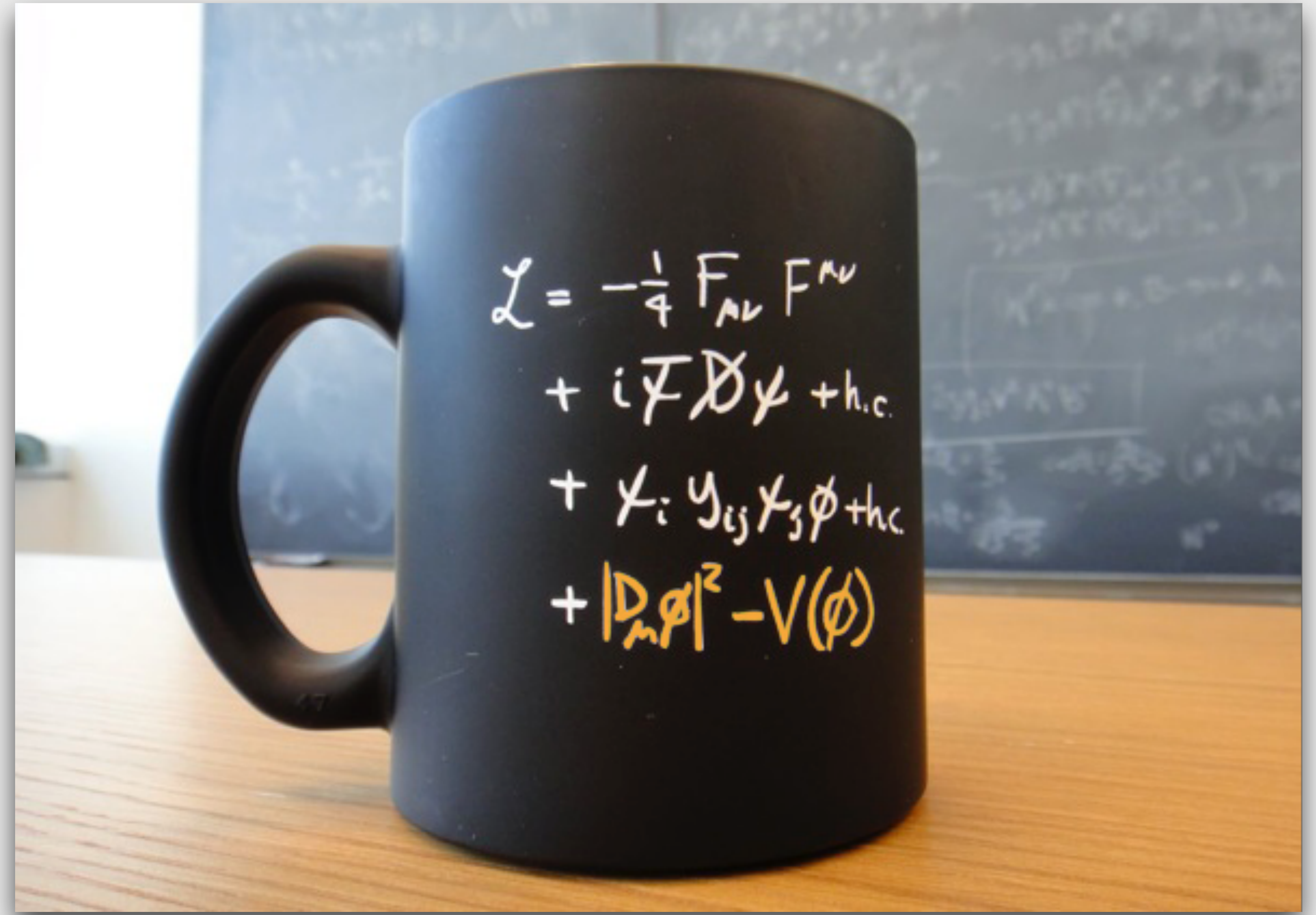
Open issues in the SM and exploration of BSM dynamics at colliders

SEP. 13 2021

ROBERTO FRANCESCHINI (ROMA 3 UNIVERSITY)

Where do we stand?



We have got “the” formula

… and it is surprisingly short!

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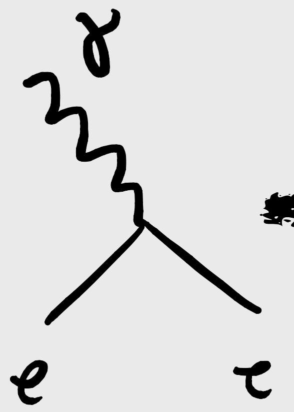
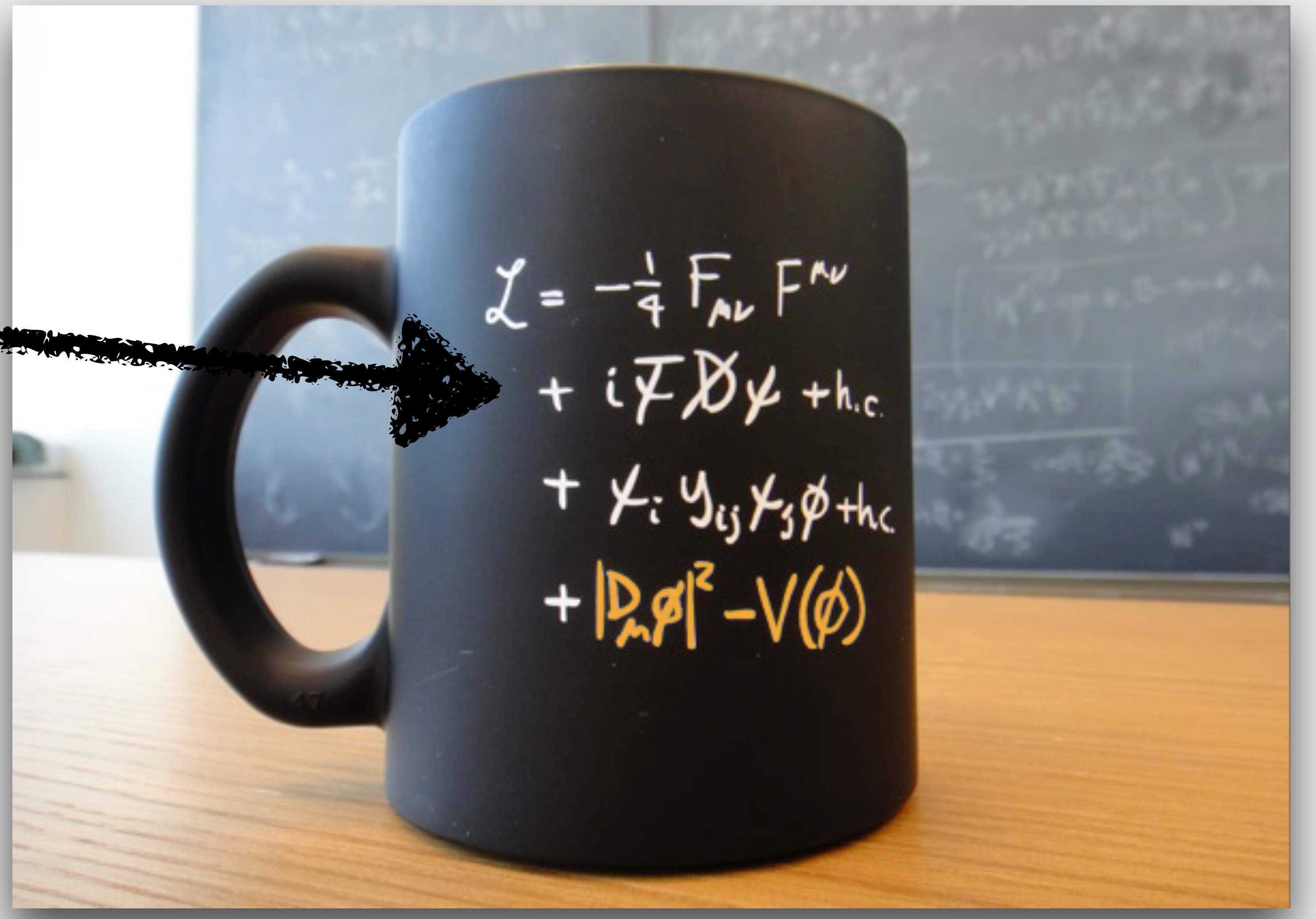
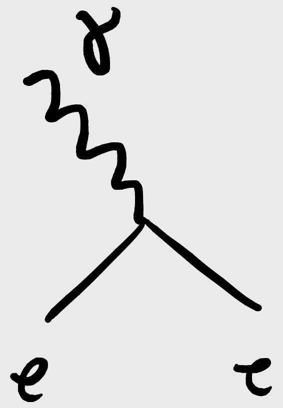
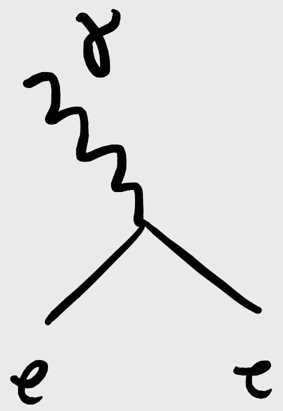






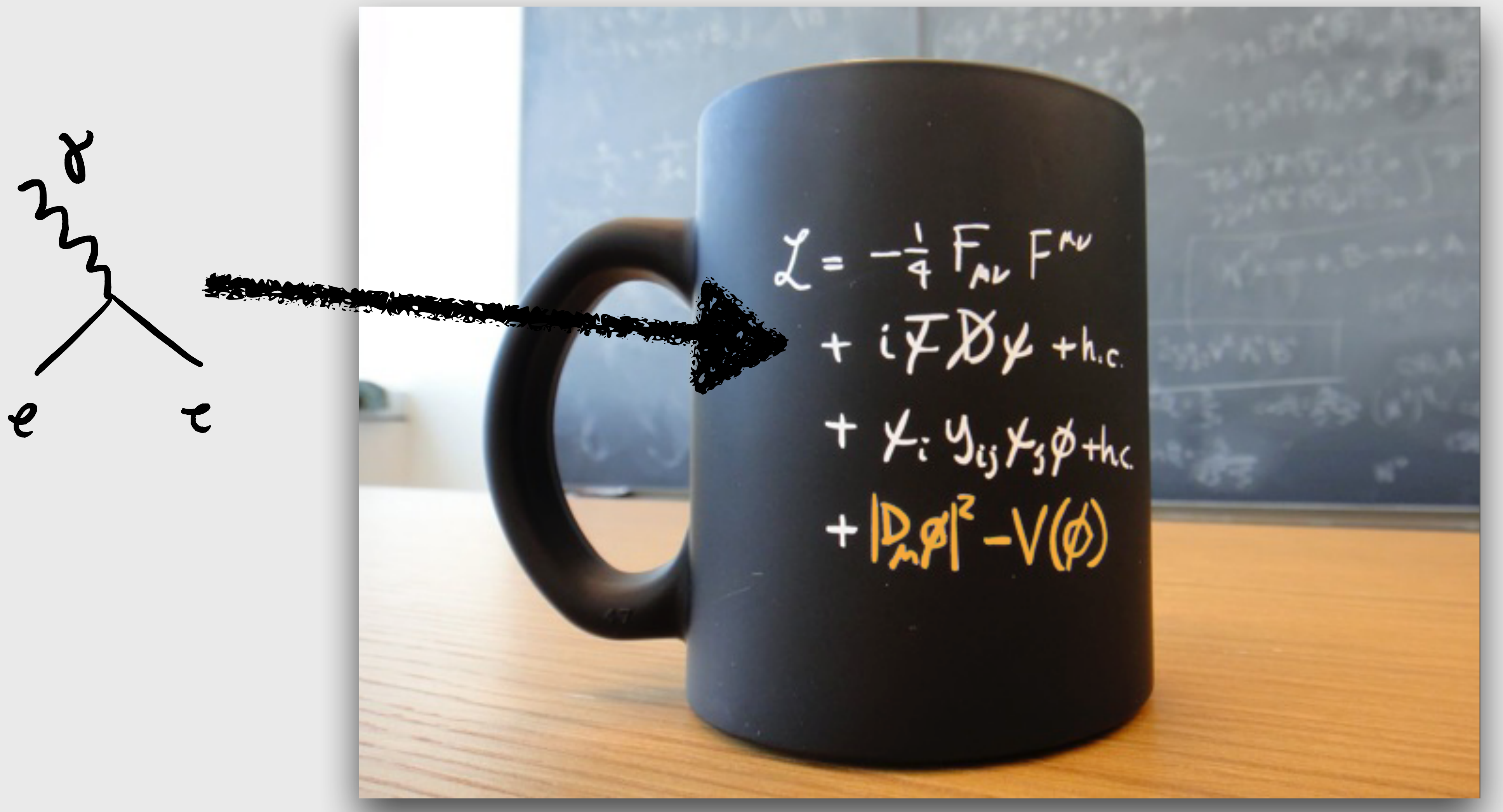
electro-weak interactions

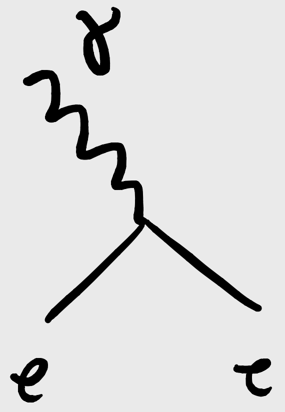


strong interactions

Where do we stand?

SYMMETRY AS A FUNDAMENTAL CHARACTER OF NATURE





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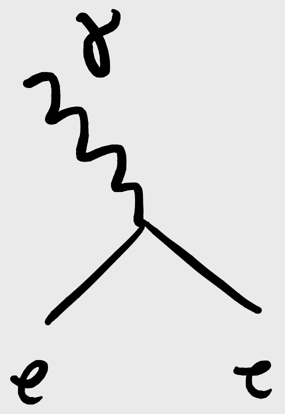

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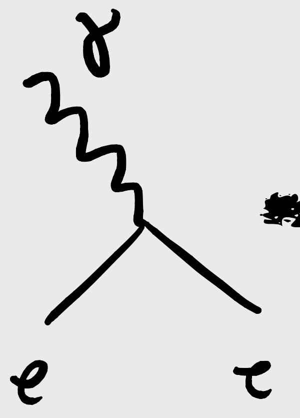

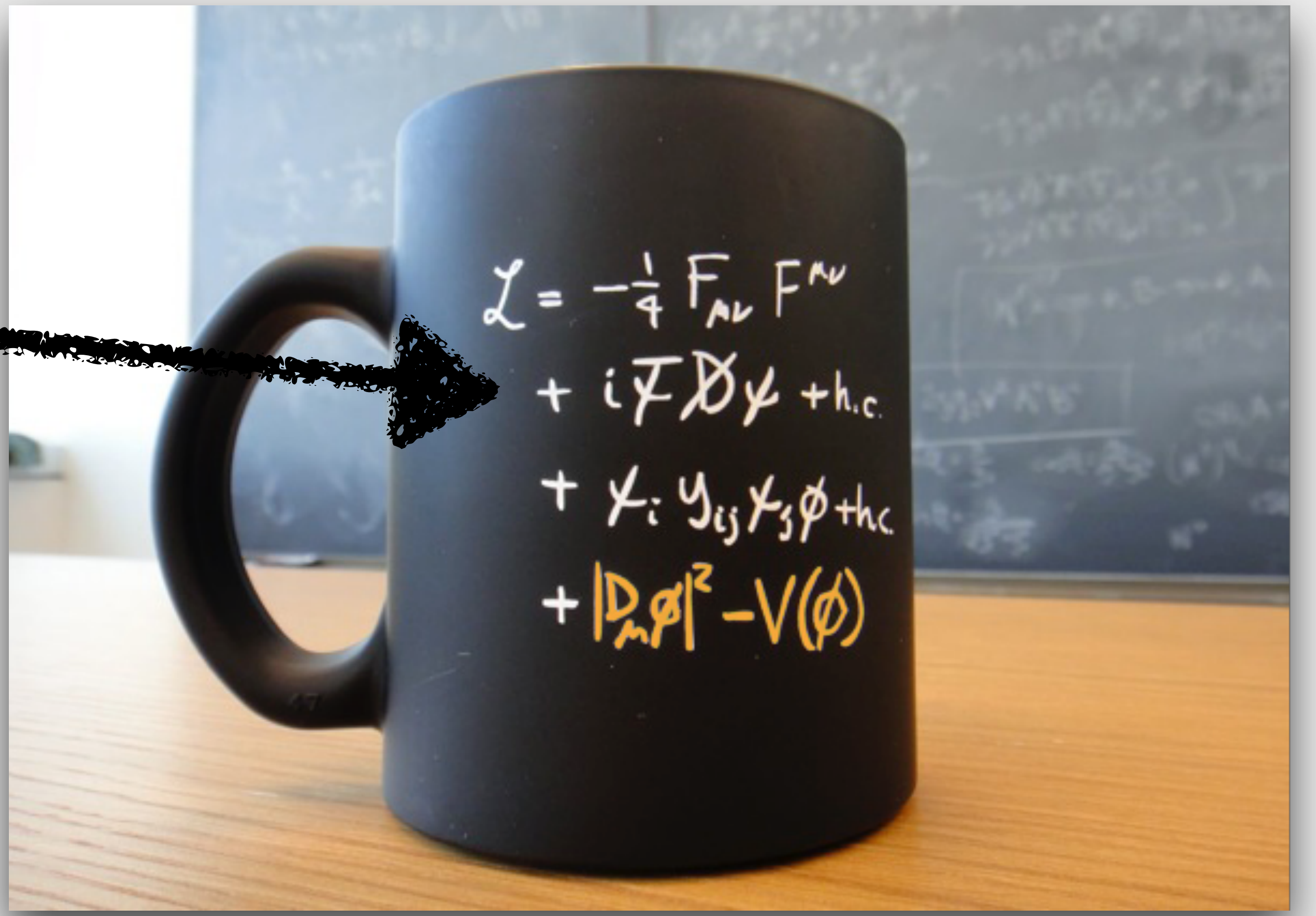

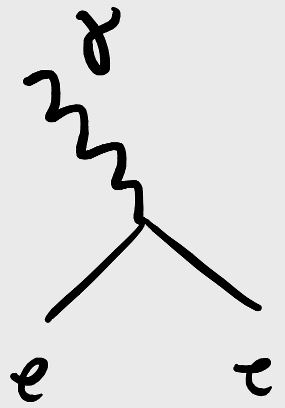

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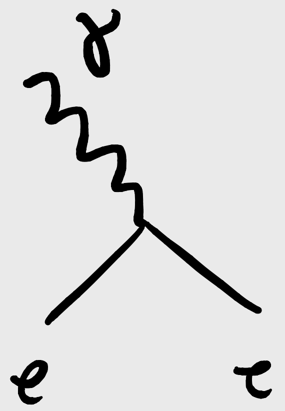

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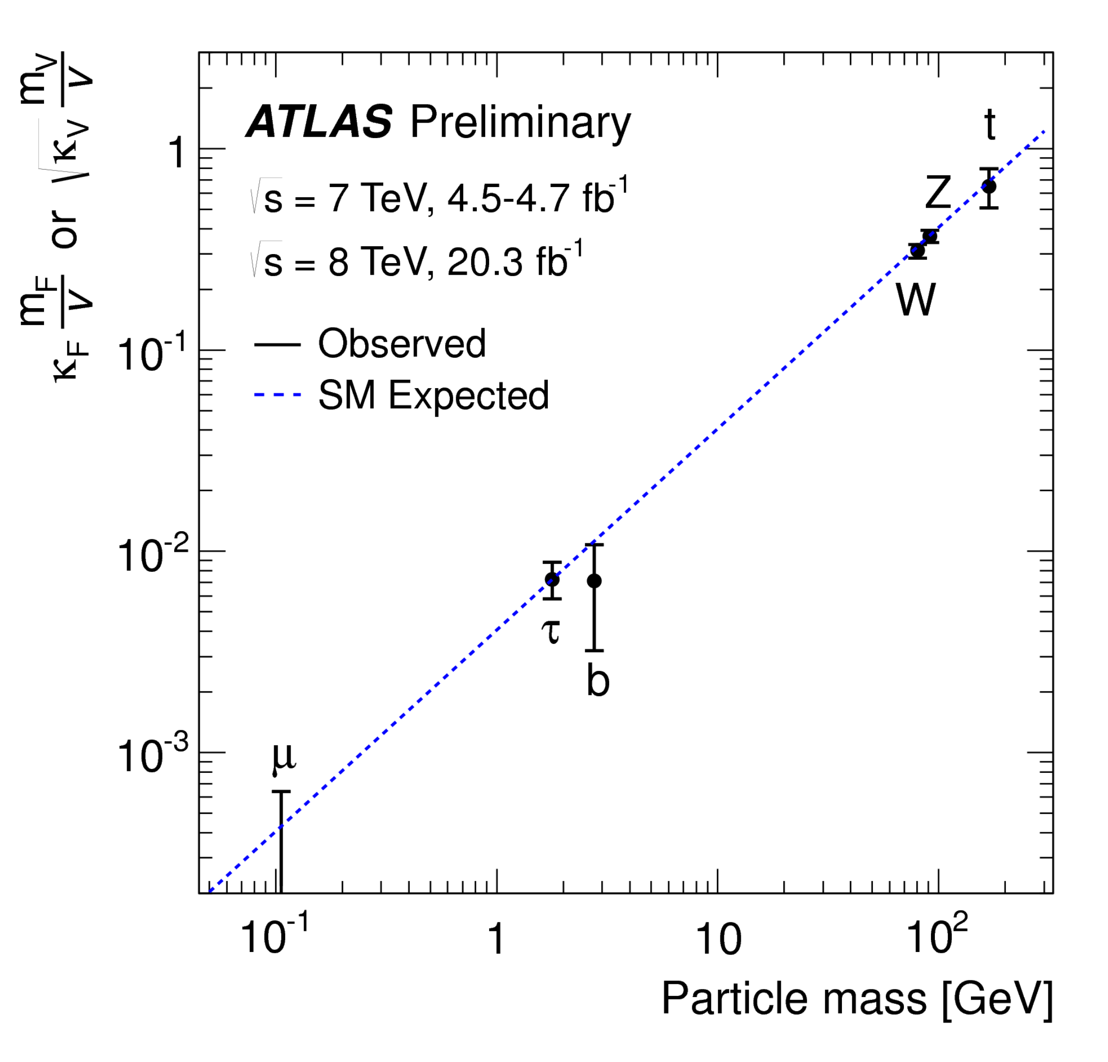

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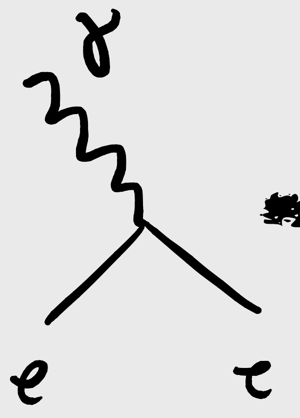
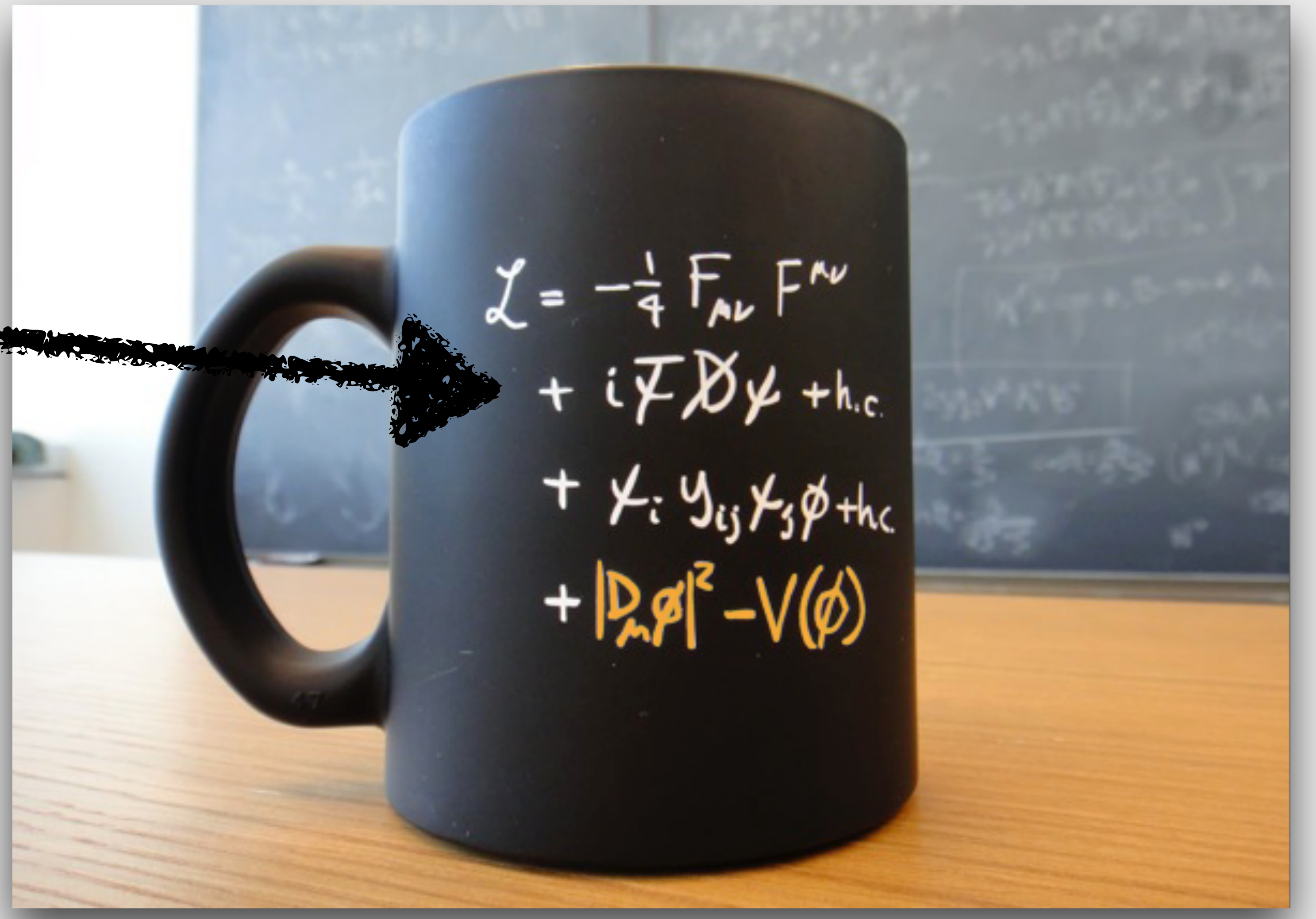
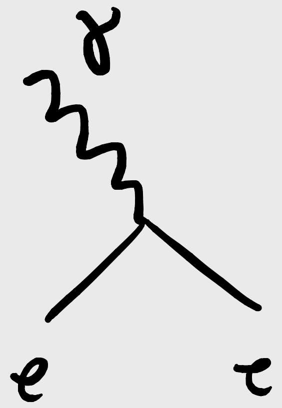
SYMMETRY | AS A FUNDAMENTAL CHARACTER OF NATURE | ?????







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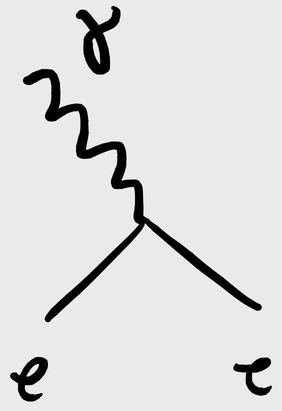

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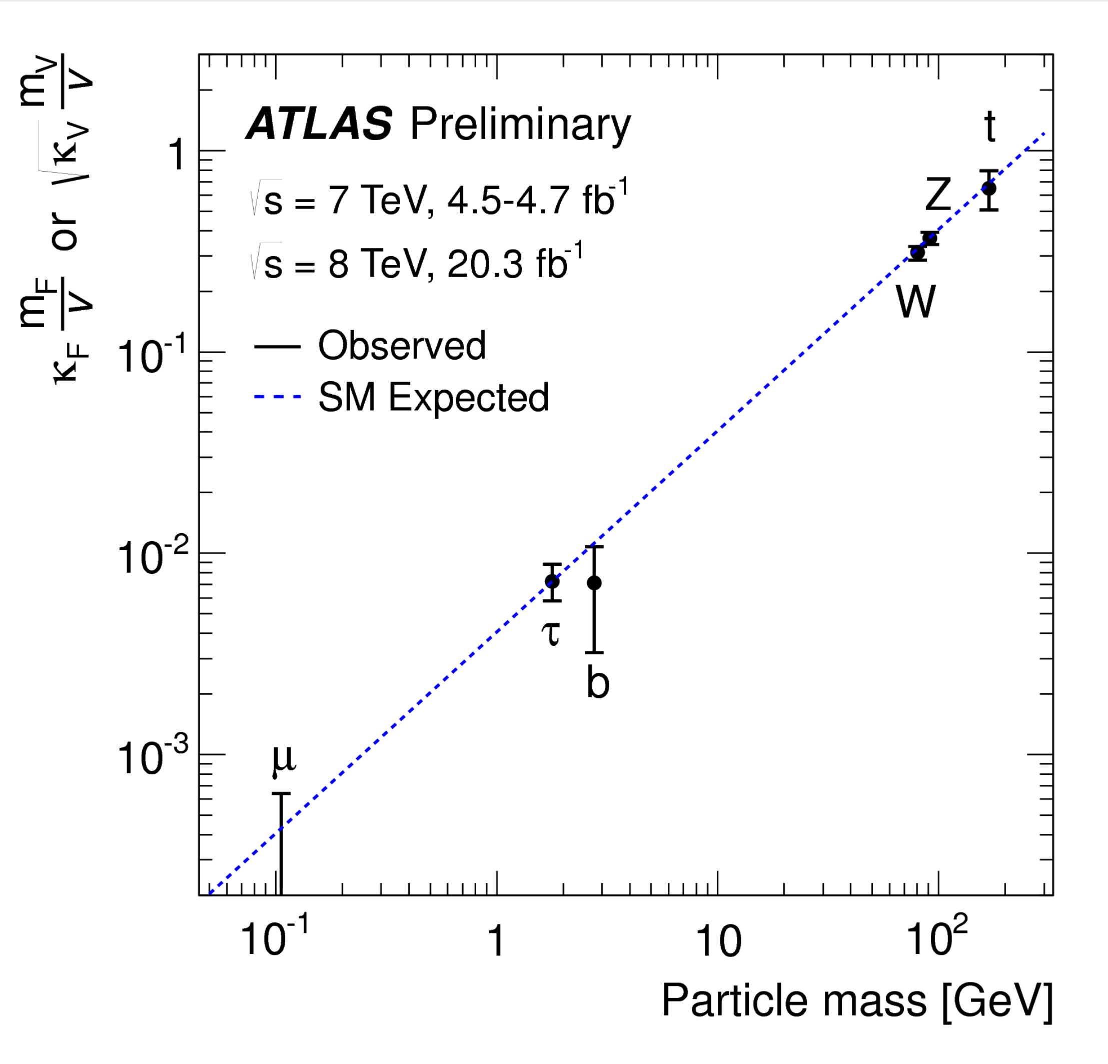

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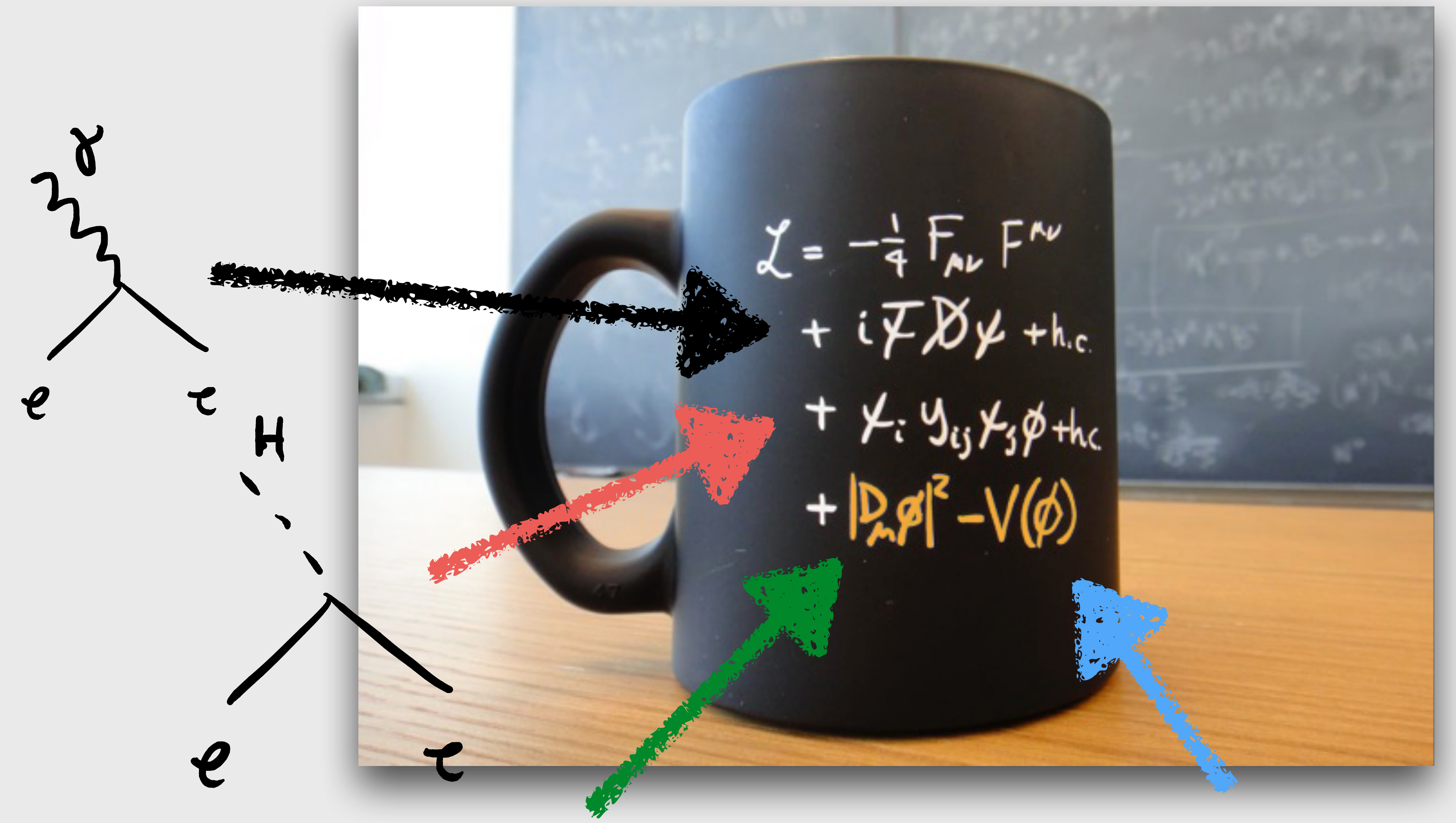

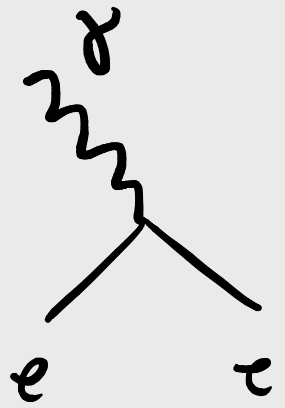

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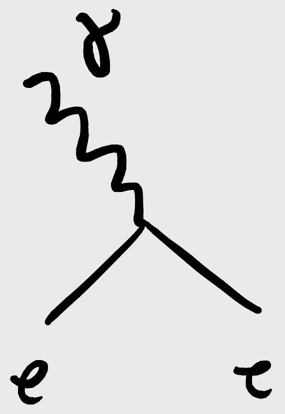
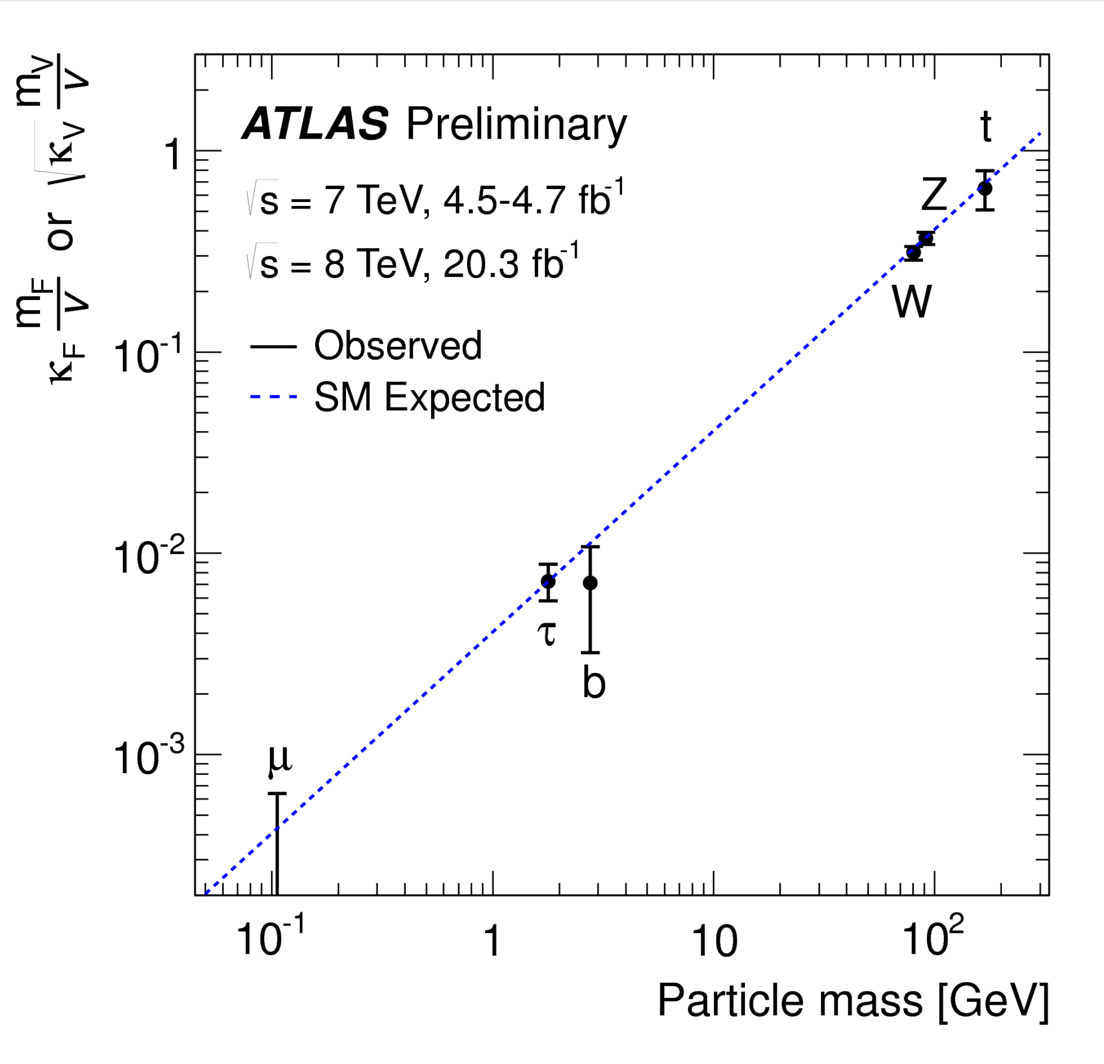


strong interactions

$|D\phi|^2$

$V(\phi)$

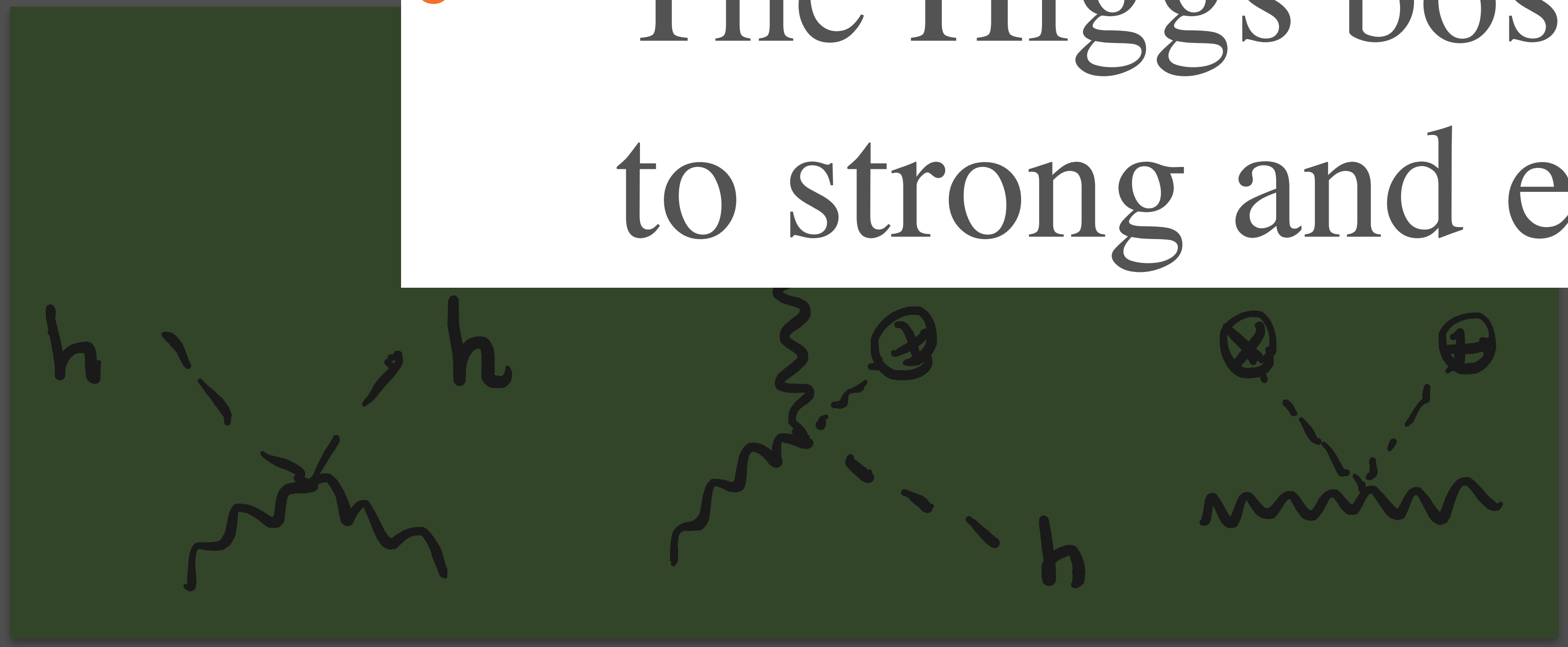


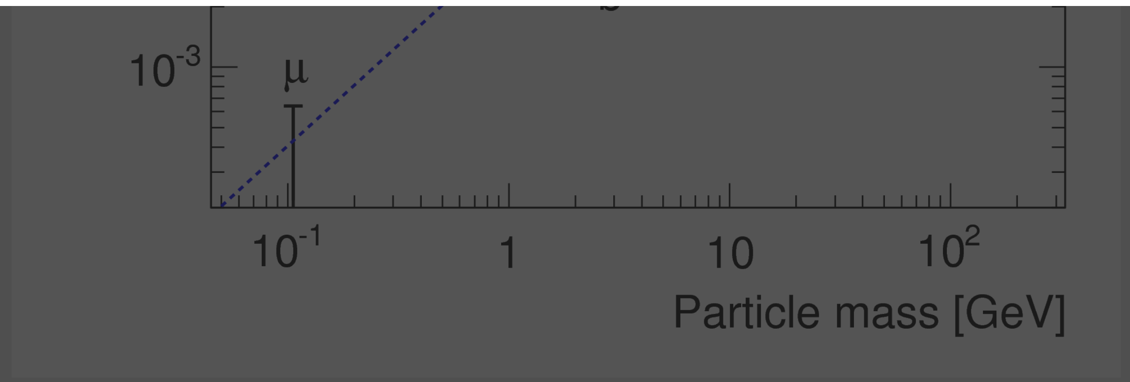
Where do we stand?

