Discovery Physics at Future Colliders

Roberto Franceschini - May 7th 2024

ROMA TRE UNIVERSITÀ DEGLI STUDI
INFN Roma3
Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

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at Future Colliders

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Roma 6-7 maggio 2024
Centro Congresso Frentani
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Italiadomani

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

?	Need new matter (or even bigger modifications to the SM)
	Adjusting one SM parameter might do
	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

- ? 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

NEED SOME COSMOLOGY INPUTS

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

weak interactions

- ? • what is the dark matter in the Universe?
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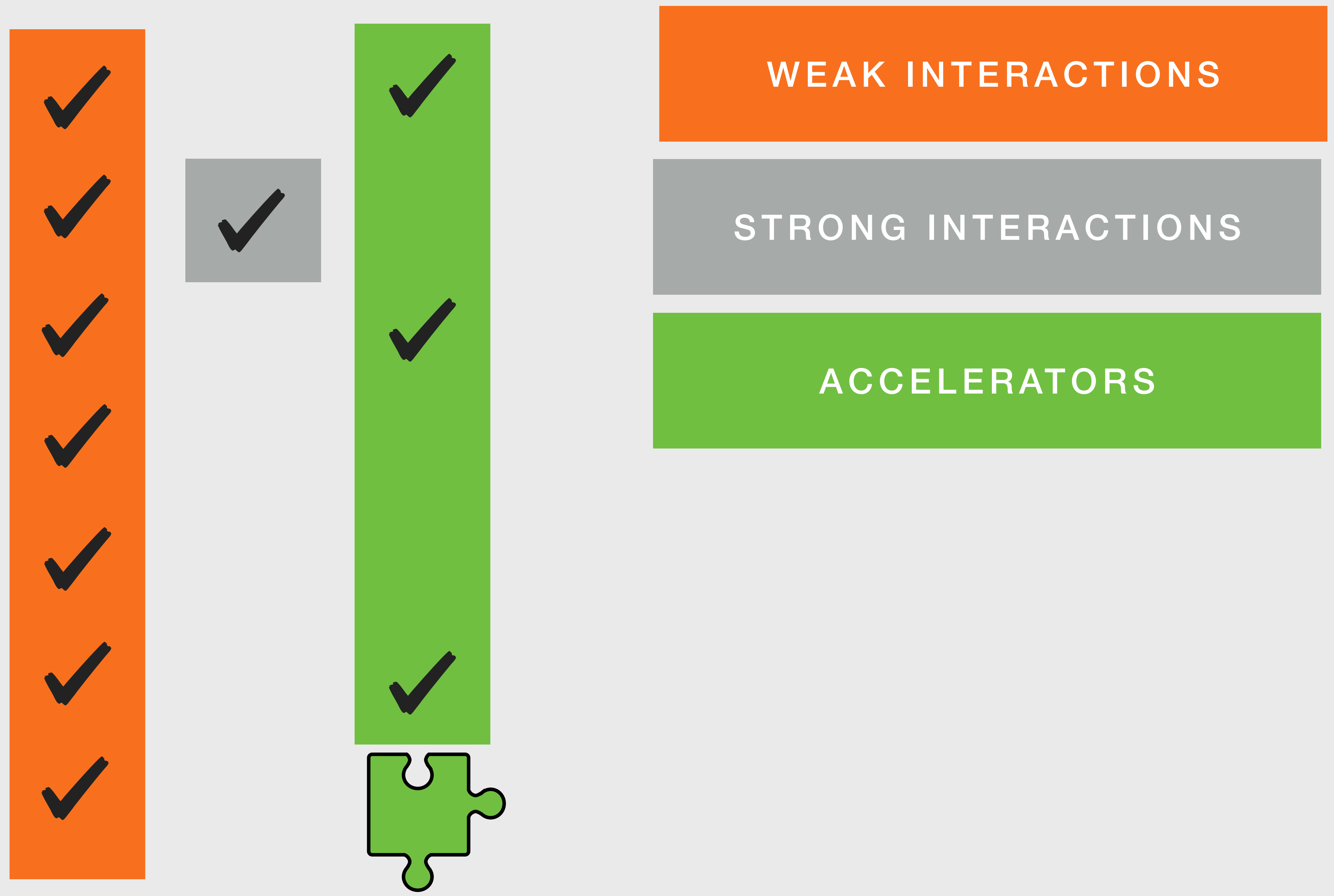


Accelerators are excellent probes

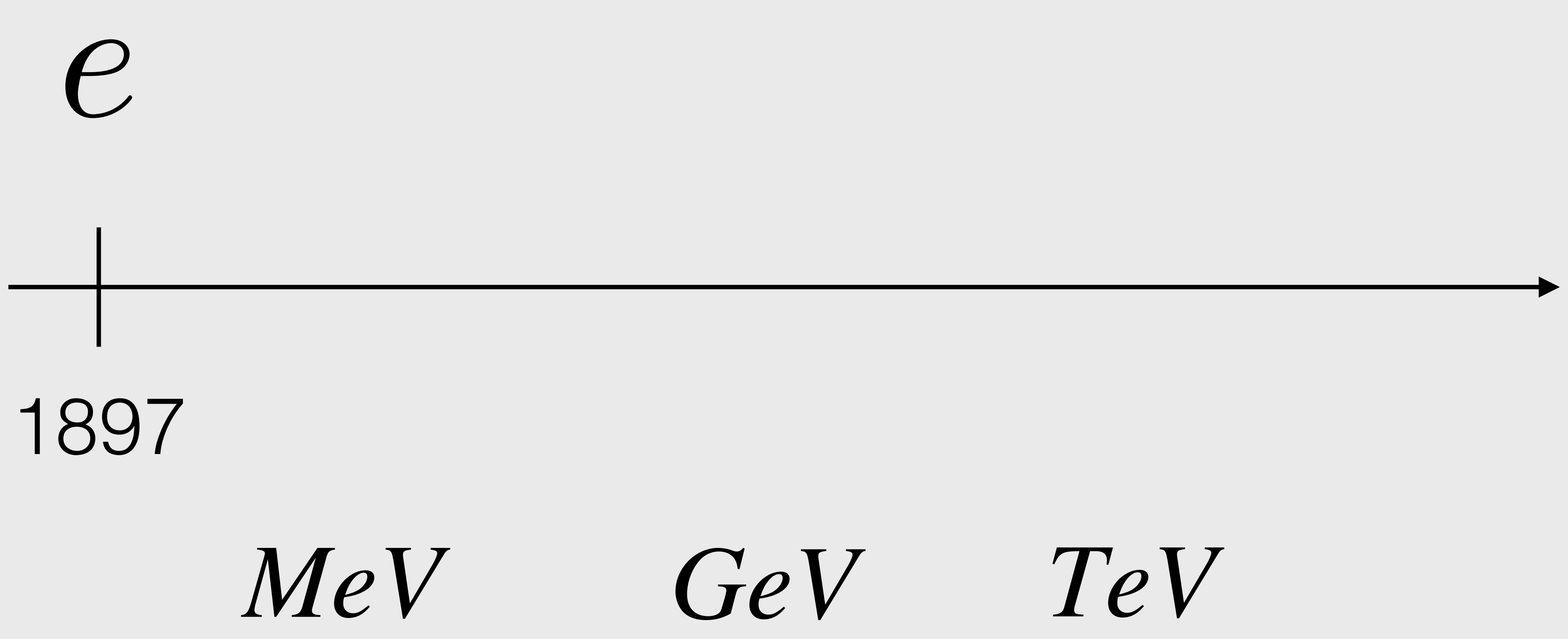
A gauge of the progress we can make with any future collider

- 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 enjoys this enviable position … **back to regular science exploration**

The march of symmetry

SYMMETRY | AS A FUNDAMENTAL CHARACTER OF NATURE

Symmetries and particles



The march of symmetry

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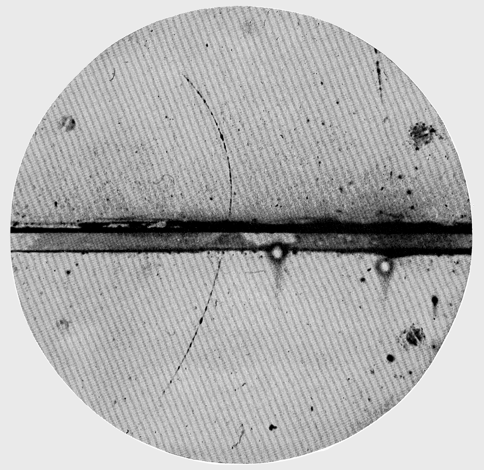
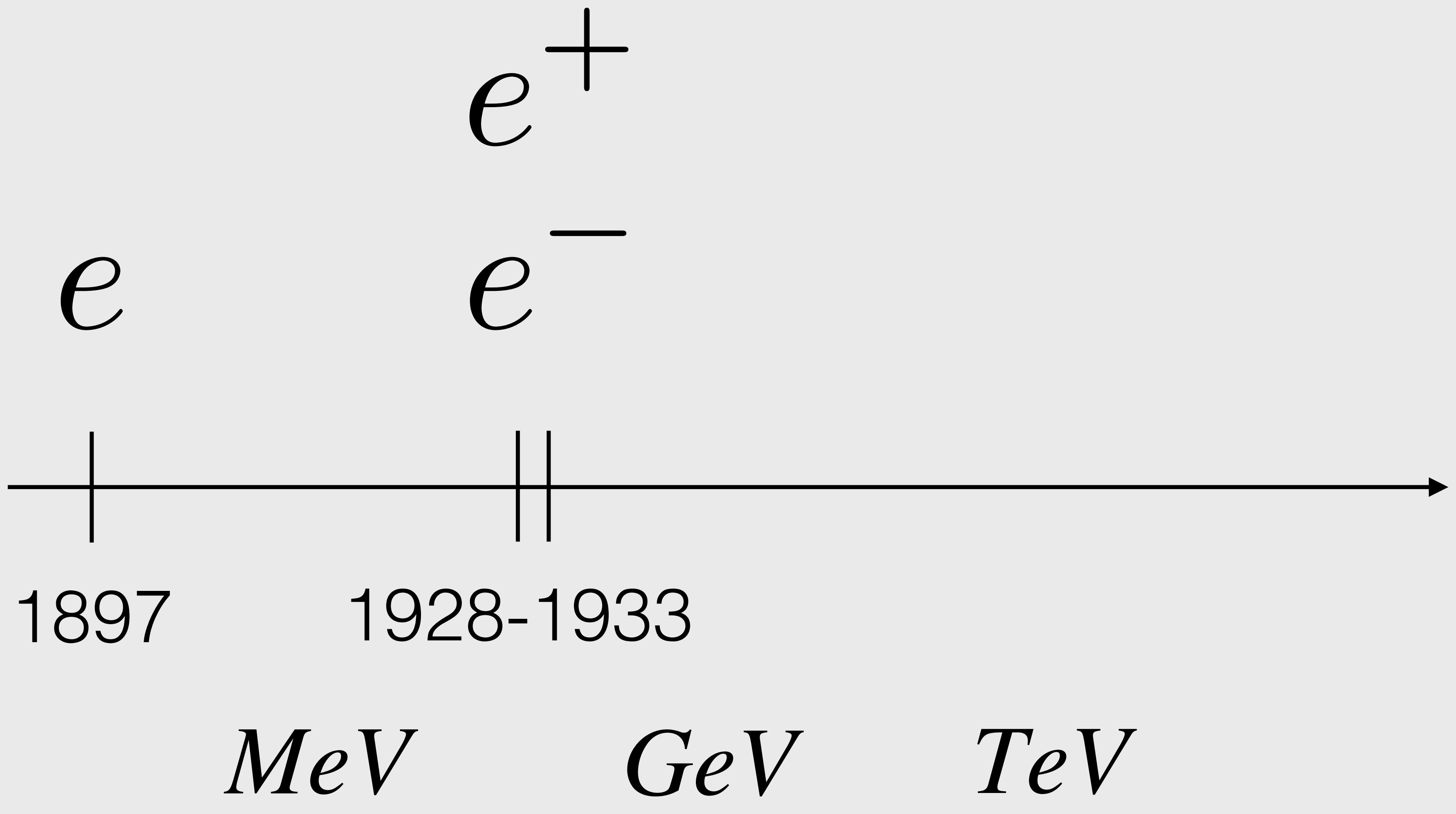


$B = 1.5\,\mathrm{T}$



The march of symmetry

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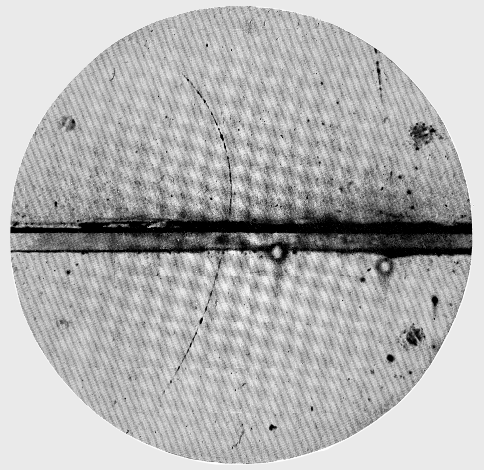

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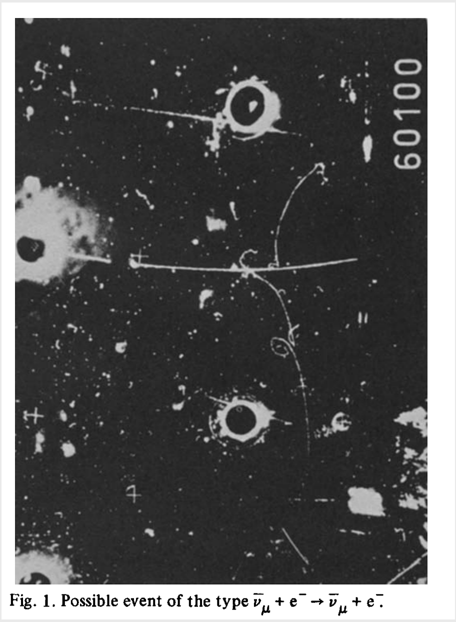
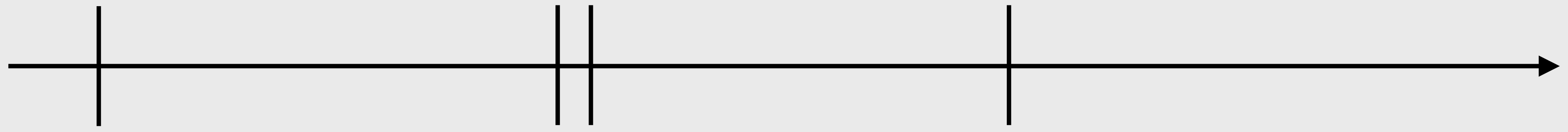


$B = 2$ T

e^+ ν_e

e e^- e



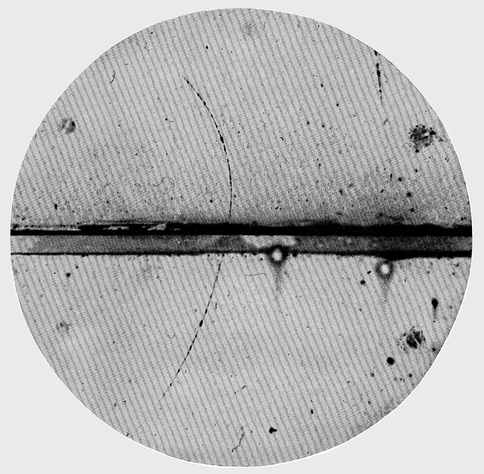
1897 1928-1933 196x-1973

MeV GeV TeV

The march of symmetry

SYMMETRY AS A FUNDAMENTAL CHARACTER OF NATURE

Symmetries and particles



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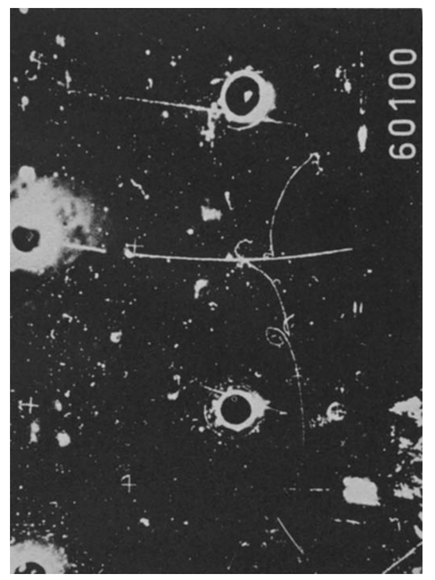

Fig. 1. Possible event of the type $\bar{\nu}_\mu + e^- \to \bar{\nu}_\mu + e^-$.

$B = 2\,\mathrm{T}$

e^+ ν_e

e e^- e

1897 1928-1933 196x-1973 2020s

MeV GeV TeV

The march of symmetry

SYMMETRY | AS A FUNDAMENTAL CHARACTER OF NATURE

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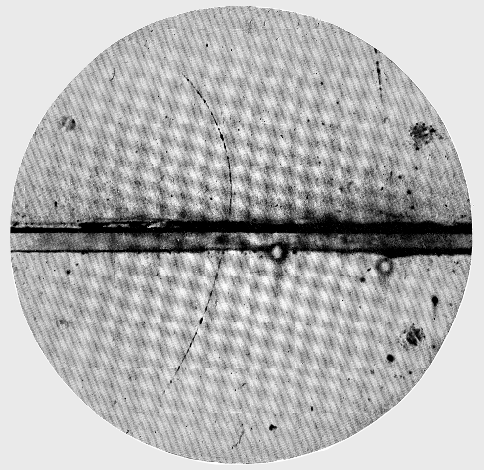

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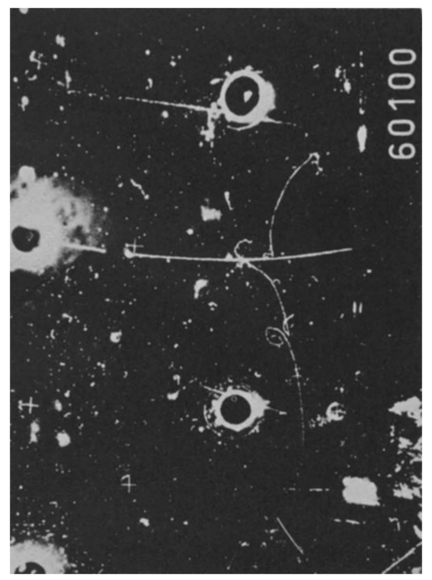

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$B = 2$ T

e — 1897

e^+, e^- — 1928-1933

ν_e, e — 196x-1973

? — 2020s

MeV *GeV* *TeV*

Especially in absence of (Direct) Discoveries

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

Coincidences ?

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

Cosmological Constant
(galaxy formation)

Fermi constant
(periodic table)

Higgs boson mass
(meta-)stability of the Universe

Steven Weinberg Phys. Rev. Lett. 59, 2607 - If $c > 200\ c_{\text{measured}}$ galaxies would not 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

Especially in absence of (Direct) Discoveries

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

Coincidences ?

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

- One of the ways in which, even in absence of discoveries, we still make progress in understanding the Universe

(periodic table)

Higgs boson mass
(meta-)stability of the Universe

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Direct discovery

inevitably linked to Indirect Hints for New Physics

Higgs factory

TARGETS

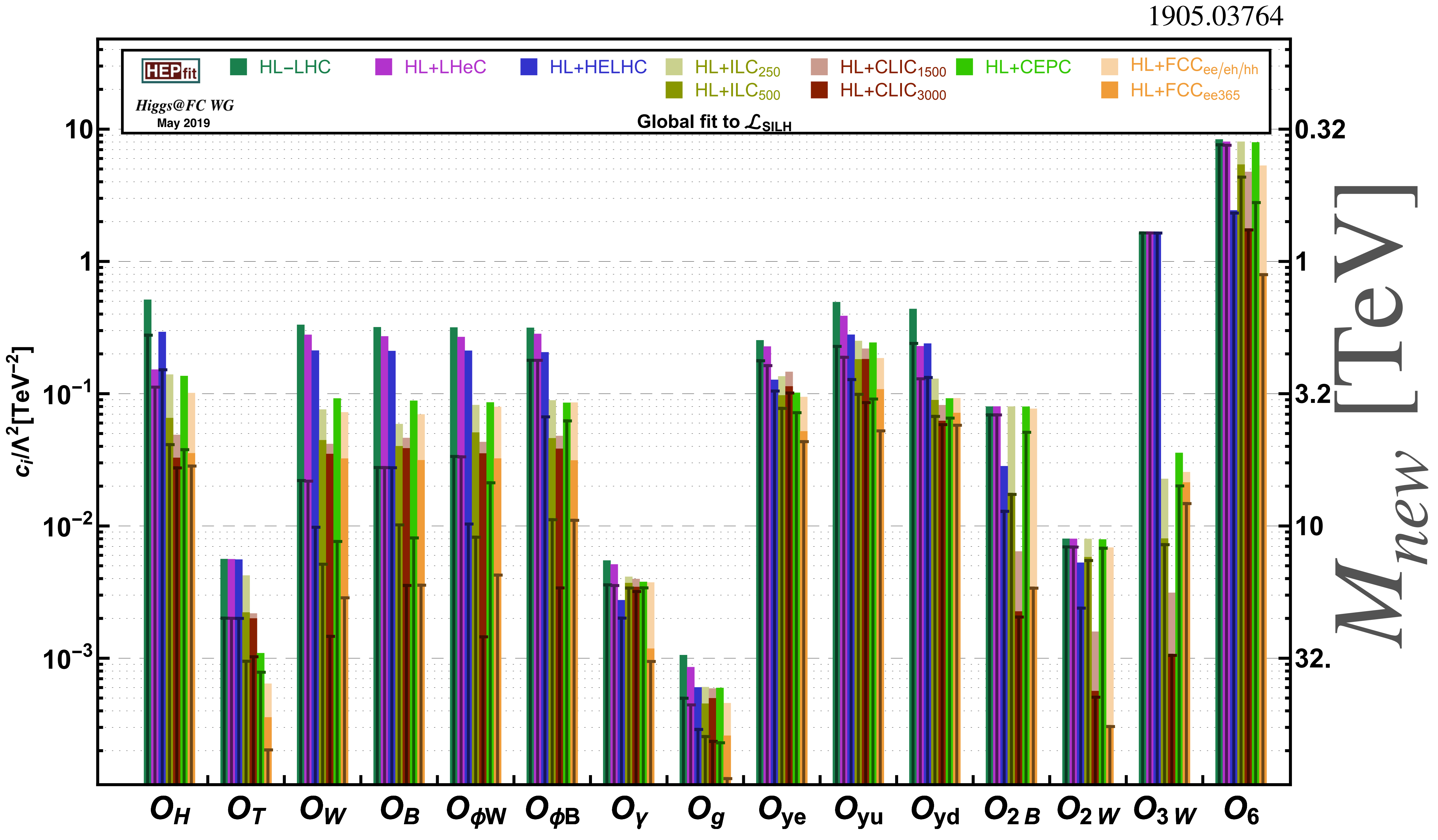


Figure 6. Global fit to the EFT operators in the Lagrangian (19). We show the marginalized 68% probability reach for each Wilson coefficient c_i/Λ^2 in Eq. (19) from the global fit (solid bars). The reach of the vertical lines indicate the results assuming only the corresponding operator is generated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

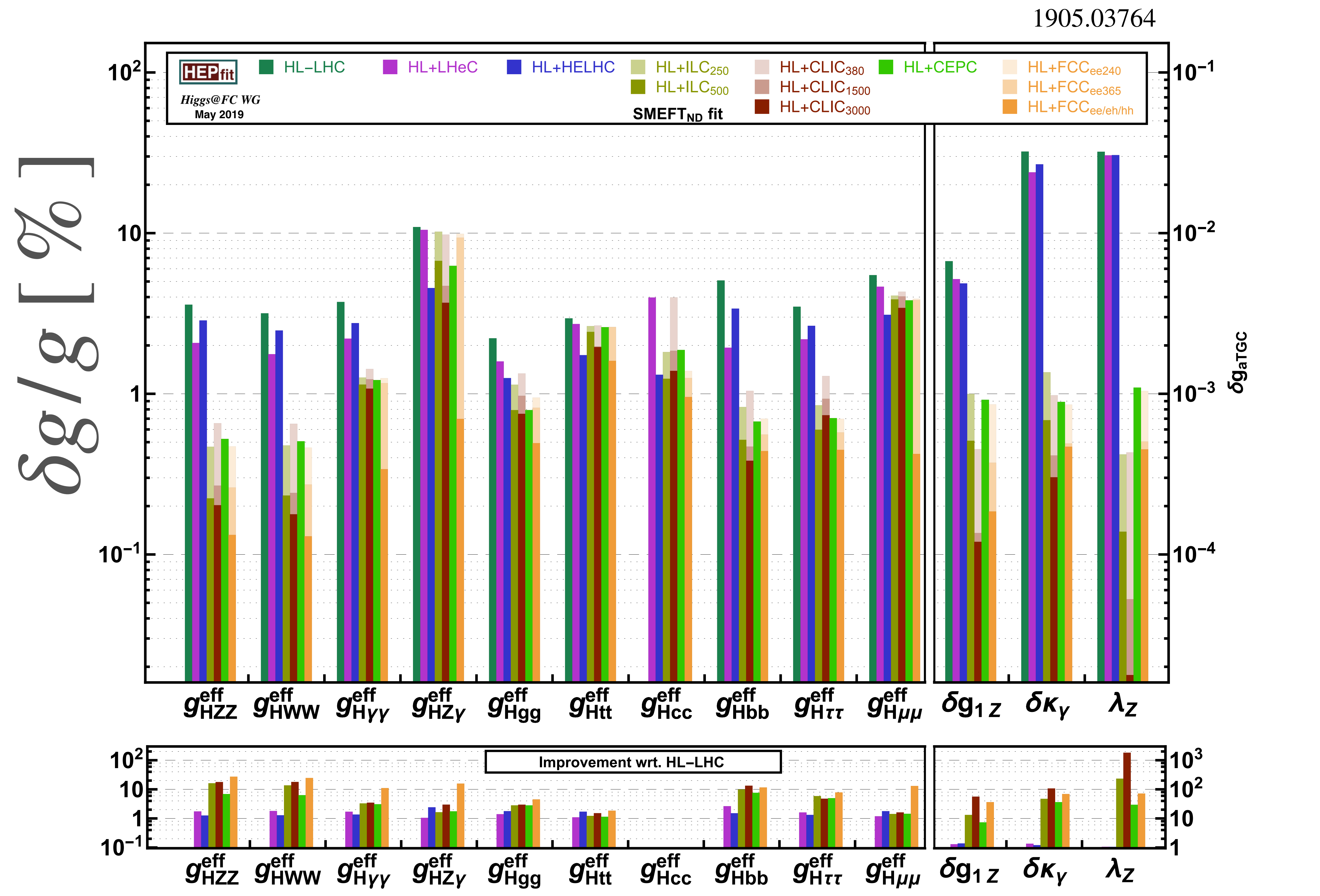
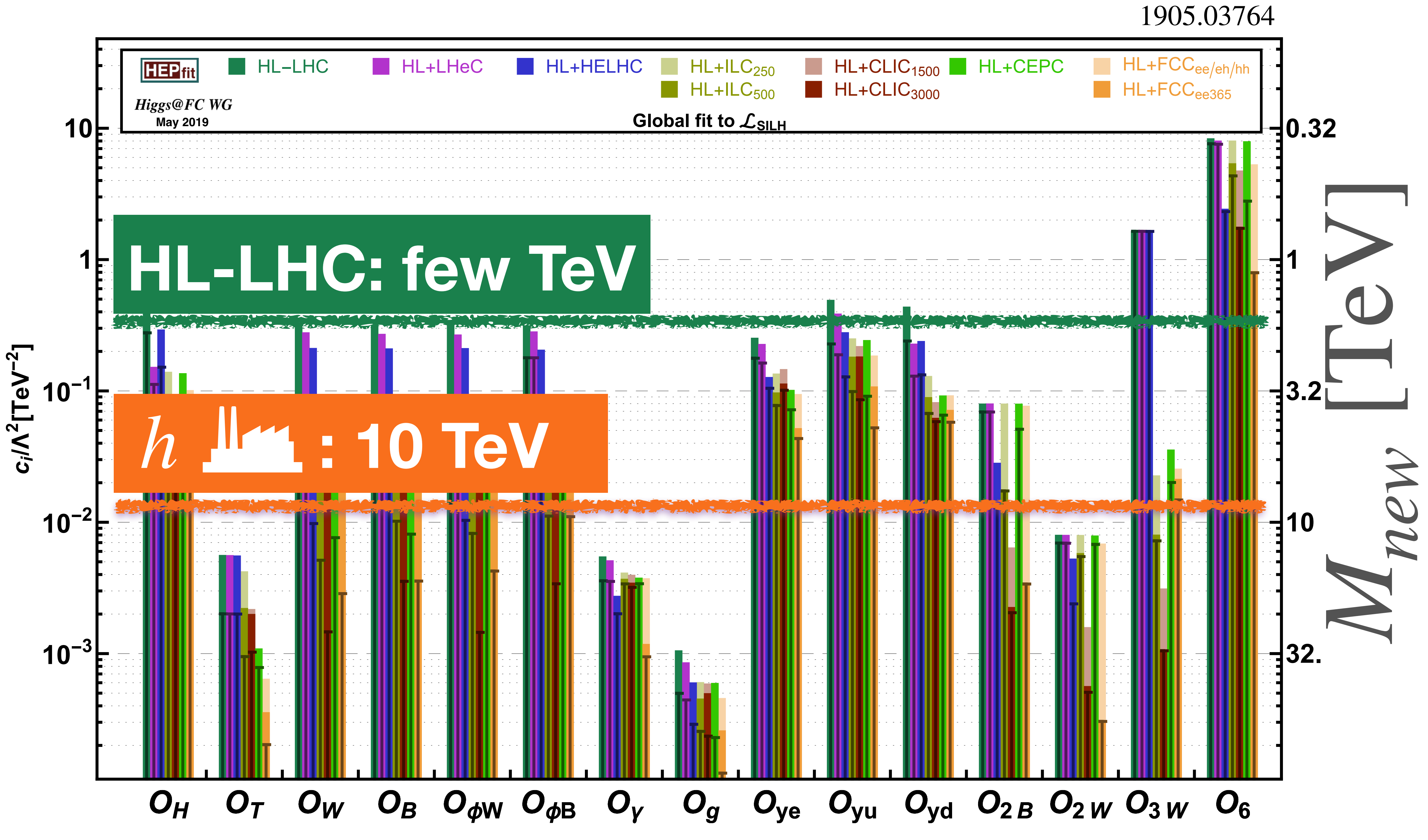


Figure 3. Sensitivity at 68% probability to deviations in the different effective Higgs couplings and aTGC from a global fit to the projections available at each future collider project. Results obtained within the SMEFT framework in the benchmark $\mathrm{SMEFT_{ND}}$.

Higgs factory

TARGETS



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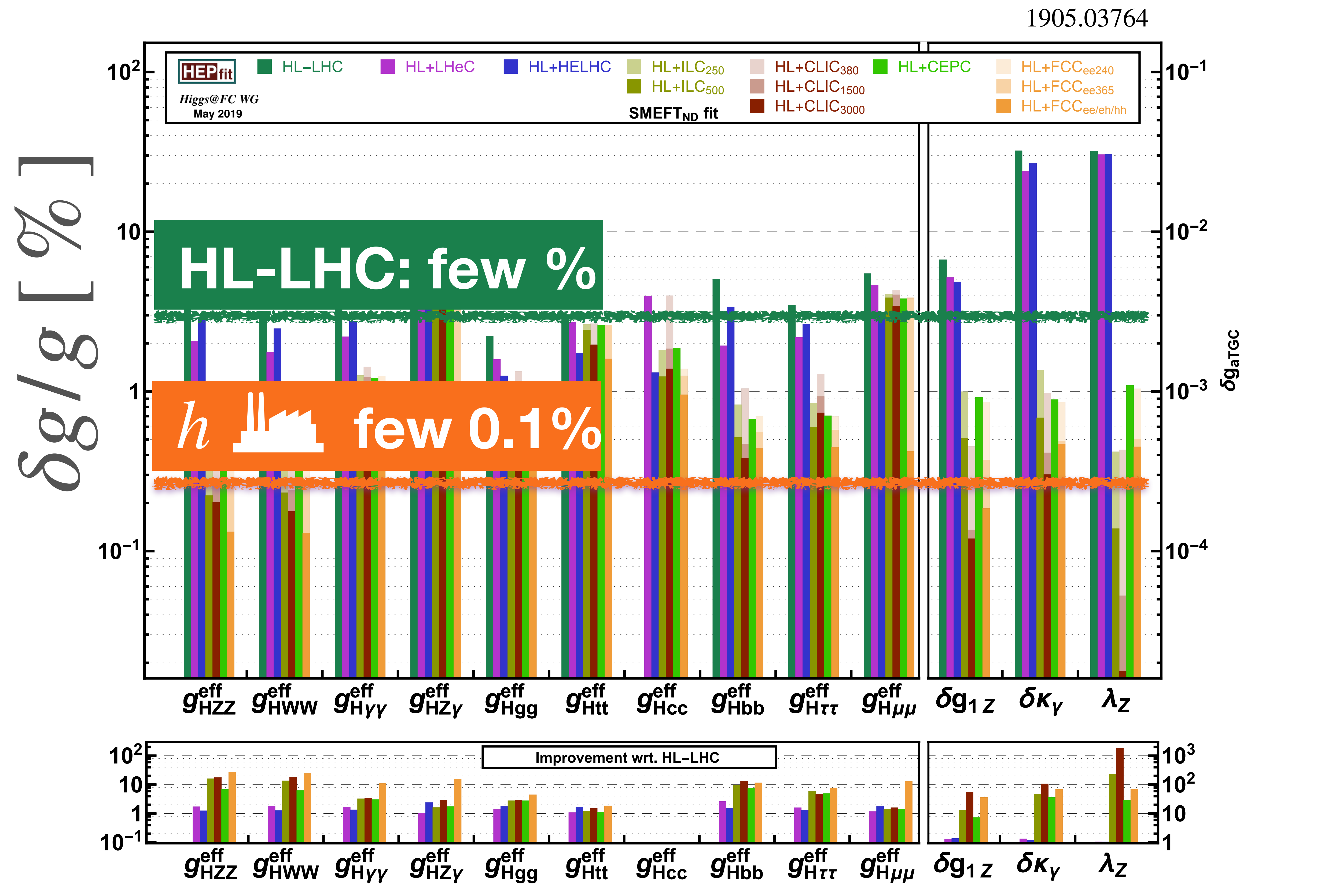

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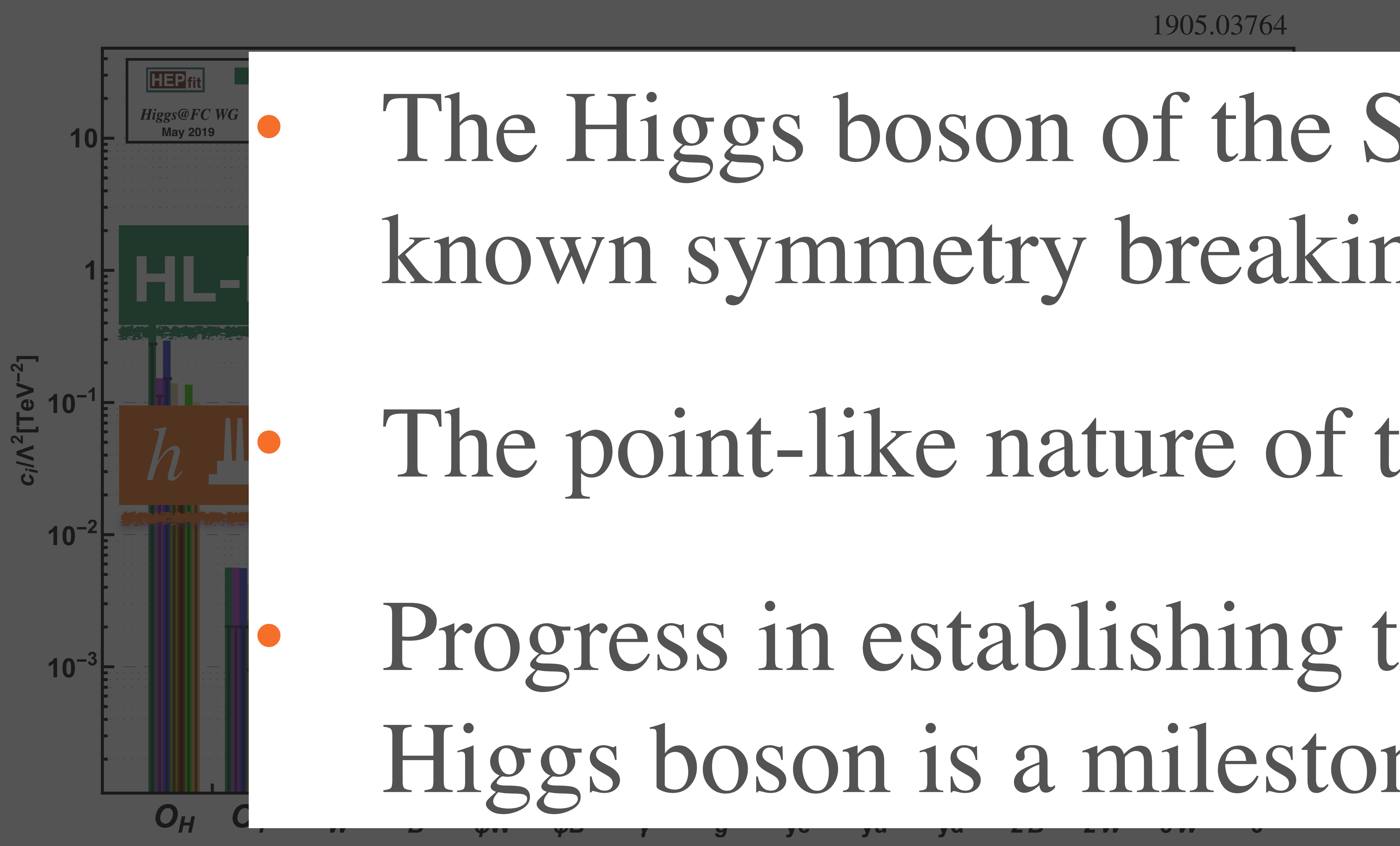
Higgs factory

TARGETS

- 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 point-like nature of the Higgs boson is a milestone (with or without associated discoveries)



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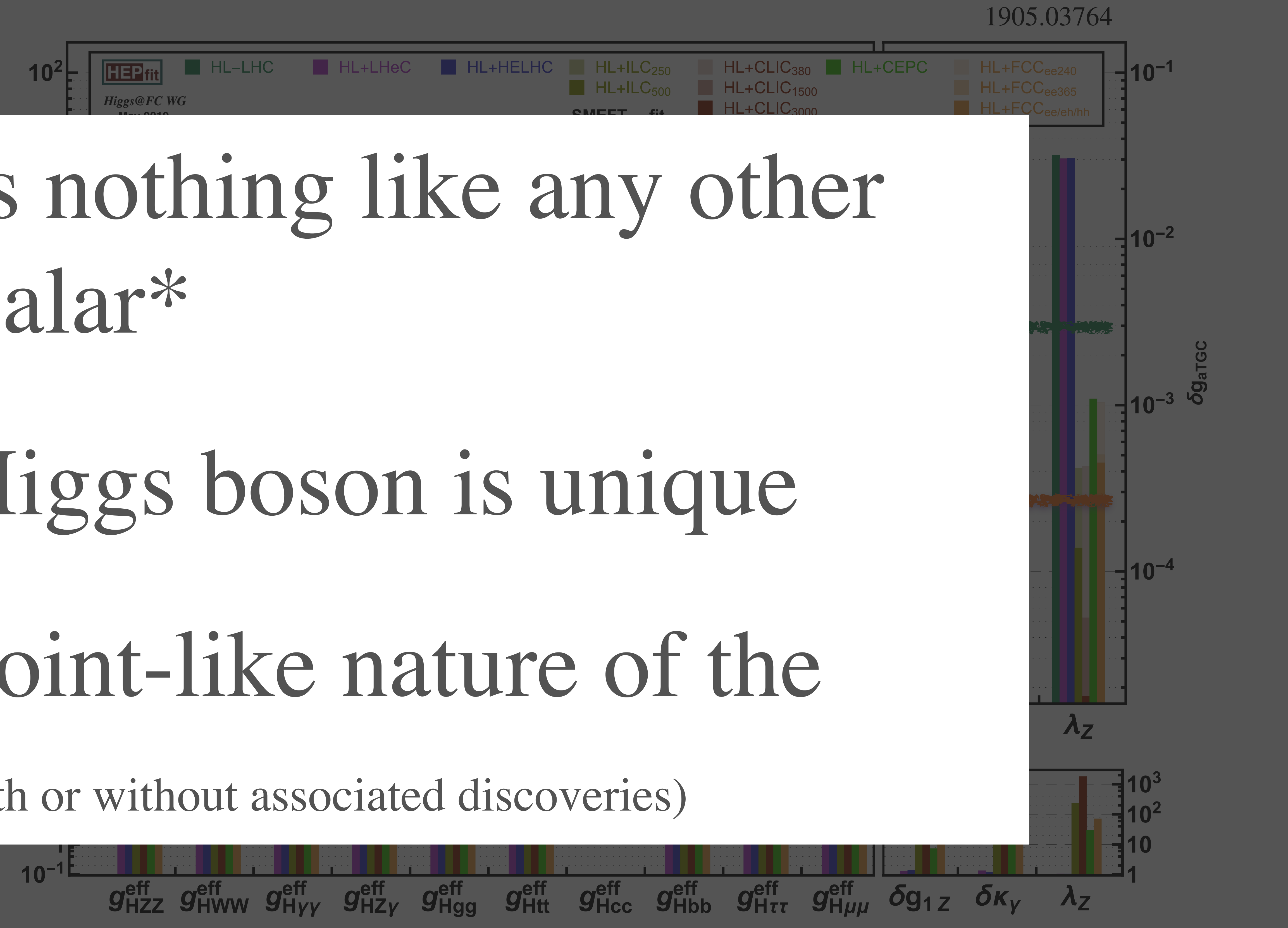

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Electroweak symmetry breaking

Big picture questions:

- Higgs compositeness

  Dario's Talk

- Extended Higgs Sector

Electroweak symmetry breaking

Big picture questions:

- Higgs compositeness — Dario's Talk
- Extended Higgs Sector

Electroweak symmetry breaking

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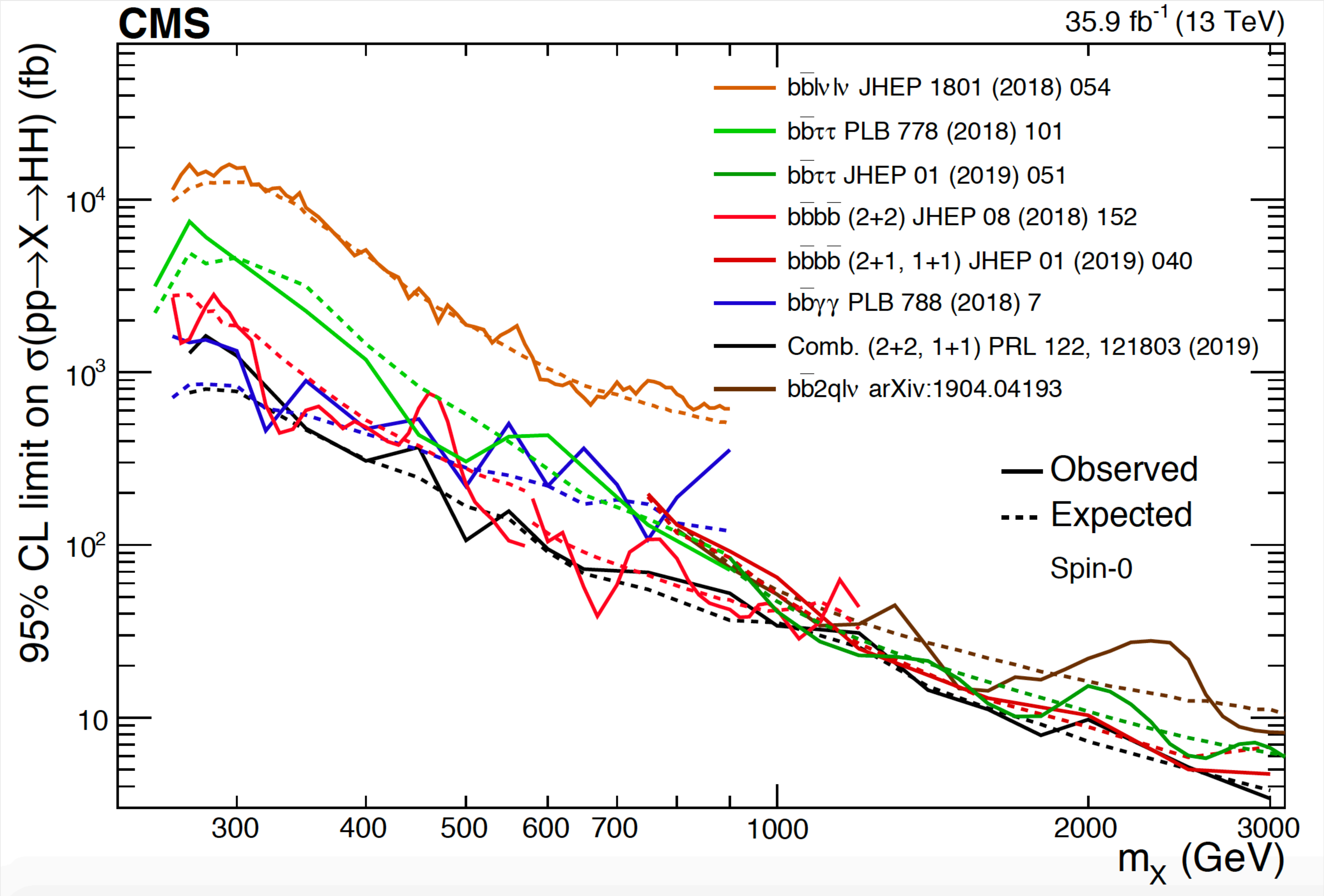
Electroweak symmetry breaking

Big picture questions:

- Higgs compositeness
- Extended Higgs Sector

Extended Higgs Sector: Singlets

SINGLETS ARE ELUSIVE



Extended Higgs Sector: Singlets

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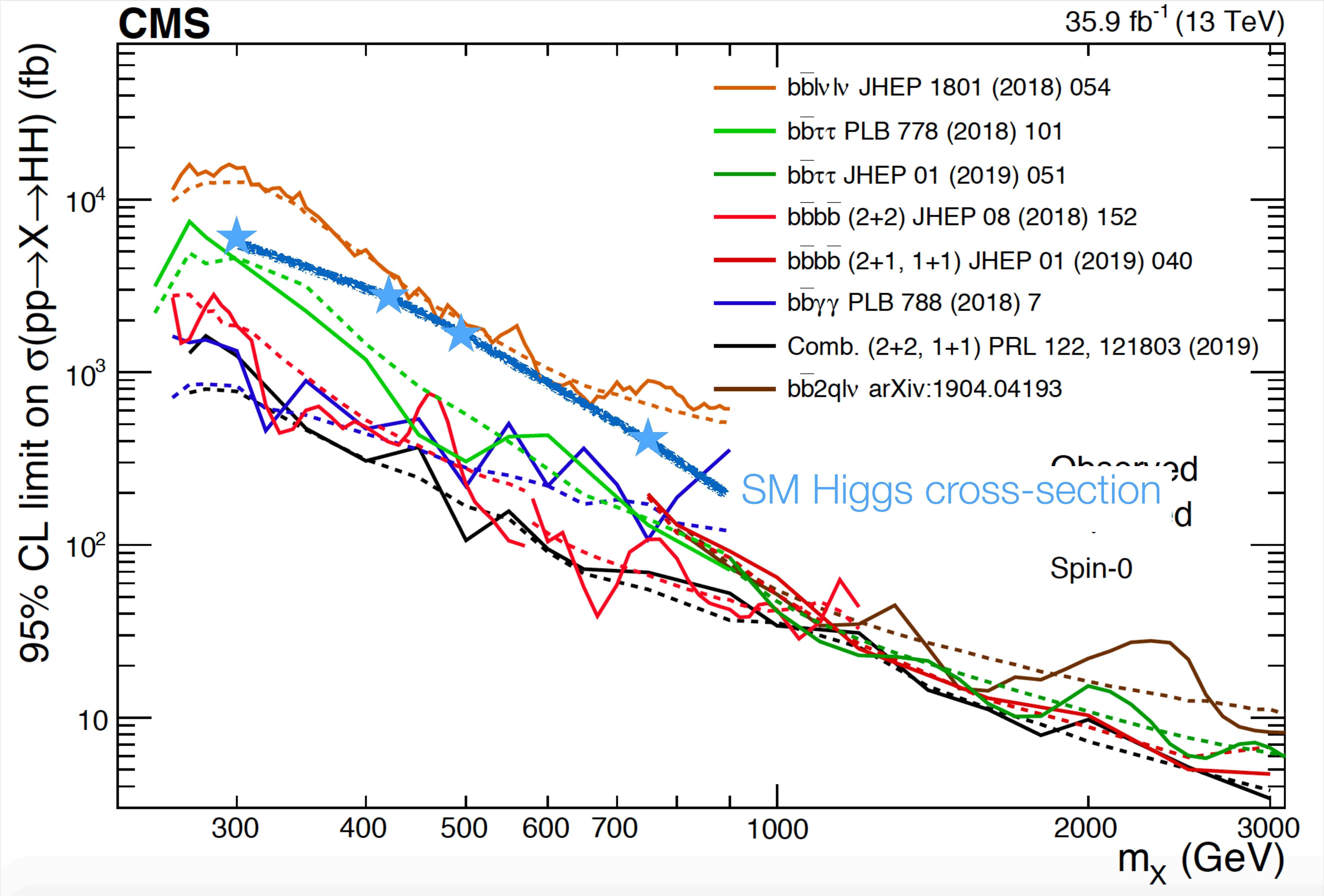

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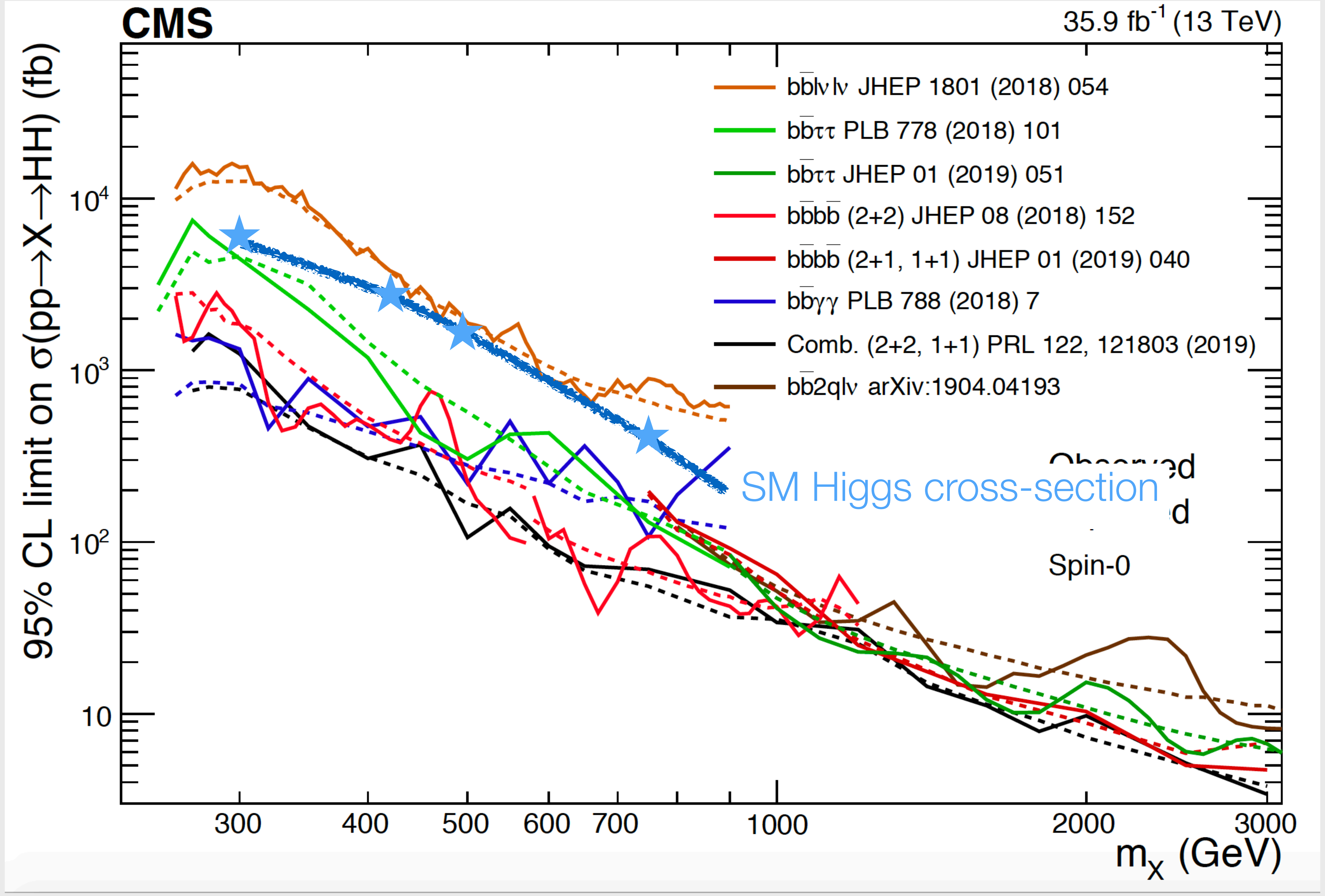
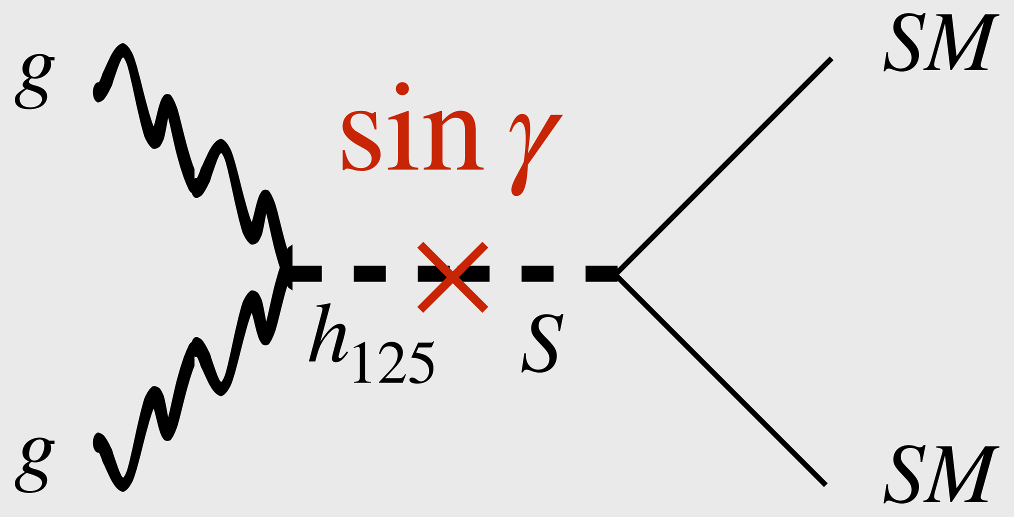


$$\sigma(\phi) \sim \sin^2\theta_{h\phi} \cdot \sigma(h_{SM} \text{ with } m_\phi)$$



$$\Rightarrow \sin\theta \lesssim 0.3$$

$$\sin\theta \simeq \left(\frac{m_h}{m_H}\right)^{\alpha} \Rightarrow m_H \simeq 2 \div 3 \cdot m_h$$

Extended Higgs Sector: Singlets

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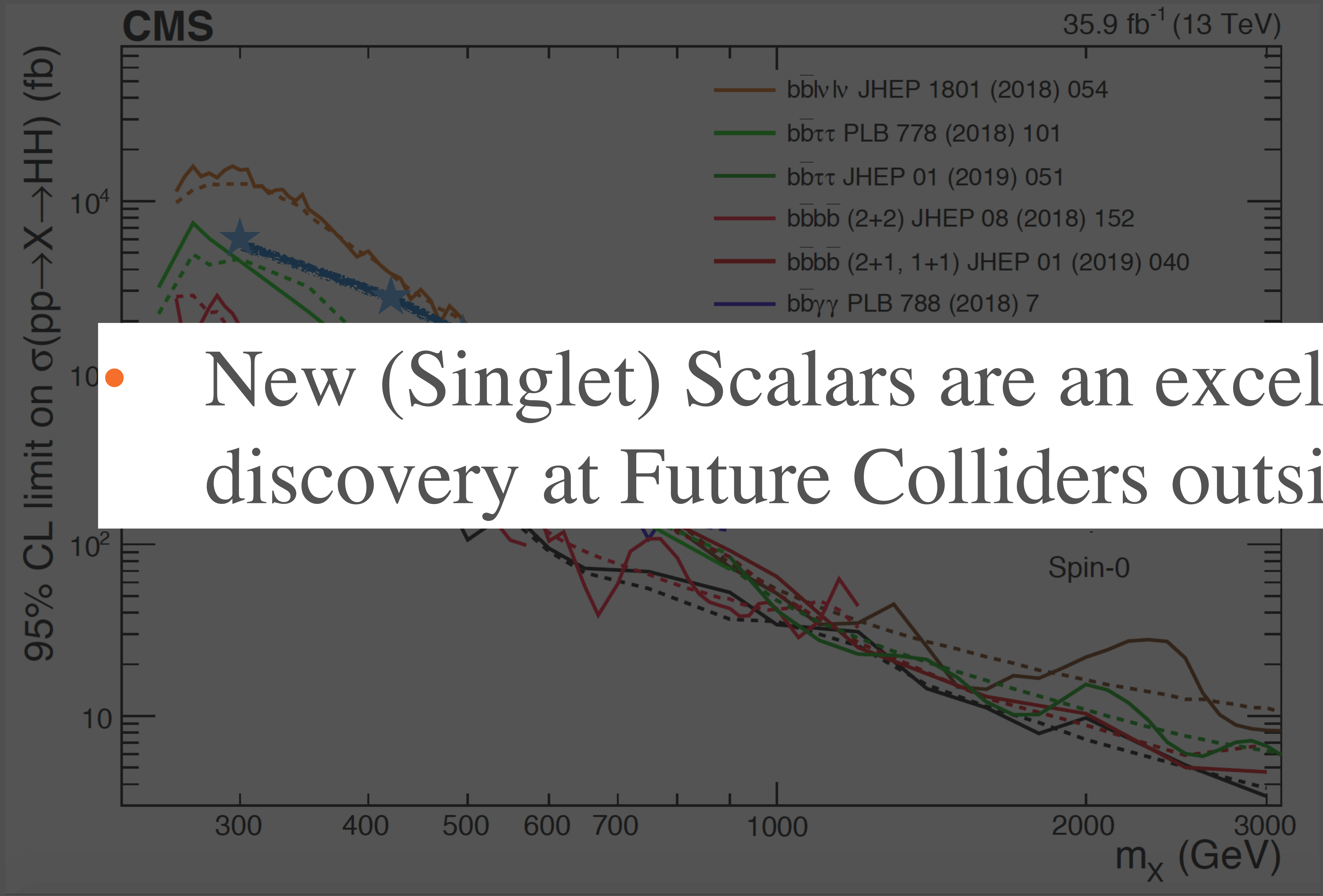

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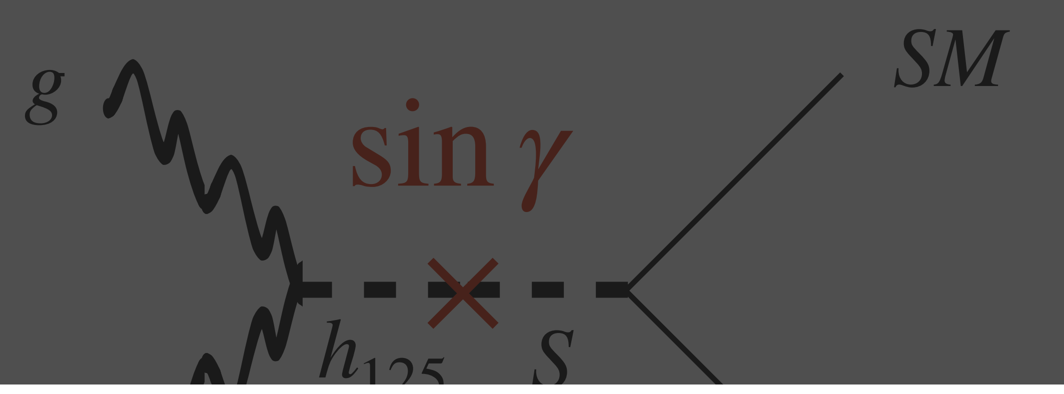
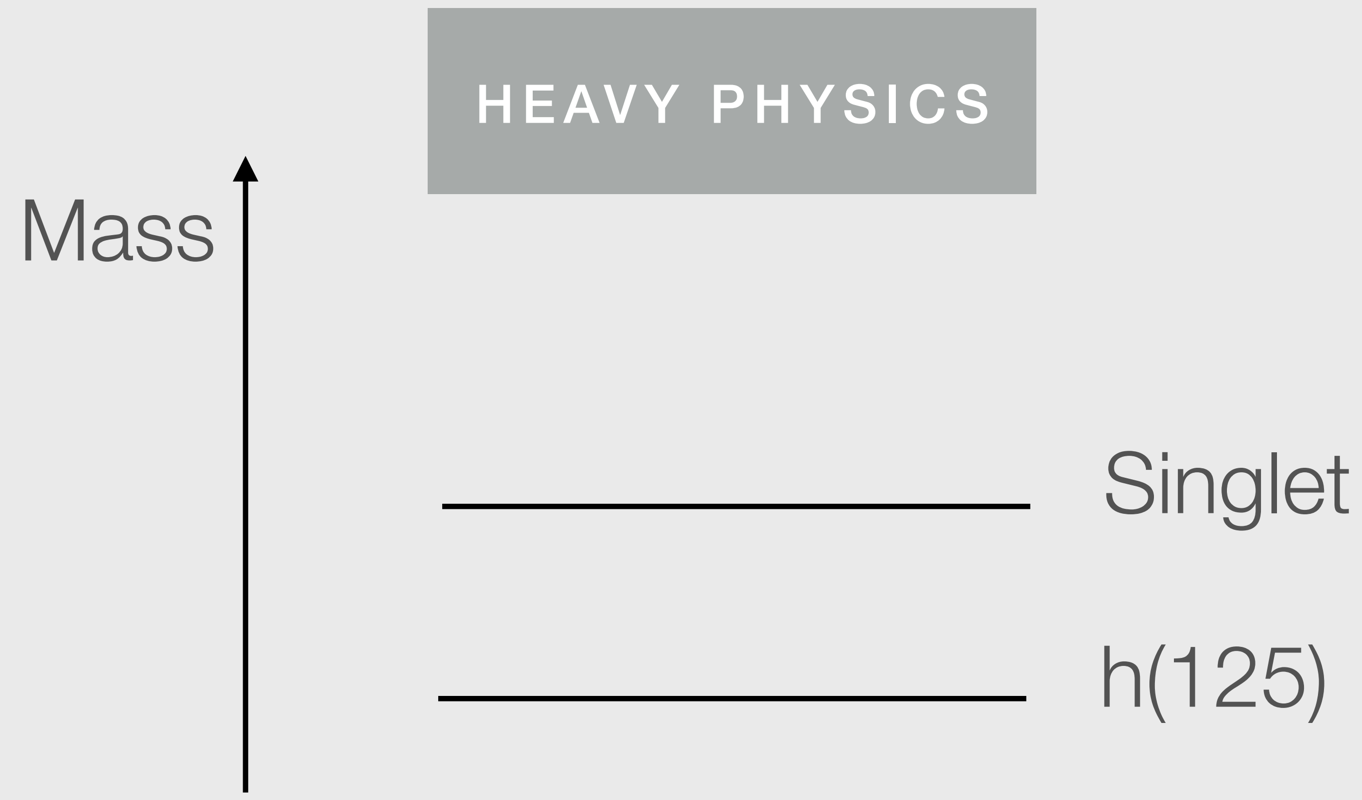


- New (Singlet) Scalars are an excellent target for direct discovery at Future Colliders outside the reach of HL-LHC

$$\sin\theta \simeq \left(\frac{m_h}{m_H}\right)^\alpha \Rightarrow m_H \simeq 2 \div 3 \cdot m_h$$

Impact on BSM

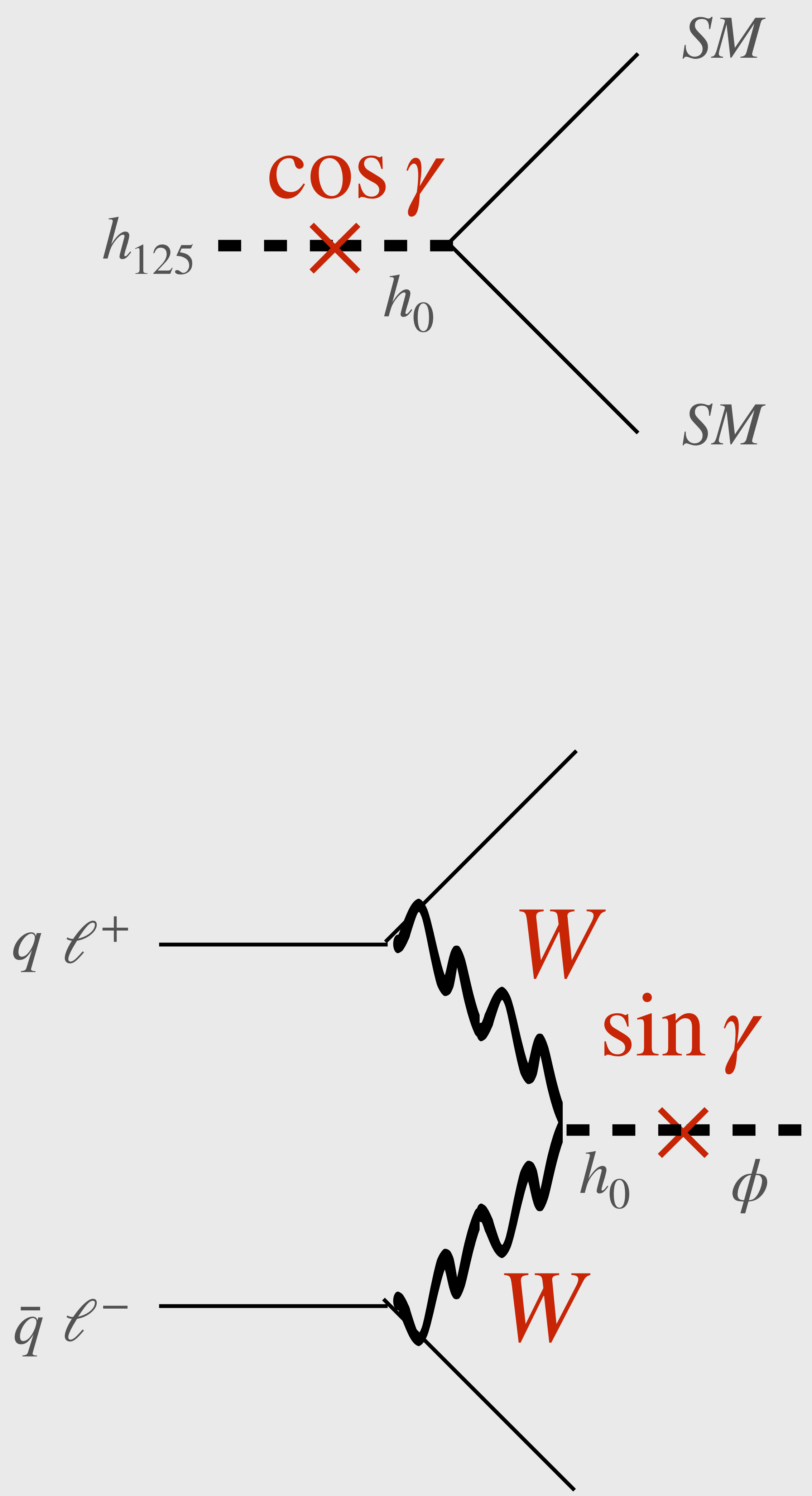
Higgs + Singlet

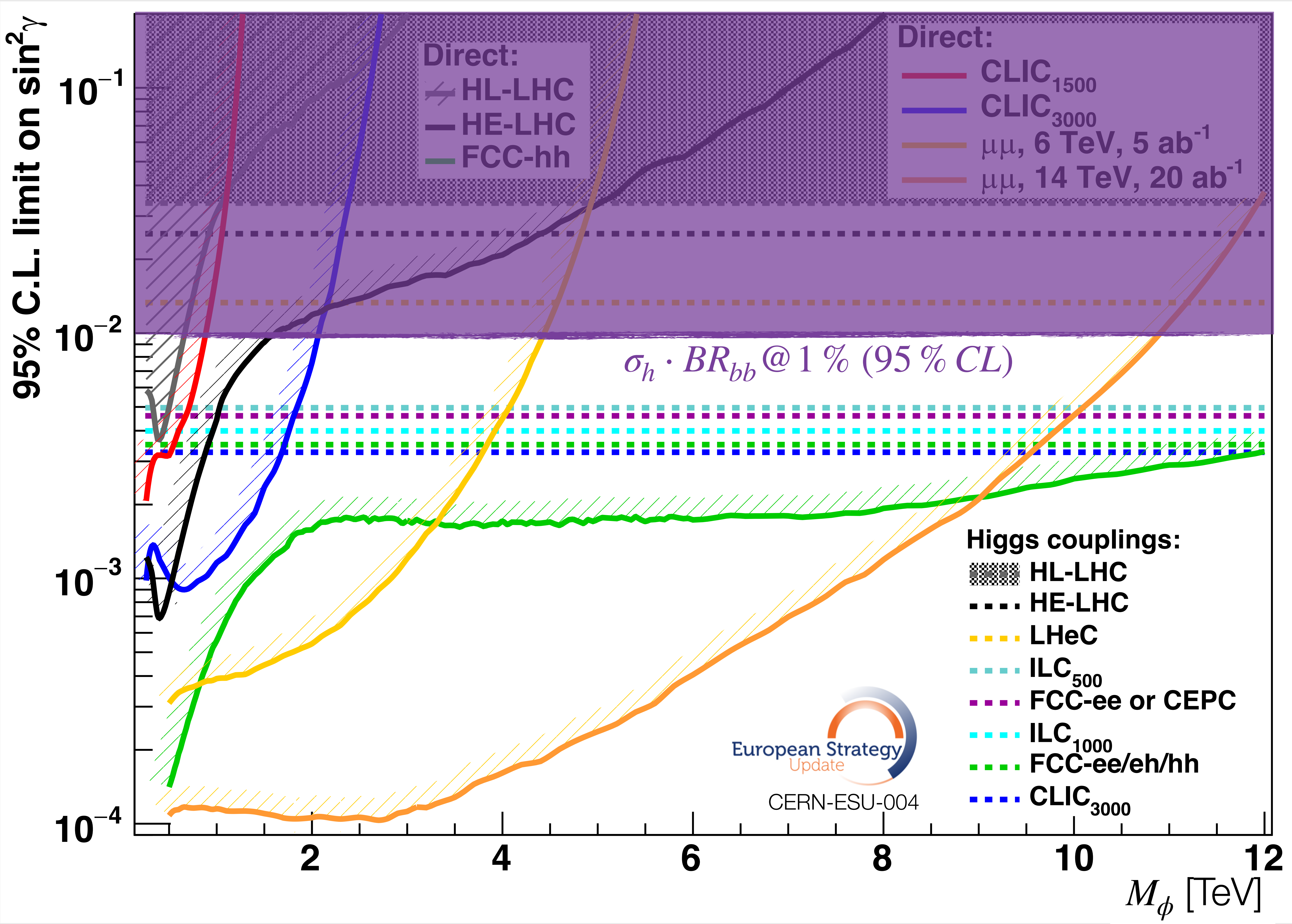


- Broad coverage of BSM scenarios: *(N)MSSM, Twin Higgs, Higgs portal, modified Higgs potential (Baryogenesis)*

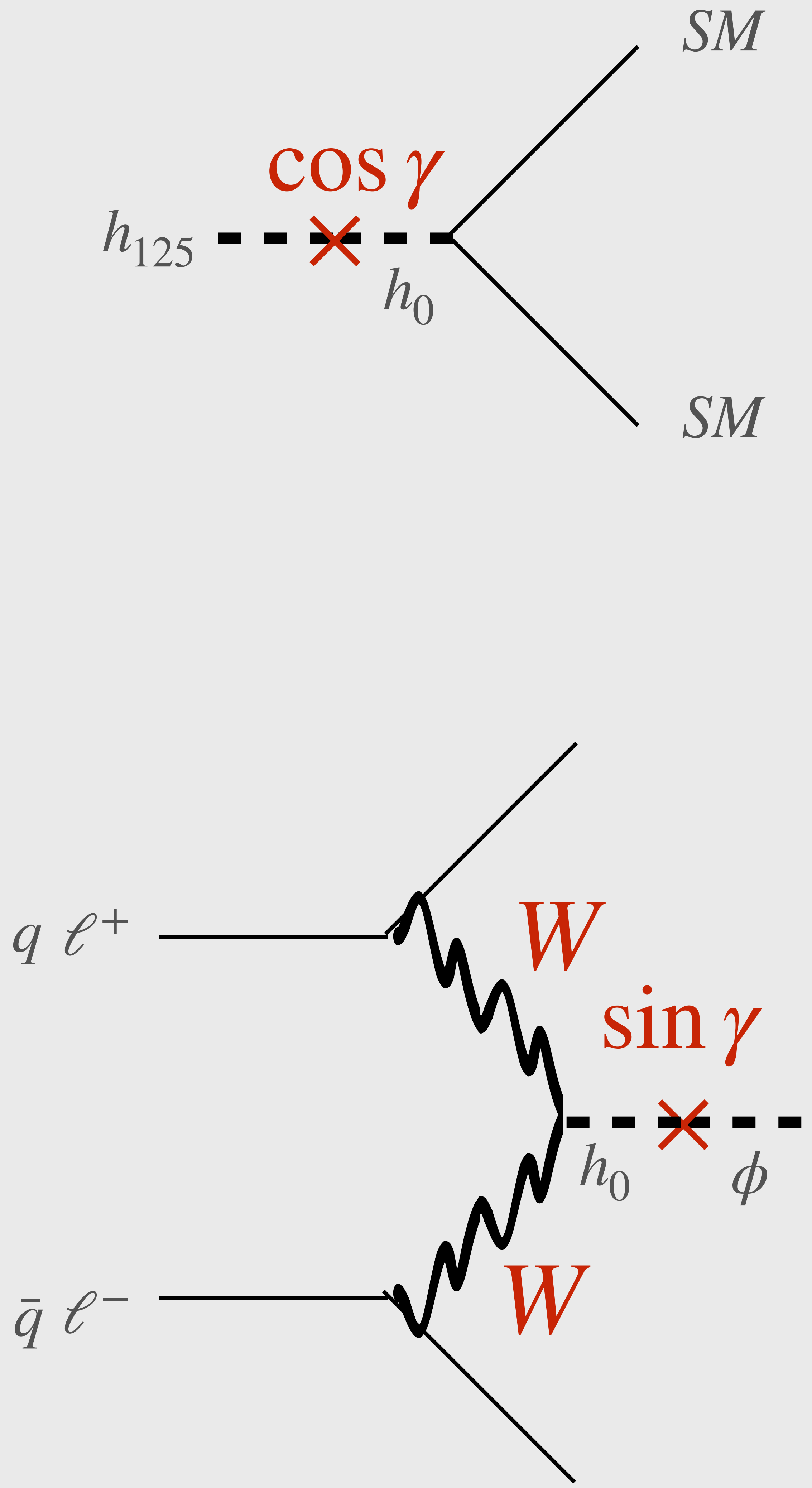
- Phenomenology is also useful as "simplified model"
- Widely studied in the various Future Colliders projects

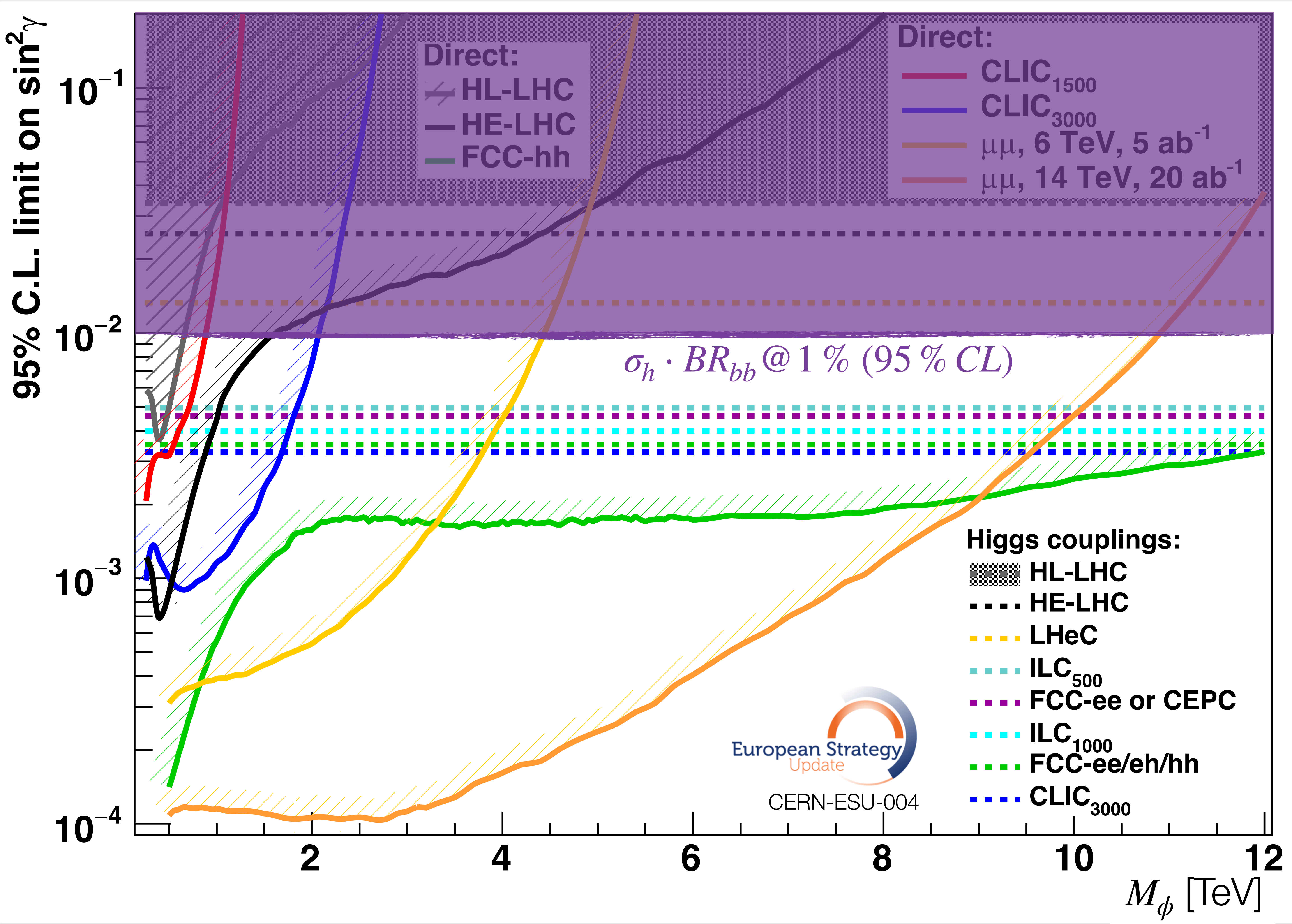
Higgs + Singlet





Higgs + Singlet





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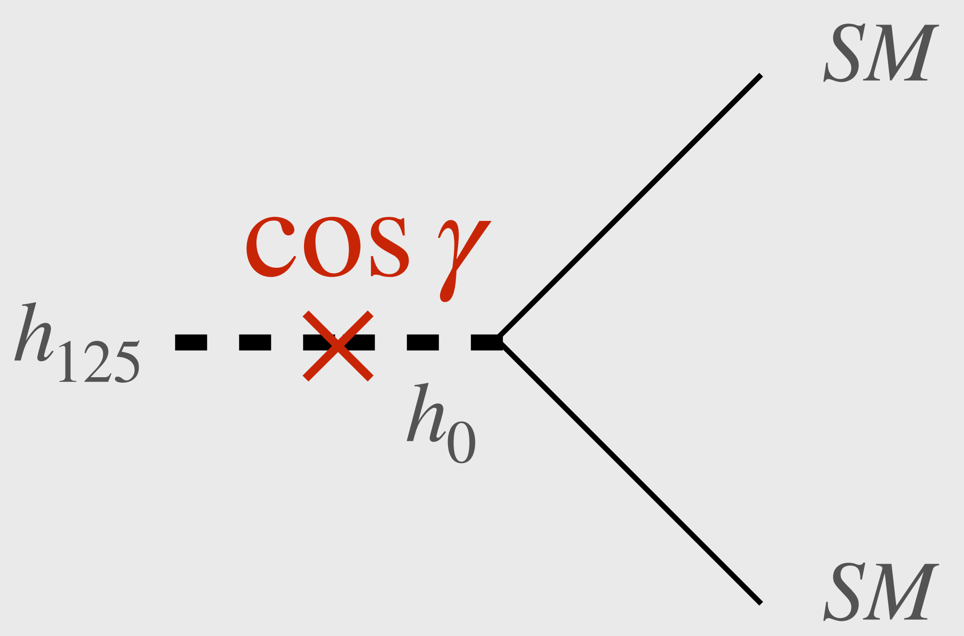
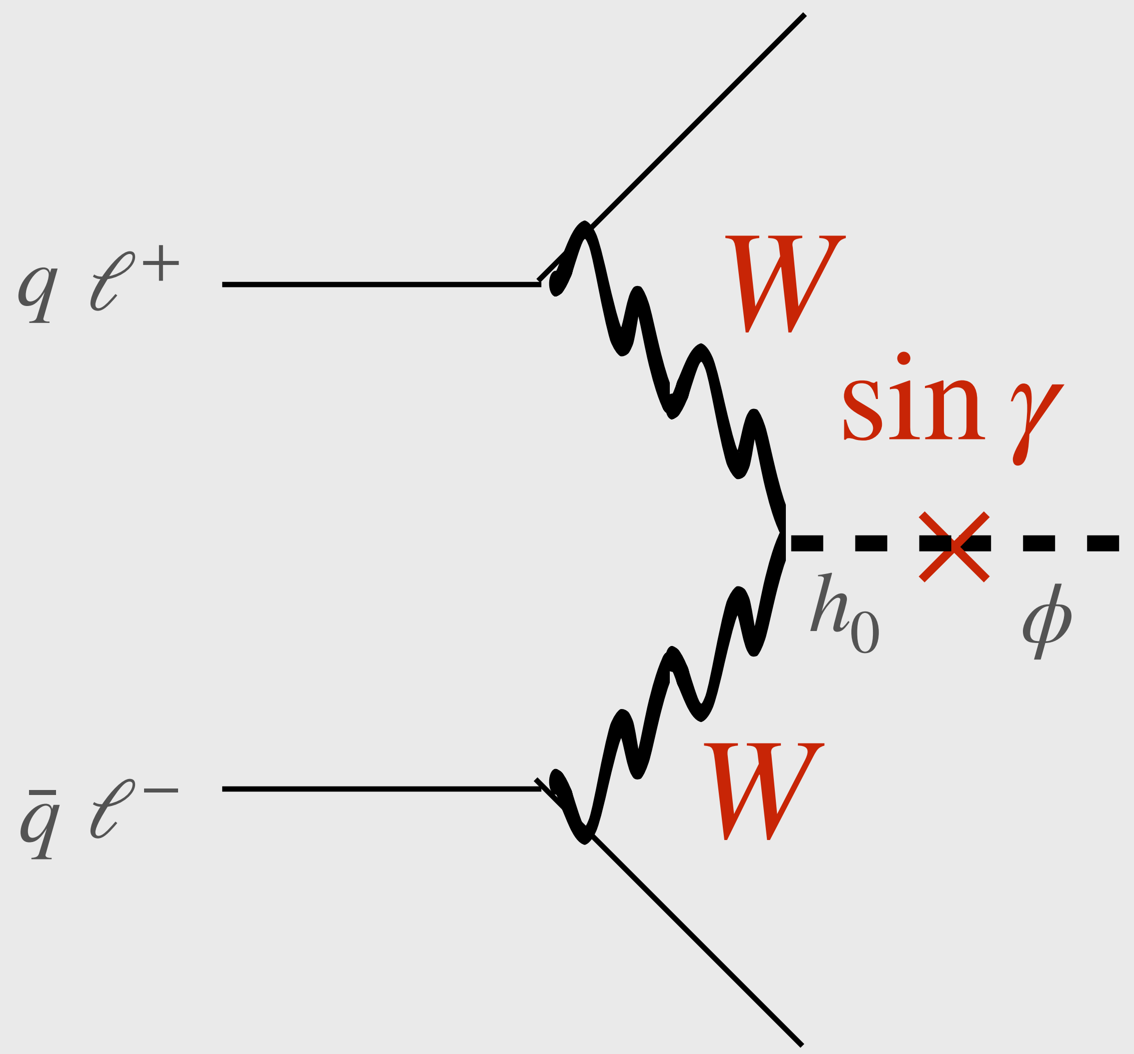
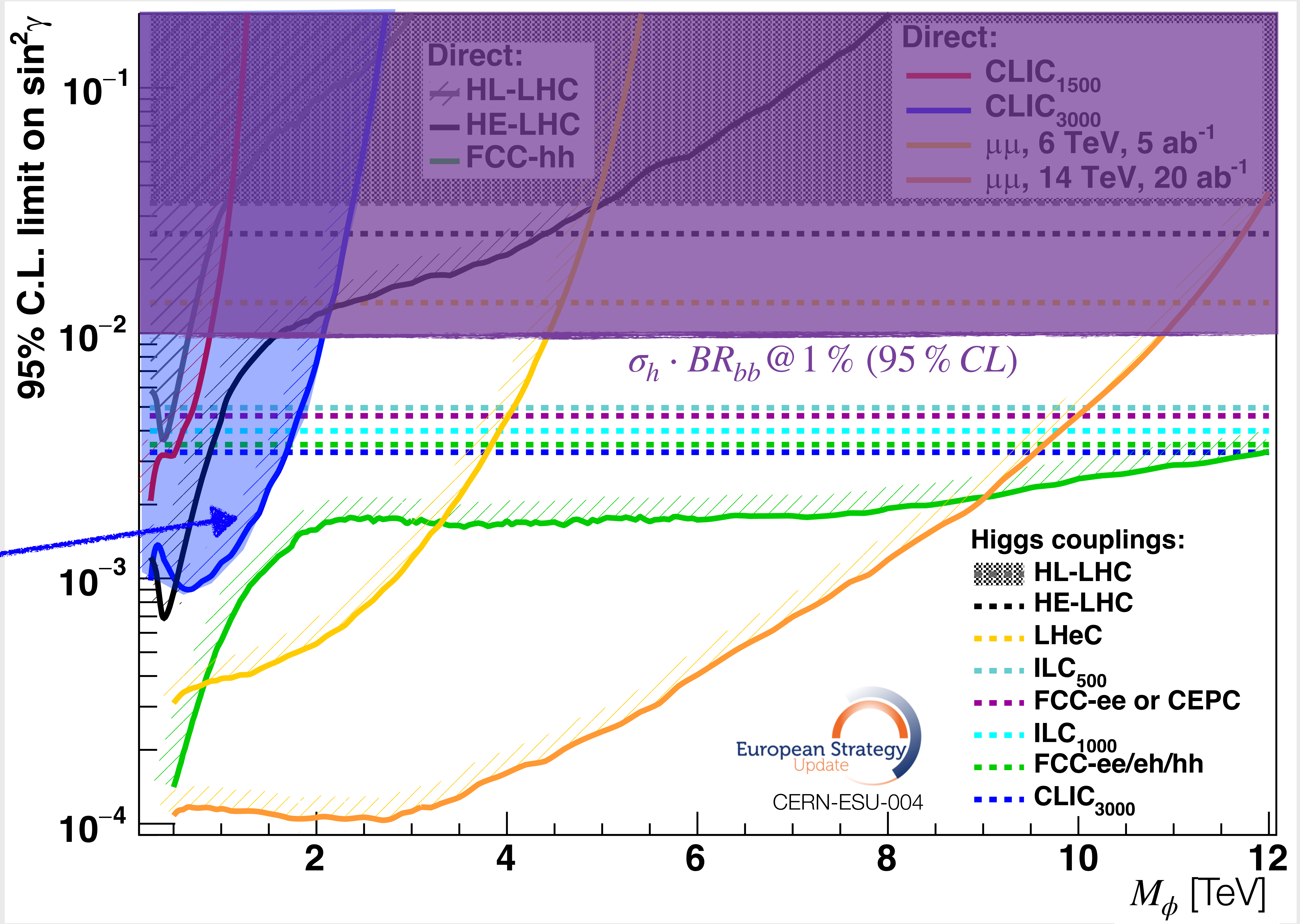
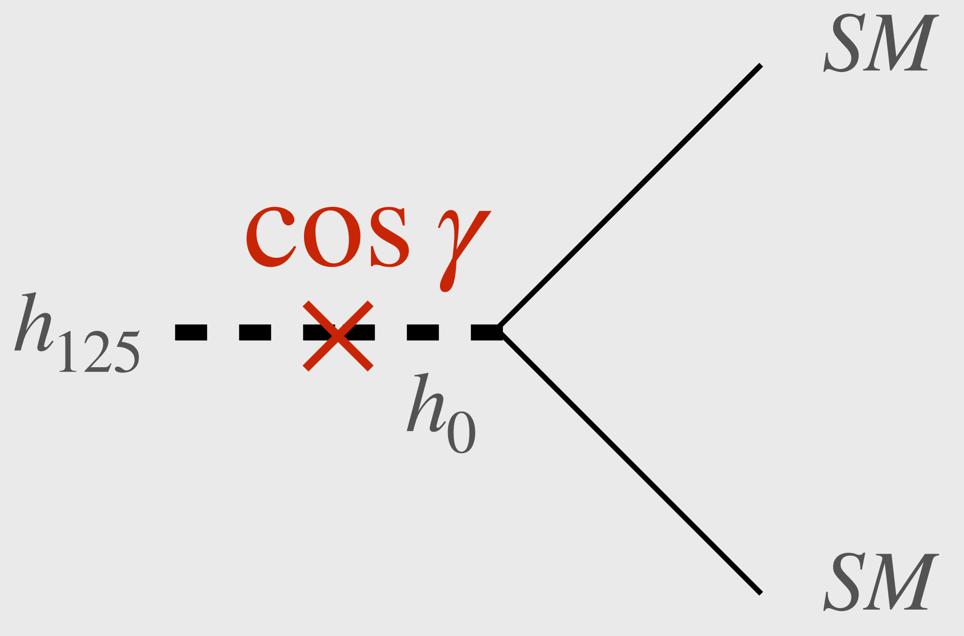


