Christoph Englert

New physics at 10 TeV pcm

ECFA-UK meeting

Durham, 24/09/24

LEVERHULME TRUST

UKRI Science and Technology Facilities Council

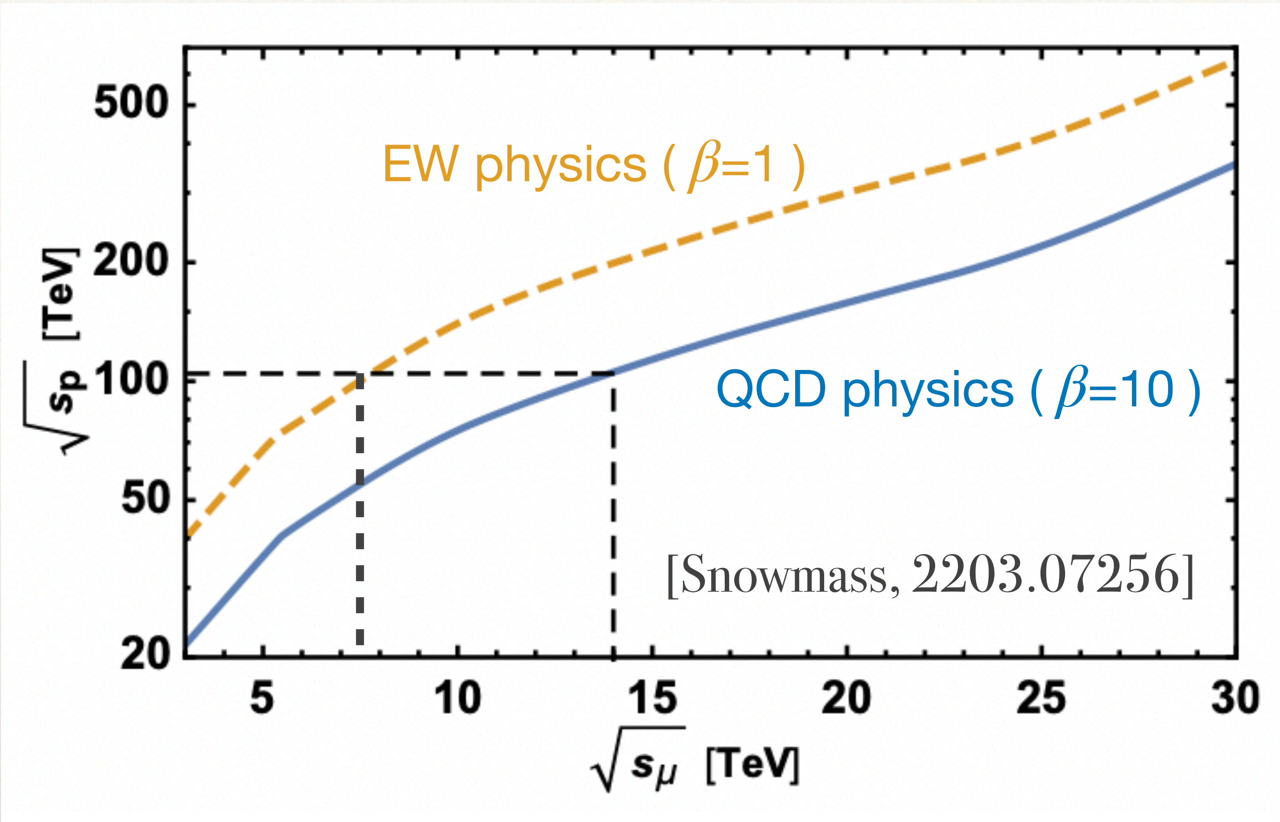
University of Glasgow

…not possible to provide a comprehensive overview in 20+x mins

→ dedicated session on Wednesday

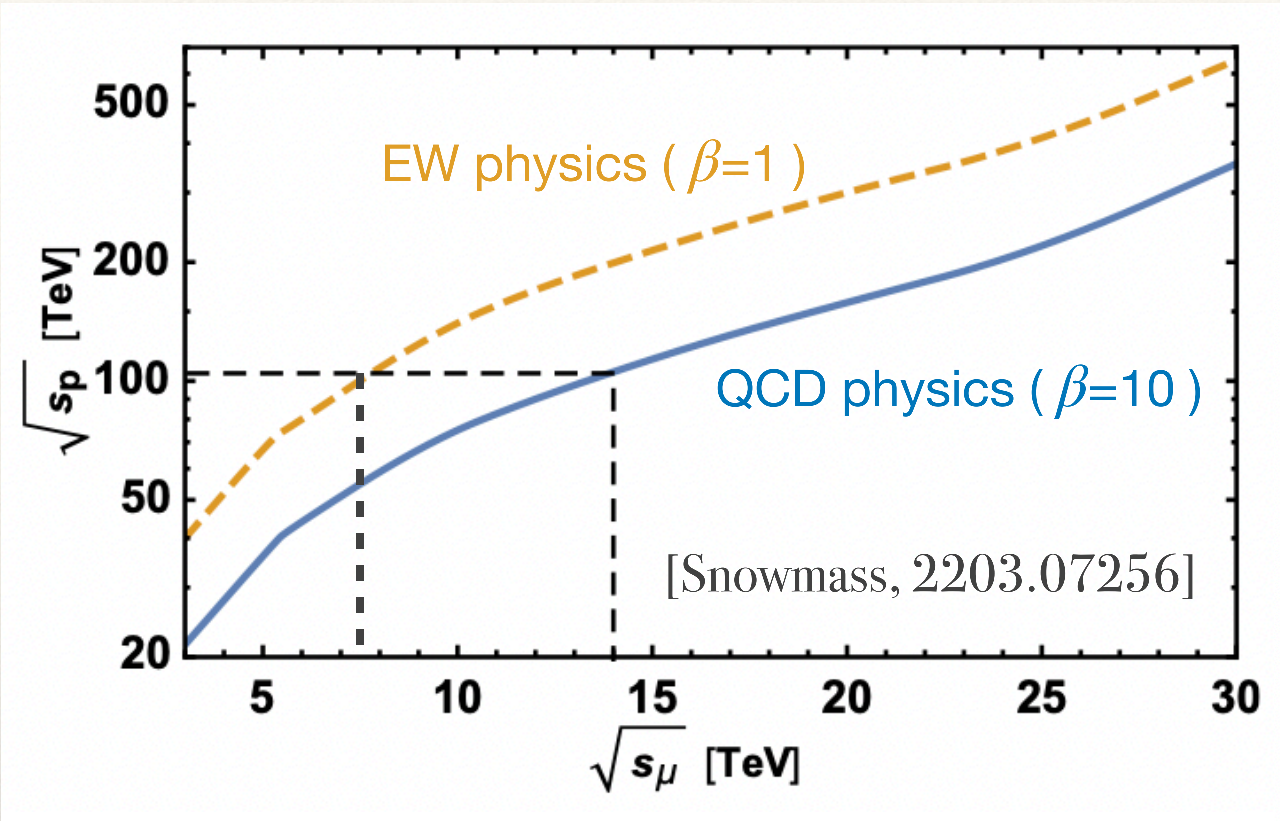
Here & now:

- highlight conceptual difference
- isolate common themes
- a qualitative overview of arising opportunities given HL-LHC
- all of this from a theoretical/phenomenological perspective
    - ☛ …no disclaimers on unknown performance differences…



10 TeV $\mu\mu$ stage option *roughly* equates to FCC-hh@100 TeV

...process dependent statement!



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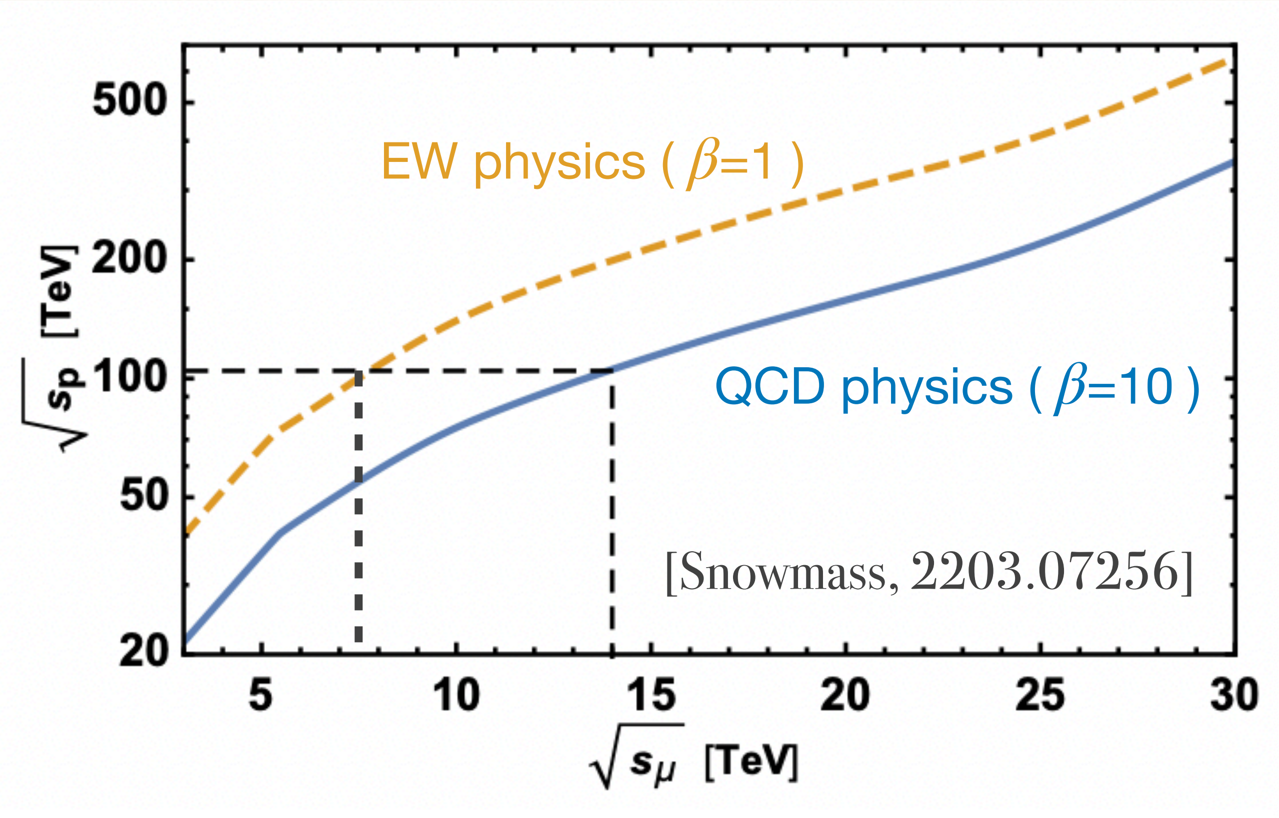

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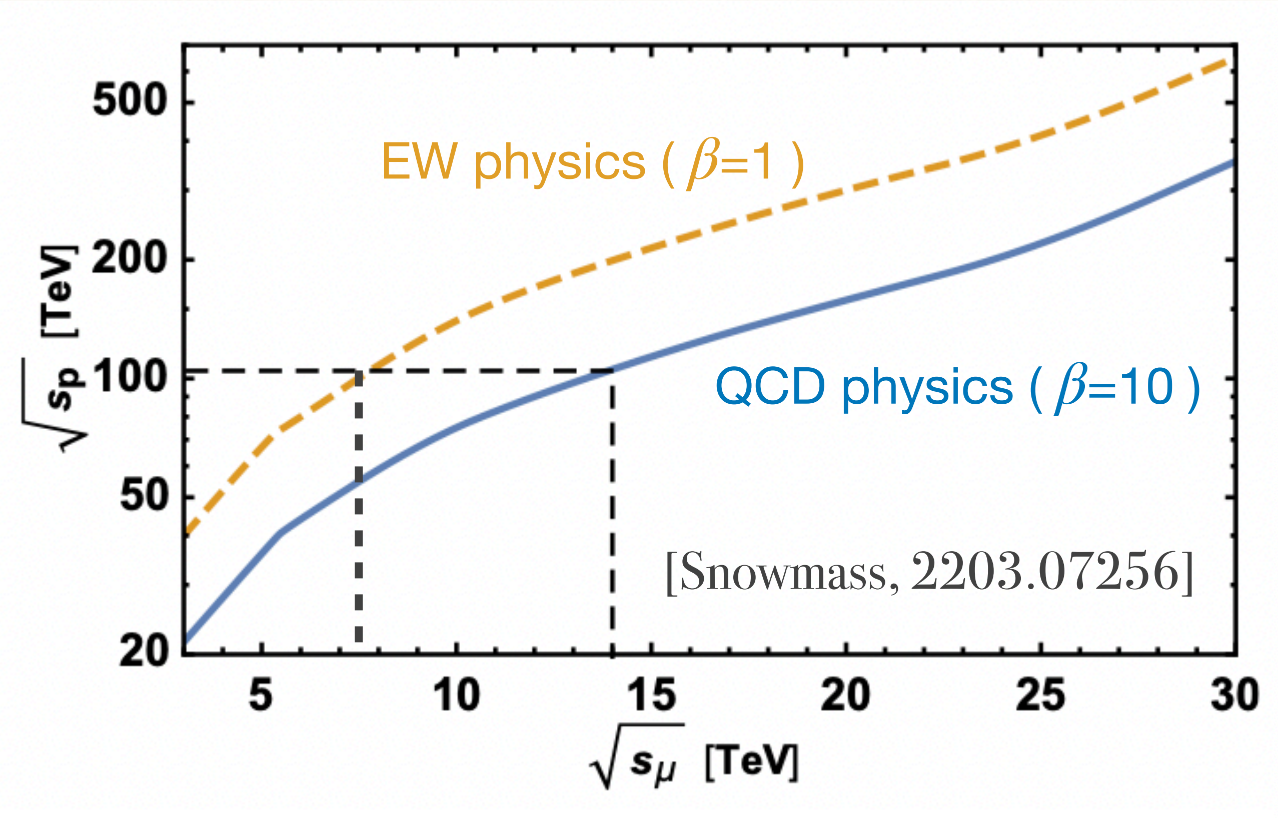
‣ expand reach to coloured exotics (SUSY…) ‣ multi-Higgs in WBF and GF ‣ WBF + multi-boson in many channels ‣ challenging environment: QCD/pile-up…	



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$\mu\mu$ @ 10 TeV

- 2nd generation specific new physics
- a *W* collider!
  - ☛ fine-grained picture of EW/*H* sector
  - ☛ unitarisation, *H* off-shellness, ...
  - ☛ elw. Sudakovs...

→ *Marek's talk*

- naturalness ≃ compositeness/SUSY ≃ top partners + exotics

coloured exotica vs lepton-specific

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$(\mathbf{3},\mathbf{1})_{2/3}$ vs. $(\bar{\mathbf{6}},\mathbf{1})_{2/3}$ ← UV flavour structures — down-type sector

identical leading IR physics $\sim O_{dd}$

[de Blas et al., 1711.10391]

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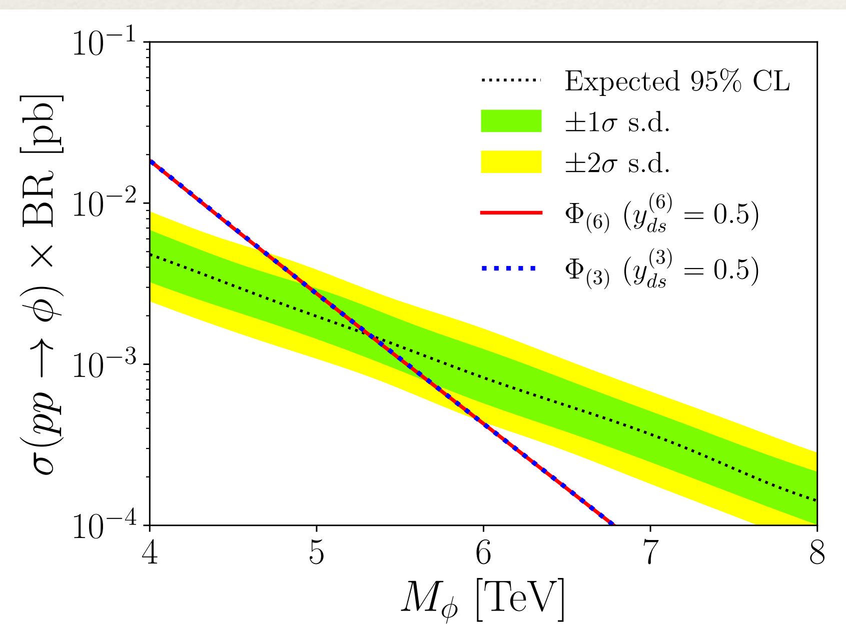
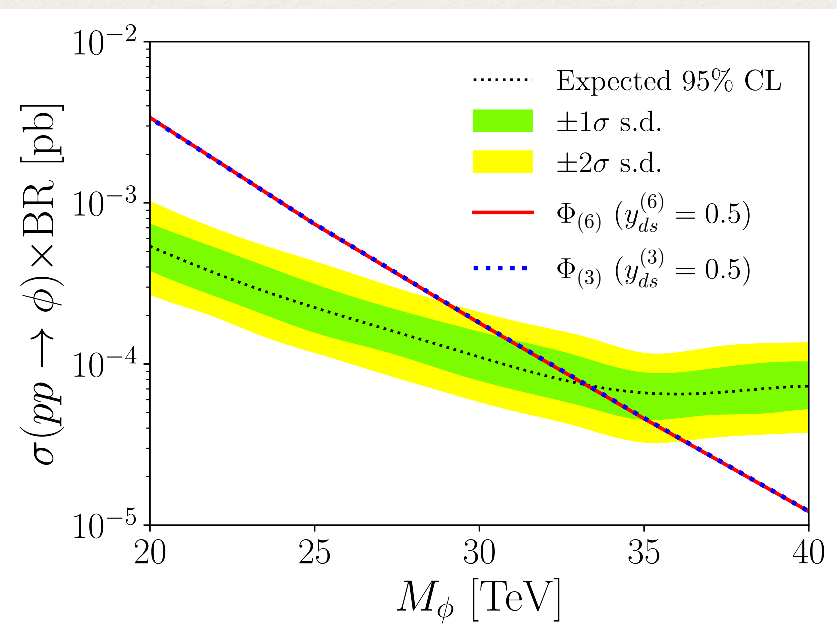


HL-LHC



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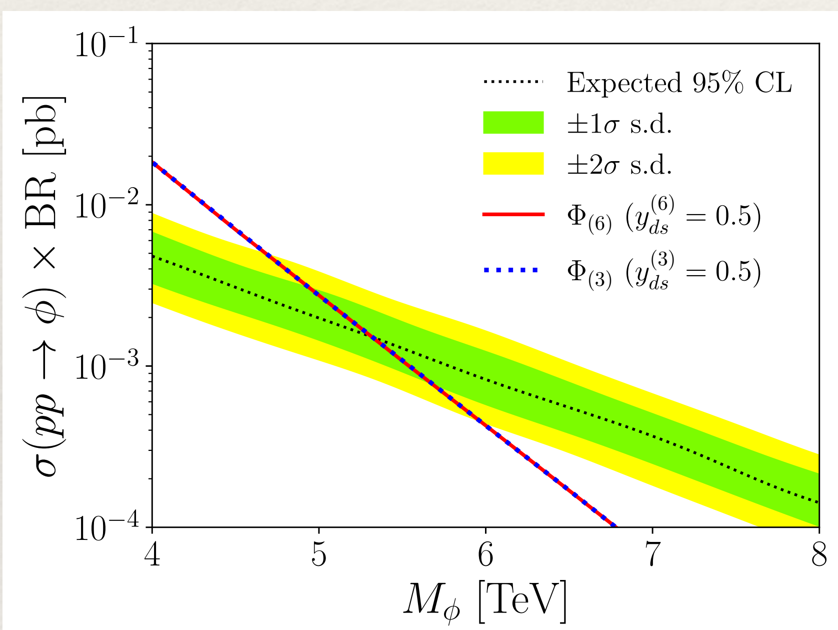

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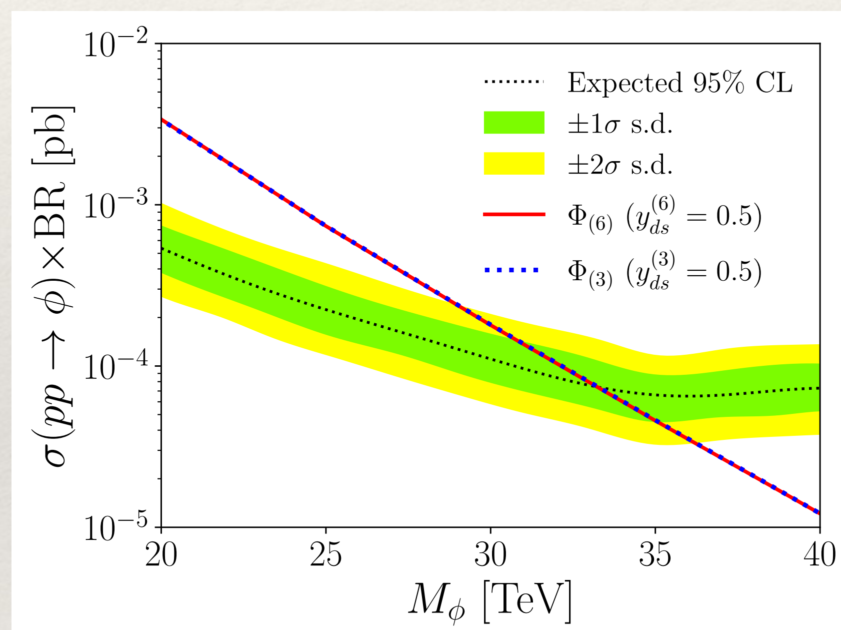