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

electro-weak interactions

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





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.

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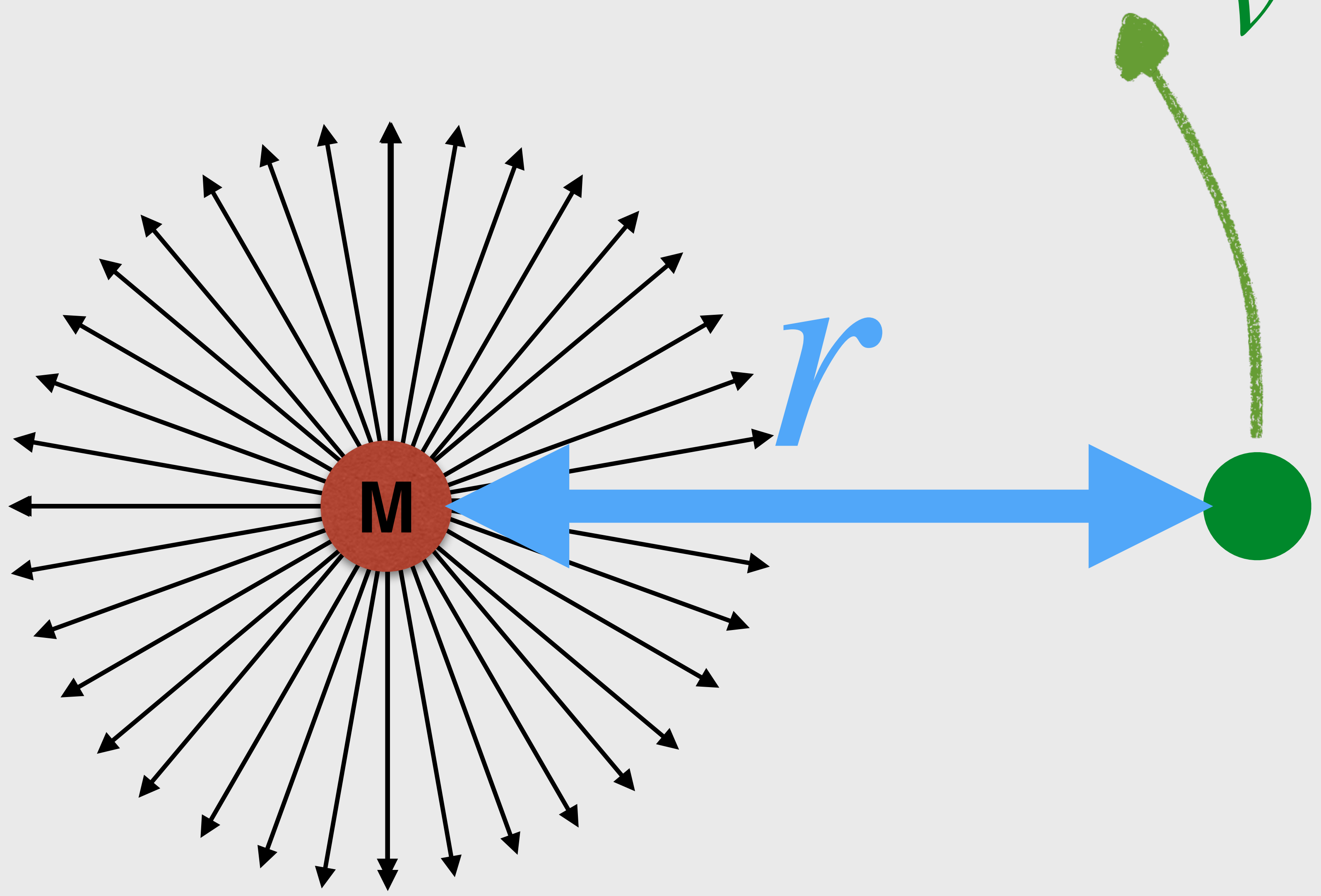
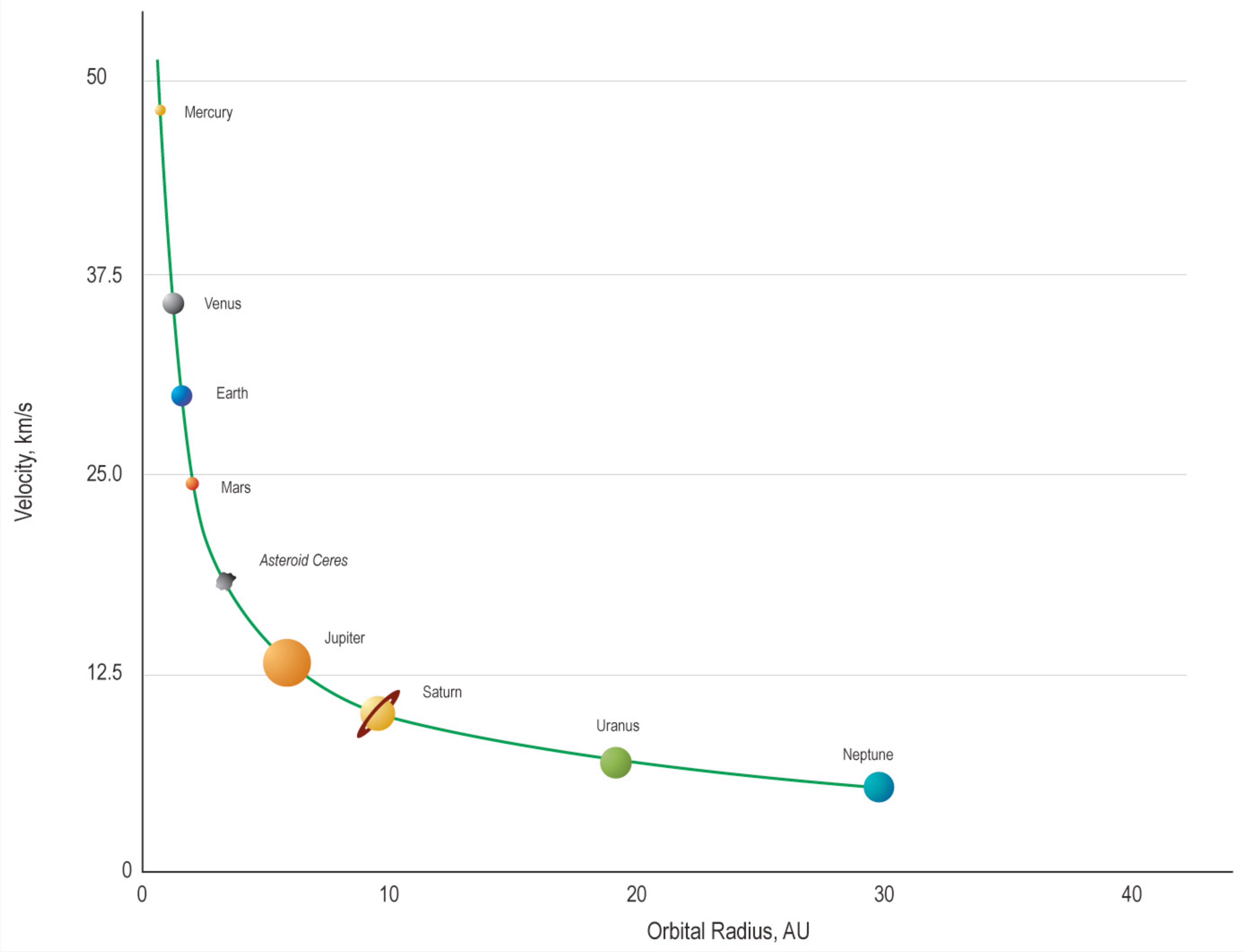
A puzzle we have no idea how to solve

NEWTONIAN MECHANICS FAILS?



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

Perfect in our "neighborhood"



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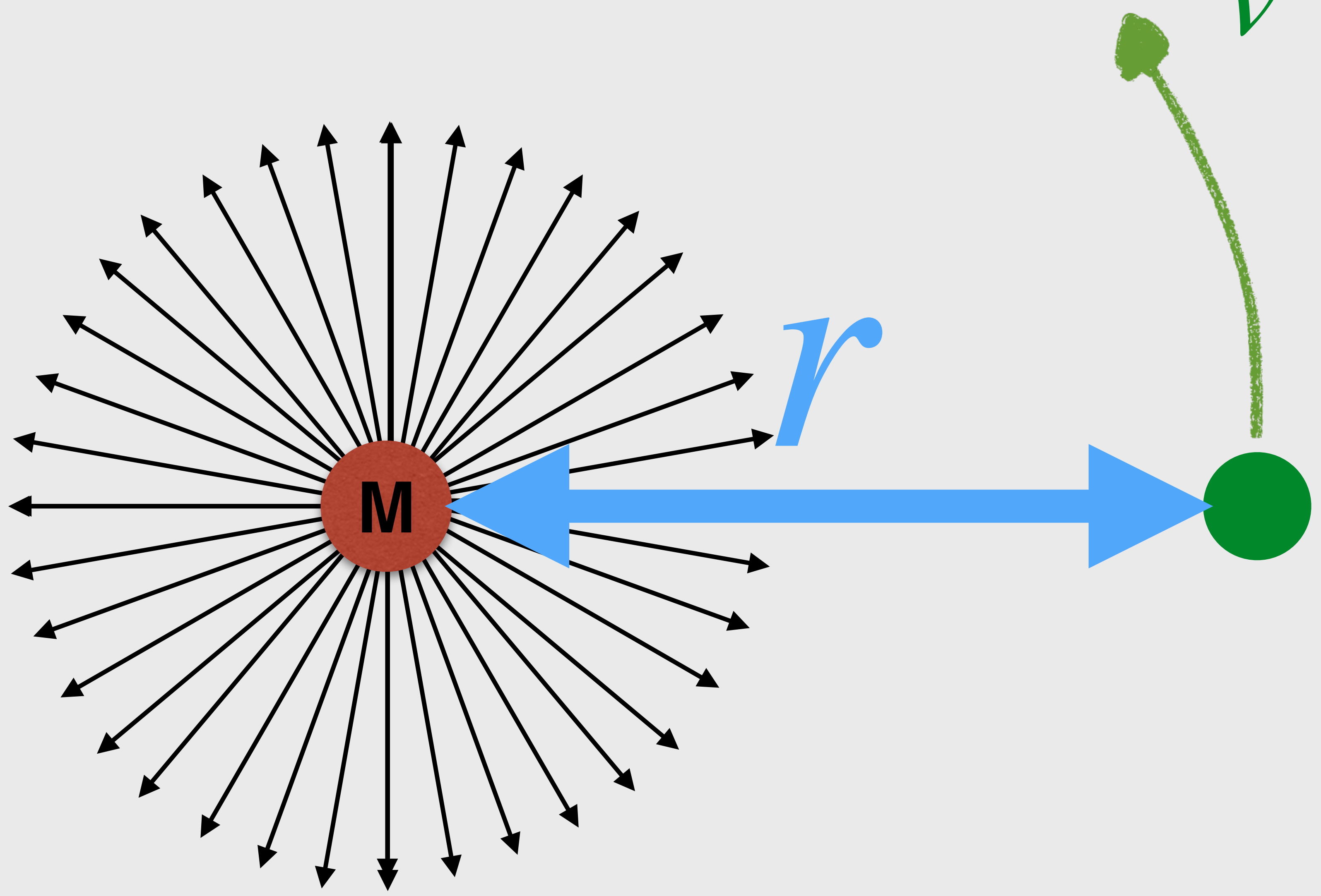

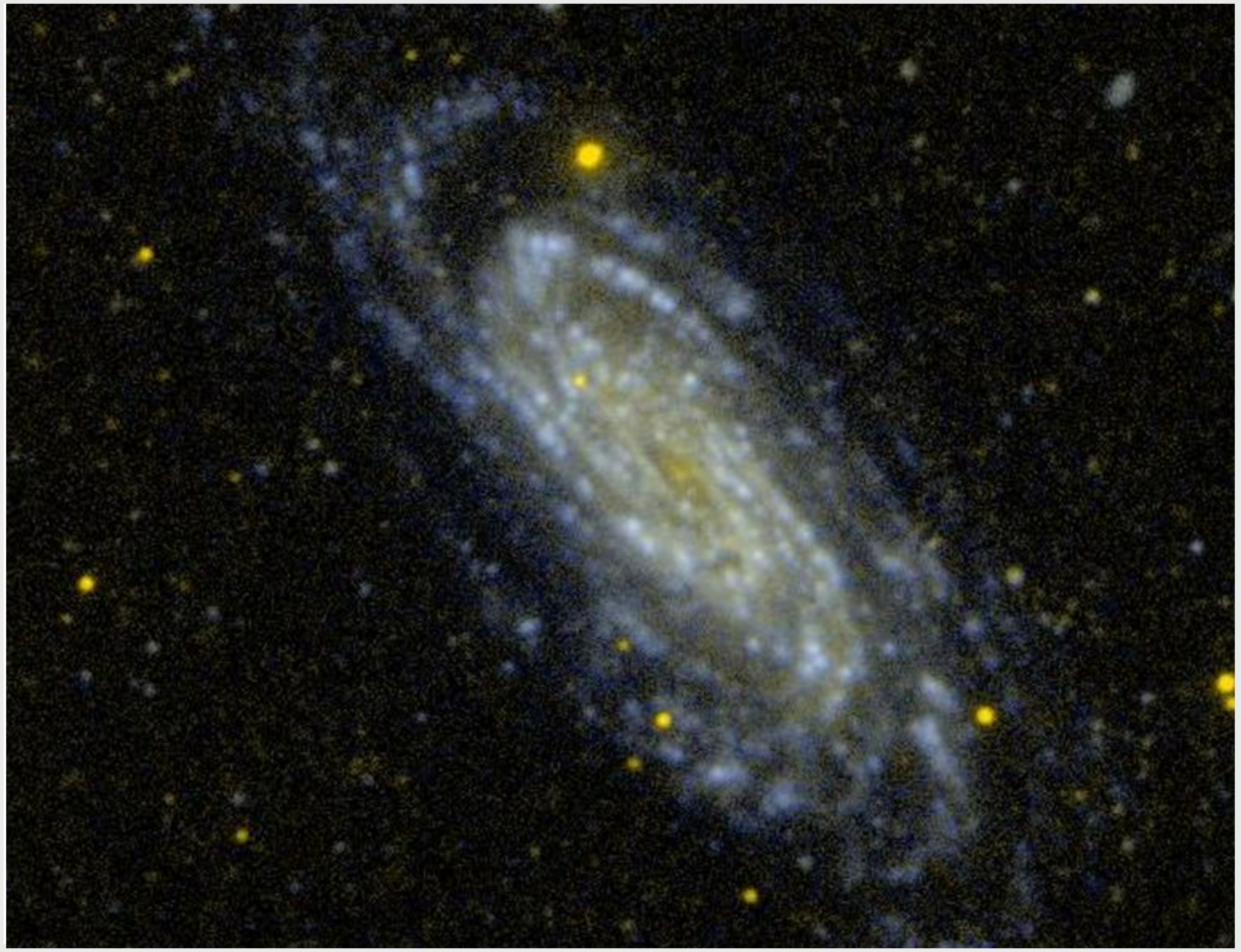

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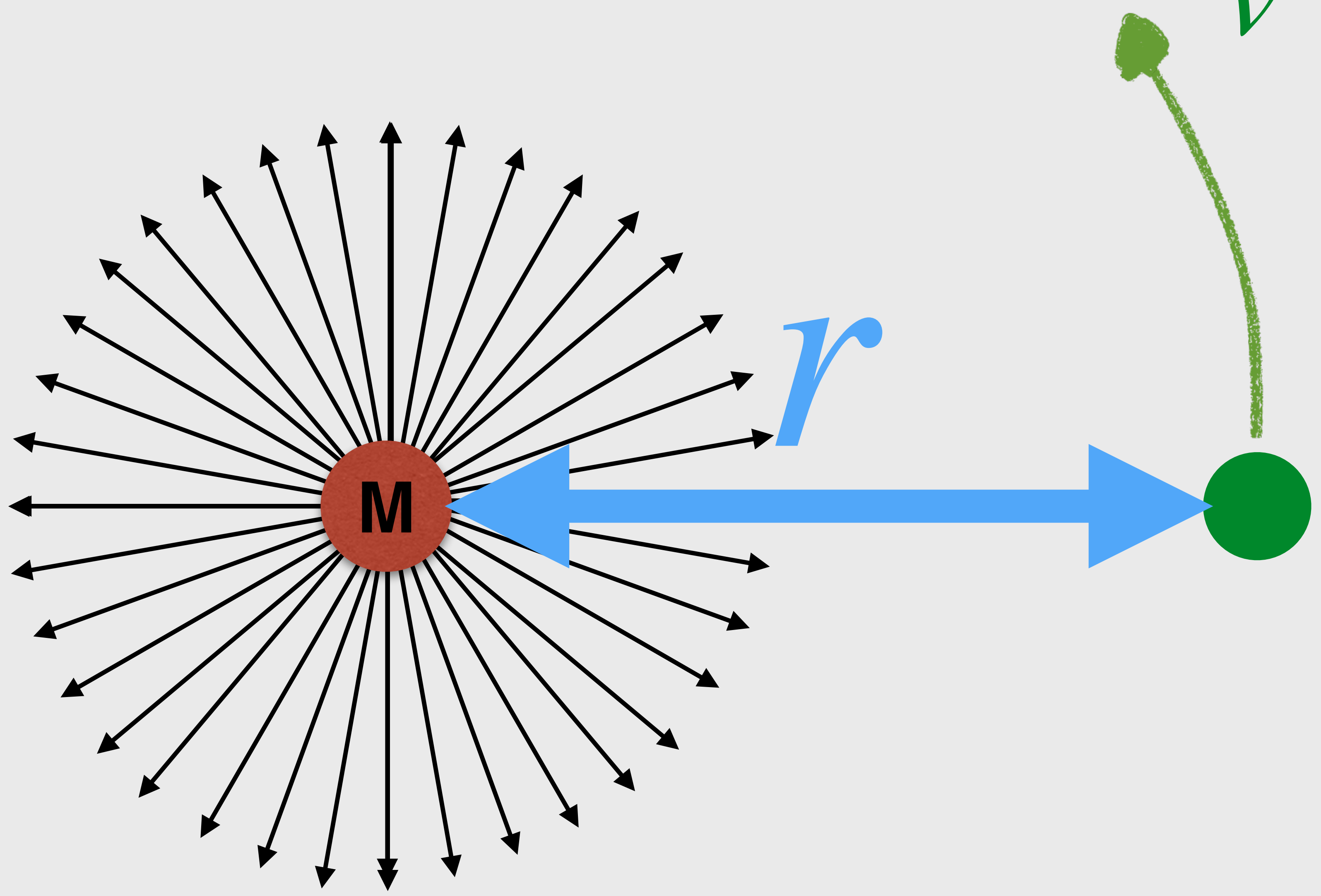

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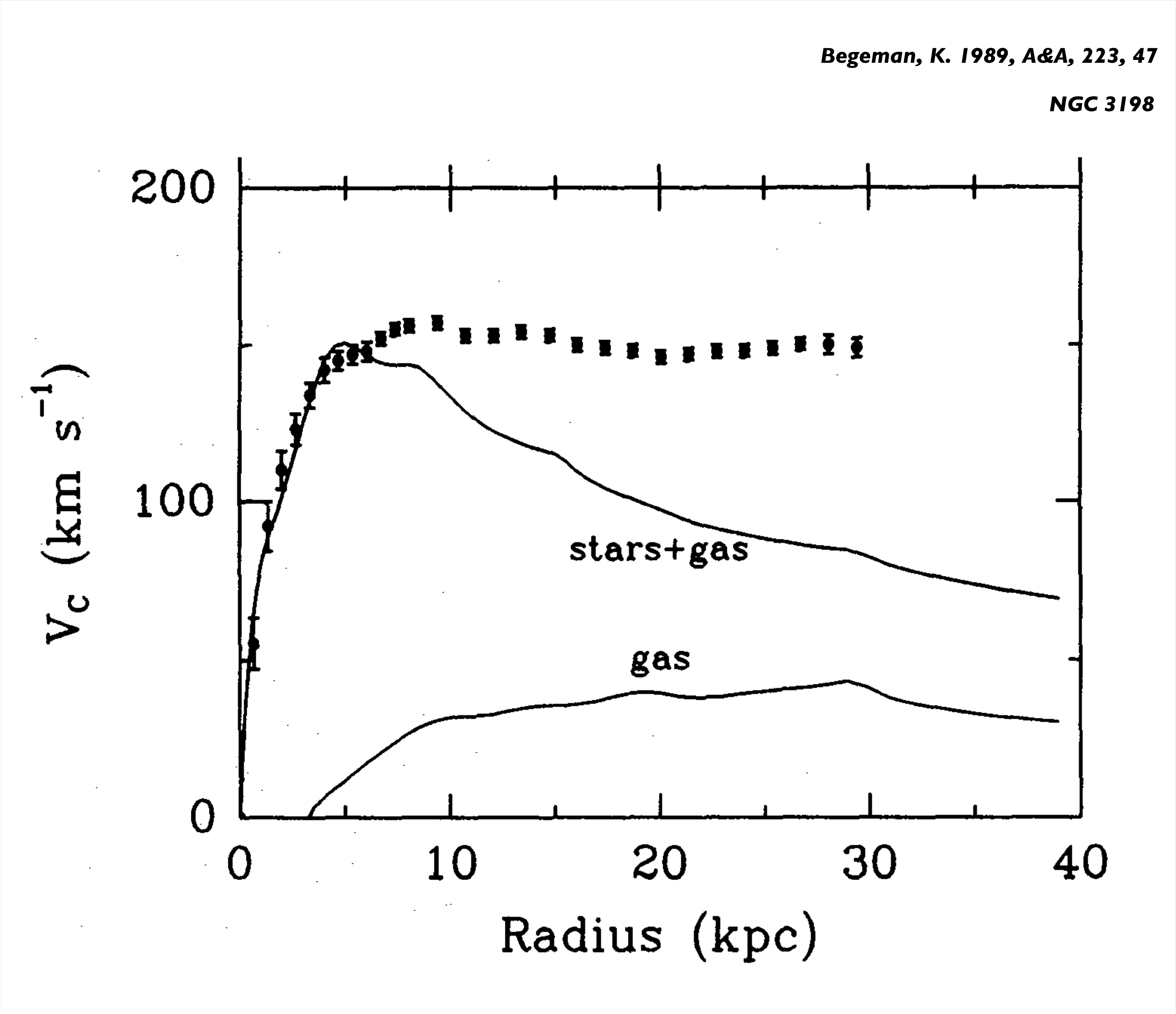

A puzzle we have no idea how to solve

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

a new form of matter must exist

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

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

It is not necessarily material for particle physics and accelerators

A puzzle we have no idea how to solve

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

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

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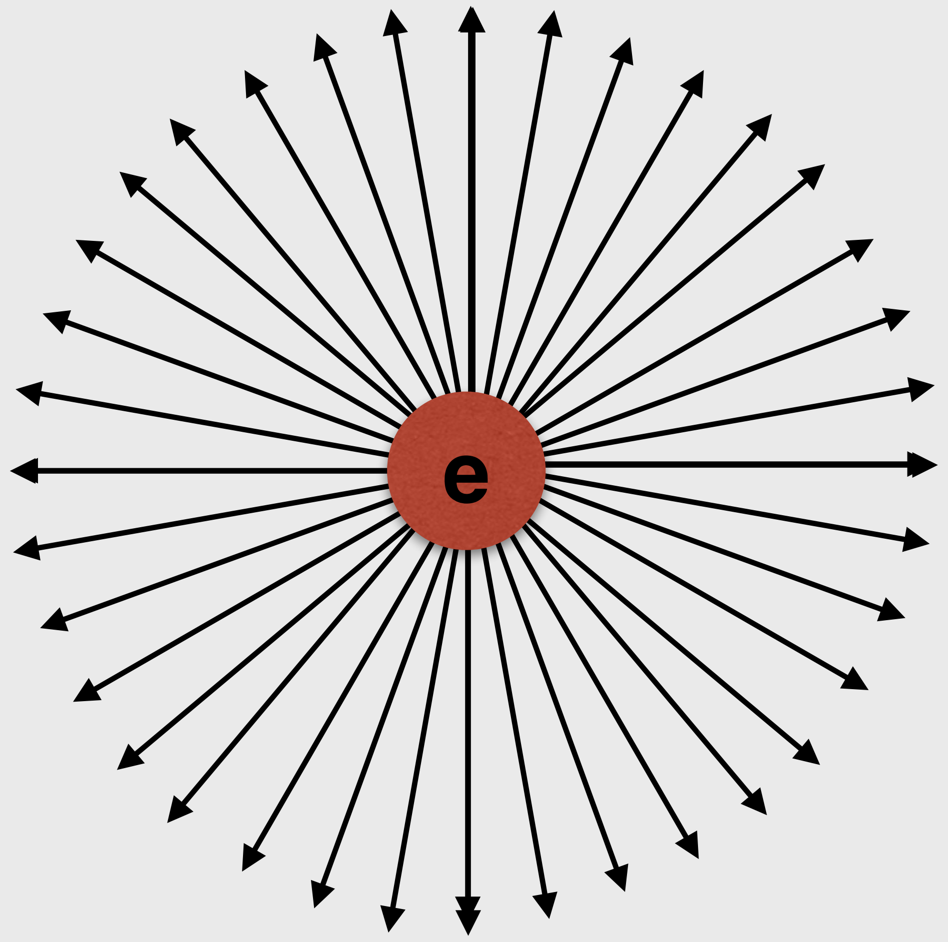
A puzzle (today) we know how to solve

AFTER RELATIVITY



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

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

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

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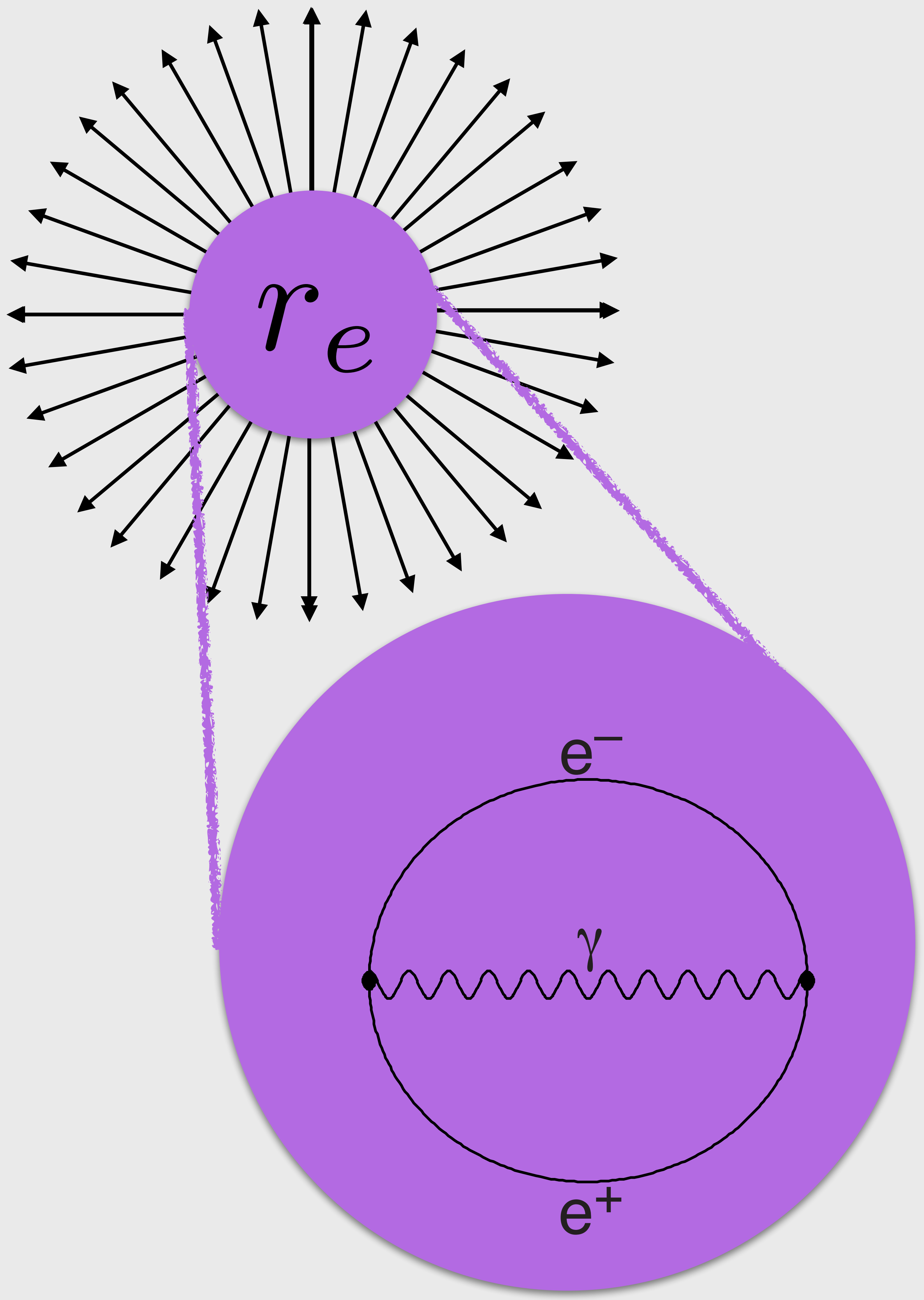
RELATIVITY & QUANTUM MECHANICS



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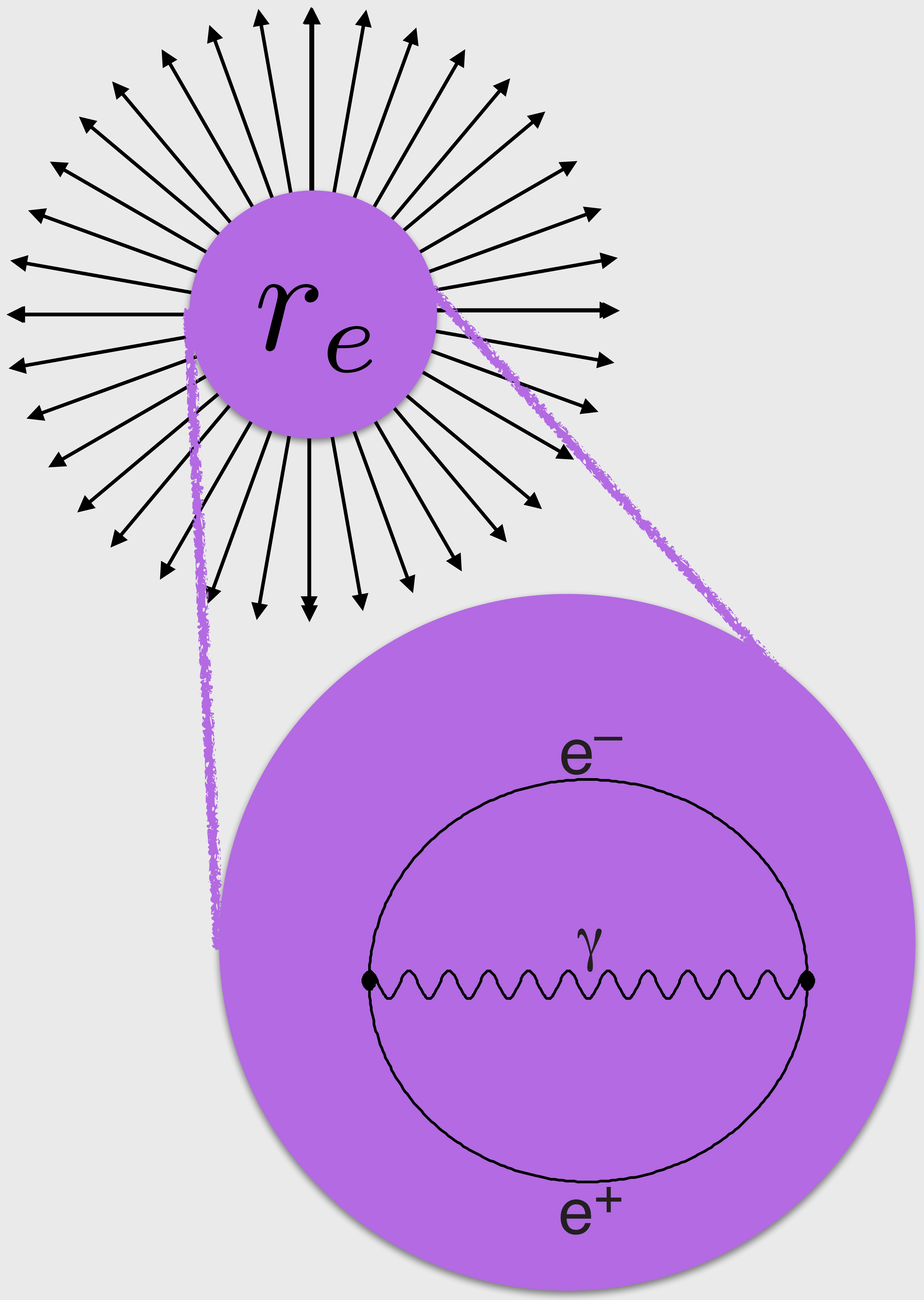


New symmetry (particle-antiparticle) which brought a new particle: the positron

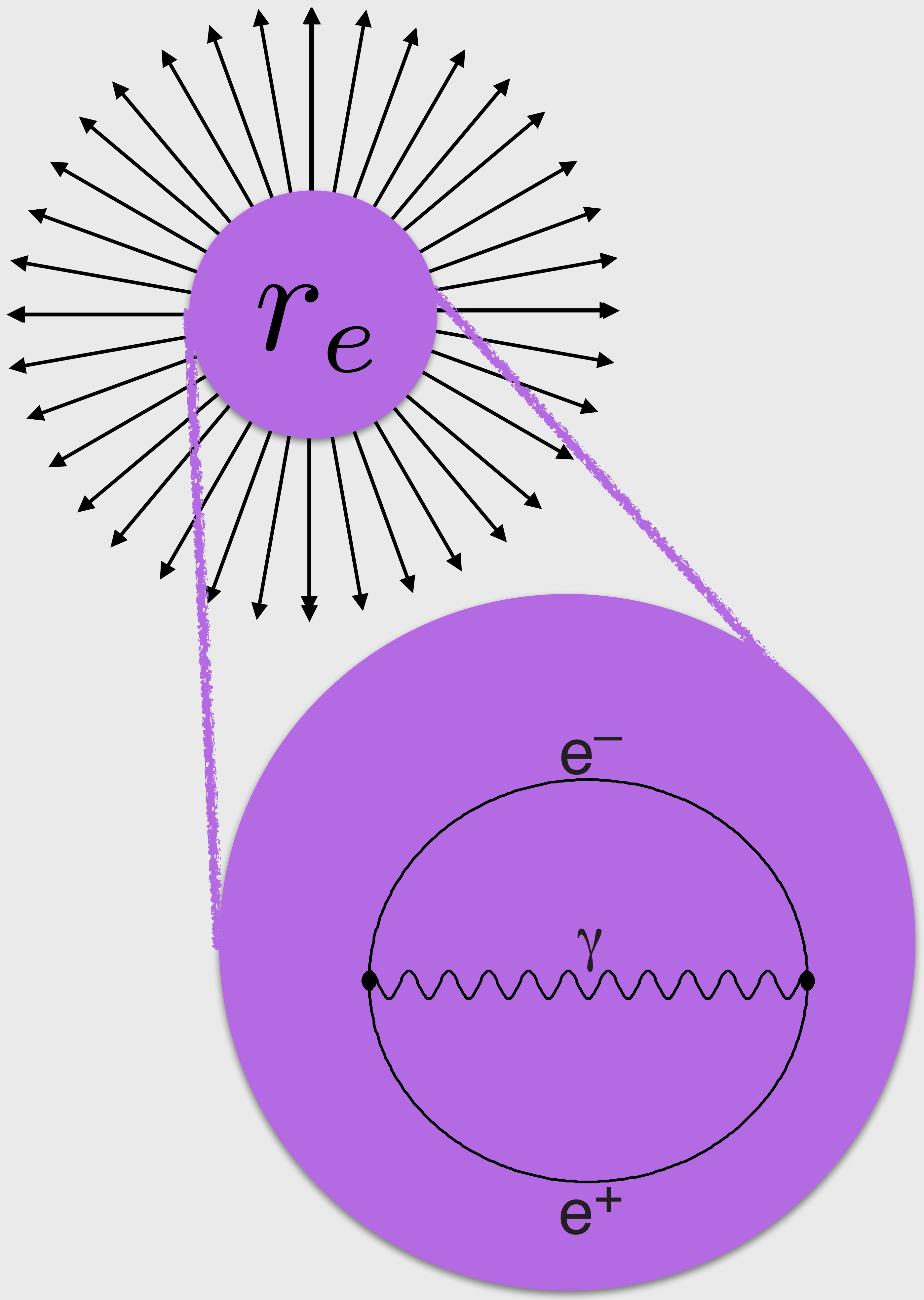
We learned a lesson on physics **at the same mass scale** as where the puzzle arises:

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

A puzzle (today) we know how to solve

AFTER

RELATIVITY & QUANTUM MECHANICS



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RELATIVITY & QUANTUM MECHANICS

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

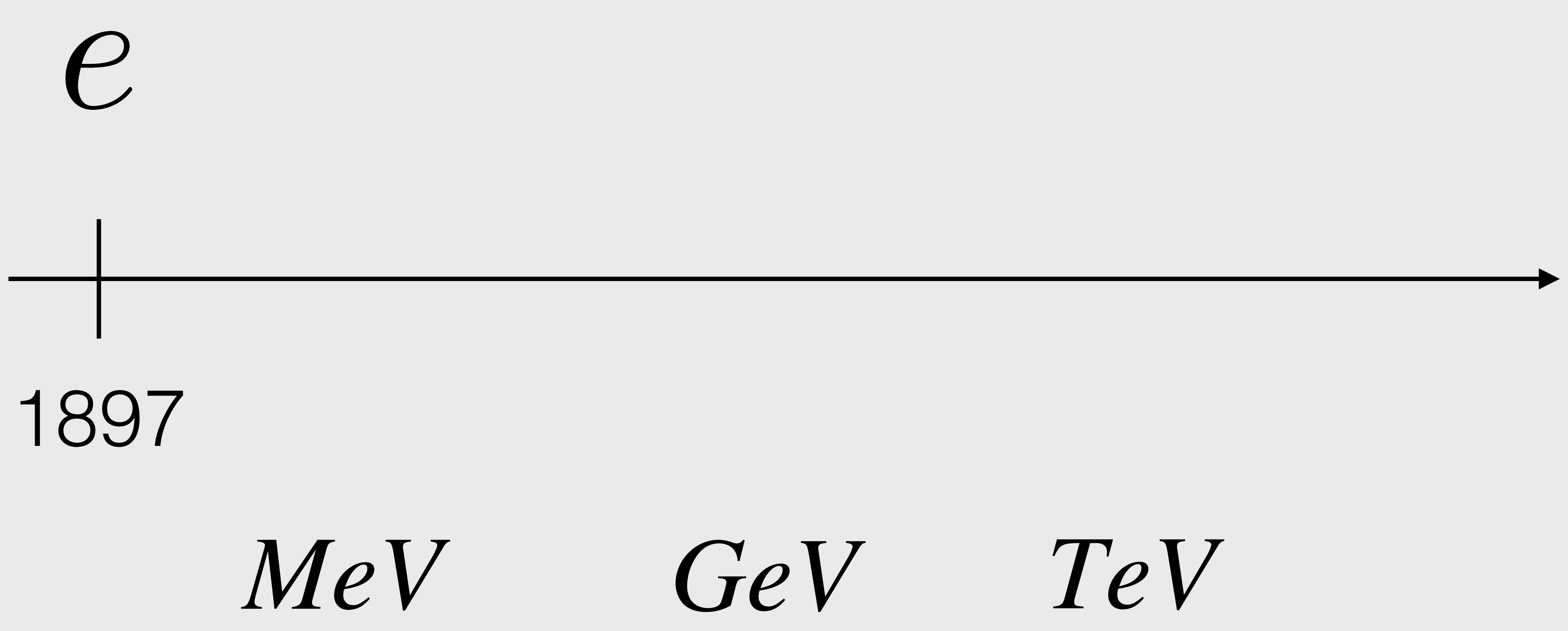
e+

How we got there

SYMMETRY

AS A FUNDAMENTAL CHARACTER OF NATURE

Symmetries and particles



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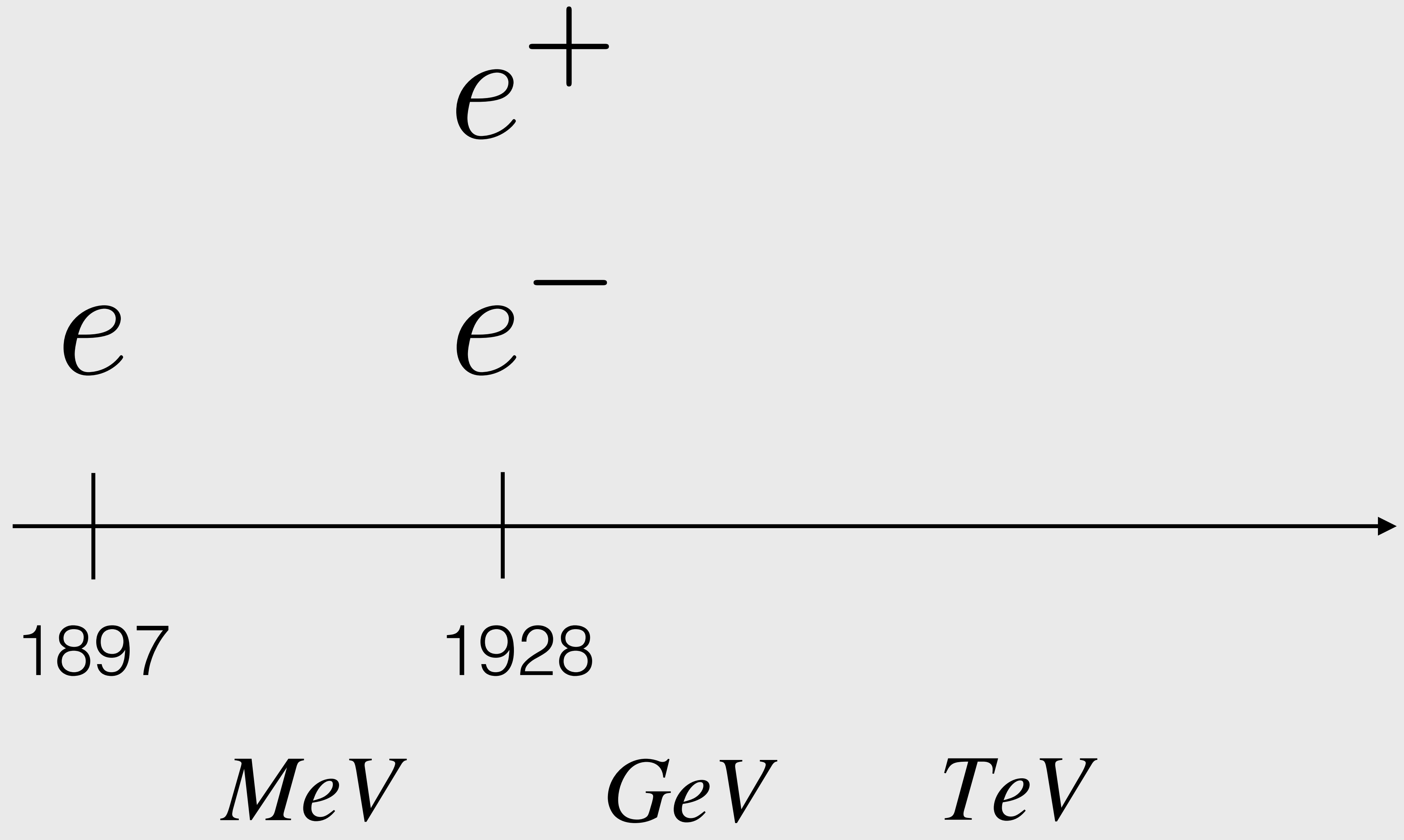