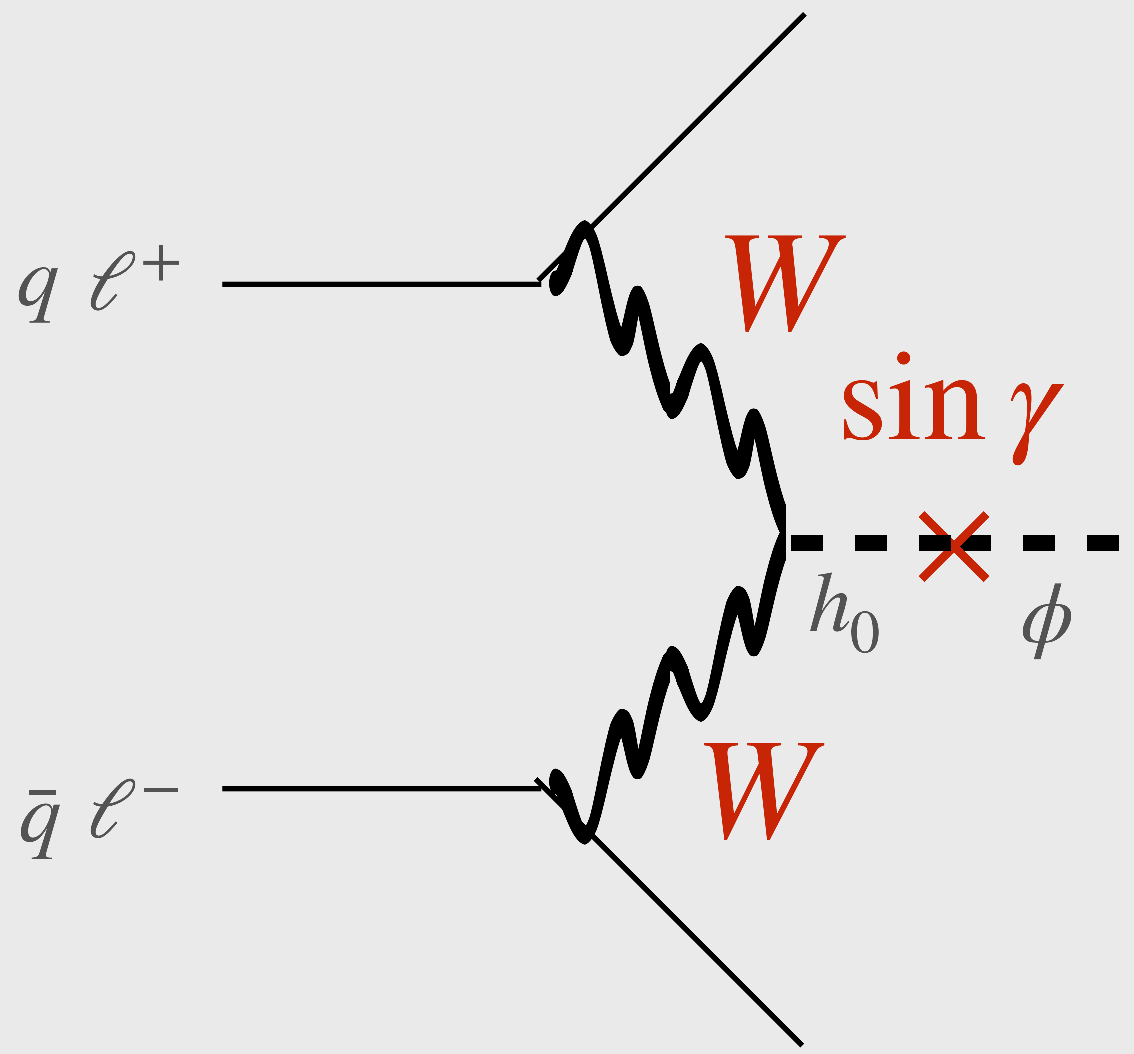


direct observation
3 TeV
CLIC $\simeq \mu^+\mu^-$ 3 TeV



Higgs + Singlet

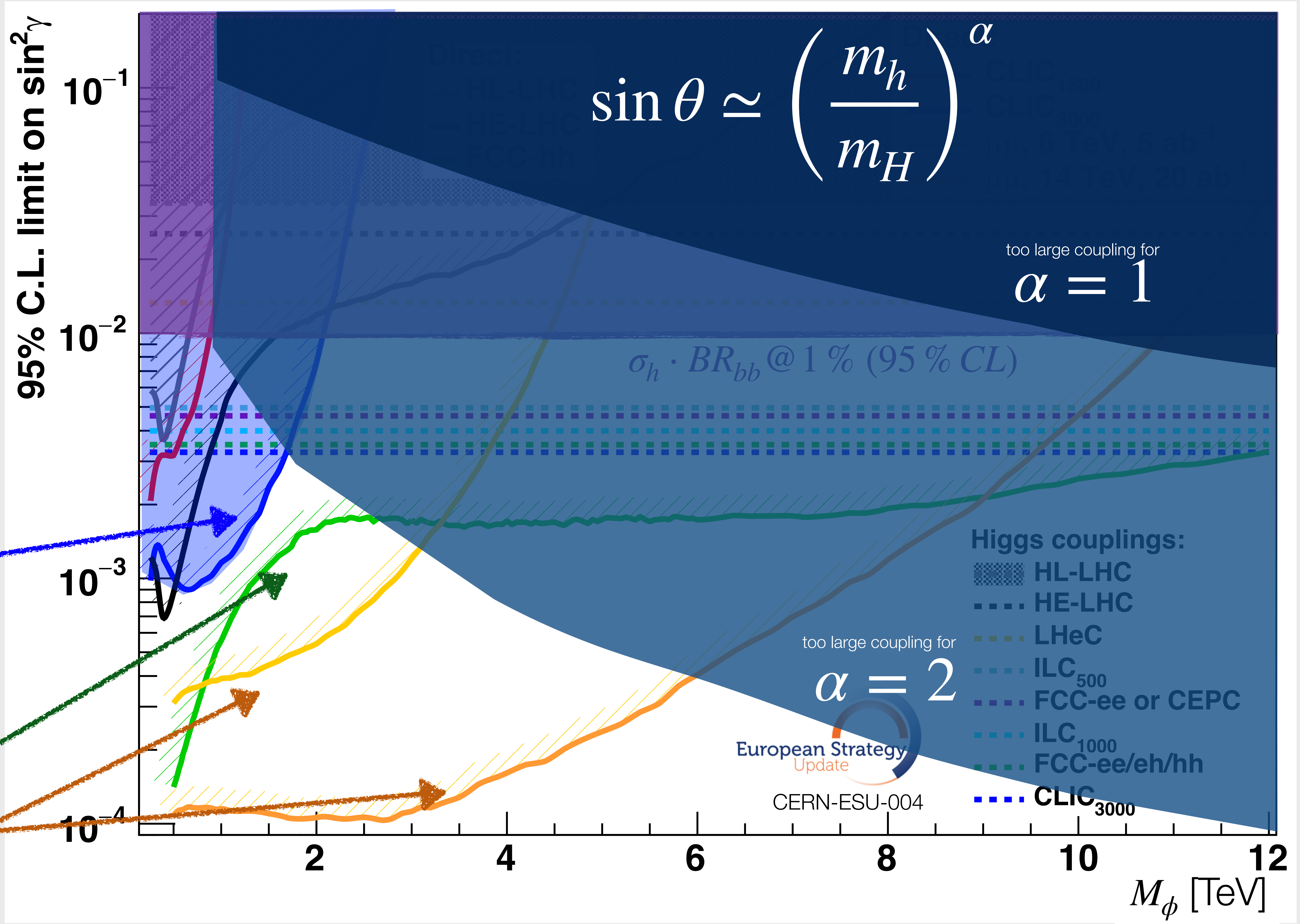




direct observation
3 TeV
CLIC $\simeq \mu^+\mu^-$ 3 TeV

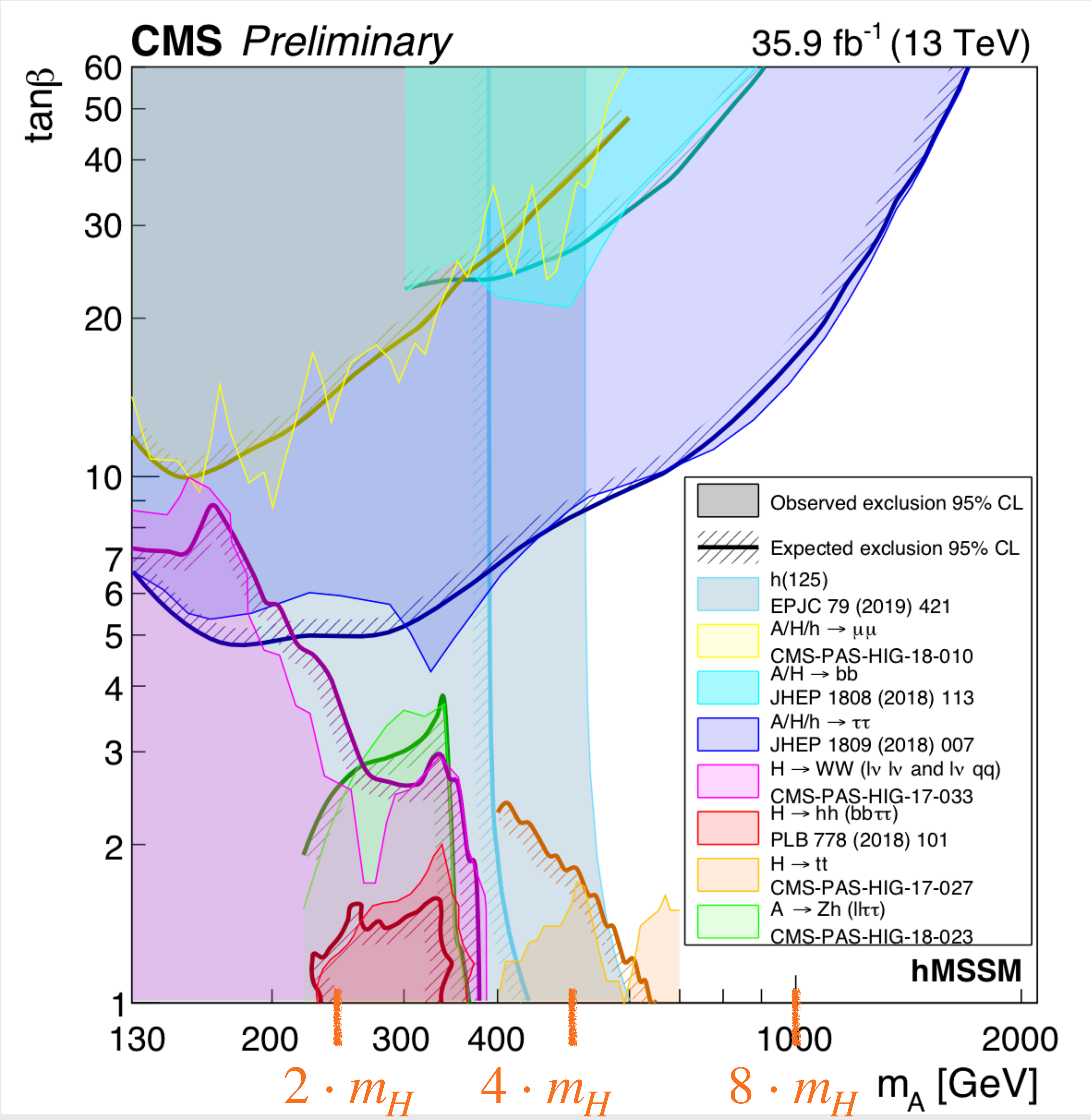
direct observation
FCChh

direct observation
$\mu^+\mu^-$ 3+ TeV



Extended Higgs Sector: Doublets

DOUBLETS | ARE ABOUT AS TOUGH TO CATCH



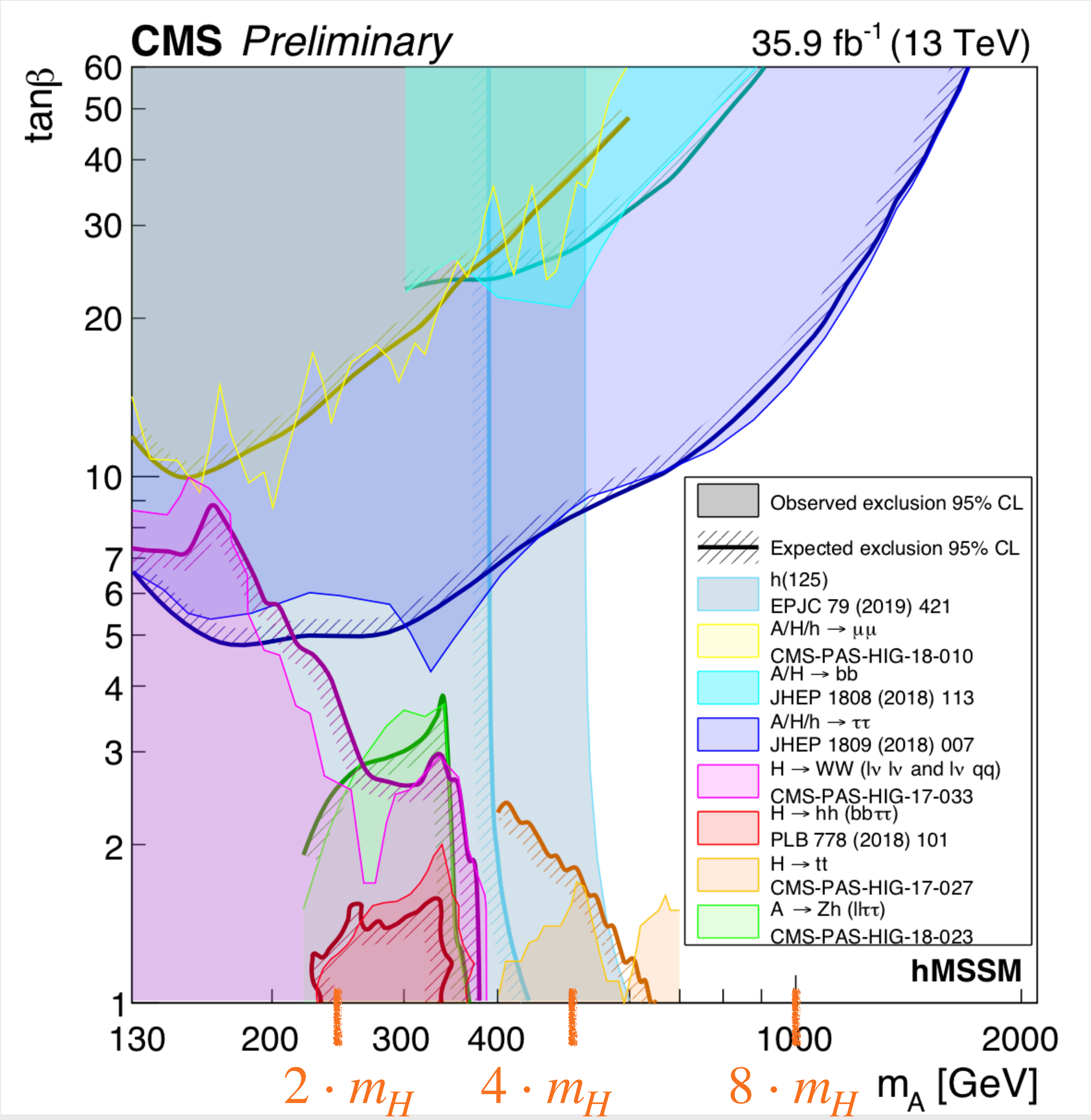
There is in general a weak sensitivity to new scalars, because of:

- **“small” cross-sections**
- **large backgrounds**

it is hard to explore the scalar sector and the only big discovery of the LHC may be left unmatched … even if light scalars may exist.

Extended Higgs Sector: Doublets

DOUBLETS ARE ABOUT AS TOUGH TO CATCH



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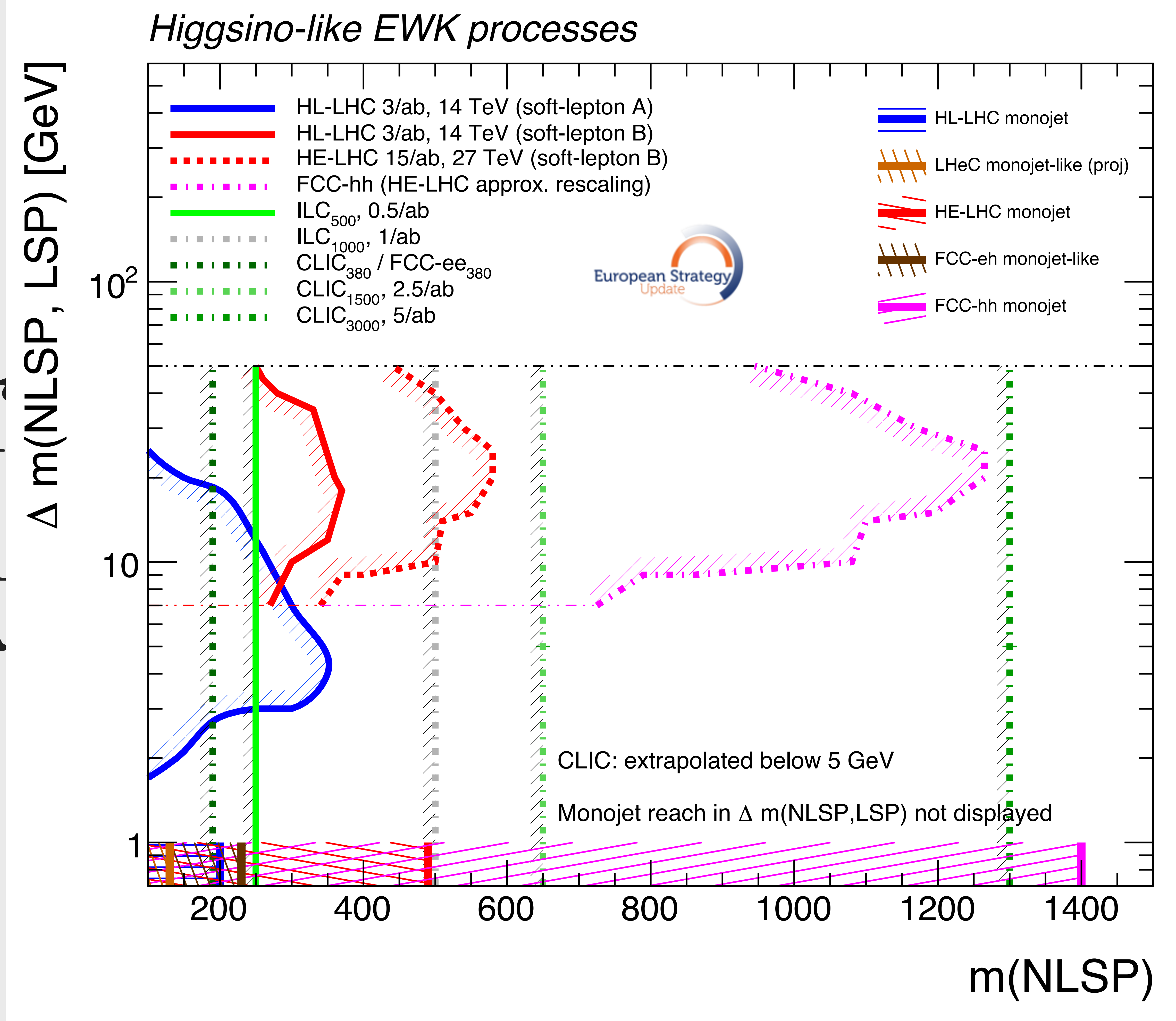
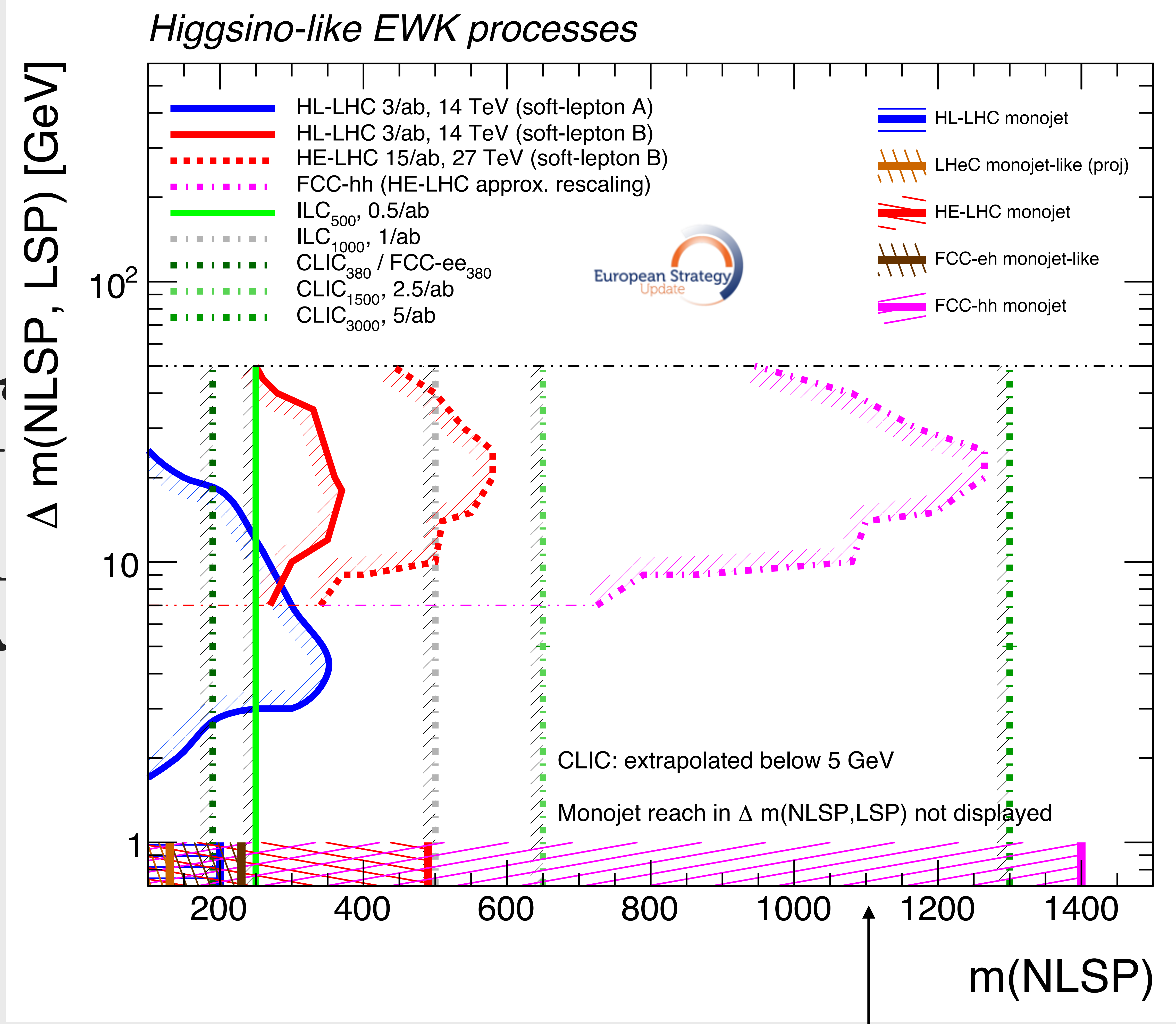
this problem is common to lots of electroweak new physics states this pr lots of

elect states

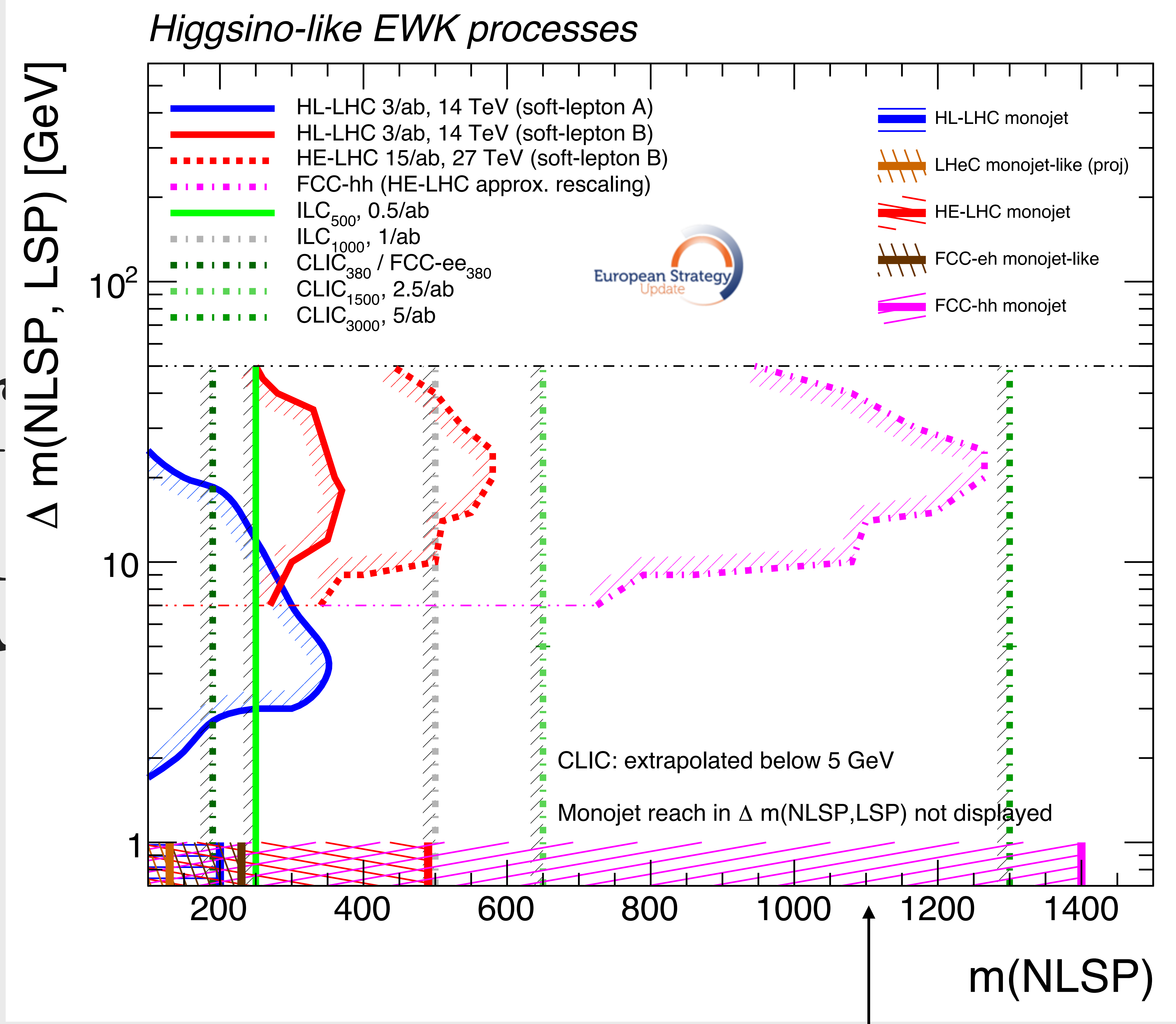


this pr lots of
elect states



This could be Dark Matter

this pr… lots of
elect… states



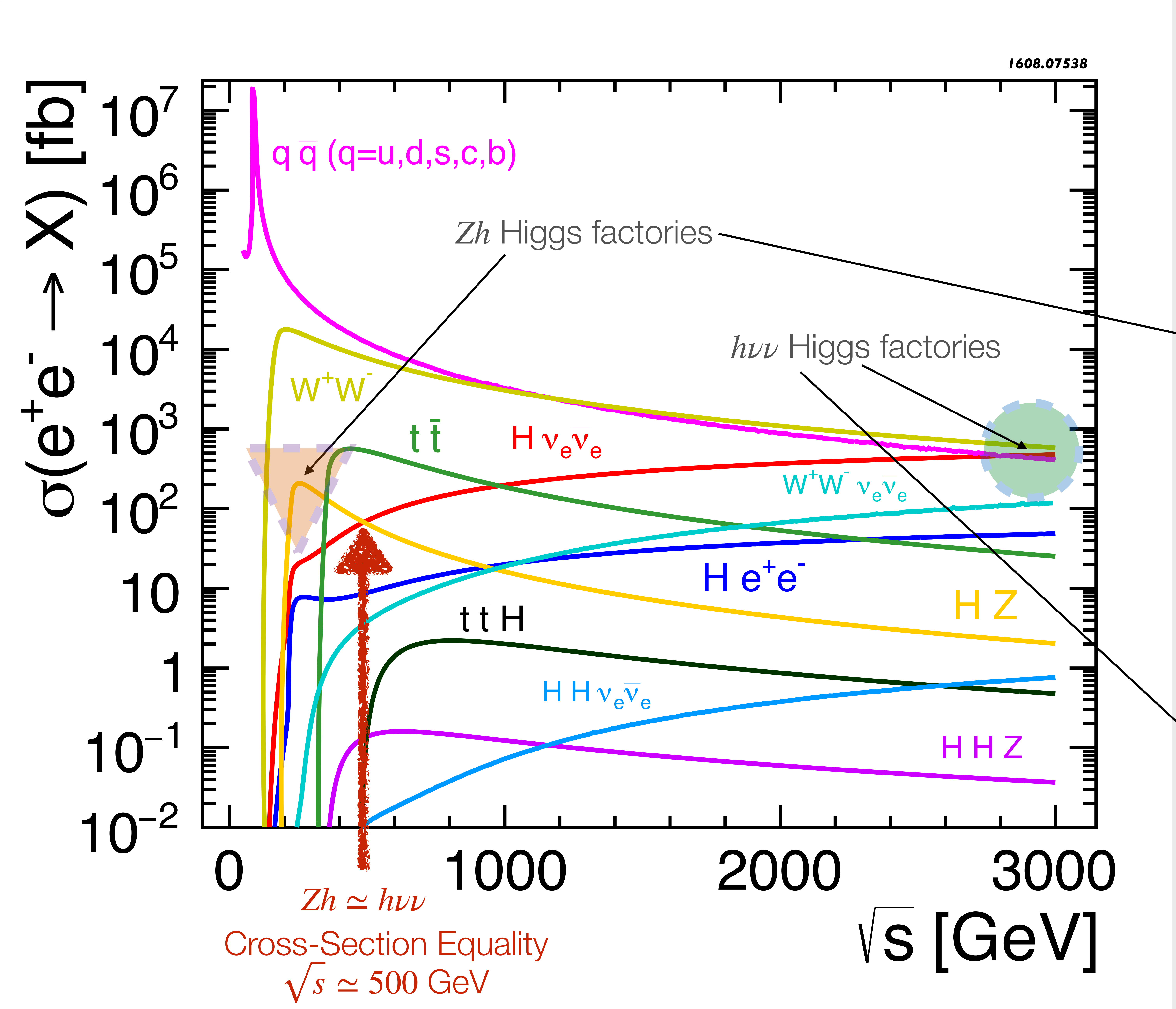
This could be Dark Matter
(inaccessible in Direct Detection!)

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) *

Not all the Higgs Factories are the same for direct discovery

Types of Higgs Factories



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

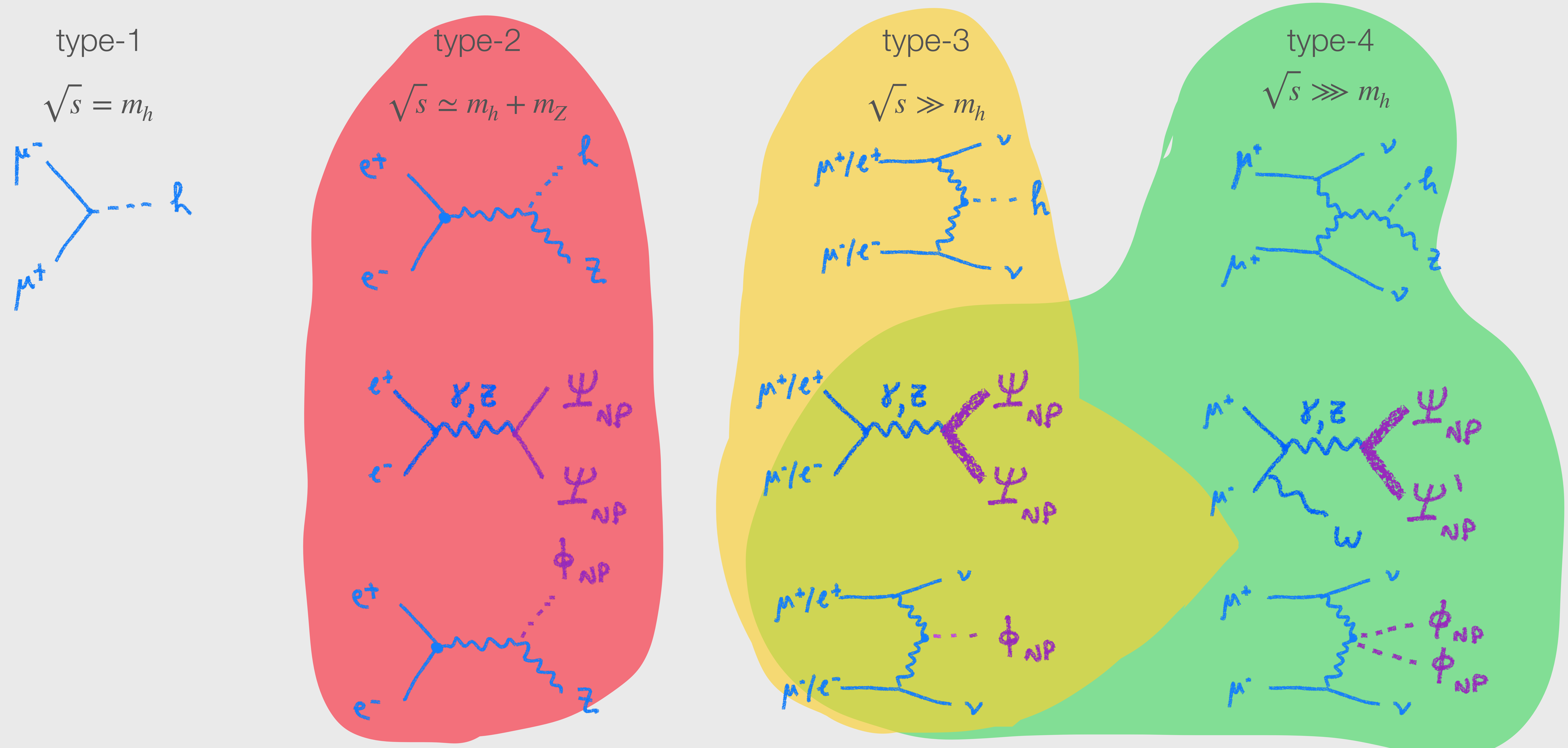
$$\sigma(Zh) \sim \frac{1}{s}$$

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

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

Types of Higgs factory

Direct Search inevitably limited by available energy



(Very) light new physics possibly (very) weakly coupled

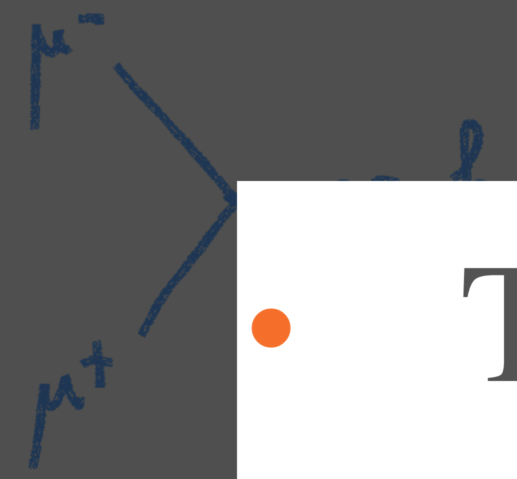
Much larger range of new physics mass scale directly accessible

Types of Higgs factory

Direct Search inevitably limited by available energy

type-1

$\sqrt{s} = m_h$



type-2

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

type-3

$\sqrt{s} \gg m_h$

type-4

$\sqrt{s} \ggg m_h$

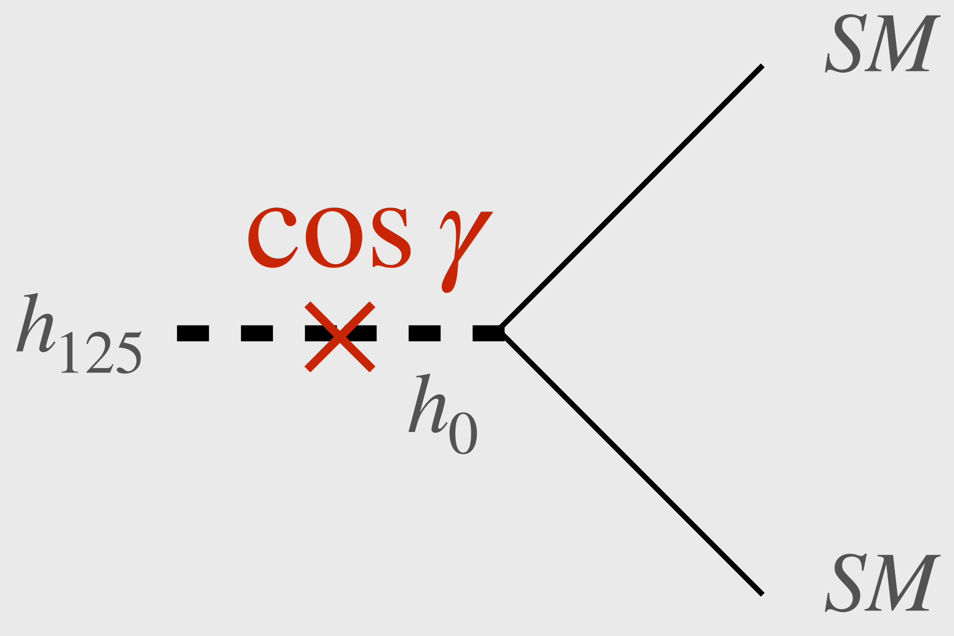
- The Zh type of Higgs factory can probe light new physics up to very weak couplings

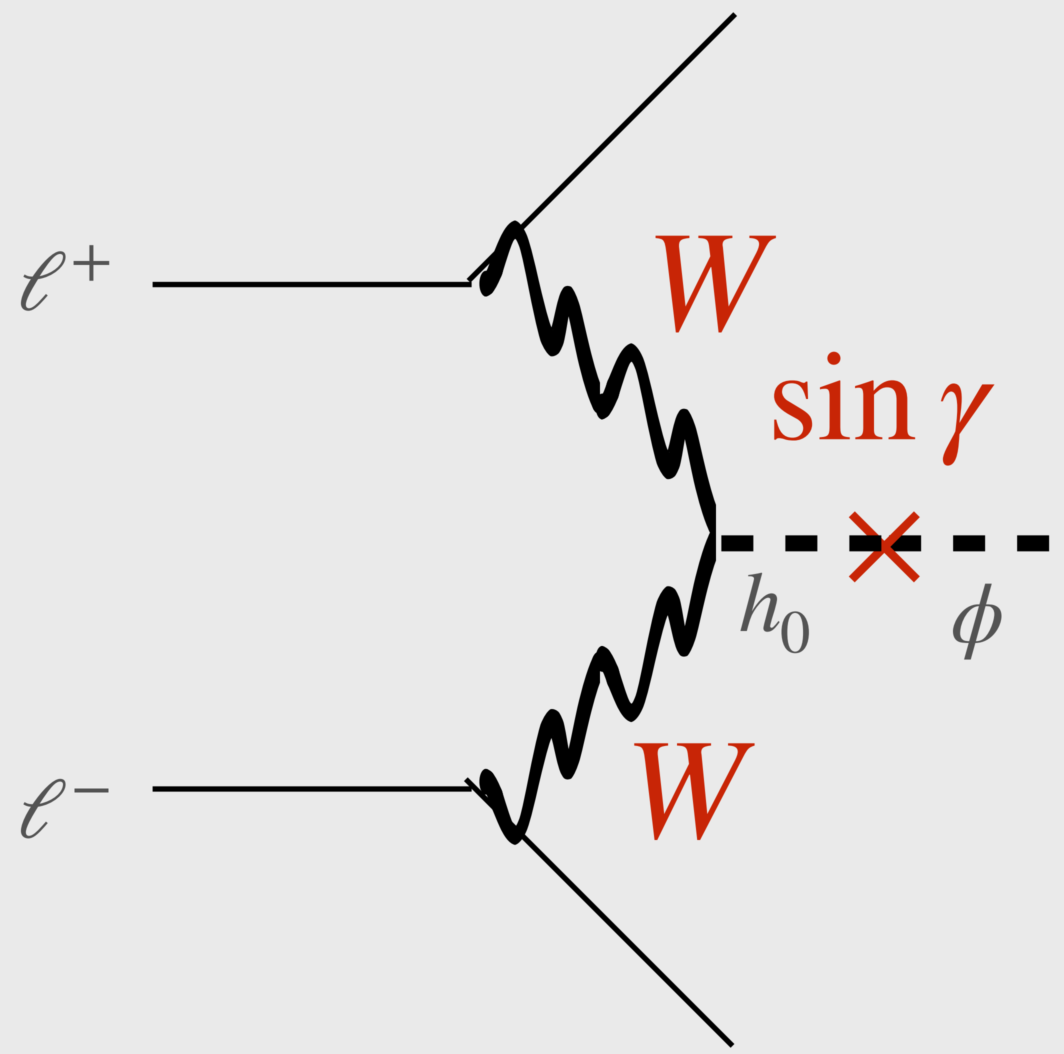
- The $h\nu\nu$ type of Higgs factory can probe heavy new physics & potentially observe the particles responsible for the h couplings deviations measured at the same machine

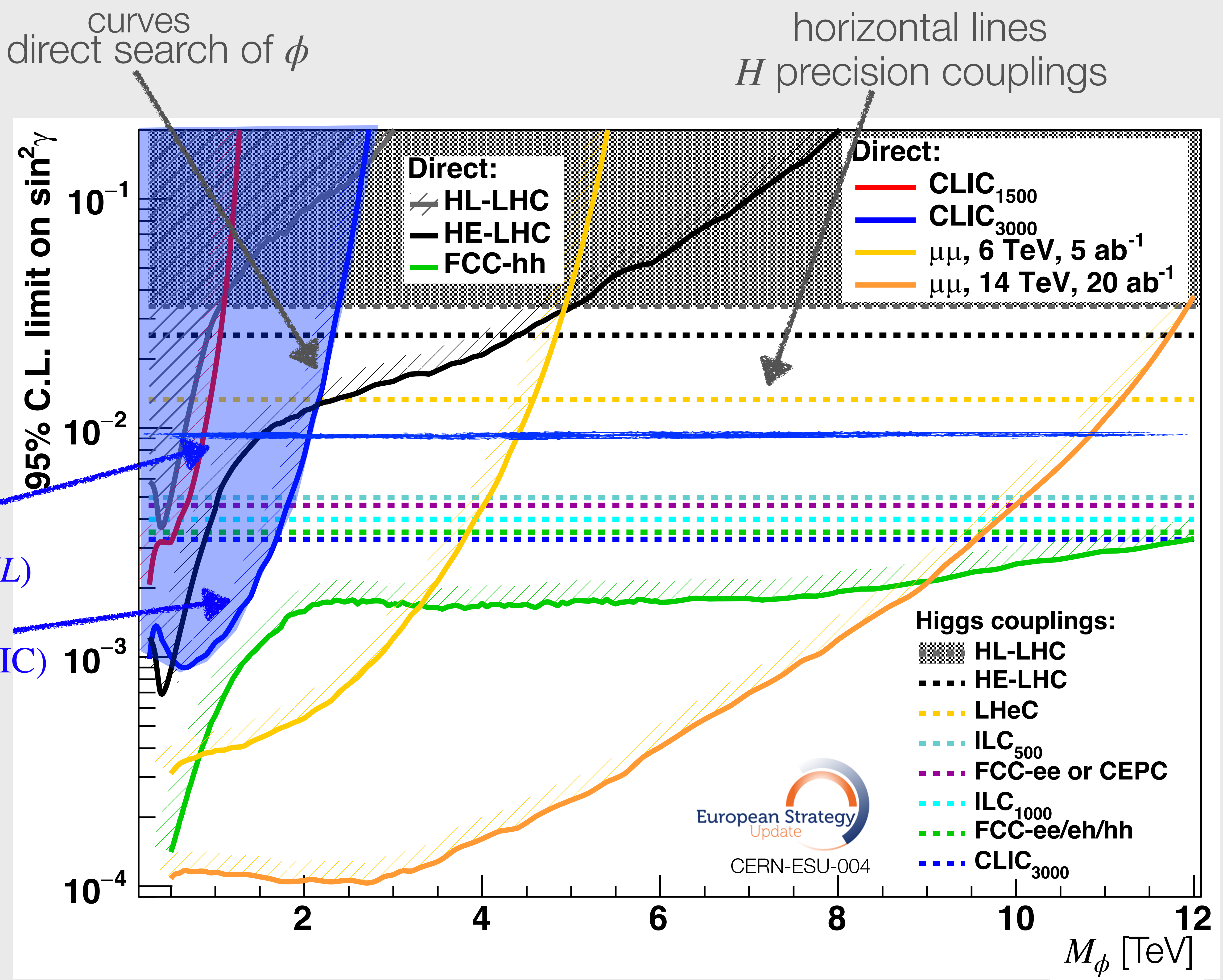
(Very) light new physics possibly (very) weakly coupled

Much larger range of new physics mass scale directly accessible

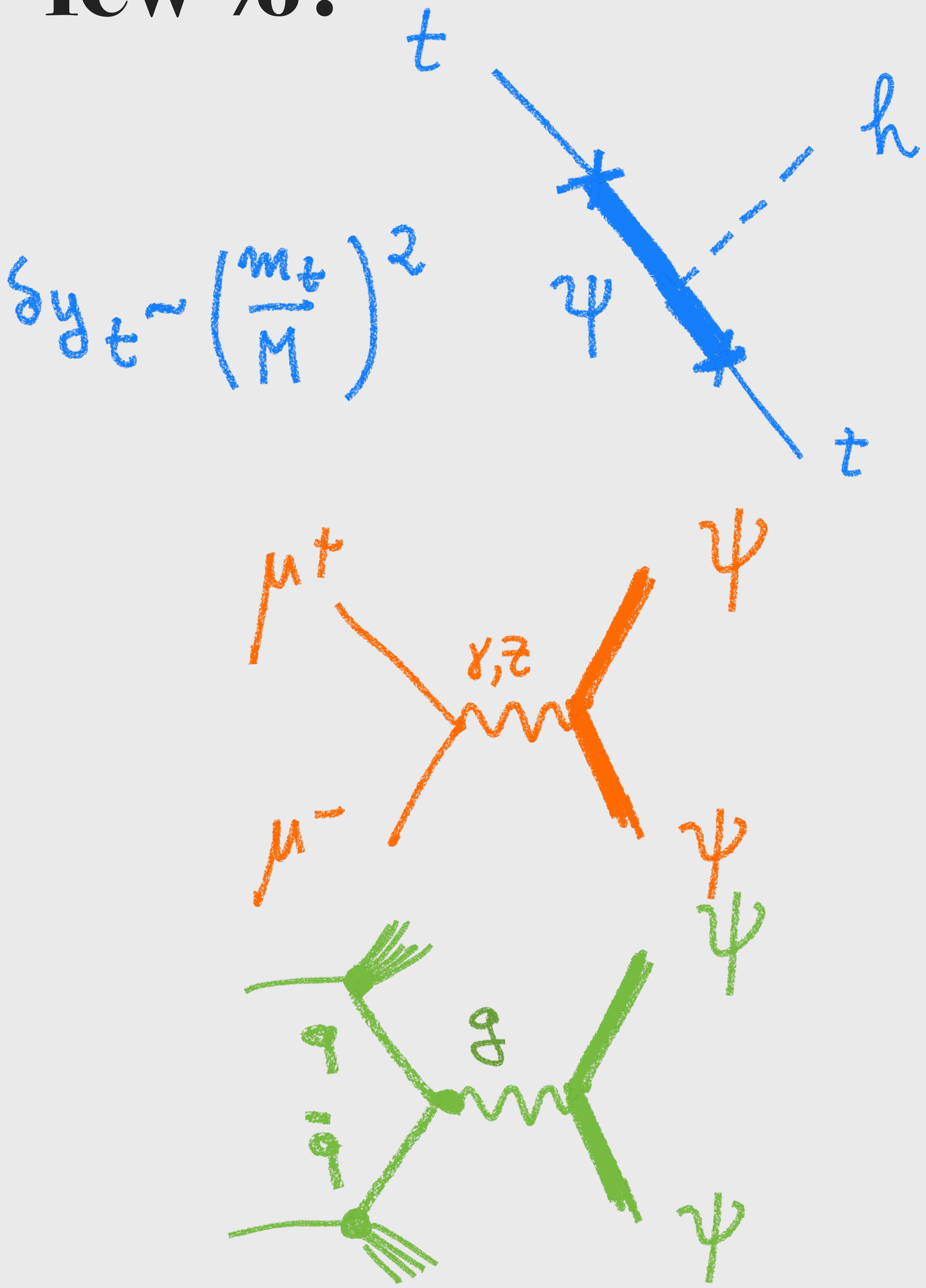
You got an overall mismatch of the Higgs couplings? → Search for a new scalar singlet!

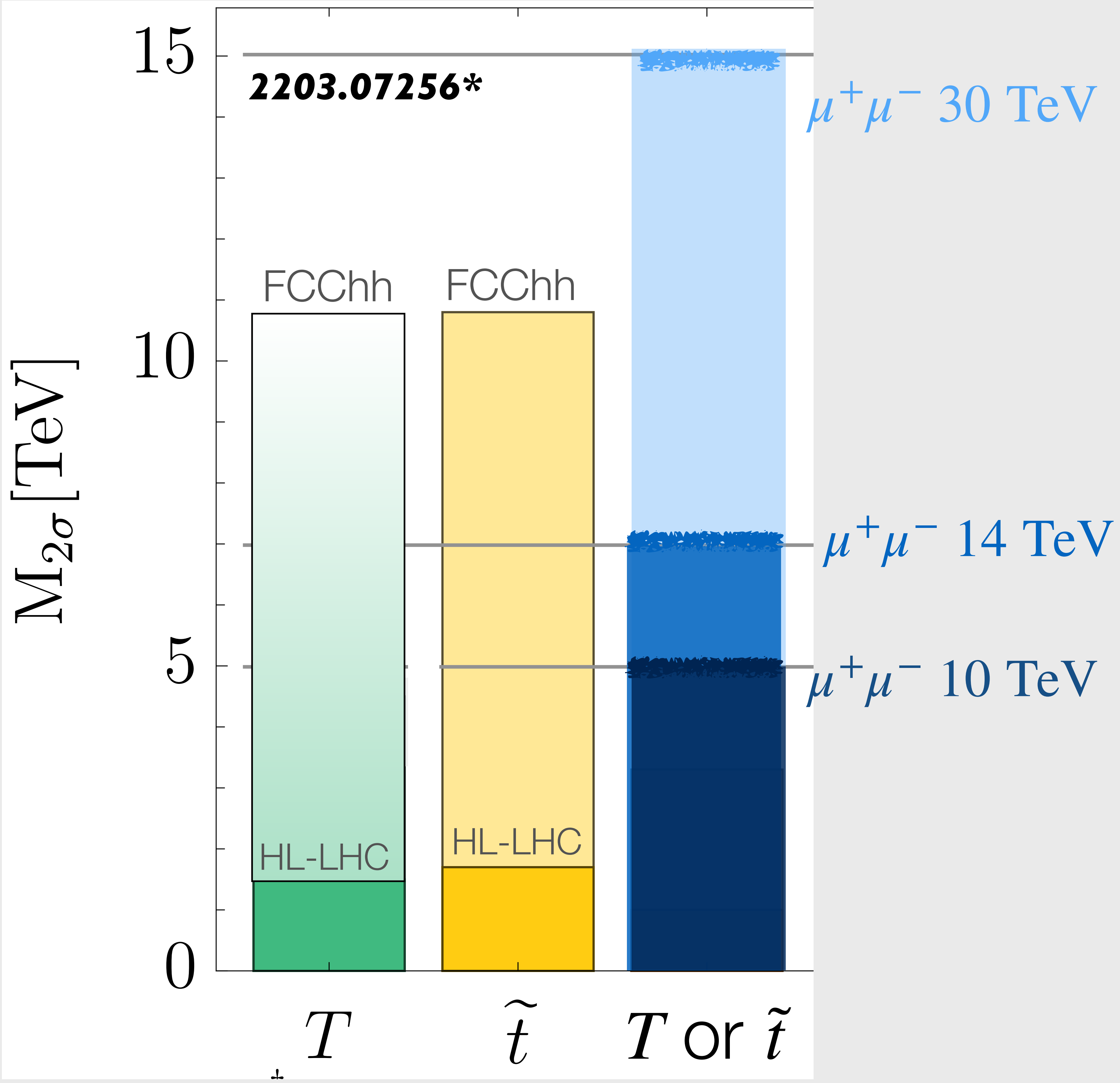


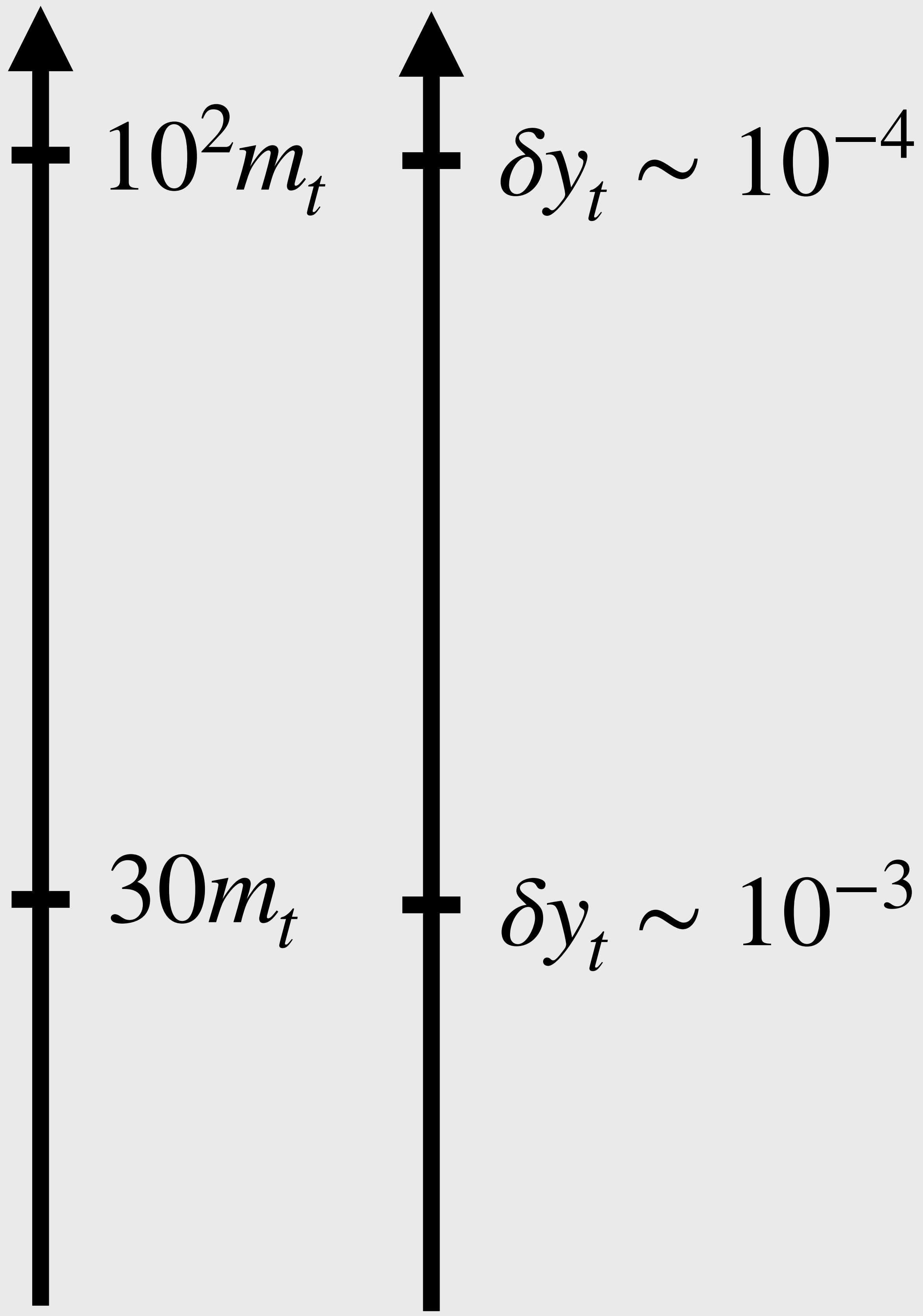




The top quark Yukawa is off by few %? → Search for a new heavy top quark T!



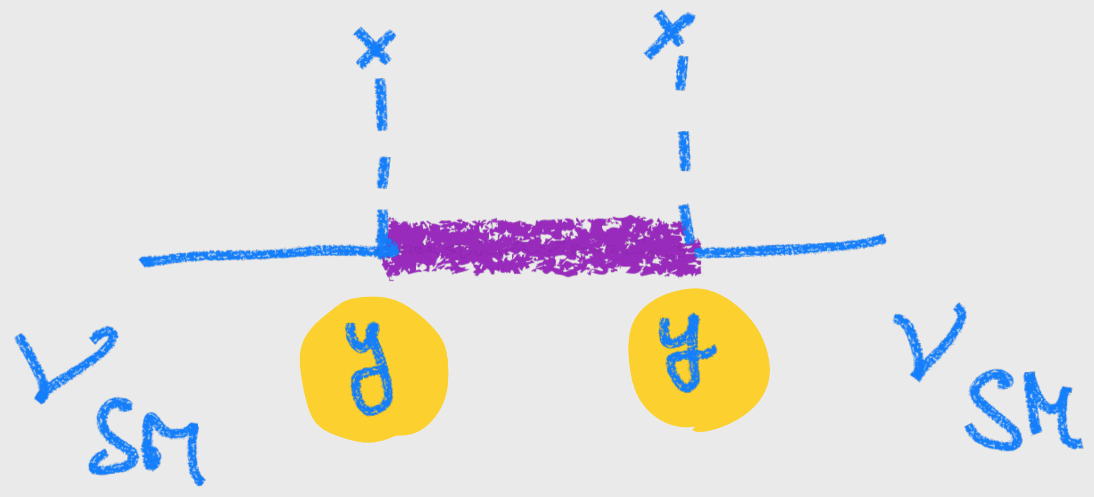


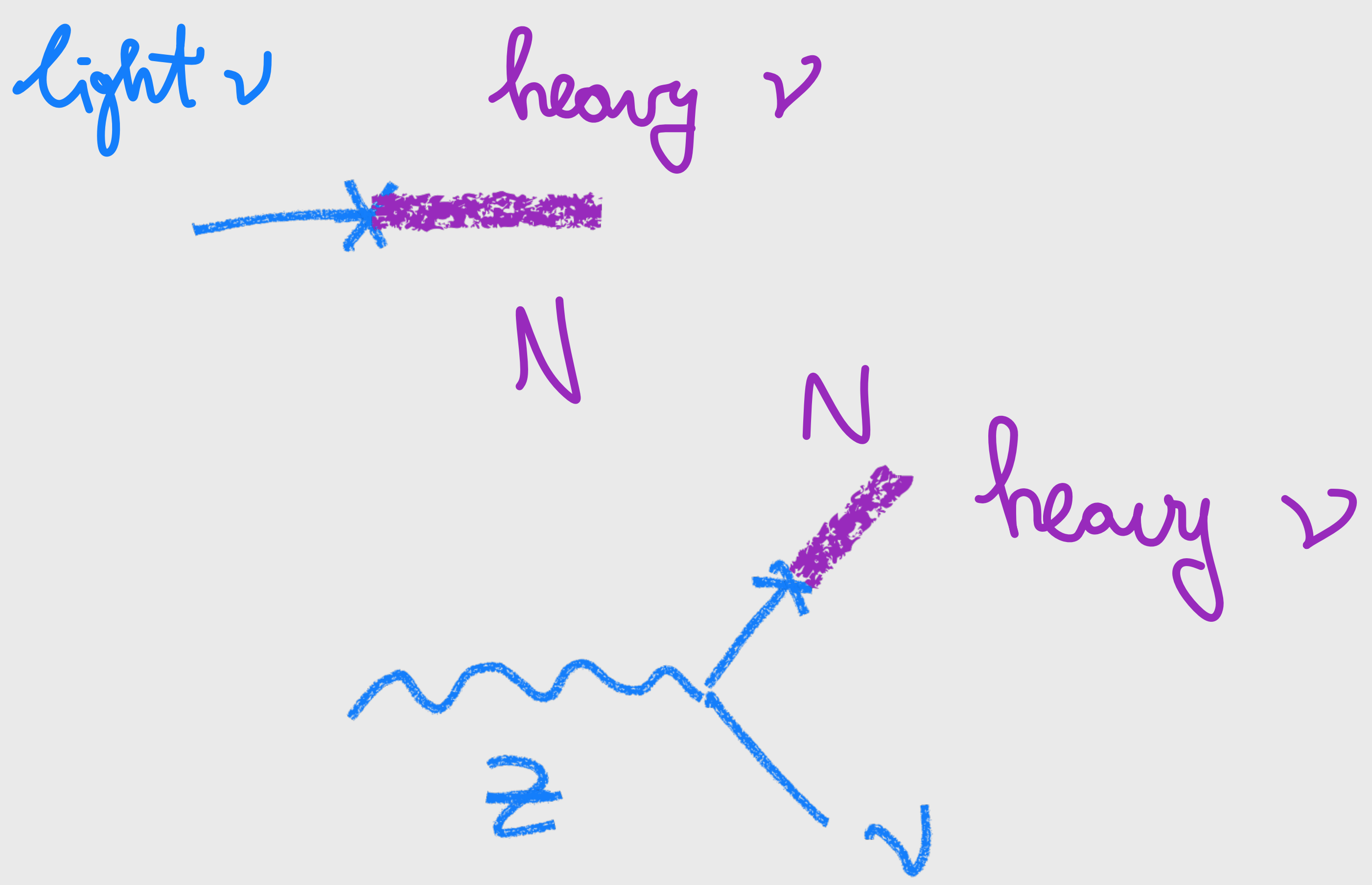


New physics might be not be (immediately) related to the Higgs boson couplings

Neutrino masses

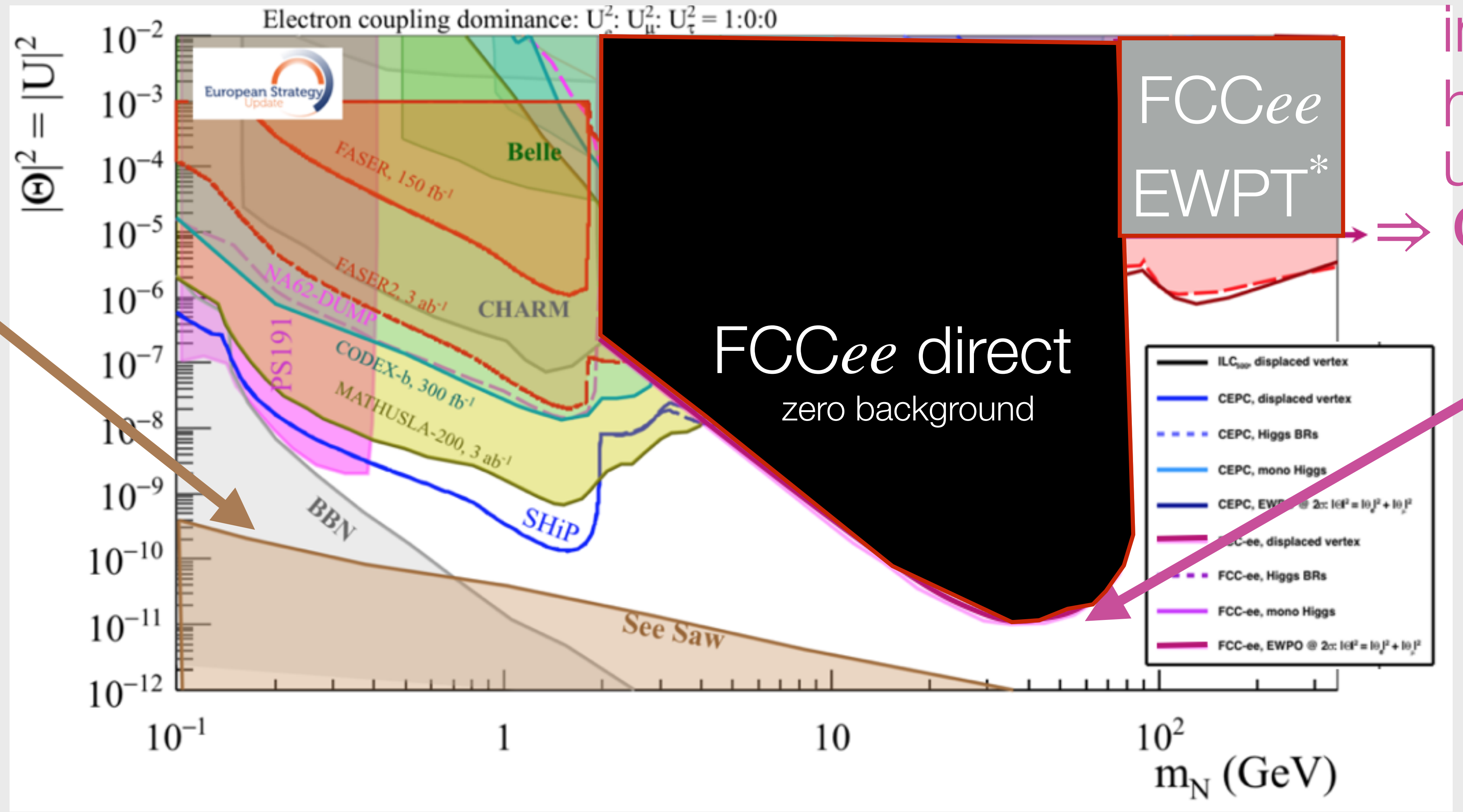
The “first” kind of see-saw





$$m_\nu \sim \frac{y^2 v^2}{M} = \Theta^2 M \simeq 0.1\ \text{eV}$$

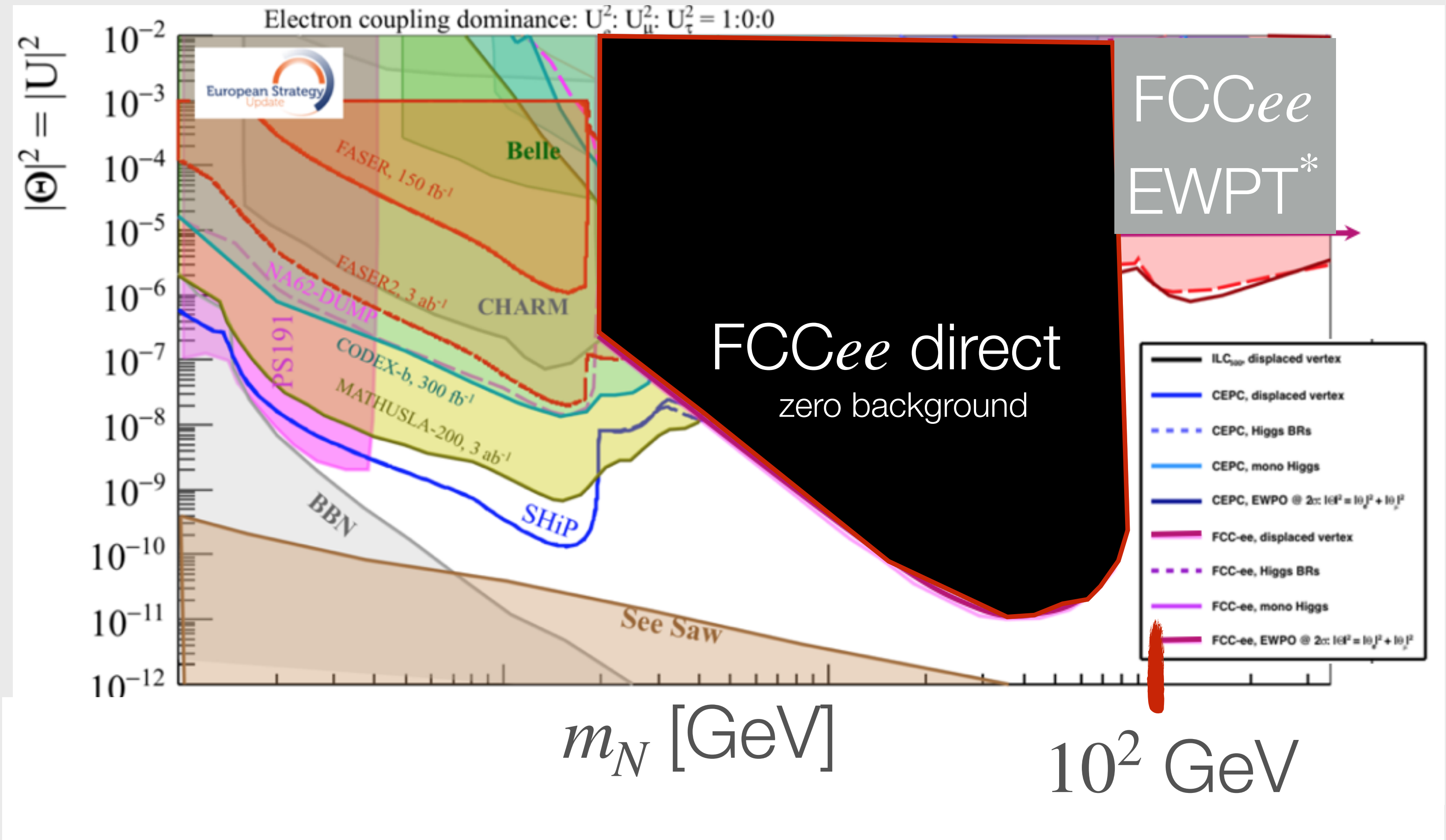
$$\Theta \lesssim \sqrt{\frac{eV}{M}}$$

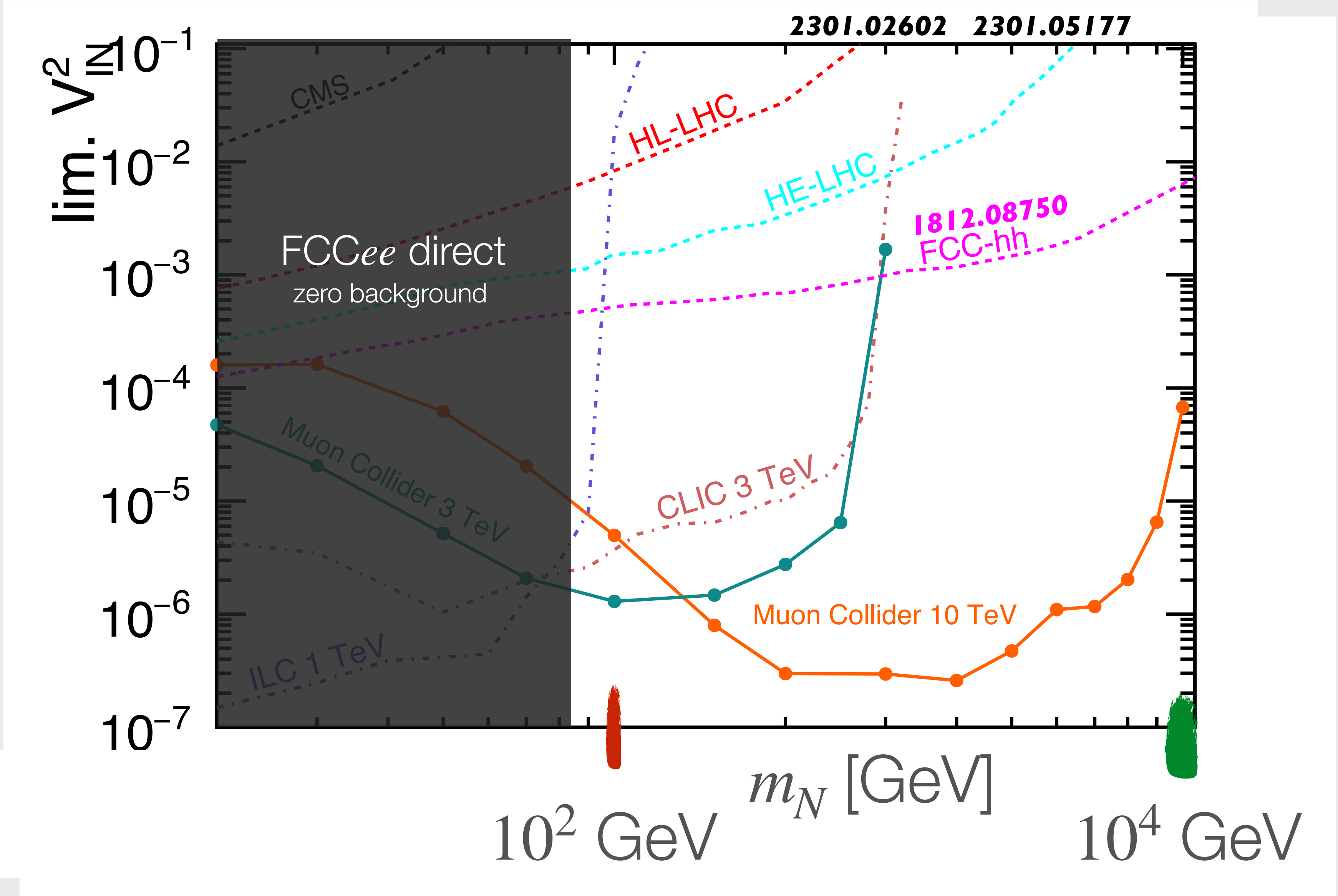


indirect from
high-precision Z pole
up to $M \gg 100$ GeV
$\Rightarrow\ \Theta \lesssim 0.3 \cdot 10^{-2}$

$\Rightarrow\ \Theta \lesssim 3 \cdot 10^{-6}$
$M \simeq 100$ GeV

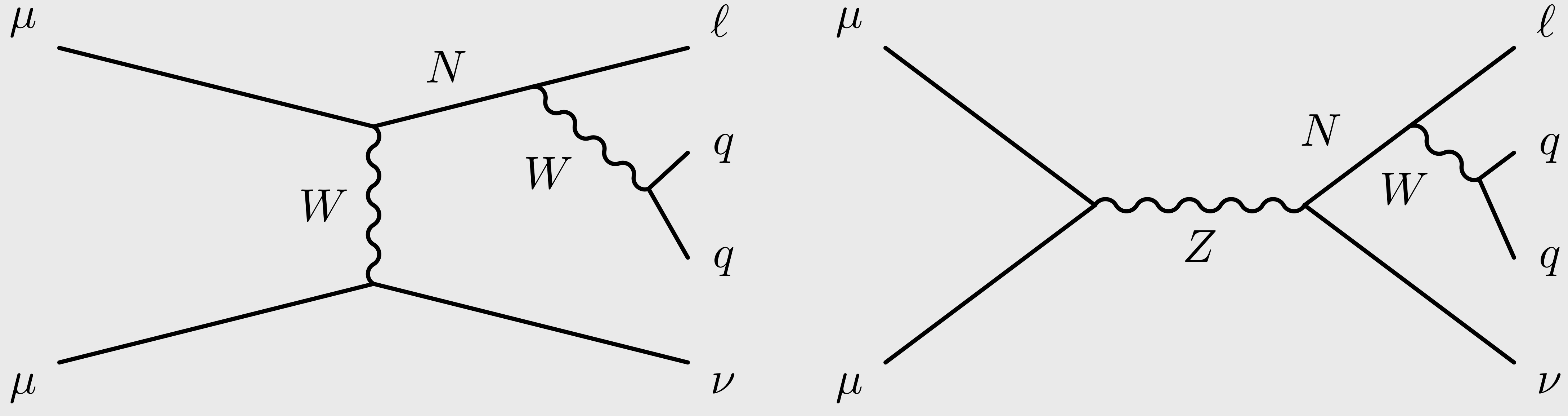
Neutrino masses The "first" kind of see-saw





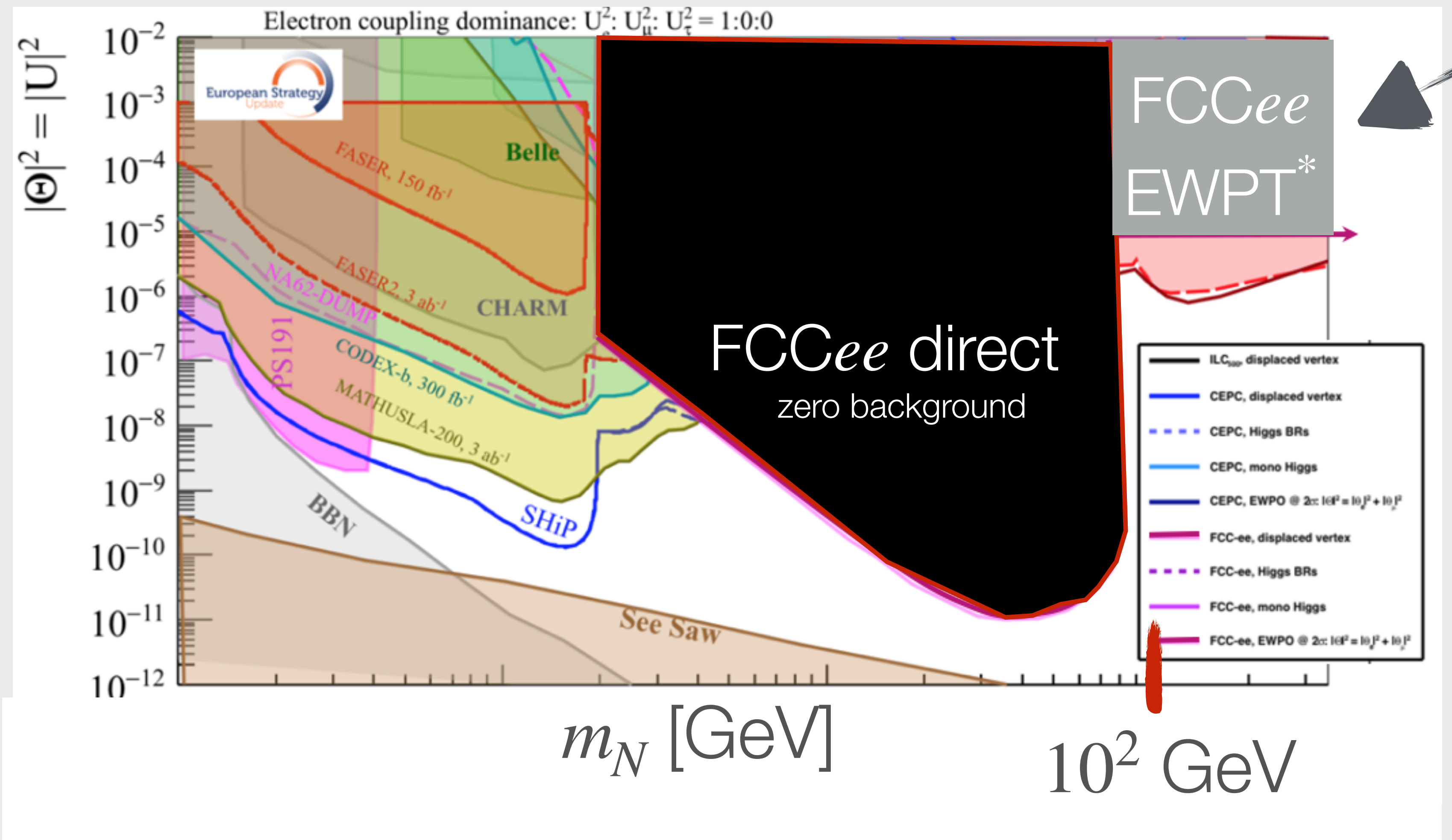
FCC*ee* has fantastic sensitivity, but only to light N