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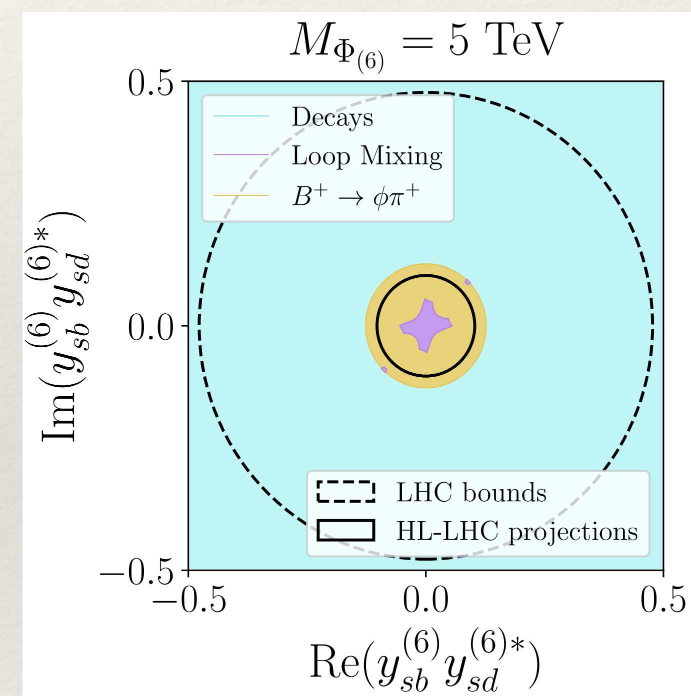

collider+flavour

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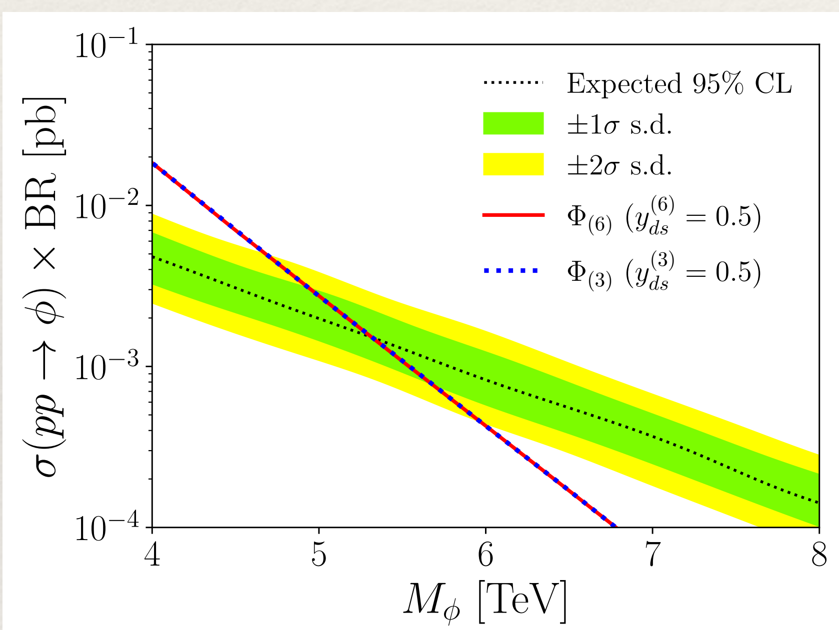

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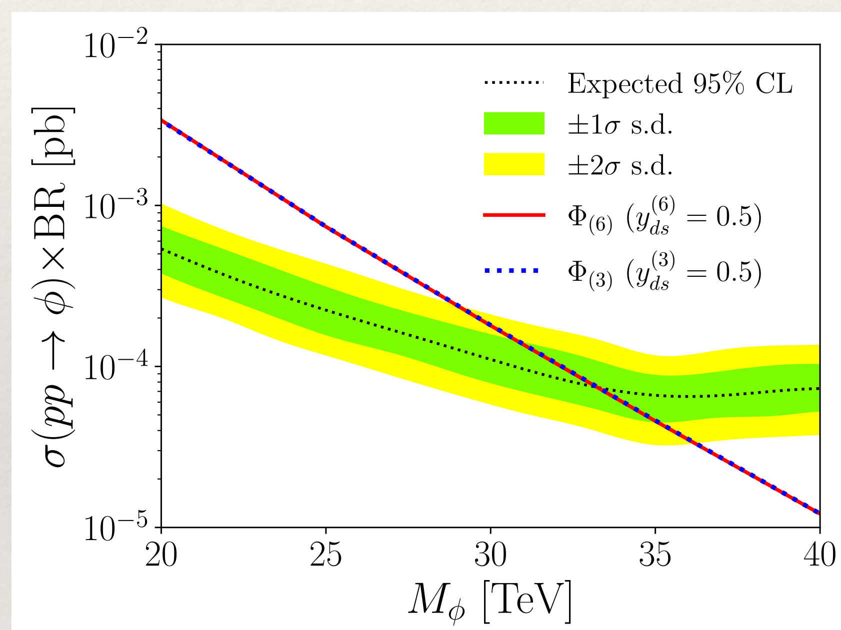

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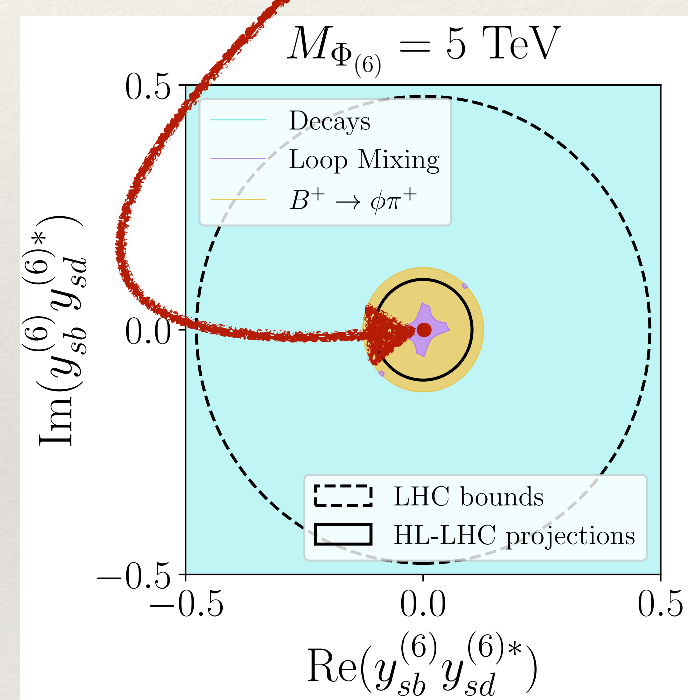

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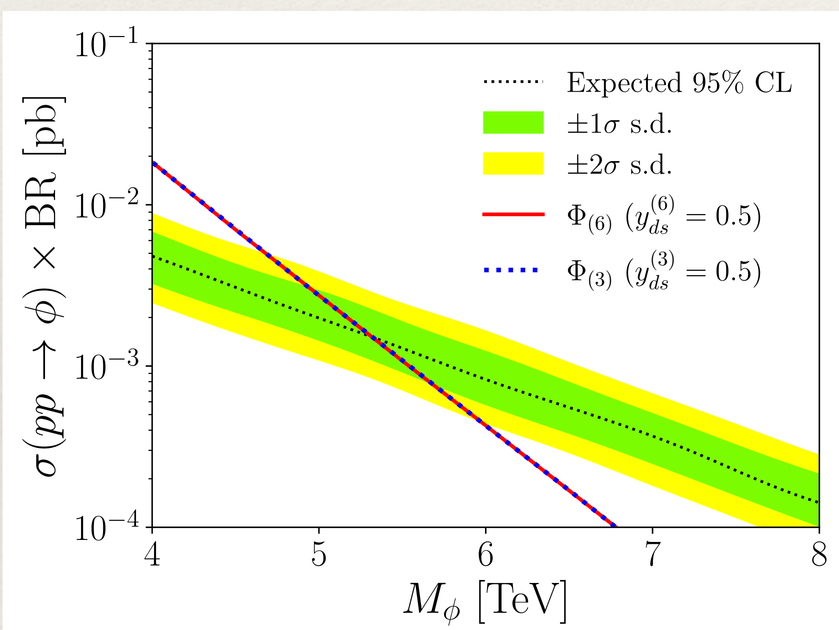

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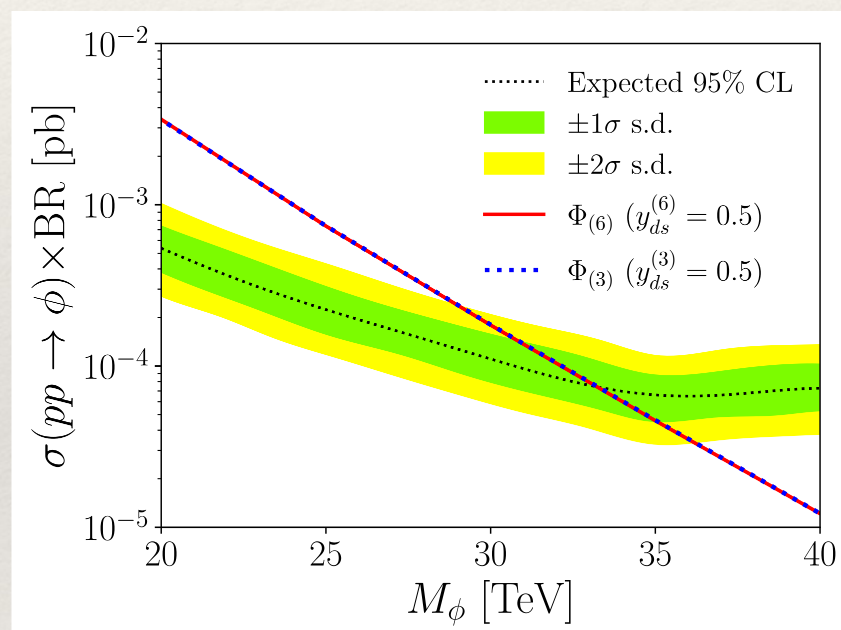

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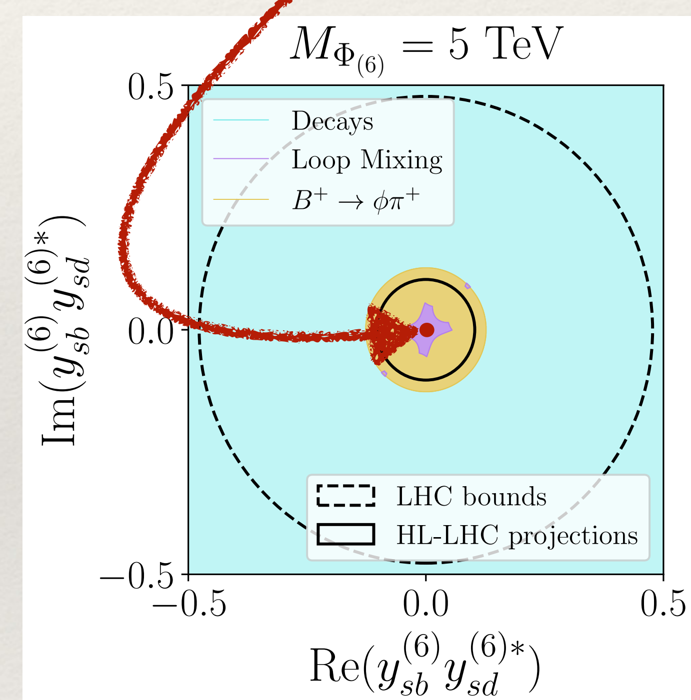

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WBF pair production at $\mu\mu$ is $U(1)_Y$ gauge suppressed

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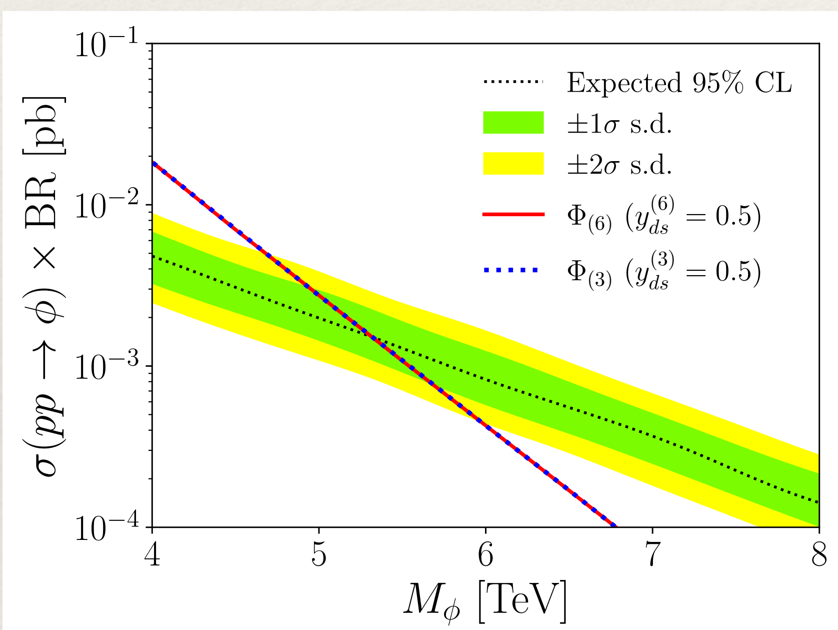

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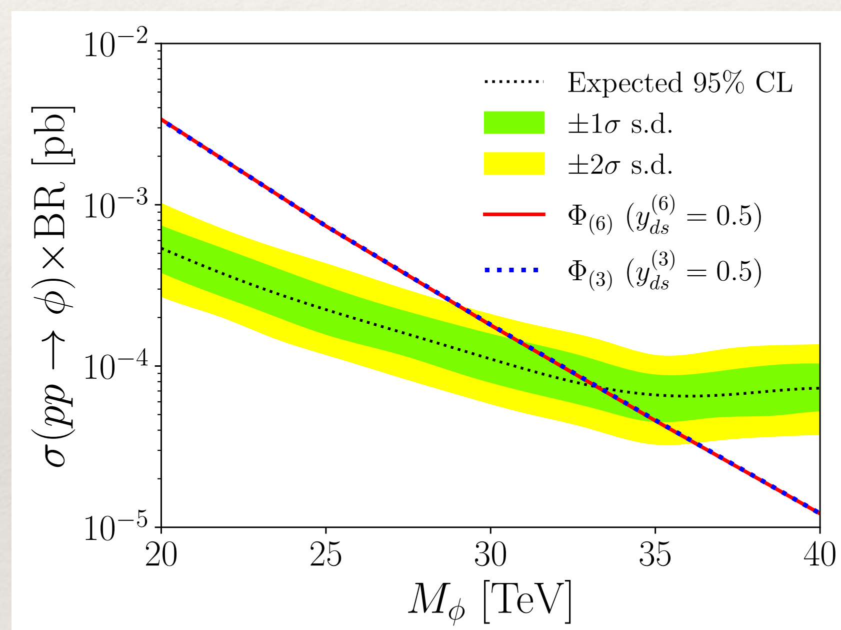

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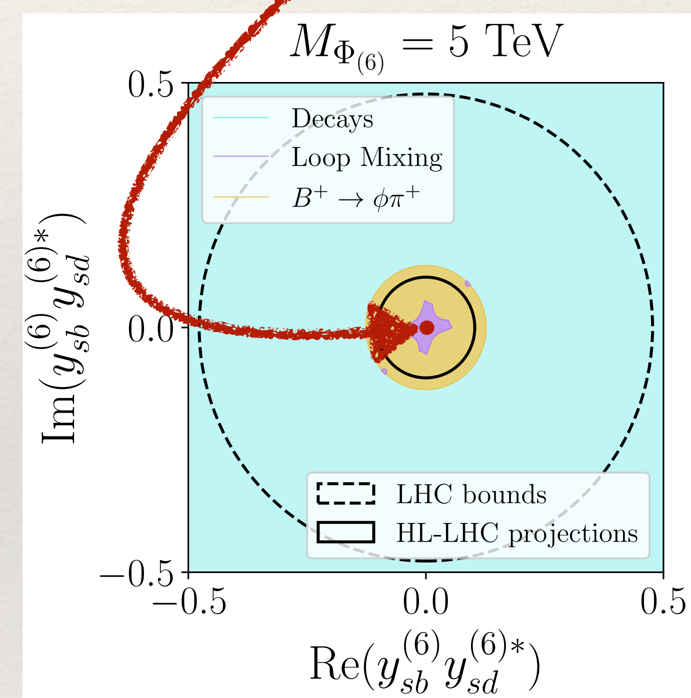

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coloured exotica vs lepton-specific

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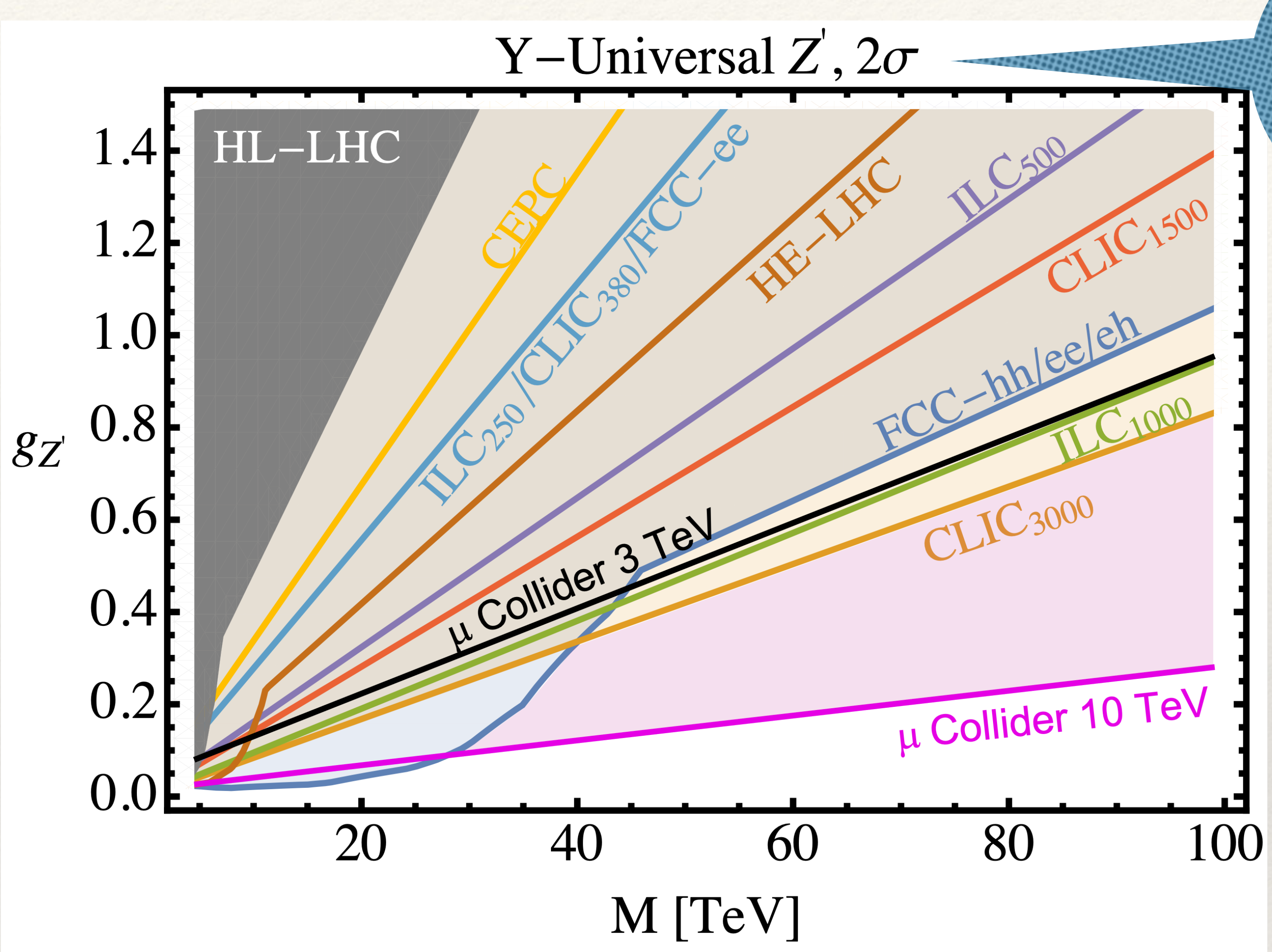

[Snowmass, 2209.13128]

SM quantum numbers anticipate unification: *Z′ from GUTs*

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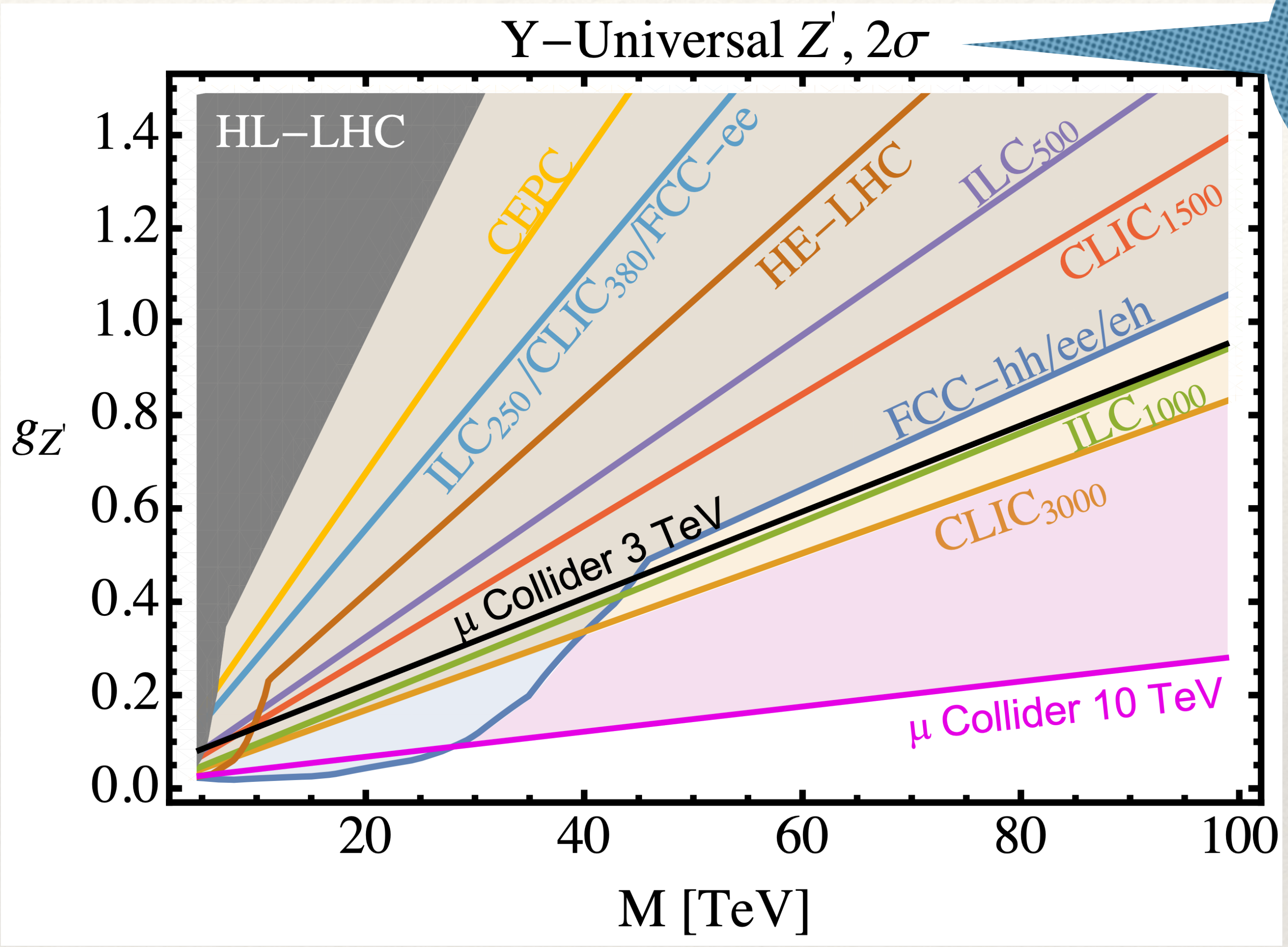

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trivial to make one look better than the other

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- areas of synergy with electroweak motivation?

