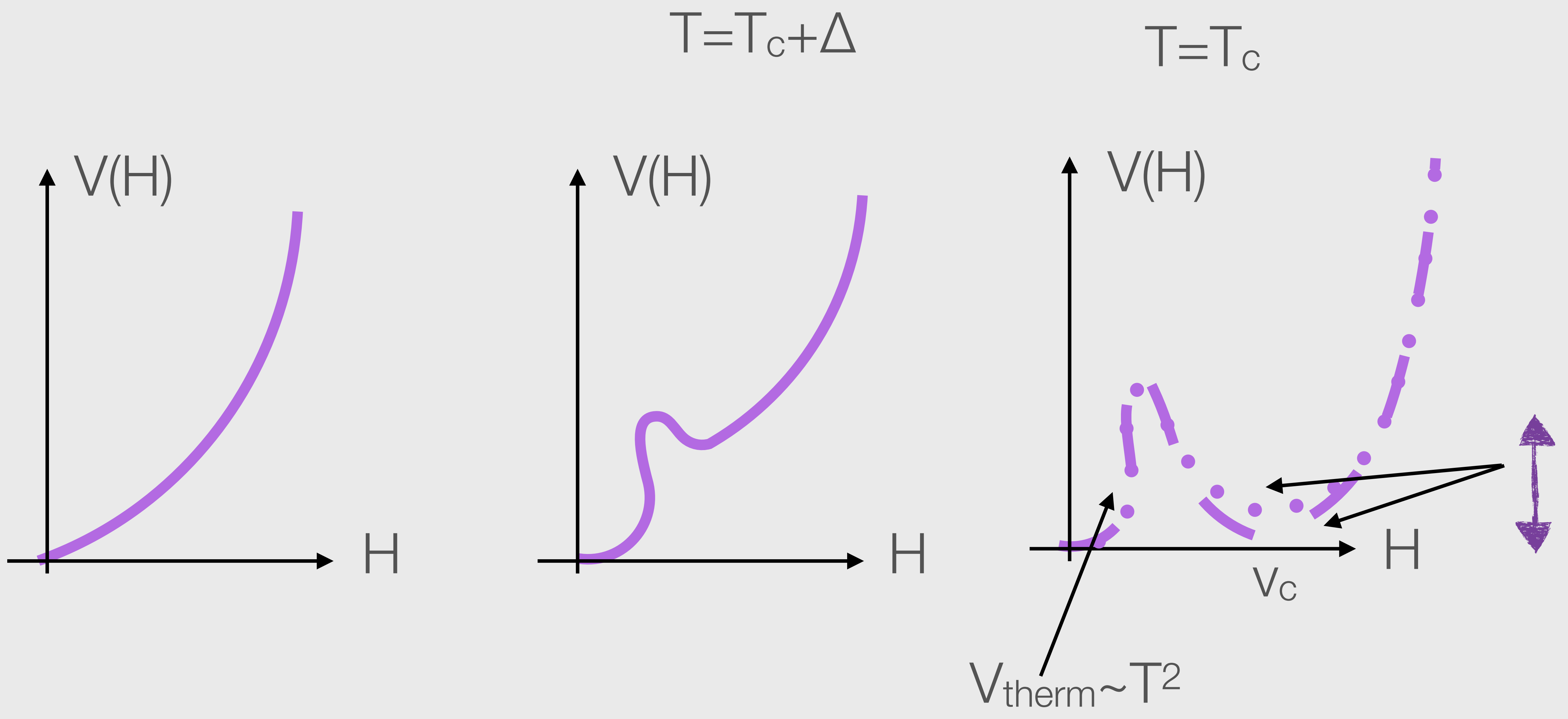
- High-Energy lepton collider has large flux of “partonic” W bosons

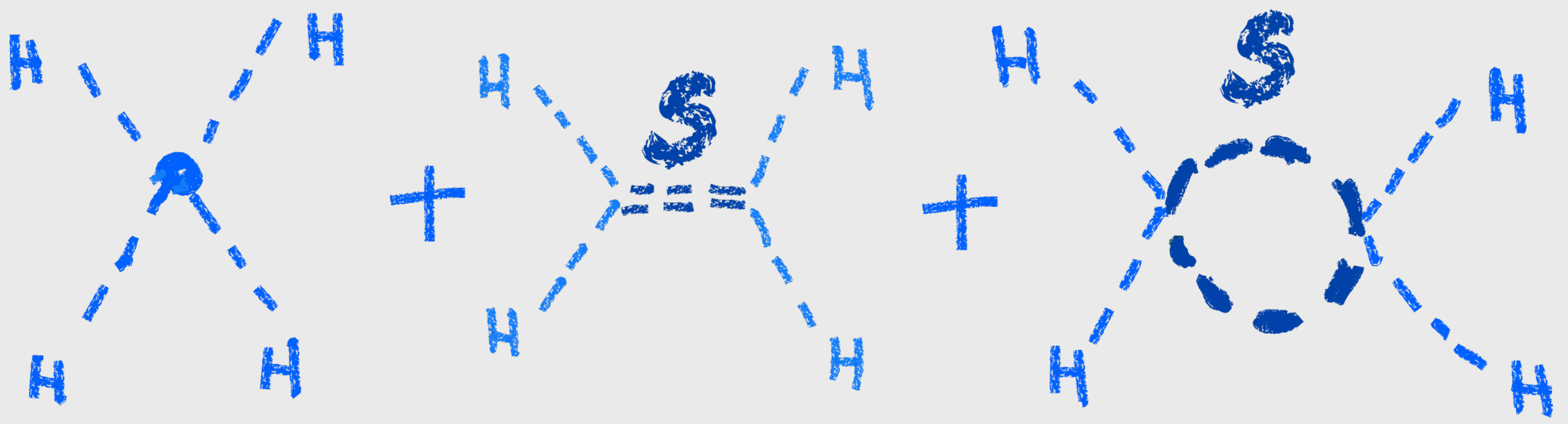


- gg collisions as usual



Electroweak phase transition





Singlet tree and loop makes V(0,v) deeper

EW phase transition

DIRECT & INDIRECT

INTERPLAY

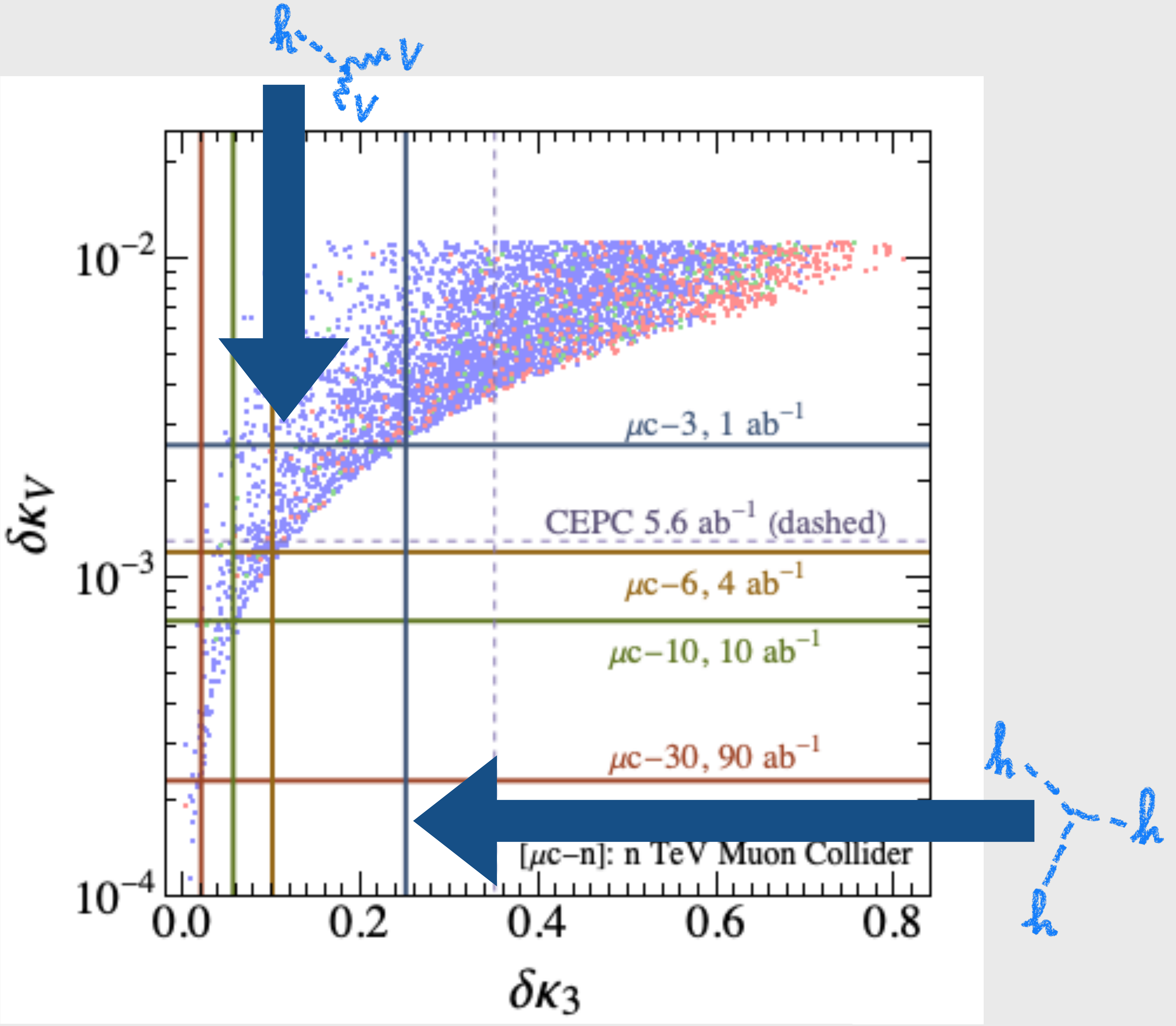
$$V(\Phi, S) = -\mu^2 \left(\Phi^\dagger \Phi\right) + \lambda \left(\Phi^\dagger \Phi\right)^2 + \frac{a_1}{2}\left(\Phi^\dagger \Phi\right) S + \frac{a_2}{2}\left(\Phi^\dagger \Phi\right) S^2 + b_1 S + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4 .$$

independent parameters

$$\{M_{h_2}, \theta, v_s, b_3, b_4\}$$

strong First Order EW phase transition on all points

Gravity Wave SNR



EW phase transition

DIRECT & INDIRECT | INTERPLAY

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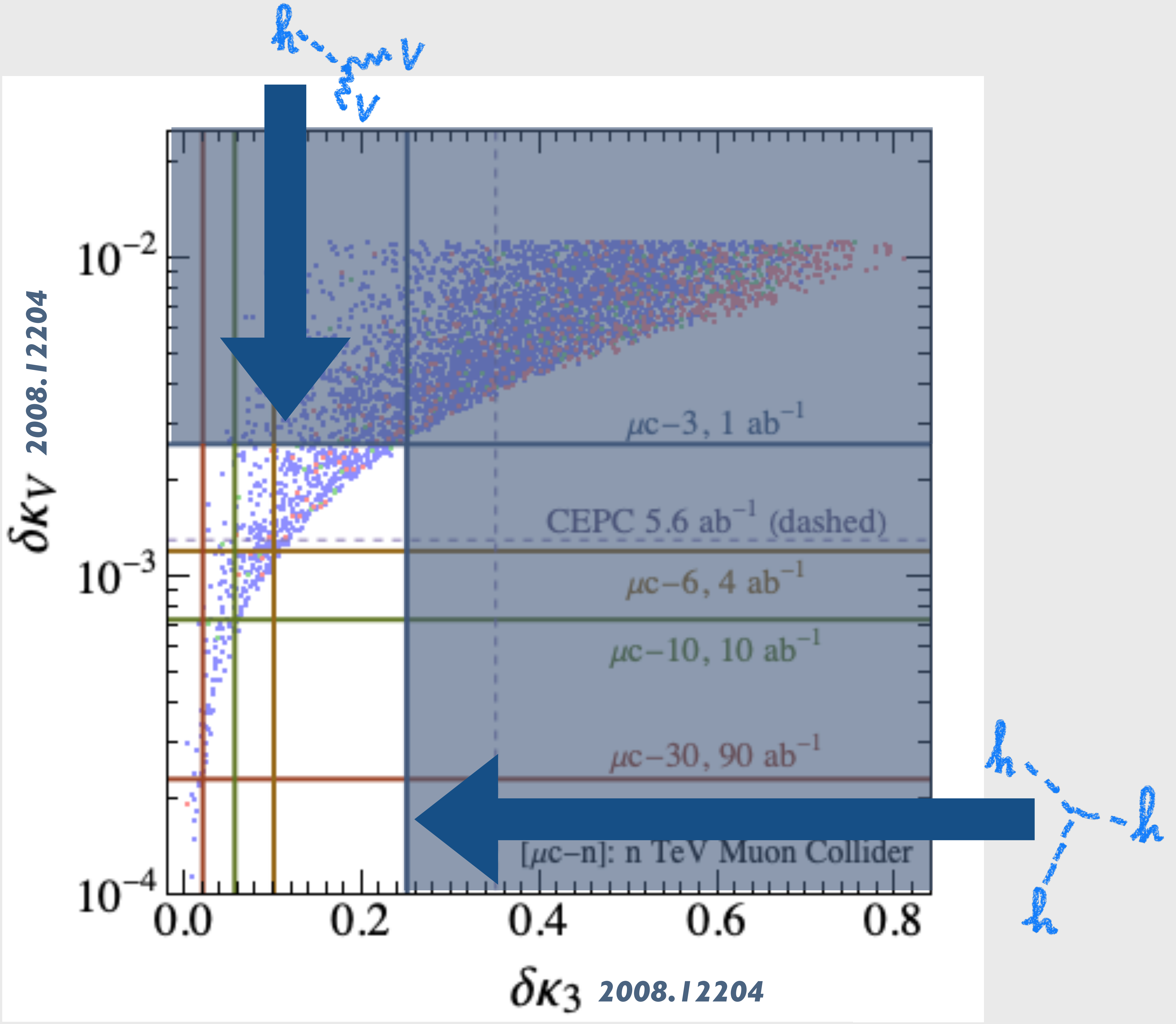


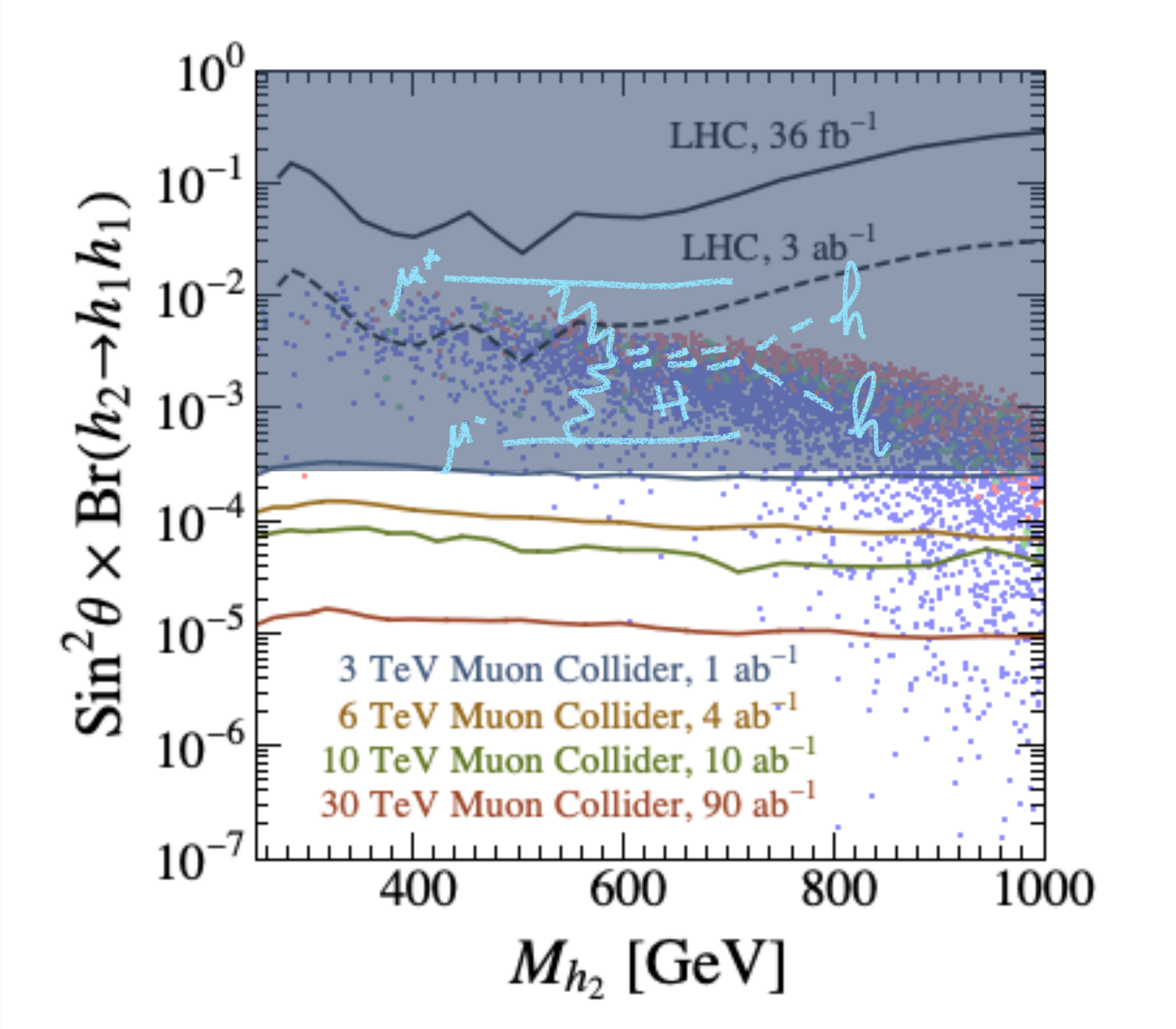
EW phase transition

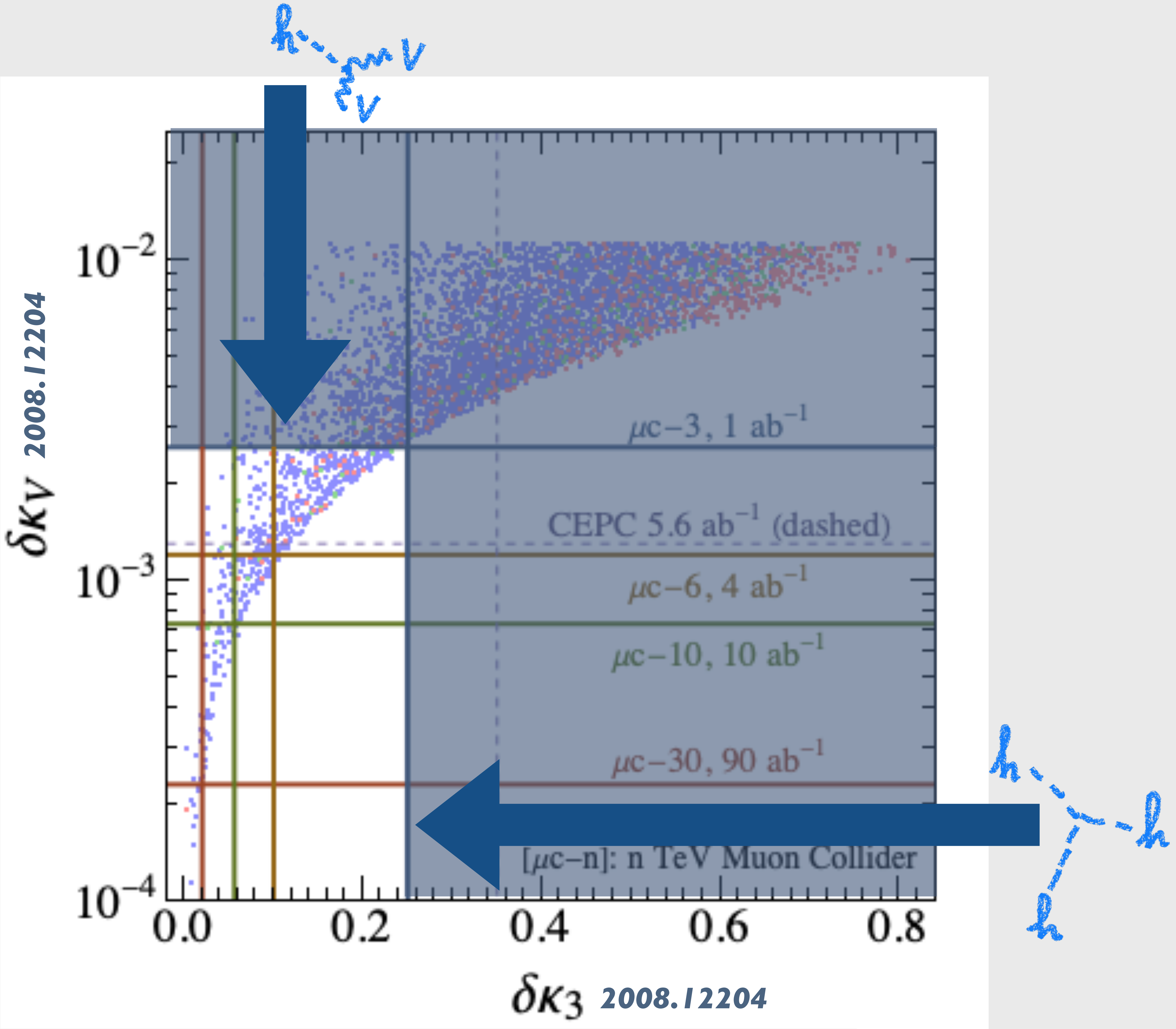
DIRECT & INDIRECT

INTERPLAY

strong First Order EW phase transition on all points

Gravity Wave SNR





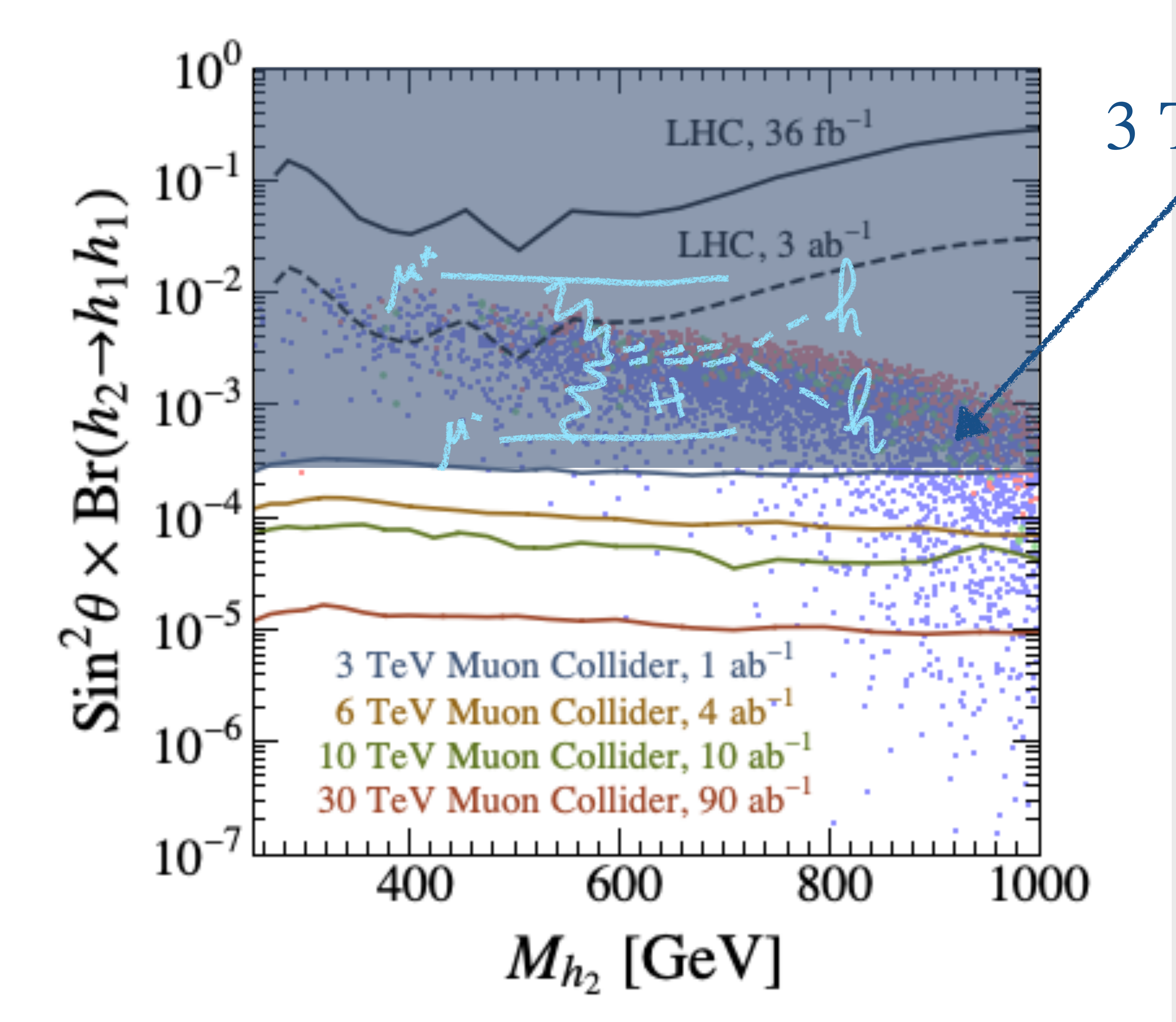
EW phase transition

DIRECT & INDIRECT

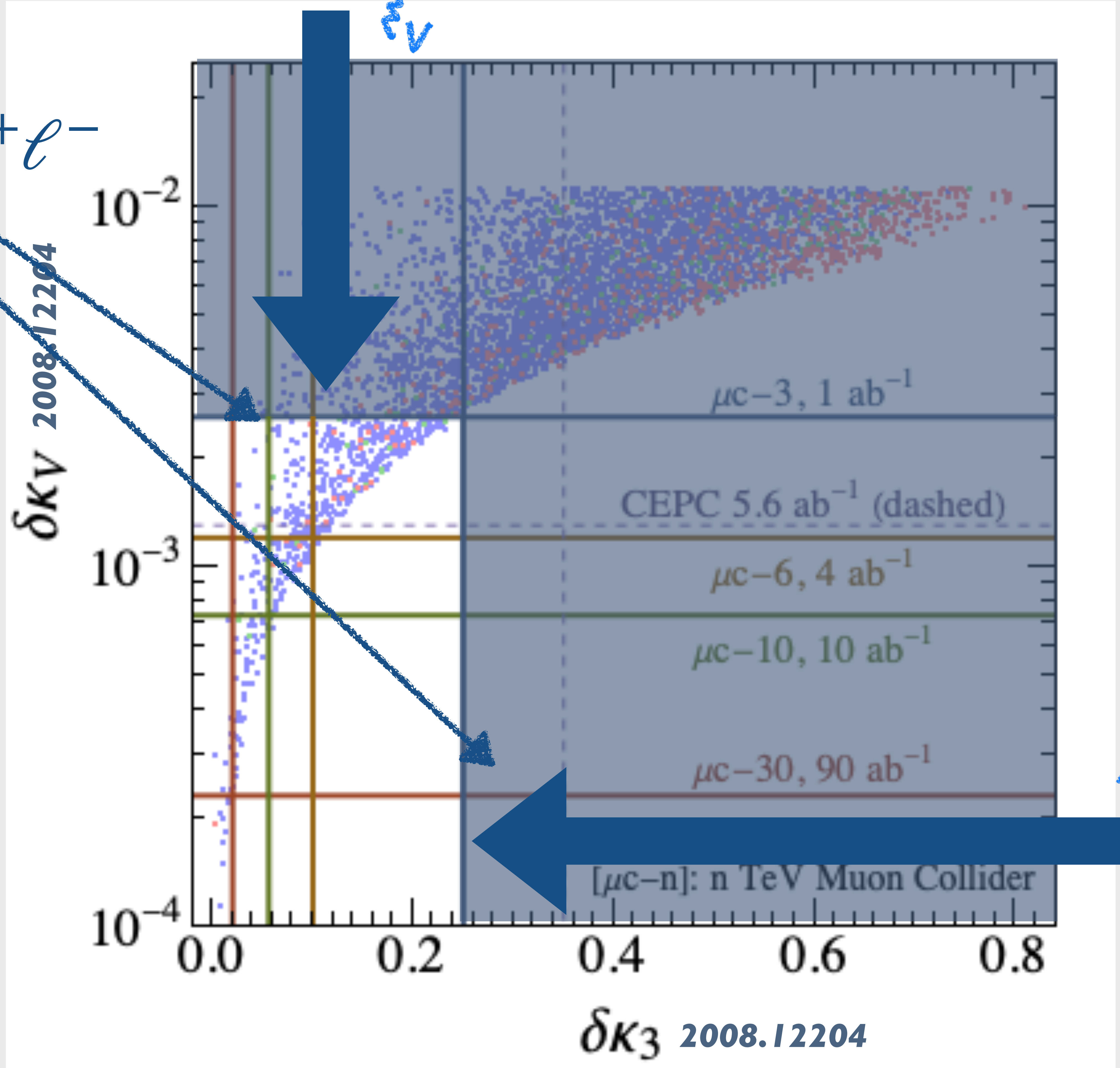
INTERPLAY

strong First Order EW phase transition on all points

Gravity Wave SNR



3 TeV $\ell^+\ell^-$



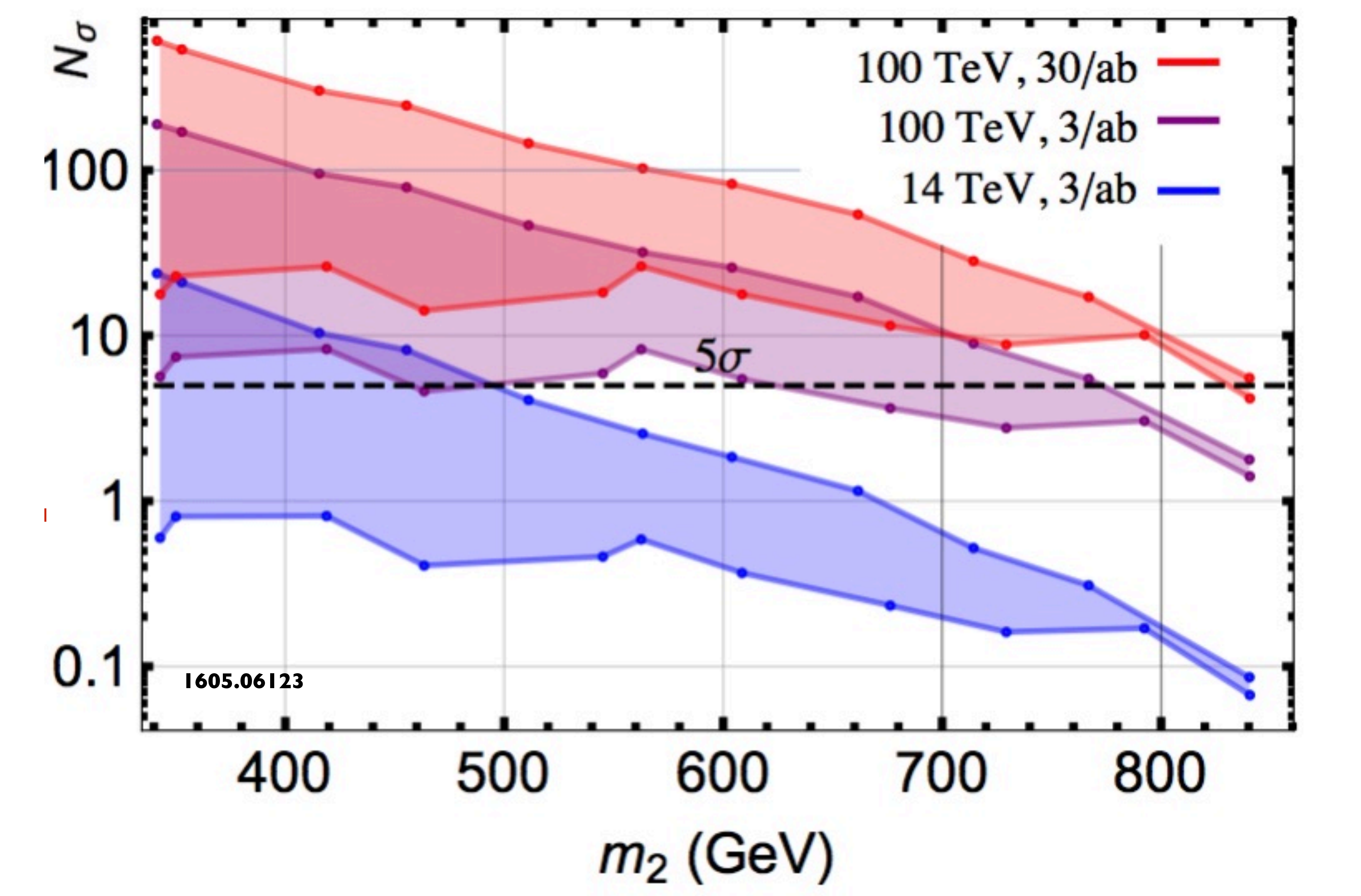
parameters space of 1st order phase transition accessible by **several measurements available at the** 3 TeV $\ell^+\ell^-$ **collider**

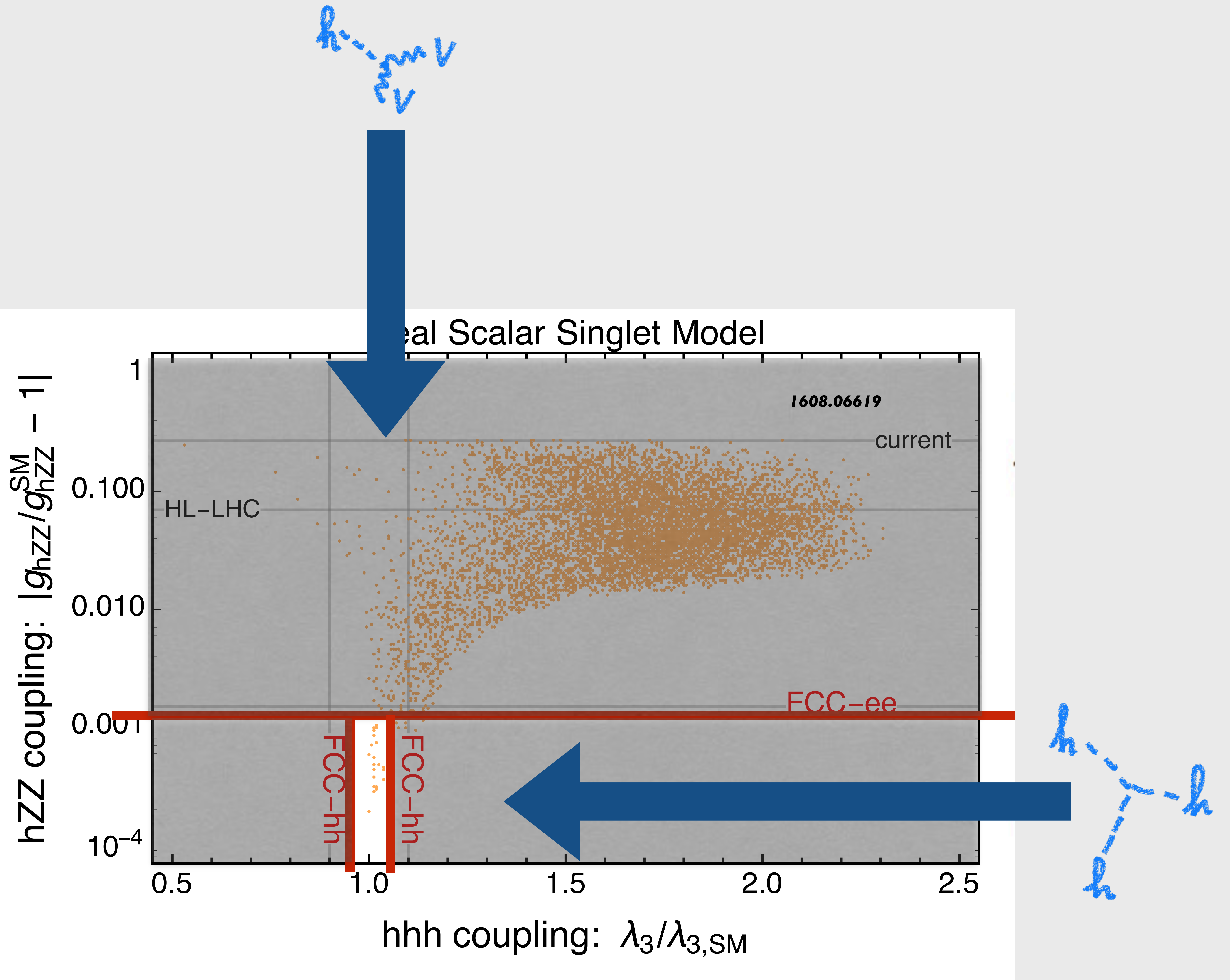
EW phase transition

DIRECT & INDIRECT

INTERPLAY

$$pp \to h_2 \to h^{(125)}h^{(125)}$$





EW phase transition

DIRECT & INDIRECT | INTERPLAY

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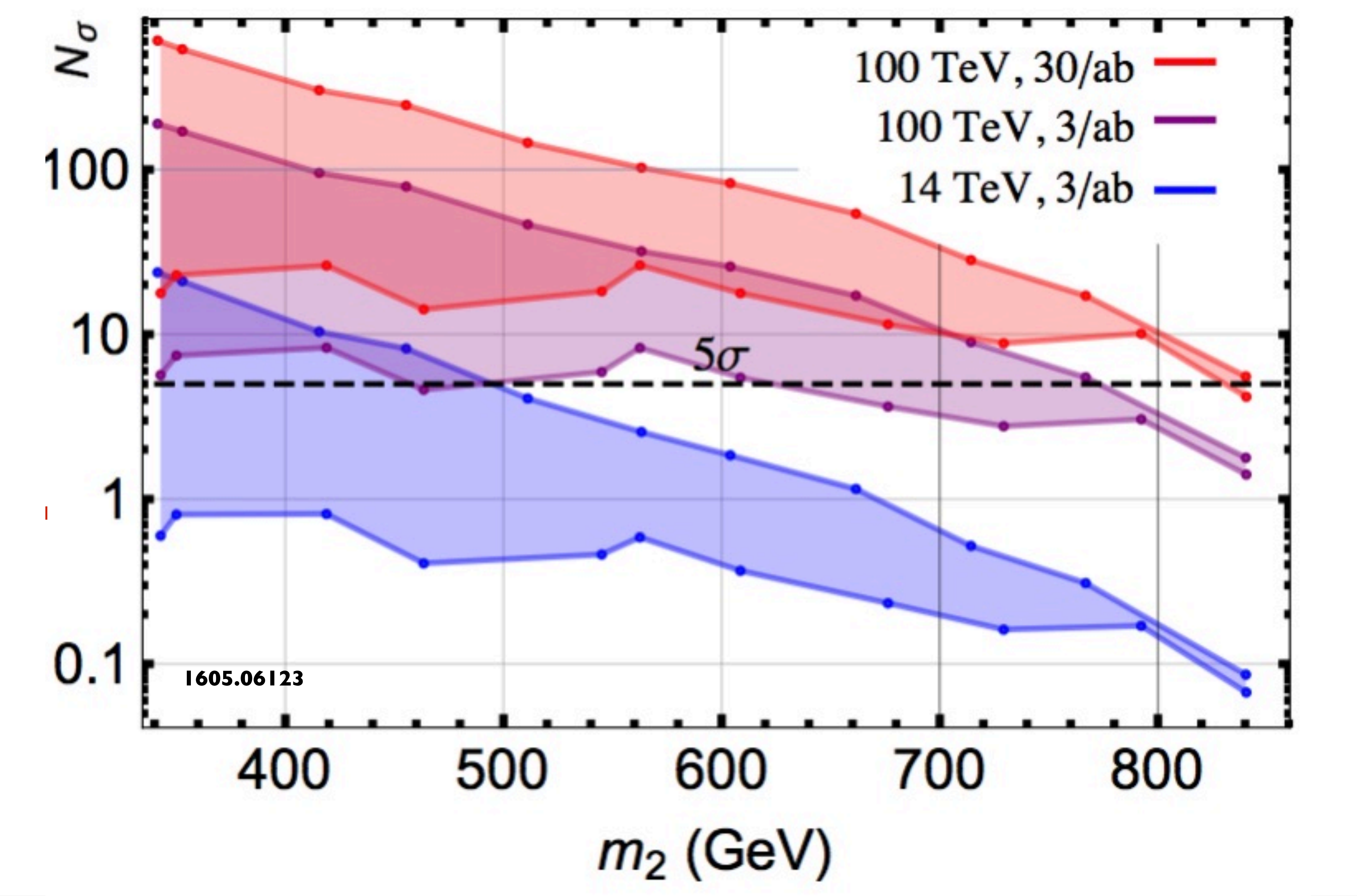
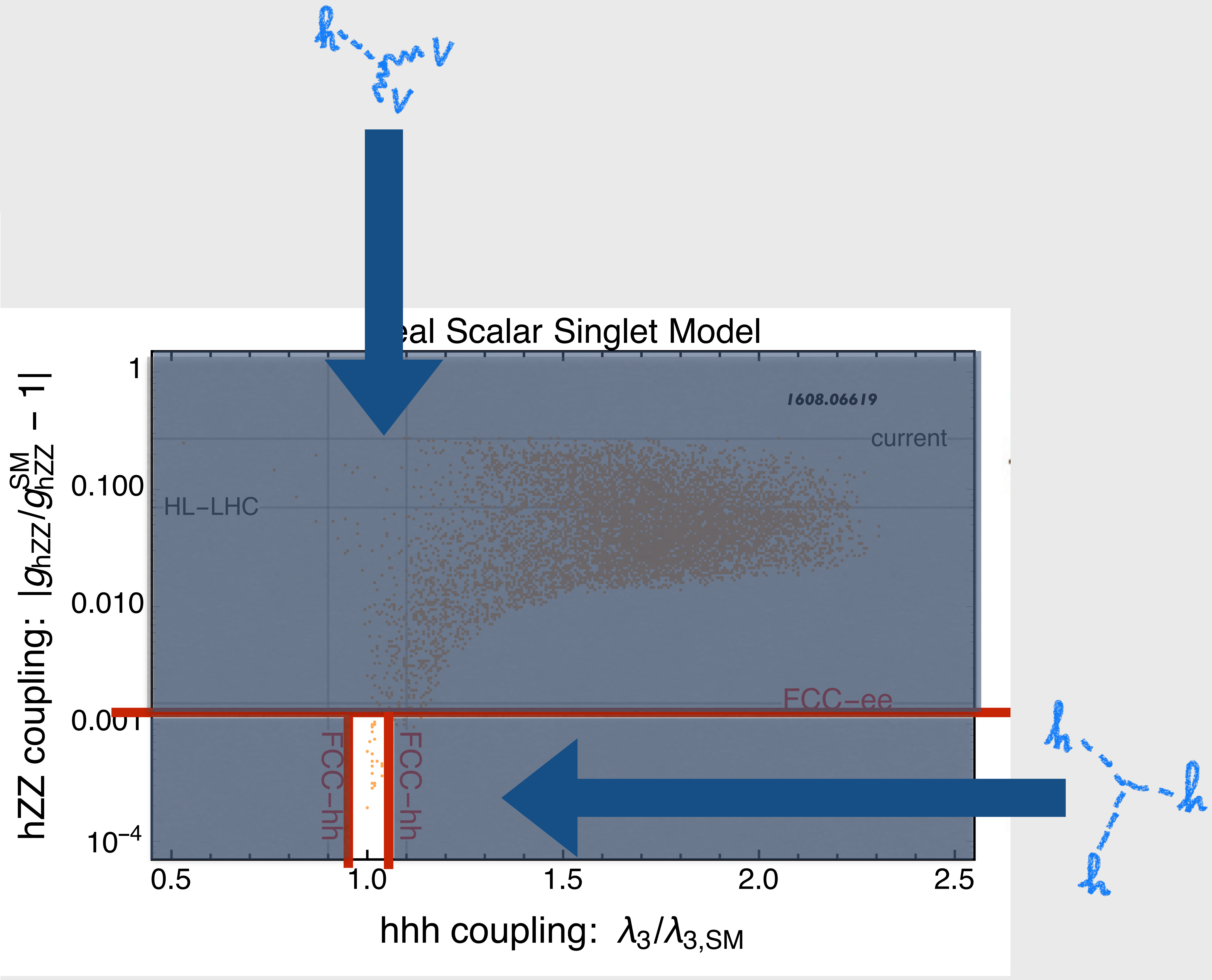


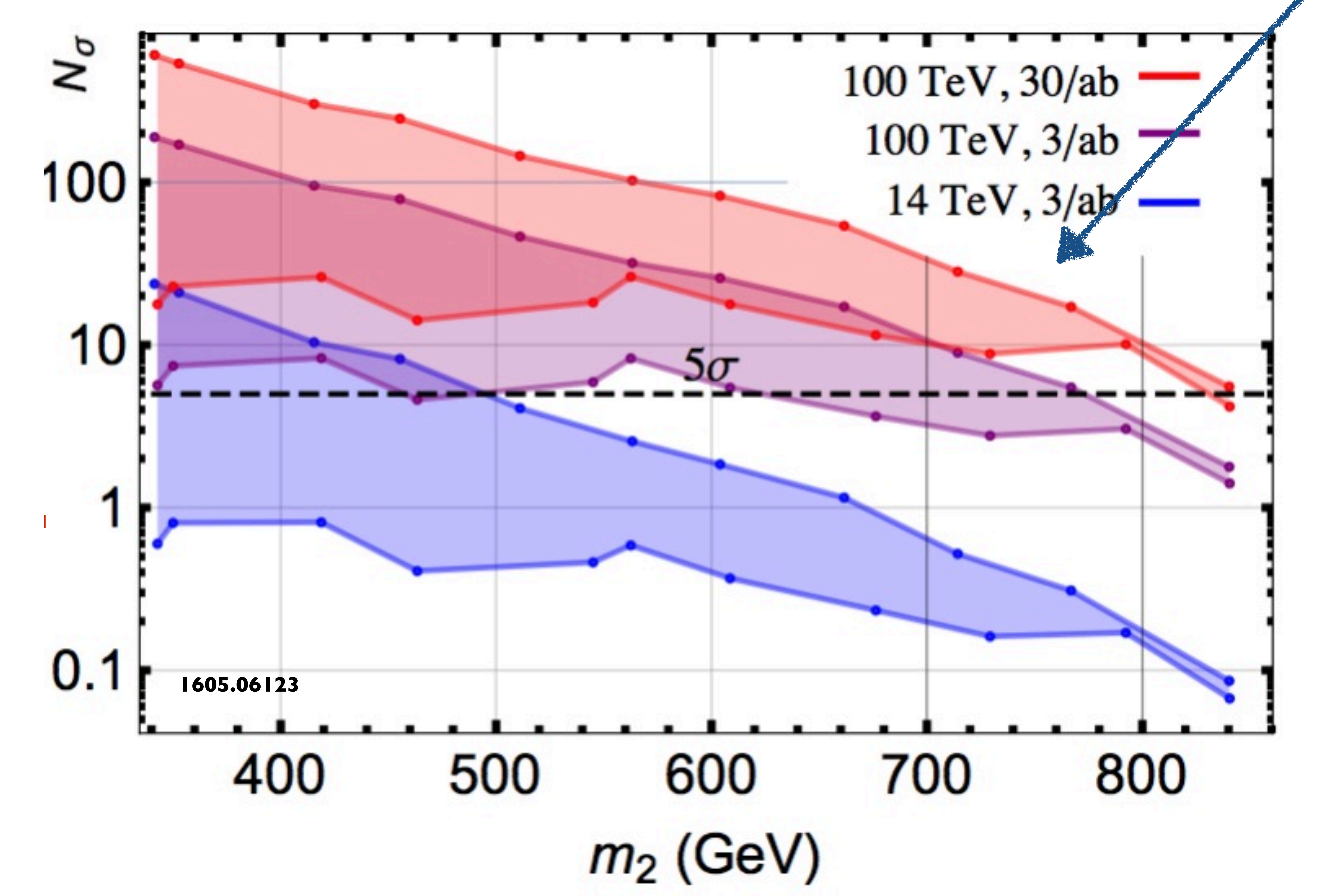


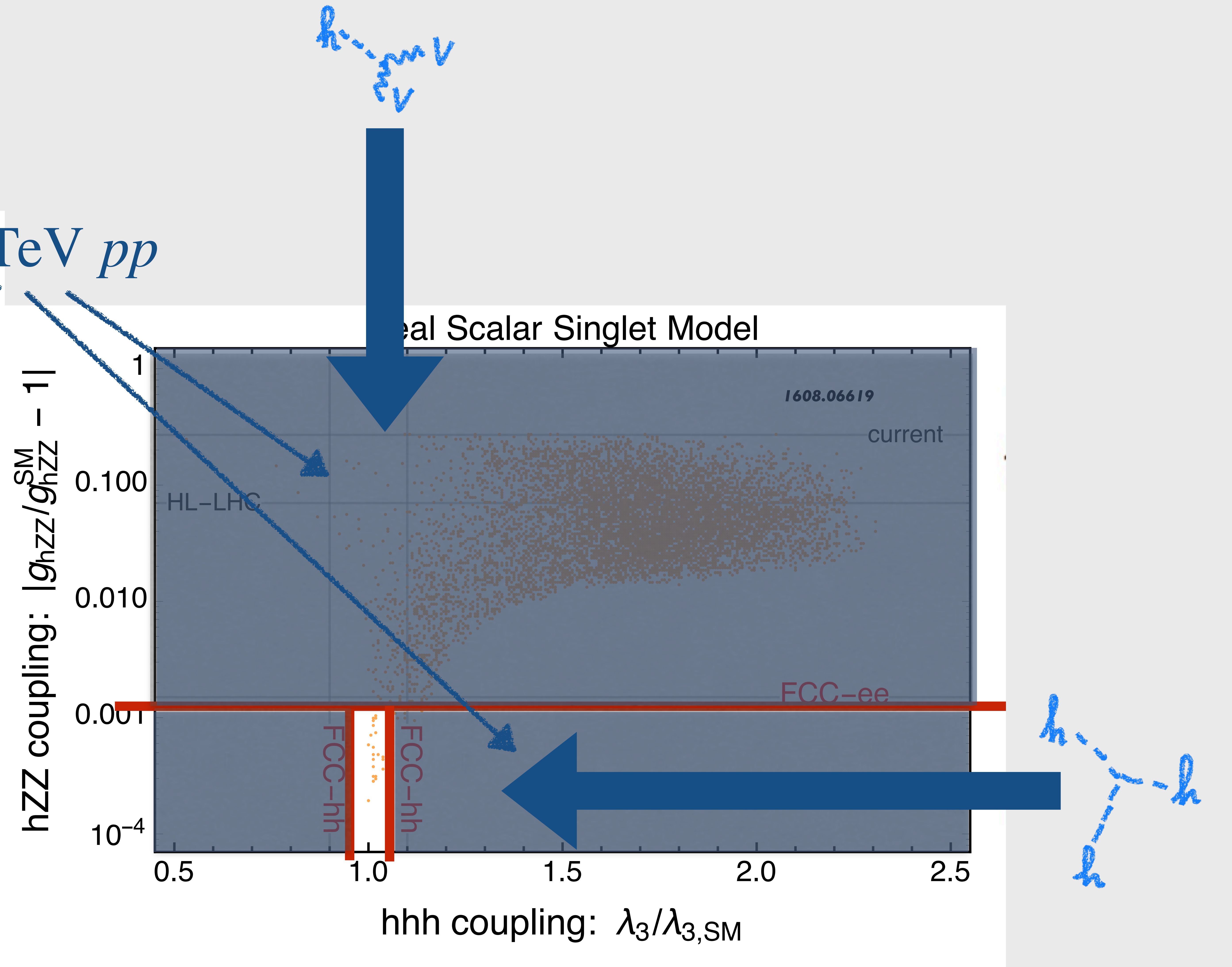
EW phase transition

DIRECT & INDIRECT | INTERPLAY

$pp \to h_2 \to h^{(125)}h^{(125)}$

100 TeV *pp*

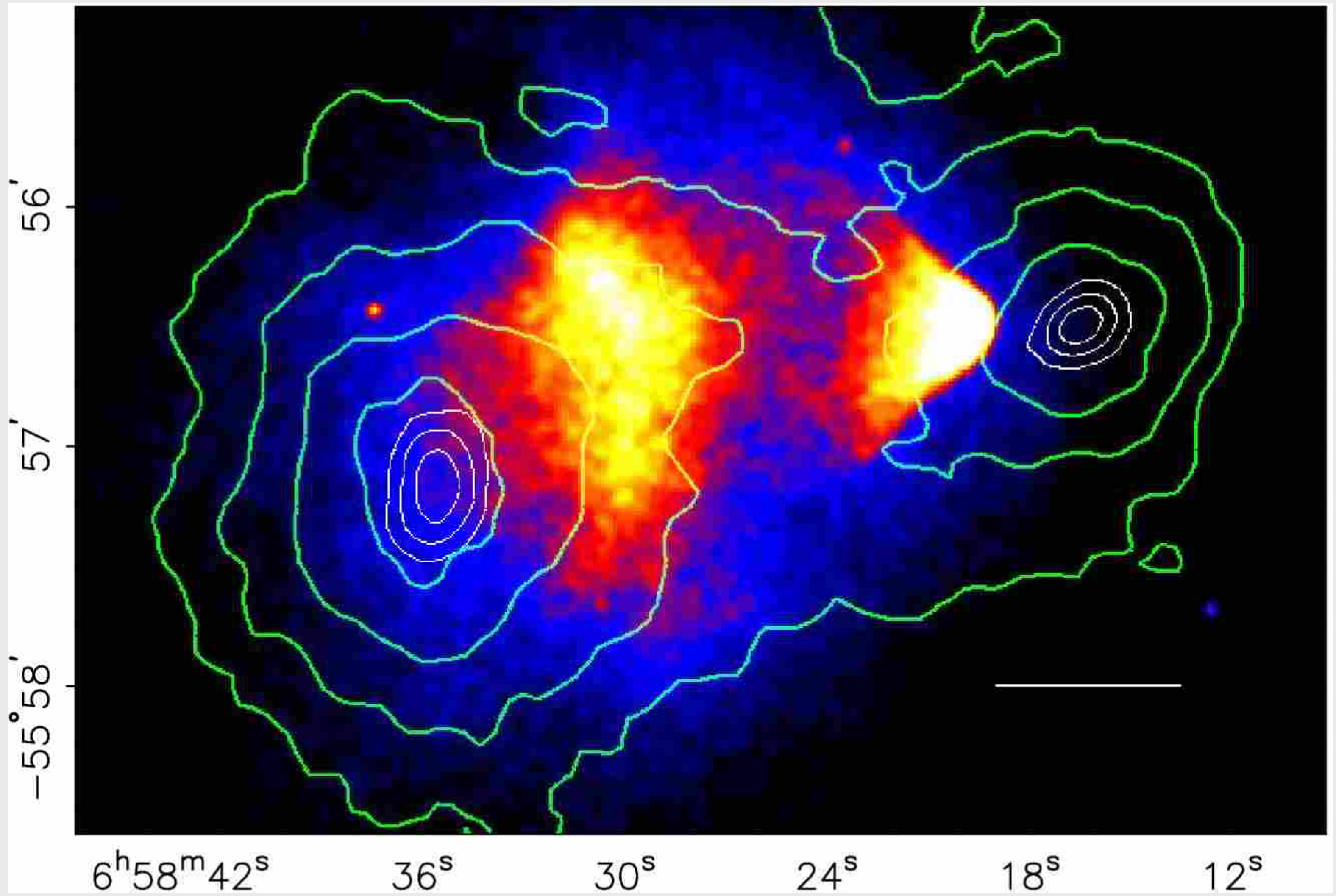




parameters space of 1st order phase transition accessible by **several measurements available at the 100 TeV pp collider**

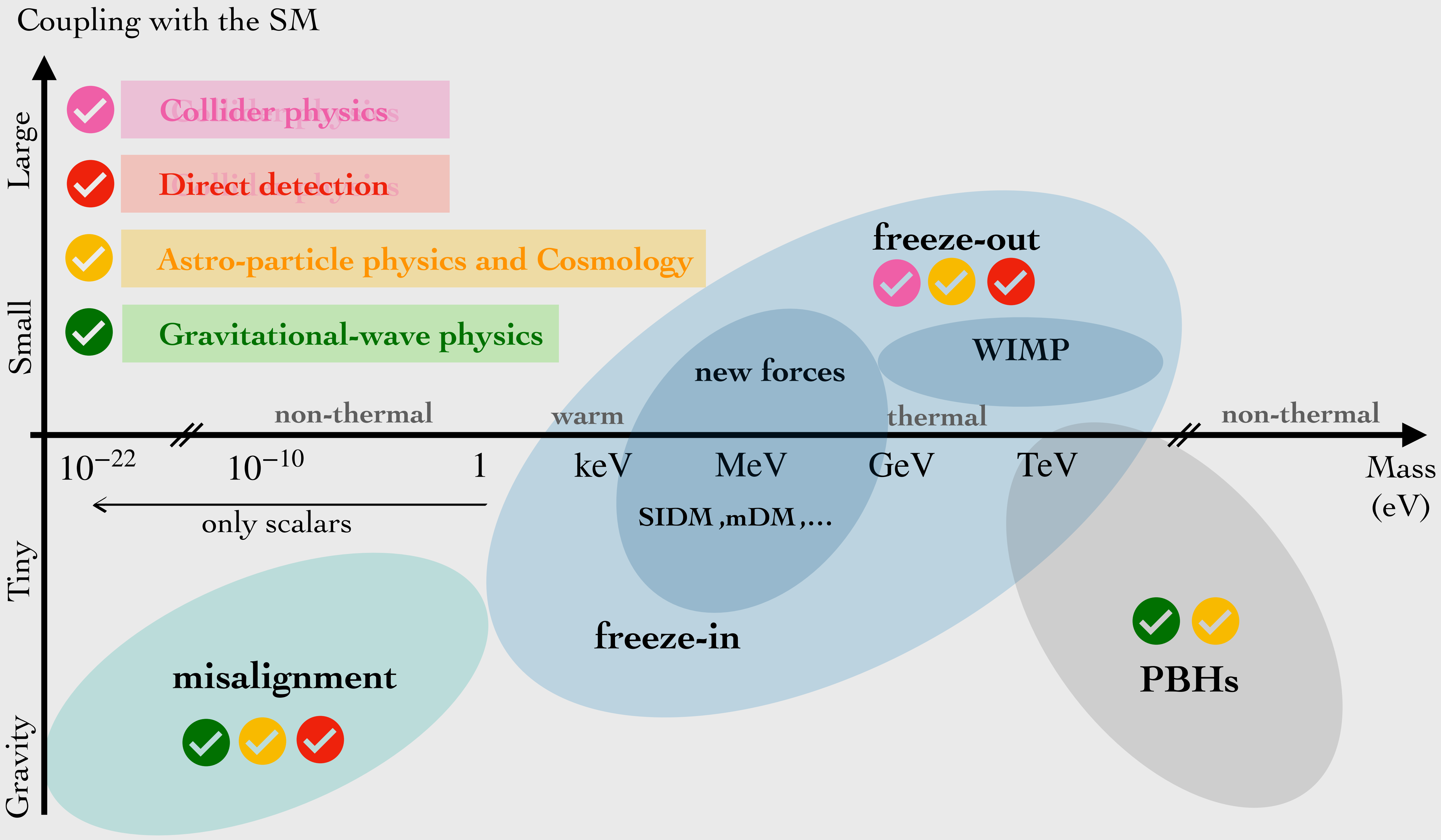
The mystery of

the Dark Matter of the Universe



Electroweak Dark Matter: LSP (+NLSP)

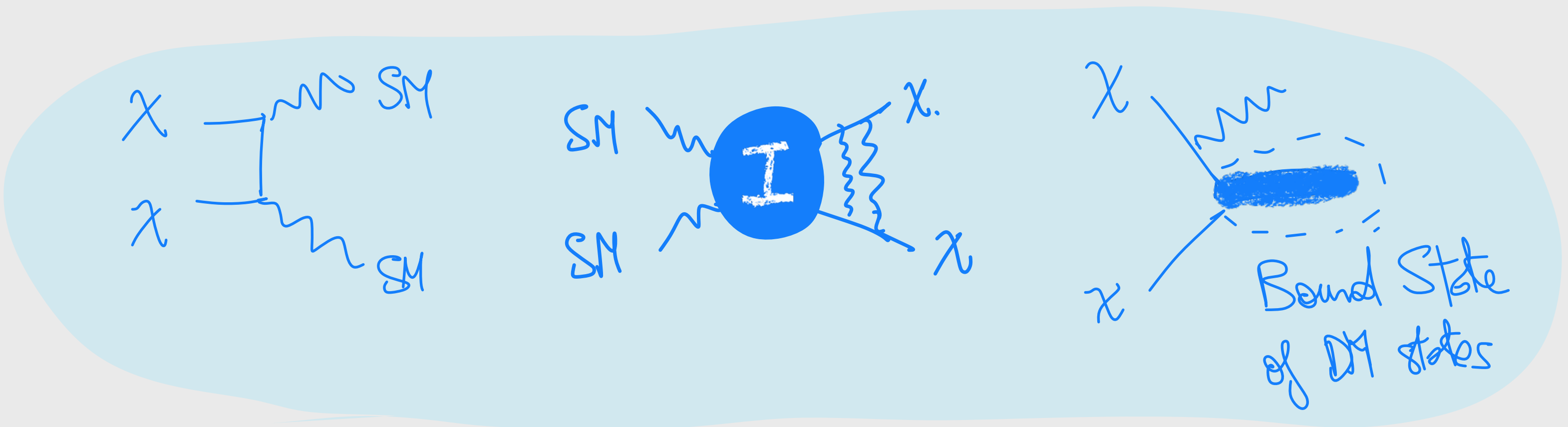
- The chessboard of DM is very large!