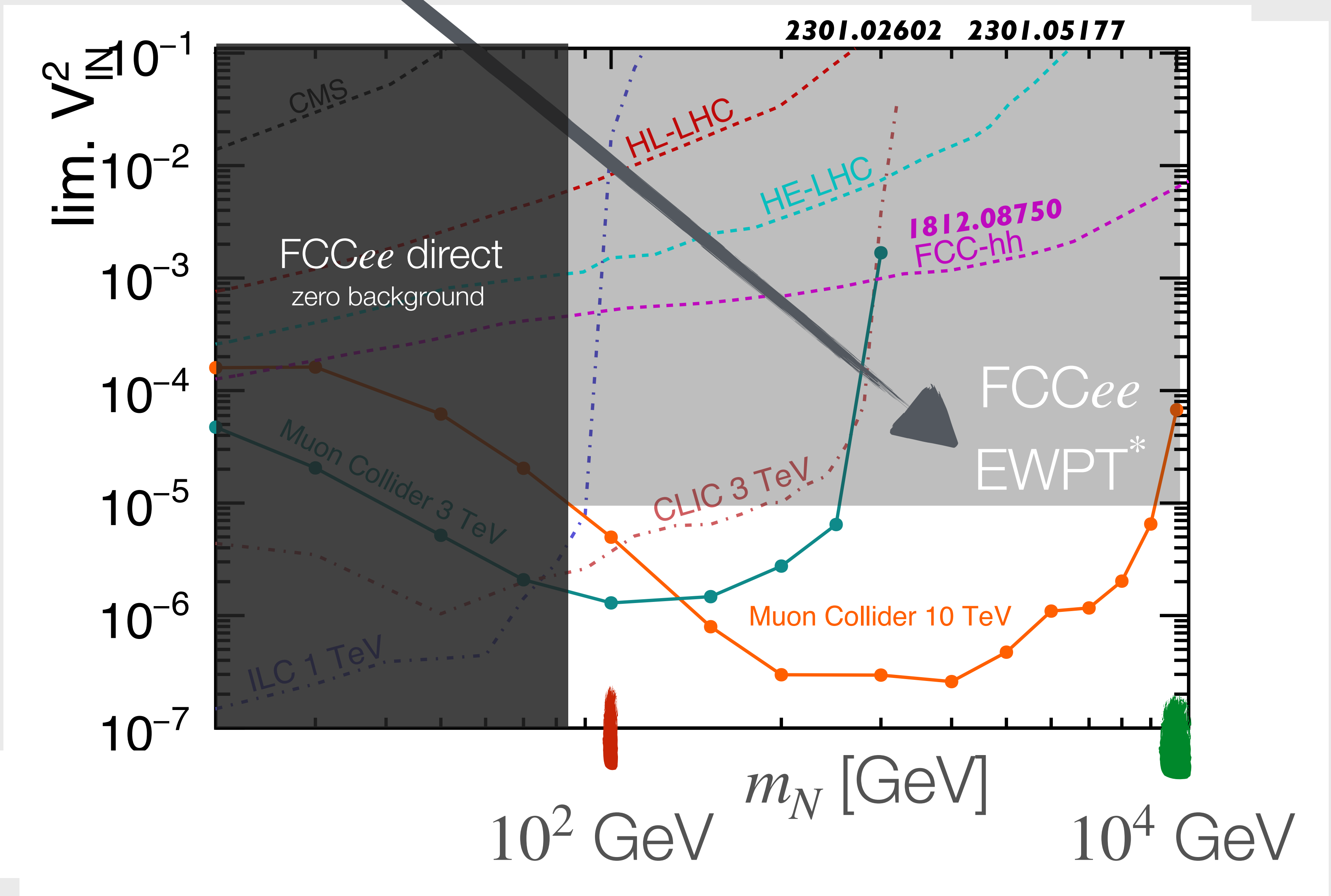
heavy N can be tested at FCC*hh* and even deeper at $\mu\mu$



Neutrino masses The "first" kind of see-saw

if Z pole high-precision theory delivers





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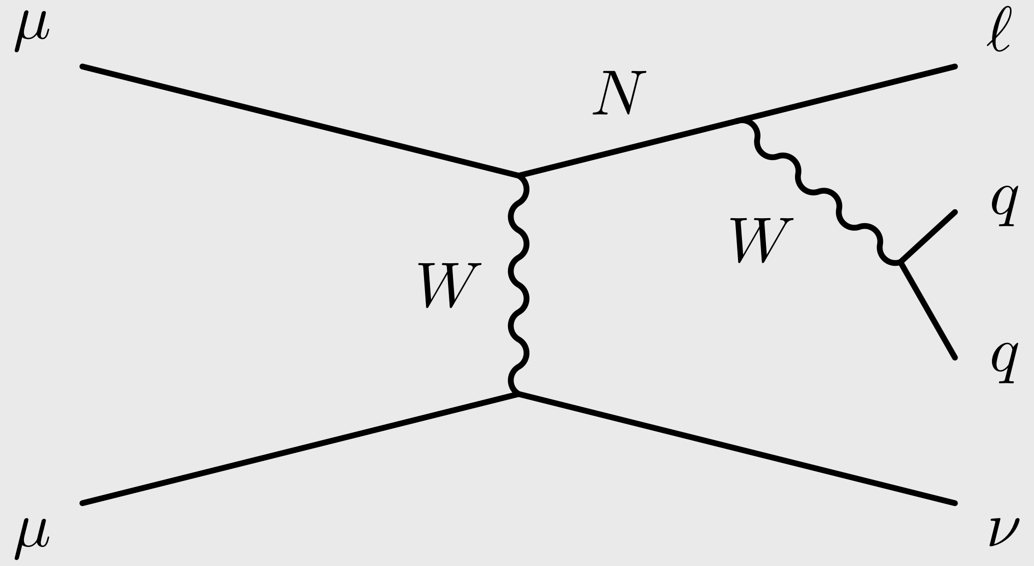

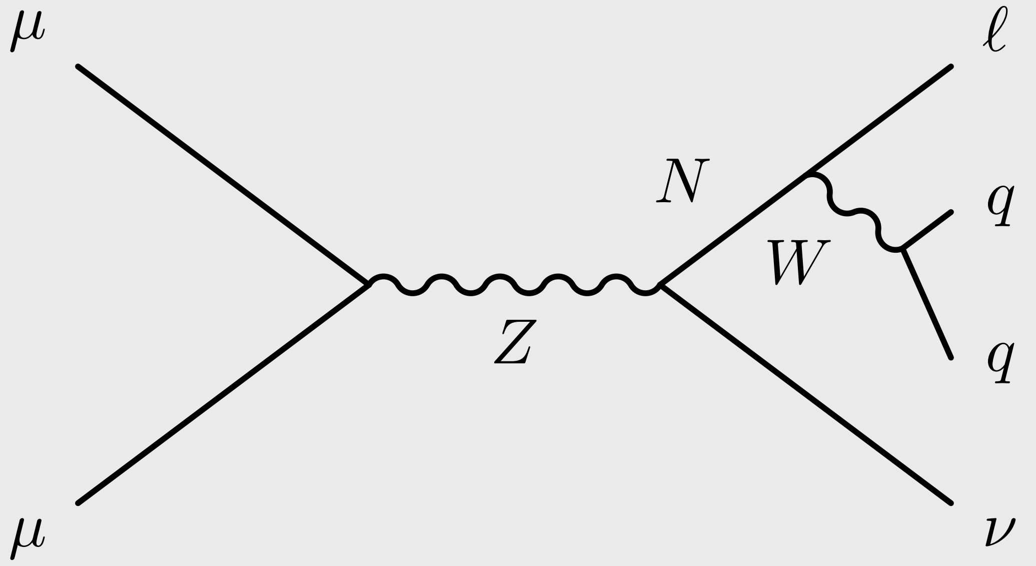

Neutrino masses The "first" kind of see-saw

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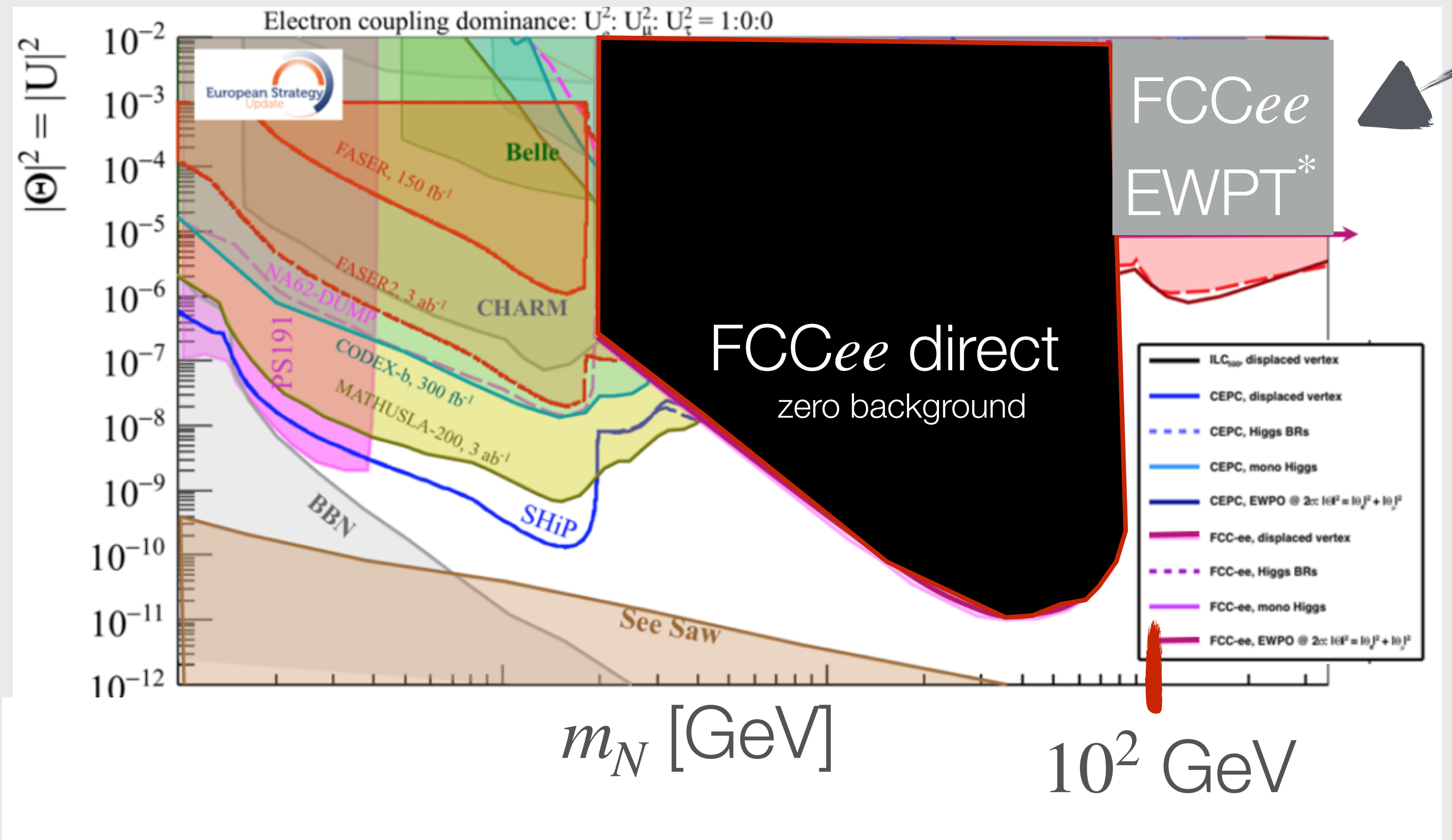

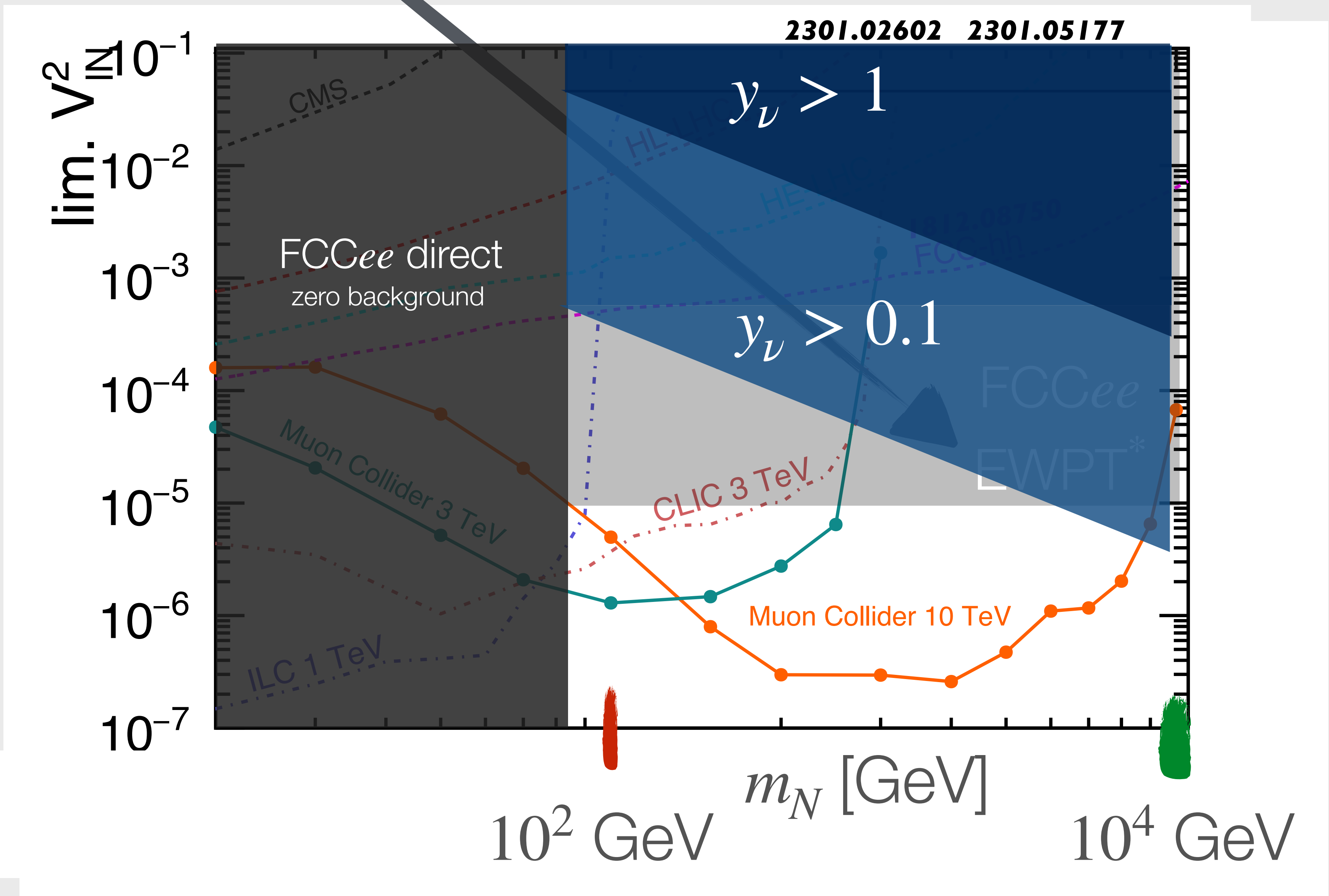

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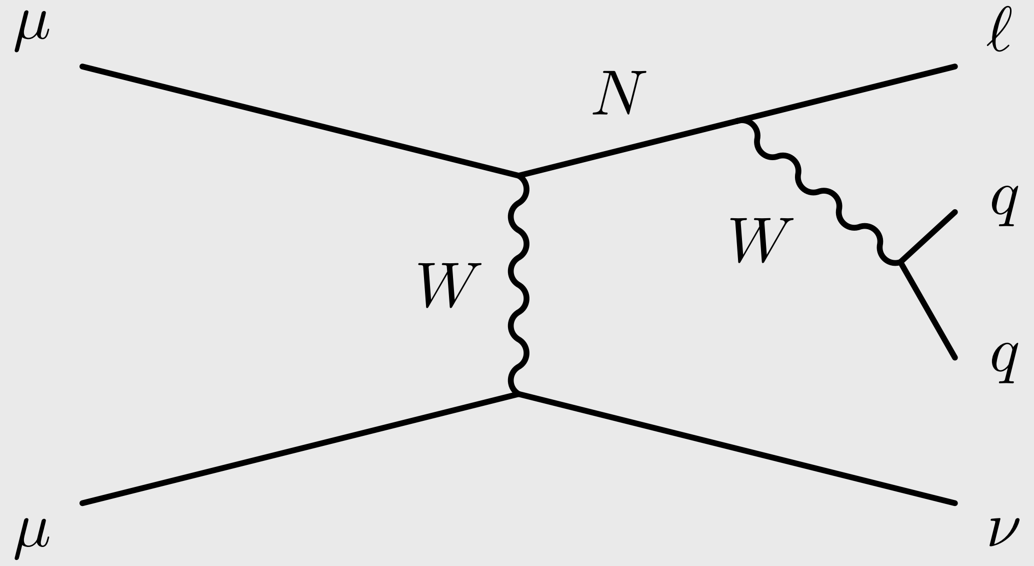

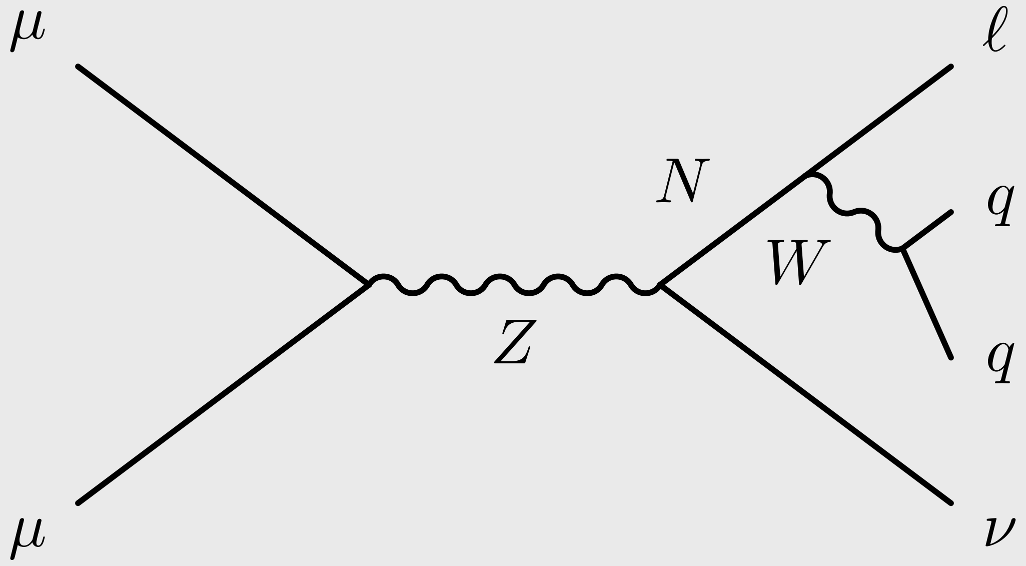

Neutrino masses The “first” kind of see-saw

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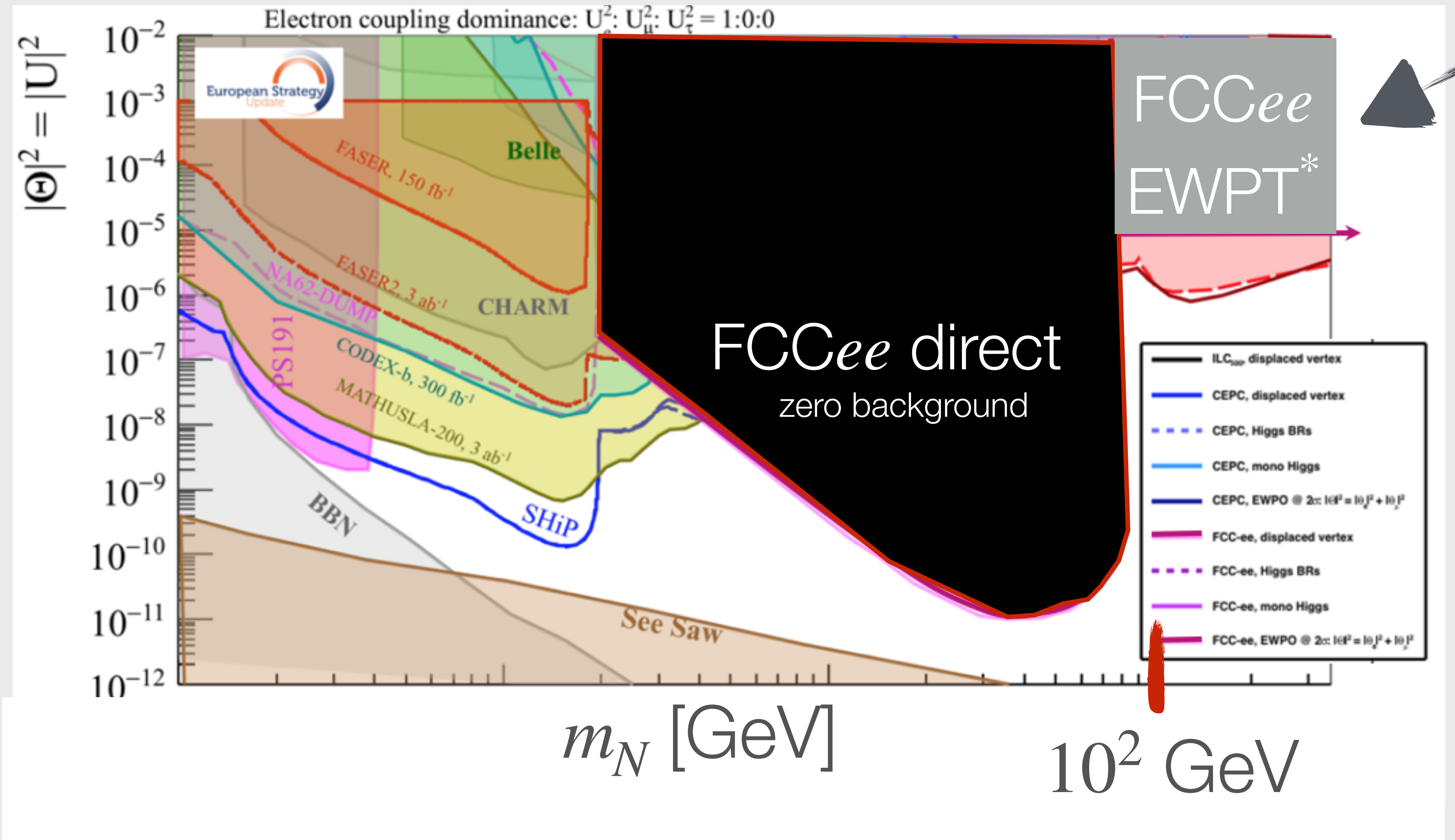

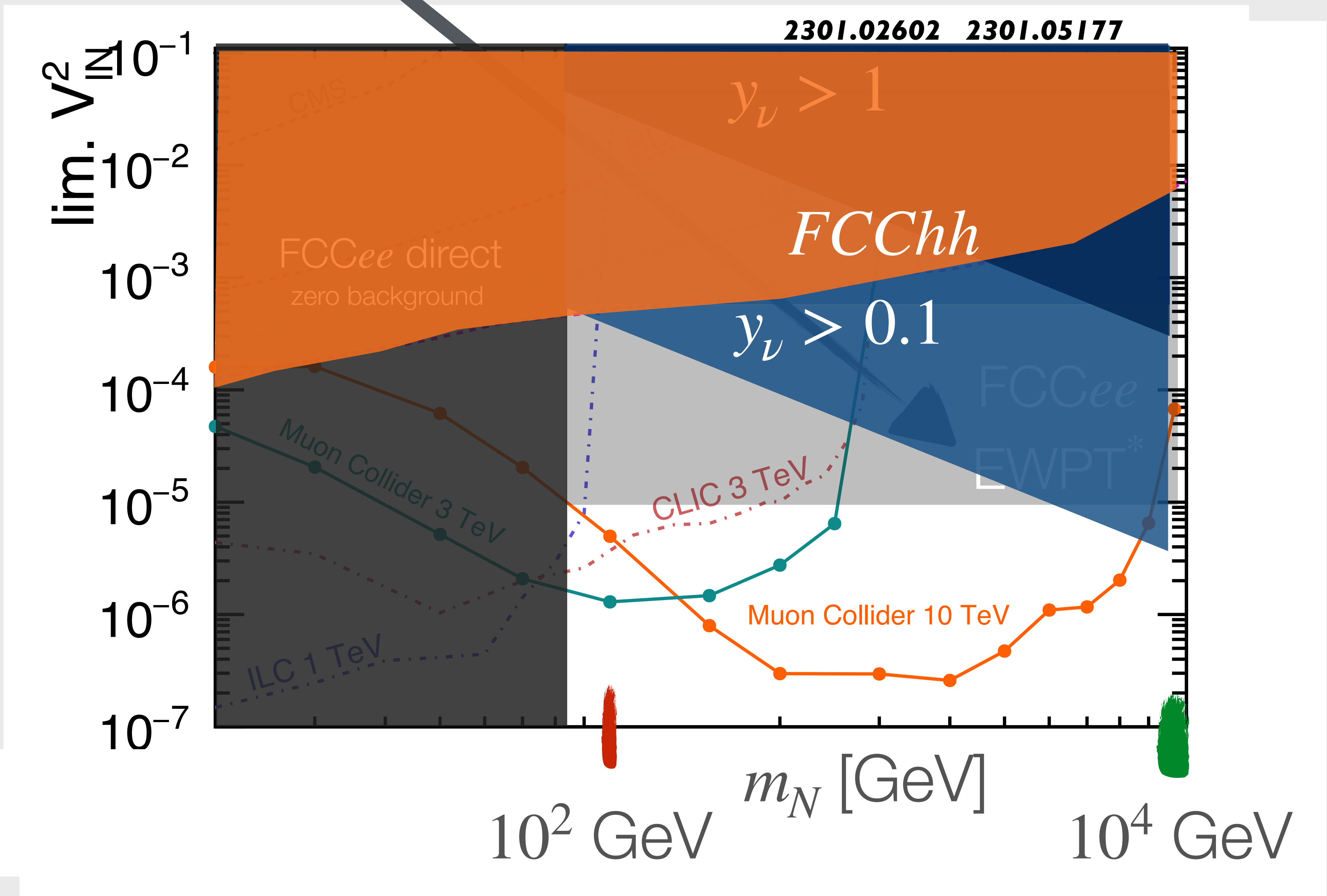

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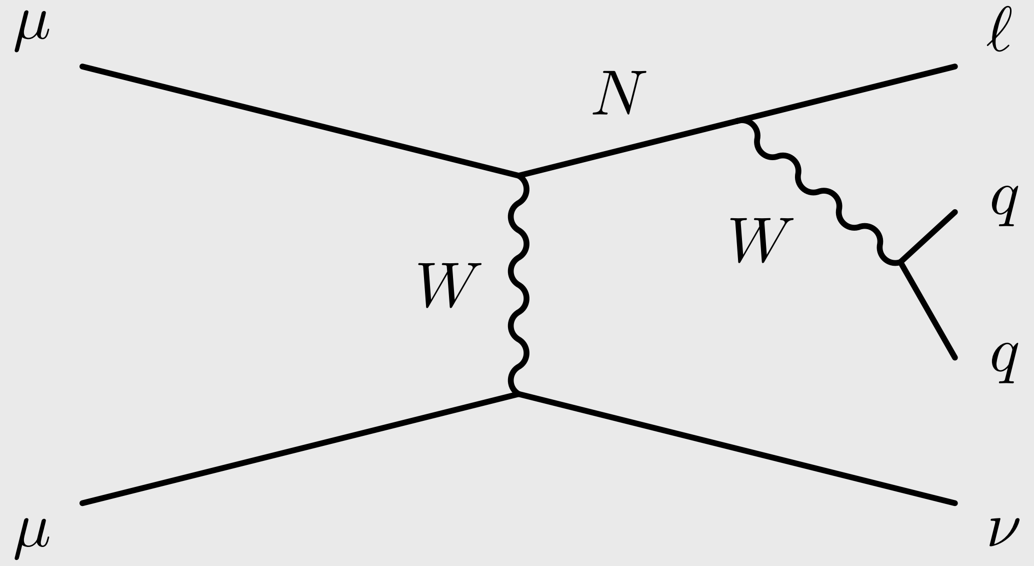

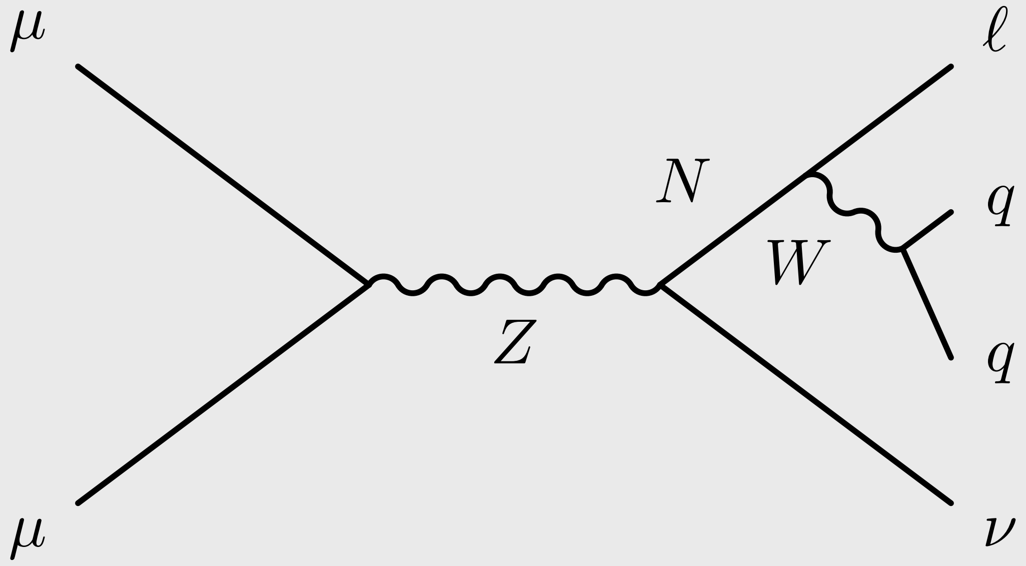

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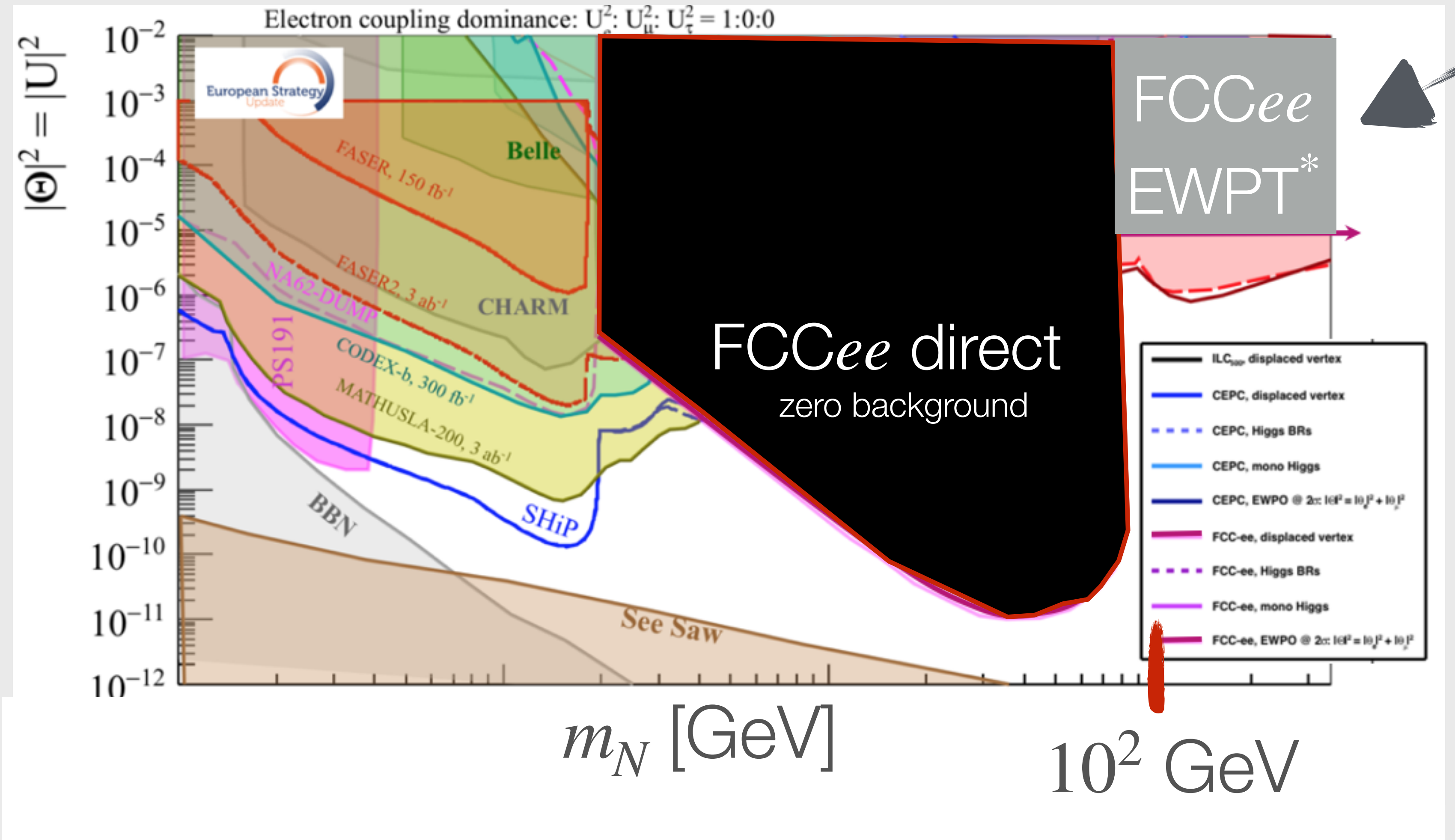

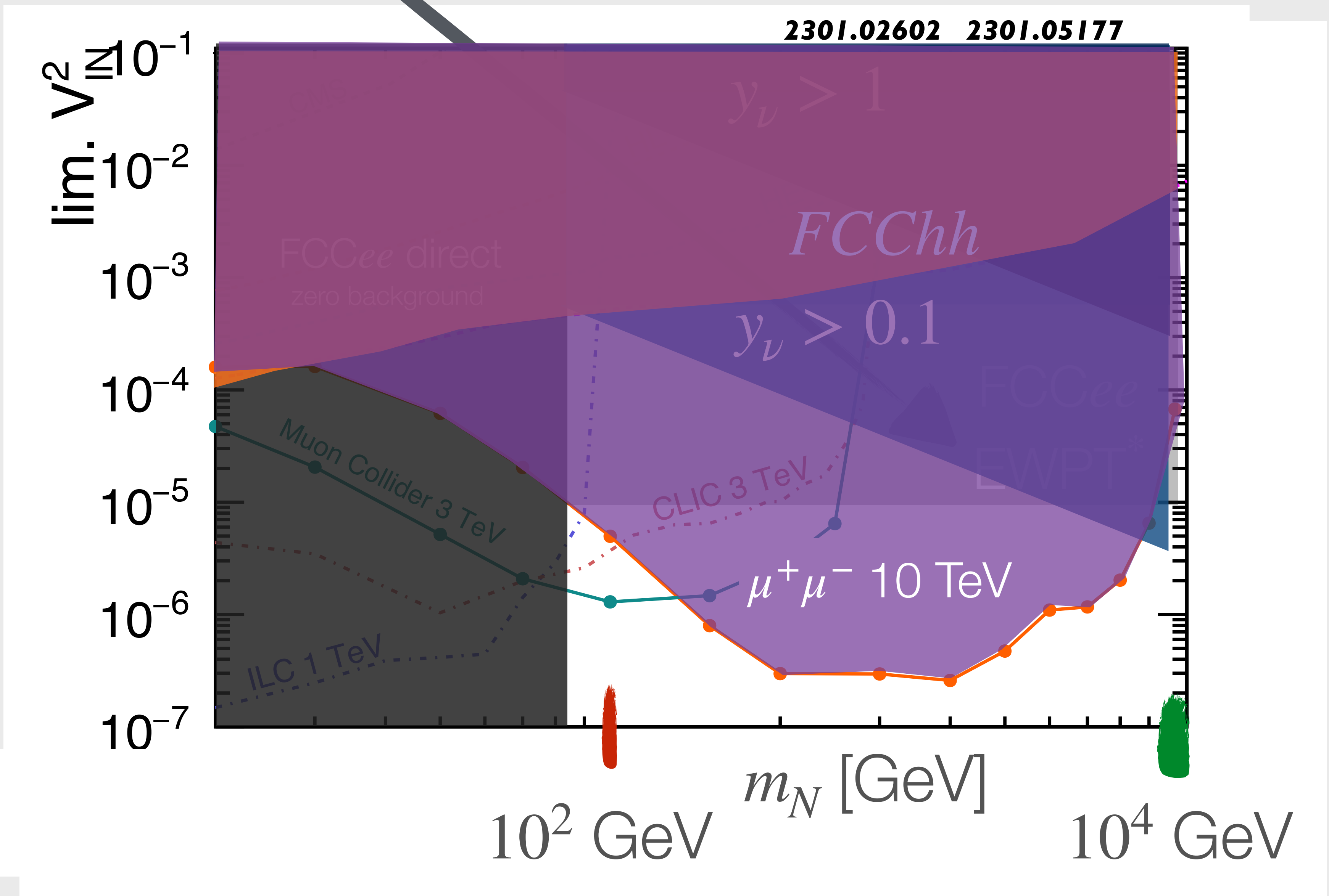

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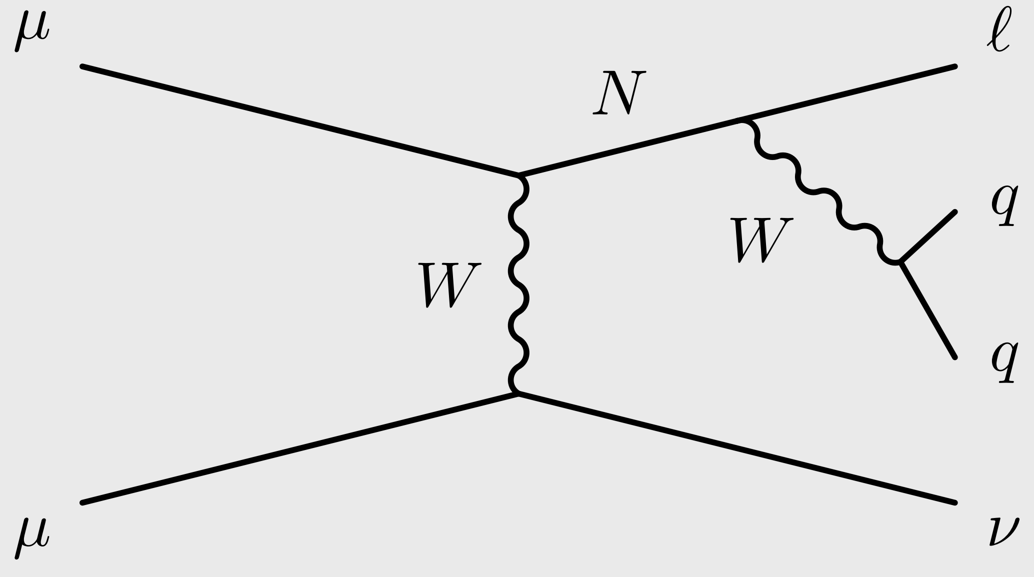
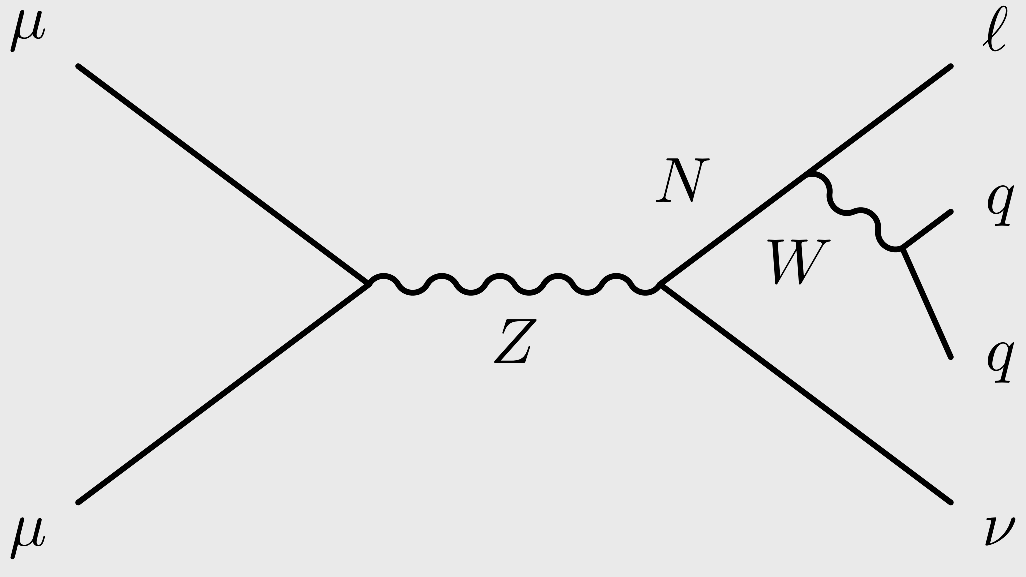
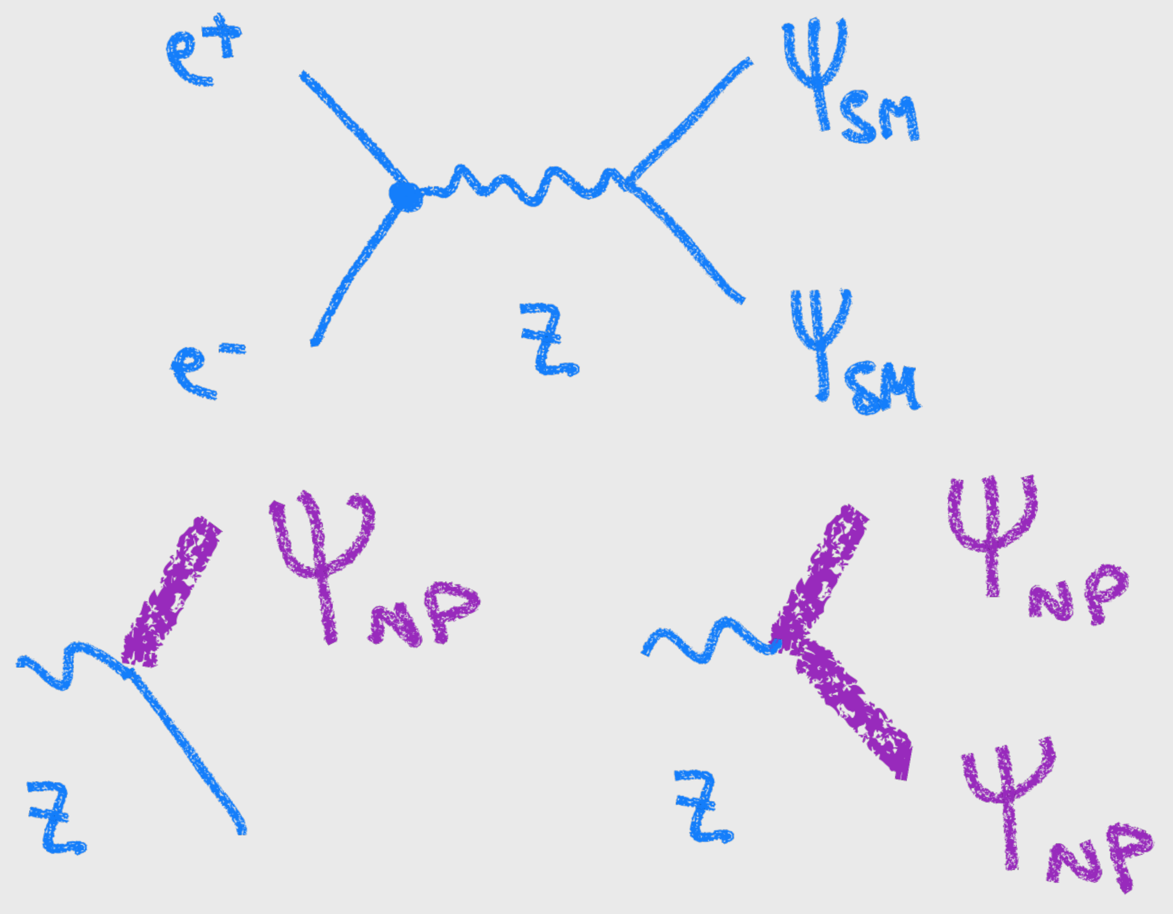


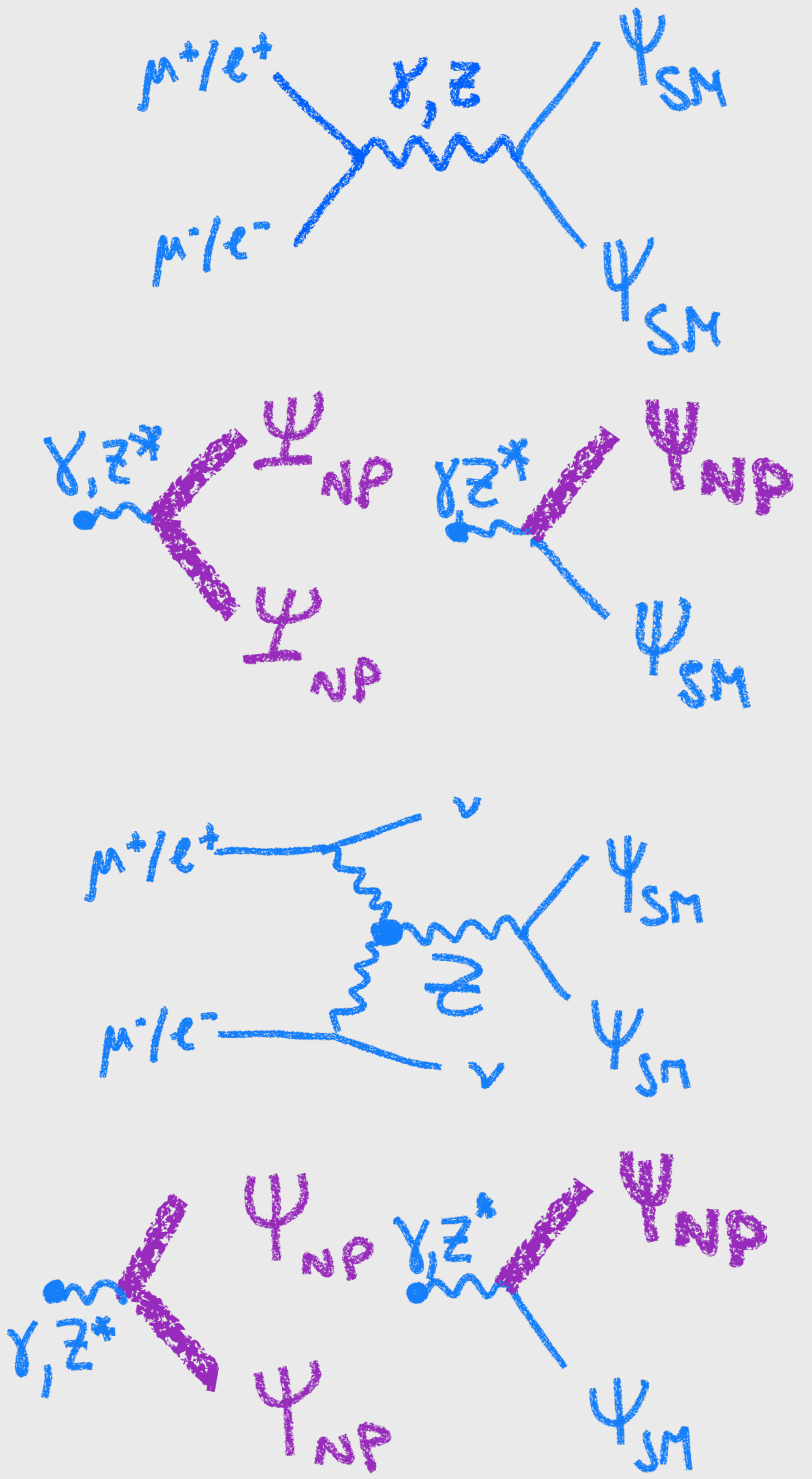


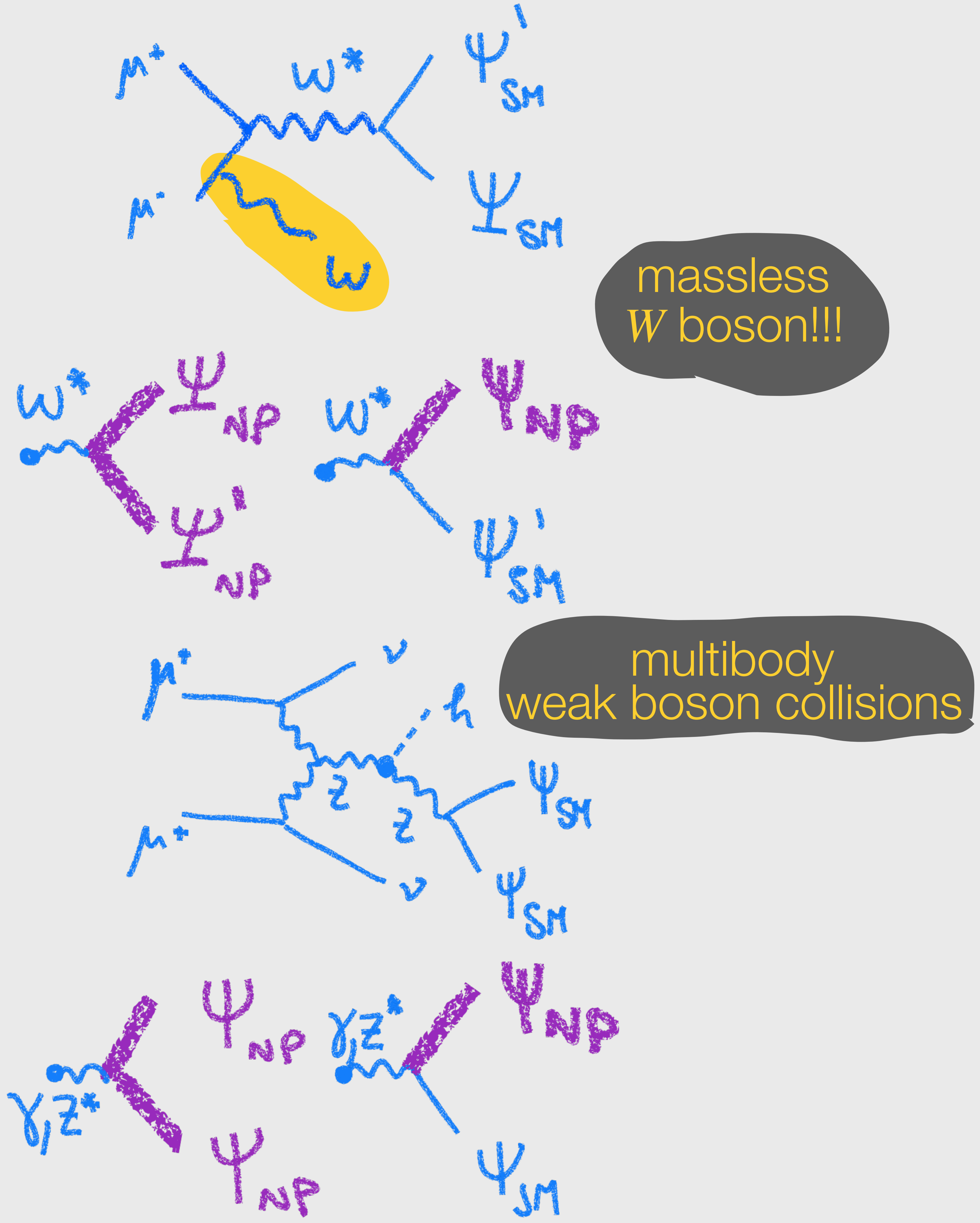
Types of Electroweak factories

LEP style $\sqrt{s} \simeq m_Z$



$\sqrt{s} \gg m_h$ *LHC* style $\sqrt{s} \ggg m_h$





Types of Electroweak factories

LEP style $\sqrt{s} \simeq m_Z$

$\sqrt{s} \gg m_h$ *LHC* style $\sqrt{s} \ggg m_h$

- The *LEP* style Electroweak factory can probe light new physics up to very weak couplings

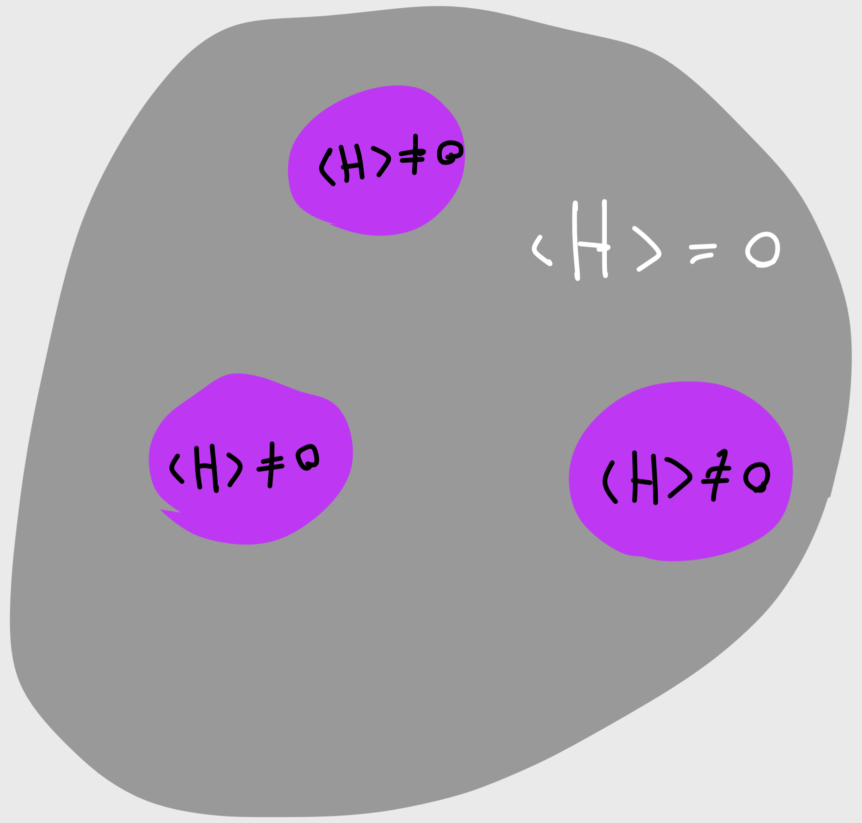
- The *LHC* style of Electroweak factory can probe heavy new physics plus study "new electroweak physics": the unprecedented "massless *W* bosons"

A couple of problems on which we might see the “bottom line”

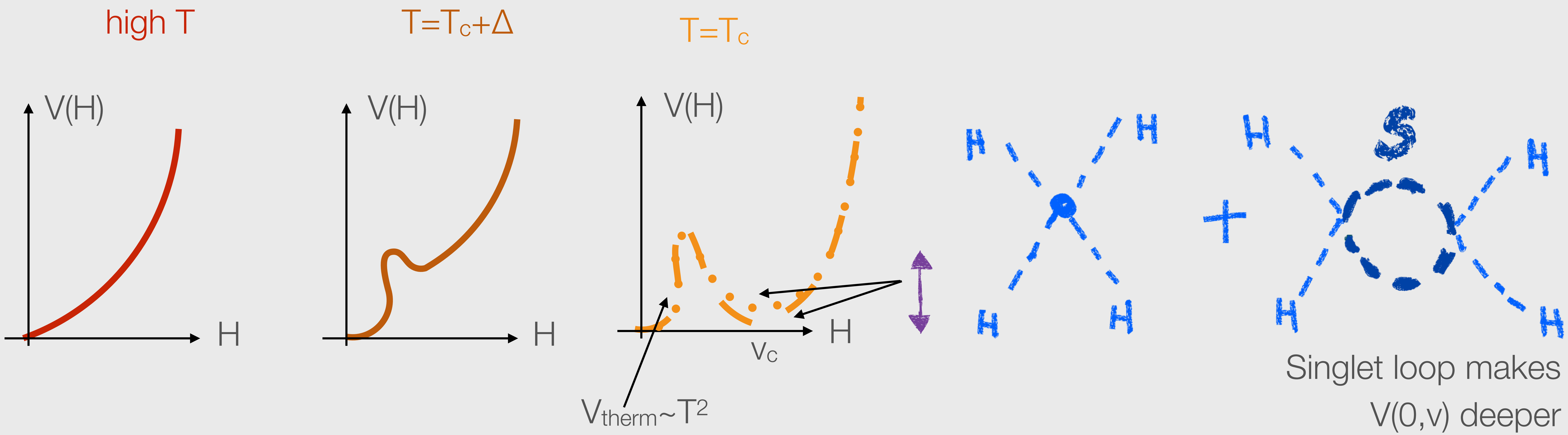
EW phase transition

Was the electroweak symmetry broken abruptly in the early universe?

Electroweak phase transition

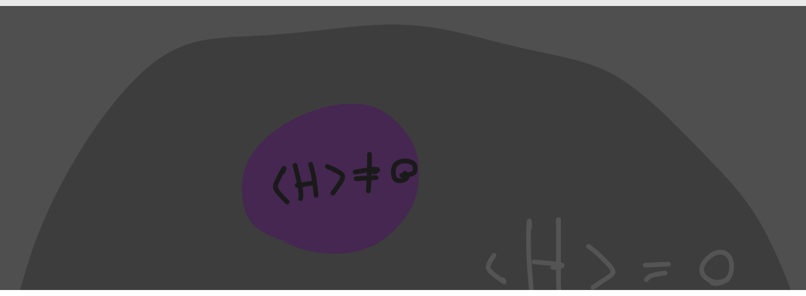


- Modifications of the Higgs potential ⇒ Out of Equilibrium transition from one vacuum to a new energetically favorable one



Singlet loop makes
V(0,v) deeper

Electroweak phase transition



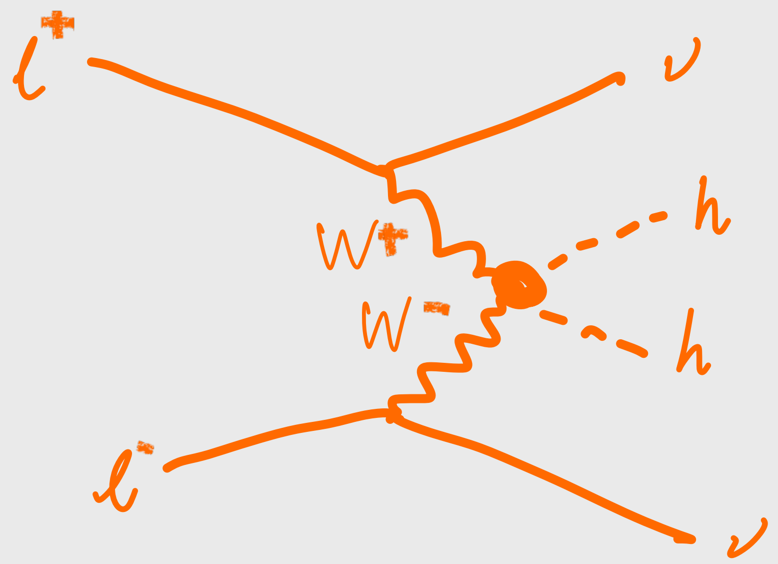
- We need to study all possible new states that induce a change in the Higgs boson potential.
- For these new state to have sizable effects in the early Universe they must be light, around 1 TeV at most.
- All searches for new Higgs bosons (or general electroweak particles) probe such fundamental issue of the origin of matter in the early Universe!

$V_{therm} \sim T^2$

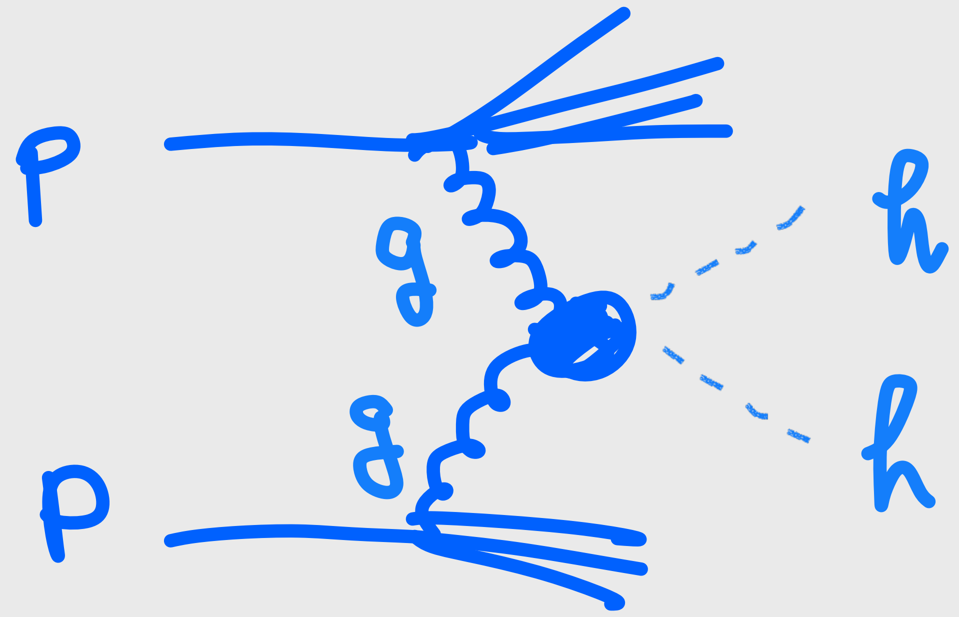
V(0,v) deeper

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

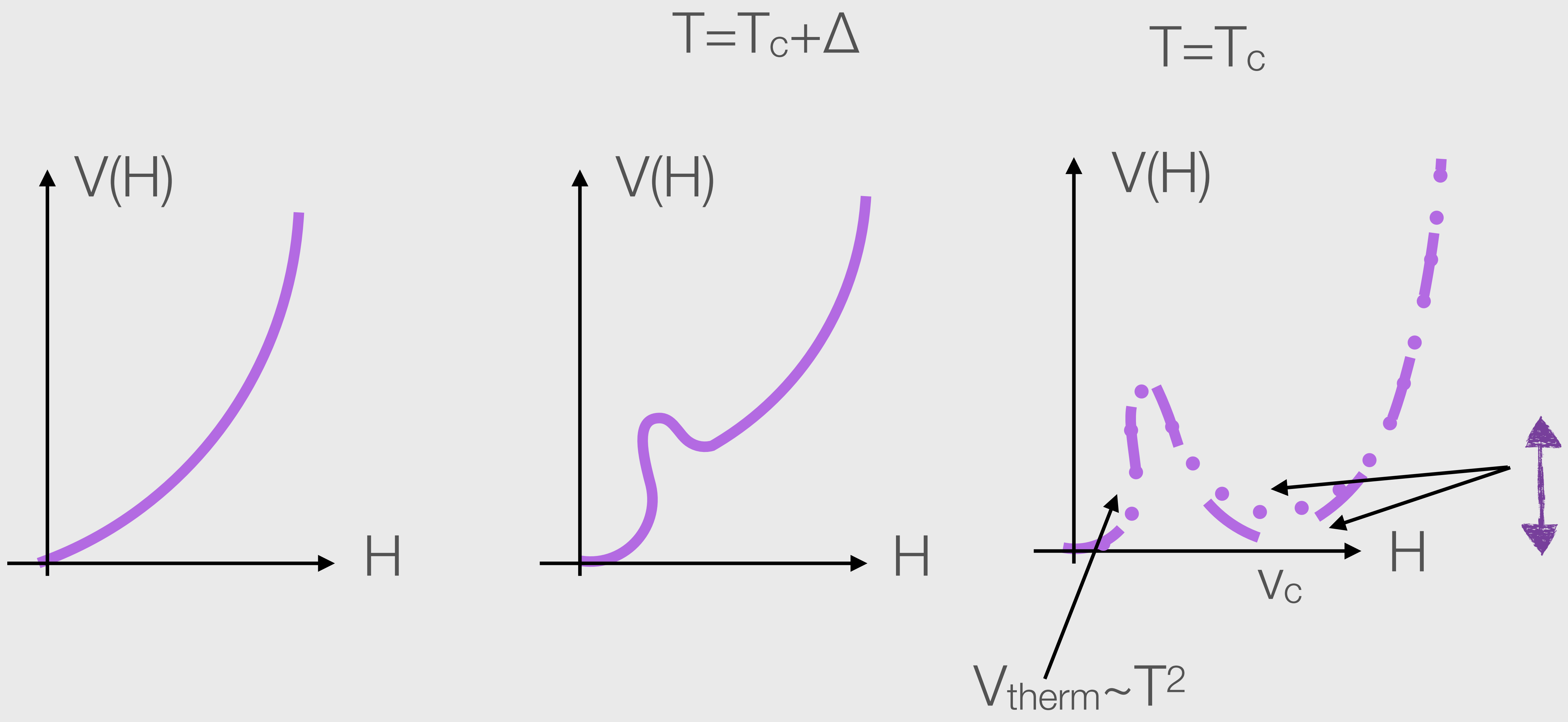
- High-Energy lepton collider has large flux of “partonic” W bosons

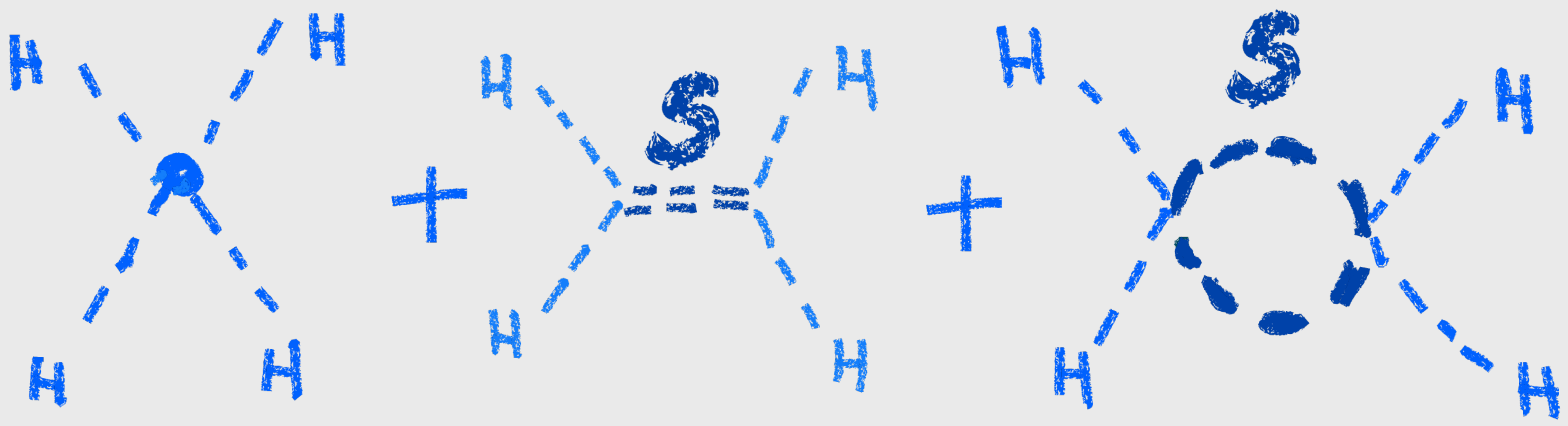


- gg collisions as usual



Electroweak phase transition





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

EW phase transition

DIRECT & INDIRECT | INTERPLAY

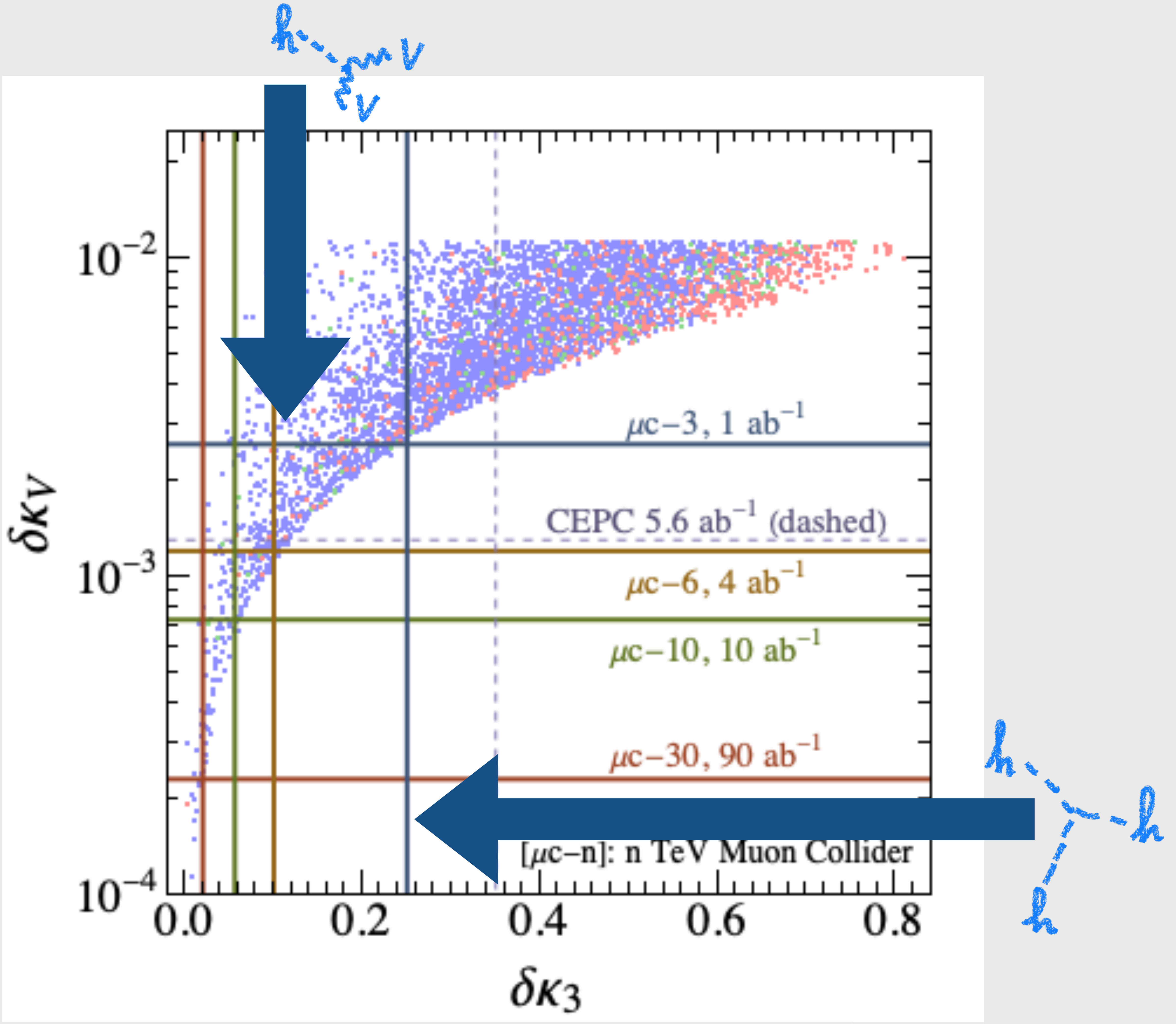
strong First Order EW phase transition on all points

Gravity Wave SNR

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

independent parameters

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



EW phase transition

DIRECT & INDIRECT

INTERPLAY

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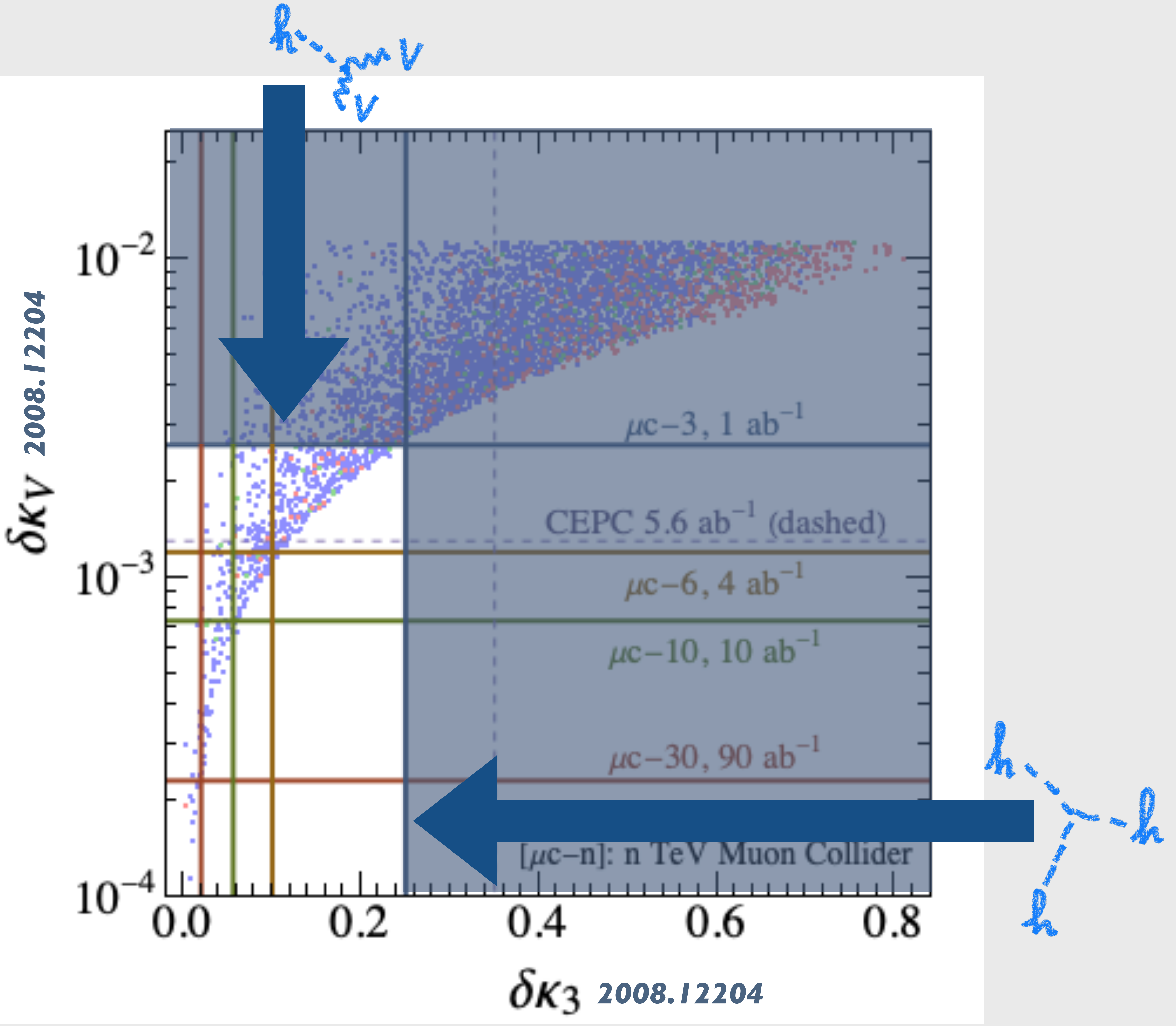
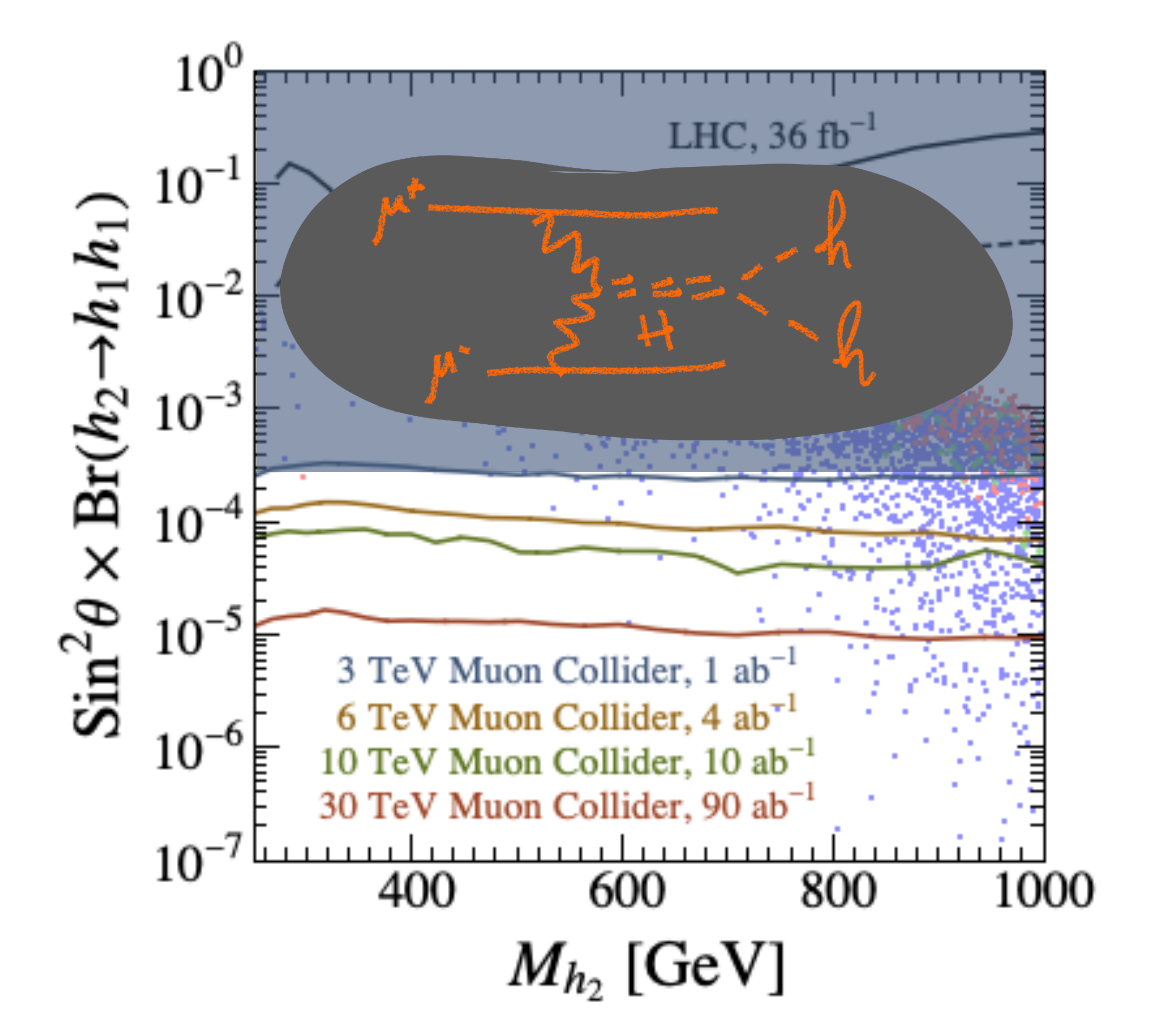
strong First Order EW phase transition on all points

Gravity Wave SNR



EW phase transition

DIRECT & INDIRECT INTERPLAY



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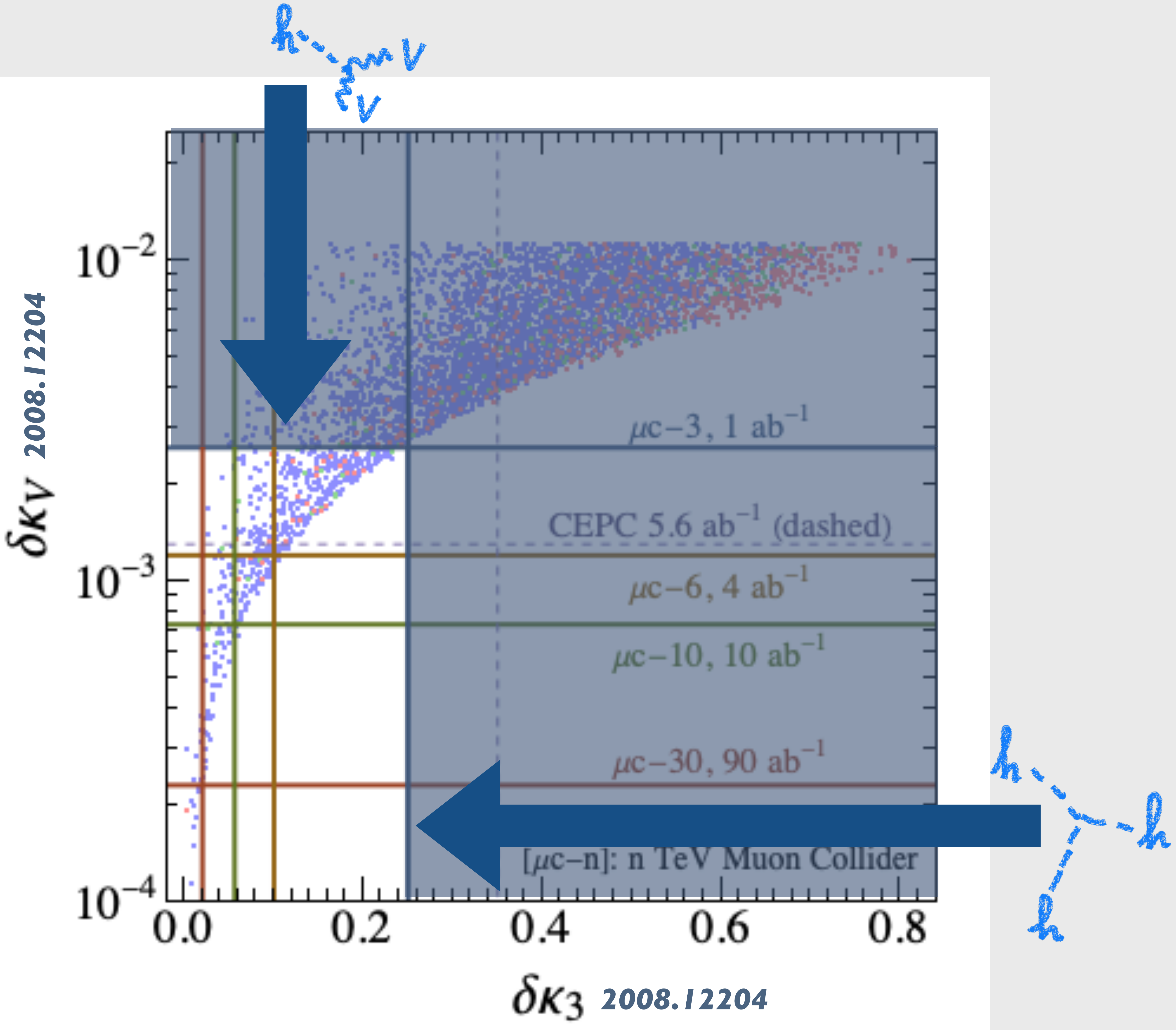
Gravity Wave SNR