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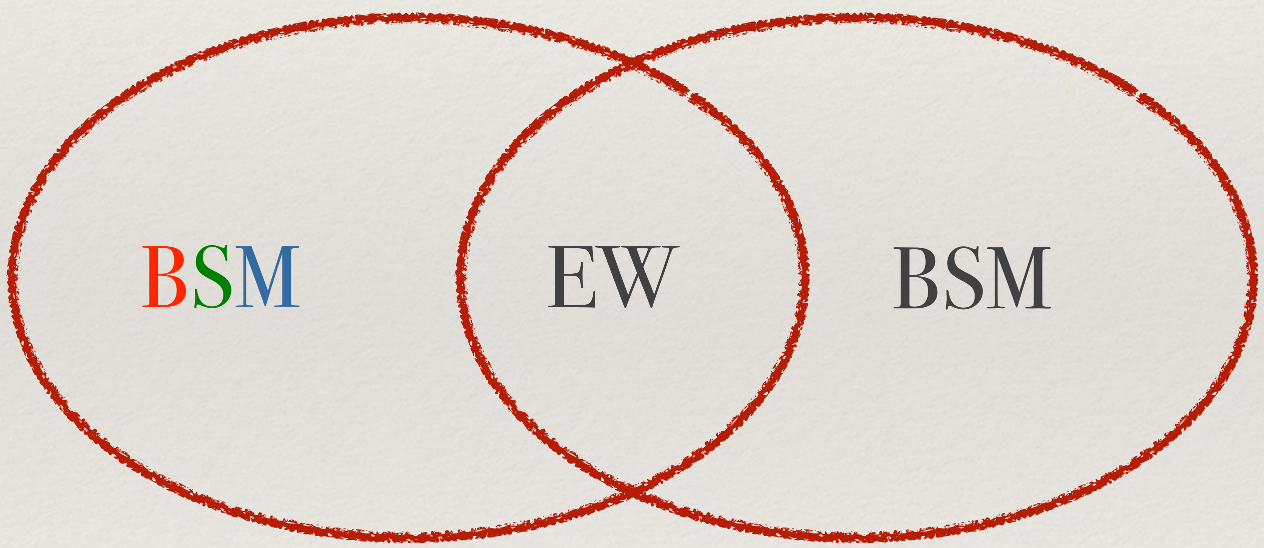

complementarity vs overlap

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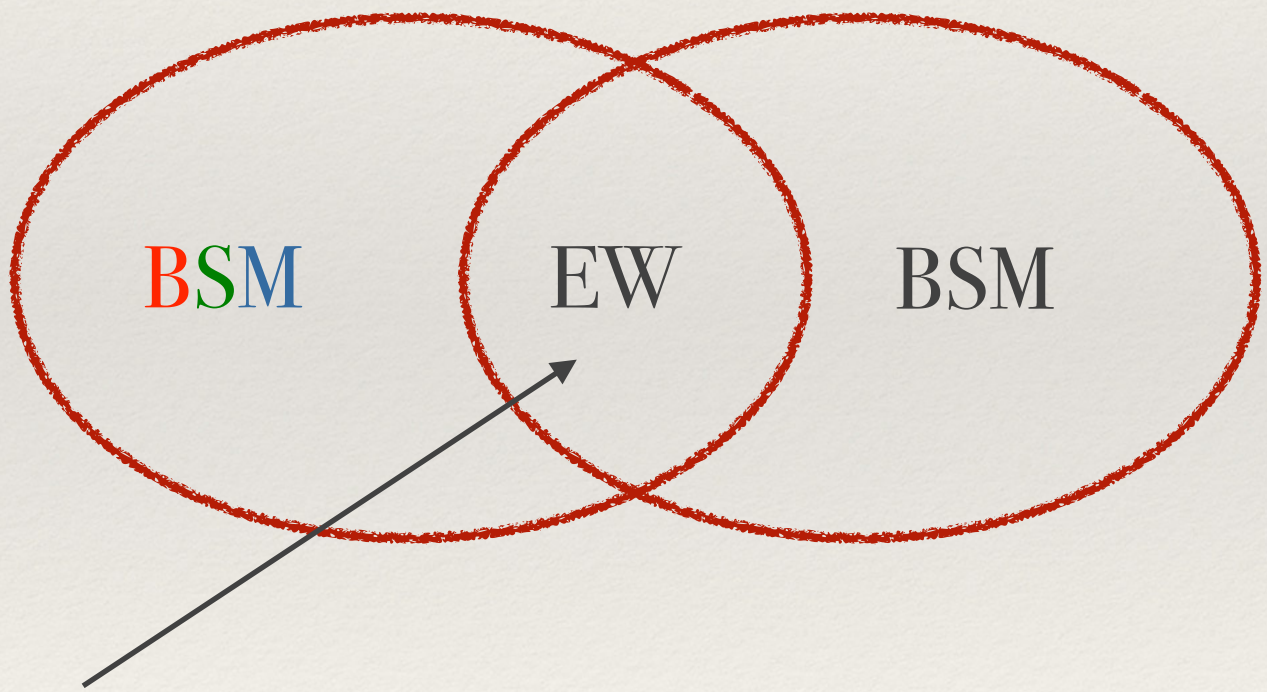

(multi-)boson, WBF, (multi-)Higgs,…

gauge-Higgs interactions

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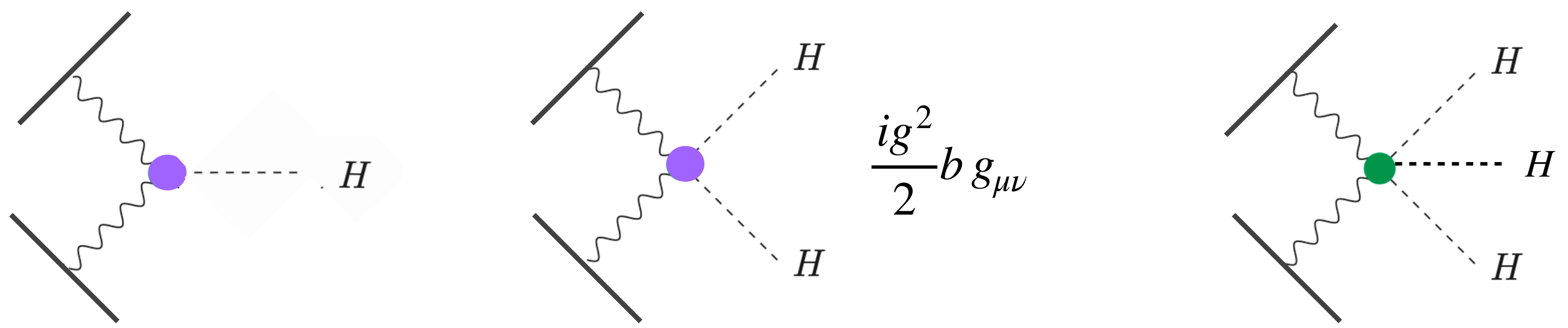

$$\frac{ig^2}{2} b\, g_{\mu\nu} \qquad \frac{i3g^2}{2v} c\, g_{\mu\nu}$$

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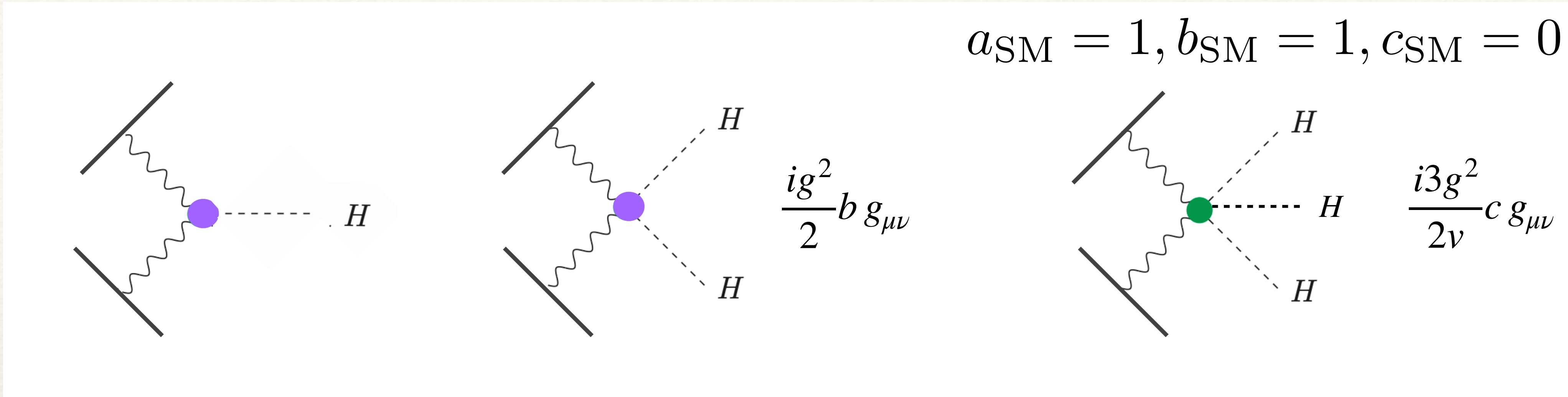
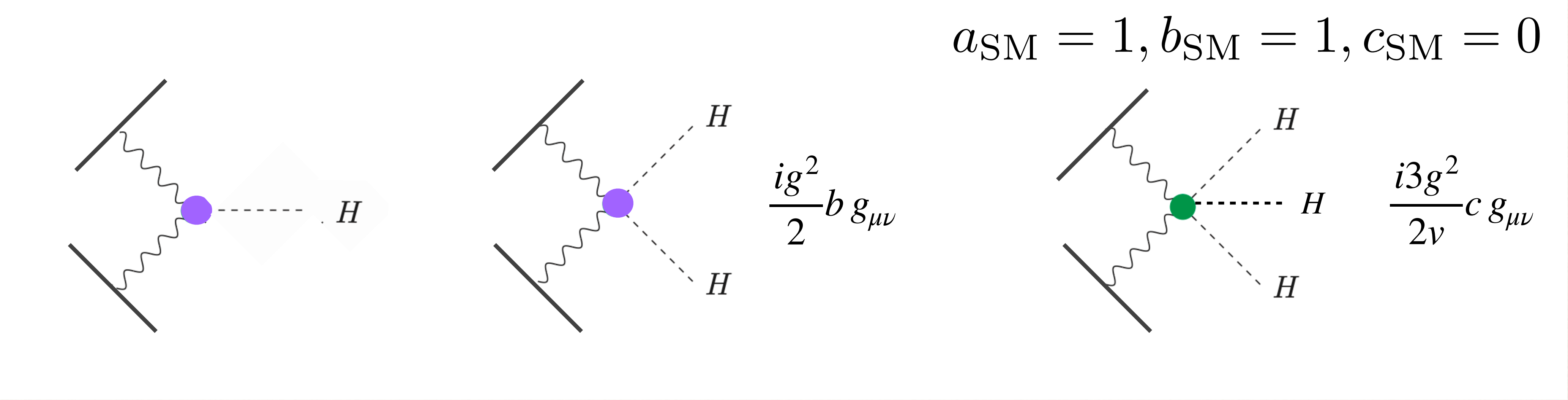


theoretical value

pp @ 100 TeV

$\mu\mu$ @ 10 TeV



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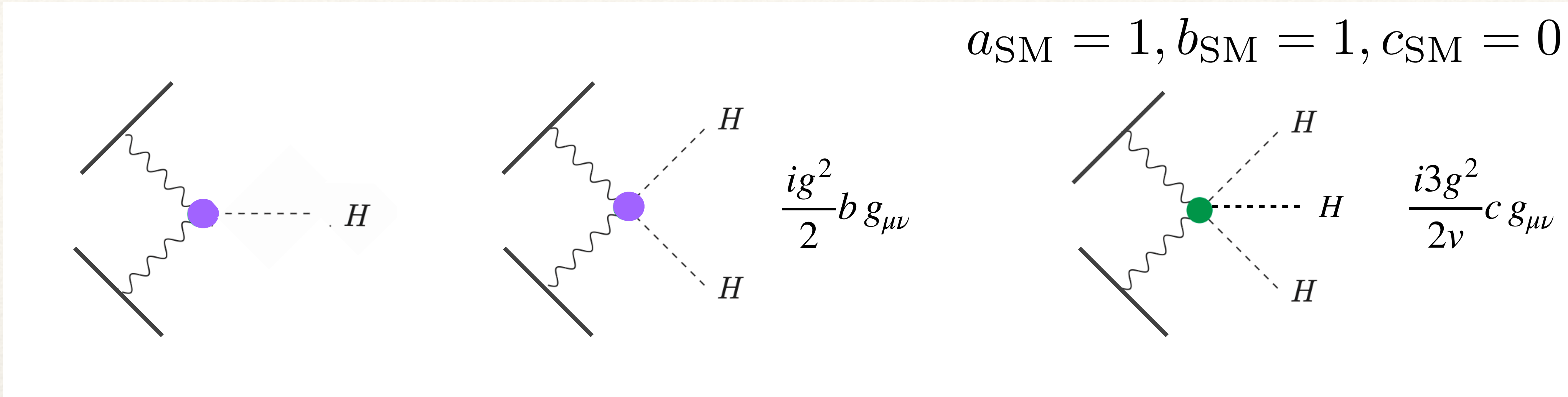
[Alonso et al., 1602.00706, 1605.03602, 2109.13290]



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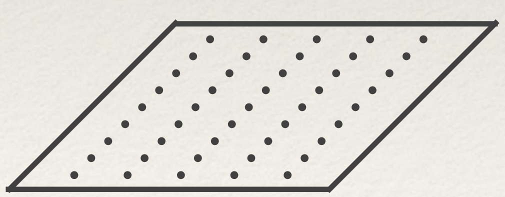

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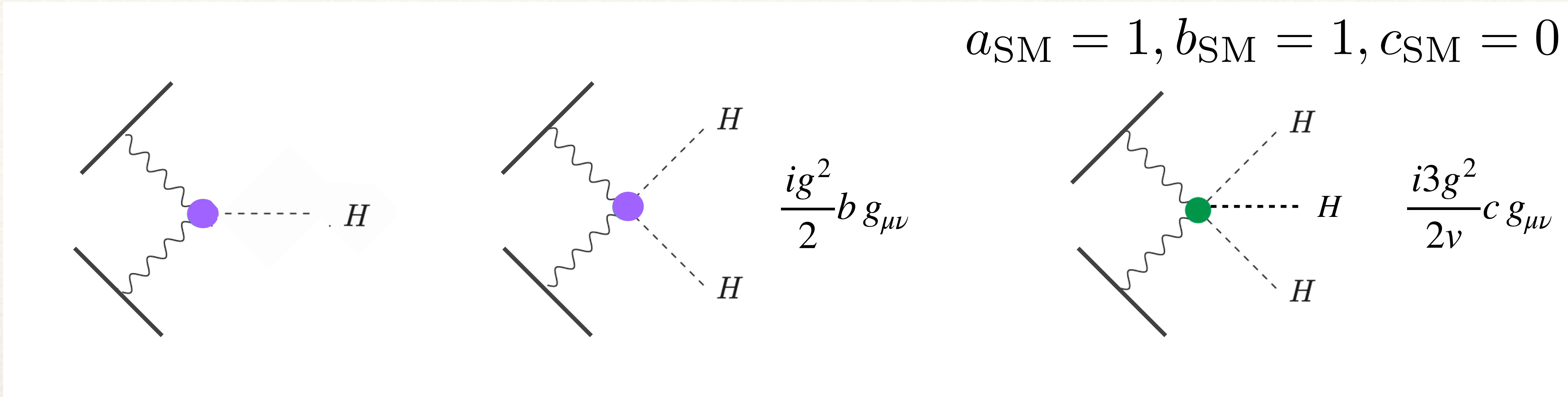

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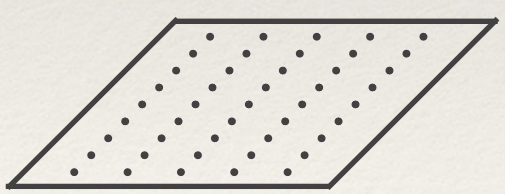

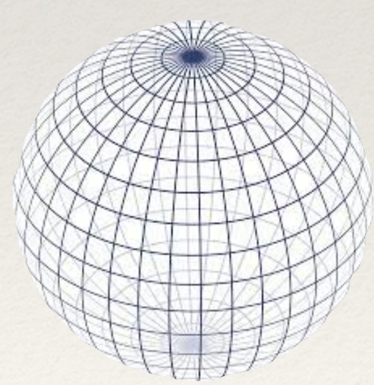

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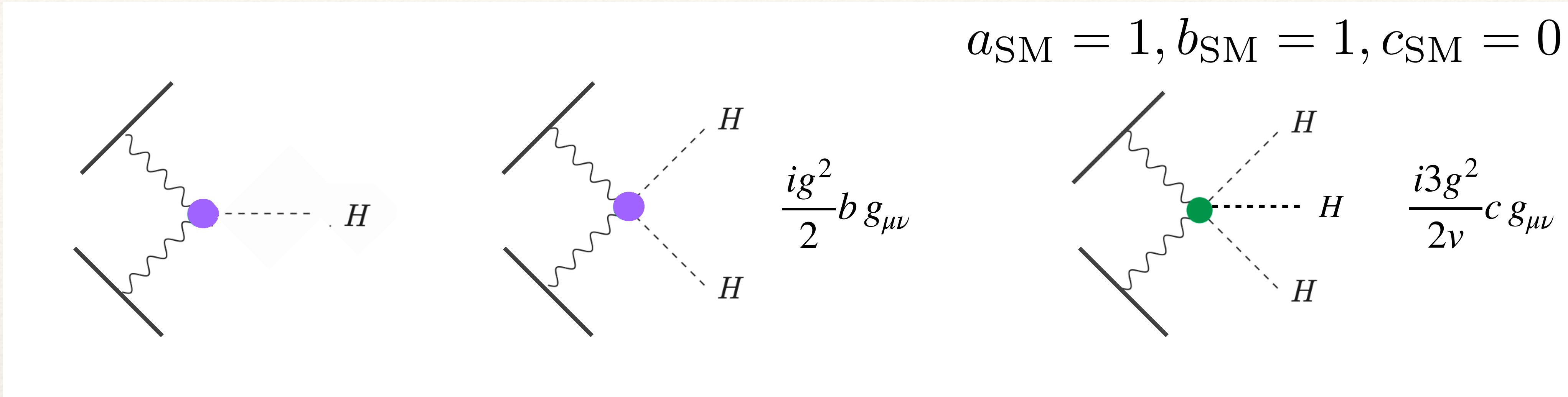

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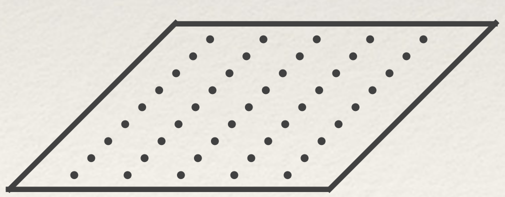

