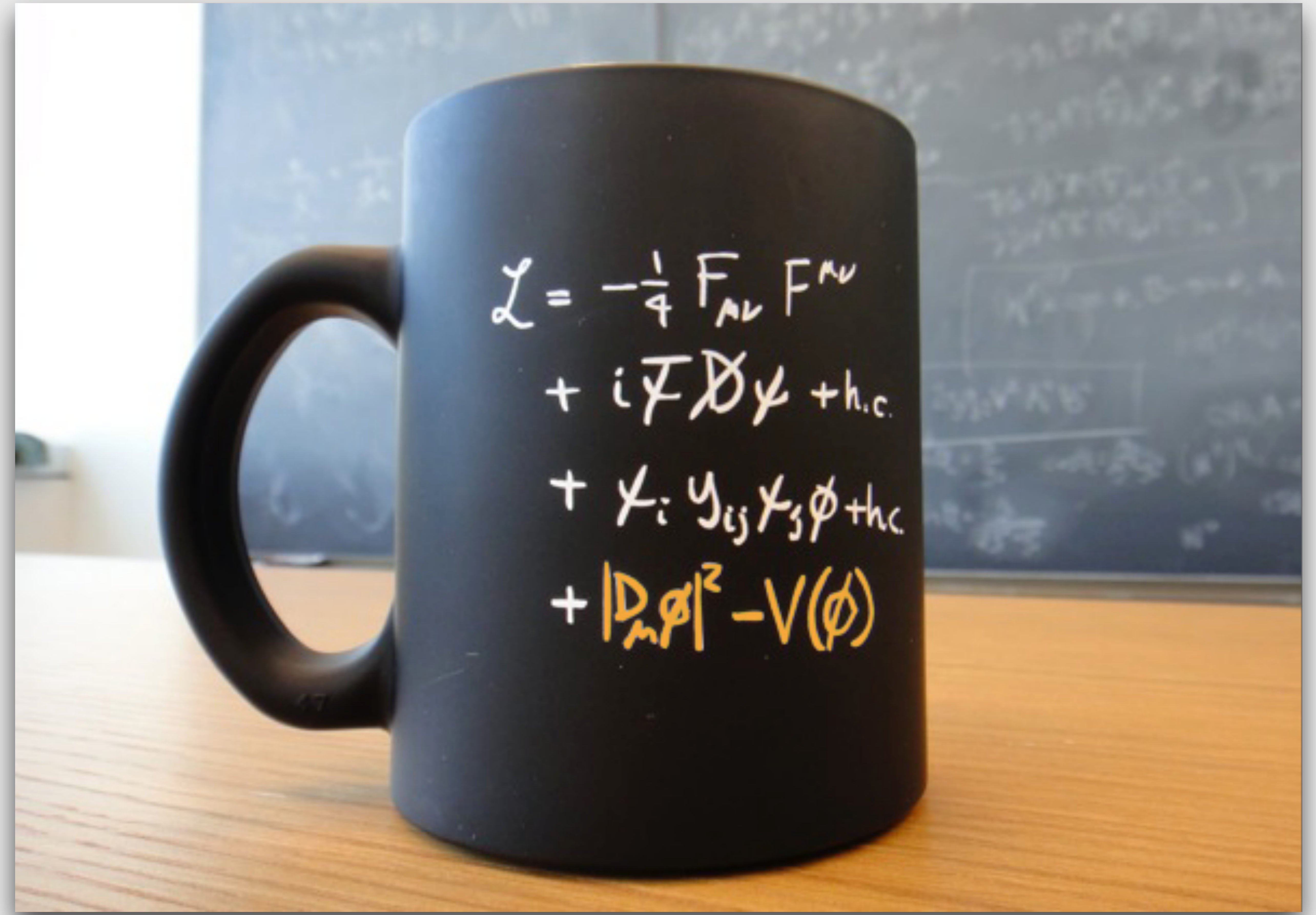
Motivation for high energy lepton colliders

APR. 29 2020

ROBERTO FRANCESCHINI (ROMA 3 UNIVERSITY)

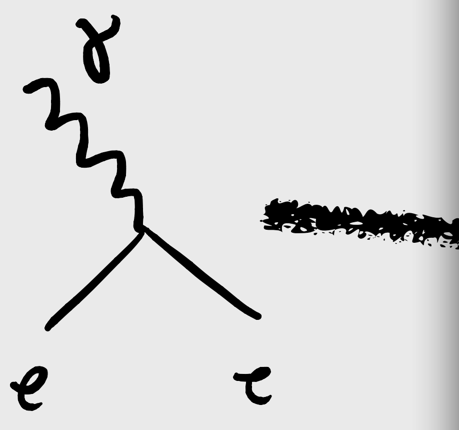
Where do we stand?

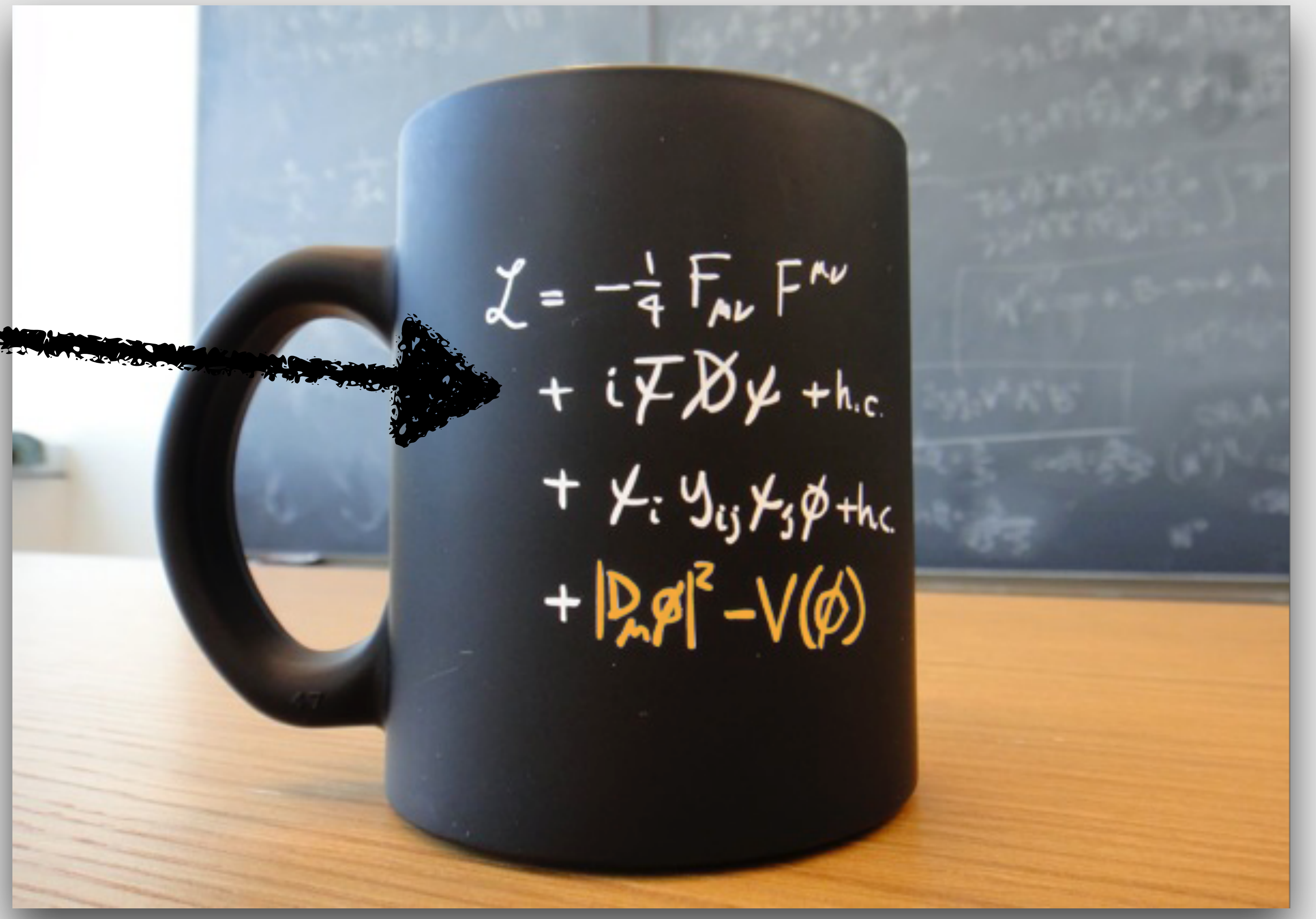


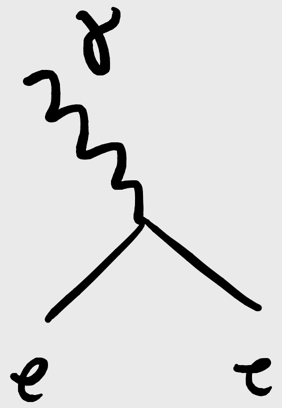
We have got "the" formula

… and it is surprisingly short!

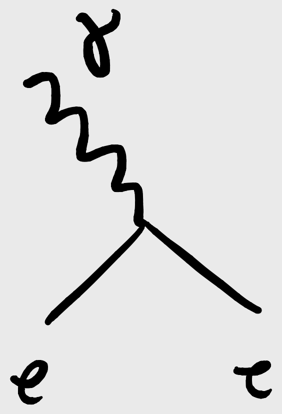
Where do we stand?







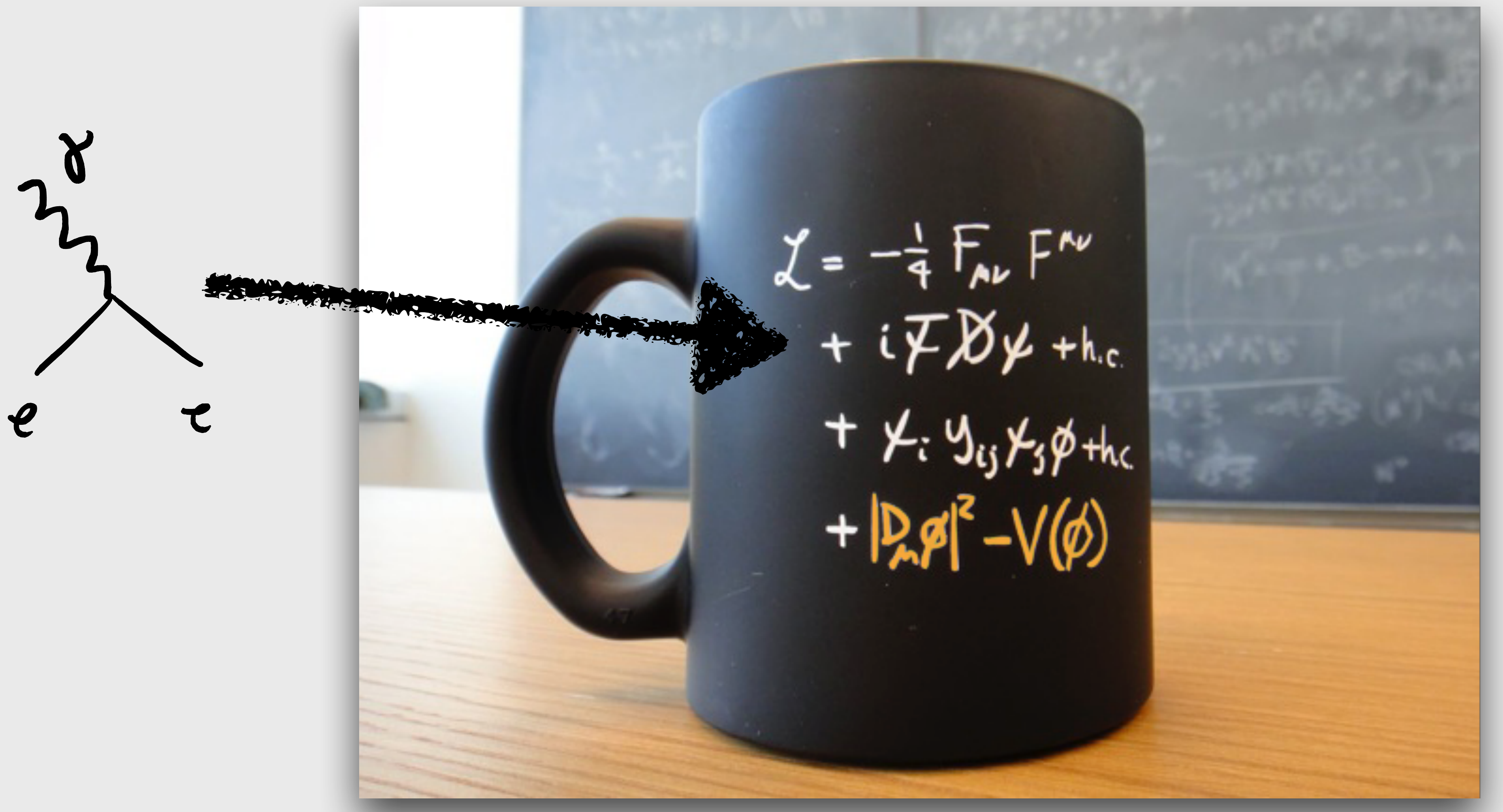
electro-weak interactions

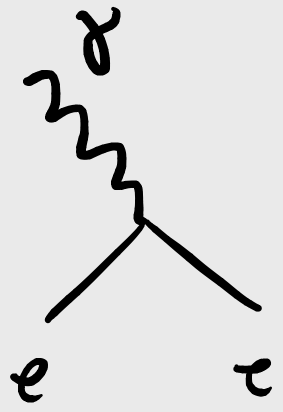


strong interactions

Where do we stand?

SYMMETRY AS A FUNDAMENTAL CHARACTER OF NATURE





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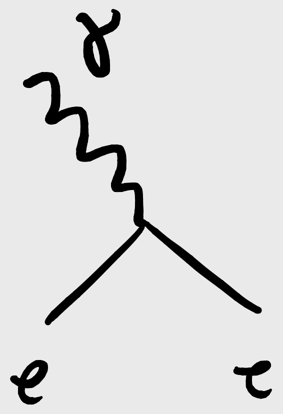

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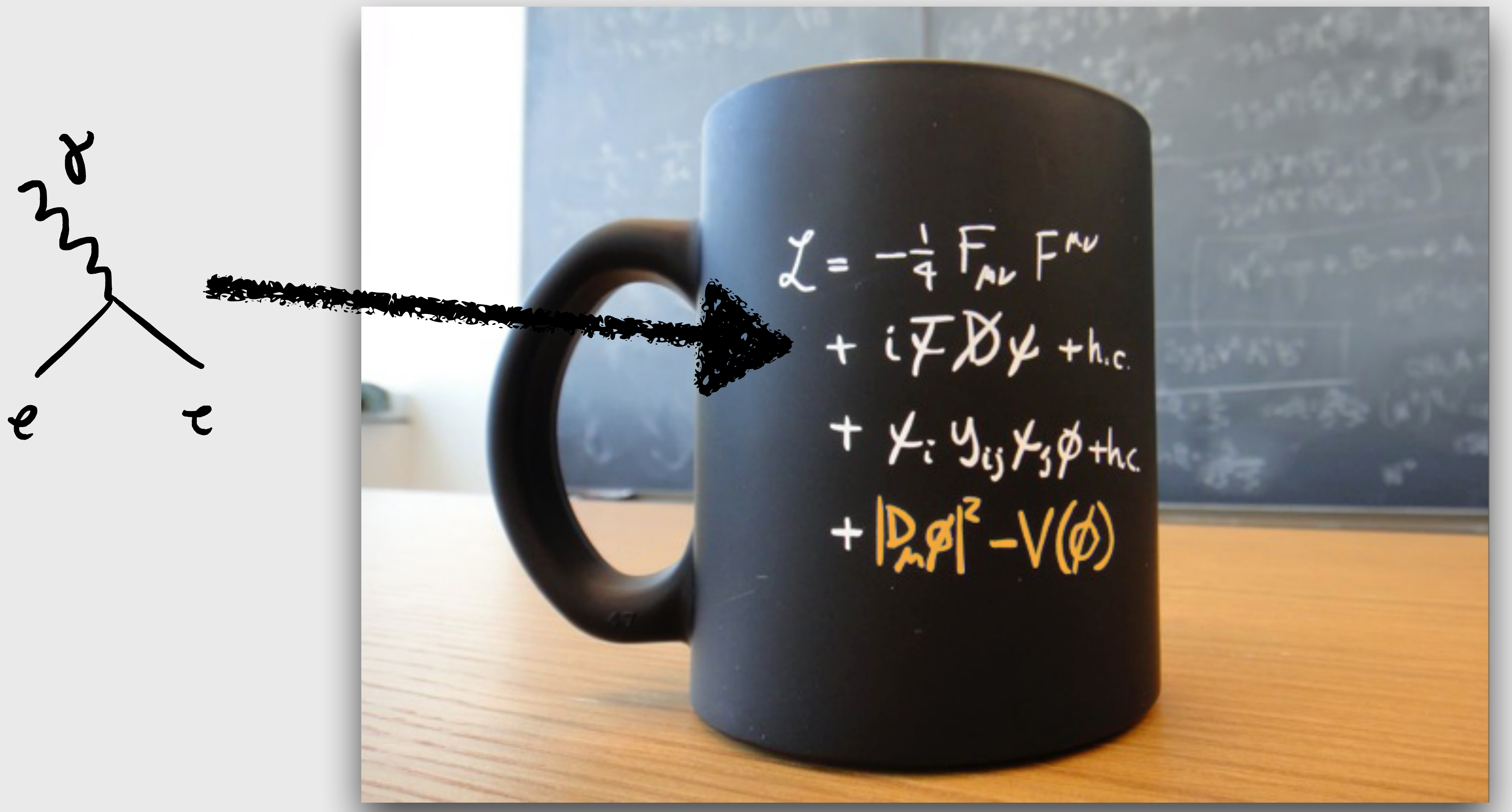

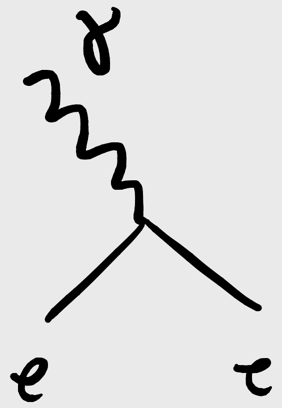

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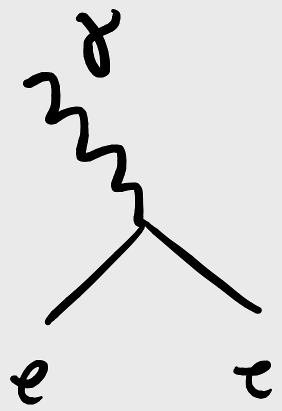

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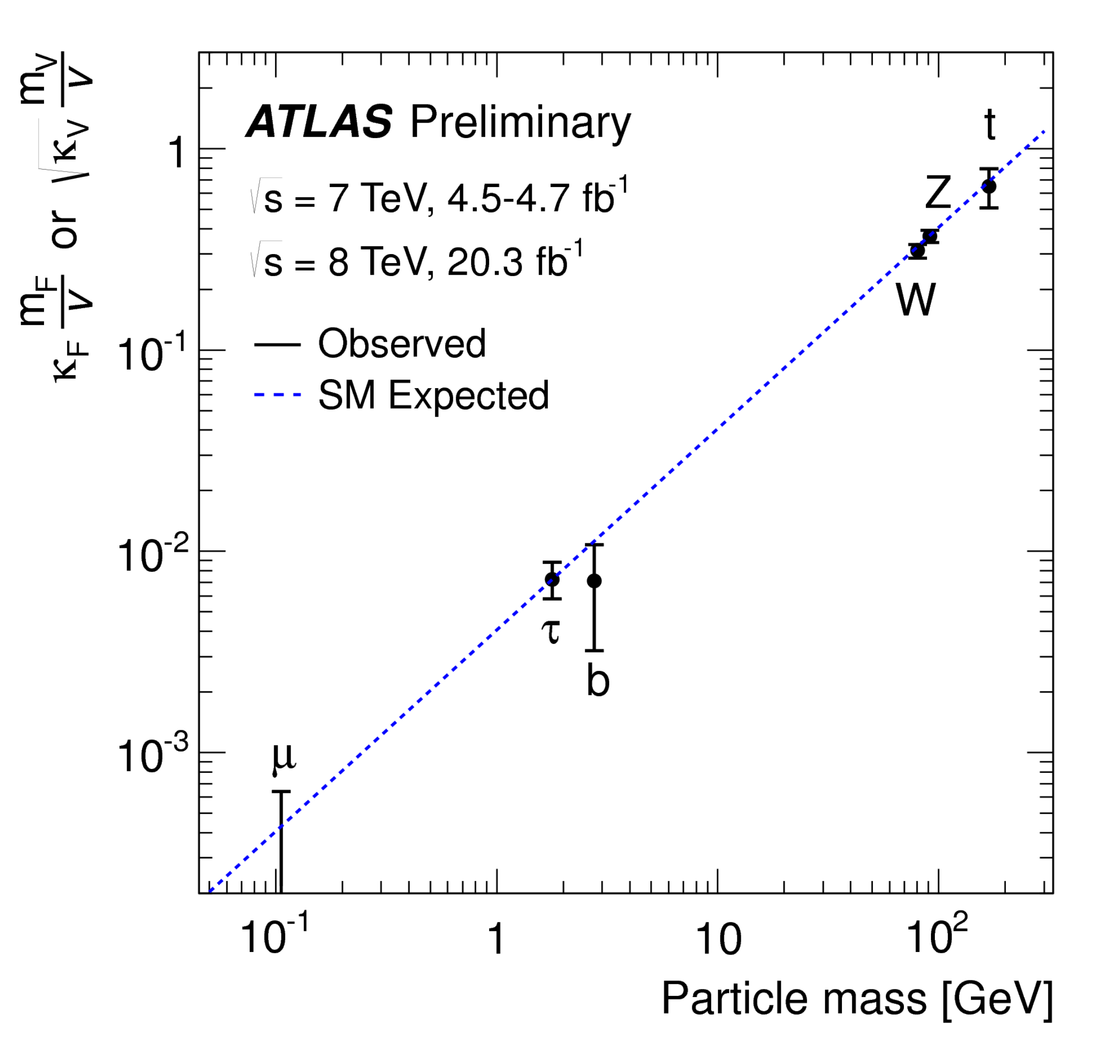

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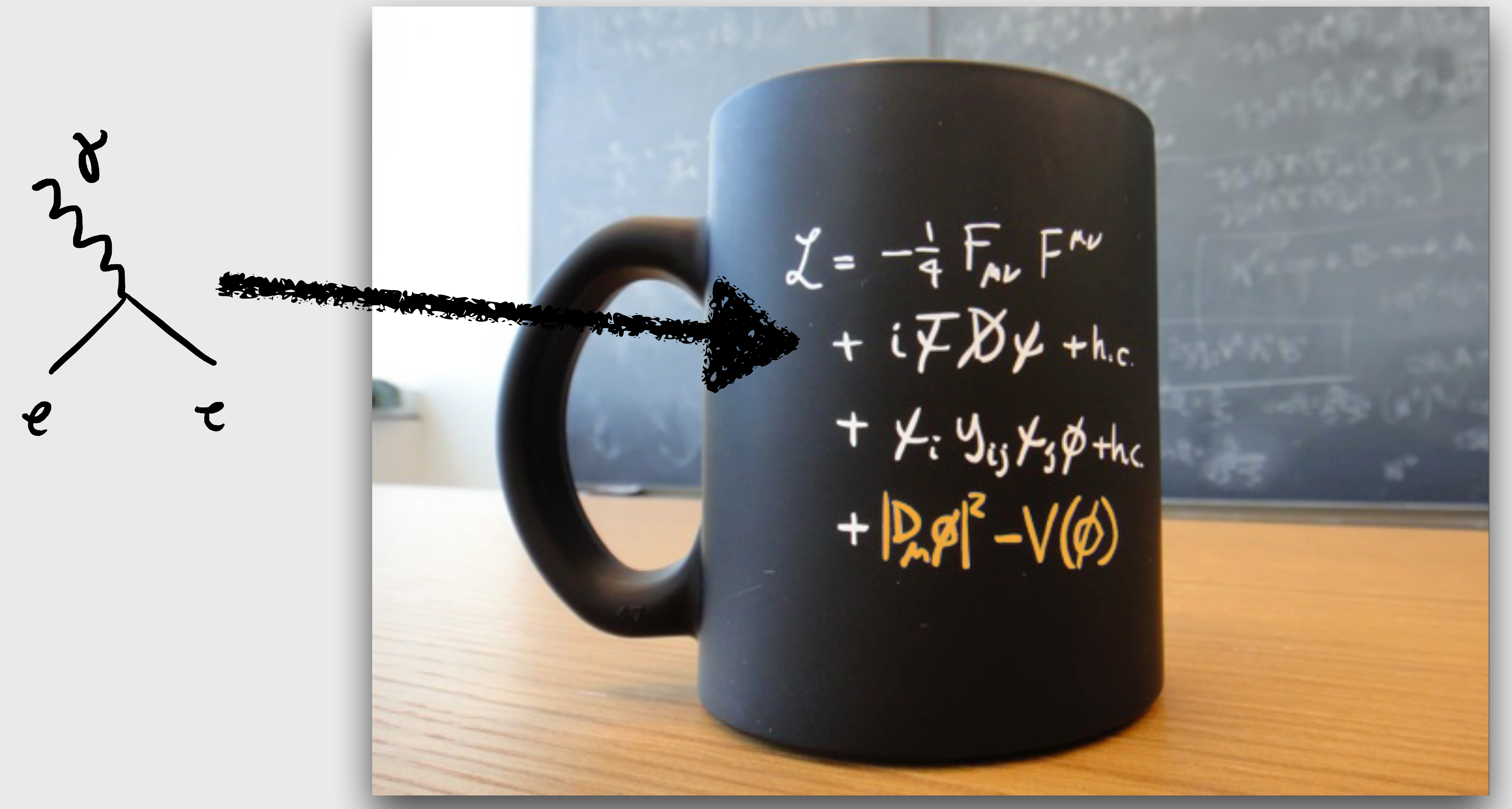

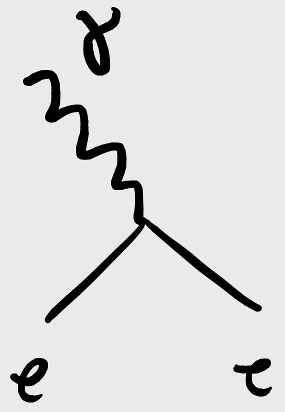

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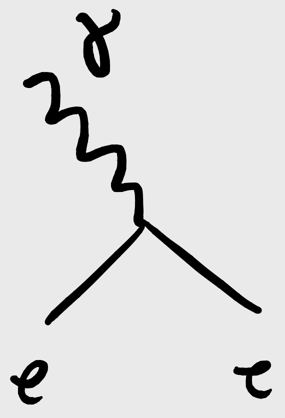

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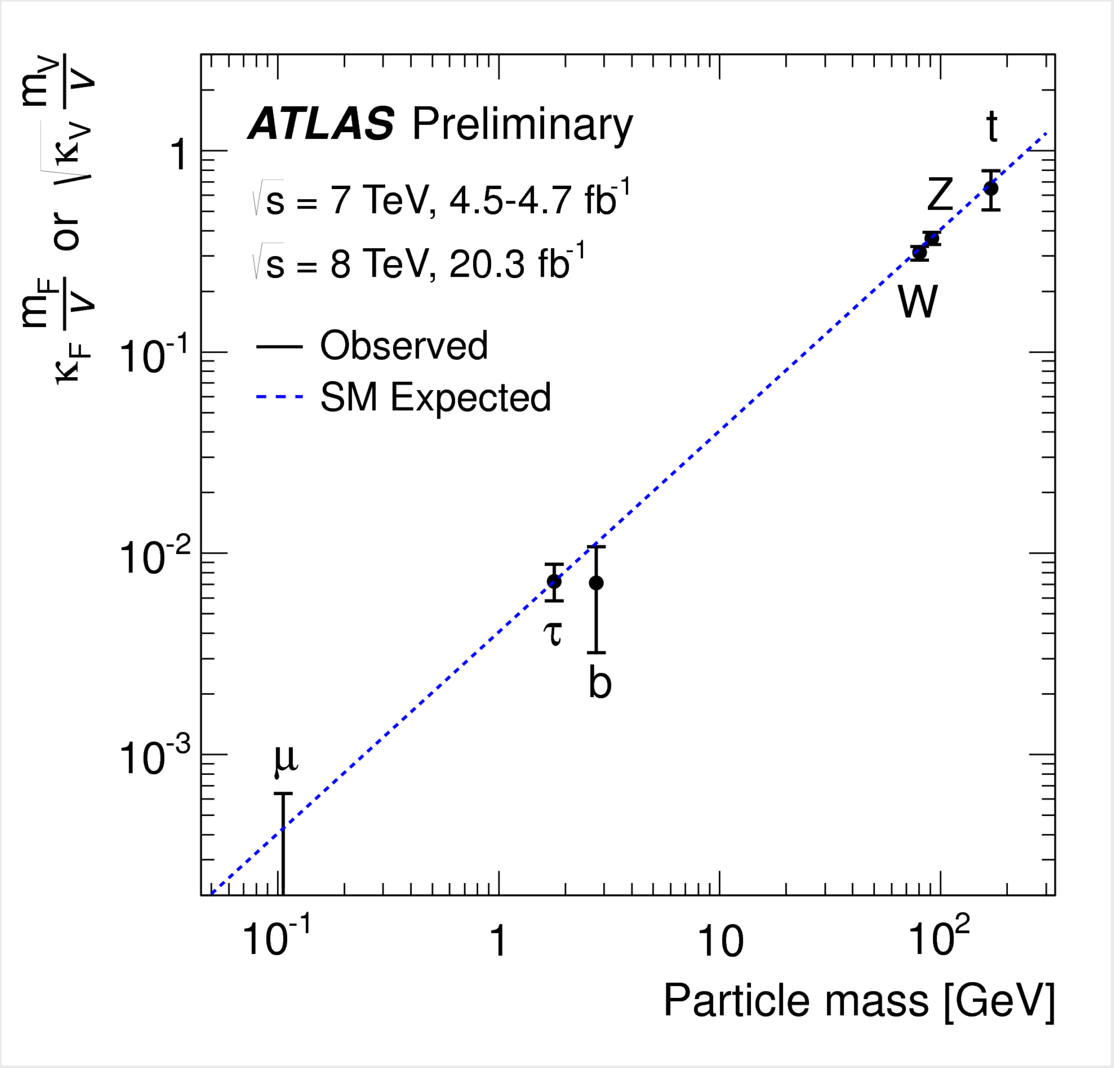

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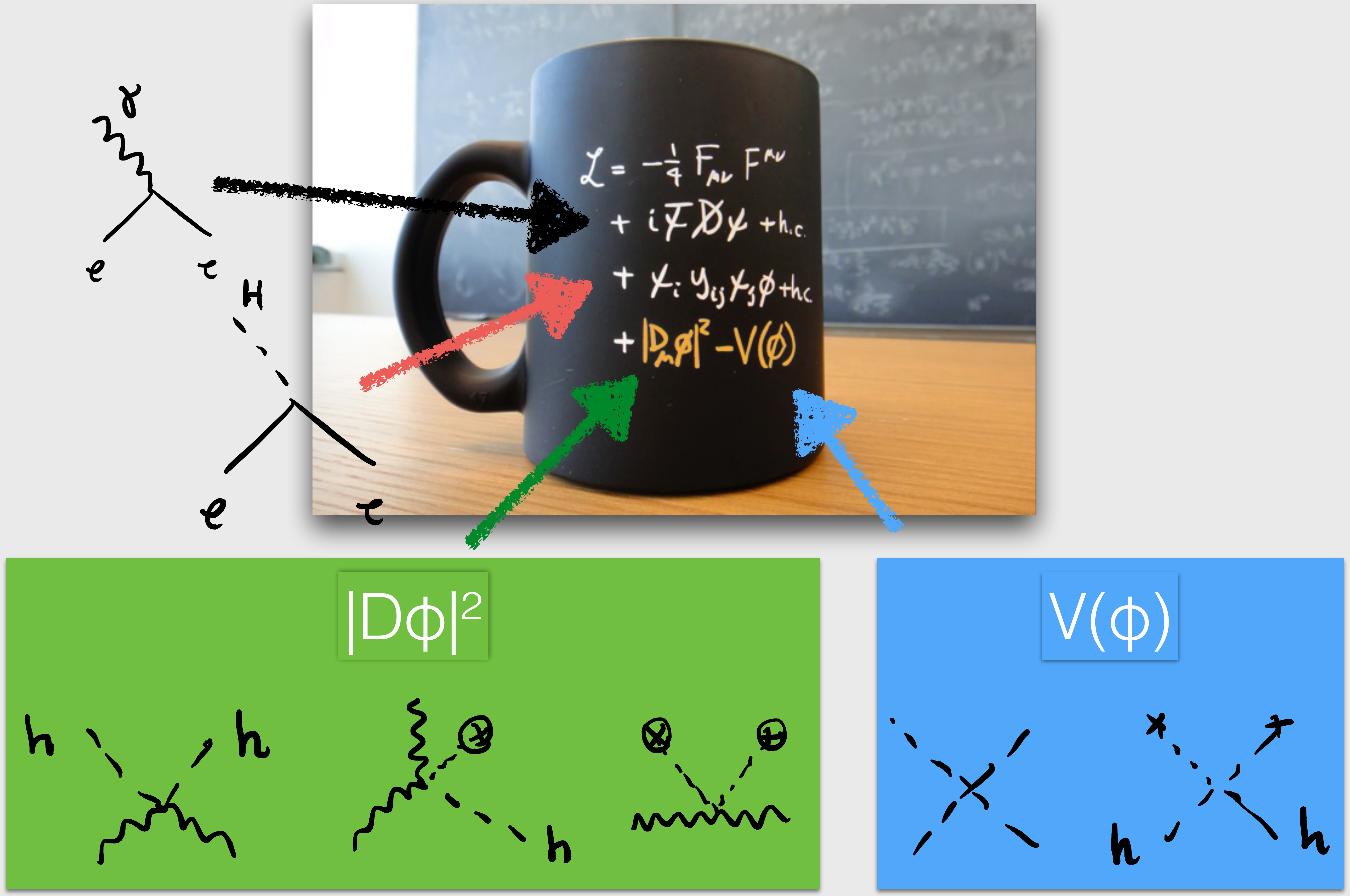

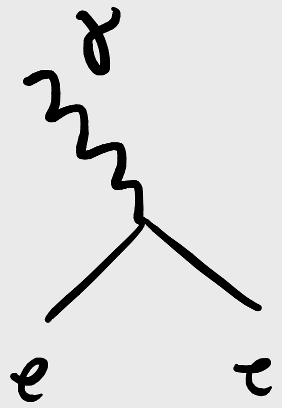

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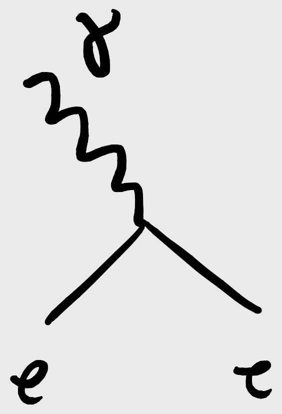

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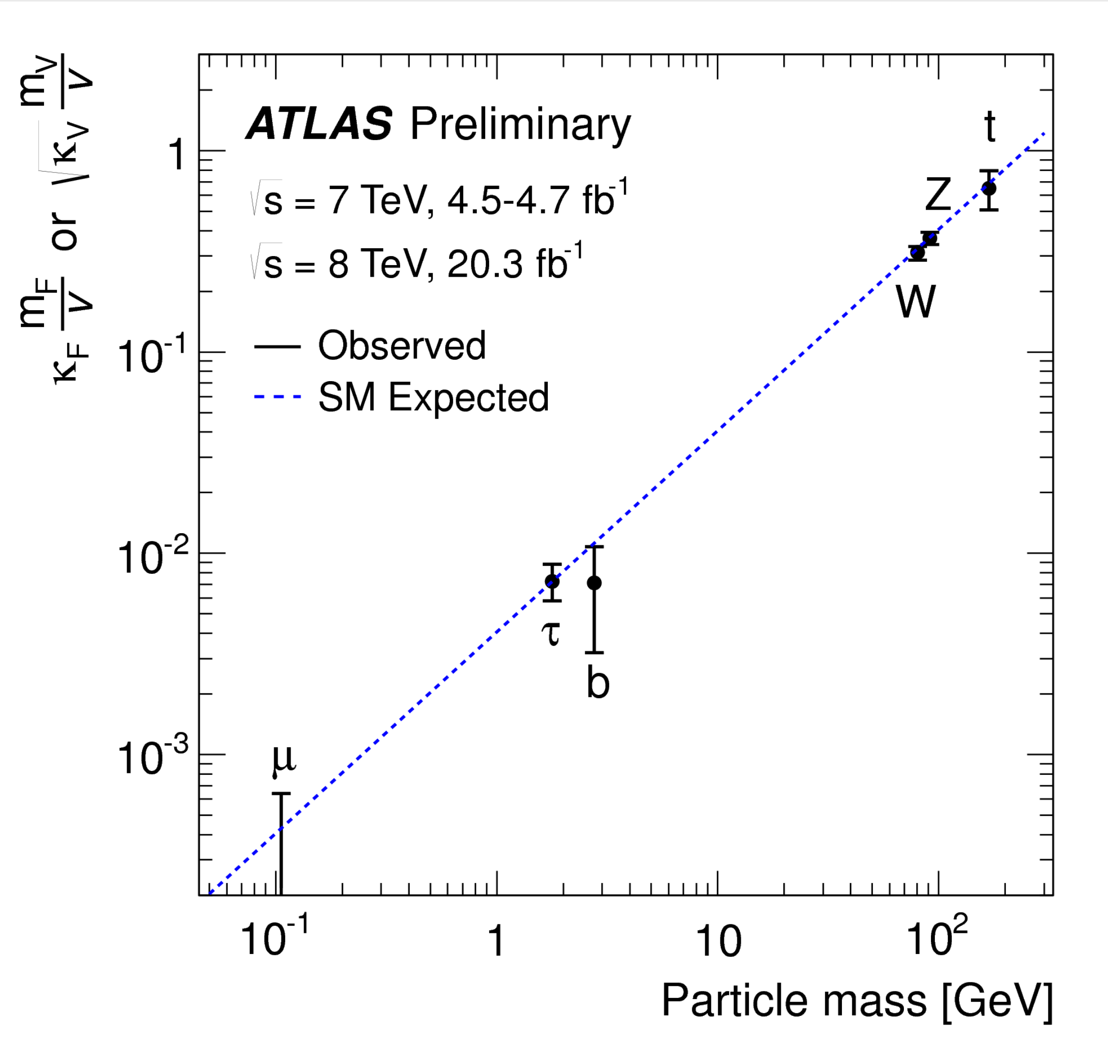

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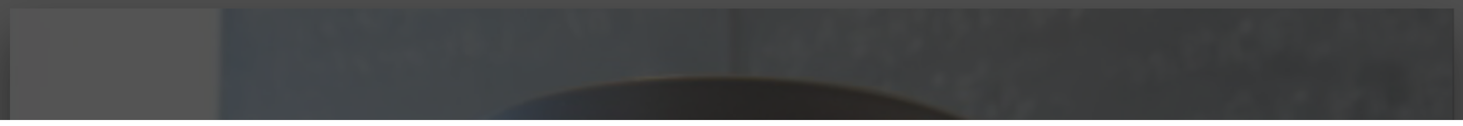
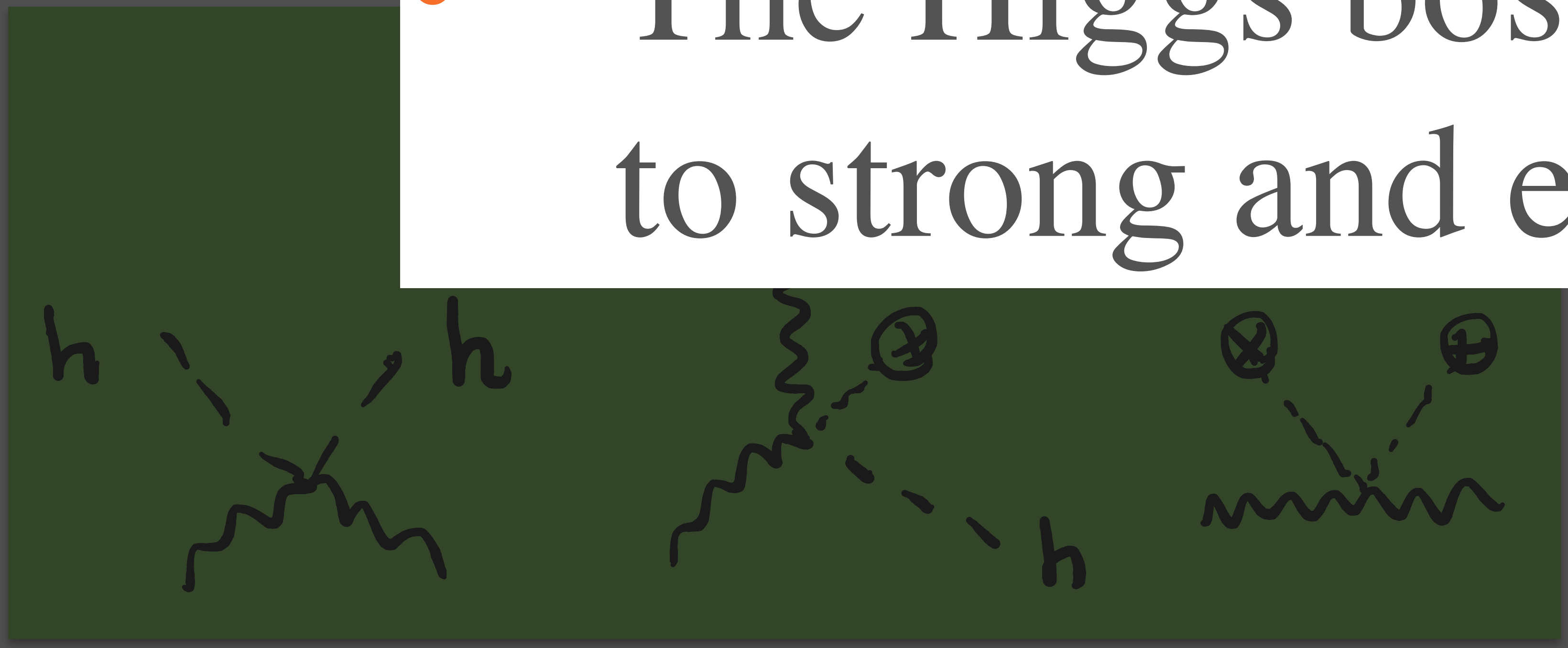
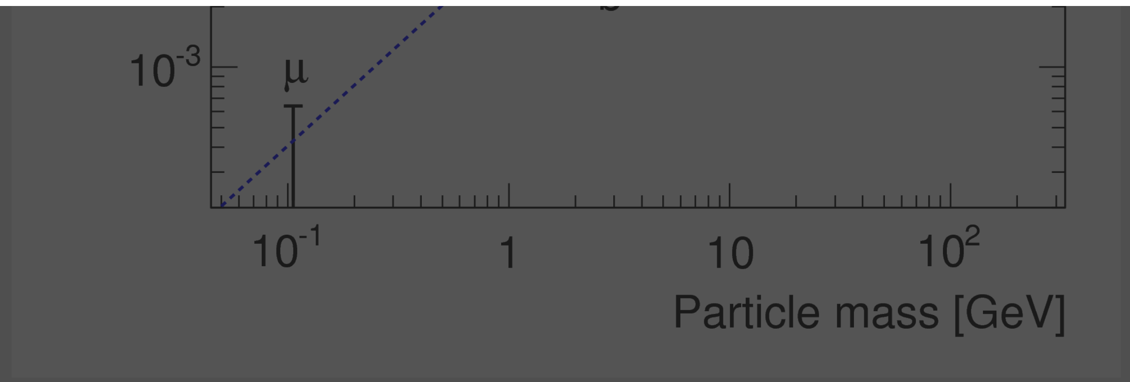


- We established the principles behind electroweak and strong interaction very well
- We measured the Higgs boson only very "broad brush"
- The Higgs boson may be a whole new thing compared to strong and electroweak interactions





And there is more than "just" the Higgs boson

The Standard Model is:

- Observationally "unfit" (misses Gravity, Dark Matter, …)
- 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.

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

?
- what is the dark matter in the Universe?
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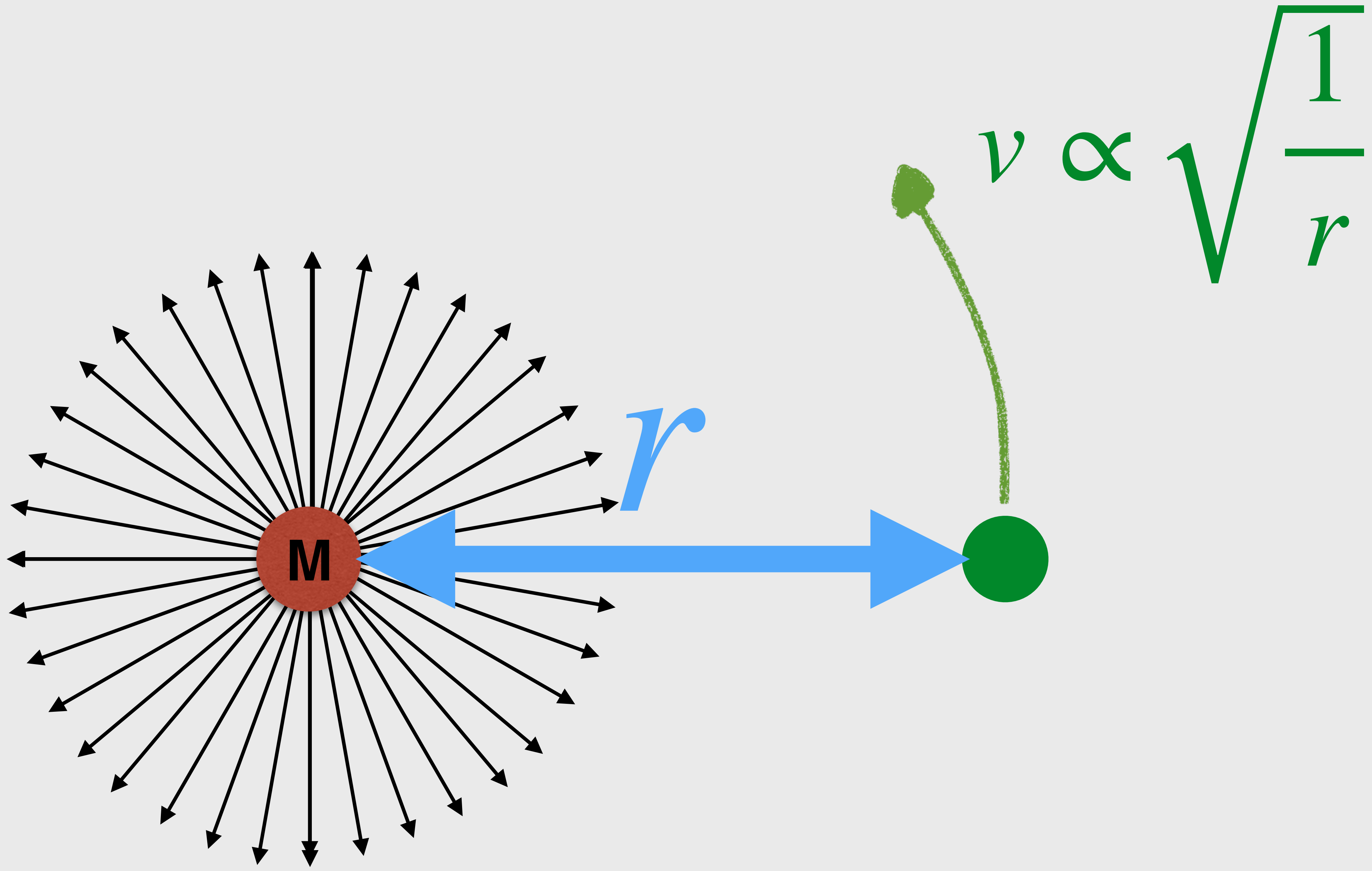
EFT
- why gravity and weak interactions are so different?

EFT
- what fixes the cosmological constant?

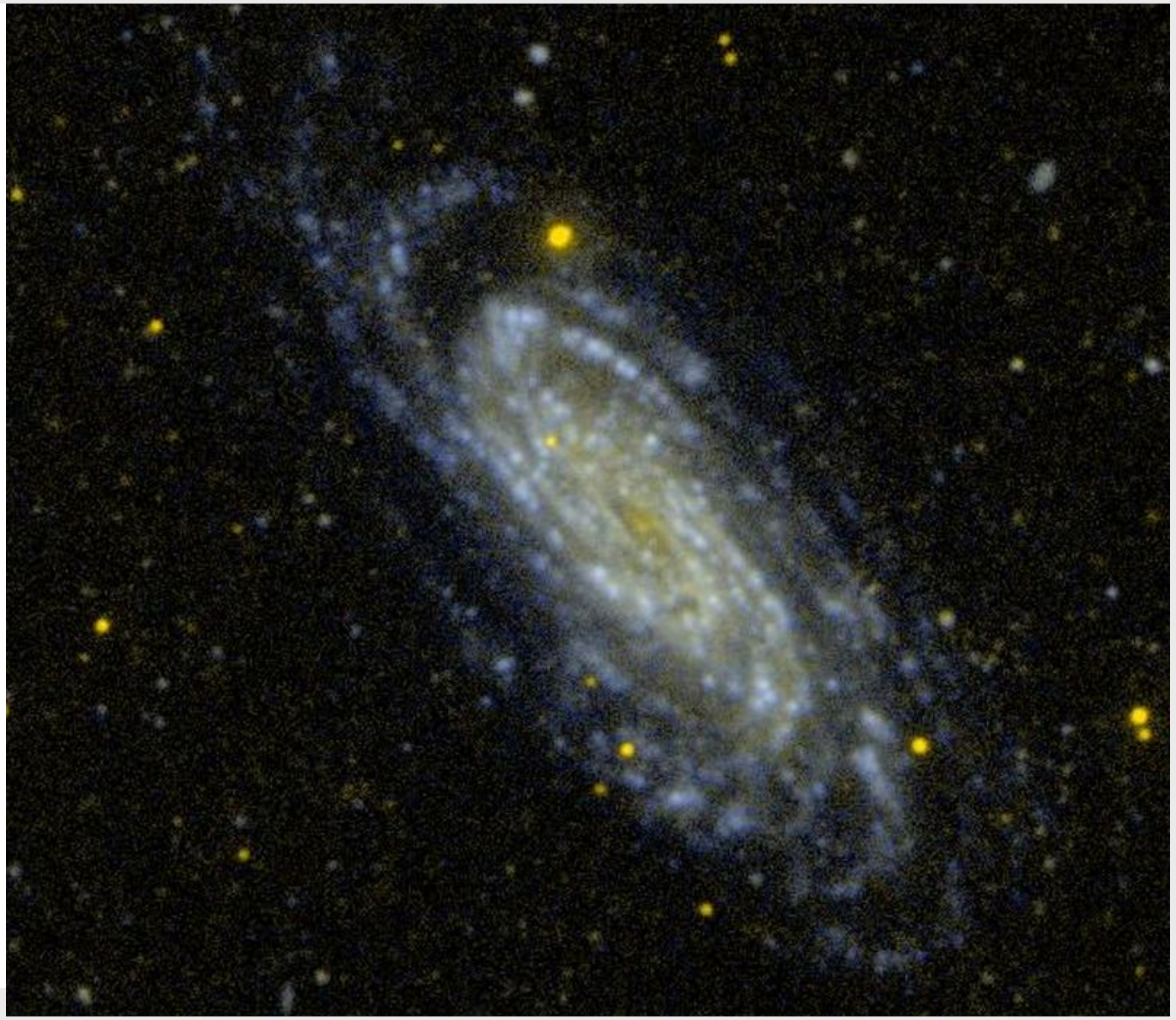
EACH of these issues one day will teach us a lesson

A puzzle we have no idea how to solve

NEWTONIAN MECHANICS FAILS?



Perfect in our "neighborhood"



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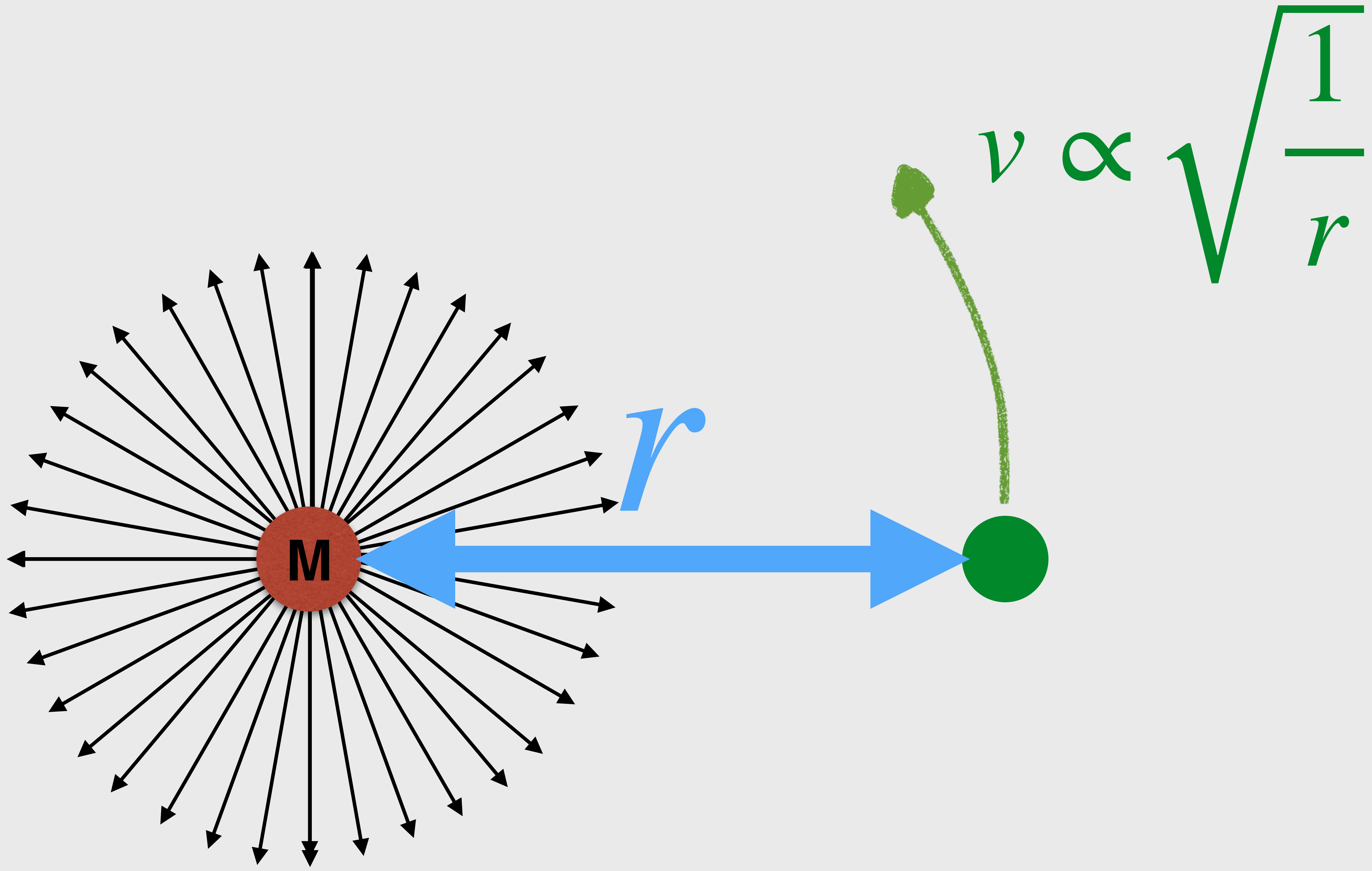

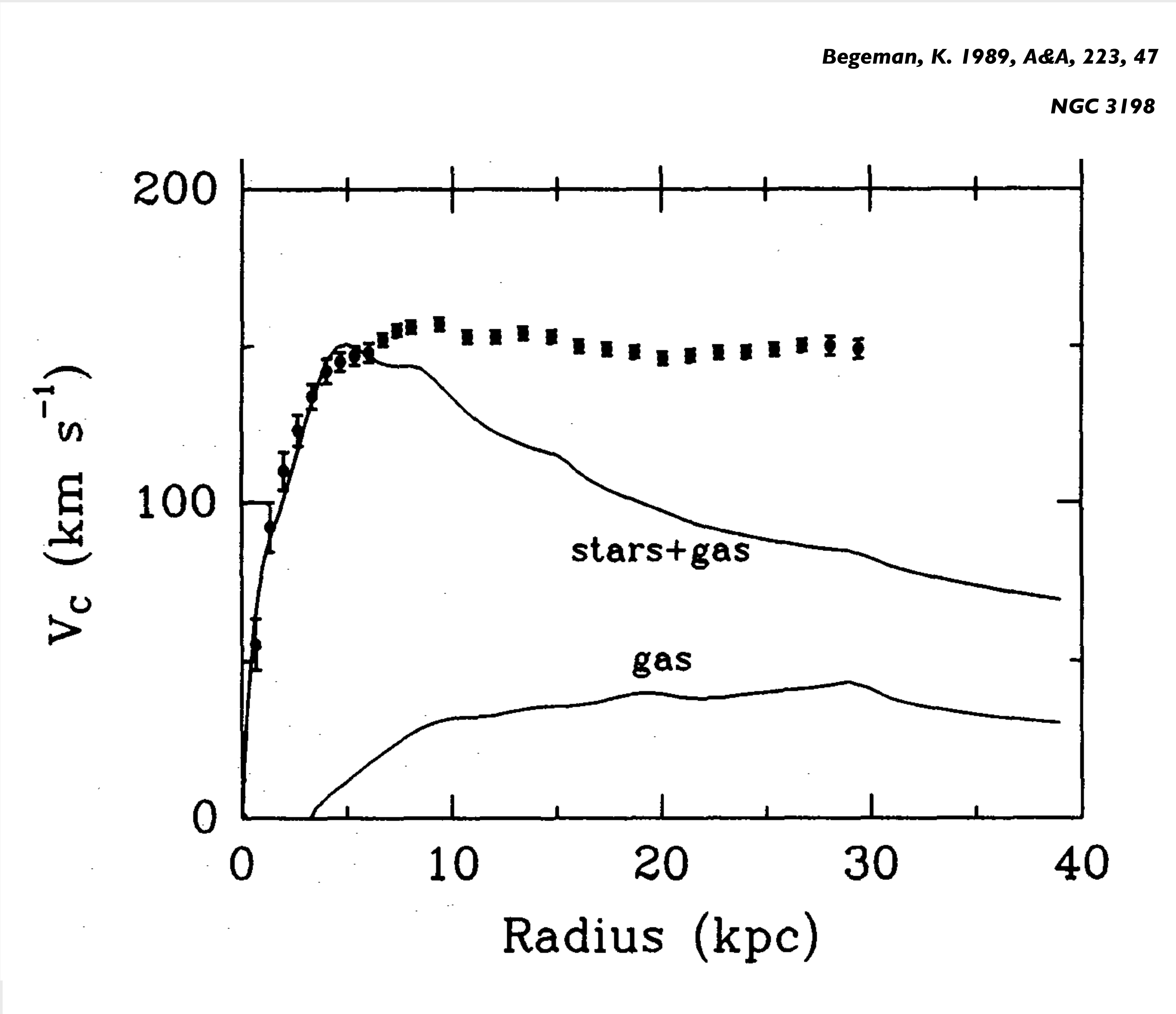

A puzzle we have no idea how to solve

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

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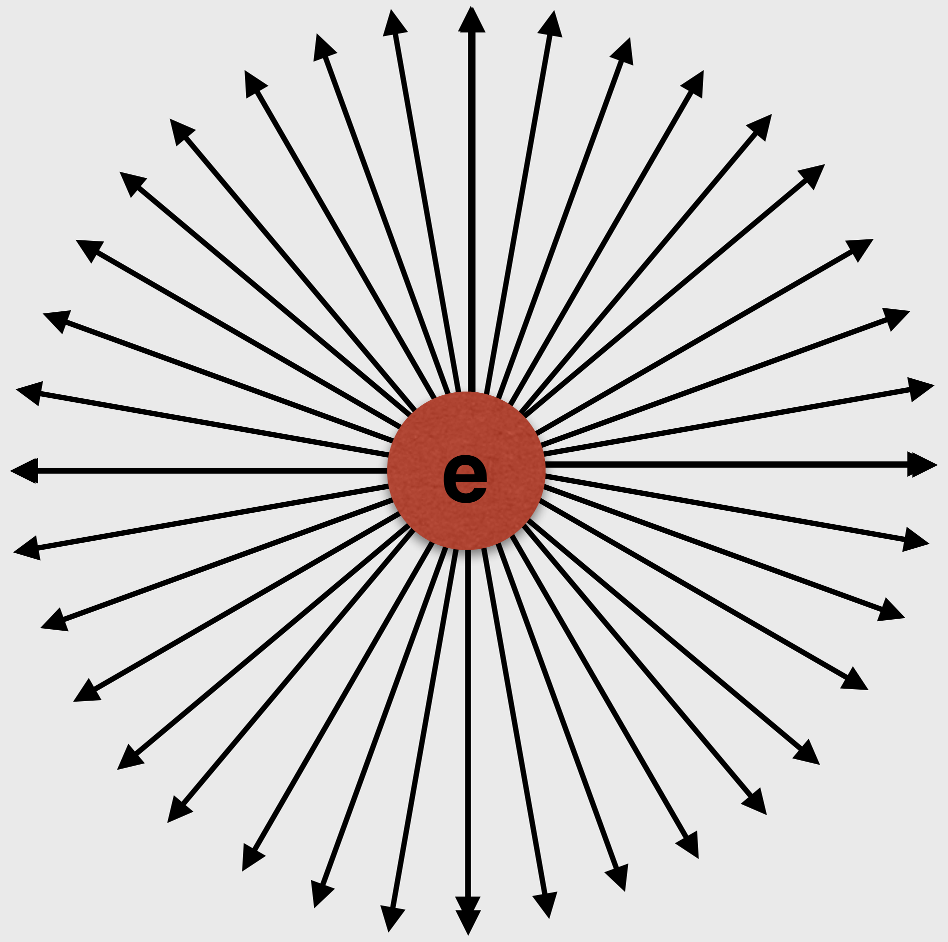
AFTER RELATIVITY



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

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

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

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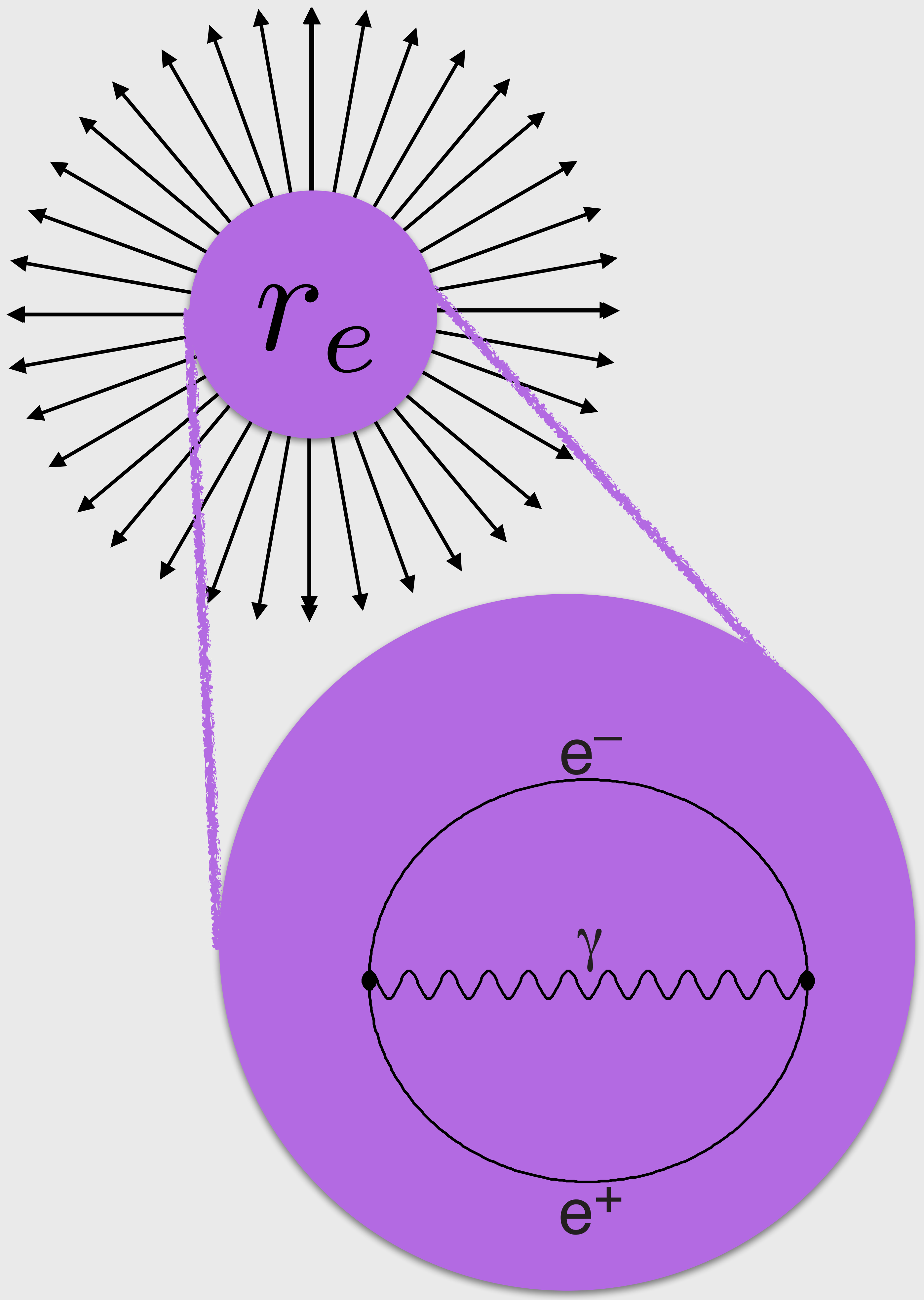
RELATIVITY & QUANTUM MECHANICS