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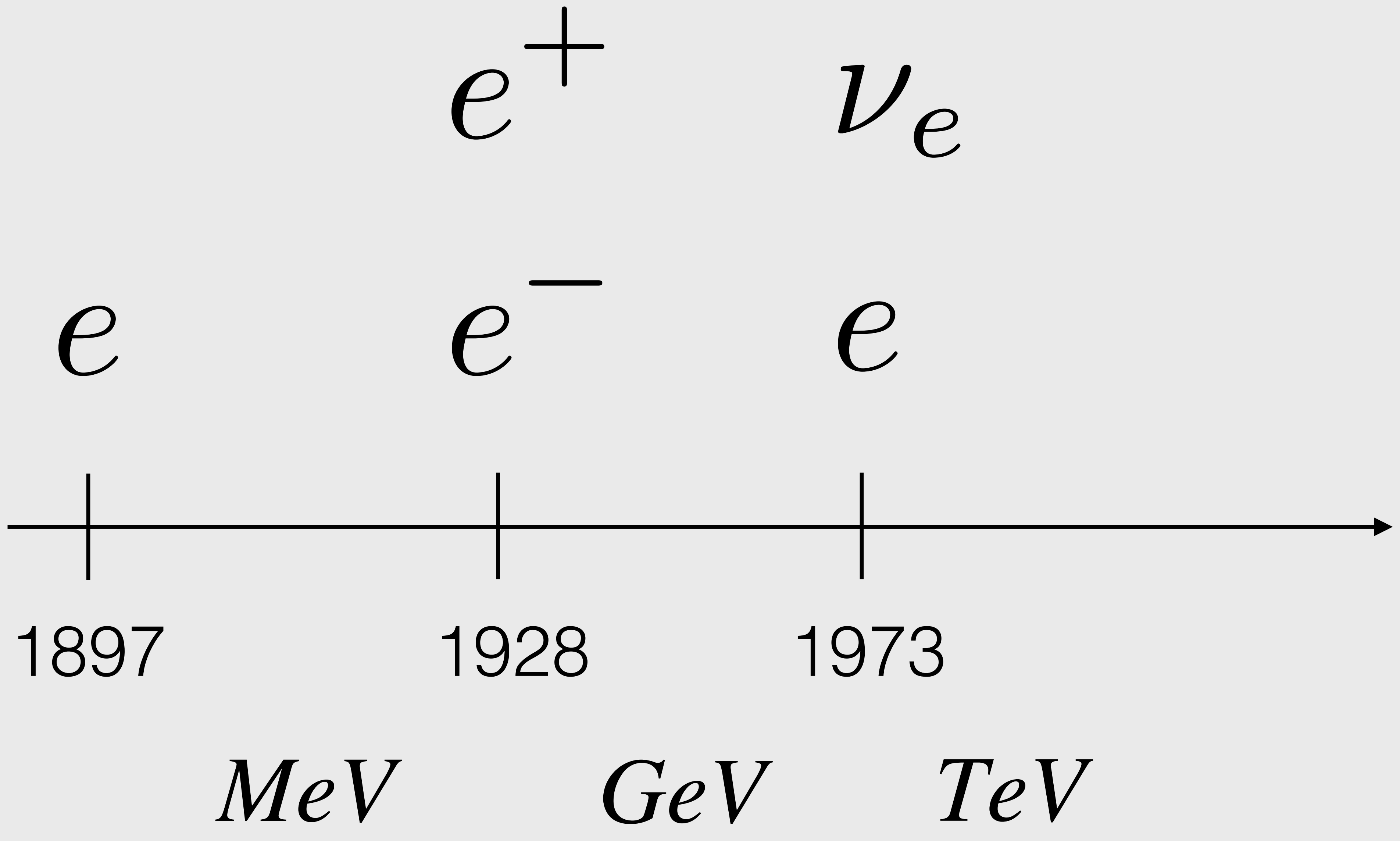

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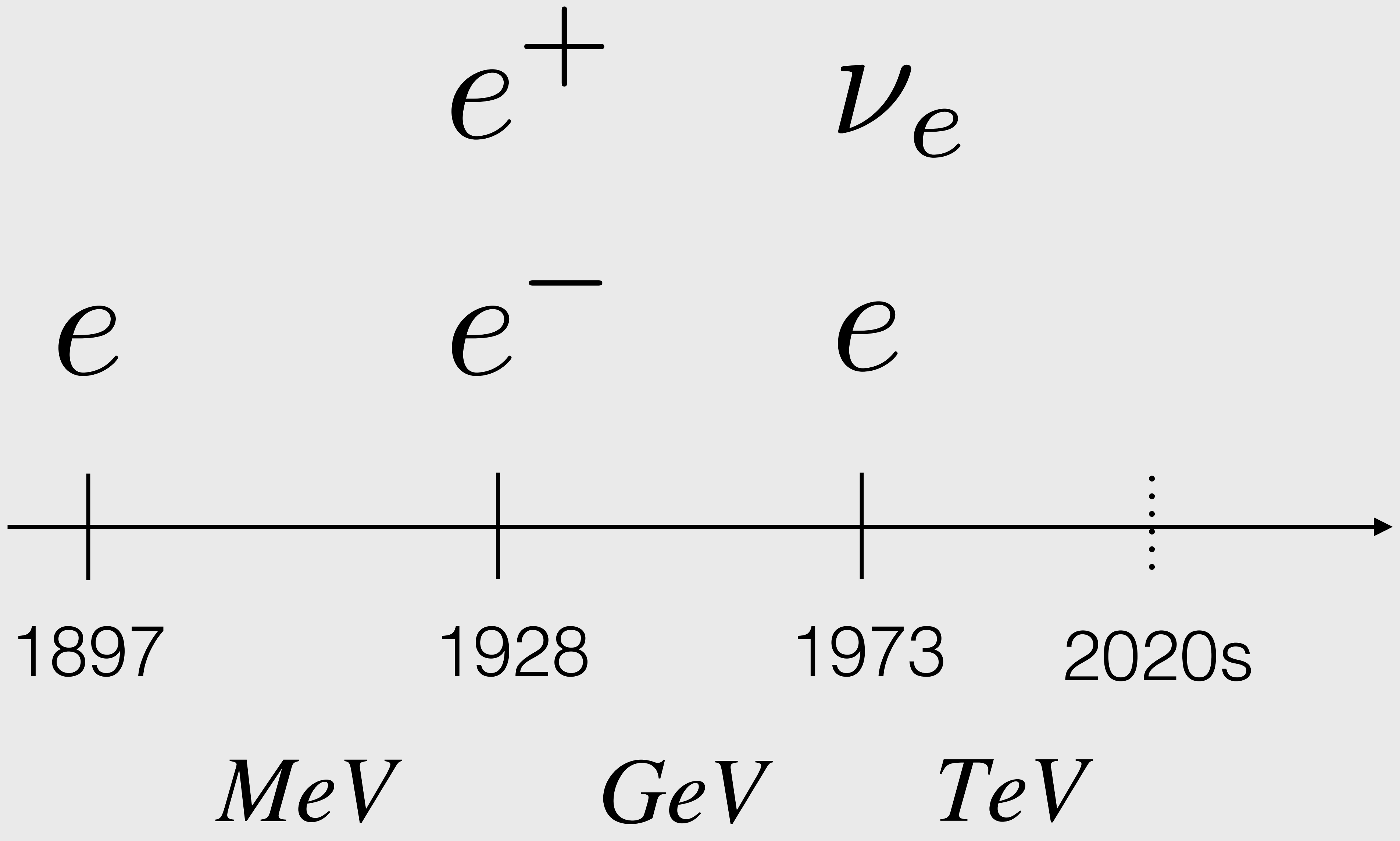

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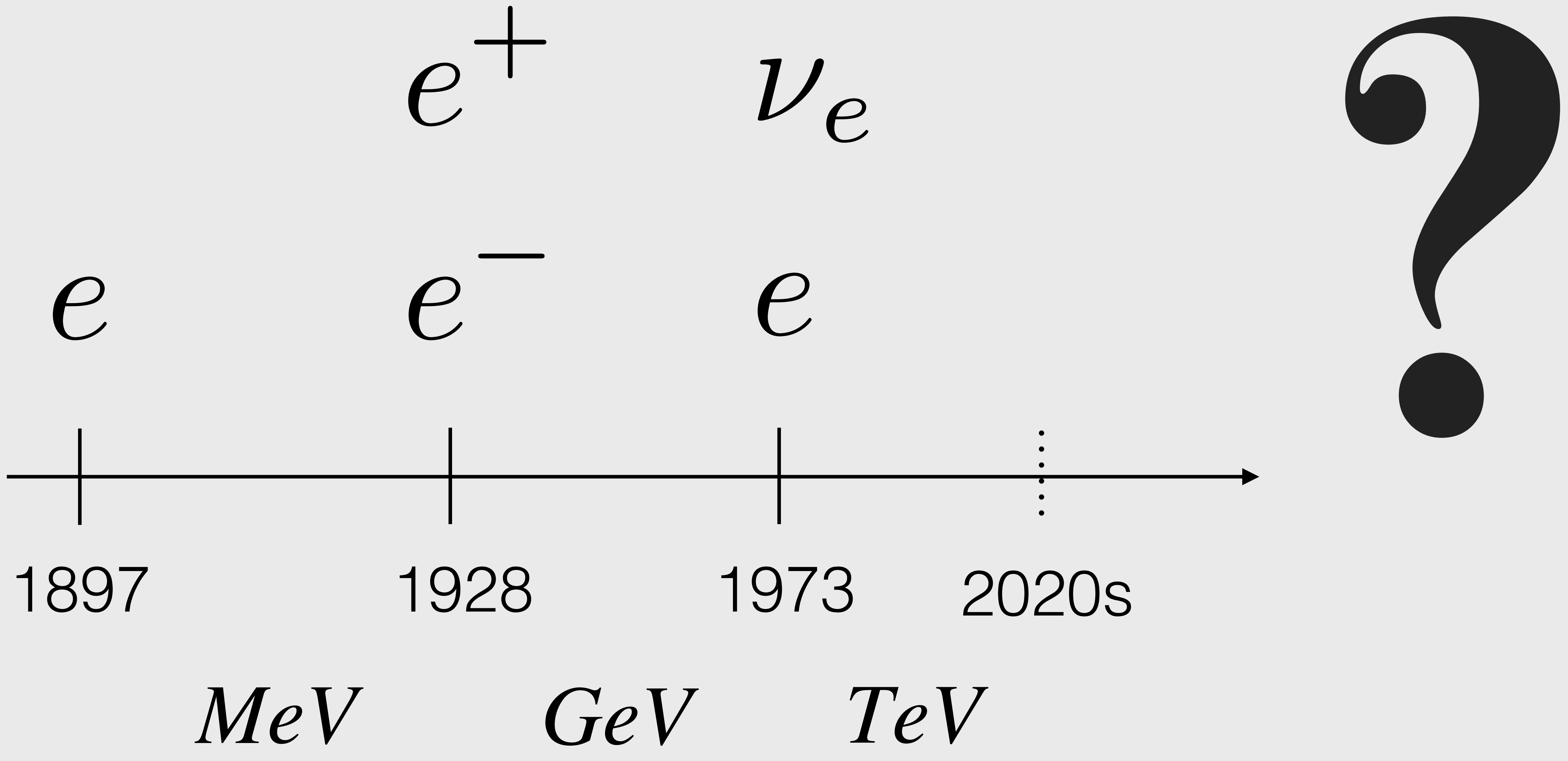

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STRONG INTERACTIONS

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✓ ✓ ✓ ✓ ✓ ✓ ✓

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We need to explore weak interactions

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NEED SOME COSMOLOGY INPUTS

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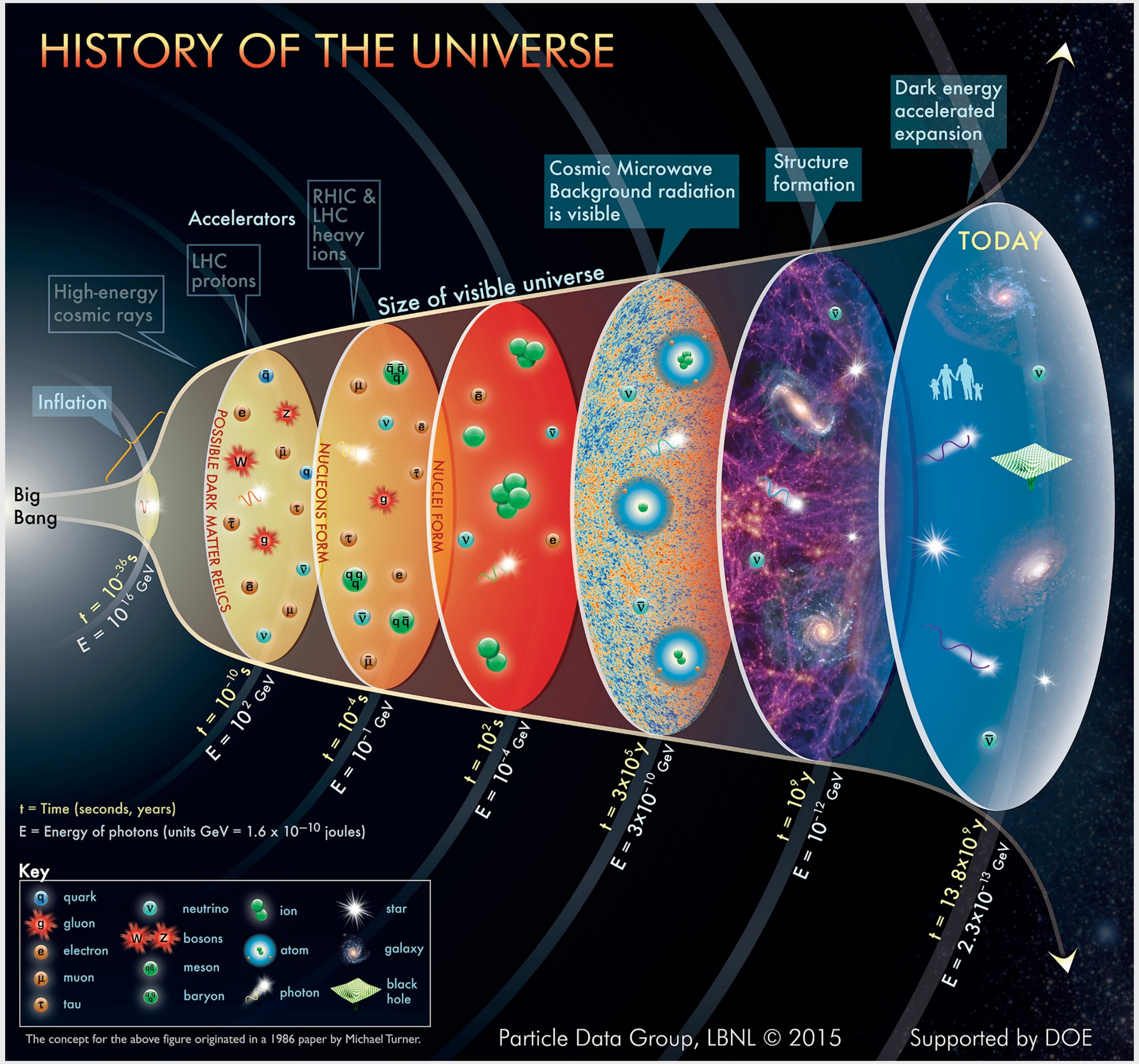
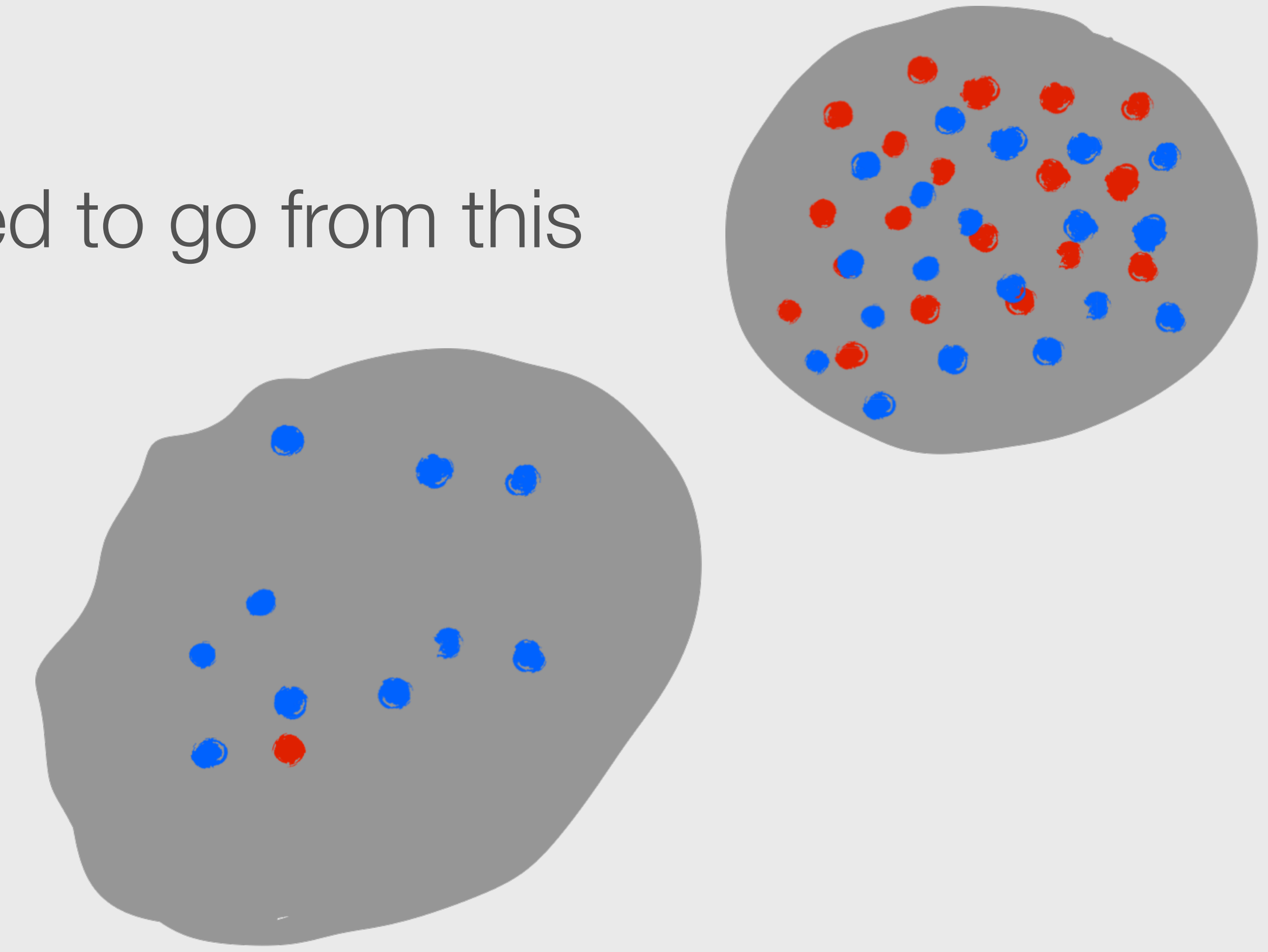


Nothing we have measured in high energy physics makes so much of a distinction between particles and anti-particles.

The observable Universe is made of matter, no antimatter

We need to go from this

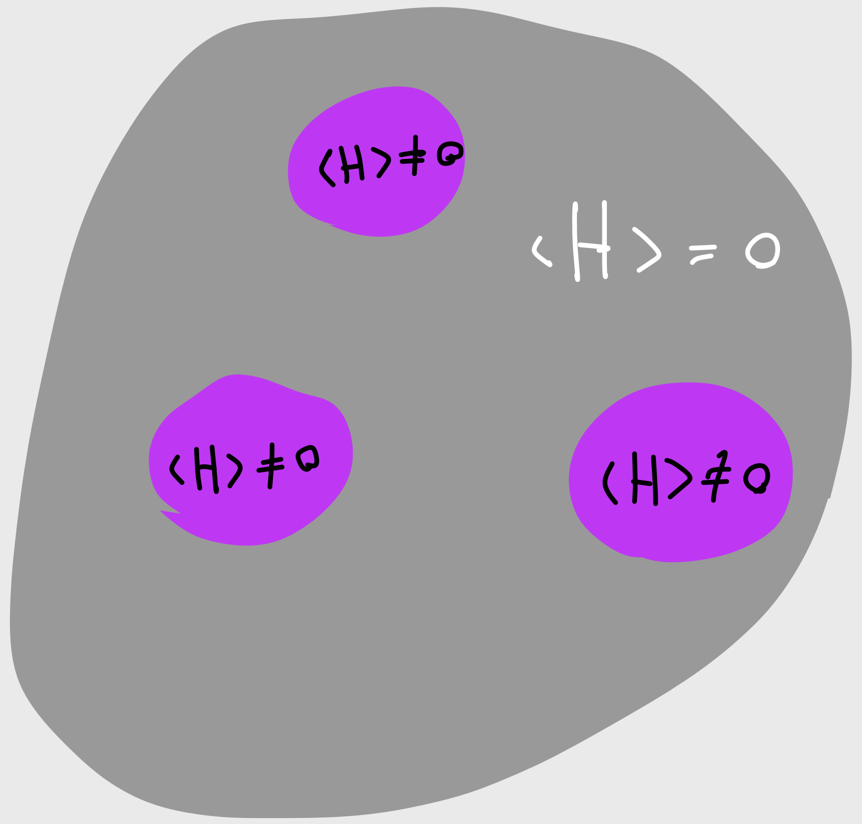
to this



particles
antiparticles

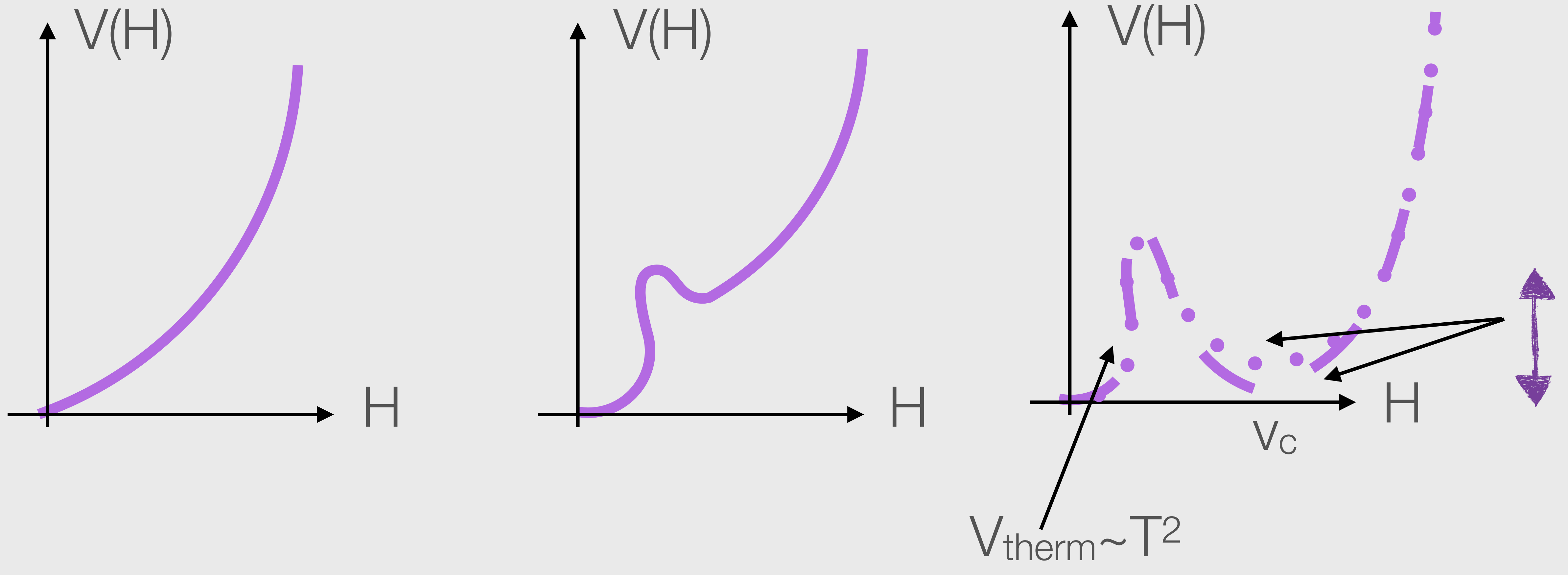
out-of-equilibrium processes are necessary

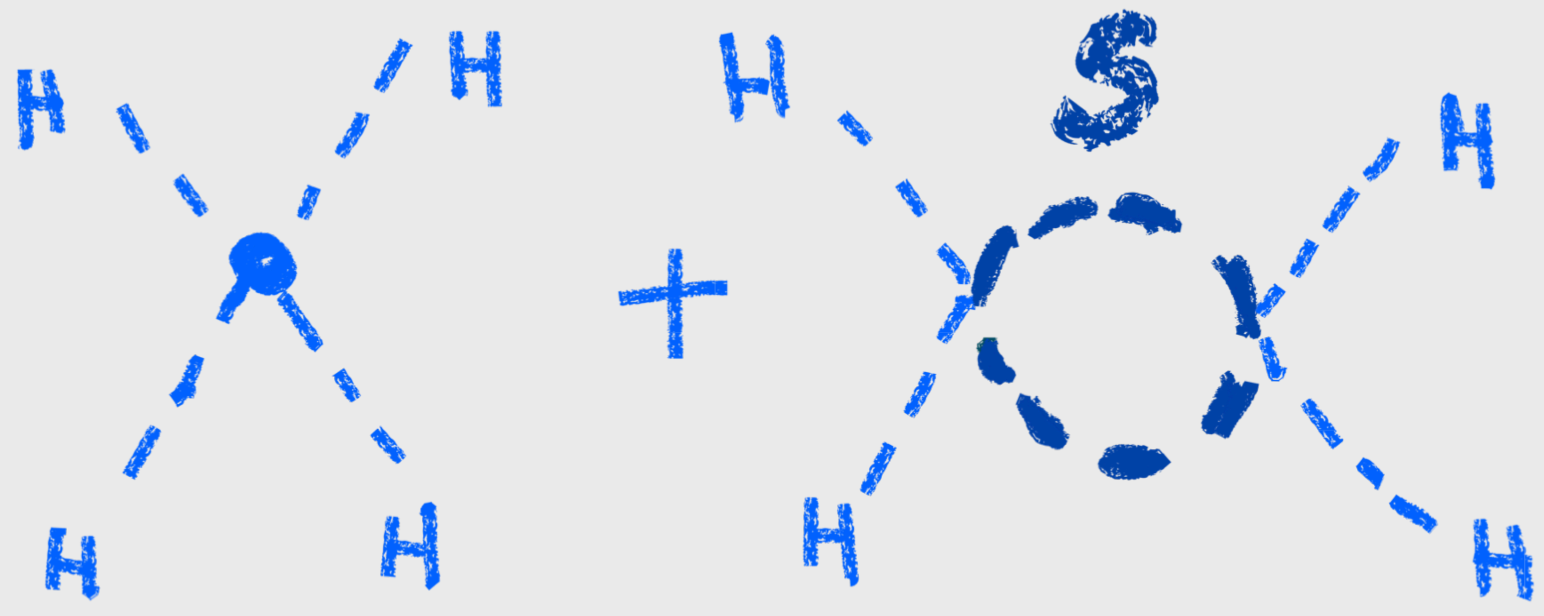
Electroweak phase transition



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

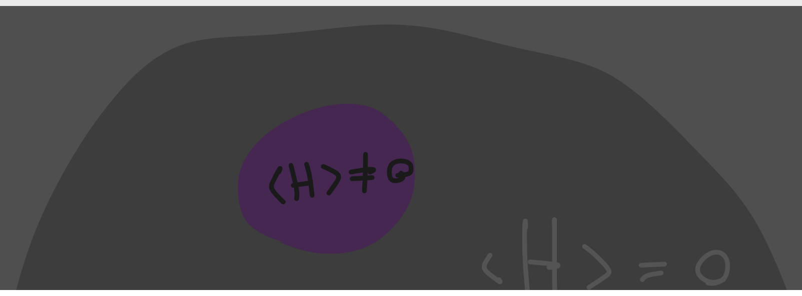
$T=T_c+\Delta$ $T=T_c$





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}~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 sampled y-axis scanned

x-axis [0, 4π/3]

"healthy" potential (no runaway, minimum v=246 GeV, perturbative)

1st order phase transition

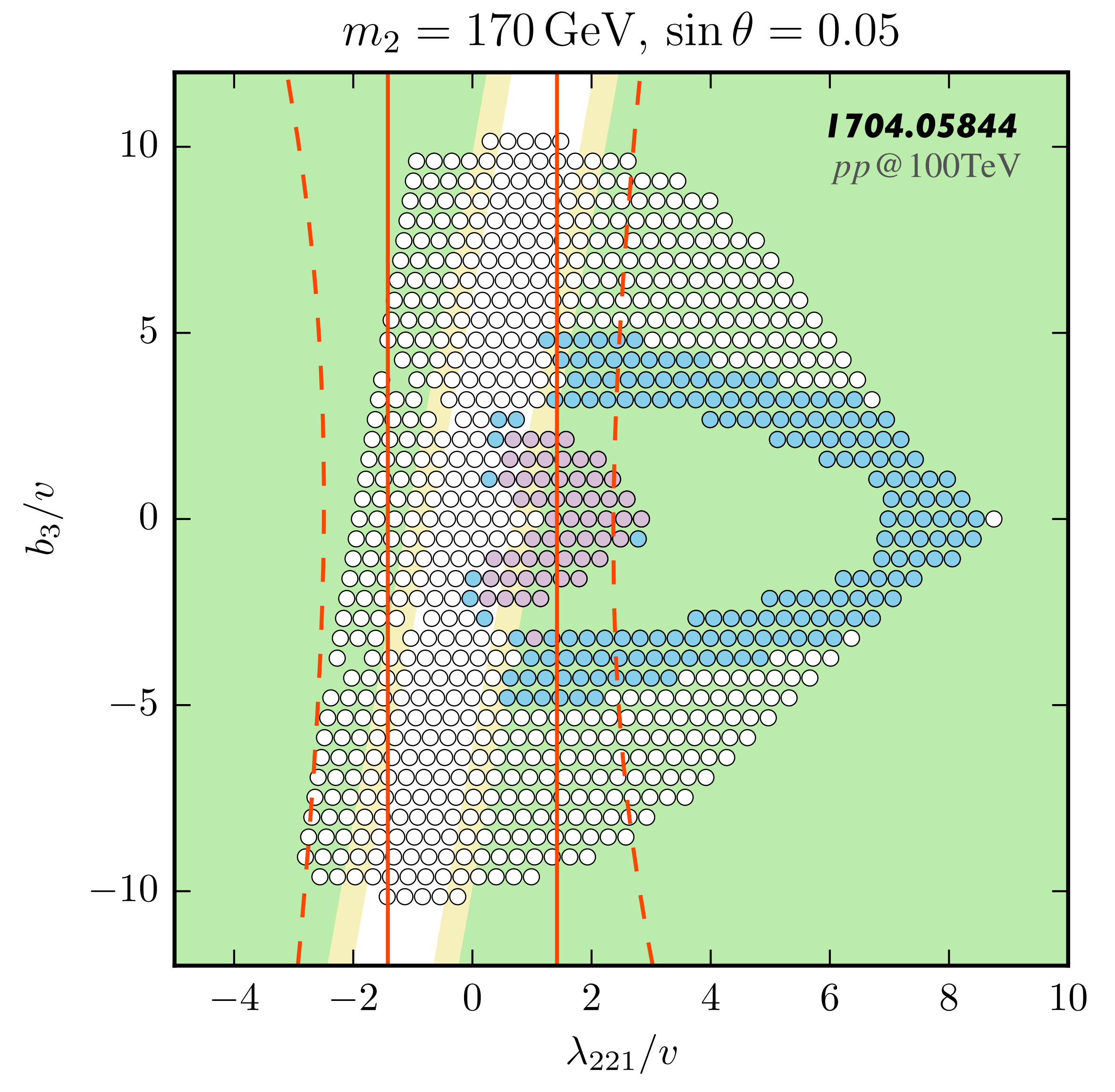
CLIC380/3TeV Single Higgs couplings

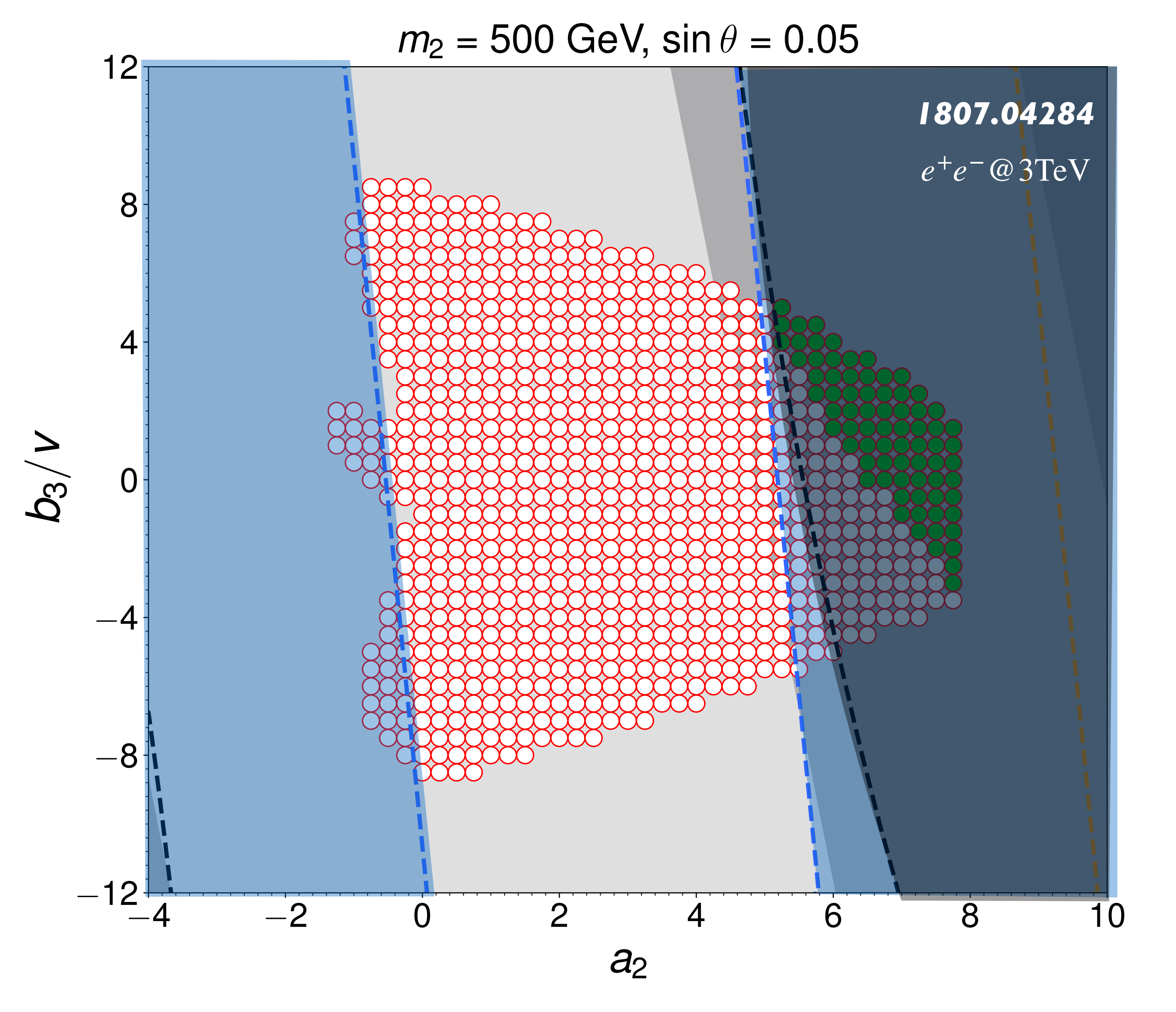
CLIC 1.4 TeV 3 TeV WBF S → h h → 4b

CLIC hhh 20% @ 95% CL coupling measurement

FCC-hh hhh 15% @ 95% CL coupling measurement

FCC-ee hZZ 0.5% @ 68% 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?

"healthy" potential (no runaway, minimum v=246 GeV, perturbative)

1st order phase transition

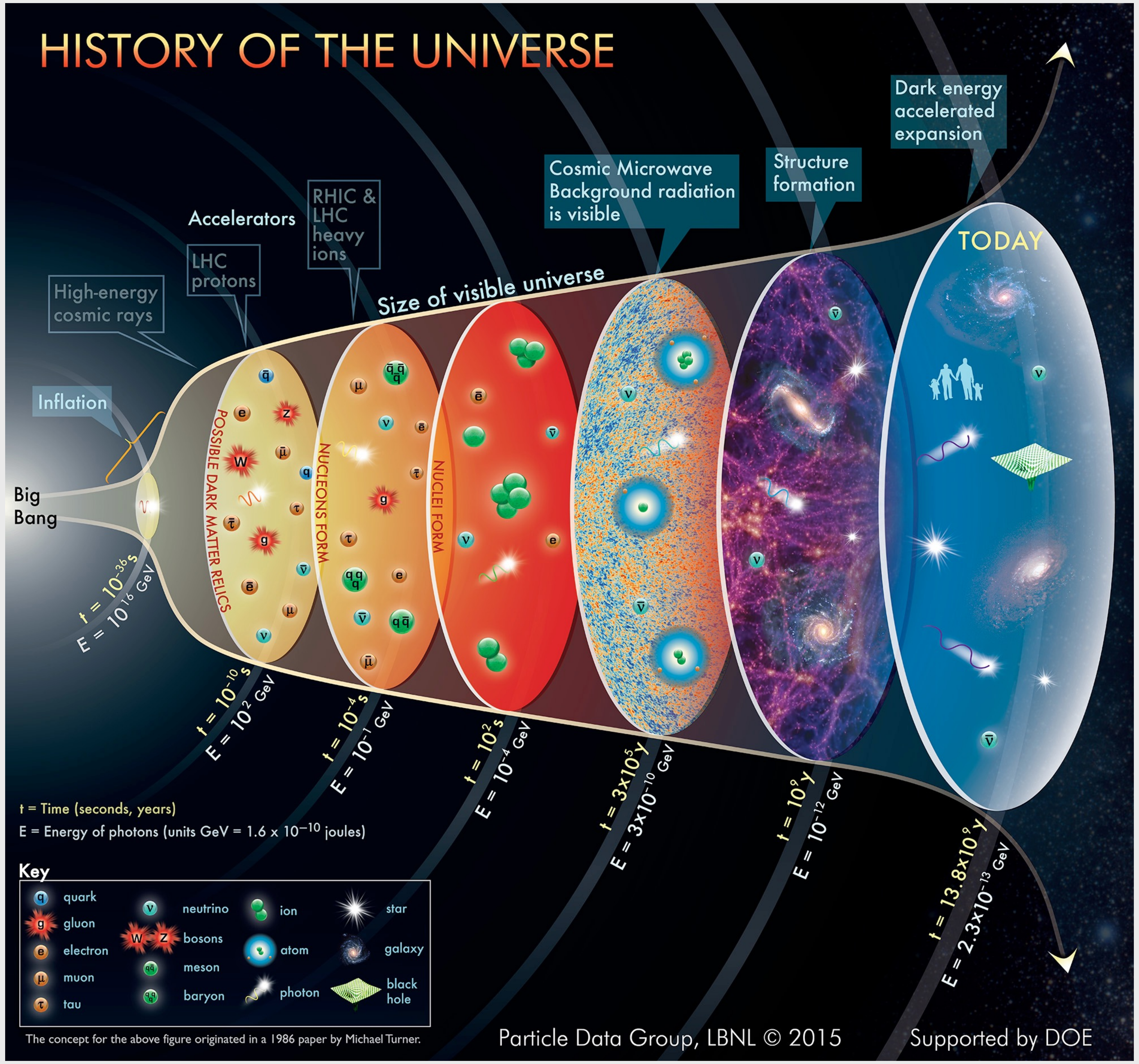
- Both Hadron and Lepton colliders can observe directly these states
- Indirect information from H couplings is also crucial
- The mass range is clearly well above the ZH threshold, we need higher energies in lepton colliders than H factories (!)