- High energy colliders are excellent and very robust probes of WIMPs!

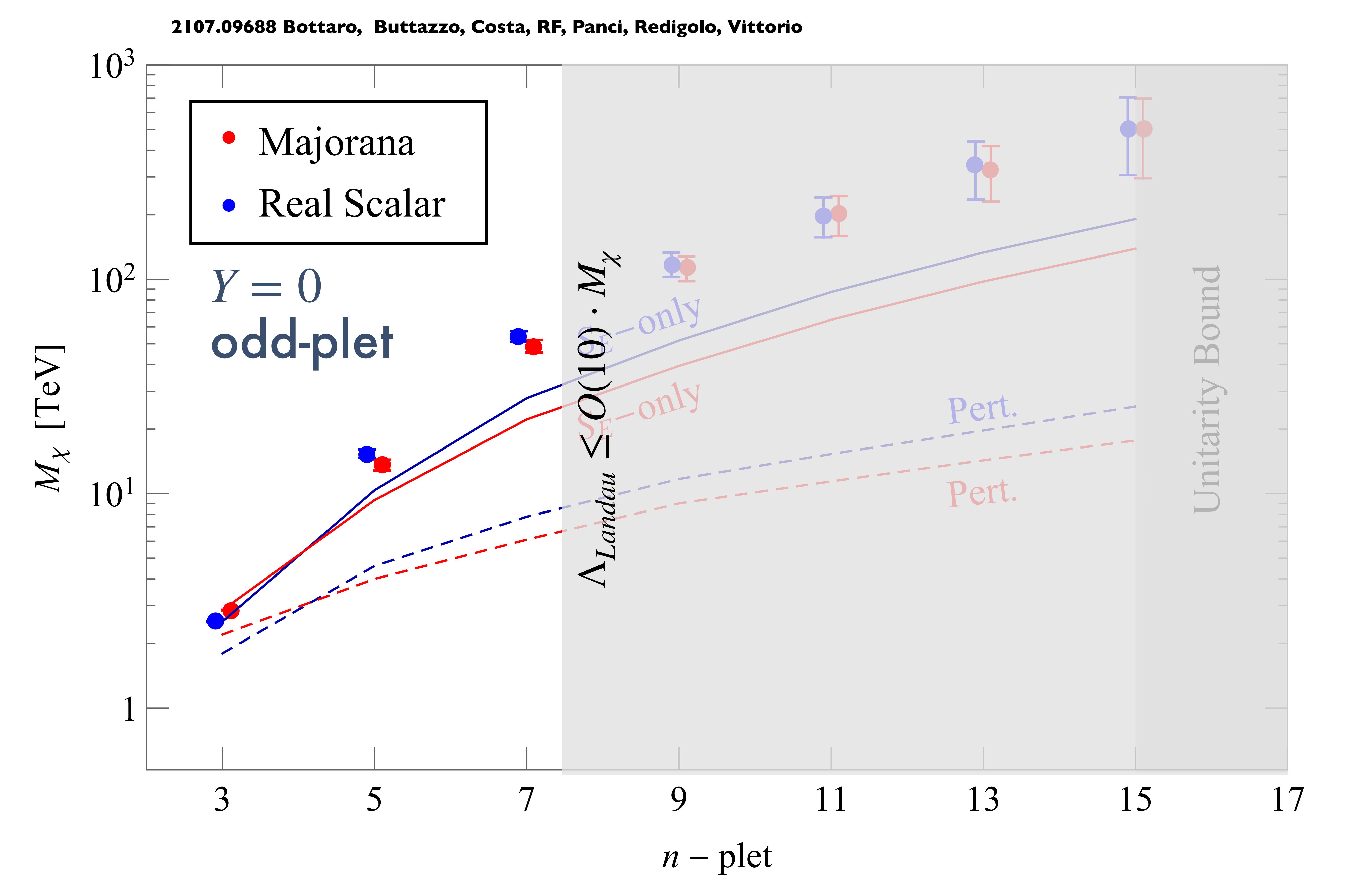
An "interpolator" model

$$\Omega_{nr} \sim \frac{1}{\sigma_{ann}} \sim \frac{M^2}{C_n \cdot g^2}$$



given n the mass is predicted

understood as the maximal mass for that n



IF DARK MATTER FEELS SM WEAK INTERACTIONS WE CAN USE THE GENERAL n-PLET WIMP TO MEASURE HOW WELL WE ARE ABLE TO TEST THIS HYPOTHESIS AND POSSIBLY DISCOVER OR EXCLUDE ONE OR SEVERAL OR THE WHOLE CATEGORY OF DM CANDIDATES.

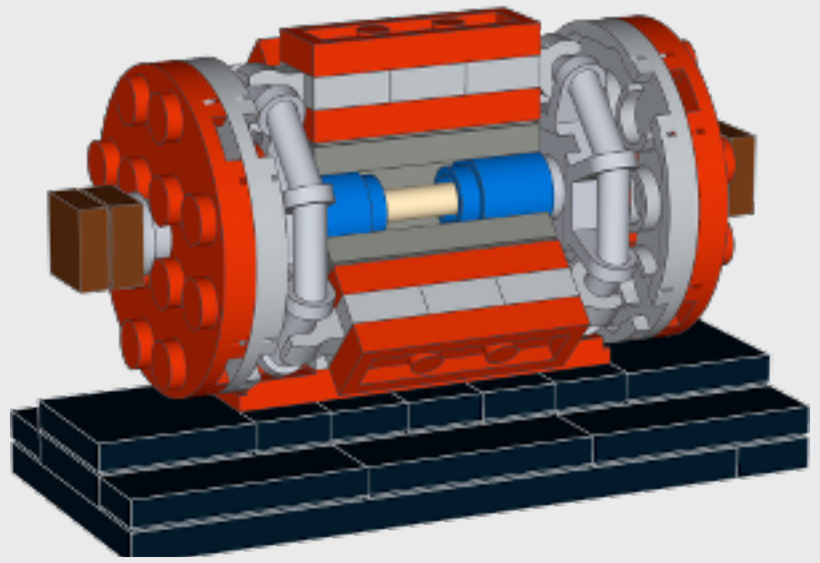
2107.09688, 2205.04486

After decades of WIMPs we might start to see the end of the way (!)

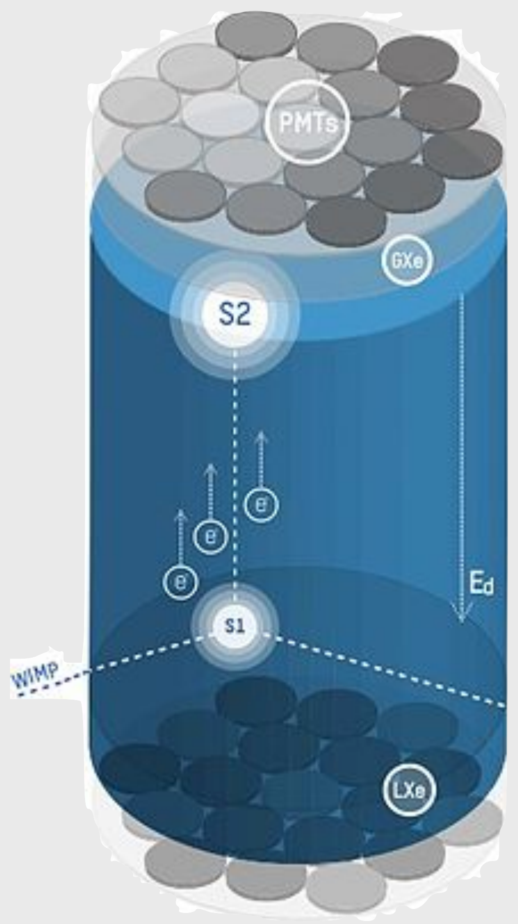
HOW TO THOROUGHLY TEST IT?

- Produce WIMPs in the lab
- Detect a WIMPs from natural source (big-bang)
- Observe WIMPs interactions (annihilation)

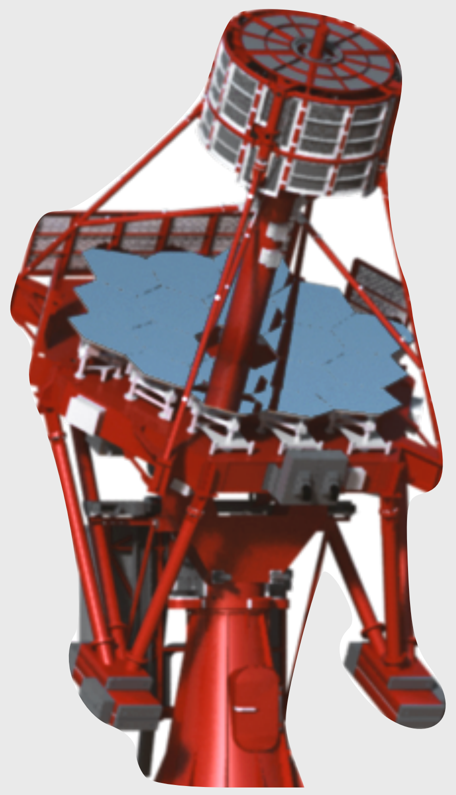
- Future Colliders sensitive to O(100) TeV
- Upcoming nT Xe detectors
- Upcoming Cosmic Rays observatories



Future Collider

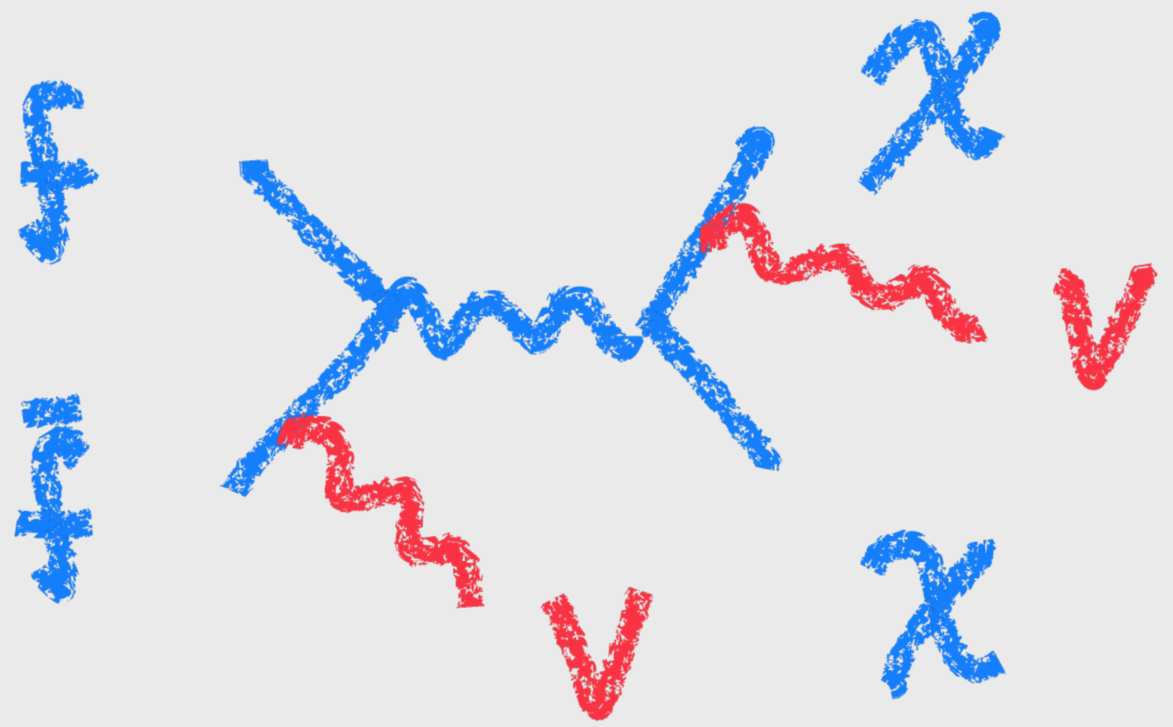


Xenon



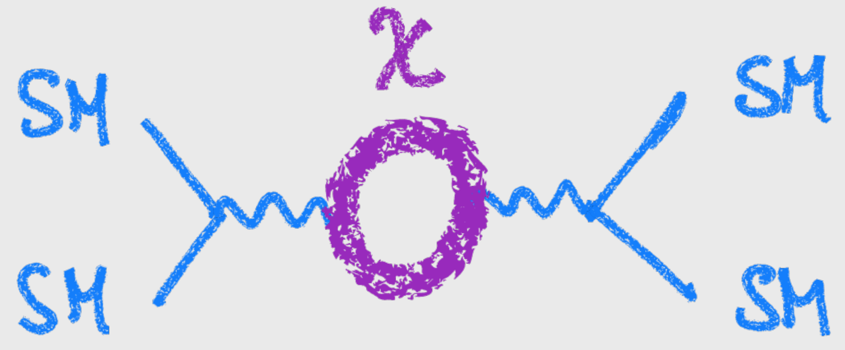
CTA

Electroweak Dark Matter: LSP (+NLSP)



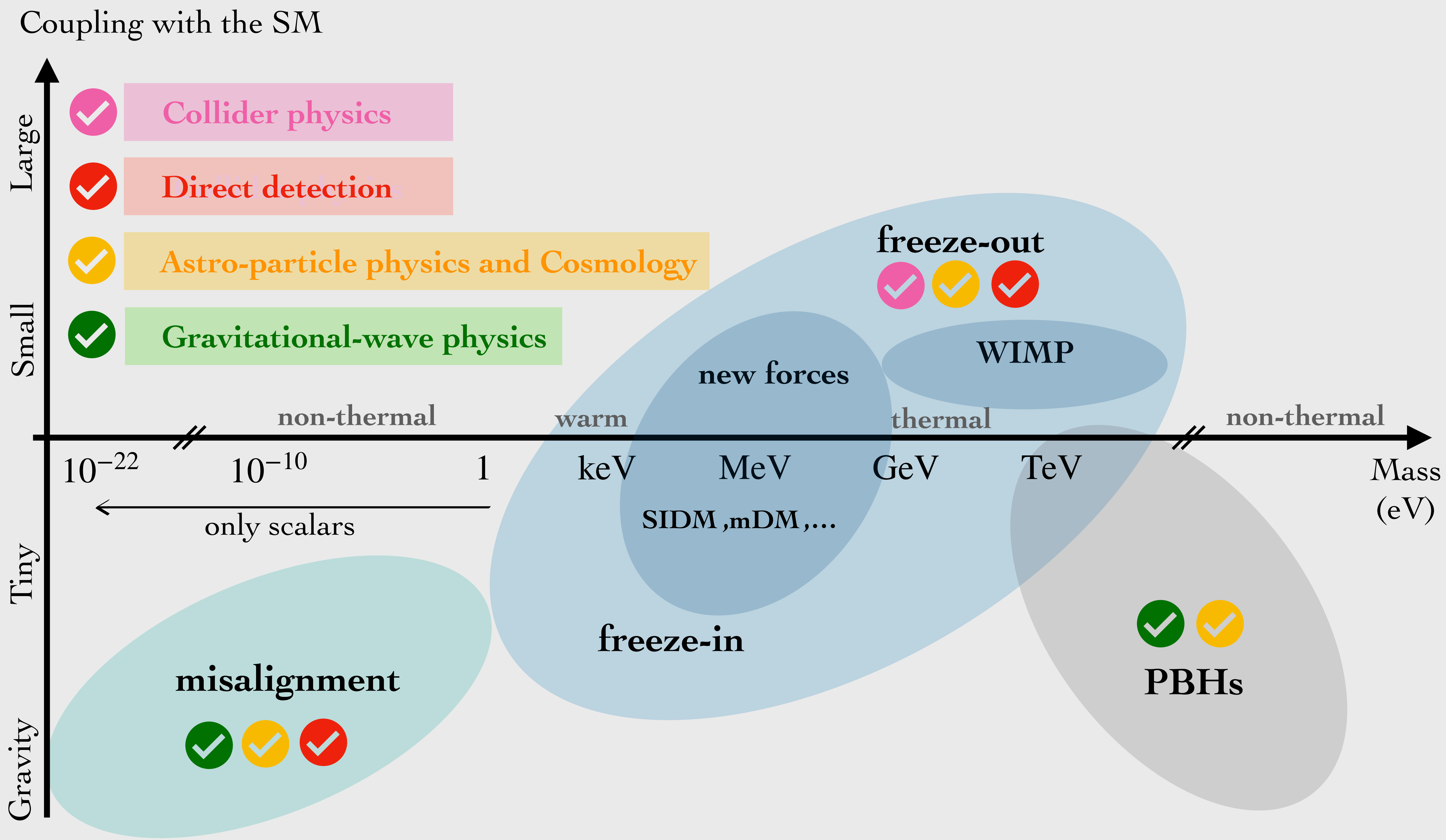
Δm

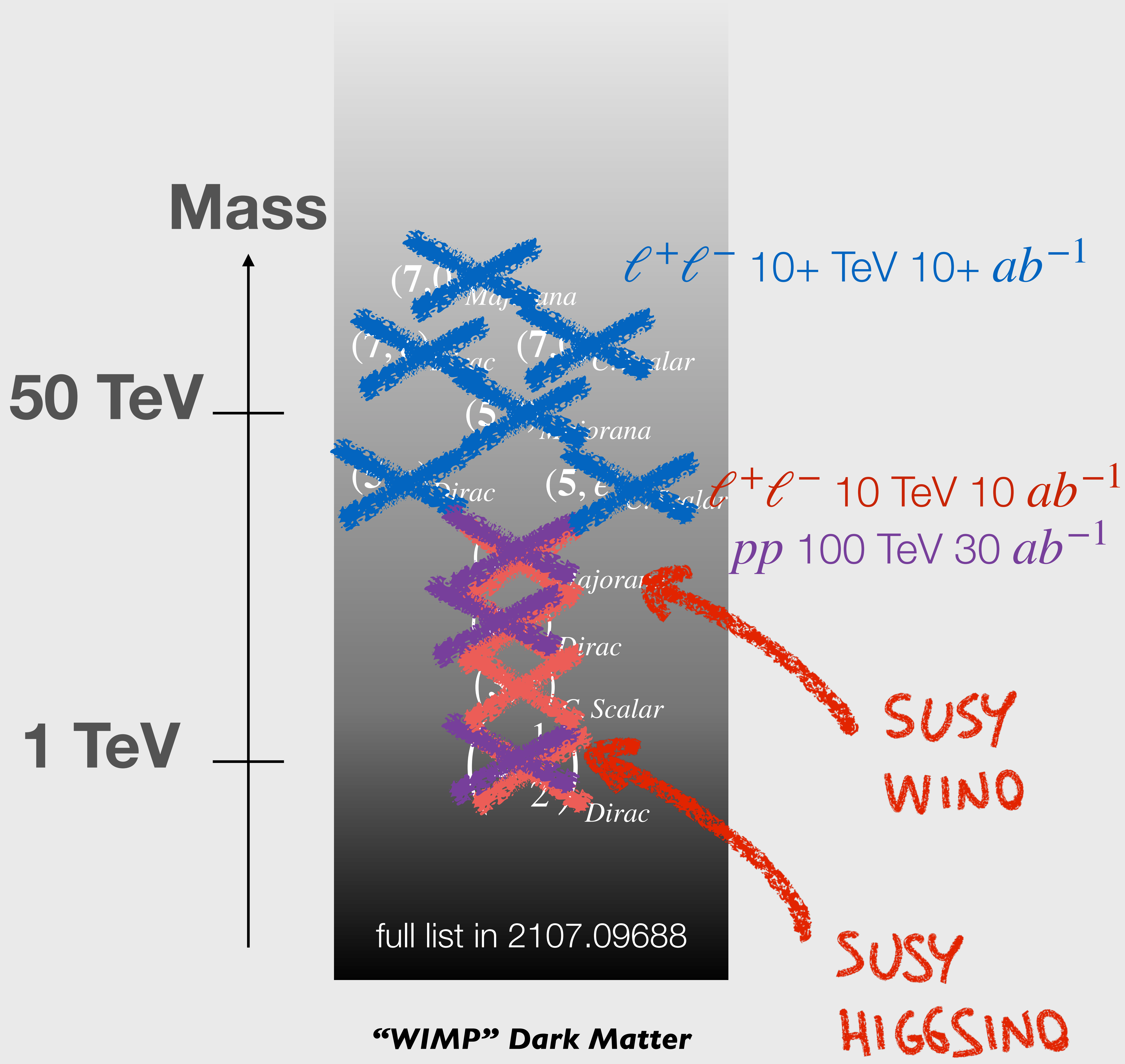
Wide open spectra		Generic leptons+missing momentum
Co-annihilation		Soft-objects + missing momentum
	GeV	
WIMP-like multiplet Accidental Dark Matter		Short (disappearing) tracks
DM SM singlet *pp* or $\ell^+\ell^- \to$ Z' $\to \chi\,\chi$	0	Mono-X



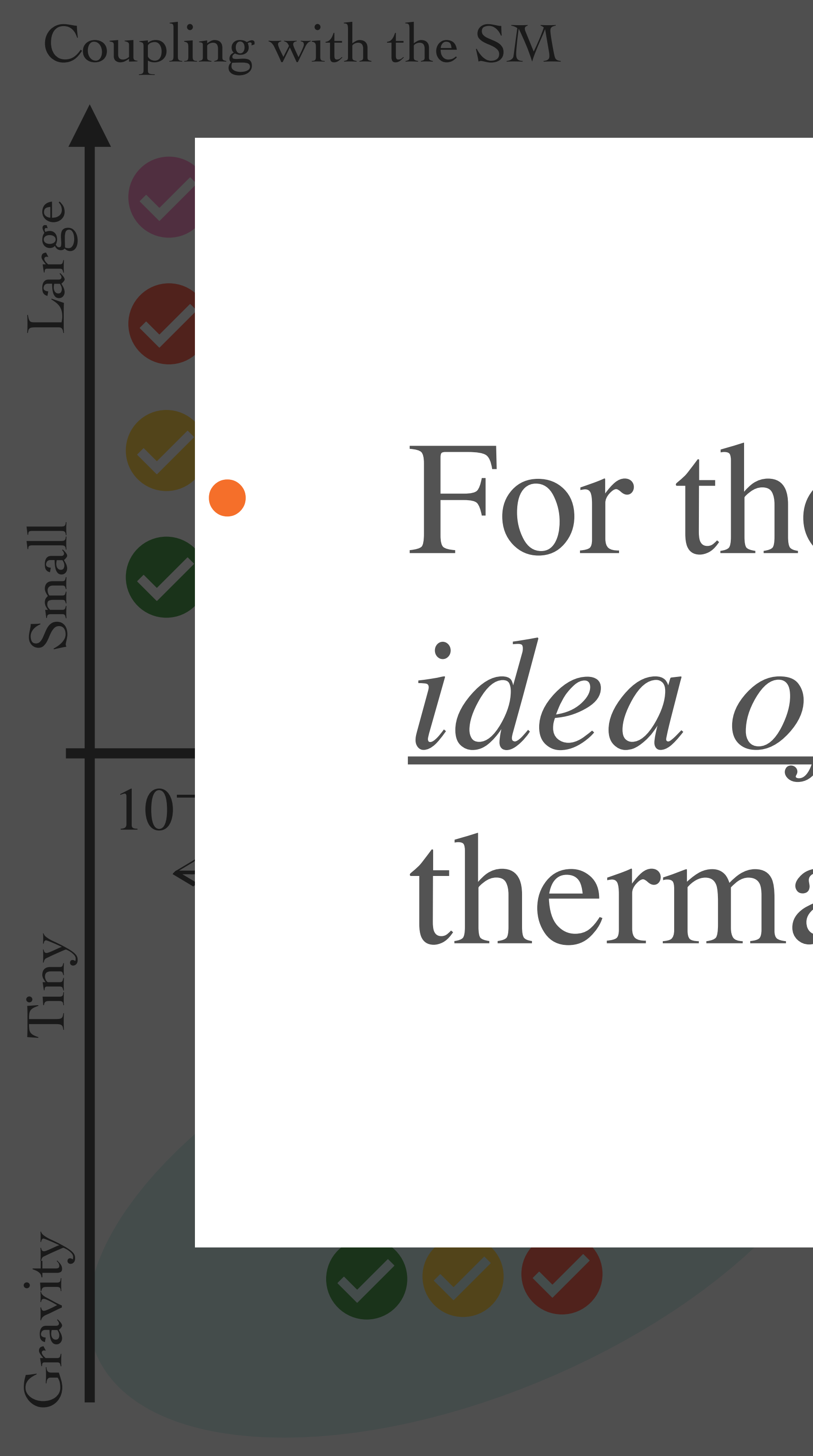
Precision Tests

Electroweak Dark Matter: LSP (+NLSP)

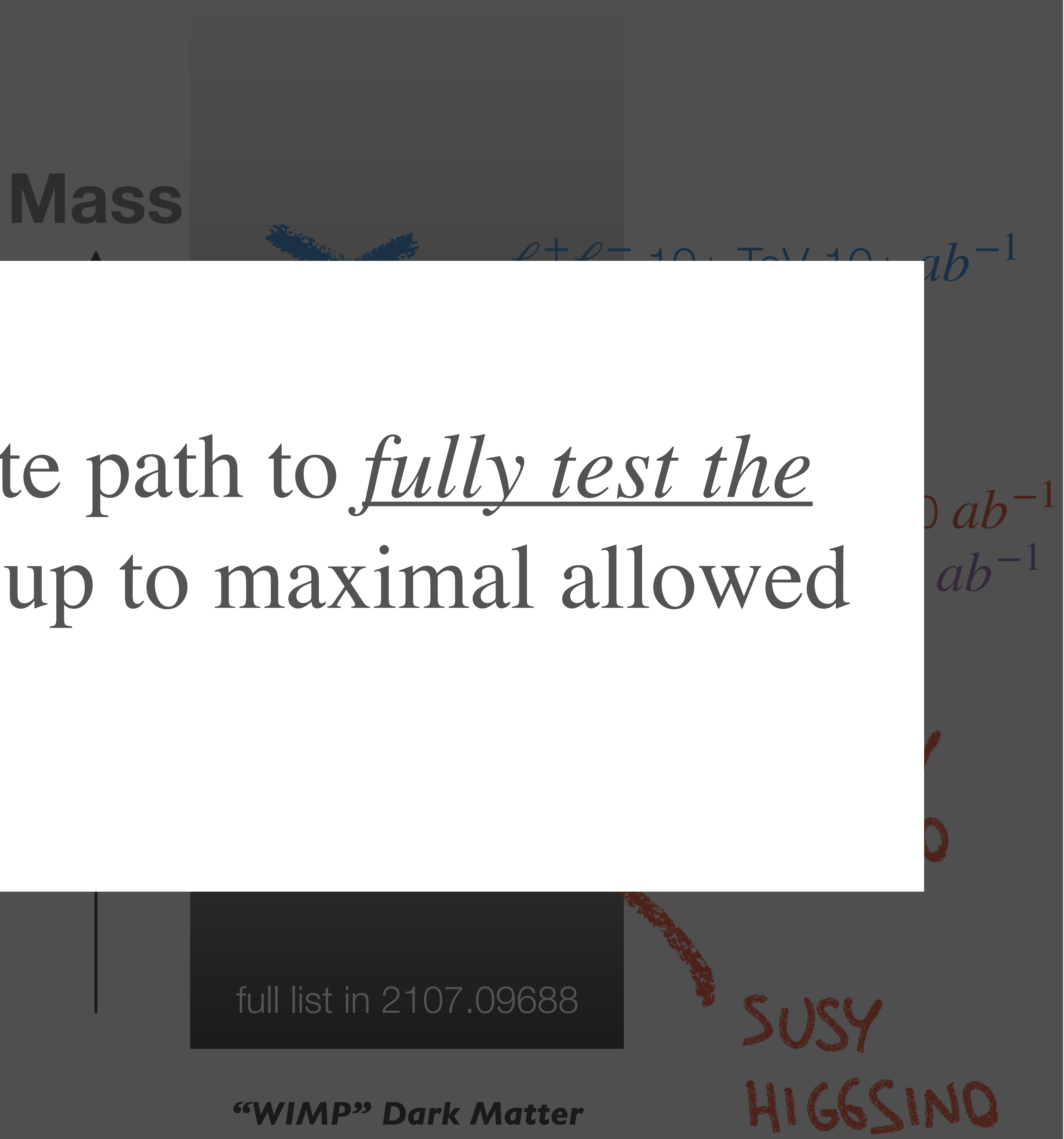




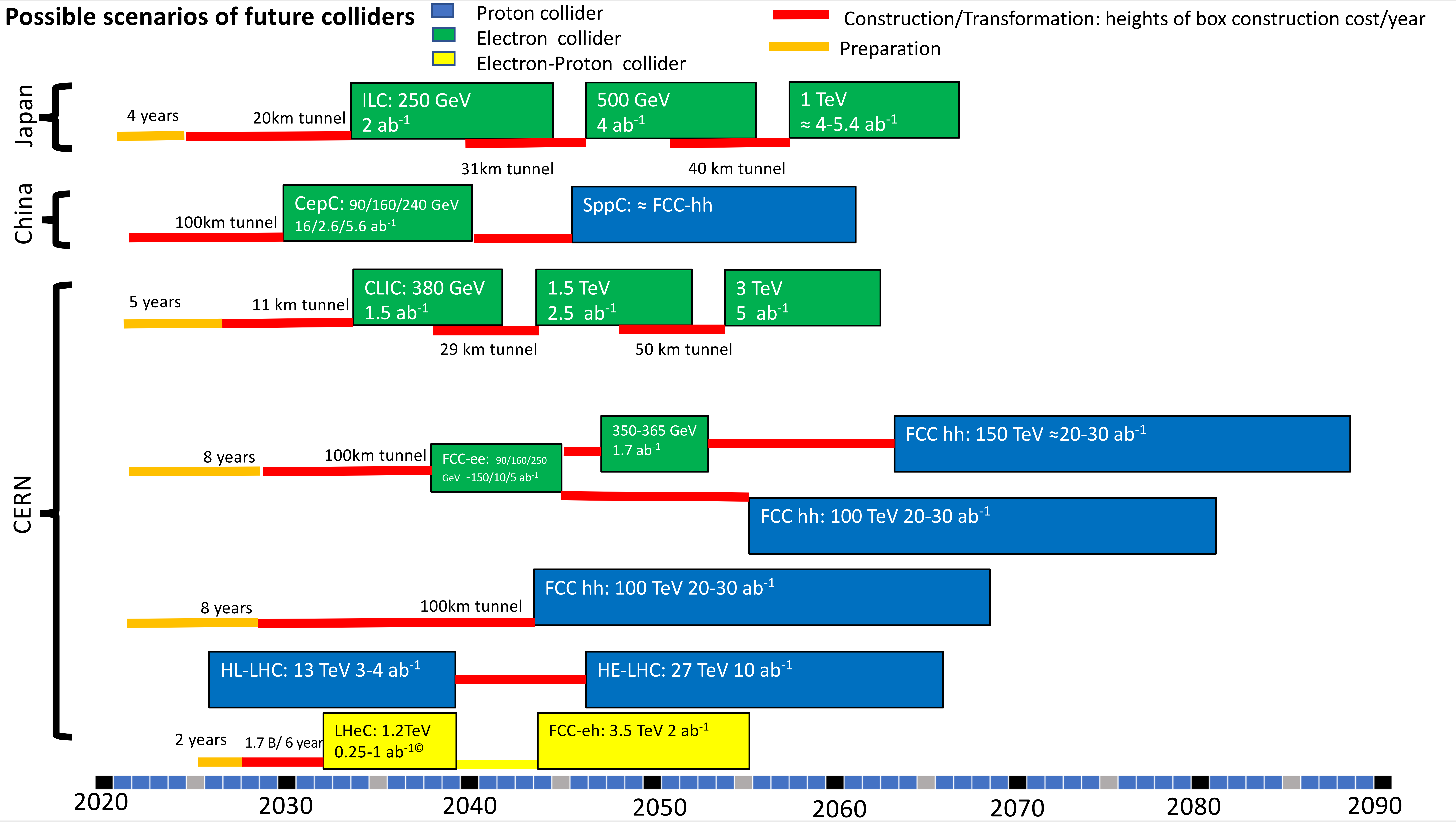
Electroweak Dark Matter: LSP (+NLSP)



- For the first time ever there is a concrete path to *fully test the idea of Dark Matter as a thermal relic* up to maximal allowed thermals mass $O(100)$ TeV



Collider plans


Possible scenarios of future colliders
Proton collider
Electron collider
Electron-Proton collider
Construction/Transformation: heights of box construction cost/year
Preparation
Japan
4 years
20km tunnel
ILC: 250 GeV
2 ab-1
500 GeV
4 ab-1
1 TeV
≈ 4-5.4 ab-1
31km tunnel
40 km tunnel
China
100km tunnel
CepC: 90/160/240 GeV
16/2.6/5.6 ab-1
SppC: ≈ FCC-hh
CERN
5 years
11 km tunnel
CLIC: 380 GeV
1.5 ab-1
1.5 TeV
2.5 ab-1
3 TeV
5 ab-1
29 km tunnel
50 km tunnel
8 years
100km tunnel
FCC-ee: 90/160/250 GeV -150/10/5 ab-1
350-365 GeV
1.7 ab-1
FCC hh: 150 TeV ≈20-30 ab-1
FCC hh: 100 TeV 20-30 ab-1
8 years
100km tunnel
FCC hh: 100 TeV 20-30 ab-1
HL-LHC: 13 TeV 3-4 ab-1
HE-LHC: 27 TeV 10 ab-1
2 years
1.7 B/ 6 year
LHeC: 1.2TeV
0.25-1 ab-1©
FCC-eh: 3.5 TeV 2 ab-1
2020
2030
2040
2050
2060
2070
2080
2090

Higgs factory

TARGETS

pp colliders make a large number of Higgs bosons $\sigma(gg \to h) = 54.72$ pb at LHC14

- LHC will make some **200M Higgs** bosons in the High Luminosity phase, but
- we observed clearly only final states with $BR \simeq 10^{-3}$
- there are backgrounds and degenerations

the overall result of HL-LHC is $\dfrac{\delta g}{g} \simeq \text{few} \cdot 10^{-2}$

this is the size of deviation fior

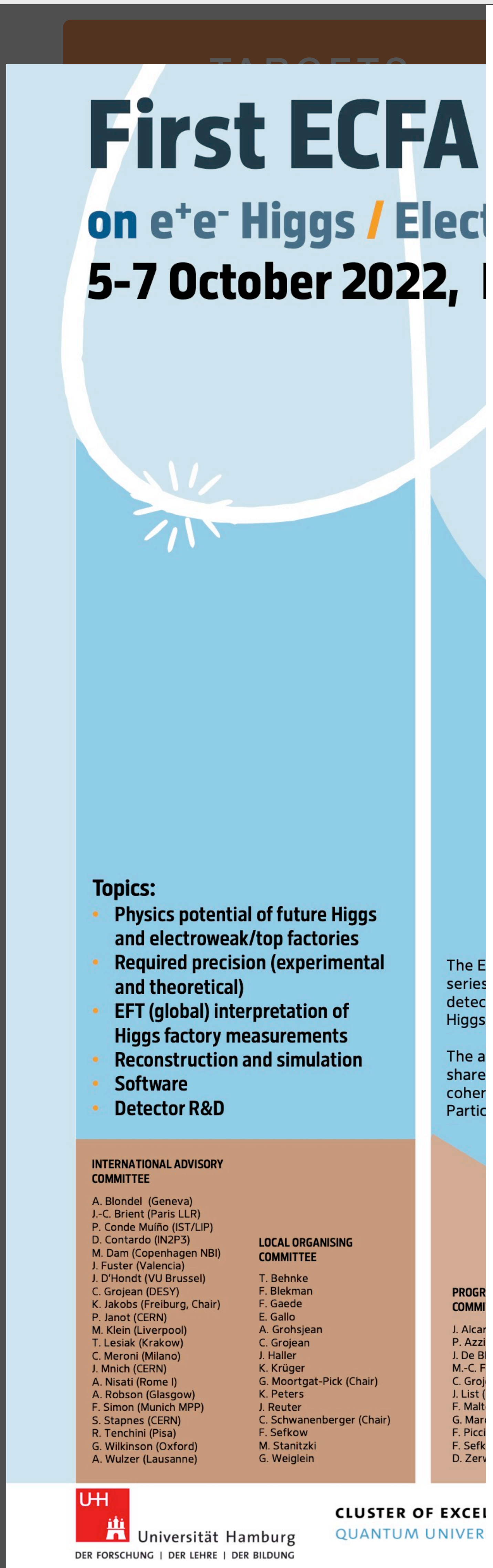
$$M_{new} \simeq \text{few TeV}$$

1905.03764

	HL-LHC
$g^{eff}_{HZZ}[\%]$	3.2
	3.6
$g^{eff}_{HWW}[\%]$	2.9
	3.2
$g^{eff}_{H\gamma\gamma}[\%]$	3.4
	3.7
$g^{eff}_{HZ\gamma}[\%]$	11.
	11.
$g^{eff}_{Hgg}[\%]$	2.2
	2.2
$g^{eff}_{Htt}[\%]$	2.9
	2.9
$g^{eff}_{Hcc}[\%]$	
	–
$g^{eff}_{Hbb}[\%]$	4.7
	5.1
$g^{eff}_{H\tau\tau}[\%]$	3.2
	3.5
$g^{eff}_{H\mu\mu}[\%]$	
	5.5

Higgs factory

Higgs factory



2401.07564 - de Blas, Jorge and others - Focus topics for the ECFA study on Higgs / Top / EW factories

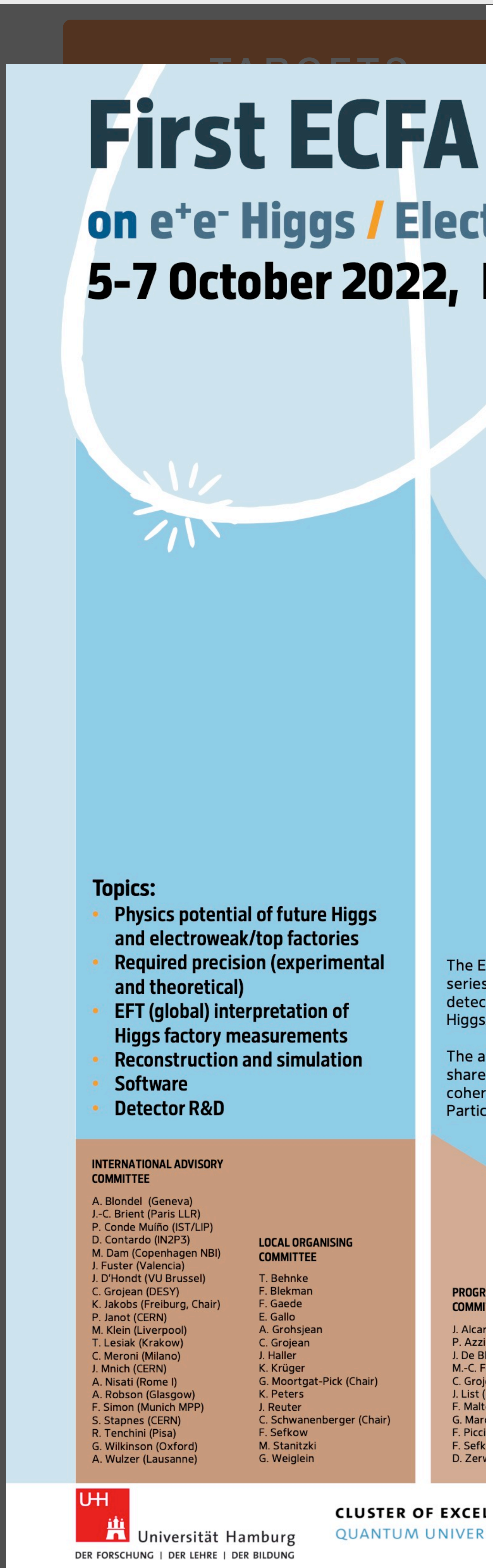
Focus topics for the ECFA study on Higgs / Top / EW factories

[hep-ph] 15 Jan 2024

Abstract

In order to stimulate new engagement and trigger some concrete studies in areas where further work would be beneficial towards fully understanding the physics potential of an e^+e^- Higgs / Top / Electroweak factory, we propose to define a set of focus topics. The general reasoning and the proposed topics are described in this document.

Higgs factory



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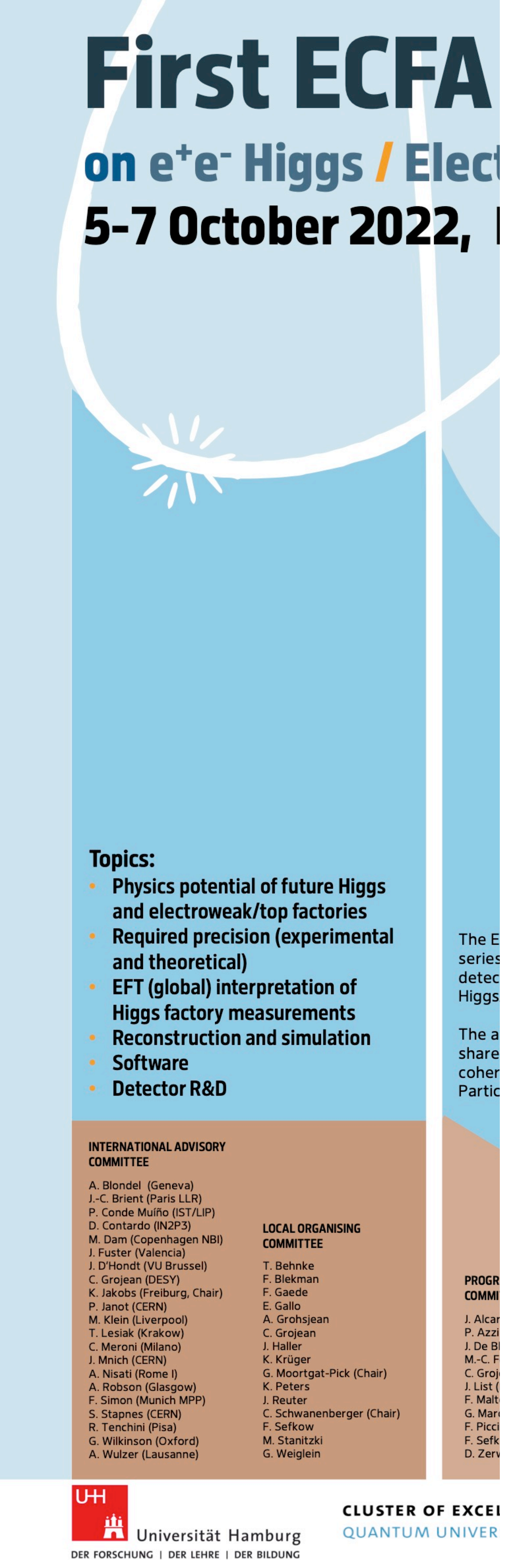
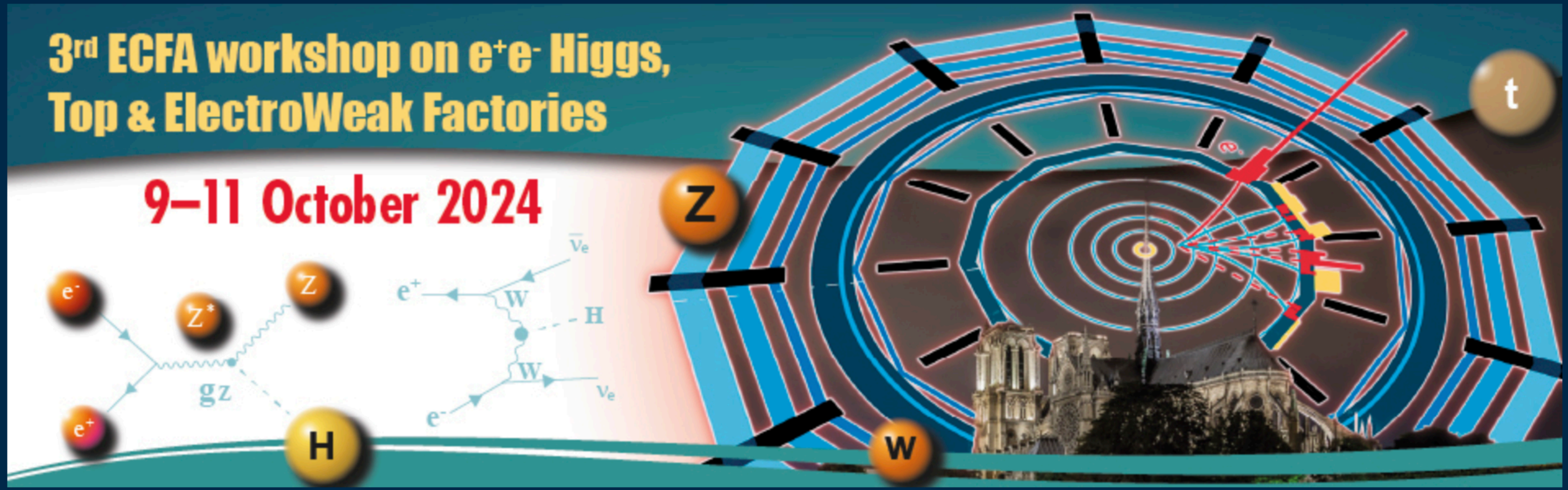
Focus topics for the ECFA study on Higgs / Top / EW factories

[hep-ph] 15 Jan 2024

Contents

Higgs factory





9–11 Oct 2024
Campus des Cordeliers, Paris, Metro Odeon

Europe/Paris timezone

Enter your search term

- **Overview**
- Committees
- Timetable
- Registration
- Participant List
- Payment of Registration fee
- Call for Abstracts
- Poster session
- Venue
- Accommodation / Lunches
- Workshop poster

Dear Colleagues,

The third 3rd ECFA workshop on e^+e^- Higgs, Electroweak and Top Factories will take place in the center of **Paris** in an **in-person** mode.

The Workshop will last **from Wednesday, October 9th, 2024, 09:00 to Friday, October 11th, 16:00.**

Registration is now opened.

The scientific program will continue developing in the coming months, according to the draft block schedule given in the timetable and following the call for abstracts which has started.

This workshop will be the last of the series of workshops on the physics, experiment and detectors for future e+e- factories before the start of the process of the next updated of the European Strategy on Particle Physics. It thus provides a crucial opportunity for the community working on the future e+e- factories to gather together and discuss the

Colliders reach

Higgs factory (mainstream option)

TARGETS

e^+e^- colliders make a large number of Higgs bosons $\sigma(e^+e^- \to Zh) \simeq 200$ fb at 240 GeV

- the Higgs factory will make some **1M Higgs** bosons
- we can observed clearly **all** final states
- there are no backgrounds and no degenerations

the overall result of Higgs Factory is $\frac{\delta g}{g} \simeq \text{few} \cdot 10^{-3}$

this is the size of deviation for

$$M_{new} \simeq 10 \text{ TeV}$$

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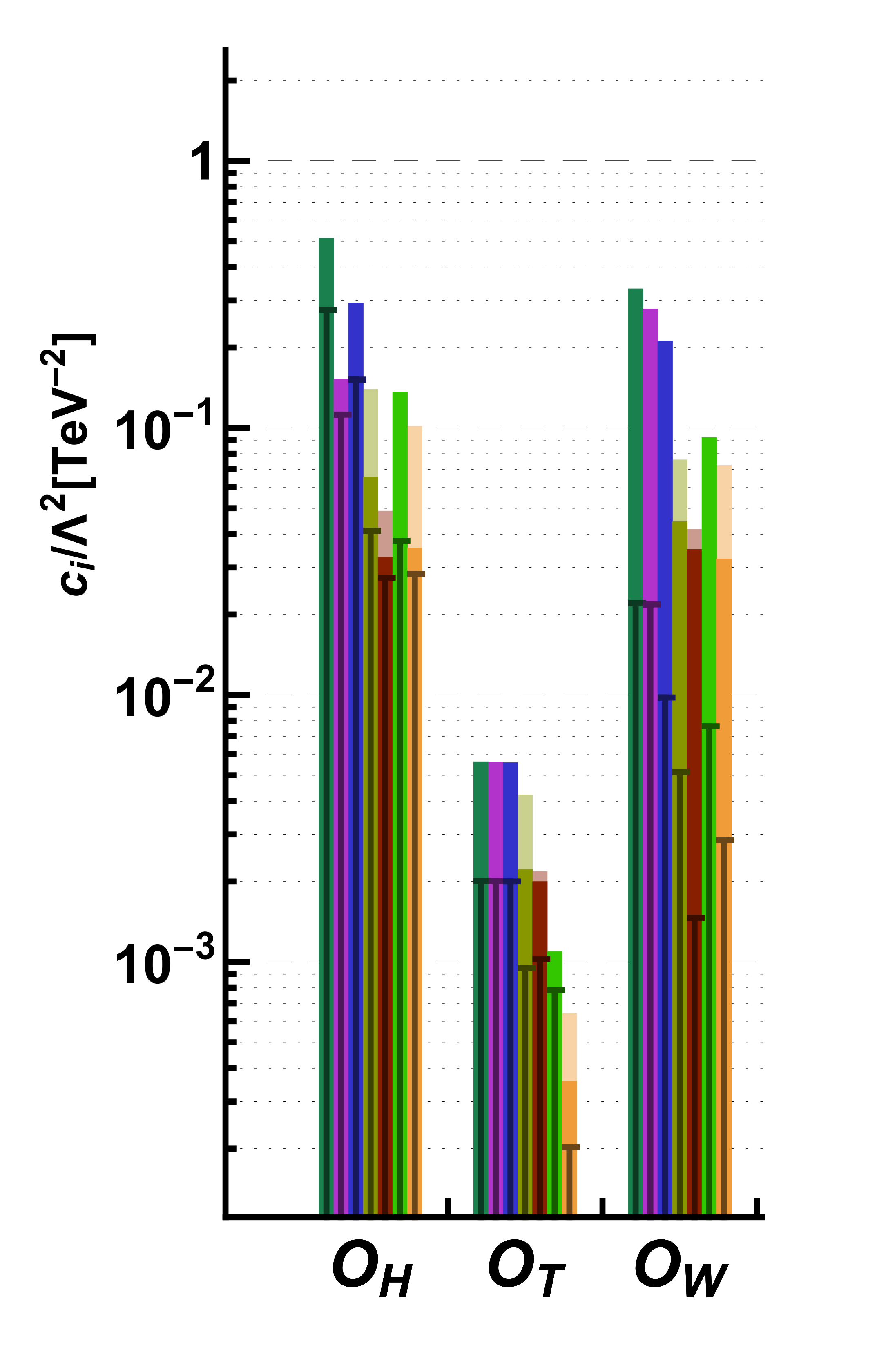
1905.03764



Higgs factory

TARGETS

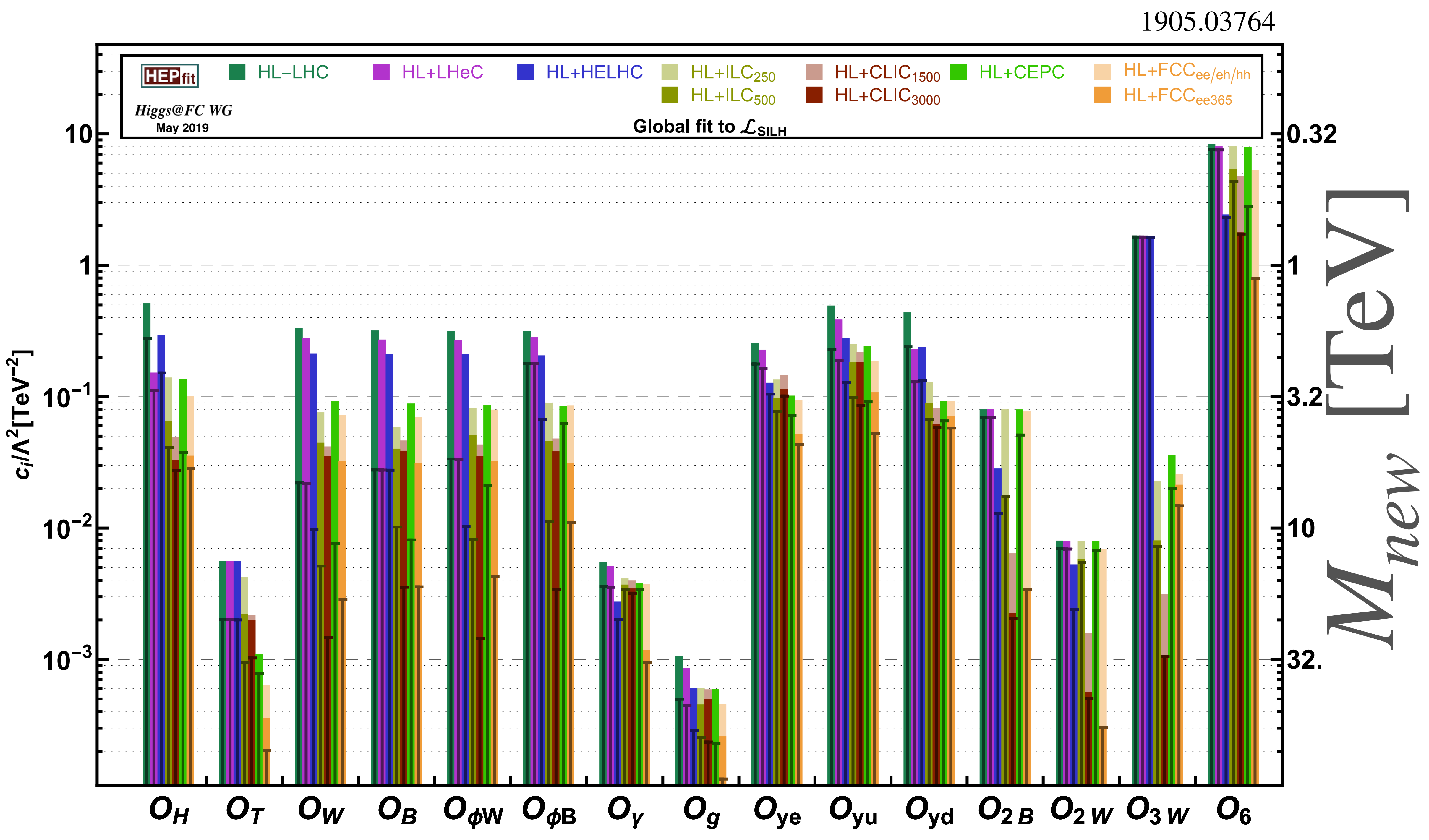


Figure 6. Global fit to the EFT operators in the Lagrangian (19). We show the marginalized 68% probability reach for each Wilson coefficient c_i/Λ^2 in Eq. (19) from the global fit (solid bars). The reach of the vertical lines indicate the results assuming only the corresponding operator is generated by the new physics.

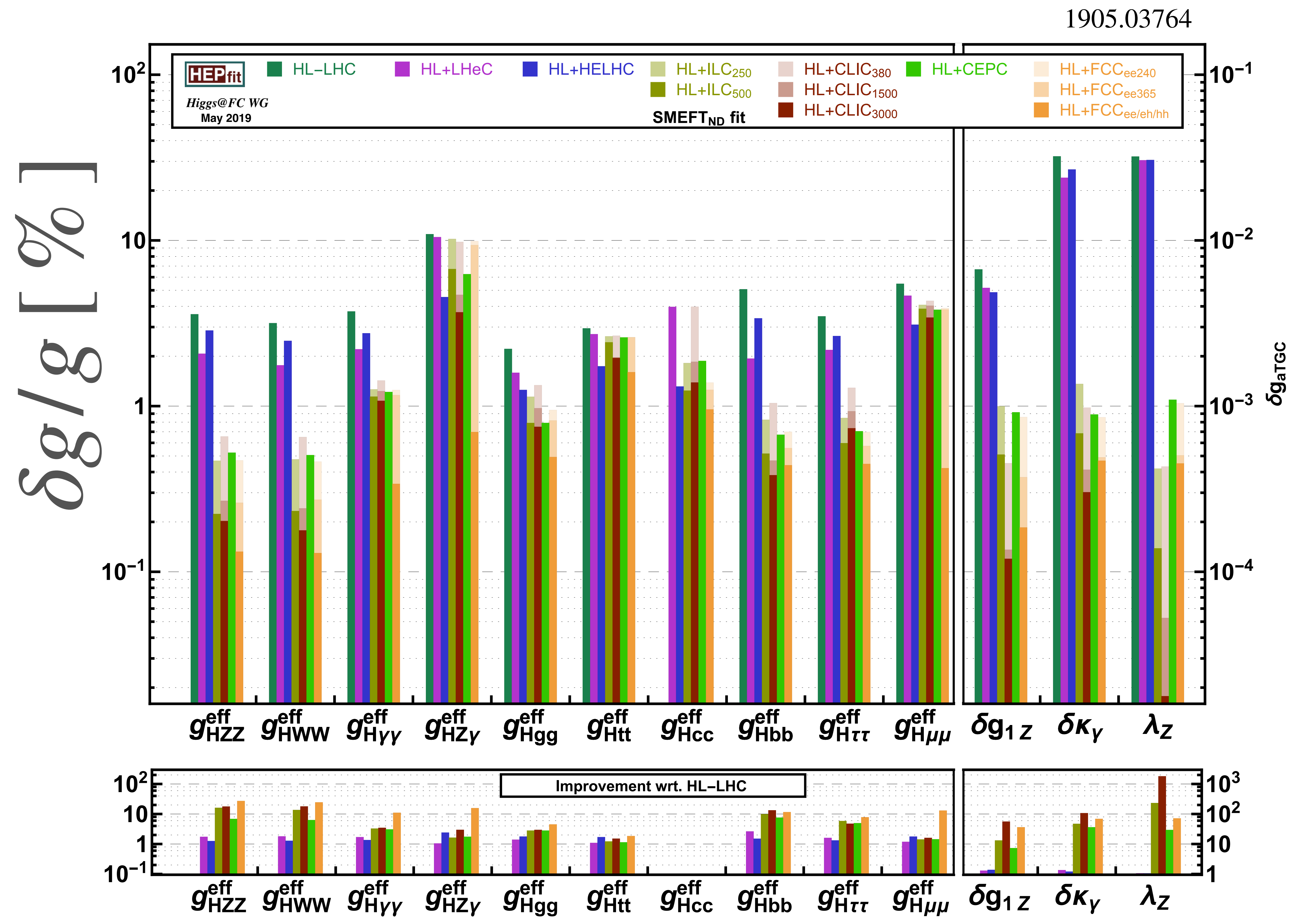
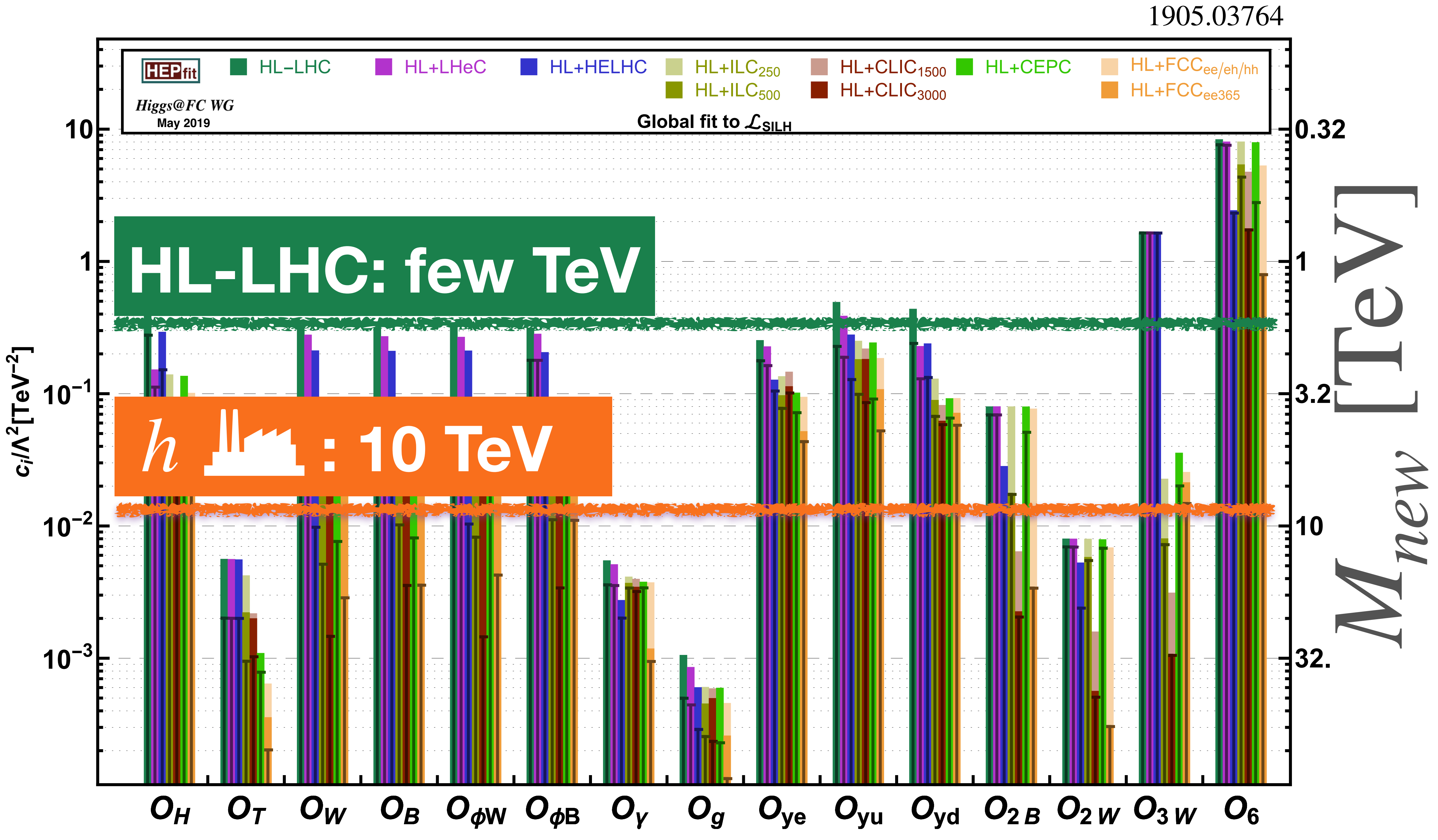


Figure 3. Sensitivity at 68% probability to deviations in the different effective Higgs couplings and aTGC from a global fit to the projections available at each future collider project. Results obtained within the SMEFT framework in the benchmark $SMEFT_{ND}$.