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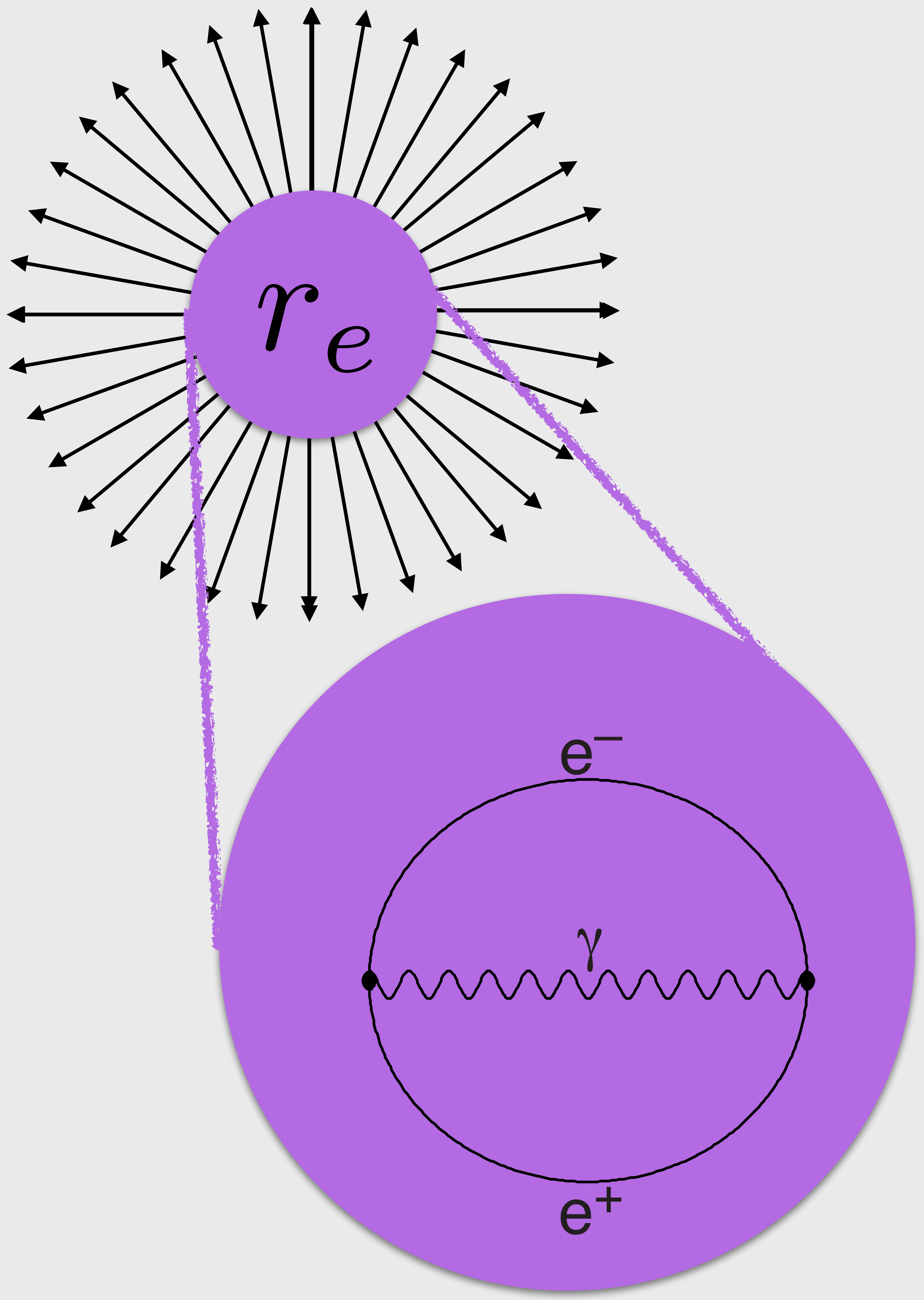


New symmetry (particle-antiparticle) which brought a new particle: the positron

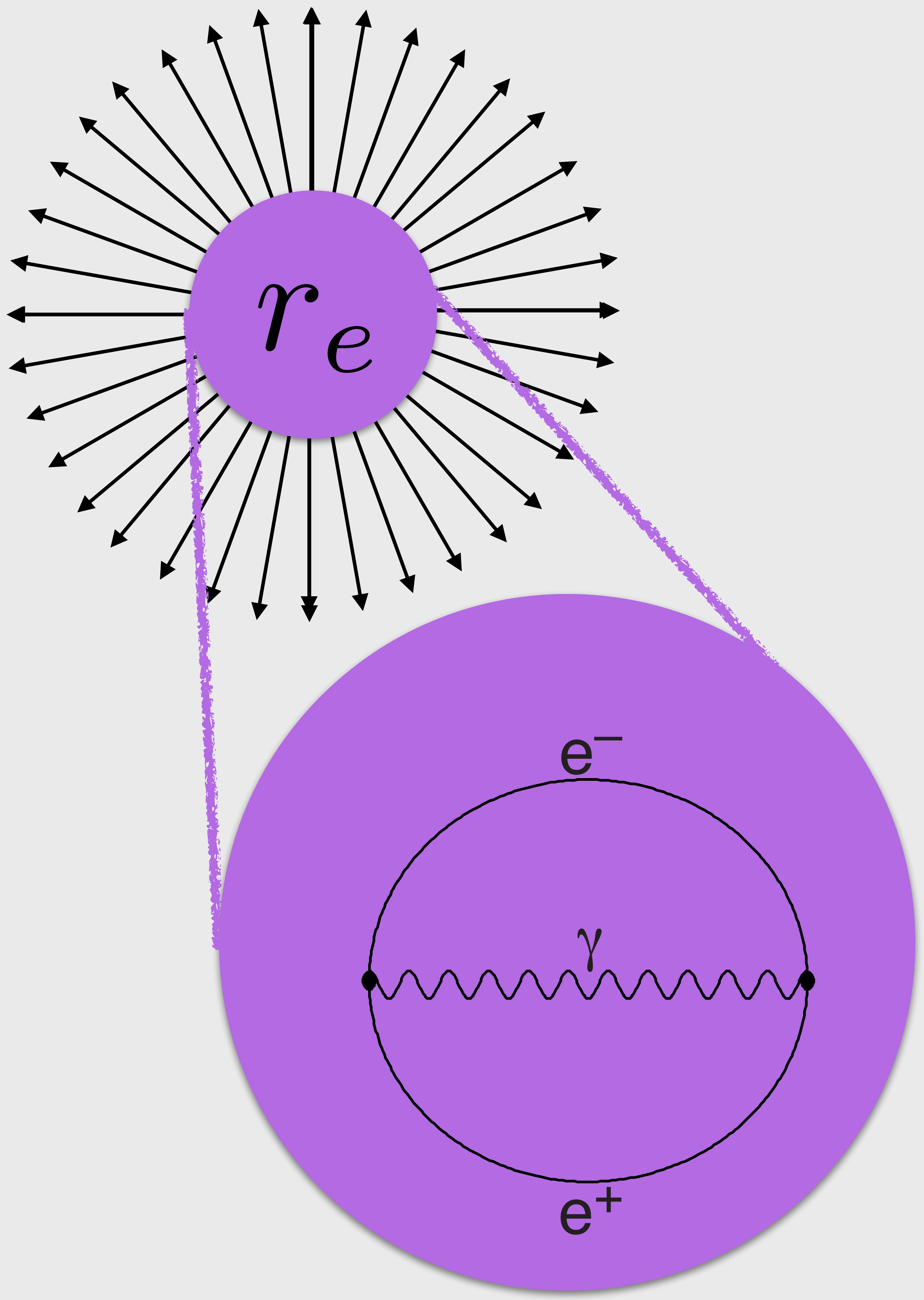
We learned a lesson on physics **at the same mass scale** as where the puzzle arises:

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

A puzzle (today) we know how to solve

AFTER

RELATIVITY & QUANTUM MECHANICS



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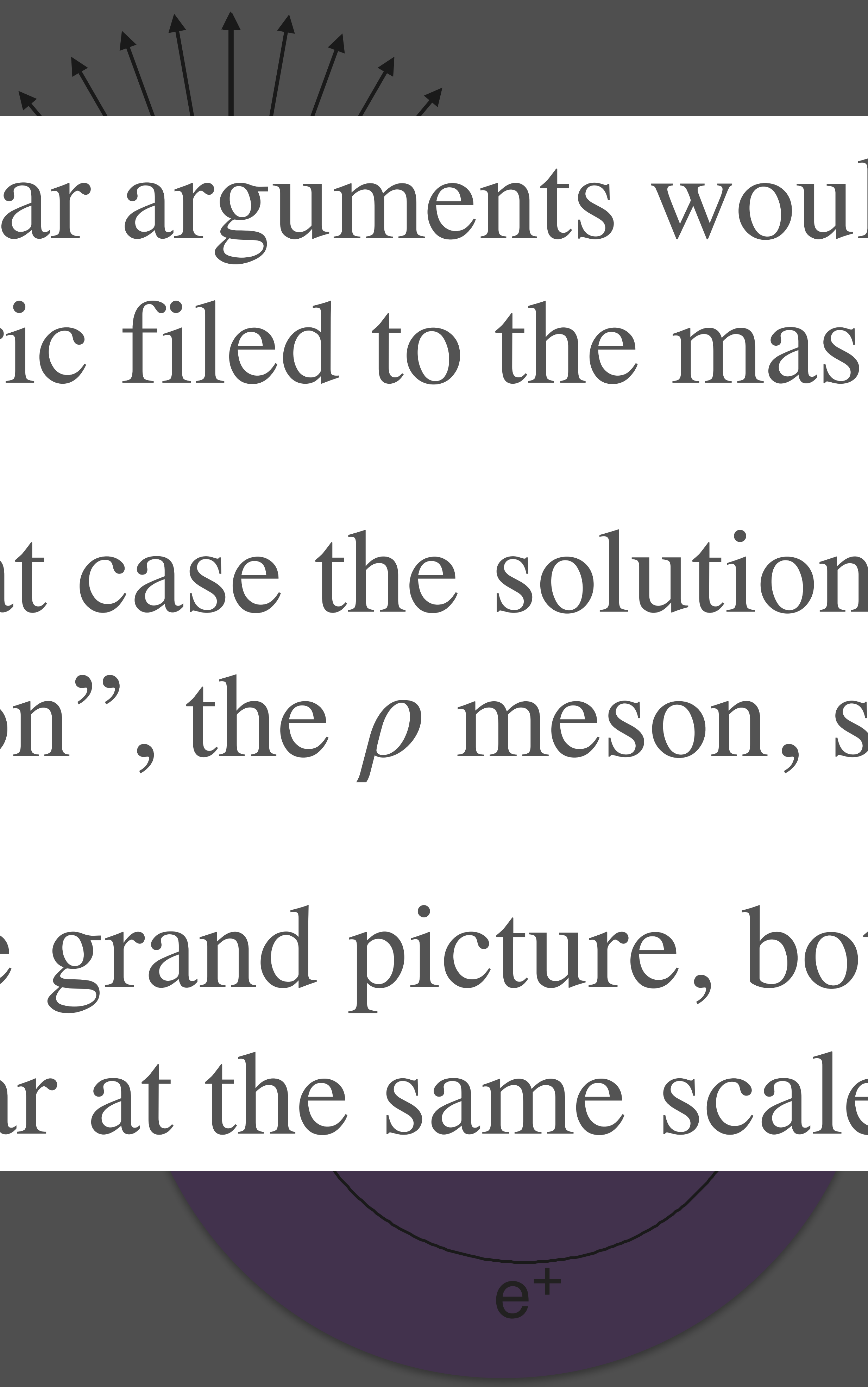
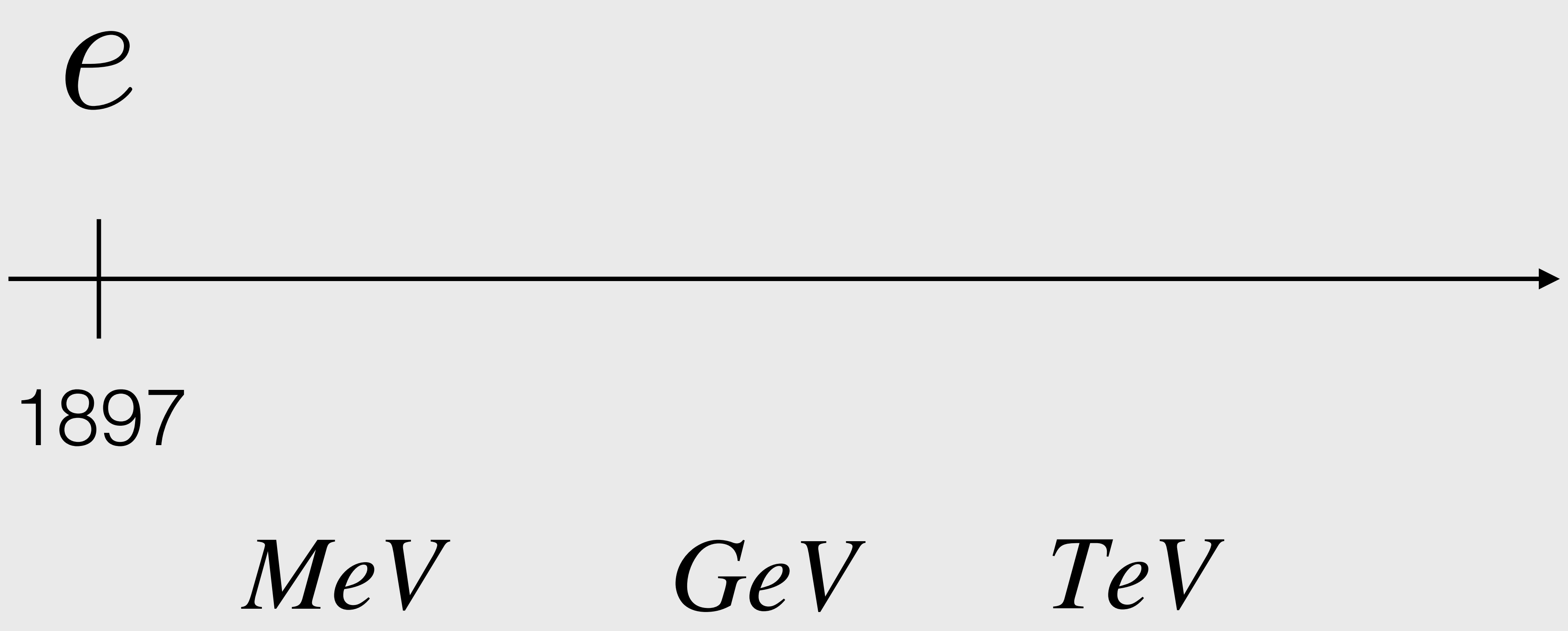


- Similar arguments would require a contribution of the electric filed to the mass of the charged pion
- In that case the solution is not an antiparticle, but a “heavy photon”, the ρ meson, somewhat heavier than the pion
- In the grand picture, both the positron and the ρ meson appear at the same scale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

How we got there

SYMMETRY AS A FUNDAMENTAL CHARACTER OF NATURE

Symmetries and particles



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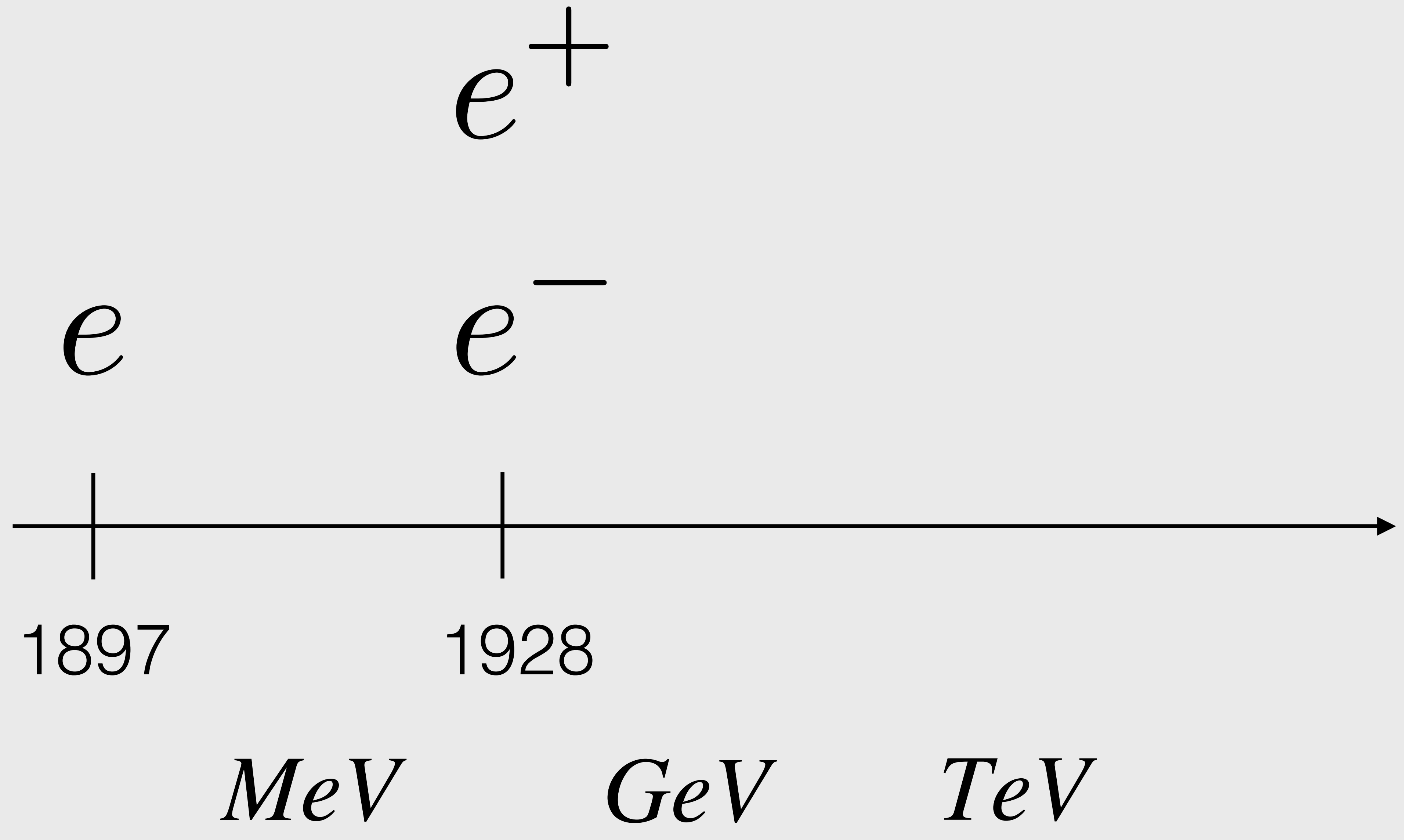

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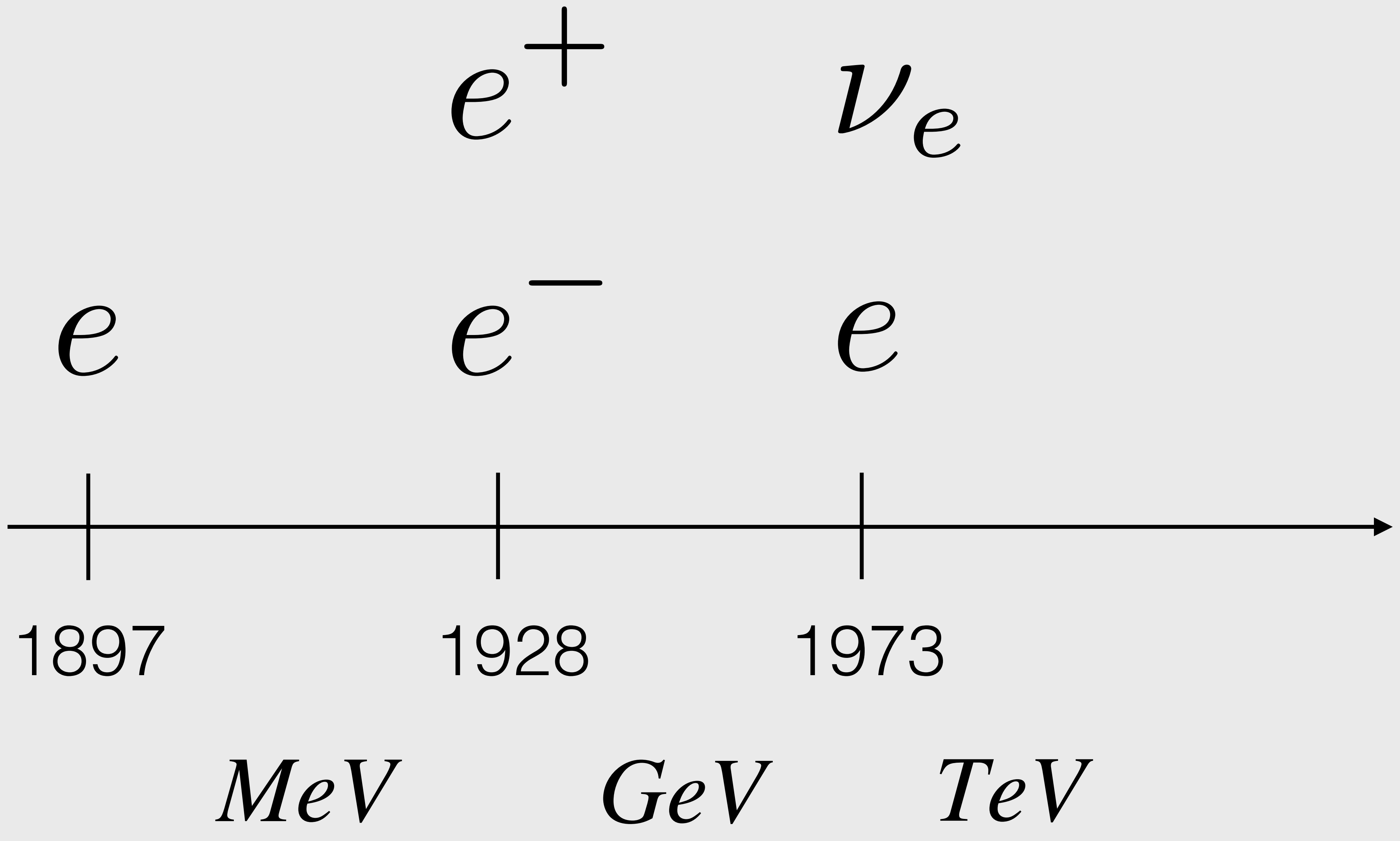

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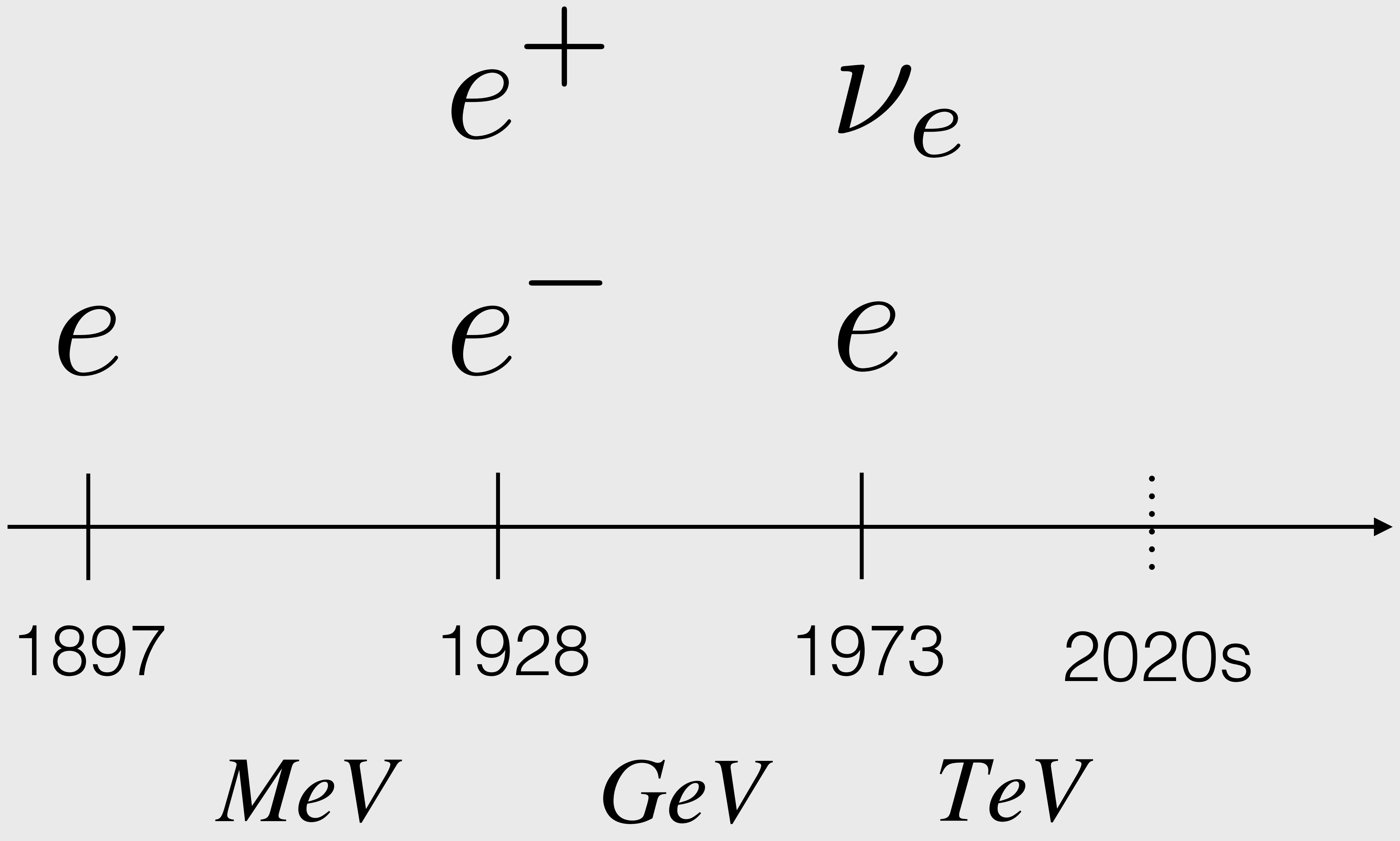

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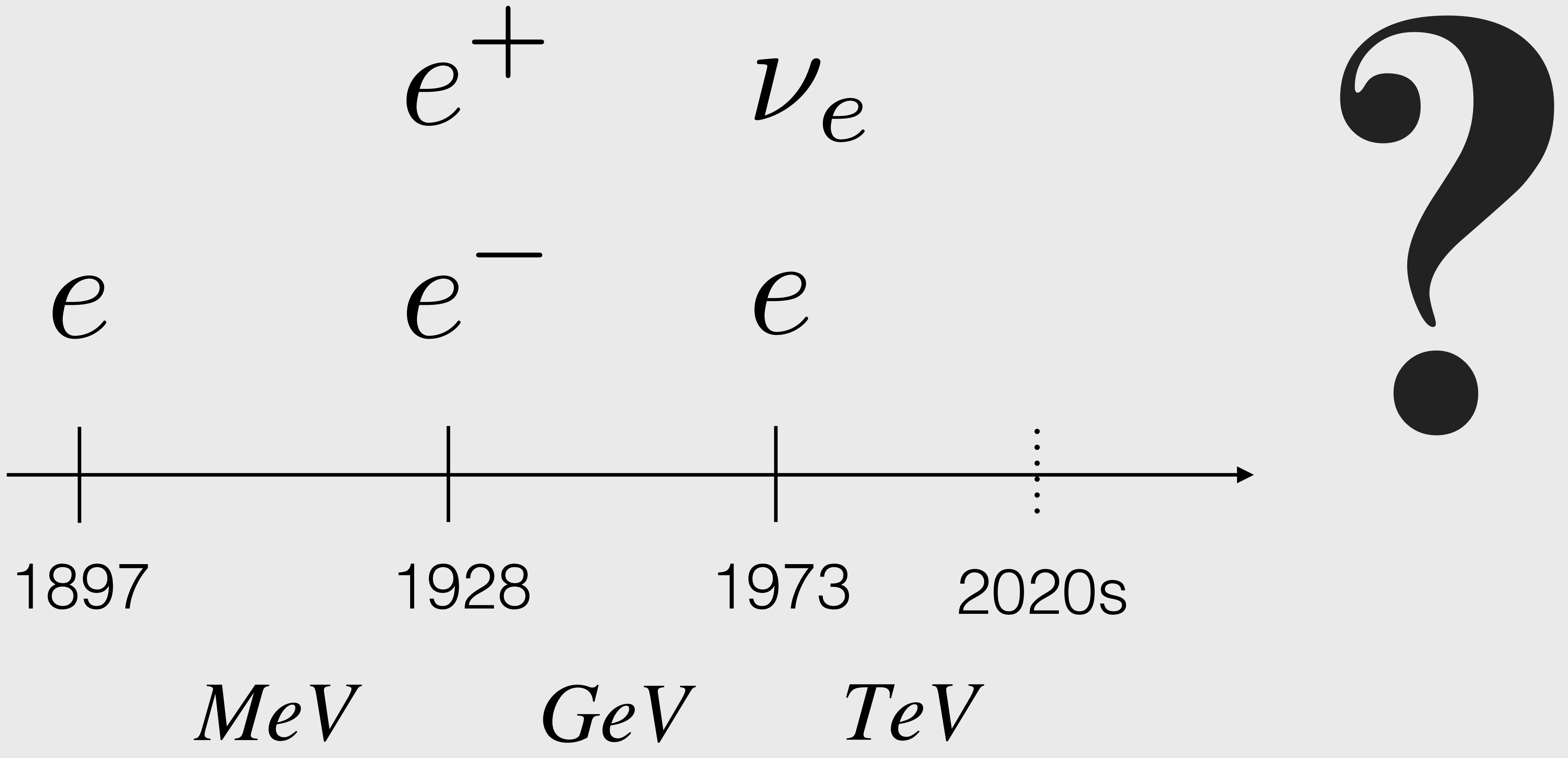

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EACH of these issues one day will teach us a lesson

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WEAK INTERACTIONS

STRONG INTERACTIONS

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We need to explore weak interactions

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WEAK INTERACTIONS

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NEED SOME COSMOLOGY INPUTS

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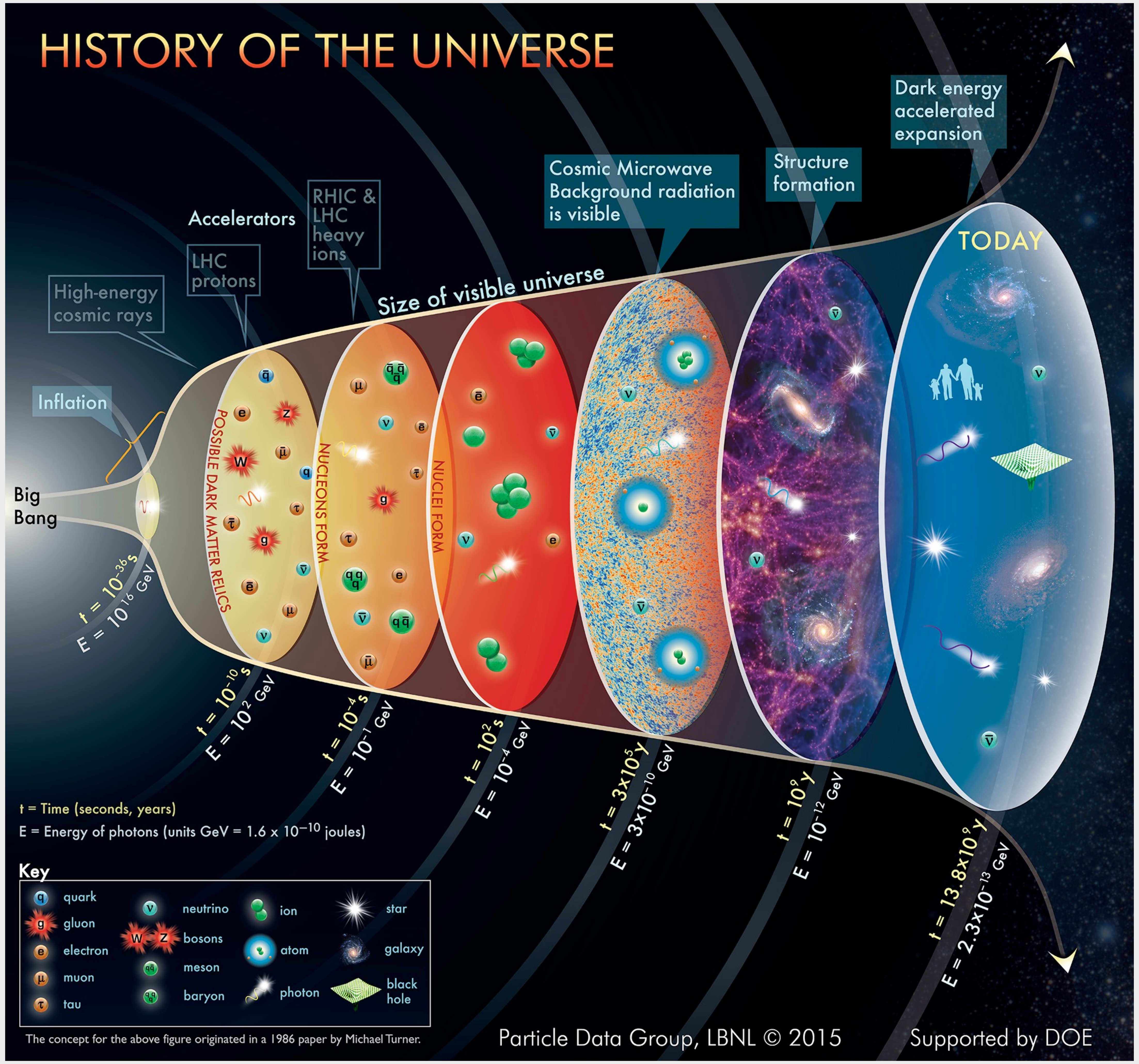
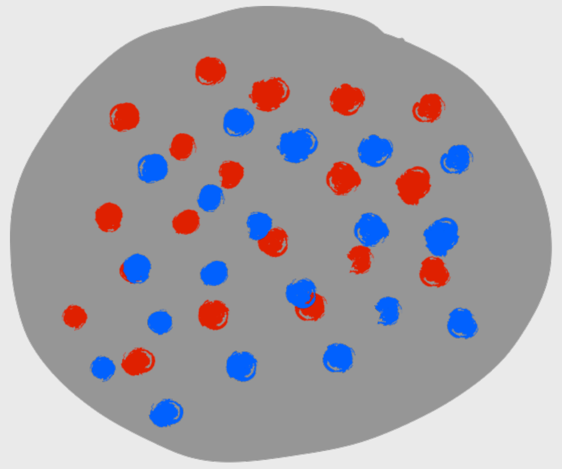


Nothing we have measured in high energy physics makes so much of a distinction between particles and anti-particles.

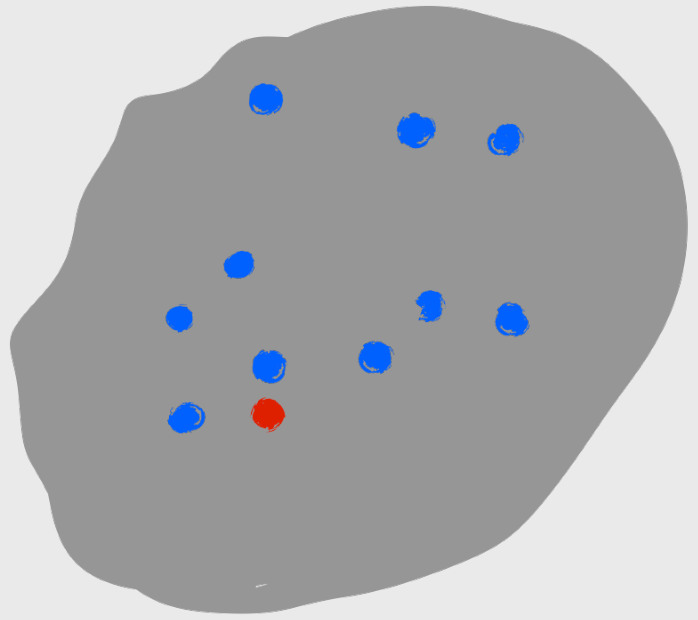
The observable Universe is made of matter, no antimatter

We need to go from this



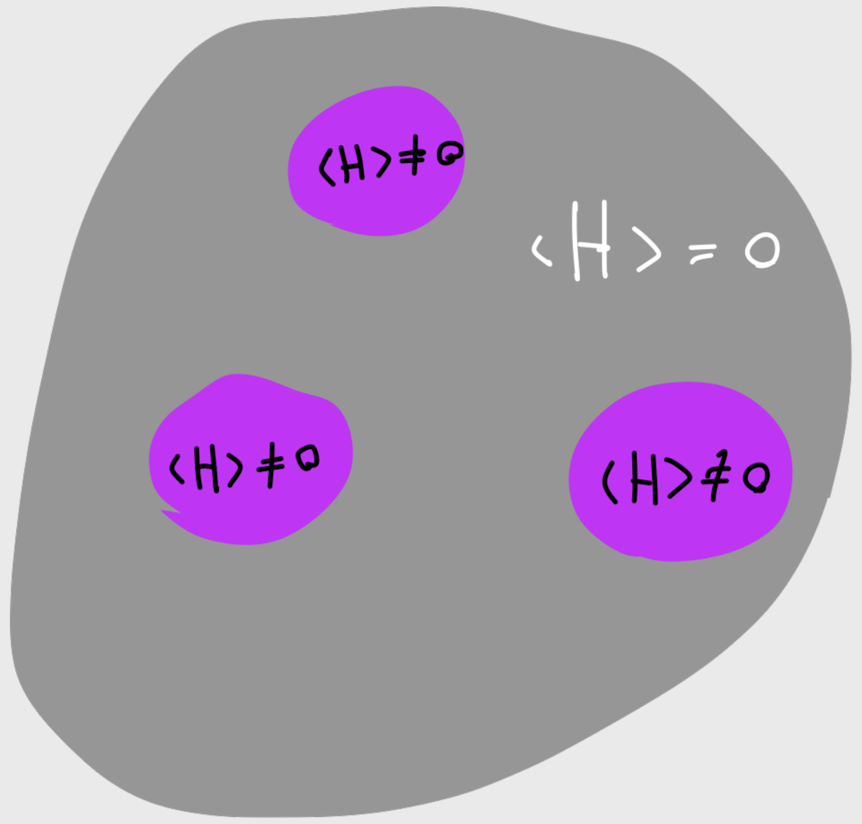
particles
antiparticles

to this

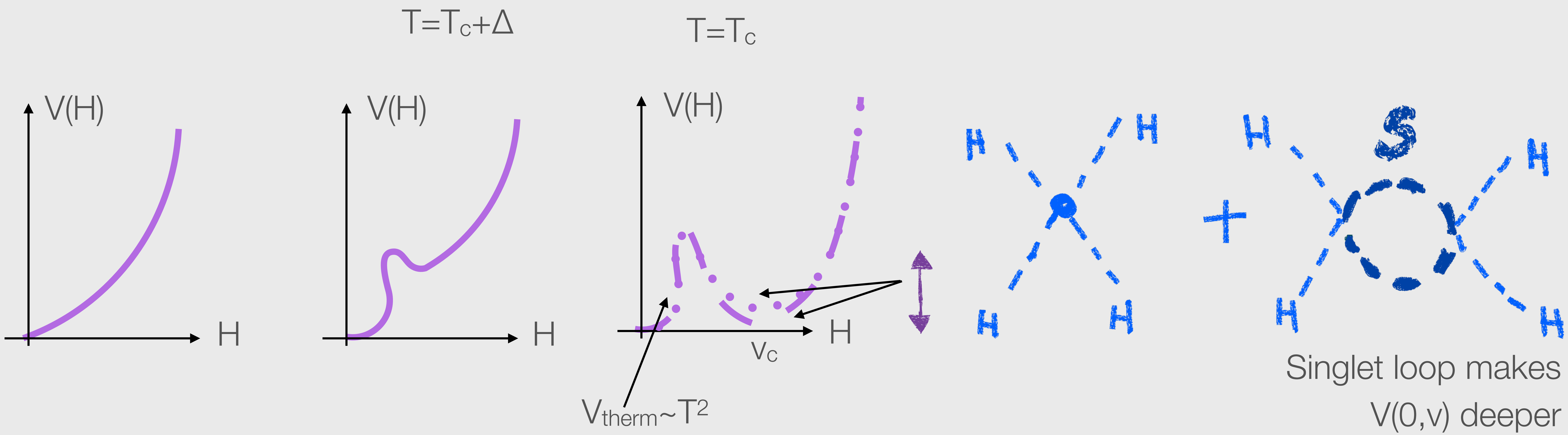


out-of-equilibrium processes are necessary

Electroweak phase transition



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



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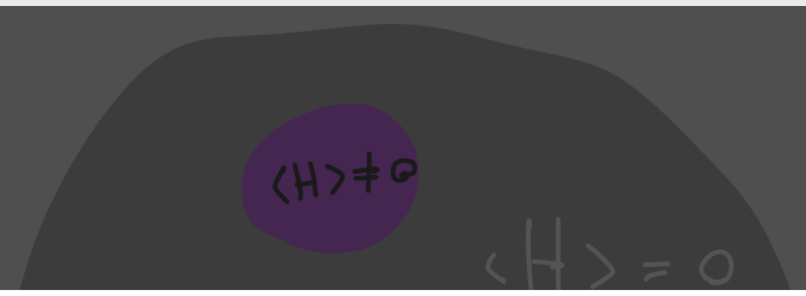


- We need to study all possible new states that induce a change in the Higgs boson potential.
- For these new state to have sizable effects in the early Universe they must be light, around 1 TeV at most.
- All searches for new Higgs bosons (or general electroweak particles) probe such fundamental issue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

$V_{therm} \sim T^2$ V(0,v) deeper

flashing concrete results for

EW phase transition

Mixed Singlet for EW phase transition

EW PHASE TRANSITION | IS IT FIRST ORDER?

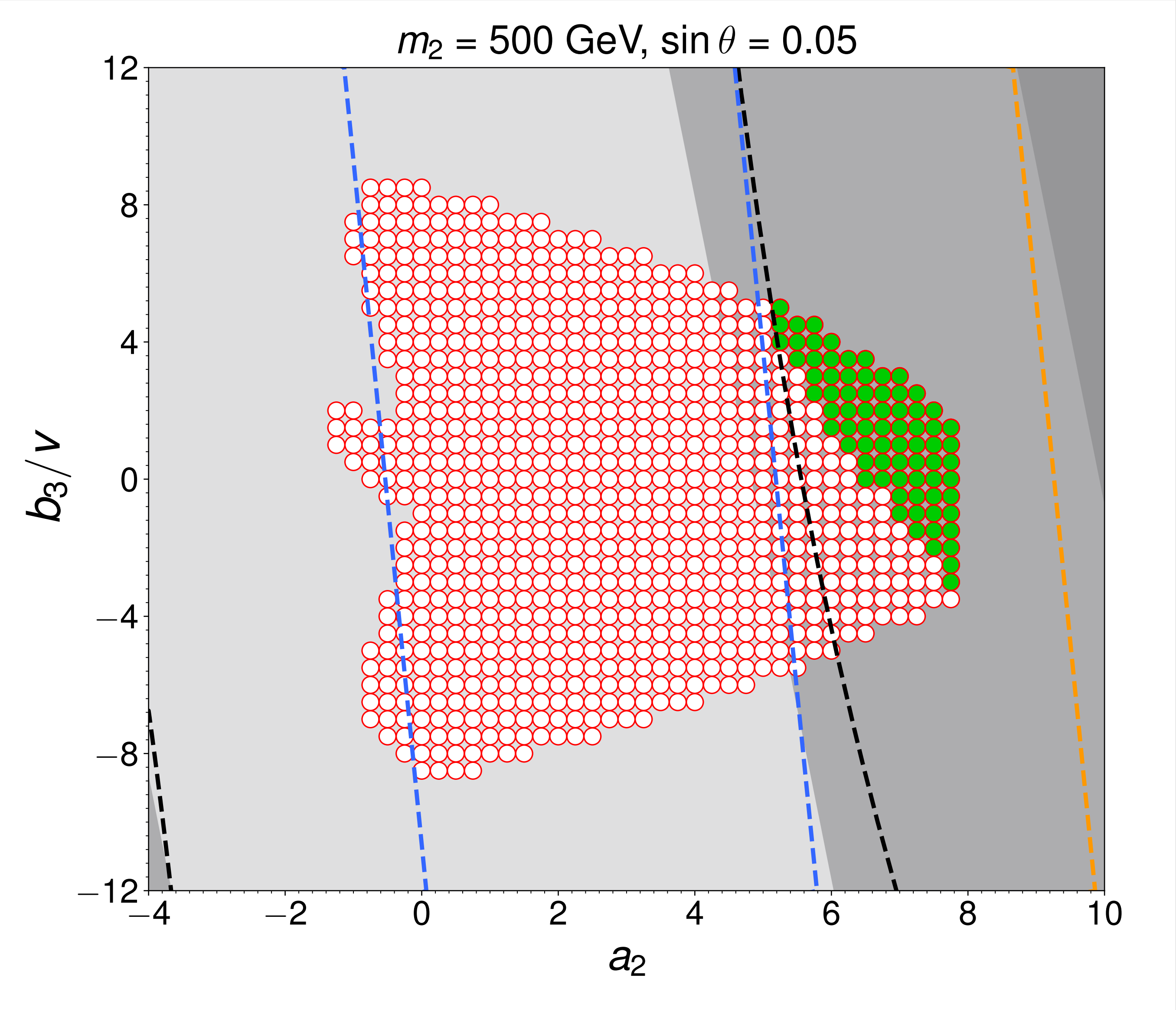
$$V(\Phi,S) = -\mu^2\left(\Phi^\dagger\Phi\right) + \lambda\left(\Phi^\dagger\Phi\right)^2 + \frac{a_1}{2}\left(\Phi^\dagger\Phi\right)S + \frac{a_2}{2}\left(\Phi^\dagger\Phi\right)S^2 + b_1 S + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4.$$

independent parameters

$$\{v,\, m_1,\, m_2,\, \theta,\, a_2,\, b_3,\, b_4\}.$$

fixed (v, m_1) · sampled (m_2, θ) · x-axis (a_2) · y-axis (b_3) · scanned [0, 4π/3] (b_4)

- “healty” potential (no runaway, minimum v=246 GeV, perturbative)
- 1st order phase transition
- HL-LHC sensitivity (from pp → S→ ZZ)
- CLIC380/3TeV Single Higgs couplings
- CLIC 1.4 TeV 3 TeV WBF S → h h → 4b
- CLIC hhh 20% @ 95% CL coupling measurement



parameters space of 1st order phase transition accessible by several probes

Mixed Singlet for EW phase transition

EW PHASE TRANSITION | **IS IT FIRST ORDER?**

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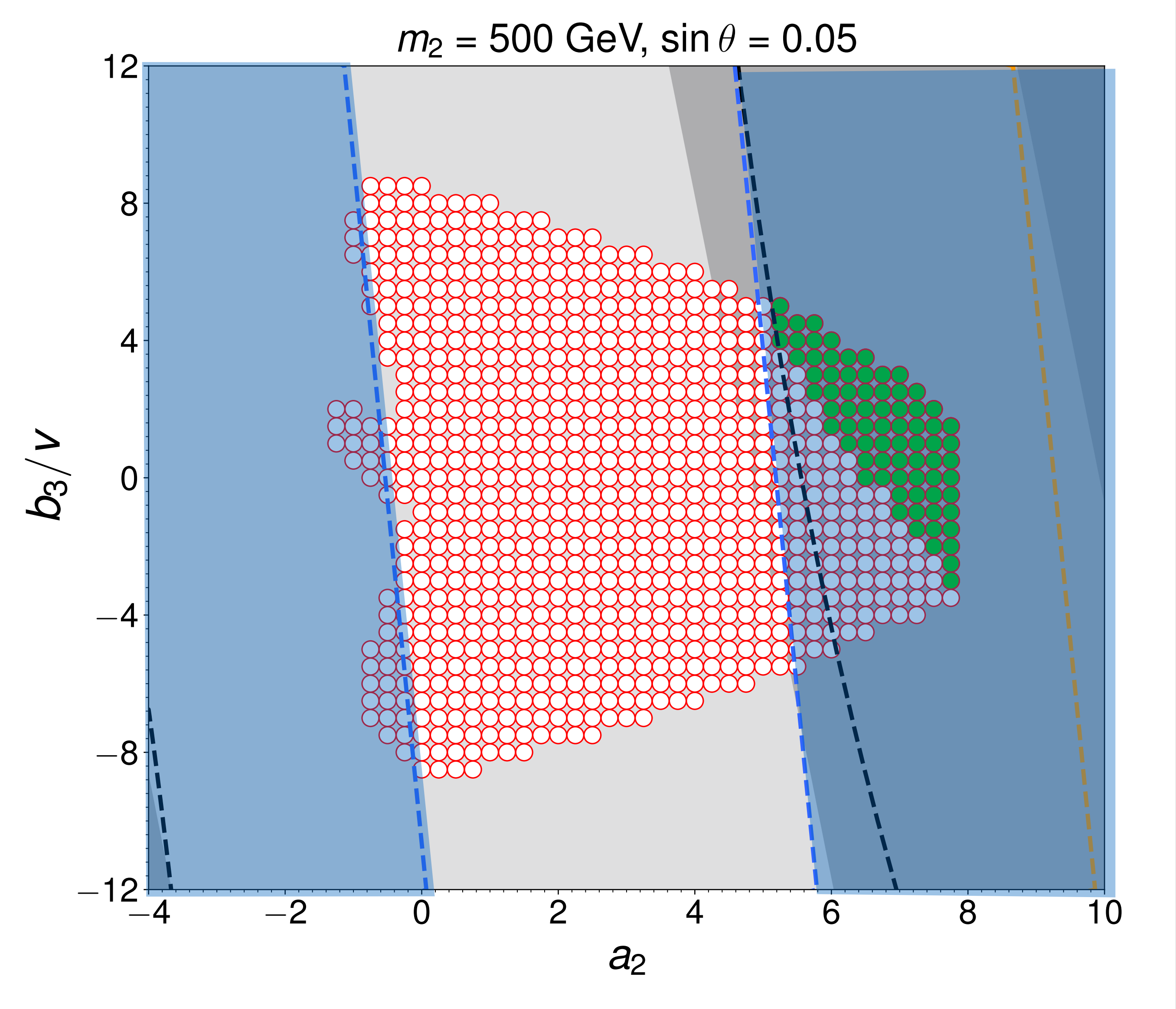

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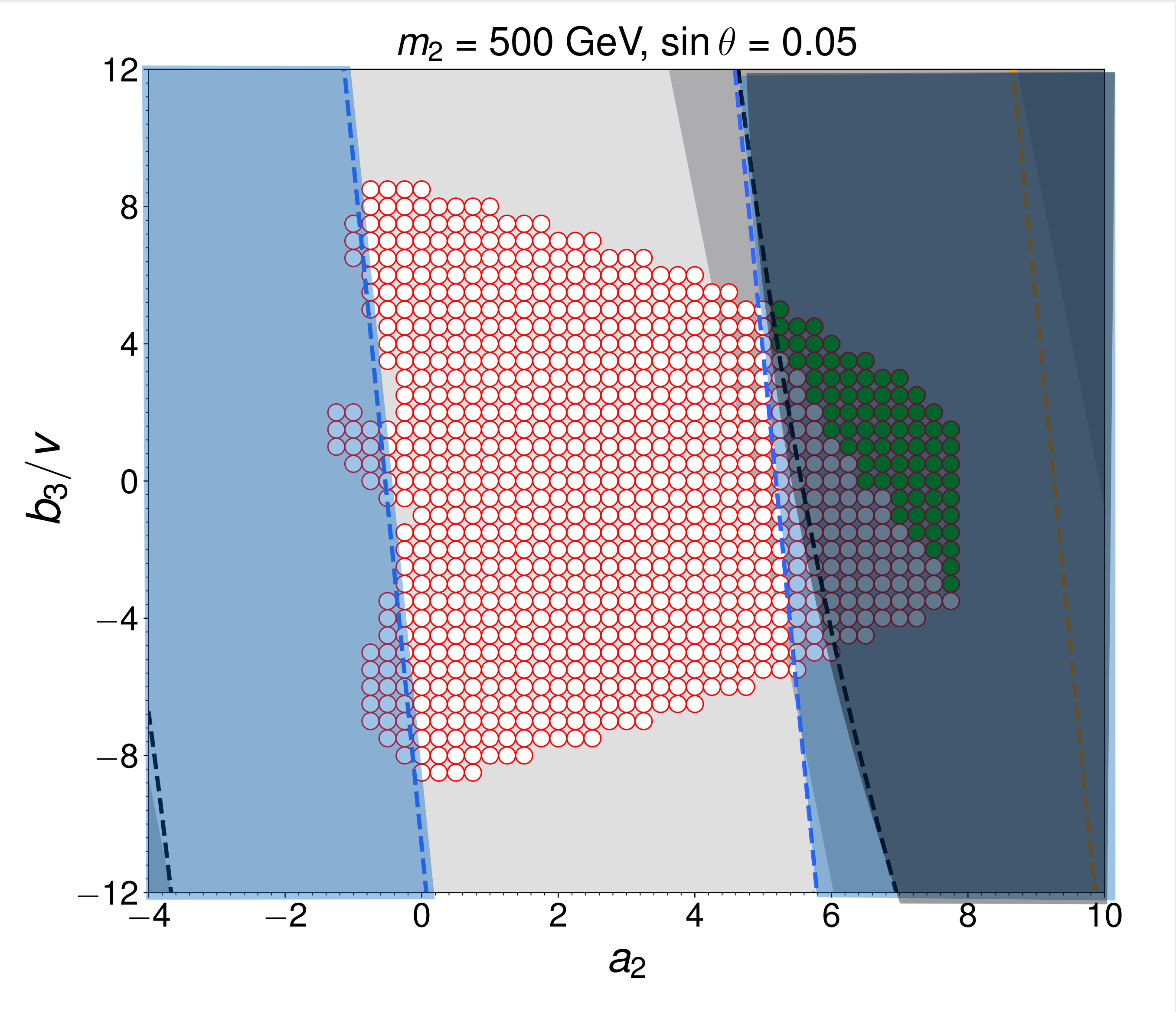
independent parameters

$$\{v,\ m_1,\ m_2,\ \theta,\ a_2,\ b_3,\ b_4\}.$$

- v, m_1: fixed
- m_2, θ: sampled
- a_2: x-axis
- b_3: y-axis
- b_4: scanned [0, 4π/3]

- "healty" potential (no runaway, minimum v=246 GeV, perturbative)
- 1st order phase transition
- HL-LHC sensitivity (from pp → S→ ZZ)
- CLIC380/3TeV Single Higgs couplings
- CLIC 1.4 TeV 3 TeV WBF S → h h → 4b
- CLIC hhh 20% @ 95% CL coupling measurement



parameters space of 1st order phase transition accessible by several probes

Mixed Singlet for EW phase transition

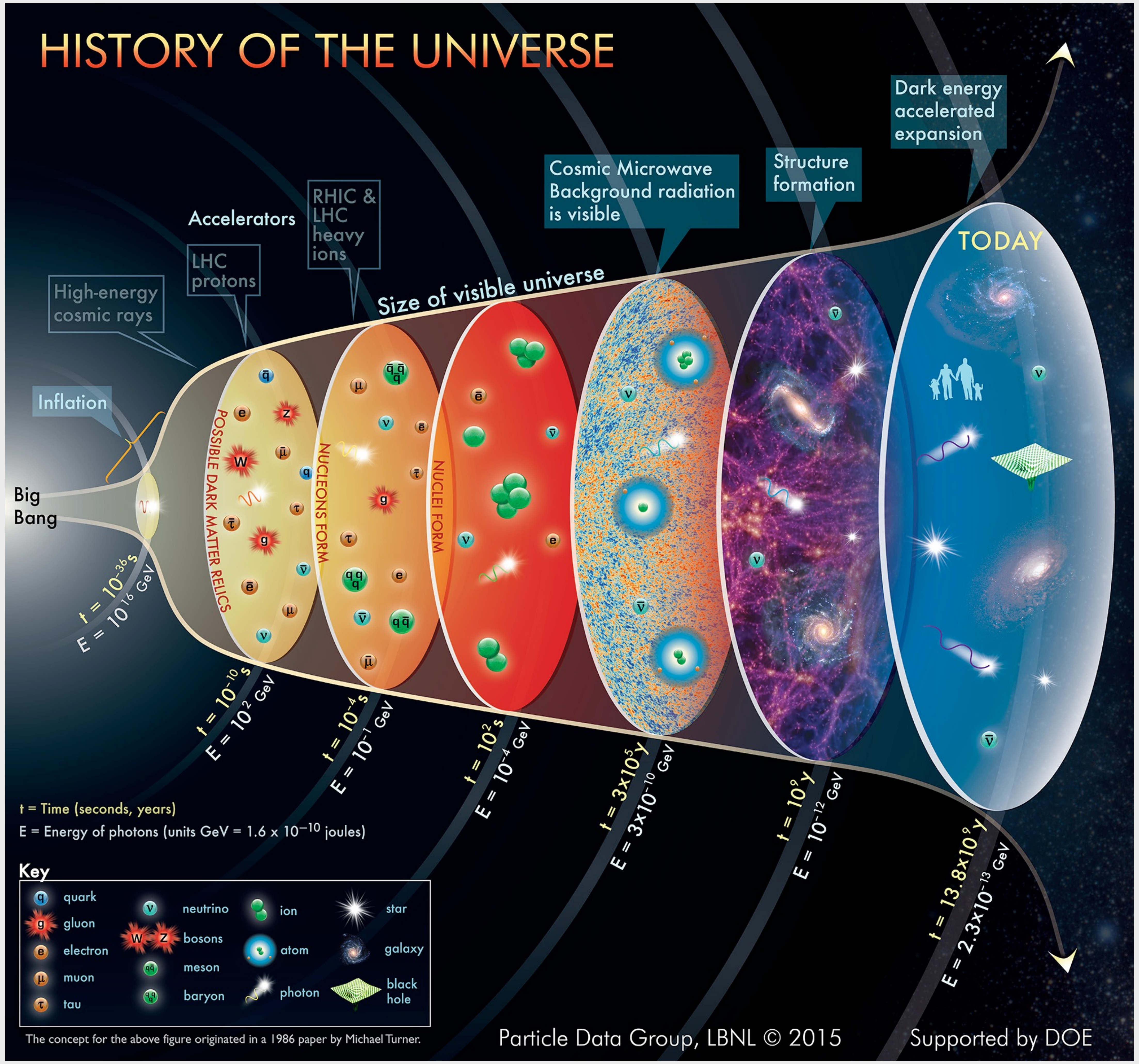
EW PHASE TRANSITION | IS IT FIRST ORDER?

- "healty" potential (no runaway, minimum v=246 GeV, perturbative)
- 1st order phase transition

- Lepton colliders can observe directly these states
- Clean events allow to search for the most elusive particles
- The mass range is clearly well above the ZH threshold, we need higher energies!

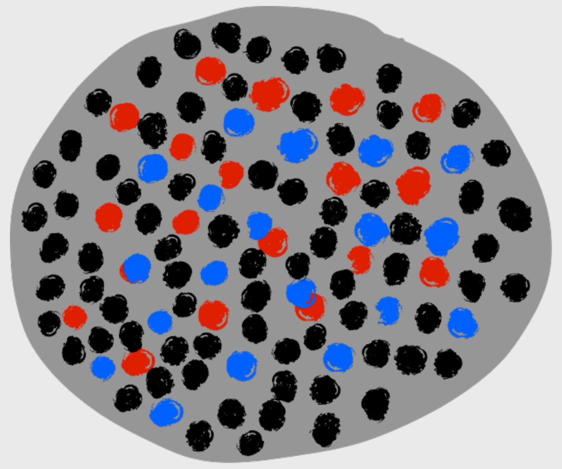
parameters space of 1st order phase transition accessible by several probes

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



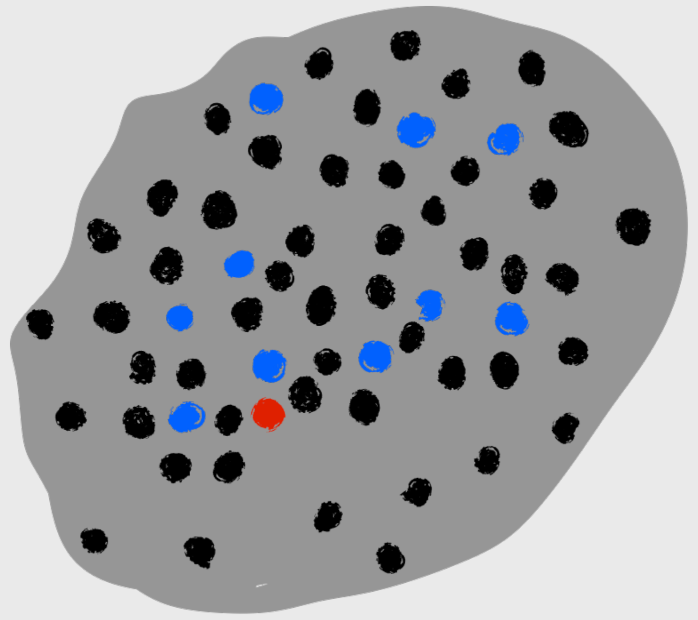
The observable Universe is made of matter, plus about 5 times as much dark matter

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!

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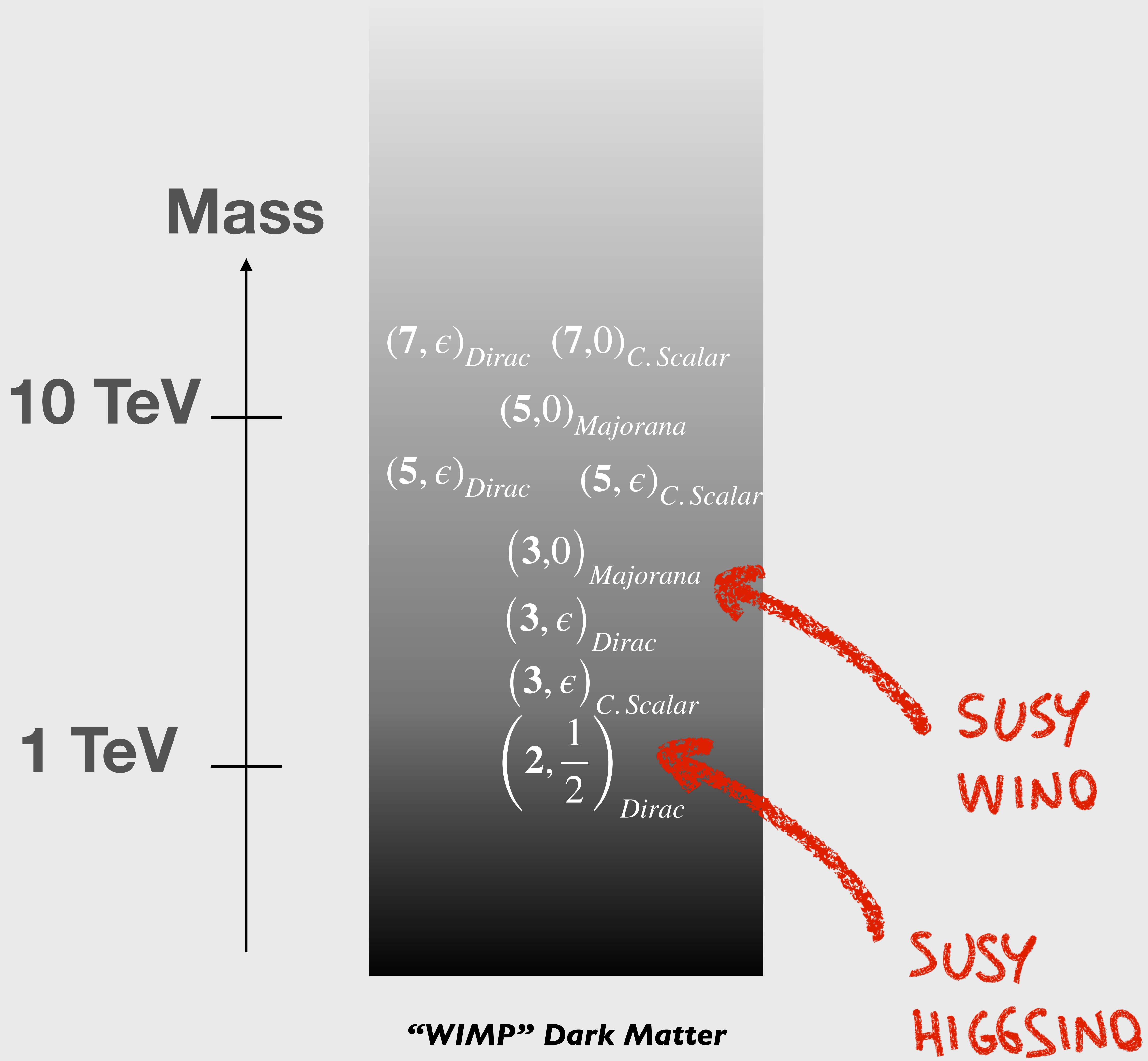

"WIMP" Dark Matter

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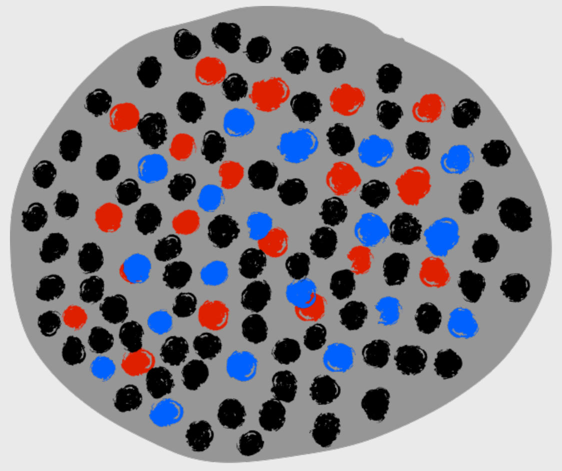

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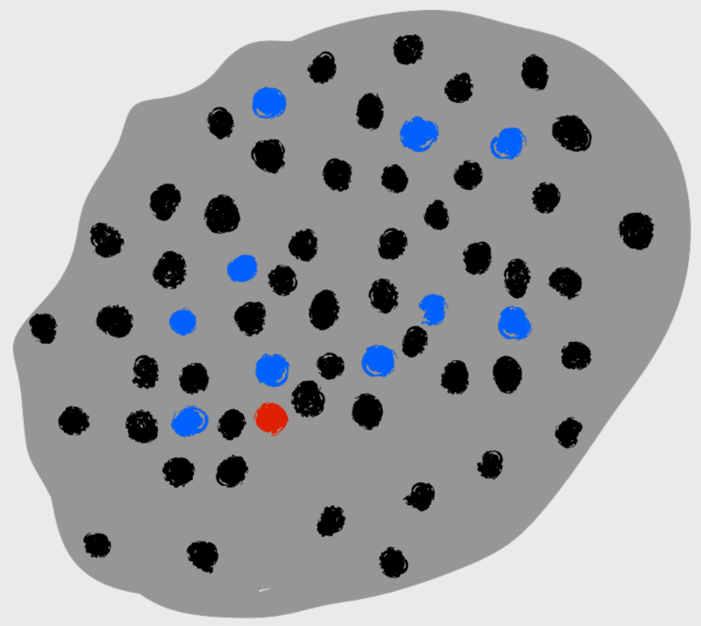


interactions rate from $\sigma = \left(\frac{g_{weak}}{M_{weak}}\right)^2$ are just about right!

