Facts and legends on the 3 TeV muon collider physics case

NOV. 5 2021

ROBERTO FRANCESCHINI (ROMA 3 UNIVERSITY)

ROMA TRE UNIVERSITÀ DEGLI STUDI

INFN Roma3

thanks to D. Buttazzo, F. Maltoni, A. Wulzer, X. Zhao

Overall picture about the SM

THE PICTURE HAS CHANGED

- a 3 TeV lepton collider is only good to measure the detailed properties of new physics particles discovered at the LHC

- >1 TeV lepton colliders are complimentary probes of the big hole the LHC has not filled!

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

$\mu^+\mu^-$ sensitivity to weak interactions

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

WEAK INTERACTIONS

STRONG INTERACTIONS

Accelerators are excellent probes

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

$\mu^+\mu^-$ sensitivity to weak interactions

		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

Accelerators are excellent probes

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

Theories to solve some of these problems can come with **associated new physics at any mass scale**, that is to say whatever the collider you will build you will not even come close to probe thoroughly the idea.

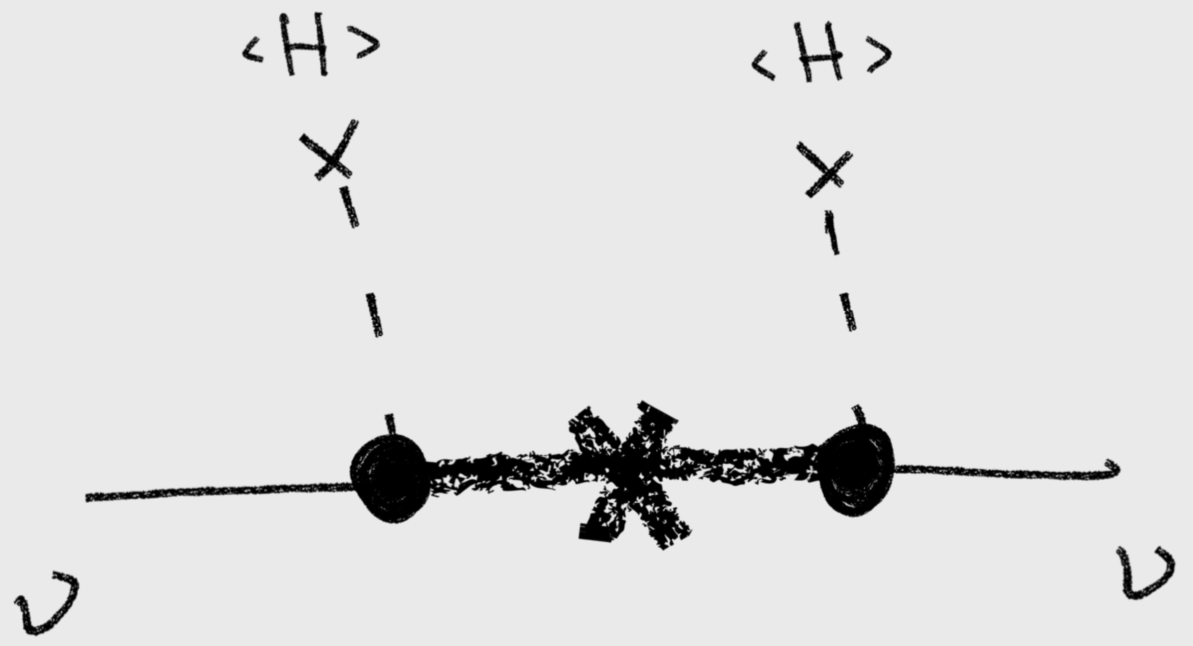
Example: The origin of neutrino mass

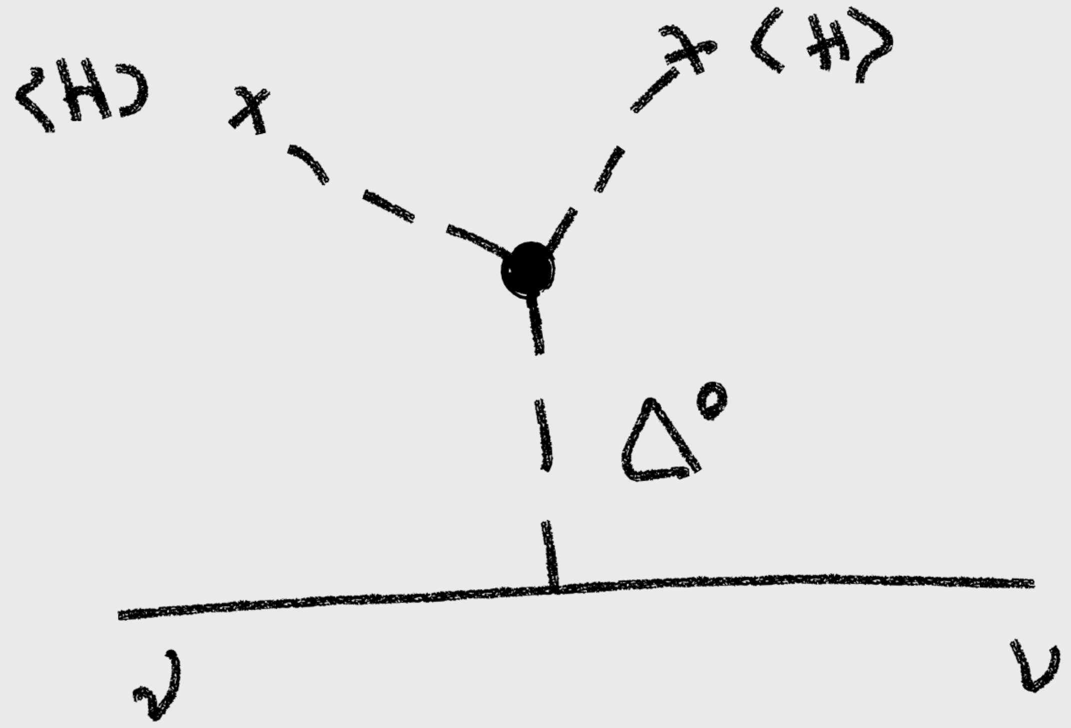
Majorana neutrino mass breaks lepton number. Neutrino mass may be explained if

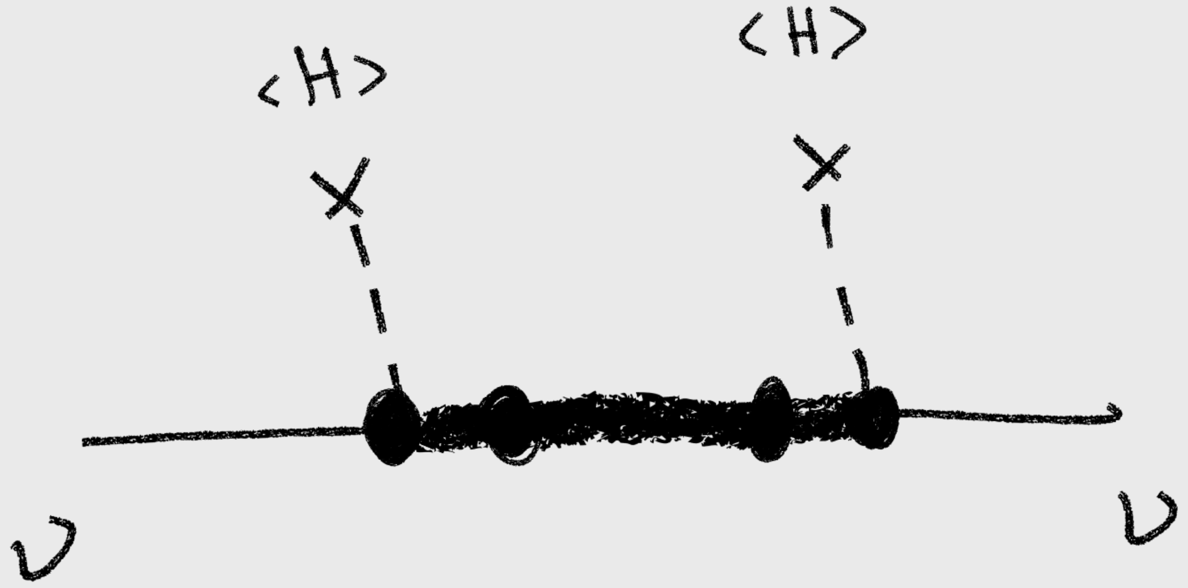
- lepton number is broken at a very large scale (very heavy Majorana right-handed neutrinos exists with big couplings to the SM)
- lepton number is broken by tiny couplings at a comparatively small scale (e.g. few TeV)

Neutrino mass mechanisms

LEPTON NUMBER BREAKING







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

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

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

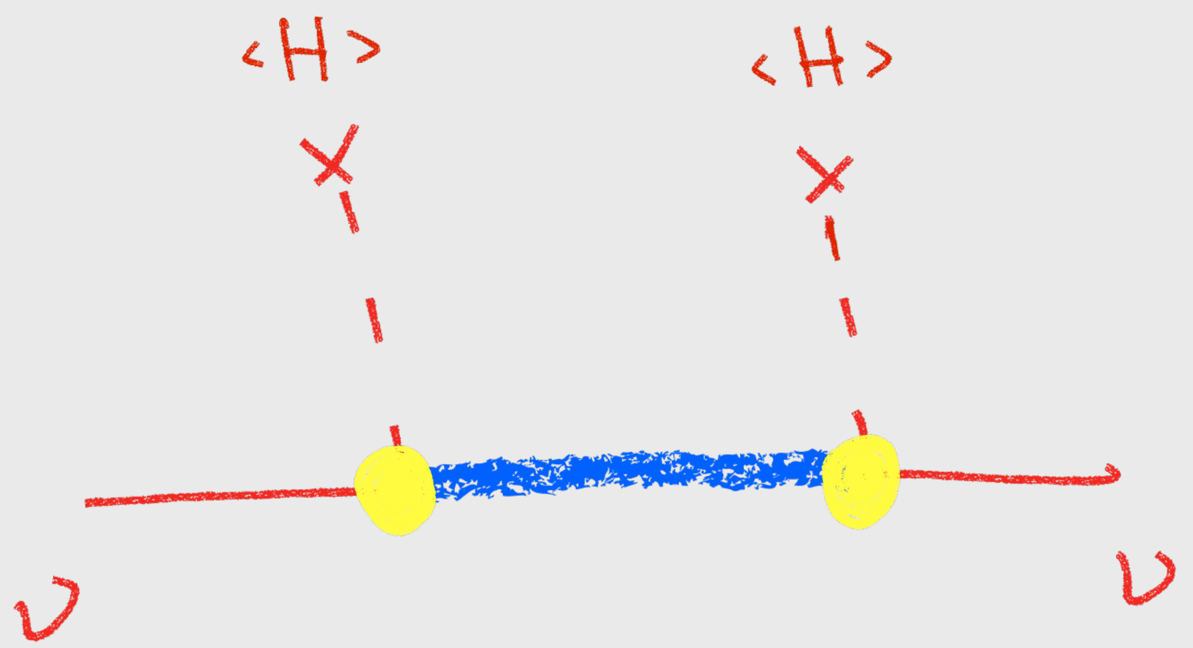
$M_{heavy} \to$ LARGE

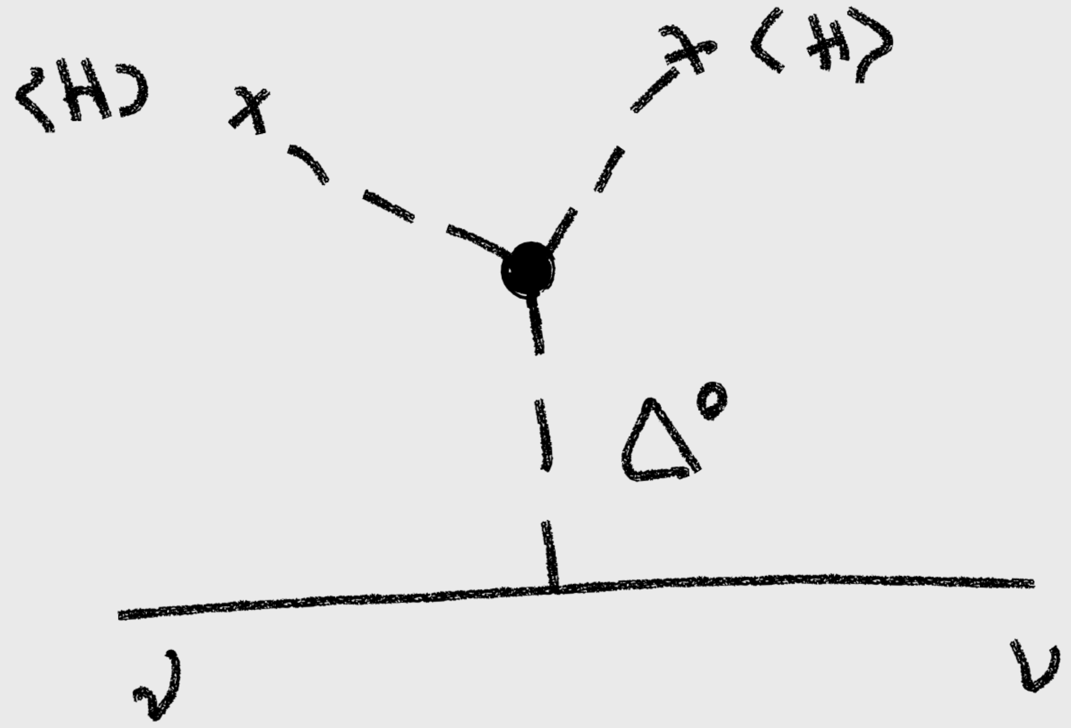
coupling $\to$ SMALL

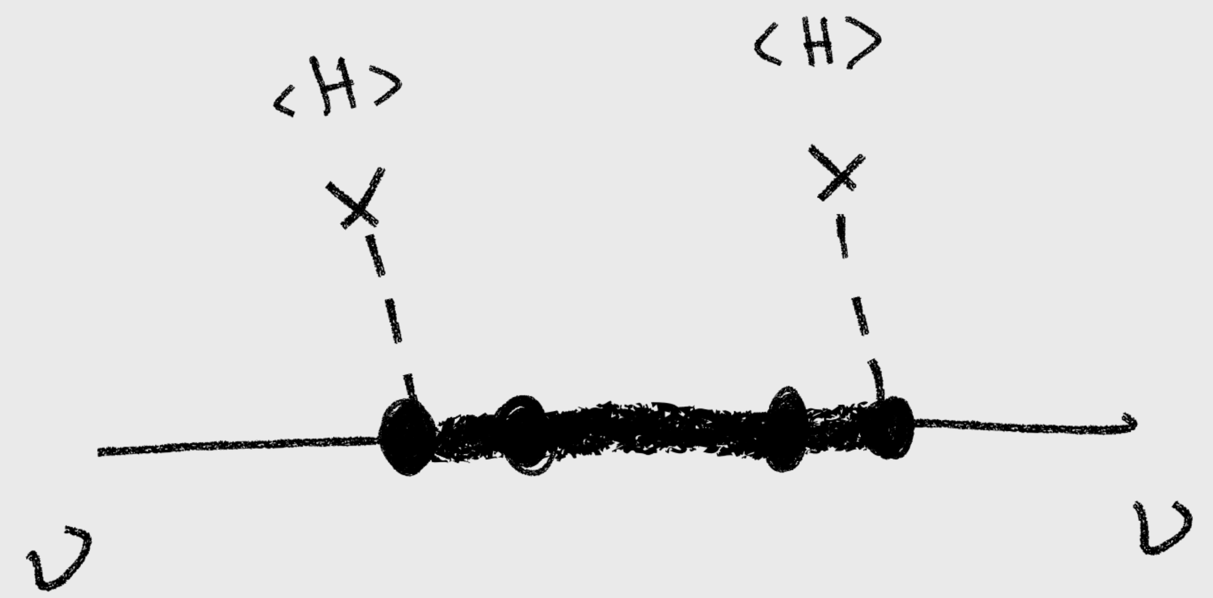
$\mu \to$ SMALL

Neutrino mass mechanisms

LEPTON NUMBER BREAKING







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

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

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

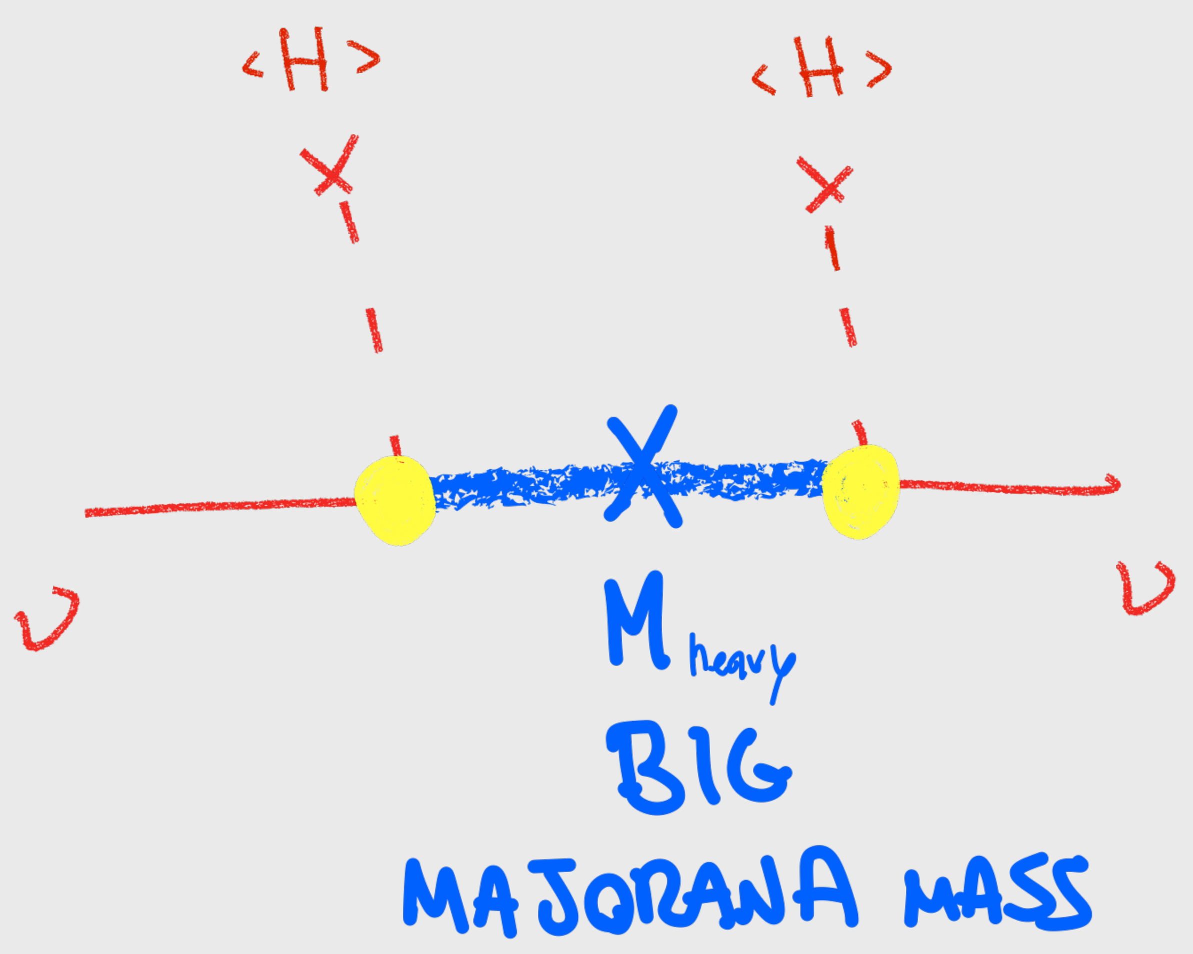
$M_{heavy} \to$ LARGE

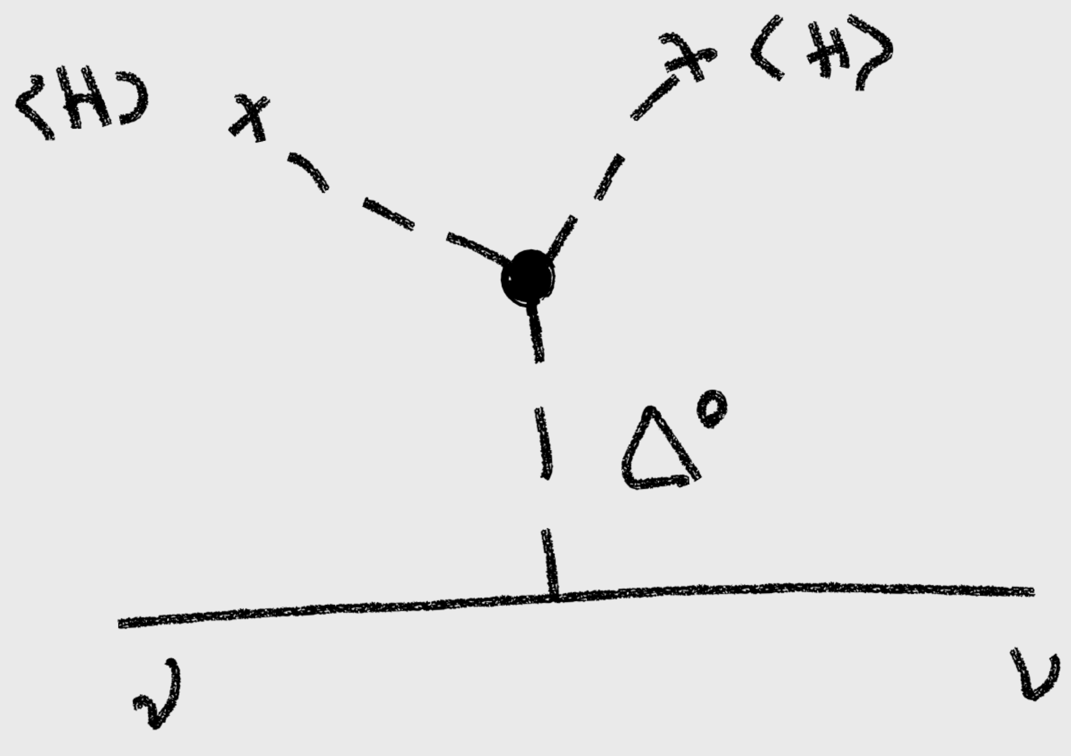
coupling $\to$ SMALL

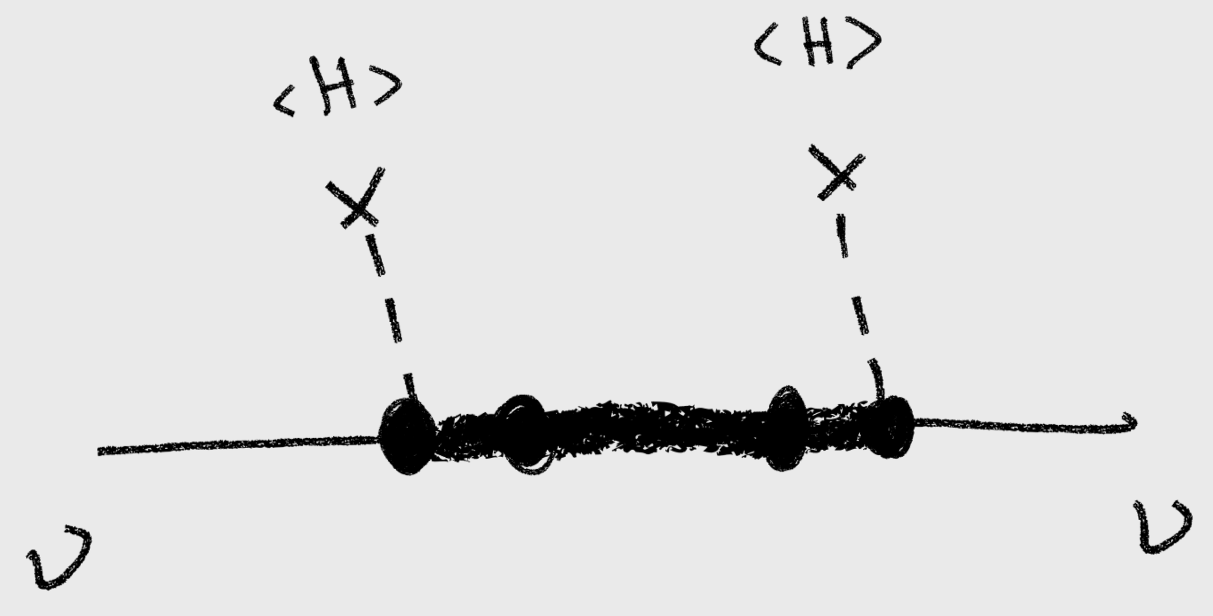
$\mu \to$ SMALL

Neutrino mass mechanisms

LEPTON NUMBER BREAKING







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

$$M_{heavy} \to \text{LARGE}$$

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

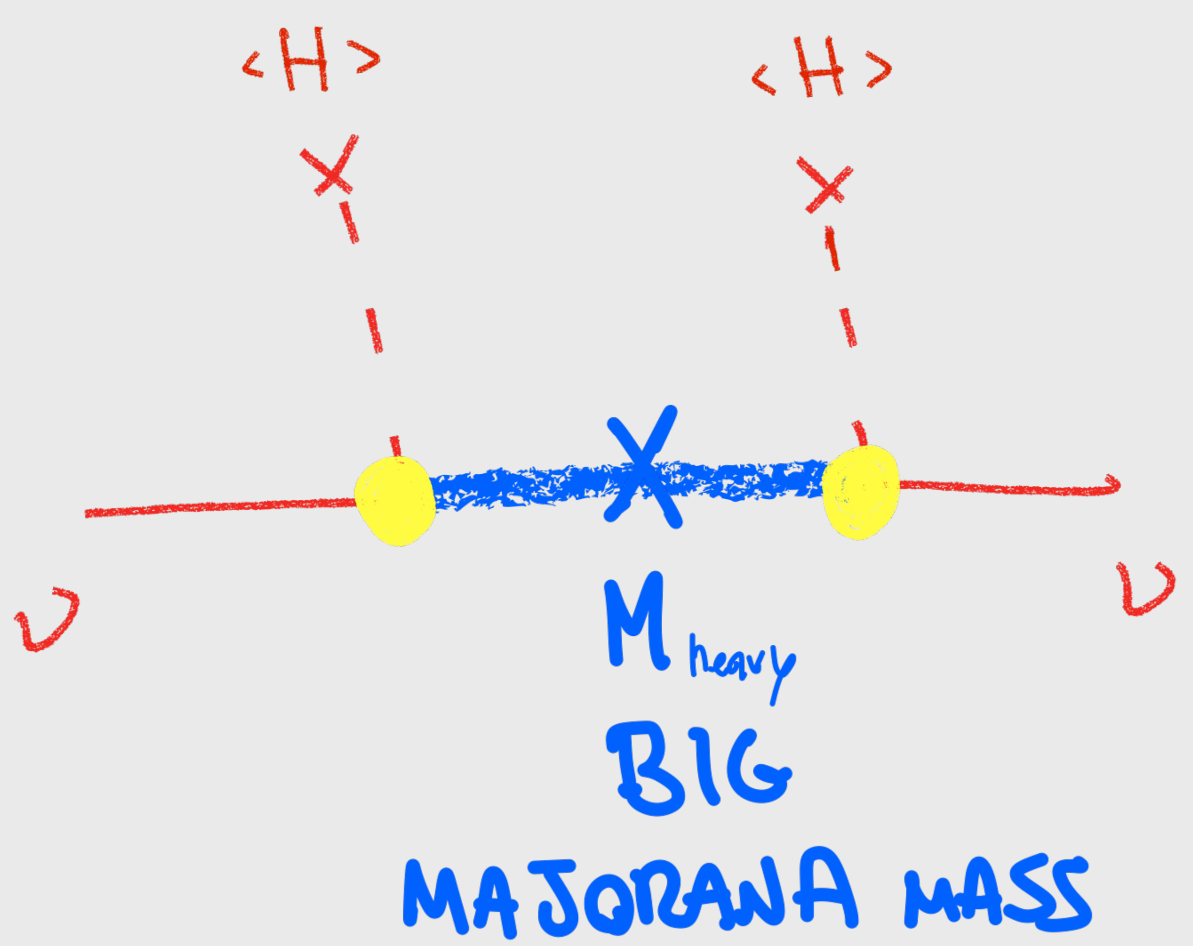
coupling → SMALL

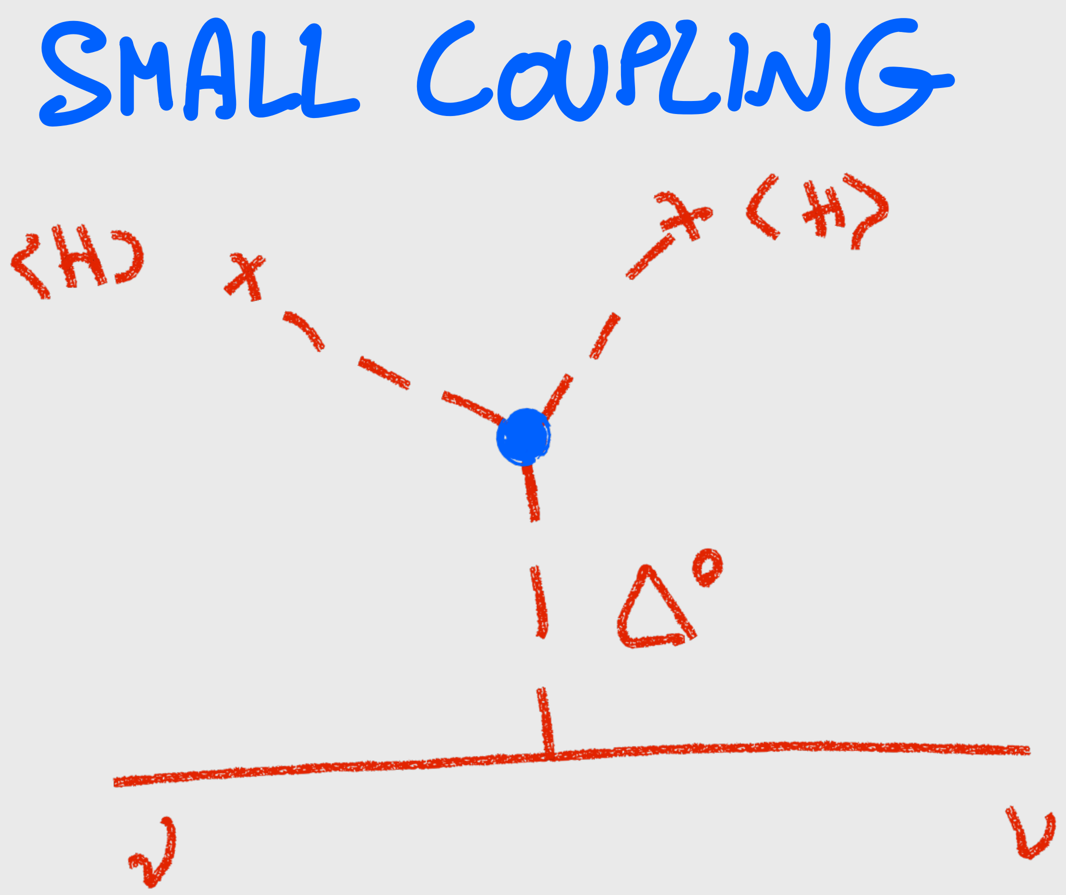
$$m_\nu = \mu \cdot \frac{(coupling)^2 < H >^2}{M_{heavy}^2} \to \text{SMALL}$$

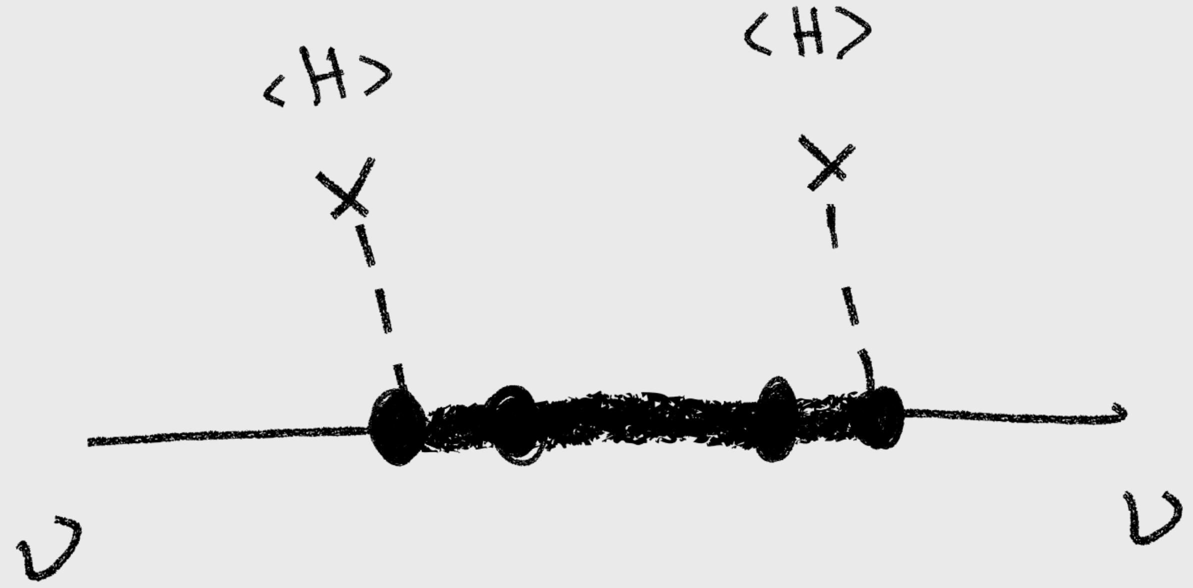
$$\mu \to \text{SMALL}$$

Neutrino mass mechanisms

LEPTON NUMBER BREAKING







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

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

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

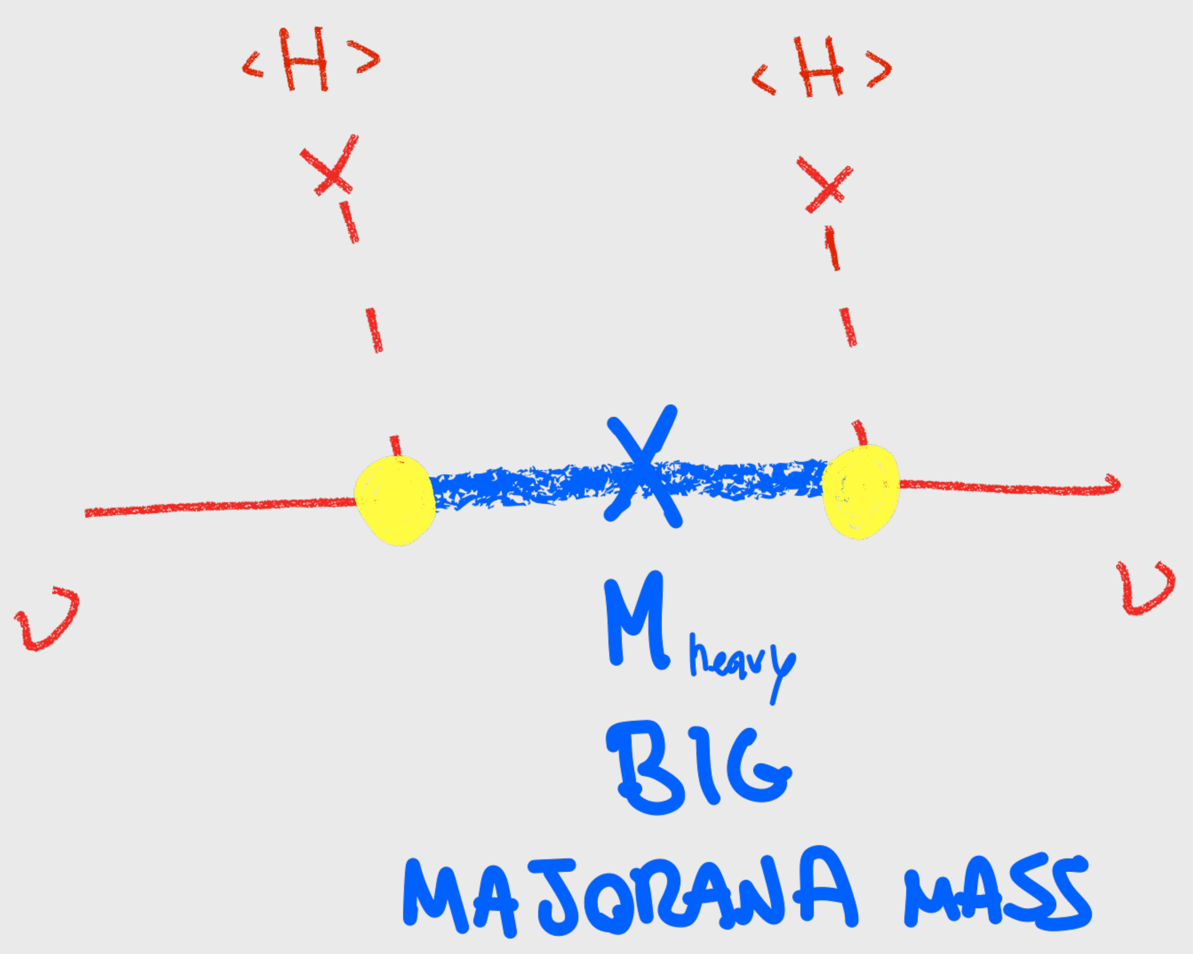
$M_{heavy} \to$ LARGE

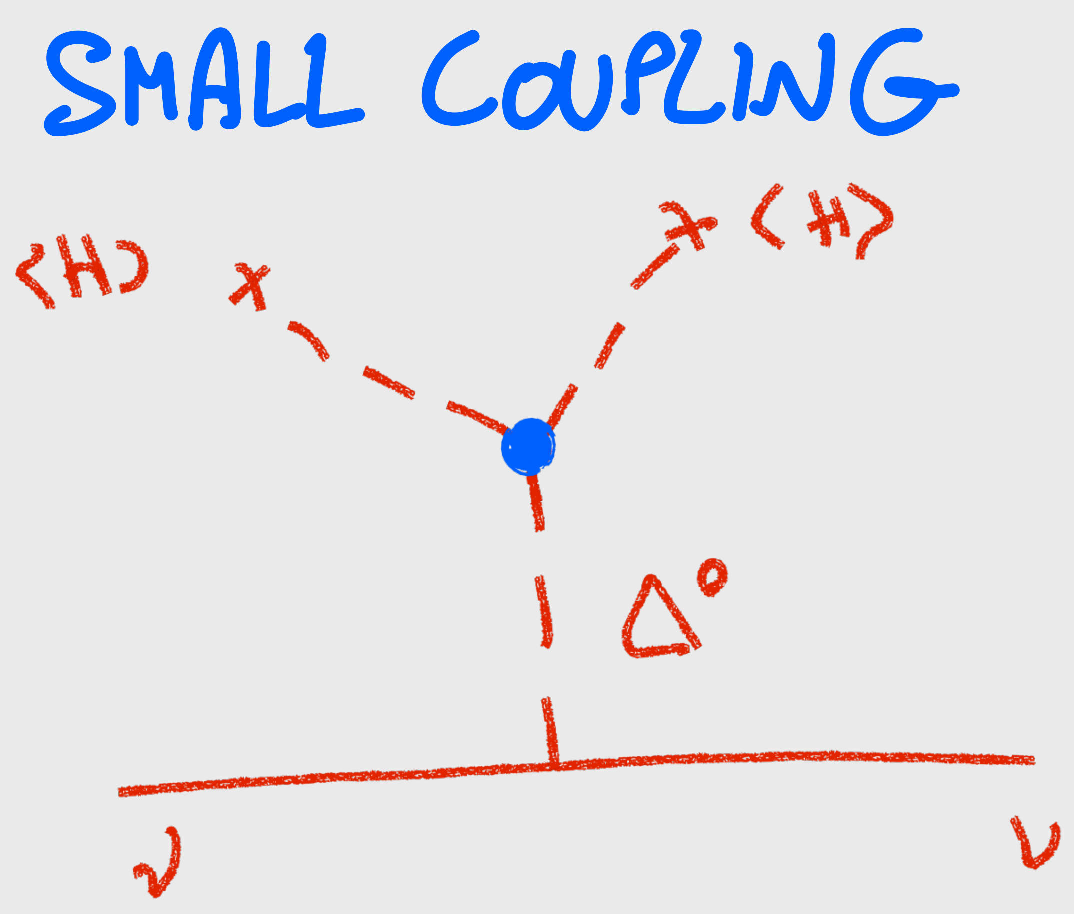
coupling → SMALL

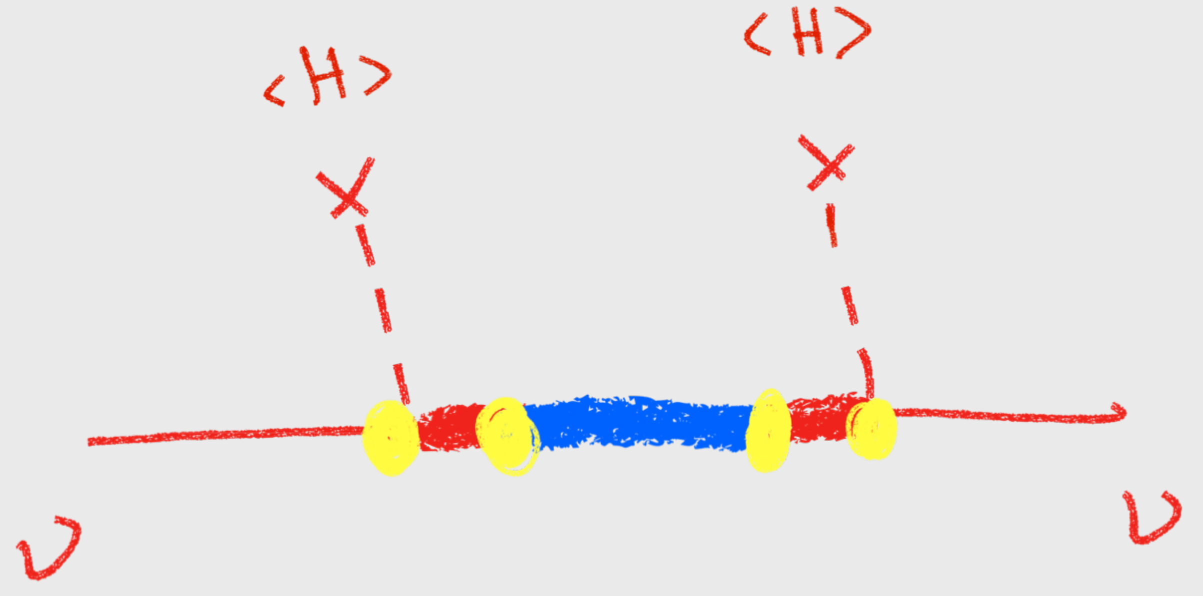
$\mu \to$ SMALL

Neutrino mass mechanisms

LEPTON NUMBER BREAKING







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

$$M_{heavy} \to \text{LARGE}$$

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

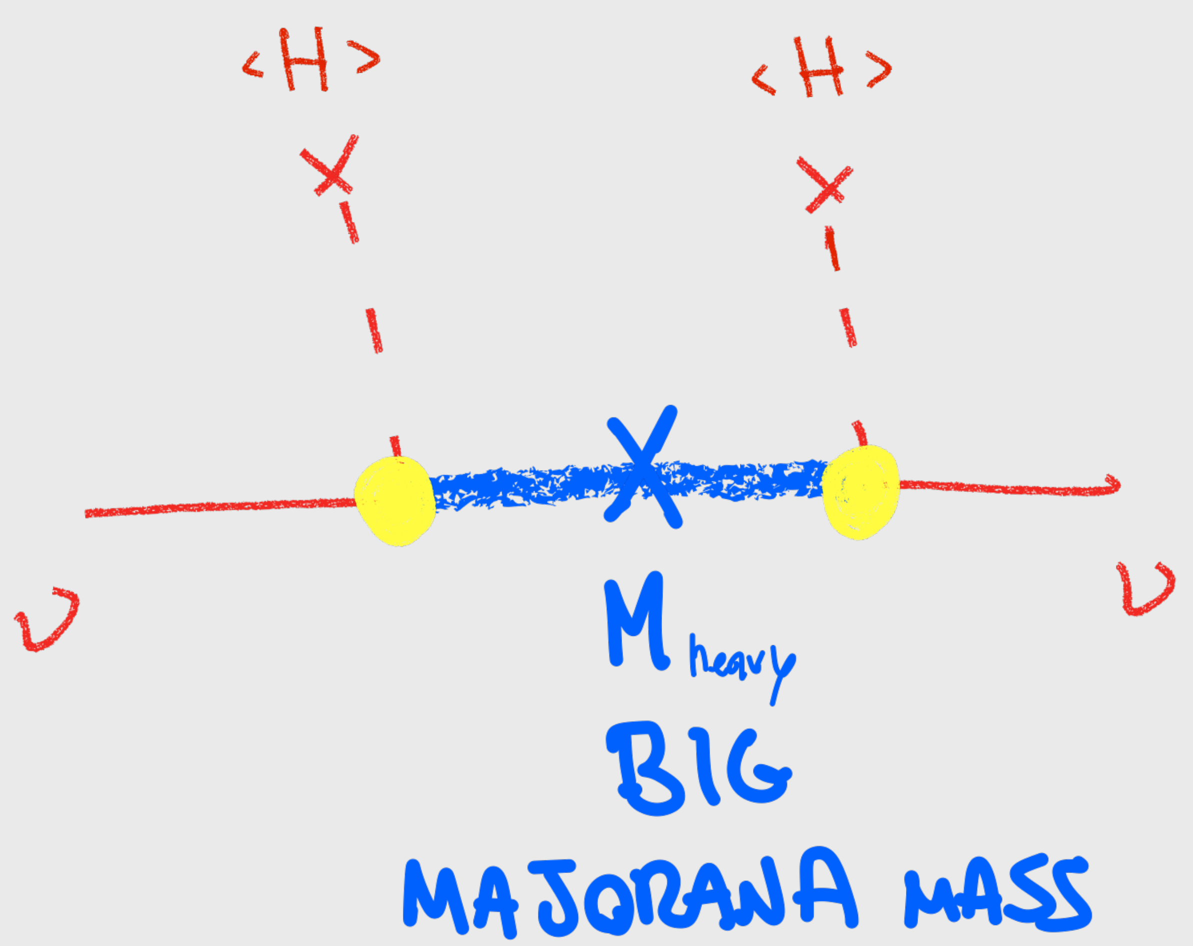
$$\text{coupling} \to \text{SMALL}$$

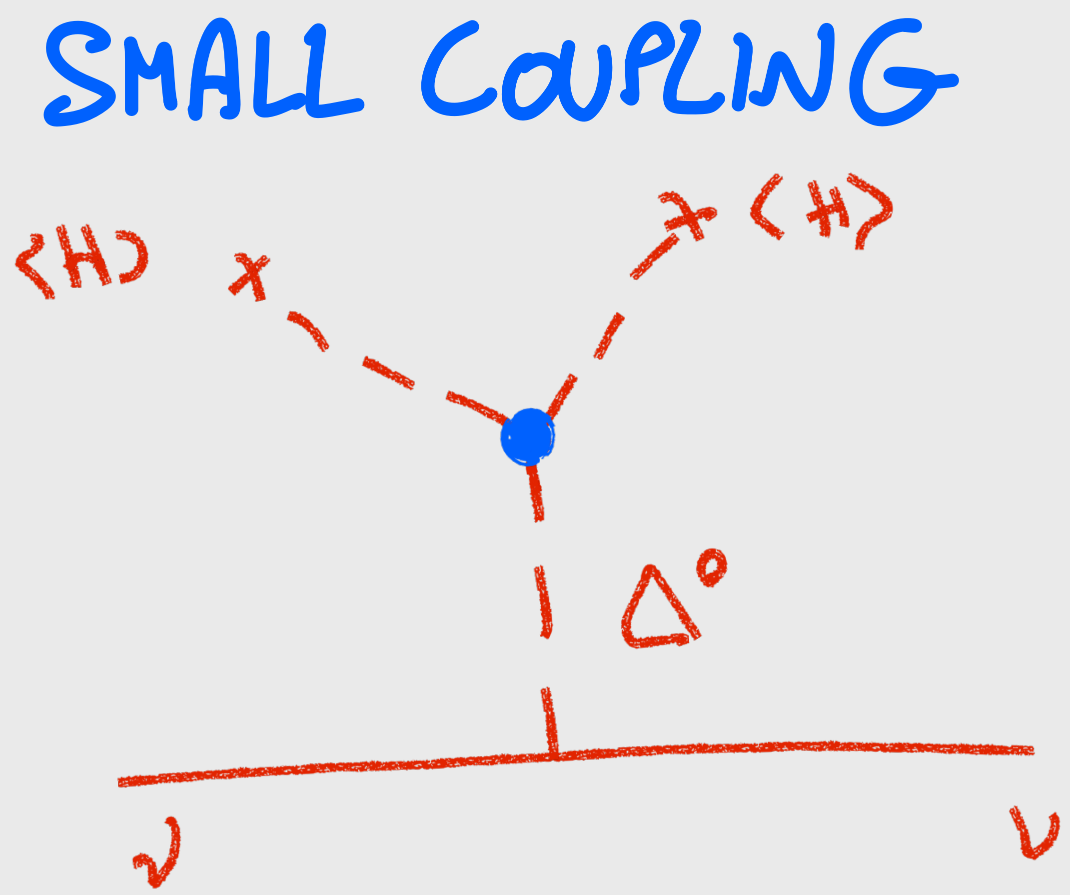
$$m_\nu = \mu \cdot \frac{(coupling)^2 < H >^2}{M_{heavy}^2} \to \text{SMALL}$$

