Collider Phenomenology

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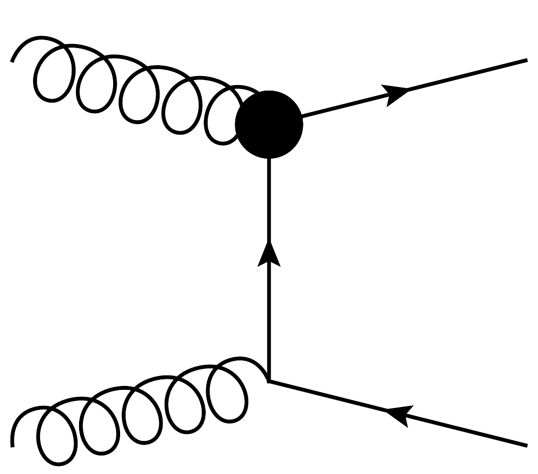
2-6/9/24

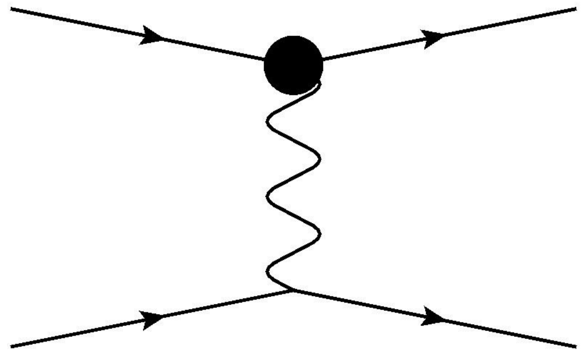
LHC is a top factory

Rich phenomenology:

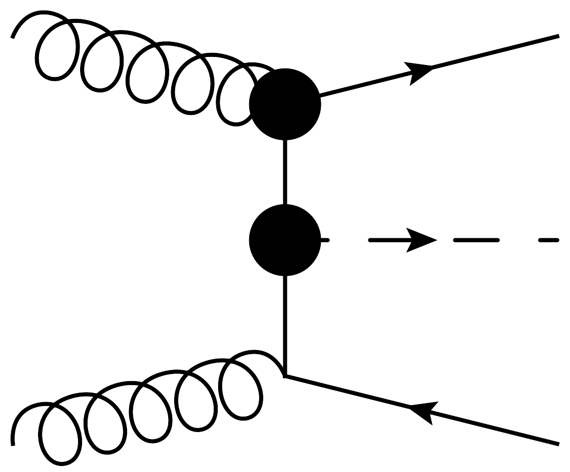
pair production

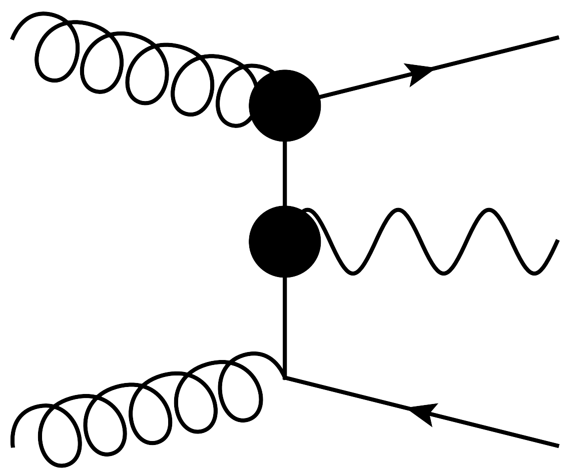


single

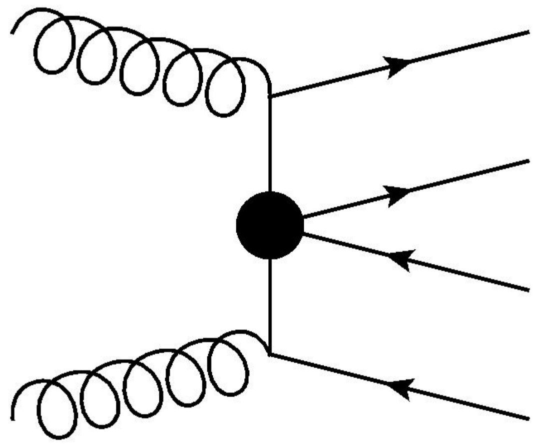


associated production

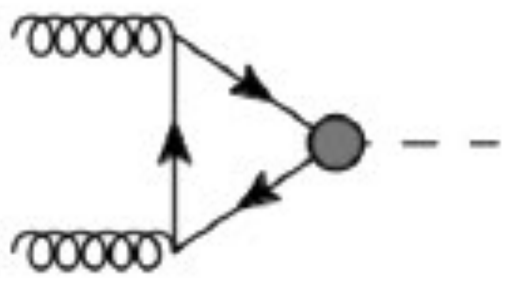


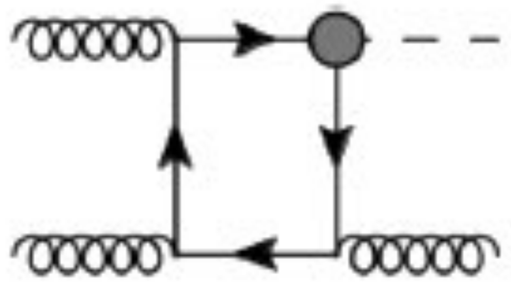


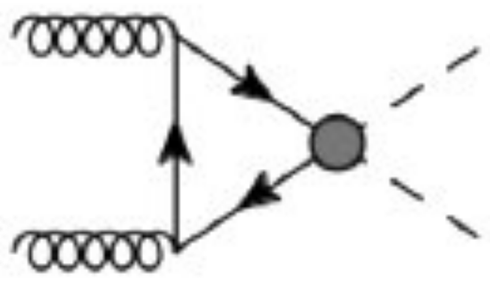
4 tops

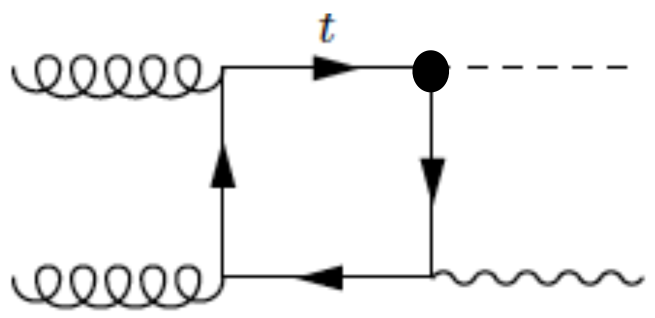


top loops









connection to Higgs physics

Top physics

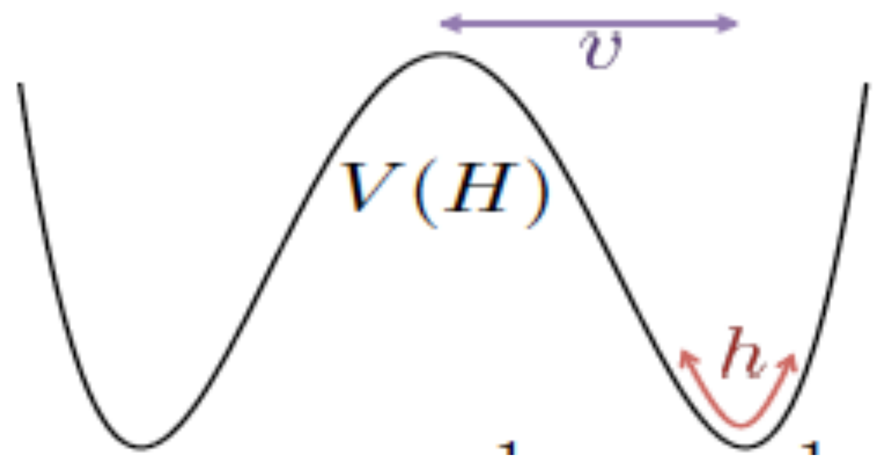
Why study the top quark ?

1. Heaviest known particle: Strong coupling to the Higgs
2. Portal to new physics: e.g. EWSB, composite Higgs
3. LHC is a top factory: precise access to top properties through a lot of production channels

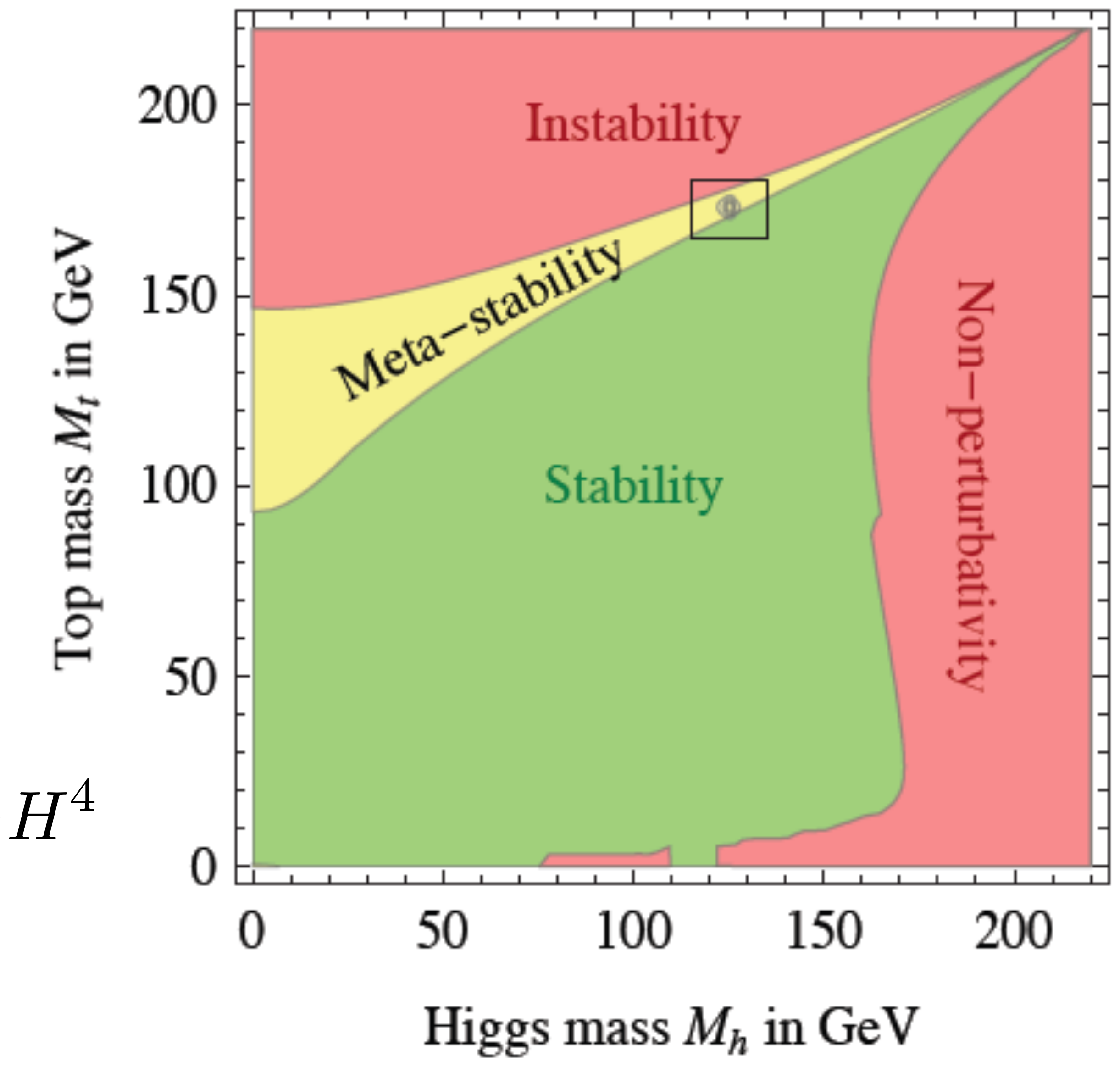
Top has a special place in the Universe

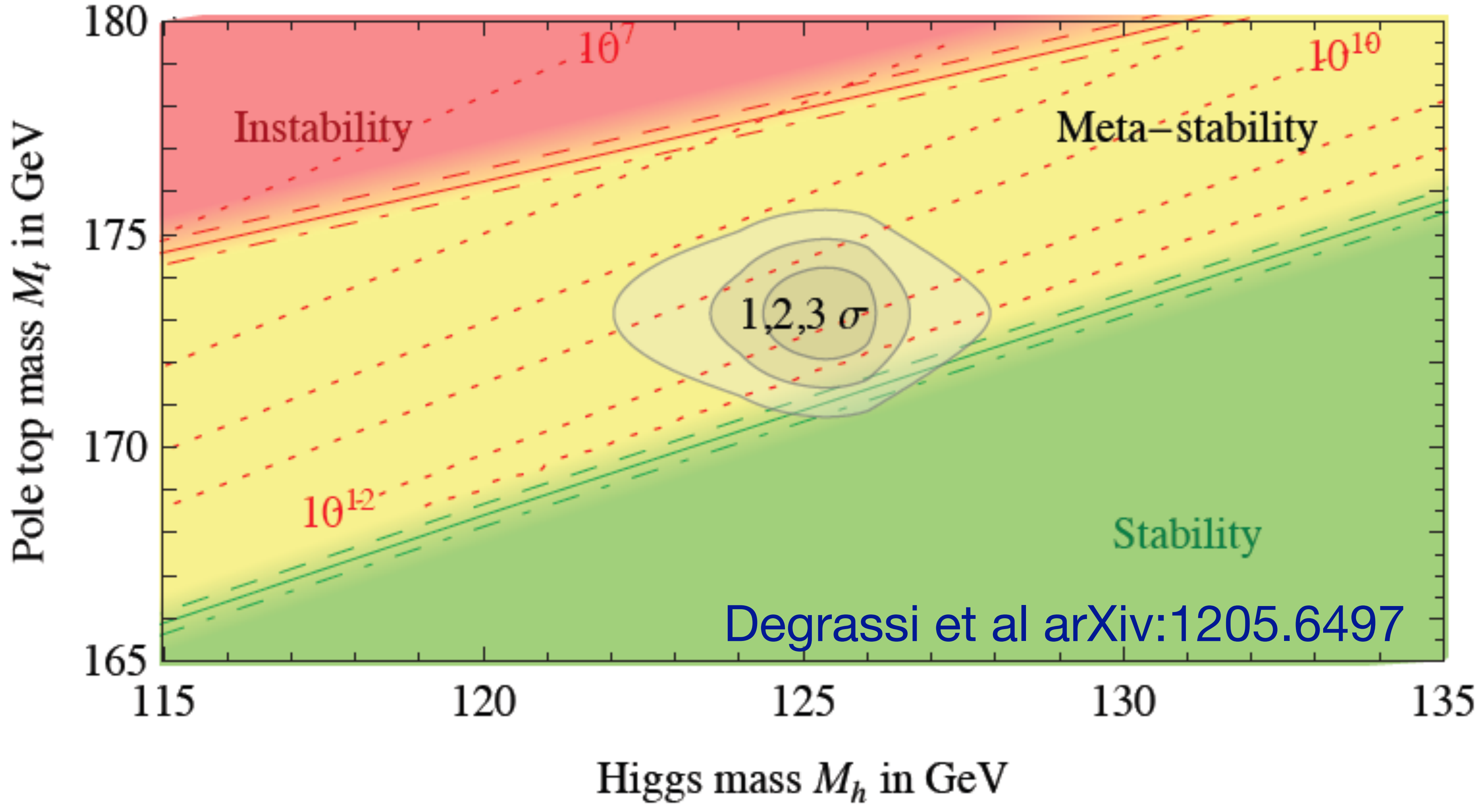
Stability of the vacuum

Higgs potential:



$$V(H) = \frac{1}{2}M_H^2 H^2 + \lambda_{HHH} v H^3 + \frac{1}{4}\lambda_{HHHH} H^4$$





Need λ to be positive (and remain positive)!

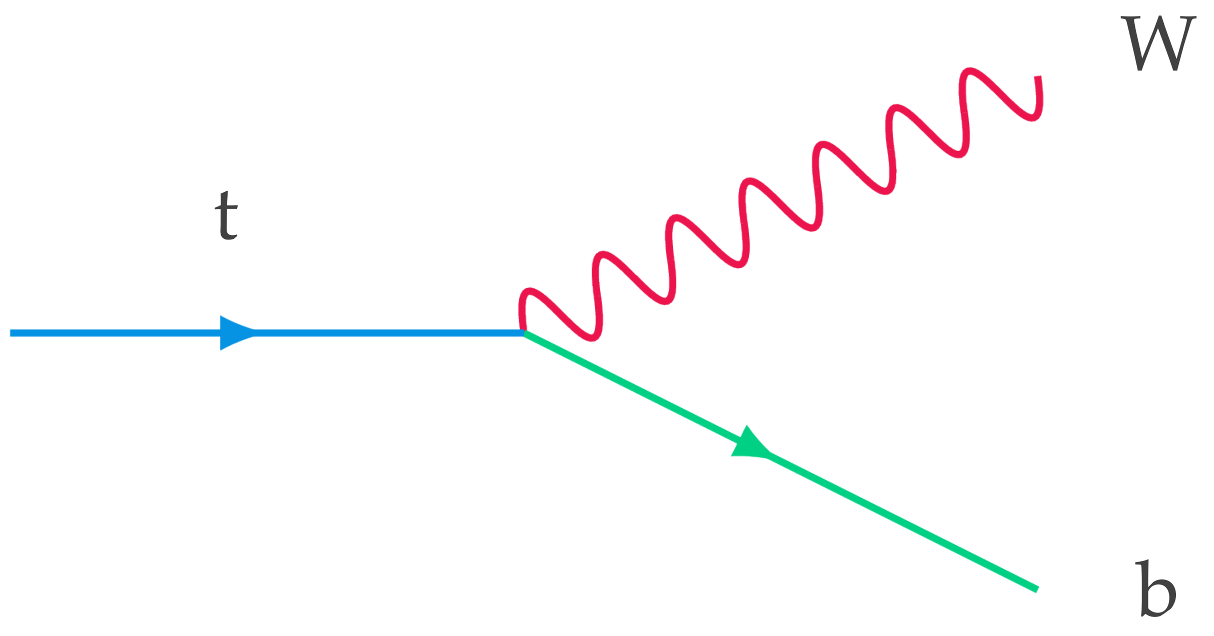
$$\frac{d\lambda(\mu)}{d\log\mu^2} = \frac{1}{16\pi^2}\left[12\lambda^2 + \frac{3}{8}g^4 + \frac{3}{16}\left(g^2+g'^2\right)^2 - 3h_t^4 - 3\lambda g^2 - \frac{3}{2}\lambda\left(g^2+g'^2\right) + 6\lambda h_t^2\right] \qquad m_t = \frac{h_t v}{\sqrt{2}} \qquad m_H^2 = 2\lambda v^2$$

$$h_t(M_t) = 0.93587 + 0.00557\left(\frac{M_t}{\text{GeV}} - 173.15\right) \ldots \pm 0.00200_{\text{th}}$$ Top Yukawa!

Top quark is a special quark

Spin Correlations

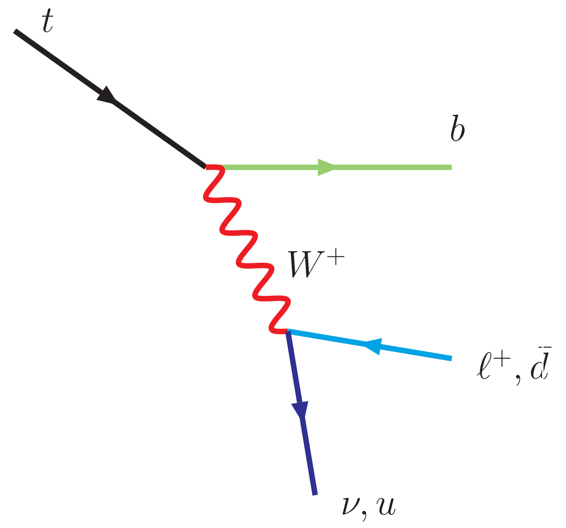
The top decays before hadronising



$\tau_{had} \approx h/\Lambda_{QCD} \approx 2 \bullet 10^{-24}$ s
$\tau_{top} \approx h/\ \Gamma_{top} = 1/(G_F\, m_t^3\, |V_{tb}|2/8\pi\sqrt{2}) \approx 5 \bullet 10^{-25}$ s
(with h=6.6 10^{-25} GeV s)

Spin information is preserved!

Top Spin effects



$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = \frac{1 + p\, k_i \cos\theta}{2}$$

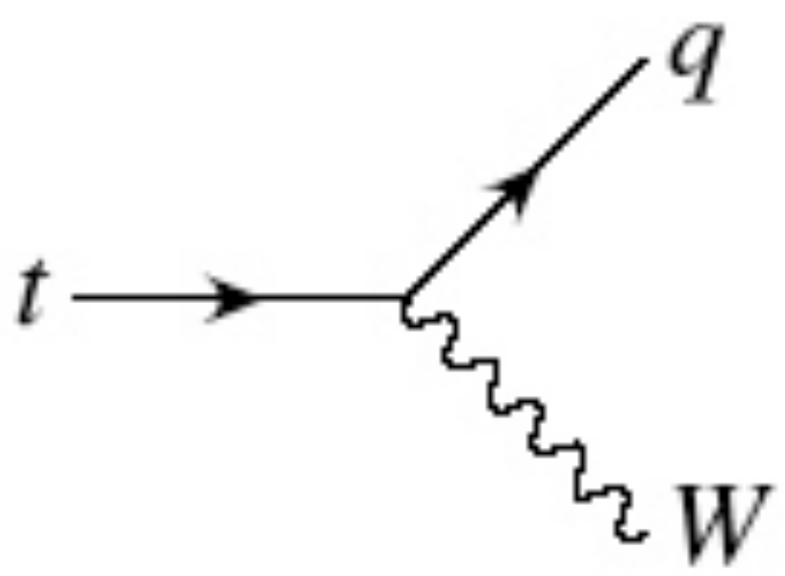
k_i	ℓ^+	$\bar{d}$	u	b
LO:	1	1	-0.32	-0.39
NLO:	0.999	0.97	-0.31	-0.37

Lepton+ or d emitted in the top spin direction

Spin analysing power

We can check how the top is produced!

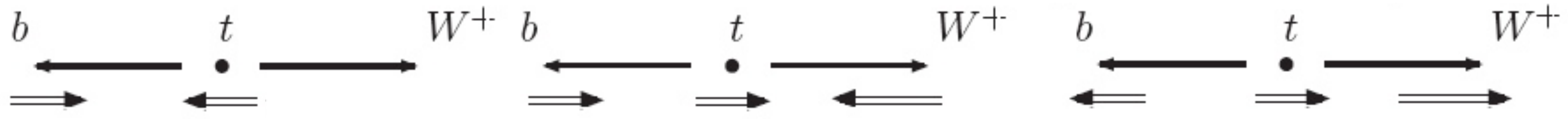
Weak interaction and W polarisation



$$-i\frac{g}{\sqrt{2}}V_{tq}\gamma^{\mu}\frac{1}{2}(1-\gamma^5)$$

Only left-handed tops in the decay!