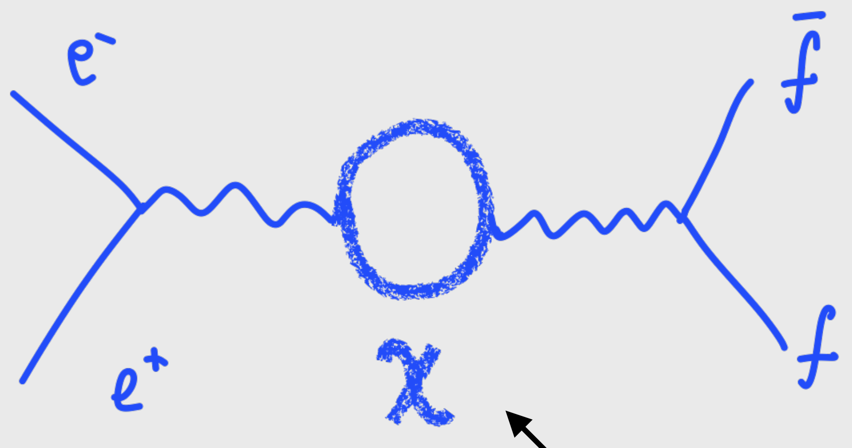
flashing concrete results for

Dark Matter at the weak scale

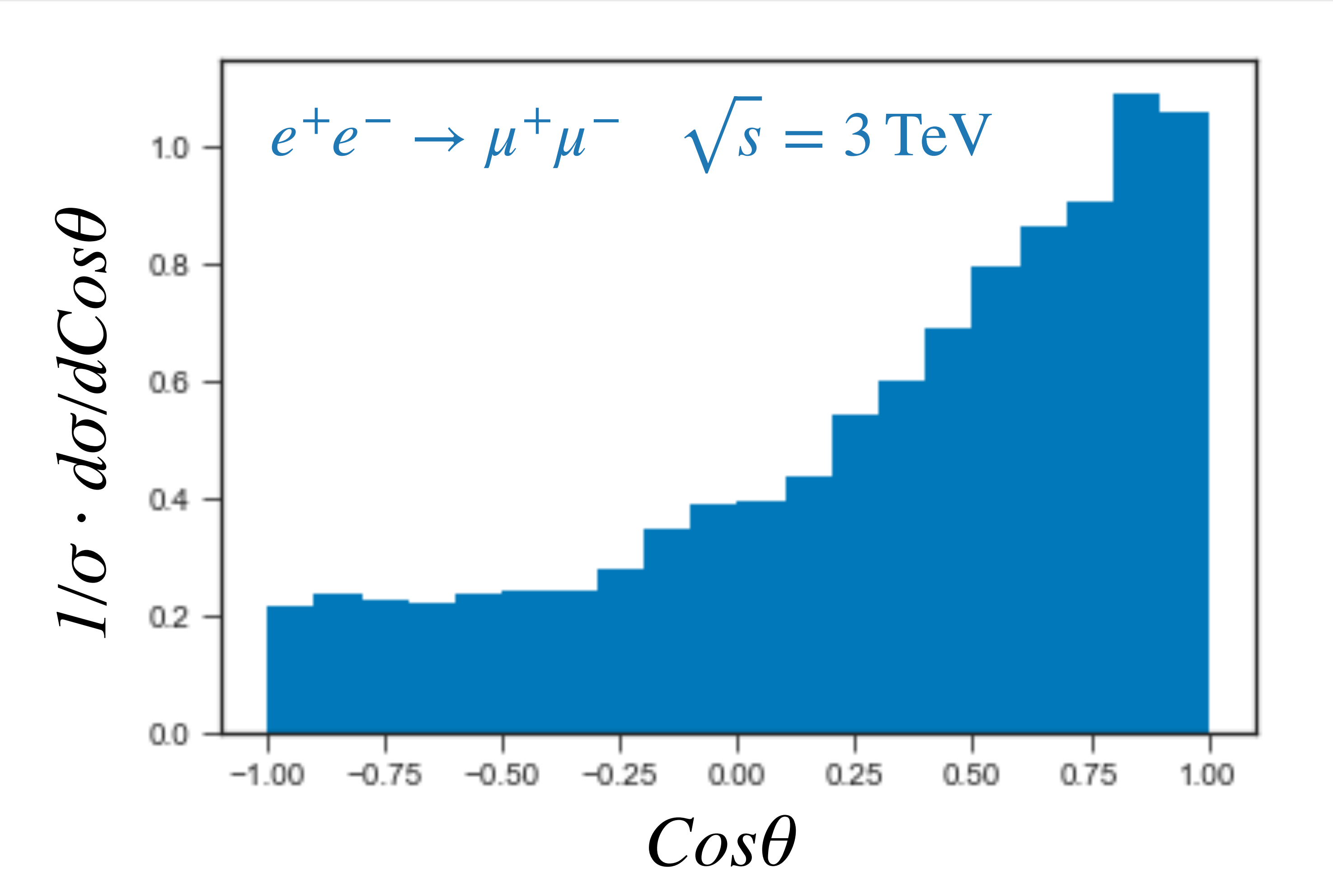
$e^+e^- \to f\bar{f}$

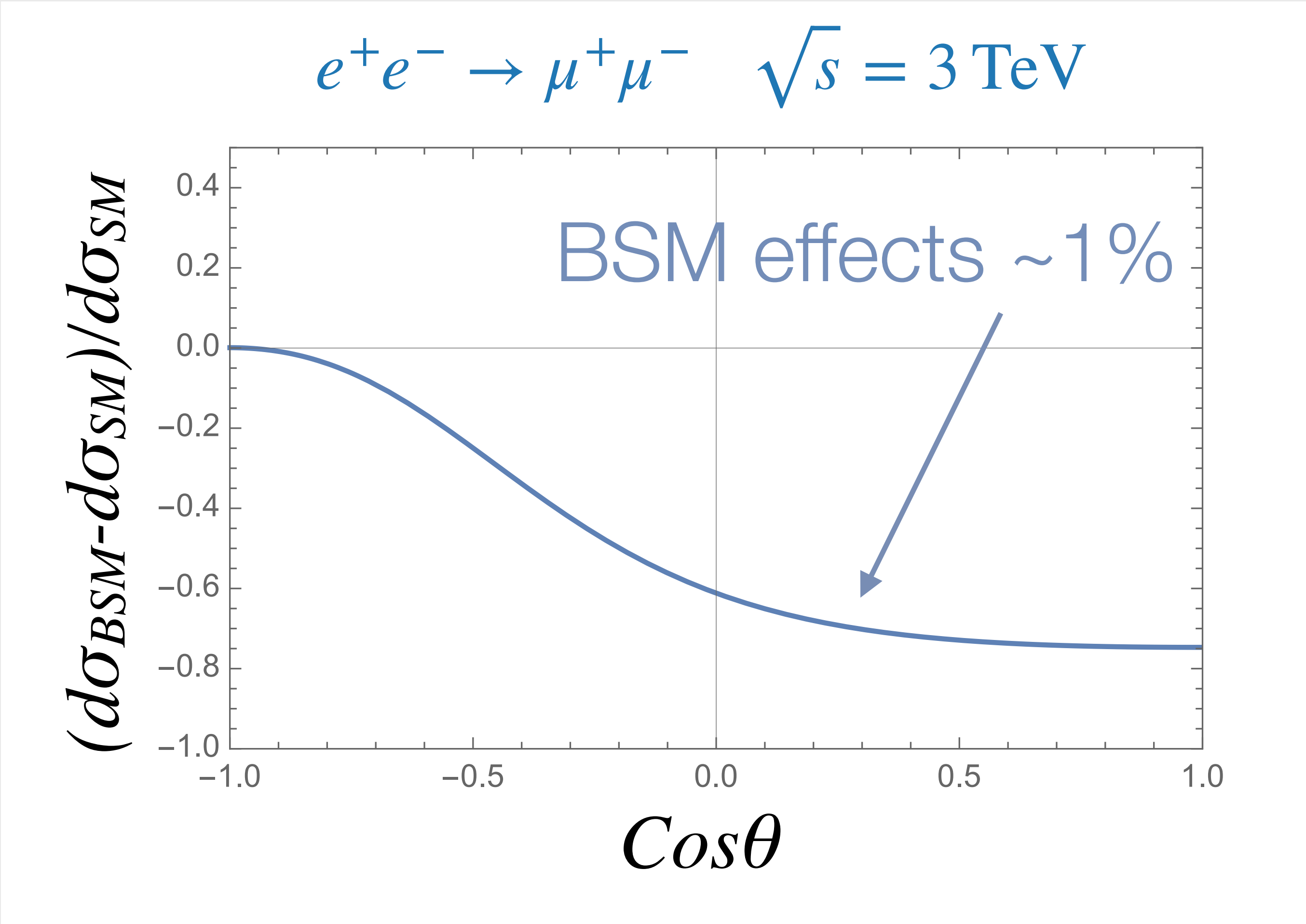
PRECISION

ANGULAR DISTRIBUTION



χ is heavy/light new physics





beams polarization is beneficial to increase NP effects

$e^+e^- \to f\bar{f}$

PRECISION

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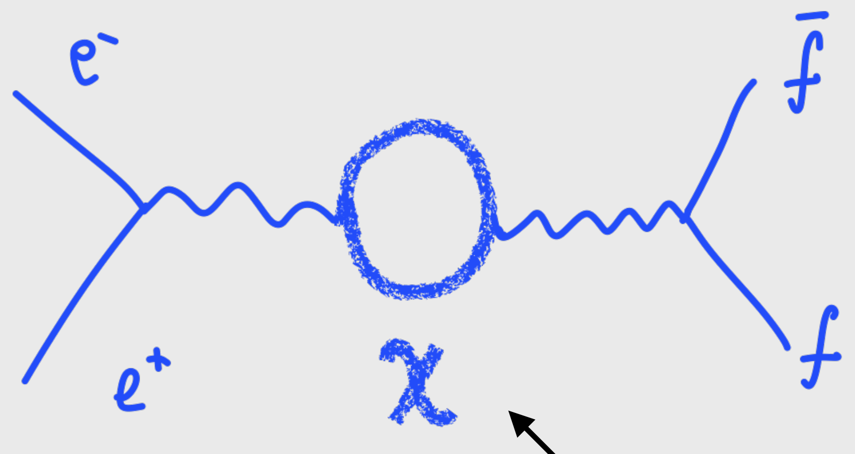

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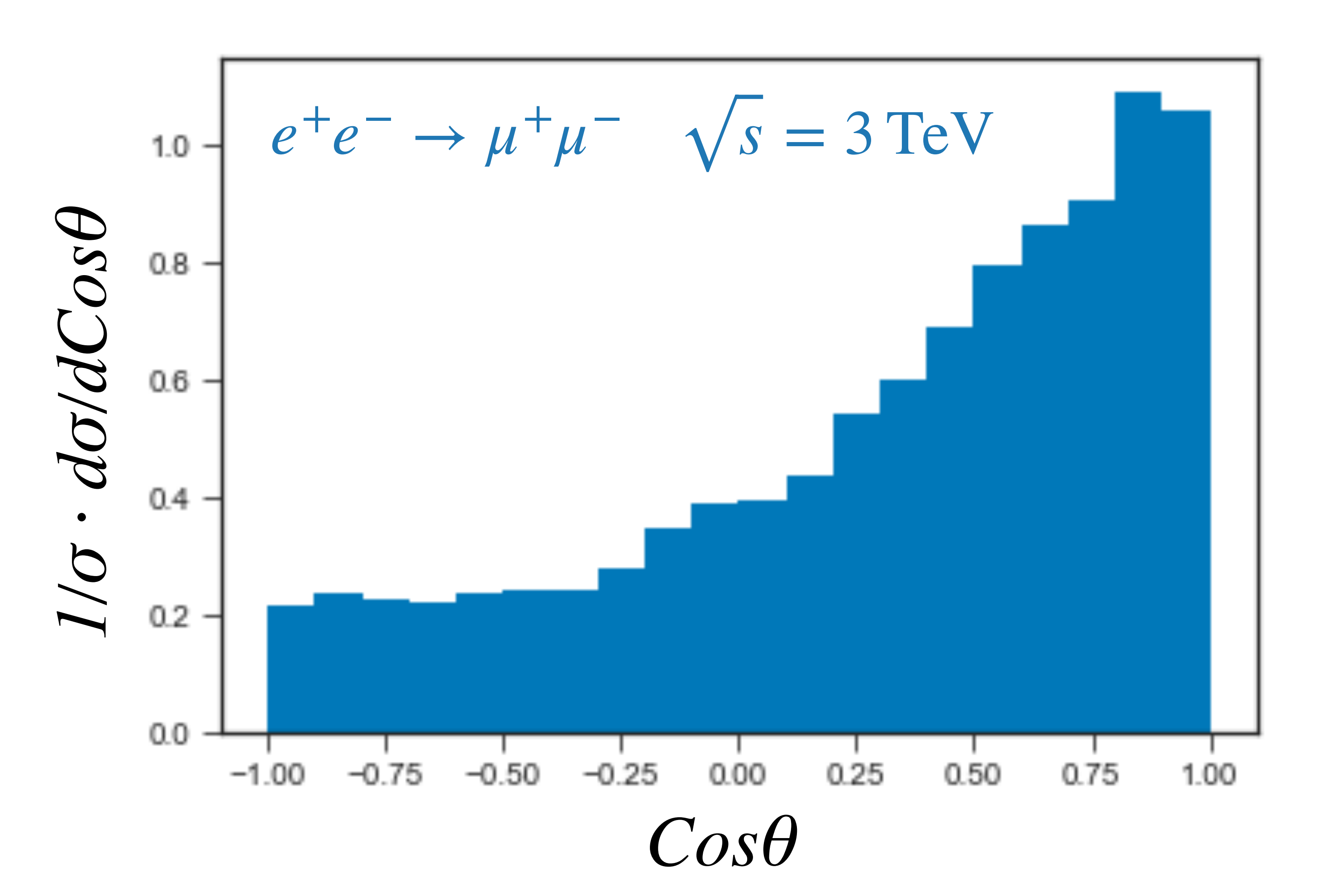

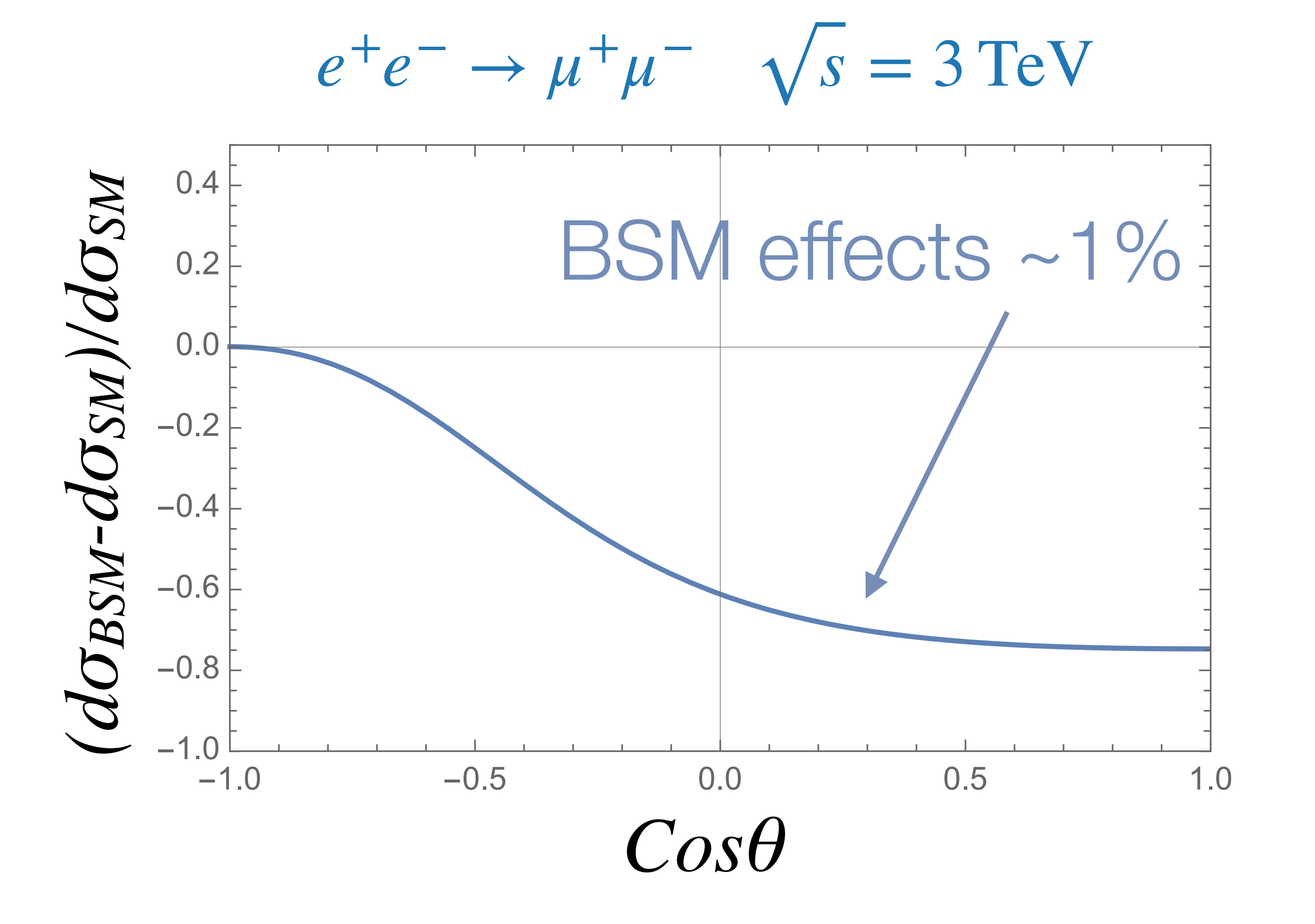

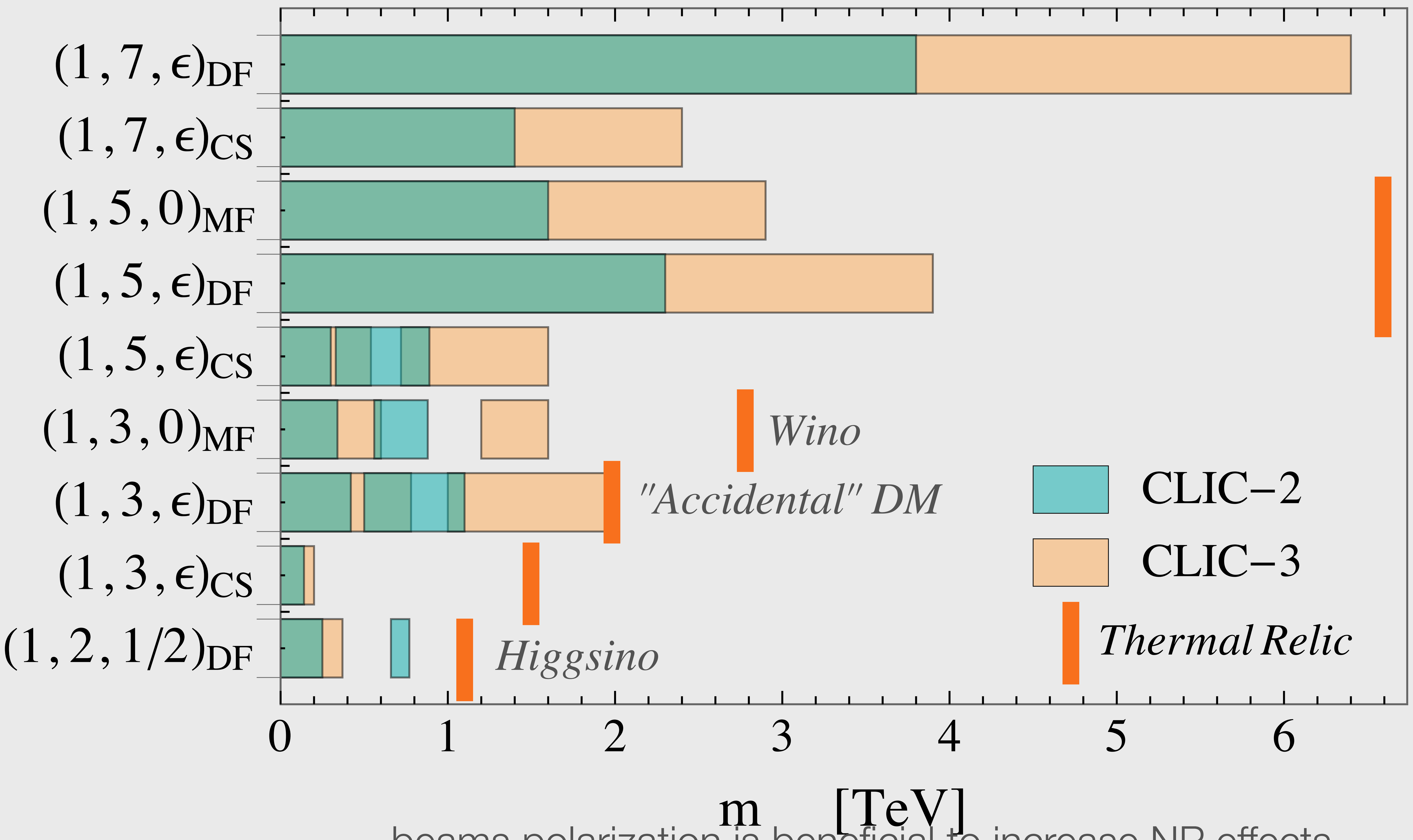

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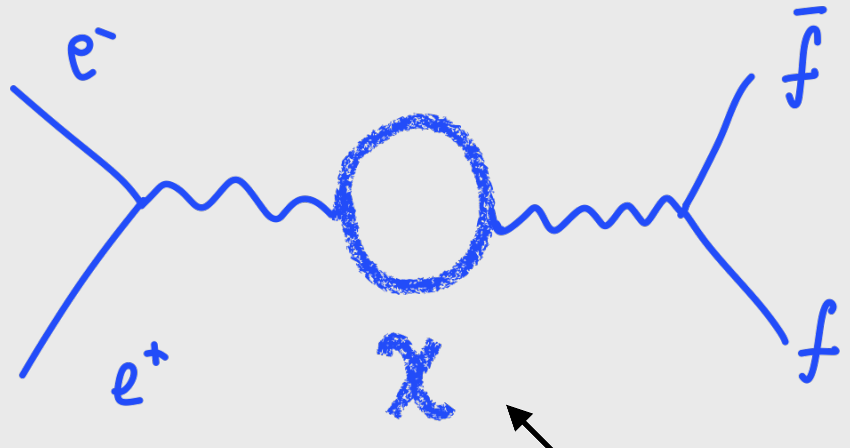

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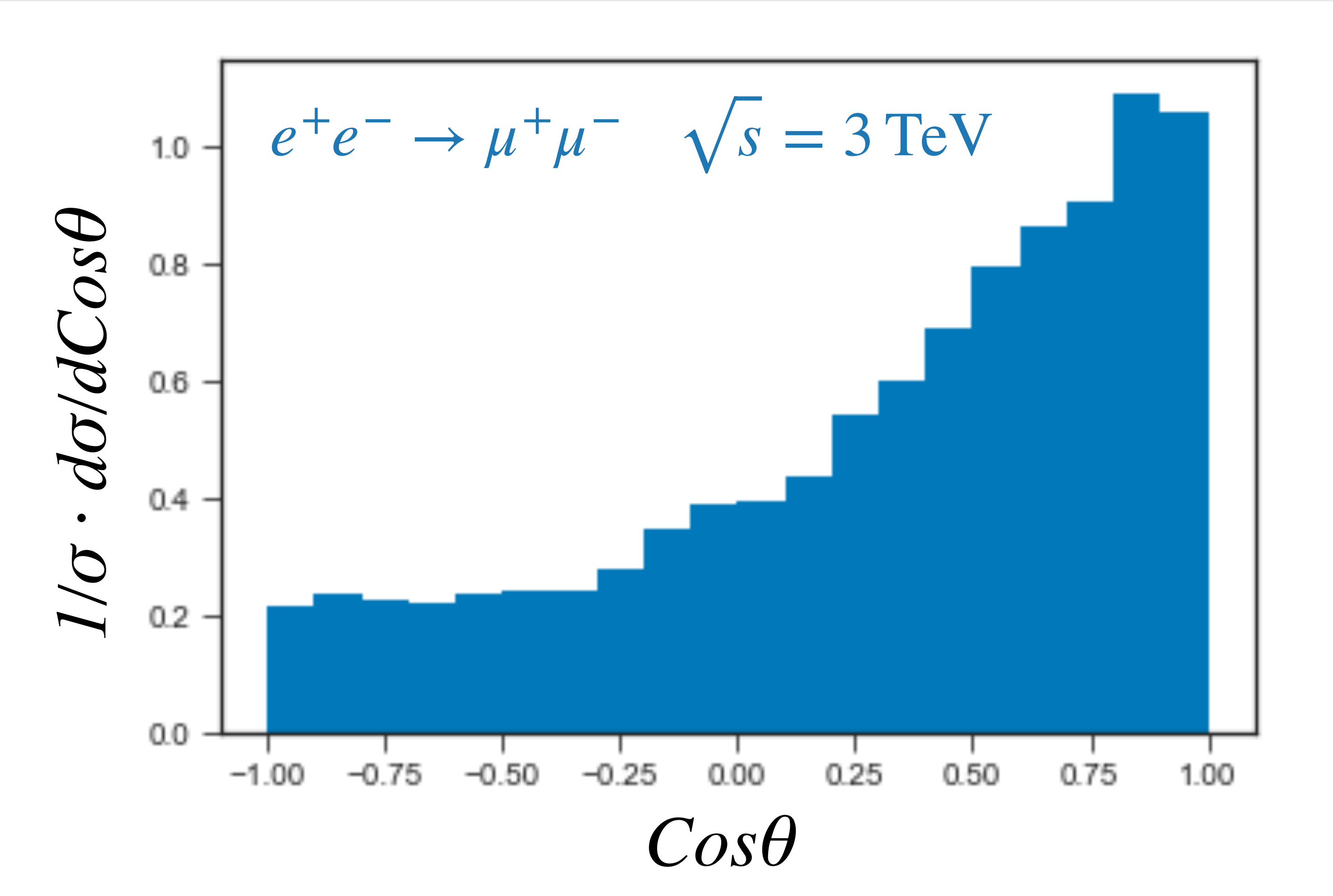
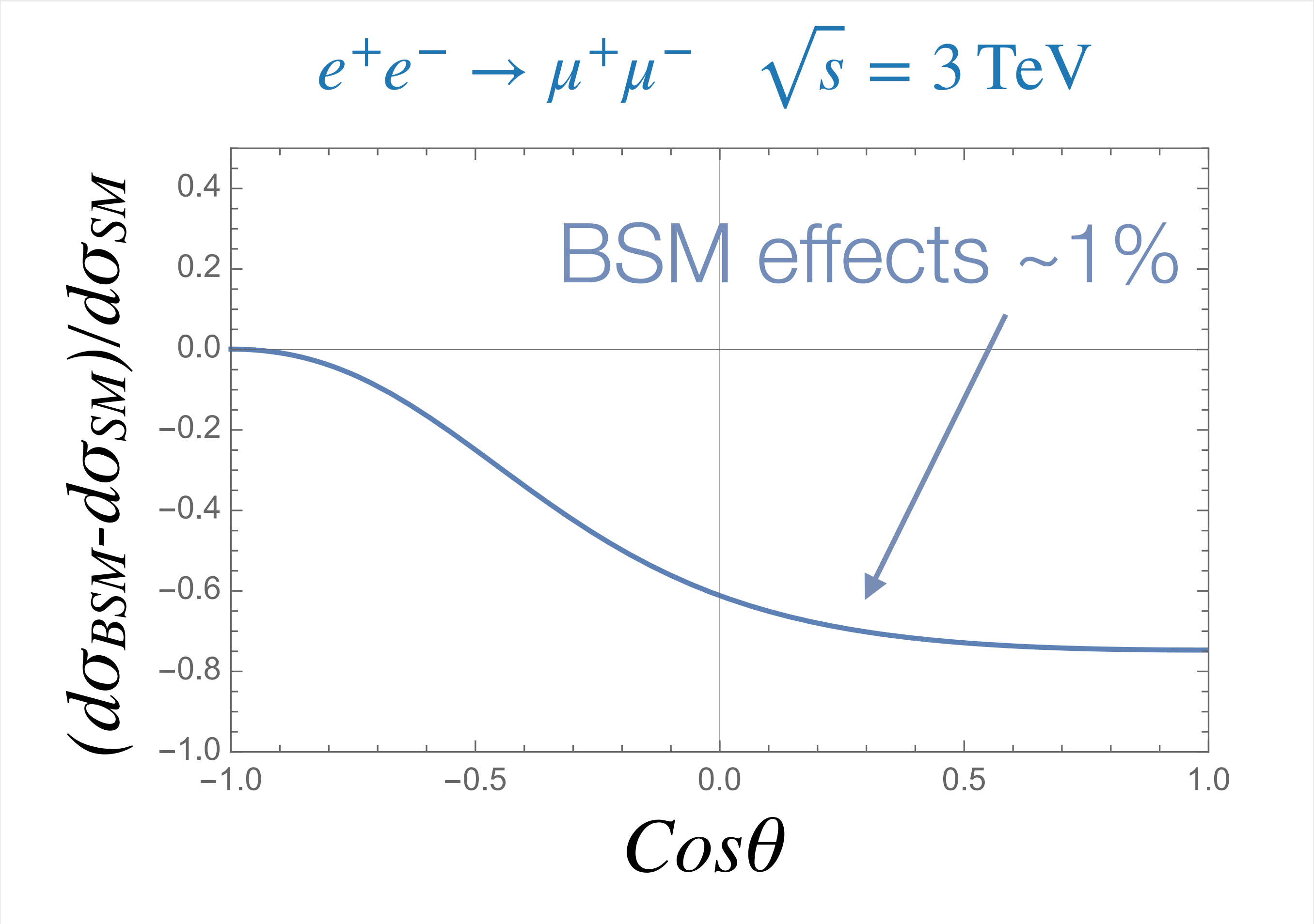
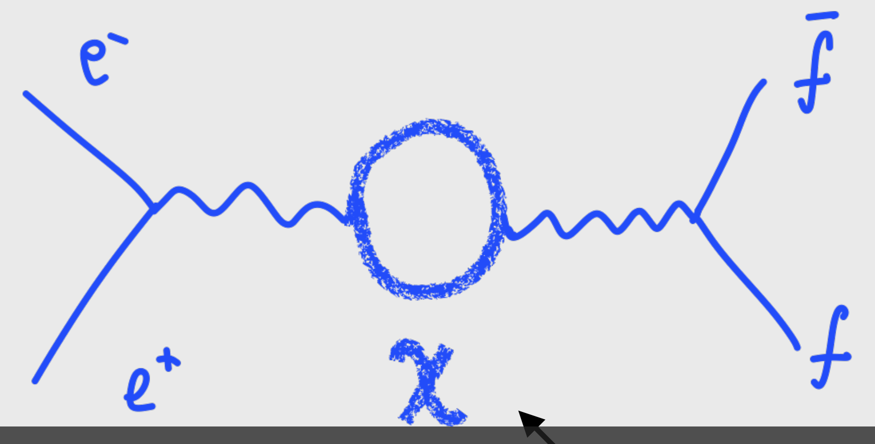




χ / m_χ [TeV]	DM	HL-LHC	HE-LHC	FCC-100	CLIC-3	Muon-14
$(1,2,1/2)_{\rm DF}$	1.1	–	–	–	0.4	0.6
$(1,3,\epsilon)_{\rm CS}$	1.6	–	–	–	0.2	0.2
$(1,3,\epsilon)_{\rm DF}$	2.0	–	0.6	1.5	0.8 & [1.0, 2.0]	2.2 & [6.3, 7.1]
$(1,3,0)_{\rm MF}$	2.8	–	–	0.4	0.6 & [1.2, 1.6]	1.0
$(1,5,\epsilon)_{\rm CS}$	6.6	0.2	0.4	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]
$(1,7,\epsilon)_{\rm CS}$	16	0.6	1.3	3.2	2.4	2.5 & [3.5, 7.4]
$(1,7,\epsilon)_{\rm DF}$	16	2.1	4.0	11	6.4	18

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

$e^+e^- \to f\bar{f}$



PRECISION | ANGULAR DISTRIBUTION

χ is heavy/light new physics

- Lepton colliders can observe these states directly and indirectly
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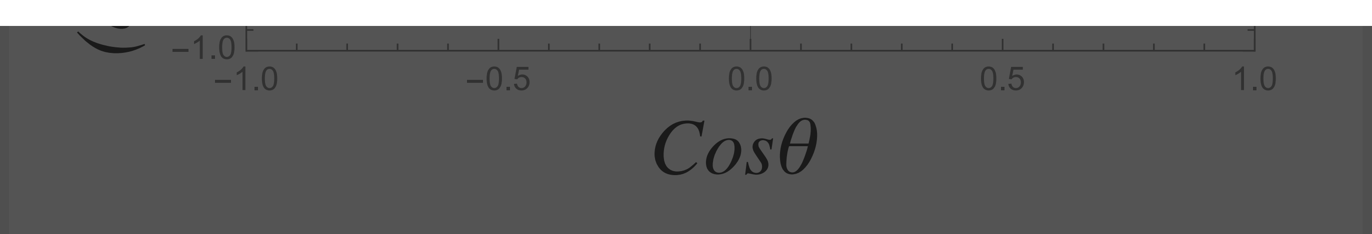

Electroweak Dark Matter: LSP (+NLSP)

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 $e^+e^- \to Z' \to \chi\,\chi$	0	Mono-photon

} Electroweak Precision Tests

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flashing concrete results for

The size of the Higgs boson

Effects of the size of the Higgs boson

h ~ π STRONGLY INTERACTING LIGHT HIGGS

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

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

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

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

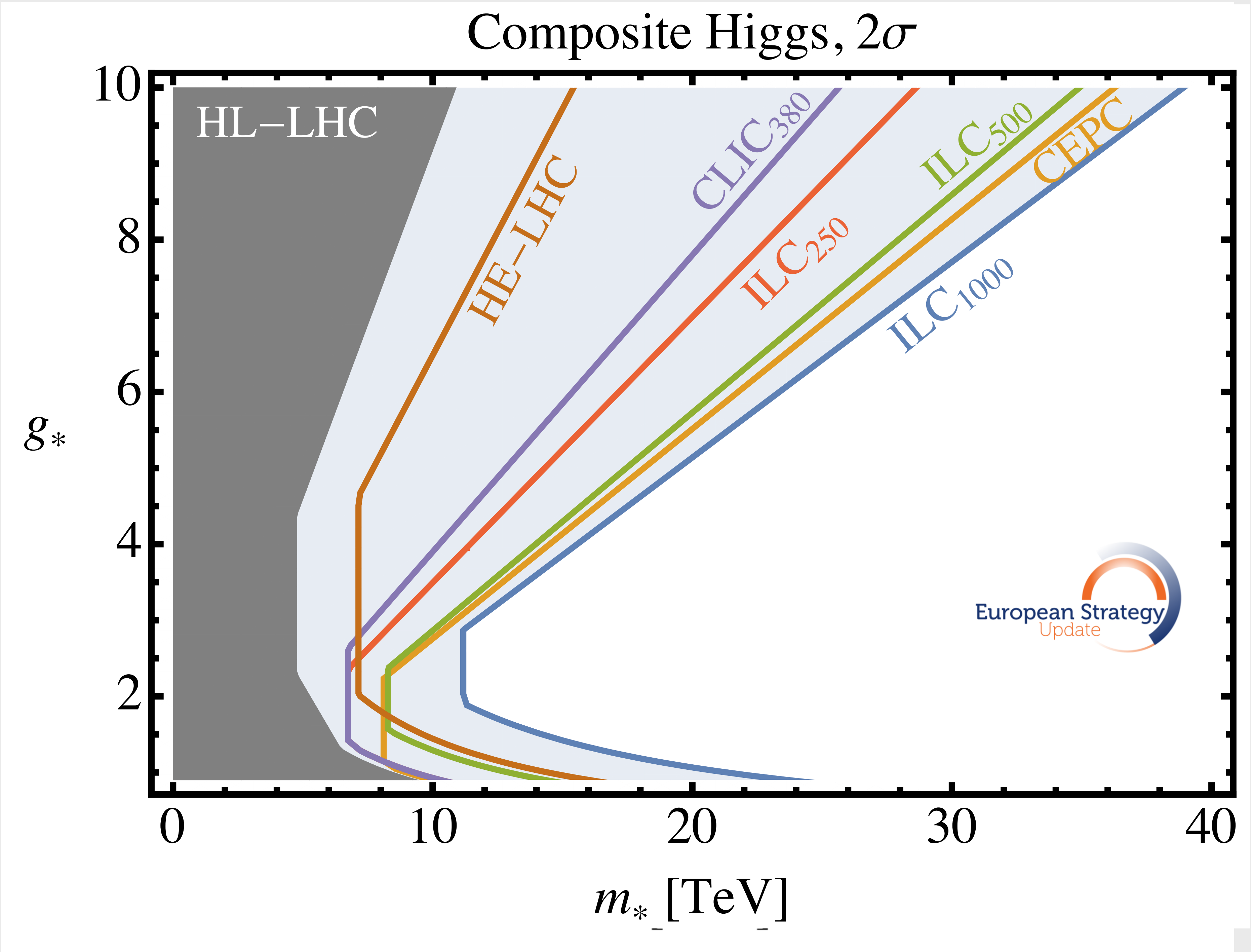
$1/f \sim g_\star/m_\star$

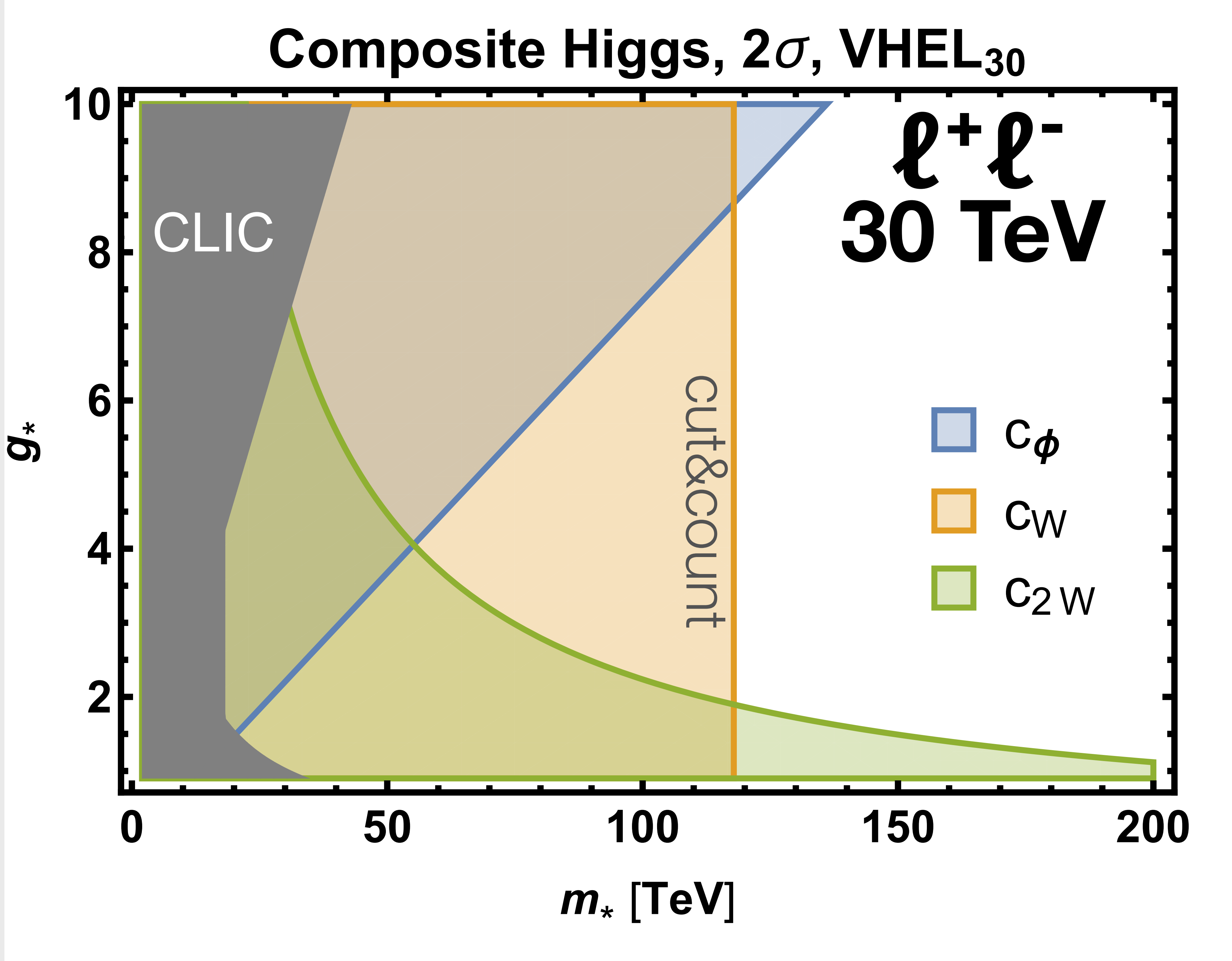
$1/(g_\star f) \sim 1/m_\star$

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

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

Looking ahead

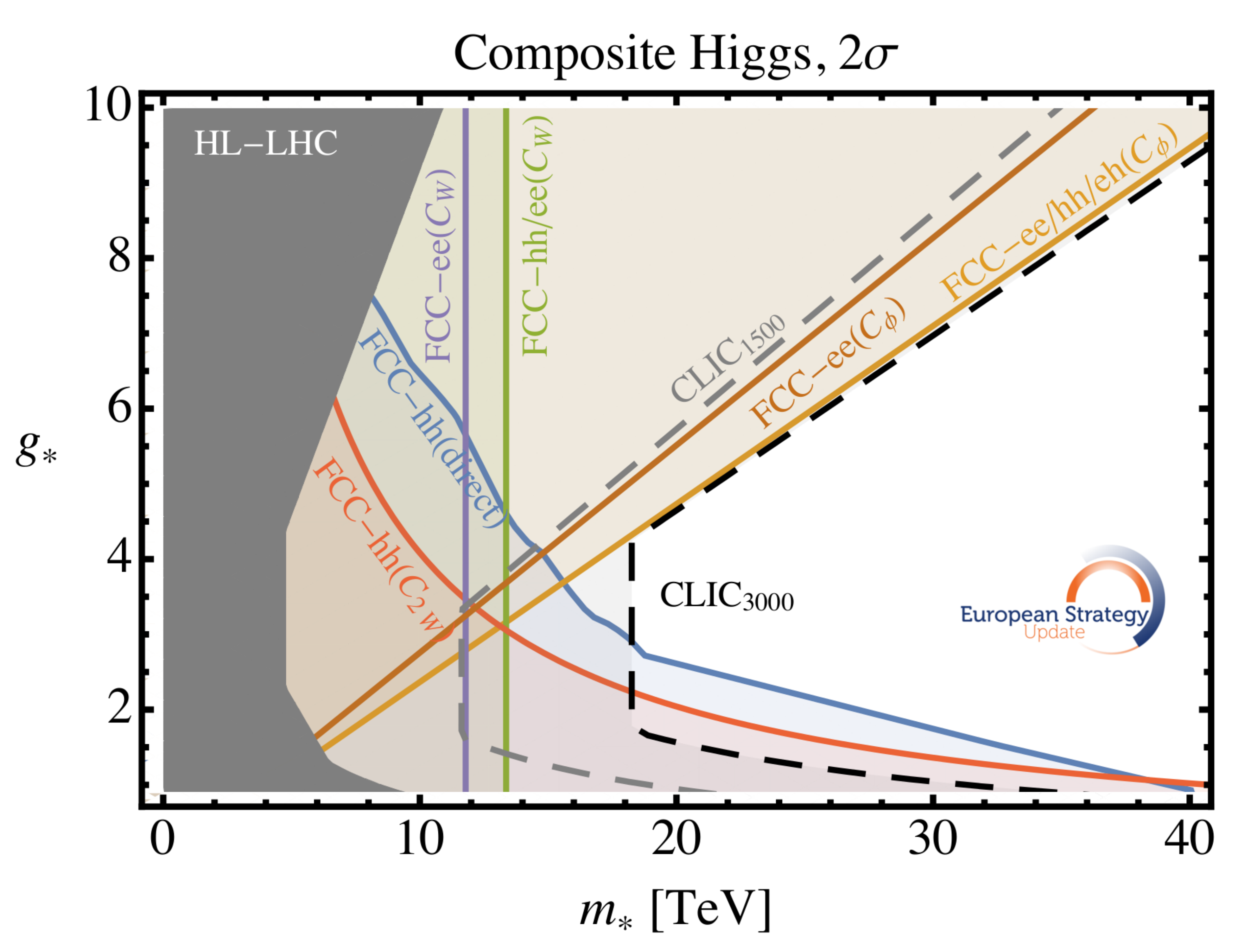


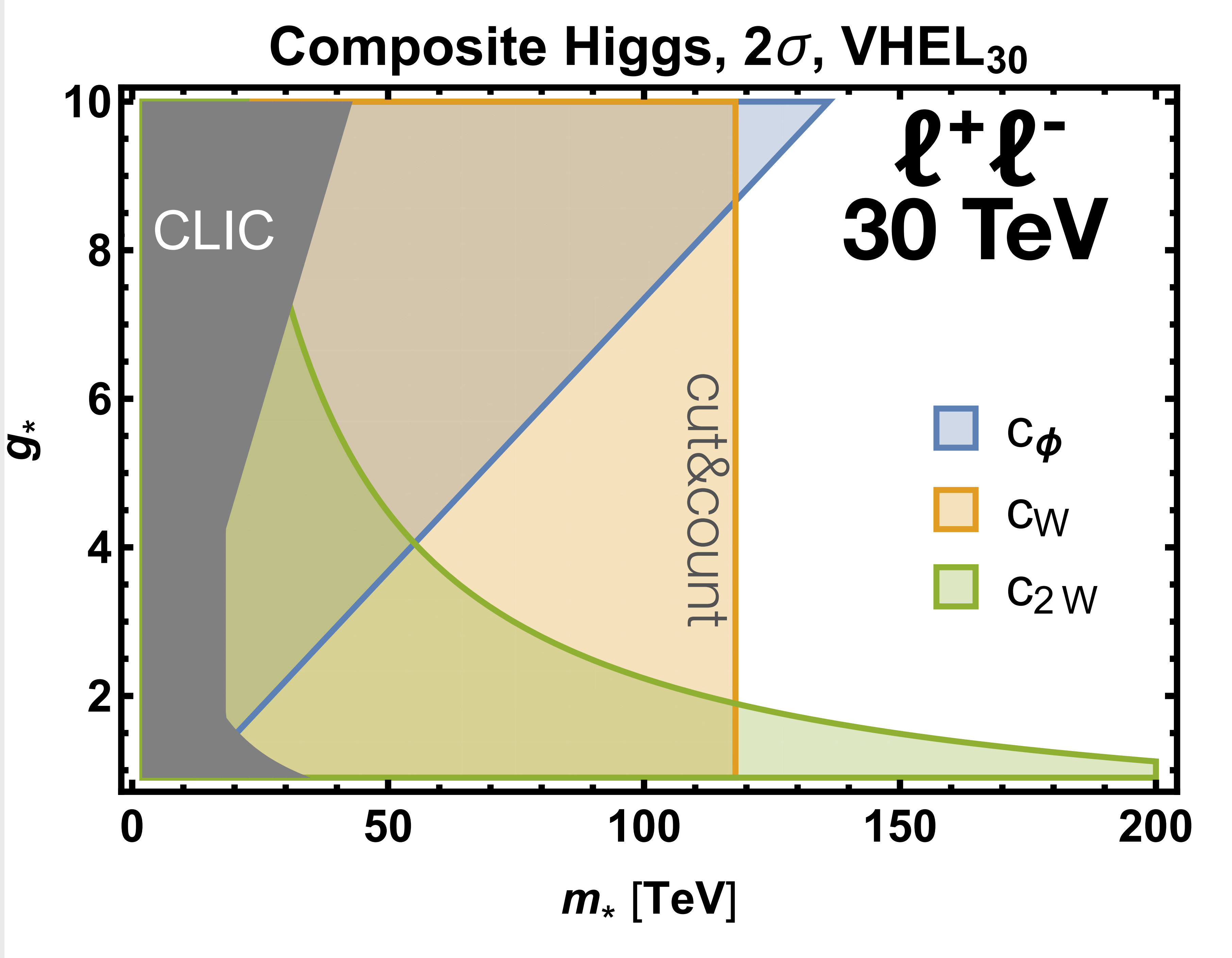


compositeness at 10 TeV-20 TeV

compositeness at 100 TeV-500 TeV

Looking ahead





compositeness at 10 TeV-20 TeV

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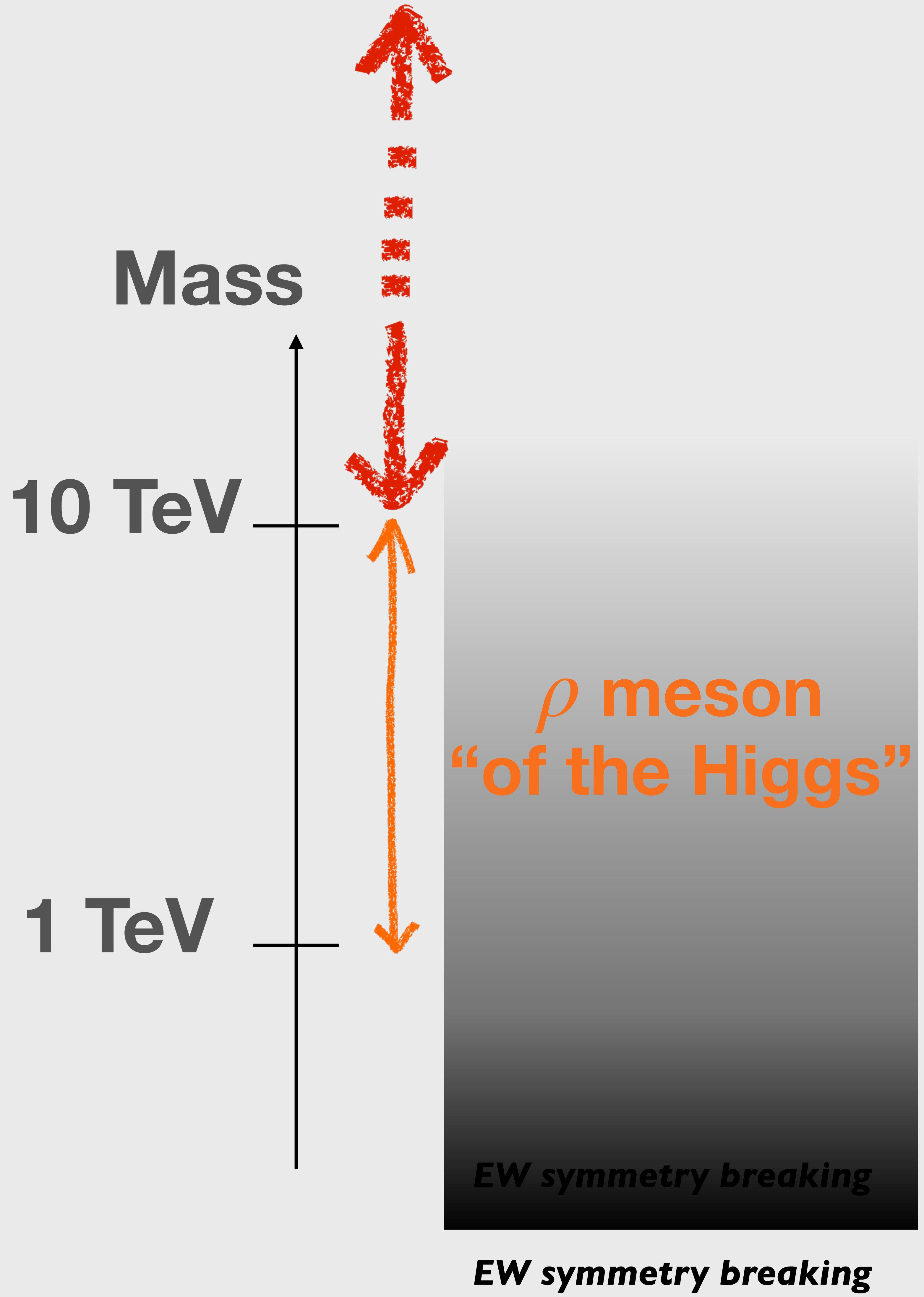
Open Questions on the “big picture” on fundamental physics circa 2020

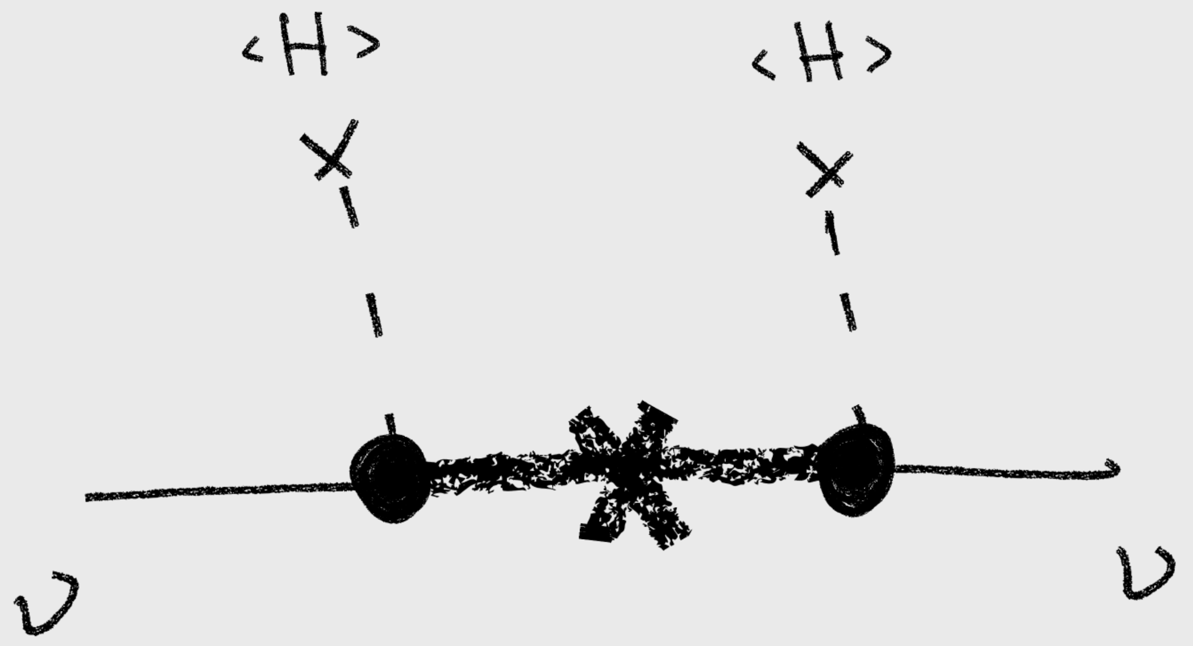


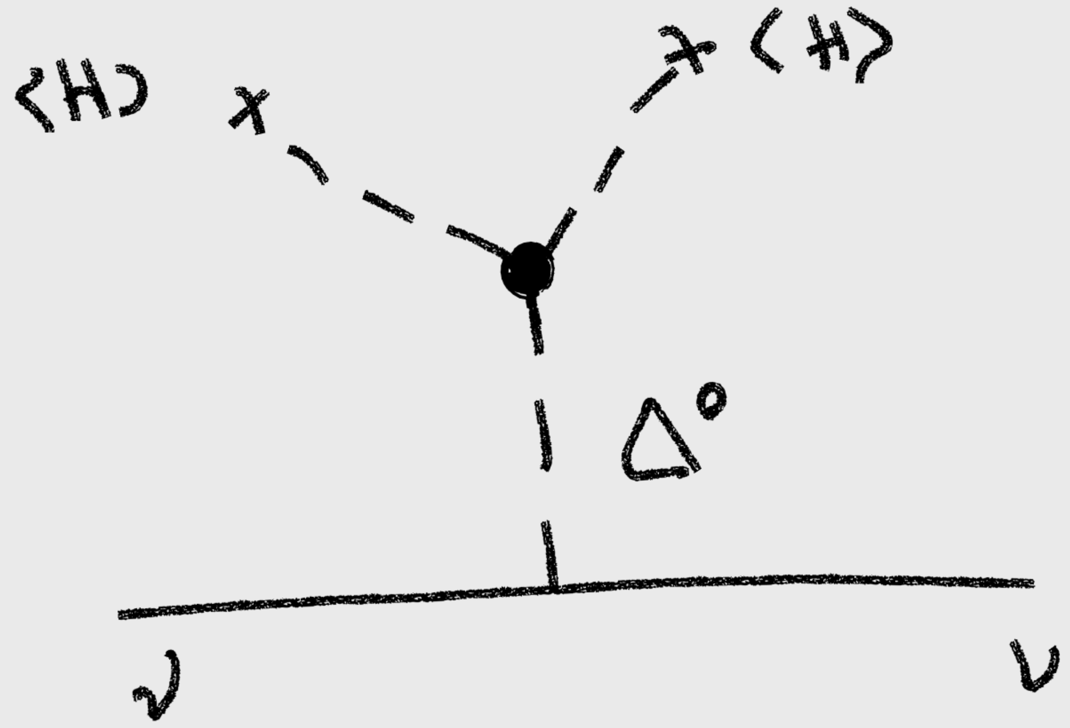
We might be in a situation like QCD, where the ρ meson is only somewhat heavier than the pion, or in a situations where it is much heavier.

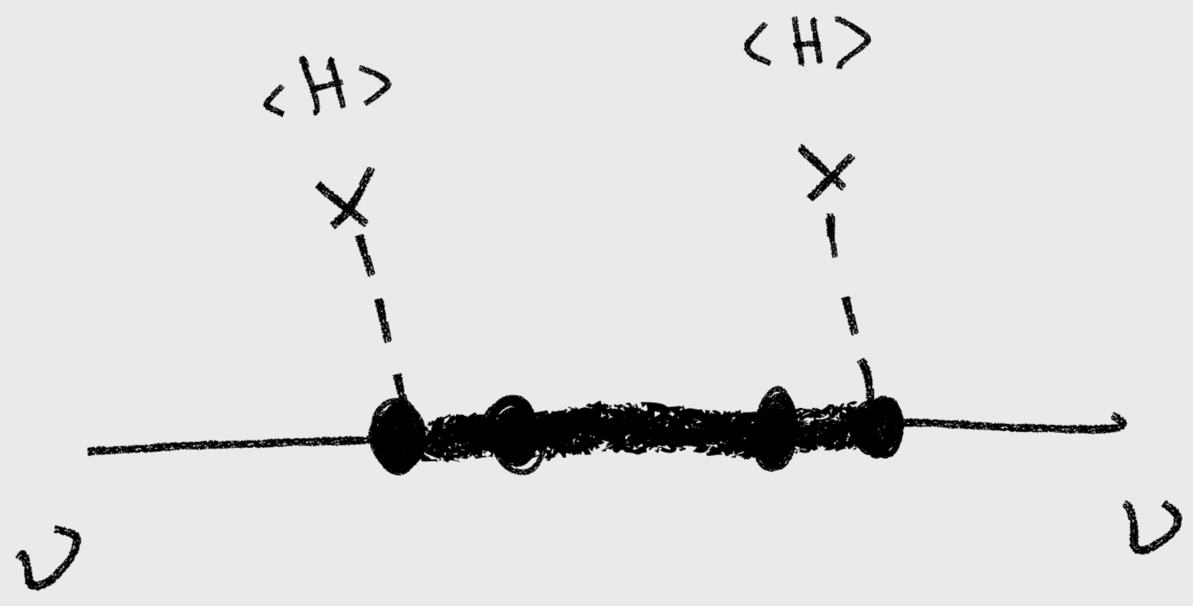
Both cases have profound consequences for telling **what the Higgs boson really is.**

Neutrino mass mechanisms

LEPTON NUMBER BREAKING







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

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

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

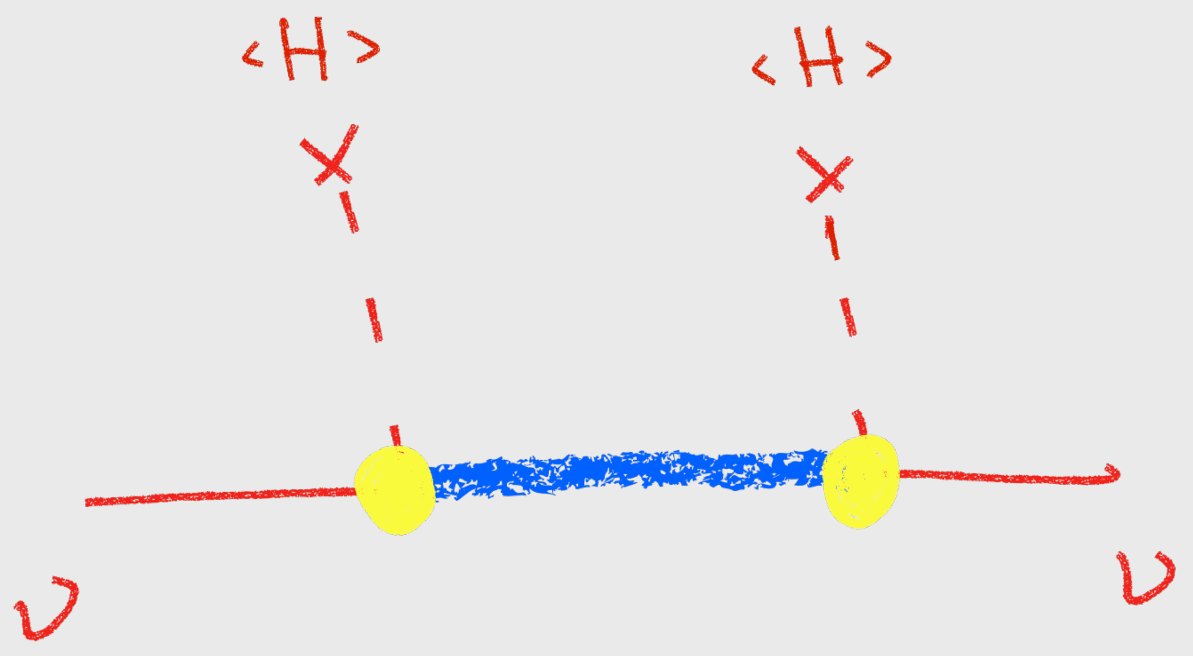
$M_{heavy} \to$ LARGE

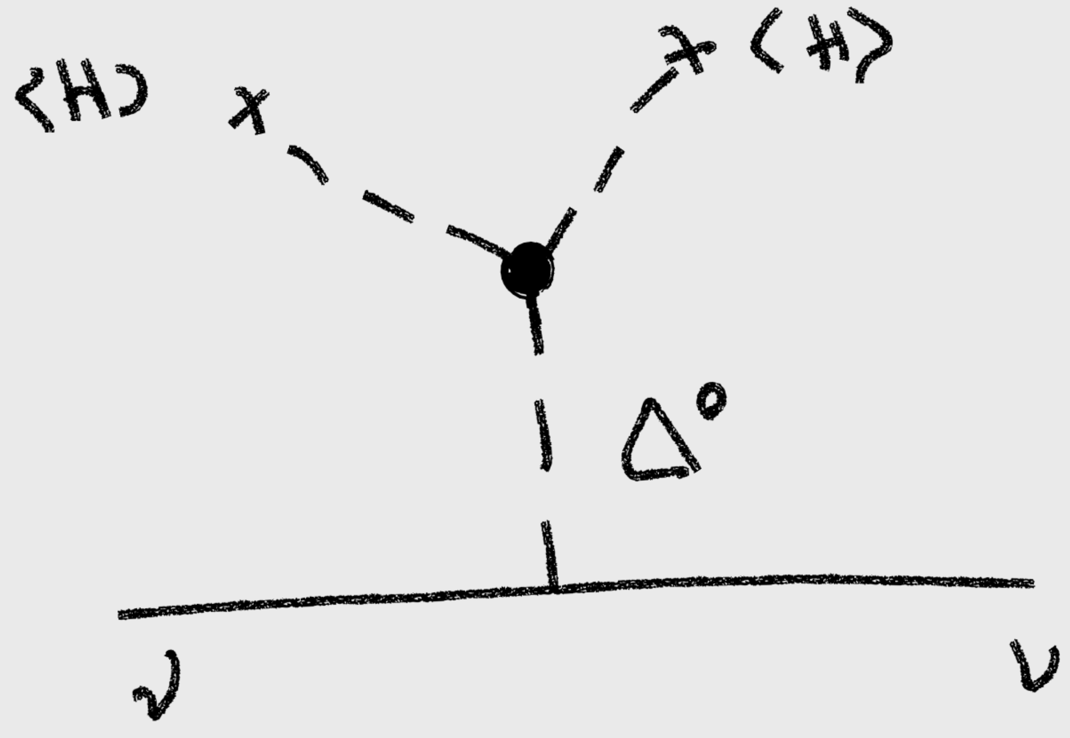
coupling $\to$ SMALL

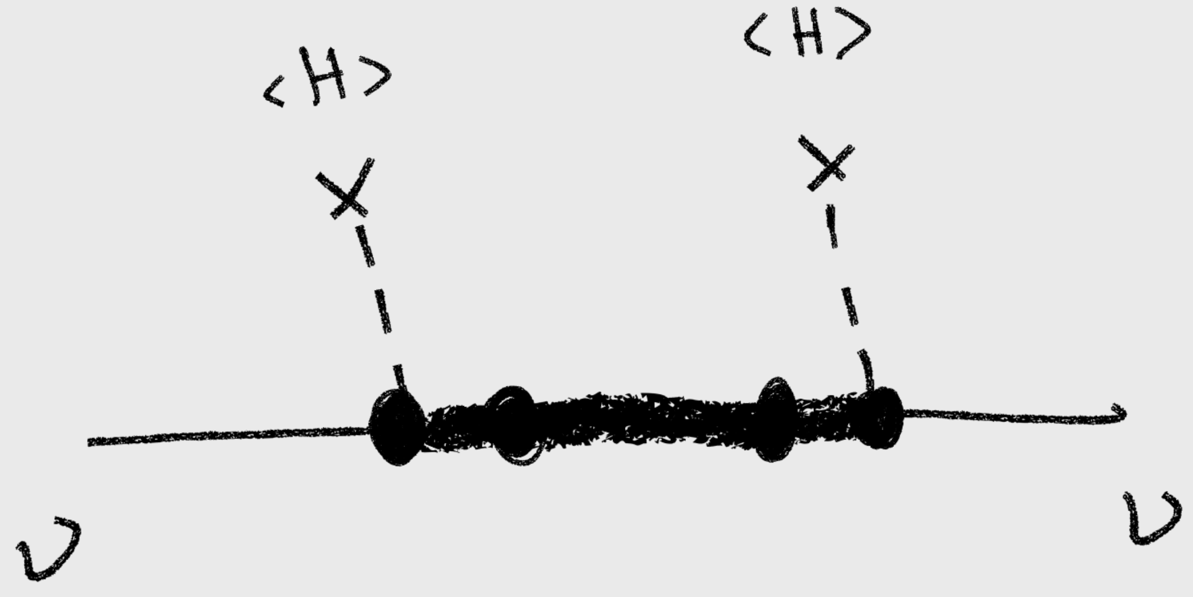
$\mu \to$ SMALL

Neutrino mass mechanisms

LEPTON NUMBER BREAKING







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Neutrino mass mechanisms

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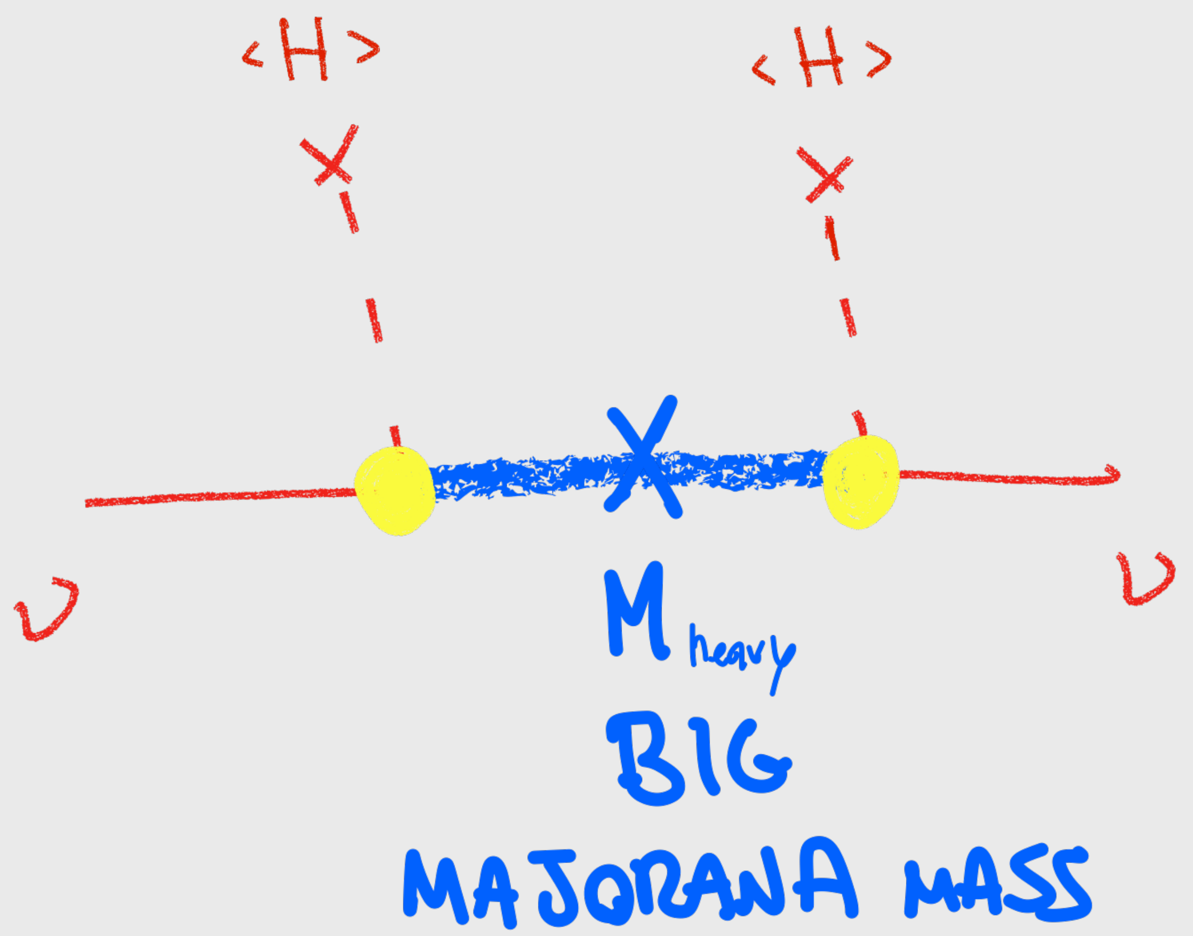