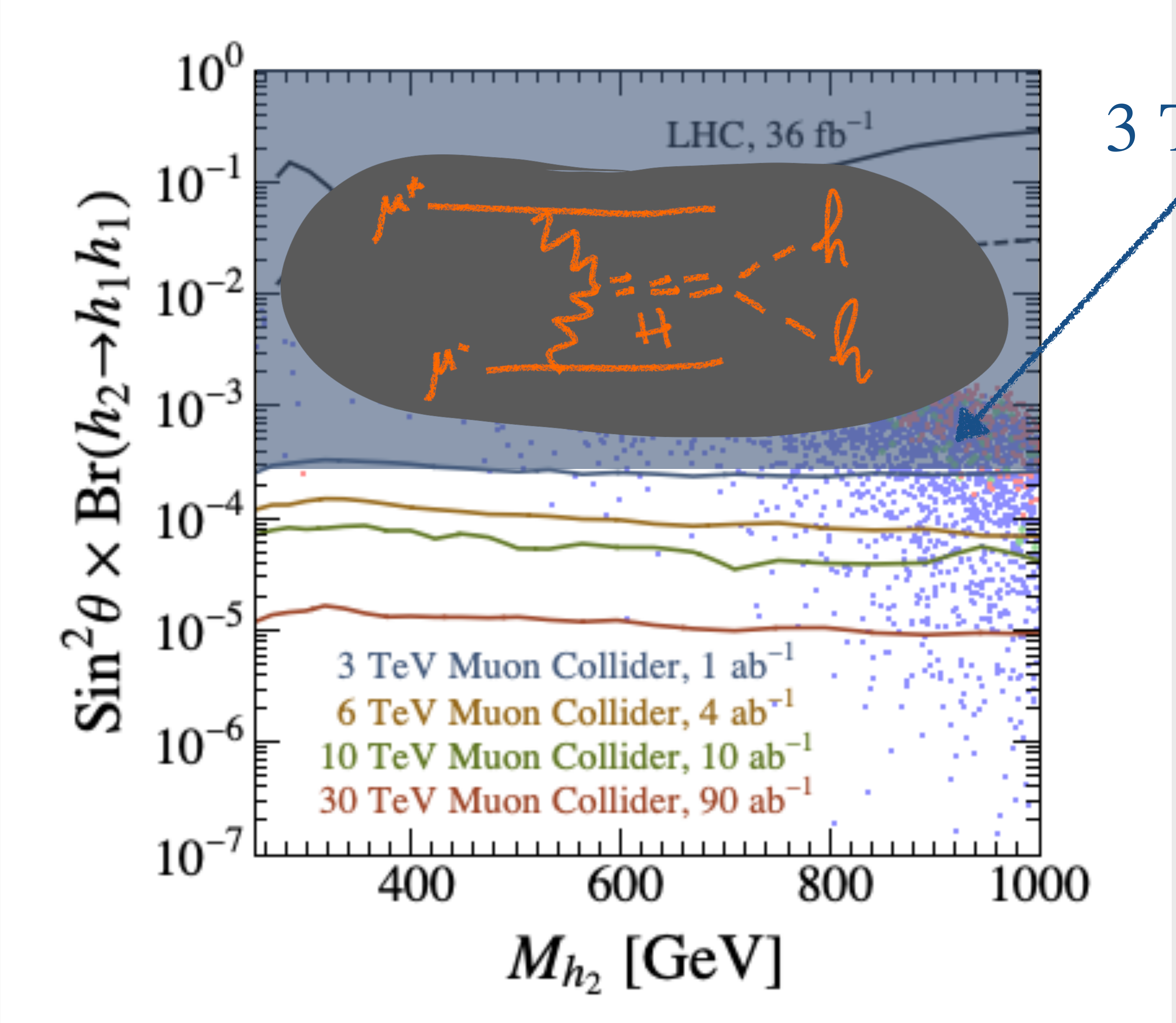


EW phase transition

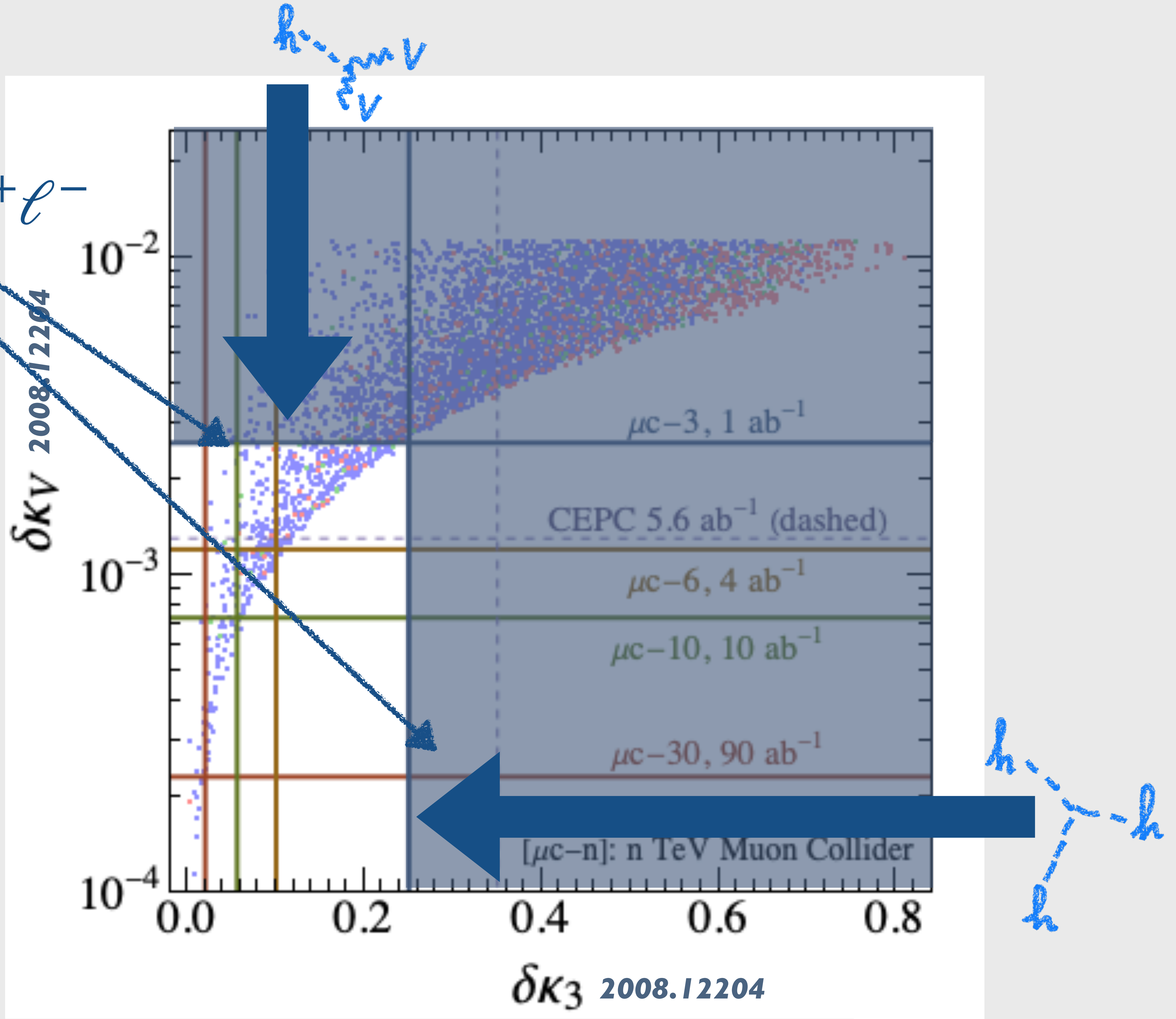
DIRECT & INDIRECT | INTERPLAY

strong First Order EW phase transition on all points

→ Gravity Wave SNR



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

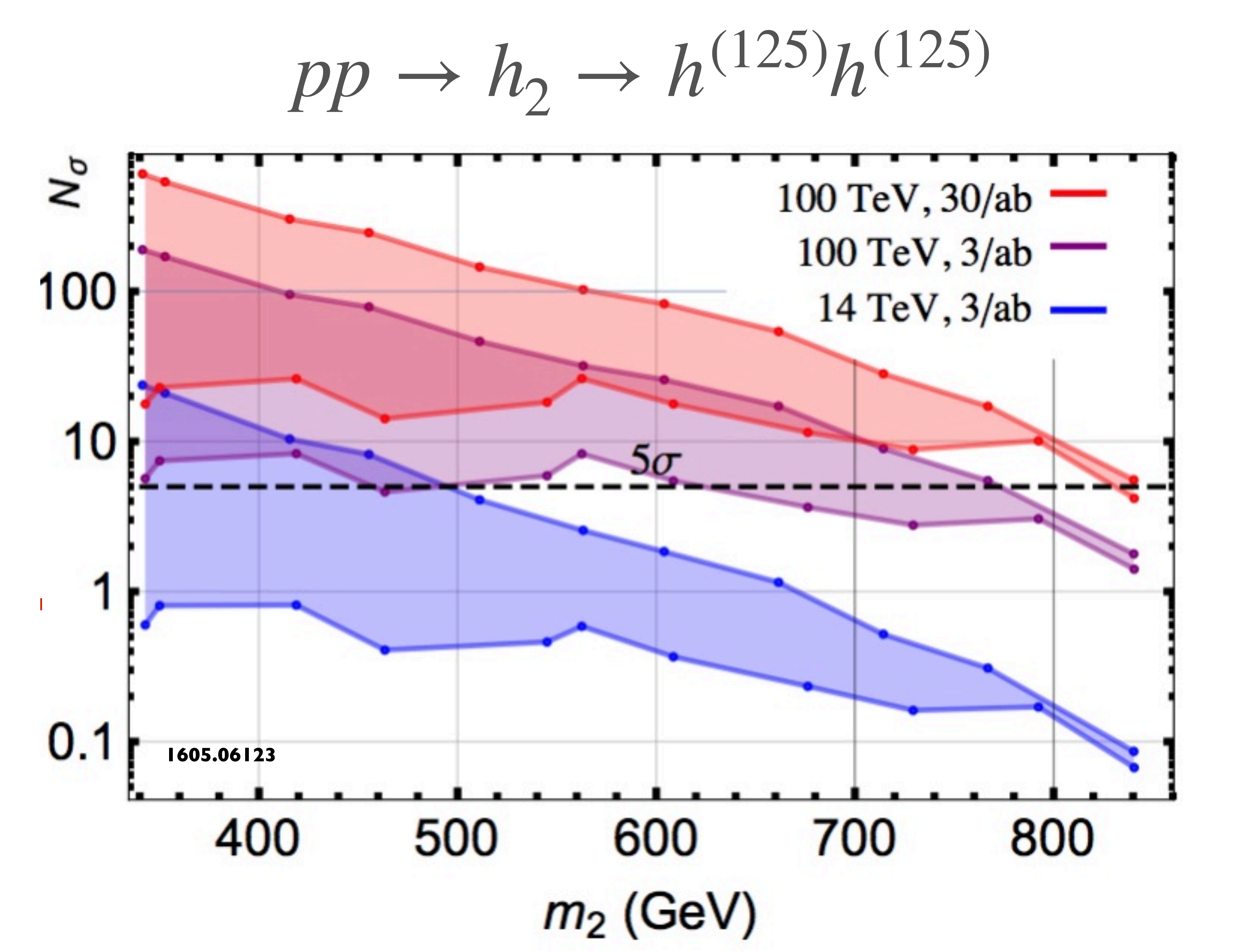


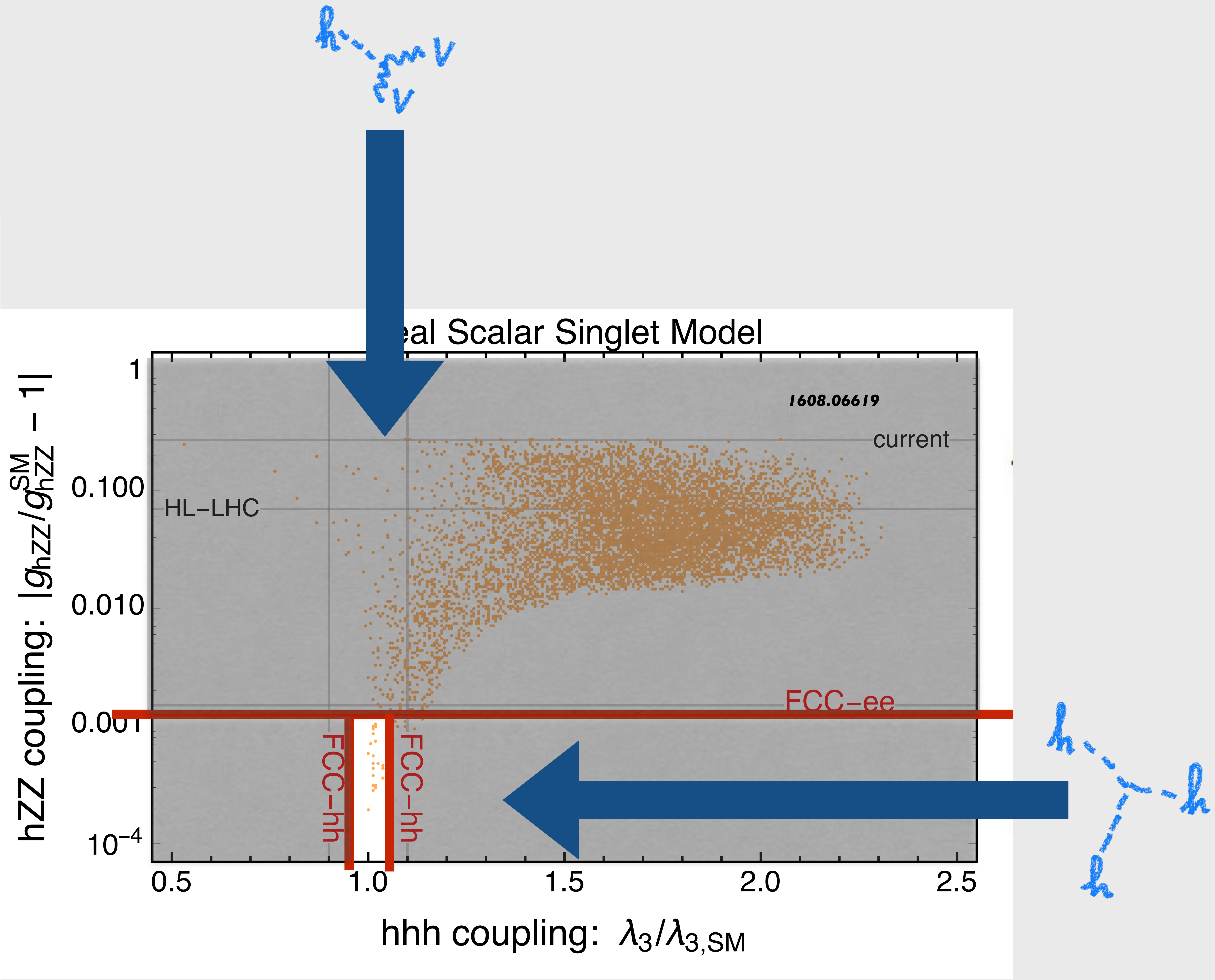
parameters space of 1st order phase transition accessible by **several measurements available at the 3 TeV $\ell^+\ell^-$ collider**

EW phase transition

DIRECT & INDIRECT

INTERPLAY



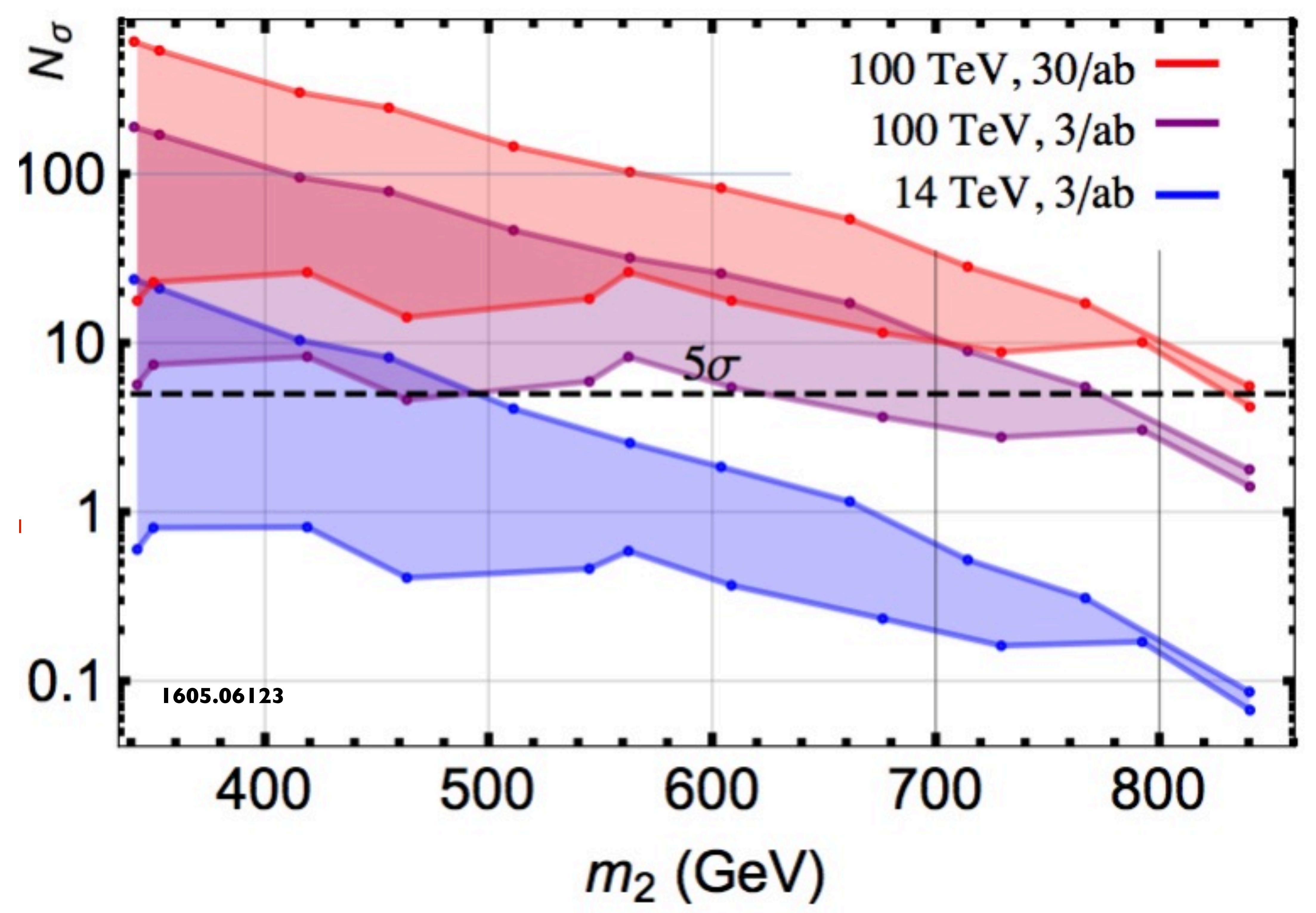


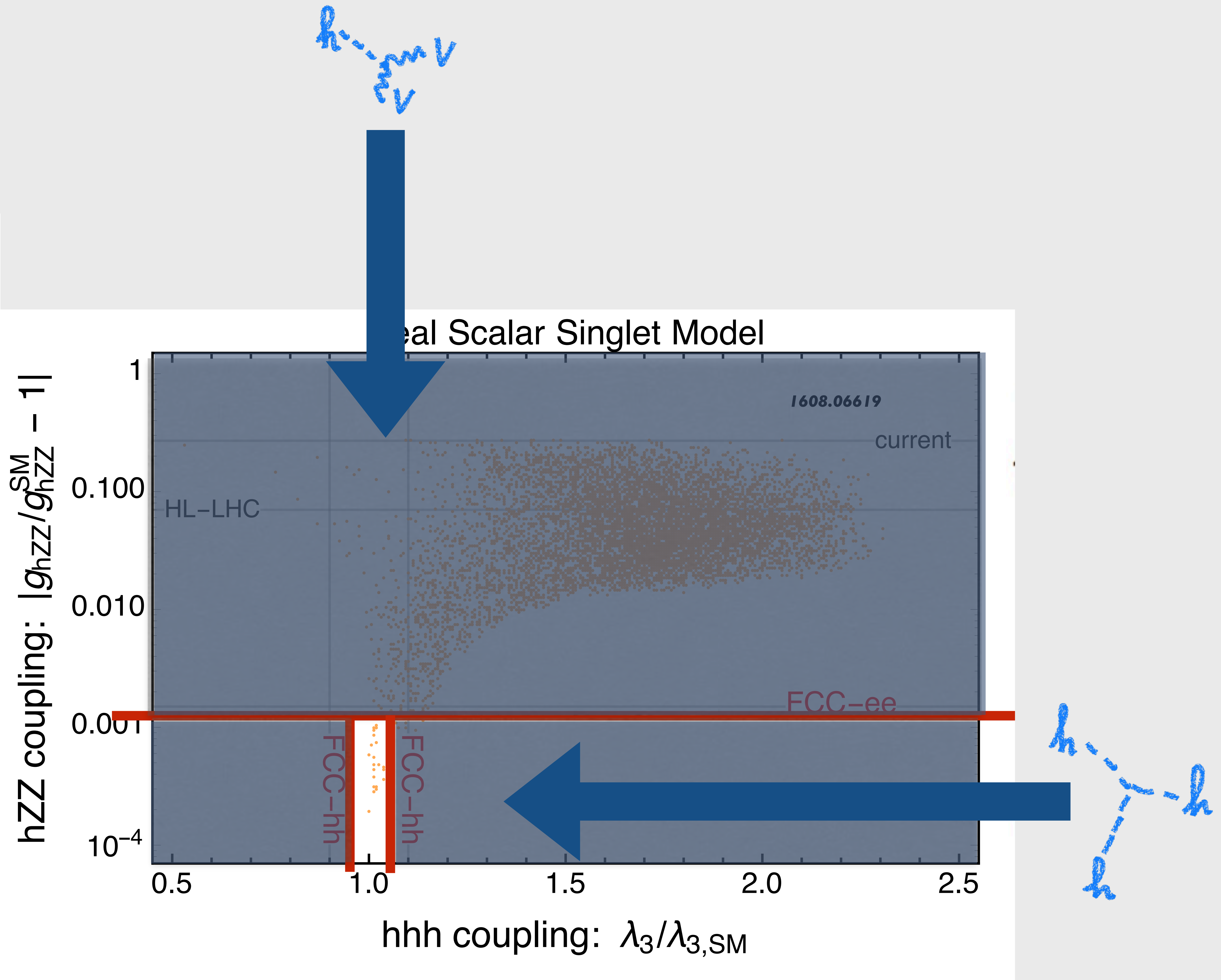
EW phase transition

DIRECT & INDIRECT

INTERPLAY

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

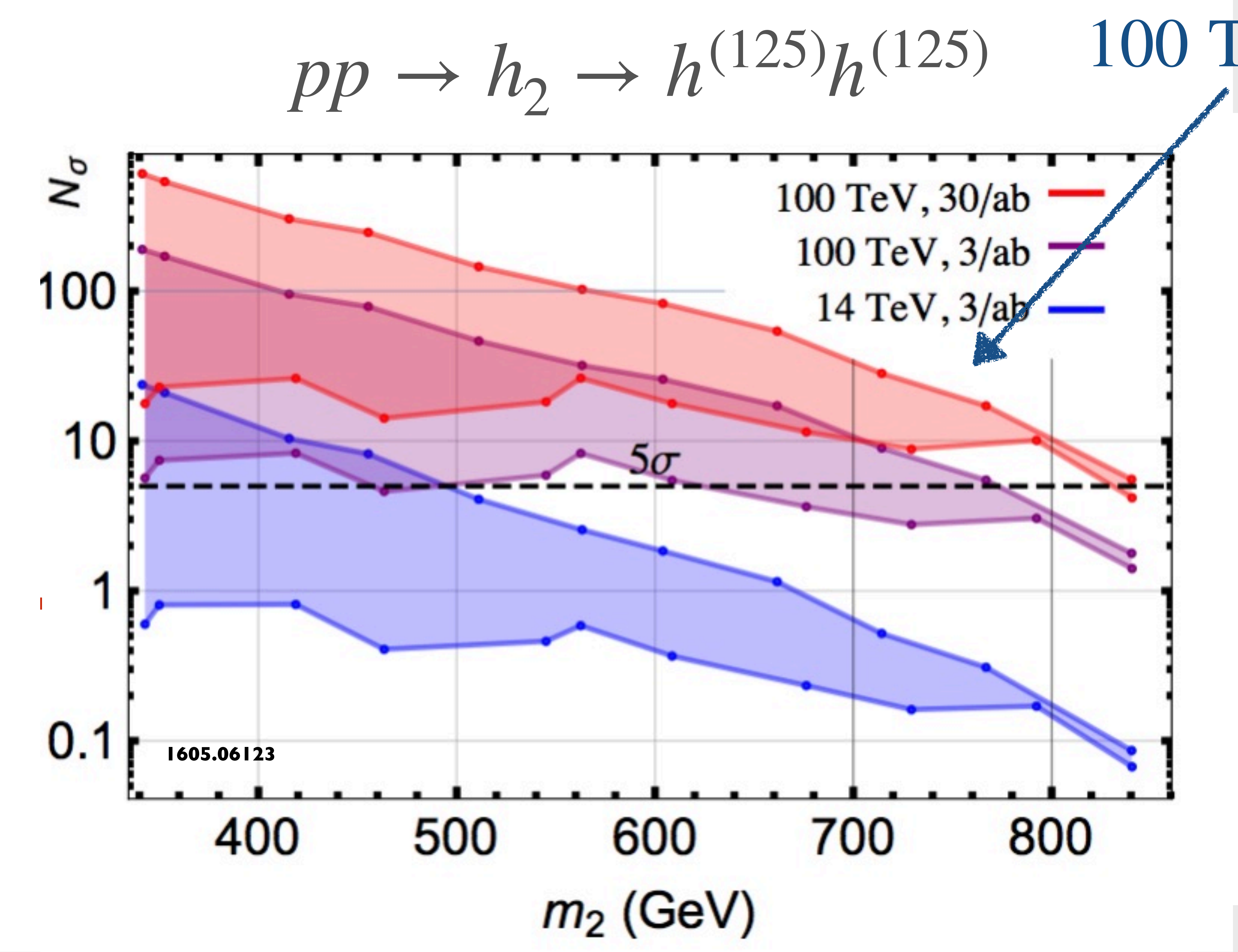


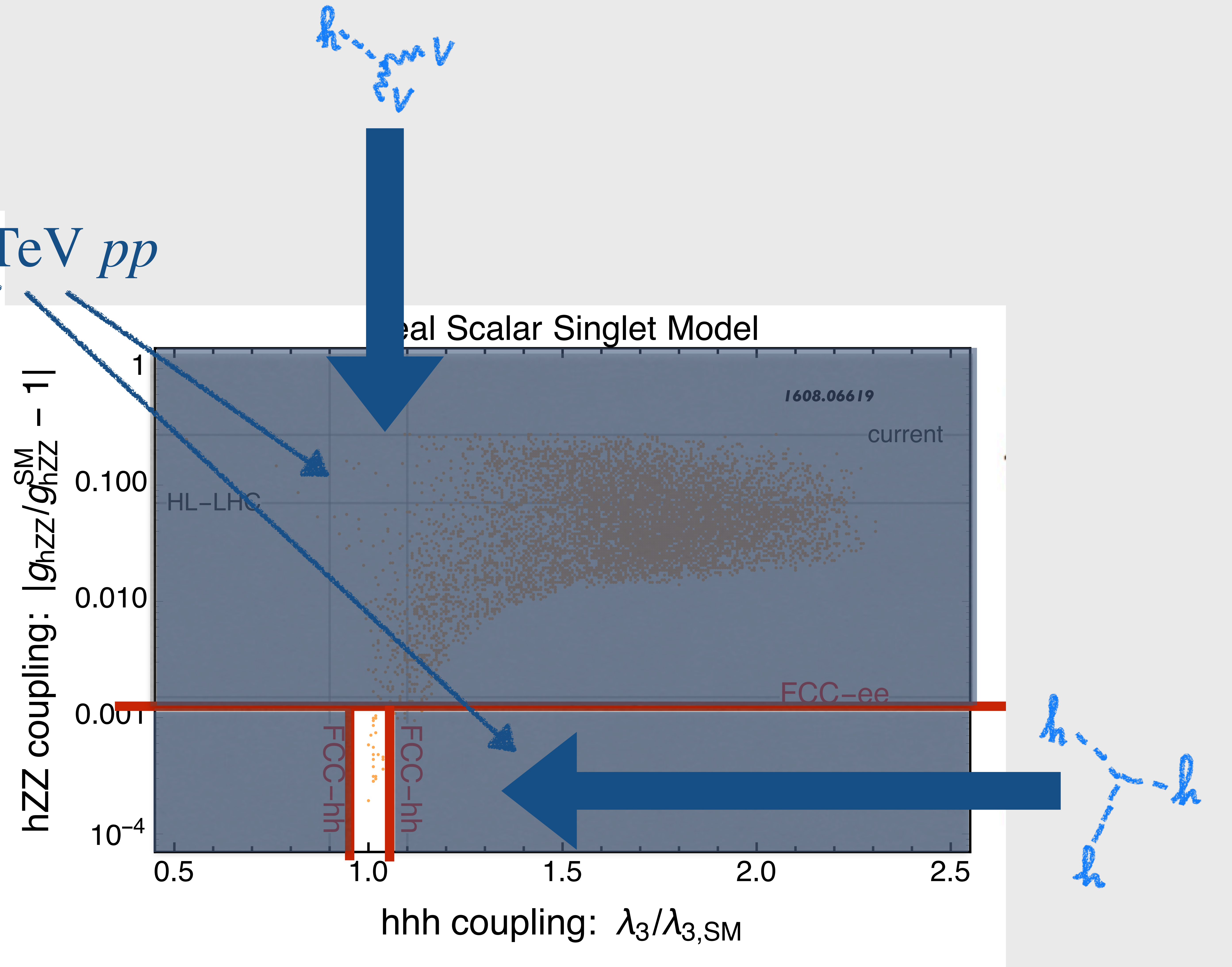


EW phase transition

DIRECT & INDIRECT

INTERPLAY





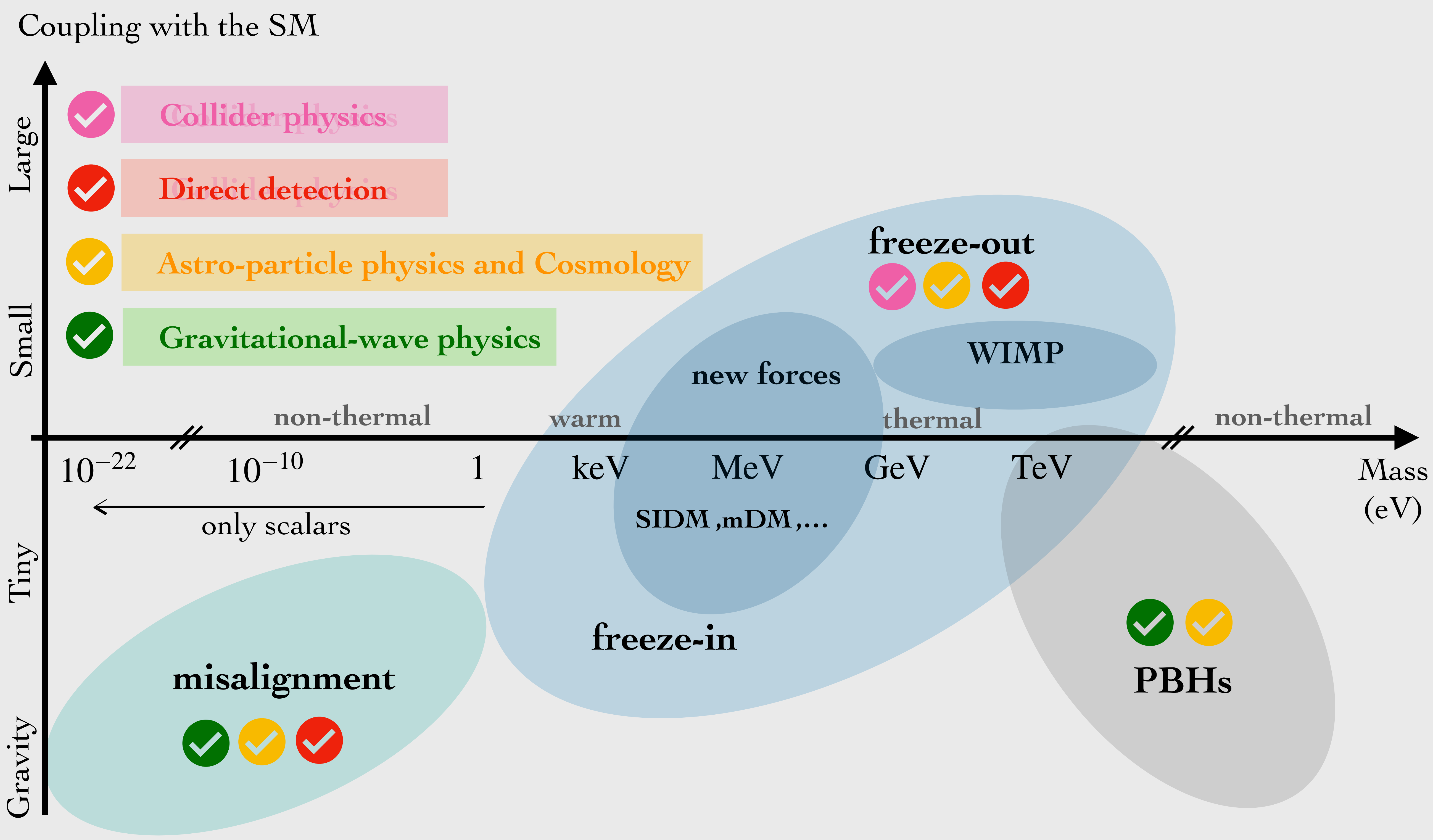
parameters space of 1st order phase transition accessible by **several measurements available at the 100 TeV pp collider**

Dark Matter at the weak scale

Can we ever conclusively probe it?

Electroweak Dark Matter: LSP (+NLSP)

- The chessboard of DM is very large!



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

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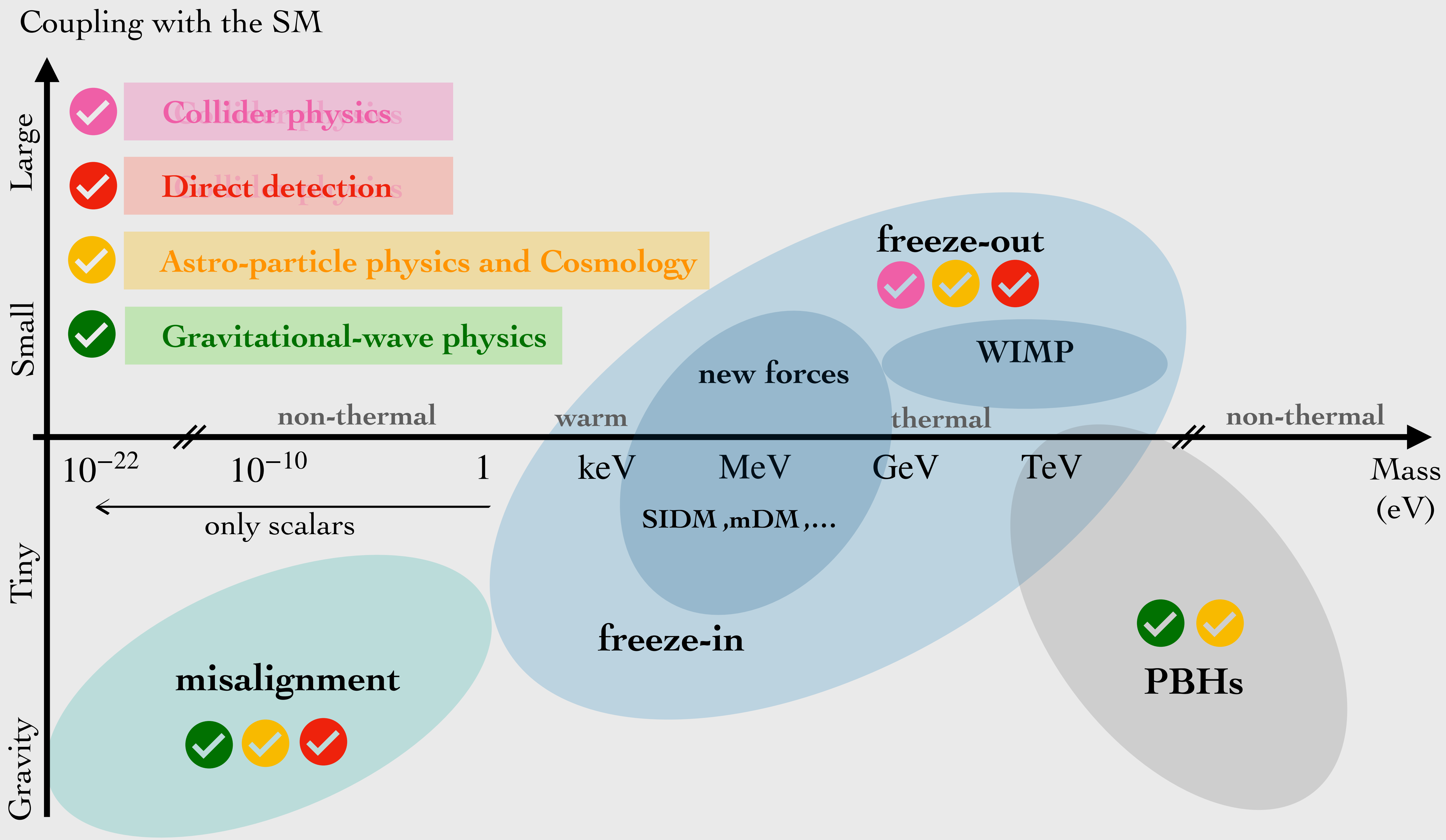

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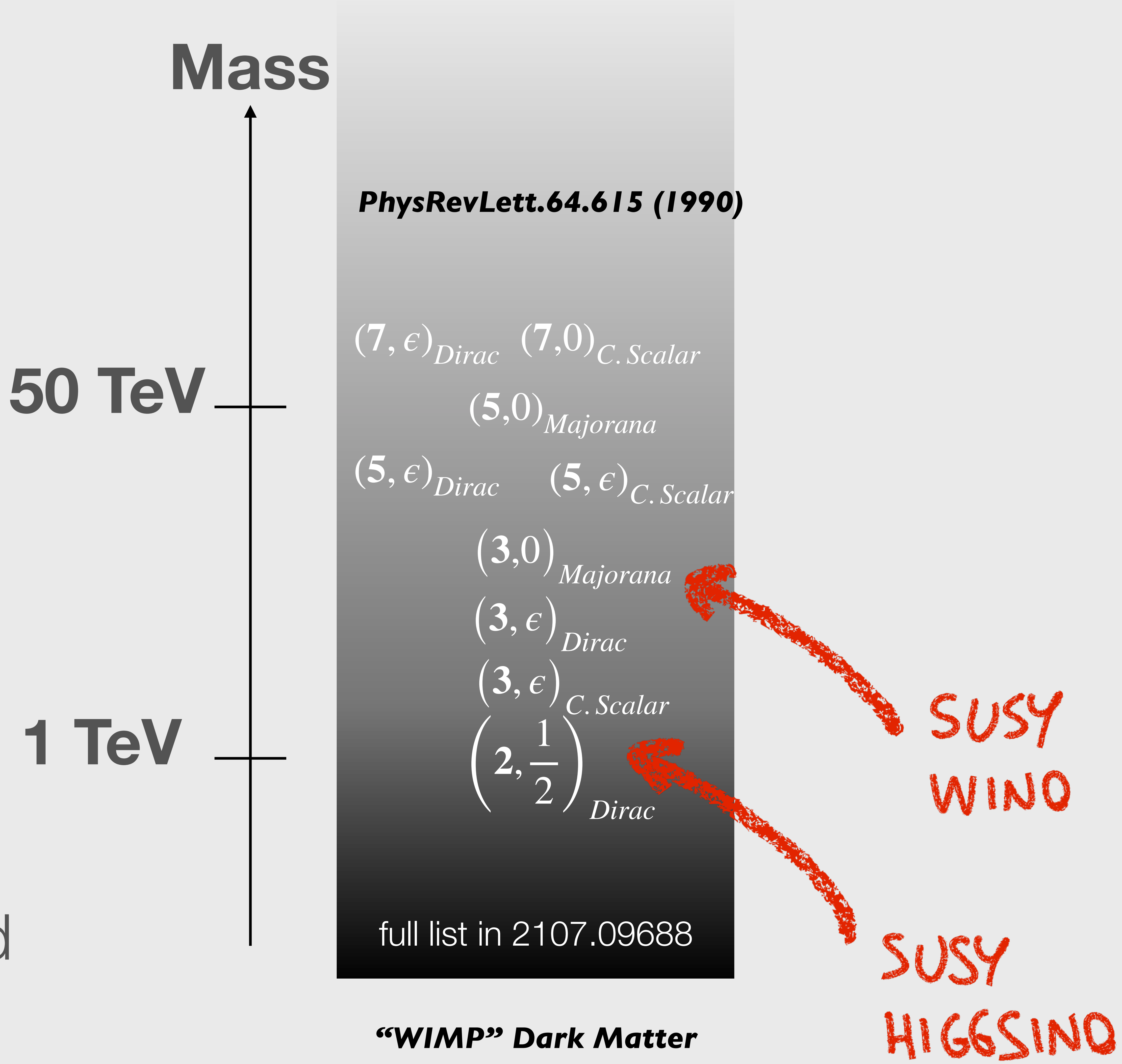

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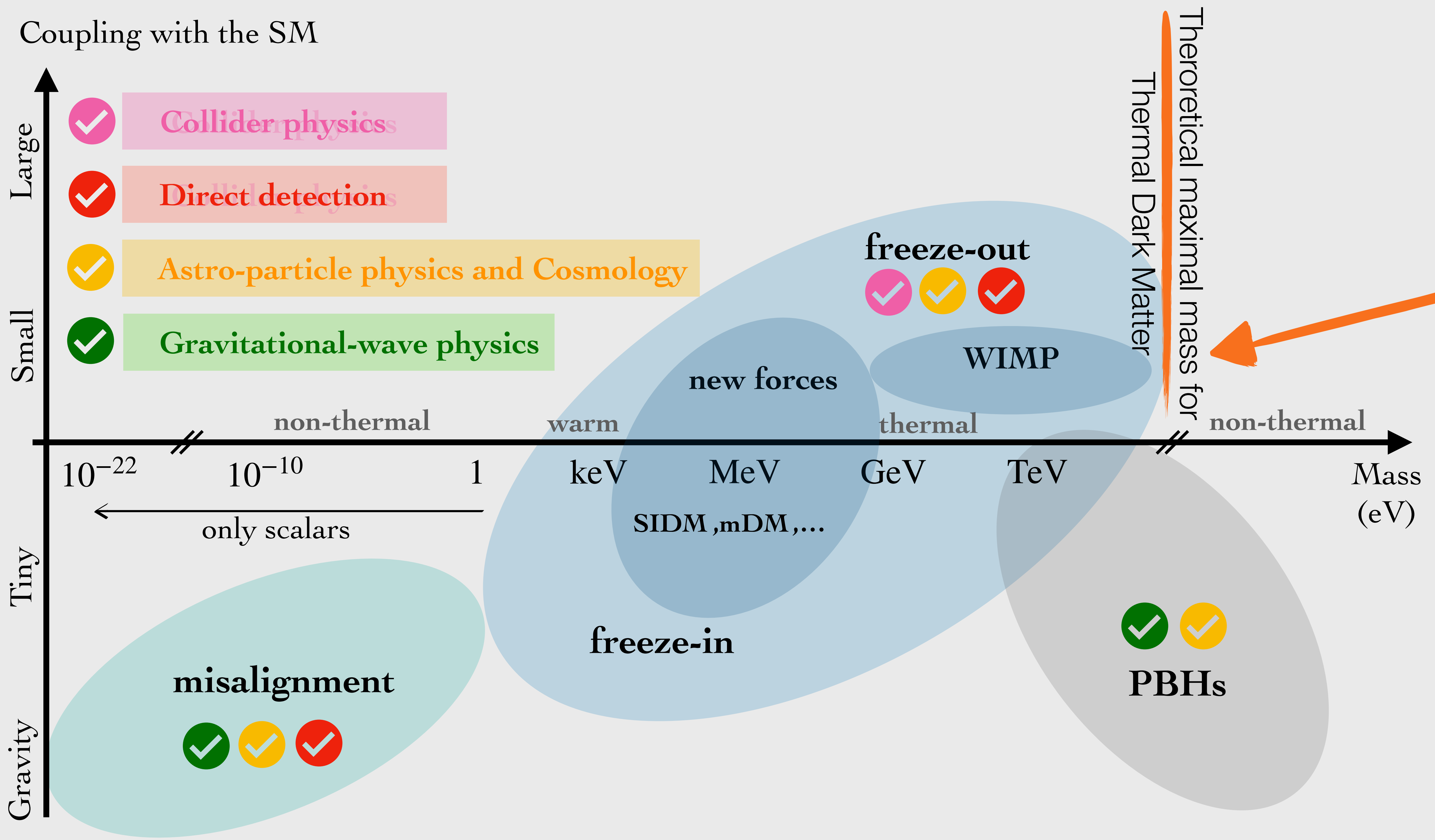

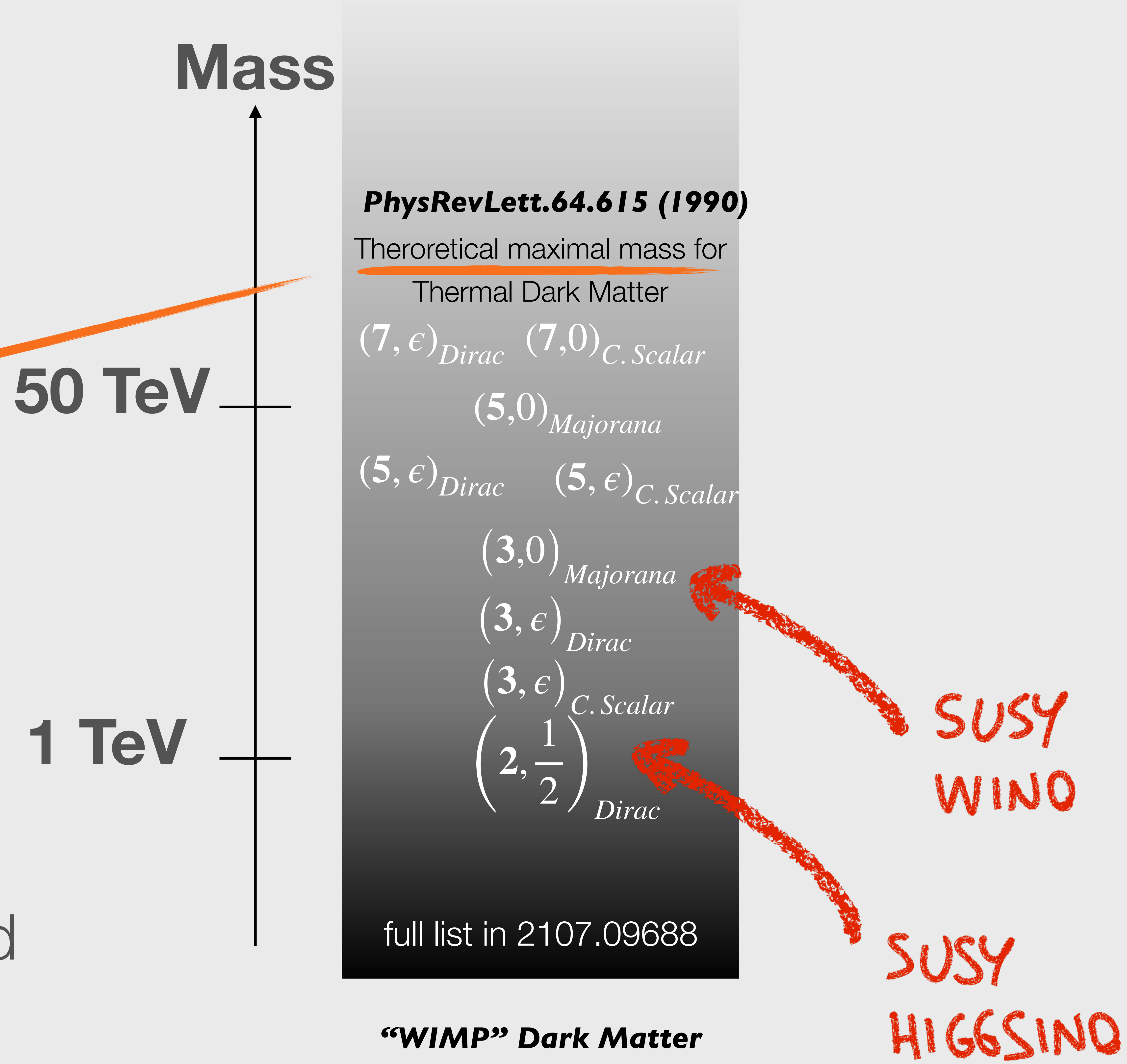

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Electroweak Dark Matter: LSP (+NLSP)

Direct Search Modes At Colliders

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 $\ell^+\ell^- \to Z' \to \chi\,\chi$ — Mono-X

0

} Precision Tests

Electroweak Dark Matter: LSP (+NLSP)

Direct Search Modes At Colliders

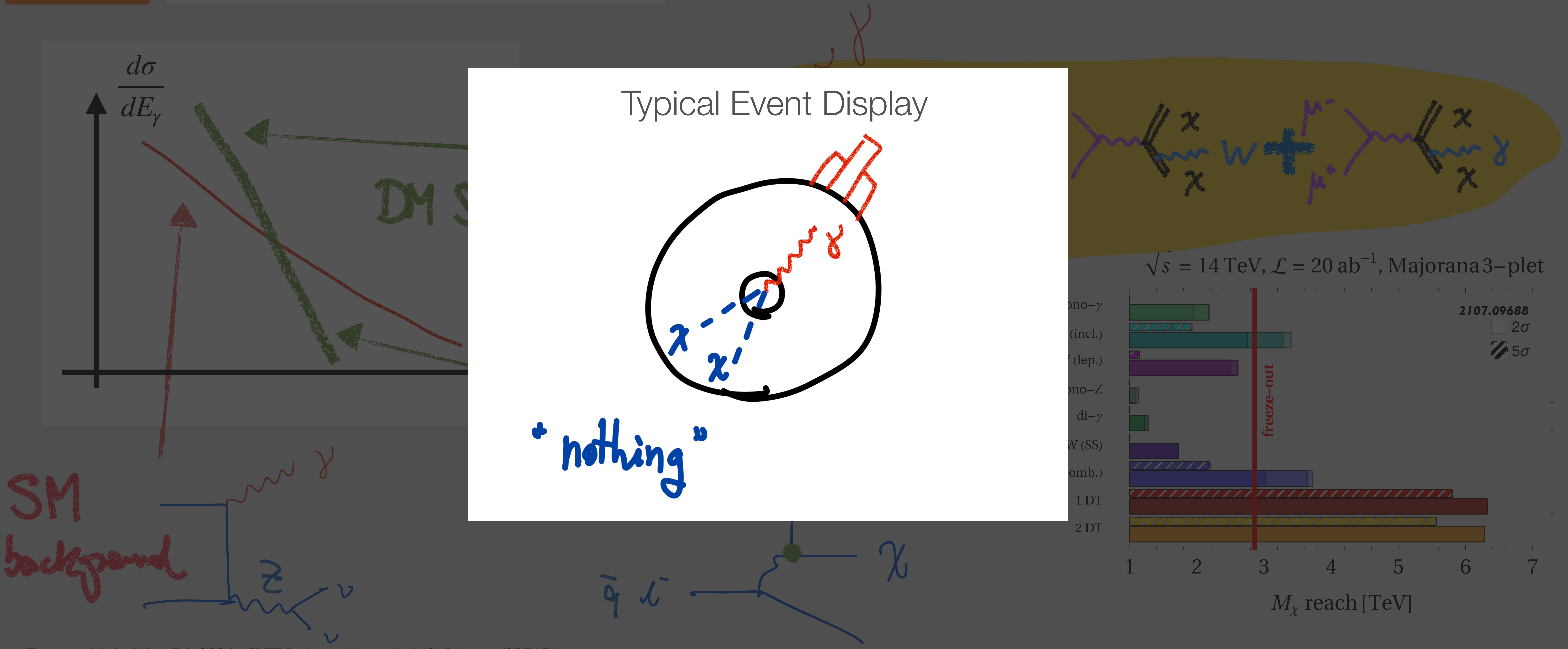
Δm

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"

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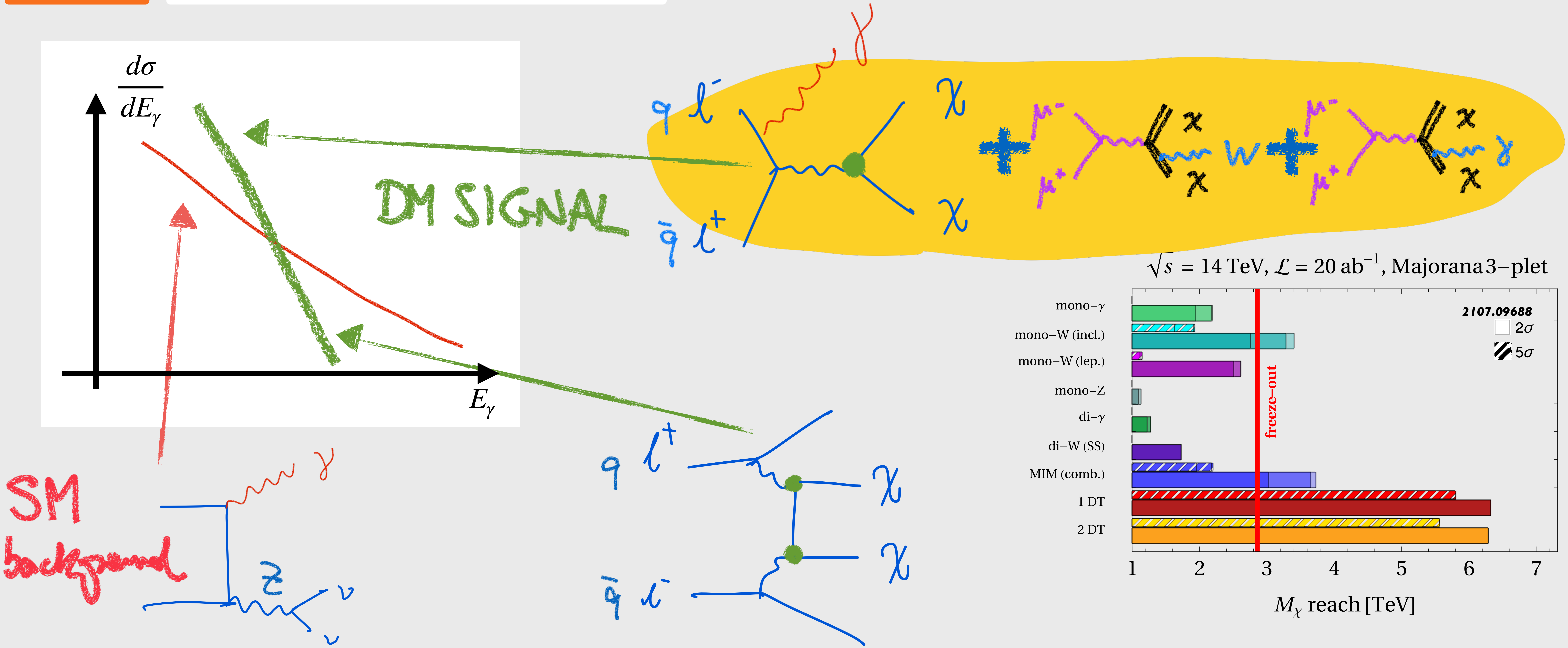

Electroweak Dark Matter: LSP (+NLSP)

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Δm

Δm		Search mode
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DM SM singlet pp or $\ell^+\ell^- \to Z' \to \chi\,\chi$	0	Mono-X

} Precision Tests

Electroweak Dark Matter: LSP (+NLSP)

Direct Search Modes At Colliders

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	GeV	
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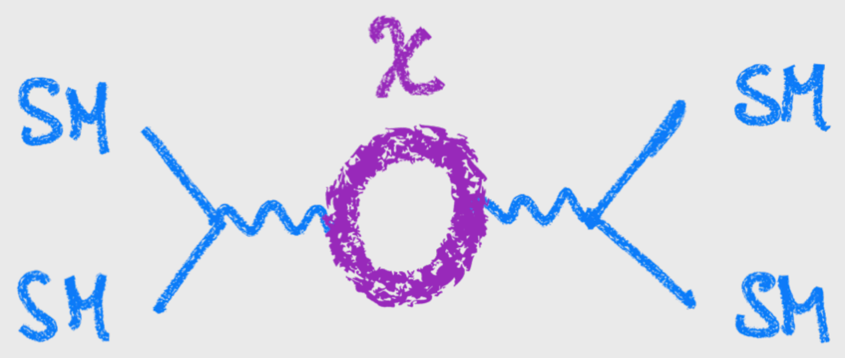
DM SM singlet *pp* or $\ell^+\ell^- \rightarrow Z' \rightarrow \chi\chi$	0	Mono-X



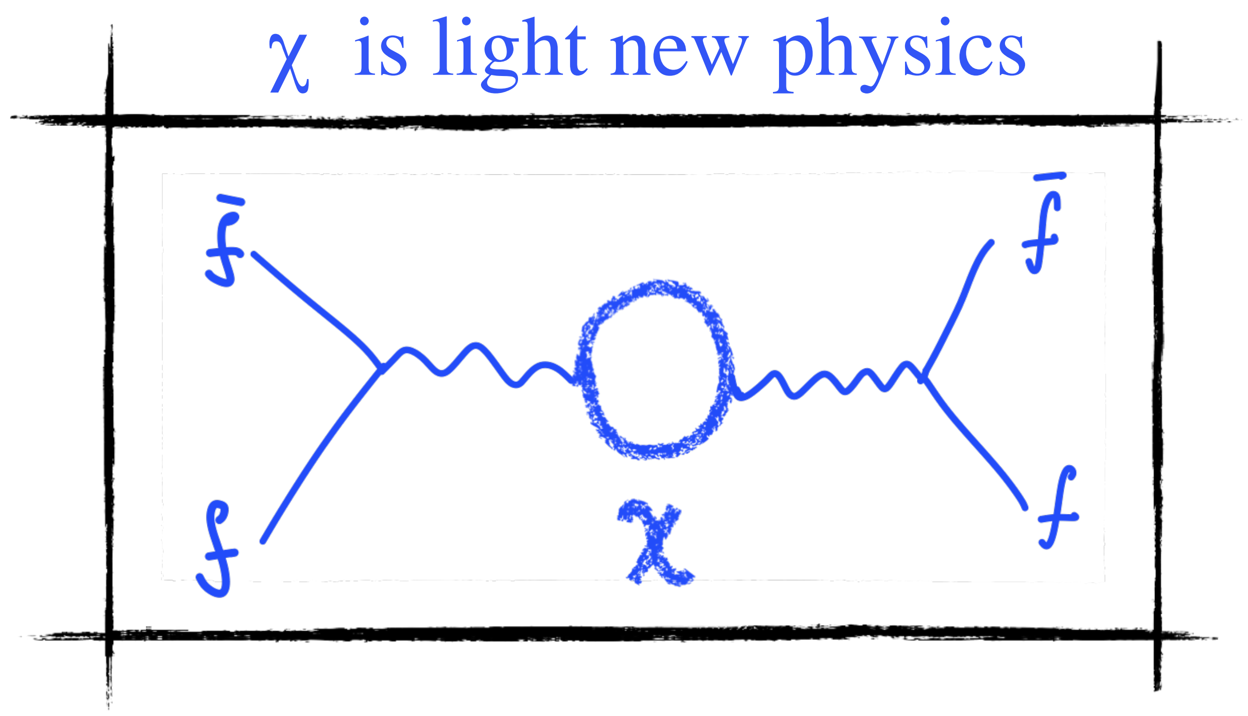
Precision Tests

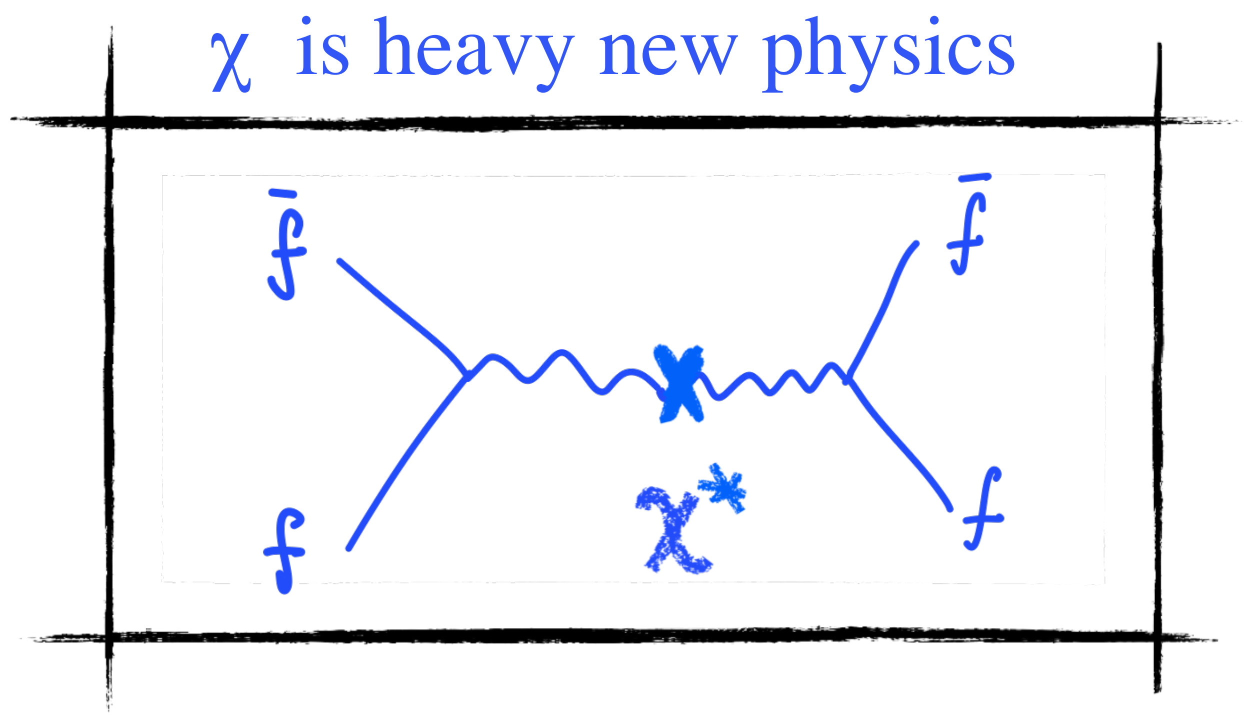
Dario's Talk

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

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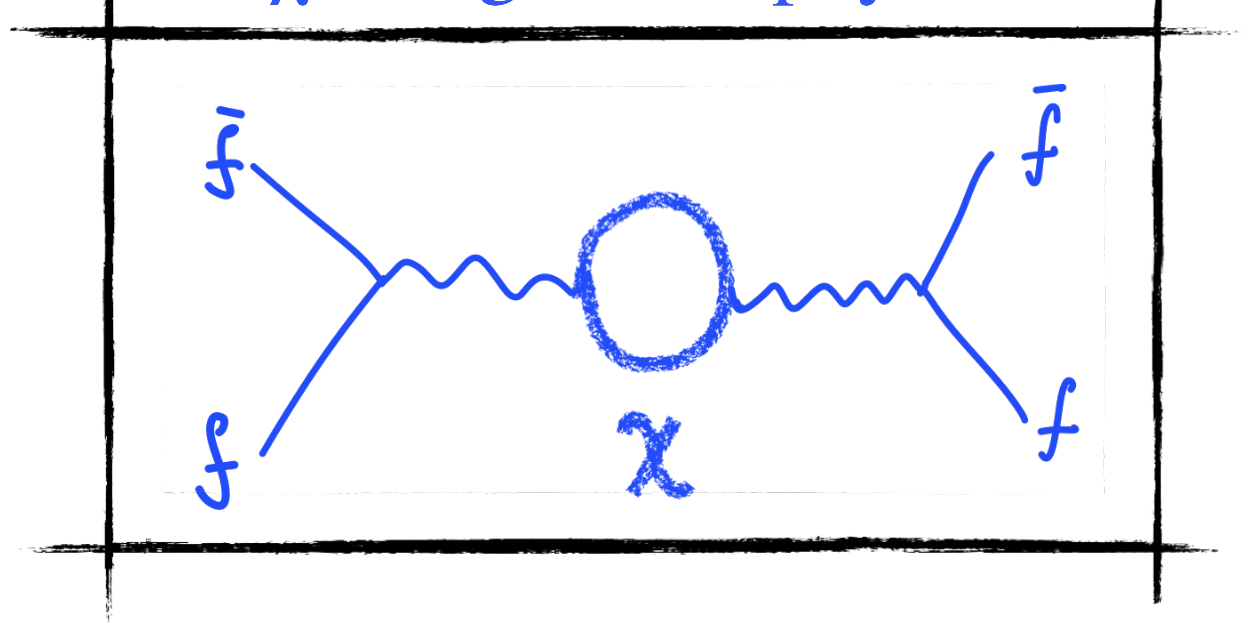
PRECISION | TOTAL CROSS-SECTION

χ is light new physics



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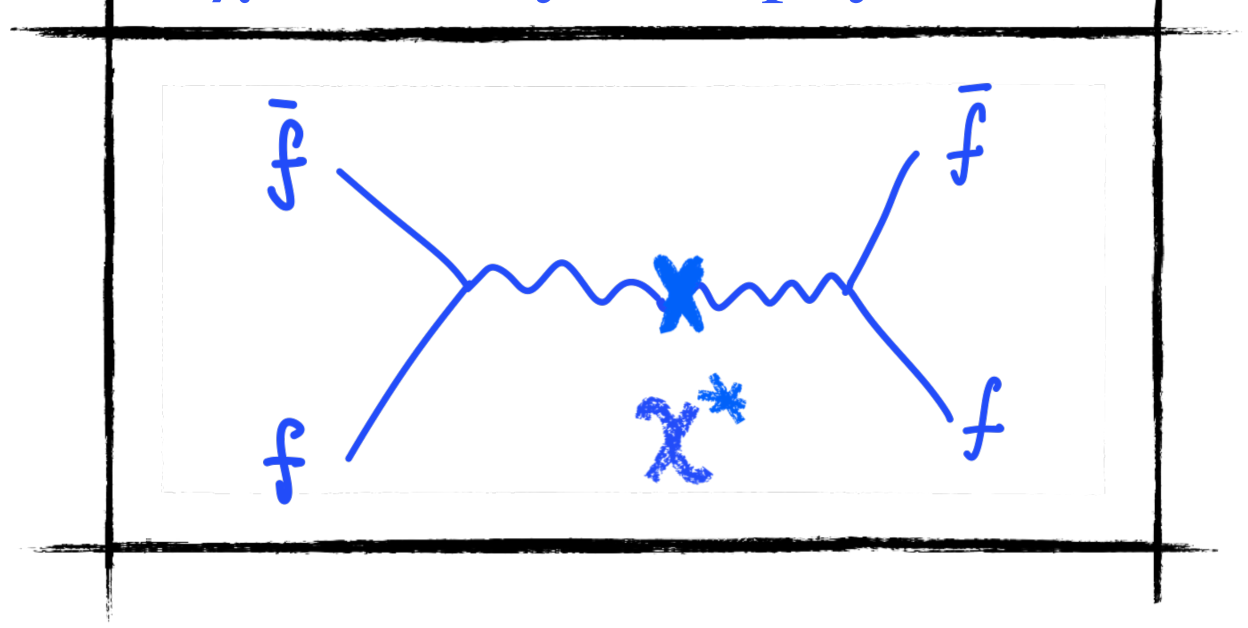
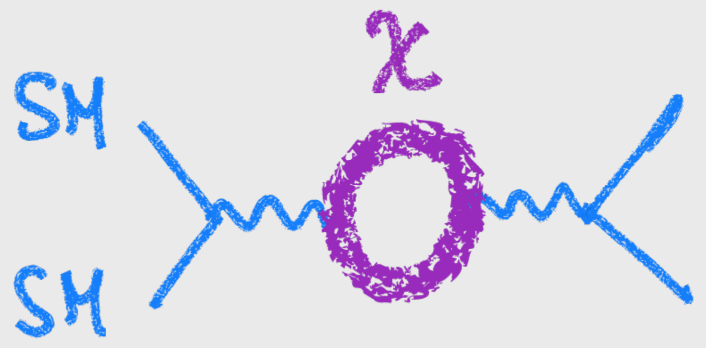


- fiducial cross-sections are significantly affected by off-shell new physics heavier than the collider kinematic reach

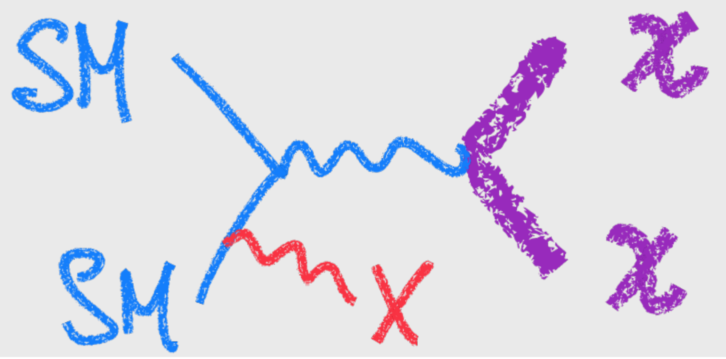
χ / m_χ [TeV]	DM	HL-LHC	HE-LHC	FCC-100	CLIC-3	Muon-14
$(1,2,1/2)_{\rm DF}$	1.1	–	–	–	0.4	0.6
$(1,3,\epsilon)_{\rm CS}$	1.6	–	–	–	0.2	0.2
$(1,3,\epsilon)_{\rm DF}$	2.0	–	0.6	1.5	0.8 & [1.0, 2.0]	2.2 & [6.3, 7.1]
$(1,3,0)_{\rm MF}$	2.8	–	–	0.4	0.6 & [1.2, 1.6]	1.0
$(1,5,\epsilon)_{\rm CS}{}^*$	6.6	0.2	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!

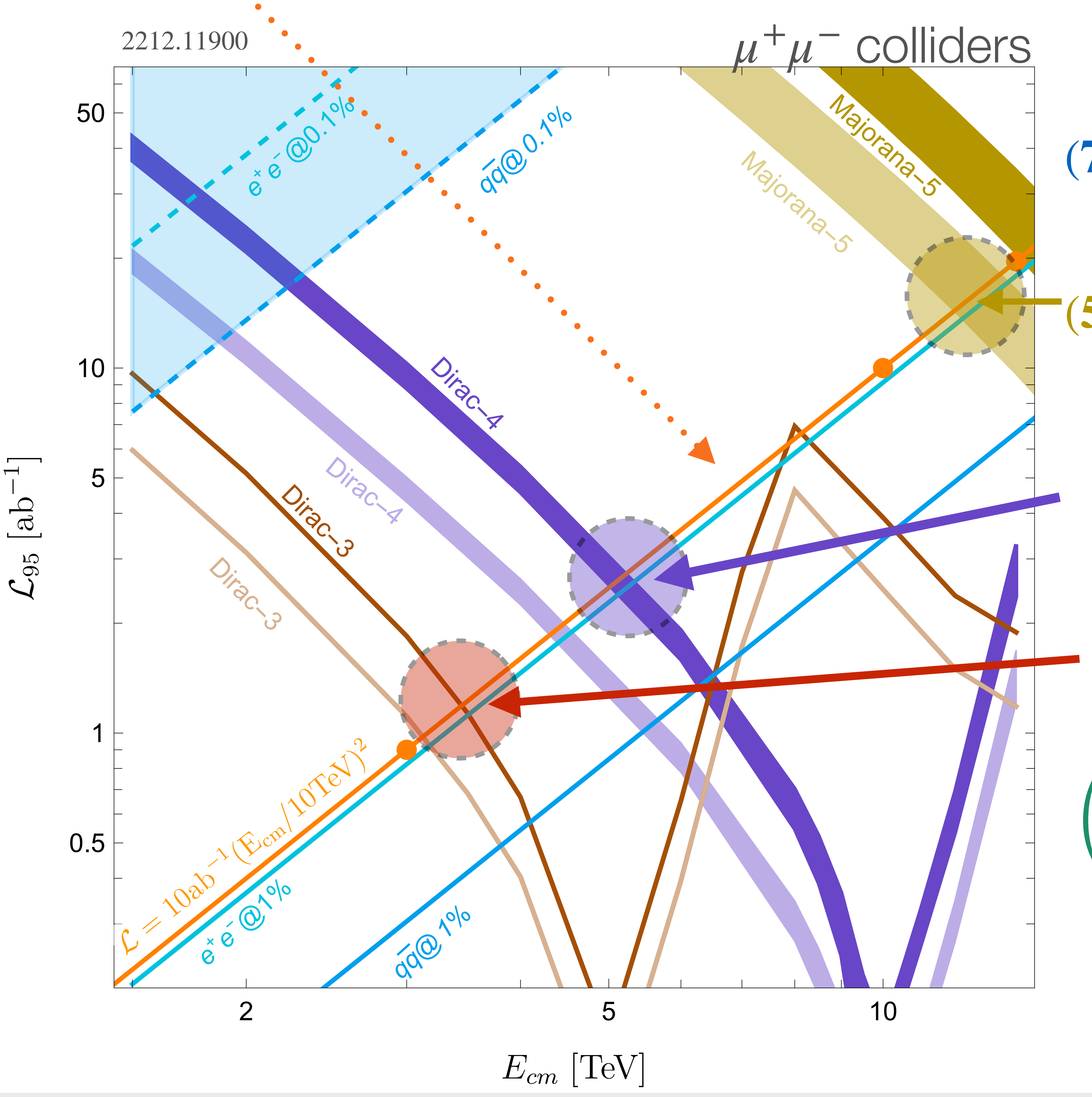
$SM\ SM \to f\bar{f}, Zh, W^+W^-, Wff'$



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



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



$(7{,}0)_{Majorana}$

$(7,\epsilon)_{Dirac}$ $\ell^+\ell^-$ 10+ TeV 10+ ab^{-1}

$(5{,}0)_{Majorana}$

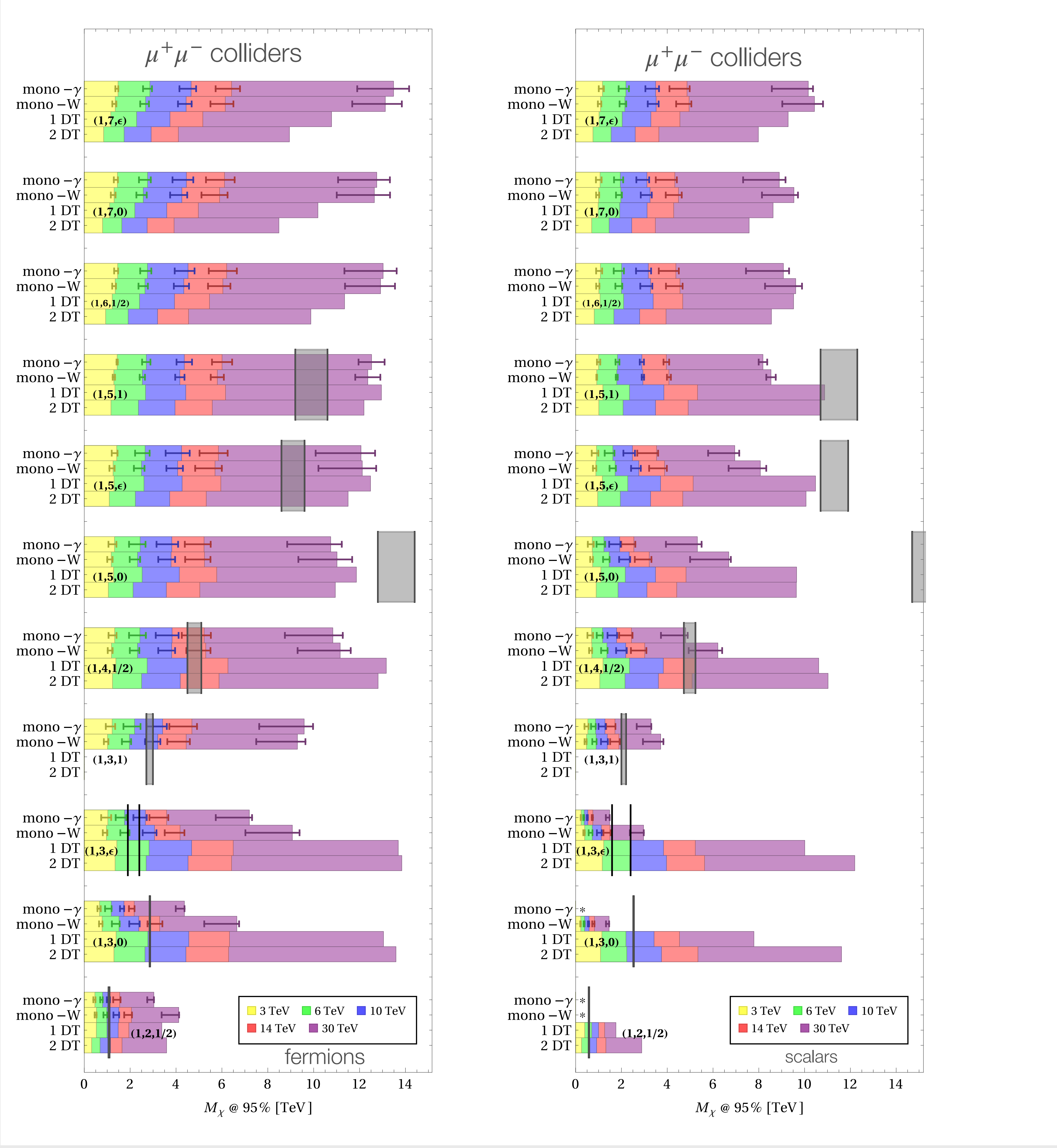
$(5,\epsilon)_{Dirac}$

$\left(4,\frac{1}{2}\right)_{Dirac}$ $\ell^+\ell^-$ 10 TeV 10 ab^{-1}

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

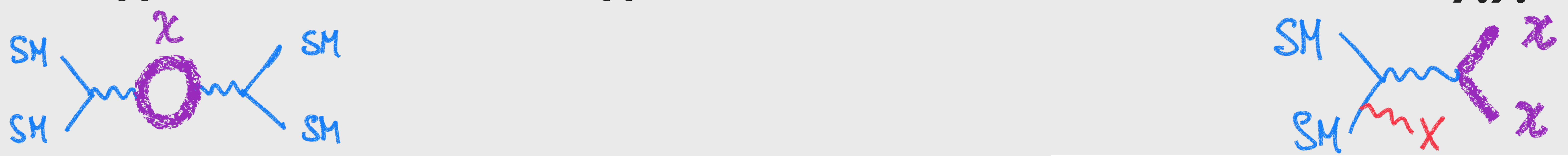
$(3,\epsilon)_{Dirac}$ $\ell^+\ell^-$ 3 TeV 1 ab^{-1}

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

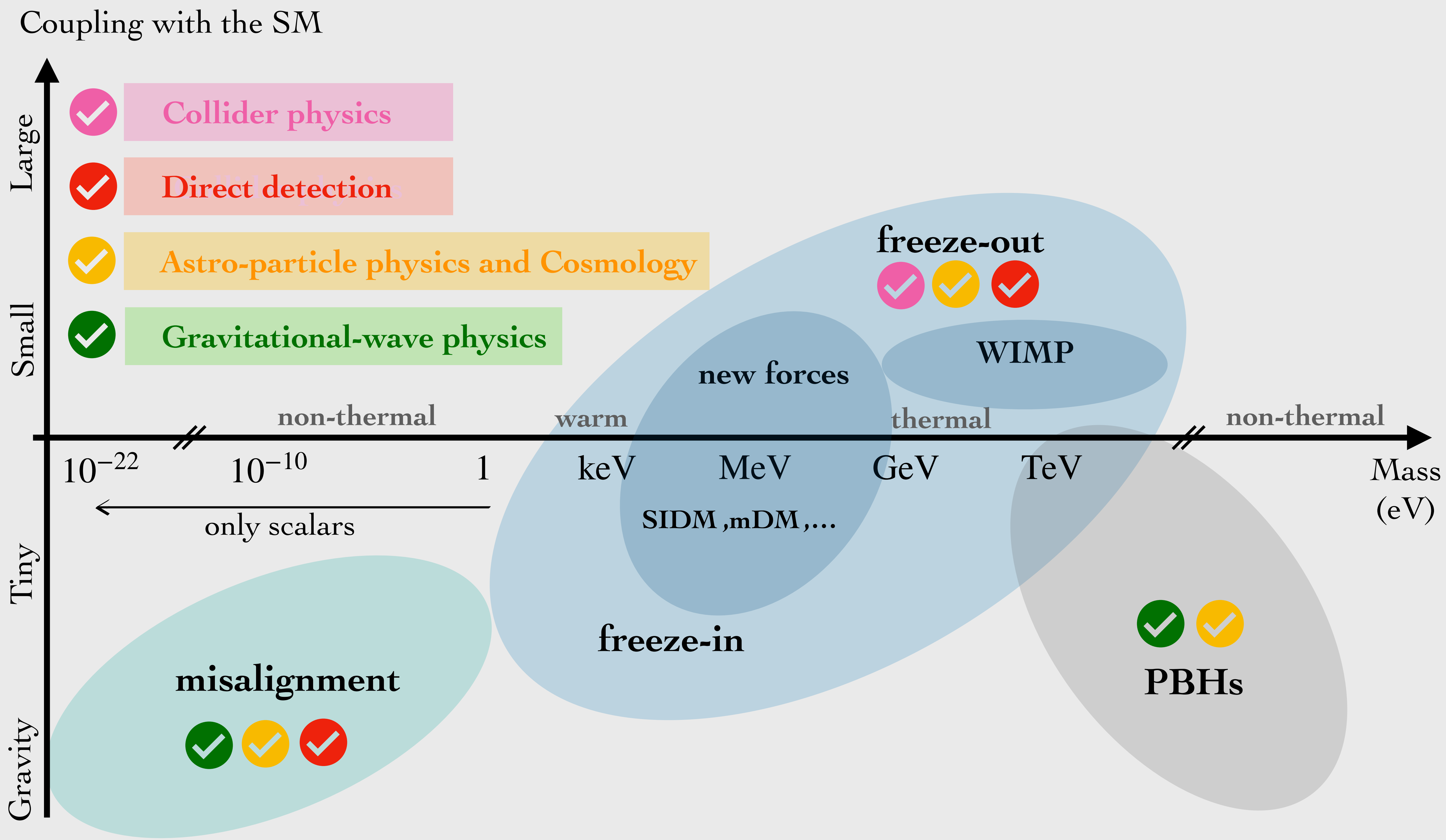


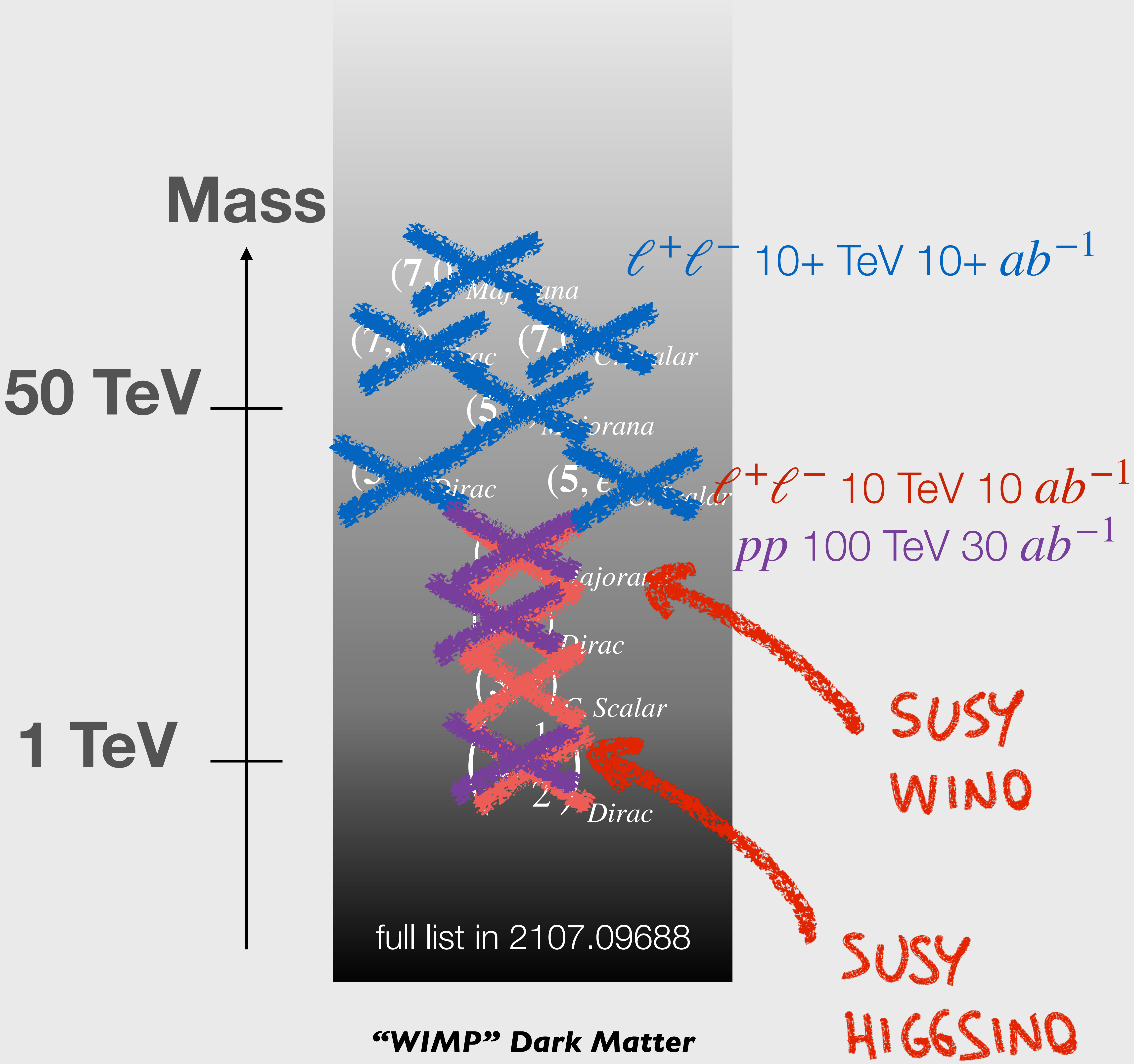
$SM\ SM \to f\bar{f}, Zh, W^+W^-, Wff'$

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



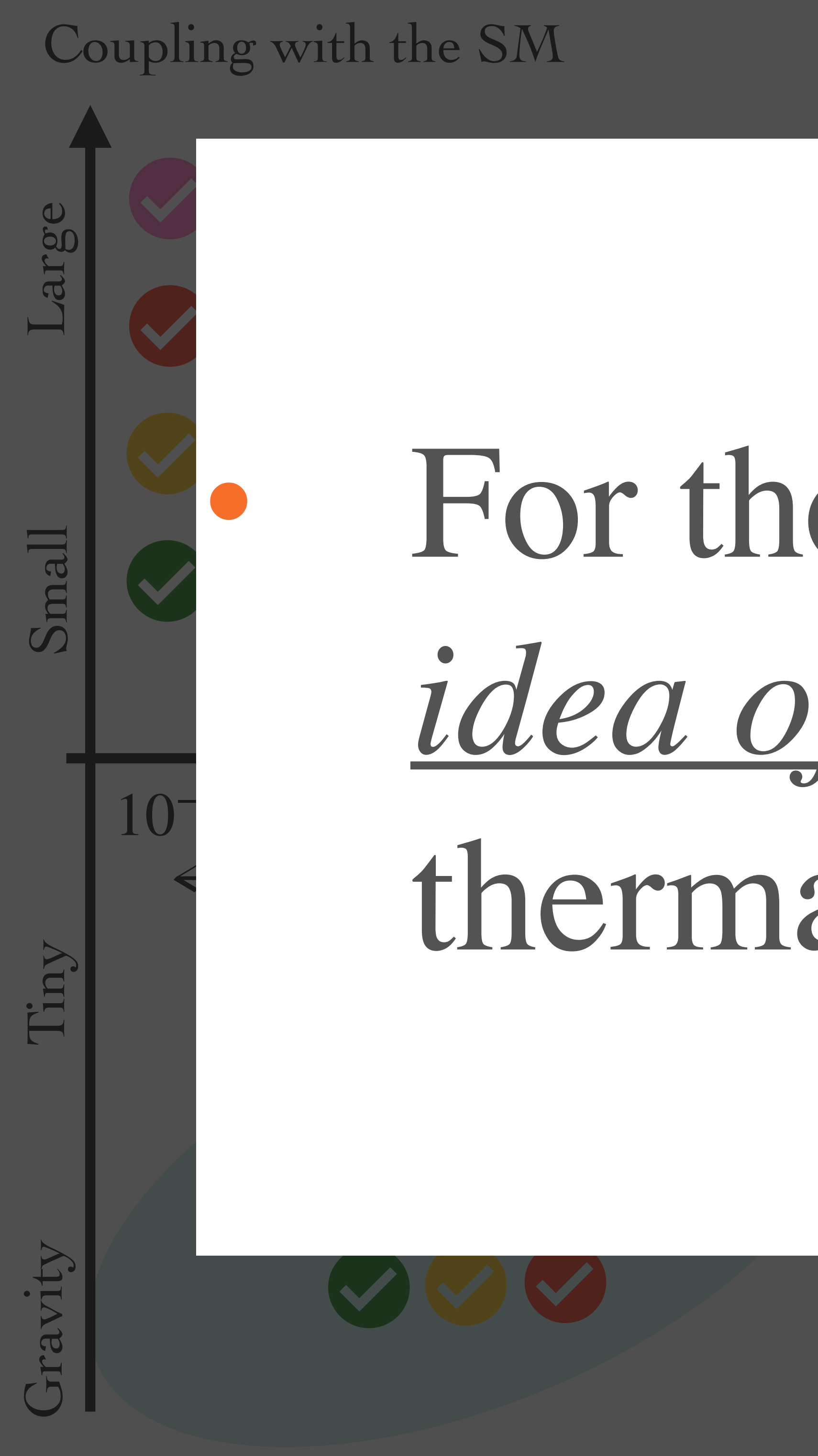
Electroweak Dark Matter: LSP (+NLSP)