Helicities of W bosons

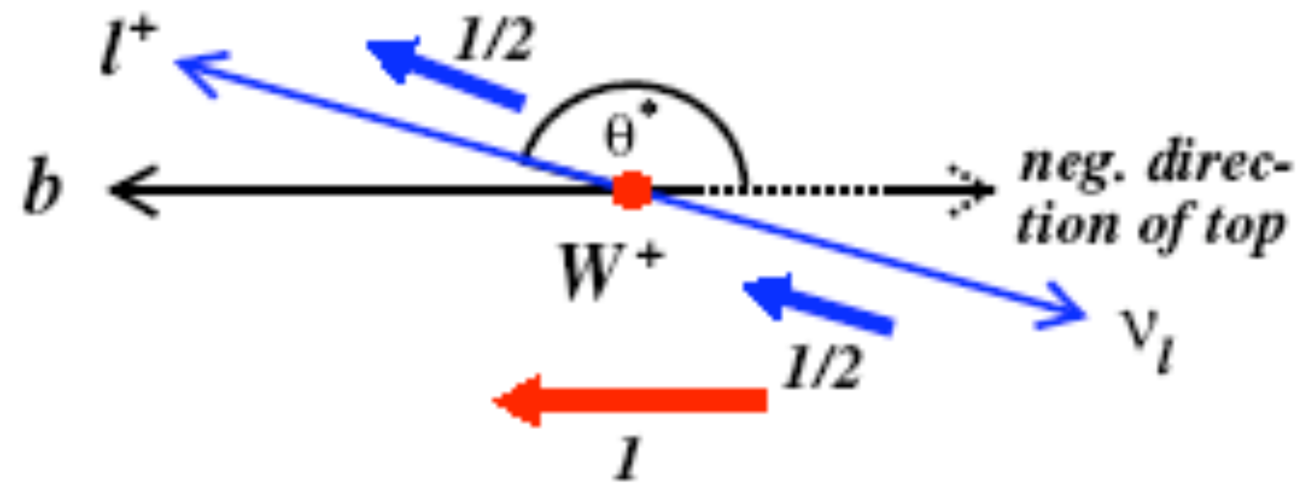


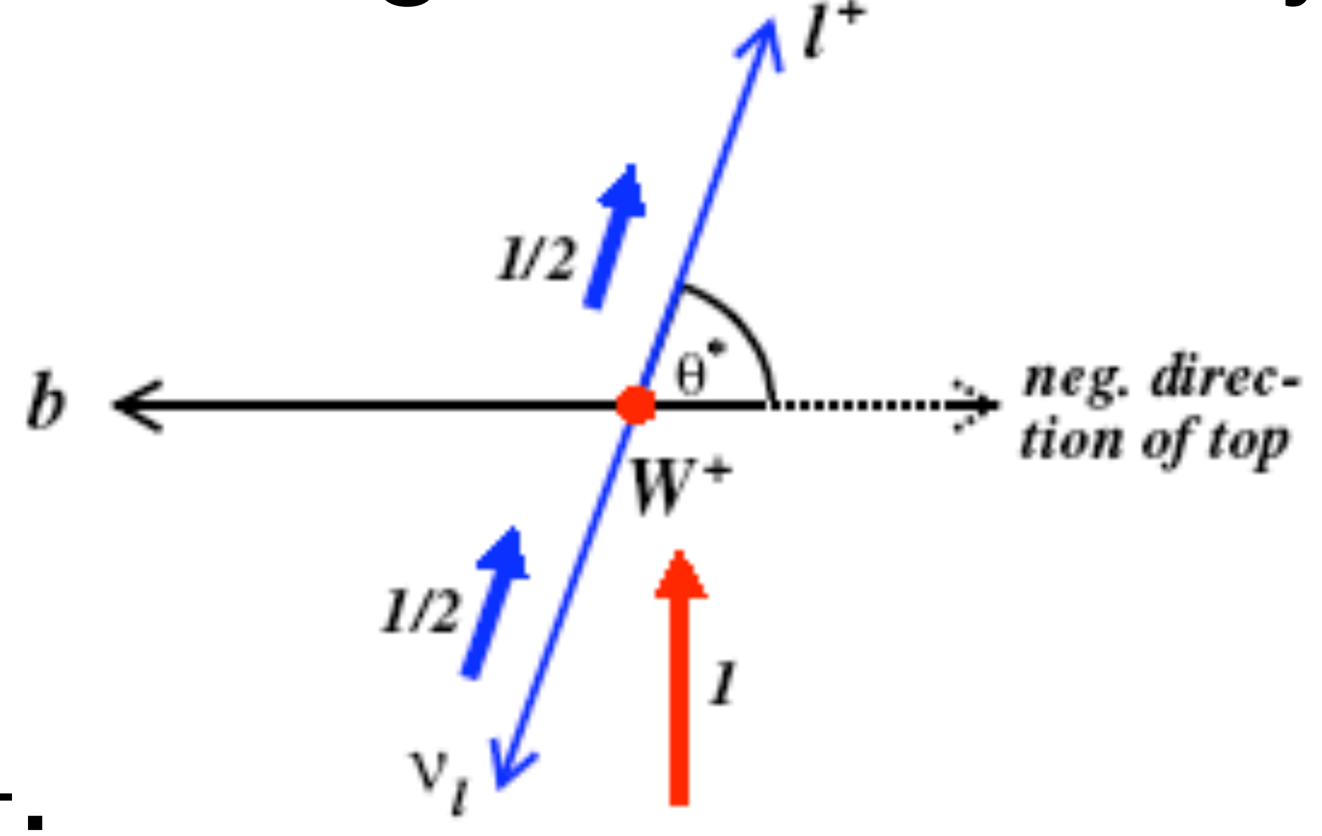
longitudinal left-handed right-handed

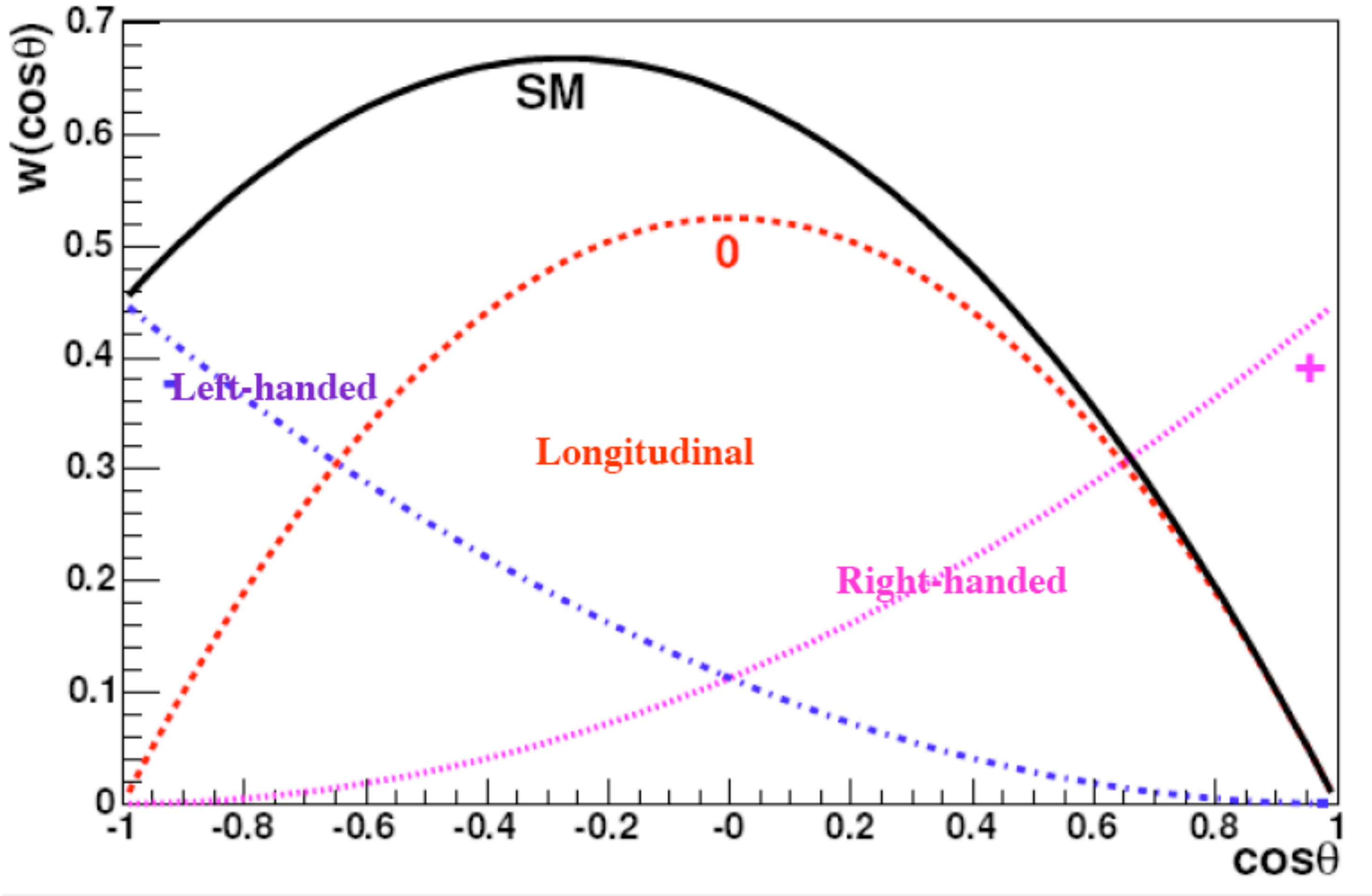
? ? ?

Weak interaction and W polarisation

Extract W polarisation by looking at the W decay products:







Angular distribution of l^+:

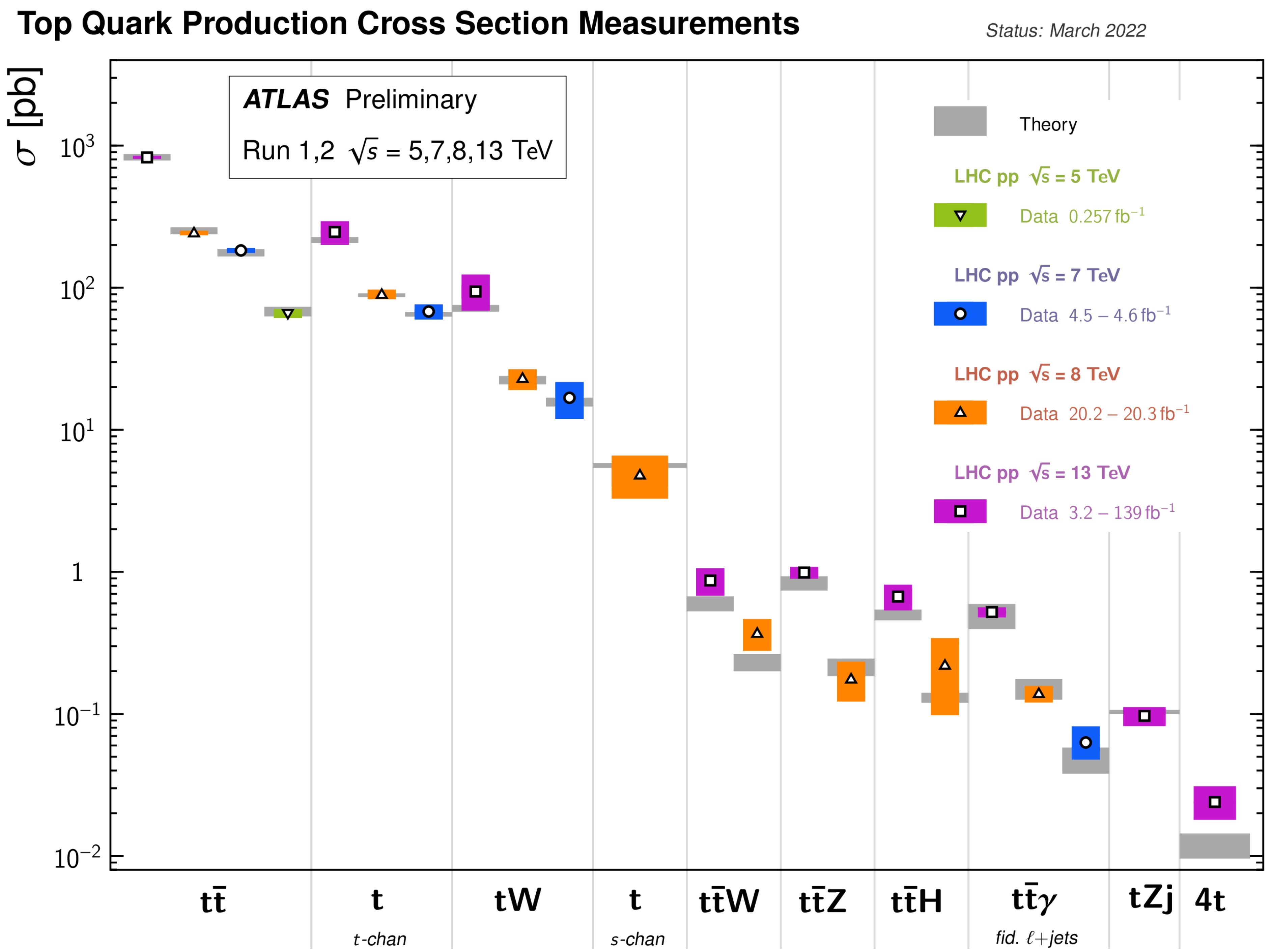
$$\frac{1}{N}\frac{dN(W\to l\nu)}{dcos\theta} = K\left[f_0 \sin^2\theta + f_L(1-\cos\theta)^2 + f_R(1+\cos\theta)^2\right]$$

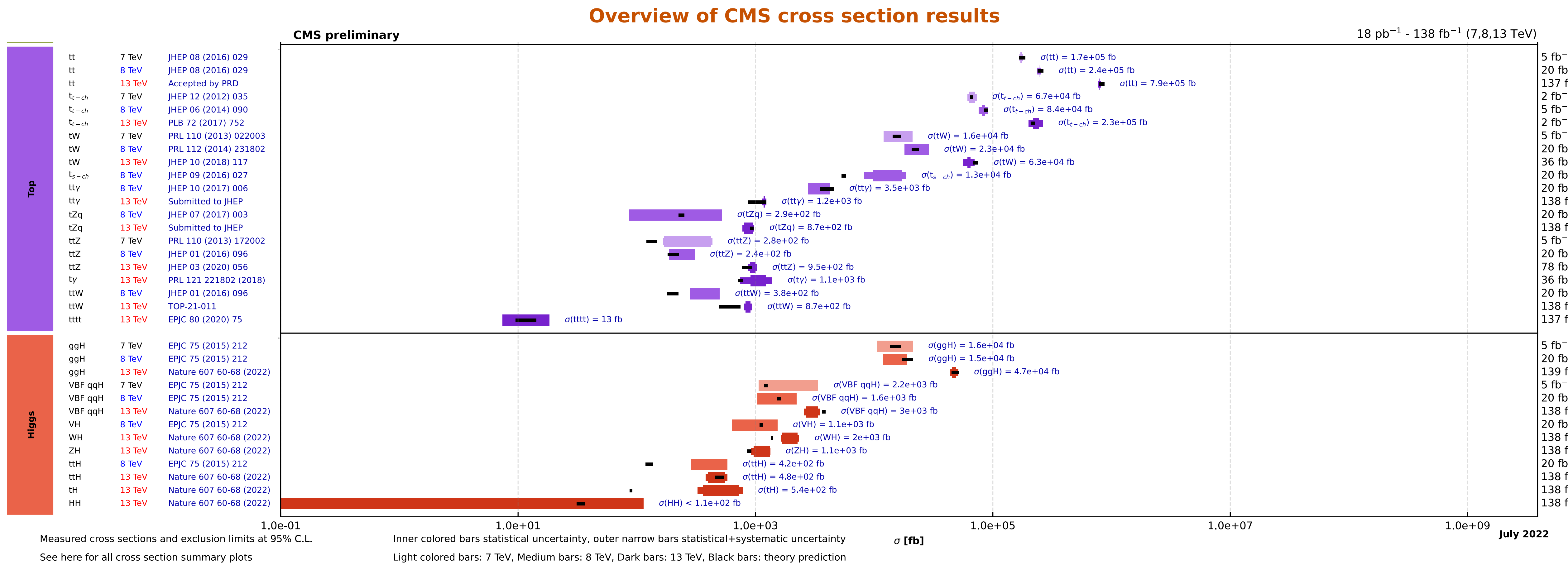
$$f_0 = \frac{m_t^2}{2m_W^2+m_t^2} \sim 70\,\% \qquad f_L = \frac{2m_W^2}{2m_W^2+m_t^2} \sim 30\,\% \qquad f_R \sim 0\,\%$$

for $m_b = 0$

Check of Wtb interaction!

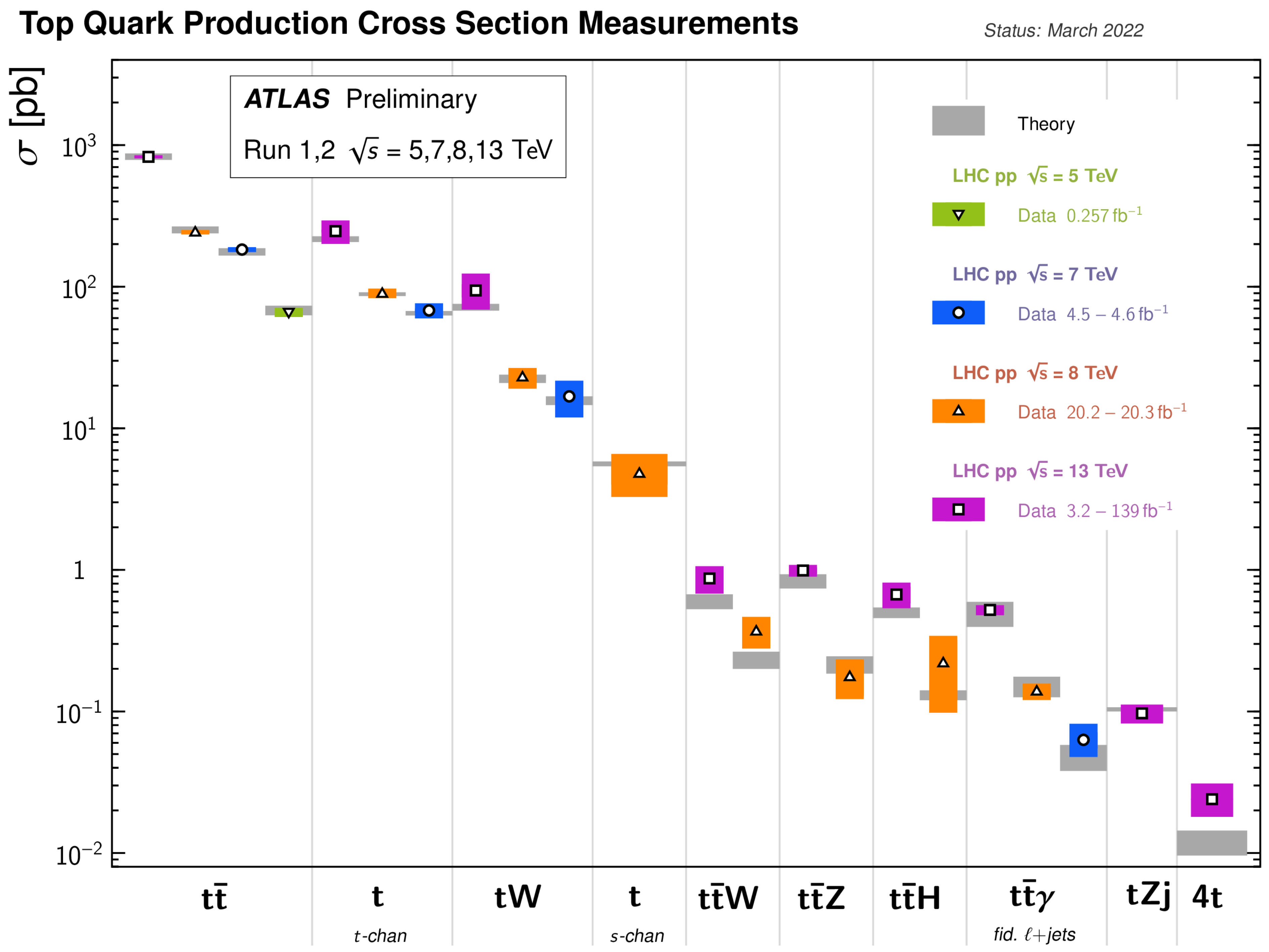
Status of top measurements

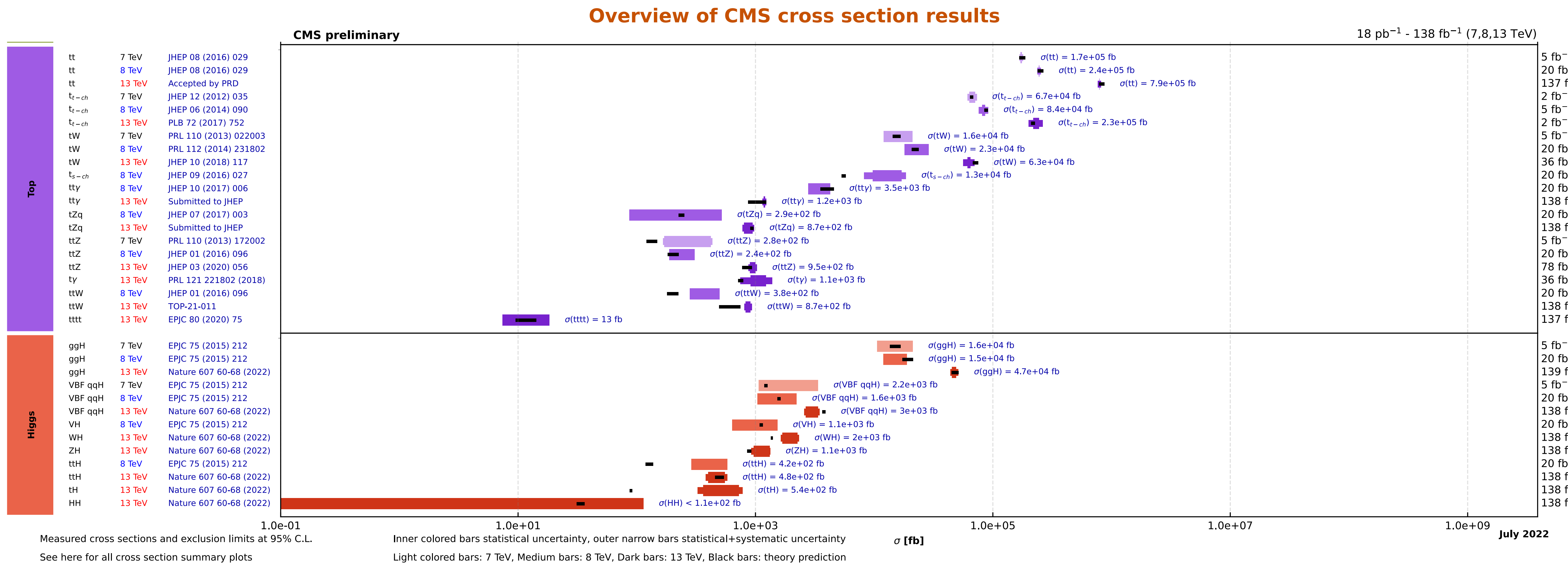




Model	E_{CM} [TeV]	$\int \mathcal{L}\,dt$ [fb^{-1}]	Measurement	Theory
$t\bar{t}$	13	36.1 fb^{-1}	$\sigma = 826.4 \pm 3.6 \pm 19.6$ pb	$\sigma = 832 + 40 - 45$ pb (top++ NNLO+NNLL)
t_{t-chan}	13	3.2 fb^{-1}	$\sigma = 247 \pm 6 \pm 46$ pb	$\sigma = 217 \pm 10$ pb (NLO+NLL)
$t\bar{t}W$	13	36.1 fb^{-1}	$\sigma = 870 \pm 130 \pm 140$ fb	$\sigma = 600 \pm 72$ fb (Madgraph5 + aMCNLO)
$t\bar{t}Z$	13	139 fb^{-1}	$\sigma = 990 \pm 50 \pm 80$ fb	$\sigma = 840 + 90 - 100$ fb (NLO QCD + EW)
$t\bar{t}H$	13	80 fb^{-1}	$\sigma = 670 \pm 90 + 110 - 100$ fb	$\sigma = 507 + 35 - 50$ fb (LHCHXSWG NLO QCD + NLO EW)
$t\bar{t}\gamma$	13	36.1 fb^{-1}	$\sigma = 521 \pm 9 \pm 41$ fb	$\sigma = 495 \pm 99$ fb (PRD 83 (2011) 074013)
tZj	13	139 fb^{-1}	$\sigma = 97 \pm 13 \pm 7$ fb	$\sigma = 102 + 5 - 2$ fb (Madgraph5 + aMCNLO (NLO))
4t	13	139 fb^{-1}	$\sigma = 24 + 7 - 6$ fb	$\sigma = 12.0 \pm 2.4$ fb (JHEP 02 (2018) 031)

Status of top measurements





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Very precise measurements!

