Complementarity of

Physics at the FCC and at the High Energy Muon Collider

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INFN
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Diverse Tools

FCC-$ee + hh$

- largely inspired by the LEP+LHC "recipe"
- "stand-alone" physics case of each energy stage
- synergy between energy stages
- dedicated high-intensity stages of e^+e^- runs
- "final" stage of hadron collisions for "exploration"
- "high-lumi" hadron stage can also do some precision, including through high-energy precision

High energy muon collider

- A lepton collider, but a completely new breed (not LEP-like)
- "stand-alone" physics case of each energy stage
- synergy between energy stages
- high-intensity and high-pT physics pursued in the same run
- high energy leads to interesting "partons" collision (e.g. $WW \to h$)
- naturally inclined toward highest energies (tens of TeV)
- high-energy precision can be a more than adequate substitute for pole precision

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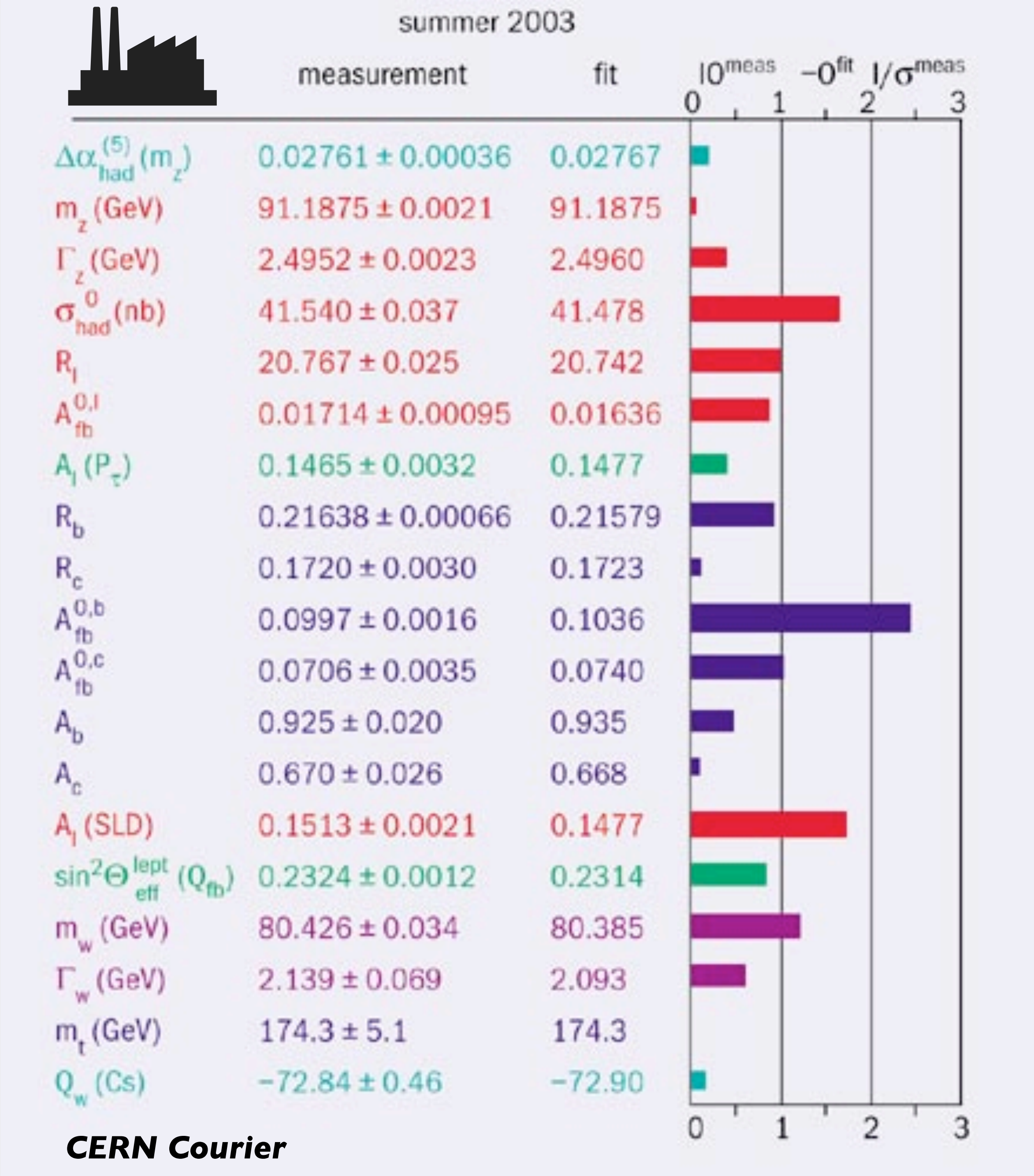
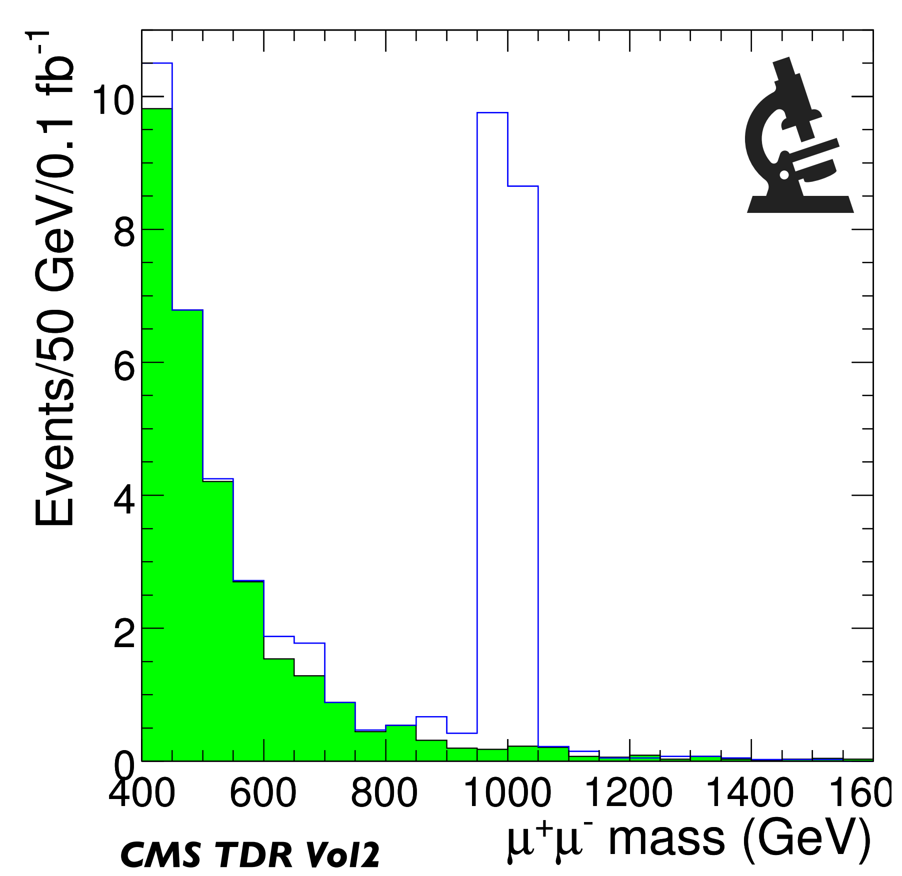


summer 2003

	measurement	fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	0.02767
m_Z (GeV)	91.1875 ± 0.0021	91.1875
Γ_Z (GeV)	2.4952 ± 0.0023	2.4960
σ_{had}^{0} (nb)	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01636
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1477
R_b	0.21638 ± 0.00066	0.21579
R_c	0.1720 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0997 ± 0.0016	0.1036
$A_{fb}^{0,c}$	0.0706 ± 0.0035	0.0740
A_b	0.925 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l (SLD)	0.1513 ± 0.0021	0.1477
$\sin^2\Theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W (GeV)	80.426 ± 0.034	80.385
Γ_W (GeV)	2.139 ± 0.069	2.093
m_t (GeV)	174.3 ± 5.1	174.3
Q_W (Cs)	−72.84 ± 0.46	−72.90

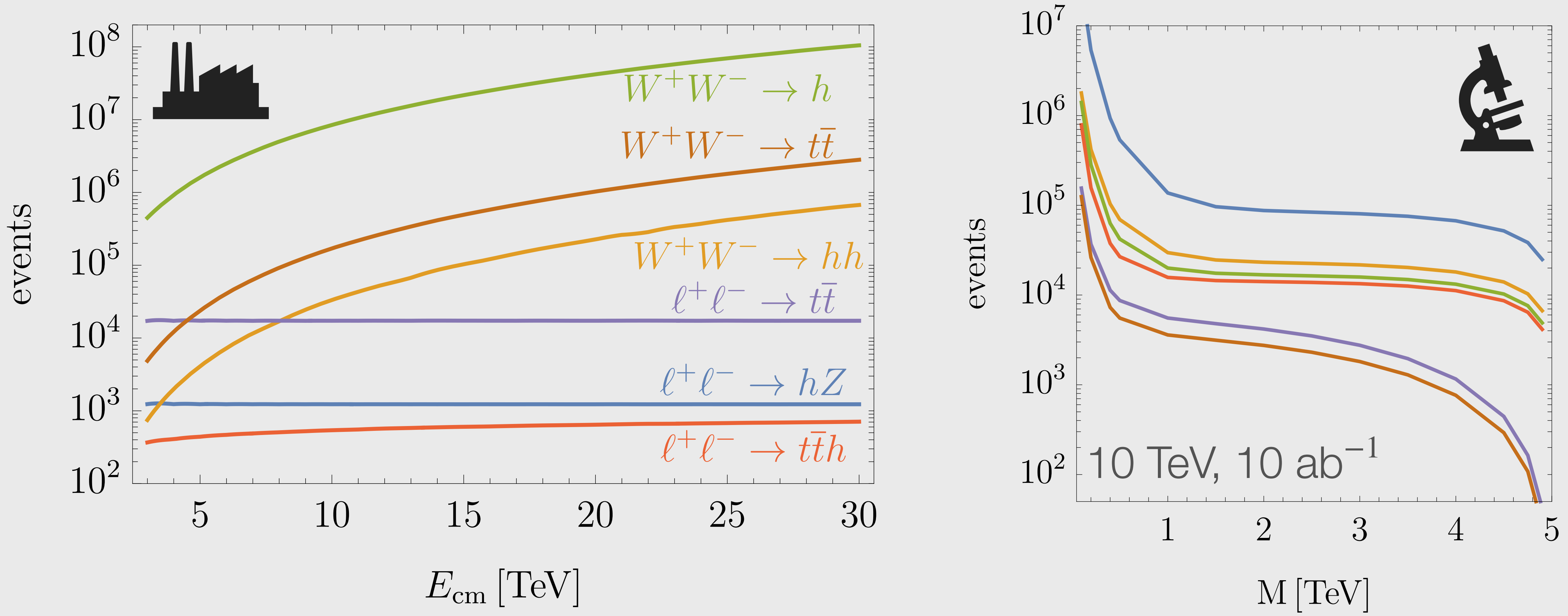
CERN Courier



CMS TDR Vol2

High energy muon collider

- Stages at several TeV: e.g. 3 TeV and 10 TeV
- possibility to foresee higher energy runs, e.g. 30 TeV
- $$\mathscr{L} = 10\text{ab}^{-1}\left(\frac{E_{cm}}{10\ \text{TeV}}\right)^2$$
  - tens of thousands of new physics states
  - millions of top quarks and Higgs bosons, billions of vector bosons, … ("multiplex” factory)



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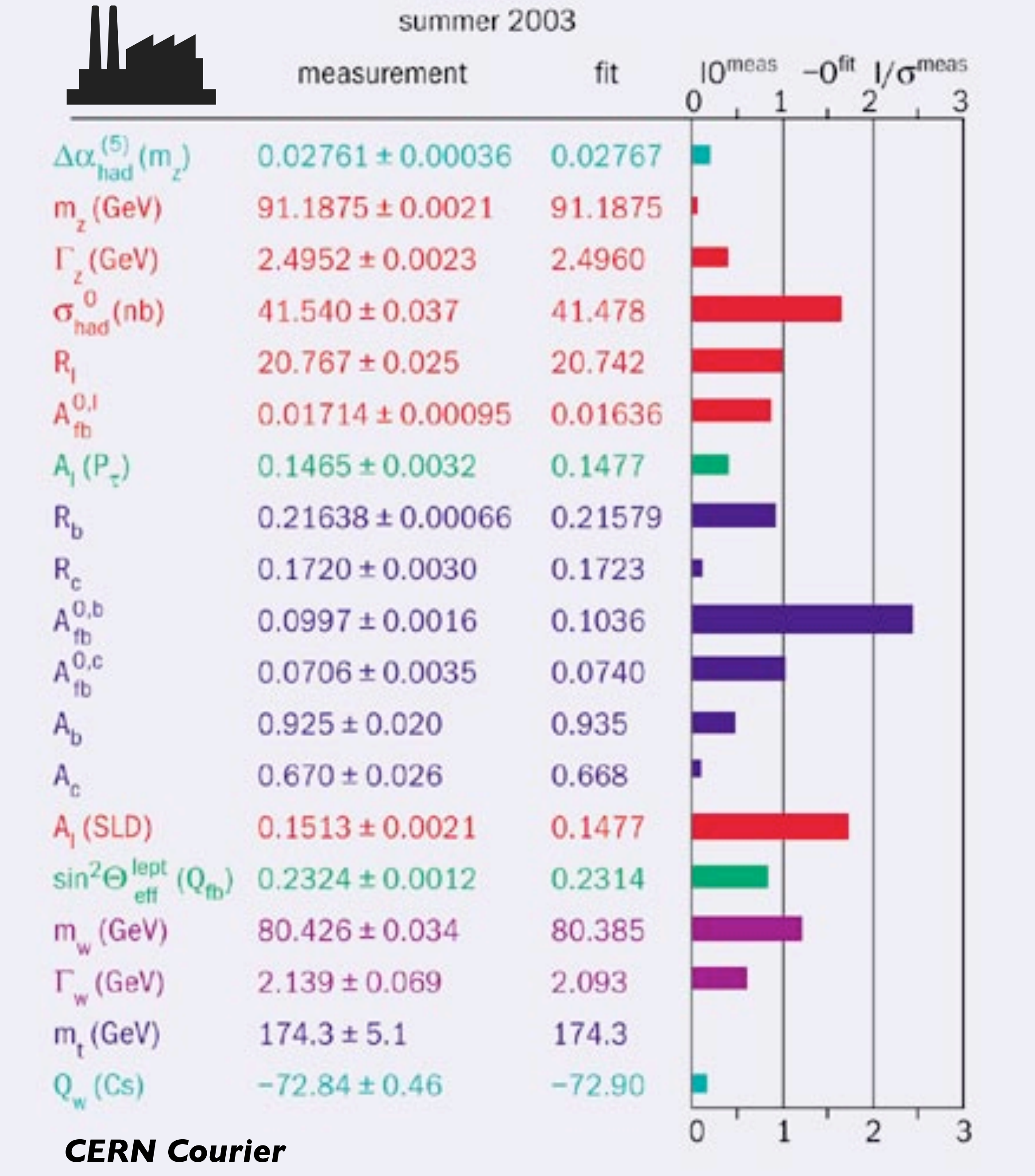

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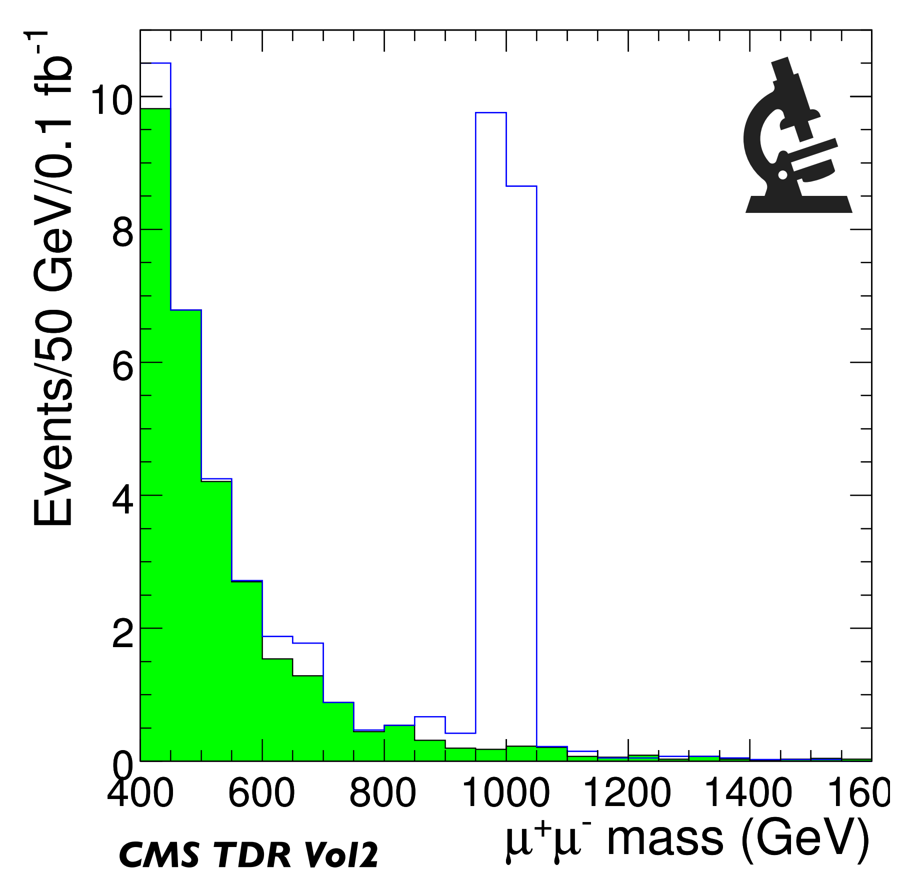
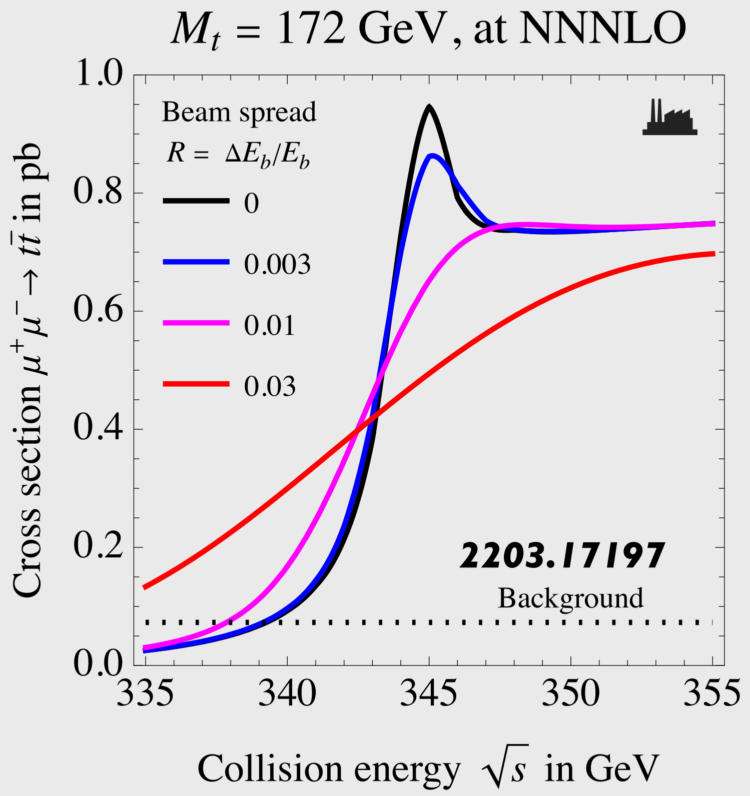


CMS TDR Vol2

High energy muon collider

- Stages at several TeV: e.g. 3 TeV and 10 TeV
- possibility to foresee higher energy runs, e.g. 30 TeV
- $$\mathscr{L} = 0.1\text{ab}^{-1}\left(\frac{E_{cm}}{10\text{ TeV}}\right)^2$$
  - hundreds of events of new physics states
  - still able to perform SM measurements e.g. threshold scans



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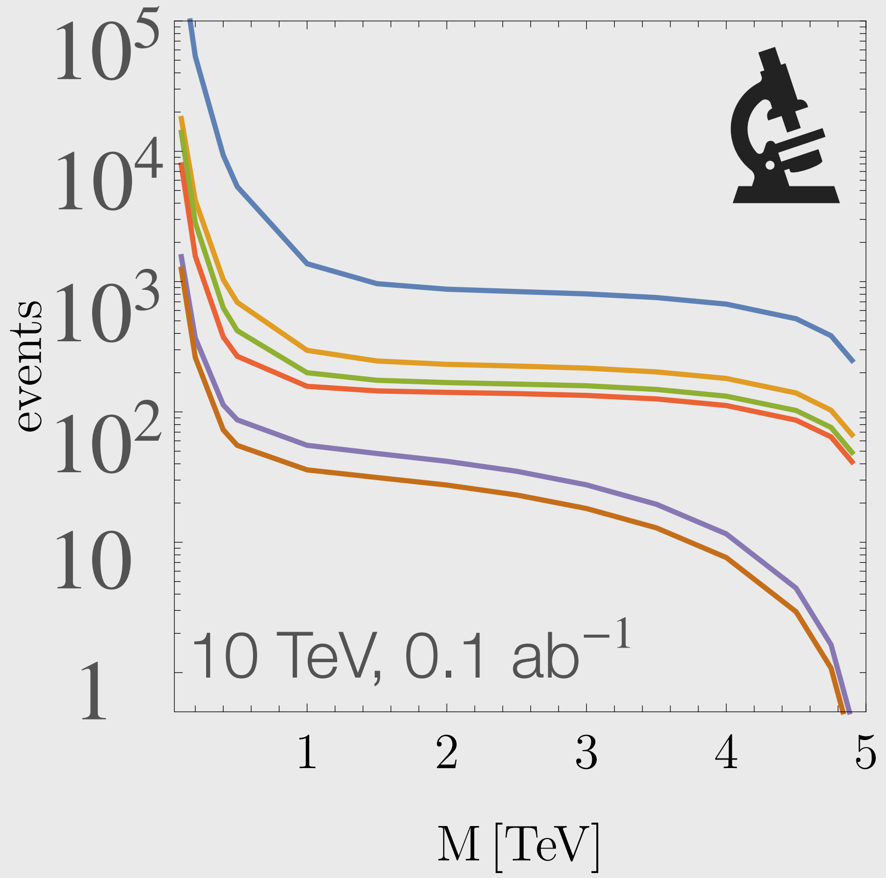

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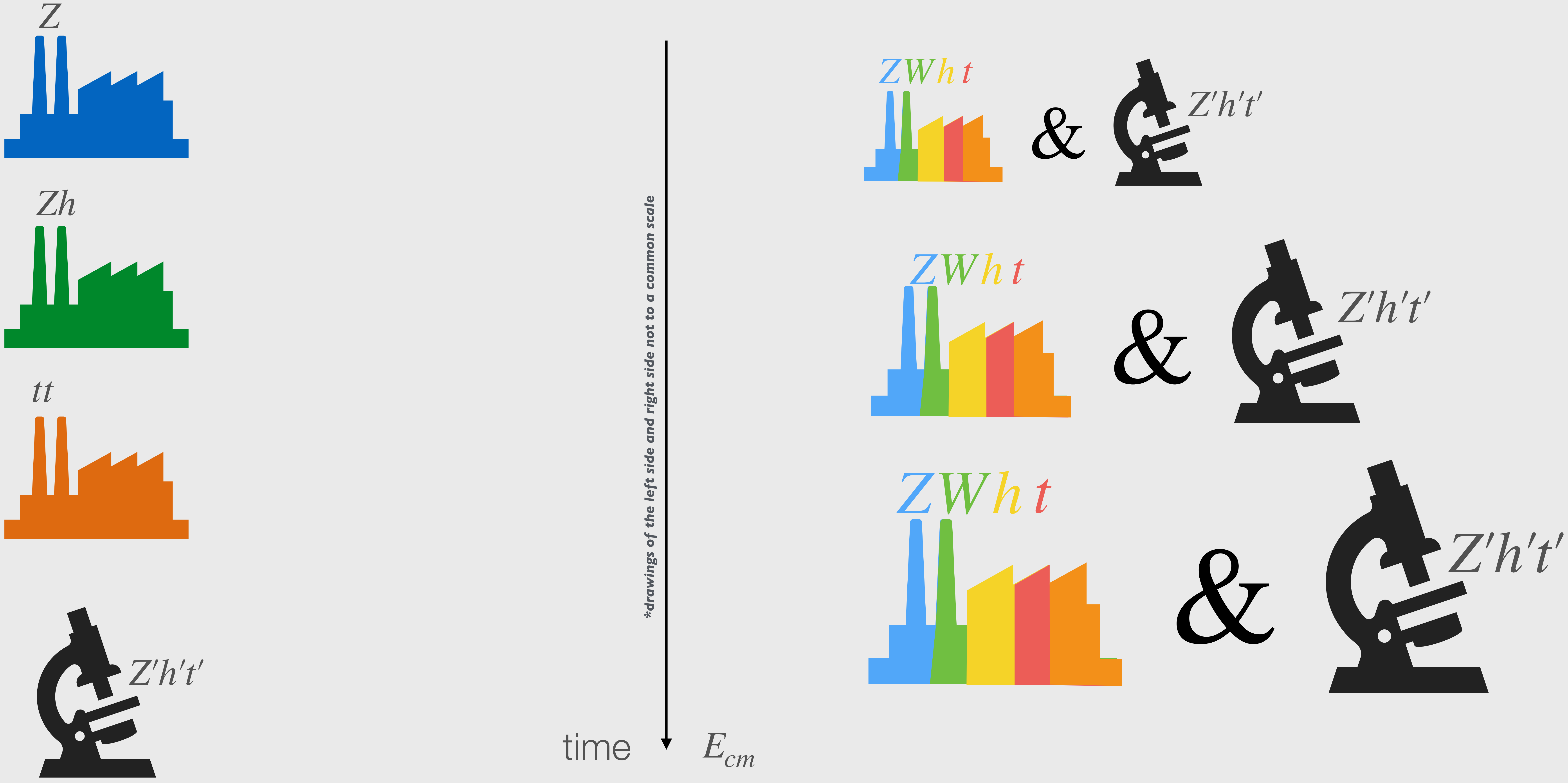


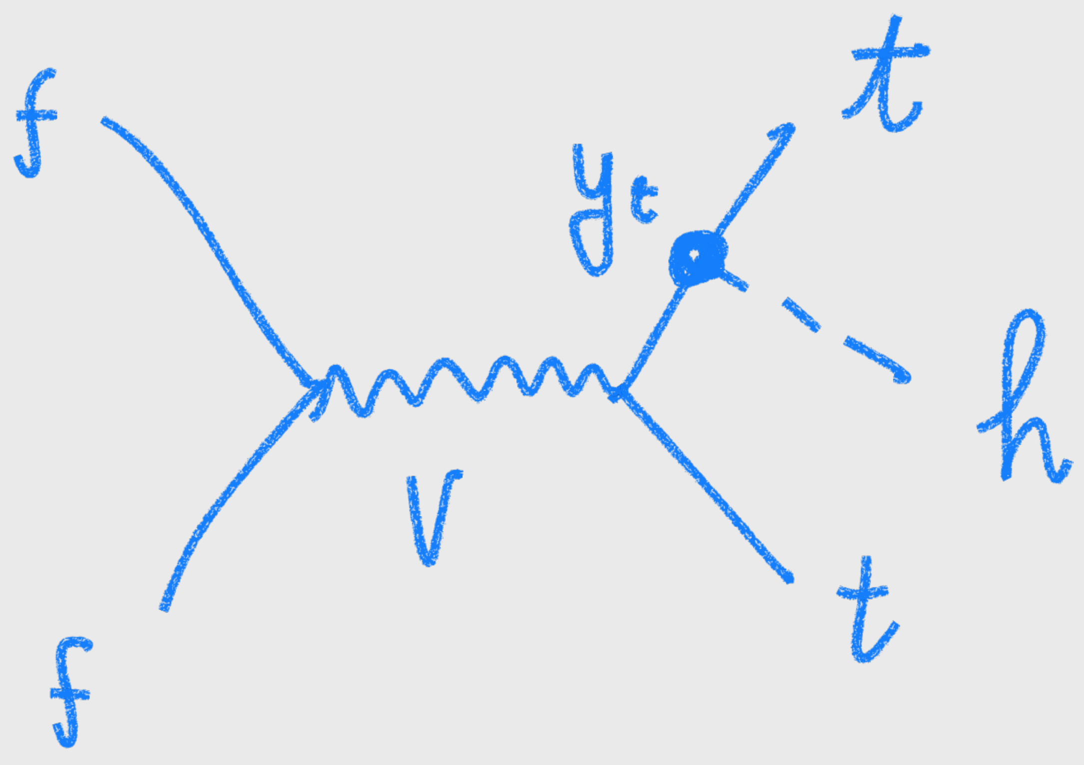
*drawings of the left side and right side not to a common scale

Common problems and solutions

a typical example of complementarity on

Top quark couplings

Joint-ventures on the Yukawa of the top quark



$$\sigma \propto g_{ttV}^2\, y_t^2\, g_{ffV}^2$$

$$\sigma_{tth}^{100\ \text{TeV}} = 33.9\,\Big(1 \pm \underbrace{0.08}_{\substack{\text{SCALE VARIATION}\\ \text{NLO}}} \pm \overbrace{0.02}^{\substack{\text{VAR.}\\ \text{PDF}}}\Big)\cdot 10^{6}\ \text{ab} \Rightarrow$$

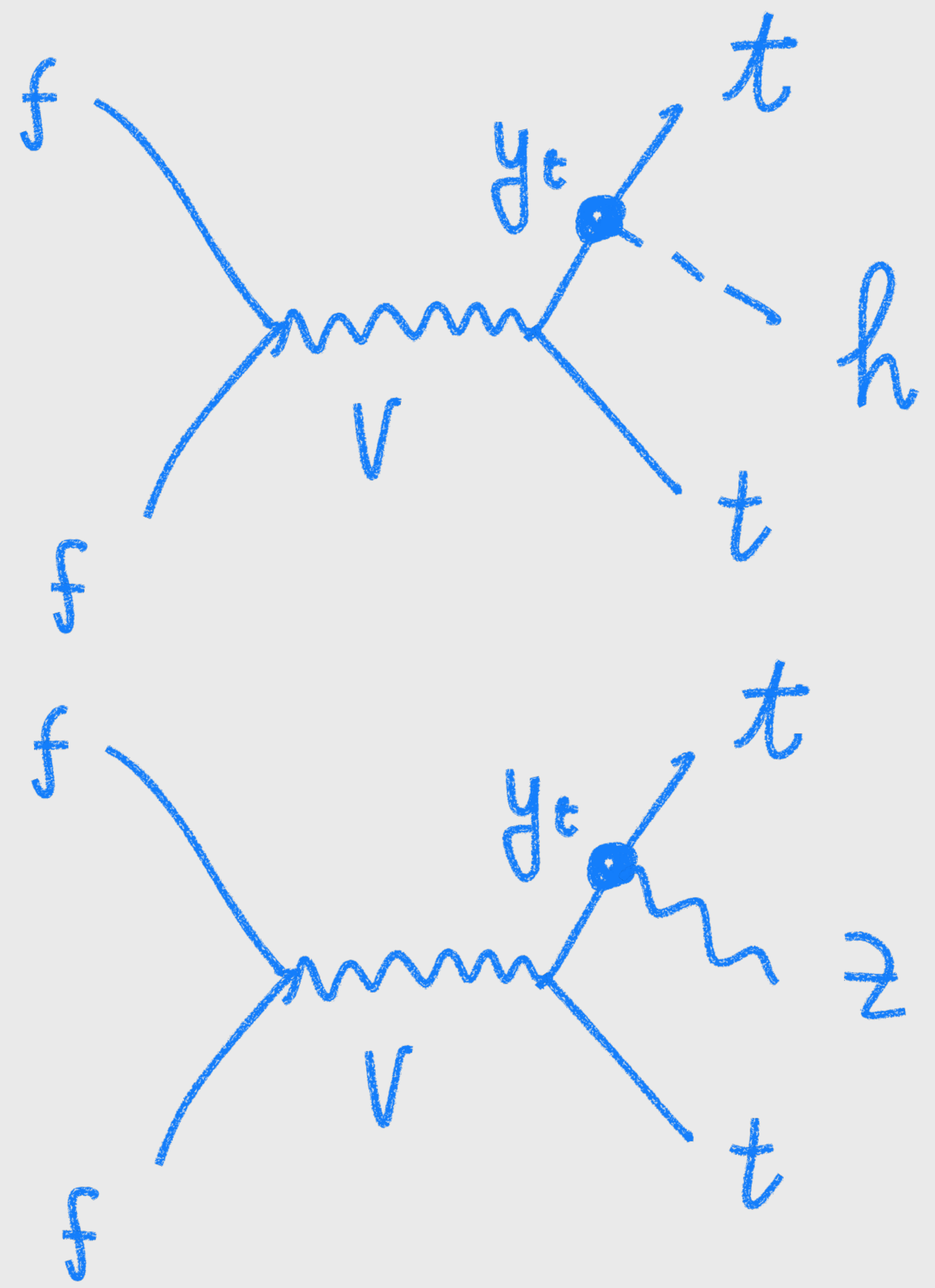
milions of tth every year!

1507.08169

$H \to 4\ell$	$H \to \gamma\gamma$	$H \to 2\ell 2\nu$	$H \to b\bar{b}$
$2.6 \cdot 10^4$	$4.6 \cdot 10^5$	$2.0 \cdot 10^6$	$1.2 \cdot 10^8$

Table 6: $t\bar{t}H$ event rates for various Higgs decay modes, with 20 ab^{-1} at 100 TeV, assuming $t\bar{t} \to \ell\nu$+jets. Here and for Higgs decays, ℓ can be either an electron or a muon.

Joint-ventures on the Yukawa of the top quark



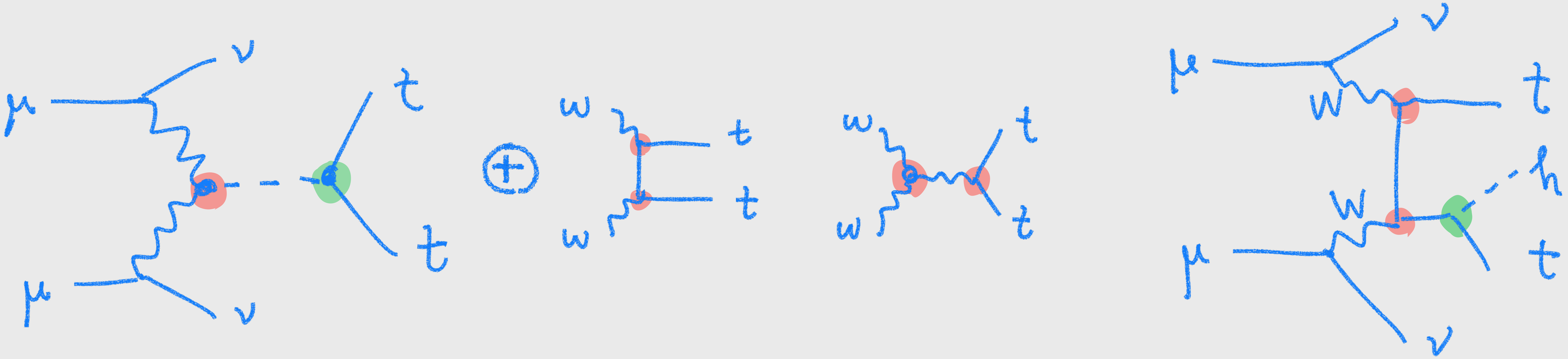
$$\left.\begin{array}{l} \sigma \propto g_{ttV}^2\, y_t^2\, g_{ffV}^2 \\ \\ \sigma \propto g_{ttV}^2\, g_{ttZ}\, g_{ffV}^2 \end{array}\right\} \frac{\sigma_{tth}}{\sigma_{ttZ}} \sim \frac{y_t}{g_{ttZ}}$$

FCC-*ee* provides an input to the next machine that can produce lots of *tth* but suffers uncertainty (on absolute rate)

Complementarity by providing precise inputs, whose poor knowledge would spoil a future measurement

Joint-ventures on the Yukawa of the top quark

2212.11067, 2104.05770

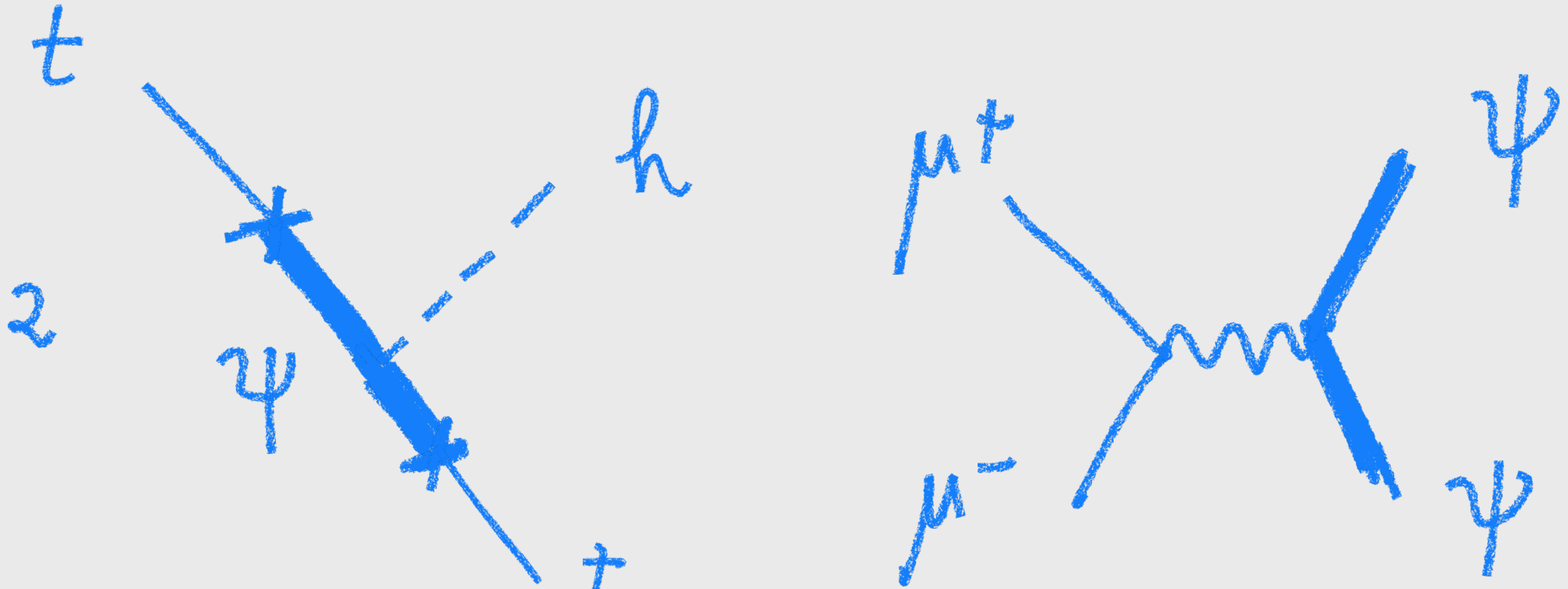


Same need for inputs on other couplings, thus can benefit from inputs from FCC-*ee*

or a global fit at the μ collider (if sufficiently precise)

The same muon collider that acts as "top factory" can also test directly the existence of new states responsible for the deviations in the couplings

$\delta y_t \sim \left(\frac{m_t}{M}\right)^2$



TYPICALLY MUON COLLIDER EXCLUSION UP TO $s_{\mu\mu}/2$

same machine can perform complementary direct and indirect tests of BSM

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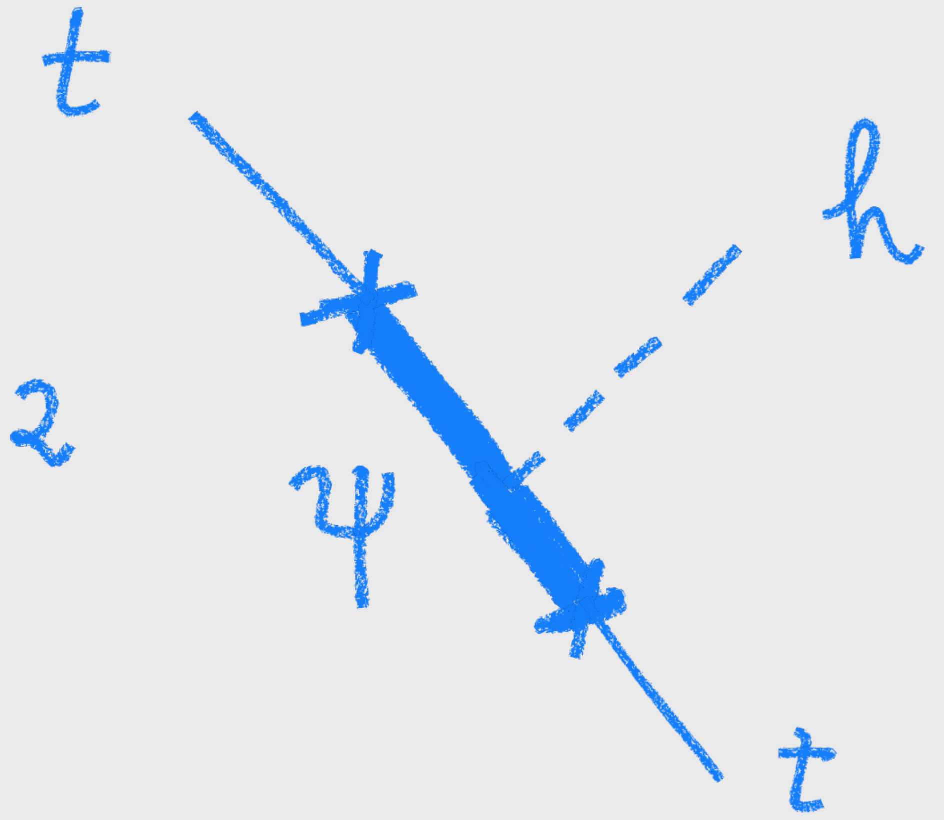

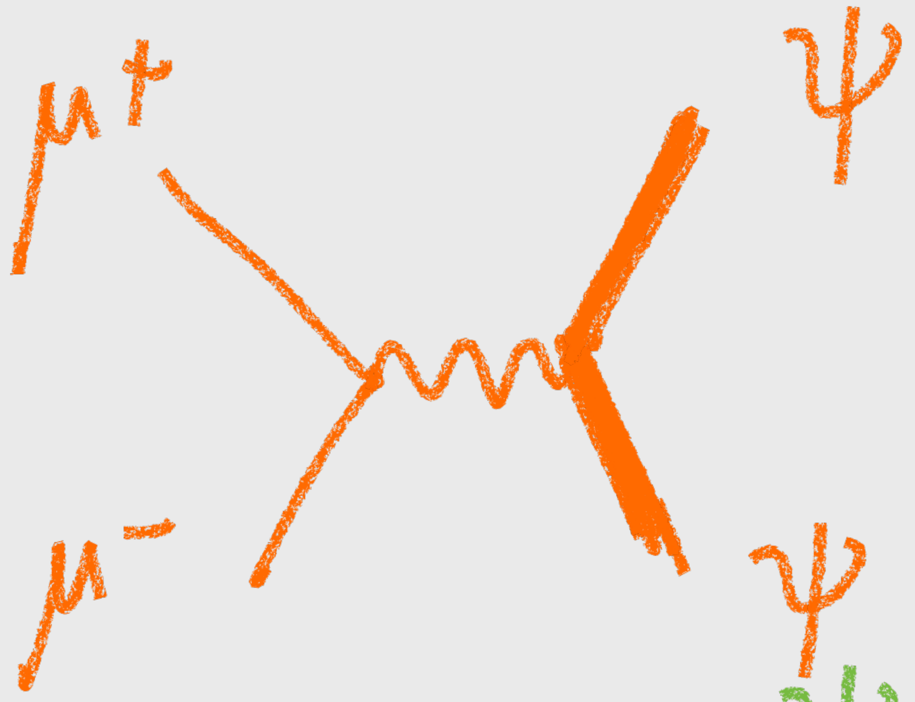

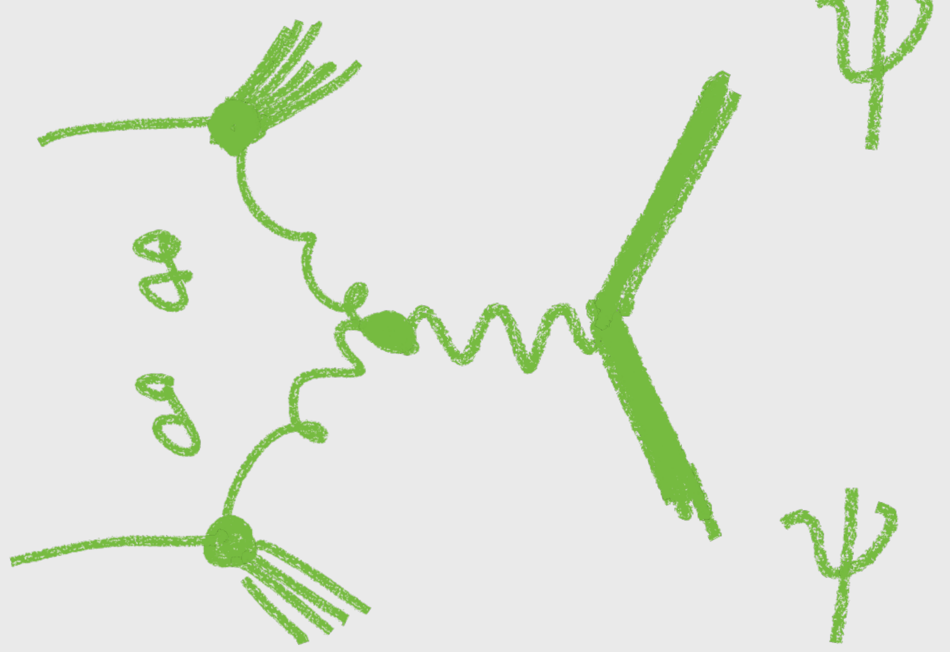

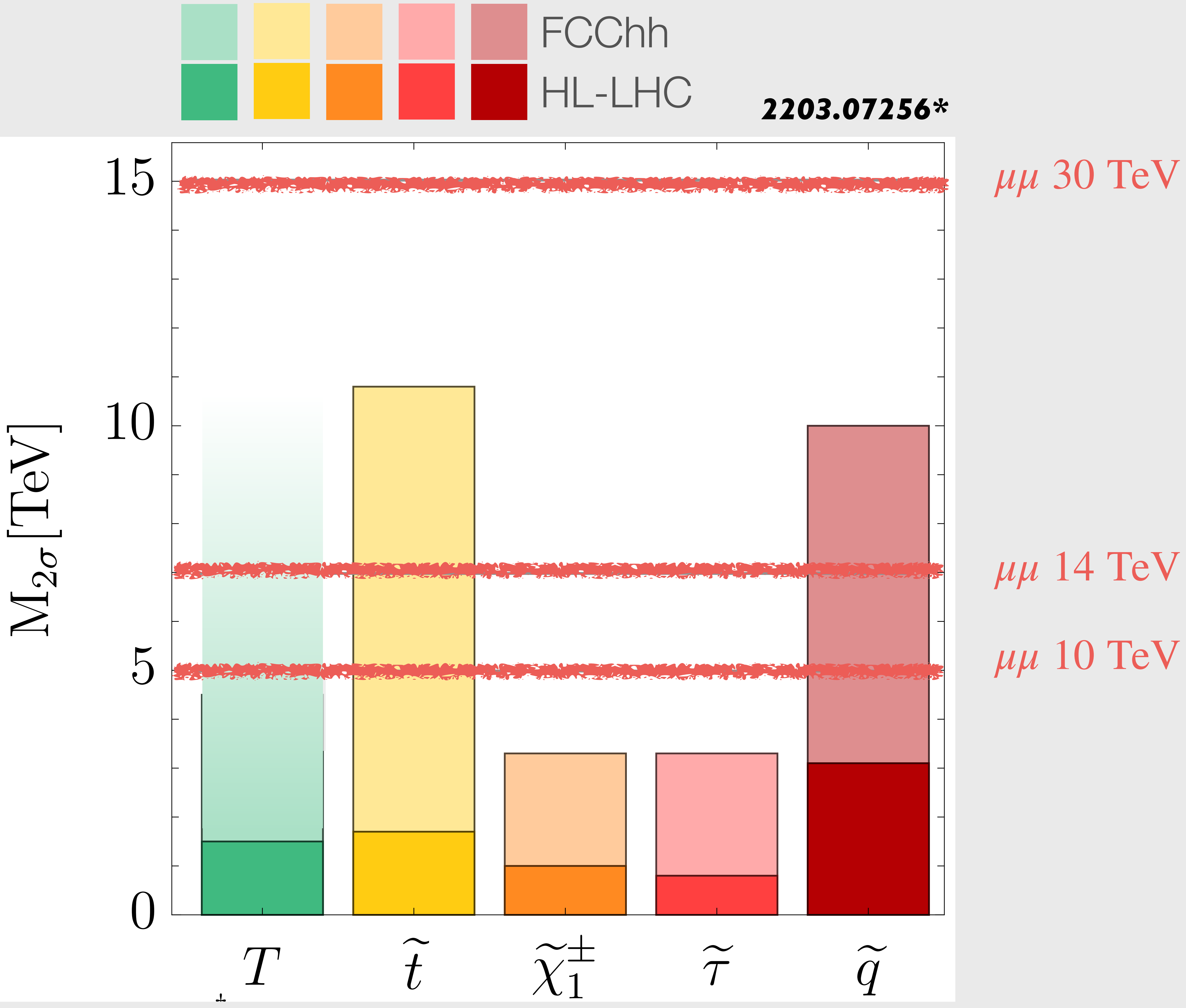

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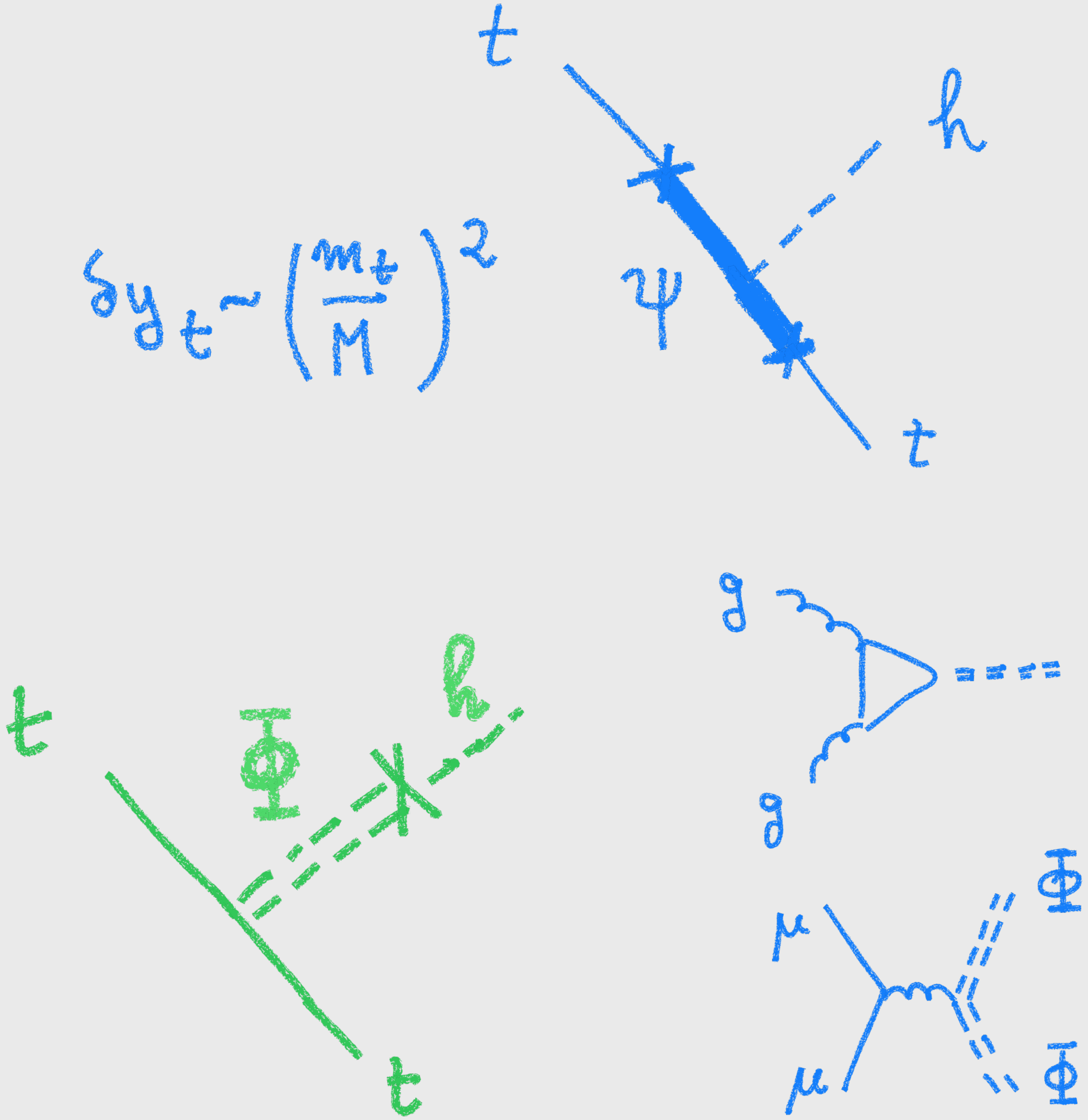

$$\delta y_t \sim \left(\frac{m_t}{M}\right)^2$$

Complementarity: results from the “next” machines can feed-back in the assumptions on the precision studies of the “previous” machine. At $\mu\mu$ “next” and “previous” happen synchronously.

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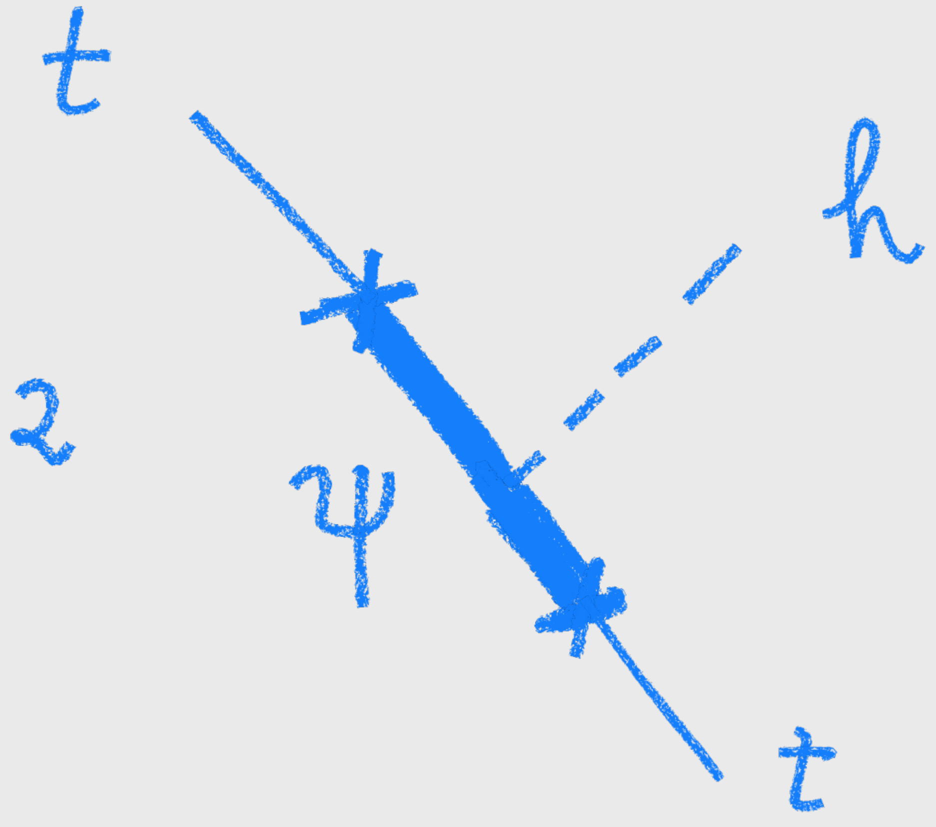

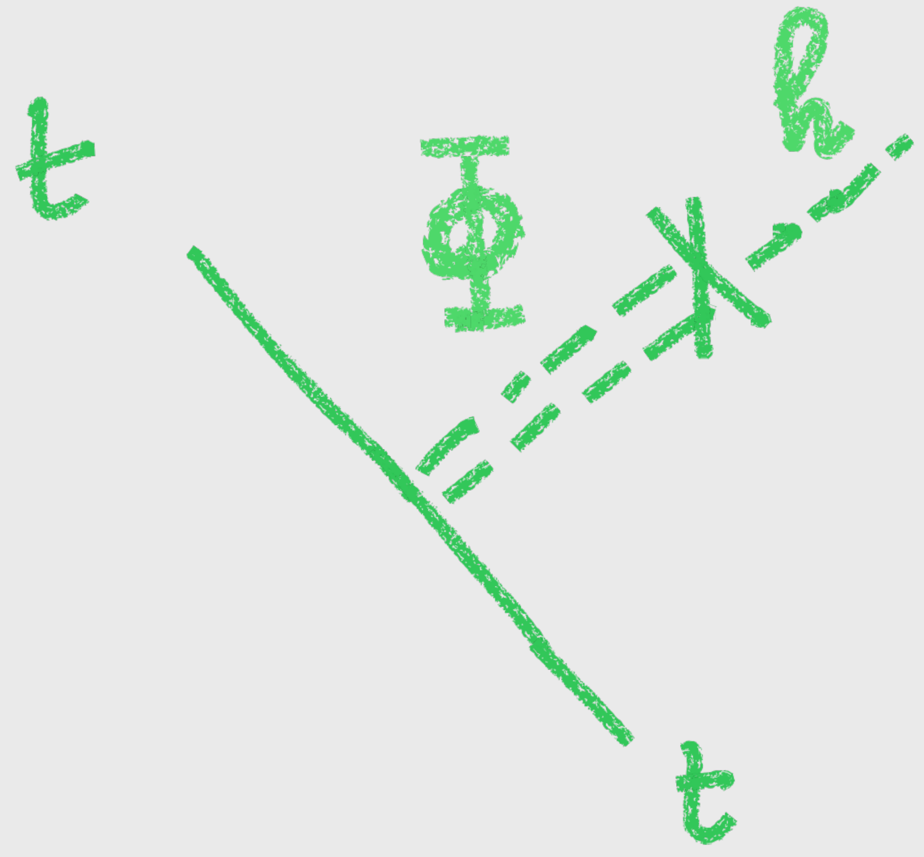

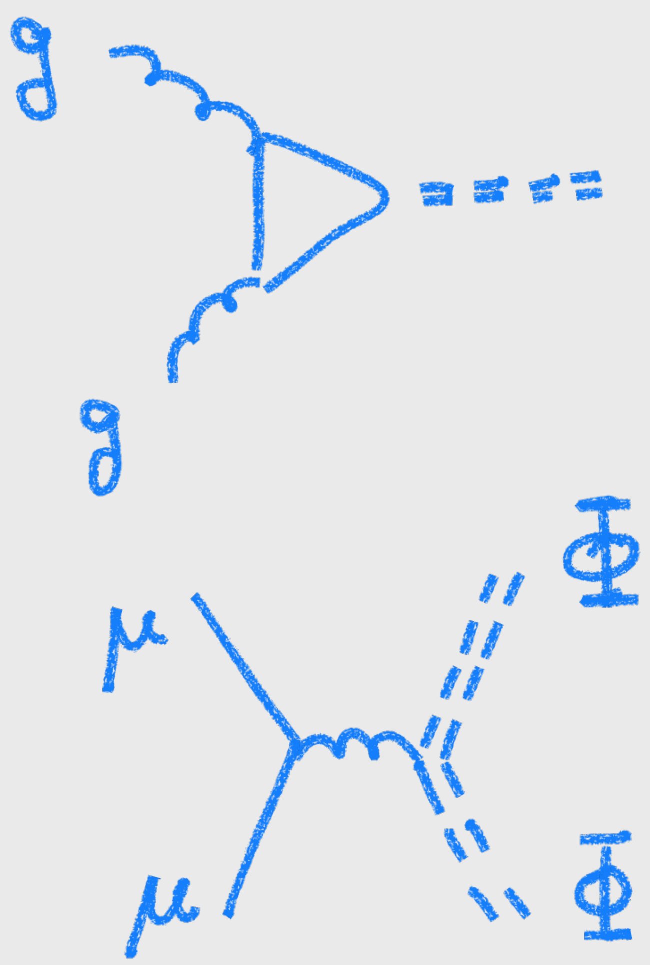

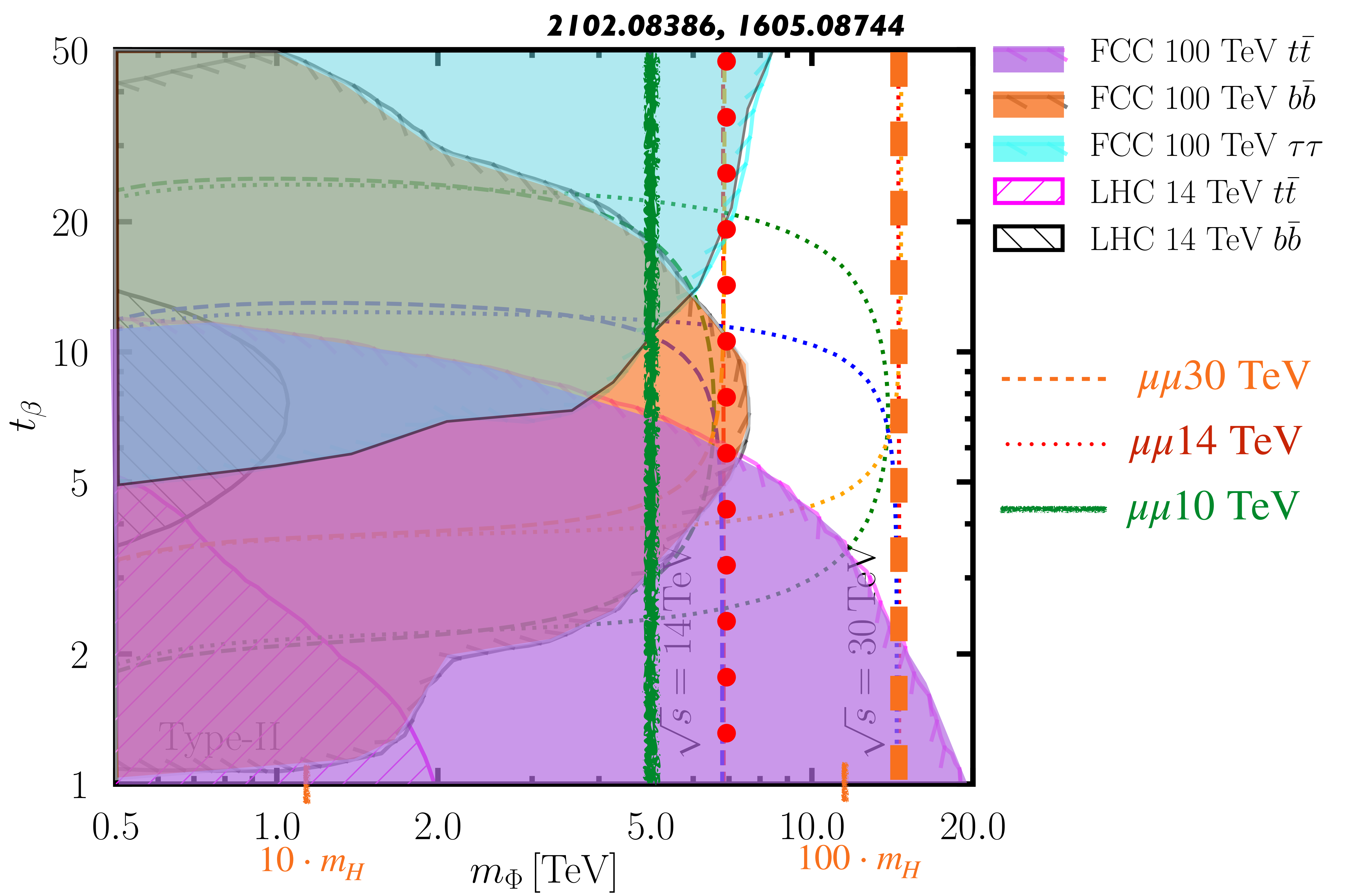

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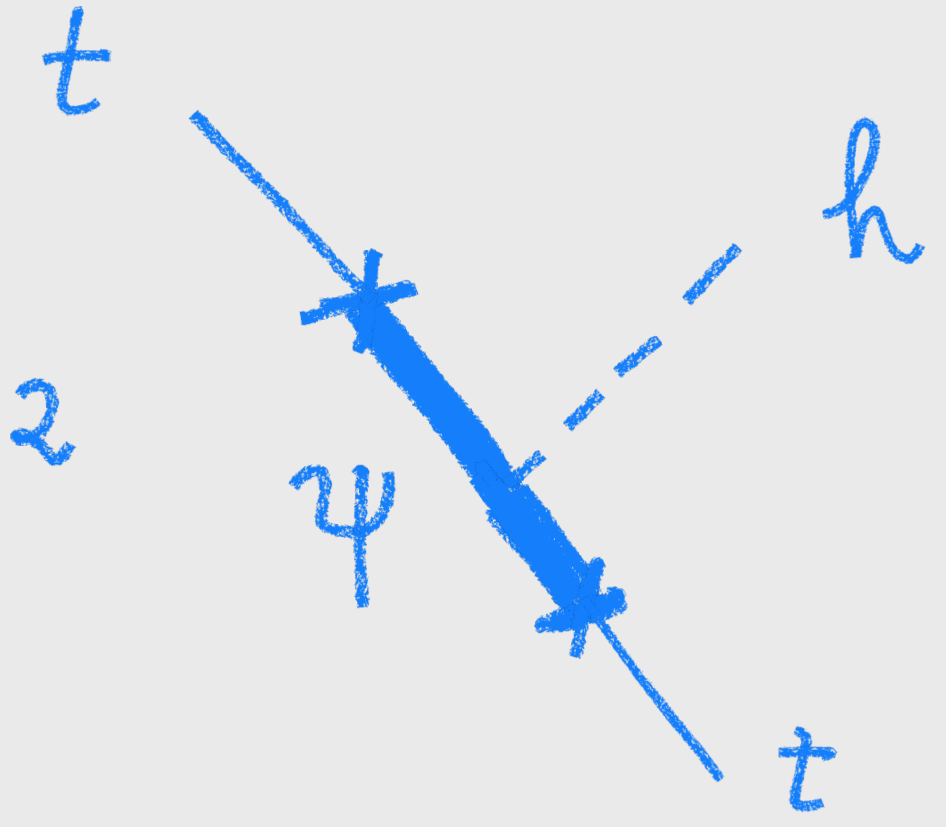