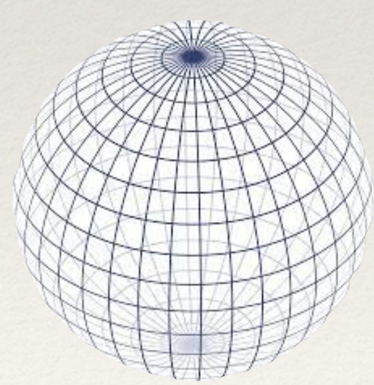

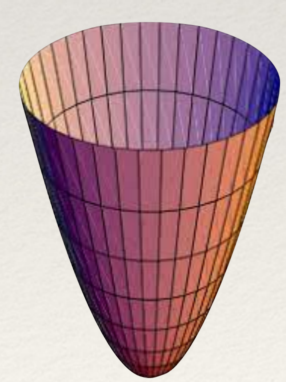

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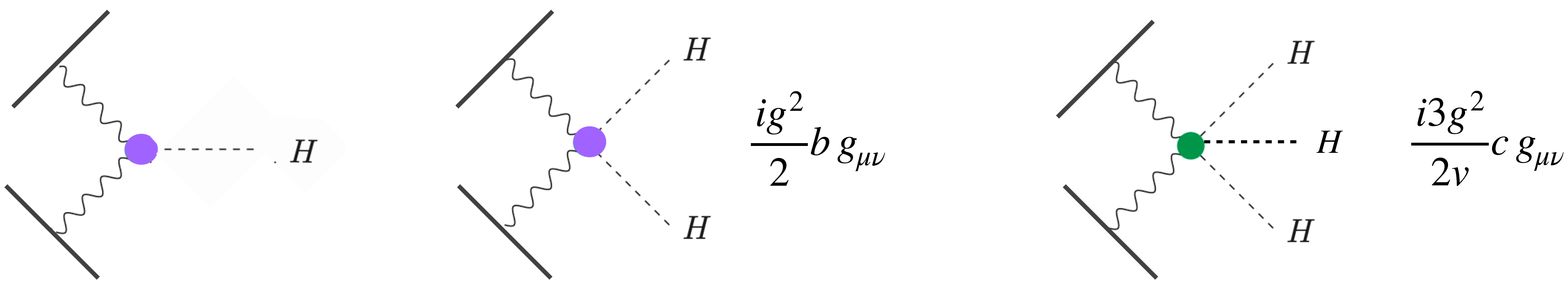

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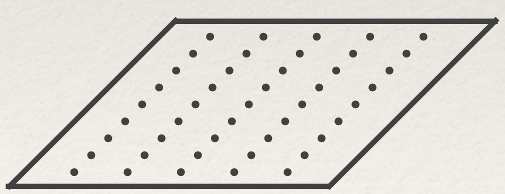

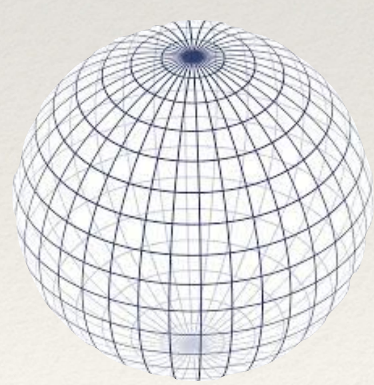

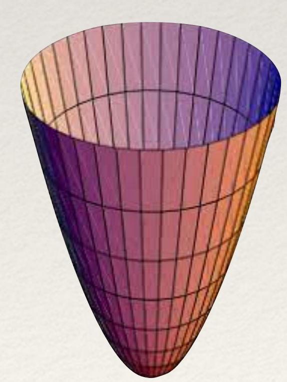

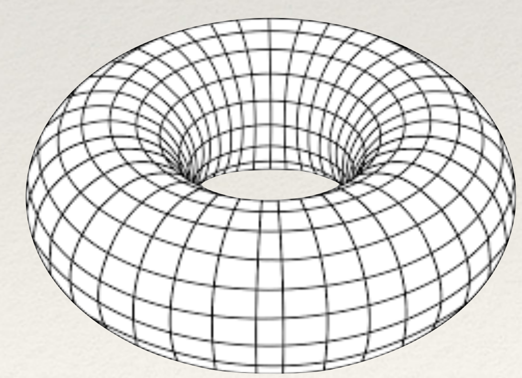

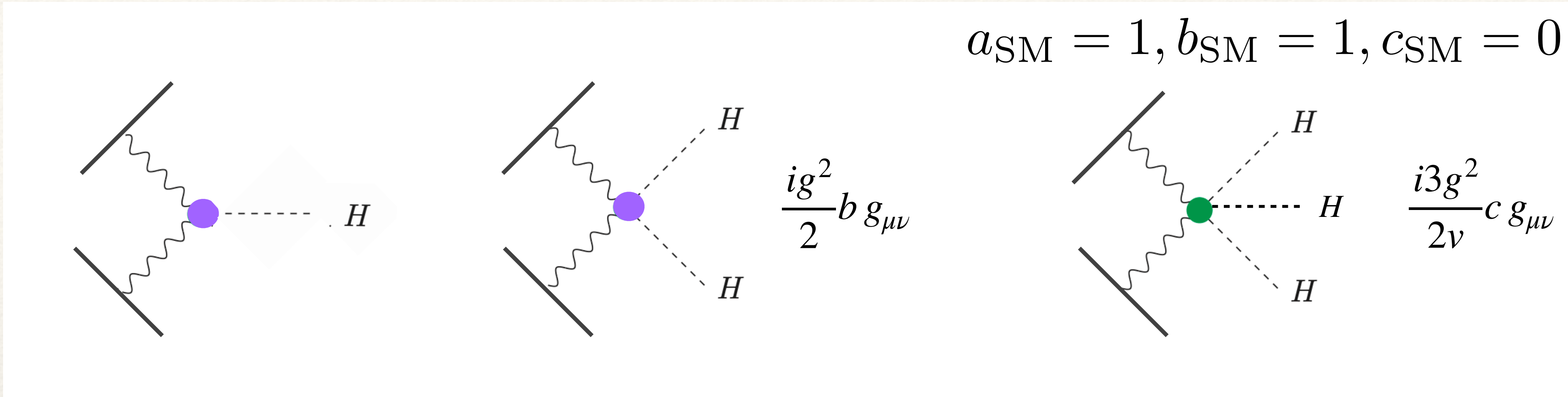

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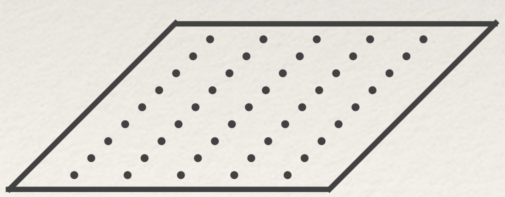

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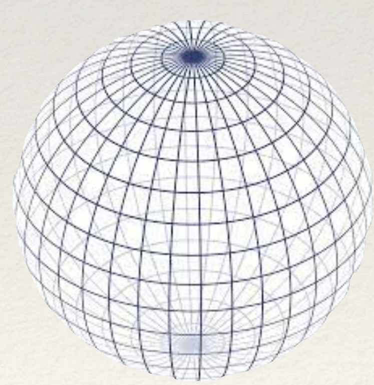

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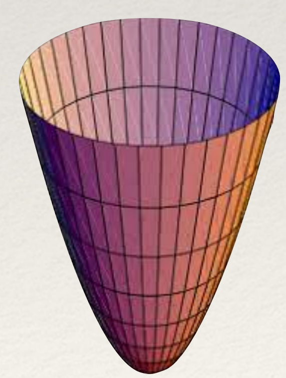

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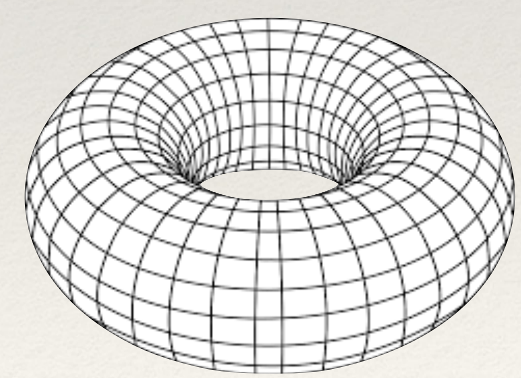
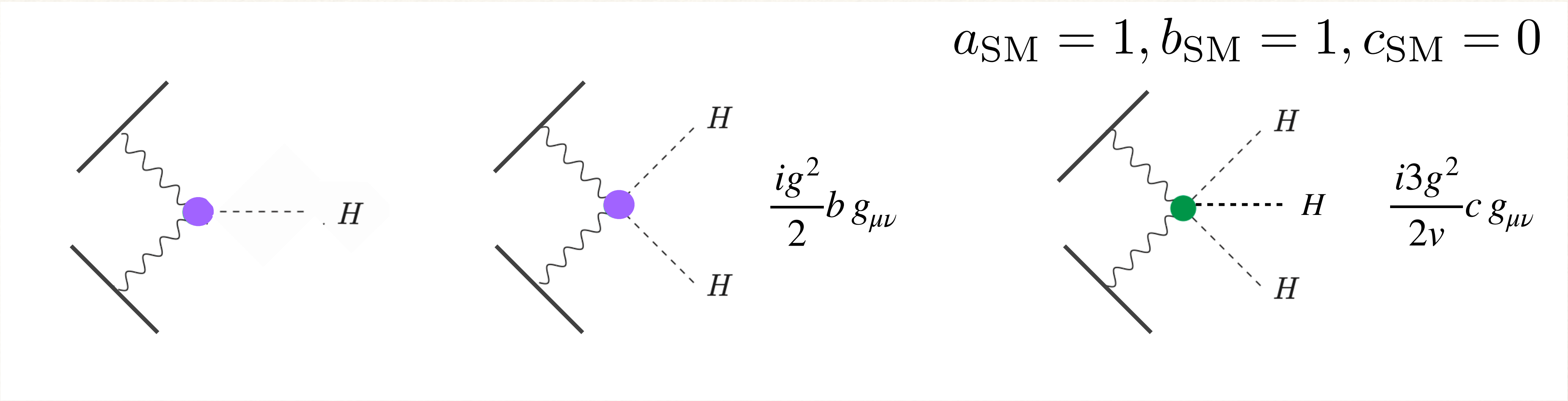


$a, b \simeq 1, c_{\rm SM} \lesssim 1$

gauge-Higgs interactions



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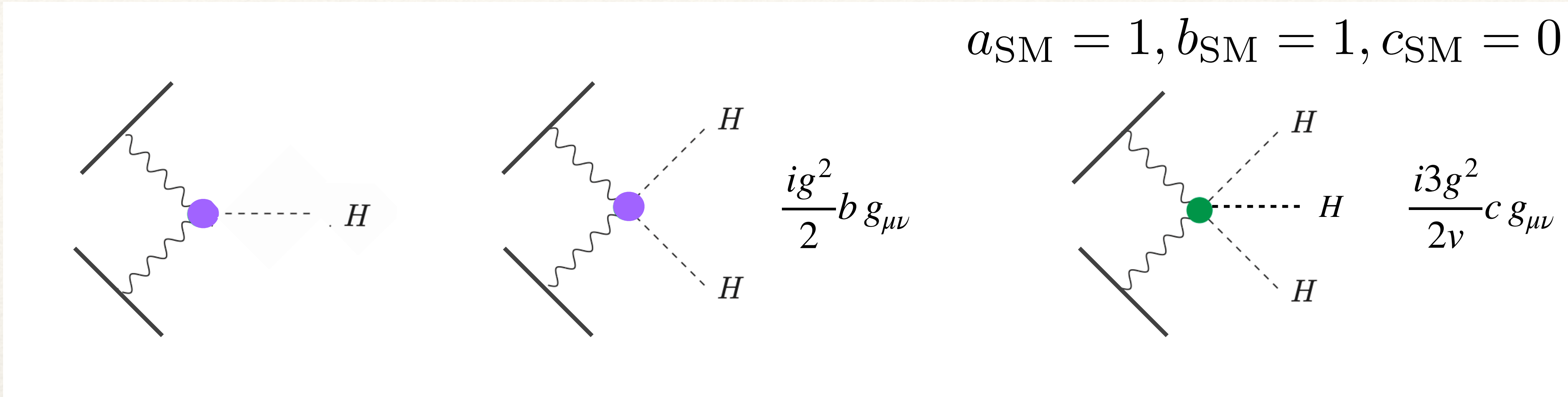
- **...reshaping the ELW PS in the early universe in addition to Higgs-Higgs interactions**

10



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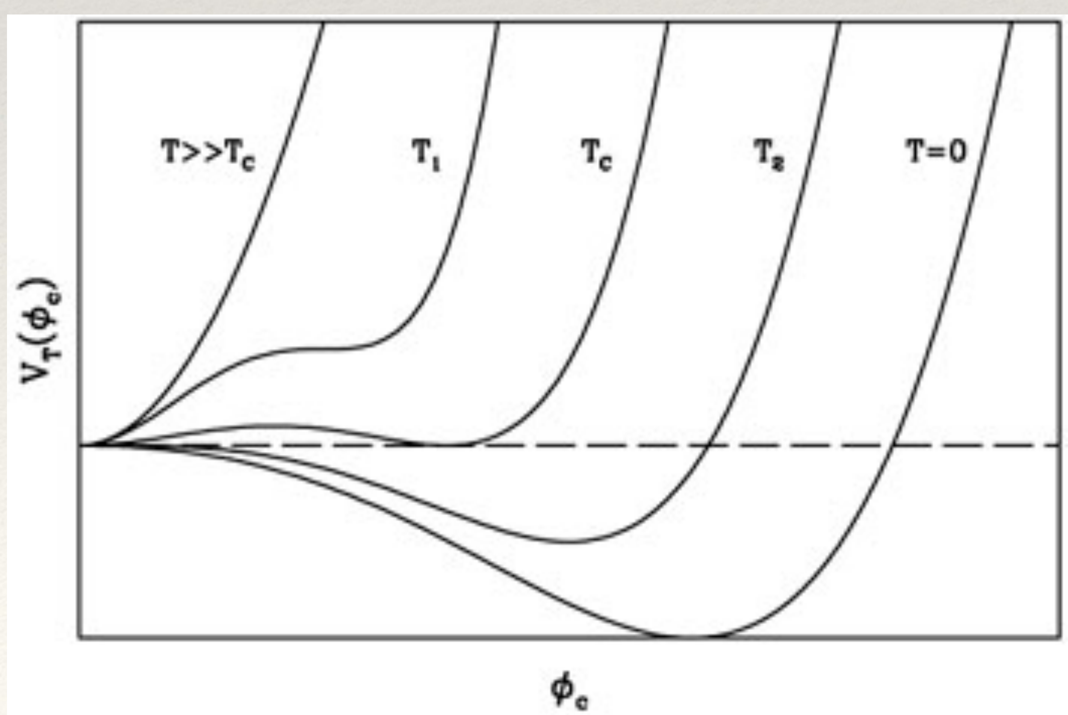

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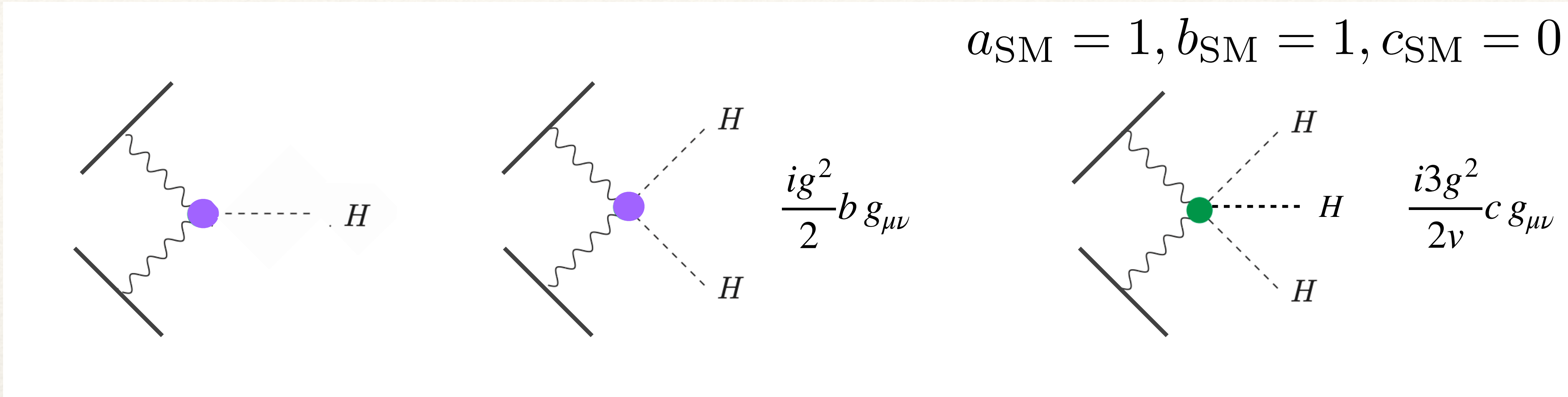

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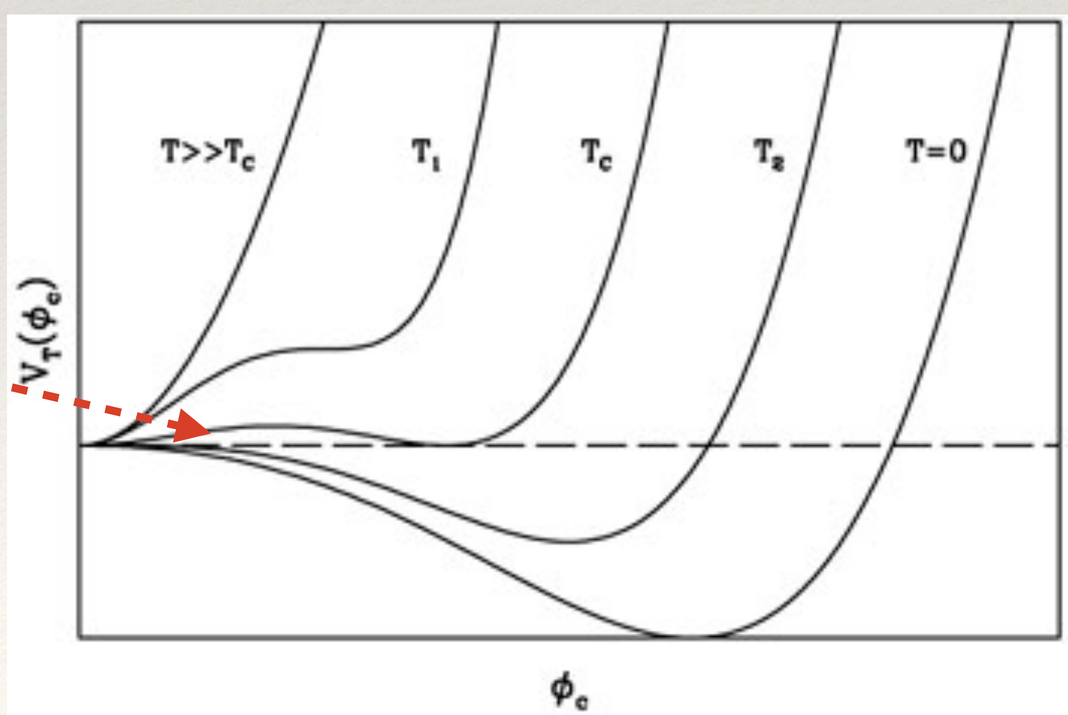

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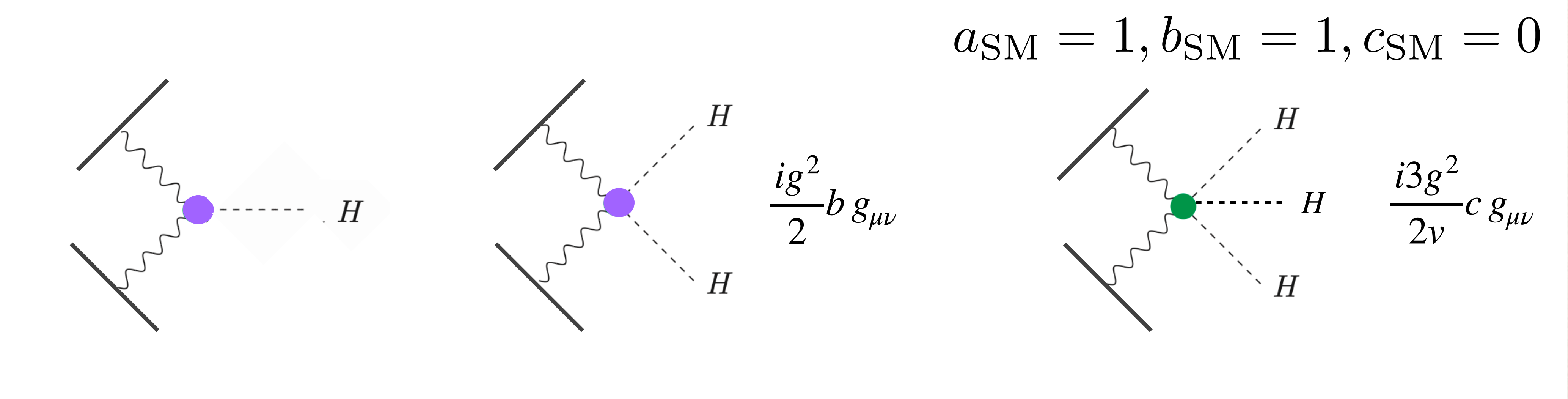