In some cases:

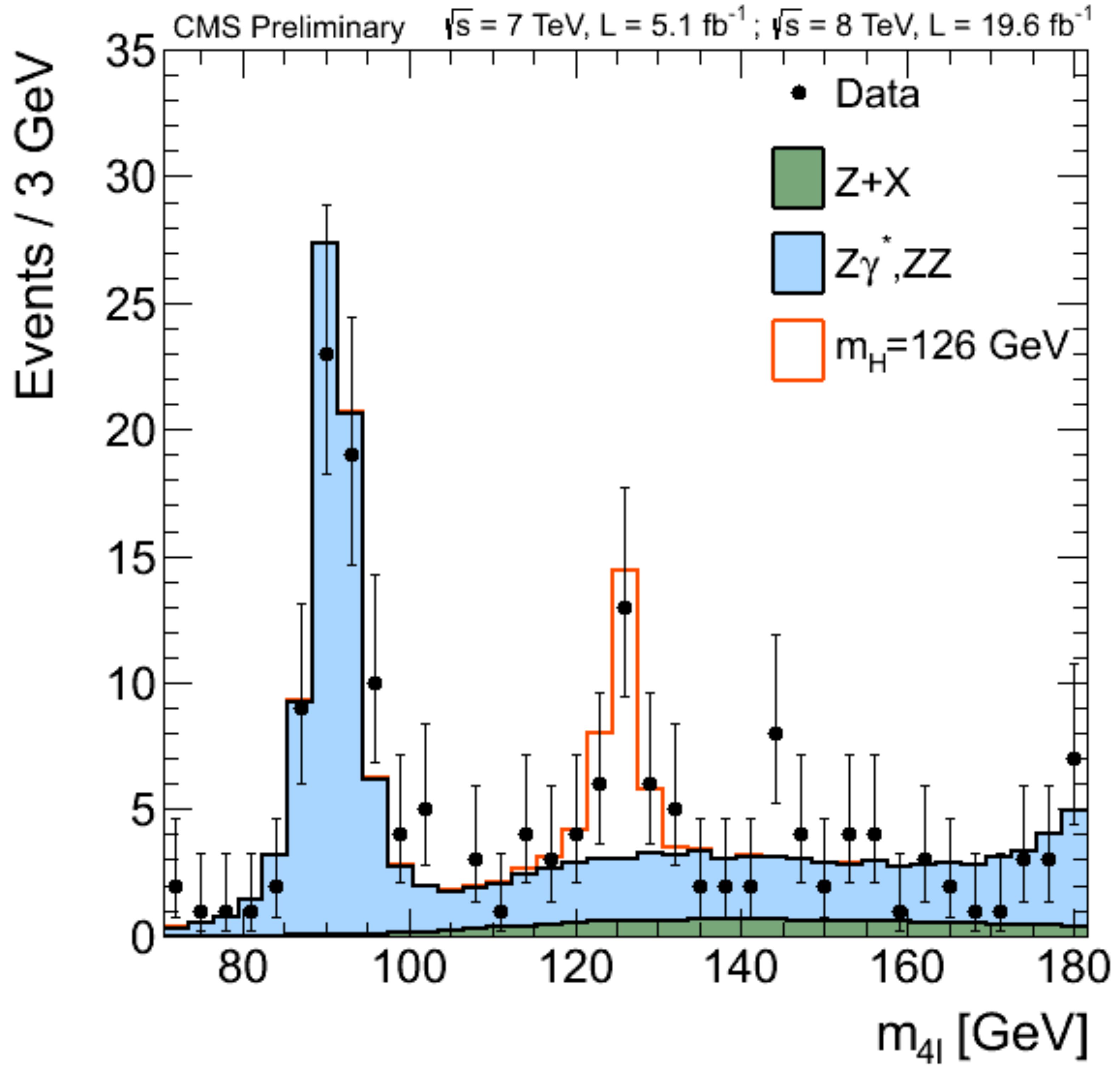
$\Delta_{EXP} < \Delta_{TH}$

New Physics searches at the LHC

Model-dependent

SUSY, 2HDM…

New particles

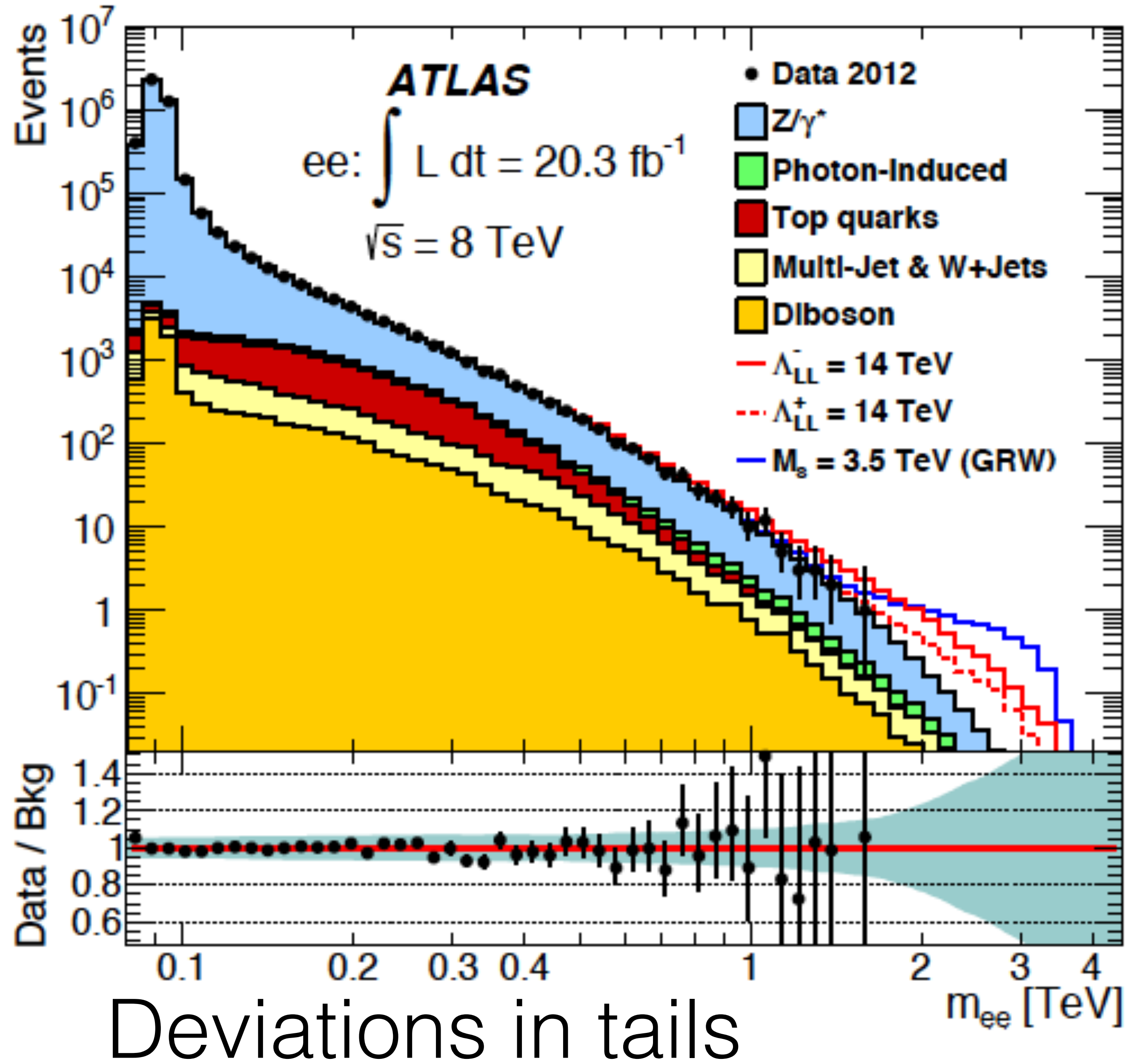


Model-Independent

simplified models,EFT

New Interactions of SM particles

anomalous couplings, EFT



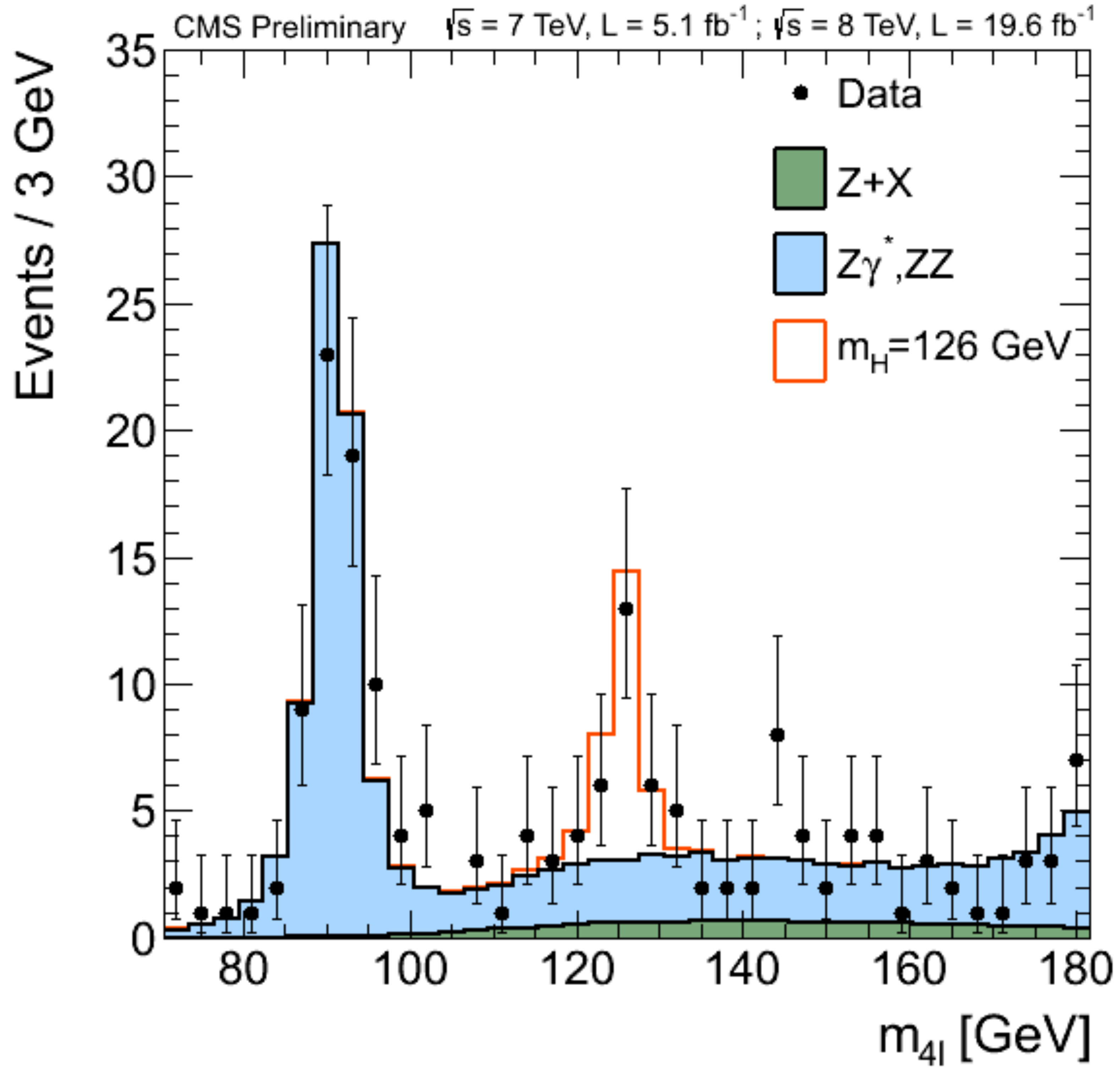
Deviations in tails

New Physics searches at the LHC

Model-dependent

SUSY, 2HDM…

New particles



Model-Independent

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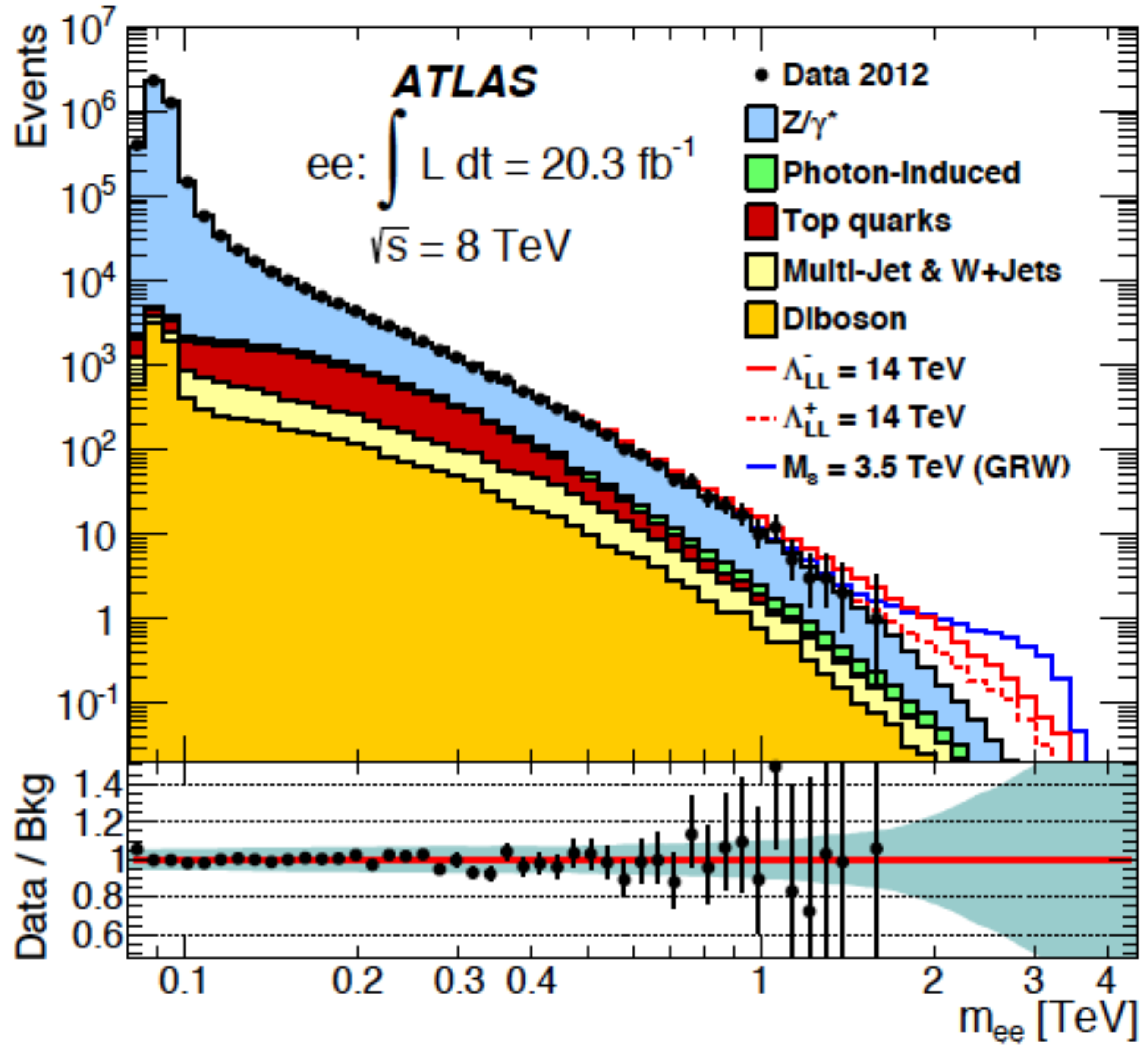
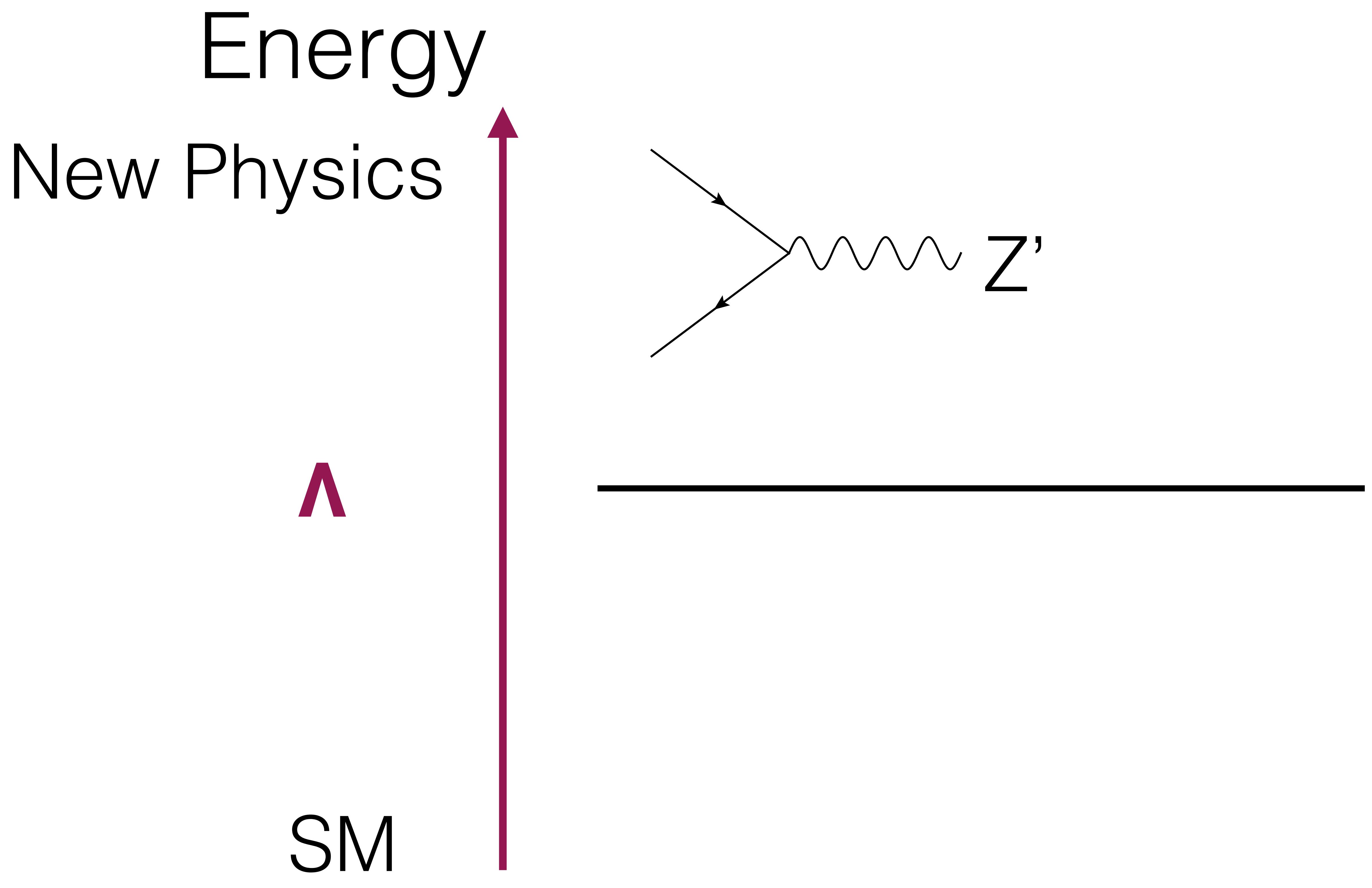


$$\mathcal{L}_{\rm Eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

EFT: What is it all about?