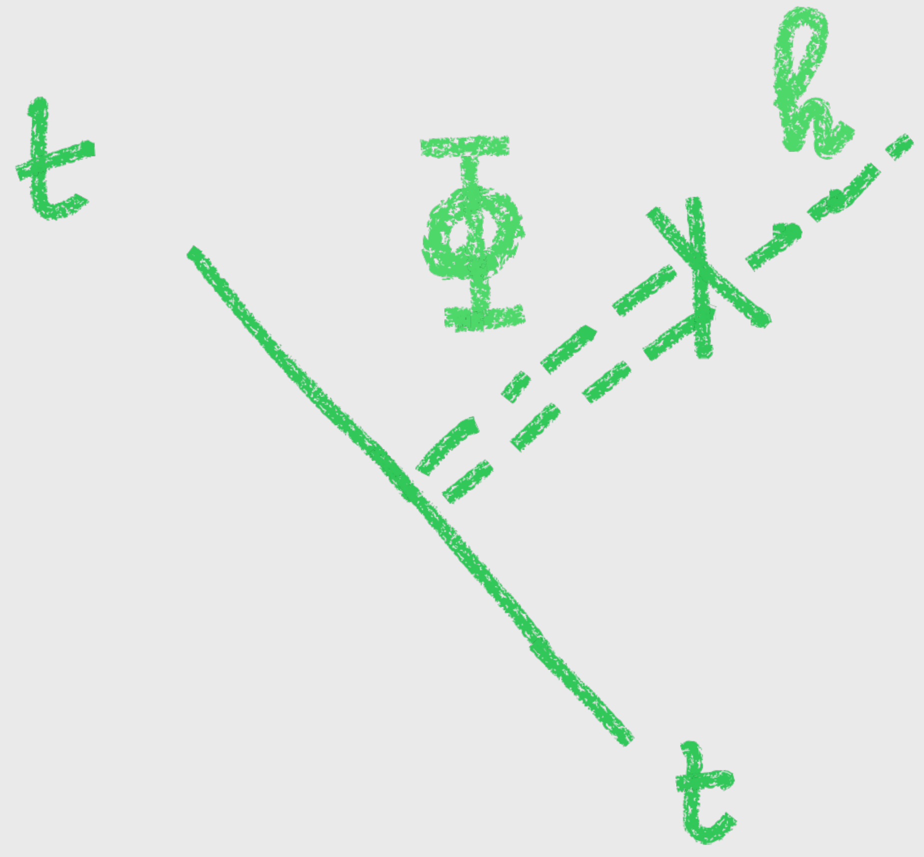

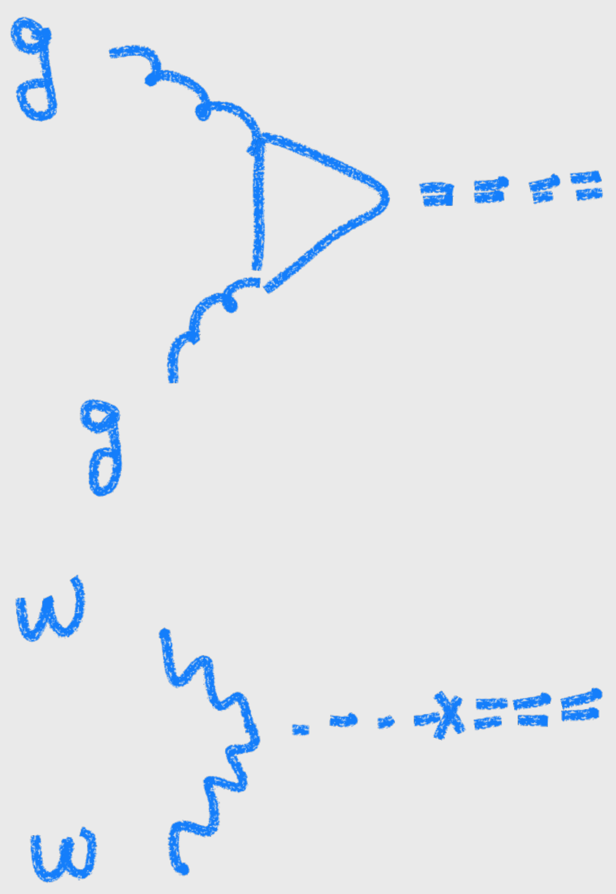

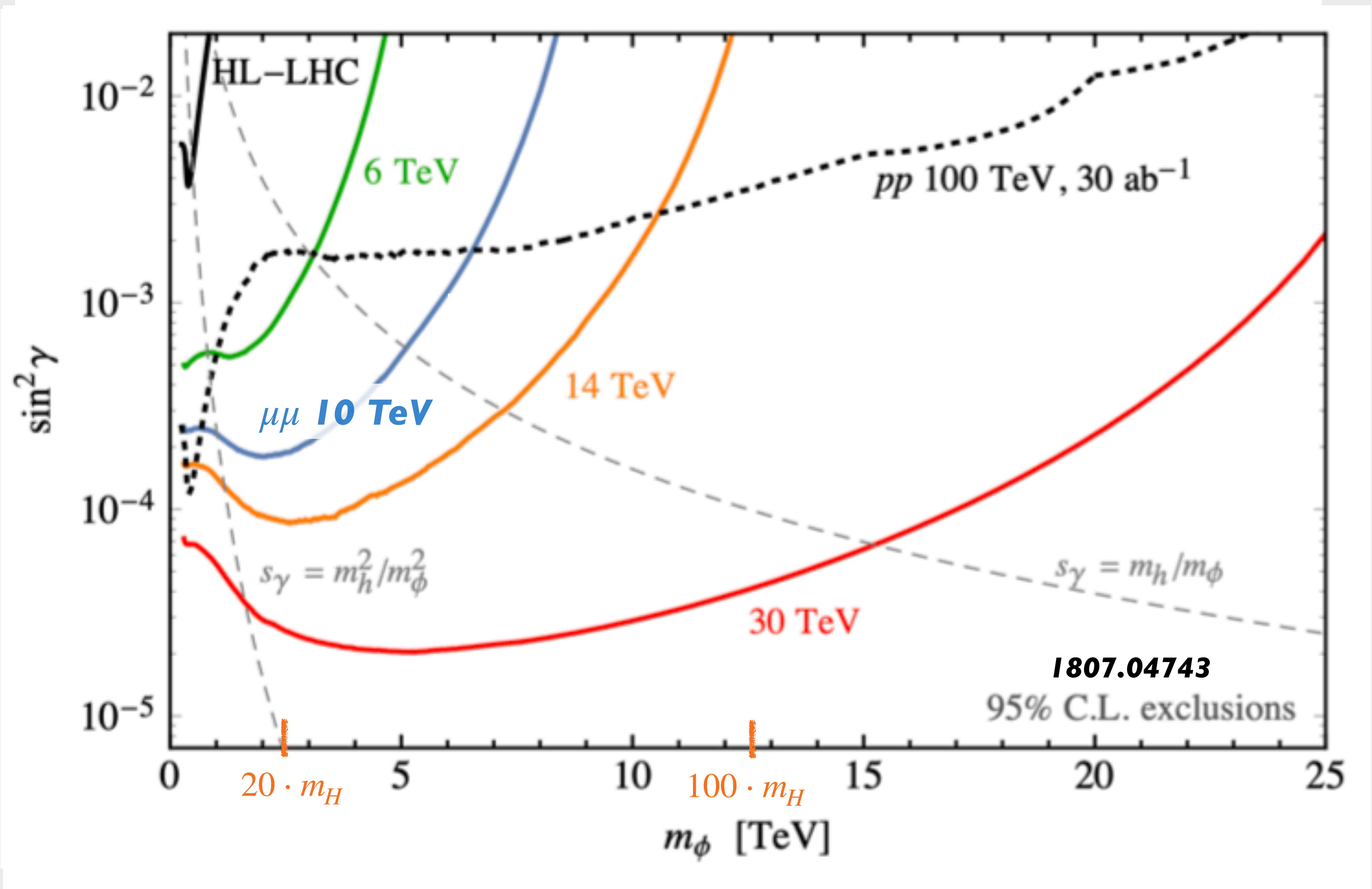

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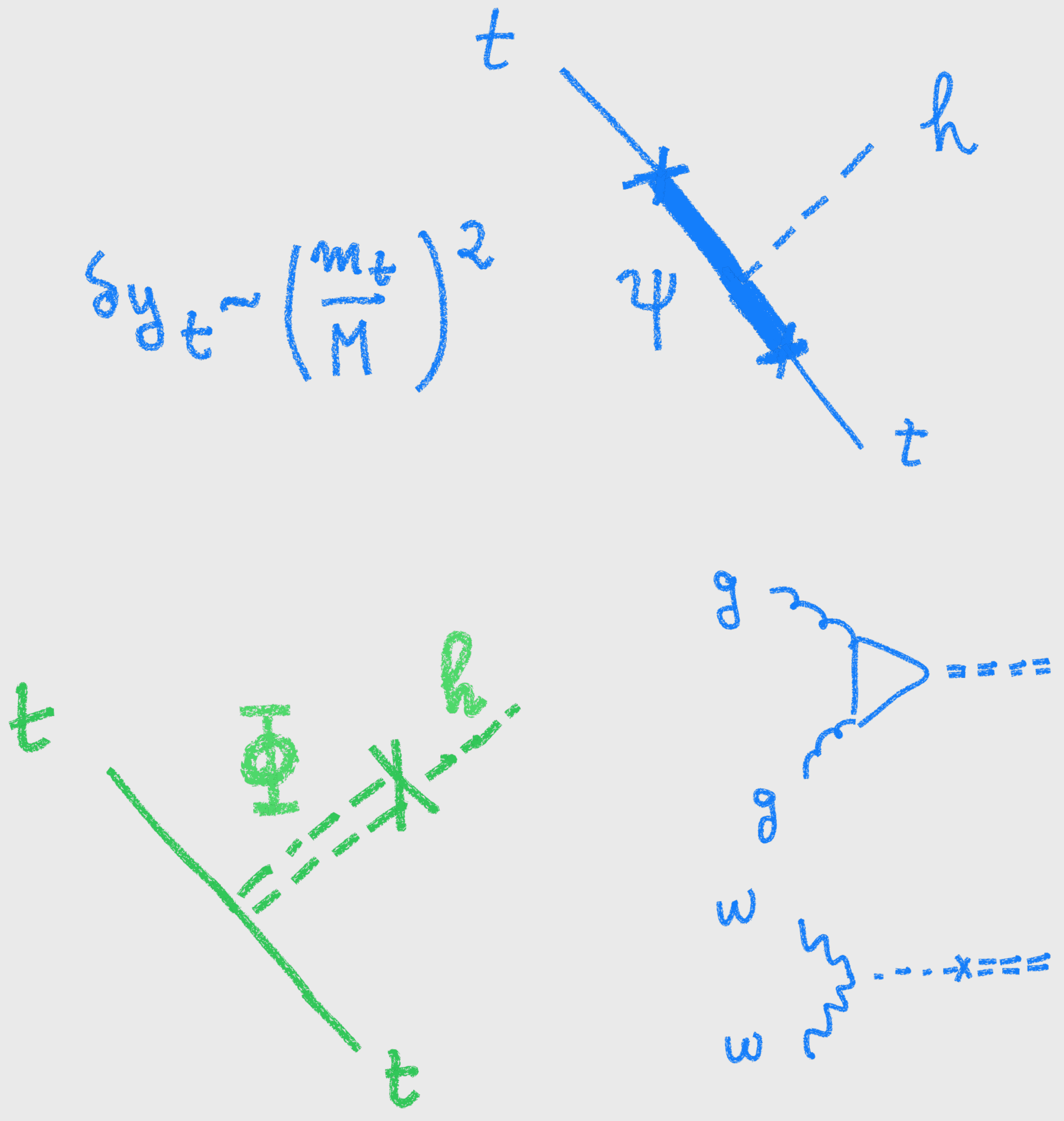

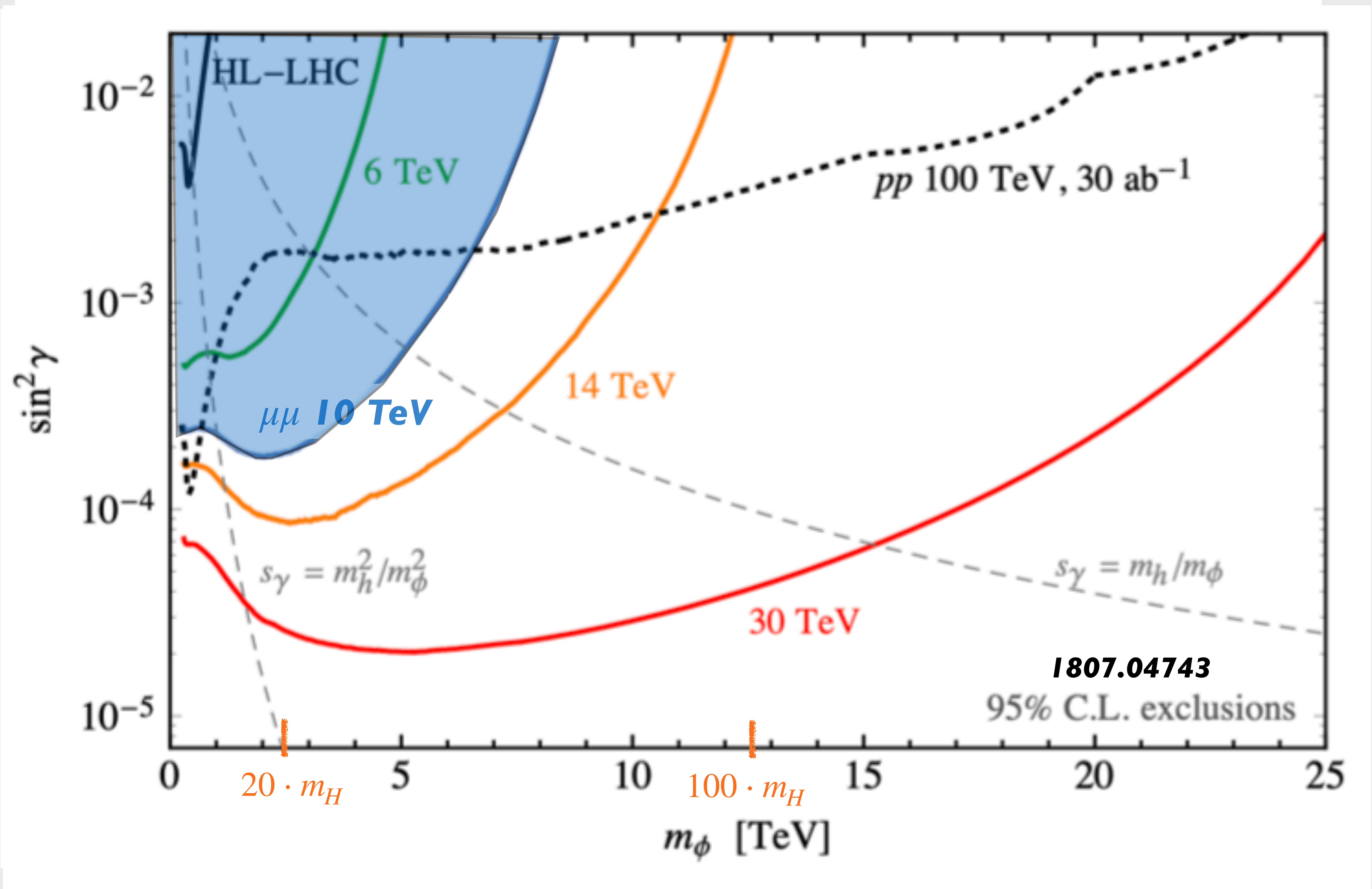

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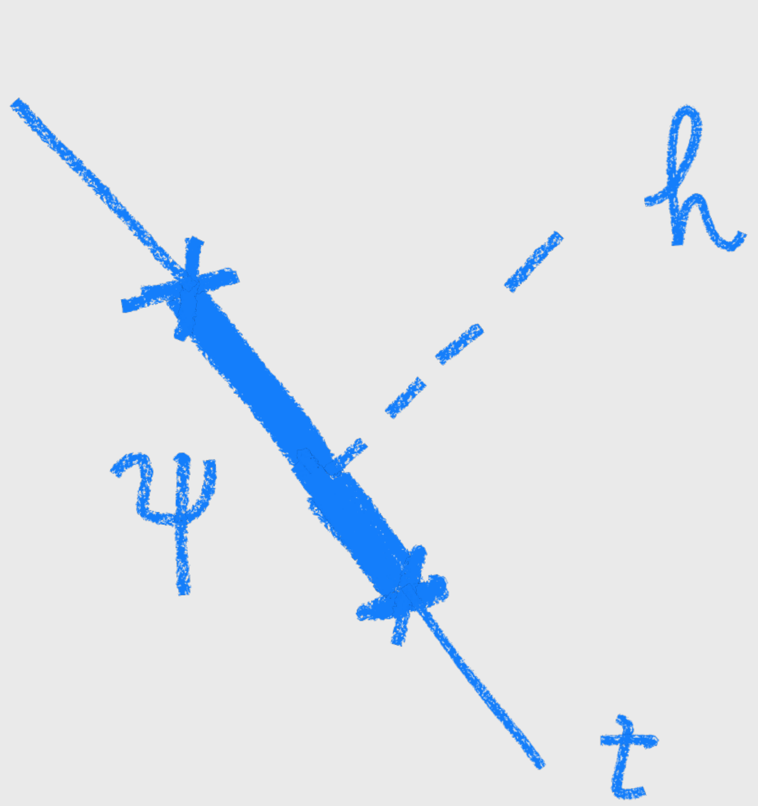

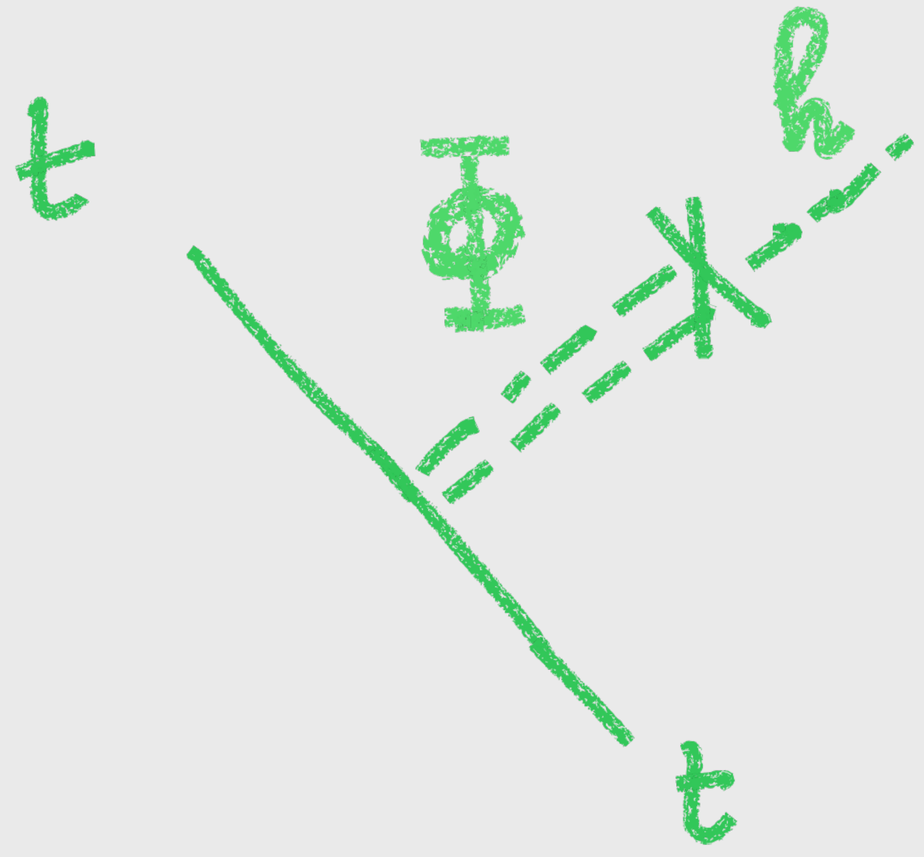

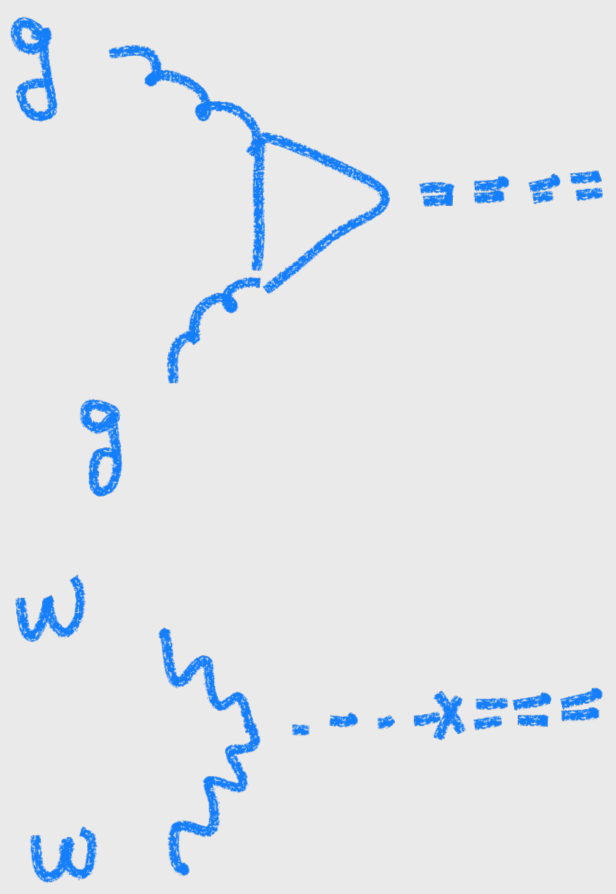

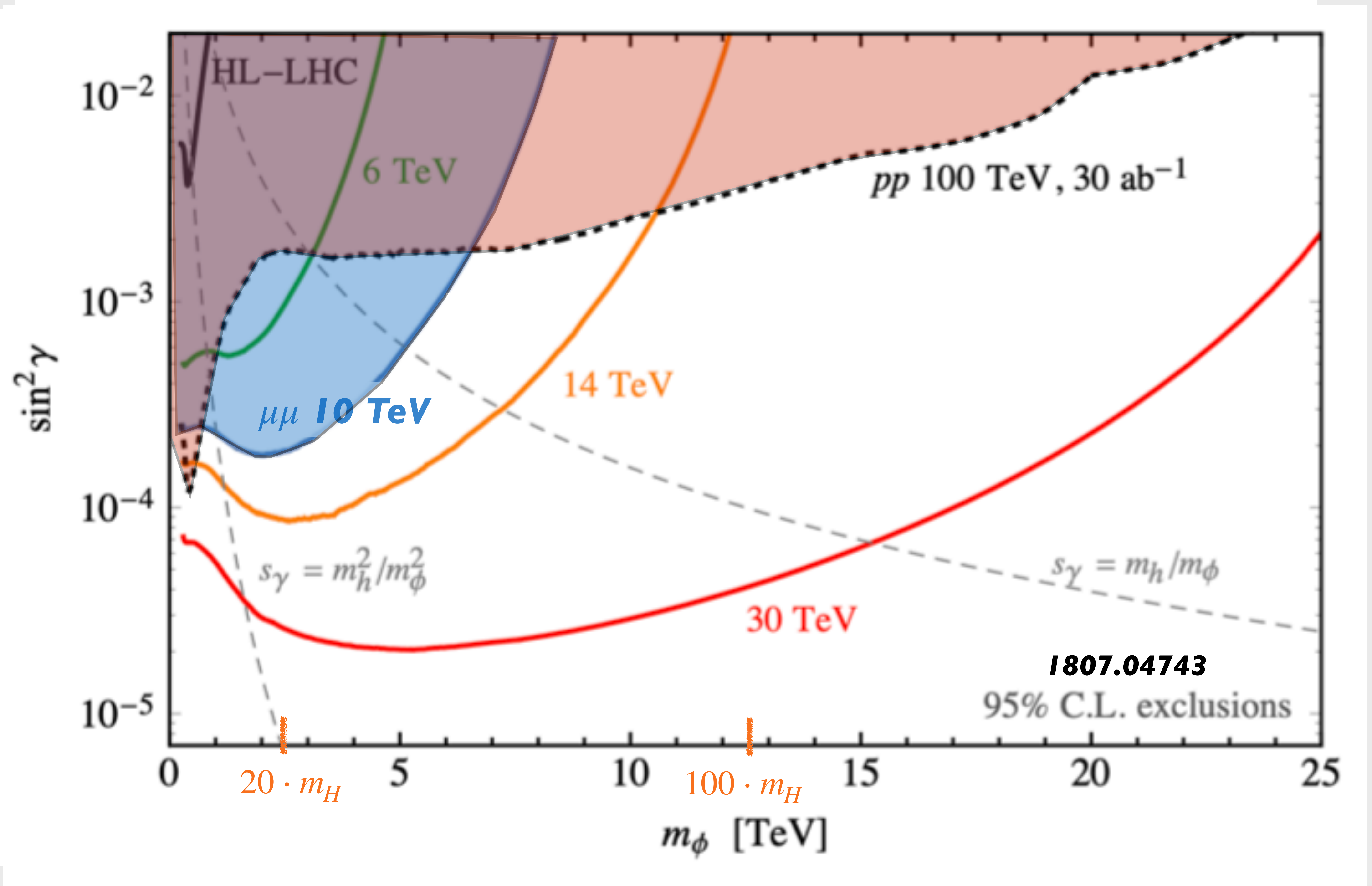

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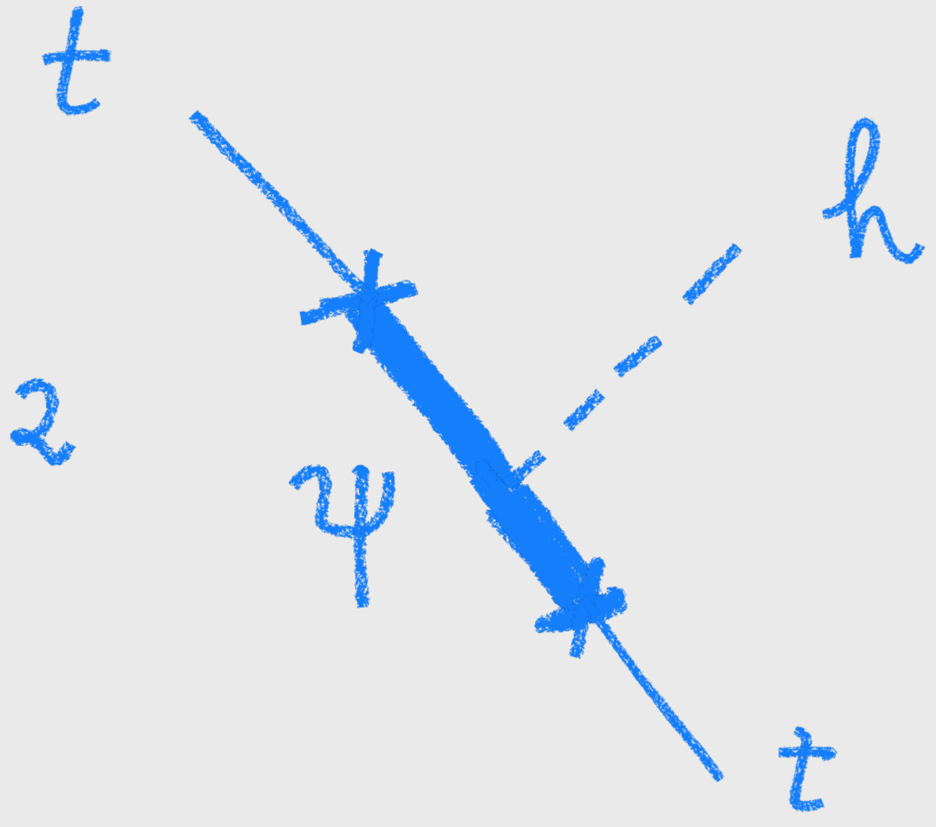

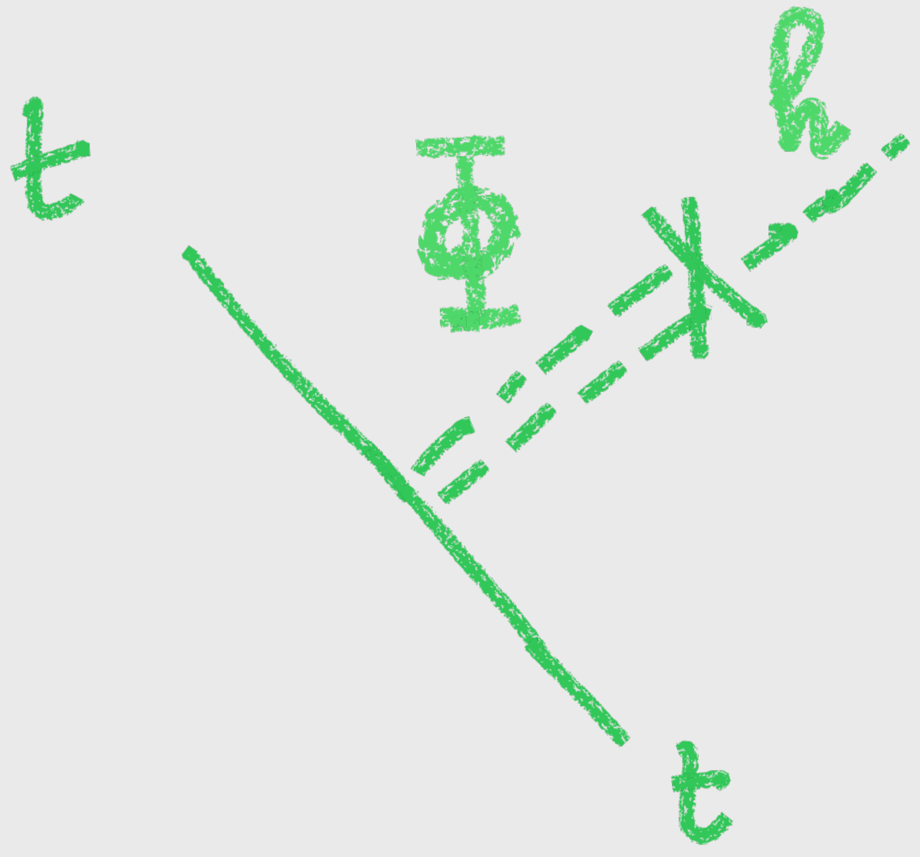

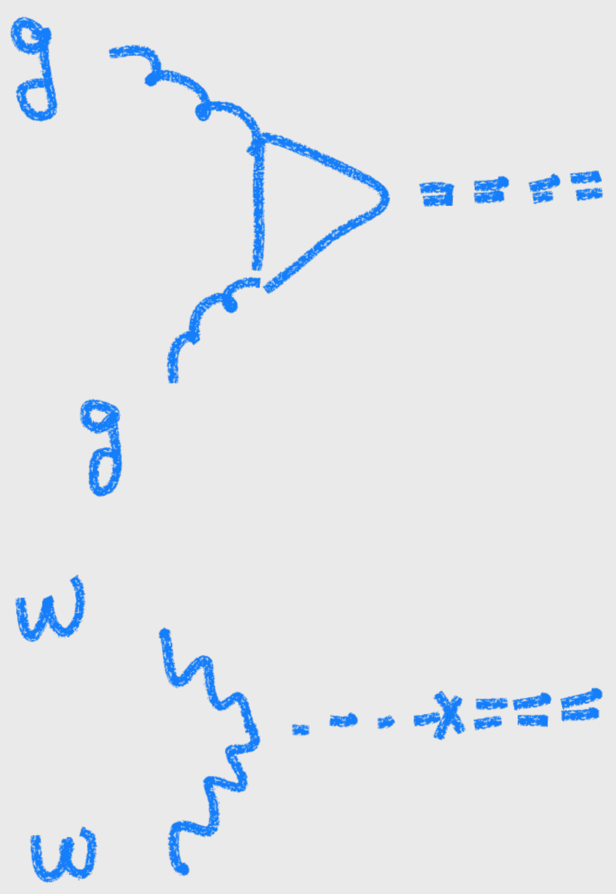

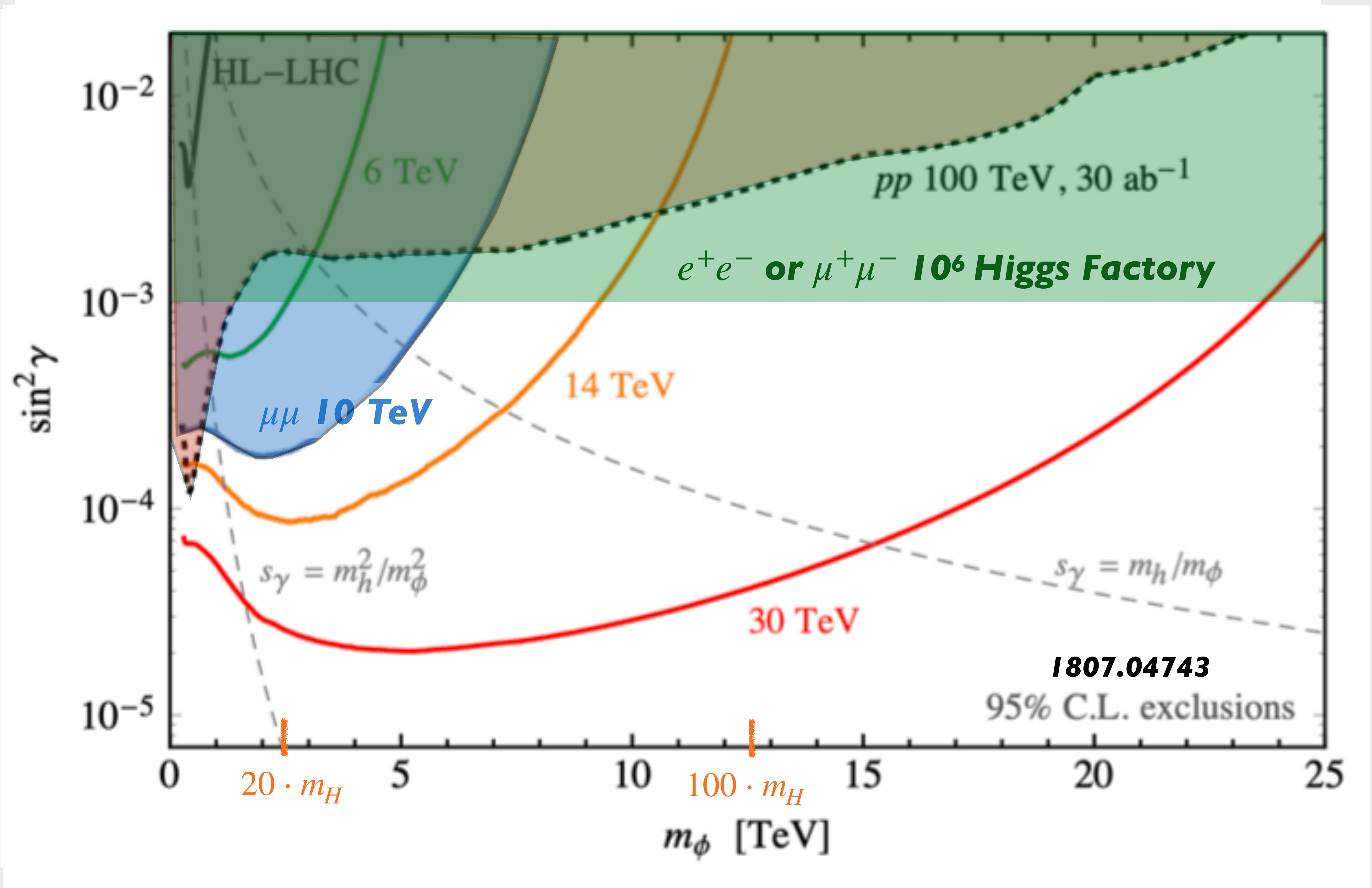

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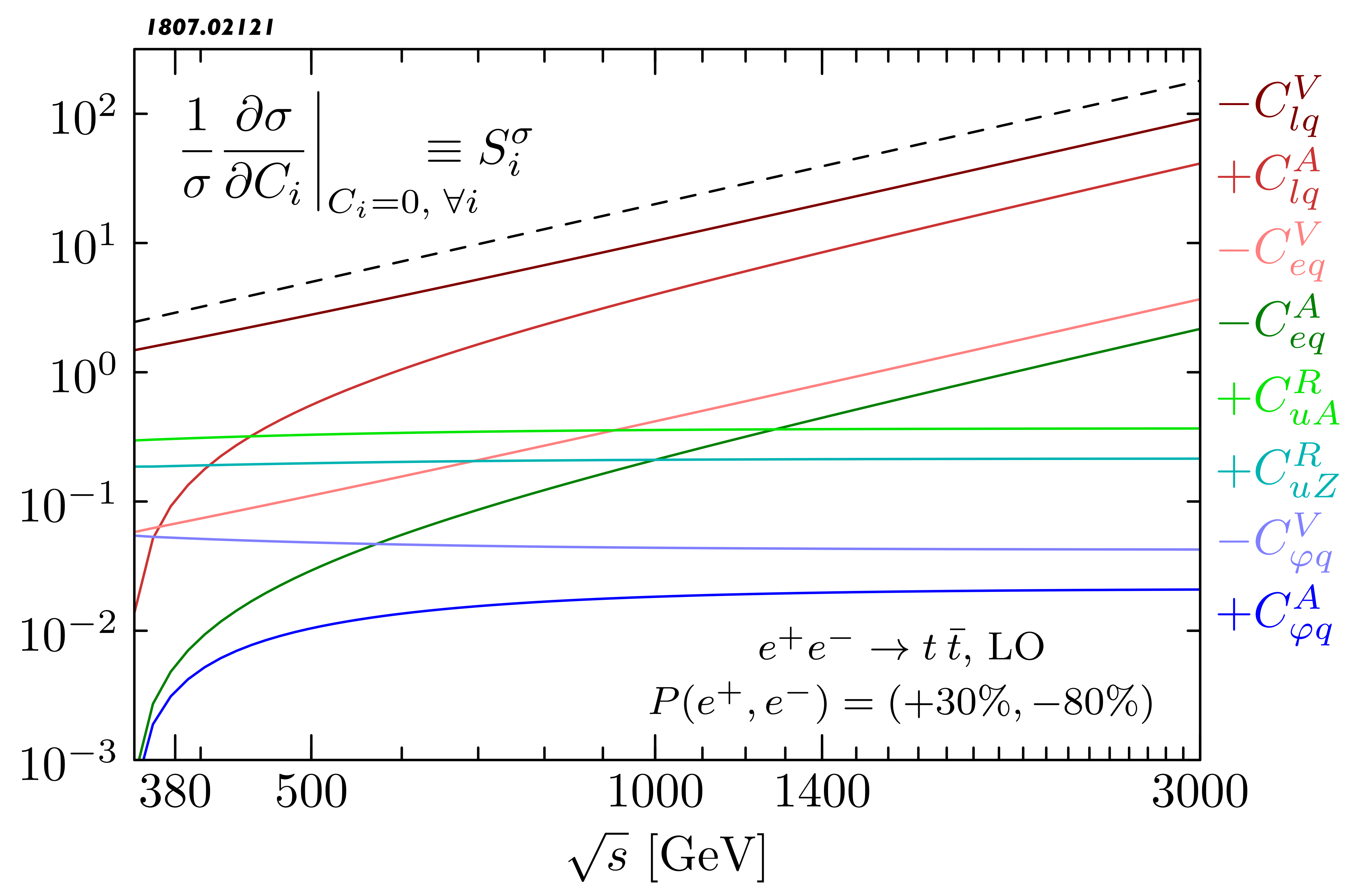
EFT

EFT benefits of multiple probes

ENERGY DEPENDENCE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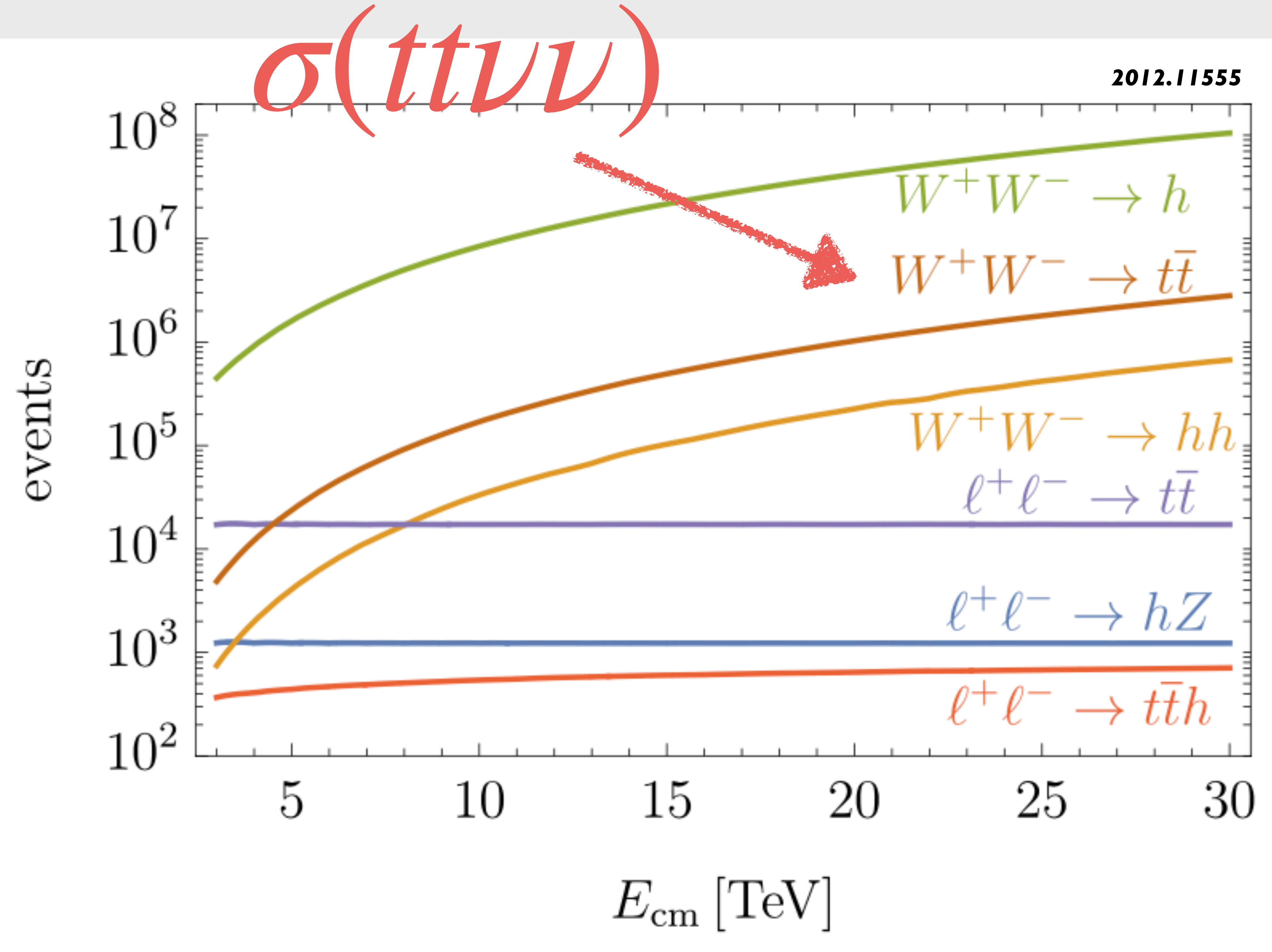

$\sigma(tt\nu\nu)$

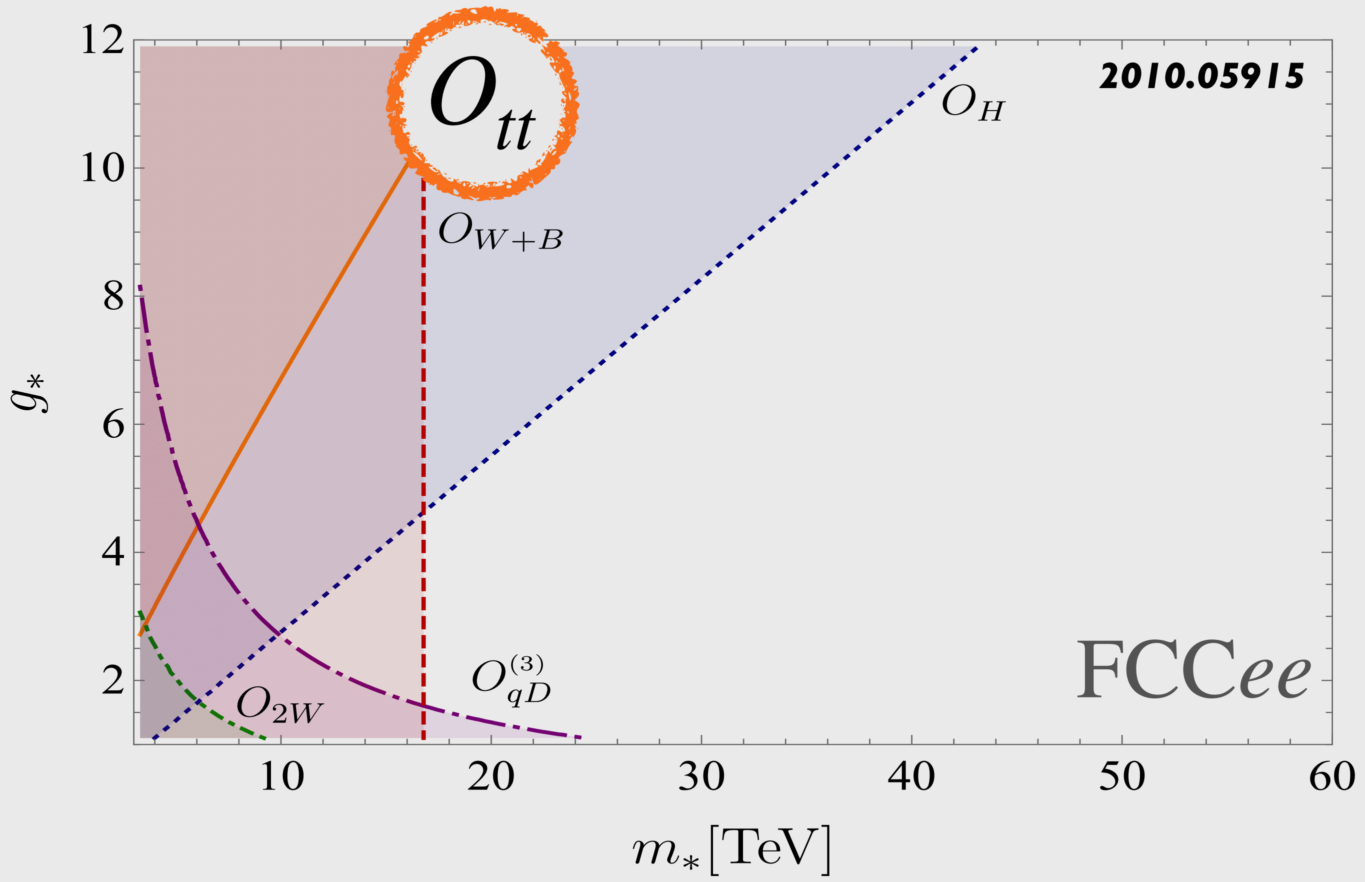
2012.11555

- contact interactions give energy-dependent effects
- measurements at different energies test/disentangle EFT

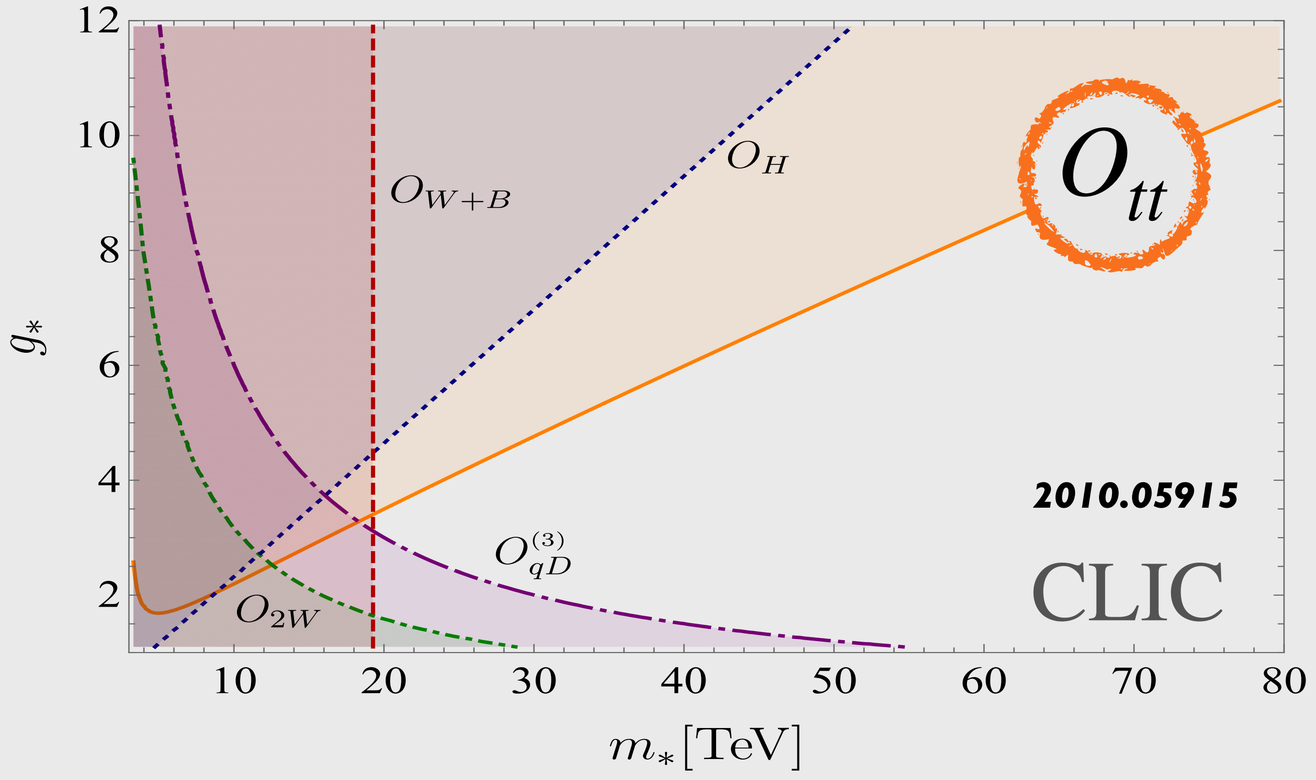
- some effects can also be seen in energy-independent effects where the high-intensity machine FCC-*ee* 350 can provide input earlier than $\mu\mu$ reaches O(10^6) $t\bar{t}$ at 30 TeV

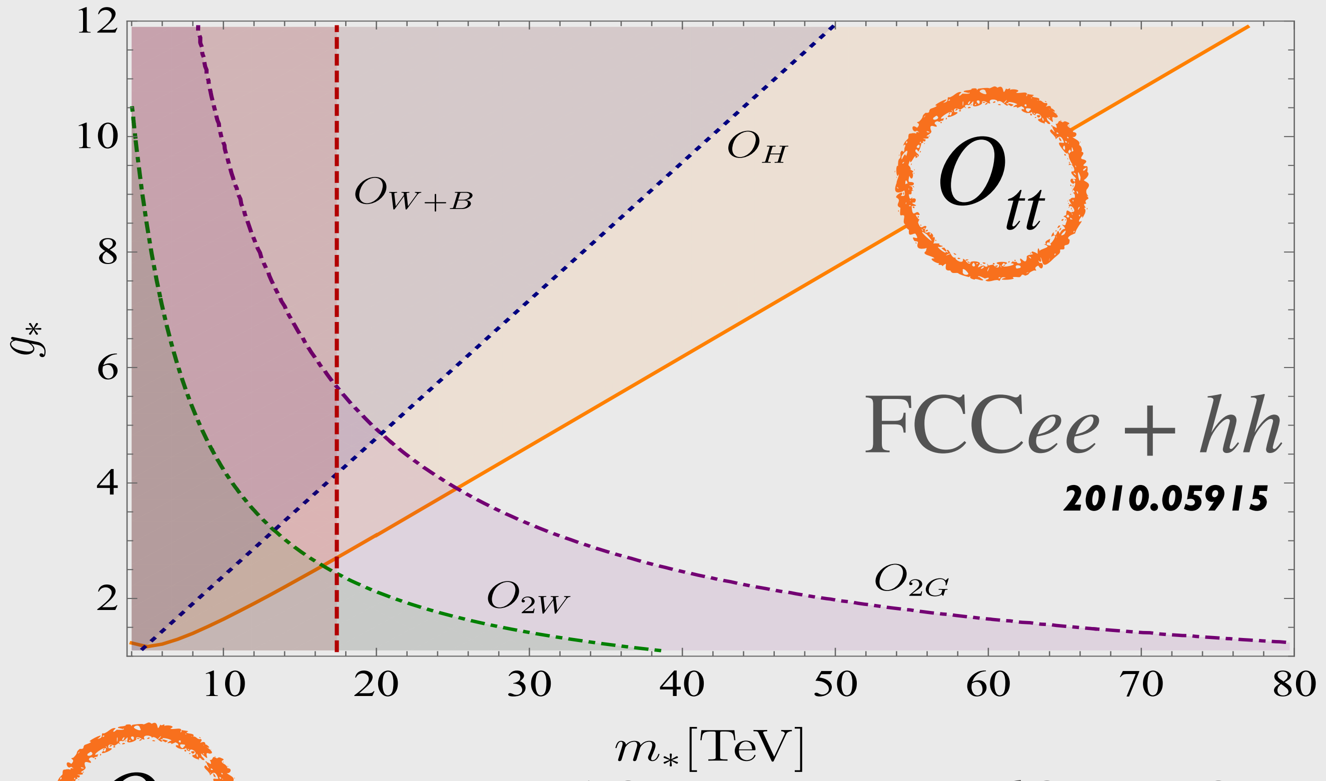
EFT benefits of high-energy probes

FOUR-TOP OPERATOR (t_R COMPOSITENESS)

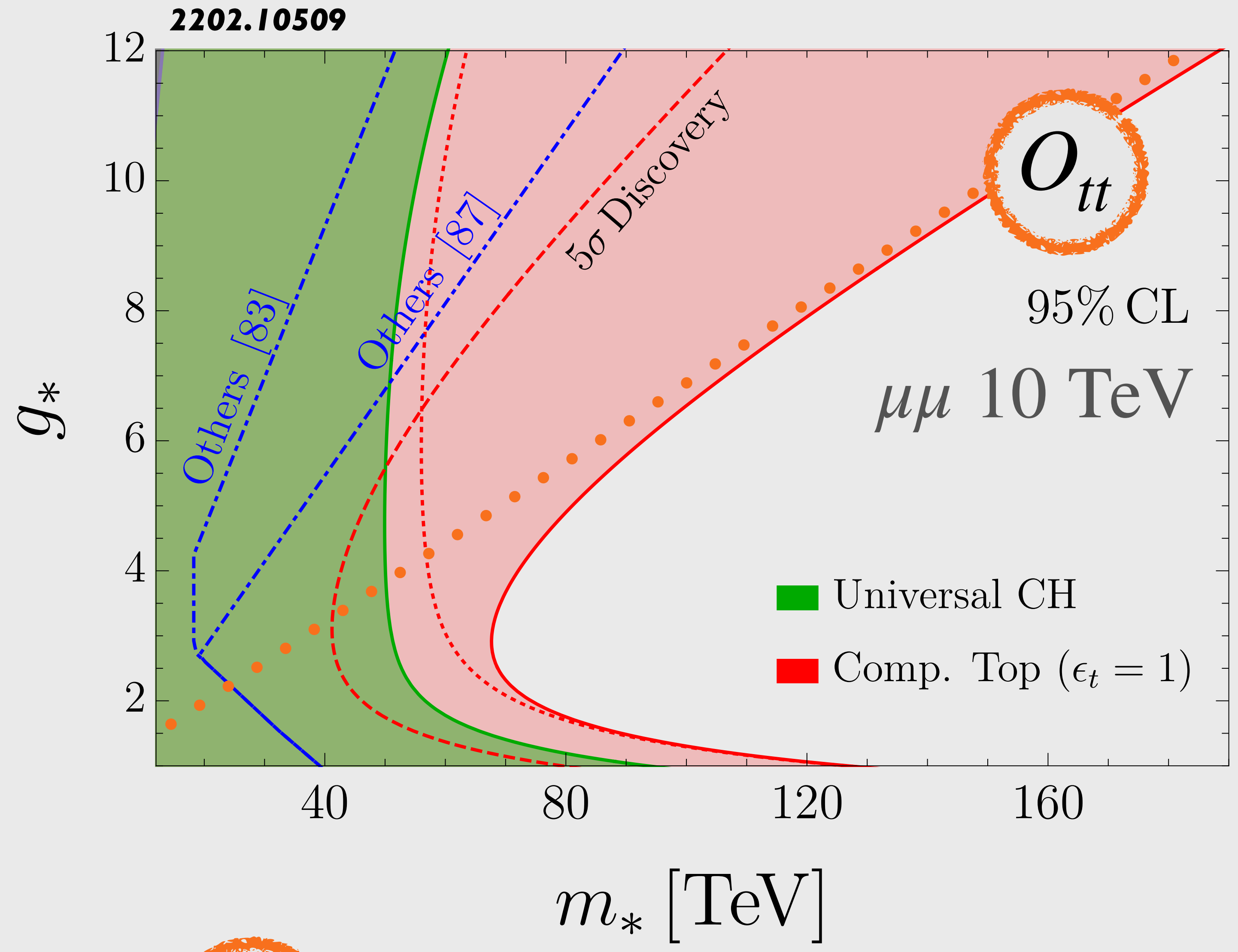


O_{tt} at $g_\star \simeq 10 \Rightarrow m_\star \simeq 18$ TeV





O_{tt} at $g_\star \simeq 10 \Rightarrow m_\star \simeq 60 \div 70$ TeV



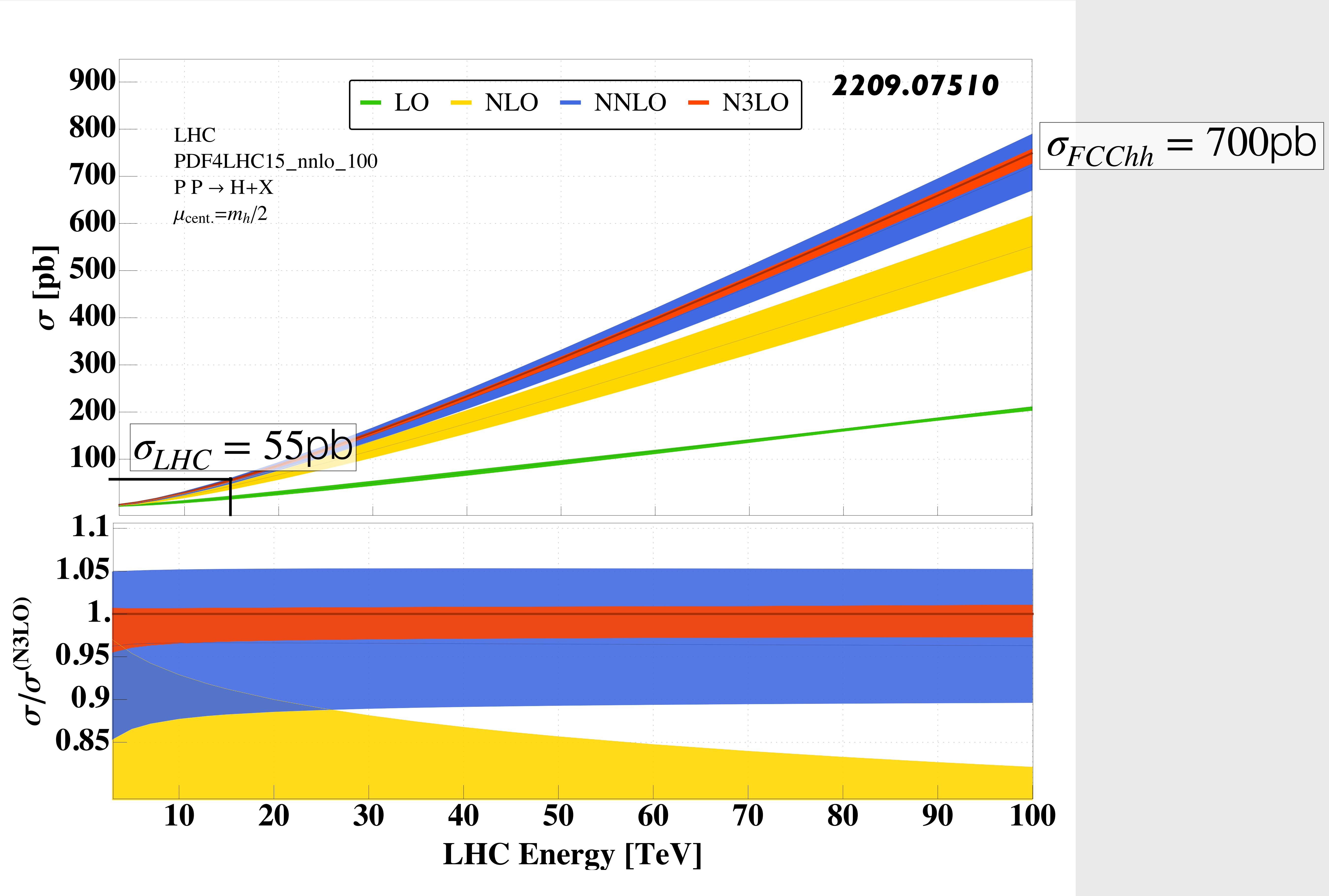
O_{tt} at $g_\star \simeq 10 \Rightarrow m_\star \simeq 180$ TeV

Higgs EFT(*s*)

$pp \to h + X$

10^6 HIGGS BOSONS

MEGA-HIGGS FACTORY



Hadron collider famous as gluon smashers

$$\sqrt{s} = 14\,\text{TeV}$$

$$\sigma \cdot \mathscr{L} \Rightarrow O(10^8)\ \text{h}$$

- large number of Higgs bosons!

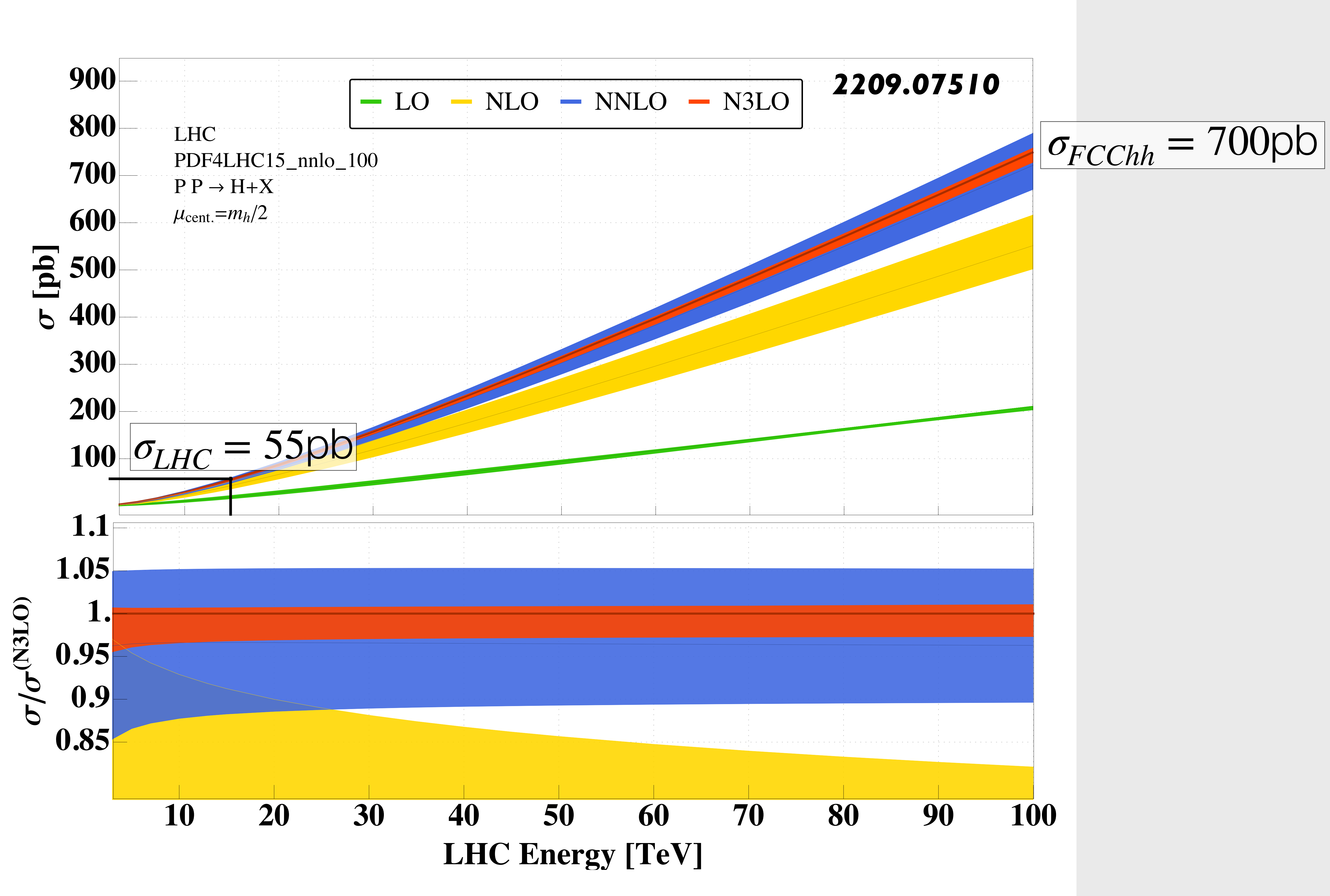
FURTHER OPPORTUNITIES

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

$pp \to h + X$

10⁶ HIGGS BOSONS

MEGA-HIGGS FACTORY



$$\sqrt{s} = 100\ \text{TeV}$$

$$\sigma \cdot \mathscr{L} \Rightarrow O(10^{10})\ \text{h}$$

- large number of Higgs bosons!

