Top-quark electroweak interactions at high energy

Luca Mantani

In collaboration with:
Ken Mimasu, Fabio Maltoni

based on arXiv:1904.05637

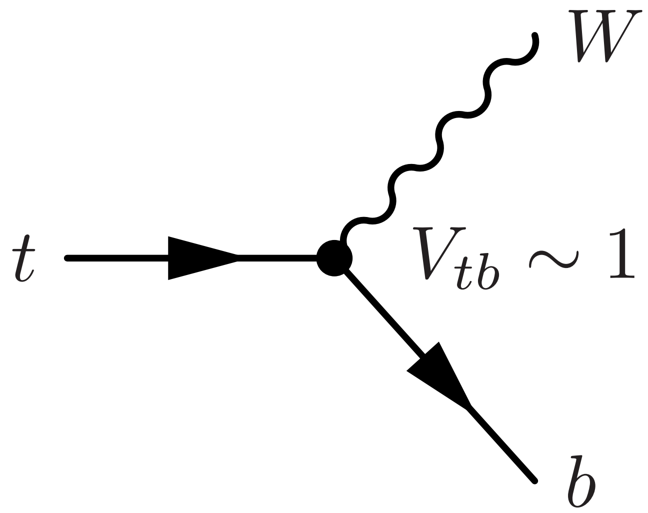
IFT

The motivations for this work are

- ❖ Top-quark EW interactions are not very precisely measured.
- ❖ Anomalous interactions lead to anomalous energy growth in amplitudes.
- ❖ Understand how to constrain couplings in order to detect hint of New Physics at LHC.
- ❖ Assess sensitivity to NP in the EW top quark sector in present colliders experiments and future ones.

The top quark is special.

- **The top couples to the Higgs strongly.**
- **It's the heaviest particle in the SM.**
- **Couples to W boson through its decay, before hadronisation (neutral gauge couplings less known).**



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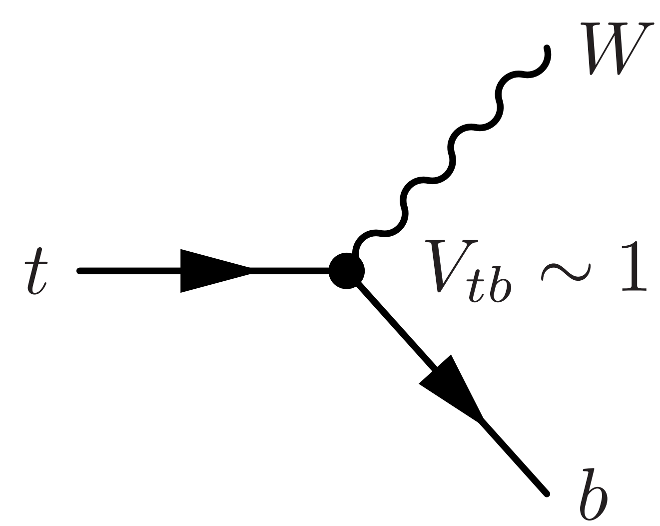


10^9 top pairs

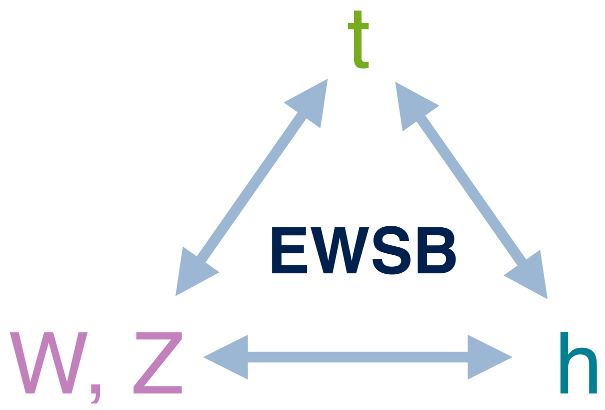
10^8 single top

The LHC is a **top factory**

10^7 tt+W/Z/γ

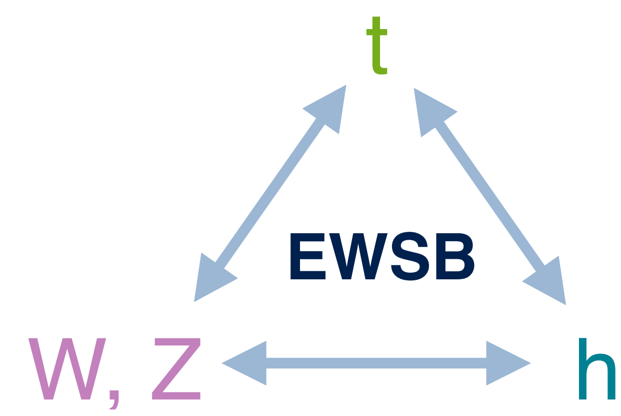
10^6 ttH

10^4 tttt



All key players are in the game now.

LHC = the machine that can lead us to the precise measurement of the EW interactions.



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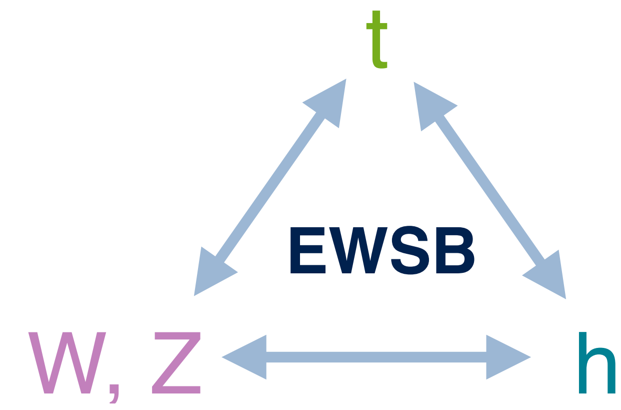
SM = Spontaneously broken Gauge Yukawa theory.

Mass - Higgs coupling

Symmetries

Gauge self-interactions - Current interactions



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Symmetries

→ **Mass - Higgs coupling**

→ **Gauge self-interactions - Current interactions**

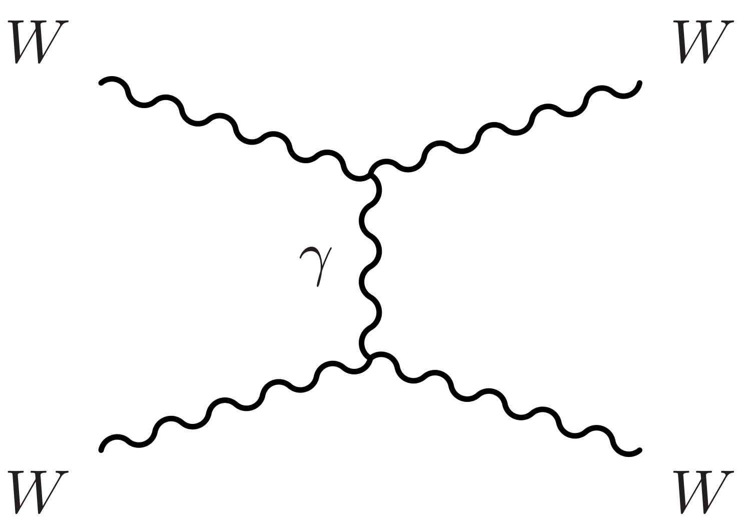
The structure of the SM safeguards the Unitarity of the theory.

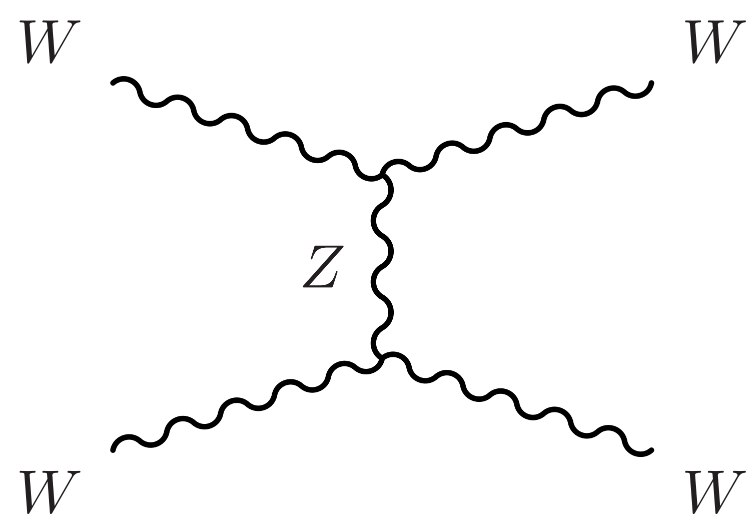
Unitarity violation

Luca Mantani

The most well-known example is longitudinal W-boson scattering

$$W_L W_L \to W_L W_L$$





$$\propto E^4$$

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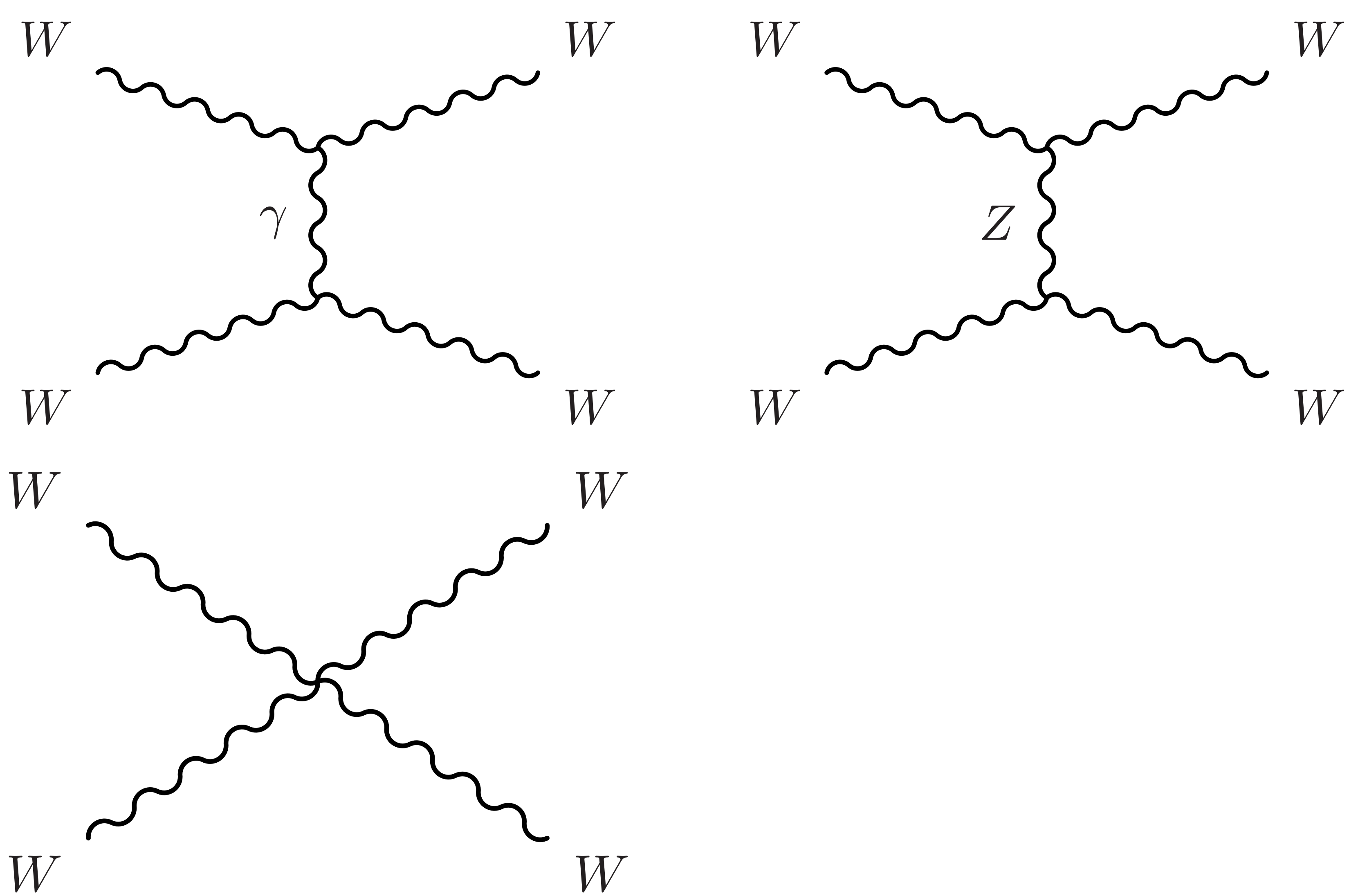

$$\propto E^2$$

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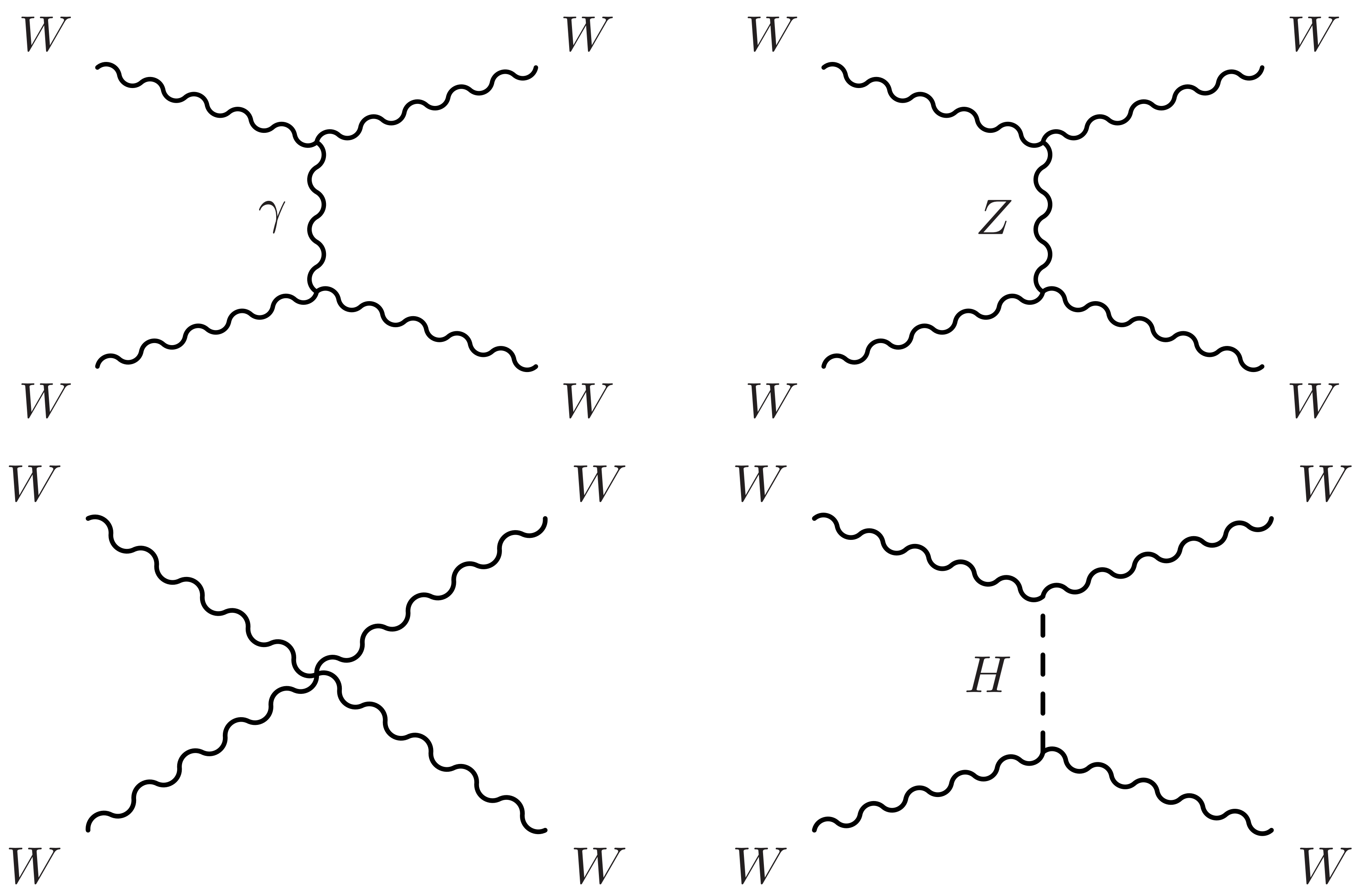
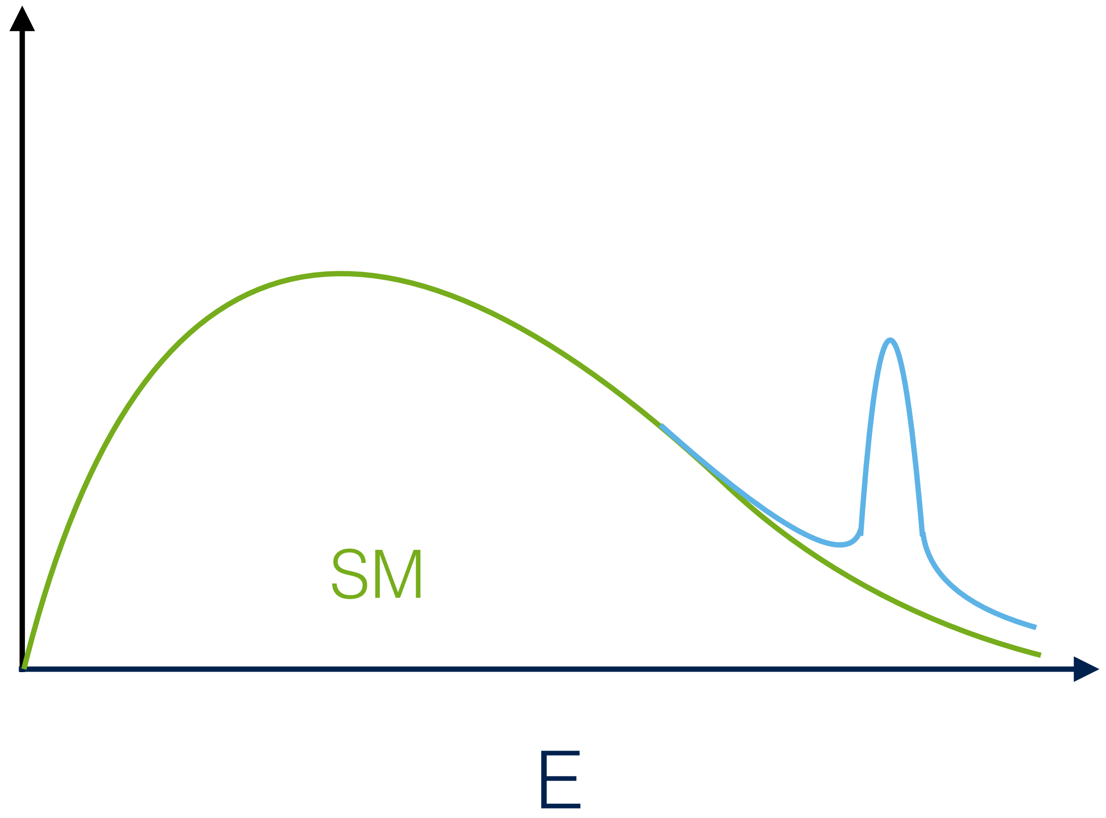