λ_{221}/v

a_2

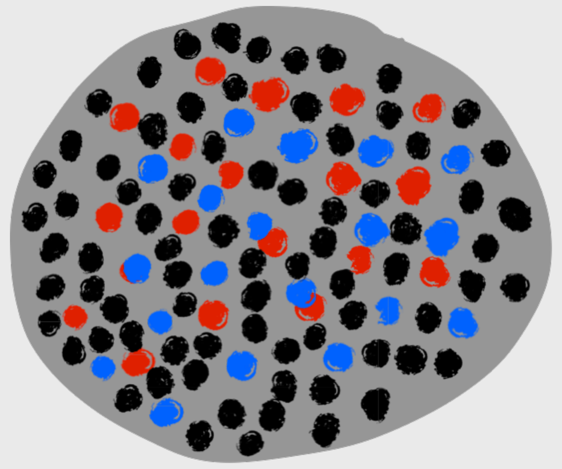
parameters space of 1st order phase transition accessible by several probes

Open Questions on the “big picture” on fundamental physics circa 2021



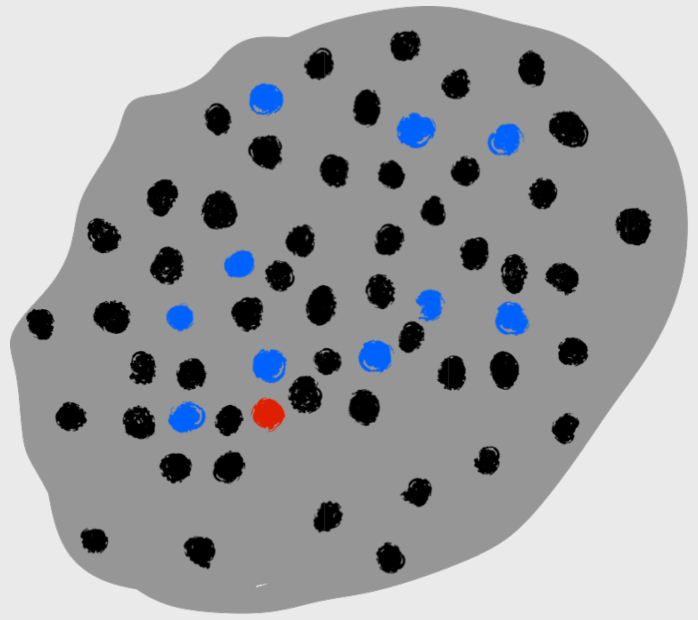
The observable Universe is made of matter, plus about 5 times as much dark matter

We need to go from this



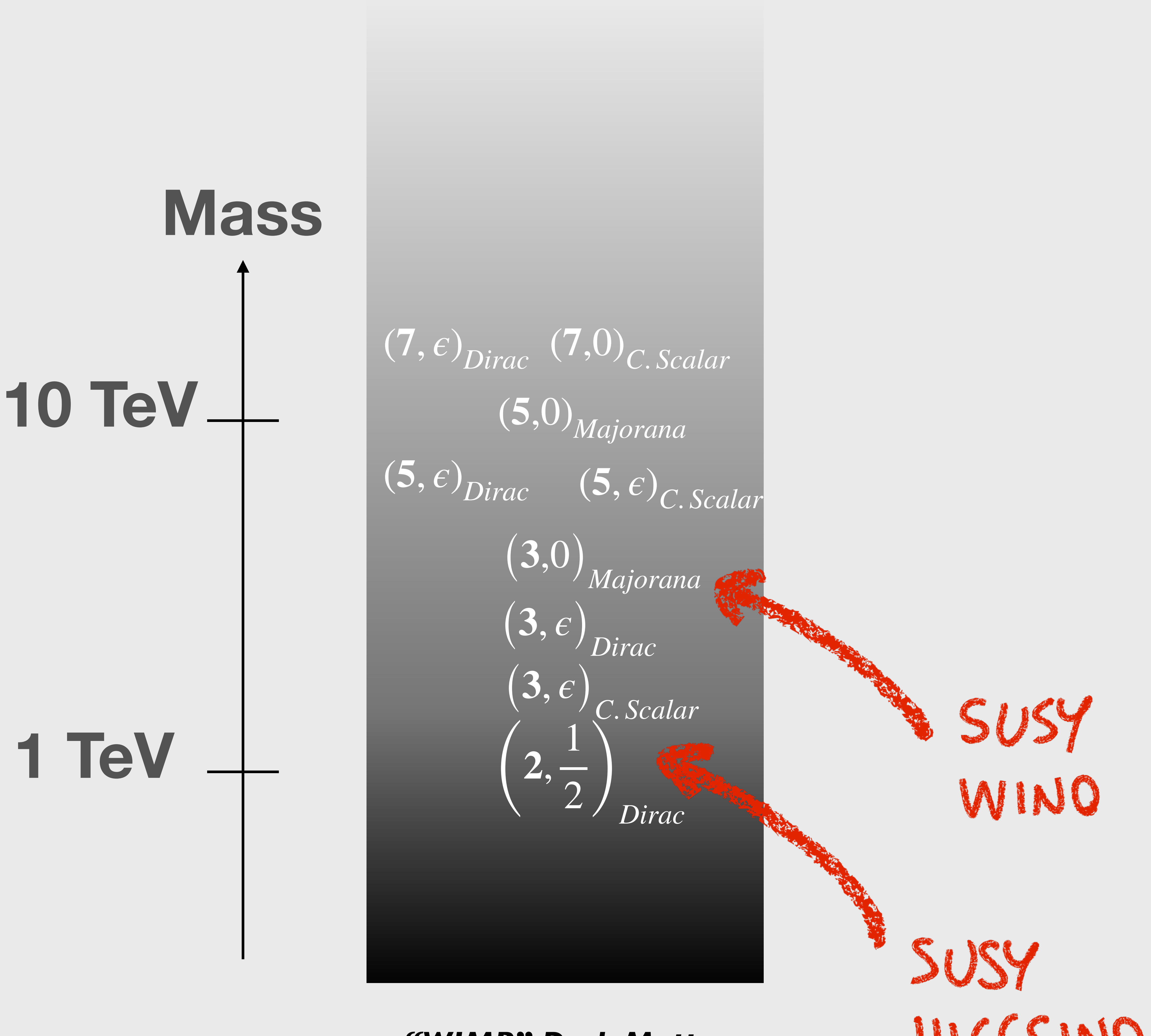
normal particles
dark matter
antiparticles

to this



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

Open Questions on the "big picture" on fundamental physics circa 2021



"WIMP" Dark Matter

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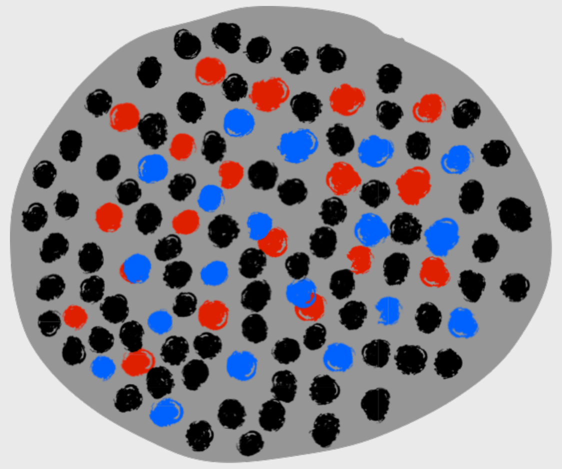

normal particles
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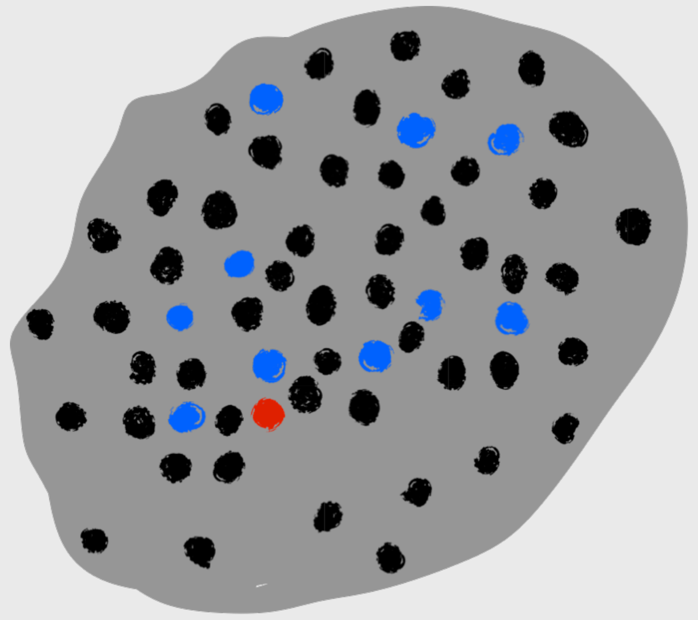

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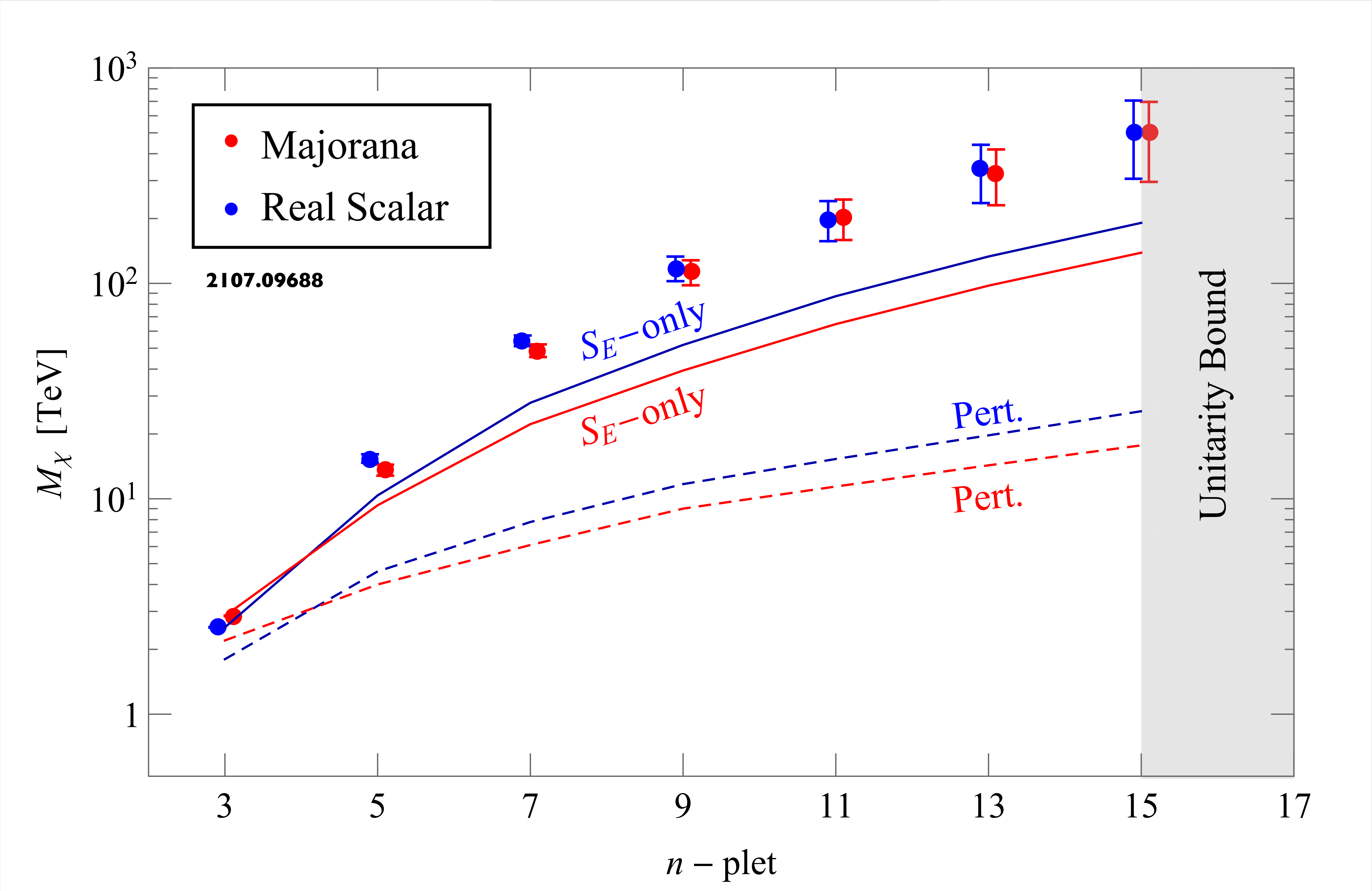

SUSY
HIGGSINO

"WIMP" Dark Matter

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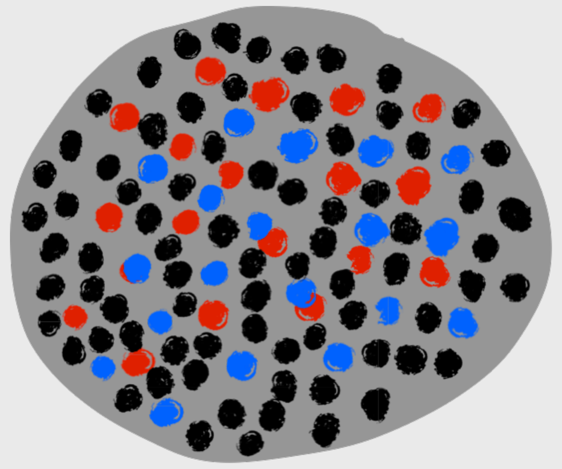

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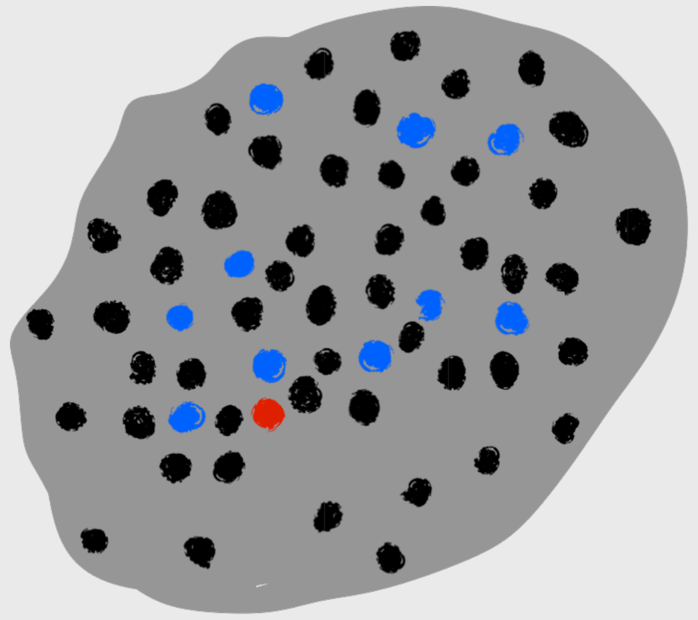

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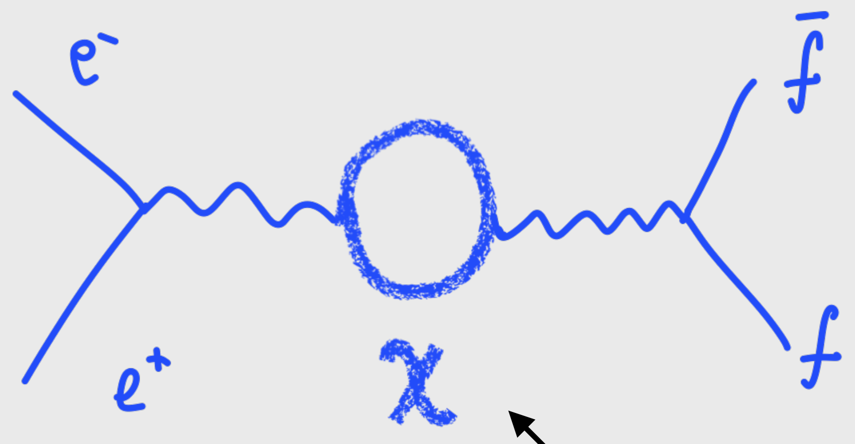
flashing concrete results for

Dark Matter at the weak scale

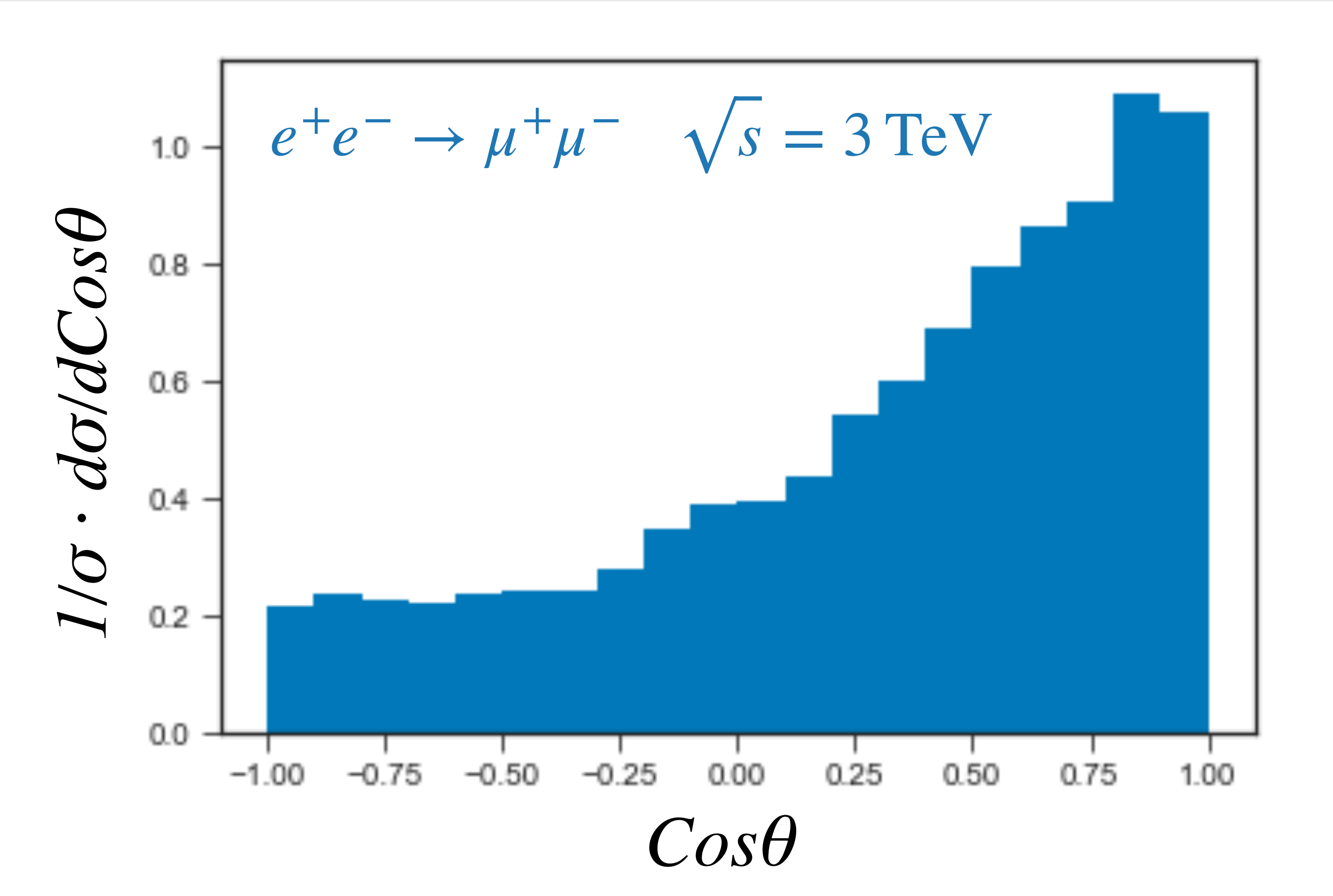
$e^+e^- \to f\bar{f}$

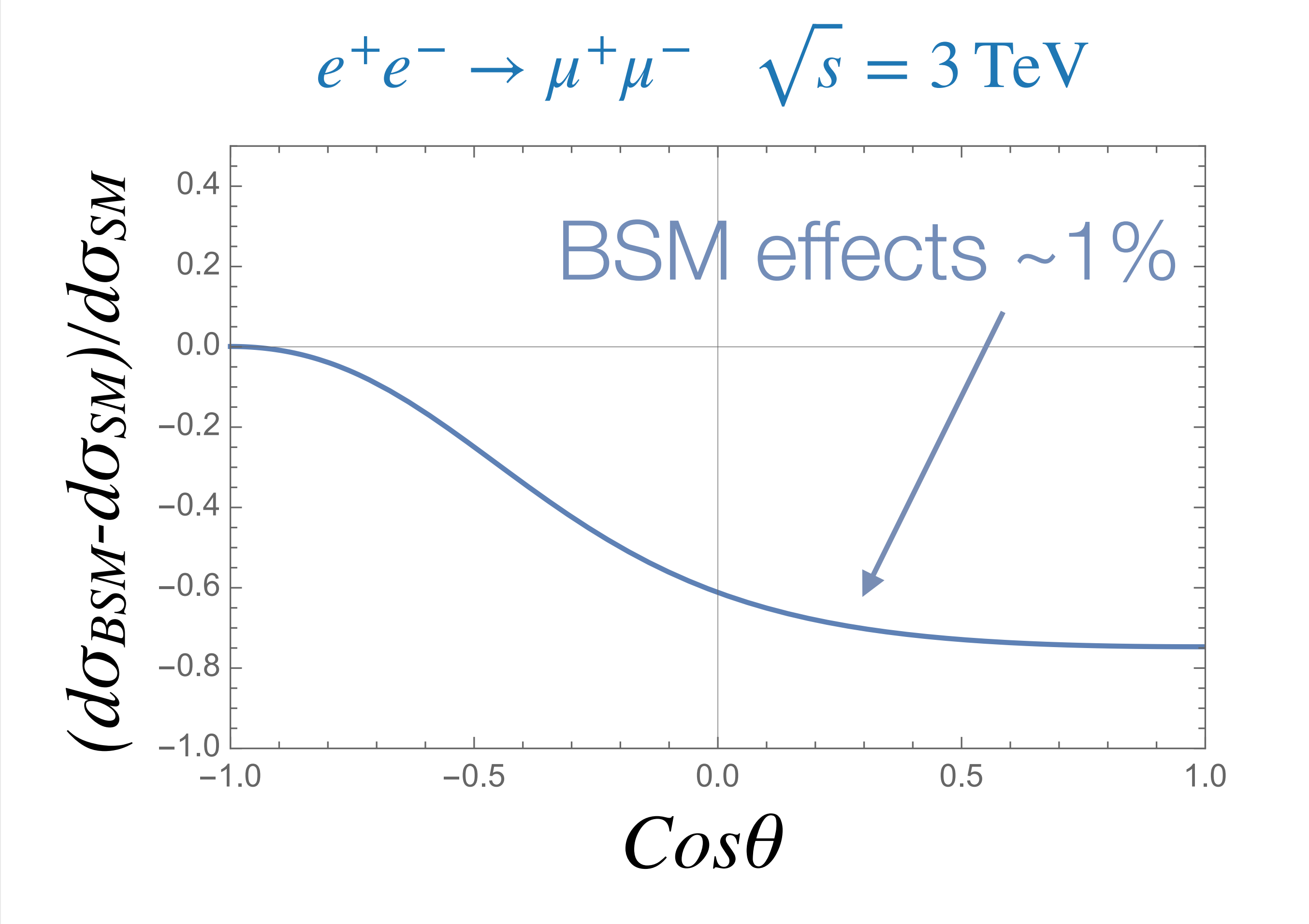
PRECISION

ANGULAR DISTRIBUTION



χ is heavy/light new physics

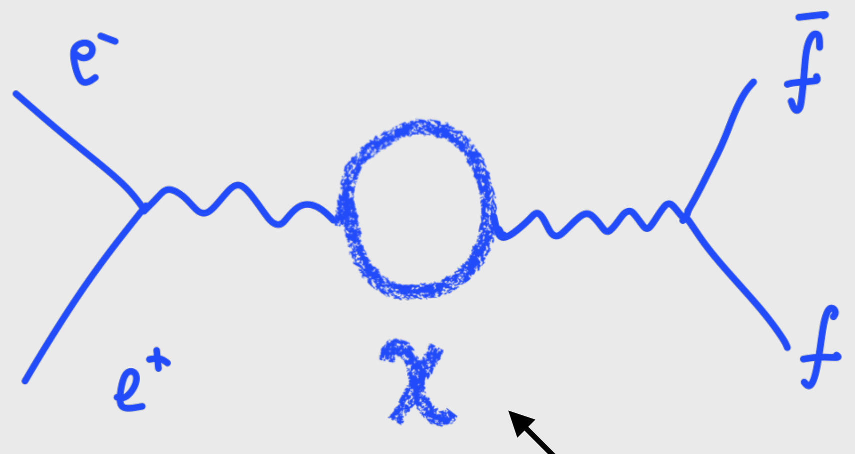




beams polarization is beneficial to increase NP effects

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

PRECISION **ANGULAR DISTRIBUTION**



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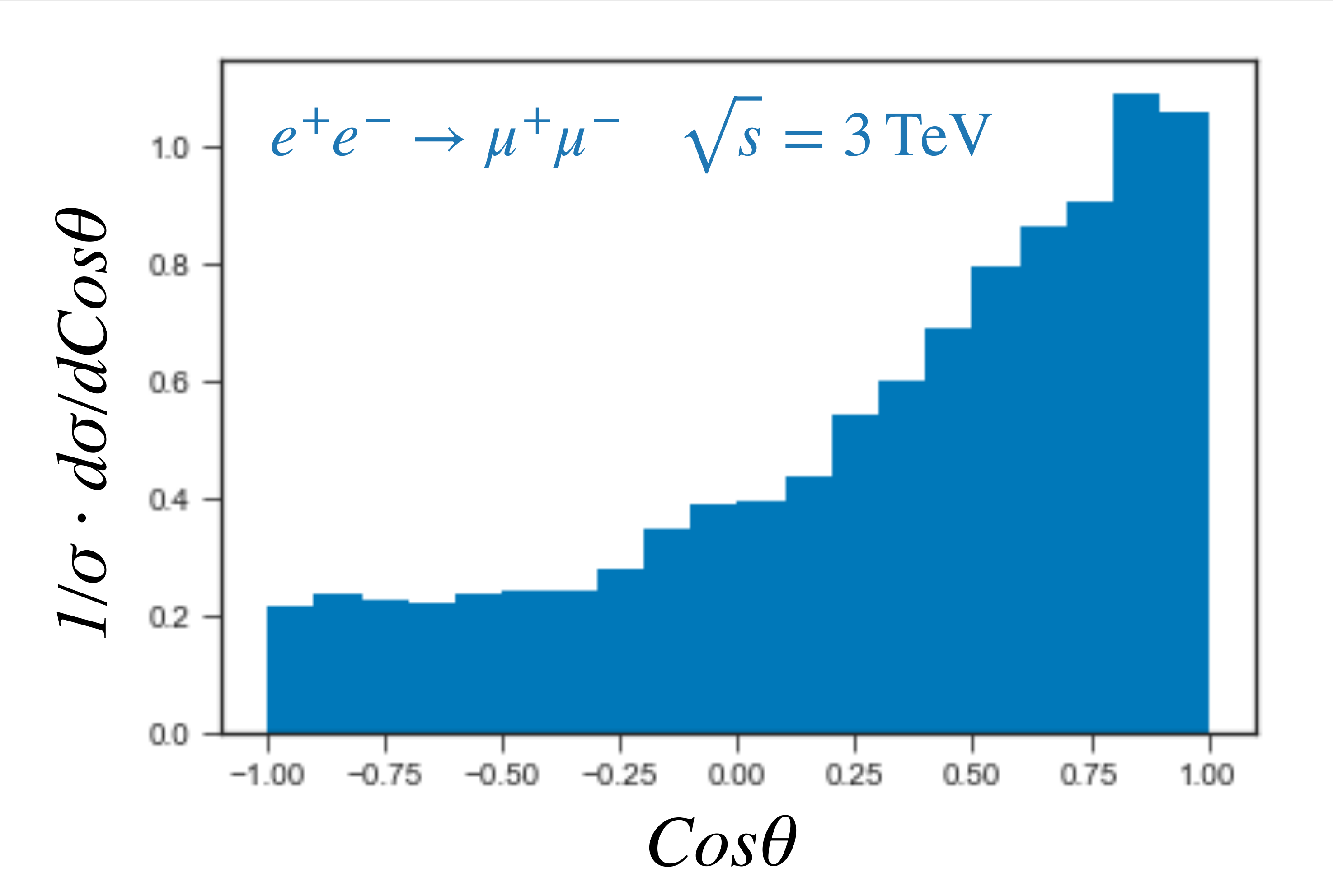

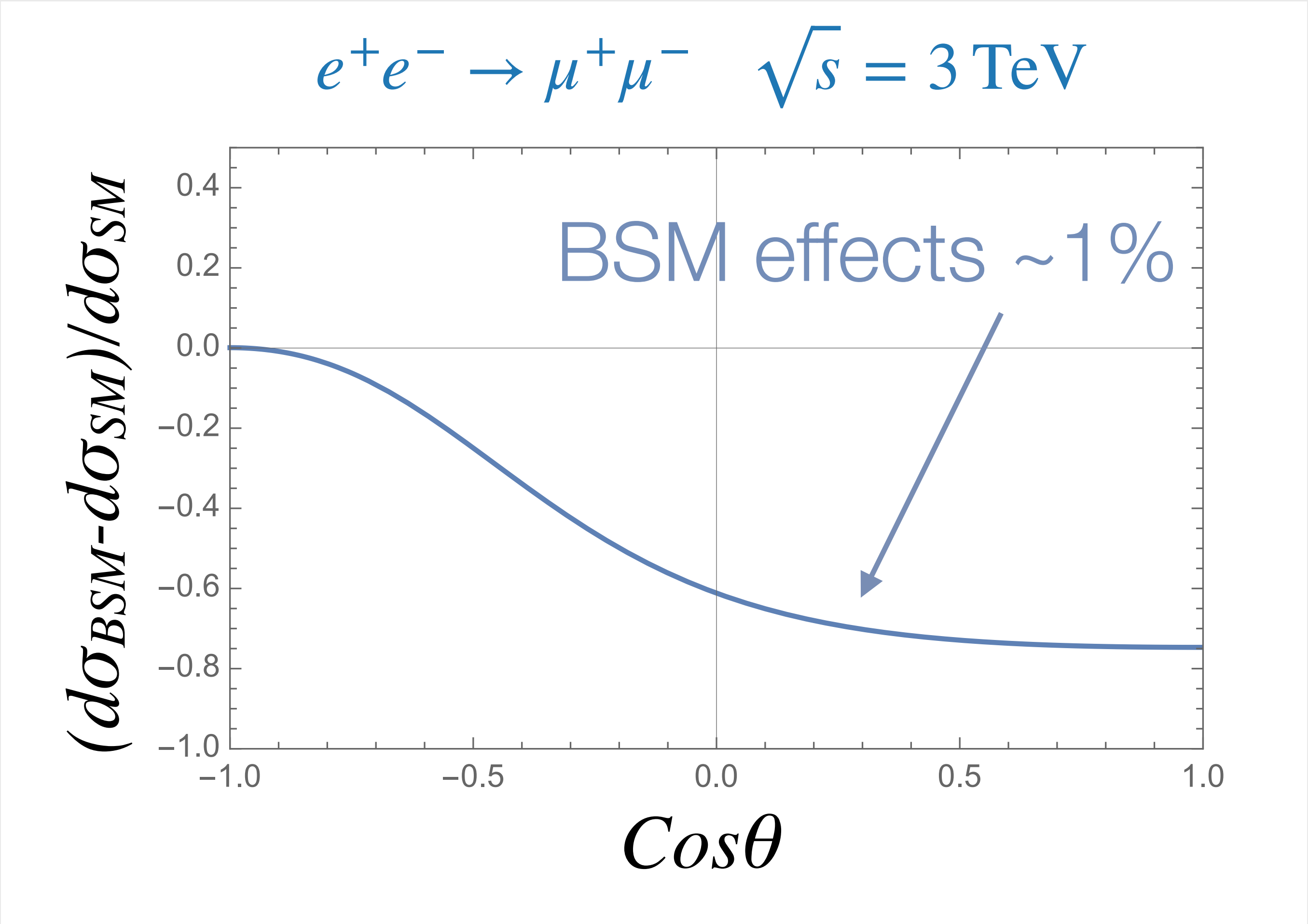

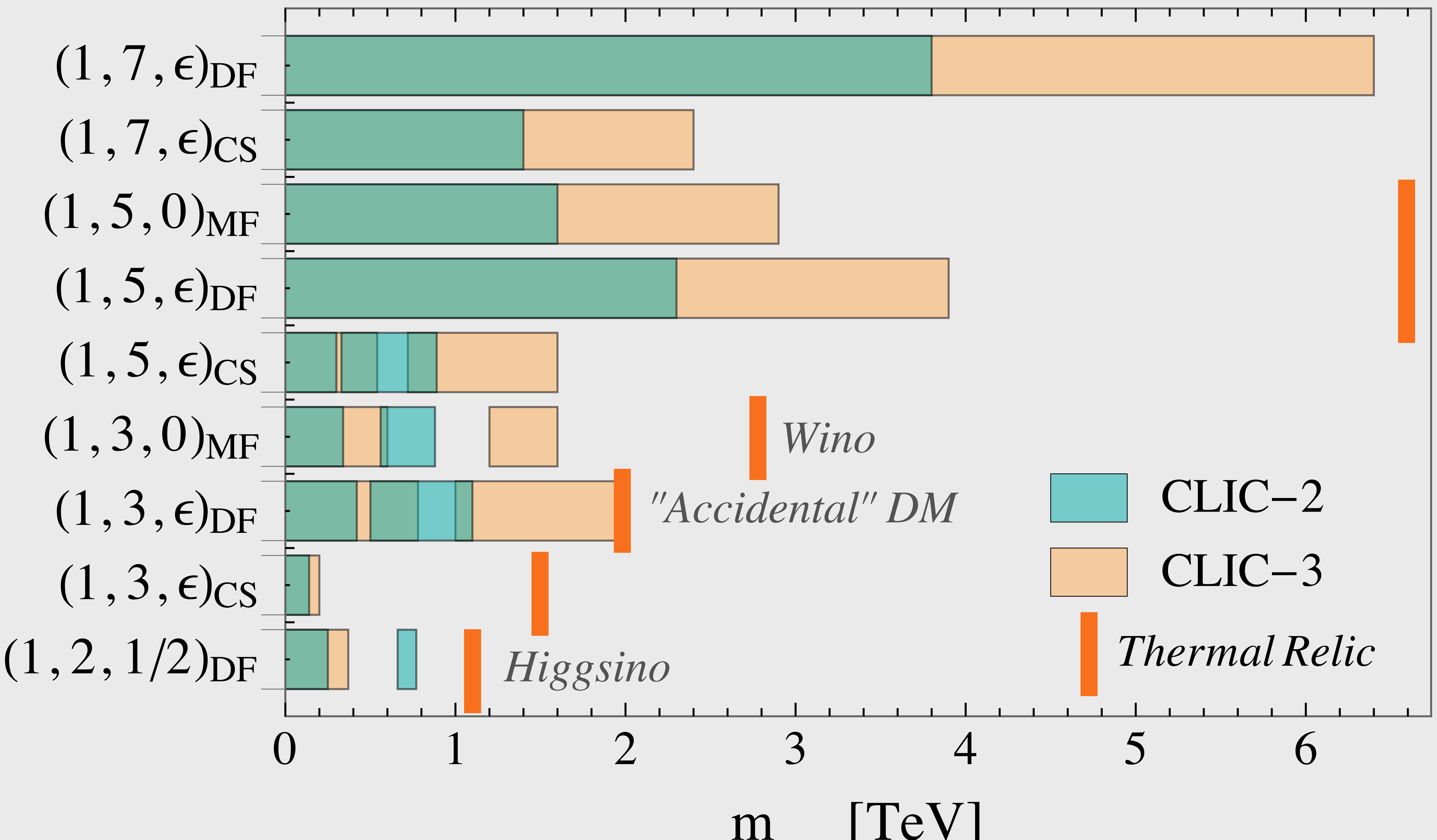

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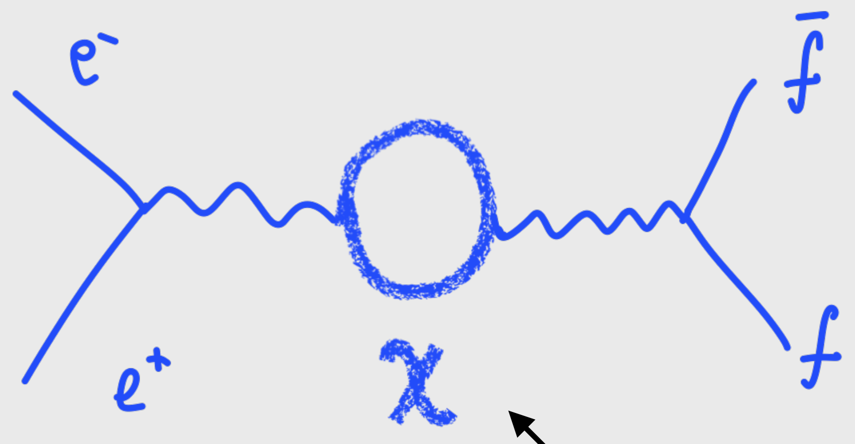

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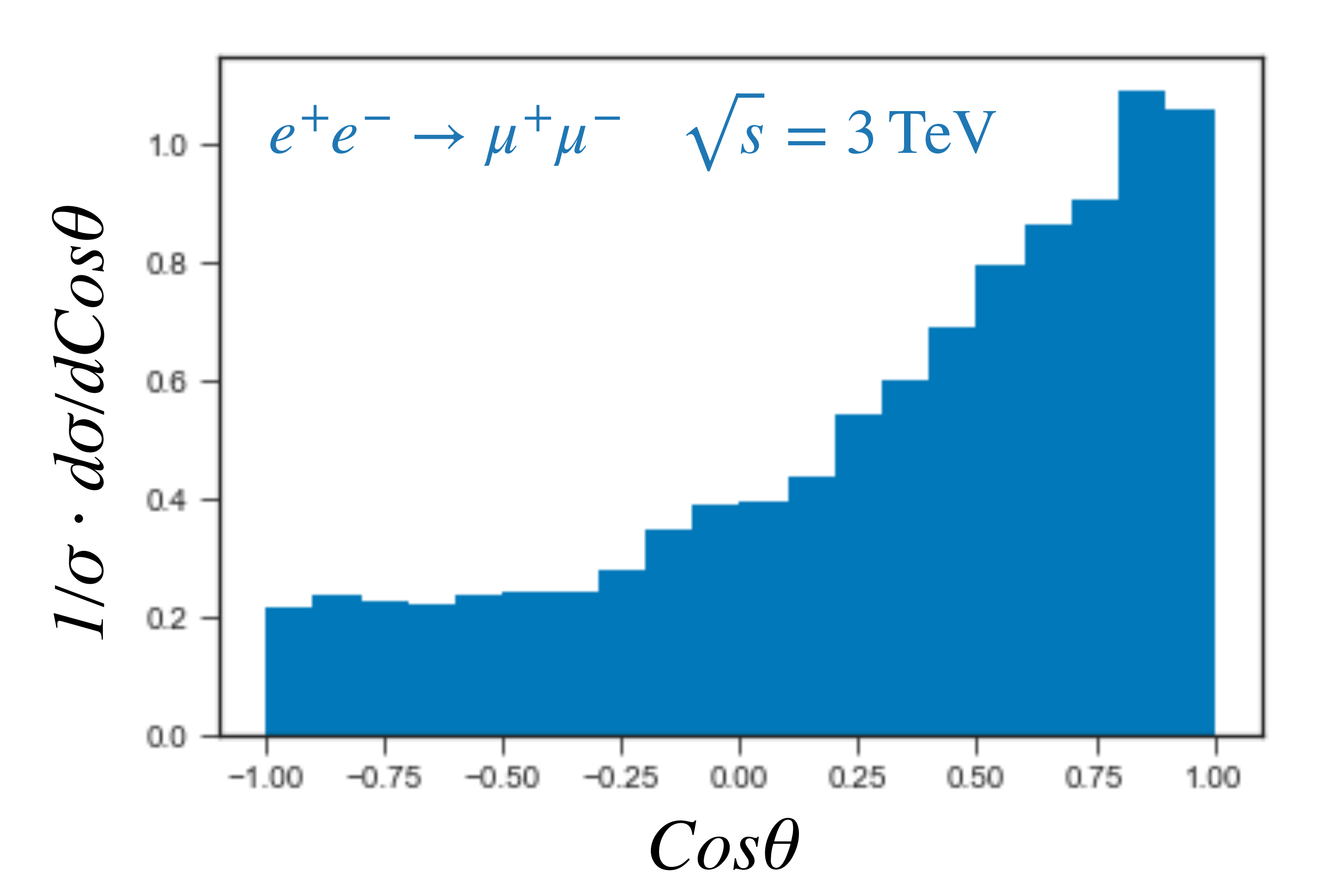
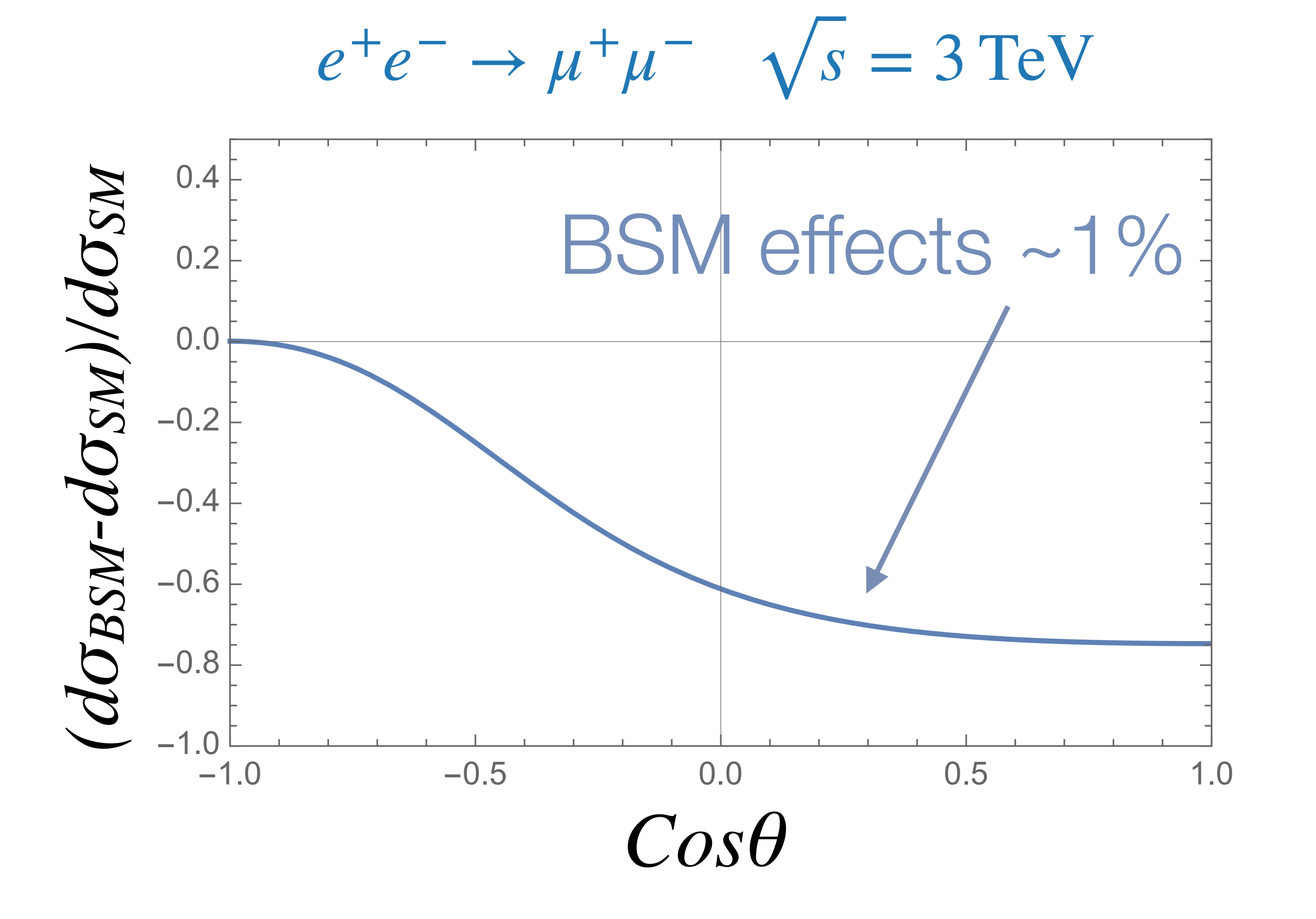