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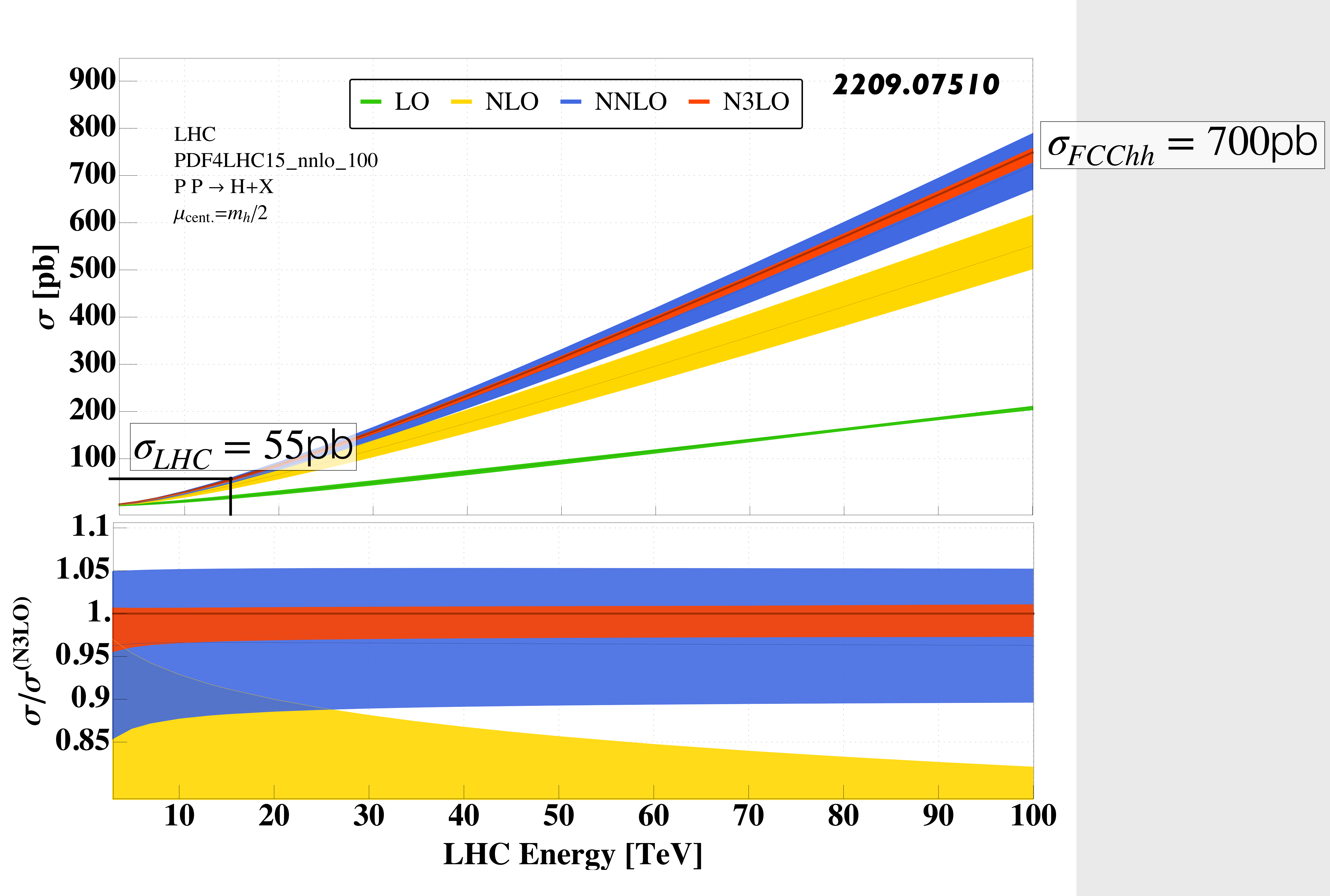

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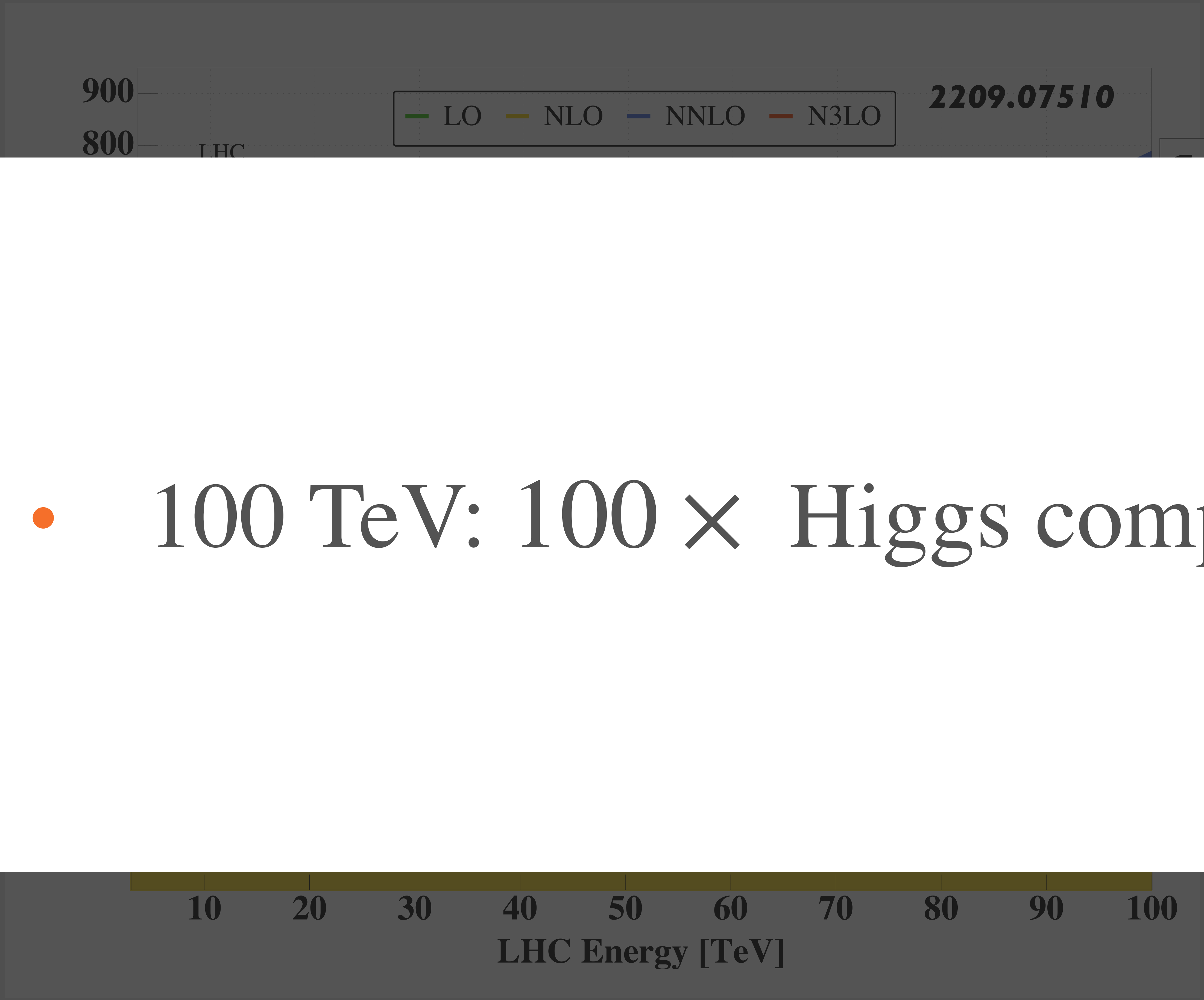


- 100 TeV: 100 × Higgs compared to HL-LHC

FUTURE CIRCULAR COLLIDER

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

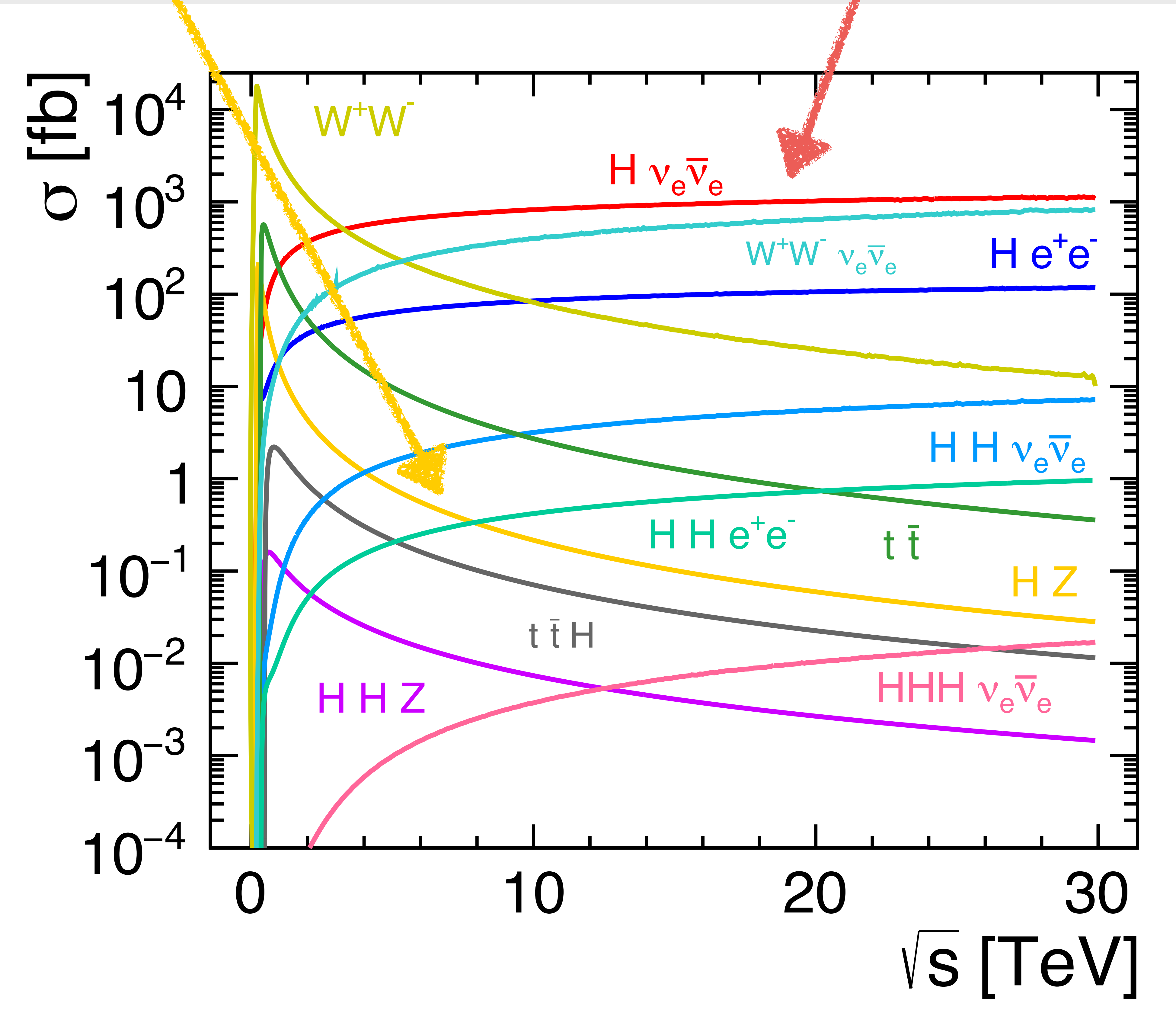
$$\mu^+\mu^- \to h\nu\bar{\nu}$$

10⁶ 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

$$\sqrt{s} = 3\,\mathrm{TeV}$$

$$\sigma \cdot \mathscr{L} \Rightarrow O(10^6)\ \mathrm{h}$$

- large number of Higgs bosons!

FURTHER OPPORTUNITIES

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

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

10^6 HIGGS BOSONS MEGA-HIGGS FACTORY

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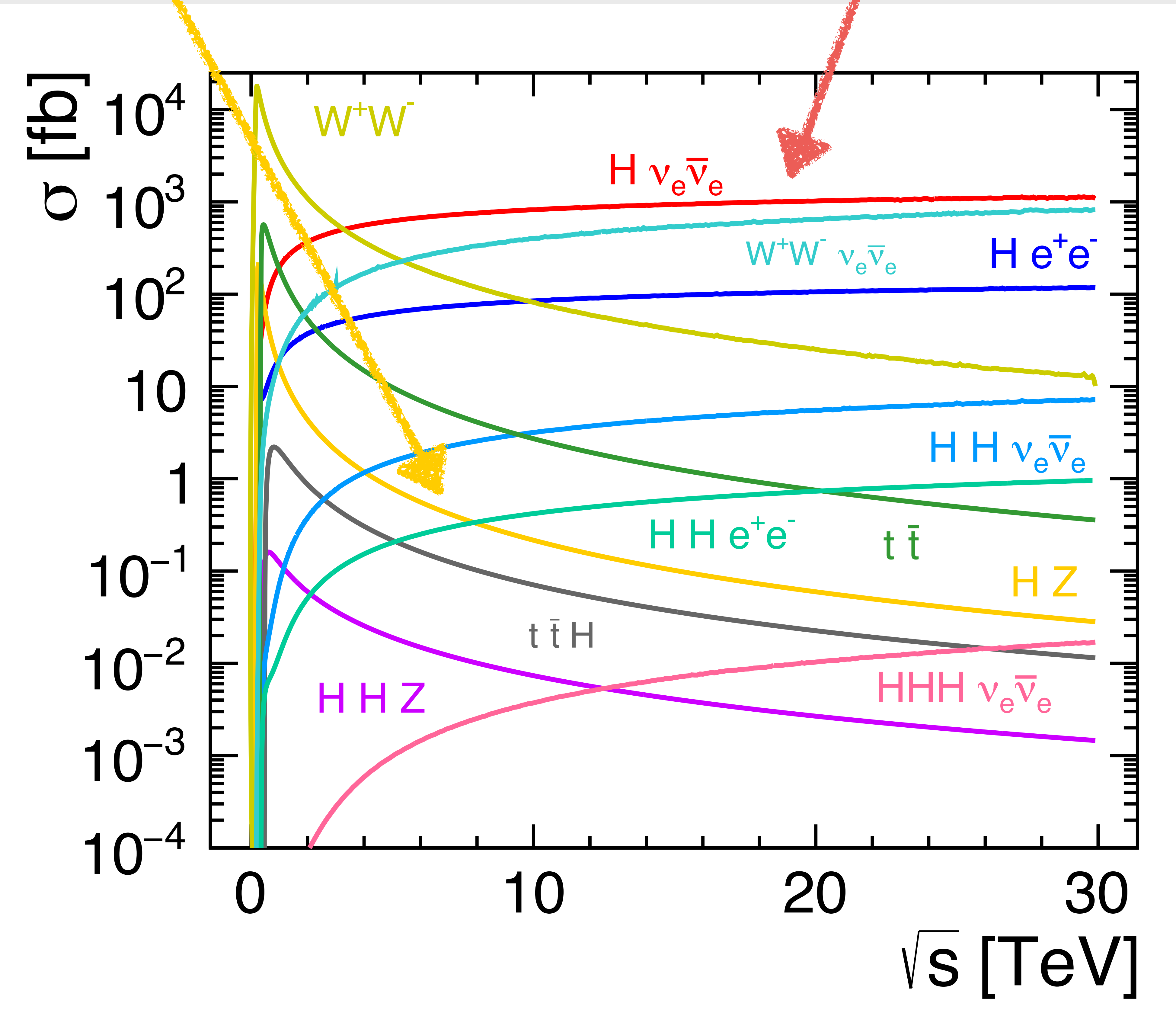


At 30 TeV the weak bosons are sufficiently light that can be radiated very efficiently

$$\sqrt{s} = 30\,\text{TeV}$$

$$\sigma \cdot \mathscr{L} \Rightarrow O(10^8)\ \text{h}$$

- large number of Higgs bosons!

FURTHER OPPORTUNITIES

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

Roberto Franceschini - FCC phenomenology workshop - July 2023 - https://indico.cern.ch/event/1278845/

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

10⁶ HIGGS BOSONS

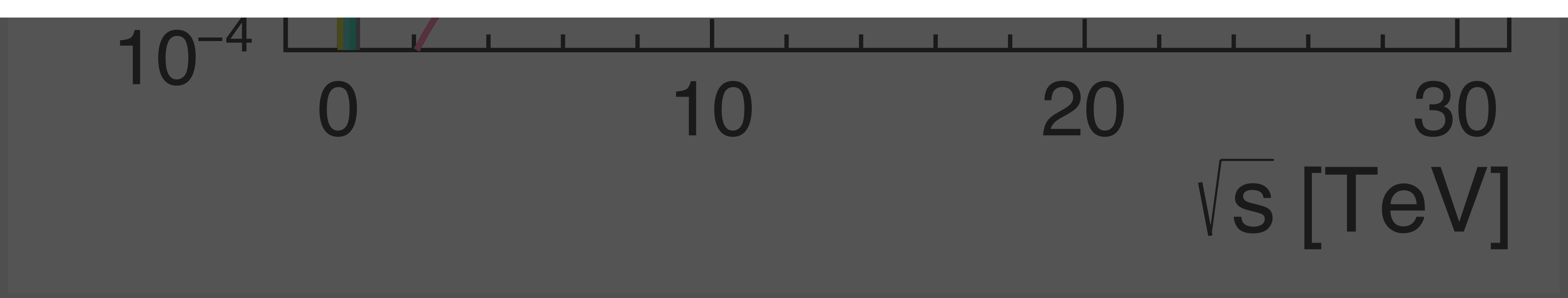
MEGA-HIGGS FACTORY

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

At 30 TeV the weak bosons are sufficiently light that can be radiated very efficiently

- Higgs factory at 3 TeV
- $10\times$ Higgs factory at 10 TeV
- $100\times$ Higgs factory at 30 TeV

International MUON Collider Collaboration



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

2209.07510

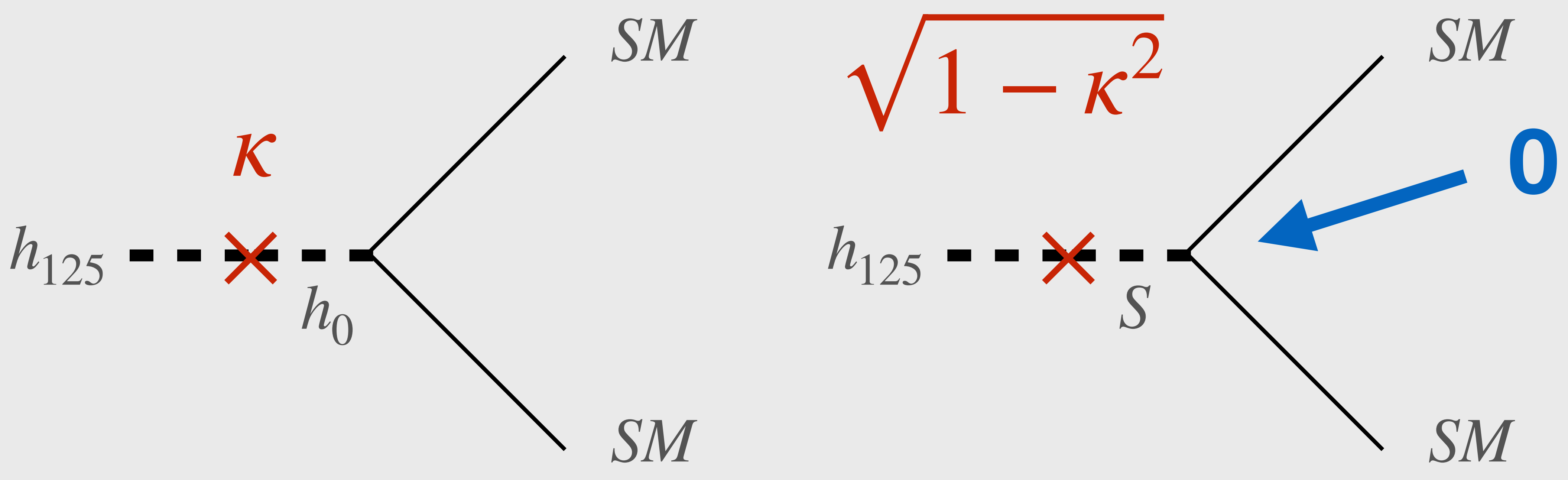
Summary: Higgs@FC (by couplings)

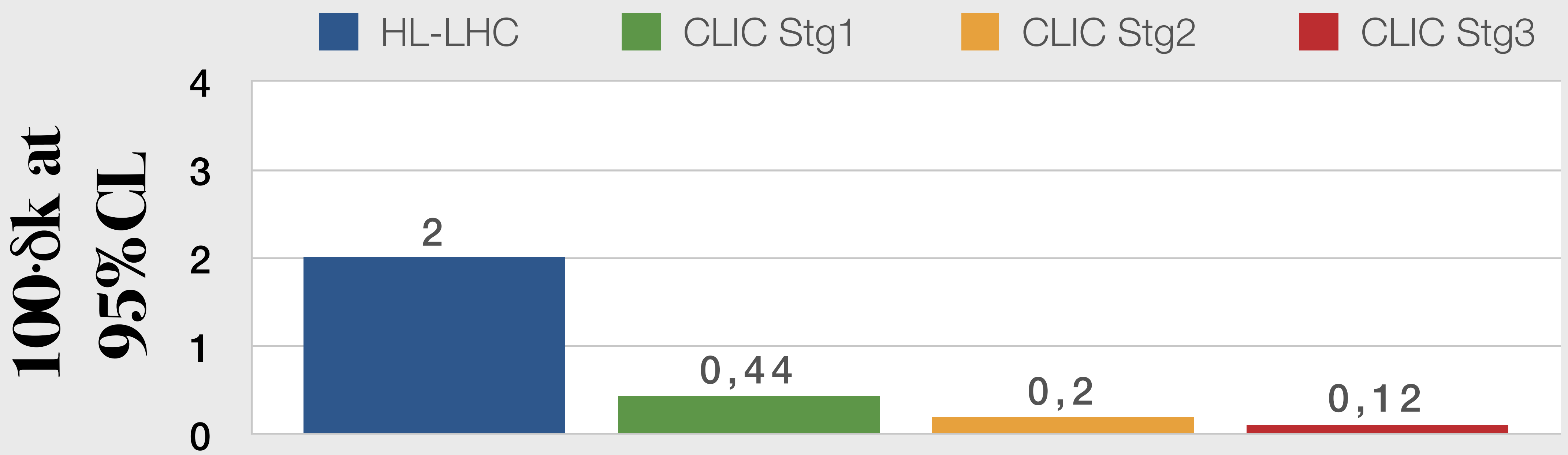
0.1% coupling precision, sensitivity to new physics at $10\ \text{TeV} \simeq 100 \cdot m_h$

A concrete case

NEW SCALAR **SM+HEAVY SINGLET**

$$h_{125} = h_0 \cdot \kappa + S \cdot \sqrt{1-\kappa^2}$$





A concrete case

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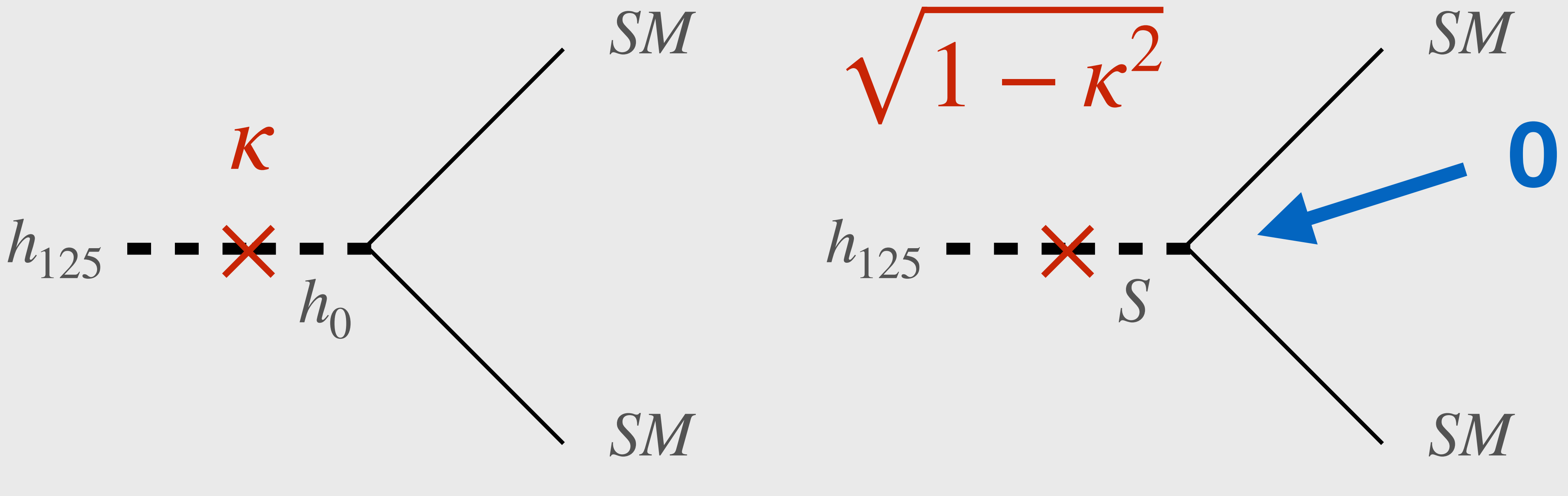
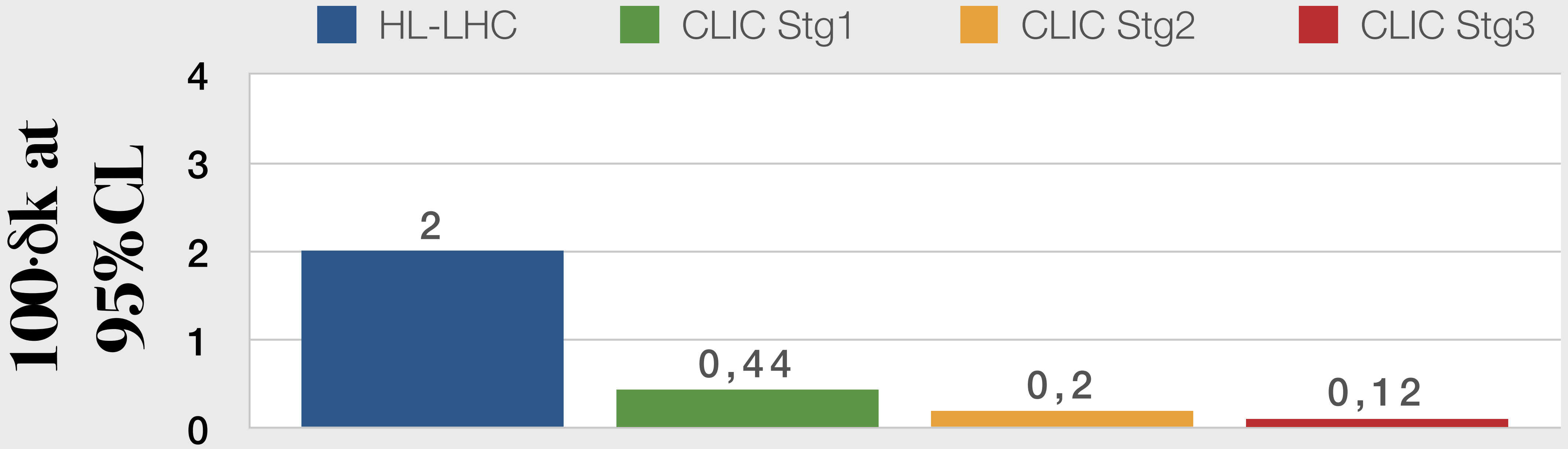
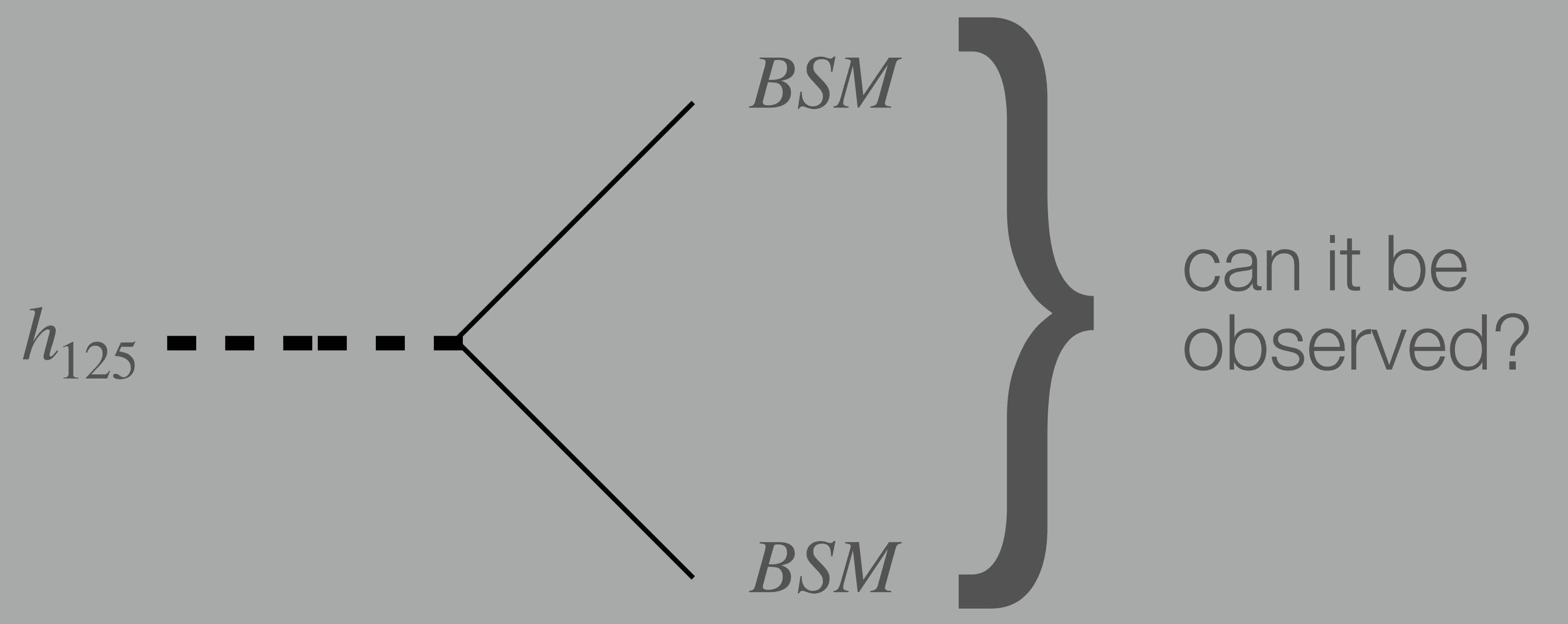




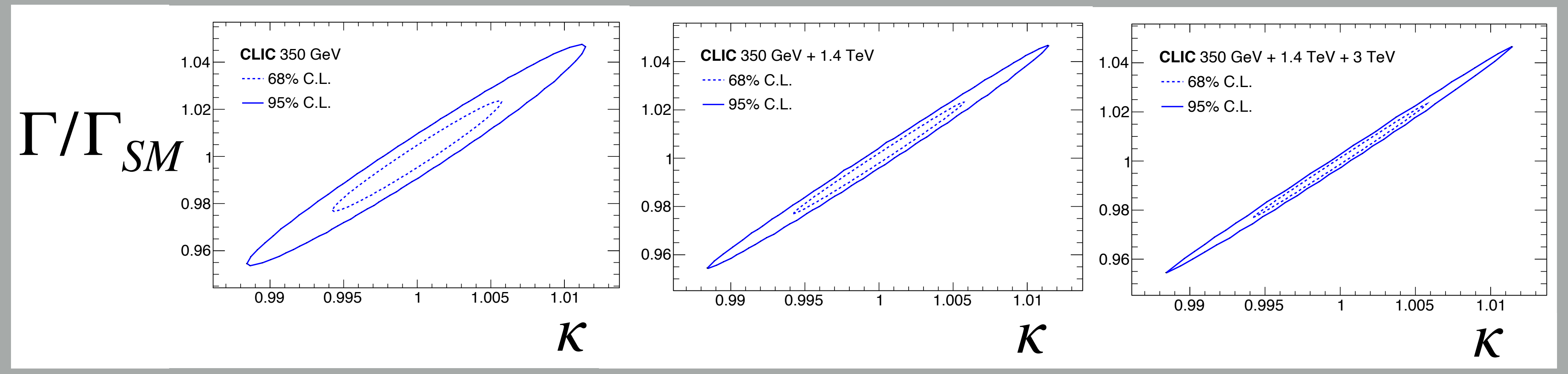
h → BSM

$$\Gamma_H = k^2\Gamma_{SM} + \Gamma_{BSM}$$



can it be observed?

1812.02093



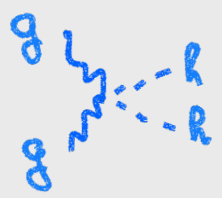
	Δg	$\Delta\Gamma_H$
Stage 1	0.58%	2.3%
Stage 1+2	0.57%	2.3%
Stage 1+2+3	0.57%	2.3%

	$\Delta\Gamma_H$
Stage 1	0.47%
Stage 1+2	0.20%
Stage 1+2+3	0.13%

The size of the Higgs boson

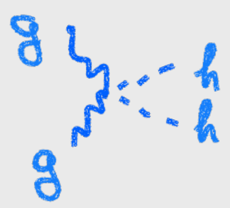
Effects of the size of the Higgs boson

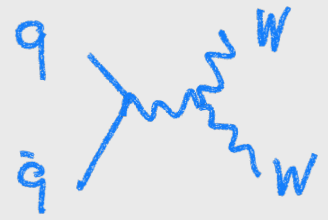
STRONGLY INTERACTING HIGGS (AND TOP)

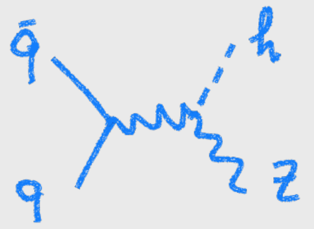


large p_T

still dominated by LEP physics

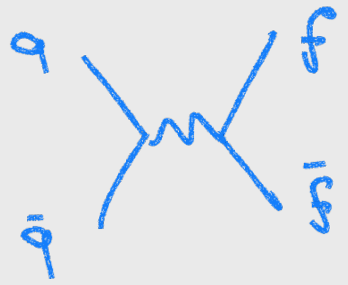






$$\mathcal{L}^{d=6}_{universal} = c_H \frac{g_*^2}{m_*^2}\mathcal{O}_H + c_T \frac{N_c \epsilon_q^4 g_*^4}{(4\pi)^2 m_*^2}\mathcal{O}_T + c_6 \lambda \frac{g_*^2}{m_*^2}\mathcal{O}_6 + \frac{1}{m_*^2}\left[c_W \mathcal{O}_W + c_B \mathcal{O}_B\right]$$

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



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

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

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

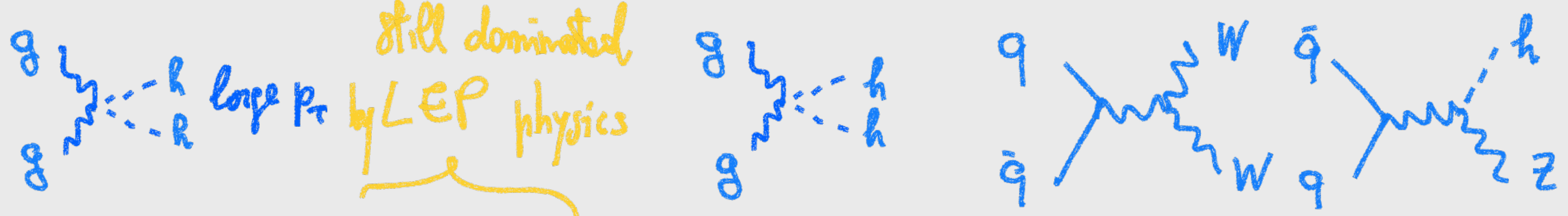
$1/(g_\star f) \sim 1/m_\star$

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

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

Effects of the size of the Higgs boson

STRONGLY INTERACTING HIGGS (AND TOP)



large p_T

still dominated by LEP physics

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

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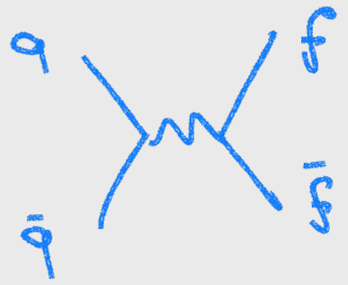

$$+ \frac{1}{g_*^2 m_*^2}\left[c_{2W} g^2 \mathcal{O}_{2W} + c_{2B} g'^2 \mathcal{O}_{2B}\right] + c_{3W}\frac{3! g^2}{(4\pi)^2 m_*^2}\mathcal{O}_{3W}$$

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

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

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

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

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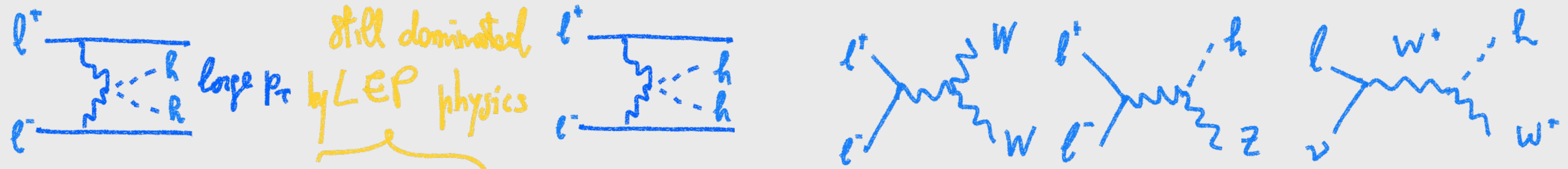

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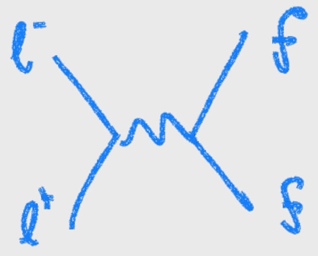

$$+ \frac{1}{g_*^2 m_*^2}\left[c_{2W} g^2 \mathcal{O}_{2W} + c_{2B} g'^2 \mathcal{O}_{2B}\right] + c_{3W}\frac{3! g^2}{(4\pi)^2 m_*^2}\mathcal{O}_{3W}$$

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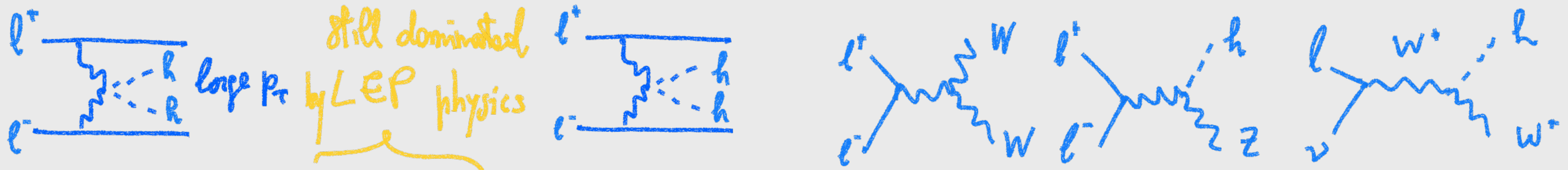

large p_T

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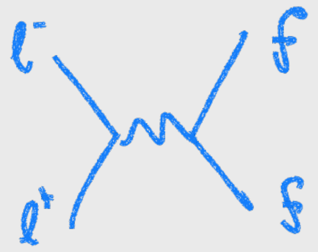

$$+ \frac{1}{g_*^2 m_*^2}\left[c_{2W} g^2 \mathcal{O}_{2W} + c_{2B} g'^2 \mathcal{O}_{2B}\right] + c_{3W}\frac{3! g^2}{(4\pi)^2 m_*^2}\mathcal{O}_{3W}$$

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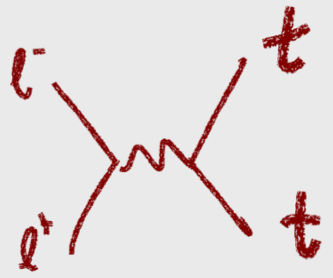

$$+ c_{tD}\frac{g_*^2}{m_*^2}\mathcal{O}_{tD}$$

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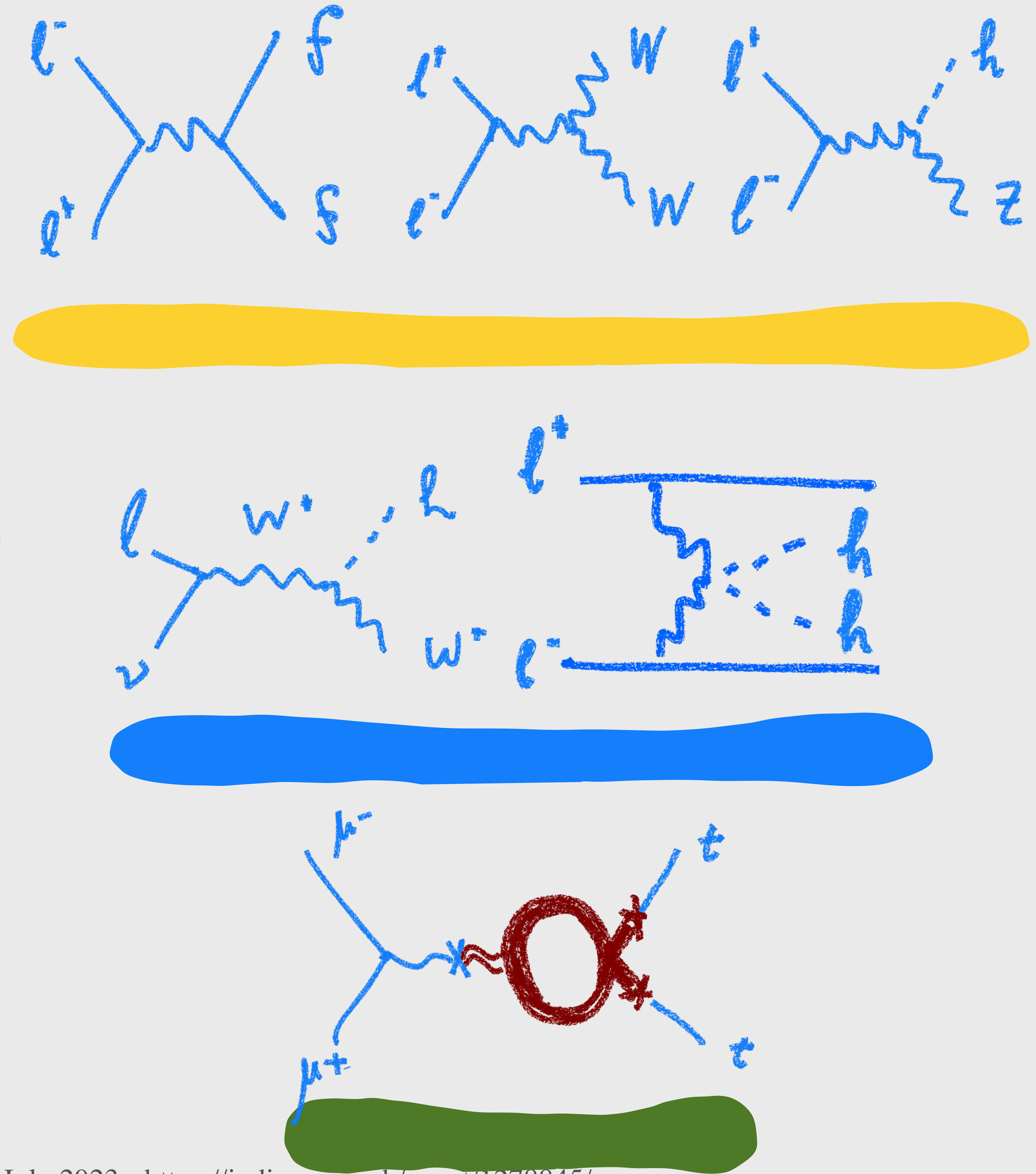
Effects of the size of the Higgs boson

STRONGLY INTERACTING HIGGS (AND TOP)

point-like beams

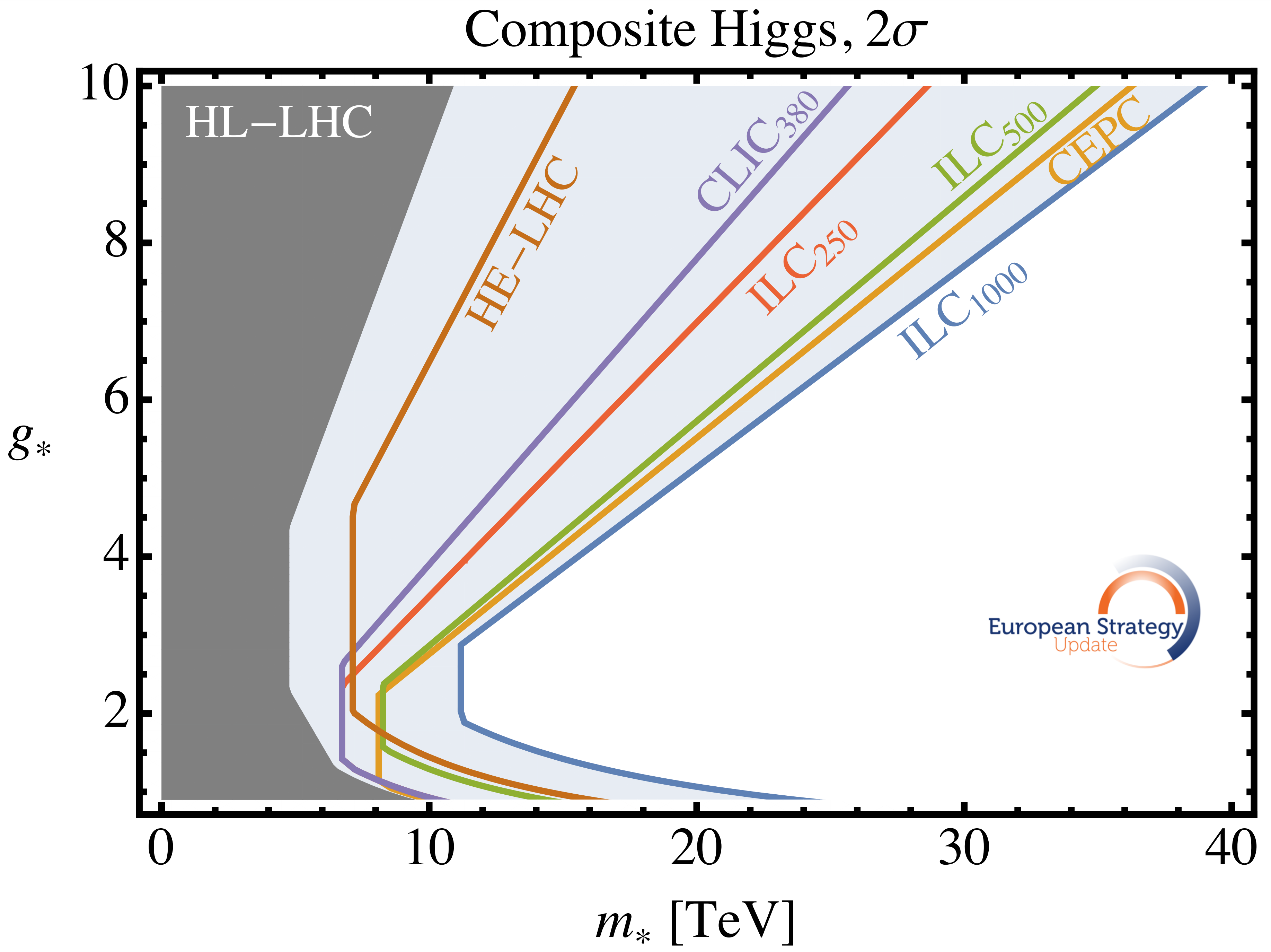
“partons”,radiative processes

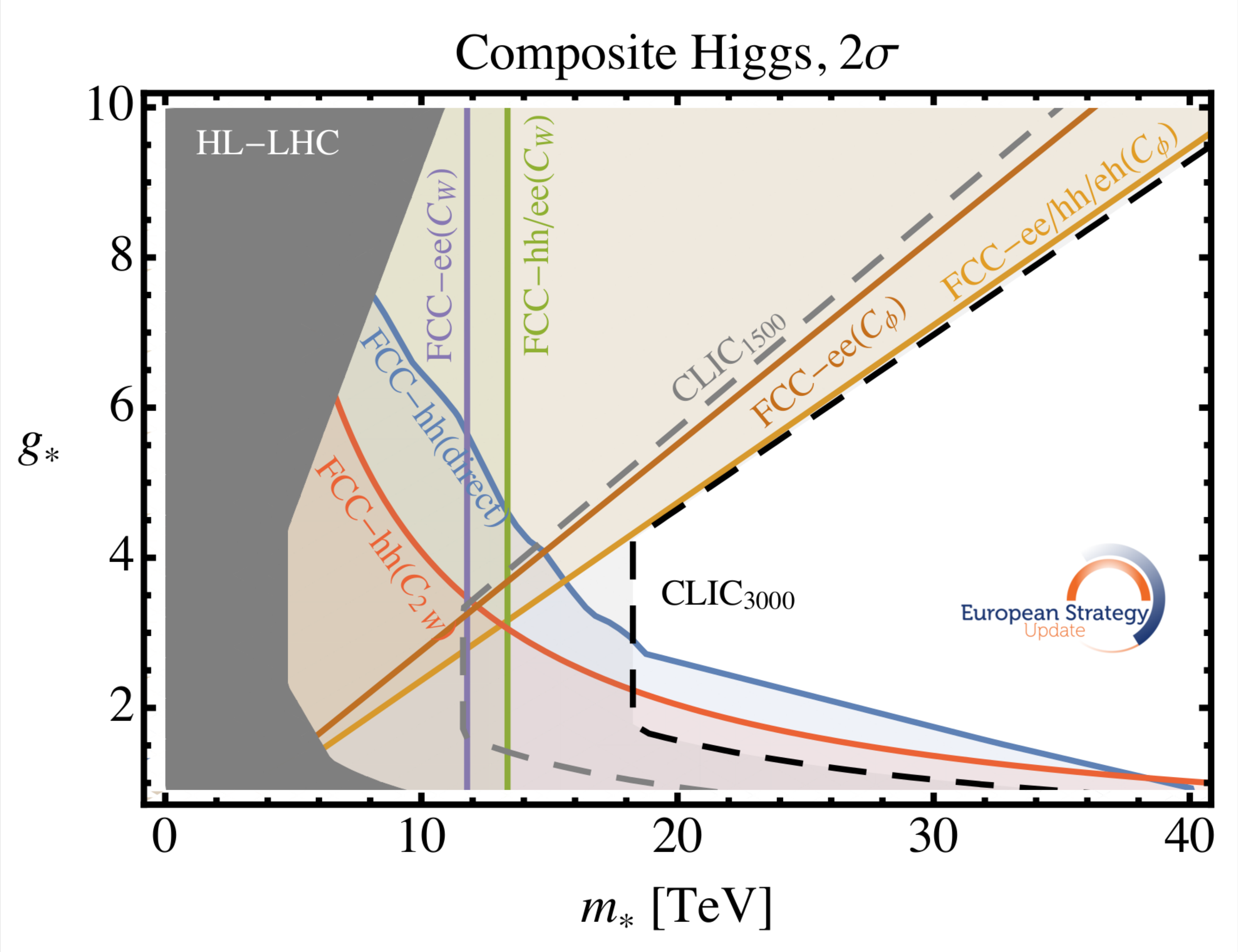
contact interactions



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

Higgs compositeness



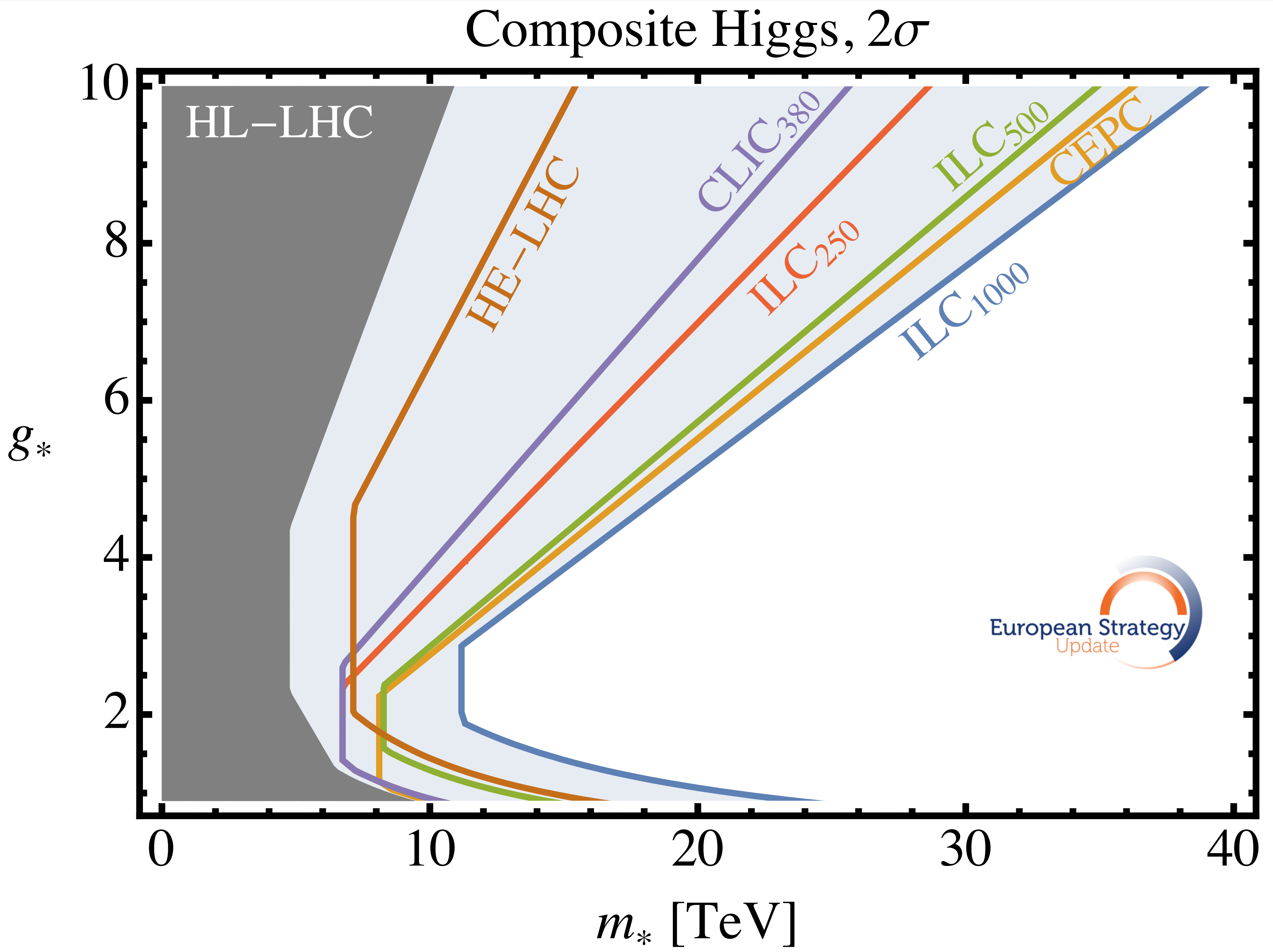


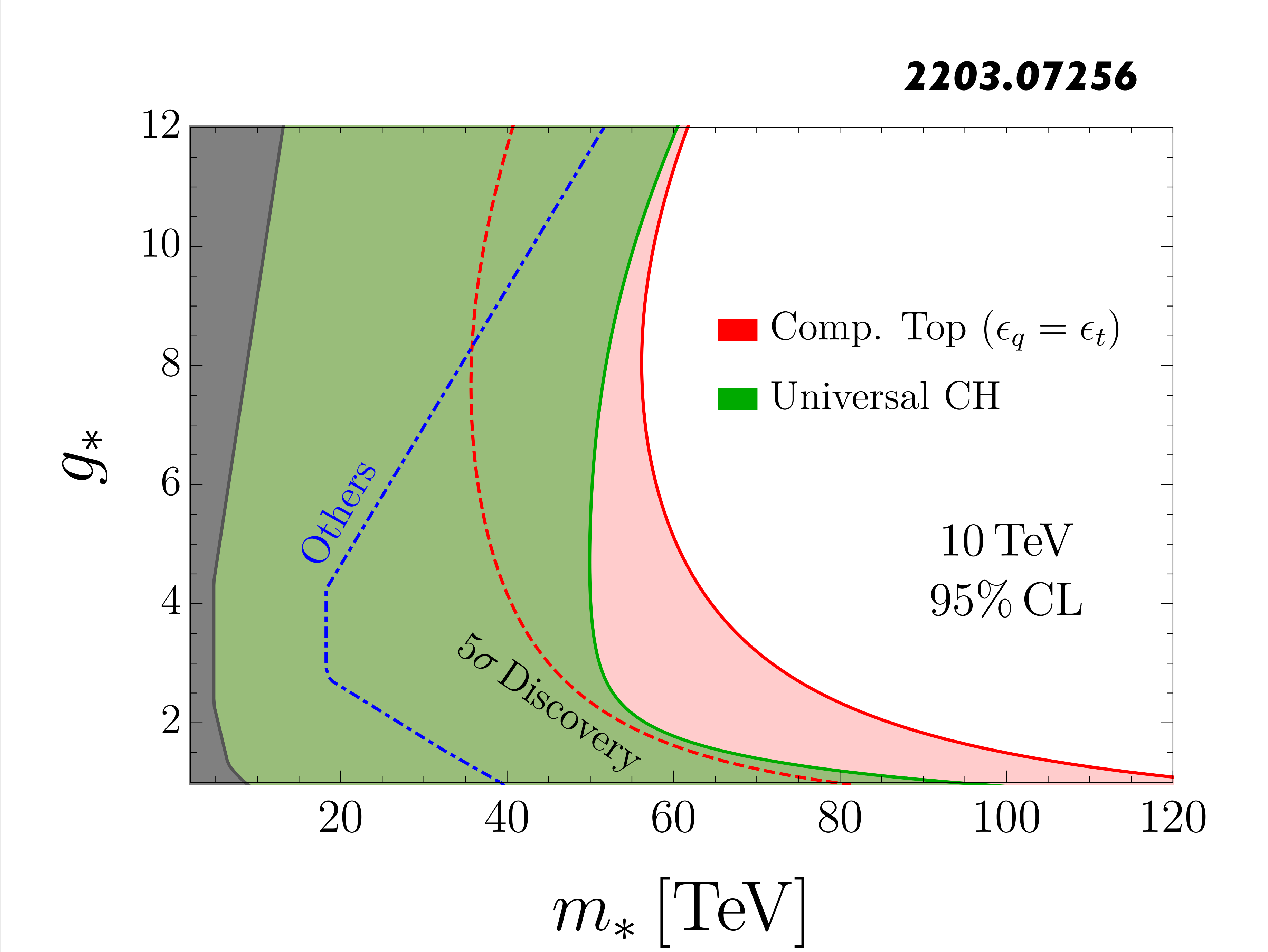
compositeness at few TeV @ HL-LHC

compositeness at few 10 TeV

Higgs compositeness

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


Composite Higgs, 2σ


2203.07256

compositeness at
few TeV @ HL-LHC

compositeness at
few 100 TeV

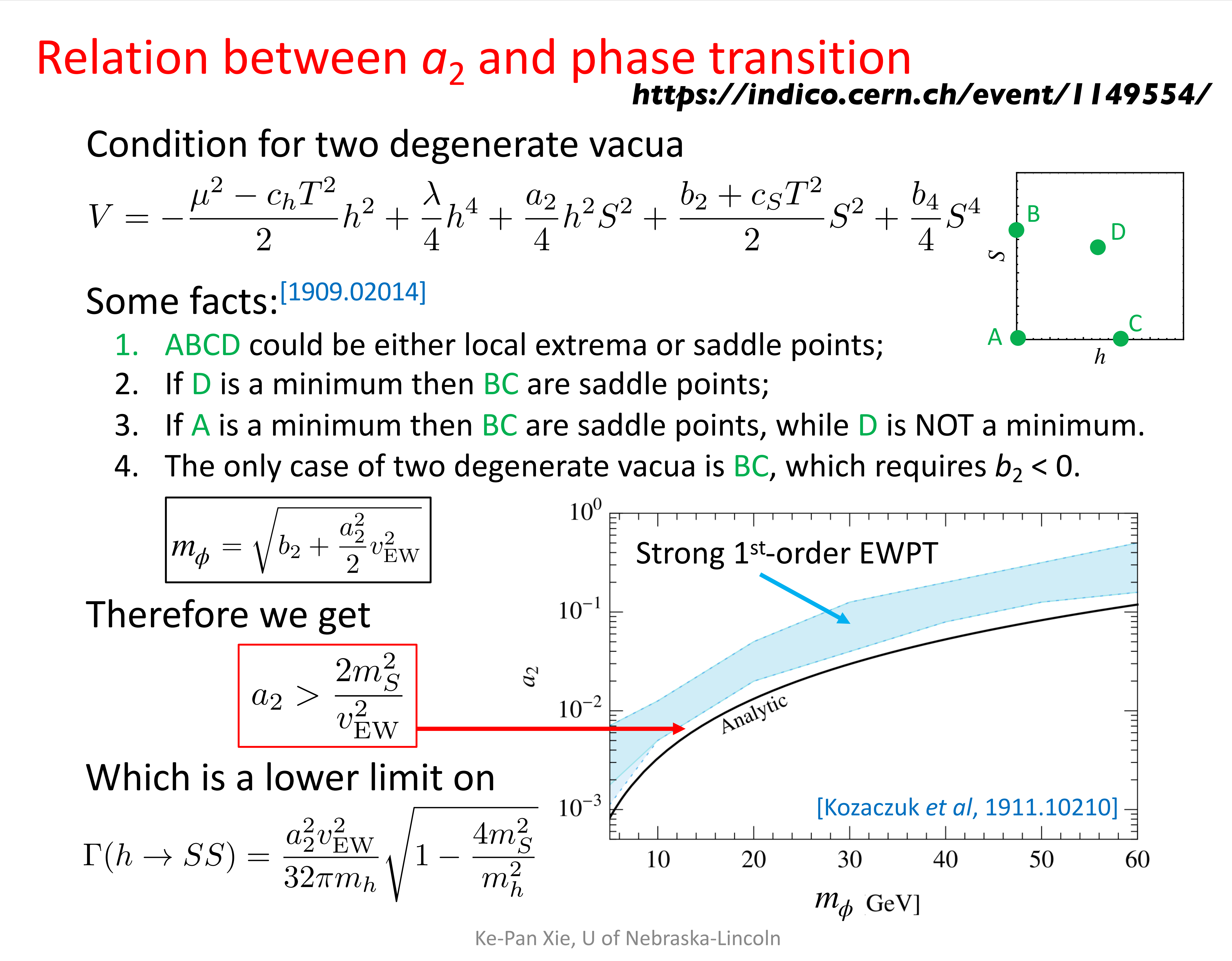
Higgs BSM decays

$h \to \phi\phi$

EW PHASE TRANSITION

DRIVEN BY A LIGHT SCALAR

a minimal $B(h \to \phi\phi)$ to insure a strong first order phase transition



Relation between a_2 and phase transition

https://indico.cern.ch/event/1149554/

Condition for two degenerate vacua

$$V = -\frac{\mu^2 - c_h T^2}{2}h^2 + \frac{\lambda}{4}h^4 + \frac{a_2}{4}h^2S^2 + \frac{b_2 + c_S T^2}{2}S^2 + \frac{b_4}{4}S^4$$

Some facts:[1909.02014]

1. ABCD could be either local extrema or saddle points;
2. If D is a minimum then BC are saddle points;
3. If A is a minimum then BC are saddle points, while D is NOT a minimum.
4. The only case of two degenerate vacua is BC, which requires $b_2 < 0$.

$$\boxed{m_\phi = \sqrt{b_2 + \frac{a_2^2}{2}v_{\rm EW}^2}}$$

Therefore we get

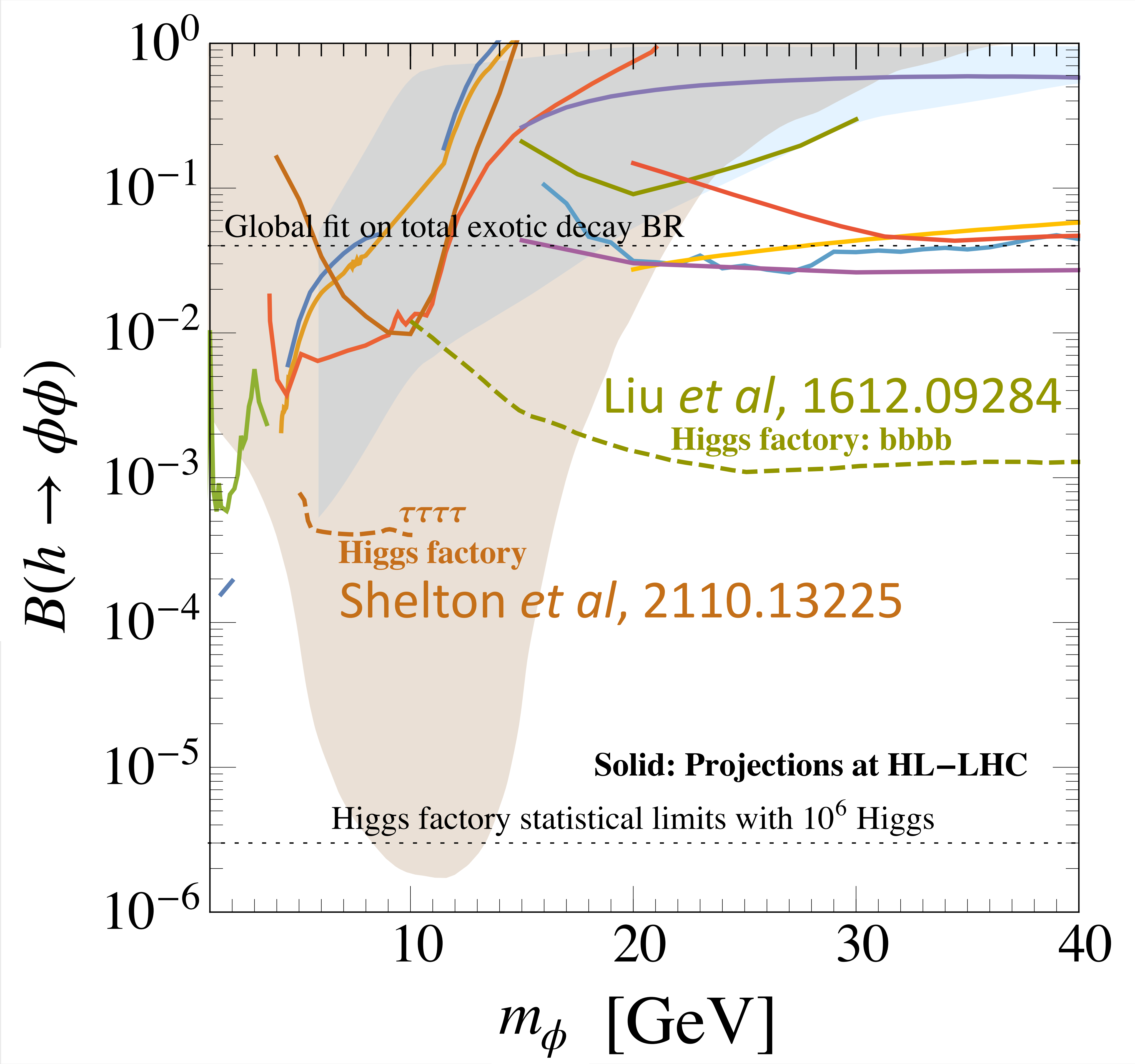
$$\boxed{a_2 > \frac{2m_S^2}{v_{\rm EW}^2}}$$