Higgs factory

TARGETS



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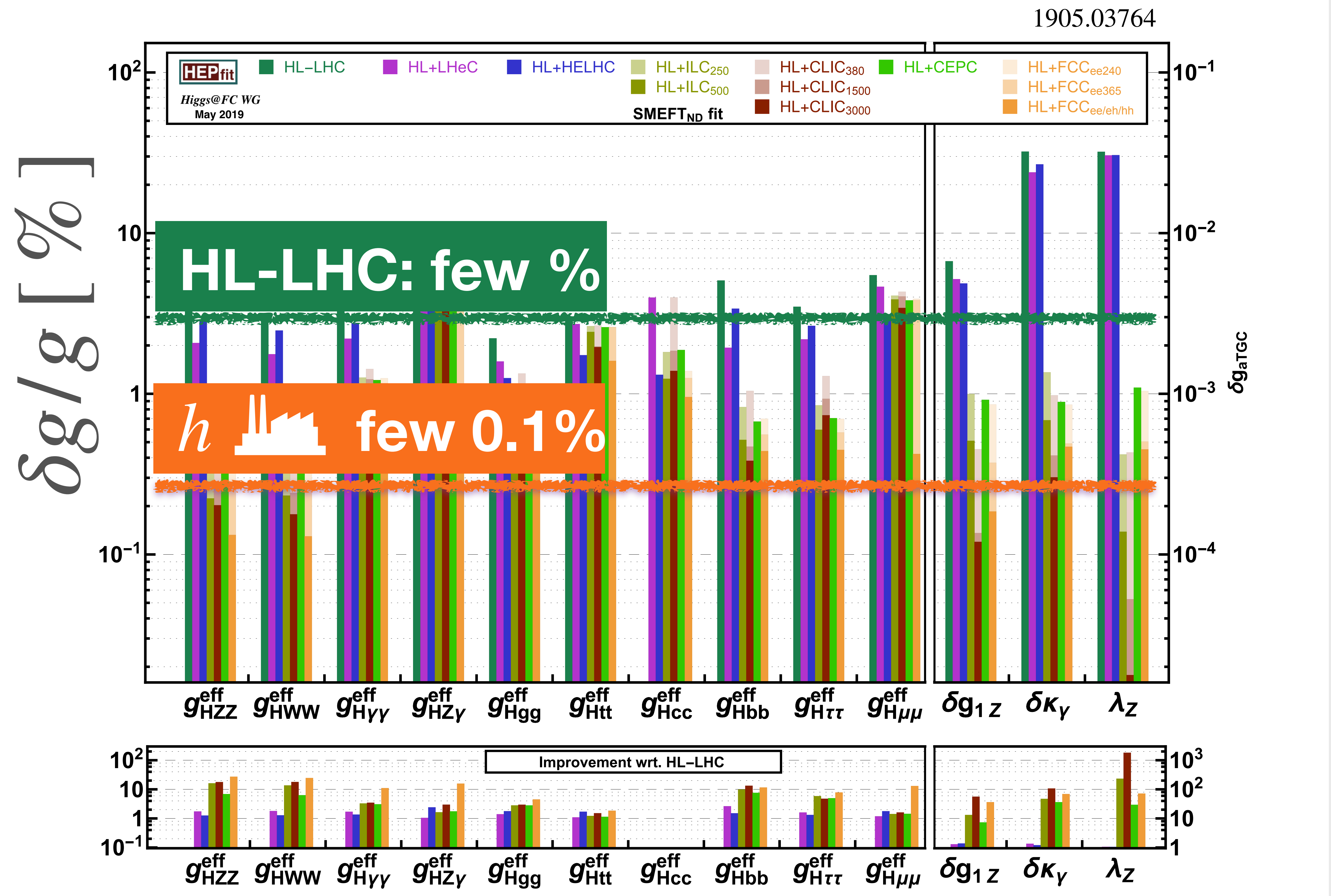

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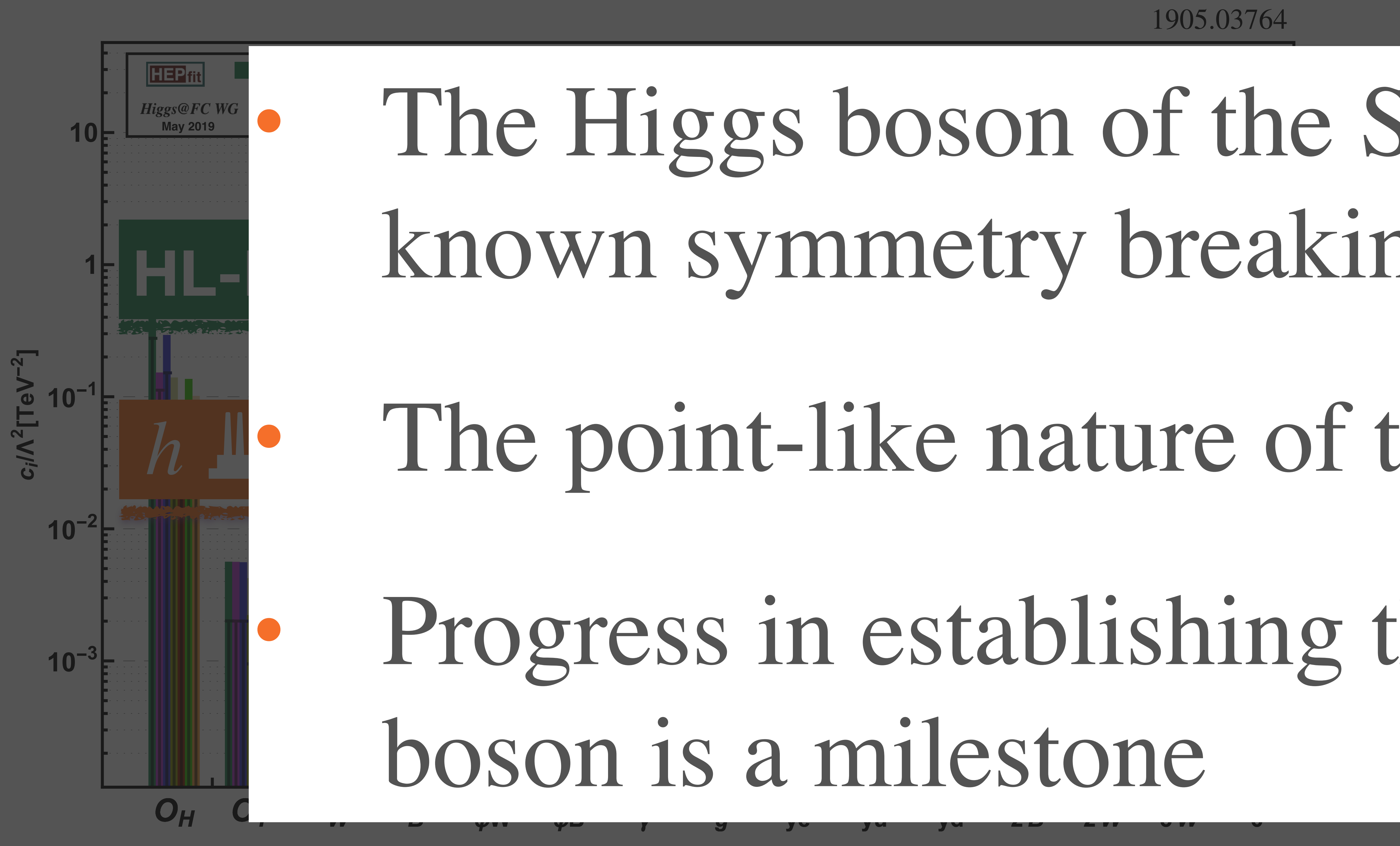

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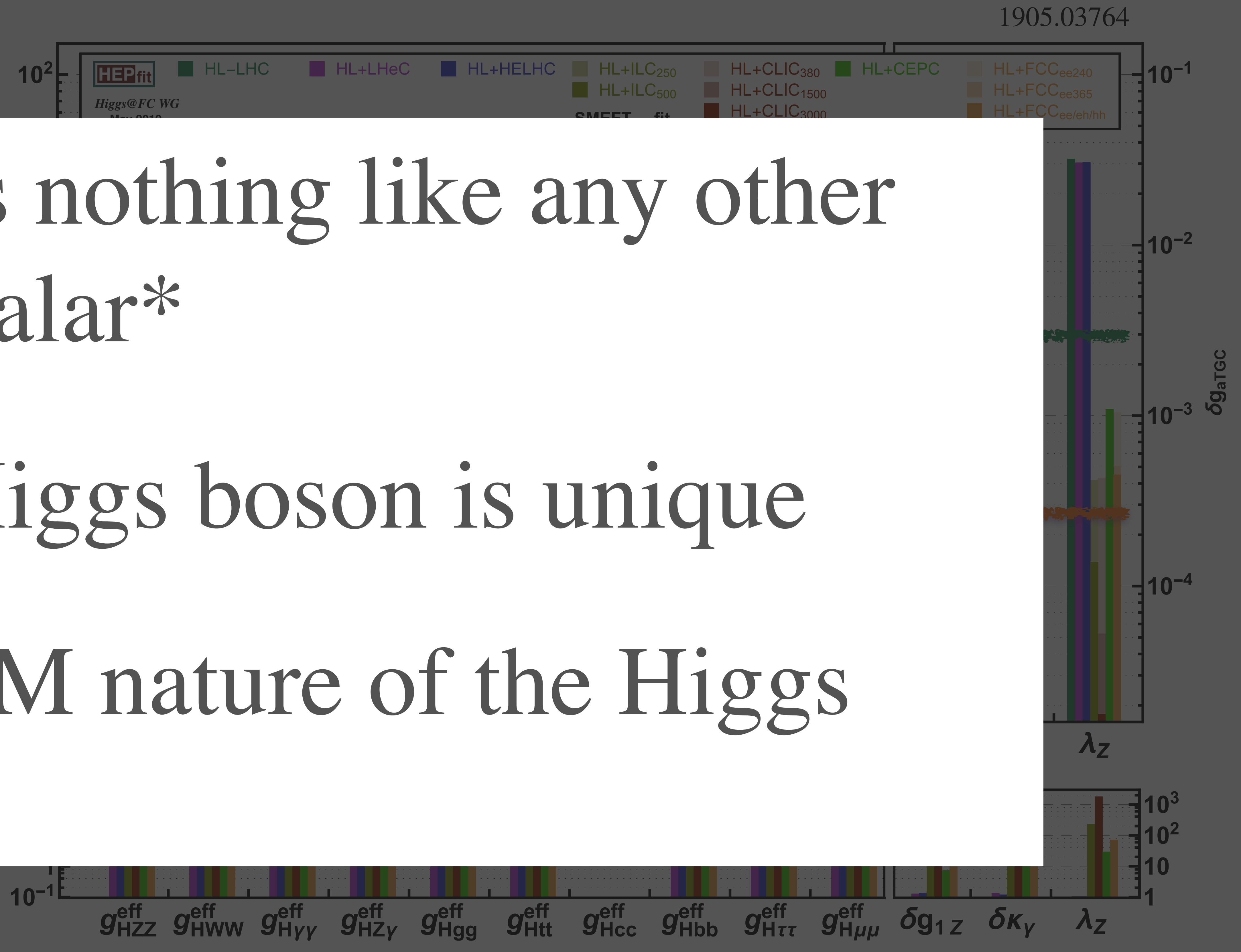
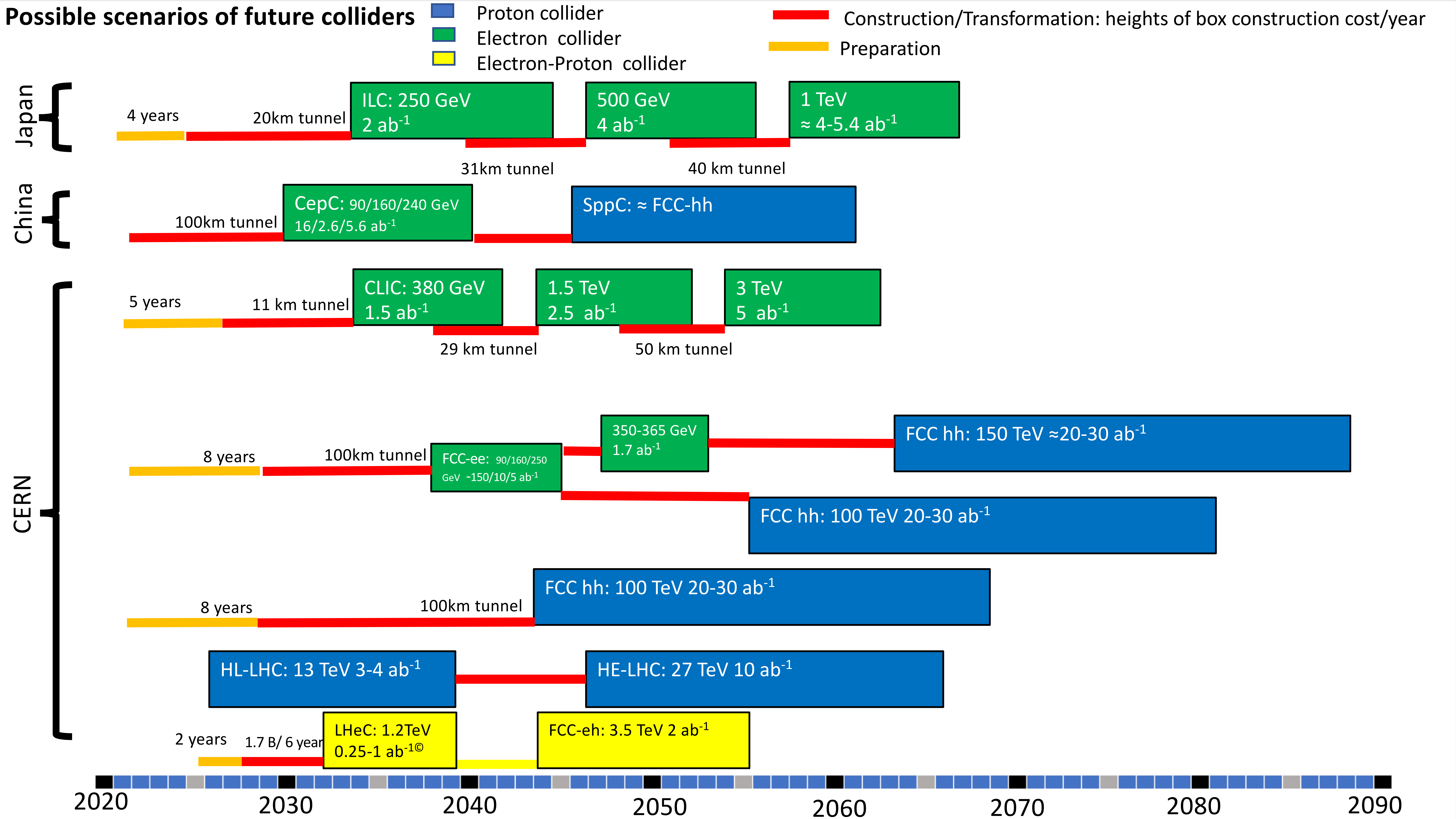
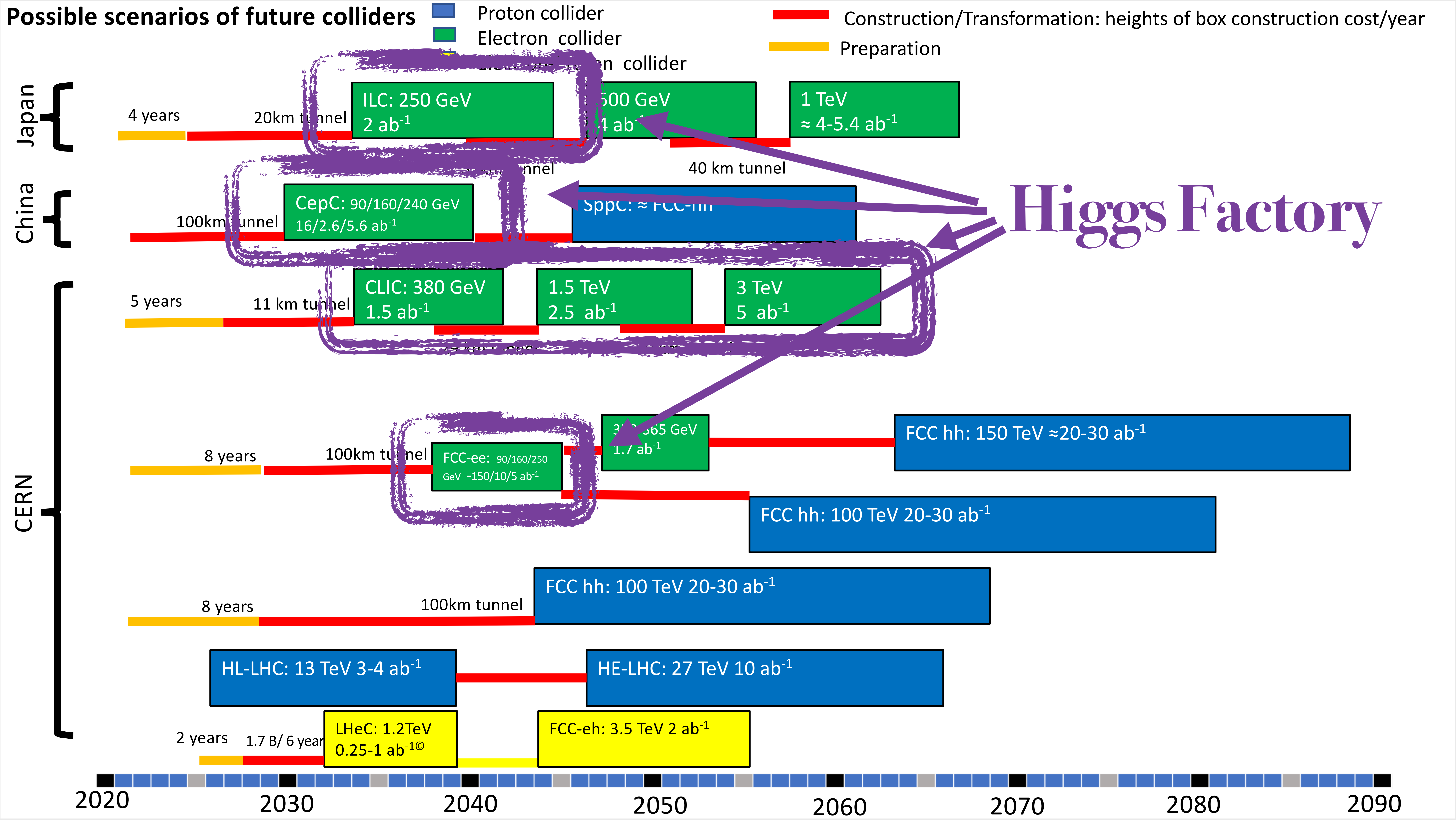


Figure 3. Sensitivity at 68% probability to deviations in the different effective Higgs couplings and aTGC from a global fit to the projections available at each future collider project. Results obtained within the SMEFT framework in the benchmark $SMEFT_{ND}$.

- The Higgs boson of the SM is nothing like any other known symmetry breaking scalar*
- The point-like nature of the Higgs boson is unique
- Progress in establishing the SM nature of the Higgs boson is a milestone



Possible scenarios of future colliders
Proton collider
Electron collider
Electron-Proton collider
Construction/Transformation: heights of box construction cost/year
Preparation
Japan
4 years
20km tunnel
ILC: 250 GeV
2 ab^{-1}
500 GeV
4 ab^{-1}
1 TeV
≈ 4-5.4 ab^{-1}
31km tunnel
40 km tunnel
China
100km tunnel
CepC: 90/160/240 GeV
16/2.6/5.6 ab^{-1}
SppC: ≈ FCC-hh
CERN
5 years
11 km tunnel
CLIC: 380 GeV
1.5 ab^{-1}
1.5 TeV
2.5 ab^{-1}
3 TeV
5 ab^{-1}
29 km tunnel
50 km tunnel
8 years
100km tunnel
FCC-ee: 90/160/250 GeV -150/10/5 ab^{-1}
350-365 GeV
1.7 ab^{-1}
FCC hh: 150 TeV ≈20-30 ab^{-1}
FCC hh: 100 TeV 20-30 ab^{-1}
8 years
100km tunnel
FCC hh: 100 TeV 20-30 ab^{-1}
HL-LHC: 13 TeV 3-4 ab^{-1}
HE-LHC: 27 TeV 10 ab^{-1}
2 years
1.7 B/ 6 year
LHeC: 1.2TeV
0.25-1 ab^{-1}©
FCC-eh: 3.5 TeV 2 ab^{-1}
2020
2030
2040
2050
2060
2070
2080
2090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Higgs Factory
CERN
5 years
11 km tunnel
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1.5 TeV 2.5 ab-1
3 TeV 5 ab-1
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2020
2030
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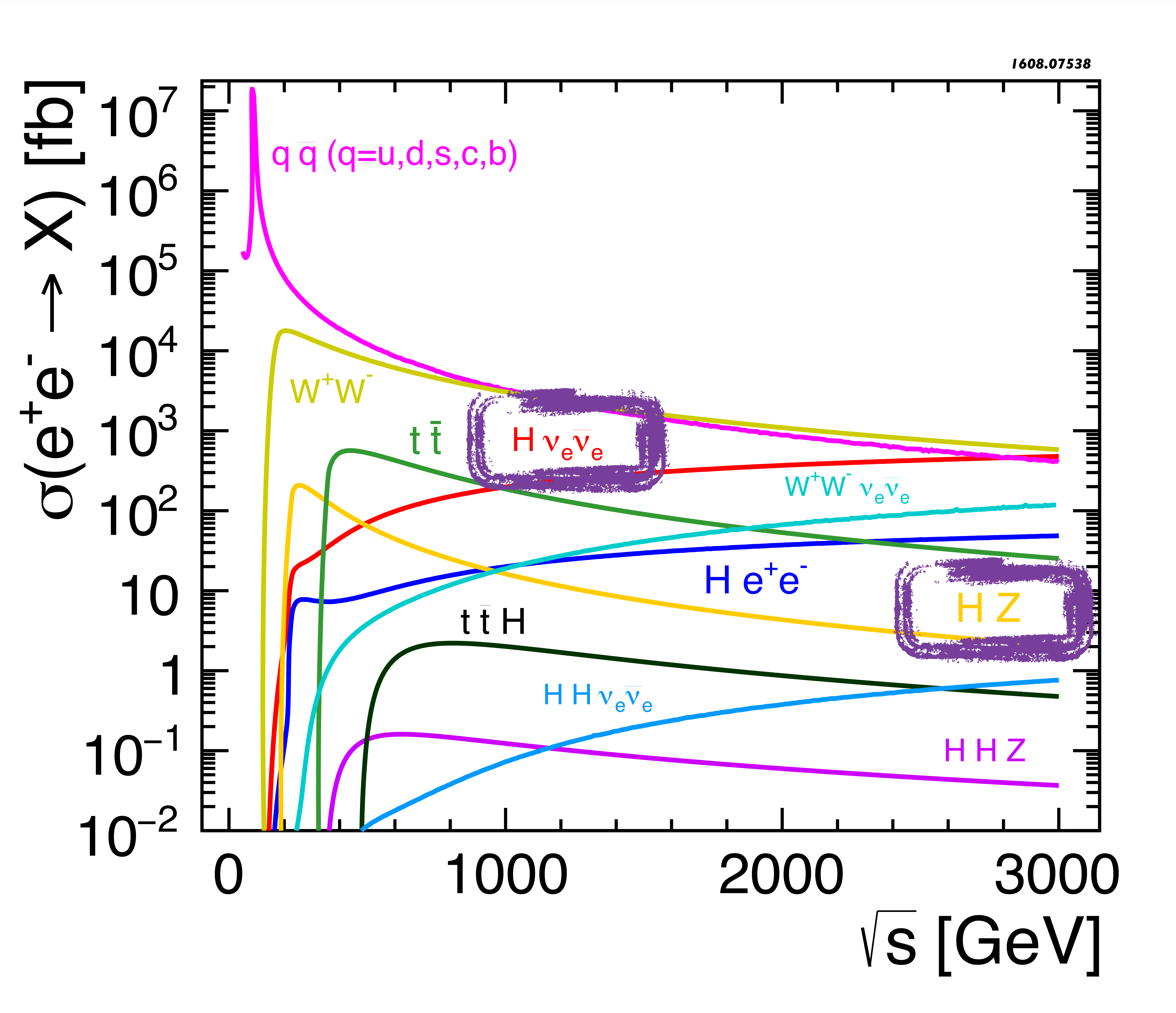
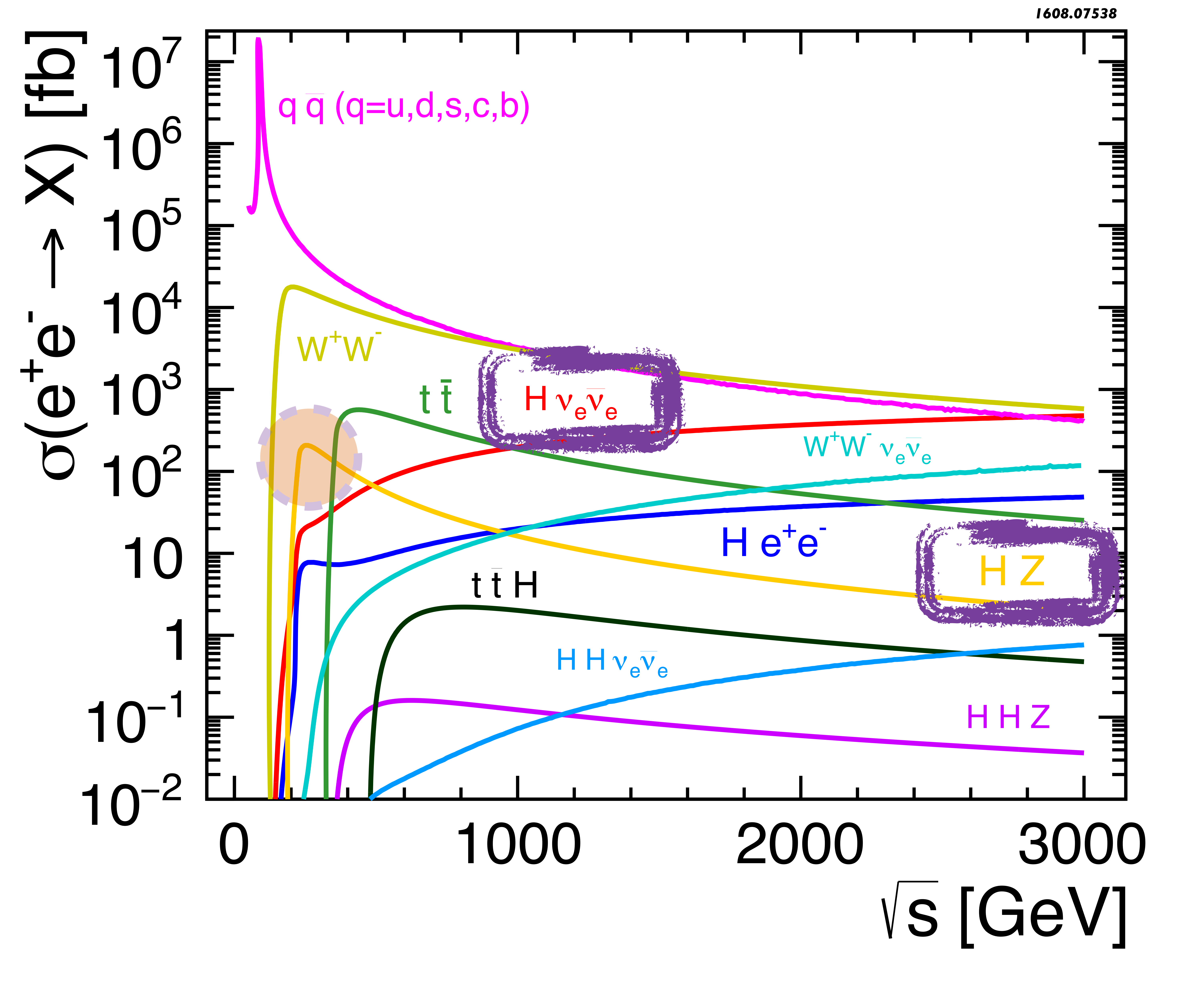


$$\sigma(Zh) \sim \frac{1}{s}$$

$$\sigma(h\nu\nu) \sim \frac{1}{v^2} \log \frac{s}{v}$$



Maximum $\sigma(e^+e^- \to Zh)$ at $\sqrt{s} \simeq 0.24$ TeV

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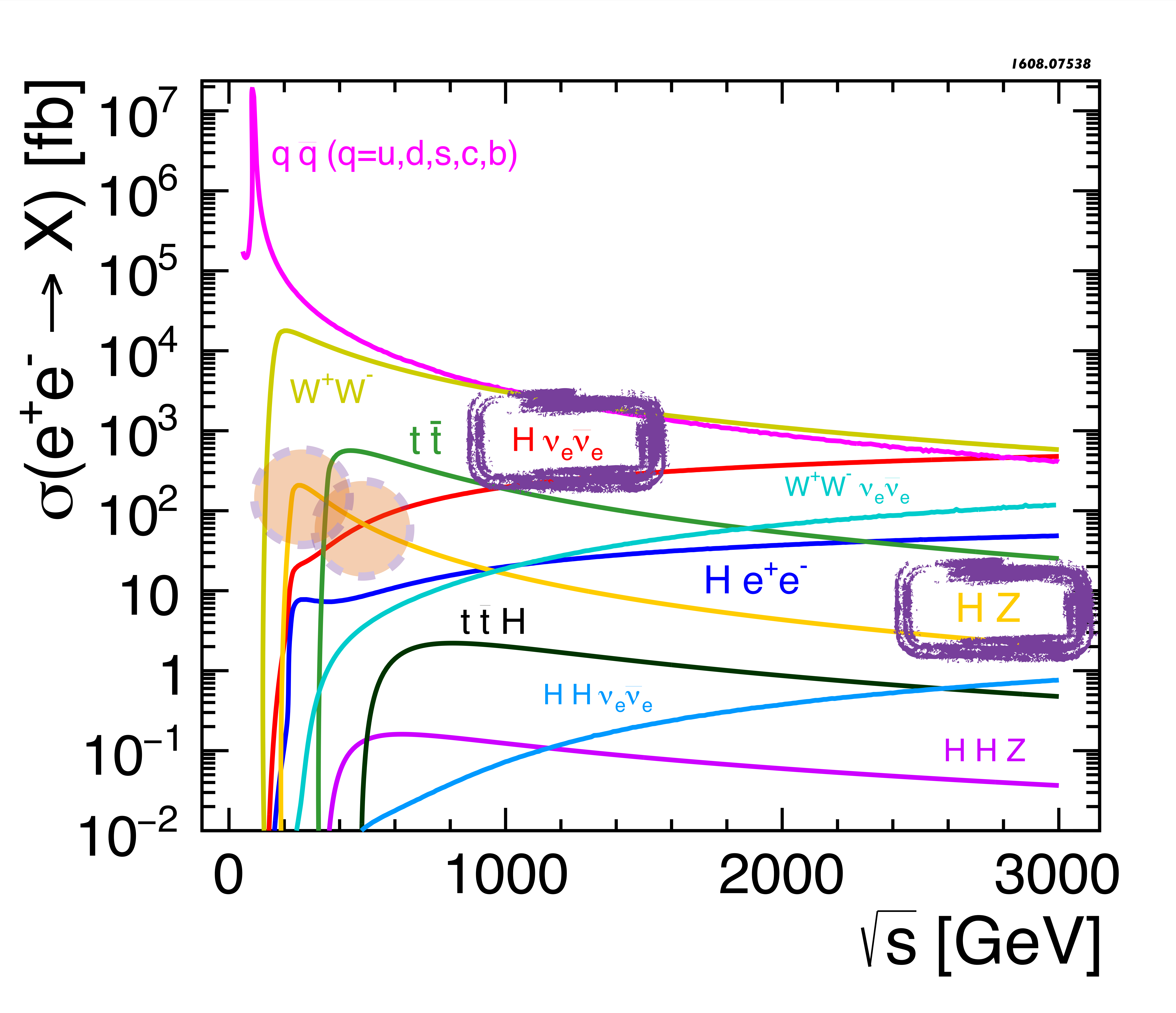

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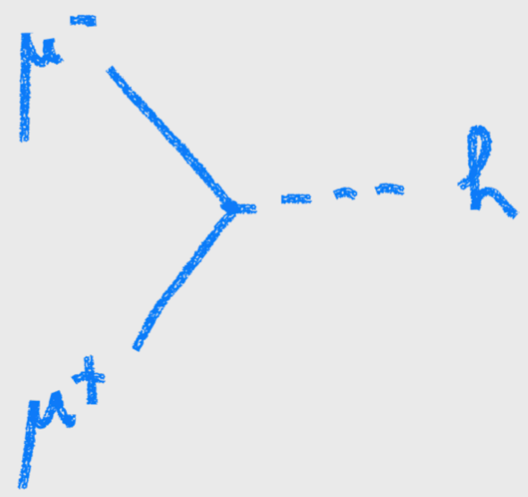
$\sigma(e^+e^- \to \nu\nu H) \gg \sigma(e^+e^- \to Zh)$ at $\sqrt{s} >$ TeV

$$\sigma(h\nu\nu) \sim \frac{1}{v^2} \log \frac{s}{v}$$

The road ahead is marked towards a Higgs factory…

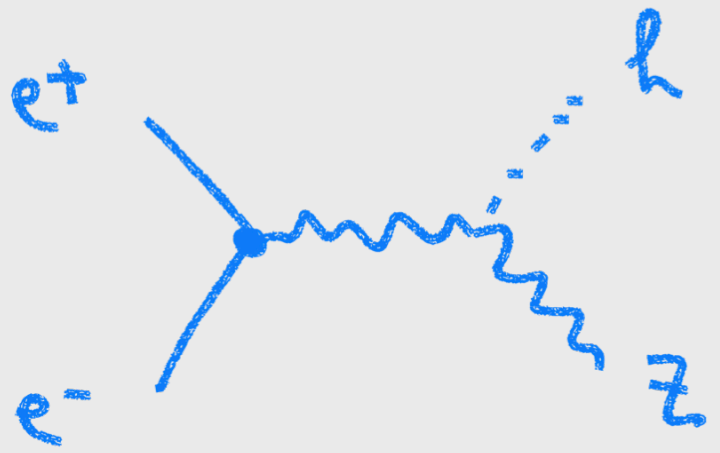
Types of Higgs factory

$\sqrt{s} = m_h$



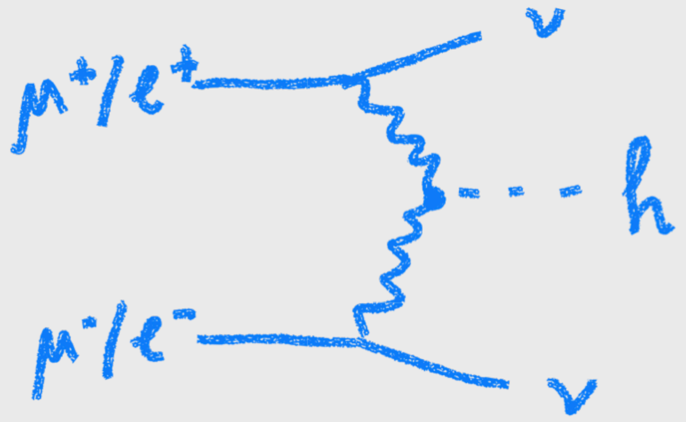
type-1

$\sqrt{s} \simeq m_h + m_Z$



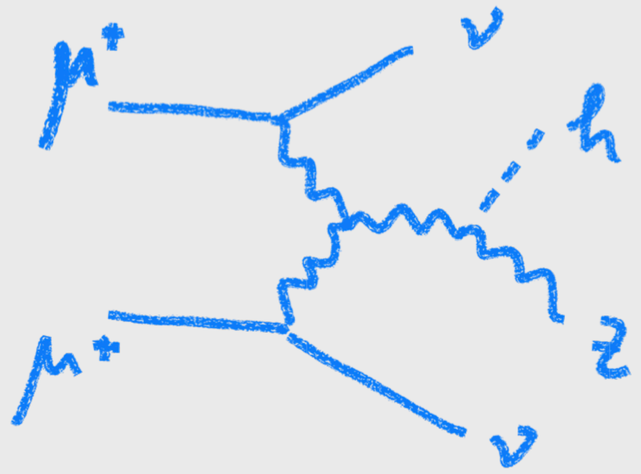
type-2

$\sqrt{s} \gg m_h$



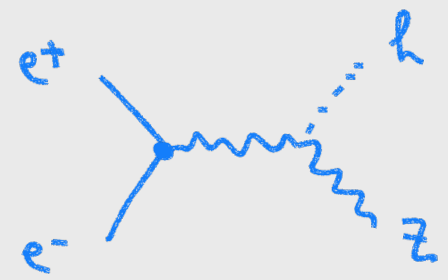
type-3

$\sqrt{s} \ggg m_h$

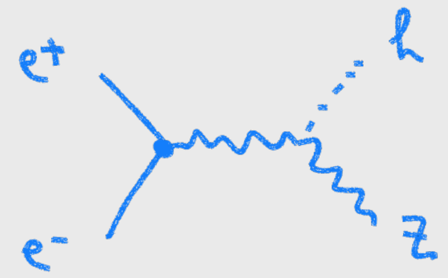


type-4

the path to the Higgs factory

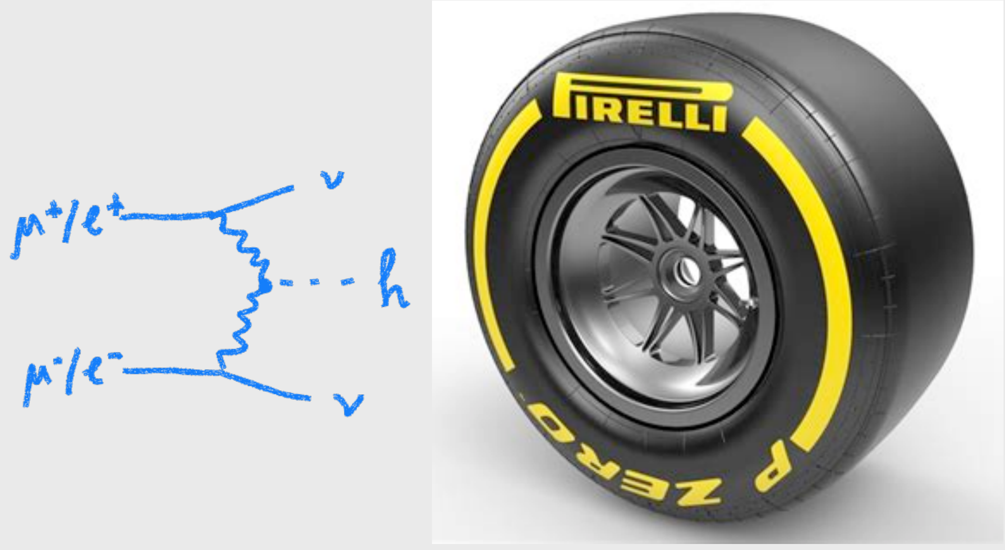


- a circular e^+e^- Higgs factory (FCC-ee or CEPC) seems to be favored because of the positive correlation with a future *pp* circular collider sharing the (big) expense for a 100Km tunnel



- a high energy linear e^+e^- Higgs factory is mature for construction (ILC250 or CLIC380). Upgrade path to higher energy linear colliders well established (up to 3 TeV c.o.m. energy)

other paths to the Higgs factory



- a High energy μ collider 3 TeV c.o.m., that means a **new type of machine** with a clear upgrade path to 10+ TeV

- a low-energy μ collider at the Higgs pole

- a Higgs factory in the LEP tunnel (it is not forbidden by the laws of physics)

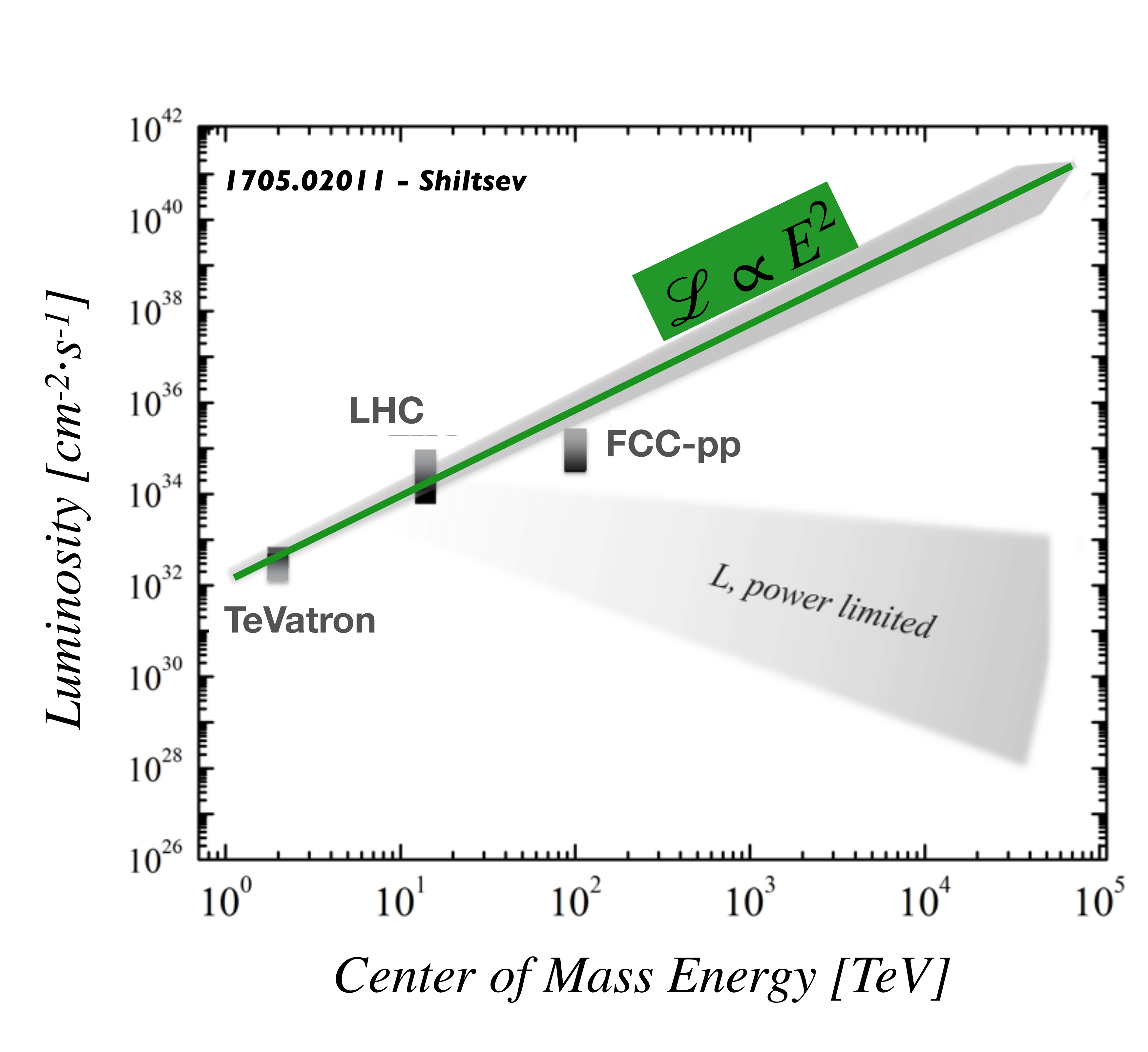
beyond the Higgs factory

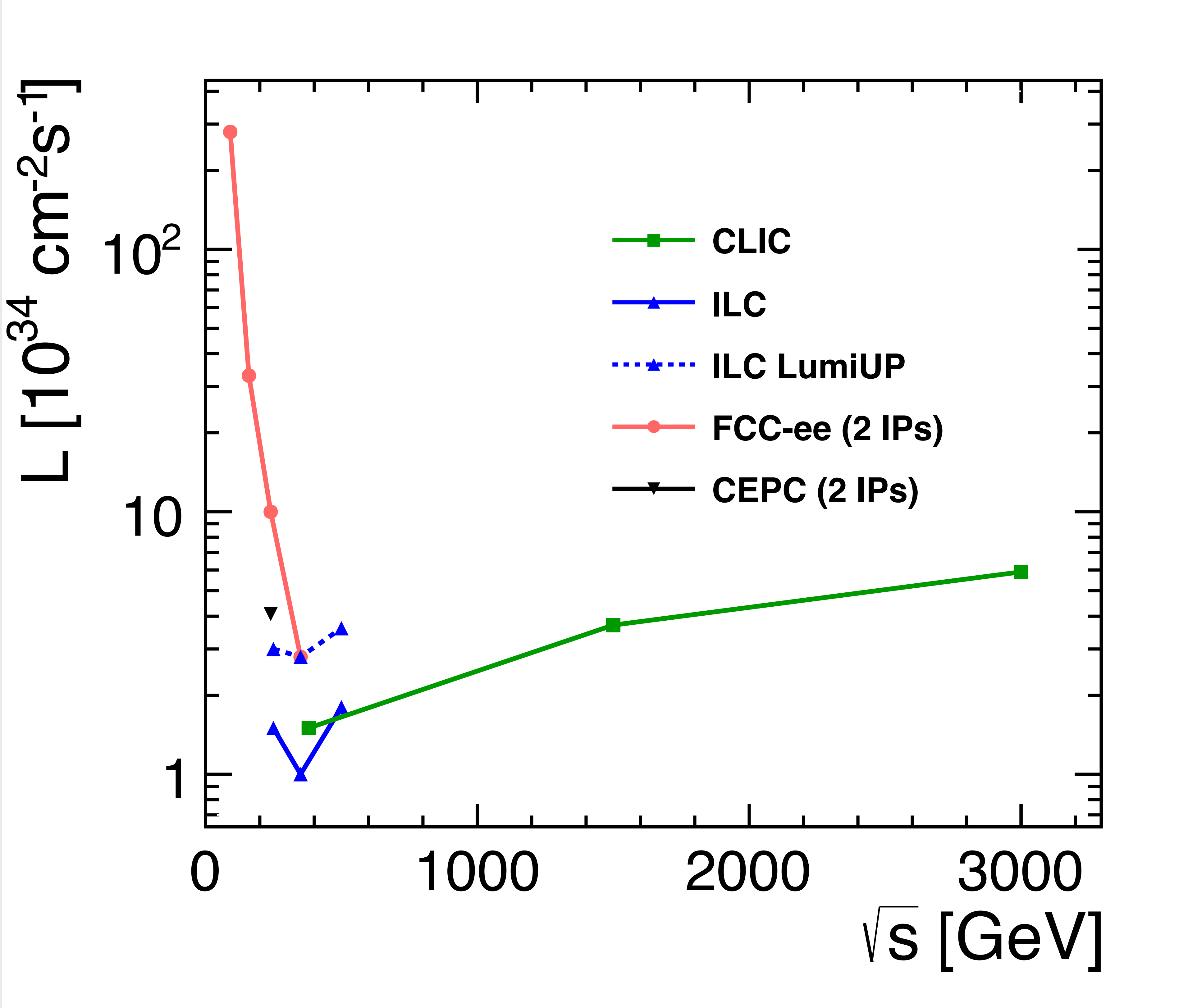
Challenges

TIME

$$\sigma(ab \to cd) \sim 1/E^2 \Rightarrow \text{you want } \mathscr{L} \sim E^2$$

$$\mathscr{L} \cdot \sigma(ab \to cd) \sim \text{const}$$





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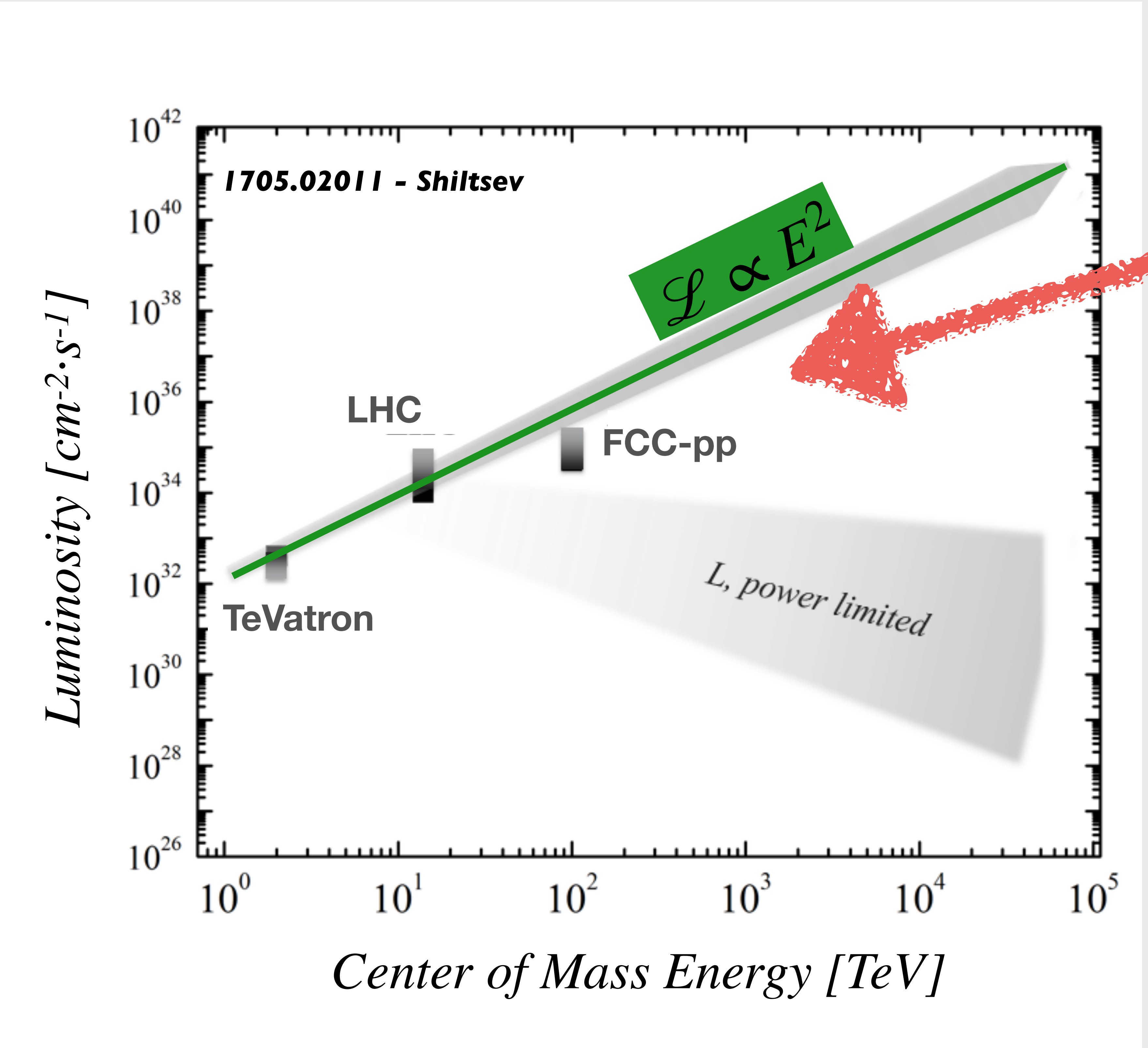
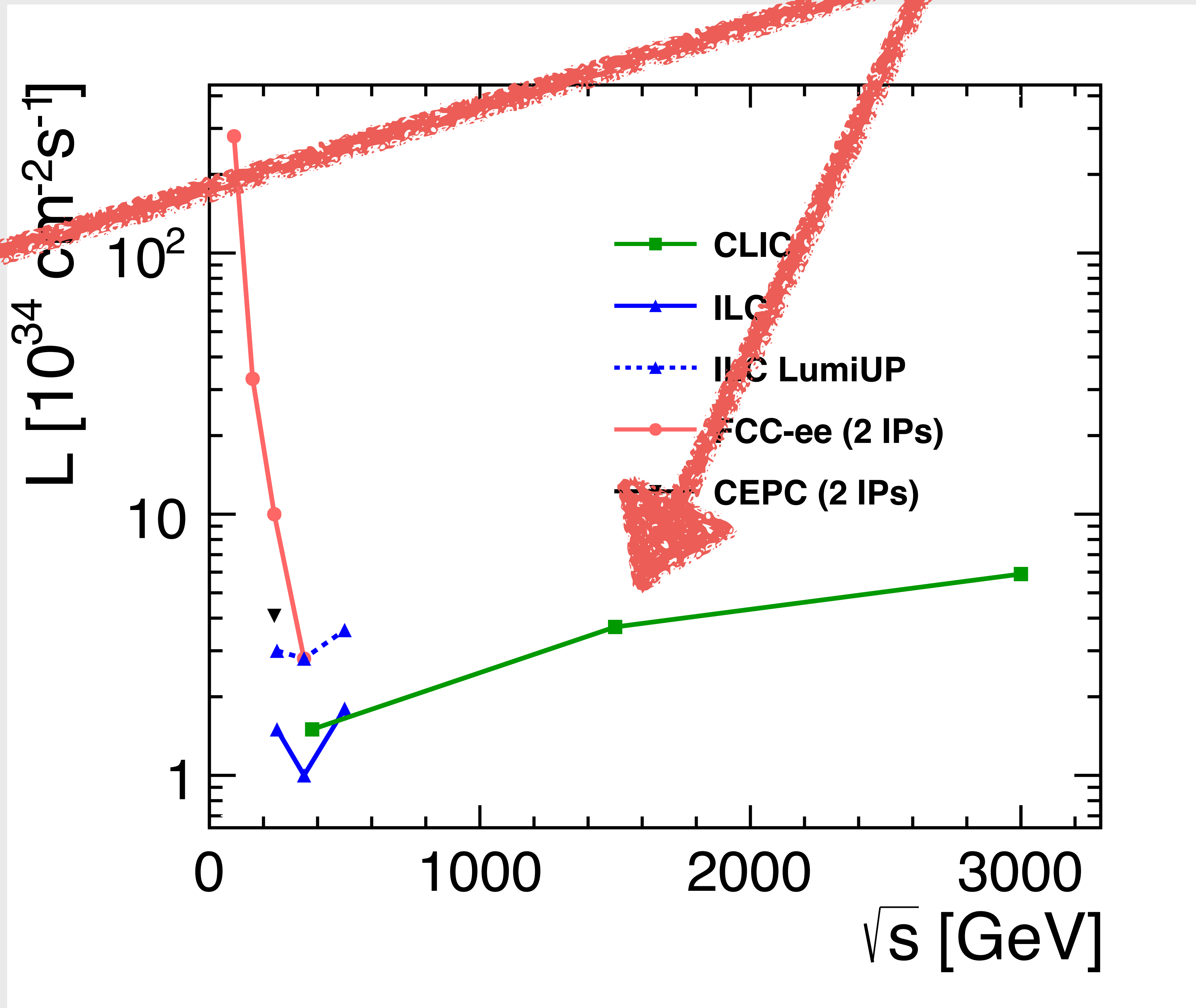
Luminosity is not growing fast enough