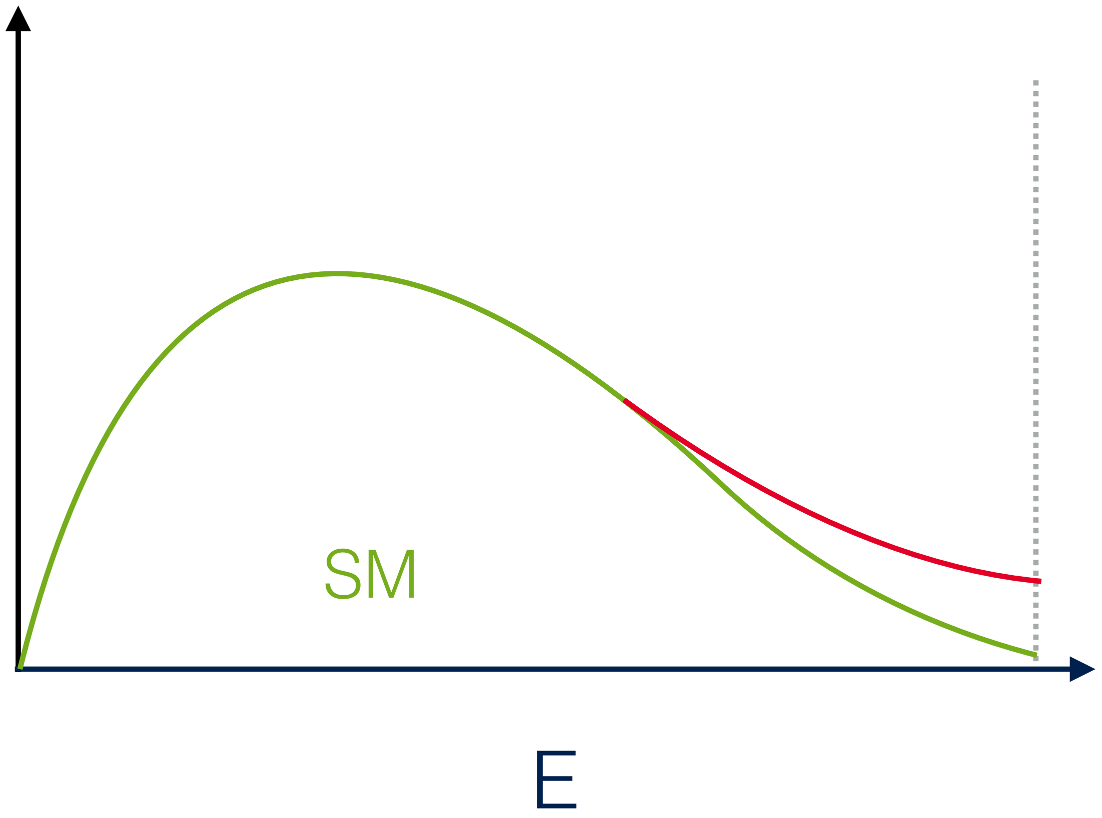
$$\propto E^0$$

Direct search (Bumps)



Direct search (Bumps)

Indirect (scouting tails)



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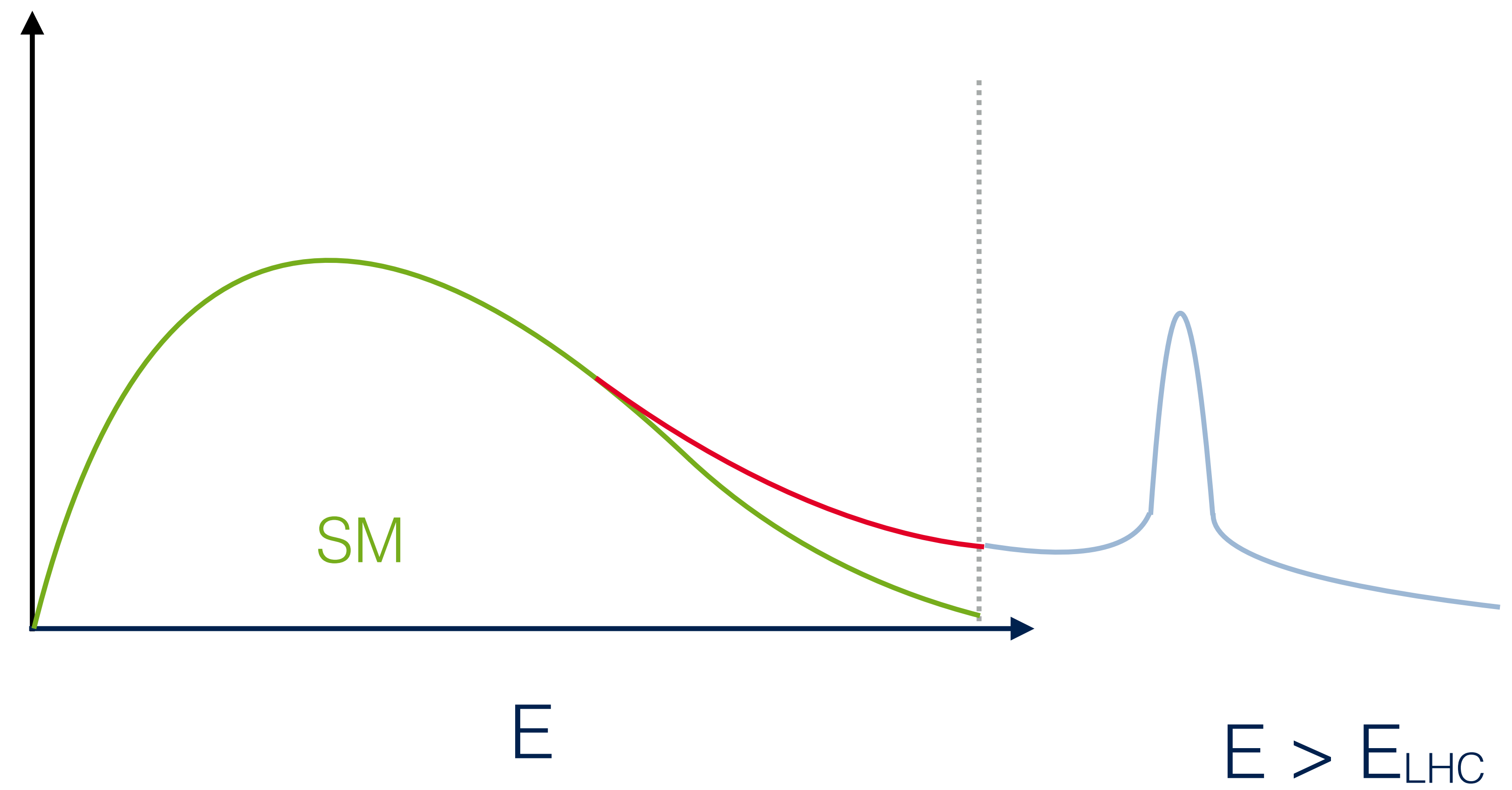
Indirect (scouting tails)

⇒ New physics is heavy



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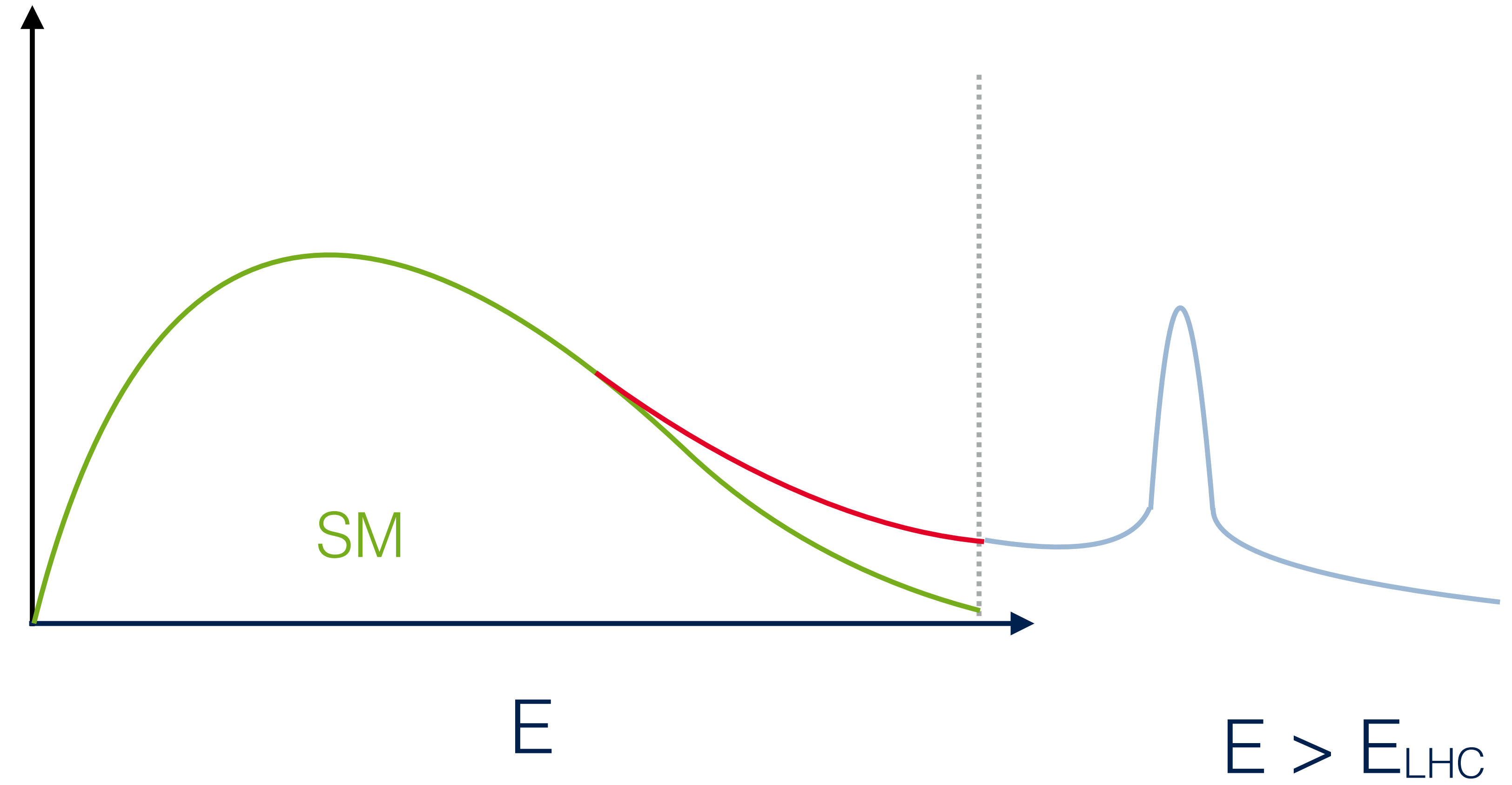

Framework to describe both precision physics and Heavy New Physics.

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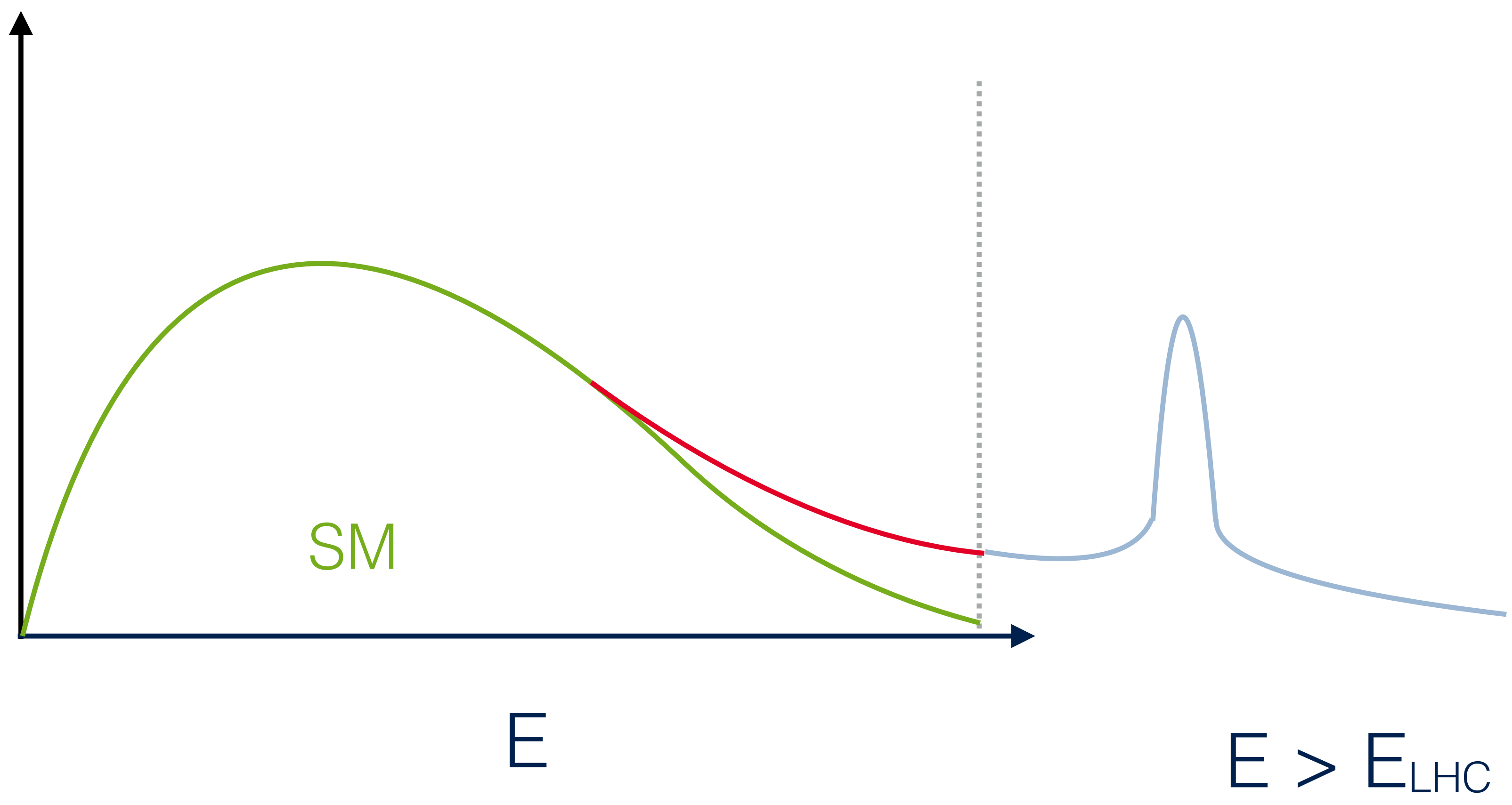

Framework to describe both precision physics and Heavy New Physics.