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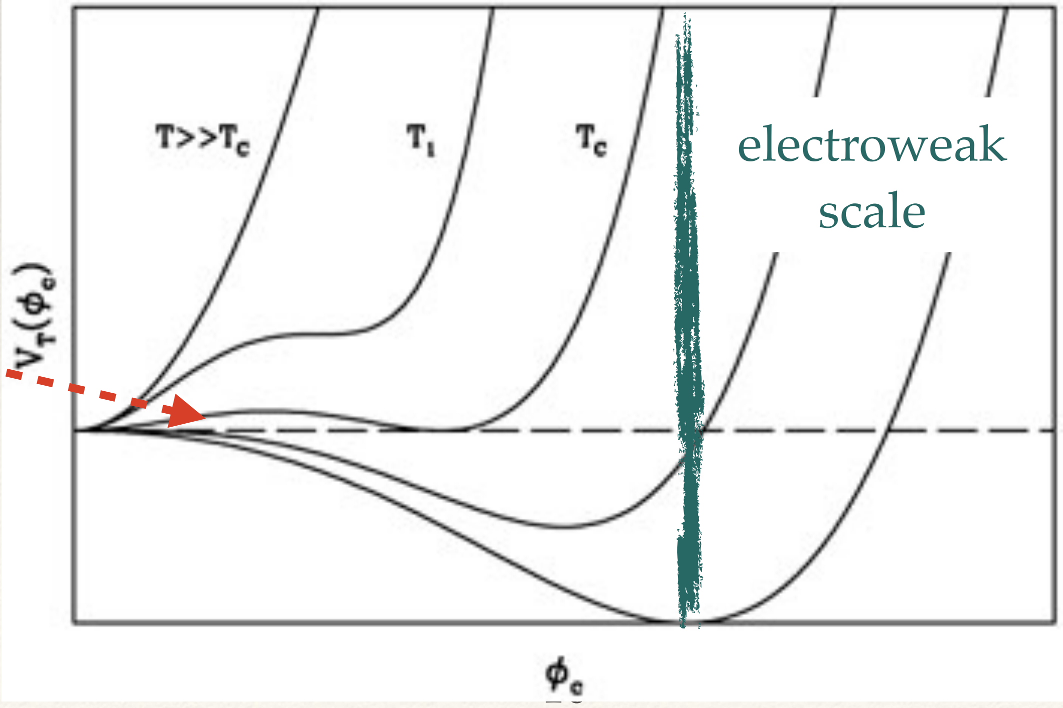

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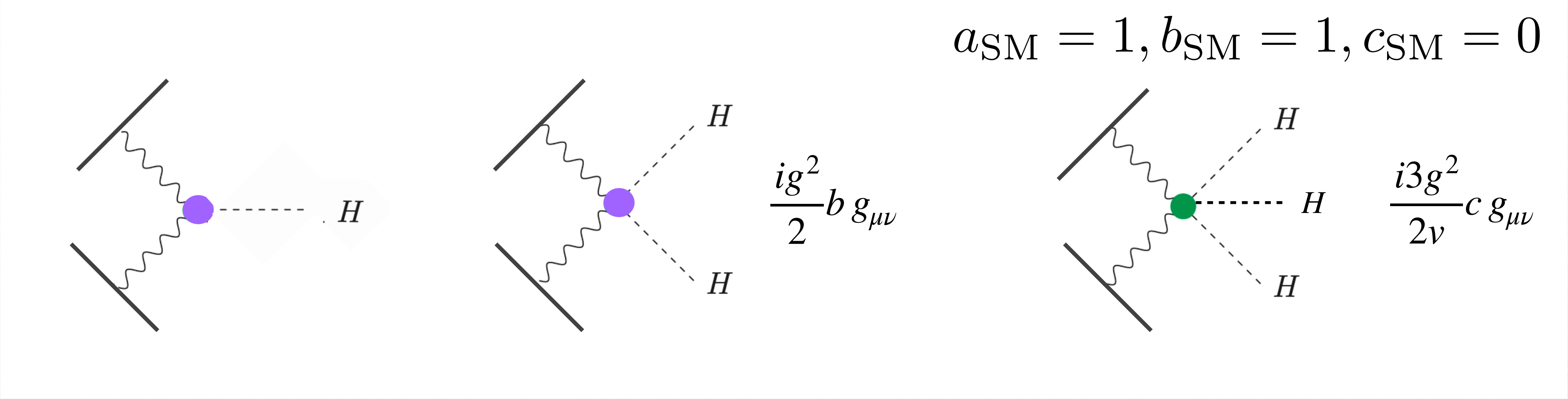

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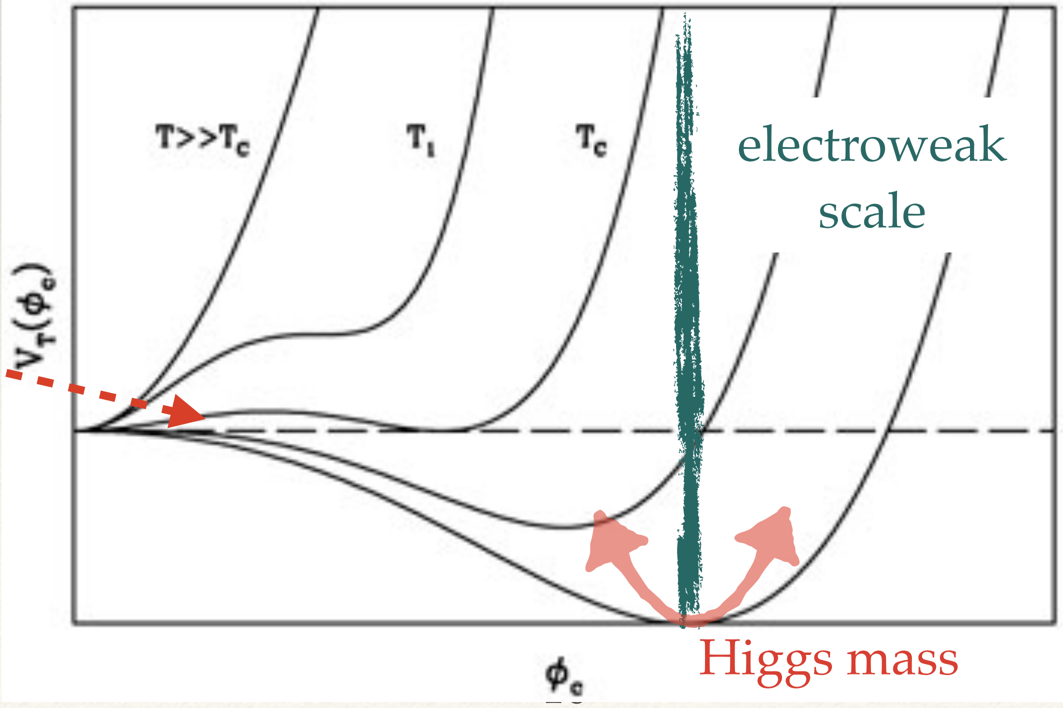

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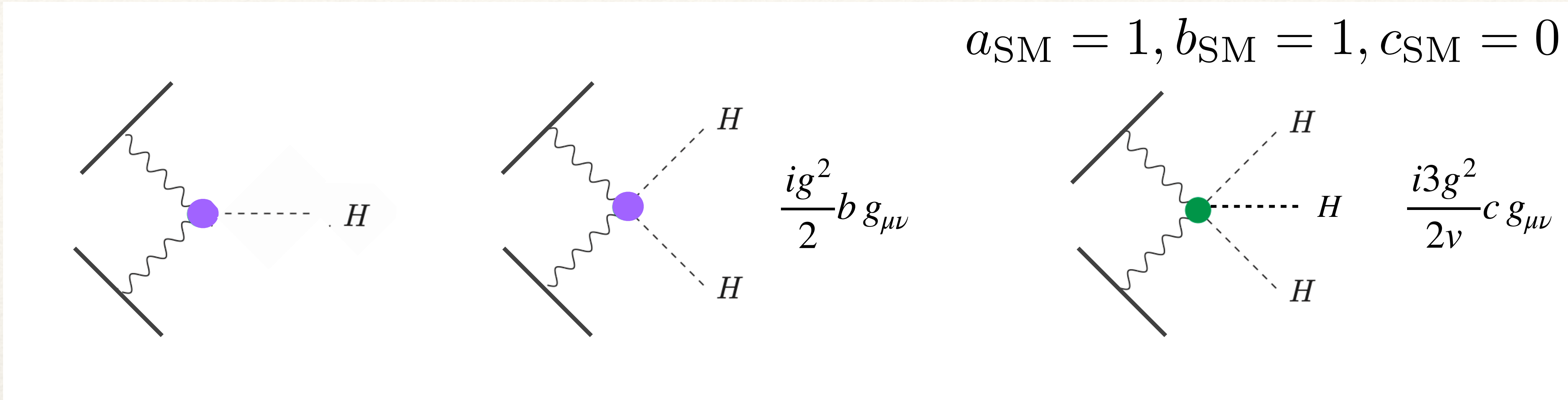
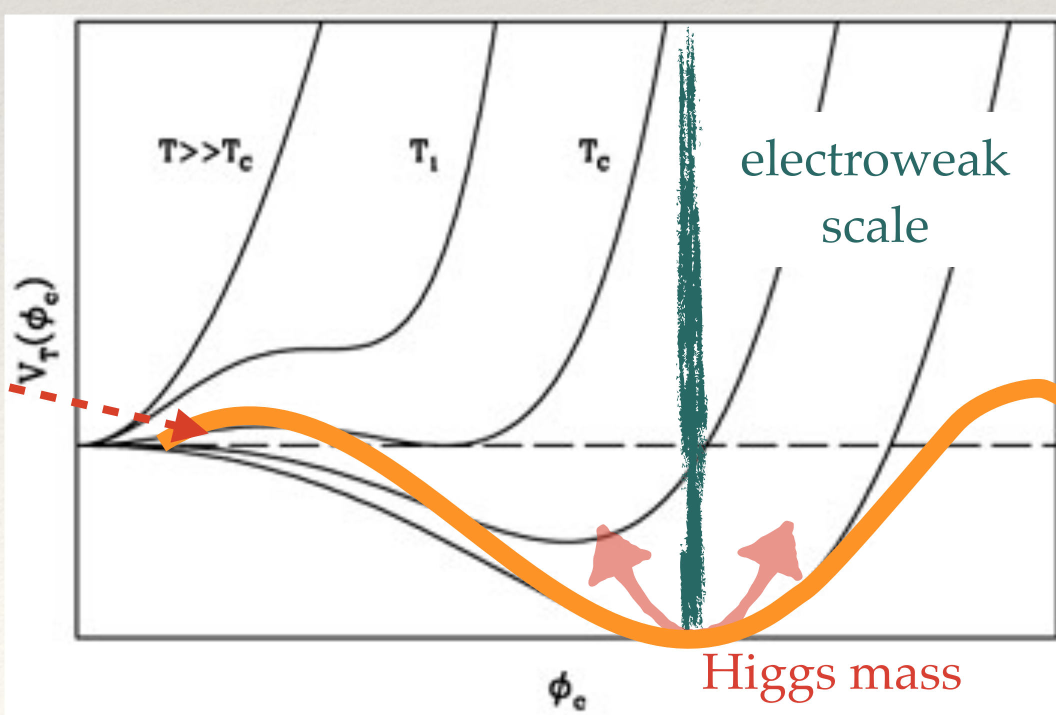
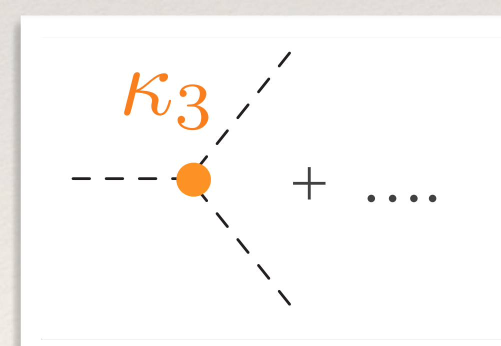


theoretical value	pp @ 100 TeV	$\mu\mu$ @ 10 TeV

- …reshaping the ELW PS in the early universe in addition to Higgs-Higgs interactions

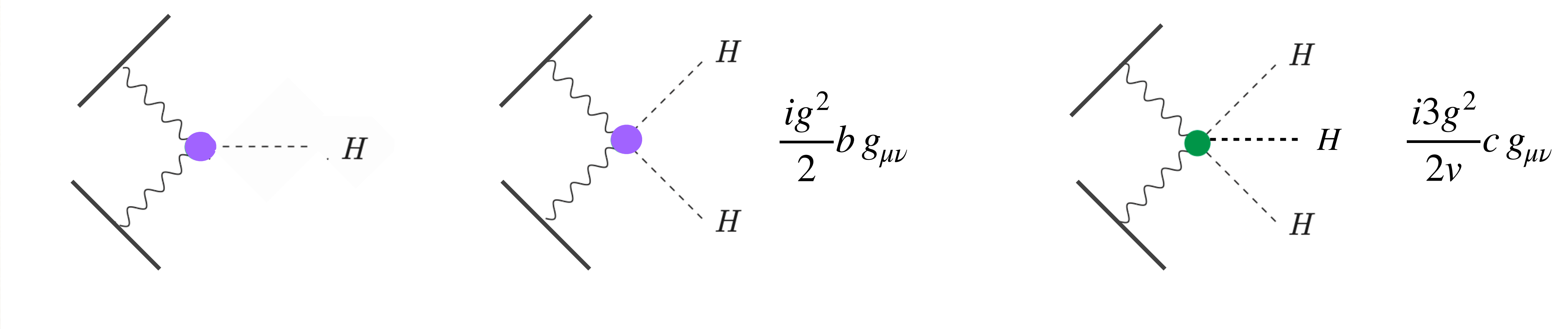
first order PT for BAU





Higgs self couplings

$$a_{\rm SM} = 1, b_{\rm SM} = 1, c_{\rm SM} = 0$$



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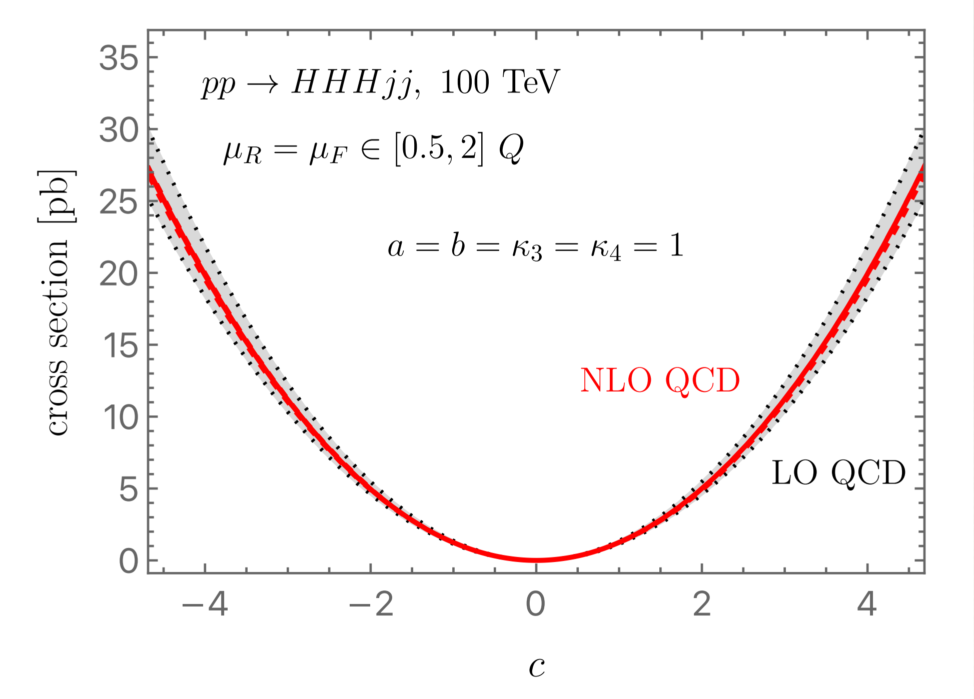

- Stability under QCD corrections of *H/HH/HHH* WBF is a clear window into (strong) ELW effects

[Anisha et al. 2407.20706]

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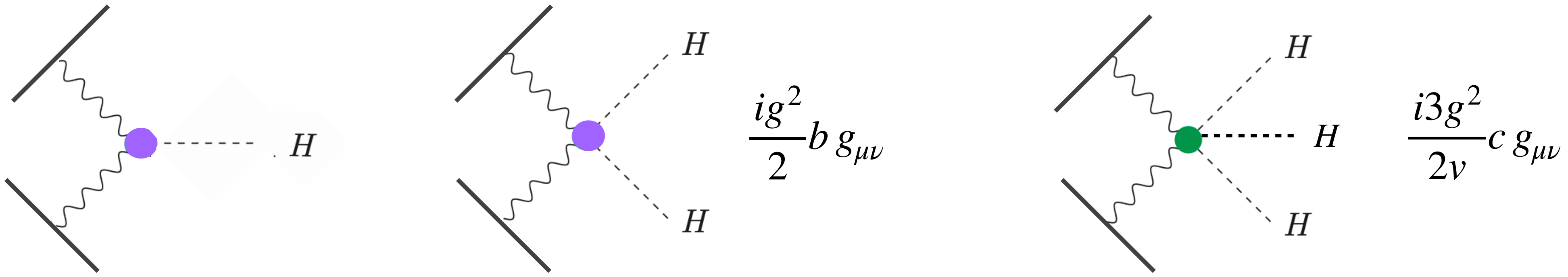

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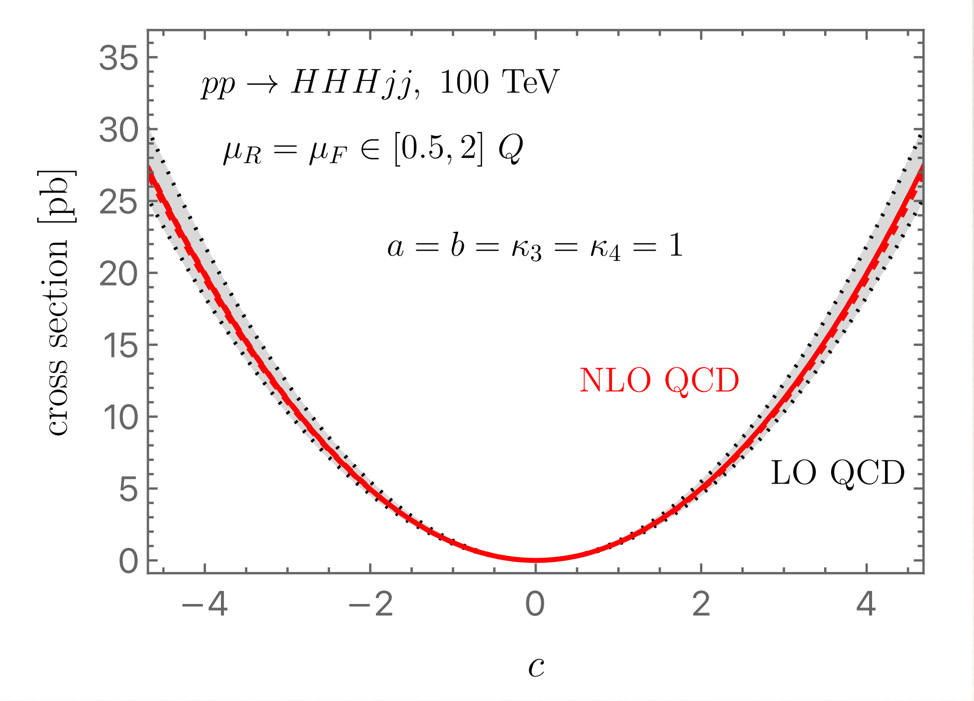

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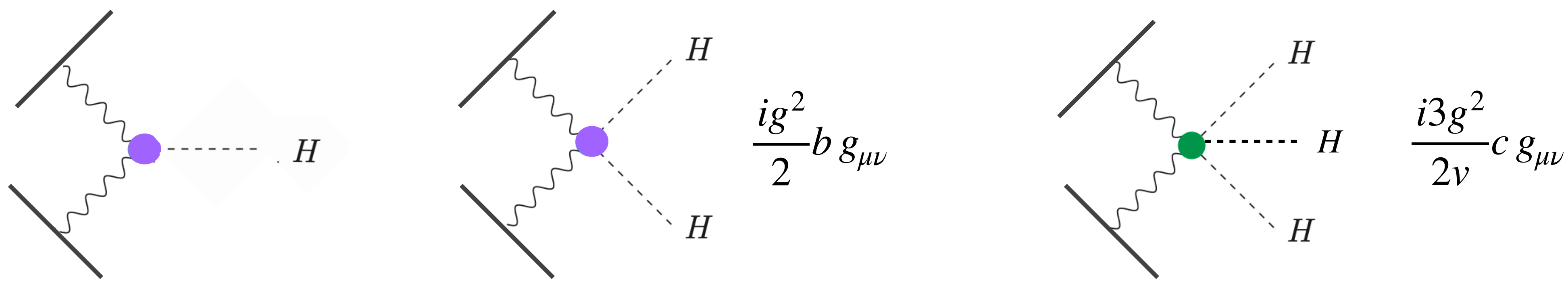

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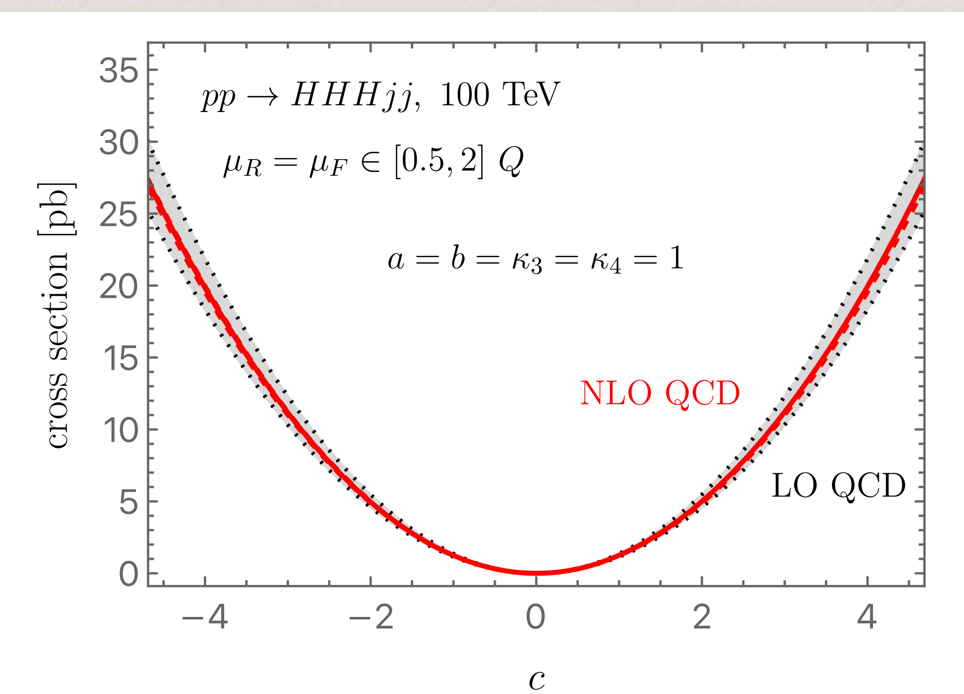