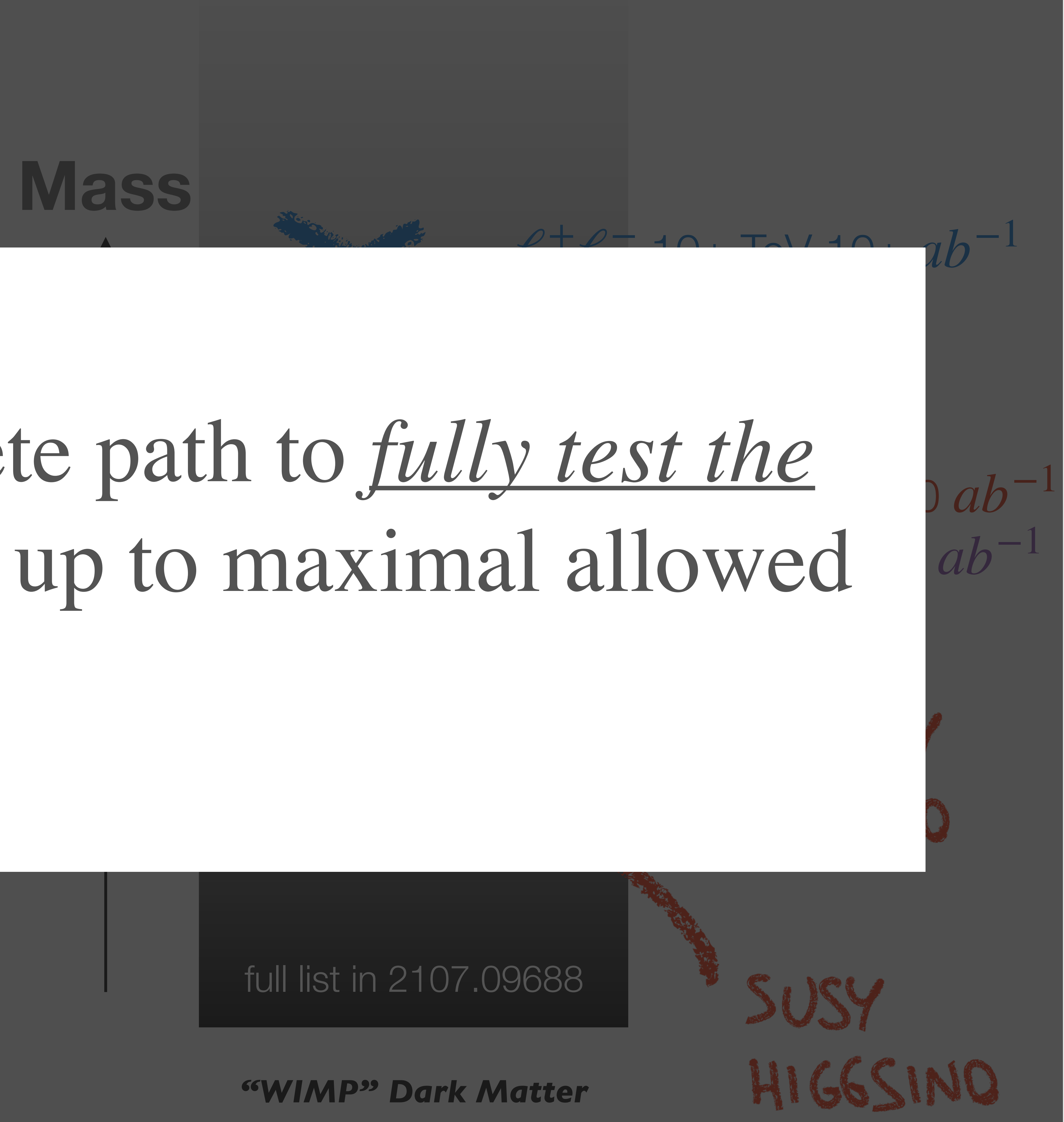


"WIMP" Dark Matter

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



Conclusions

Several deep open questions open for investigation

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? ✓
- 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

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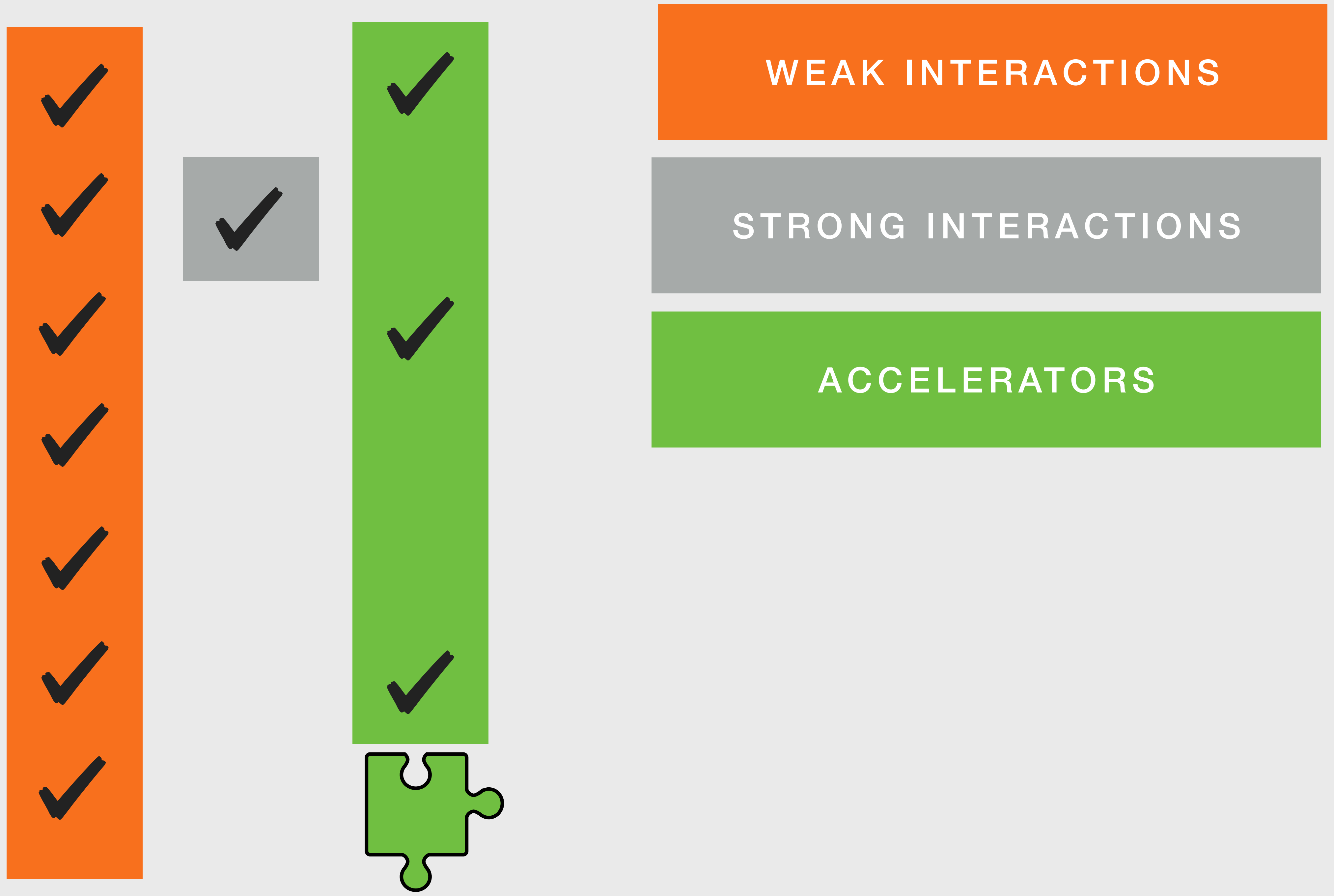
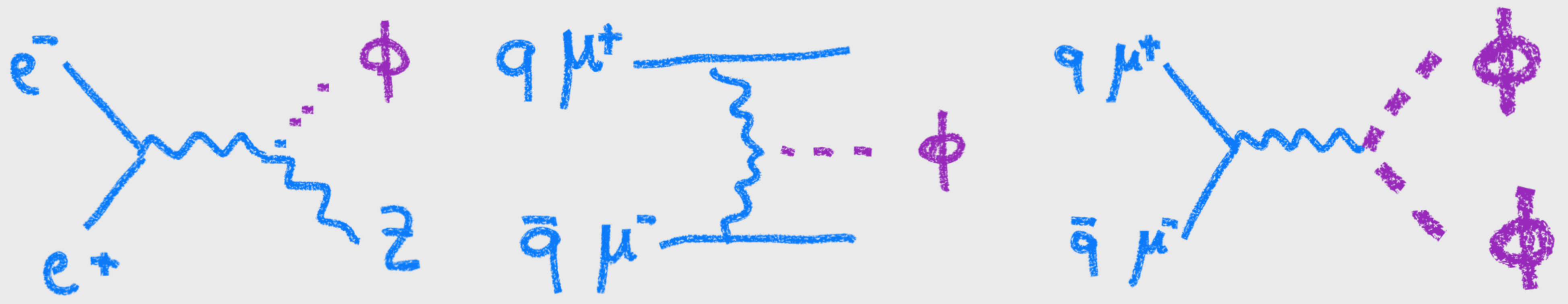


Future Colliders can provide significant advances on these issues

Conclusions

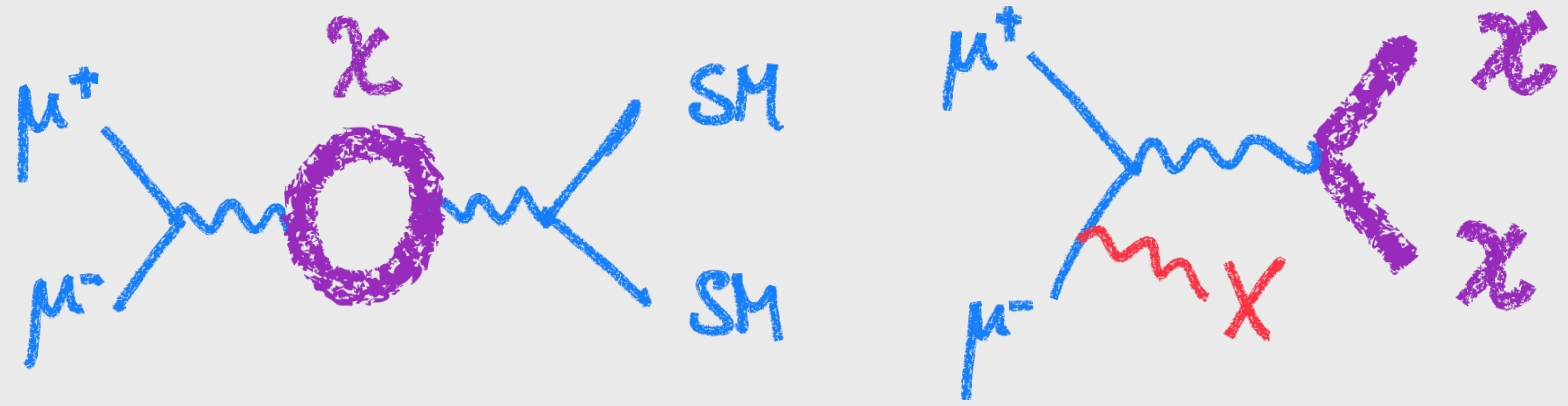
The SM has many open issues. It is not possible to “guarantee a discovery”, but we can guarantee learning from trying!

- ✔ Is there only one Higgs boson?

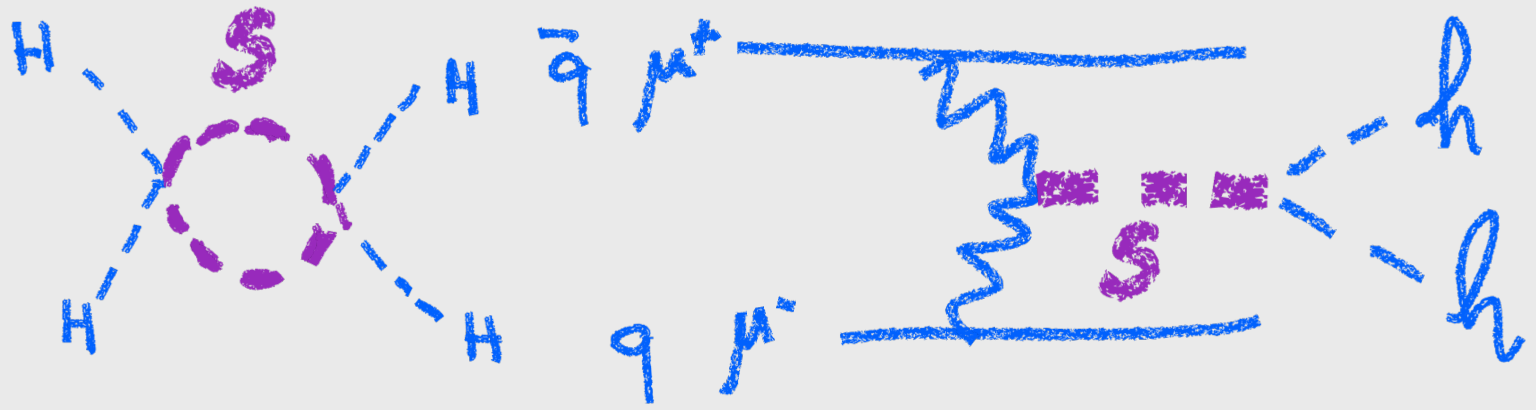


- ✔ Is the Higgs boson point-like or composite?

- ✔ Is Dark Matter a thermal relic?



- ✔ Was the electroweak symmetry broken abruptly in the early Universe?



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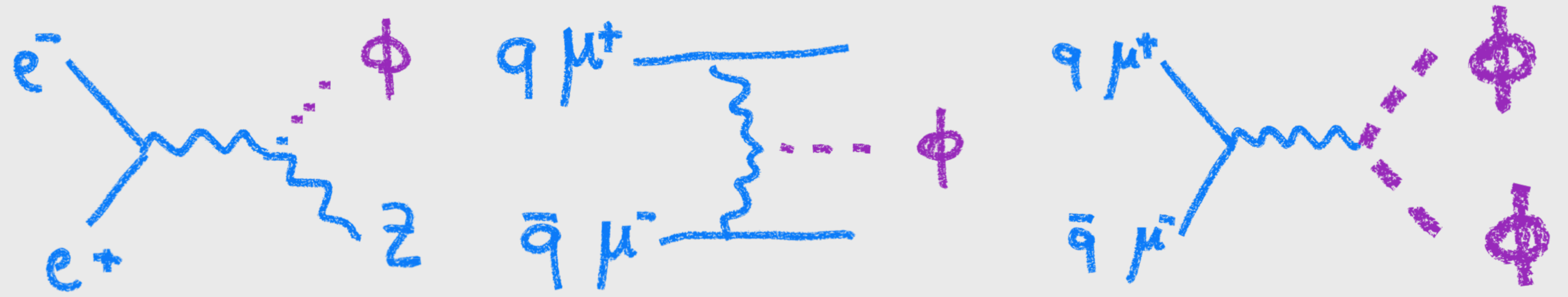

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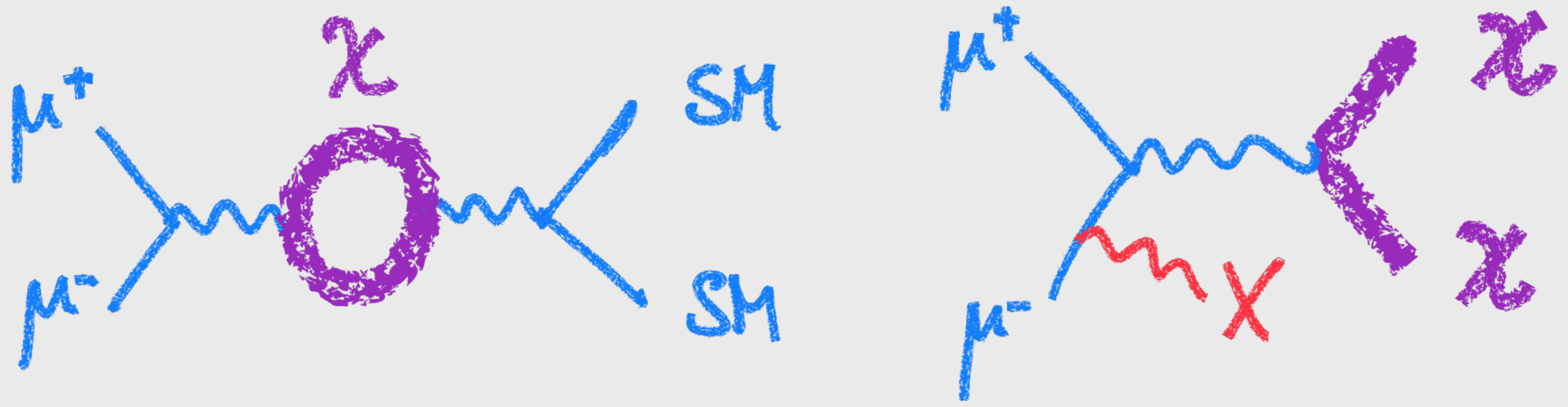

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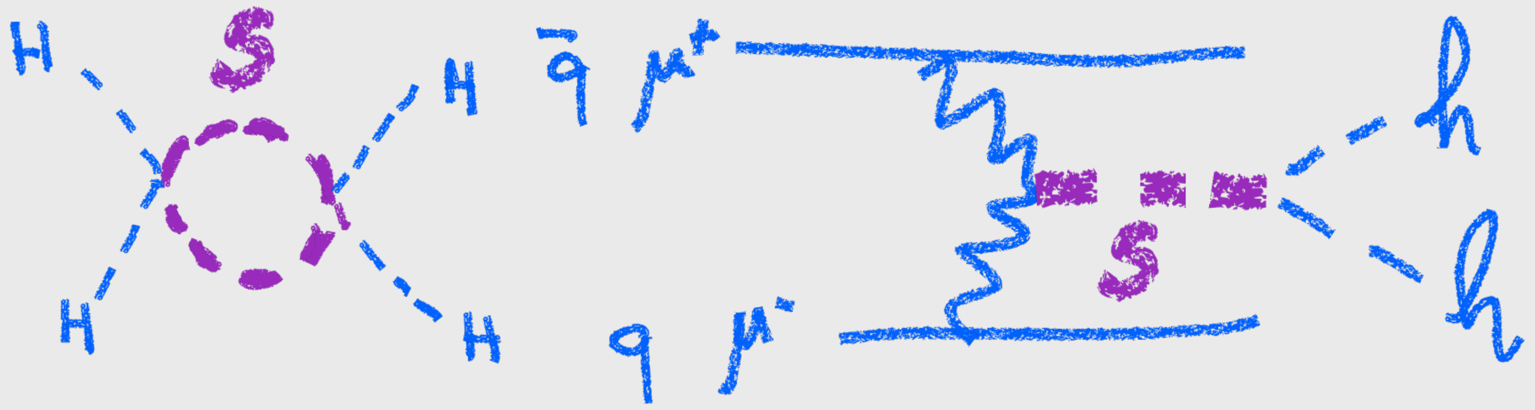
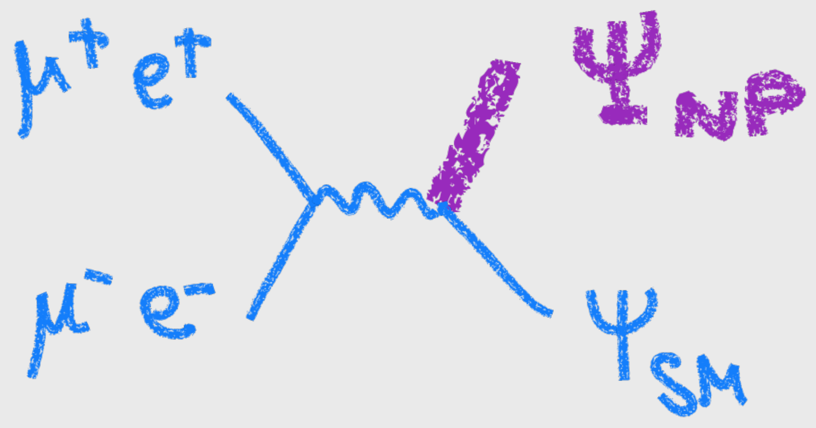


Future Colliders can provide conclusive results on some issues

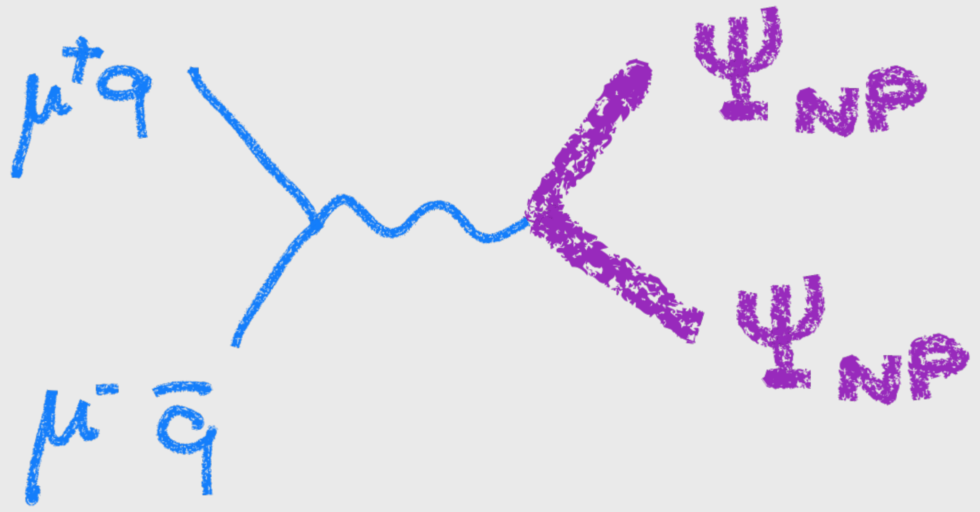
Conclusions

The SM has many open issues. It is not possible to “guarantee a discovery”, but we can guarantee learning from trying!

- ✓ Is new physics light and very weakly coupled? or is it heavy?



- ✓ When do you expect to be able to probe directly the causes of “deviations” from the SM?



Thank You!

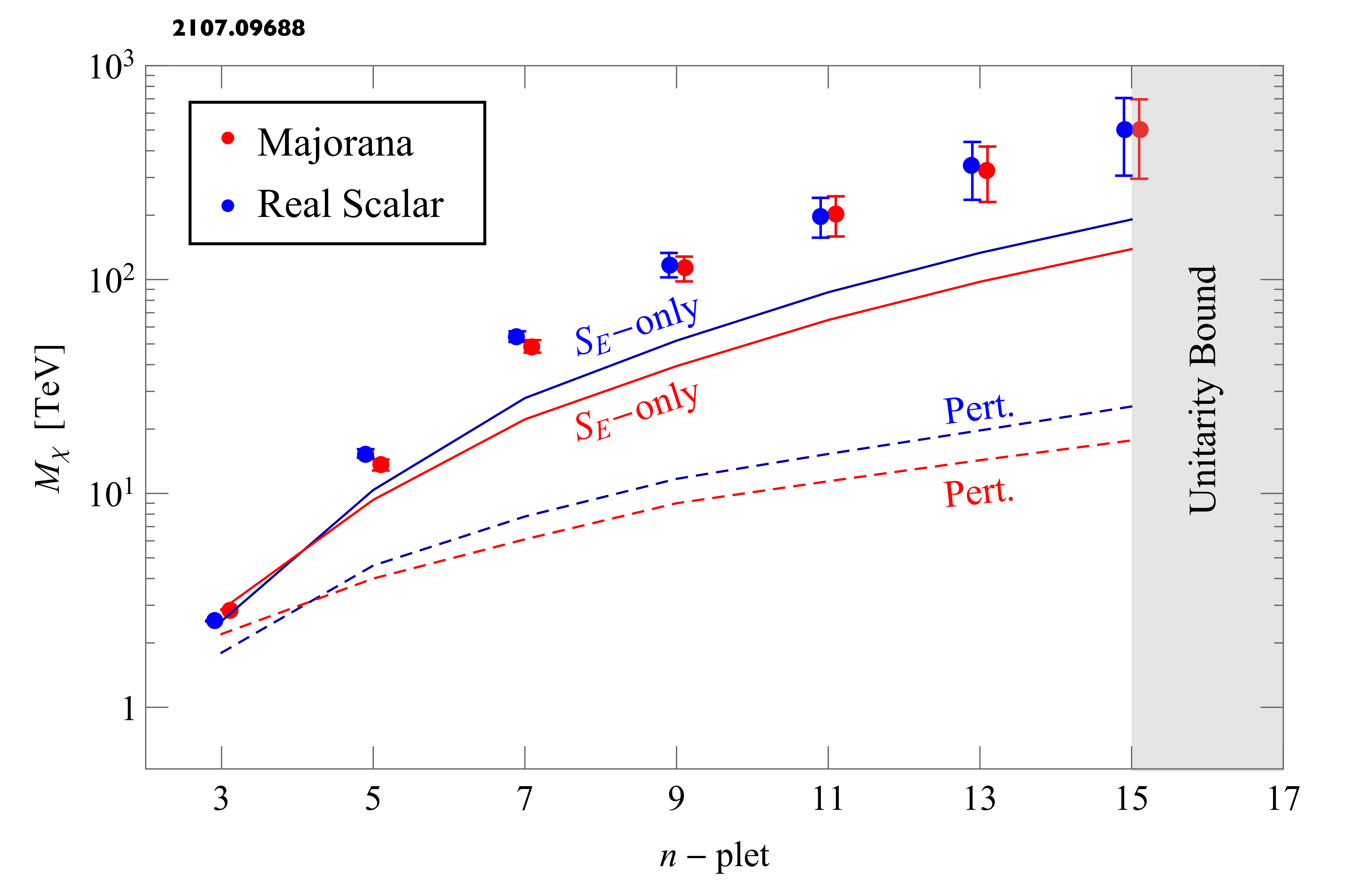
flashing concrete results for

Dark Matter at the weak scale

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

PURE SU(2) N-PLET

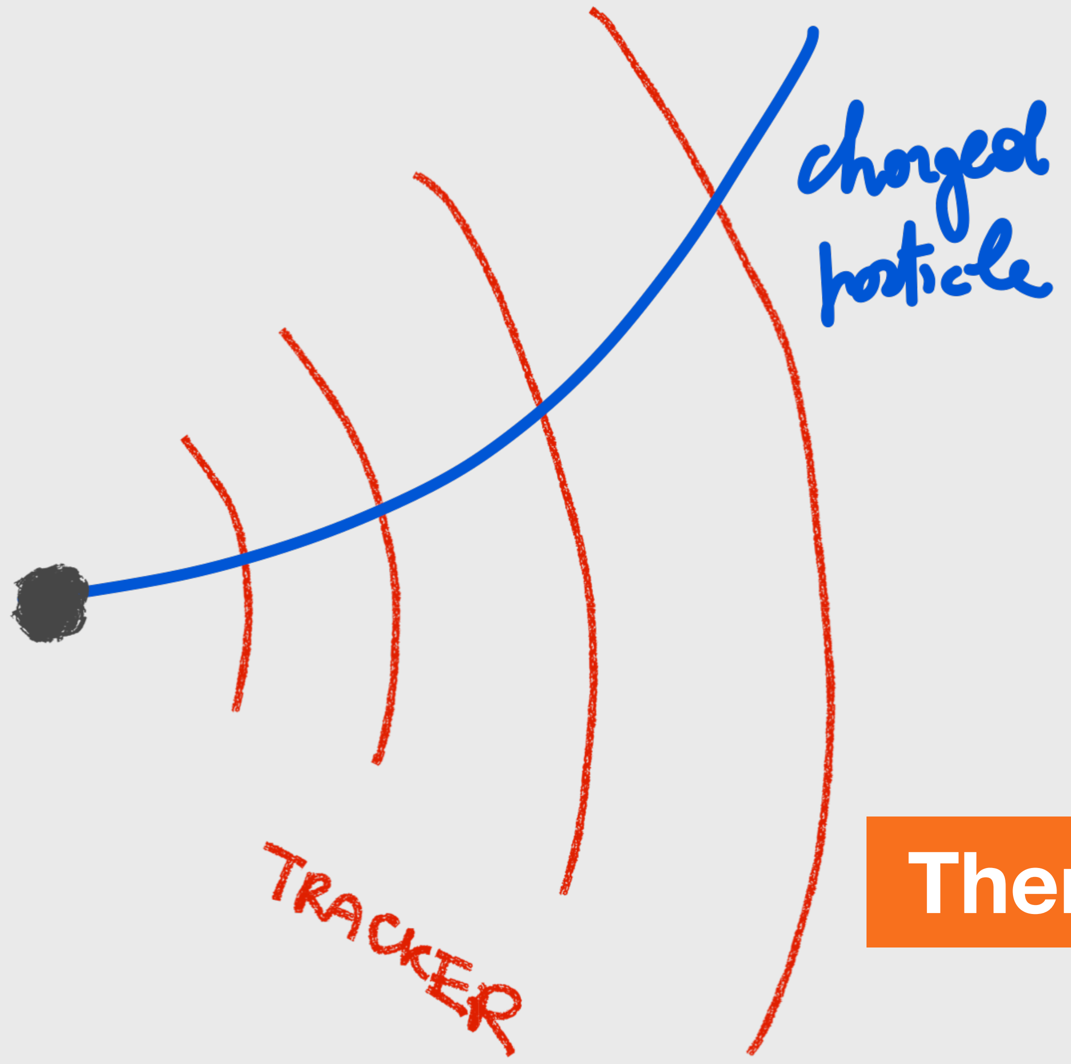
INTERPOLATOR UP TO PeV

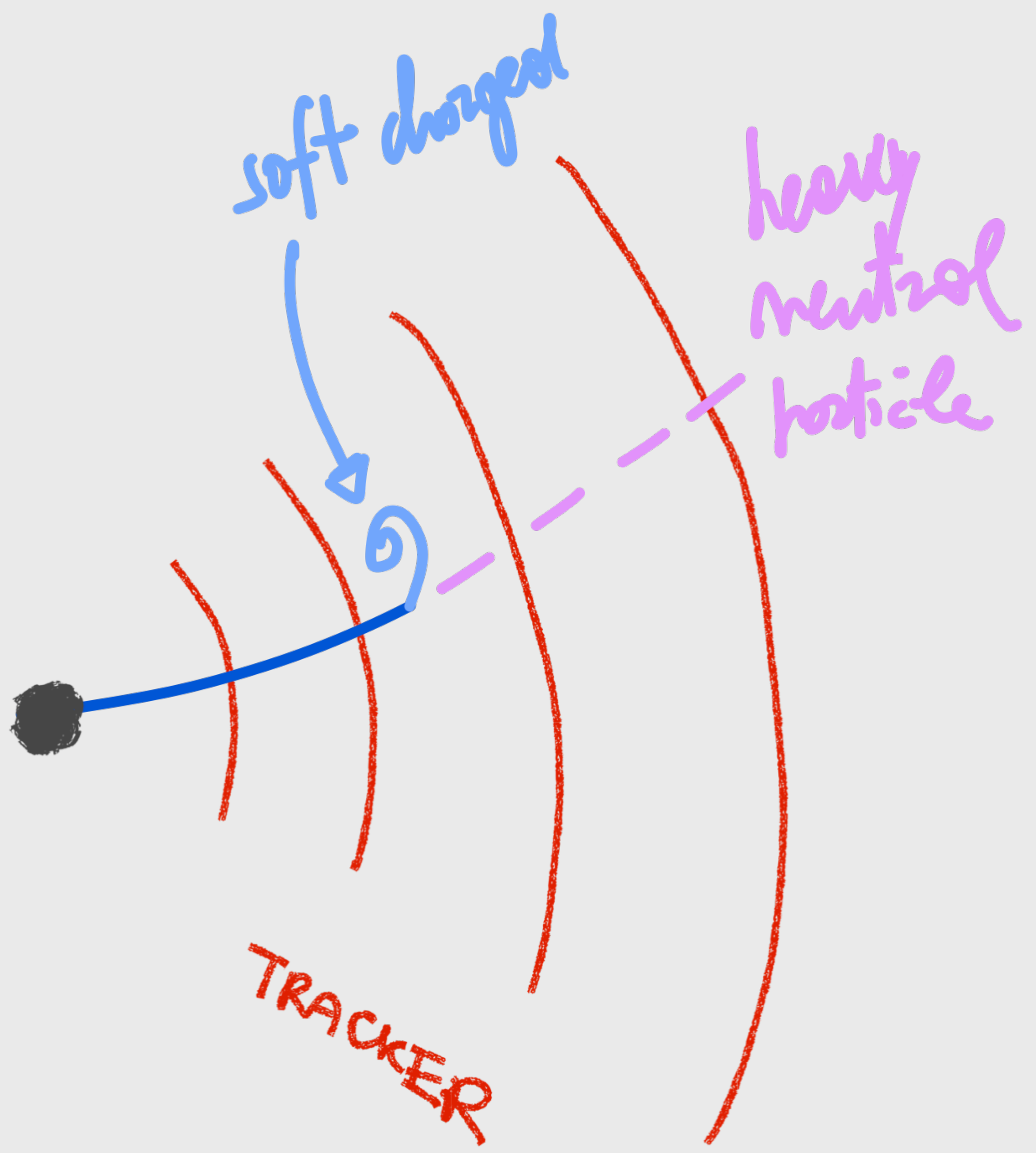


DM spin	EW n-plet	M_χ (TeV)	$(\sigma v)^{J=0}_{\rm tot}/(\sigma v)^{J=0}_{\rm max}$	$\Lambda_{\rm Landau}/M_{\rm DM}$	$\Lambda_{\rm UV}/M_{\rm DM}$
Real scalar	3	2.53 ± 0.01	–	3×10^{37}	$4 \times 10^{24}*$
	5	15.4 ± 0.7	0.002	5×10^{36}	2×10^{24}
	7	54.2 ± 3.1	0.022	2×10^{19}	2×10^{24}
	9	117.8 ± 15.4	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}

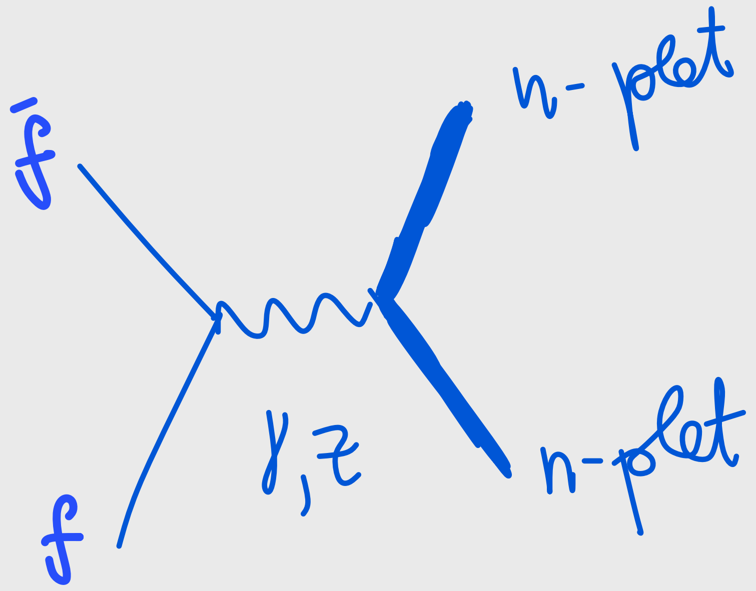
Higgsino DM

STUB-TRACKS | EXOTIC SIGNAL

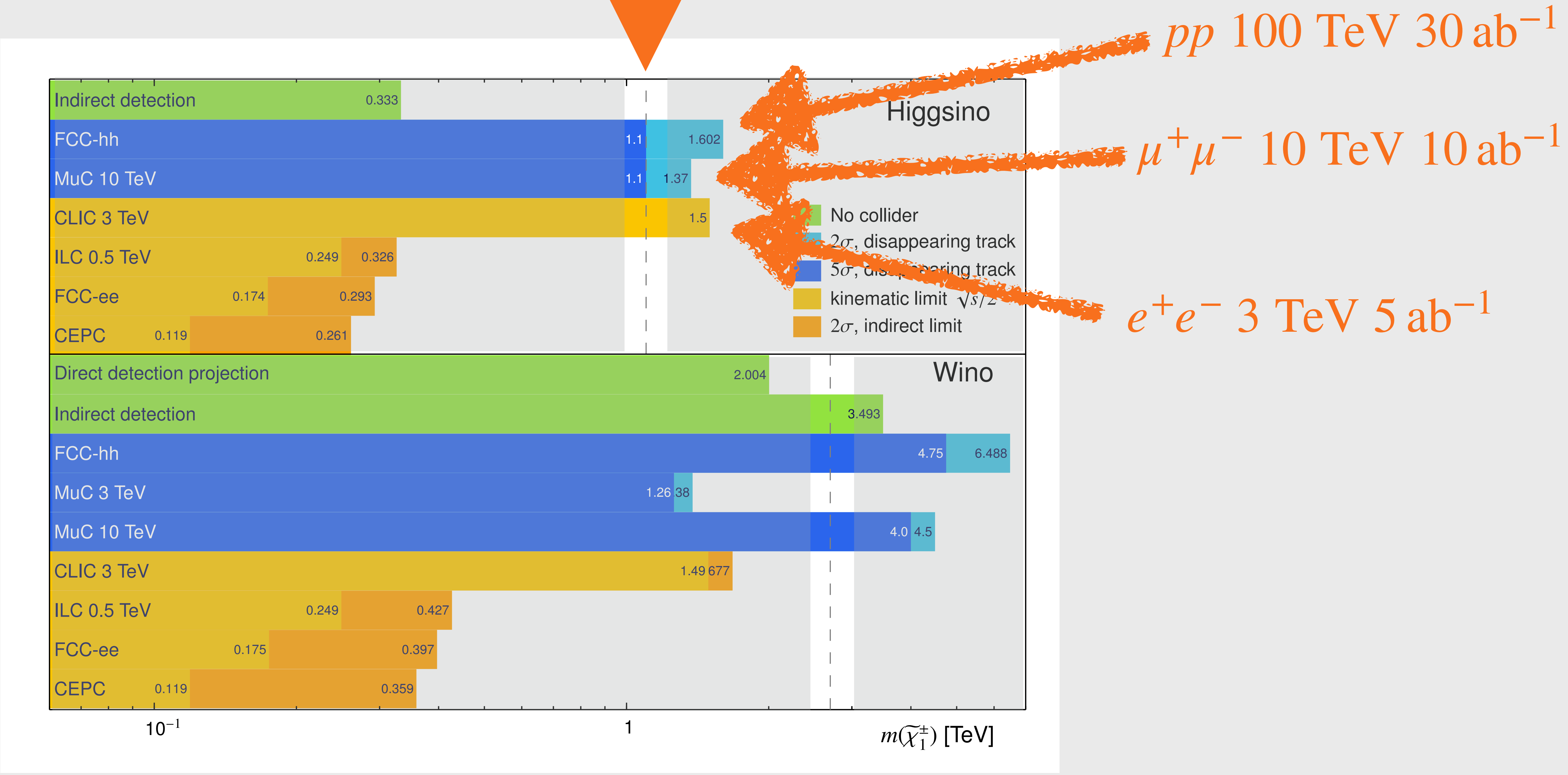




- Heavy n-plet of $SU(2)$
- Mass splitting $\sim\alpha_W \cdot m_W \sim$ 0.1 GeV - GeV

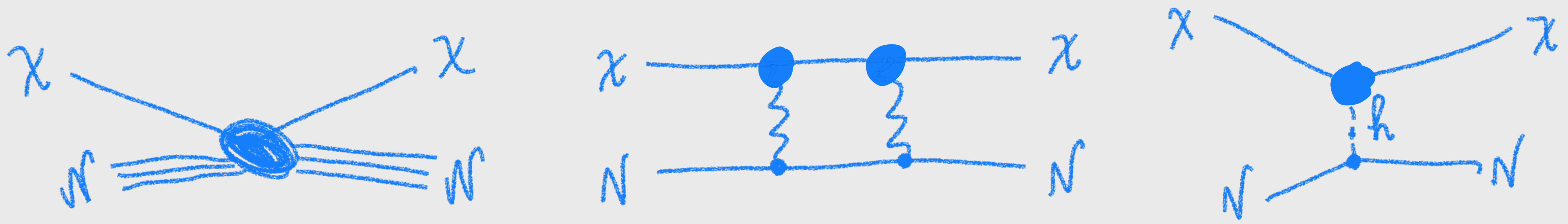


Thermal Higgsino



LARGE RATES, BUT NEEDS TO LIGHT UP THE DETECTOR IN A DISCERNIBLE WAY

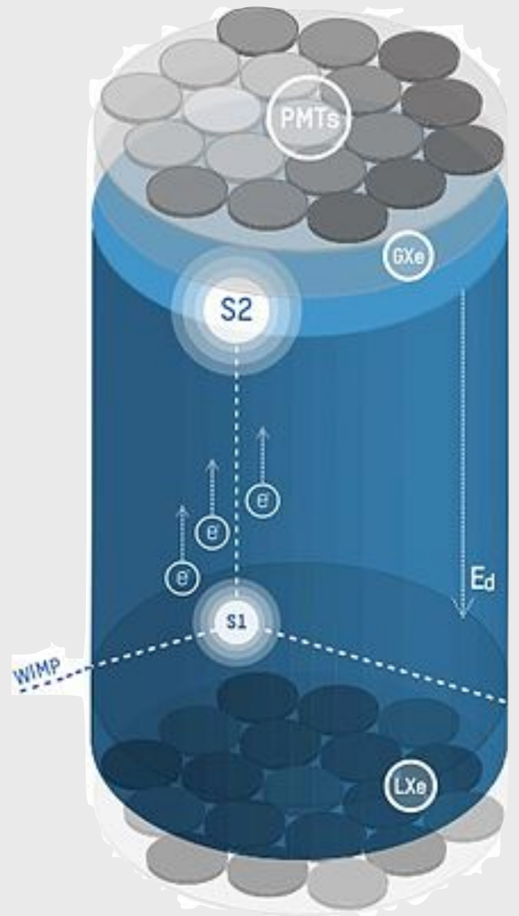
Direct Detection



Scattering on SM materials can be detected in ultra-low background experiments

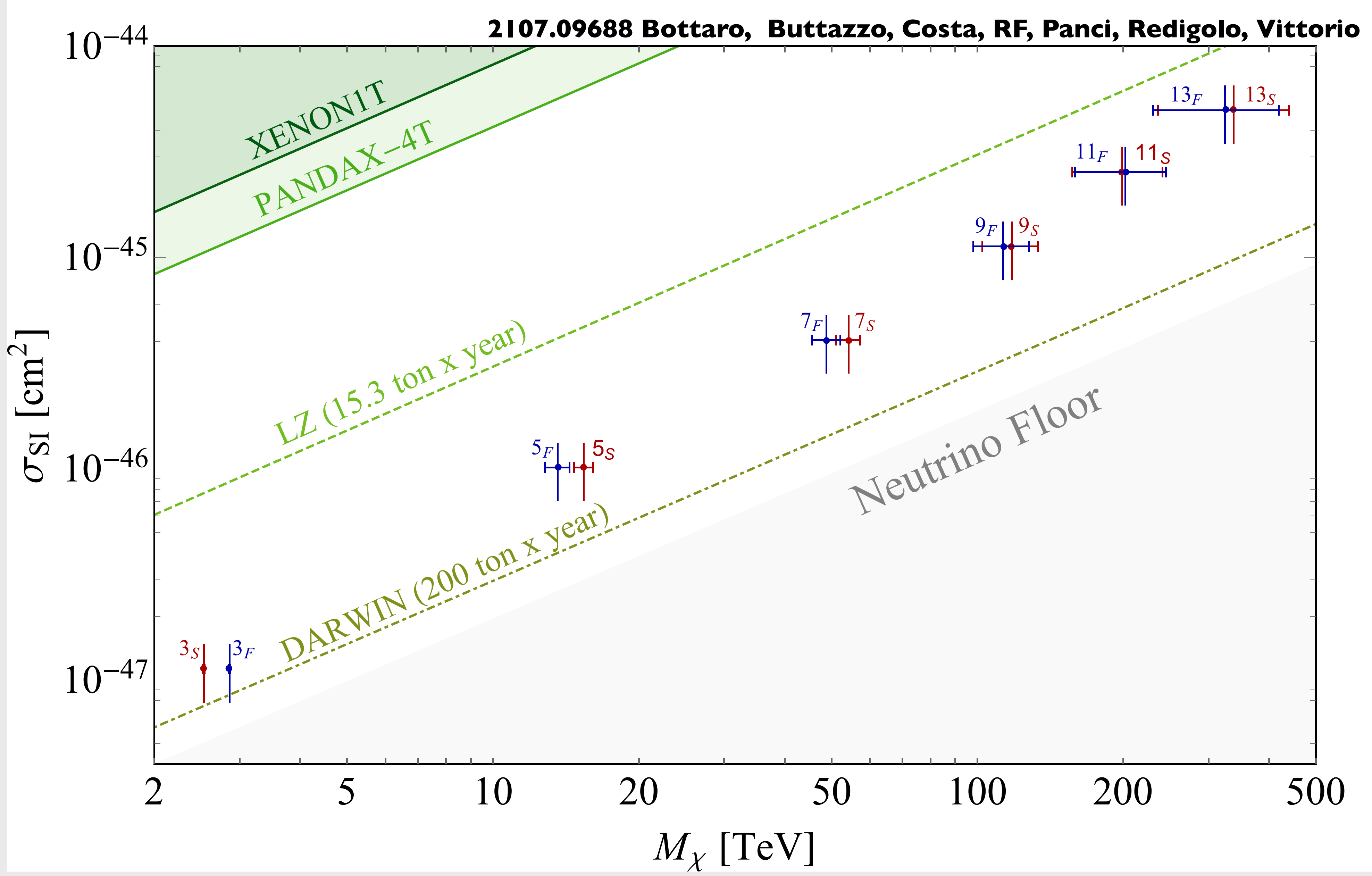
Larger rates for the larger n-plets keep them visible

For such large DM mass the signature does not depend on the DM mass.



2030s

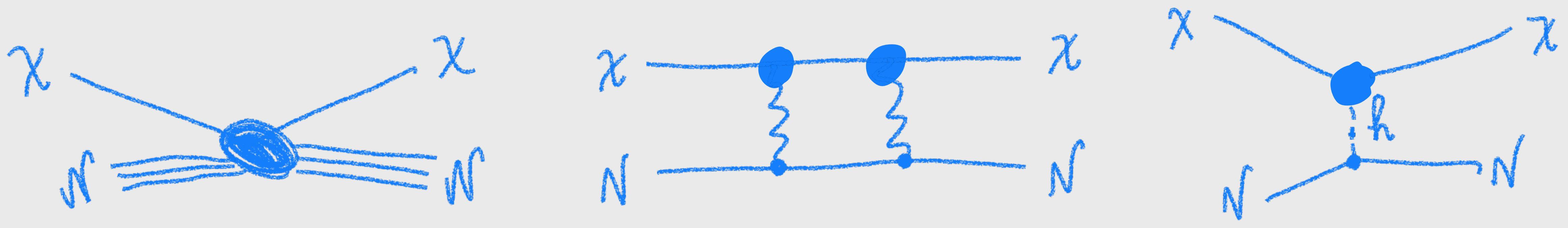
up to O(PeV)



An excess would require a "seasonality" check and maybe independent confirmation (many excesses in the past in this type of experiments, though most were at the lowest accessible masses)

Direct Detection

$Y \neq 0$, pure EW Mass-Splitting



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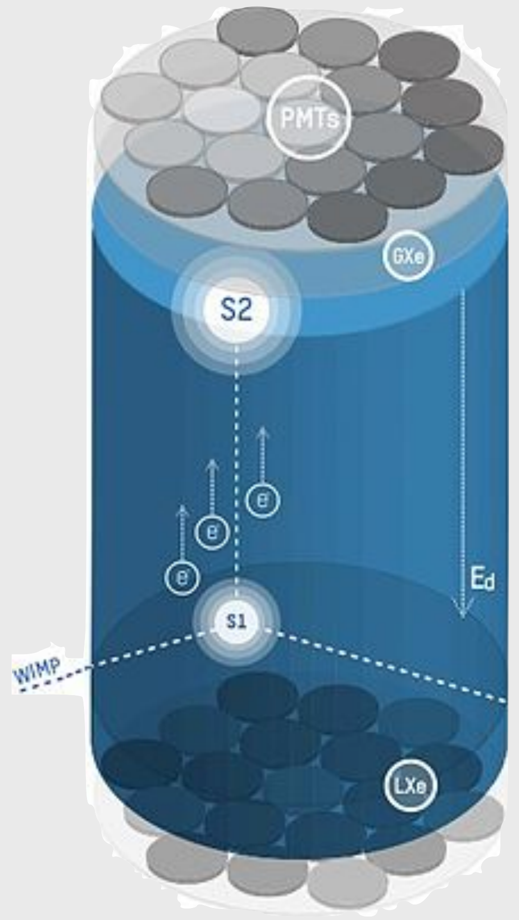

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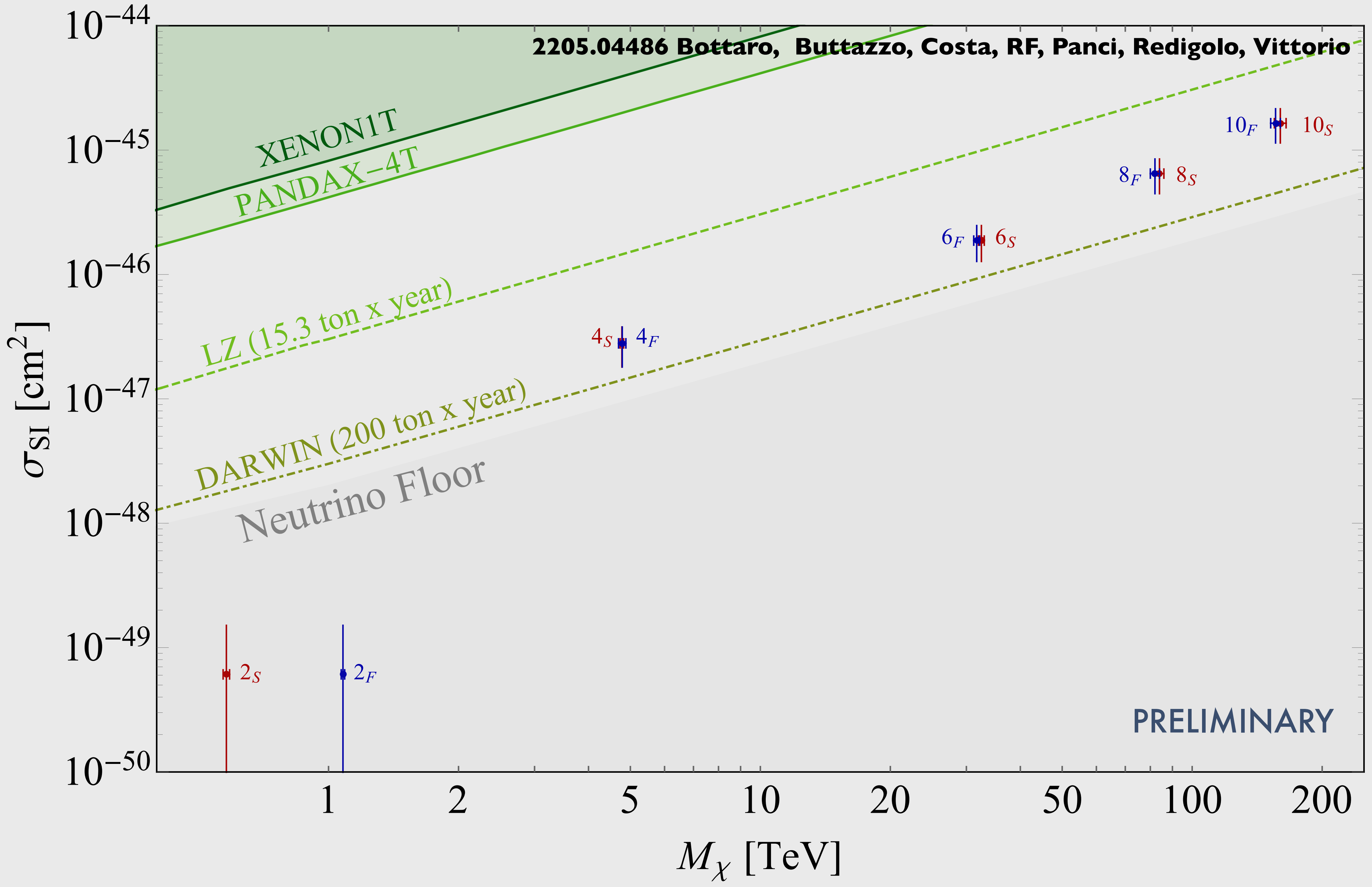

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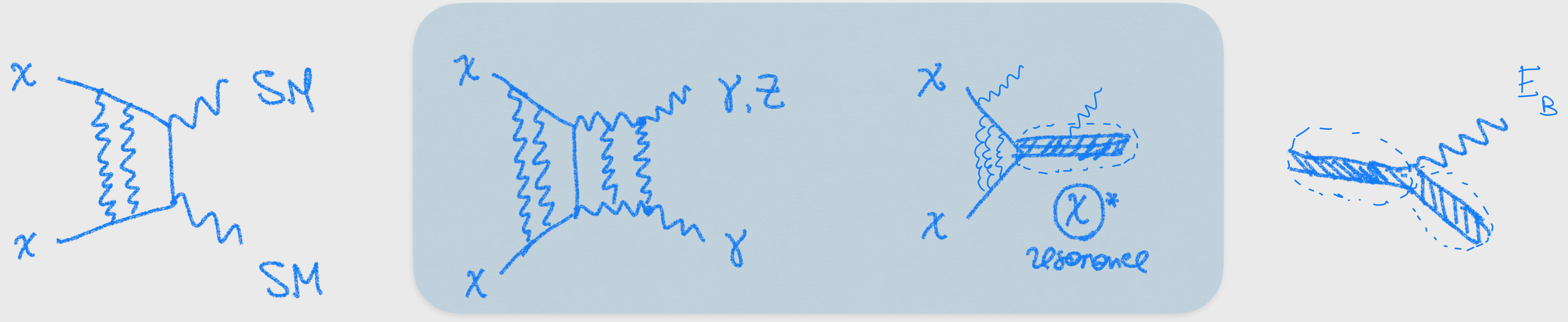
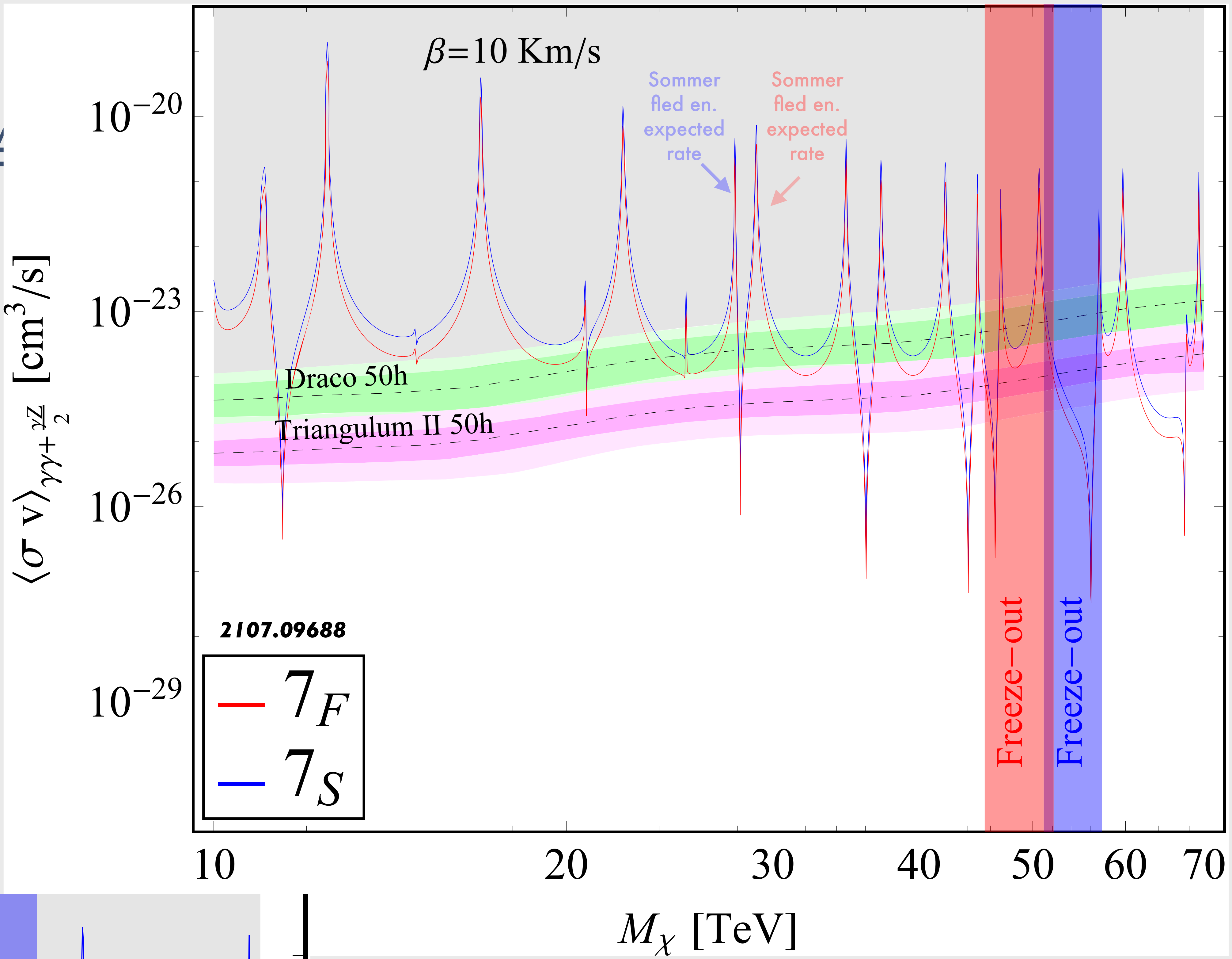
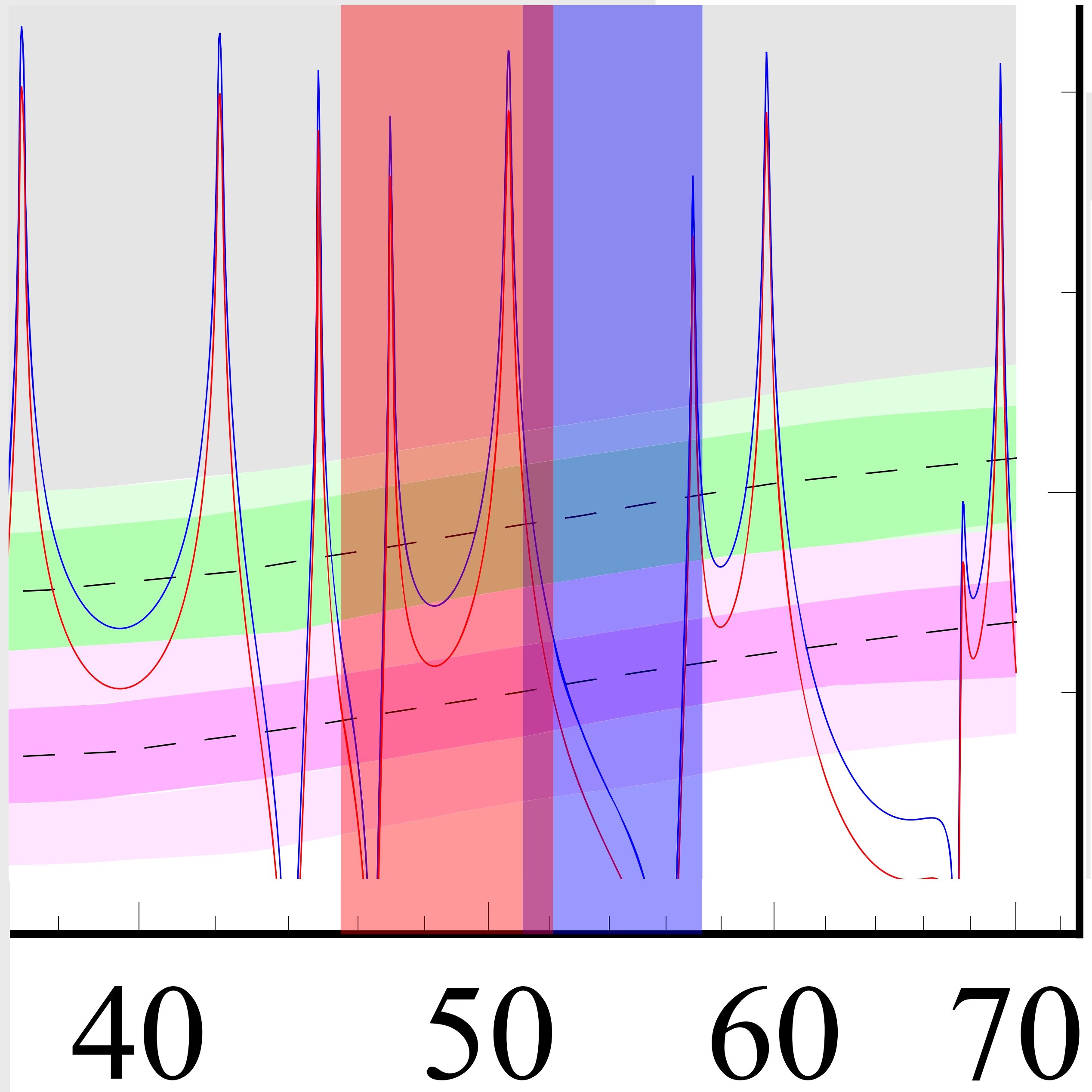
Indirect Detection



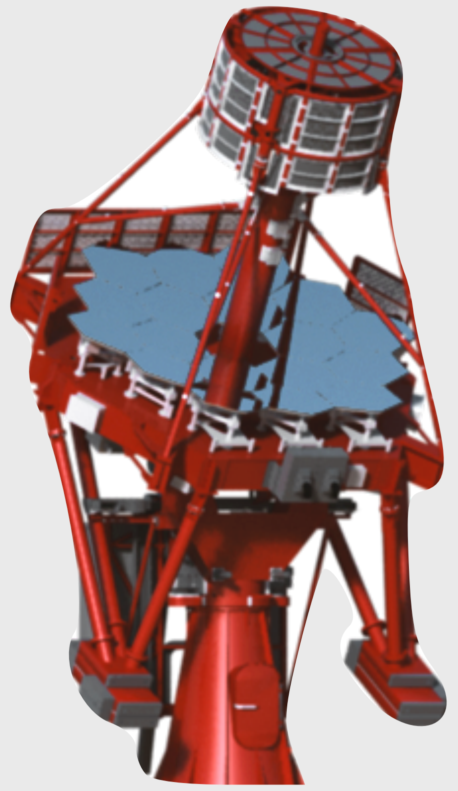


Annihilation in the astrophysical environment result in high-energy SM particle, which can be detector by cosmic rays observatories.

The signature depends on DM mass, possible resonant bound states formation and DM density profile

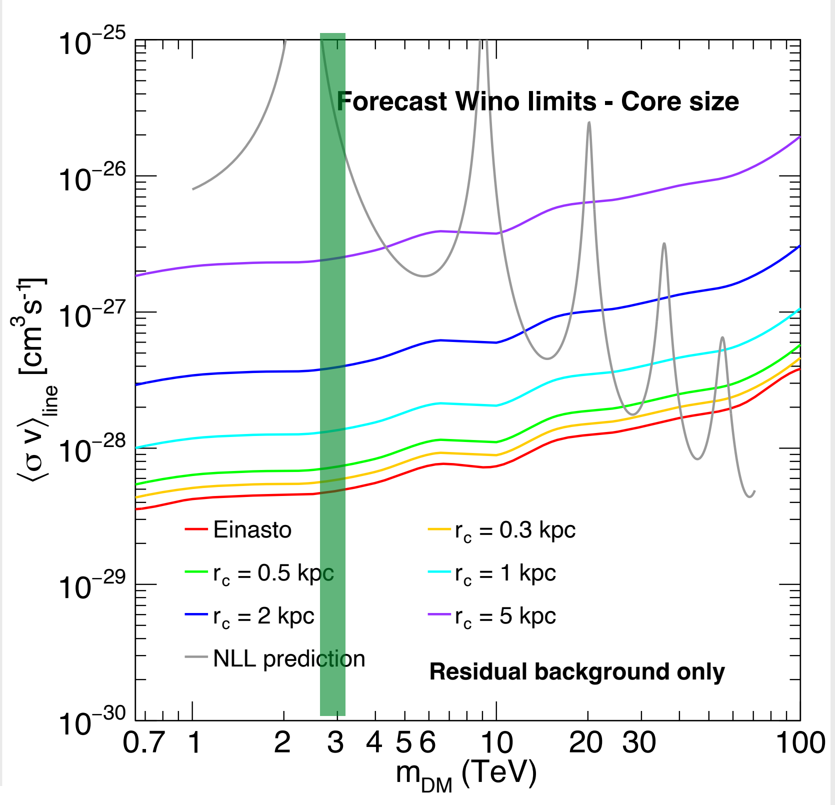


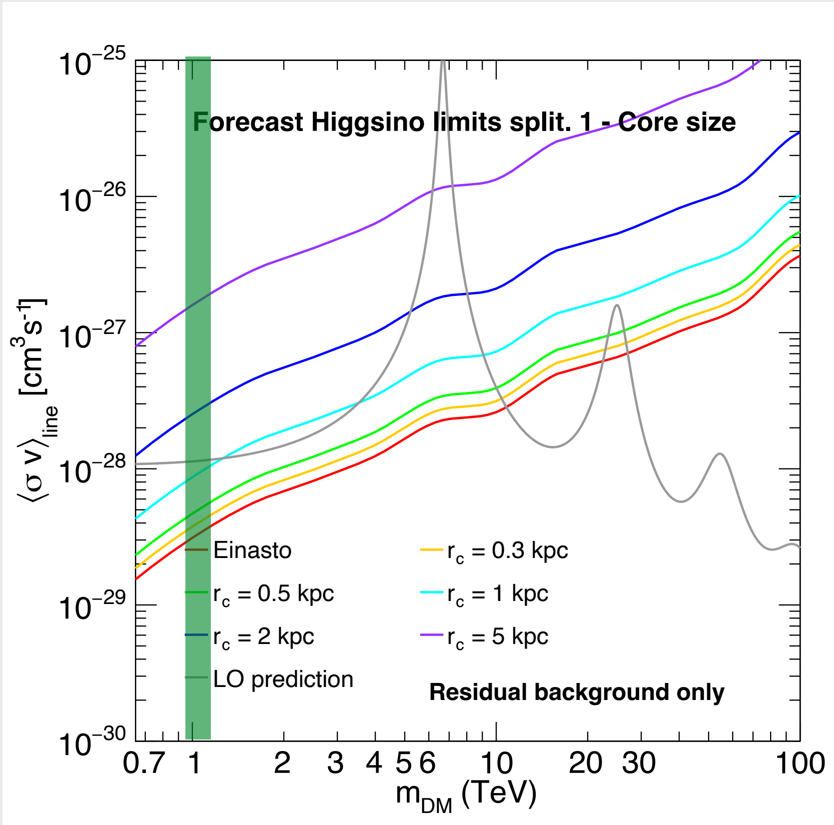
An excess on monochromatic multi-TeV photons would be quite convincing evidence of DM. The model can be even tested by the presence of multiple "lines" from bound states annihilations and lower energy de-excitation



2030s

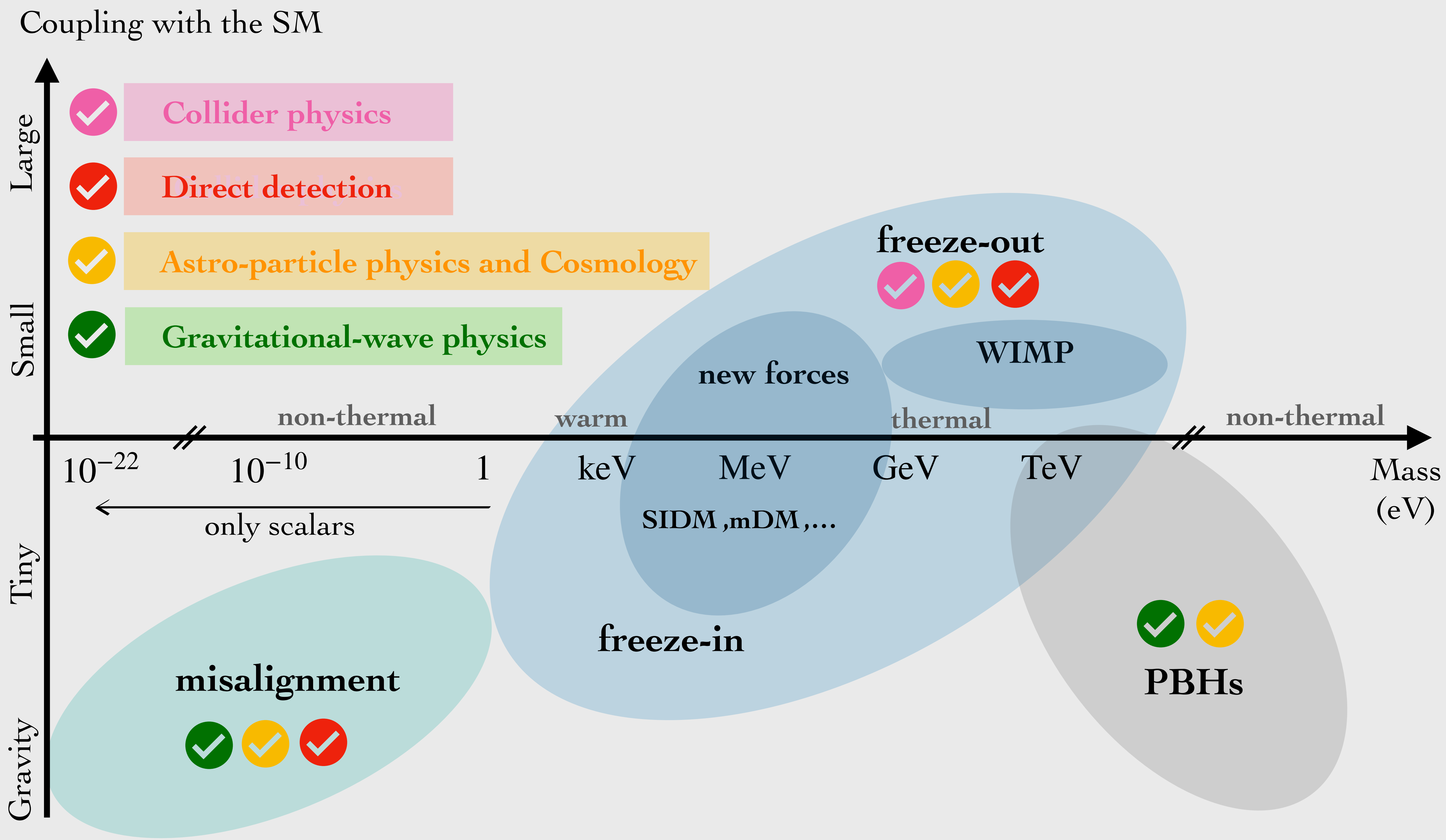
up to 300 TeV, $\frac{\Delta E}{E} \sim 10\,\%$

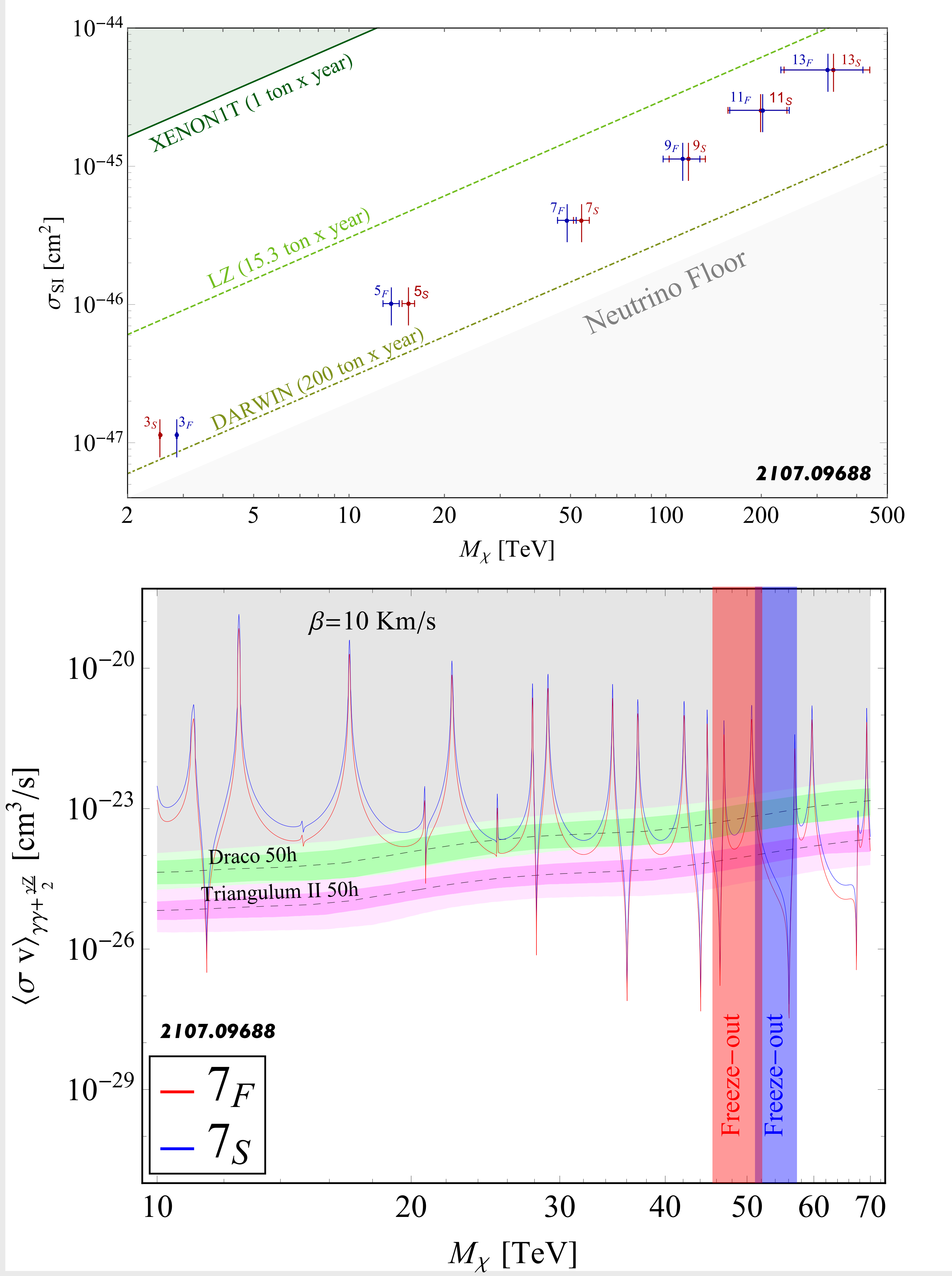




Electroweak Dark Matter: LSP (+NLSP)

INTERPLAY WITH DM DIRECT AND INDIRECT DETECTION EXPERIMENTS





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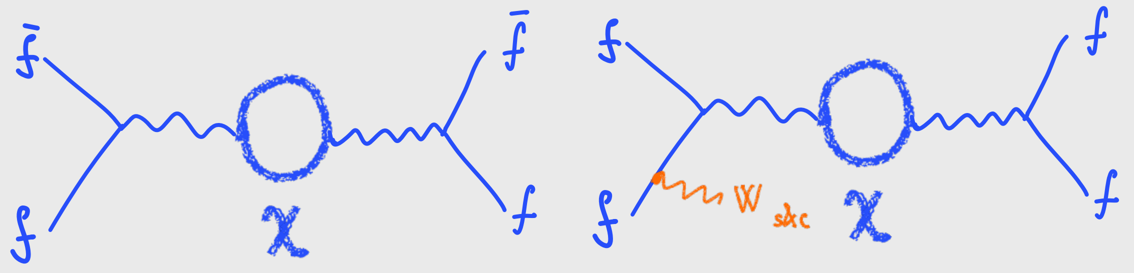
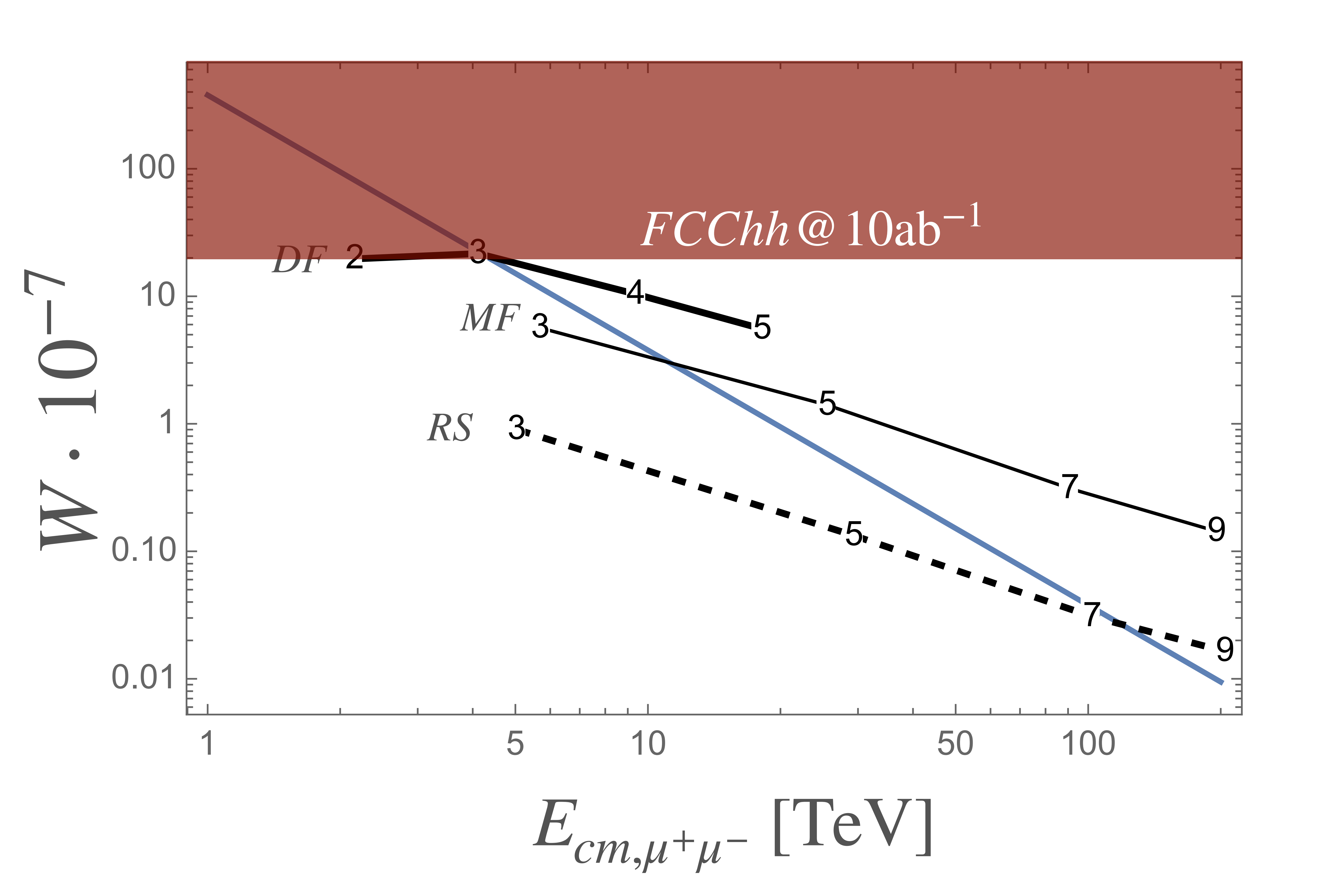


1609.08157		LEP	ATLAS 8	CMS 8	LHC 13		100 TeV	ILC	TLEP	ILC 500 GeV
luminosity		$2\times10^7\,Z$	$19.7\,\text{fb}^{-1}$	$20.3\,\text{fb}^{-1}$	$0.3\,\text{ab}^{-1}$	$3\,\text{ab}^{-1}$	$10\,\text{ab}^{-1}$	$10^9\,Z$	$10^{12}\,Z$	$3\,\text{ab}^{-1}$
NC	$W\times10^4$	$[-19,3]$	$[-3,15]$	$[-5,22]$	±1.5	±0.8	±0.04	±3	±0.7	±0.3
	$Y\times10^4$	$[-17,4]$	$[-4,24]$	$[-7,41]$	±2.3	±1.2	±0.06	±4	±1	±0.2
CC	$W\times10^4$	—	±3.9		±0.7	±0.45	±0.02	—	—	—



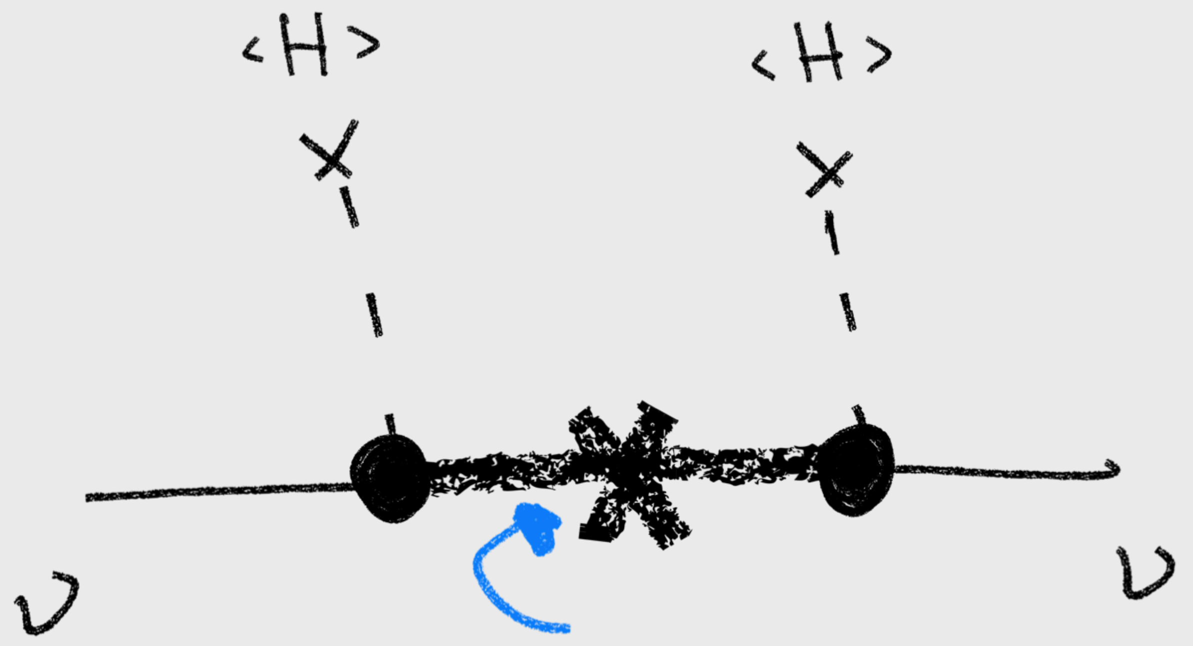
2202.10509	exclusive $W\times10^7$	inclusive $W\times10^7$
3 TeV	$[-53, 53]$	$[-41, 41]$
10 TeV	$[-5.71, 5.71]$	$[-3.71, 3.71]$
14 TeV	$[-3.11, 3.11]$	$[-1.90, 1.90]$
30 TeV	$[-0.80, 0.80]$	$[-0.42, 0.42]$