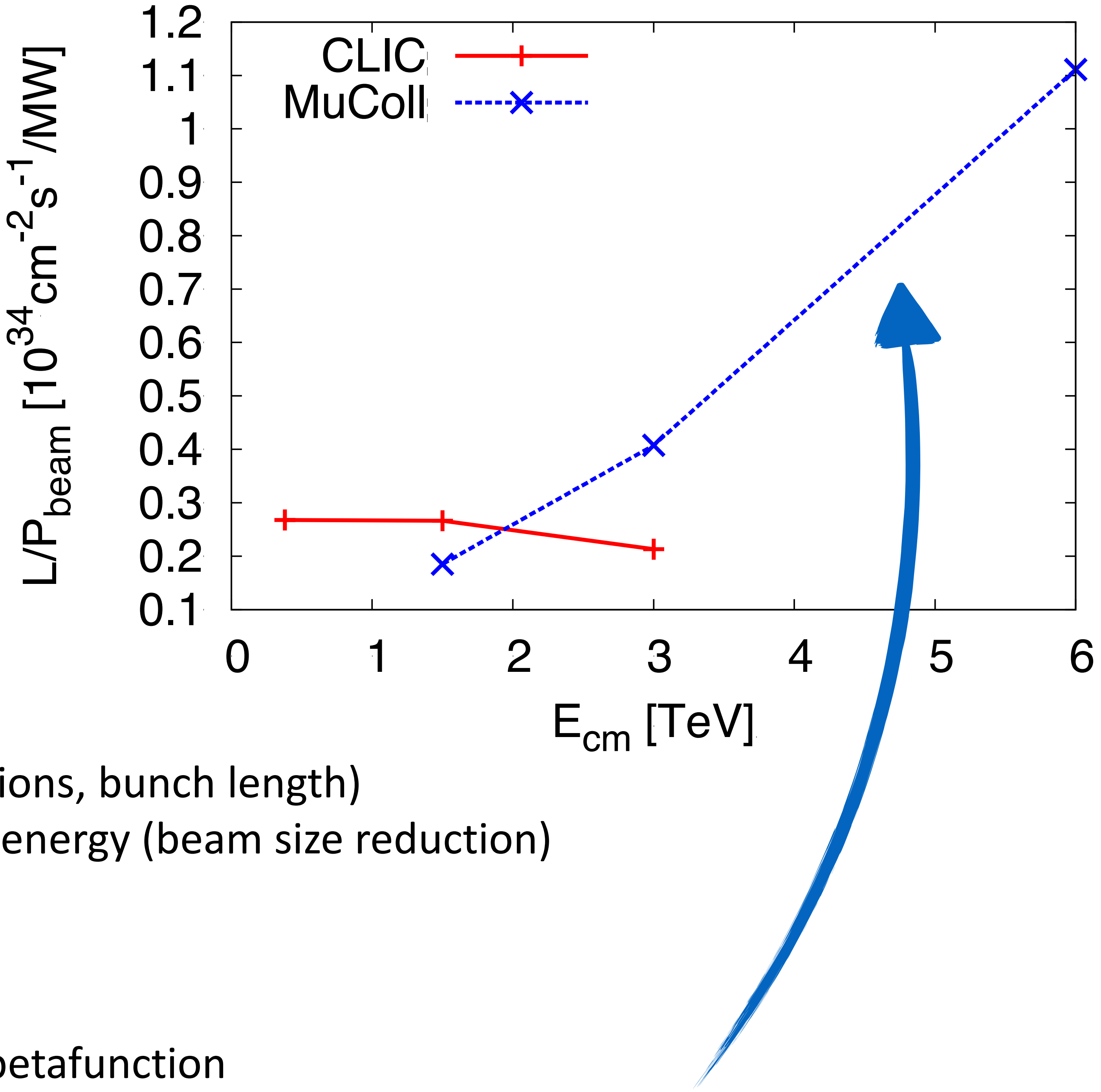
Muon colliders

HIGHLY EFFICIENT | HIGH ENERGY COLLIDER

Luminosity Comparison

The luminosity per beam power is about constant in linear colliders

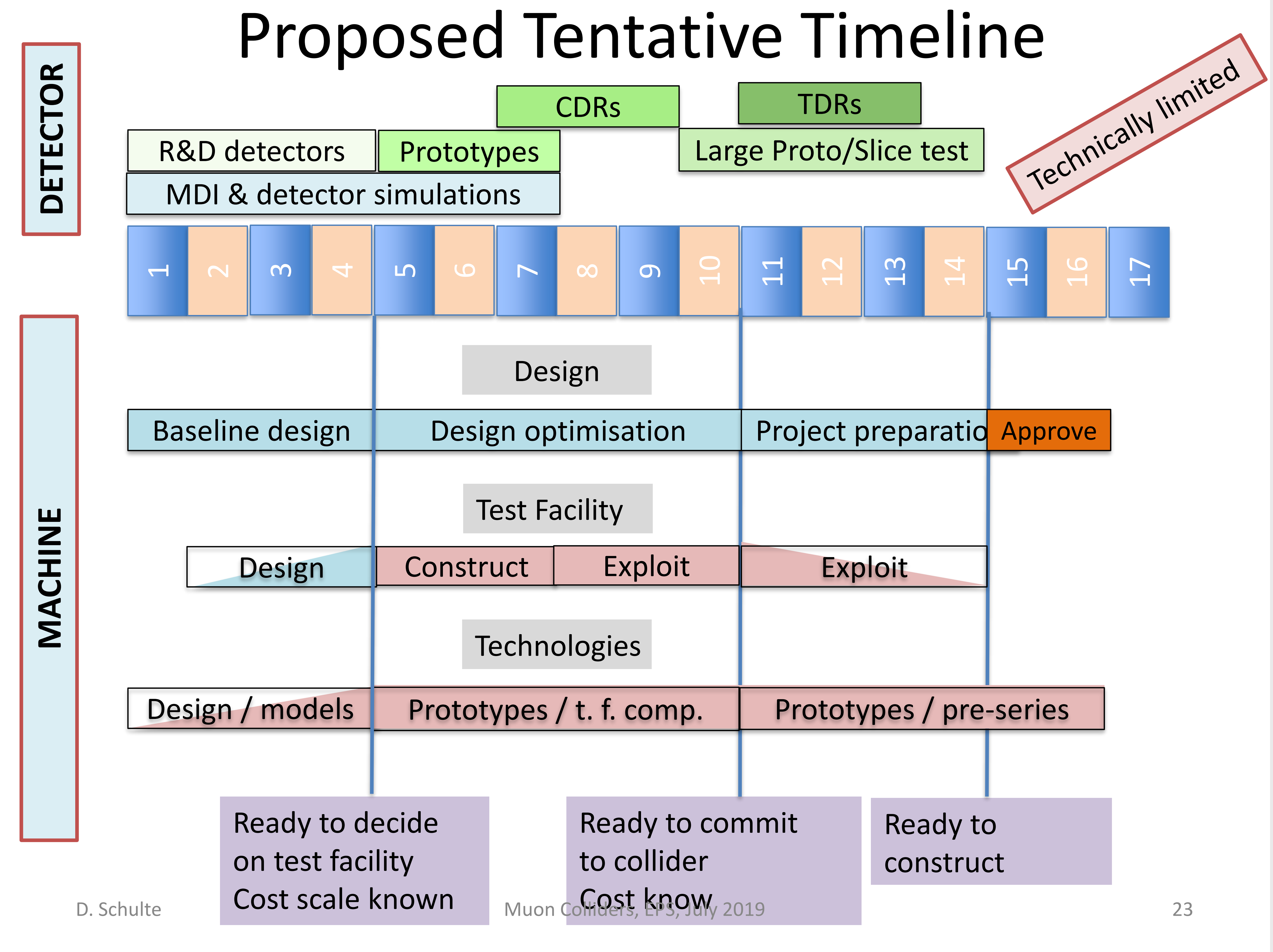
It can increase in proton-based muon colliders



Strategy CLIC:
Keep all parameters at IP constant
(charge, norm. emittances, betafunctions, bunch length)
⇒ Linear increase of luminosity with energy (beam size reduction)

Strategy muon collider:
Keep all parameters at IP constant
With exception of bunch length and betafunction
⇒ Quadratic increase of luminosity with energy (beam size reduction)

D. Schulte Muon Colliders, EPS, July 2019 7



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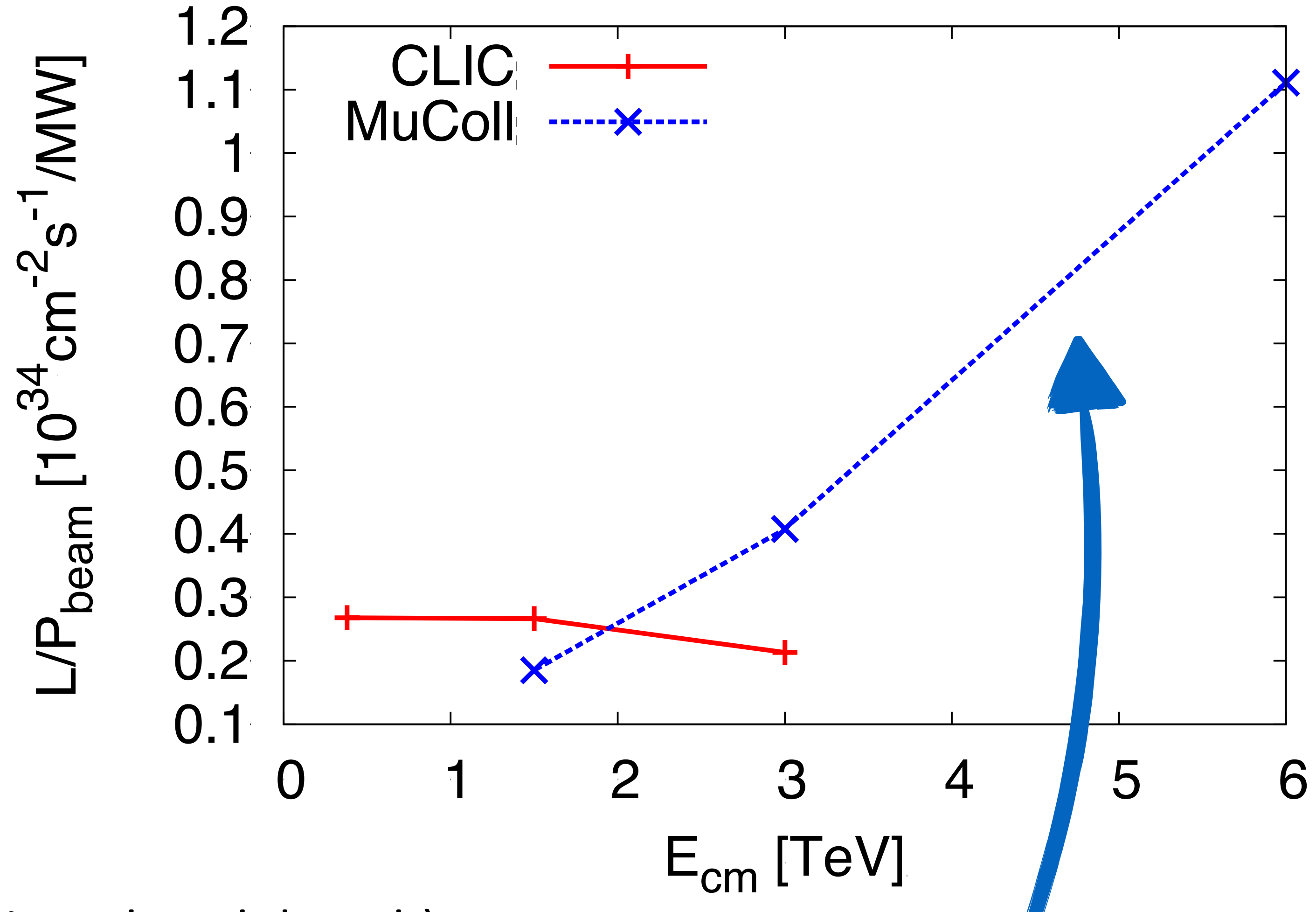

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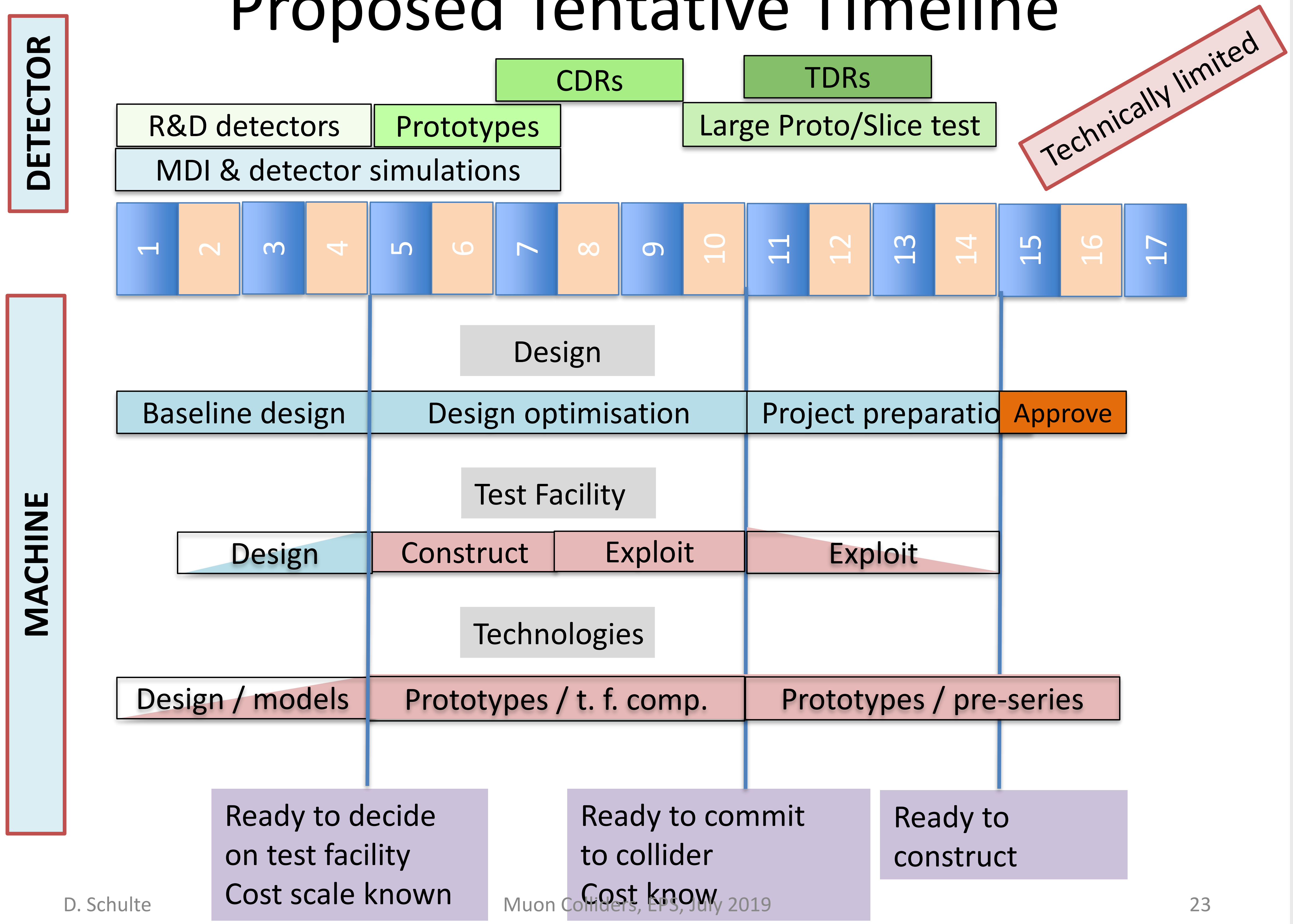
Proposed Tentative Timeline



Muon colliders

HIGHLY EFFICIENT HIGH ENERGY COLLIDER

Luminosity Comparison

Proposed Tentative Timeline

- International Muon Collider Collaboration formed to establish the physics case and the feasibility of a high energy muon collider

International MUON Collider Collaboration

Keep all parameters at IP constant
With exception of bunch length and betafunction
⇒ Quadratic increase of luminosity with energy (beam size reduction)

D. Schulte Muon Colliders, EPS, July 2019 7

Ready to decide on test facility
Cost scale known

Ready to commit to collider
Cost know

Ready to construct

D. Schulte Muon Colliders, EPS, July 2019 23

Muon colliders

HIGHLY EFFICIENT HIGH ENERGY COLLIDER

Towards a Muon Collider

Published in: *Eur.Phys.J.C* 83 (2023) 9, 864
Published: Sep 26, 2023
e-Print: 2303.08533 [physics.acc-ph]
DOI: 10.1140/epjc/s10052-023-11889-x
Report number: FERMILAB-PUB-23-123-AD-PPD-T

https://arxiv.org/abs/2303.08533

⇒ Quadratic increase of luminosity with energy (beam size reduction)

D. Schulte Muon Colliders, EPS, July 2019 7

Cost scale known Cost know

D. Schulte Muon Colliders, EPS, July 2019 23

Muon colliders

HIGHLY EFFICIENT HIGH ENERGY COLLIDER

ider

Cost scale known

Cost know

Muon Colliders, ... July 2019

23

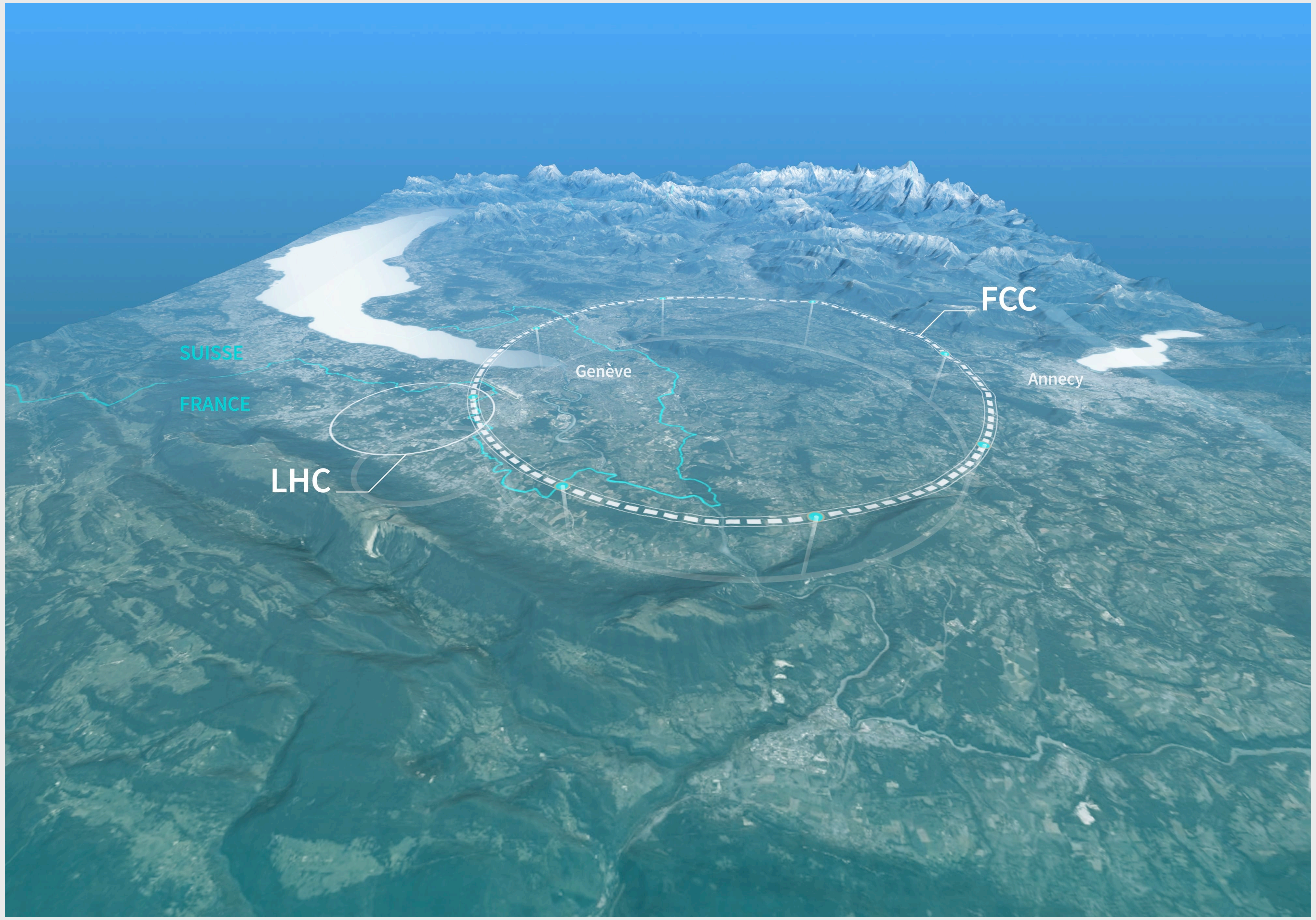
Muon colliders

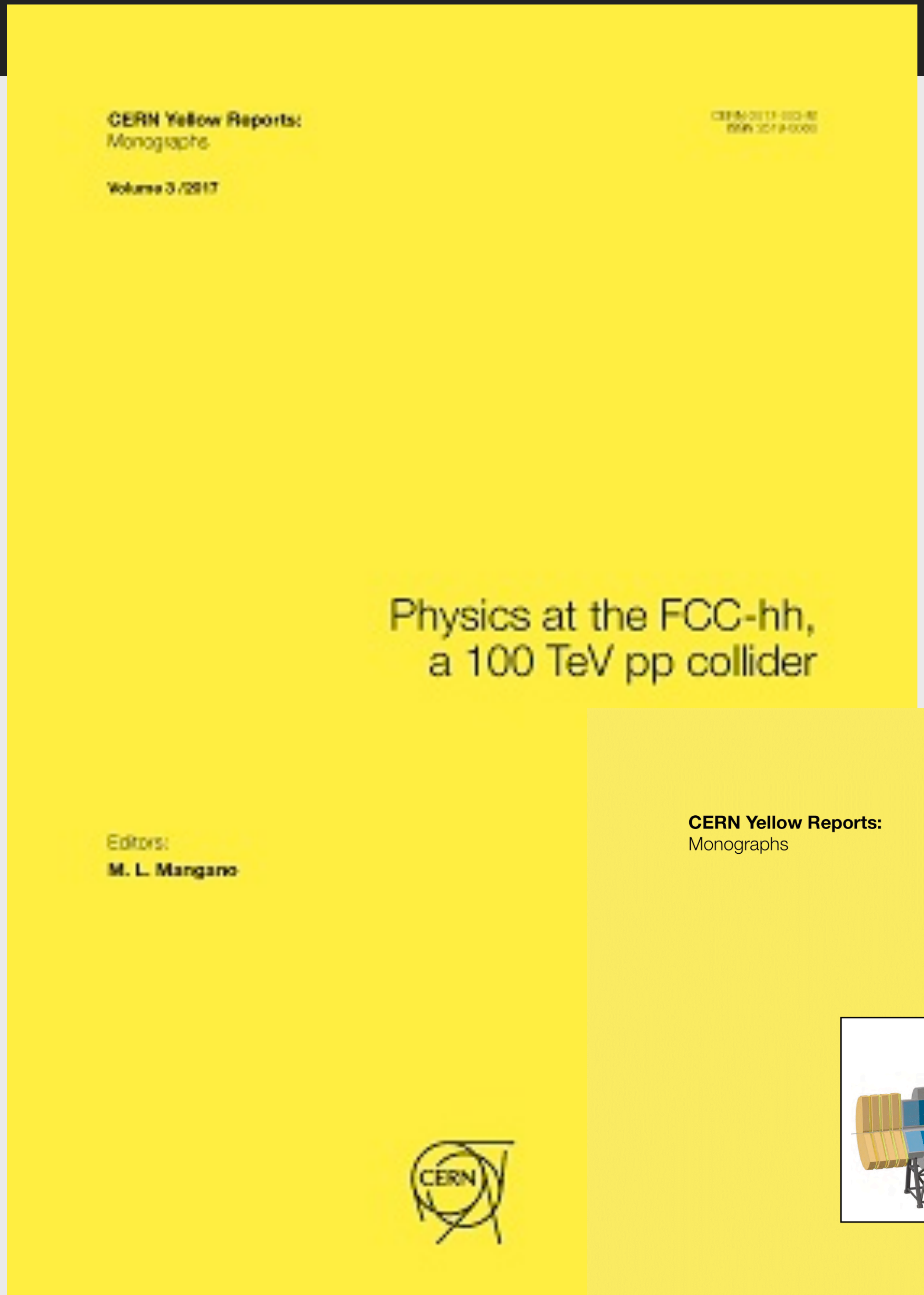
HIGHLY EFFICIENT HIGH ENERGY COLLIDER

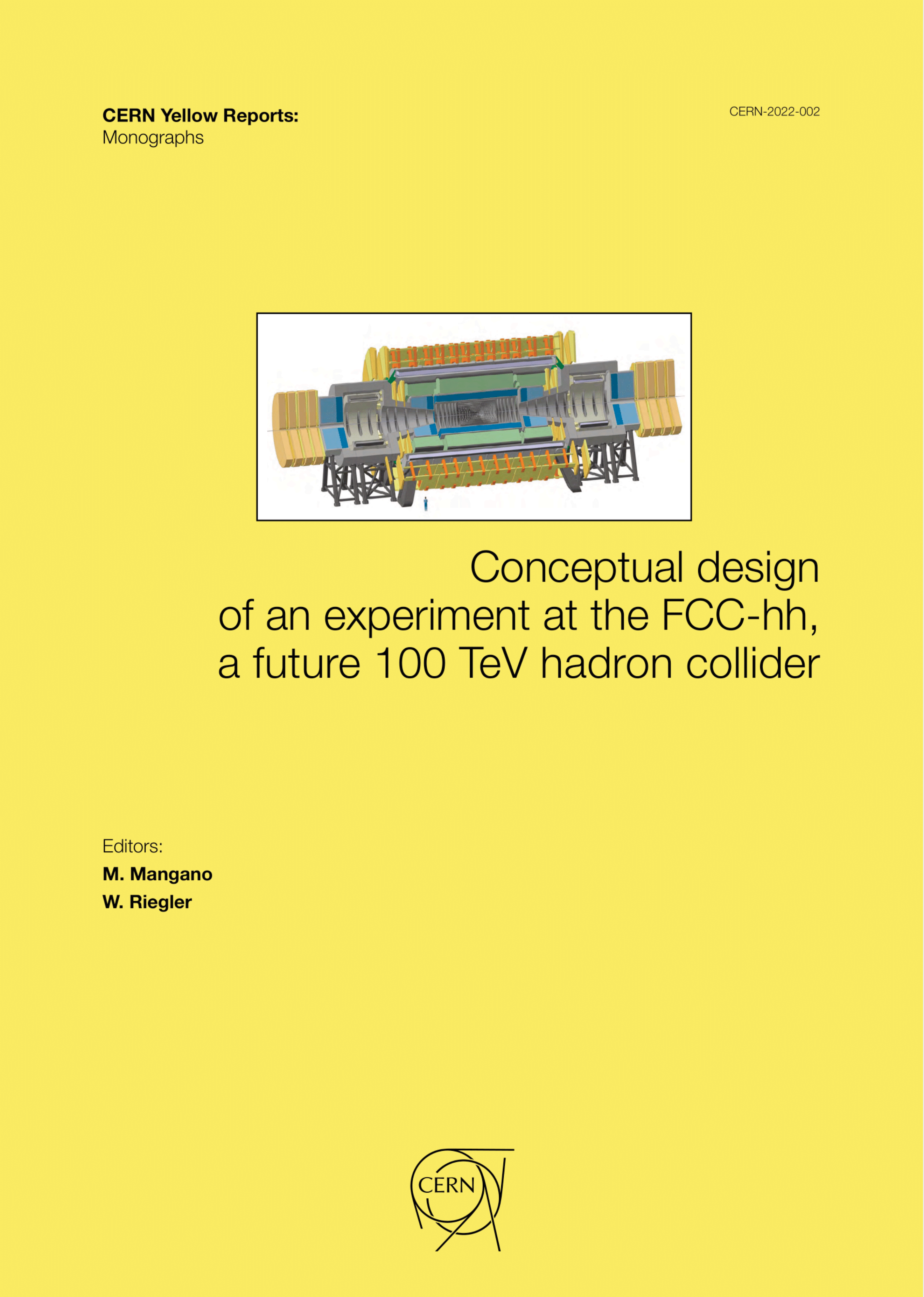
https://home.cern/science/accelerators/future-circular-collider

Hadron colliders

HIGHEST BEAM ENERGY







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Hadron colliders

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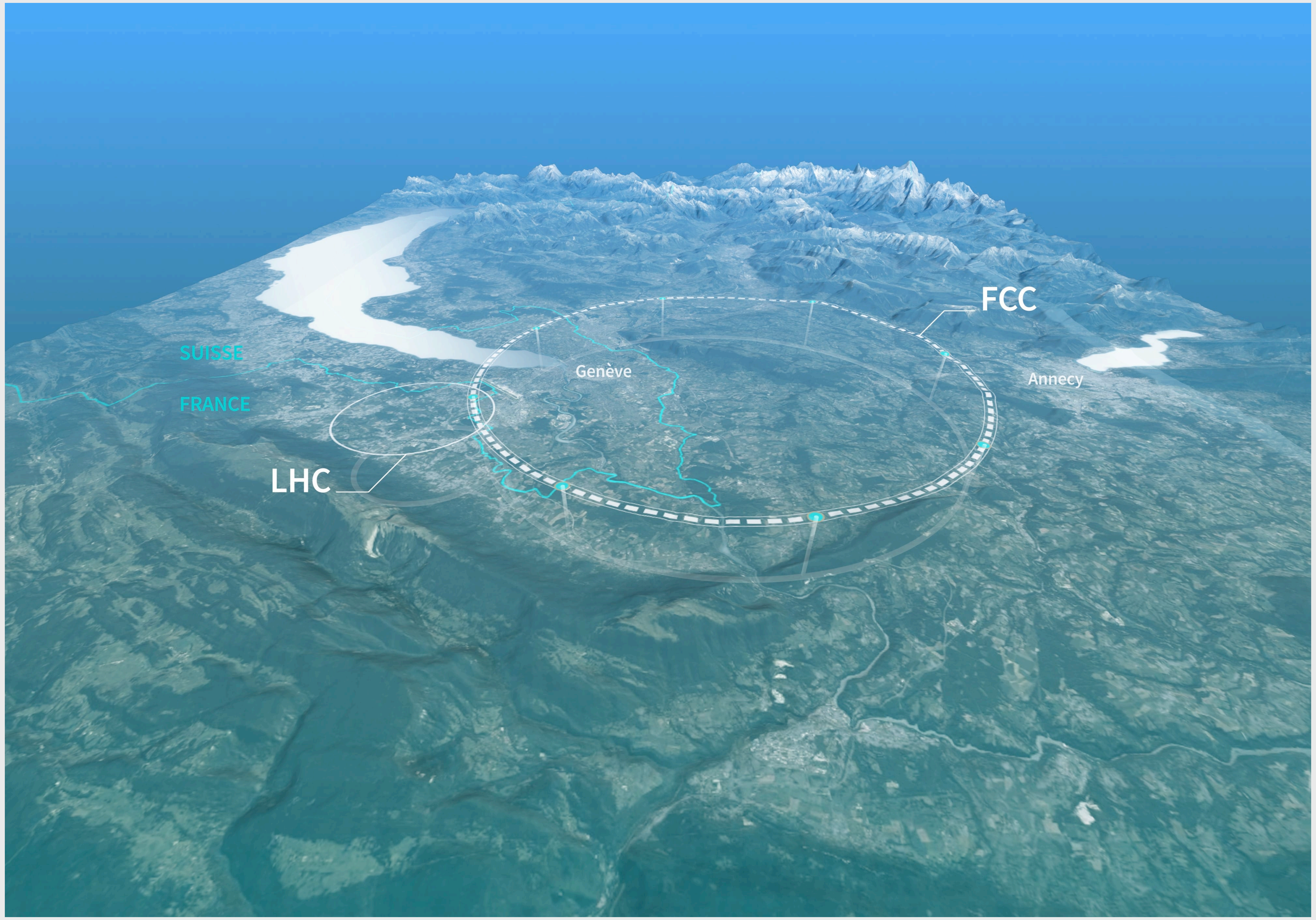
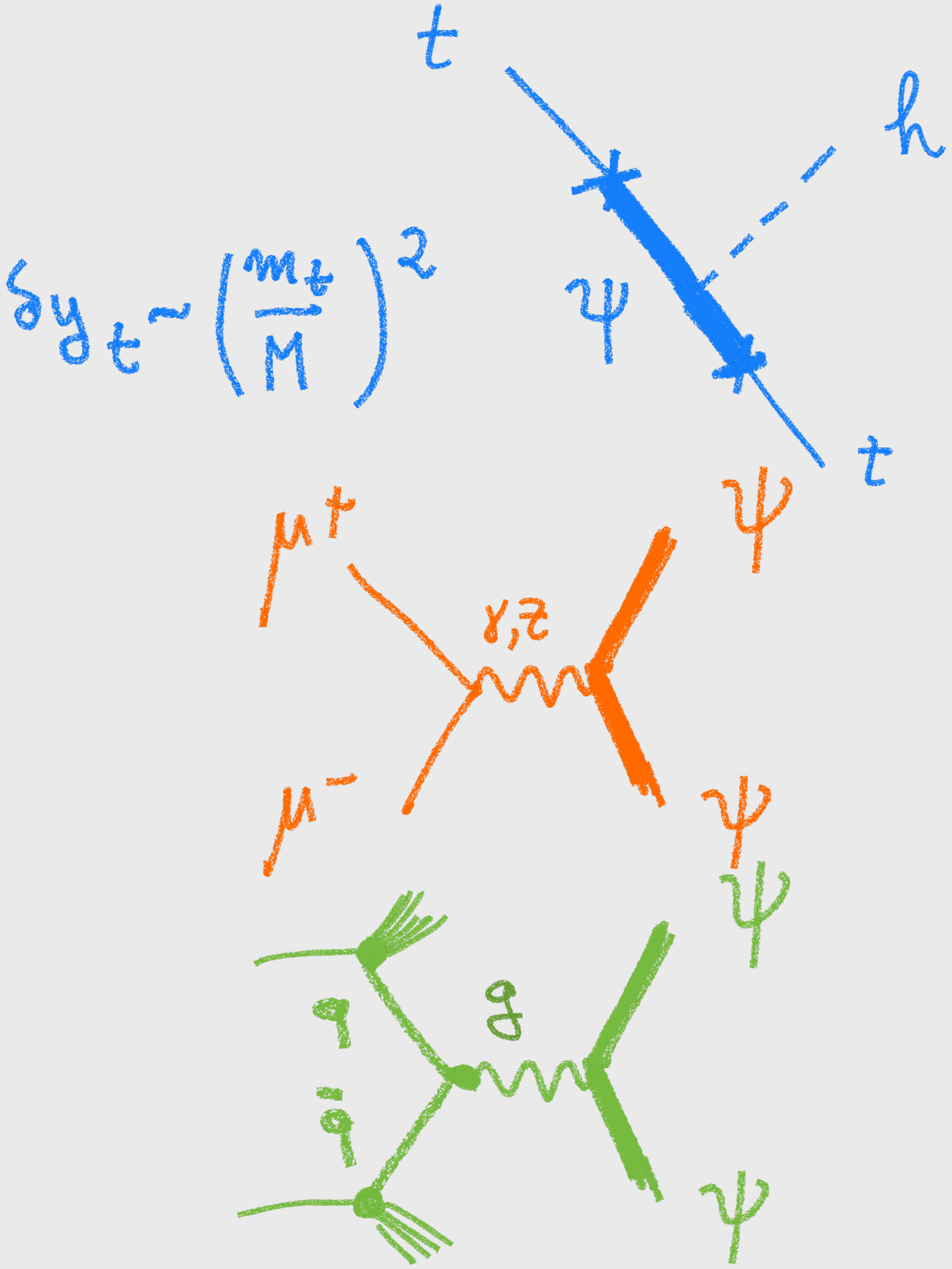
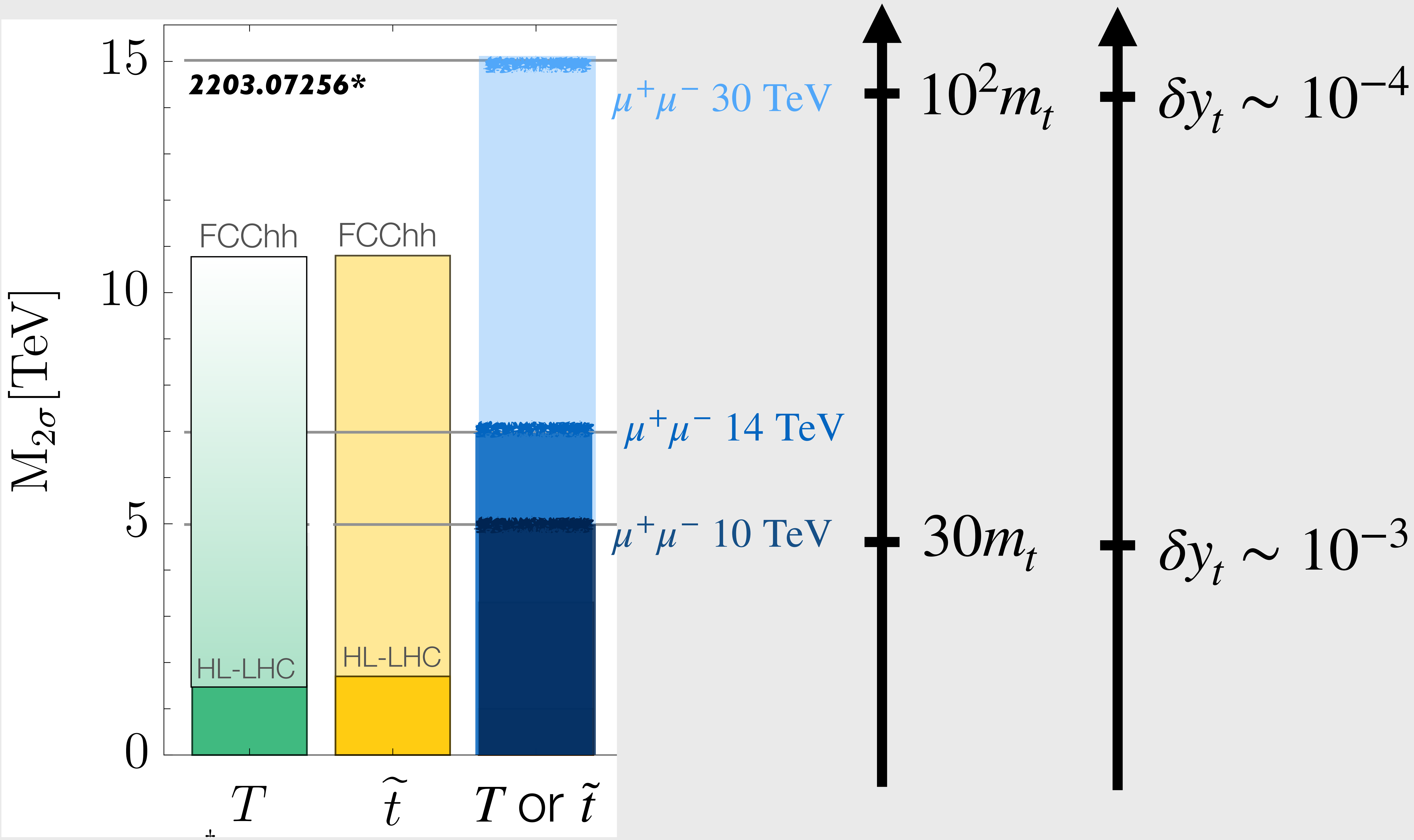


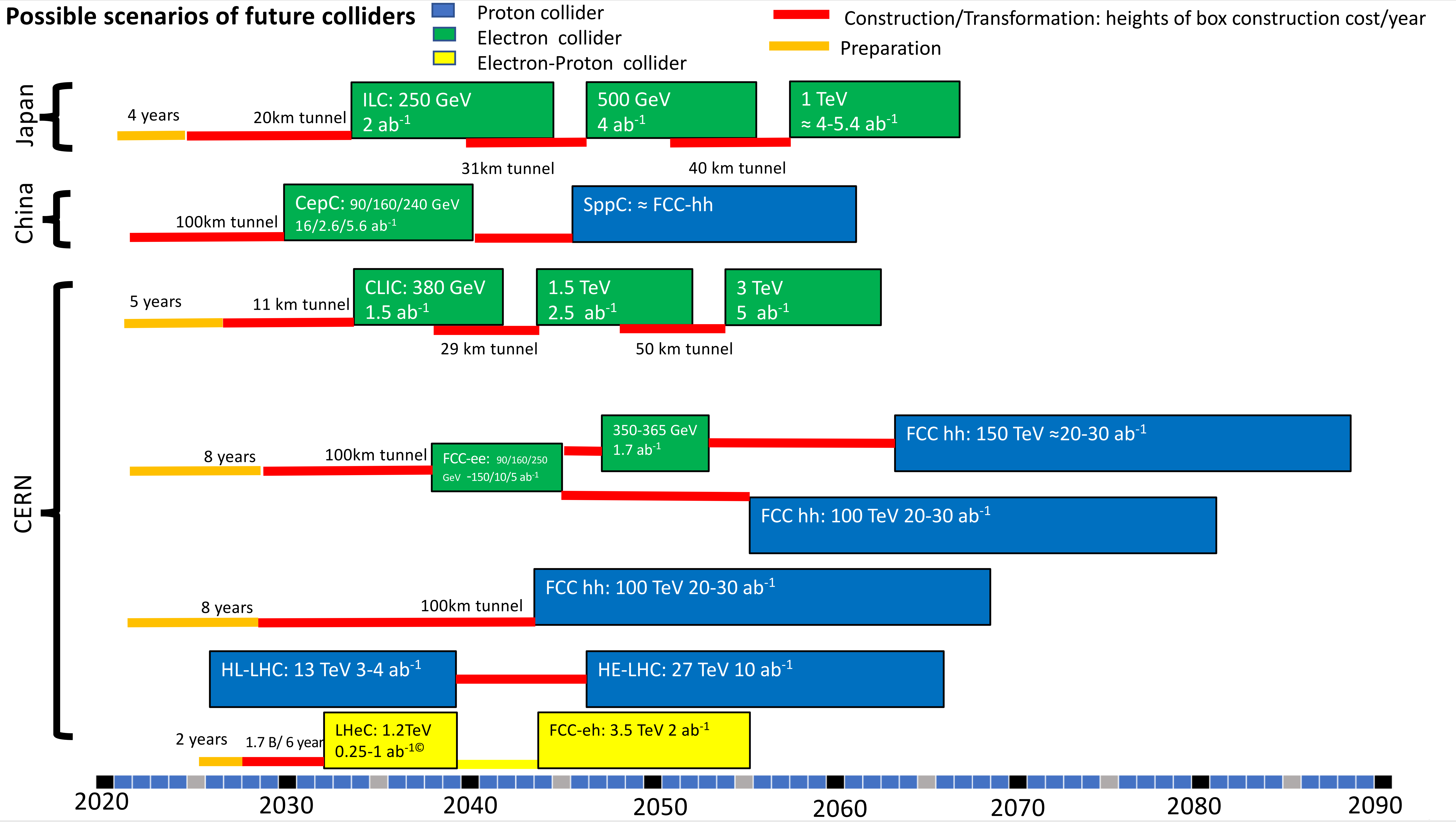
The top quark Yukawa is off by few %?

Search for a new heavy top quark T!





Are we ready?



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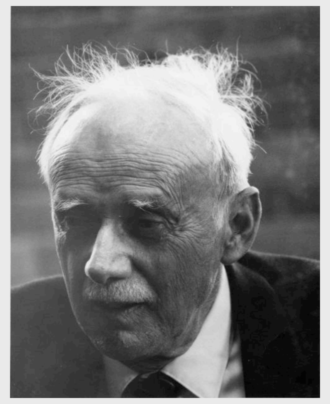
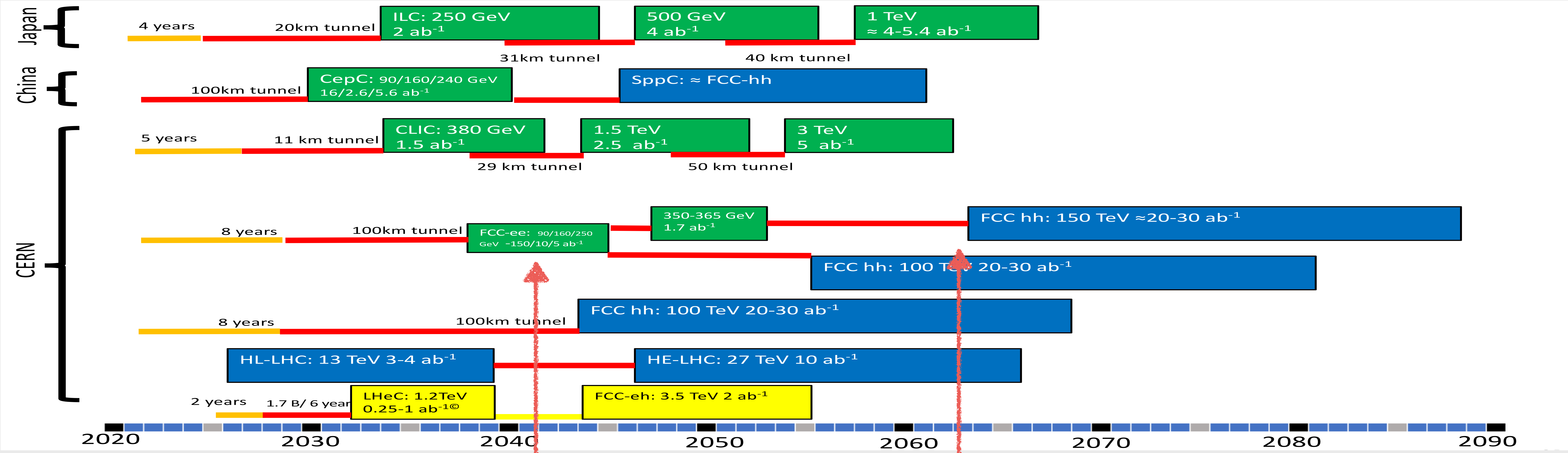
2020
2030
2040
2050
2060
2070
2080
2090

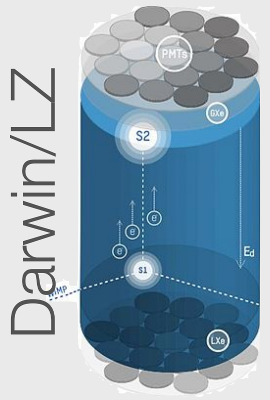
Are we ready?

$$n_i = \frac{1}{e^{(\epsilon_i - \mu)/k_B T} + 1}$$



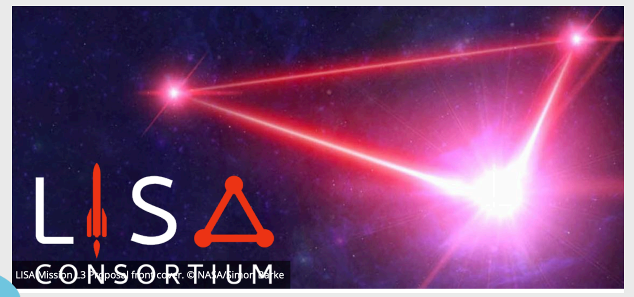


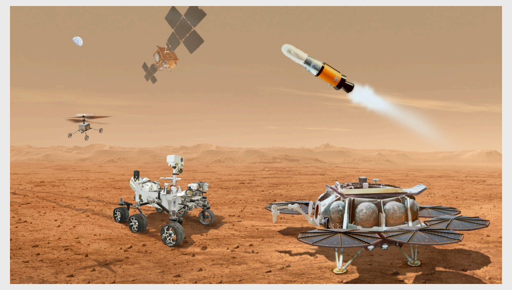
Belle II

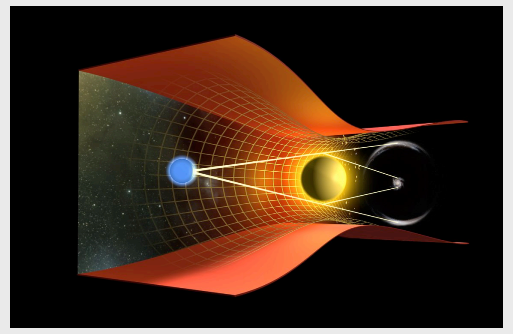


HiLumi HL-LHC PROJECT

g-2







2045 ± 5 first e^+e^- collisions pushing the intensity frontier

2060_0^{10} first pp collisions pushing the energy frontier

Are we ready for a revolution?

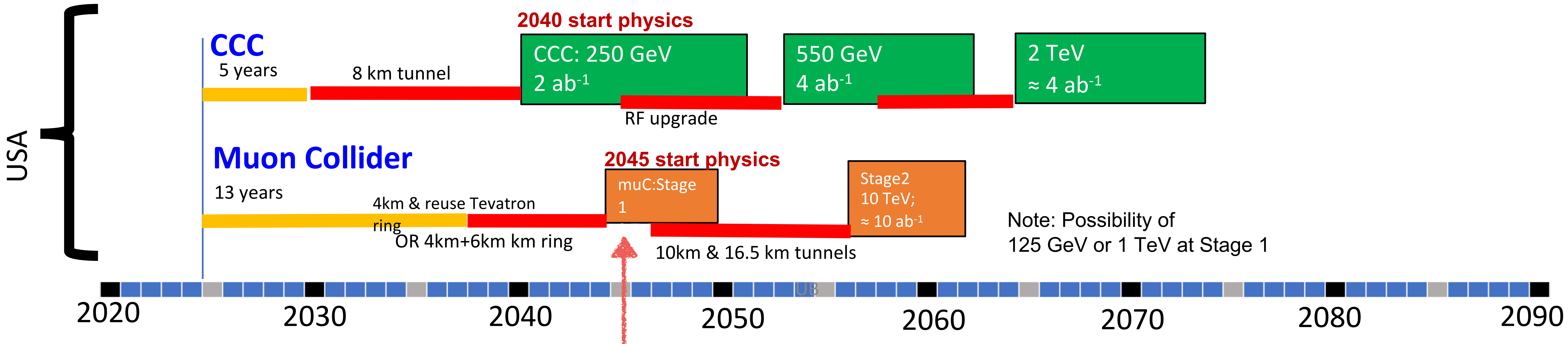
Possible scenarios of future colliders

Proton collider
Electron collider
Muon collider

Construction/Transformation
Preparation / R&D

Original from ESG by UB
Updated July 25, 2022 by MN

Proposals emerging from this Snowmass for a US based collider



- **Timelines technologically limited**
- Uncertainties to be sorted out
  - Find a contact lab(s)
  - Successful R&D and feasibility demonstration for CCC and Muon Collider
  - Evaluate CCC progress in the international context, and consider proposing an ILC/CCC [ie CCC used as an upgrade of ILC] or a CCC only option in the US.
  - International Cost Sharing

2045^{10}_{0} first $\mu^+\mu^-$ collisions pushing both the intensity and energy frontier

VERY SIGNIFICANT INTEREST FROM US COMMUNITY IN RECENT YEARS CULMINATED AT SNOWMASS 2022

Conclusions

Several deep open questions open for investigation

?	• what is the dark matter in the Universe?	✓		WEAK INTERACTIONS
	• why QCD does not violate CP?	✓	✓	STRONG INTERACTIONS
	• how have baryons originated in the early Universe?	✓		
	• what originates flavor mixing and fermions masses?	✓		
	• what gives mass to neutrinos?	✓		
~~EFT~~	• why gravity and weak interactions are so different?	✓		
~~EFT~~	• what fixes the cosmological constant?	✓		

Future Colliders can provide significant advances on these issues

Conclusions

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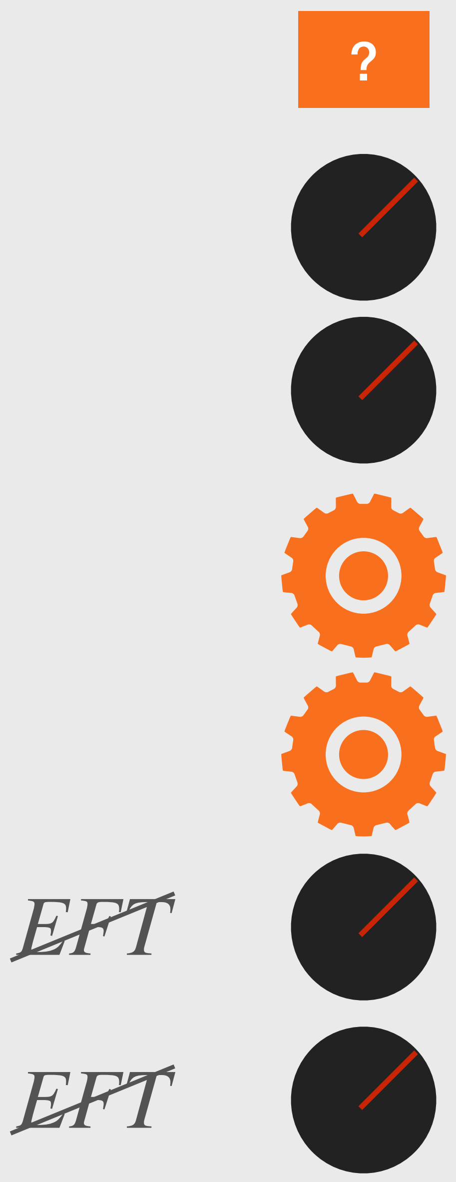

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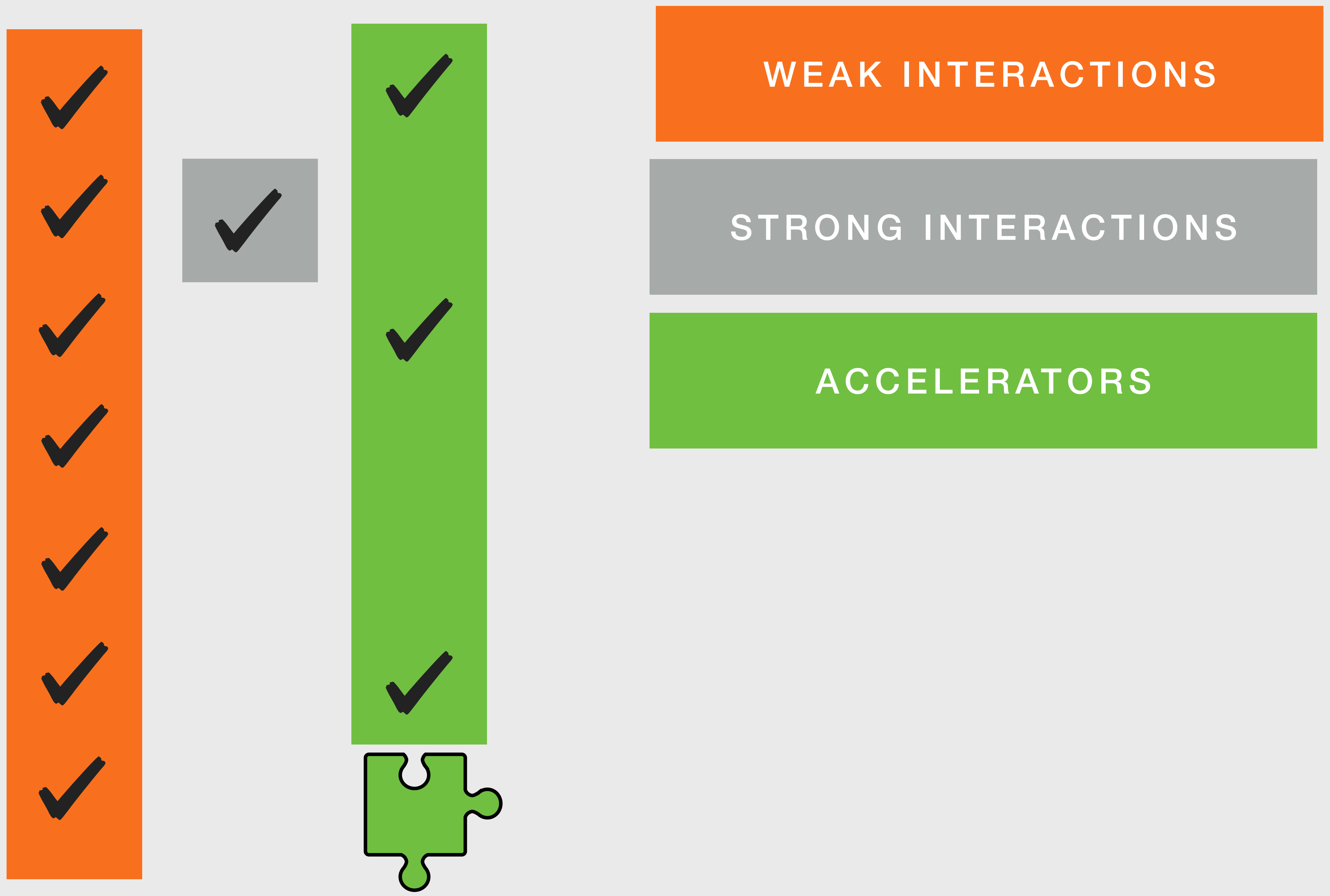