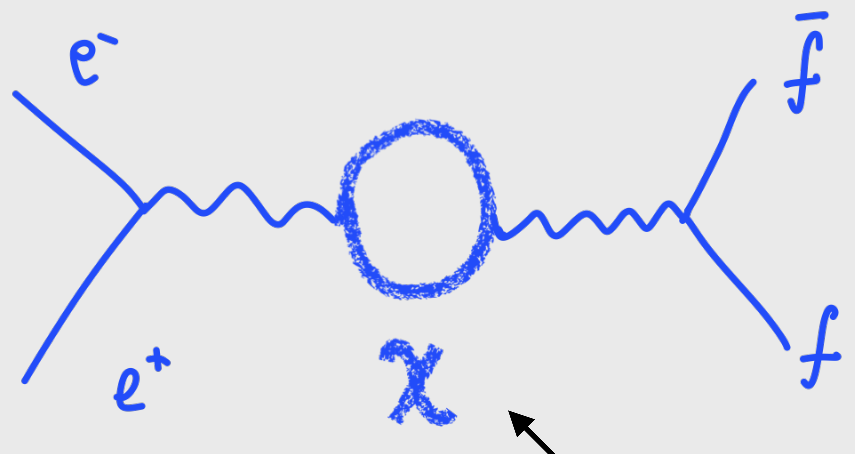
χ / m_χ [TeV]	DM	HL-LHC	HE-LHC	FCC-100	CLIC-3	Muon-14
$(1,2,1/2)_{\rm DF}$	1.1	–	–	–	0.4	0.6
$(1,3,\epsilon)_{\rm CS}$	1.6	–	–	–	0.2	0.2
$(1,3,\epsilon)_{\rm DF}$	2.0	–	0.6	1.5	0.8 & [1.0, 2.0]	2.2 & [6.3, 7.1]
$(1,3,0)_{\rm MF}$	2.8	–	–	0.4	0.6 & [1.2, 1.6]	1.0
$(1,5,\epsilon)_{\rm CS}$	6.6	0.2	0.4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

$\mu^+\mu^- \to f\bar{f}, W^+W^-$

PRECISION

TOTAL CROSS-SECTION



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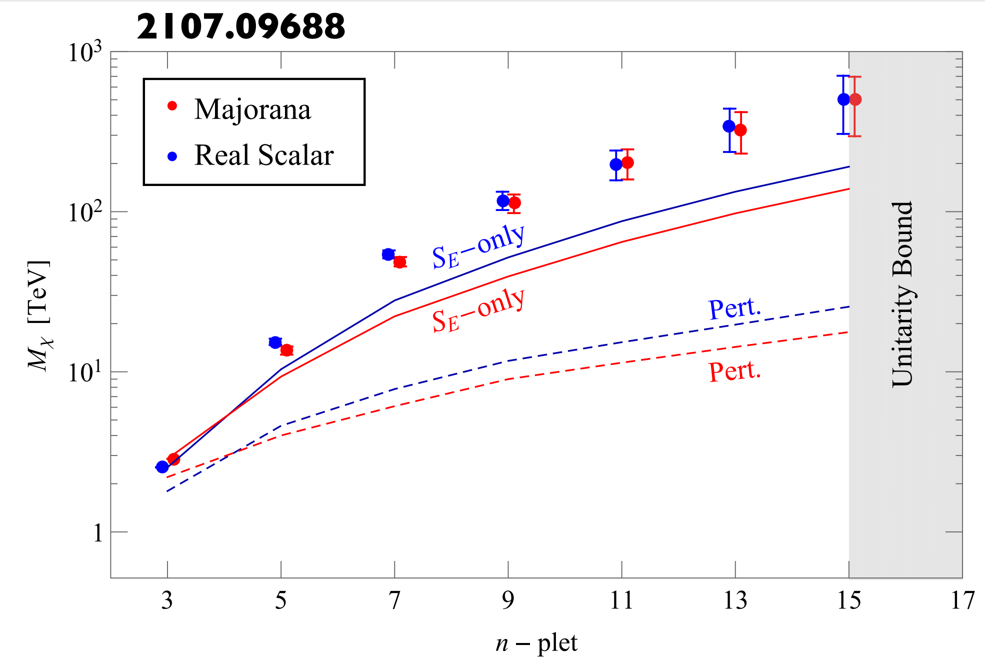
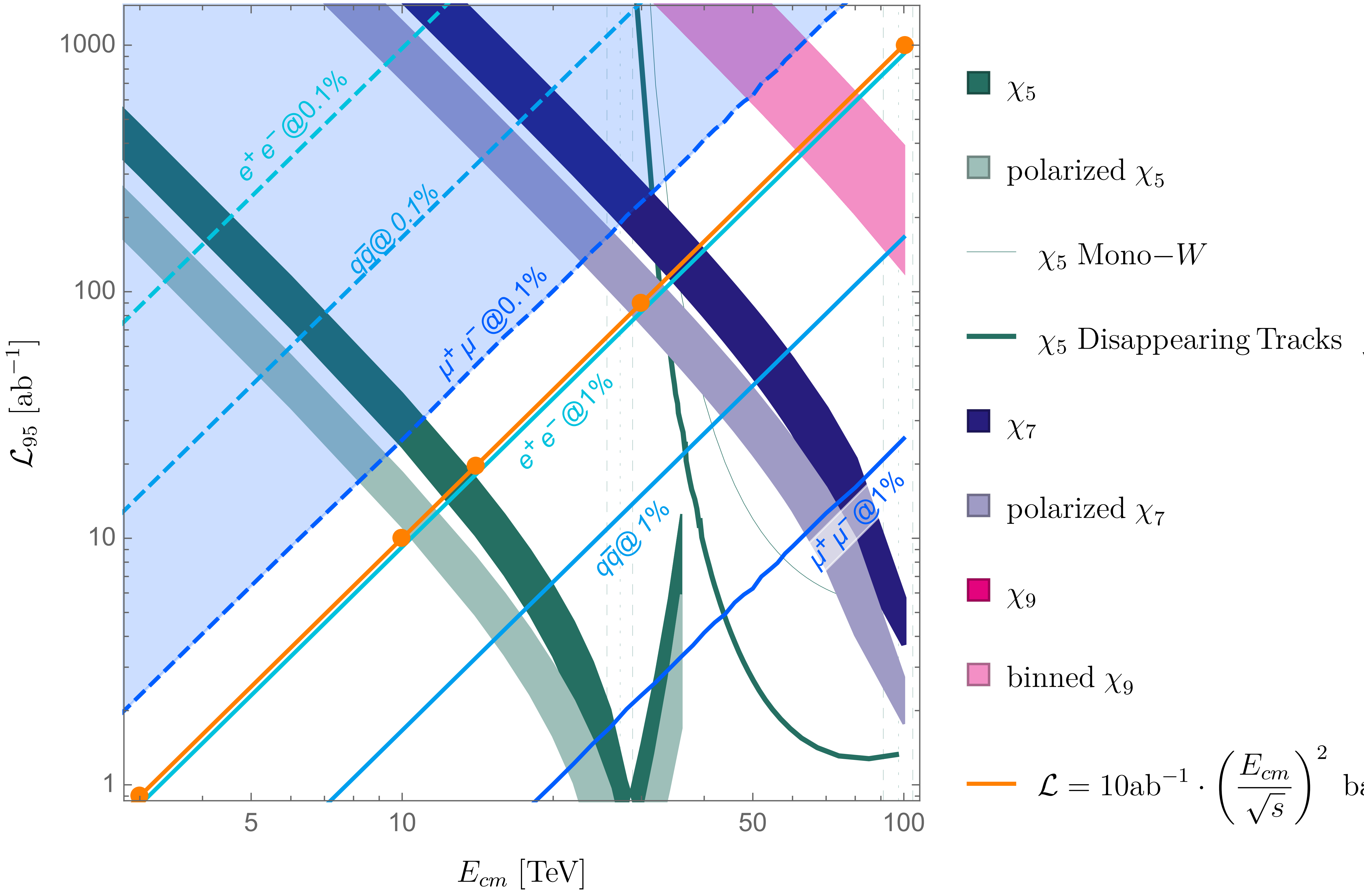
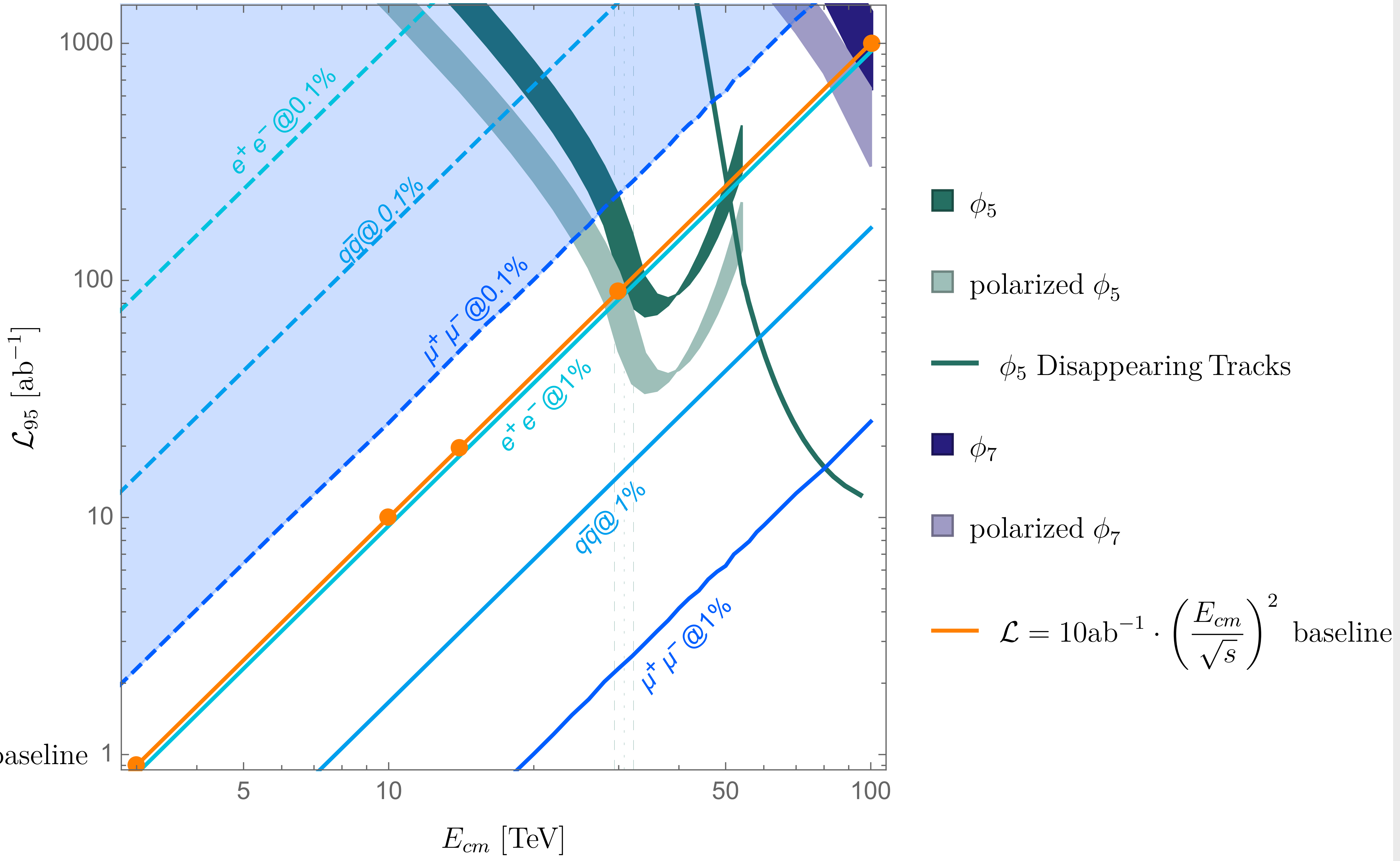


Majorana Fermion

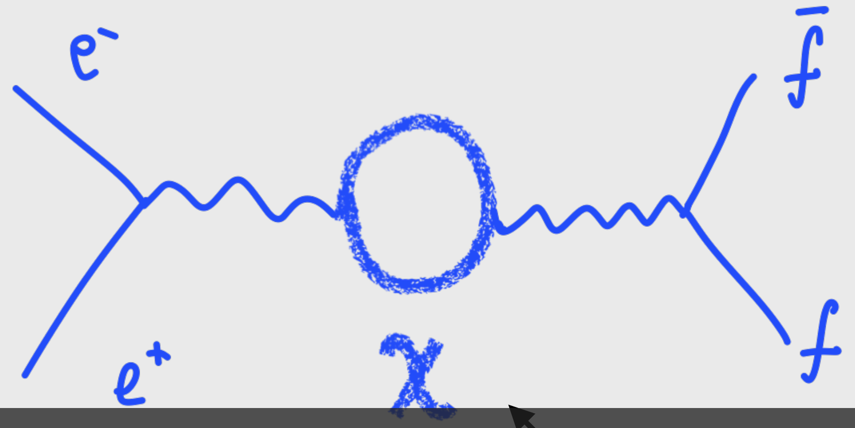


Real Scalar



beams polarization is beneficial to increase NP effects

$$\mu^+\mu^- \to f\bar{f}, W^+W^-$$



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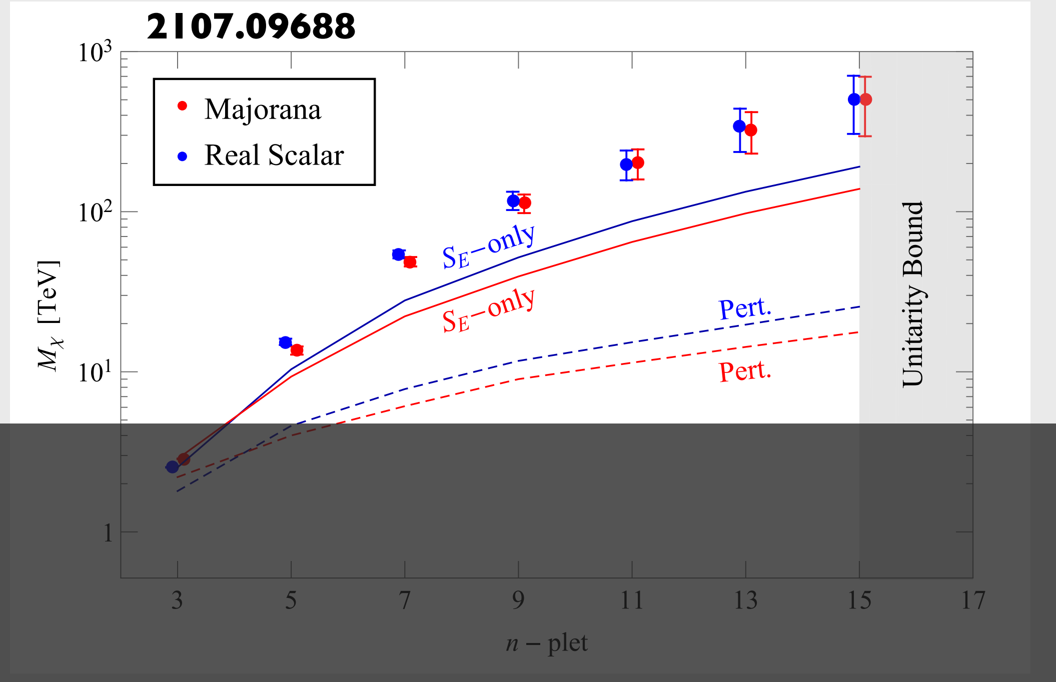
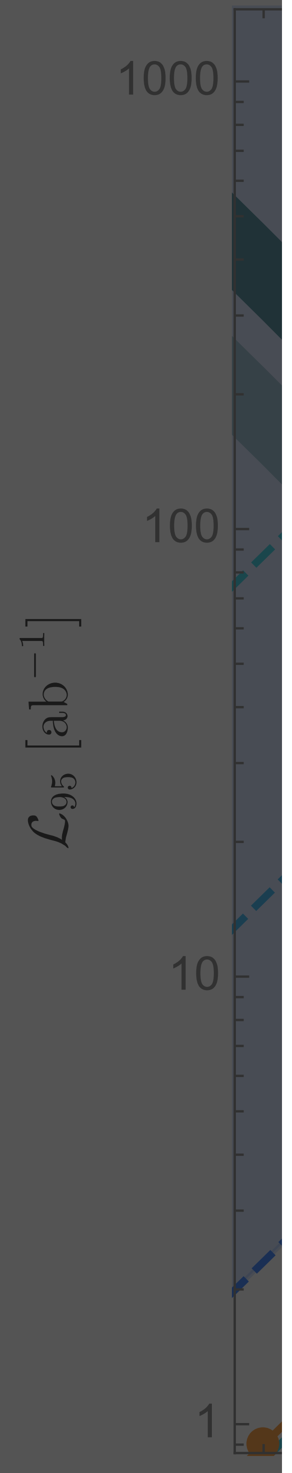


PRECISION

TOTAL CROSS-SECTION



- Hadron and Lepton colliders can observe these states directly *and* indirectly
- A complete test of the whole range of this type of Dark Matter candidates is out of reach for even most futuristic colliders
- Synergy with other approaches to search for Dark Matter is crucial

ks

baseline

beams polarization is beneficial to increase NP effects

flashing concrete results for

The size of the Higgs boson

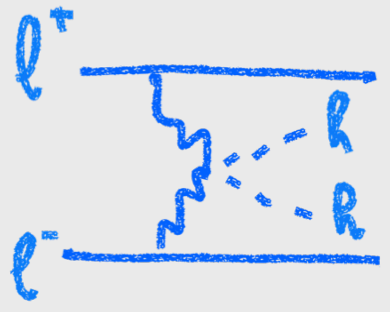
Effects of the size of the Higgs boson

h ~ π STRONGLY INTERACTING LIGHT HIGGS

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

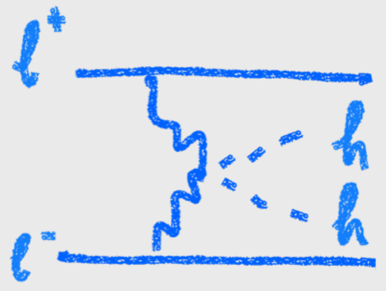
$1/(g_\star f) \sim 1/m_\star$

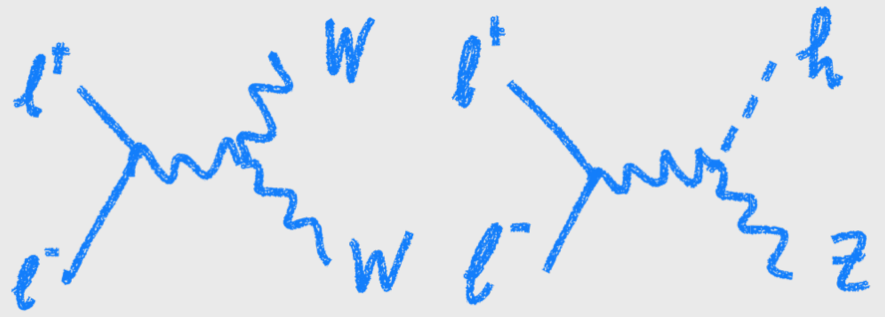
$g_{SM}/(g_\star f) \sim g_{SM}/m_\star$



large p_T

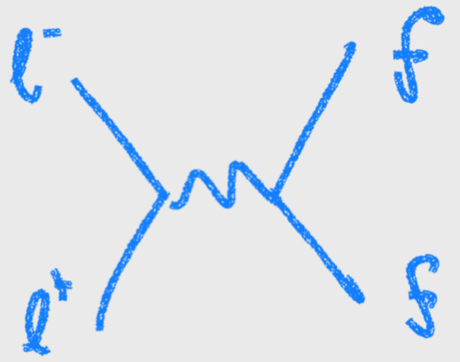
still dominated by LEP physics





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

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



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

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

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

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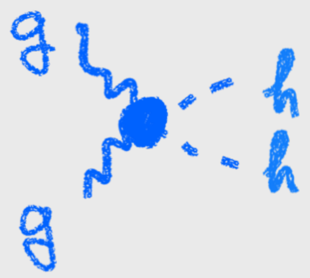

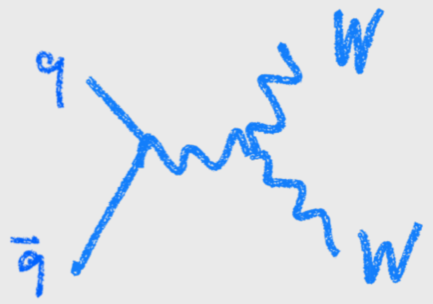

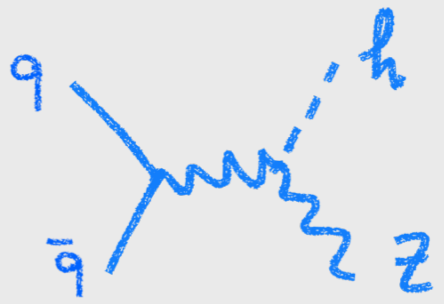

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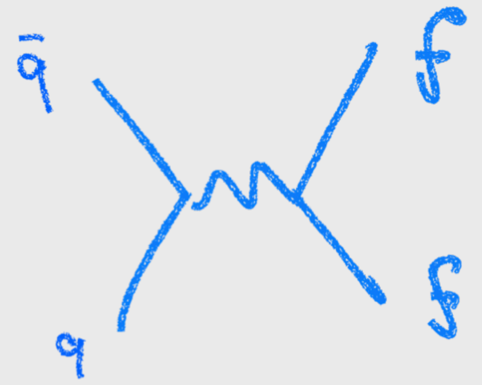

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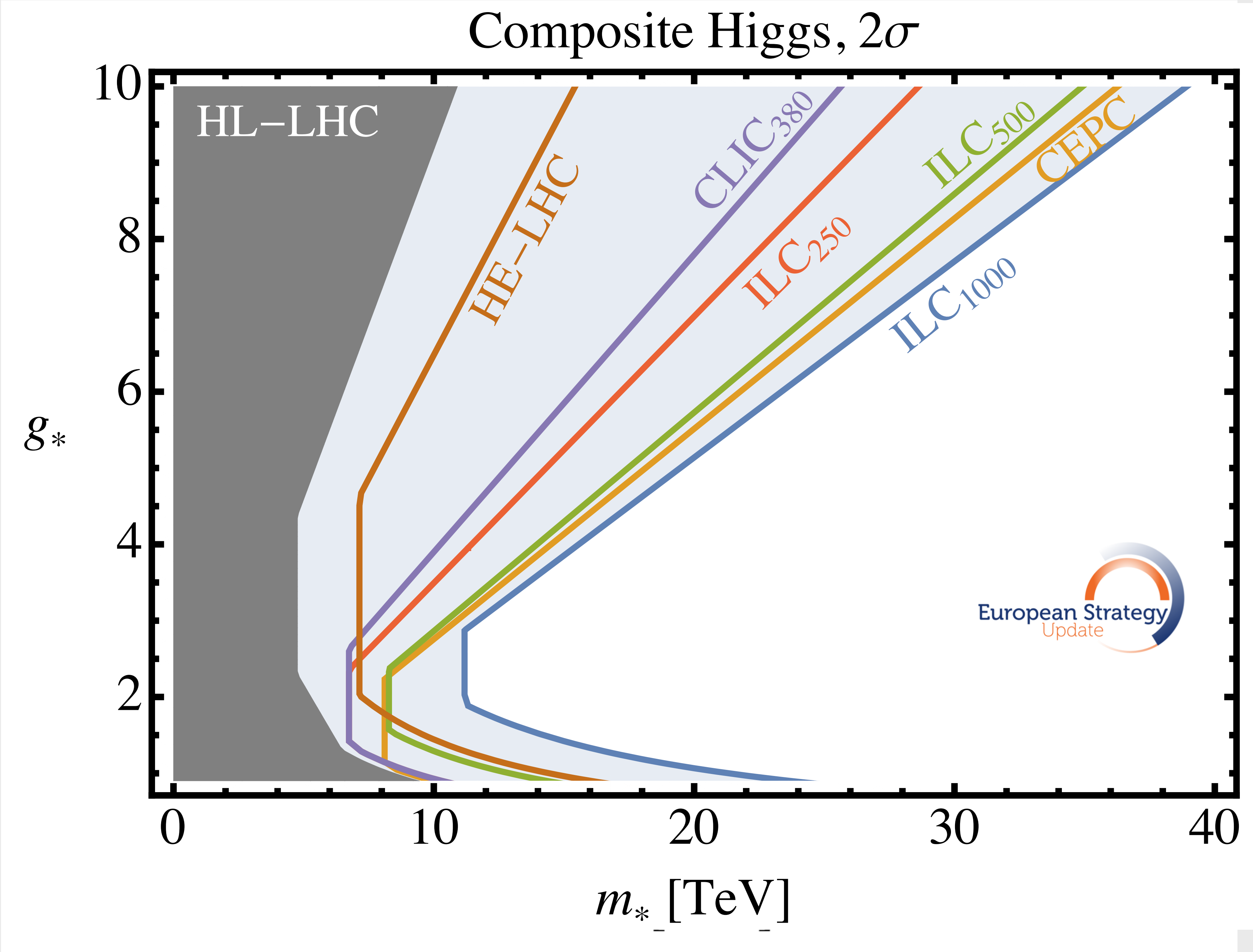
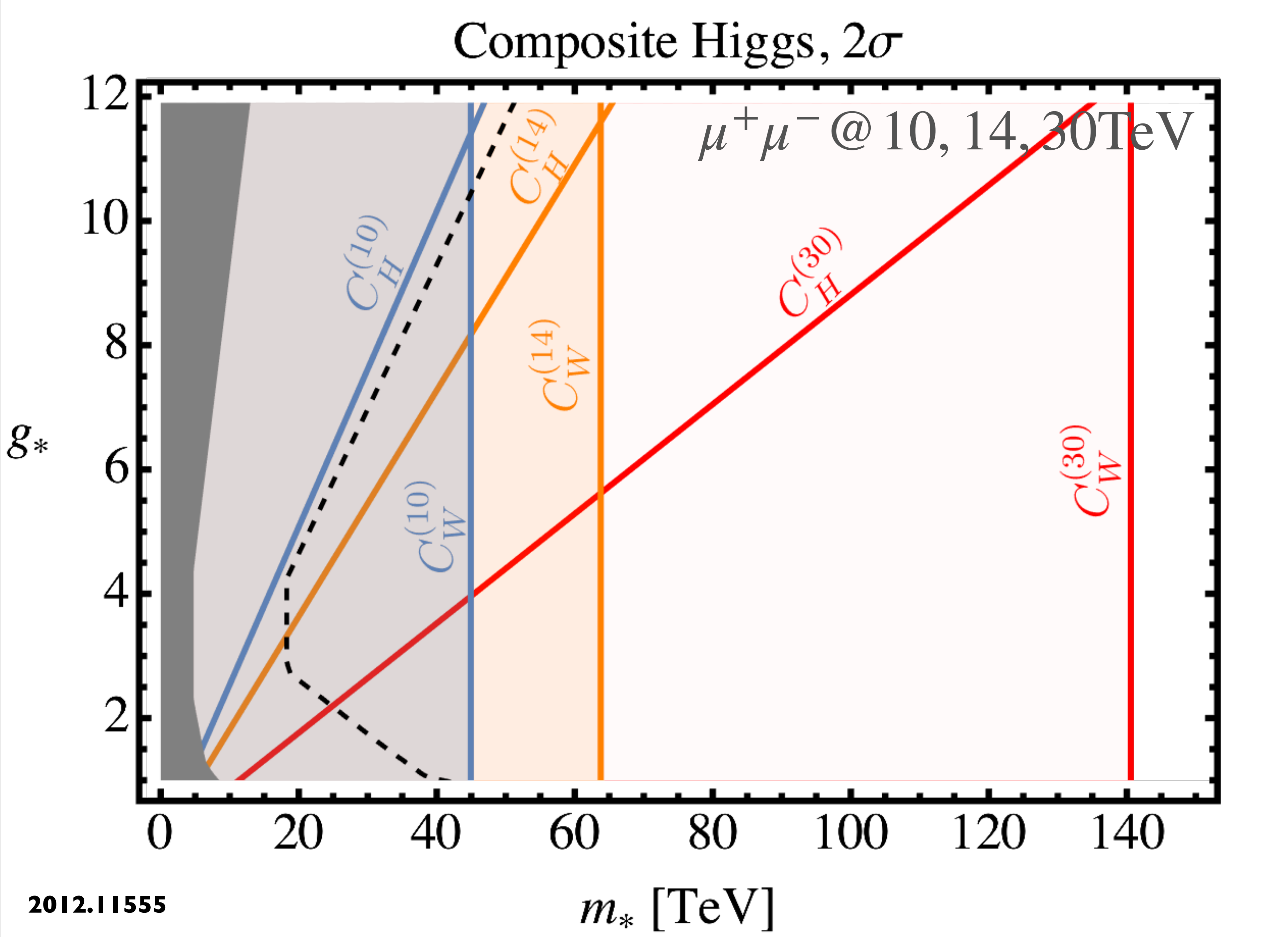
$$\ell_{Higgs} \sim 1/m_\star$$

Looking ahead

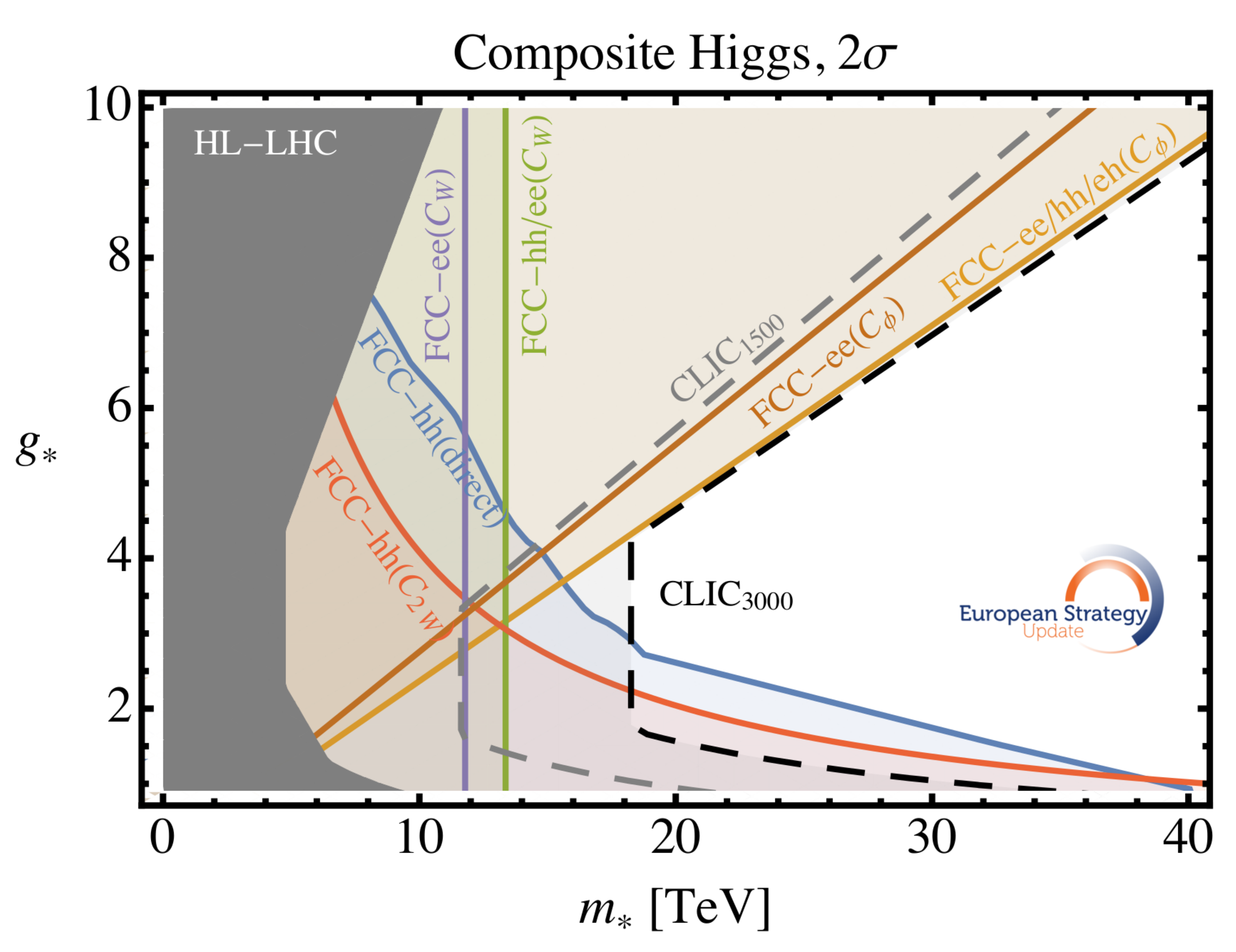


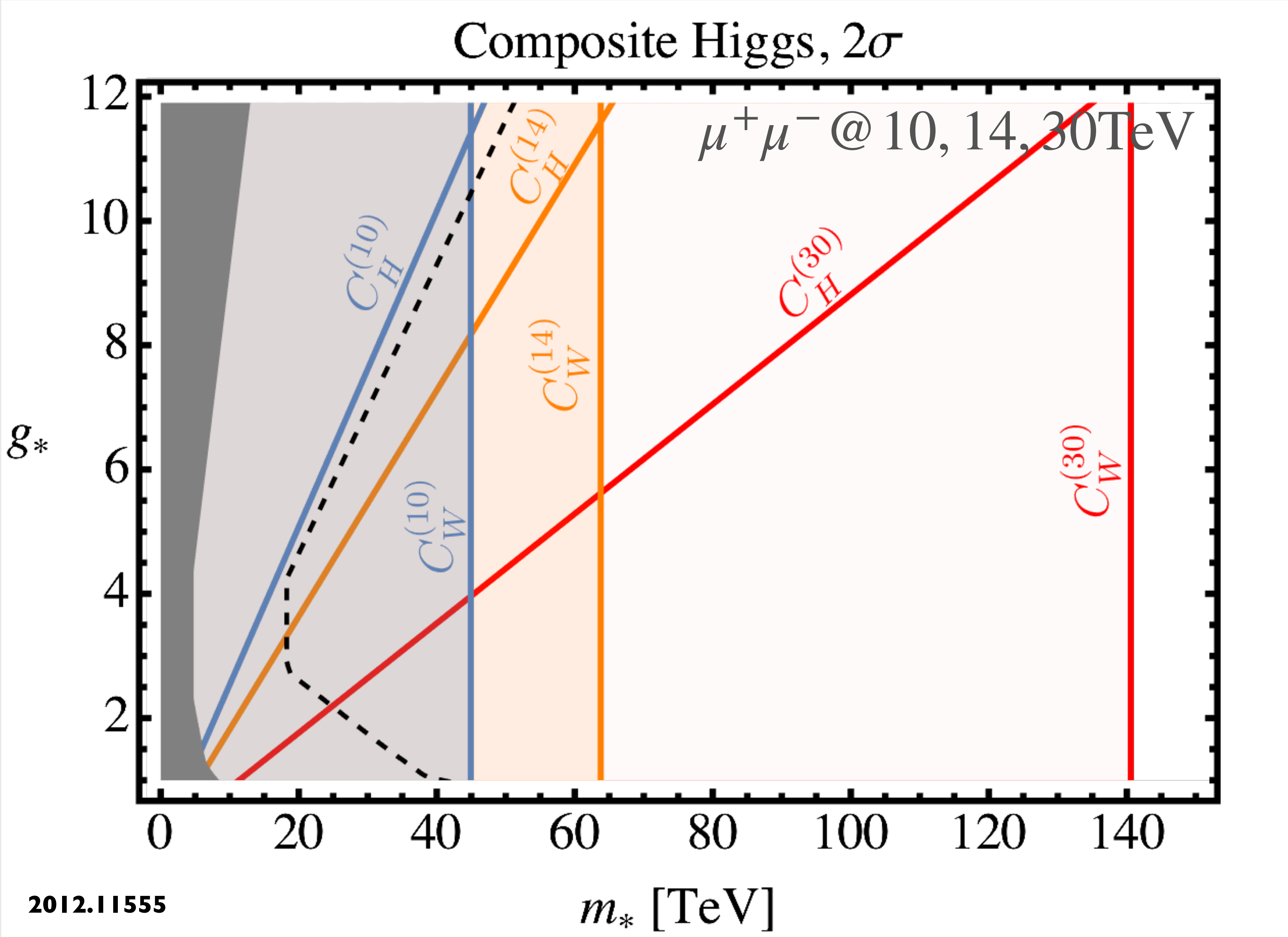


compositeness at 10 TeV-20 TeV

compositeness at 100 TeV-500 TeV

Looking ahead





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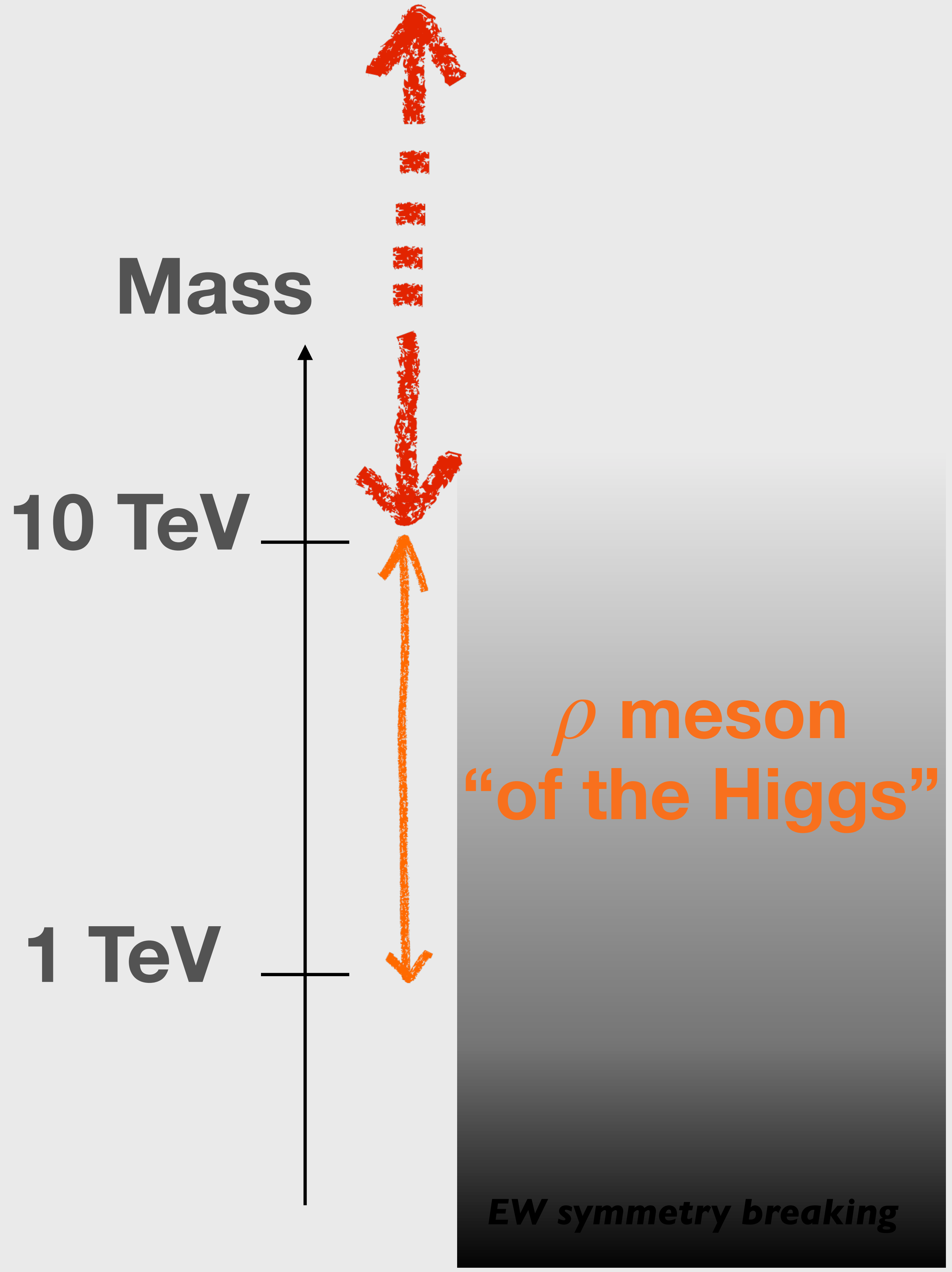
Open Questions on the “big picture” on fundamental physics circa 2021



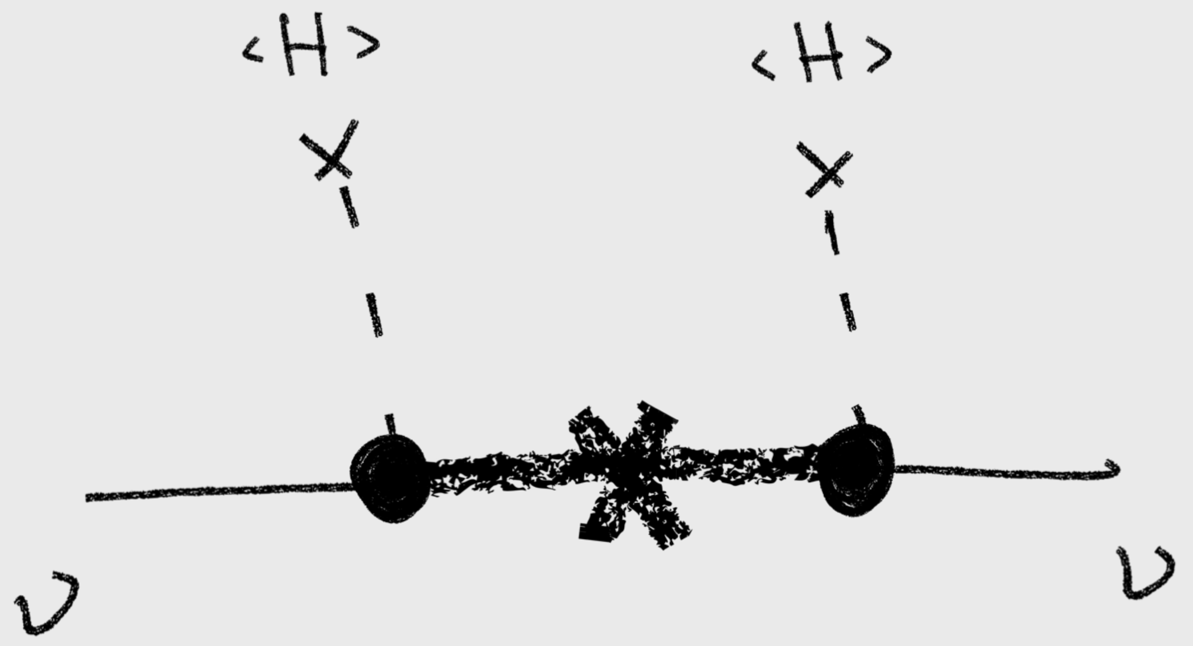
We might be in a situation like QCD, where the ρ meson is only somewhat heavier than the pion, or in a situations where it is much heavier.