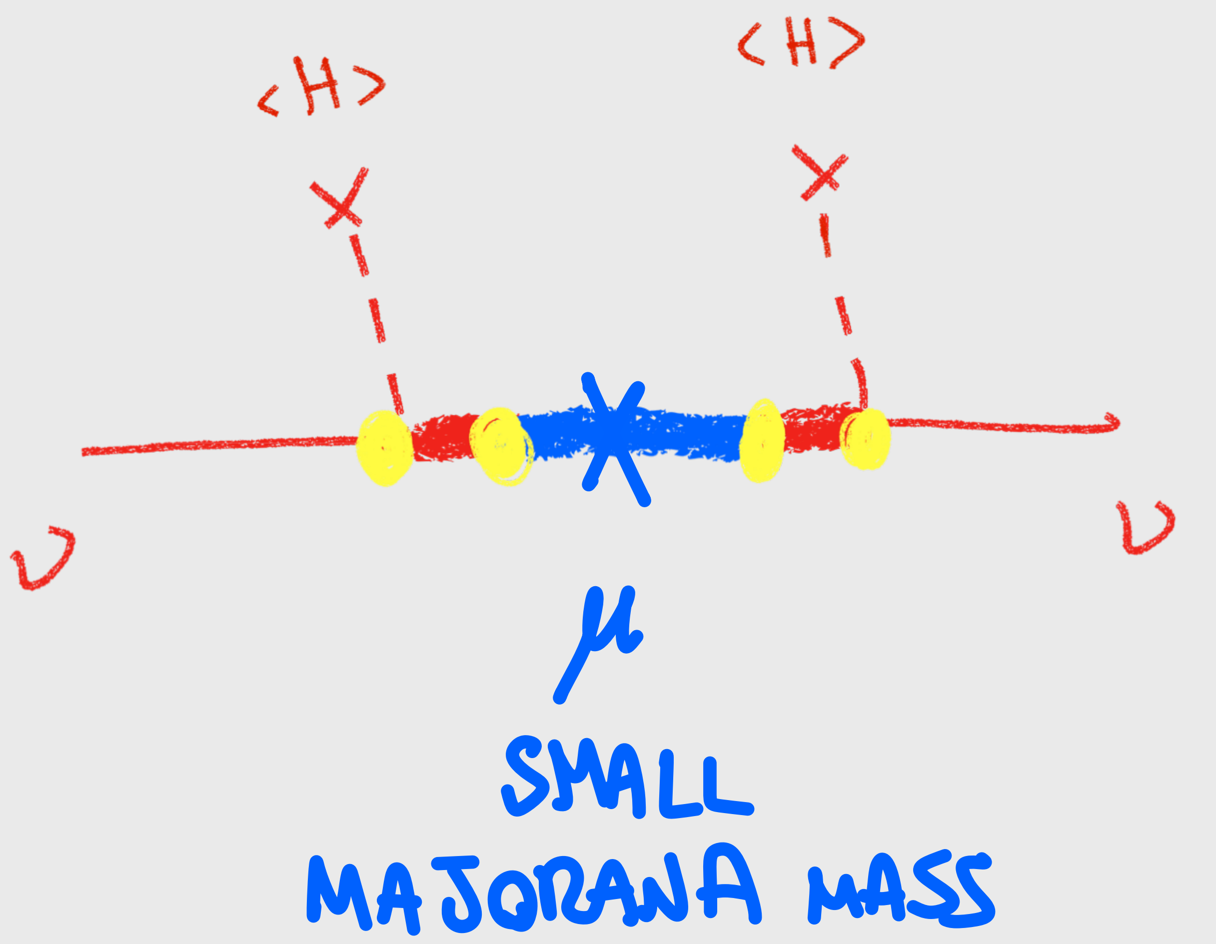
$$\mu \to \text{SMALL}$$

Neutrino mass mechanisms

LEPTON NUMBER BREAKING







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

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

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

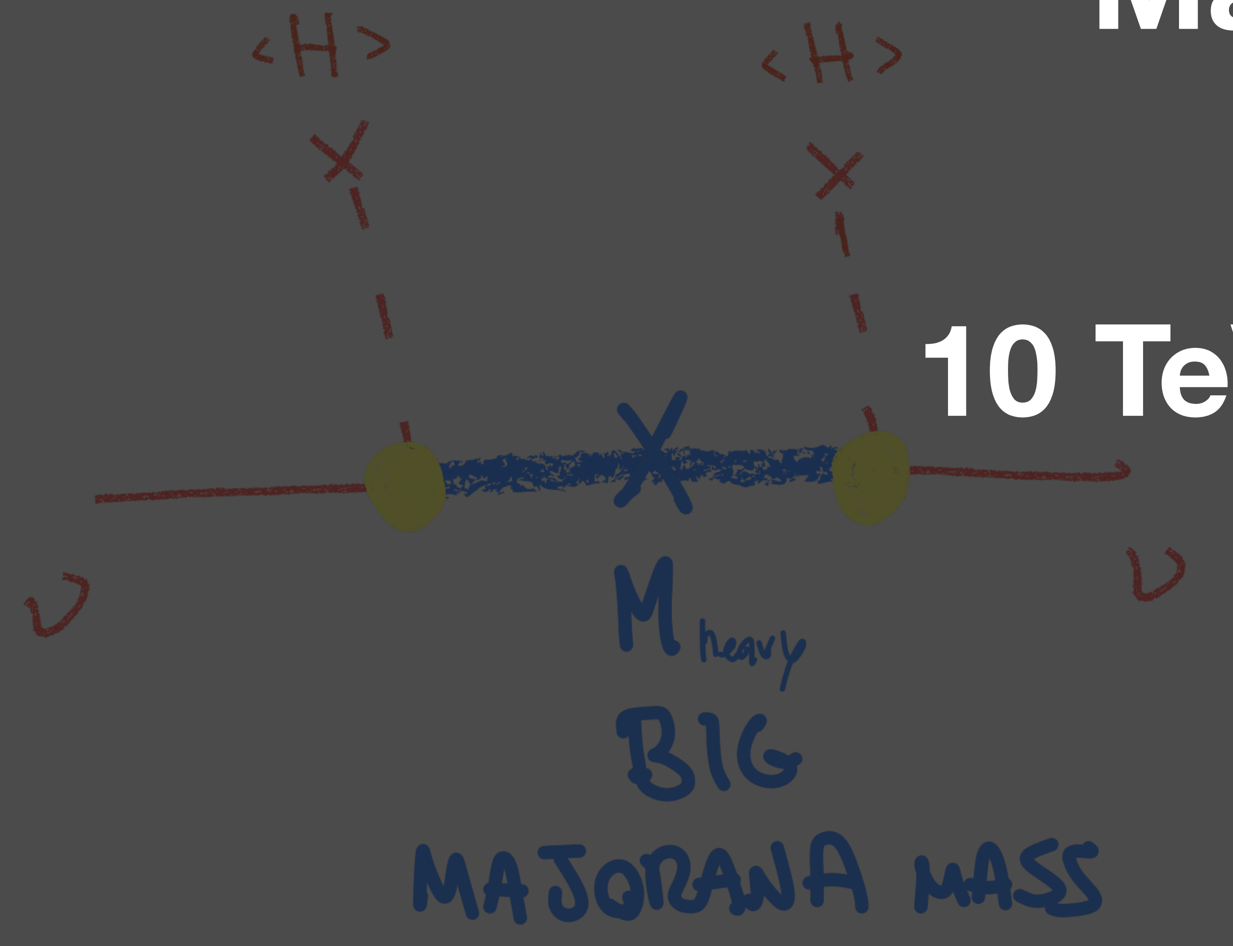
$M_{heavy} \to$ LARGE

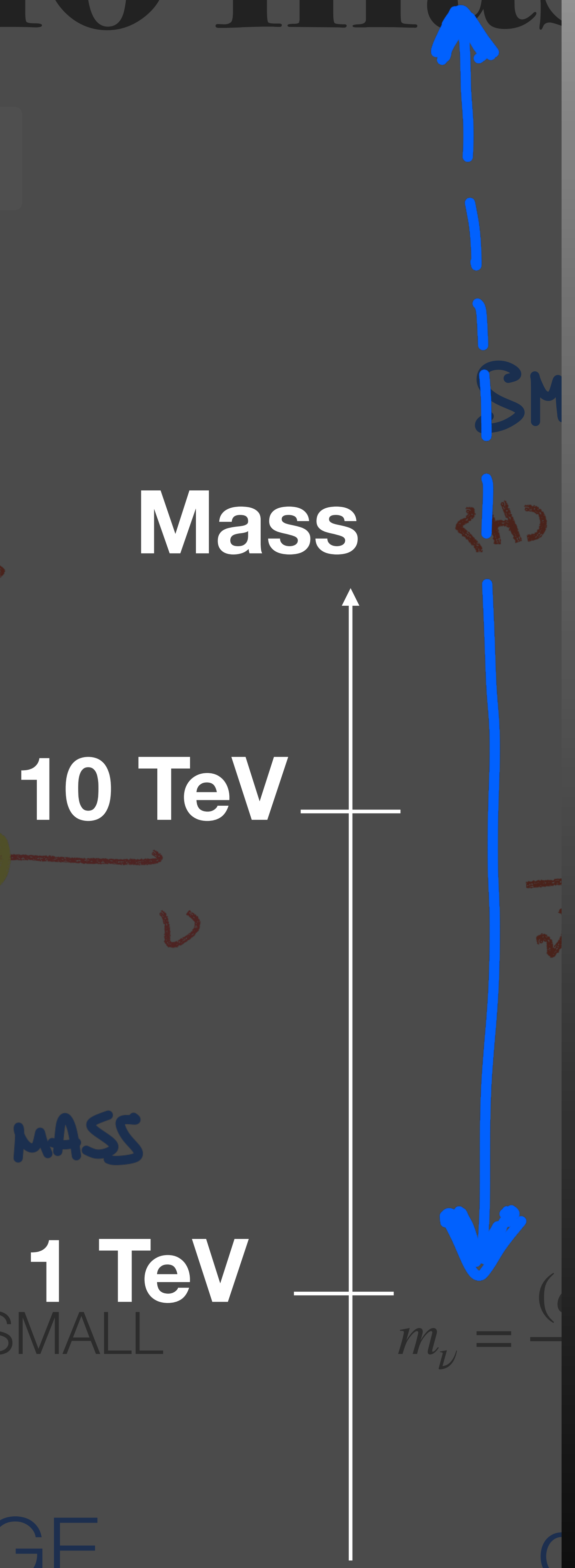
coupling → SMALL

$\mu \to$ SMALL

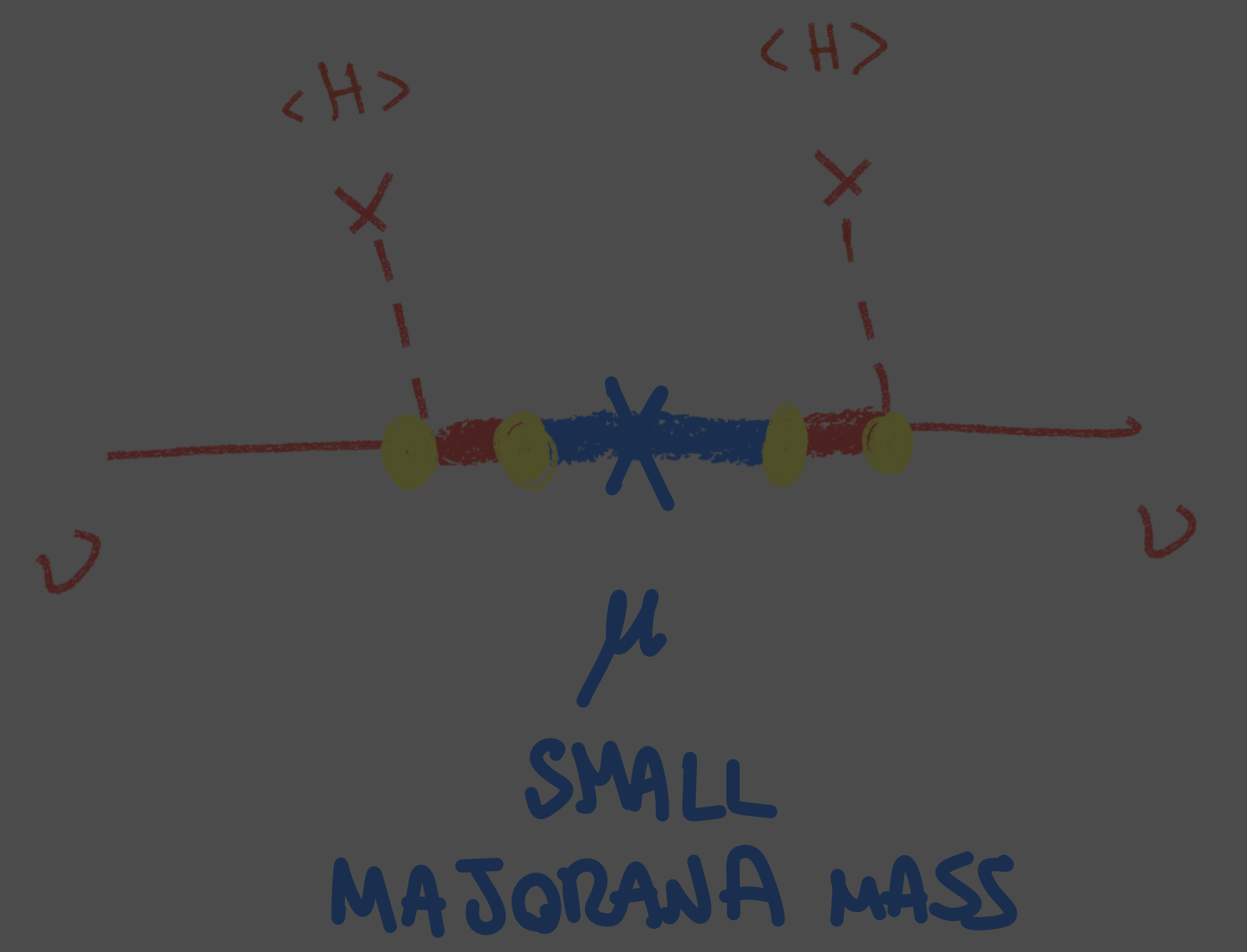
Neutrino mas … chanisms

LEPTON NUMBER BREAKING





LEPTON
NUMBER
VIOLATION



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

$M_{heavy} \to$ LARGE

$m_\nu = ($ … $\to$ SMALL

… ALL

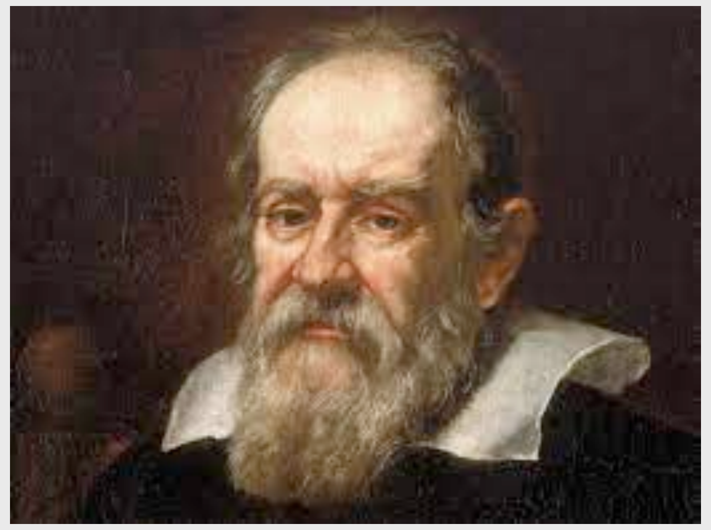
$$m_\nu = \mu \cdot \frac{(coupling)^2 < H >^2}{M^2_{heavy}} \to \text{SMALL}$$

$\mu \to$ SMALL

The value of searching and not finding

THOROUGH PROBES

Io stimo più il trovar un vero, benché di cosa leggiera, che 'l disputar lungamente delle massime questioni senza conseguir verità nissuna.



At least in my opinion there is enormously more scientific value in testing thoroughly one thing than in superficially testing any number of things.

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

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

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

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

A gauge of the progress we c[...] future collider

program
he LHC, t
s from alte
he Higgs
hich amb
rrently un
ence exp

Physics Opportunities of a 100 TeV Proton-Proton Collider

Nima Arkani-Hamed[a], Tao Han[b], Michelangelo Mangano[c], Lian-Tao Wang[d]

[a] *Institute for Advanced Study, Princeton, NJ, 08540, USA*
[b] *Department of Physics and Astronomy, Univ. of Pittsburgh, Pittsburgh, PA 15260, USA and Department of Physics, Tsinghua University, Beijing 100086, China*
[c] *Physics Department, TH Group, CERN, CH-1211 Genve 23, Switzerland*
[d] *Enrico Fermi Institute, Department of Physics, and Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637-1434, USA*

Abstract

The discovery of the Higgs boson at the LHC exposes some of the most profound mysteries fundamental physics has encountered in decades, opening the door to the next phase of experimental exploration. More than ever, this will necessitate new machines to push us deeper into the energy frontier. In this article, we discuss the physics motivation and present the physics potential of a proton-proton collider running at an energy significantly beyond that of the LHC and a luminosity comparable to that of the LHC. 100 TeV is used as a benchmark of the center of mass energy, with integrated luminosities of 3 ab^{-1}–30 ab^{-1}.

Keywords: Higgs boson; electroweak symmetry breaking; electroweak phase transition; particle dark matter; future circular collider, high energy proton-proton collider

Contents

1 Introduction **4**
1.1 LHC, The Higgs Boson and Beyond . . . 4
1.2 New Colliders for a New Frontier . . . 6
1.3 Luminosity of the 100 TeV *pp* Collider . . . 11

2 The Electroweak Phase Transition **17**
2.1 General Remarks . . . 17
2.2 Tests at the 100 TeV *pp* Collider . . . 20

3 Naturalness of the Electroweak Scale **28**
3.1 On the Mass of the Higgs Boson . . . 28
3.2 Natural Theories and the Tests at the 100 TeV *pp* Collider . . . 32

4 Dark Matter **42**
4.1 WIMP Dark Matter . . . 42
4.2 WIMP Dark Matter at the 100 TeV *pp* Collider . . . 47
4.2.1 Pure Wino . . . 49
4.2.2 Pure Higgsino . . . 50
4.2.3 Mixed dark matter . . . 51
4.2.4 Electroweak cascades . . . 52
4.2.5 Co-annihilation with Bino dark matter . . . 53

5 Other New Physics Searches **55**
5.1 New Color Resonances . . . 55
5.2 New Gauge Bosons and Vector Resonances . . . 57
5.3 Heavy Higgs Bosons in Doublet and Triplet Models . . . 57
5.4 Pair Production of Exotic Color States . . . 61
5.5 Pair Production of Heavy Leptons . . . 62

6 Benchmark Standard Model processes **63**
6.1 Jets . . . 64
6.2 W/Z Production . . . 68
6.2.1 Multiple gauge boson production . . . 69
6.2.2 FSR effects of the gauge bosons and initial state partons 70
6.3 Heavy Quarks . . . 77
6.3.1 Inclusive bottom production . . . 77
6.3.2 Inclusive top production . . . 78

2

Mind the structure

- Electroweak phase transition
- Naturalness of the EW scale
- Dark Matter
- “Others”

Contents

1 Introduction 4
1.1 LHC, The Higgs Boson and Beyond . . . 4
1.2 New Colliders for a New Frontier . . . 6
1.3 Luminosity of the 100 TeV pp Collider . . . 11

2 The Electroweak Phase Transition 17
2.1 General Remarks . . . 17
2.2 Tests at the 100 TeV pp Collider . . . 20

3 Naturalness of the Electroweak Scale 28
3.1 On the Mass of the Higgs Boson . . . 28
3.2 Natural Theories and the Tests at the 100 TeV pp Collider . . . 32

4 Dark Matter 42
4.1 WIMP Dark Matter . . . 42
4.2 WIMP Dark Matter at the 100 TeV pp Collider . . . 47
4.2.1 Pure Wino . . . 49
4.2.2 Pure Higgsino . . . 50
4.2.3 Mixed dark matter . . . 51
4.2.4 Electroweak cascades . . . 52
4.2.5 Co-annihilation with Bino dark matter . . . 53

5 Other New Physics Searches 55
5.1 New Color Resonances . . . 55
5.2 New Gauge Bosons and Vector Resonances . . . 57
5.3 Heavy Higgs Bosons in Doublet and Triplet Models . . . 57
5.4 Pair Production of Exotic Color States . . . 61
5.5 Pair Production of Heavy Leptons . . . 62

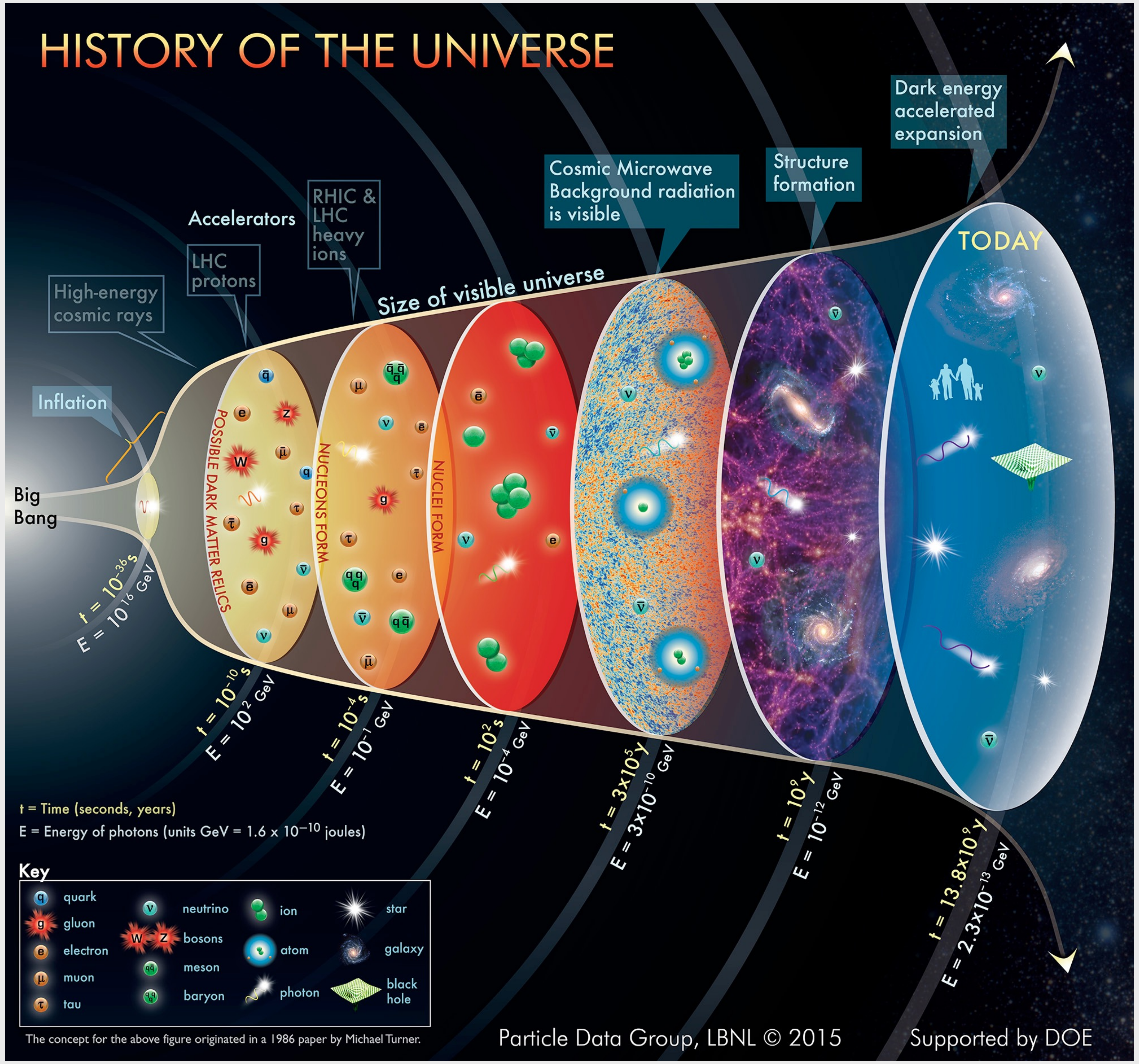
6 Benchmark Standard Model processes 63
6.1 Jets . . . 64
6.2 W/Z Production . . . 68
6.2.1 Multiple gauge boson production . . . 69
6.2.2 FSR effects of the gauge bosons and initial state partons 70
6.3 Heavy Quarks . . . 77
6.3.1 Inclusive bottom production . . . 77
6.3.2 Inclusive top production . . . 78

2

3 pillars of a very good physics program for a new machine

A closer look at these issues of the SM

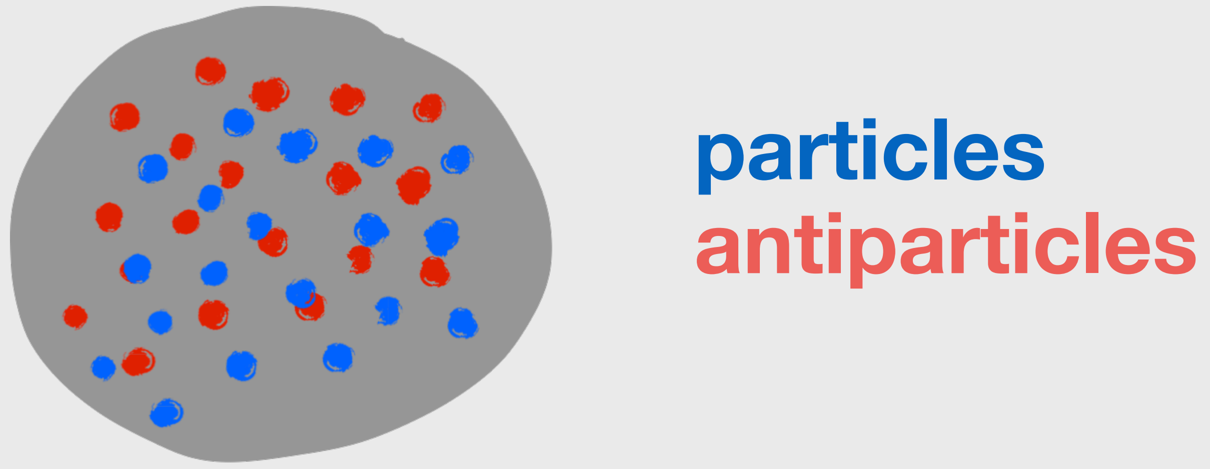
Open Questions on the "big picture" on fundamental physics circa 2020



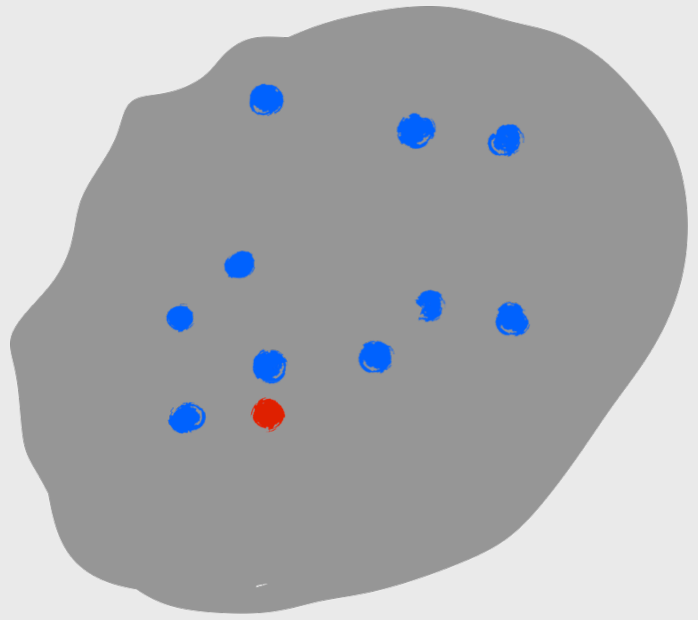
Nothing we have measured in high energy physics makes so much of a distinction between particles and anti-particles.

The observable Universe is made of matter, no antimatter

We need to go from this

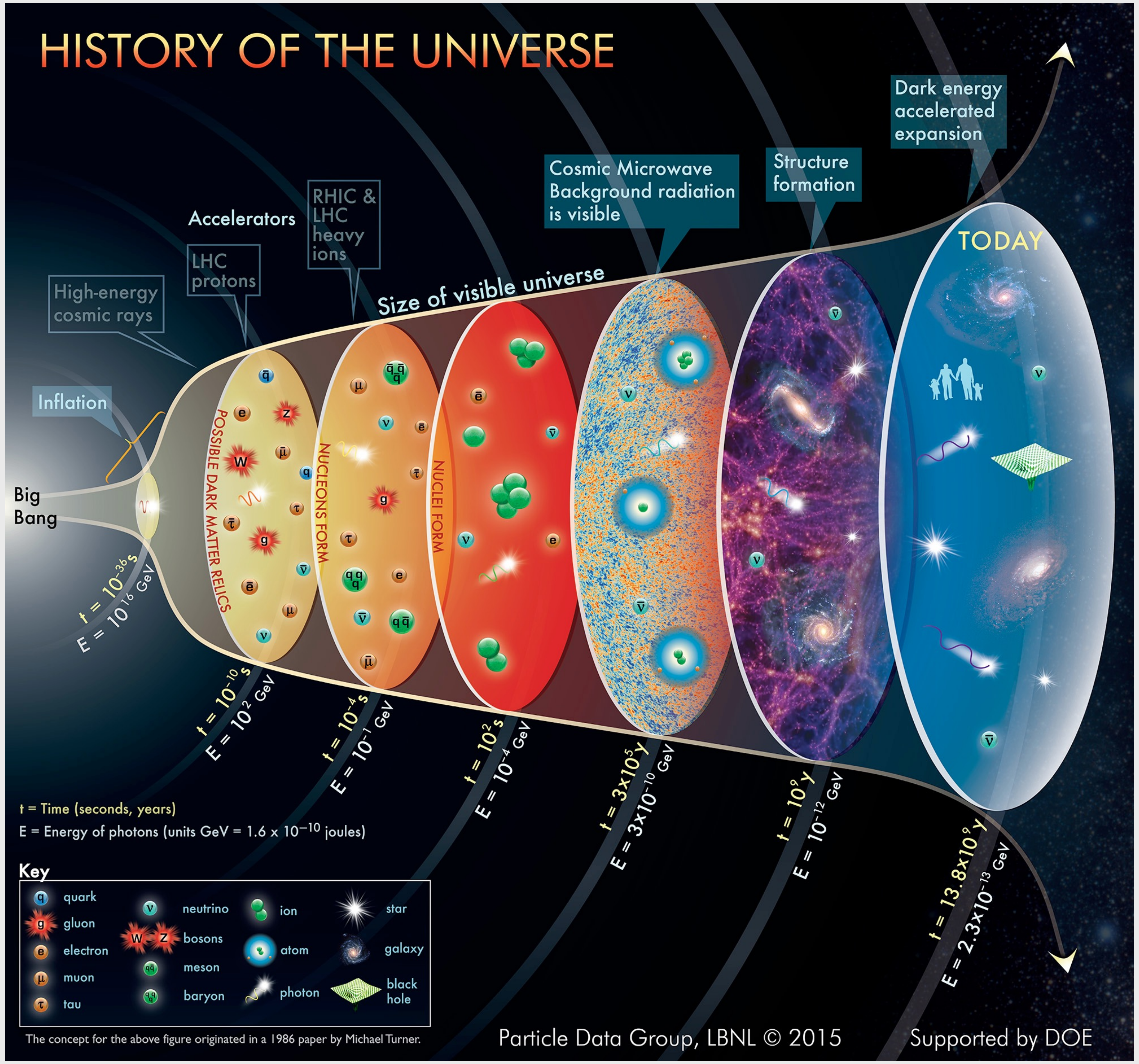


to this



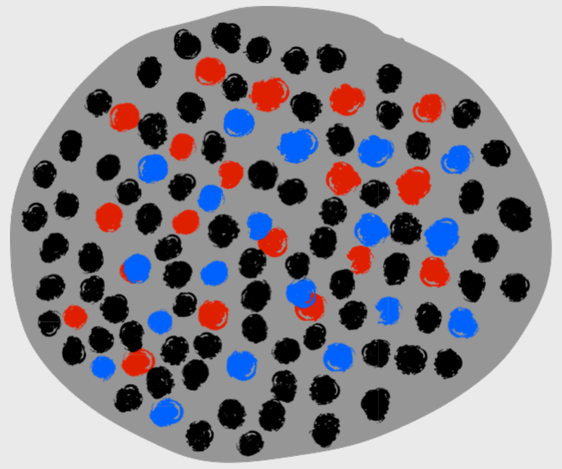
out-of-equilibrium processes are necessary

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



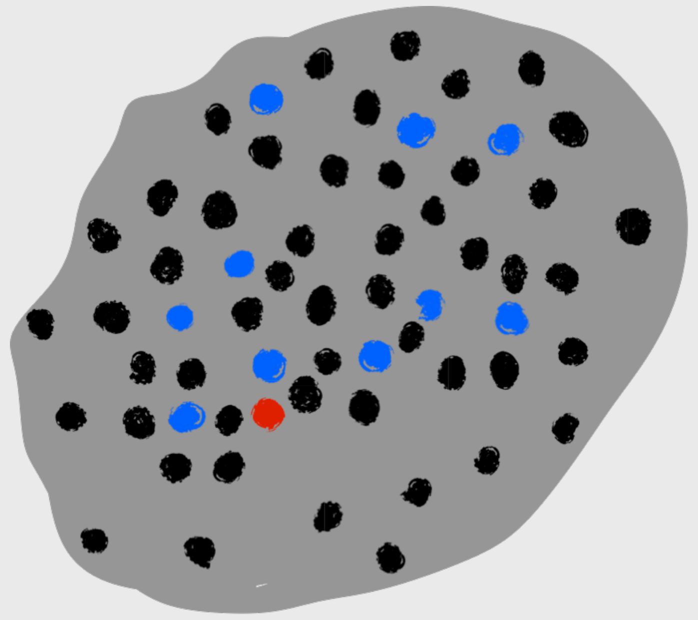
The observable Universe is made of matter, plus about 5 times as much dark matter

We need to go from this



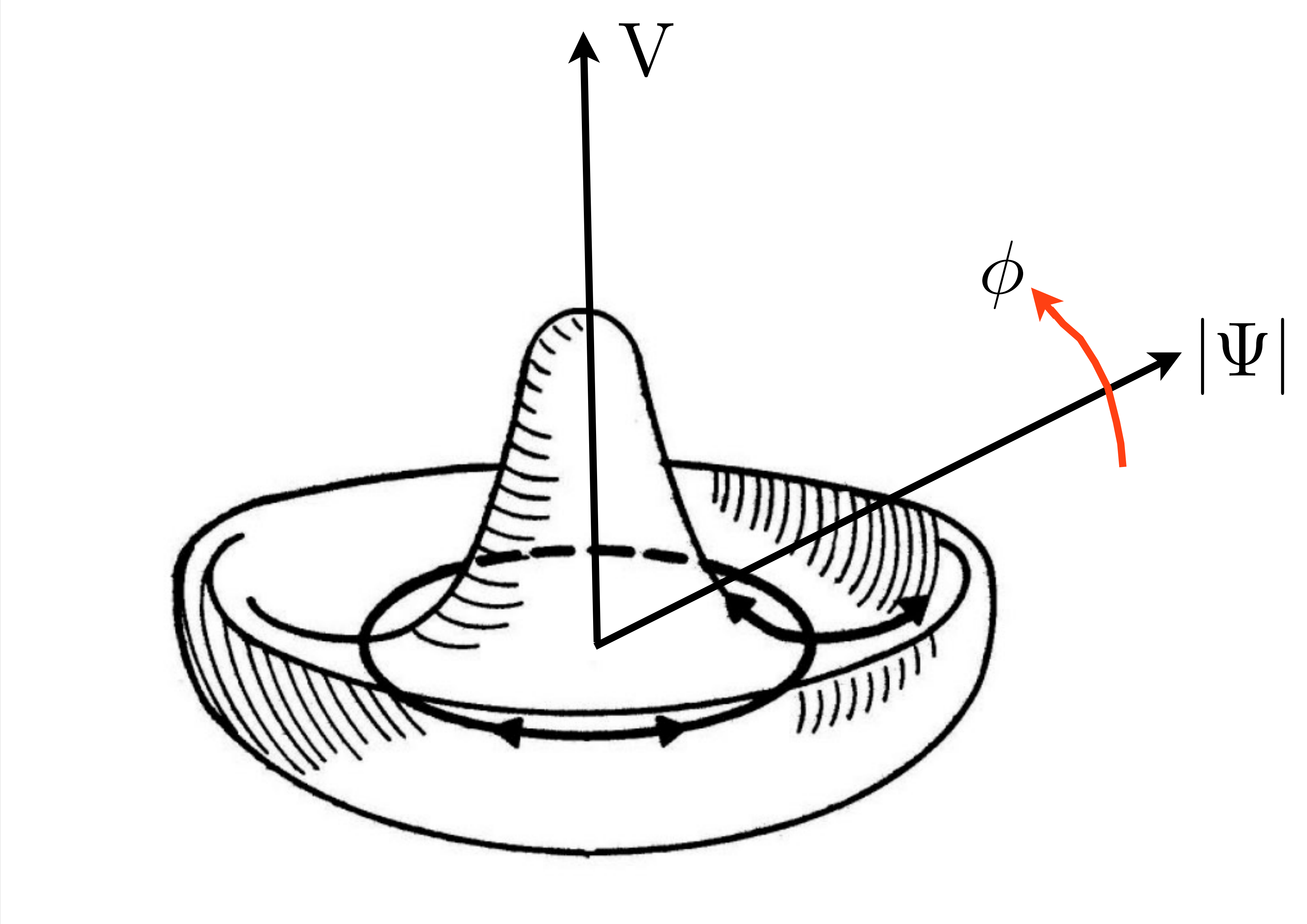
normal particles
dark matter
antiparticles

to this



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

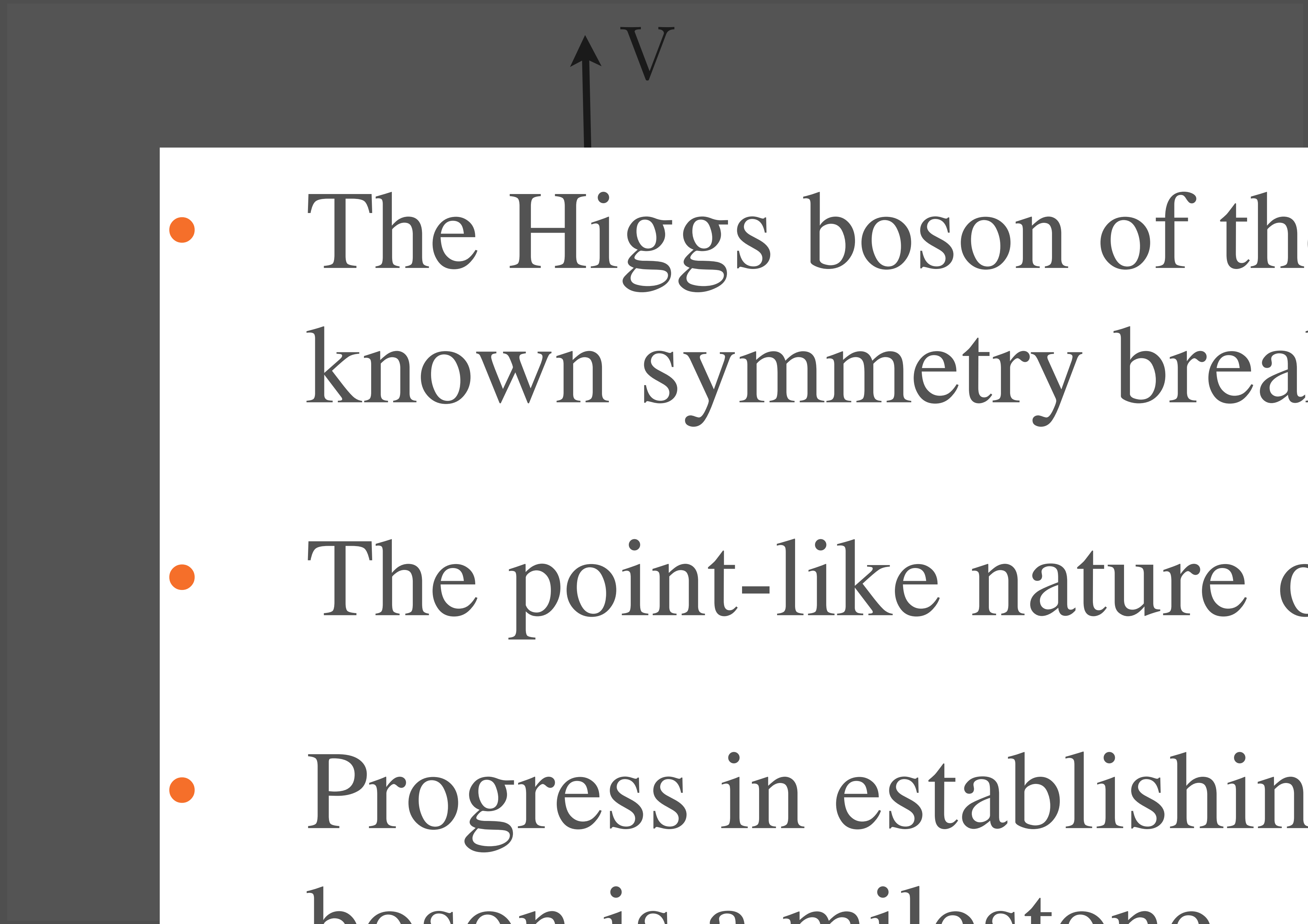
Open Questions on the "big picture" on fundamental physics circa 2020



A mexican hat is not enough to get a Higgs boson

$$S = -r\,\Psi^*\Psi + \frac{U}{2}(\Psi^*\Psi)^2 + (\tau_{GL}^{-1})\,\Psi^*\partial_t\Psi + iK_1\,\Psi^*\partial_t\Psi - K_2\,(\partial_t\Psi^*)(\partial_t\Psi) + \xi^{-2}\,(\nabla\Psi^*)(\nabla\Psi)$$

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



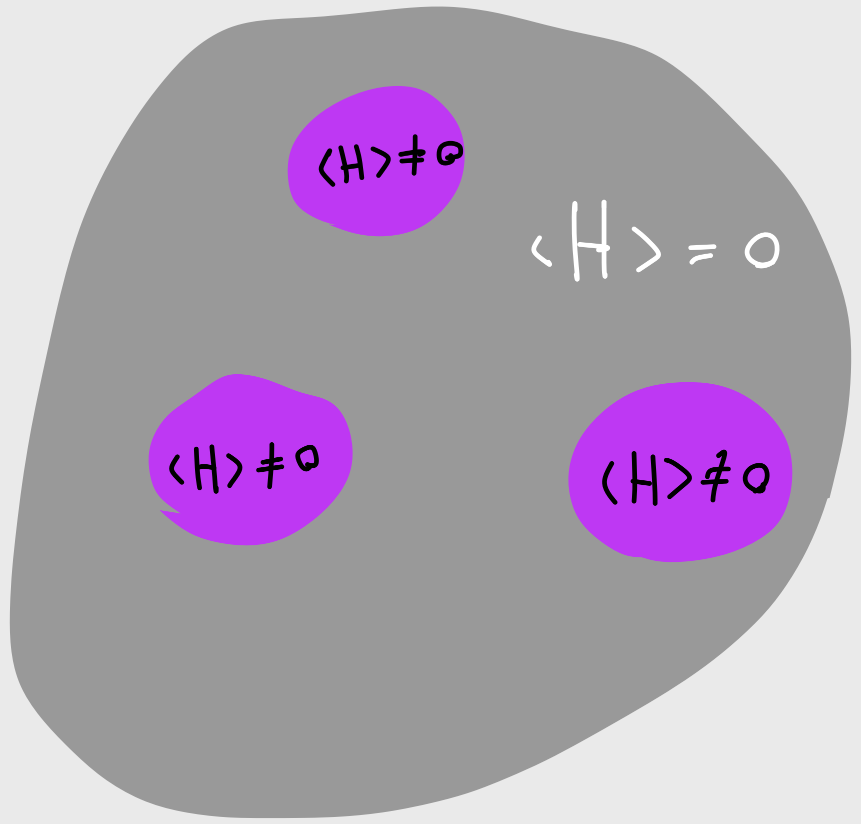
A mexican hat is not enough to get a Higgs boson

(∇Ψ)

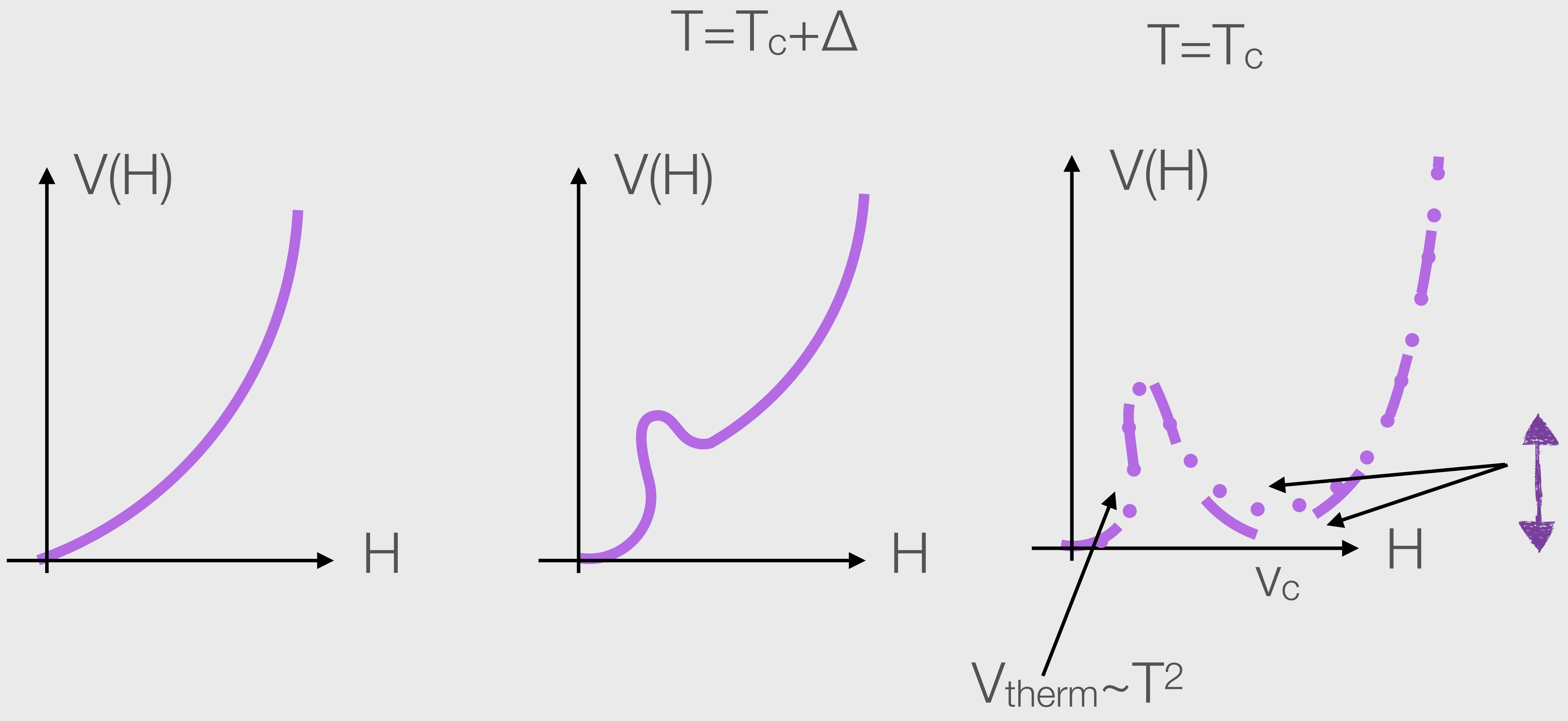
- The Higgs boson of the SM is nothing like any other known symmetry breaking scalar*
- The point-like nature of the Higgs boson is unique
- Progress in establishing the SM nature of the Higgs boson is a milestone

Electroweak Phase-Transition

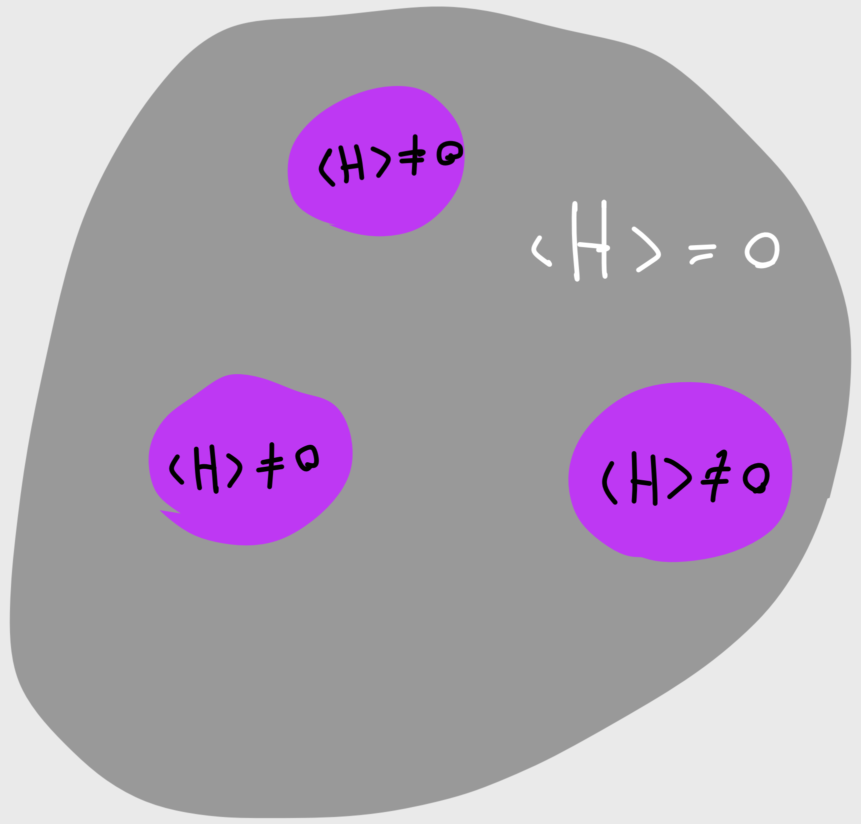
Electroweak phase transition



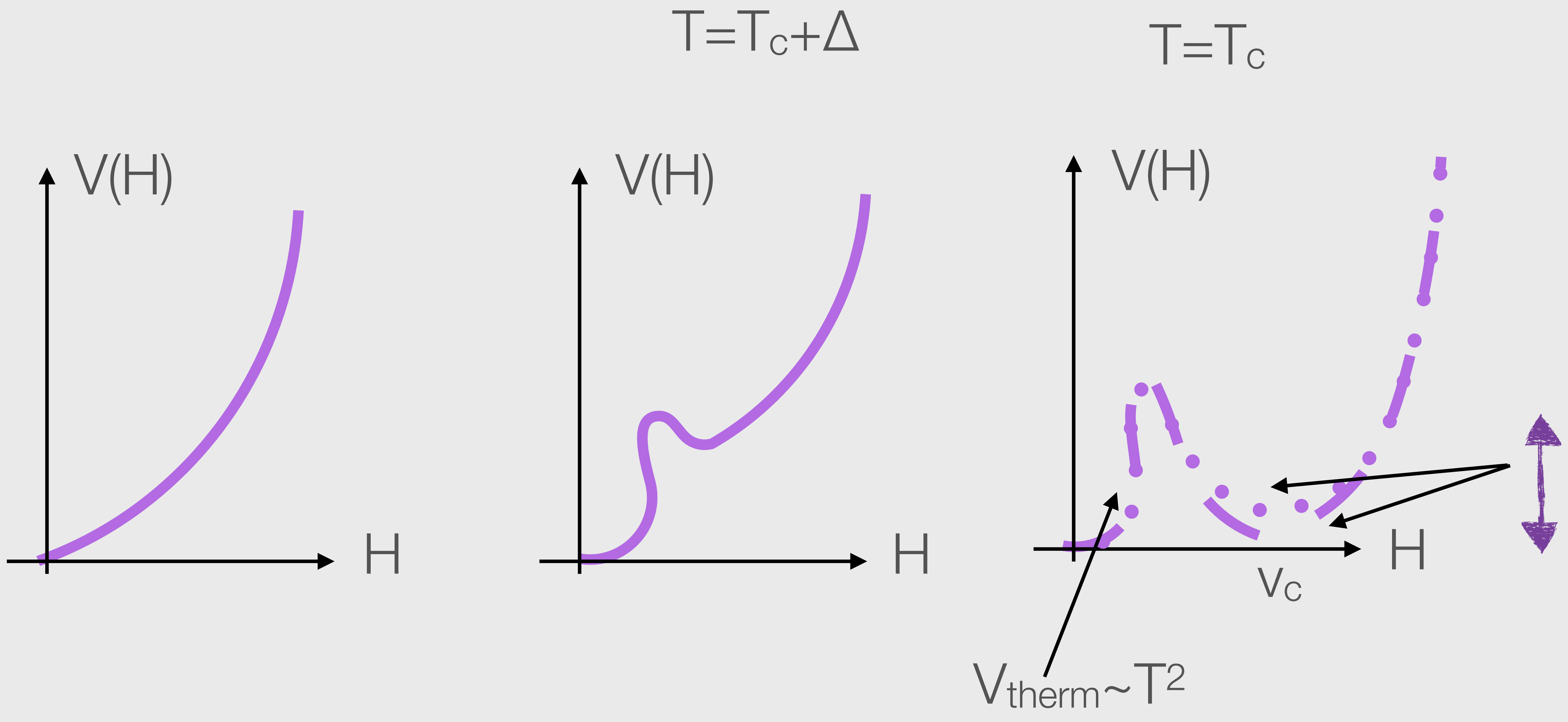
- Modifications of the Higgs potential ⇒ Out of Equilibrium transition from one vacuum to a new energetically favorable one