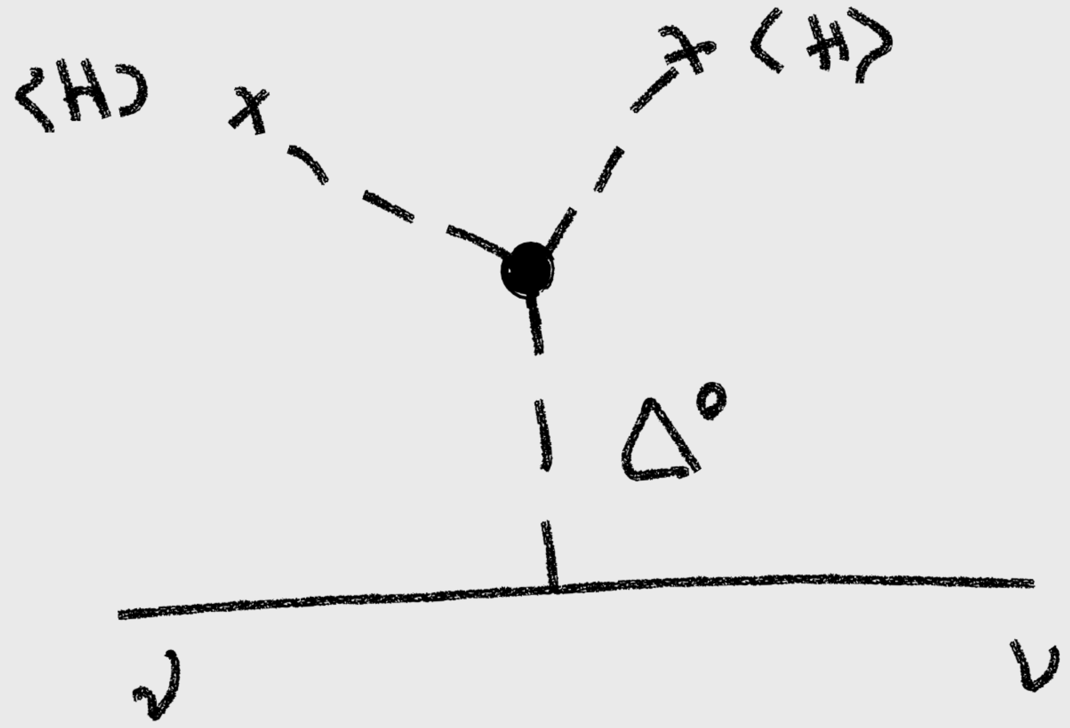

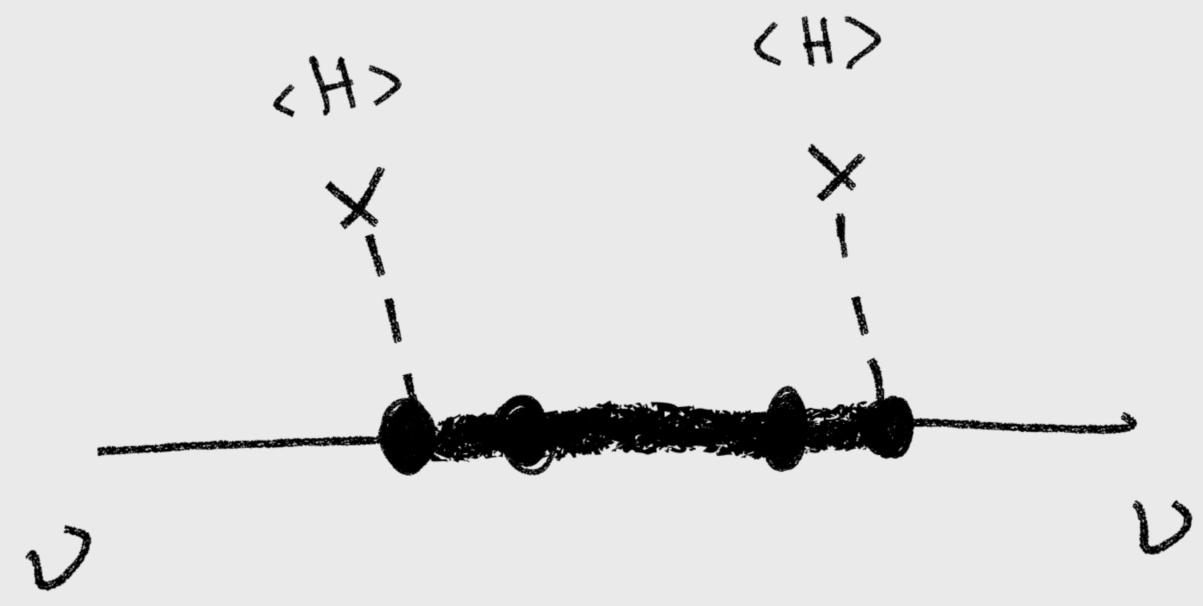

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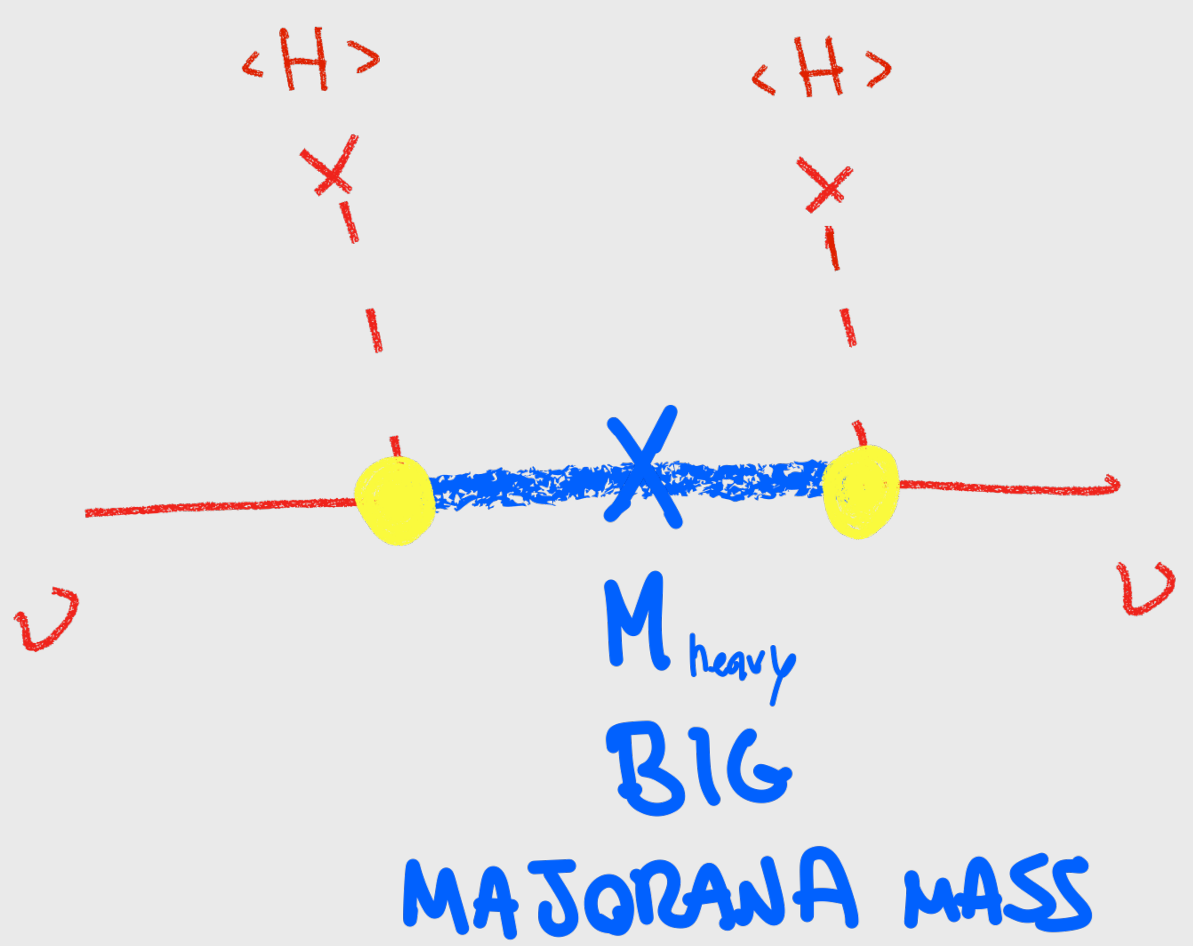
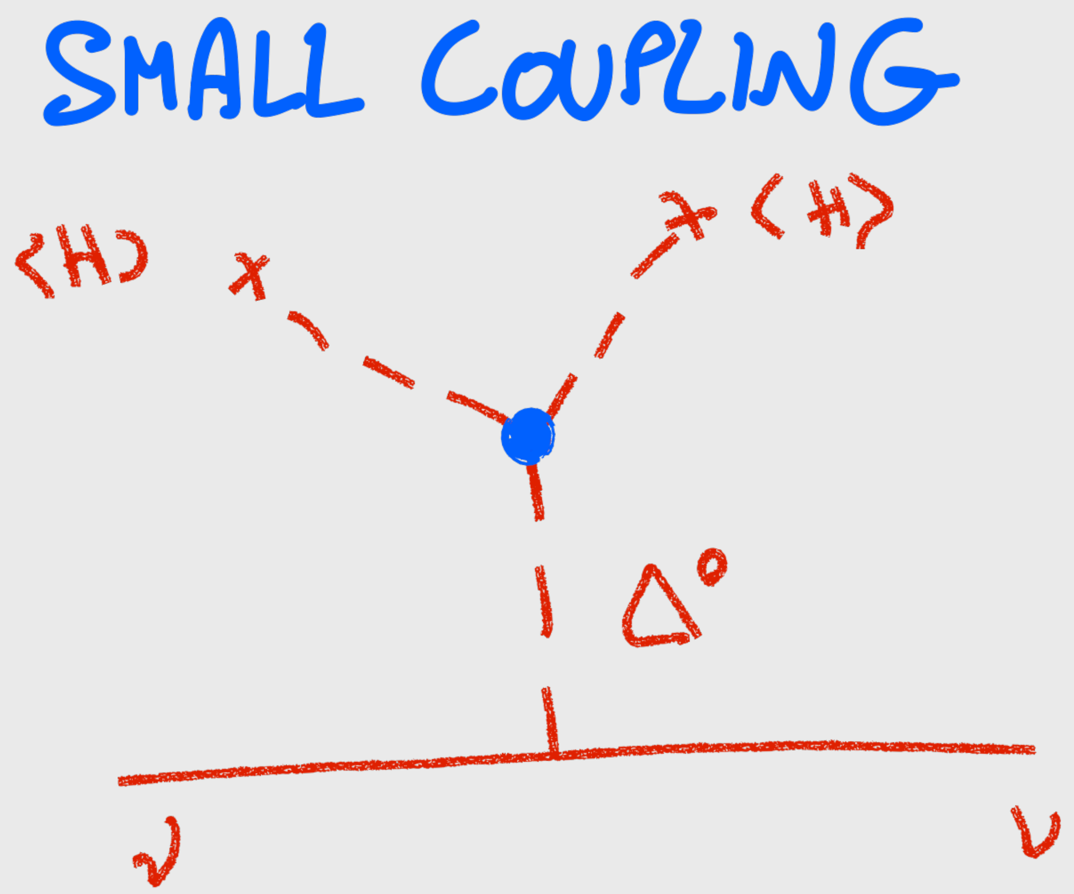
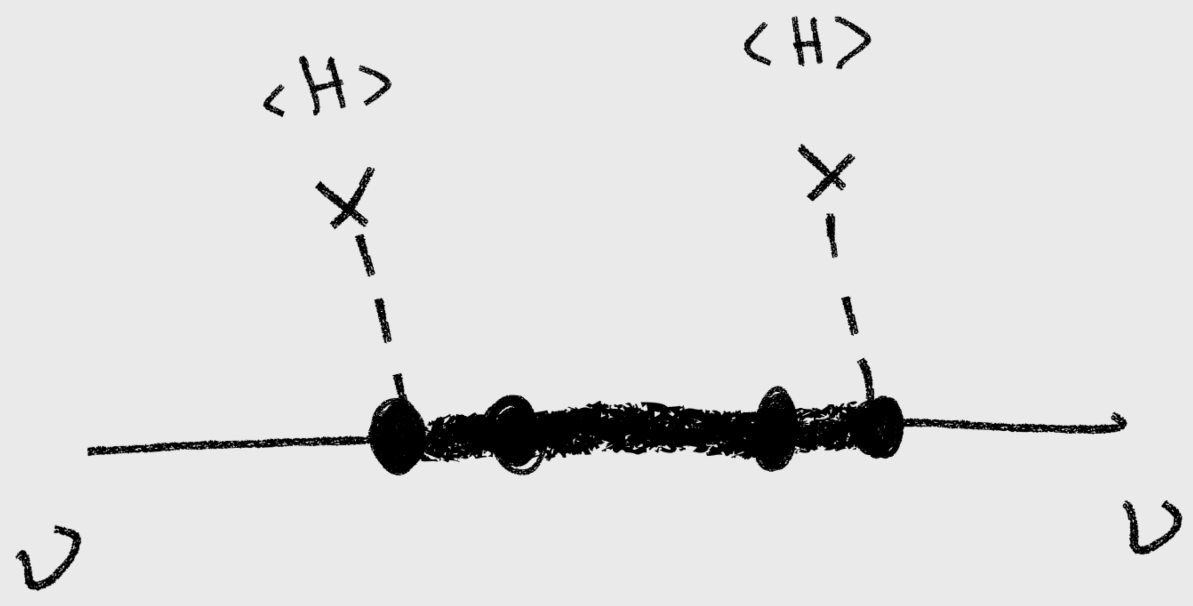
Neutrino mass mechanisms

LEPTON NUMBER BREAKING







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Neutrino mass mechanisms

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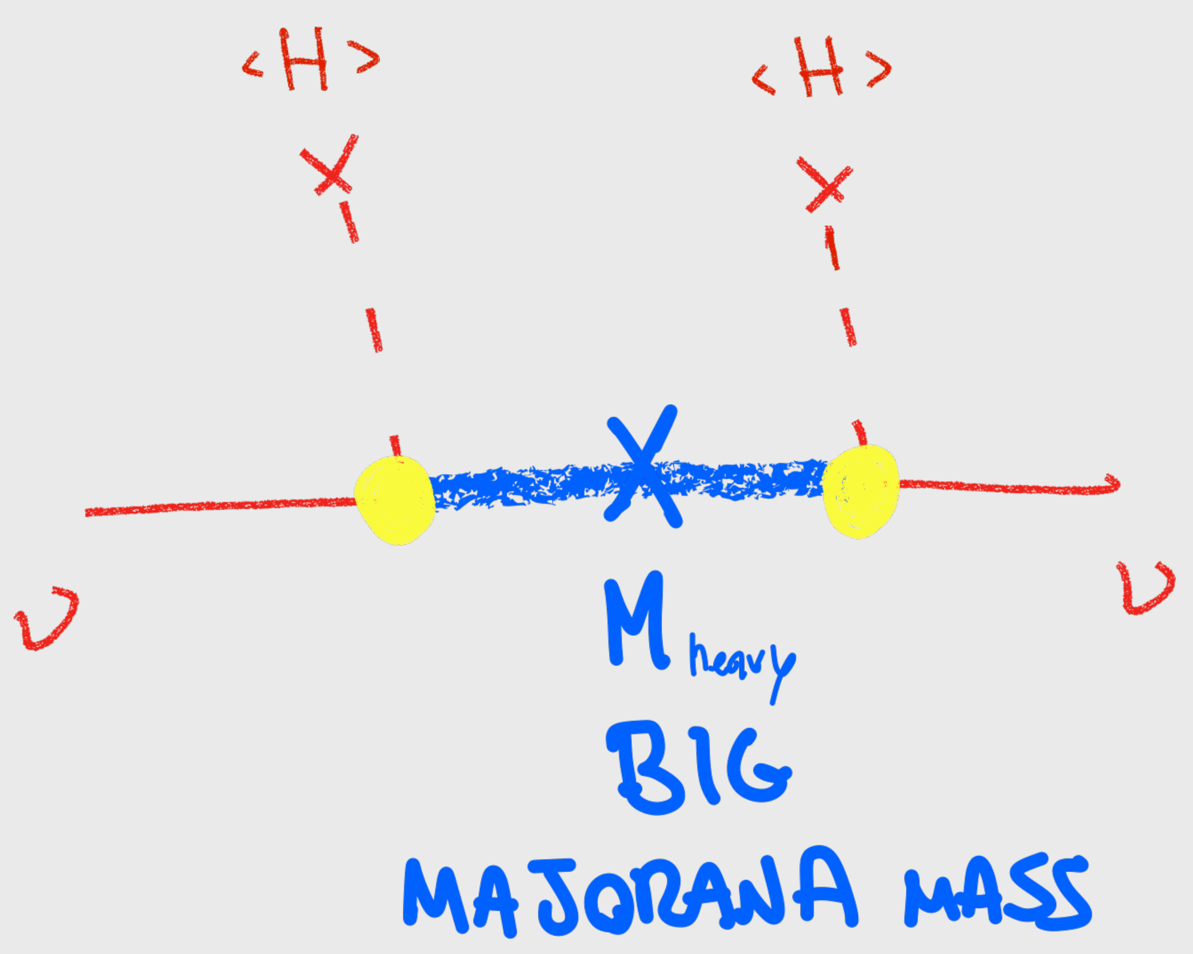

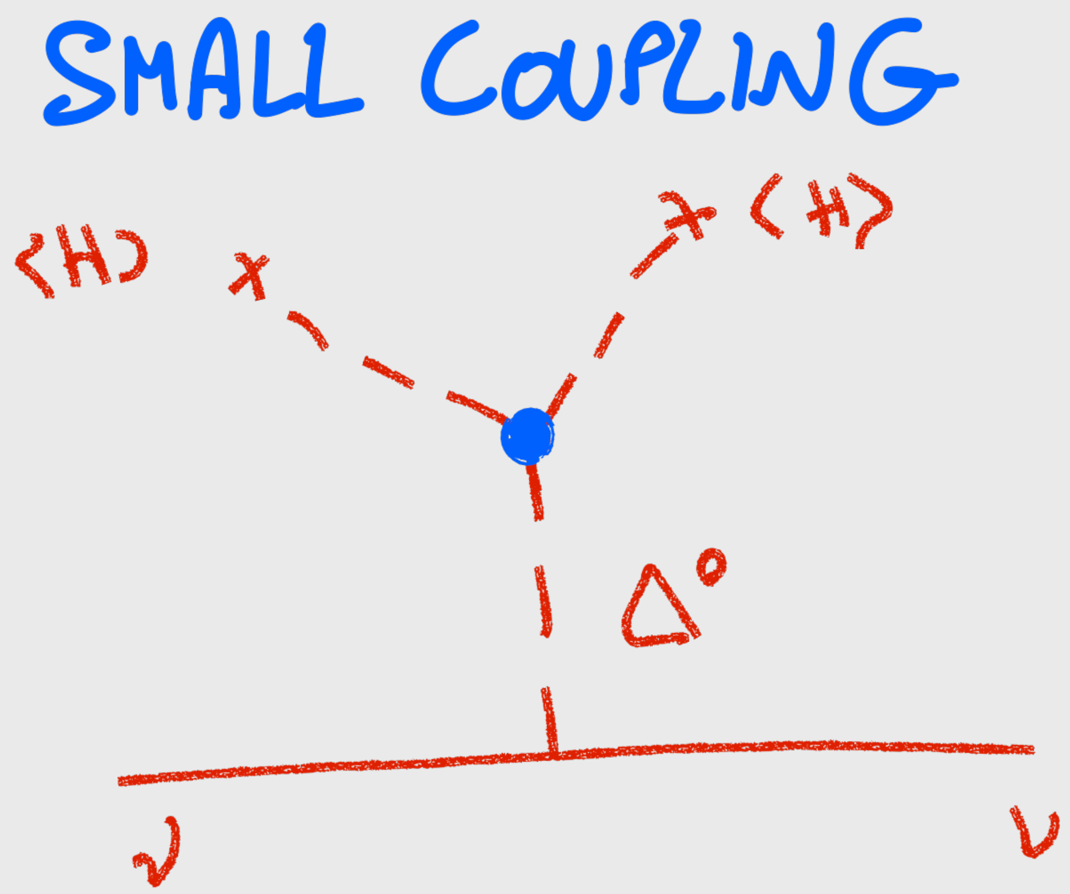

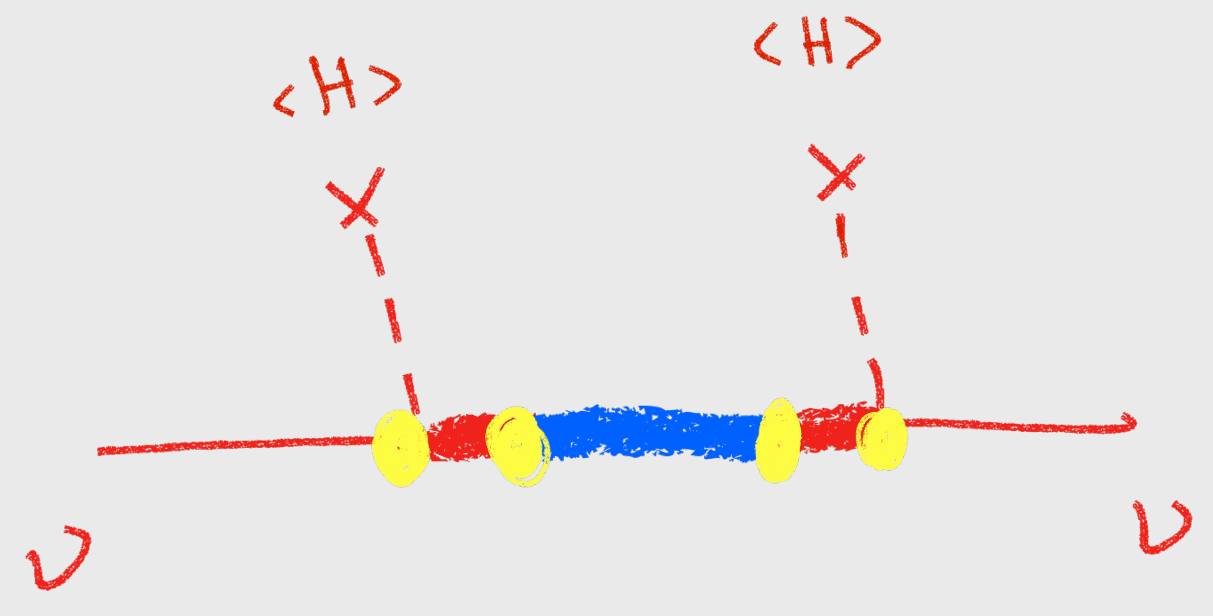

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Neutrino mass mechanisms

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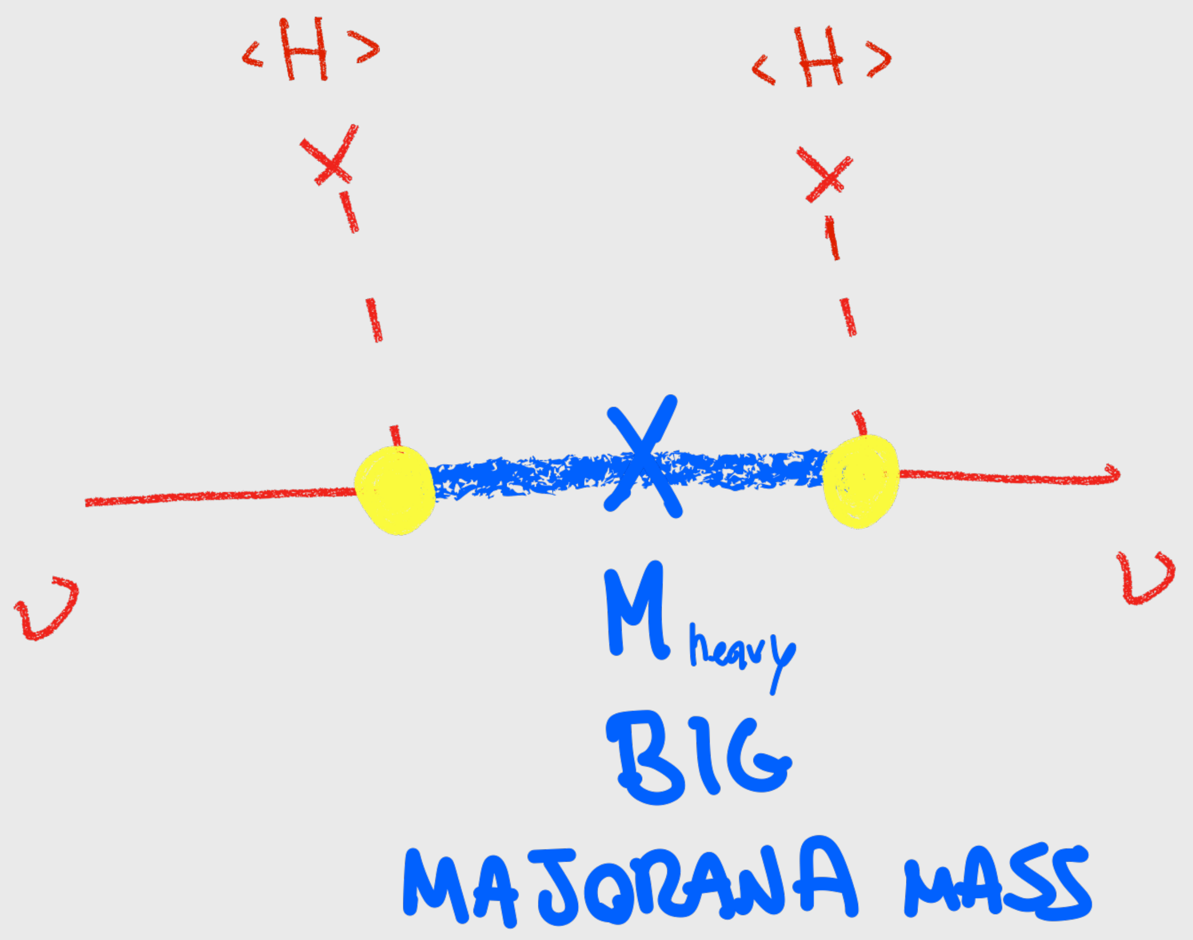

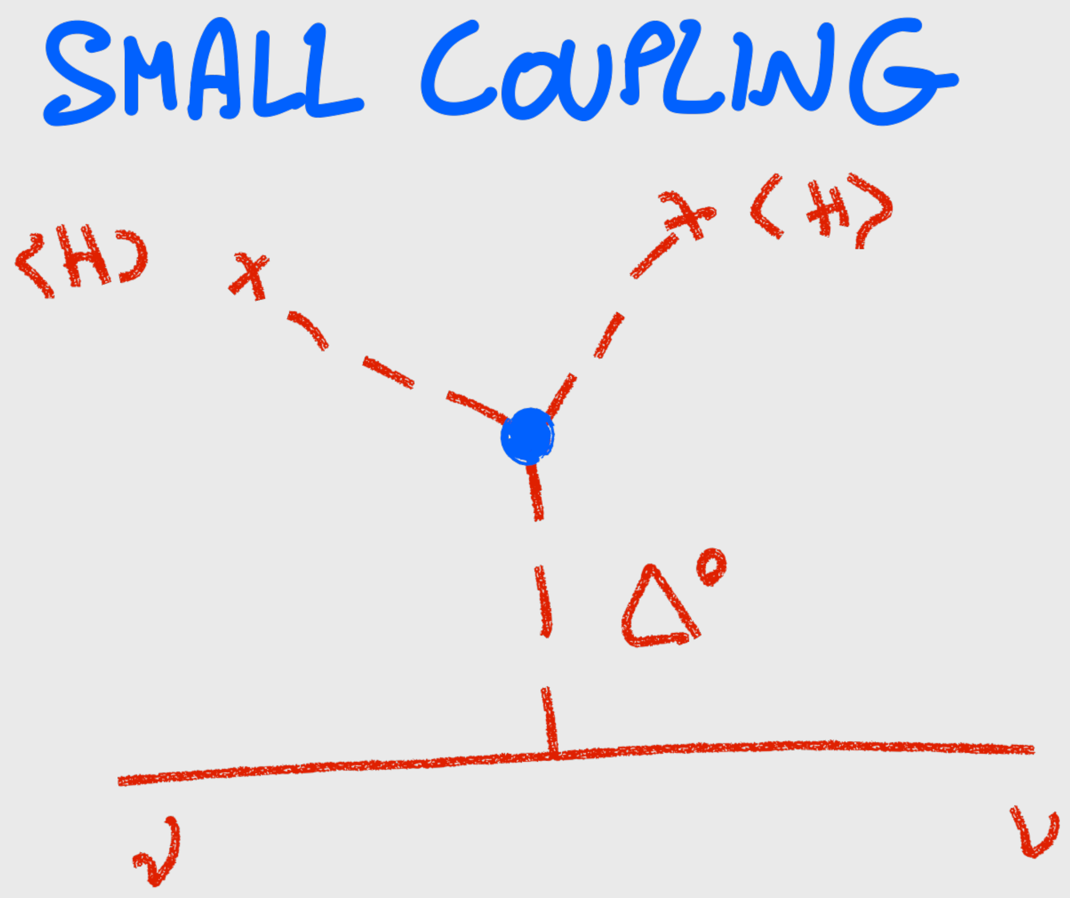

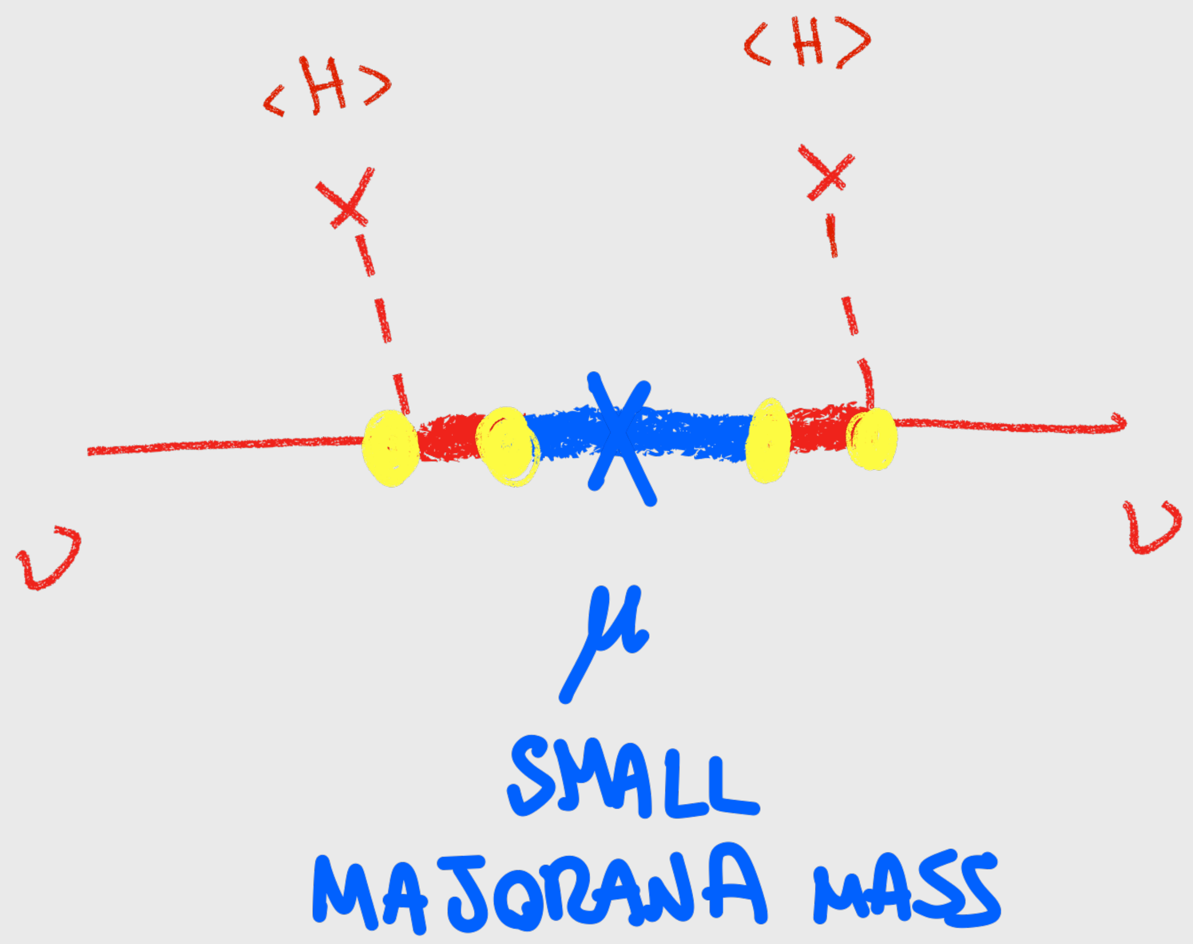

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Neutrino mas chanisms

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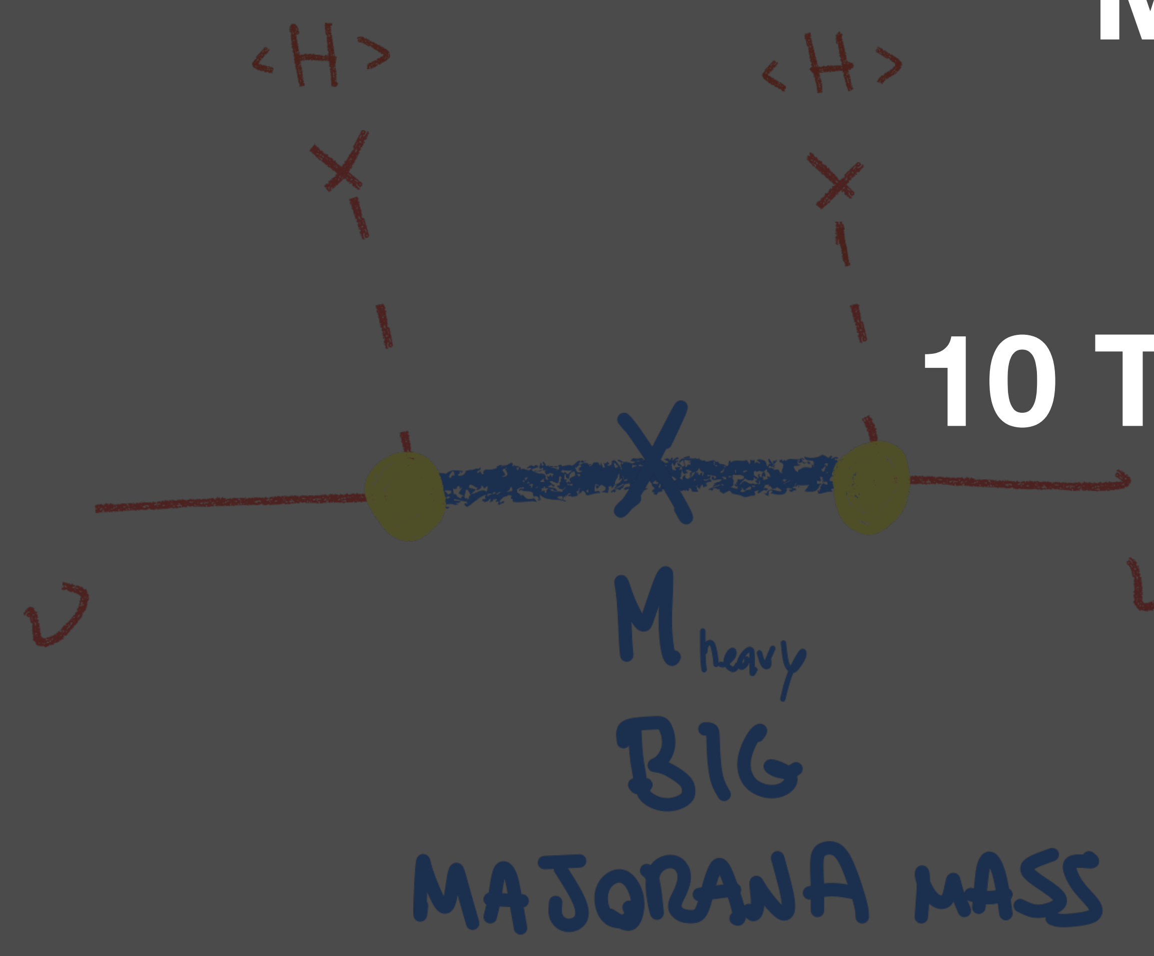

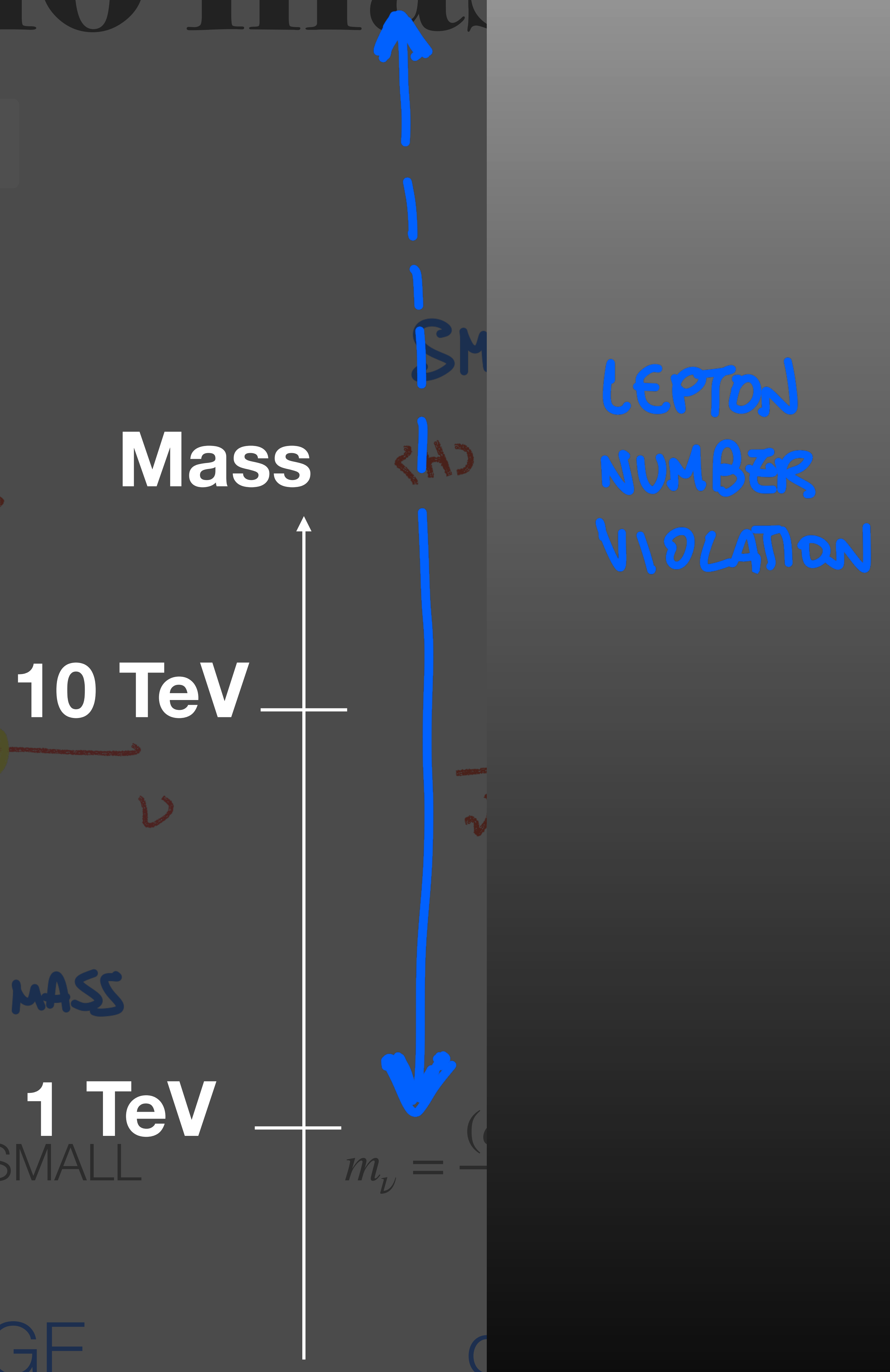

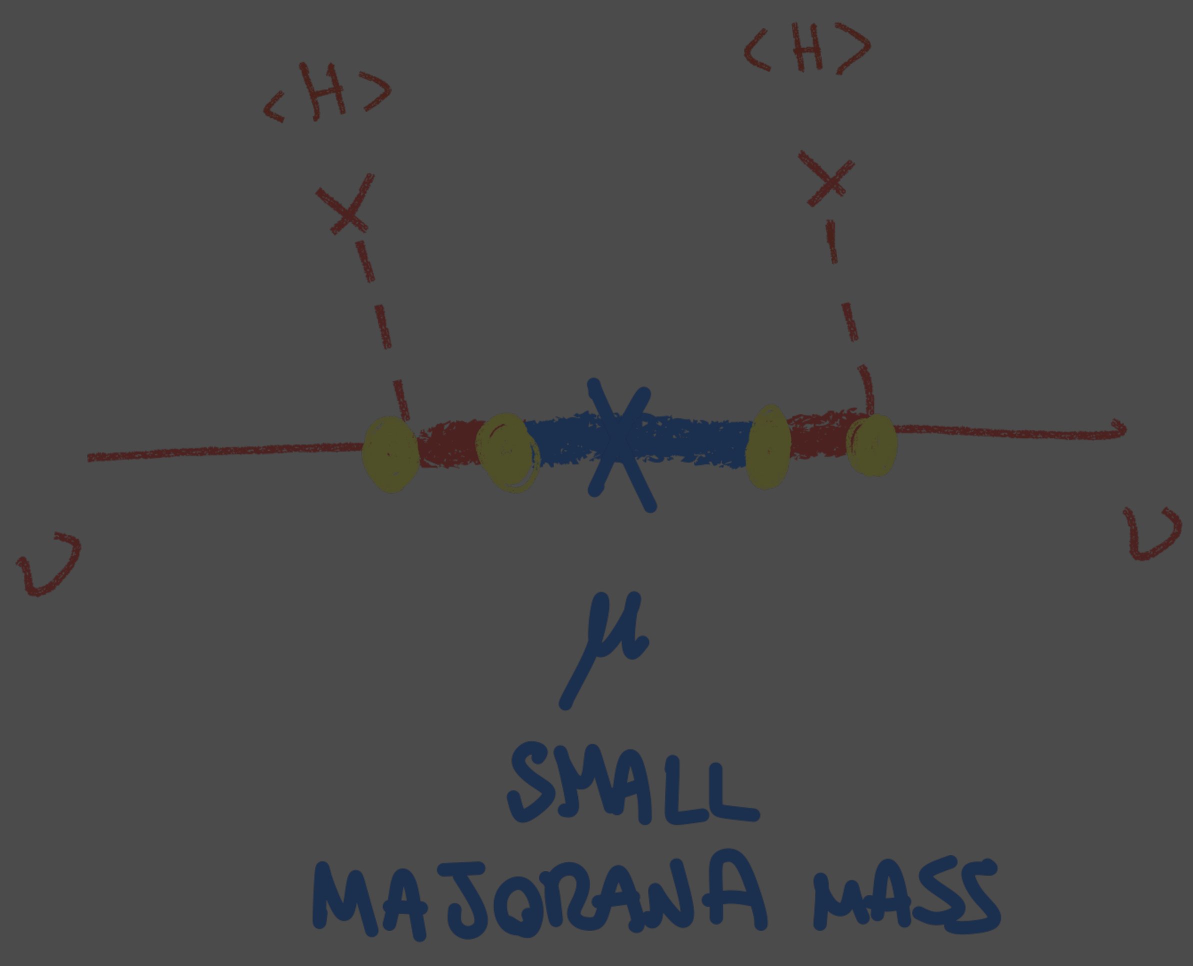

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$M_{heavy} \to$ LARGE

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ALL

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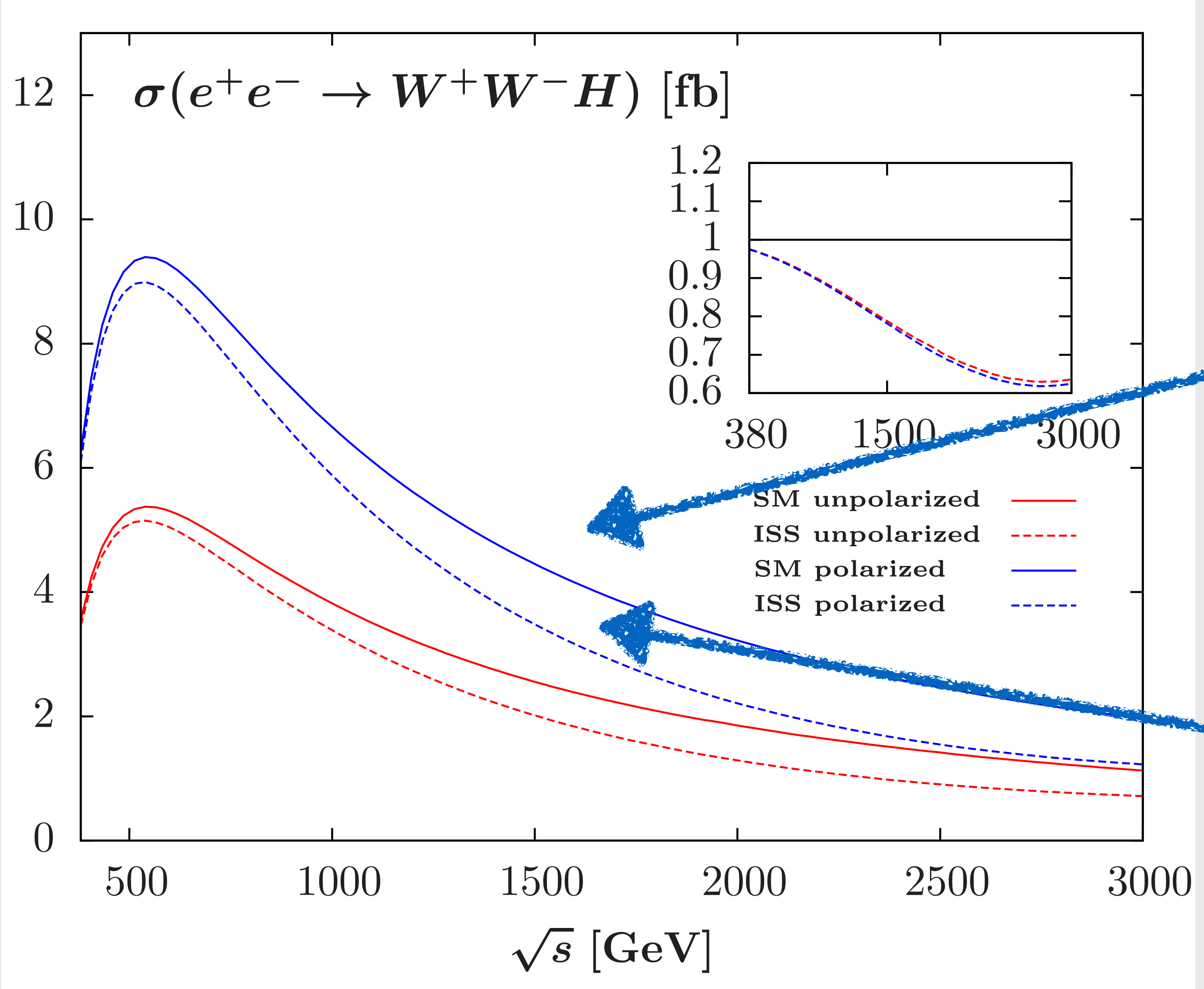
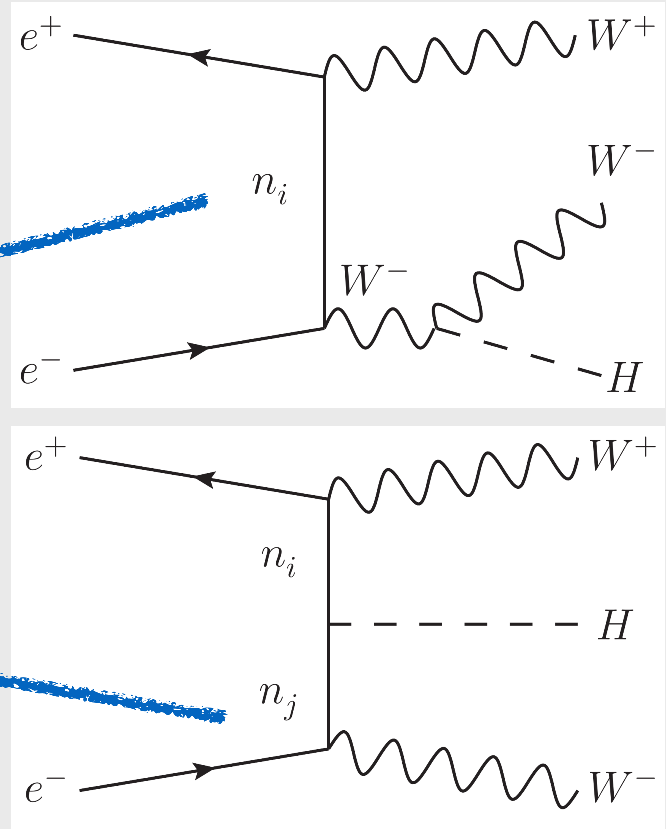
flashing concrete results for

The origin of neutrino masses

Plenty of neutrino mass models in reach

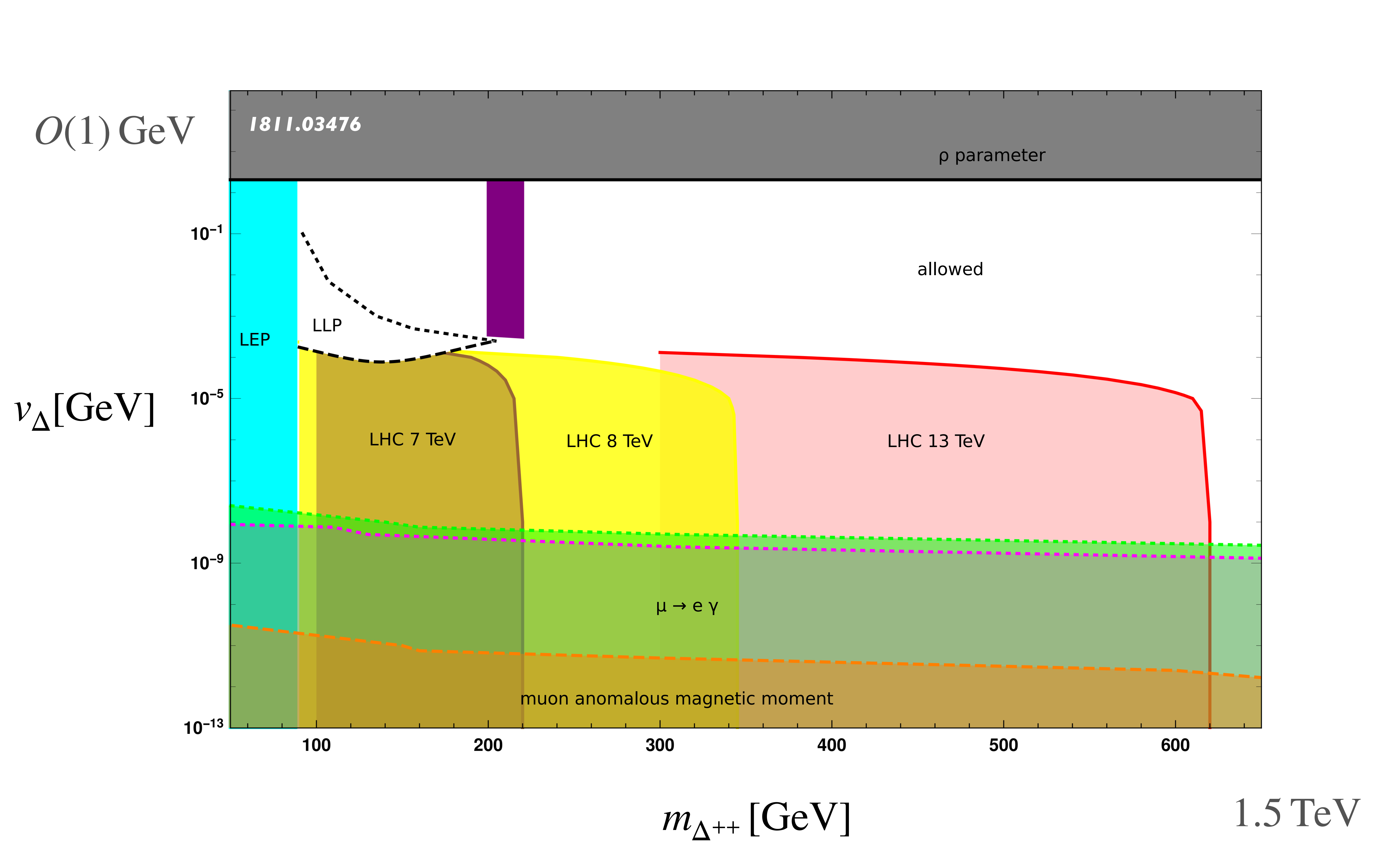
Inverse See-Saw **1712.07621 - Baglio, Pascoli, Weiland**



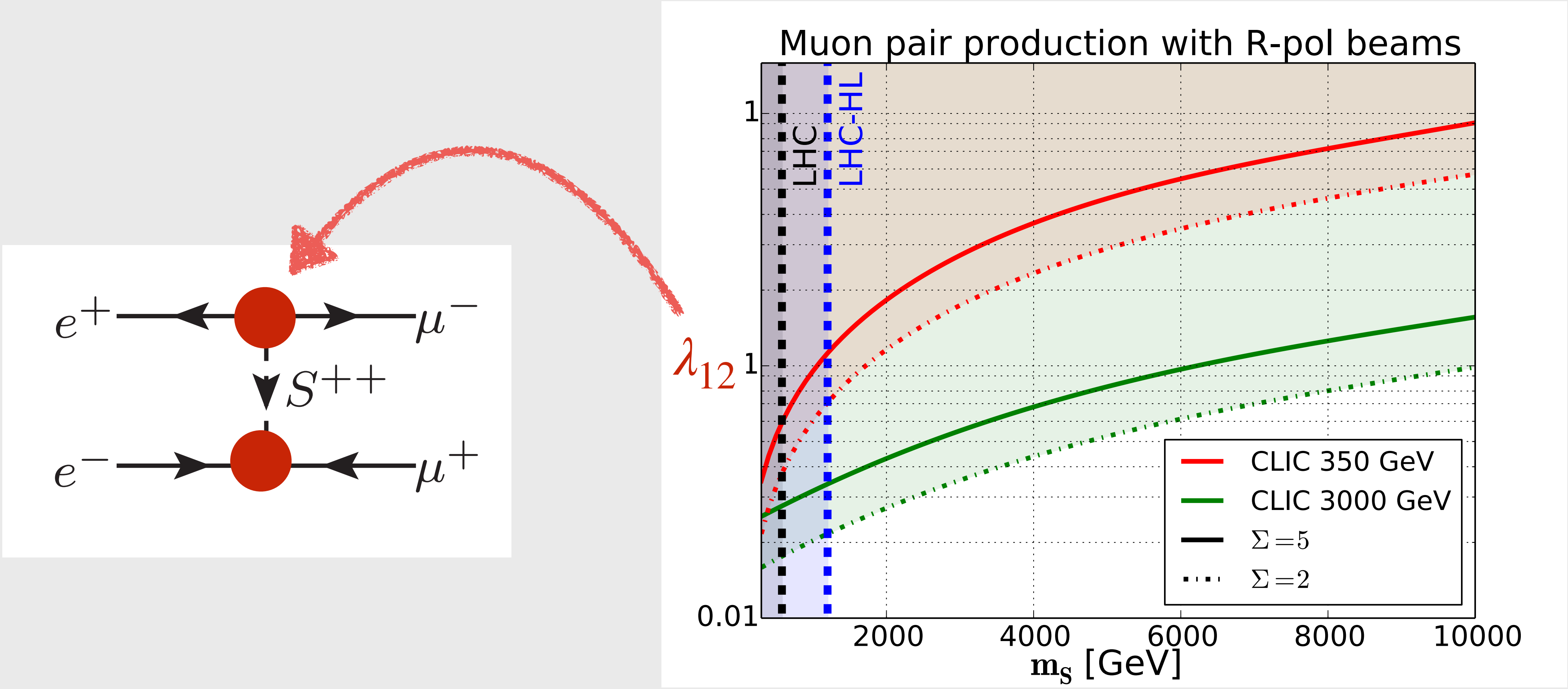


Exclude ISS RH Neutrino up to 10 TeV for Yukawa ~1

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



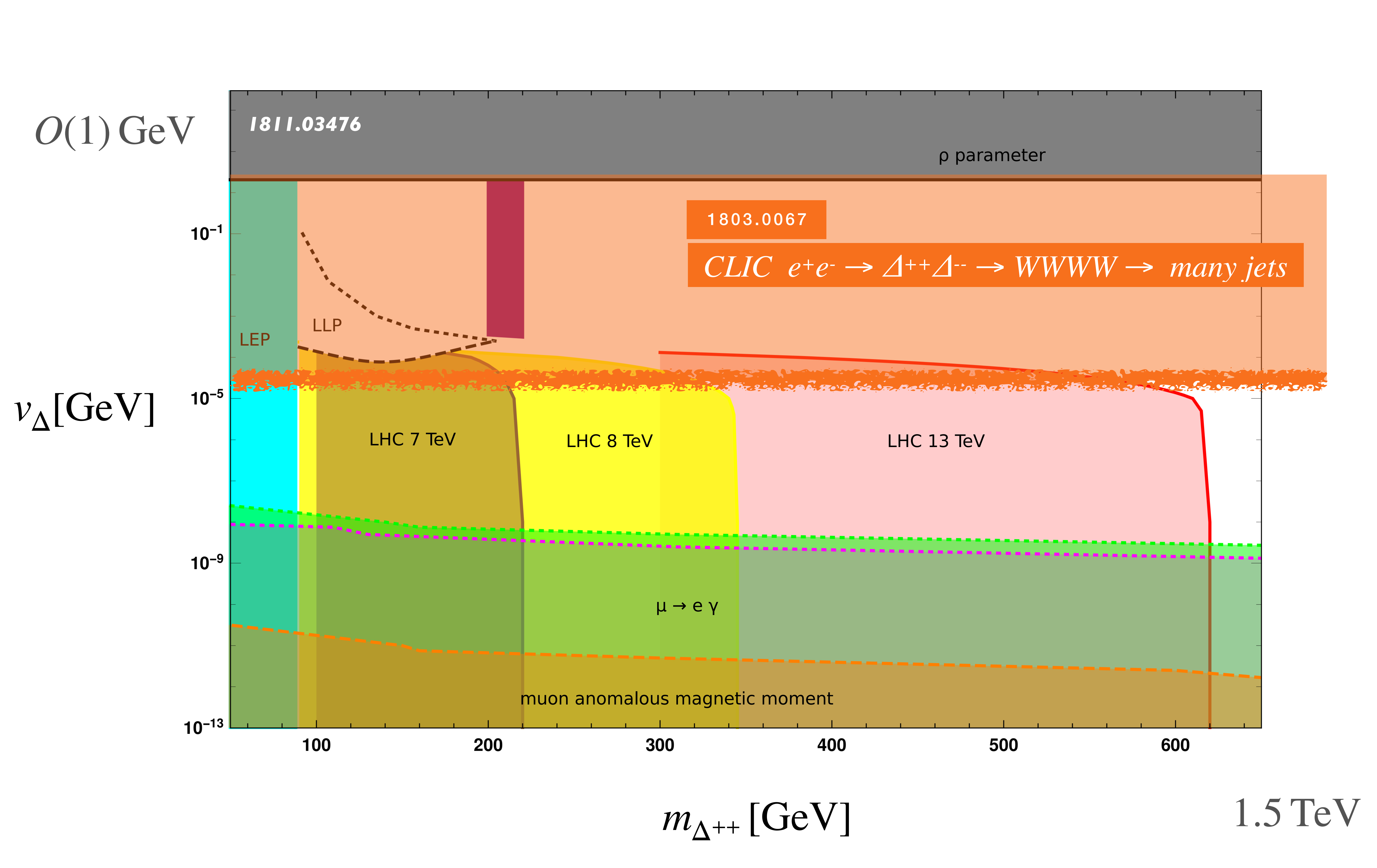
1807.10224 - Crivellin, Ghezzi, Panizzi, Pruna, Signer



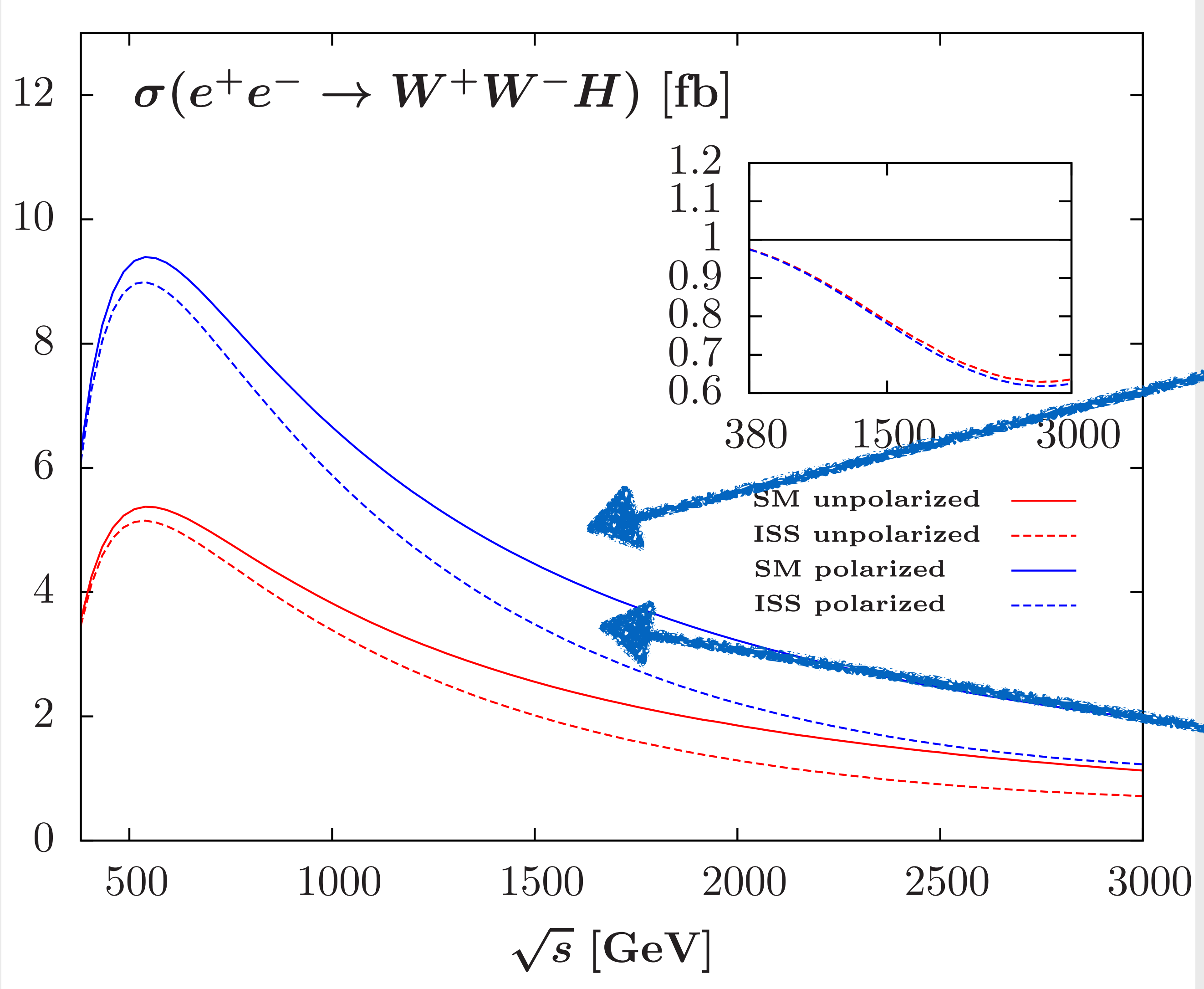
Exclude S++ up to 10 TeV for triplet Yukawa ~0.1

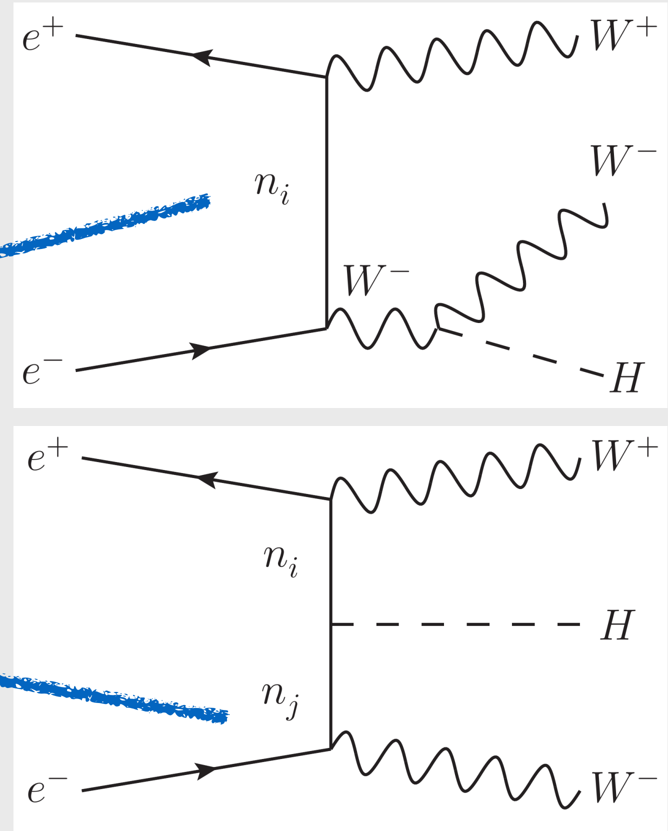
Plenty of neutrino mass models in reach

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



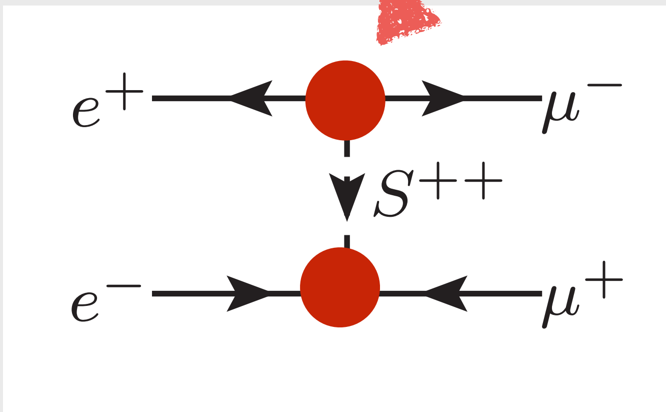
Inverse See-Saw **1712.07621 - Baglio, Pascoli, Weiland**