Which is a lower limit on

$$\Gamma(h \to SS) = \frac{a_2^2 v_{\rm EW}^2}{32\pi m_h}\sqrt{1 - \frac{4m_S^2}{m_h^2}}$$

[Kozaczuk *et al*, 1911.10210]

Ke-Pan Xie, U of Nebraska-Lincoln



Liu *et al*, 1612.09284

Shelton *et al*, 2110.13225

$h \to \phi\phi$

EW PHASE TRANSITION

DRIVEN BY A LIGHT SCALAR

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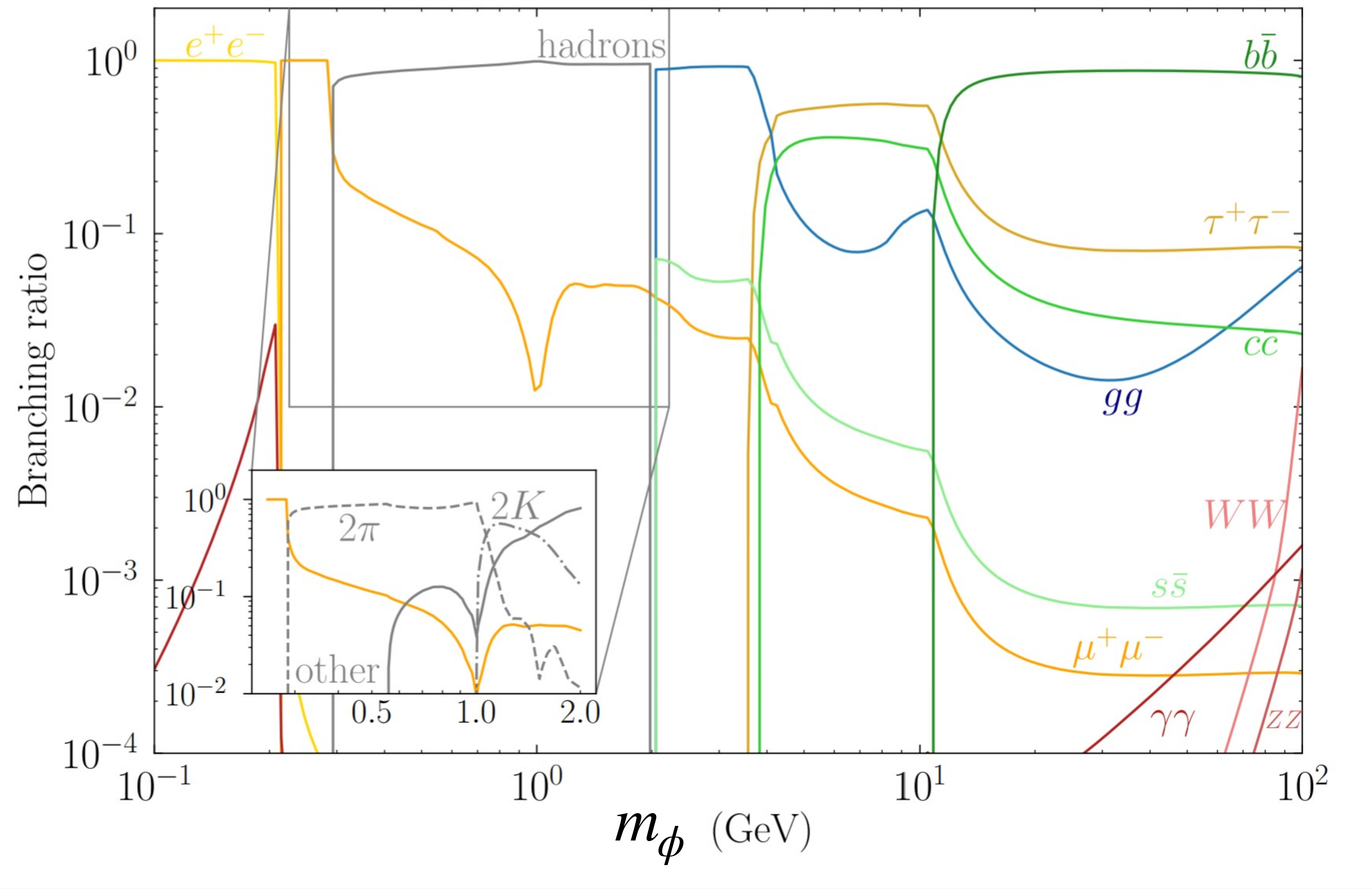
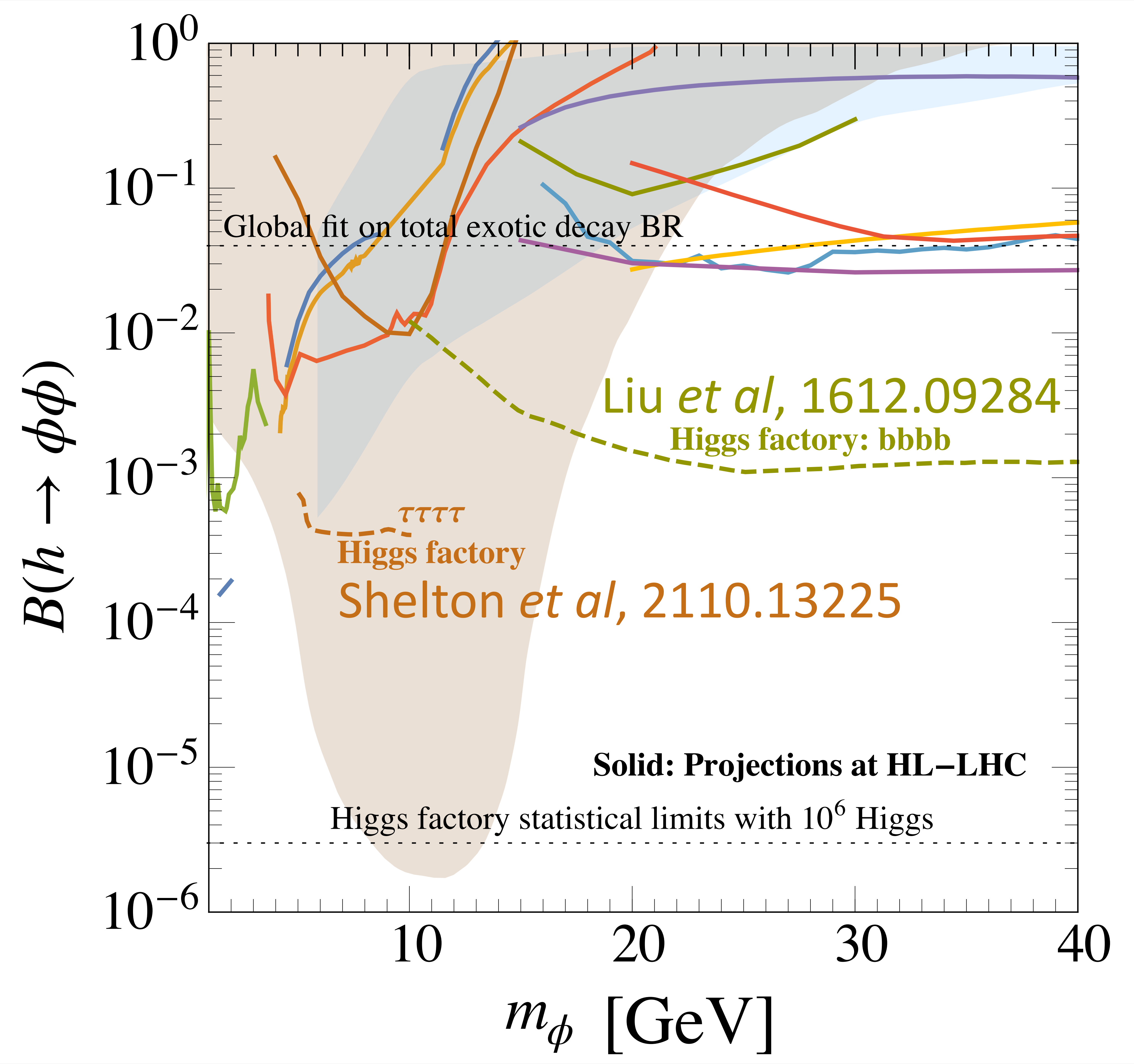
2012.07864





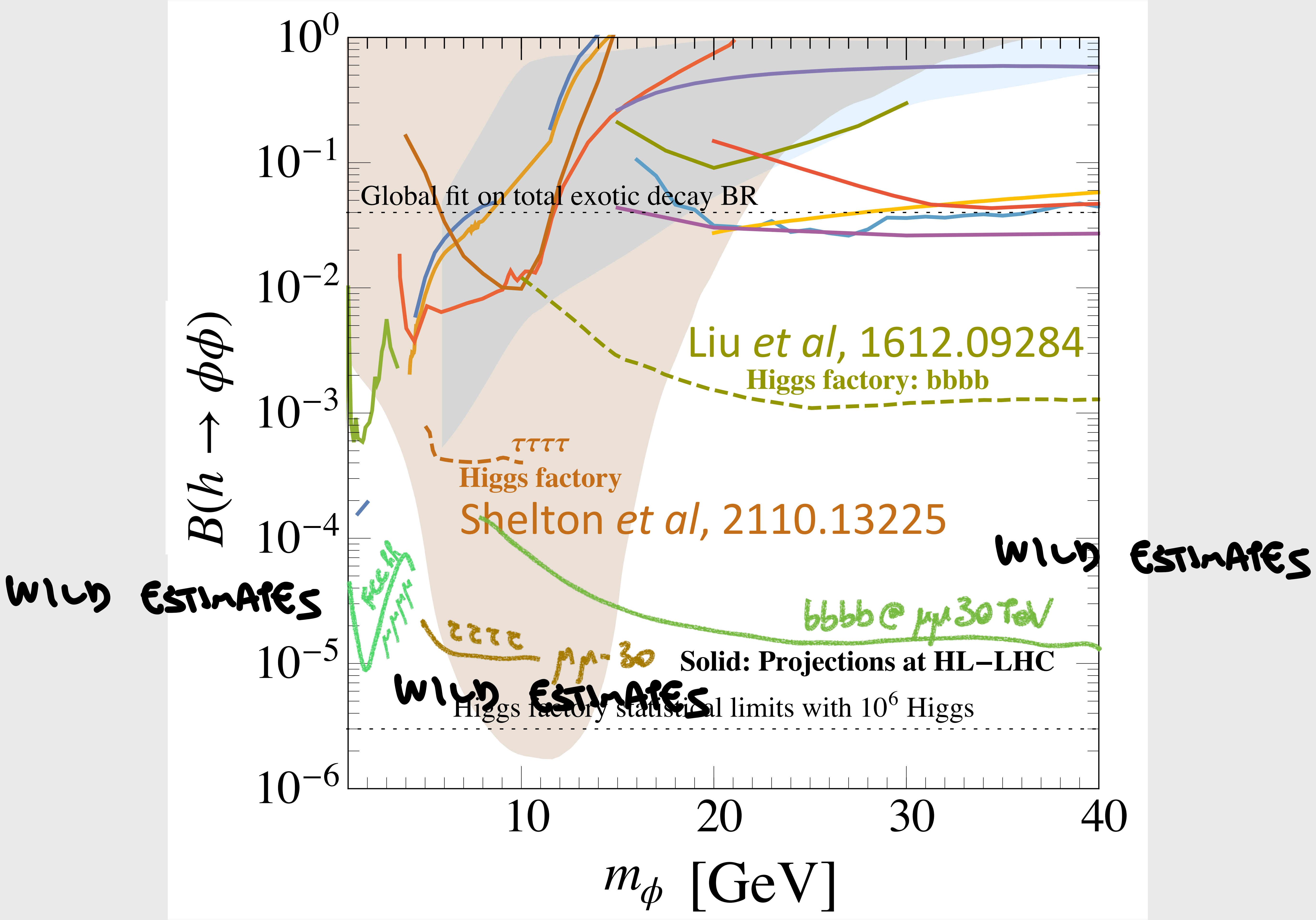
$h \to \phi\phi$

EW PHASE TRANSITION

DRIVEN BY A LIGHT SCALAR

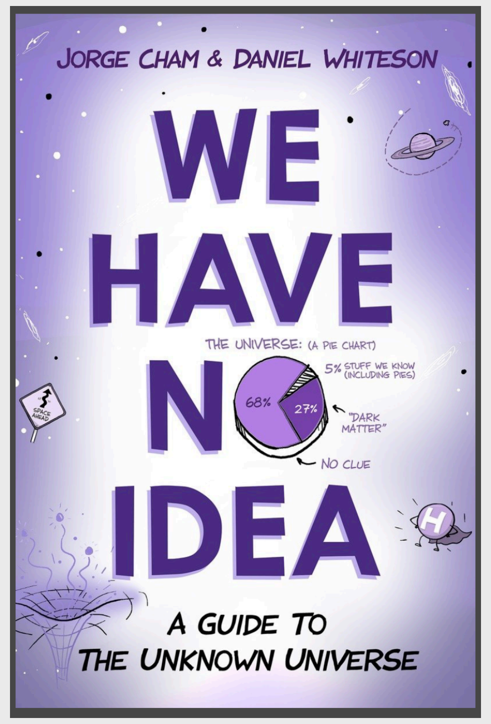
a minimal $B(h \to \phi\phi)$ to insure a strong first order phase transition

- opportunities both for FCC-hh and $\mu\mu$ to contribute new lines on this plot
- potential to be sensitive to the entire region of first order phase transition (only) by a combination of results from multiple machines



Neutrino mass models

a wide landscape of possibilities that benefits from multiple approaches

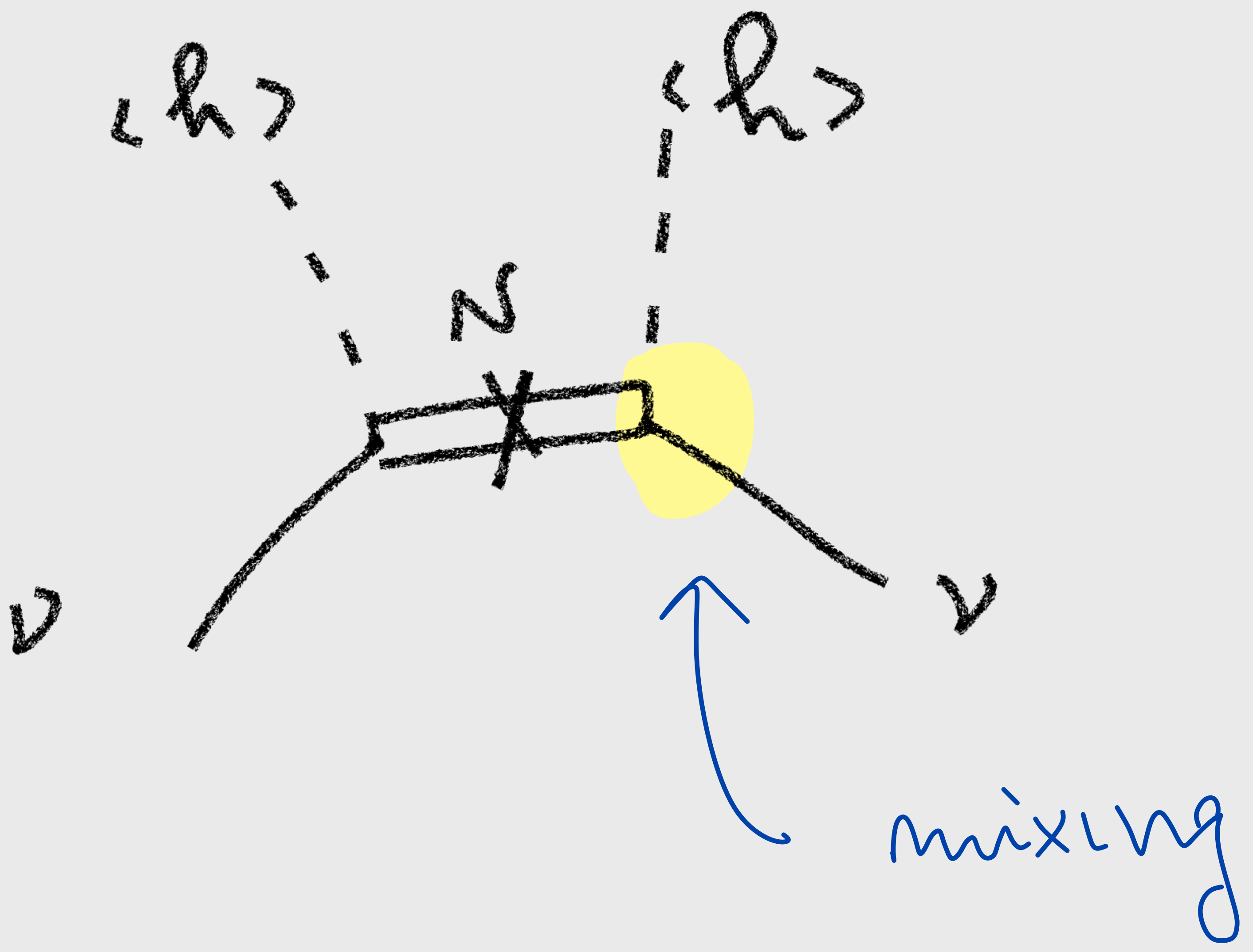


$(LH)(LH)$ from “the” seesaw

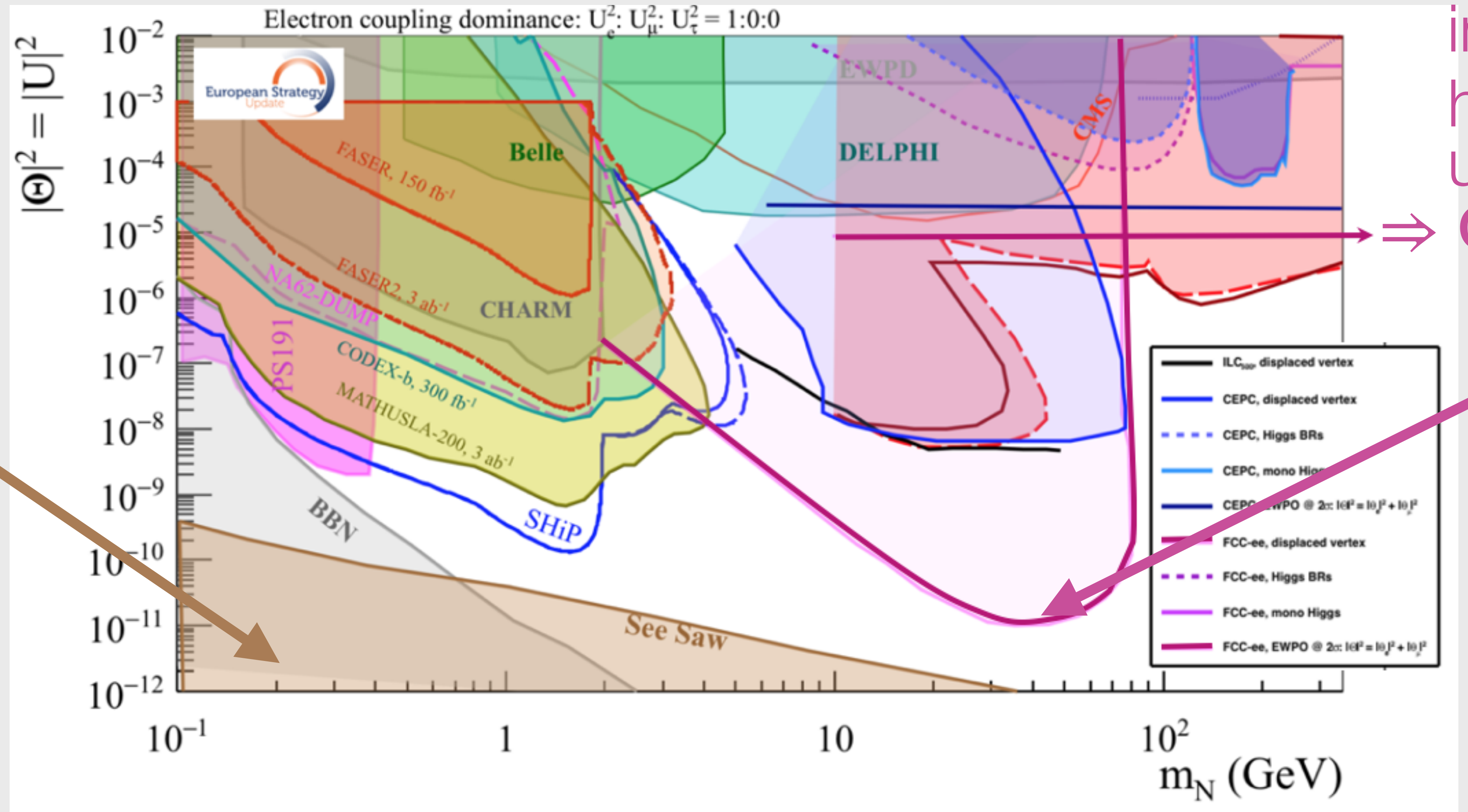
KEY INGREDIENT LEPTON NUMBER BREAKING MAJORANA MASS TERM

- light neutrino masses governed by mixing with heavy neutrinos and mass of the heavier neutrino

$$m_\nu \sim \frac{y^2 v^2}{M} = \Theta^2 M$$



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



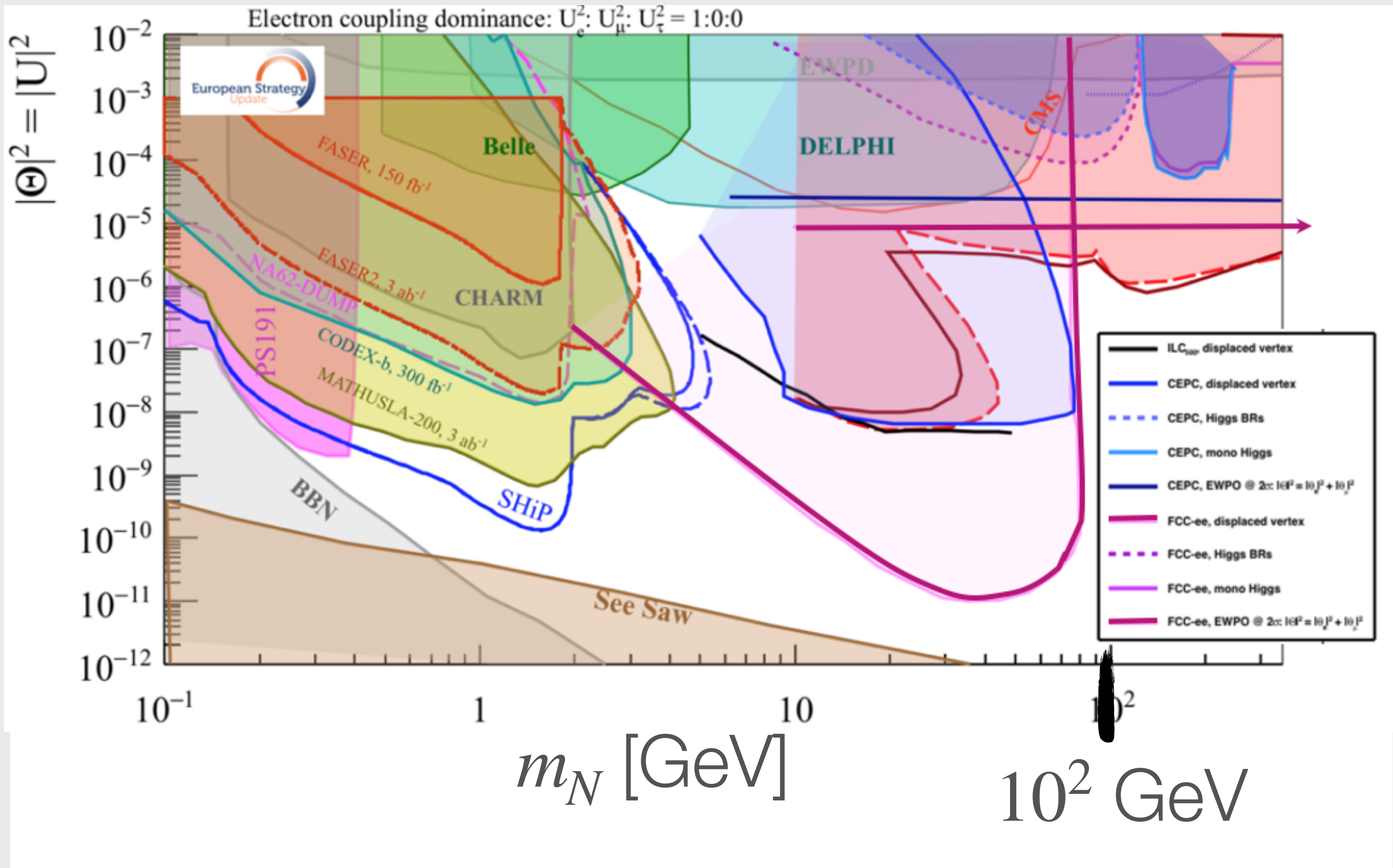
indirect from
high-precision Z pole
up to $M \gg 100$ GeV
$\Rightarrow \Theta \lesssim 0.3 \cdot 10^{-2}$

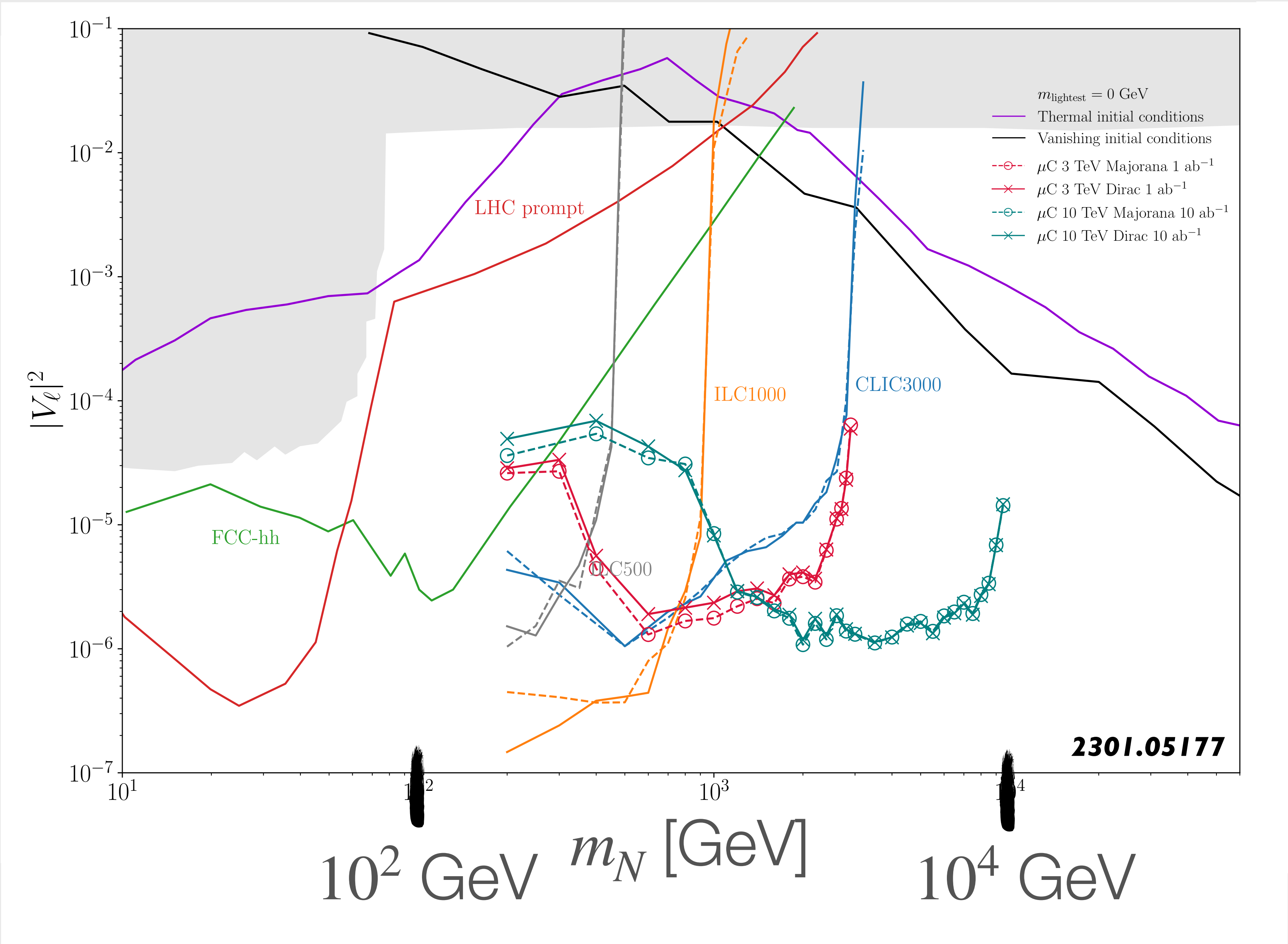
$\Rightarrow \Theta \lesssim 3 \cdot 10^{-6}$
$M \simeq 100$ GeV

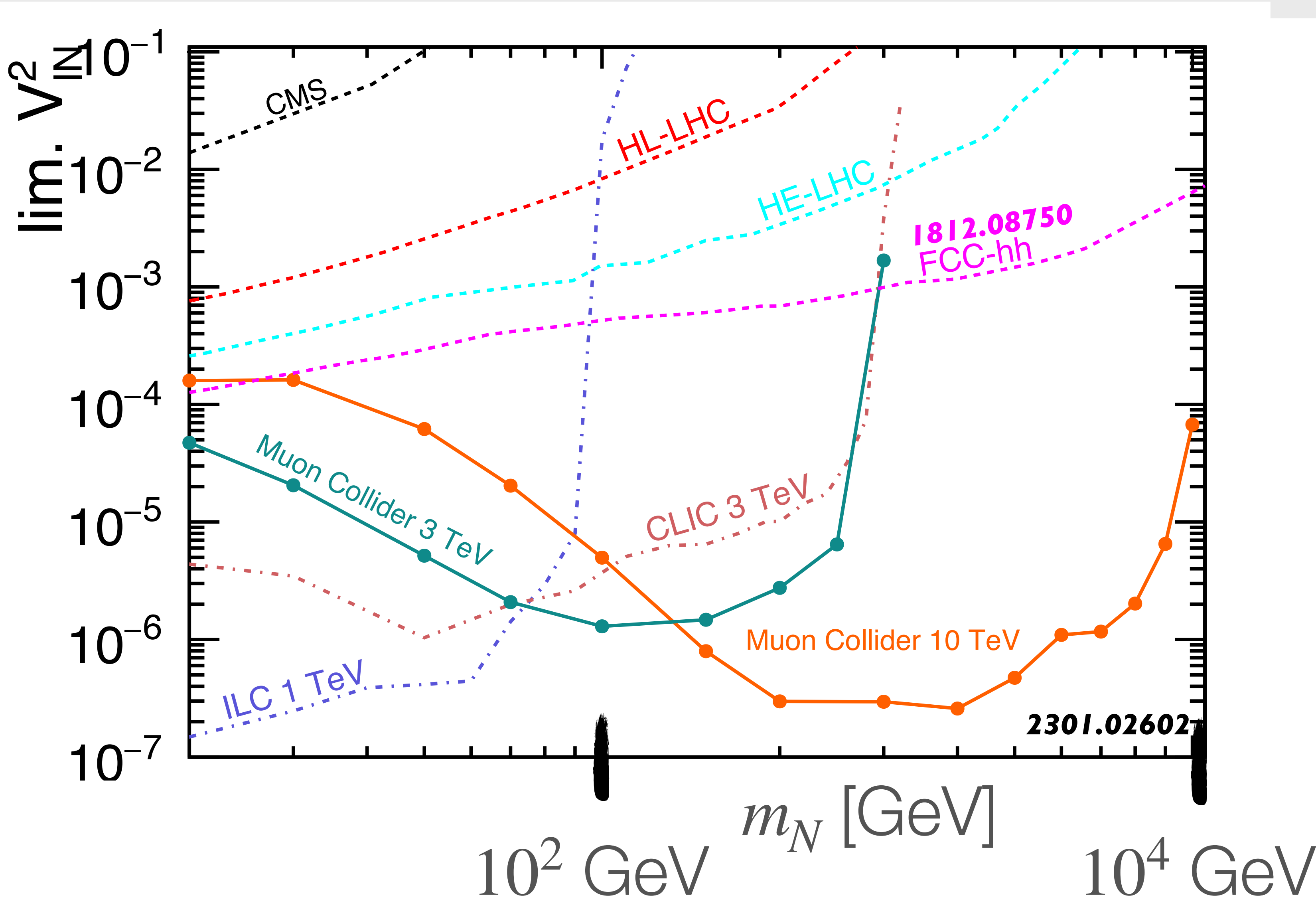
FCCee has fantastic sensitivity, but only to light N

$(LH)(LH)$ from “the” seesaw

KEY INGREDIENT LEPTON NUMBER BREAKING MAJORANA MASS TERM

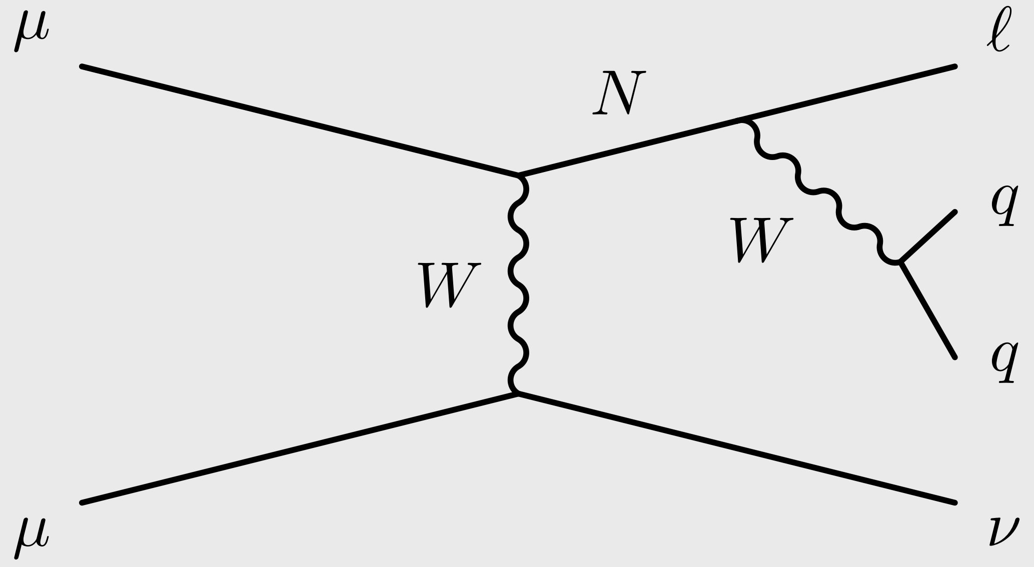


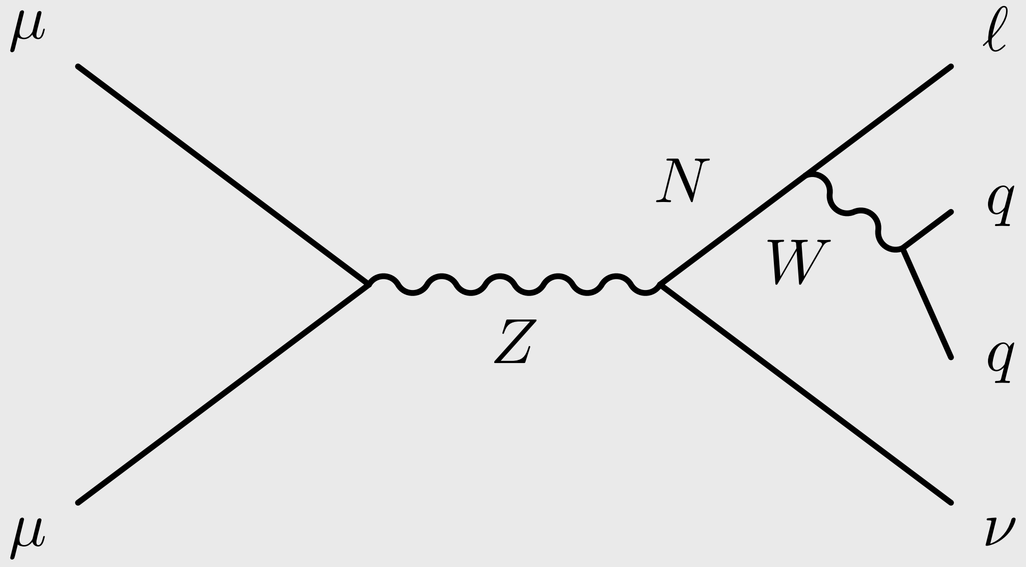




FCCee has fantastic sensitivity, but only to light N

heavy N can be tested at FCChh and even deeper at $\mu\mu$

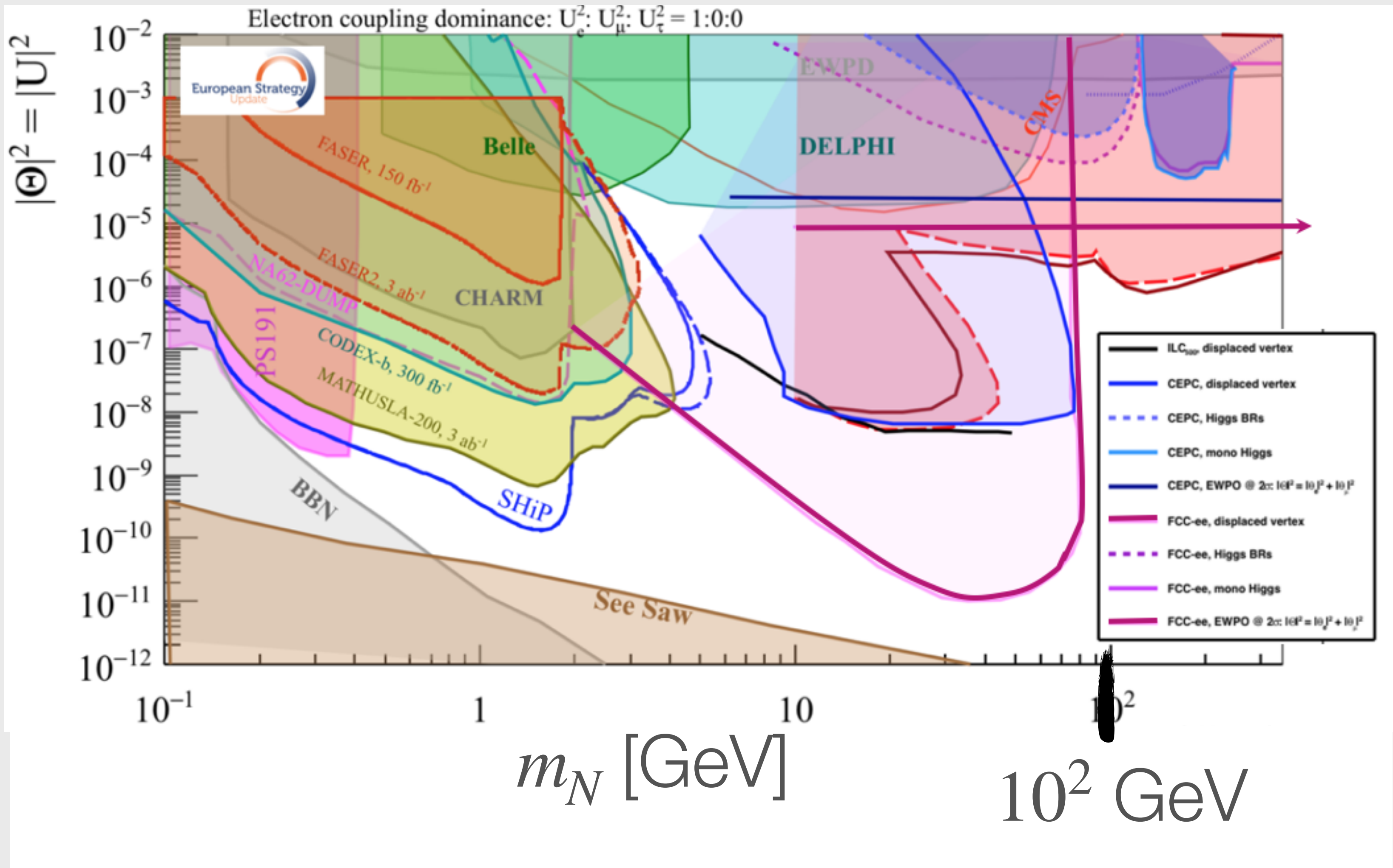


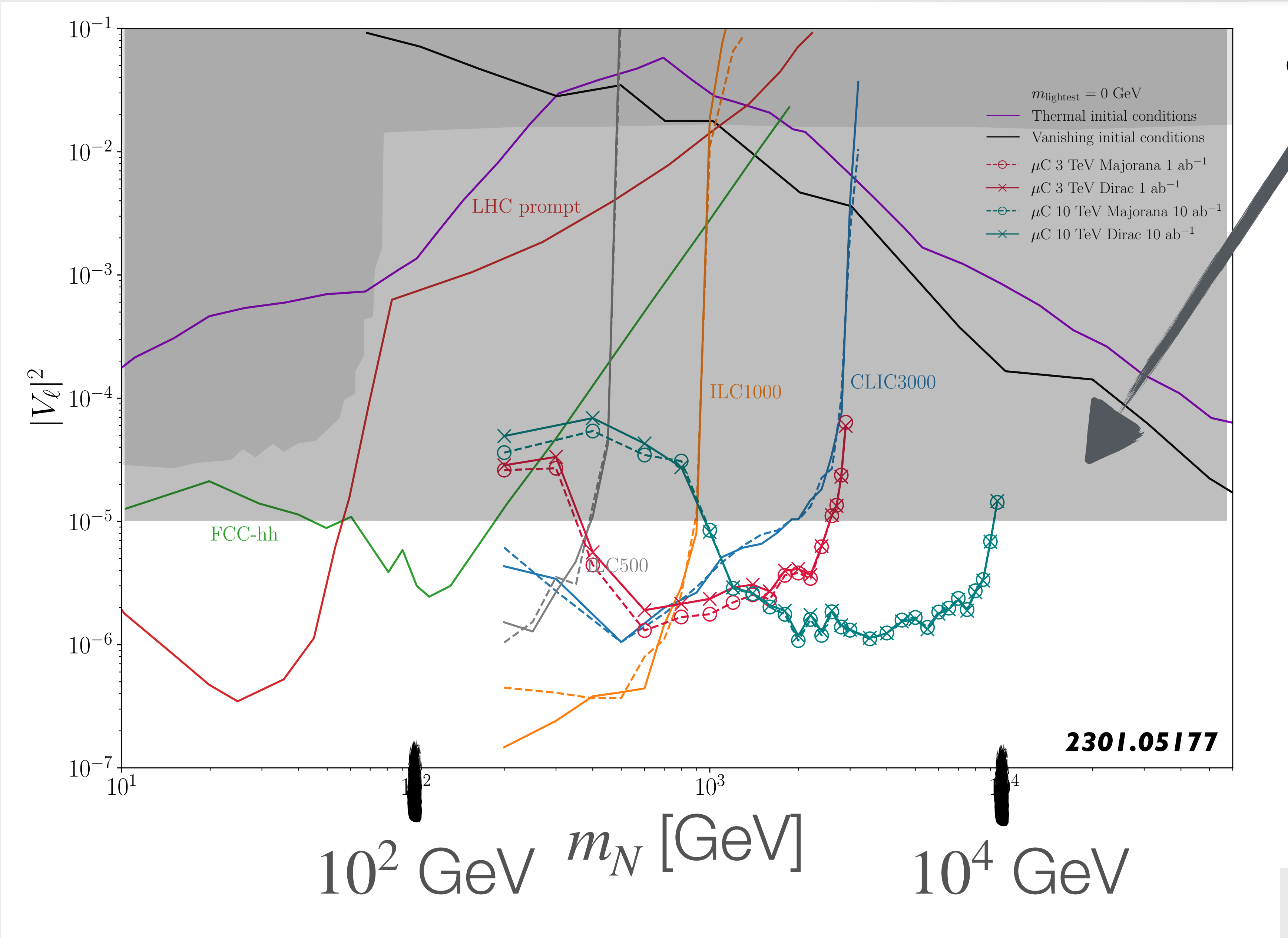


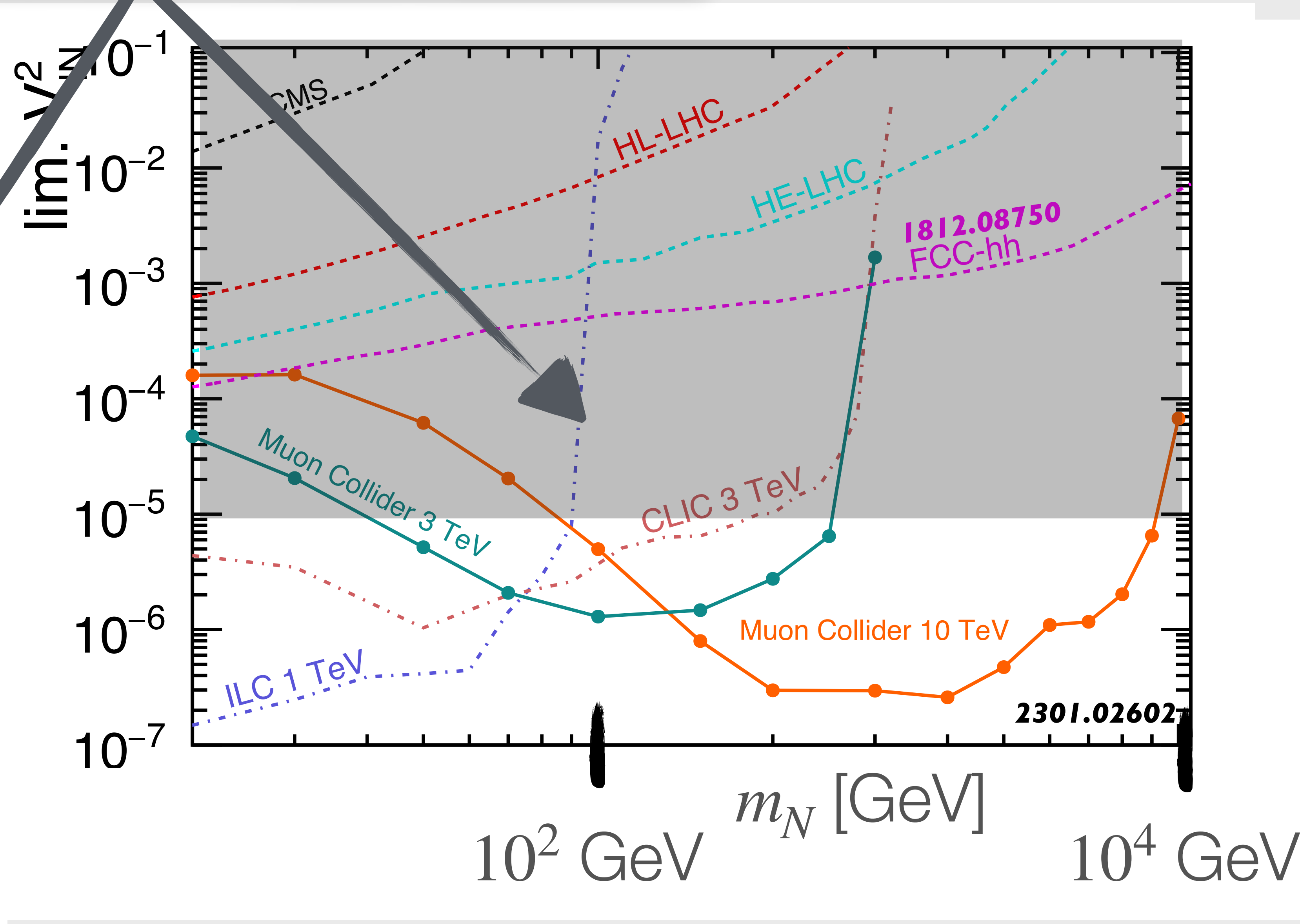
$(LH)(LH)$ from “the” seesaw

KEY INGREDIENT LEPTON NUMBER BREAKING MAJORANA MASS TERM

if Z pole high-precision theory delivers

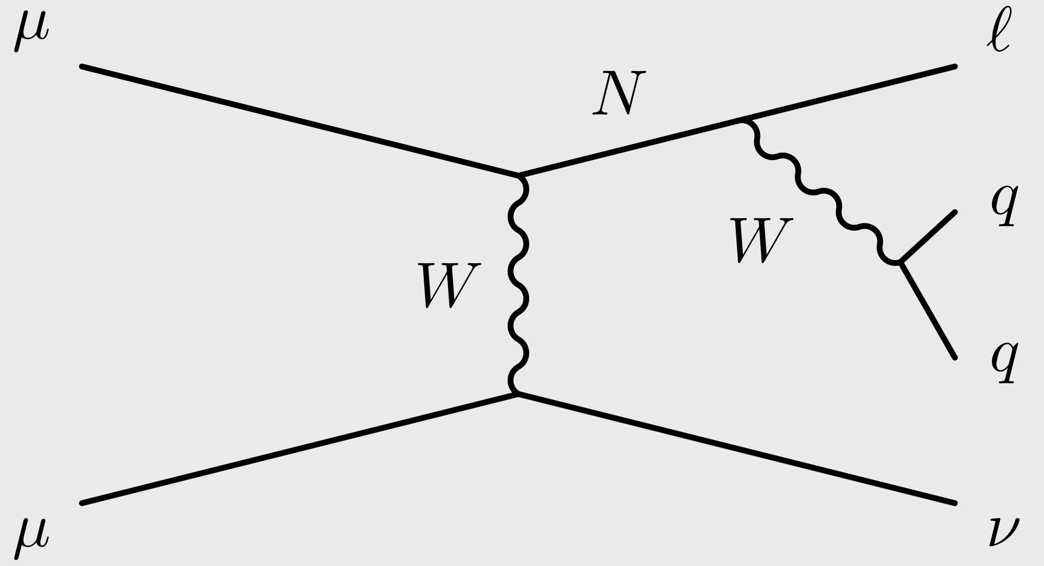


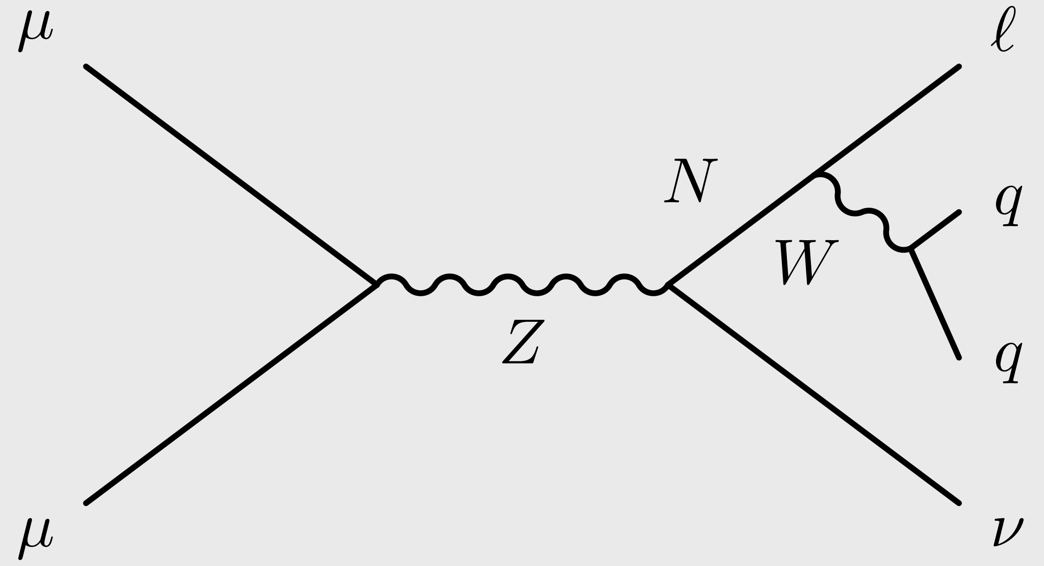




FCCee has fantastic sensitivity, but only to light N

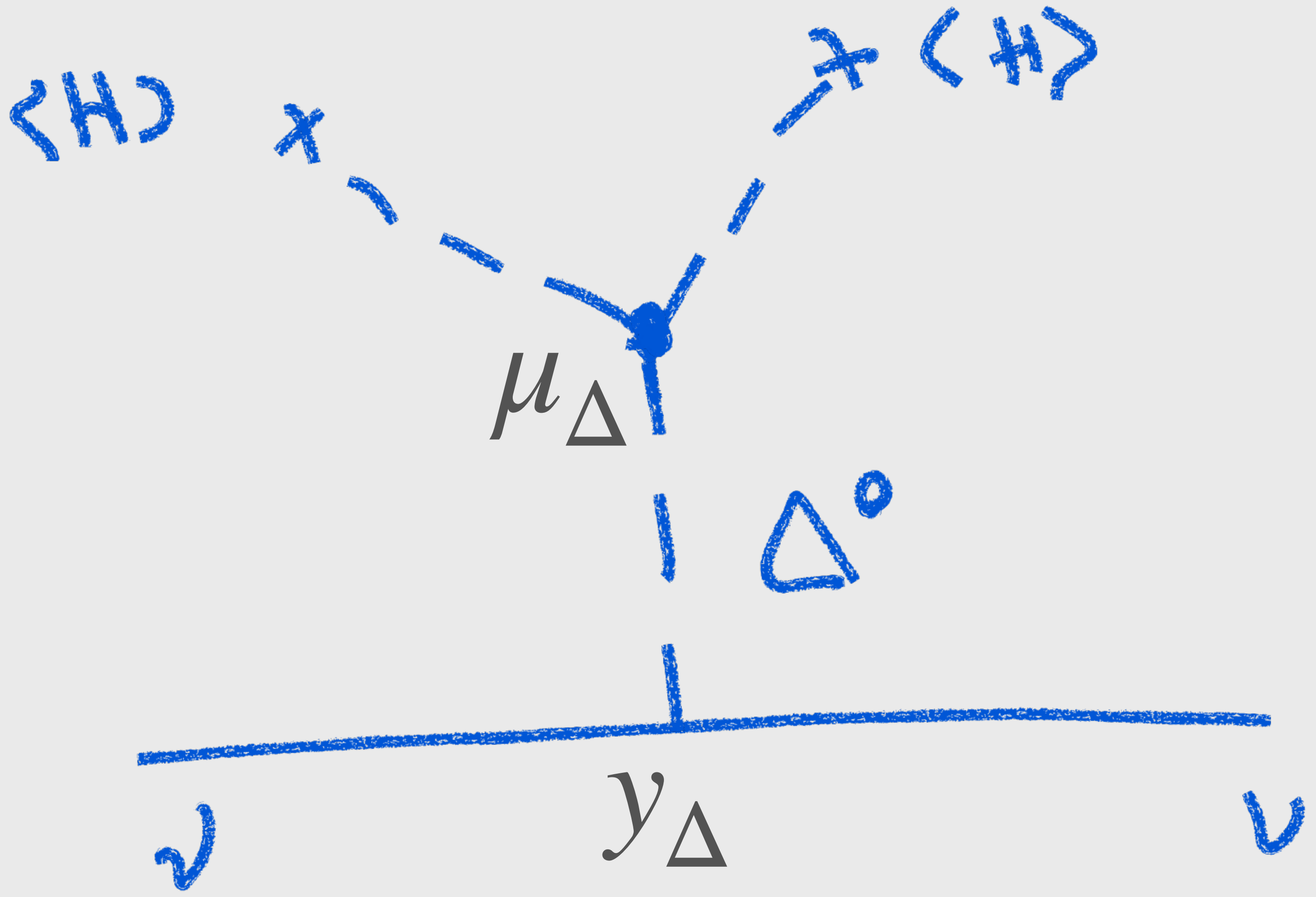
heavy N can be tested at FCChh and even deeper at $\mu\mu$





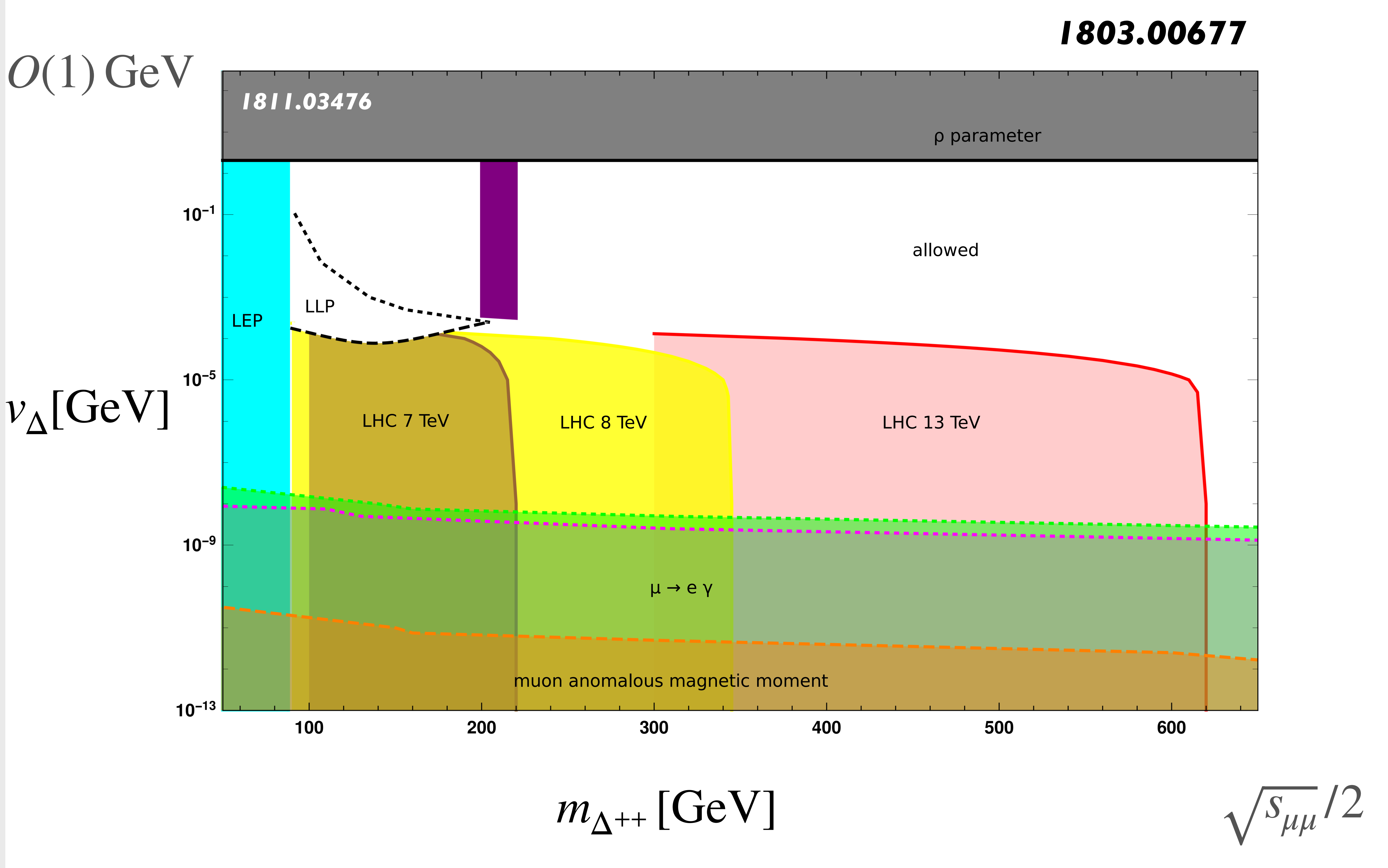
$(LH)(LH)$ from one of “the other” seesaws

KEY INGREDIENT LEPTON NUMBER BREAKING MAJORANA MASS TERM



$$m_\nu \sim \frac{y_\Delta \mu_\Delta}{m_\Delta^2}$$

- neutrino masses governed by scalar potential term of the heavy triplet scalar and mass of the heavy scalar



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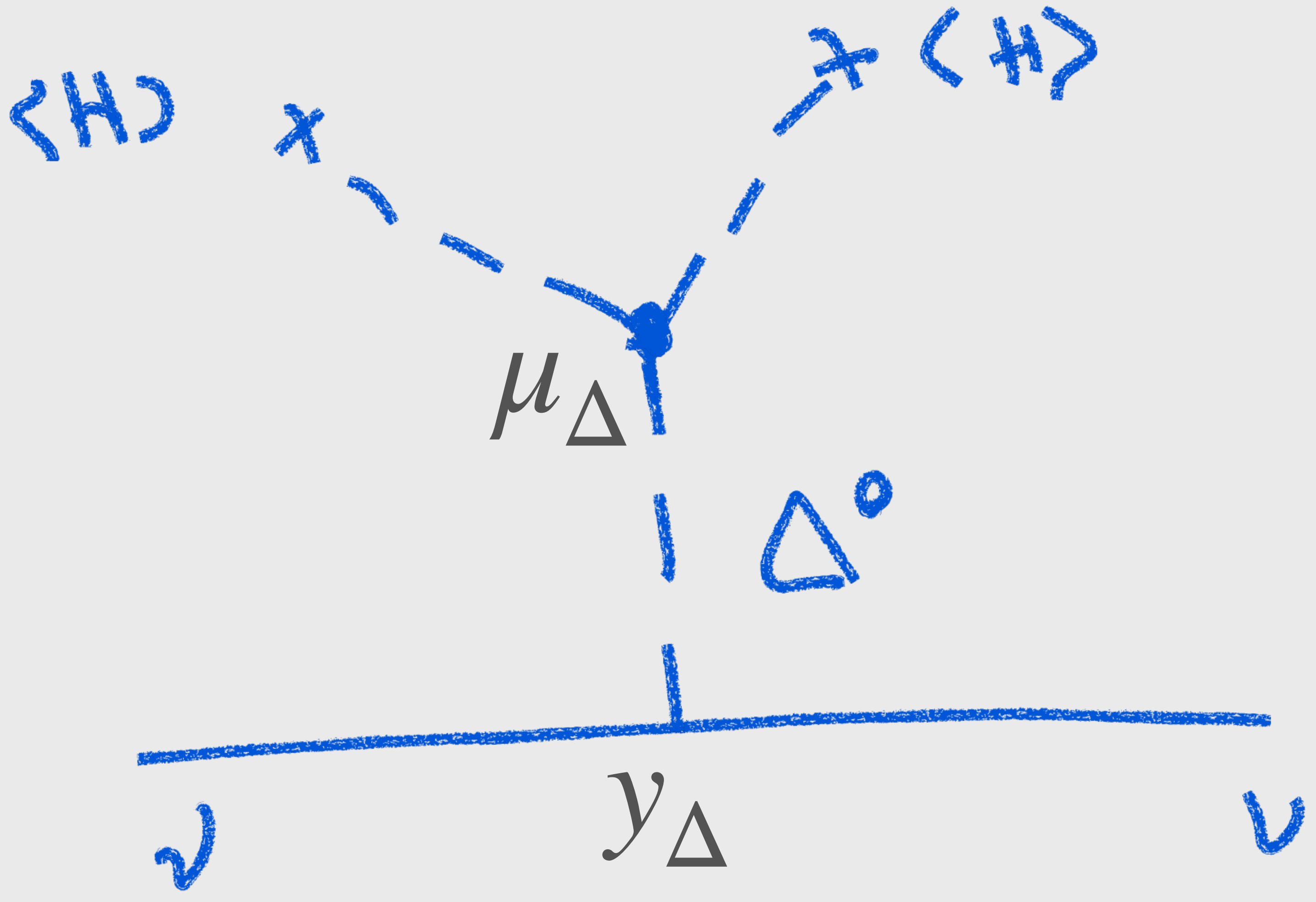

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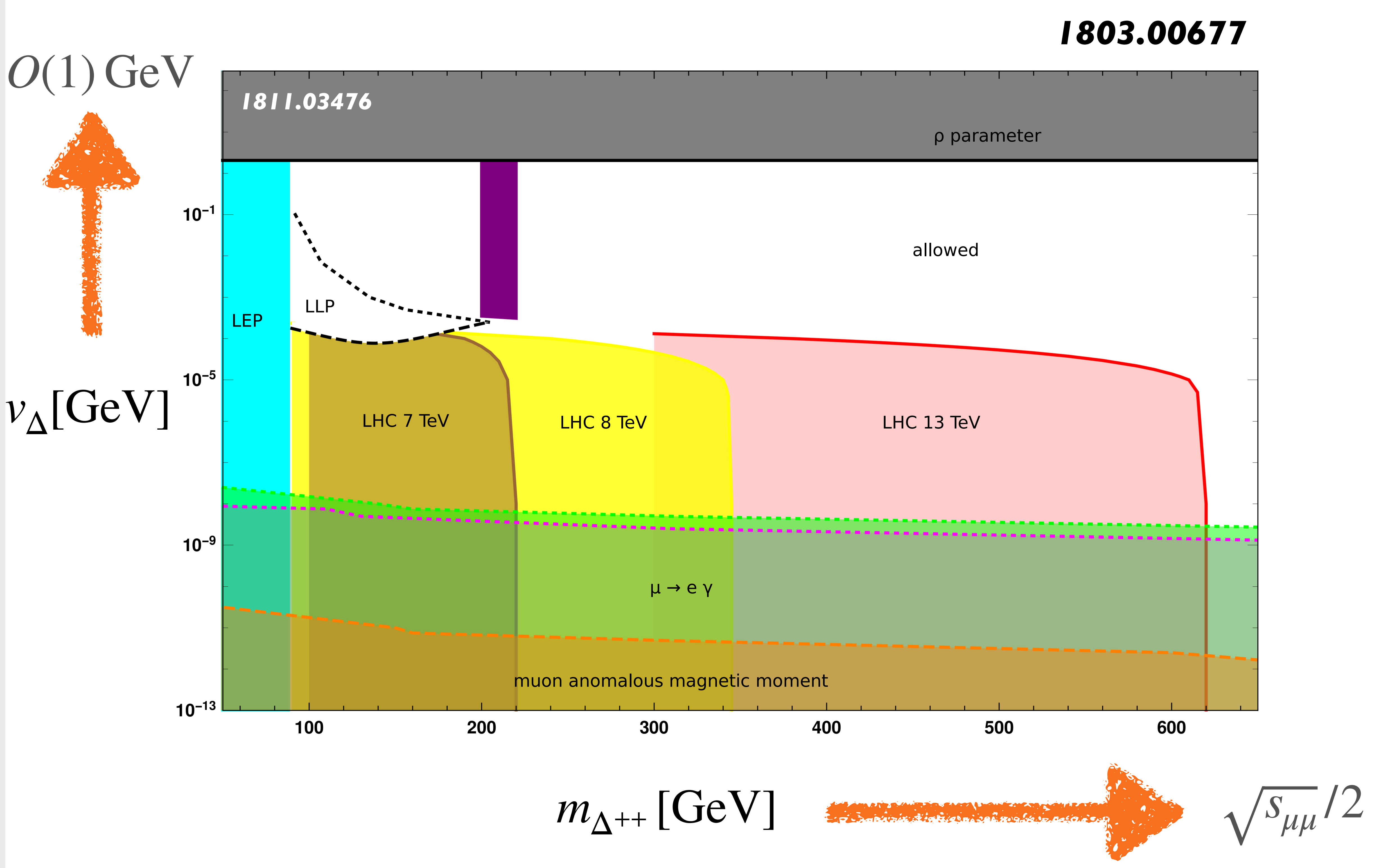