Electroweak phase transition



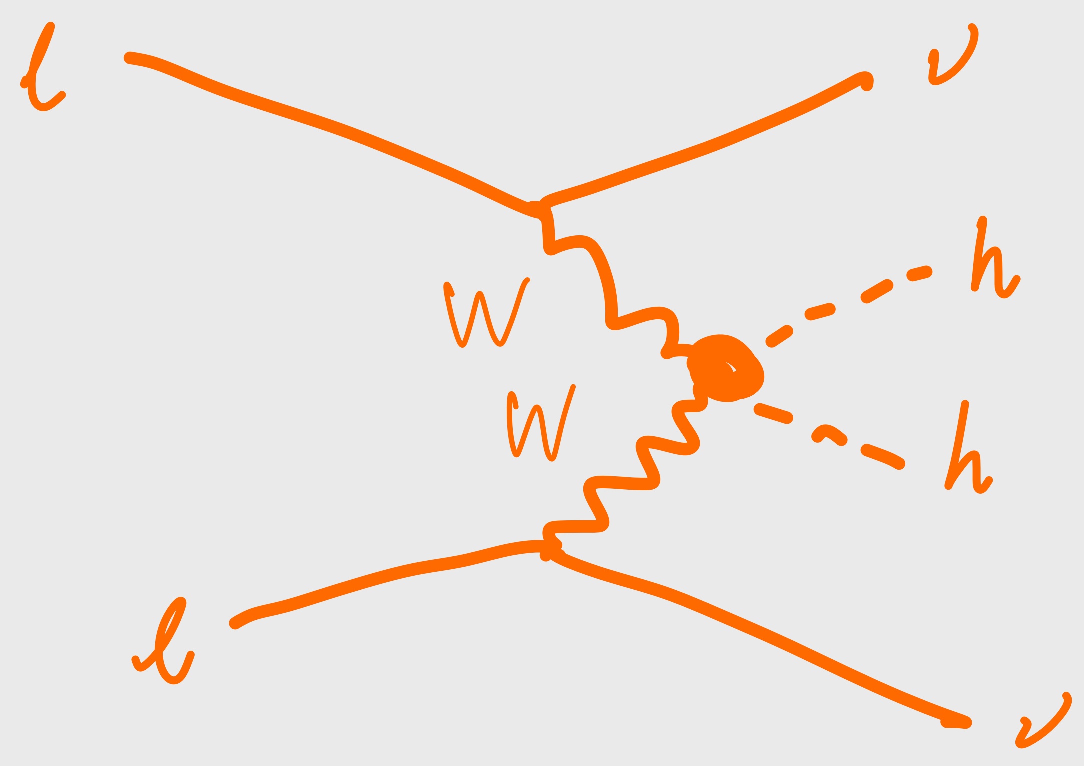
- Modifications of the Higgs potential ⇒ Out of Equilibrium transition from one vacuum to a new energetically favorable one



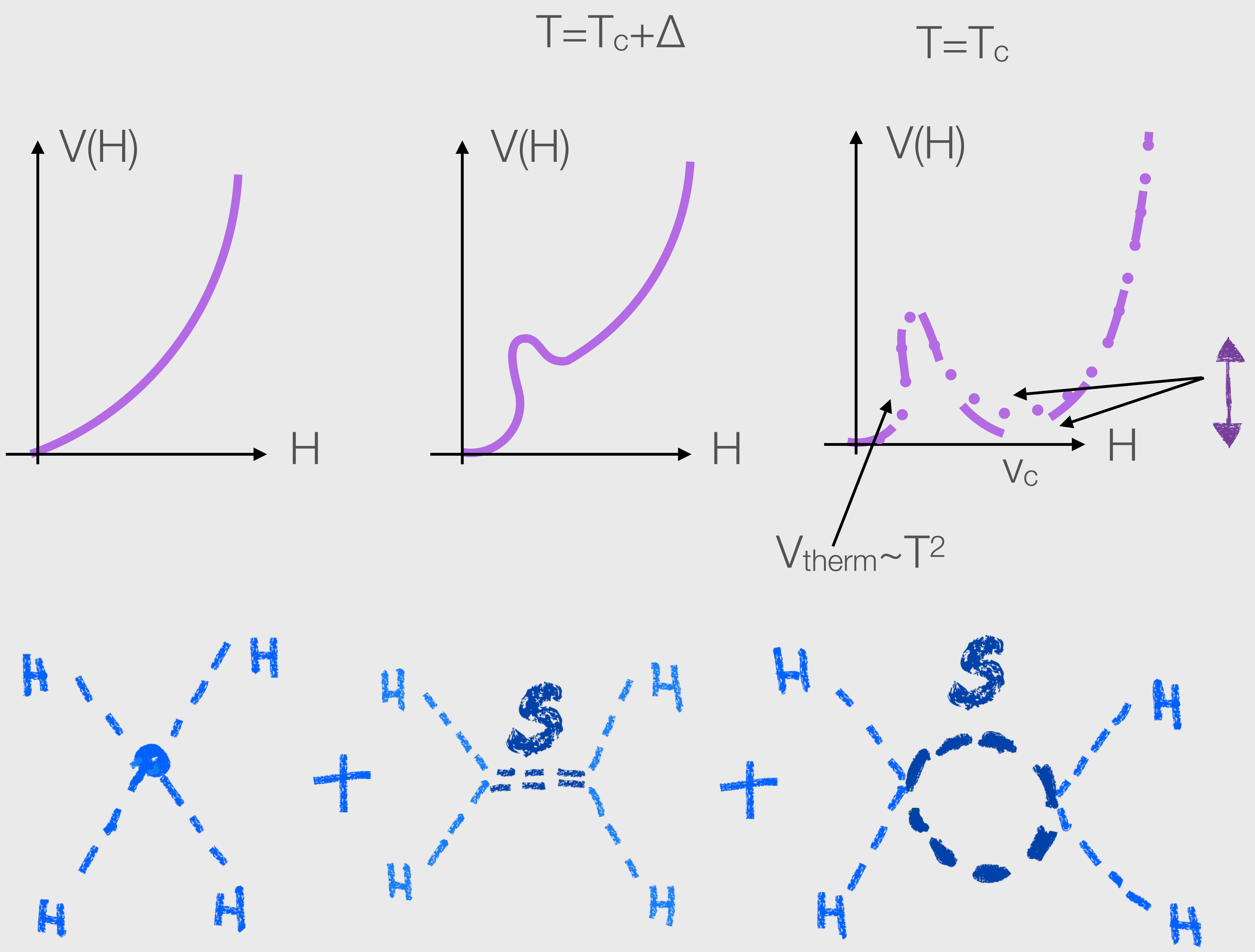
$\mu^+\mu^- \to hh$

W BOSON COLLIDER

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



Electroweak phase transition



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

EW phase transition

DIRECT & INDIRECT | INTERPLAY

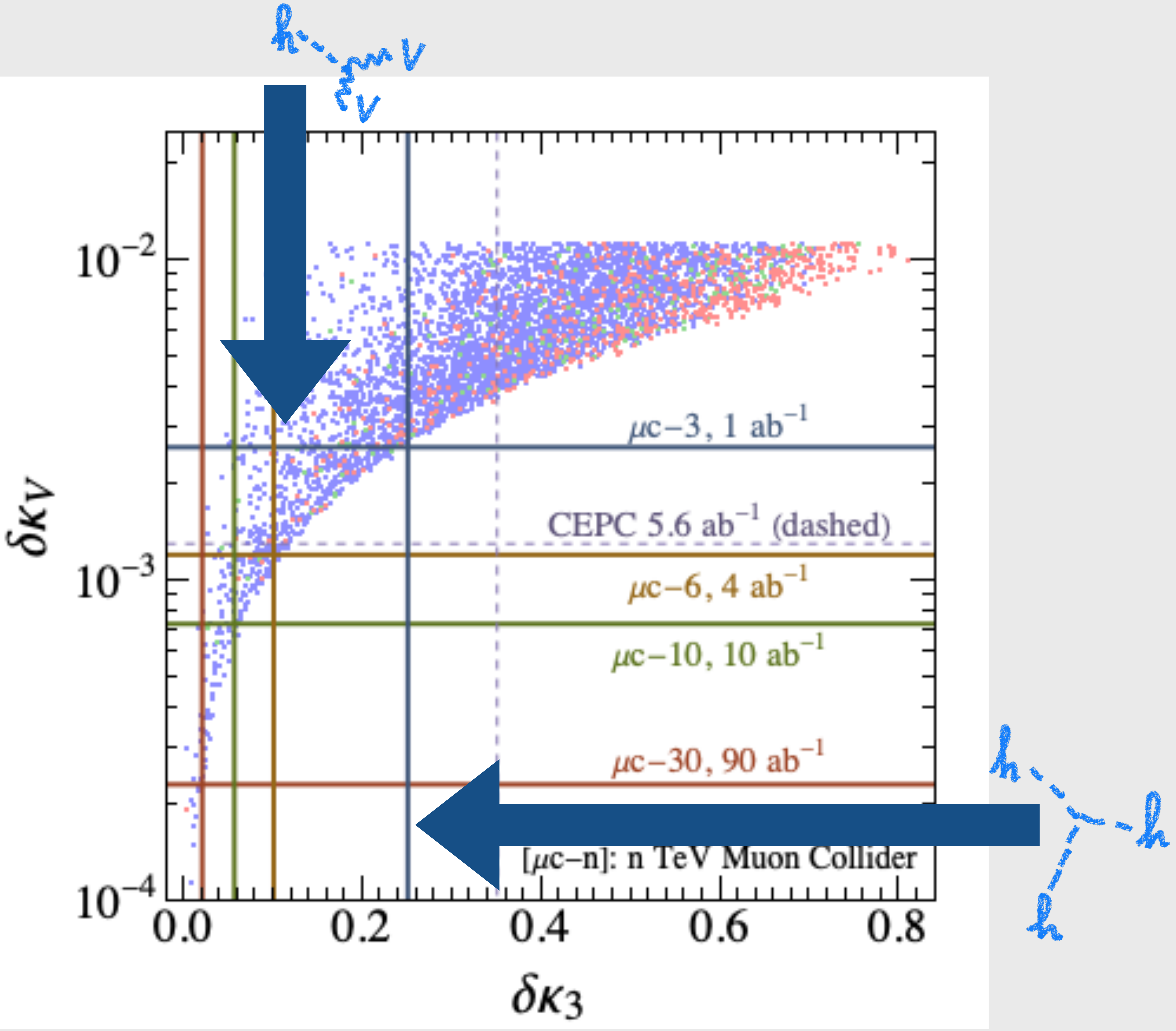
$$V(\Phi,S) = -\mu^2\left(\Phi^\dagger\Phi\right) + \lambda\left(\Phi^\dagger\Phi\right)^2 + \frac{a_1}{2}\left(\Phi^\dagger\Phi\right)S + \frac{a_2}{2}\left(\Phi^\dagger\Phi\right)S^2 + b_1 S + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4.$$

independent parameters

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

strong First Order EW phase transition on all points

Gravity Wave SNR



EW phase transition

DIRECT & INDIRECT | INTERPLAY

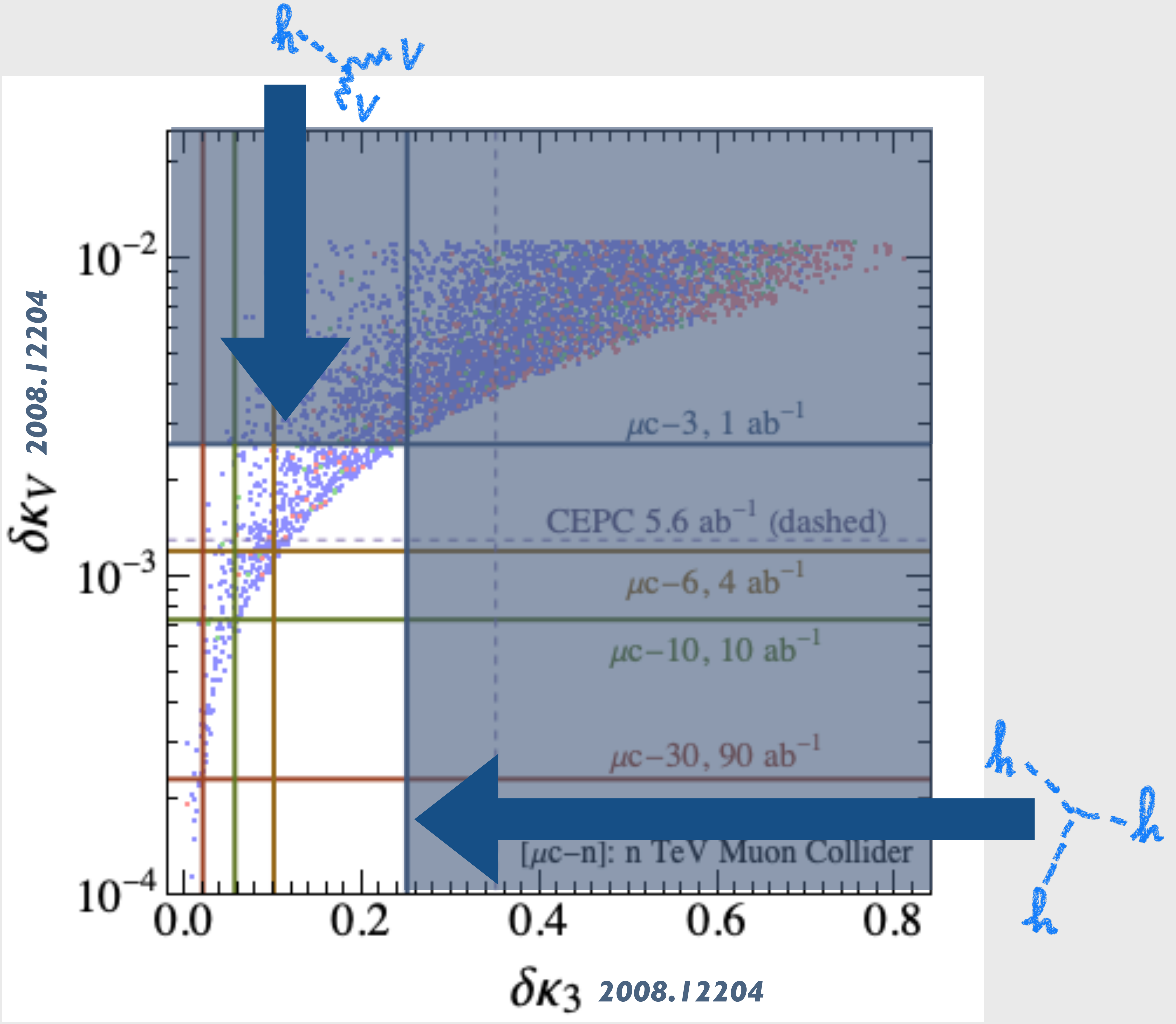
strong First Order EW phase transition on all points

Gravity Wave SNR

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

independent parameters

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

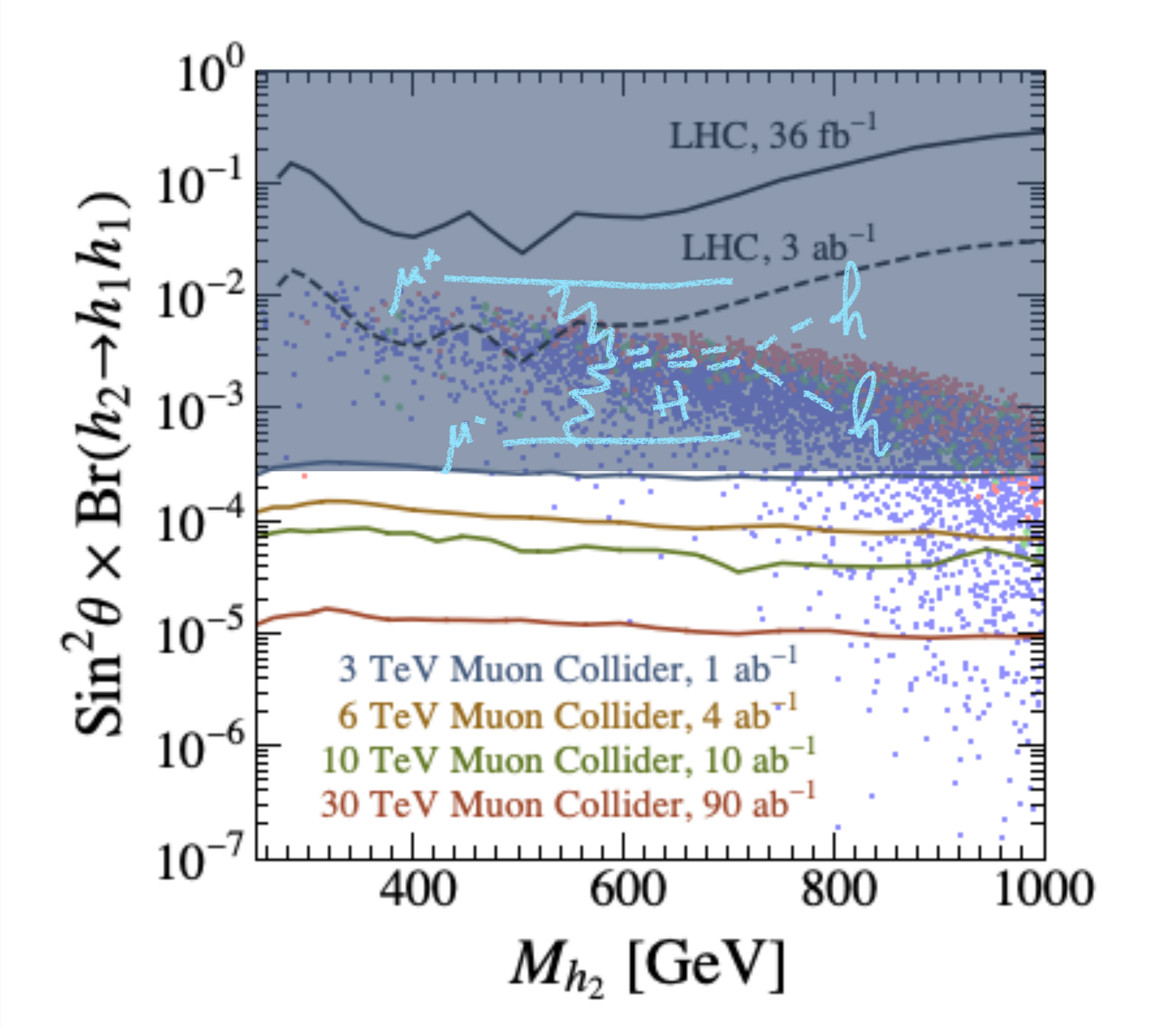


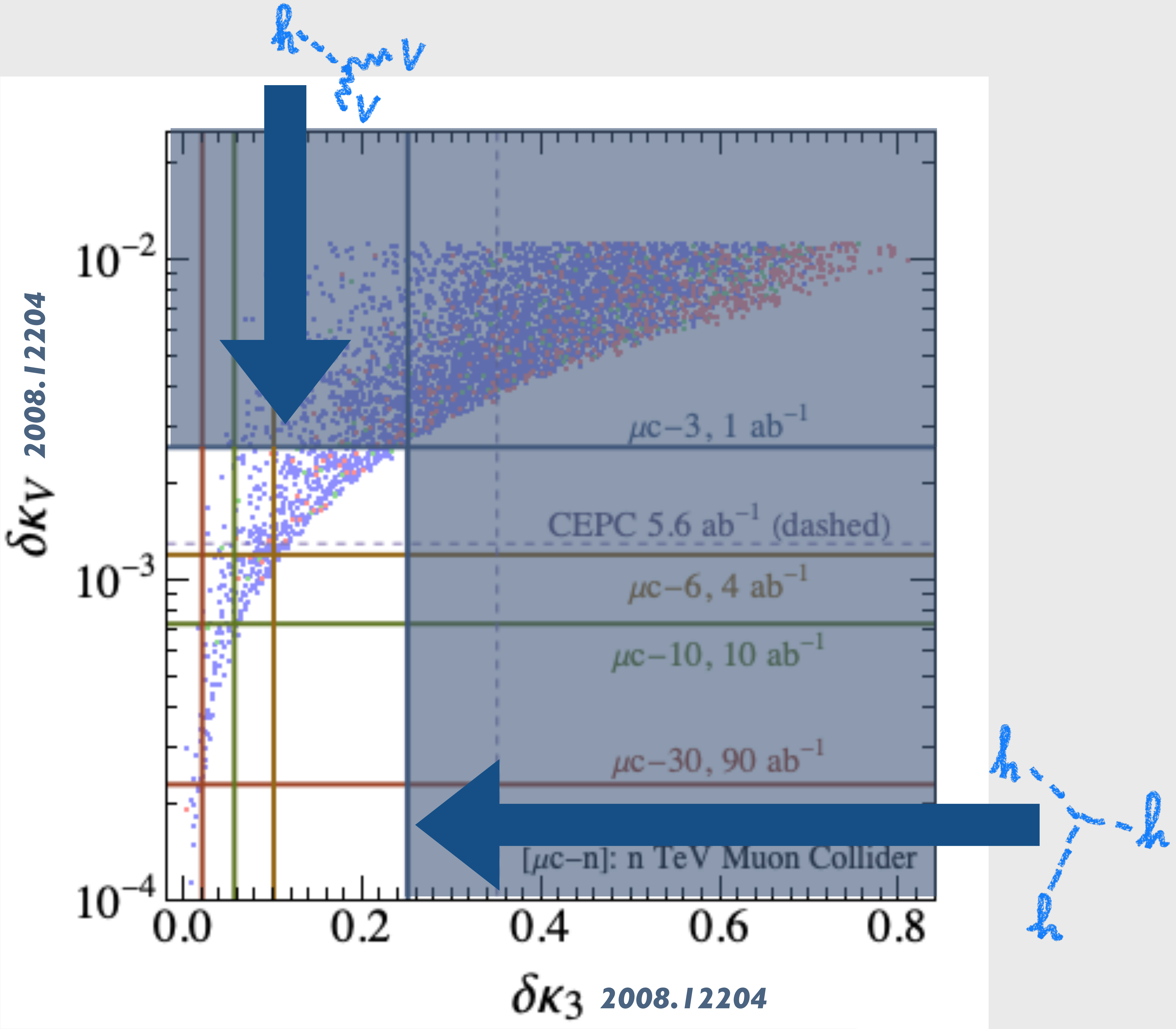
EW phase transition

DIRECT & INDIRECT | INTERPLAY

strong First Order EW phase transition on all points

Gravity Wave SNR





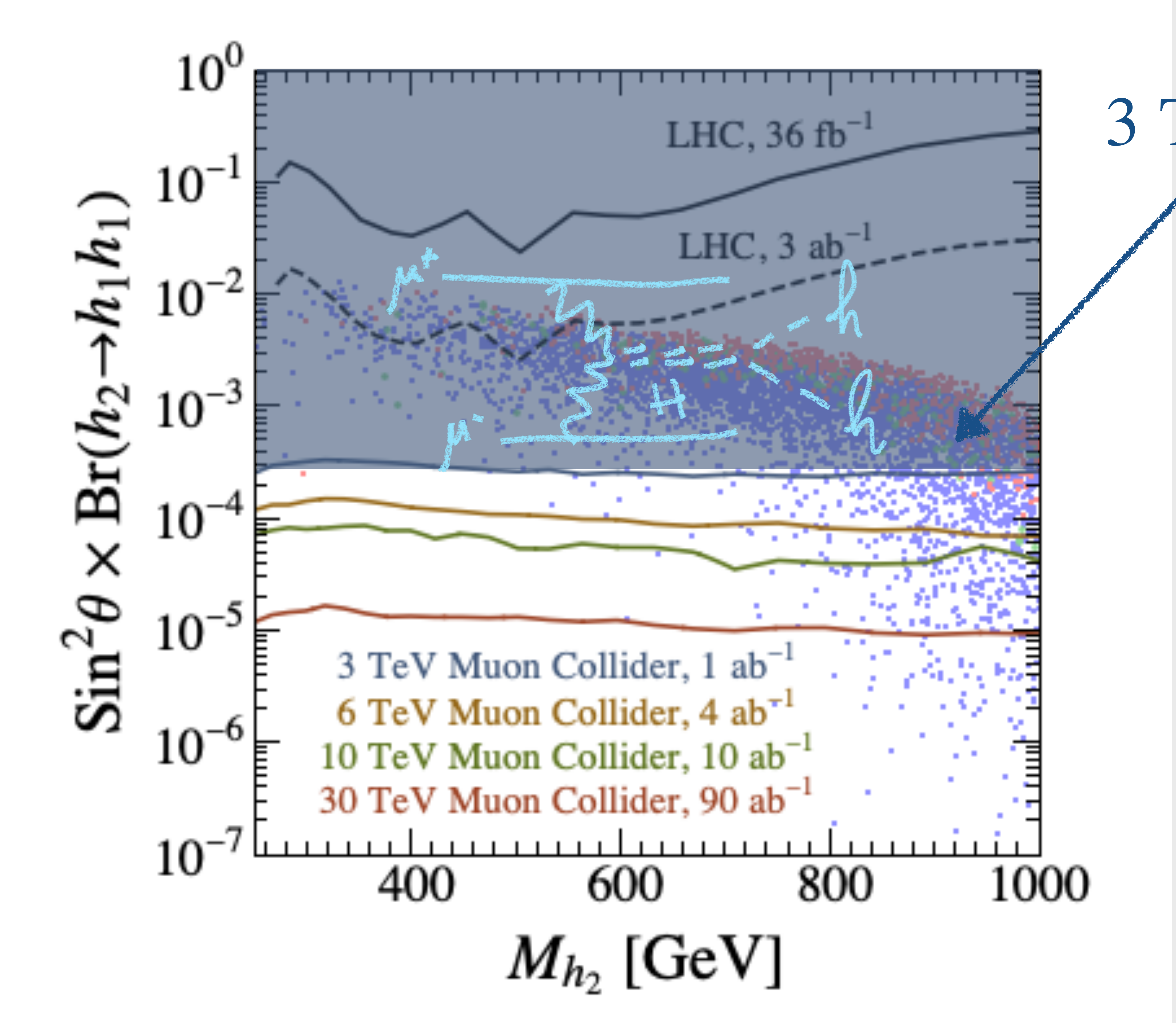
EW phase transition

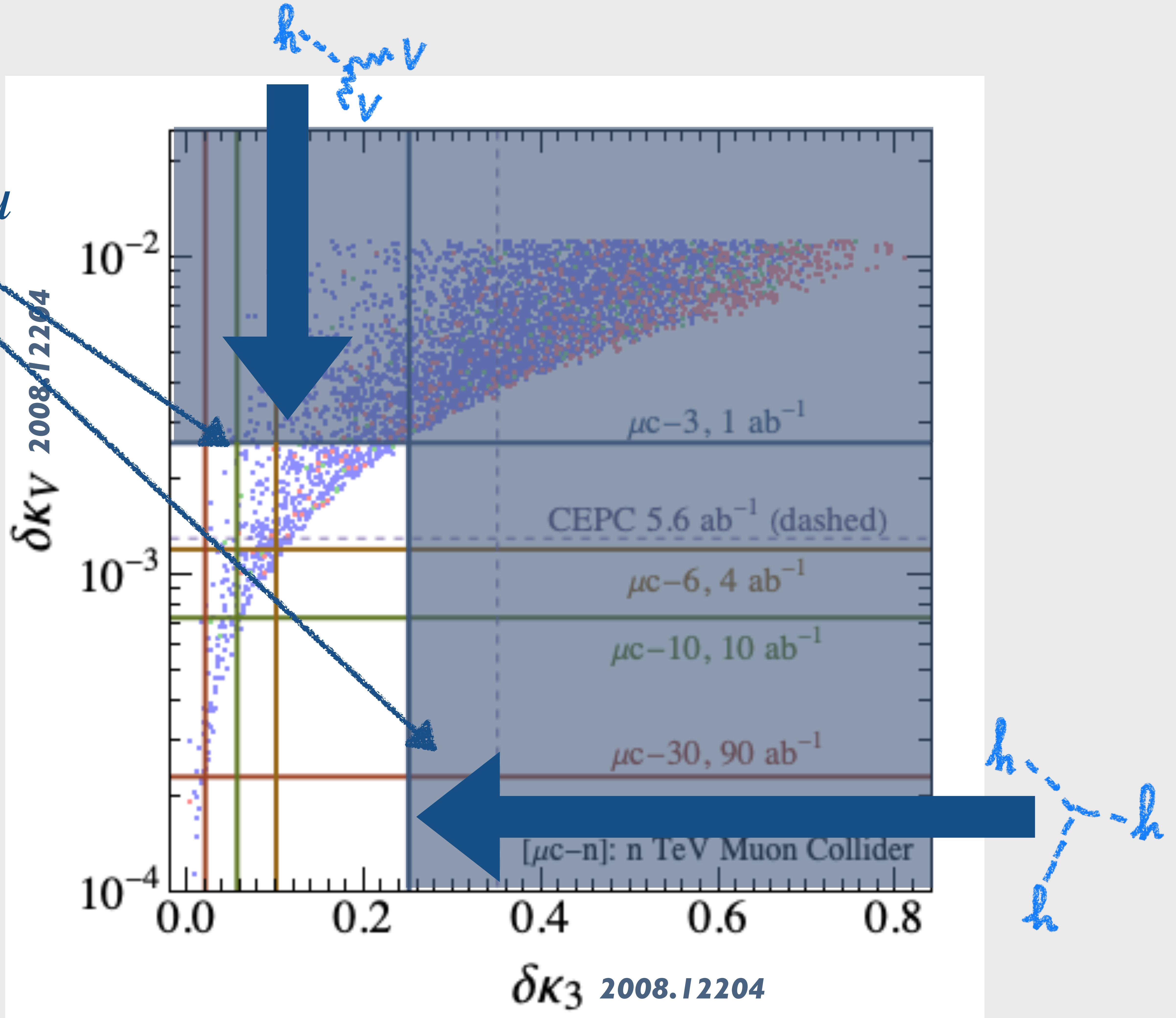
DIRECT & INDIRECT | INTERPLAY

strong First Order EW phase transition on all points

Gravity Wave SNR

3 TeV $\mu\mu$





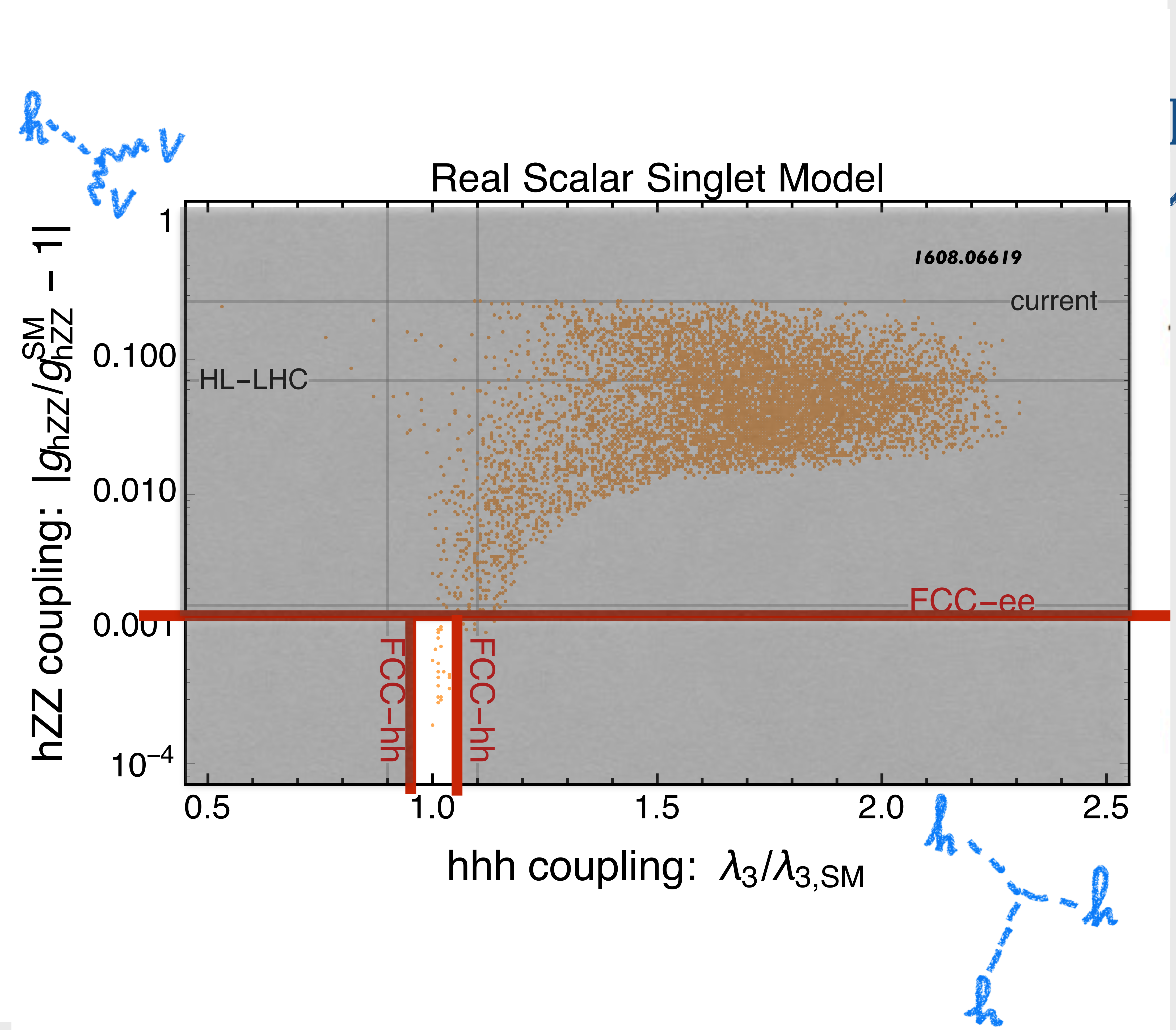
parameters space of 1st order phase transition accessible by **several measurements available at the 3 TeV $\mu\mu$ collider**

EW phase transition

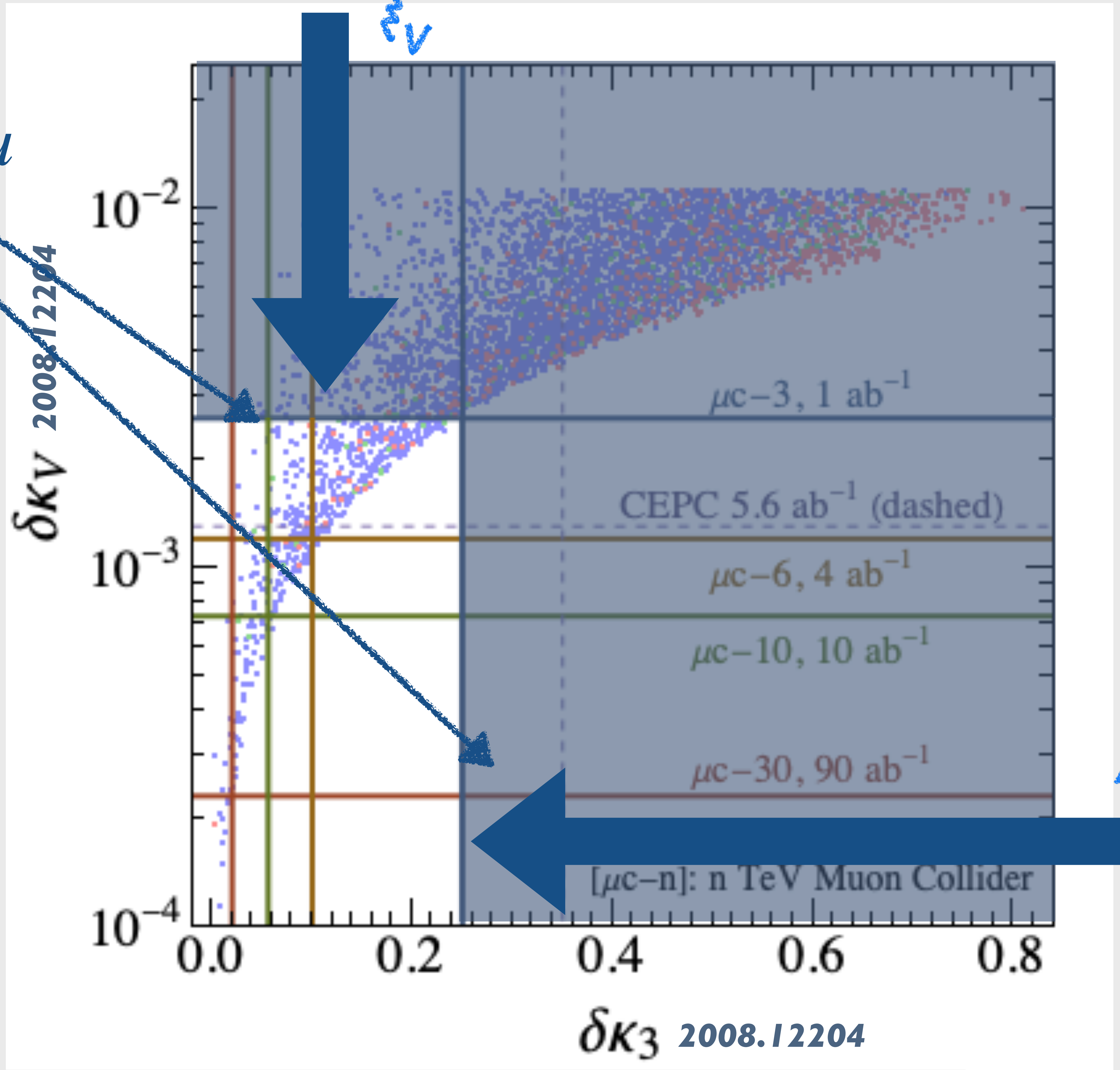
DIRECT & INDIRECT | INTERPLAY

strong First Order EW phase transition on all points

Gravity Wave SNR



3 TeV $\mu\mu$



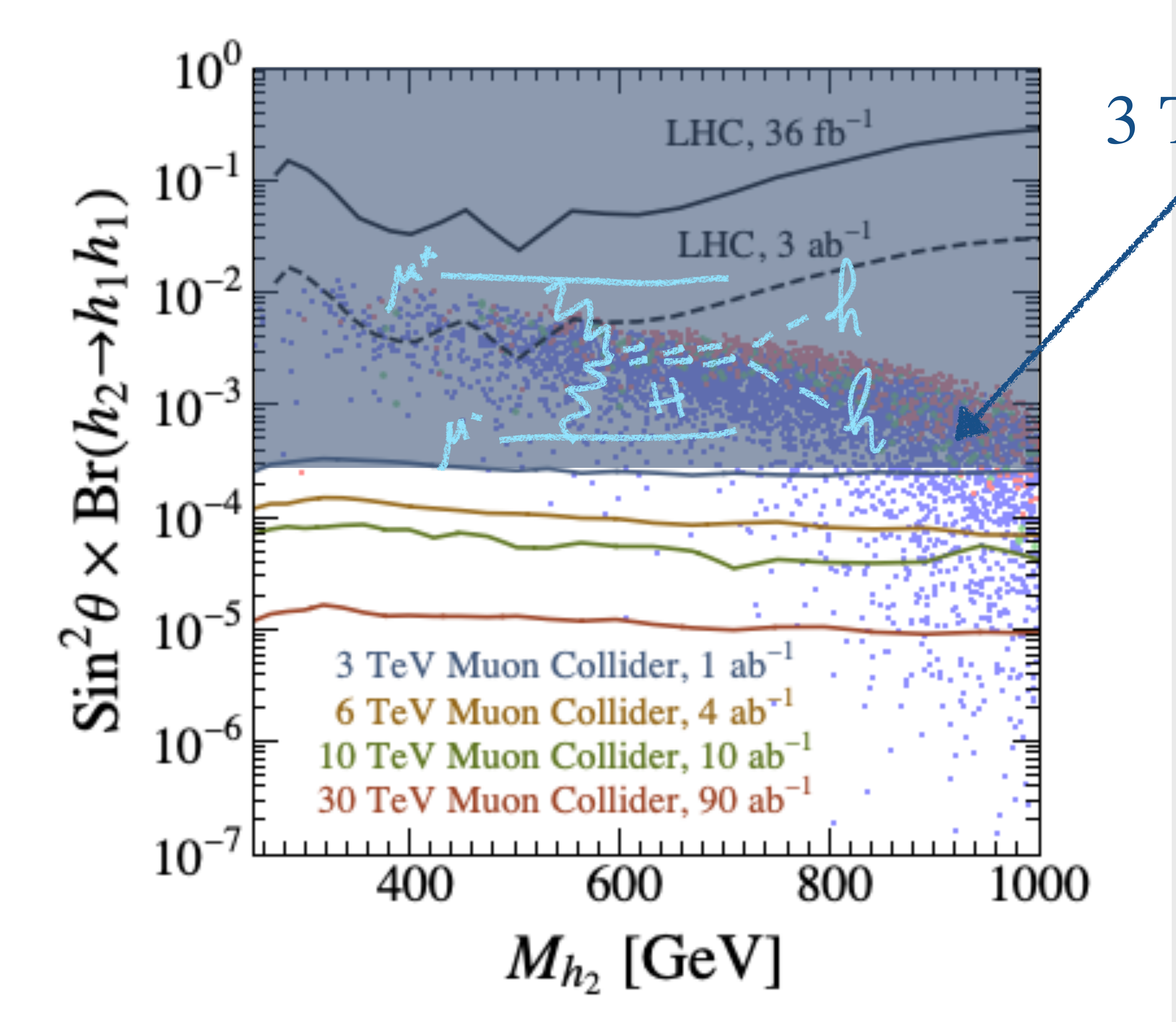
parameters space of 1st order phase transition accessible by **several measurements available at the 3 TeV $\mu\mu$ collider**

EW phase transition

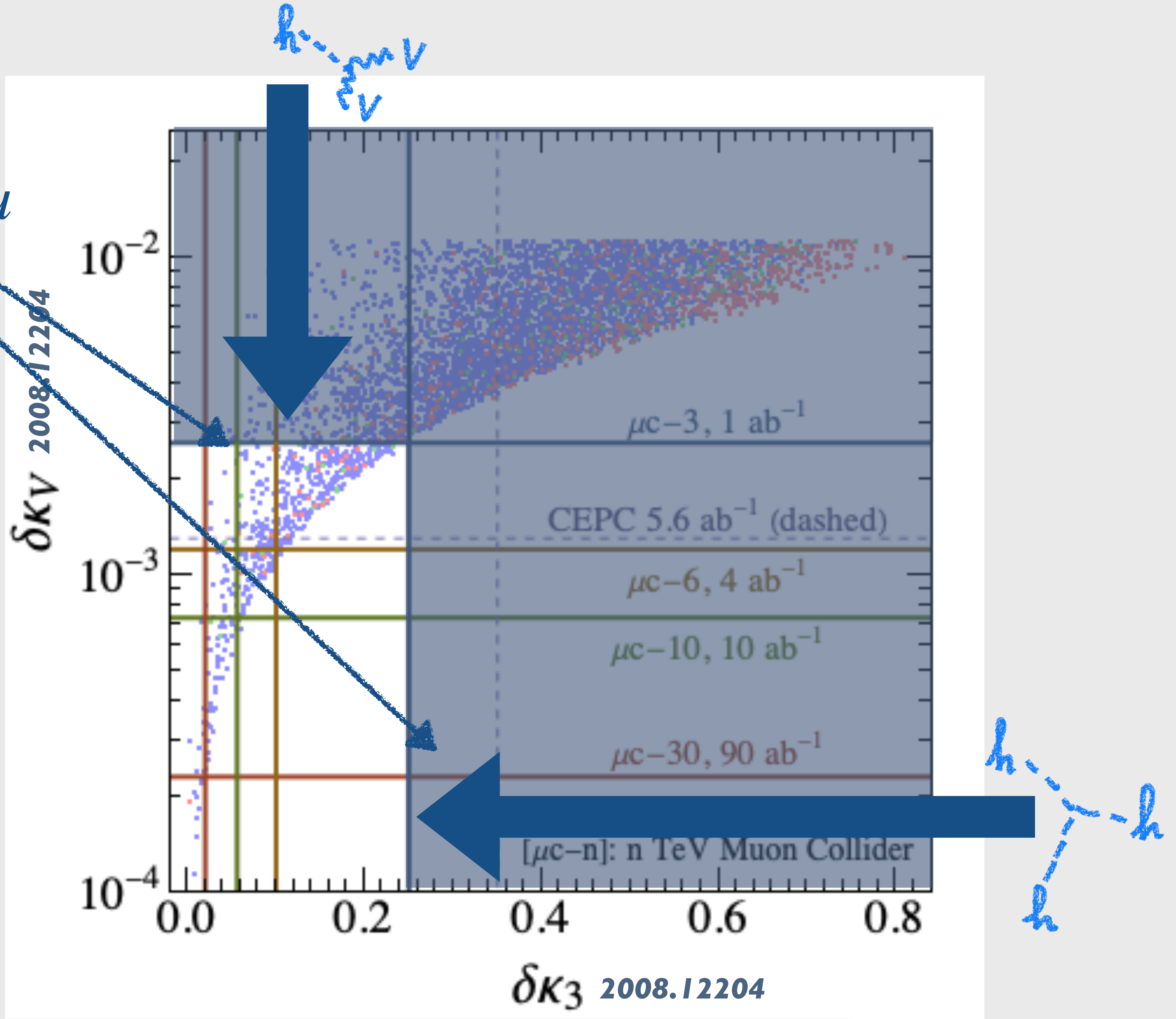
DIRECT & INDIRECT | INTERPLAY

strong First Order EW phase transition on all points

Gravity Wave SNR



3 TeV $\mu\mu$



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

Mixed Singlet for EW phase transition

EW PHASE TRANSITION | IS IT FIRST ORDER?