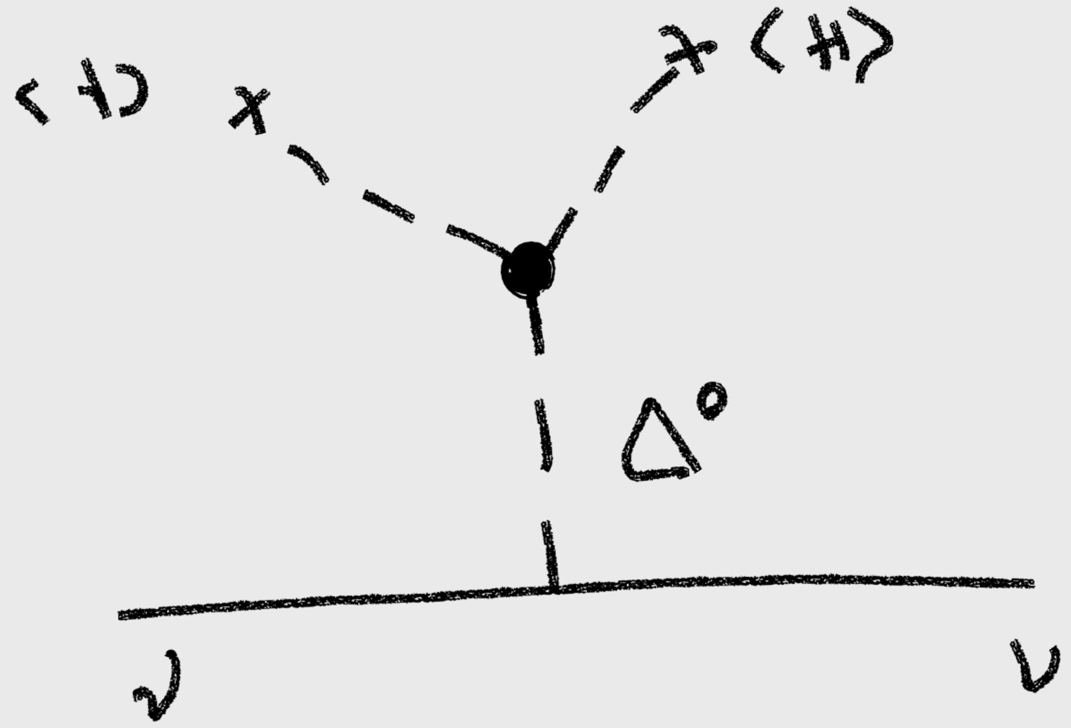
Both cases have profound consequences for telling **what the Higgs boson really is.**

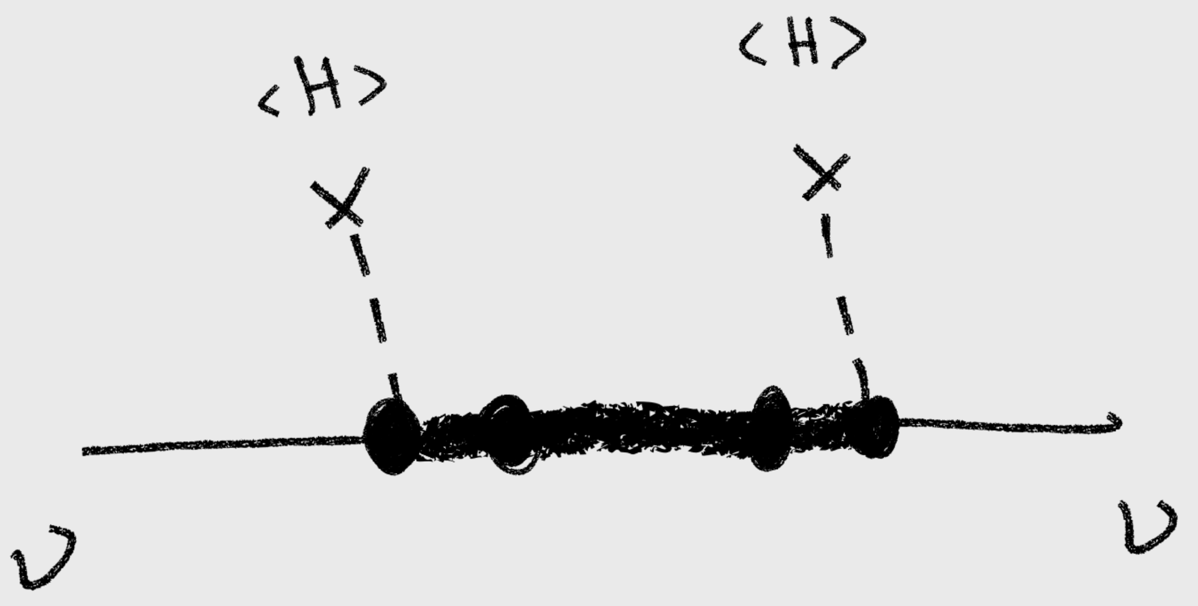
EW symmetry breaking

Neutrino mass mechanisms

LEPTON NUMBER BREAKING







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

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

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

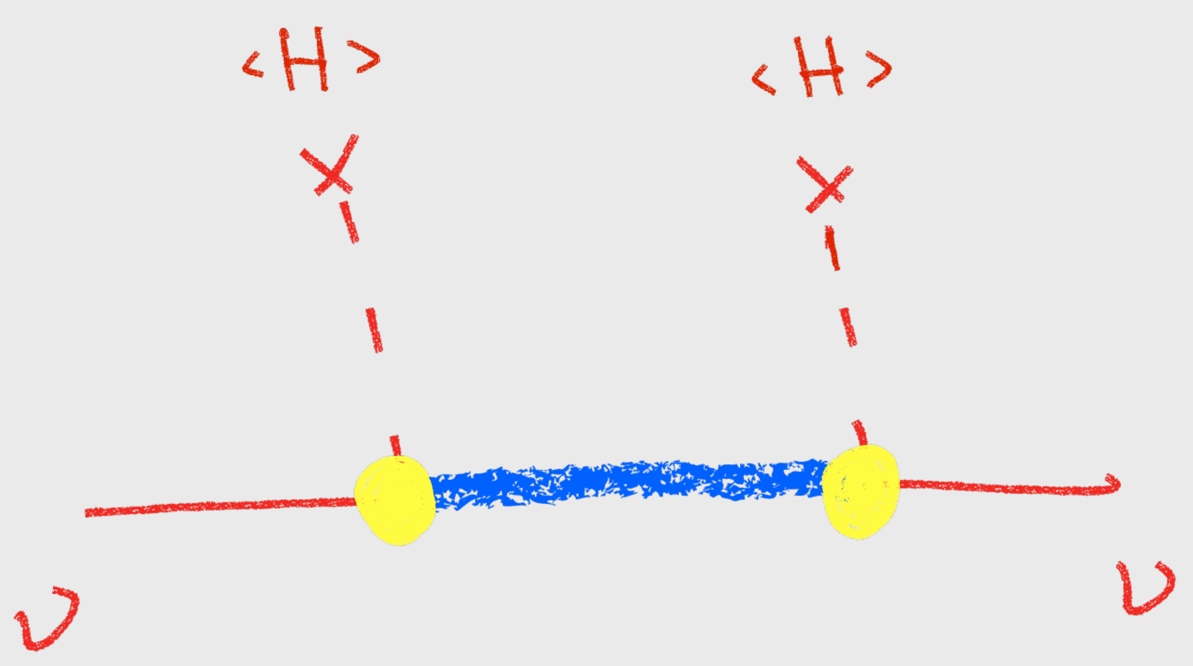
$M_{heavy} \to$ LARGE

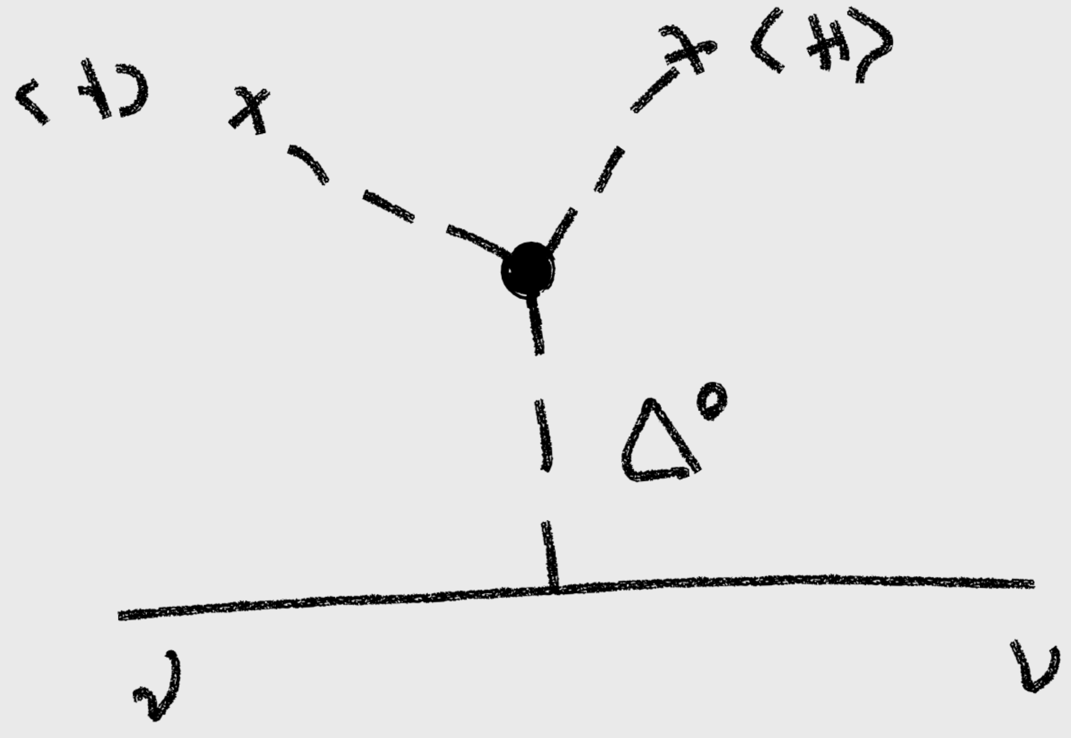
coupling $\to$ SMALL

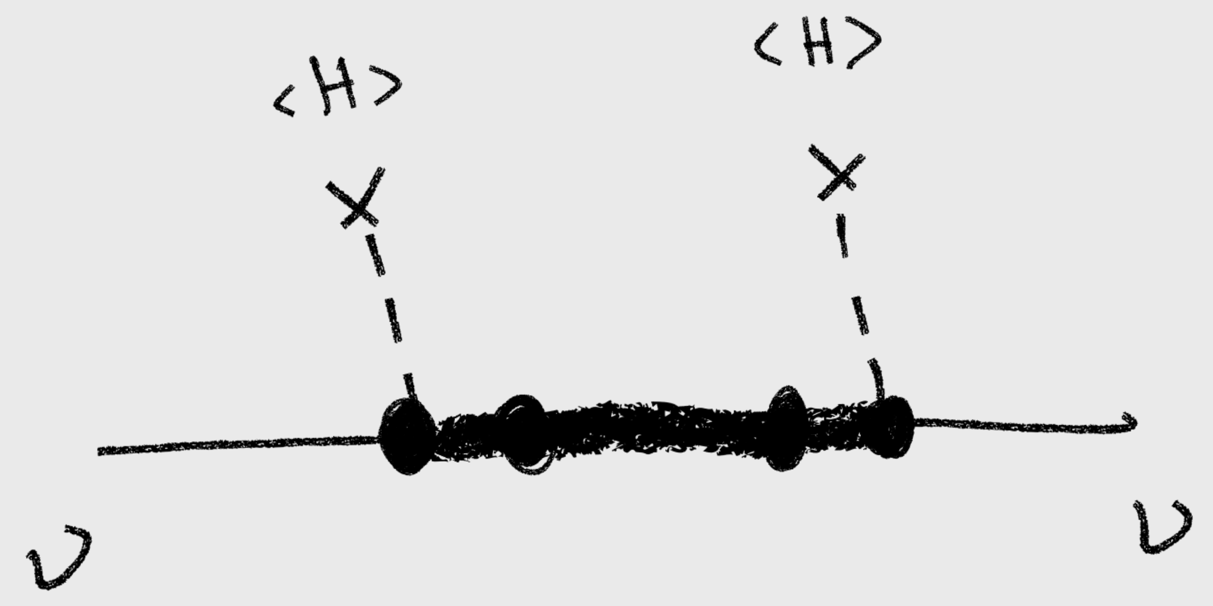
$\mu \to$ SMALL

Neutrino mass mechanisms

LEPTON NUMBER BREAKING







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$M_{heavy} \rightarrow$ LARGE

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

coupling → SMALL

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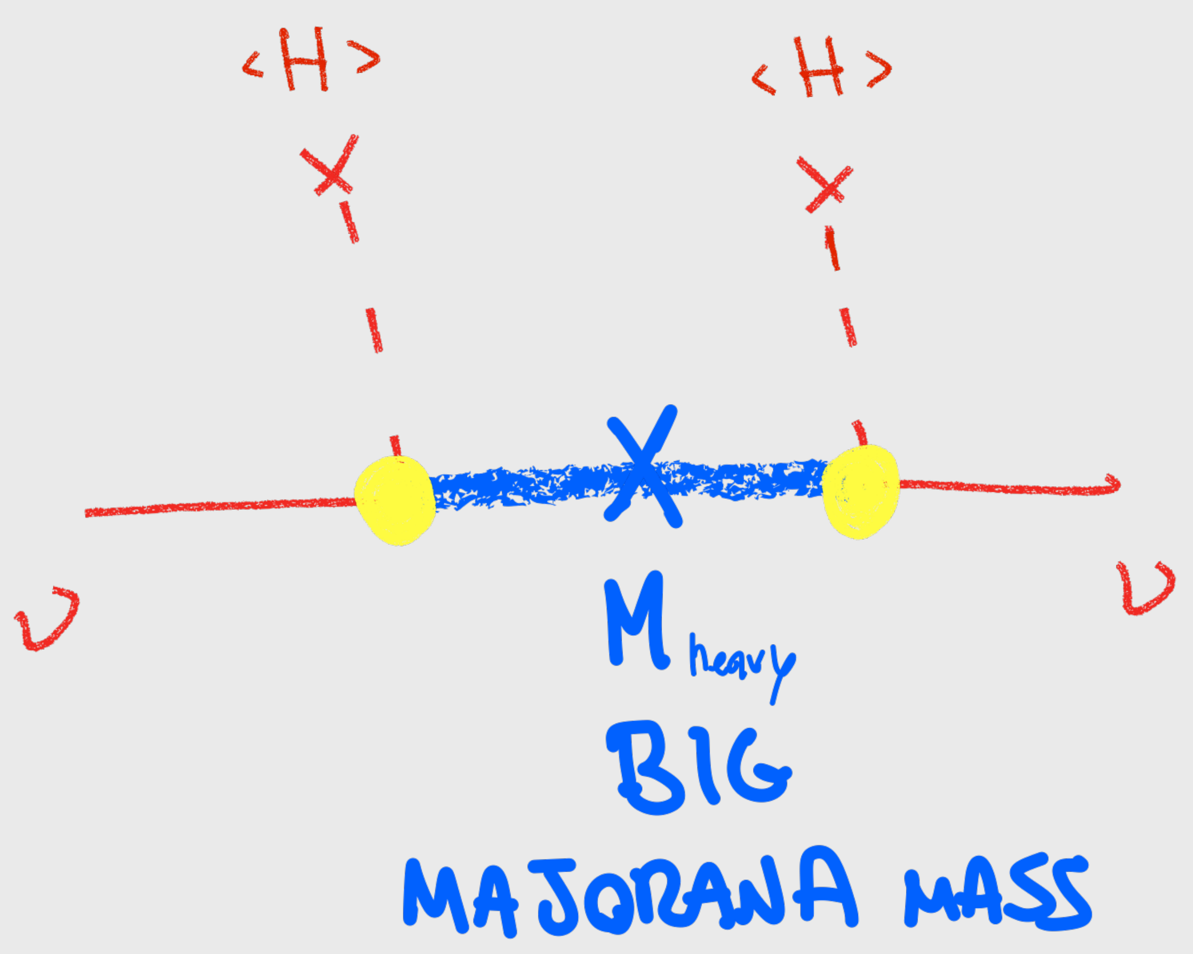
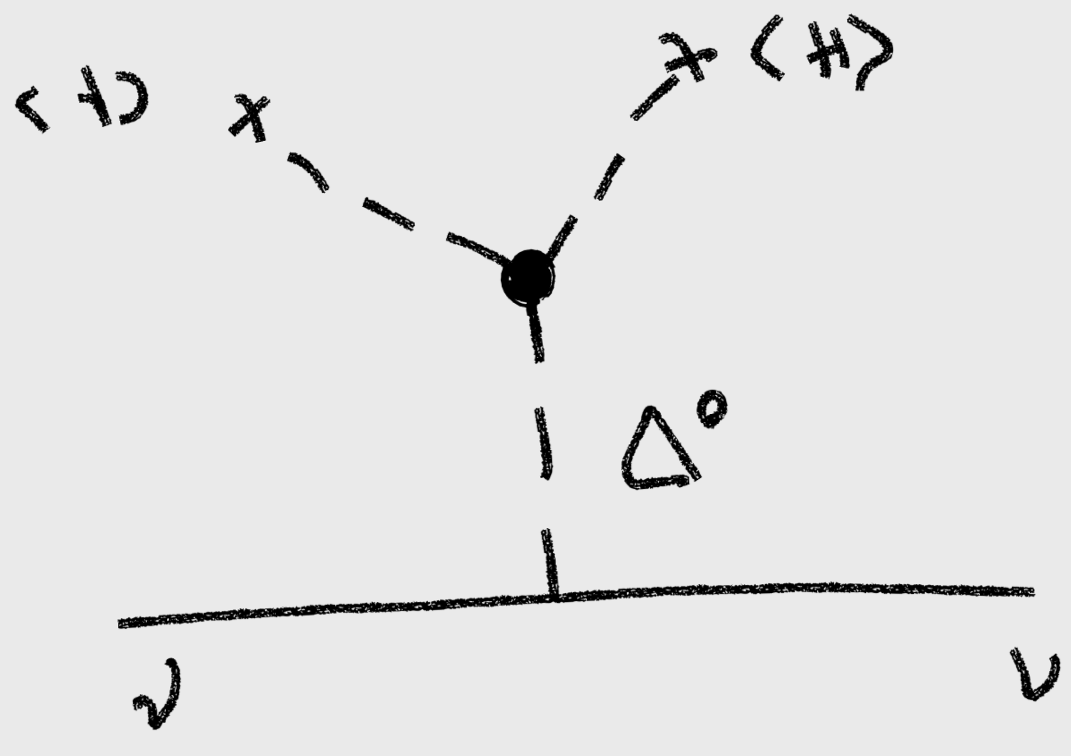
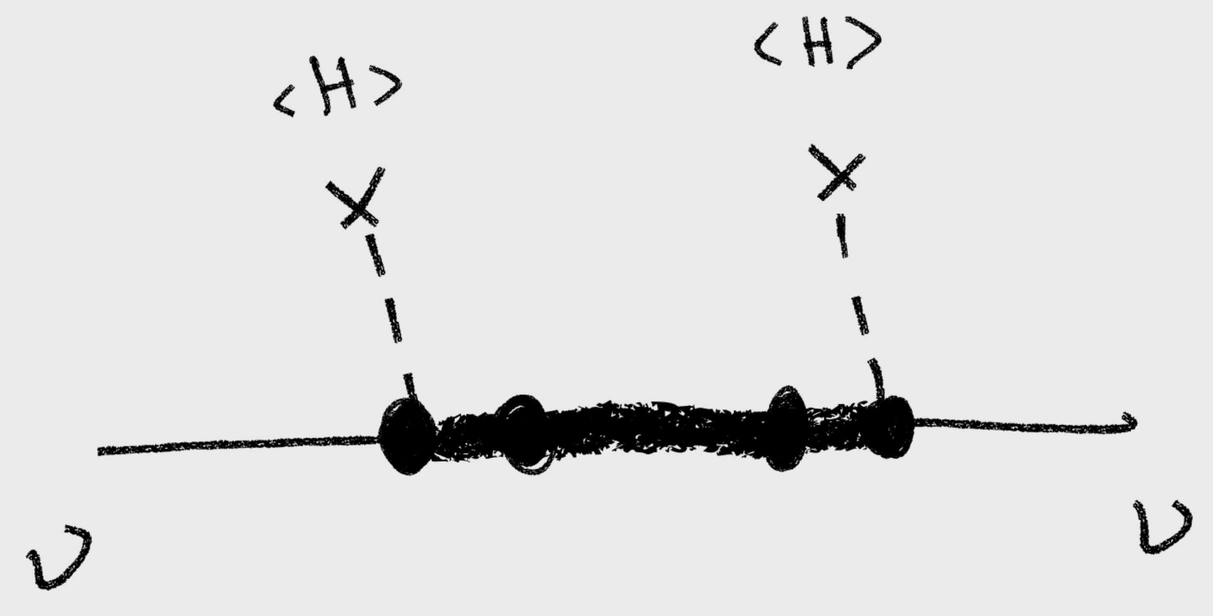
$\mu \rightarrow$ SMALL

Neutrino mass mechanisms

LEPTON NUMBER BREAKING







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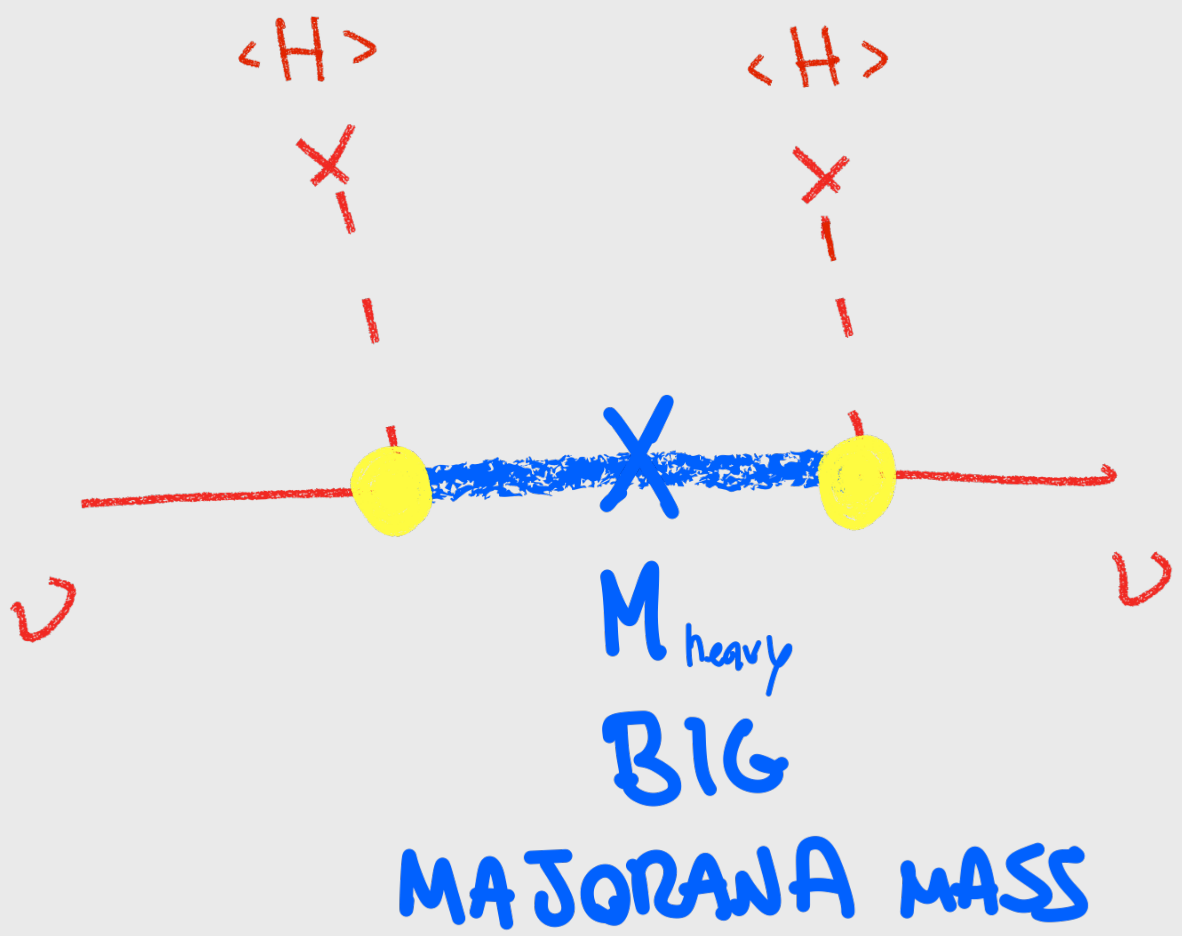
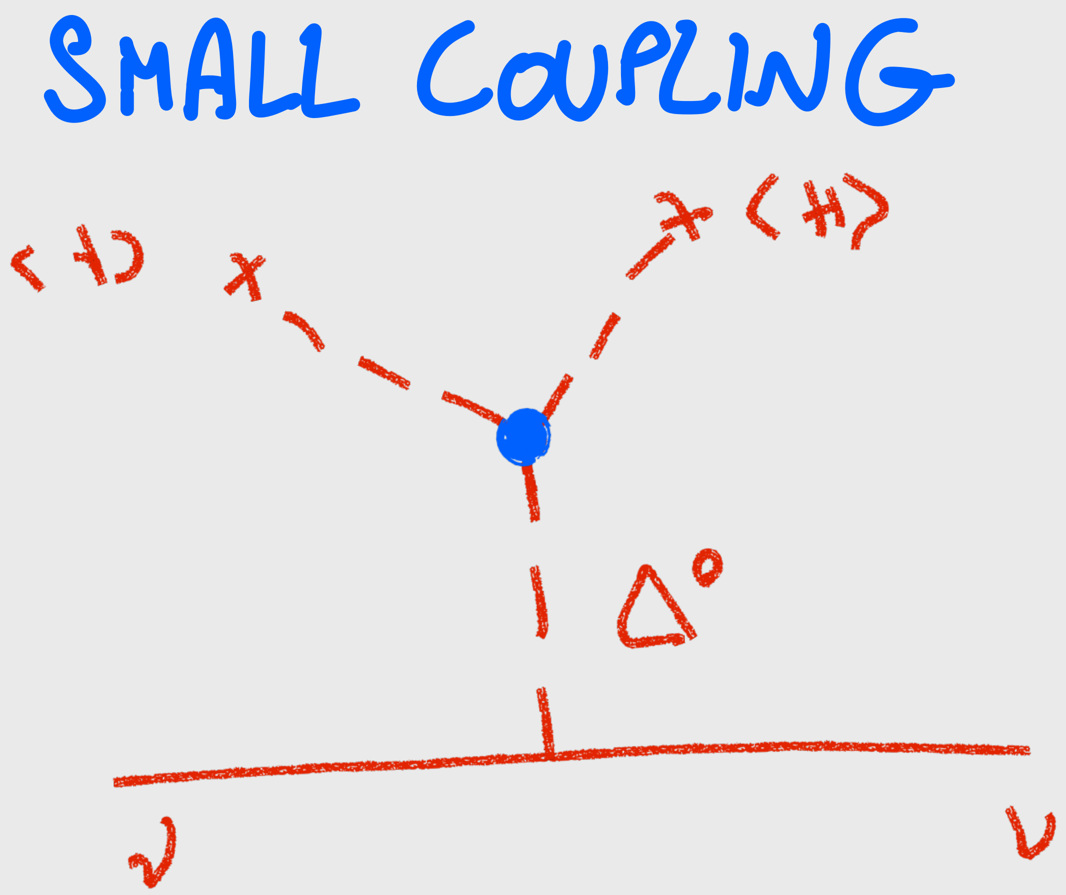
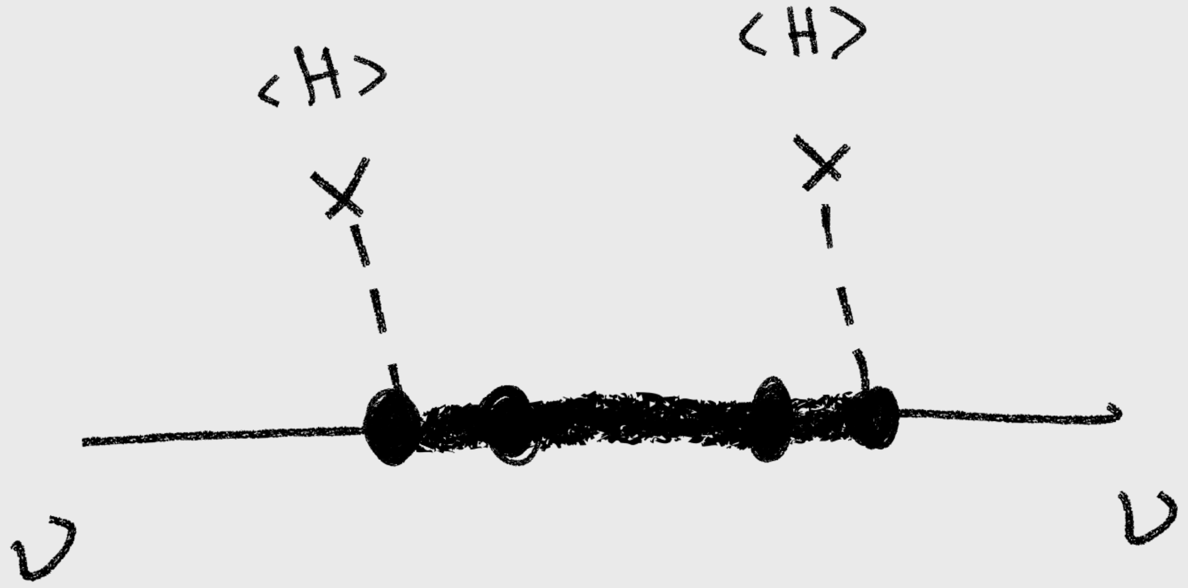
Neutrino mass mechanisms

LEPTON NUMBER BREAKING







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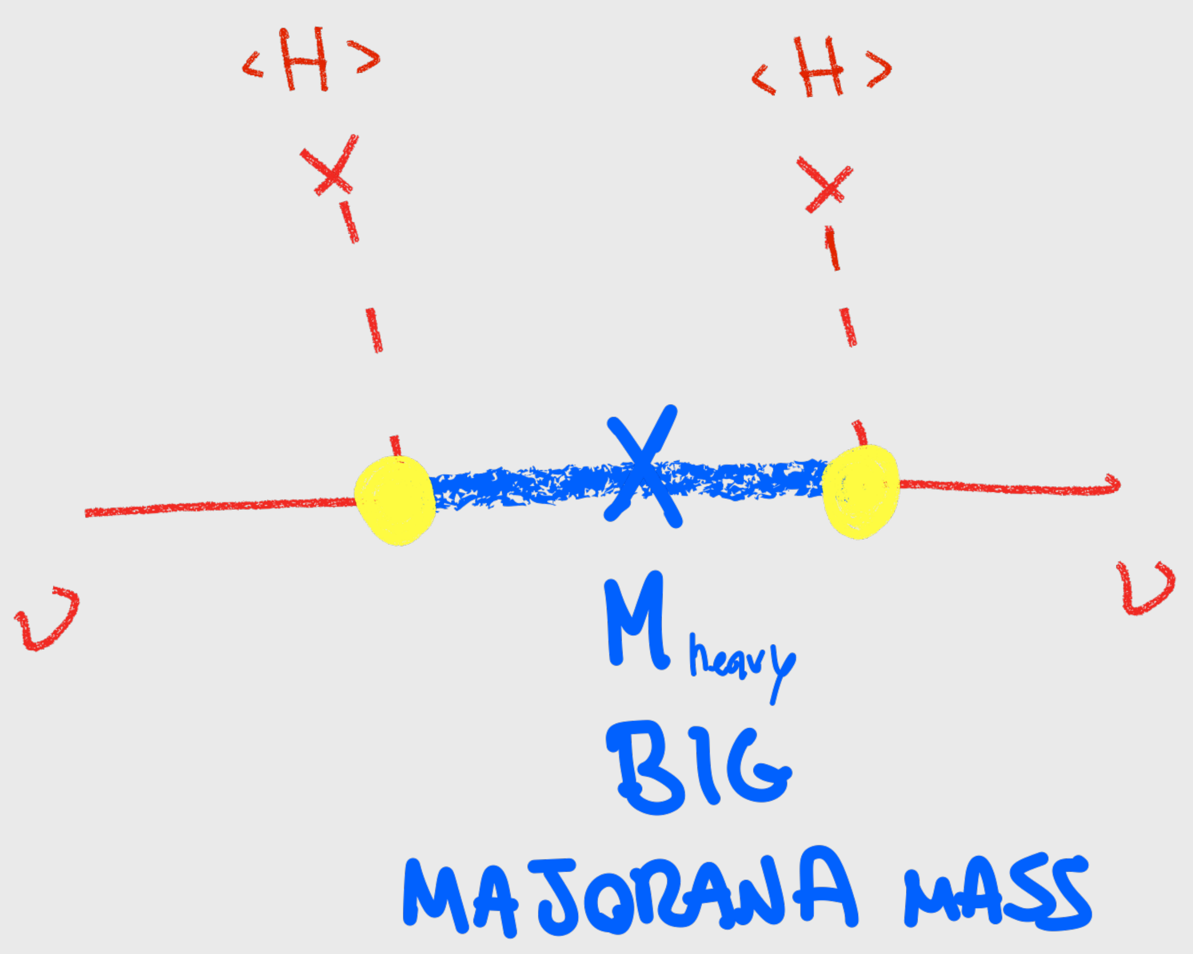
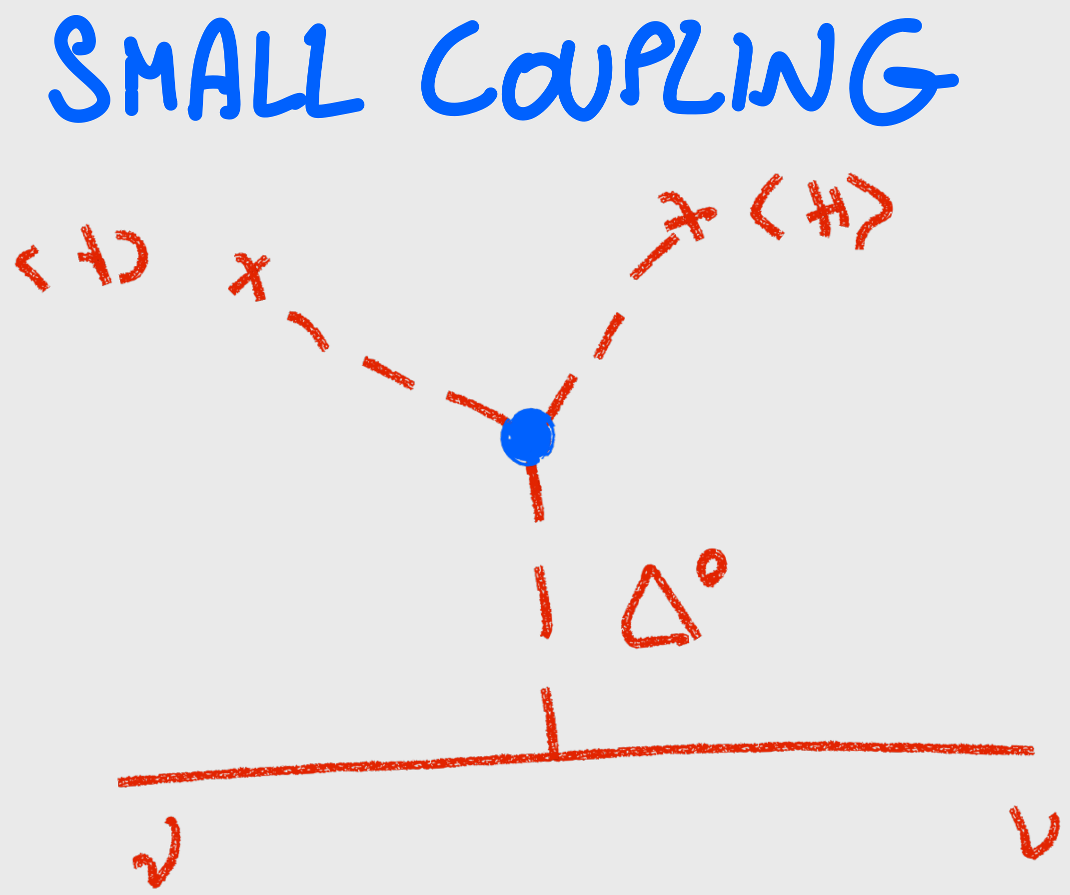
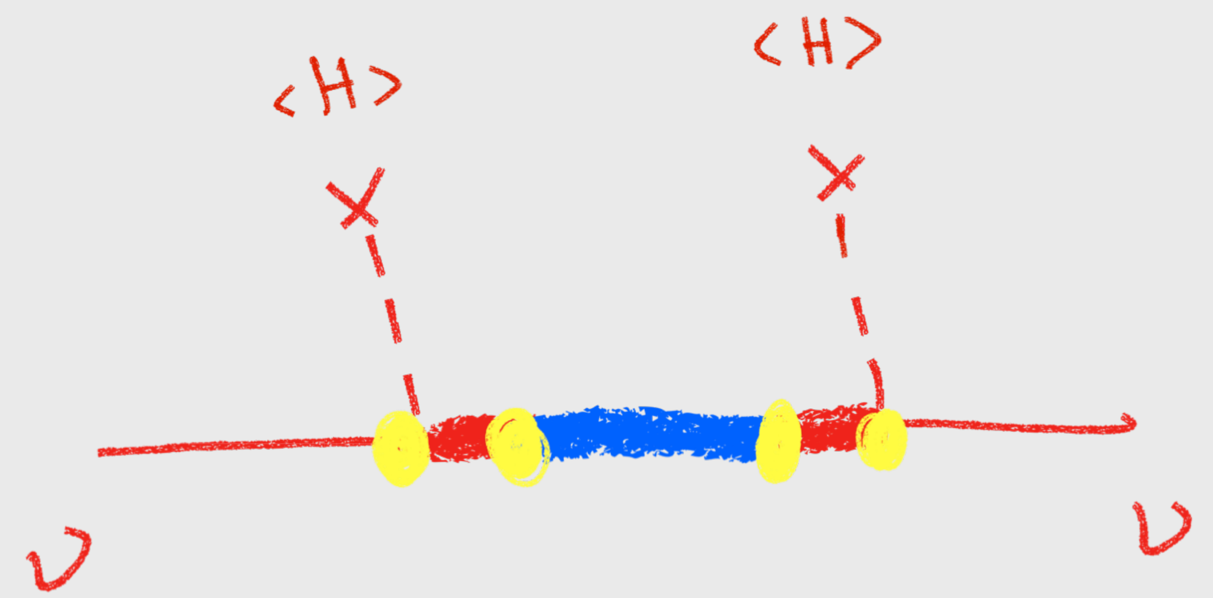
$$\mu \to \text{SMALL}$$