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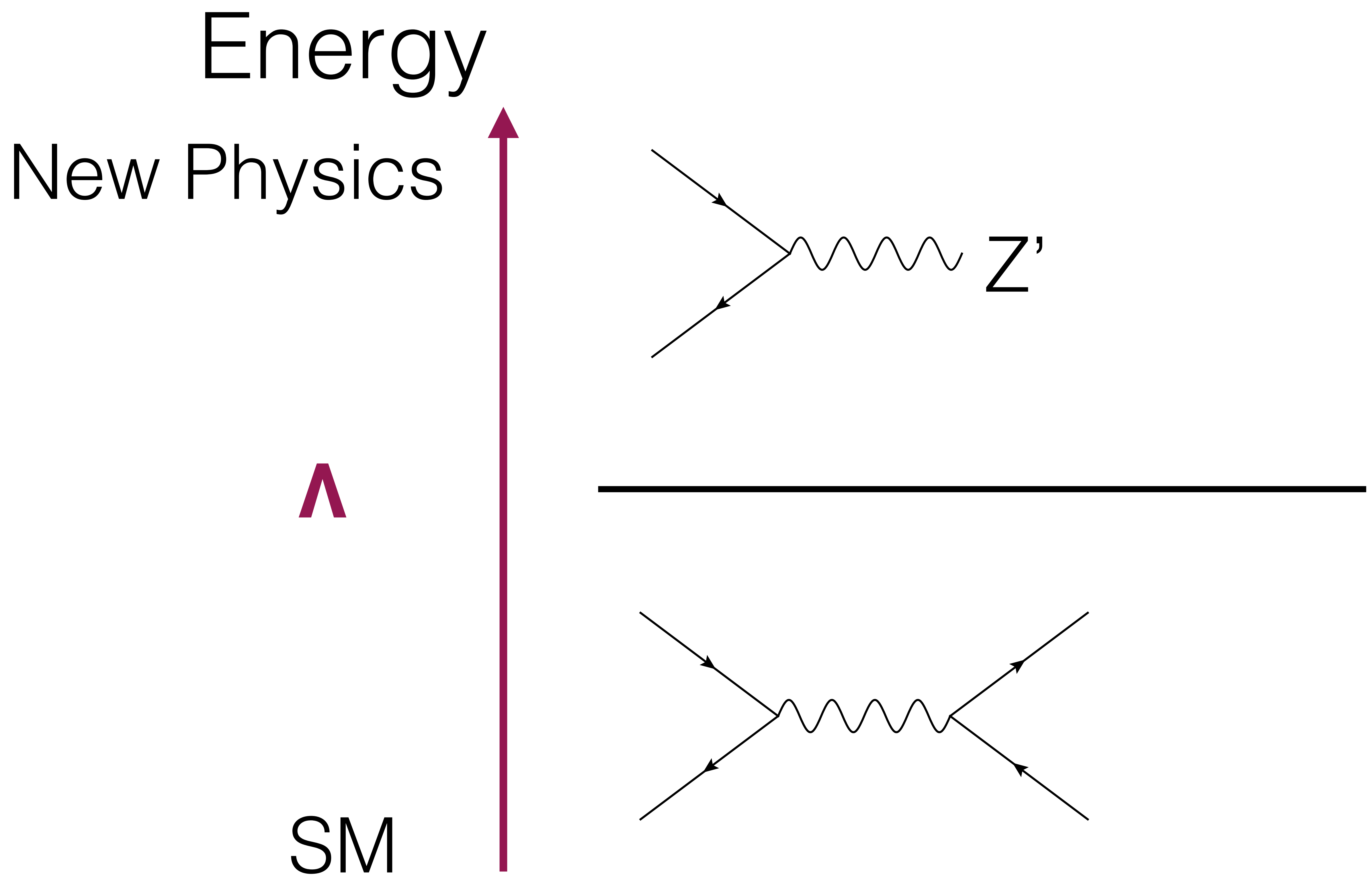

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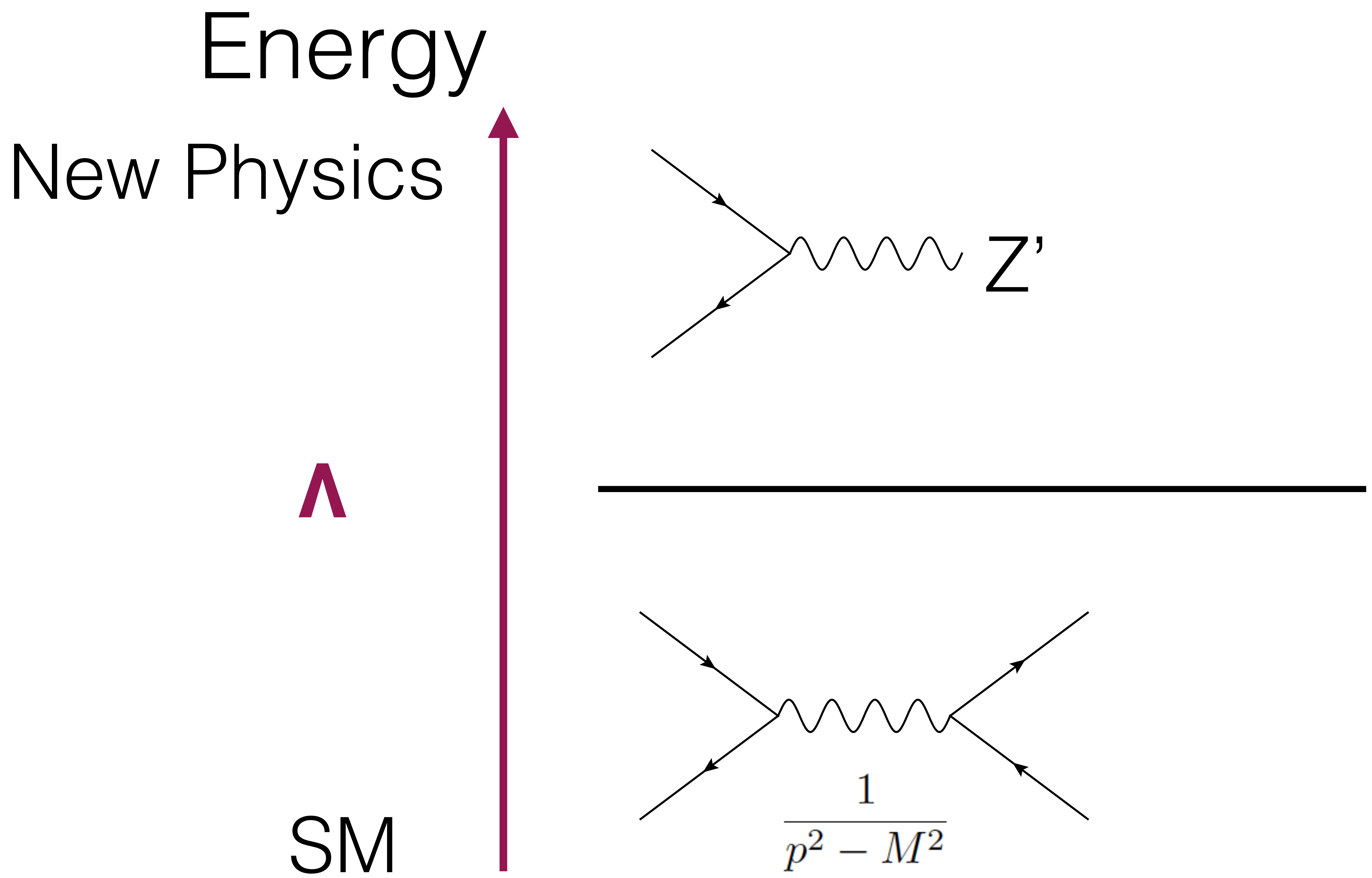

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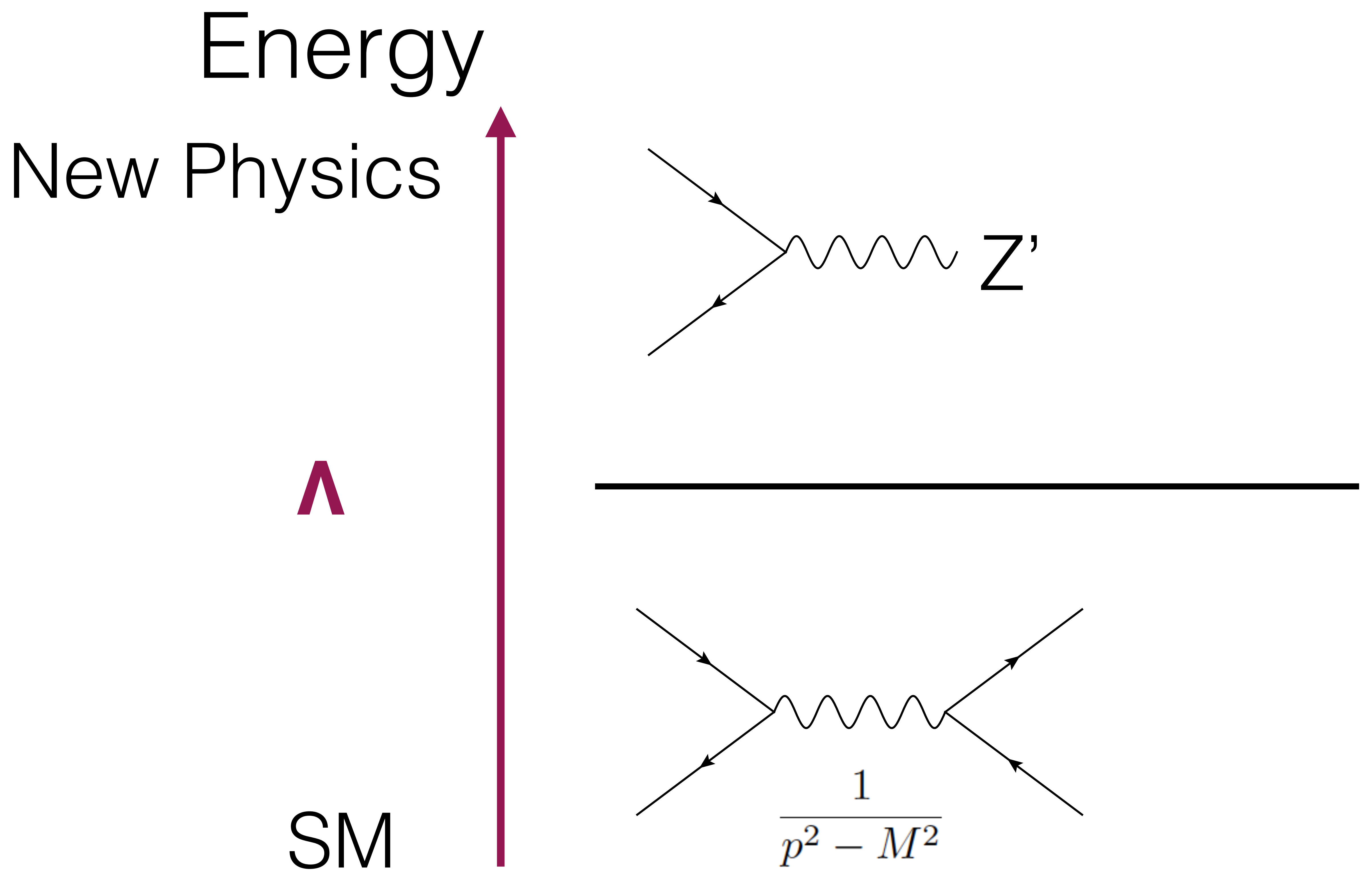
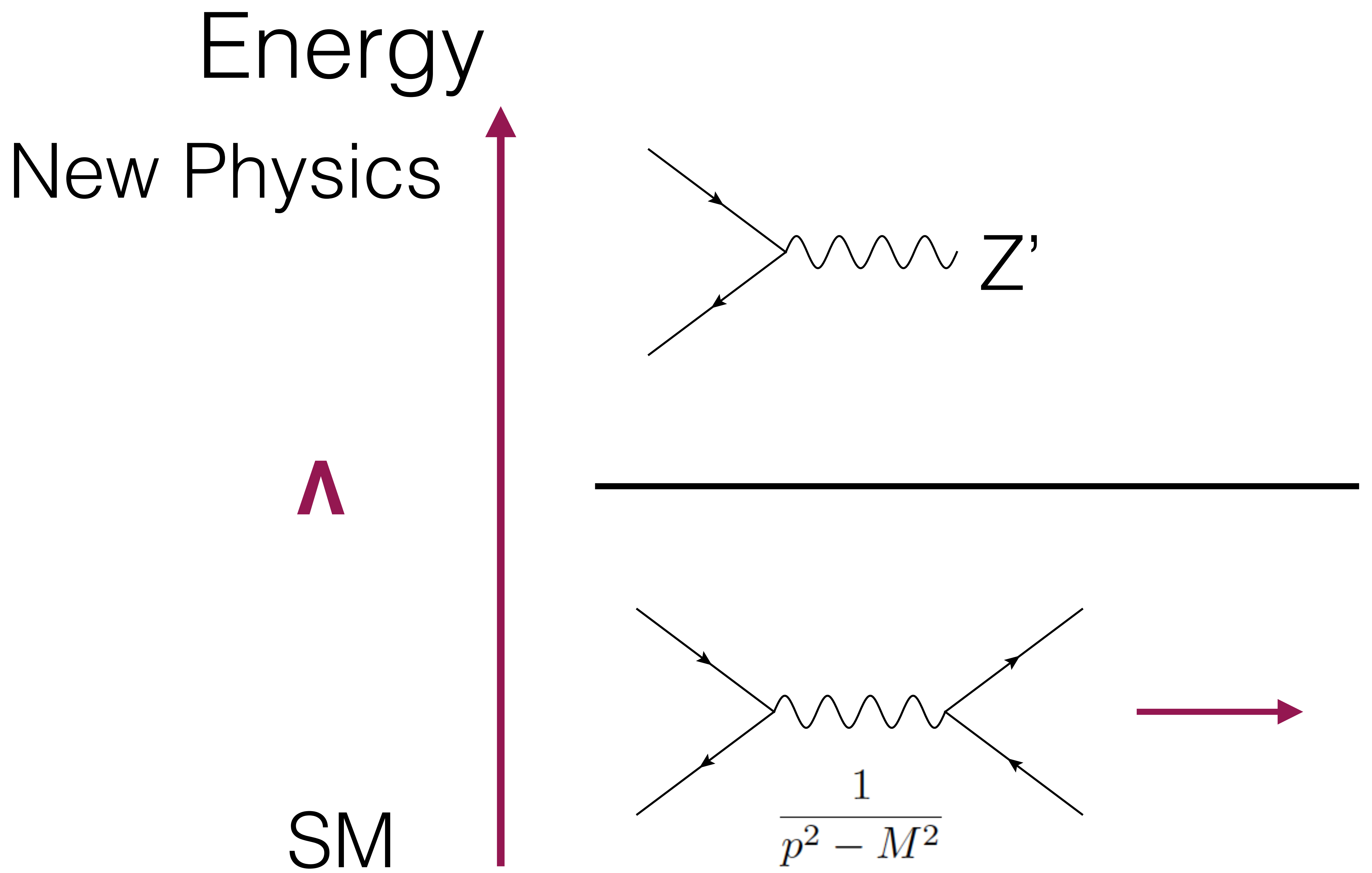


$$\frac{1}{p^2 - M^2} = \frac{1}{-M^2}\left[1 + \left(\frac{p^2}{M^2}\right) + \left(\frac{p^2}{M^2}\right)^2 + \cdots\right]$$

EFT: What is it all about?



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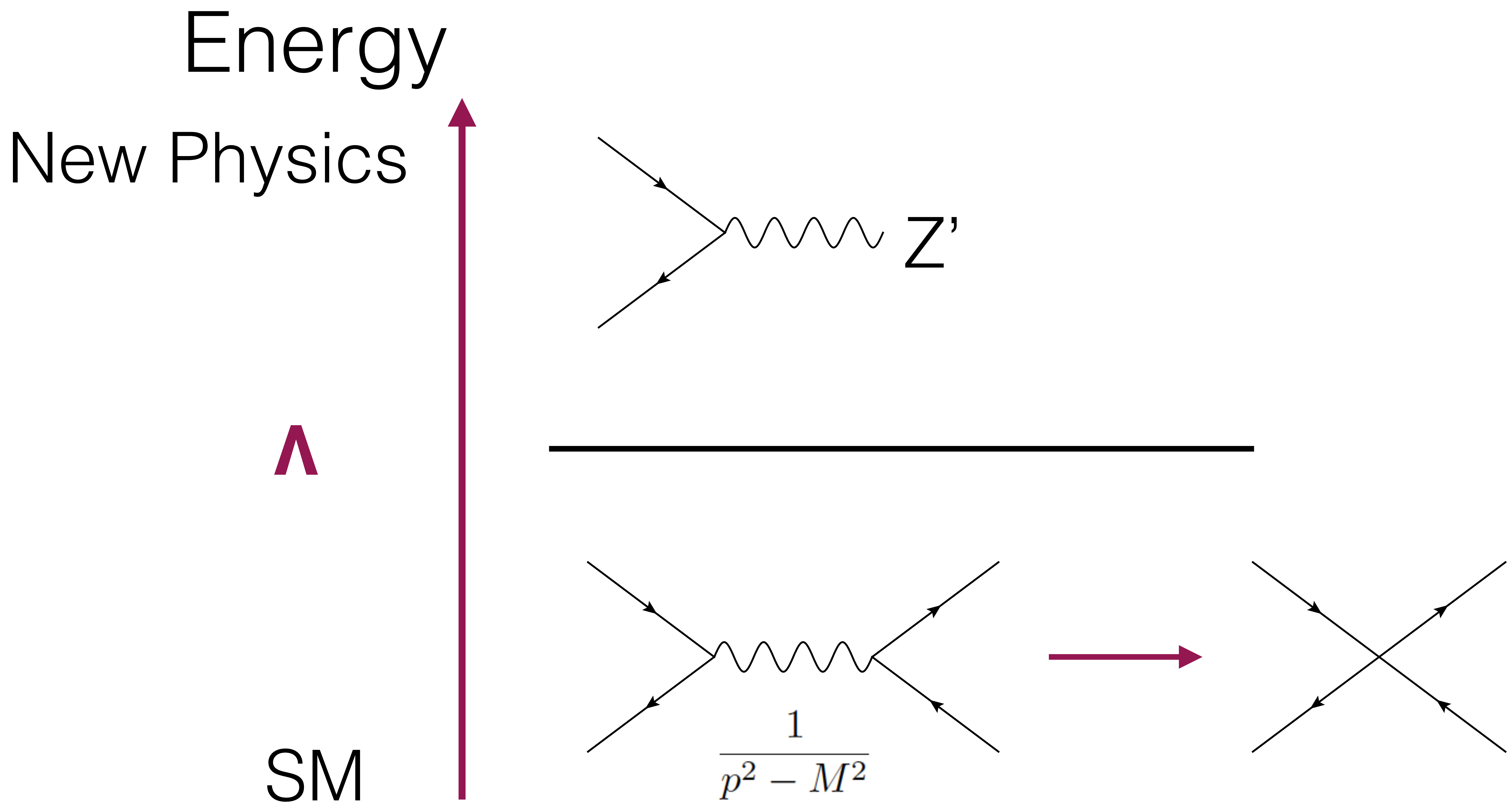

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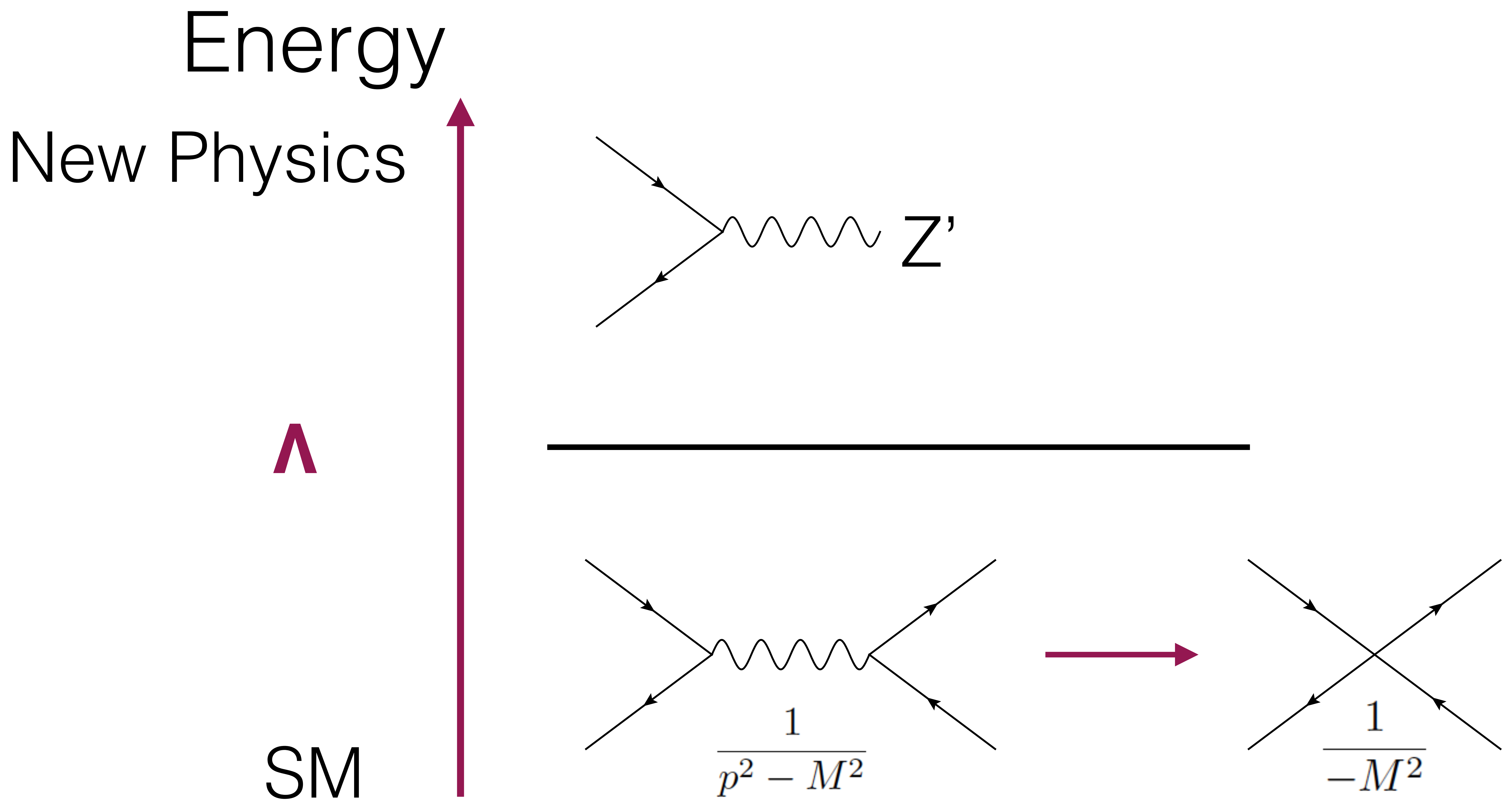

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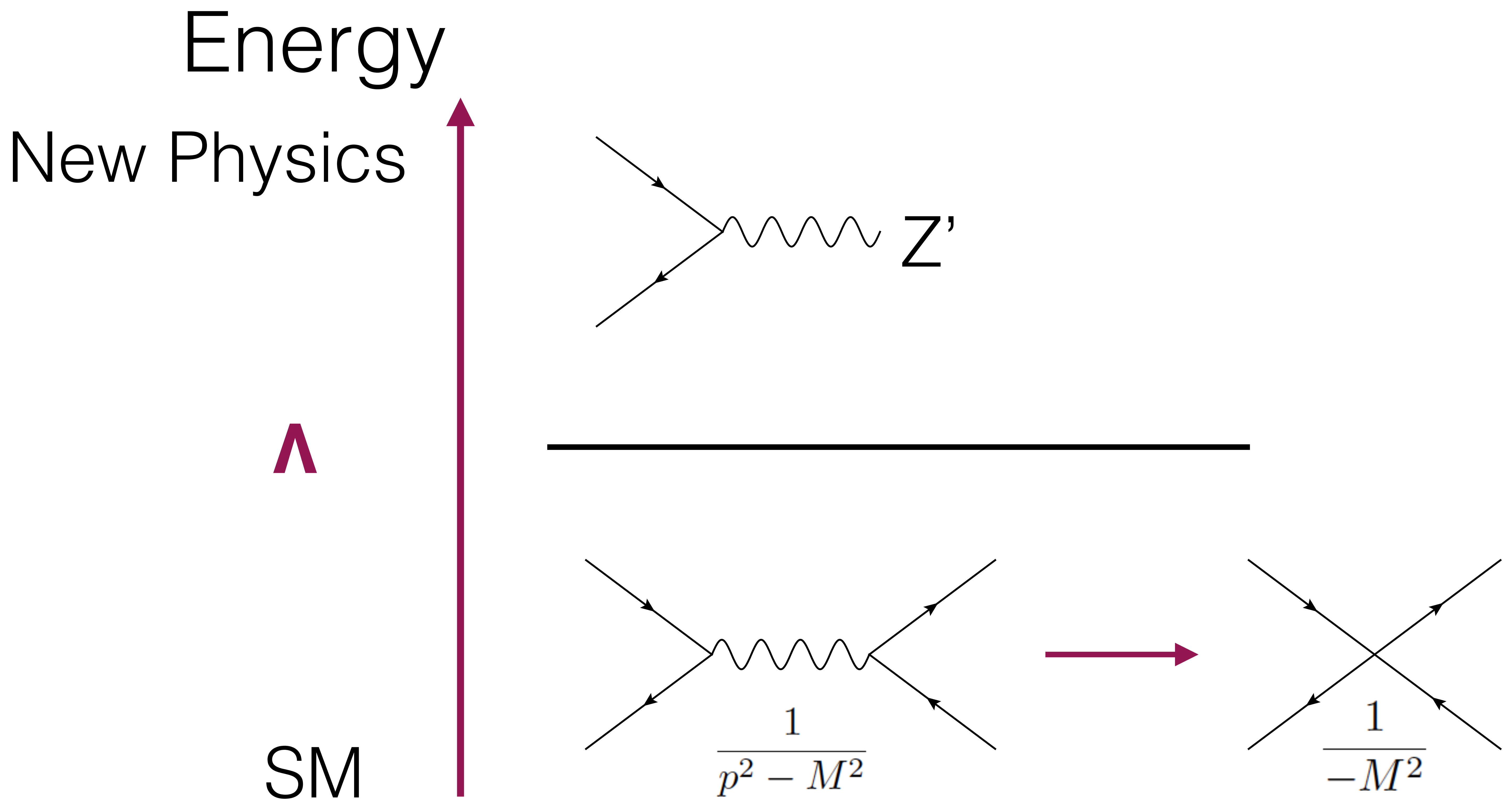