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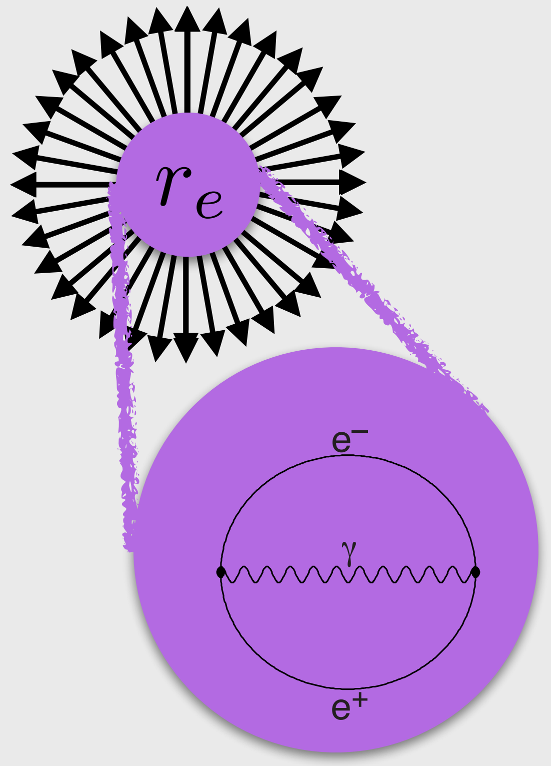
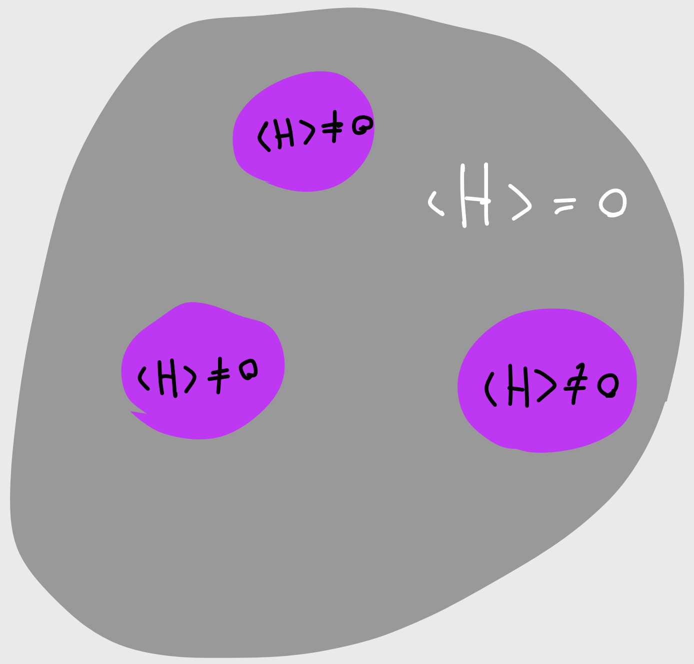
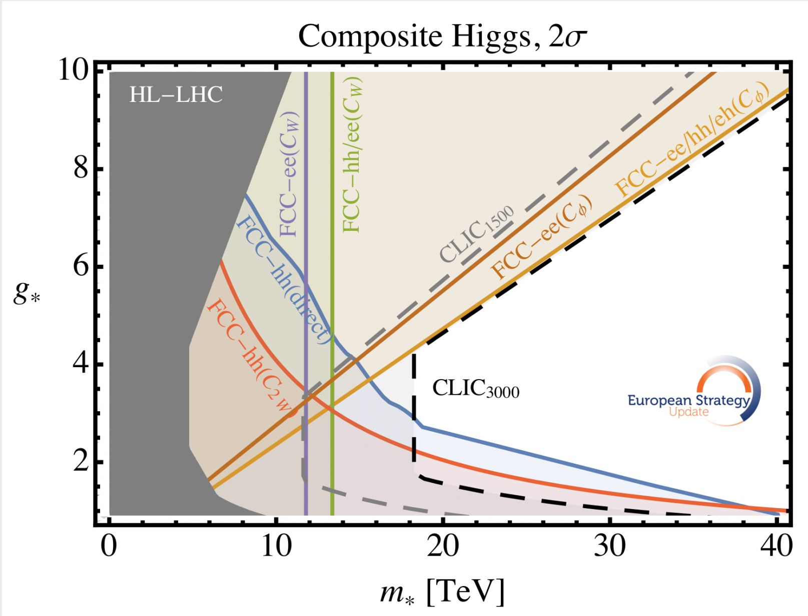
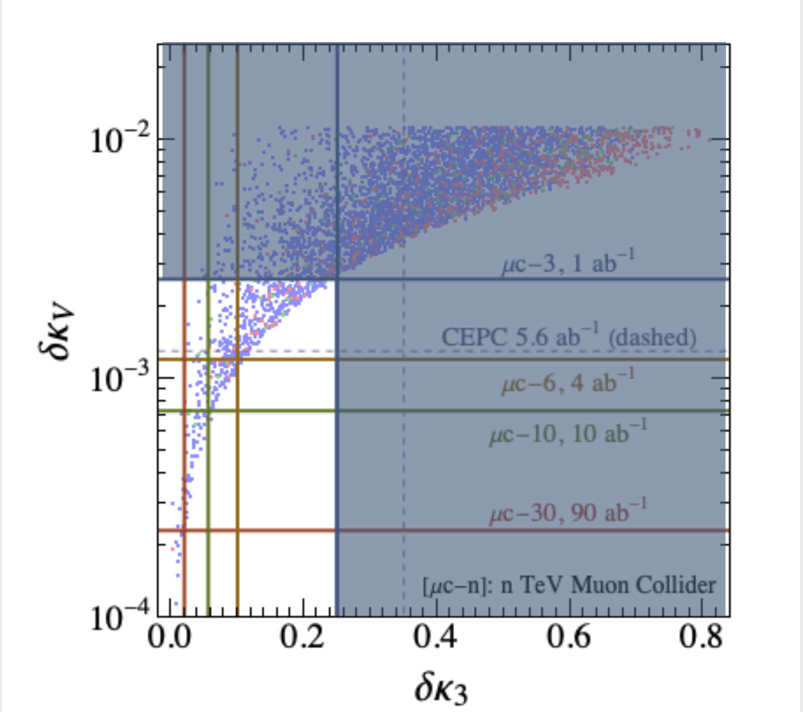
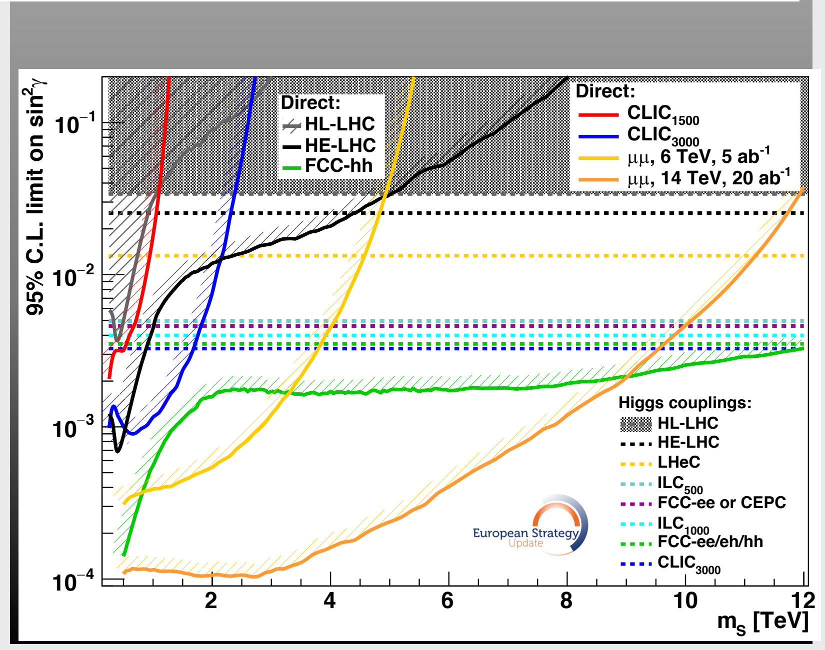
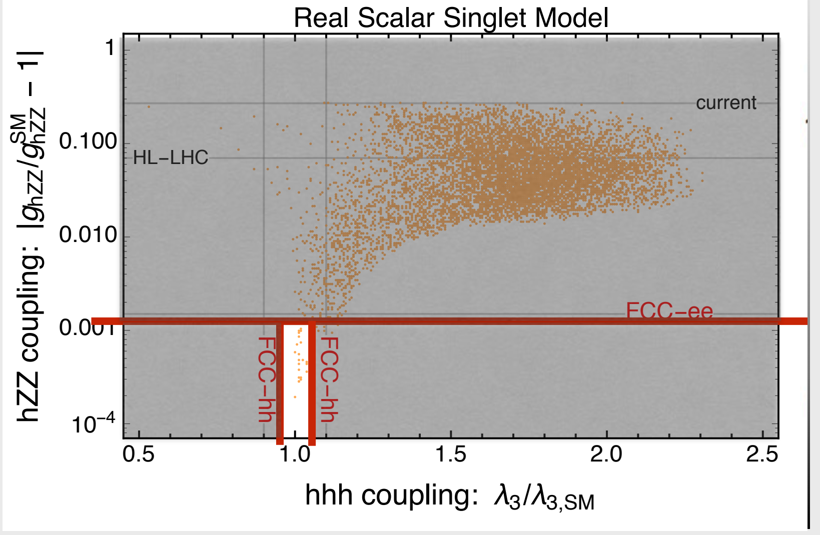












"WIMP" Dark Matter ***EW symmetry breaking*** ***EW phase transition***

effective c.o.m. energy

100 TeV

10+ TEV

Extraordinary probes of Higgs boson, electroweak new physics and Dark Matter

3 TEV

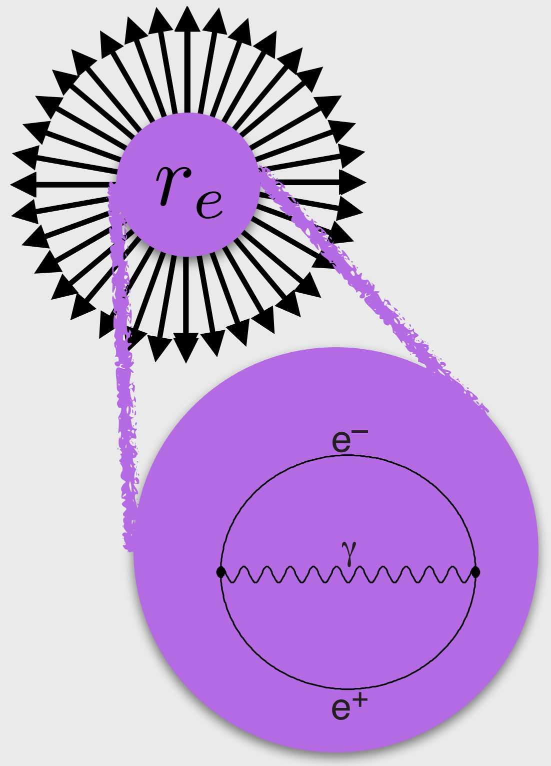
Several important milestones: **full exploration of TeV EW states, EW phase transition, TeV Dark Matter**

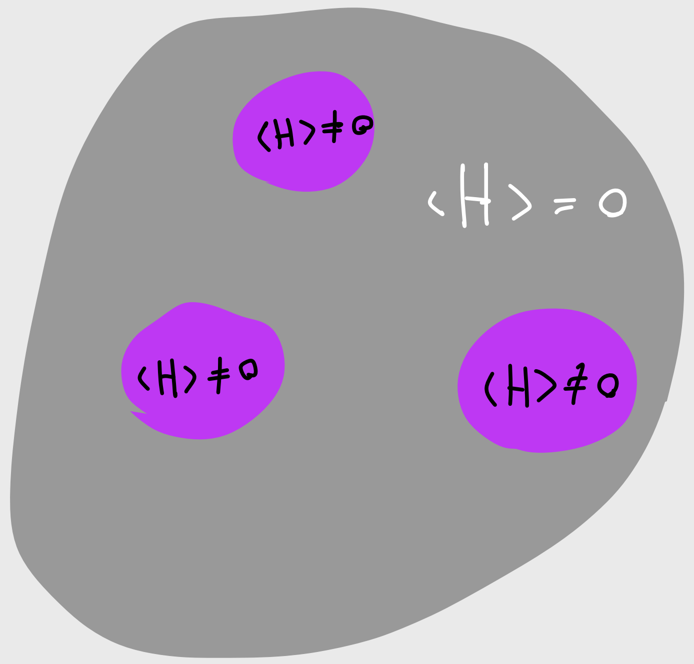
1 TeV

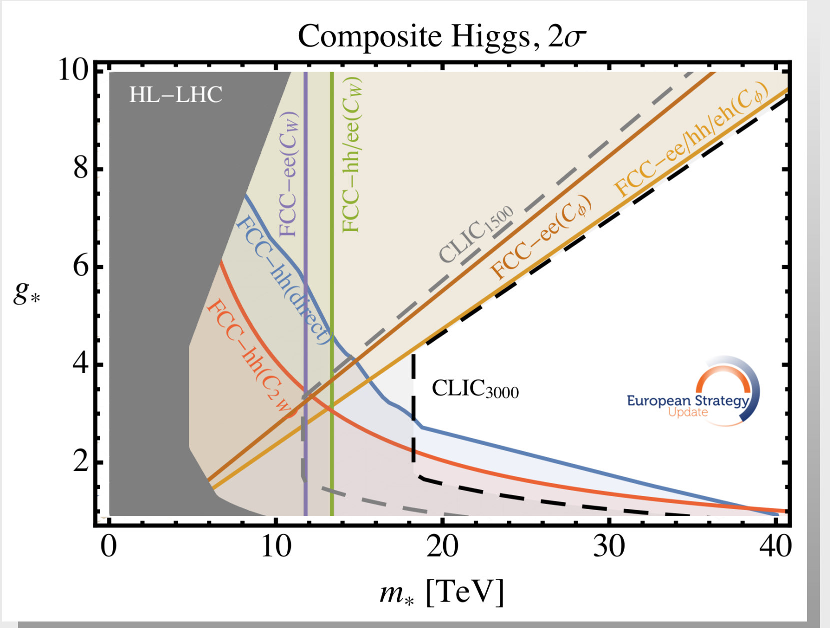
200-300 GeV

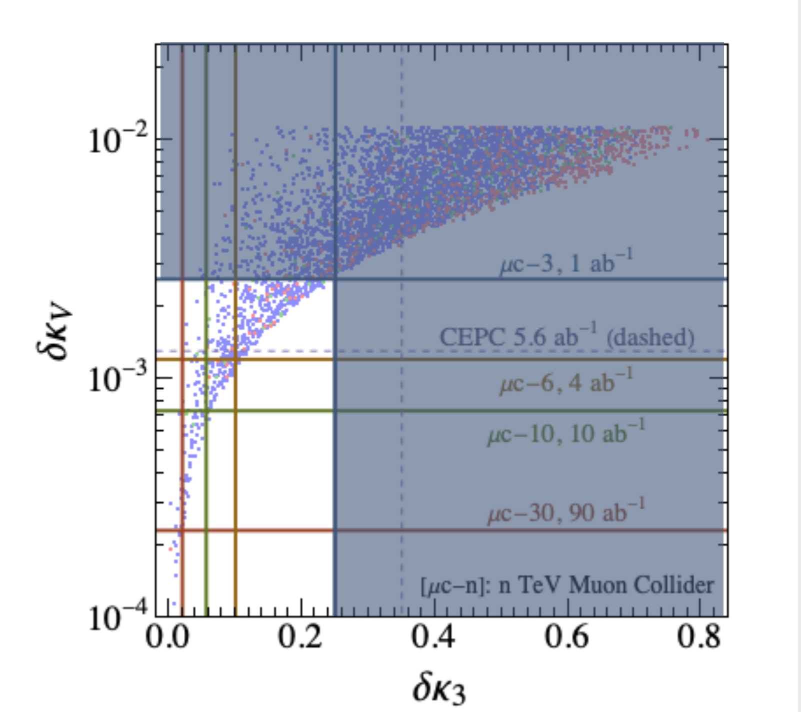
Precision study of the Higgs boson

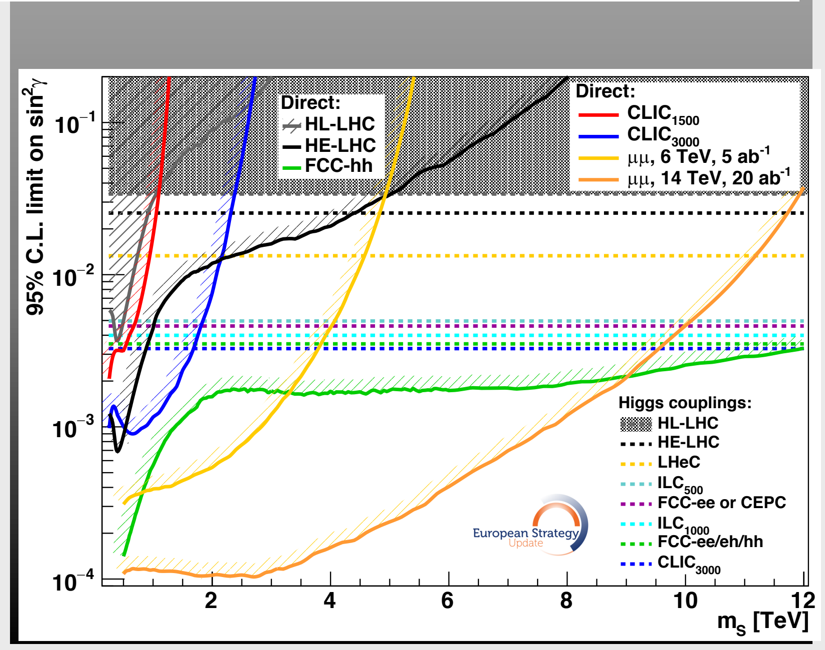
Conclusions

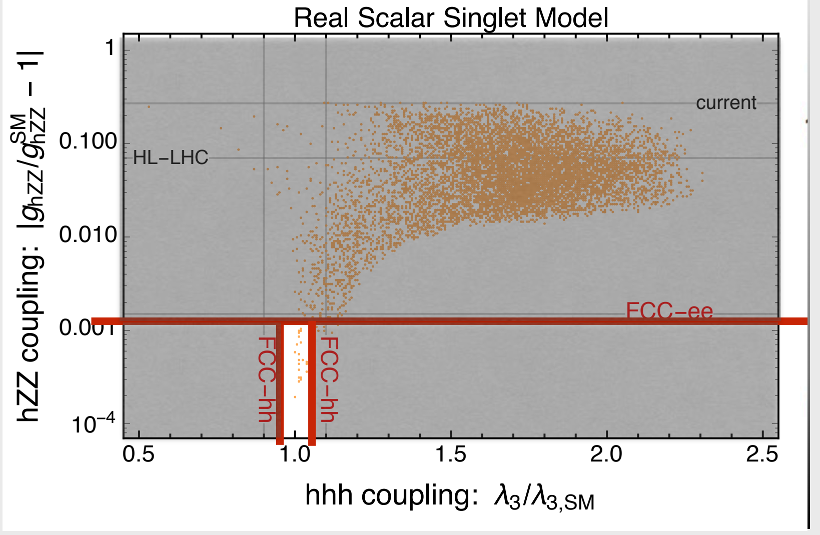












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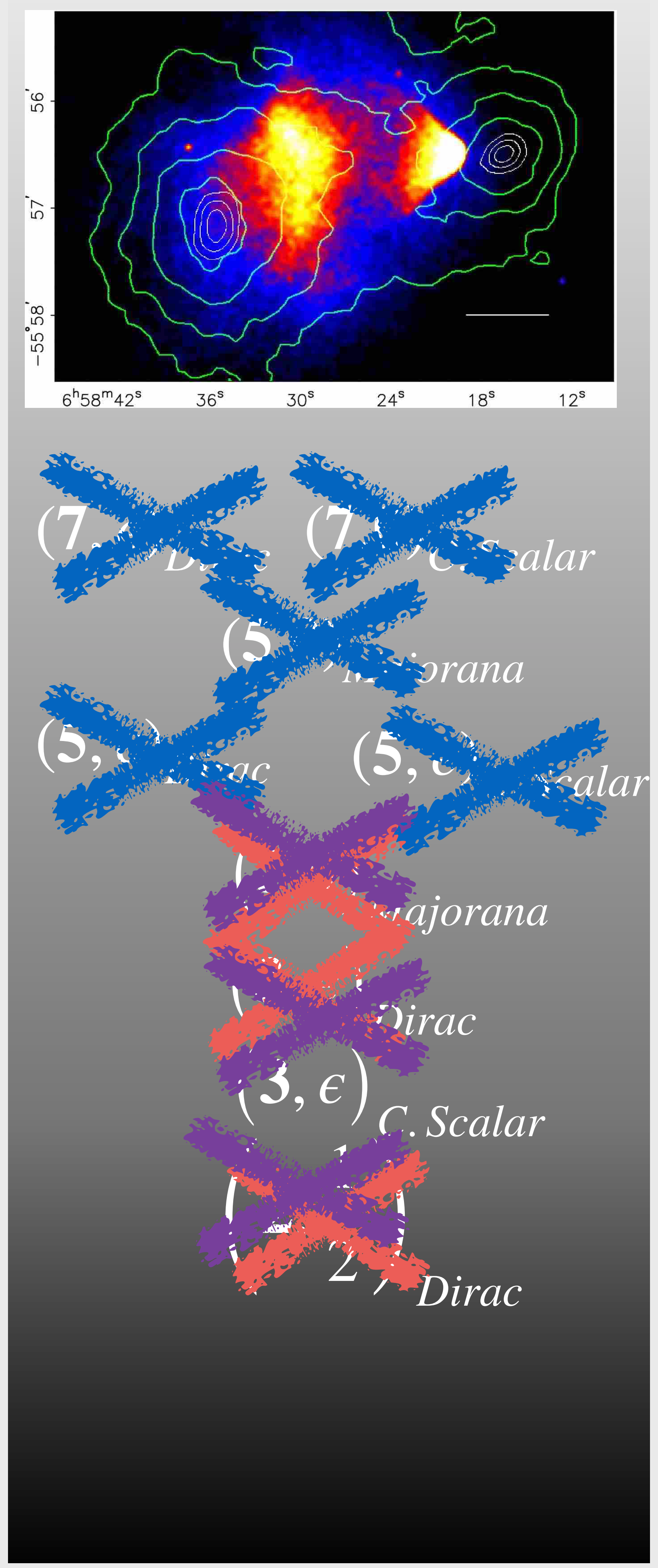

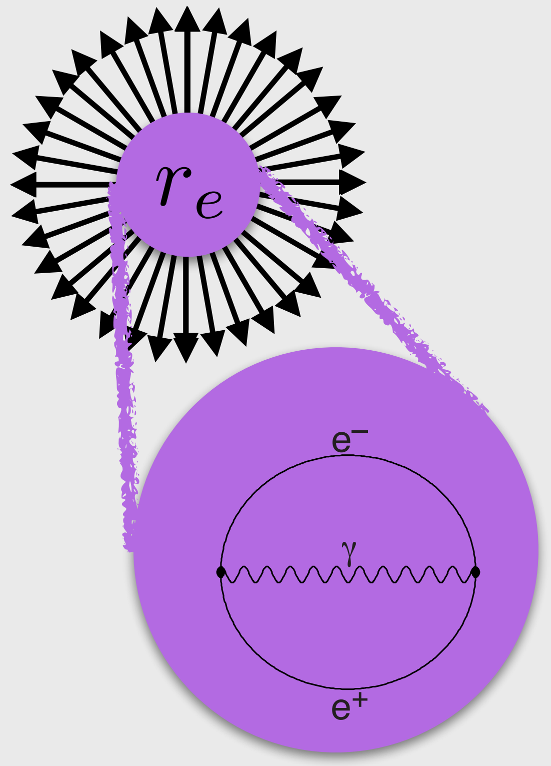

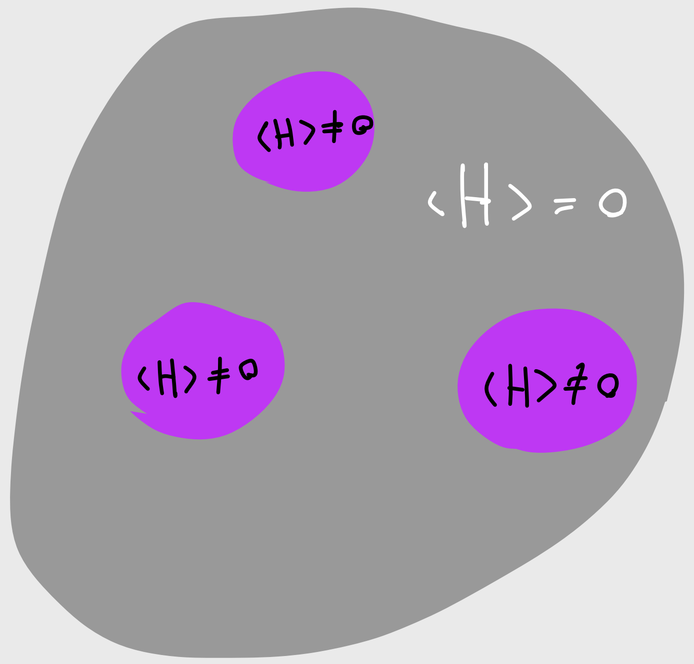

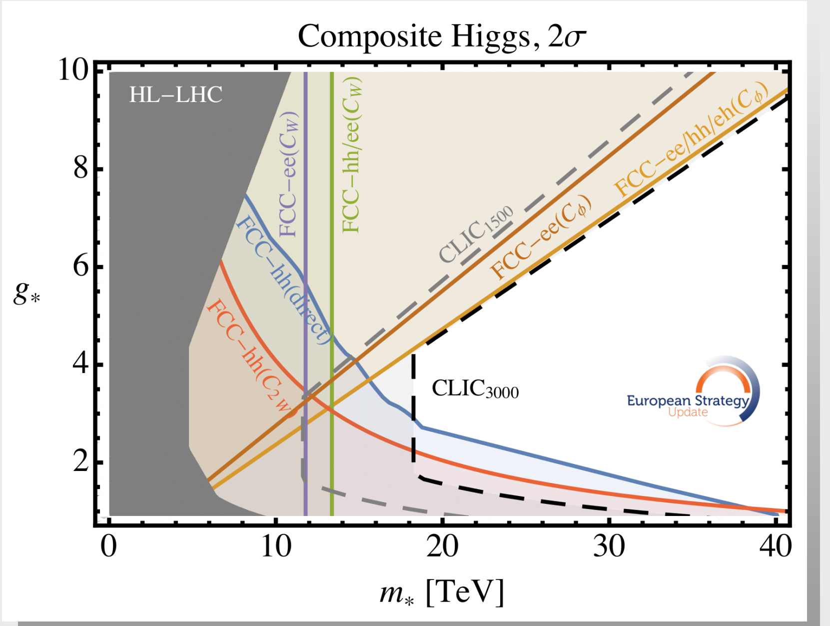

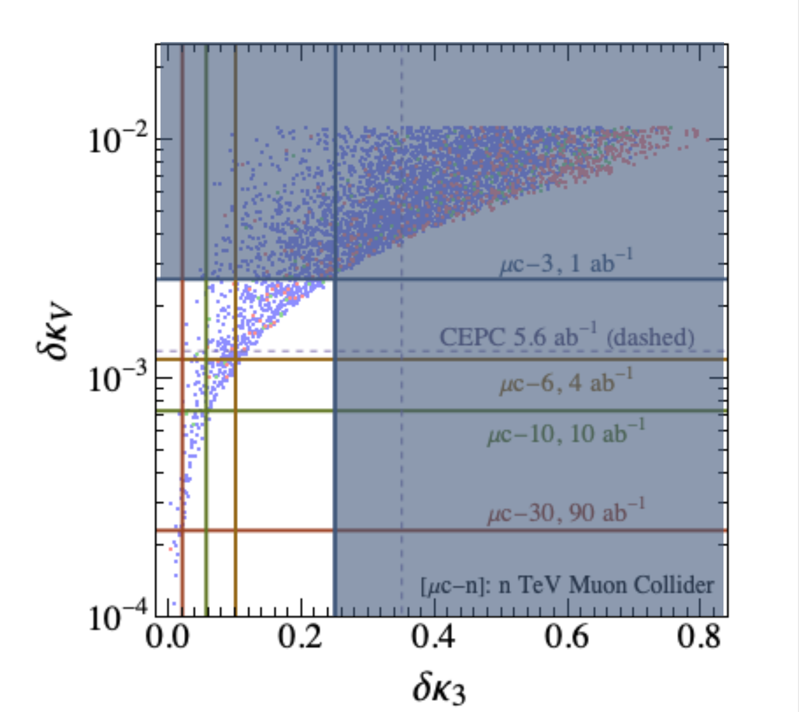

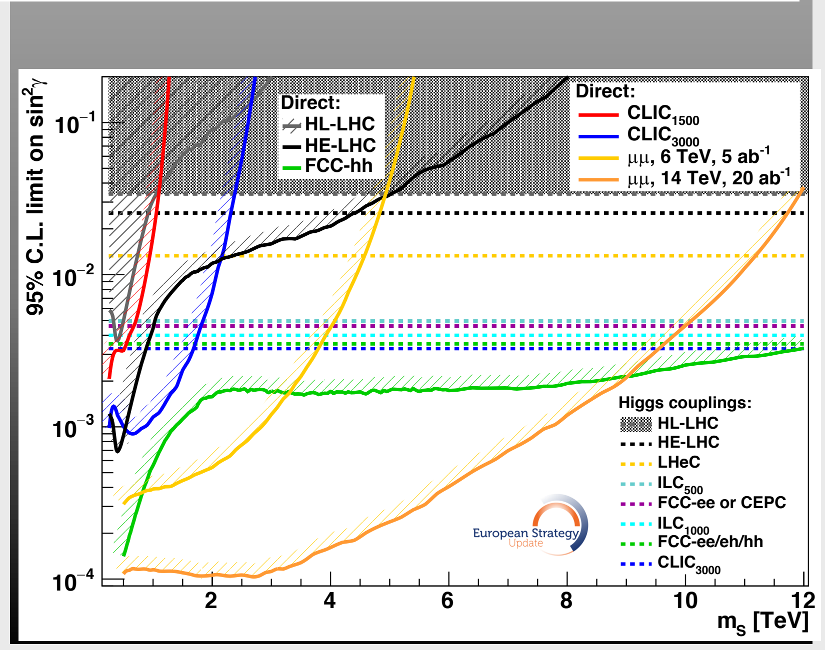

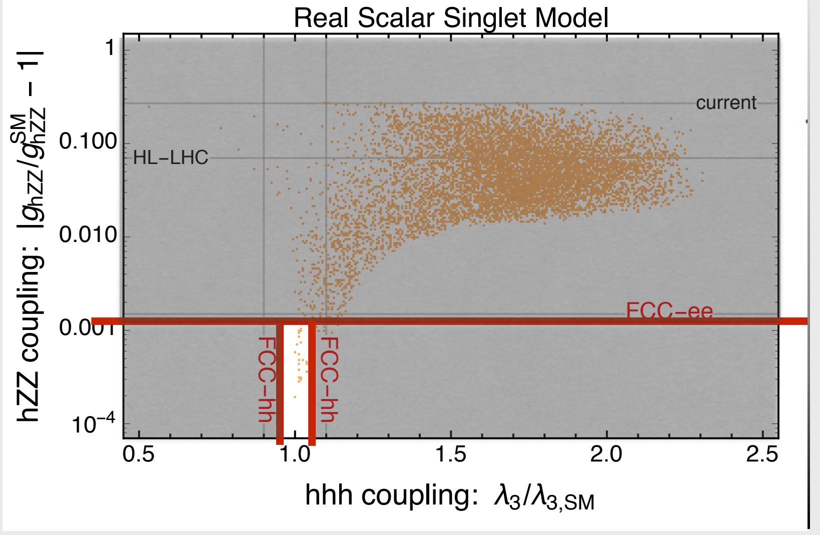

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International MUON Collider Collaboration

FCC hh ee he

SppC

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CLIC

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ILC

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CEPC

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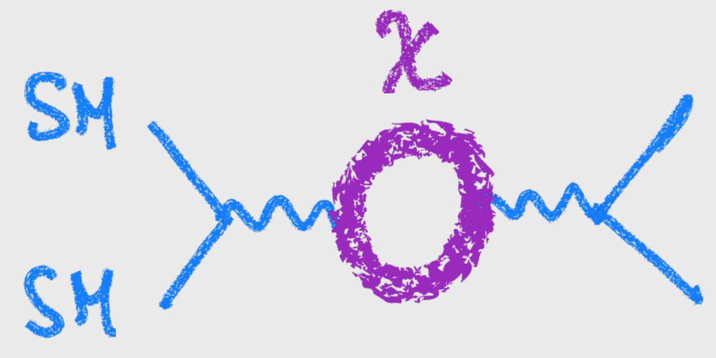
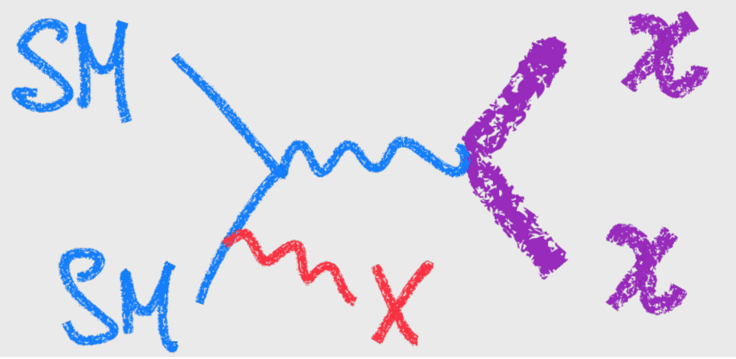
Thank you!

More results

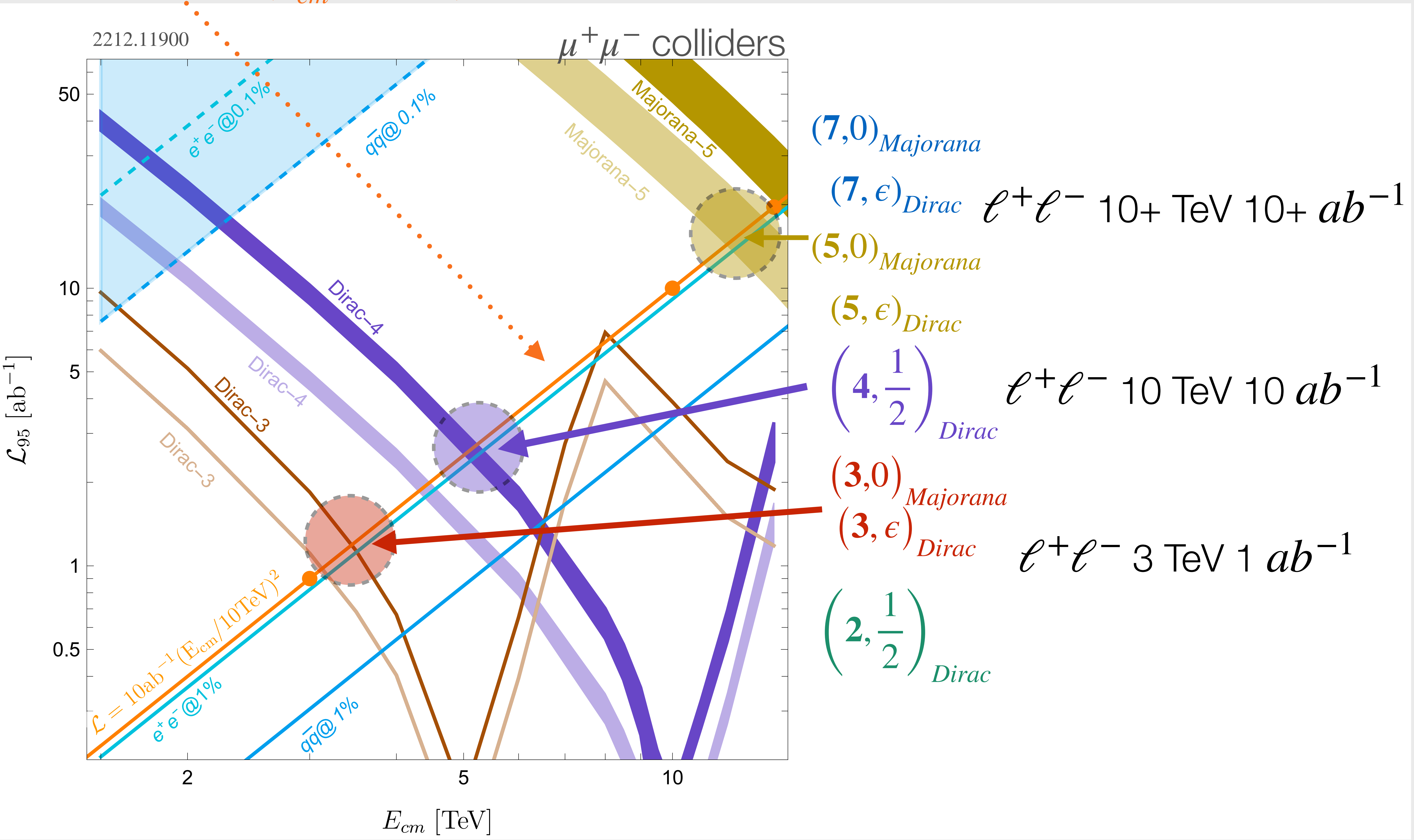
$SM\ SM \to f\bar{f}, Zh, W^+W^-, Wff'$

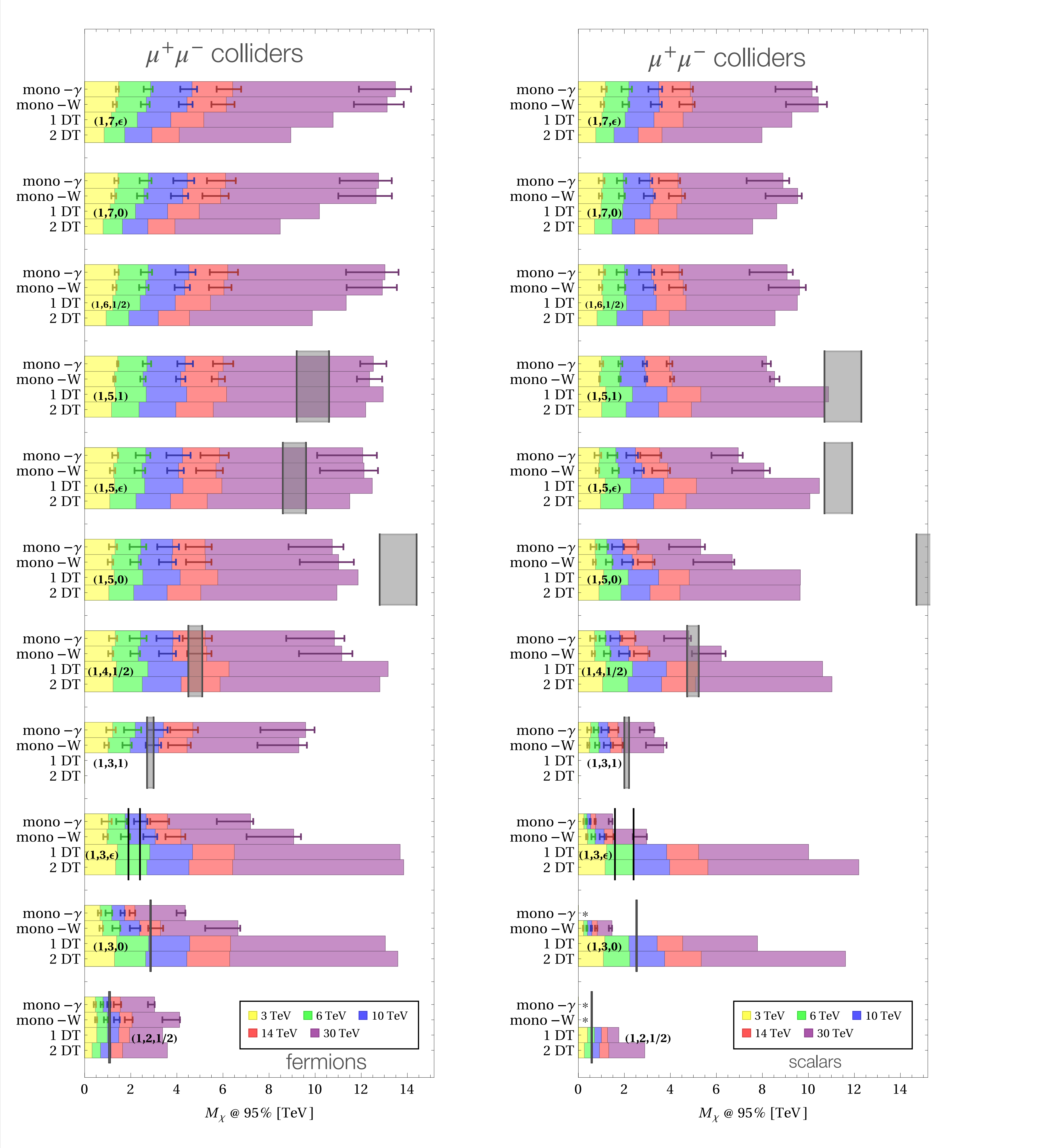


$SM\ SM \to \chi\chi + X$



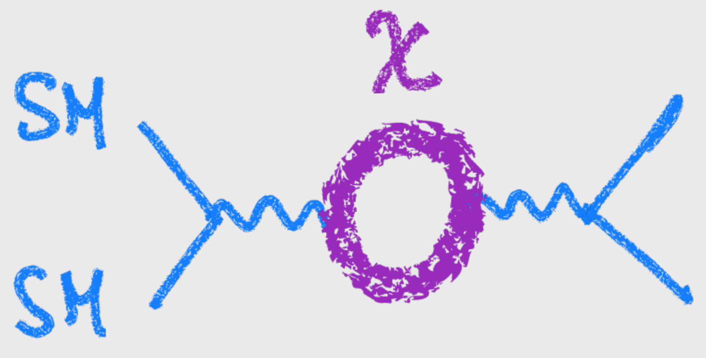
$\mathscr{L} = 10\,\text{ab}^{-1} \cdot (E_{cm}/10\,\text{TeV})^2$





2009.11287, 2107.09688, 2205.04486

$$SM\ SM \to f\bar{f}, Zh, W^+W^-, Wff'$$



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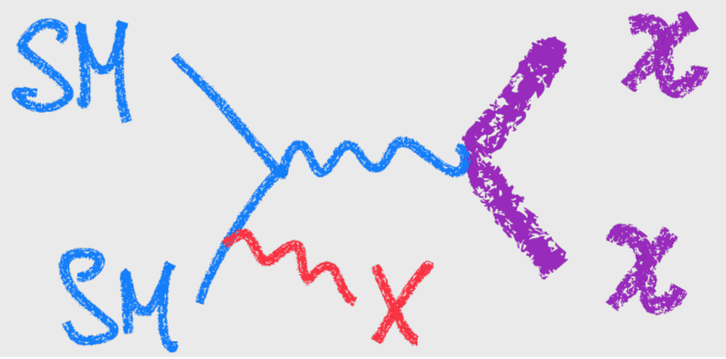

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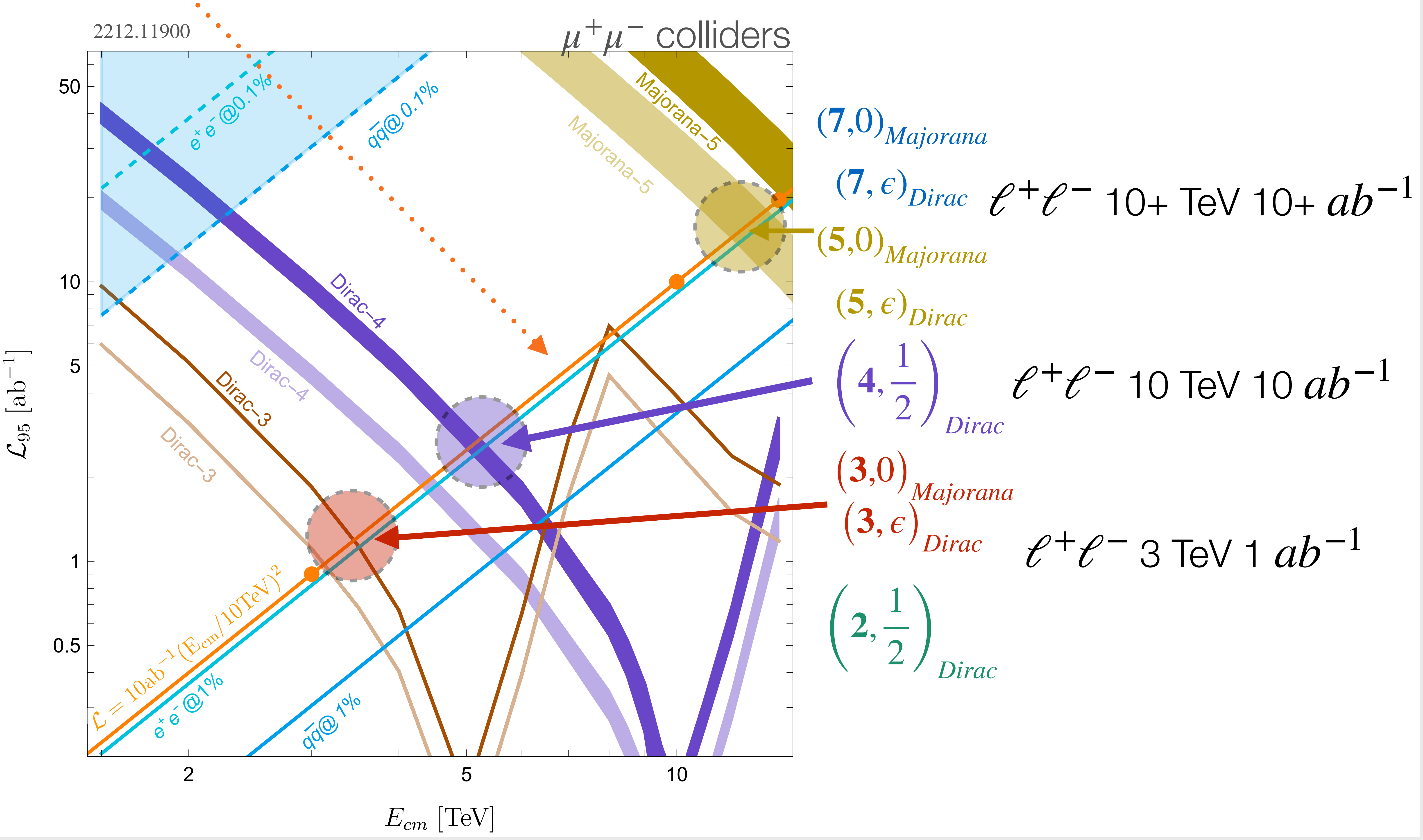

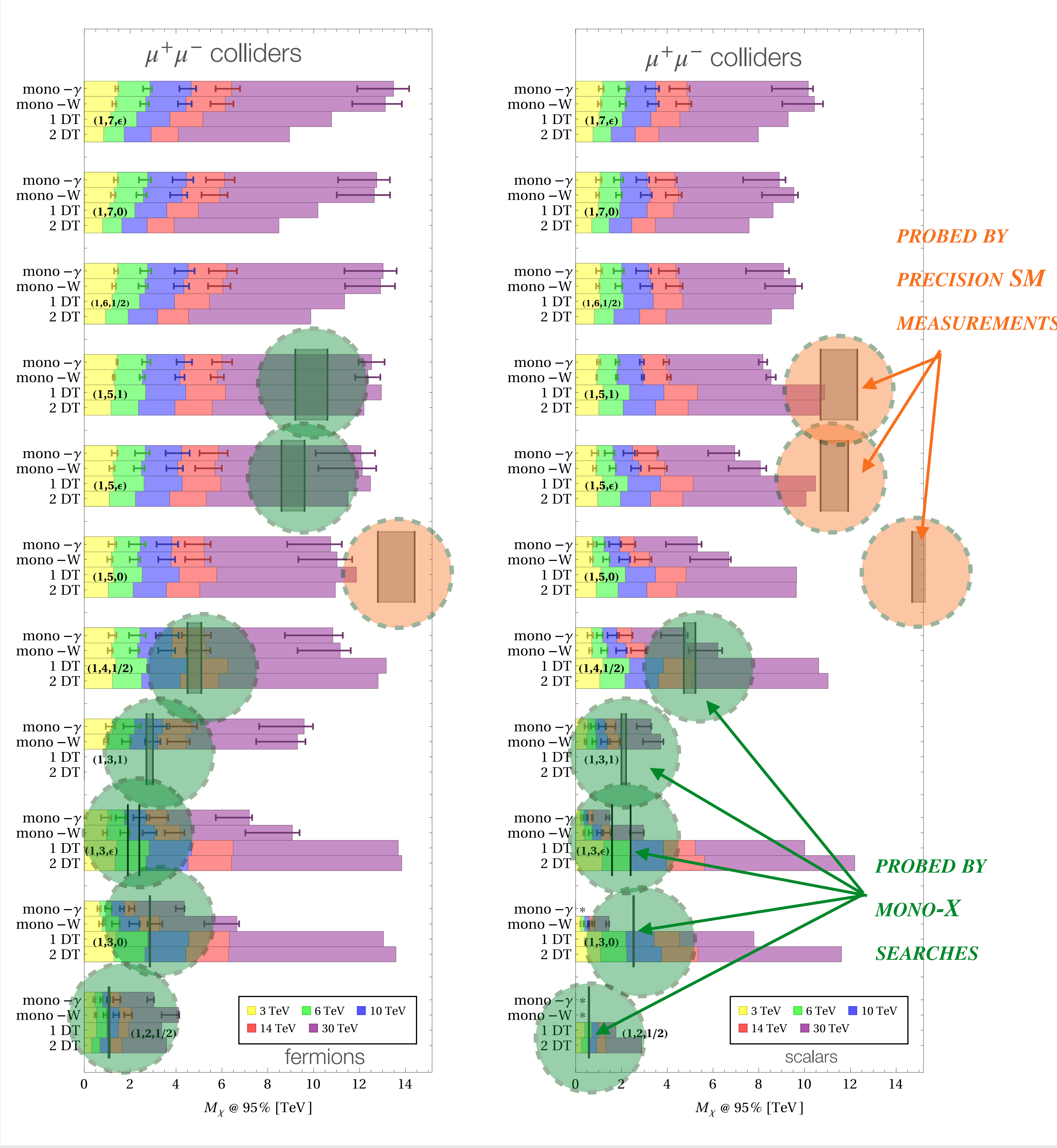

Theory $\mu^+\mu^- \to SM\ SM\ \nu\bar{\nu}$

STANDARD MODEL

“FACTORY”

tth production at the LHC (Fully hadronic)

tth production at the muC 100 TeV (F. Maltoni)

HH→4b production at a multi-TeV muC

Theory $\mu^+\mu^- \rightarrow SM\ SM\ \nu\bar{\nu}$

STANDARD MODEL | "FACTORY"

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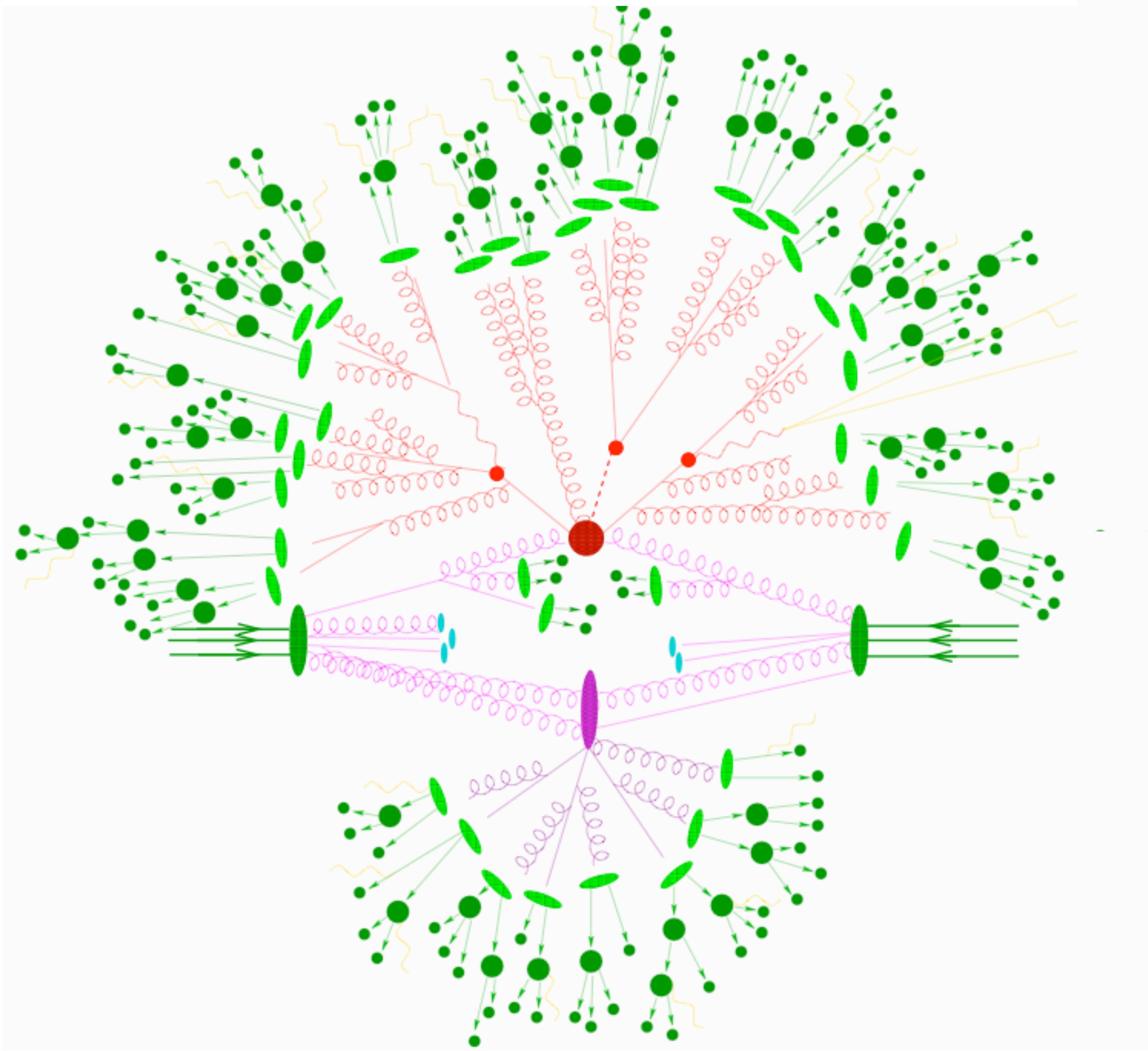

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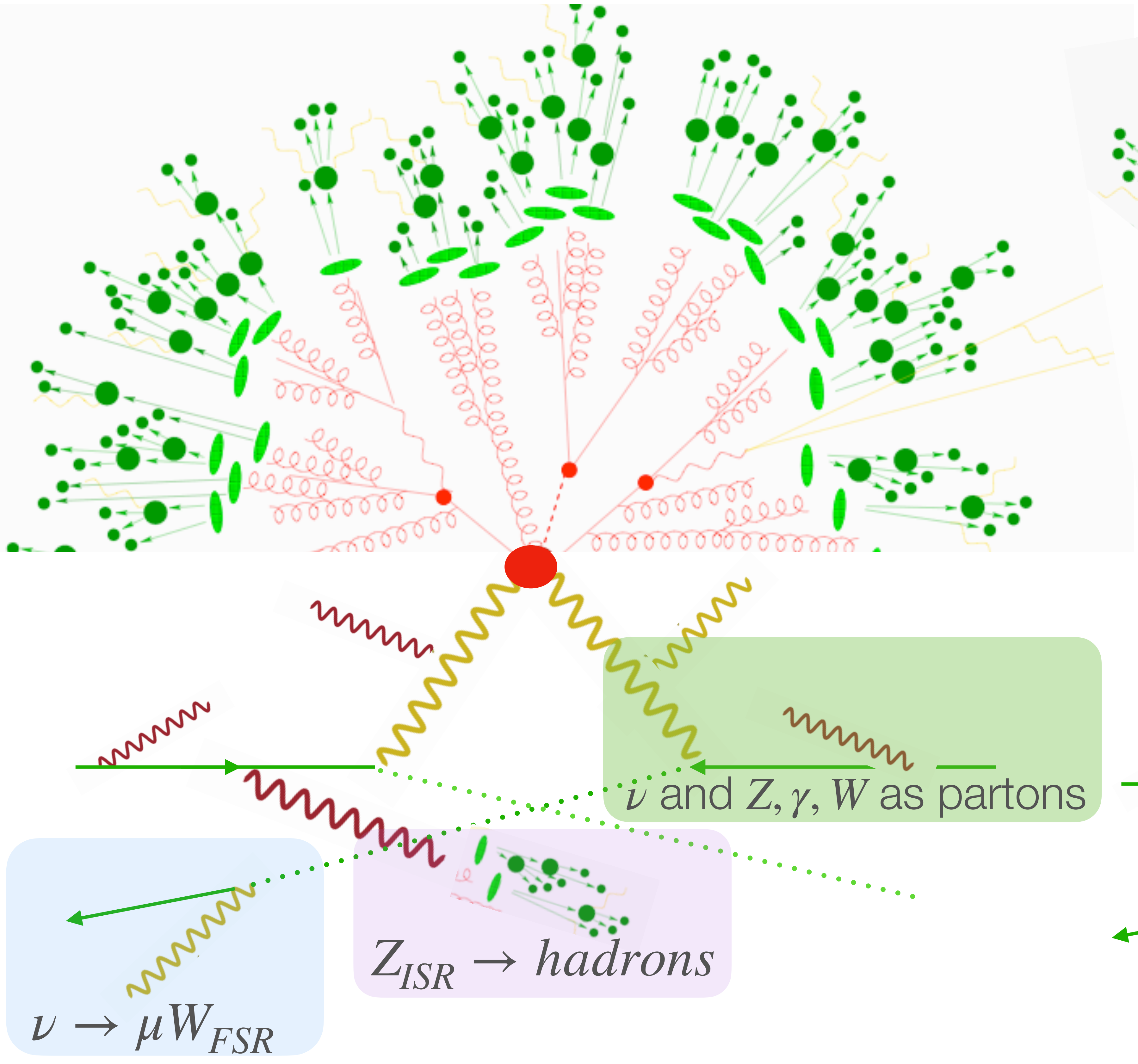

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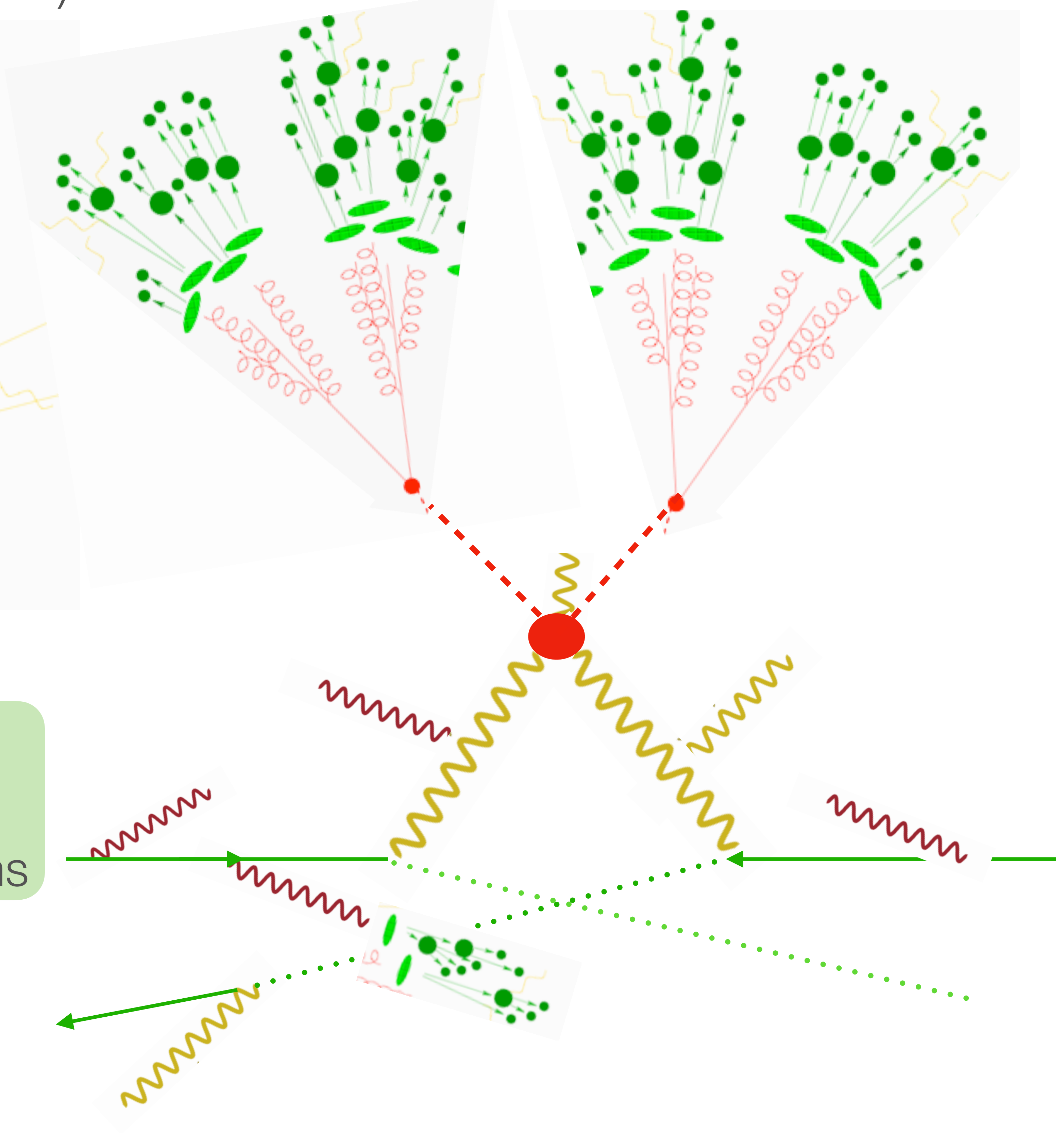

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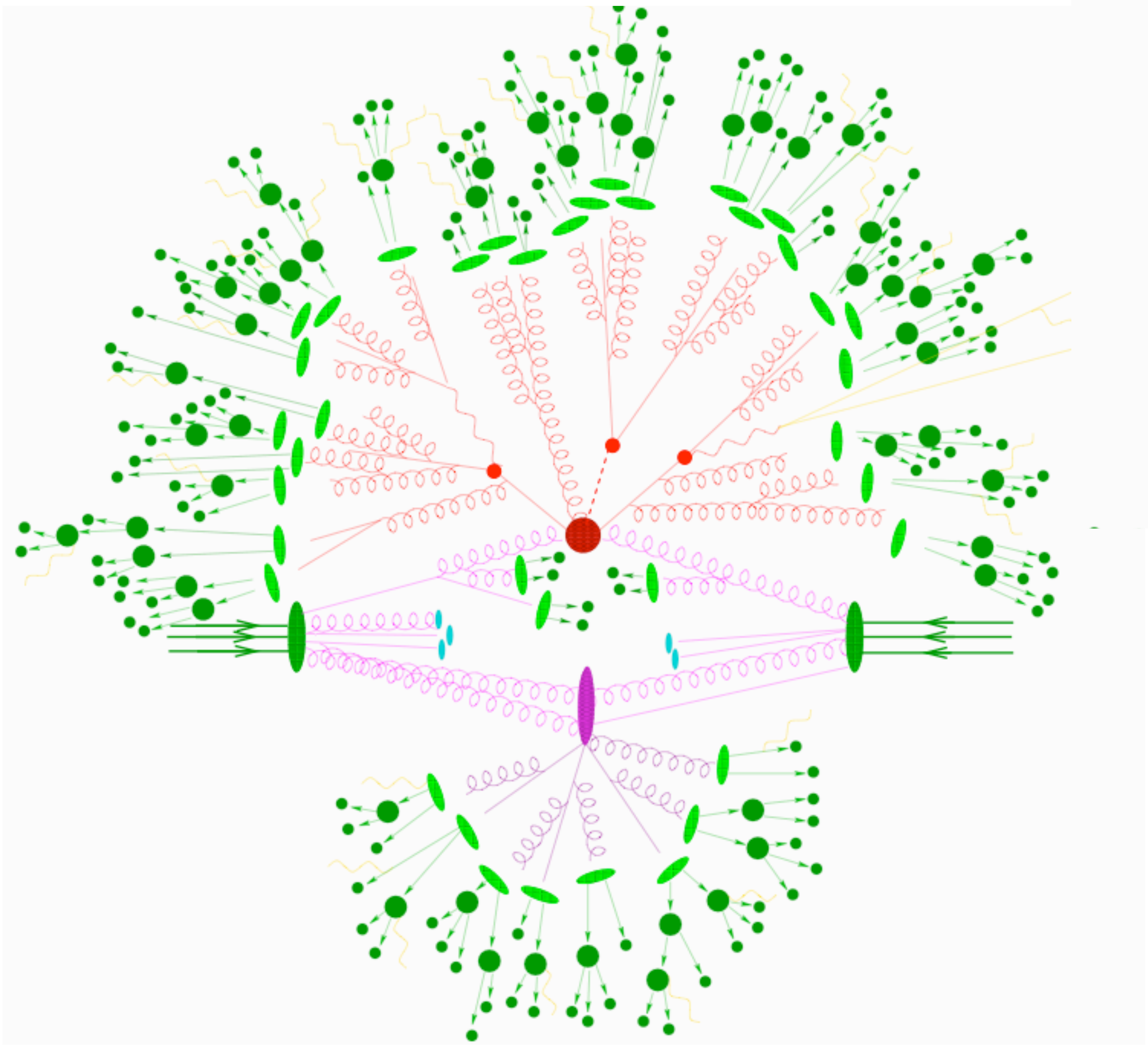