Standard Model Effective Field Theory (SMEFT)

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{1}{\Lambda}\mathcal{O}_i^5 + \sum_i \frac{1}{\Lambda^2}\mathcal{O}_i^6 + \dots$$

- **Higher dimensional operators preserve SM symmetries.**
- **Mappable to a large class of BSM models.**
- **Warsaw basis truncated at dim 6.**
- **Flavour symmetry according to LHC TOP WG.**
- **Keep only operators affecting top EW interactions.**

$\mathcal{O}_W$	$\varepsilon_{IJK}\, W^I_{\mu\nu}\, W^{J,\nu\rho}\, W^{K,\mu}_{\rho}$	$\mathcal{O}_{t\varphi}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)\bar{Q}\, t\, \tilde{\varphi} + \text{h.c.}$
$\mathcal{O}_{\varphi W}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W_I^{\mu\nu}\, W^I_{\mu\nu}$	$\mathcal{O}_{tW}$	$i\big(\bar{Q}\sigma^{\mu\nu}\,\tau_I\, t\big)\,\tilde{\varphi}\, W^I_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{\varphi B}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) B^{\mu\nu}\, B_{\mu\nu}$	$\mathcal{O}_{tB}$	$i\big(\bar{Q}\sigma^{\mu\nu}\, t\big)\,\tilde{\varphi}\, B_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{\varphi WB}$	$(\varphi^\dagger\tau_I\varphi)\, B^{\mu\nu} W^I_{\mu\nu}$	$\mathcal{O}^{(3)}_{\varphi Q}$	$i\big(\varphi^\dagger \overleftrightarrow{D}_\mu\, \tau_I\varphi\big)\big(\bar{Q}\,\gamma^\mu\, \tau^I Q\big)$
$\mathcal{O}_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\dagger(\varphi^\dagger D_\mu\varphi)$	$\mathcal{O}^{(1)}_{\varphi Q}$	$i\big(\varphi^\dagger \overleftrightarrow{D}_\mu\, \varphi\big)\big(\bar{Q}\,\gamma^\mu\, Q\big)$
$\mathcal{O}_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$\mathcal{O}_{\varphi t}$	$i\big(\varphi^\dagger \overleftrightarrow{D}_\mu\, \varphi\big)\big(\bar{t}\,\gamma^\mu\, t\big)$
		$\mathcal{O}_{\varphi tb}$	$i\big(\tilde{\varphi}\, D_\mu\, \varphi\big)\big(\bar{t}\,\gamma^\mu\, b\big) + \text{h.c.}$

We consider generic 2 to 2 processes $f\,B \to f'\,B'$

	Single-top		Two-top ($t\bar{t}$)	
w/o Higgs	$b\,W \to t\,(Z/\gamma)$	(4.1.1)	$t\,W \to t\,W$	(5.1.1)
			$t\,(Z/\gamma) \to t\,(Z/\gamma)$	(5.1.4)
w/ Higgs	$b\,W \to t\,h$	(4.2.1)	$t\,(Z/\gamma) \to t\,h$	(5.2.1)
			$t\,h \to t\,h$	(5.2.4)

We study the processes in the high energy limit (s >> -t >> v²) for each helicity configuration, including the effects of the dim 6 operators. As expected the maximum degree of growth of each amplitude is E², while for the SM they are at most constant in energy.

$$b\,W^+ \to t\,H$$

$\lambda_b,\ \lambda_W,\ \lambda_t$	SM	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{\varphi Q}^{(3)}$	$\mathcal{O}_{\varphi tb}$
$-, 0, -$	s^0	s^0	s^0	s^0	$\sqrt{s(s+t)}$	$-$
$-, 0, +$	$\frac{1}{\sqrt{s}}$	$-$	$\sqrt{-t}v$	$\frac{sm_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$	$-$
$+, 0, -$	$-$	$-$	$-$	$-$	$-$	$\sqrt{-t}m_t$
$+, 0, +$	$-$	$-$	$-$	$-$	$-$	$\sqrt{s(s+t)}$
$-, -, -$	$\frac{1}{\sqrt{s}}$	$\frac{sm_W}{\sqrt{-t}}$	$-$	$\sqrt{-t}m_t$	$\sqrt{-t}m_W$	$-$
$-, -, +$	$\frac{1}{s}$	$-$	s^0	$\sqrt{s(s+t)}$	s^0	$-$
$-, +, -$	$\frac{1}{\sqrt{s}}$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$-$	$-$	$-$	$-$
$-, +, +$	s^0	s^0	$-$	s^0	s^0	$-$
$+, \pm, -$	$-$	$-$	$-$	$-$	$-$	s^0
$+, -, +$	$-$	$-$	$-$	$-$	$-$	$-$
$+, +, +$	$-$	$-$	$-$	$-$	$-$	$\sqrt{-t}m_W$

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$\lambda_b,\,\lambda_W,\,\lambda_t$	SM	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{tW}$	$\mathcal{O}^{(3)}_{\varphi Q}$	$\mathcal{O}_{\varphi tb}$
$-,0,-$	s^0	s^0	s^0	s^0	$\sqrt{s(s+t)}$	$-$
$-,0,+$	$\frac{1}{\sqrt{s}}$	$-$	$\sqrt{-t}v$	$\frac{sm_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$	$-$
$+,0,-$	$-$	$-$	$-$	$-$	$-$	$\sqrt{-t}m_t$
$+,0,+$	$-$	$-$	$-$	$-$	$-$	$\sqrt{s(s+t)}$
$-,-,-$	$\frac{1}{\sqrt{s}}$	$\frac{sm_W}{\sqrt{-t}}$	$-$	$\sqrt{-t}m_t$	$\sqrt{-t}m_W$	$-$
$-,-,+$	$\frac{1}{s}$	$-$	s^0	$\sqrt{s(s+t)}$	s^0	$-$
$-,+,-$	$\frac{1}{\sqrt{s}}$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$-$	$-$	$-$	$-$
$-,+,+$	s^0	s^0	$-$	s^0	s^0	$-$
$+,\pm,-$	$-$	$-$	$-$	$-$	$-$	s^0
$+,-,+$	$-$	$-$	$-$	$-$	$-$	$-$
$+,+,+$	$-$	$-$	$-$	$-$	$-$	$\sqrt{-t}m_W$

The maximum energy growth of an amplitude can be guessed from the contact term generated by higher dimension operators.

Let's consider a 2 to N scattering amplitude (mass dim 2-N):

$$\mathcal{L} \supset \frac{1}{\Lambda^{K-4}} \mathcal{O}_K \quad \Rightarrow \quad \mathcal{M} \propto \frac{1}{\Lambda^{K-4}} E^{K-N-2}$$

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$$V_L \rightarrow \frac{\partial_\mu G}{M_V}$$

$$H \rightarrow v$$

$$\Rightarrow \quad \mathcal{M} \propto \frac{v^m}{\Lambda^{K-4}} \frac{E^{K-N-2-m+n}}{M_V^n}$$

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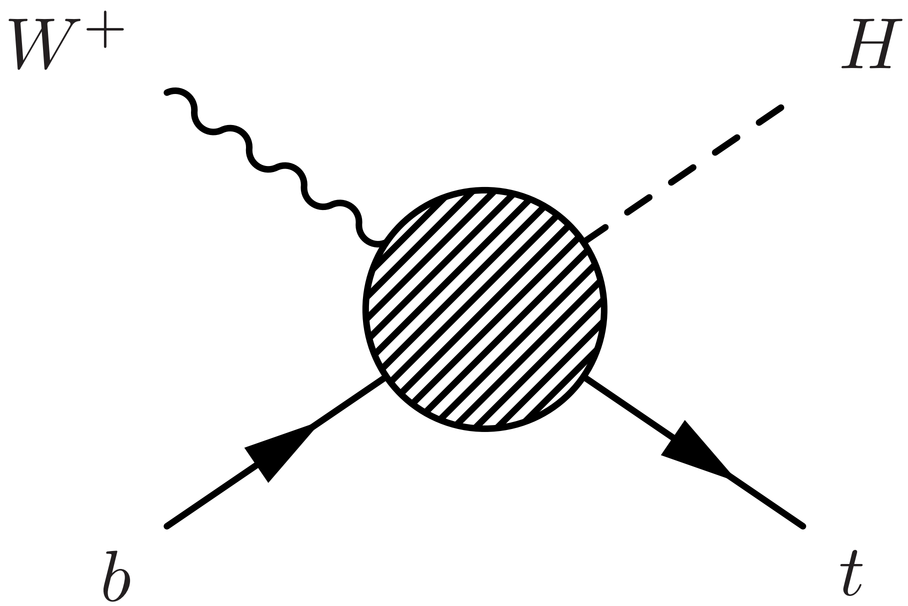
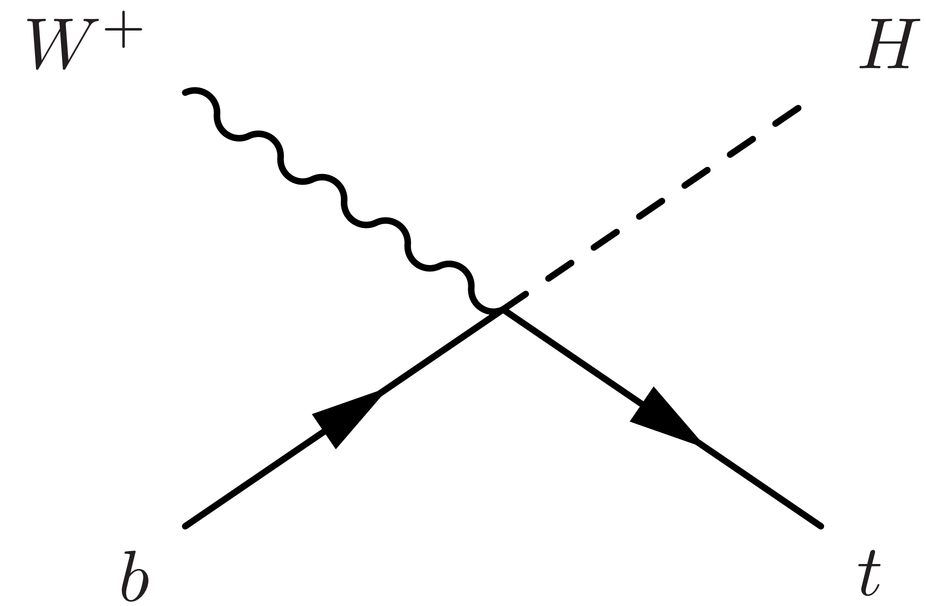
Dim 6, 2 to 2

$$\mathcal{M} \propto \frac{v^m}{\Lambda^2} \frac{E^{2-m+n}}{M_V^n}$$

$$b\,W^+ \to t\,H$$

$$\mathcal{O}^{(3)}_{\varphi Q} \to v\,H\,W^+\,\bar{t}_L\,\gamma^\mu\,b_L + \text{h.c.}$$





$$\mathcal{M} \propto \frac{v^m}{\Lambda^2}\,\frac{E^{2-m+n}}{M_V^n}$$

Contact term: an example

$\lambda_b,\ \lambda_W,\ \lambda_t$	SM	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{\varphi Q}^{(3)}$	$\mathcal{O}_{\varphi tb}$
$-, 0, -$	s^0	s^0	s^0	s^0	$\sqrt{s(s+t)}$	$-$
$-, 0, +$	$\frac{1}{\sqrt{s}}$	$-$	$\sqrt{-t}v$	$\frac{s m_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$	$-$
$+, 0, -$	$-$	$-$	$-$	$-$	$-$	$\sqrt{-t}m_t$
$+, 0, +$	$-$	$-$	$-$	$-$	$-$	$\sqrt{s(s+t)}$
$-, -, -$	$\frac{1}{\sqrt{s}}$	$\frac{s m_W}{\sqrt{-t}}$	$-$	$\sqrt{-t}m_t$	$\sqrt{-t}m_W$	$-$
$-, -, +$	$\frac{1}{s}$	$-$	s^0	$\sqrt{s(s+t)}$	s^0	$-$
$-, +, -$	$\frac{1}{\sqrt{s}}$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$-$	$-$	$-$	$-$
$-, +, +$	s^0	s^0	$-$	s^0	s^0	$-$
$+, \pm, -$	$-$	$-$	$-$	$-$	$-$	s^0
$+, -, +$	$-$	$-$	$-$	$-$	$-$	$-$
$+, +, +$	$-$	$-$	$-$	$-$	$-$	$\sqrt{-t}m_W$

We indeed observe a E^2 growth in the (-,0,-) amplitude.

How to access the high energy behaviour of the 2 to 2 scatterings?

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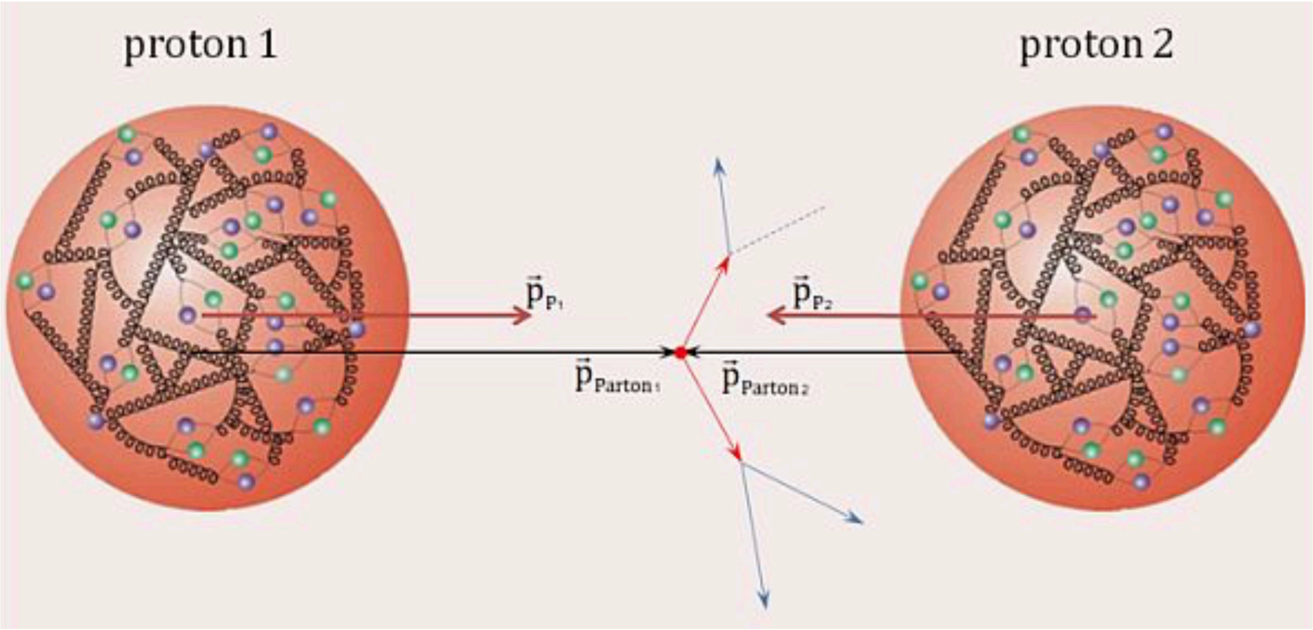
LHC collides protons



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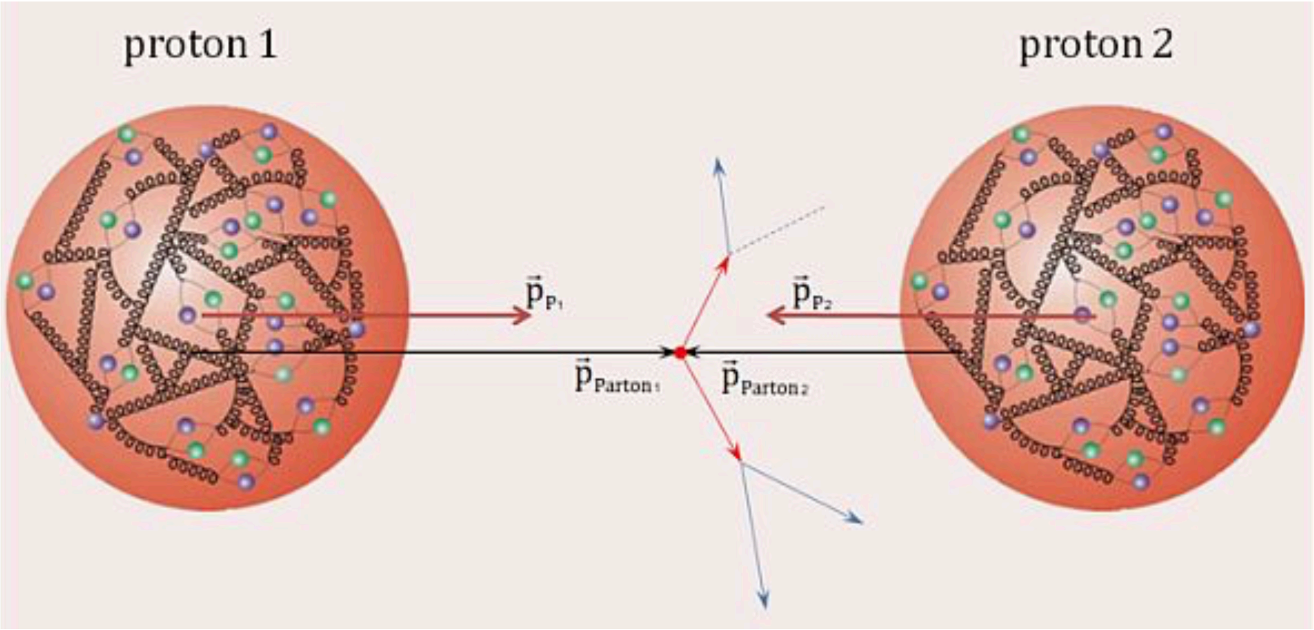
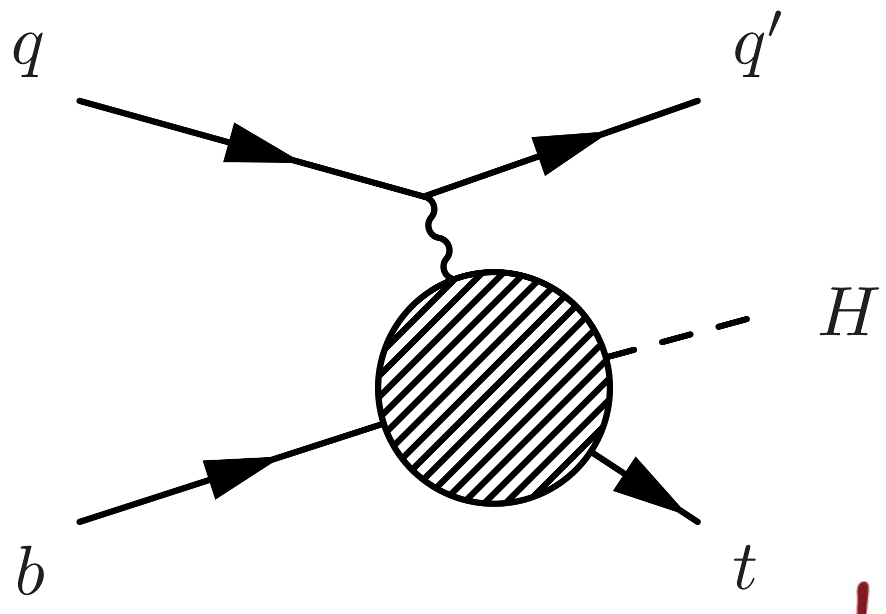
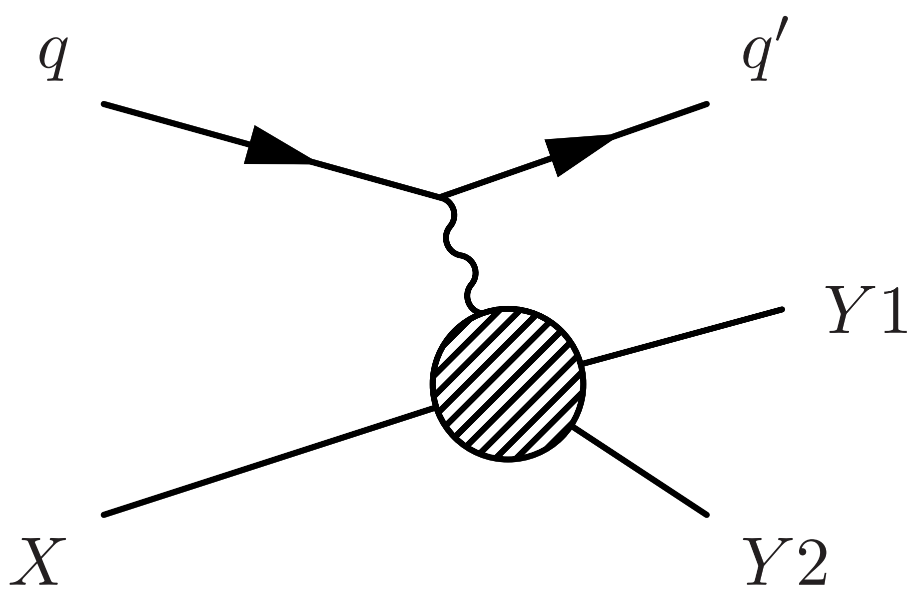


