ΔEFT: An Effective Field Theory of the Type-2 Seesaw Mechanism

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HIDDeν Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

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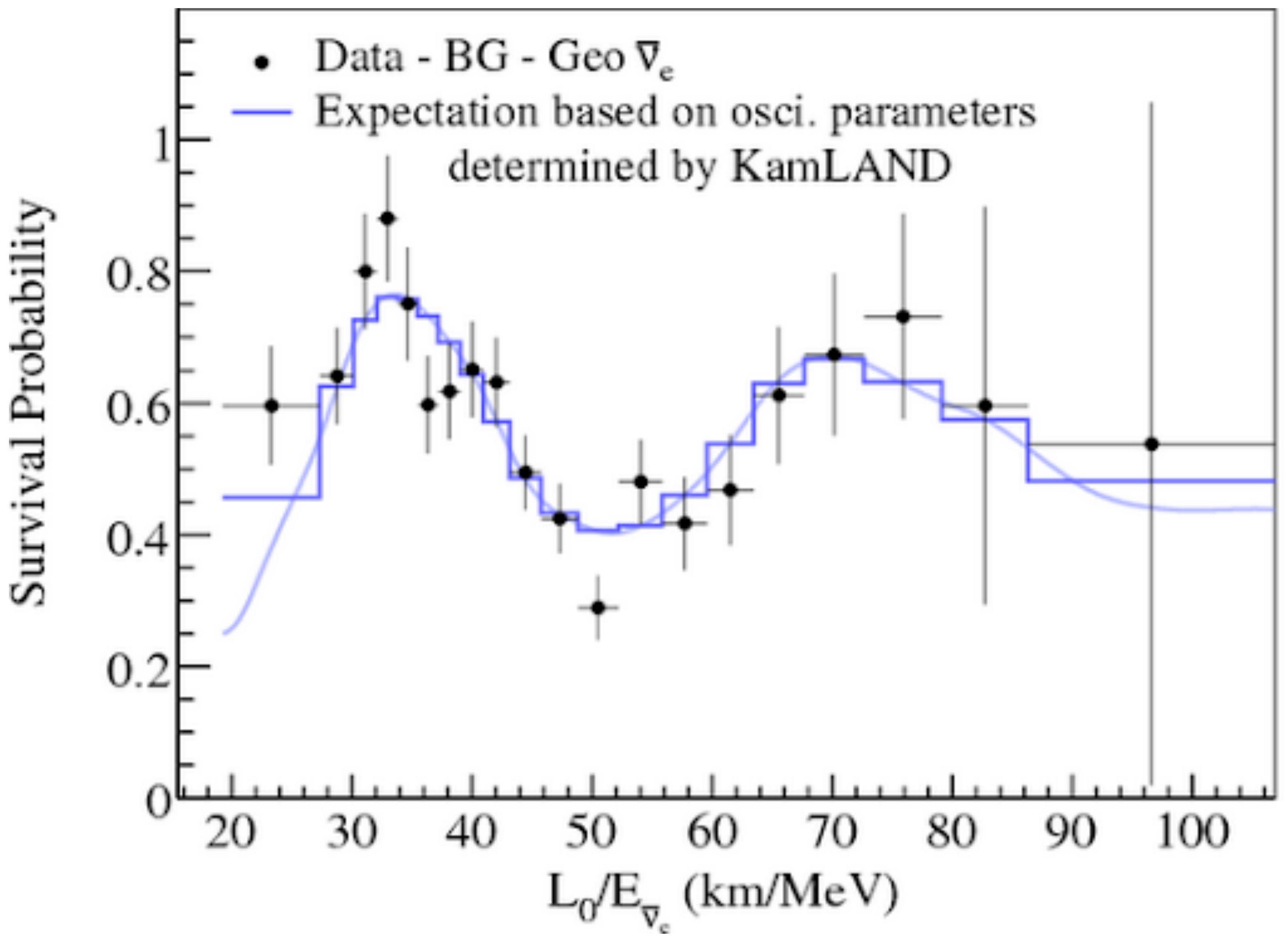
Neutrino Masses



The oscillation between different neutrino species implies a mass:

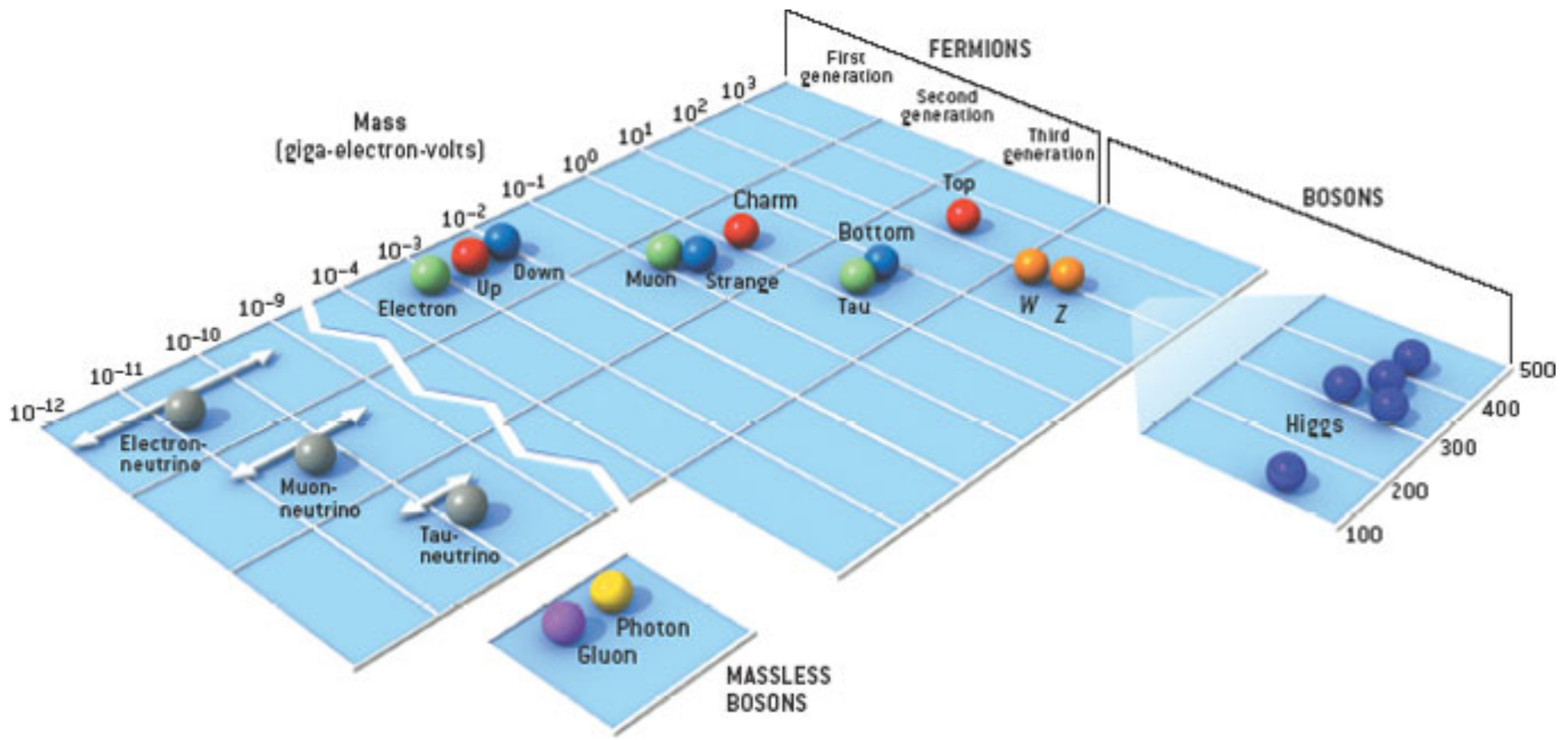
$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E}L\right)$$

KATRIN: $m_\nu^2 < 1.1$ eV^2 at 90% C.L.

Planck: $\sum m_\nu \lesssim 0.12$ eV at 95% C.L.