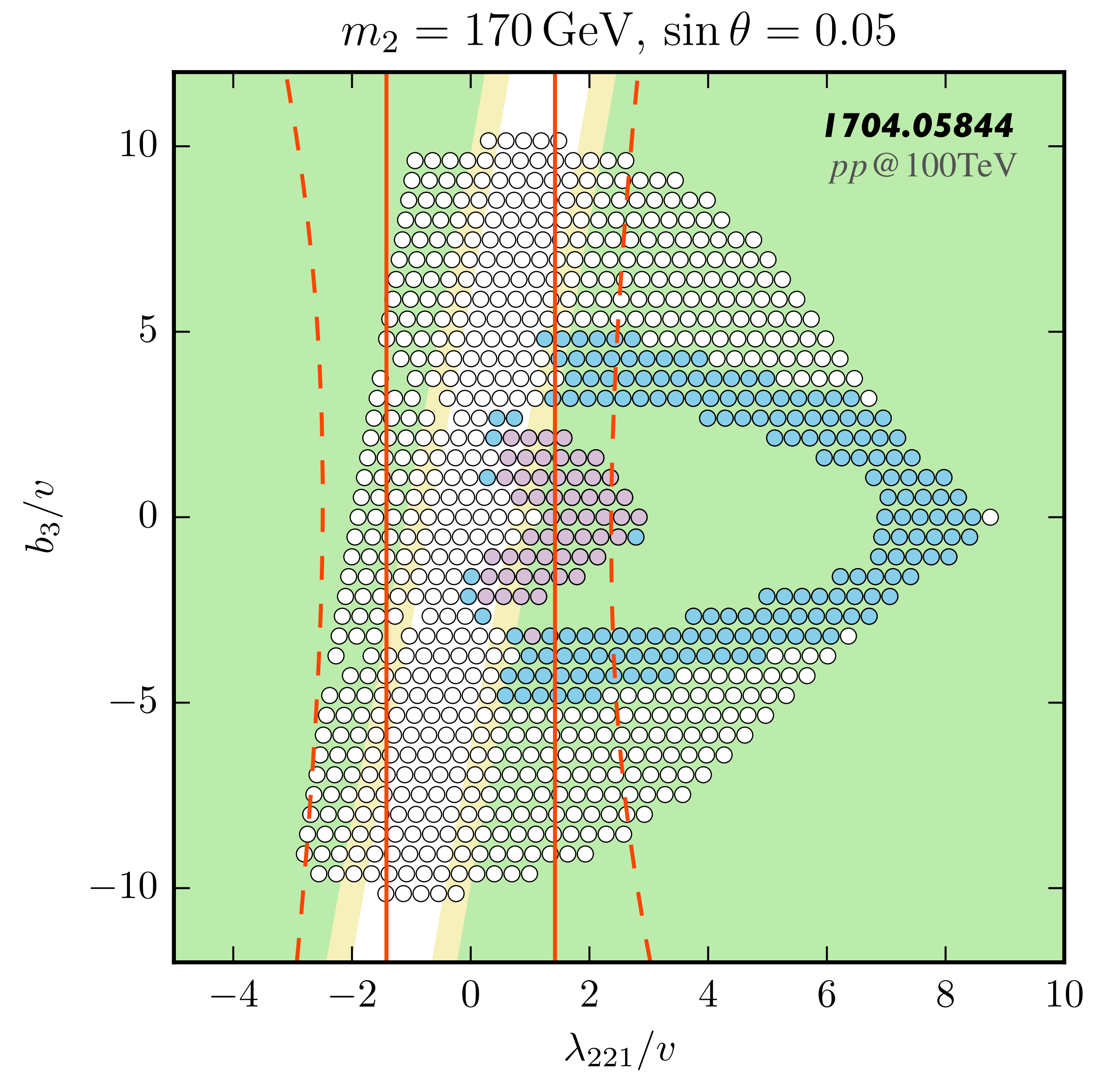
$$V(\Phi,S) = -\mu^2\left(\Phi^\dagger\Phi\right) + \lambda\left(\Phi^\dagger\Phi\right)^2 + \frac{a_1}{2}\left(\Phi^\dagger\Phi\right)S + \frac{a_2}{2}\left(\Phi^\dagger\Phi\right)S^2 + b_1 S + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4.$$

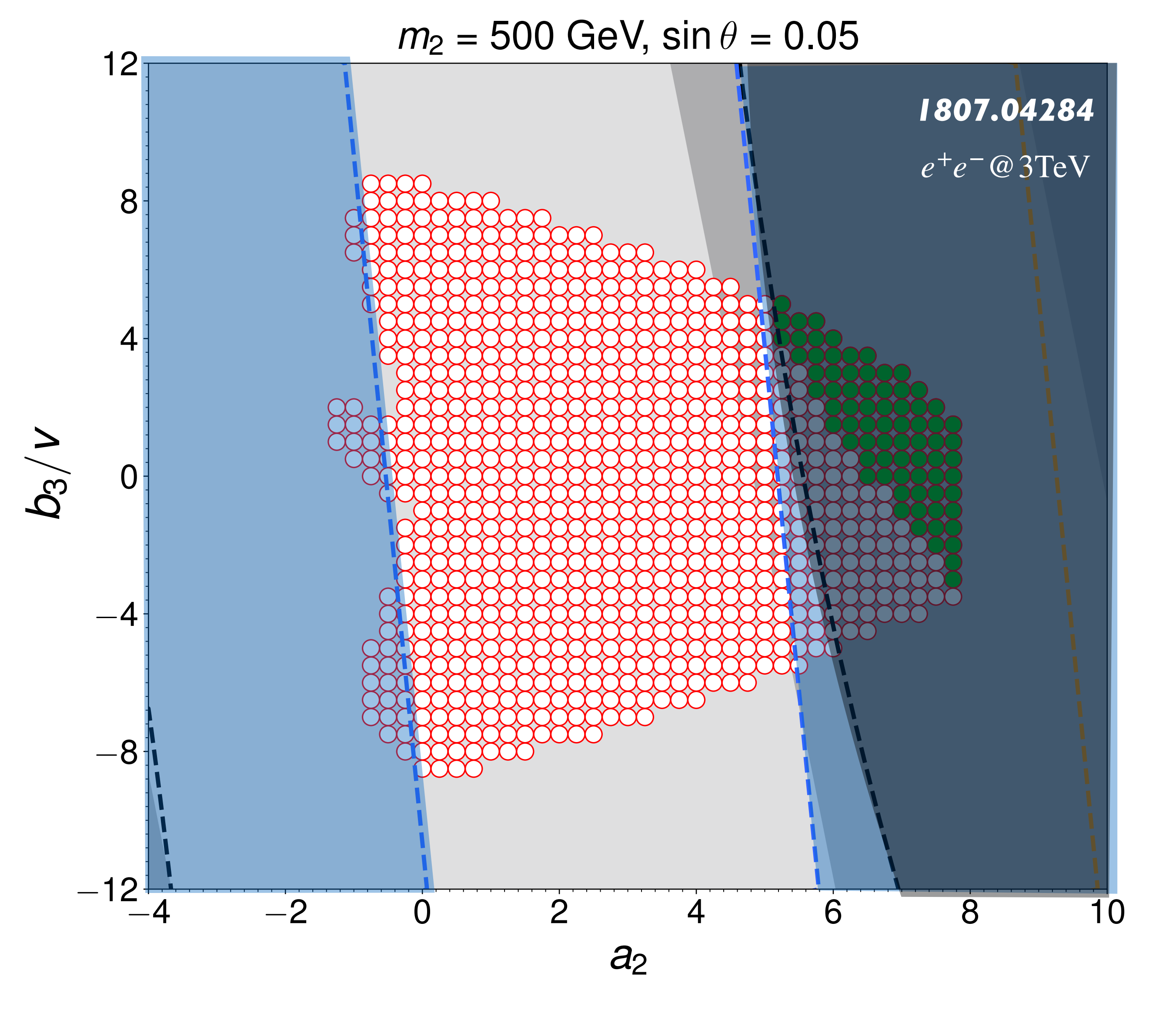
independent parameters

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

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

- "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



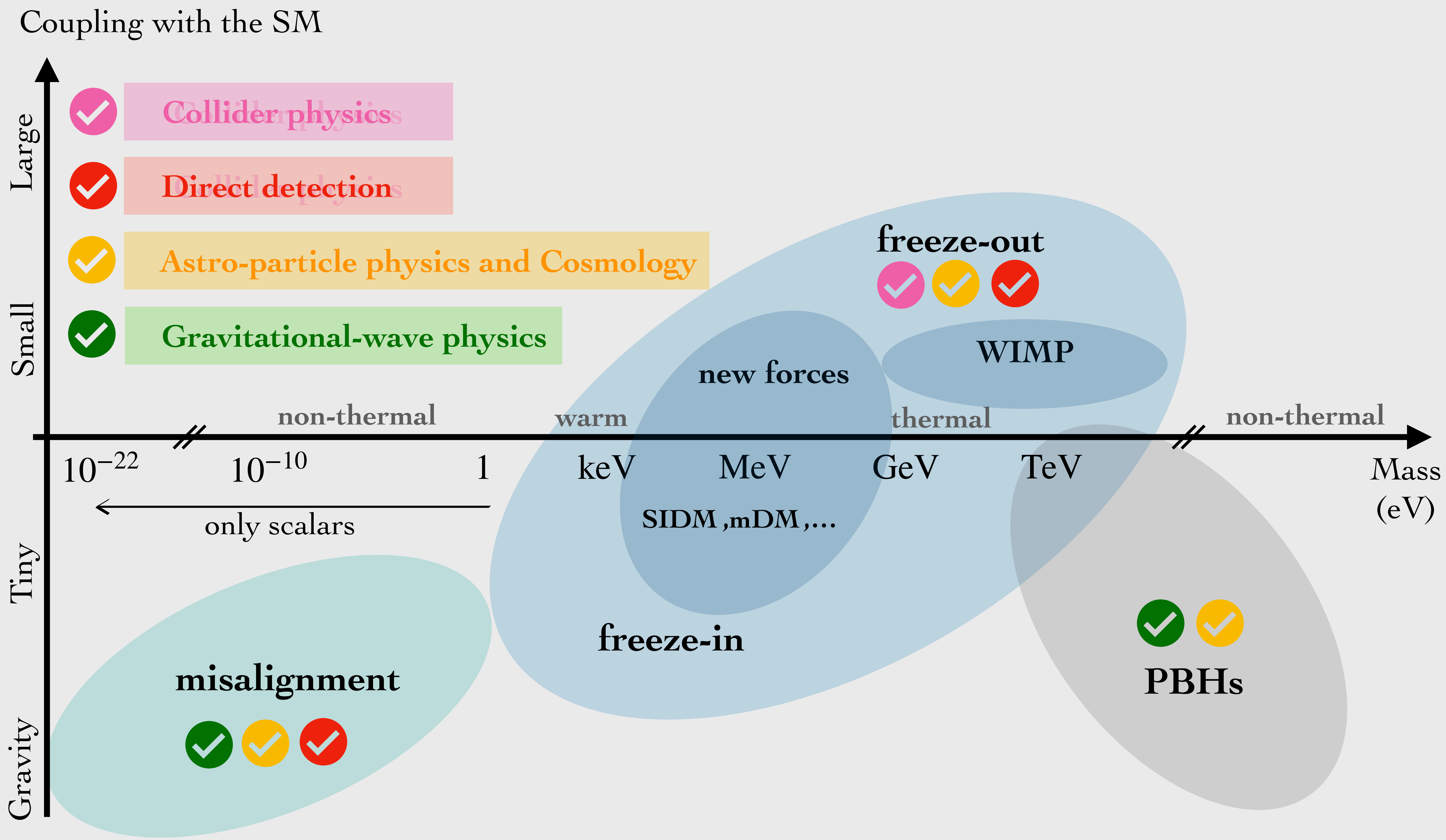


parameters space of 1st order phase transition accessible by several probes

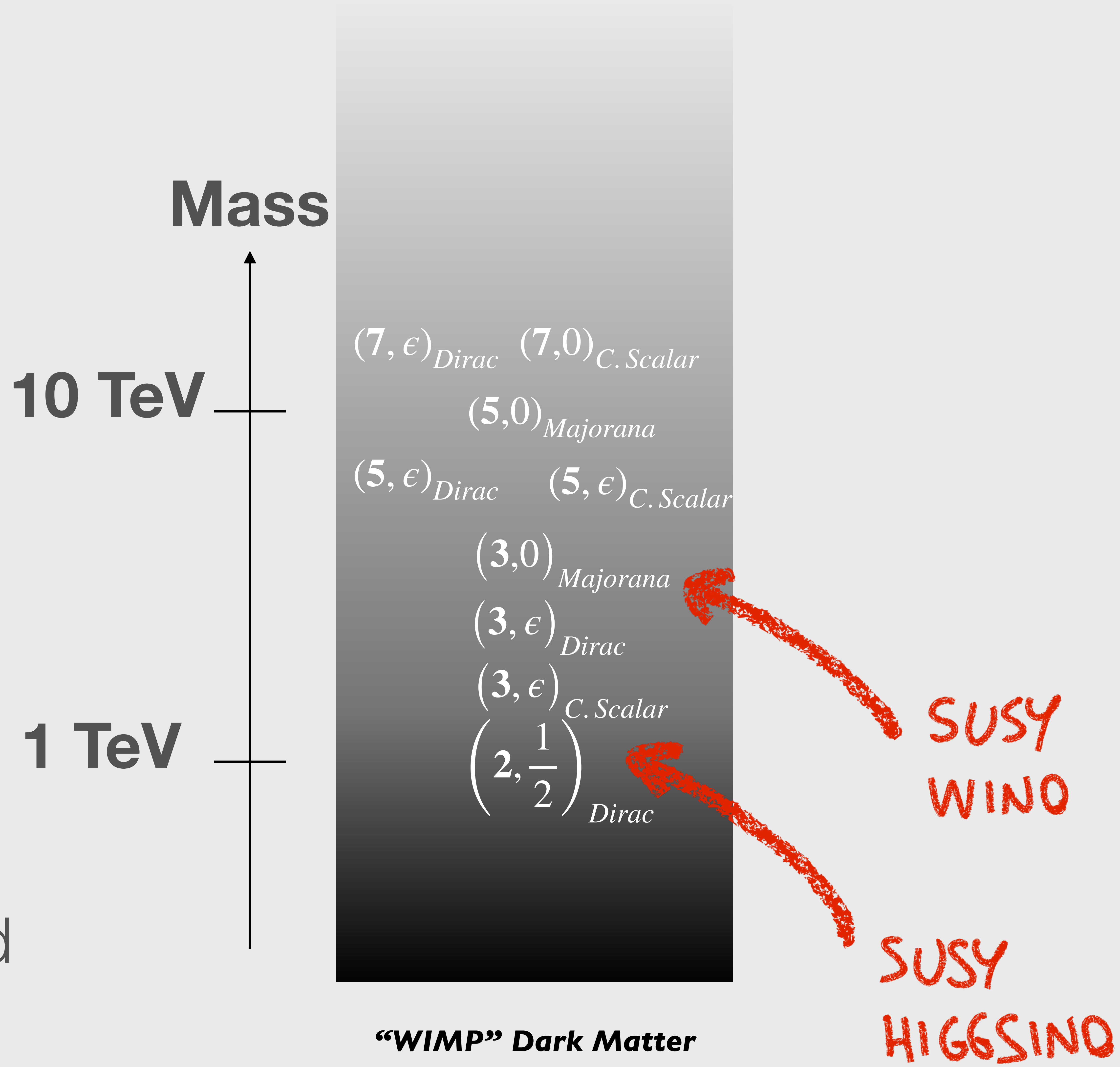
Dark Matter

Electroweak Dark Matter: LSP (+NLSP)

- The chessboard of DM is very large!



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



"WIMP" Dark Matter

Electroweak Dark Matter: LSP (+NLSP)

Δm

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

Electroweak Dark Matter: LSP (+NLSP)

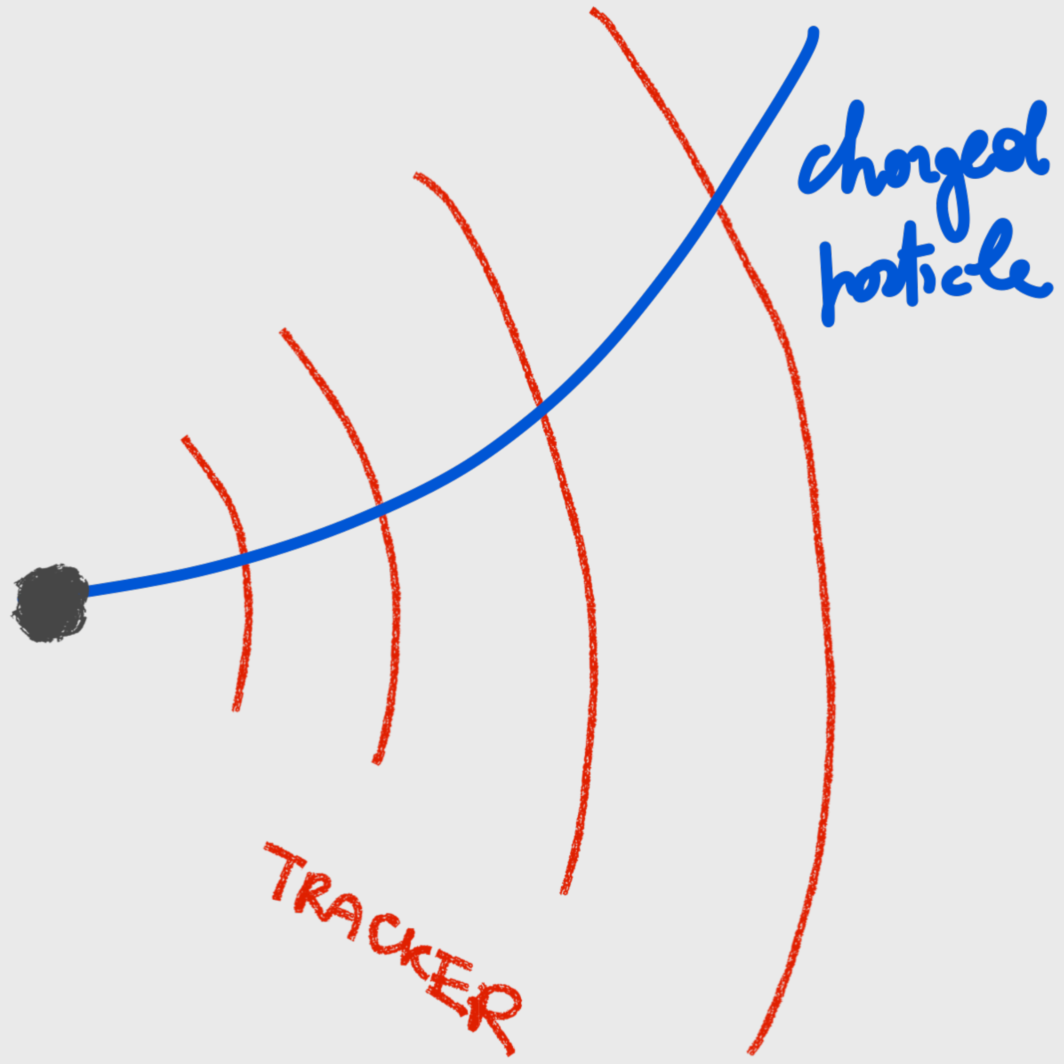
Δm

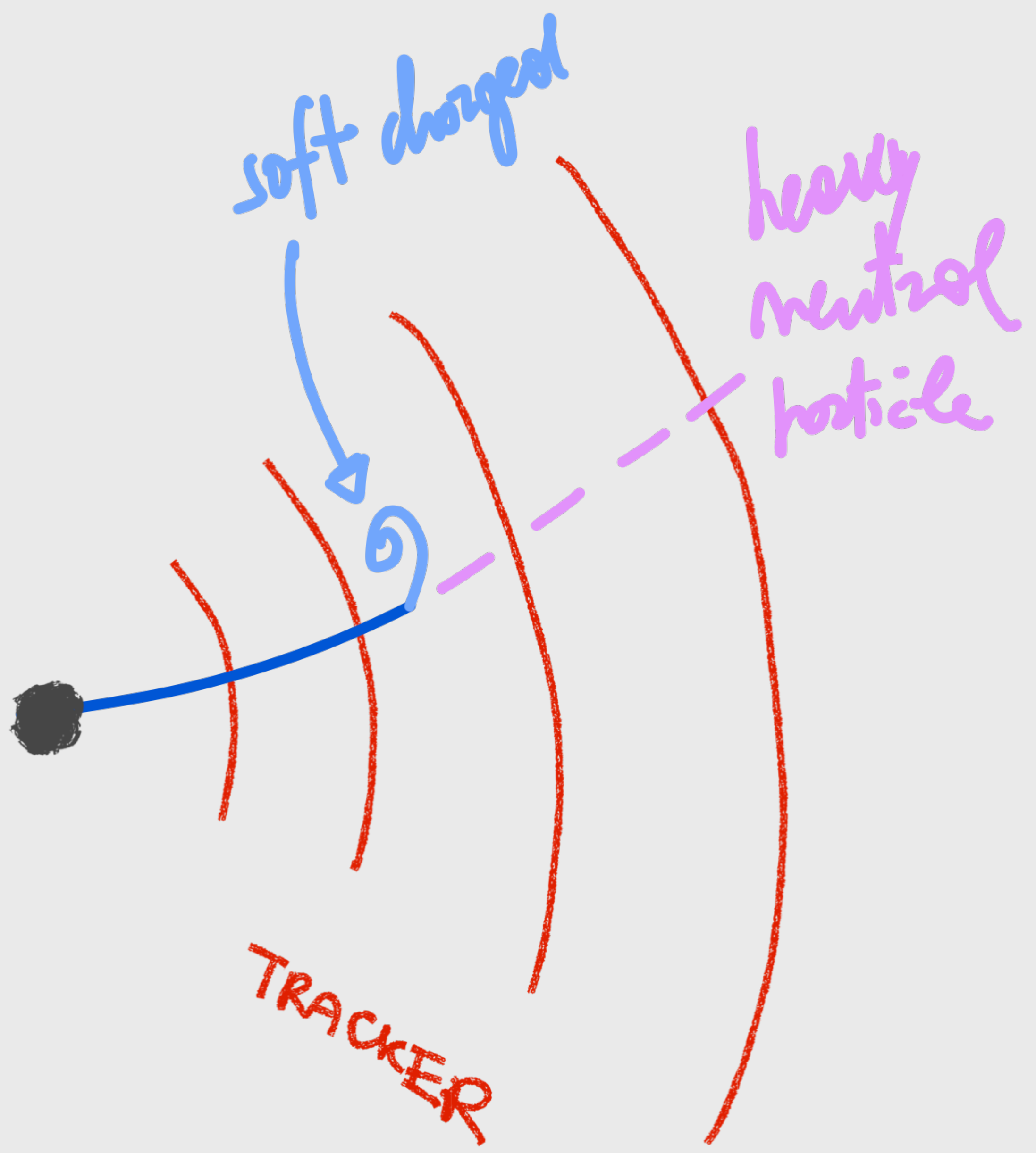
Wide open spectra		Generic leptons+missing momentum
Co-annihilation		Soft-objects + missing momentum
	GeV	
WIMP-like multiplet Accidental Dark Matter		**Short (disappearing) tracks**
DM SM singlet $e^+e^- \to Z' \to \chi\,\chi$	0	Mono-photon

} Precision Tests

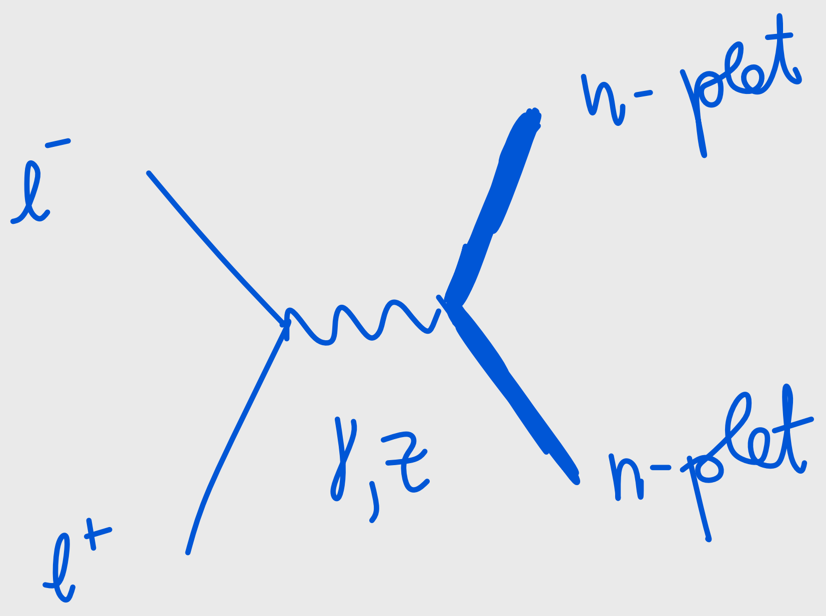
Higgsino DM

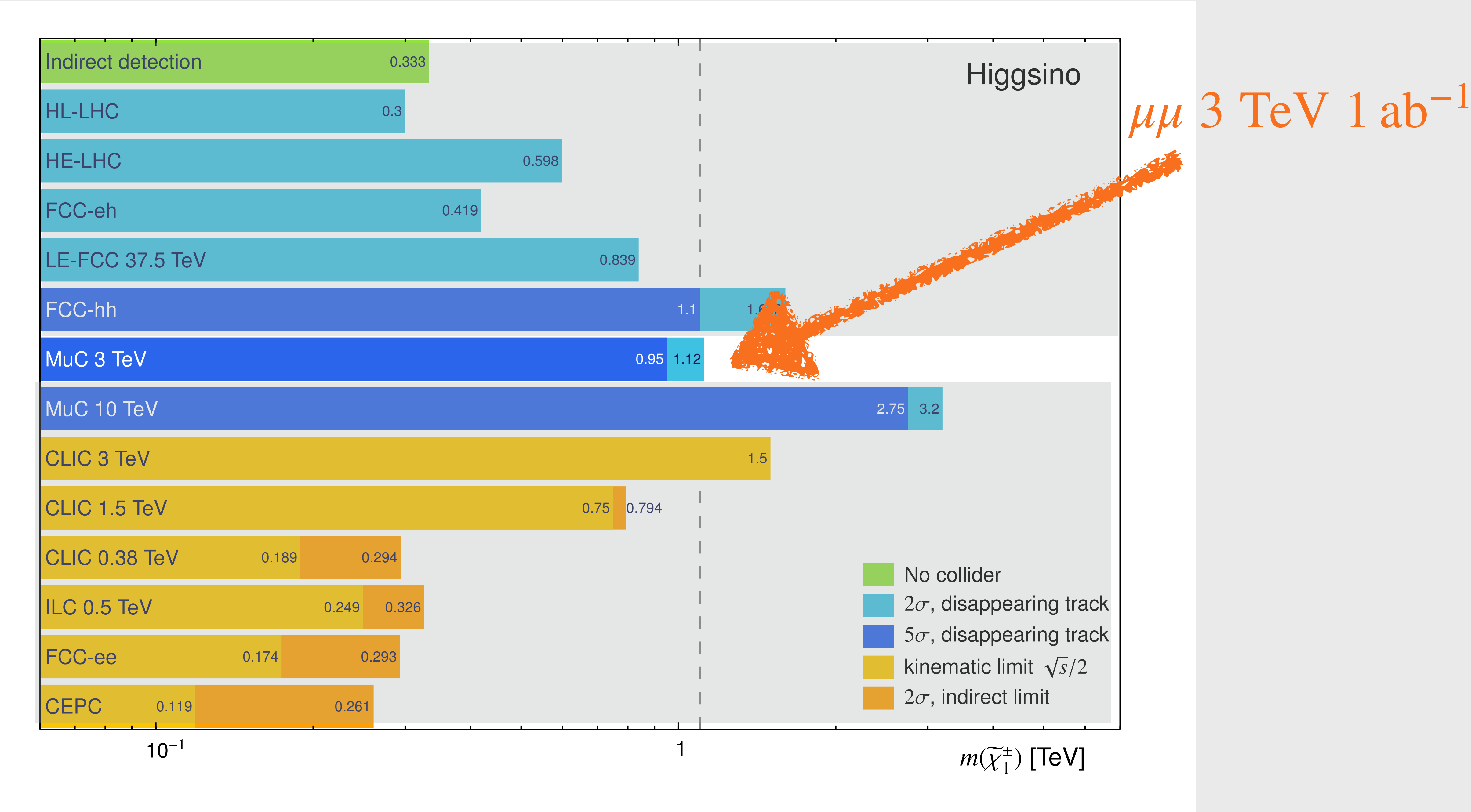
STUB-TRACKS EXOTIC SIGNAL





- Heavy n-plet of SU(2)
- Mass splitting ~ α_W m_W ~ 0.1 GeV - GeV





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

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

} Precision Tests

Electroweak Dark Matter: LSP (+NLSP)

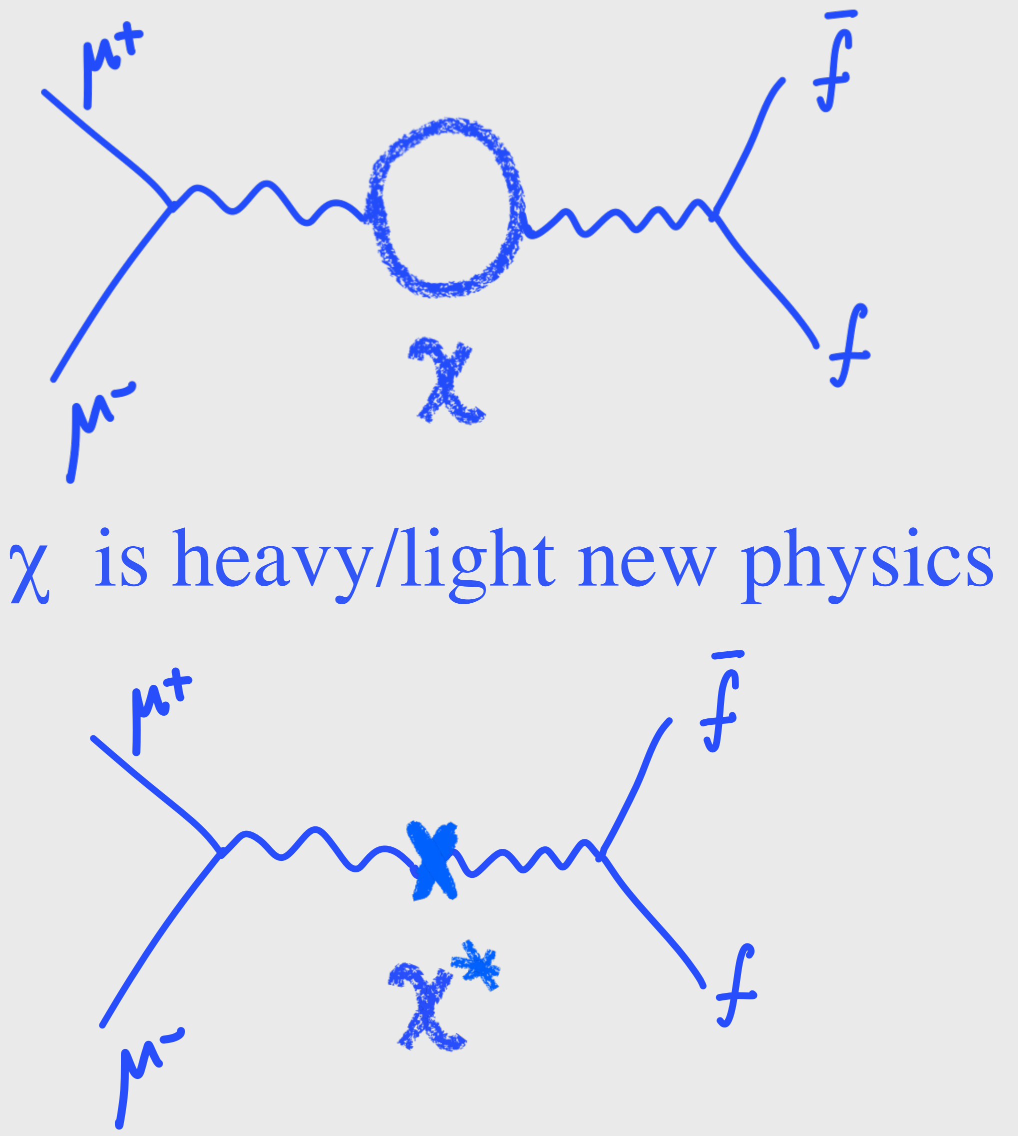
Δm

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

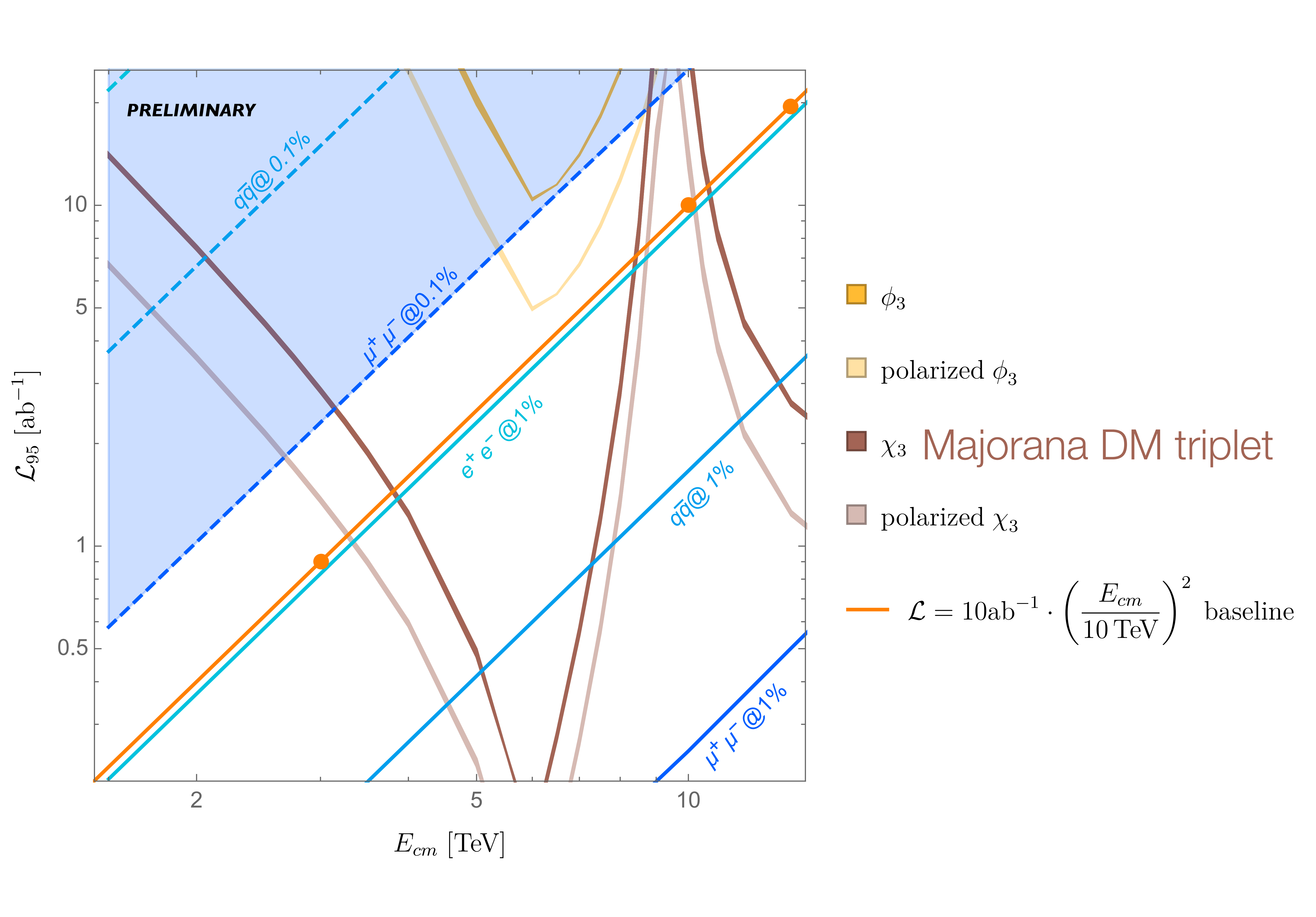
} **Precision Tests**

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

PRECISION | TOTAL CROSS-SECTION

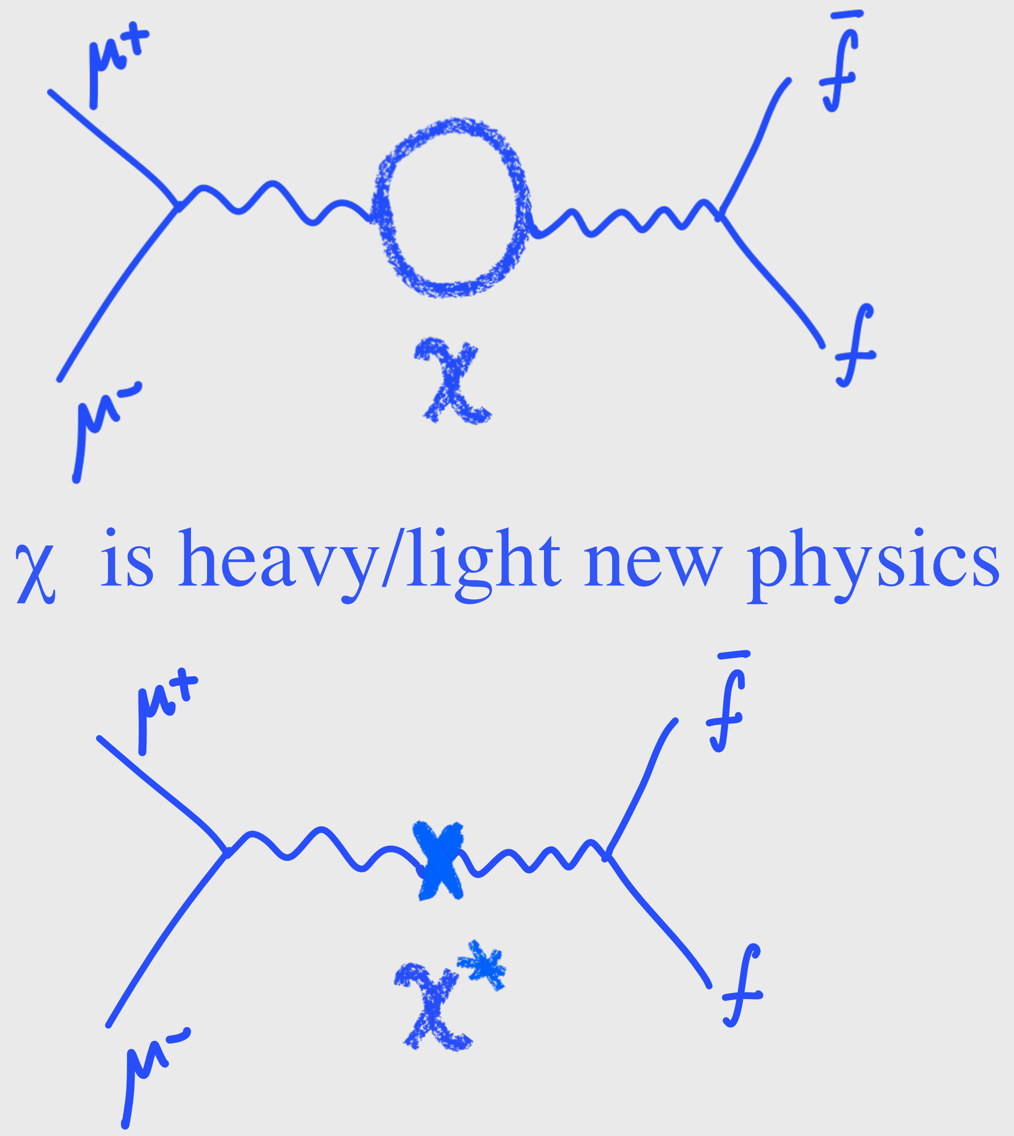


- fiducial cross-sections are significantly affected by off-shell new physics heavier than the collider kinematic reach

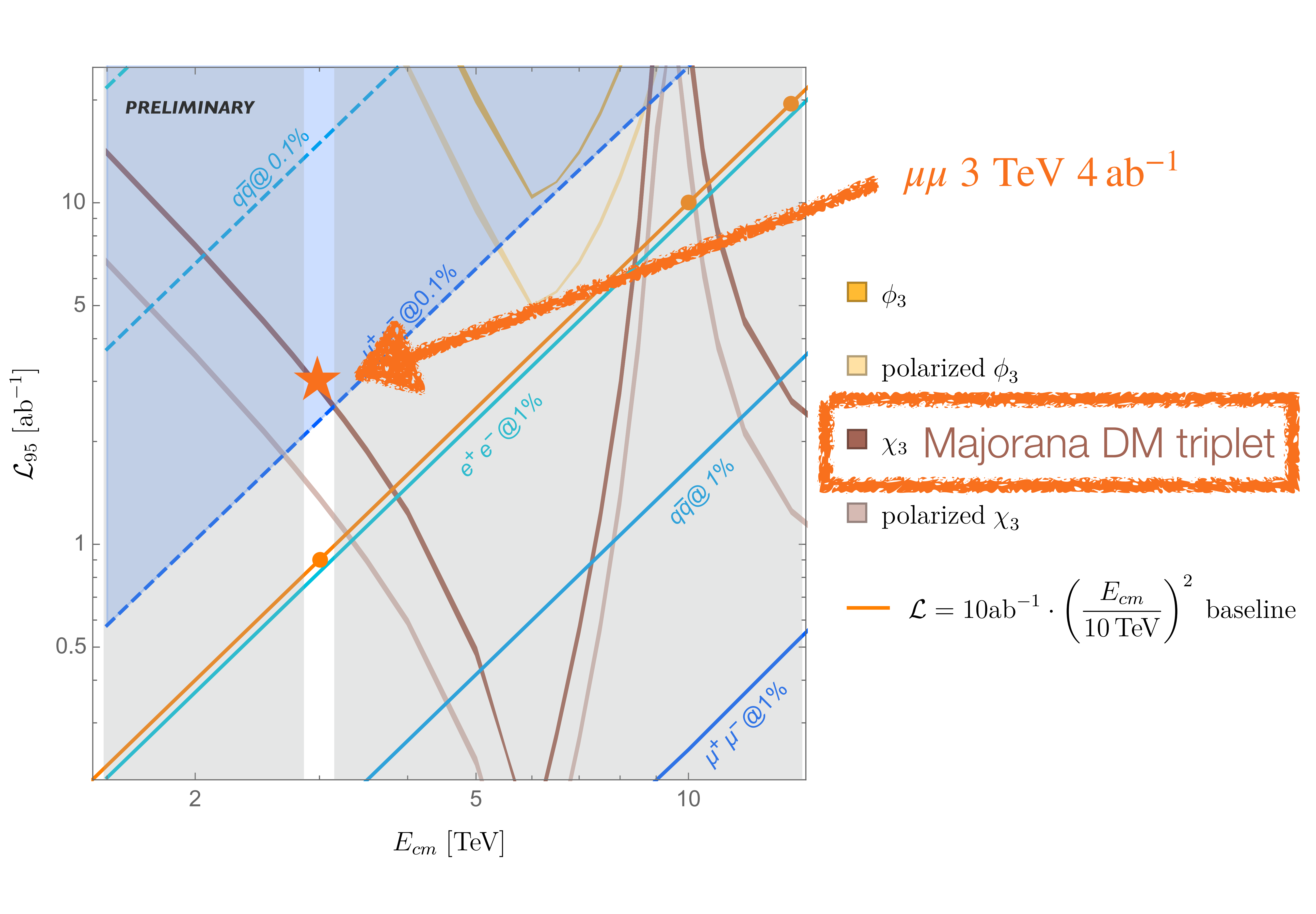


$\mu^+\mu^- \to f\bar{f}, W^+W^-$

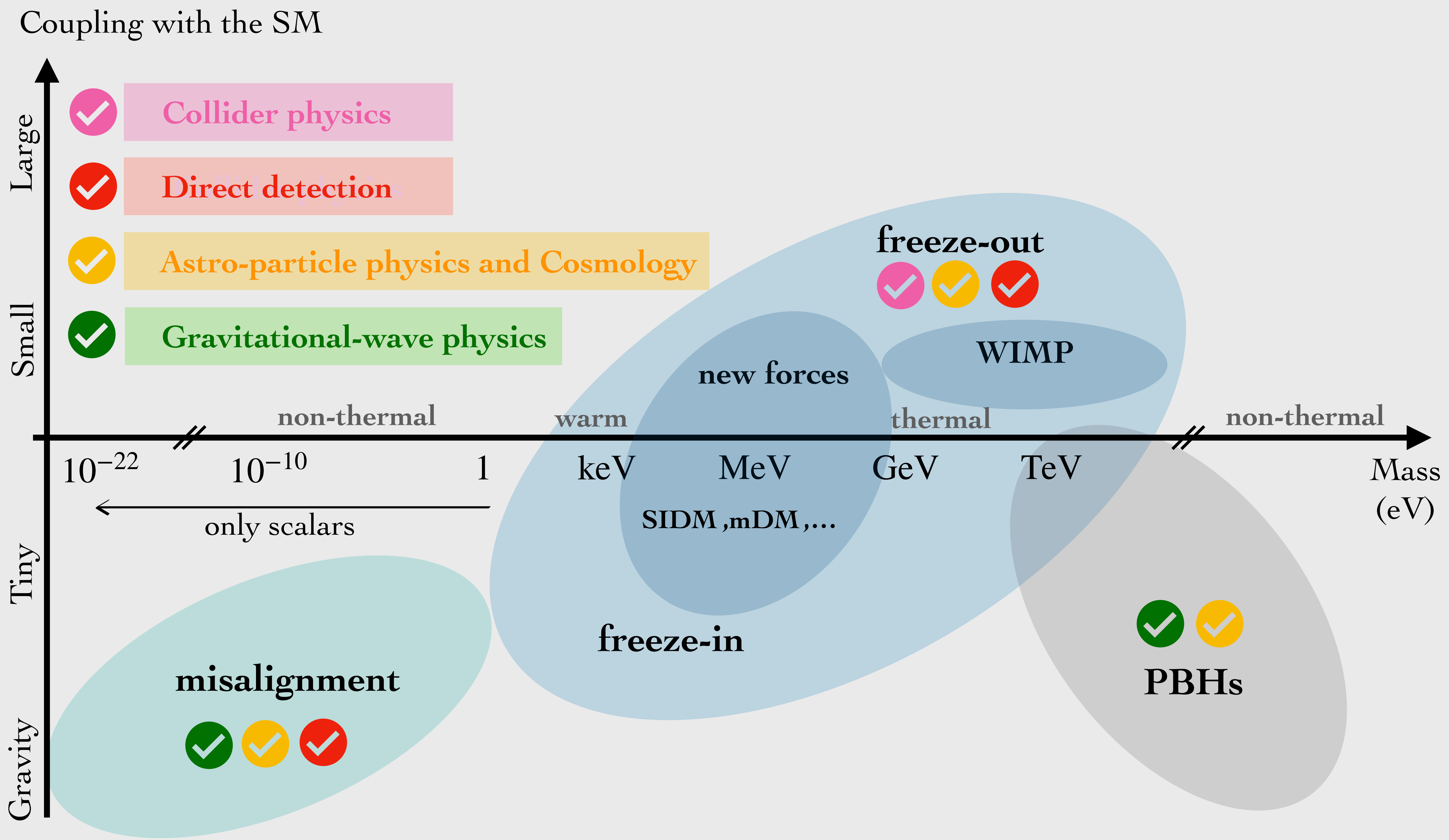
PRECISION **TOTAL CROSS-SECTION**

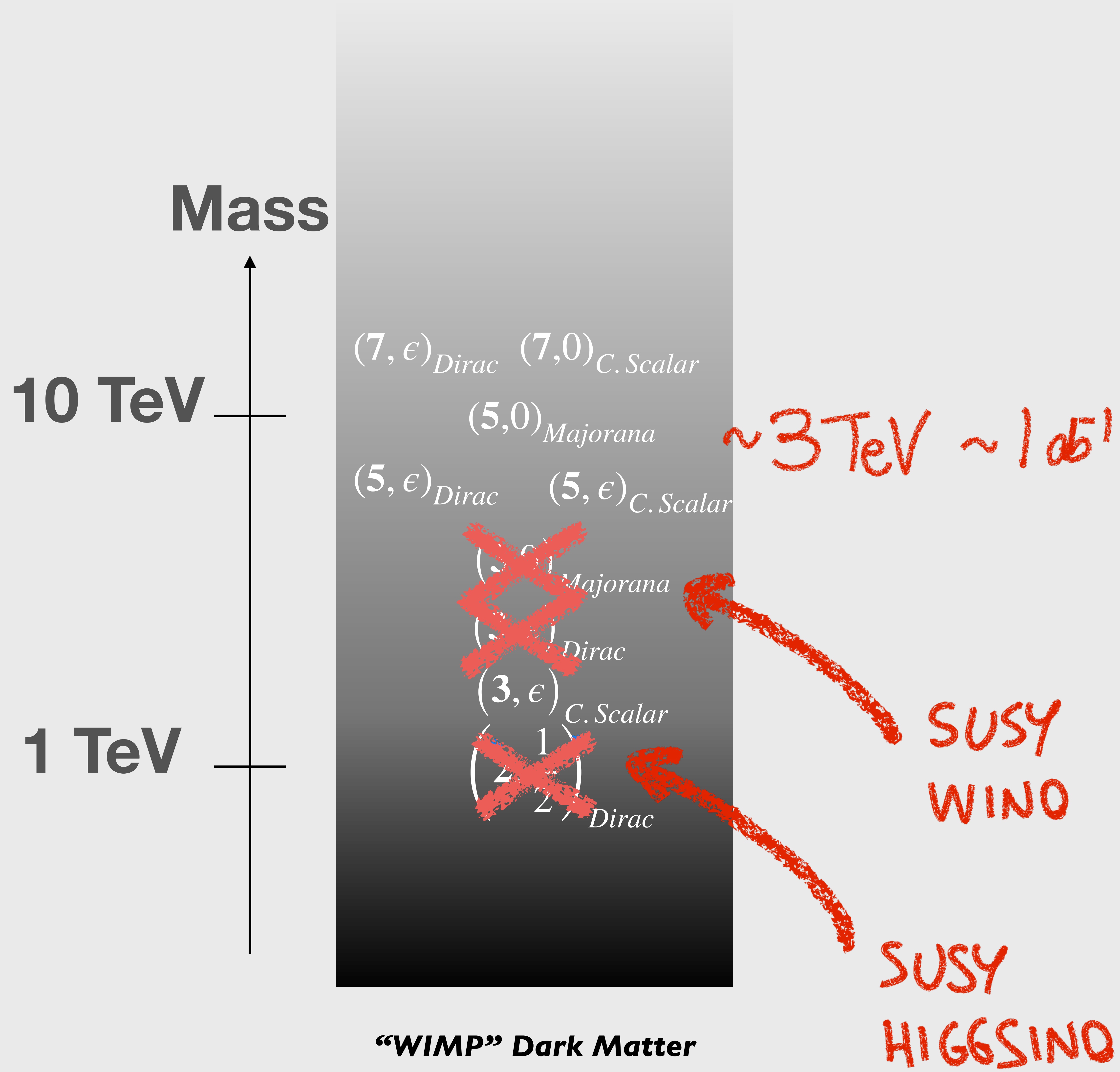


- fiducial cross-sections are significantly affected by off-shell new physics heavier than the collider kinematic reach