Embed the 2 to 2 scattering



How does the 2 to 2 behaviour translates to 2 to n?
We can have an analytical insight with EWA (P. Borel et al. arxiv:1202.1904)



$$E \sim xE \sim (1-x)E, \qquad \frac{m}{E} \ll 1, \qquad \frac{p_\perp}{E} \ll 1$$

$$f_+ = \frac{(1-x)^2}{x} \frac{p_\perp^3}{(m^2(1-x)+p_\perp^2)^2},$$

$$f_- = \frac{1}{x} \frac{p_\perp^3}{(m^2(1-x)+p_\perp^2)^2},$$

$$f_0 = \frac{(1-x)^2}{x} \frac{2m^2 p_\perp}{(m^2(1-x)+p_\perp^2)^2}.$$

$$\frac{d\sigma_{EWA}}{dx dp_\perp}(qX \to q\prime Y) = \frac{C^2}{2\pi^2} \sum_{i=+,-,0} f_i \times d\sigma(W_i X \to Y)$$

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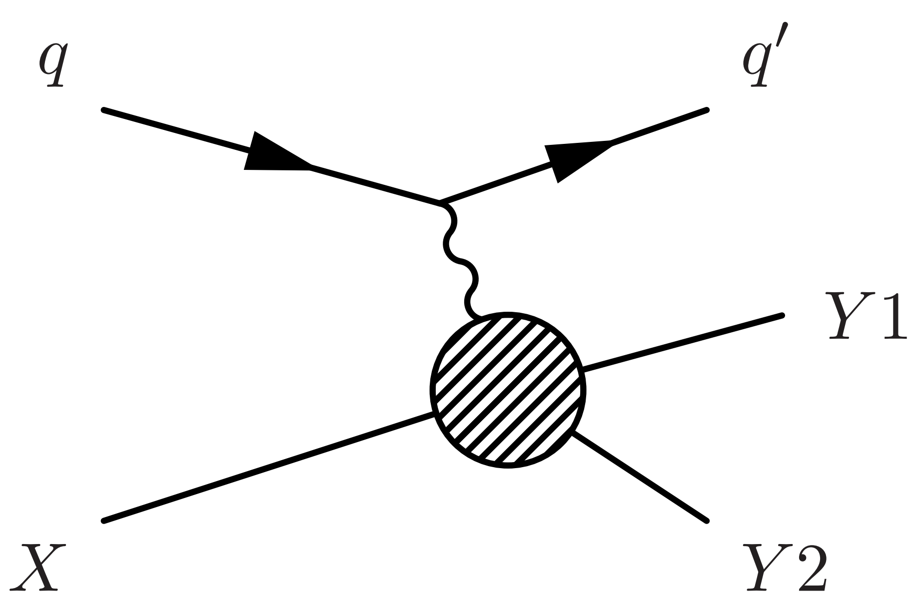

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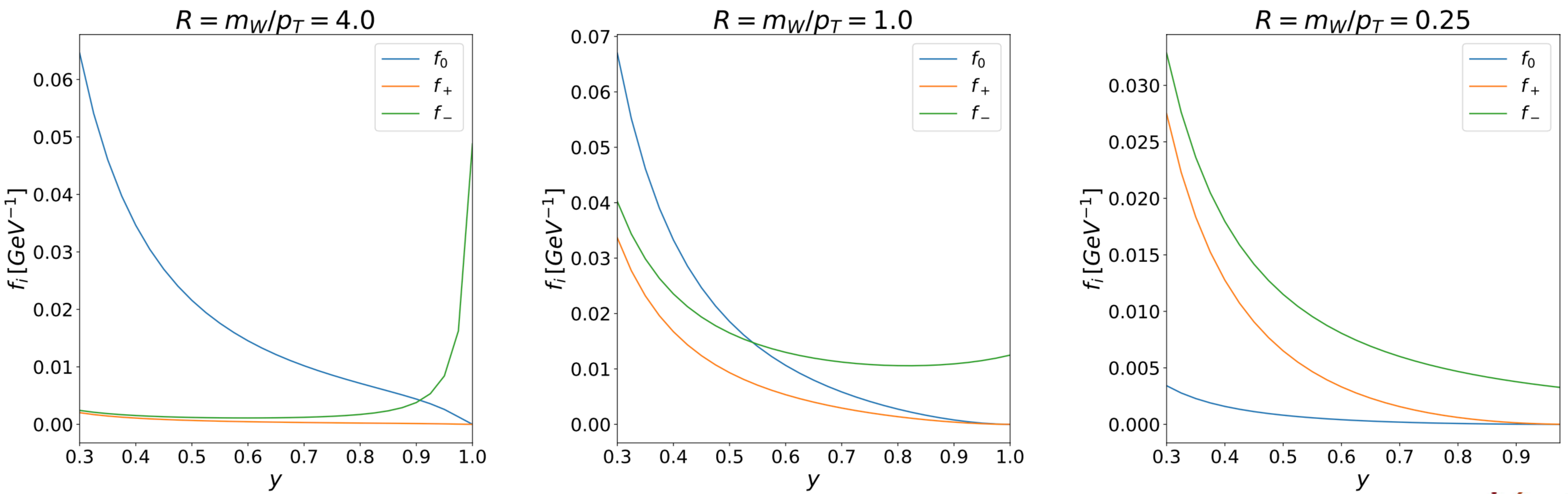
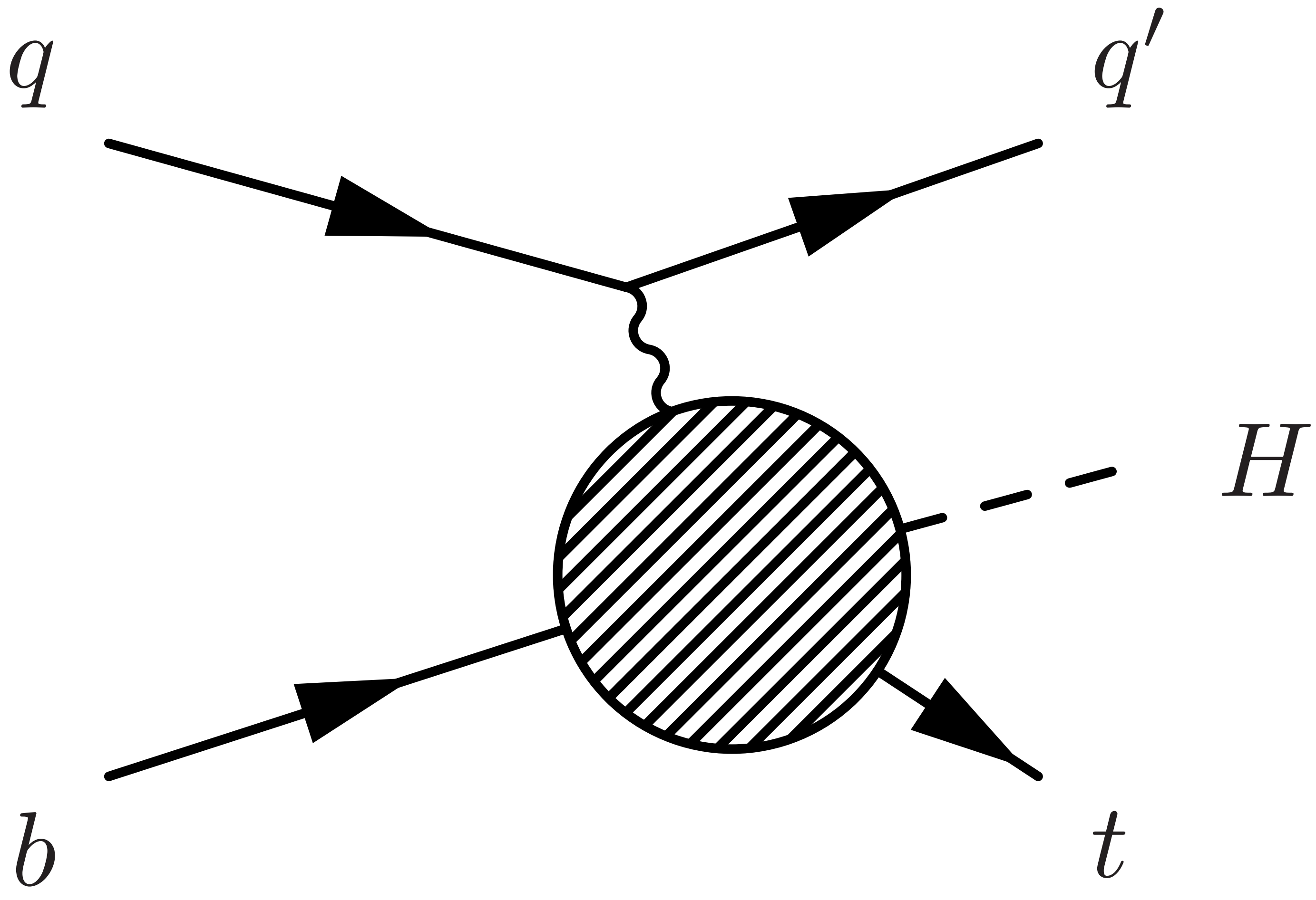


E = 2 TeV



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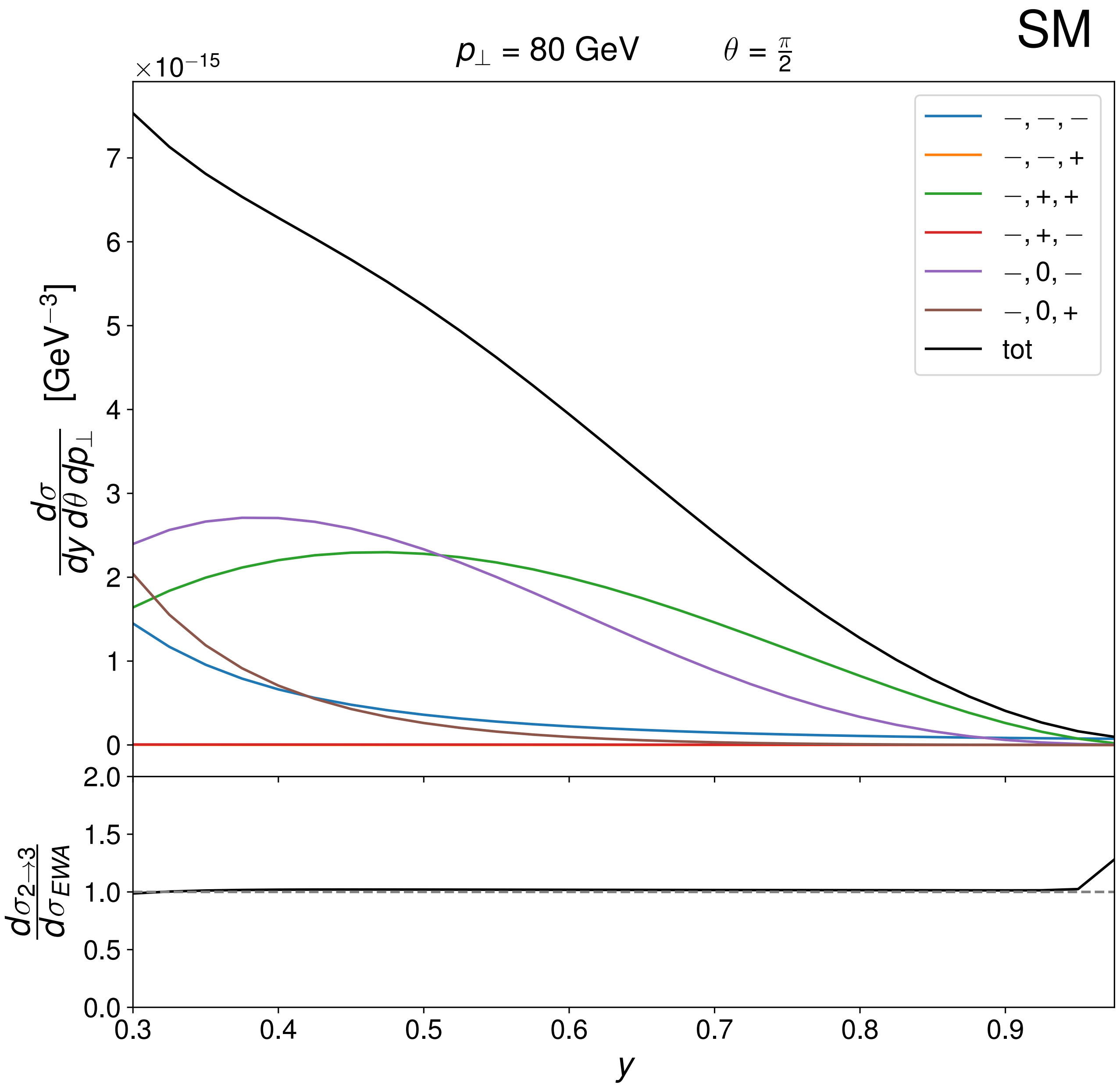
SM
$p_\perp$ = 80 GeV
$\theta = \frac{\pi}{2}$
$\times 10^{-15}$
$\frac{d\sigma}{dy\, d\theta\, dp_\perp}$ [GeV^{-3}]
$-,-,-$
$-,-,+$
$-,+,+$
$-,+,-$
$-,0,-$
$-,0,+$
tot
$\frac{d\sigma_{2\to3}}{d\sigma_{EWA}}$
y

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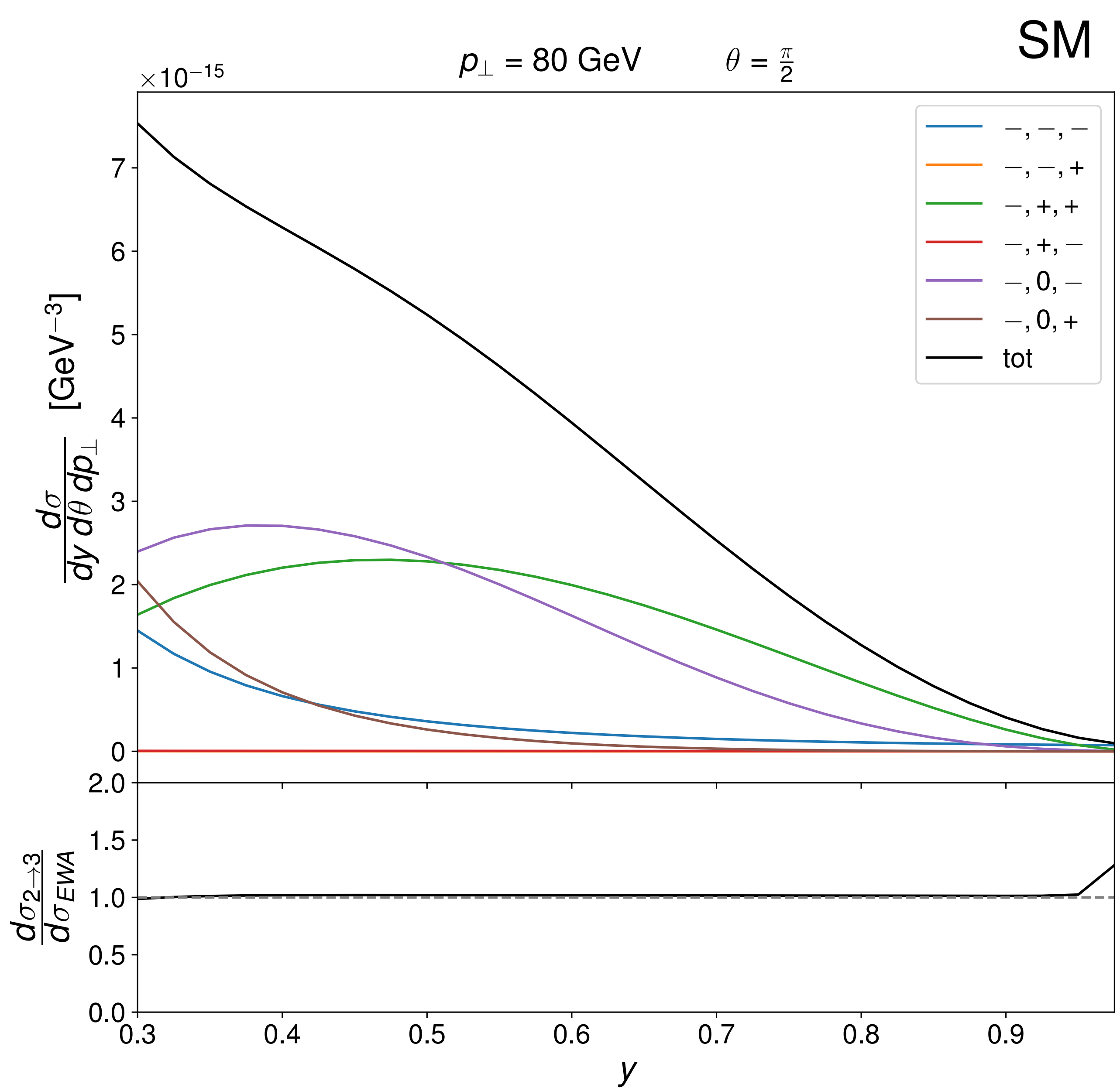
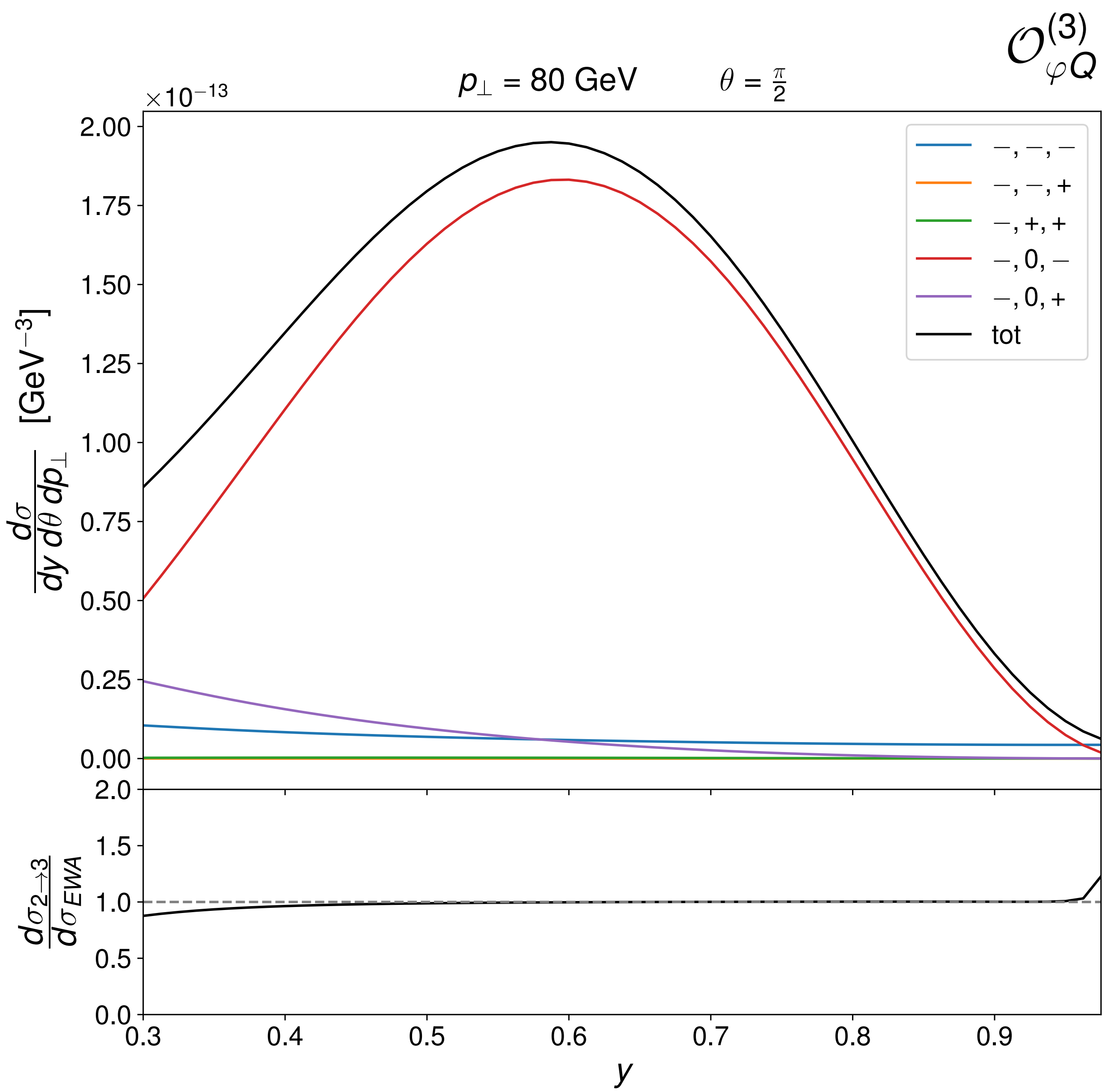