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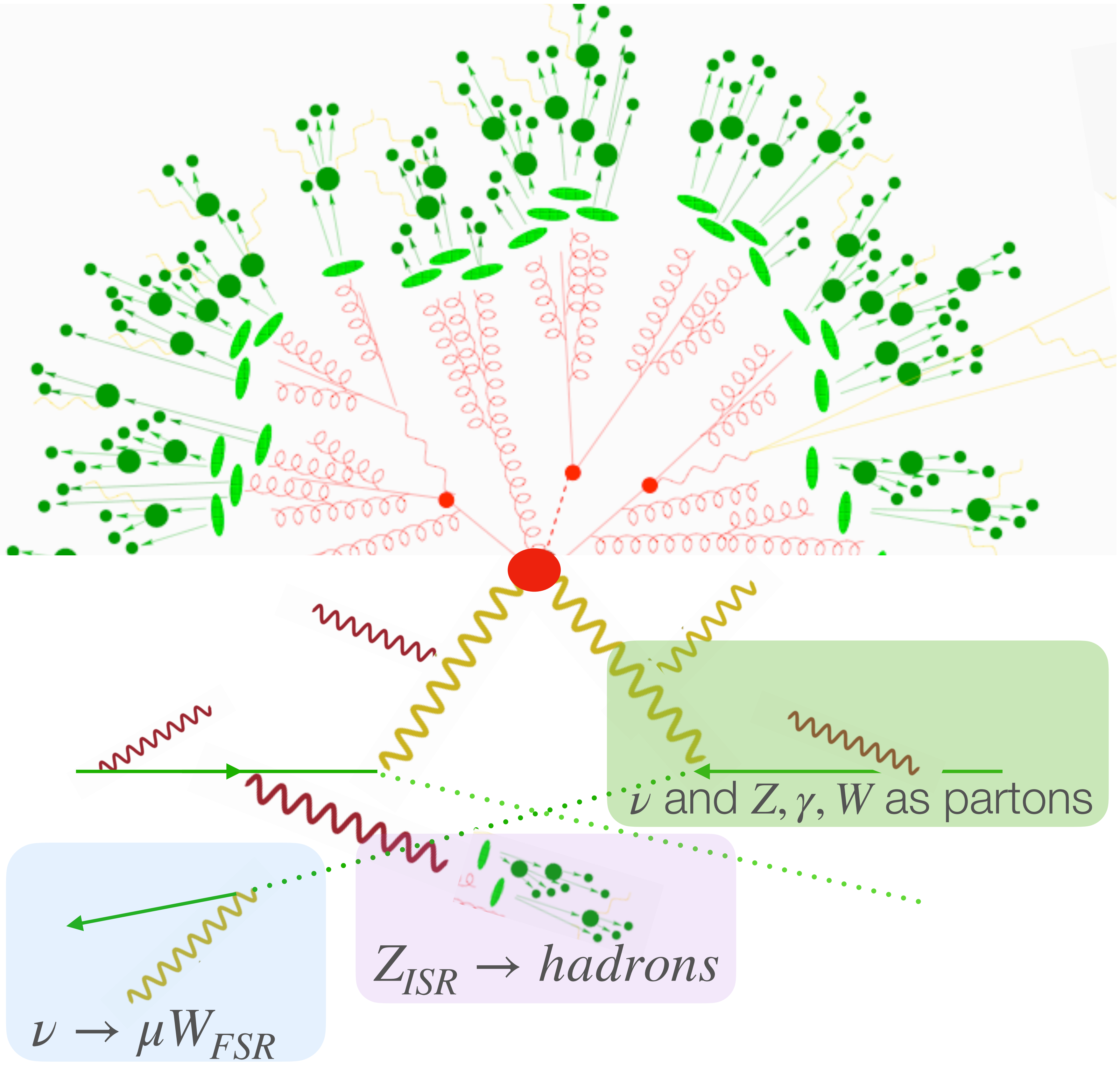


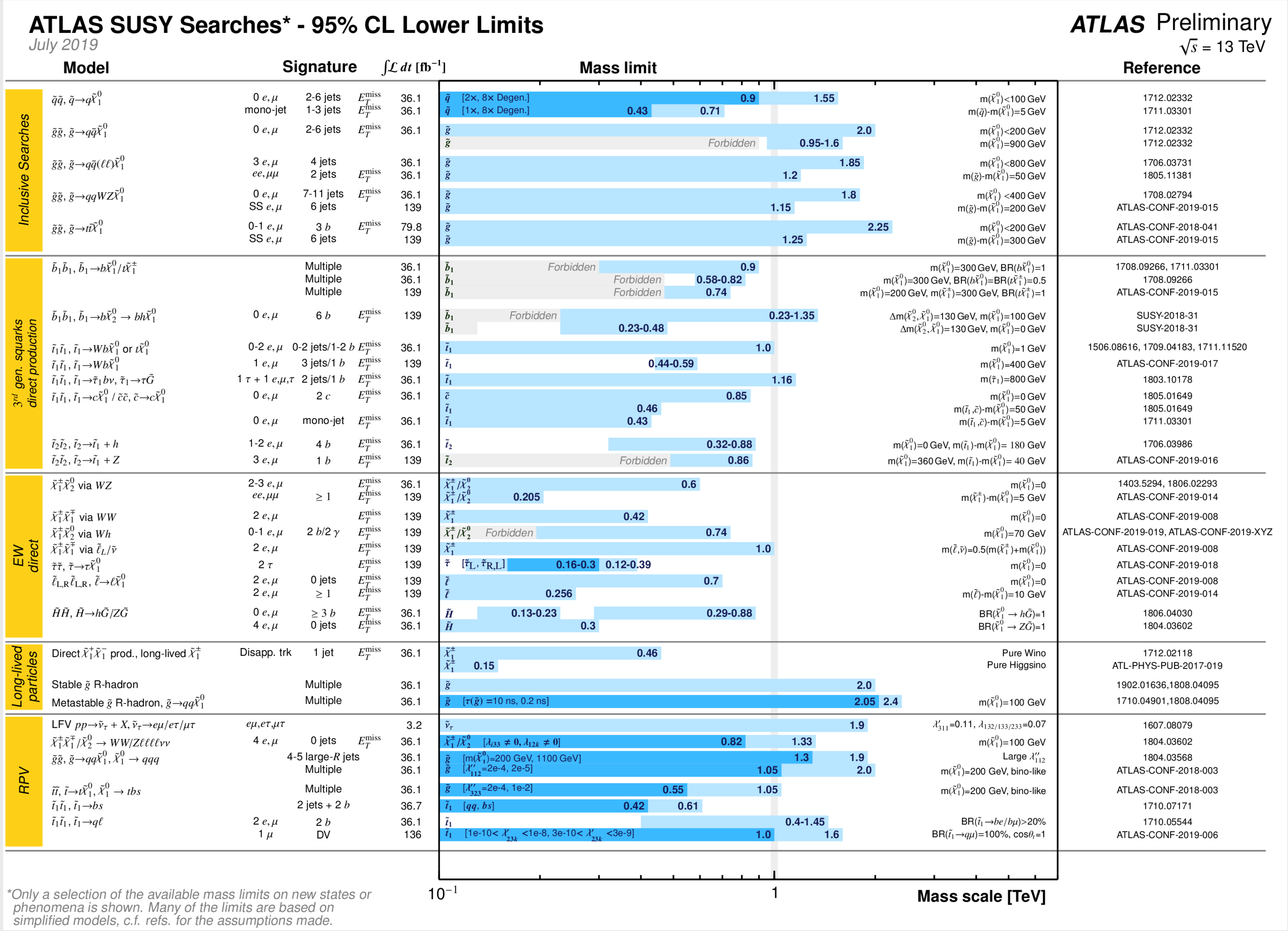
NEW PHENOMENA AND NEW REGIMES IN pQFT

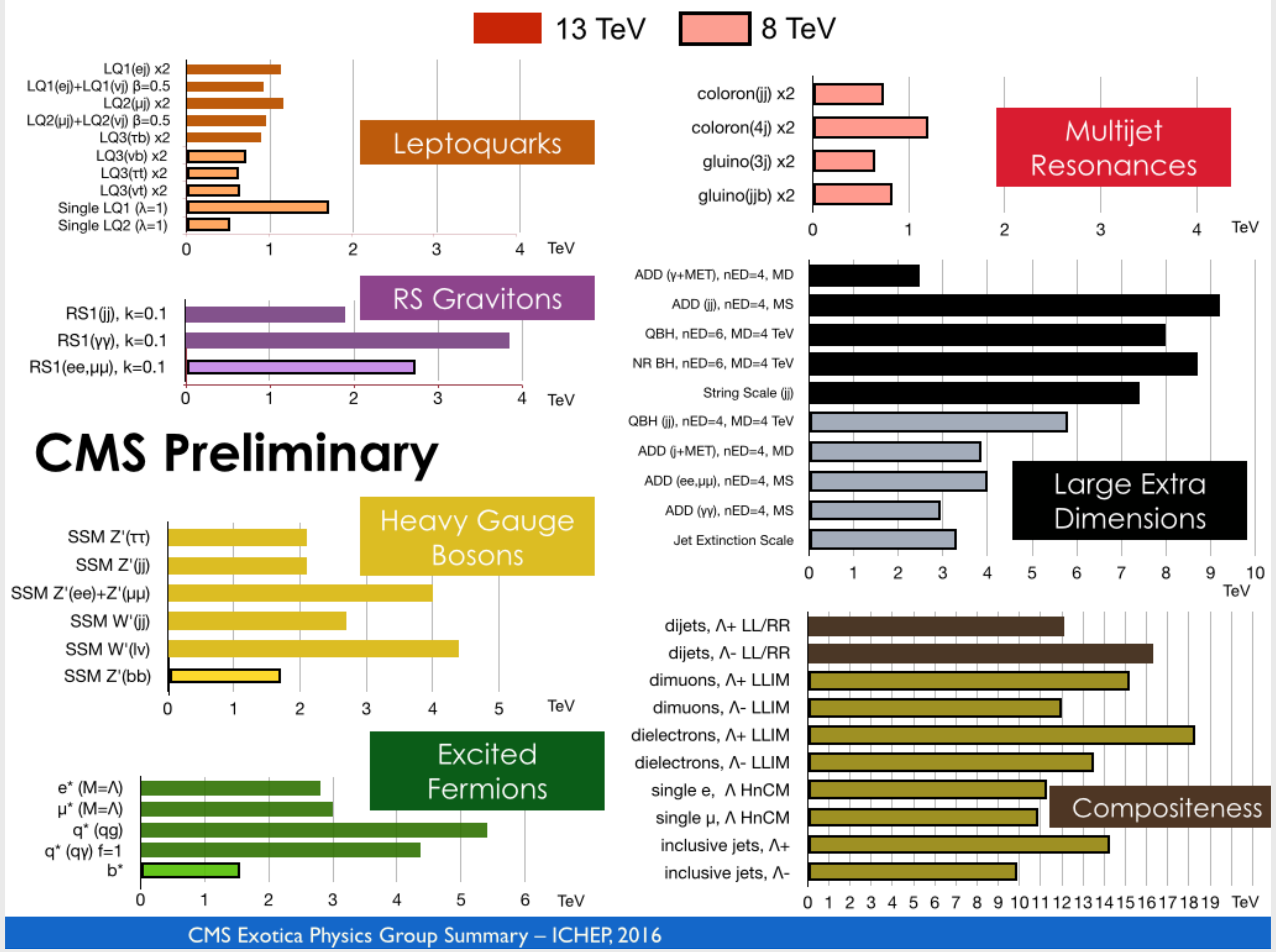
- weak corrections become "ordinary"
- weak "partons"
- large EW logarithms

LHC ruled out new physics at Λ TeV …

LHC ruled out new physics at the TeV …

SUMMARY OF THE SUMMARIES





Yes, after HL-LHC there is going to be a uncharted territory as low as

- Fermionic pure Doublet: 200 GeV; 400 GeV if you are really pessi/opti-misitc
- Scalar Doublet: 1 TeV
- Scalar Singlet: 500-900 GeV (depending on the UV origin of the singlet) *

flashing concrete results for

The size of the Higgs boson

Effects of the size of the Higgs boson

h ~ π

STRONGLY INTERACTING LIGHT HIGGS

$$\mathcal{L}^{d=6}_{universal} = c_H \frac{g_*^2}{m_*^2}\mathcal{O}_H + c_T \frac{N_c \epsilon_q^4 g_*^4}{(4\pi)^2 m_*^2}\mathcal{O}_T + c_6 \lambda \frac{g_*^2}{m_*^2}\mathcal{O}_6 + \frac{1}{m_*^2}\left[c_W \mathcal{O}_W + c_B \mathcal{O}_B\right]$$

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$1/(g_\star f) \sim 1/m_\star$

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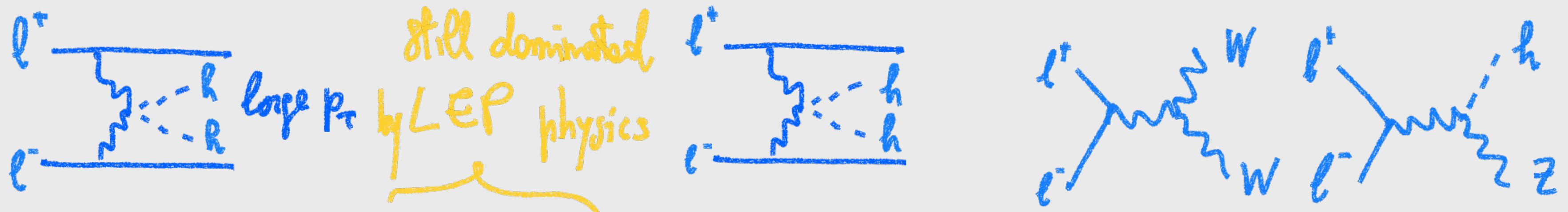
Effects of the size of the Higgs boson

STRONGLY INTERACTING TOP AND HIGGS



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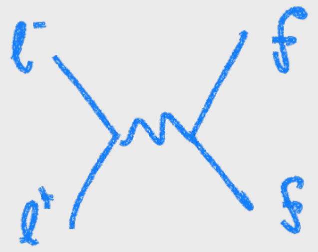

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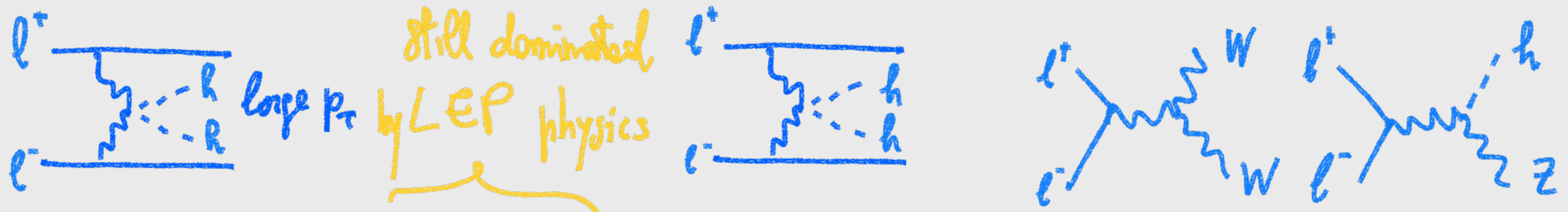

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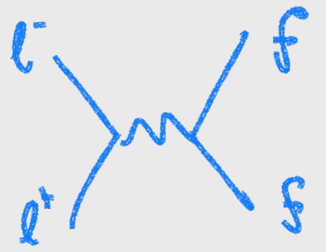

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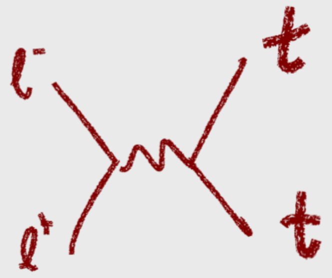

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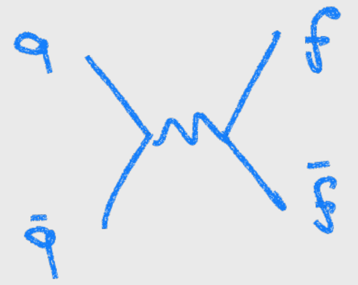

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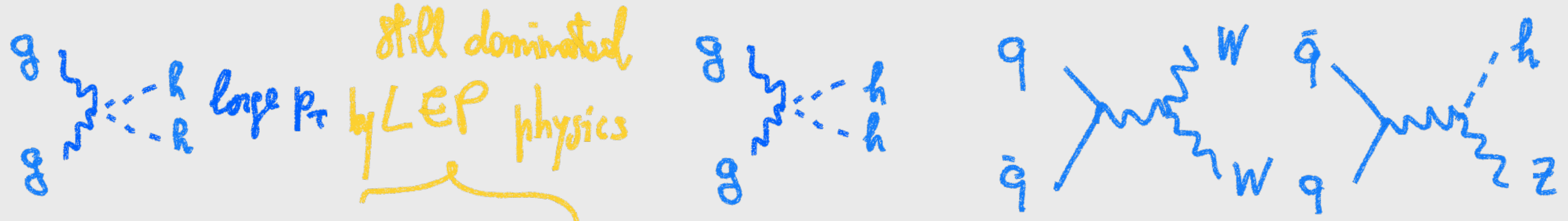

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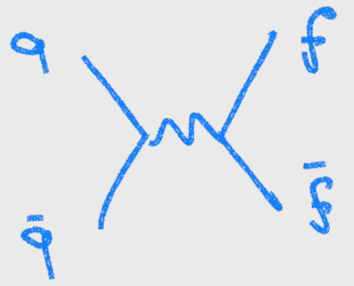


$$+ \frac{1}{g_*^2 m_*^2}\left[c_{2W} g^2 \mathcal{O}_{2W} + c_{2B} g'^2 \mathcal{O}_{2B}\right] + c_{3W}\frac{3! g^2}{(4\pi)^2 m_*^2}\mathcal{O}_{3W}$$

$$+ c_{y_t}\frac{g_*^2}{m_*^2}\mathcal{O}_{y_t} + c_{y_b}\frac{g_*^2}{m_*^2}\mathcal{O}_{y_b}$$

$$+ c_{tD}\frac{g_*^2}{m_*^2}\mathcal{O}_{tD}$$

$1/f \sim g_\star / m_\star$

$1/(g_\star f) \sim 1/m_\star$

$g_{SM}/(g_\star f) \sim g_{SM}/m_\star$

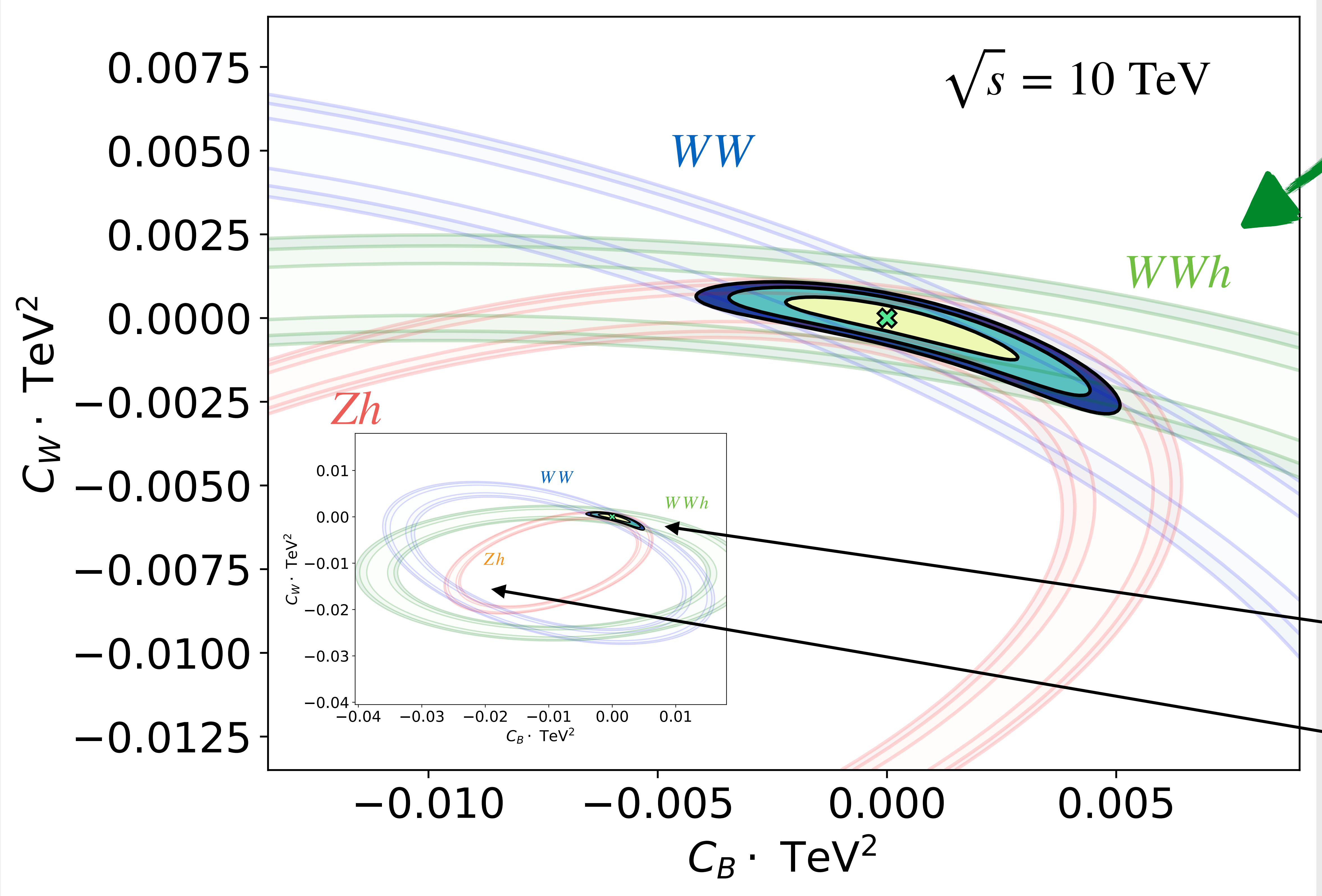
$$\ell_{top} \sim 1/m_\star \sim \ell_{Higgs}$$

$\ell^+\ell^- \to VV, VVH$

MULTI-BODY WEAK RADIATION

multi-body can contain hard sub-scattering with net electric charge, e.g. $e\nu \to Wh, WZ$ with new BSM couplings dependence

very relevant weak radiation effect

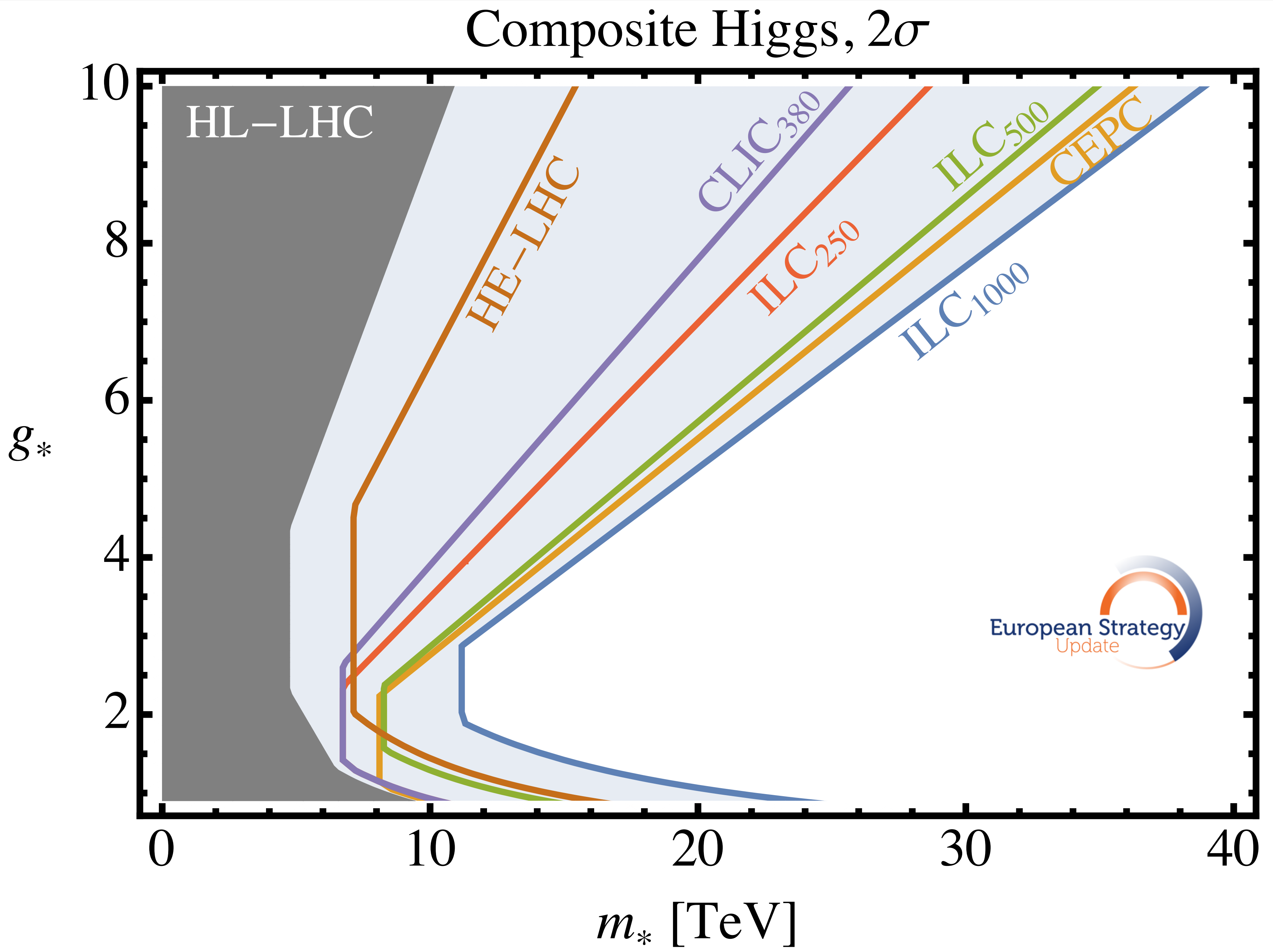


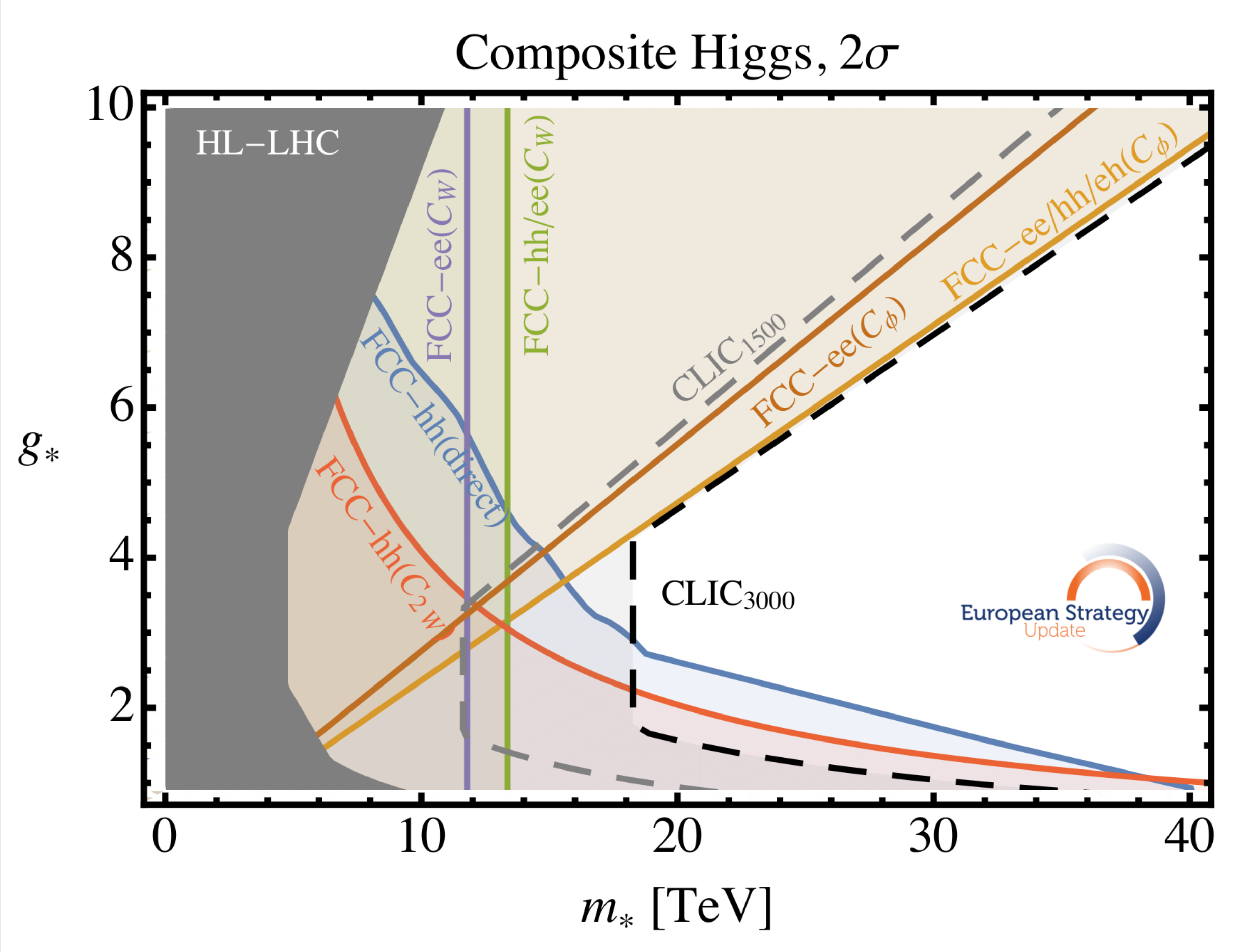
- ZH: elliptical belt in 2D BSM coupling space
- WW: elliptical belt in 2D BSM coupling space
- WWh: elliptical belt in 2D BSM coupling space

SM

SM-like rate but very large BSM couplings which correspond to new physics directly accessible at the same collider

Higgs compositeness



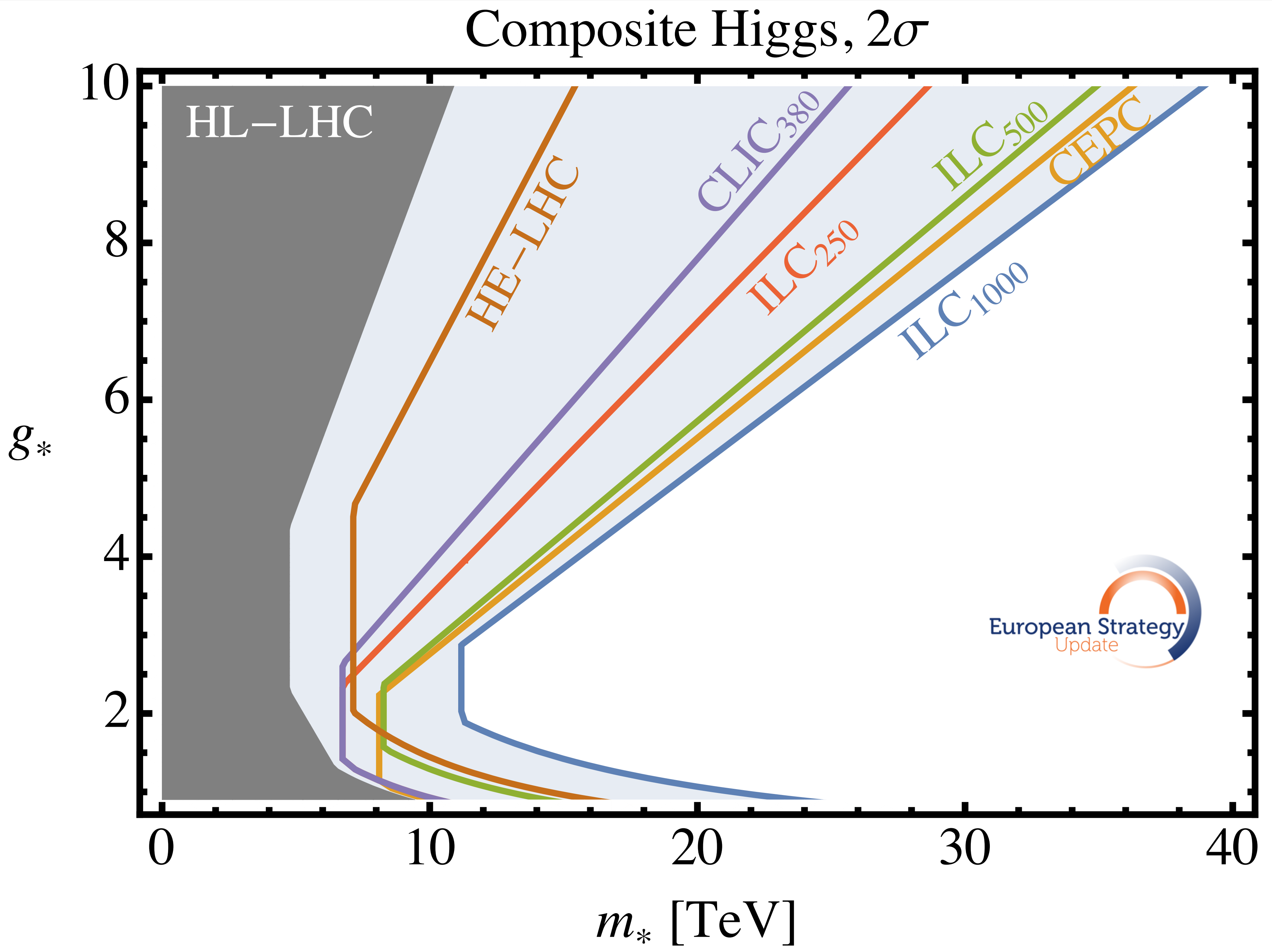


compositeness at few TeV @ HL-LHC

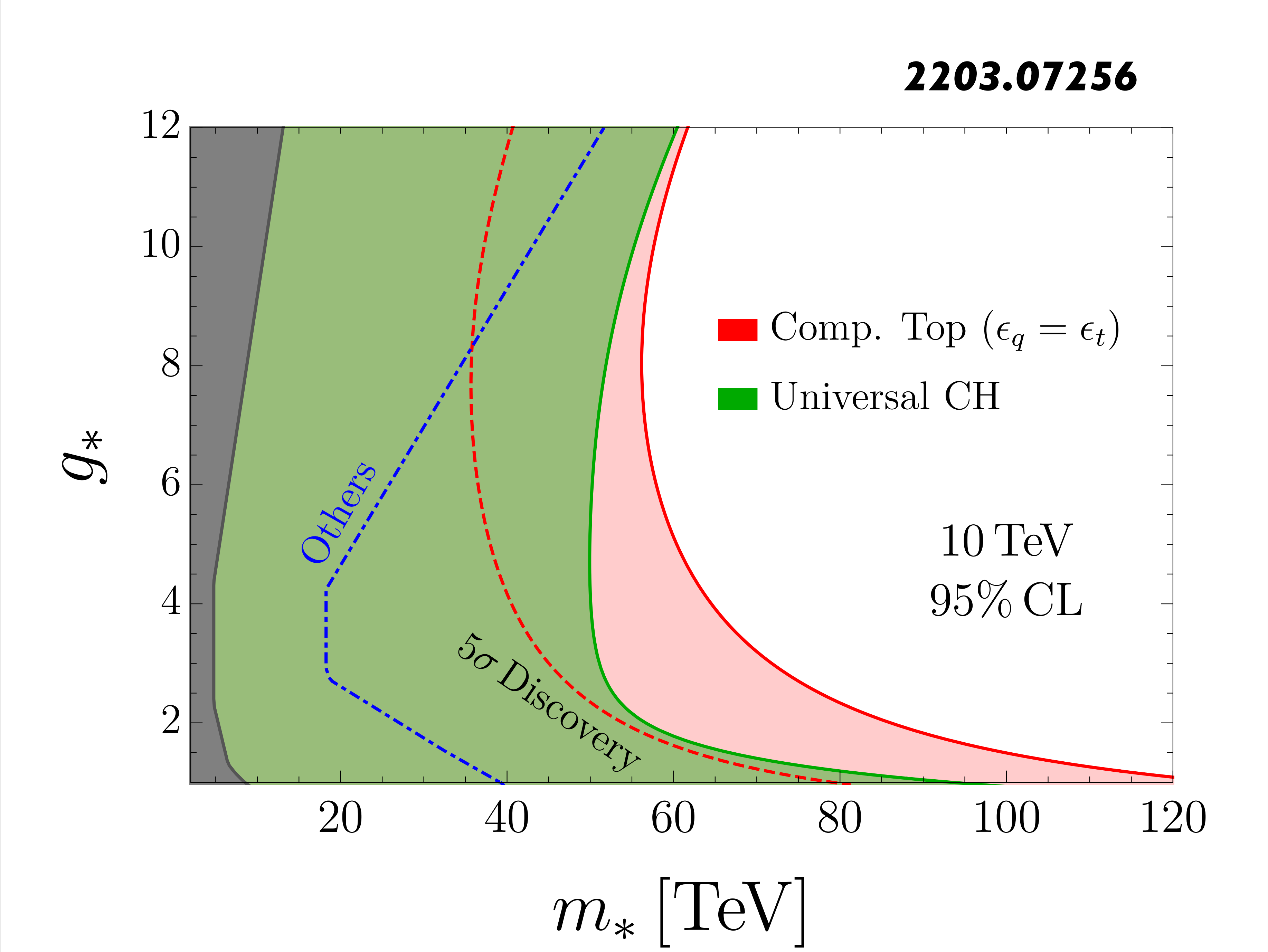
Higgs as composite as QCD pion

compositeness at few 10 TeV

Higgs compositeness



UNIQUE AVENUE TO EXPLORE WEAK INTERACTIONS FAR OFFSHORE FROM THE WEAK SCALE



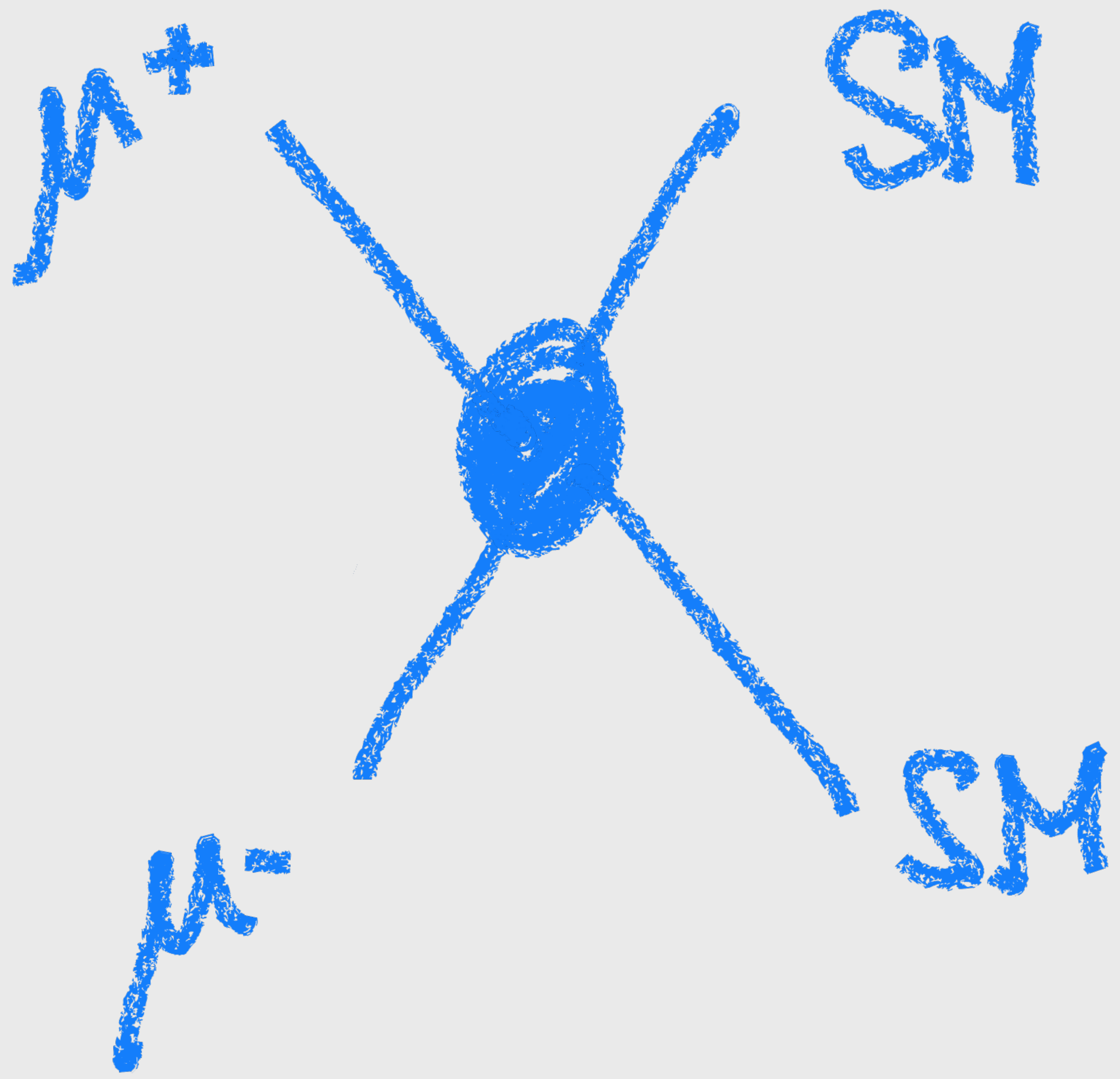
compositeness at few TeV @ HL-LHC

Higgs as composite as QCD pion

compositeness at few 100 TeV

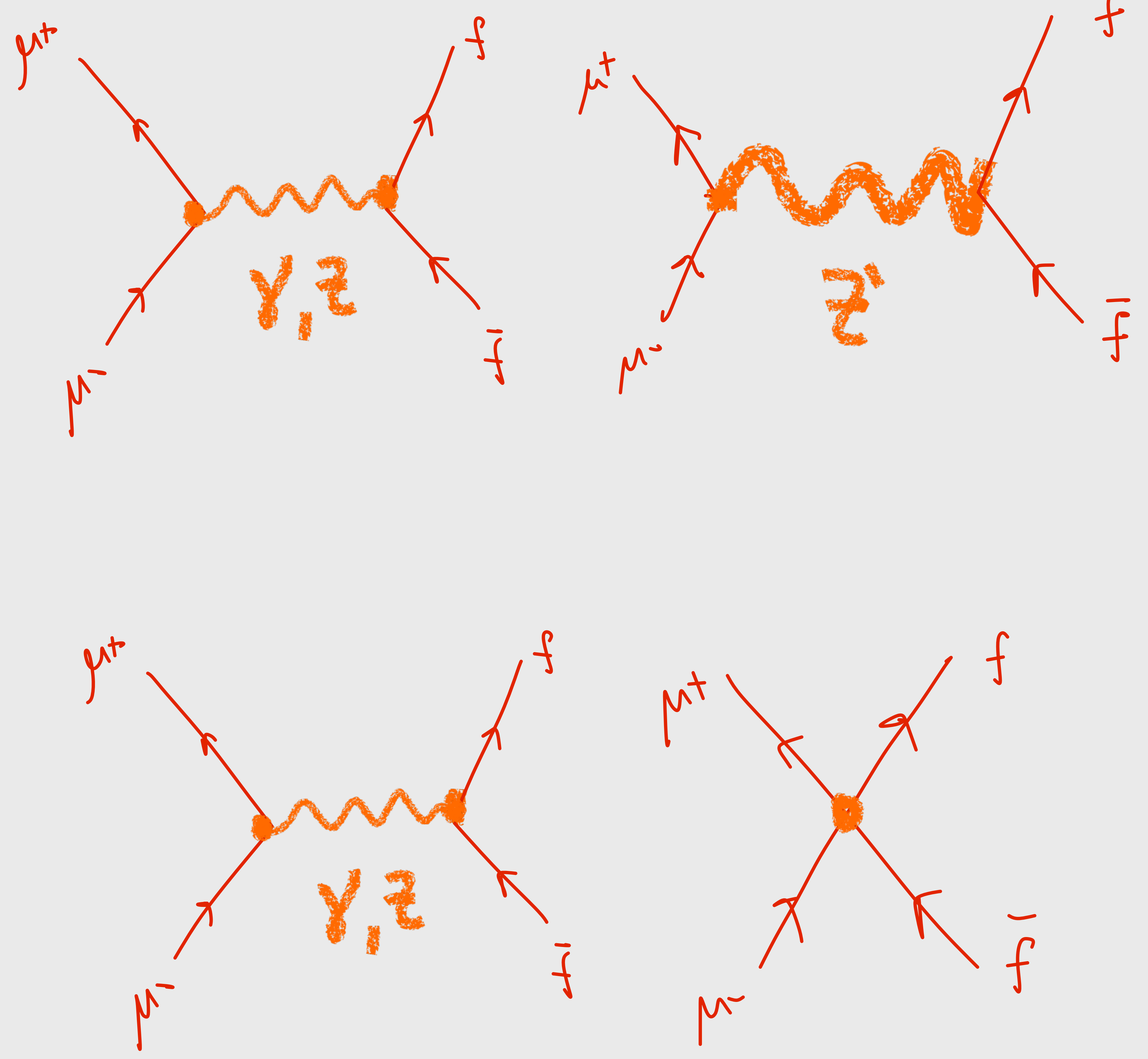
Higgs 100x more point-like than QCD pion at $\sqrt{s} \gg 100$ GeV

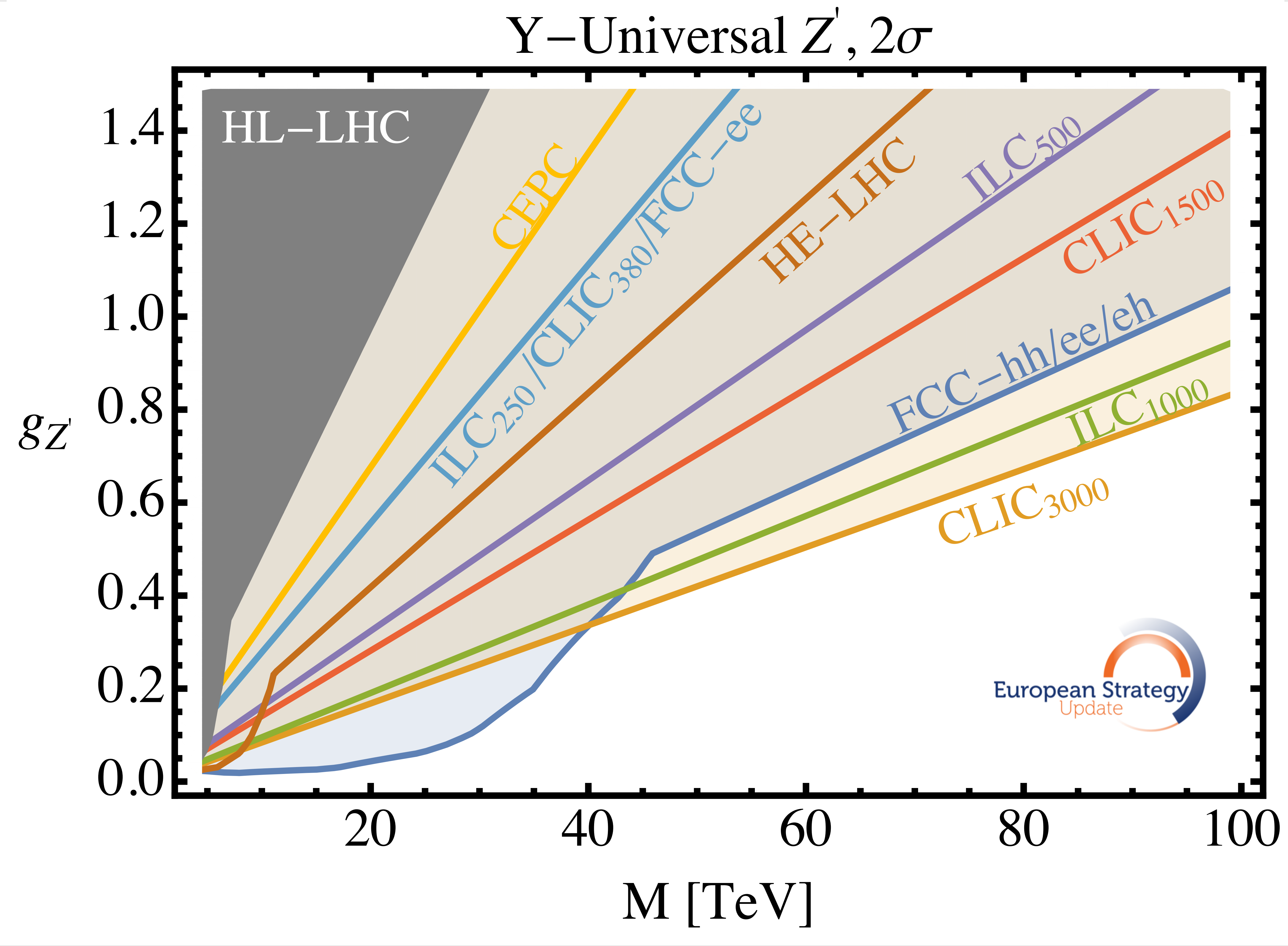
Indirect Effects



A heavy Z'

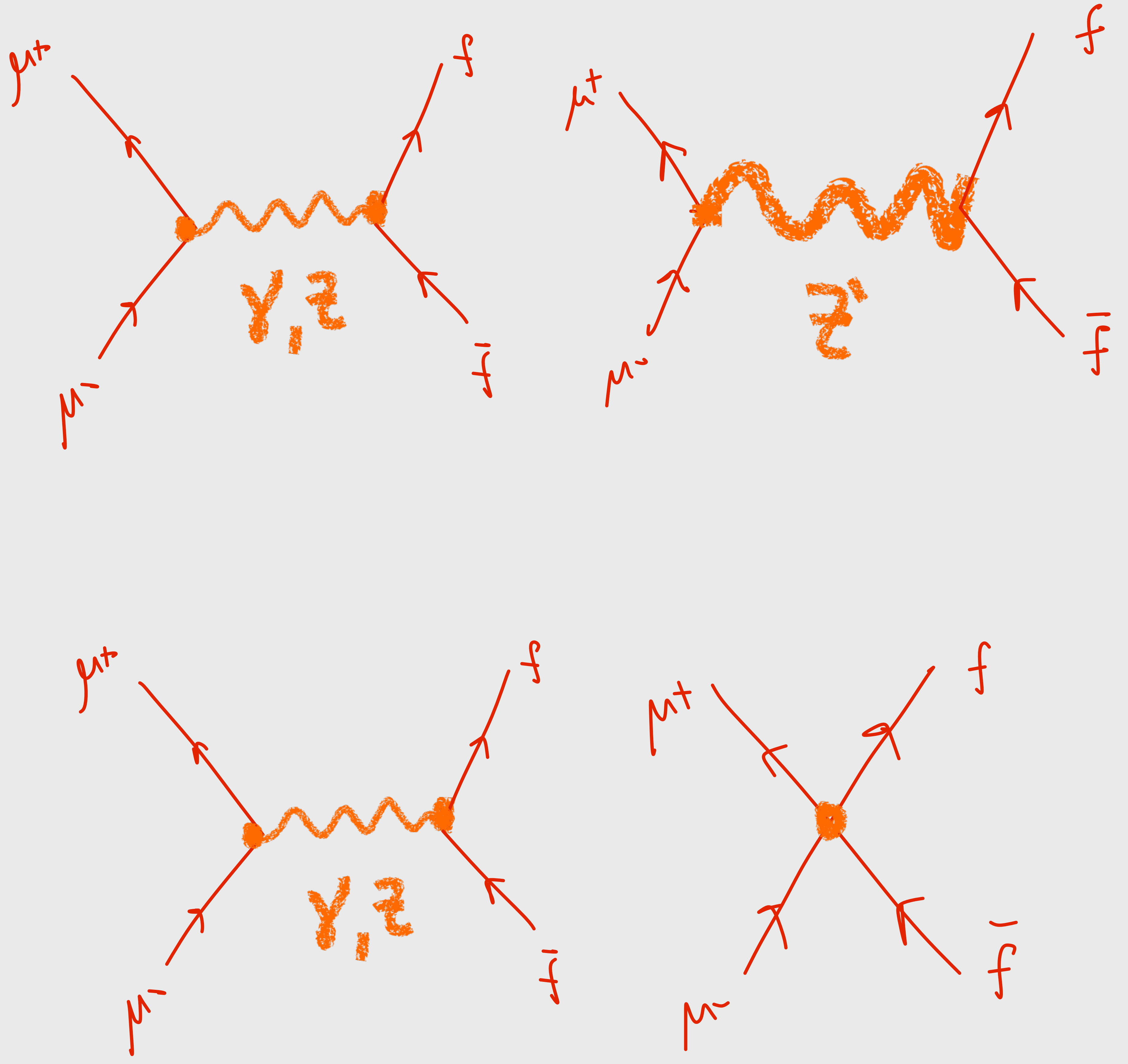
DRELL-YAN | RATES AND ANGULAR DISTRIBUTIONS

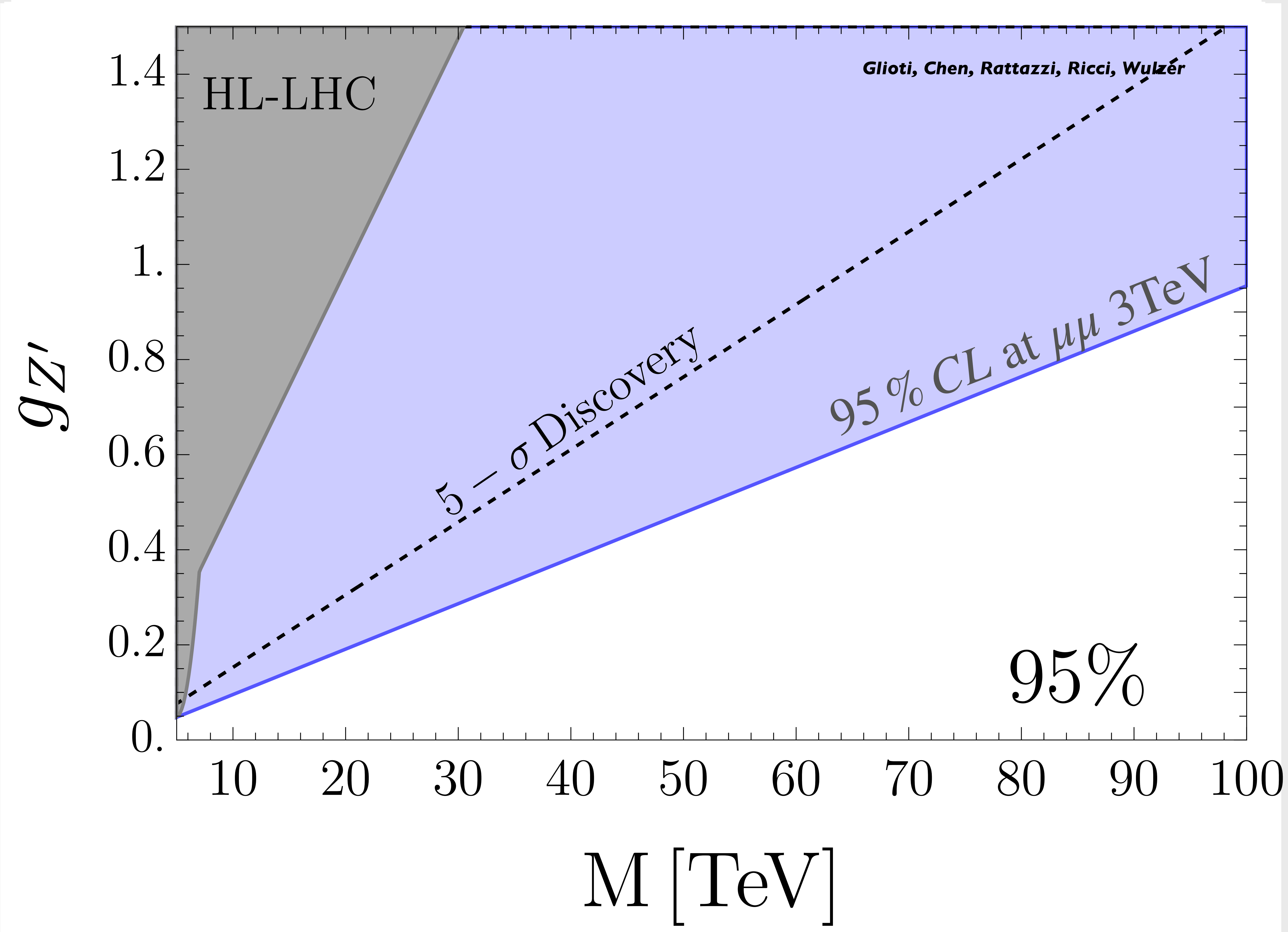




A heavy Z'