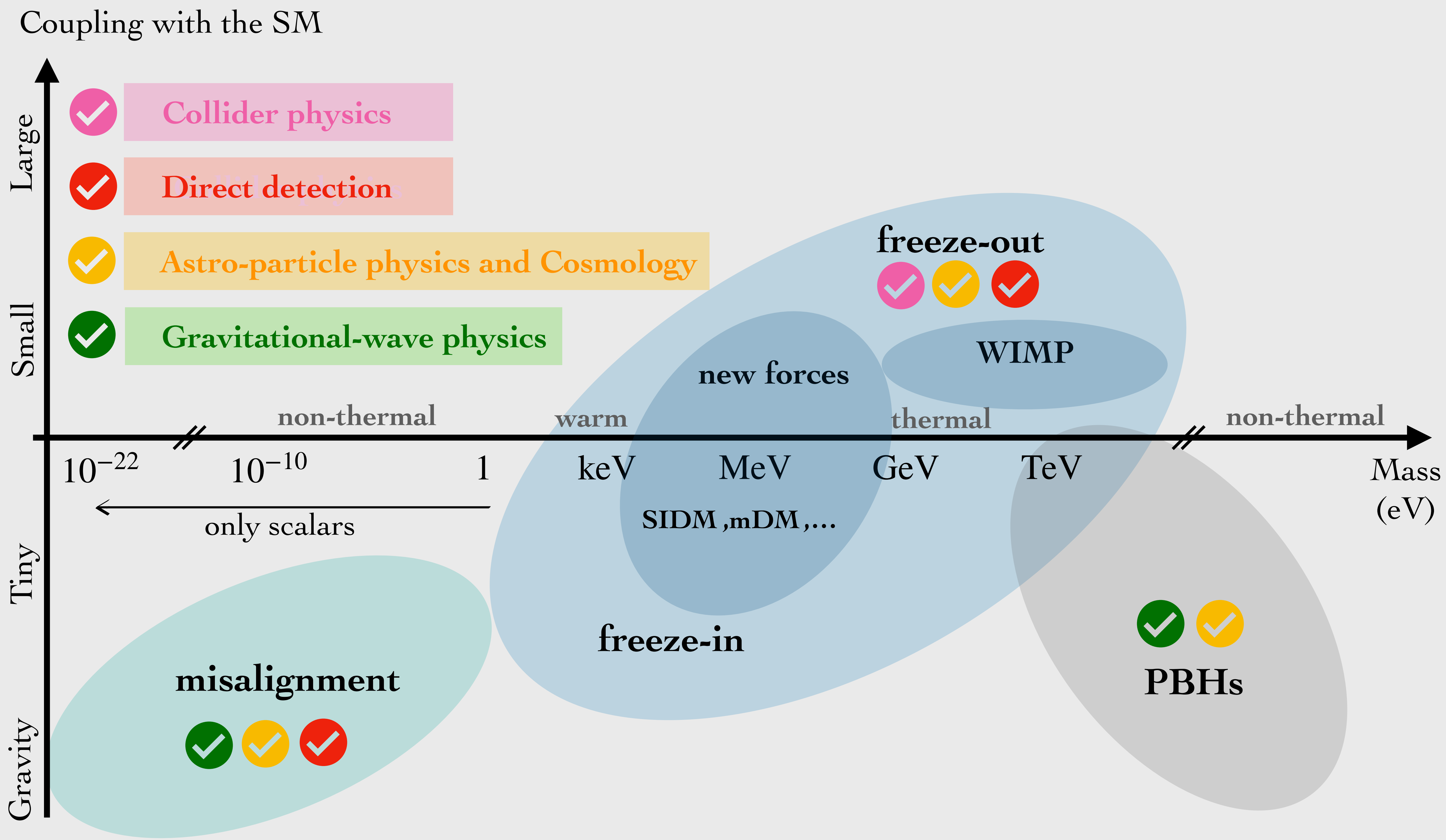


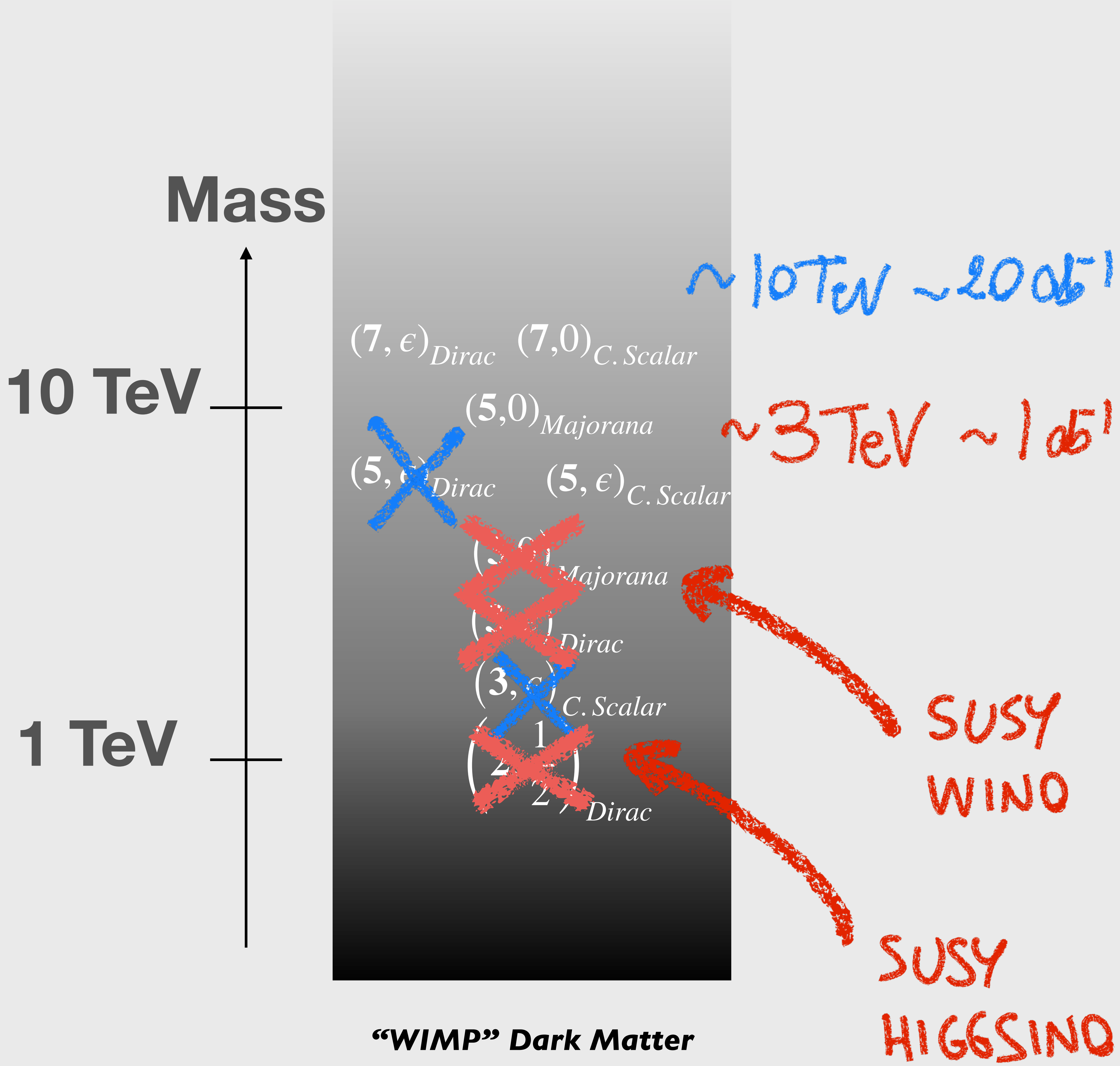
Electroweak Dark Matter: LSP (+NLSP)





Electroweak Dark Matter: LSP (+NLSP)





Electroweak symmetry breaking

Electroweak symmetry breaking

Big picture questions:

- Extended Higgs Sector

  back to “valence” muon collisions
  and direct production of new physics

- Higgs compositeness

Electroweak symmetry breaking

Big picture questions:

- Extended Higgs Sector

  back to “valence” muon collisions

  and direct production of new physics

- Higgs compositeness

“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

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

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

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

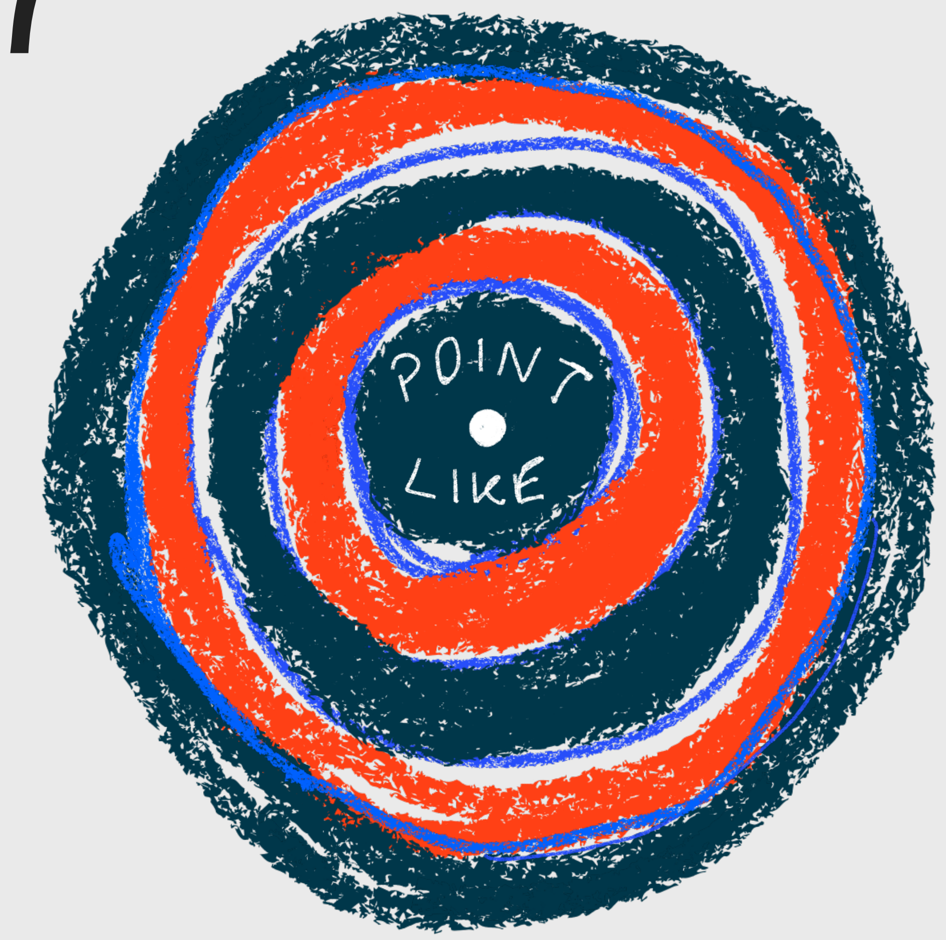
$$+ c_{y_t}\frac{g_*^2}{m_*^2}\mathcal{O}_{y_t} + c_{y_b}\frac{g_*^2}{m_*^2}\mathcal{O}_{y_b}$$

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

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

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

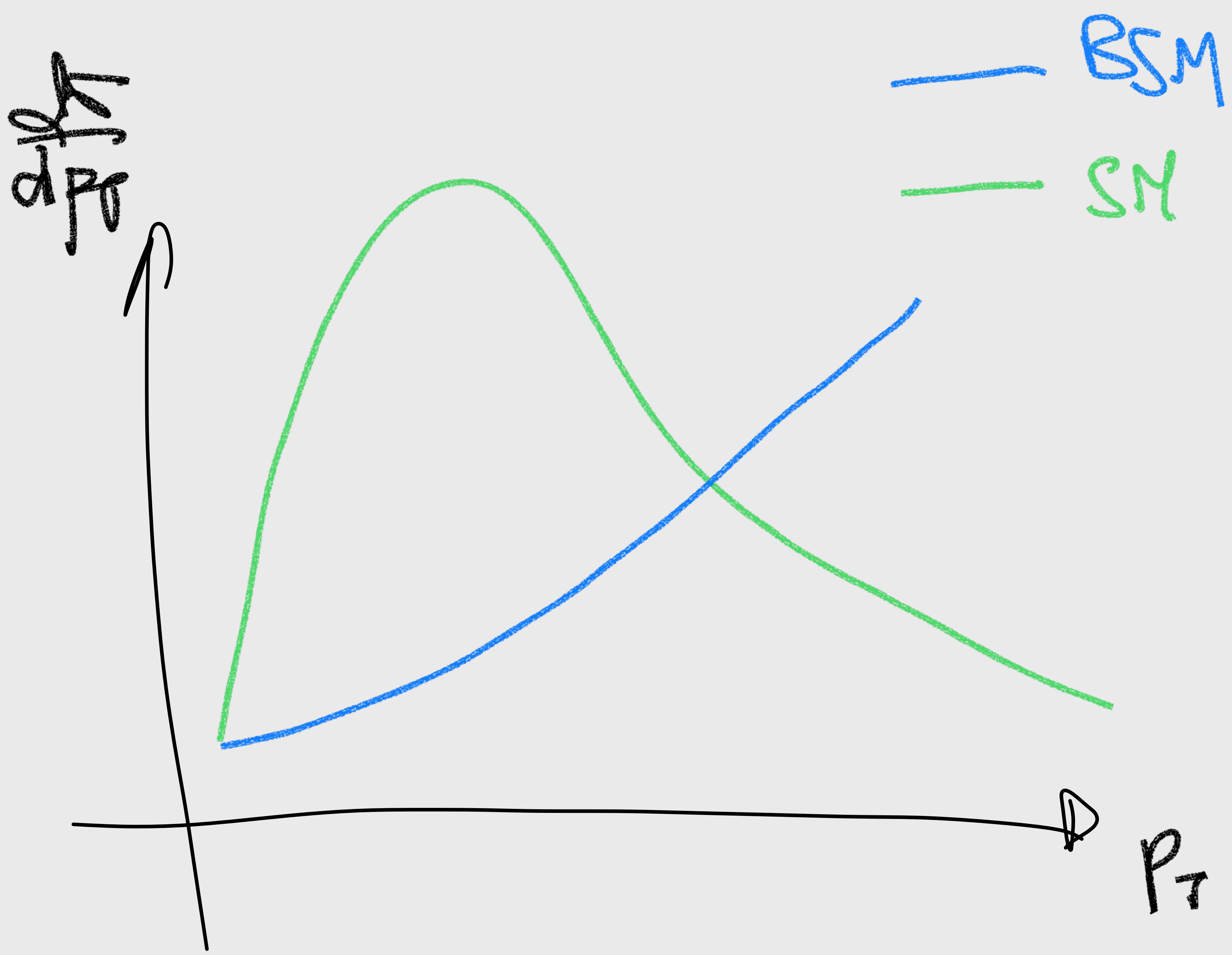
$\ell_{Higgs} \sim 1/m_\star$



SM works wonderfully!

New Physics may fit well in a EFT (new contact interactions)

- effects grow at larger energies like $\nu e^- \to \nu e^-$ in Fermi Theory



$$\frac{d\sigma}{dp_T}$$

measurements sensitive to a range of mass scales

- sensitive to a range of energy scales
- progress is easy to measure: bounds on new Fermi constants

as NP effects may grow quadratically with energy

$$\Delta O = O_{NP} - O_{SM} \sim \left(\frac{E}{v}\right)^2$$

1% at m_Z is worse than 10% at 1 TeV

SM works wonderfully!

New Physics may fit well in a EFT (new contact interactions)

- effects grow at larger energies like $\nu e^- \to \nu e^-$ in Fermi Theory

HIGH-LUMI PROBES

$$m_W, m_Z, \sin\theta_W, A_{FB}^{whatever}, h \to Z\gamma, h \to ZZ, t \to b\tau\nu, \sigma_{tot}(\ell\ell \to hh)$$

measurements dominated by a single mass scale

- dominant energy scale is low
- measurement is simple to grasp
- progress is easy to measure (in)significant digits

NP effects may show up in the combination of many precise measurements

fight against systematics

HIGH-ENERGY PROBES

$$\frac{d\sigma}{dp_T}$$

measurements sensitive to a range of mass scales

- sensitive to a range of energy scales
- measurement of a spectrum (not so?!?) simple to grasp
- progress is easy to measure: bounds on new Fermi constants

as NP effects may grow quadratically with energy

$$\Delta O = O_{NP} - O_{SM} \sim \left(\frac{E}{v}\right)^2$$

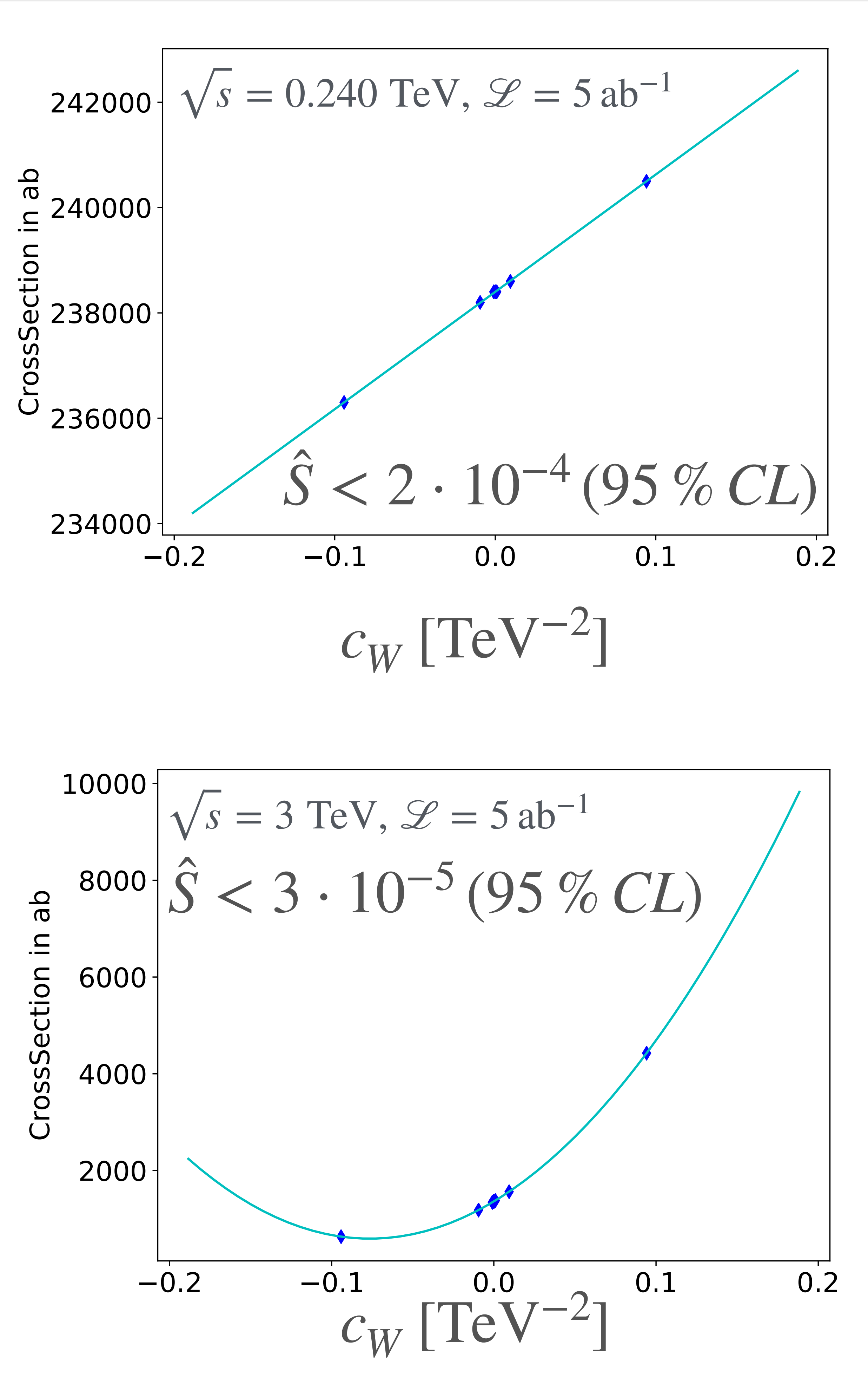
1% at m_Z is worse than 10% at 1 TeV

$\mu^+\mu^- \to Zh$

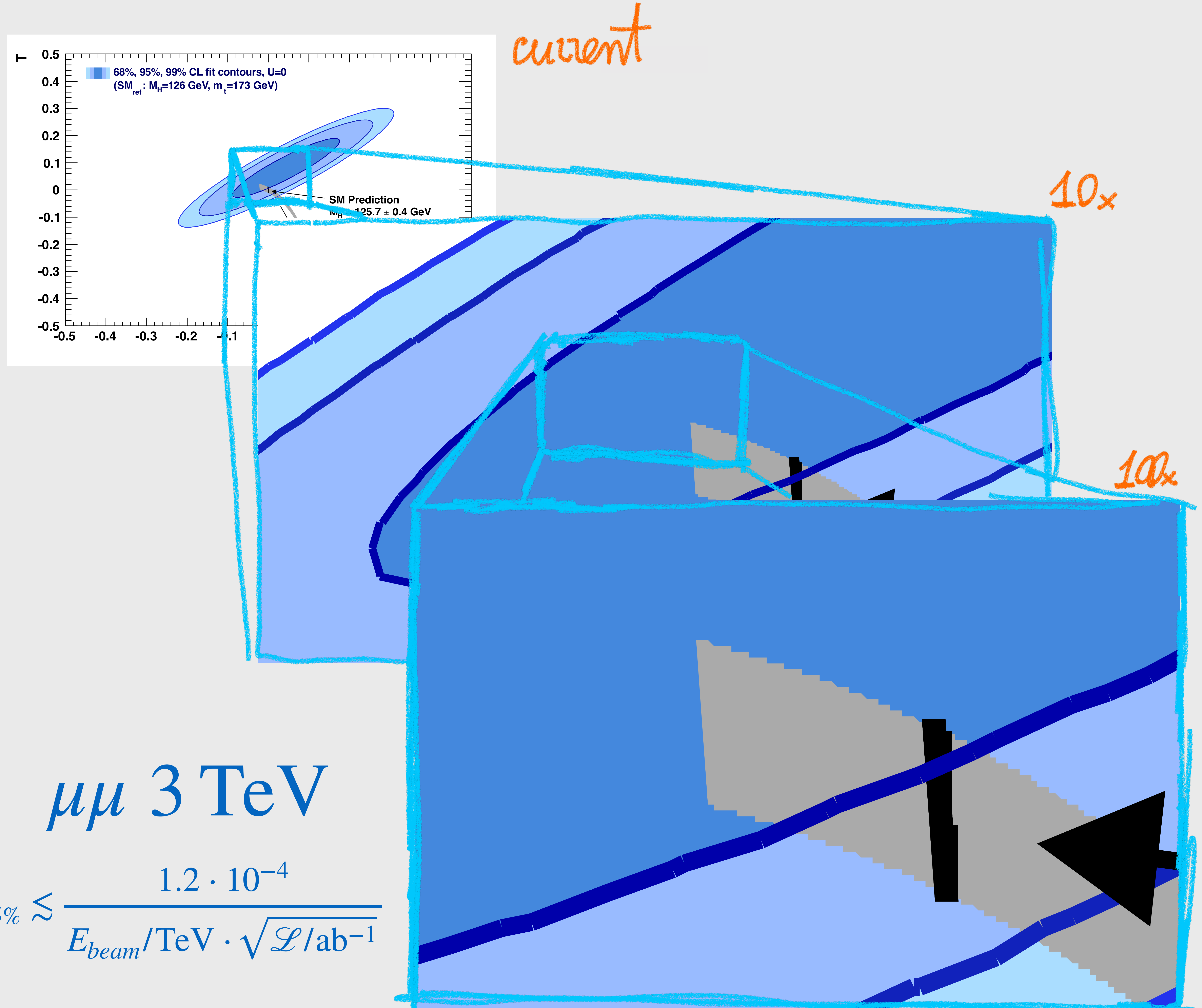
TOTAL RATE

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

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



LEP



$\mu\mu$ 3 TeV

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

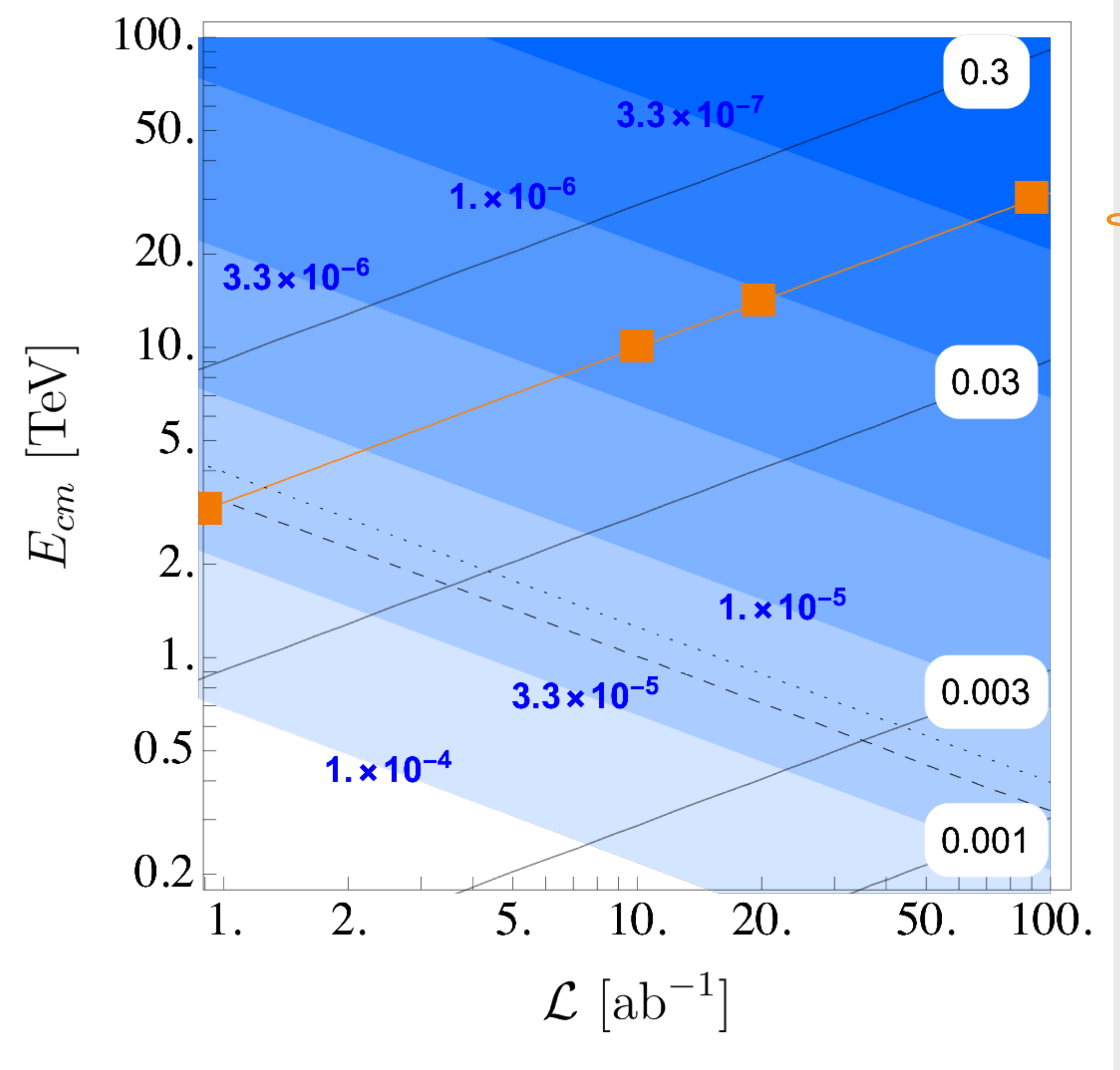
$\ell^+\ell^- \to Zh$

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

TOTAL RATE

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

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



$\mathscr{L} \sim E_{cm}^2$

VHEL

$\hat{S}$@FCC-ee

$\hat{S}$@FCC-ee+hh

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

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

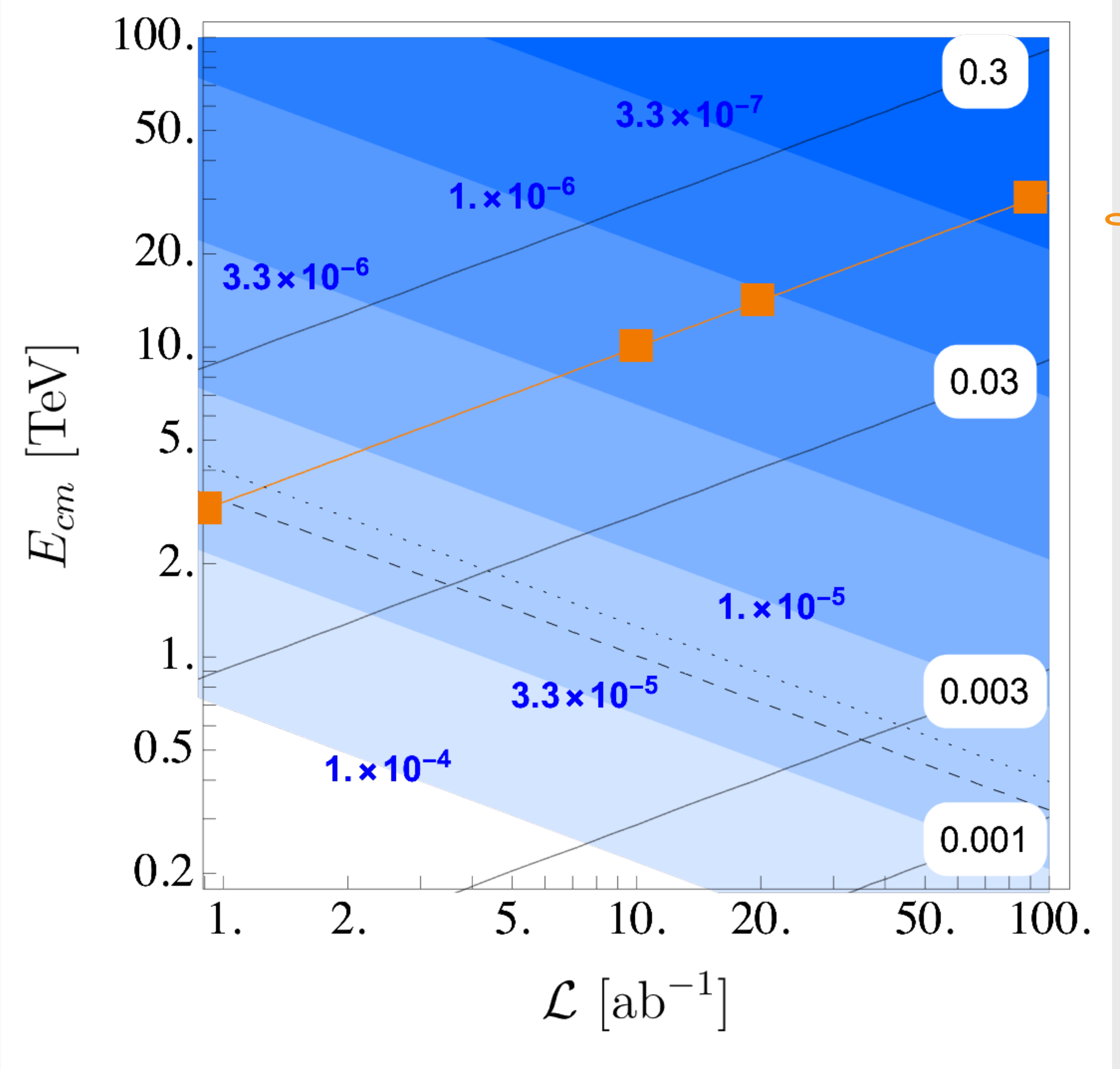
$$c_W = \hat{S}/m_W^2$$

TOTAL RATE

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

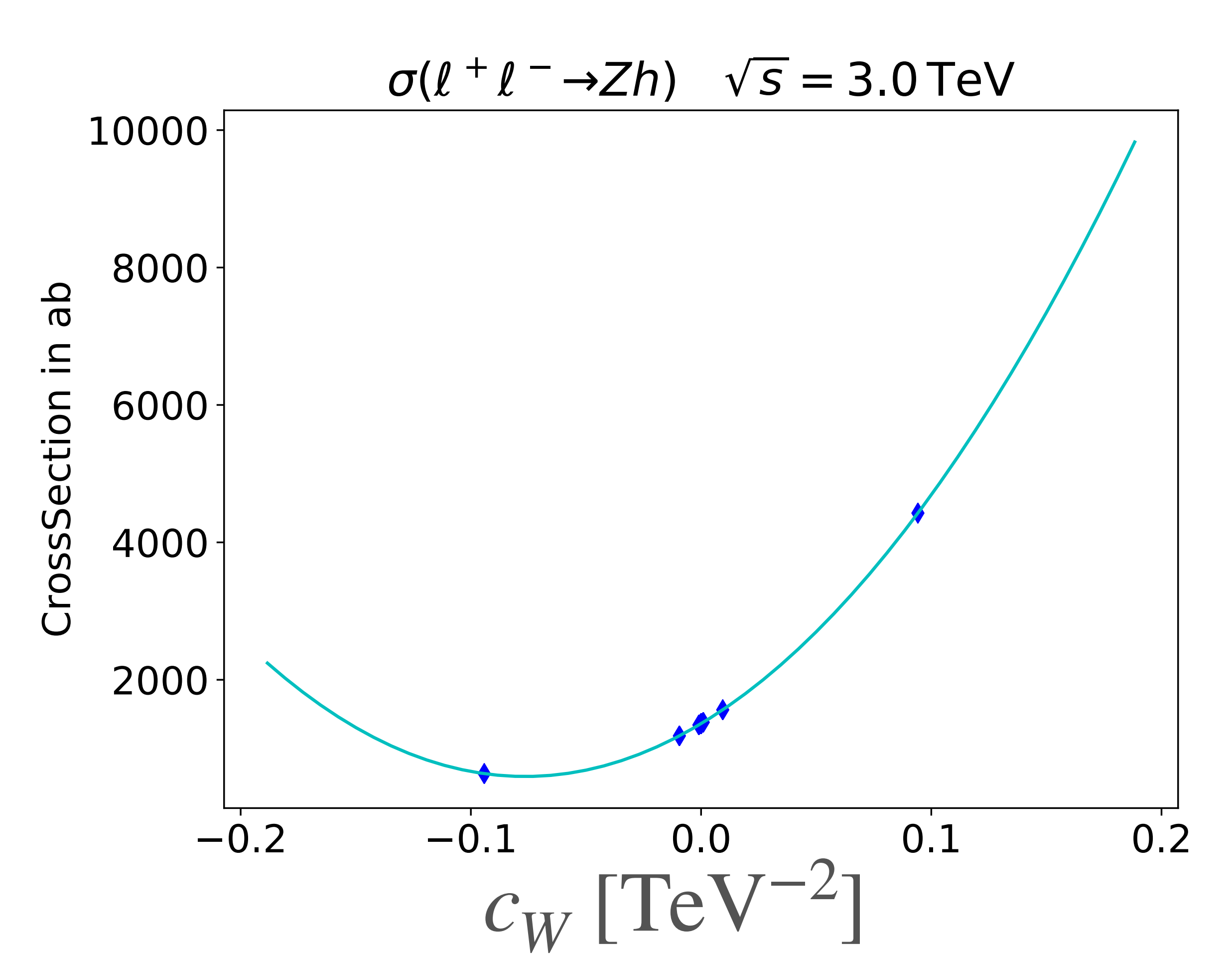
$$c_W \lesssim 0.02\,\mathrm{TeV}^{-2}\frac{1}{E_{beam}/\mathrm{TeV}}\cdot\frac{1}{\sqrt{\mathscr{L}/\mathrm{ab}^{-1}}}$$

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

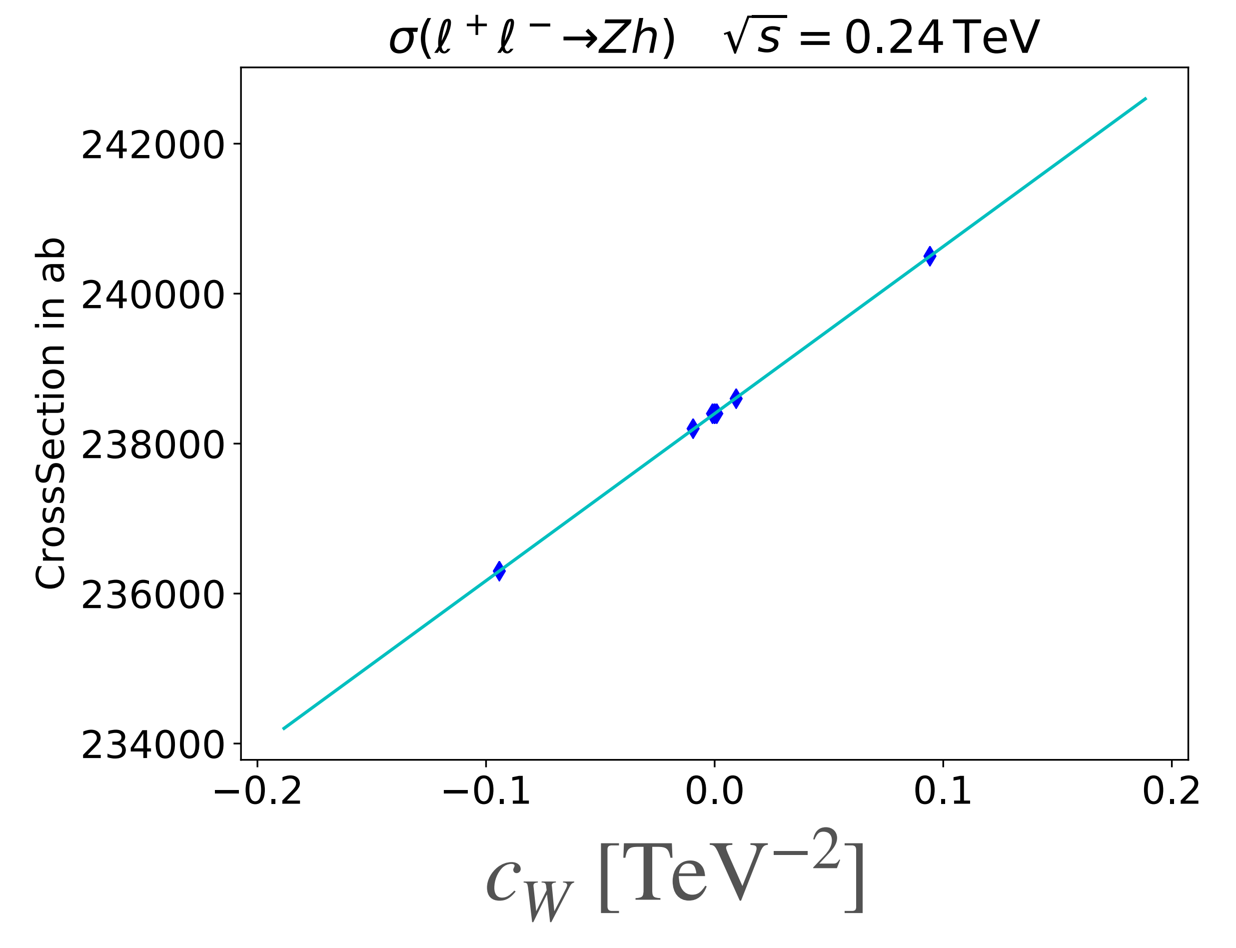


$$\mathscr{L} \sim E_{cm}^2$$

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



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



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

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

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

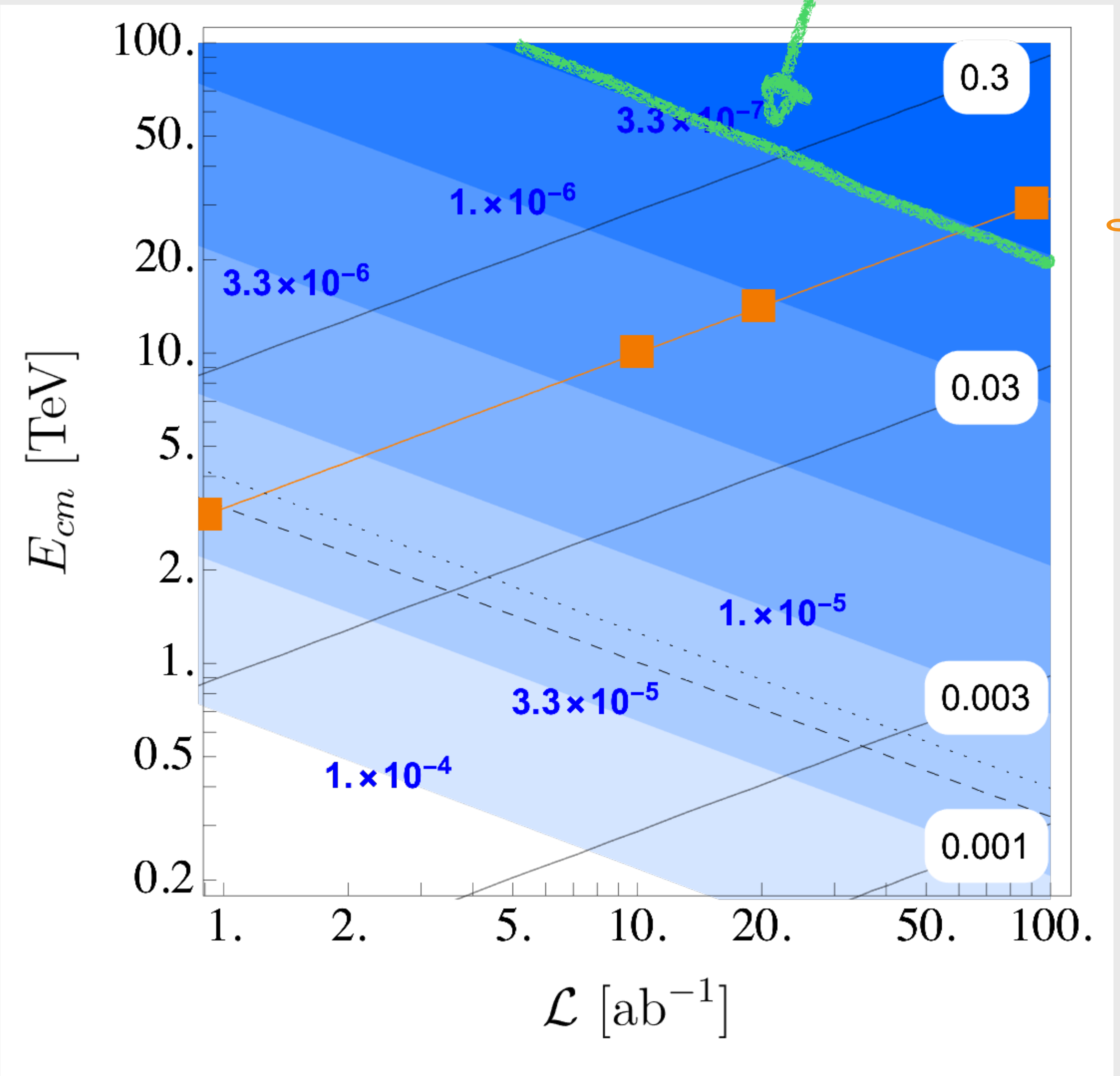
TOTAL **RATE**

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

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

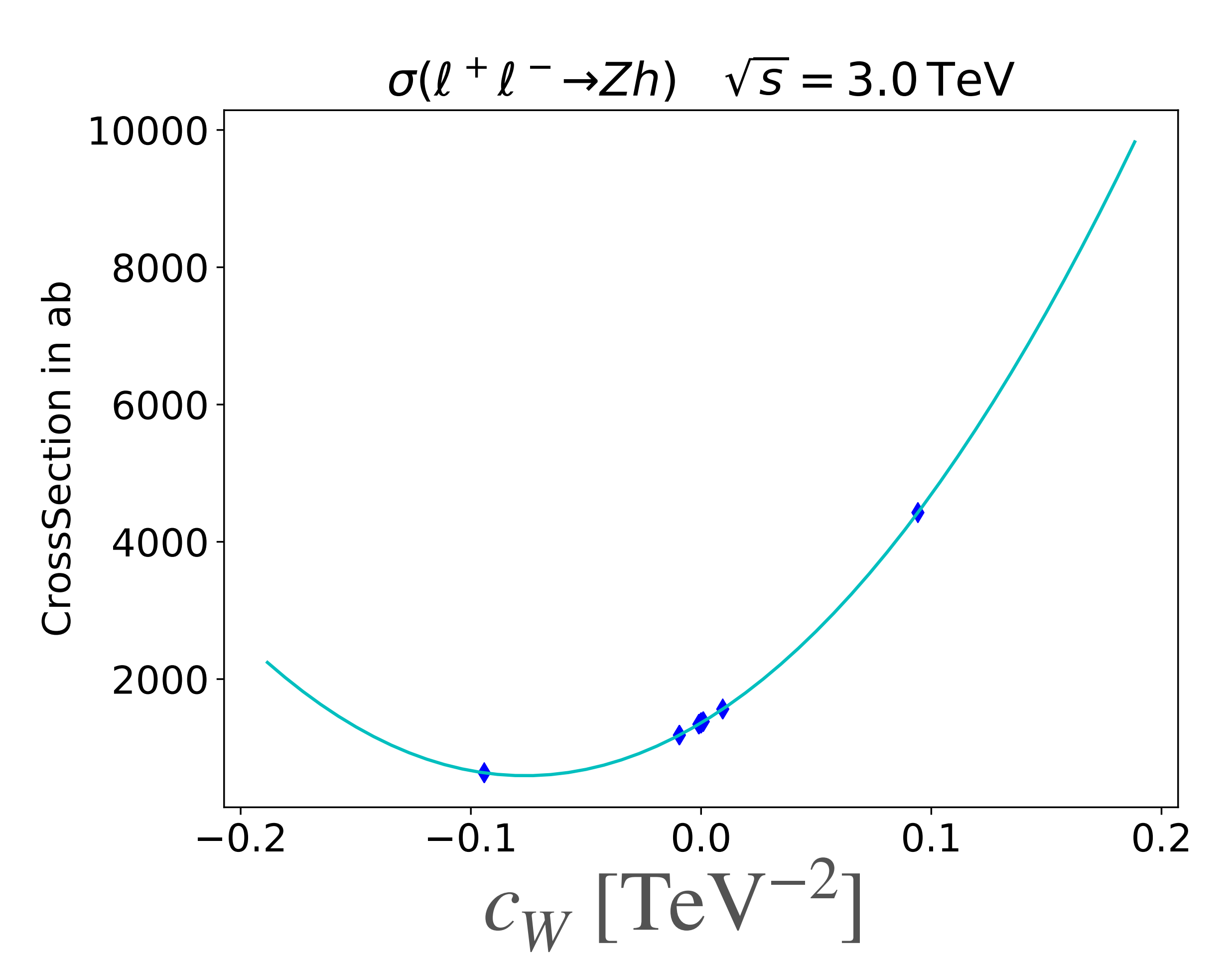
$$\hat{S}_{95\%} \lesssim 1.2 \cdot 10^{-4} \frac{1}{E_{beam}/\text{TeV}} \cdot \frac{1}{\sqrt{\mathscr{L}/\text{ab}^{-1}}}$$

$\hat{S} \sim 10^{-7}$

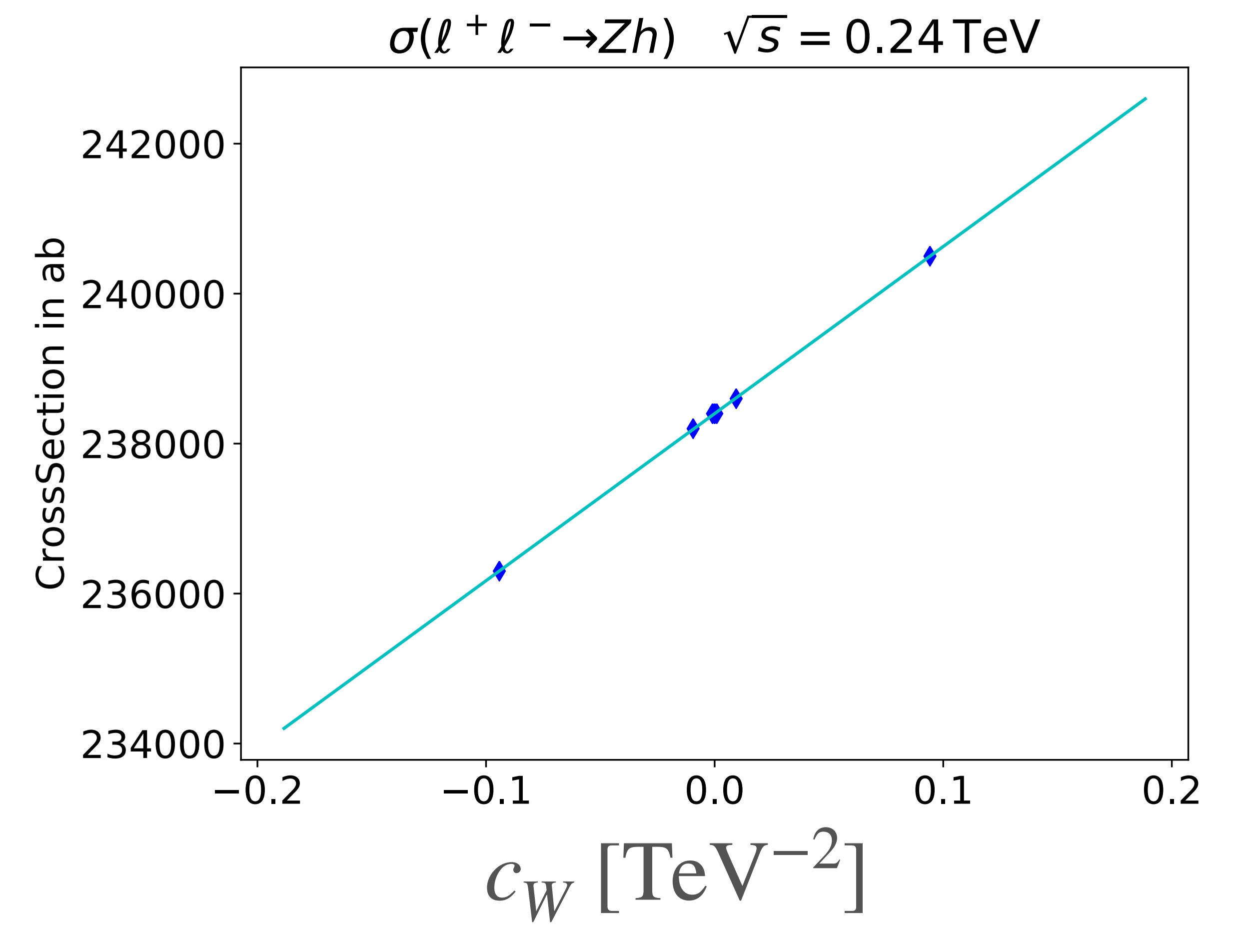


$\mathscr{L} \sim E_{cm}^2$

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



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



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

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

TOTAL RATE

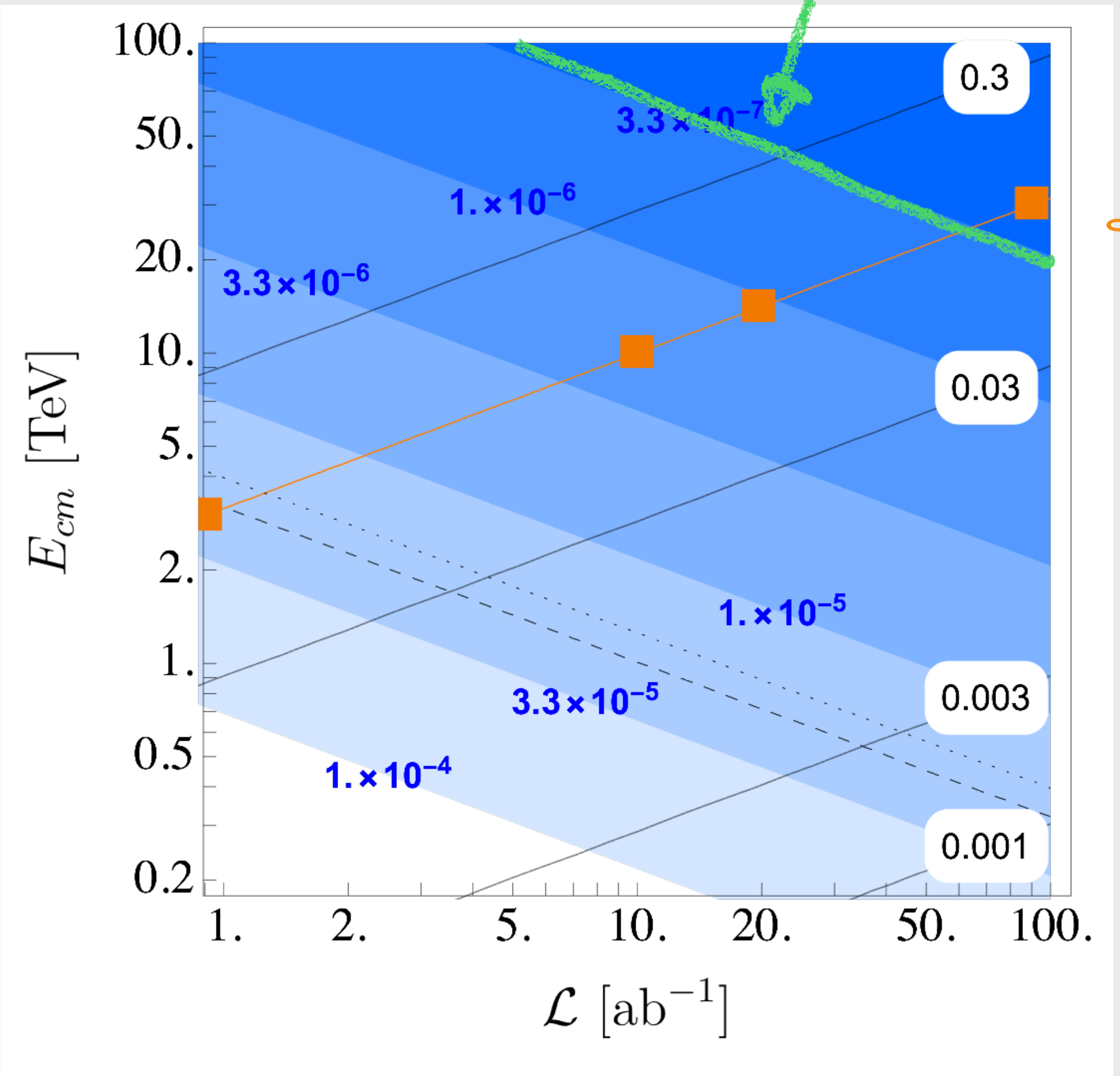
$$\left|A_{SM}^{(00)}\right|^2 + A_{SM}^{00}\cdot A_{BSM}^{00} + \dots$$