SM
$p_\perp$ = 80 GeV
$\theta = \frac{\pi}{2}$
$\times 10^{-15}$
−, −, −
−, −, +
−, +, +
−, +, −
−, 0, −
−, 0, +
tot
$\frac{d\sigma}{dy\, d\theta\, dp_\perp}$ [GeV^{-3}]
$\frac{d\sigma_{2\to3}}{d\sigma_{EWA}}$
y



$\mathcal{O}^{(3)}_{\varphi Q}$
$p_\perp$ = 80 GeV
$\theta = \frac{\pi}{2}$
$\times 10^{-13}$
−, −, −
−, −, +
−, +, +
−, 0, −
−, 0, +
tot
$\frac{d\sigma}{dy\, d\theta\, dp_\perp}$ [GeV^{-3}]
$\frac{d\sigma_{2\to3}}{d\sigma_{EWA}}$
y

We turn to study how the energy growing behaviour can be probed by physical processes at colliders.

- **2 to 3 and 2 to 4 scattering processes.**
- **Assess the sensitivity to the Wilson coefficients.**
- **We considered pp collider at 13 and 27 TeV as well as ee collider operating at 380, 1500 and 3000 GeV.**

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Operator	Limit on c_i $[\mathrm{TeV}^{-2}]$		Operator	Limit on c_i $[\mathrm{TeV}^{-2}]$	
	Individual	Marginalised		Individual	Marginalised
$\mathcal{O}_{\varphi D}$	[-0.021,0.0055] [16]	[-0.45,0.50] [16]	$\mathcal{O}_{t\varphi}$	[-5.3,1.6] [17]	[-60,10] [17]
$\mathcal{O}_{\varphi\Box}$	[-0.78,1.44] [16]	[-1.24,16.2] [16]	$\mathcal{O}_{tB}$	[-7.09,4.68] [18]	–
$\mathcal{O}_{\varphi B}$	[-0.0033,0.0031] [16]	[-0.13,0.21] [16]	$\mathcal{O}_{tW}$	[-0.4,0.2] [17]	[-1.8,0.9] [17]
$\mathcal{O}_{\varphi W}$	[-0.0093,0.011] [16]	[-0.50,0.40] [16]	$\mathcal{O}_{\varphi Q}^{(1)}$	[-3.10,3.10] [18]	–
$\mathcal{O}_{\varphi WB}$	[-0.0051,0.0020] [16]	[-0.17,0.33] [16]	$\mathcal{O}_{\varphi Q}^{(3)}$	[-0.9,0.6] [17]	[-5.5,5.8] [17]
$\mathcal{O}_{W}$	[-0.18,0.18] [19]	–	$\mathcal{O}_{\varphi t}$	[-6.4,7.3] [17]	[-13,18] [17]
			$\mathcal{O}_{\varphi tb}$	[-5.28,5.28] [20]	[27,8.7] [17]

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$\mathcal{O}_{\varphi\Box}$	[-0.78,1.44] [16]	[-1.24,16.2] [16]	$\mathcal{O}_{tB}$	[-7.09,4.68] [18]	–
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$\mathcal{O}_{\varphi W}$	[-0.0093,0.011] [16]	[-0.50,0.40] [16]	$\mathcal{O}_{\varphi Q}^{(1)}$	[-3.10,3.10] [18]	–
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$\mathcal{O}_{W}$	[-0.18,0.18] [19]	–	$\mathcal{O}_{\varphi t}$	[-6.4,7.3] [17]	[-13,18] [17]
			$\mathcal{O}_{\varphi tb}$	[-5.28,5.28] [20]	[27,8.7] [17]

$$\sigma = \sigma_{SM} + \frac{c}{\Lambda^2}\sigma_i + \frac{c^2}{\Lambda^4}\sigma_{ii}$$

- **Computation performed with MG5 and SMEFT UFO, in 5 flavour scheme.**
- **We compute the interference and square contribution for each operator relative to the EW SM cross section for p p (e e) collisions. (r_i, $r_{i,i}$)**
- **The relative impact is computed for each operator with Wilson coefficient set to 1 TeV^{-2} and saturating limits from the table.**
- **Compute both inclusive and high-energy restricted cross section.**
- **QCD background.**

	tWj	tZj	$t\gamma j$	tWZ	$tW\gamma$	thj	thW
$bW \to tZ$	✓	✓		✓			
$bW \to t\gamma$	✓		✓		✓		
$bW \to th$						✓	✓

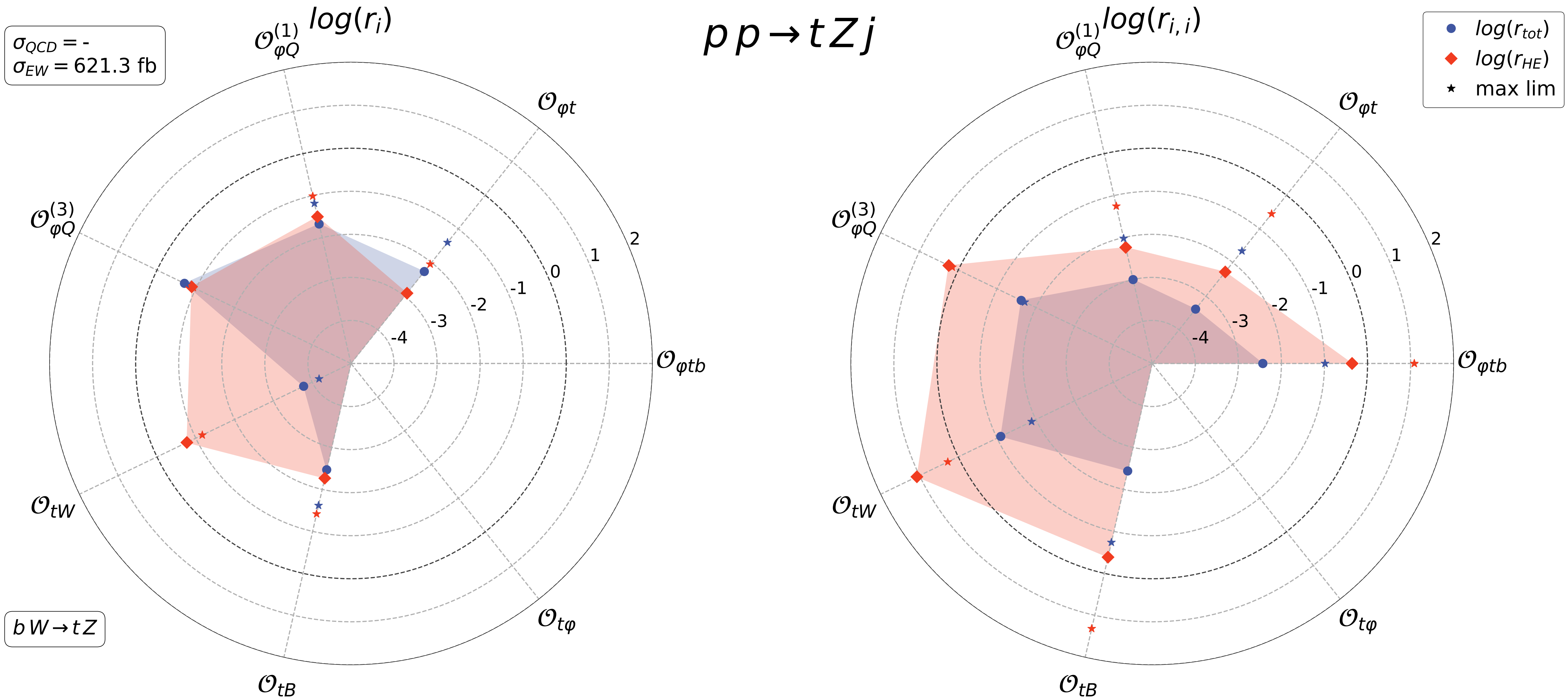
	$t\bar{t}W(j)$	$t\bar{t}WW$	$t\bar{t}Z(j)$	$t\bar{t}\gamma(j)$	$t\bar{t}\gamma\gamma$	$t\bar{t}\gamma Z$	$t\bar{t}ZZ$	VBF
$tW \to tW$	✓	✓						✓
$tZ \to tZ$			✓				✓	✓
$tZ \to t\gamma$			✓	✓		✓		✓
$t\gamma \to t\gamma$				✓	✓			✓

	$t\bar{t}h(j)$	$t\bar{t}Zh$	$t\bar{t}\gamma h$	$t\bar{t}hh$
$tZ \to th$	✓	✓		
$t\gamma \to th$	✓		✓	
$th \to th$				✓

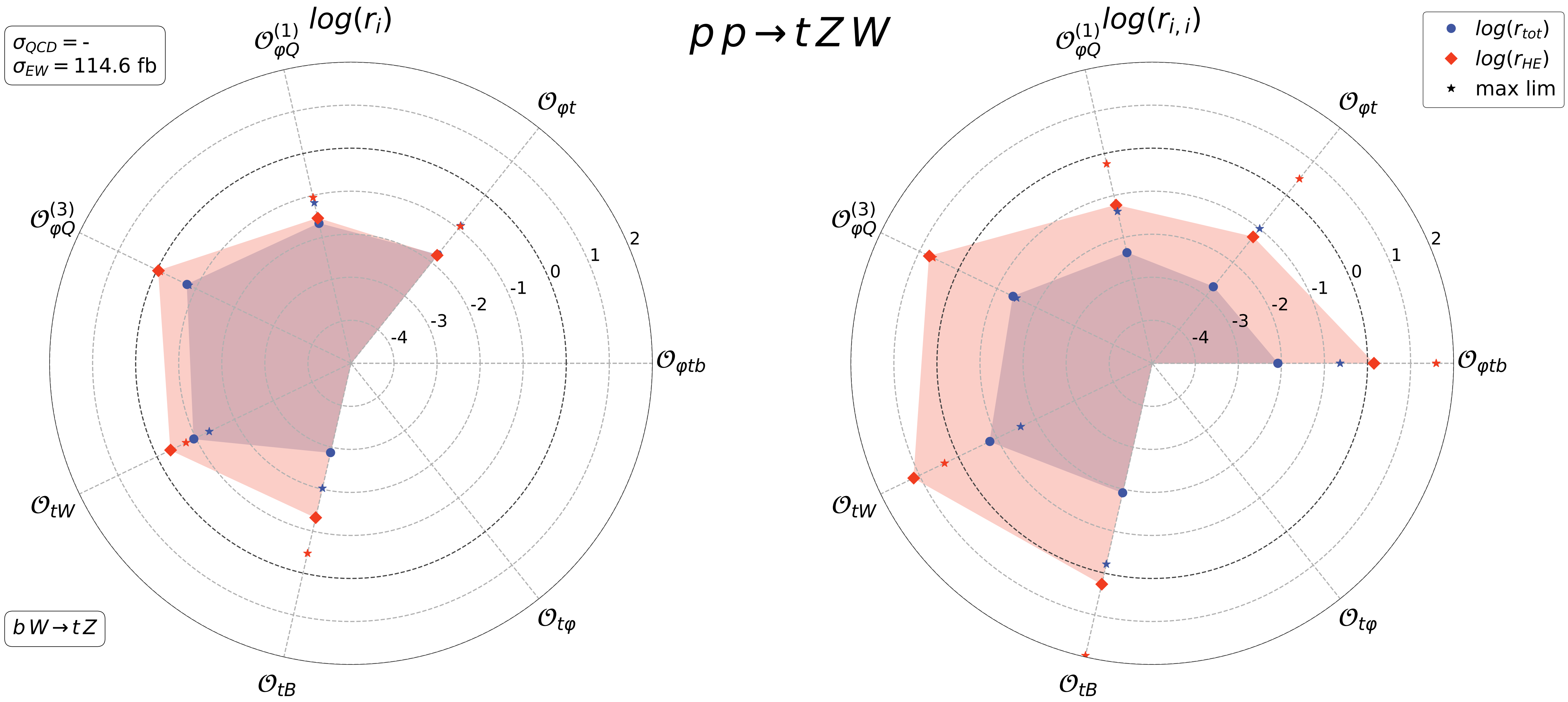
	tWj	tZj	$t\gamma j$	tWZ	$tW\gamma$	thj	thW
$bW \to tZ$	✓	✓		✓			
$bW \to t\gamma$	✓		✓		✓		
$bW \to th$						✓	✓

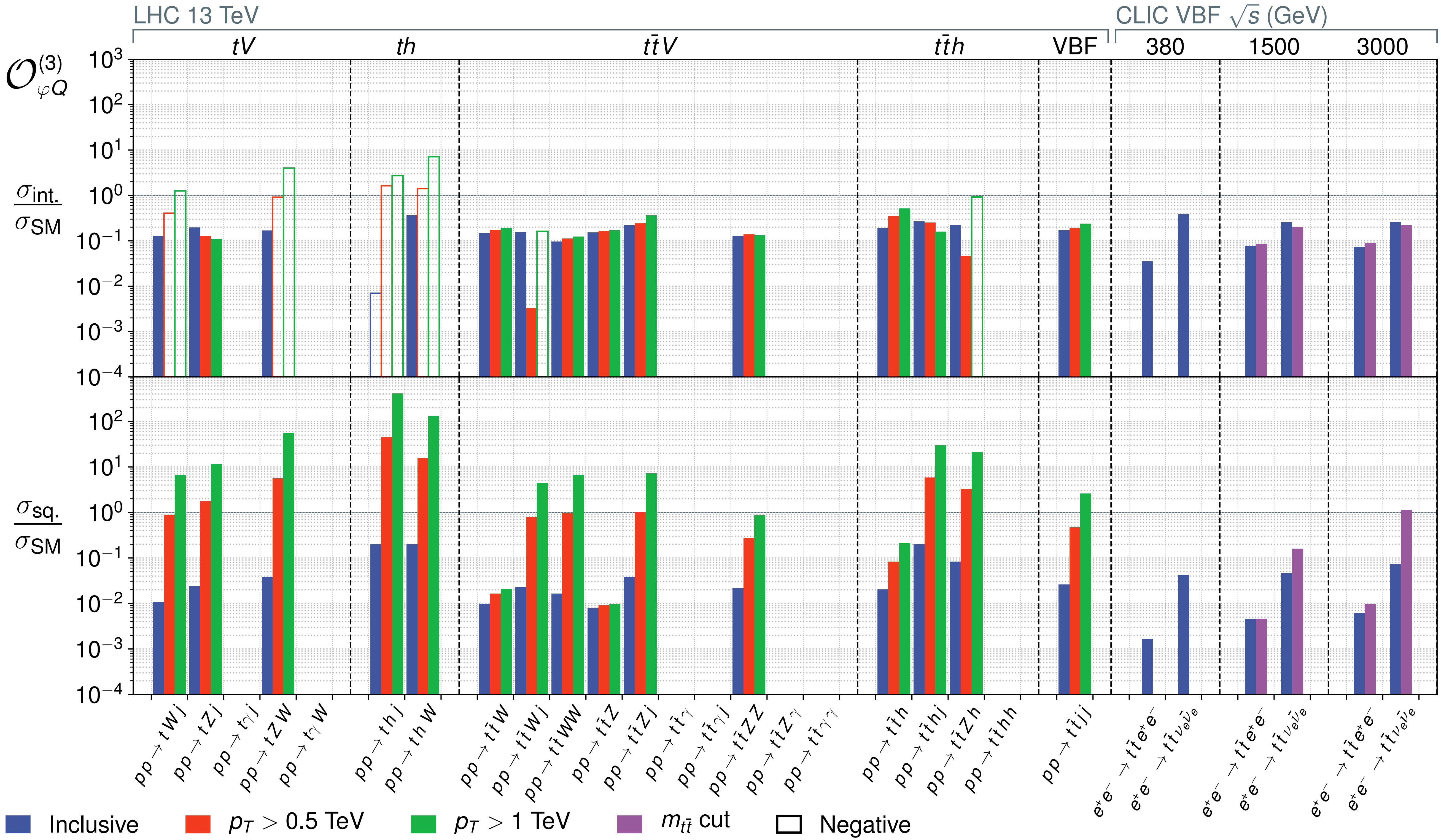
	$t\bar{t}W(j)$	$t\bar{t}WW$	$t\bar{t}Z(j)$	$t\bar{t}\gamma(j)$	$t\bar{t}\gamma\gamma$	$t\bar{t}\gamma Z$	$t\bar{t}ZZ$	VBF
$tW \to tW$	✓	✓						✓
$tZ \to tZ$			✓				✓	✓
$tZ \to t\gamma$			✓	✓		✓		✓
$t\gamma \to t\gamma$				✓	✓			✓