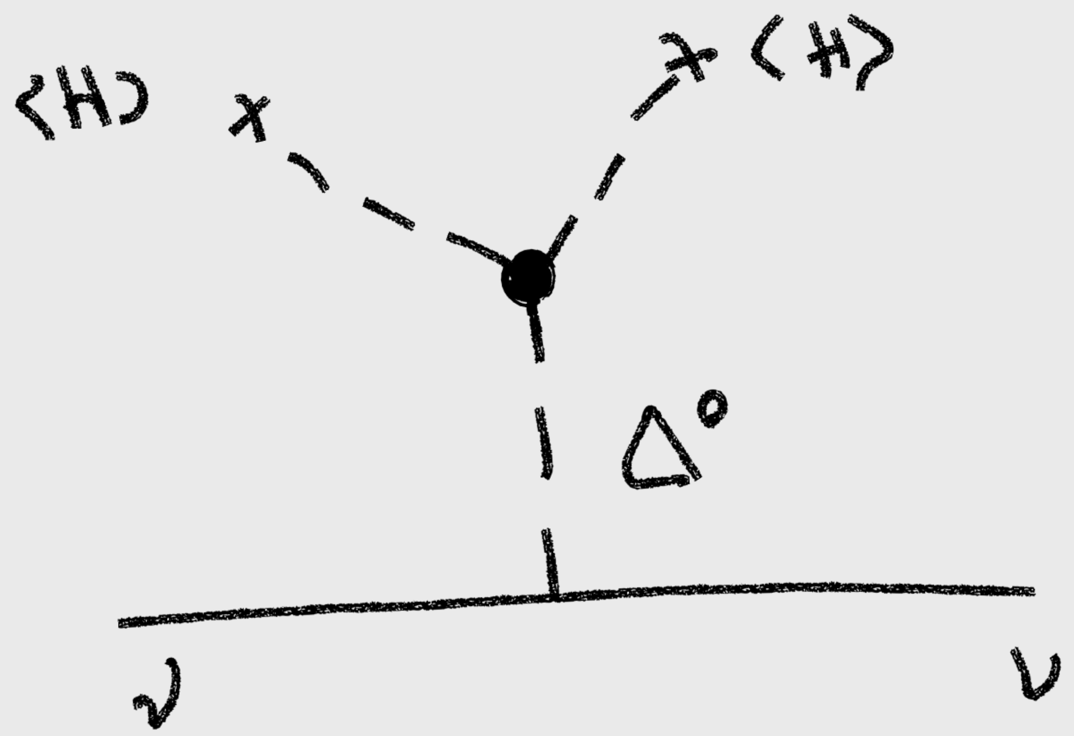
10 TeV	DL	$e^{\text{DL}}-1$	SL$(\frac{\pi}{2})$
$\ell_L \to \ell'_L$	-0.82	-0.56	0.33
$\ell_L \to q_L$	-0.78	-0.54	0.34
$\ell_L \to e_R$	-0.56	-0.43	0.17
$\ell_L \to u_R$	-0.48	-0.38	0.15
$\ell_L \to d_R$	-0.43	-0.35	0.13
$\ell_R \to \ell'_L$	-0.56	-0.43	0.17
$\ell_R \to q_L$	-0.53	-0.41	0.16
$\ell_R \to \ell'_R$	-0.30	-0.26	0.09
$\ell_R \to u_R$	-0.22	-0.20	0.07
$\ell_R \to d_R$	-0.17	-0.16	0.05

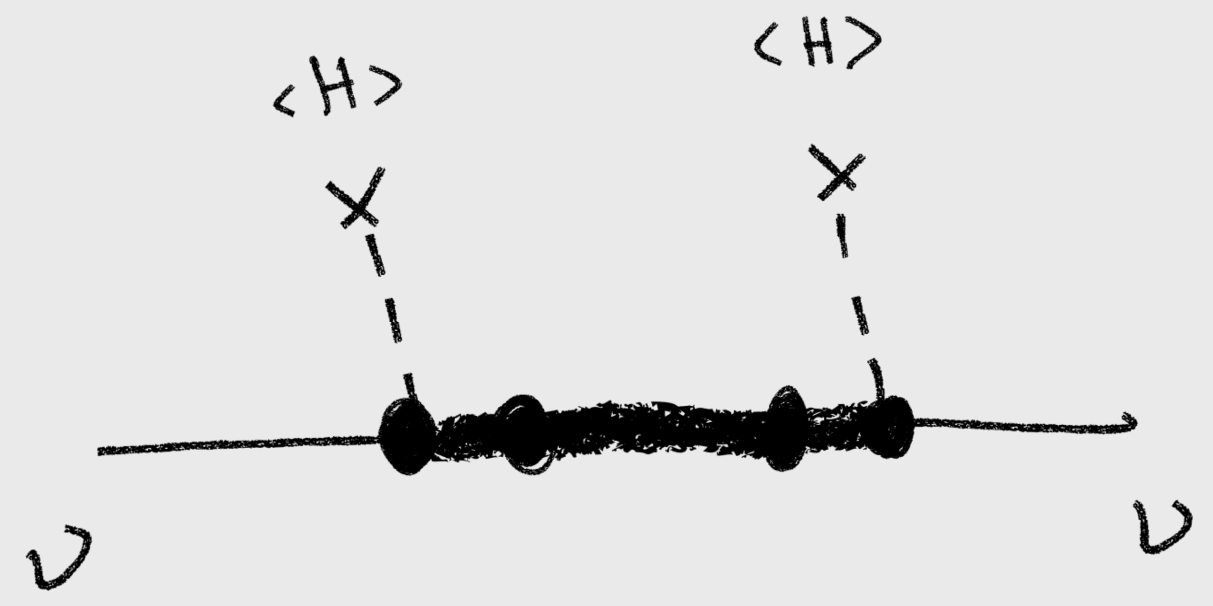
A word about flavor

Neutrino mass mechanisms

LEPTON NUMBER BREAKING







$m_\nu = \frac{(coupling)^2 < H >^2}{M_{heavy}} \to$ SMALL

$M_{heavy} \to$ LARGE

$m_\nu = \frac{(coupling)^2 < H >^2}{M_{heavy}} \to$ SMALL

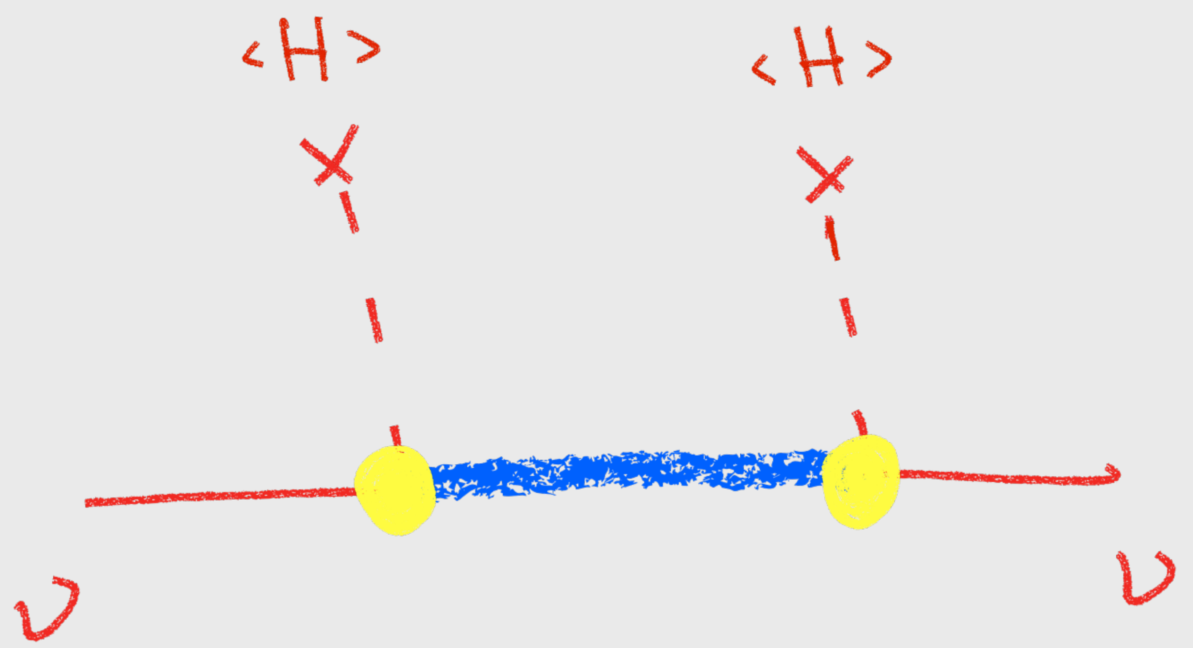
coupling → SMALL

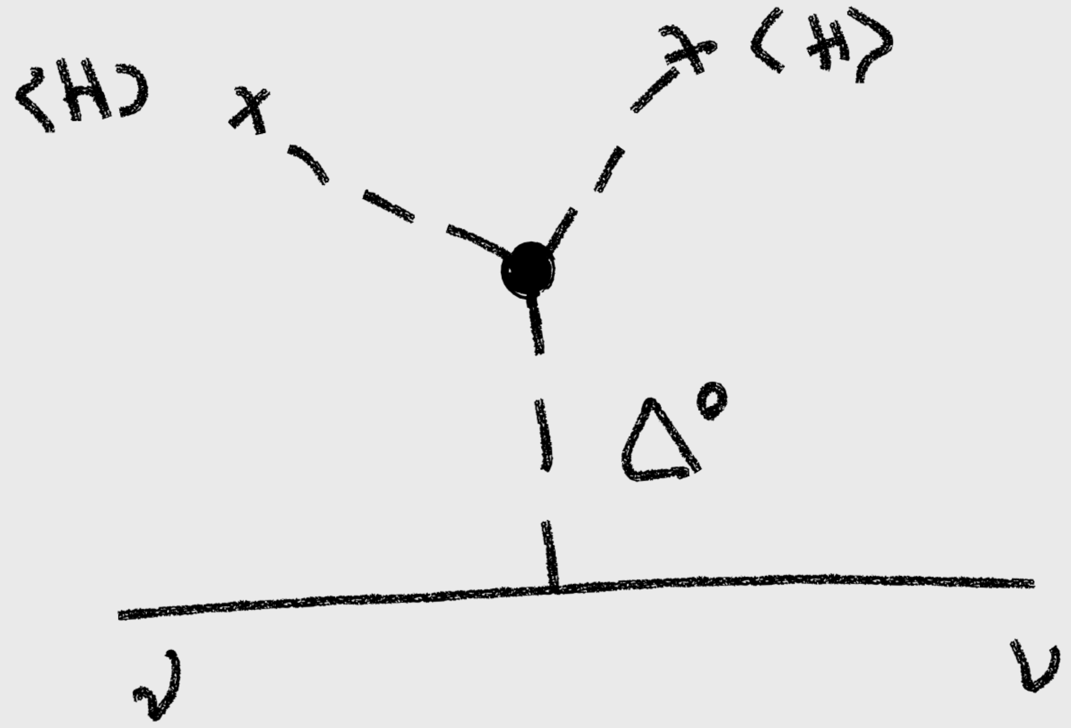
$m_\nu = \mu \cdot \frac{(coupling)^2 < H >^2}{M^2_{heavy}} \to$ SMALL

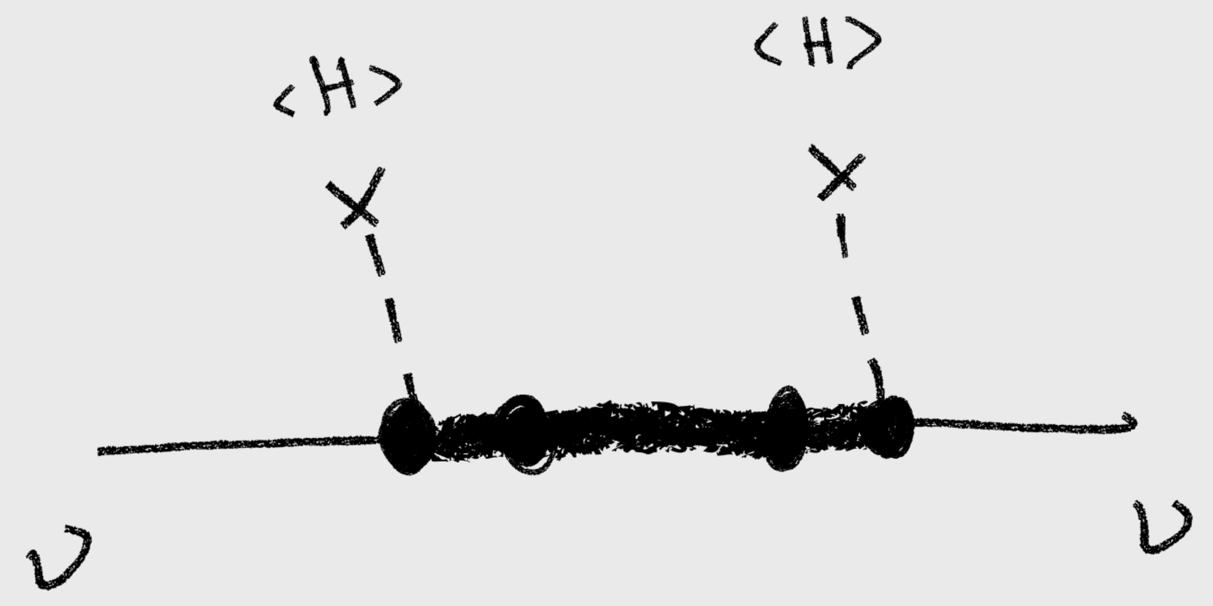
$\mu \to$ SMALL

Neutrino mass mechanisms

LEPTON NUMBER BREAKING







$$m_\nu = \frac{(coupling)^2 < H >^2}{M_{heavy}} \to \text{SMALL}$$

$M_{heavy} \to$ LARGE

$$m_\nu = \frac{(coupling)^2 < H >^2}{M_{heavy}} \to \text{SMALL}$$

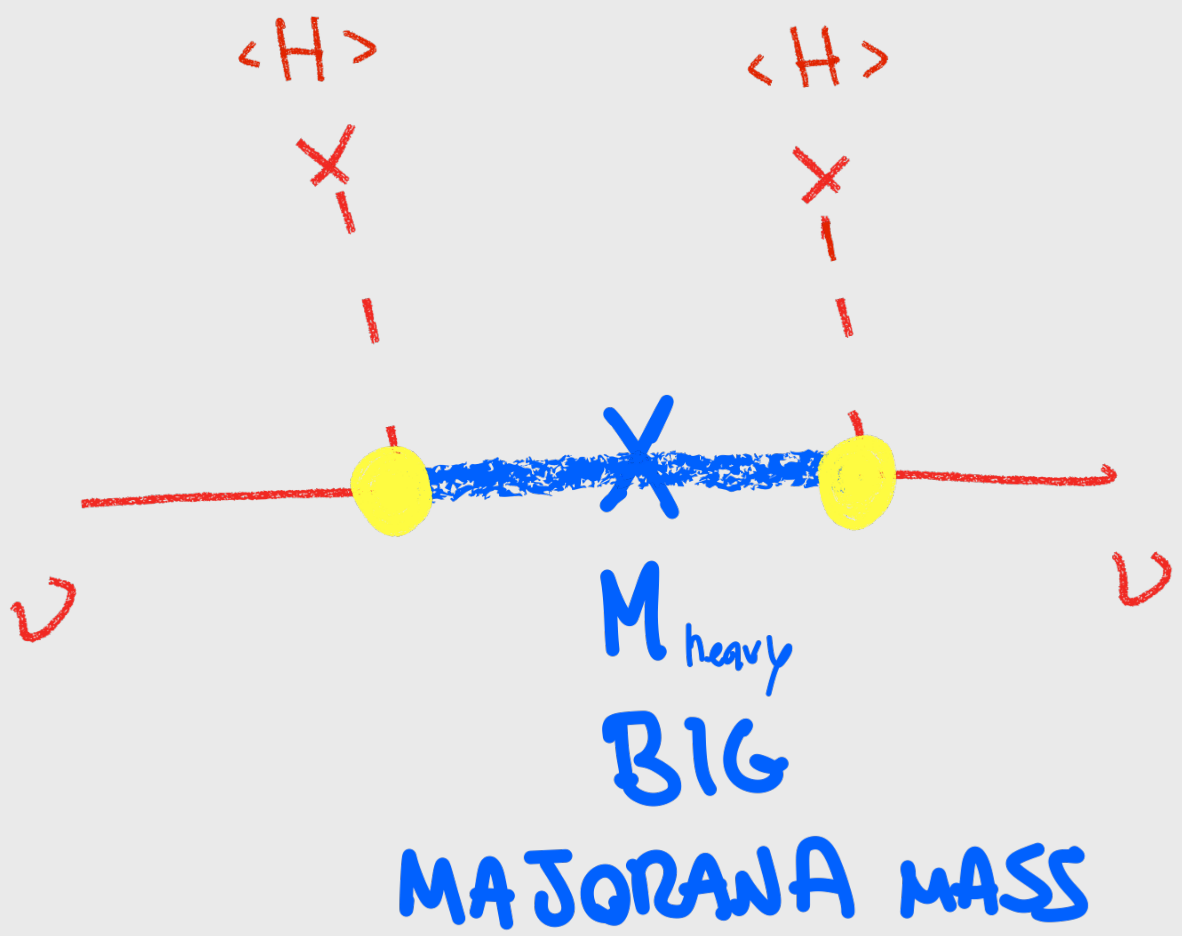
coupling → SMALL

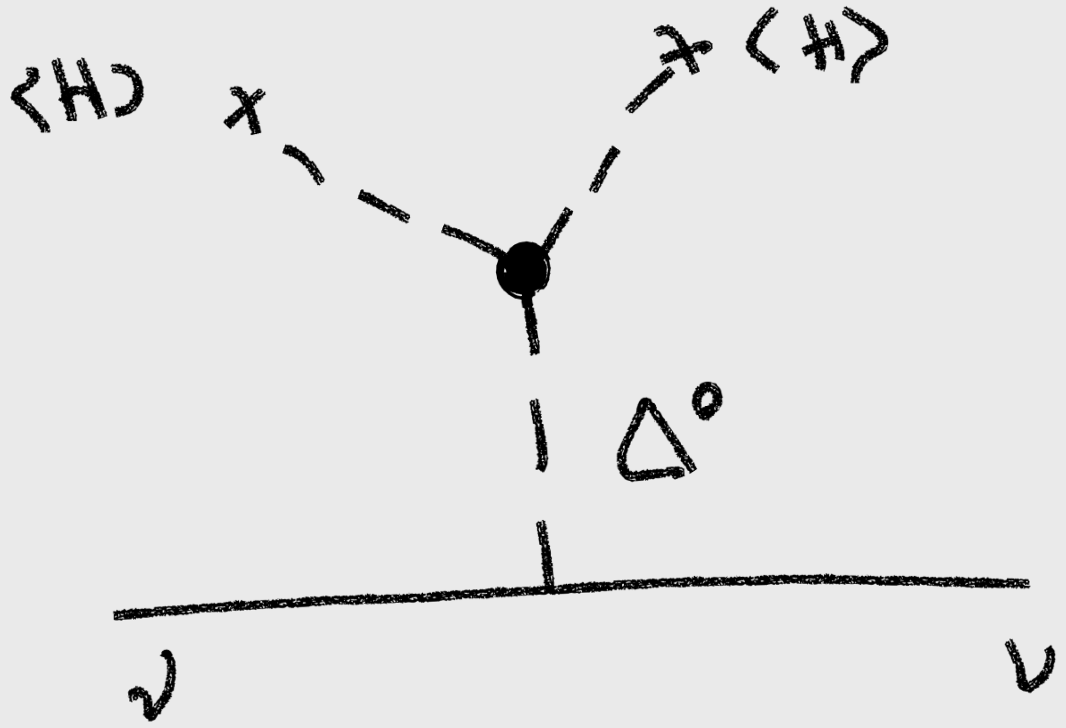
$$m_\nu = \mu \cdot \frac{(coupling)^2 < H >^2}{M_{heavy}^2} \to \text{SMALL}$$

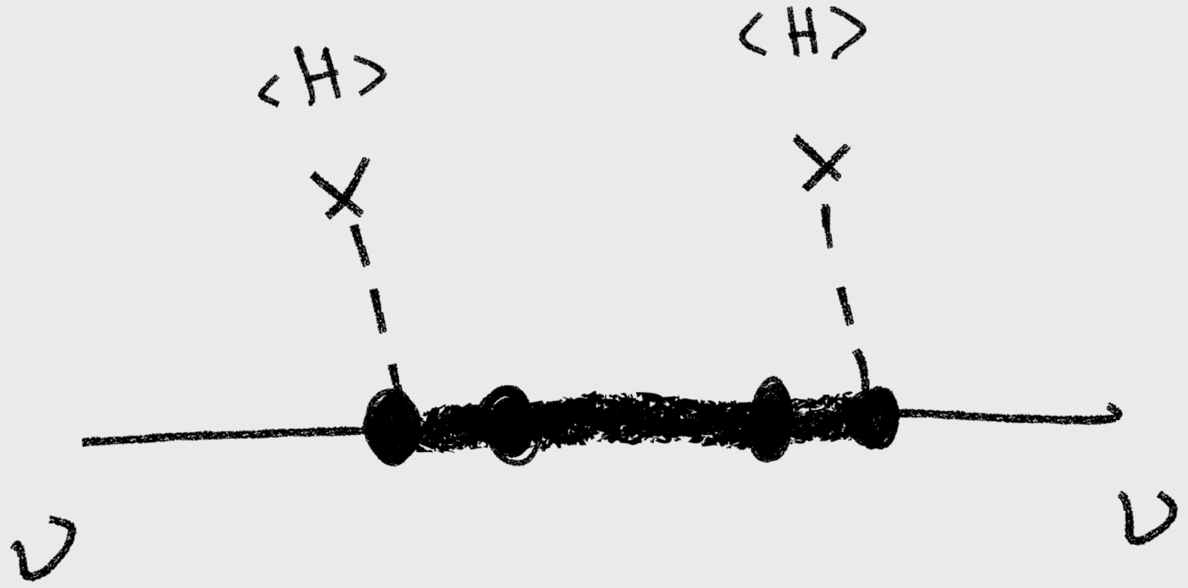
$\mu \to$ SMALL

Neutrino mass mechanisms

LEPTON NUMBER BREAKING







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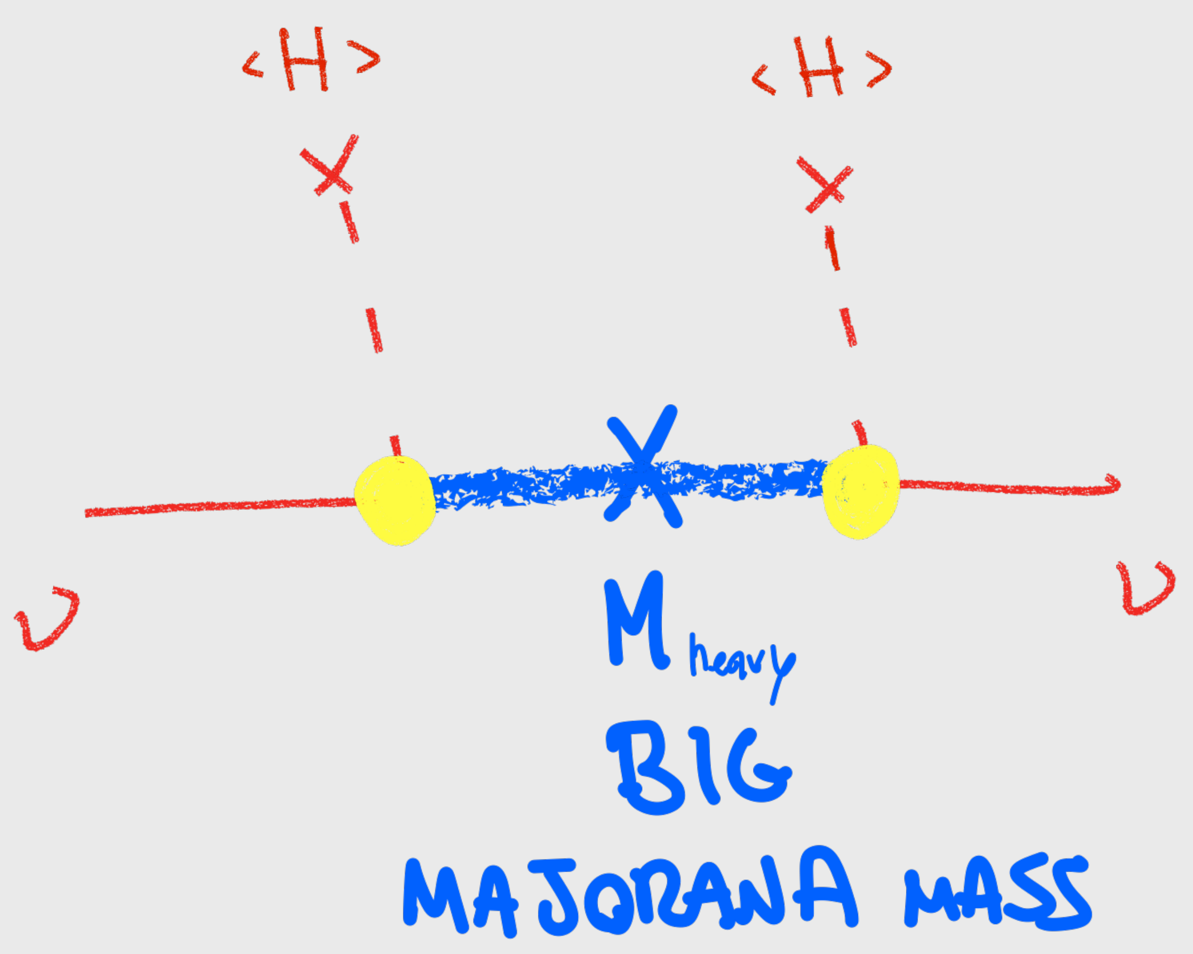

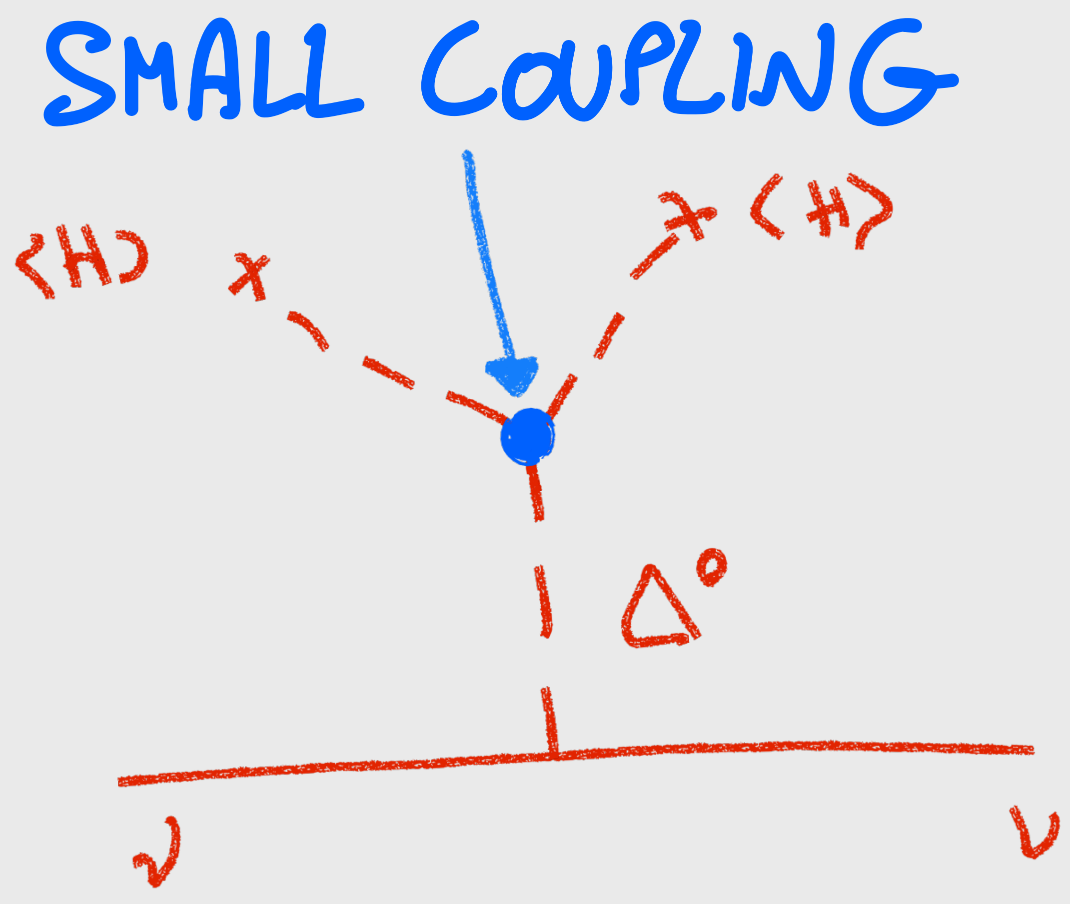

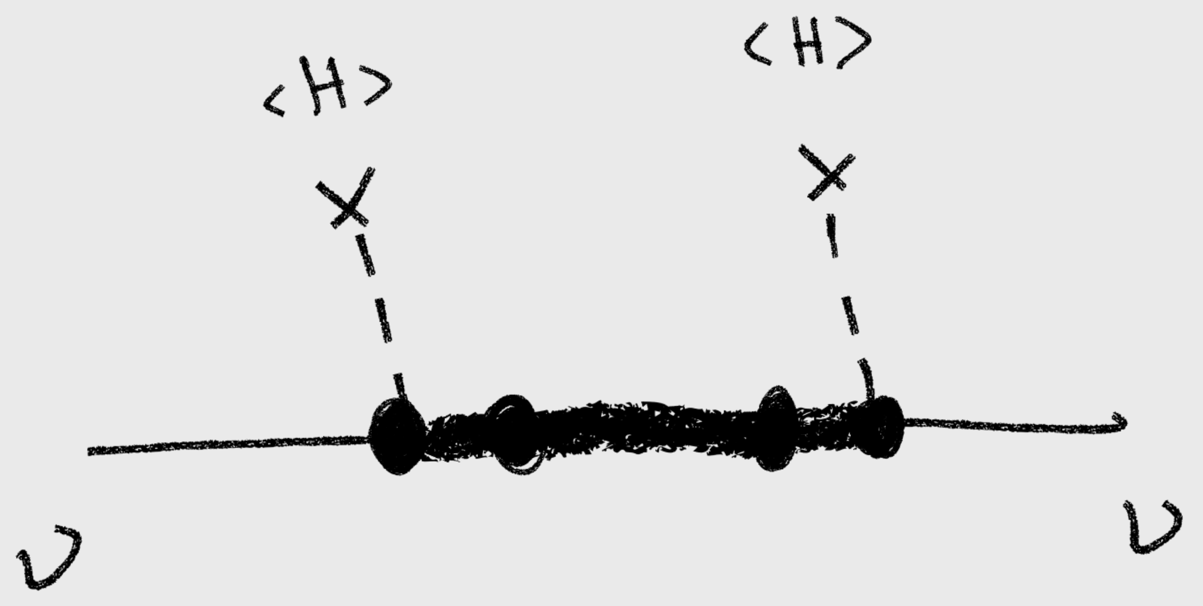

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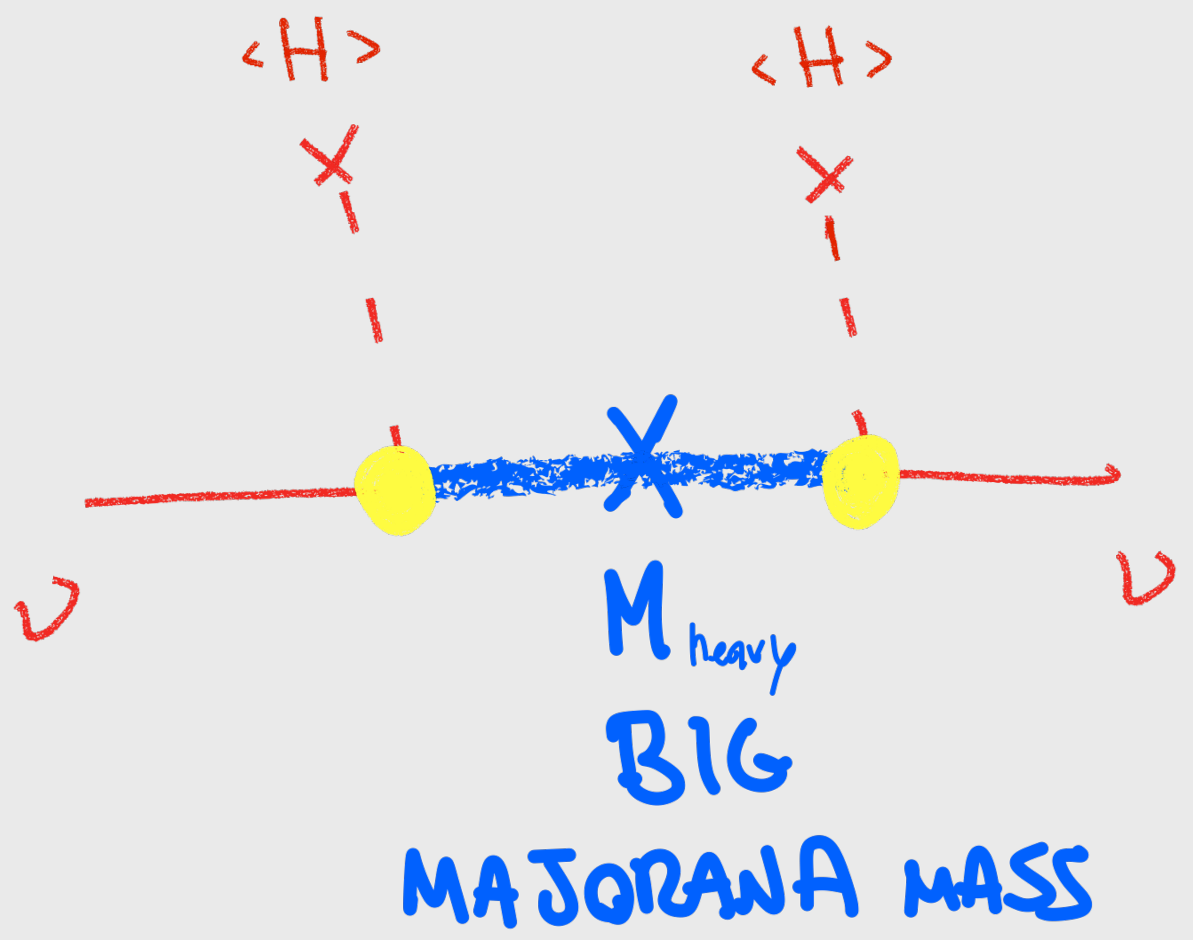
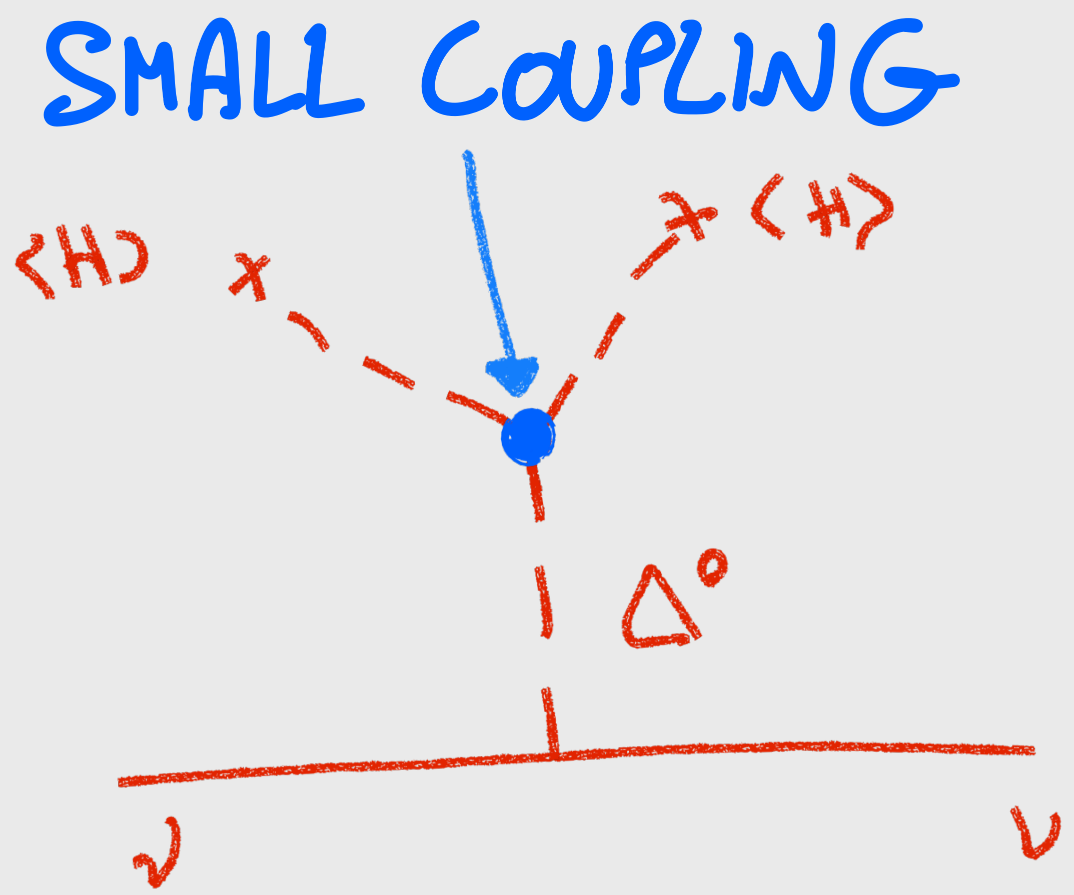
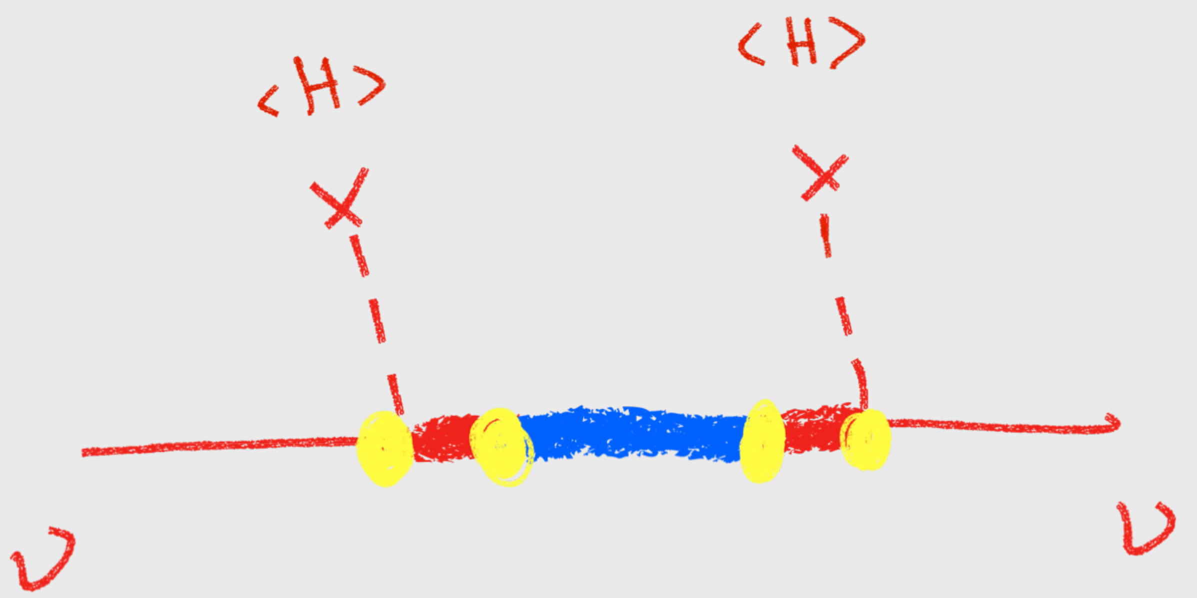
LEPTON NUMBER BREAKING







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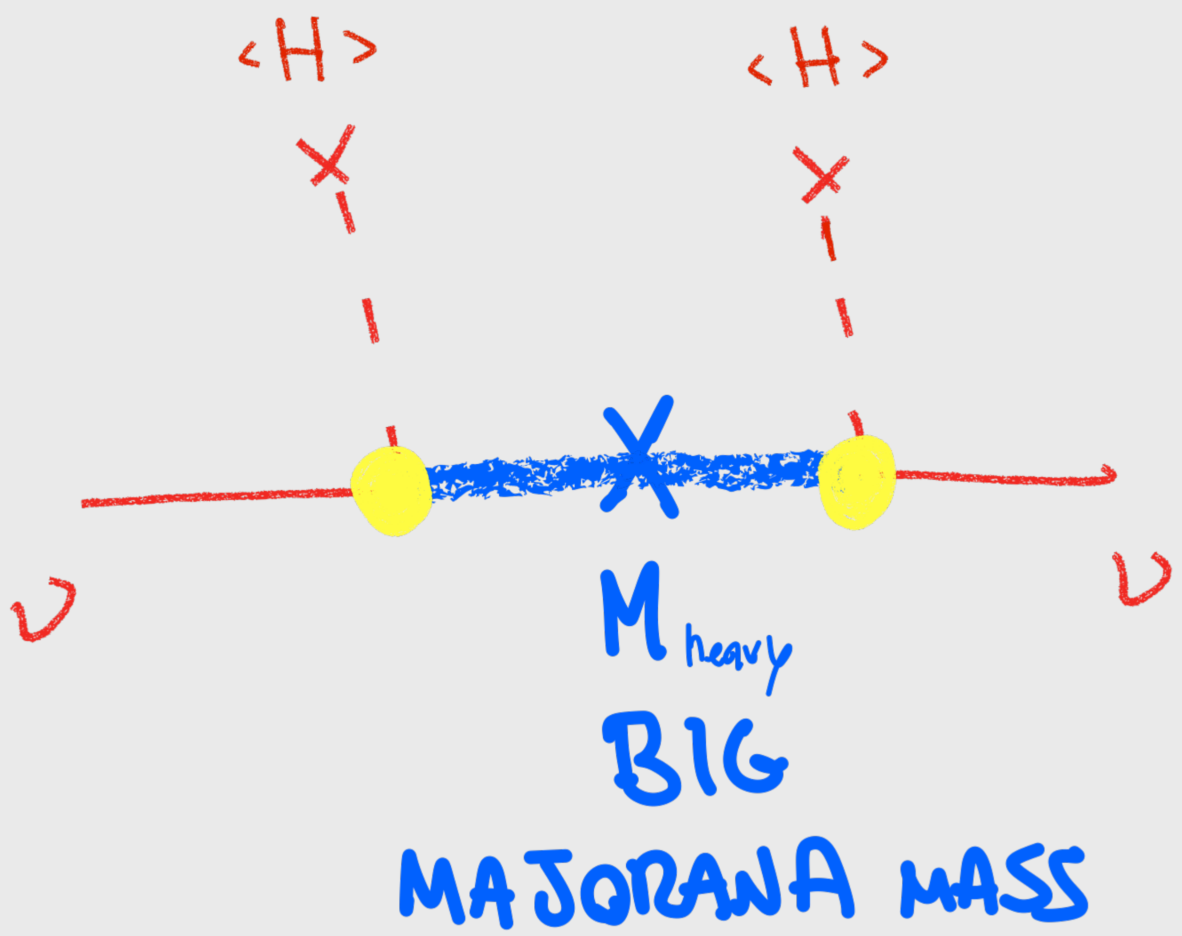

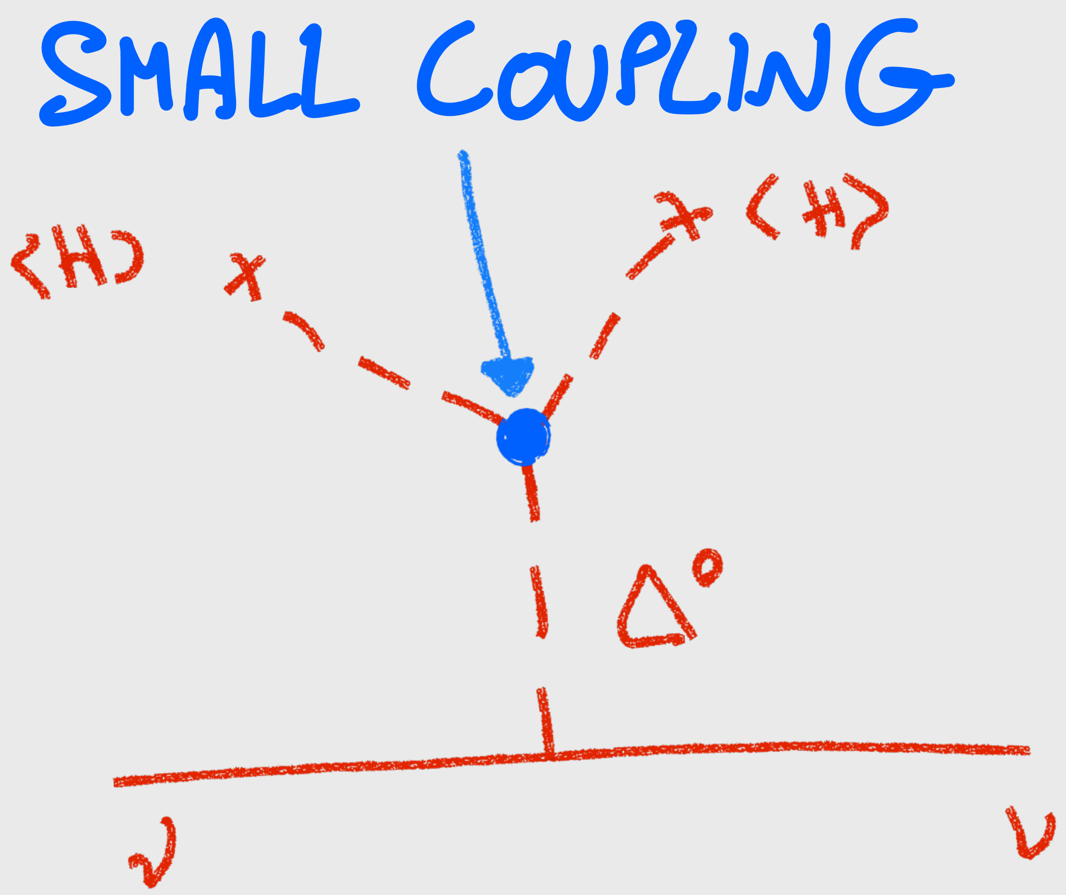

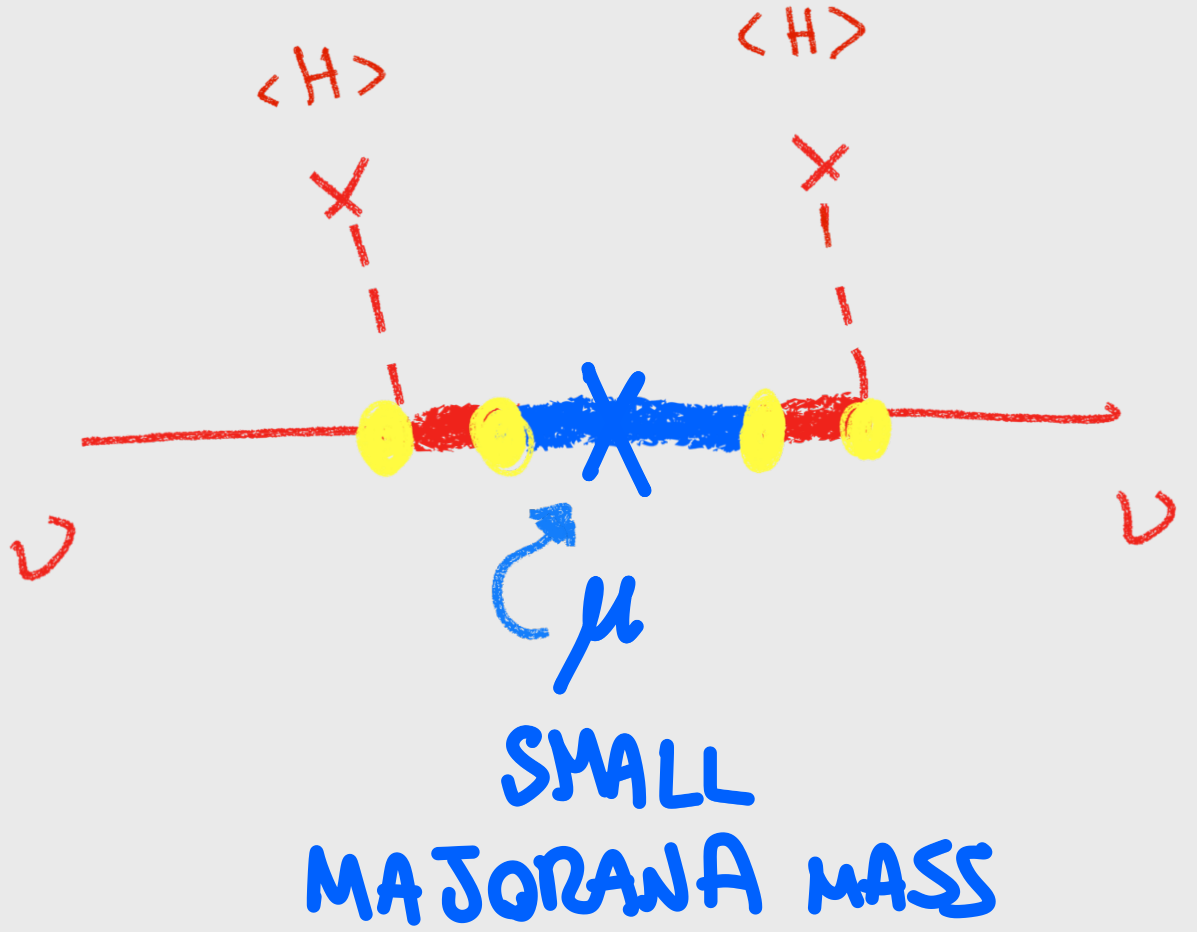

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Neutrino mass mechanisms

LEPTON NUMBER BREAKING

- There are plentiful of mechanisms to generate the neutrino masses. Similar situation for other "flavor problems"
- Only corners of parameter-space can be investigated at colliders or any other experiment (i.e. the breaking of lepton number may originate at an unaccessible high scale)

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coupling $\rightarrow$ SMALL

$\mu \rightarrow$ SMALL

Learning from not discovering

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)

Higgs boson mass
(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)
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Rev. Mod. Phys. 68, 951 - Cahn, Robert N. - The eighteen arbitrary parameters of the standard model in your everyday life
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Cosmological Constant (galaxy formation) — c

Fermi constant (periodic table) — μ^2

Higgs boson mass (meta-)stability of the Universe — λ

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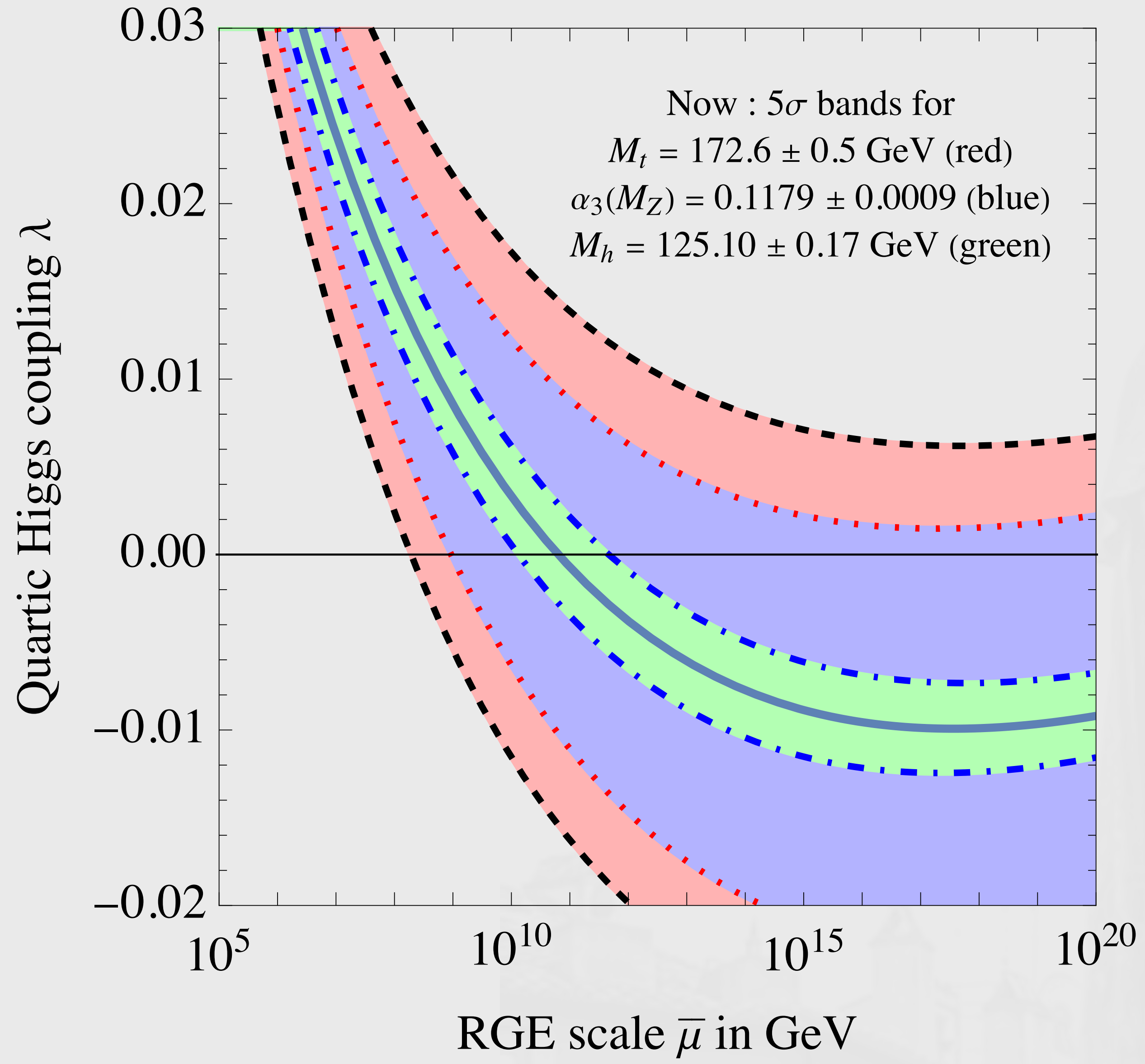
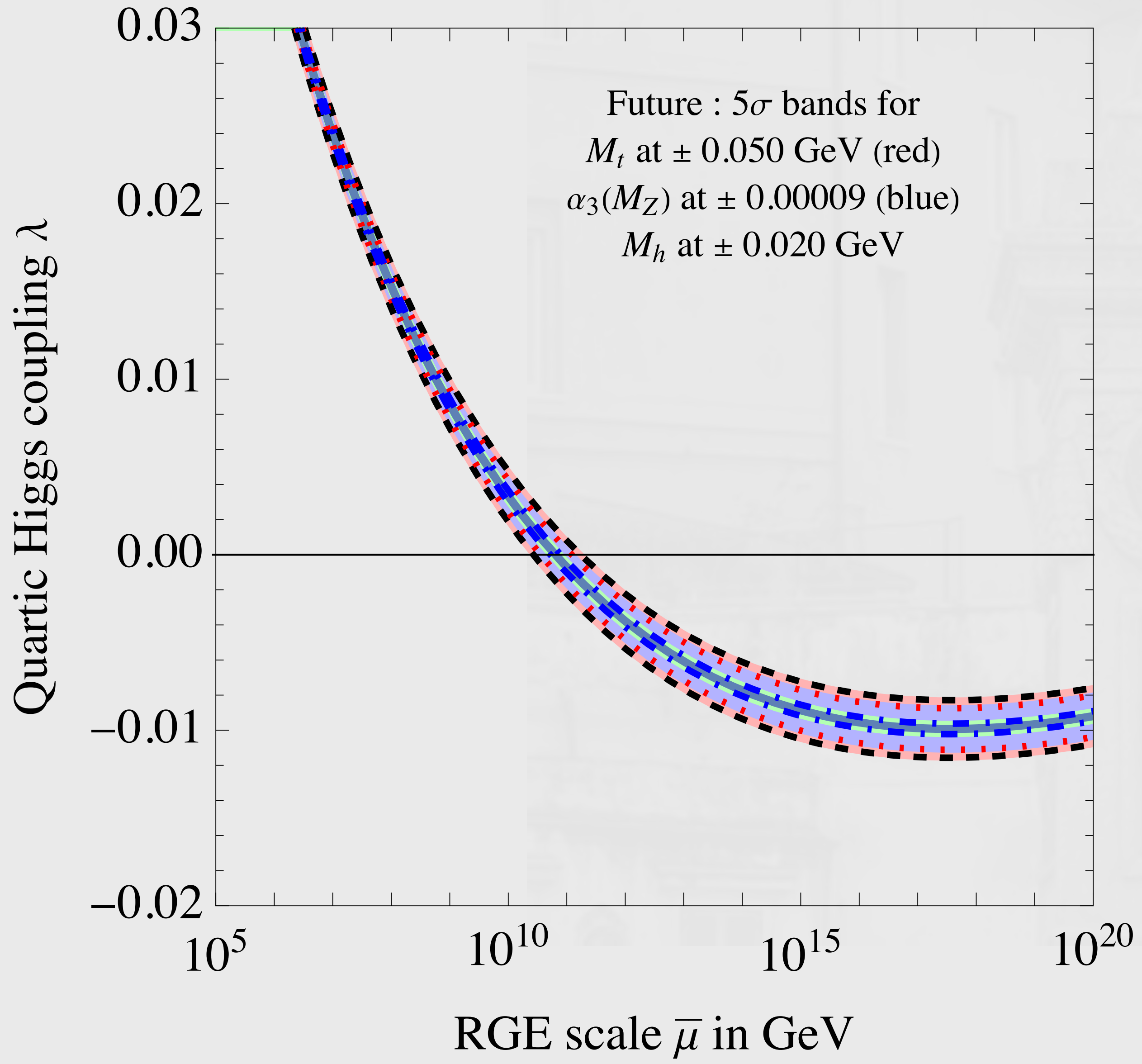
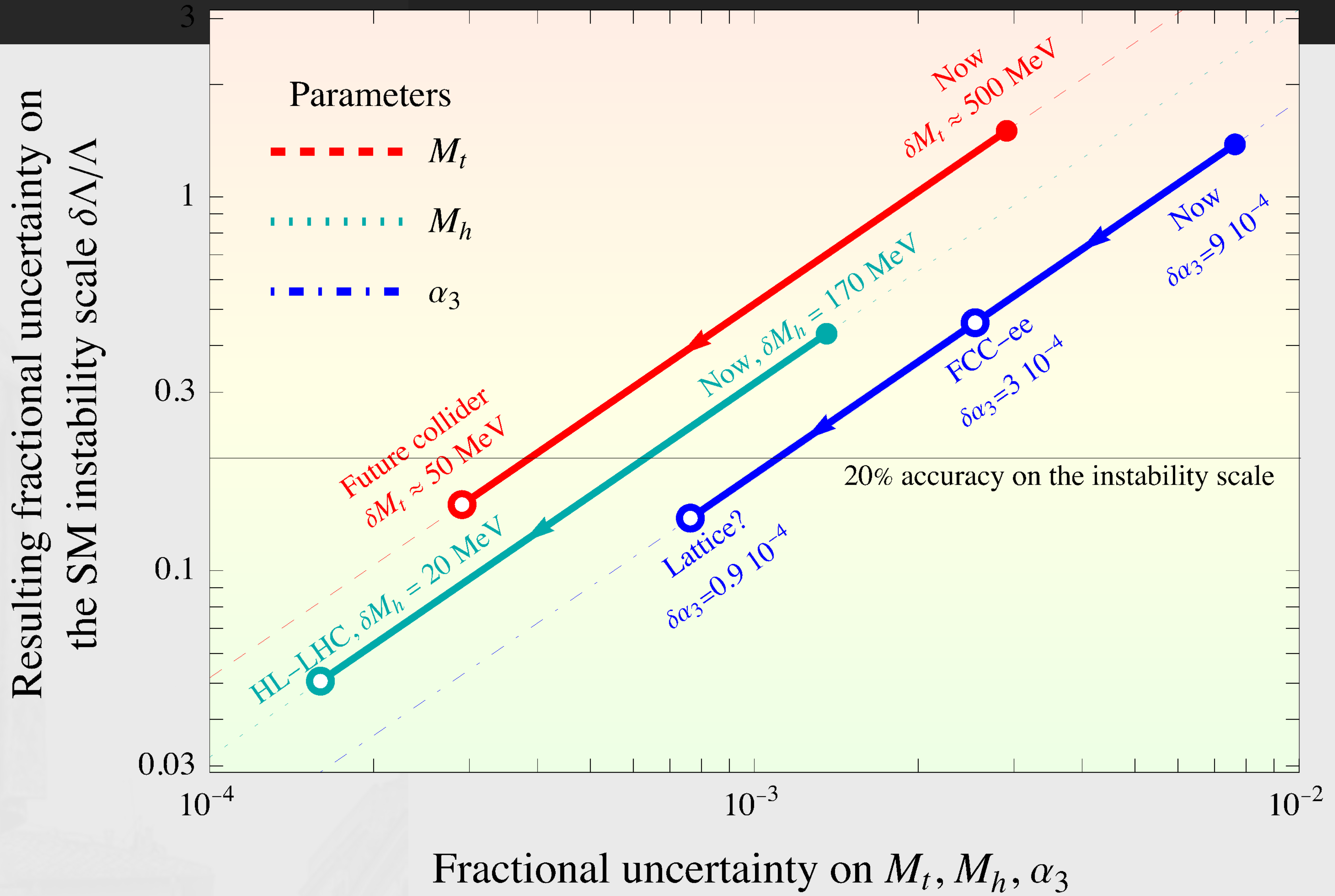
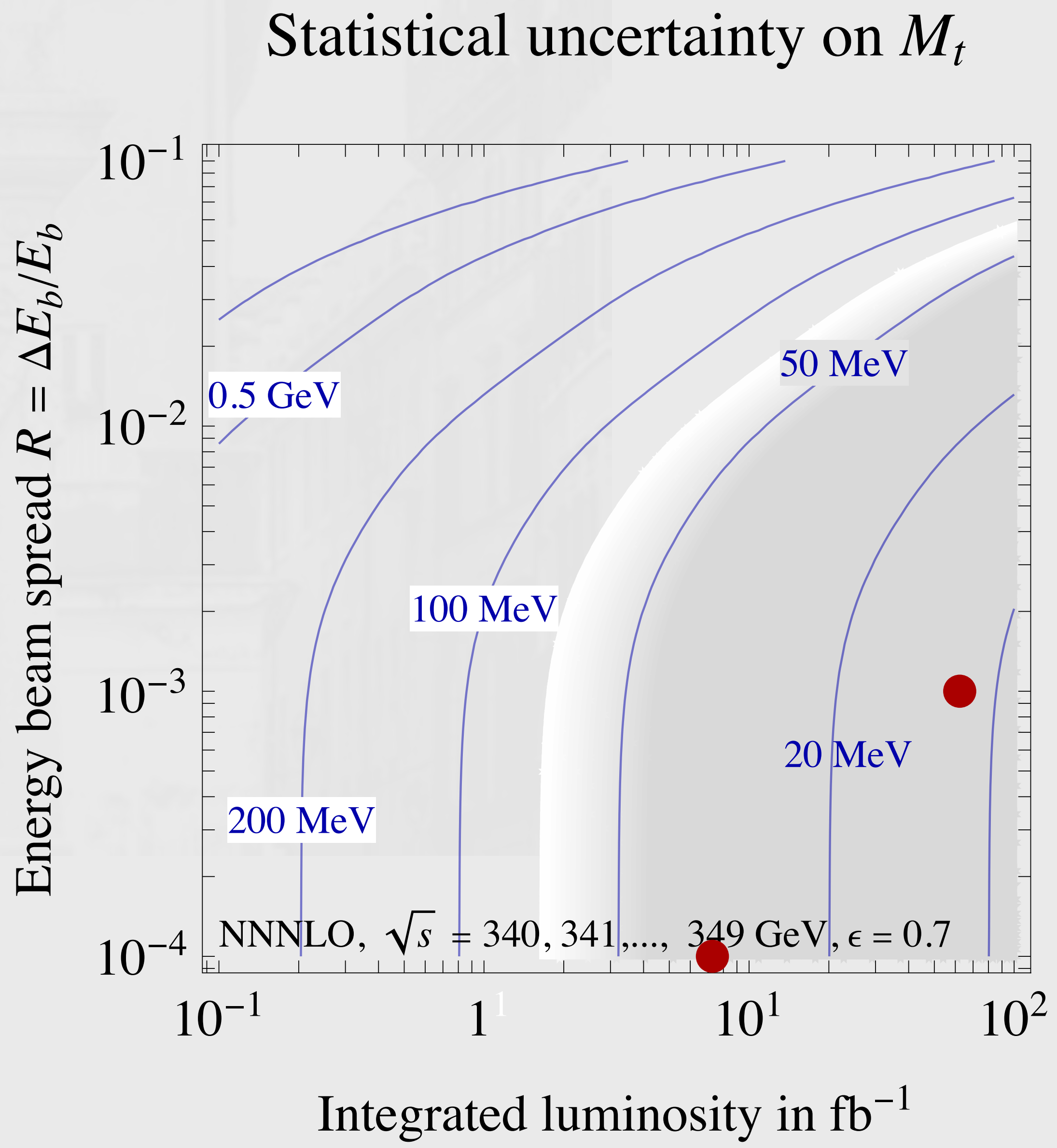
2203.17197

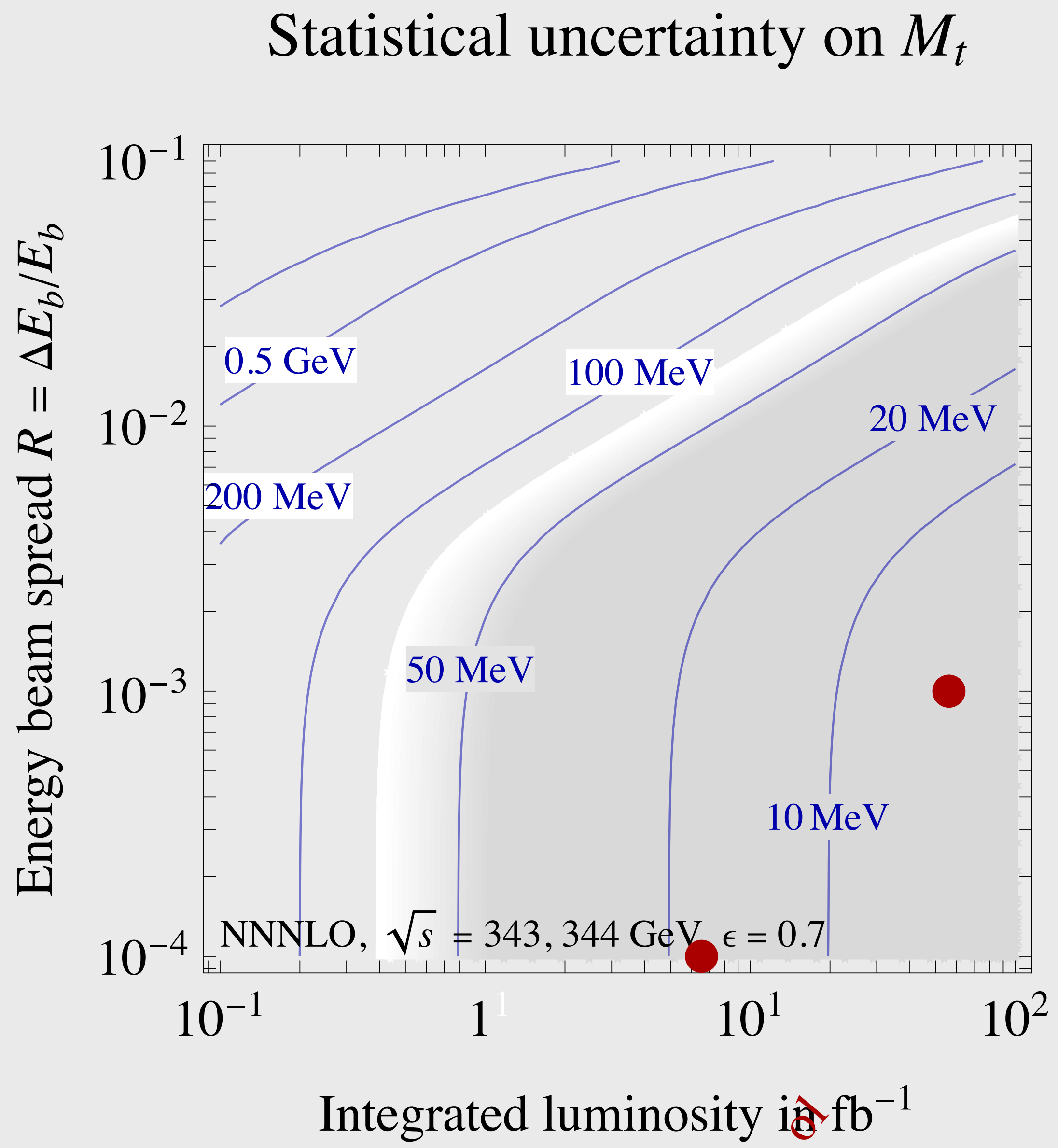
Are we ready for a revolution?





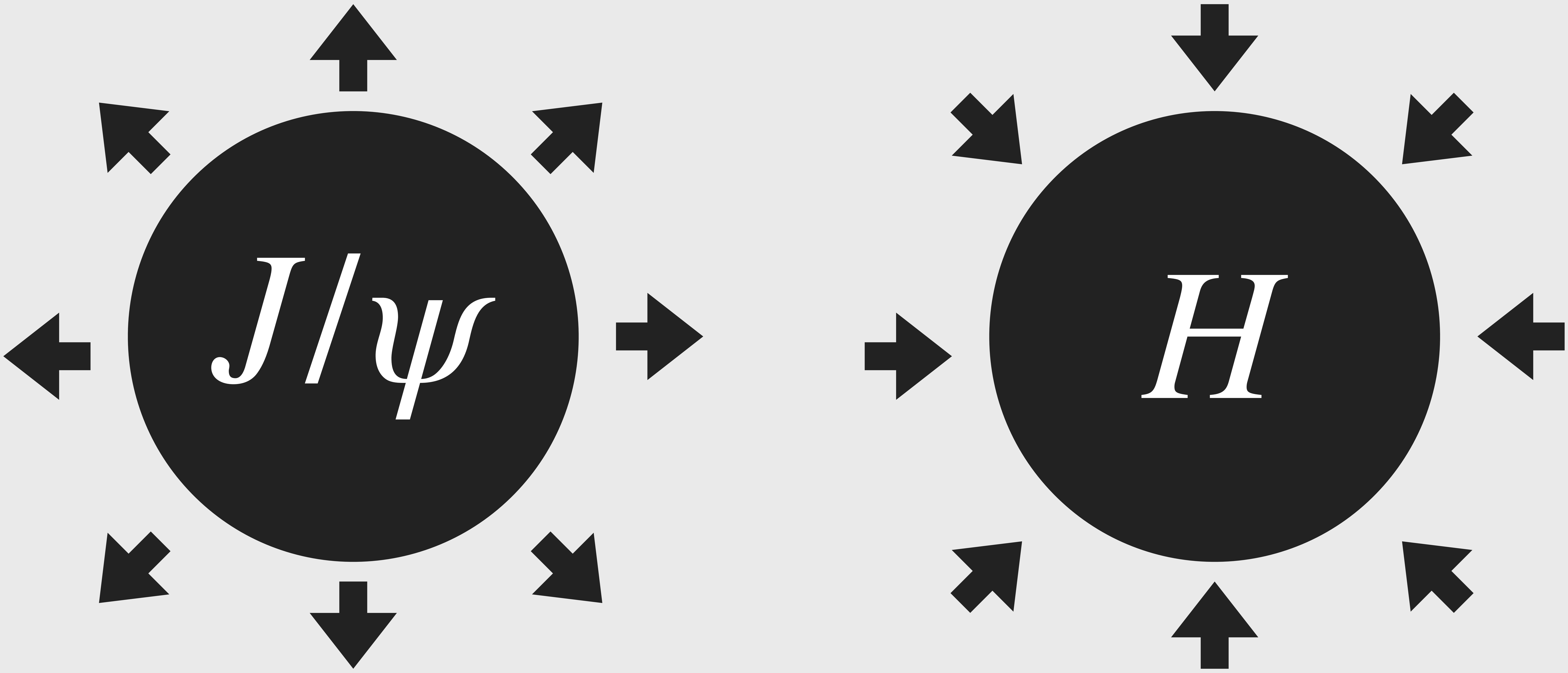






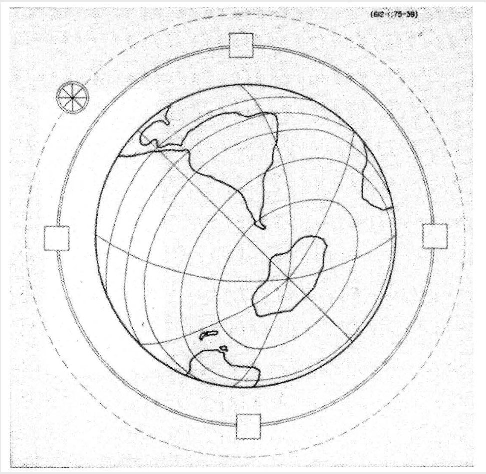
A driver for cooperation

Driver for Cooperation

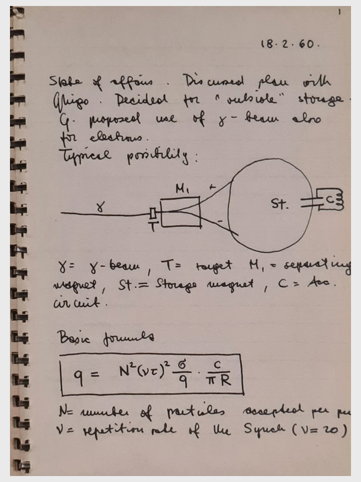


Driver for Cooperation

1954



1960



1968-

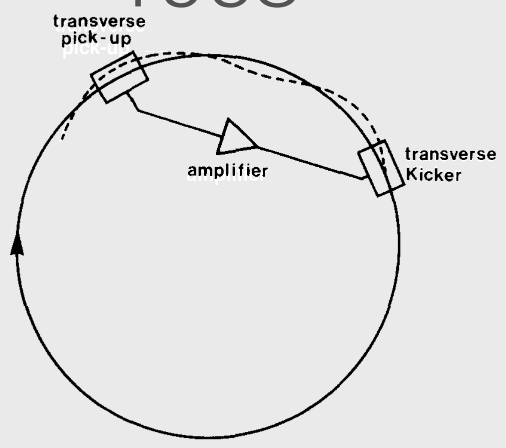


Fig. 1.1. Block diagram of a betatron cooling system.

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.