DRELL-YAN | RATES AND ANGULAR DISTRIBUTIONS





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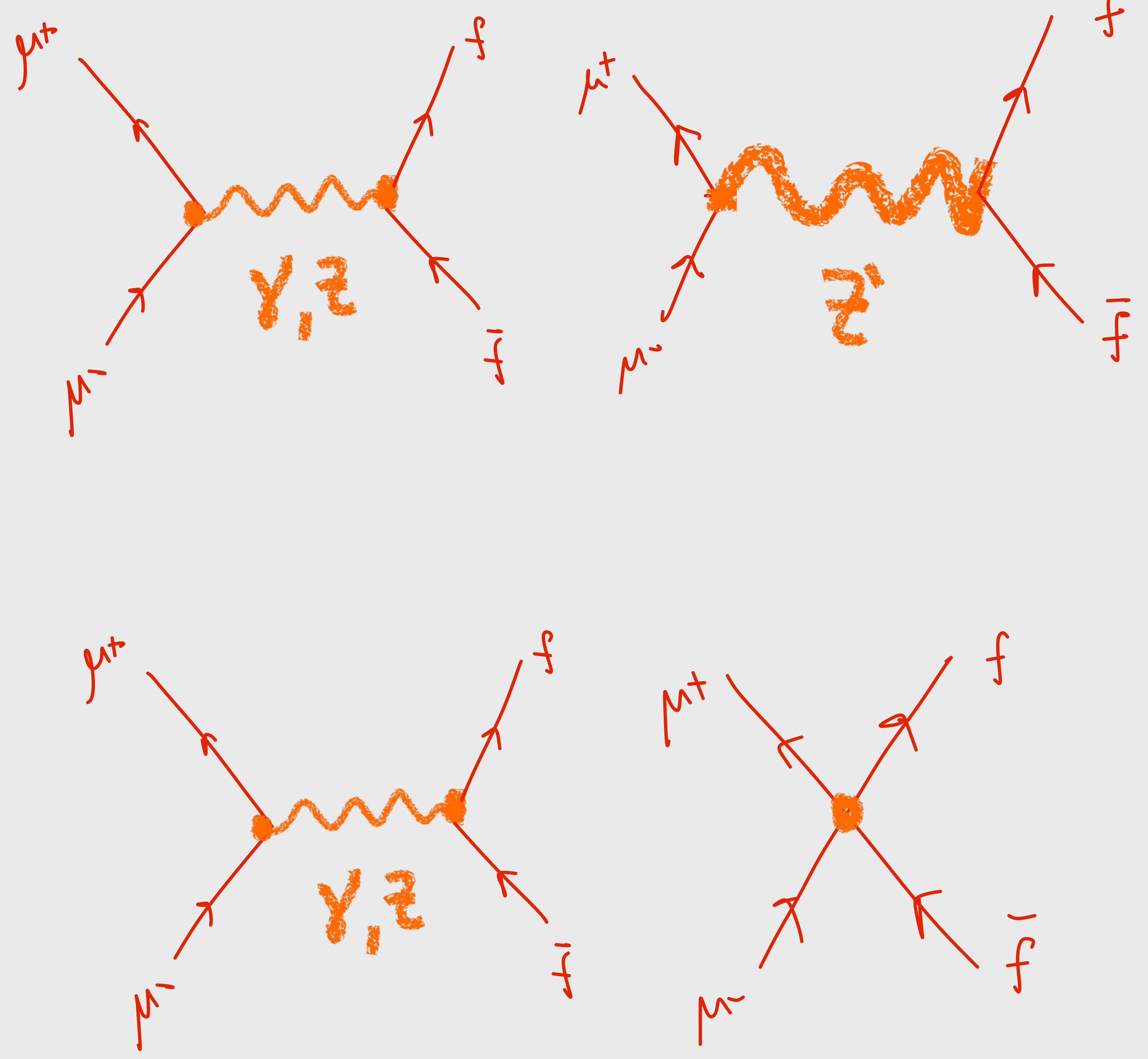
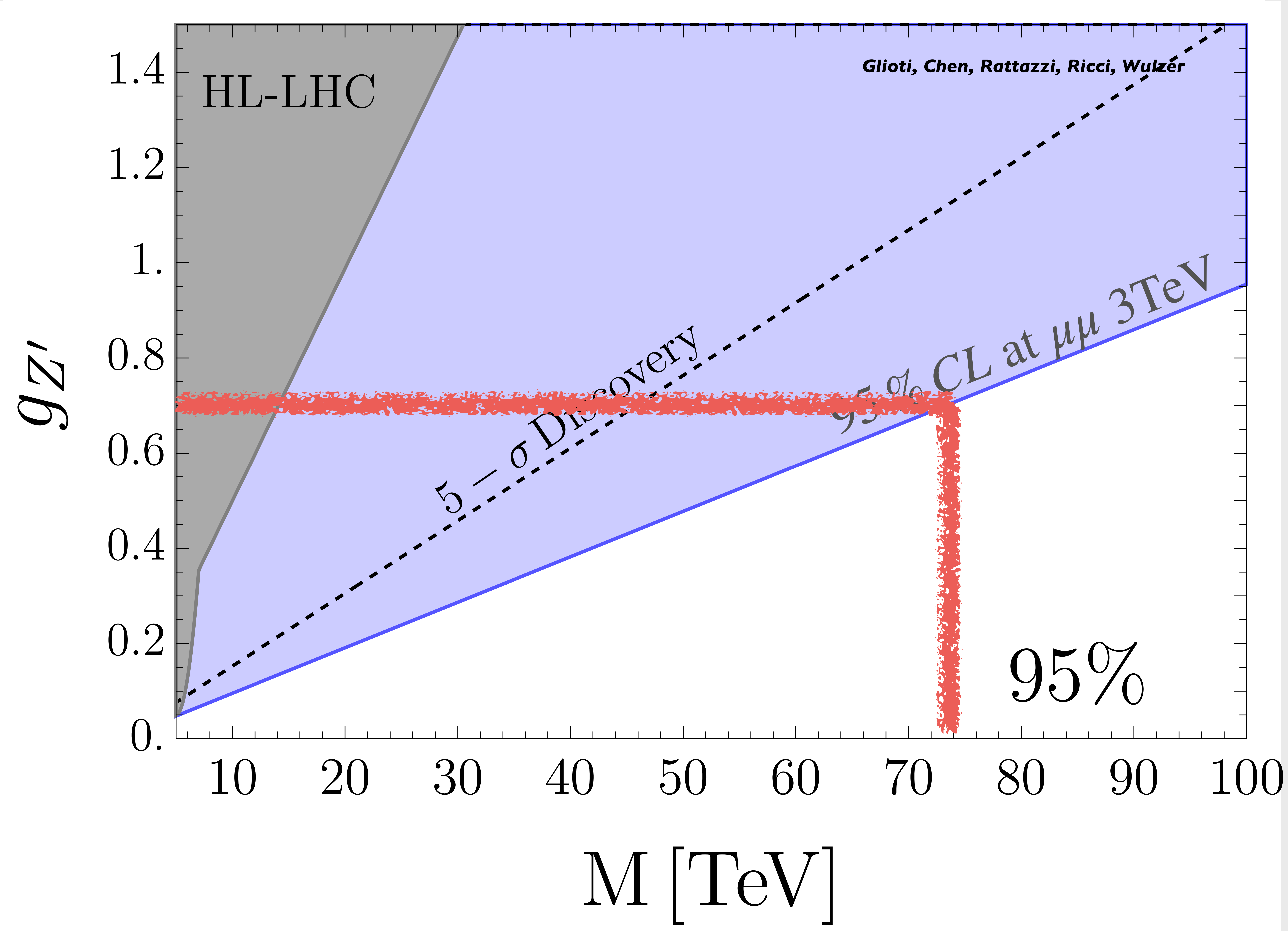
DRELL-YAN | RATES AND ANGULAR DISTRIBUTIONS

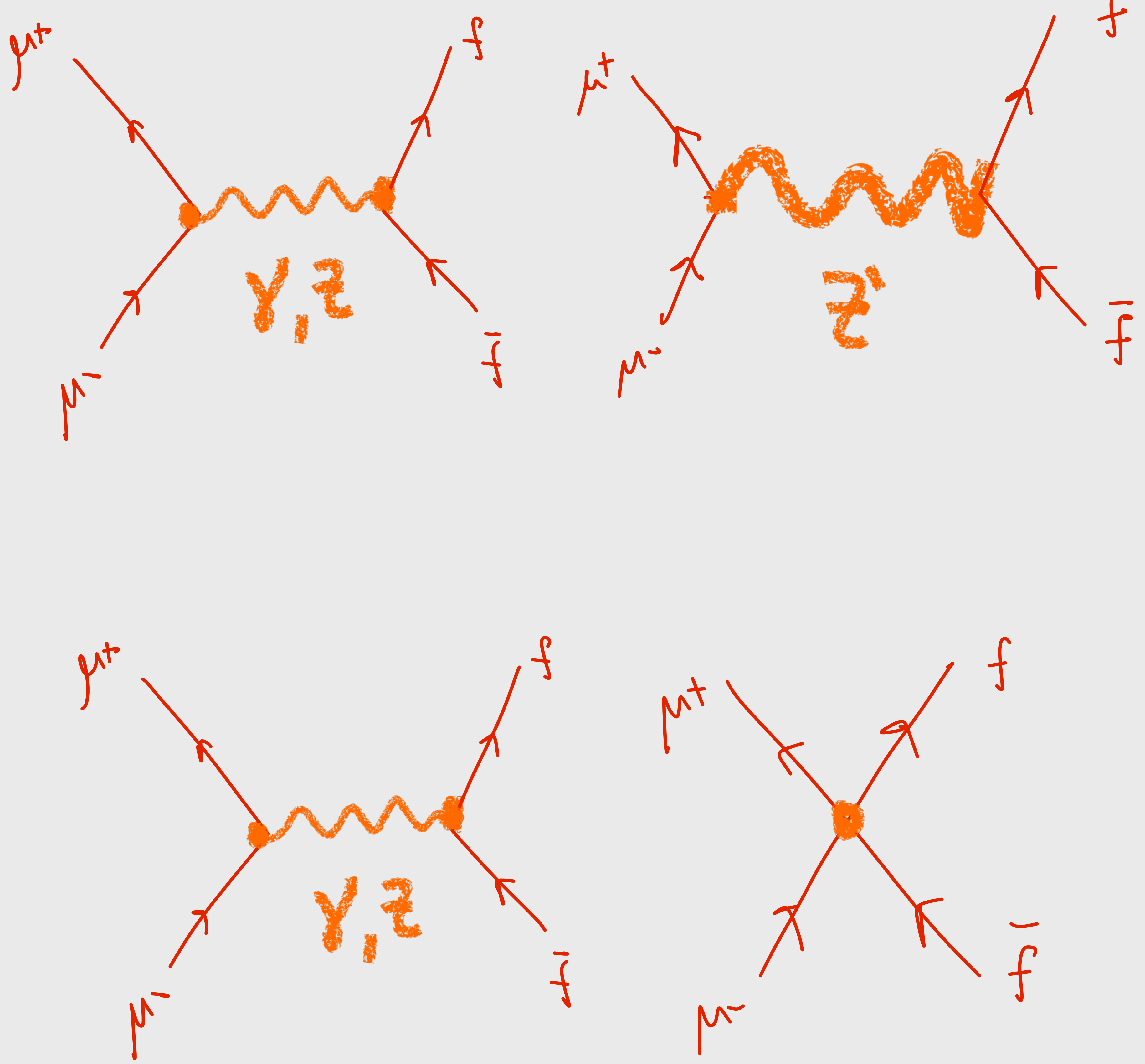


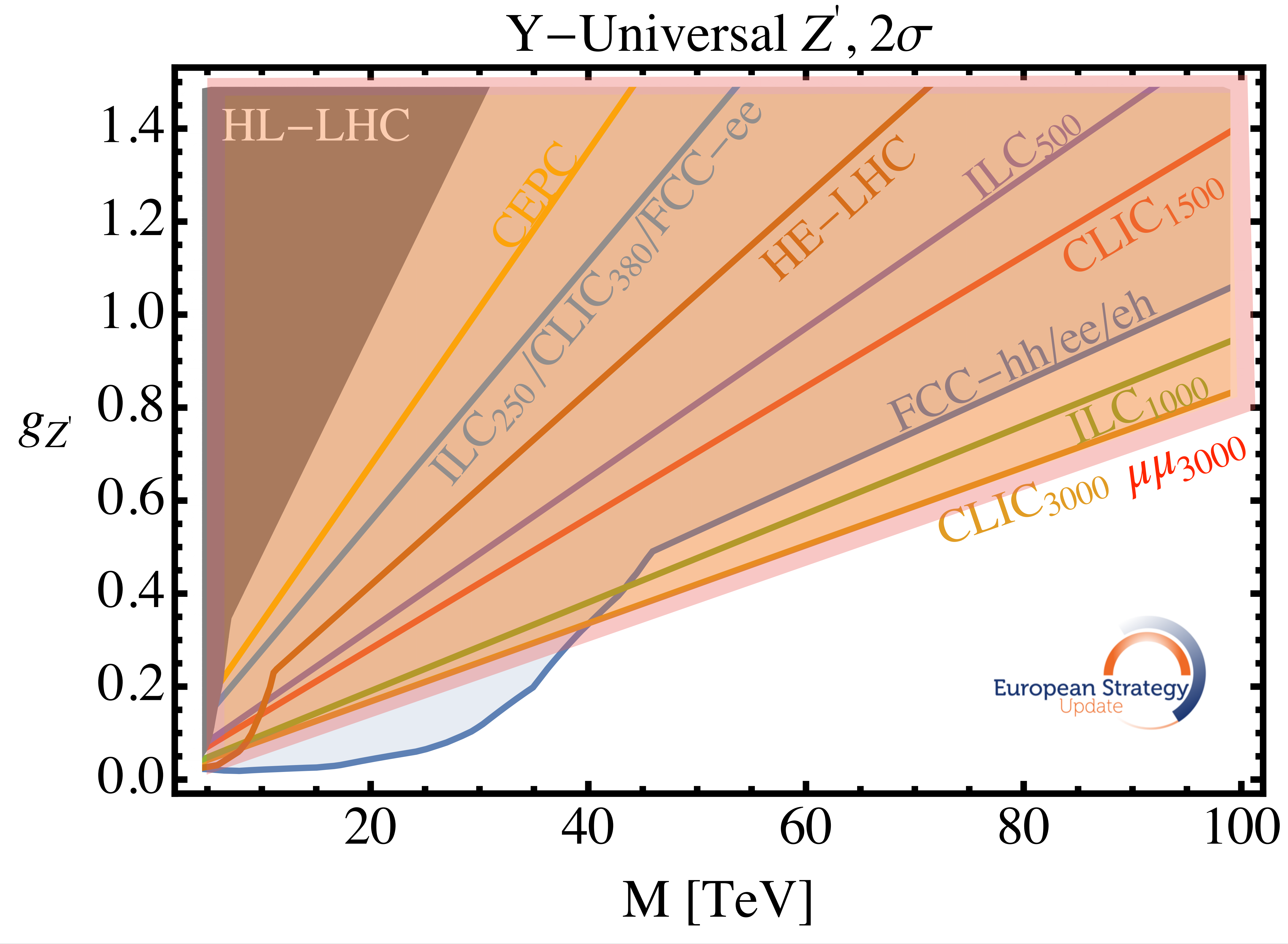


$\sqrt{s} \simeq 3$ TeV can probe 70+ TeV mass for $g_{Z'} \simeq g_{SM} \simeq 0.67$

A heavy Z'

DRELL-YAN | RATES AND ANGULAR DISTRIBUTIONS



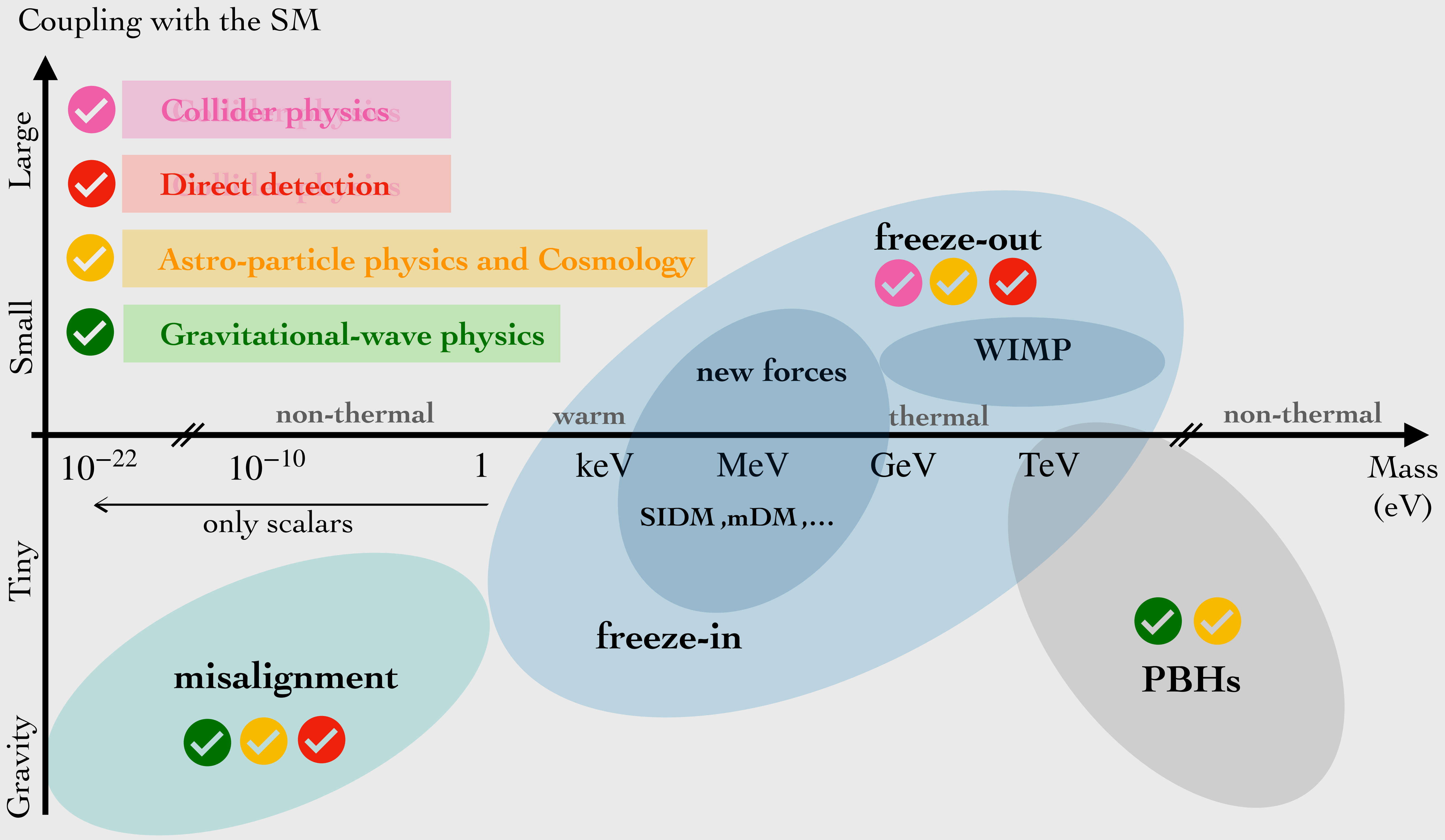


flashing concrete results for

Dark Matter at the weak scale

Electroweak Dark Matter: LSP (+NLSP)

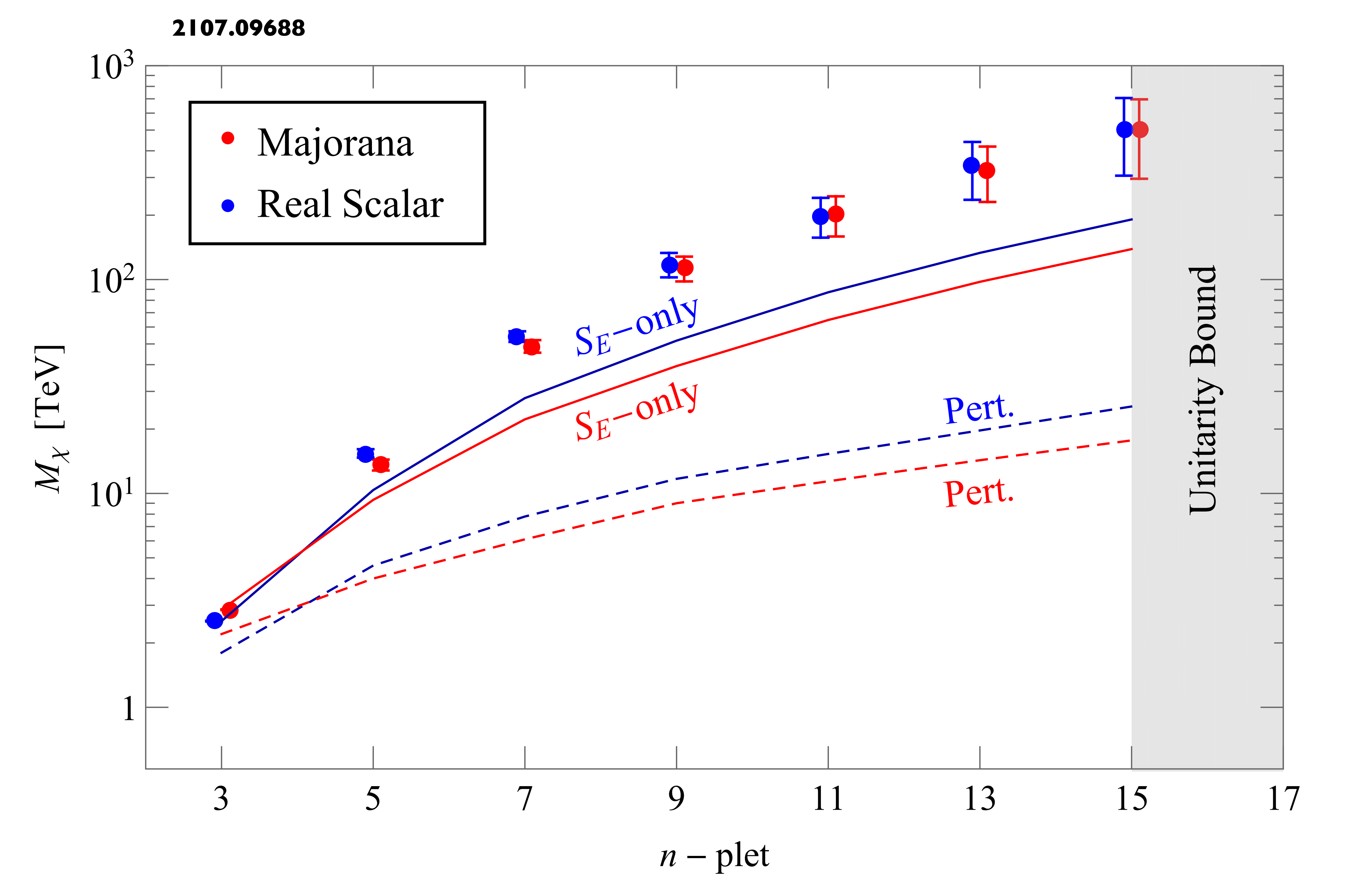
- The chessboard of DM is very large!



- High energy colliders are excellent and very robust probes of WIMPs!

Dark Matter as $SU(2)$ $n-$plet

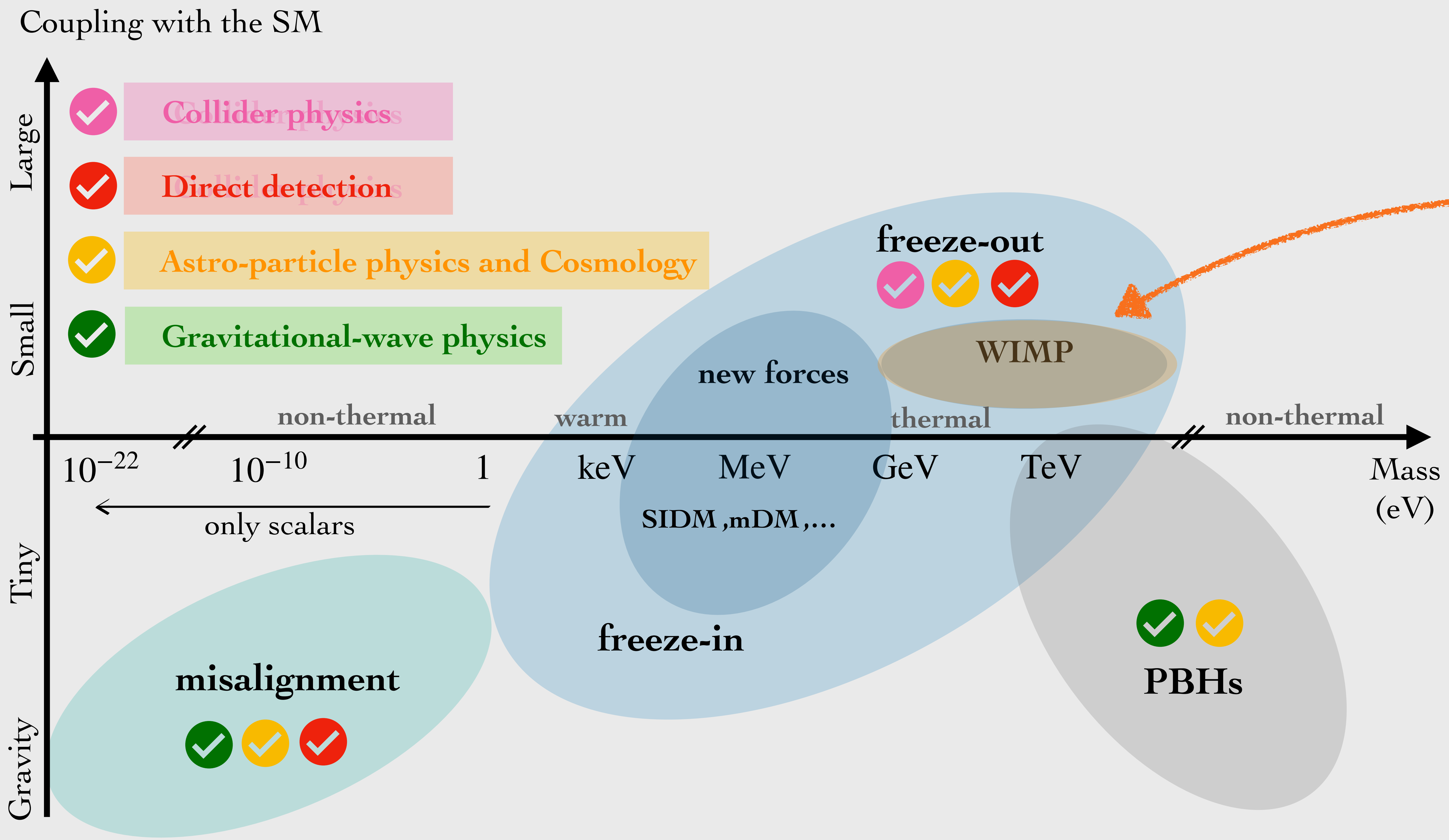
PURE SU(2) N-PLET | INTERPOLATOR UP TO *PeV*

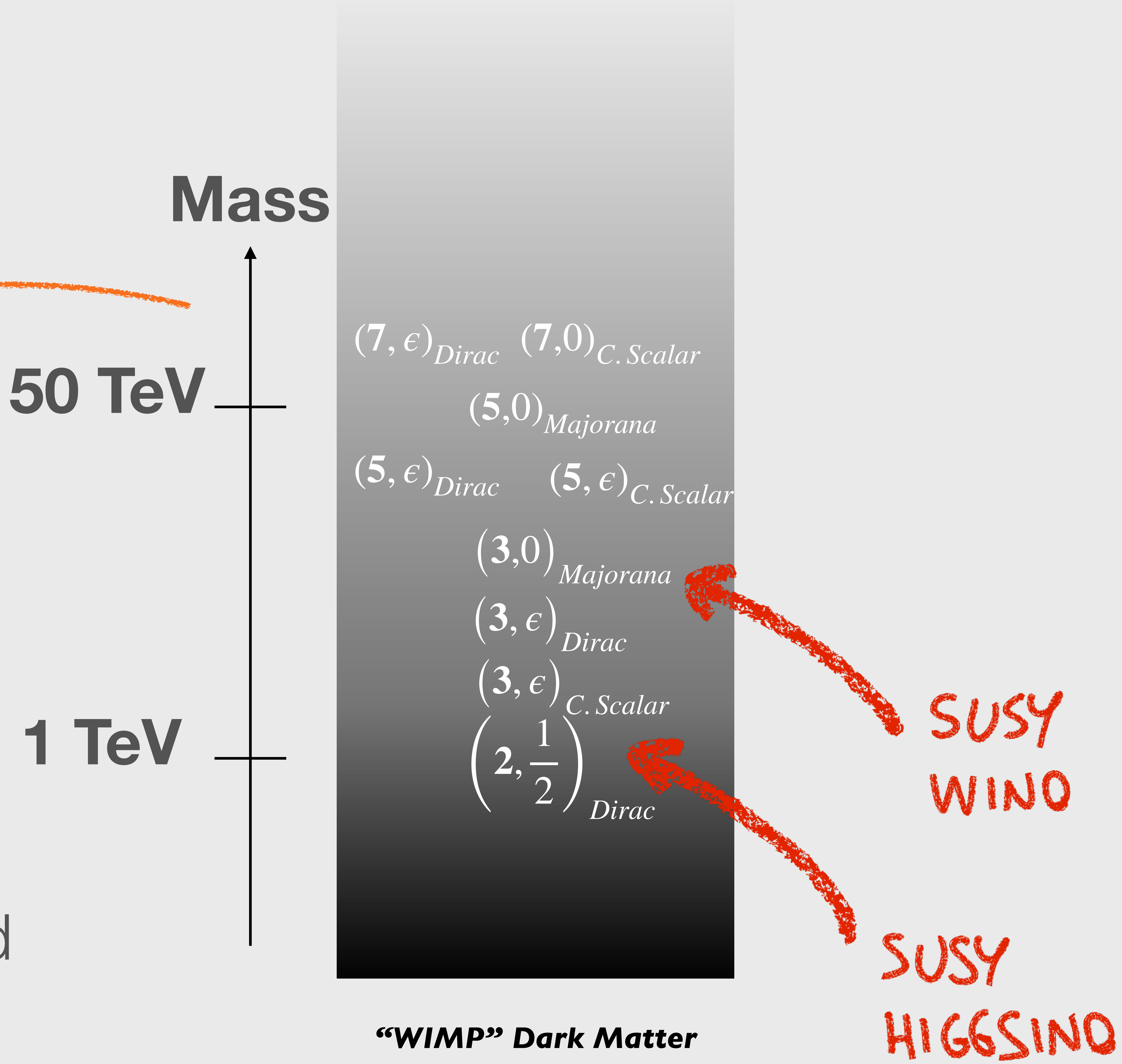


DM spin	EW n-plet	M_χ (TeV)	$(\sigma v)^{J=0}_{\rm tot}/(\sigma v)^{J=0}_{\rm max}$	$\Lambda_{\rm Landau}/M_{\rm DM}$	$\Lambda_{\rm UV}/M_{\rm DM}$
Real scalar	3	2.53 ± 0.01	–	3×10^{37}	$4 \times 10^{24}*$
	5	15.4 ± 0.7	0.002	5×10^{36}	2×10^{24}
	7	54.2 ± 3.1	0.022	2×10^{19}	2×10^{24}
	9	117.8 ± 15.4	0.088	3×10^{3}	2×10^{24}
	11	199 ± 42	0.25	20	3×10^{24}
	13	338 ± 102	0.6	3.5	3×10^{24}
Majorana fermion	3	2.86 ± 0.01	–	3×10^{37}	$8 \times 10^{12}*$
	5	13.6 ± 0.8	0.003	3×10^{17}	5×10^{12}
	7	48.8 ± 3.3	0.019	1×10^{4}	4×10^{7}
	9	113 ± 15	0.07	30	3×10^{7}
	11	202 ± 43	0.2	6	3×10^{7}
	13	324.6 ± 94	0.5	2.6	3×10^{7}

Electroweak Dark Matter: LSP (+NLSP)

- The chessboard of DM is very large!





- High energy colliders are excellent and very robust probes of WIMPs!

Electroweak Dark Matter: LSP (+NLSP)

Δm

	Δm	
Wide open spectra		Generic leptons+missing momentum
Co-annihilation		Soft-objects + missing momentum
	GeV	
WIMP-like multiplet Accidental Dark Matter		Short (disappearing) tracks
DM SM singlet pp or $\ell^+\ell^- \to Z' \to \chi\,\chi$	0	Mono-X

} Precision Tests

Electroweak Dark Matter: LSP (+NLSP)

Δm

Wide open spectra	Generic leptons+missing momentum	Precision Tests
Co-annihilation	Soft-objects + missing momentum	
GeV		
WIMP-like multiplet Accidental Dark Matter	Short (disappearing) tracks	
DM SM singlet pp or $\ell^+\ell^- \to Z' \to \chi\,\chi$ 0	Mono-X	

Recoil on “nothing”

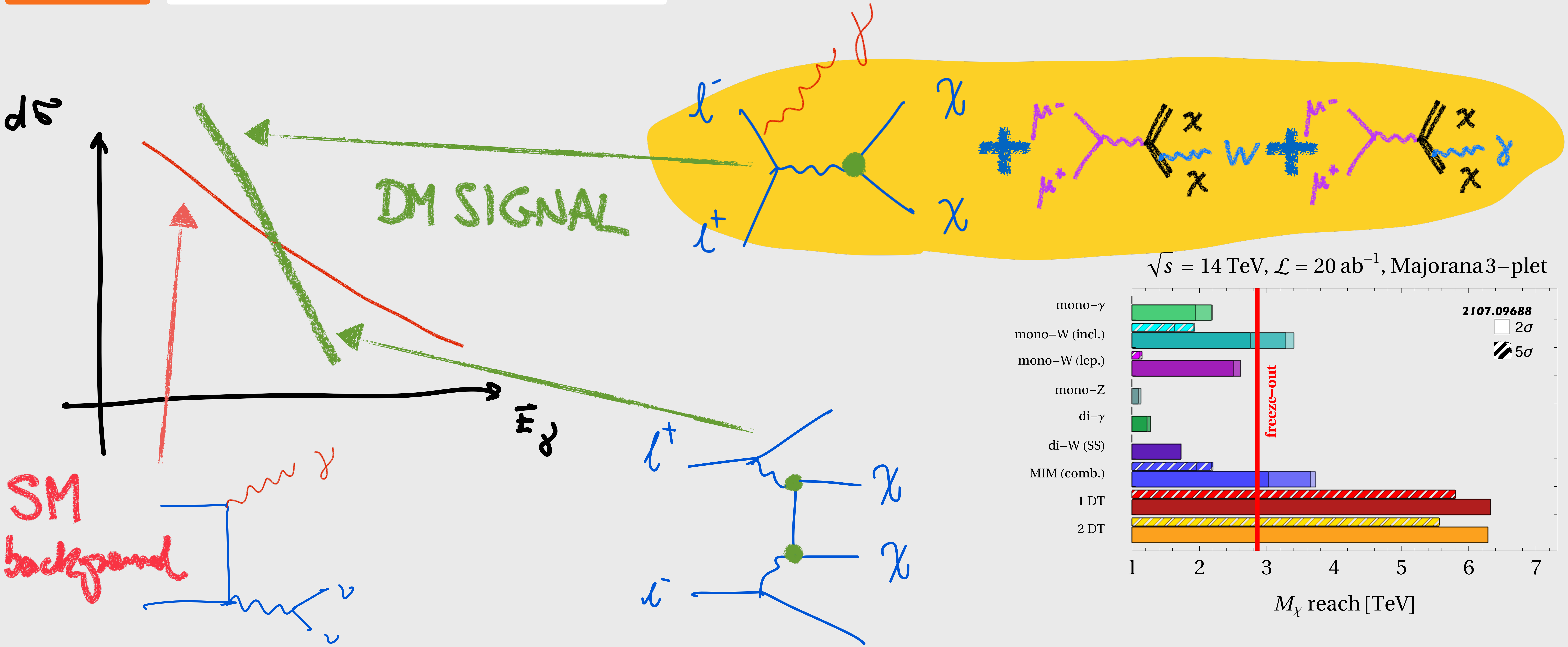
GENERIC

SEARCH INTERPRETED FOR DARK MATTER

Recoil on “nothing”

GENERIC

SEARCH INTERPRETED FOR DARK MATTER



Electroweak Dark Matter: LSP (+NLSP)

Δm

Wide open spectra		Generic leptons+missing momentum	Precision Tests
Co-annihilation		Soft-objects + missing momentum	
	GeV		
WIMP-like multiplet Accidental Dark Matter		Short (disappearing) tracks	
DM SM singlet pp or $\ell^+\ell^- \to Z' \to \chi\,\chi$	0	Mono-X	

Electroweak Dark Matter: LSP (+NLSP)

Δm

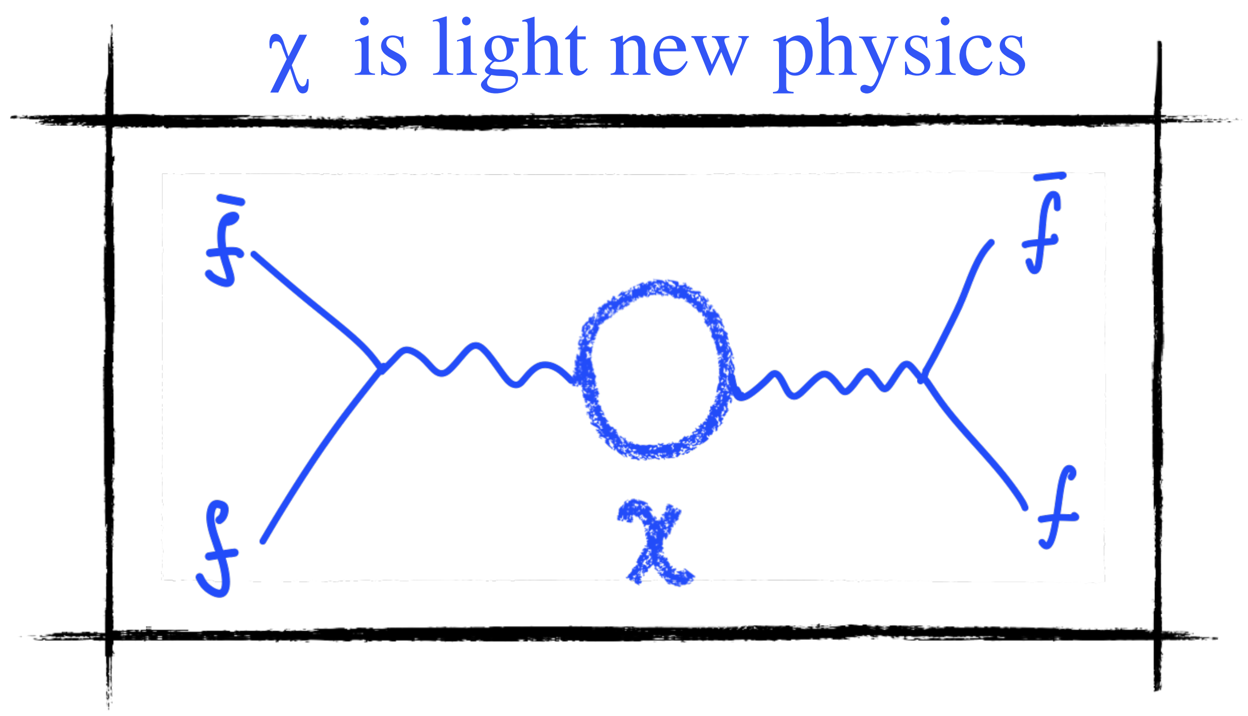
Wide open spectra		Generic leptons+missing momentum
Co-annihilation		Soft-objects + missing momentum
	GeV	
WIMP-like multiplet Accidental Dark Matter		Short (disappearing) tracks
DM SM singlet *pp* or $\ell^+\ell^- \to Z' \to \chi\,\chi$	0	Mono-X

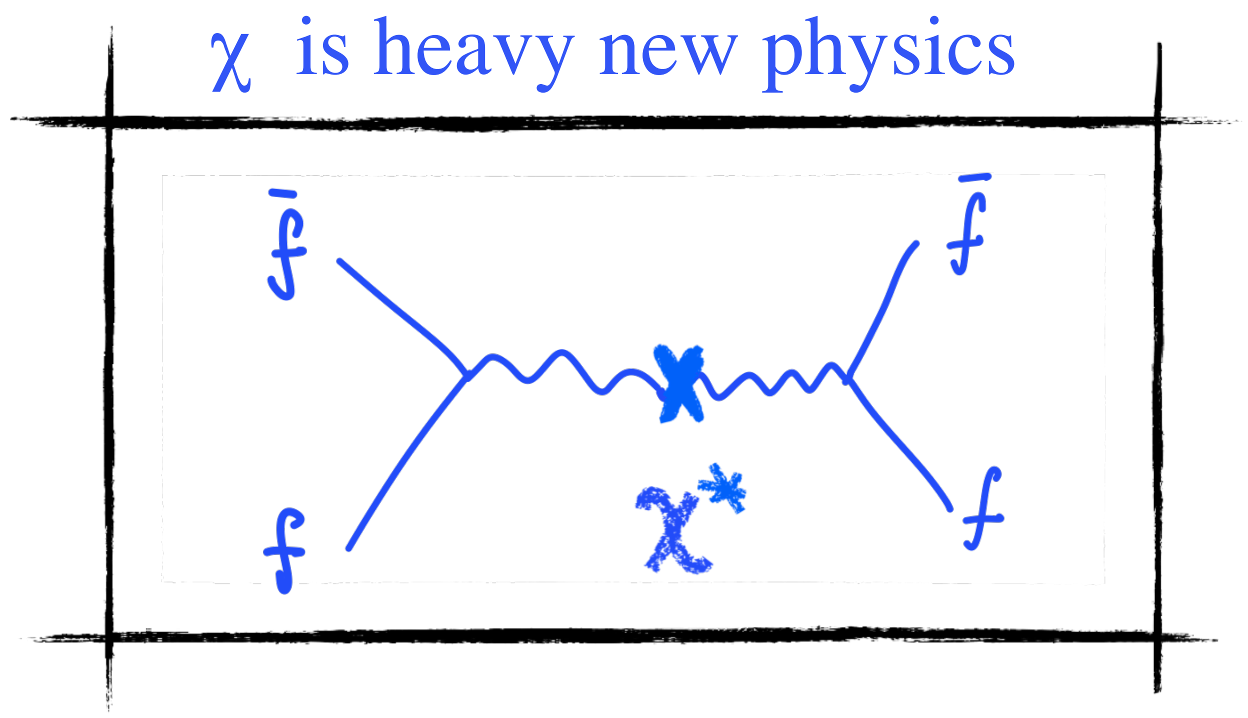
} **Precision Tests**

pp or $\ell^+\ell^- \to f\bar{f}, W^+W^-$

PRECISION

TOTAL CROSS-SECTION



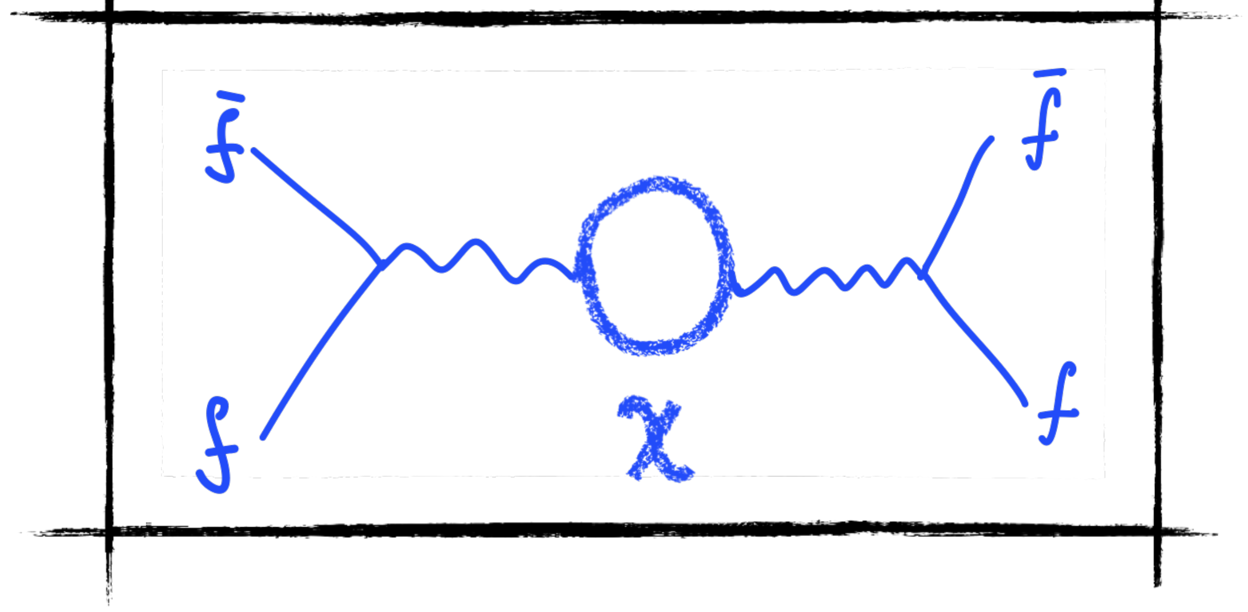


- fiducial cross-sections are significantly affected by off-shell new physics heavier than the collider kinematic reach

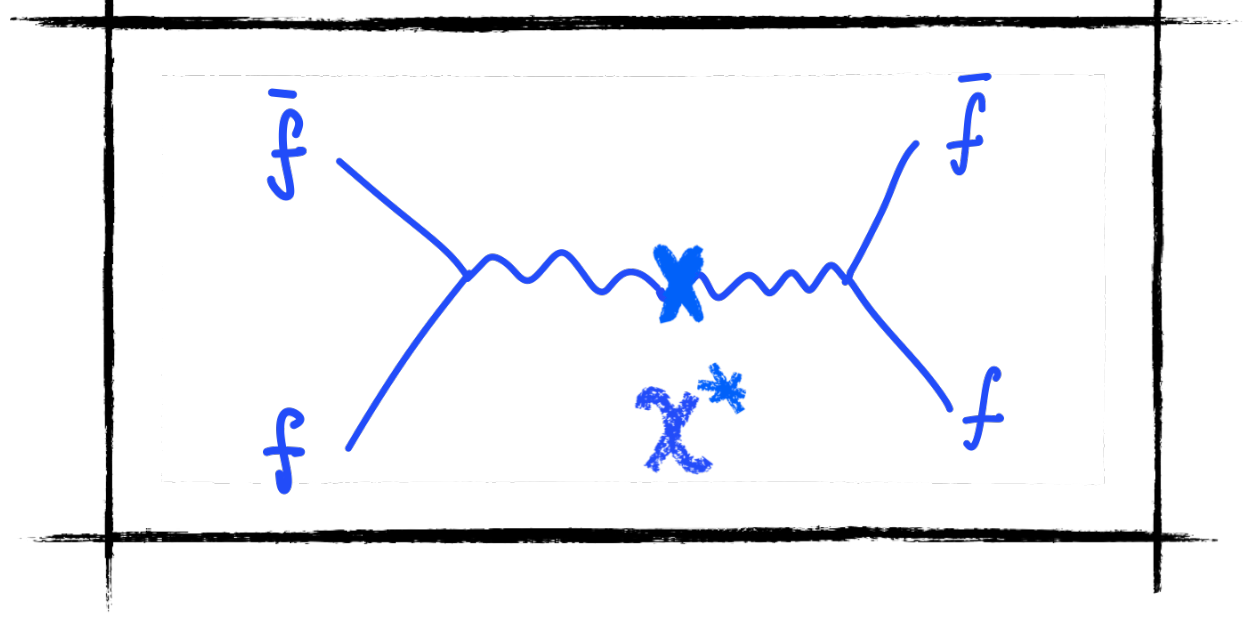
pp or $\ell^+\ell^- \to f\bar{f}, W^+W^-$

PRECISION **TOTAL CROSS-SECTION**

χ is light new physics



χ is heavy new physics

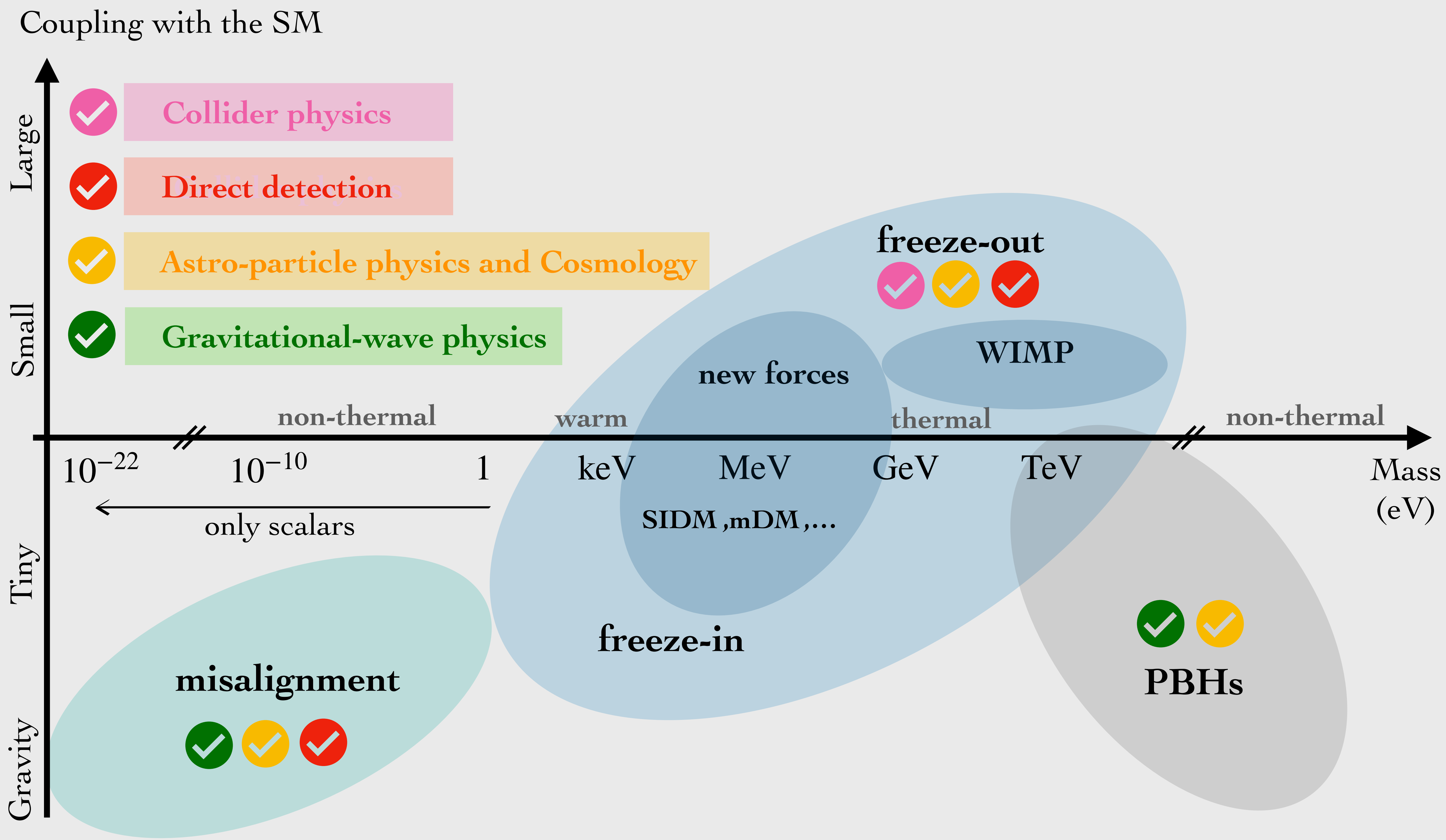


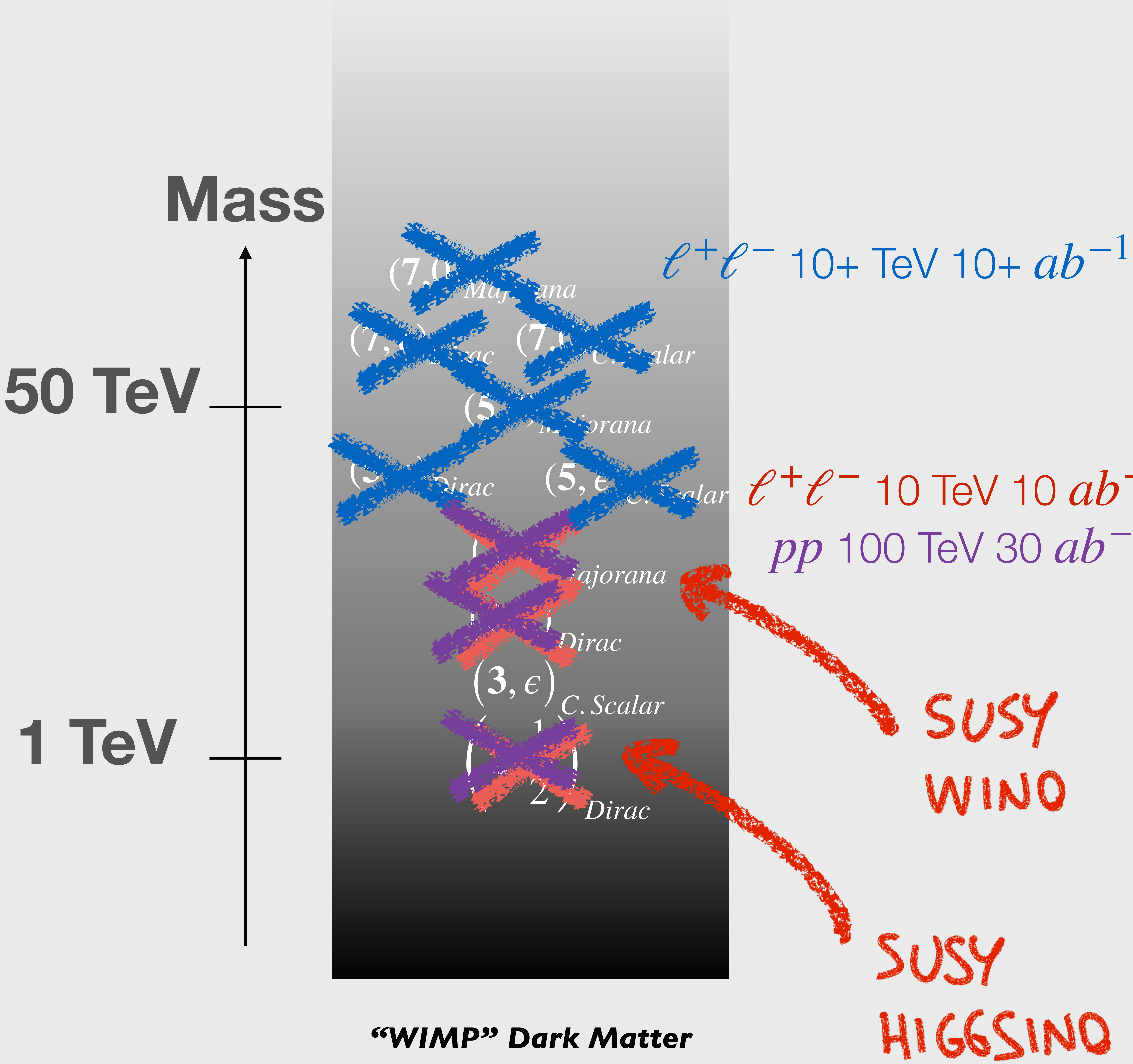
- fiducial cross-sections are significantly affected by off-shell new physics heavier than the collider kinematic reach

χ / m_χ [TeV]	DM	HL-LHC	HE-LHC	FCC-100	CLIC-3	Muon-14
$(1,2,1/2)_{\rm DF}$	1.1	–	–	–	0.4	0.6
$(1,3,\epsilon)_{\rm CS}$	1.6	–	–	–	0.2	0.2
$(1,3,\epsilon)_{\rm DF}$	2.0	–	0.6	1.5	0.8 & [1.0, 2.0]	2.2 & [6.3, 7.1]
$(1,3,0)_{\rm MF}$	2.8	–	–	0.4	0.6 & [1.2, 1.6]	1.0
$(1,5,\epsilon)_{\rm CS}{}^*$	6.6	0.2	0.4	1.0	0.5 & [0.7,1.6]	1.6
$(1,5,\epsilon)_{\rm DF}{}^*$	6.6	1.5	2.8	7.1	3.9	11
$(1,5,0)_{\rm MF}$	14	0.9	1.8	4.4	2.9	3.5 & [5.1, 8.7]
$(1,7,\epsilon)_{\rm CS}$	54	0.6	1.3	3.2	2.4	2.5 & [3.5, 7.4]
$(1,7,\epsilon)_{\rm MF}$	48	2.1	4.0	11	6.4	18

- Comprehensive tool to explore new electroweak particles
- Can probe valid dark matter candidates!