	$t\bar{t}h(j)$	$t\bar{t}Zh$	$t\bar{t}\gamma h$	$t\bar{t}hh$
$tZ \to th$	✓	✓		
$t\gamma \to th$	✓		✓	
$th \to th$				✓



CMS collaboration arXiv:1812.05900


σ_{QCD} = -
σ_{EW} = 114.6 fb
$log(r_i)$
$\mathcal{O}_{\varphi Q}^{(1)}$
$\mathcal{O}_{\varphi t}$
$\mathcal{O}_{\varphi Q}^{(3)}$
$\mathcal{O}_{\varphi tb}$
$\mathcal{O}_{tW}$
$\mathcal{O}_{tB}$
$\mathcal{O}_{t\varphi}$
-4
-3
-2
-1
0
1
2
$b\,W \to t\,Z$
$p\,p \to t\,Z\,W$
$log(r_{i,i})$
$log(r_{tot})$
$log(r_{HE})$
max lim



LHC 13 TeV
CLIC VBF $\sqrt{s}$ (GeV)
tV
th
$t\bar{t}V$
$t\bar{t}h$
VBF
380
1500
3000
$\mathcal{O}^{(3)}_{\varphi Q}$
$\sigma_{\text{int.}}/\sigma_{\text{SM}}$
$\sigma_{\text{sq.}}/\sigma_{\text{SM}}$
Inclusive
$p_T > 0.5$ TeV
$p_T > 1$ TeV
$m_{t\bar{t}}$ cut
Negative

In summary, we found that:

- ❖ **tZW and tZj optimal to access b W to t Z.**
- ❖ **tHW and tHj optimal for b W to t H.**
- ❖ **ttX processes are challenging because suppressed by s-channel propagator.**
- ❖ **Adding a jet increase the sensitivity (J. A. Dror et al. arXiv:1511.03674).**
- ❖ **ttXY and VBF-tt are promising but rate-limited (e+ e- collider for VBF).**
- ❖ **t Z to t H and t H to t H are the most difficult (future colliders).**

- Comprehensive study of energy growing effects in top quark EW sector.
- Almost all of the operators lead to maximal energy growth E^2 in 2 to 2 amplitudes.
- Energy growing interference is rare (A. Azatov et al. arXiv:1607.05236).
- Identified interesting processes to probe each of the 2 to 2 amplitudes.
- Interesting processes need further phenomenological study (QCD background, reconstruction efficiencies).

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THANKS!

Back-up slides

The SM does not explain everything.

ν masses

Gravity

Dark Matter

Baryon asymmetry

The SM does not explain everything.

ν masses

Gravity

Dark Matter

Baryon asymmetry

We look for New Physics or BSM to explain the deficiencies.

ν masses

Gravity

Dark Matter

Baryon asymmetry

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So far, the SM is undefeated: not been able to discover new particles at the LHC.

ν masses

Gravity Dark Matter

Baryon asymmetry

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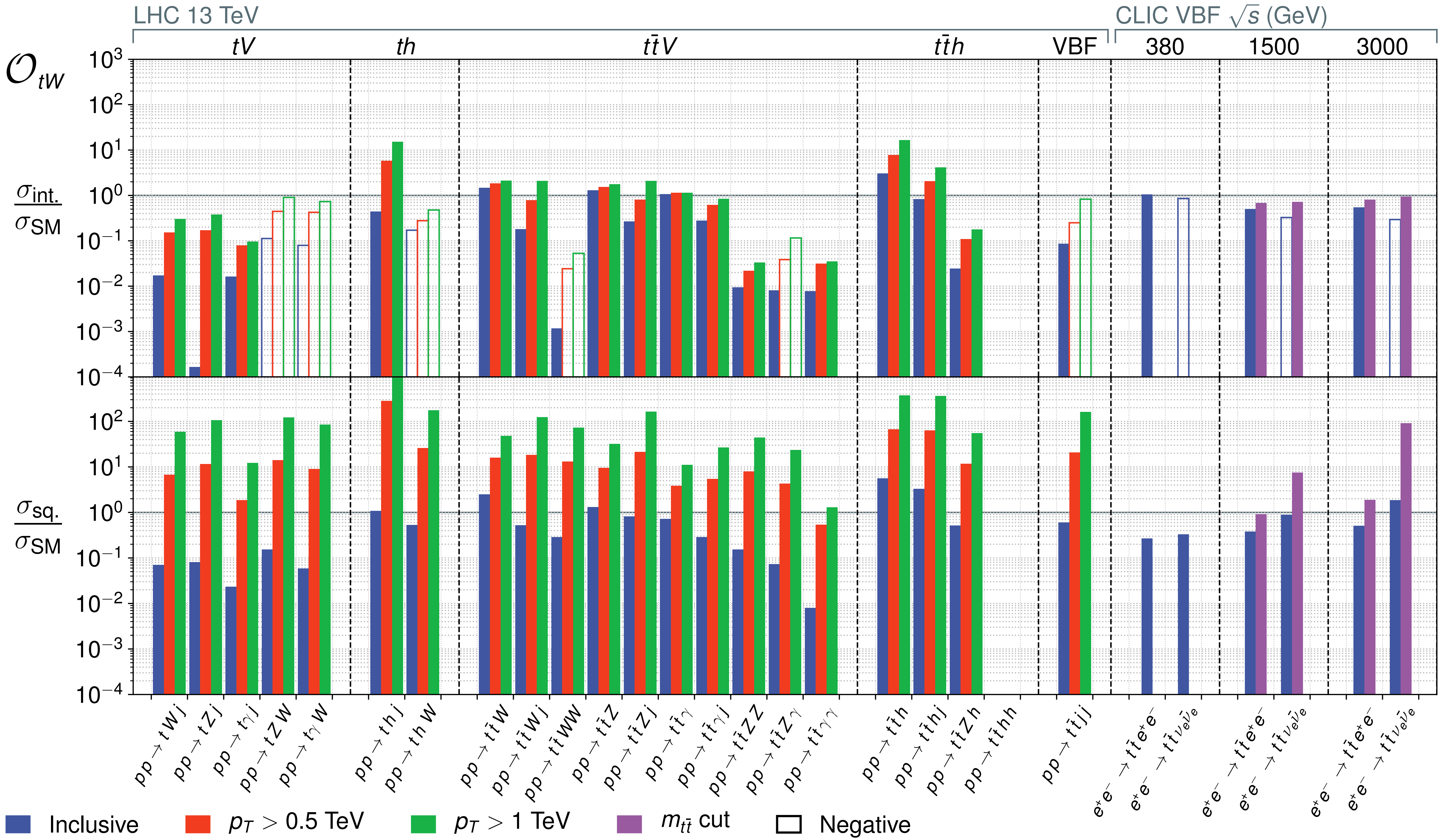
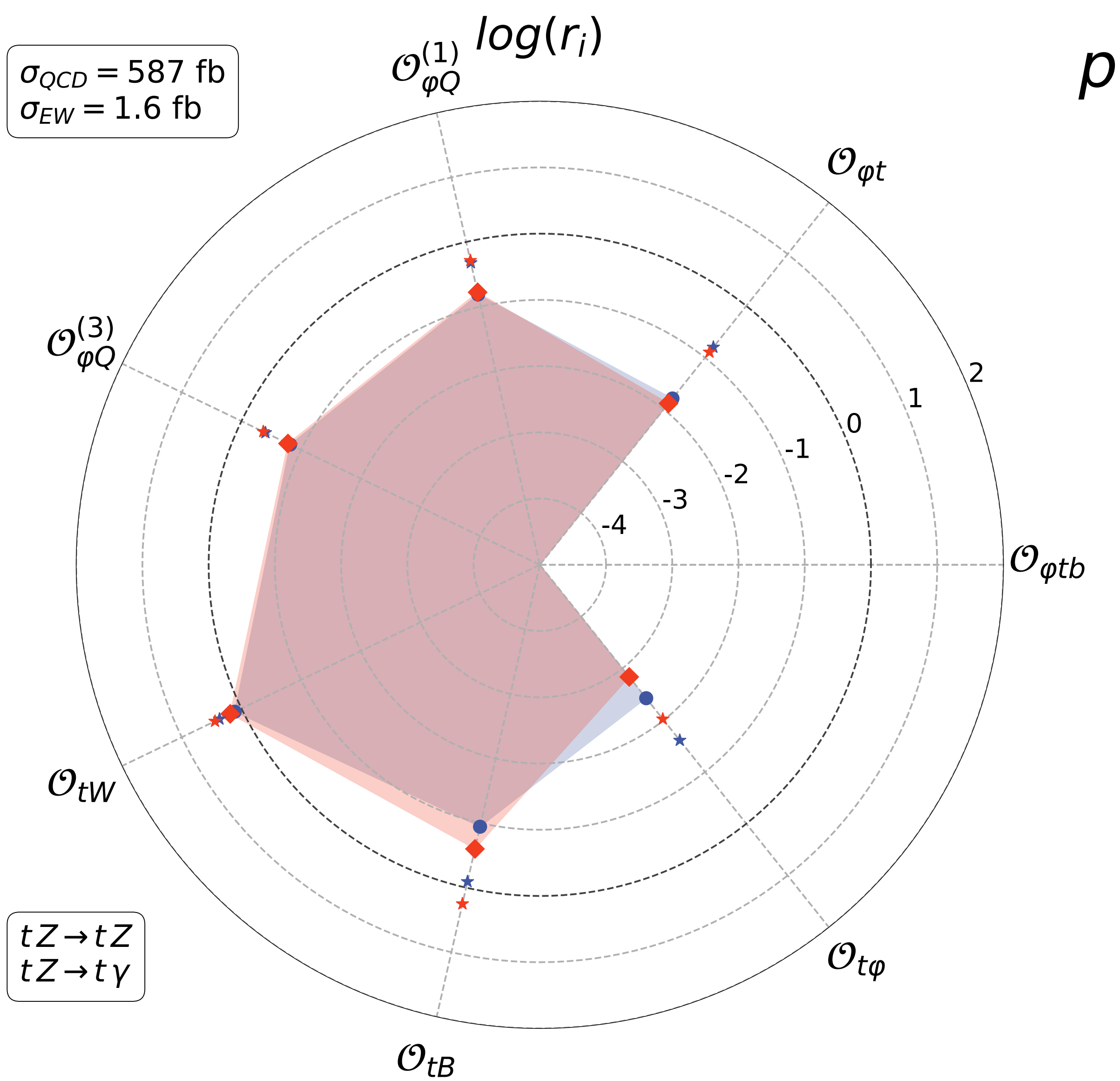
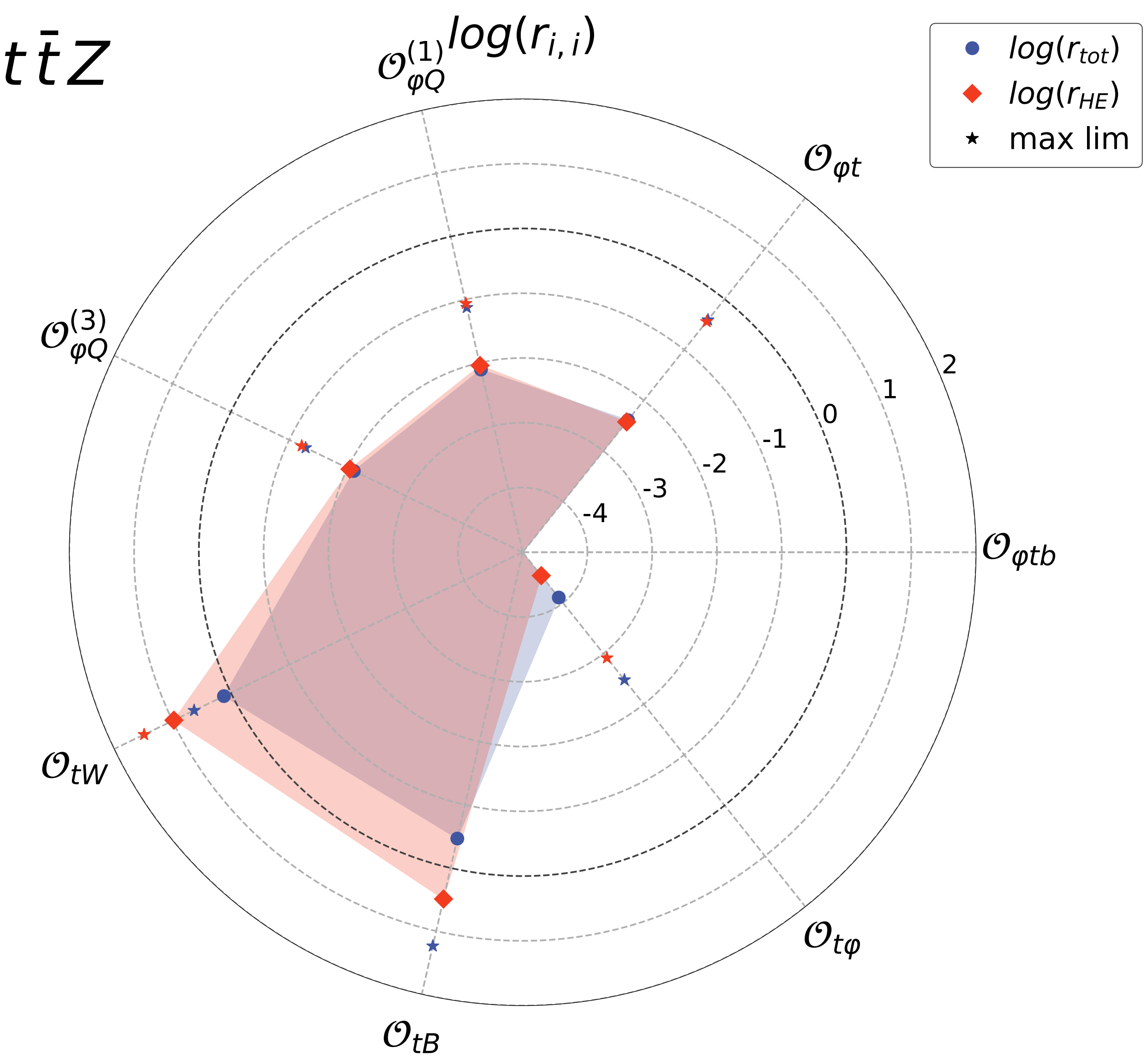
So far, the SM is undefeated: not been able to discover new particles at the LHC.

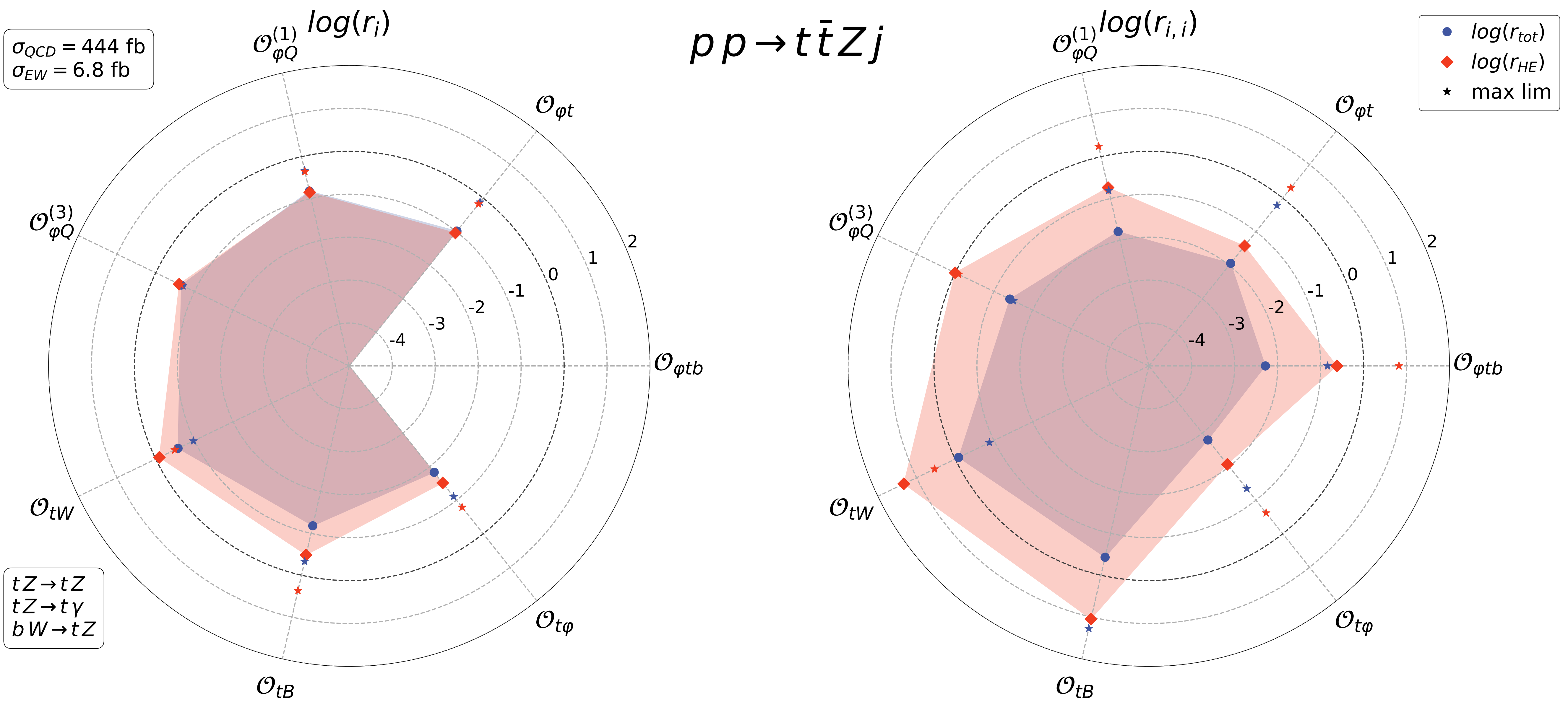
Where do we go from here?