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

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

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

$\hat{S} \sim 10^{-7}$ minus 7



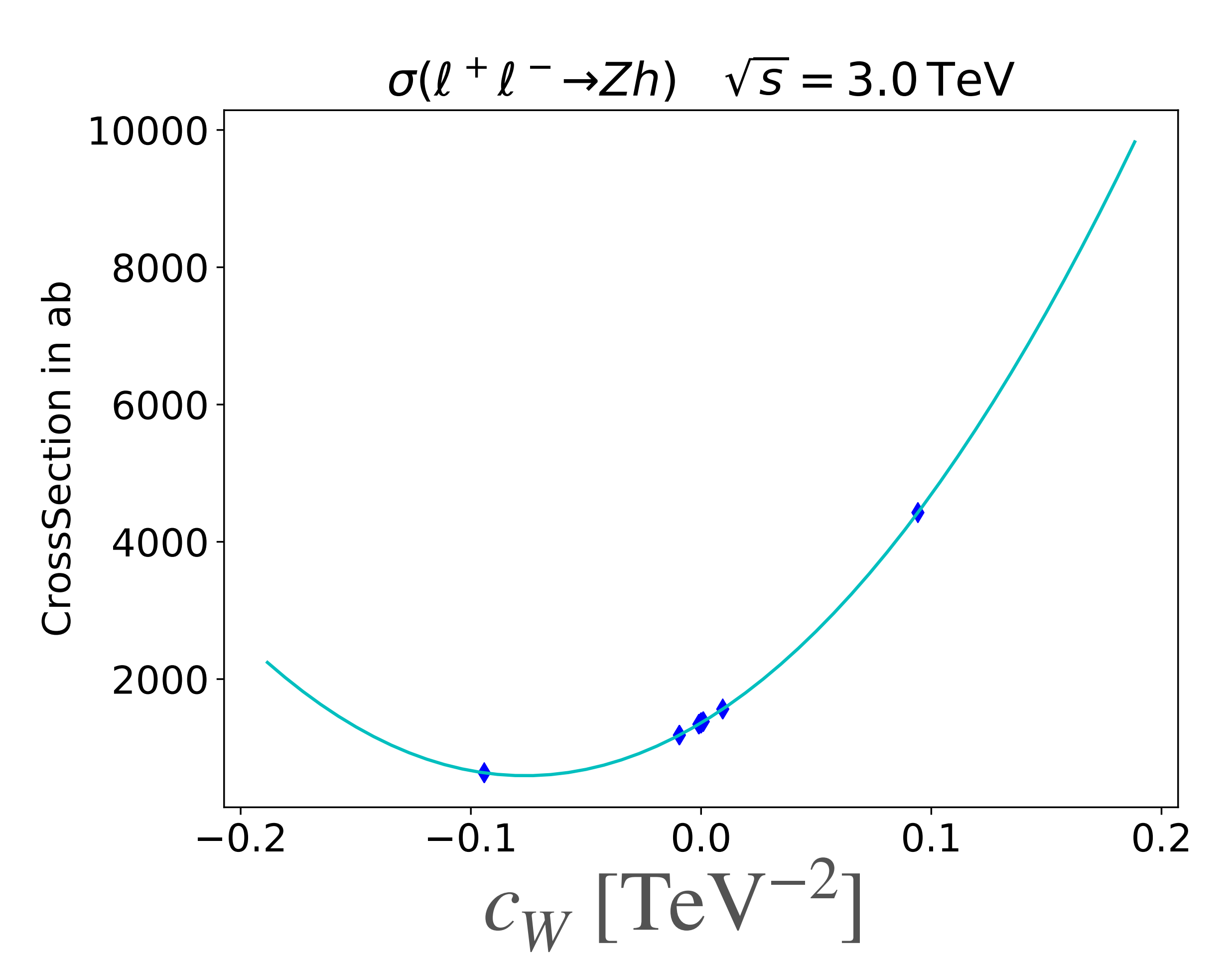
VHEL

$\hat{S}$@FCC-ee

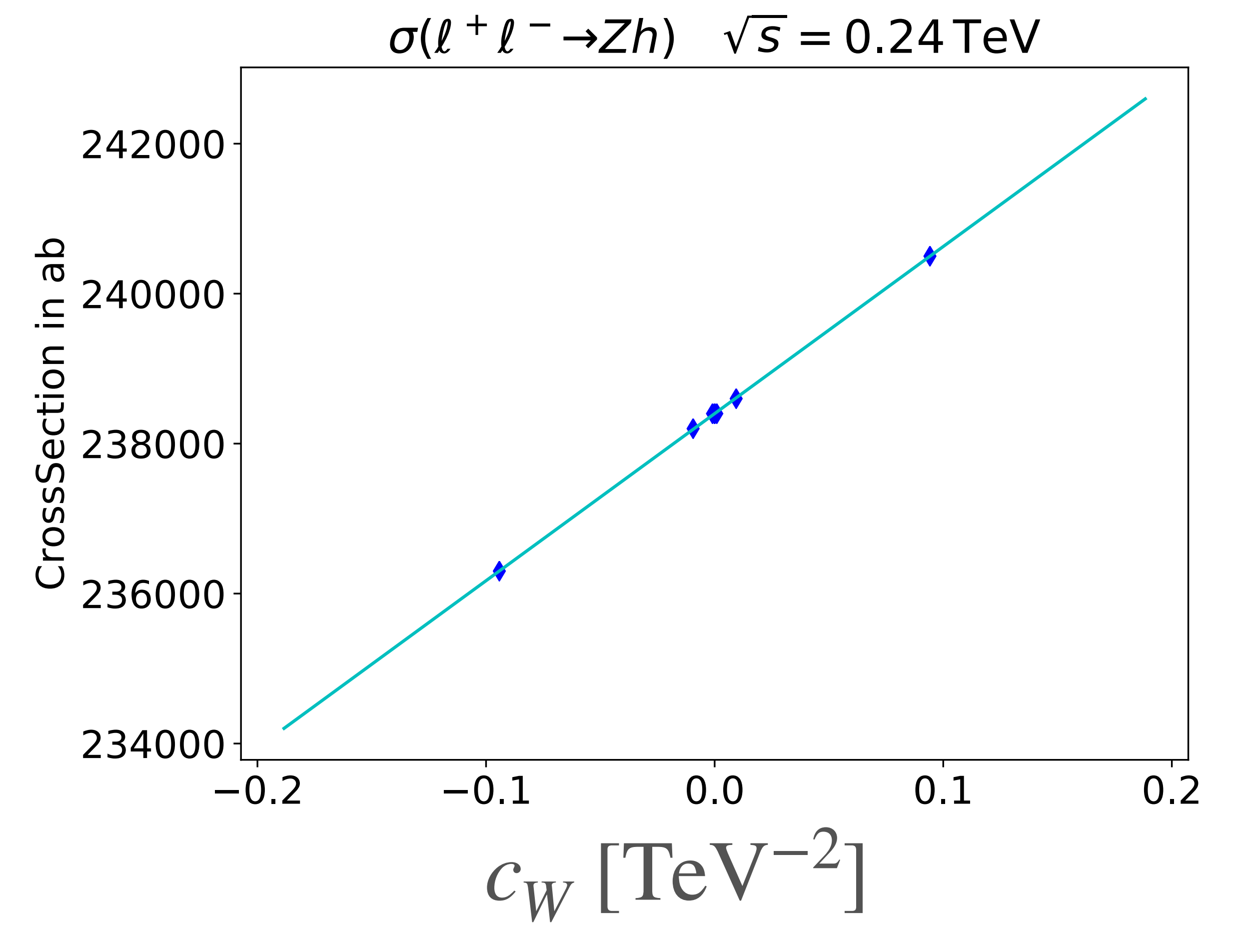
$\hat{S}$@FCC-ee+hh

$\mathcal{L} \sim E_{cm}^2$

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



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



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

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

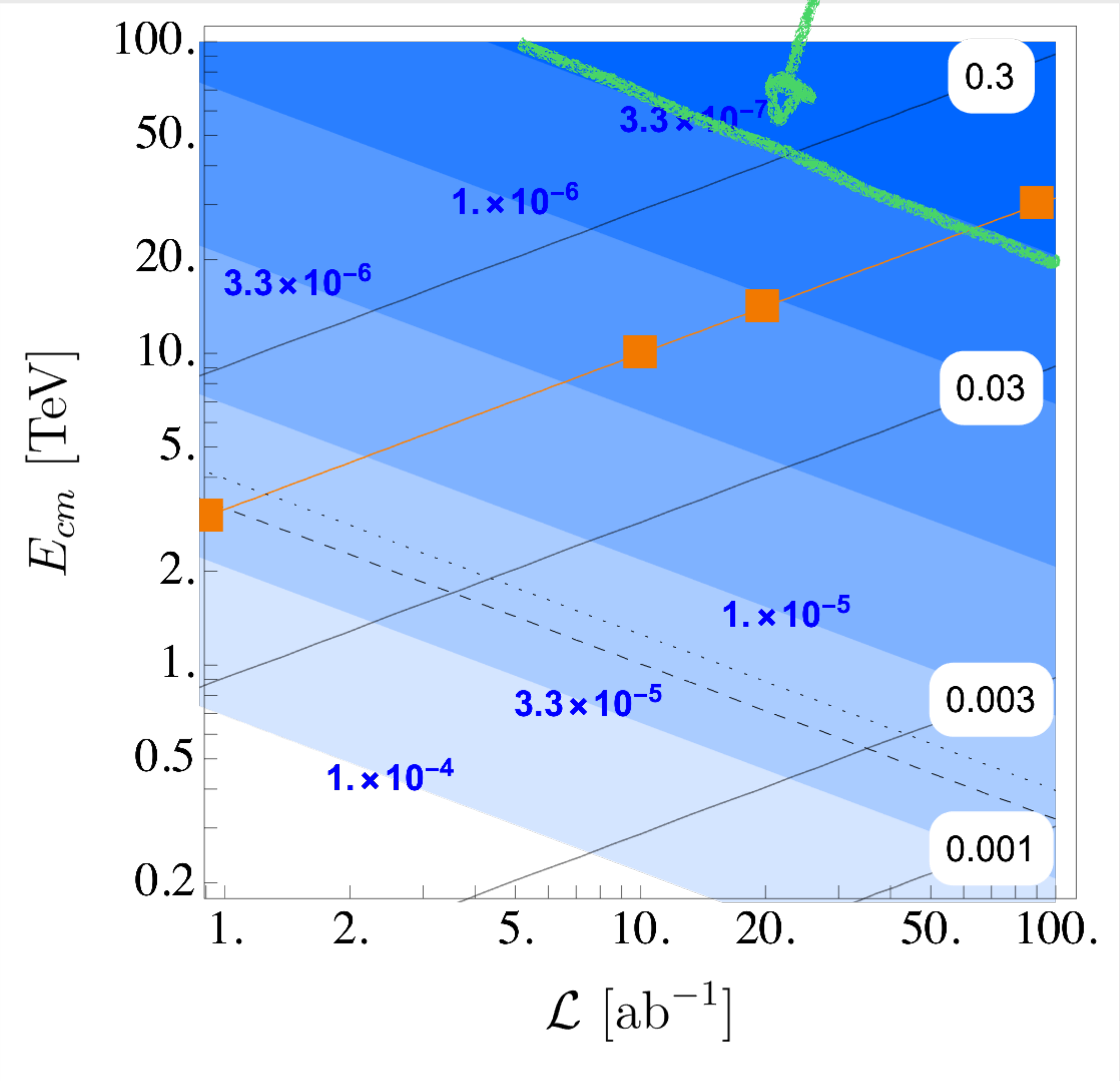
TOTAL RATE

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

minus 7

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

$\hat{S} \sim 10^{-7}$



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

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

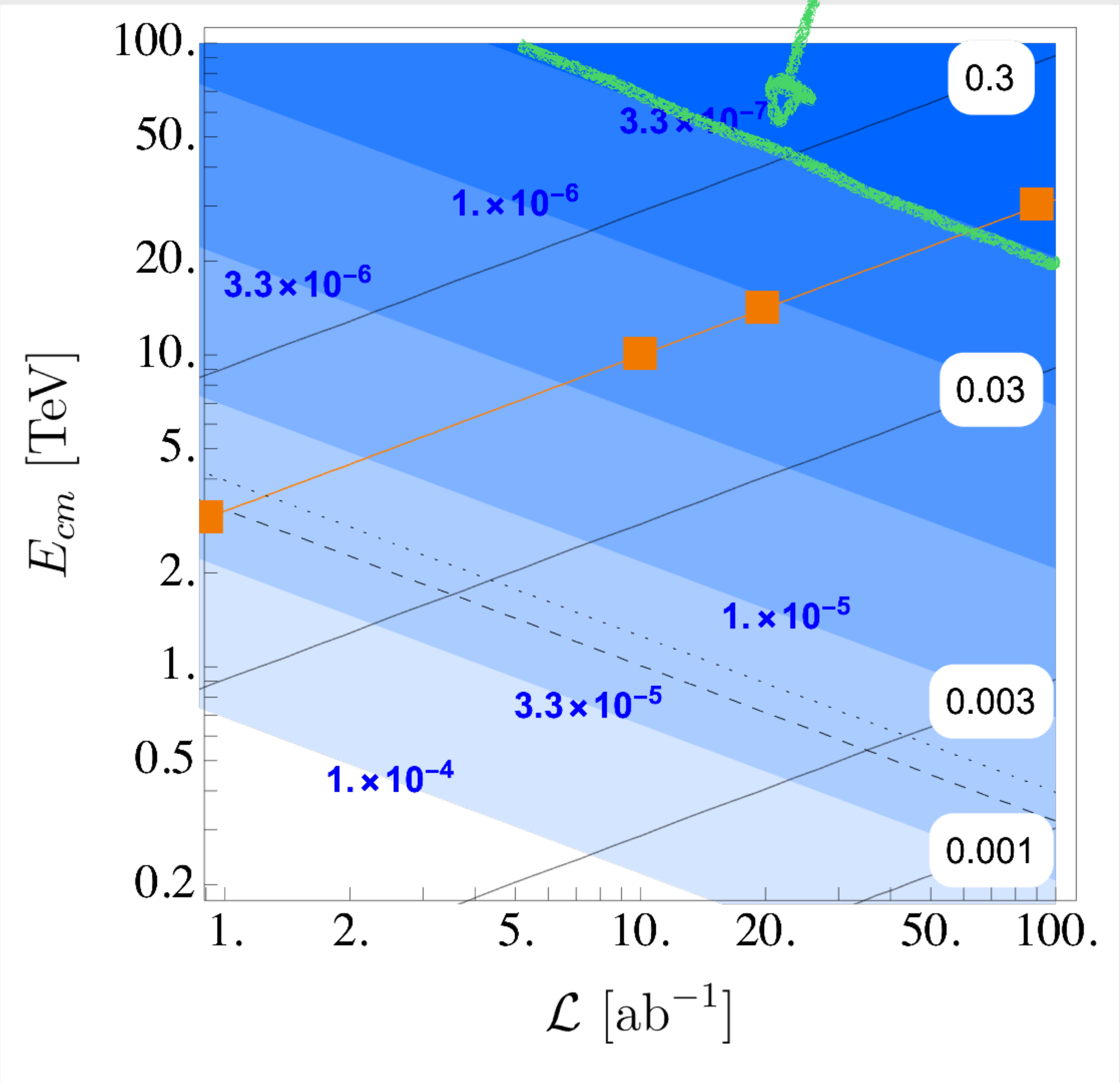
TOTAL RATE $\left|A^{(00)}_{SM}\right|^2 + A^{00}_{SM} \cdot A^{00}_{BSM} + \ldots$

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

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

minus 7

$\hat{S} \sim 10^{-7}$



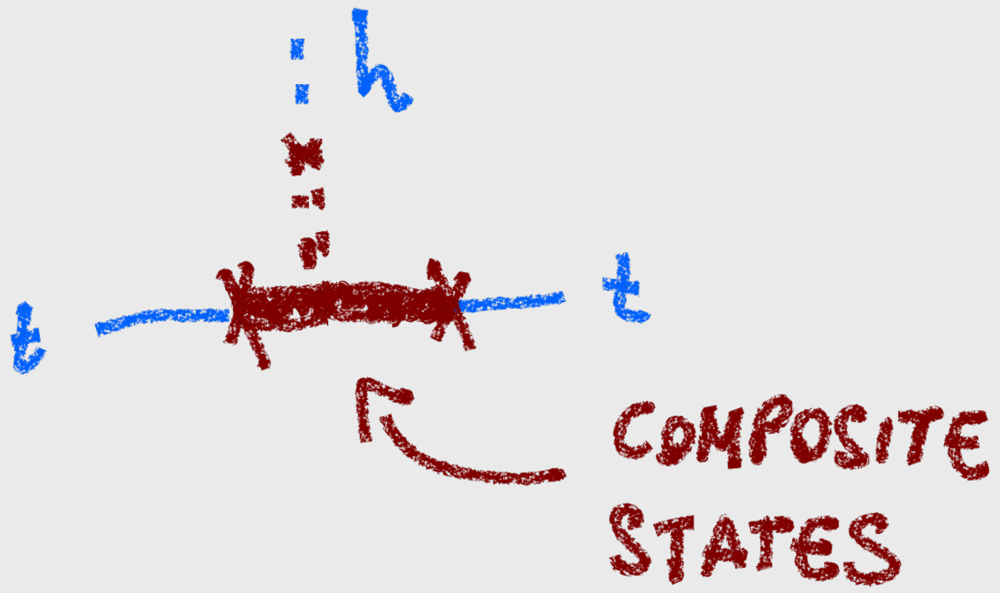
$$\hat{S} \equiv c_W/m_W^2 \simeq \frac{\delta O}{O} \text{ at Z pole}$$

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

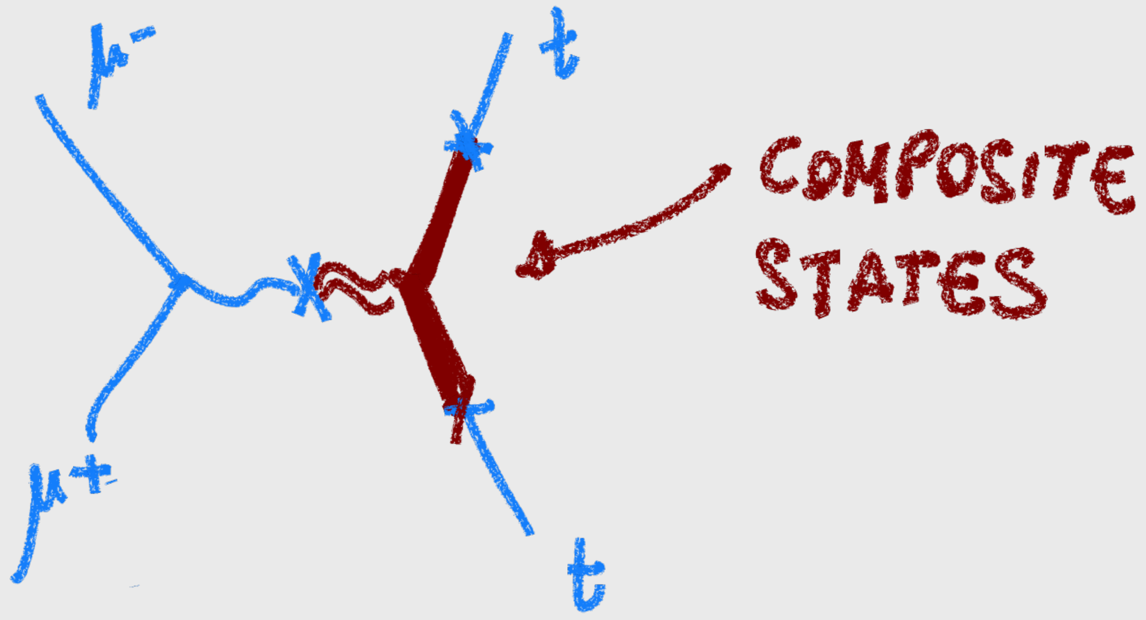
Effects of the size of the top quark

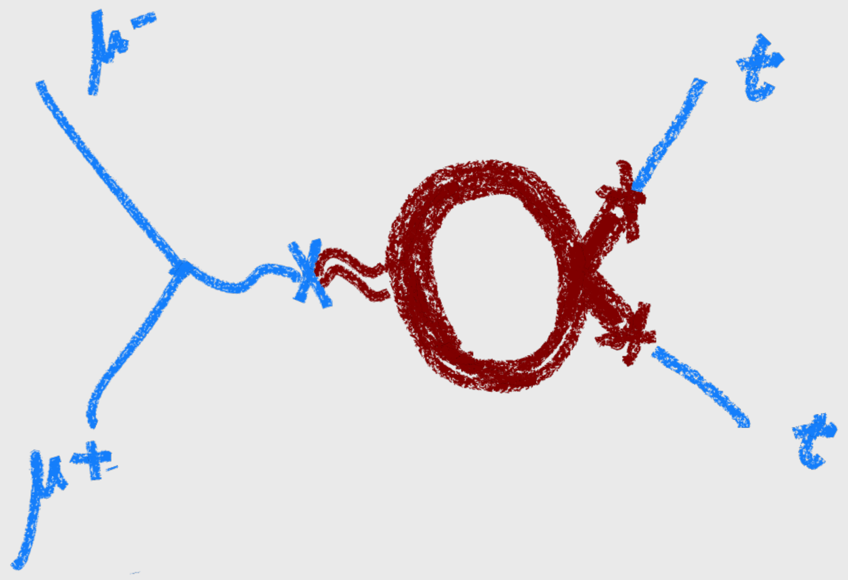
STRONGLY INTERACTING TOP AND HIGGS

- Top quarks are naturally involved in a composite Higgs sector.



- $t\bar{t}$ final states contain new information not present in generic $f\bar{f}$ Drell-Yan

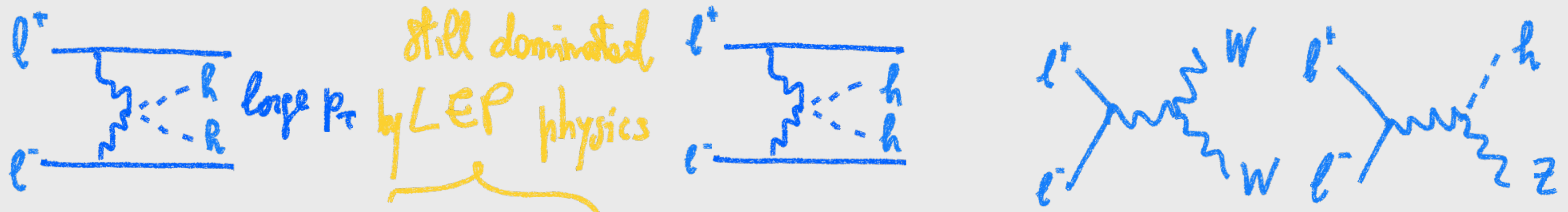




- enhanced $\mu\bar{\mu}t\bar{t}$ contact interaction!

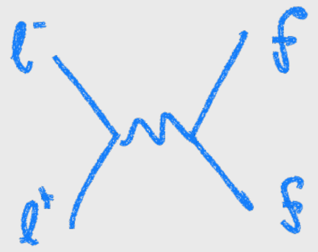
Effects of the size of the Higgs boson

STRONGLY INTERACTING TOP AND HIGGS



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

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



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

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

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

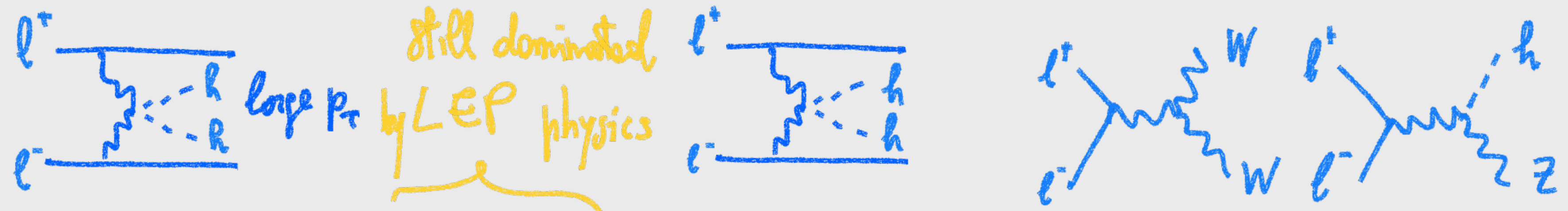
$1/(g_\star f) \sim 1/m_\star$

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

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

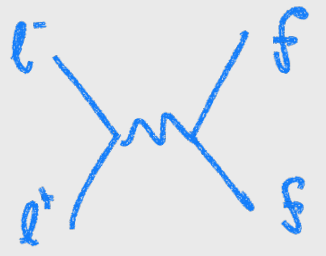
Effects of the size of the Higgs boson

STRONGLY INTERACTING TOP AND HIGGS



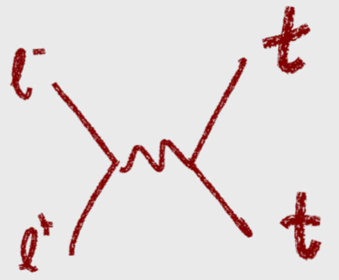
$$\mathcal{L}^{d=6}_{universal} = c_H \frac{g_*^2}{m_*^2}\mathcal{O}_H + c_T \frac{N_c \epsilon_q^4 g_*^4}{(4\pi)^2 m_*^2}\mathcal{O}_T + c_6 \lambda \frac{g_*^2}{m_*^2}\mathcal{O}_6 + \frac{1}{m_*^2}\left[c_W \mathcal{O}_W + c_B \mathcal{O}_B\right]$$

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



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

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



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

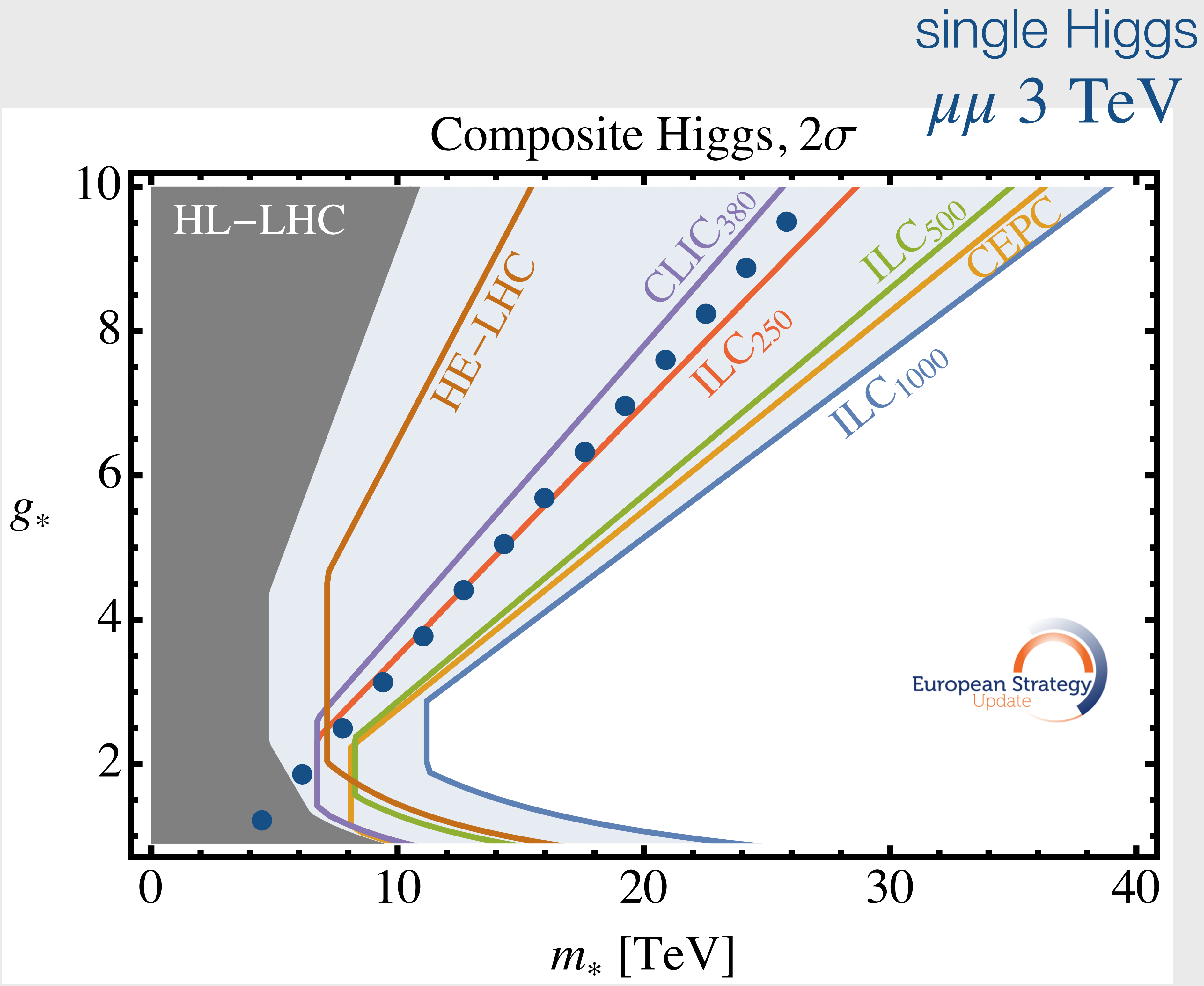
$1/f \sim g_\star/m_\star$

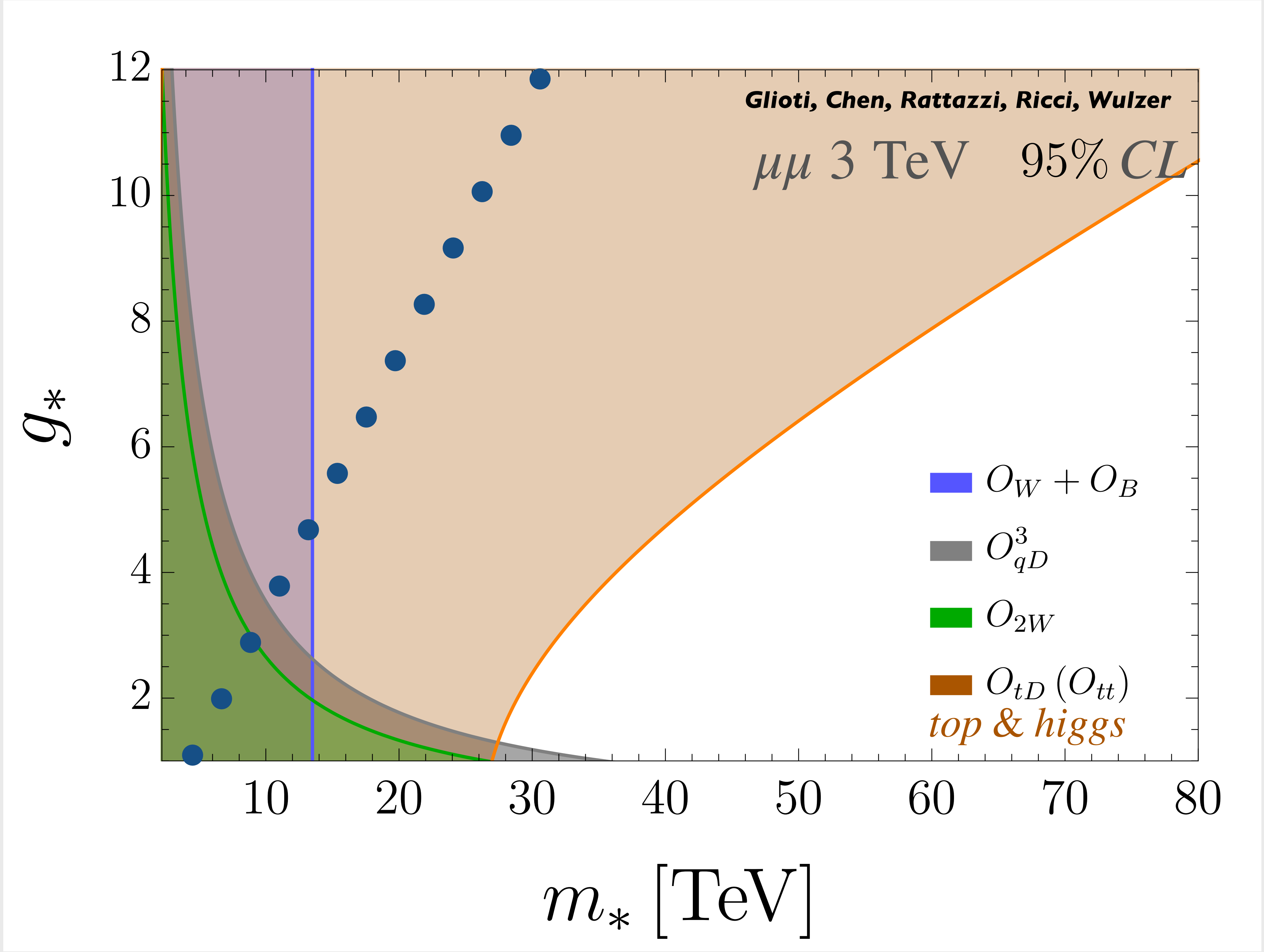
$1/(g_\star f) \sim 1/m_\star$

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

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

Looking ahead



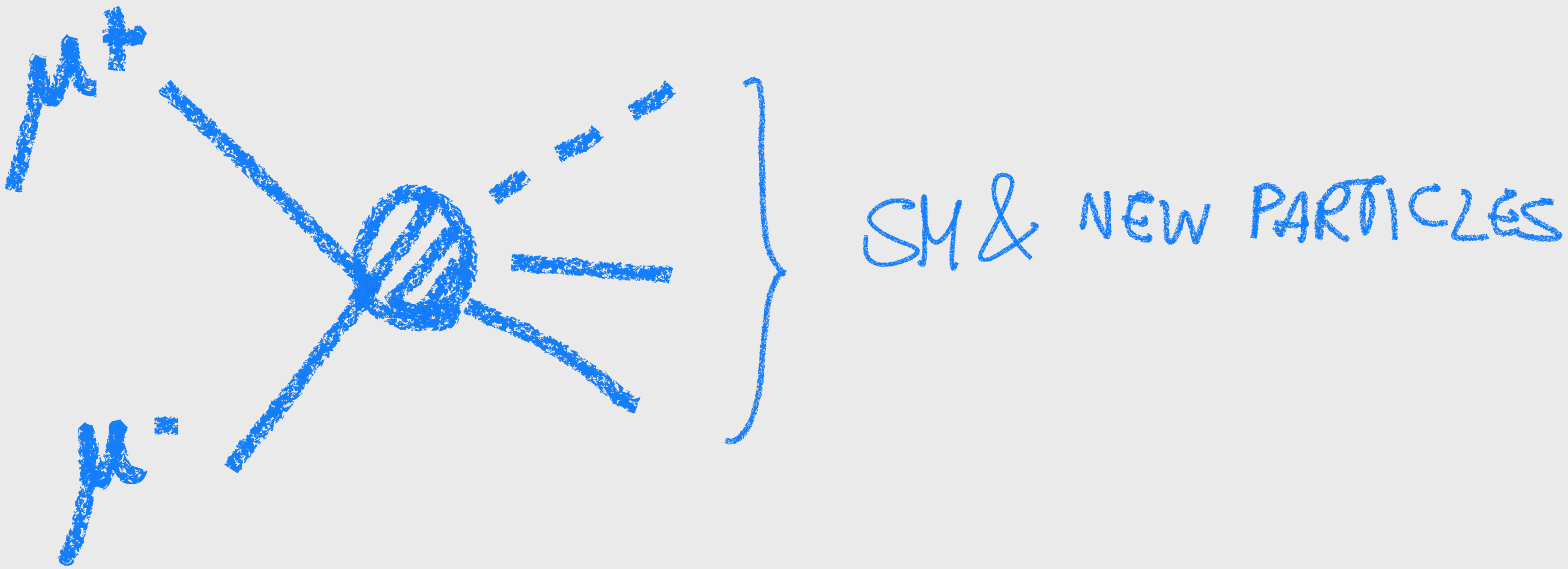


compositeness at few TeV @ HL-LHC

compositeness at few 10 TeV

“Others”

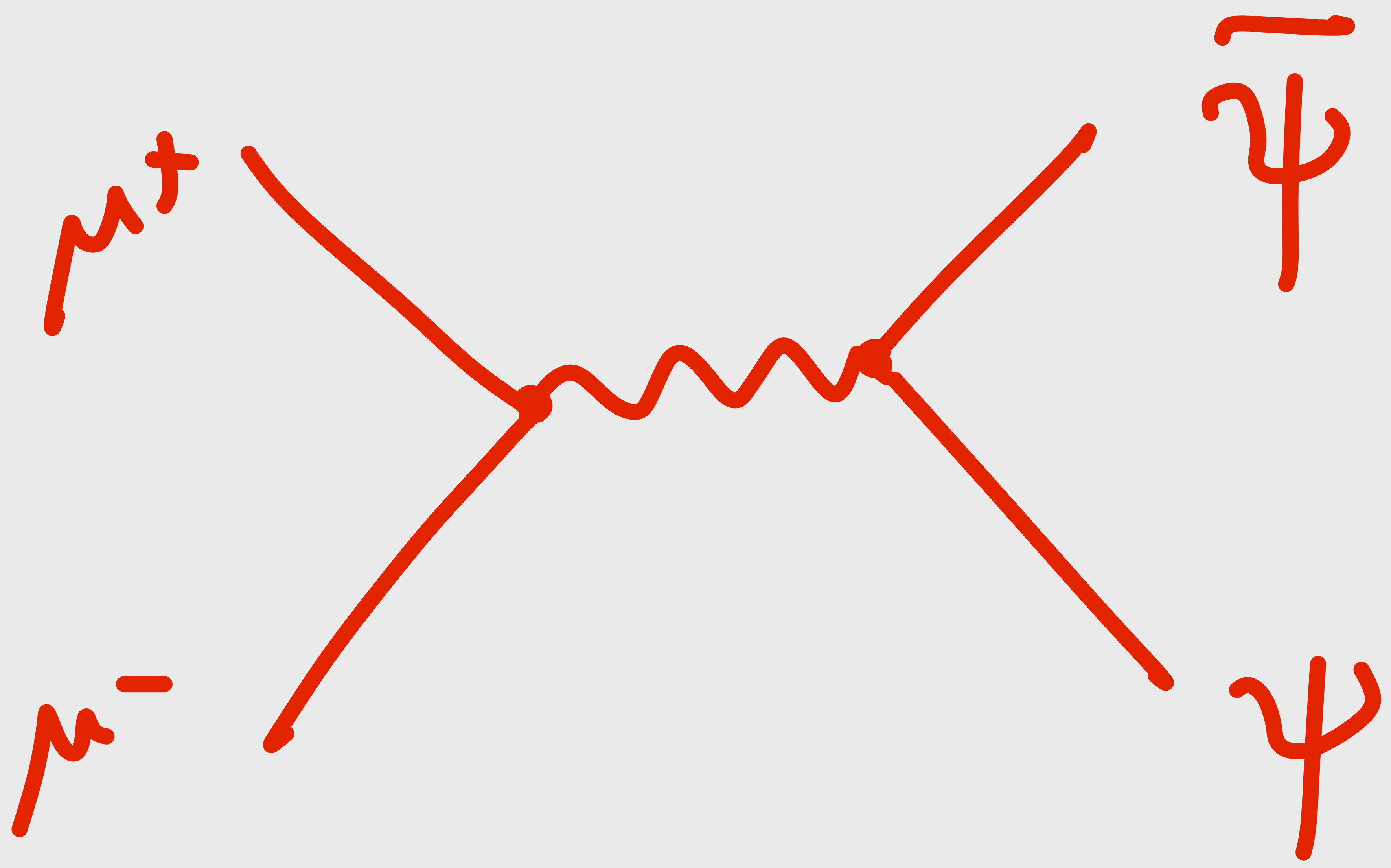
“Valence” Leptons



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

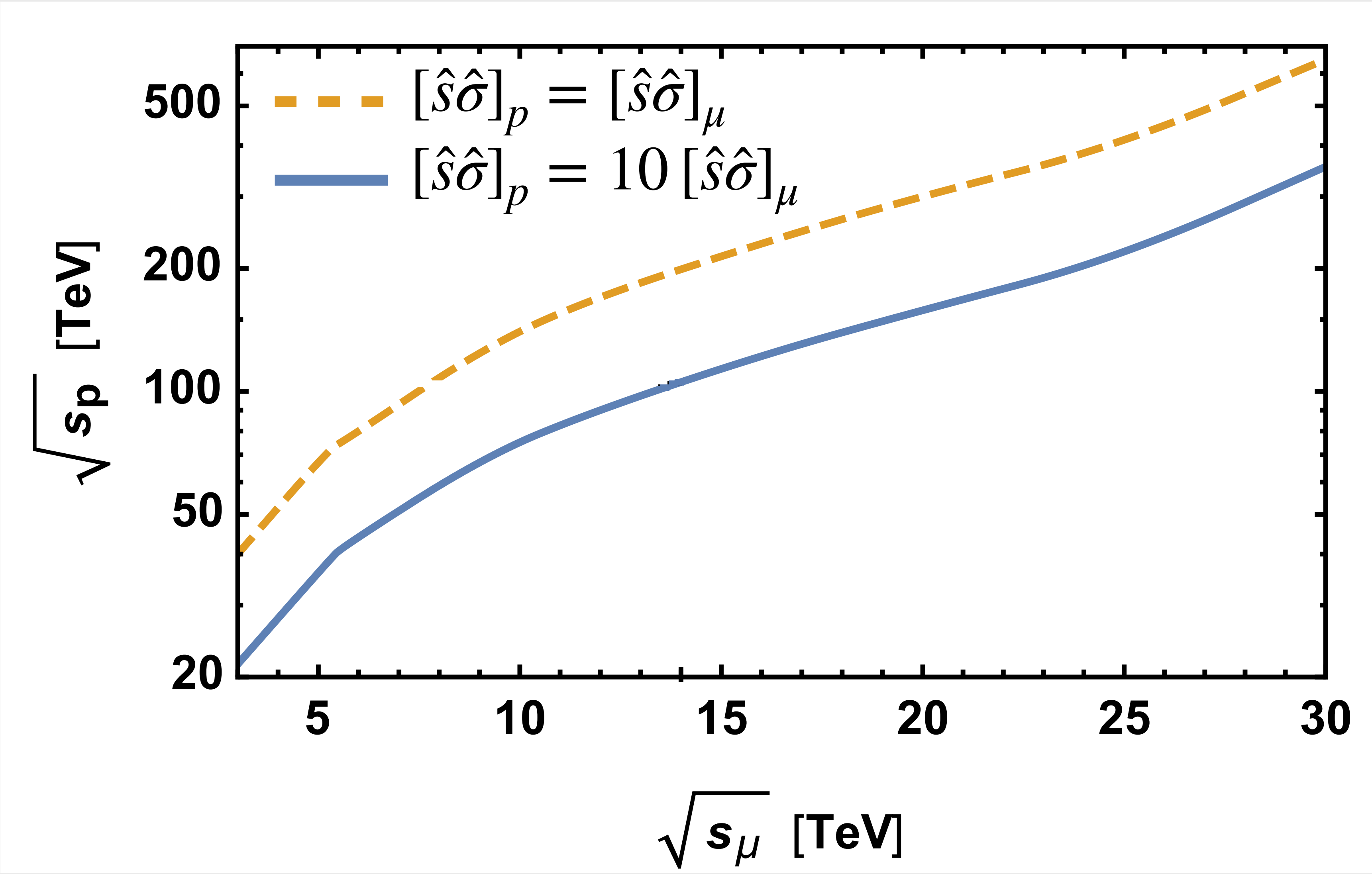
VALENCE MUONS

Can produce heavy new physics (colored or not)



in principle can probe directly new states at $\frac{\sqrt{s}}{2}$ scale!

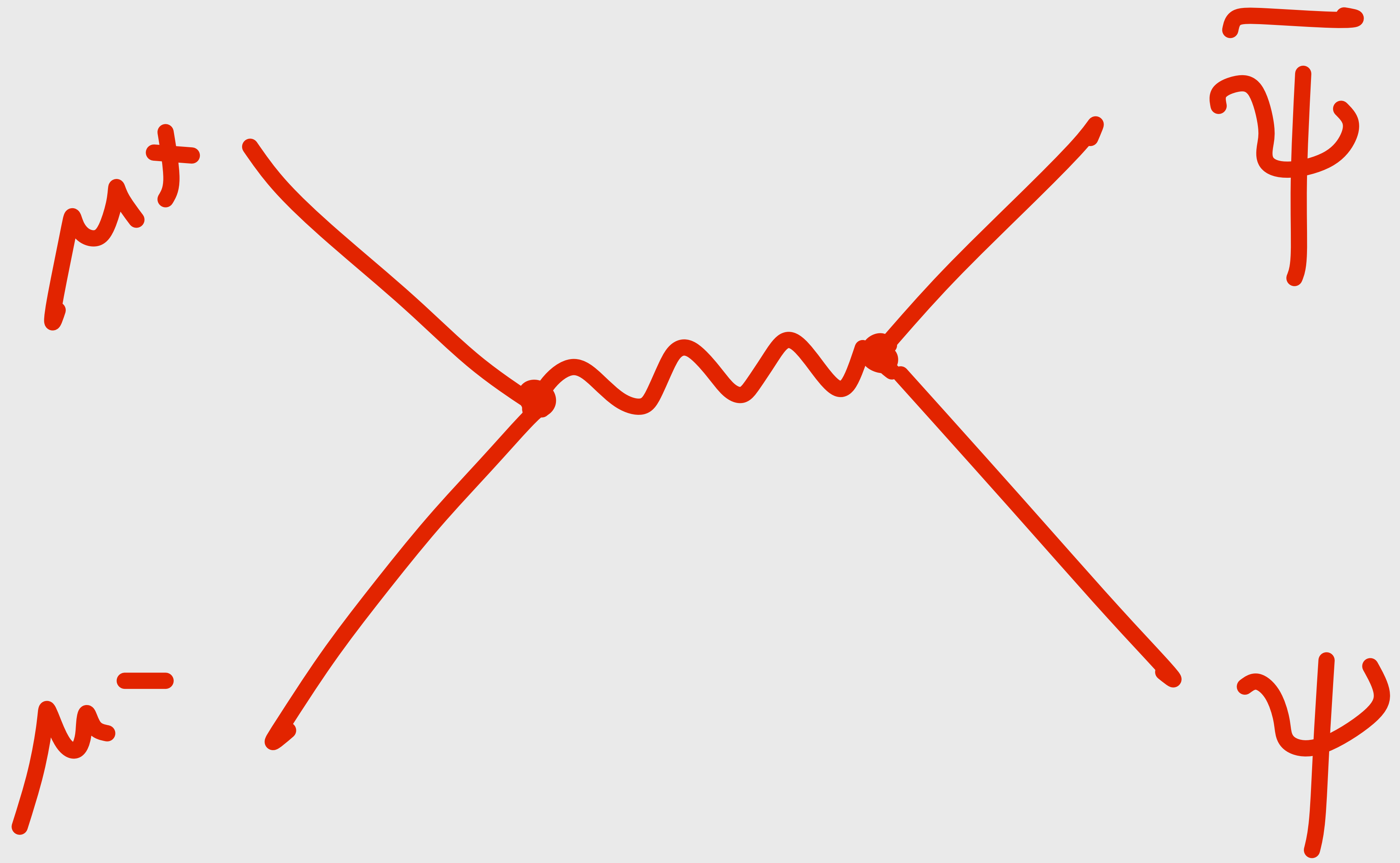
Compares pretty well with a *pp* collider 2005.10289



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

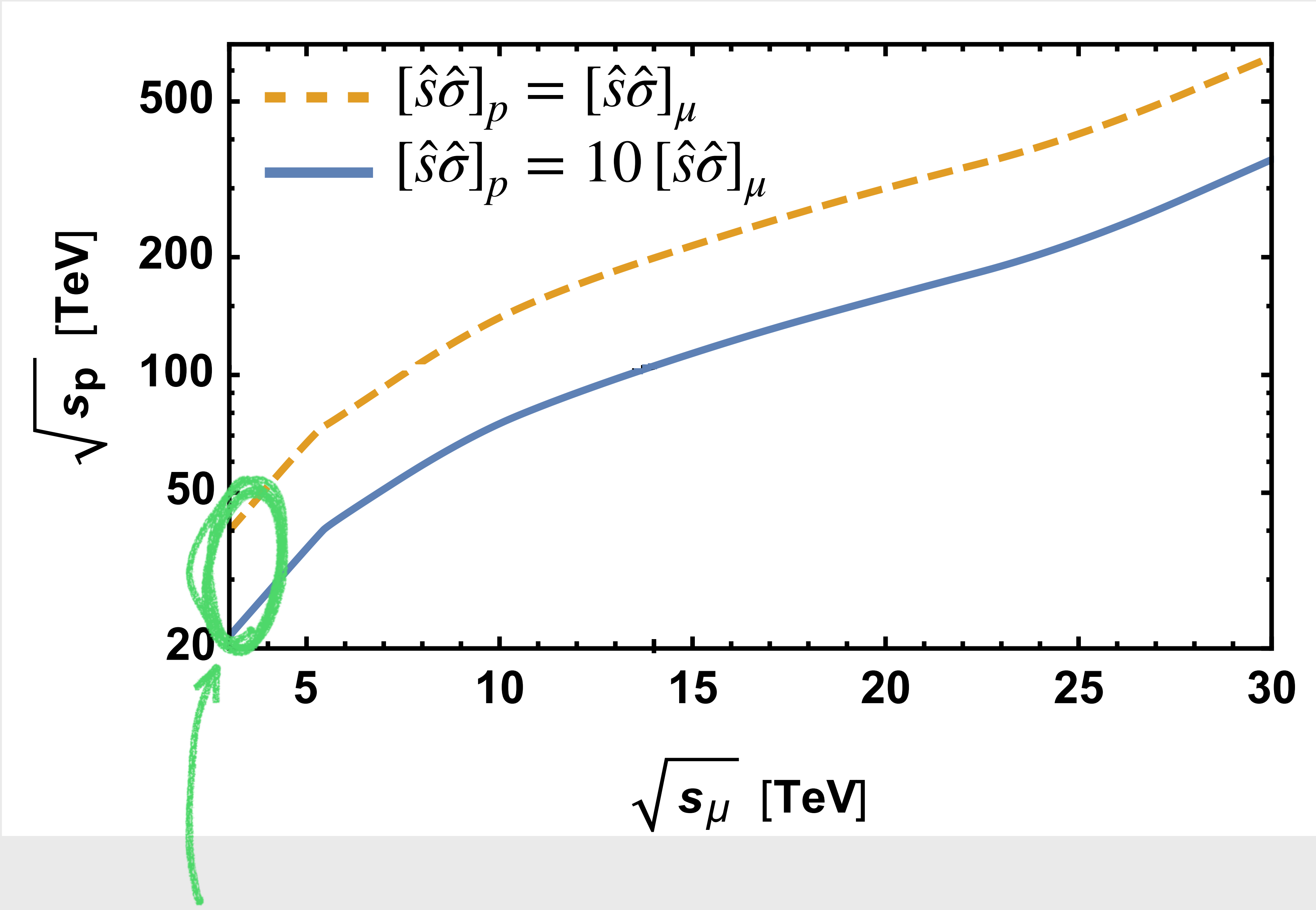
VALENCE MUONS

Can produce heavy new physics (colored or not)



in principle can probe directly new states at $\frac{\sqrt{s}}{2}$ scale!