Neutrino mass mechanisms

LEPTON NUMBER BREAKING







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

$M_{heavy} \rightarrow$ LARGE

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

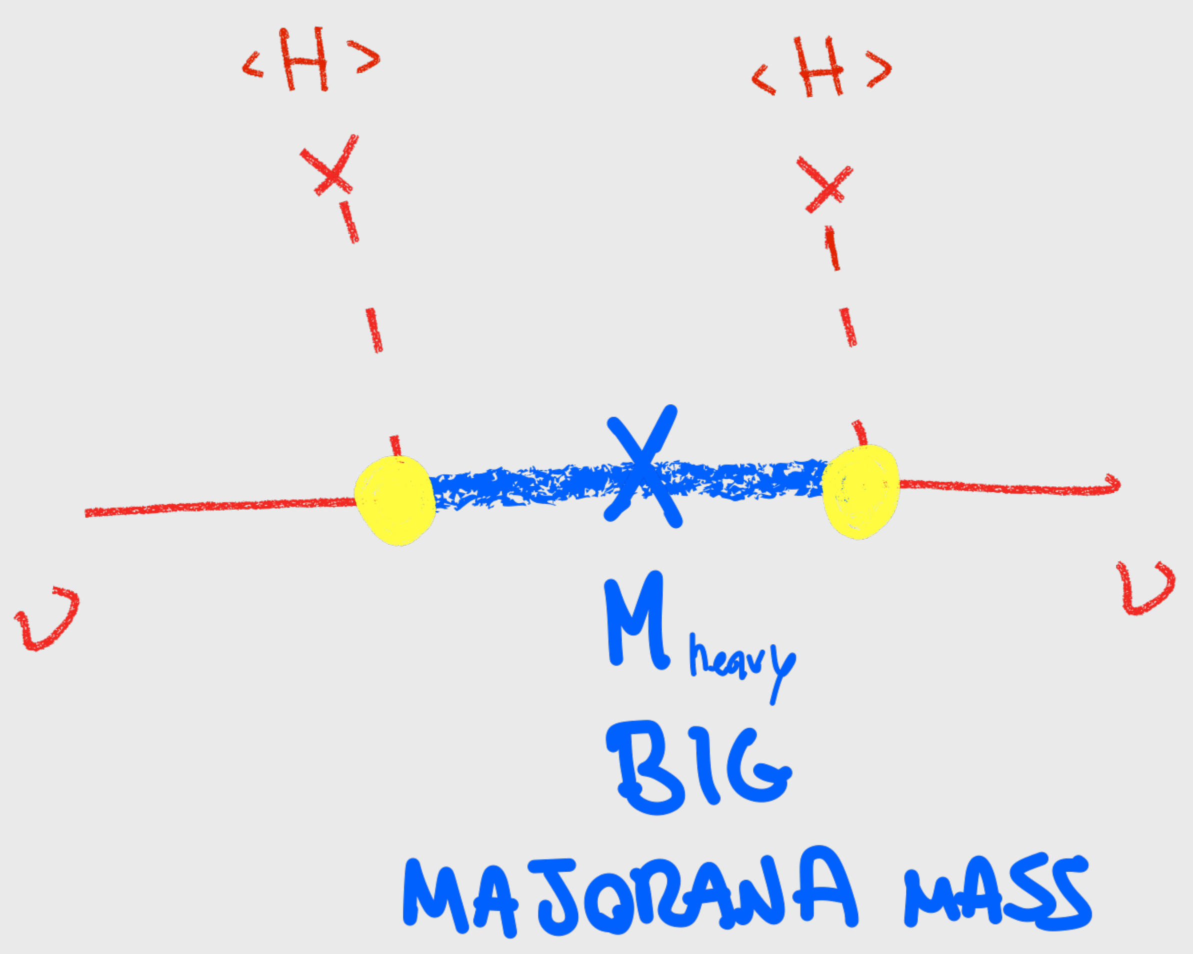
coupling → SMALL

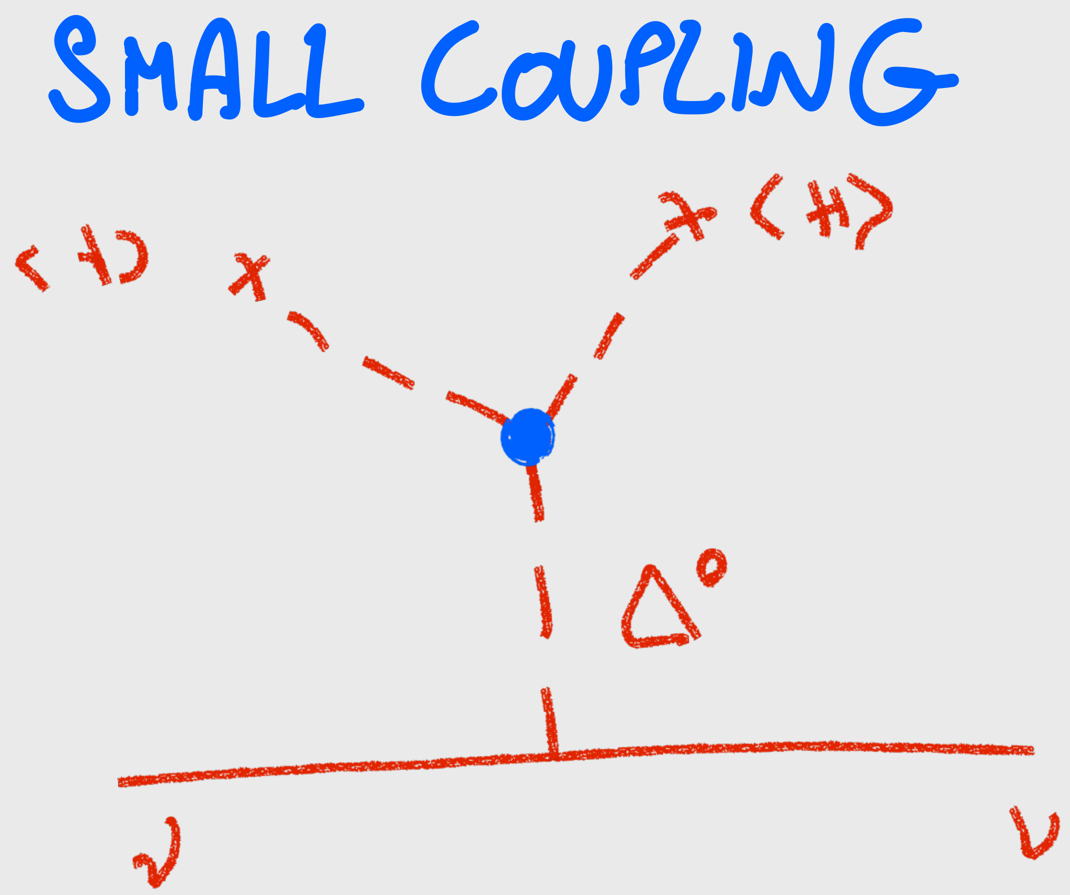
$$m_\nu = \mu \cdot \frac{(coupling)^2 < H >^2}{M^2_{heavy}} \rightarrow \text{SMALL}$$

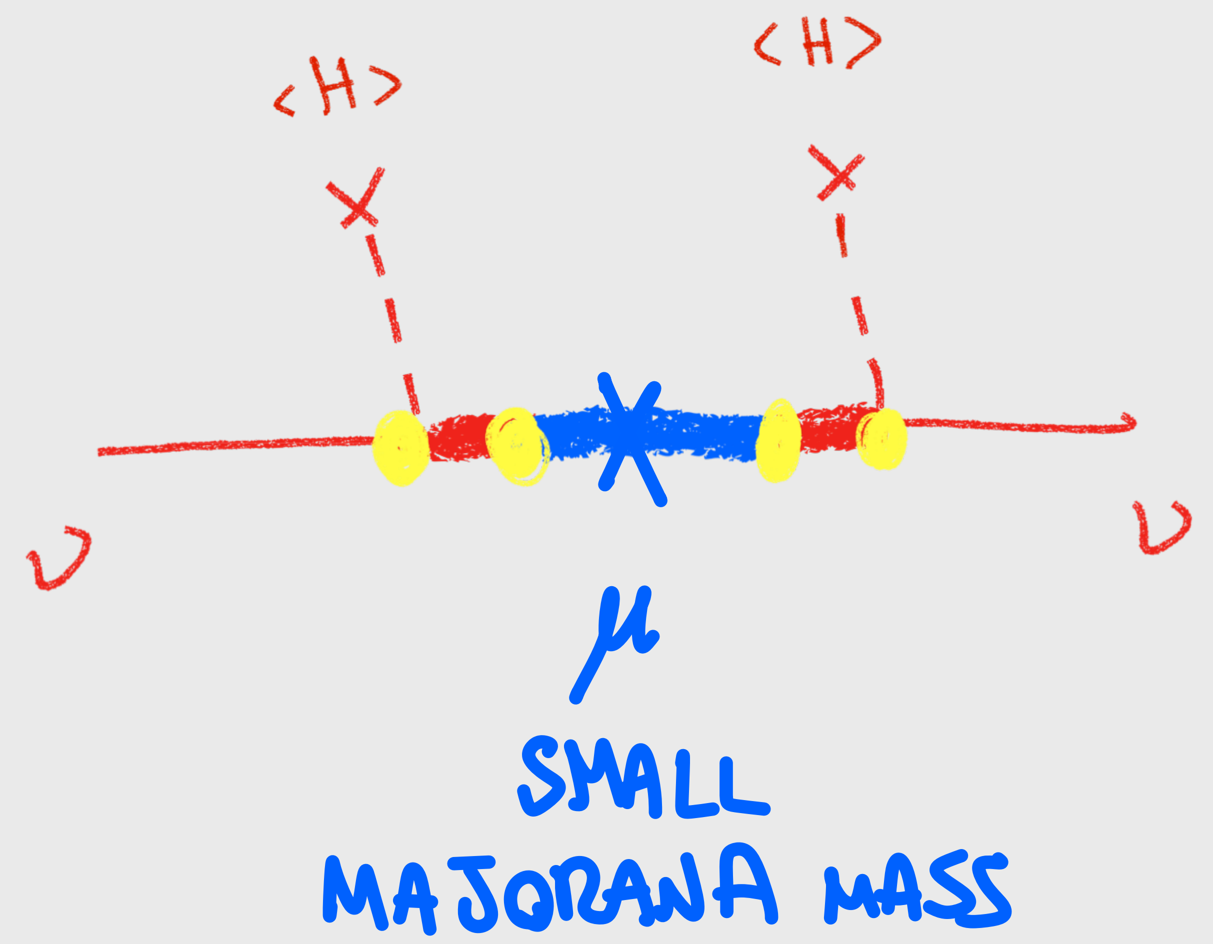
$\mu \rightarrow$ SMALL

Neutrino mass mechanisms

LEPTON NUMBER BREAKING







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

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

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

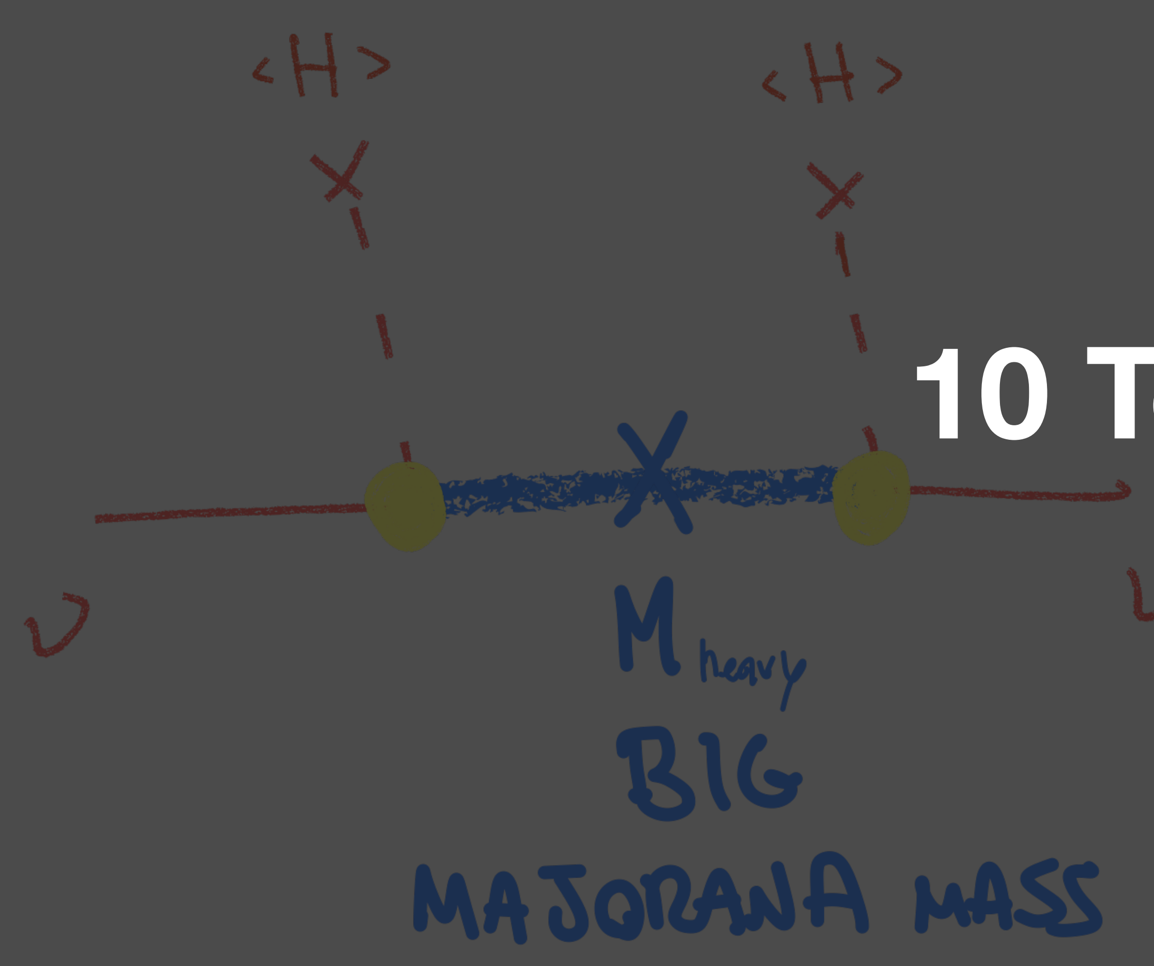
$M_{heavy} \to$ LARGE

coupling $\to$ SMALL

$\mu \to$ SMALL

Neutrino mas… chanisms

LEPTON NUMBER BREAKING



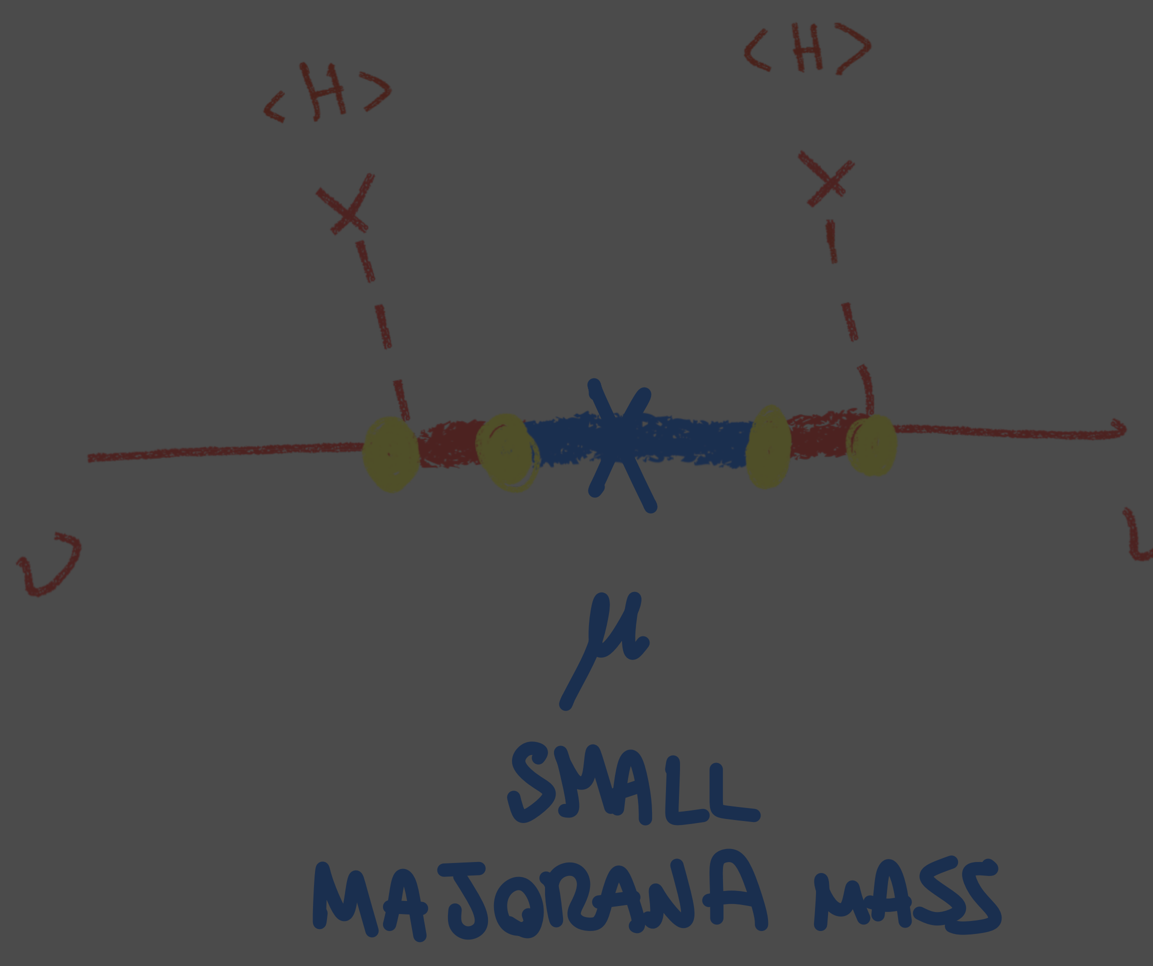
$$m_\nu = \frac{(coupling)^2 < H >^2}{M_{heavy}} \rightarrow \text{SMALL}$$

$M_{heavy} \rightarrow$ LARGE

LEPTON NUMBER VIOLATION

$m_\nu =$ … SMALL

…ALL



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

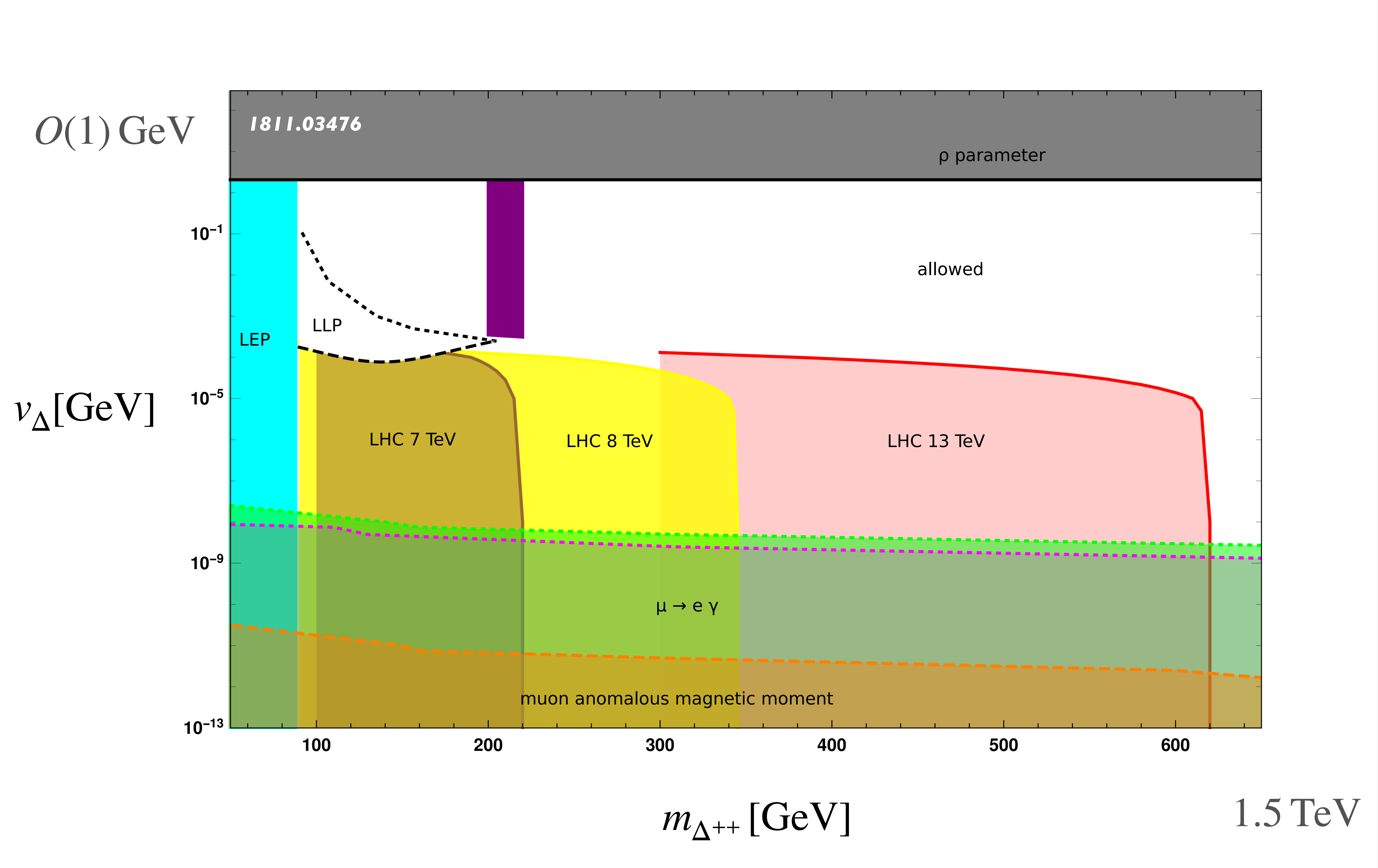
$\mu \rightarrow$ SMALL

flashing concrete results for

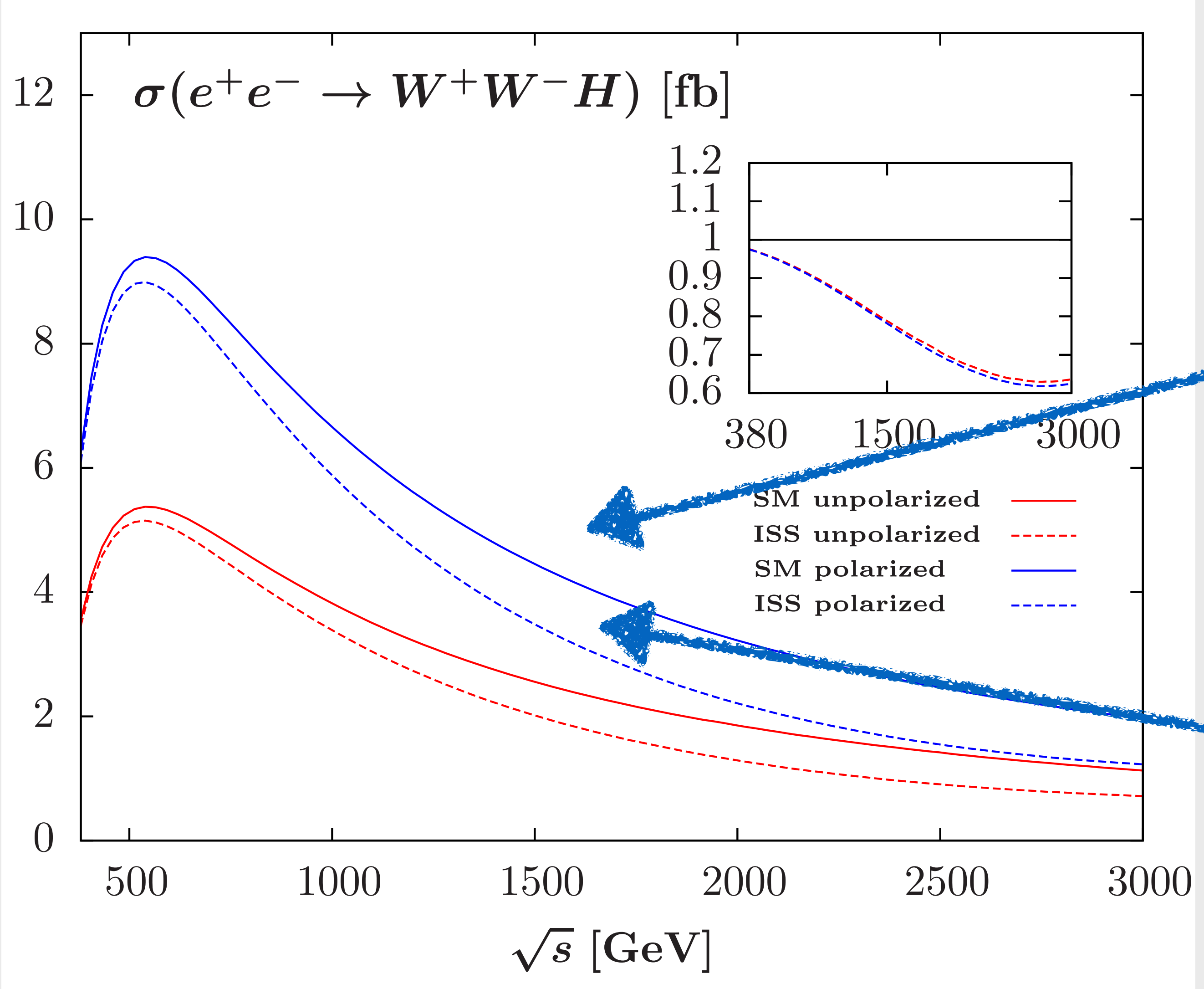
The origin of neutrino masses

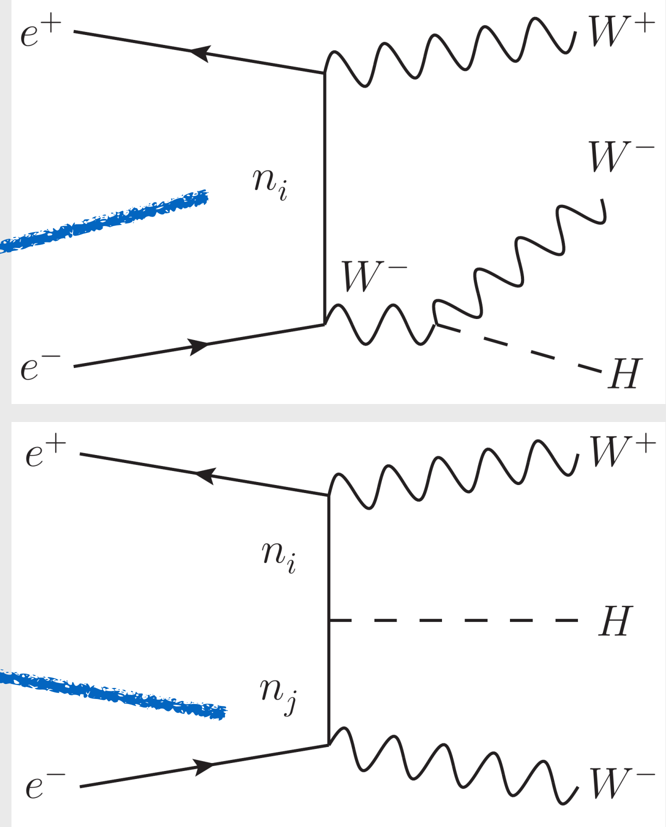
Plenty of neutrino mass models in reach

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



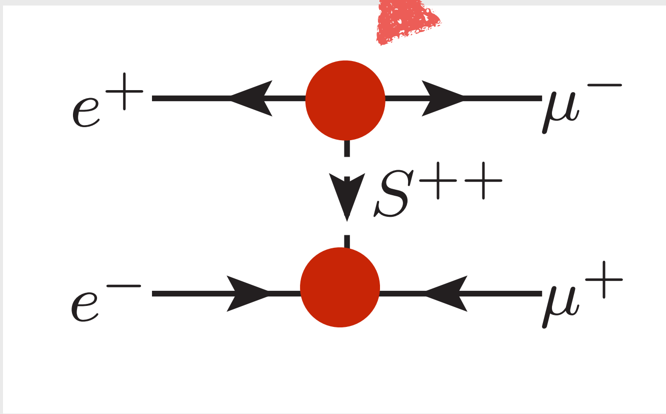
Inverse See-Saw ***1712.07621 - Baglio, Pascoli, Weiland***

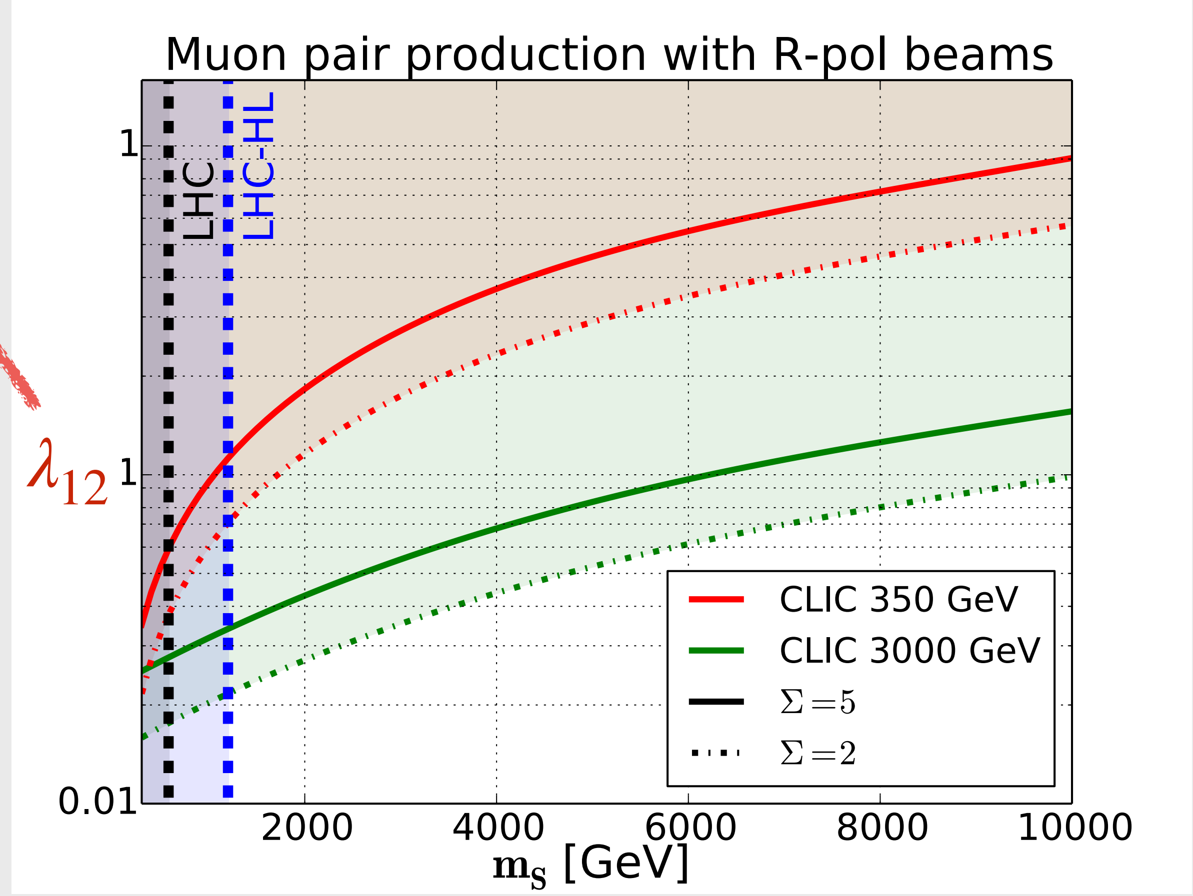




Exclude ISS RH Neutrino up to 10 TeV for Yukawa ~1

1807.10224 - Crivellin, Ghezzi, Panizzi, Pruna, Signer

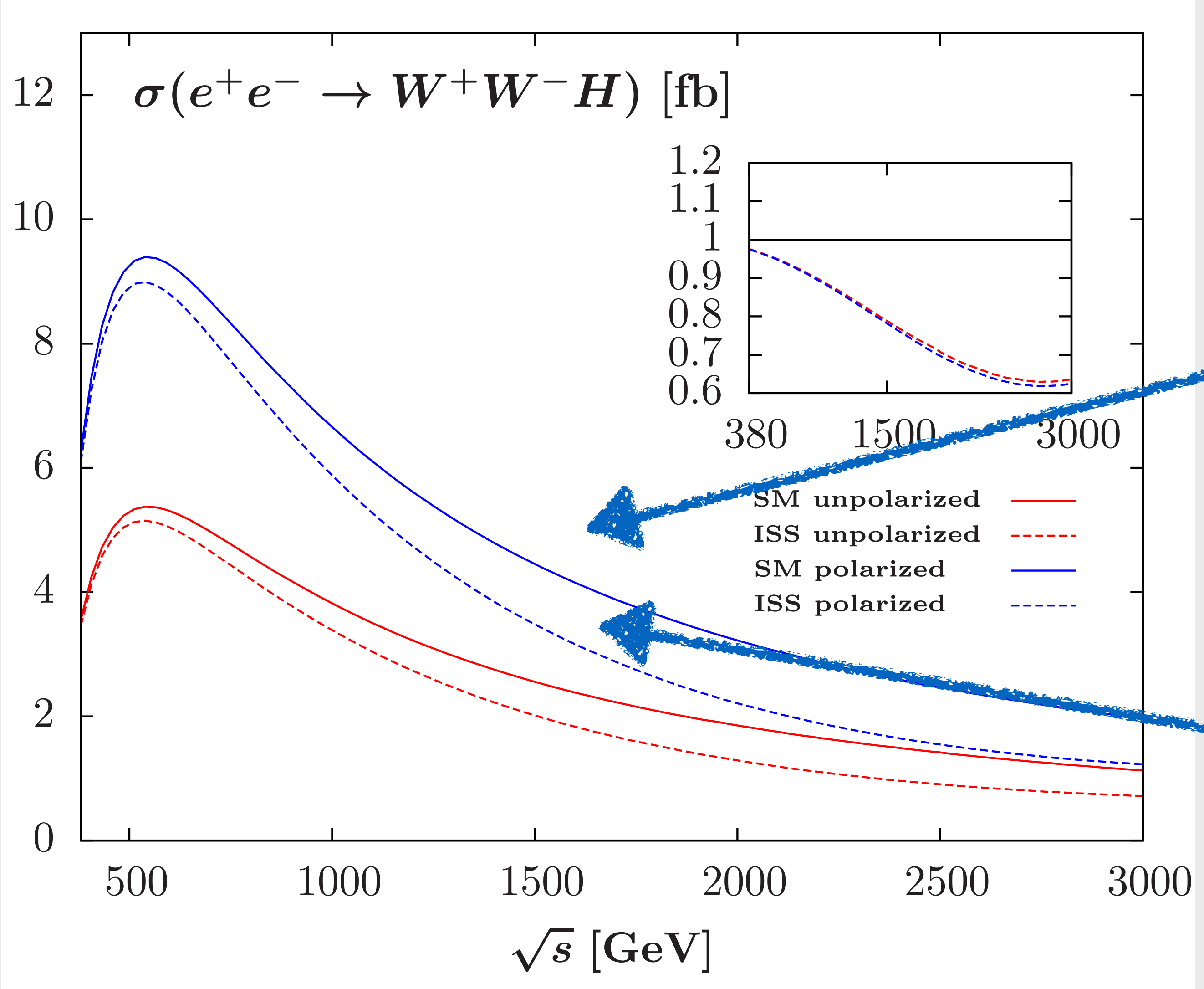


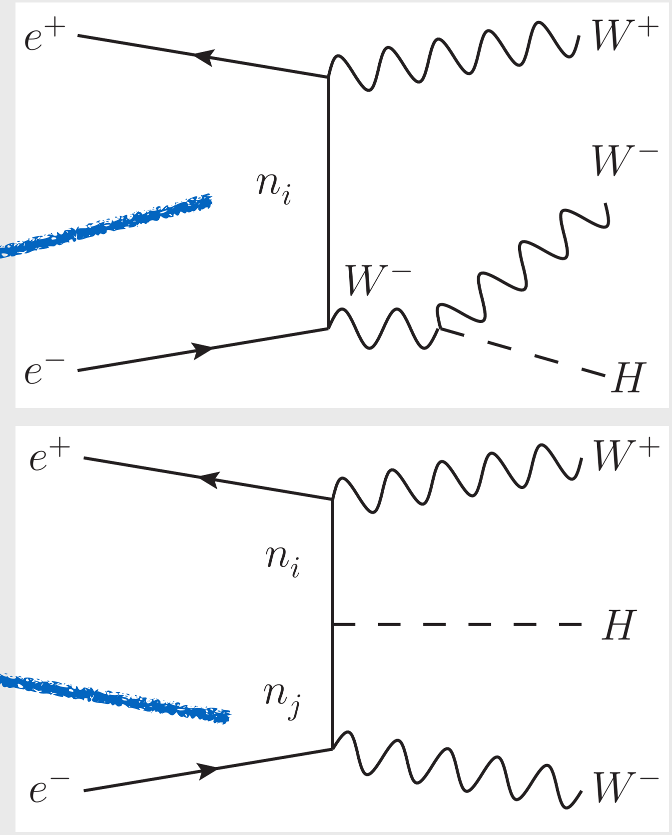


Exclude S^{++} up to 10 TeV for triplet Yukawa ~0.1

Plenty of neutrino mass models in reach

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





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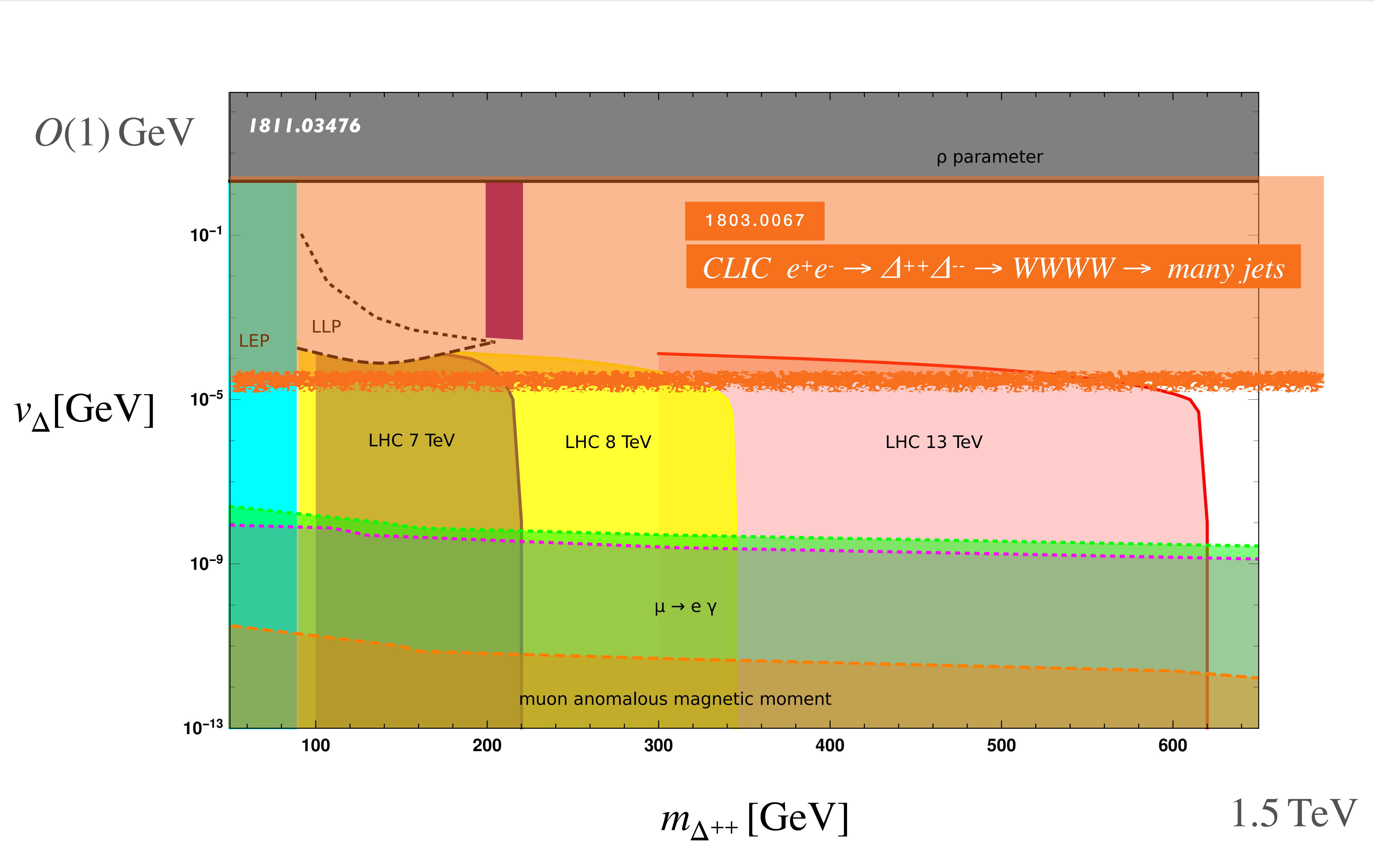

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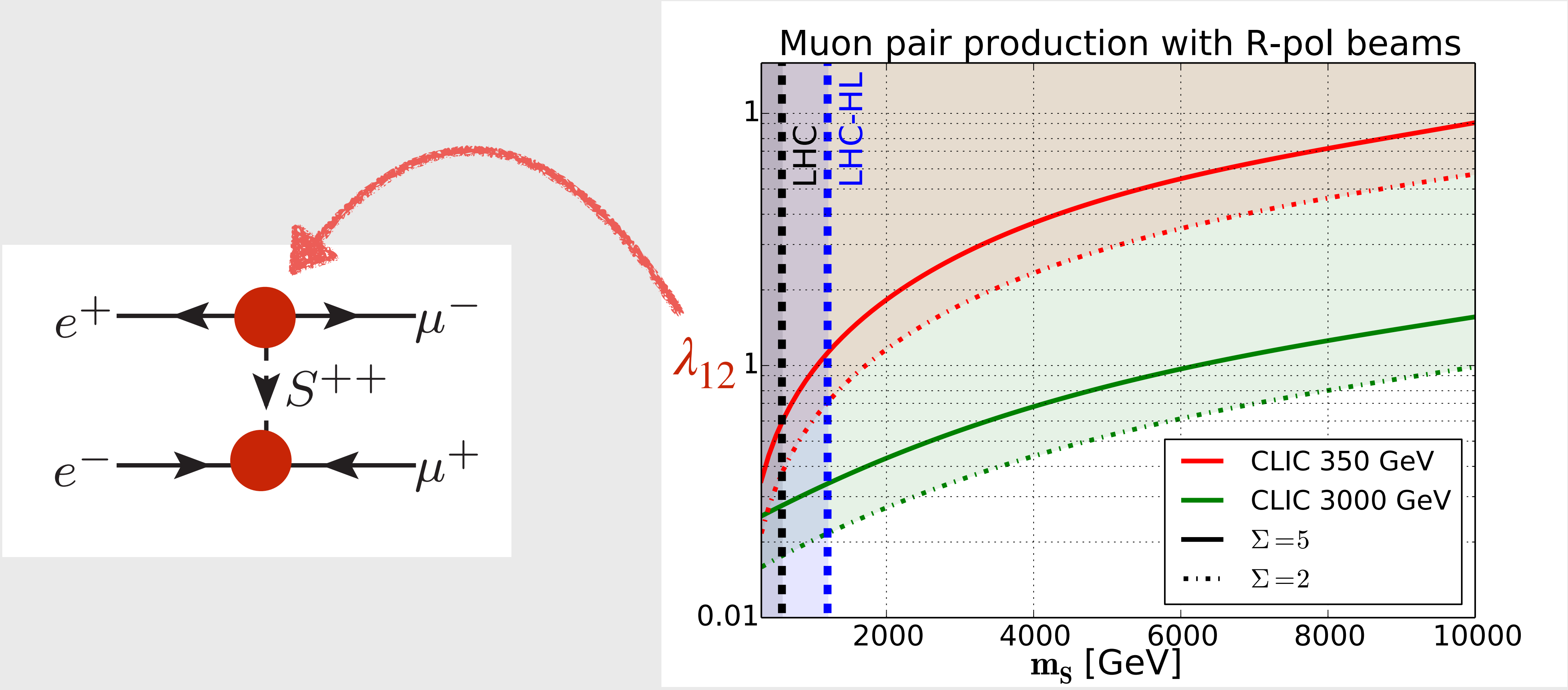