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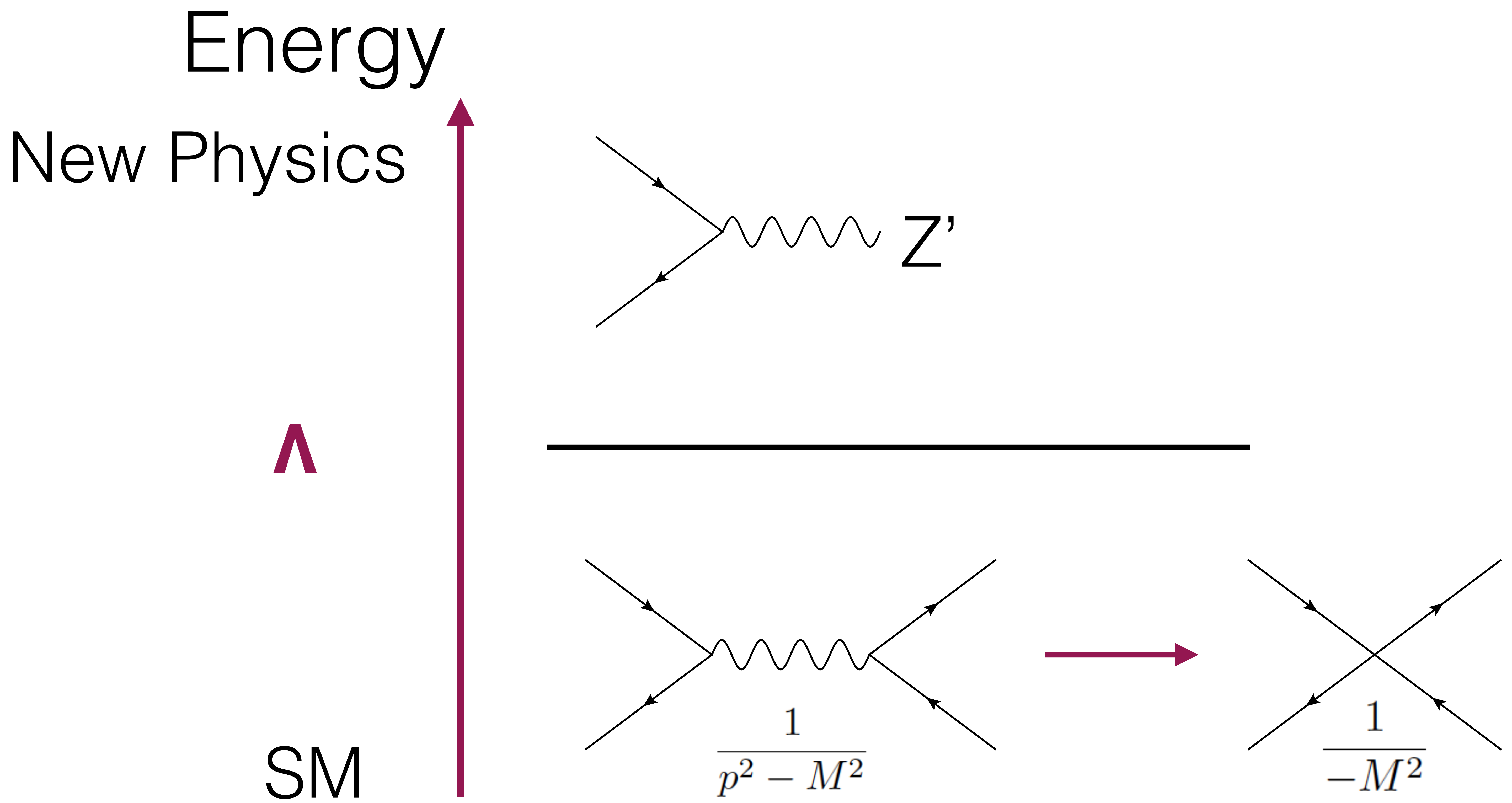
EFT: What is it all about?



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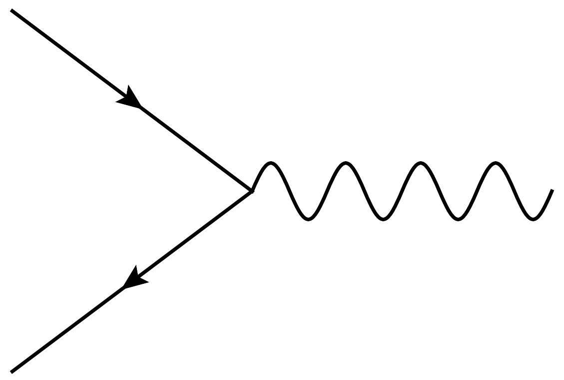
We have integrated out the Z’

EFT: What is it all about?

Energy

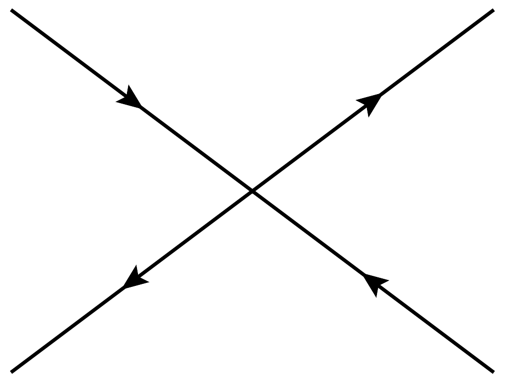
New Physics



$$\mathcal{L}_{NP}(\varphi, Z')$$

Λ=M

SM



$$\frac{1}{-M^2}$$

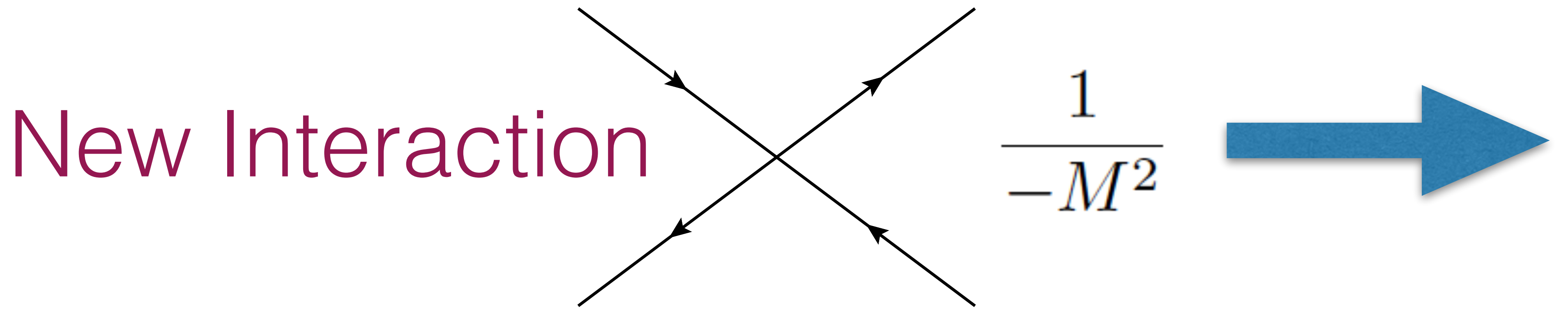
$$\mathcal{L}_{SM}(\varphi) + \mathcal{L}_{Dim6}(\varphi) + \cdots$$

$$\mathcal{L}_{Dim6}(\varphi) = \frac{C}{\Lambda^2}(\bar{f}\gamma^\mu f)(\bar{f}\gamma_\mu f)$$

c/Λ^2 can be linked to High Scale physics: Matching and Running

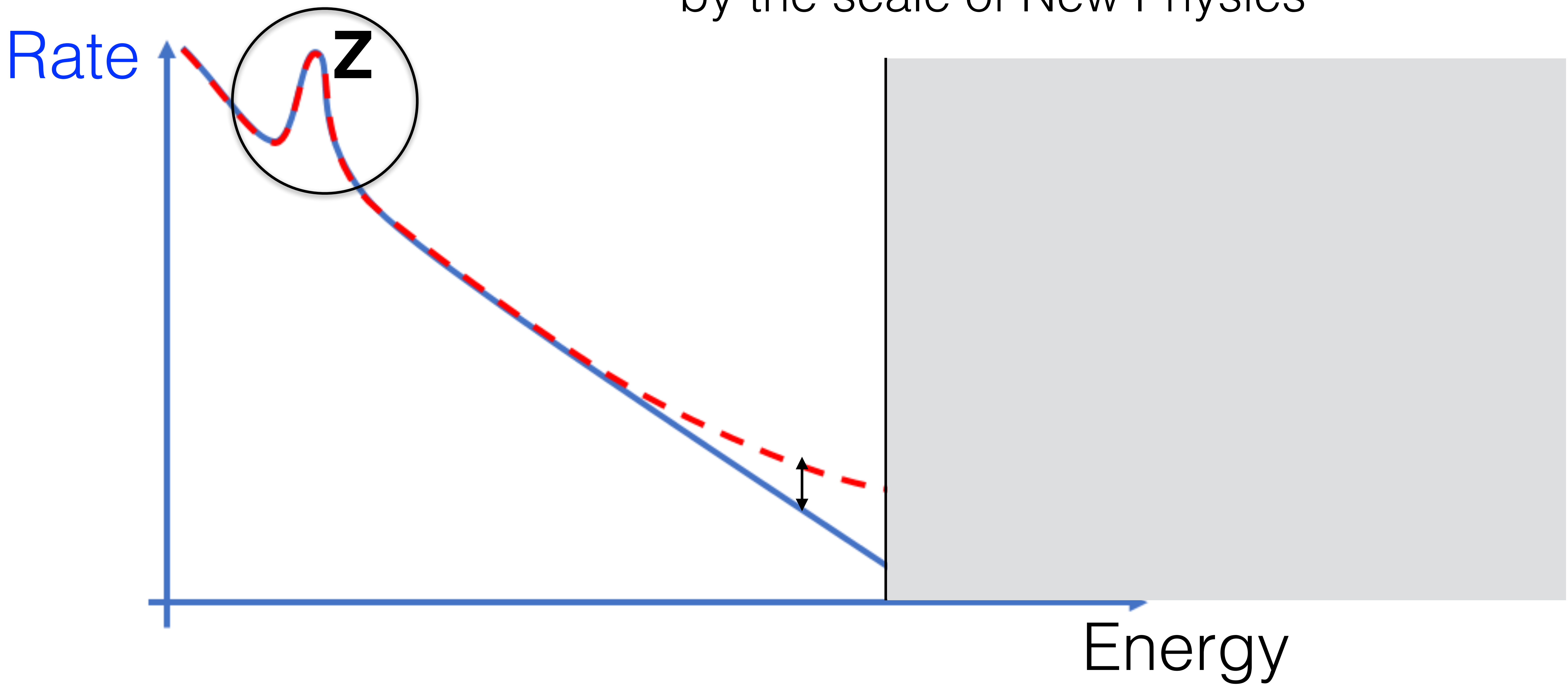
EFT for New Physics

Low Energy Effective Theory without the Z'



$$\mathcal{L}_{SM}(\varphi) + \mathcal{L}_{Dim6}(\varphi) + \cdots$$

Modified interactions suppressed by the scale of New Physics

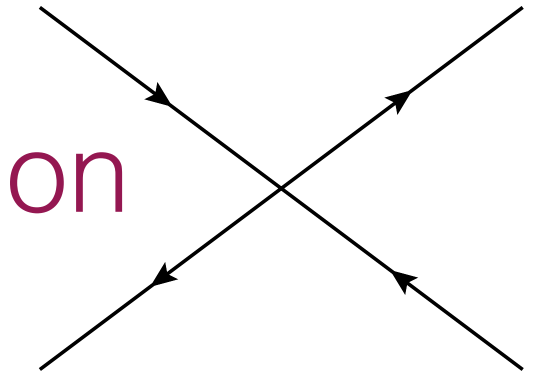


The way to probe New Physics in the absence of light states

EFT for New Physics

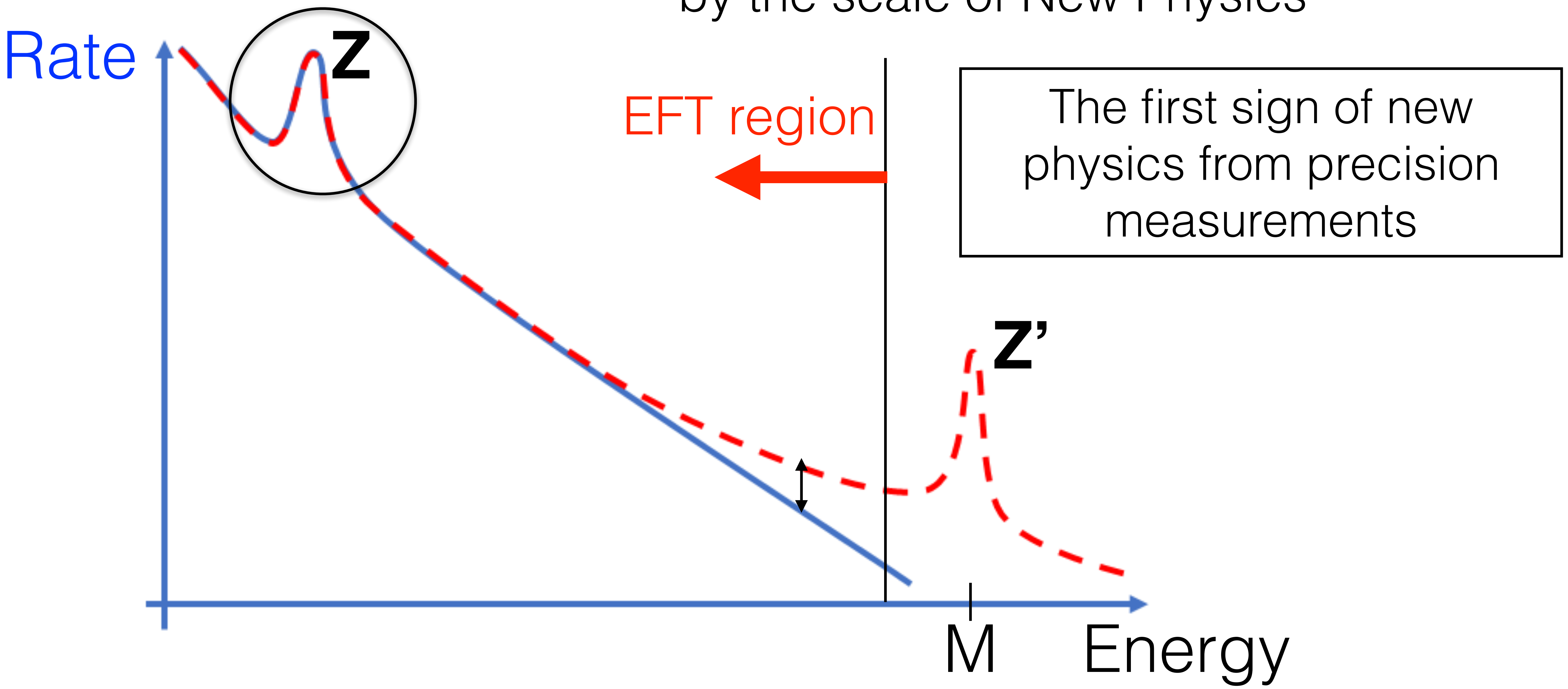
Low Energy Effective Theory without the Z’

New Interaction



$$\frac{1}{-M^2} \quad \Rightarrow \quad \mathcal{L}_{SM}(\varphi) + \mathcal{L}_{Dim6}(\varphi) + \cdots$$

Modified interactions suppressed
by the scale of New Physics

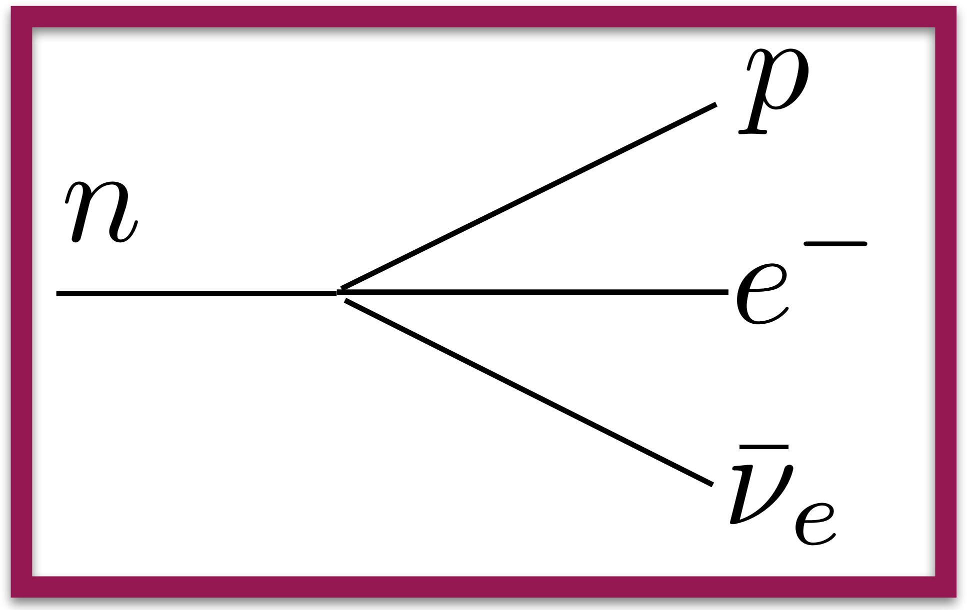


The way to probe New Physics in the absence of light states

Does the effective theory work?

An example of a successful EFT:

$$n \to p + e^- + \bar{\nu}_e$$

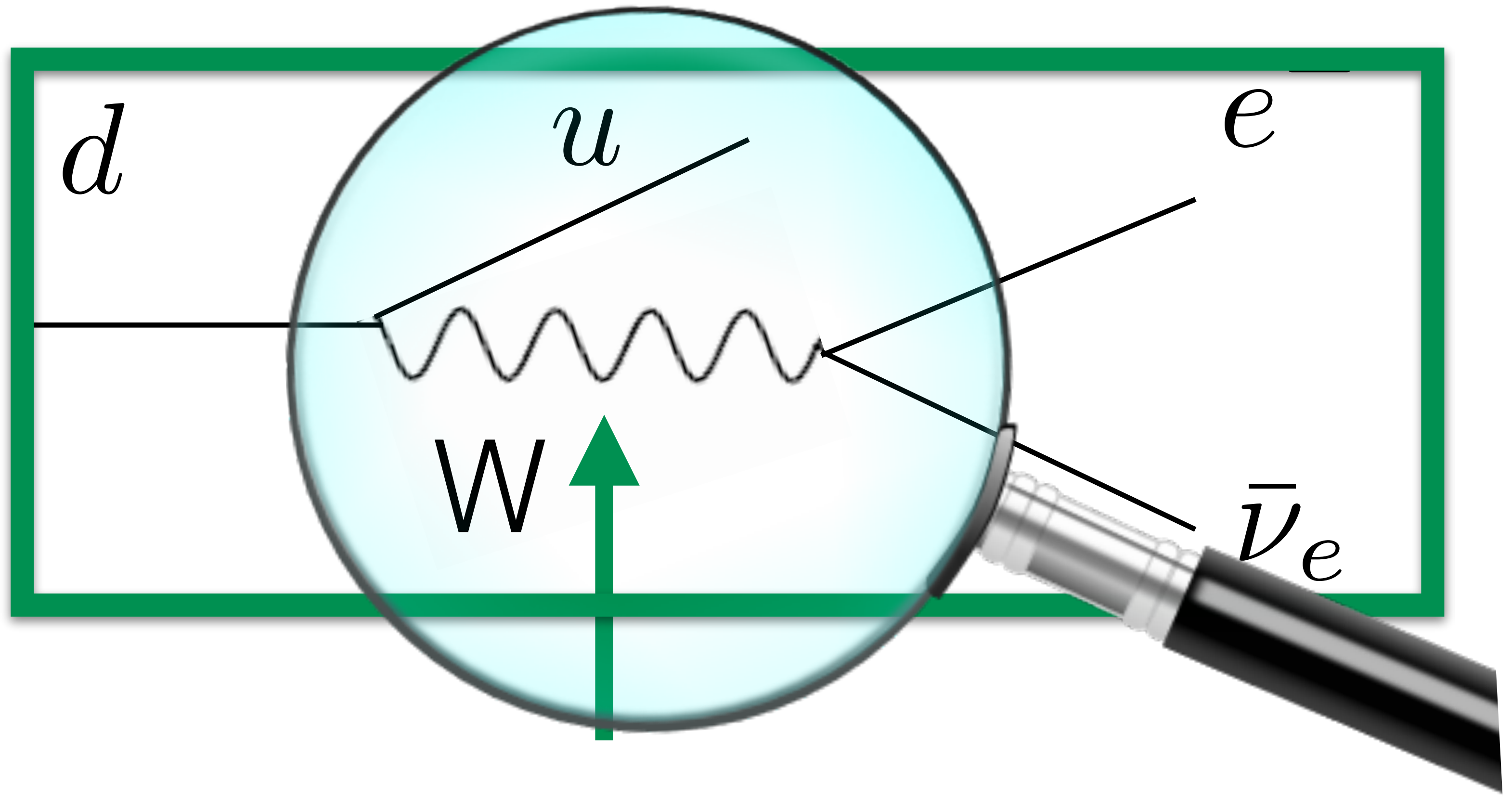


Fermi formulated his theory in the 1930's

It described β-decay data very well

Energy of β-decay: ~MeV

But this is not the full theory: cross-section rising with energy, violating unitarity



1983 Discovery of W-boson at CERN UA1 and UA2
M_W=80 GeV >> Q_β

Energy borrowed from the vacuum
A virtual W-boson exchange

Why use an effective theory?