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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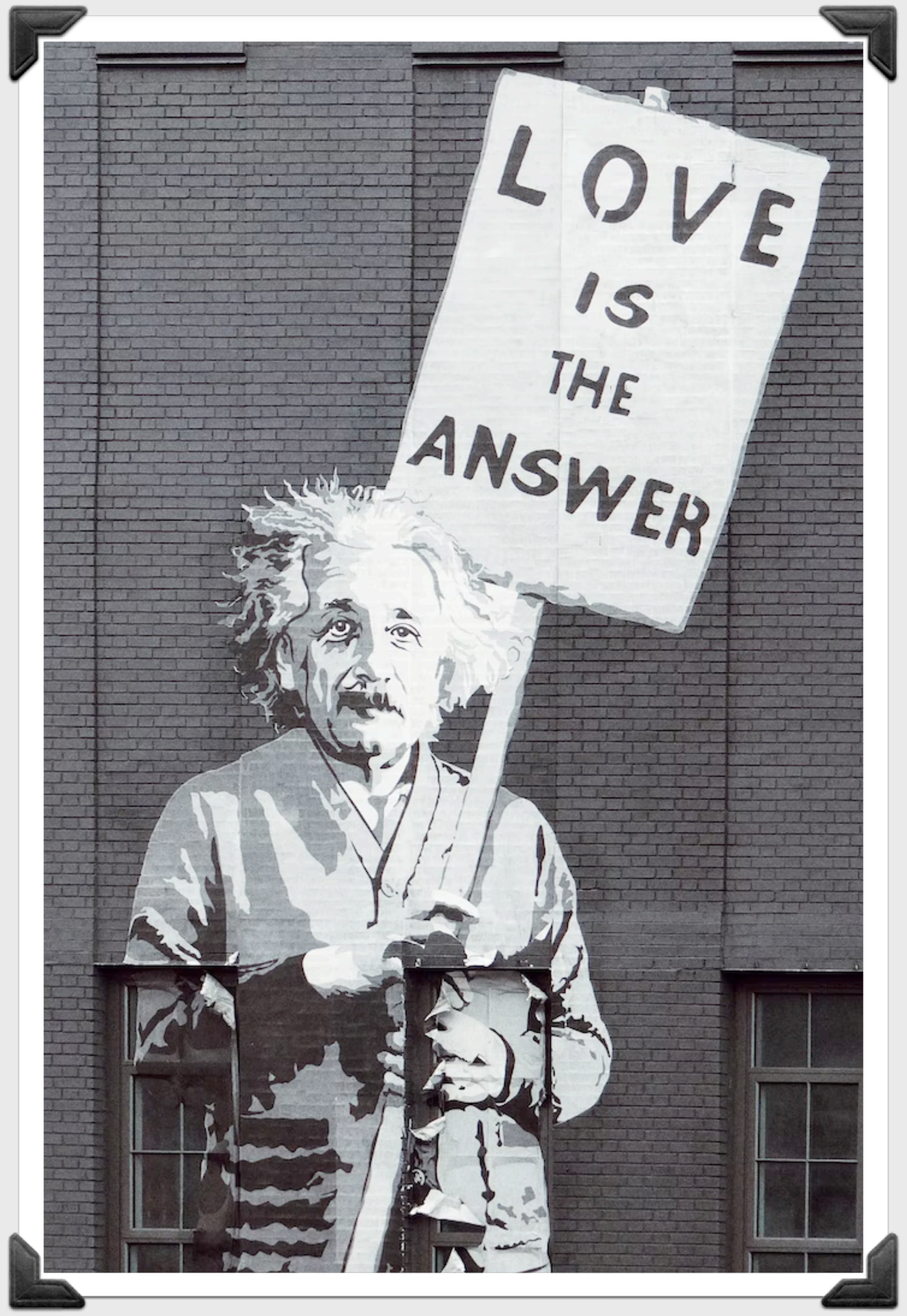
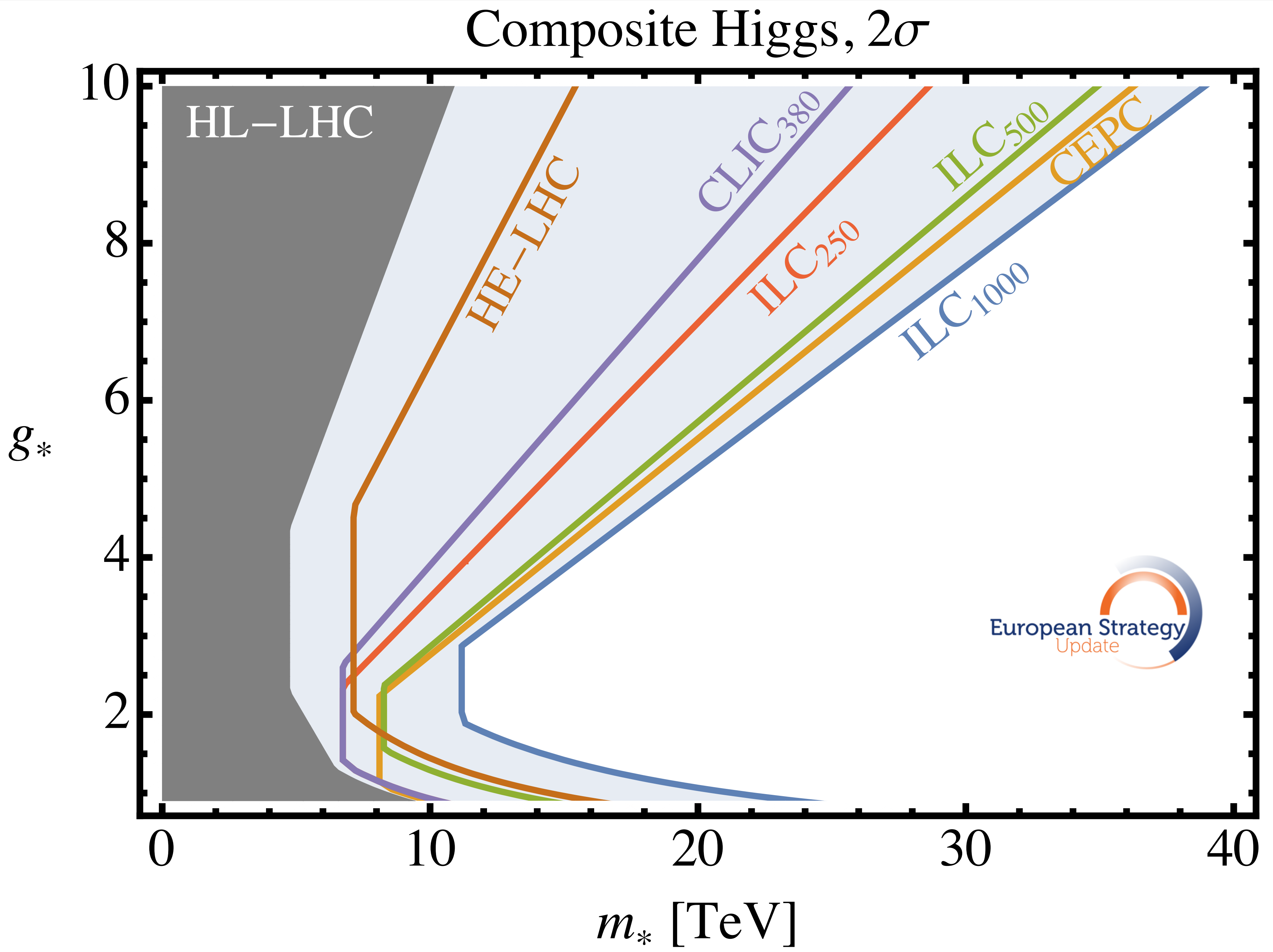


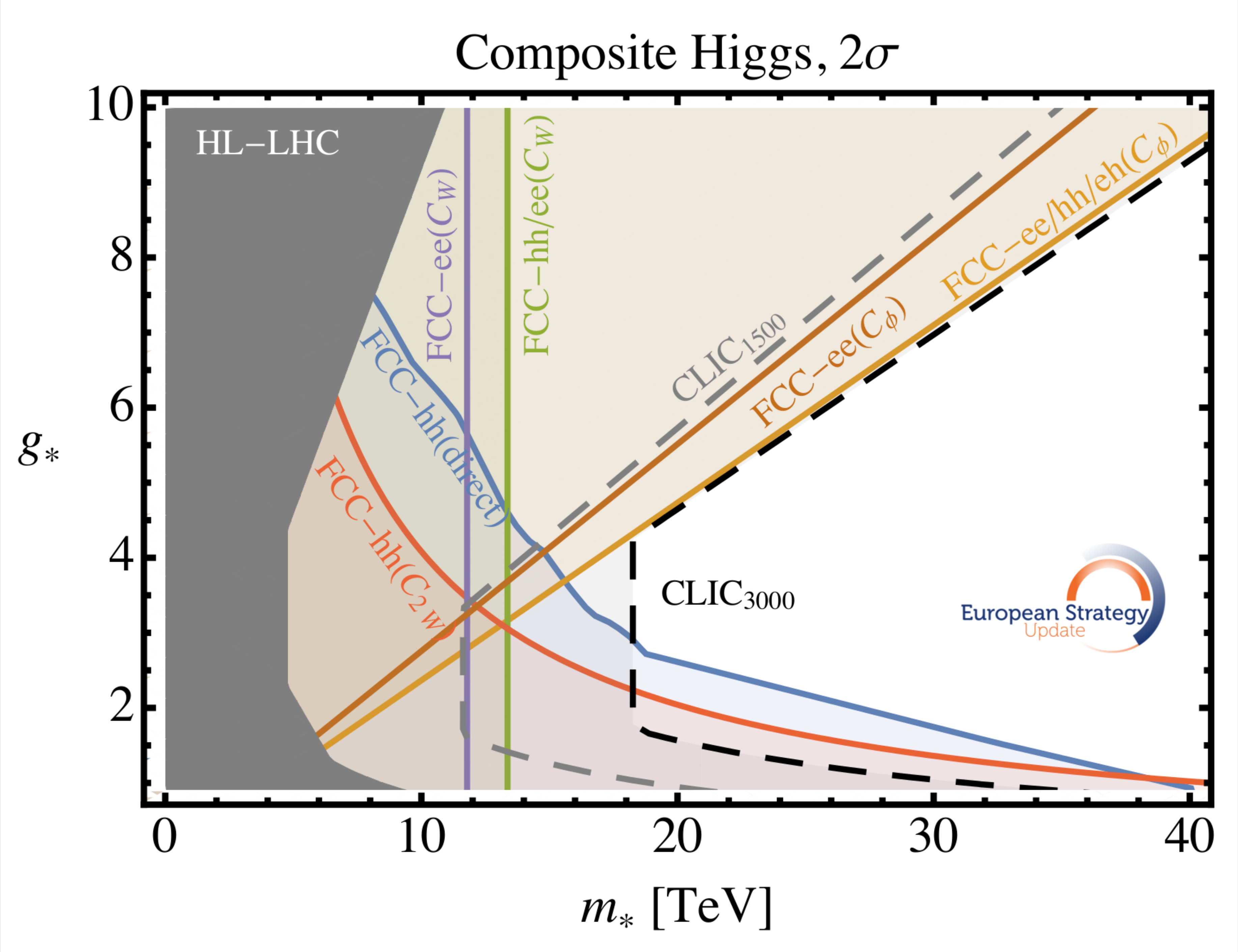
- deep understanding of the present laws of physics
- formulation of deep and far-reaching questions
- performing experiments that can conclusively answer these questions

flashing concrete results for

The size of the Higgs boson

Higgs compositeness



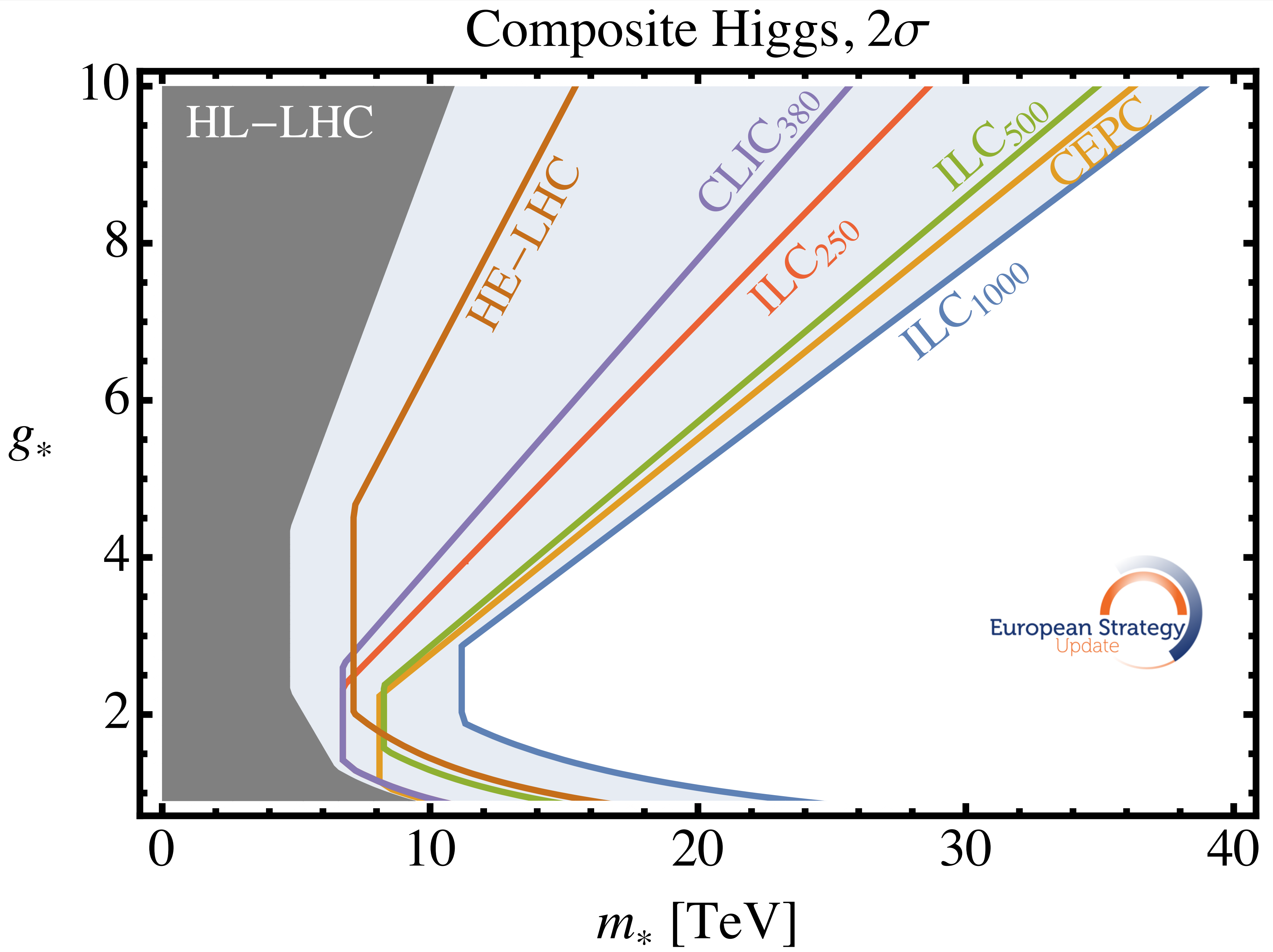


compositeness at few TeV @ HL-LHC

Higgs as composite as QCD pion

compositeness at few 10 TeV

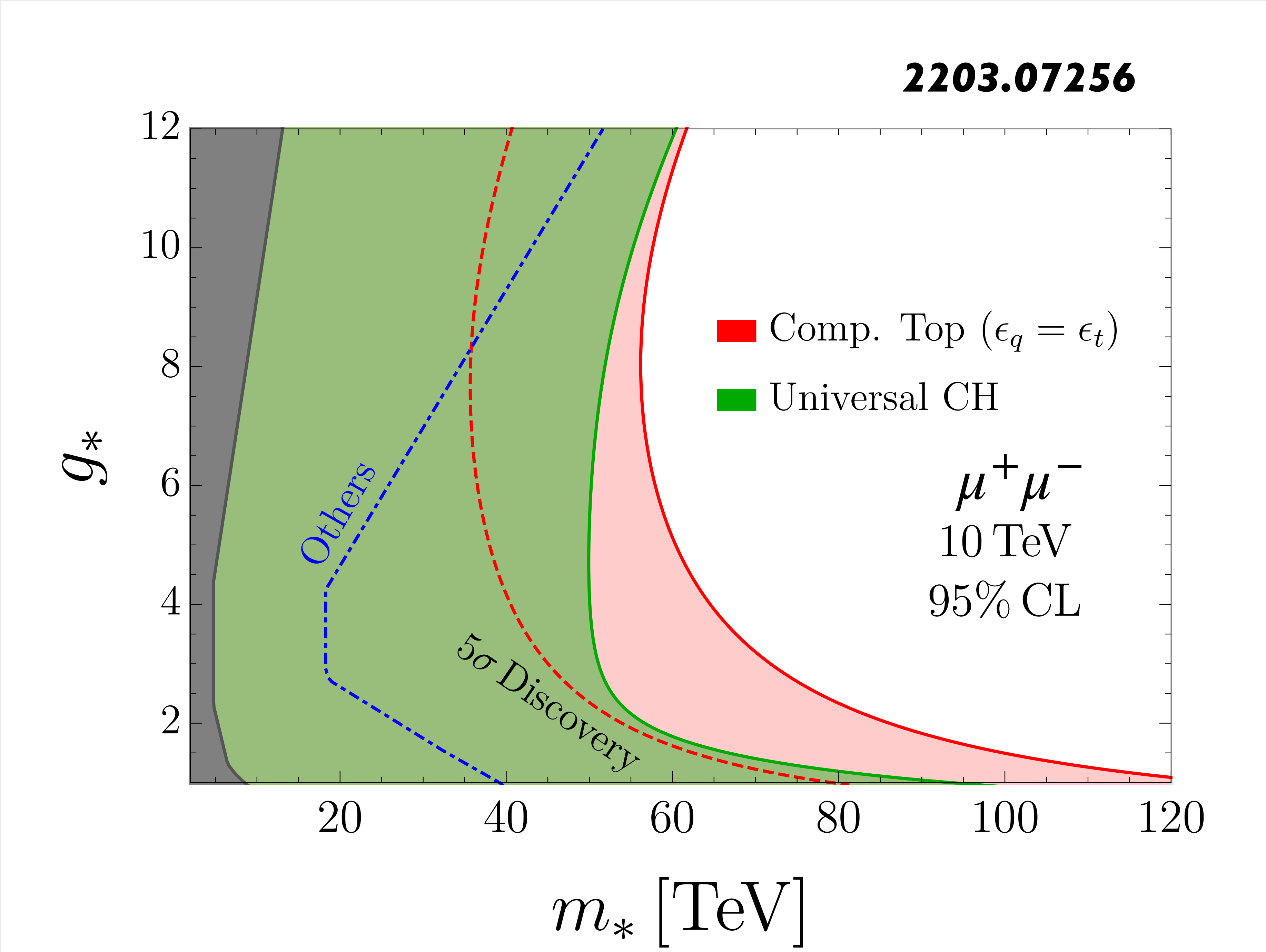
Higgs compositeness



compositeness at few TeV @ HL-LHC

Higgs as composite as QCD pion

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



compositeness at 100 TeV

Higgs 100x more point-like than QCD pion

Effects of the size of the Higgs boson

h ~ π STRONGLY INTERACTING LIGHT HIGGS

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

$$+ \frac{g_*^2}{(4\pi)^2 m_*^2}\left[c_{HW}\mathcal{O}_{HW} + c_{HB}\mathcal{O}_{HB}\right] + \frac{y_t^2}{(4\pi)^2 m_*^2}\left[c_{BB}\mathcal{O}_{BB} + c_{GG}\mathcal{O}_{GG}\right]$$

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

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

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

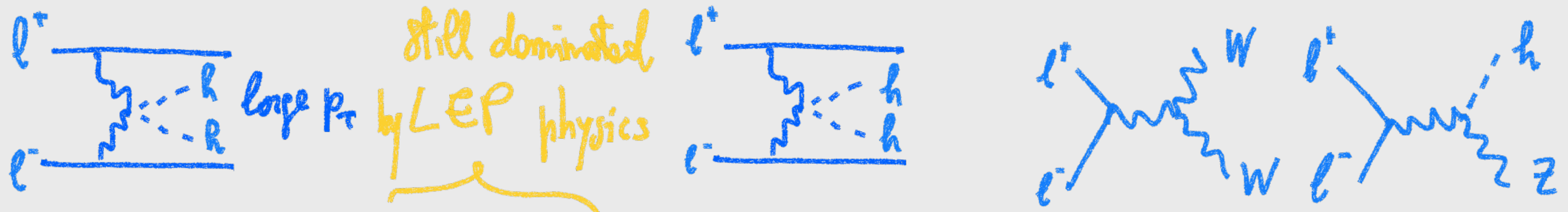
$1/(g_\star f) \sim 1/m_\star$

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

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

Effects of the size of the Higgs boson

STRONGLY INTERACTING TOP AND HIGGS



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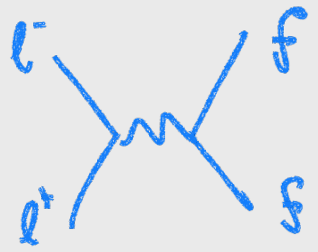

$$+ \frac{1}{g_*^2 m_*^2}\left[c_{2W} g^2 \mathcal{O}_{2W} + c_{2B} g'^2 \mathcal{O}_{2B}\right] + c_{3W}\frac{3! g^2}{(4\pi)^2 m_*^2}\mathcal{O}_{3W}$$

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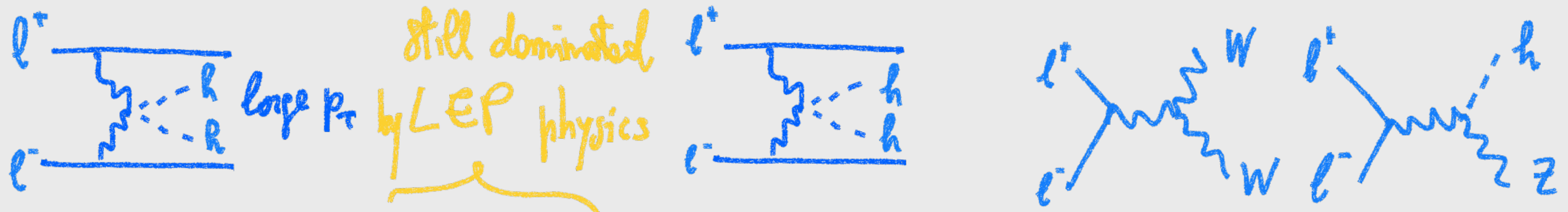

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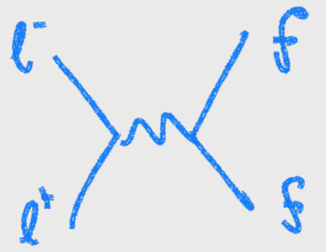

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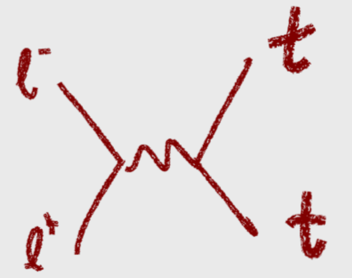

$$+ c_{tD}\frac{g_*^2}{m_*^2}\mathcal{O}_{tD}$$

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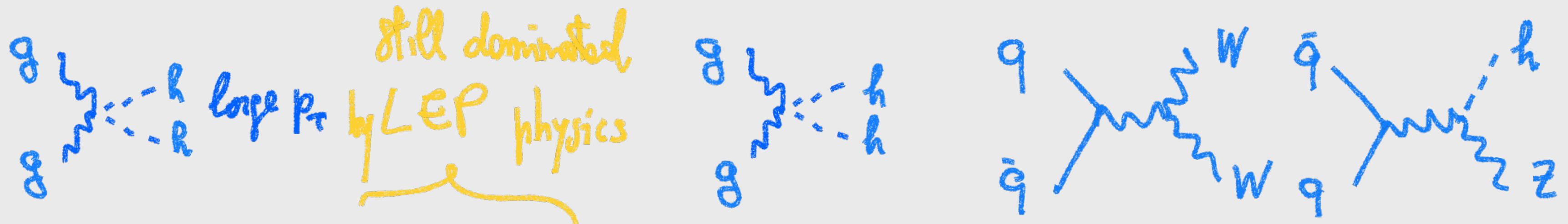

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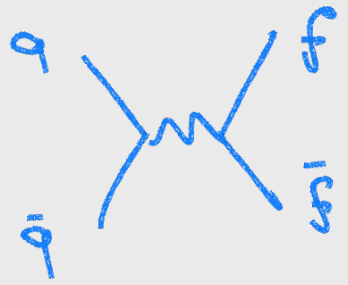

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$$+ c_{y_t}\frac{g_*^2}{m_*^2}\mathcal{O}_{y_t} + c_{y_b}\frac{g_*^2}{m_*^2}\mathcal{O}_{y_b}$$

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

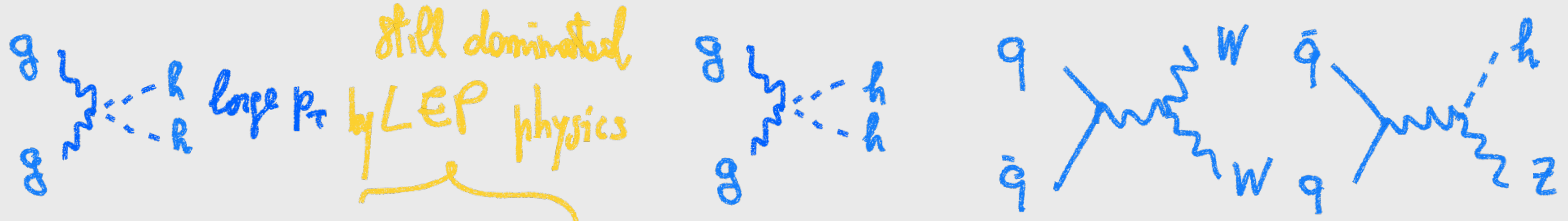
$1/(g_\star f) \sim 1/m_\star$

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

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

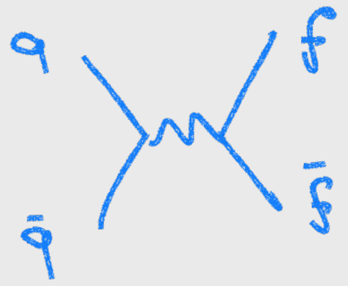
Effects of the size of the Higgs boson

STRONGLY INTERACTING TOP AND HIGGS



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

$$+ \frac{g_*^2}{(4\pi)^2 m_*^2}\left[c_{HW}\mathcal{O}_{HW} + c_{HB}\mathcal{O}_{HB}\right] + \frac{y_t^2}{(4\pi)^2 m_*^2}\left[c_{BB}\mathcal{O}_{BB} + c_{GG}\mathcal{O}_{GG}\right]$$



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

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

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

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

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

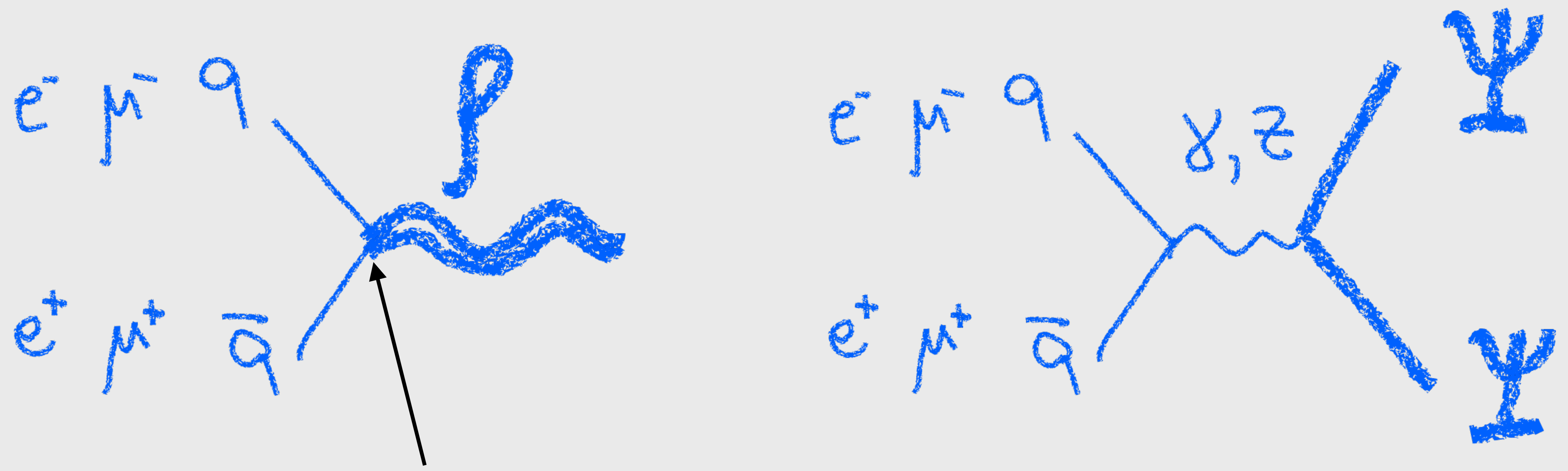
$g_{SM}/(g_\star f) \sim g_{SM}/m_\star$

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

pp or $\ell^+\ell^- \to$ new physics

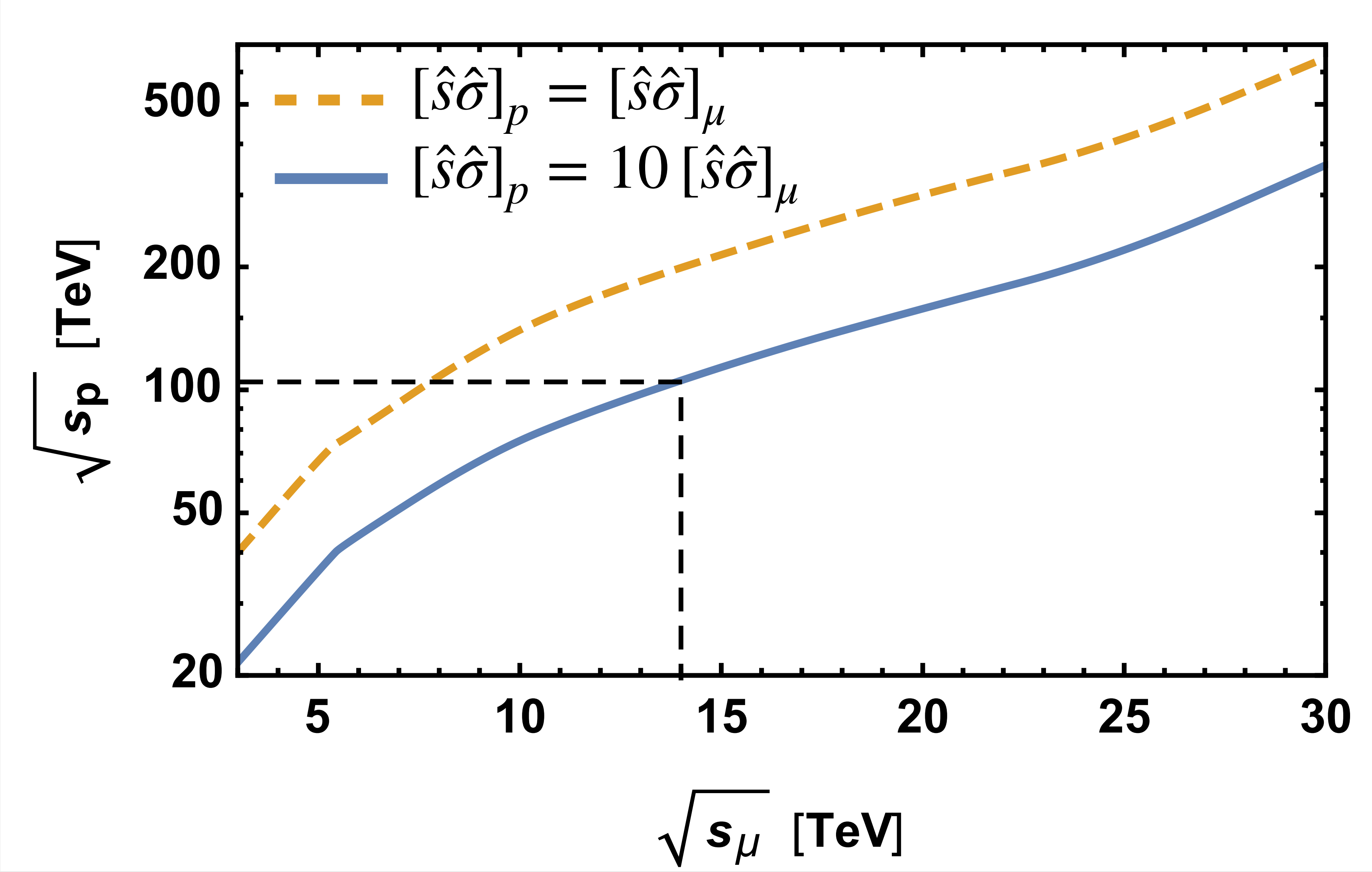
VALENCE LEPTONS

Can produce heavy new physics (colored or not)



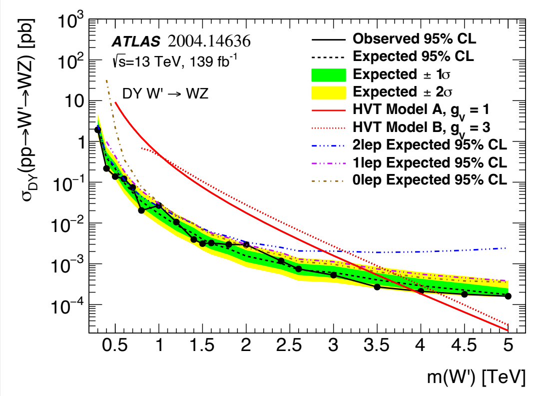
in principle can probe directly new states at O(10) TeV scale!

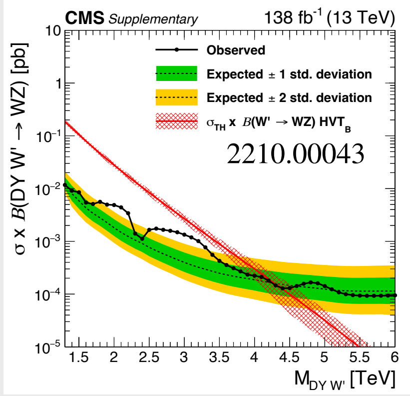
Compares pretty well with a *pp* collider



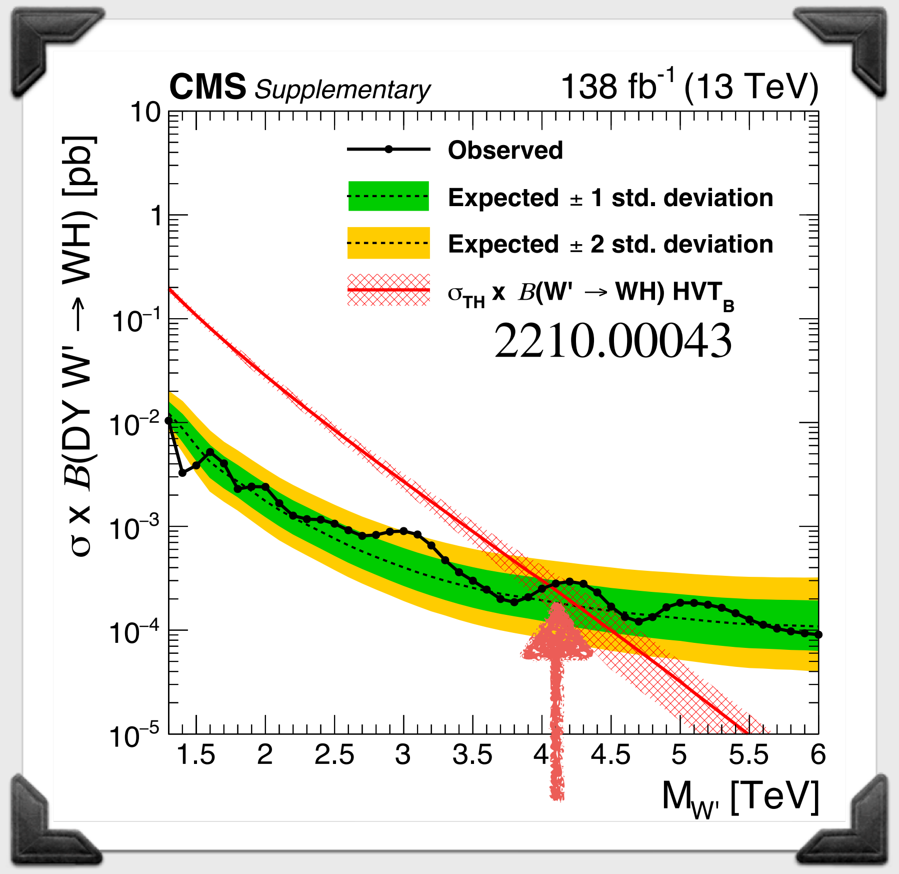
14 TeV μμ roughly equivalent to 100 TeV *pp*

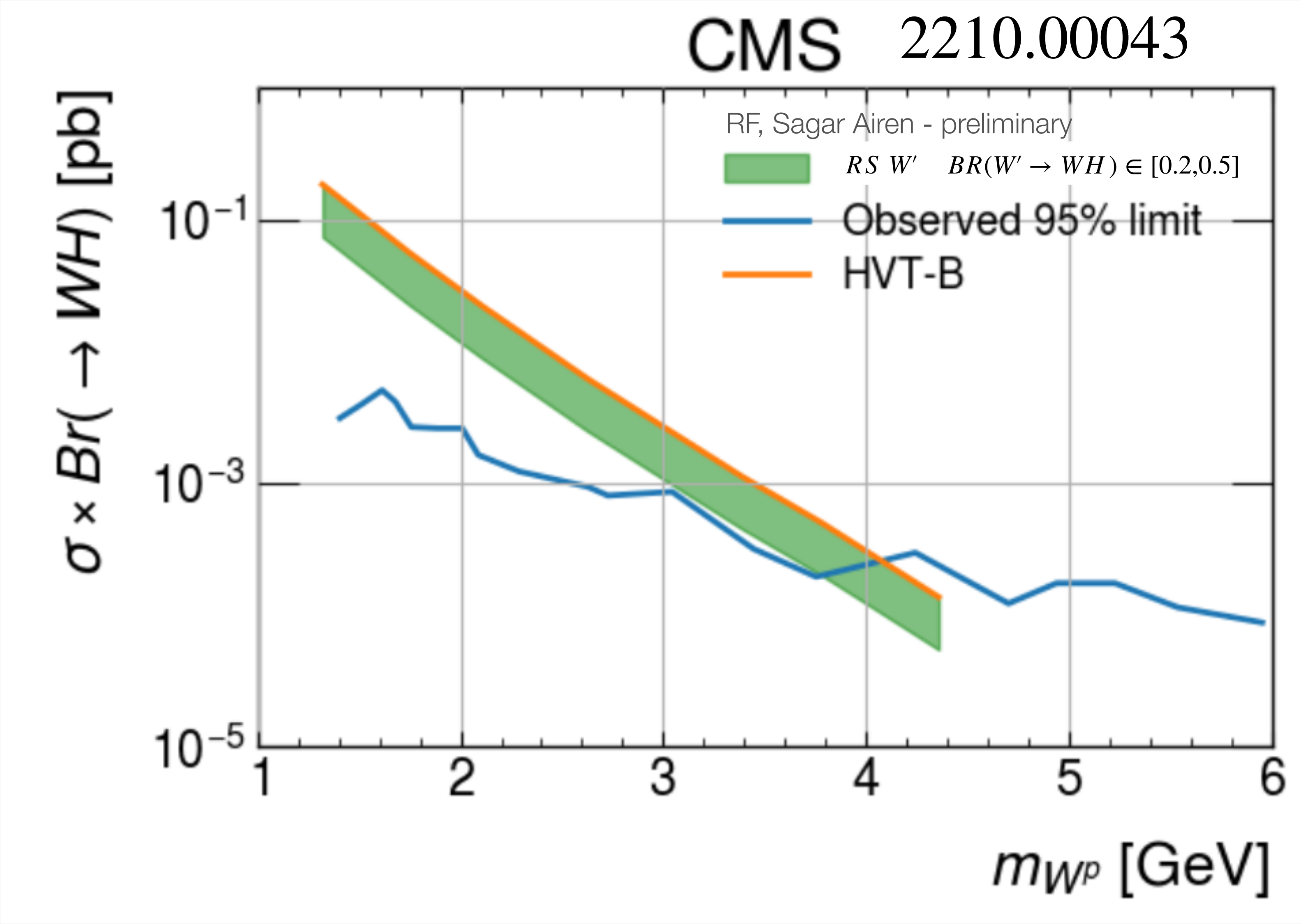
Companions of a composite Higgs

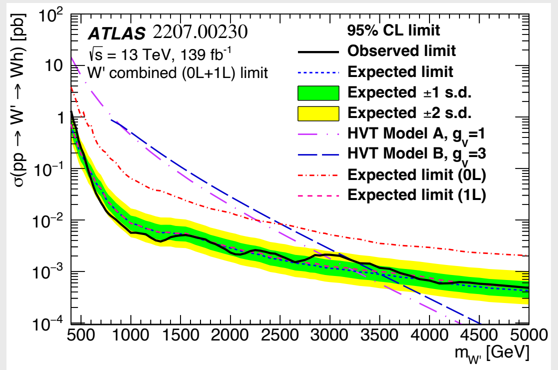


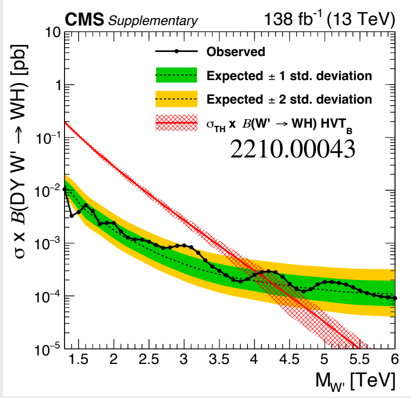


WZ









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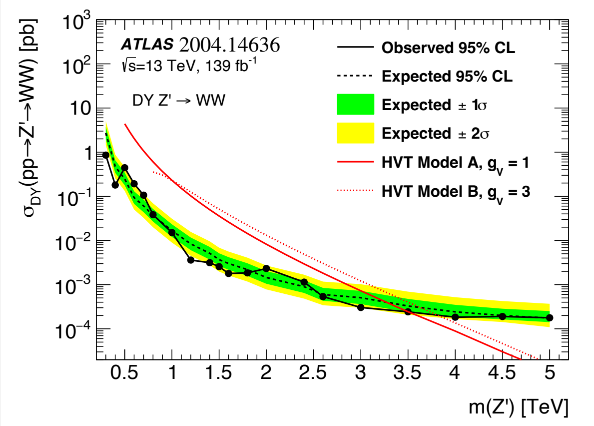

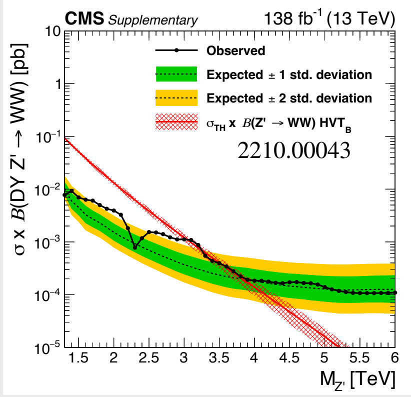

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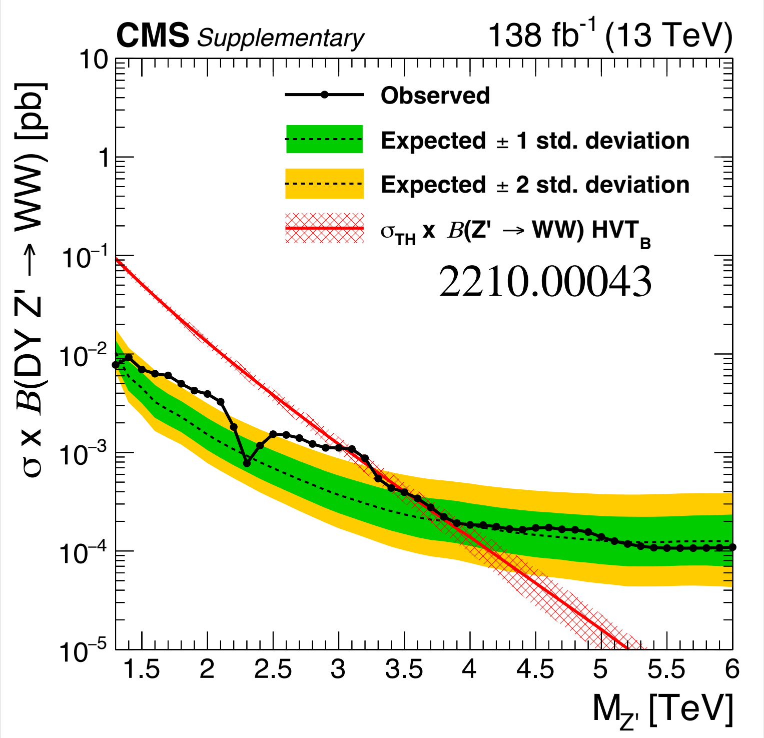
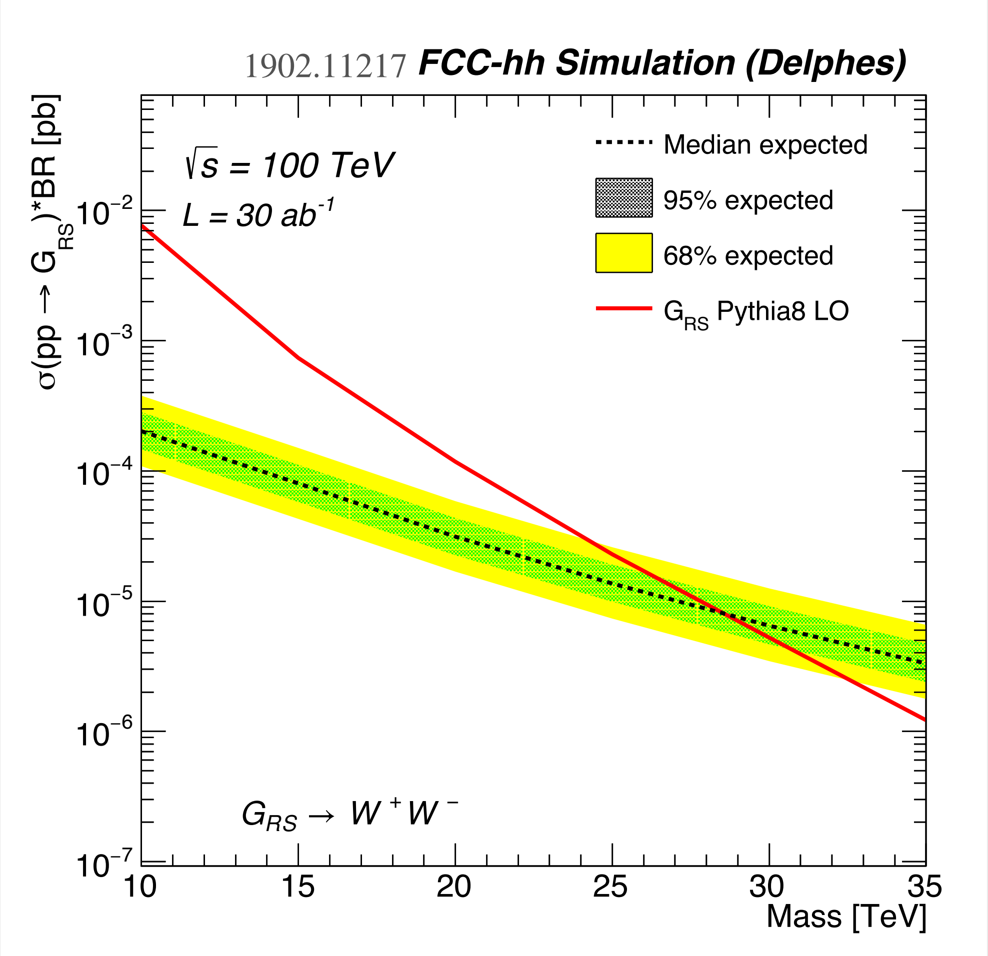
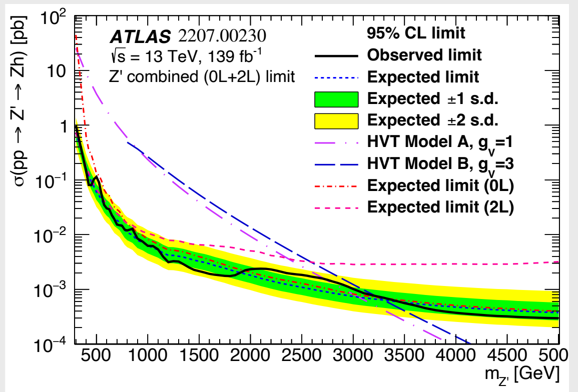
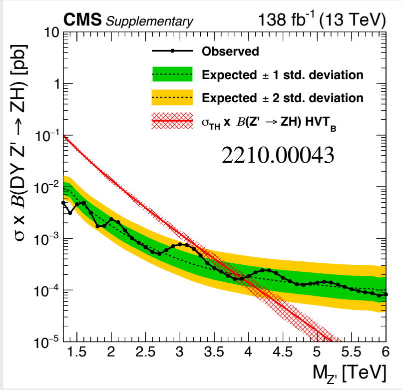








ZH

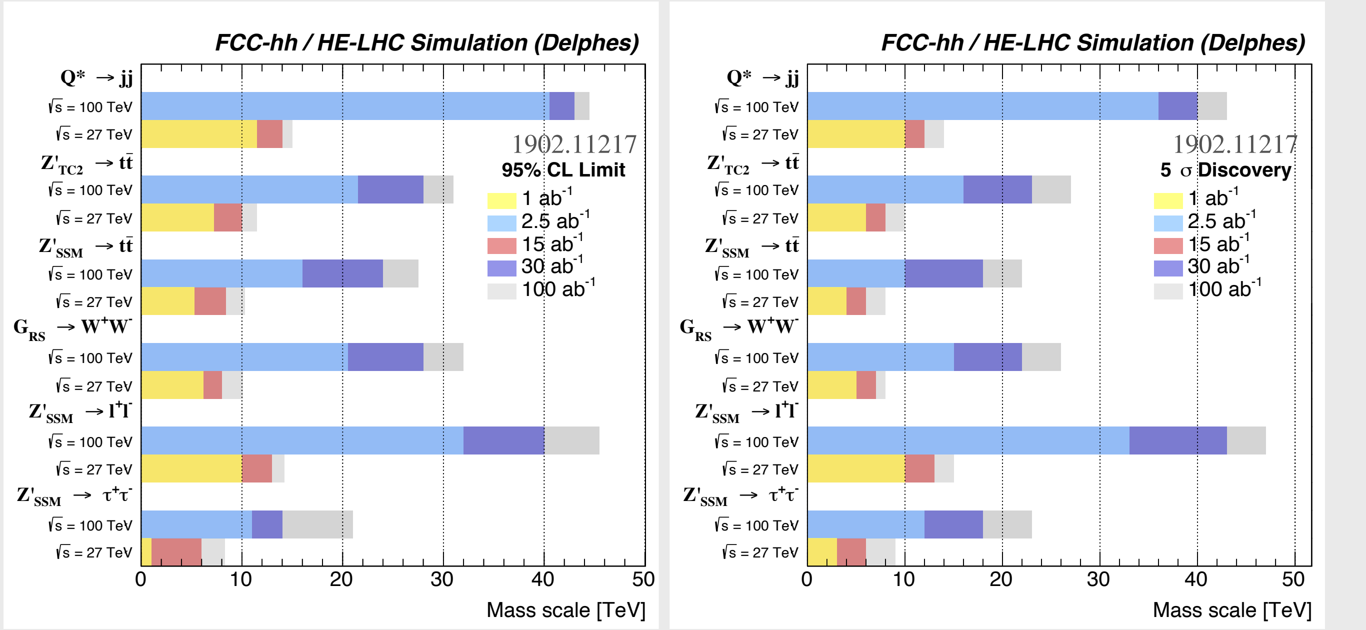


Fig. 10. Summary of the 95% CL limits (left) and 5σ discovery reach (right) as a function of the resonance mass for different luminosity scenario of FCC-hh and HE-LHC.

Luminosity

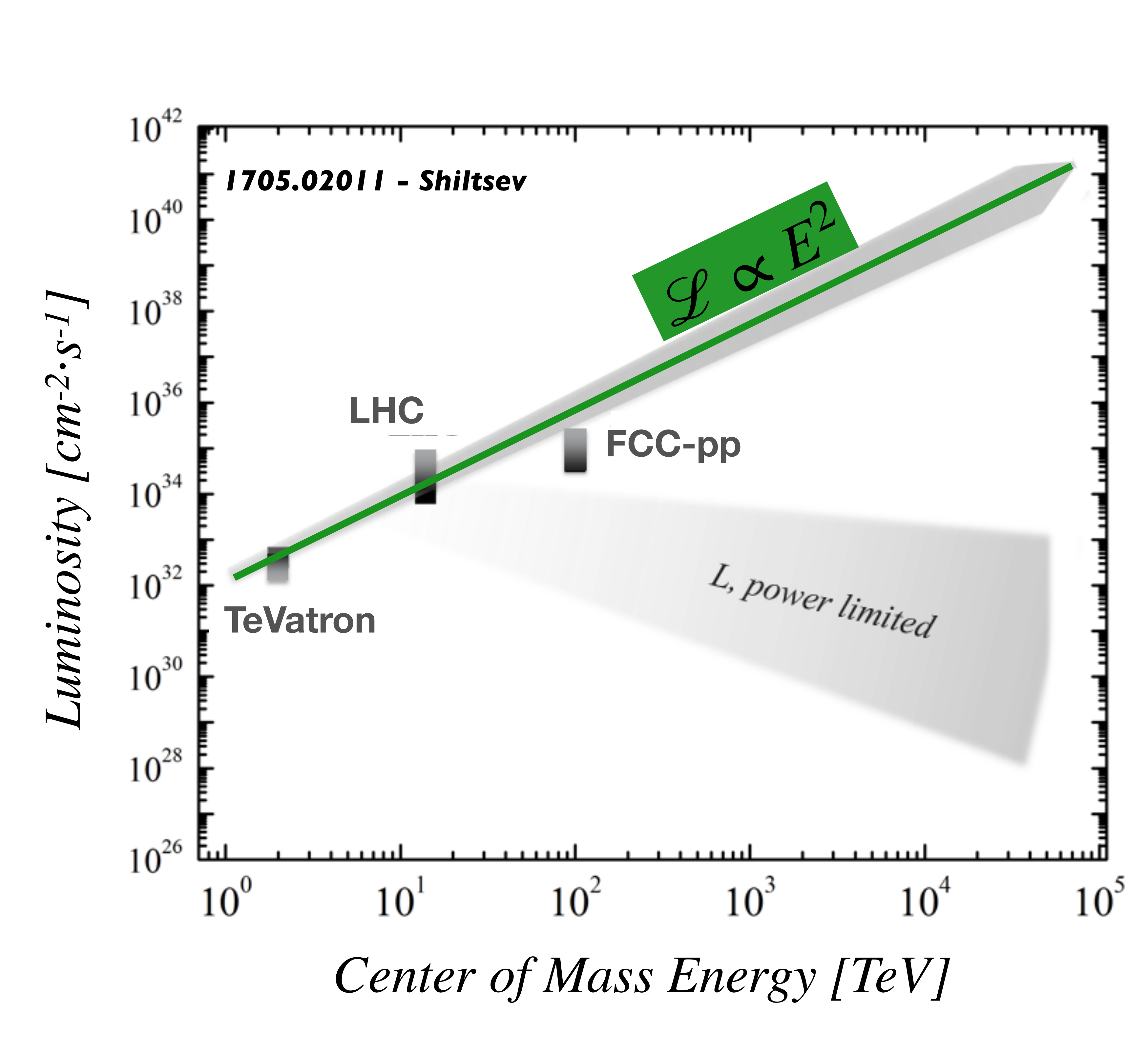
Luminosity

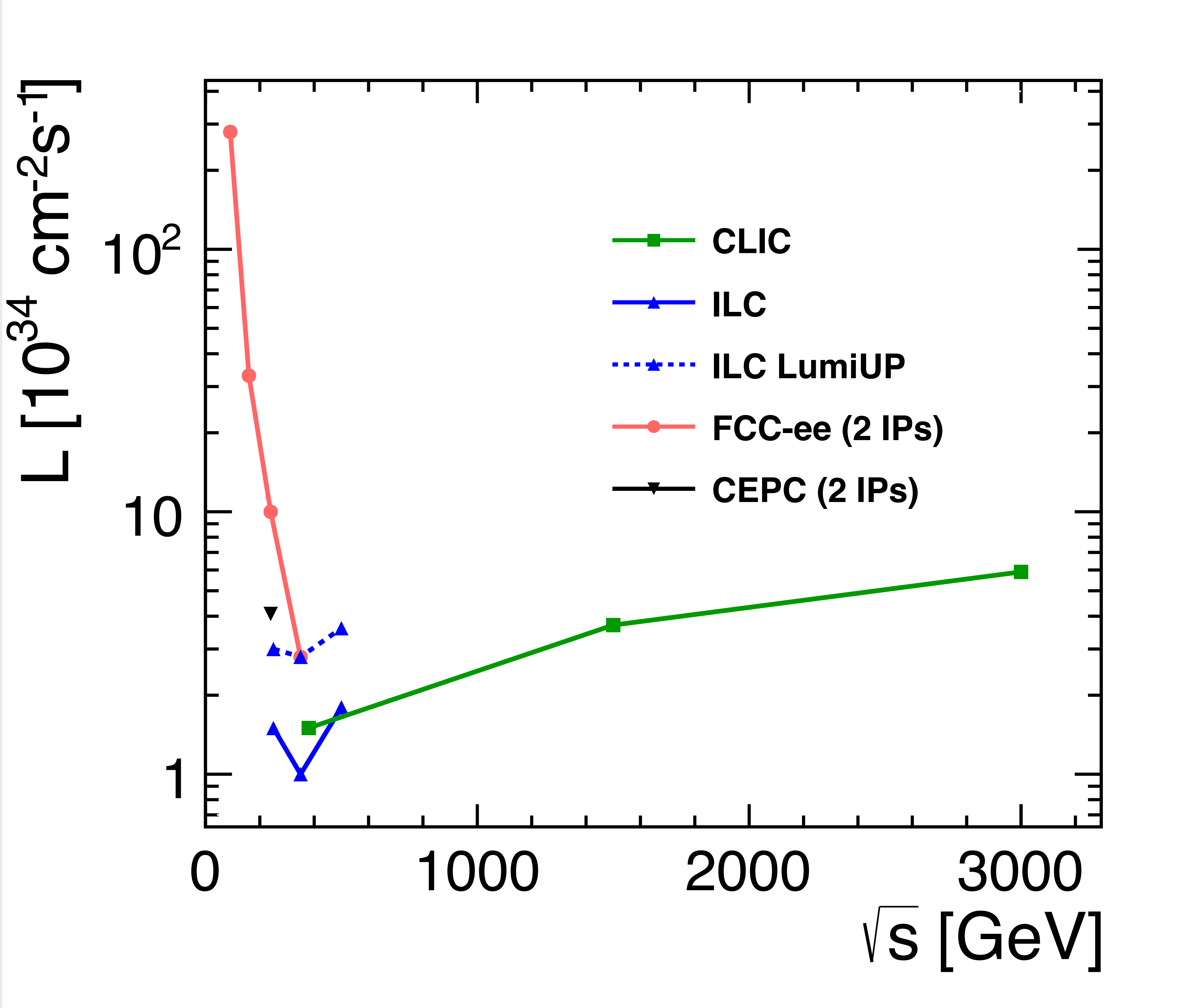
Challenges

TIME

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

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





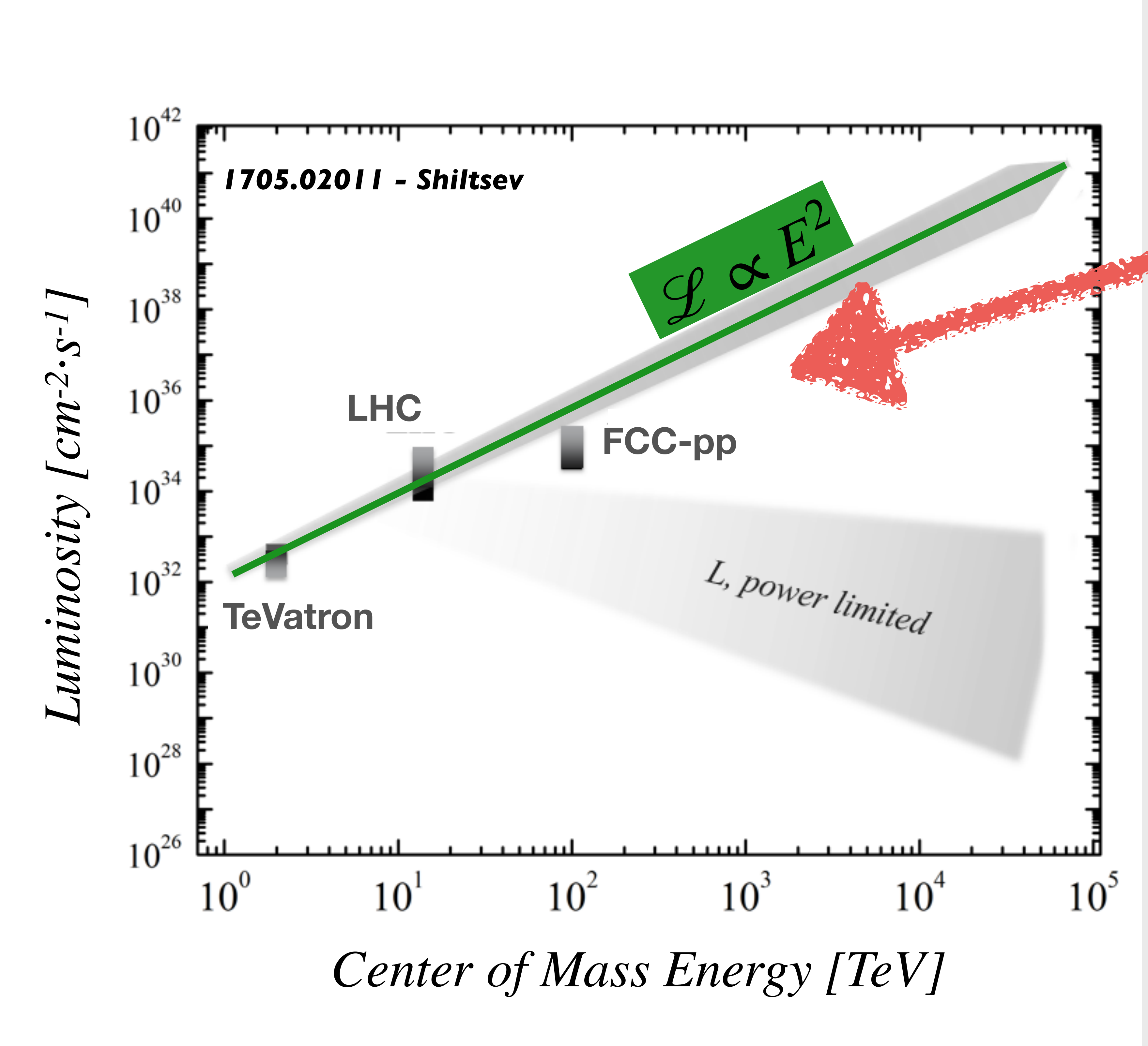
Challenges

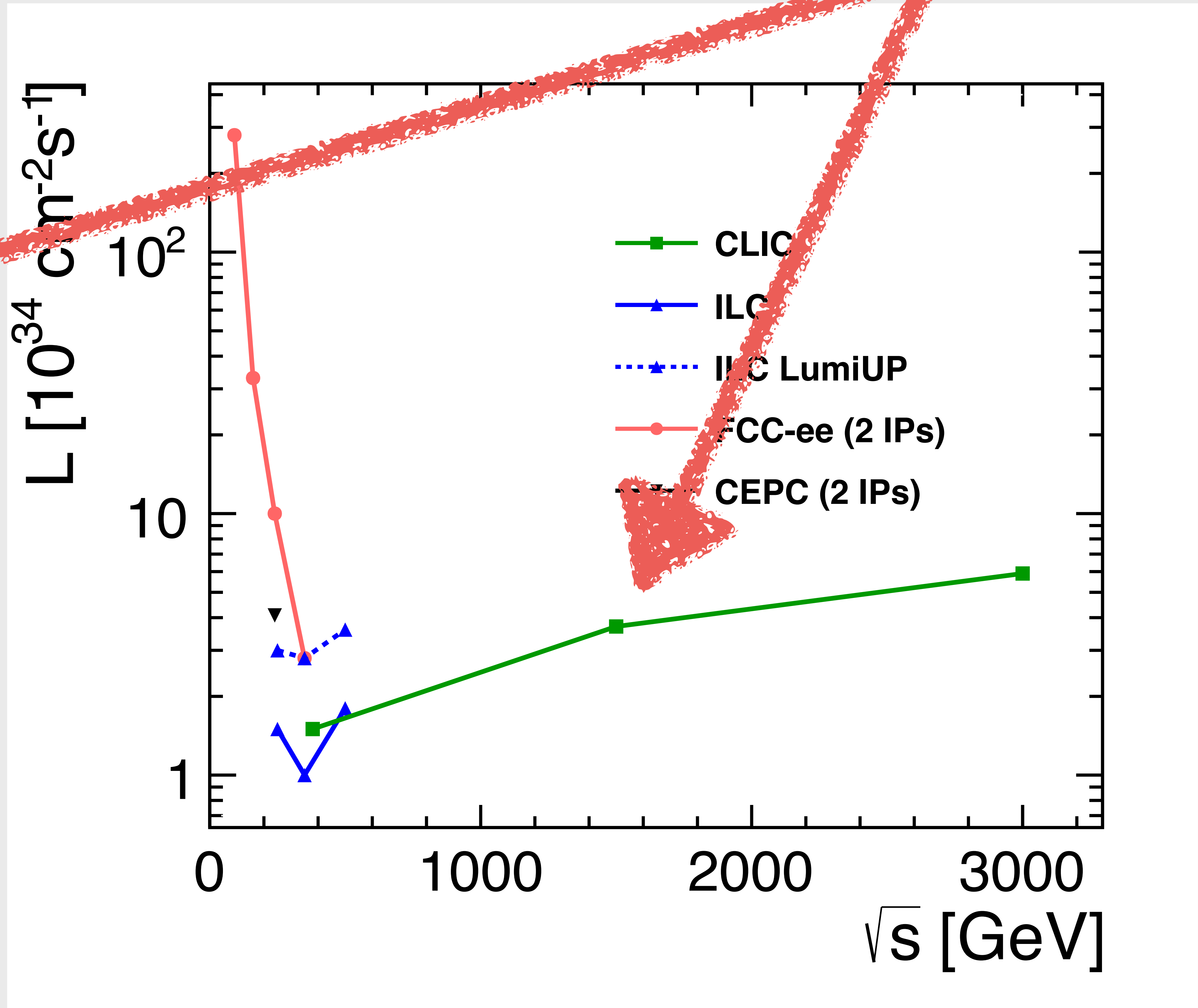
TIME

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

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

Luminosity is not growing fast enough





Discovery Physics  at Future Colliders

Muon colliders

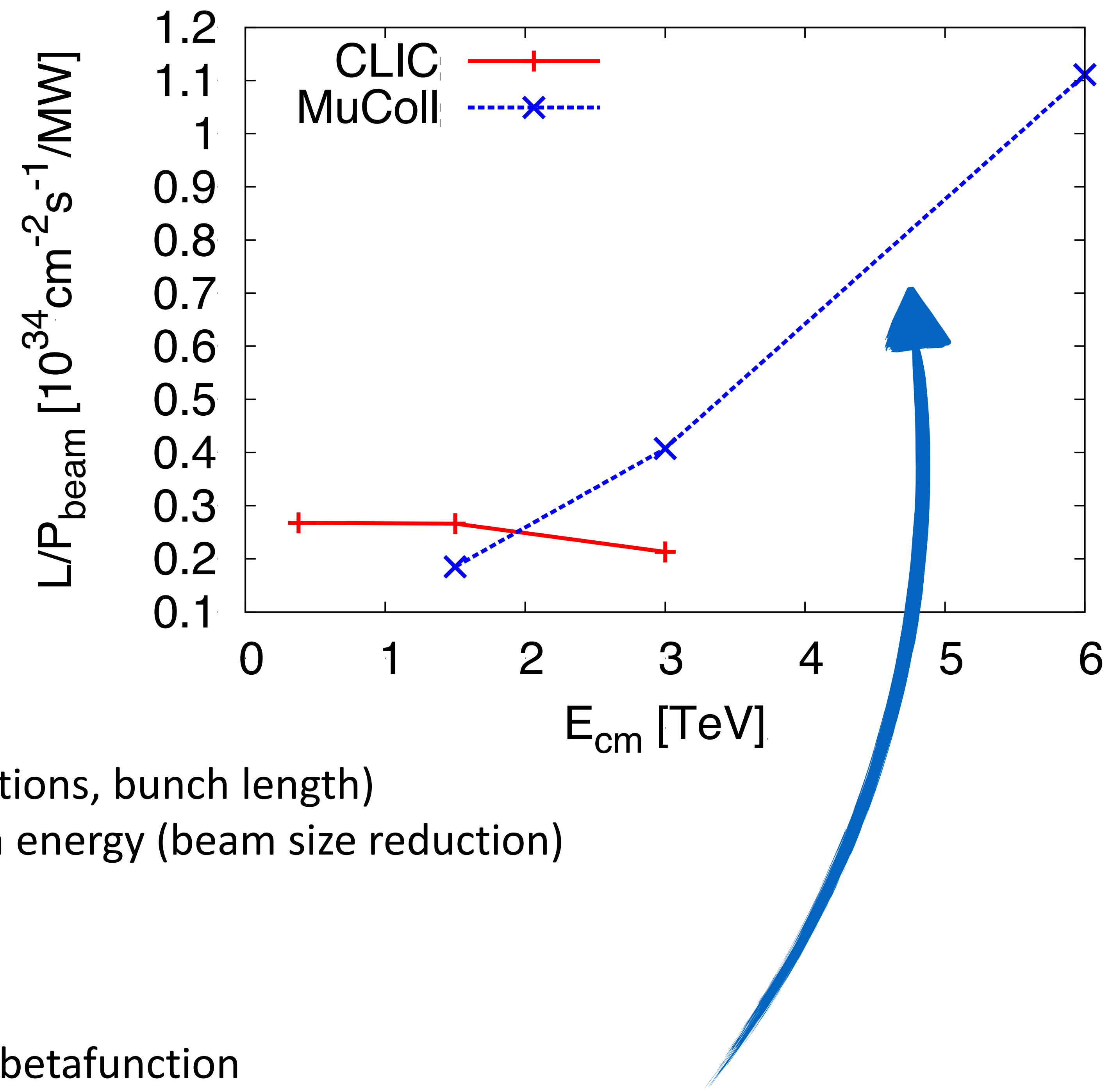
HIGHLY EFFICIENT

HIGH ENERGY COLLIDER

Luminosity Comparison

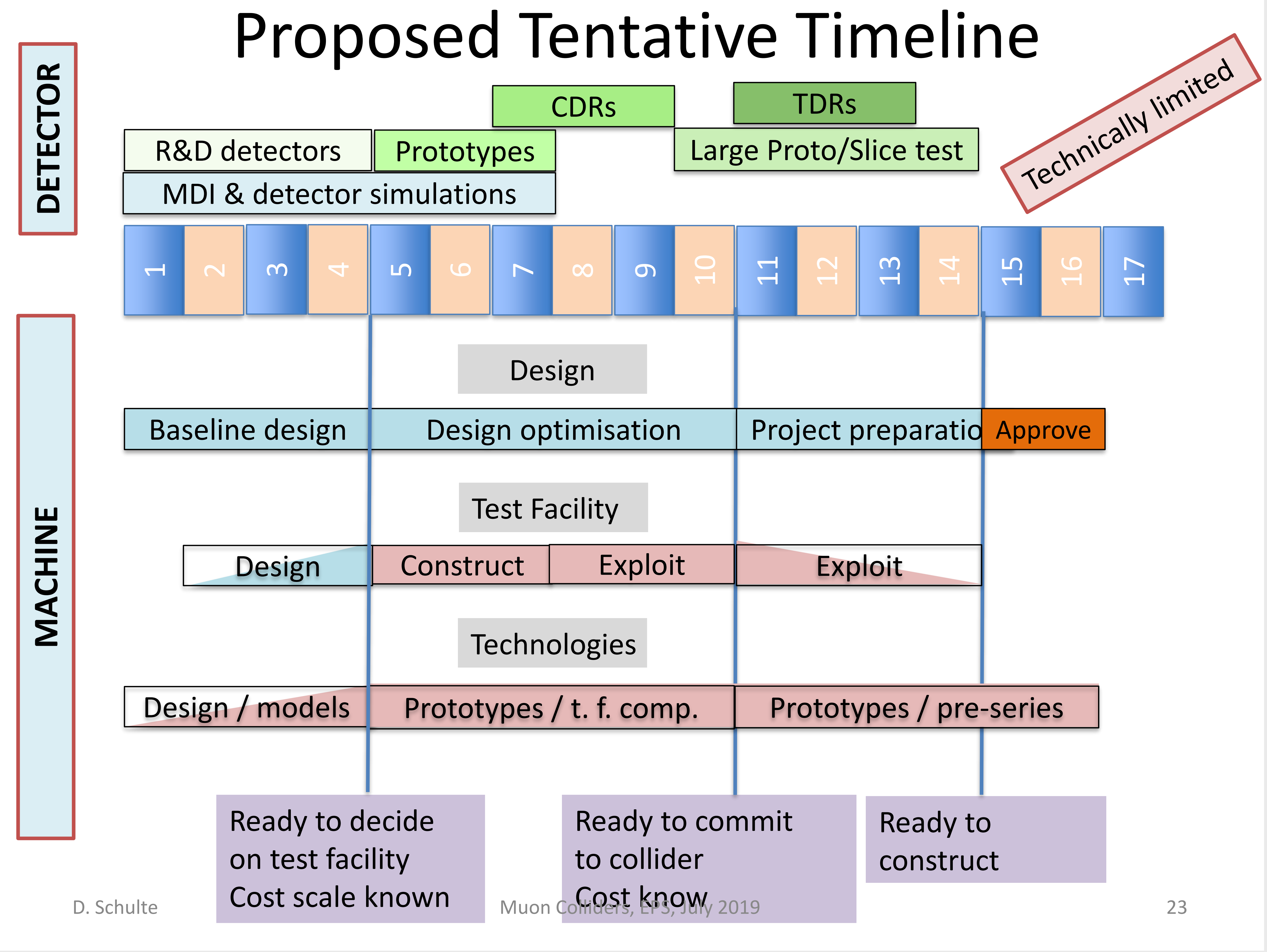
The luminosity per beam power is about constant in linear colliders

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)



Muon colliders

HIGHLY EFFICIENT | HIGH ENERGY COLLIDER

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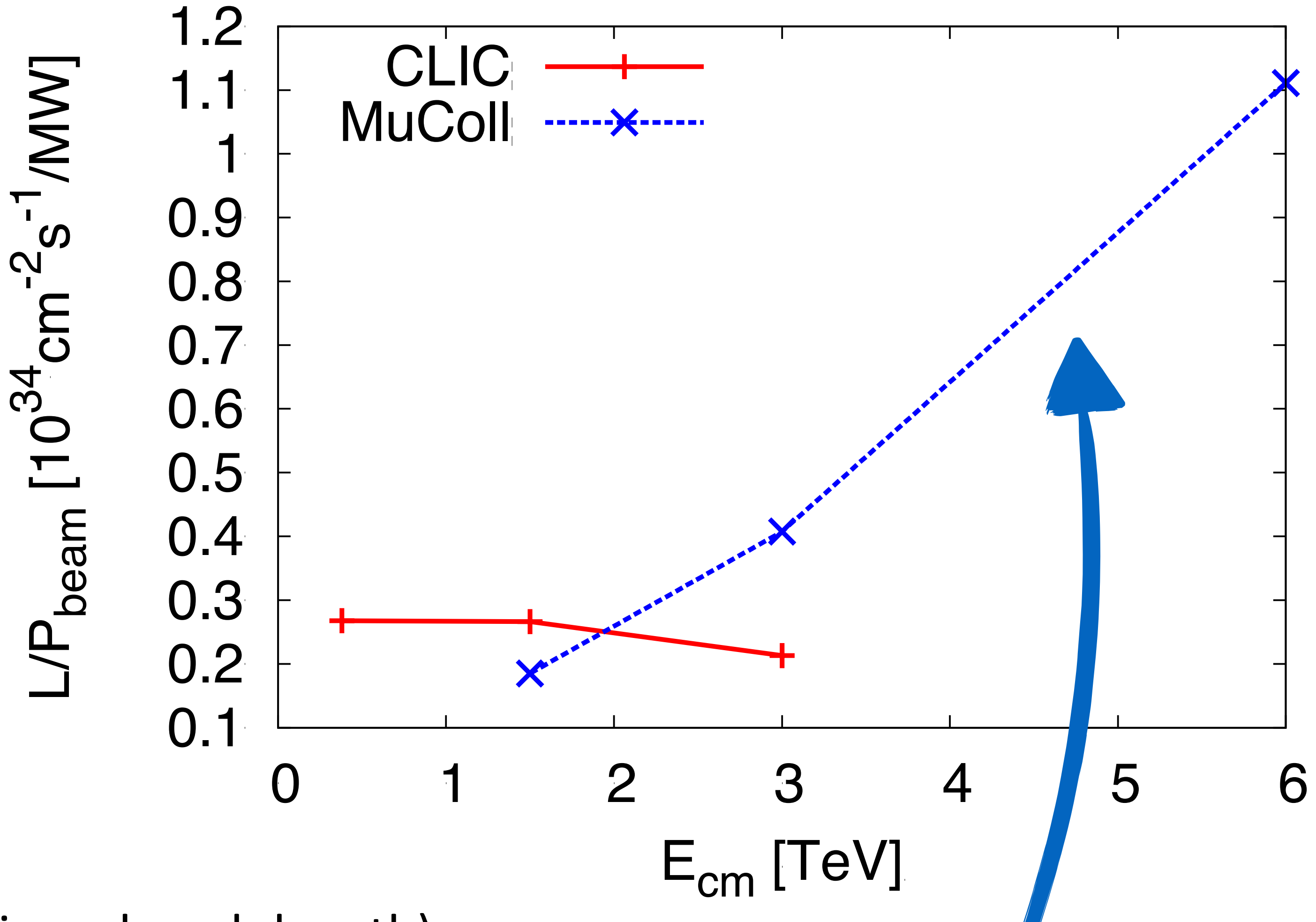

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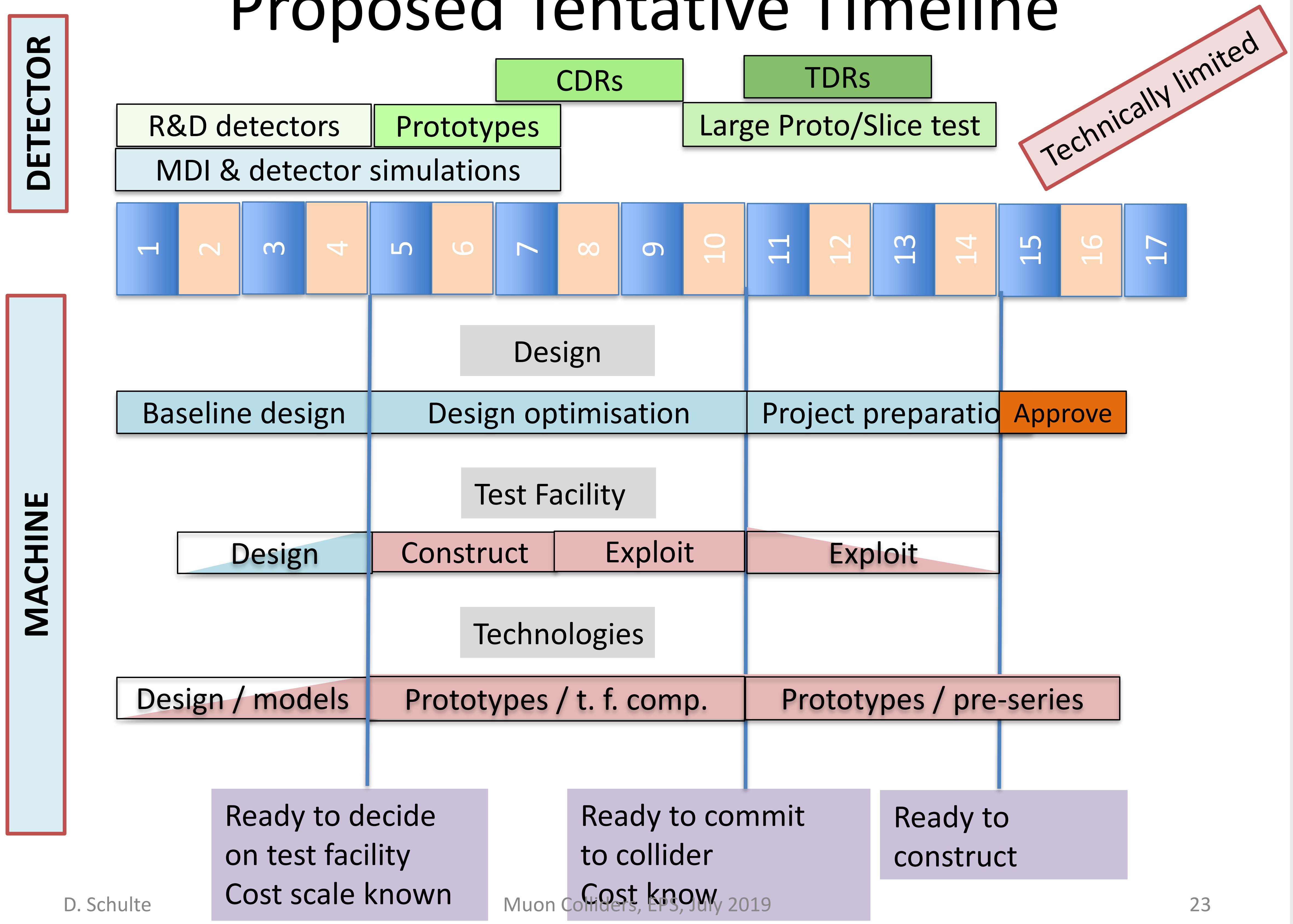
D. Schulte Muon Colliders, EPS, July 2019 7

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)

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Ready to decide on test facility
Cost scale known

Ready to commit to collider
Cost know

Ready to construct

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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

D. Schulte Cost scale known Muon Colliders, EPS, July 2019 Cost know 23

flashing concrete results for

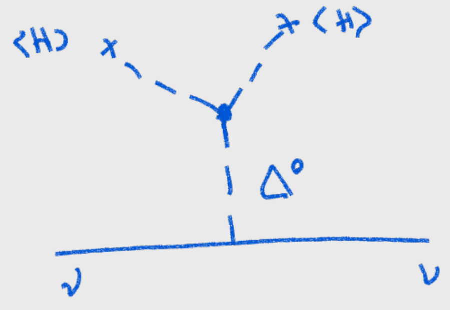
The origin of neutrino masses

Neutrino mass mechanisms

LEPTON NUMBER BREAKING

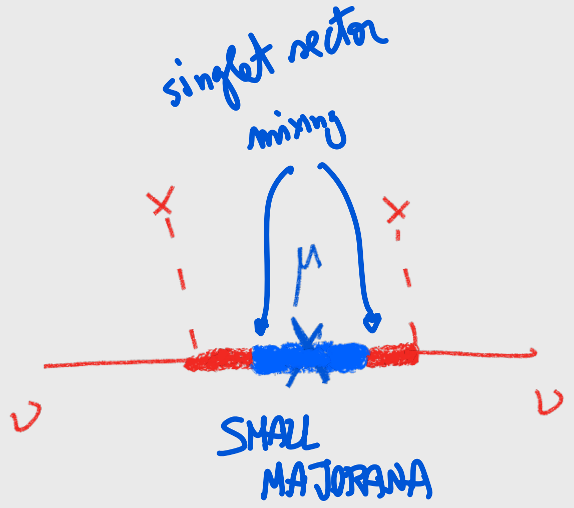
$L-$ violation

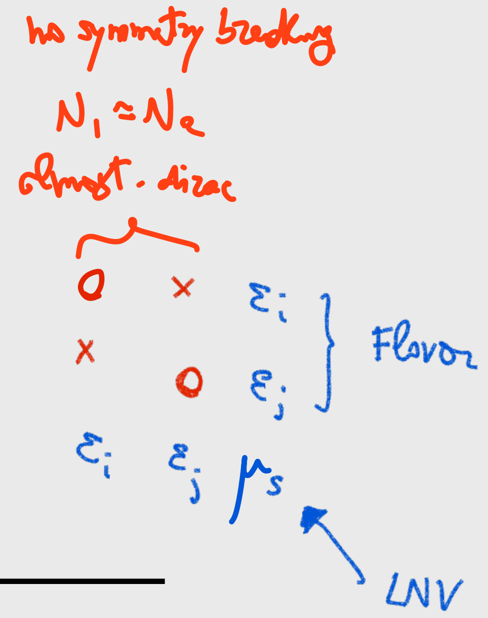
(1,1,0) (at least 2)



(1,3,1) (1 is enough)

(1,1,0) (at least 2+1)



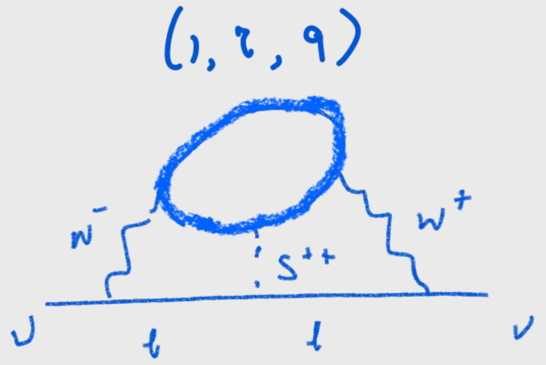


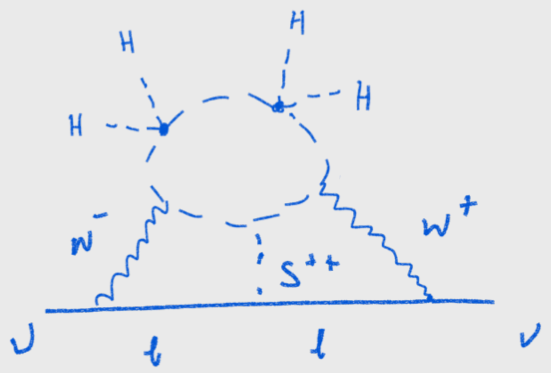
$L-$ not accidental

new physics before 2012

$d=5 \quad (1,2,1/2)$ $\dfrac{(LH)^2}{\Lambda}$ UV

$d=7 \quad (1,1,2)$ $\dfrac{\left(DH\sigma_2 H\right)^2 S^{--}}{\Lambda^3}$ UV





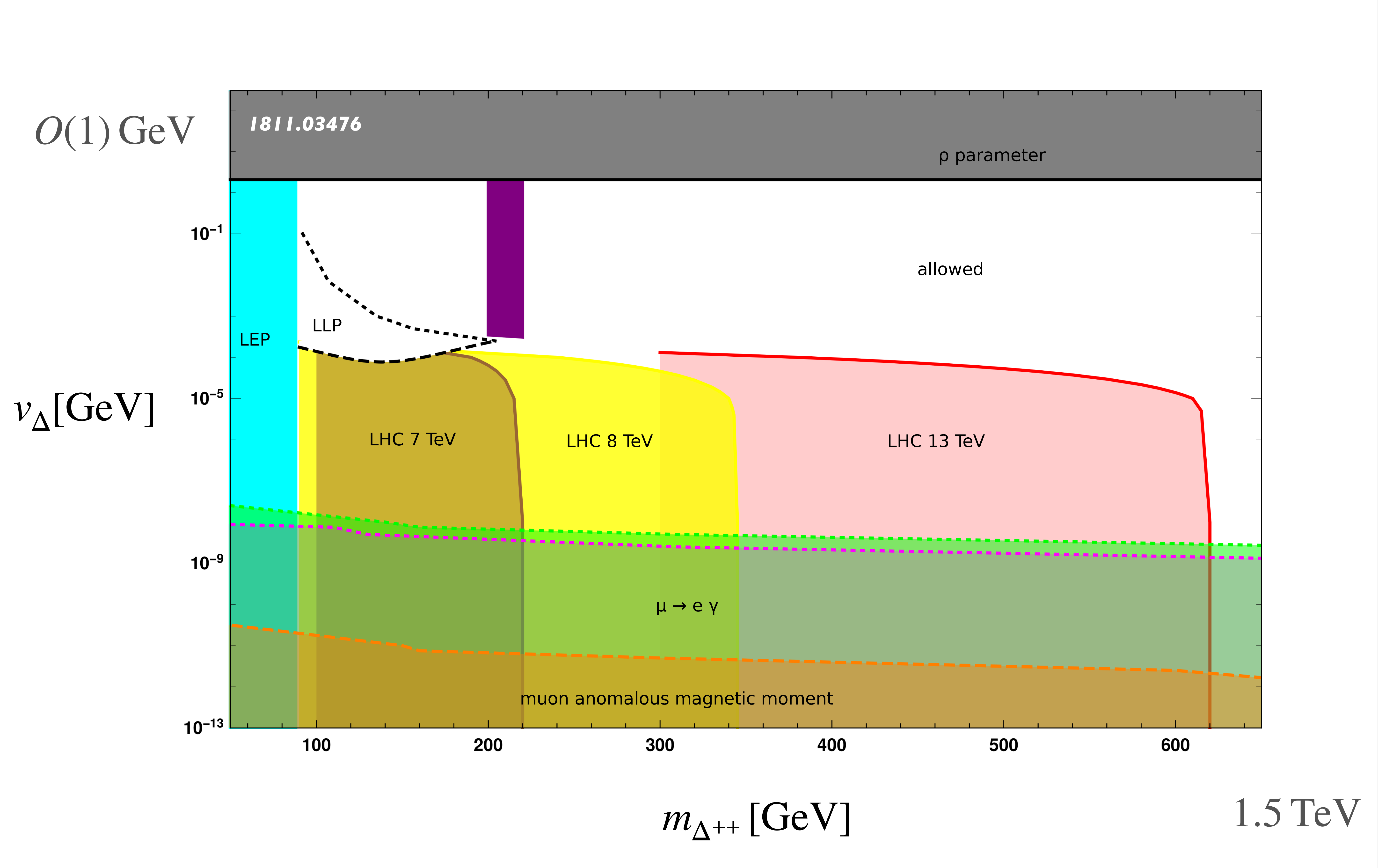
$L-$ gauged, SSB

$SU(3) \otimes SU(2)_L \otimes SU(2)_L \otimes U(1)_{B-L}$

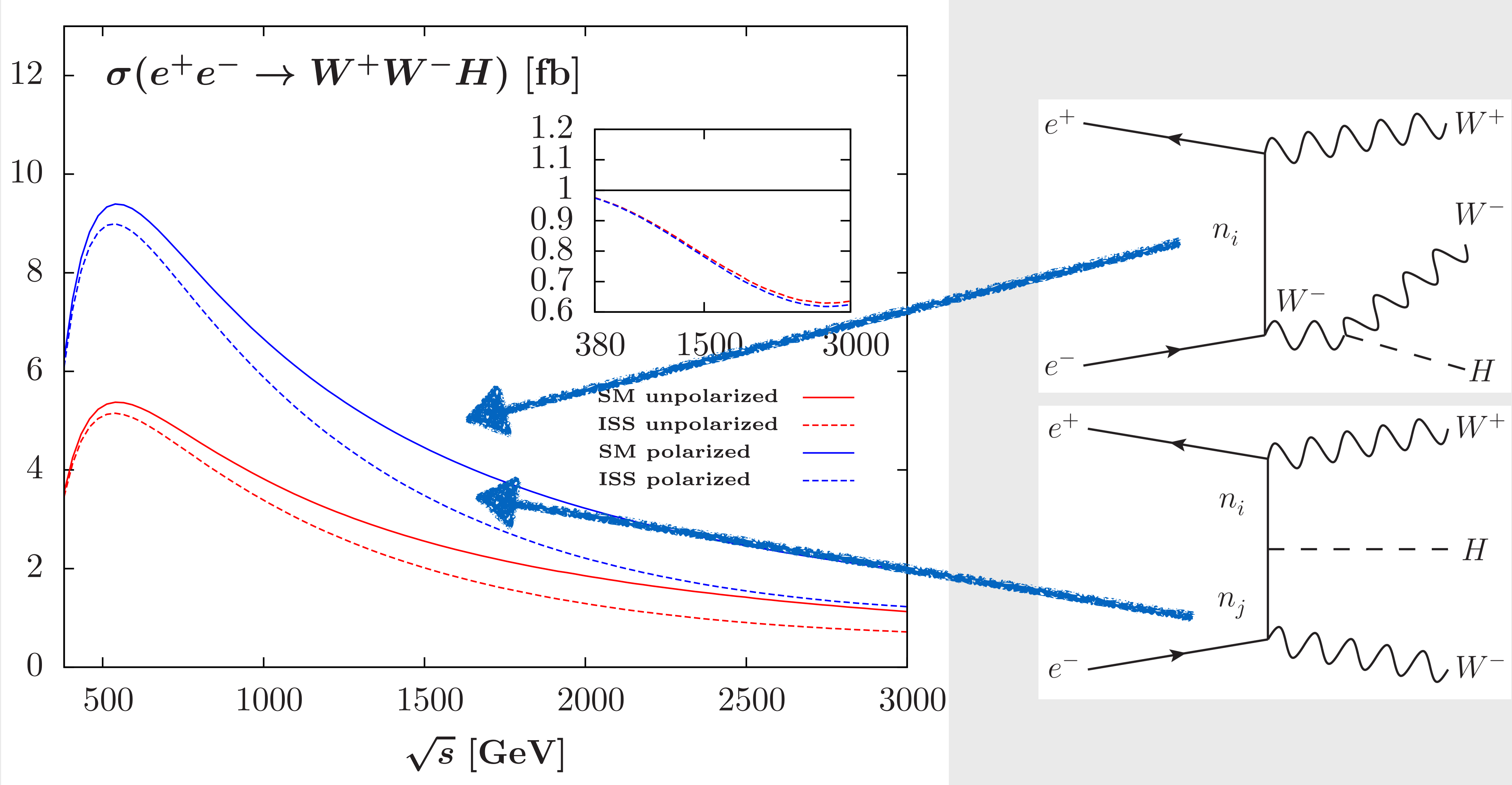
(1,2,1,1), (1,1,2,1), (1,2,2,1), (1,1,1,2),