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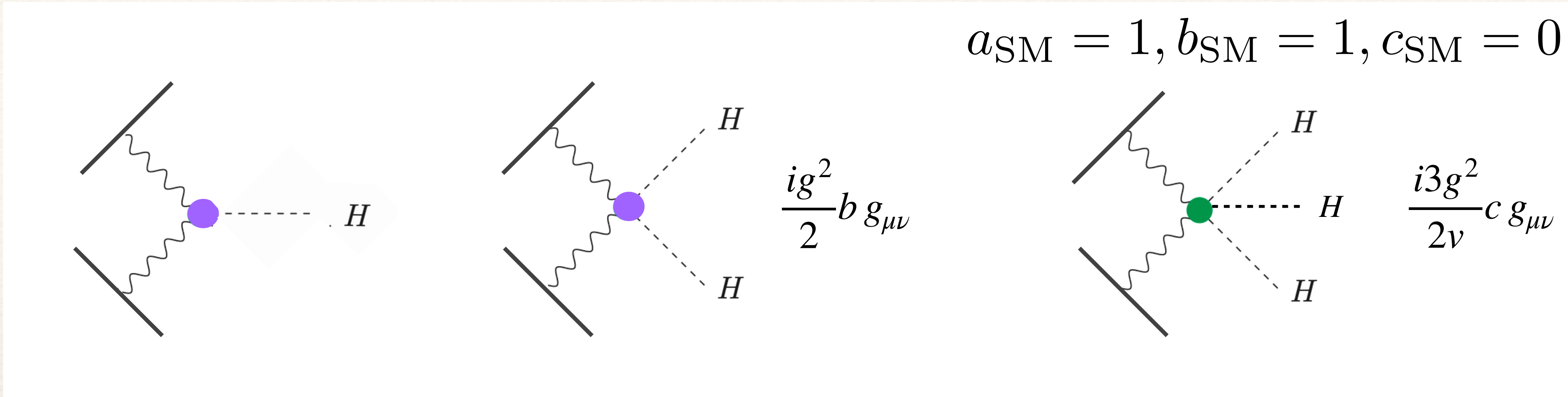
- context with fixed order perturbation theory

c=0.1 → 85% events in the non-perturbative regime

gauge-Higgs interactions



theoretical value

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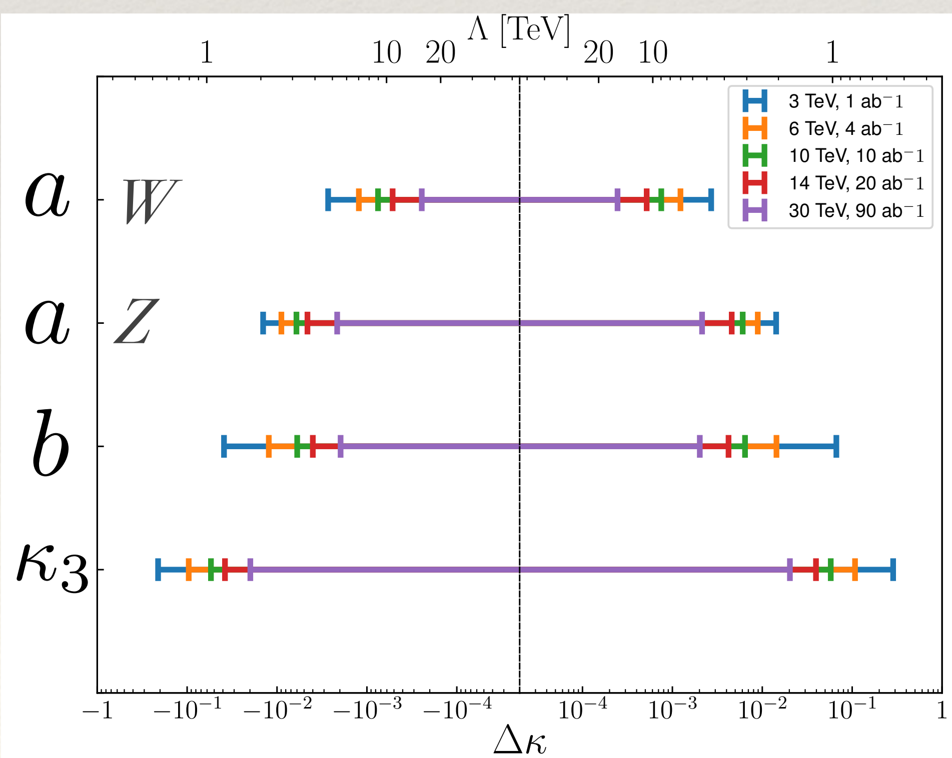
[Chiesa et al., 2003.13628]
[Constantini et al., 2005.10289]
[Celada et al. 2312.13082]



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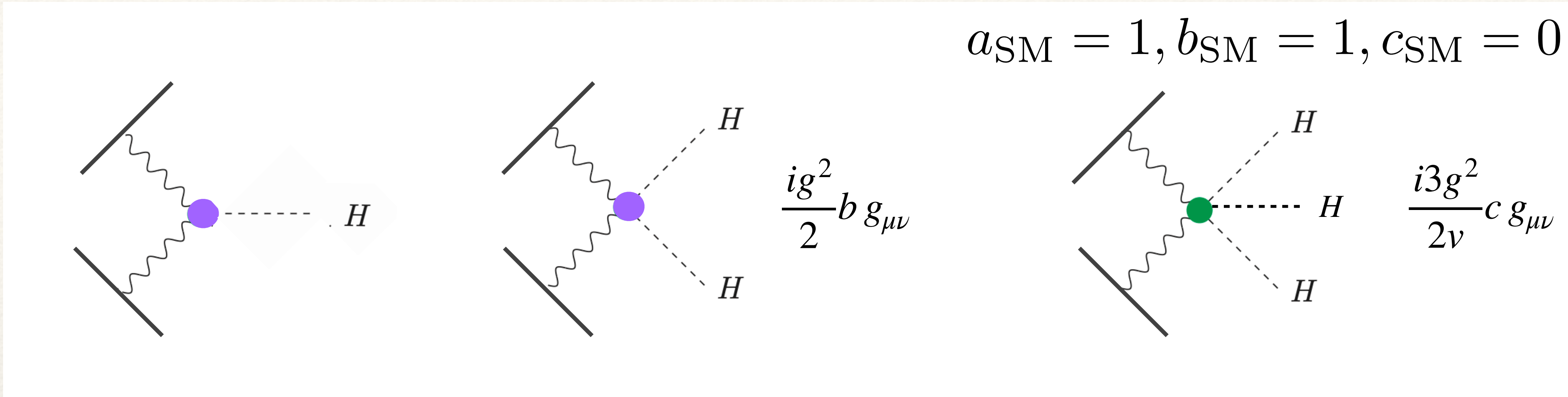

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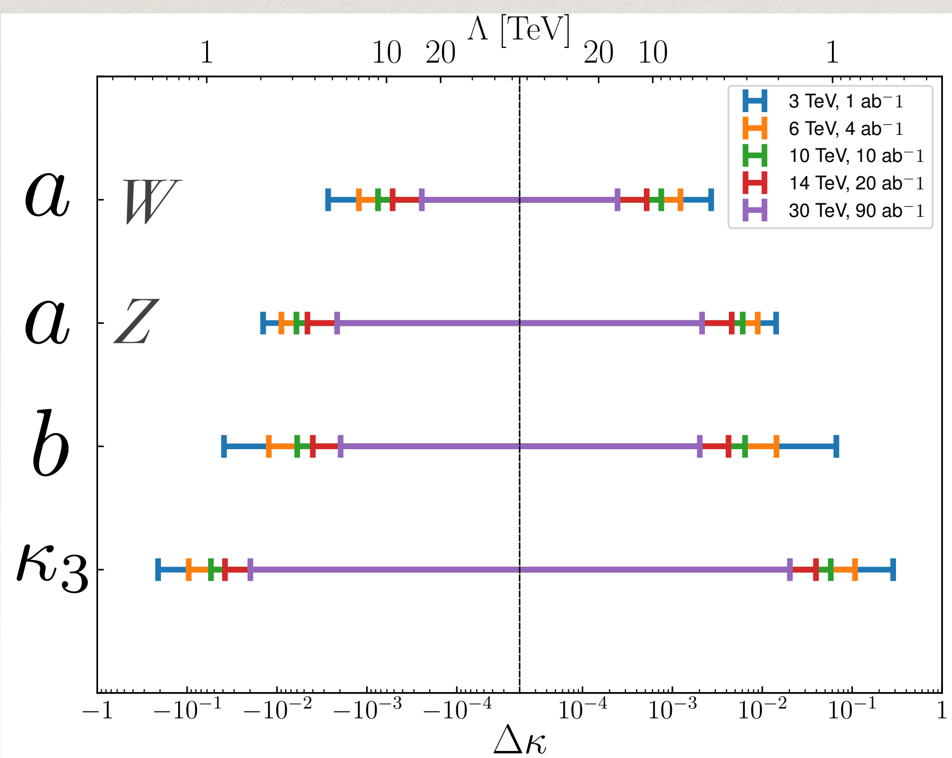

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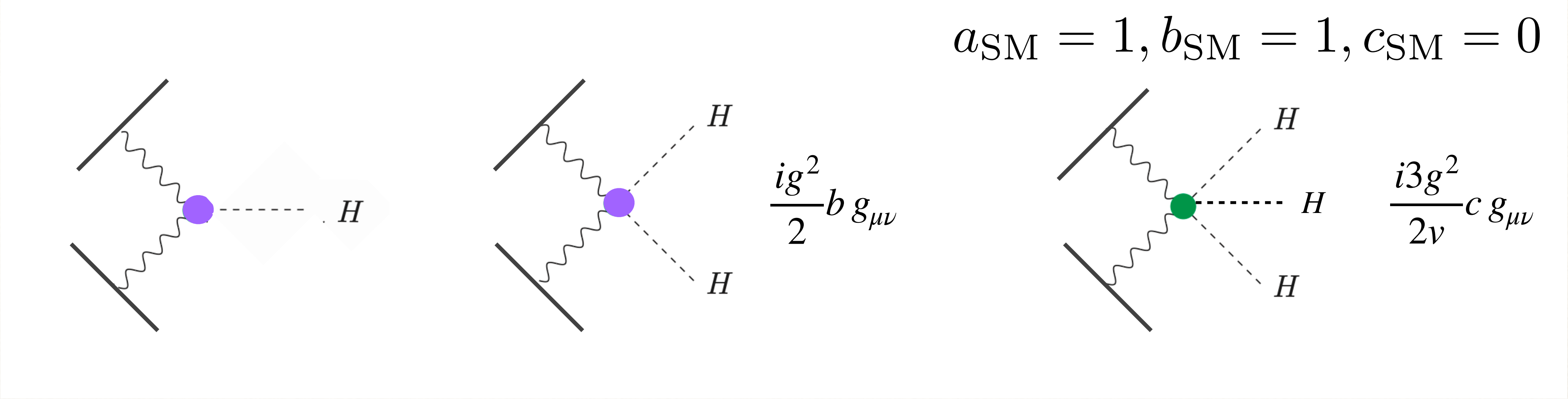

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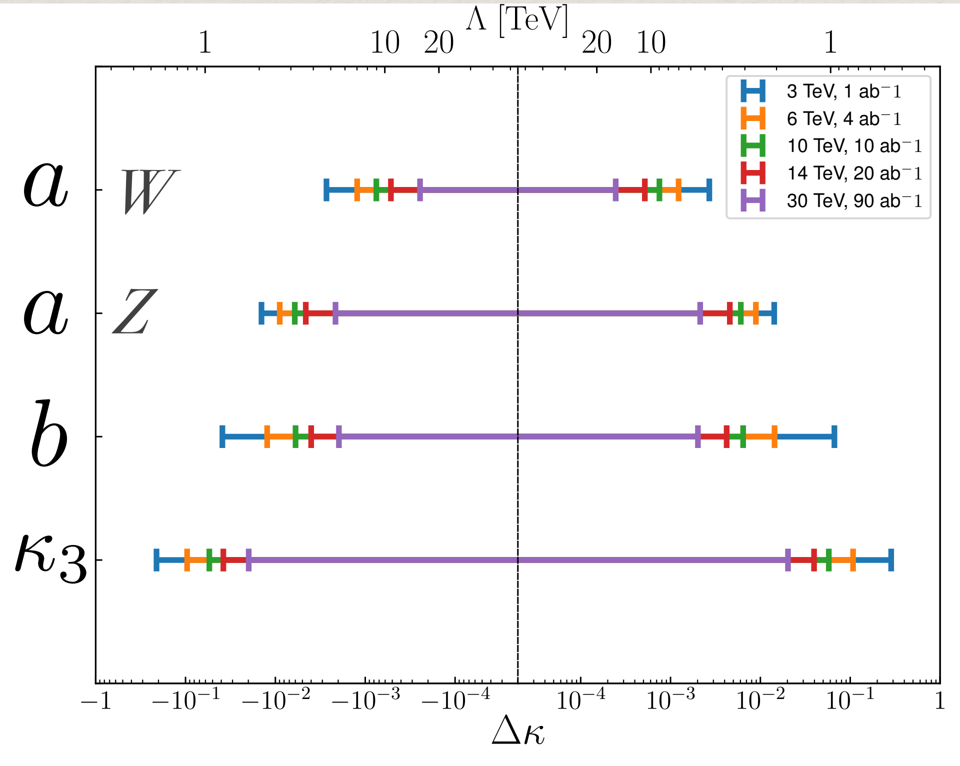

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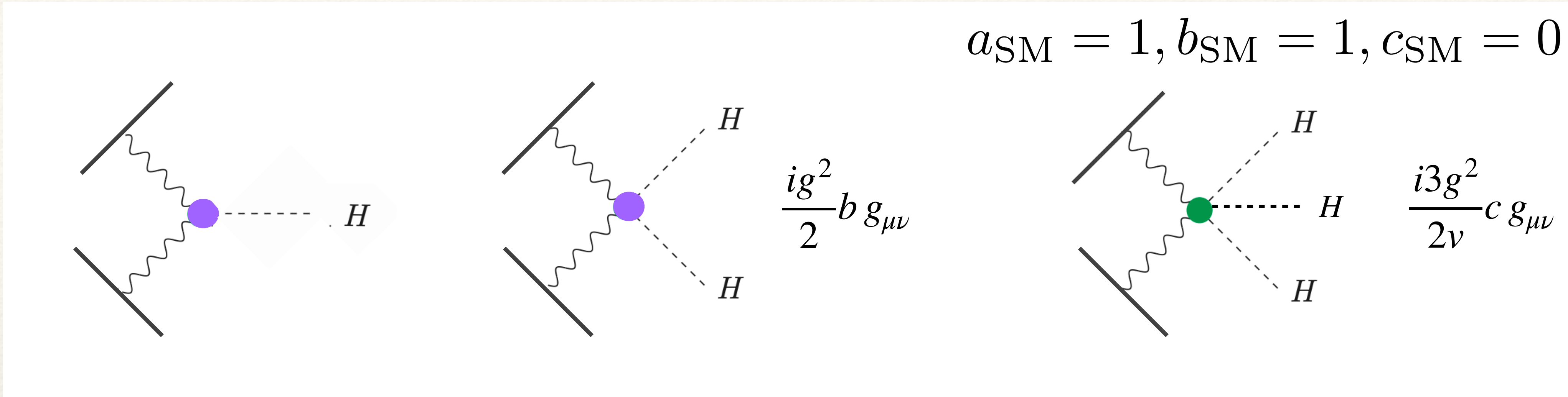

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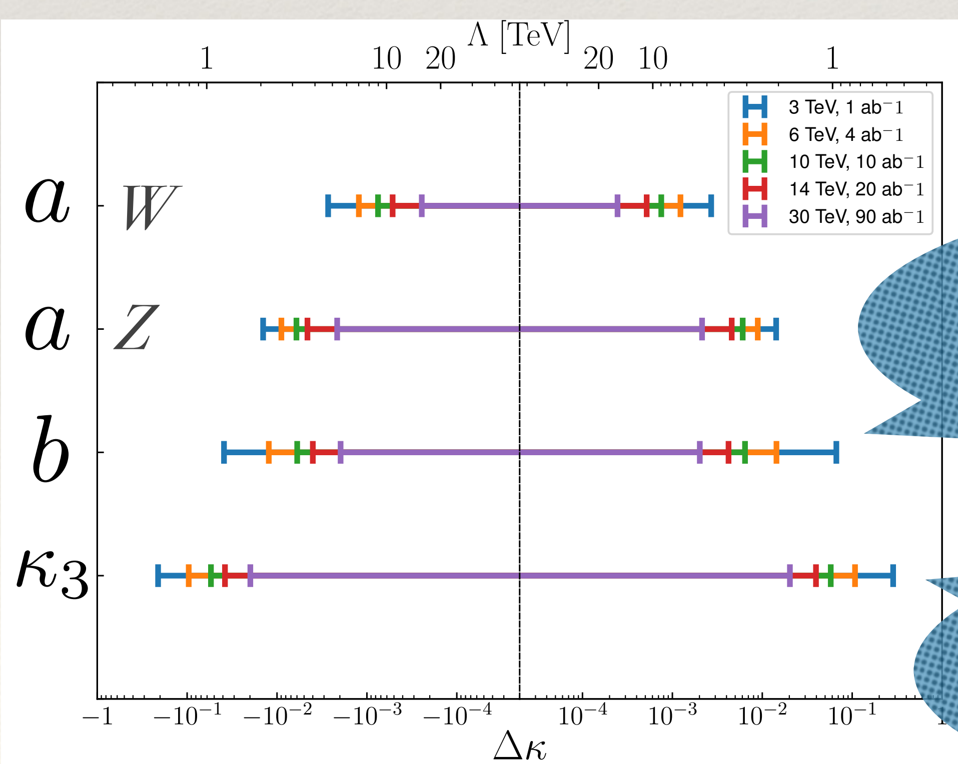

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HL-LHC ~30%
FCC-hh ~ 1%

HL-LHC ~100%
FCC-hh ~ 5%

weak interactions

sensitivity from sampling processes' energy dependence across a few TeV

- many different channels at hadron machines
  - ☛ Drell-Yan/WBF scan a wide range of energies at FCC-hh
  - ☛ pair/triple gauge boson production + EFT + anomalous couplings

LHC dim 6 context [Celada et al. 2407.09600]

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WBF WWjj @ FCC

[Degrande et al. 1309.7452]

Parameter	$\sqrt{s}$ [TeV]	Luminosity [fb^{-1}]	pileup	5σ [TeV^{-4}]	95% CL [TeV^{-4}]
f_{T1}/Λ^4	14	300	50	0.2 (0.4)	0.1 (0.2)
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GeV^{-4}	No form factor		$\Lambda = 1\,\text{TeV}$, n=2	
	lower limit	upper limit	lower limit	upper limit
$\frac{f_{S0}}{\Lambda^4}$	-4.56×10^{-10}	4.58×10^{-10}	-3.08×10^{-9}	3.39×10^{-9}
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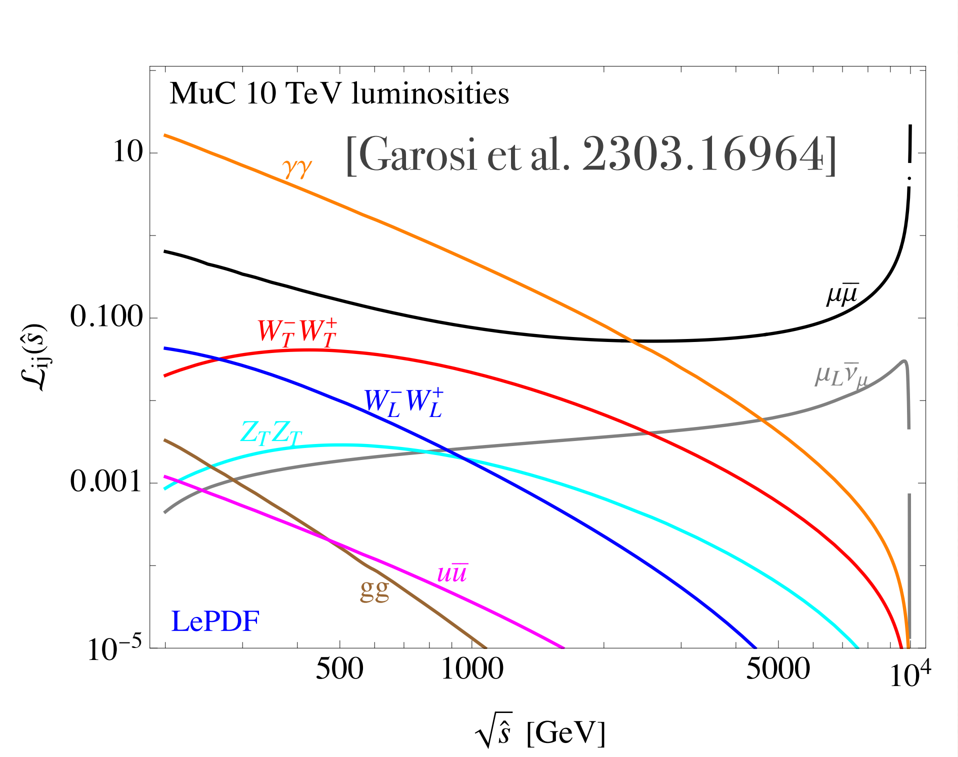
weak interactions