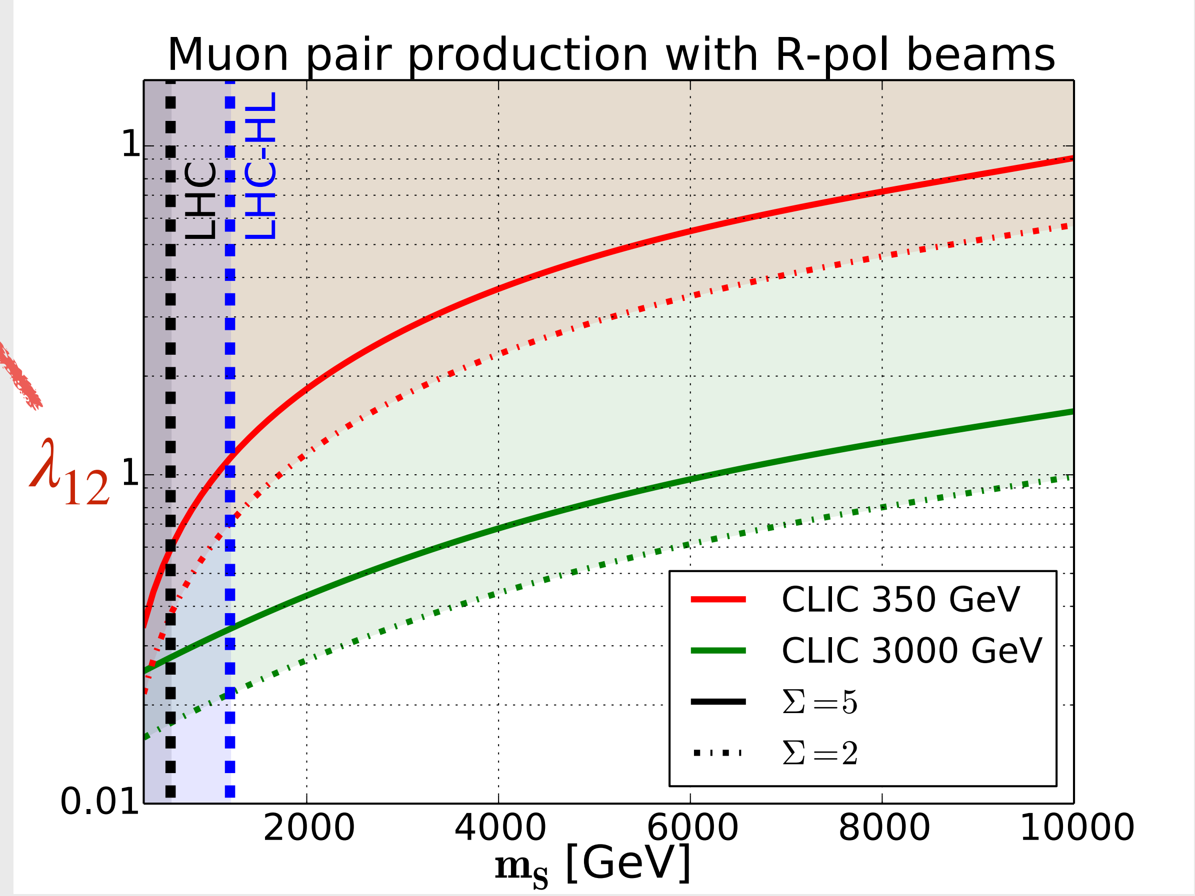




Exclude ISS RH Neutrino up to 10 TeV for Yukawa ~1

1807.10224 - Crivellin, Ghezzi, Panizzi, Pruna, Signer





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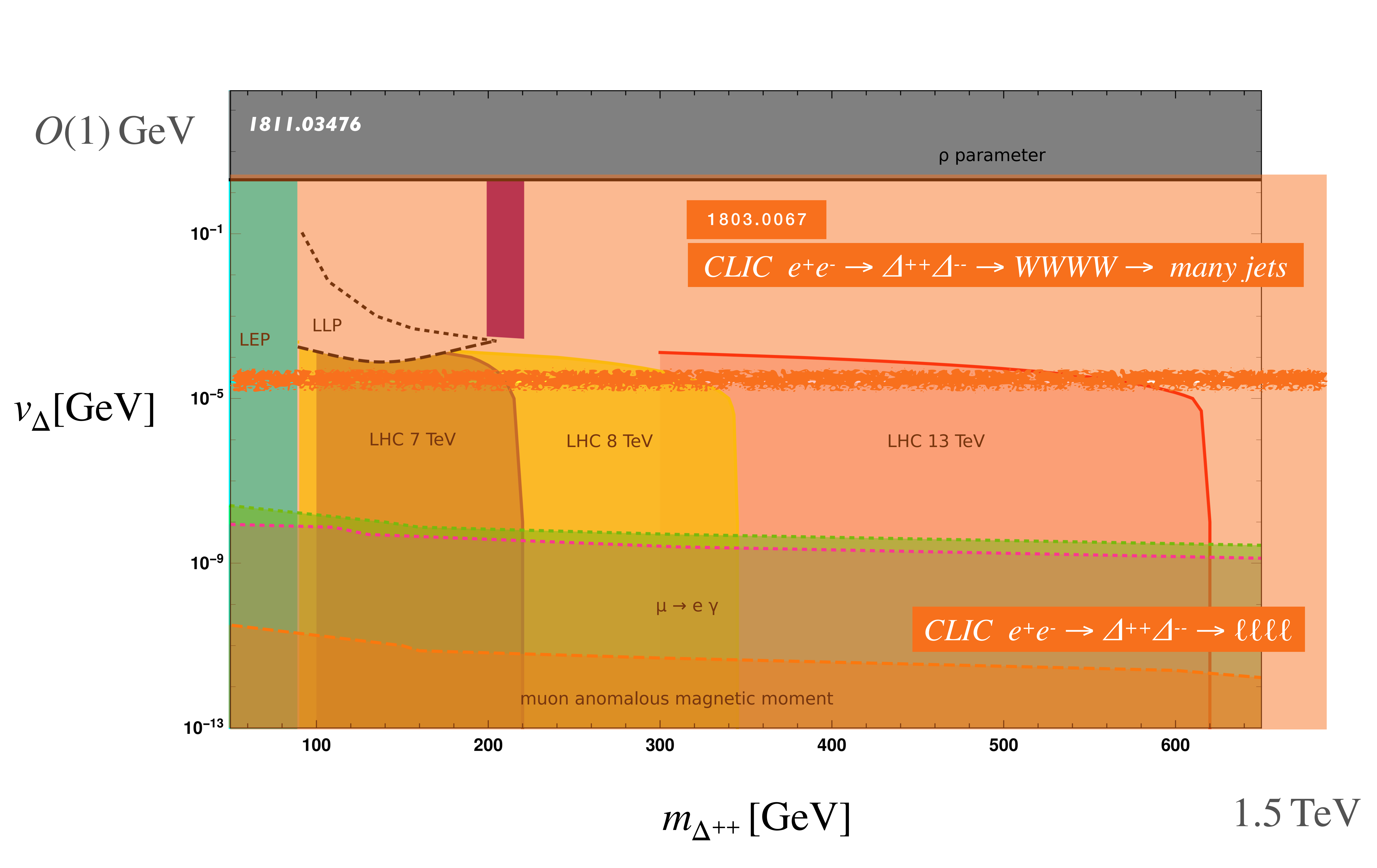

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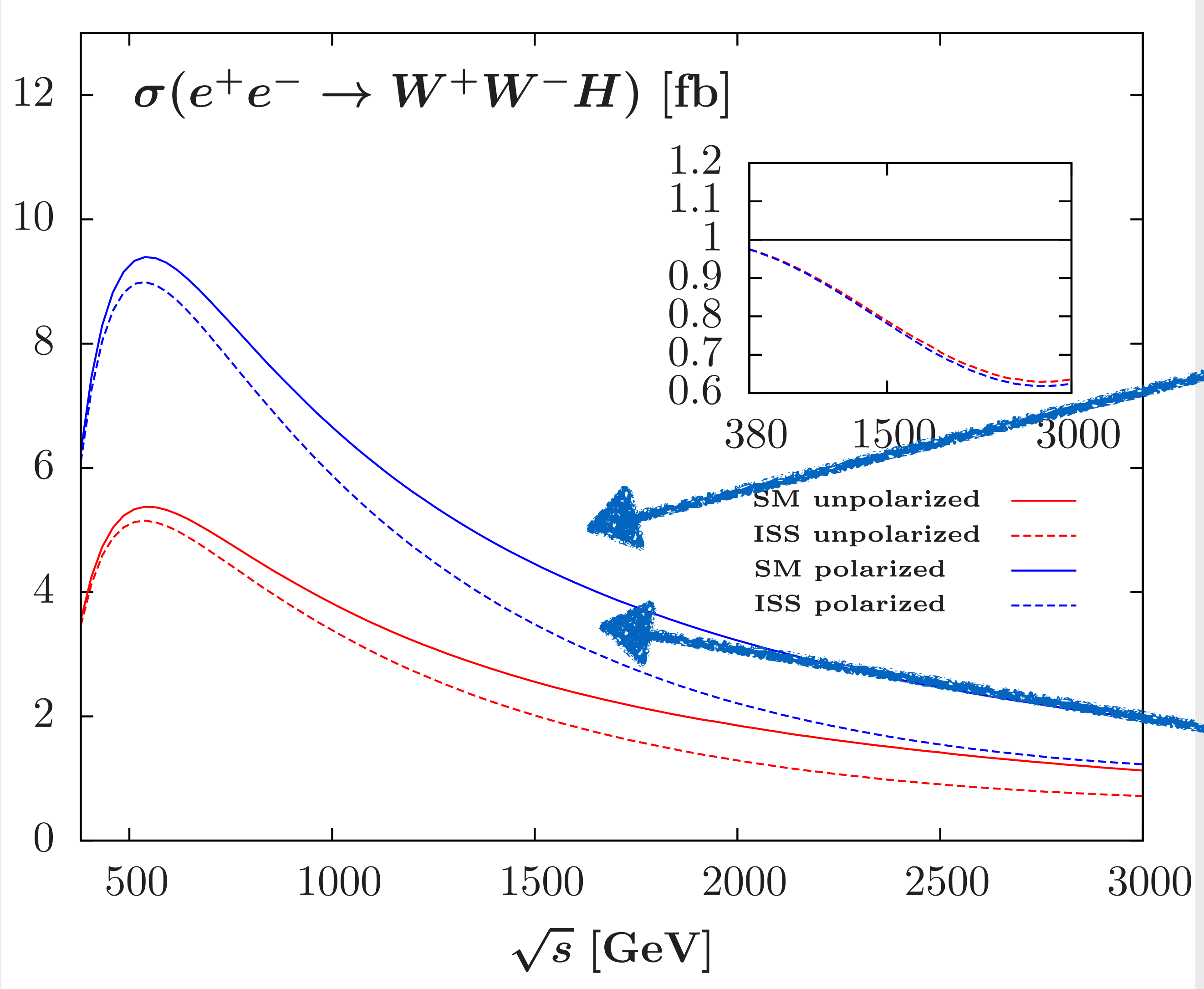

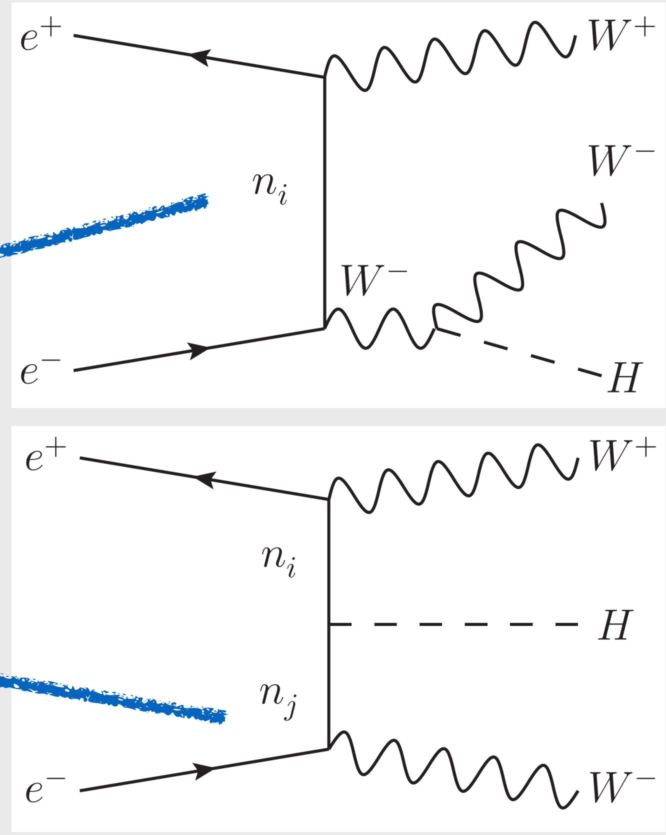

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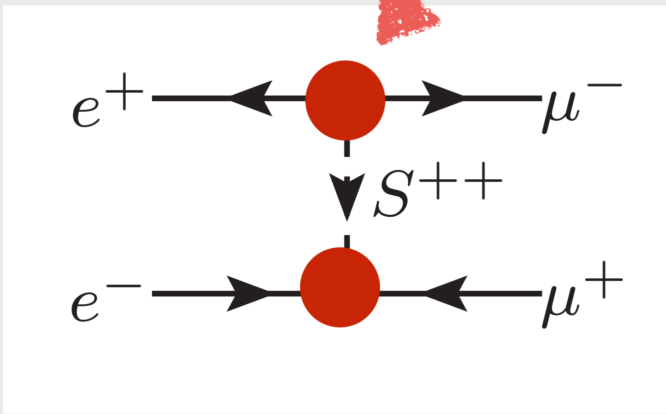

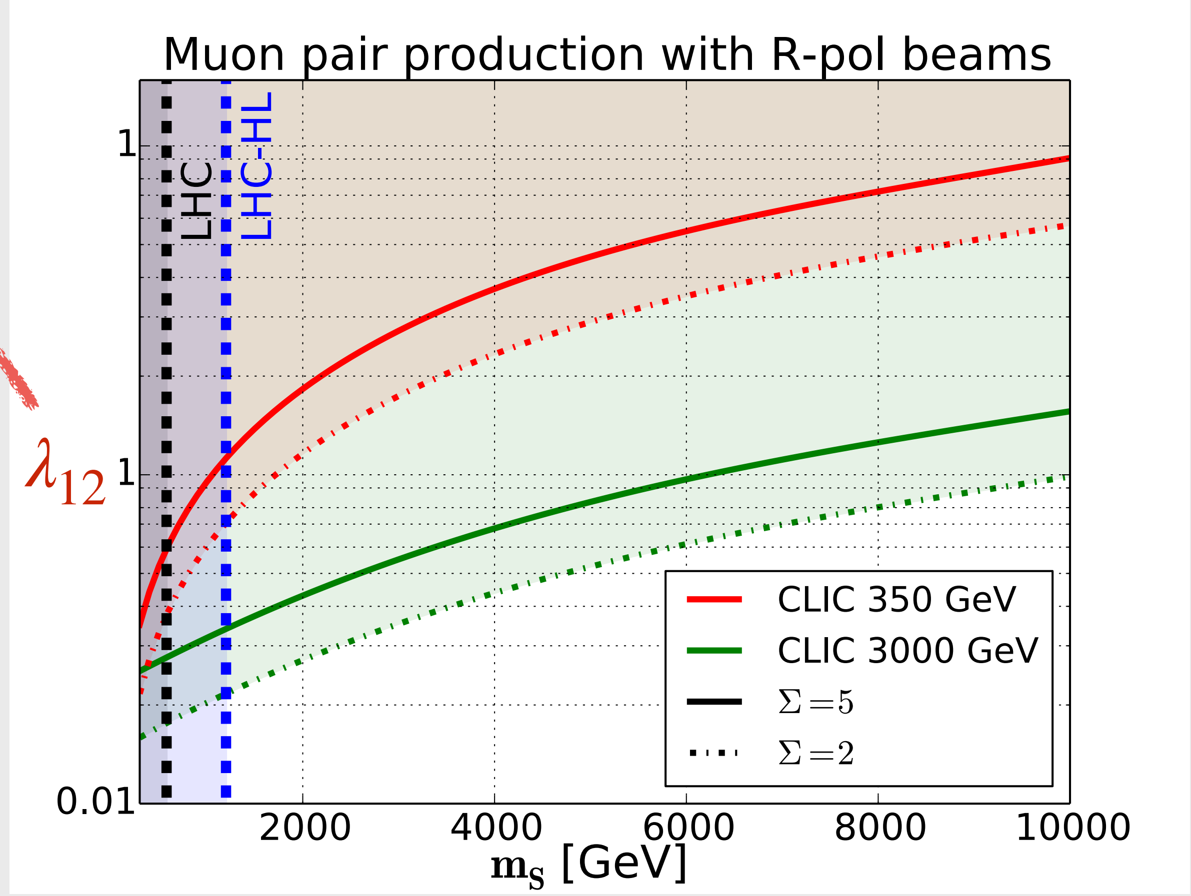

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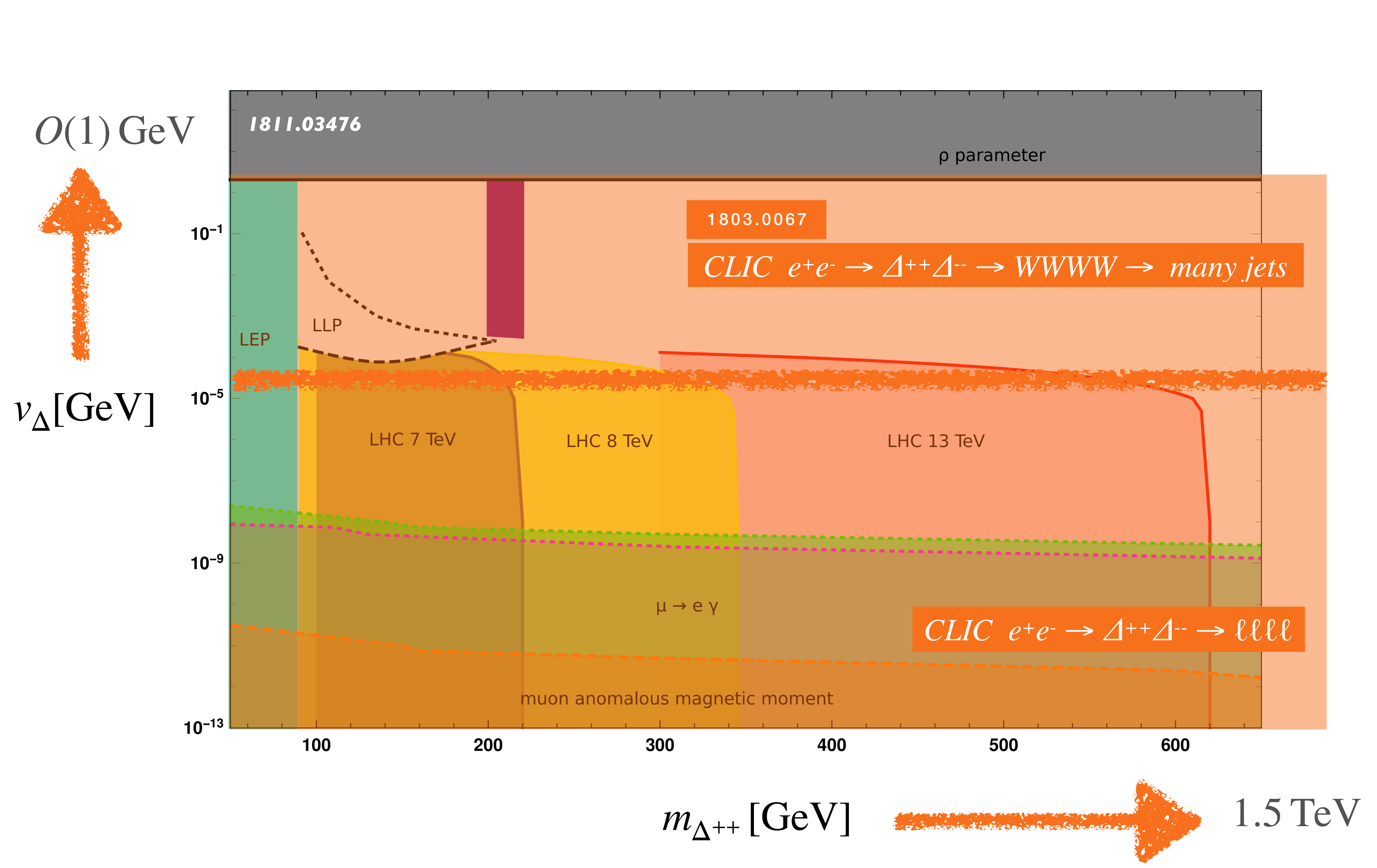

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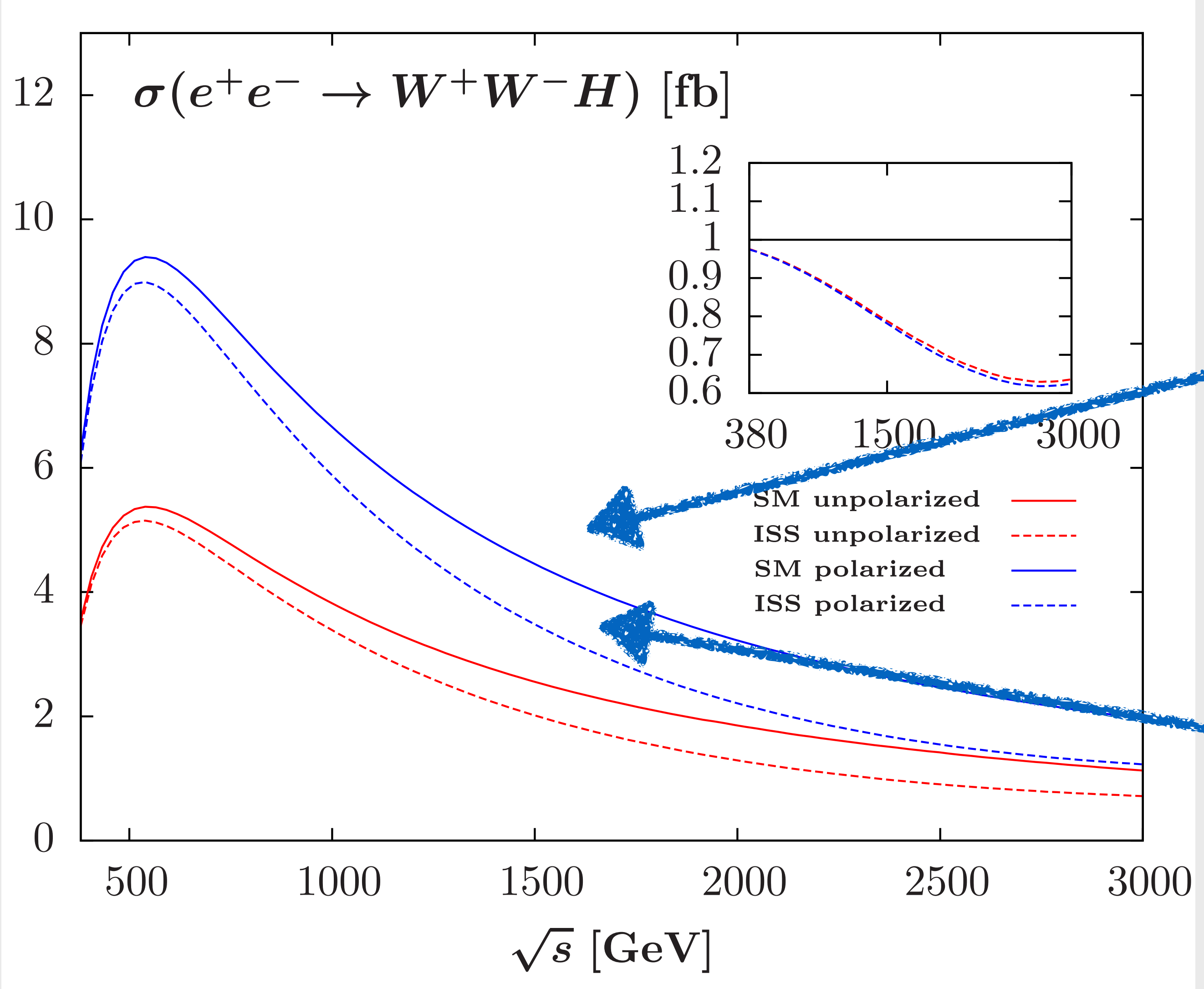

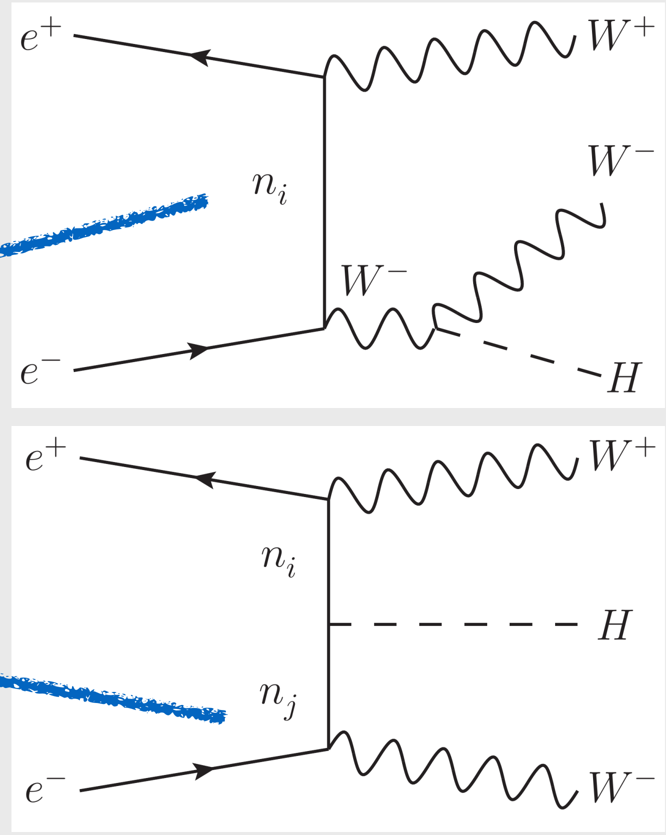

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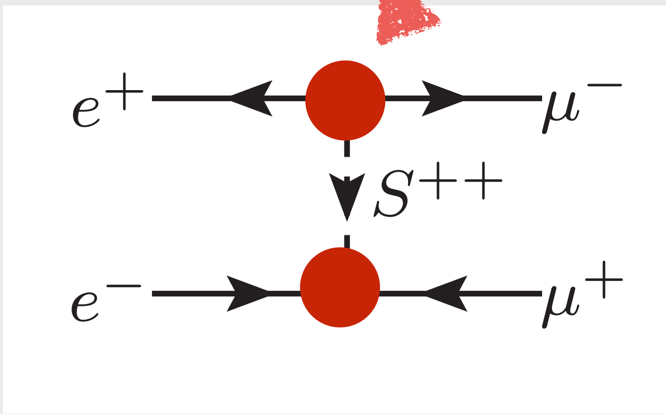
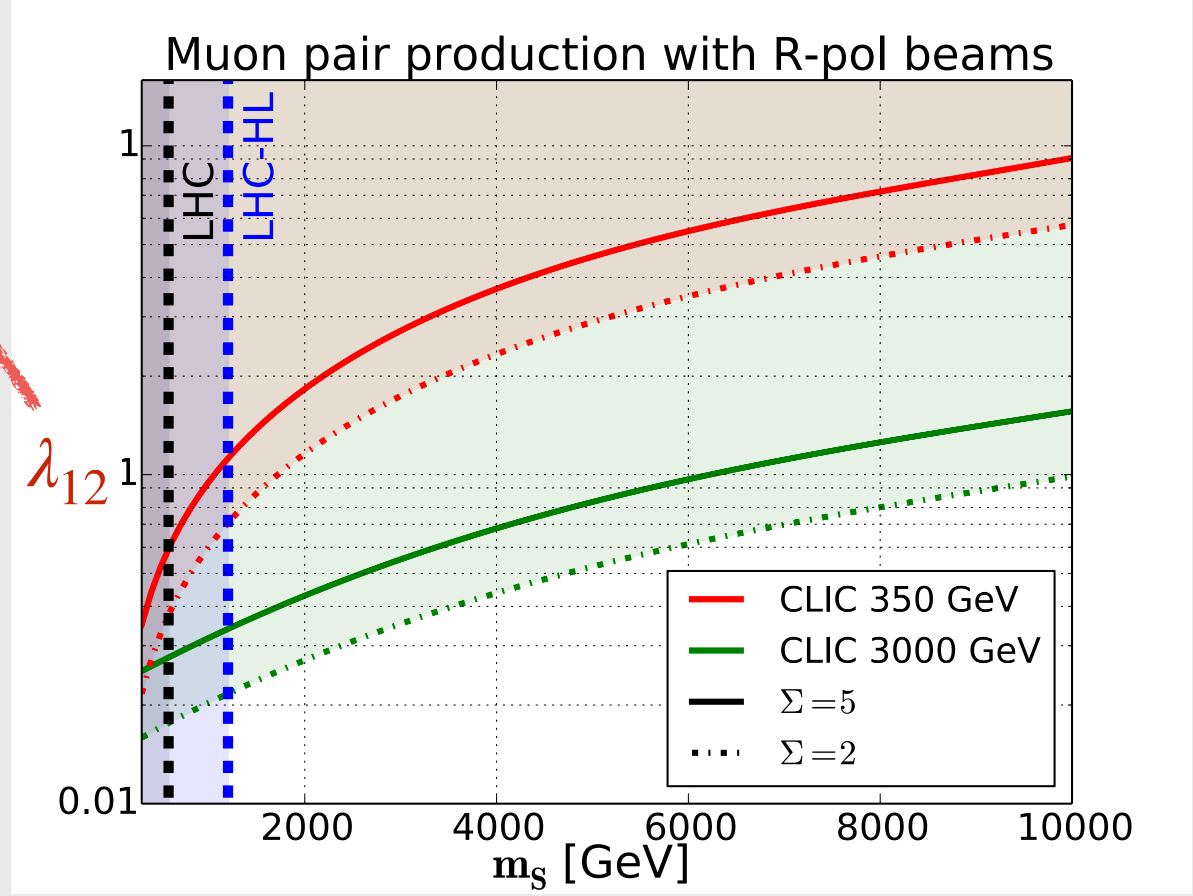




Exclude S++ up to 10 TeV for triplet Yukawa ~0.1

Relevant mass scales

100 TeV

10-30 TeV

PWFA

3 TeV

1 TeV

200-300 GeV

Relevant mass scales

EW symmetry breaking

100 TeV

10-30 TeV

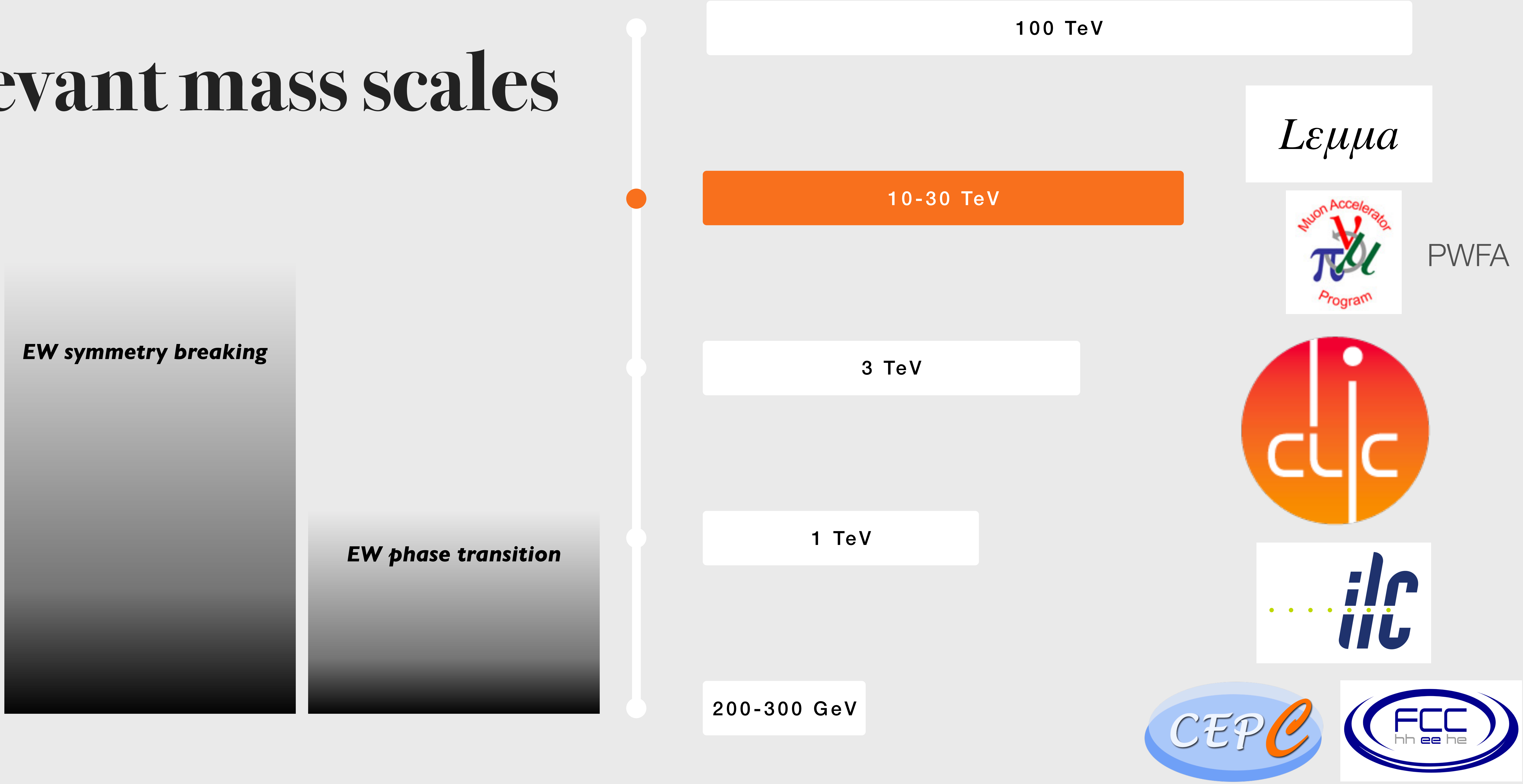
PWFA

3 TeV

1 TeV

200-300 GeV

Relevant mass scales



Relevant mass scales

WIMP Dark Matter

EW symmetry breaking

EW phase transition

100 TeV

Lεμμα

10-30 TeV

Muon Accelerator Program

PWFA

3 TeV

CLIC

1 TeV

ILC

200-300 GeV

CEPC

FCC hh ee he

Relevant mass scales

100 TeV

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200-300 GeV

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Relevant mass scales

Fermions masses and mixings

100 TeV

Lεμμα

10-30 TeV

PWFA

3 TeV

1 TeV

200-300 GeV

Relevant mass scales

Fermions masses and mixings

BSM source of CPV

100 TeV

Λεμμα

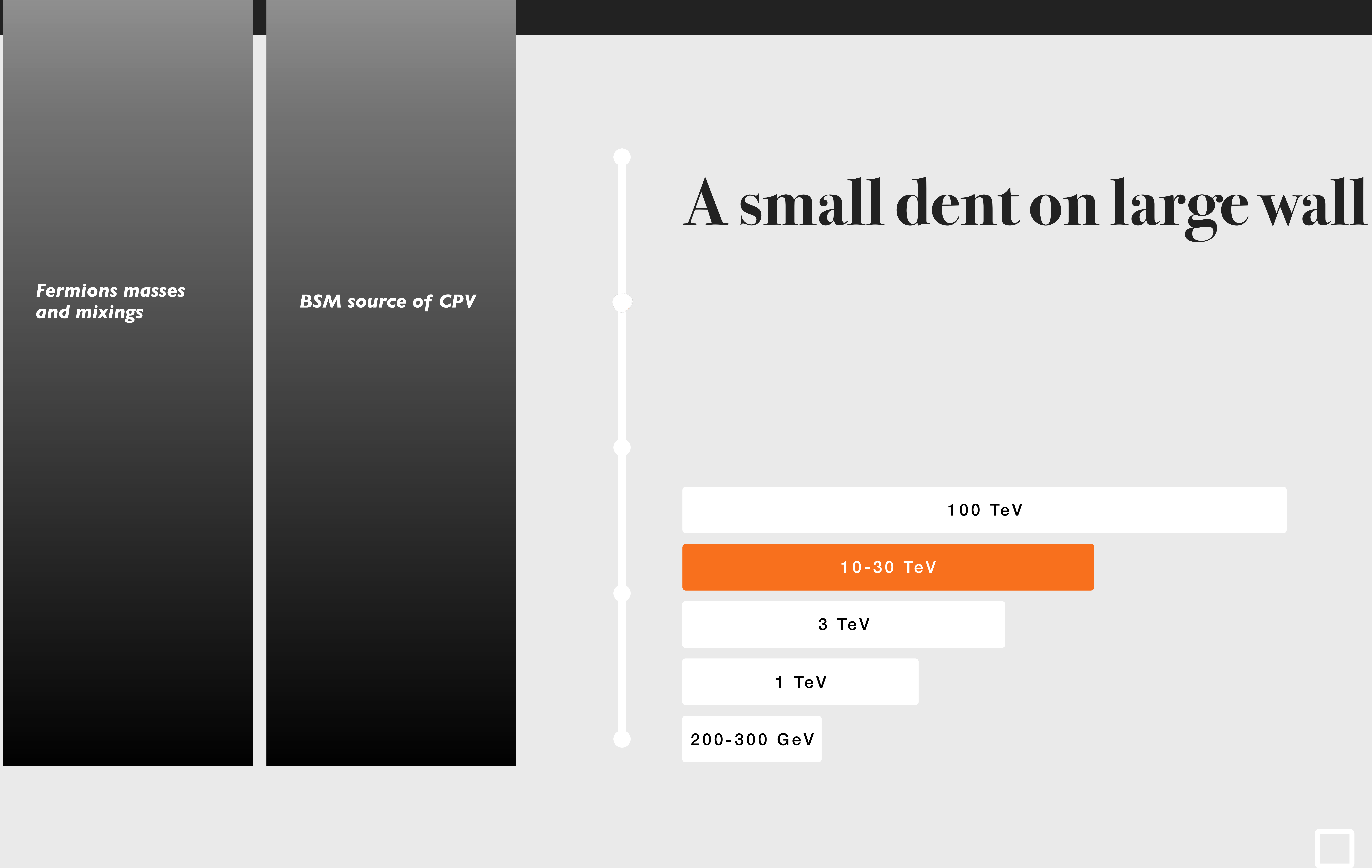
10-30 TeV

PWFA

3 TeV

1 TeV

200-300 GeV


A small dent on large wall
Fermions masses and mixings
BSM source of CPV
100 TeV
10-30 TeV
3 TeV
1 TeV
200-300 GeV

Open Questions on the “big picture” on fundamental physics circa 2020

	?	• 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

We need to explore weak interactions

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

		Question	Weak interactions	Strong interactions	Accelerators
	?	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

We need to explore weak interactions

Motivations?

Future Lepton Colliders can deliver if they have
mass reach
far enough to see states beyond the LHC exclusions
(unless LHC leaves “light blindspots” as a legacy)**,**
AND have convincing indirect sensitivity to NP through
precision

$(\mathbf{7},\epsilon)_{Dirac}$ $(\mathbf{7},0)_{C.\,Scalar}$

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

$(\mathbf{5},\epsilon)_{Dirac}$ $(\mathbf{5},\epsilon)_{C.\,Scalar}$

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

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

$(\mathbf{3},\epsilon)_{C.\,Scalar}$

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

"WIMP" Dark Matter

100 TeV

10-30 TEV

3 TEV

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

1 TeV

200-300 GeV

$(\mathbf{7}, \epsilon)_{Dirac}$ $(\mathbf{7}, 0)_{C.Scalar}$

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

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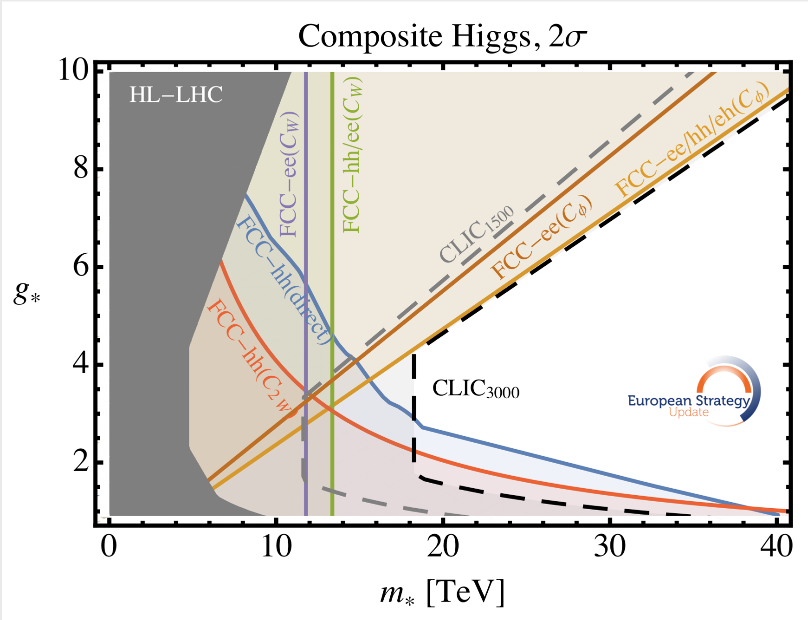

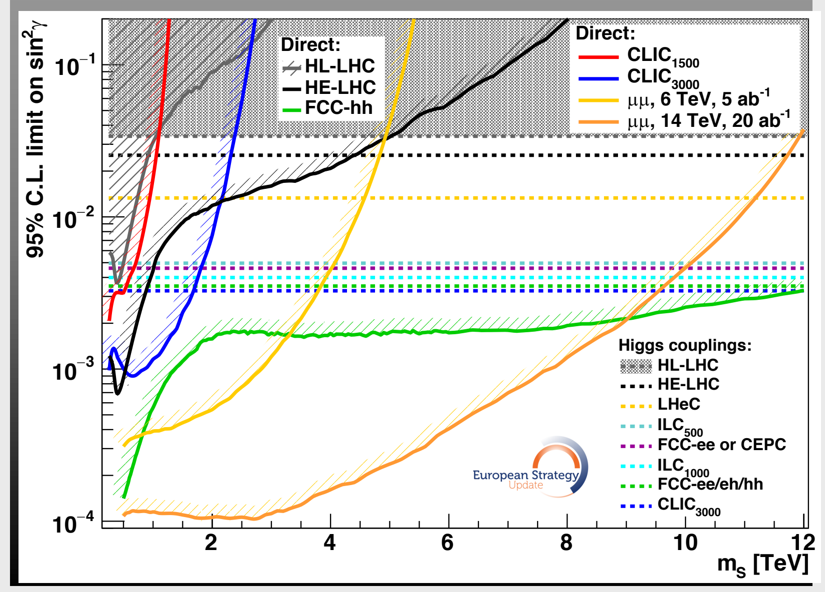

"WIMP" Dark Matter

EW symmetry breaking

100 TeV

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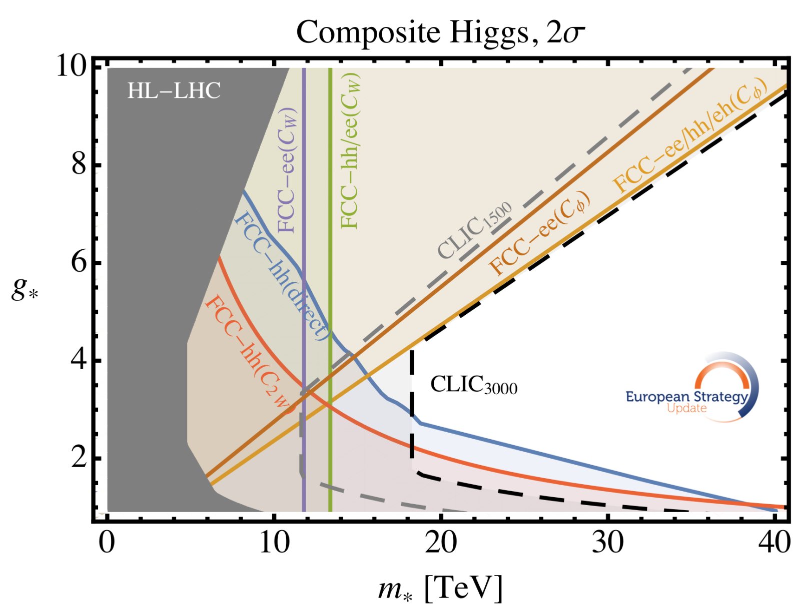
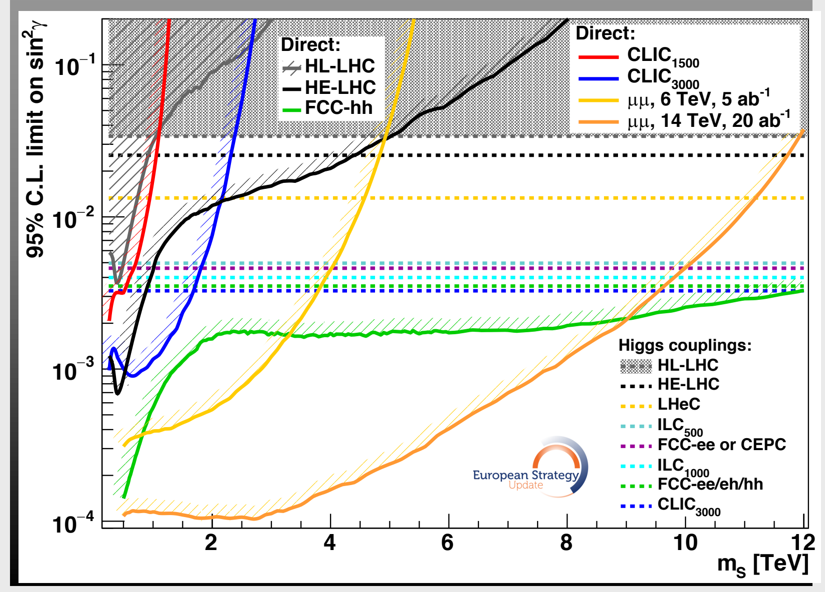
"WIMP" Dark Matter





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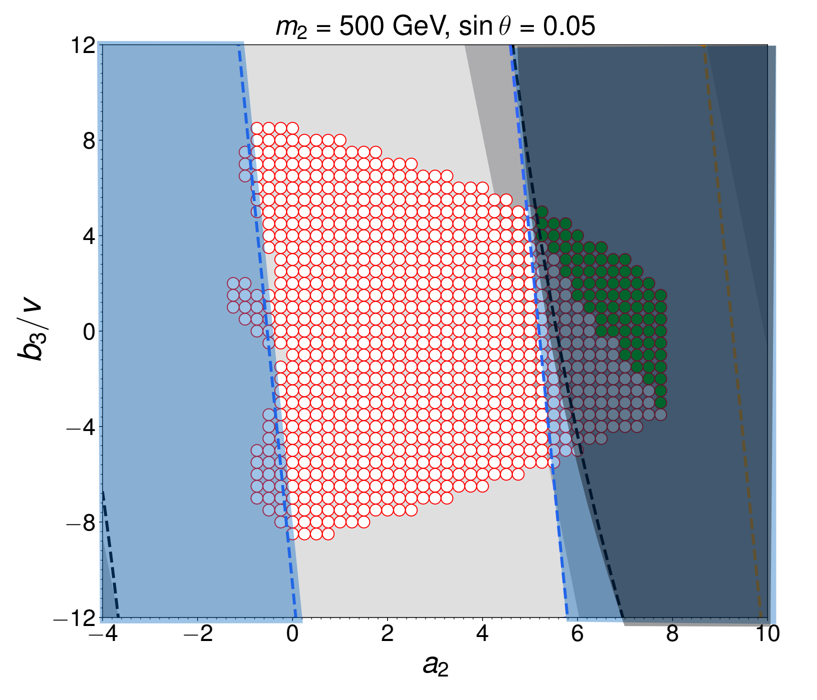

EW phase transition

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10-30 TEV

3 TEV

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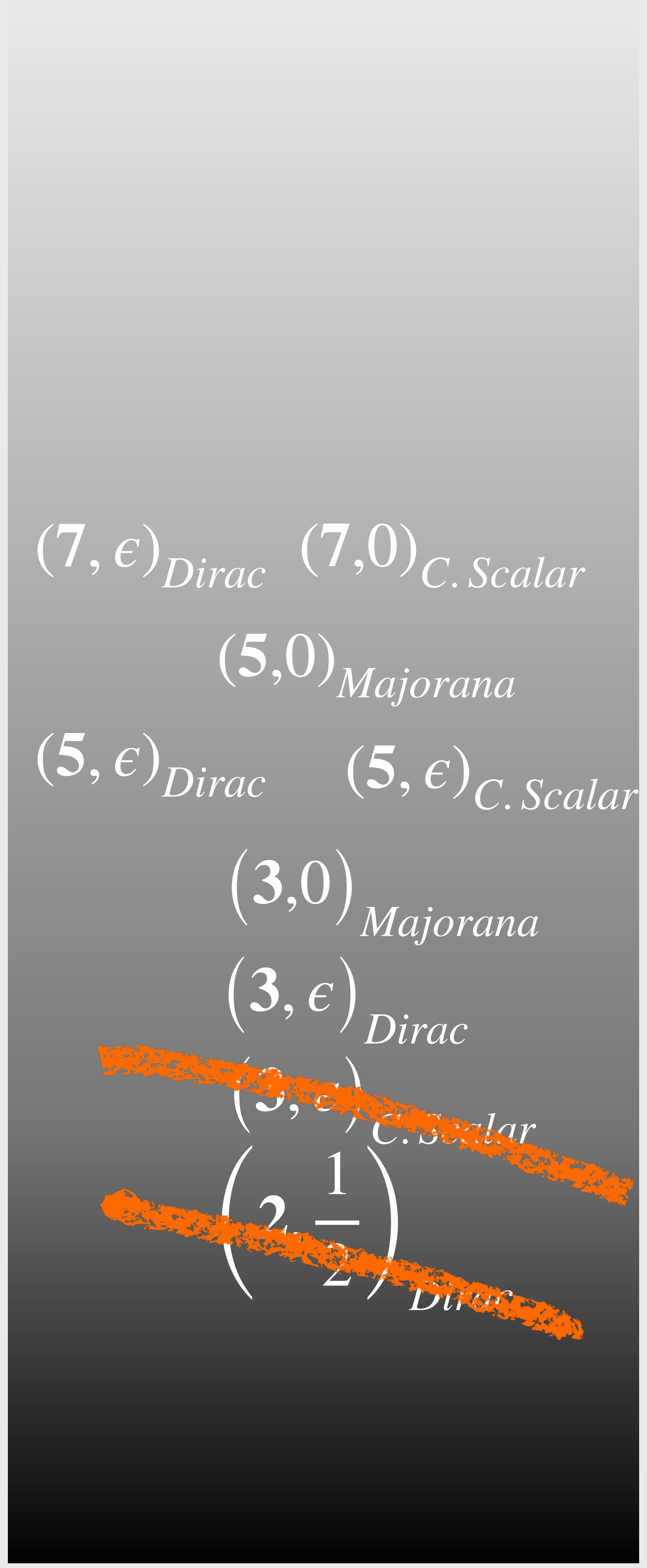

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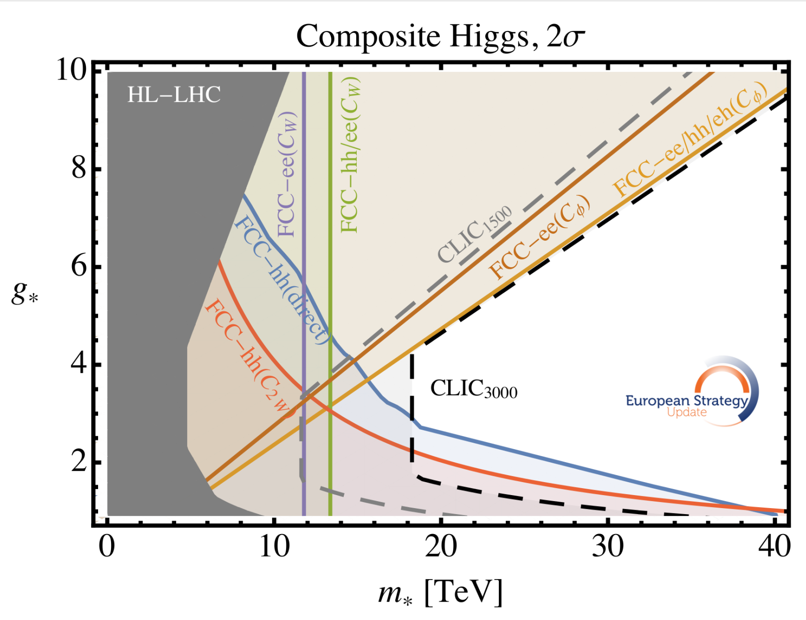

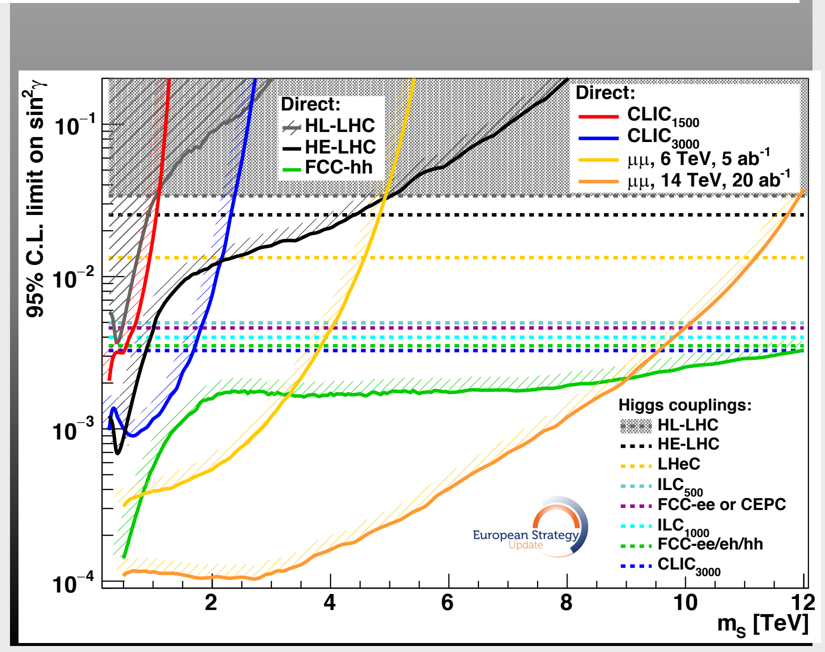

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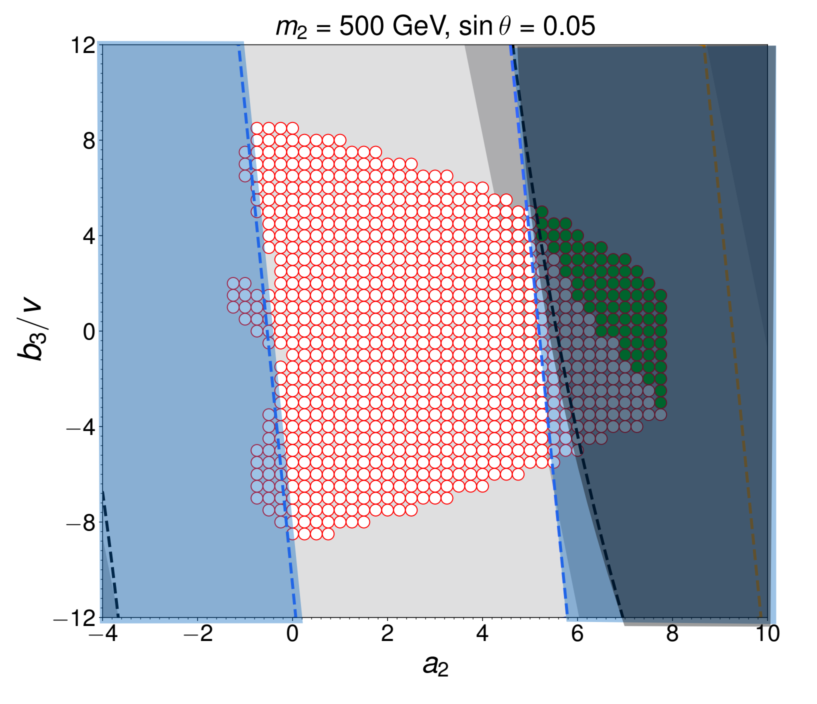

EW phase transition

100 TeV

$L\epsilon\mu\mu a$

10-30 TEV

30ish TeV probes fully the set of WIMPs stabilized by SM selection rules

PWFA

3 TEV

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1 TeV

200-300 GeV

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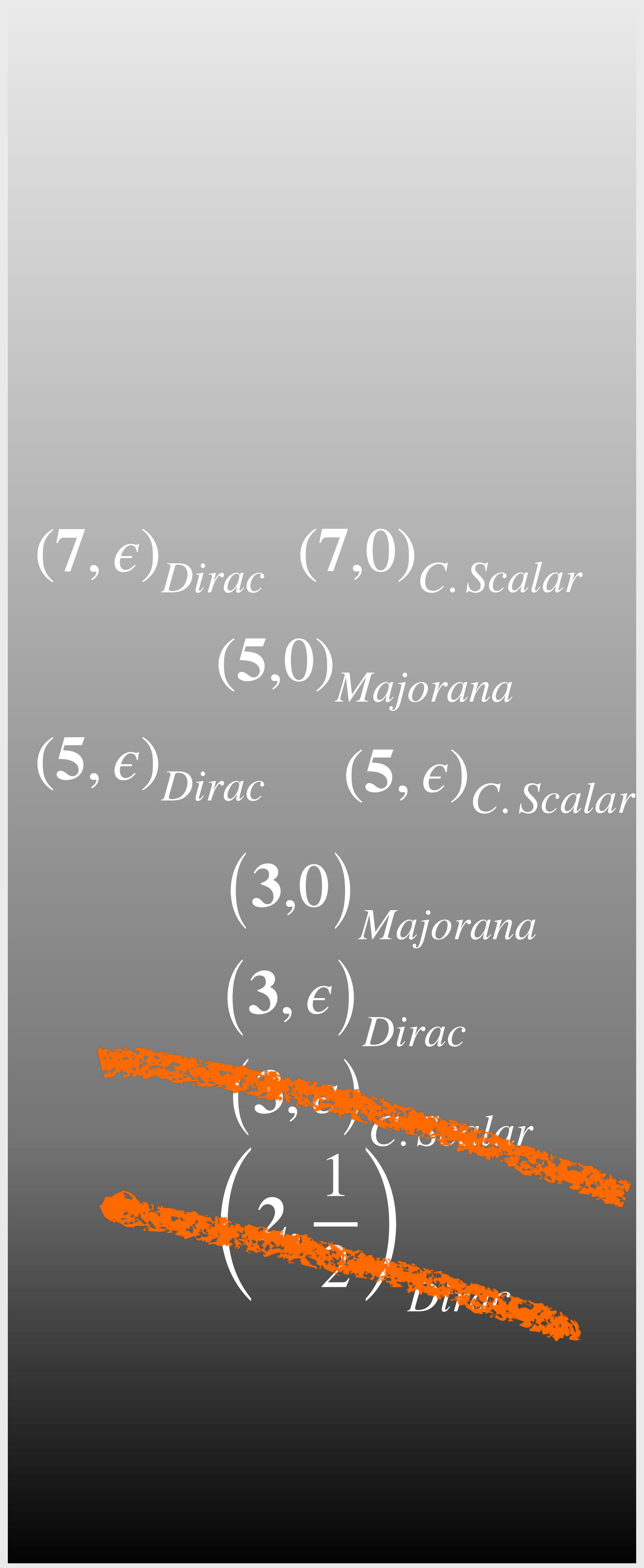

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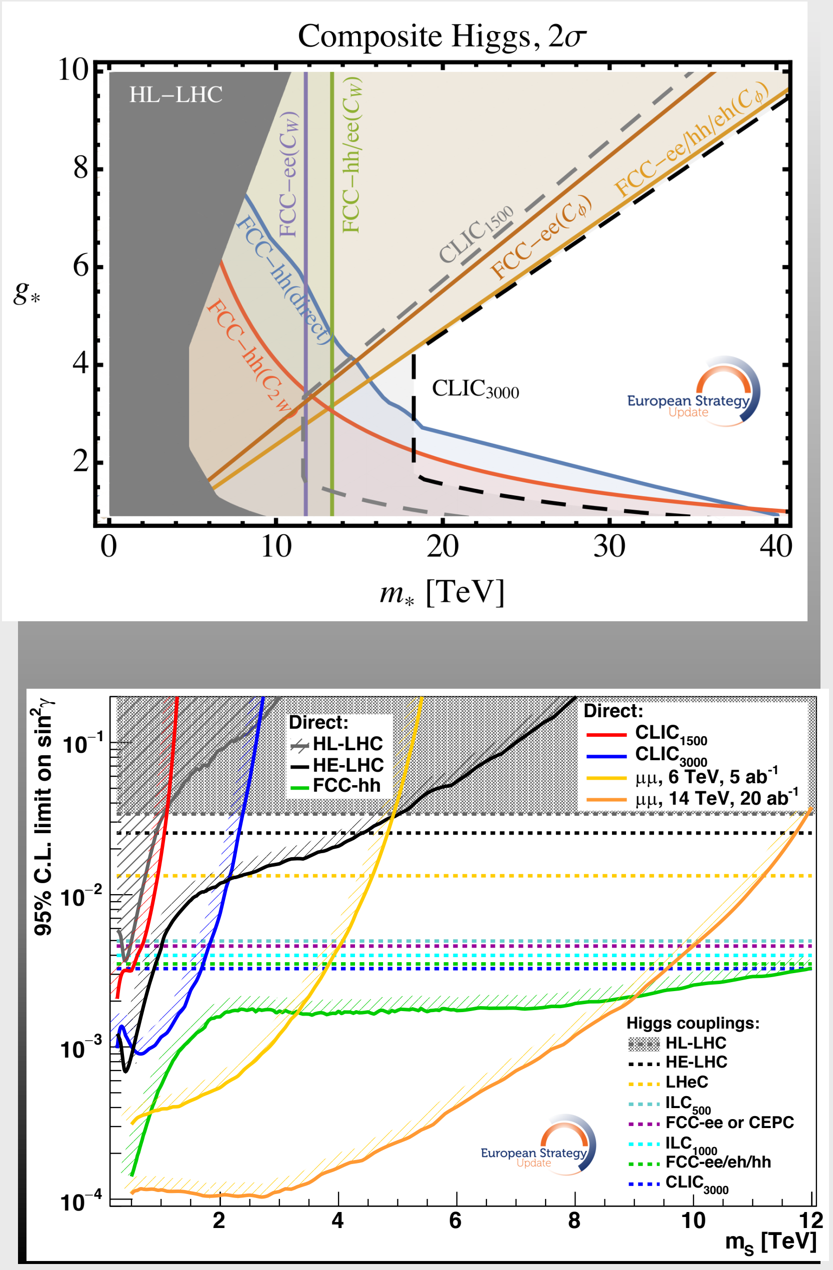

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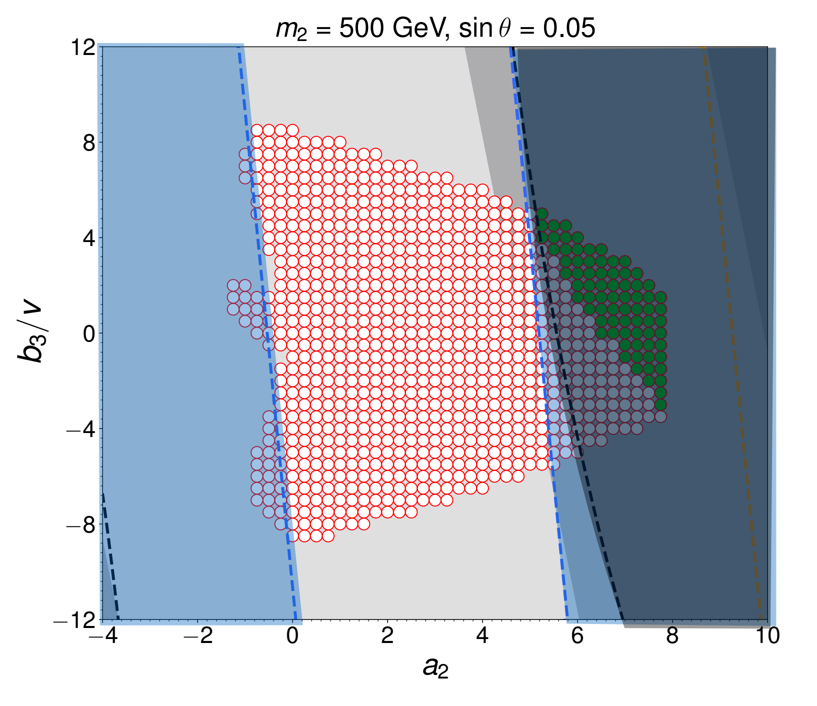

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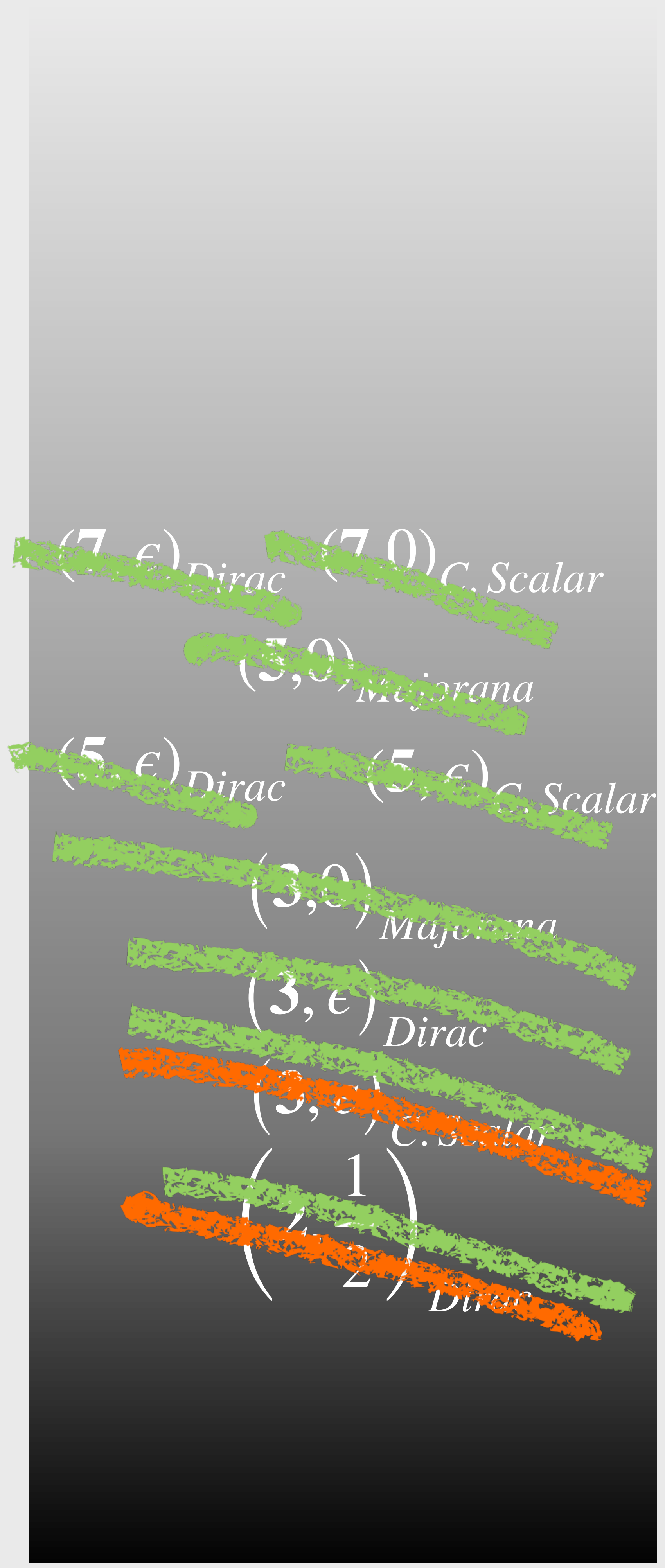