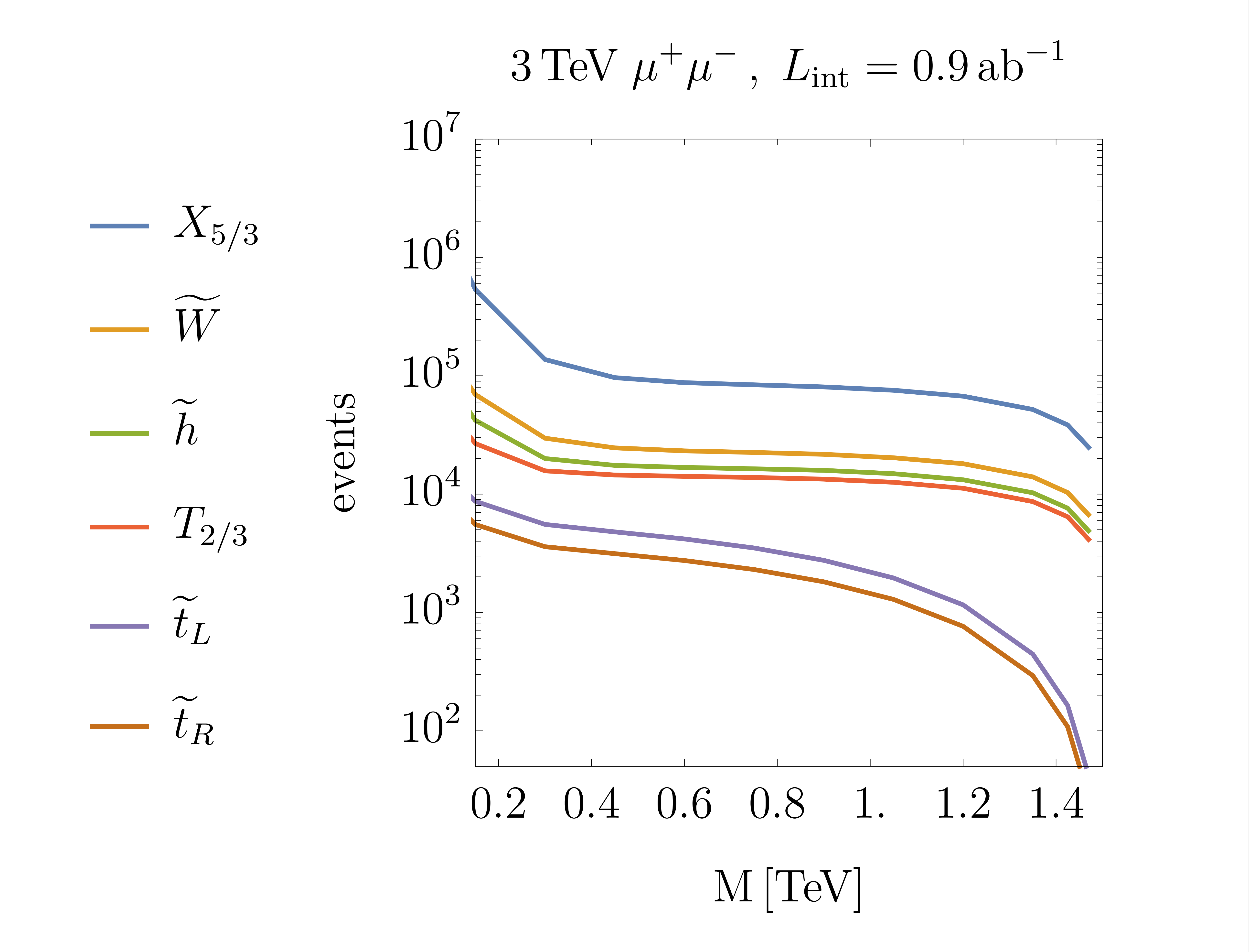
Compares pretty well with a *pp* collider 2005.10289



3 TeV $\mu^+\mu^-$ roughly equivalent to 20+ TeV *pp*

$\mu^+\mu^- \rightarrow$ new physics

VALENCE MUONS



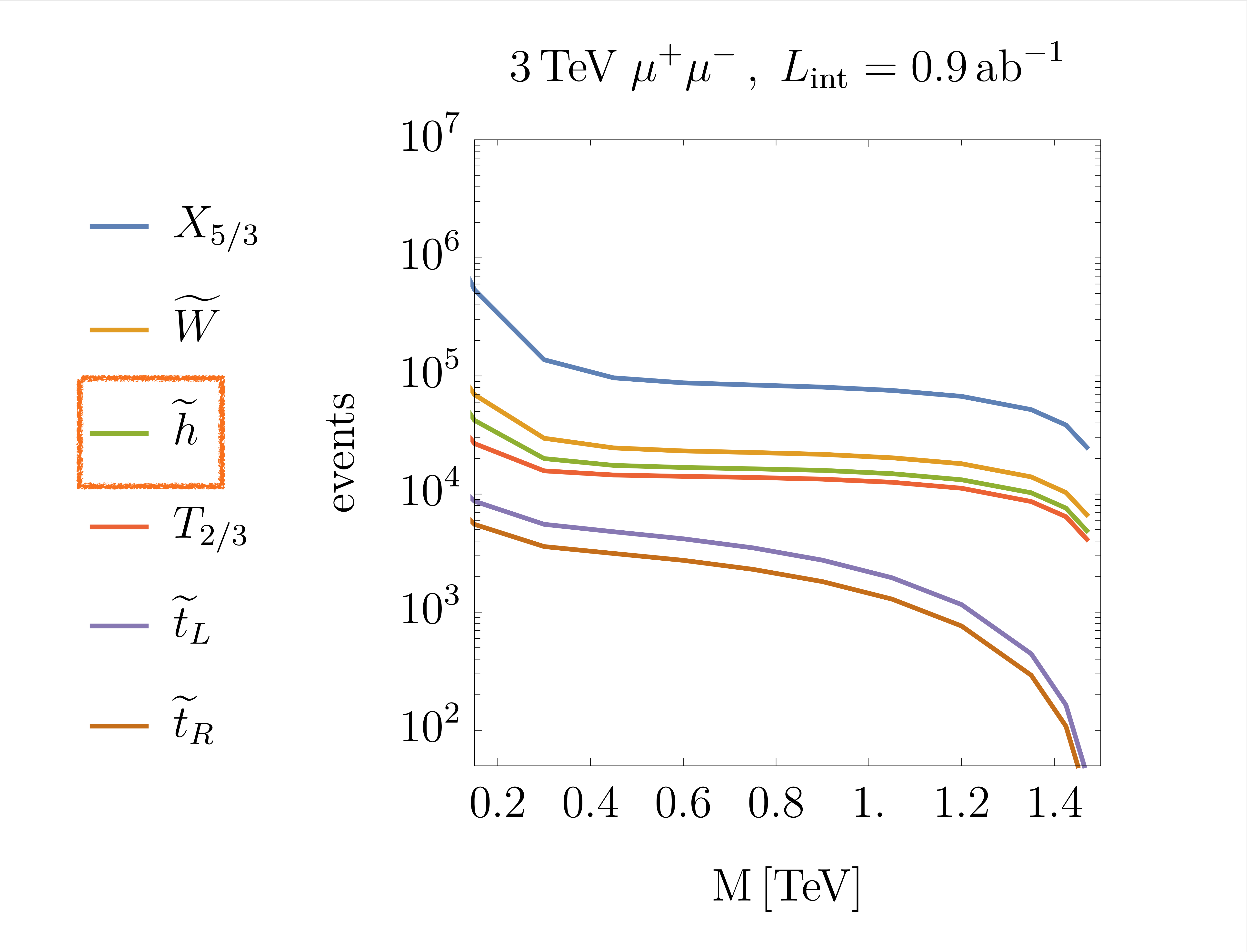
BEST POSITION TO OBSERVE ANY SIGN OF ELECTROWEAK NEW PHYSICS

(e.g. in the Higgs sector, or from new strong interactions at the TeV, fermions mass and mixing generation at the TeV)

Any sign of SUSY below the TeV will be observable, no matter if the sparticles are colored or not.

$\mu^+\mu^- \rightarrow$ new physics

VALENCE MUONS



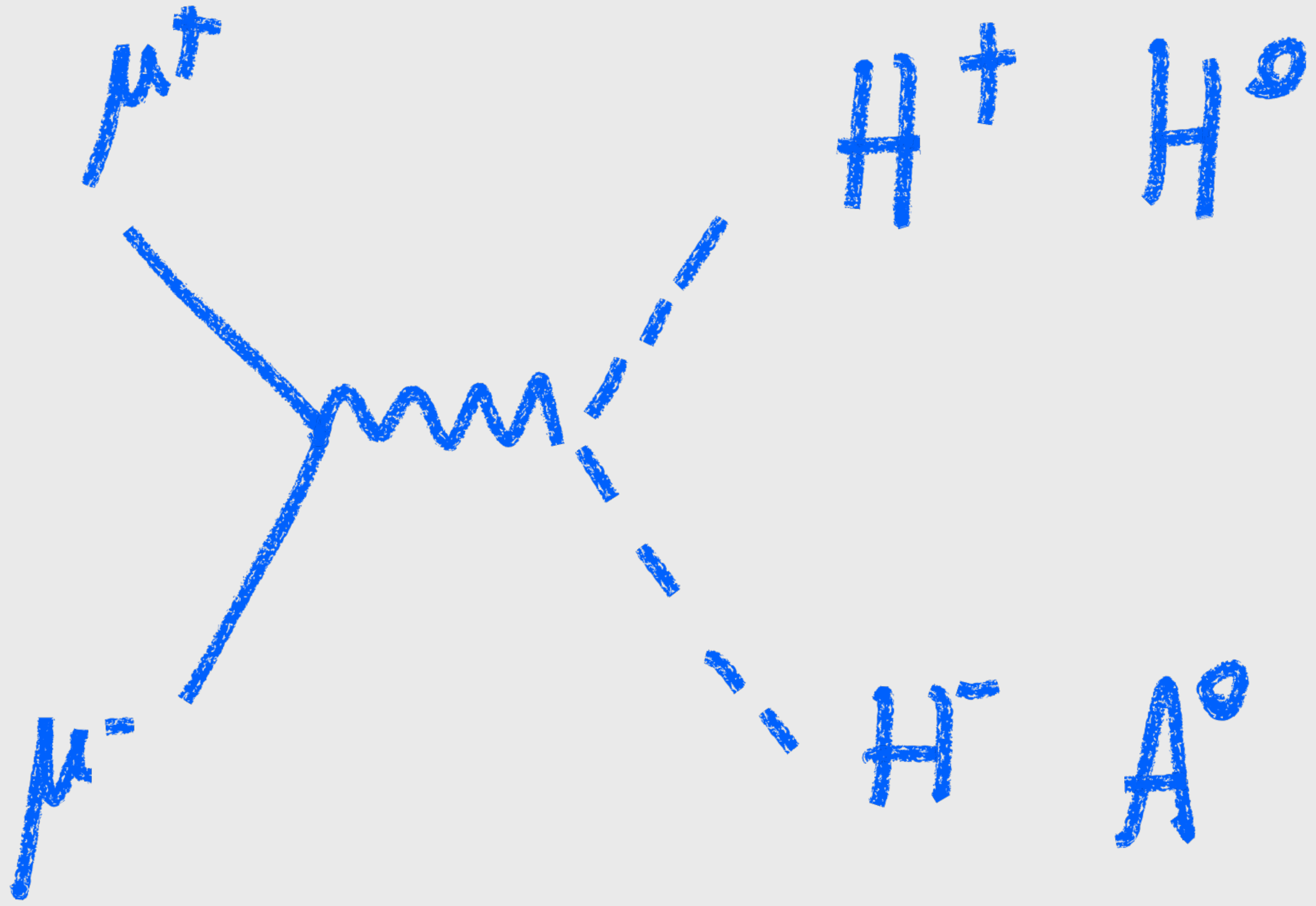
BEST POSITION TO OBSERVE ANY SIGN OF ELECTROWEAK NEW PHYSICS

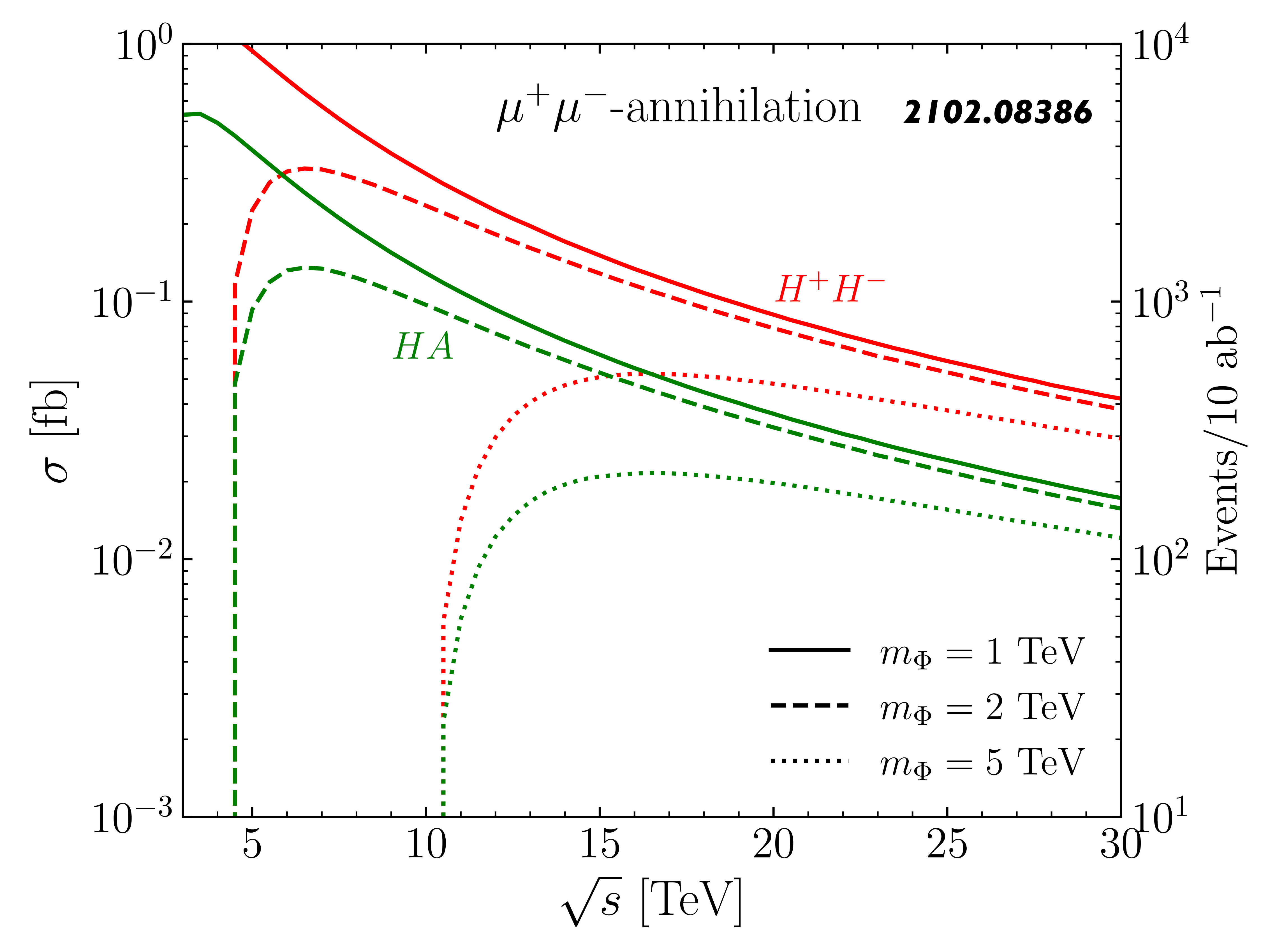
(e.g. in the Higgs sector or from new strong interactions at the TeV, fermions mass and mixing generation at the TeV)

Any sign of SUSY below the TeV will be observable, no matter if the sparticles are colored or not.

2HDM

VALENCE MUONS



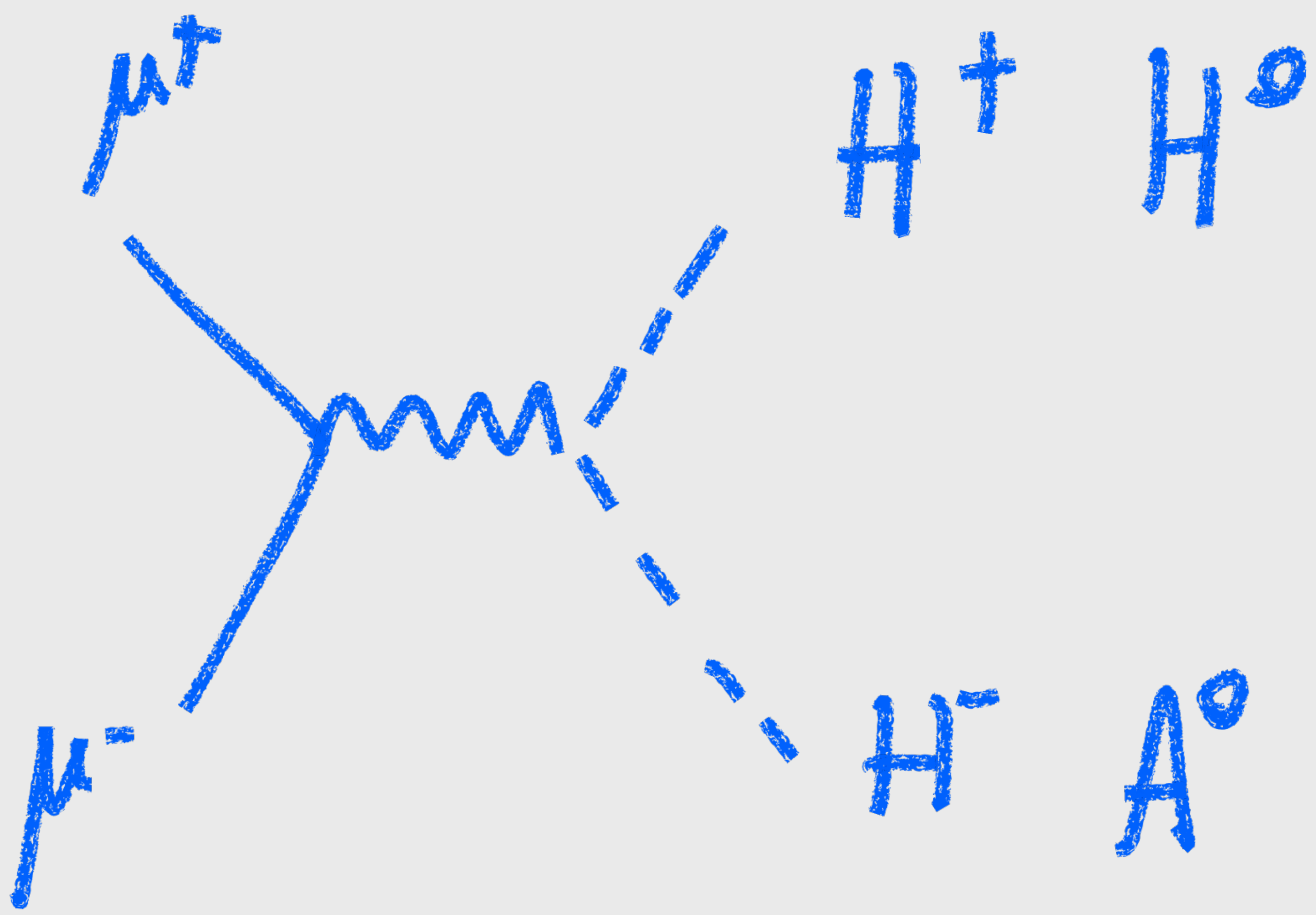


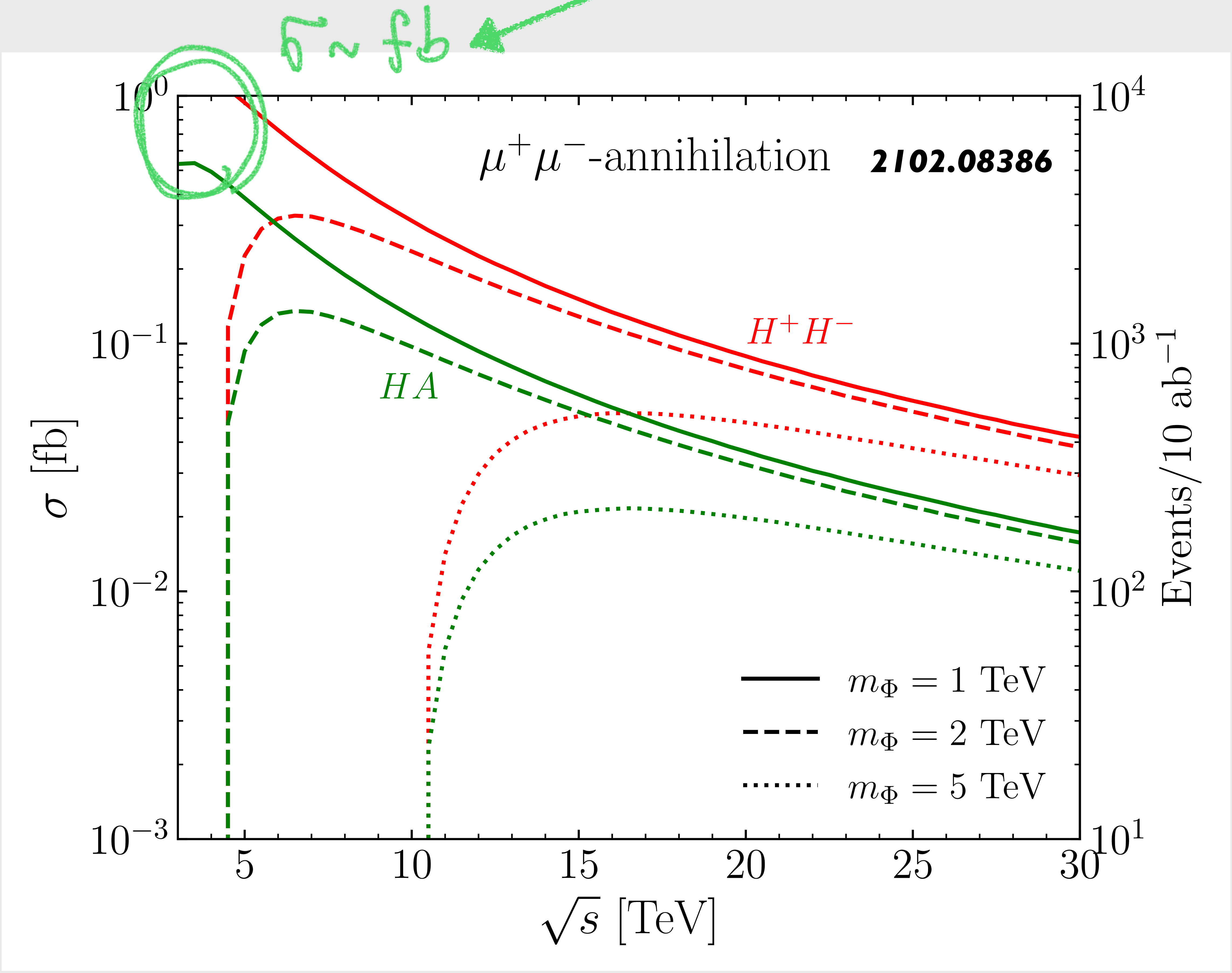
- HL-LHC coverage ends well below TeV
- detailed model analysis for 3 TeV desirable
- reach close to $\sqrt{s}/2$

2HDM

VALENCE MUONS

thousands of events per ab^{-1}
$\mu\mu$ 3 TeV
$\sigma \simeq 1$ fb





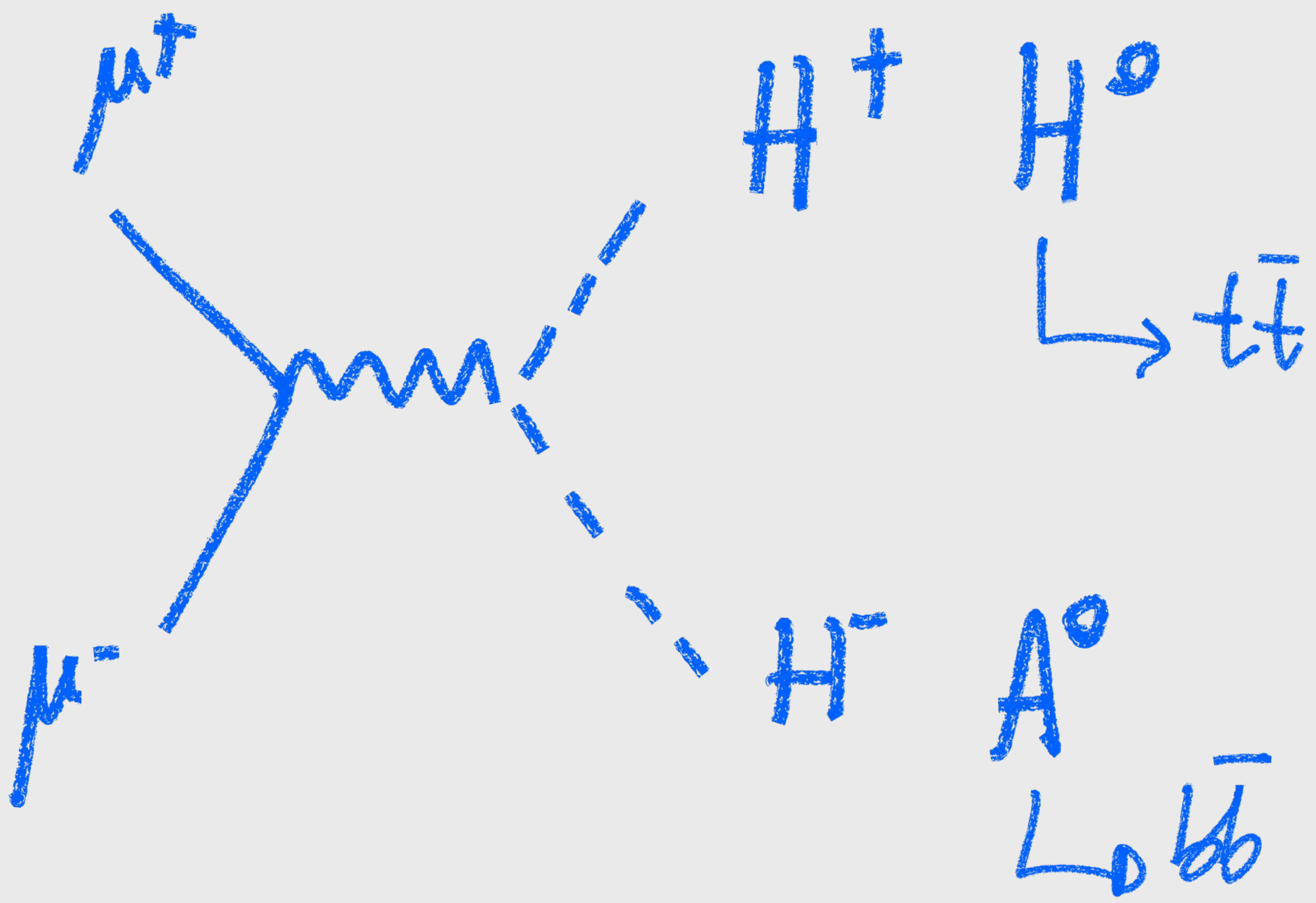
- HL-LHC coverage ends well below TeV
- detailed model analysis for 3 TeV desirable
- reach close to $\sqrt{s}/2$

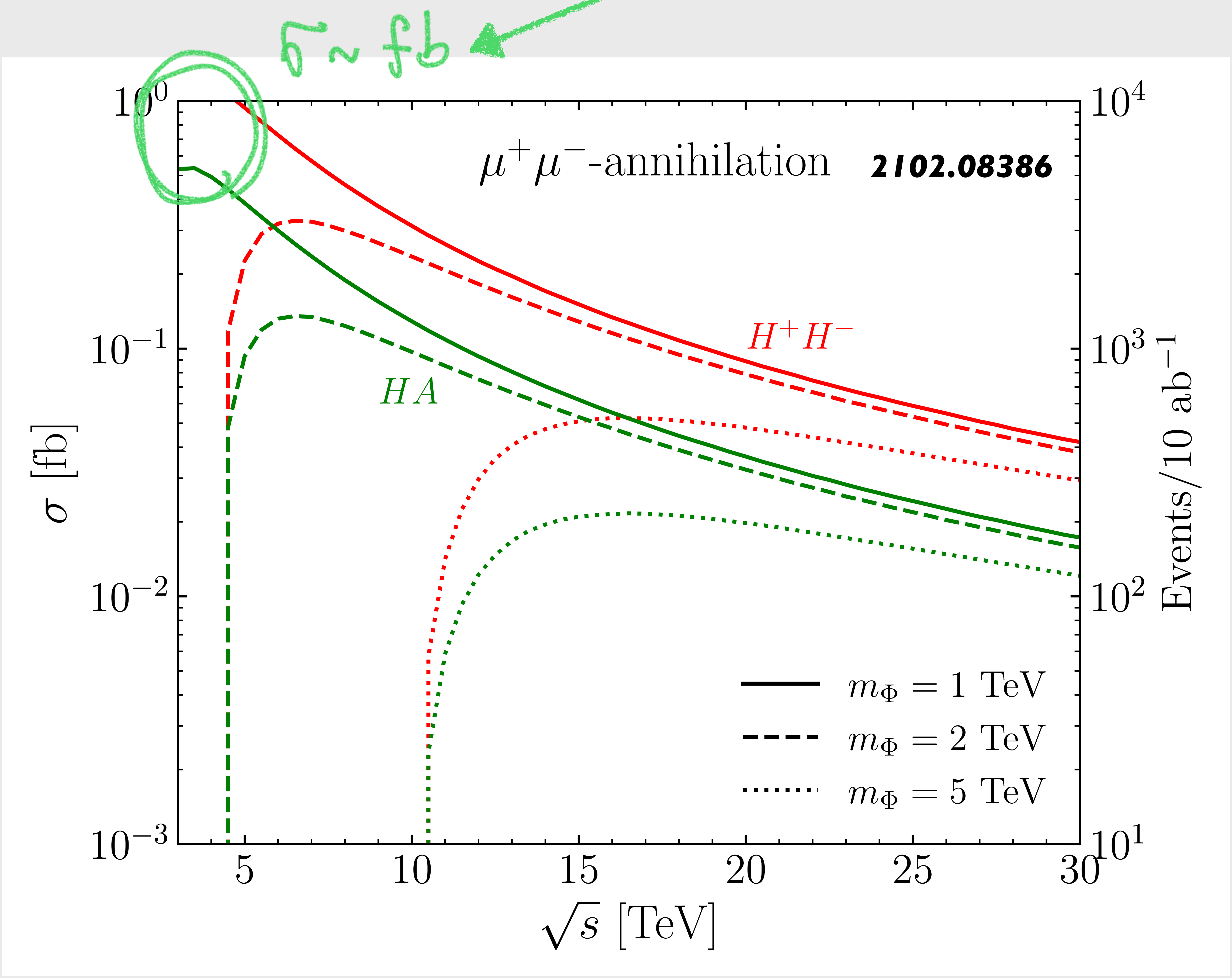
2HDM

VALENCE MUONS

thousands of events per ab^{-1}

$\mu\mu$ 3 TeV
$\sigma \simeq 1$ fb

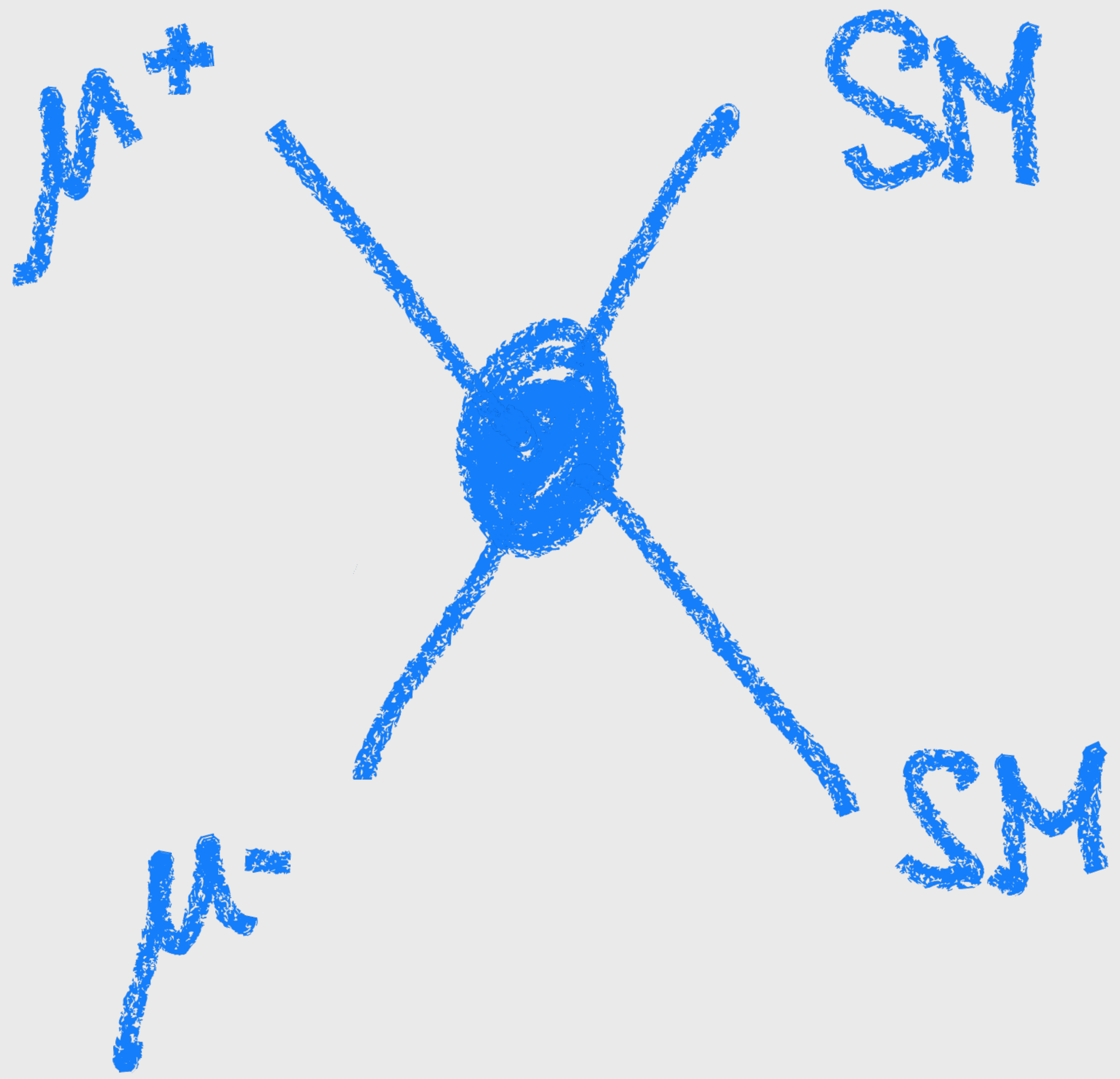




- HL-LHC coverage ends well below TeV
- detailed model analysis for 3 TeV desirable
- reach close to $\sqrt{s}/2$

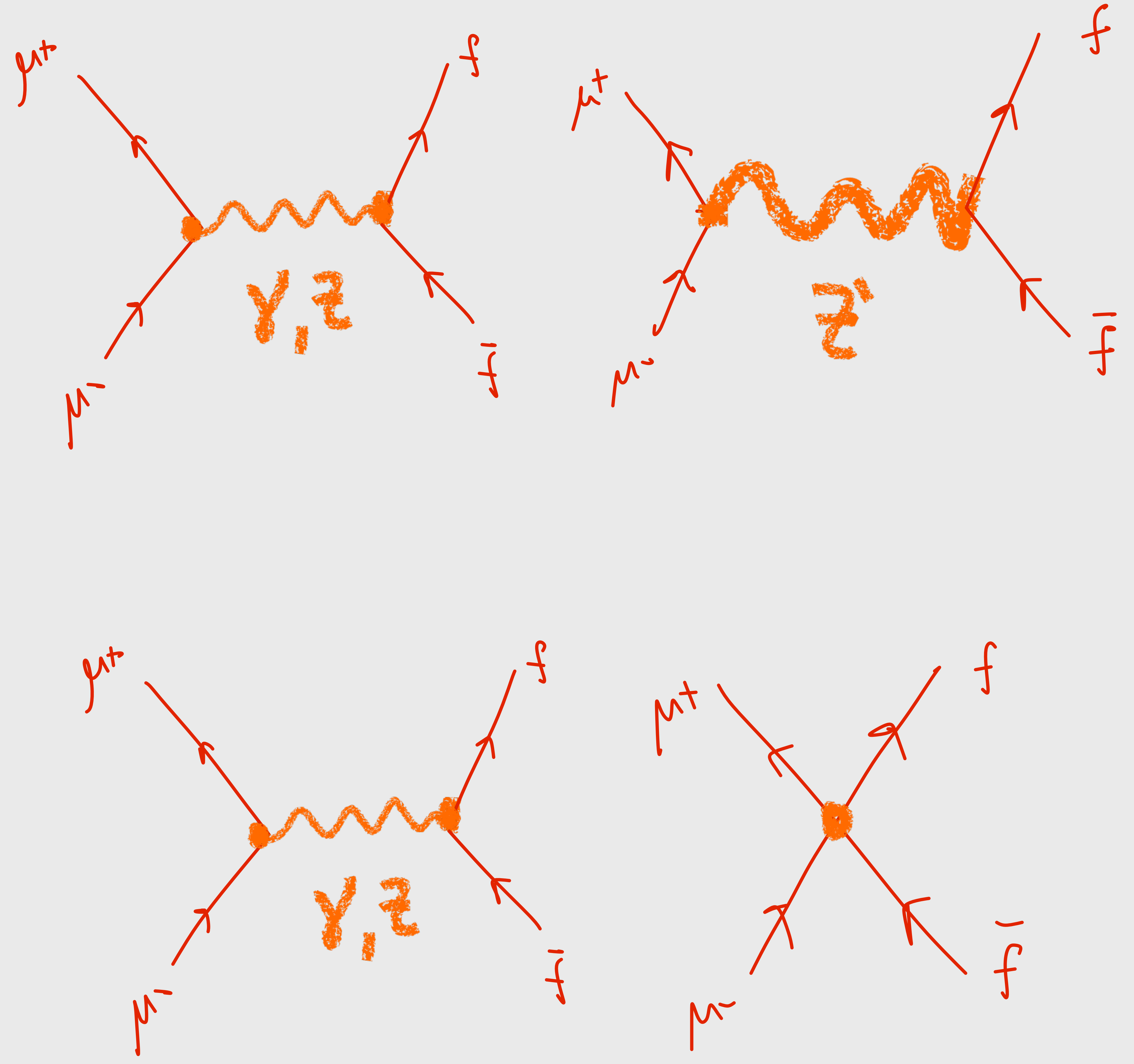
at $\sqrt{s} \gg 100$ GeV

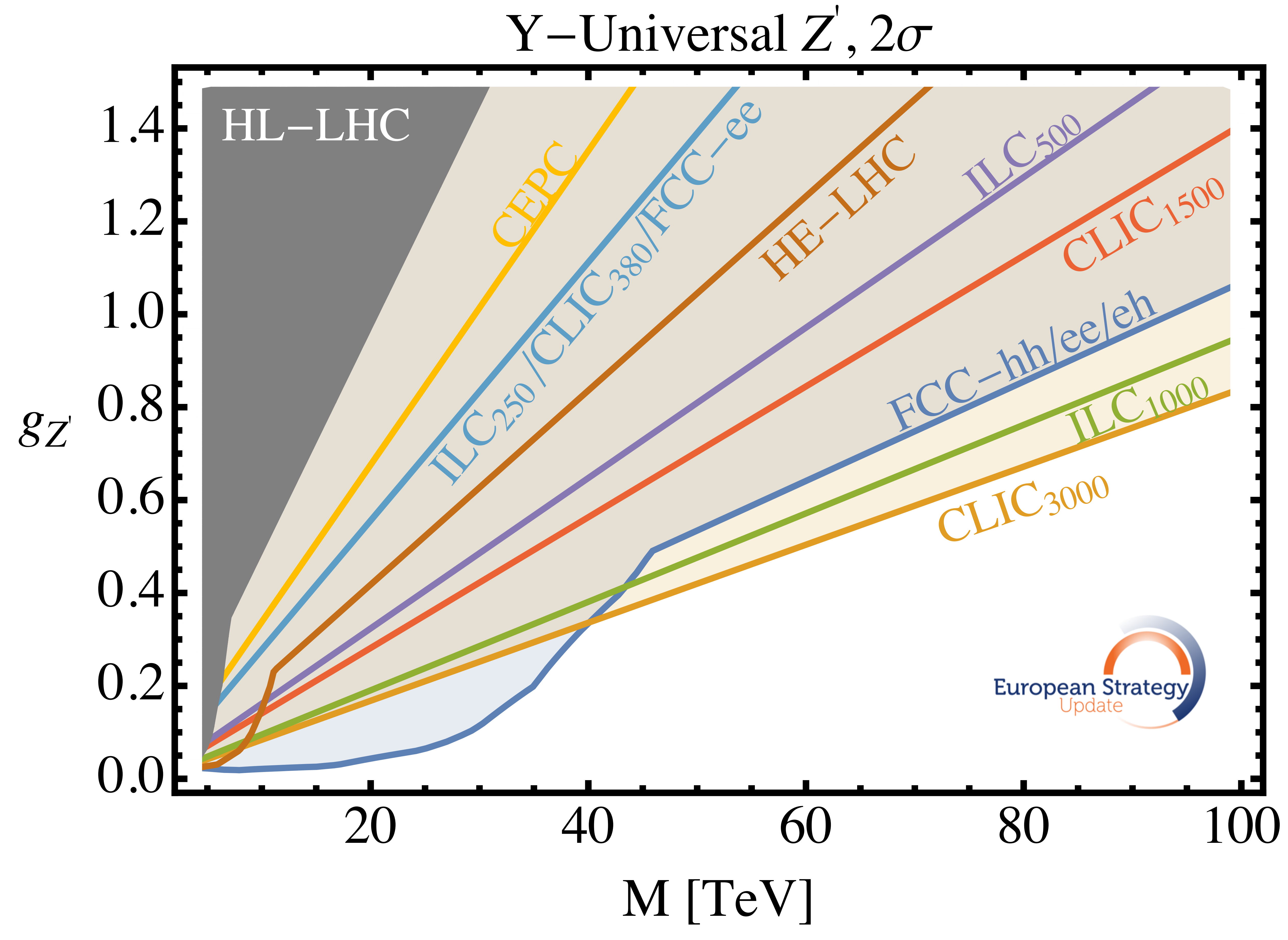
Indirect Effects



A heavy Z'

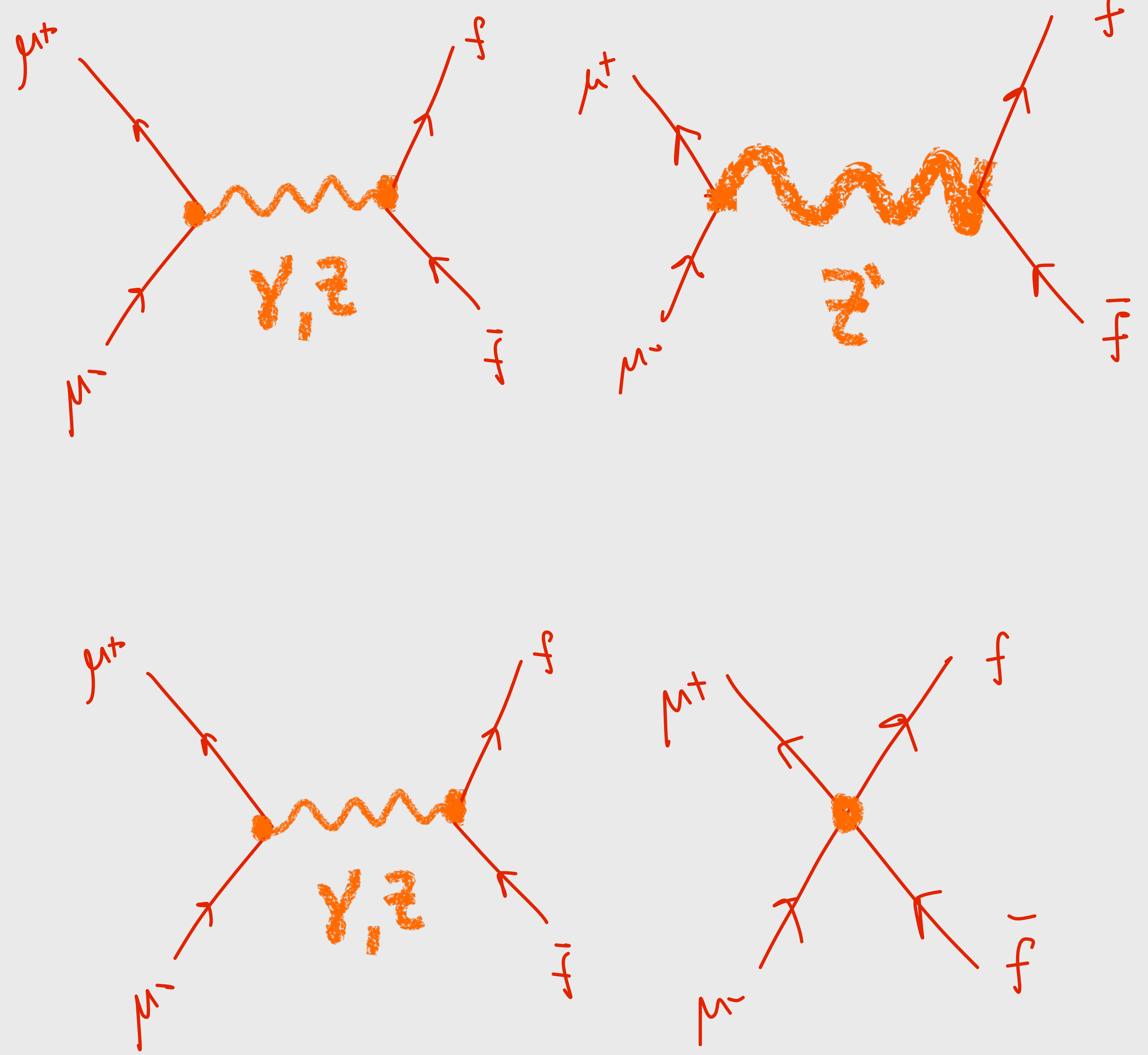
DRELL-YAN | RATES AND ANGULAR DISTRIBUTIONS