Plenty of neutrino mass models in reach

Type-2 See-Saw **1803.00677 - Agrawal, Mitra, Niyogi, Shil, Spannowsky**

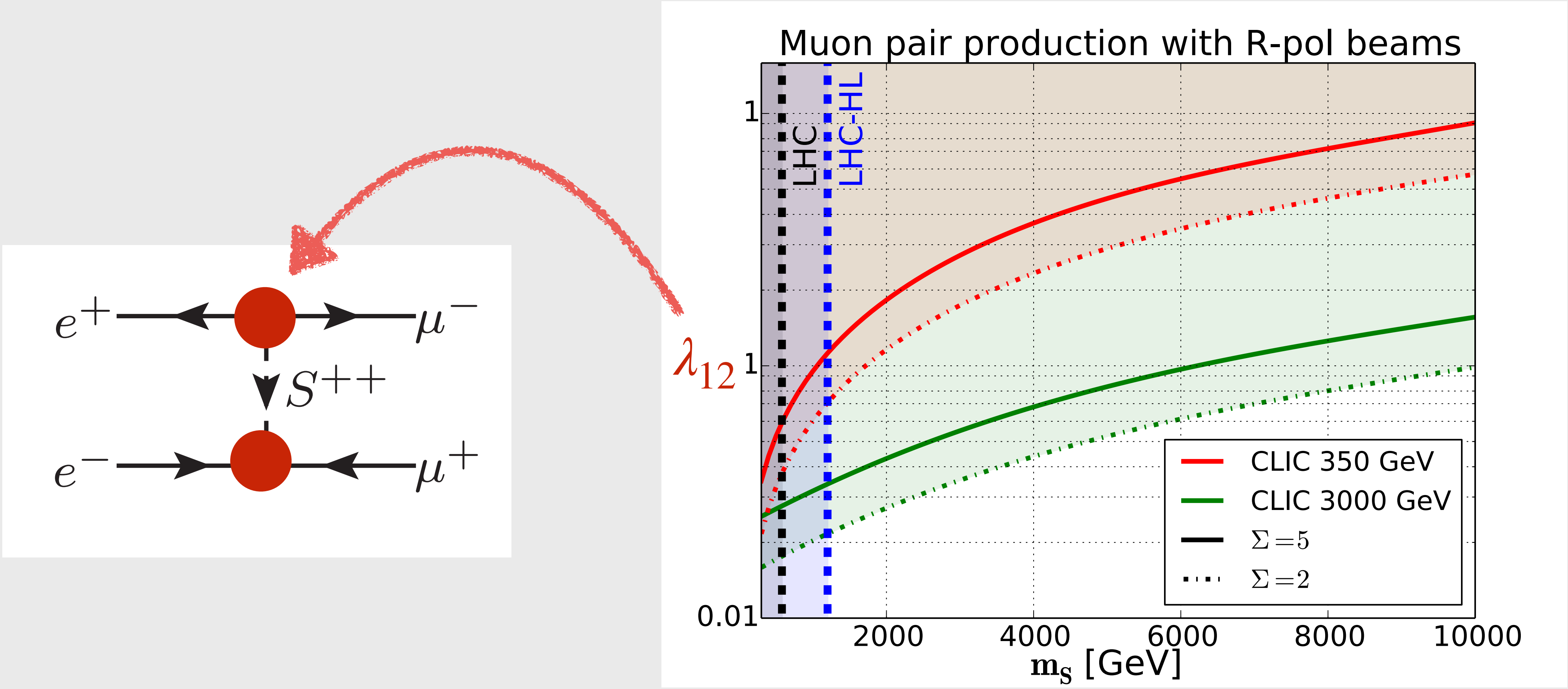


Inverse See-Saw **1712.07621 - Baglio, Pascoli, Weiland**



Exclude ISS RH Neutrino up to 10 TeV for Yukawa ~1

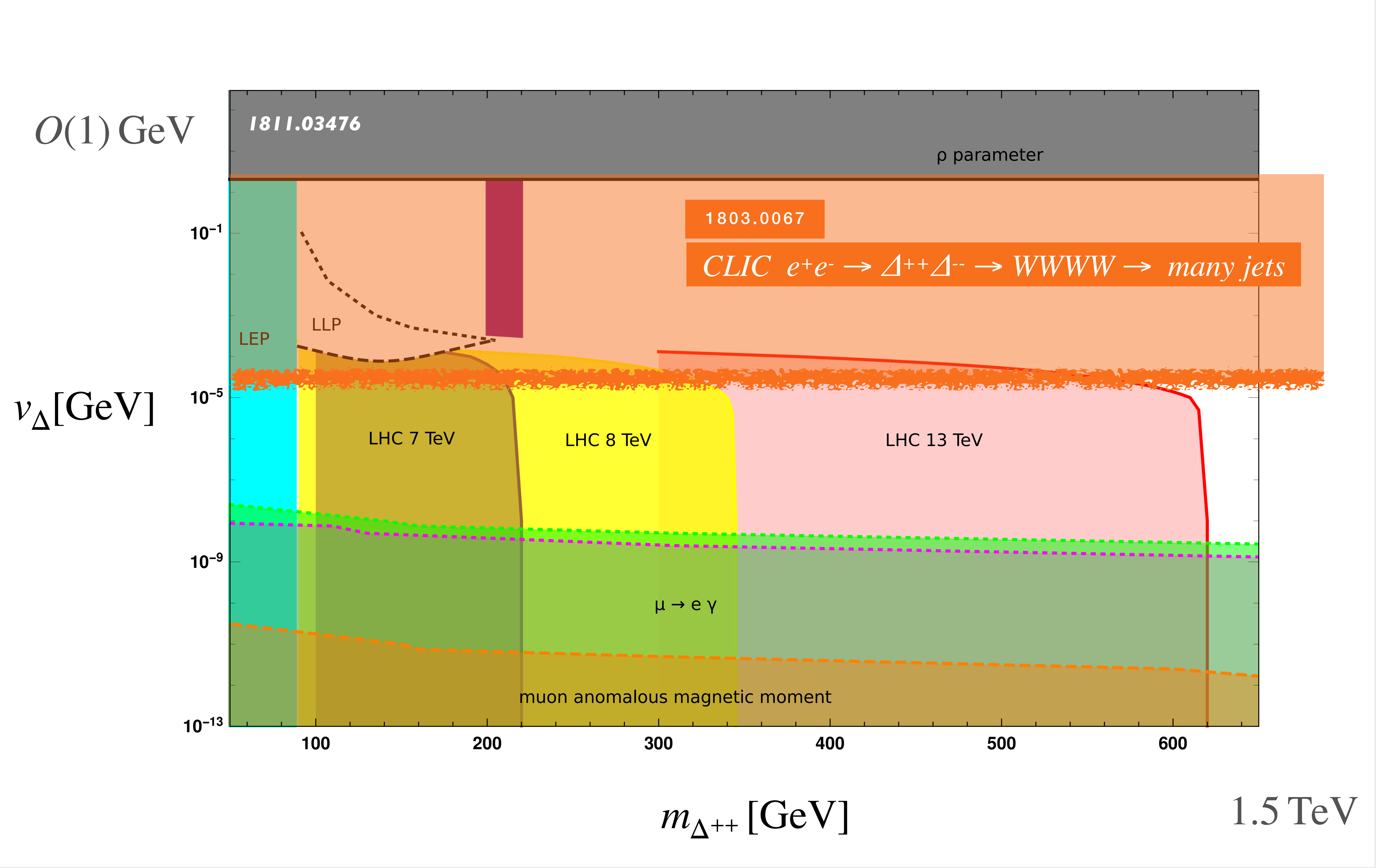
1807.10224 - Crivellin, Ghezzi, Panizzi, Pruna, Signer



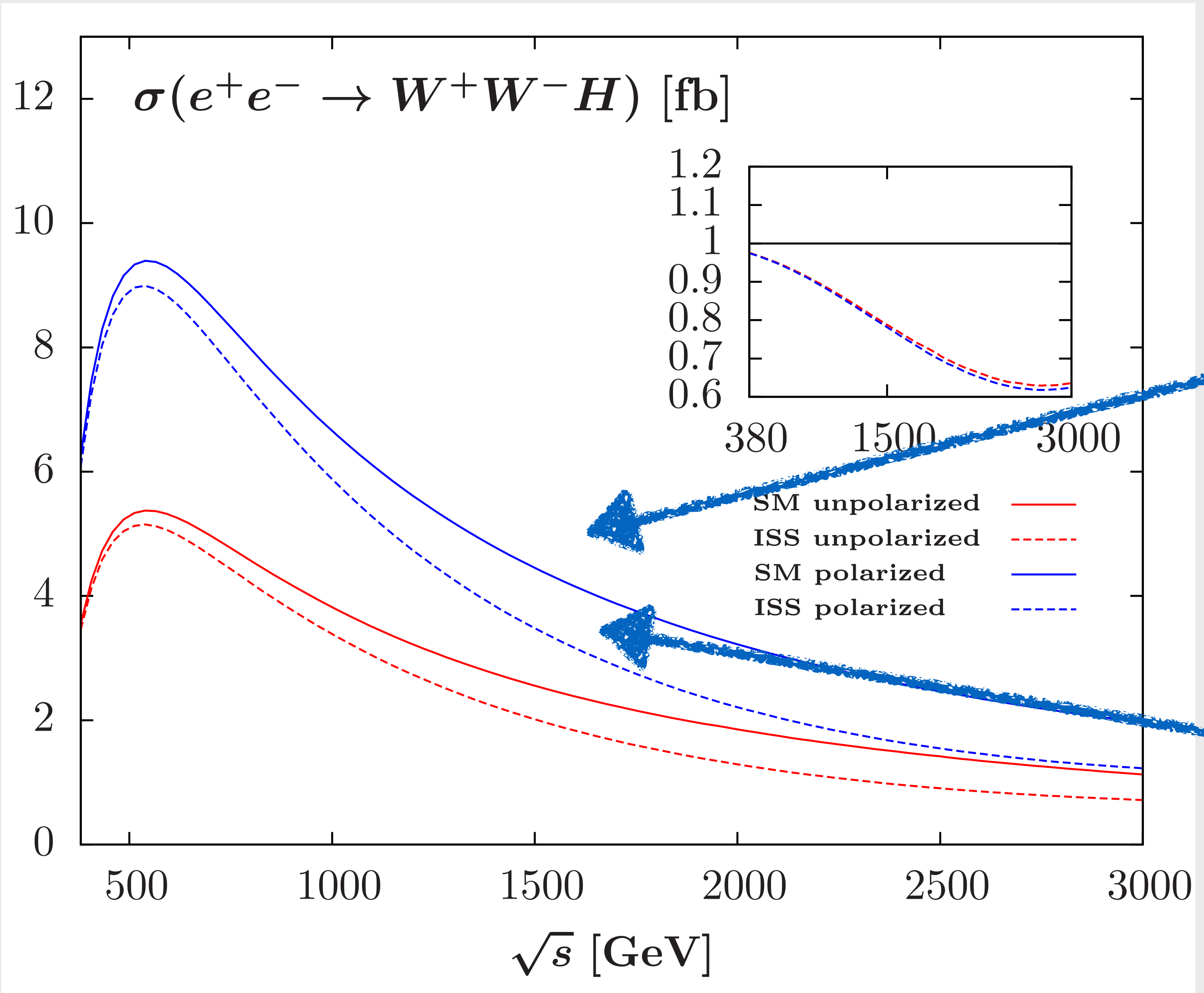
Exclude S++ up to 10 TeV for triplet Yukawa ~0.1

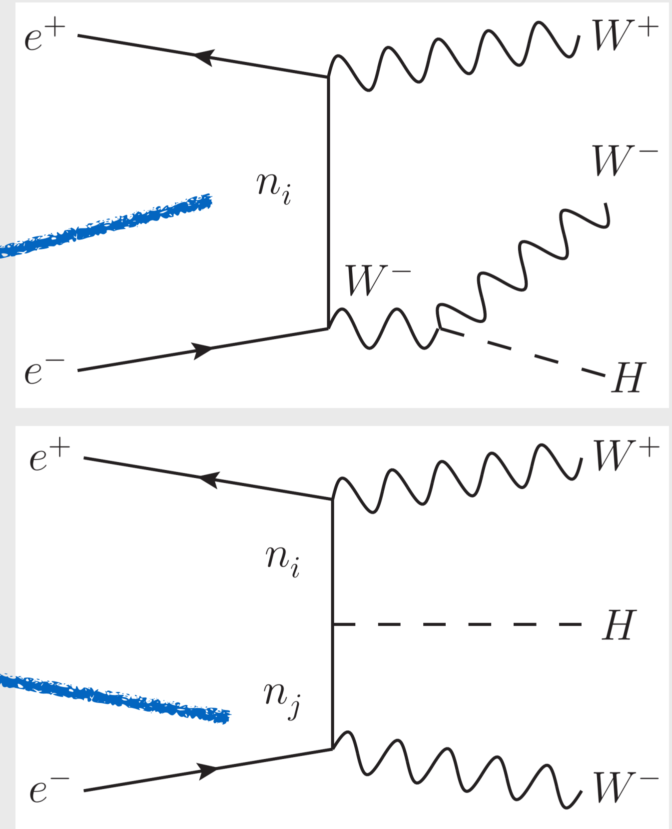
Plenty of neutrino mass models in reach

Type-2 See-Saw **1803.00677 - Agrawal, Mitra, Niyogi, Shil, Spannowsky**



Inverse See-Saw **1712.07621 - Baglio, Pascoli, Weiland**





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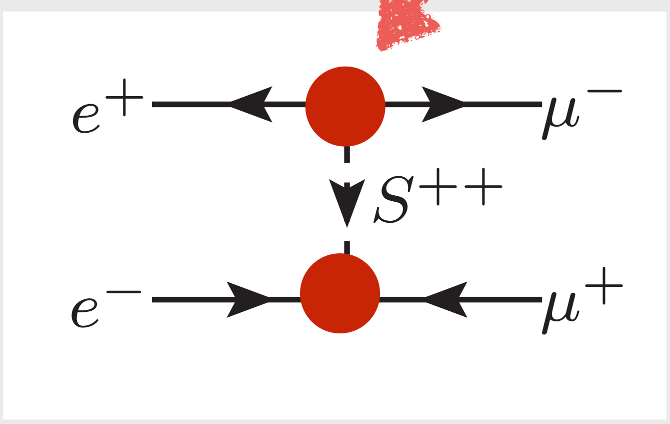

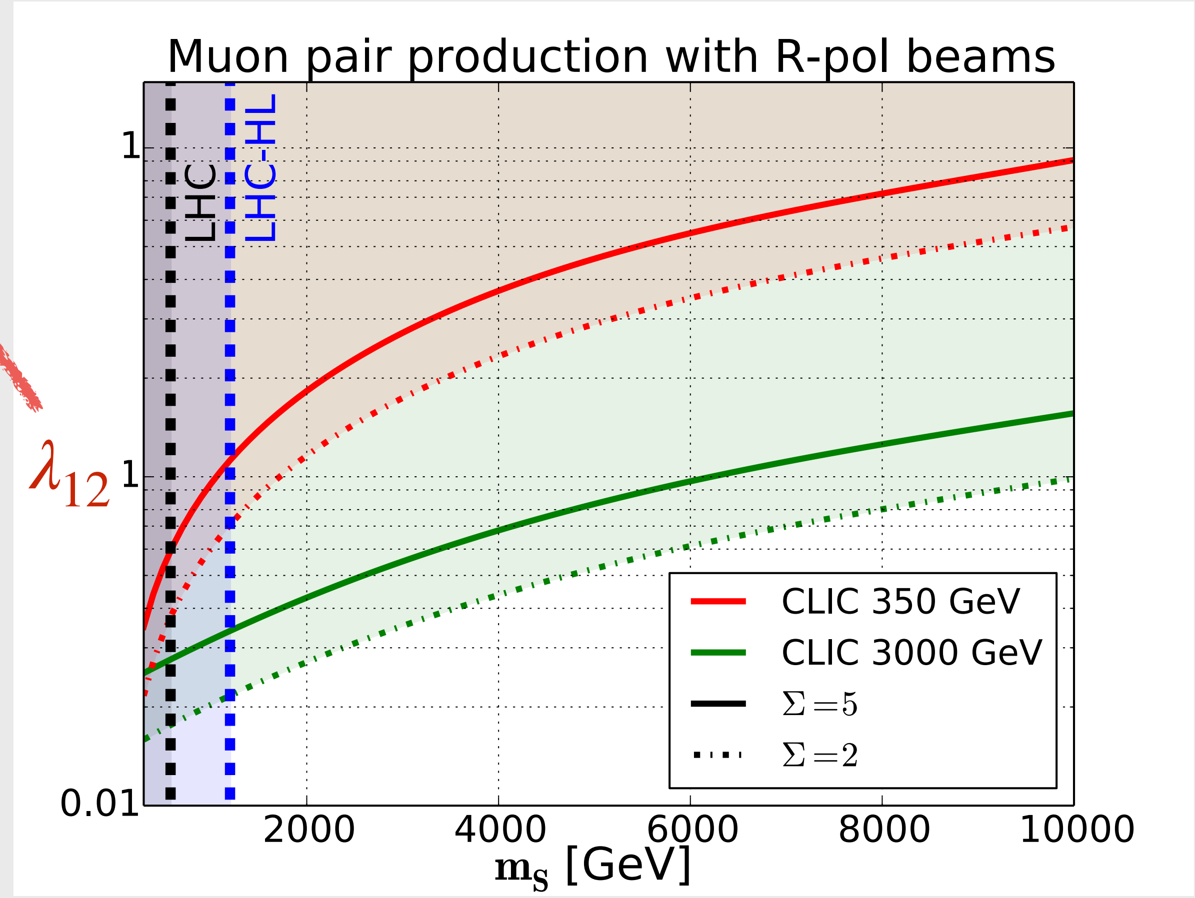

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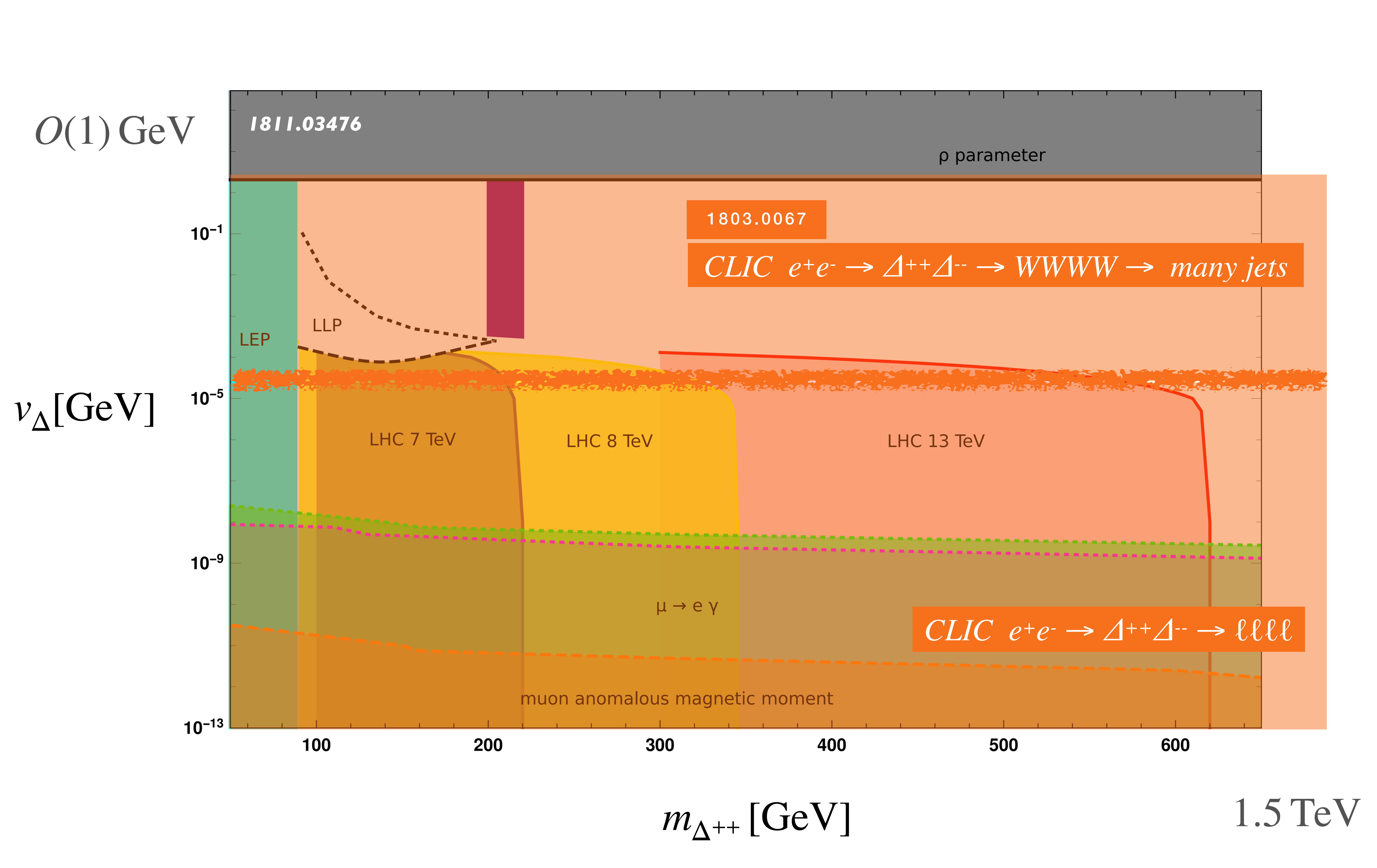

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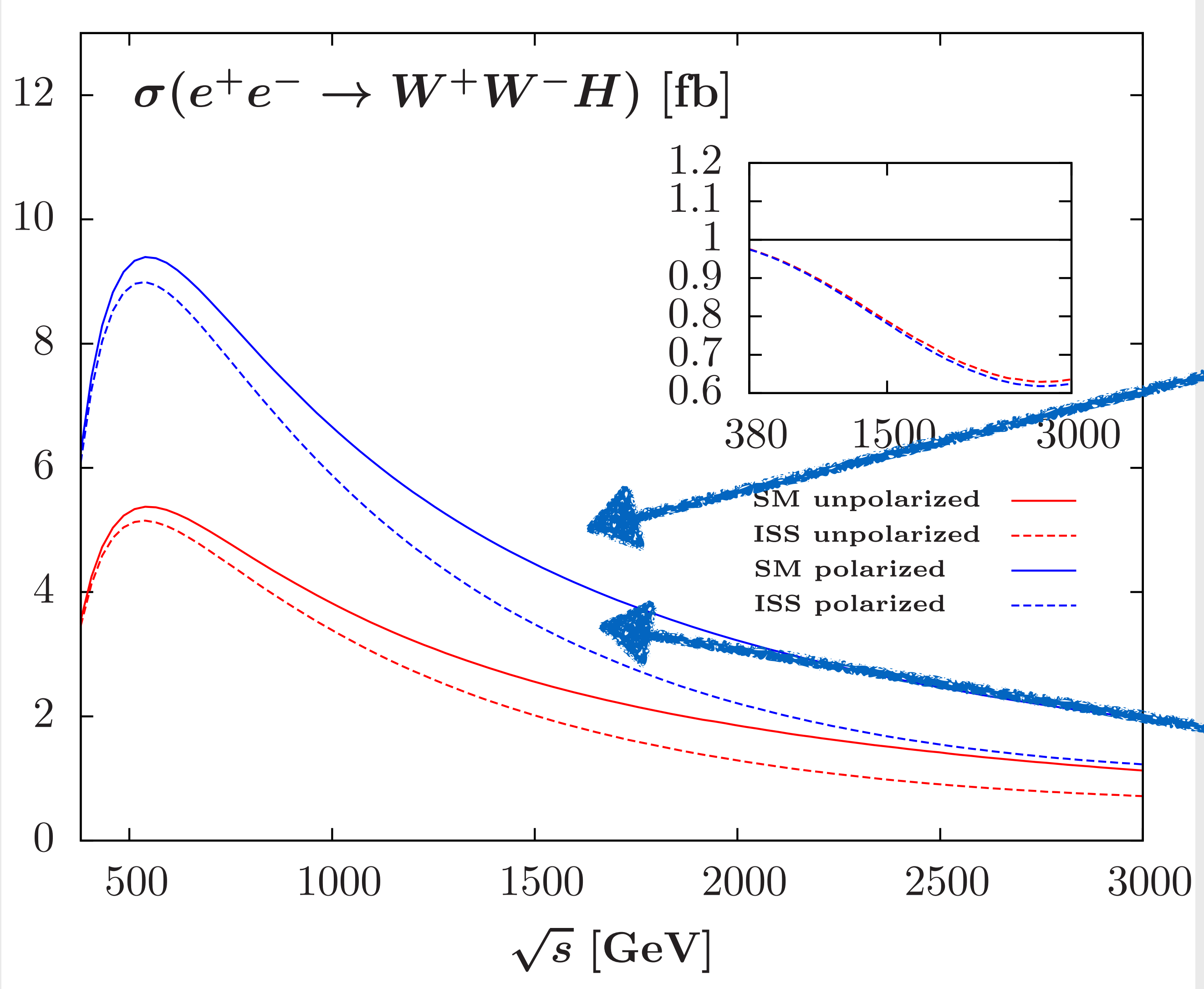

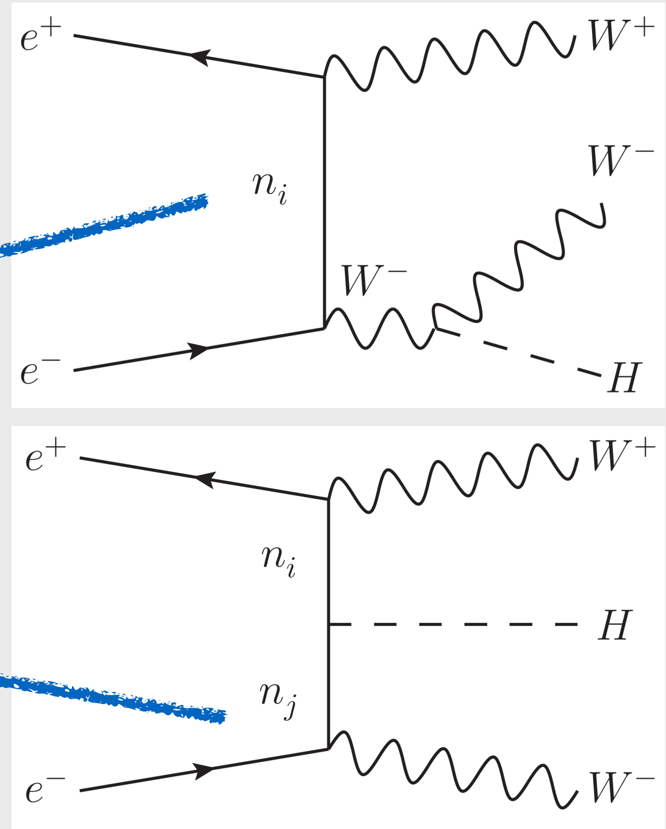

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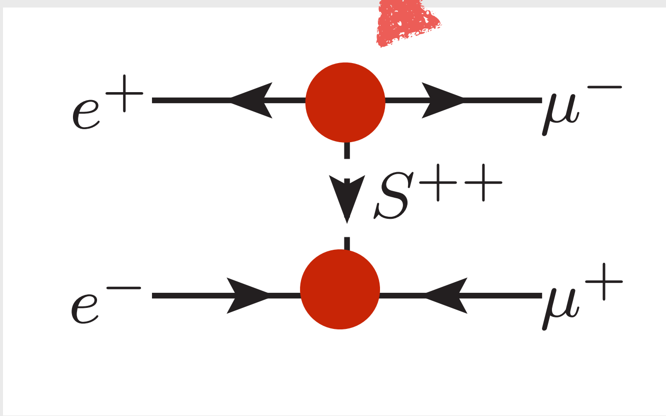

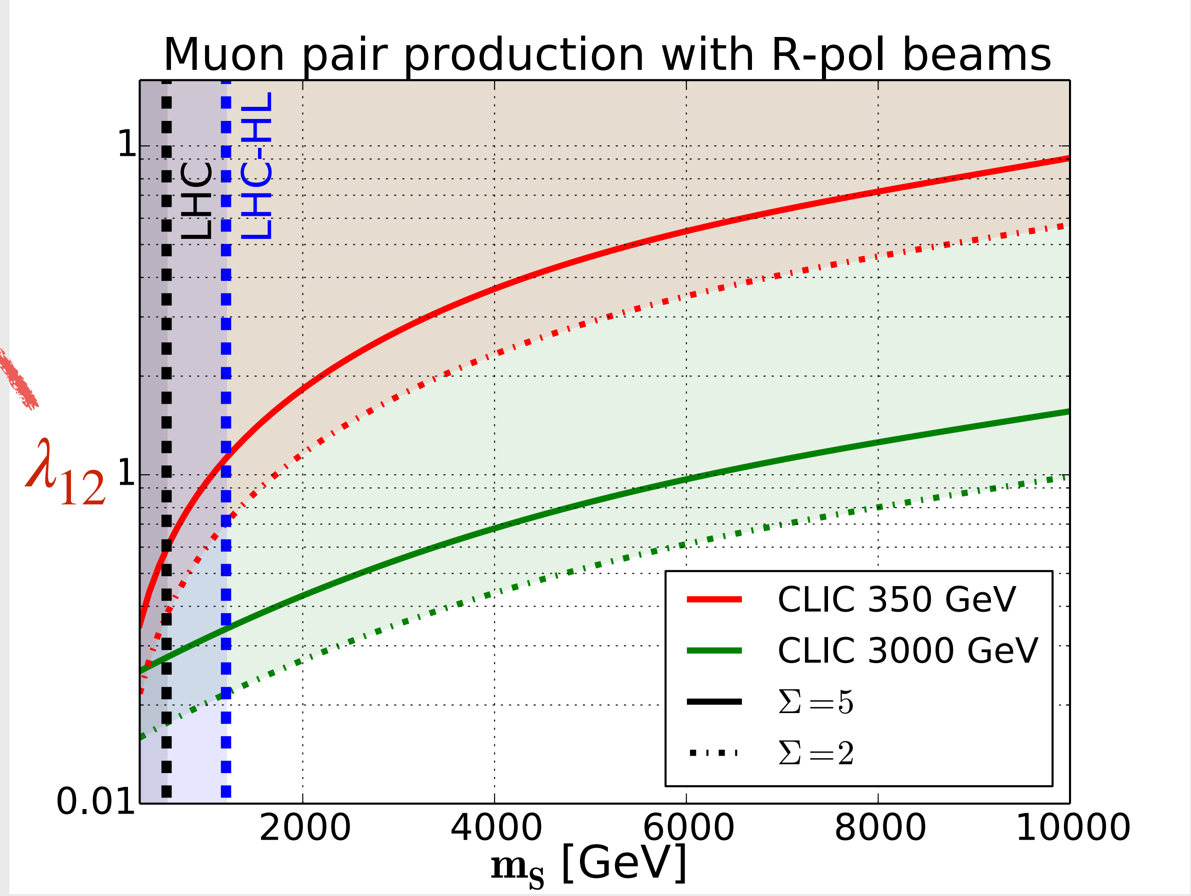

Exclude S++ up to 10 TeV for triplet Yukawa ~0.1

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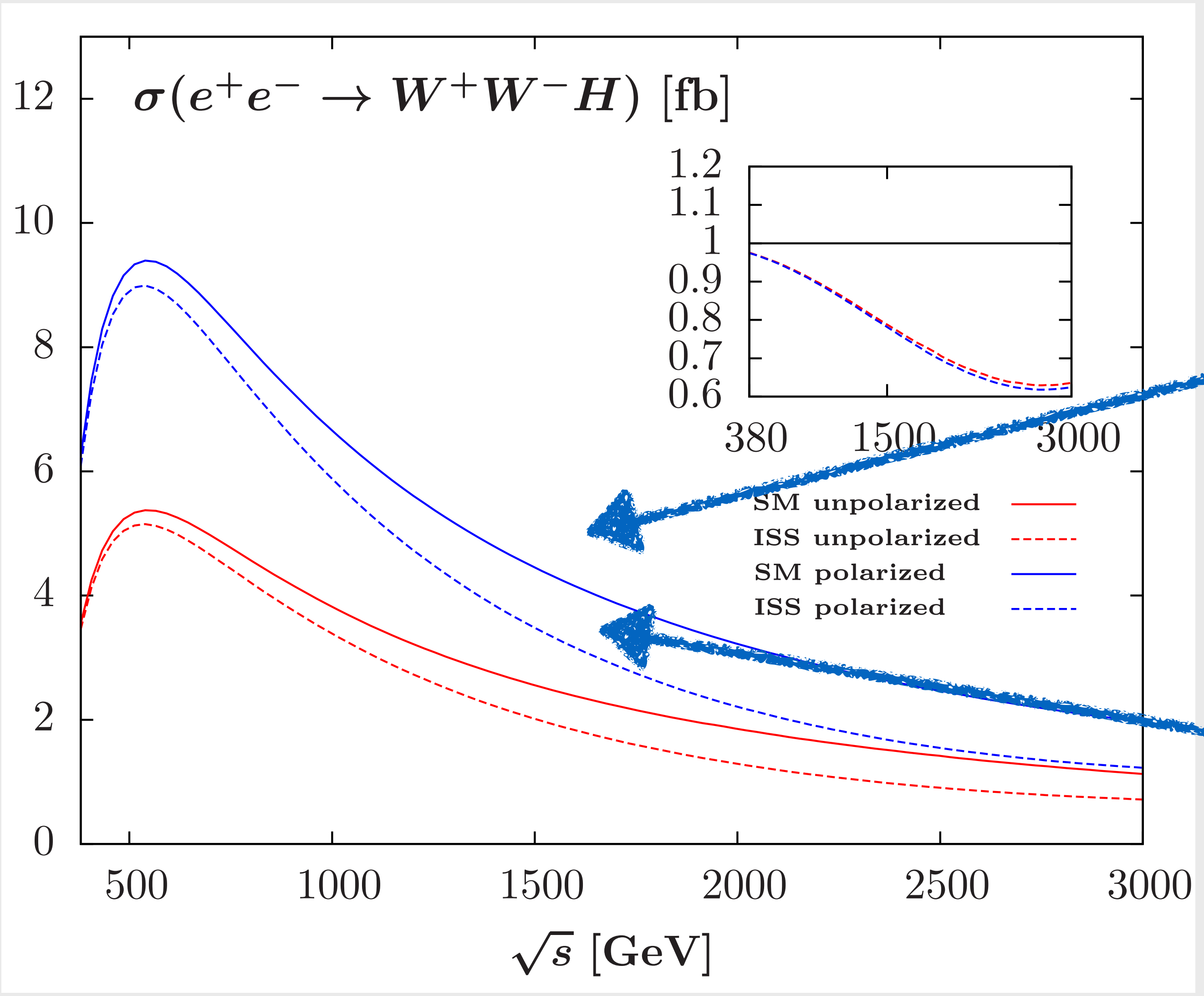
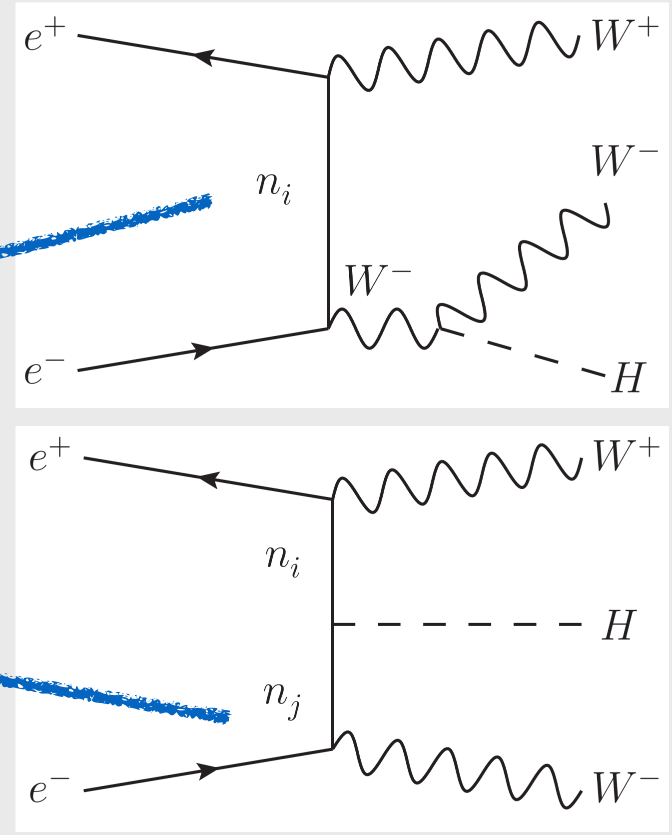
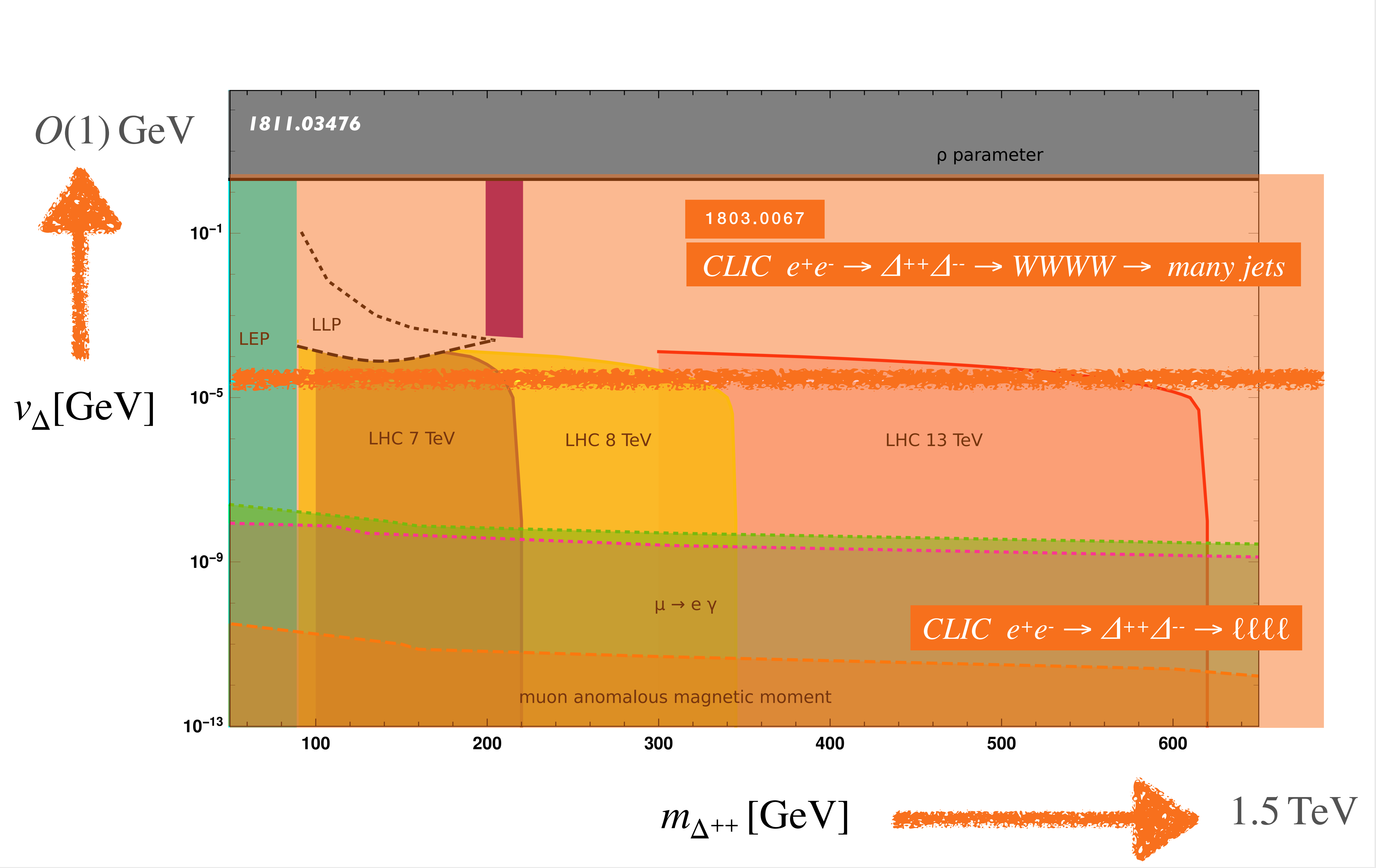


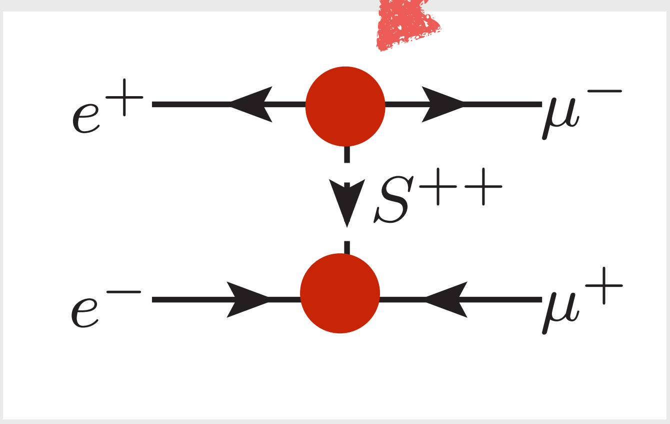


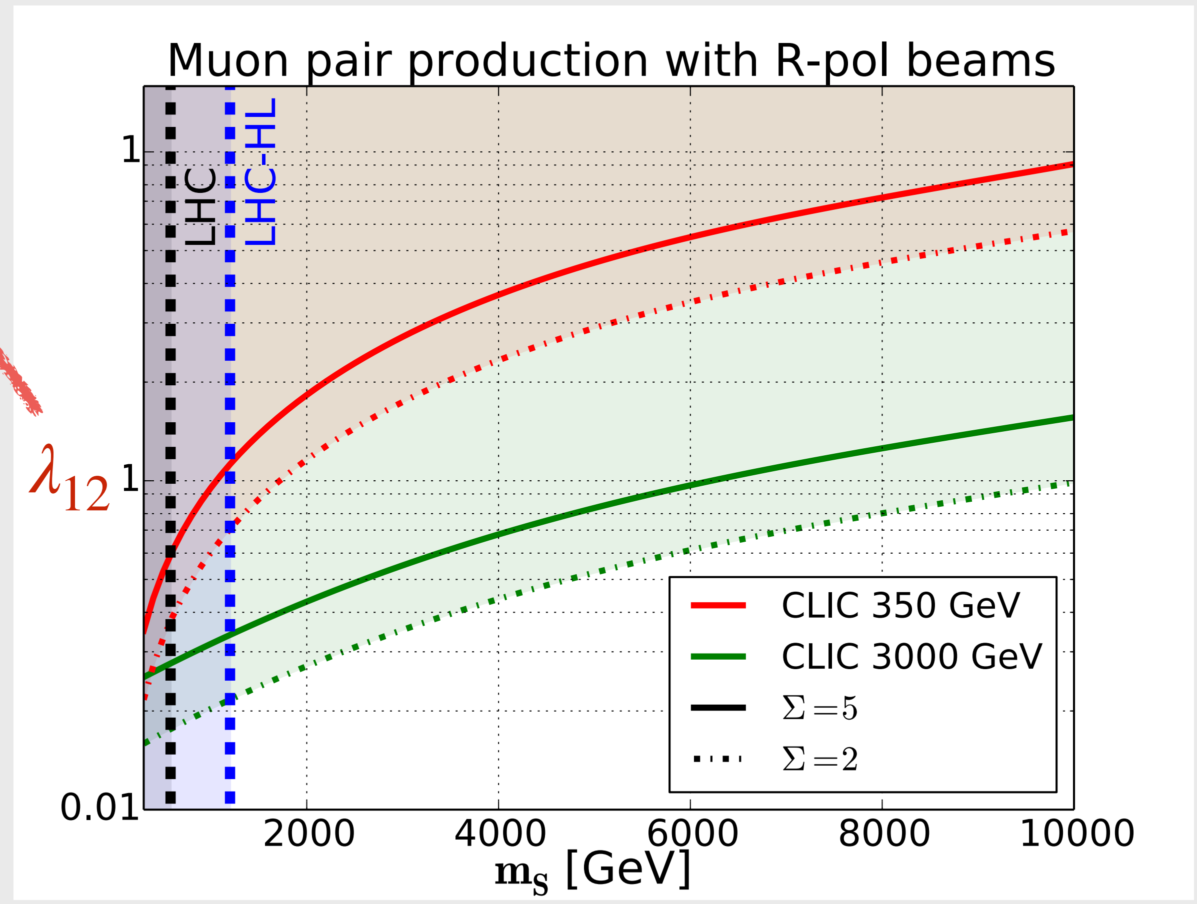
Exclude ISS RH Neutrino up to 10 TeV for Yukawa ~1

Type-2 See-Saw **1803.00677 - Agrawal, Mitra, Niyogi, Shil, Spannowsky**



1807.10224 - Crivellin, Ghezzi, Panizzi, Pruna, Signer

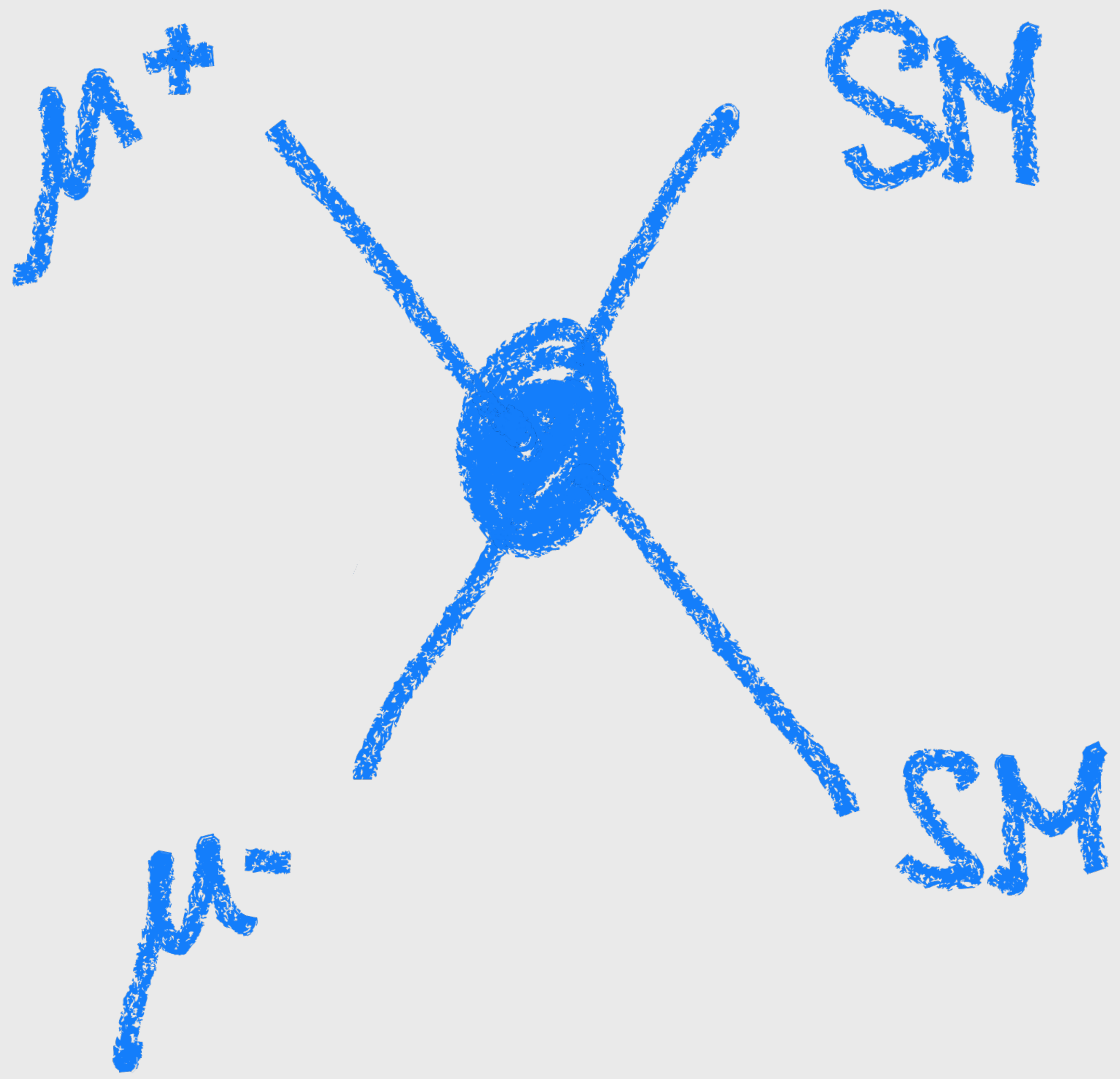




Exclude S++ up to 10 TeV for triplet Yukawa ~0.1

at $\sqrt{s} \gg 100$ GeV

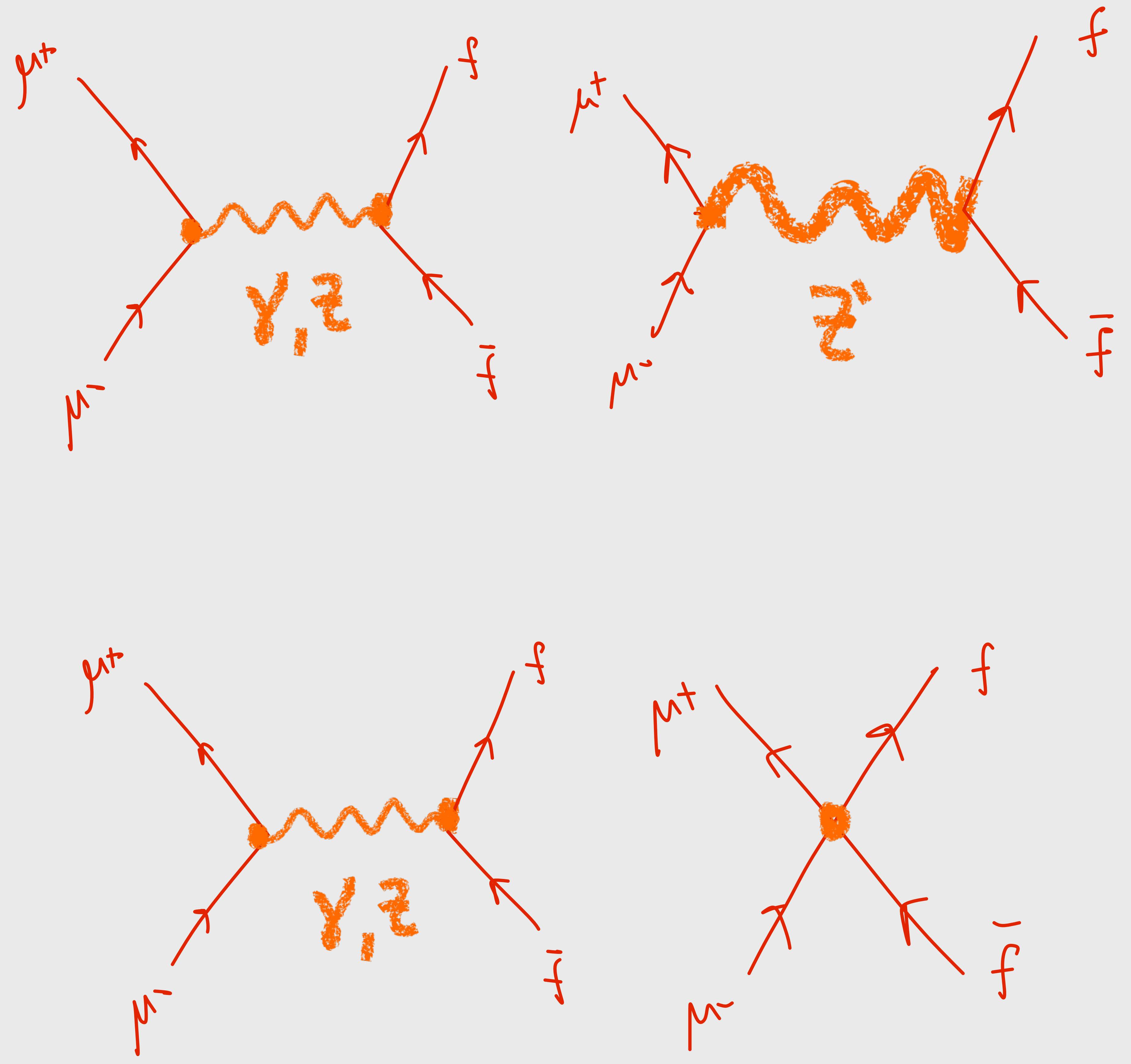
Indirect Effects

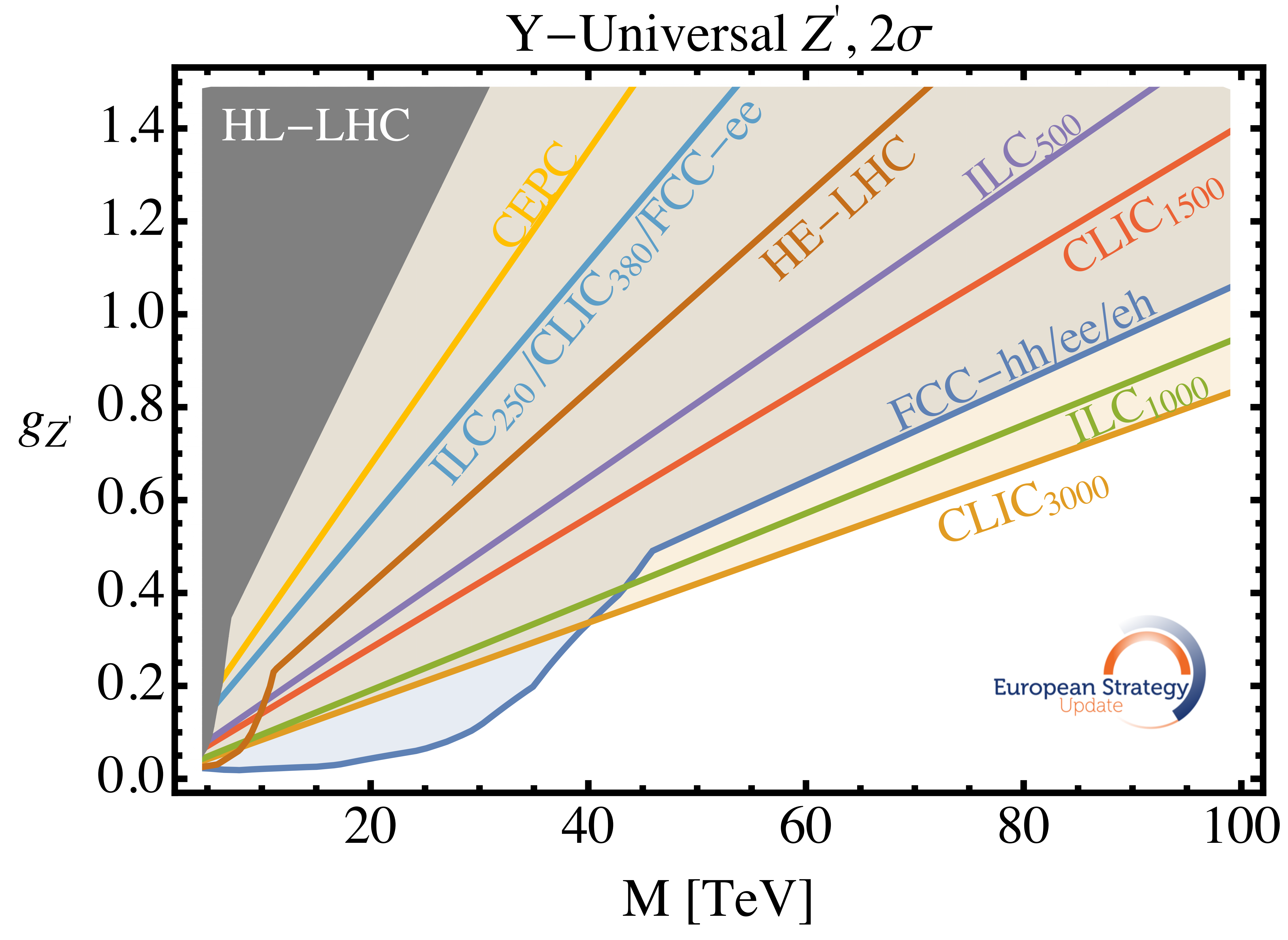


A heavy Z'

DRELL-YAN

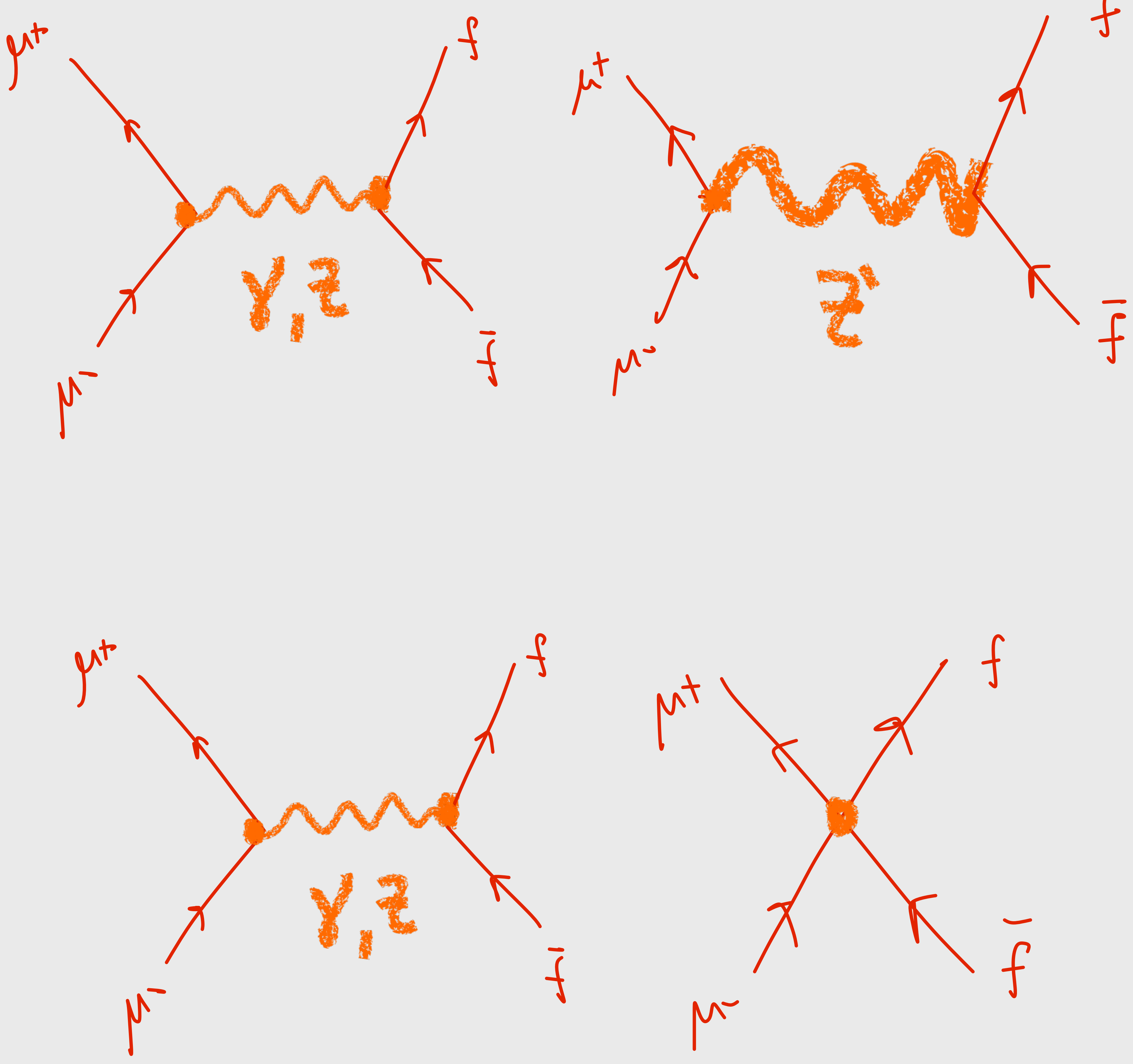
RATES AND ANGULAR DISTRIBUTIONS

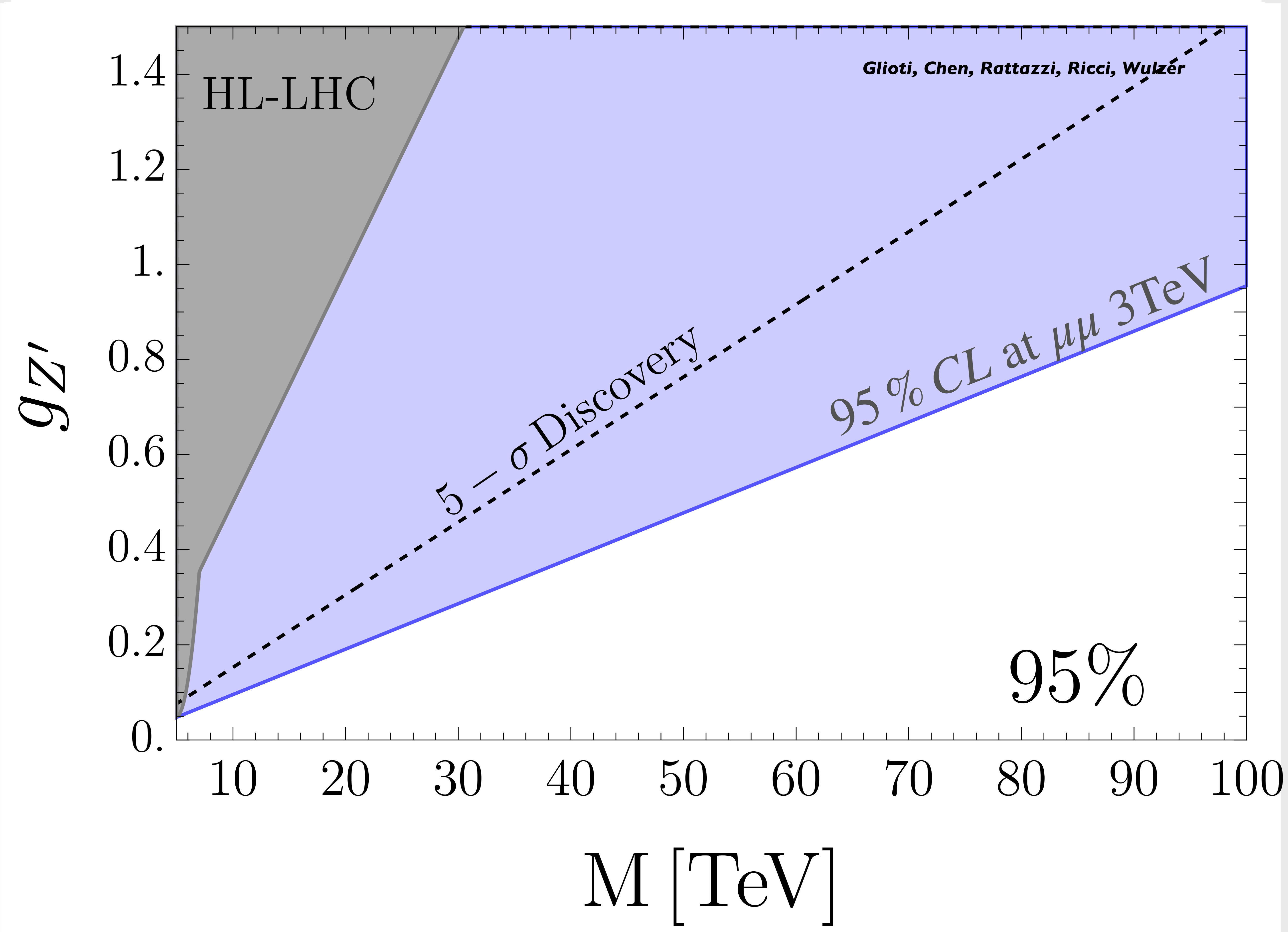




A heavy Z'

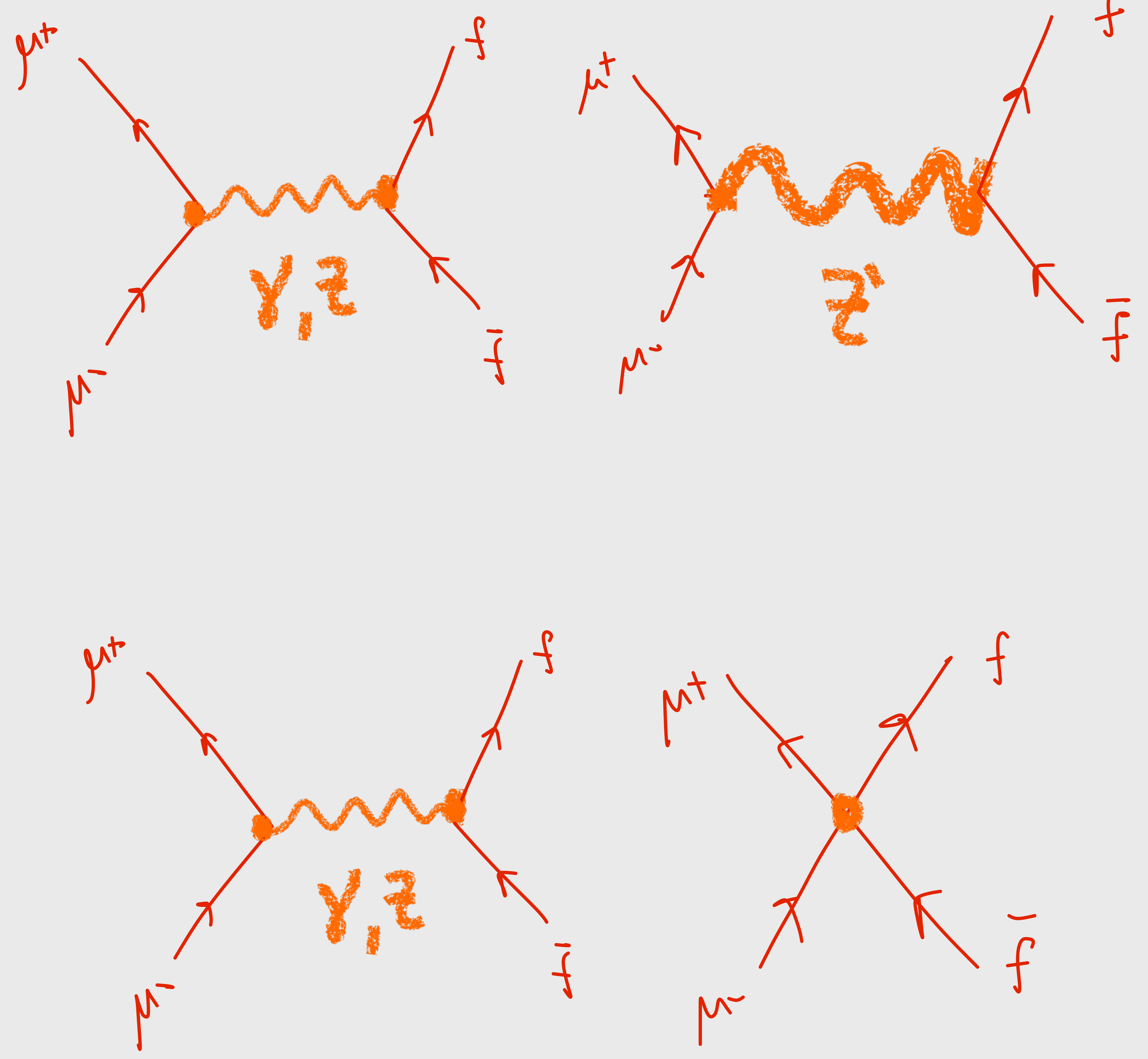
DRELL-YAN | RATES AND ANGULAR DISTRIBUTIONS

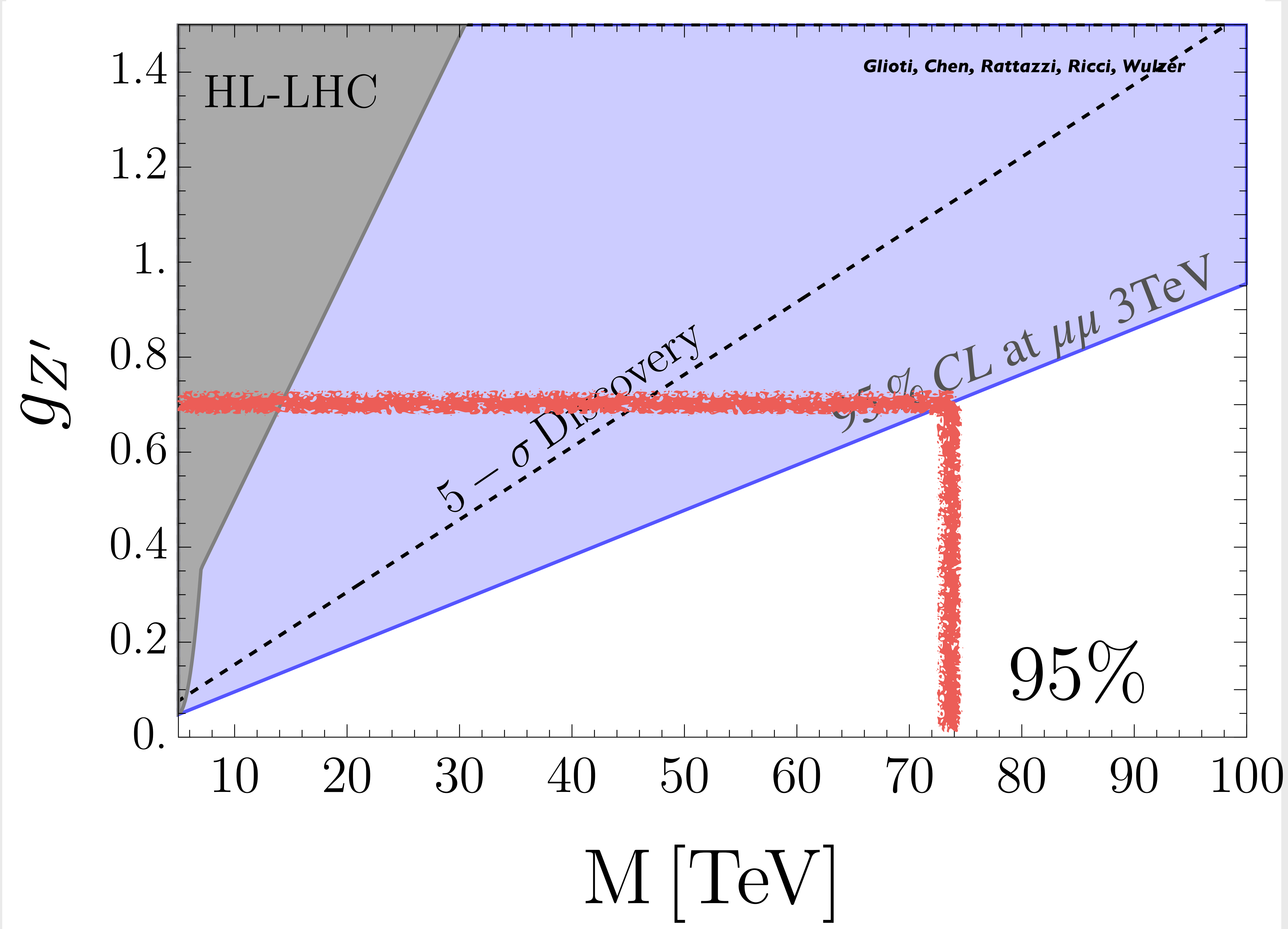




A heavy Z'

DRELL-YAN | RATES AND ANGULAR DISTRIBUTIONS

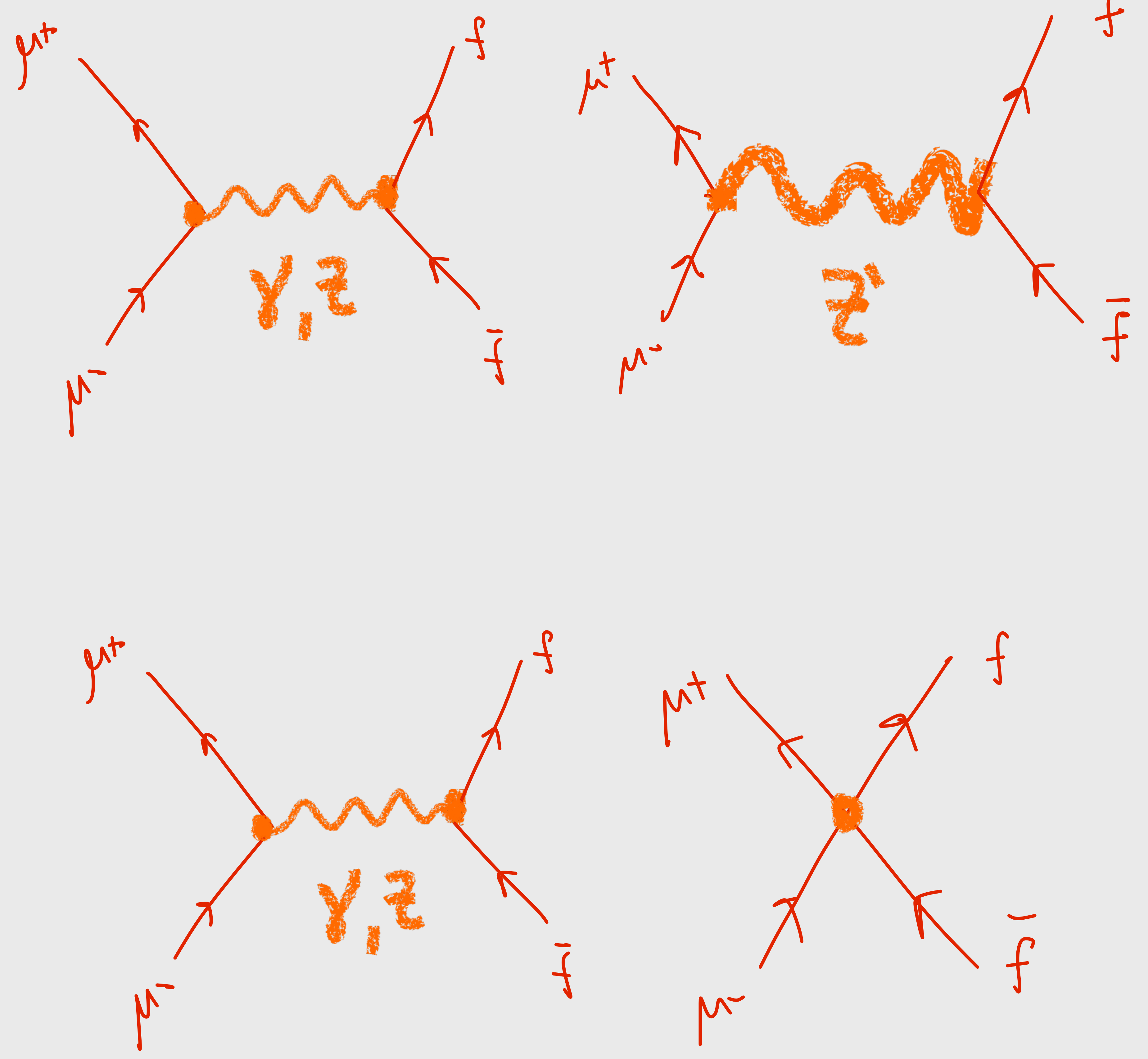


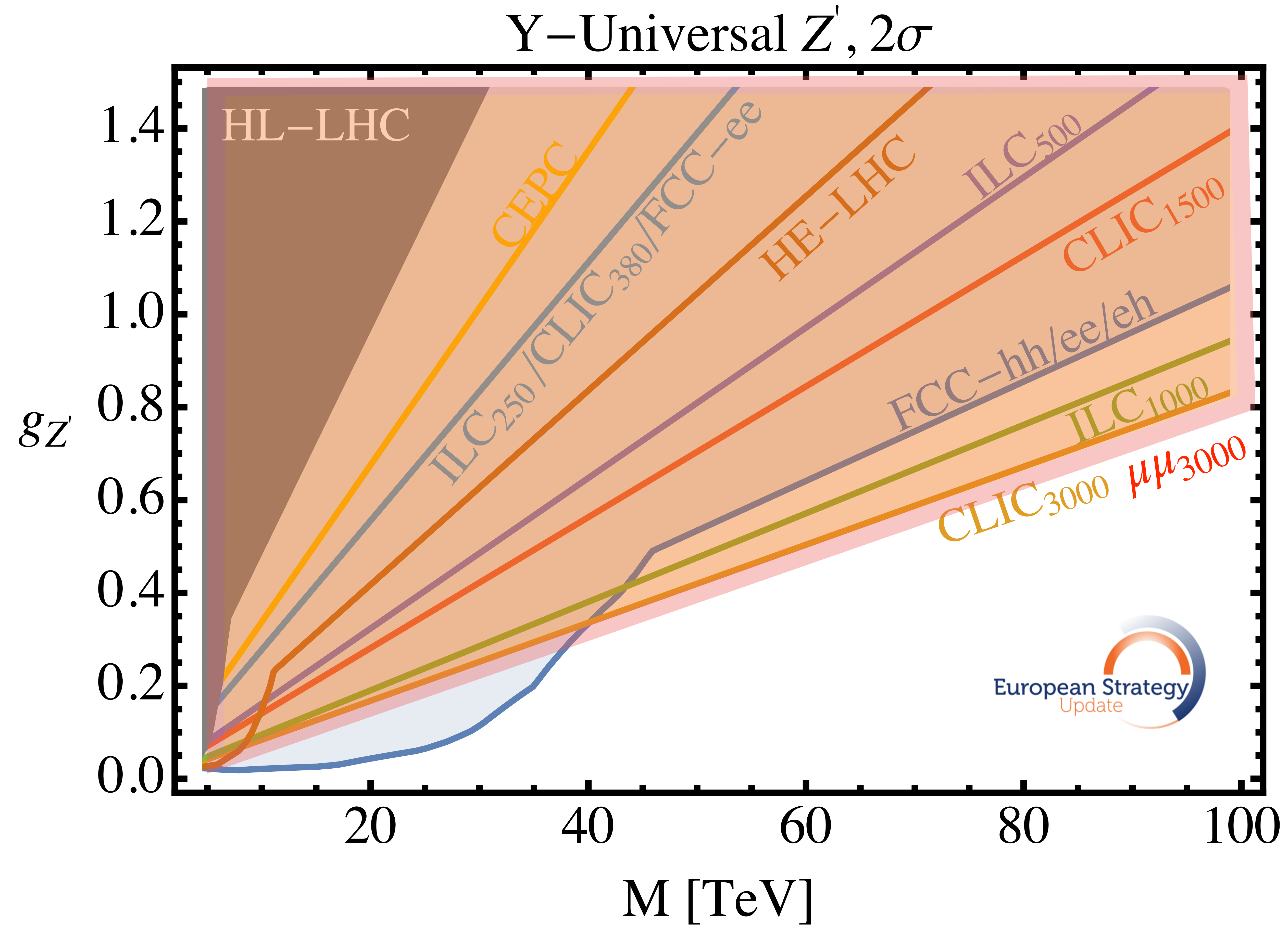


$\sqrt{s} \simeq 3$ TeV can probe 70+ TeV mass for $g_{Z'} \simeq g_{SM} \simeq 0.67$

A heavy Z'

DRELL-YAN | RATES AND ANGULAR DISTRIBUTIONS

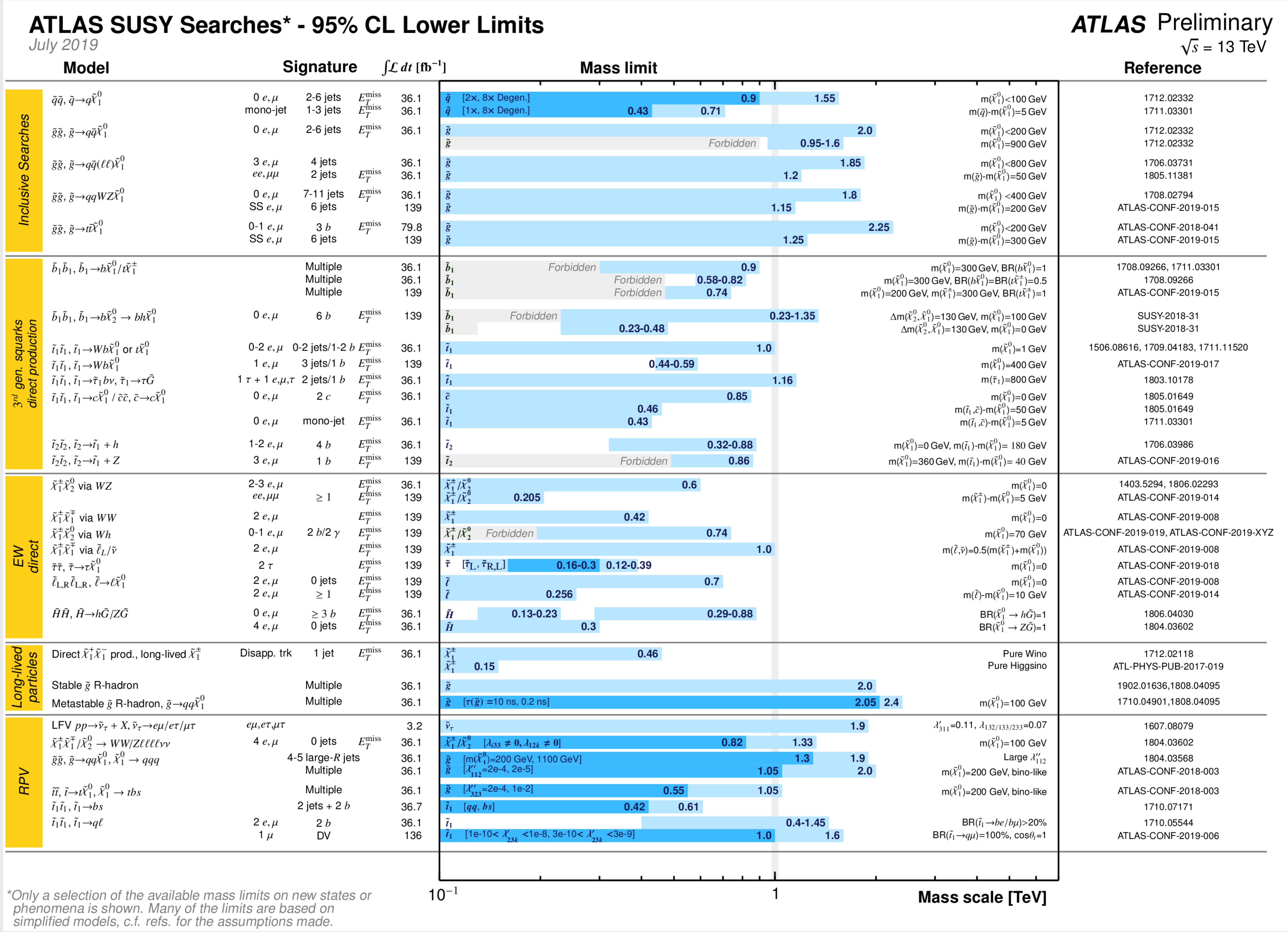


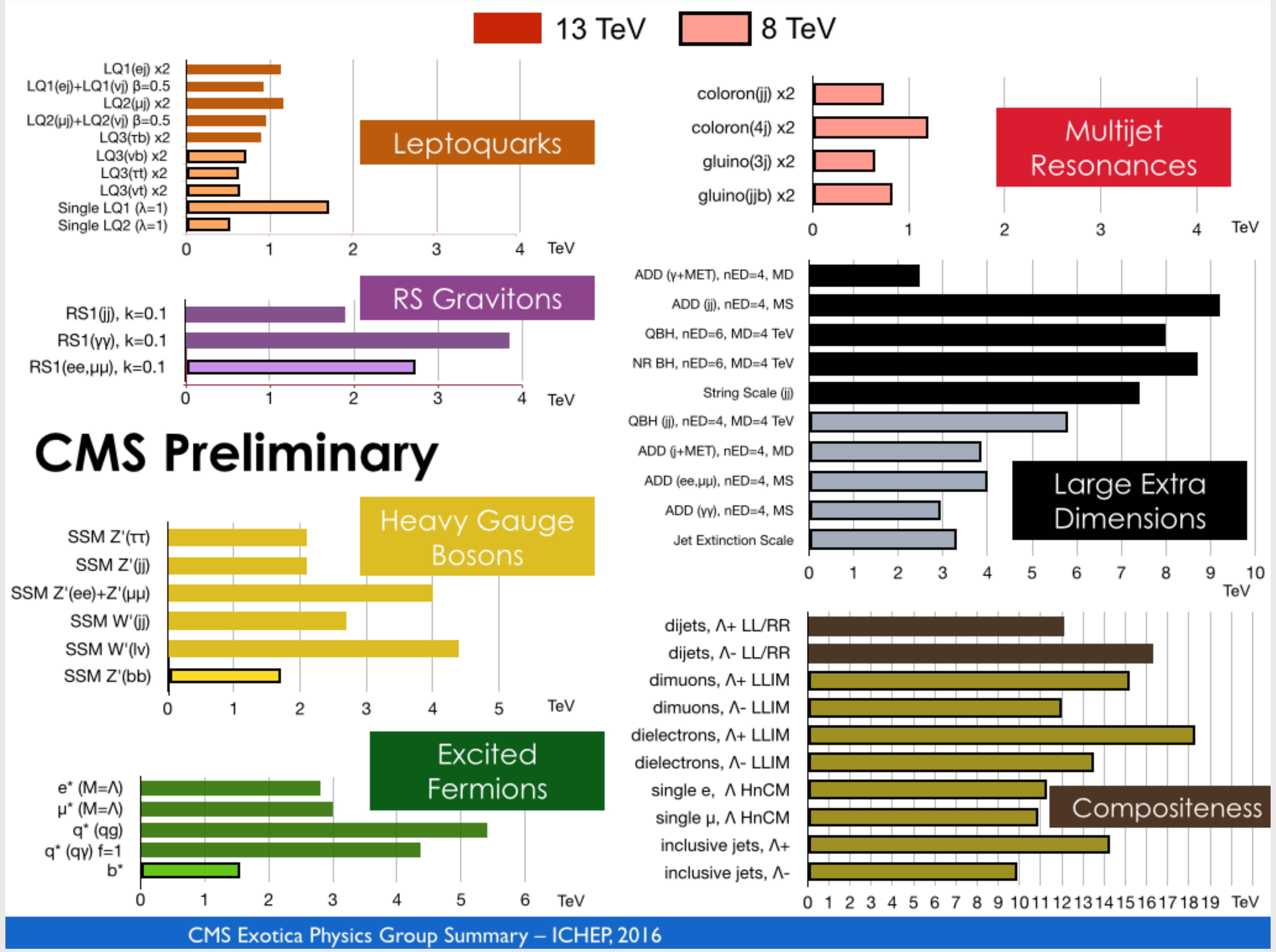


LHC ruled out new physics at Λ TeV …

LHC ruled out new physics at the TeV …

SUMMARY OF THE SUMMARIES





Thank You! (Again)