- $\mu\mu$@10 TeV efficiently collides Ws above the weak threshold



WBF @ $\mu\mu$

WW$\nu\nu$	$\sqrt{s} = 6$ TeV Limit (TeV^{-4})	$\sqrt{s} = 6$ TeV Unitarity Bound (TeV)	$\sqrt{s} = 10$ TeV Limit (TeV^{-4})	$\sqrt{s} = 10$ TeV Unitarity Bound (TeV)
$f_{S,0}/\Lambda^4$	[−0.19, 0.18]	[3.8, 4.4]	[−0.034, 0.033]	[5.8, 6.8]
$f_{S,1}/\Lambda^4$	[−0.11, 0.11]	[4.5, 4.3]	[−0.019, 0.019]	[6.8, 6.6]
$f_{T,0}/\Lambda^4$	[−0.0049, 0.0025]	[6.2, 6.3]	[−0.00070, 0.00051]	[10.0, 9.3]
$f_{T,1}/\Lambda^4$	[−0.0017, 0.0014]	[7.7, 8.1]	[−0.00089, 0.00053]	[9.0, 10.3]
$f_{T,2}/\Lambda^4$	[−0.011, 0.0046]	[6.6, 7.0]	[−0.0015, 0.00082]	[10.8, 10.7]

[Abbott et al. 2203.08135]

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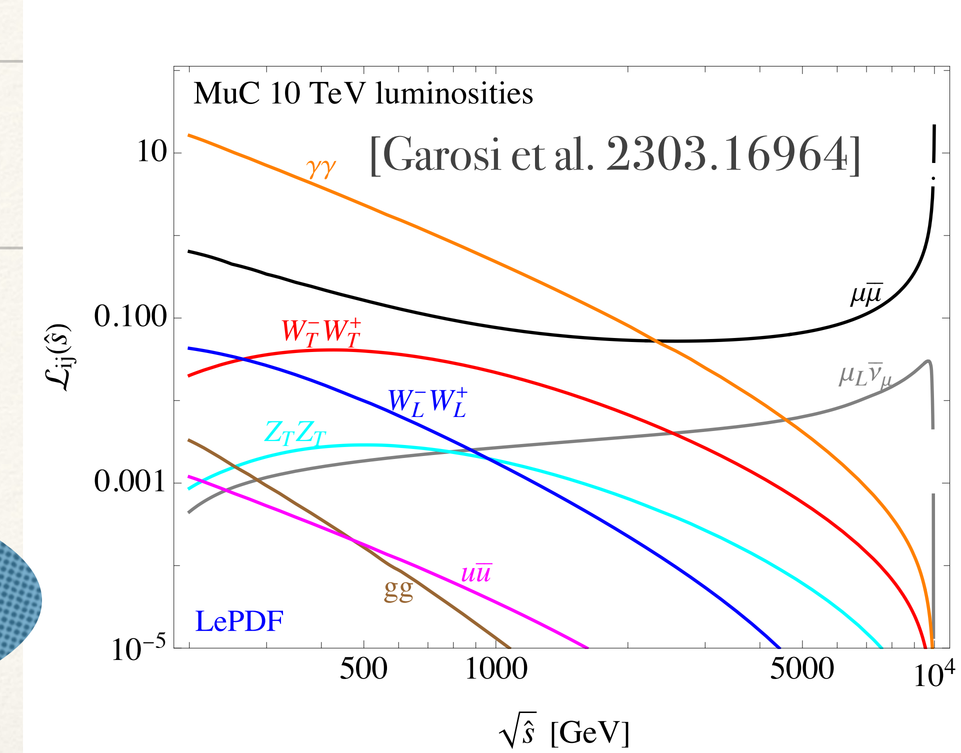
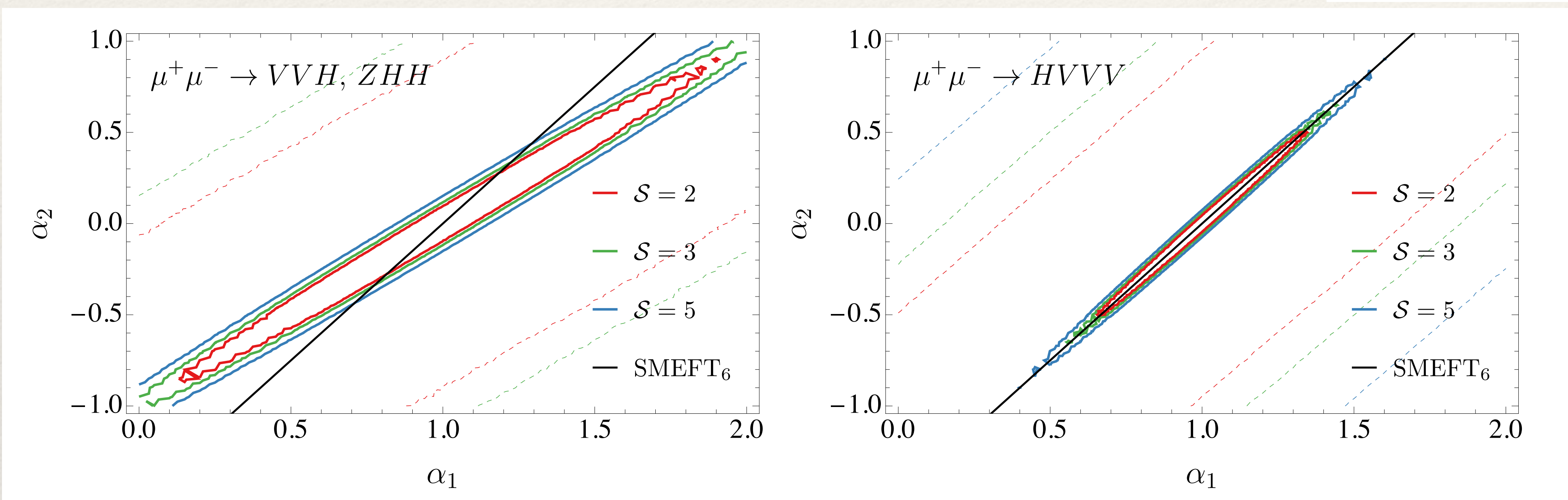
sensitivity from (rare) processes @ 10 TeV



[Celada et al. 2312.13082]



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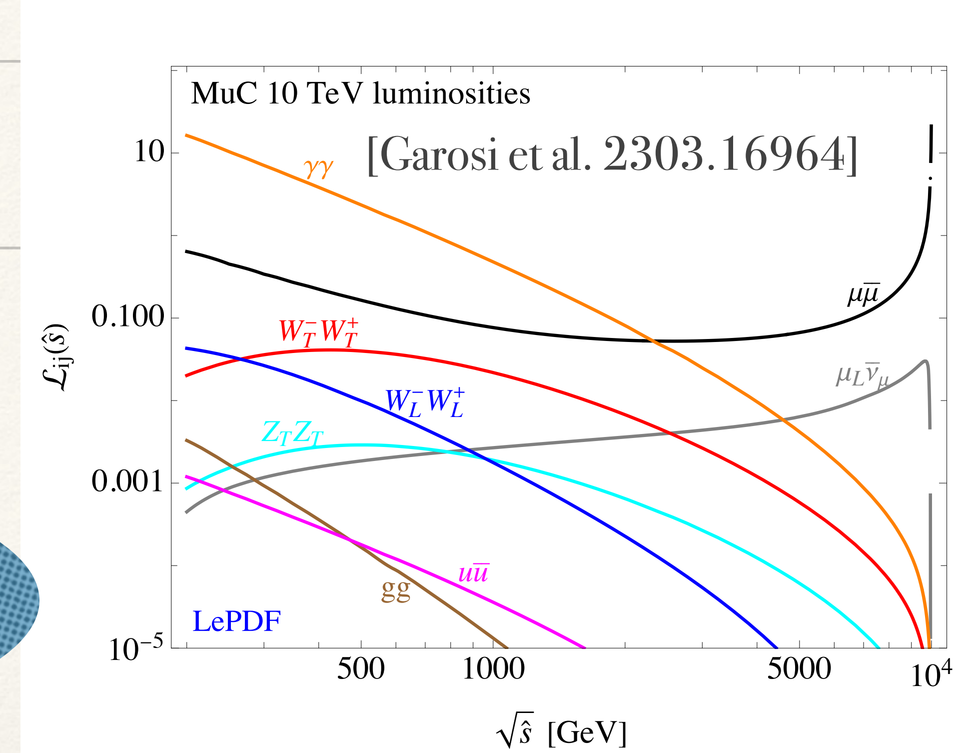

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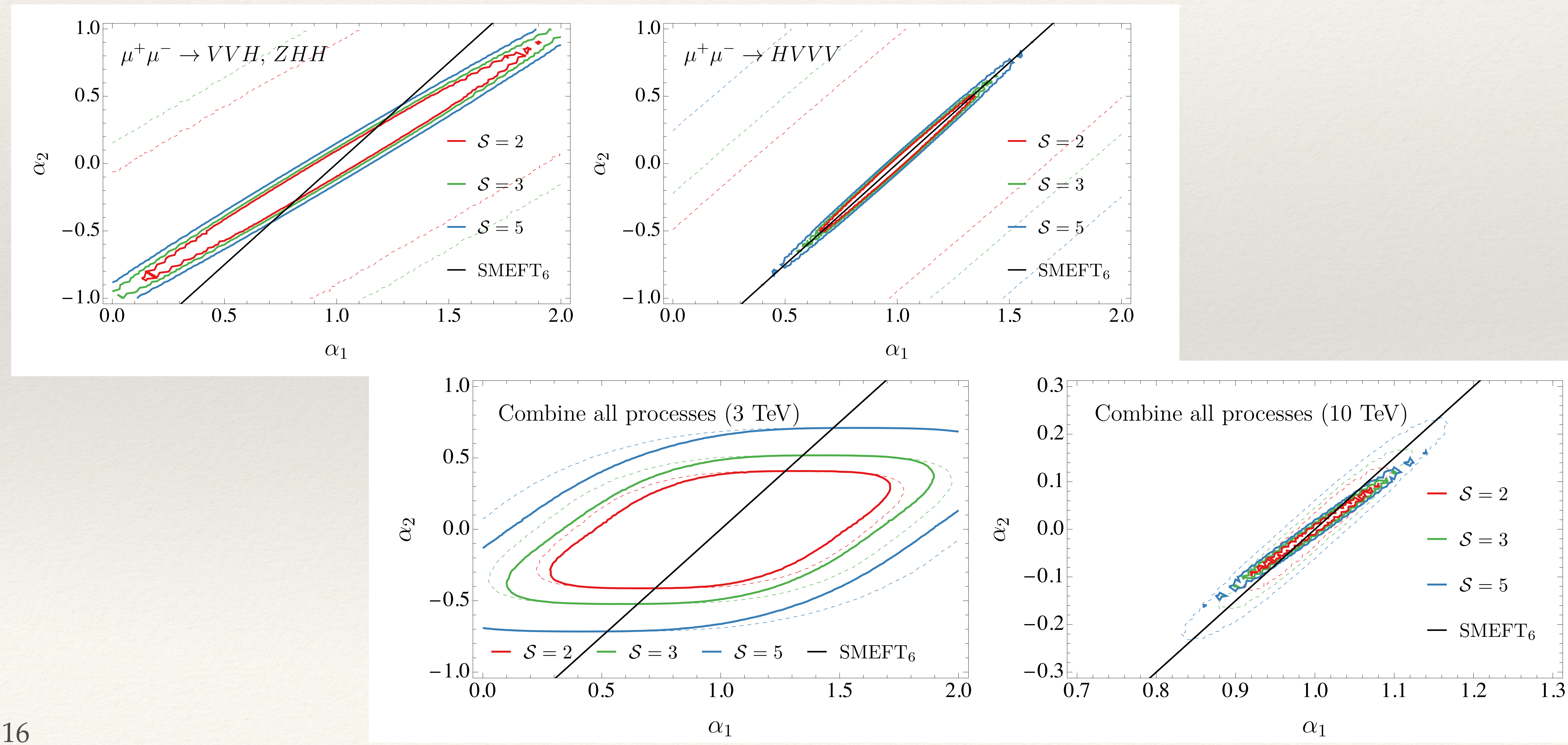

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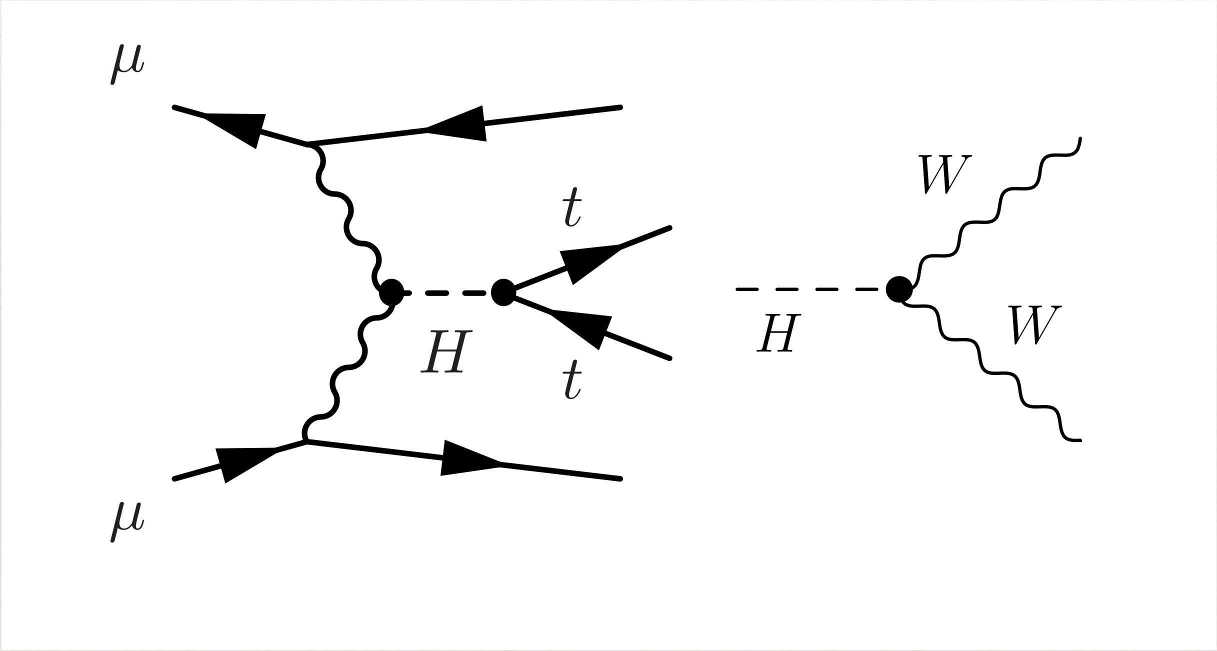

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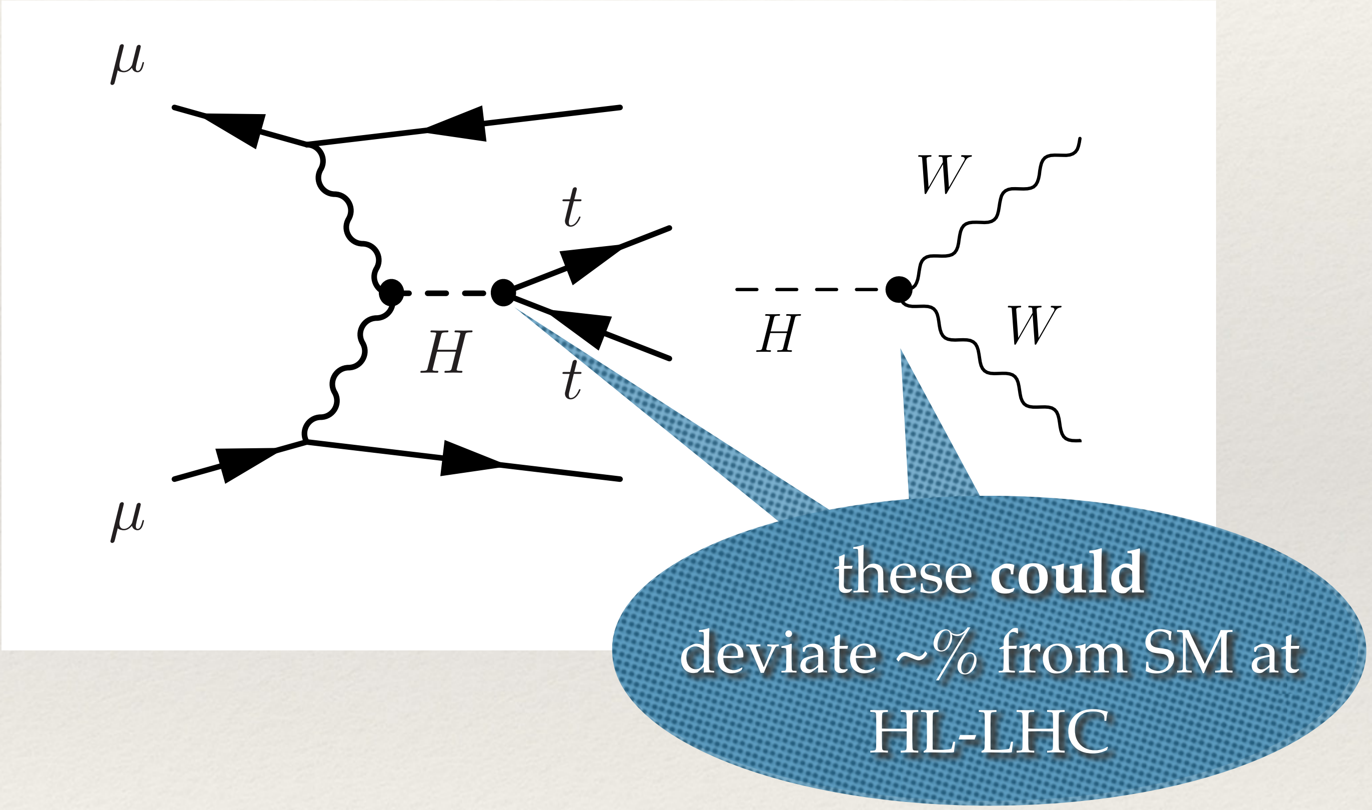

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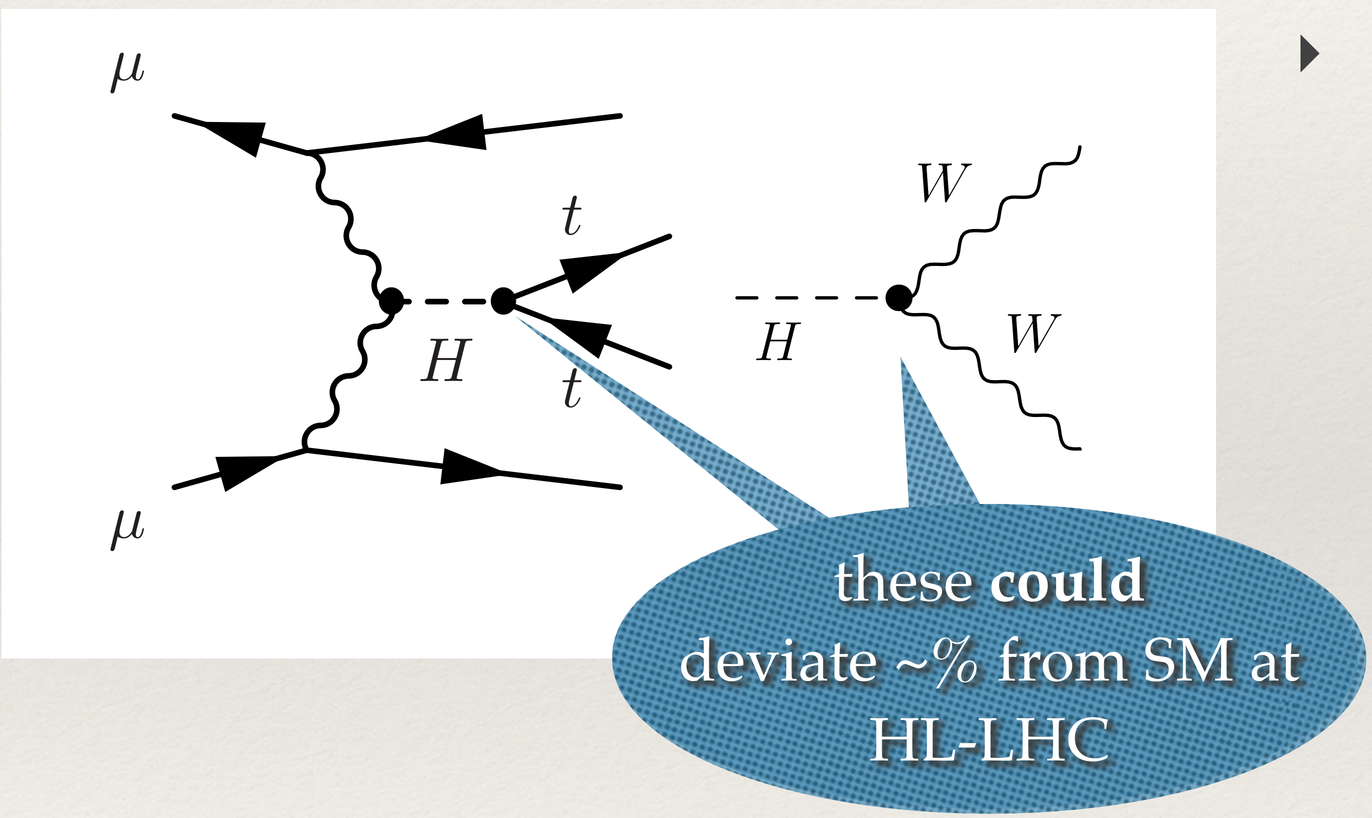