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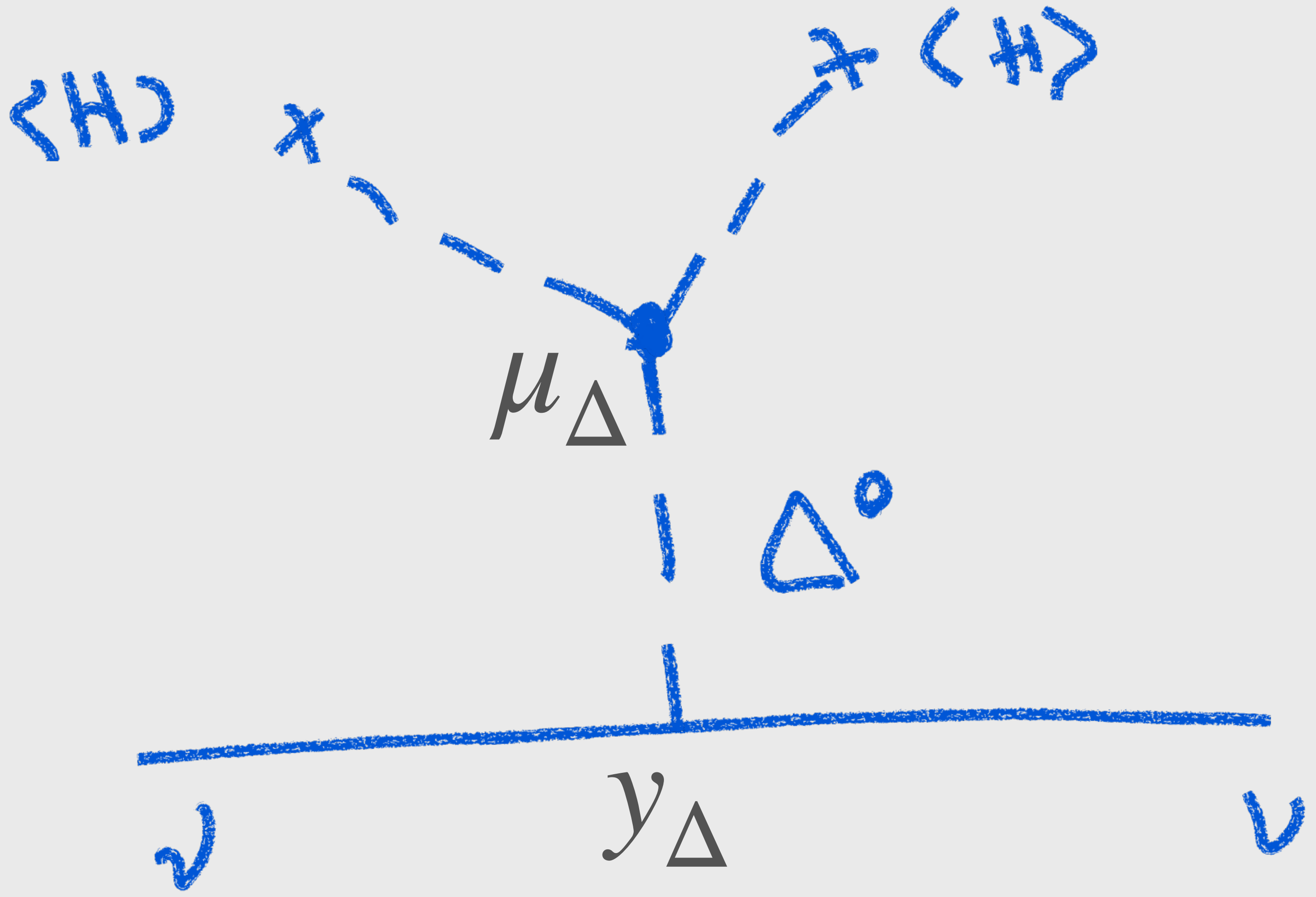

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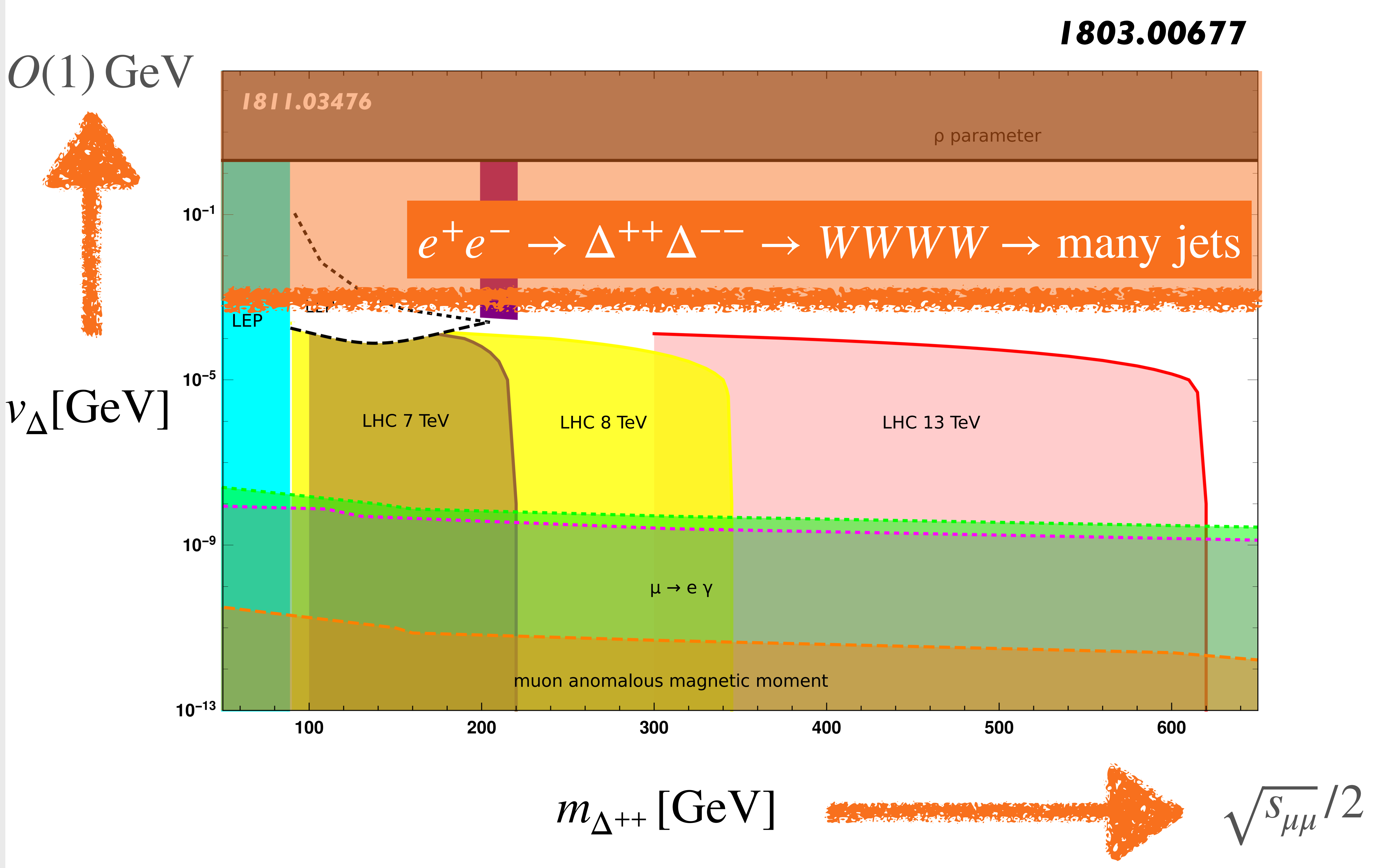
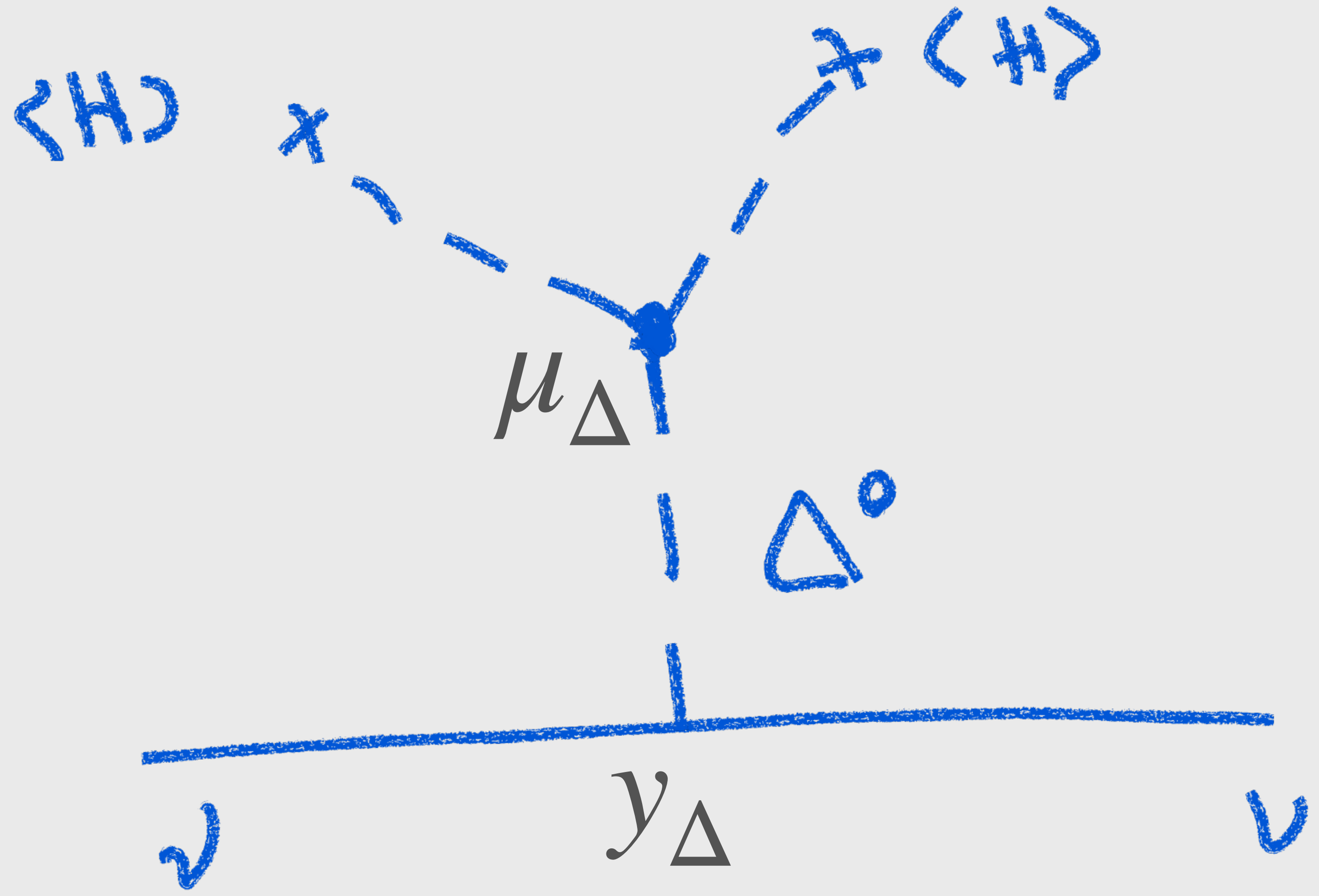

1803.00677

$e^+e^- \to \Delta^{++}\Delta^{--} \to WWWW \to$ many jets

$(LH)(LH)$ from one of “the other” seesaws

KEY INGREDIENT LEPTON NUMBER BREAKING MAJORANA MASS TERM



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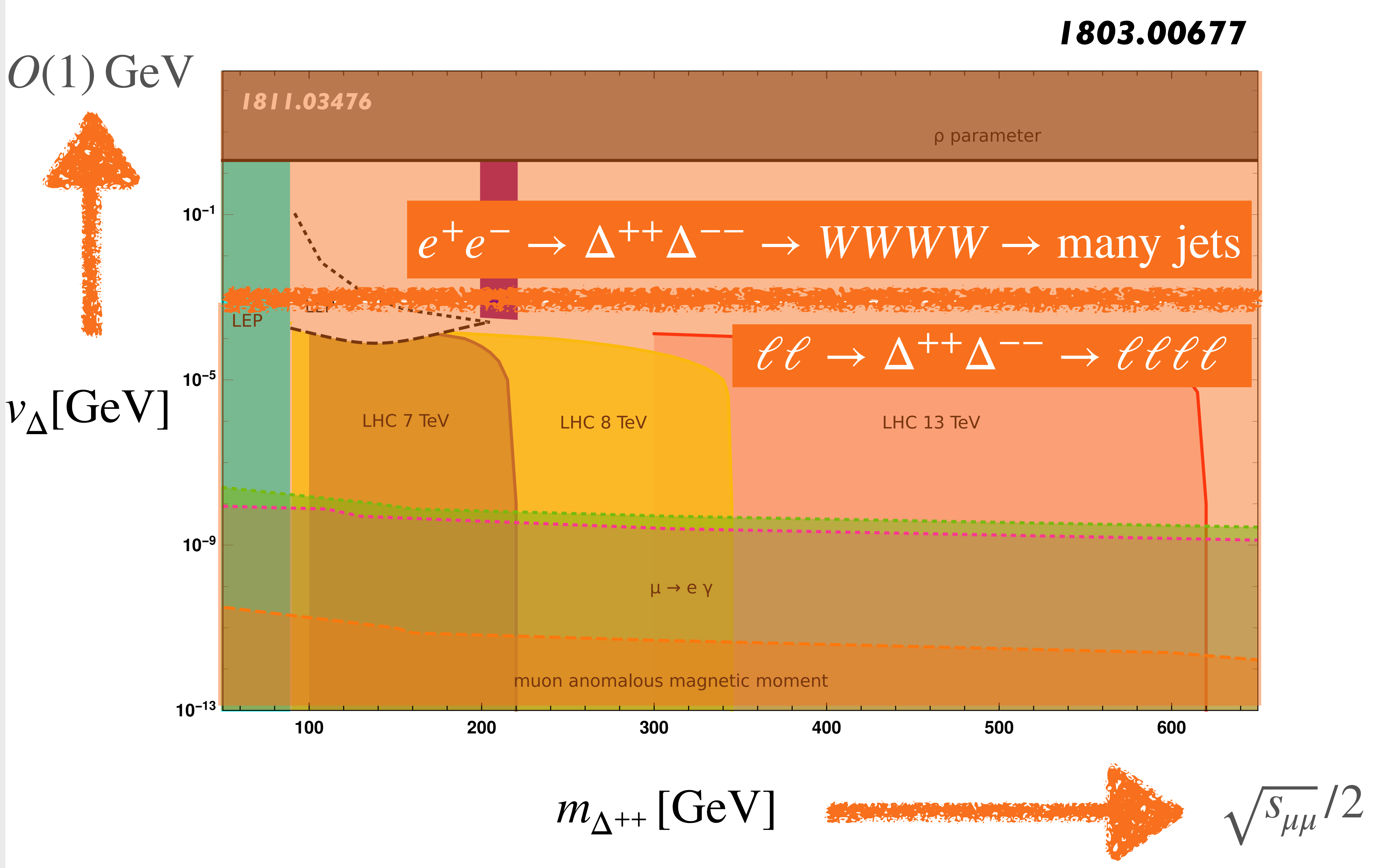
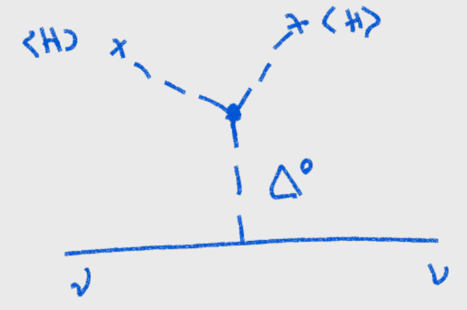


Neutrino mass mechanisms

LEPTON NUMBER BREAKING

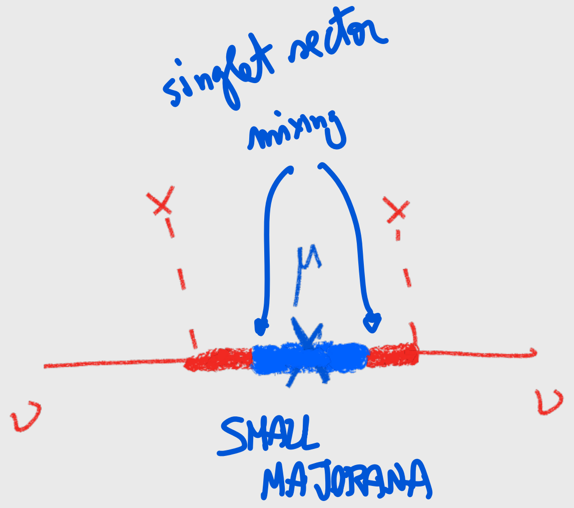
L – violation

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



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

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



no symmetry breaking

$N_1 \simeq N_2$

almost. dirac

$$\begin{matrix} \overbrace{0 \quad \times} & \varepsilon_i \\ \times \quad 0 & \varepsilon_j \\ \varepsilon_i \quad \varepsilon_j & \mu_s \end{matrix}$$

Flavor

LNV

L – not accidental

new physics before 2012

$d = 5 \quad (1,2,1/2)$

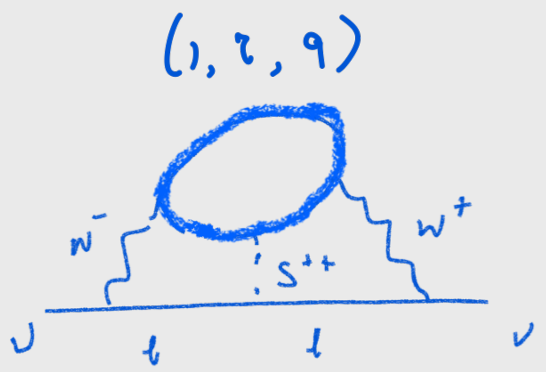
$$\frac{(LH)^2}{\Lambda}$$

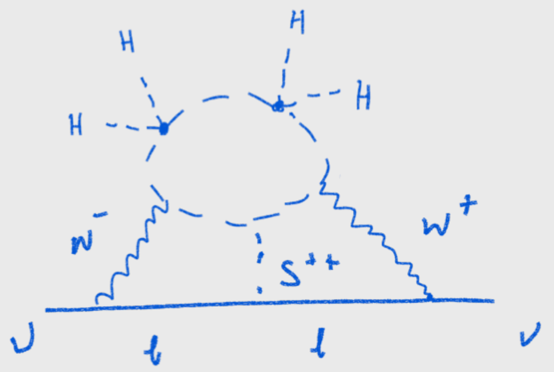
UV

$d = 7 \quad (1,1,2)$

$$\frac{\left(DH\sigma_2 H\right)^2 S^{--}}{\Lambda^3}$$

UV





L – gauged, SSB

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

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

Neutrino mass mechanisms

LEPTON NUMBER BREAKING

$L-$ violation

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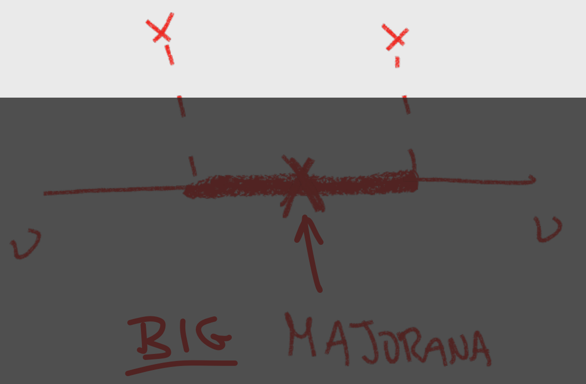
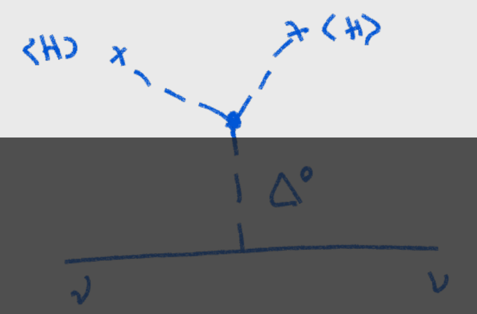




(1,3,1) (1 is enough)

sector

no symmetry breaking

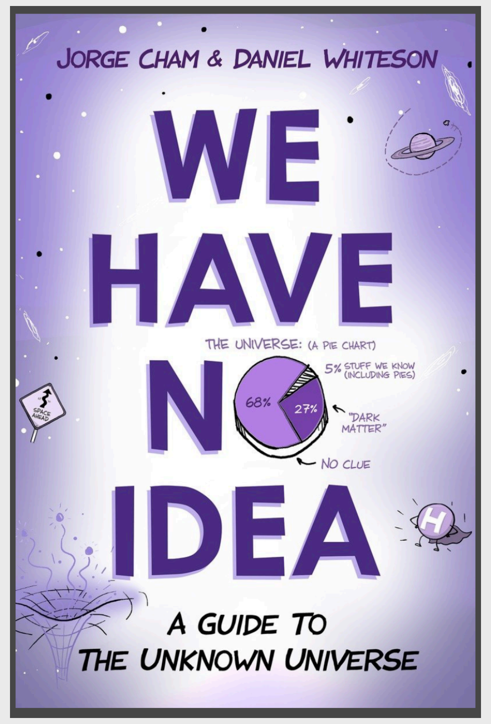
- A wide-open problem that benefits from multiple angles of attack

$L-$ gauged, SSB

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

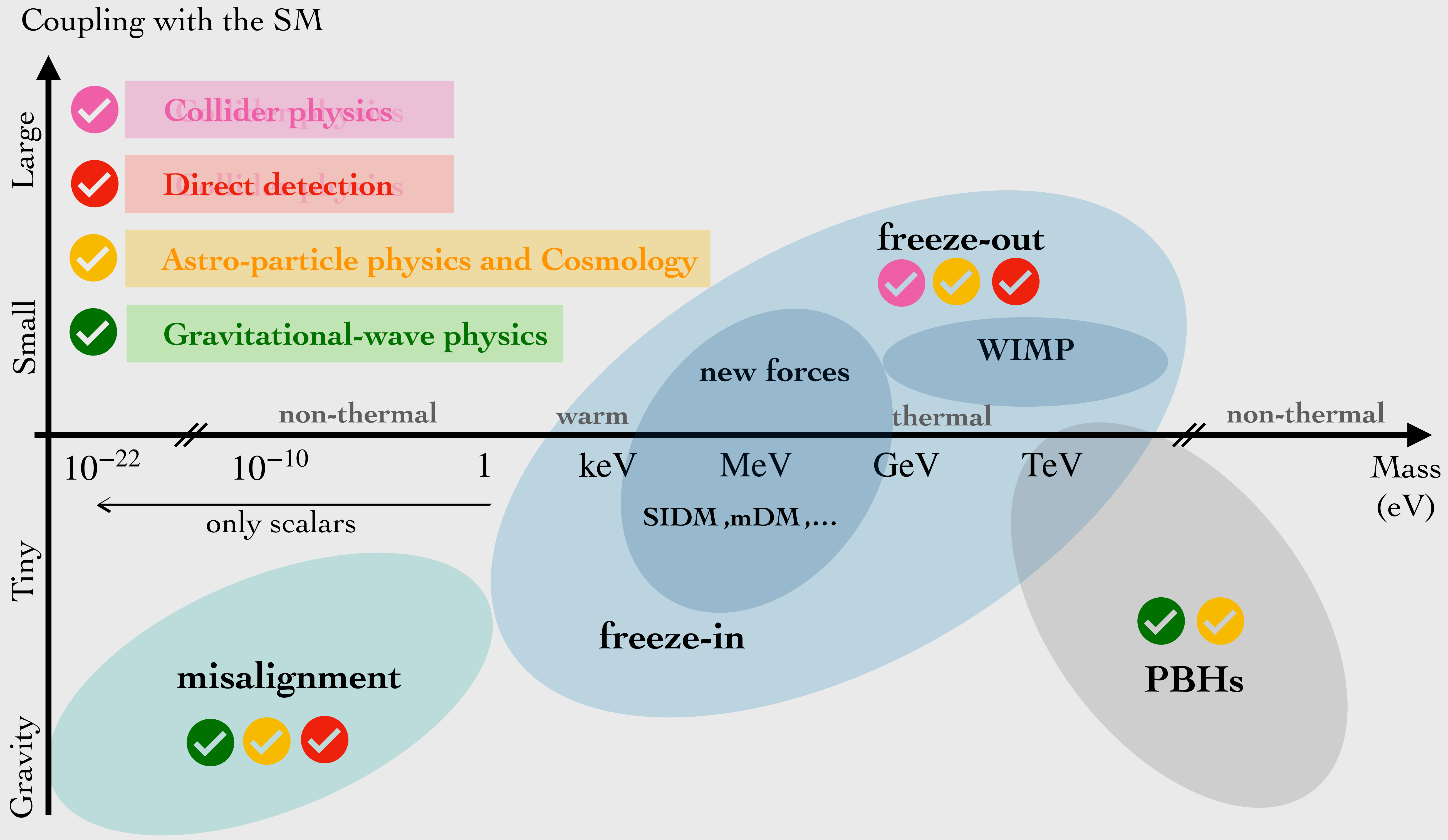
(1,2,1,1), (1,1,2,1), (1,2,2,1), (1,1,1,2),

Dark matter


JORGE CHAM & DANIEL WHITESON
WE HAVE NO IDEA
THE UNIVERSE: (A PIE CHART)
5% STUFF WE KNOW (INCLUDING PIES)
68%
27%
"DARK MATTER"
NO CLUE
SPACE AHEAD
H
A GUIDE TO THE UNKNOWN UNIVERSE

The Chase Is Wide Open

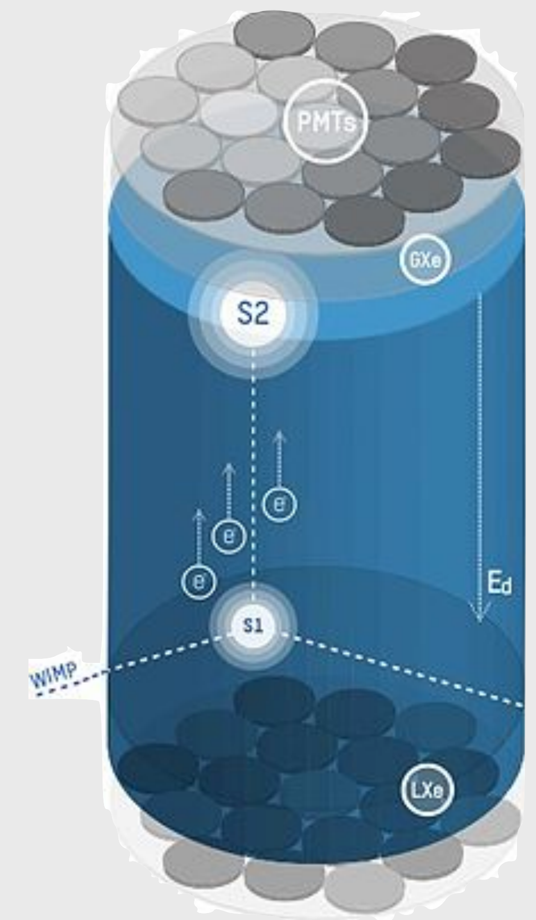
- The chessboard of DM is very large!

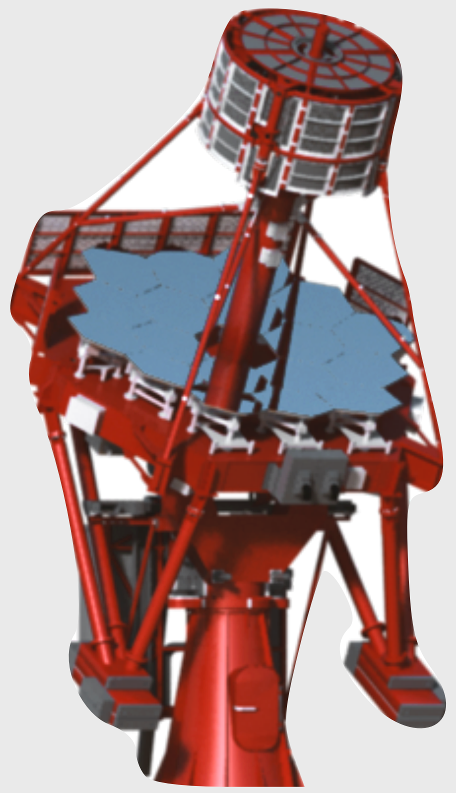


- High energy colliders are excellent and very robust probes of WIMPs!

Diverse Tools

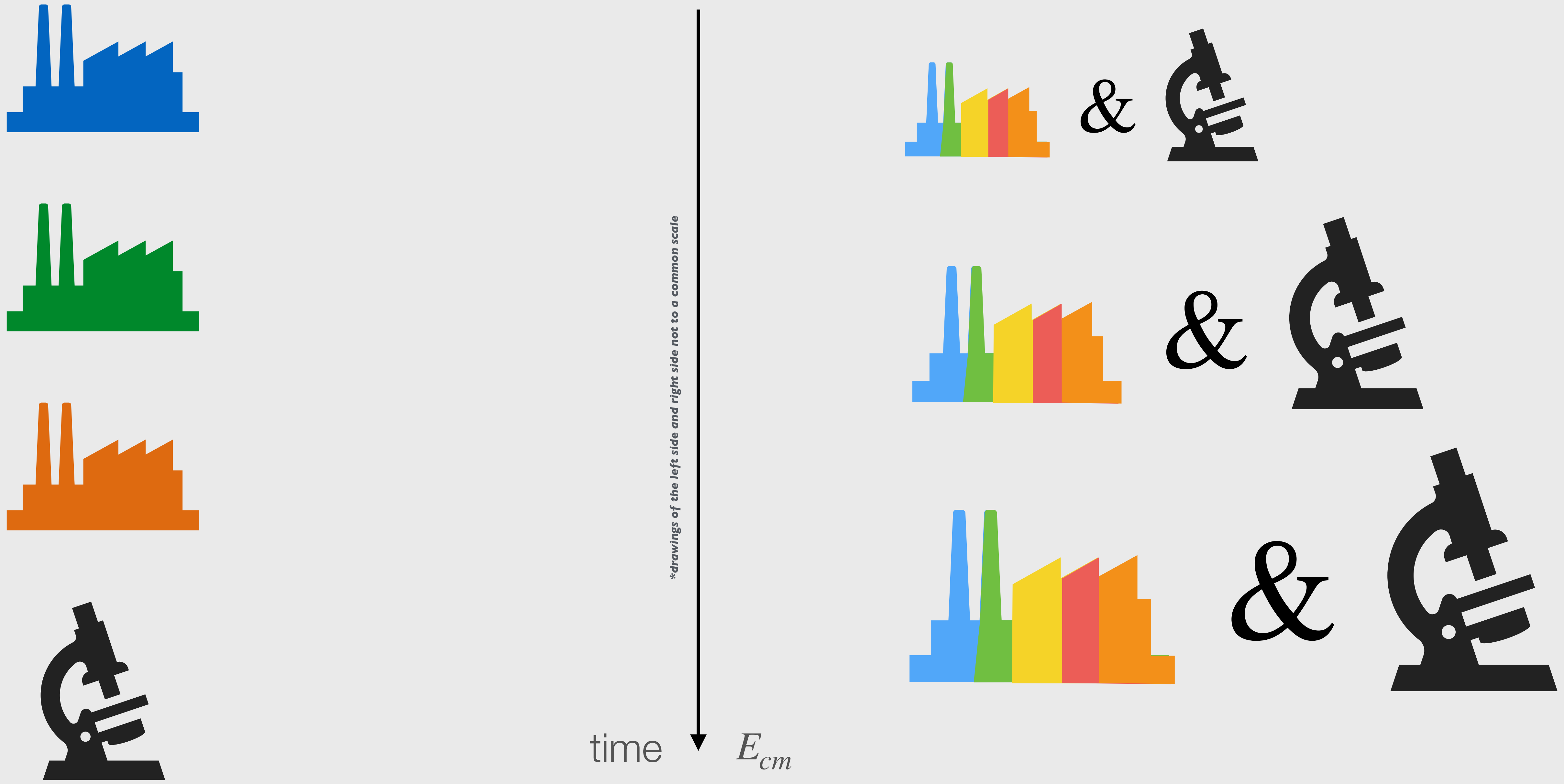
HiLumi HL-LHC PROJECT until late 2040s





FCC-*ee* + *hh*

High energy muon collider

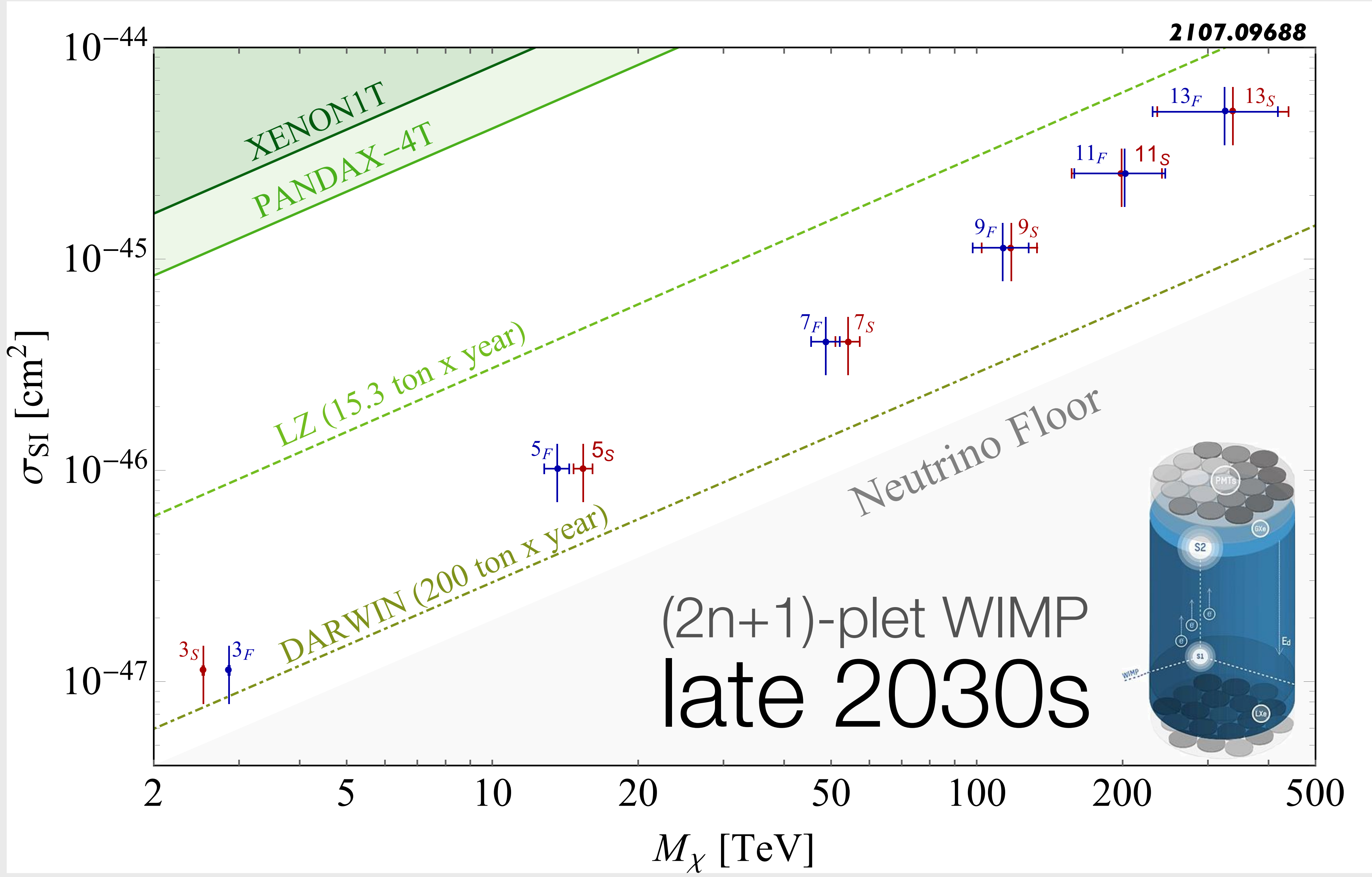


*drawings of the left side and right side not to a common scale

time E_{cm}

Diverse Tools

until late 2040s

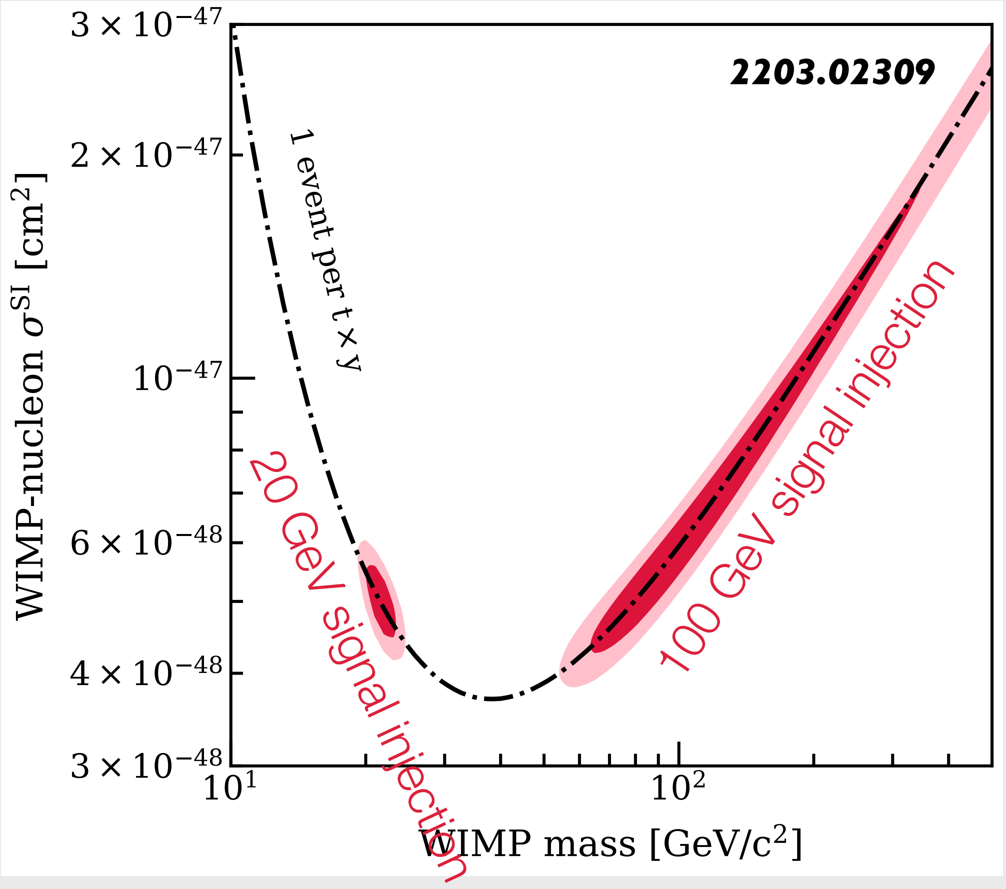


(2n+1)-plet WIMP

late 2030s

Sc1: no hints of WIMPs at Xenon, might be Higgsino

Sc2: hints of WIMPs at Xenon! little hints on its mass



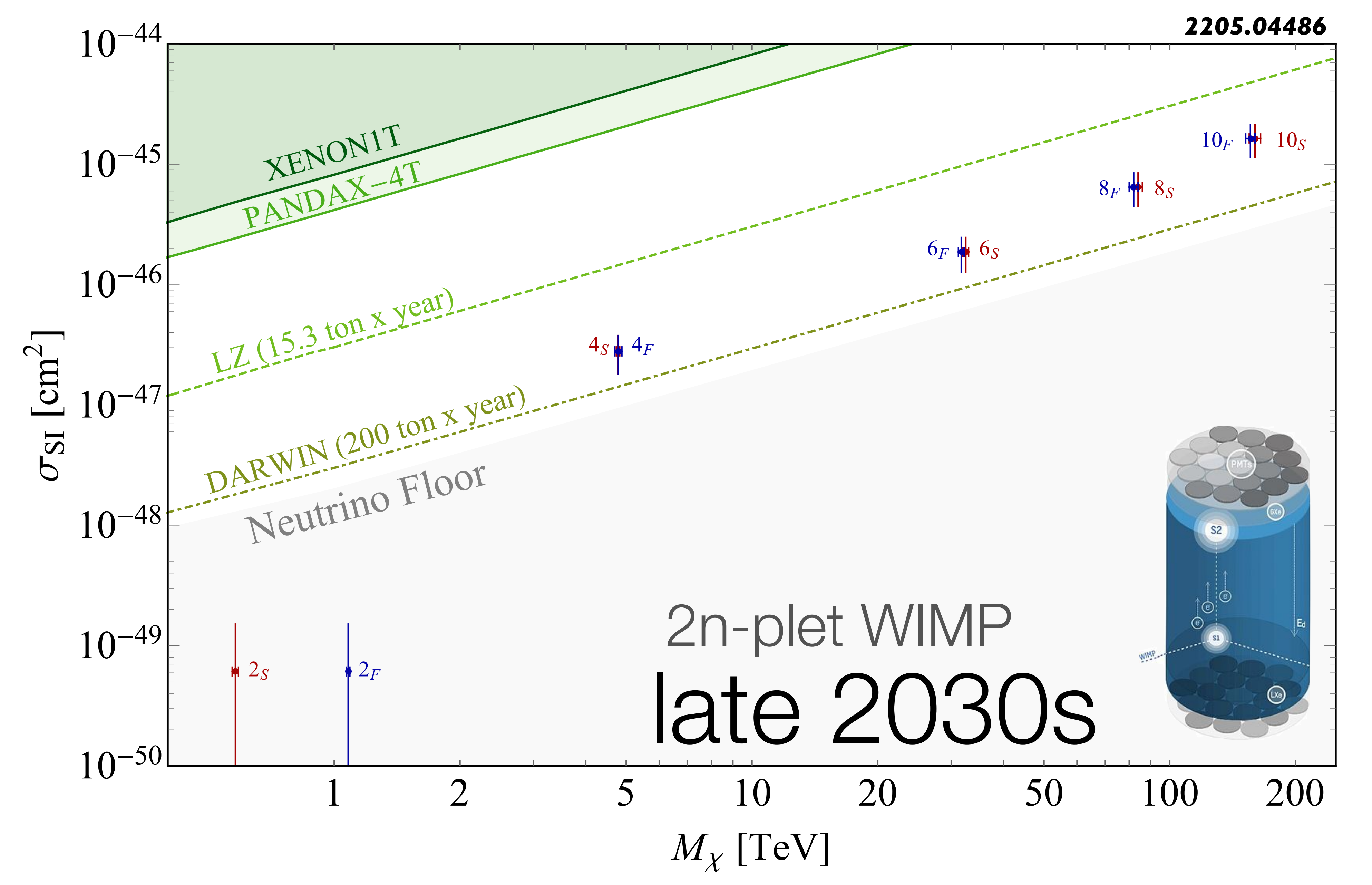
FCC-*ee* + *hh*

High energy muon collider

URGENT NEED FOR A HIGH-ENERGY MACHINE BOTH IN SC1 AND SC2

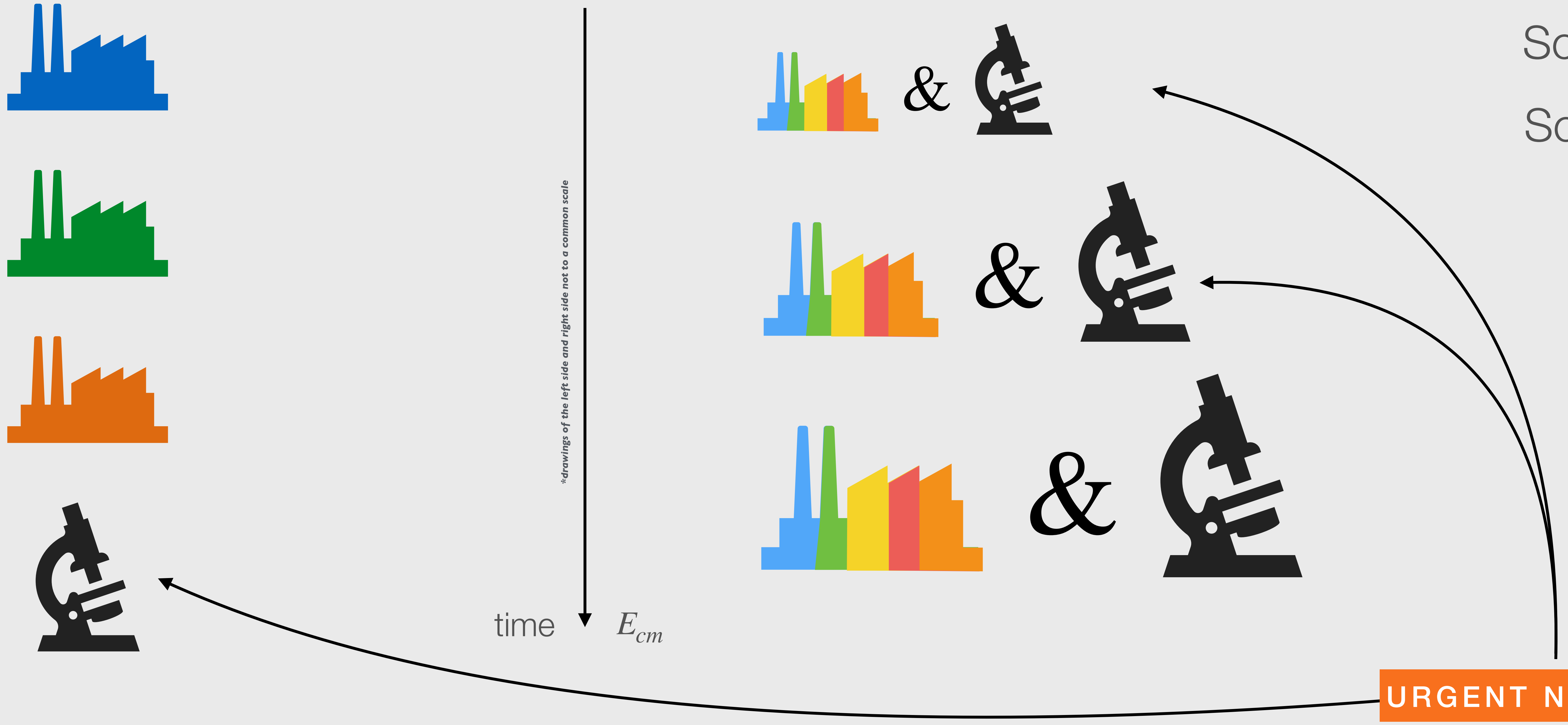
Diverse Tools

HiLumi HL-LHC PROJECT until late 2040s



FCC-*ee* + *hh*

High energy muon collider



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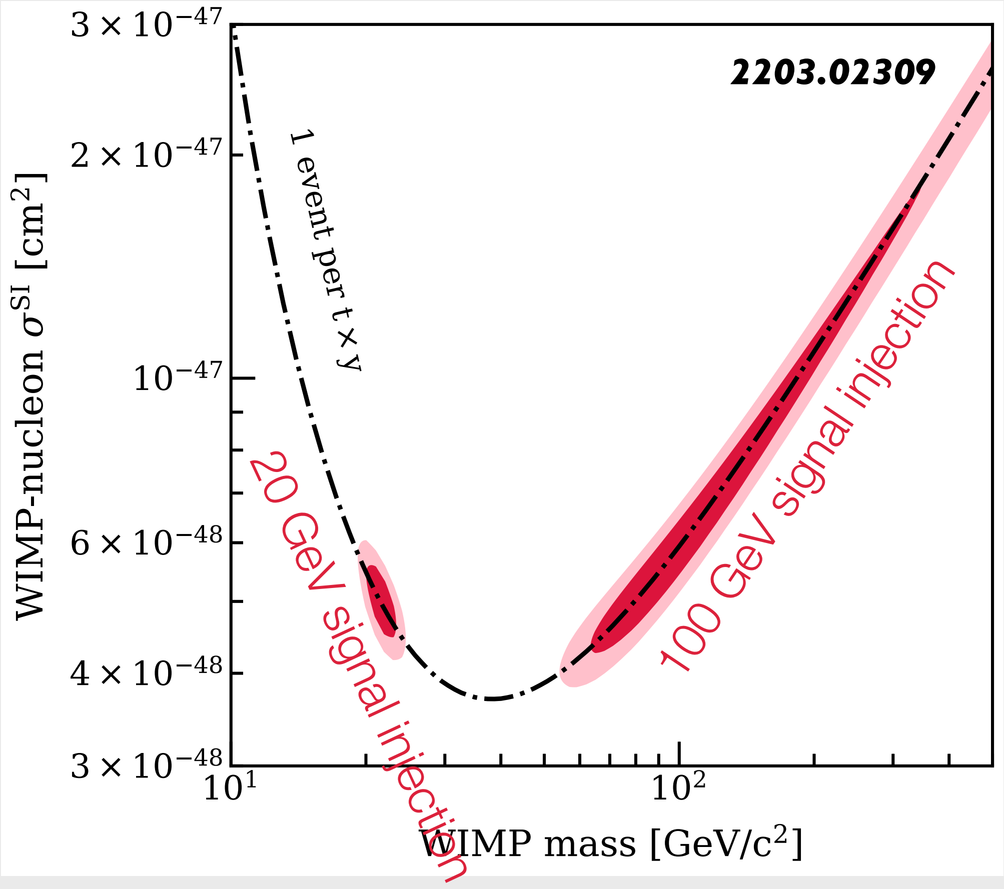

URGENT NEED FOR A HIGH-ENERGY MACHINE BOTH IN SC1 AND SC2

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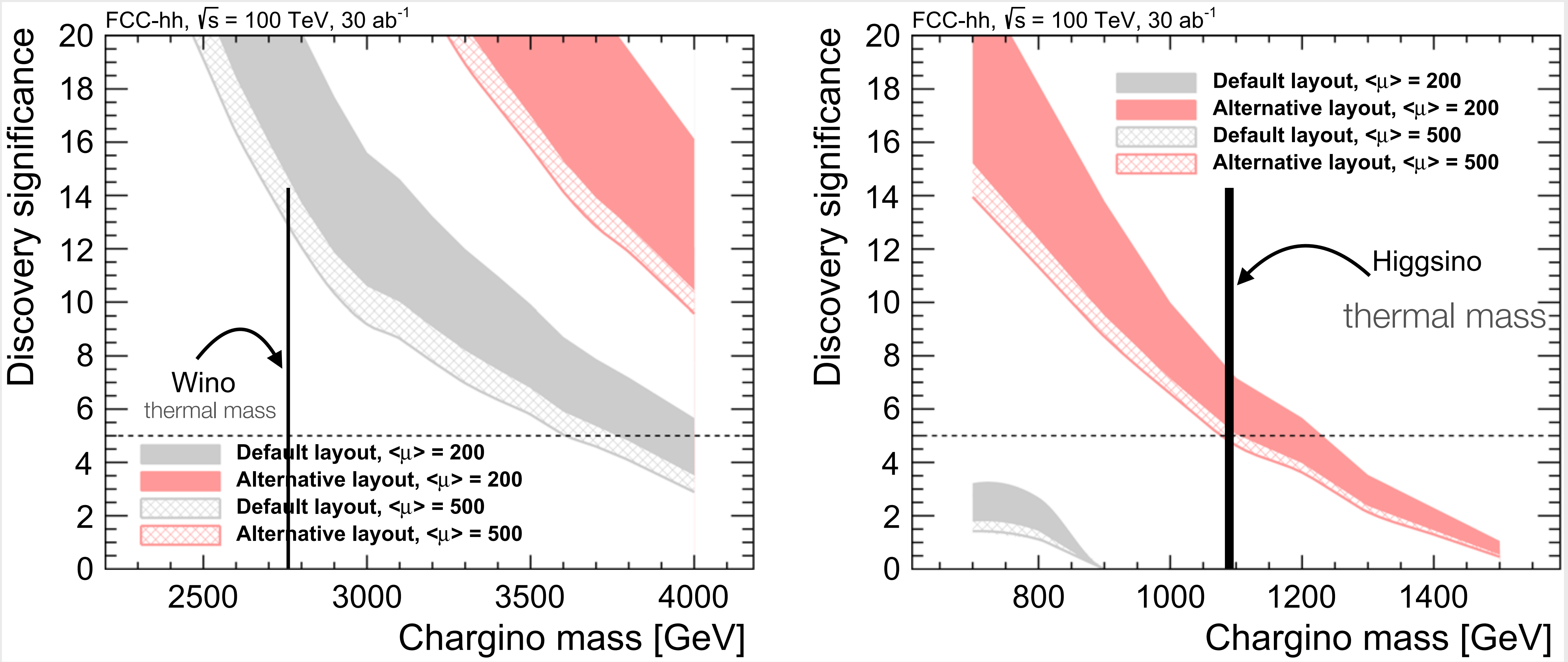
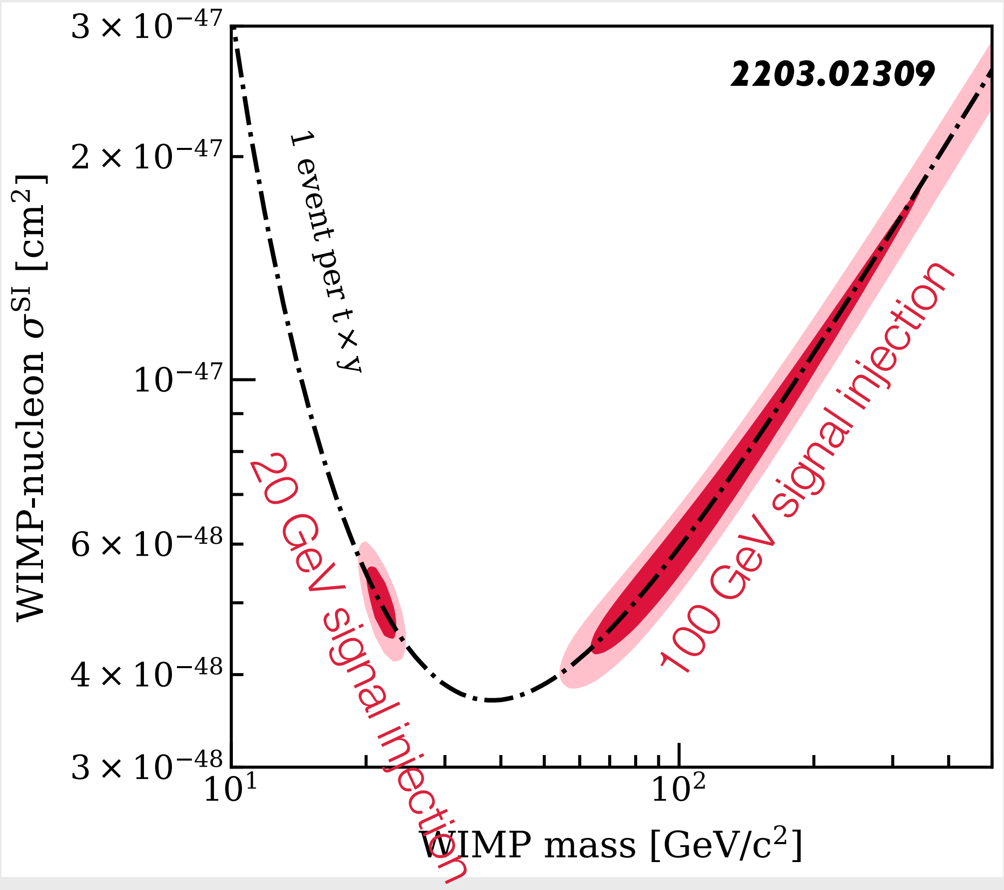
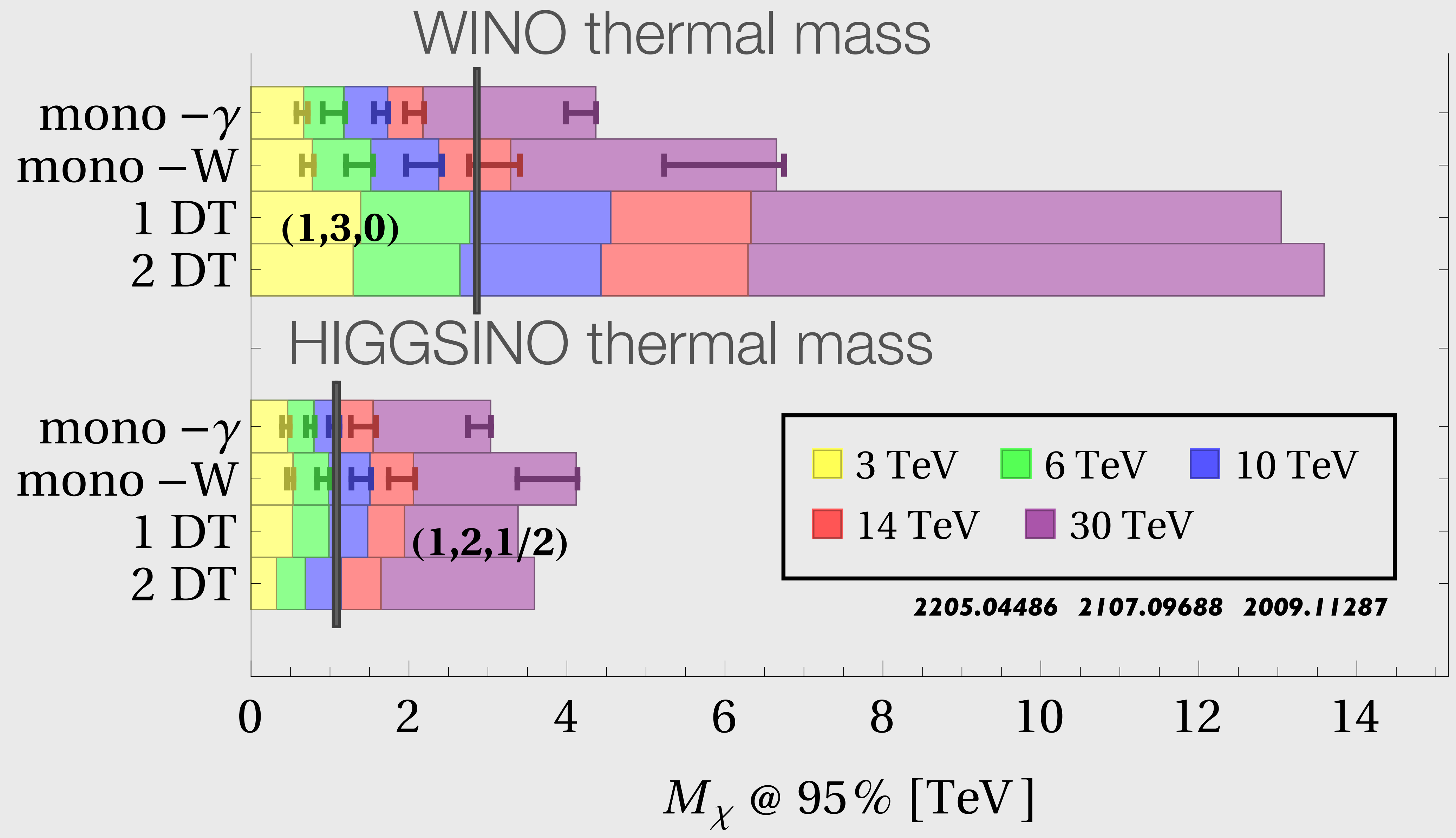




URGENT NEED FOR A HIGH-ENERGY MACHINE BOTH IN SC1 AND SC2

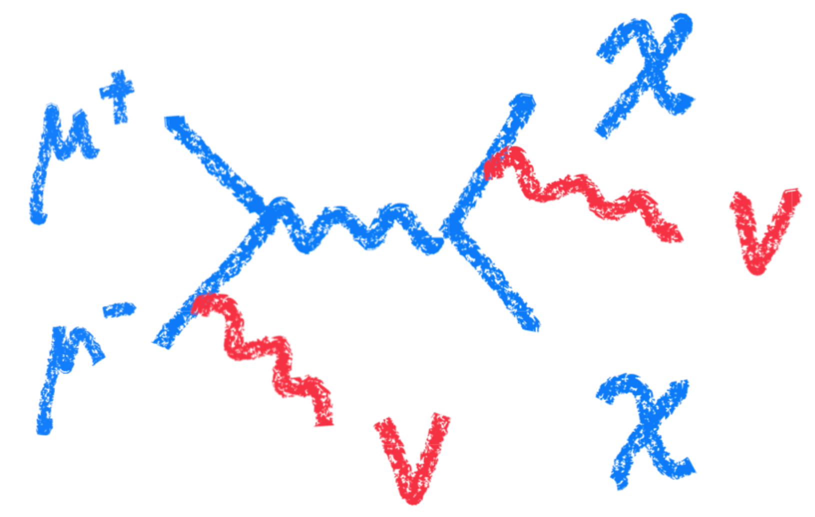


- Absence of Xe signals would require a 100 TeV pp or 6-10 TeV $\mu\mu$ to conclusively probe WIMPs by testing Higgsino
- Xe signal of heavy WIMP opens the chase from 1 TeV to fraction of PeV mass

Projects specialties

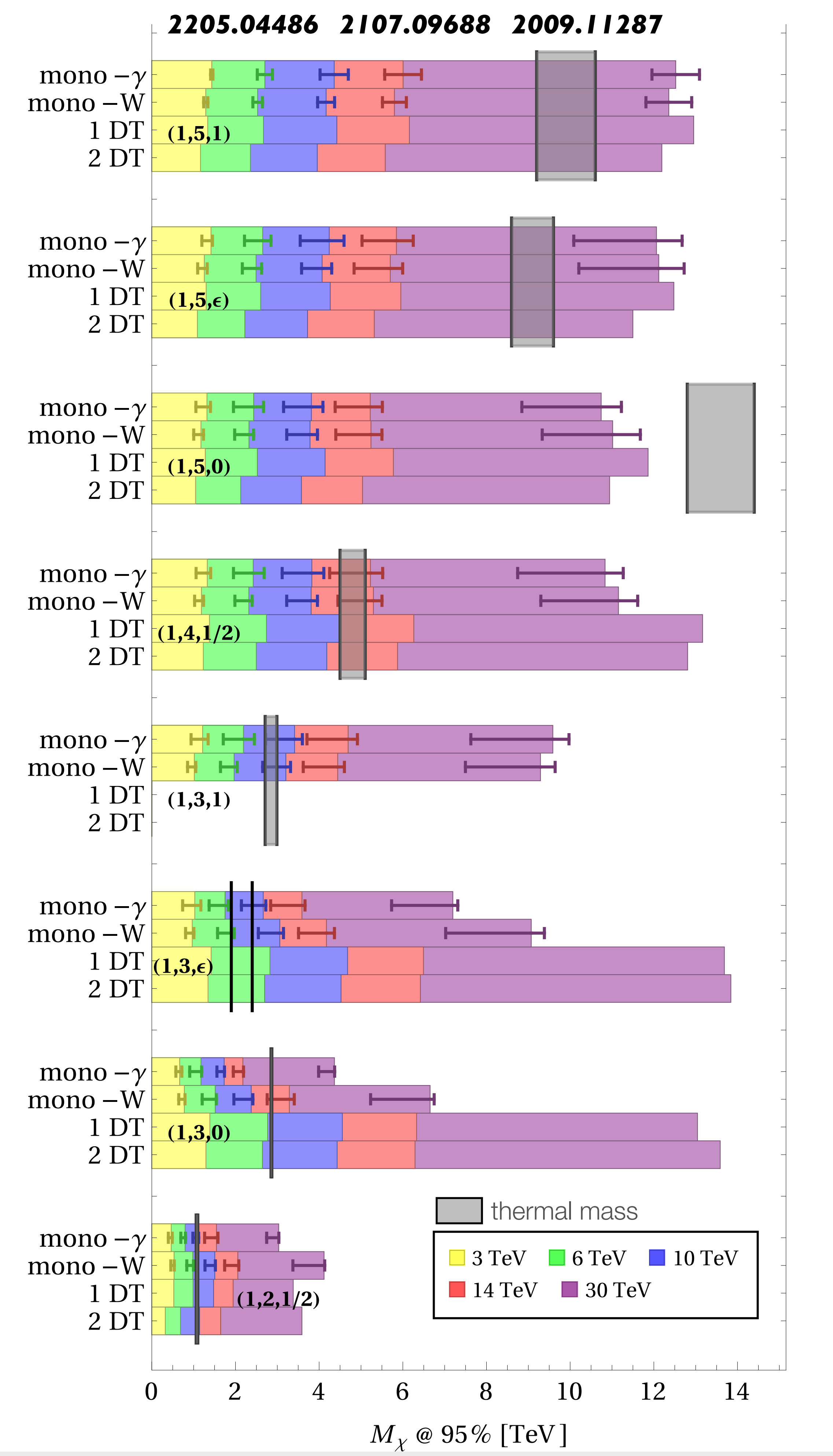
Search for EW matter at $\mu\mu$

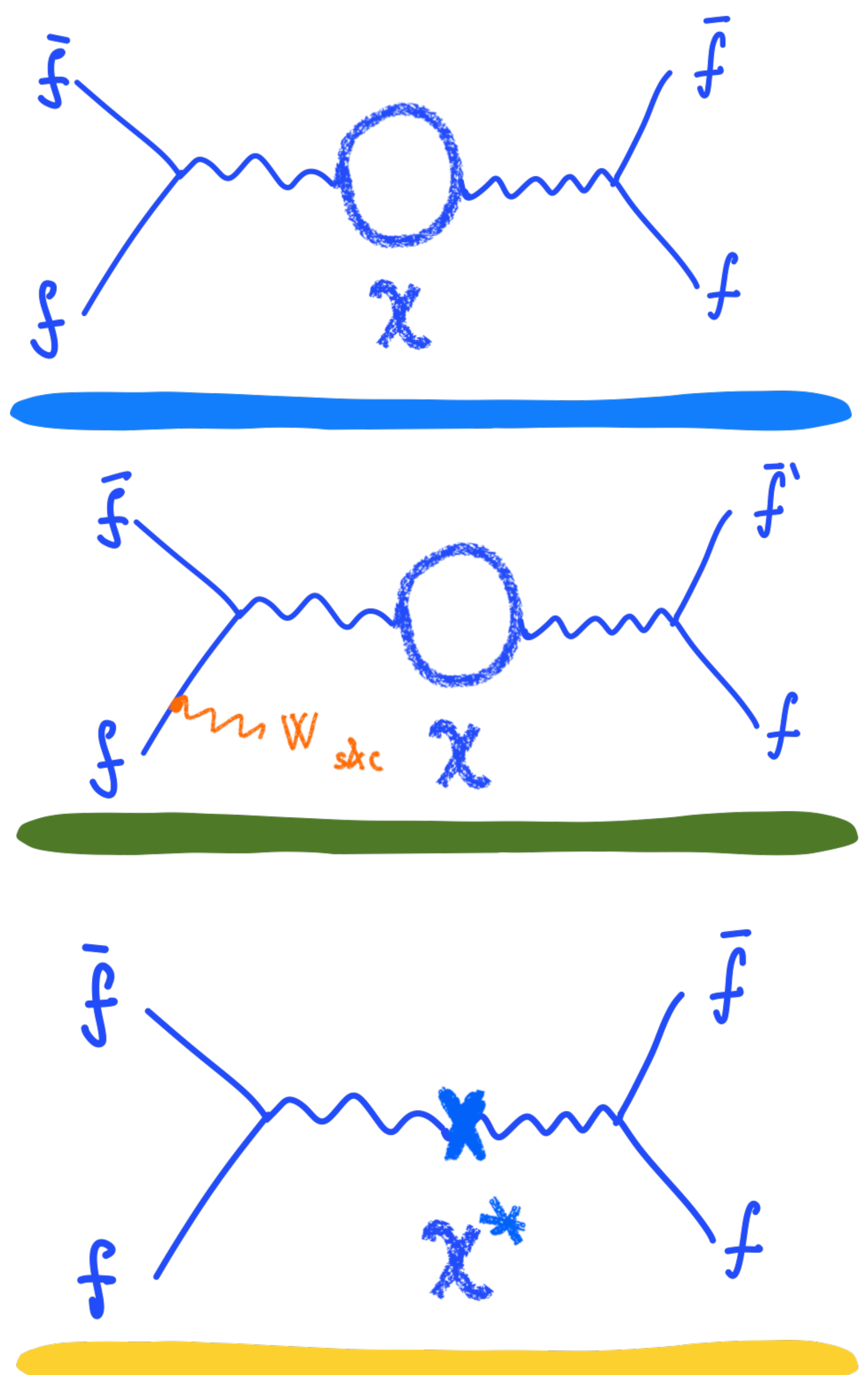
- Xe signal of heavy WIMP opens the chase from 1 TeV to fraction of PeV mass
- most solutions to open issues of the SM require new EW particles



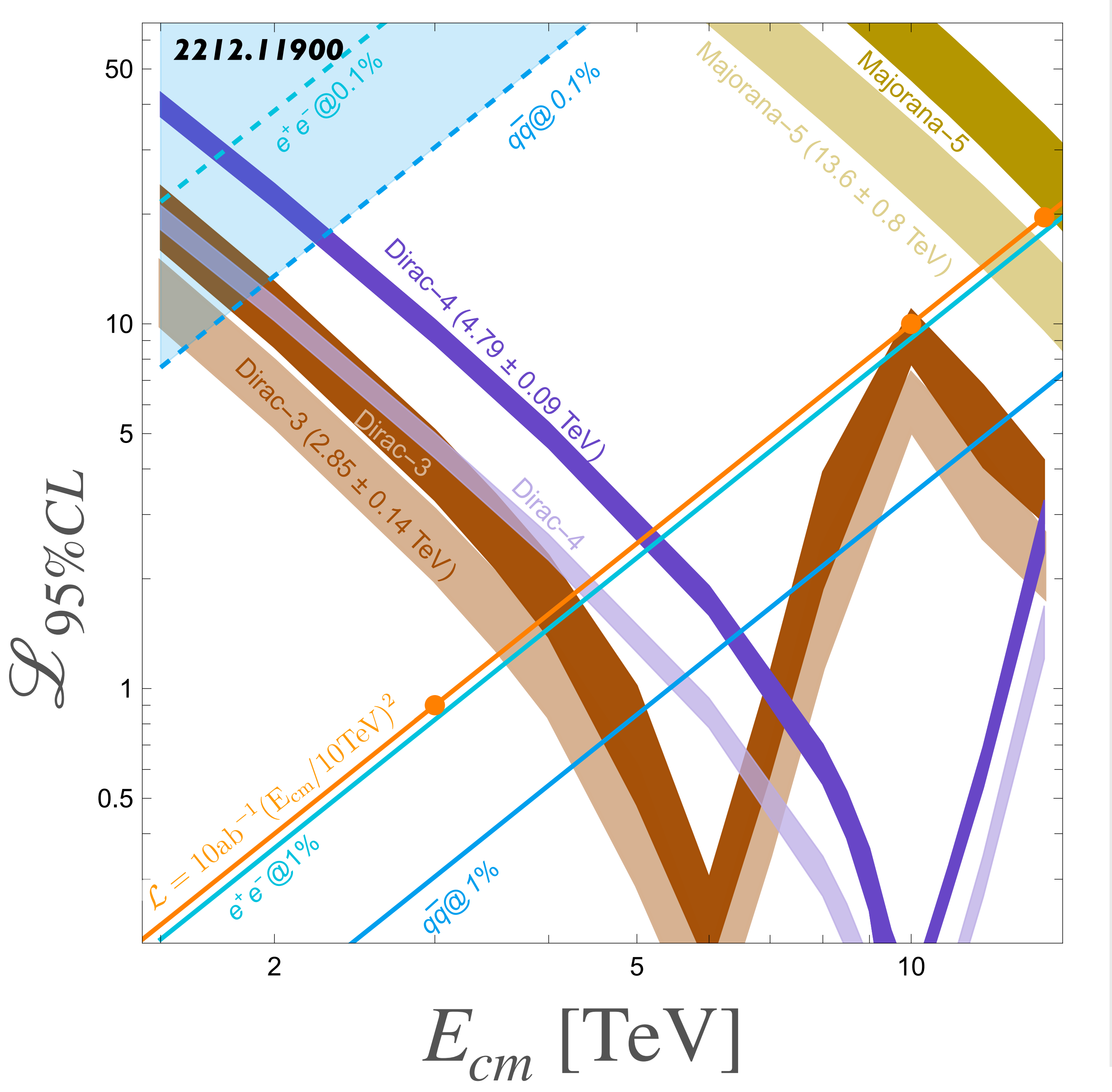
Large χ mass needs CoM energy!