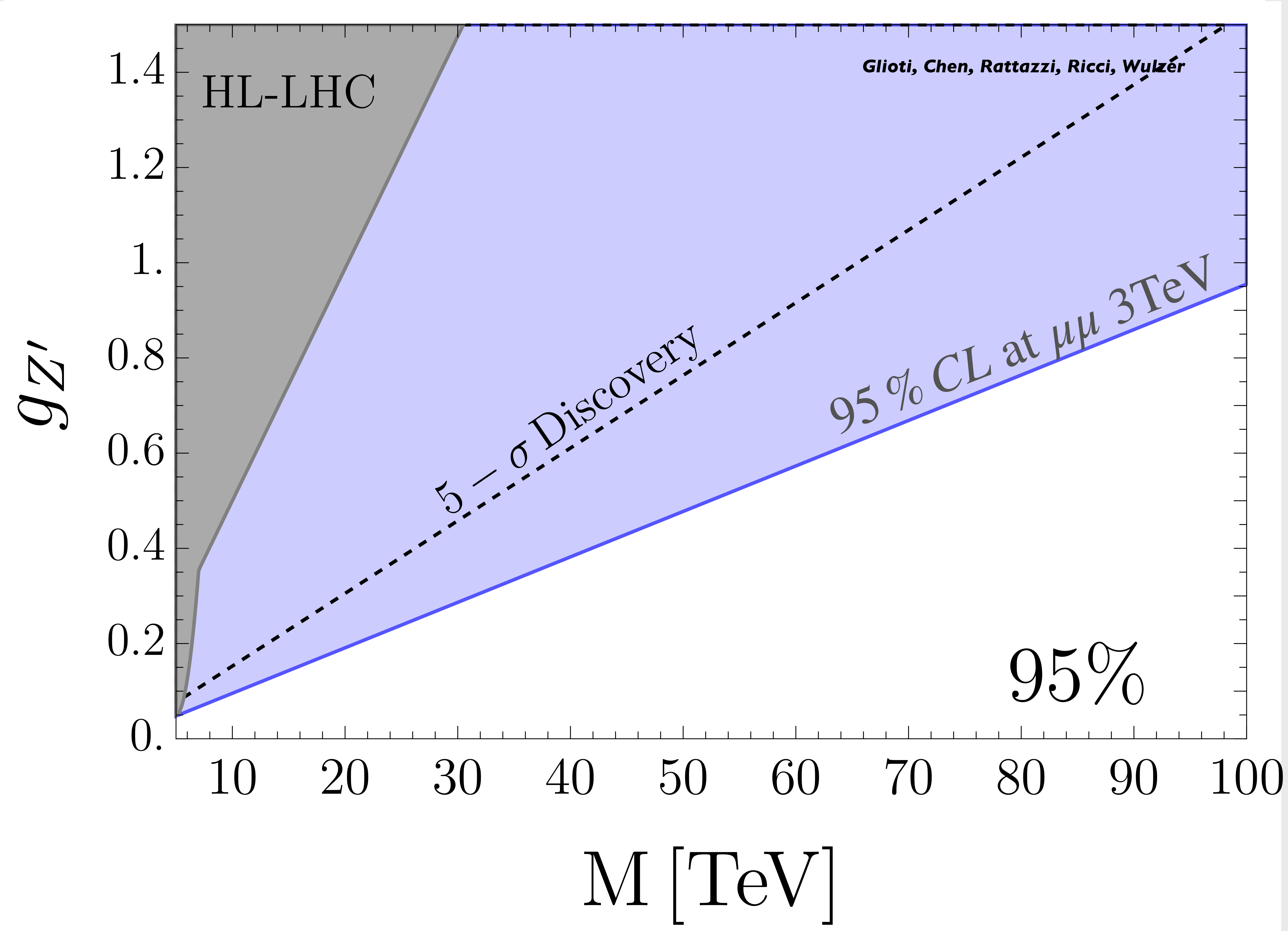




A heavy Z'

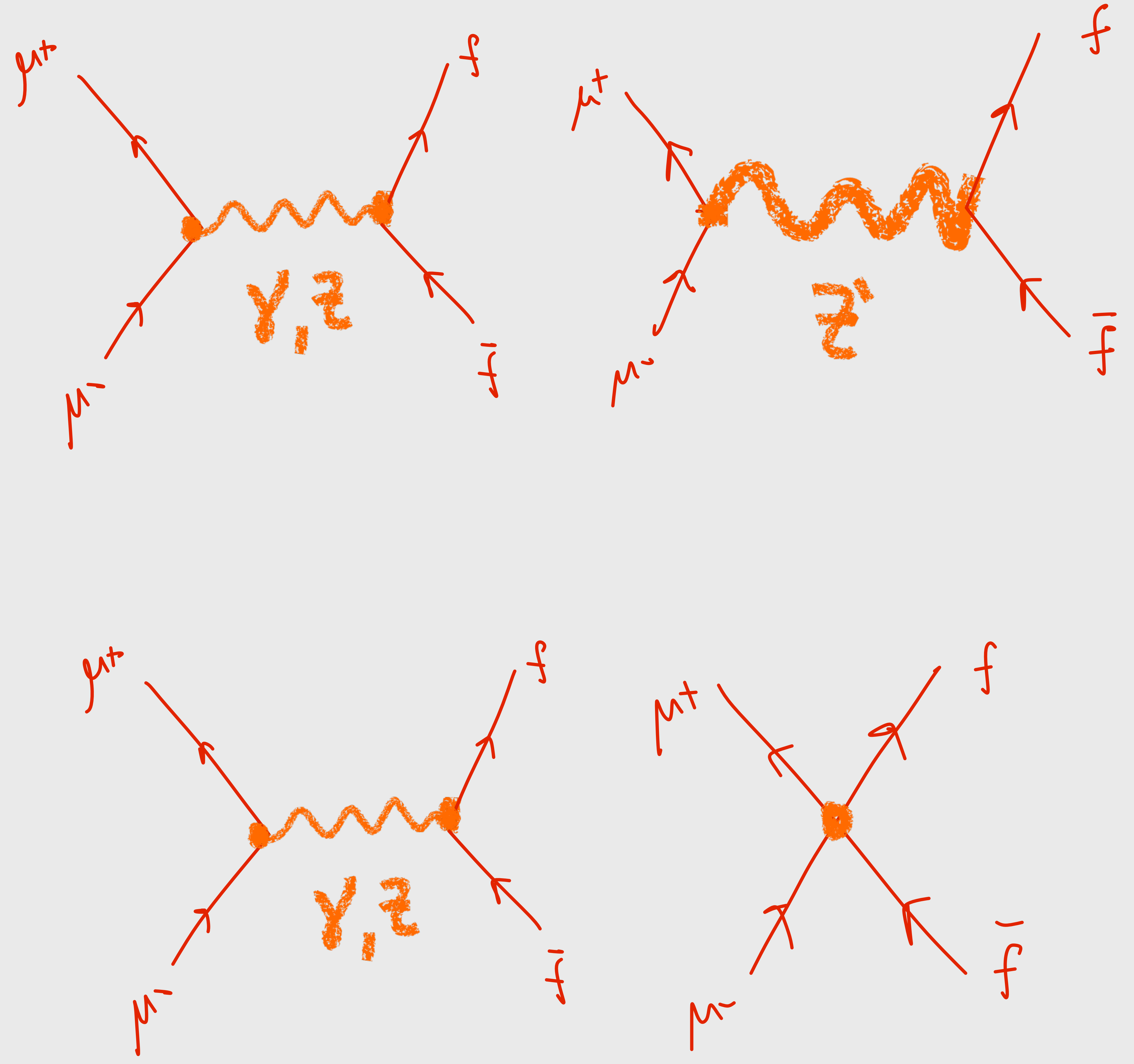
DRELL-YAN | RATES AND ANGULAR DISTRIBUTIONS

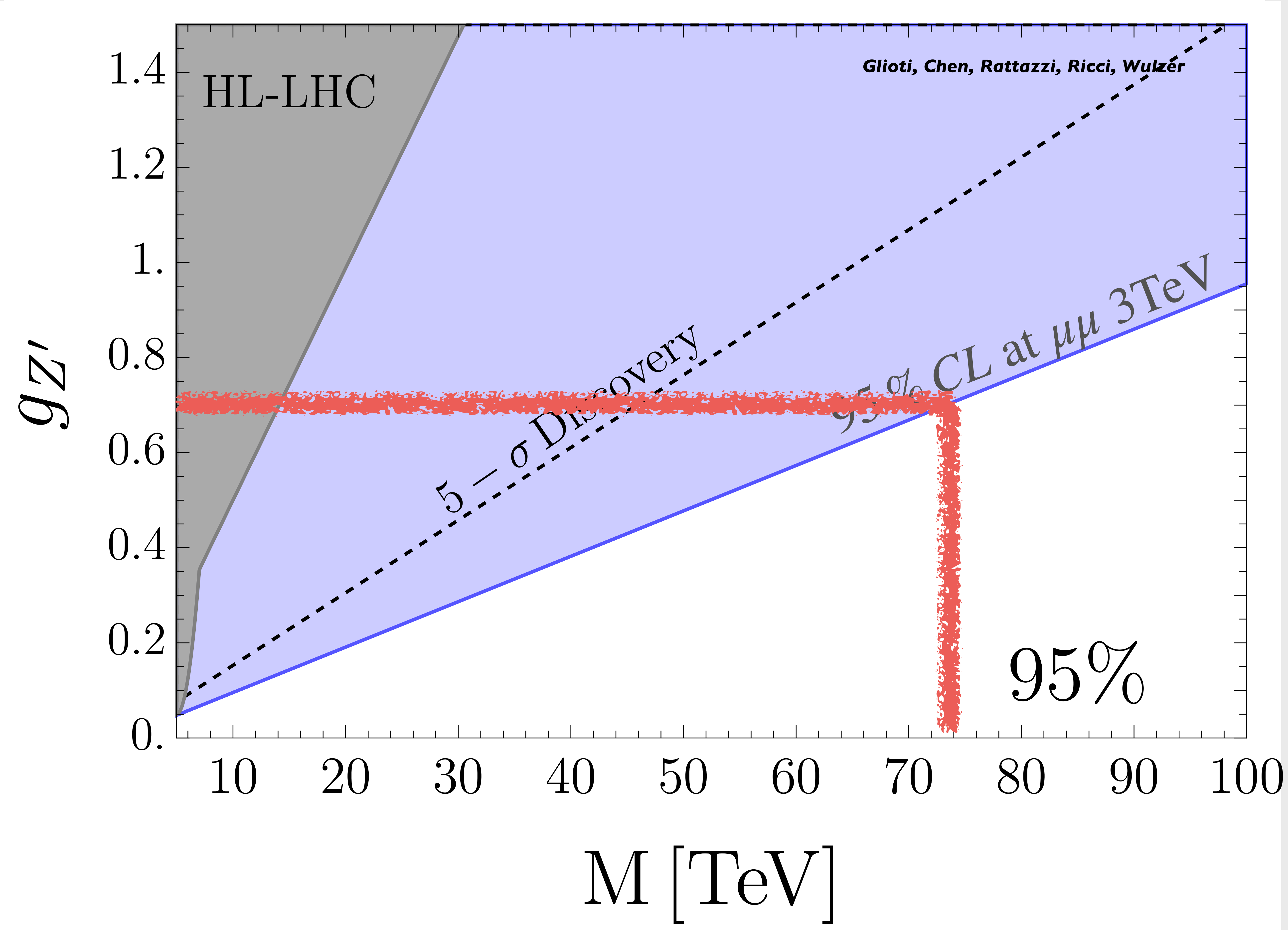




A heavy Z'

DRELL-YAN | RATES AND ANGULAR DISTRIBUTIONS

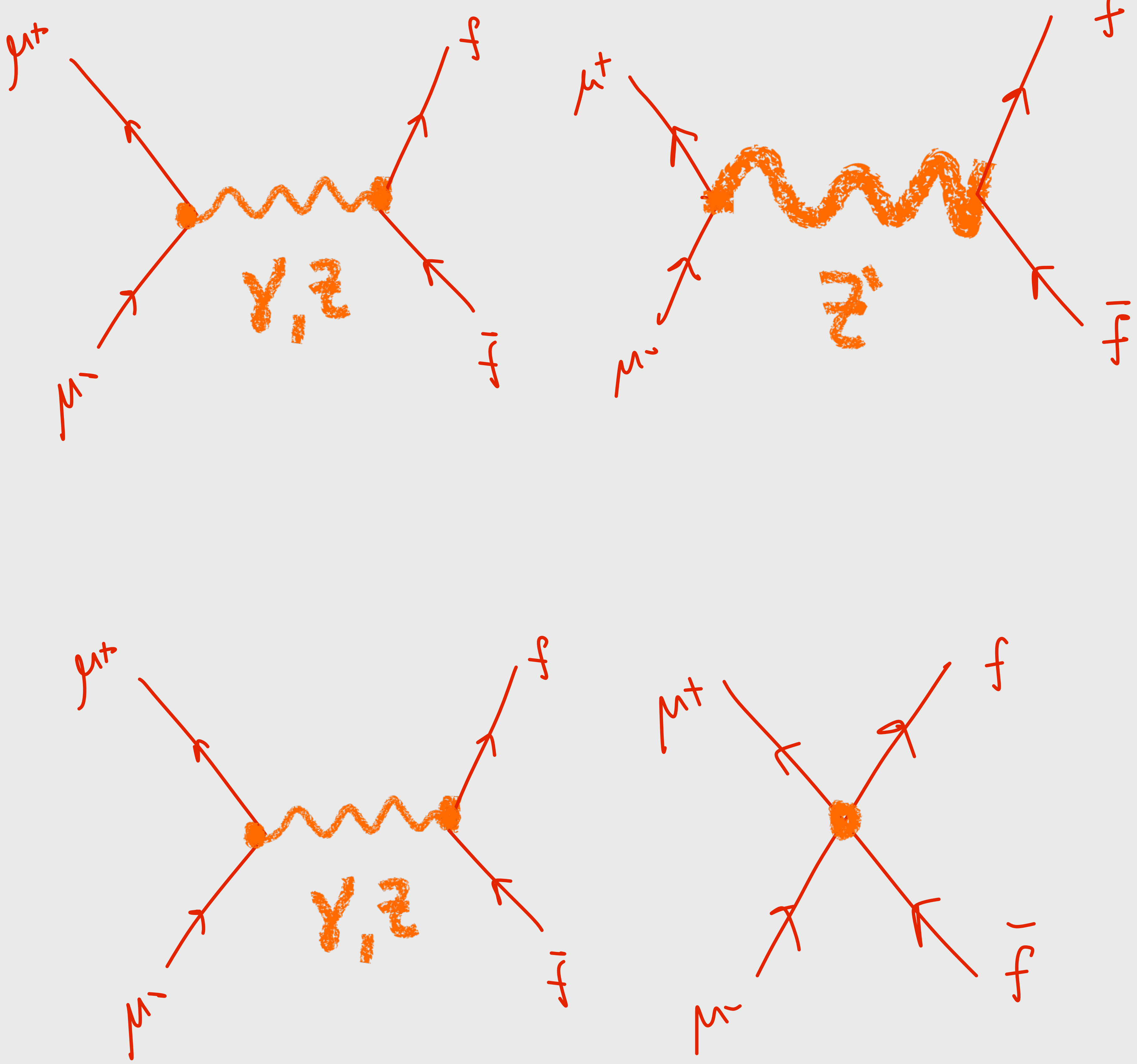


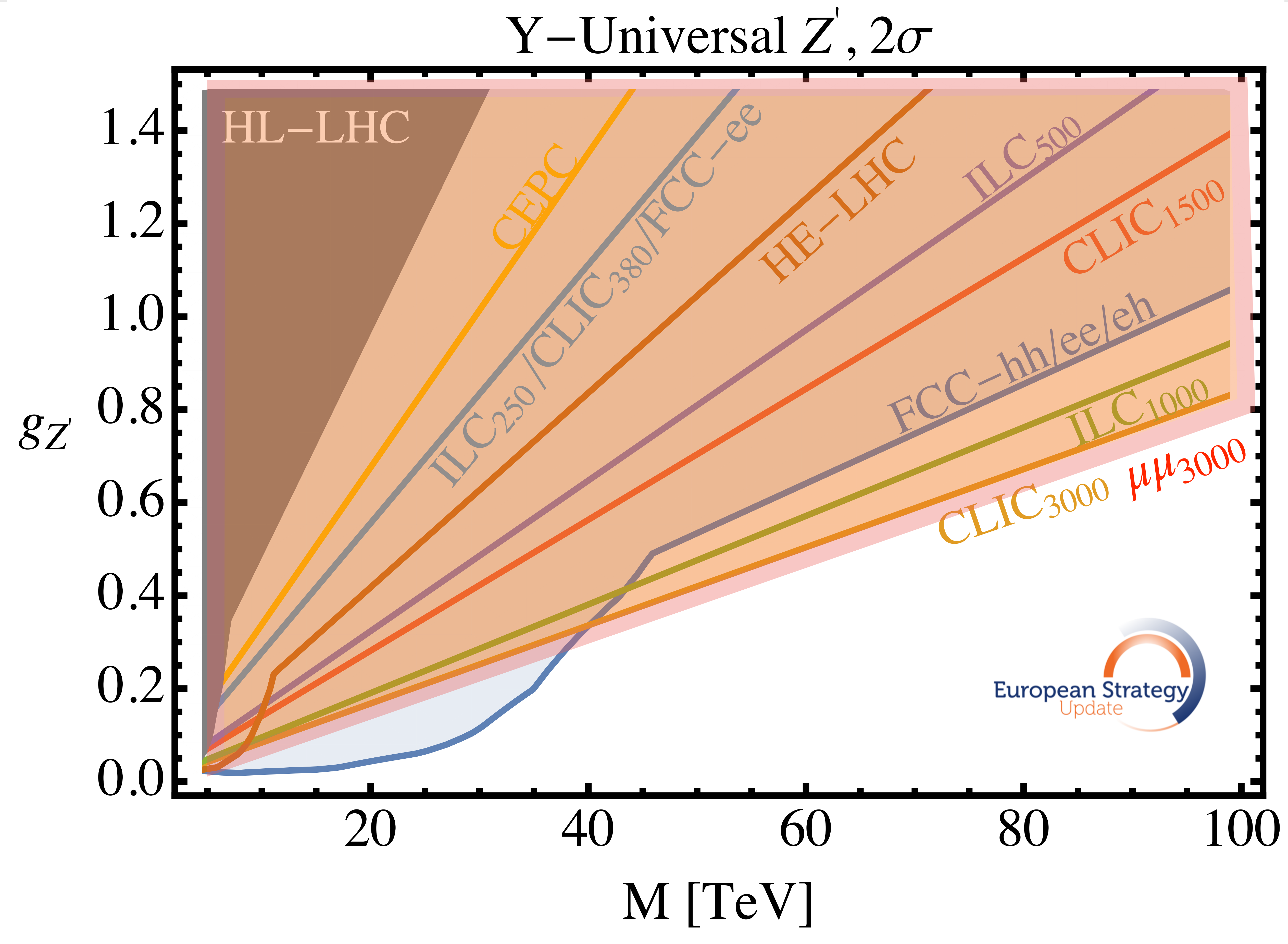


$\sqrt{s} \simeq 3$ TeV can probe 70+ TeV mass for $g_{Z'} \simeq g_{SM} \simeq 0.67$

A heavy Z'

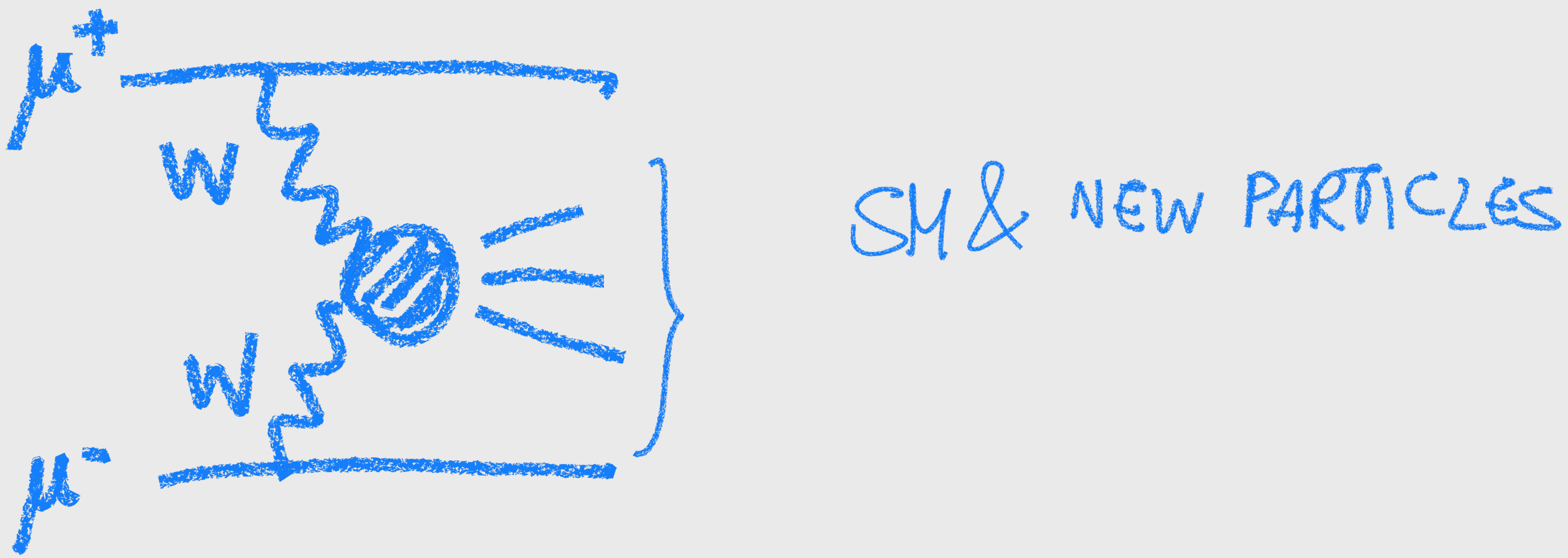
DRELL-YAN | RATES AND ANGULAR DISTRIBUTIONS





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

Weak Bosons collider

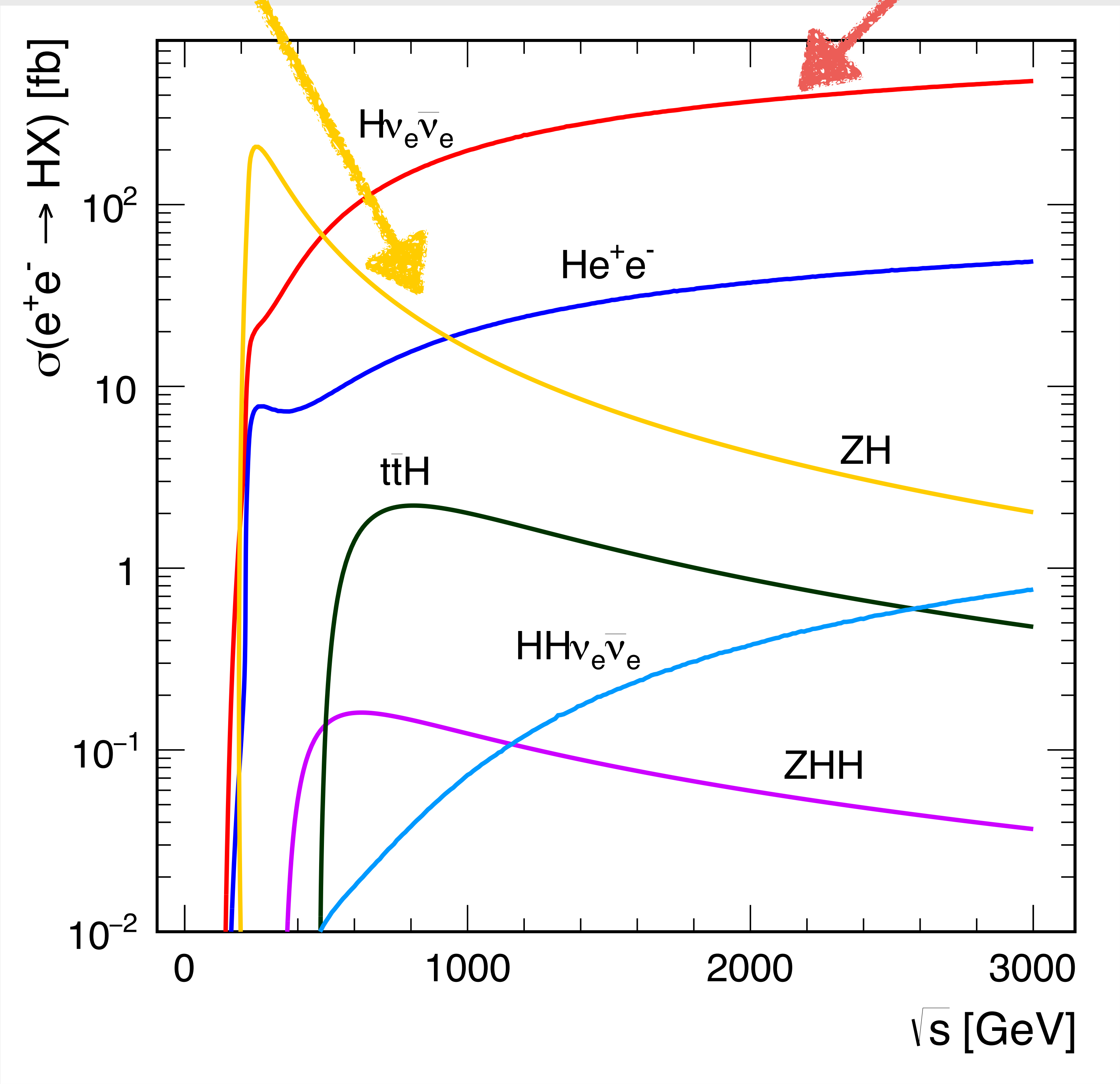


Higgs boson

$\mu^+\mu^- \to h\nu\bar{\nu}$

10^6 HIGGS BOSONS MEGA-HIGGS FACTORY

$\sigma \sim 1/s$ $\sigma \sim log(s)$



At 3 TeV the weak bosons are sufficiently light that can be radiated very efficiently

$$\sqrt{s} = 3\,\text{TeV}$$
$$\sigma \cdot \mathscr{L} \Rightarrow O(10^6)\ \text{h}$$

- large number of Higgs bosons!

NEXT TALK BY L. SESTINI

FURTHER OPPORTUNITIES

- ultra-rare Higgs decays
- differential distribution
- off-shell Higgs bosons
- rare production modes

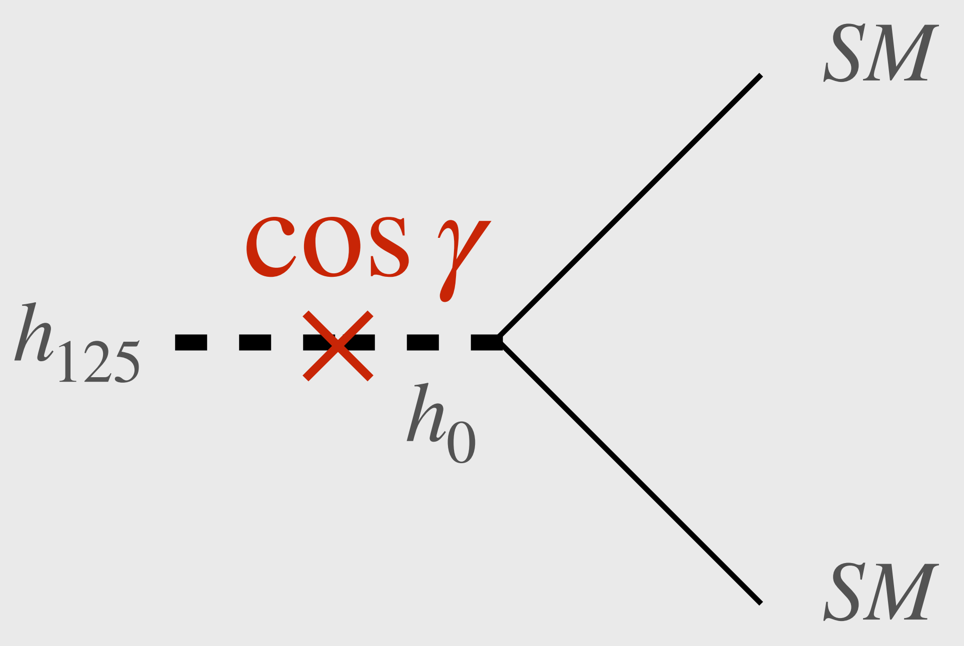
Impact on BSM

HEAVY PHYSICS

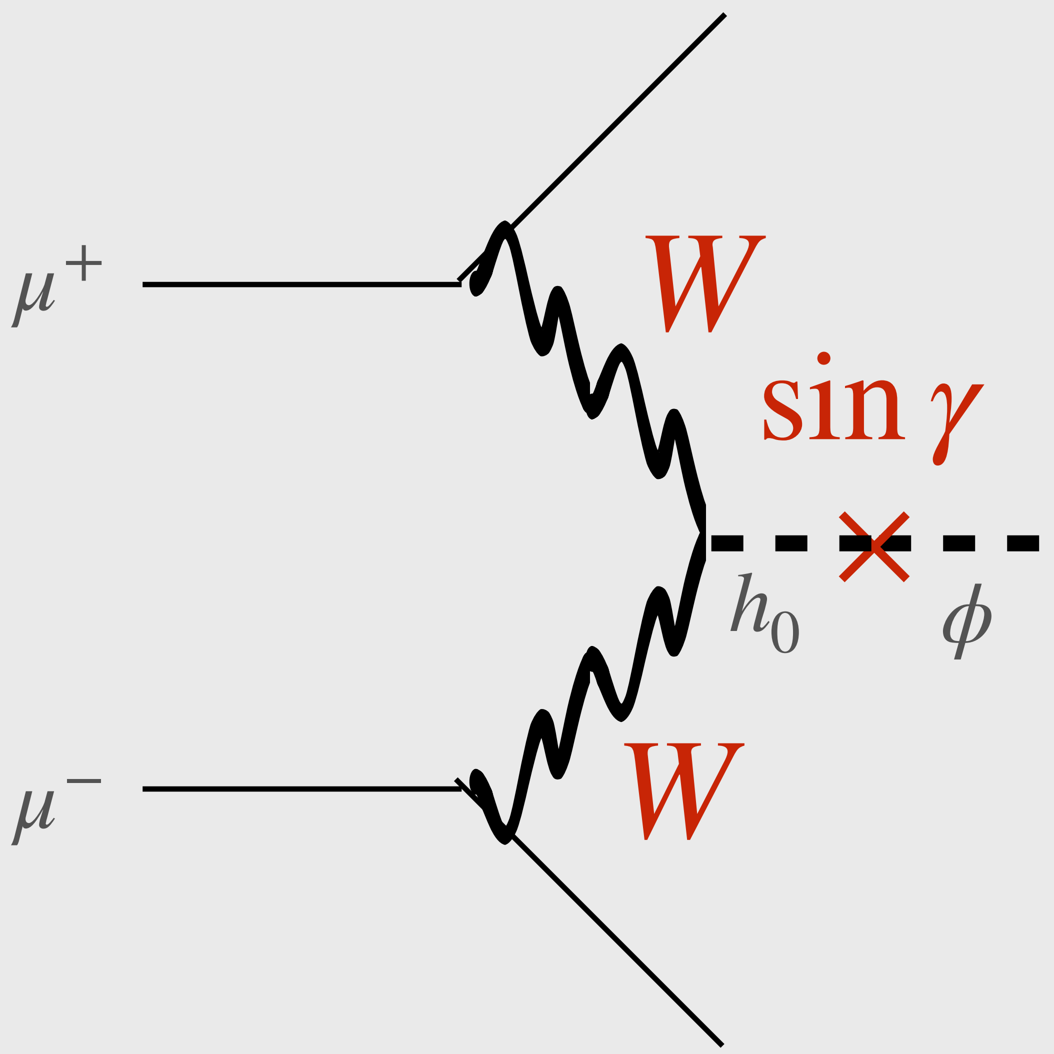
Higgs + Singlet

- Broad coverage of BSM scenarios: *(N)MSSM, Twin Higgs, Higgs portal, modified Higgs potential (Baryogenesis)*
- Phenomenology is also useful as "simplified model"

Higgs + Singlet



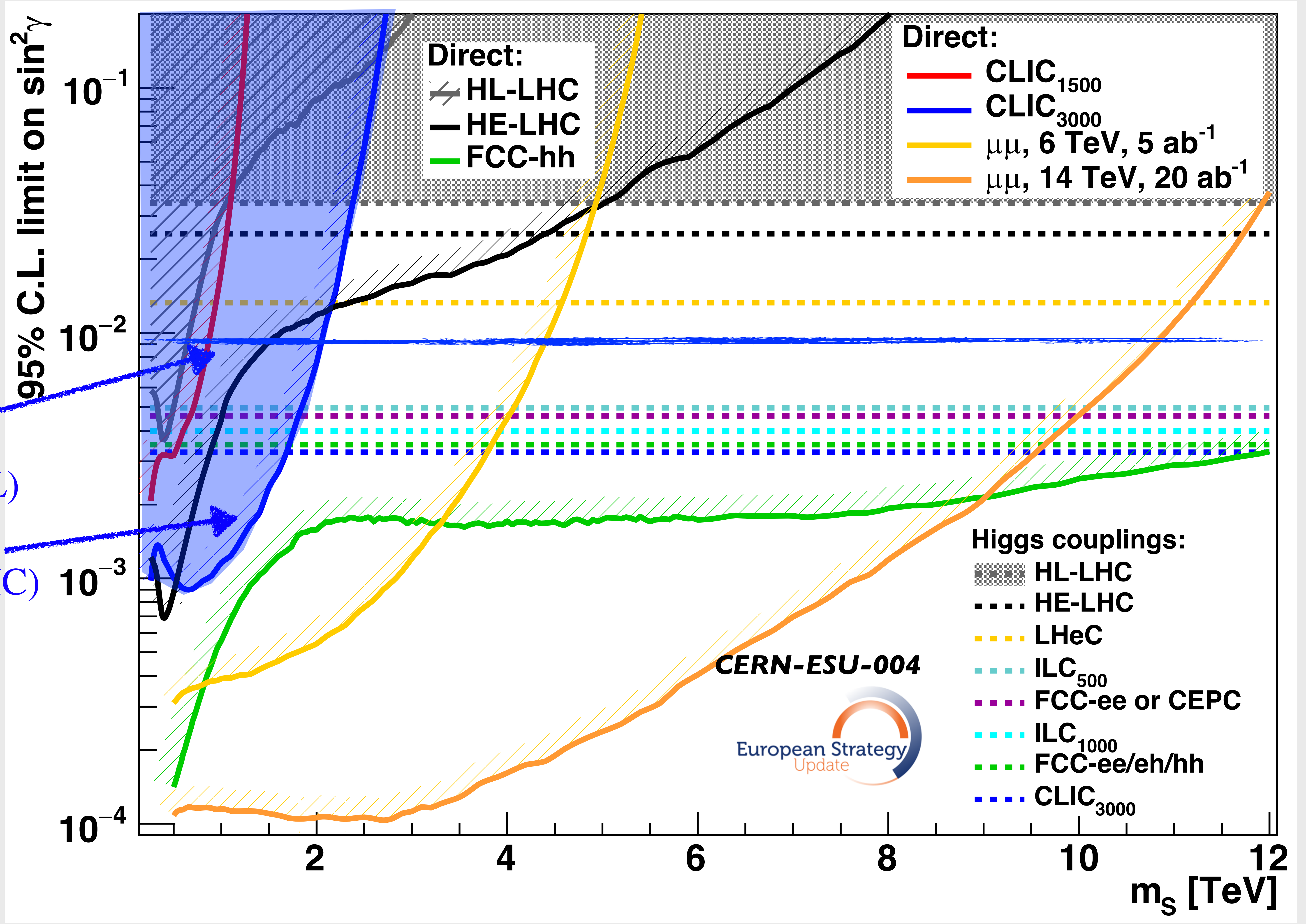
EXPLOIT ONCE MORE THE W BOSON LUMINOSITY



3 TeV

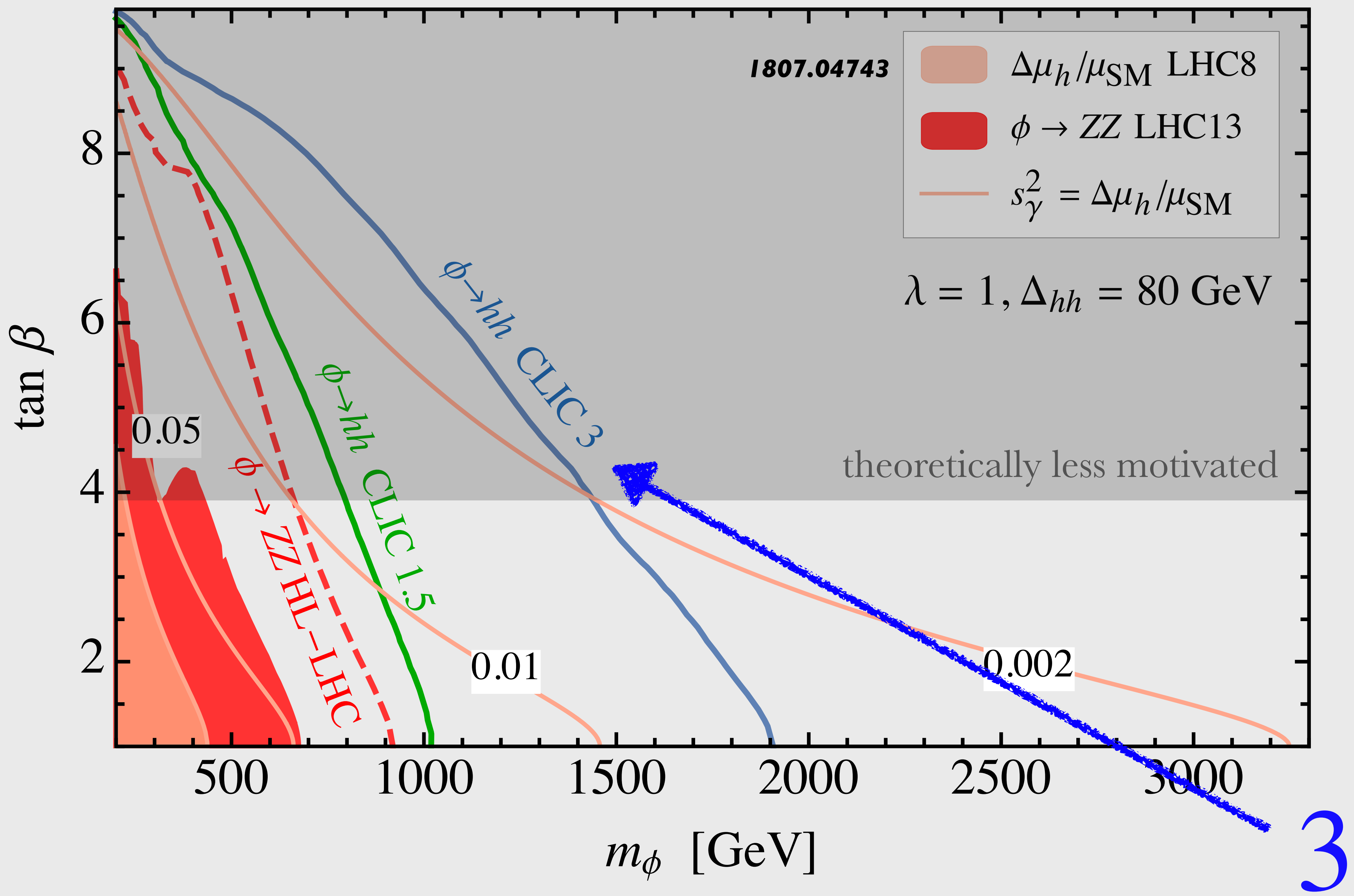
$\sigma_h \cdot BR_{bb}$ @ 1 % (95 % CL)

3 $\text{TeV}_{\text{(CLIC)}}$

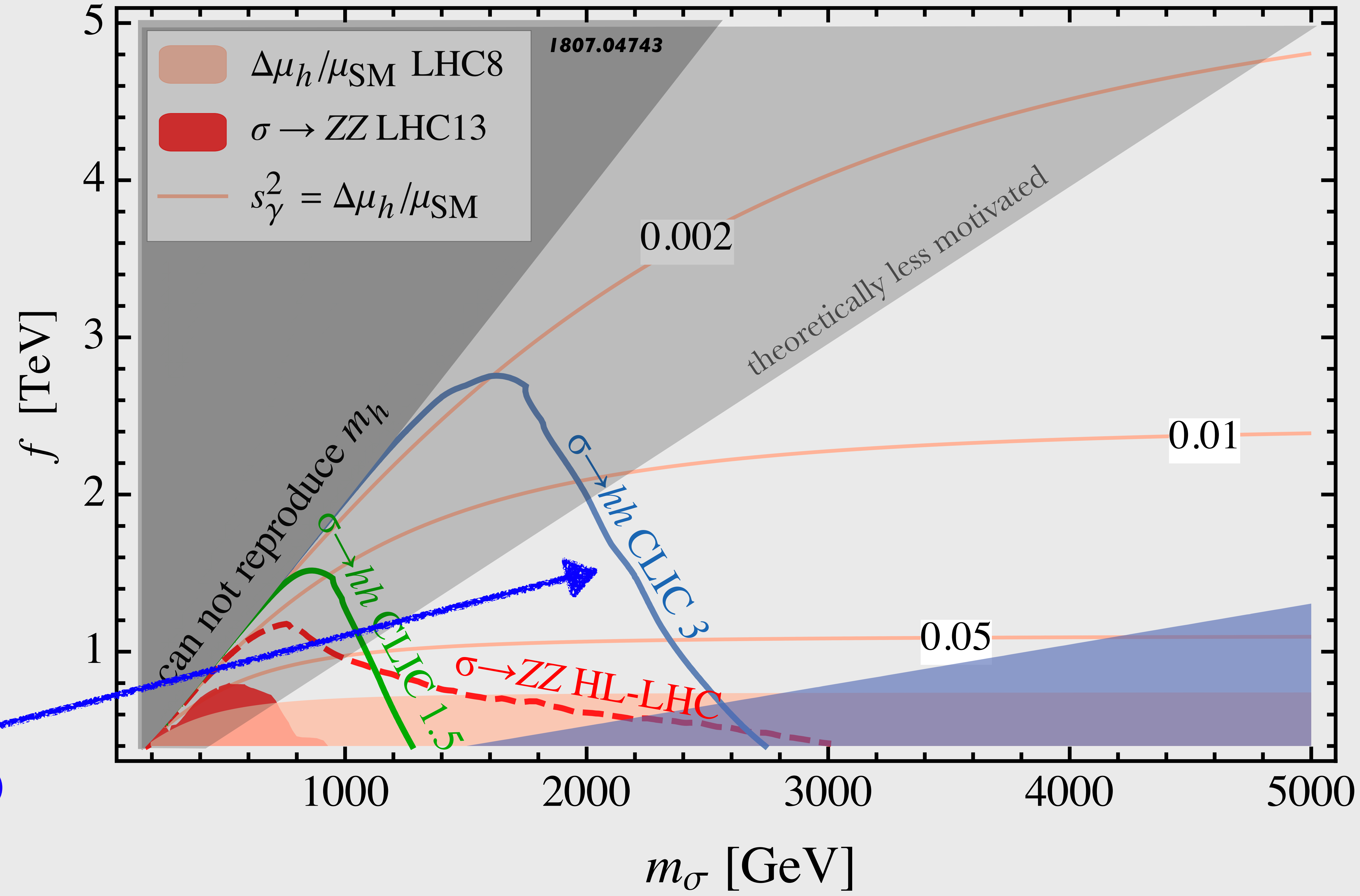


Higgs + Singlet: BSM interpretations

NMSSM



TWIN HIGGS



3 TeV$_{\text{(CLIC)}}$

$m_\phi > 1.5$ TeV
for $\tan\beta < 4$ (most motivated range of the model)

$m_\sigma > 2$ TeV
for $m_\sigma/f > 1$ (most motivated range of the model)

Physics at 3 TeV $\mu^+\mu^-$ collider

- A 3 TeV muon collider can bring excellent progress over HL-LHC about key questions on fundamental interactions (nature of the Higgs bosons, nature of Dark Matter, nature of the EW phase transition)

- 3 TeV is a sufficiently high energy to enable both modes of exploration as
  - high energy machine (e.g. Dark Matter direct production, Higgs and top compositeness, …)
  - high intensity machine (e.g. SM Higgs boson production)

- These two modes complement each other very nicely (e.g. EW phase transition, extended Higgs sector)

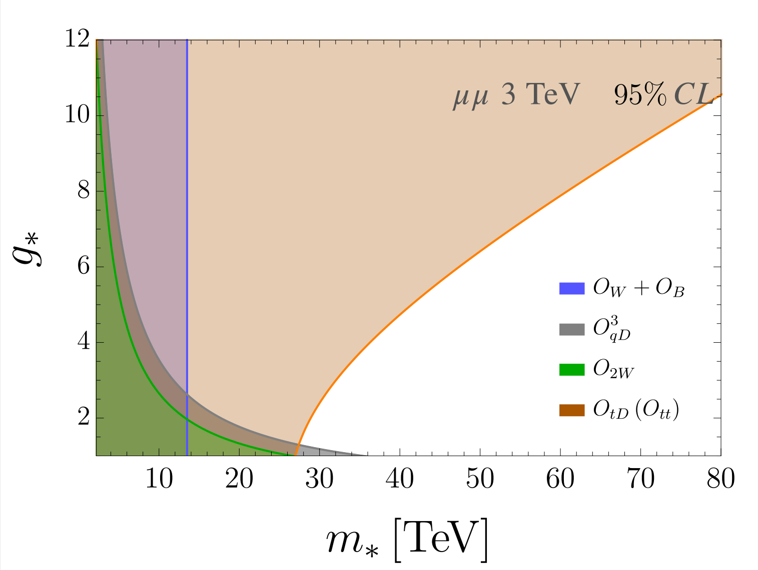
- The relatively clean environment makes it suitable for searches of subtle exotic signals (e.g. tracklets from Dark Matter)

Physics at 3 TeV $\mu^+\mu^-$ collider

$\mu\mu$ 3 TeV

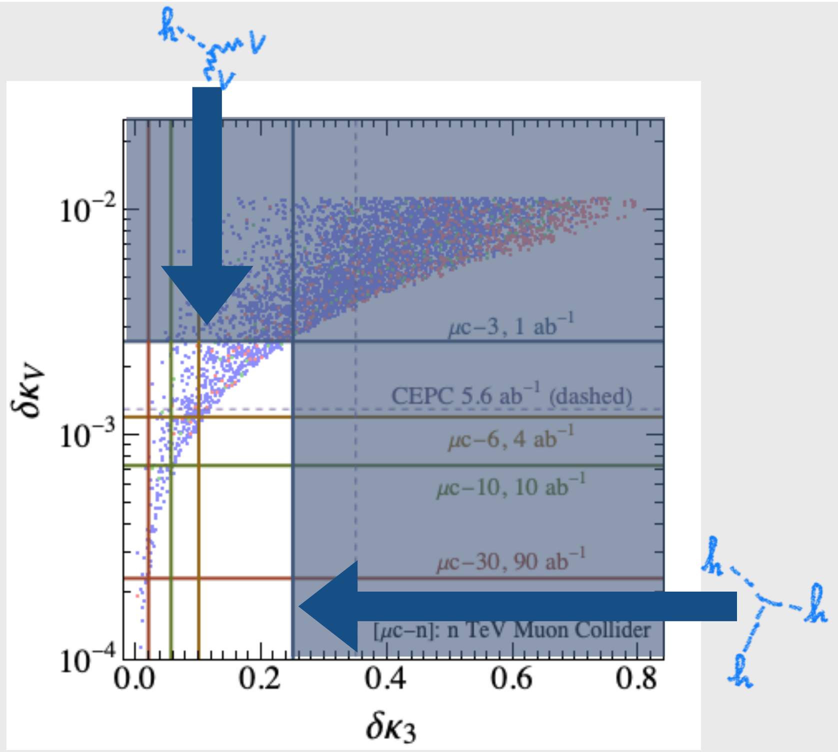
COMPOSITENESS

WELL ABOVE THE WEAK SCALE



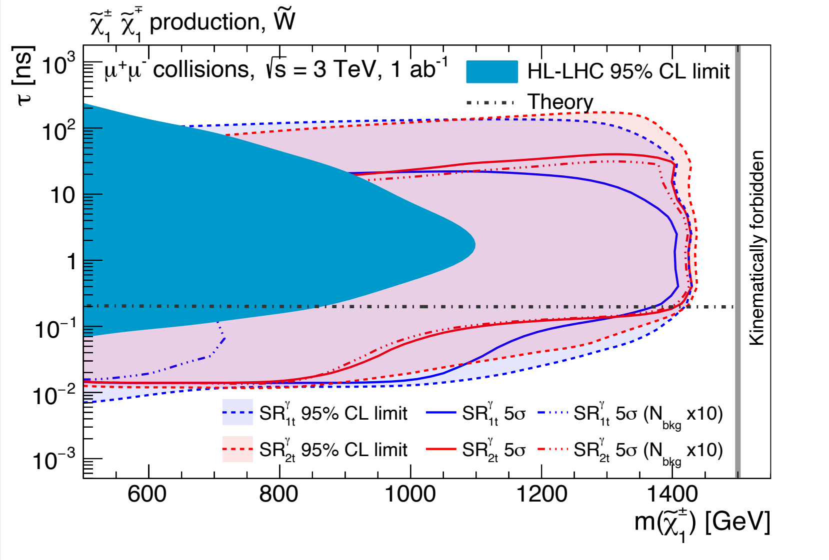
EW PHASE TRANSITION

SINGLETS AND EW CHARGED



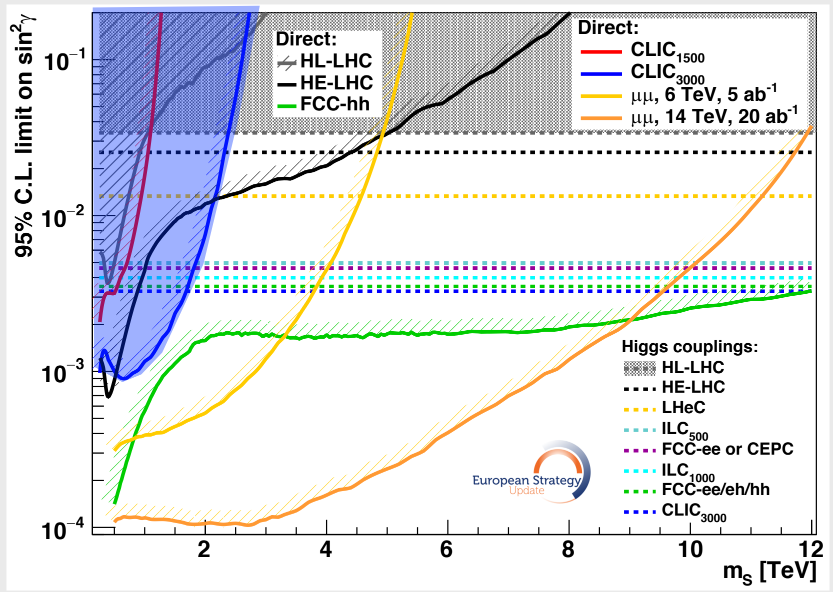
DARK MATTER

WIMP CANDIDATES including HIGGSINO and WINO



NEW SCALARS

SINGLETS AND EW CHARGED



Thank you!

https://agenda.infn.it/event/28843/