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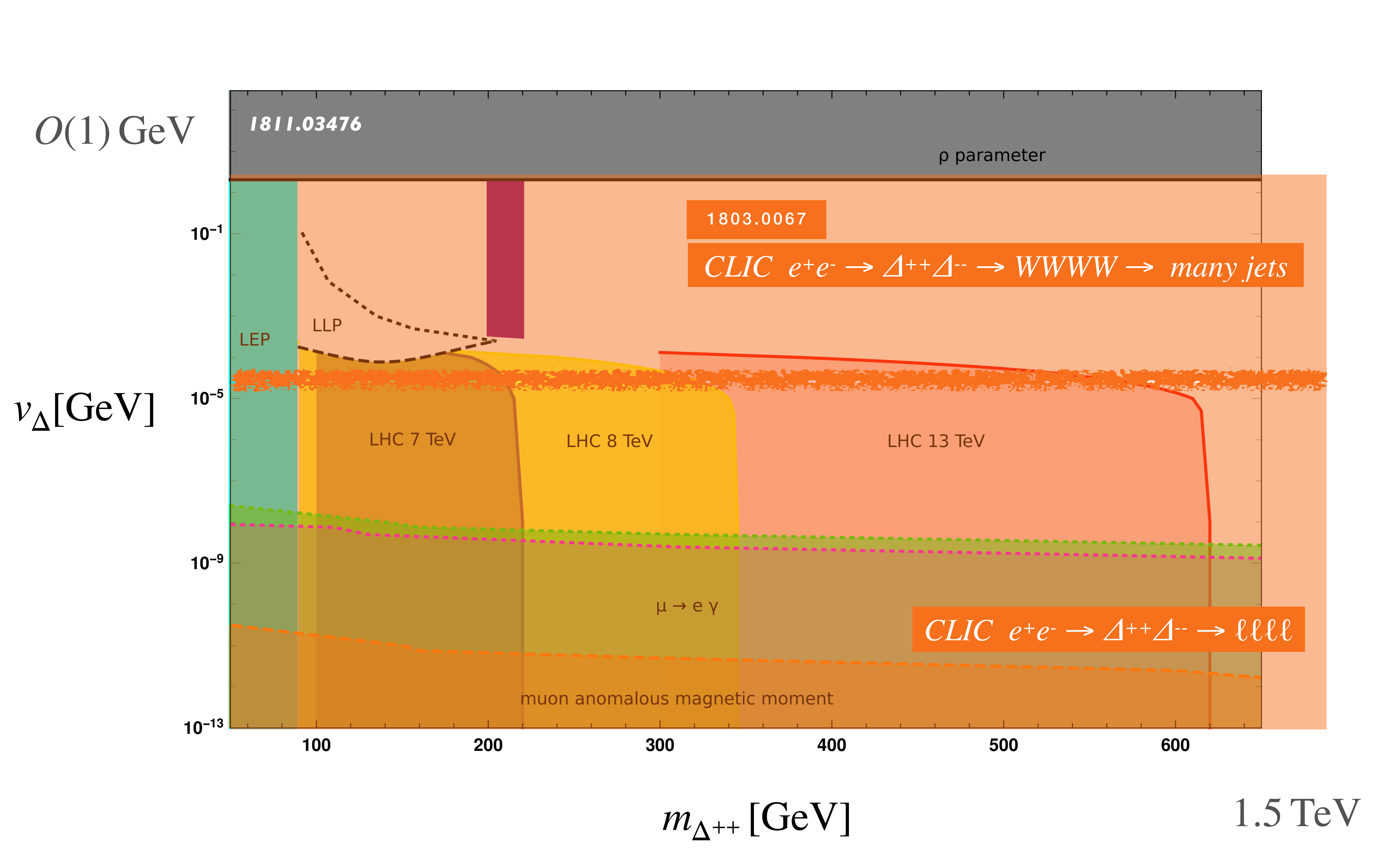

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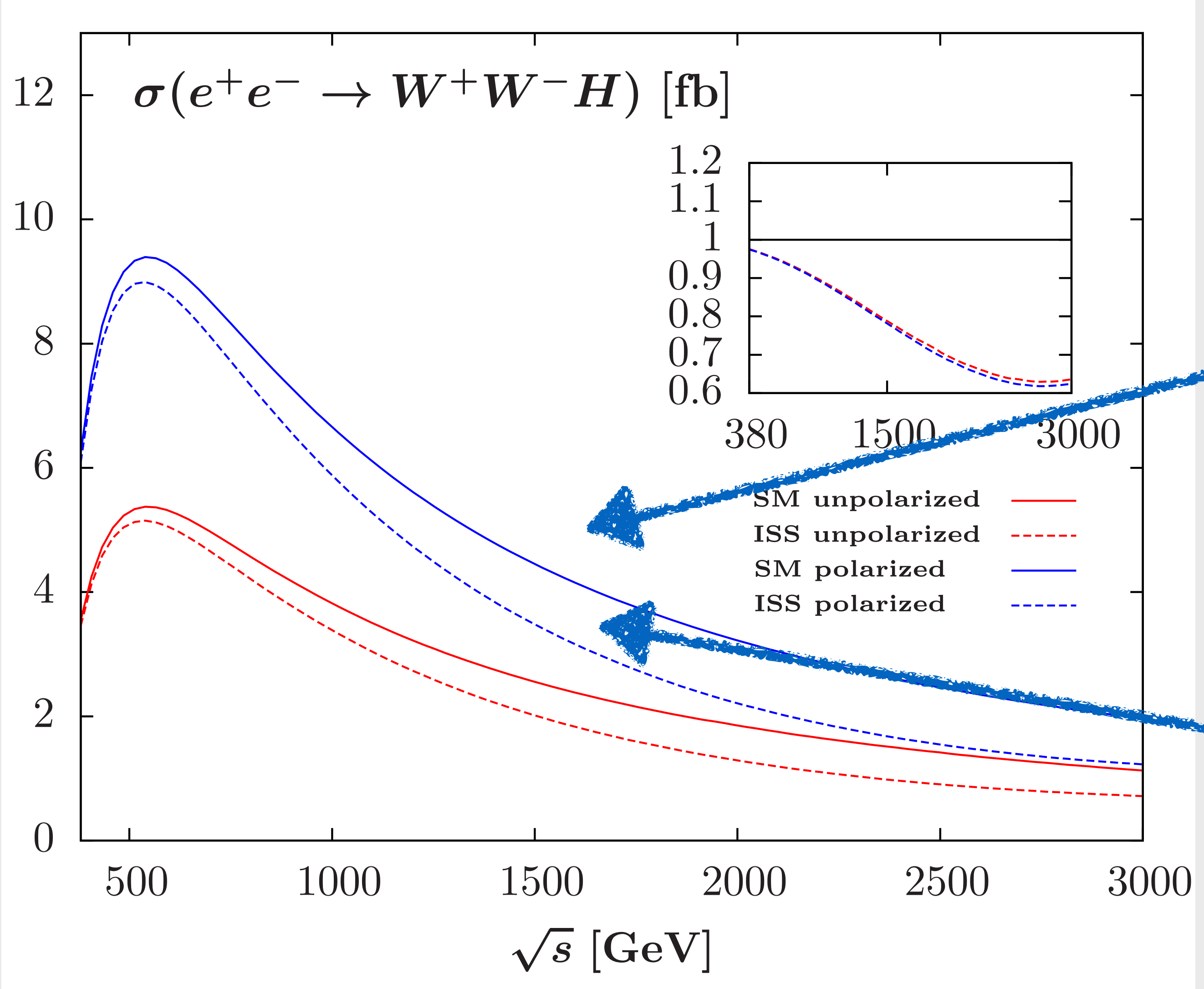

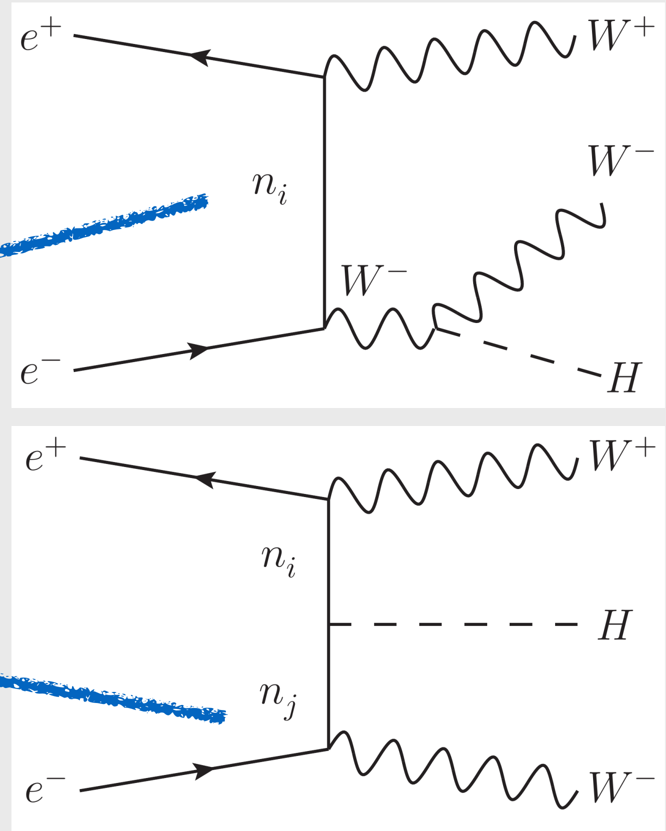

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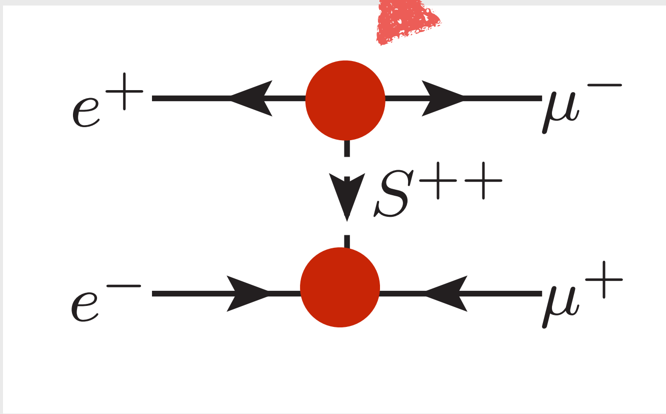

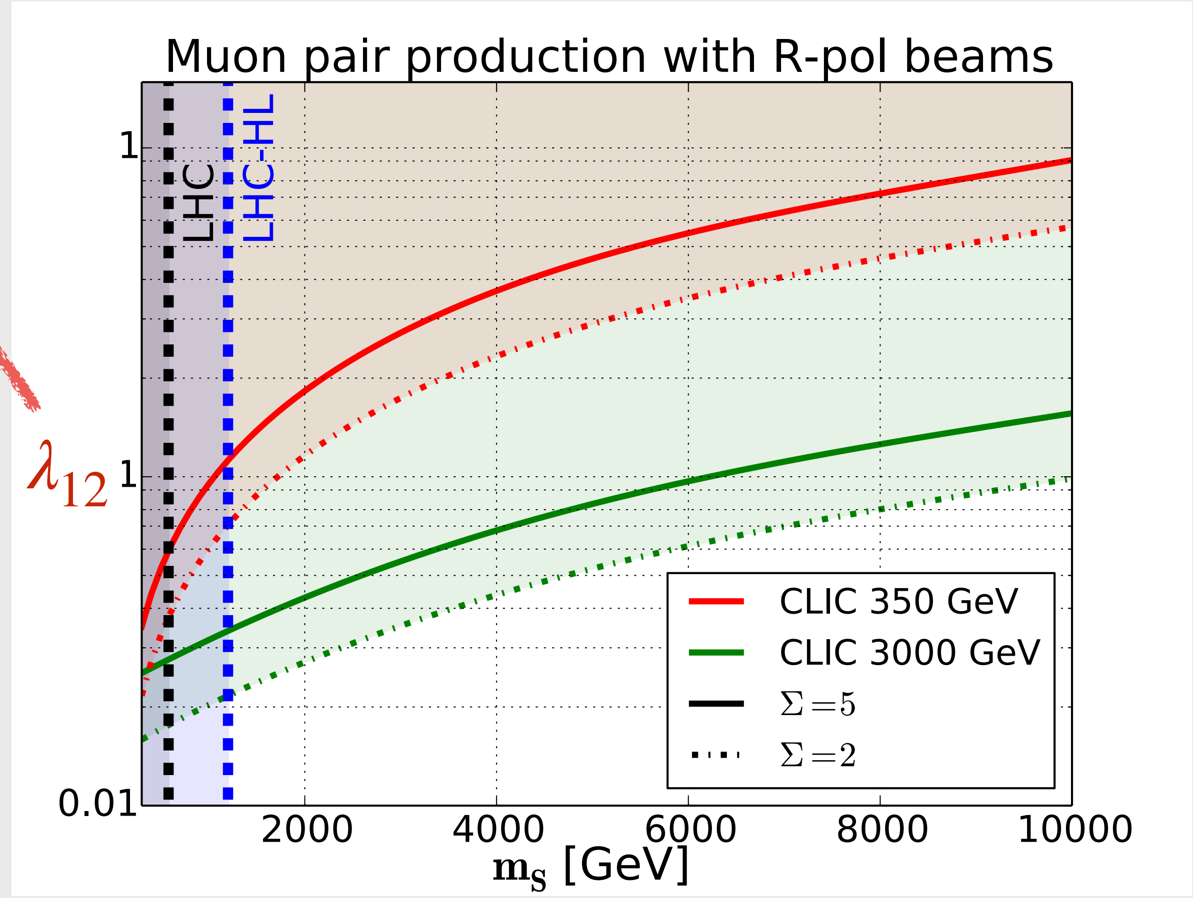

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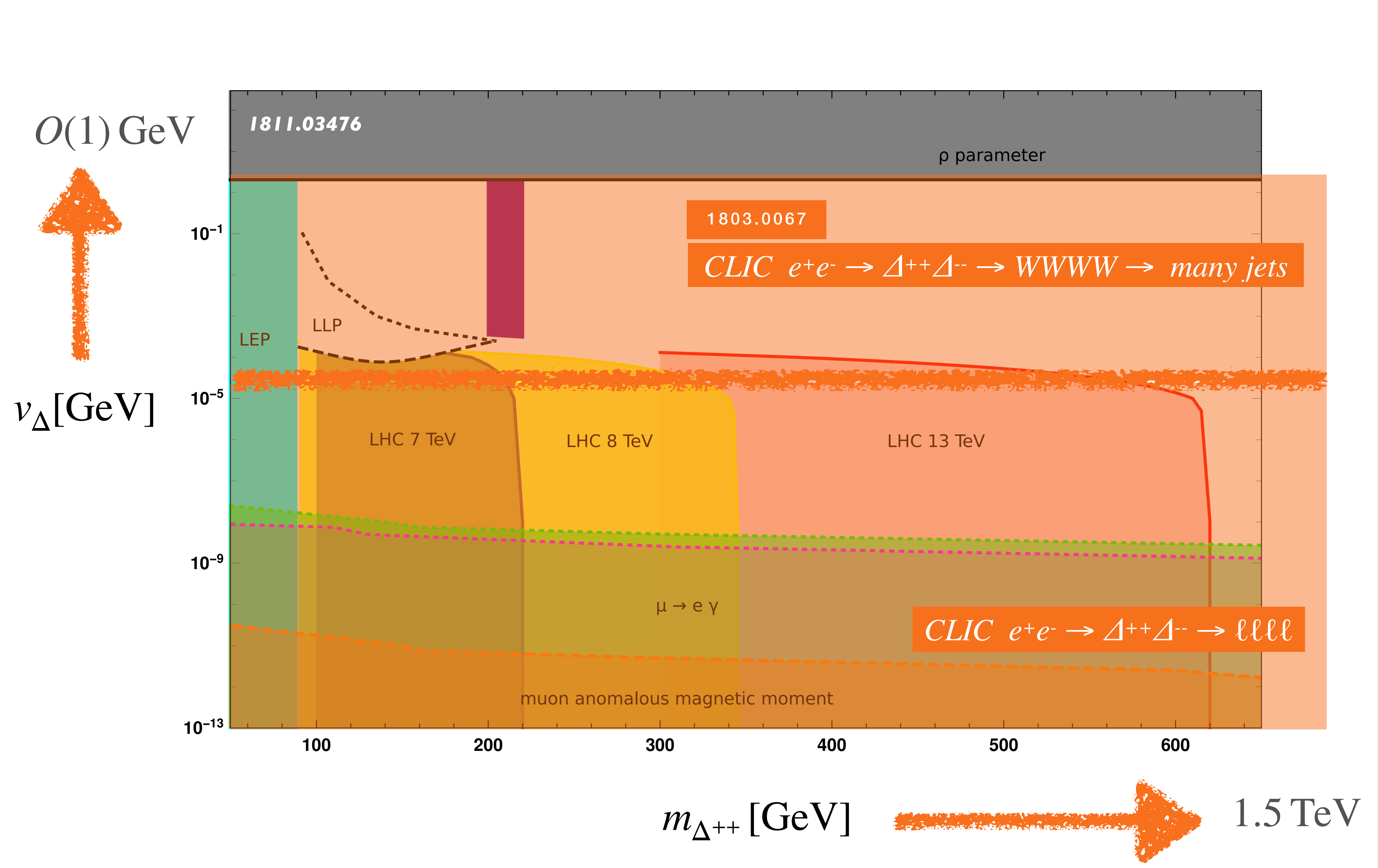

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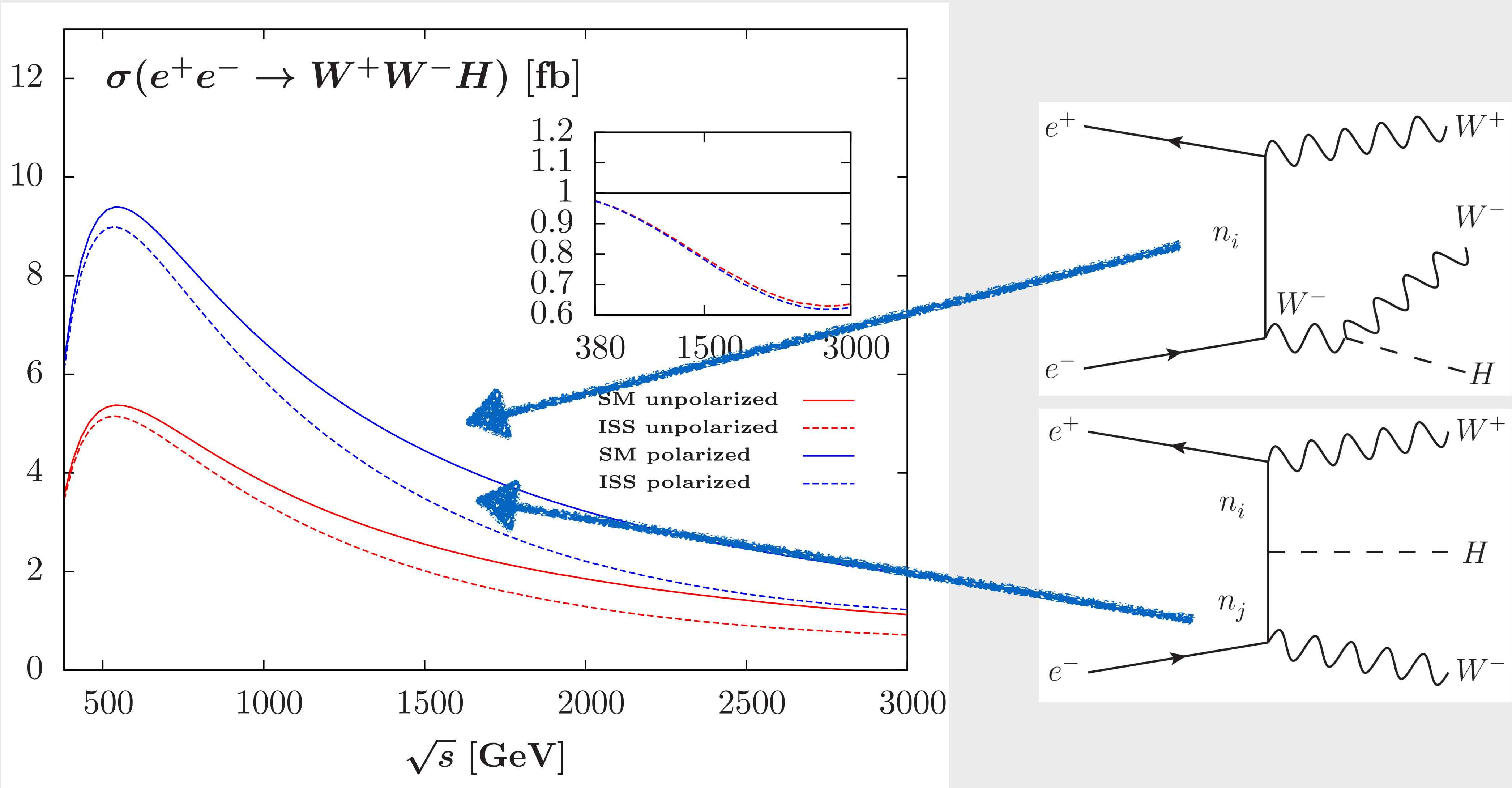

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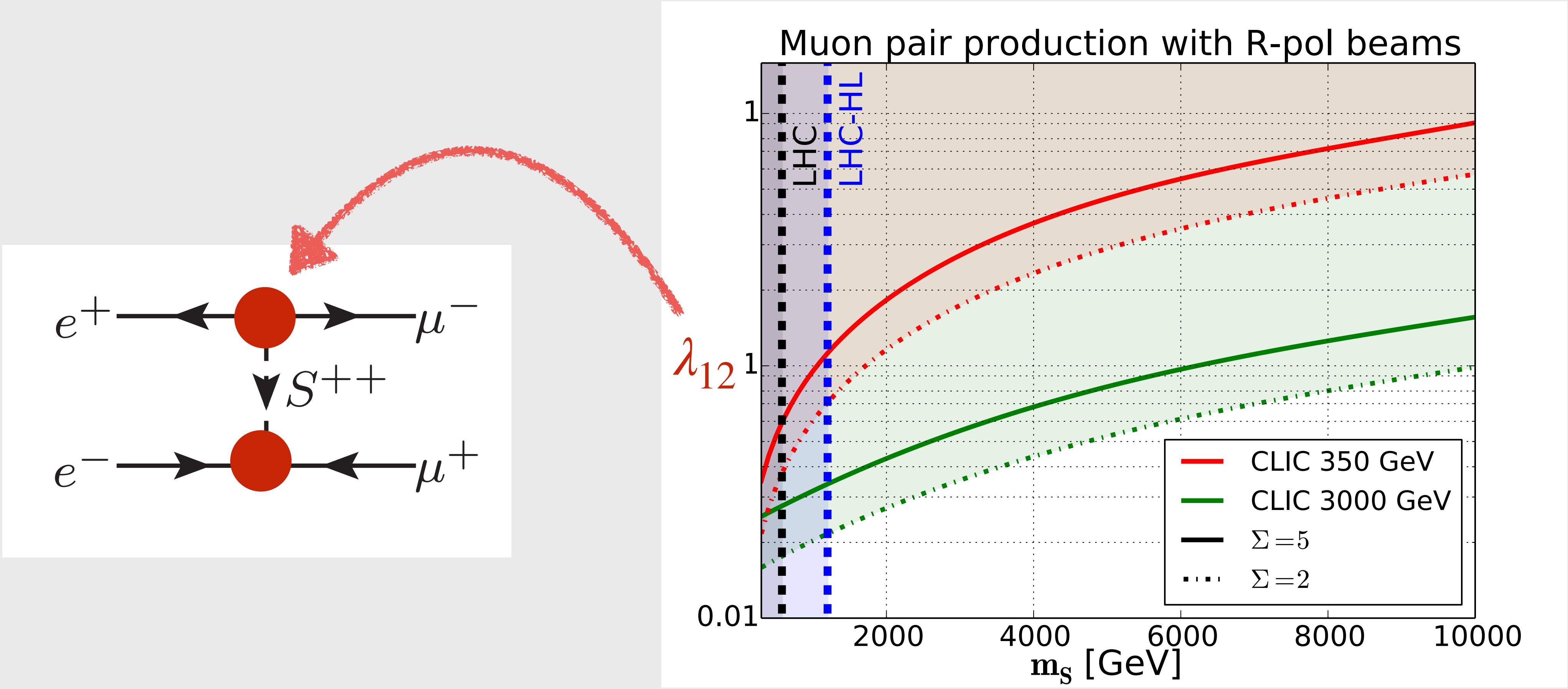

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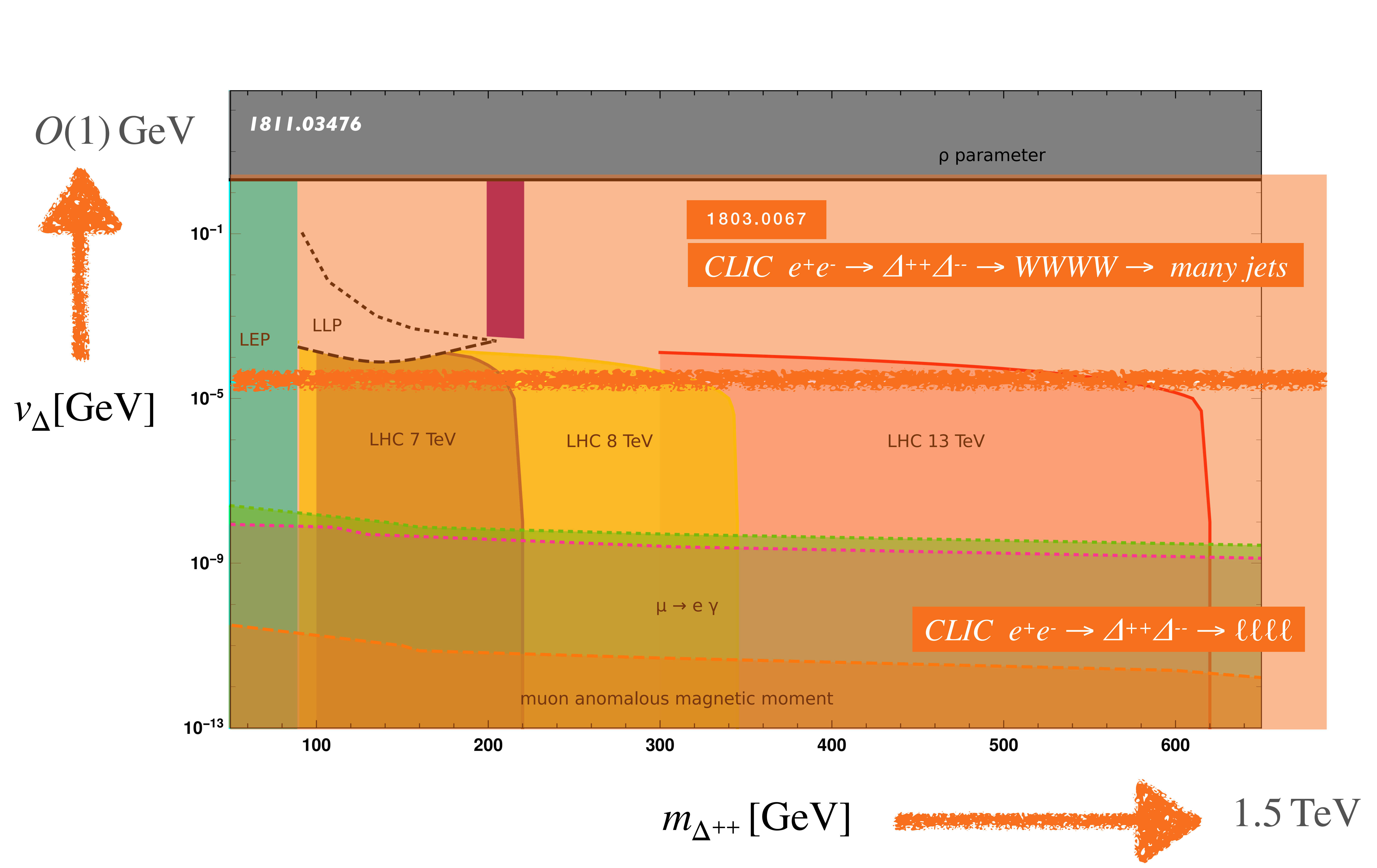

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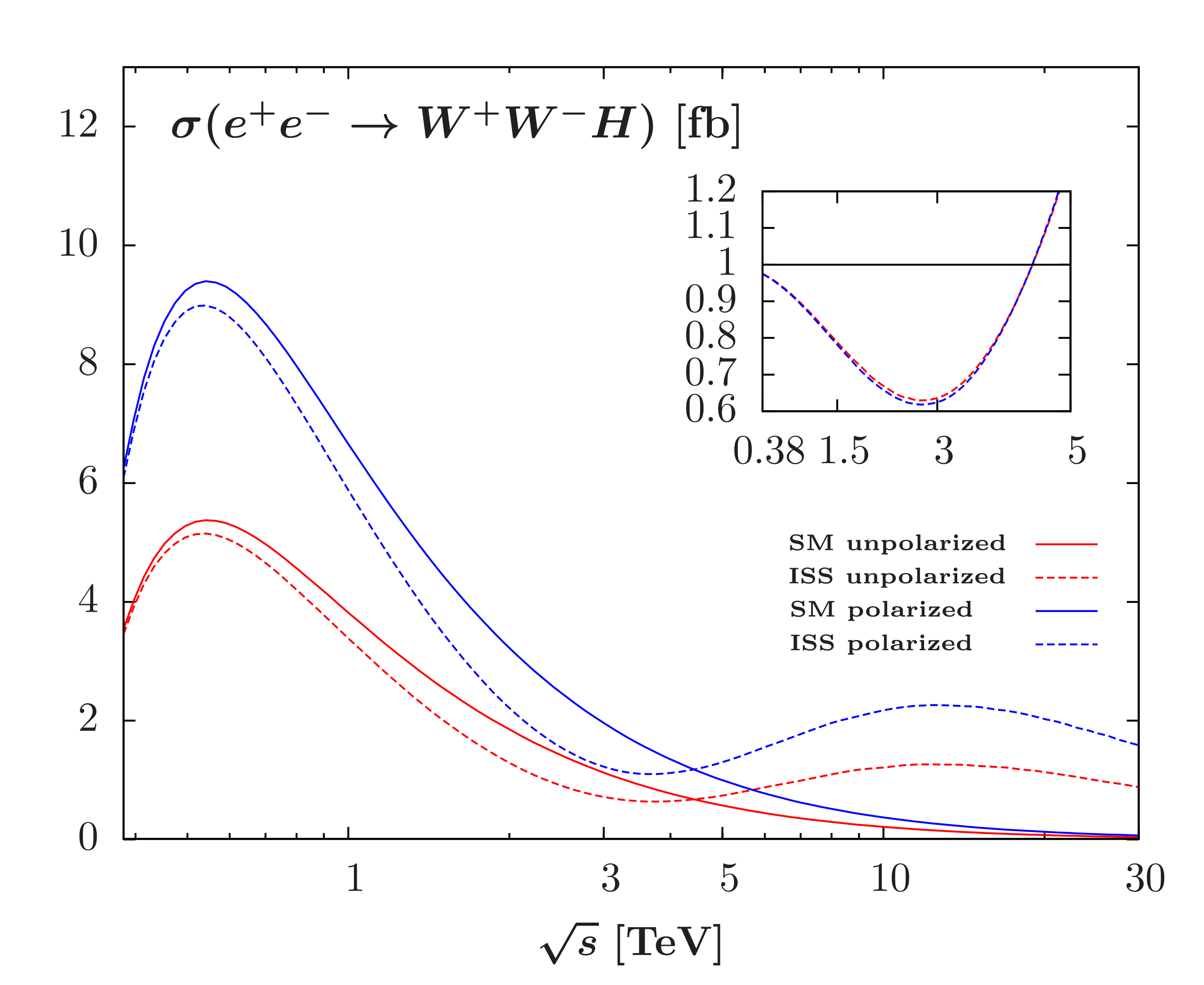

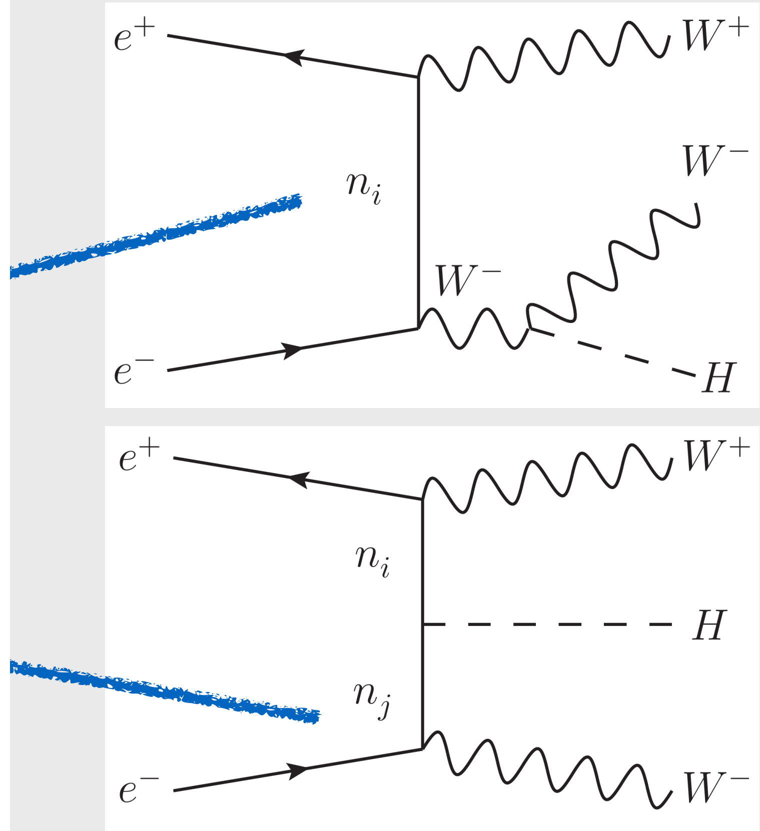

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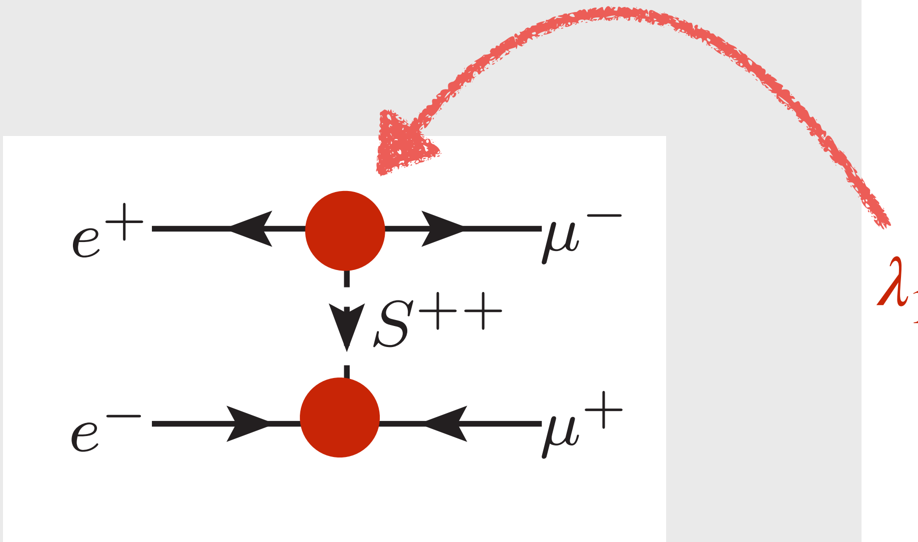

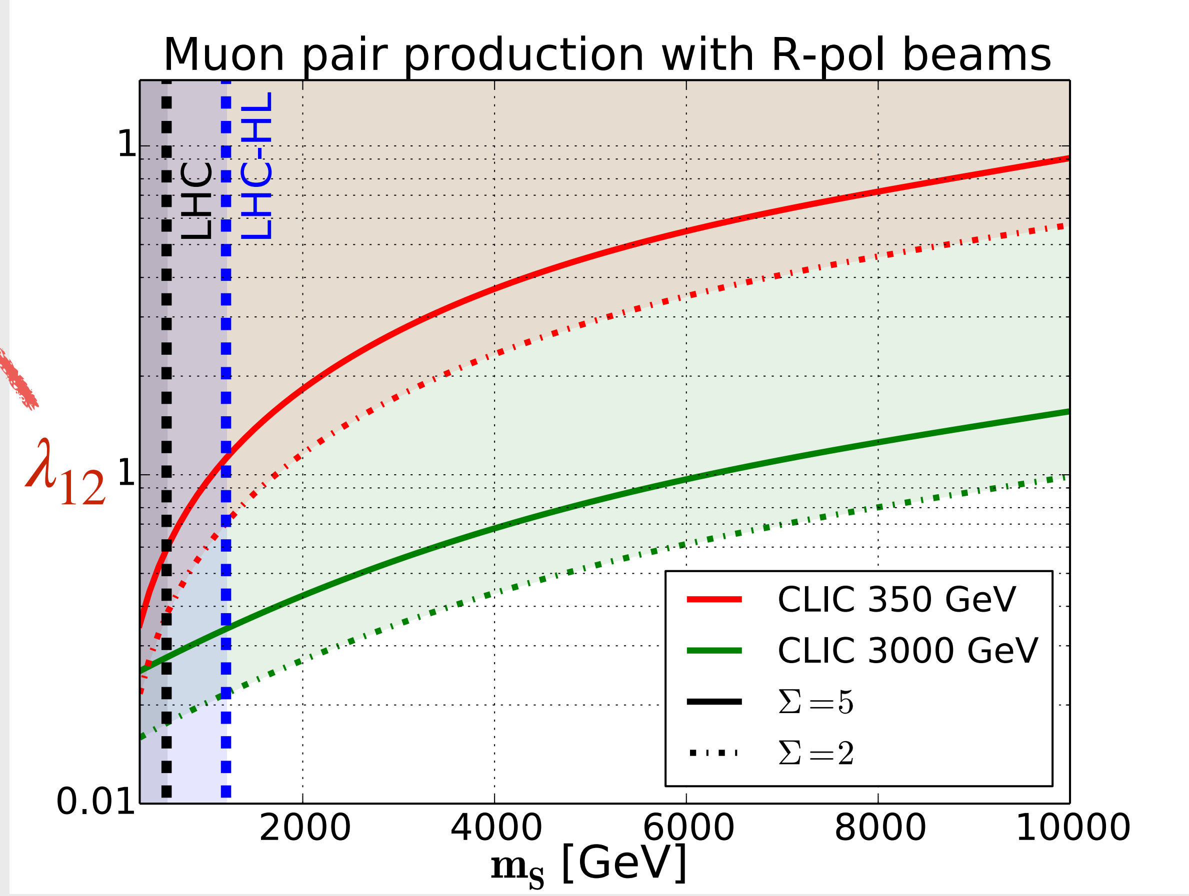

Exclude S^{++} up to 10 TeV for triplet Yukawa ~0.1

Plenty of neutrino mass models in reach

Type-1 See-Saw $\Theta^2 \approx \frac{m_\nu}{M} \lesssim 10^{-11}\left(\frac{m_\nu}{0.1\text{ eV}}\right)\left(\frac{10\text{ GeV}}{M}\right)$

Problems that we can probe conclusively at colliders

Relevant mass scales

100 TeV

Λεμμα

10-30 TeV

PWFA

3 TeV

1 TeV

200-300 GeV

Problems that we can probe conclusively at colliders

Relevant mass scales

EW symmetry breaking

100 TeV

10-30 TeV

PWFA

3 TeV

1 TeV

200-300 GeV

Problems that we can probe conclusively at colliders

Relevant mass scales

100 TeV

$L\varepsilon\mu\mu a$

10-30 TeV

PWFA

3 TeV

1 TeV

200-300 GeV

EW symmetry breaking

EW phase transition

Problems that we can probe conclusively at colliders

Relevant mass scales

WIMP Dark Matter

EW symmetry breaking

EW phase transition

100 TeV

Λεμμα

10-30 TeV

FCC hh ee he

Muon Accelerator Program

PWFA

3 TeV

CLIC

1 TeV

ILC

200-300 GeV

CEPC

FCC hh ee he

Relevant mass scales

100 TeV

Lεμμα

10-30 TeV

PWFA

3 TeV

1 TeV

200-300 GeV

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

10-30 TeV

PWFA

3 TeV

1 TeV

200-300 GeV

Problems that we cannot even remotely probe conclusively at colliders

Fermions masses and mixings

BSM source of CPV

A small dent on large wall

100 TeV

10-30 TeV

3 TeV

1 TeV

200-300 GeV

Open Questions on the "big picture" on fundamental physics circa 2021

	?	• 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

Open Questions on the "big picture" on fundamental physics circa 2021

- ? what is the dark matter in the Universe?
- why QCD does not violate CP?
- how have baryons originated in the early Universe?
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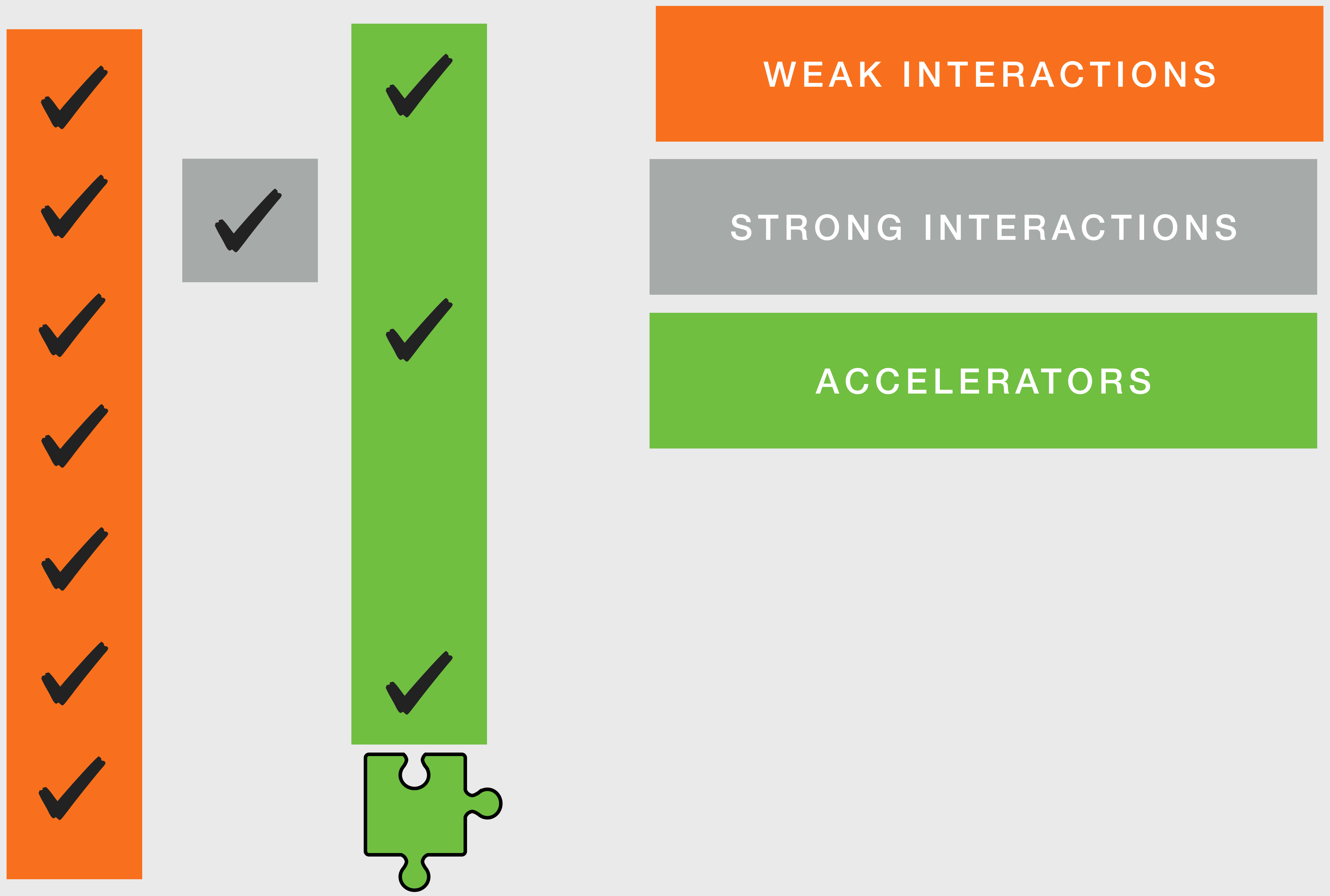
- ~~EFT~~ why gravity and weak interactions are so different?
- ~~EFT~~ what fixes the cosmological constant?



Thank You!