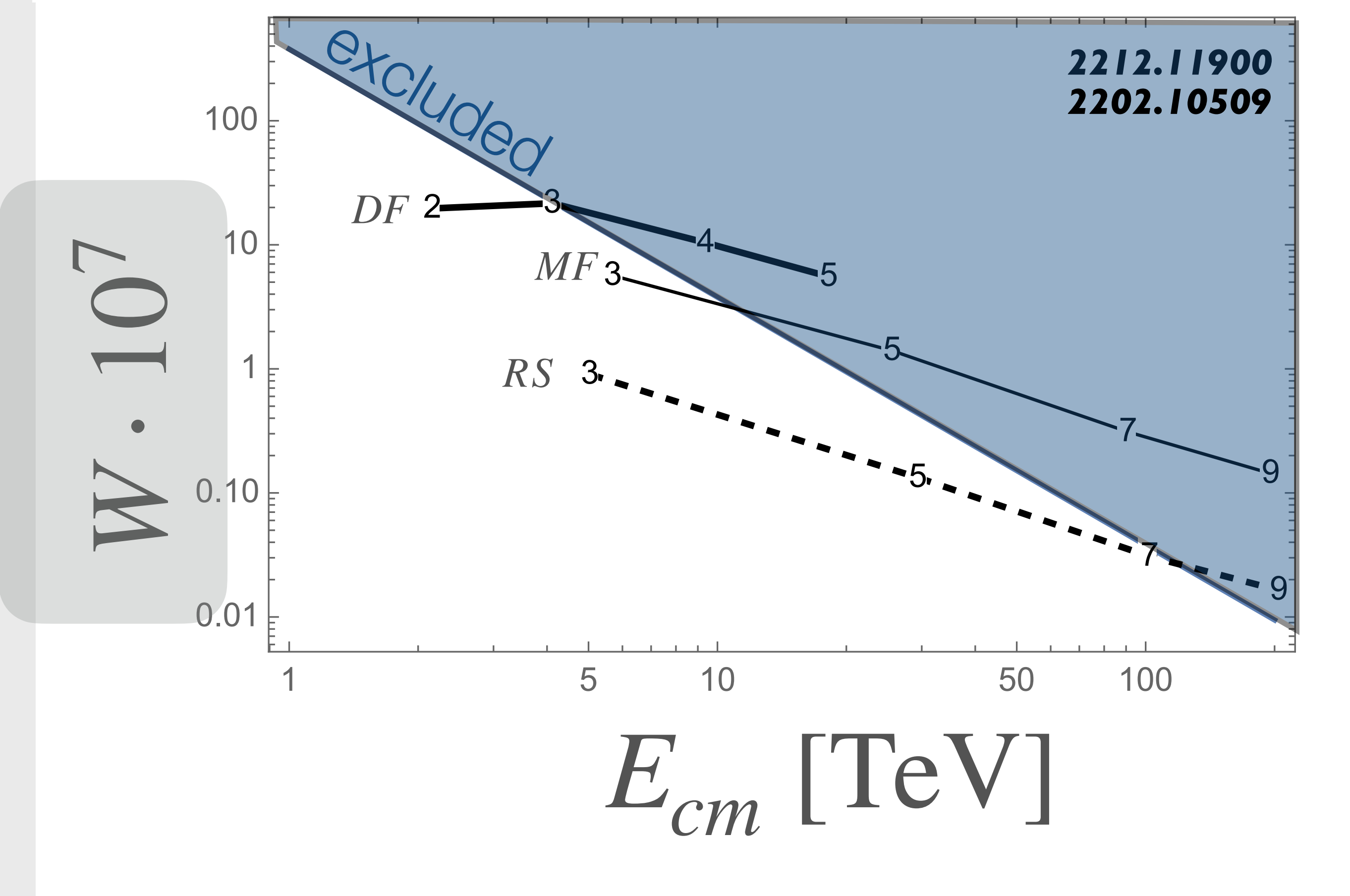
Weak radiation yield the most constraining channel “mono-W”





$$O_{2W} \propto (D_\mu W^{\mu\nu})^2$$





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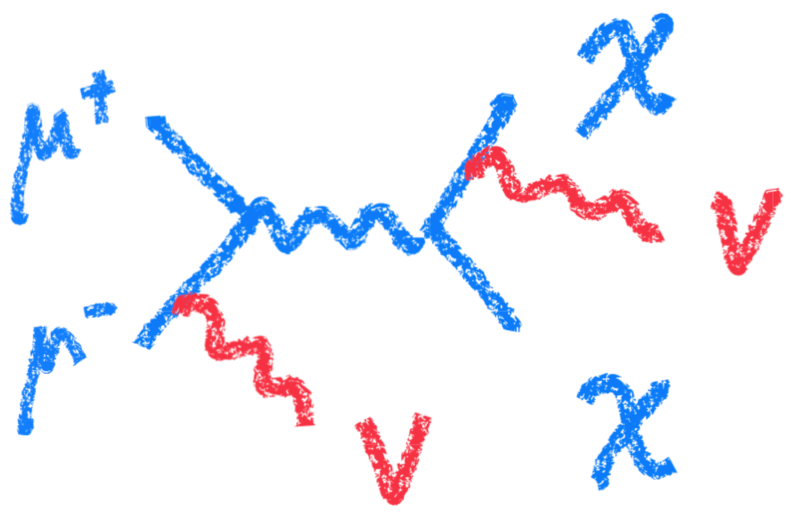

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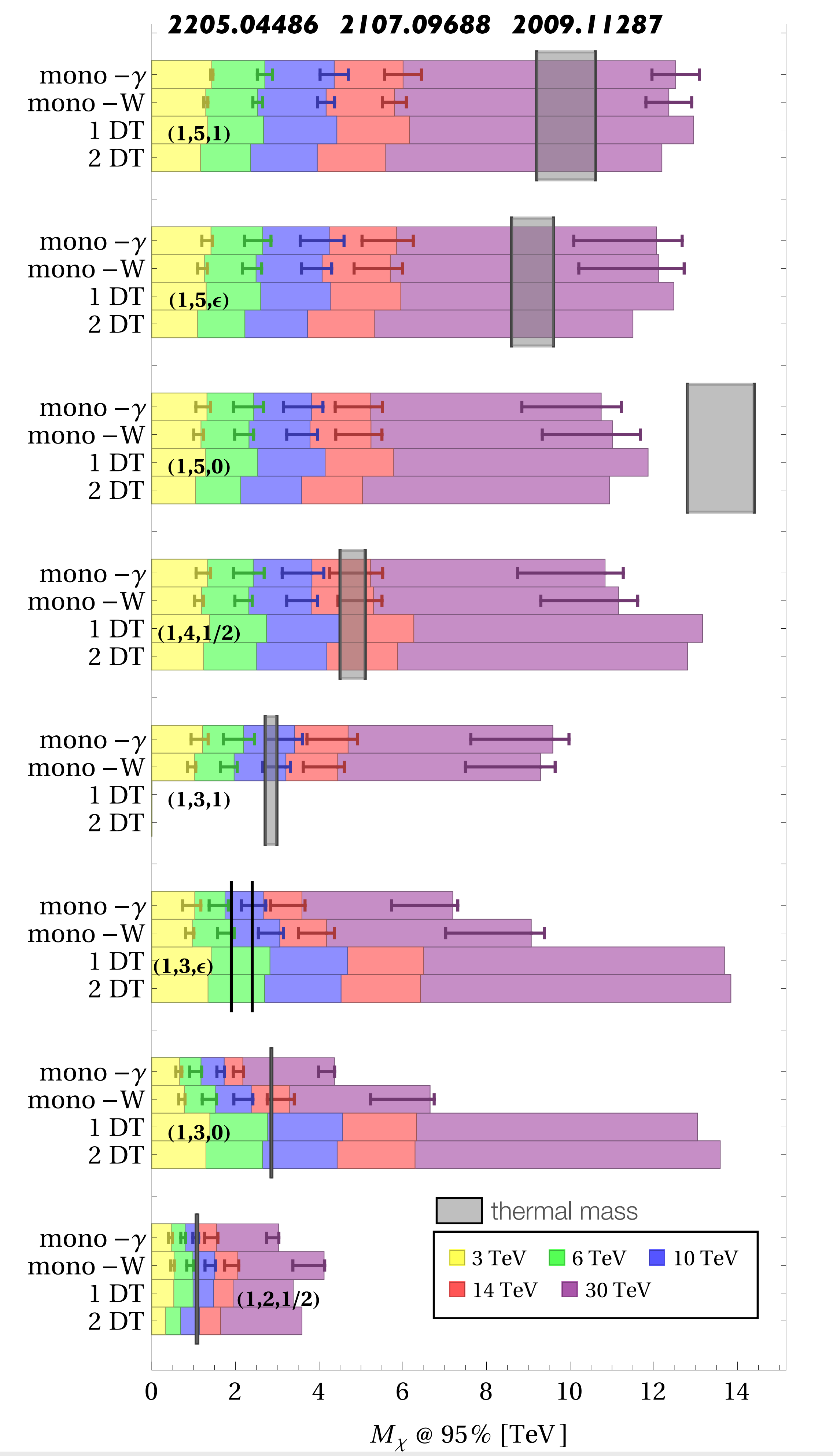
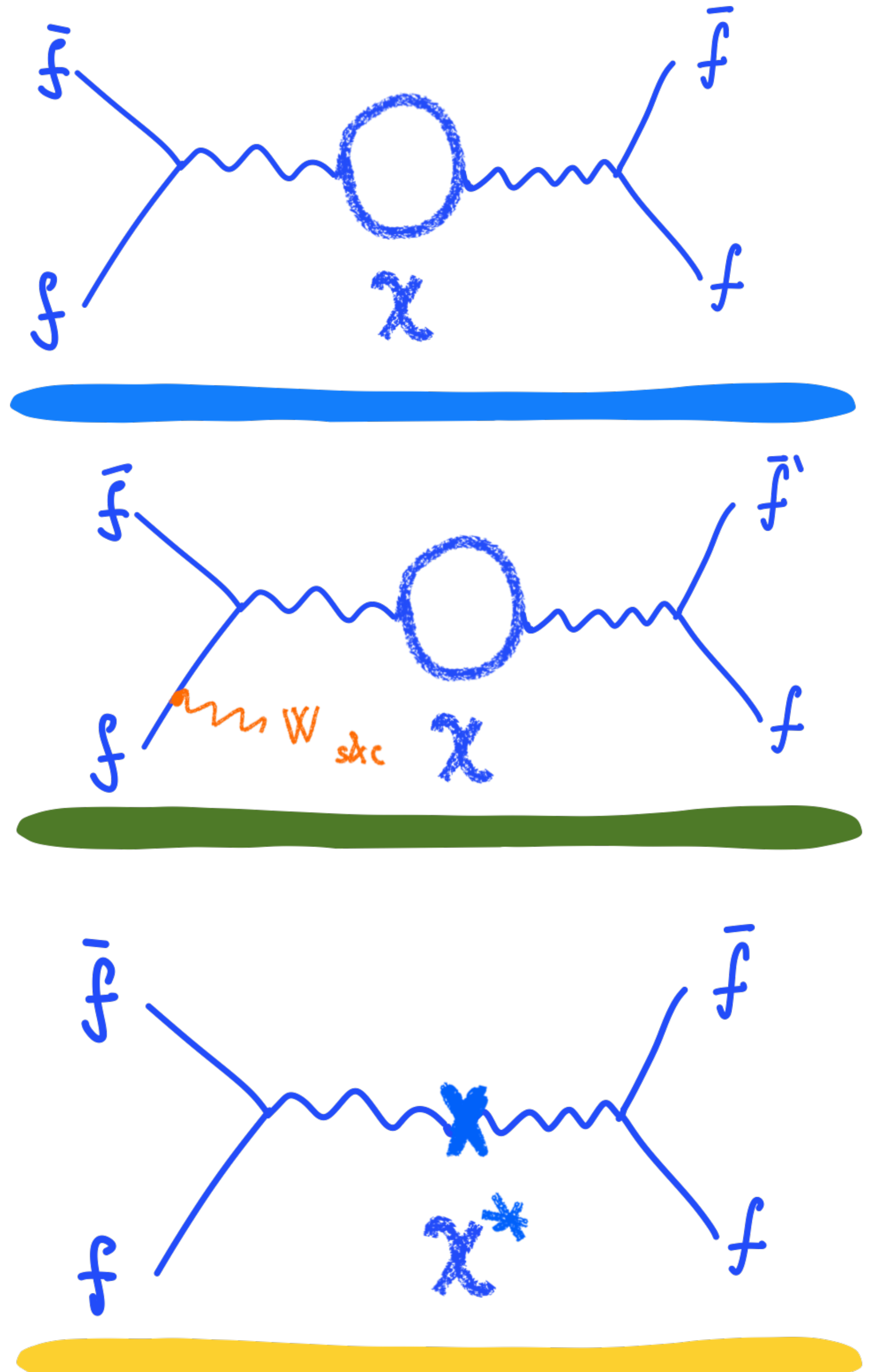


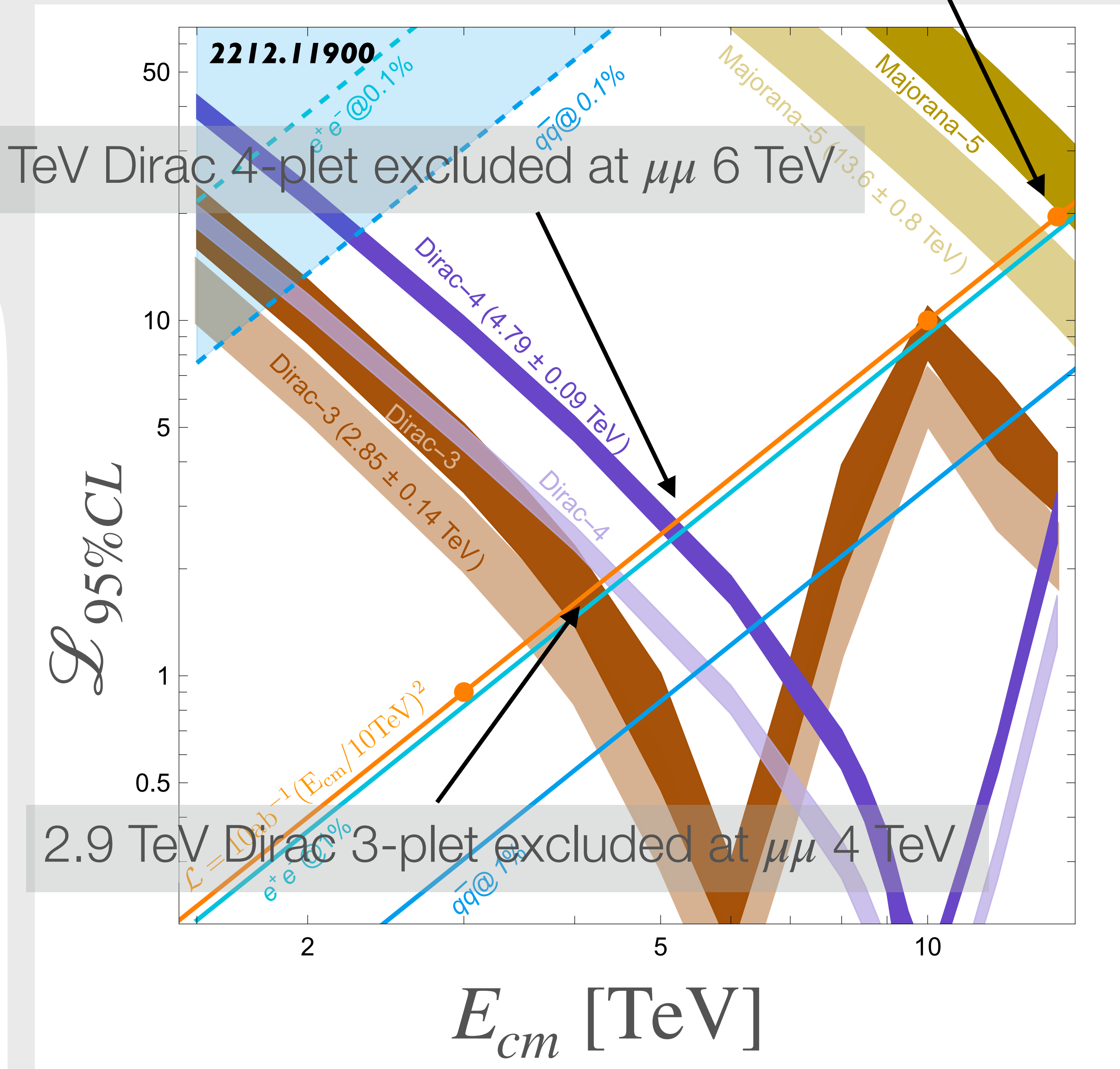


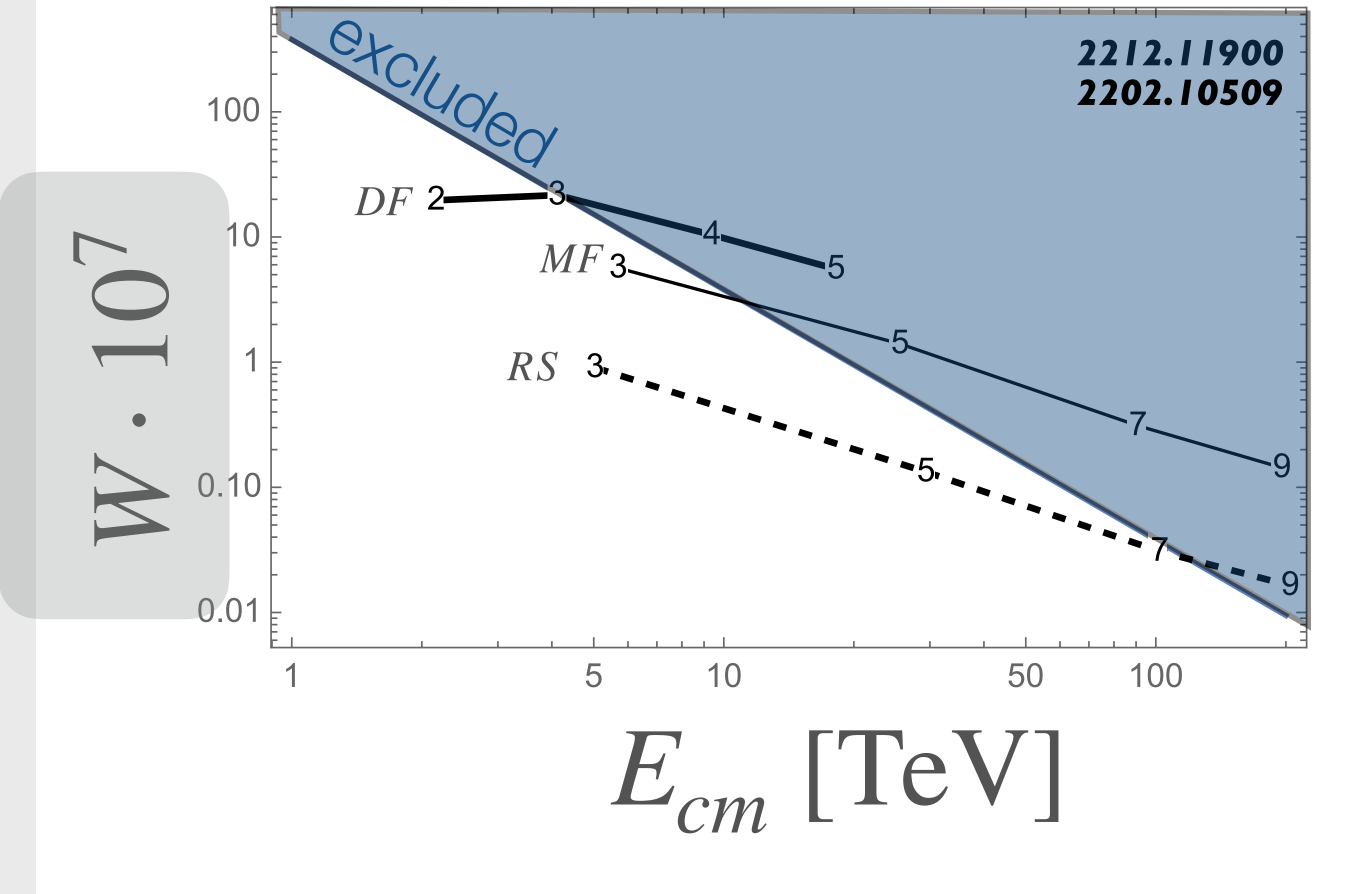
$$O_{2W} \propto (D_\mu W^{\mu\nu})^2$$

14 TeV Majorana 5-plet excluded at $\mu\mu$ 14 TeV

4.8 TeV Dirac 4-plet excluded at $\mu\mu$ 6 TeV

2.9 TeV Dirac 3-plet excluded at $\mu\mu$ 4 TeV





Search for EW matter at $\mu\mu$

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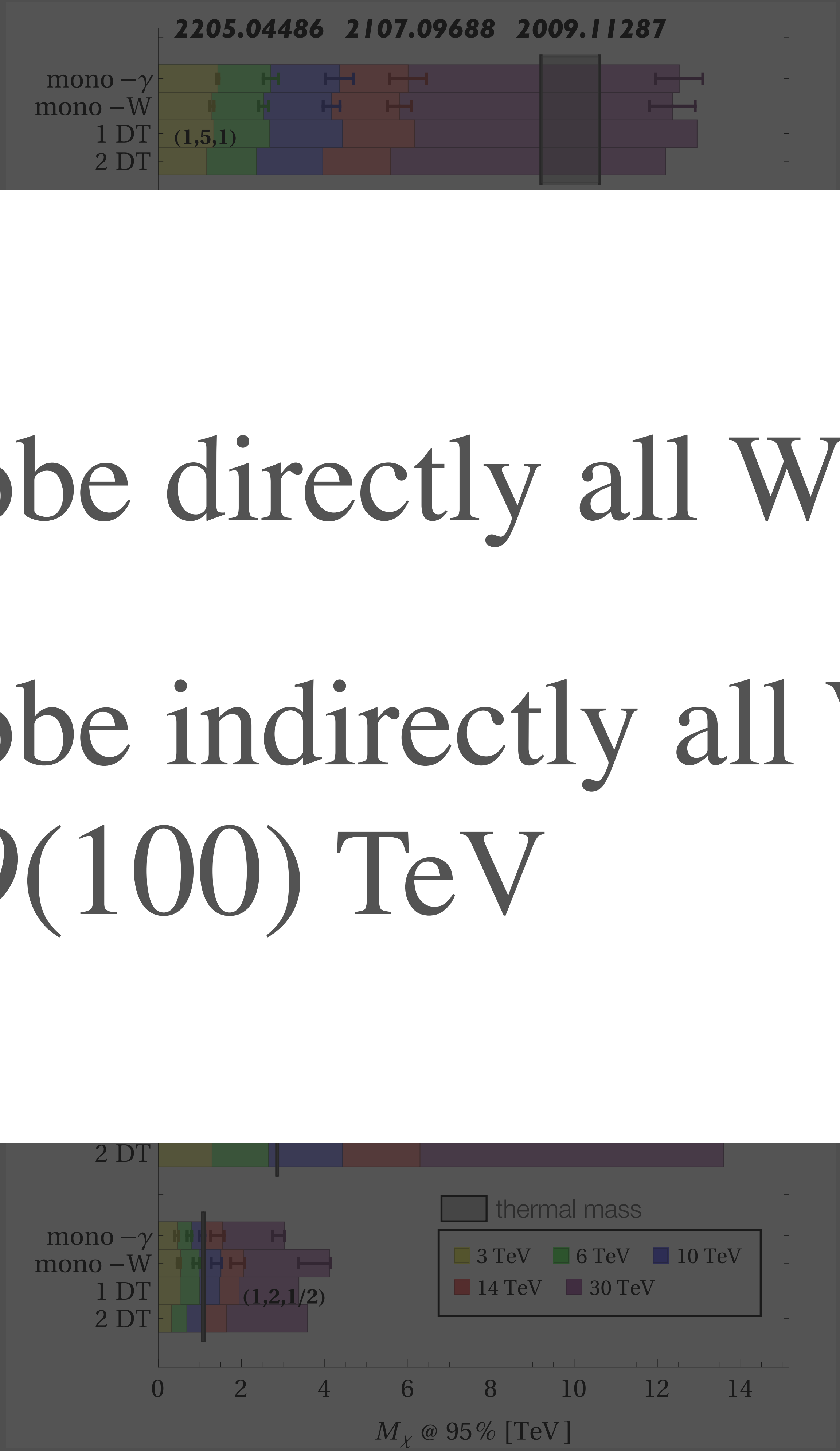
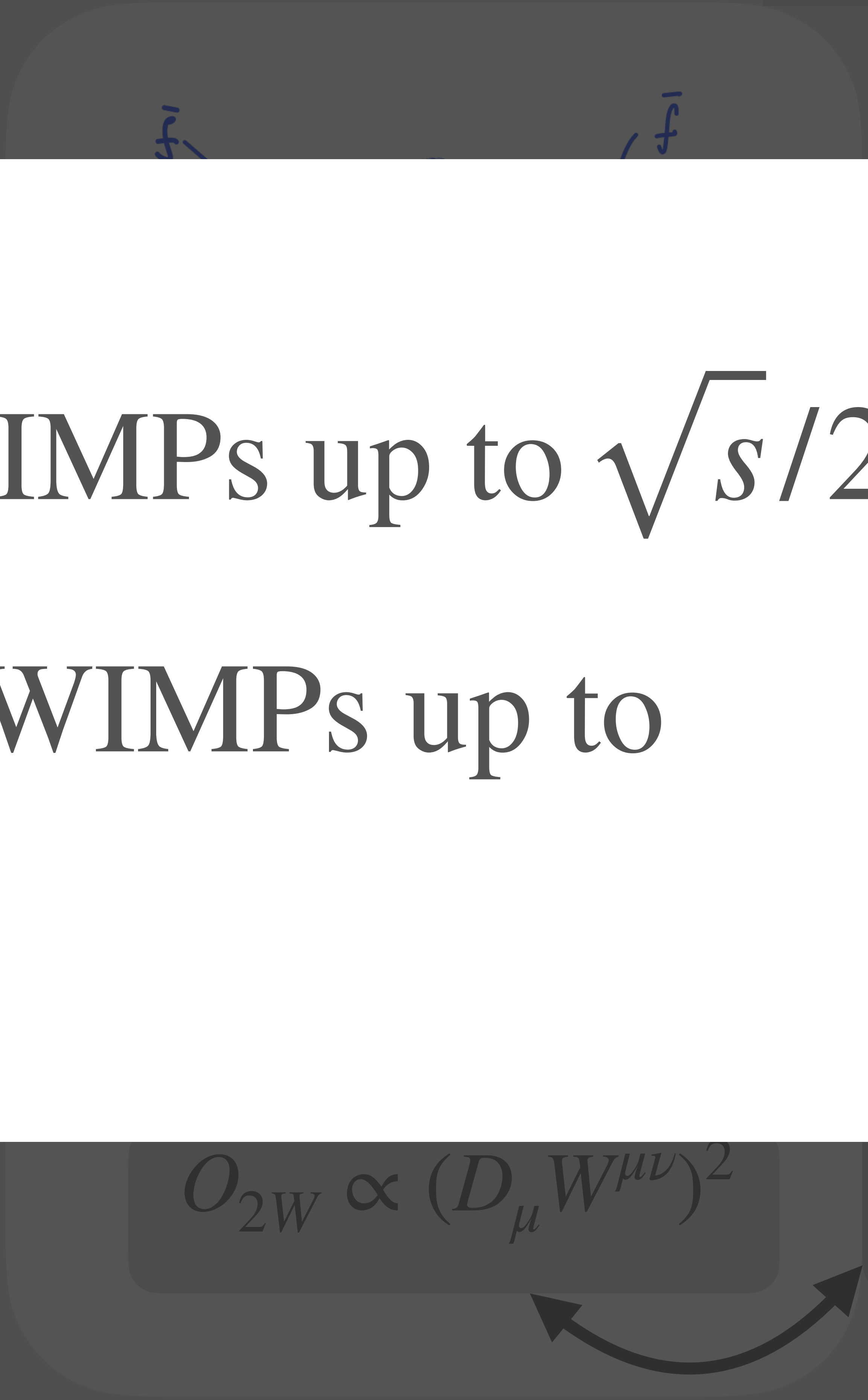




$O_{2W} \propto (D_\mu W^{\mu\nu})^2$

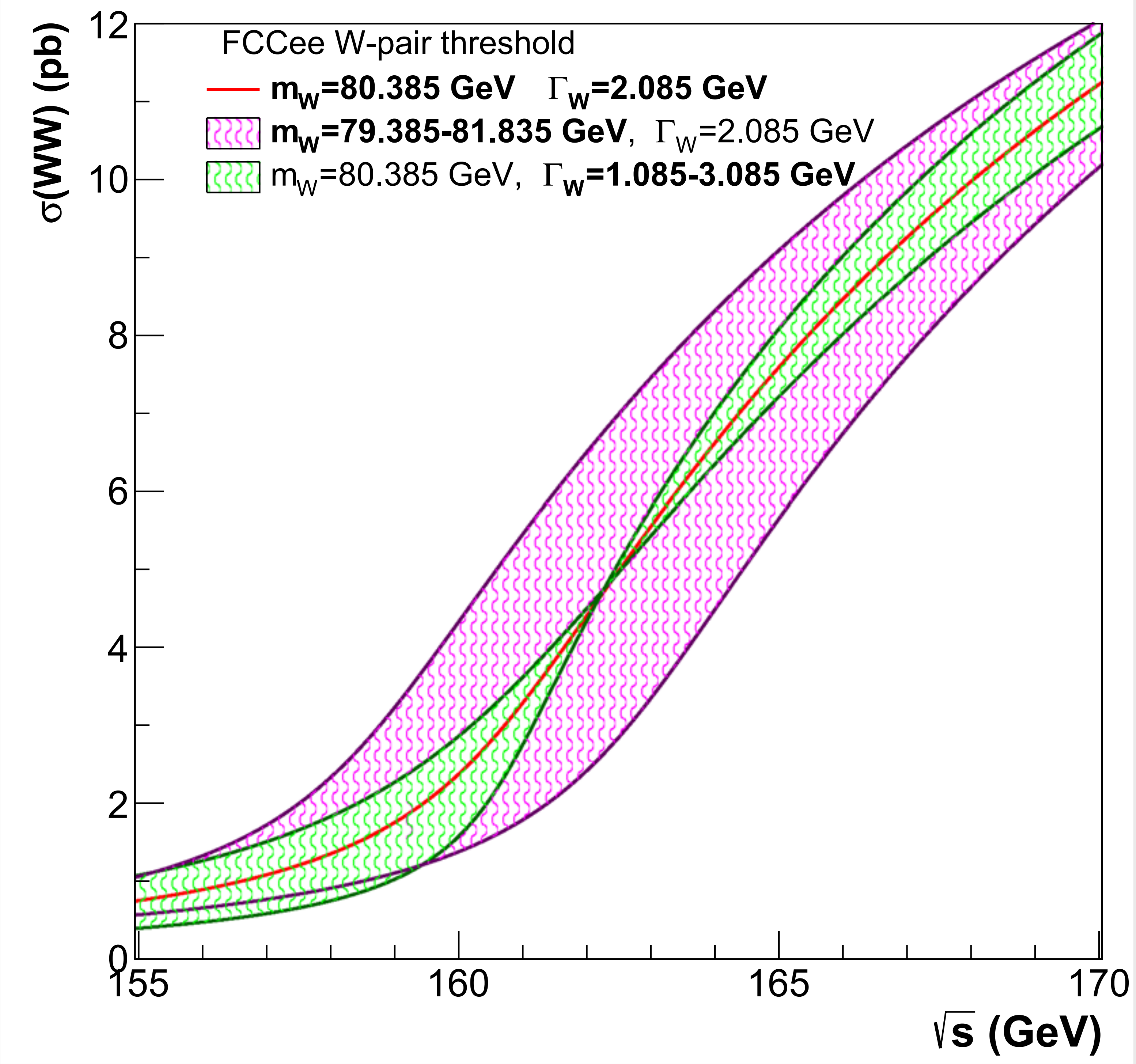
4.8 TeV Dirac 4-plet excluded at $\mu\mu$ 6 TeV

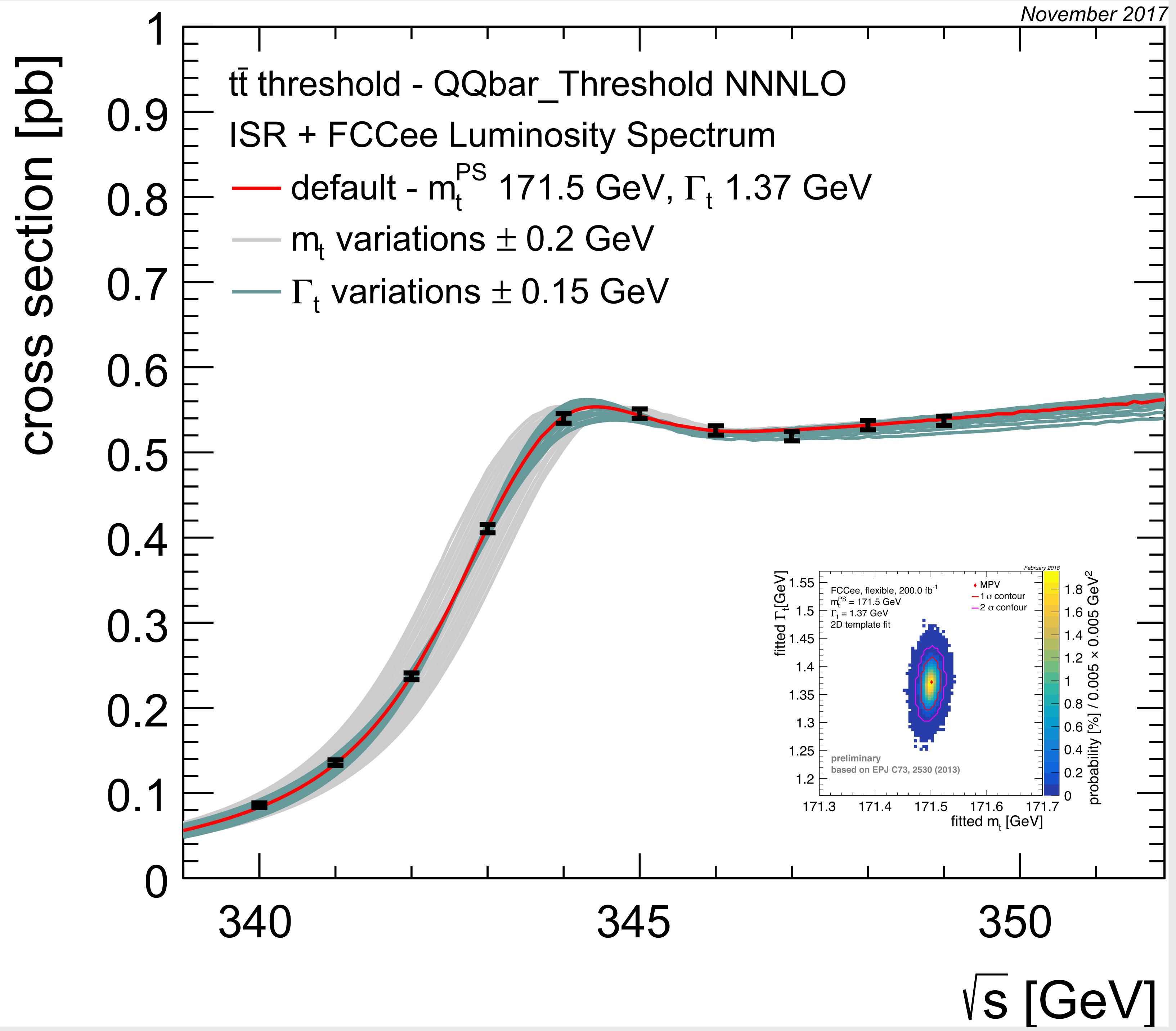
- Potential to probe directly all WIMPs up to $\sqrt{s}/2$
- Potential to probe indirectly all WIMPs up to thermal limit $O(100)$ TeV

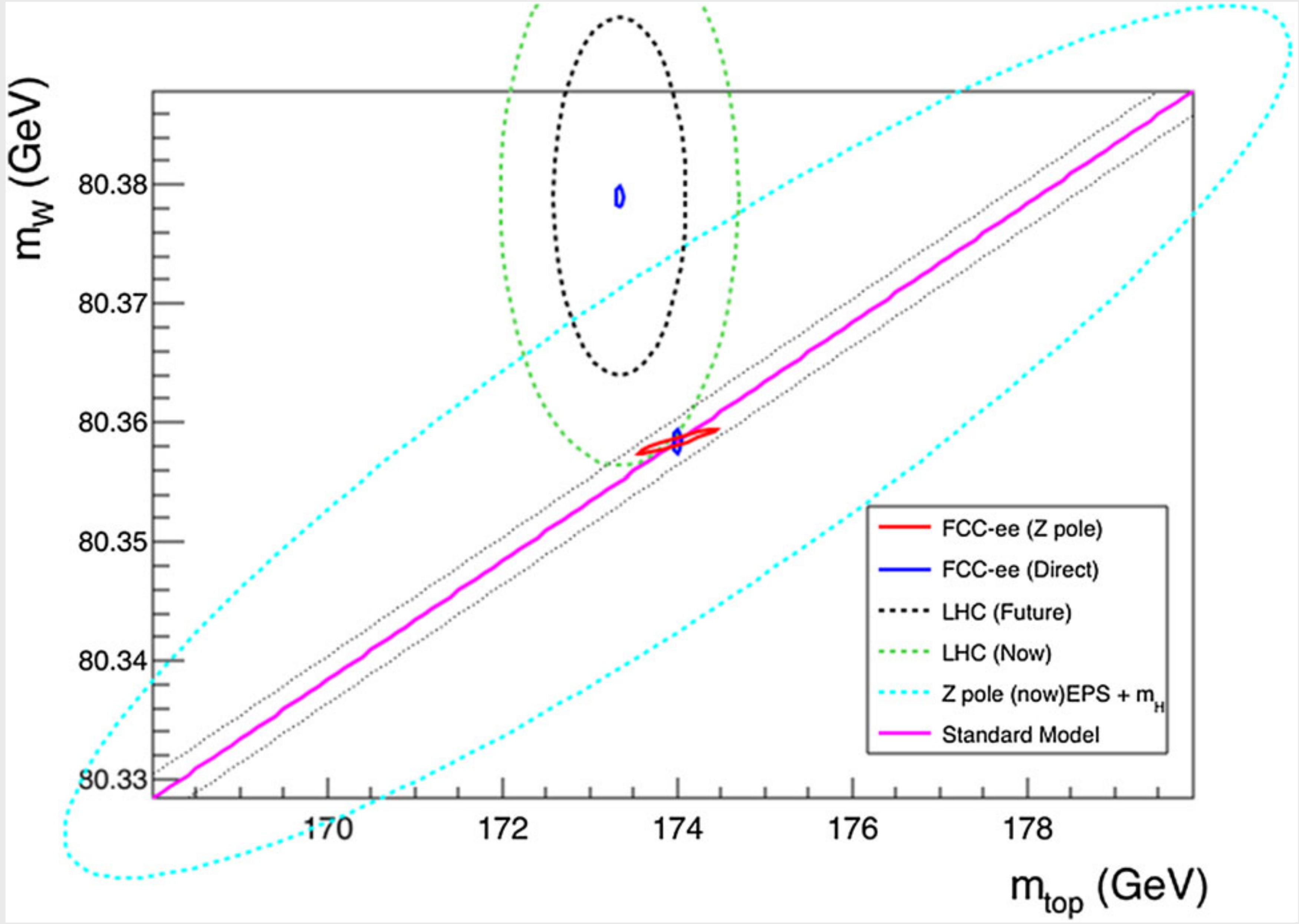
International
MUON Collider
Collaboration

Threshold Scan Mass Measurement

- anomalies in the electroweak fit, hints of electroweak new physics at LHC







$\delta m_W \lesssim 1$ MeV

$\delta m_t \lesssim 10$ MeV

Theory Challenges In Both Paths!

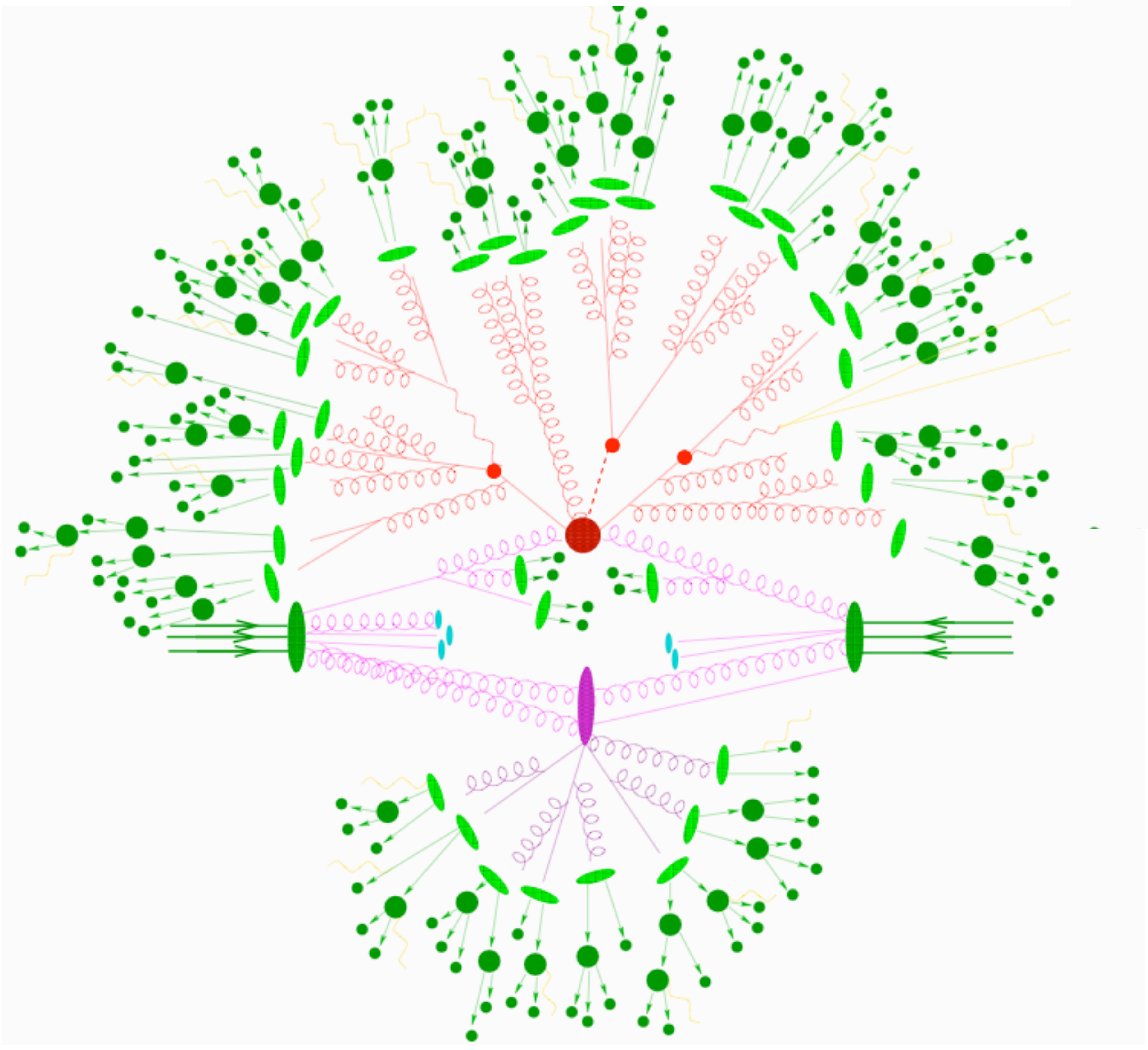
- Z pole N^kLO $\Rightarrow$ learning how to think about scattering at such high precision
- Non perturbative power corrections to $QCD\,jets$
- fragmentation functions (e.g for $b \rightarrowtail B$ and $c \rightarrowtail D$) high precision measurement, needs matching theory development (parton showers, universality, …)
- ultra-rare phenomena(l) $backgrounds\ to\ exotic\ NP$
- Threshold computations for W^+W^- and $t\bar{t}$ to exploit total/fiducial rate measurements and further differential measurements
- Weak corrections essential to every process from $\sqrt{\hat{s}_{ij}} \equiv \sqrt{s_{\mu\mu}} \gtrsim$ 10 TeV
- Non-abelian charge exclusive scattering initial state $|\,i\rangle = |\uparrow\uparrow\rangle_{SU(2)_W}$ in nearly unbroken phase
- Weak partons and μ $PDFs$
- $Electroweak\ jets$ at $\sqrt{s_{\mu\mu}} \geq$ few TeV

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

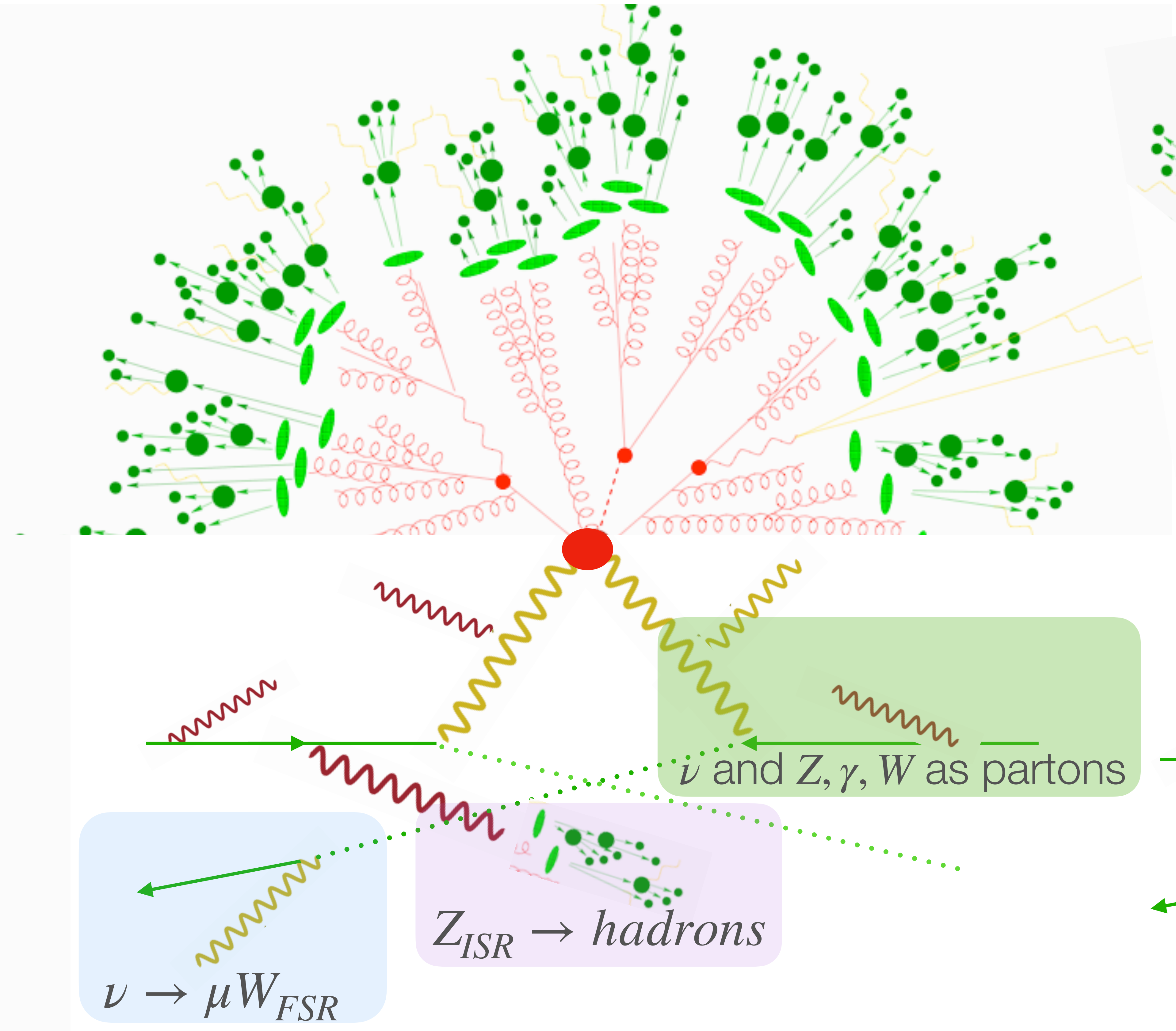
STANDARD MODEL

“FACTORY”

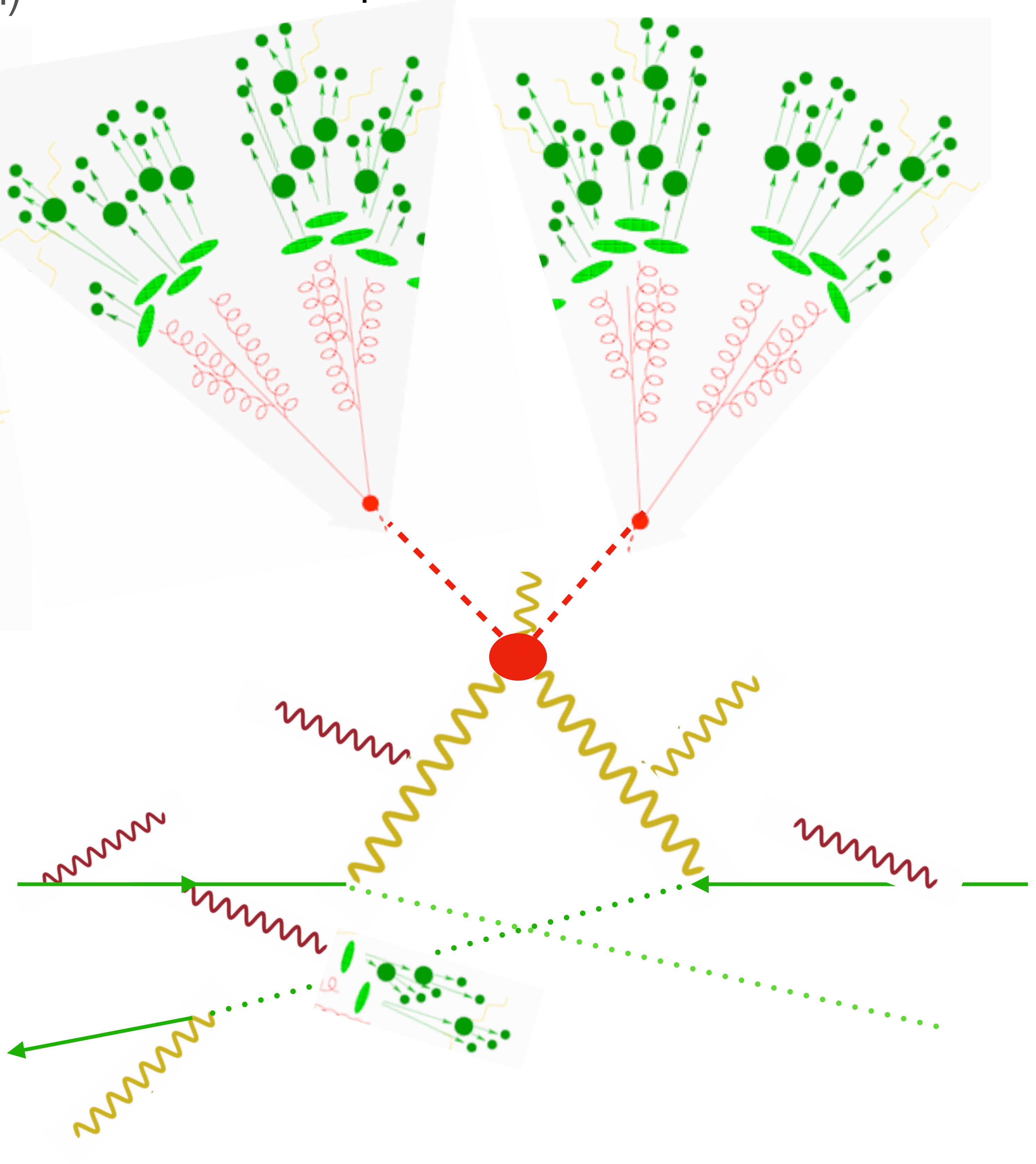
tth production at the LHC (Fully hadronic)



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



HH→4b production at a multi-TeV muC



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

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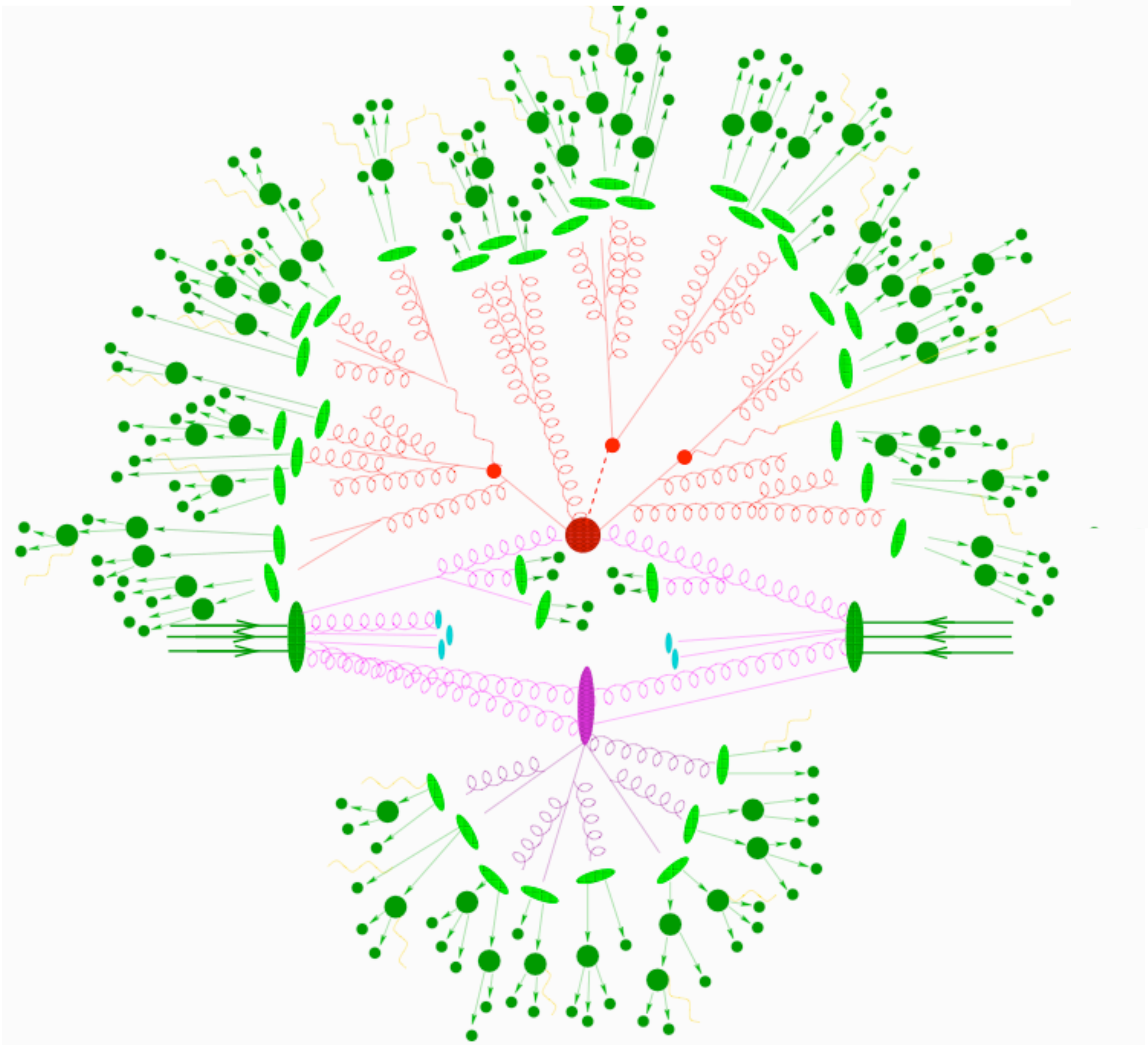