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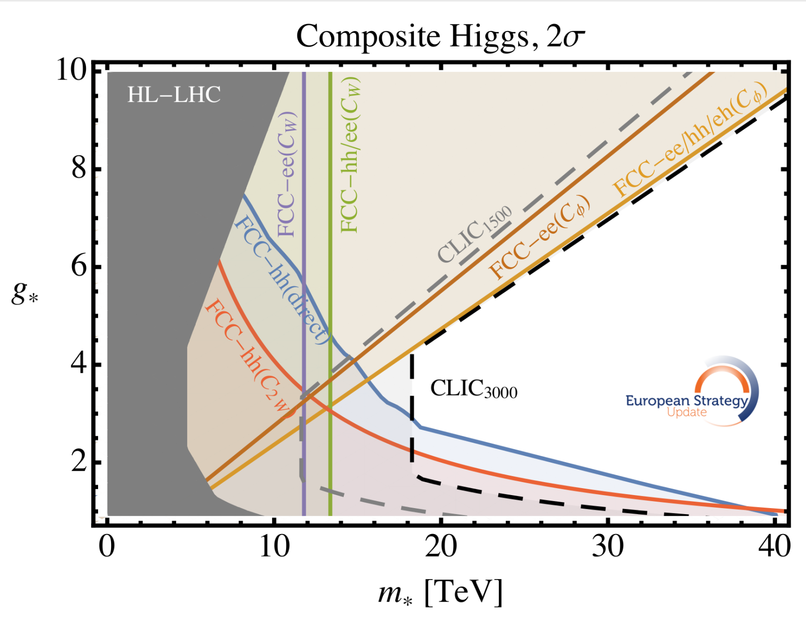

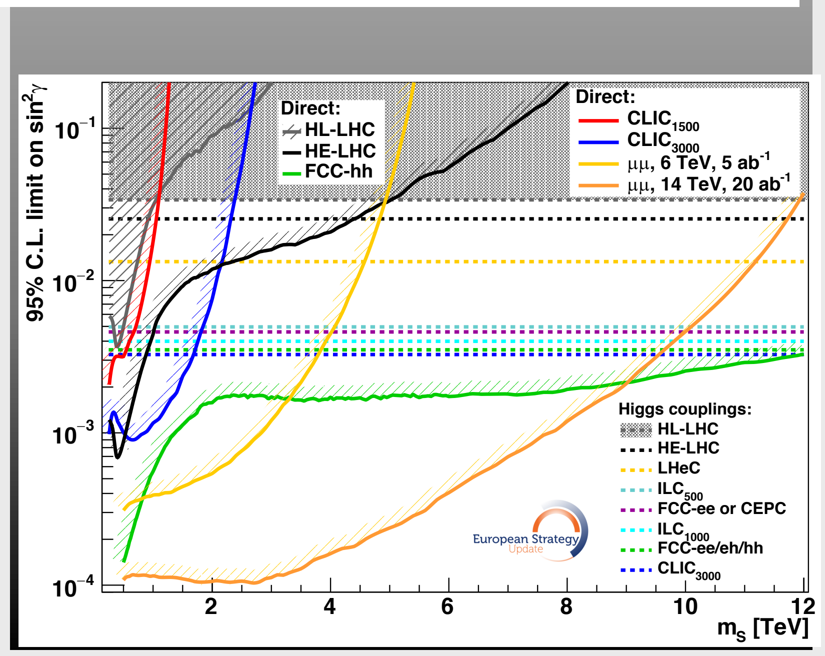

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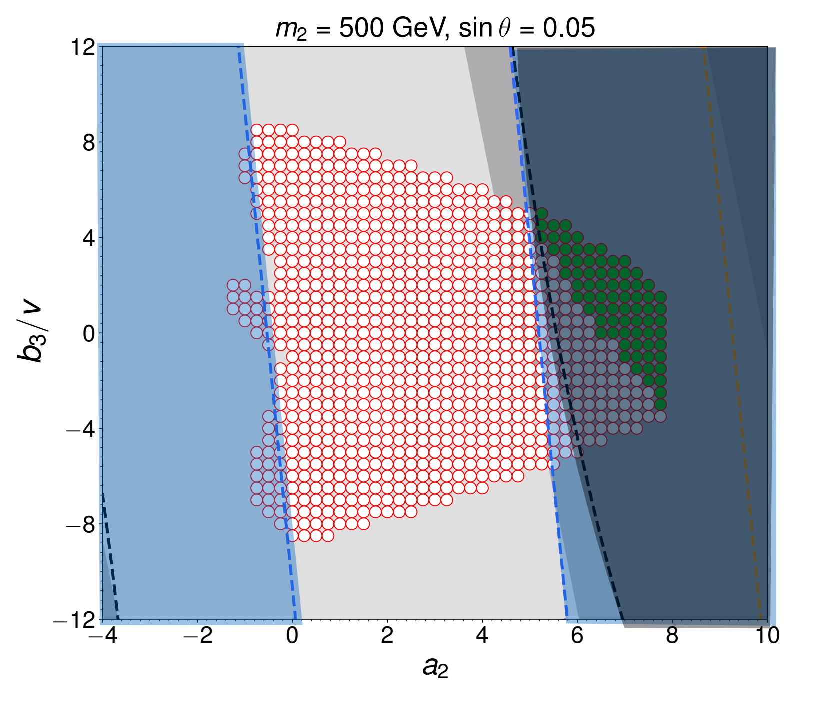

EW phase transition

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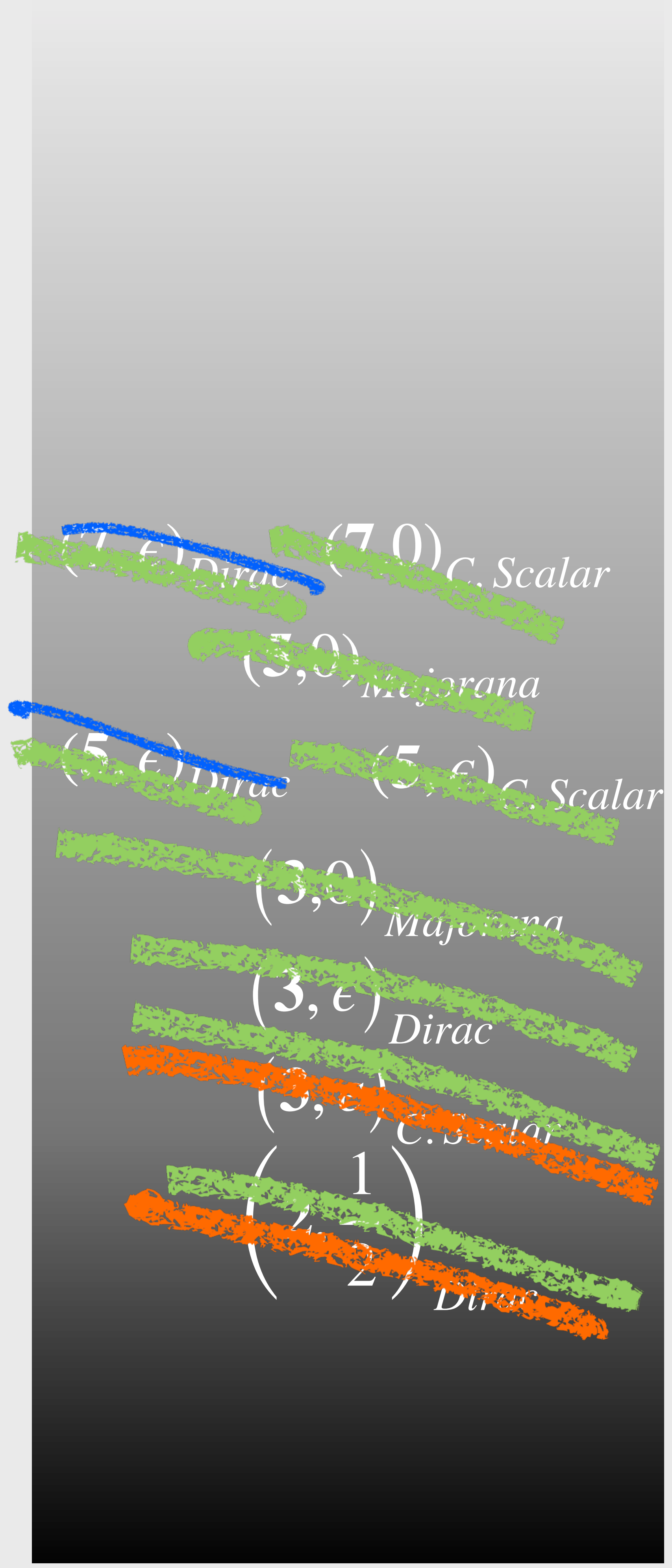

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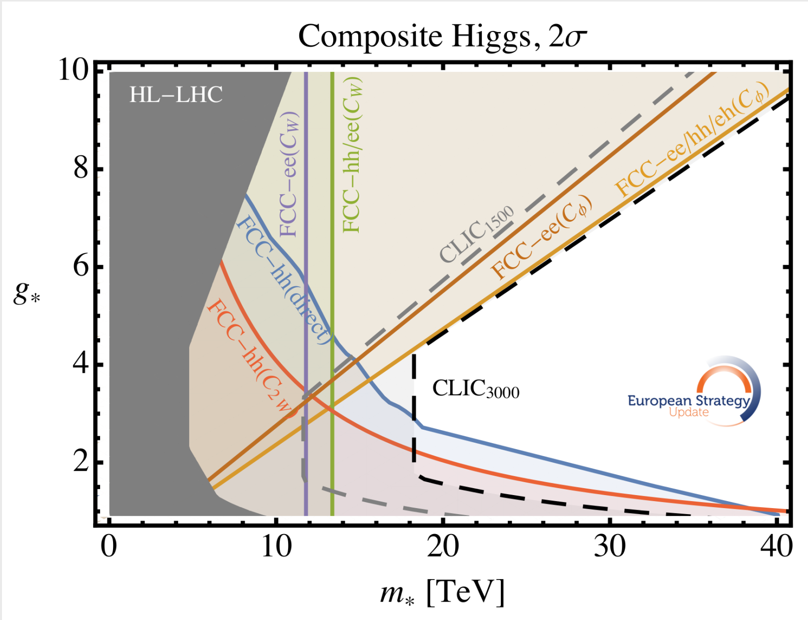

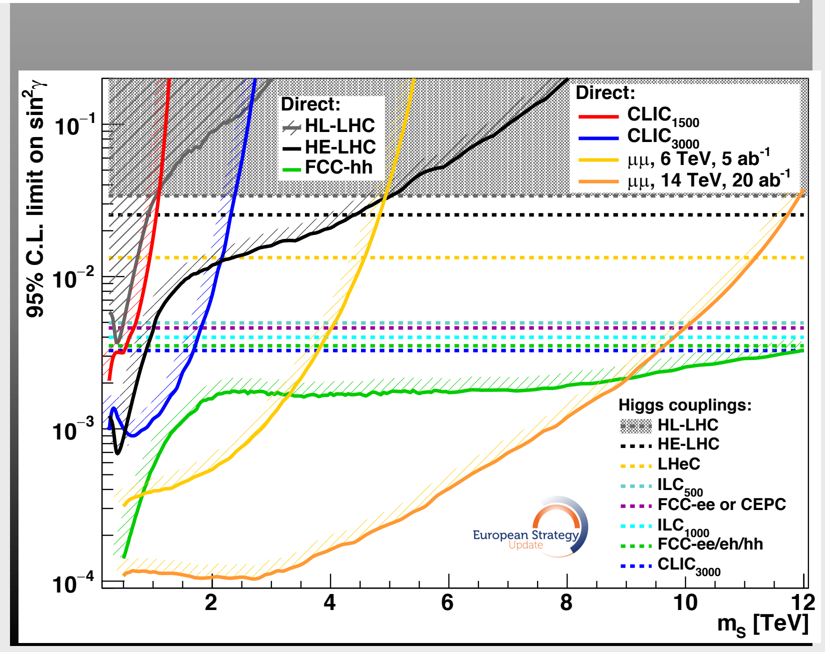

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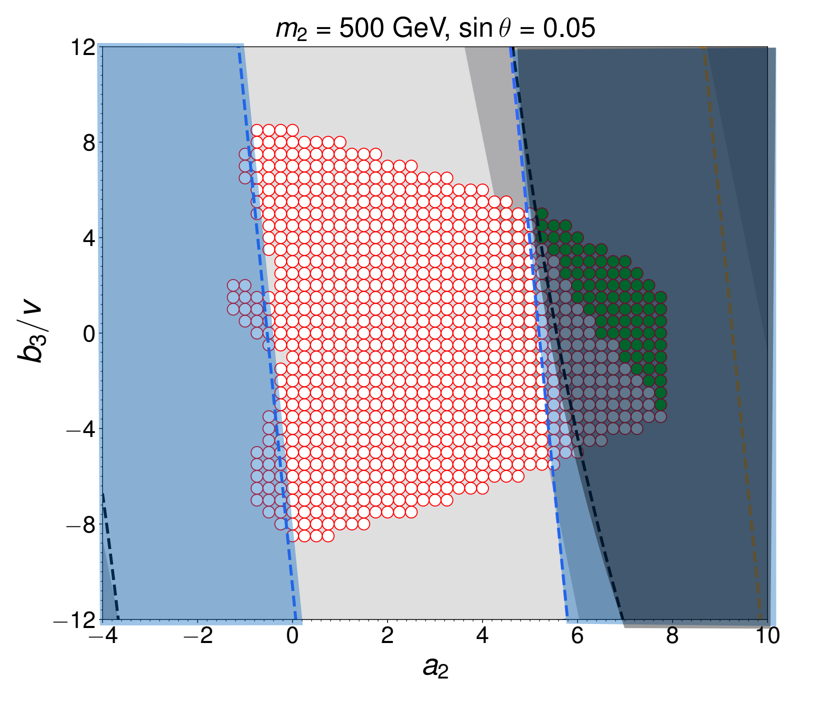

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1 TeV

200-300 GeV

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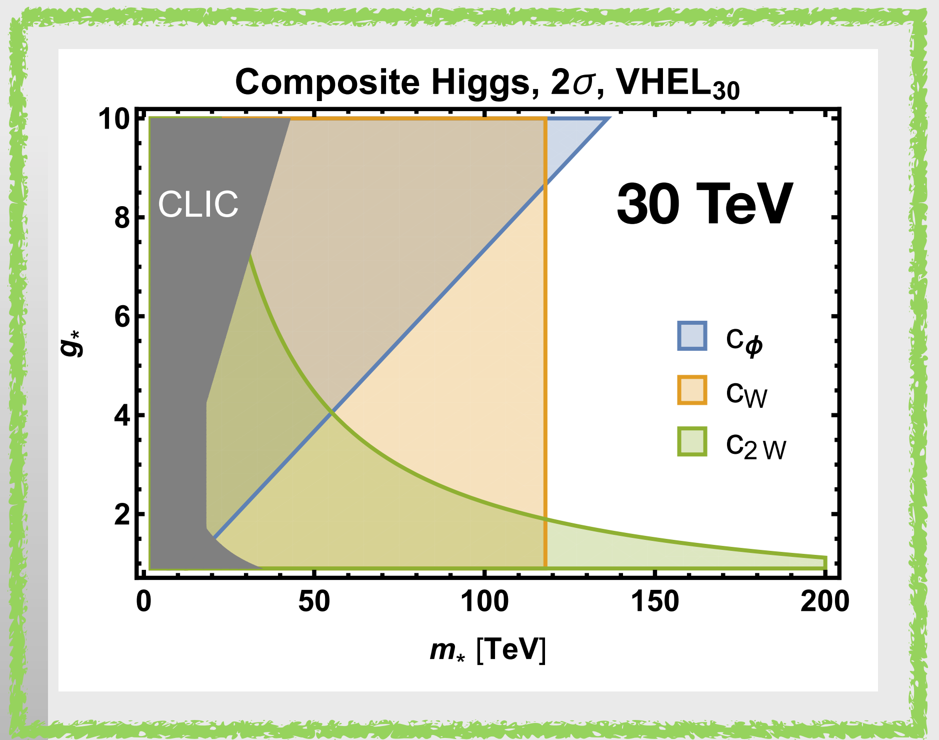

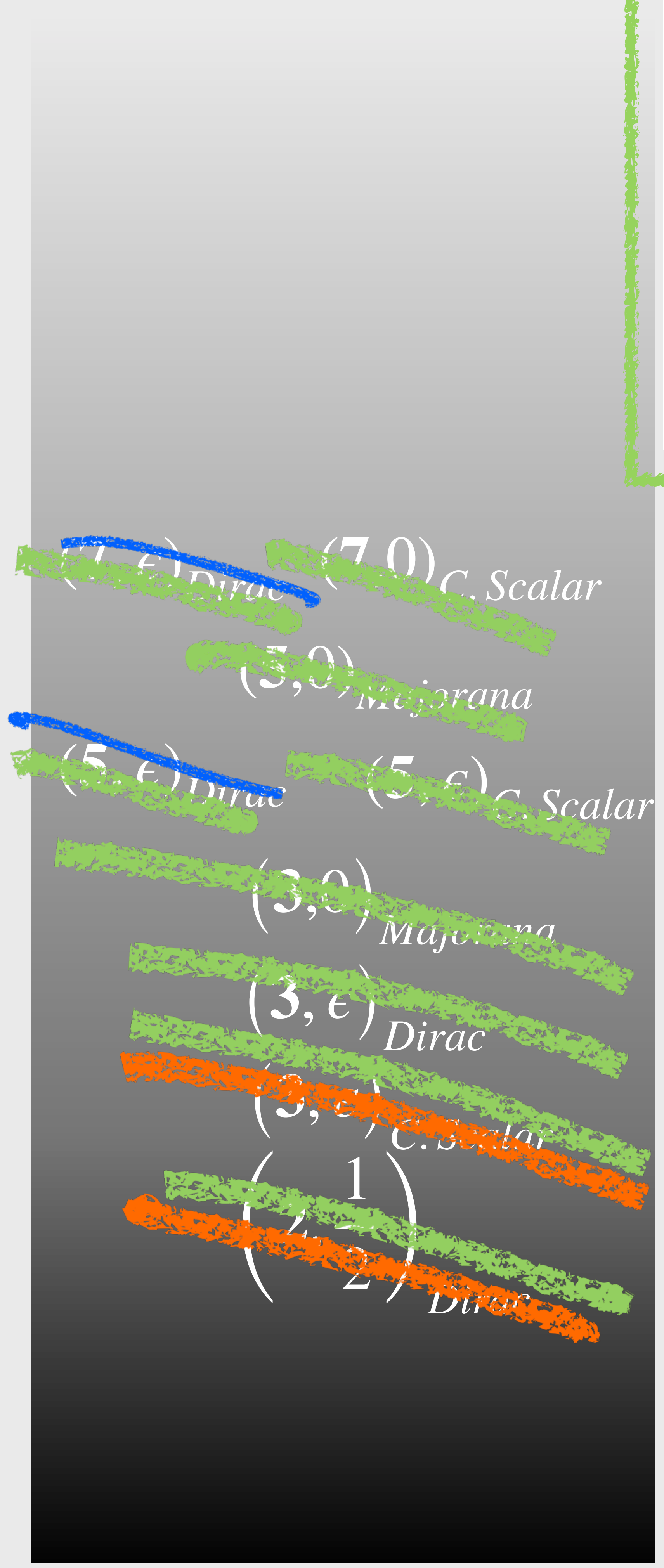

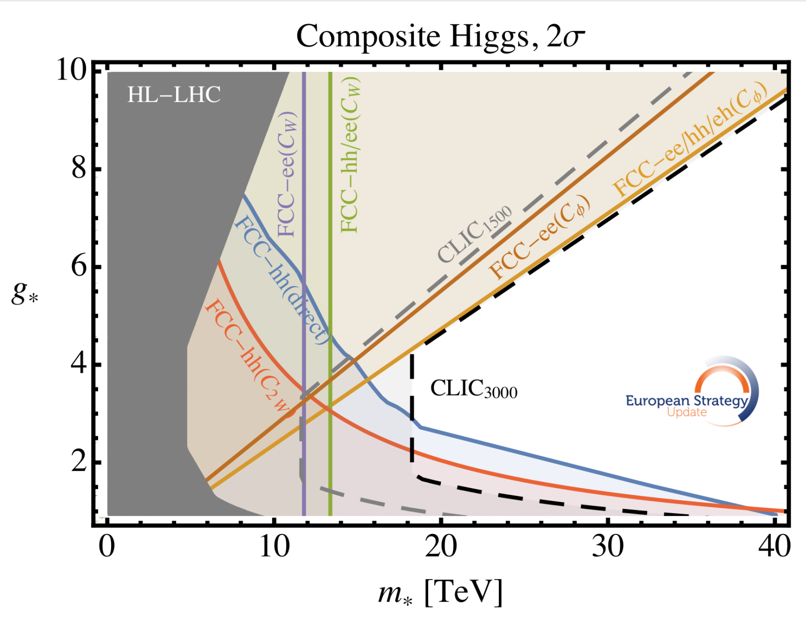

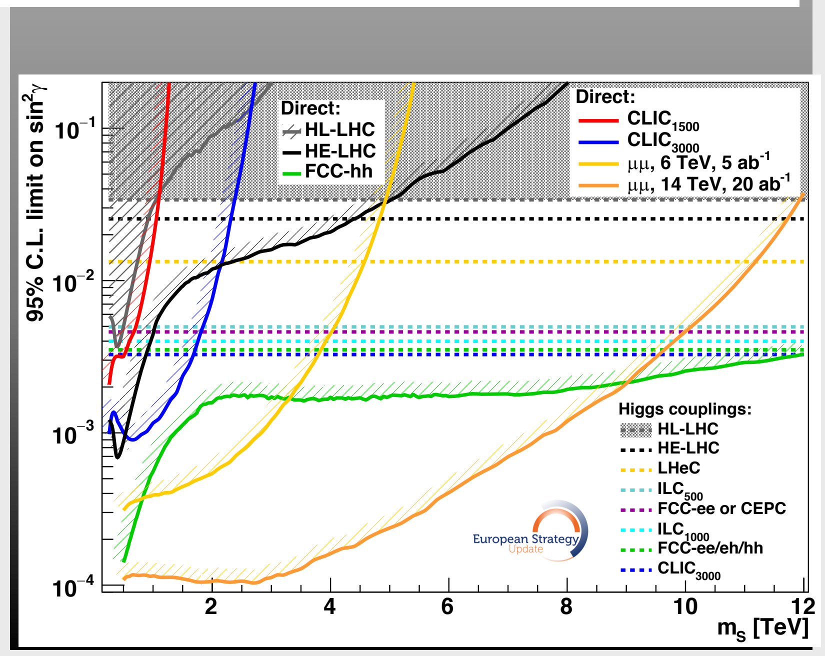

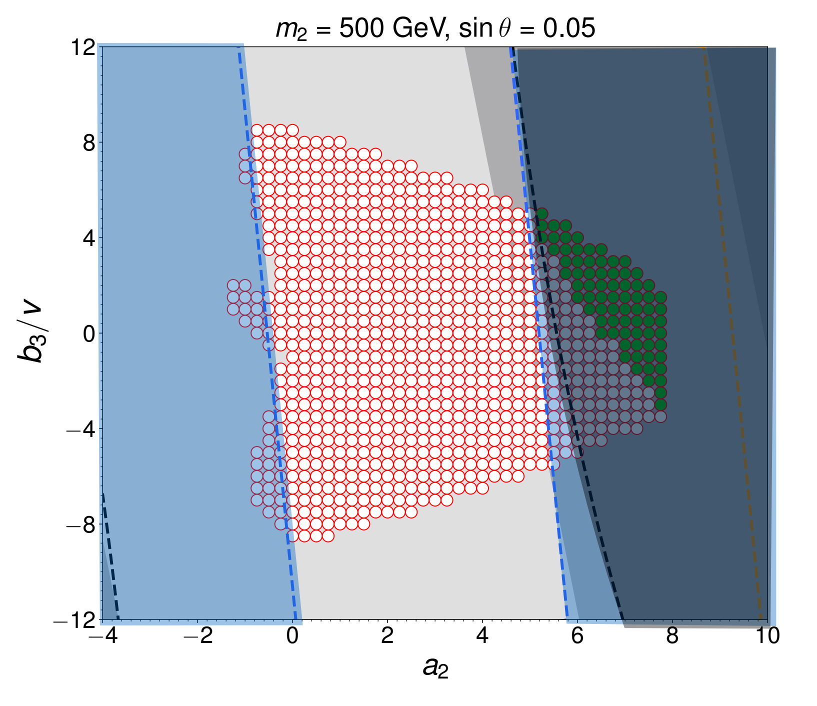

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Lεμμα

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Muon Accelerator Program

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

CLIC

1 TeV

ILC

200-300 GeV

CEPC

FCC hh ee he

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Conclusion

- Leptons beam structure enables *qualitatively new investigations* of the electroweak/Higgs sector

- CLIC definitively shows that lepton colliders can have *both precision and mass reach* to probe new physics well beyond TeV

- If novel acceleration technologies can deliver even larger *energy and* keep the *luminosity* on track with $\mathscr{L} \propto E_{com}^2$ we can start probing fundamental interactions in novel and deeper ways.

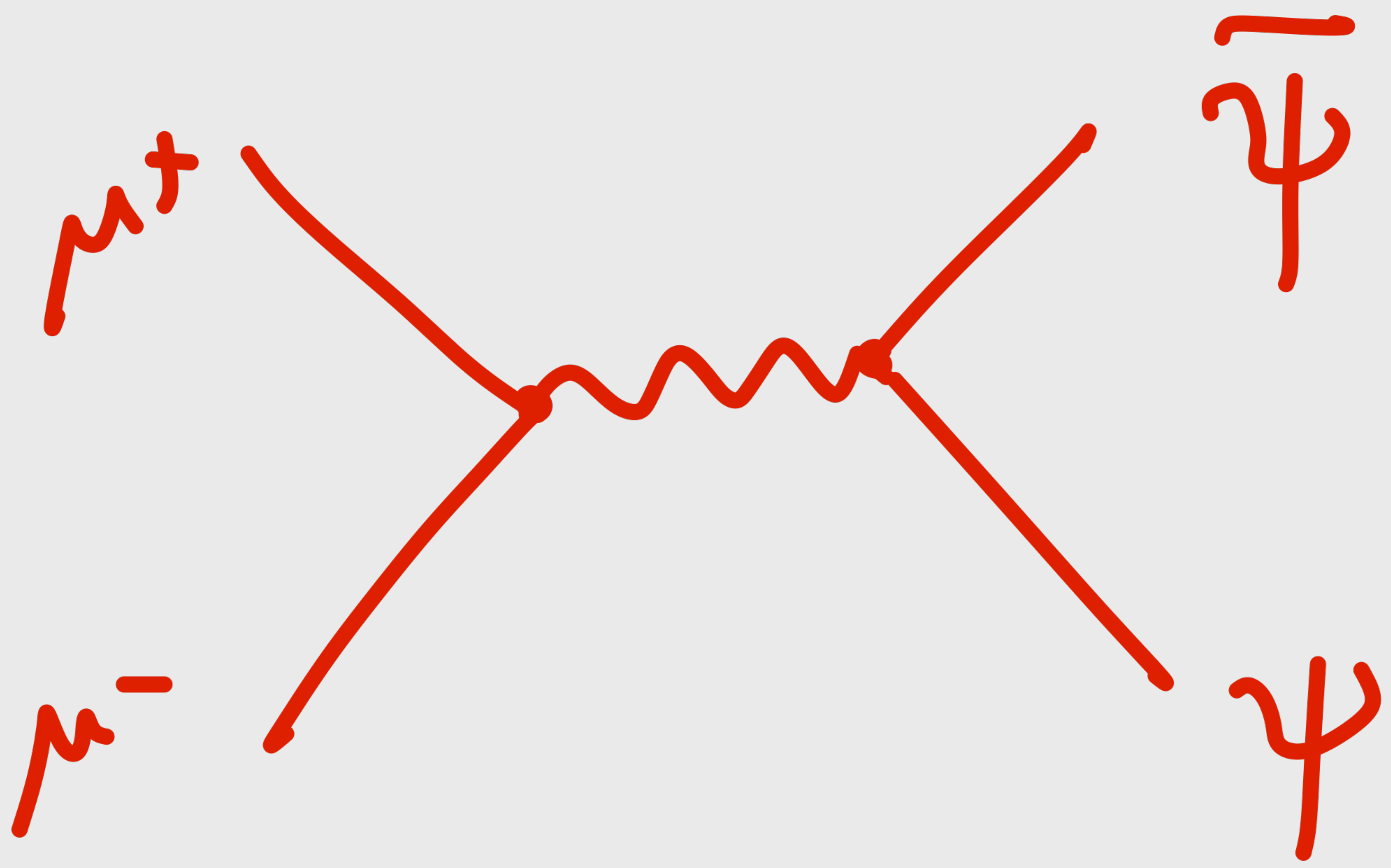
Thank You!

“Valence” Leptons

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

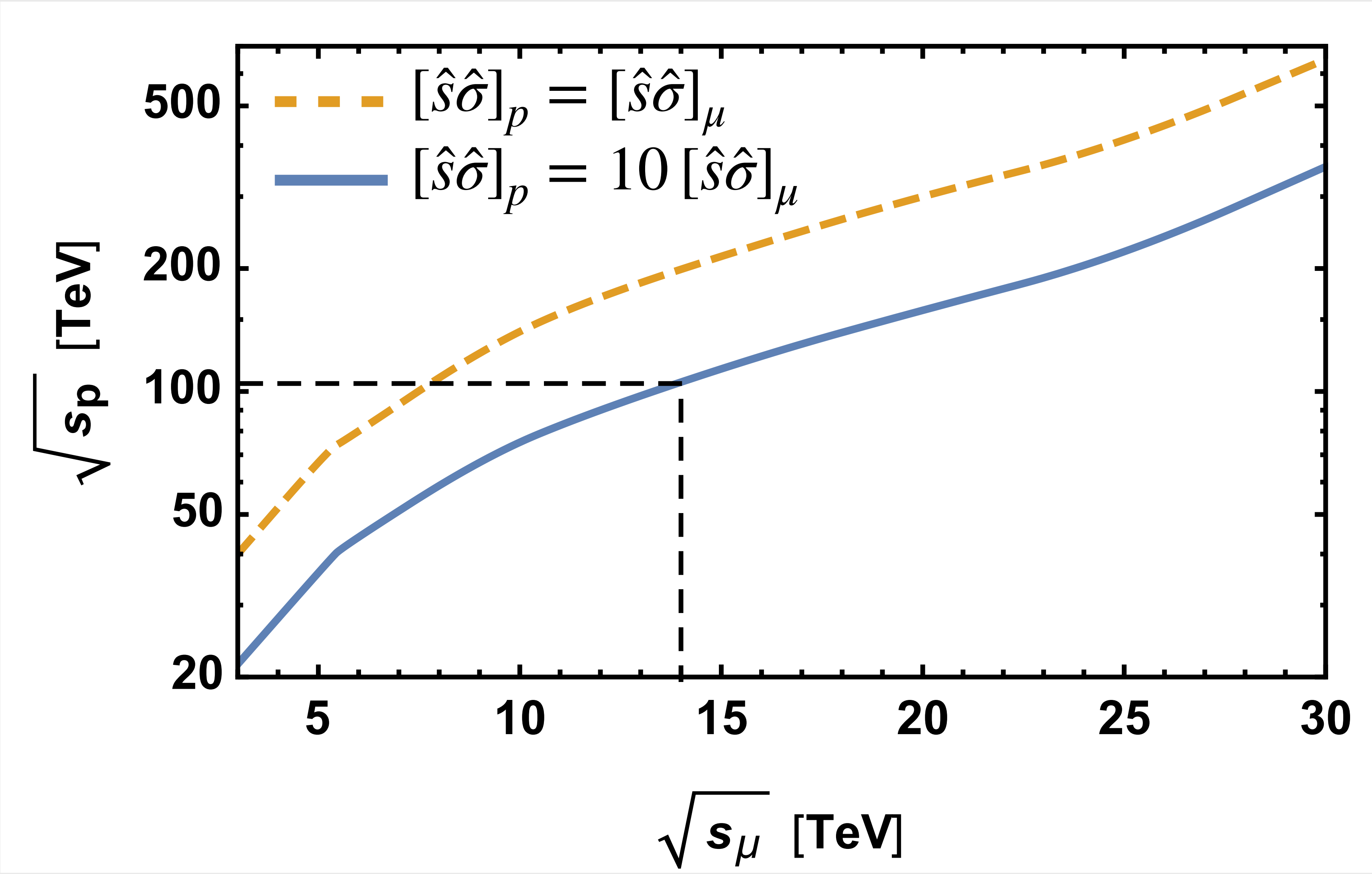
VALENCE LEPTONS

Can produce heavy new physics (colored or not)



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

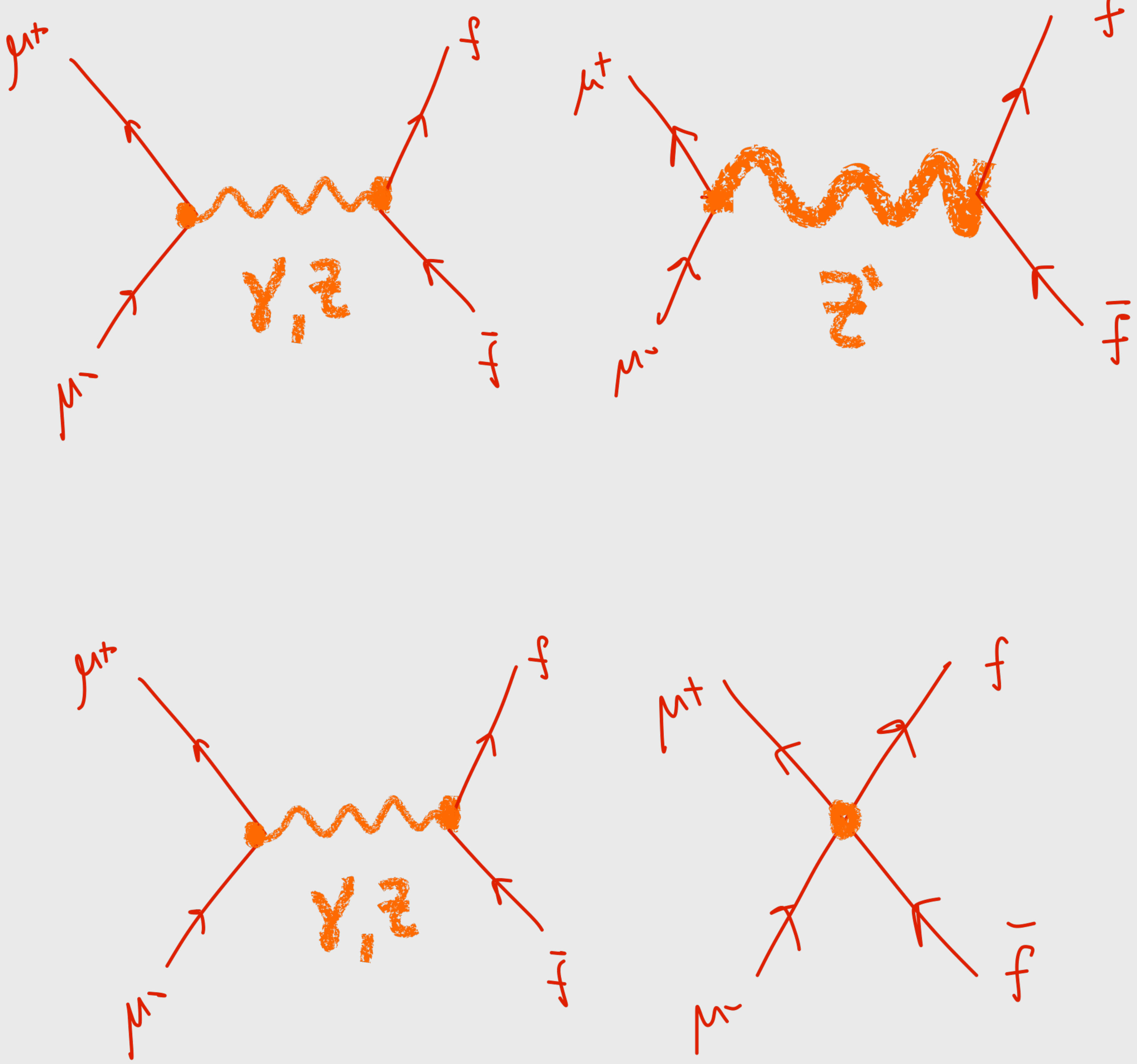
Compares pretty well with a *pp* collider

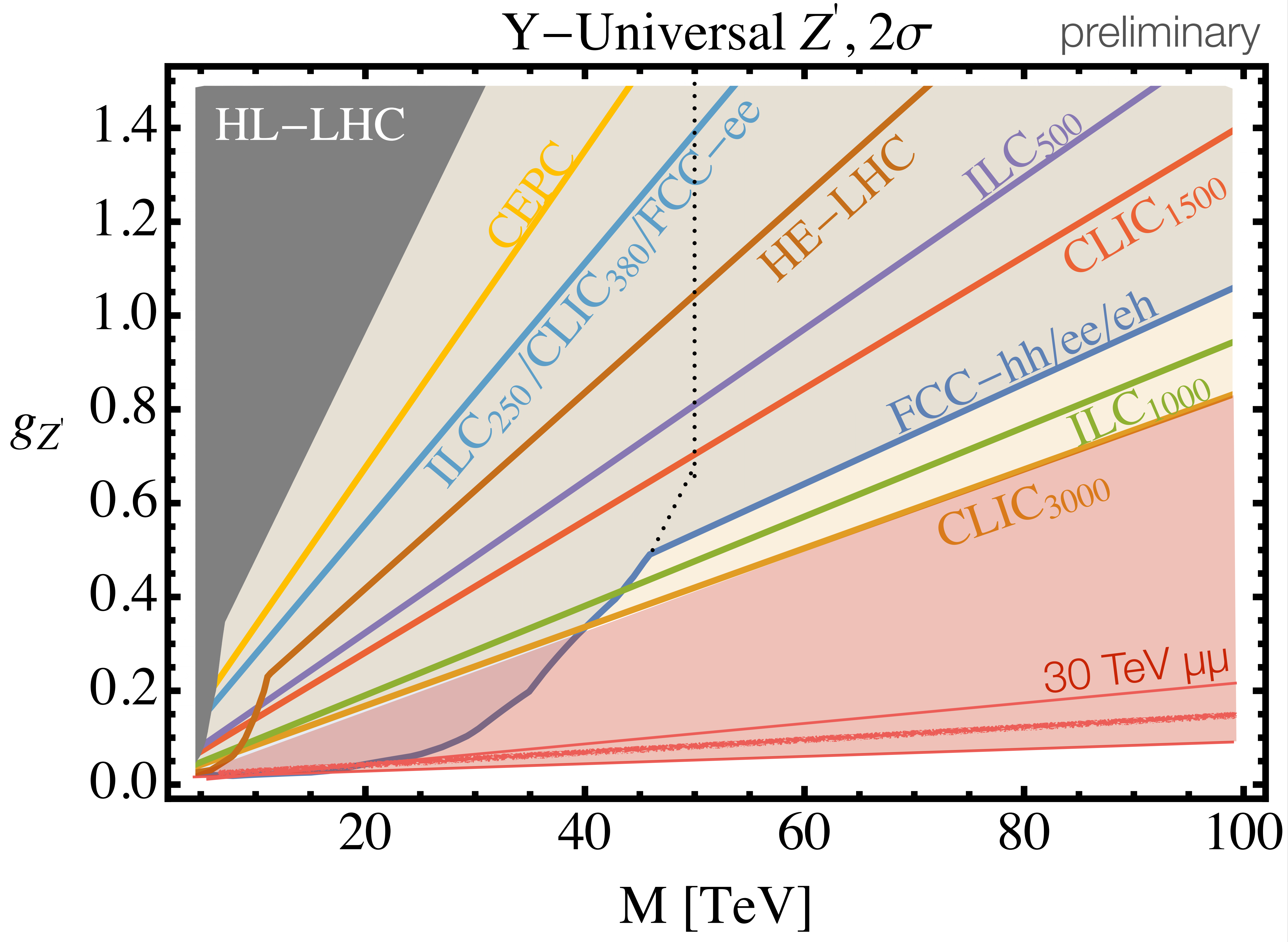


14 TeV μμ roughly equivalent to 100 TeV *pp*

A heavy Z'

DRELL-YAN | RATES AND ANGULAR DISTRIBUTIONS





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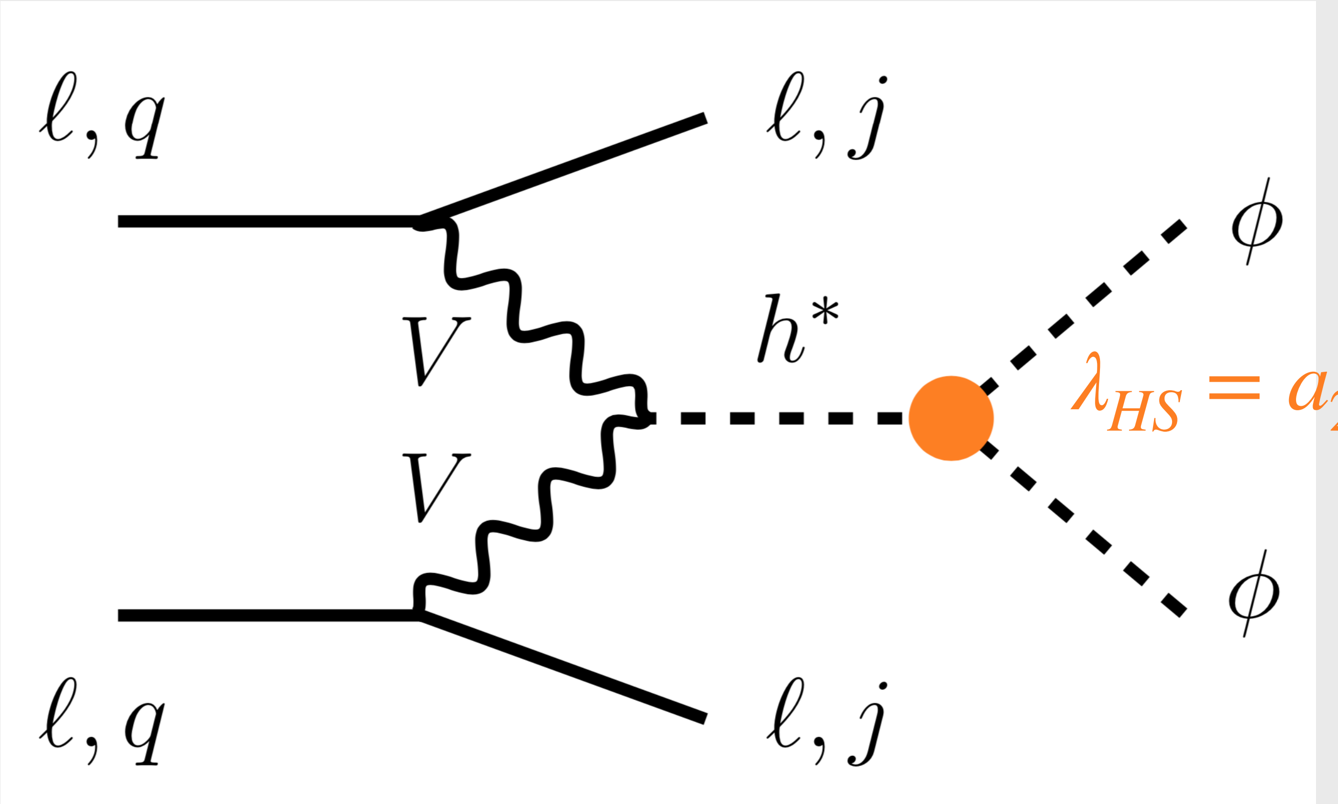
UnMixed Singlet for EW phase transition

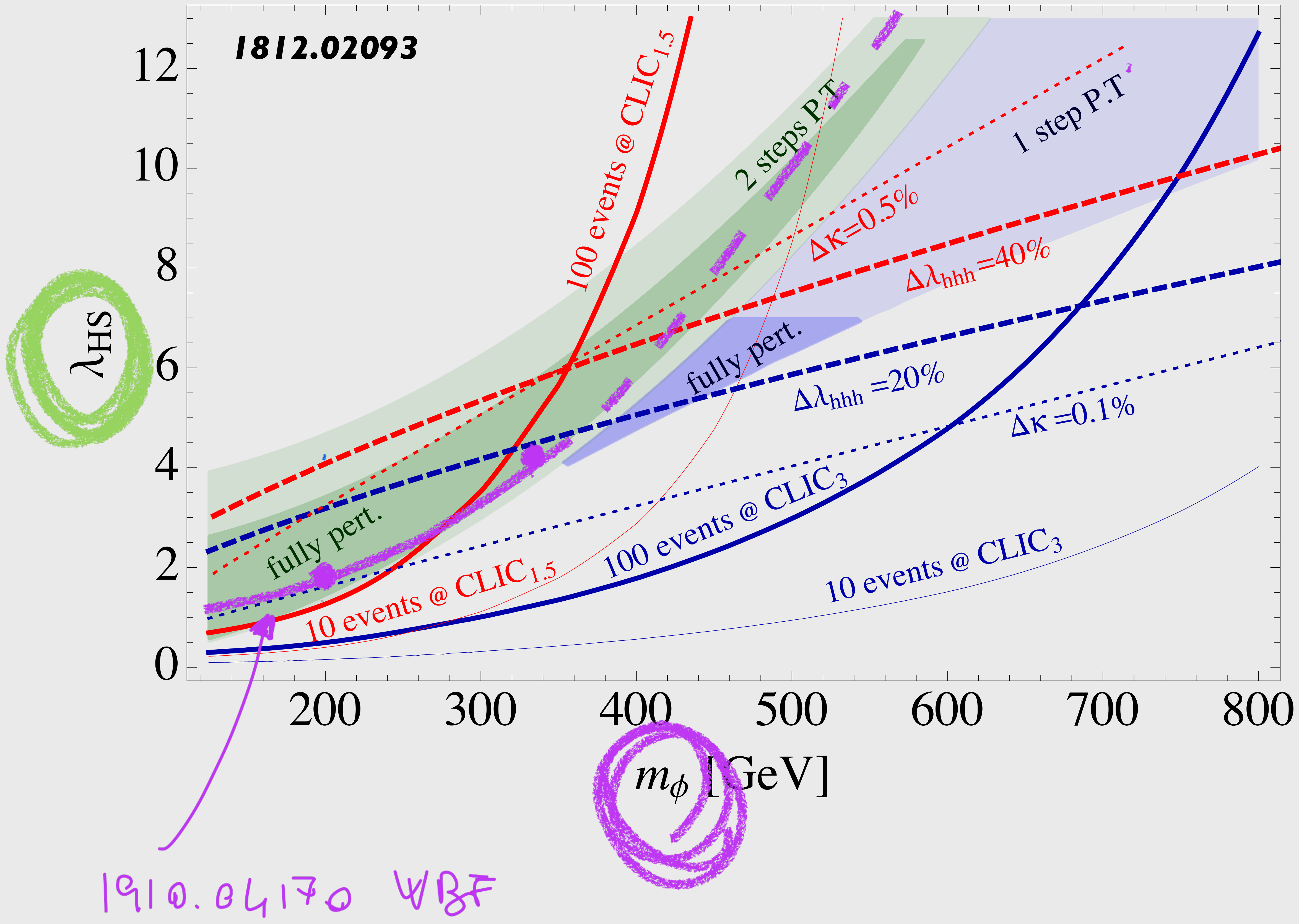
EW PHASE TRANSITION | IS IT FIRST ORDER?

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

independent parameters

$$\{v, m_1, m_2, \ell, a_2, b_3, b_4\}.$$





zero-mixing: Higgs couplings as good or better than VBF

tiny mixing: displaced decays events

parameters space of 1st order phase transition accessible by several probes

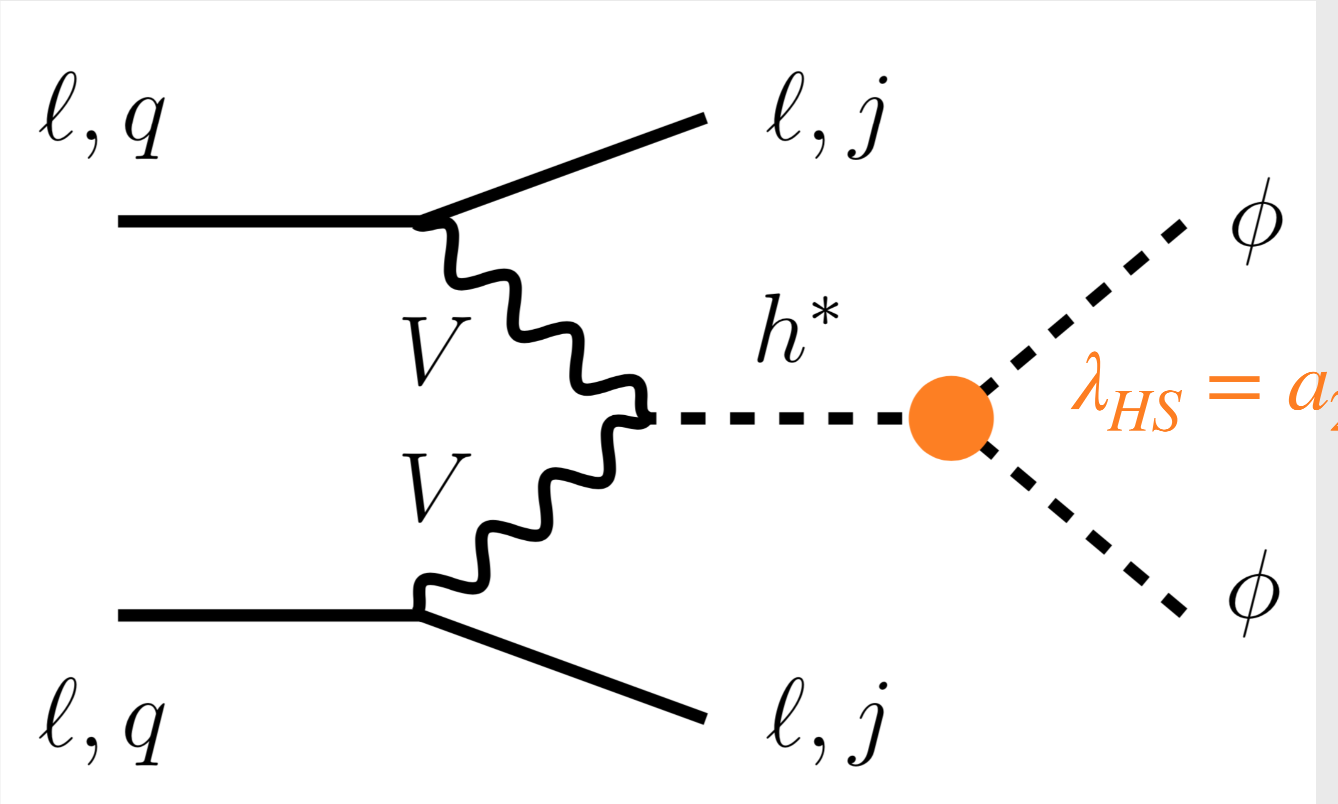
UnMixed Singlet for EW phase transition

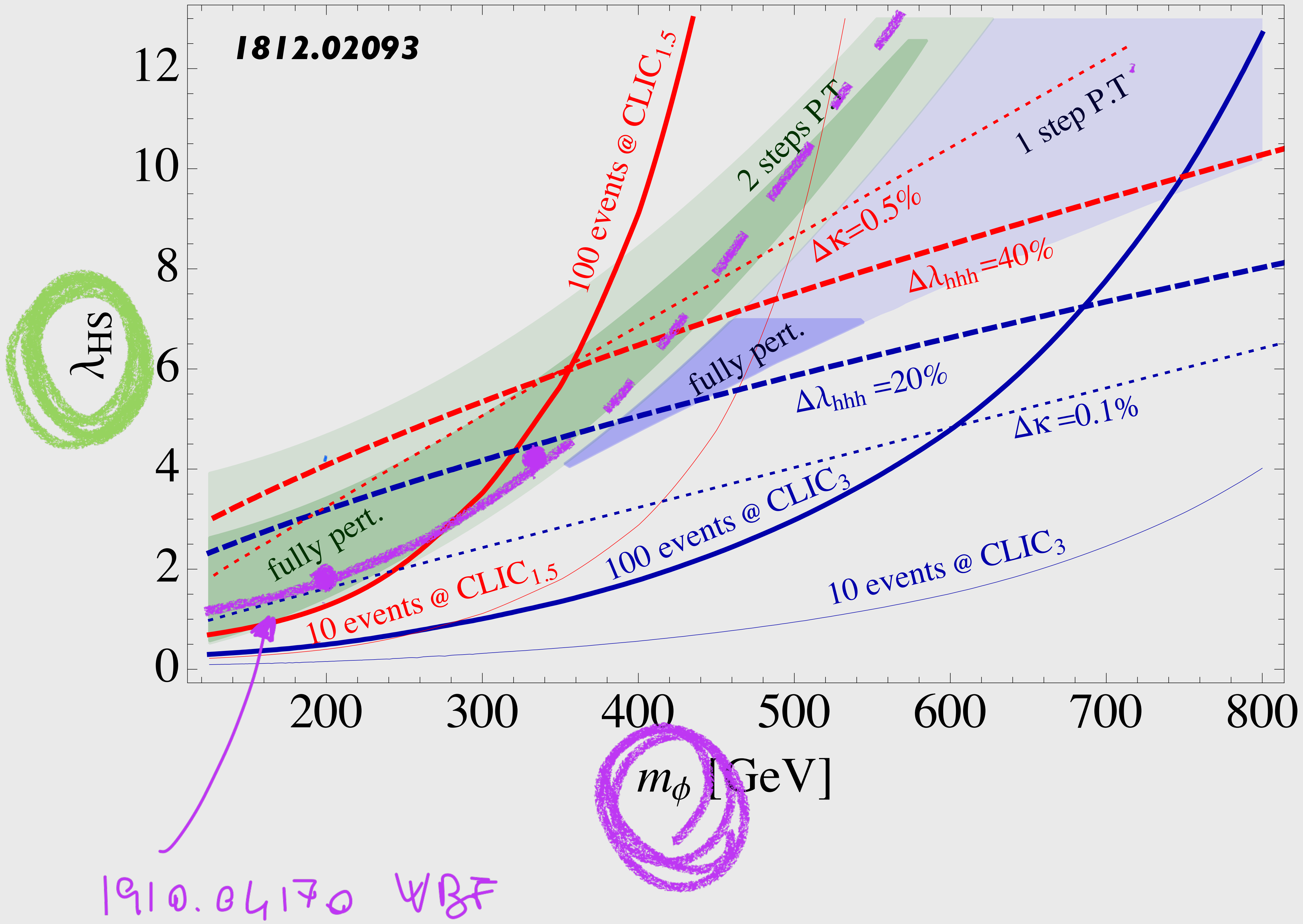
EW PHASE TRANSITION | IS IT FIRST ORDER?

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

independent parameters

$$\{v,\, m_1,\, m_2,\, \theta,\, a_2,\, b_3,\, b_4\}.$$





zero-mixing: Higgs couplings as good or better than VBF

tiny mixing: displaced decays events

parameters space of 1st order phase transition accessible by several probes

EW symmetry breaking

Electroweak symmetry breaking

Big picture questions:

- Higgs compositeness
- Extended Higgs Sector

Electroweak symmetry breaking

Big picture questions:

- Higgs compositeness
- Extended Higgs Sector

“The size of the Higgs boson”

it matters because being “point-like” is the source of all the theoretical questions on the Higgs boson and weak scale

… and if it is not … well, that is physics beyond the Standard Model!

Effects of the size of the Higgs boson

h ~ π

STRONGLY INTERACTING LIGHT HIGGS

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

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

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

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

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

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

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

Effects of the size of the Higgs boson

h ~ π STRONGLY INTERACTING LIGHT HIGGS

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

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

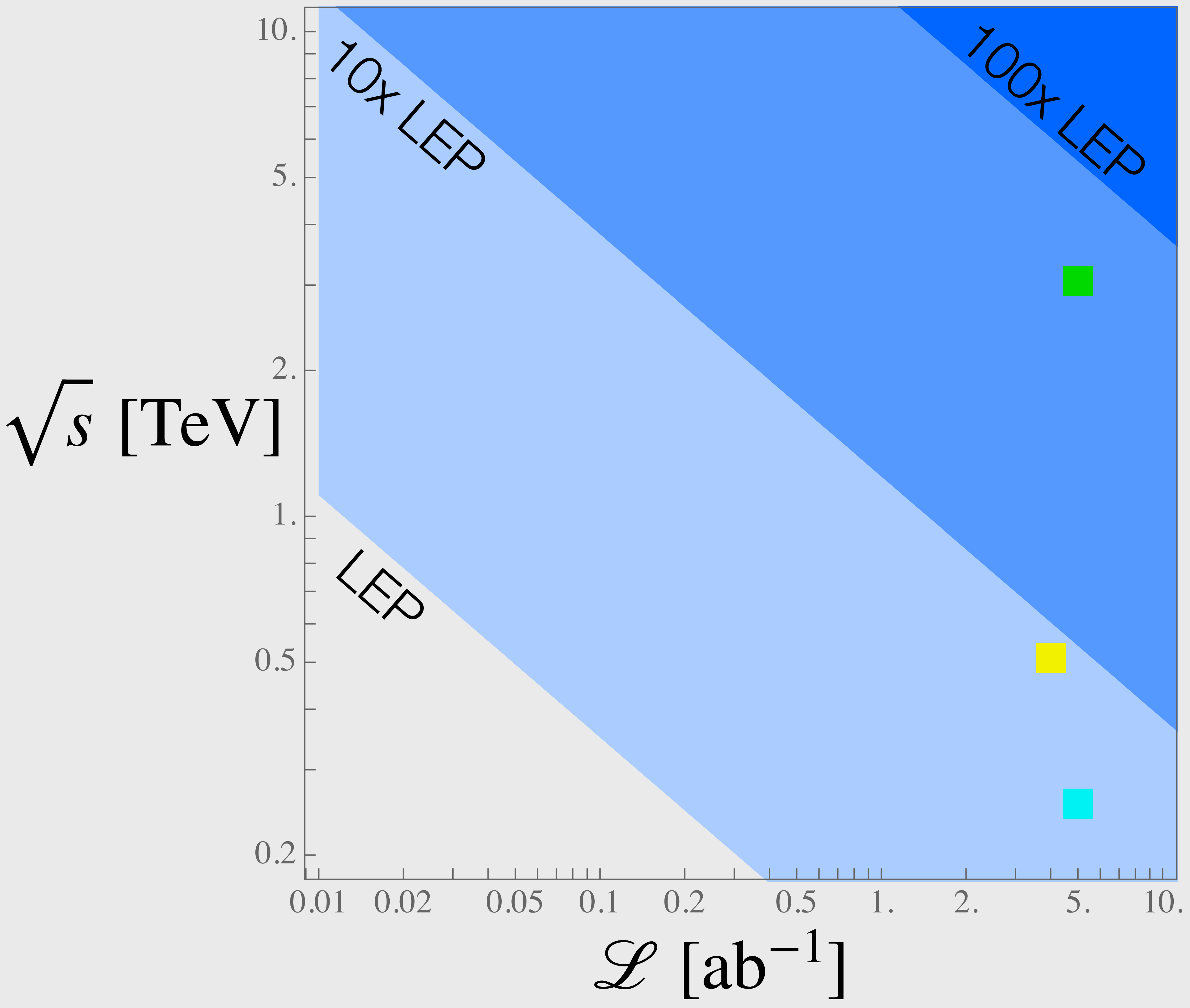
$\ell^+\ell^- \to Zh$

Ever higher energy colliders can exploit "precise" measurements at the 10% level

TOTAL RATE

$$\left|A_{SM}^{(00)}\right|^2 + A_{SM}^{00} \cdot A_{BSM}^{00} + \dots$$

$$\hat{S}_{95\%} \lesssim 1.2 \cdot 10^{-4} \frac{1}{E_{beam}/\text{TeV}} \cdot \frac{1}{\sqrt{\mathscr{L}/\text{ab}^{-1}}}$$



$\ell^+\ell^- \to Zh$

TOTAL RATE

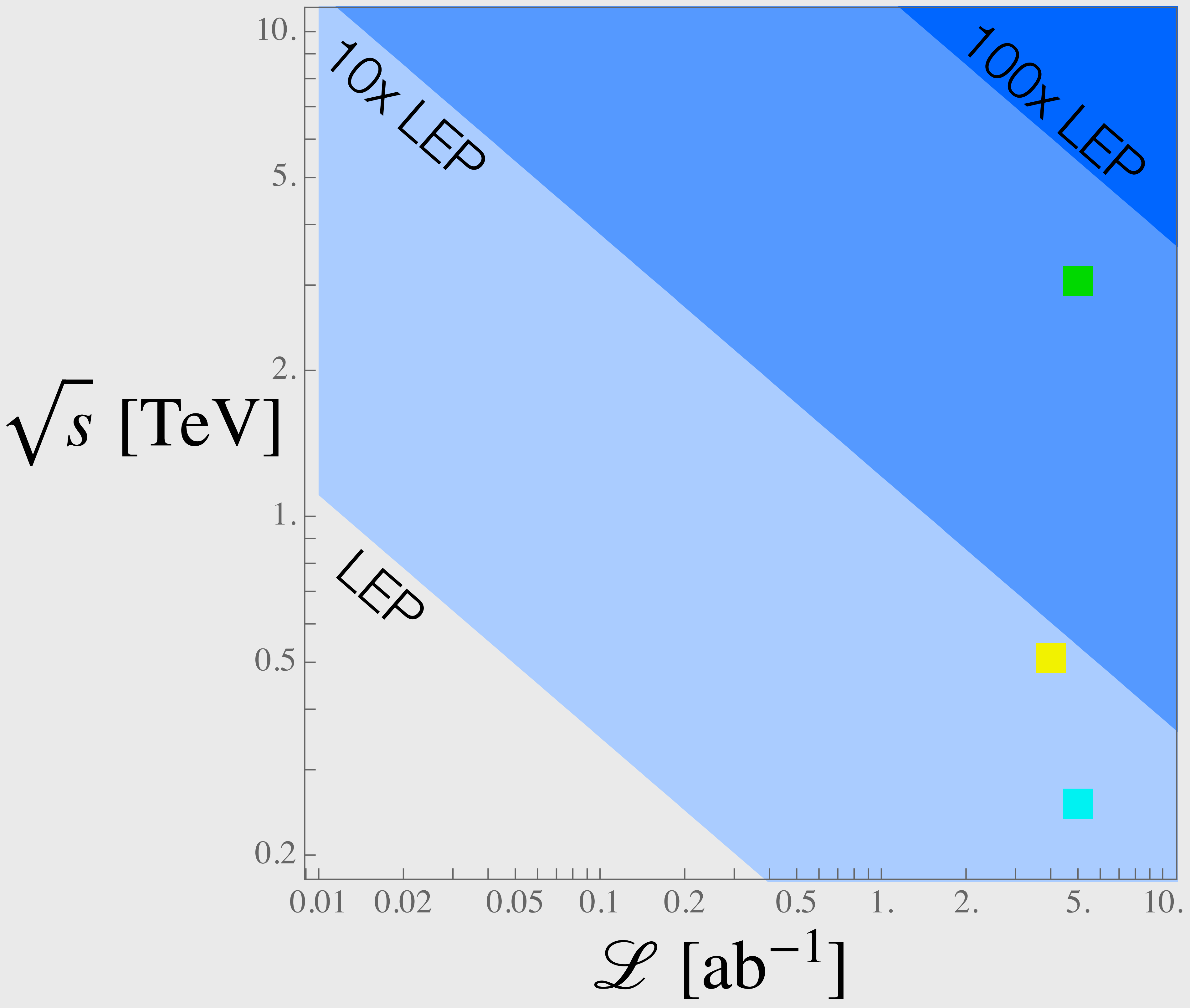
$$\left|A^{(00)}_{SM}\right|^2 + A^{00}_{SM}\cdot A^{00}_{BSM} + \ldots$$

Ever higher energy colliders can exploit "precise" measurements at the 10% level

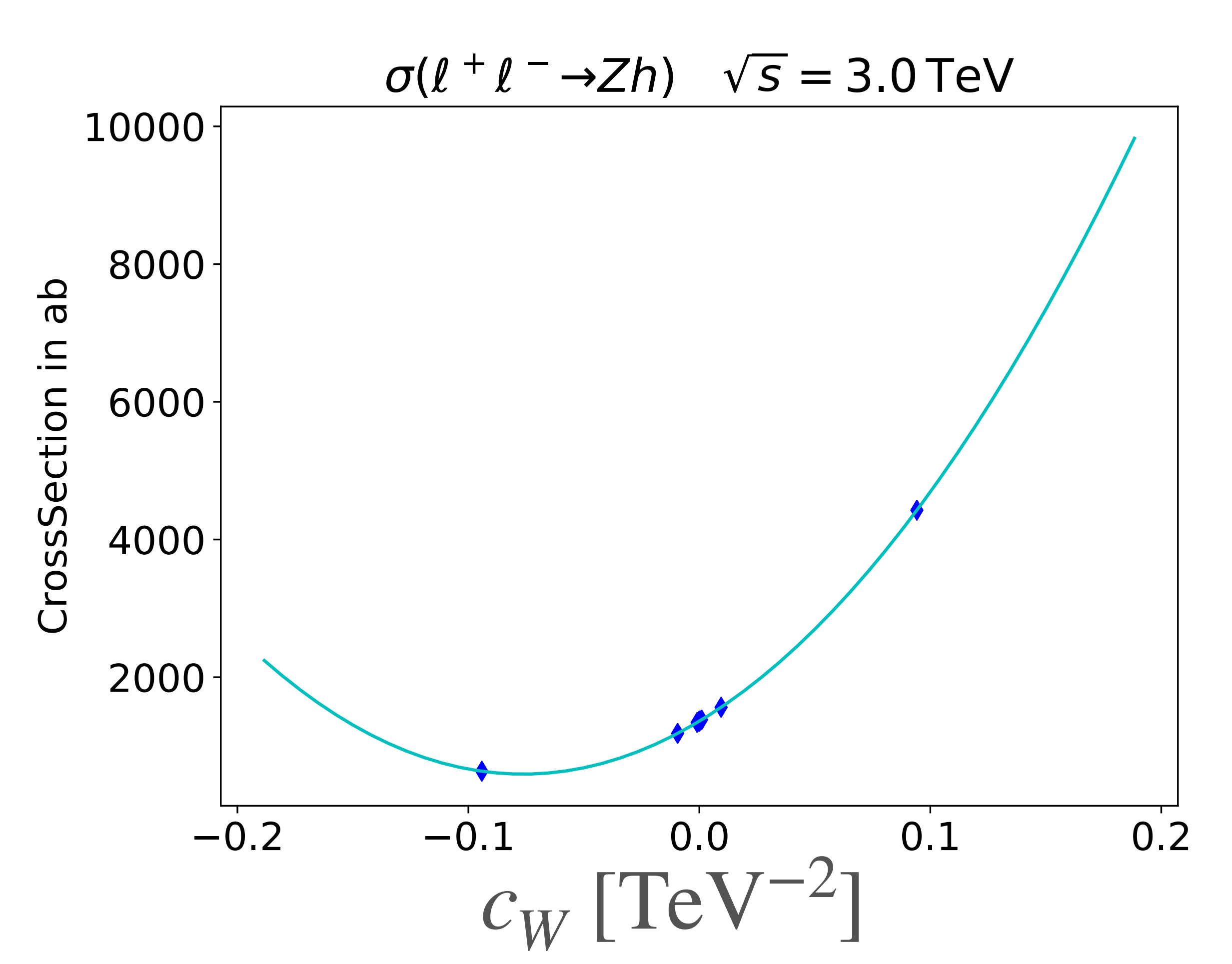
$$c_W = \hat{S}/m_W^2$$

$$c_W \lesssim 0.02\,\mathrm{TeV}^{-2}\frac{1}{E_{beam}/\mathrm{TeV}}\cdot\frac{1}{\sqrt{\mathscr{L}/\mathrm{ab}^{-1}}}$$