Top-bottom: We know the full theory but it's too complicated
EFT simplifies the calculation by only including the relevant interactions
It focuses on the relevant scale
Examples: SCET, HQEFT

Bottom-up: We don't know the full theory, we are trying to describe measurements and guess the full theory
Efficient to characterise new physics
Examples: **SMEFT**, Fermi Theory (when formulated in the 1930's)

SMEFT for New Physics

- Focus on SMEFT:
  - only SM fields
  - respecting SM symmetries ✔
  - valid below scale Λ

- Gauge invariant ✔
- Higher-order corrections: renormalisable order by order in $1/\Lambda$ ✔

$$\mathcal{O}(\alpha_s) + \mathcal{O}\left(\frac{1}{\Lambda^2}\right) + \mathcal{O}\left(\frac{\alpha_s}{\Lambda^2}\right) + \cdots$$

- Complete description ✔
- Model Independent (apart from symmetries and no new light states) ✔

Let's take a tour of SMEFT

$$\mathcal{L}_{\rm eff} = \mathcal{L}^{(4)} + \sum_{D>4} \sum_{i} \frac{c_i^{(D)}}{\Lambda^{D-4}} \mathcal{O}_i^{(D)}$$

Let’s take a tour of SMEFT

$$\mathcal{L}_{\text{eff}} = \mathcal{L}^{(4)} + \sum_{D>4} \sum_{i} \frac{c_i^{(D)}}{\Lambda^{D-4}} \mathcal{O}_i^{(D)} \longrightarrow$$ Processes and observables

Let’s take a tour of SMEFT

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

→ Processes and observables

→ Sensitivity

Let’s take a tour of SMEFT

$$\mathcal{L}_{\text{eff}} = \mathcal{L}^{(4)} + \sum_{D>4} \sum_{i} \frac{c_i^{(D)}}{\Lambda^{D-4}} \mathcal{O}_i^{(D)}$$

→ Processes and observables

→ Sensitivity → Measurements

Let's take a tour of SMEFT

$$\mathcal{L}_{\rm eff} = \mathcal{L}^{(4)} + \sum_{D>4} \sum_i \frac{c_i^{(D)}}{\Lambda^{D-4}} \mathcal{O}_i^{(D)}$$

→ Processes and observables

→ Sensitivity → Measurements → Constraints

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→ Sensitivity → Measurements → Constraints → UV

Let’s take a tour of SMEFT

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→ Processes and observables

→ Sensitivity → Measurements → Constraints

→ UV

Huge effort to improve each one of these steps!

SMEFT dimension-5

One lepton number violating operator at dim-5 Weinberg (1979)

$$\mathcal{L} = \frac{c}{\Lambda}(L^T\epsilon\phi)C(\phi^T\epsilon L) + h.c.$$

$$m_\nu = c\frac{v^2}{\Lambda}$$ Majorana neutrino mass

Neutrino masses of 0.01-0.1eV imply $\Lambda \sim 10^{15}$ TeV!!!

Possible UV completion: see-saw model

$$\mathcal{L} = -y_D \bar{L}\epsilon\phi^* \nu_R - \frac{1}{2}M_R \nu_R^T C \nu_R + \text{H.c.}$$

$\Rightarrow$

$\nu \sim \nu_L$ $\quad m_\nu \sim m_D^2/M_R$

$N \sim \nu_R$ $\quad M_R$

SMEFT dimension-5

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→

$\nu \sim \nu_L$	$m_\nu \sim m_D^2 / M_R$
$N \sim \nu_R$	M_R

Not relevant for LHC physics

SMEFT@dim-6

$$\mathcal{L}_{\rm Eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

59(2499) operators at dim-6:

Buchmuller, Wyler Nucl.Phys. B268 (1986) 621-653

Grzadkowski et al arxiv:1008.4884

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating			
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$		
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		

Warsaw basis of dimension-6 operators

SMEFT@dim6

59 operators in flavour universal scenario

2499 if fully general

SMEFT@dim6

59 operators in flavour universal scenario

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Is there any hope?

- Not all operators enter in all observables
- Many observables available
- We can make “reasonable” assumptions

SMEFT@dim6

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- Many observables available
- We can make “reasonable” assumptions
  - no B,L violation
  - Flavour (universality, MFV…)
  - CP conservation

<100 operators for the LHC

SMEFT@dim6

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2499 if fully general ⛔

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- Many observables available
- We can make "reasonable" assumptions → no B,L violation; Flavour (universality, MFV…); CP conservation

<100 operators for the LHC ✔

Examples of operators

Dimension-6 operators of the SMEFT:

Class	Warsaw Example	Interaction	Impact

$$\psi^2 H^3 : (\varphi^\dagger \varphi)\ (\bar{q}_i\, u_j\, \tilde{\varphi})$$

$$\psi^2 H^2 D : (\varphi^\dagger \overleftrightarrow{D}_\mu\, \varphi)(\bar{q}_i\, \gamma^\mu\, q_j)$$

$$\psi^2 X H : (\bar{q}_i\, \sigma^{\mu\nu}\, u_j\, \tilde{\varphi}) B_{\mu\nu}$$

$$\psi^4 : (\bar{q}_i\, \gamma^\mu\, q_j)(\bar{q}_k\, \gamma_\mu\, q_l)$$

Assuming $i = j = 3$

Examples of operators

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$\psi^2 H^3$	$(\varphi^\dagger\varphi)\ (\bar{q}_i\, u_j\, \tilde{\varphi})$		
$\psi^2 H^2 D$	$(\varphi^\dagger \overleftrightarrow{D}_\mu\, \varphi)(\bar{q}_i\, \gamma^\mu\, q_j)$		
$\psi^2 X H$	$(\bar{q}_i\, \sigma^{\mu\nu}\, u_j\, \tilde{\varphi}) B_{\mu\nu}$		
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?

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Assuming $i = j = 3$

Examples of operators

Dimension-6 operators of the SMEFT:

Class	Warsaw Example	Interaction	Impact
$\psi^2 H^3$	$(\varphi^\dagger \varphi)\ (\bar{q}_i\, u_j\, \tilde{\varphi})$	Higgs-fermion (Yukawa)	ttH
$\psi^2 H^2 D$	$(\varphi^\dagger \overleftrightarrow{D}_\mu\, \varphi)(\bar{q}_i\, \gamma^\mu\, q_j)$	gauge-fermion (Z,W)	ttZ production, Wtb, single top
$\psi^2 X H$	$(\bar{q}_i\, \sigma^{\mu\nu}\, u_j\, \tilde{\varphi}) B_{\mu\nu}$	dipole	ttZ, ttA, WtB (ttVH)
ψ^4	$(\bar{q}_i\, \gamma^\mu\, q_j)(\bar{q}_k\, \gamma_\mu\, q_l)$	four fermion	top pair production, single top, ttH, ttV, tttt

Assuming $i = j = 3$

From Operators to Observables

Operators have different impact on particle interactions

1) Modification of SM vertices

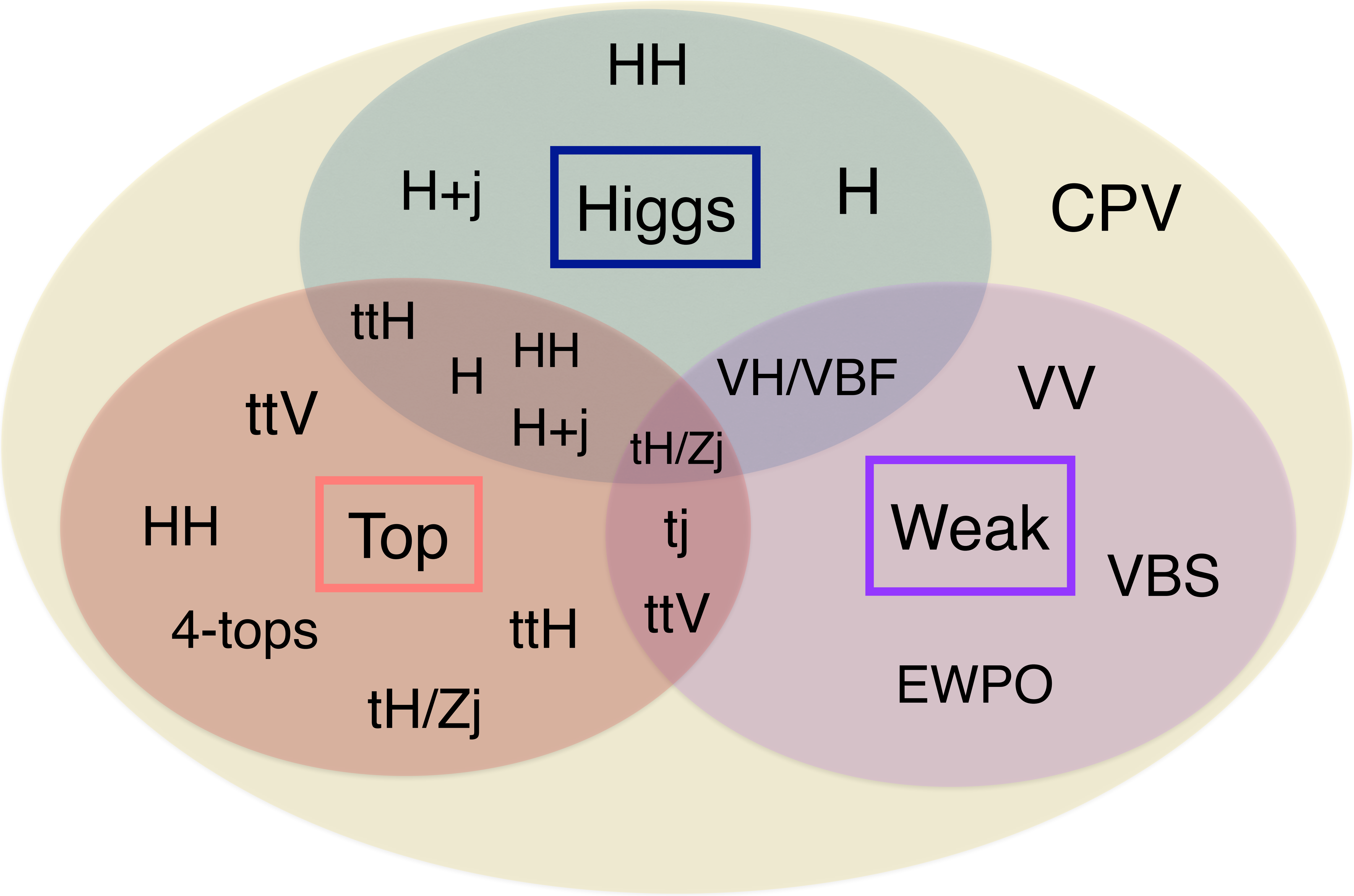
2) New Lorentz structures

(3) Indirect effect due to impact on input parameters and canonical normalisation of fields

What is next? Study particular processes and observables to maximise sensitivity on different operators

Fit data to extract EFT coefficients

SMEFT in practice



EFT has a global character

EFT pathway to New Physics

$$\Delta \mathrm{Obs}_n = \mathrm{Obs}_n^{\mathrm{EXP}} - \mathrm{Obs}_n^{\mathrm{SM}} = \sum_i \frac{c_i^6(\mu)}{\Lambda^2} a_{n,i}^6(\mu) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

Precise EFT predictions

Precise SM predictions

Precise experimental measurements

EFT pathway to New Physics

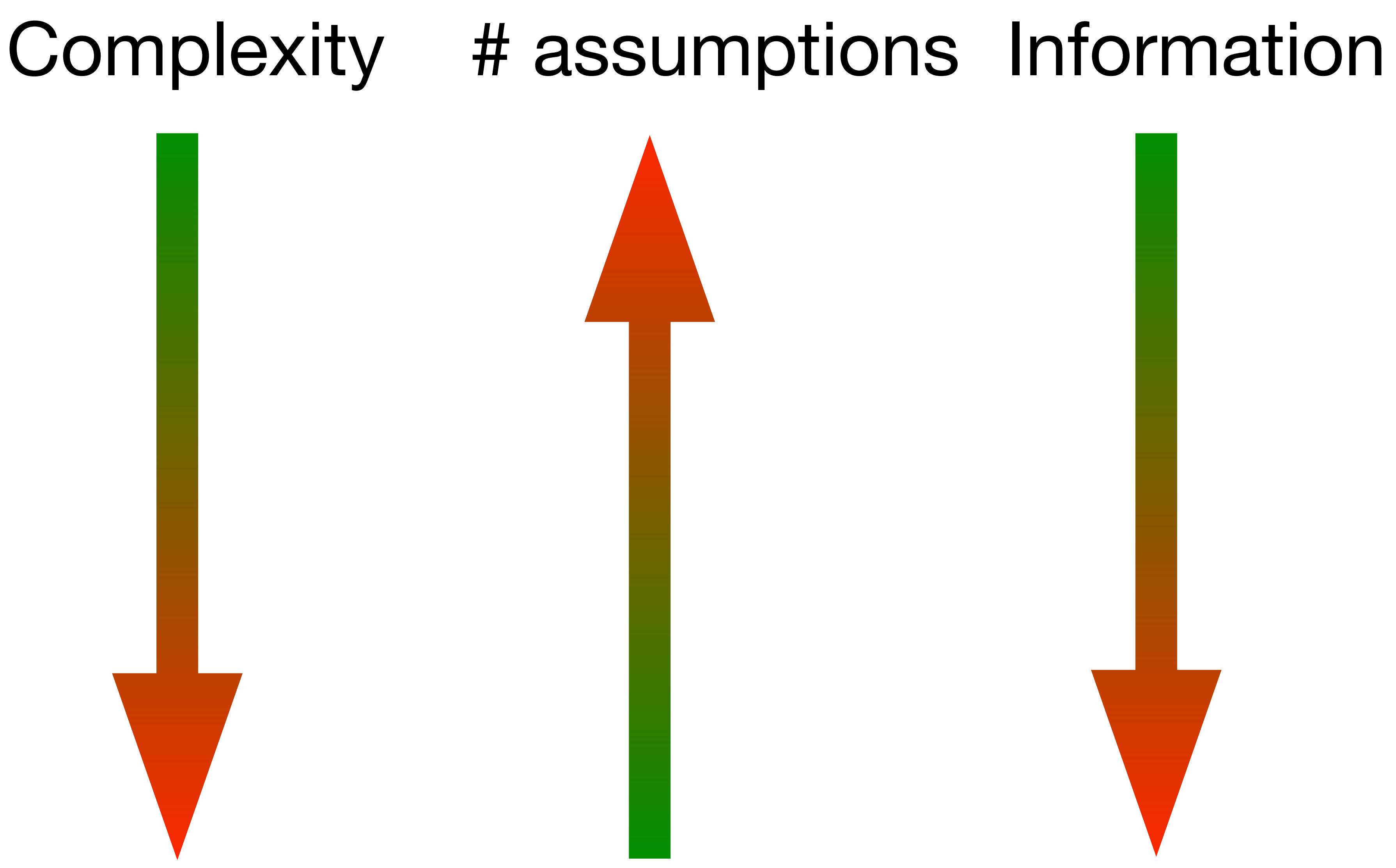
EFT pathway to New Physics

$$\frac{c_i^6(\mu)}{\Lambda^2}$$

EFT interpretations

Data interpretation at different levels

- Inclusive (fiducial) cross-section
- Differential parton level
- Differential particle level
- Detector level



LHC EFT WG effort:

https://indico.cern.ch/category/12671/

Global fit Setup

Theory

Best available prediction for the SM
NLO QCD for SMEFT

Data

Top pair production and single top (differential)
Associated production with W,Z,H
W helicity fractions

Global SMEFT fit of the top-quark sector

Fit Methodology

Faithful uncertainty estimate
Avoid under- and over-fitting
Validated on pseudo-data (closure test)

Output

Constraints on the Wilson coefficients
Fit results can be used to bound specific UV complete models

Observables

Data

Top-pair production
W-helicities,
asymmetry

Dataset	$\sqrt{s}, \mathcal{L}$	Info	Observables	$n_{\rm dat}$	Ref
ATLAS_tt_8TeV_ljets	**8 TeV, 20.3 fb^{-1}**	lepton+jets	$d\sigma/dm_{t\bar{t}}$	7	[46]
CMS_tt_8TeV_ljets	**8 TeV, 20.3 fb^{-1}**	lepton+jets	$1/\sigma d\sigma/dy_{t\bar{t}}$	10	[47]
CMS_tt2D_8TeV_dilep	**8 TeV, 20.3 fb^{-1}**	dileptons	$1/\sigma d^2\sigma/dy_{t\bar{t}}dm_{t\bar{t}}$	16	[48]
ATLAS_tt_8TeV_dilep (*)	**8 TeV, 20.3 fb^{-1}**	dileptons	$d\sigma/dm_{t\bar{t}}$	6	[54]
CMS_tt_13TeV_ljets_2015	**13 TeV, 2.3 fb^{-1}**	lepton+jets	$d\sigma/dm_{t\bar{t}}$	8	[51]
CMS_tt_13TeV_dilep_2015	**13 TeV, 2.1 fb^{-1}**	dileptons	$d\sigma/dm_{t\bar{t}}$	6	[53]
CMS_tt_13TeV_ljets_2016	**13 TeV, 35.8 fb^{-1}**	lepton+jets	$d\sigma/dm_{t\bar{t}}$	10	[52]
CMS_tt_13TeV_dilep_2016 (*)	**13 TeV, 35.8 fb^{-1}**	dileptons	$d\sigma/dm_{t\bar{t}}$	7	[56]
ATLAS_tt_13TeV_ljets_2016 (*)	**13 TeV, 35.8 fb^{-1}**	lepton+jets	$d\sigma/dm_{t\bar{t}}$	9	[55]
ATLAS_WhelF_8TeV	**8 TeV, 20.3 fb^{-1}**	W hel. fract	F_0, F_L, F_R	3	[49]
CMS_WhelF_8TeV	**8 TeV, 20.3 fb^{-1}**	W hel. fract	F_0, F_L, F_R	3	[50]
ATLAS_CMS_tt_AC_8TeV (*)	**8 TeV, 20.3 fb^{-1}**	charge asymmetry	A_C	6	[57]
ATLAS_tt_AC_13TeV (*)	**8 TeV, 20.3 fb^{-1}**	charge asymmetry	A_C	5	[58]

Dataset	$\sqrt{s}, \mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref
CMS_t_tch_8TeV_inc	**8 TeV, 19.7 fb^{-1}**	t-channel	$\sigma_{\rm tot}(t), \sigma_{\rm tot}(\bar{t})$	2	[83]
ATLAS_t_tch_8TeV	**8 TeV, 20.2 fb^{-1}**	t-channel	$d\sigma(tq)/dy_t$	4	[85]
CMS_t_tch_8TeV_dif	**8 TeV, 19.7 fb^{-1}**	t-channel	$d\sigma/d\|y^{(t+\bar{t})}\|$	6	[84]
CMS_t_sch_8TeV	**8 TeV, 19.7 fb^{-1}**	s-channel	$\sigma_{\rm tot}(t+\bar{t})$	1	[87]
ATLAS_t_sch_8TeV	**8 TeV, 20.3 fb^{-1}**	s-channel	$\sigma_{\rm tot}(t+\bar{t})$	1	[86]
ATLAS_t_tch_13TeV	**13 TeV, 3.2 fb^{-1}**	t-channel	$\sigma_{\rm tot}(t), \sigma_{\rm tot}(\bar{t})$	2	[88]
CMS_t_tch_13TeV_inc	**13 TeV, 2.2 fb^{-1}**	t-channel	$\sigma_{\rm tot}(t), \sigma_{\rm tot}(\bar{t})$	2	[90]
CMS_t_tch_13TeV_dif	**13 TeV, 2.3 fb^{-1}**	t-channel	$d\sigma/d\|y^{(t+\bar{t})}\|$	4	[89]
CMS_t_tch_13TeV_2016 (*)	**13 TeV, 35.9 fb^{-1}**	t-channel	$d\sigma/d\|y^{(t)}\|$	5	[91]

Single top t-, s-channel

Dataset	$\sqrt{s}, \mathcal{L}$	Info	Observables	$n_{\rm dat}$	Ref.
ATLAS_CMS_SSinc_RunI (*)	**7+8 TeV, 20 fb^{-1}**	Incl. μ_i^f	ggF, VBF, Vh, $t\bar{t}h$ $h \to \gamma\gamma, VV, \tau\tau, b\bar{b}$	20	[114]
ATLAS_SSinc_RunI (*)	**8 TeV, 20 fb^{-1}**	Incl. μ_i^f	$h \to Z\gamma, \mu\mu$	2	[115]
ATLAS_SSinc_RunII (*)	**13 TeV, 80 fb^{-1}**	Incl. μ_i^f	ggF, VBF, Vh, $t\bar{t}h$ $h \to \gamma\gamma, WW, ZZ, \tau\tau, b\bar{b}$	16	[116]
CMS_SSinc_RunII (*)	**13 TeV, 36.9 fb^{-1}**	Incl. μ_i^f	ggF, VBF, Wh, Zh $t\bar{t}h$ $h \to \gamma\gamma, WW, ZZ, \tau\tau, b\bar{b}$	24	[117]

Higgs signal strengths

Dataset	$\sqrt{s}, \mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref
CMS_H_13TeV_2015 (*)	**13 TeV, 35.9 fb^{-1}**	ggF, VBF, Vh, $t\bar{t}h$ $h \to ZZ, \gamma\gamma, b\bar{b}$	$d\sigma/dp_T^h$	9	[121]
ATLAS_ggF_13TeV_2015 (*)	**13 TeV, 36.1 fb^{-1}**	ggF, VBF, Vh, $t\bar{t}h$ $h \to ZZ(\to 4l)$	$d\sigma/dp_T^h$	9	[122]
ATLAS_Vh_hbb_13TeV (*)	**13 TeV, 79.8 fb^{-1}**	Wh, Zh	$d\sigma^{\rm (fid)}/dp_T^W$ $d\sigma^{\rm (fid)}/dp_T^Z$	2 3	[123]
ATLAS_ggF_ZZ_13TeV (*)	**13 TeV, 79.8 fb^{-1}**	ggF, $h \to ZZ$	$\sigma_{\rm ggF}(p_T^h, N_{\rm jets})$	6	[116]
CMS_ggF_aa_13TeV (*)	**13 TeV, 77.4 fb^{-1}**	ggF, $h \to \gamma\gamma$	$\sigma_{\rm ggF}(p_T^h, N_{\rm jets})$	6	[124]