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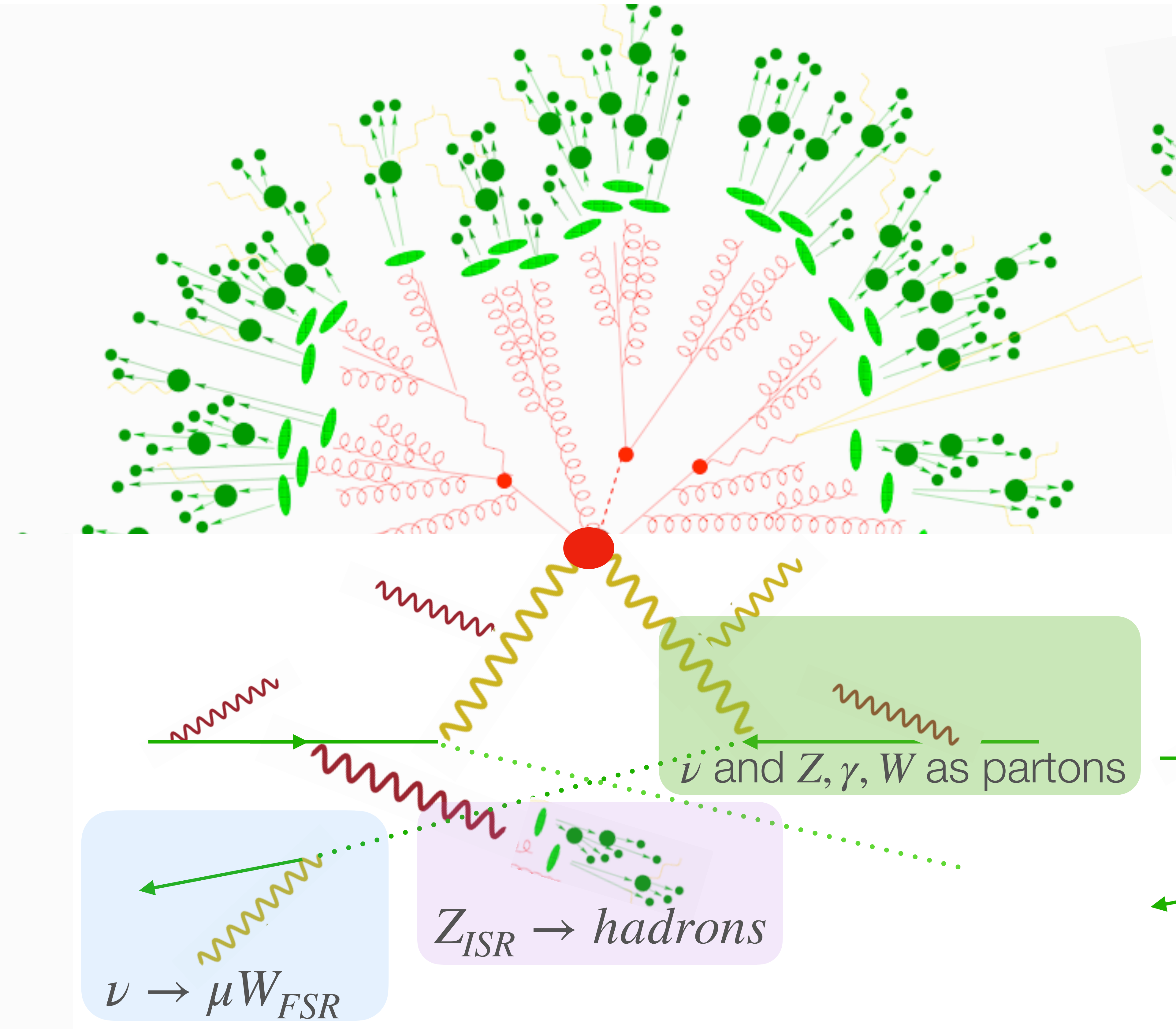
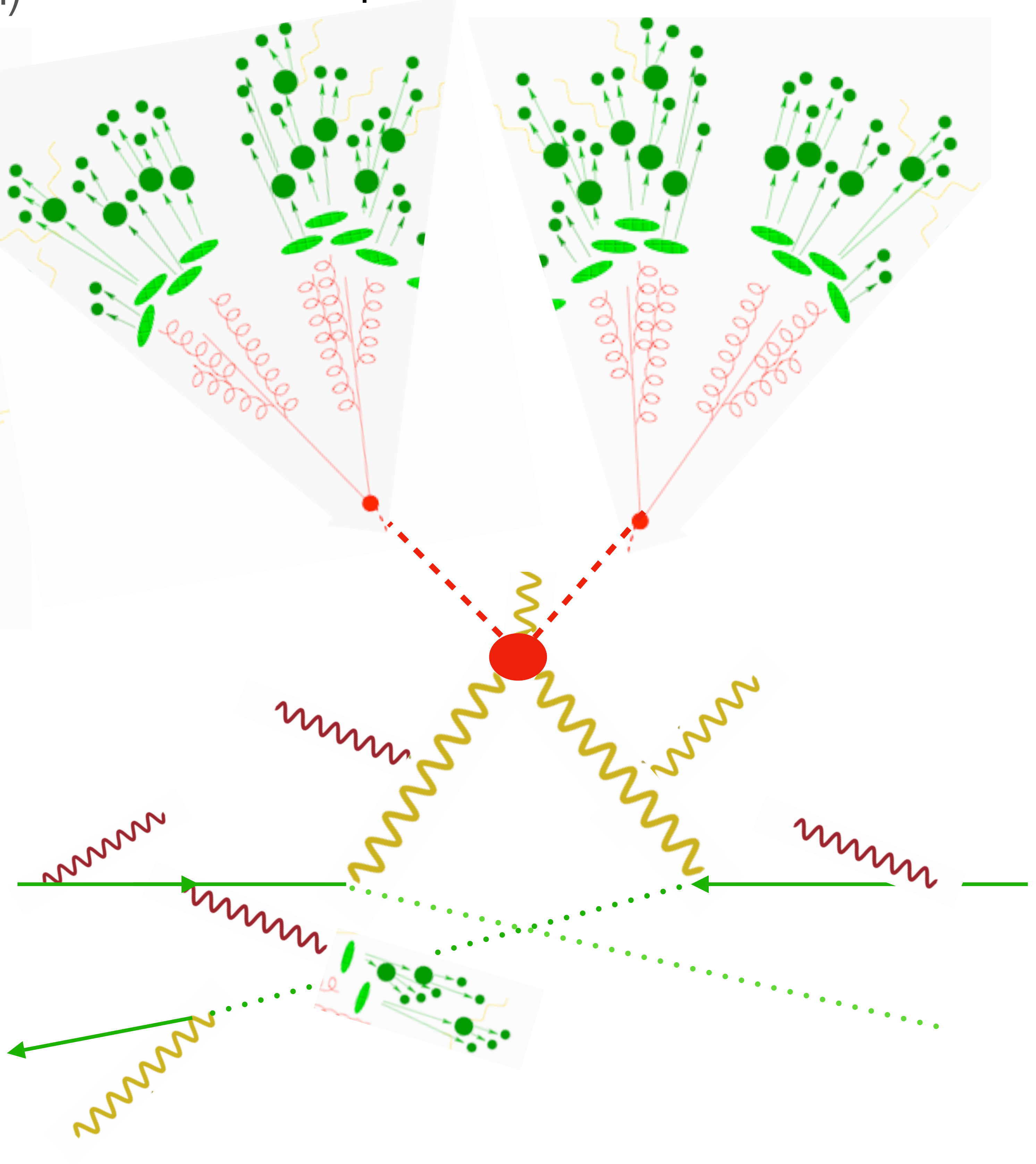


HH→4b production at a multi-TeV muC



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

STANDARD MODEL

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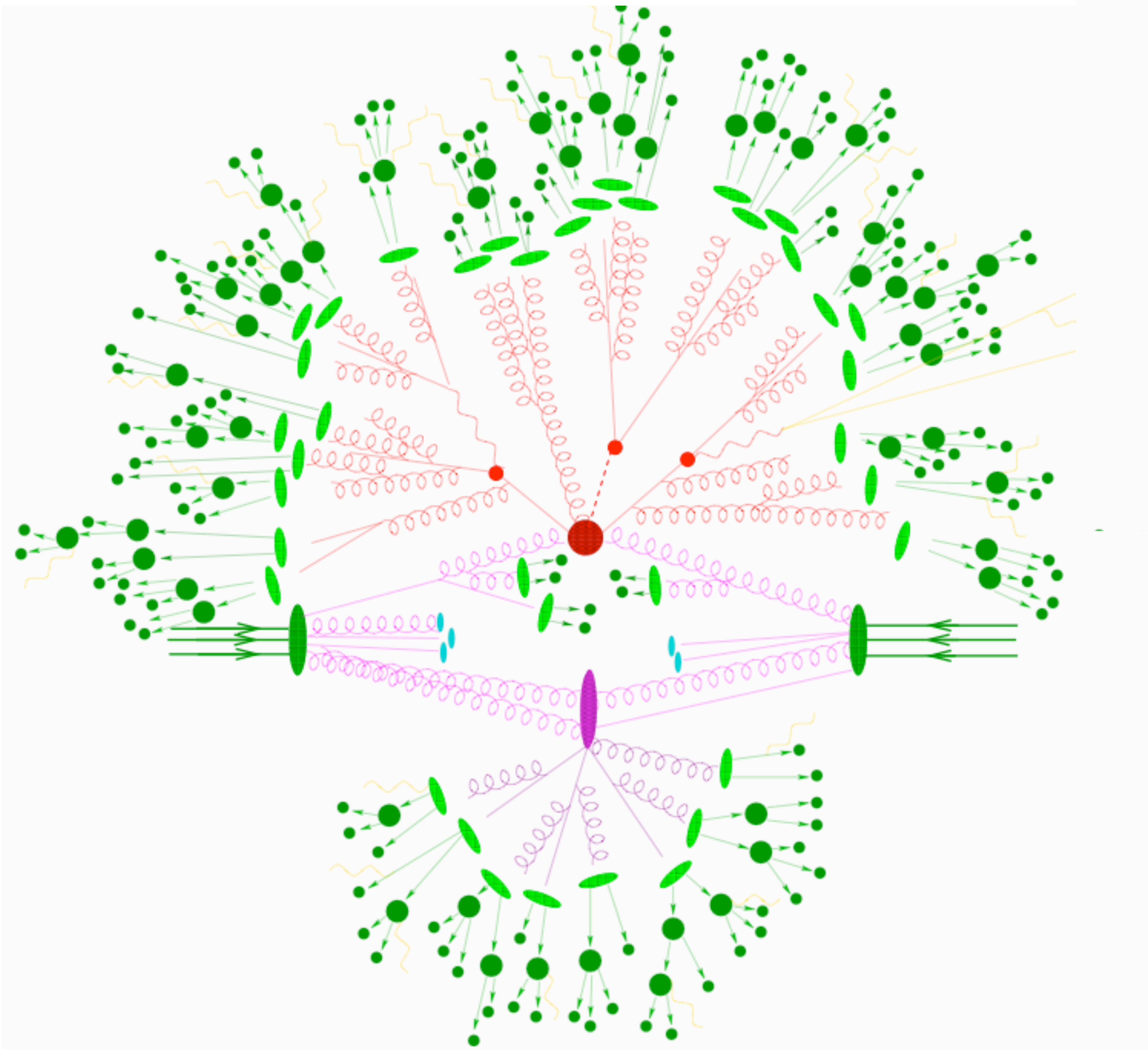

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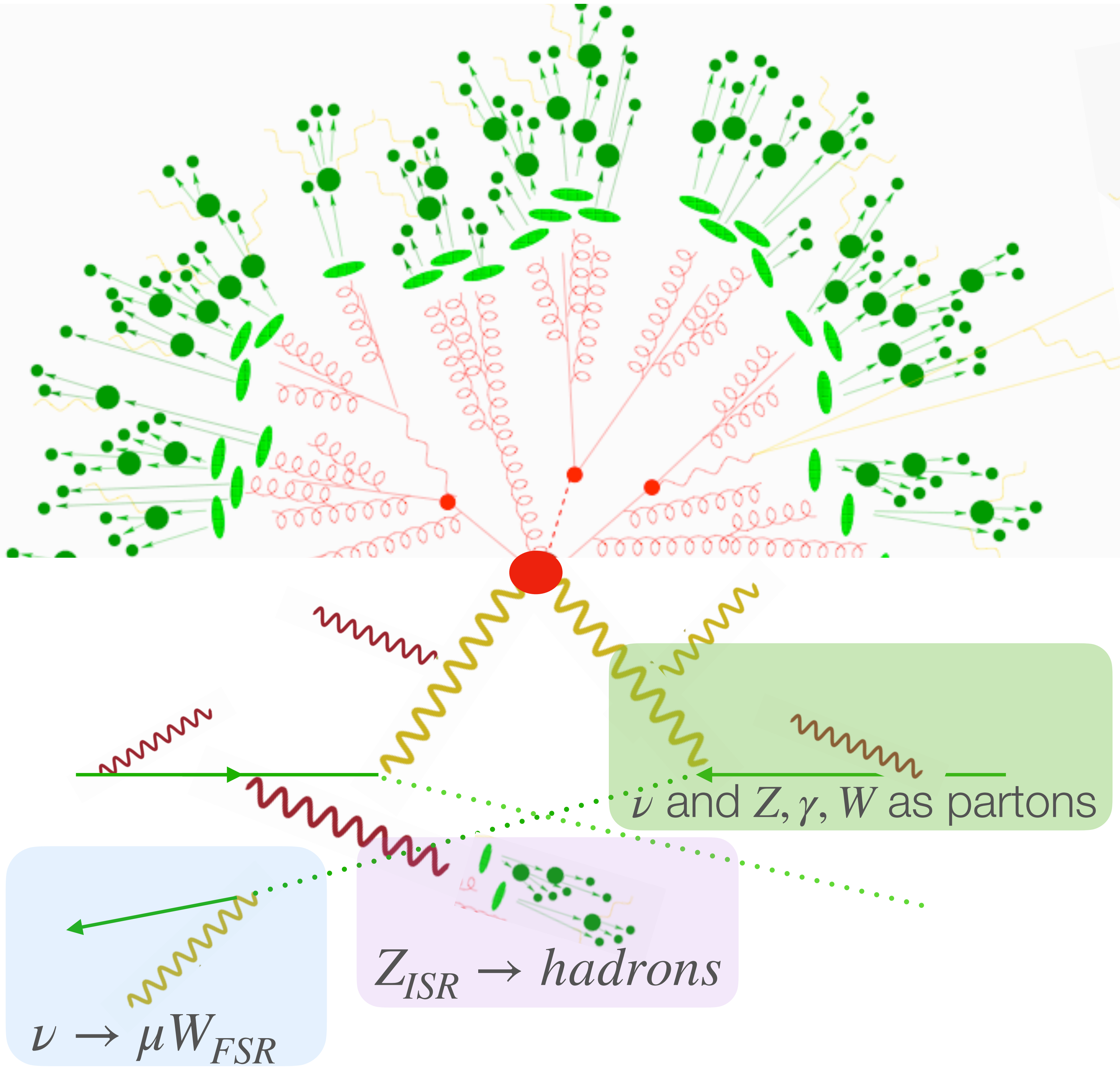
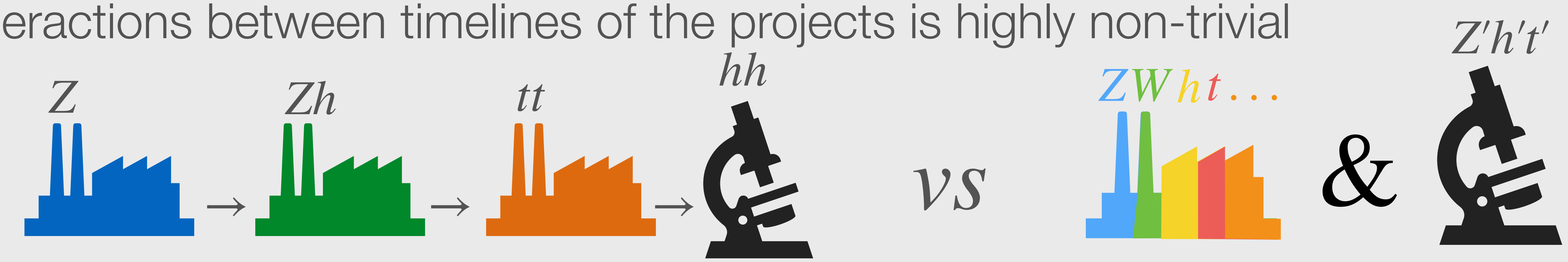


NEW PHENOMENA AND NEW REGIMES IN pQFT

- weak corrections become “ordinary”
- weak “partons”
- large EW logarithms

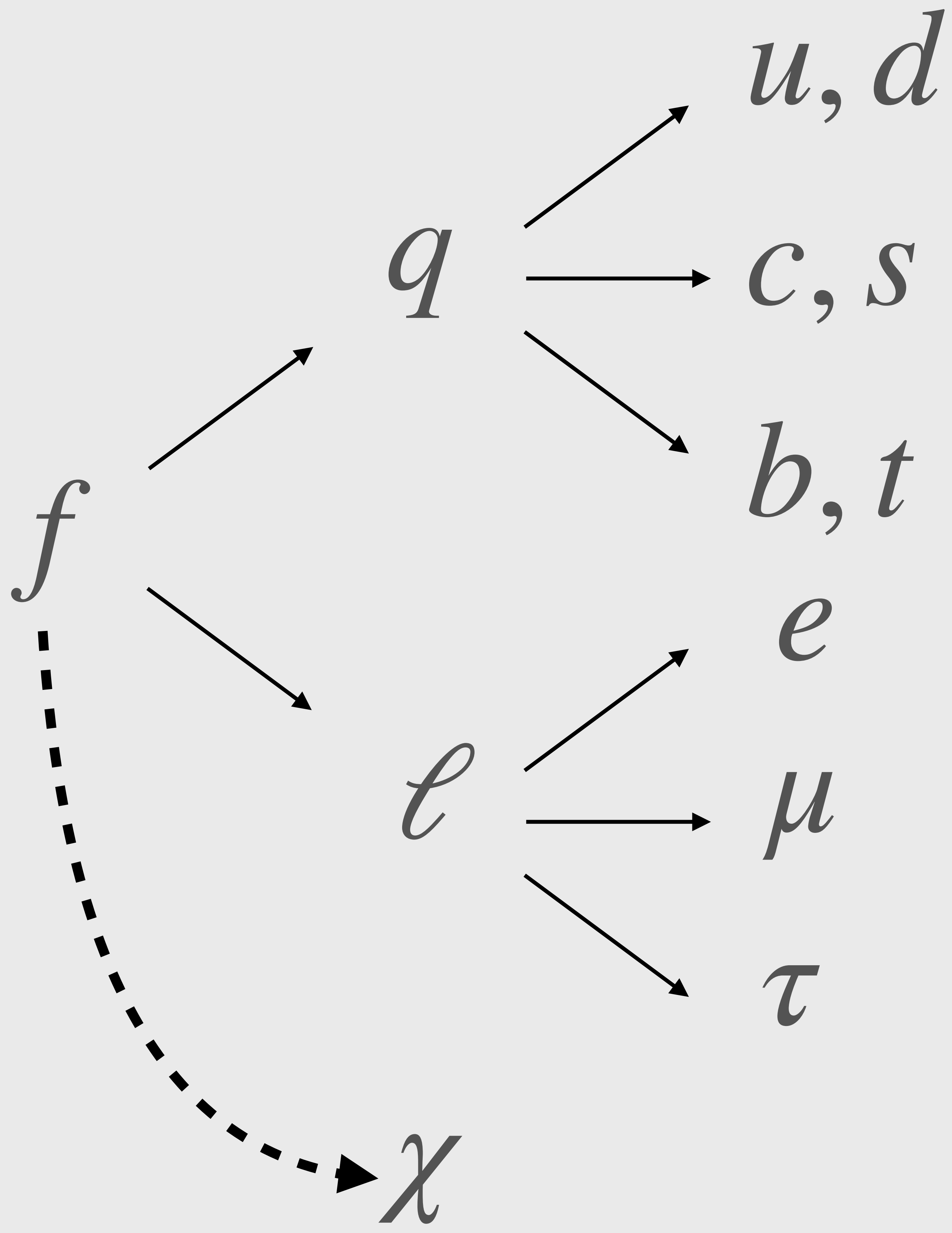
Conclusions

- dedicated e^+e^- factory stages prove to be the “easiest” factories to operate (and to interpret) when it comes to precision measurements ($\delta m_W, \delta m_t, \delta m_Z, \ldots$)
- high-energy machines (pp or $\mu\mu$) can often probe the microscopic phenomena that motivate the precision measurements and often surpass it by far (see t_R compositeness example, EWPT in SMEFT)
- in many instances the $\mu\mu$ collider can play the role of the hh in finishing the job started by ee with the bonus of potentially operating in the same years while also contributing as a “multiplex”-factory)
- well motivated scenarios require inputs from all projects to reach a conclusion ($h \to \phi\phi$ for ϕ driving EWpt, mechanism**s** for neutrino mass, …)
- interactions between timelines of the projects is highly non-trivial
  - 

  - during the long time from now to the next collider results from outside highest-energy colliders might give a strong hint of where BSM might lie (e.g. for WIMPs, flavor, GWs, EDMs)

Thank you!

Flavor



f

q

u, d

c, s

b, t

ℓ

e

μ

τ

χ

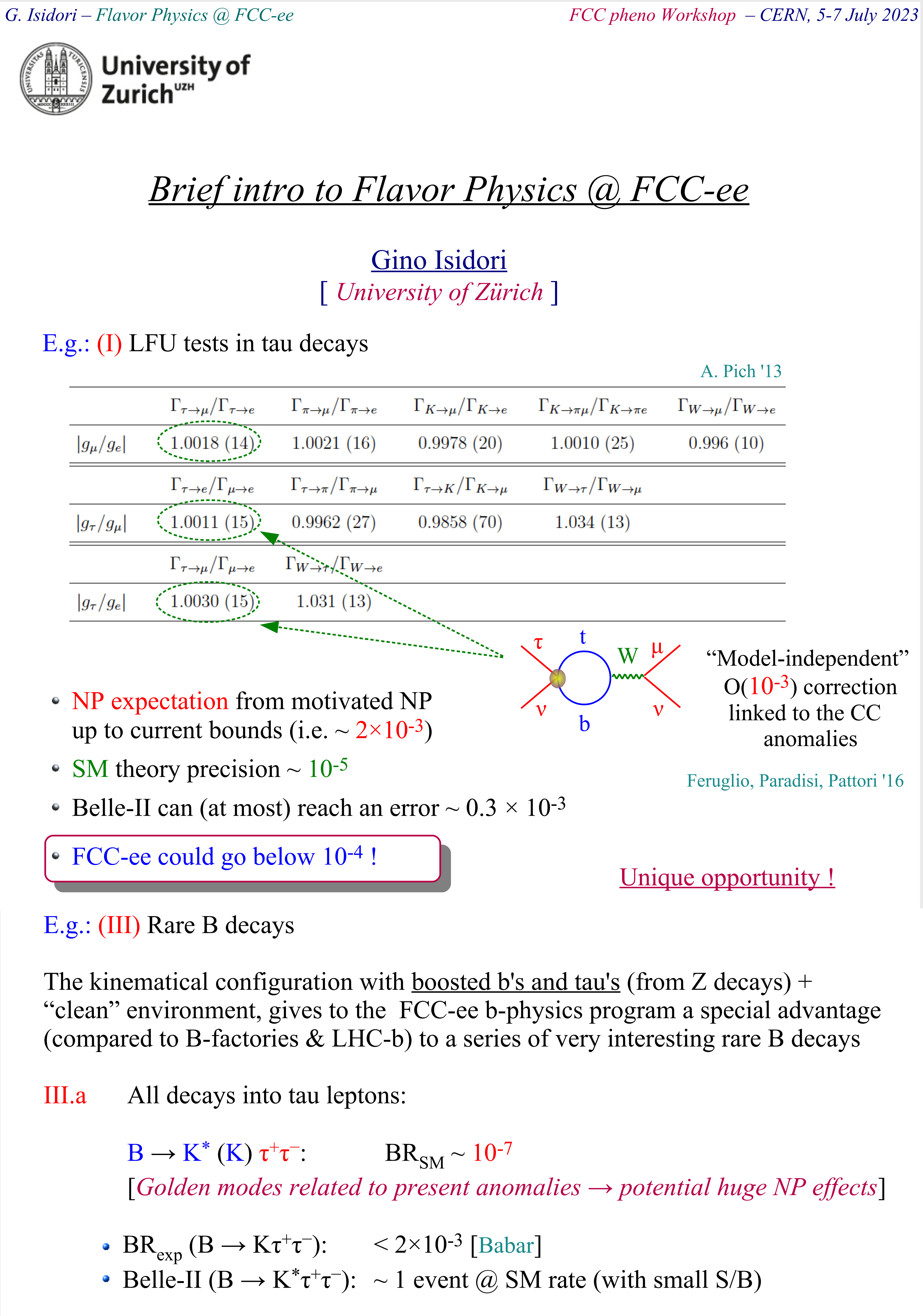
always offers more possibilities

Flavor Physics *FCCee*

Particle production (10^9)	$B^0/\bar{B}^0$	B^+/B^-	$B^0_s/\bar{B}^0_s$	$\Lambda_b/\bar{\Lambda}_b$	$c\bar{c}$	$\tau^+\tau^-$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-ee	1000	1000	250	250	550	170

progress by production of more and more flavored particles

- LFV $h, Z^0 \to \ell_j^+ \ell_k^-$
- $\ell_i \to \ell_k$ (*cLFV*)
- *B* and *D* fragmentation functions measurement ⇒ matching theory development (parton showers, …)



G. Isidori – Flavor Physics @ FCC-ee

FCC pheno Workshop – CERN, 5-7 July 2023

University of Zurich^{UZH}

Brief intro to Flavor Physics @ FCC-ee

Gino Isidori

[*University of Zürich*]

E.g.: (I) LFU tests in tau decays

A. Pich '13

	$\Gamma_{\tau\to\mu}/\Gamma_{\tau\to e}$	$\Gamma_{\pi\to\mu}/\Gamma_{\pi\to e}$	$\Gamma_{K\to\mu}/\Gamma_{K\to e}$	$\Gamma_{K\to\pi\mu}/\Gamma_{K\to\pi e}$	$\Gamma_{W\to\mu}/\Gamma_{W\to e}$
$\lvert g_\mu/g_e\rvert$	1.0018 (14)	1.0021 (16)	0.9978 (20)	1.0010 (25)	0.996 (10)
	$\Gamma_{\tau\to e}/\Gamma_{\mu\to e}$	$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	$\Gamma_{W\to\tau}/\Gamma_{W\to\mu}$	
$\lvert g_\tau/g_\mu\rvert$	1.0011 (15)	0.9962 (27)	0.9858 (70)	1.034 (13)	
	$\Gamma_{\tau\to\mu}/\Gamma_{\mu\to e}$	$\Gamma_{W\to\tau}/\Gamma_{W\to e}$			
$\lvert g_\tau/g_e\rvert$	1.0030 (15)	1.031 (13)			

"Model-independent" O(10^{-3}) correction linked to the CC anomalies

Feruglio, Paradisi, Pattori '16

- NP expectation from motivated NP up to current bounds (i.e. ~ 2×10^{-3})
- SM theory precision ~ 10^{-5}
- Belle-II can (at most) reach an error ~ 0.3×10^{-3}
- FCC-ee could go below 10^{-4} !

Unique opportunity !

E.g.: (III) Rare B decays

The kinematical configuration with boosted b's and tau's (from Z decays) + "clean" environment, gives to the FCC-ee b-physics program a special advantage (compared to B-factories & LHC-b) to a series of very interesting rare B decays

III.a All decays into tau leptons:

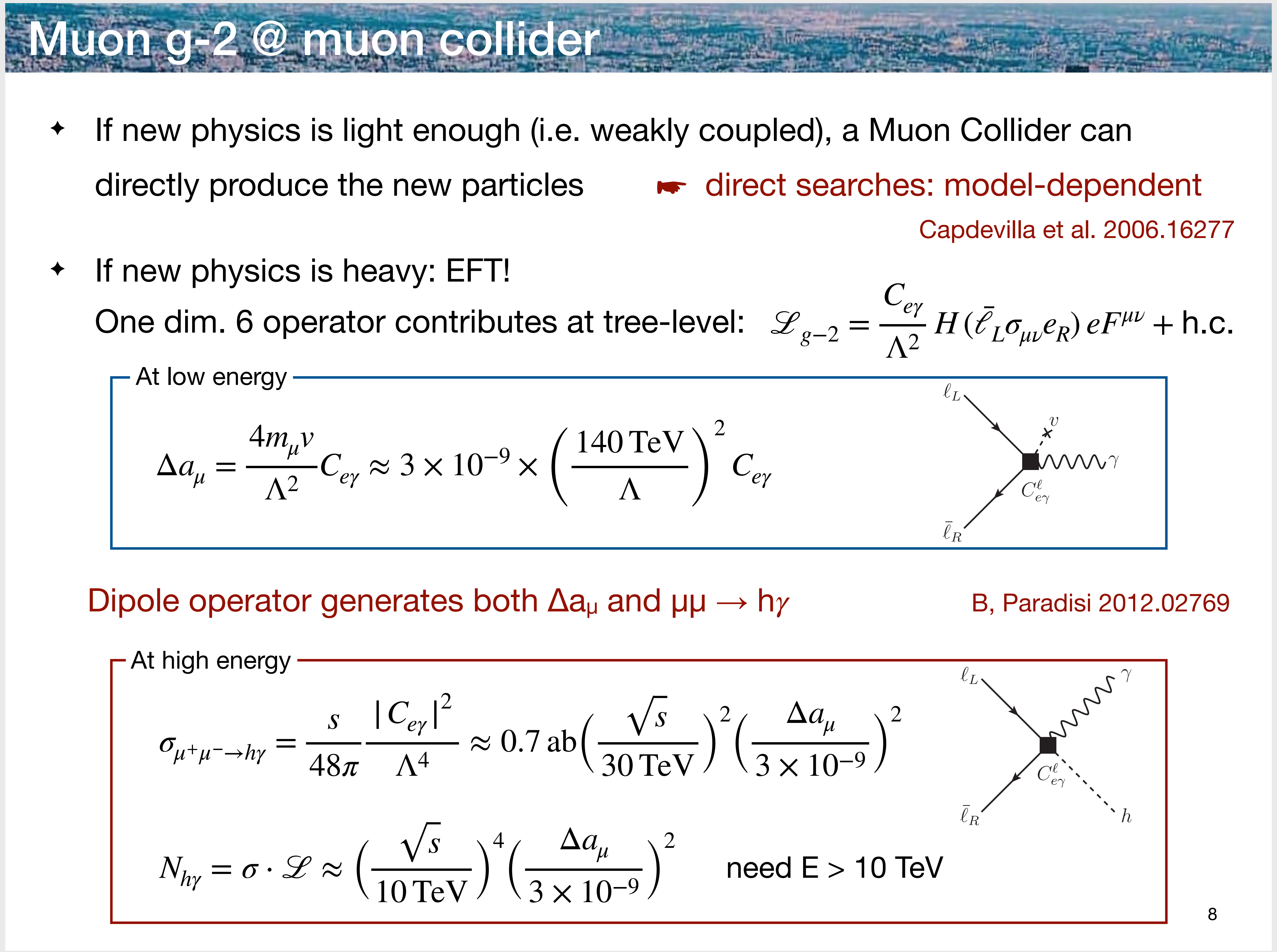
$B \to K^* (K)\, \tau^+\tau^-$: $BR_{SM} \sim 10^{-7}$

[*Golden modes related to present anomalies → potential huge NP effects*]

- BR_{exp} ($B \to K\tau^+\tau^-$): $< 2\times10^{-3}$ [Babar]
- Belle-II ($B \to K^*\tau^+\tau^-$): ~ 1 event @ SM rate (with small S/B)

Flavor Physics At $\mu\mu$

Buttazzo - IMCC annual meeting June 2023



Muon g-2 @ muon collider

- If new physics is light enough (i.e. weakly coupled), a Muon Collider can directly produce the new particles ☛ direct searches: model-dependent

Capdevilla et al. 2006.16277

- If new physics is heavy: EFT!

One dim. 6 operator contributes at tree-level: $\mathcal{L}_{g-2} = \frac{C_{e\gamma}}{\Lambda^2} H(\bar{\ell}_L \sigma_{\mu\nu} e_R)\, eF^{\mu\nu}$ + h.c.

At low energy

$$\Delta a_\mu = \frac{4 m_\mu v}{\Lambda^2} C_{e\gamma} \approx 3 \times 10^{-9} \times \left(\frac{140\text{ TeV}}{\Lambda}\right)^2 C_{e\gamma}$$

Dipole operator generates both Δa_μ and $\mu\mu \to h\gamma$

B, Paradisi 2012.02769

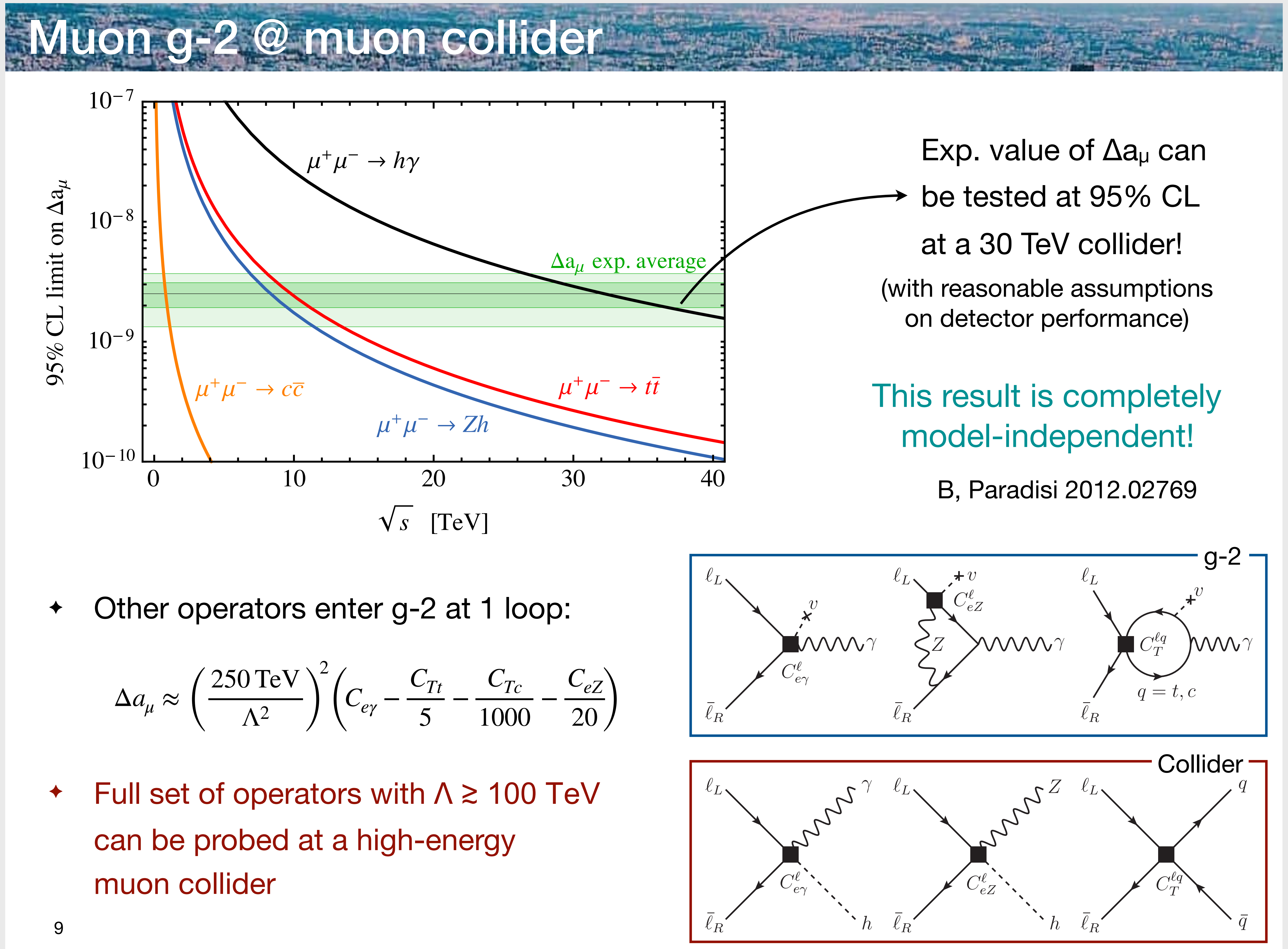
At high energy

$$\sigma_{\mu^+\mu^- \to h\gamma} = \frac{s}{48\pi} \frac{|C_{e\gamma}|^2}{\Lambda^4} \approx 0.7\text{ ab} \left(\frac{\sqrt{s}}{30\text{ TeV}}\right)^2 \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right)^2$$

$$N_{h\gamma} = \sigma \cdot \mathcal{L} \approx \left(\frac{\sqrt{s}}{10\text{ TeV}}\right)^4 \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right)^2$$

need E > 10 TeV

8



Muon g-2 @ muon collider

Exp. value of Δa_μ can be tested at 95% CL at a 30 TeV collider!

(with reasonable assumptions on detector performance)

This result is completely model-independent!

B, Paradisi 2012.02769

- Other operators enter g-2 at 1 loop:

$$\Delta a_\mu \approx \left(\frac{250\text{ TeV}}{\Lambda^2}\right)^2 \left(C_{e\gamma} - \frac{C_{Tt}}{5} - \frac{C_{Tc}}{1000} - \frac{C_{eZ}}{20}\right)$$

- Full set of operators with $\Lambda \gtrsim 100$ TeV can be probed at a high-energy muon collider

9

Flavor Physics At $\mu\mu$

Buttazzo - IMCC annua

Muon g-2 @ muon c

- If new physics is light en
  directly produce the new
- If new physics is heavy:
  One dim. 6 operator con

At low energy

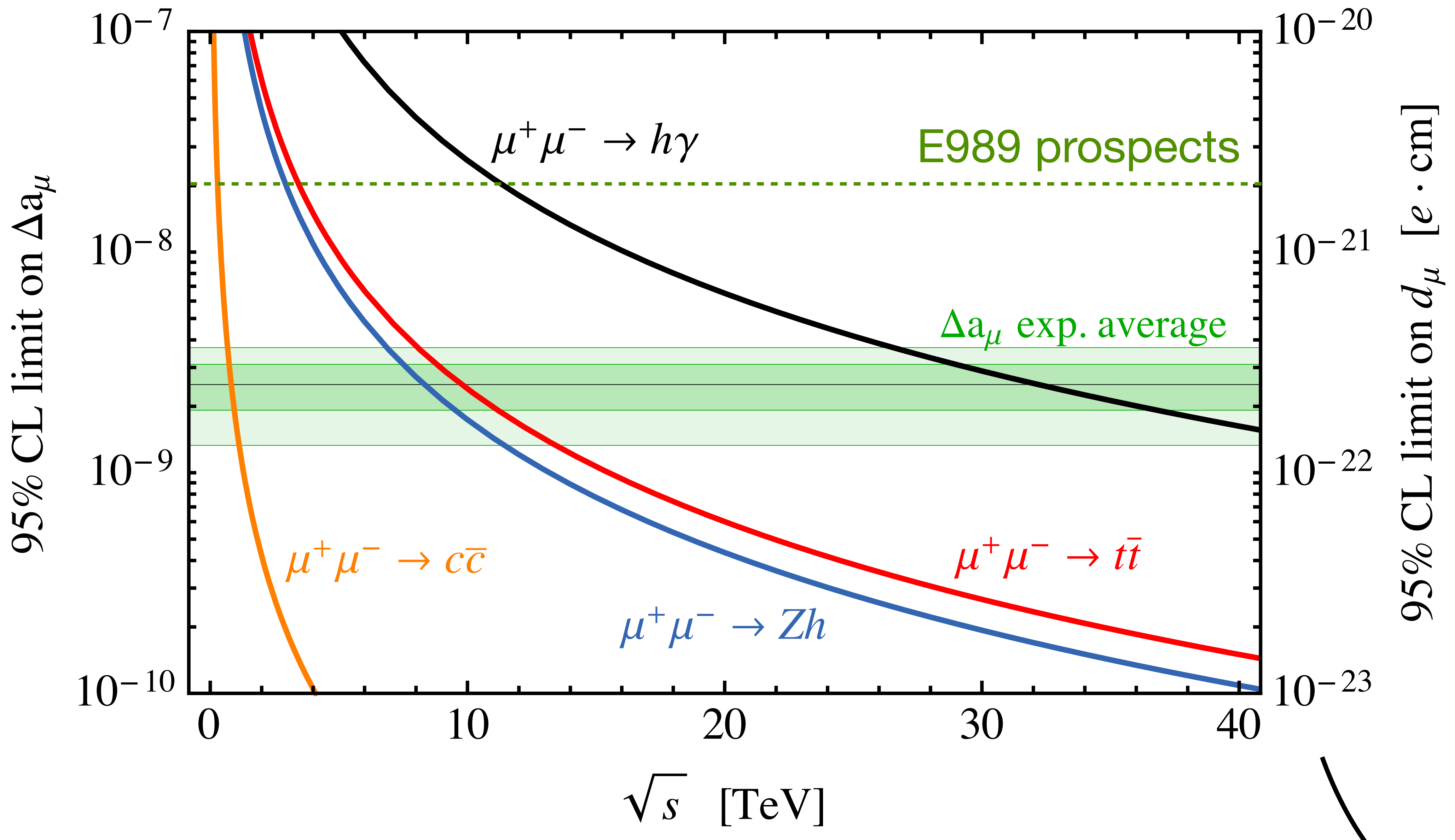
$$\Delta a_\mu = \frac{4m_\mu v}{\Lambda^2} C_{e\gamma} \approx 3 \times$$

Dipole operator generate

At high energy

$$\sigma_{\mu^+\mu^-\to h\gamma} = \frac{s}{48\pi}\frac{|C_{e\gamma}|^2}{\Lambda^4}$$

$$N_{h\gamma} = \sigma \cdot \mathscr{L} \approx \Big(\frac{\sqrt{s}}{10\,\mathrm{Te}}$$



Muon EDM for free!

$$\Delta a_\mu = \frac{4 v m_\mu \mathrm{Re}(C_{e\gamma})}{\Lambda^2}$$

$$d_\mu = \frac{2v\,\mathrm{Im}(C_{e\gamma})}{\Lambda^2} = \frac{\Delta a_\mu}{2m_\mu} \tan\phi_\mu\, e$$

Collider constrains $|C_{e\gamma}|^2$

2102.08838

$\Rightarrow$ $d_\mu \lesssim 10^{-22}\, e \cdot \mathrm{cm}$ (comparable with future $d_\mu \lesssim 0.6 \cdot 10^{-22}\, e \cdot cm$)

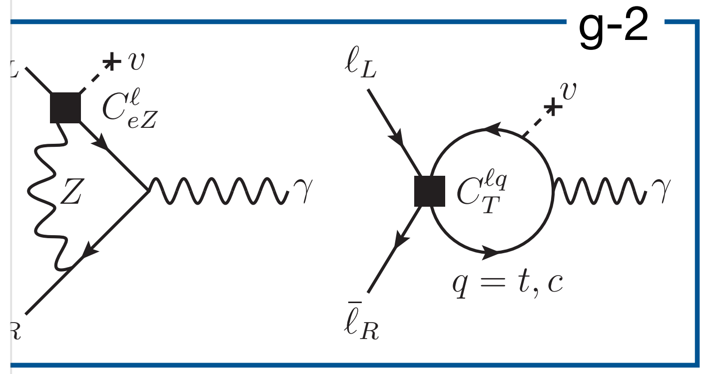
3 o.o.m. stronger than present bound! @ $10^{-19}\, e \cdot cm$

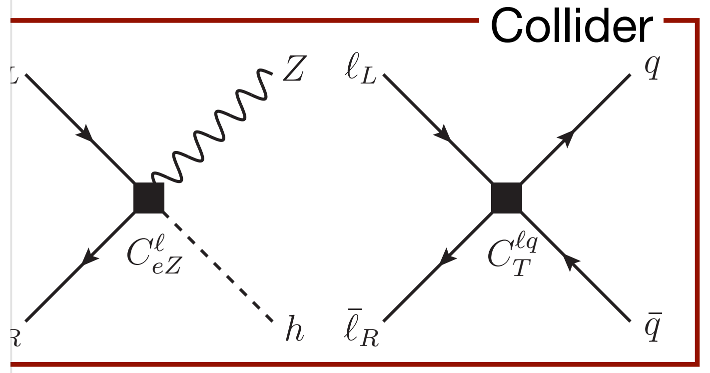
Exp. value of Δa_μ can be tested at 95% CL at a 30 TeV collider!

ith reasonable assumptions on detector performance)

is result is completely model-independent!

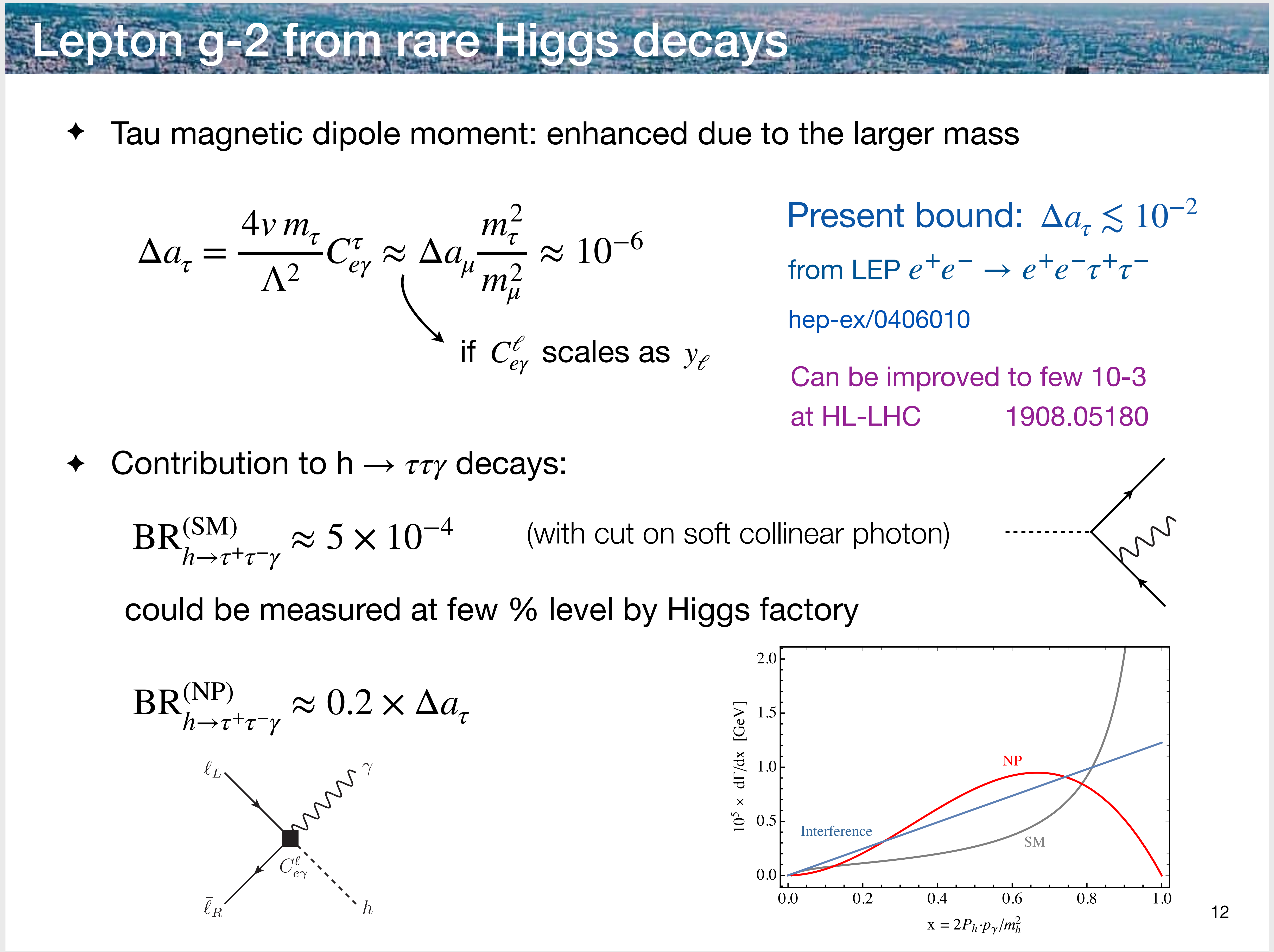
B, Paradisi 2012.02769





Flavor Physics At $\mu\mu$

Buttazzo - IMCC annual meeting June 2023



Lepton g-2 from rare Higgs decays

- Tau magnetic dipole moment: enhanced due to the larger mass

$$\Delta a_\tau = \frac{4v\, m_\tau}{\Lambda^2} C^\tau_{e\gamma} \approx \Delta a_\mu \frac{m_\tau^2}{m_\mu^2} \approx 10^{-6}$$

if $C^\ell_{e\gamma}$ scales as y_ℓ

Present bound: $\Delta a_\tau \lesssim 10^{-2}$

from LEP $e^+e^- \to e^+e^-\tau^+\tau^-$

hep-ex/0406010

Can be improved to few 10-3 at HL-LHC 1908.05180

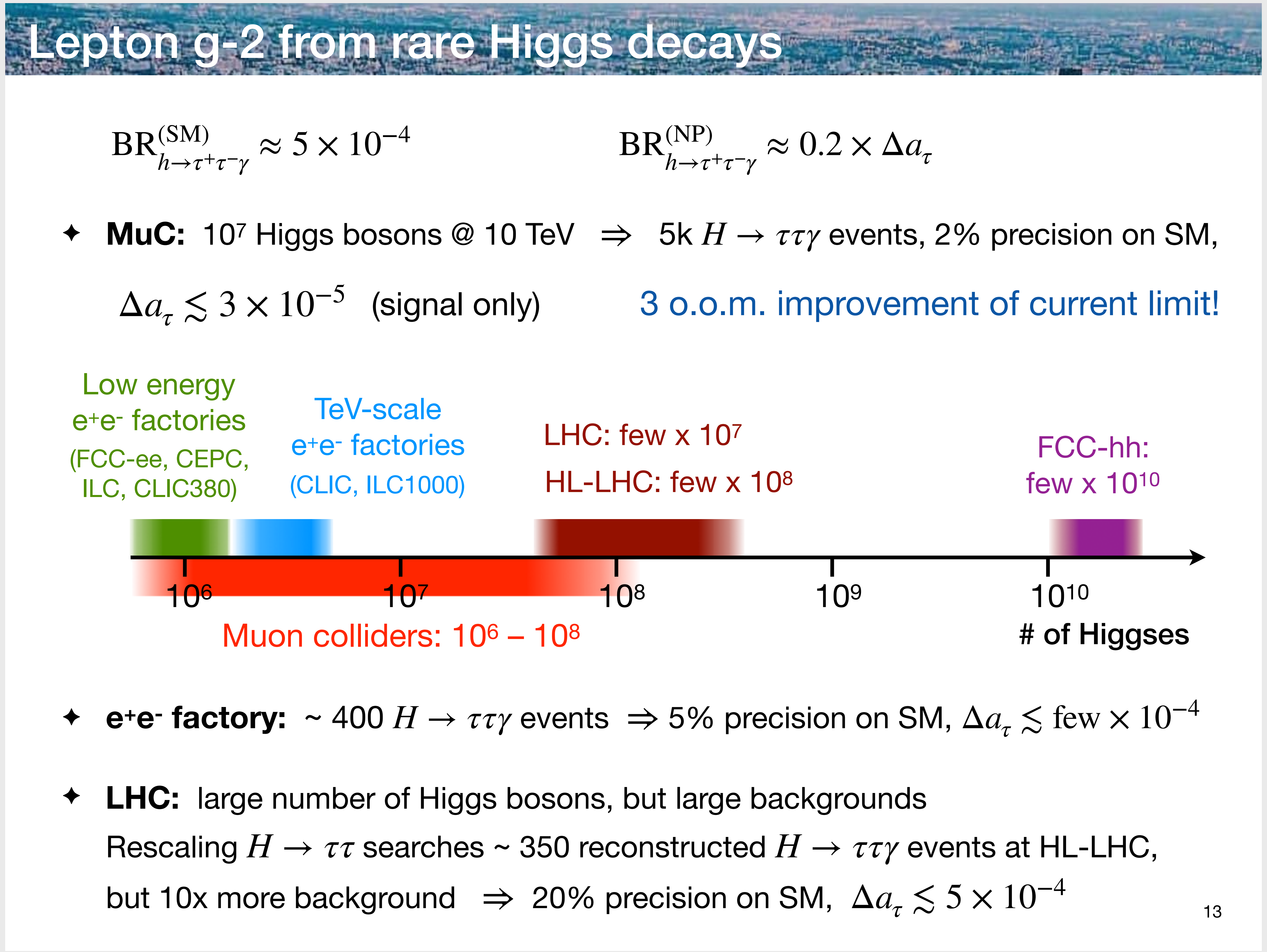
- Contribution to h → $\tau\tau\gamma$ decays:

$$\mathrm{BR}^{(\mathrm{SM})}_{h\to\tau^+\tau^-\gamma} \approx 5\times 10^{-4}$$ (with cut on soft collinear photon)

could be measured at few % level by Higgs factory

$$\mathrm{BR}^{(\mathrm{NP})}_{h\to\tau^+\tau^-\gamma} \approx 0.2\times \Delta a_\tau$$

12



Lepton g-2 from rare Higgs decays

$$\mathrm{BR}^{(\mathrm{SM})}_{h\to\tau^+\tau^-\gamma} \approx 5\times 10^{-4} \qquad \mathrm{BR}^{(\mathrm{NP})}_{h\to\tau^+\tau^-\gamma} \approx 0.2\times \Delta a_\tau$$

- **MuC:** 10^7 Higgs bosons @ 10 TeV ⇒ 5k $H\to\tau\tau\gamma$ events, 2% precision on SM,

  $\Delta a_\tau \lesssim 3\times 10^{-5}$ (signal only) 3 o.o.m. improvement of current limit!

- **e^+e^- factory:** ~ 400 $H\to\tau\tau\gamma$ events ⇒ 5% precision on SM, $\Delta a_\tau \lesssim$ few $\times 10^{-4}$
- **LHC:** large number of Higgs bosons, but large backgrounds

  Rescaling $H\to\tau\tau$ searches ~ 350 reconstructed $H\to\tau\tau\gamma$ events at HL-LHC, but 10x more background ⇒ 20% precision on SM, $\Delta a_\tau \lesssim 5\times 10^{-4}$

13

Flavor Physics At $\mu\mu$

Buttazzo - IMCC annua

Lepton g-2 from r

- Tau magnetic dipole

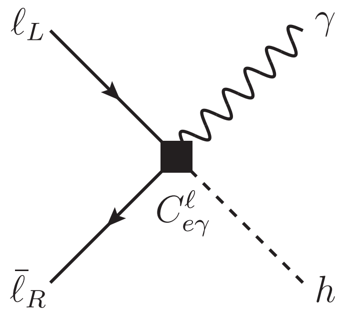
$$\Delta a_\tau = \frac{4v\, m_\tau}{\Lambda^2} C^\tau_{e\gamma} \approx$$

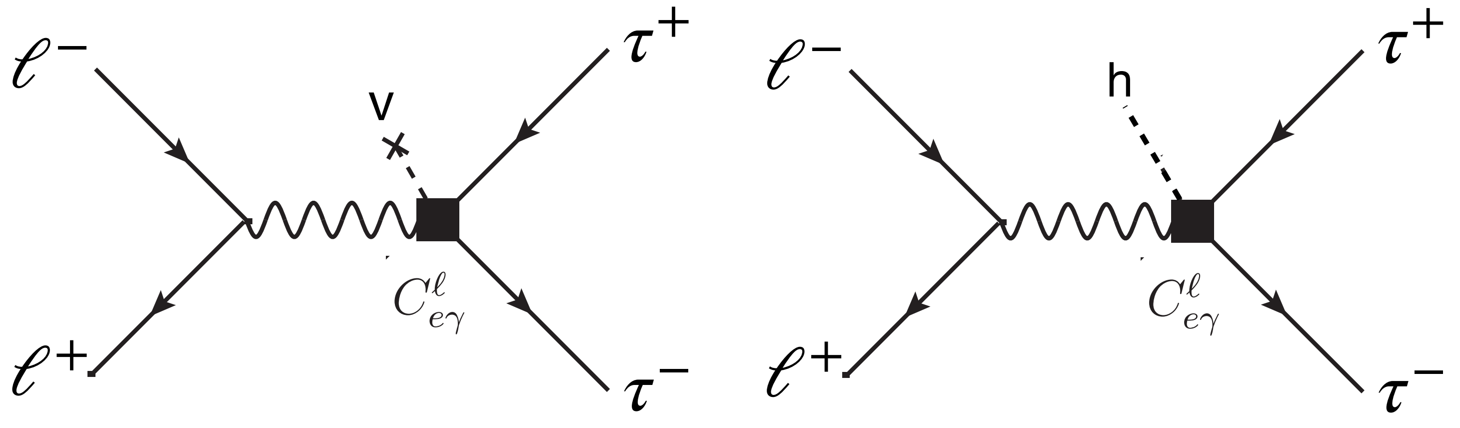
- Contribution to h →

$\mathrm{BR}^{(\mathrm{SM})}_{h\to\tau^+\tau^-\gamma} \approx 5\times 1$

could be measured

$\mathrm{BR}^{(\mathrm{NP})}_{h\to\tau^+\tau^-\gamma} \approx 0.2\times$



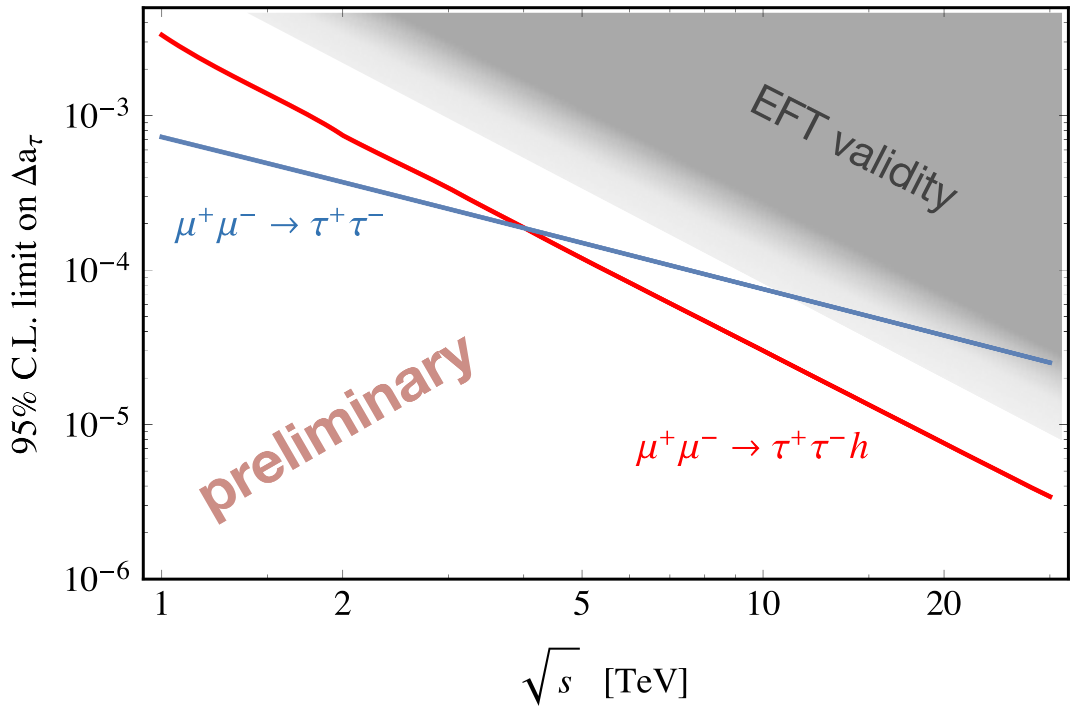


work in progress with Levati, Paradisi, Maltoni, Wang

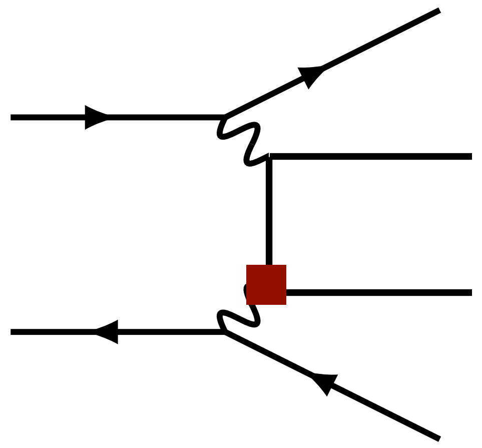
- Main background from μμ → Zγ

(where Z is mistaken for H)

Could probe Δa_τ ~ 10^{-5} @ 10 TeV



also a bound on tau EDM!



$$\sim \left(\frac{C_{e\gamma}}{\Lambda^2}\right)^2 + \mathcal{O}\left(m_\tau^2/\Lambda^2\right)$$

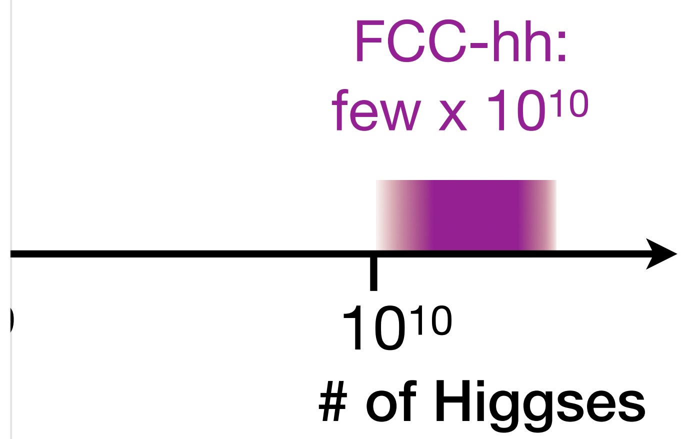
- Caveat: VBF is a “soft” process, EFT mainly affects high-mass region

Still, could probe Δa_τ ~ few 10^{-5}

$\times\, \Delta a_\tau$

ents, 2% precision on SM,

ovement of current limit!



on SM, $\Delta a_\tau \lesssim \text{few}\times 10^{-4}$

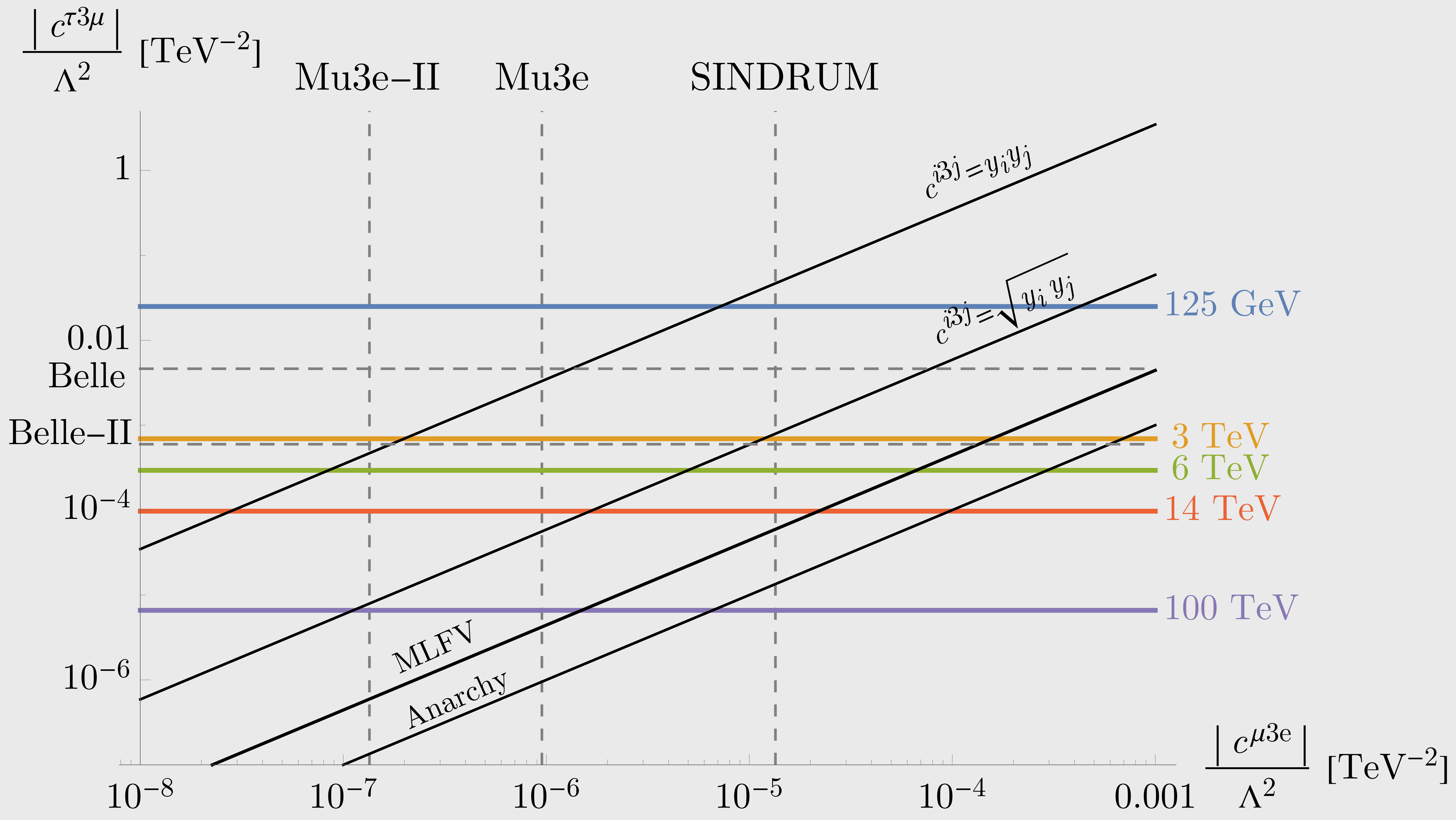
unds

$\tau\tau\gamma$ events at HL-LHC,

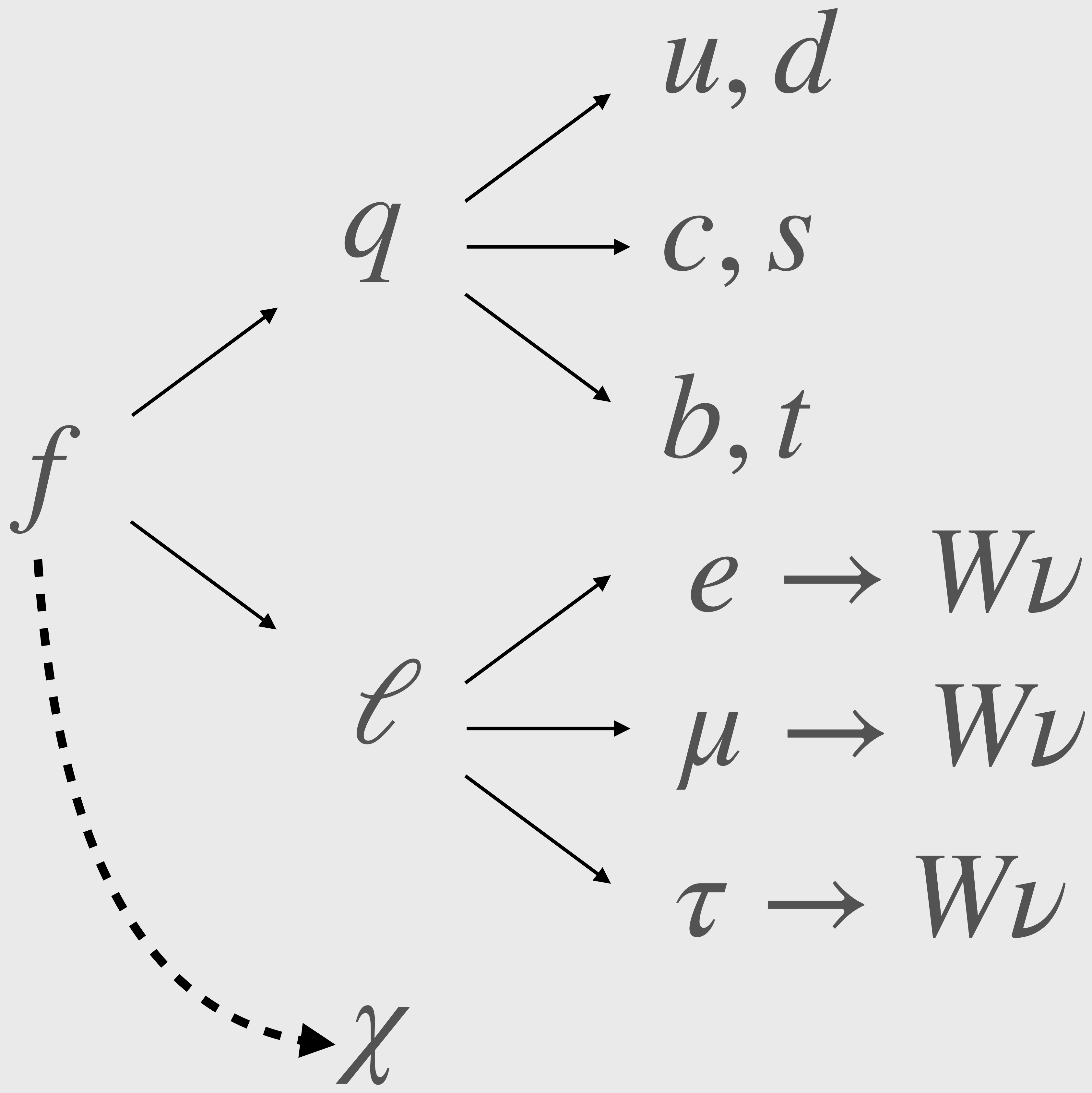
$\Delta a_\tau \lesssim 5\times 10^{-4}$