When compared with other SM particles we observe a large scale separation:

$$\frac{m_\nu}{m_t} = \frac{y_\nu}{y_t} \lesssim \mathcal{O}(10^{-12})$$



Type-1 Seesaw Mechanism

Introducing a right-handed neutrino $N_R(1,1,0)$ we can explain the “tininess” of the Yukawa couplings

$$\mathscr{L}_m^\nu = -\frac{m_R}{2}\overline{N_R^c}N_R - m_D\bar{N}_R\nu_L + \text{h.c.}$$

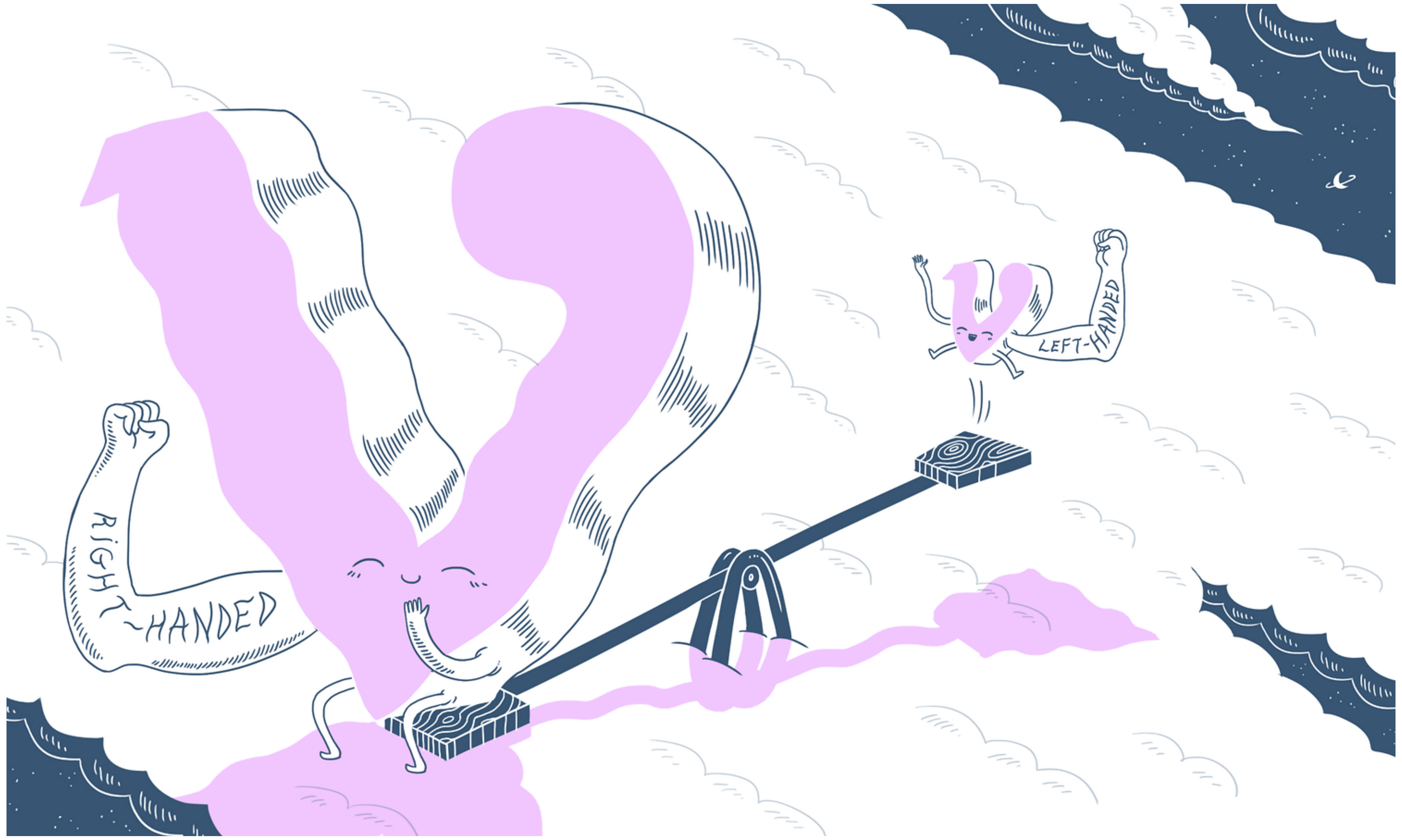
Which can be rewritten as:

$$\mathscr{L}_m^\nu = -\frac{1}{2}\begin{pmatrix}\bar{\nu}_L & \overline{N_R^C}\end{pmatrix}\begin{pmatrix}0 & m_D \\ m_D & m_R\end{pmatrix}\begin{pmatrix}\nu_L^C \\ N_R\end{pmatrix}$$