Higgs differential

4 tops, ttbb, top-pair associated production

Dataset	$\sqrt{s}, \mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref
CMS_ttbb_13TeV	**13 TeV, 2.3 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[70]
CMS_ttbb_13TeV_2016 (*)	**13 TeV, 35.9 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[79]
ATLAS_ttbb_13TeV_2016 (*)	**13 TeV, 35.9 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[78]
CMS_tttt_13TeV	**13 TeV, 35.9 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[71]
CMS_tttt_13TeV_run2 (*)	**13 TeV, 137 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[76]
ATLAS_tttt_13TeV_run2 (*)	**13 TeV, 137 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[77]
CMS_ttZ_8TeV	**8 TeV, 19.5 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[72]
CMS_ttZ_13TeV	**13 TeV, 35.9 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[73]
CMS_ttZ_ptZ_13TeV (*)	**13 TeV, 77.5 fb^{-1}**	total xsec	$d\sigma(t\bar{t}Z)/dp_T^Z$	4	[81]
ATLAS_ttZ_8TeV	**8 TeV, 20.3 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[74]
ATLAS_ttZ_13TeV	**13 TeV, 3.2 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[75]
ATLAS_ttZ_13TeV_2016 (*)	**13 TeV, 36 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[80]
CMS_ttW_8_TeV	**8 TeV, 19.5 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[72]
CMS_ttW_13TeV	**13 TeV, 35.9 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[73]
ATLAS_ttW_8TeV	**8 TeV, 20.3 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[74]
ATLAS_ttW_13TeV	**13 TeV, 3.2 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[75]
ATLAS_ttW_13TeV_2016 (*)	**13 TeV, 36 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[80]

Dataset	$\sqrt{s}, \mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref
ATLAS_tW_8TeV_inc	**8 TeV, 20.2 fb^{-1}**	inclusive (dilepton)	$\sigma_{\rm tot}(tW)$	1	[95]
ATLAS_tW_inc_slep_8TeV (*)	**8 TeV, 20.2 fb^{-1}**	inclusive (single lepton)	$\sigma_{\rm tot}(tW)$	1	[101]
CMS_tW_8TeV_inc	**8 TeV, 19.7 fb^{-1}**	inclusive	$\sigma_{\rm tot}(tW)$	1	[96]
ATLAS_tW_inc_13TeV	**13 TeV, 3.2 fb^{-1}**	inclusive	$\sigma_{\rm tot}(tW)$	1	[97]
CMS_tW_13TeV_inc	**13 TeV, 35.9 fb^{-1}**	inclusive	$\sigma_{\rm tot}(tW)$	1	[98]
ATLAS_tZ_13TeV_inc	**13 TeV, 36.1 fb^{-1}**	inclusive	$\sigma_{\rm tot}(tZq)$	1	[100]
ATLAS_tZ_13TeV_run2_inc (*)	**13 TeV, 139.1 fb^{-1}**	inclusive	$\sigma_{\rm fid}(t\ell^+\ell^-q)$	1	[102]
CMS_tZ_13TeV_inc	**13 TeV, 35.9 fb^{-1}**	inclusive	$\sigma_{\rm fid}(Wb\ell^+\ell^-q)$	1	[99]
CMS_tZ_13TeV_2016_inc (*)	**13 TeV, 77.4 fb^{-1}**	inclusive	$\sigma_{\rm fid}(t\ell^+\ell^-q)$	1	[103]

tW, tZ

Dataset	$\sqrt{s}, \mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref
LEP2_WW_diff (*)	**[182, 296] GeV**	LEP-2 comb	$d^2\sigma(WW)/dE_{\rm cm}d\cos\theta_W$	40	[128]
ATLAS_WZ_13TeV_2016 (*)	**13 TeV, 36.1 fb^{-1}**	fully leptonic	$d\sigma^{\rm (fid)}/dm_T^{WZ}$	6	[129]
ATLAS_WW_13TeV_2016 (*)	**13 TeV, 36.1 fb^{-1}**	fully leptonic	$d\sigma^{\rm (fid)}/dm_{e\mu}$	13	[130]
CMS_WZ_13TeV_2016 (*)	**13 TeV, 35.9 fb^{-1}**	fully leptonic	$d\sigma^{\rm (fid)}/dp_T^Z$	11	[131]

Diboson

Observables

Data

Top-pair production
W-helicities,
asymmetry

Dataset	$\sqrt{s}$, $\mathcal{L}$	Info	Observables	$n_{\rm dat}$	Ref
ATLAS_tt_8TeV_ljets	**8 TeV, 20.3 fb^{-1}**	lepton+jets	$d\sigma/dm_{t\bar{t}}$	7	[46]
CMS_tt_8TeV_ljets	**8 TeV, 20.3 fb^{-1}**	lepton+jets	$1/\sigma d\sigma/dy_{t\bar{t}}$	10	[47]
CMS_tt2D_8TeV_dilep	**8 TeV, 20.3 fb^{-1}**	dileptons	$1/\sigma d^2\sigma/dy_{t\bar{t}}dm_{t\bar{t}}$	16	[48]
ATLAS_tt_8TeV_dilep (*)	**8 TeV, 20.3 fb^{-1}**	dileptons	$d\sigma/dm_{t\bar{t}}$	6	[54]
CMS_tt_13TeV_ljets_2015	**13 TeV, 2.3 fb^{-1}**	lepton+jets	$d\sigma/dm_{t\bar{t}}$	8	[51]
CMS_tt_13TeV_dilep_2015	**13 TeV, 2.1 fb^{-1}**	dileptons	$d\sigma/dm_{t\bar{t}}$	6	[53]
CMS_tt_13TeV_ljets_2016	**13 TeV, 35.8 fb^{-1}**	lepton+jets	$d\sigma/dm_{t\bar{t}}$	10	[52]
CMS_tt_13TeV_dilep_2016 (*)	**13 TeV, 35.8 fb^{-1}**	dileptons	$d\sigma/dm_{t\bar{t}}$	7	[56]
ATLAS_tt_13TeV_ljets_2016 (*)	**13 TeV, 35.8 fb^{-1}**	lepton+jets	$d\sigma/dm_{t\bar{t}}$	9	[55]
ATLAS_WhelF_8TeV	**8 TeV, 20.3 fb^{-1}**	W hel. fract	F_0, F_L, F_R	3	[49]
CMS_WhelF_8TeV	**8 TeV, 20.3 fb^{-1}**	W hel. fract	F_0, F_L, F_R	3	[50]
ATLAS_CMS_tt_AC_8TeV (*)	**8 TeV, 20.3 fb^{-1}**	charge asymmetry	A_C	6	[57]
ATLAS_tt_AC_13TeV (*)	**8 TeV, 20.3 fb^{-1}**	charge asymmetry	A_C	5	[58]

Dataset	$\sqrt{s}, \mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref
CMS_t_tch_8TeV_inc	**8 TeV, 19.7 fb^{-1}**	t-channel	$\sigma_{\rm tot}(t), \sigma_{\rm tot}(\bar{t})$	2	[83]
ATLAS_t_tch_8TeV	**8 TeV, 20.2 fb^{-1}**	t-channel	$d\sigma(tq)/dy_t$	4	[85]
CMS_t_tch_8TeV_dif	**8 TeV, 19.7 fb^{-1}**	t-channel	$d\sigma/d\lvert y^{(t+\bar{t})}\rvert$	6	[84]
CMS_t_sch_8TeV	**8 TeV, 19.7 fb^{-1}**	s-channel	$\sigma_{\rm tot}(t+\bar{t})$	1	[87]
ATLAS_t_sch_8TeV	**8 TeV, 20.3 fb^{-1}**	s-channel	$\sigma_{\rm tot}(t+\bar{t})$	1	[86]
ATLAS_t_tch_13TeV	**13 TeV, 3.2 fb^{-1}**	t-channel	$\sigma_{\rm tot}(t), \sigma_{\rm tot}(\bar{t})$	2	[88]
CMS_t_tch_13TeV_inc	**13 TeV, 2.2 fb^{-1}**	t-channel	$\sigma_{\rm tot}(t), \sigma_{\rm tot}(\bar{t})$	2	[90]
CMS_t_tch_13TeV_dif	**13 TeV, 2.3 fb^{-1}**	t-channel	$d\sigma/d\lvert y^{(t+\bar{t})}\rvert$	4	[89]
CMS_t_tch_13TeV_2016 (*)	**13 TeV, 35.9 fb^{-1}**	t-channel	$d\sigma/d\lvert y^{(t)}\rvert$	5	[91]

Single top t-, s-channel

Dataset	$\sqrt{s}$, $\mathcal{L}$	Info	Observables	$n_{\rm dat}$	Ref.
ATLAS_CMS_SSinc_RunI (*)	**7+8 TeV, 20 fb^{-1}**	Incl. μ_i^f	ggF, VBF, Vh, $t\bar{t}h$ $h \to \gamma\gamma, VV, \tau\tau, b\bar{b}$	20	[114]
ATLAS_SSinc_RunI (*)	**8 TeV, 20 fb^{-1}**	Incl. μ_i^f	$h \to Z\gamma, \mu\mu$	2	[115]
ATLAS_SSinc_RunII (*)	**13 TeV, 80 fb^{-1}**	Incl. μ_i^f	ggF, VBF, Vh, $t\bar{t}h$ $h \to \gamma\gamma, WW, ZZ, \tau\tau, b\bar{b}$	16	[116]
CMS_SSinc_RunII (*)	**13 TeV, 36.9 fb^{-1}**	Incl. μ_i^f	ggF, VBF, Wh, Zh $t\bar{t}h$ $h \to \gamma\gamma, WW, ZZ, \tau\tau, b\bar{b}$	24	[117]

Higgs signal strengths

4 tops, ttbb, top-pair associated production

Dataset	$\sqrt{s}, \mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref
CMS_ttbb_13TeV	**13 TeV, 2.3 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[70]
CMS_ttbb_13TeV_2016 (*)	**13 TeV, 35.9 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[79]
ATLAS_ttbb_13TeV_2016 (*)	**13 TeV, 35.9 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[78]
CMS_tttt_13TeV	**13 TeV, 35.9 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[71]
CMS_tttt_13TeV_run2 (*)	**13 TeV, 137 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[76]
ATLAS_tttt_13TeV_run2 (*)	**13 TeV, 137 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[77]
CMS_ttZ_8TeV	**8 TeV, 19.5 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[72]
CMS_ttZ_13TeV	**13 TeV, 35.9 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[73]
CMS_ttZ_ptZ_13TeV (*)	**13 TeV, 77.5 fb^{-1}**	total xsec	$d\sigma(t\bar{t}Z)/dp_T^Z$	4	[81]
ATLAS_ttZ_8TeV	**8 TeV, 20.3 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[74]
ATLAS_ttZ_13TeV	**13 TeV, 3.2 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[75]
ATLAS_ttZ_13TeV_2016 (*)	**13 TeV, 36 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[80]
CMS_ttW_8_TeV	**8 TeV, 19.5 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[72]
CMS_ttW_13TeV	**13 TeV, 35.9 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[73]
ATLAS_ttW_8TeV	**8 TeV, 20.3 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[74]
ATLAS_ttW_13TeV	**13 TeV, 3.2 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[75]
ATLAS_ttW_13TeV_2016 (*)	**13 TeV, 36 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[80]

Dataset	$\sqrt{s}, \mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref
ATLAS_tW_8TeV_inc	**8 TeV, 20.2 fb^{-1}**	inclusive (dilepton)	$\sigma_{\rm tot}(tW)$	1	[95]
ATLAS_tW_inc_slep_8TeV (*)	**8 TeV, 20.2 fb^{-1}**	inclusive (single lepton)	$\sigma_{\rm tot}(tW)$	1	[101]
CMS_tW_8TeV_inc	**8 TeV, 19.7 fb^{-1}**	inclusive	$\sigma_{\rm tot}(tW)$	1	[96]
ATLAS_tW_inc_13TeV	**13 TeV, 3.2 fb^{-1}**	inclusive	$\sigma_{\rm tot}(tW)$	1	[97]
CMS_tW_13TeV_inc	**13 TeV, 35.9 fb^{-1}**	inclusive	$\sigma_{\rm tot}(tW)$	1	[98]
ATLAS_tZ_13TeV_inc	**13 TeV, 36.1 fb^{-1}**	inclusive	$\sigma_{\rm tot}(tZq)$	1	[100]
ATLAS_tZ_13TeV_run2_inc (*)	**13 TeV, 139.1 fb^{-1}**	inclusive	$\sigma_{\rm fid}(t\ell^+\ell^-q)$	1	[102]
CMS_tZ_13TeV_inc	**13 TeV, 35.9 fb^{-1}**	inclusive	$\sigma_{\rm fid}(Wb\ell^+\ell^-q)$	1	[99]
CMS_tZ_13TeV_2016_inc (*)	**13 TeV, 77.4 fb^{-1}**	inclusive	$\sigma_{\rm fid}(t\ell^+\ell^-q)$	1	[103]

tW, tZ

Dataset	$\sqrt{s}, \mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref
CMS_H_13TeV_2015 (*)	**13 TeV, 35.9 fb^{-1}**	ggF, VBF, Vh, $t\bar{t}h$ $h \to ZZ, \gamma\gamma, b\bar{b}$	$d\sigma/dp_T^h$	9	[121]
ATLAS_ggF_13TeV_2015 (*)	**13 TeV, 36.1 fb^{-1}**	ggF, VBF, Vh, $t\bar{t}h$ $h \to ZZ(\to 4l)$	$d\sigma/dp_T^h$	9	[122]
ATLAS_Vh_hbb_13TeV (*)	**13 TeV, 79.8 fb^{-1}**	Wh, Zh	$d\sigma^{(\rm fid)}/dp_T^W$ $d\sigma^{(\rm fid)}/dp_T^Z$	2 3	[123]
ATLAS_ggF_ZZ_13TeV (*)	**13 TeV, 79.8 fb^{-1}**	ggF, $h \to ZZ$	$\sigma_{\rm ggF}(p_T^h, N_{\rm jets})$	6	[116]
CMS_ggF_aa_13TeV (*)	**13 TeV, 77.4 fb^{-1}**	ggF, $h \to \gamma\gamma$	$\sigma_{\rm ggF}(p_T^h, N_{\rm jets})$	6	[124]

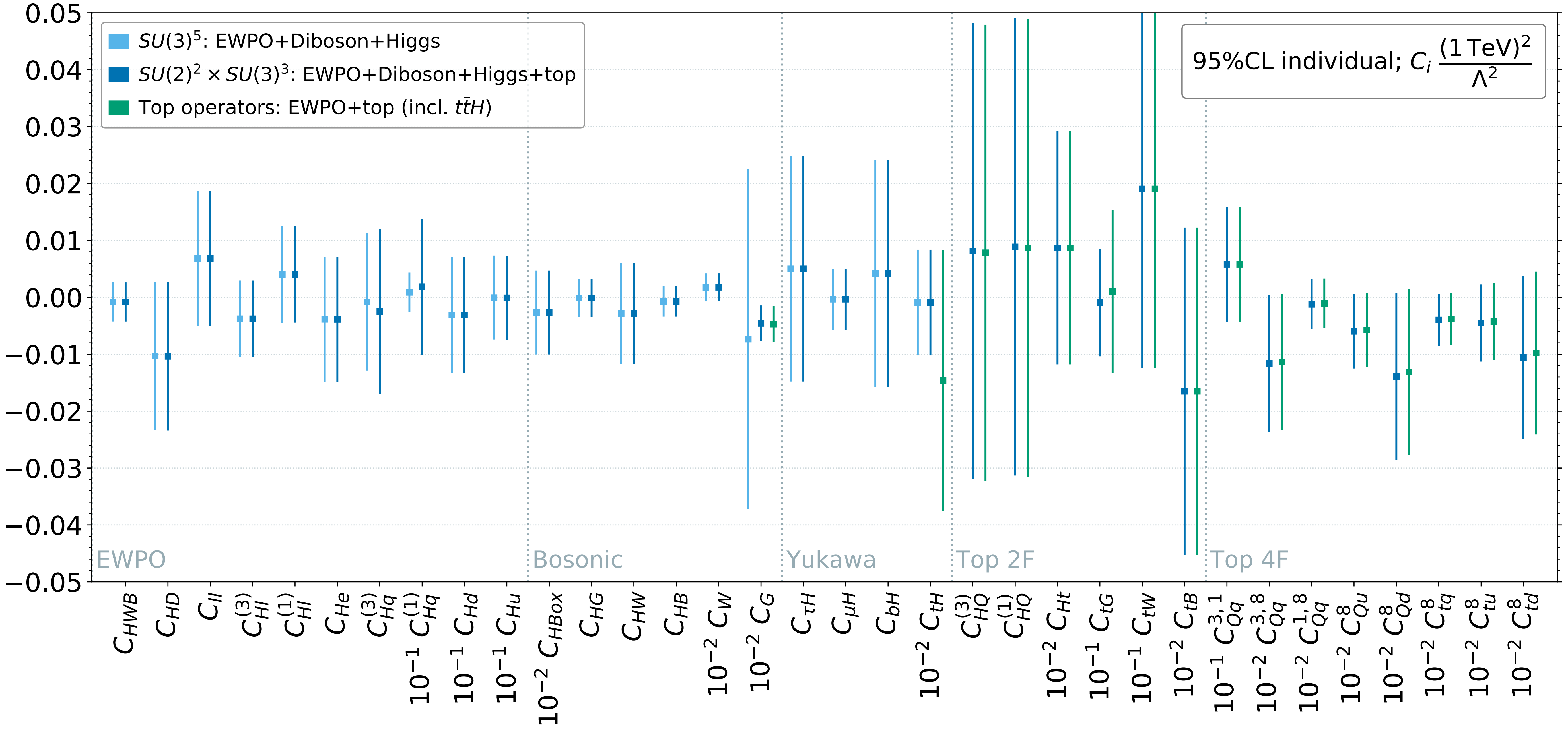
Higgs differential

Dataset	$\sqrt{s}$, $\mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref
LEP2_WW_diff (*)	**[182, 296] GeV**	LEP-2 comb	$d^2\sigma(WW)/dE_{\rm cm}d\cos\theta_W$	40	[128]
ATLAS_WZ_13TeV_2016 (*)	**13 TeV, 36.1 fb^{-1}**	fully leptonic	$d\sigma^{(\rm fid)}/dm_T^{WZ}$	6	[129]
ATLAS_WW_13TeV_2016 (*)	**13 TeV, 36.1 fb^{-1}**	fully leptonic	$d\sigma^{(\rm fid)}/dm_{e\mu}$	13	[130]
CMS_WZ_13TeV_2016 (*)	**13 TeV, 35.9 fb^{-1}**	fully leptonic	$d\sigma^{(\rm fid)}/dp_T^Z$	11	[131]

Diboson

Category	Processes	$n_{\rm dat}$
Top quark production	$t\bar{t}$ (inclusive)	94
	$t\bar{t}Z$, $t\bar{t}W$	14
	single top (inclusive)	27
	tZ, tW	9
	$t\bar{t}t\bar{t}$, $t\bar{t}b\bar{b}$	6
	Total	**150**
Higgs production and decay	Run I signal strengths	22
	Run II signal strengths	40
	Run II, differential distributions & STXS	35
	Total	**97**
Diboson production	LEP-2	40
	LHC	30
	Total	**70**
Baseline dataset	**Total**	**317**

Full fit: individual



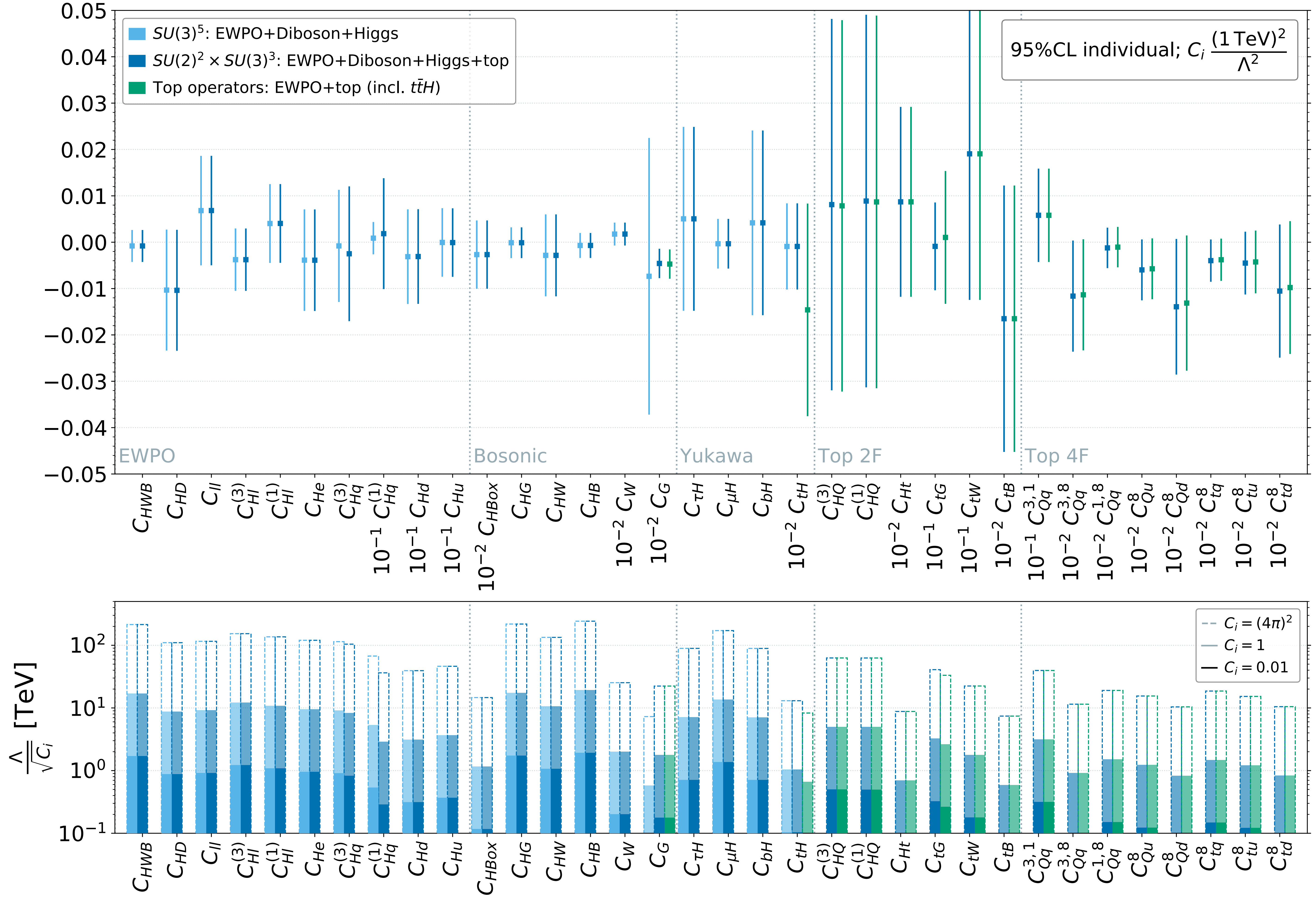
Individual: only one non-zero c_i

(optimistic, unrealistic)

What does that mean for the UV scale?