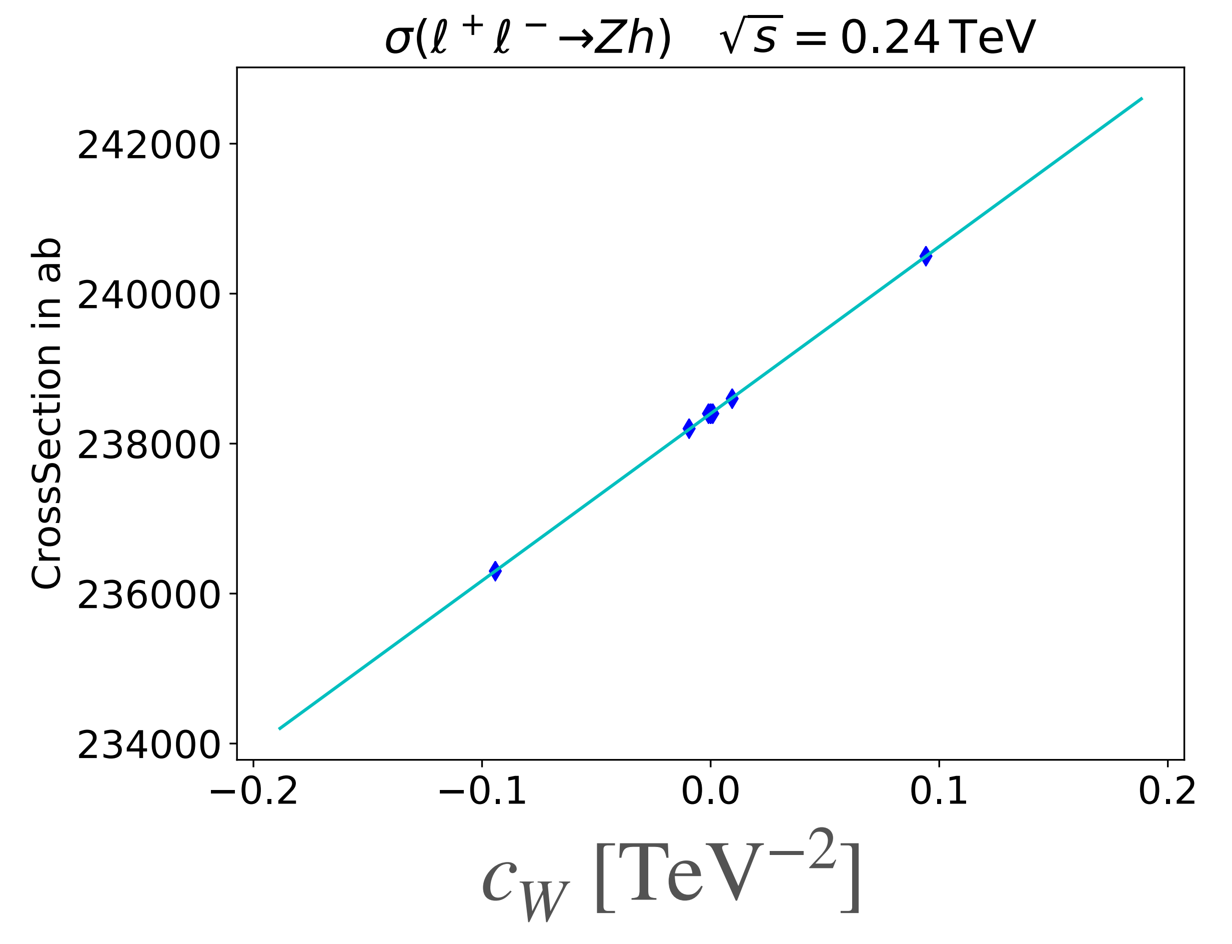
$$\hat{S}_{95\%} \lesssim 1.2\cdot 10^{-4}\frac{1}{E_{beam}/\mathrm{TeV}}\cdot\frac{1}{\sqrt{\mathscr{L}/\mathrm{ab}^{-1}}}$$



$\hat{S} < 3\cdot 10^{-5}$ (95 % CL) ← $\mathscr{L} = 5\,\mathrm{ab}^{-1}$



$\hat{S} < 2\cdot 10^{-4}$ (95 % CL) ← $\mathscr{L} = 5\,\mathrm{ab}^{-1}$



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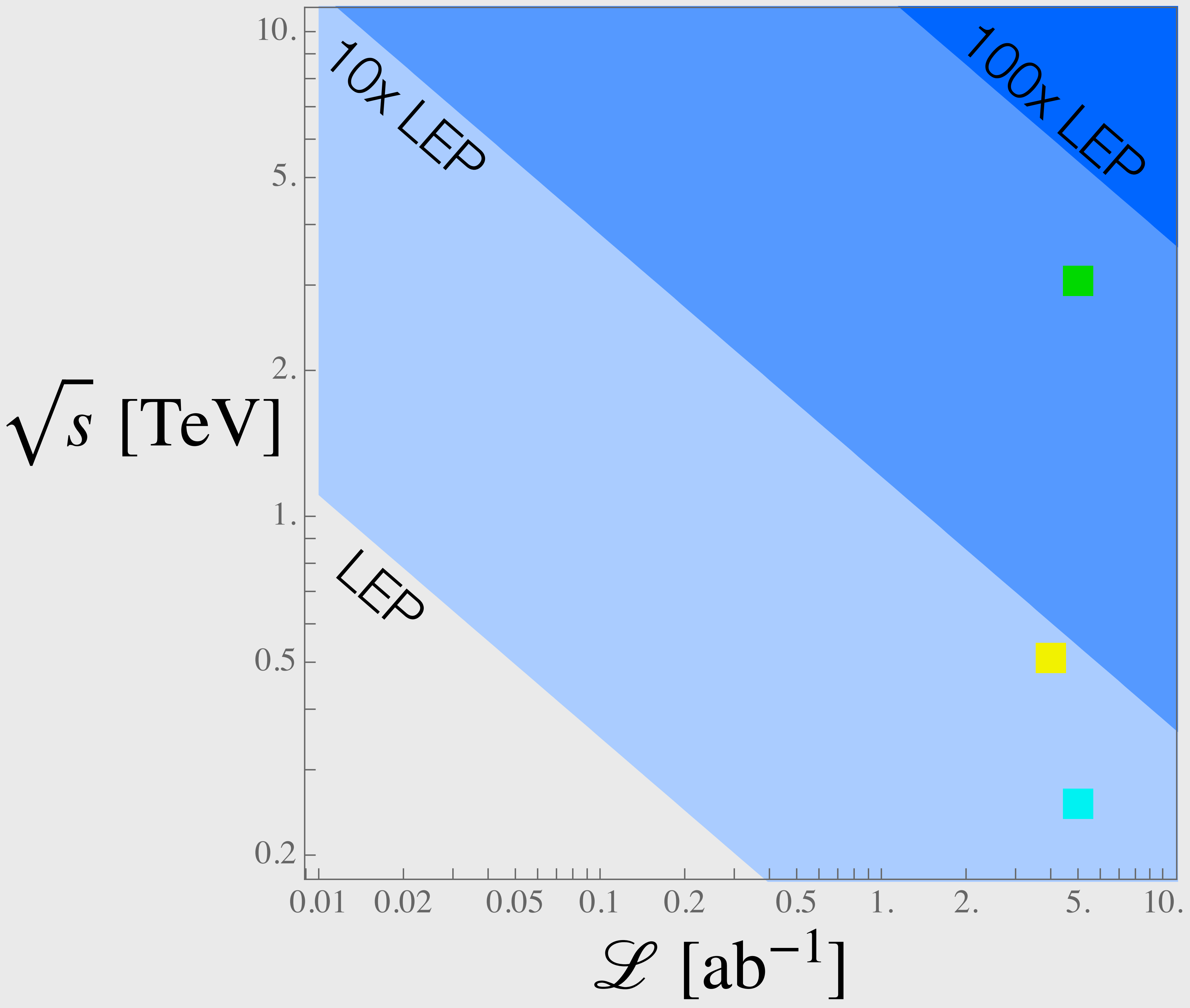

$$\hat{S} \equiv c_W/m_W^2 \simeq \frac{\delta O}{O} \text{ at Z pole}$$

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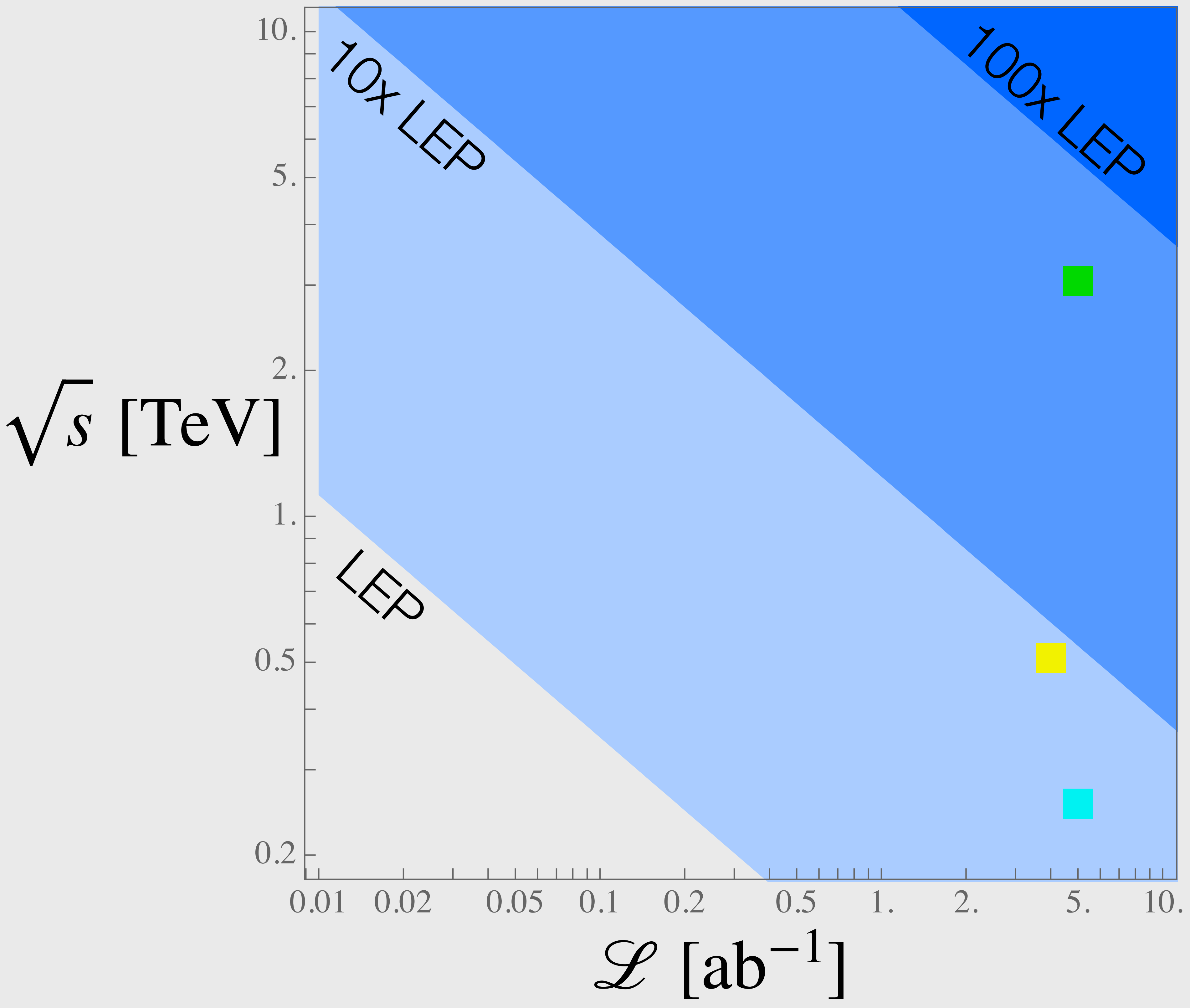

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GOING TO HIGHER ENERGY WE CAN EXPLOIT "PRECISE" MEASUREMENTS AT THE 10% LEVEL, AVOIDING THE BOTTLENECK OF SYSTEMATIC UNCERTAINTIES

$\ell^+\ell^- \to Zh$

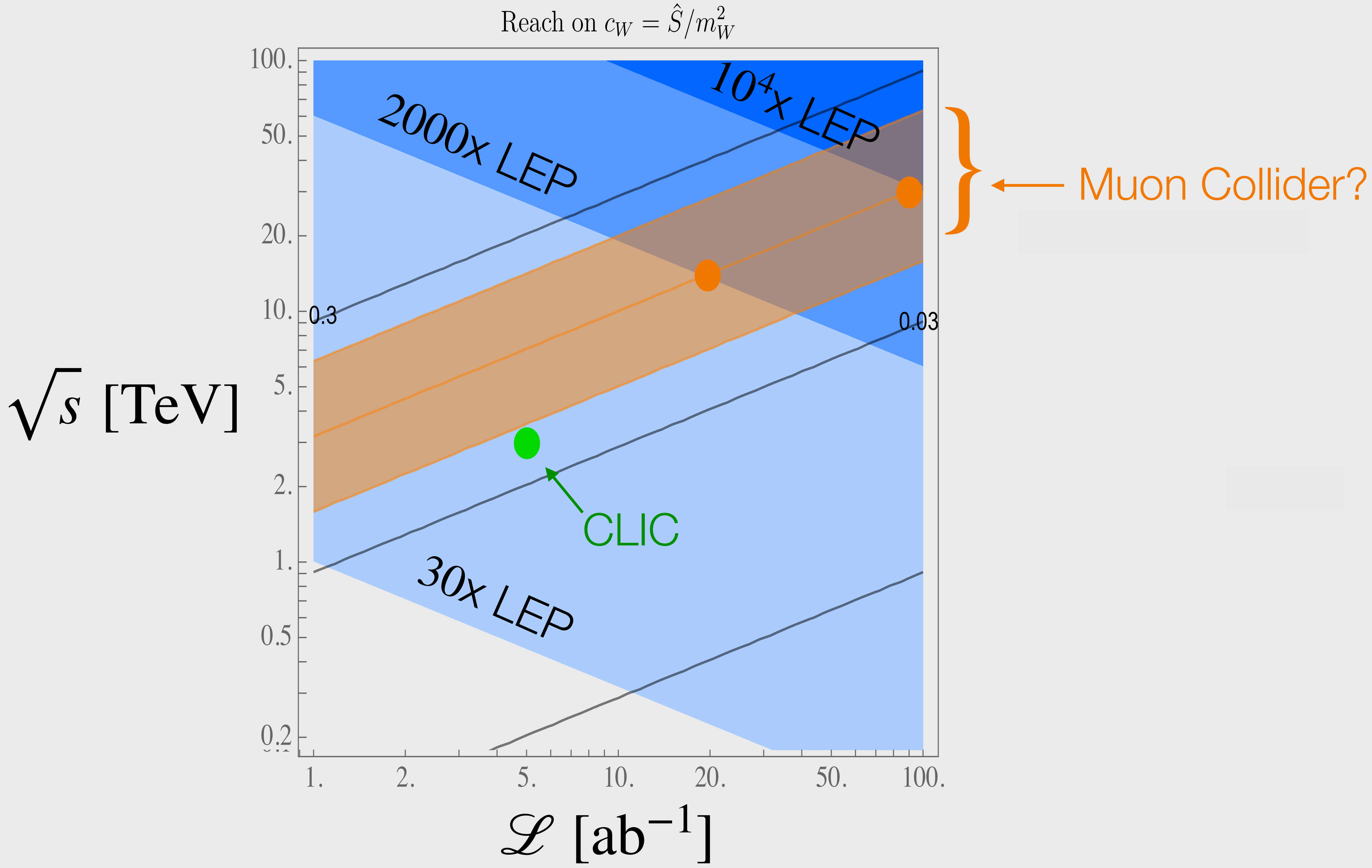
TOTAL RATE

$$\left|A_{SM}^{(00)}\right|^2 + A_{SM}^{00} \cdot A_{BSM}^{00} + \ldots$$

ZH	Cross-Section	m* 95% CL
3 TeV	1362 ab	12 TeV
14 TeV	62 ab	57 TeV
30 TeV	13 ab	120 TeV

Very important to keep up the lumi $\mathscr{L} \propto E^2$

Ever higher energy colliders can exploit "precise" measurements at the 10% level



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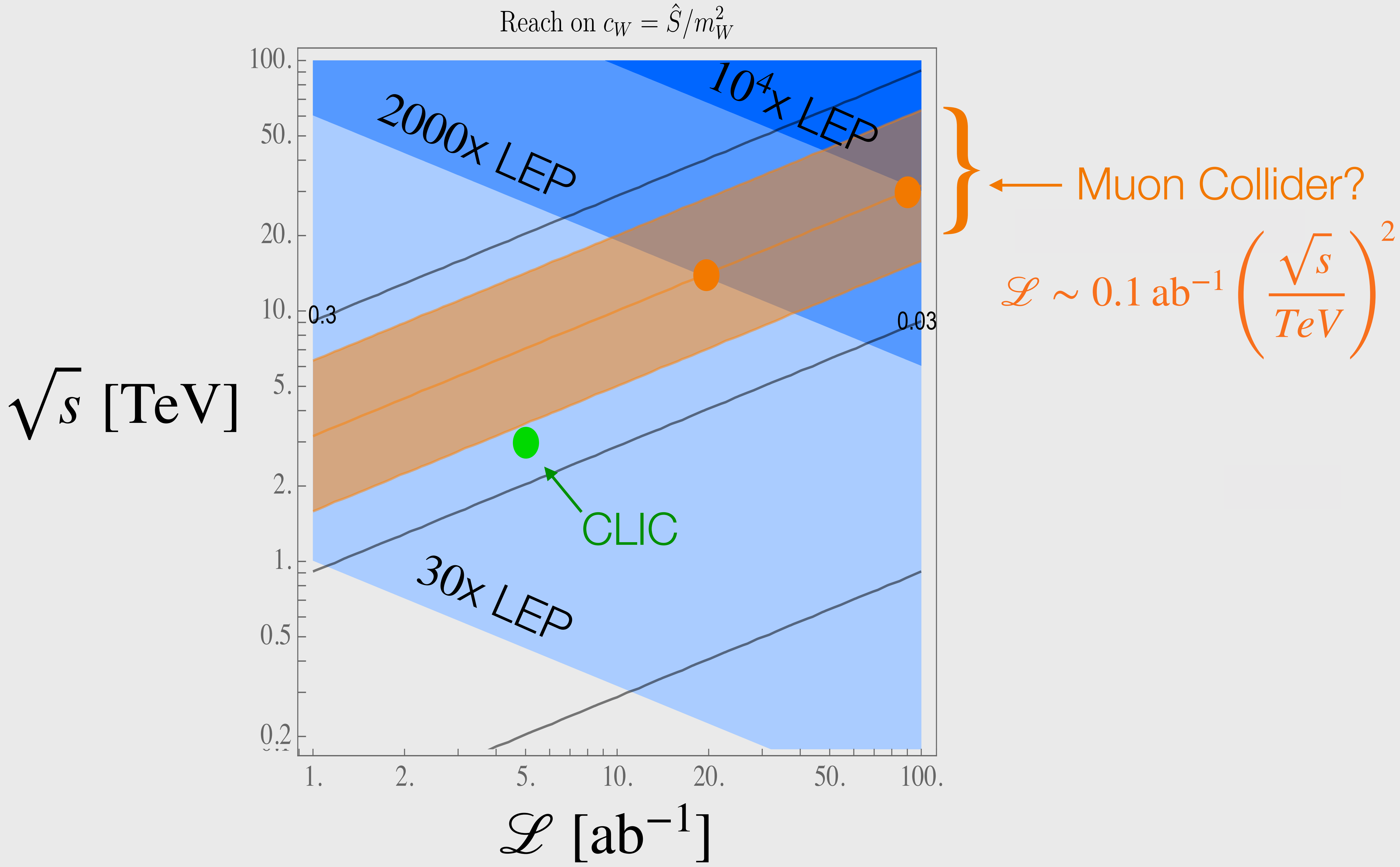
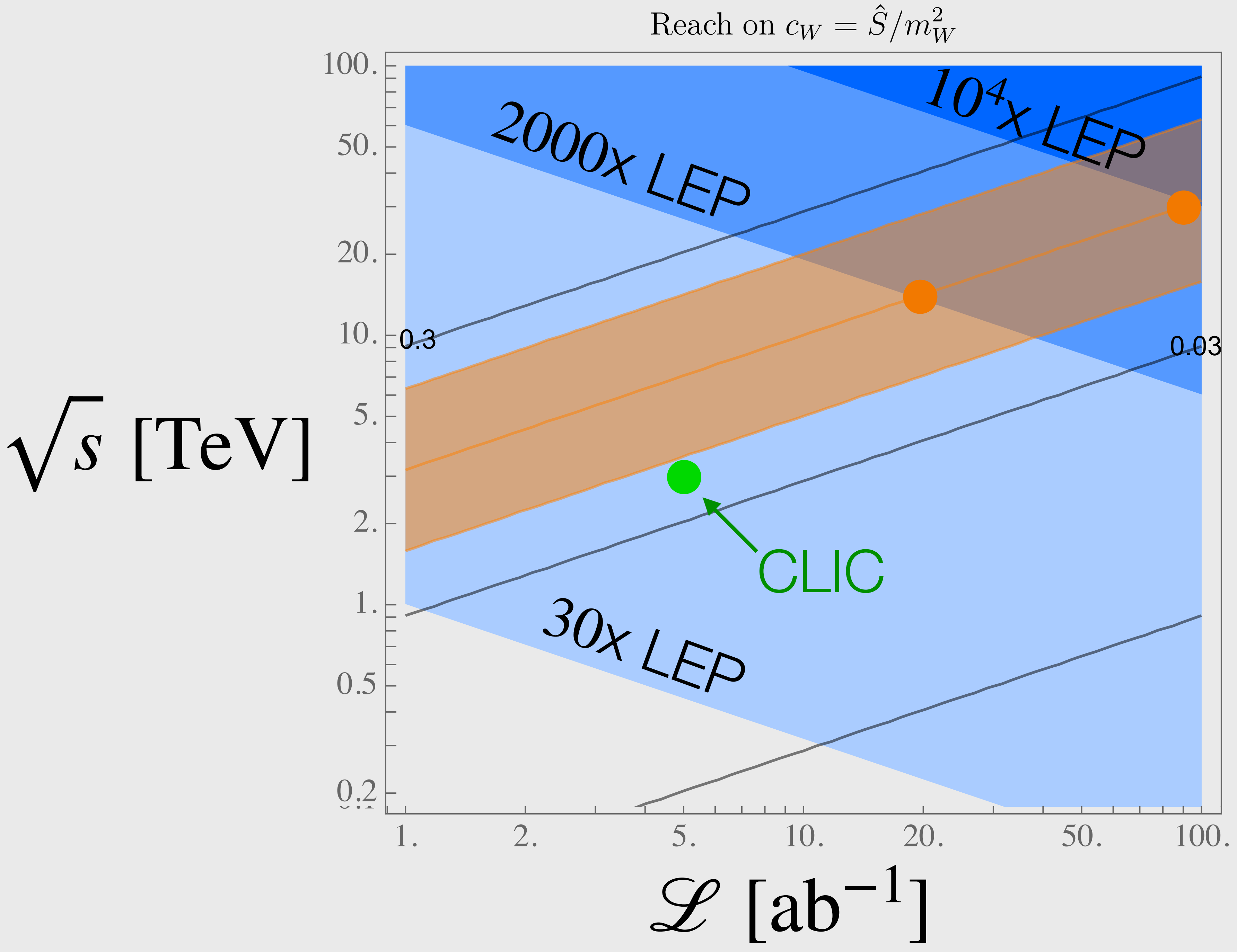


GOING TO HIGHER ENERGY WE CAN EXPLOIT "PRECISE" MEASUREMENTS AT THE 10% LEVEL, AVOIDING THE BOTTLENECK OF SYSTEMATIC UNCERTAINTIES

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

EFT EPOCH

LESSON FROM LHC

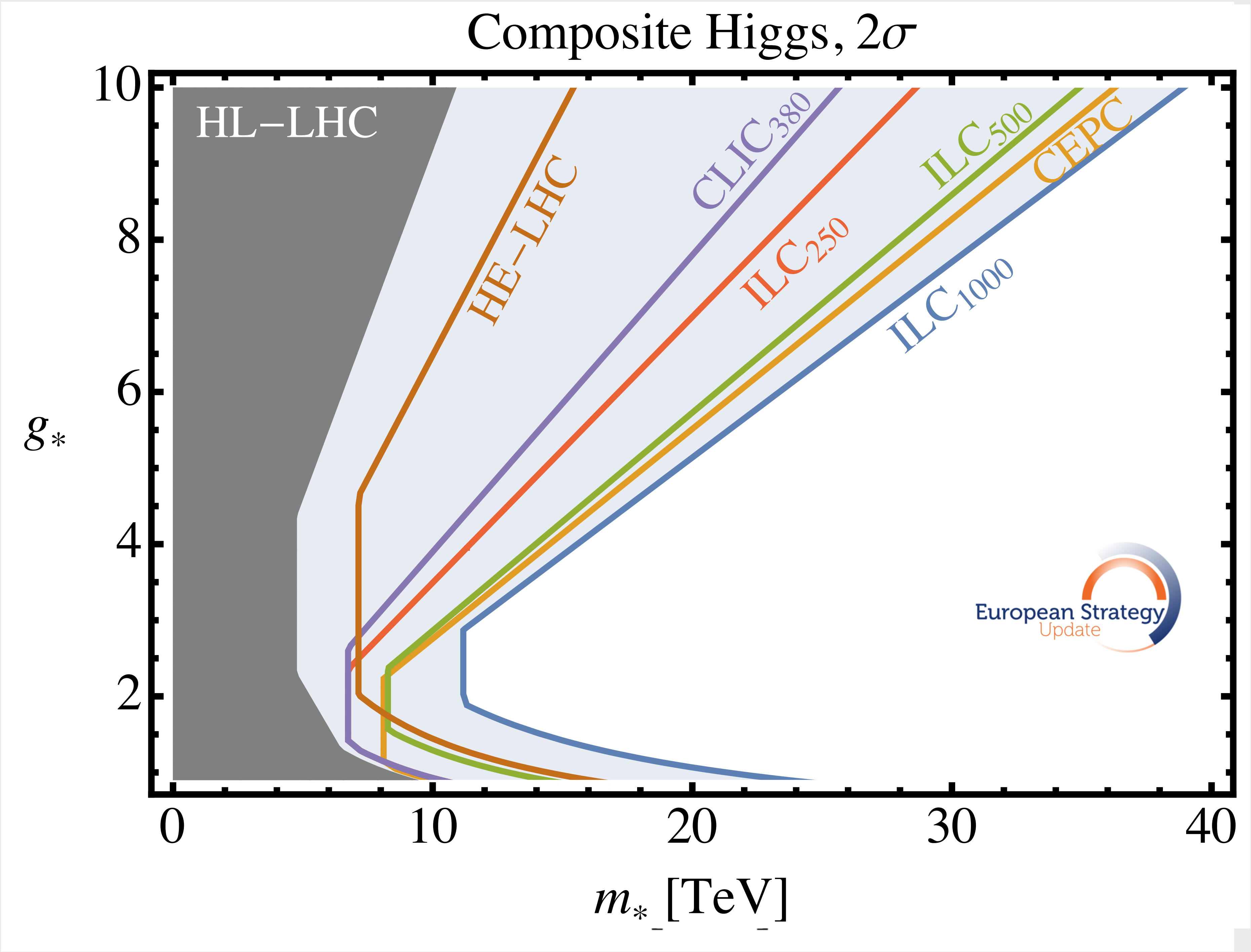


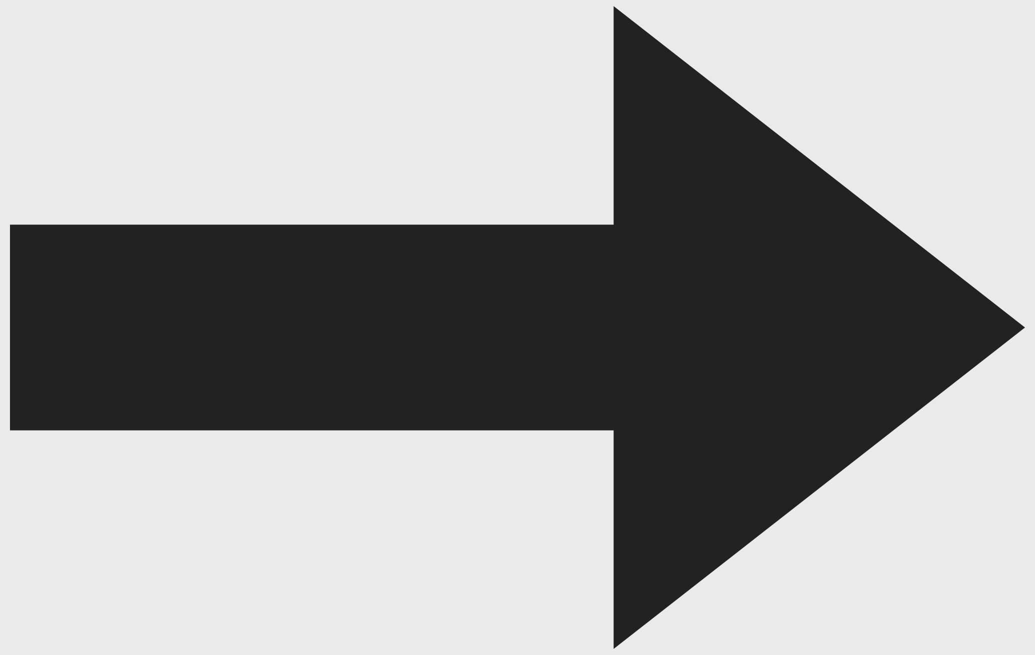
Orders of magnitude of improvement of the bunds on the mass scale of new physics

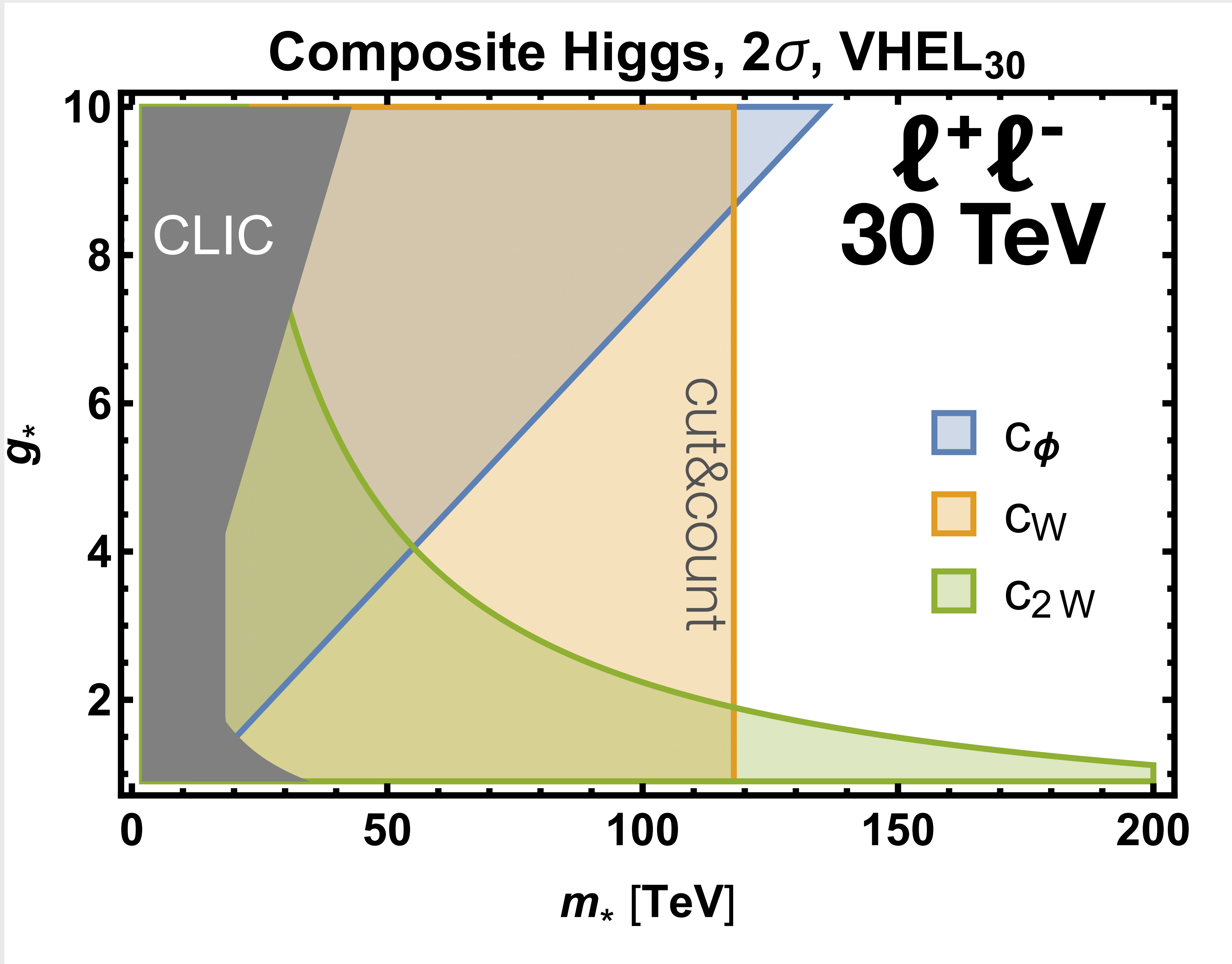
	Cross-Section @ 30 TeV	m* 95% CL	
HH	non trivial c&c analysis	60 TeV (g*/4)	$\mathcal{O}_H$
WW	pTW>7.5TeV: 180 ab	84 ⊕ 76 TeV ≃113 TeV	$a_q^{(3)}$
ZH	inclusive: 13 ab	120 TeV	$a_q^{(1)}$
ff	angular analysis	120 TeV (4/g*)	W,Y

All-round progress up to m* ~ 10^3 m_{Higgs}

Looking ahead



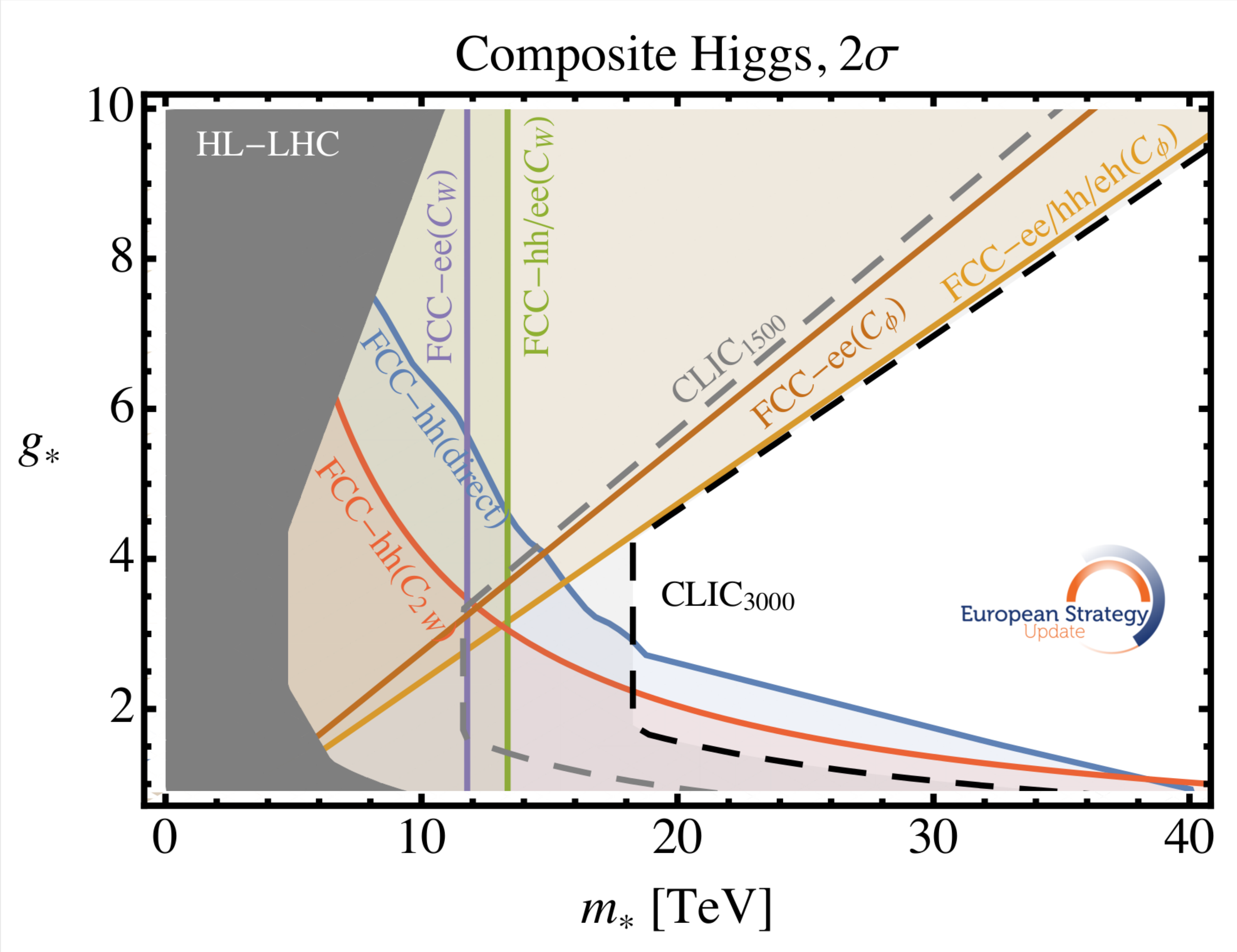




compositeness at 10 TeV-20 TeV

compositeness at 100 TeV-500 TeV

Looking ahead



compositeness at
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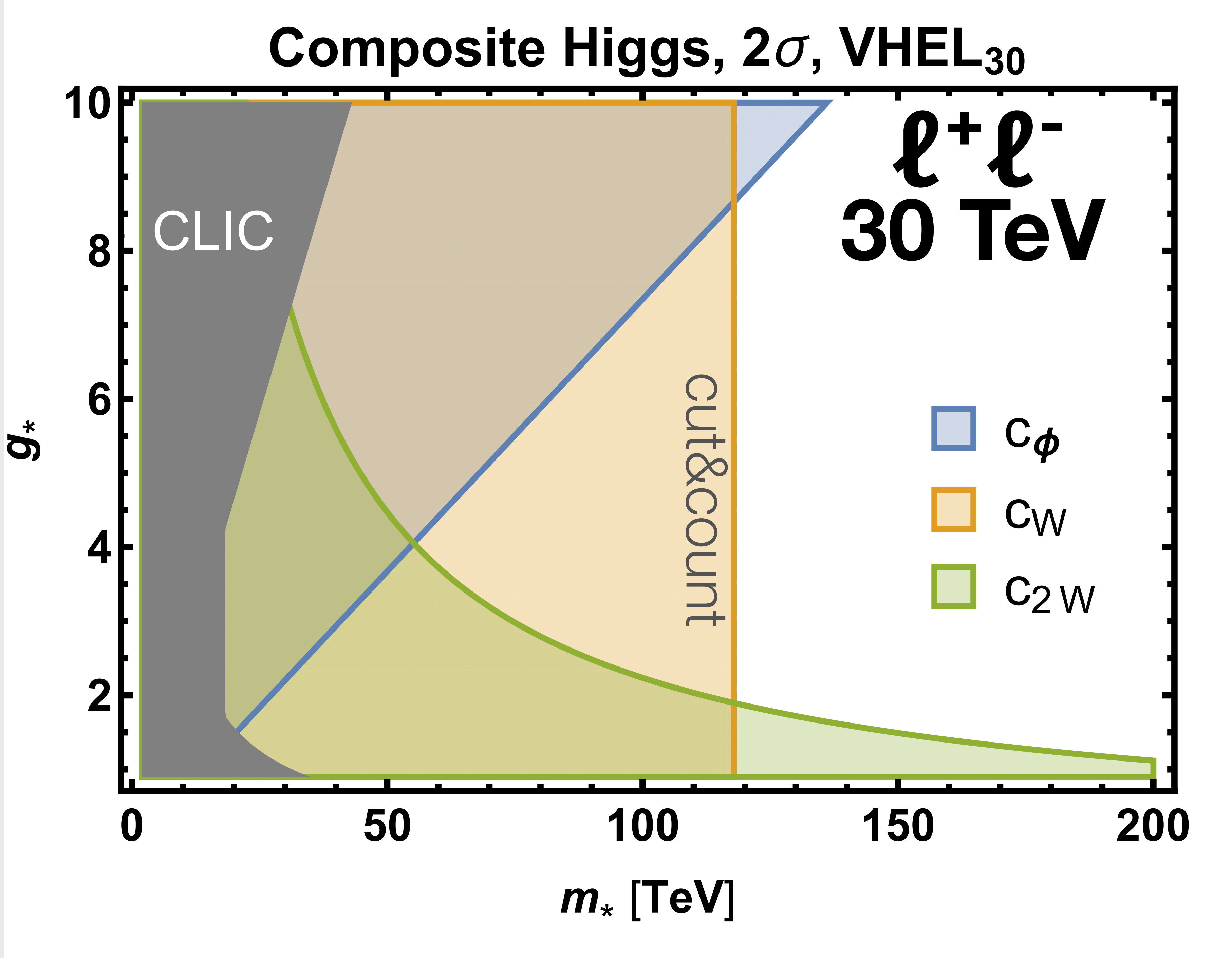

compositeness at
100 TeV-500 TeV

Wimp Dark Matter

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 $e^+e^- \to Z' \to \chi\,\chi$	0	Mono-photon

} Electroweak Precision Tests

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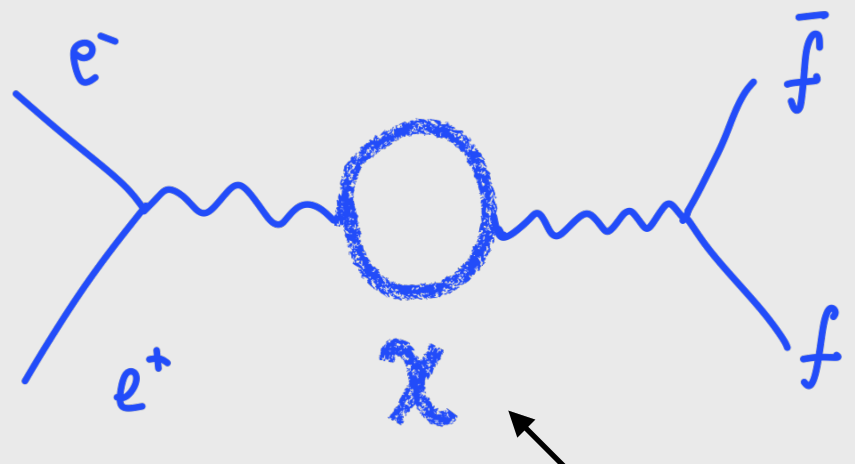
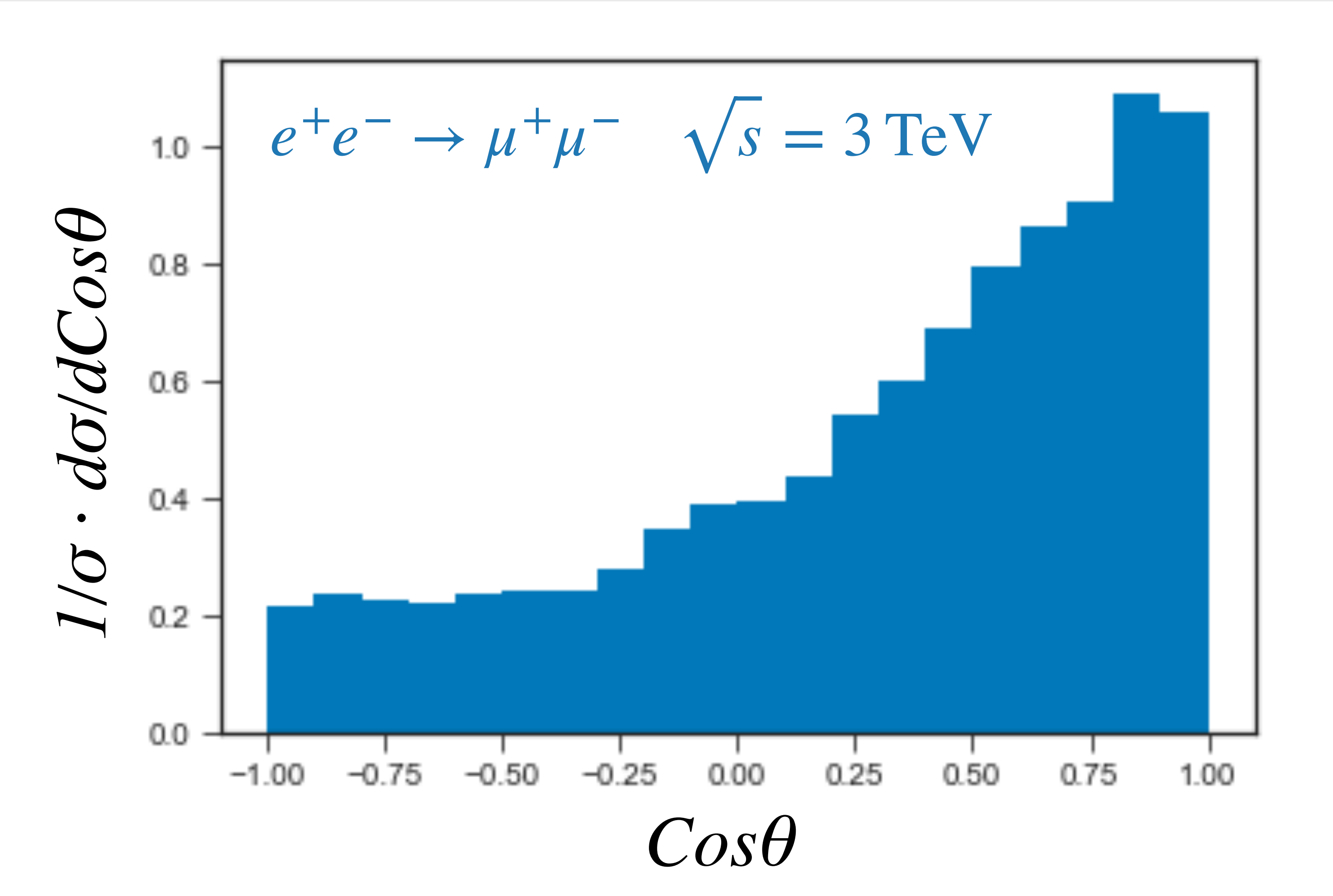
} Electroweak Precision Tests

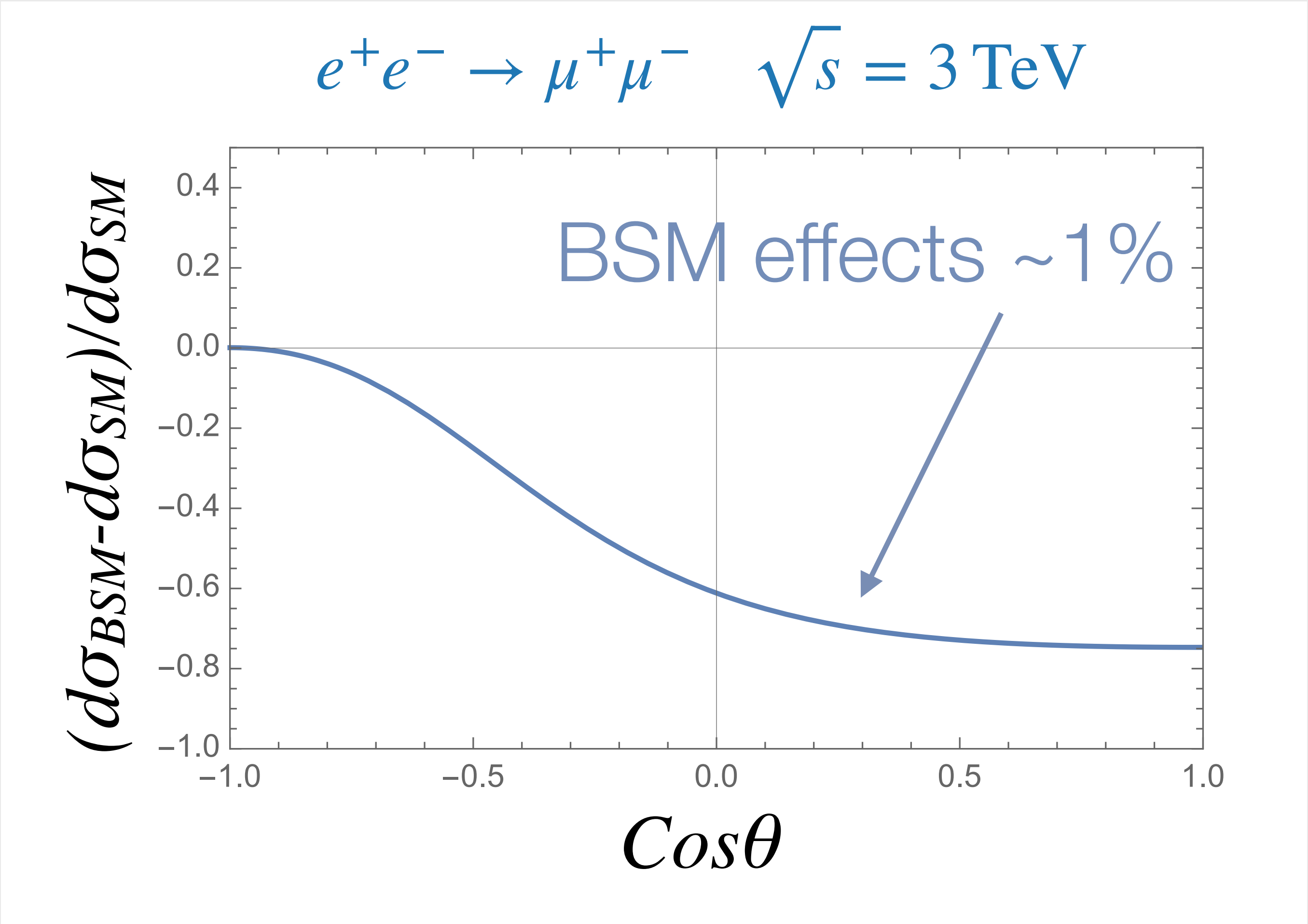
$e^+e^- \to f\bar{f}$

PRECISION | ANGULAR DISTRIBUTION



χ is heavy/light new physics

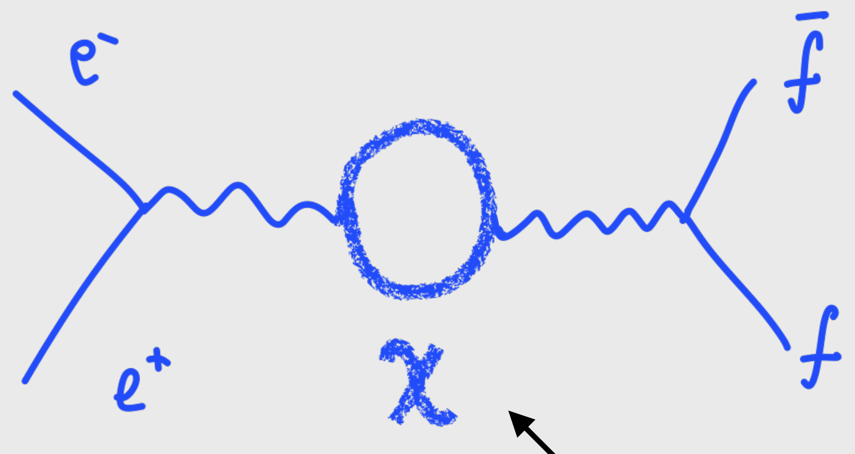




beams polarization is beneficial to increase NP effects

$e^+e^- \to f\bar{f}$

PRECISION | **ANGULAR DISTRIBUTION**



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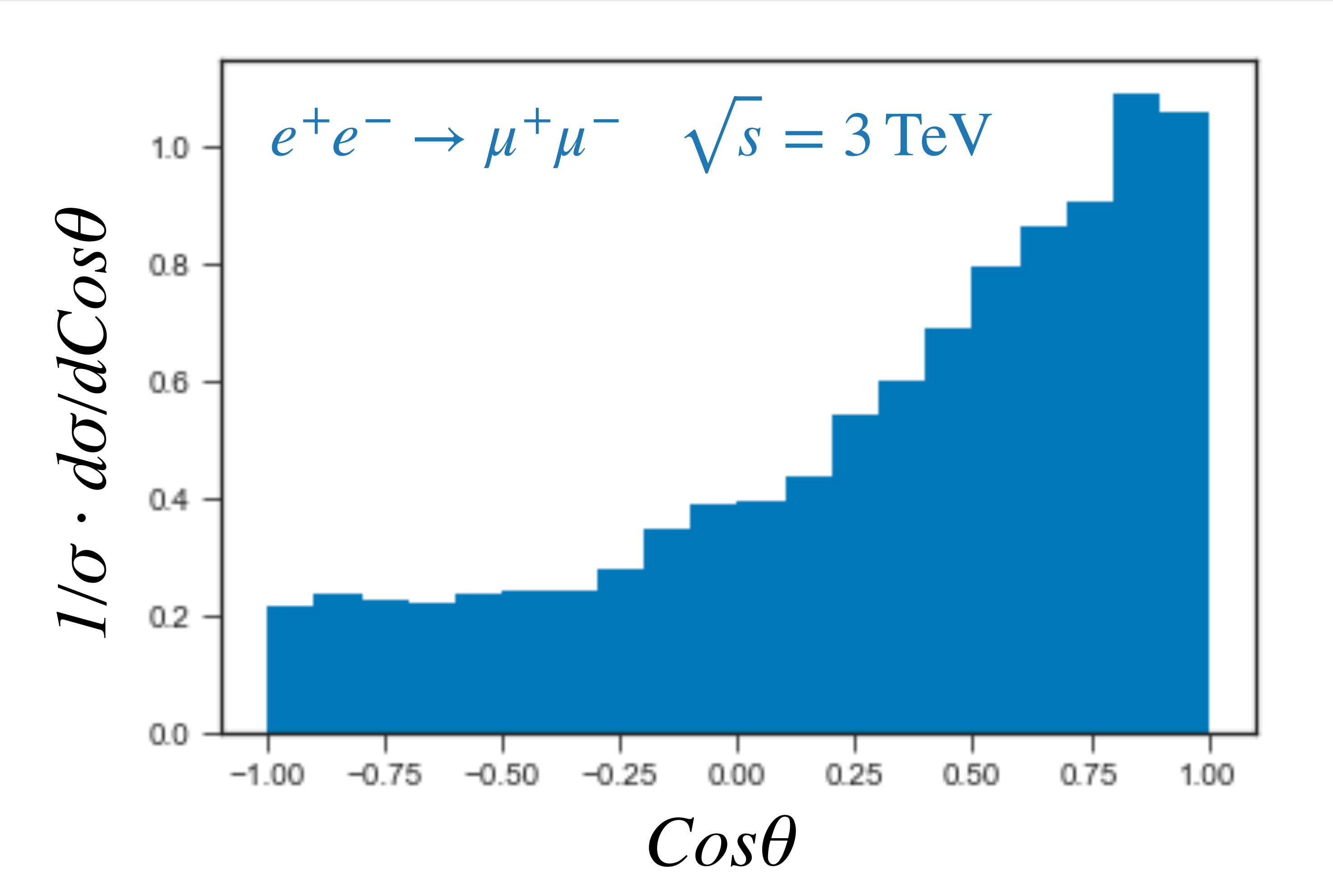

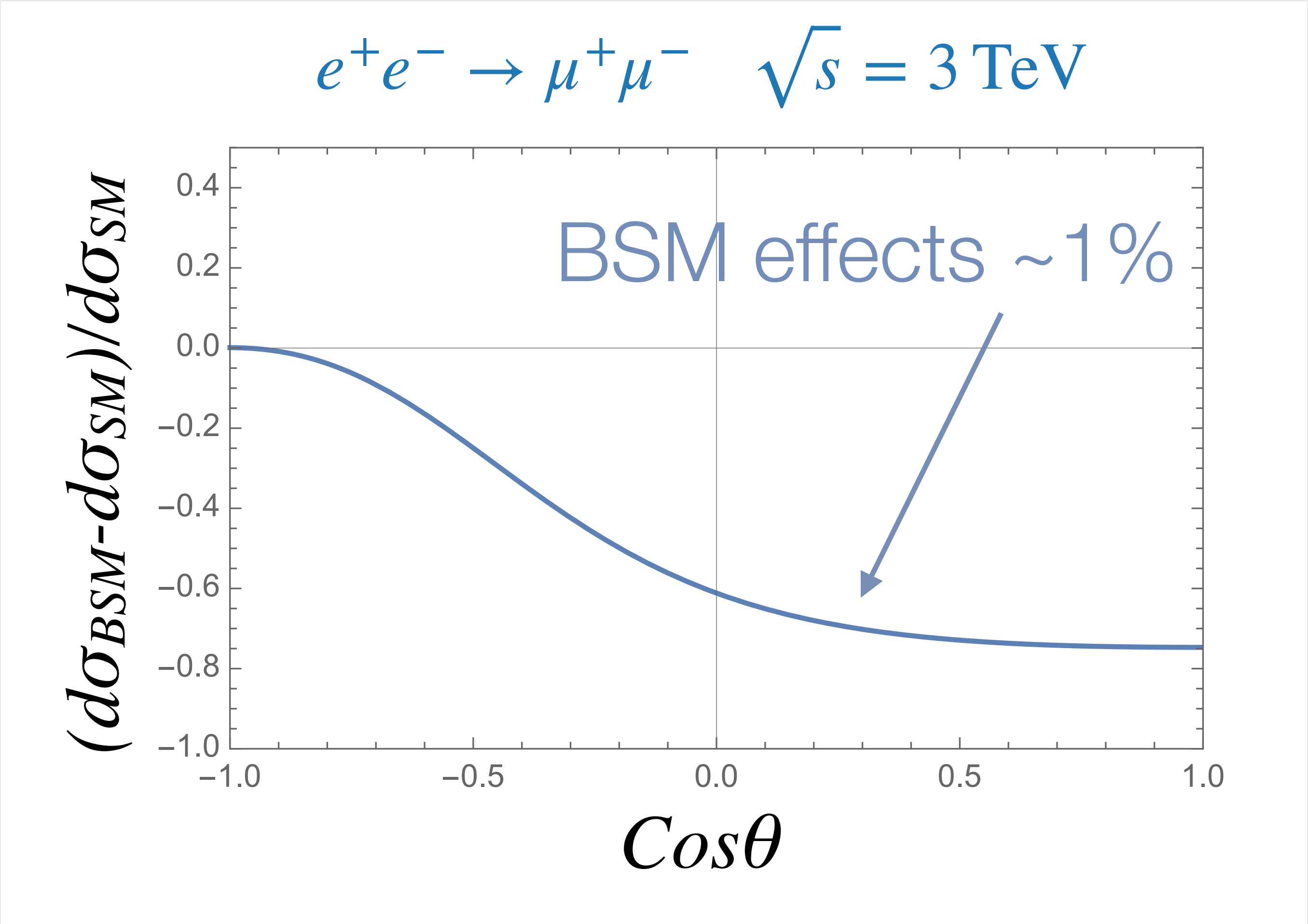

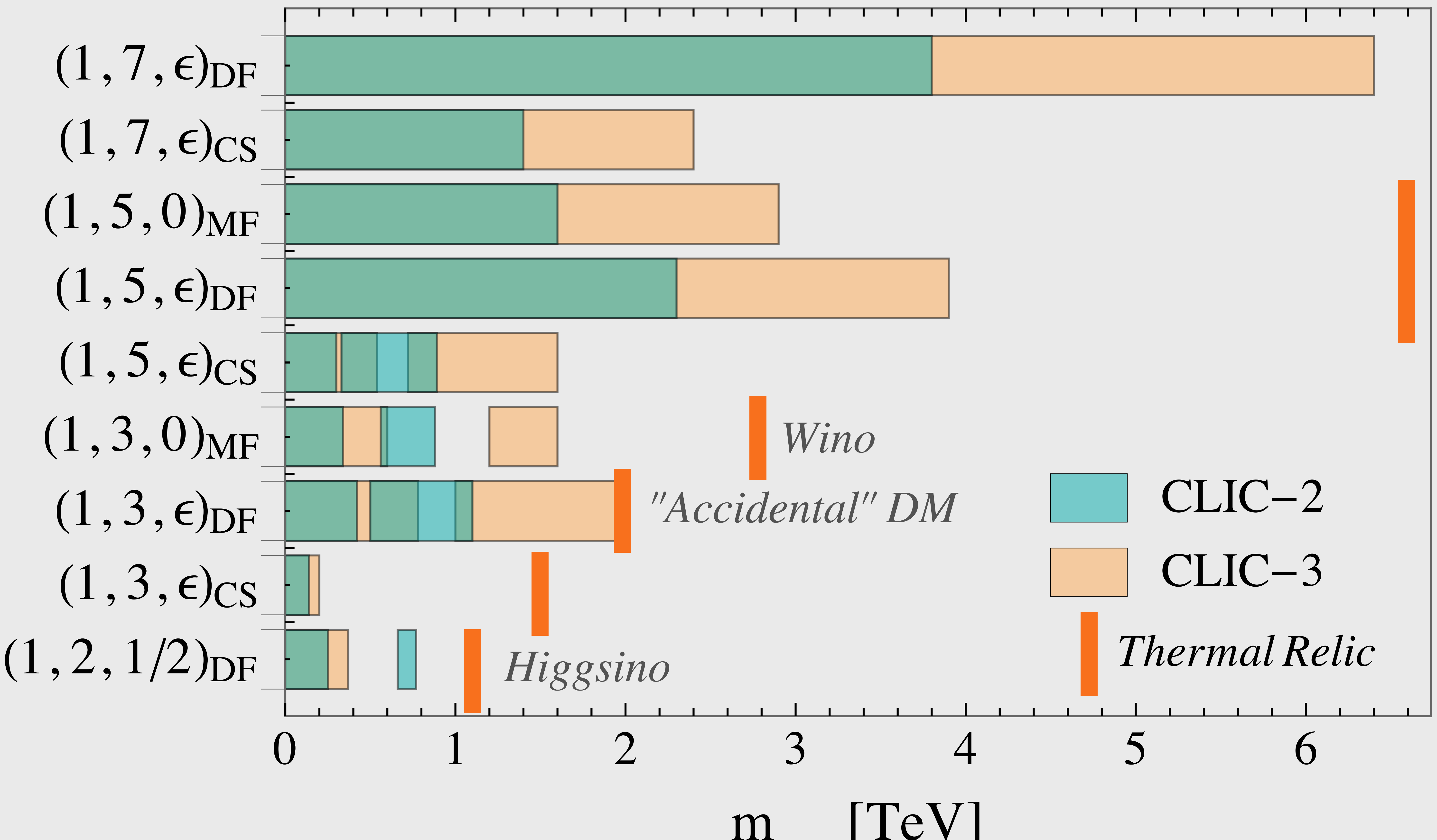

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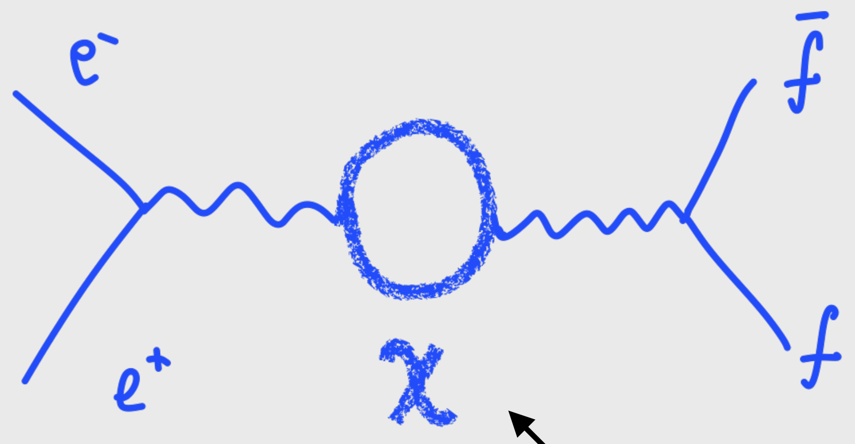
PRECISION

ANGULAR DISTRIBUTION



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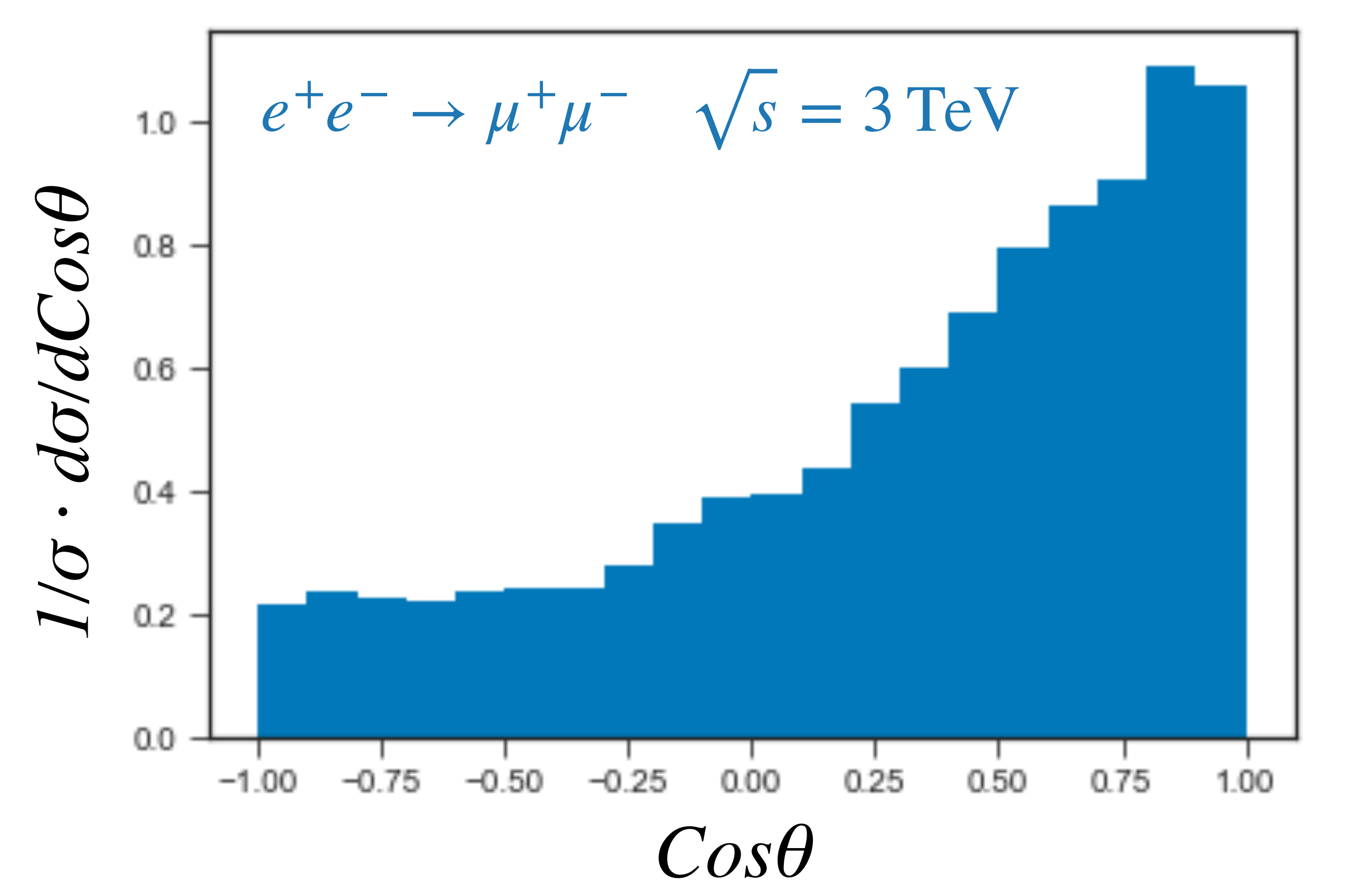