Using $m_D \ll m_R$ the mass eigenvalues are:

$$m_N \simeq m_R \qquad m_\nu \simeq \frac{m_D^2}{m_R} = \left(\frac{v_d}{\sqrt{2}}y_\nu\right)^2\frac{1}{m_R}$$

Which for $y_\nu \sim \mathcal{O}(1)$ gives
$m_R \sim 10^{15}$ GeV



Type-2 Seesaw Mechanism

$$\mathscr{L}^{\nu}_{m} = -\frac{1}{2}\left(\bar{\nu}_L \quad \overline{N^C_R}\right)\begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix}\begin{pmatrix} \nu^C_L \\ N_R \end{pmatrix}$$

What about this term? $\frac{m_L}{2}\overline{\nu^c_L}\nu_L$

In $SU(2)_L$ the left handed neutrino is embedded in the lepton left-handed doublet: $l = \begin{pmatrix} \nu \\ e \end{pmatrix}$, so a mass-term like the above should come from a combination l^c and l.

Requires an extension of the SM: $\Delta(1,3,+1) = \frac{\sigma^i}{\sqrt{2}}\Delta^i = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & \Delta^+/\sqrt{2} \end{pmatrix}$

Allowing us to add a term in the Lagrangian: $\mathscr{L}^{\Delta}_{Y} = f_{ab}\overline{l^c_a} i\sigma^2 \Delta l_b + \text{h.c}\,.$

Let the neutral component acquire a vev: $\langle \Delta^0 \rangle = \frac{v_t}{\sqrt{2}}$ $\quad \mathscr{L}^{\Delta}_{Y} \to f_{ab}\frac{v_t}{\sqrt{2}}\overline{\nu^c_a}\nu_b$

Type-2 Seesaw Mechanism

The Higgs potential now is a bit more complicated….

$$V(\varphi, \Delta) = -m_\varphi^2 \varphi^\dagger \varphi + M^2 \mathrm{Tr}\Delta^\dagger\Delta + (\mu \varphi^T i\sigma^2 \Delta^\dagger \varphi + \text{h.c.}) + \frac{\lambda}{4}(\varphi^\dagger\varphi)^2 + \lambda_1 \varphi^\dagger\varphi \mathrm{Tr}\Delta^\dagger\Delta + \lambda_2(\mathrm{Tr}\Delta^\dagger\Delta)^2 + \lambda_3 \mathrm{Tr}(\Delta^\dagger\Delta)^2 + \lambda_4 \varphi^\dagger\Delta\Delta^\dagger\varphi$$