Electroweak Dark Matter: LSP (+NLSP)





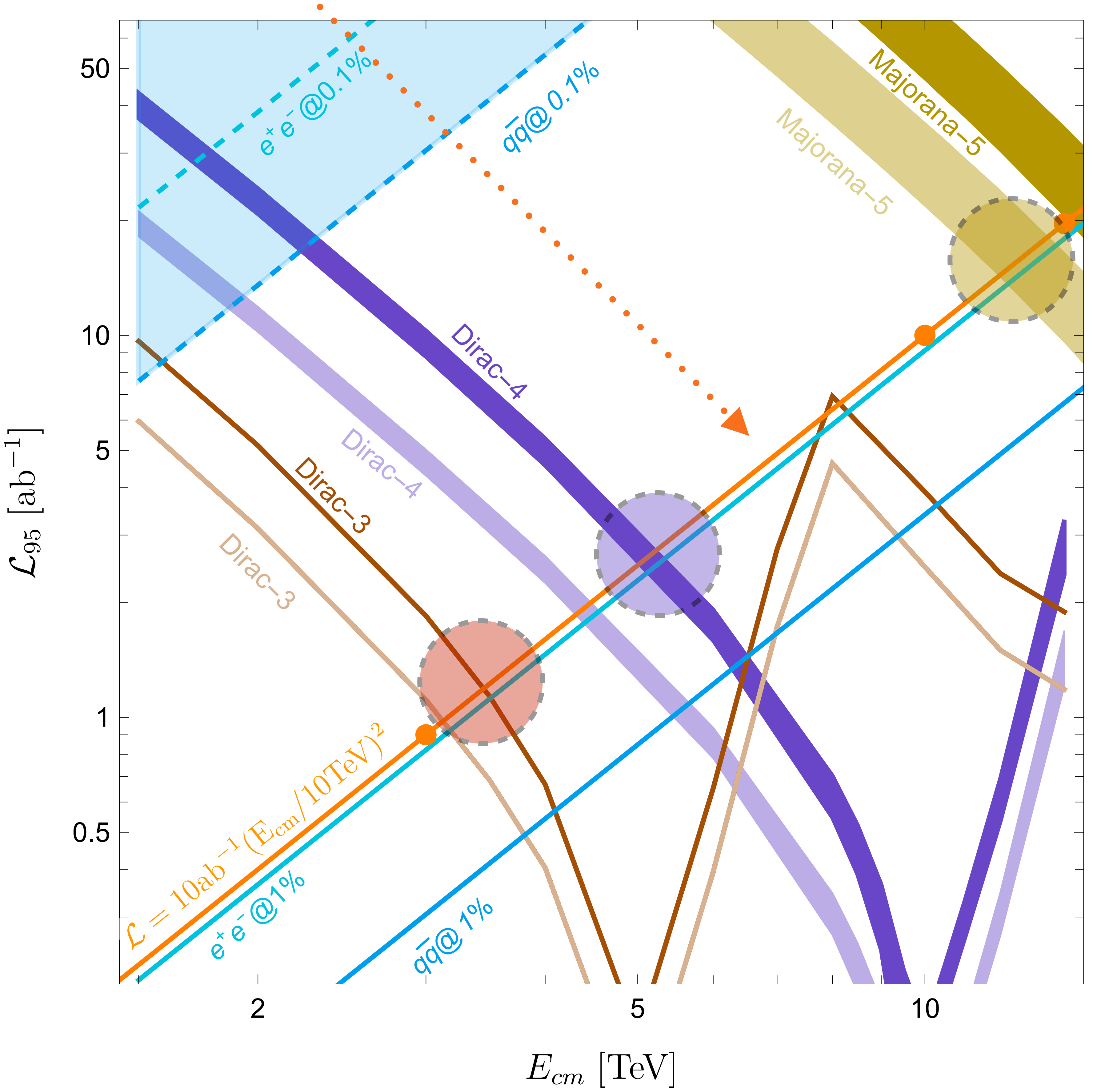
$\ell^+\ell^- \to f\bar{f}, Zh, W^+W^-, Wff'$

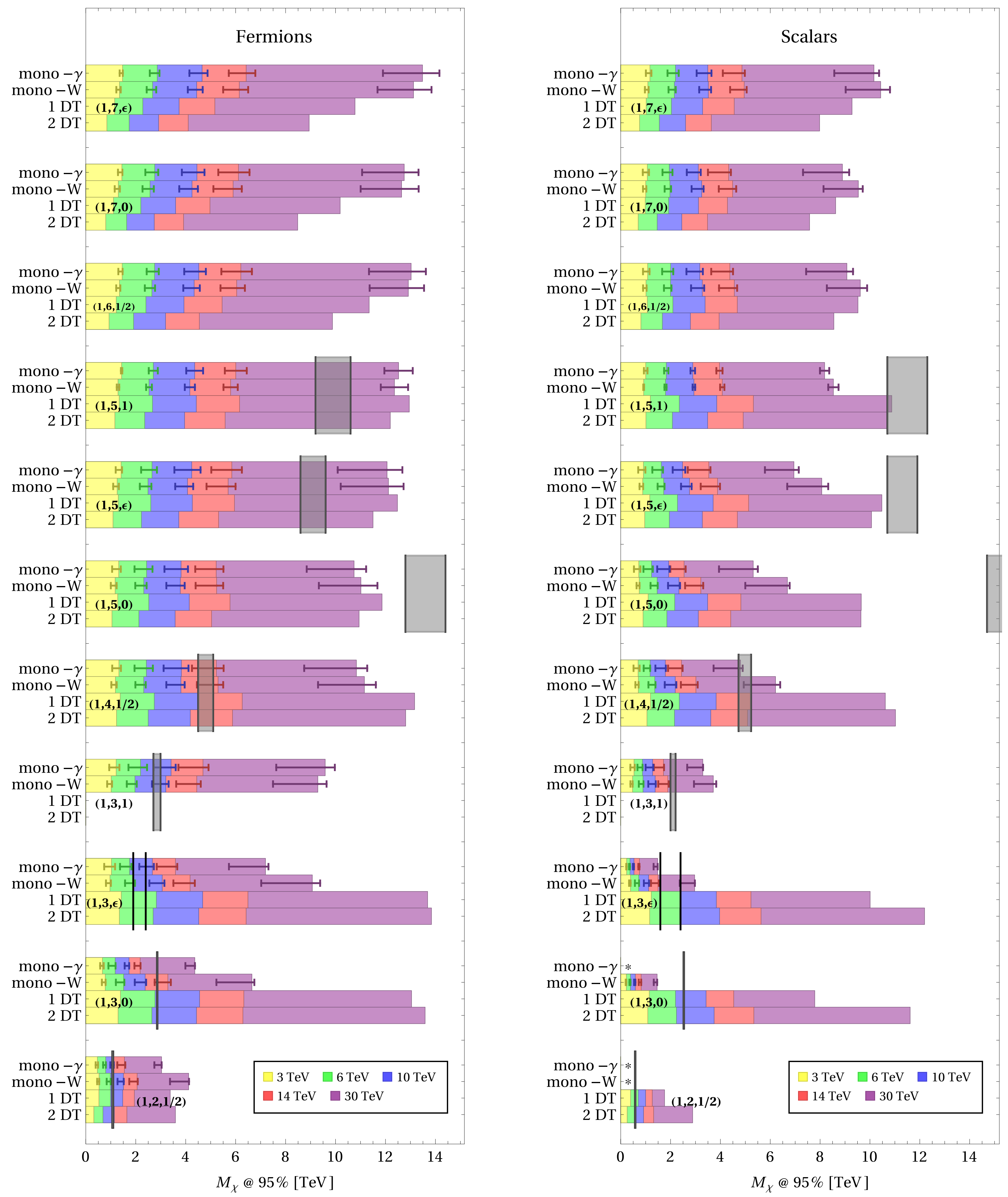
$\mu^+\mu^- \to \chi\chi + X$

SM

PRECISION MEASUREMENTS

$\mathscr{L} = 10\,\text{ab}^{-1} \cdot (E_{com}/10\,\text{TeV})^2$





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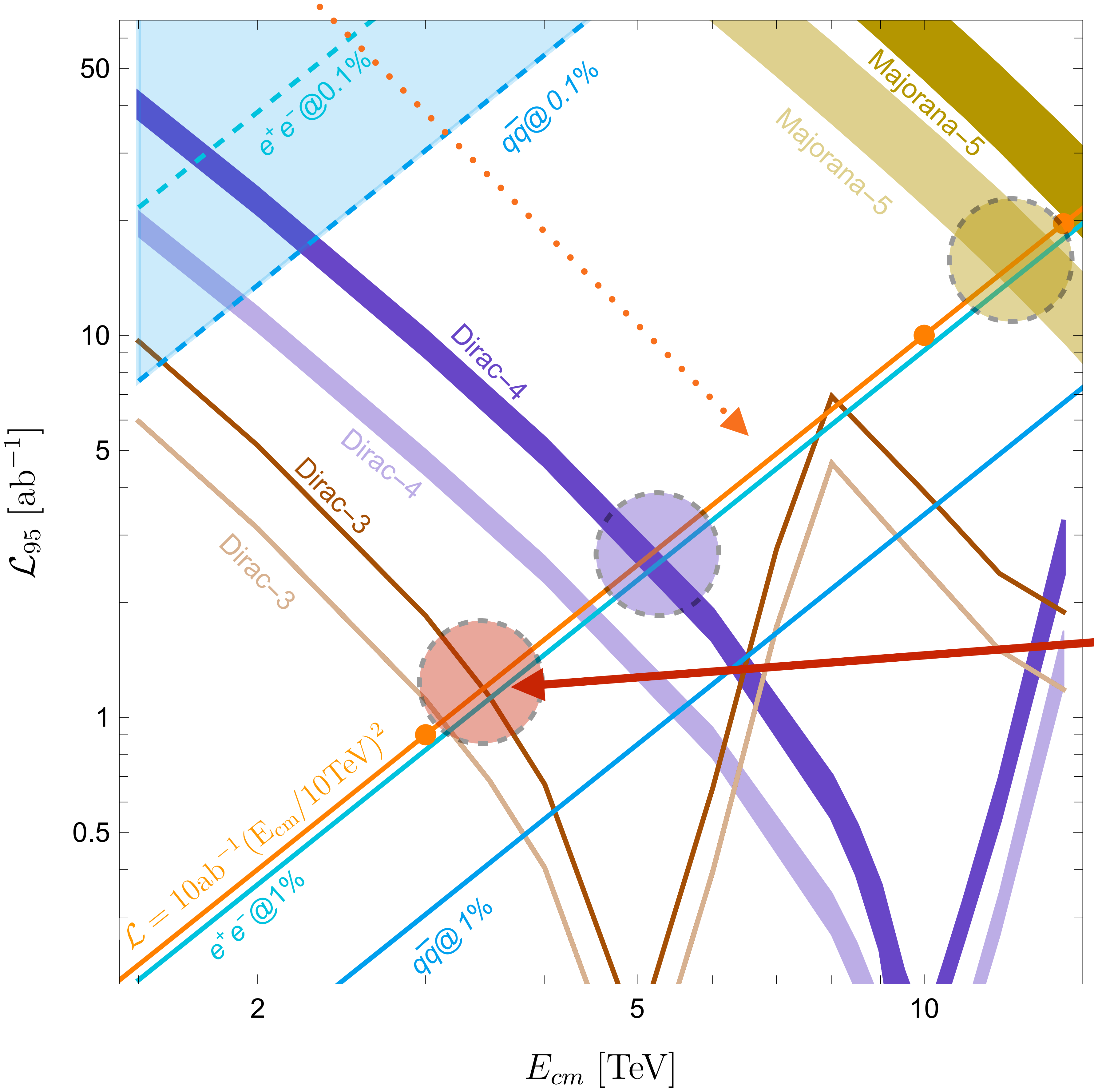
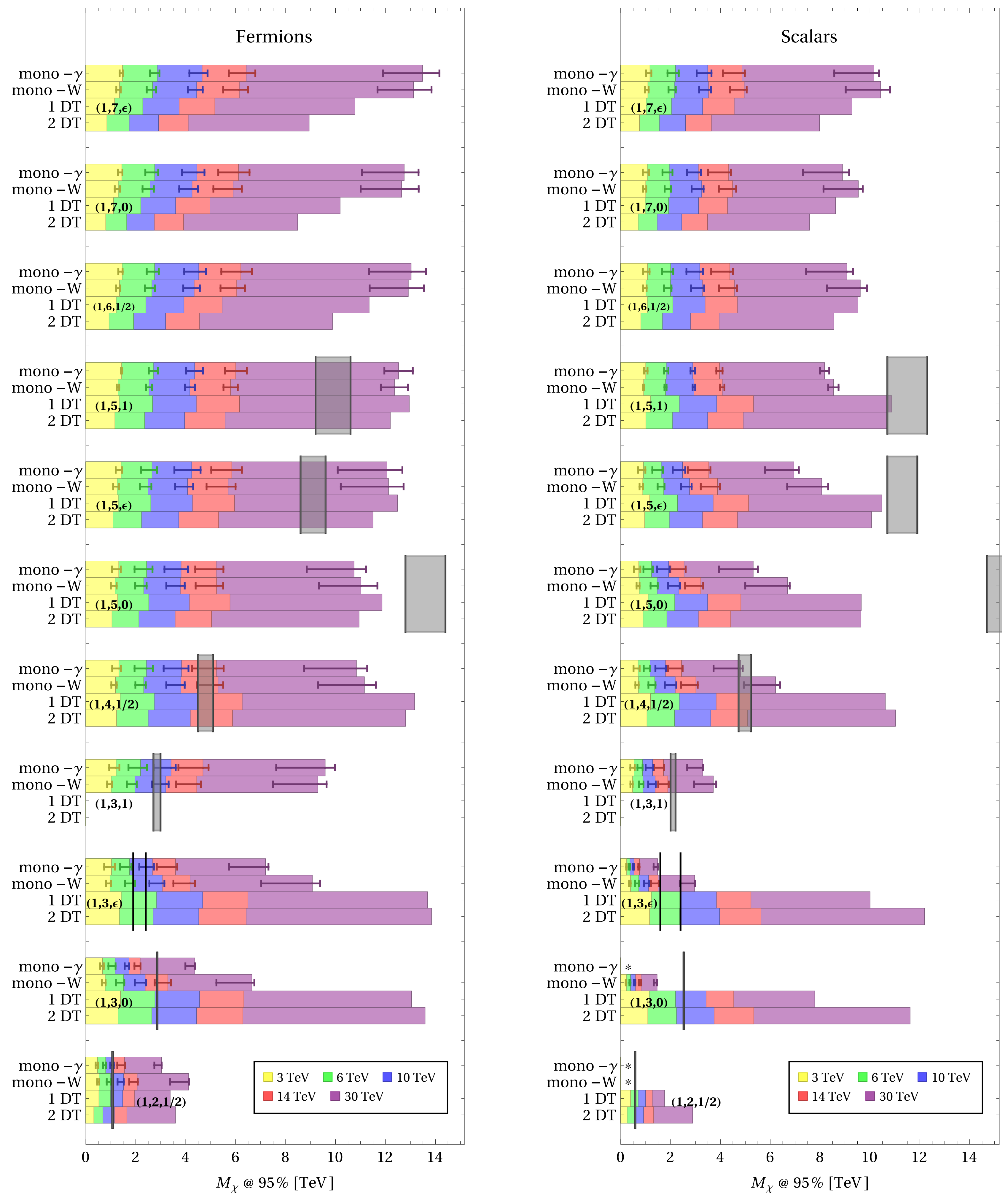


$(\mathbf{3},0)_{Majorana}$

$(\mathbf{3},\epsilon)_{Dirac}$

$\left(\mathbf{2},\frac{1}{2}\right)_{Dirac}$

$\ell^+\ell^-$ 3 TeV 1 ab^{-1}



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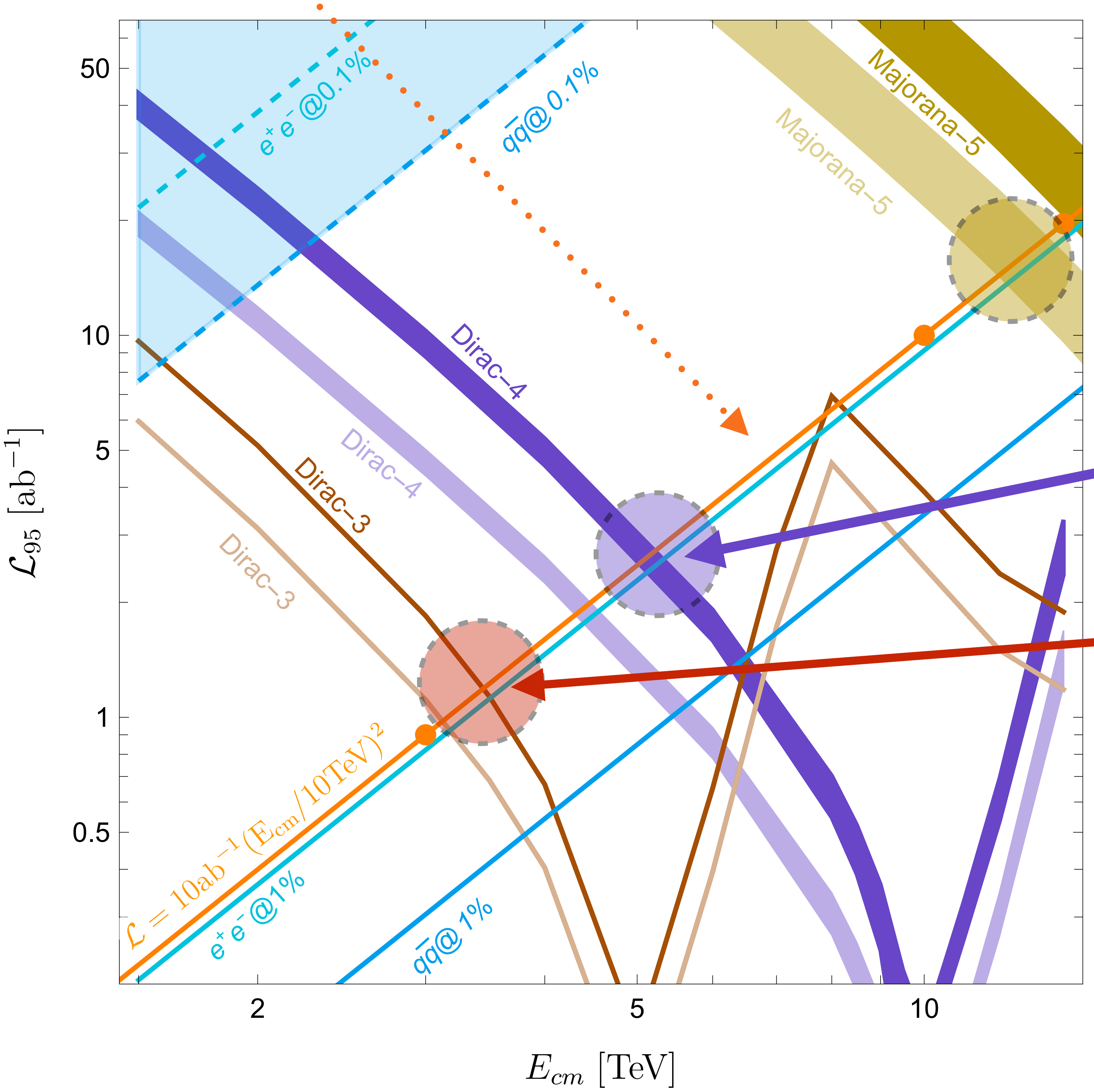


$\left(4, \frac{1}{2}\right)_{Dirac}$

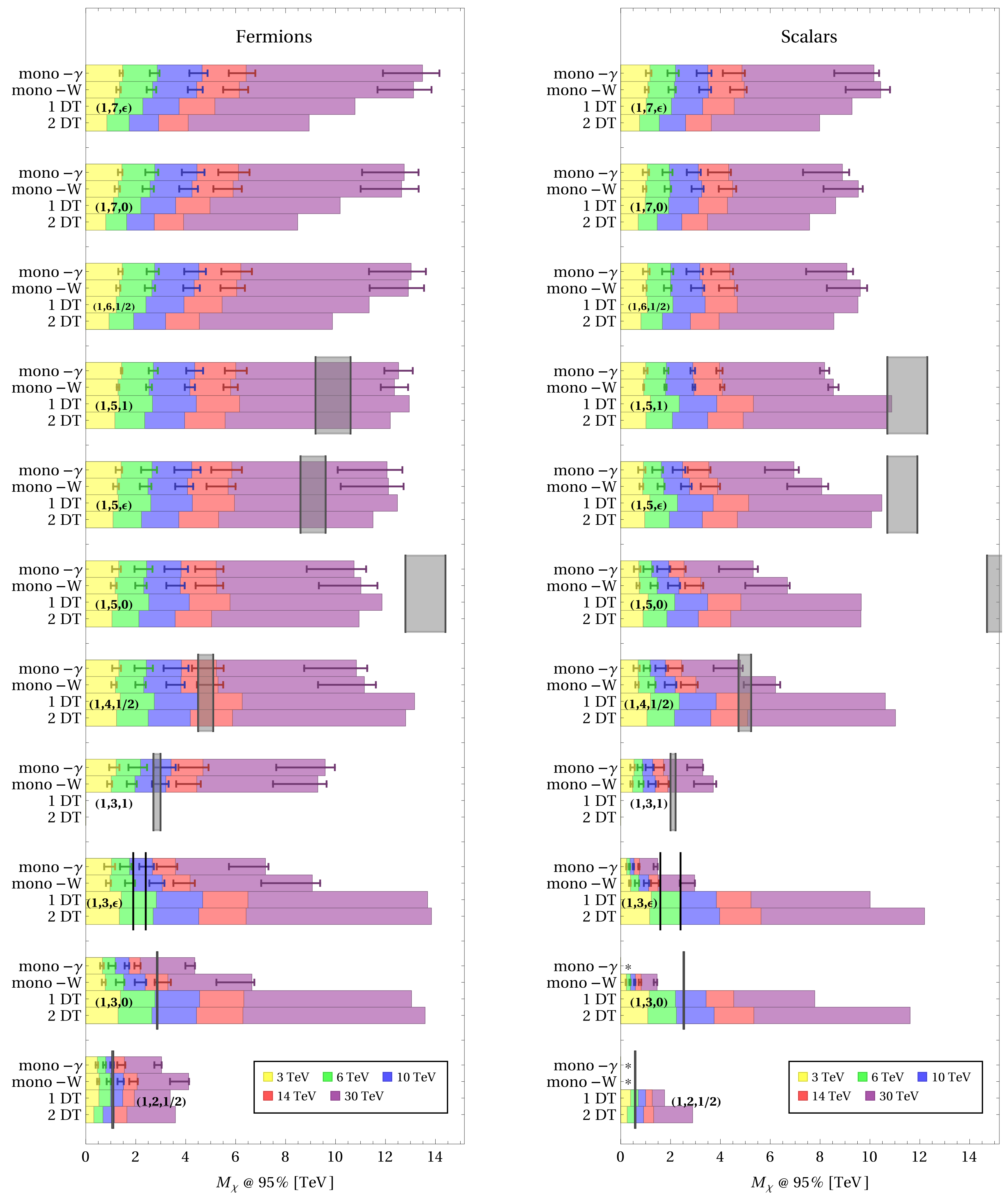
$\ell^+\ell^-$ 10 TeV 10 ab^{-1}

$(3, 0)_{Majorana}$

$(3, \epsilon)_{Dirac}$

$\ell^+\ell^-$ 3 TeV 1 ab^{-1}

$\left(2, \frac{1}{2}\right)_{Dirac}$



$\ell^+\ell^- \to f\bar{f}, Zh, W^+W^-, Wff'$

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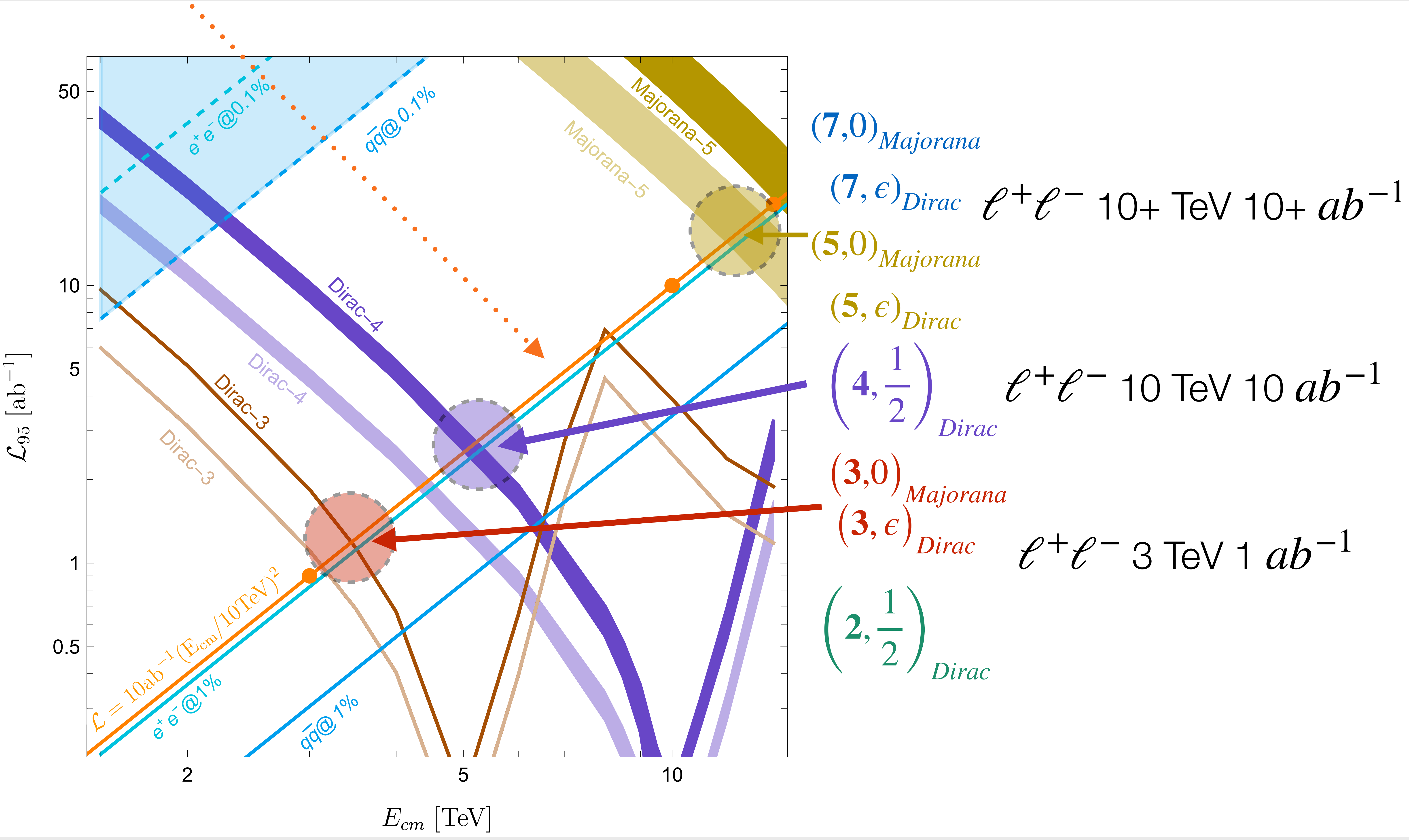

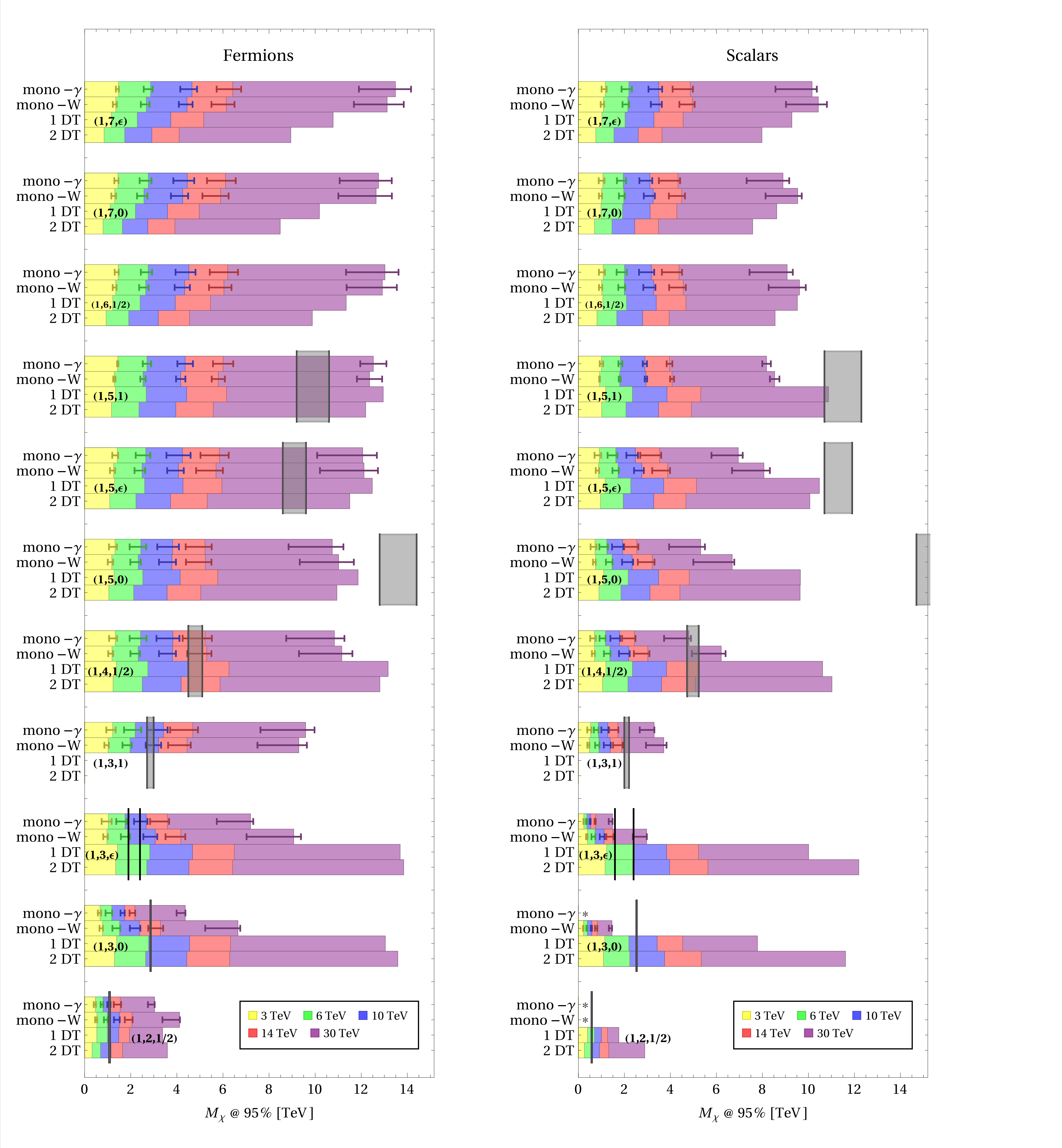

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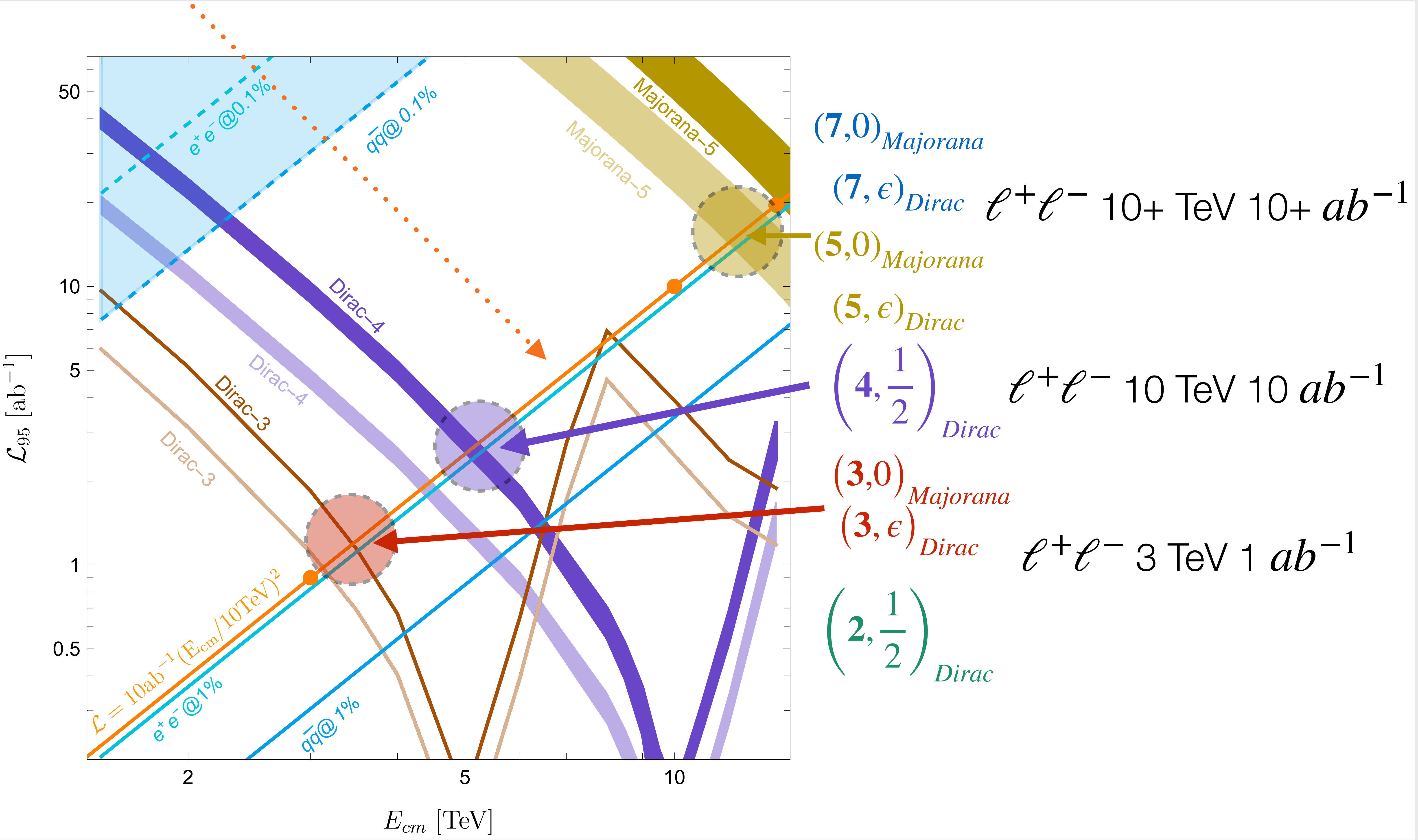
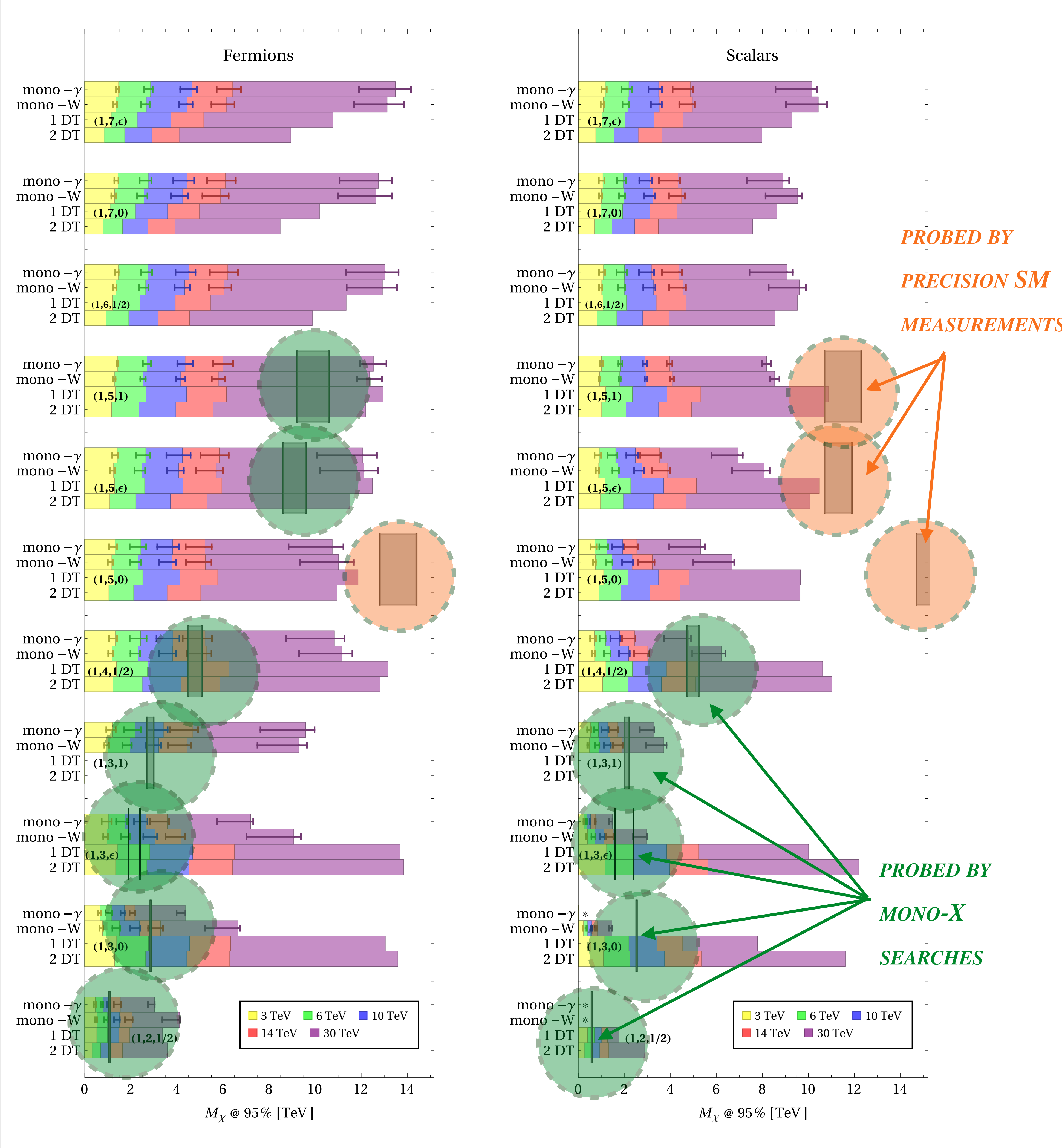
SM

PRECISION MEASUREMENTS

$\mathcal{L} = 10\,\text{ab}^{-1} \cdot (E_{com}/10\,\text{TeV})^2$





Winter HEPAP meeting: December 7-8, 9AM

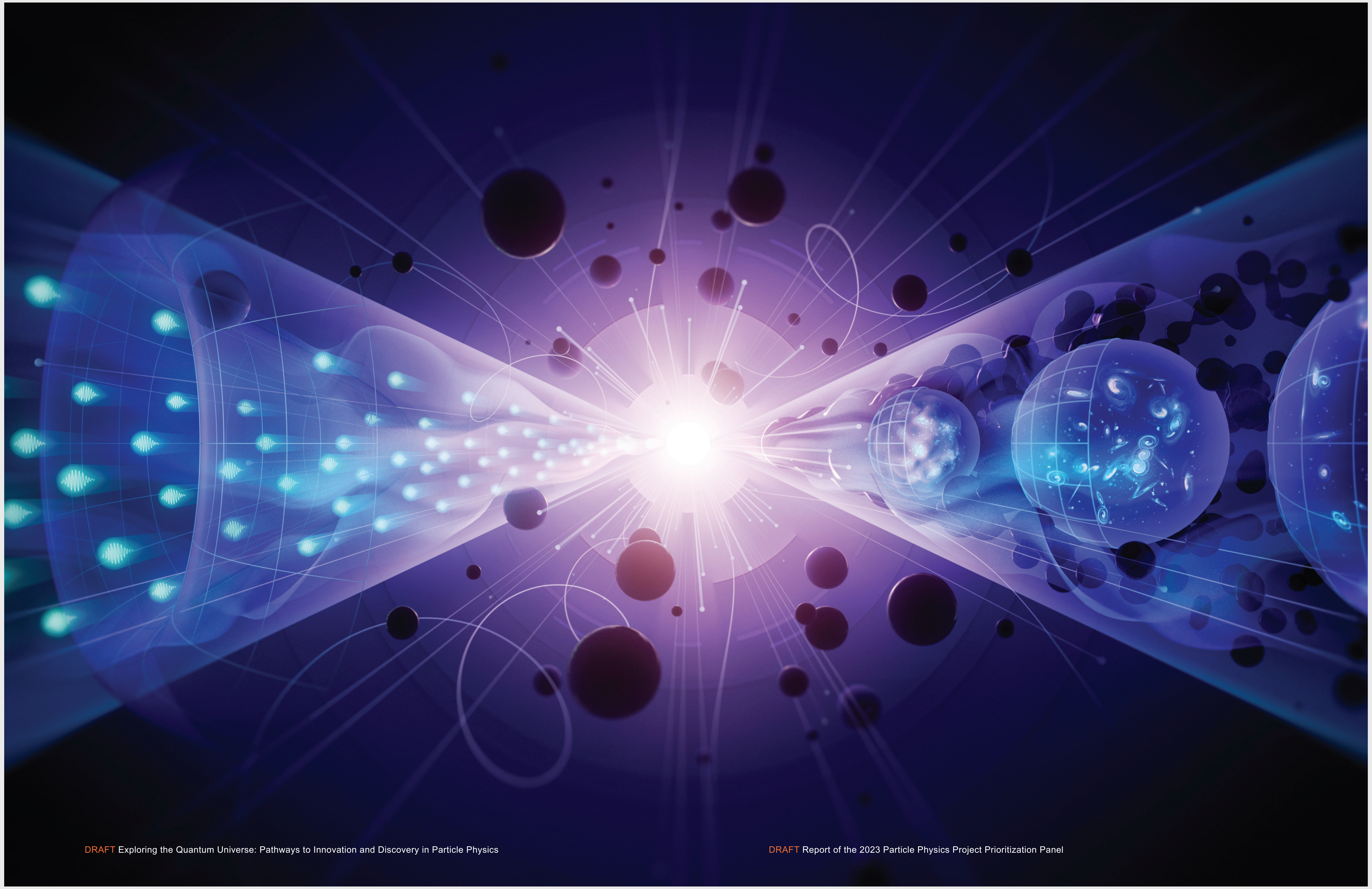
https://science.osti.gov/hep/hepap/Meetings

Exploring the Quantum Universe

Pathways to Innovation and Discovery in Particle Physics

Draft for Approval 1 December 2023

Particle Physics Project Prioritization Panel
High Energy Physics Advisory Panel
December 7, 2023



2.3 The Path to a 10 TeV pCM

Realization of a future collider will require resources at a global scale and will be built through a world-wide collaborative effort where decisions will be taken collectively from the outset by the partners. This differs from current and past international projects in particle physics, where individual laboratories started projects that were later joined by other laboratories. The proposed program aligns with **the long-term ambition of hosting a major international collider facility in the US, leading the global effort** to understand the fundamental nature of the universe.

…

In particular, a muon collider presents an attractive option both for technological innovation and for bringing energy frontier colliders back to the US. The footprint of **a 10 TeV pCM muon collider is almost exactly the size of the Fermilab campus**. A muon collider would rely on a powerful multi-megawatt proton driver delivering very intense and short beam pulses to a target, resulting in the production of pions, which in turn decay into muons. This cloud of muons needs to be captured and cooled before the bulk of the muons have decayed. Once cooled into a beam, fast acceleration is required to further suppress decay losses.

…

Although **we do not know if a muon collider is ultimately feasible**, the road toward it leads from current Fermilab strengths and capabilities to **a series of proton beam improvements and neutrino beam facilities**, each producing world-class science while performing critical R&D towards a muon collider. At the end of the path is an unparalleled global facility on US soil. **This is our Muon Shot.**

2.5 International and Inter-Agency Partnerships

In the case of the Higgs factory, crucial decisions must be made in consultation with potential international partners. The FCC-ee feasibility study is expected to be completed by 2025 and will be followed by a European Strategy Group update and a CERN council decision on the 2028 timescale. The ILC design is technically ready and awaiting a formulation as a global project. **A dedicated panel should review the plan for a specific Higgs factory once it is deemed feasible and well-defined;** evaluate the schedule, budget and risks of US participation; and give recommendations to the US funding agencies later this decade (Recommendation 6). When a clear choice for a specific Higgs factory emerges, US efforts will focus on that project, and R&D related to other Higgs factory projects would ramp down.

Parallel to the R&D for a Higgs factory, **the US R&D effort should develop a 10 TeV pCM collider (design and technology)**, such as a muon collider, a proton collider, or possibly an electron-positron collider based on wakefield technology. The US should participate in the International Muon Collider Collaboration (IMCC) and take a leading role in defining a reference design. We note that there are many synergies between muon and proton colliders, especially in the area of development of high-field magnets. R&D efforts in the next 5-year timescale will define the scope of test facilities for later in the decade, paving the way for initiating **demonstrator facilities within a 10-year timescale** (Recommendation 6).

Outlook

SYMMETRY | AS A FUNDAMENTAL CHARACTER OF NATURE | ?????

Coincidences ?

$$\mathcal{L} = c + \mu^2 H^2 + \lambda H^4$$

- Symmetry, the very idea at the basis of "the" formula, is challenged by a number of phenomena, which may, at best, be described in this language

Cosmological Constant
(galaxy formation)

(meta-)stability of the Universe

Steven Weinberg Phys. Rev. Lett. 59, 2607 - If $c > 200\, c_{measured}$ galaxies would ne be able to form (matter-domination phase too short)

arXiv:hep-ph/9707380 Agrawal et al. - If $\mu > 5 \cdot \mu_{SM}$ periodic table disappears! (neutron decay too fast)

arXiv:1205.6497 - Degrassi et al. - If m_{Higgs} grew by 1%, Universe would be unstable (in the SM)

Rev. Mod. Phys. 68, 951 - Cahn, Robert N. - The eighteen arbitrary parameters of the standard model in your everyday life

Phys.Rept. 807 (2019) 1-111 - Adams, F.~C. - The Degree of Fine-Tuning in our Universe - and Others

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Cosmological Constant
(galaxy formation)

Fermi constant
(periodic table)

Higgs boson mass
(meta-)stability of the Universe

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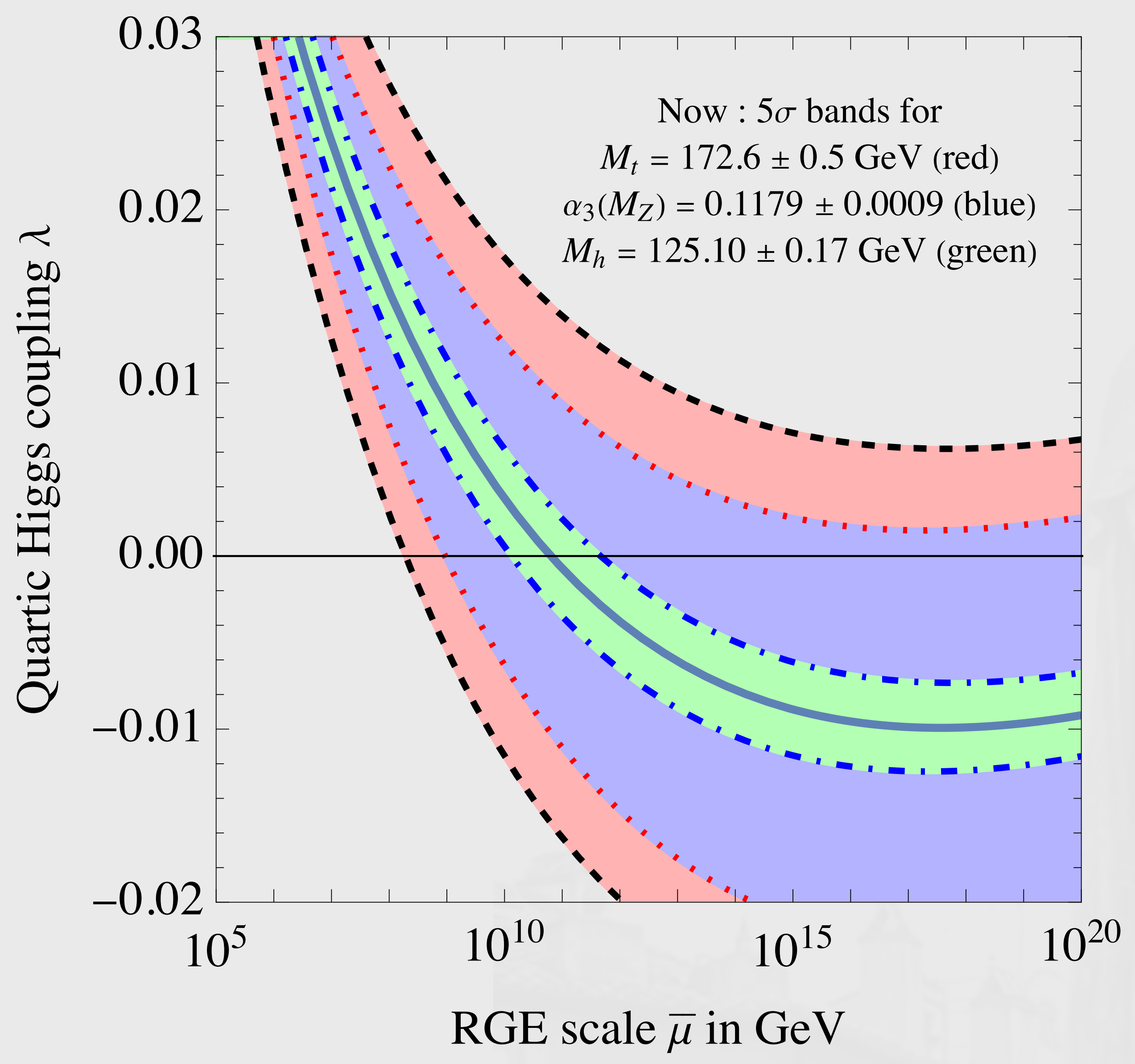
arXiv:hep-ph/9707380 Agrawal et al. - If $\mu > 5 \cdot \mu_{SM}$ periodic table disappears! (neutron decay too fast)

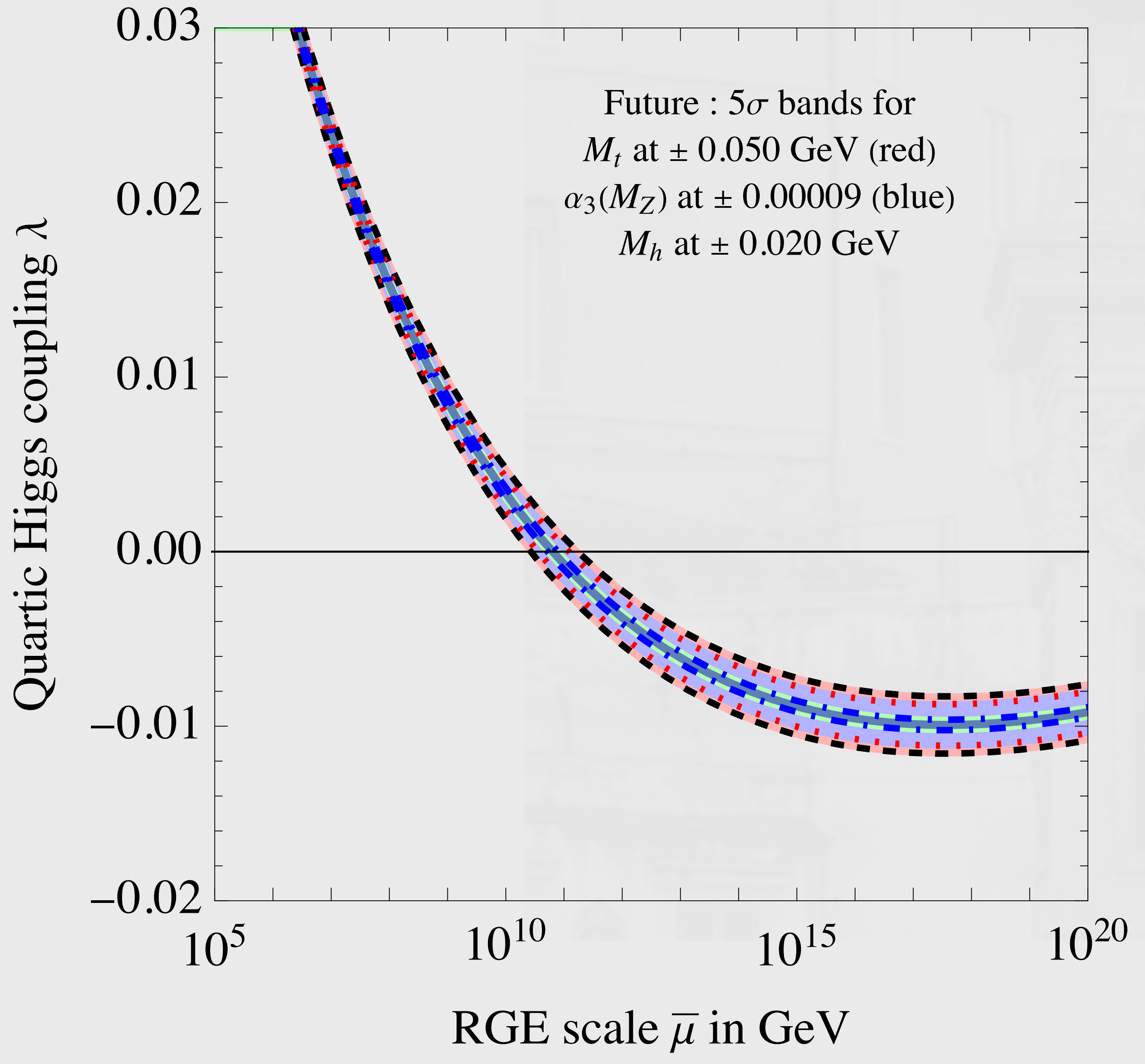
arXiv:1205.6497 - Degrassi et al. - If m_{Higgs} grew by 1%, Universe would be unstable (in the SM)

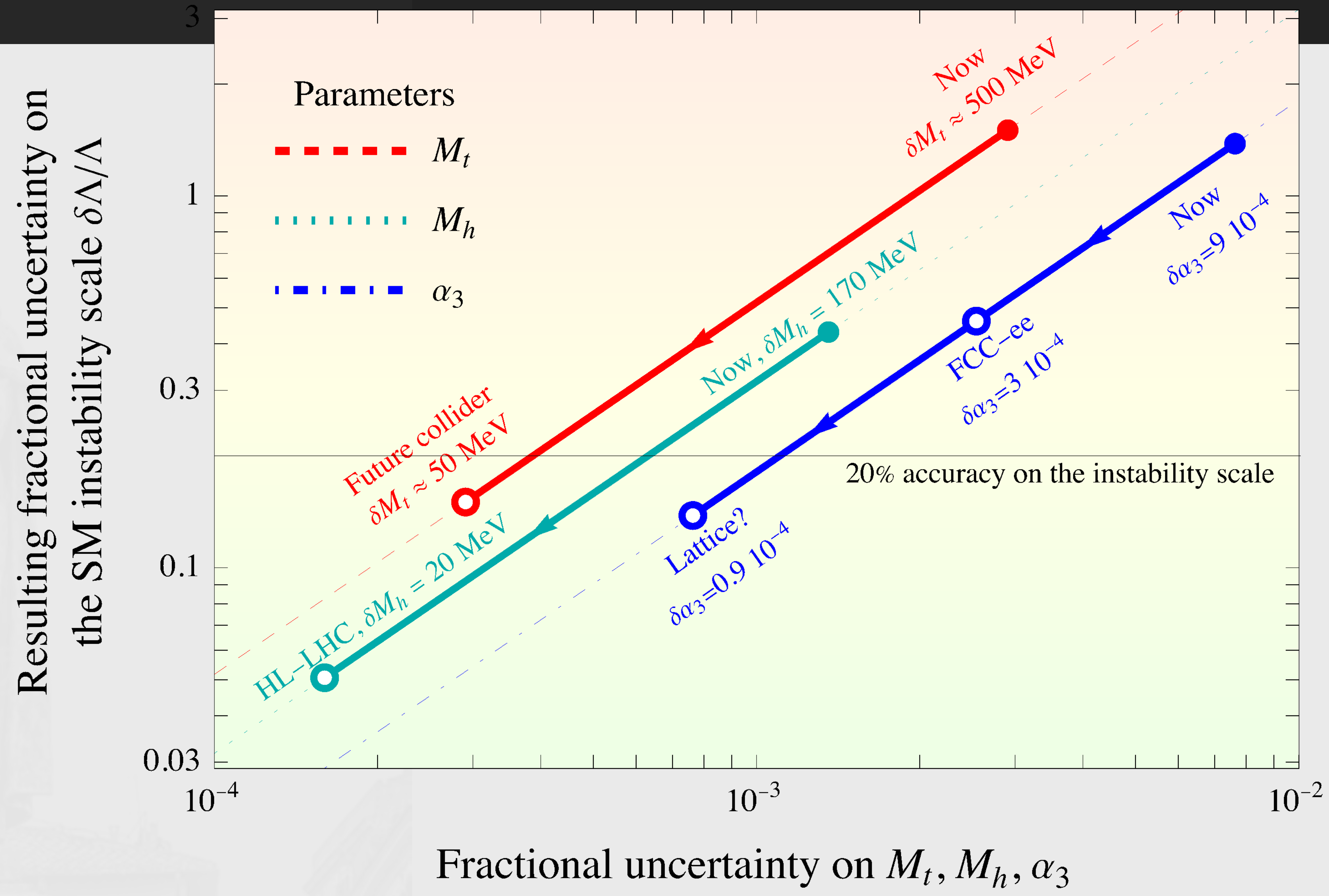
Rev. Mod. Phys. 68, 951 - Cahn, Robert N. - The eighteen arbitrary parameters of the standard model in your everyday life

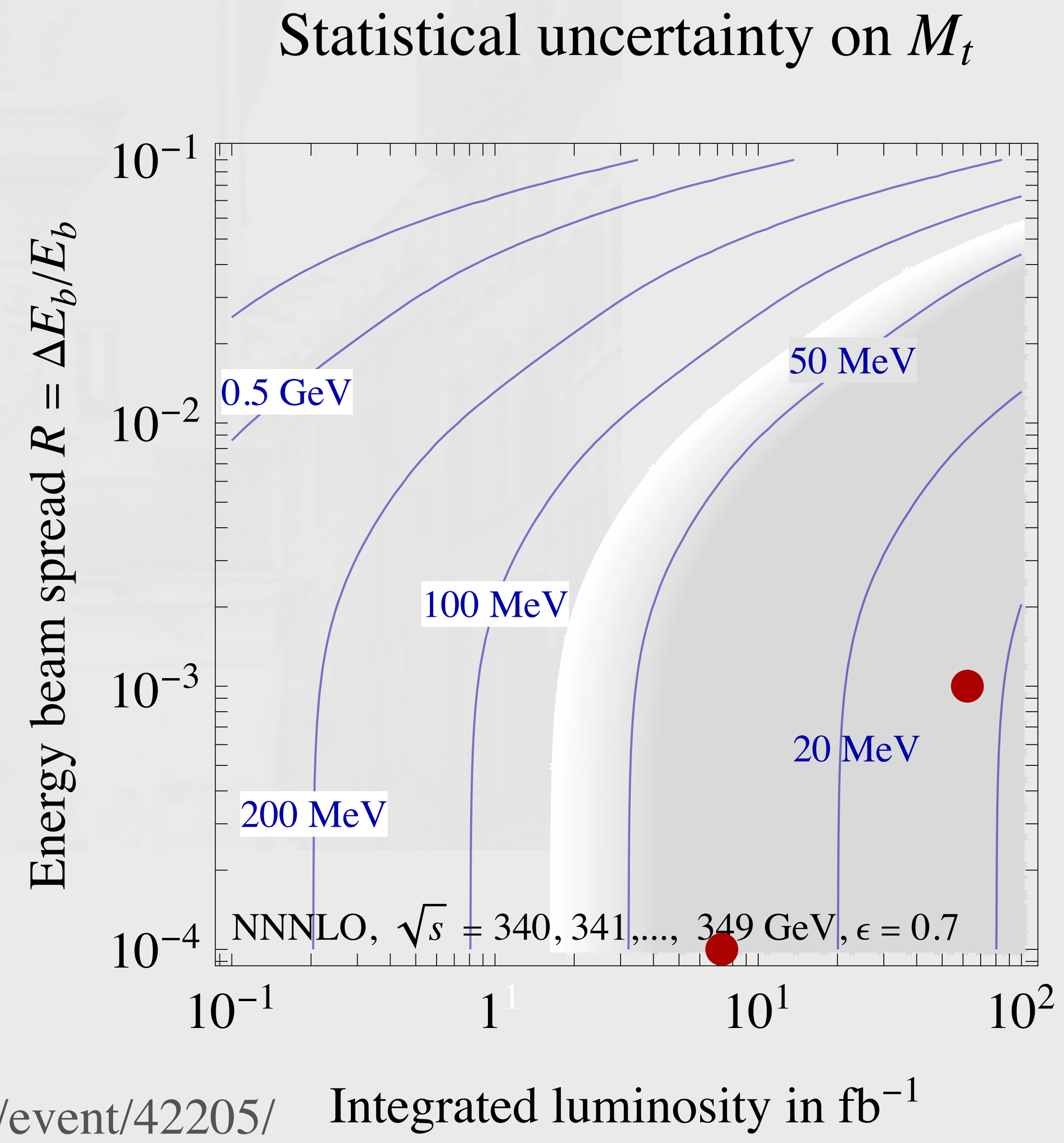
Phys.Rept. 807 (2019) 1-111 - Adams, F.~C. - The Degree of Fine-Tuning in our Universe - and Others

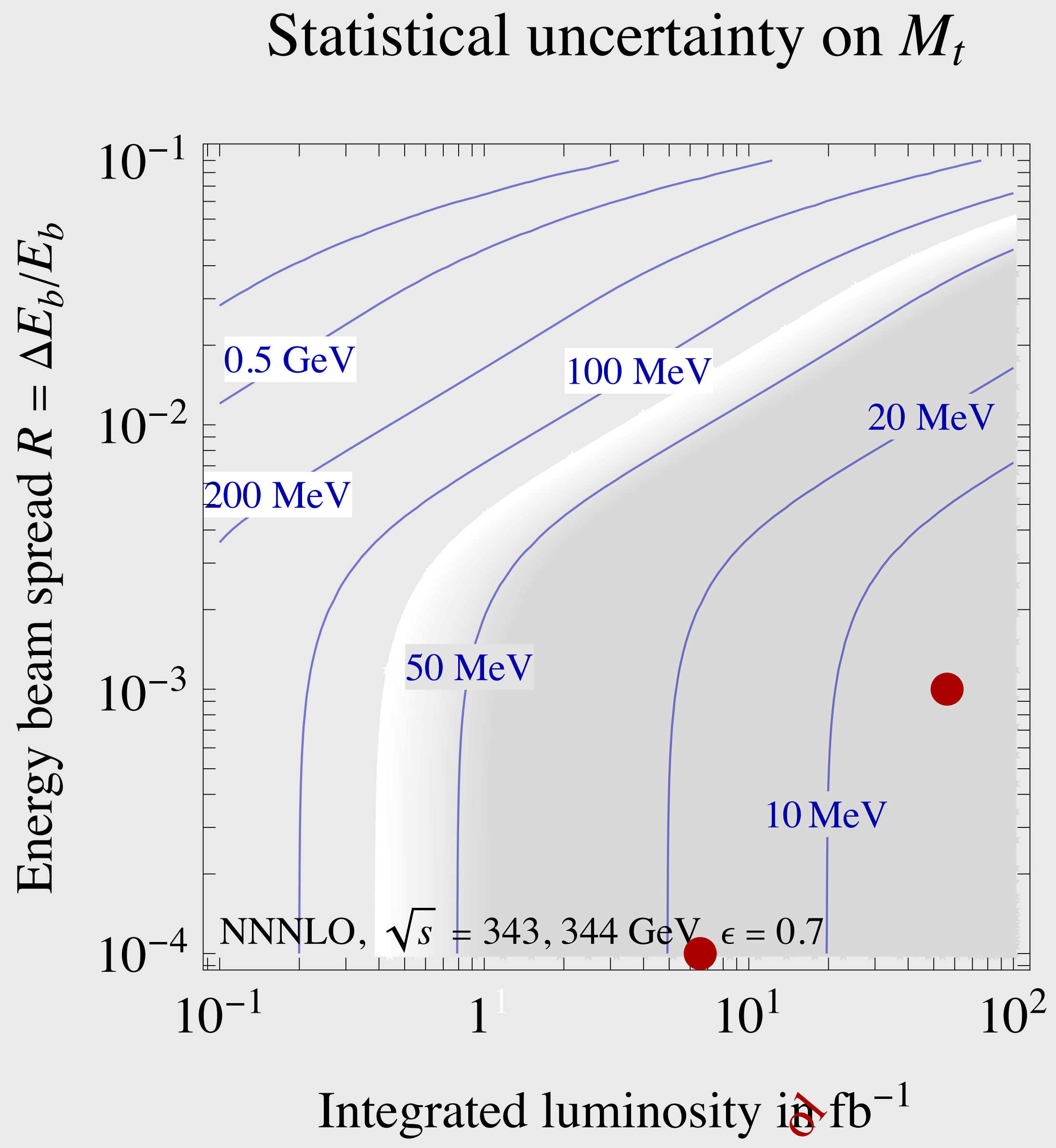
Are we ready for a revolution?











Thank You!

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