Ellis, Madigan, Mimasu, Sanz, You arXiv:2012.02779

Full fit: individual



Ellis, Madigan, Mimasu, Sanz, You arXiv:2012.02779

Individual: only one non-zero c_i

(optimistic, unrealistic)

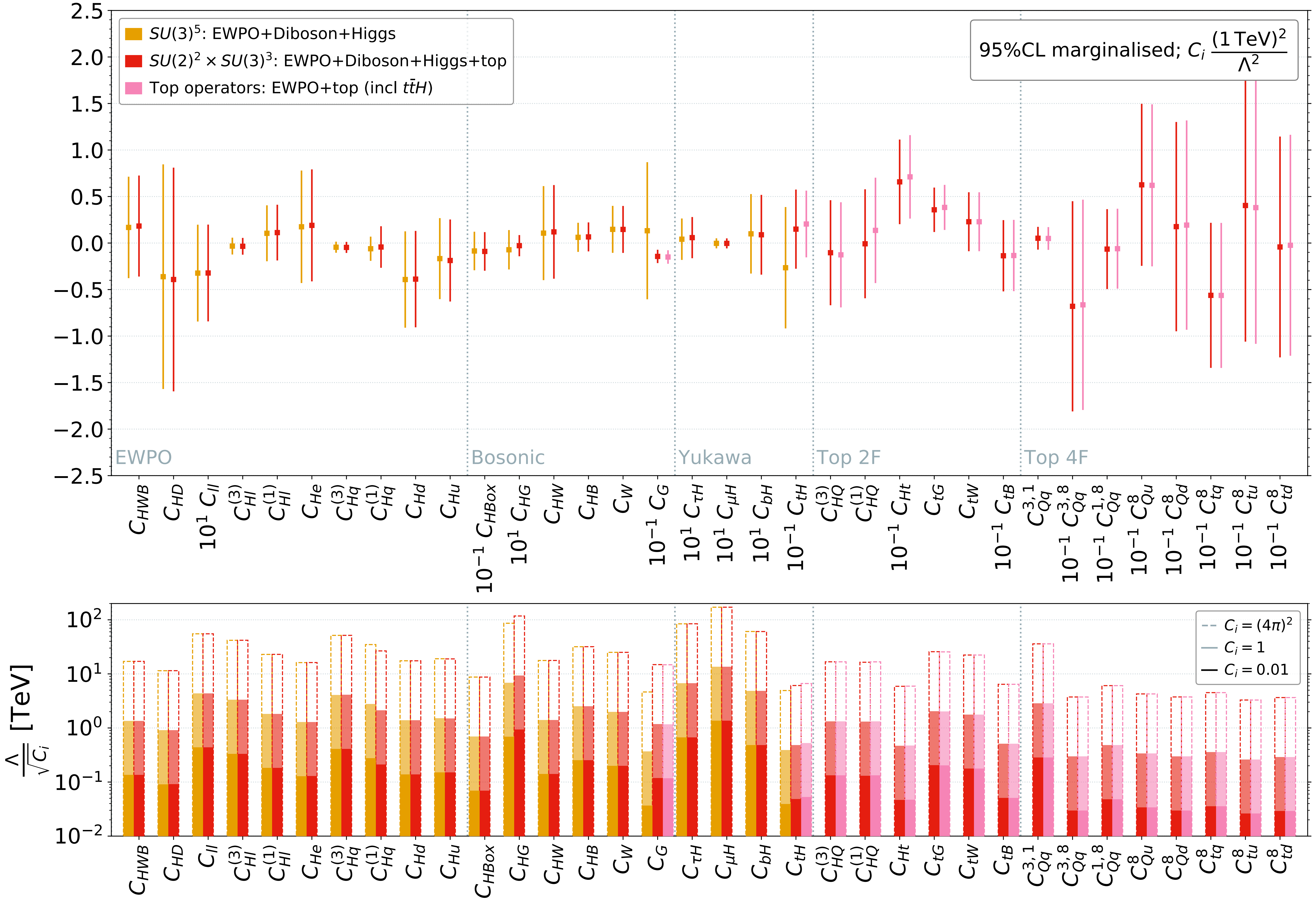
What does that mean for the UV scale?

Strongly coupled

Weakly coupled

$$\frac{c_i^6(\mu)}{\Lambda^2}$$

Full fit: marginalised



All coefficients allowed to be non-zero

Bounds significantly worse in a marginalised fit

For weakly coupled theories Λ bound below the TeV scale: **EFT Validity???**

Ellis, Madigan, Mimasu, Sanz, You arXiv:2012.02779

What do we learn from global fits?

Bounds on new physics scale vary from 0.1 TeV (unconstrained) to 10s of TeV. Bounds depend on

- the operator
- assumption of a strongly or weakly coupled theory
- individual or marginalised bounds (reality is somewhere in-between)
- linear or quadratic bounds

What do we learn from global fits?

Bounds on new physics scale vary from 0.1 TeV (unconstrained) to 10s of TeV. Bounds depend on

- the operator
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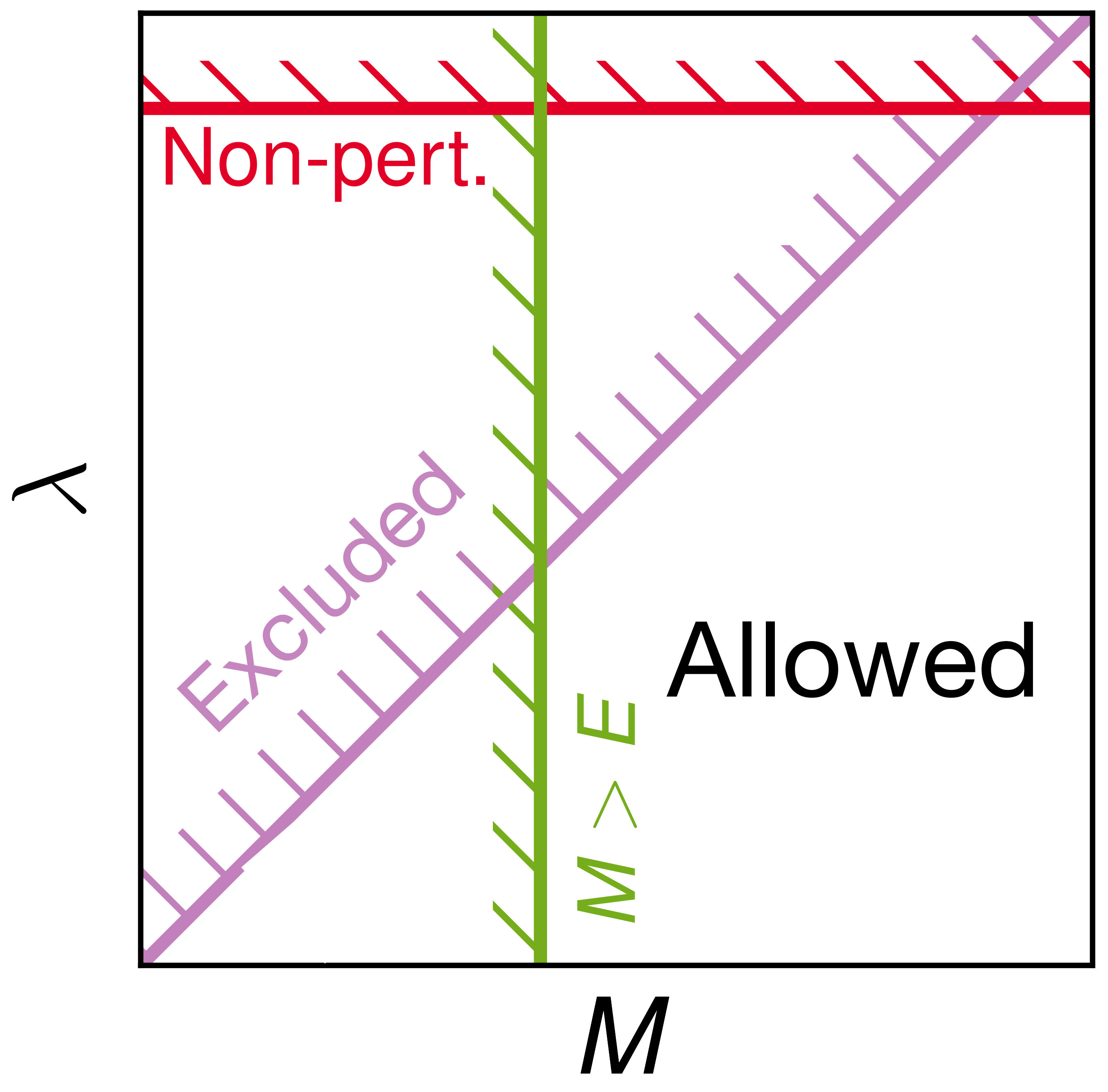
- linear or quadratic bounds

constraint: $\frac{c_i^6(\mu)}{\Lambda^2} = \frac{\lambda^2}{M^2} < X$



From EFT to the UV

Single-field extensions of the SM

	Name	Spin	SU(3)	SU(2)	U(1)	Param.	Name	Spin	SU(3)	SU(2)	U(1)	Param.	
	S	0	1	1	0	$(M_S,\, \kappa_S)$	Δ_1	$\frac{1}{2}$	1	2	$-\frac{1}{2}$	$(M_{\Delta_1},\lambda_{\Delta_1})$	
	S_1	0	1	1	1	(M_{S_1},y_{S_1})	Δ_3	$\frac{1}{2}$	1	2	$-\frac{1}{2}$	$(M_{\Delta_3},\lambda_{\Delta_3})$	
Scalars	φ	0	1	2	$\frac{1}{2}$	$(M_\varphi,Z_6\cos\beta)$	Σ	$\frac{1}{2}$	1	3	0	$(M_\Sigma,\lambda_\Sigma)$	VLL
	Ξ	0	1	3	0	(M_Ξ,κ_Ξ)	Σ_1	$\frac{1}{2}$	1	3	-1	$(M_{\Sigma_1},\lambda_{\Sigma_1})$	
	Ξ_1	0	1	3	1	$(M_{\Xi_1},\kappa_{\Xi_1})$	U	$\frac{1}{2}$	3	1	$\frac{2}{3}$	(M_U,λ_U)	
Z'	B	1	1	1	0	$(M_B,\hat{g}_H^B)$	D	$\frac{1}{2}$	3	1	$-\frac{1}{3}$	(M_D,λ_D)	
W'	B_1	1	1	1	1	(M_{B_1},g_{B_1})	Q_1	$\frac{1}{2}$	3	2	$\frac{1}{6}$	(M_{Q_1},λ_{Q_1})	
	W	1	1	3	0	$(M_W,\hat{g}_H^W)$	Q_5	$\frac{1}{2}$	3	2	$-\frac{5}{6}$	(M_{Q_5},λ_{Q_5})	
	W_1	1	1	3	1	$(M_{W_1},\hat{g}_{W_1}^\varphi)$	Q_7	$\frac{1}{2}$	3	2	$\frac{7}{6}$	(M_{Q_7},λ_{Q_7})	VLQ
VLL	N	$\frac{1}{2}$	1	1	0	(M_N,λ_N)	T_1	$\frac{1}{2}$	3	3	$-\frac{1}{3}$	(M_{T_1},λ_{T_1})	
	E	$\frac{1}{2}$	1	1	-1	(M_E,λ_E)	T_2	$\frac{1}{2}$	3	3	$\frac{2}{3}$	(M_{T_2},λ_{T_2})	
VLQ	T	$\frac{1}{2}$	3	1	$\frac{2}{3}$	(M_T,s_L^t)	TB	$\frac{1}{2}$	3	2	$\frac{1}{6}$	$(M_{TB},s_L^{t,b})$	

- EFT bounds translate to constraints on parameters of UV models
- Simplest case: single-field extensions of the SM

From EFT to the UV

Single-field extensions of the SM

	Name	Spin	SU(3)	SU(2)	U(1)	Param.	Name	Spin	SU(3)	SU(2)	U(1)	Param.	
	S	0	1	1	0	$(M_S,\ \kappa_S)$	Δ_1	$\frac{1}{2}$	1	2	$-\frac{1}{2}$	$(M_{\Delta_1},\lambda_{\Delta_1})$	
	S_1	0	1	1	1	(M_{S_1},y_{S_1})	Δ_3	$\frac{1}{2}$	1	2	$-\frac{1}{2}$	$(M_{\Delta_3},\lambda_{\Delta_3})$	
Scalars	φ	0	1	2	$\frac{1}{2}$	$(M_\varphi,Z_6\cos\beta)$	Σ	$\frac{1}{2}$	1	3	0	$(M_\Sigma,\lambda_\Sigma)$	VLL
	Ξ	0	1	3	0	(M_Ξ,κ_Ξ)	Σ_1	$\frac{1}{2}$	1	3	-1	$(M_{\Sigma_1},\lambda_{\Sigma_1})$	
	Ξ_1	0	1	3	1	$(M_{\Xi_1},\kappa_{\Xi_1})$	U	$\frac{1}{2}$	3	1	$\frac{2}{3}$	(M_U,λ_U)	
Z'	B	1	1	1	0	$(M_B,\hat{g}_H^B)$	D	$\frac{1}{2}$	3	1	$-\frac{1}{3}$	(M_D,λ_D)	
W'	B_1	1	1	1	1	(M_{B_1},g_{B_1})	Q_1	$\frac{1}{2}$	3	2	$\frac{1}{6}$	(M_{Q_1},λ_{Q_1})	
	W	1	1	3	0	$(M_W,\hat{g}_H^W)$	Q_5	$\frac{1}{2}$	3	2	$-\frac{5}{6}$	(M_{Q_5},λ_{Q_5})	
	W_1	1	1	3	1	$(M_{W_1},\hat{g}_{W_1}^{\varphi})$	Q_7	$\frac{1}{2}$	3	2	$\frac{7}{6}$	(M_{Q_7},λ_{Q_7})	VLQ
VLL	N	$\frac{1}{2}$	1	1	0	(M_N,λ_N)	T_1	$\frac{1}{2}$	3	3	$-\frac{1}{3}$	(M_{T_1},λ_{T_1})	
	E	$\frac{1}{2}$	1	1	-1	(M_E,λ_E)	T_2	$\frac{1}{2}$	3	3	$\frac{2}{3}$	(M_{T_2},λ_{T_2})	
VLQ	T	$\frac{1}{2}$	3	1	$\frac{2}{3}$	(M_T,s_L^t)	TB	$\frac{1}{2}$	3	2	$\frac{1}{6}$	$(M_{TB},s_L^{t,b})$	

Matching

Model	C_{HD}	C_{ll}	C_{Hl}^3	C_{Hl}^1	C_{He}	$C_{H\square}$	$C_{\tau H}$	C_{tH}	C_{bH}
S						$-\frac{1}{2}$			
S_1		1							
Σ			$\frac{1}{16}$	$\frac{3}{16}$			$\frac{y_\tau}{4}$		
Σ_1			$-\frac{1}{16}$	$-\frac{3}{16}$			$\frac{y_\tau}{8}$		
N			$-\frac{1}{4}$	$\frac{1}{4}$					
E			$-\frac{1}{4}$	$-\frac{1}{4}$			$\frac{y_\tau}{2}$		
Δ_1					$\frac{1}{2}$		$\frac{y_\tau}{2}$		
Δ_3					$-\frac{1}{2}$		$\frac{y_\tau}{2}$		
B_1	1					$-\frac{1}{2}$	$-\frac{y_\tau}{2}$	$-\frac{y_t}{2}$	$-\frac{y_b}{2}$
Ξ	-2					$\frac{1}{2}$	y_τ	y_t	y_b
W_1	$-\frac{1}{4}$					$-\frac{1}{8}$	$-\frac{y_\tau}{8}$	$-\frac{y_t}{8}$	$-\frac{y_b}{8}$
φ							$-y_\tau$	$-y_t$	$-y_b$
$\{B,B_1\}$						$-\frac{3}{2}$	$-\ y_\tau$	$-\ y_t$	$-\ y_b$
$\{Q_1,Q_7\}$								y_t	
Model	C_{Hq}^3	C_{Hq}^1	$(C_{Hq}^3)_{33}$	$(C_{Hq}^1)_{33}$	C_{Hu}	C_{Hd}	C_{tH}	C_{bH}	
U	$-\frac{1}{4}$	$\frac{1}{4}$	$-\frac{1}{4}$	$\frac{1}{4}$			$\frac{y_t}{2}$		
D	$-\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{4}$				$\frac{y_b}{2}$	
Q_5						$-\frac{1}{2}$		$\frac{y_b}{2}$	
Q_7					$\frac{1}{2}$		$\frac{y_t}{2}$		
T_1	$-\frac{1}{16}$	$-\frac{3}{16}$	$-\frac{1}{16}$	$-\frac{3}{16}$			$\frac{y_t}{4}$	$\frac{y_b}{8}$	
T_2	$-\frac{1}{16}$	$\frac{3}{16}$	$-\frac{1}{16}$	$\frac{3}{16}$			$\frac{y_t}{8}$	$\frac{y_b}{4}$	
T			$-\frac{1}{2}\frac{M_T^2}{v^2}$	$\frac{1}{2}\frac{M_T^2}{v^2}$			$y_t\frac{M_T^2}{v^2}$		

Tree-level matching dictionary
de Blas et al. JHEP 03 (2018) 109

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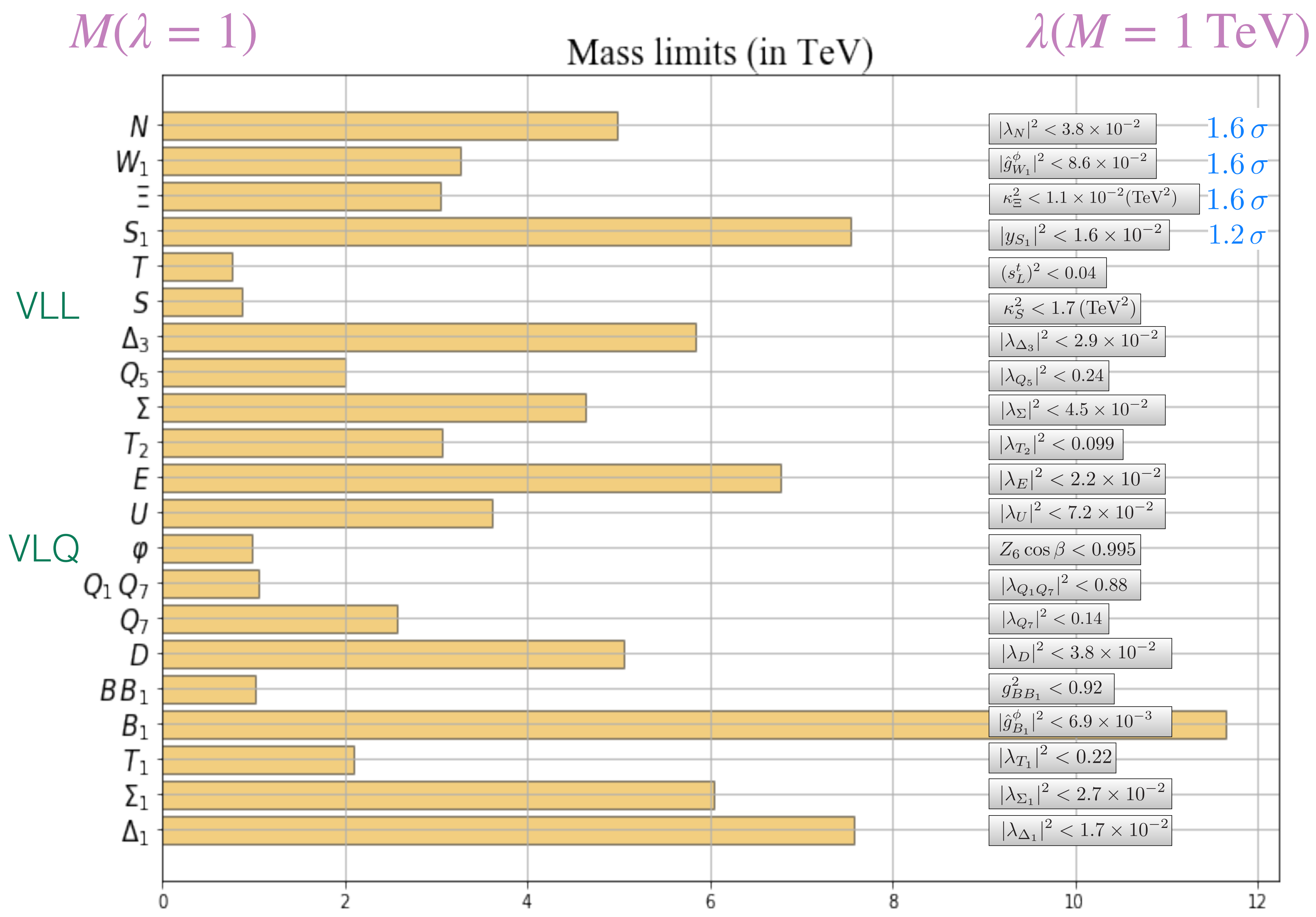
- Simplest case: single-field extensions of the SM

From EFT to UV

Single-field extensions of the SM

	Name	Spin	SU(3)	SU(2)	U(1)	Param.	Name	Spin	SU(3)	SU(2)	U(1)	Param.
	S	0	1	1	0	(M_S, κ_S)	Δ_1	$\frac{1}{2}$	1	2	$-\frac{1}{2}$	$(M_{\Delta_1},\lambda_{\Delta_1})$
	S_1	0	1	1	1	(M_{S_1},y_{S_1})	Δ_3	$\frac{1}{2}$	1	2	$-\frac{1}{2}$	$(M_{\Delta_3},\lambda_{\Delta_3})$
Scalars	φ	0	1	2	$\frac{1}{2}$	$(M_\varphi,Z_6\cos\beta)$	Σ	$\frac{1}{2}$	1	3	0	$(M_\Sigma,\lambda_\Sigma)$
	Ξ	0	1	3	0	(M_Ξ,κ_Ξ)	Σ_1	$\frac{1}{2}$	1	3	-1	$(M_{\Sigma_1},\lambda_{\Sigma_1})$
	Ξ_1	0	1	3	1	$(M_{\Xi_1},\kappa_{\Xi_1})$	U	$\frac{1}{2}$	3	1	$\frac{2}{3}$	(M_U,λ_U)
Z’	B	1	1	1	0	$(M_B,\hat{g}_H^B)$	D	$\frac{1}{2}$	3	1	$-\frac{1}{3}$	(M_D,λ_D)
W’	B_1	1	1	1	1	(M_{B_1},g_{B_1})	Q_1	$\frac{1}{2}$	3	2	$\frac{1}{6}$	(M_{Q_1},λ_{Q_1})
	W	1	1	3	0	$(M_W,\hat{g}_H^W)$	Q_5	$\frac{1}{2}$	3	2	$-\frac{5}{6}$	(M_{Q_5},λ_{Q_5})
	W_1	1	1	3	1	$(M_{W_1},\hat{g}_{W_1}^\varphi)$	Q_7	$\frac{1}{2}$	3	2	$\frac{7}{6}$	(M_{Q_7},λ_{Q_7})
VLL	N	$\frac{1}{2}$	1	1	0	(M_N,λ_N)	T_1	$\frac{1}{2}$	3	3	$-\frac{1}{3}$	(M_{T_1},λ_{T_1})
	E	$\frac{1}{2}$	1	1	-1	(M_E,λ_E)	T_2	$\frac{1}{2}$	3	3	$\frac{2}{3}$	(M_{T_2},λ_{T_2})
VLQ	T	$\frac{1}{2}$	3	1	$\frac{2}{3}$	(M_T,s_L^t)	TB	$\frac{1}{2}$	3	2	$\frac{1}{6}$	$(M_{TB},s_L^{t,b})$



Ellis, Madigan, Mimasu, Sanz, You arXiv:2012.02779

- EFT bounds translate to constraints on parameters of UV models
- Simplest case: single-field extensions of the SM

Fix coupling and set bound on mass or the other way round

THANK YOU