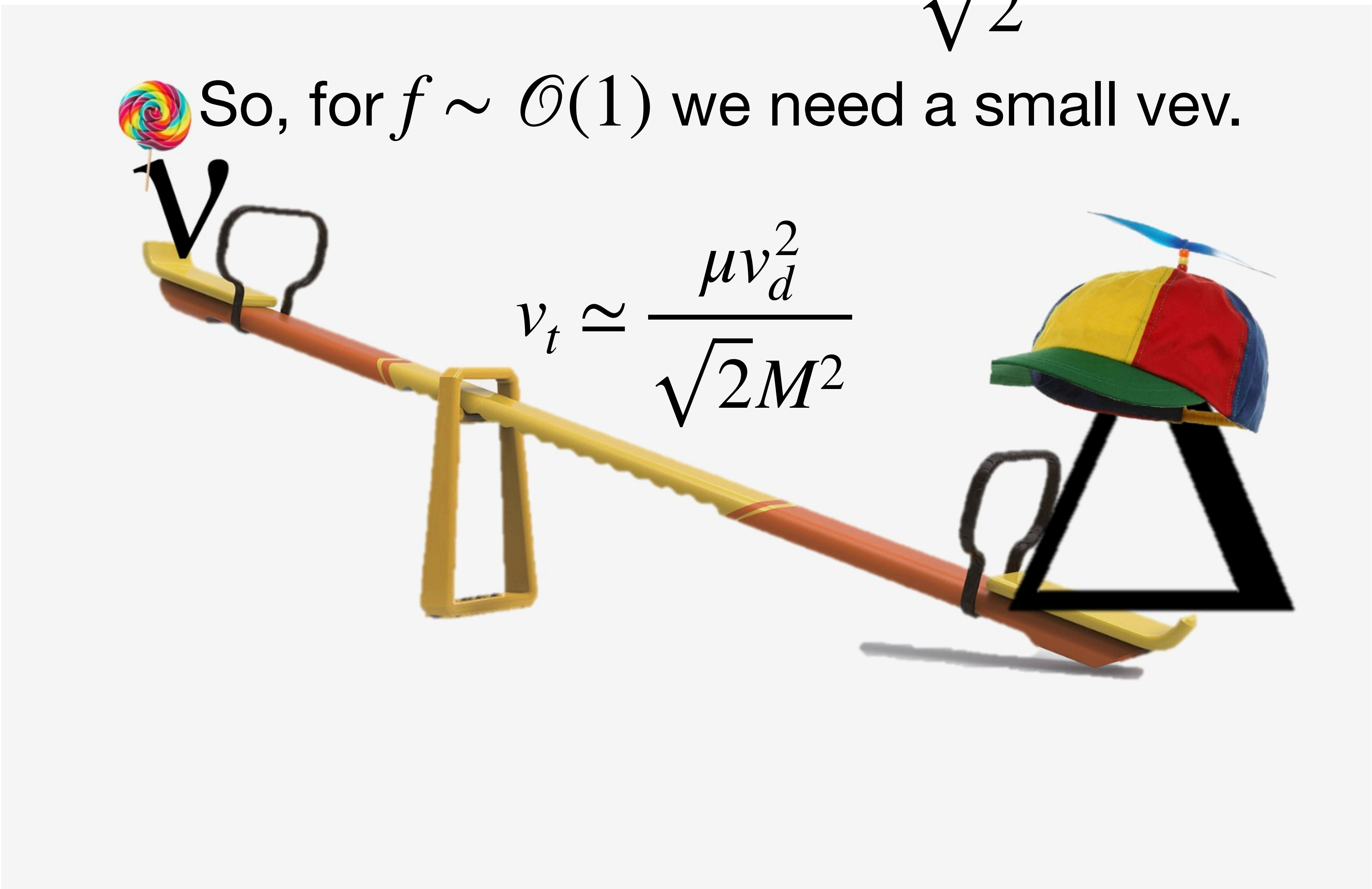
One can still find that this potential has a minimum at:

$$M^2 = -\frac{\lambda_1+\lambda_4}{2}v_d^2 - (\lambda_2+\lambda_3)v_t^2 + \frac{\mu v_d^2}{\sqrt{2}v_t} \qquad \langle \Delta^0 \rangle = \frac{v_t}{\sqrt{2}}$$

$$m_\varphi^2 = \frac{\lambda}{4}v_d^2 + \frac{\lambda_1+\lambda_4}{2}v_t^2 - \sqrt{2}\mu v_t \qquad \langle \varphi^0 \rangle = \frac{v_d}{\sqrt{2}}$$

So, the vev is suppressed if the mass of the triplet is really large

Remember: $\mathscr{L}_Y^\Delta \to f_{ab}\frac{v_t}{\sqrt{2}}\overline{\nu}_a^c \nu_b$



A few comments before moving on…

Let's do some counting:
Before SSB: 4 (doublet) + 6 (triplet) d.o.f
After SSB: 3 GB + 7 physical particles

The GB: $G^{\pm}, G^0$ are now a combination of triplet and doublet fields breaking the relation:

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_w} = 1 - \frac{2v_t^2}{v_d^2 + 4v_t} = 1.00037 \pm 0.00023 \to v_t \leq 2.1 \text{ GeV}$$

The physical states are: $H^{\pm\pm}, H^{\pm}, A, H, h,$ which except $H^{\pm\pm} = \Delta^{\pm\pm}$, mix doublet and triplet fields

$$\varphi = \begin{pmatrix} \varphi^+ \\ \frac{v_d + h_d + iz_d}{\sqrt{2}} \end{pmatrix}$$

$$\Delta = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ \frac{v_t + h_t + iz_t}{\sqrt{2}} & \frac{\Delta^+}{\sqrt{2}} \end{pmatrix}$$

$$\begin{pmatrix} H^+ \\ G^+ \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \Delta^+ \\ \varphi^+ \end{pmatrix}$$

$$\begin{pmatrix} A \\ G^0 \end{pmatrix} = \begin{pmatrix} \cos\beta' & -\sin\beta' \\ \sin\beta' & \cos\beta' \end{pmatrix} \begin{pmatrix} z_t \\ z_d \end{pmatrix} \longrightarrow \tan\beta \sim \tan\beta' \sim \frac{v_t}{v_d}$$