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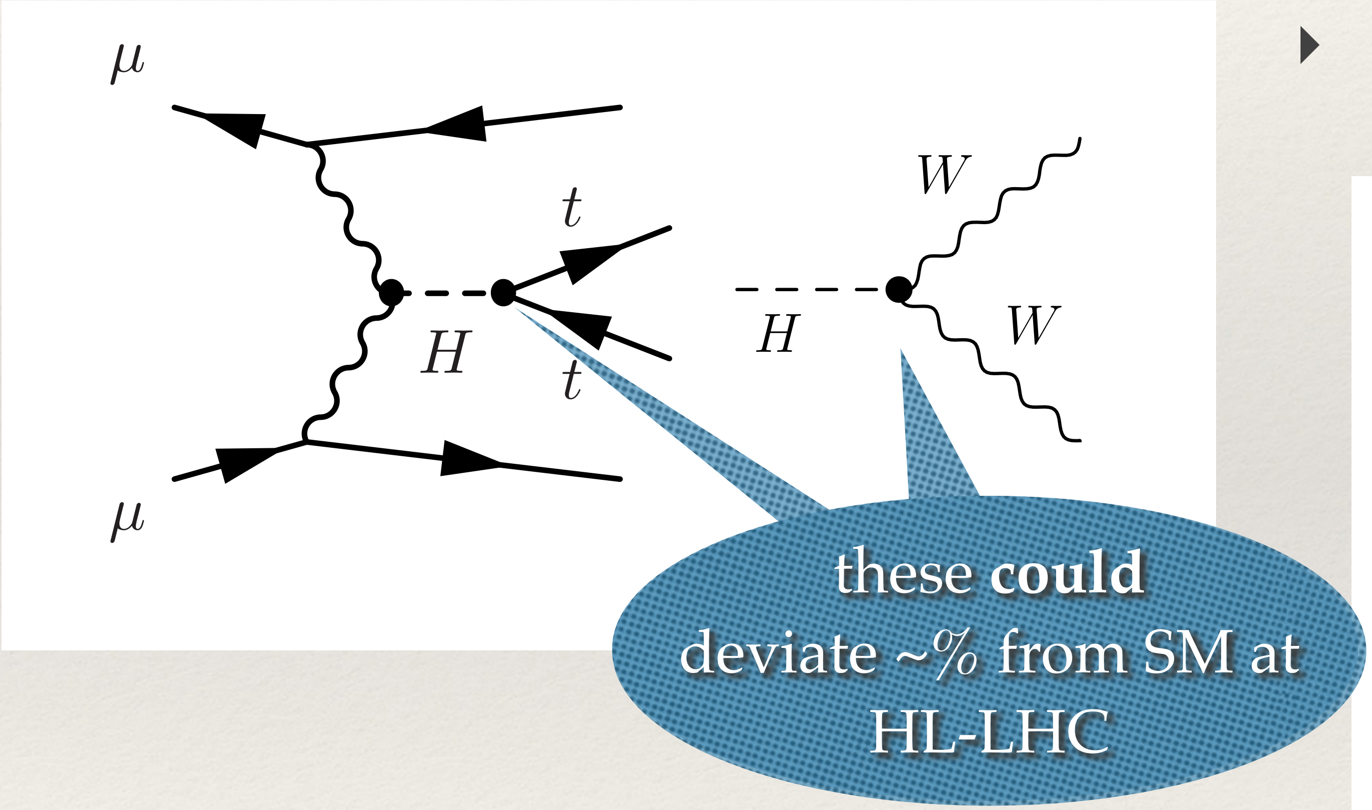

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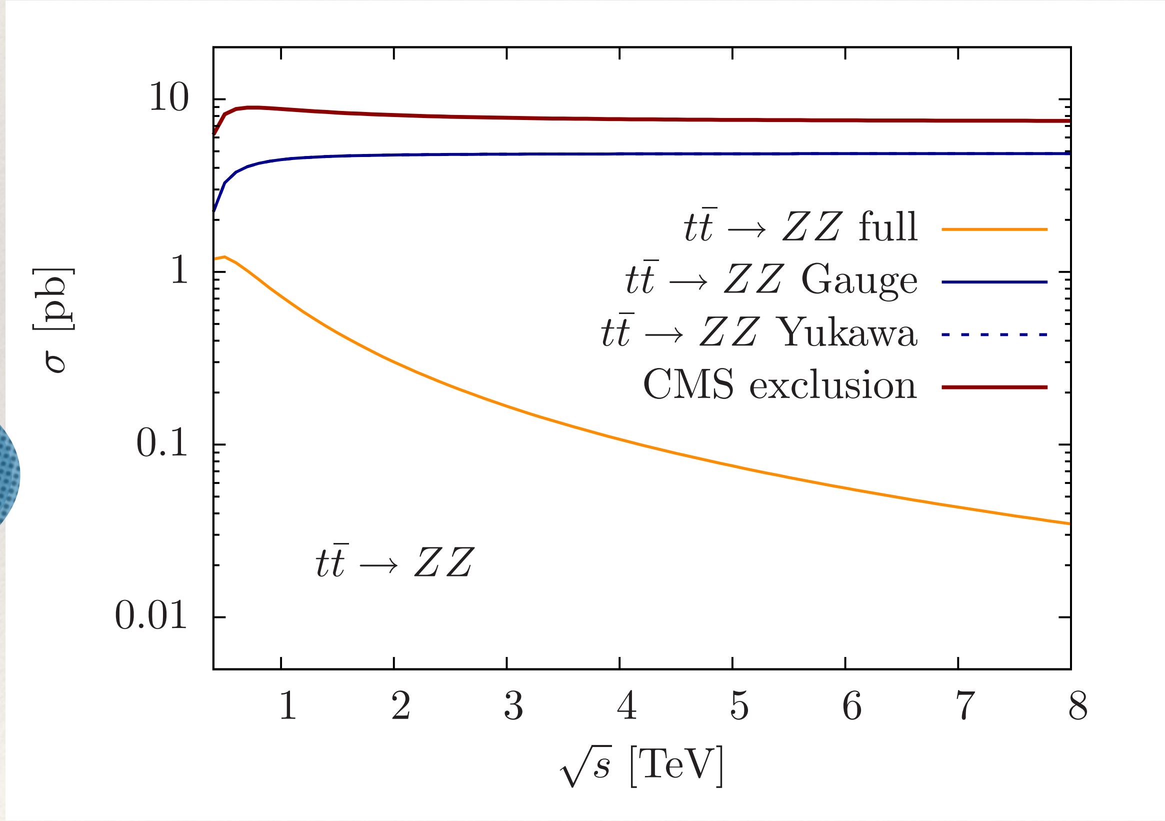

[CE, Spannowsky 1405.0285]

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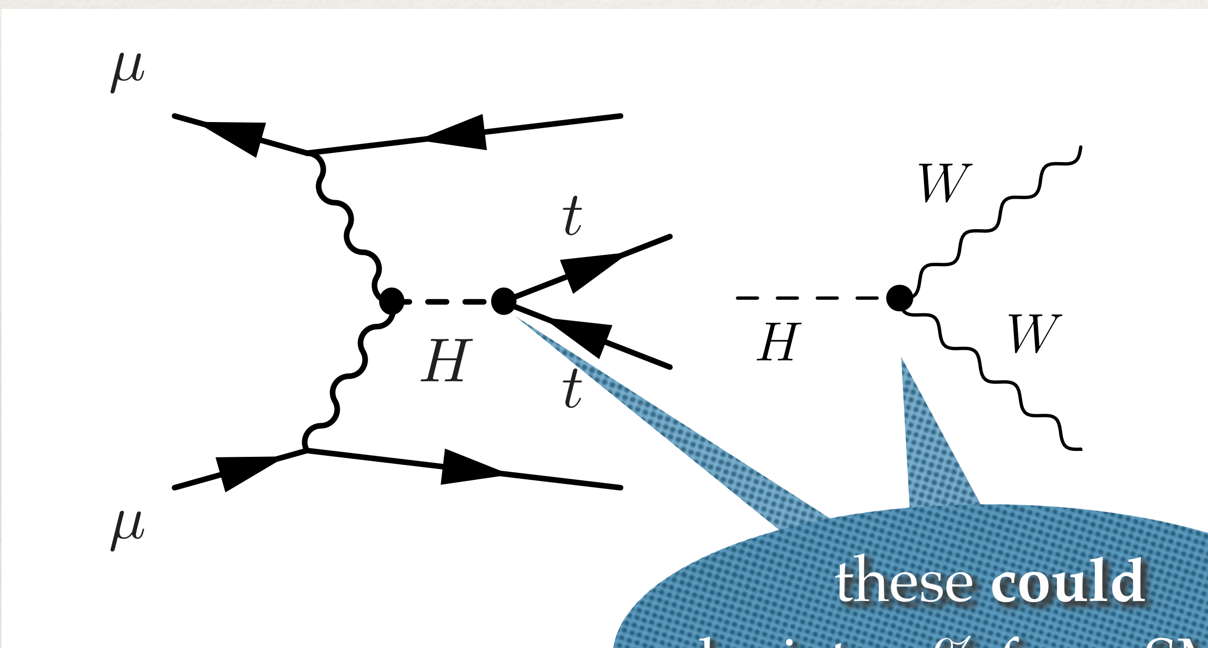

these **could** deviate ~% from SM at HL-LHC

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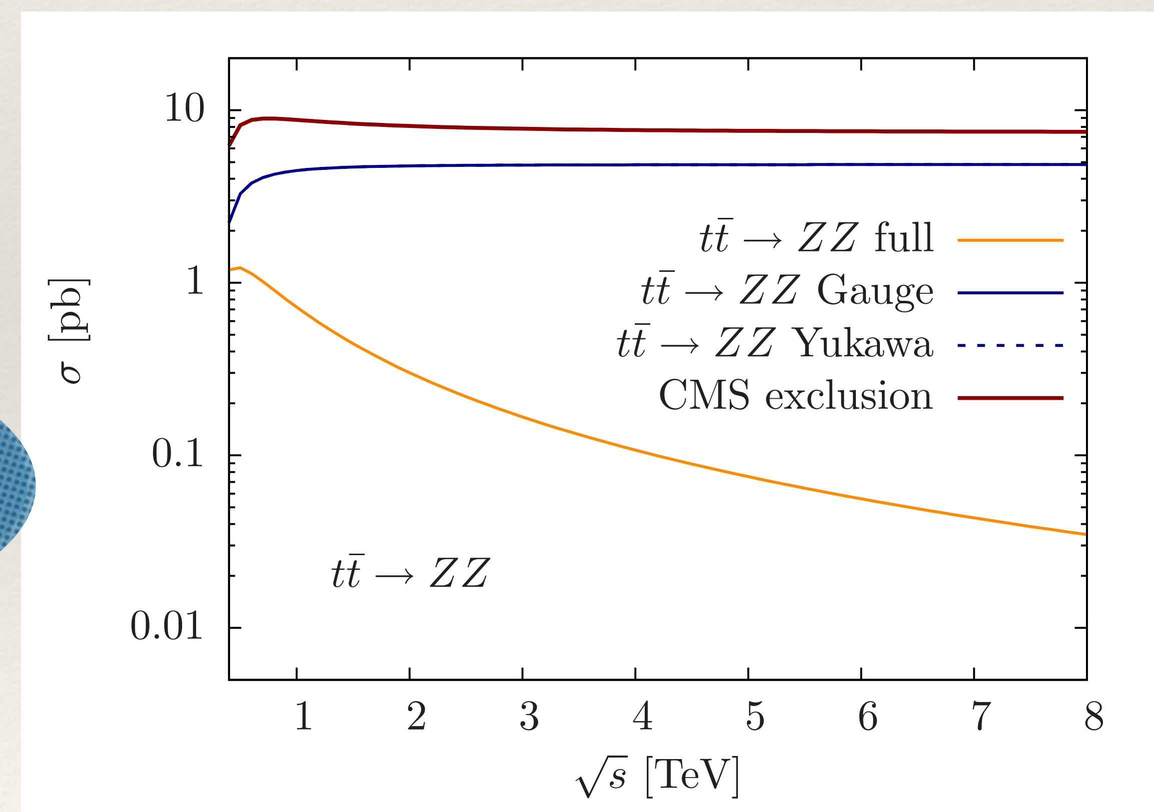

[CE, Spannowsky 1405.0285]

- constraints that violate unitarity have no meaning in a perturbative analysis chain

- **FCC-hh and $\mu\mu$@10TeV: formidable avenues for BSM exploration**

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  - each concept has its unique strengths and weaknesses
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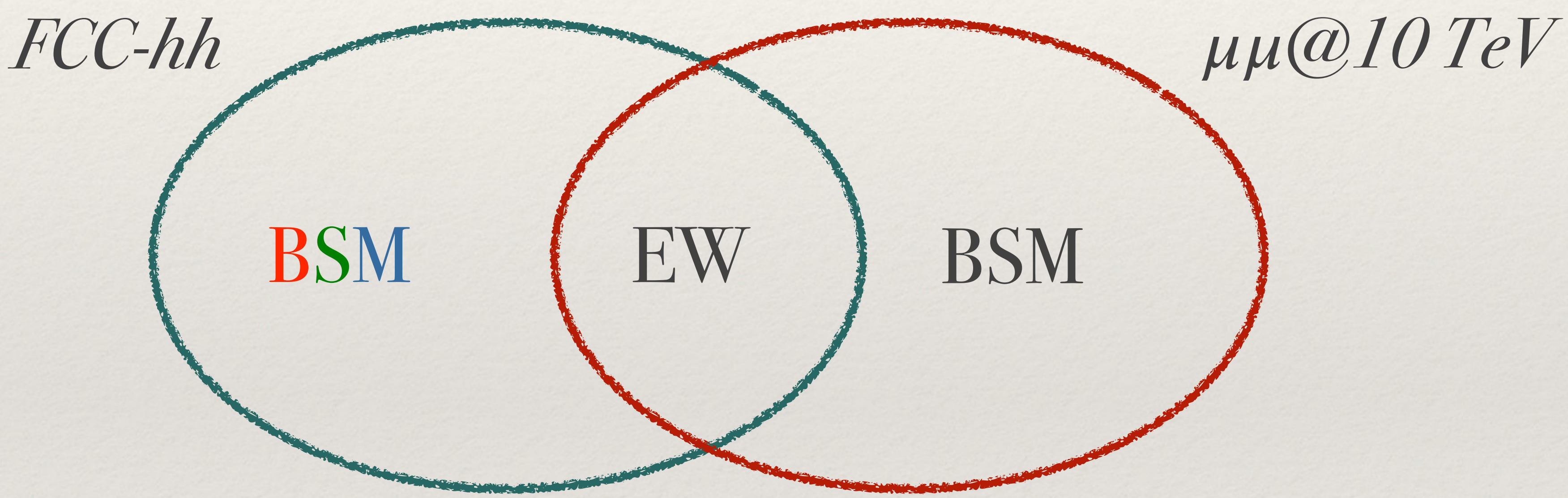

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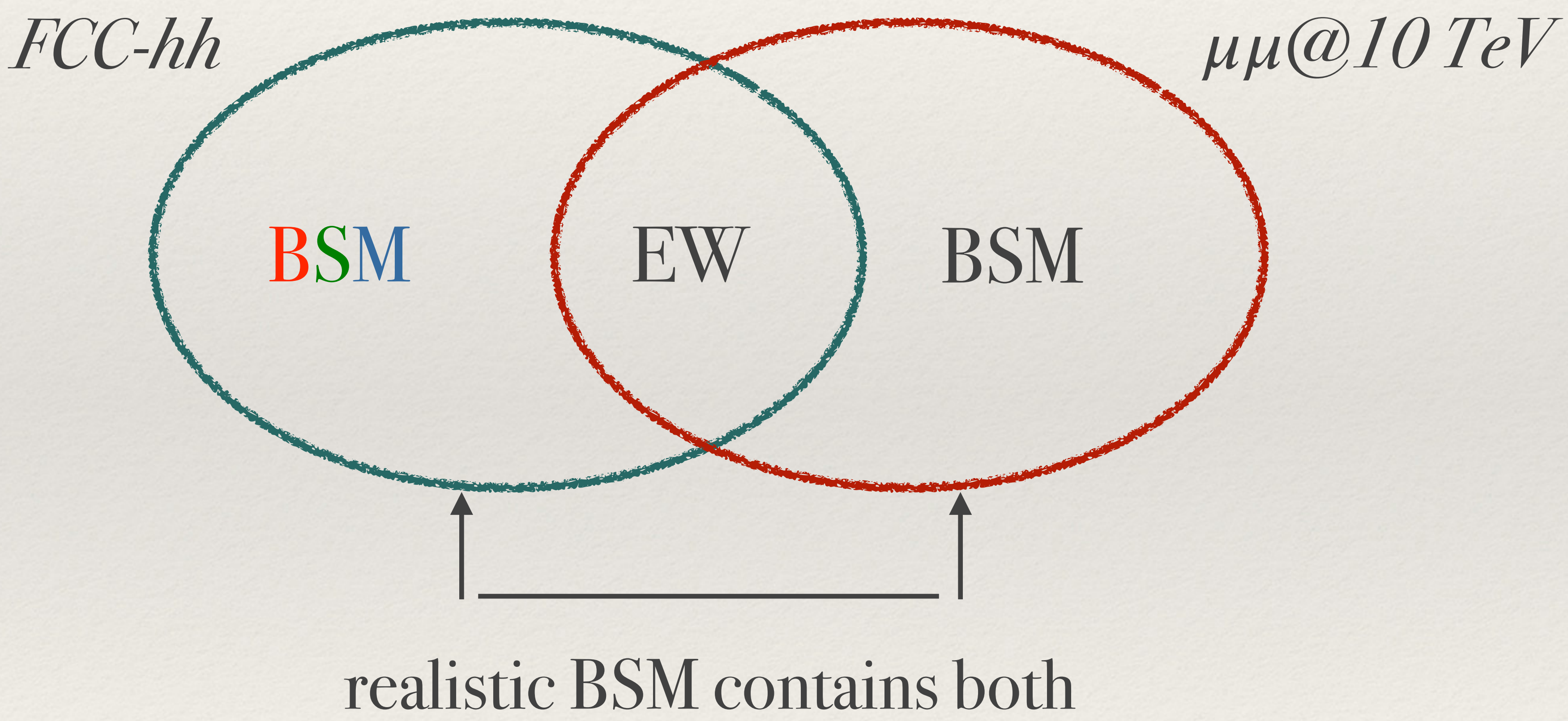

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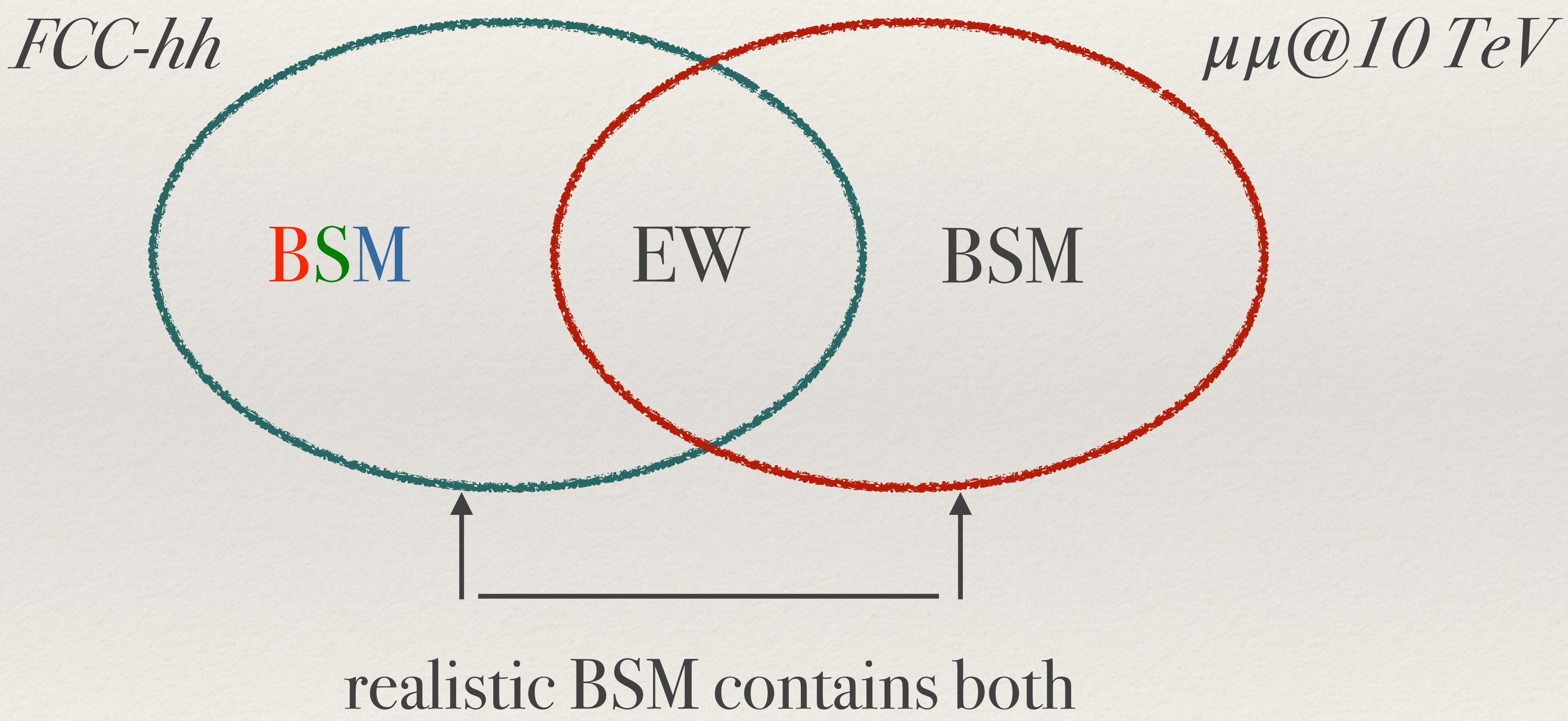

- **every time we increase pCM 10-fold….**

…we learn something entirely new!