LHC 13 TeV
CLIC VBF $\sqrt{s}$ (GeV)
tV
th
$t\bar{t}V$
$t\bar{t}h$
VBF
380
1500
3000
$\mathcal{O}_{tW}$
$\frac{\sigma_{\text{int.}}}{\sigma_{\text{SM}}}$
$\frac{\sigma_{\text{sq.}}}{\sigma_{\text{SM}}}$
Inclusive
$p_T > 0.5$ TeV
$p_T > 1$ TeV
$m_{t\bar{t}}$ cut
Negative

$pp \to t\bar{t}Z$

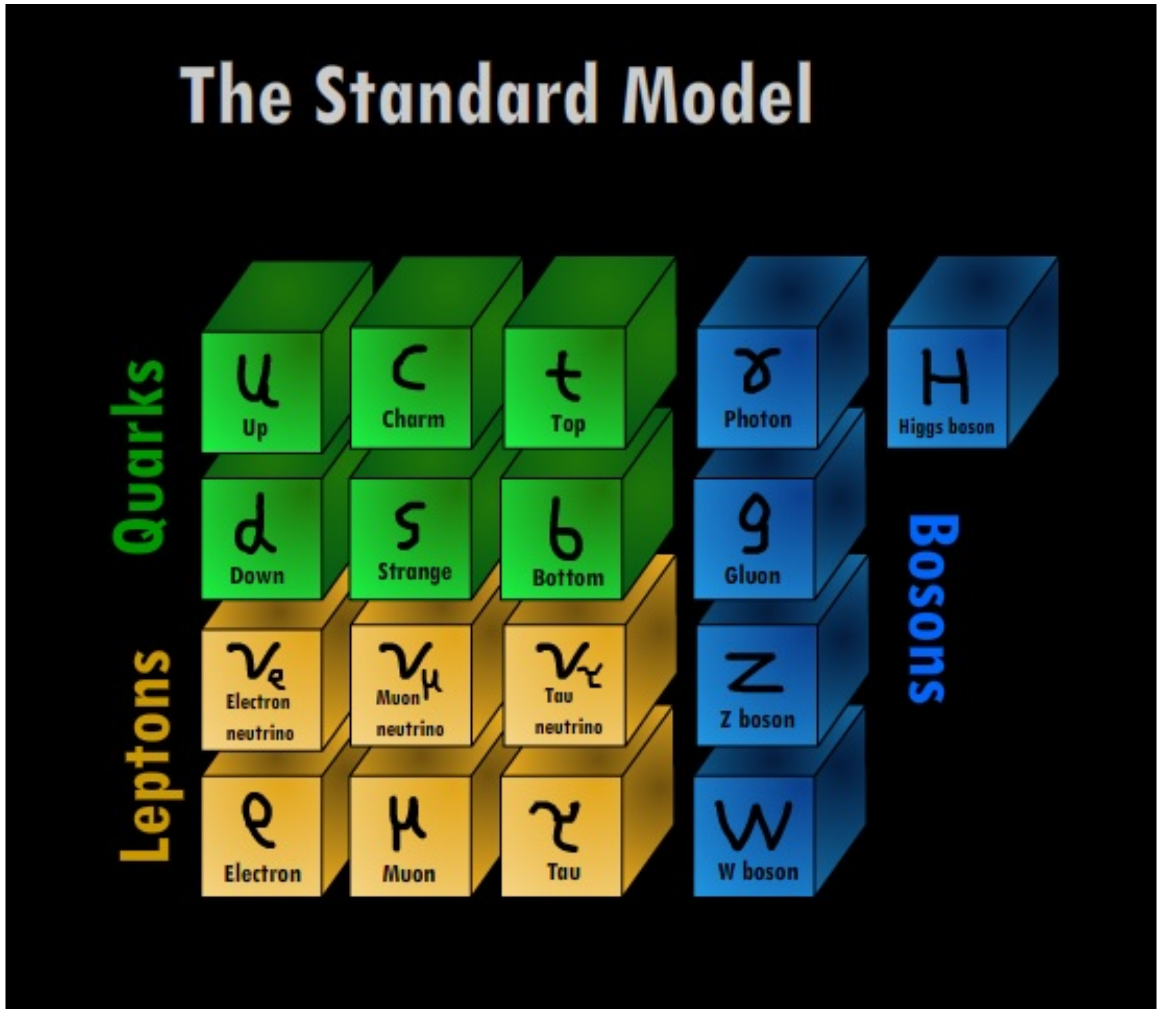

$\sigma_{QCD} = 587$ fb
$\sigma_{EW} = 1.6$ fb
$log(r_i)$
$\mathcal{O}_{\varphi Q}^{(1)}$
$\mathcal{O}_{\varphi t}$
$\mathcal{O}_{\varphi Q}^{(3)}$
$\mathcal{O}_{\varphi tb}$
$\mathcal{O}_{tW}$
$\mathcal{O}_{t\varphi}$
$\mathcal{O}_{tB}$
2
1
0
-1
-2
-3
-4
$tZ \to tZ$
$tZ \to t\gamma$


$log(r_{i,i})$
$log(r_{tot})$
$log(r_{HE})$
max lim
$\mathcal{O}_{\varphi Q}^{(1)}$
$\mathcal{O}_{\varphi t}$
$\mathcal{O}_{\varphi Q}^{(3)}$
$\mathcal{O}_{\varphi tb}$
$\mathcal{O}_{tW}$
$\mathcal{O}_{t\varphi}$
$\mathcal{O}_{tB}$
2
1
0
-1
-2
-3
-4


$\sigma_{QCD} = 444$ fb
$\sigma_{EW} = 6.8$ fb
$log(r_i)$
$pp \to t\bar{t}Zj$
$log(r_{i,i})$
$log(r_{tot})$
$log(r_{HE})$
max lim
$\mathcal{O}_{\varphi Q}^{(1)}$
$\mathcal{O}_{\varphi t}$
$\mathcal{O}_{\varphi Q}^{(3)}$
$\mathcal{O}_{\varphi tb}$
$\mathcal{O}_{tW}$
$\mathcal{O}_{t\varphi}$
$\mathcal{O}_{tB}$
$tZ \to tZ$
$tZ \to t\gamma$
$bW \to tZ$

Theories and discoveries in particle physics in the last century lead us to have a deep insight into the structure and behaviour of matter.

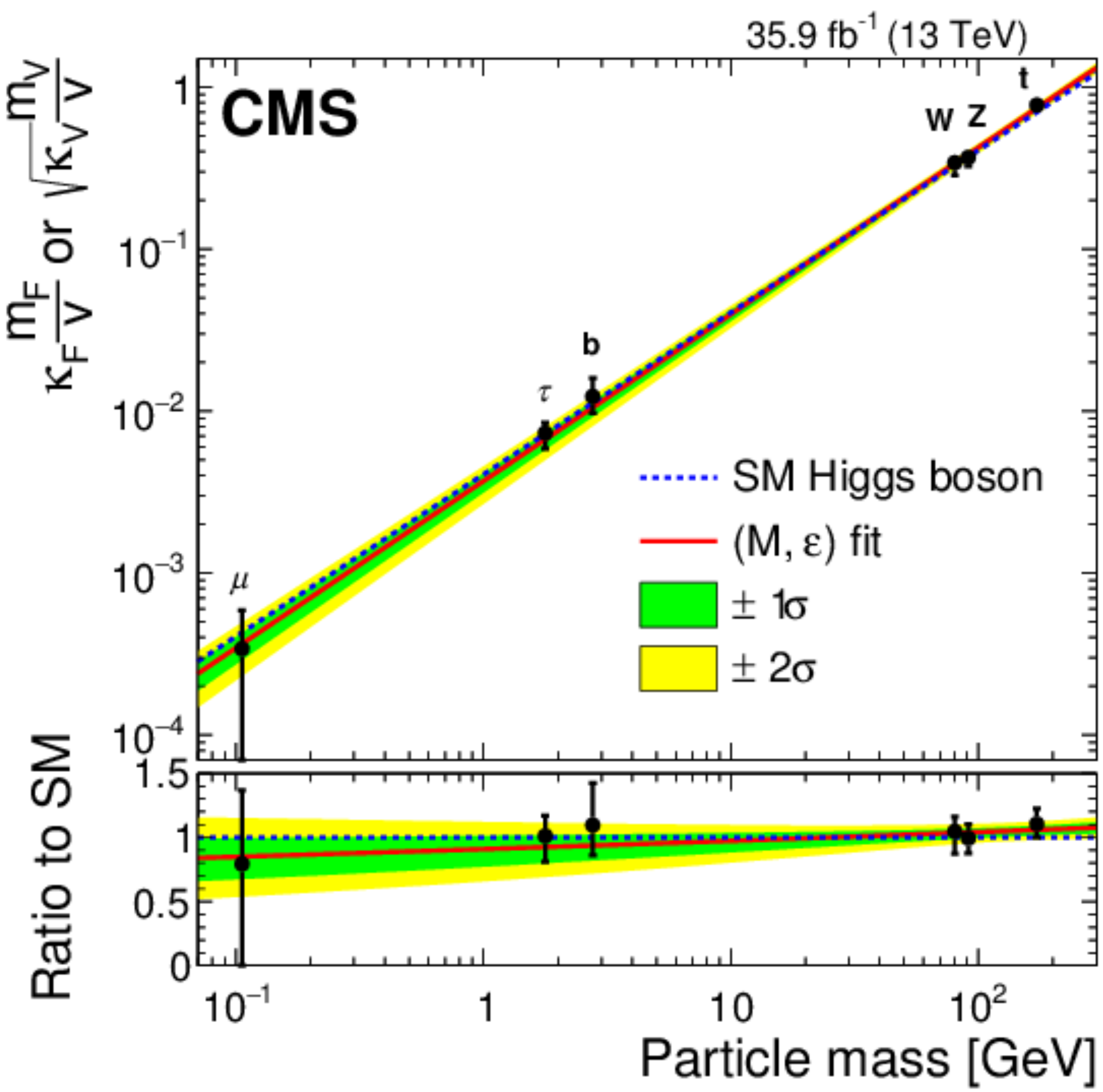
Standard Model = fundamental constituents + 3 fundamental interactions



Overtime the SM has explained a wide variety of experiments and phenomena.

The LHC has found a scalar particle that behaves like the SM Higgs.

It couples to masses.



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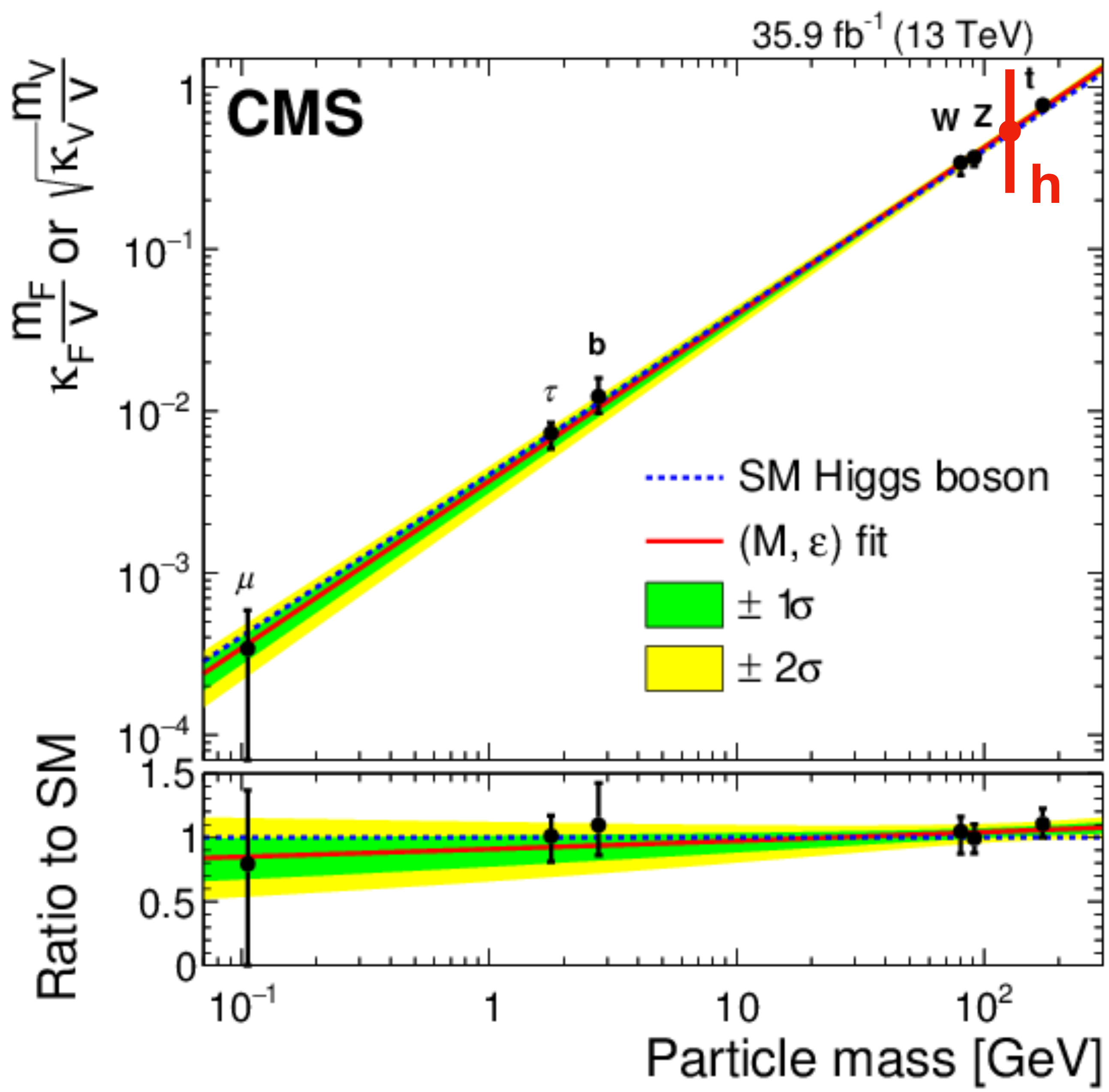

H trilinear coupling missing

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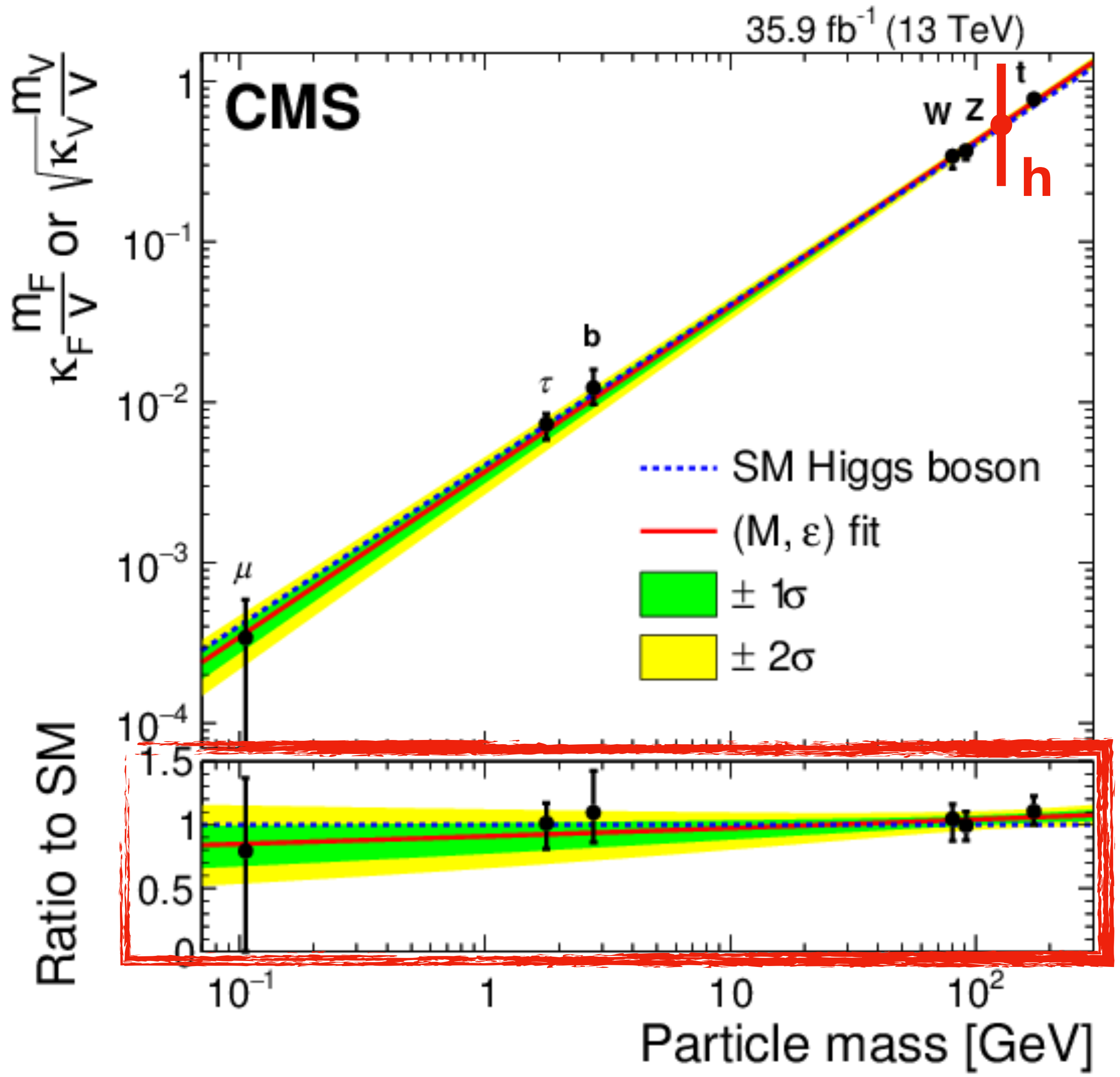