Flavor Physics At $\mu\mu$

$$\tau \to 3\mu \;\Leftrightarrow\; \mu\mu \to \mu\tau$$

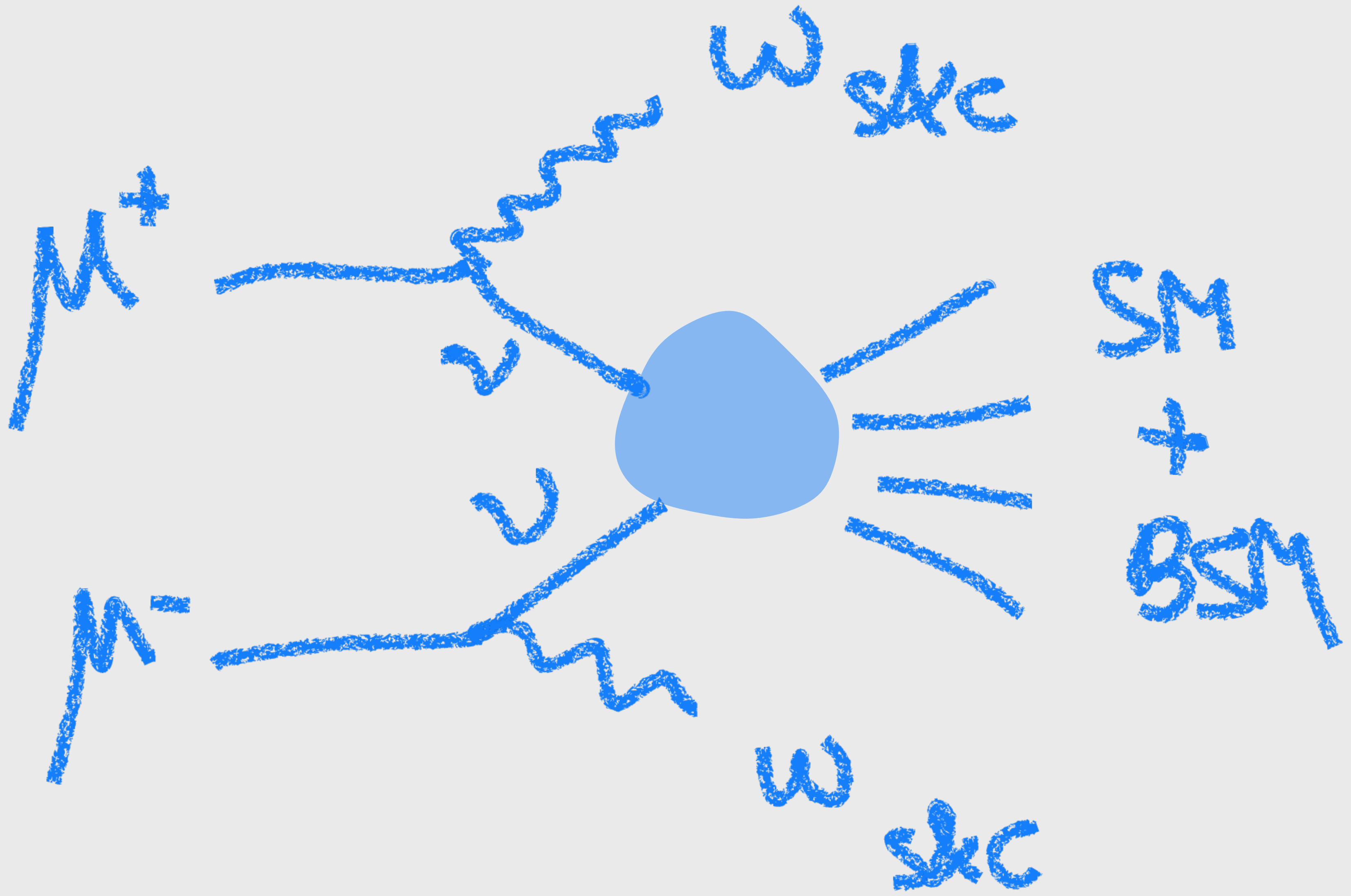


Flavor



always offers more possibilities

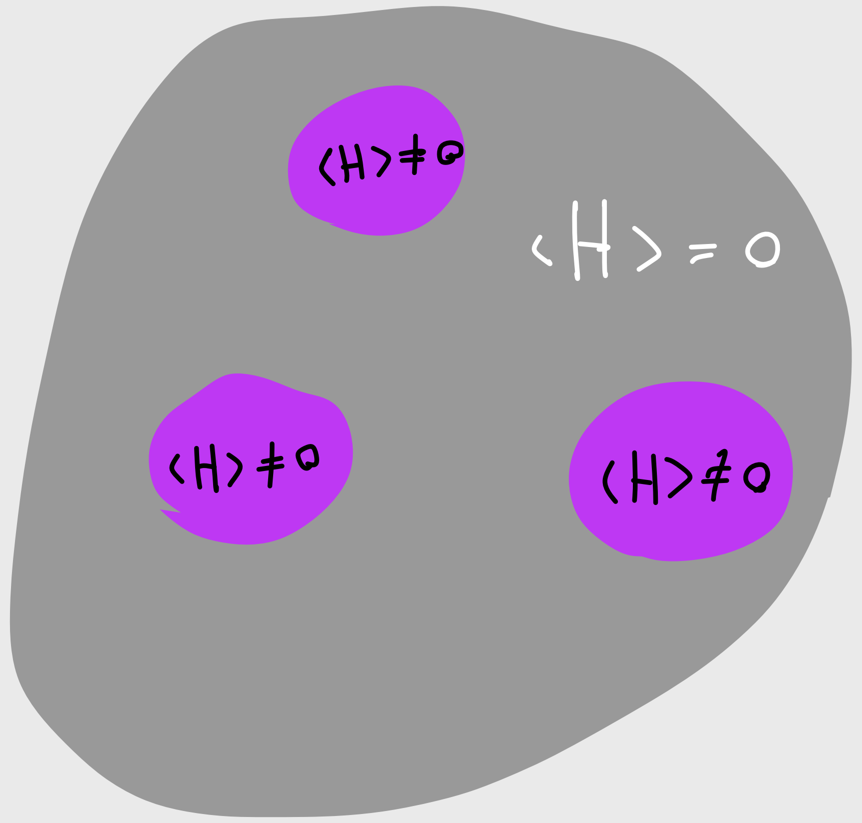
Flavor Physics At “$\nu\nu$”



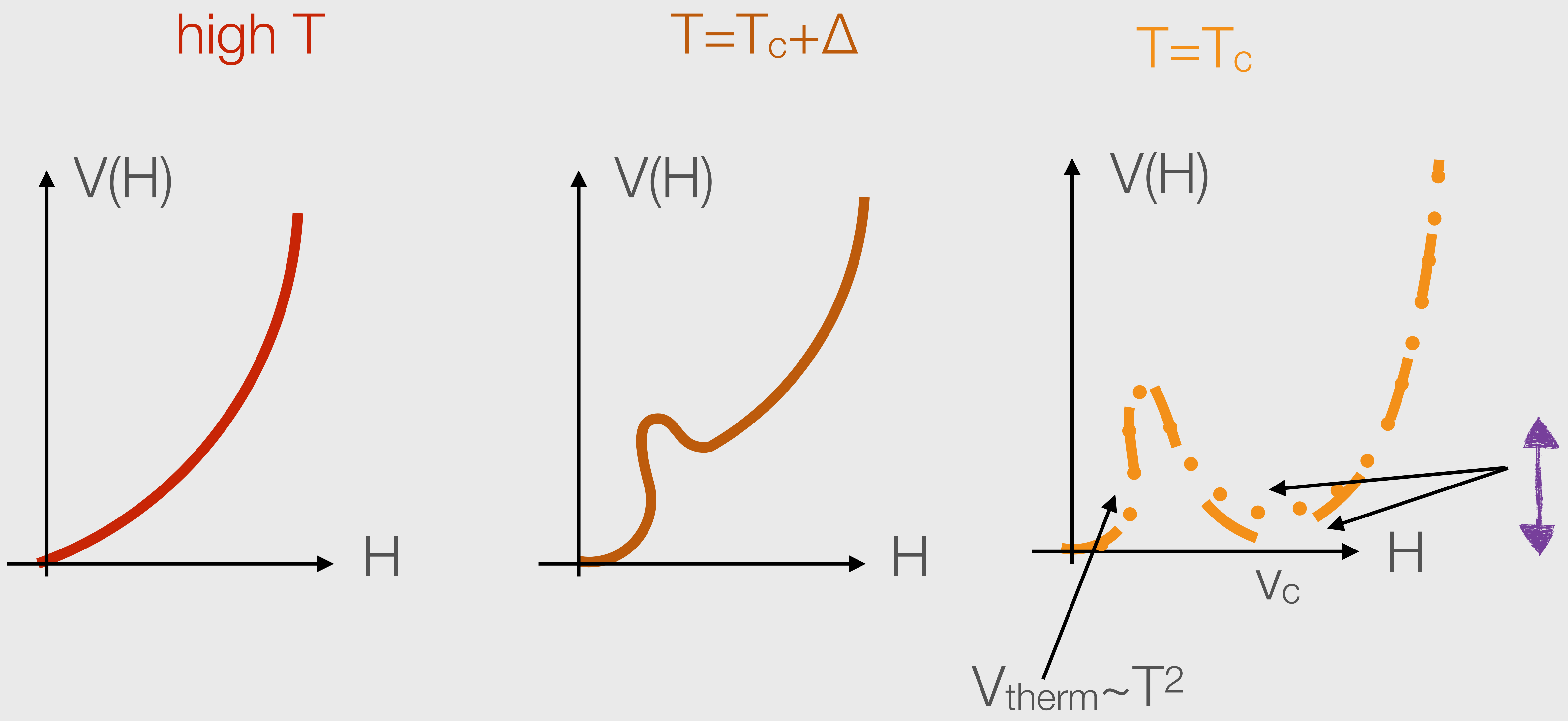
flashing concrete results for

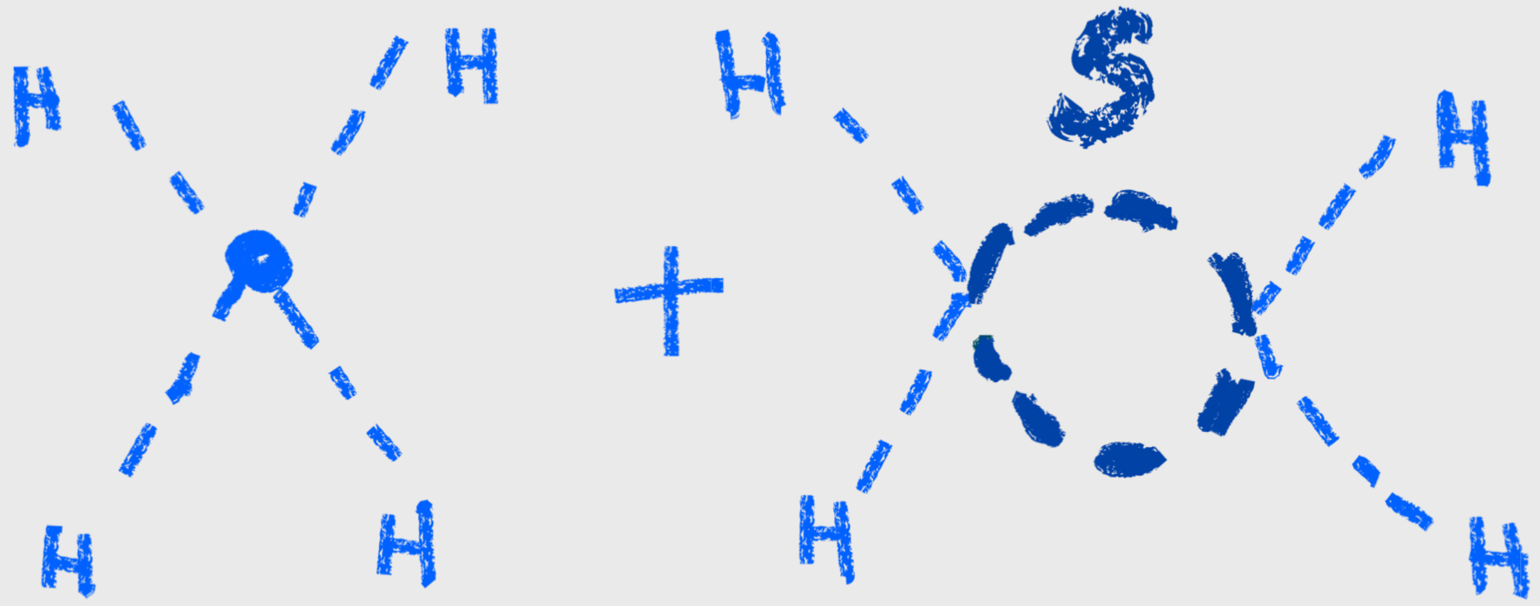
Electroweak phase transition

Electroweak phase transition



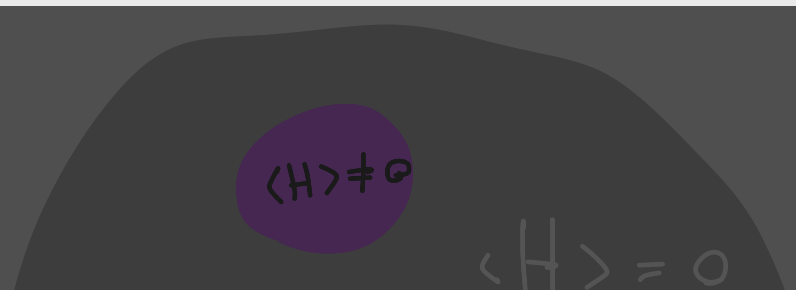
- Modifications of the Higgs potential ⇒ Out of Equilibrium transition from one vacuum to a new energetically favorable one





Singlet loop makes
V(0,v) deeper

Electroweak phase transition



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

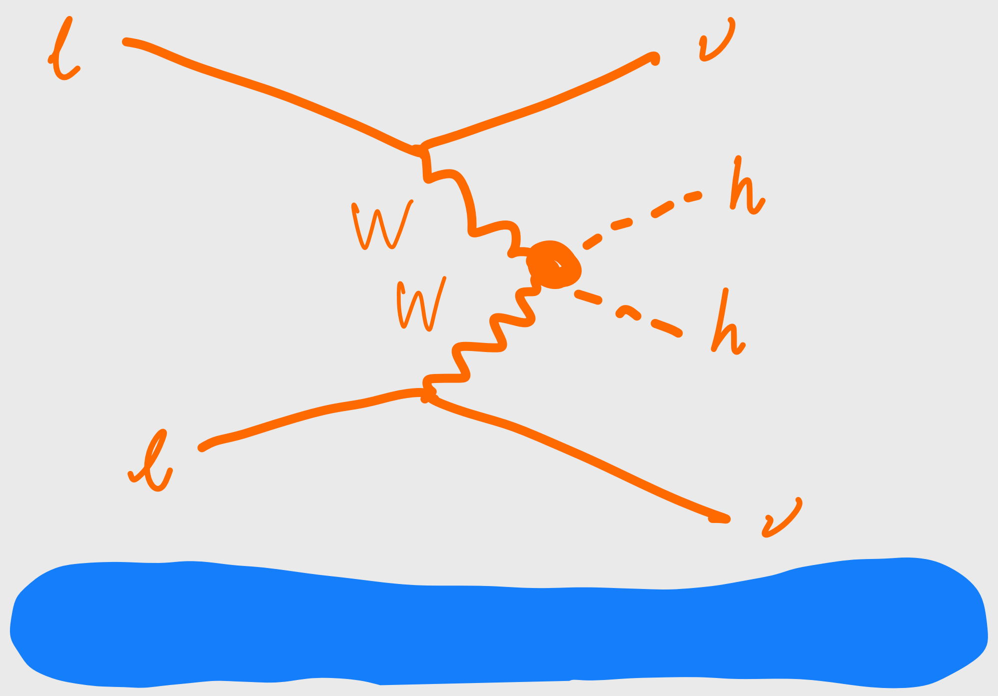
$V_{\text{therm}} \sim T^2$

V(0,v) deeper

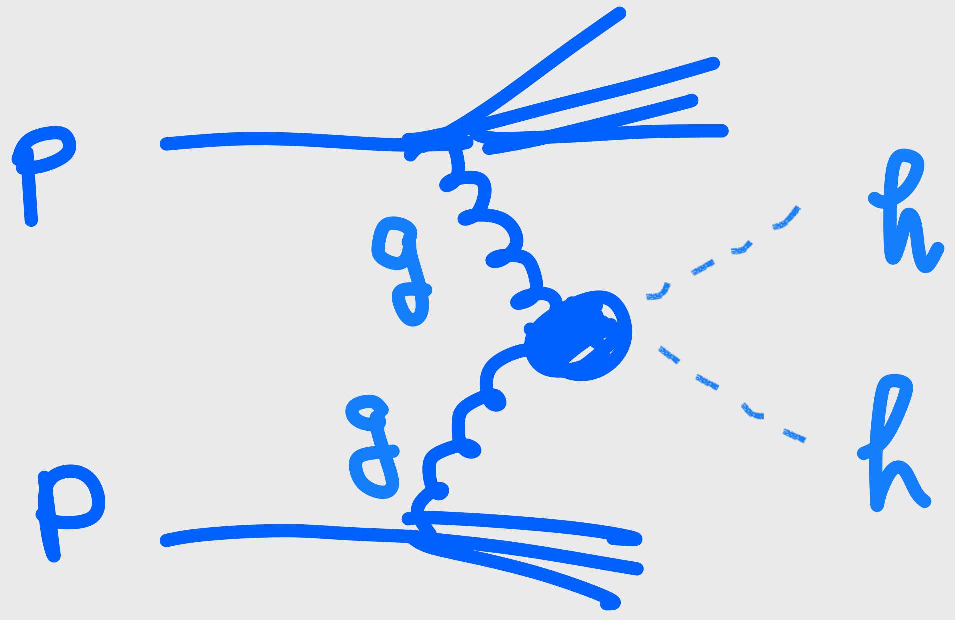
pp or $\ell^+\ell^- \to hh$

W BOSON **COLLIDER**

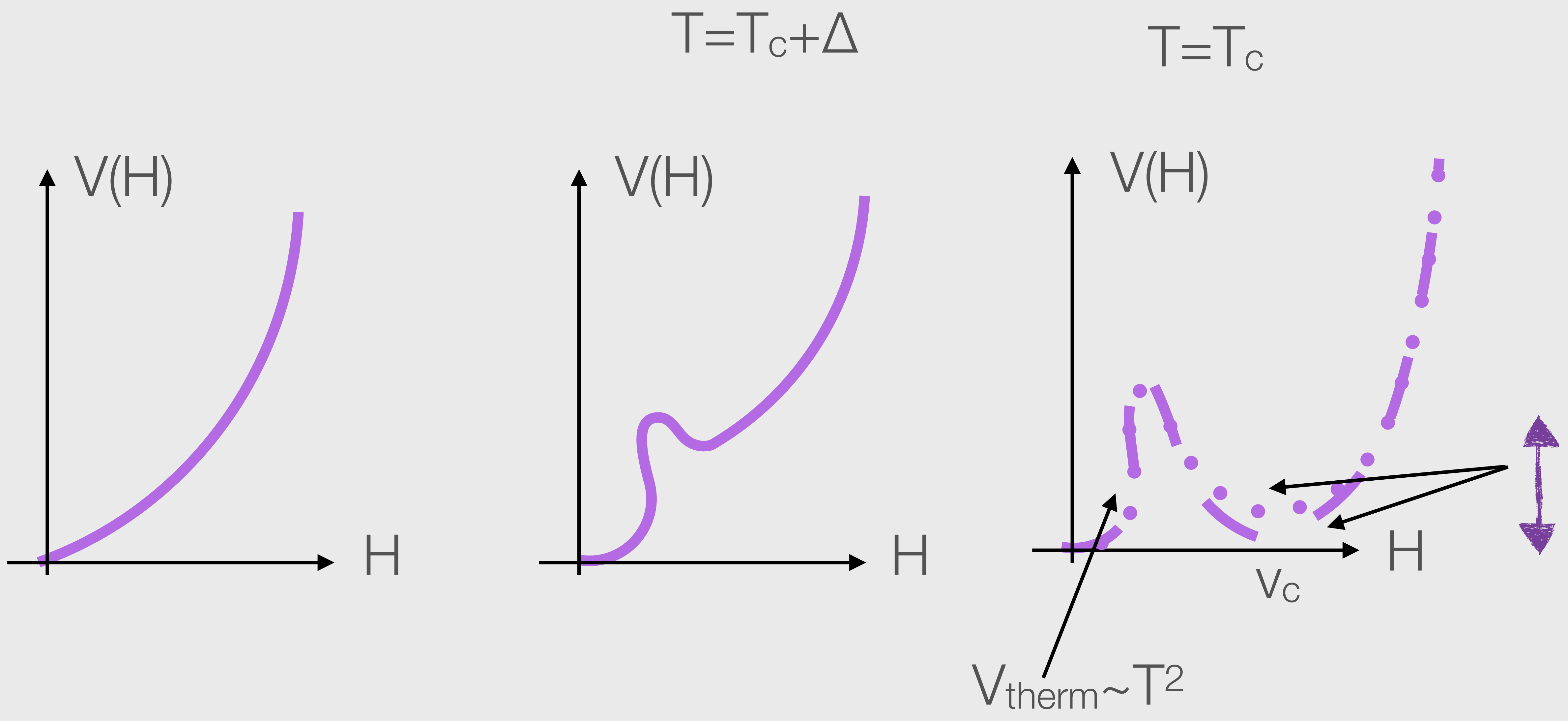
- High-Energy lepton collider has large flux of “partonic” W bosons

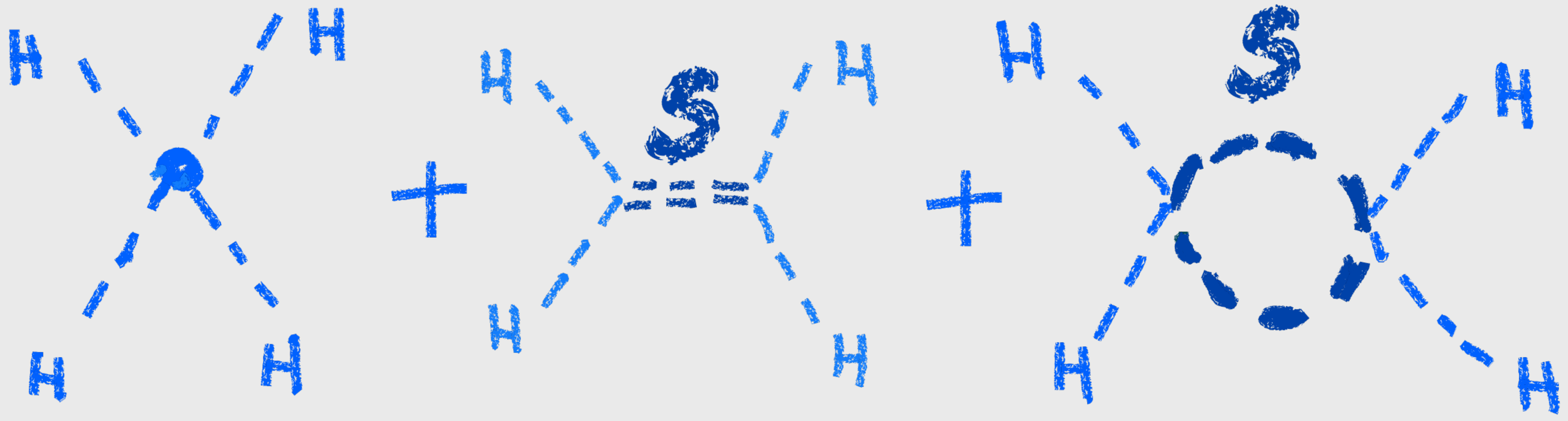


- gg collisions as usual



Electroweak phase transition





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

Roberto Franceschini - Complementarity at FCC and muon collider - https://indico.cern.ch/event/1176398/

2101.10469

1807.04743, 1910.04170, 2101.10469

EW phase transition

DIRECT & INDIRECT

INTERPLAY

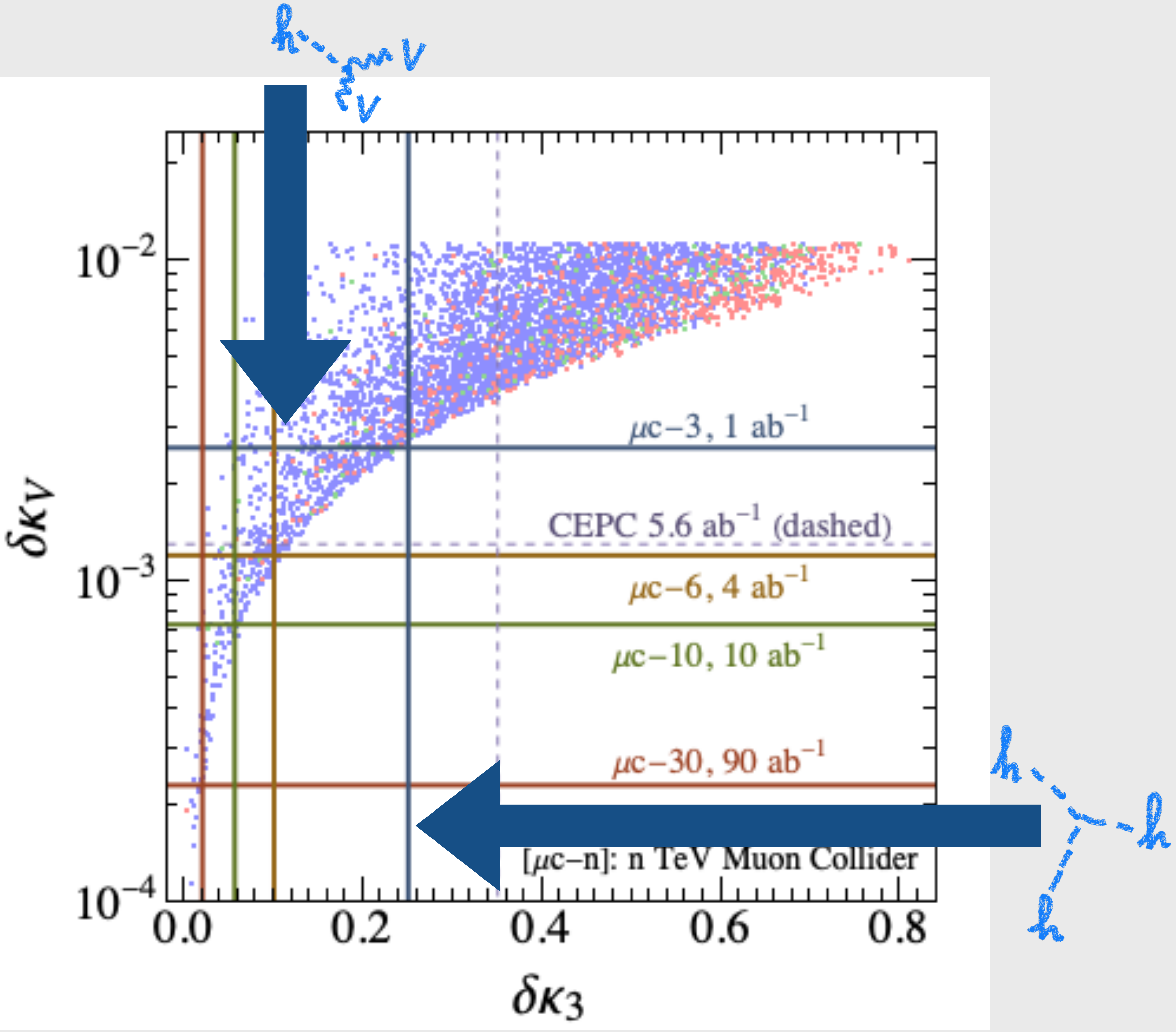
$$V(\Phi, S) = -\mu^2\left(\Phi^\dagger\Phi\right) + \lambda\left(\Phi^\dagger\Phi\right)^2 + \frac{a_1}{2}\left(\Phi^\dagger\Phi\right)S + \frac{a_2}{2}\left(\Phi^\dagger\Phi\right)S^2 + b_1 S + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4.$$

independent parameters

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

strong First Order EW phase transition on all points

⊗●● → Gravity Wave SNR



2101.10469

1807.04743, 1910.04170, 2101.10469

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

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

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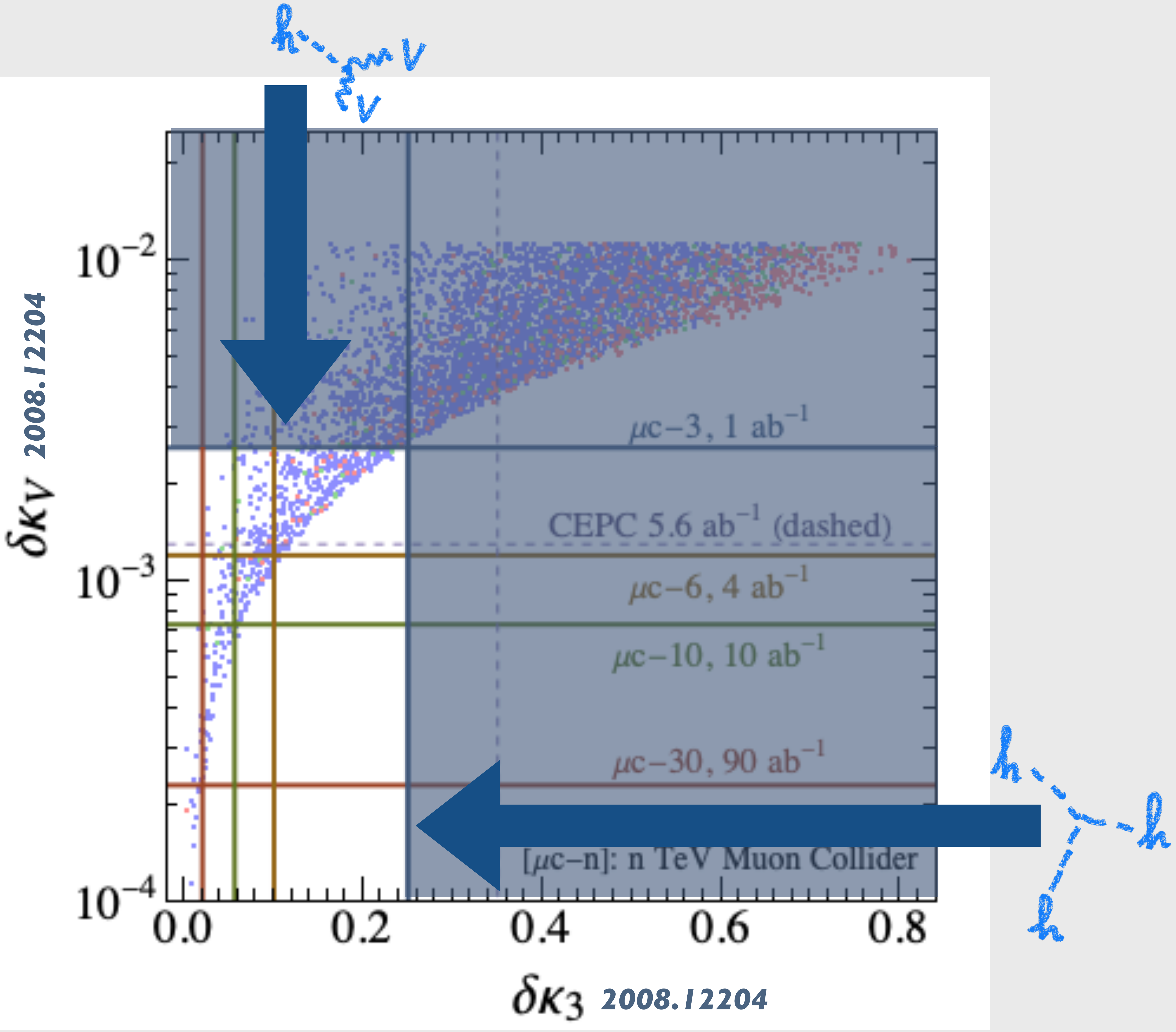
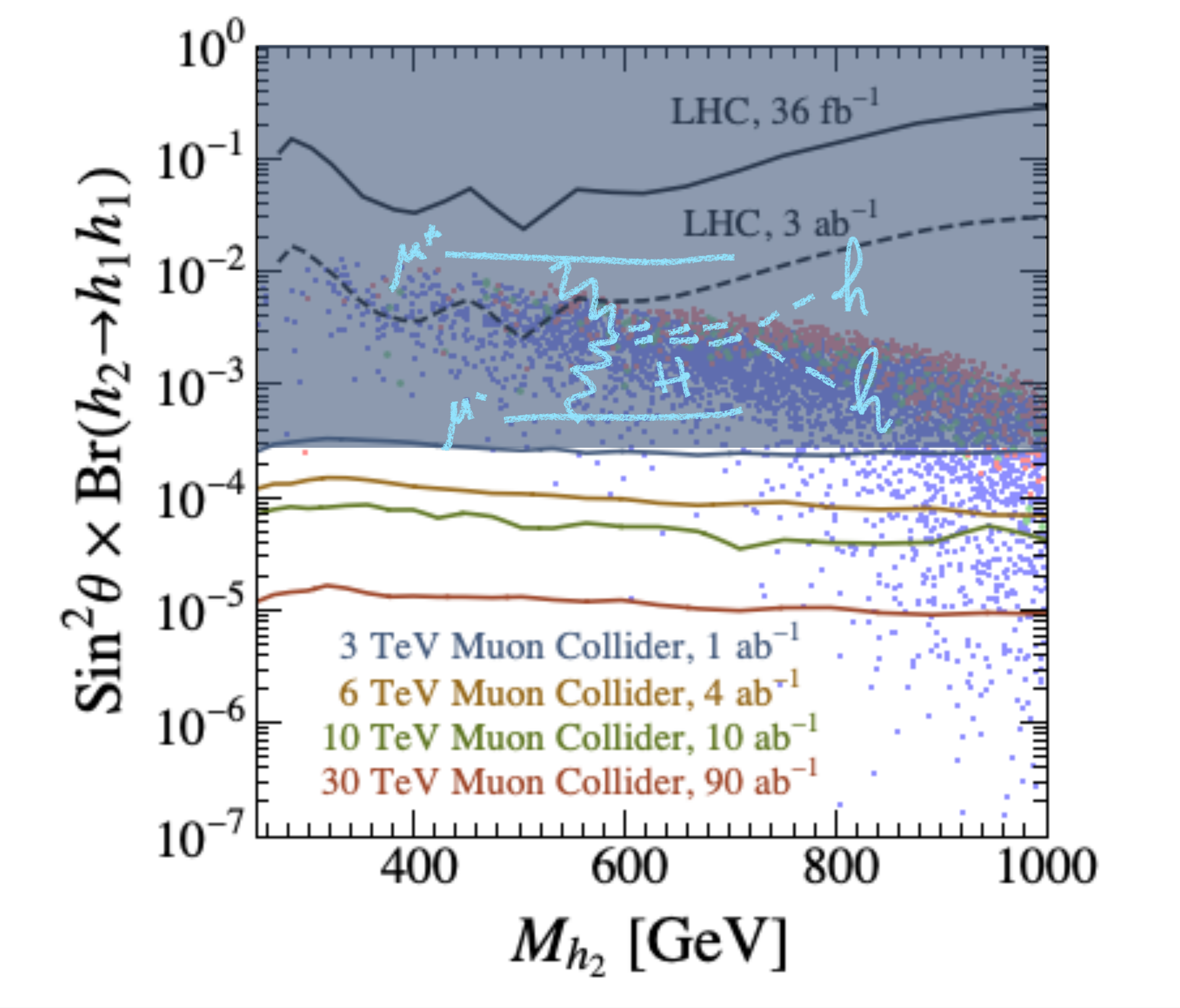


2101.10469

1807.04743, 1910.04170, 2101.10469

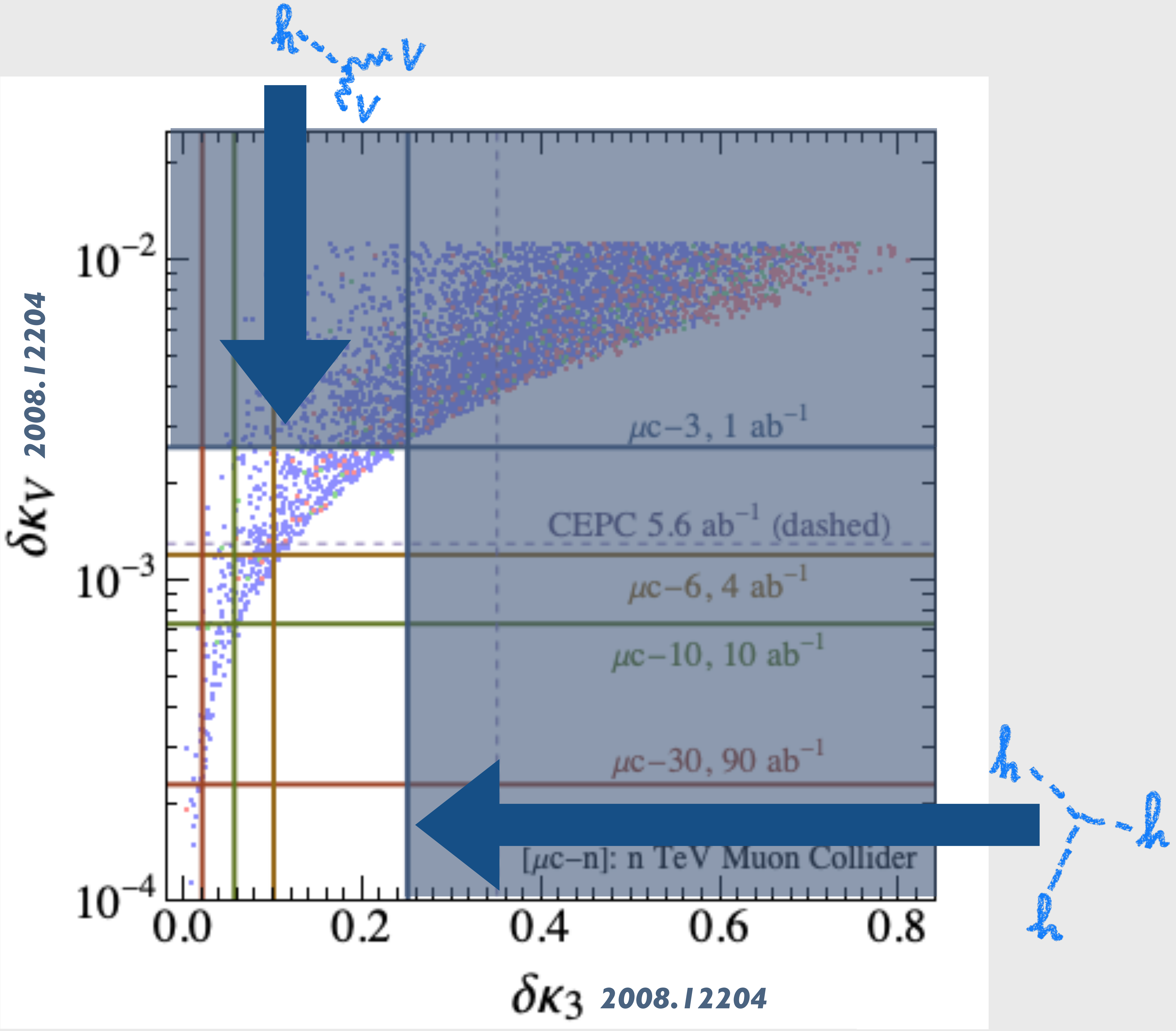
EW phase transition

DIRECT & INDIRECT INTERPLAY



strong First Order EW phase transition on all points

⊗ ● ● → Gravity Wave SNR



2101.10469

1807.04743, 1910.04170, 2101.10469

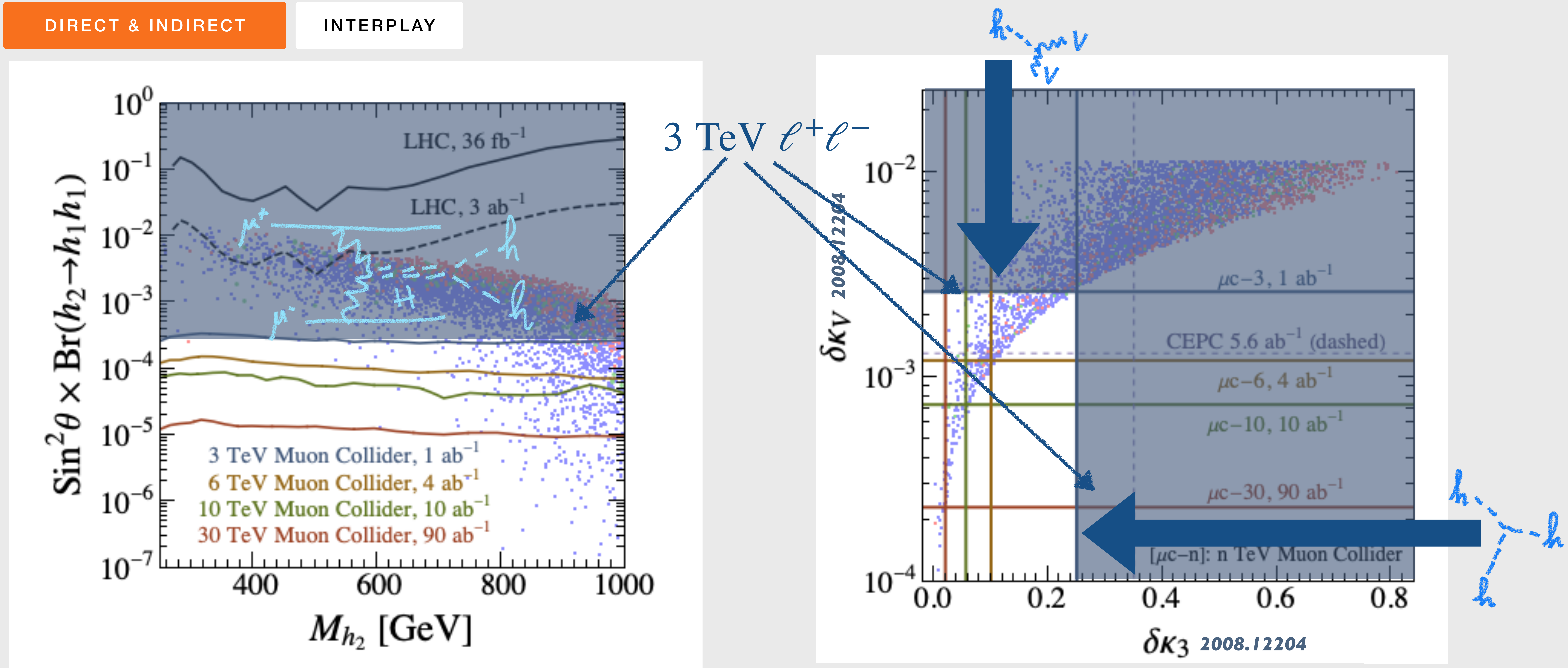
EW phase transition

DIRECT & INDIRECT

INTERPLAY

strong First Order EW phase transition on all points

⊗●● → Gravity Wave SNR



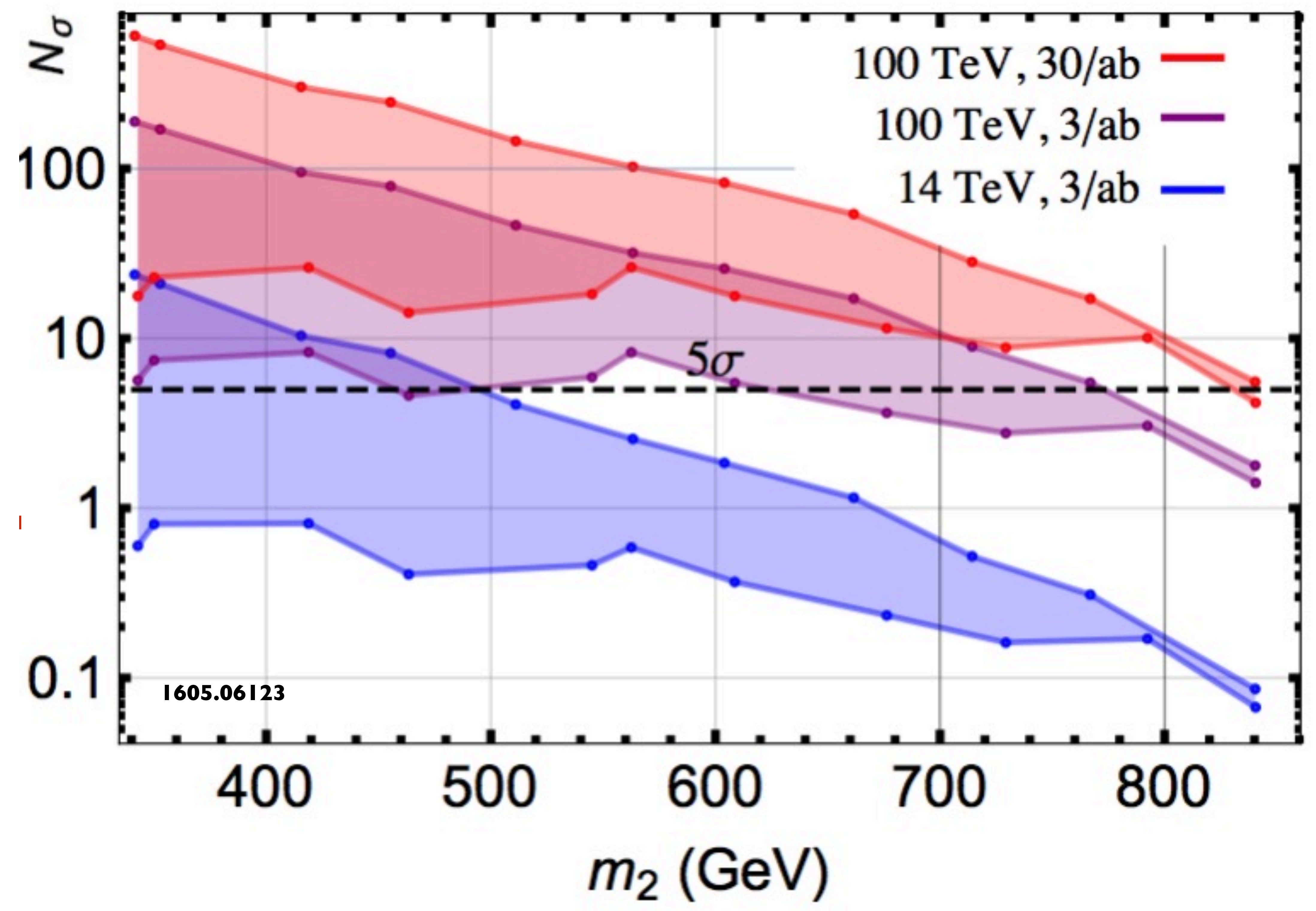
parameters space of 1st order phase transition accessible by **several measurements available at the 3 TeV $\ell^+\ell^-$ collider**

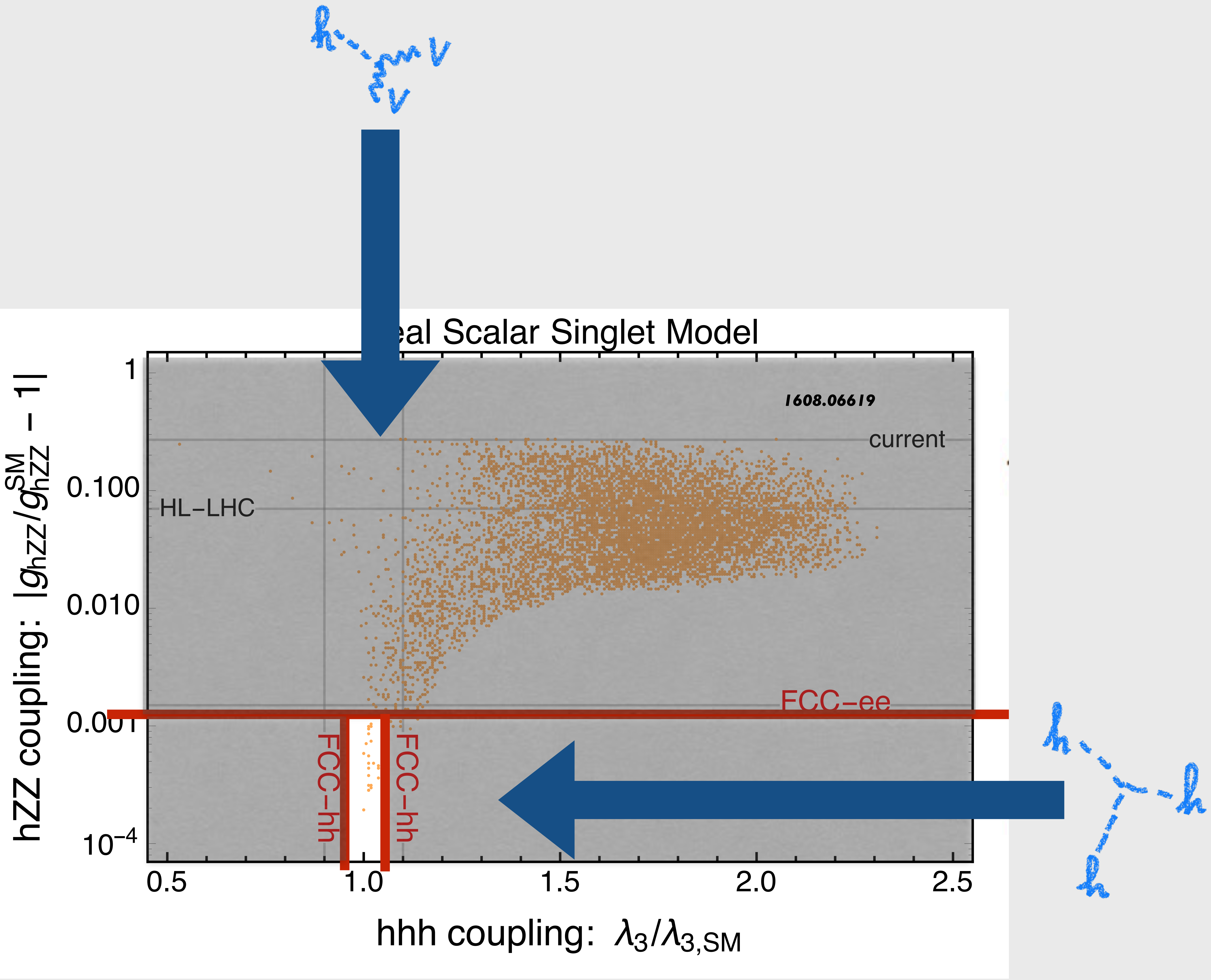
EW phase transition

DIRECT & INDIRECT

INTERPLAY

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



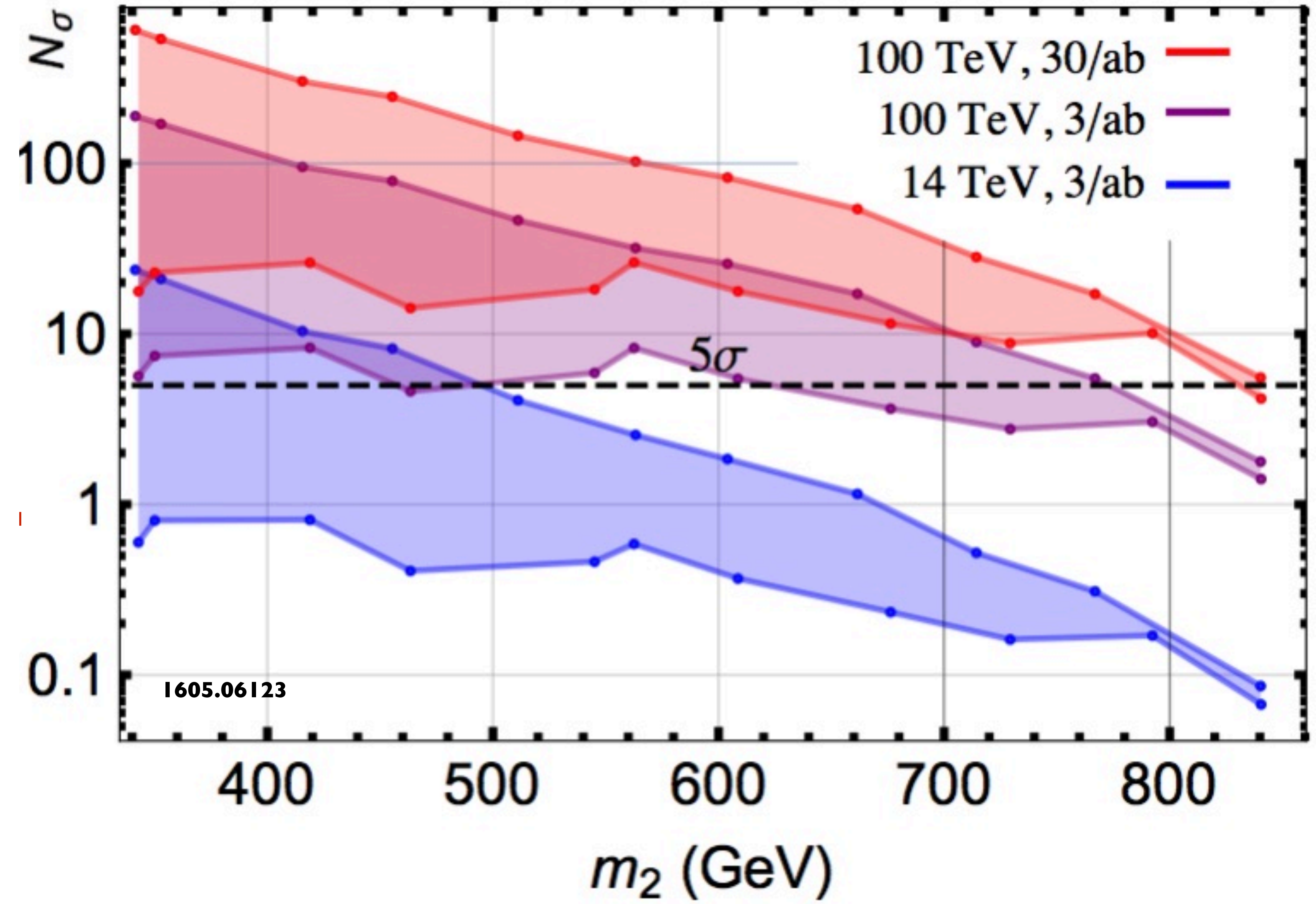


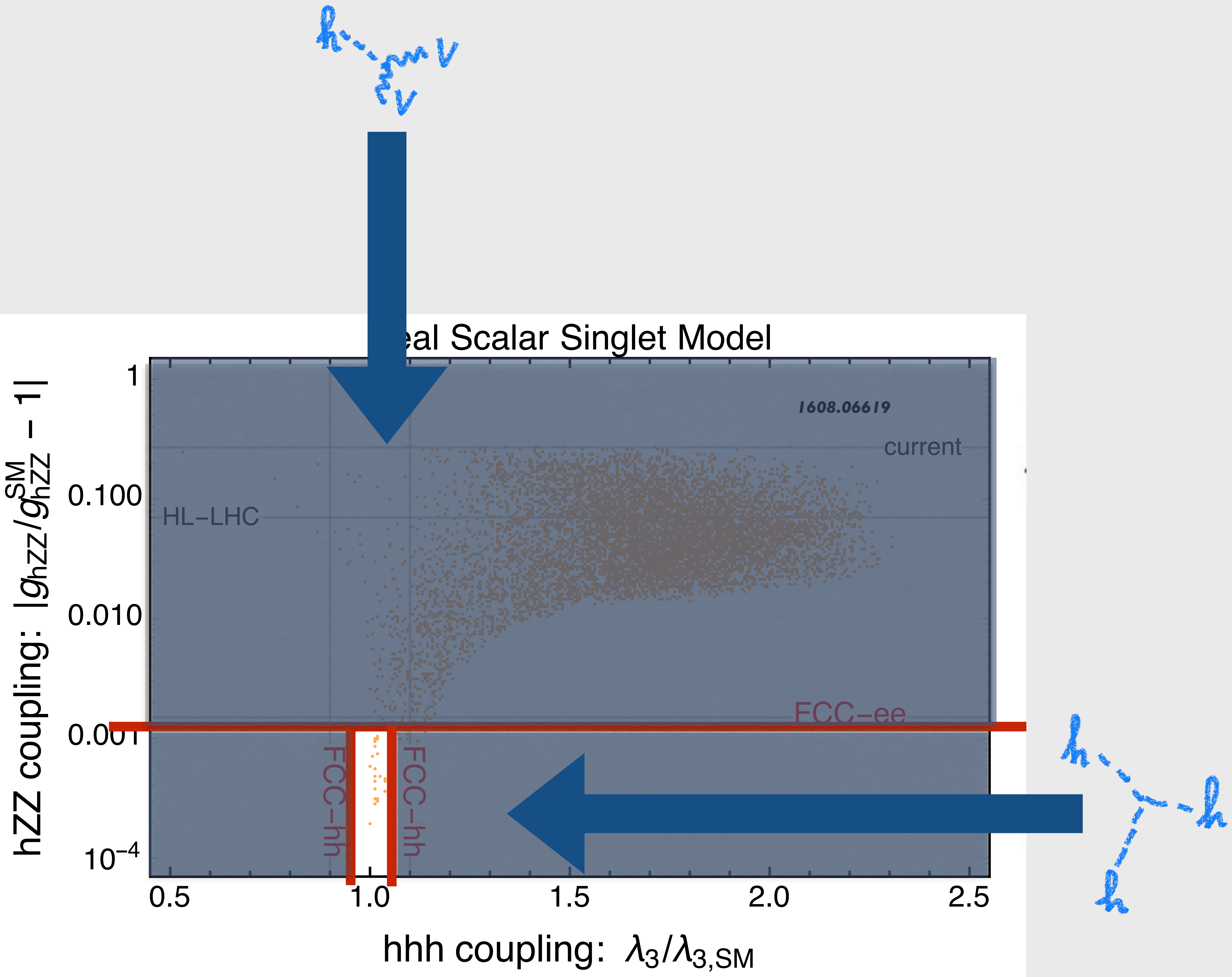
EW phase transition

DIRECT & INDIRECT

INTERPLAY

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

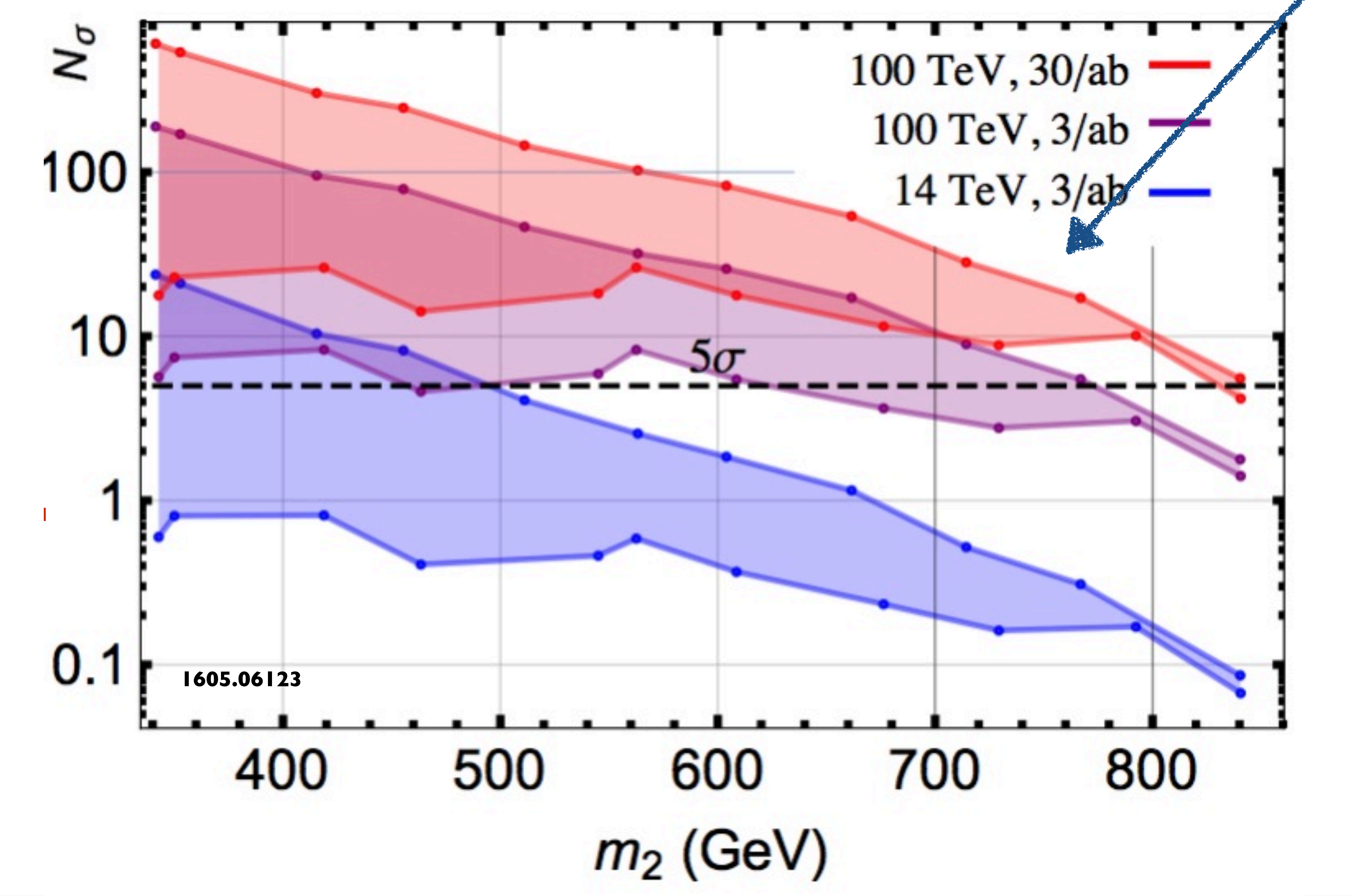




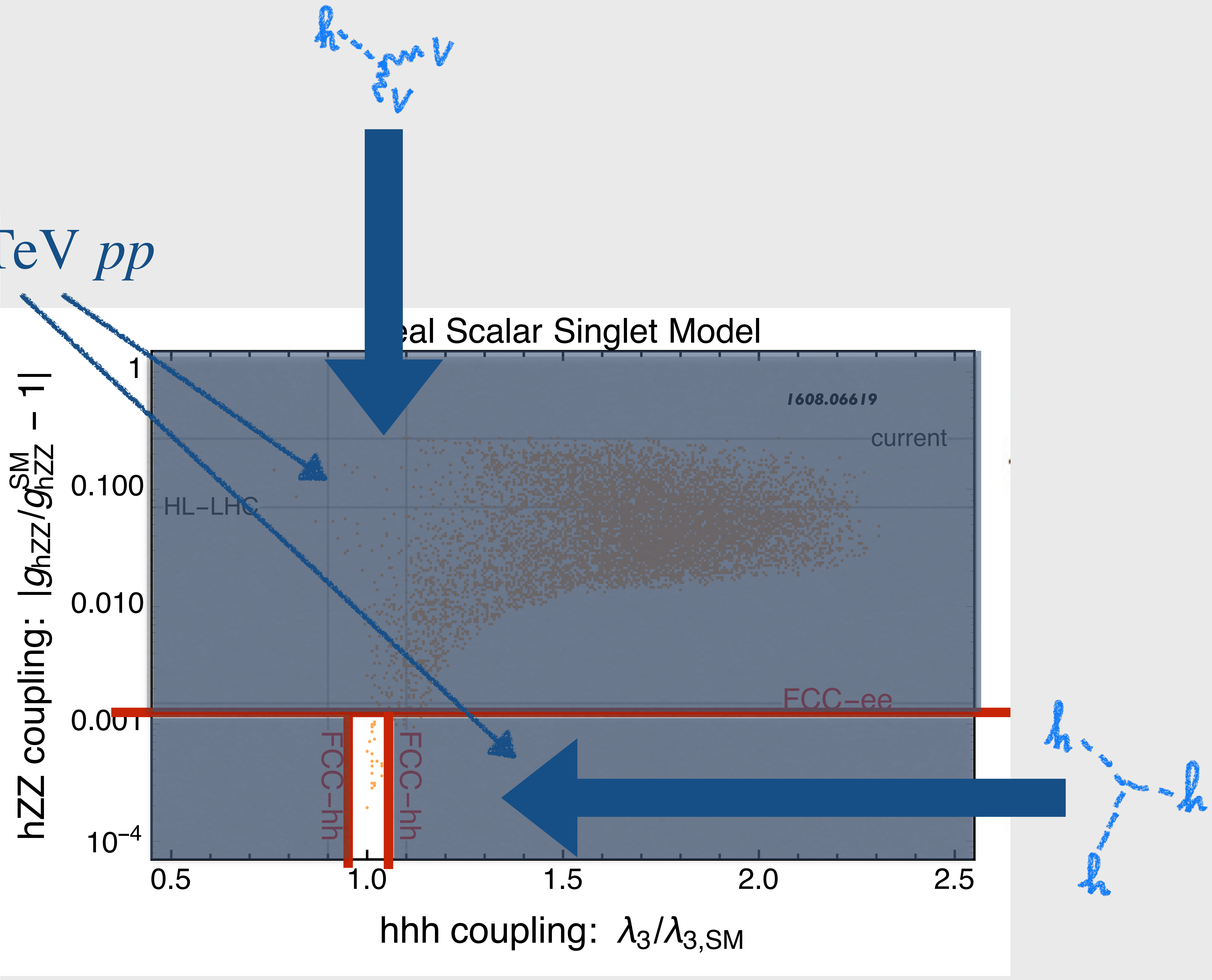
EW phase transition

DIRECT & INDIRECT INTERPLAY

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



100 TeV *pp*



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