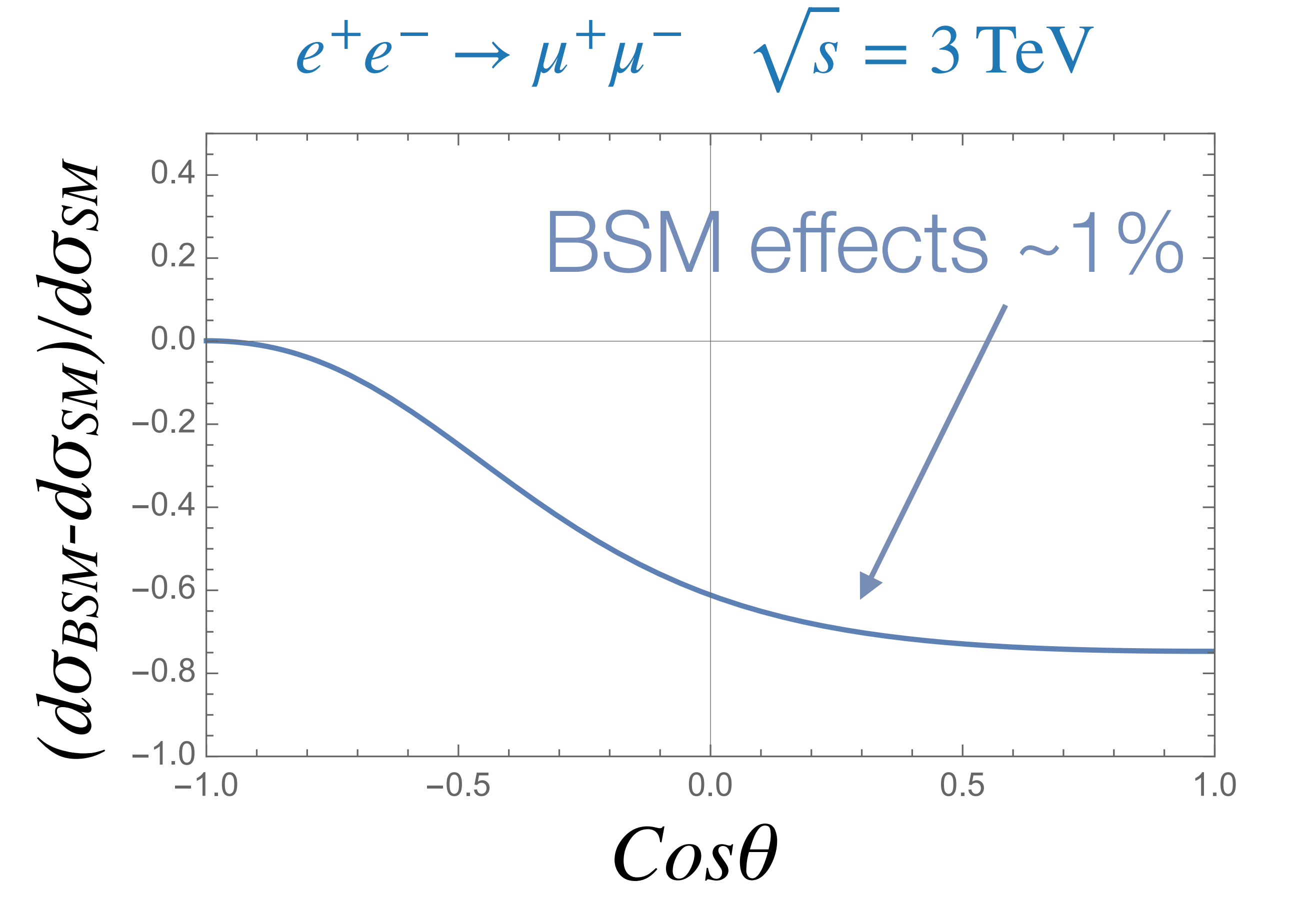

χ / m_χ [TeV]	DM	HL-LHC	HE-LHC	FCC-100	CLIC-3	Muon-14
$(1,2,1/2)_{DF}$	1.1	–	–	–	0.4	0.6
$(1,3,\epsilon)_{CS}$	1.6	–	–	–	0.2	0.2
$(1,3,\epsilon)_{DF}$	2.0	–	0.6	1.5	0.8 & [1.0, 2.0]	2.2 & [6.3, 7.1]
$(1,3,0)_{MF}$	2.8	–	–	0.4	0.6 & [1.2, 1.6]	1.0
$(1,5,\epsilon)_{CS}$	6.6	0.2	0.4	1.0	0.5 & [0.7,1.6]	1.6
$(1,5,\epsilon)_{DF}$	6.6	1.5	2.8	7.1	3.9	11
$(1,5,0)_{MF}$	14	0.9	1.8	4.4	2.9	3.5 & [5.1, 8.7]
$(1,7,\epsilon)_{CS}$	16	0.6	1.3	3.2	2.4	2.5 & [3.5, 7.4]
$(1,7,\epsilon)_{DF}$	16	2.1	4.0	11	6.4	18

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

beams polarization is beneficial to increase NP effects

Electroweak Dark Matter: LSP (+NLSP)

Electroweak Dark Matter: LSP (+NLSP)

Δm

Model	Δm scale	Search channel
Wide open spectra		Generic leptons+missing momentum
Co-annihilation		Soft-objects + missing momentum
	GeV	
WIMP-like multiplet Accidental Dark Matter		**Short (disappearing) tracks**
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} Electroweak Precision Tests

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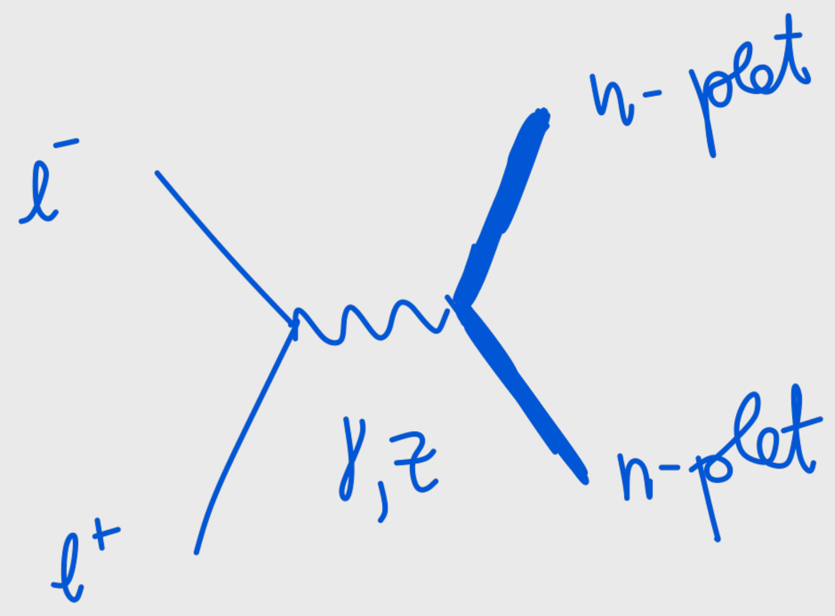
Degenerate EW multiplets

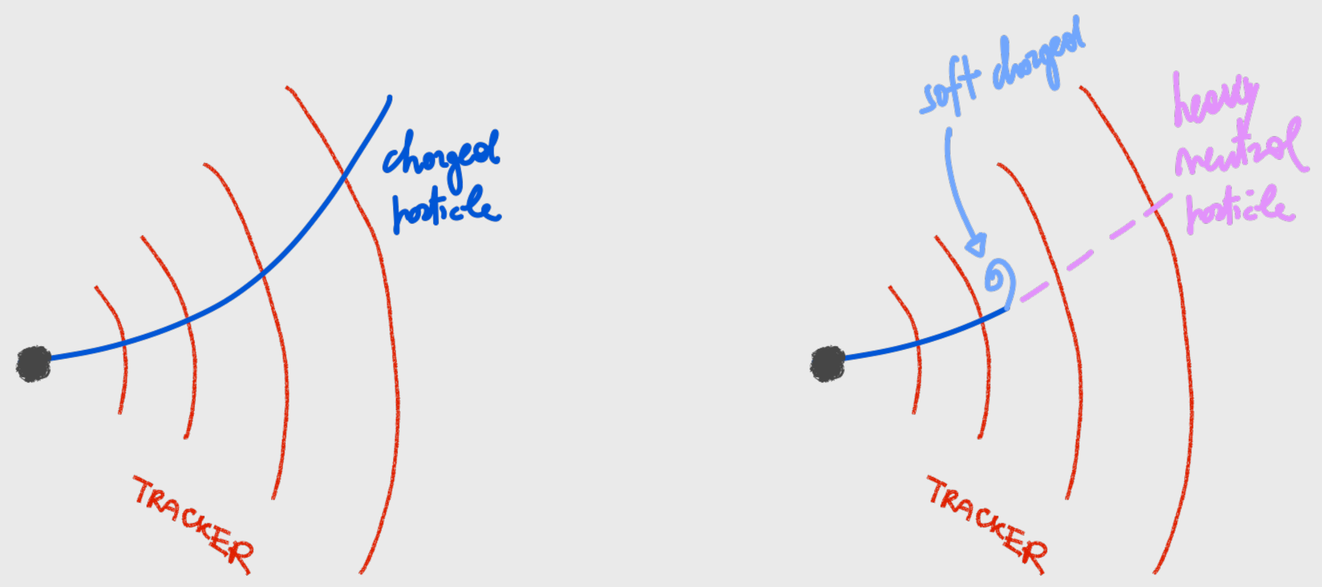
STUB-TRACKS | **EXTRAPOLATION FROM CLIC**

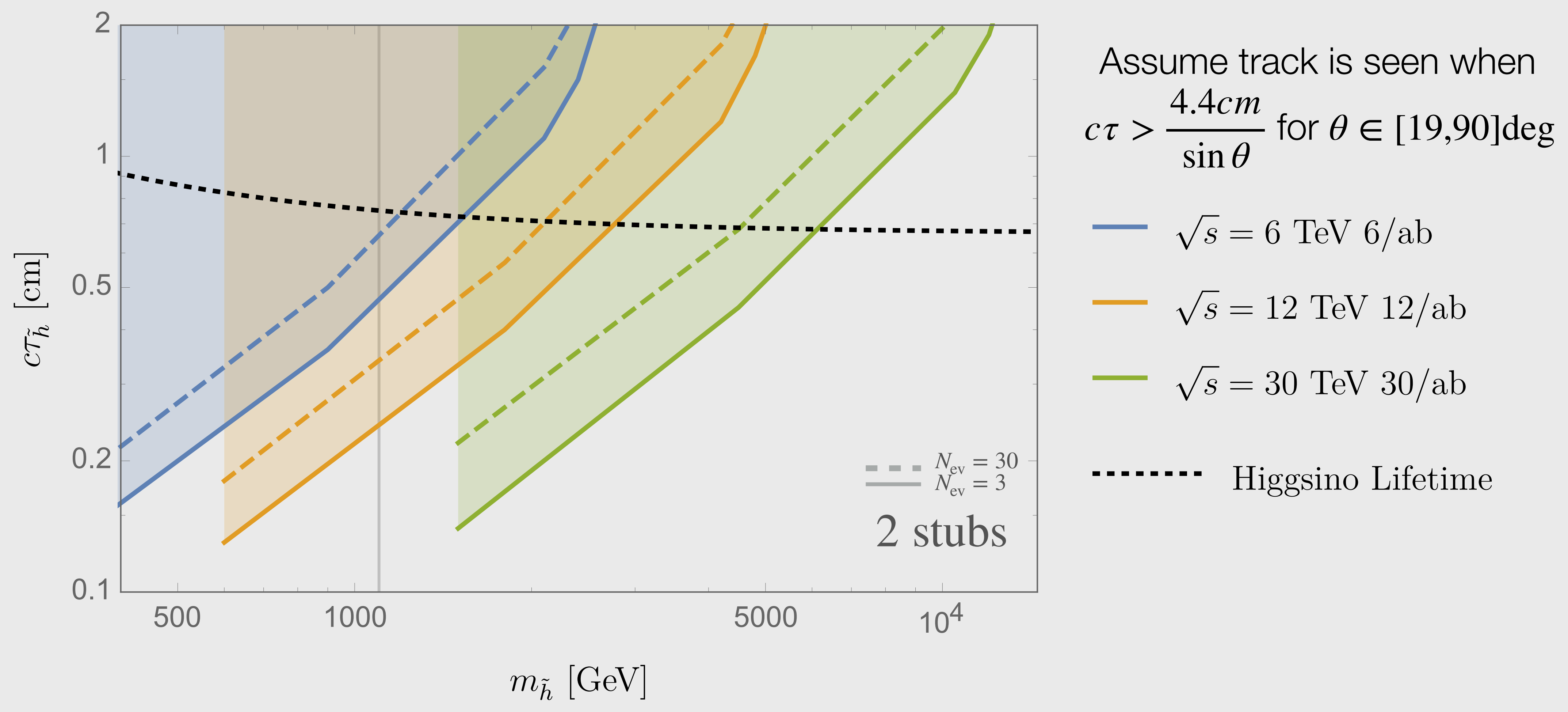
- Heavy n-plet of SU(2)
- Mass splitting ~ $\alpha_W\, m_W$ ~ 0.1 GeV - GeV



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

- Heavily subject to detector design issues
- Even in CLIC needs full detector simulation





Full detector simulation study

Long-lived particles at CLIC

Ulrike Schnoor (CERN)
Erica Brondolin, Cecilia Ferrari, Emilia Leogrande
on behalf of the CLICdp collaboration

LCWS 2019

Long-lived particle reconstruction at CLIC

30 Oct 2019, 15:08
20m
Room1 (Conference building)

Parallel : Physics/Detect...

Speaker

Ulrike Schnoor

Primary author

Ulrike Schnoor

Presentation Materials

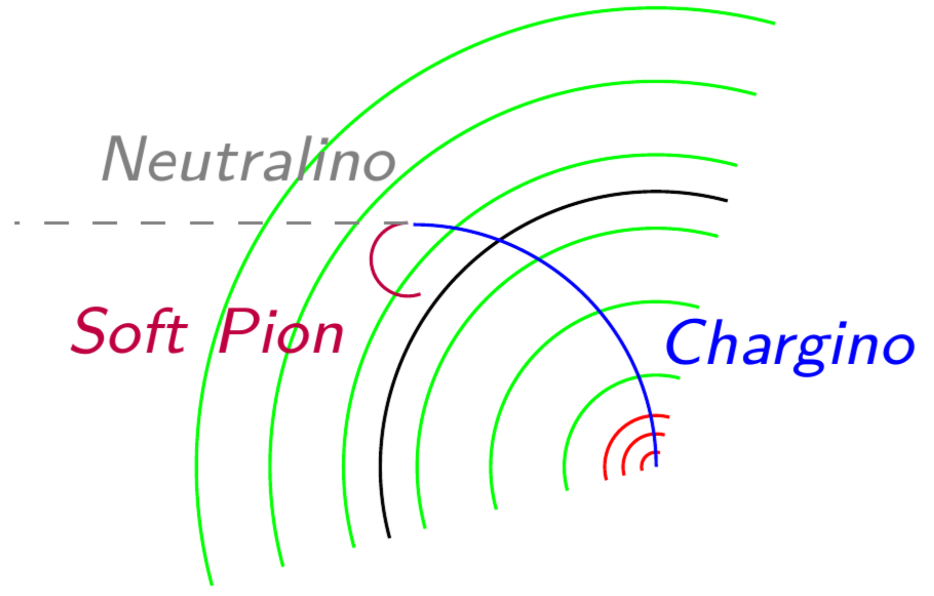
UlrikeSchnoor_chargedLLP_CLIC3TeV.pdf

Analysis strategy

Stub track analysis at 3 TeV with CLICdet

Signal selection

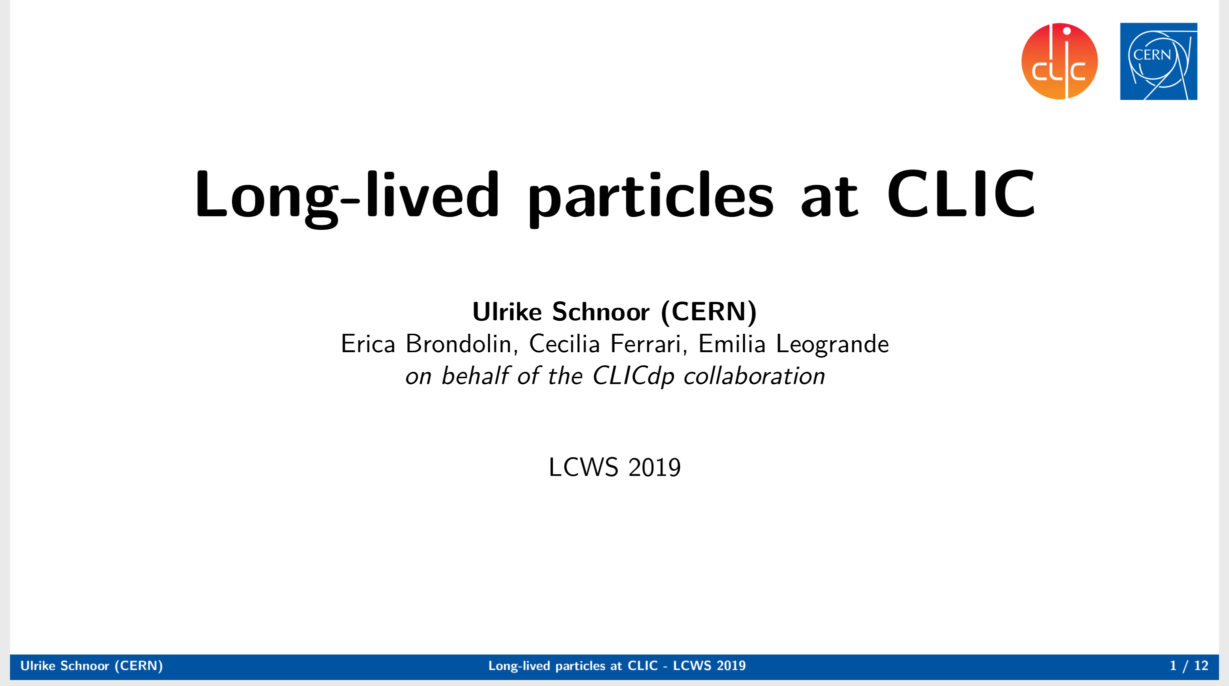
- Stub track candidate definition:
  - at least four hits in the tracking system
  - disappearing within the tracking system volume
  - no energy deposition in the calorimeter
  - prompt, isolated track
  - minimum transverse momentum
  - dE/dx requirement
- At least one stub candidate per event
- Additional: Requirements on soft displaced pion(s)
- Additional: Requirements on additional photons



Backgrounds:

- Beam-induced $\gamma\gamma \to$ hadrons:
  - algorithmic
  - split tracks
  - conversion
- final states with low multiplicity of isolated leptons

Full detector simulation study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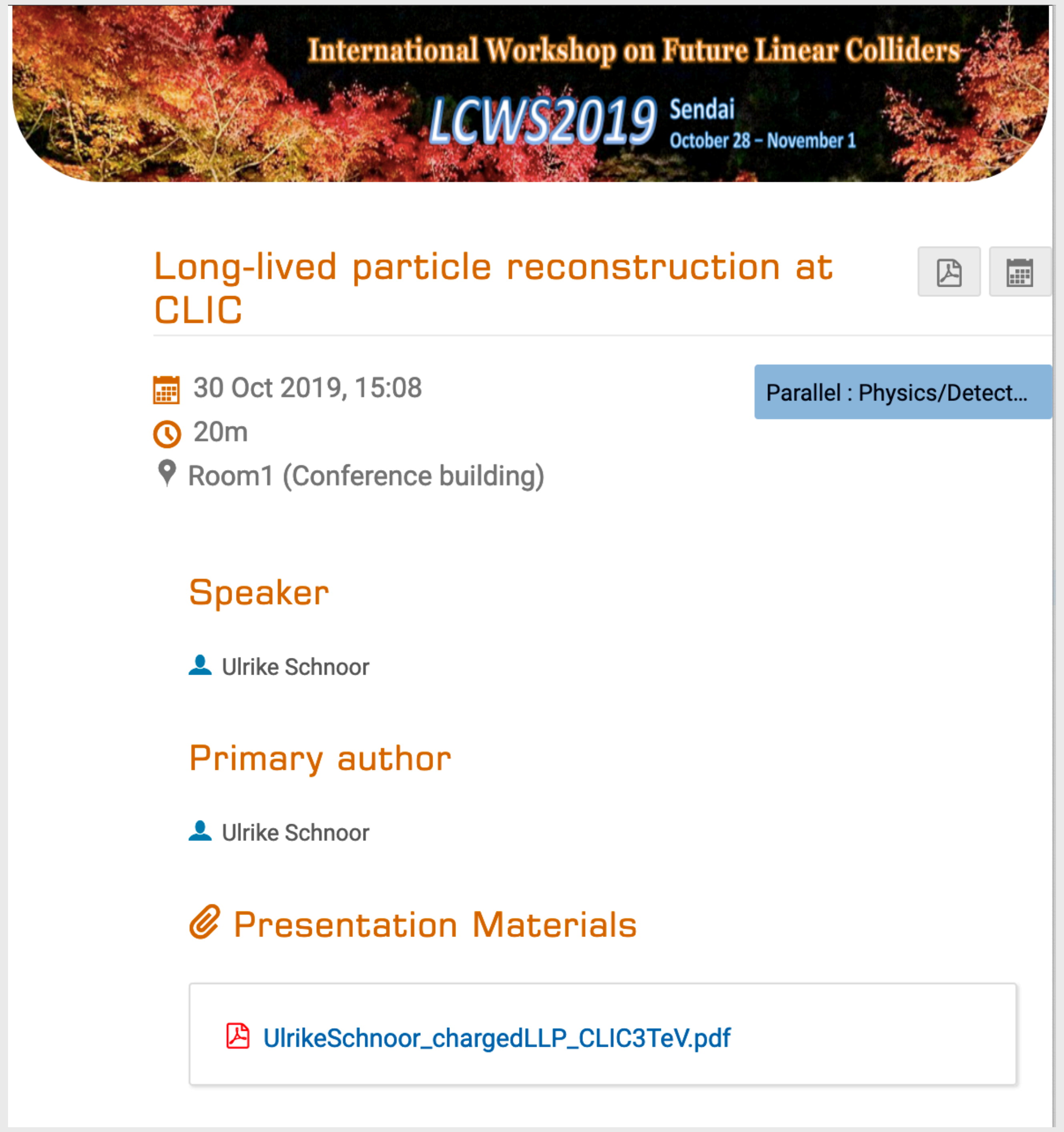
Ulrike Schnoor (CERN) Long-lived particles at CLIC - LCWS 2019 1 / 12


International Workshop on Future Linear Colliders
LCWS2019 Sendai October 28 – November 1

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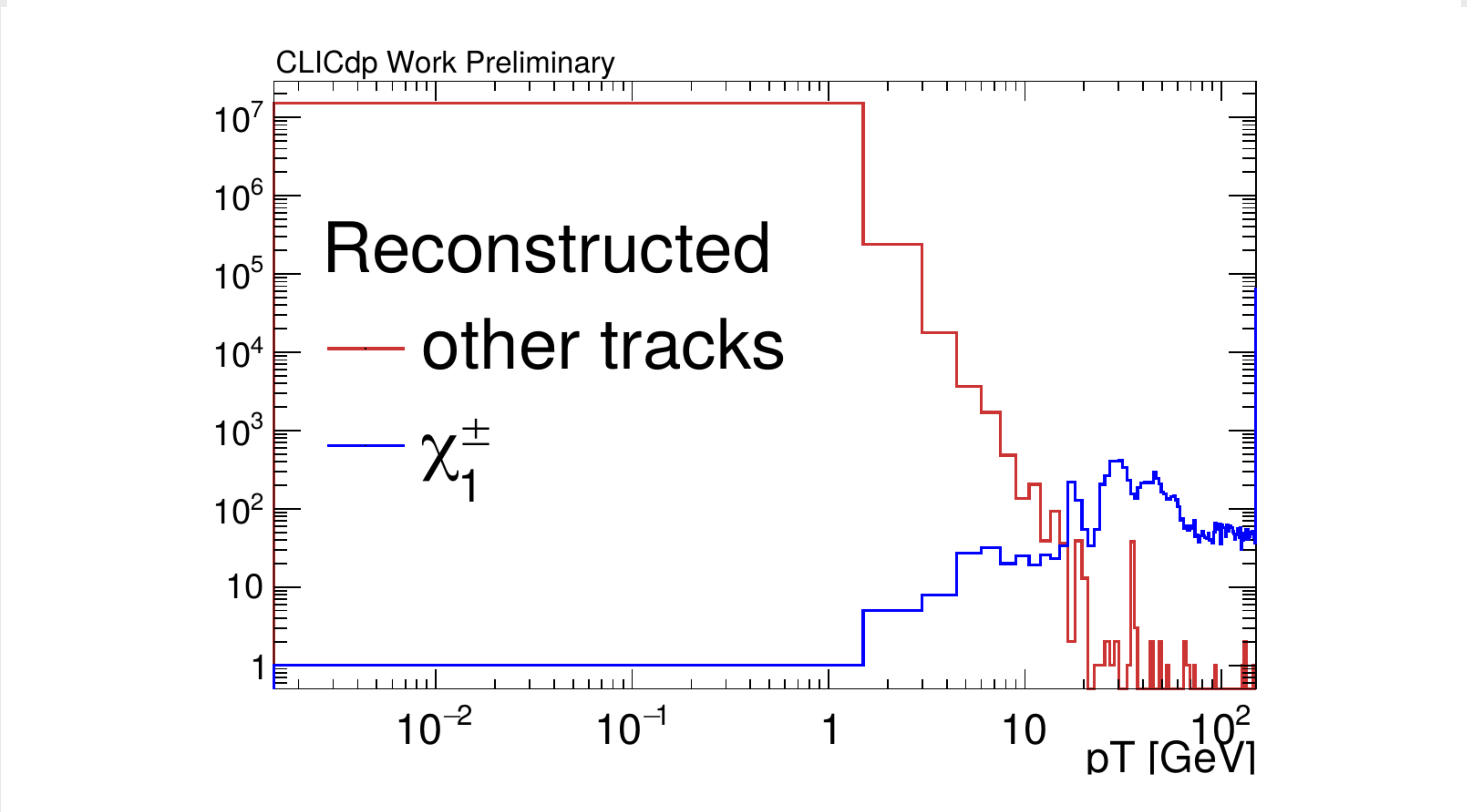
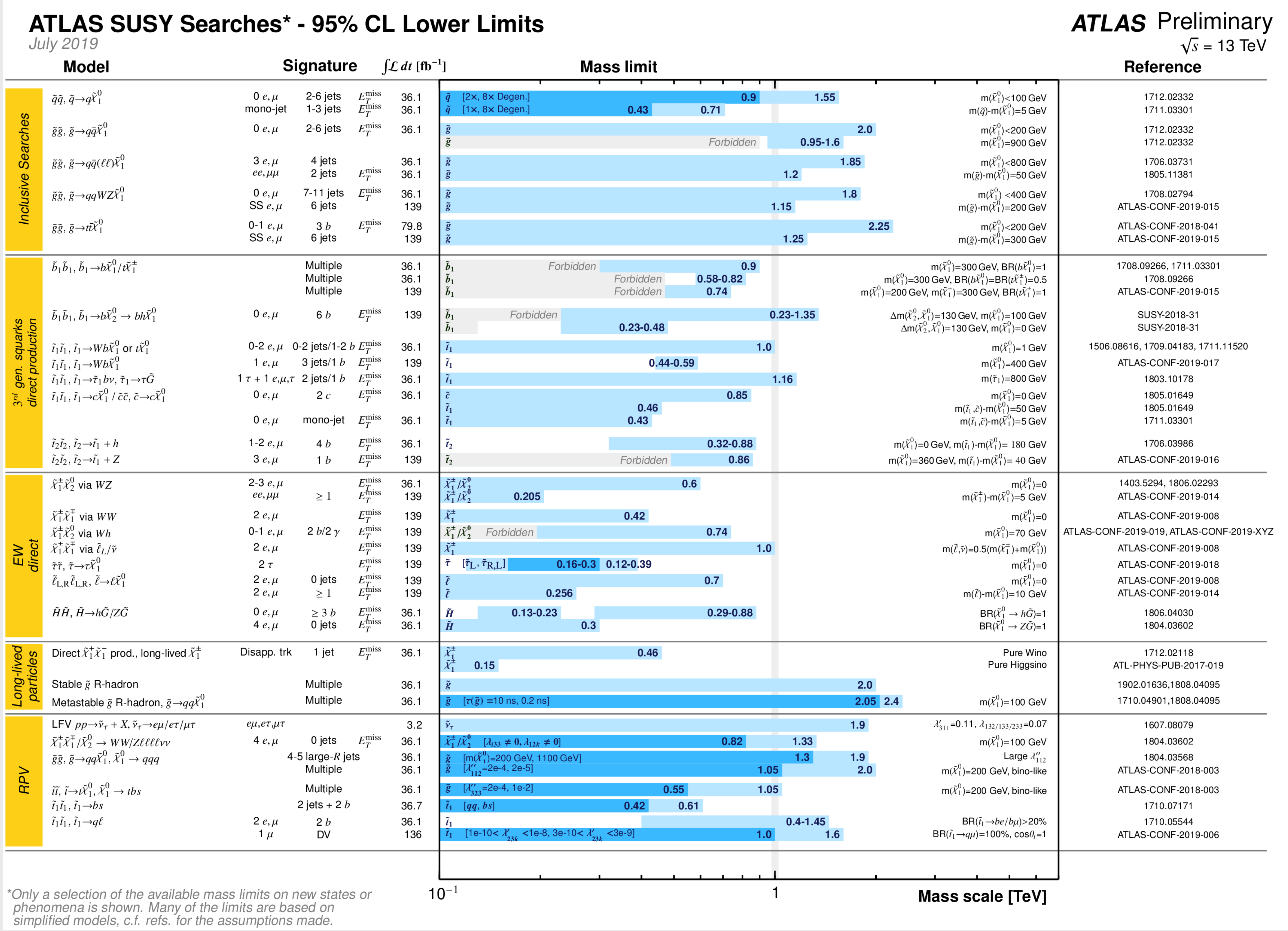
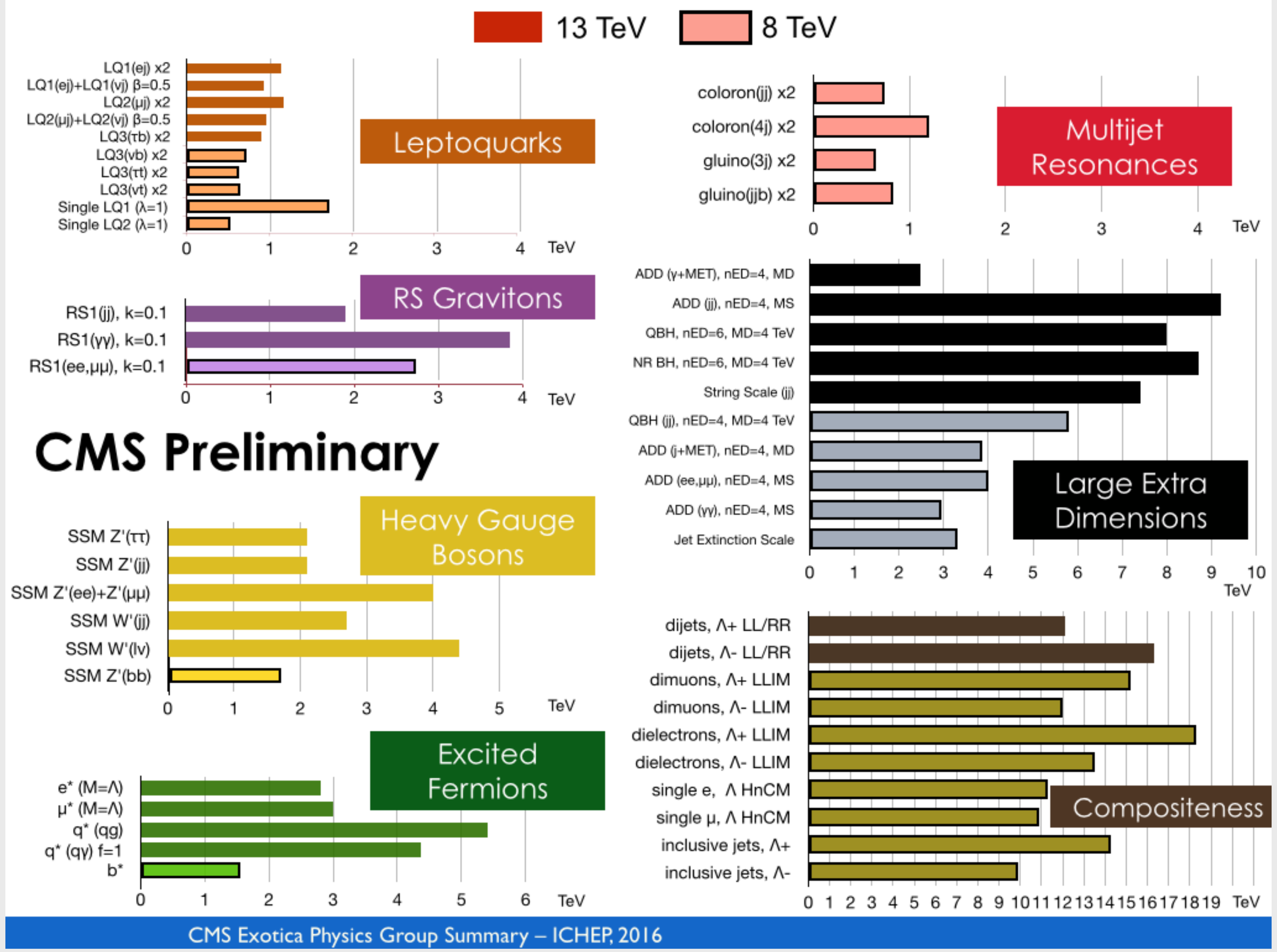


LHC ruled out new physics at Λ TeV …

LHC ruled out new physics at the TeV …

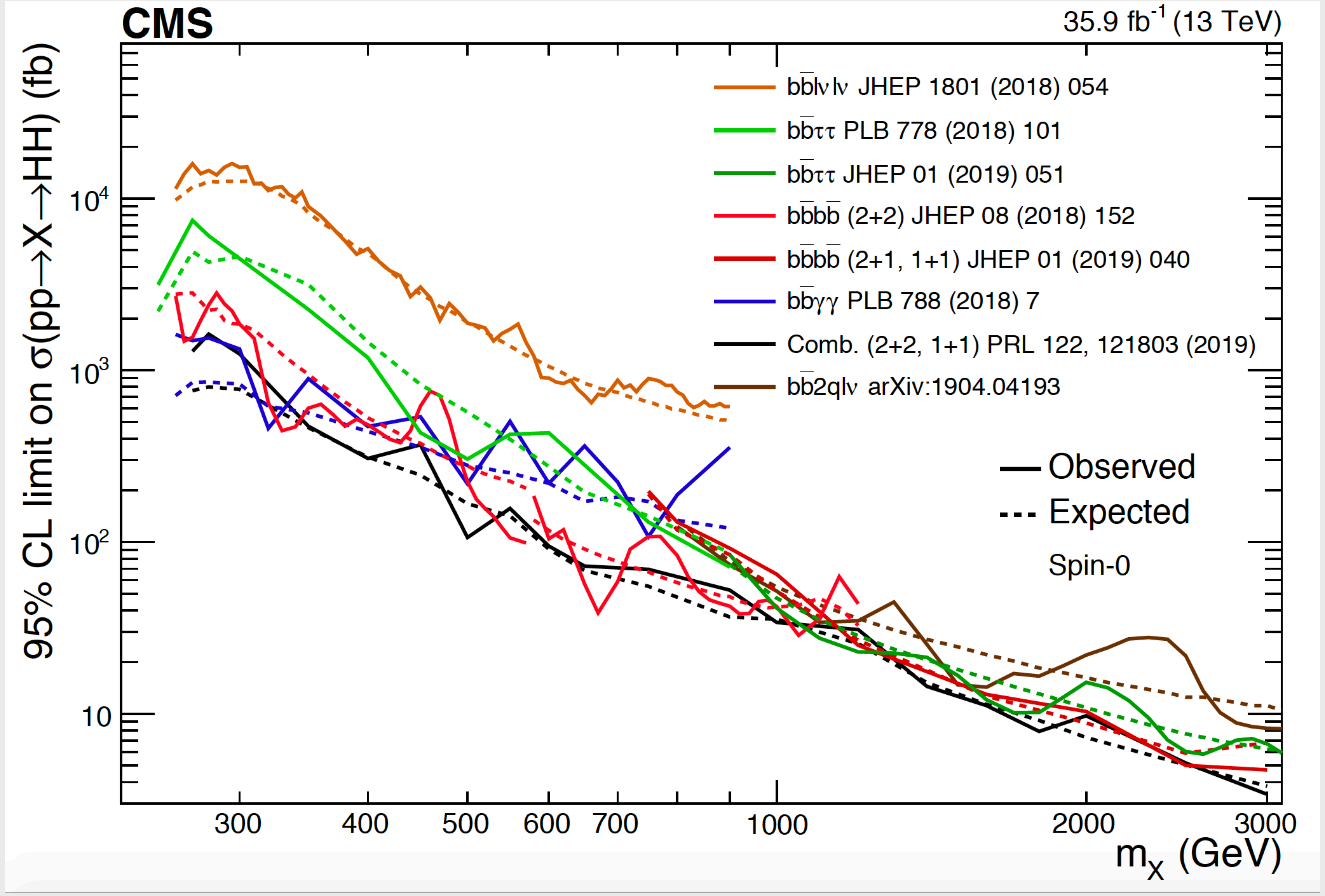
SUMMARY OF THE SUMMARIES





What about electroweak scalars?

SINGLETS ARE ELUSIVE



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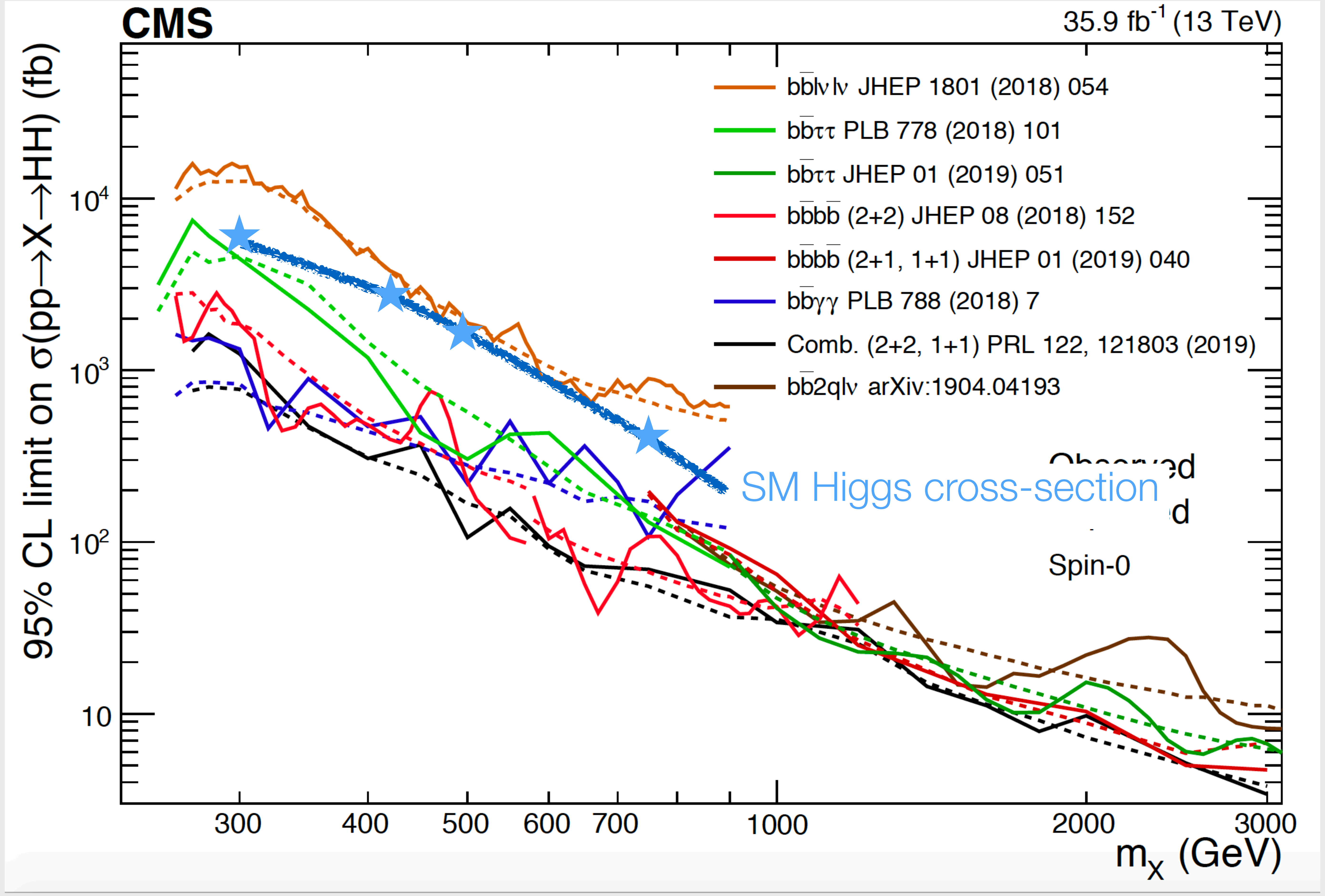

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What about electroweak scalars?

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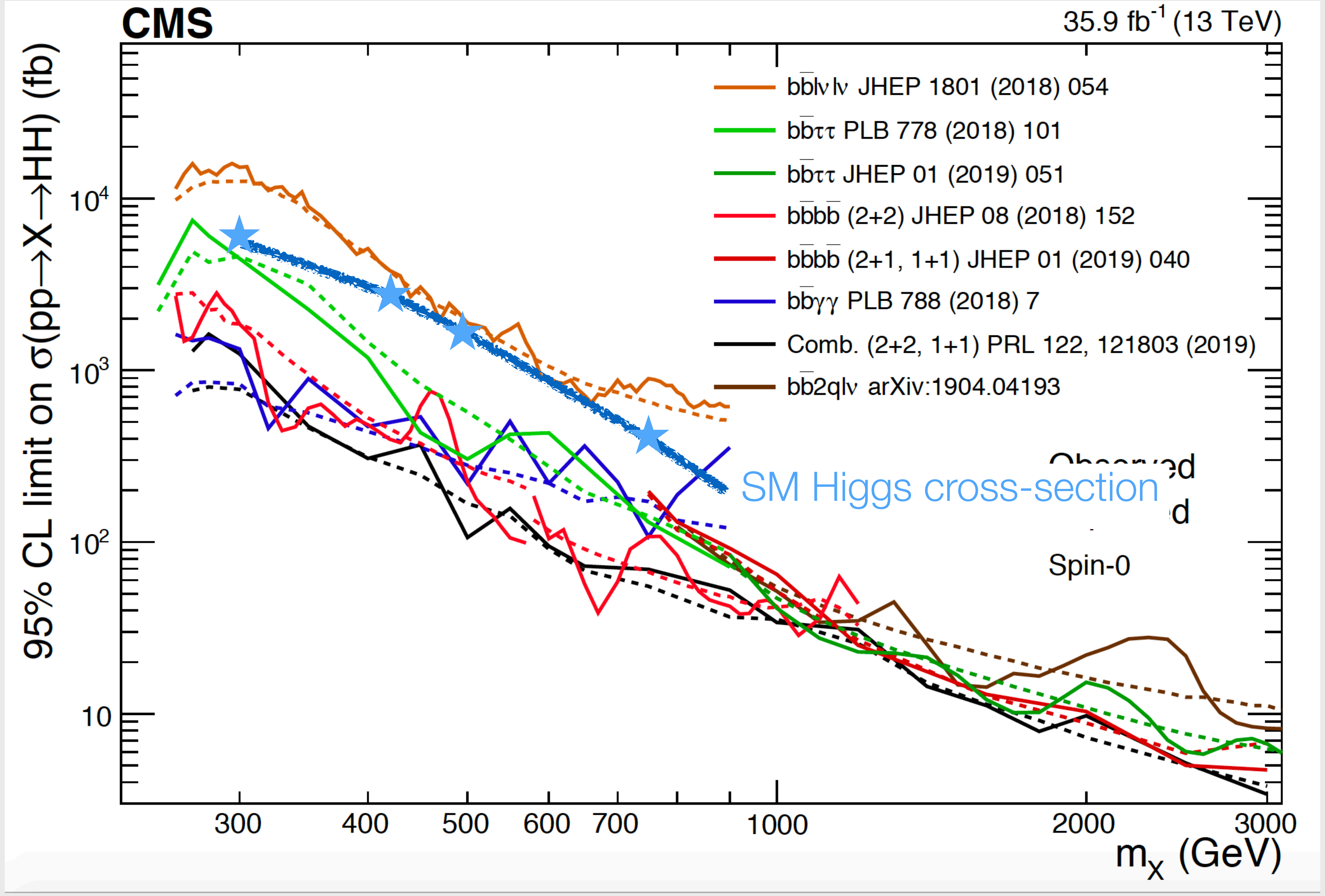
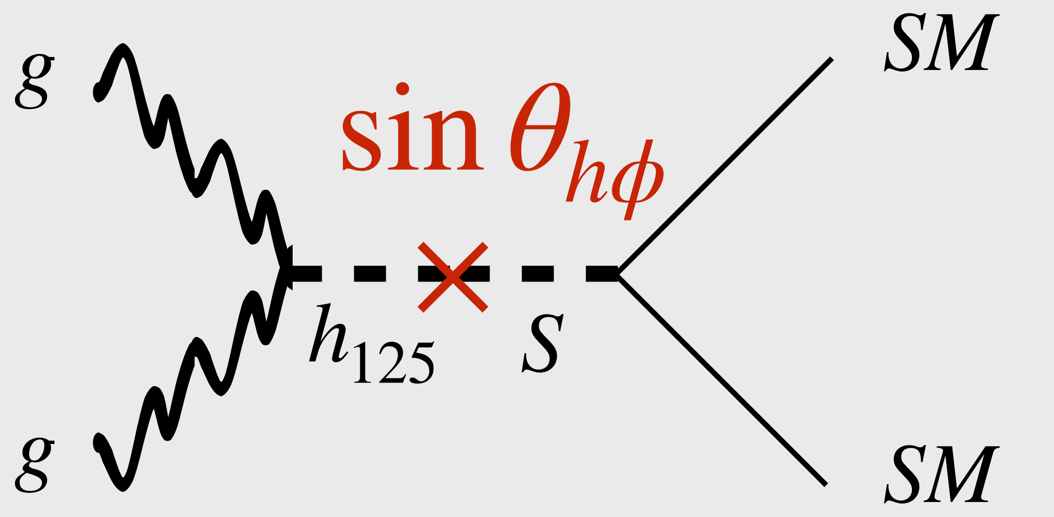


$$\sigma(\phi) \sim \sin^2\theta_{h\phi} \cdot \sigma(h_{SM} \text{ with } m_\phi)$$



$$\Rightarrow \sin\theta_{h\phi} \lesssim 0.3$$

$$\sin\theta_{h\phi} \simeq \left(\frac{m_h}{m_\phi}\right)^\alpha \Rightarrow m_\phi \simeq 2 \div 3 \cdot m_h$$

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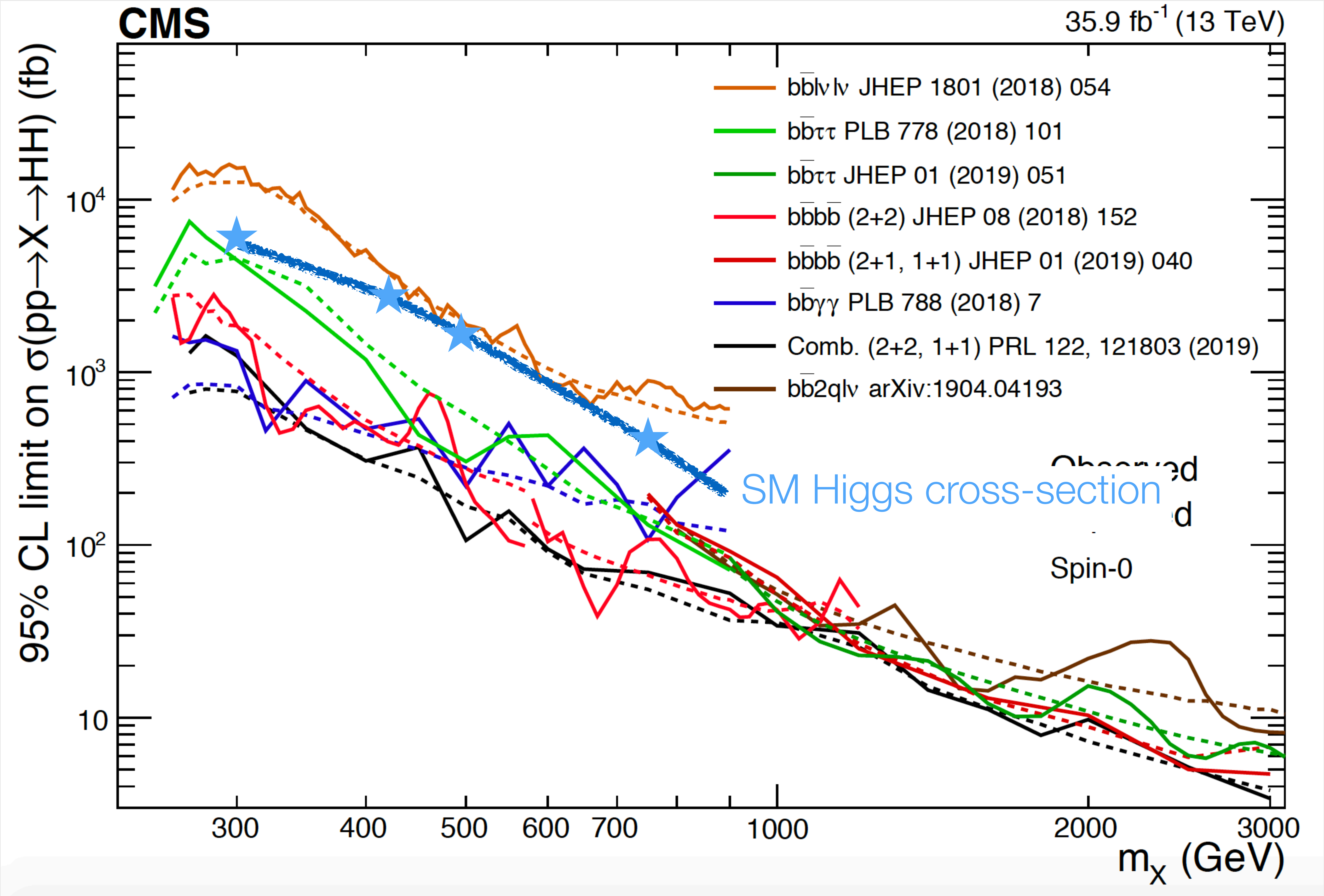

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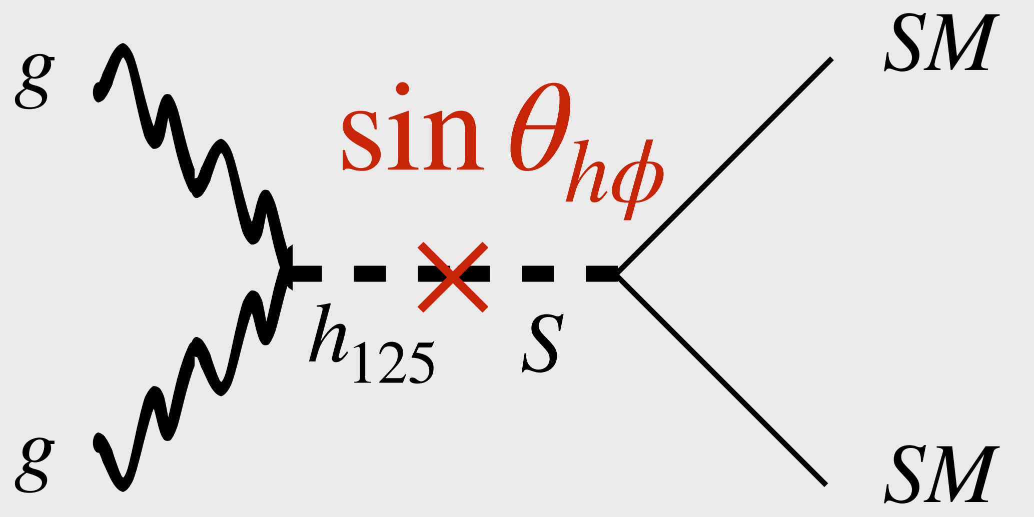

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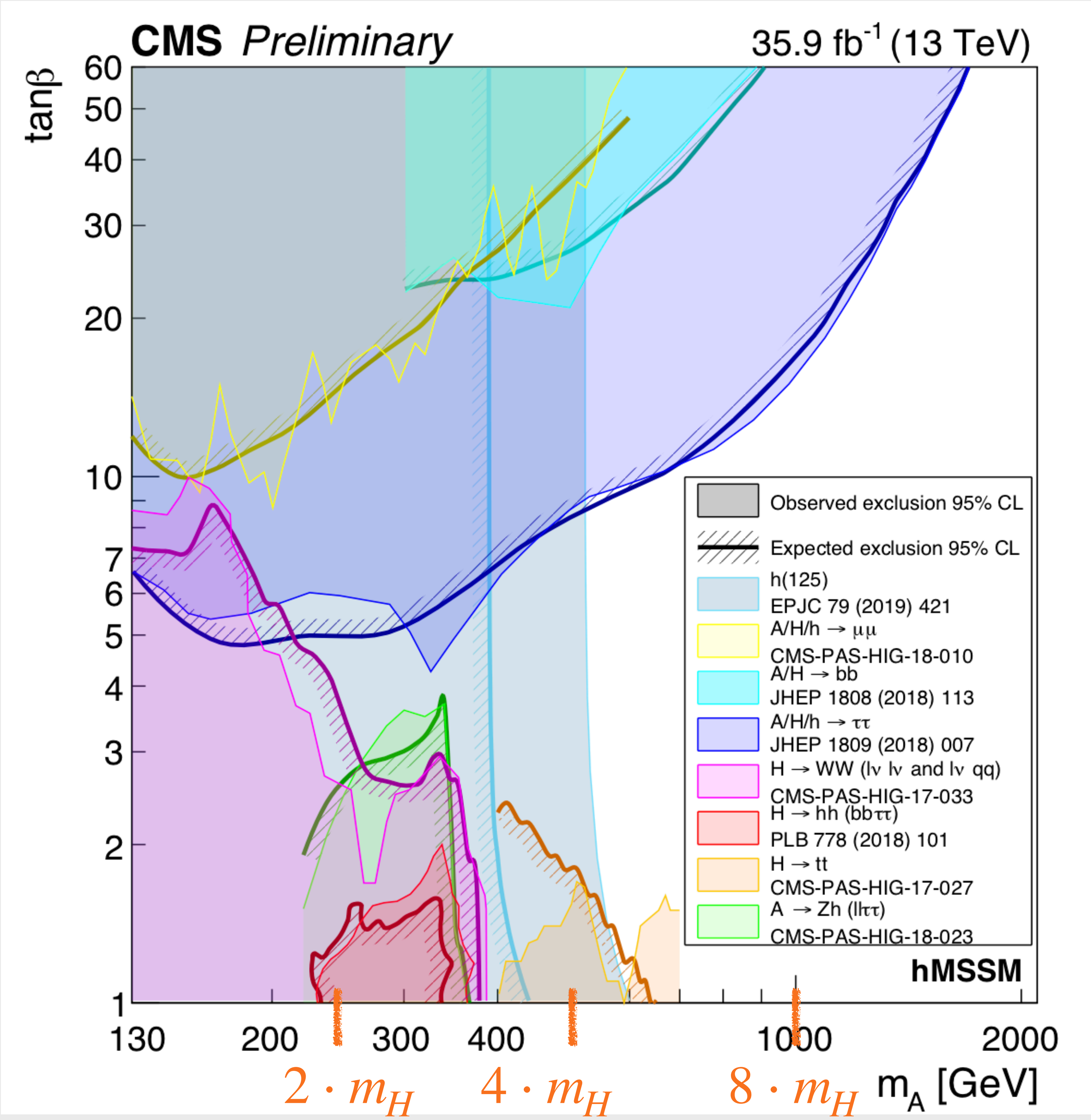
$$\sin\theta_{h\phi} \simeq \left(\frac{m_h}{m_\phi}\right)^{\alpha} \Rightarrow m_\phi \simeq 2 \div 3 \cdot m_h \qquad 1 \lesssim \alpha \lesssim 2$$

What about electroweak scalars?

DOUBLETS

ARE ABOUT AS TOUGH TO CATCH

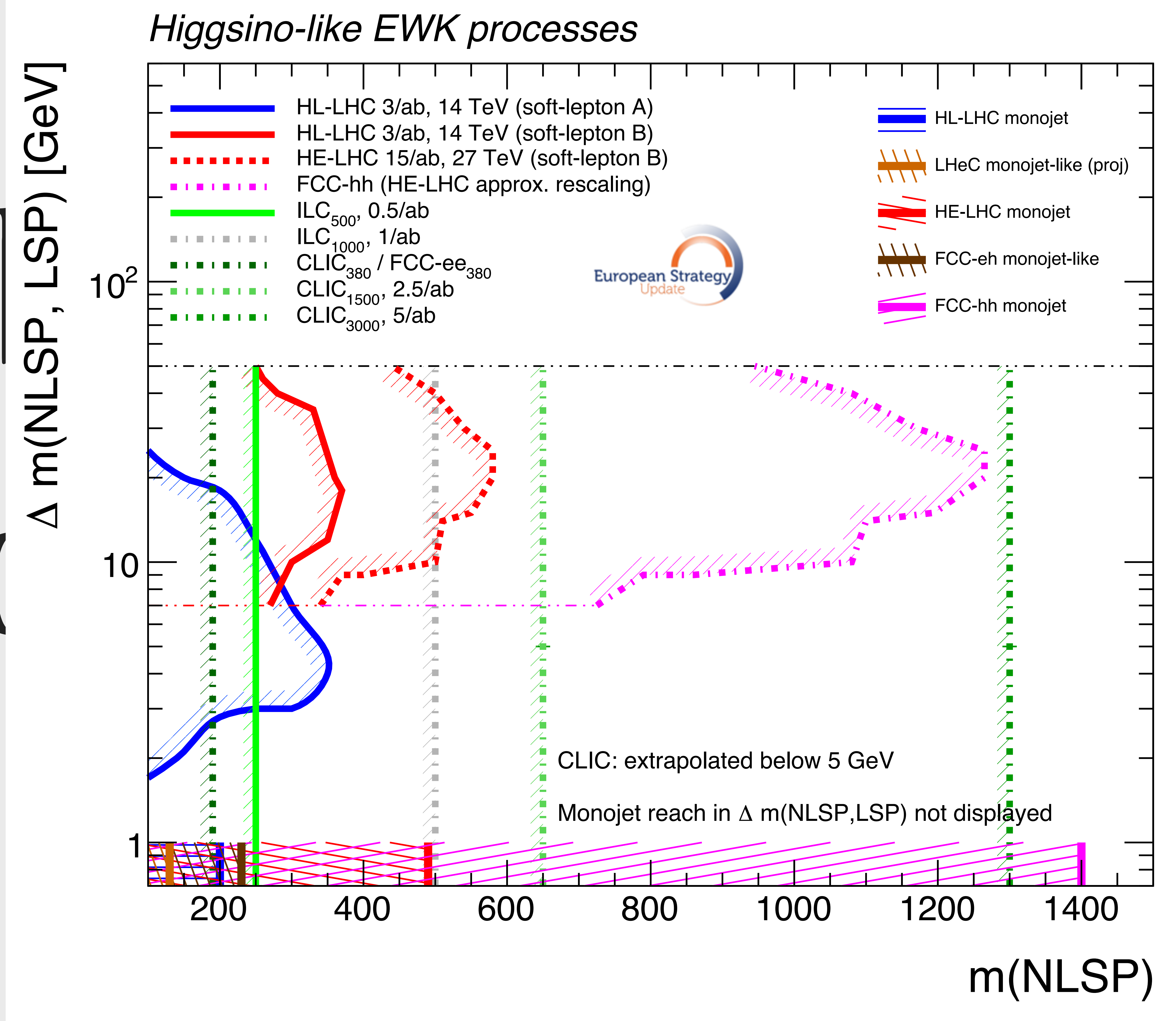


There is in general a weak sensitivity to new scalars, because of:

- “small” cross-sections
- large backgrounds

this problem is common to lots of electroweak new physics states

this pro… on to lots
of electr… sics states



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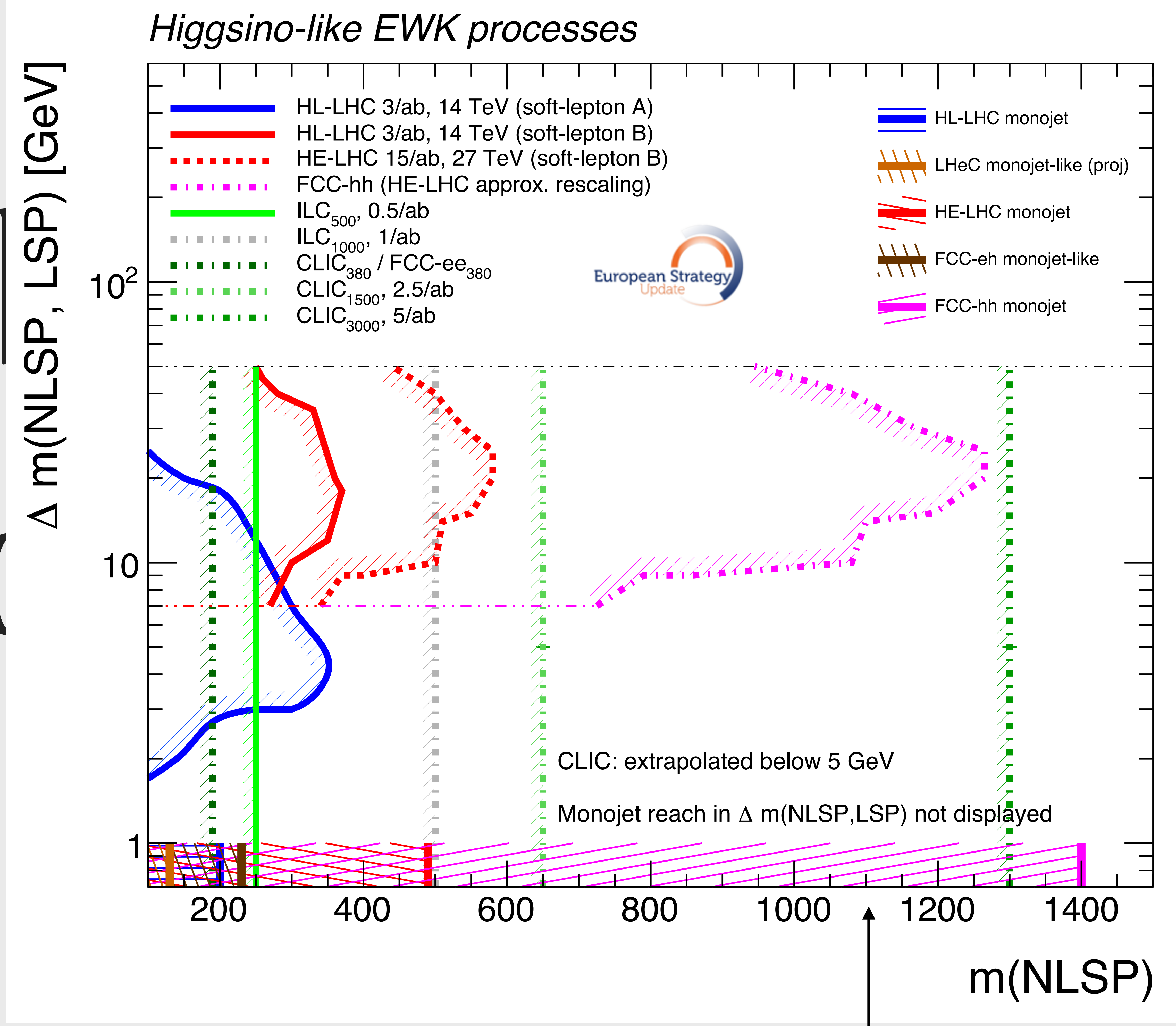

This could be Dark Matter

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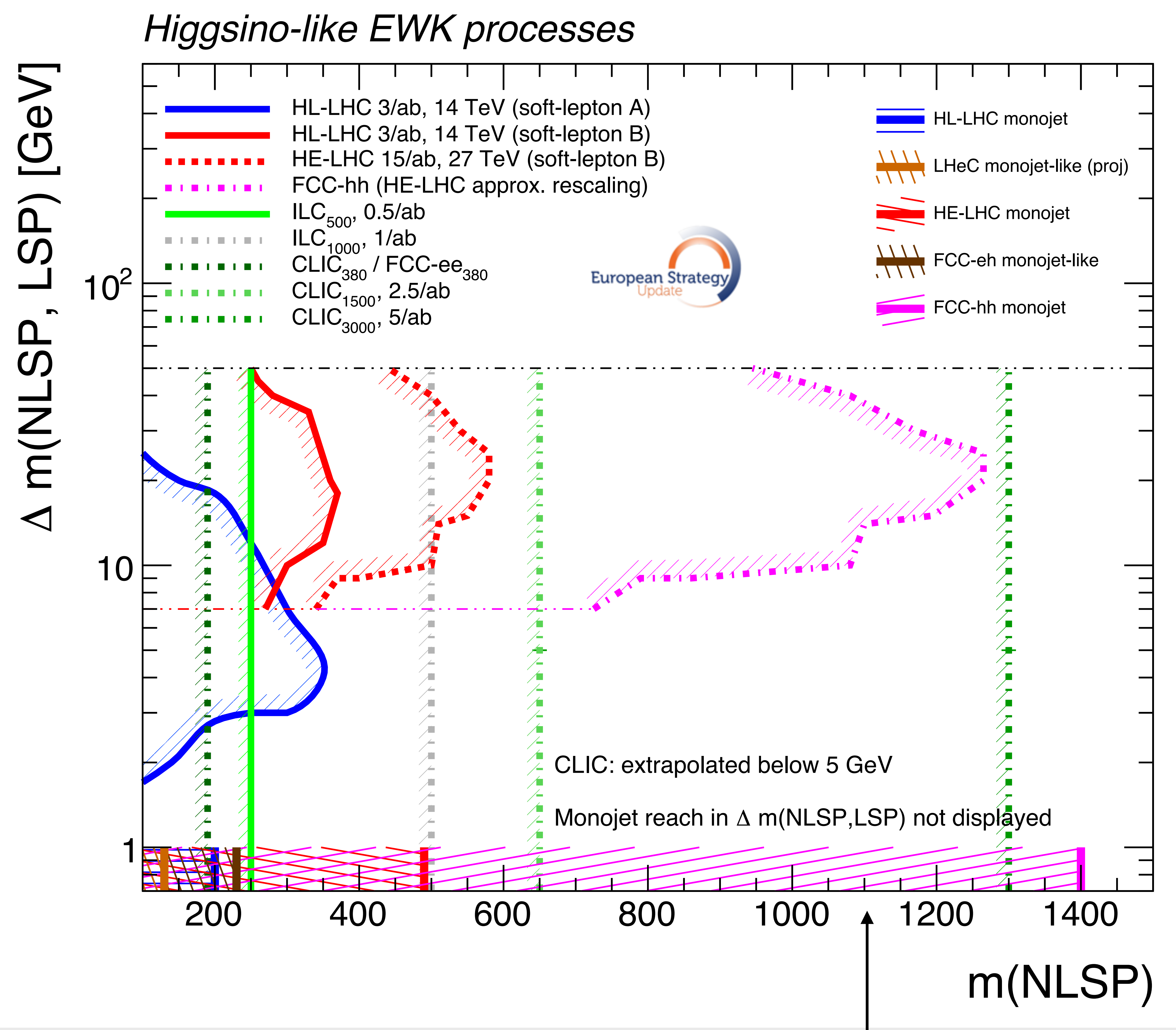

This could be Dark Matter
(inaccessible in Direct Detection!)

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) *

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- Scalar Doublet: 1 TeV
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- Some searches have “loopholes”