H trilinear coupling missing

Still some improvements to be made regarding precision

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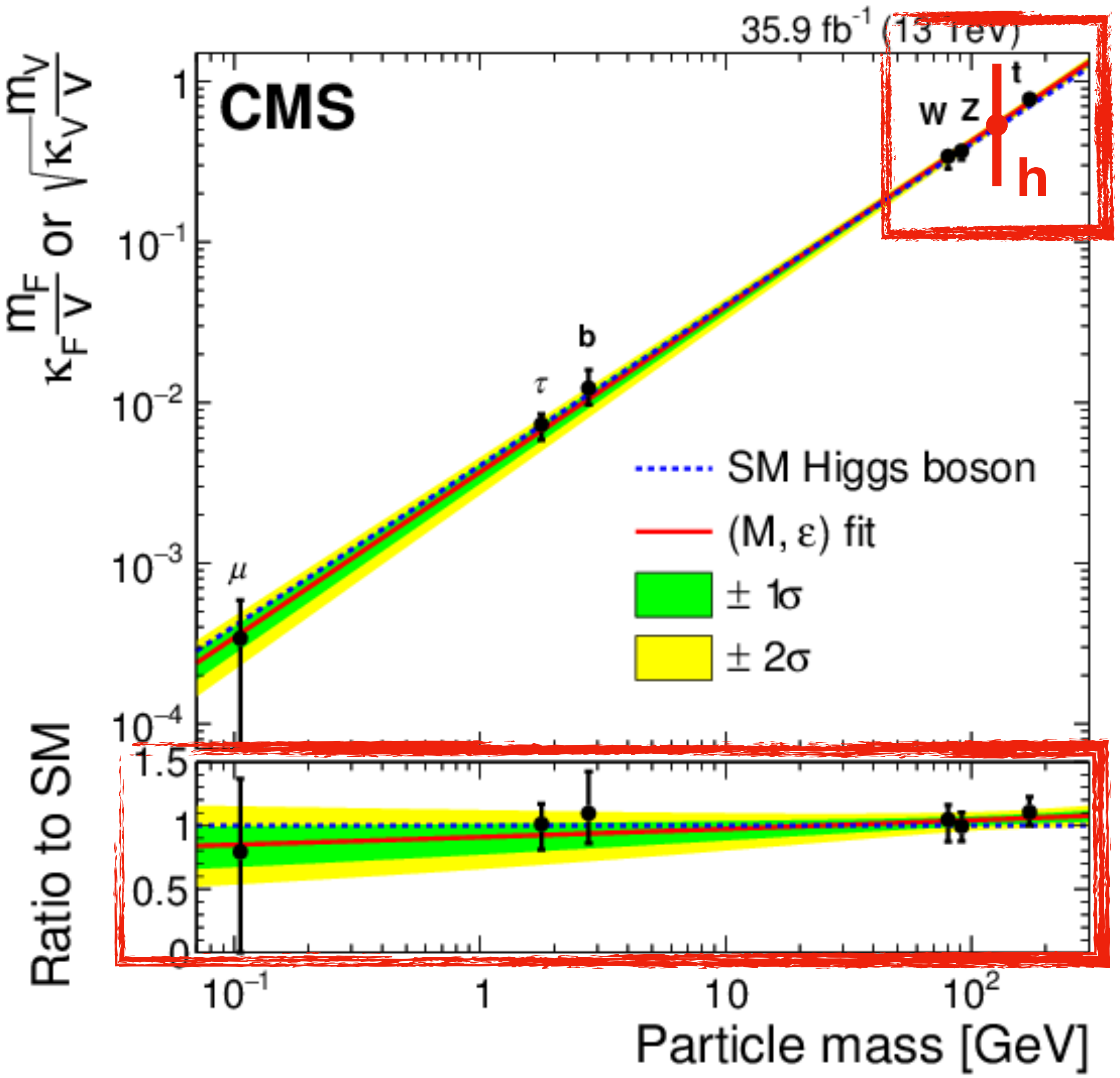

H trilinear coupling missing

Still some improvements to be made regarding precision

The priority mission of the LHC is to characterise the EWSB sector.

The existing constraints on the set of operators we study are:

Operator	Limit on c_i $[\mathrm{TeV}^{-2}]$		Operator	Limit on c_i $[\mathrm{TeV}^{-2}]$	
	Individual	Marginalised		Individual	Marginalised
$\mathcal{O}_{\varphi D}$	[-0.021,0.0055] [16]	[-0.45,0.50] [16]	$\mathcal{O}_{t\varphi}$	[-5.3,1.6] [17]	[-60,10] [17]
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Anomalous coupling Lagrangian

$$\mathcal{L} \supset -\, g_{th}\, \bar{t}\, t\, h + g_{Wh}\, W^{\mu} W_{\mu}\, h + g_{Zh}\, Z^{\mu} Z_{\mu}\, h + g_{btW}\, (\bar{t}\, \gamma^{\mu}\, P_L\, b\, W_{\mu} + \mathrm{h.c})$$
$$+\, \bar{t}\, \gamma^{\mu} (g^{Z}_{t_R}\, P_R + g^{Z}_{t_L}\, P_L)\, t\, Z_{\mu} + \bar{b}\, \gamma^{\mu} (g^{Z}_{b_R}\, P_R + g^{Z}_{b_L}\, P_L)\, t\, Z_{\mu} - g_{t\gamma}\, \bar{t}\, \gamma^{\mu}\, t\, A_{\mu}$$
$$+\, g_{W\gamma}\, (W^{\mu}\, W^{\nu}\, \partial_{\mu}\, A_{\nu} + \mathrm{perm.}) + g_{WZ}\, (W^{\mu}\, W^{\nu}\, \partial_{\mu}\, Z_{\nu} + \mathrm{perm.}),$$

Mapping to SMEFT not always obvious

- **New Lorentz structure**
- **4-point interactions**
- **SMEFT modifies multiple interactions at once, predicts correlations**

While SMEFT respects SSB, the Anomalous Coupling framework does not automatically.

AC parametrisation can lead to stronger energy growth.
The weak dipole operator in addition to modifications to tbW and ttZ interactions generate corresponding contact terms:

$$\mathcal{O}_{tW} = i\big(\bar{Q}\sigma^{\mu\nu}\,\tau_I\,t\big)\,\tilde{\phi}\,W^I_{\mu\nu} + \text{h.c.} \quad \rightarrow \quad gv\,\bar{t}_L\sigma^{\mu\nu}t_R\,W^+_\mu W^-_\nu\,,\; gv\,\bar{b}_L\sigma^{\mu\nu}t_R\,Z_\mu W^-_\nu$$

These terms generate a E^3 energy growth which is exactly canceled by other contributions due to SU(2) gauge invariance.
On the other hand in the AC framework, including dipole-like interaction

$$\mathcal{L}_{\text{dip.}} \supset -\frac{g}{\sqrt{2}}\bar{b}\,\sigma^{\mu\nu}\,(g_L P_L + g_R P_R)\,t\,\partial_\mu\,W_\nu$$

Top decay is fine, tZj would be described differently.

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\gamma^{\mu}D_{\mu}\psi + Y_{ij}\bar{\psi}_i\psi_j\phi + D_{\mu}\phi D^{\mu}\phi - V(\phi)$$

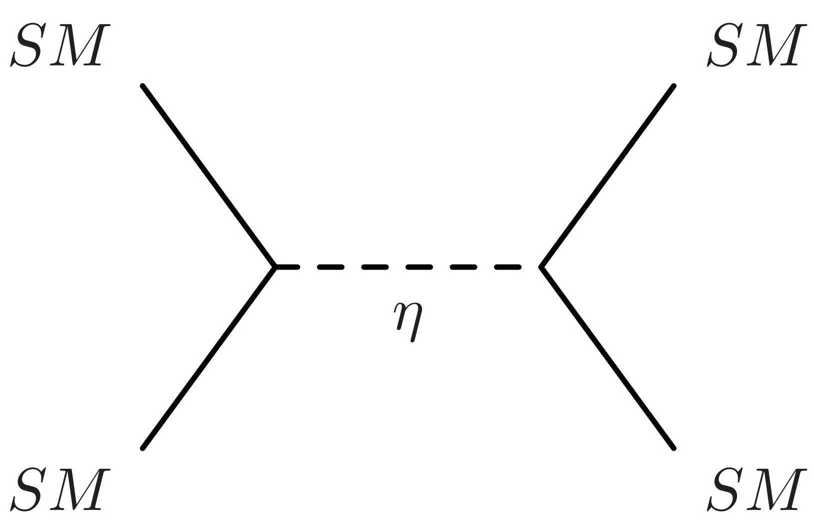
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\gamma^{\mu}D_{\mu}\psi + Y_{ij}\bar{\psi}_i\psi_j\phi + D_{\mu}\phi D^{\mu}\phi - V(\phi)$$

$$+\frac{1}{2}D_{\mu}\eta D^{\mu}\eta - \frac{1}{2}M^2\eta^2 + V(\eta, SM)$$

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\gamma^{\mu}D_{\mu}\psi + Y_{ij}\bar{\psi}_i\psi_j\phi + D_{\mu}\phi D^{\mu}\phi - V(\phi)$$

$$+\frac{1}{2}D_{\mu}\eta D^{\mu}\eta - \frac{1}{2}M^2\eta^2 + V(\eta, SM)$$

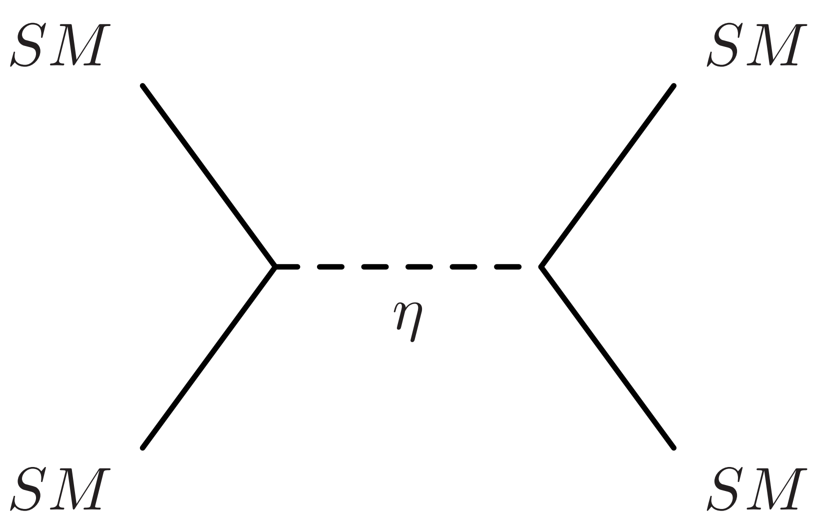
$$\frac{g^2}{p^2 - M^2}$$



$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\gamma^{\mu}D_{\mu}\psi + Y_{ij}\bar{\psi}_i\psi_j\phi + D_{\mu}\phi D^{\mu}\phi - V(\phi)$$

$$+\frac{1}{2}D_{\mu}\eta D^{\mu}\eta - \frac{1}{2}M^2\eta^2 + V(\eta, SM)$$

$$\frac{g^2}{p^2 - M^2}$$

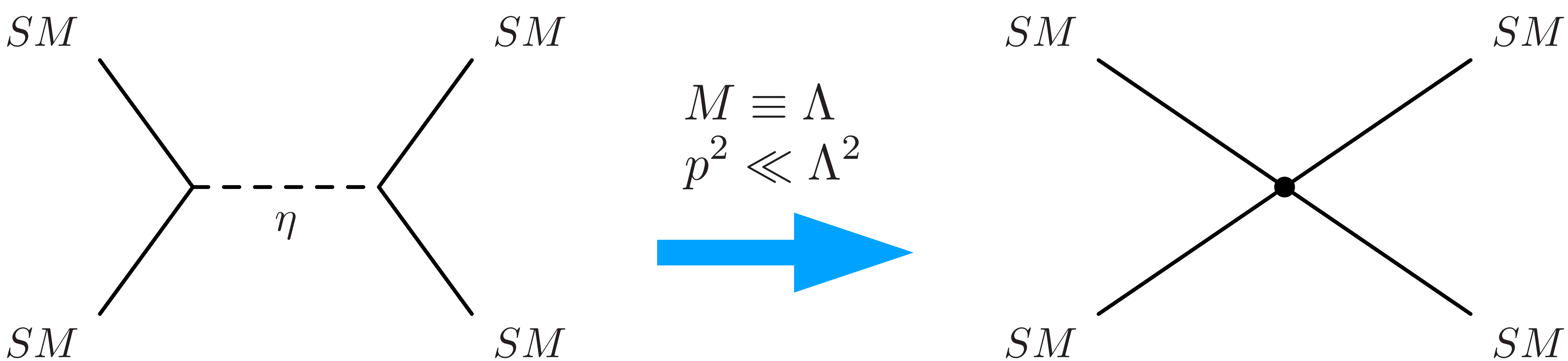


$$M \equiv \Lambda$$
$$p^2 \ll \Lambda^2$$

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\gamma^{\mu}D_{\mu}\psi + Y_{ij}\bar{\psi}_i\psi_j\phi + D_{\mu}\phi D^{\mu}\phi - V(\phi)$$

$$+\frac{1}{2}D_{\mu}\eta D^{\mu}\eta - \frac{1}{2}M^2\eta^2 + V(\eta, SM)$$

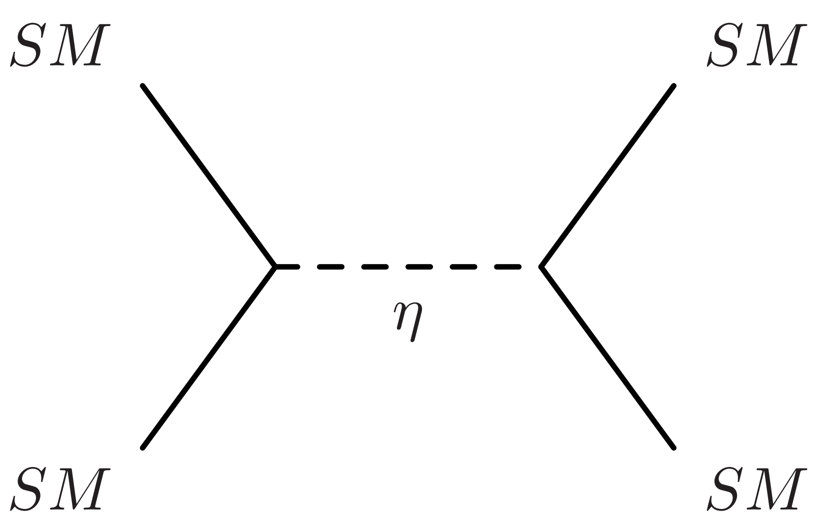
$$\frac{g^2}{p^2 - M^2}$$



$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\gamma^\mu D_\mu\psi + Y_{ij}\bar{\psi}_i\psi_j\phi + D_\mu\phi D^\mu\phi - V(\phi)$$

$$+\frac{1}{2}D_\mu\eta D^\mu\eta - \frac{1}{2}M^2\eta^2 + V(\eta, SM)$$

$$\frac{g^2}{p^2 - M^2}$$



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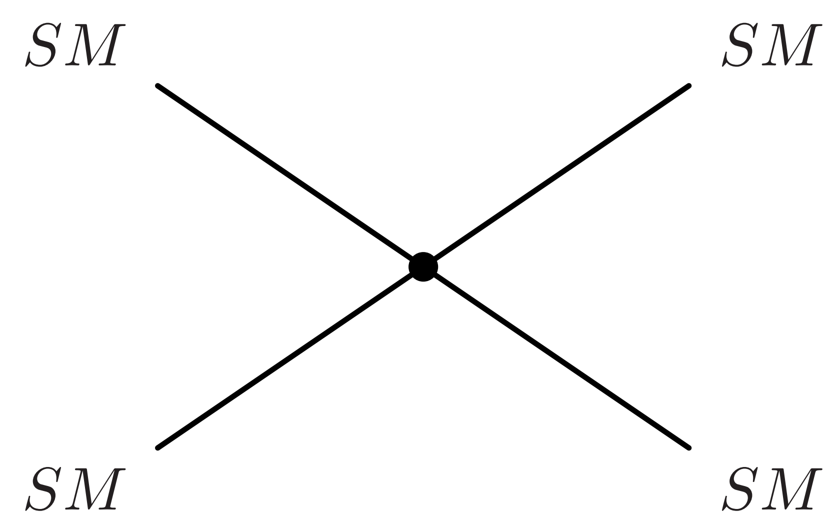

Heavy states are integrated out

$$\mathcal{L}_{\text{eff}} = \sum_i \frac{c_i \mathcal{O}_i^D}{\Lambda^{D-4}}$$