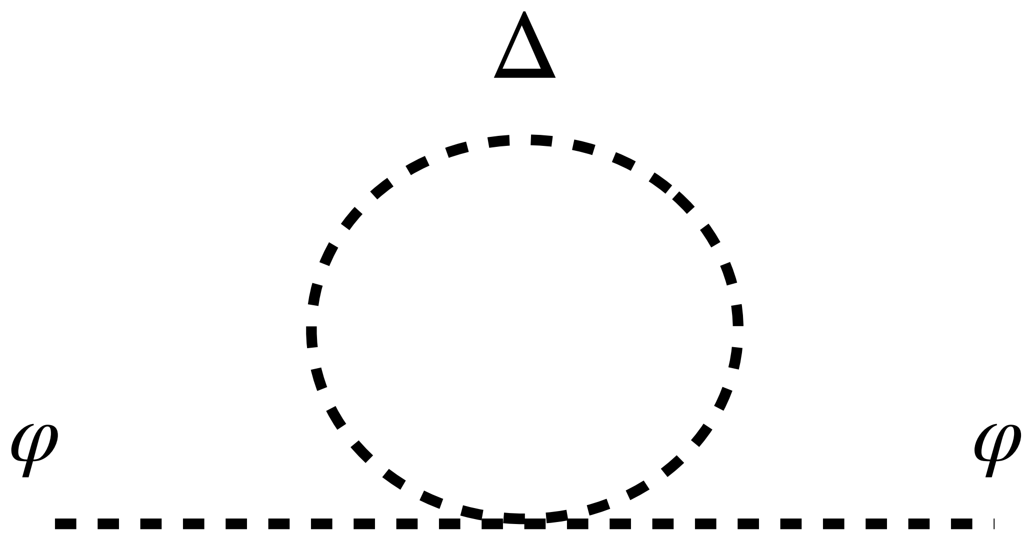
$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h_t \\ h_d \end{pmatrix} \longrightarrow \tan 2\alpha = \frac{-2\sqrt{2}\,\mu\, v_d + 2(\lambda_1 + \lambda_4)\, v_t\, v_d}{\frac{\lambda}{2}v_d^2 - \frac{\mu}{\sqrt{2}v_t}v_d^2 - 2(\lambda_2 + \lambda_3)v_t^2} \leq 0.3 \text{ at 95\% C.L.}$$

arXiv:1903.02493

Are we done?

Well, there are some “issues”

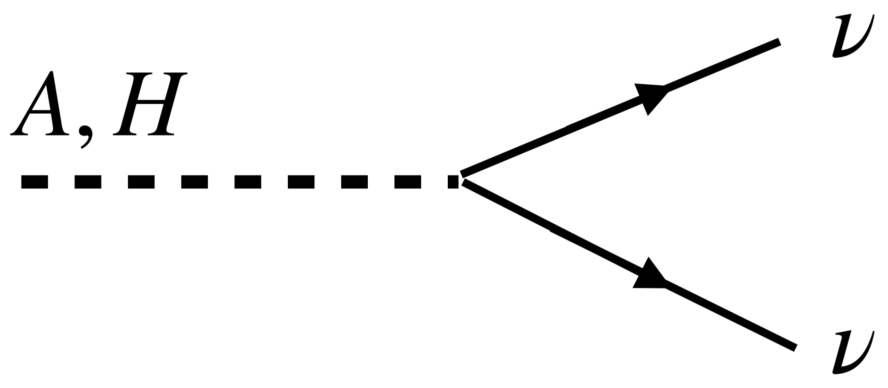
- We explain neutrino masses in a natural way, however…



$$-\frac{3}{16\pi^2}M^2\left(\lambda_4+\frac{|\hat{\mu}|^2}{2}\right)\left(1+\ln\frac{\mu_R^2}{M^2}\right)$$

- We also know type-2 seesaw mechanism cannot solve all the open questions of the SM, one of the most important: Dark Matter.

→ Neutral components are unstable, they will always have a decay channel:

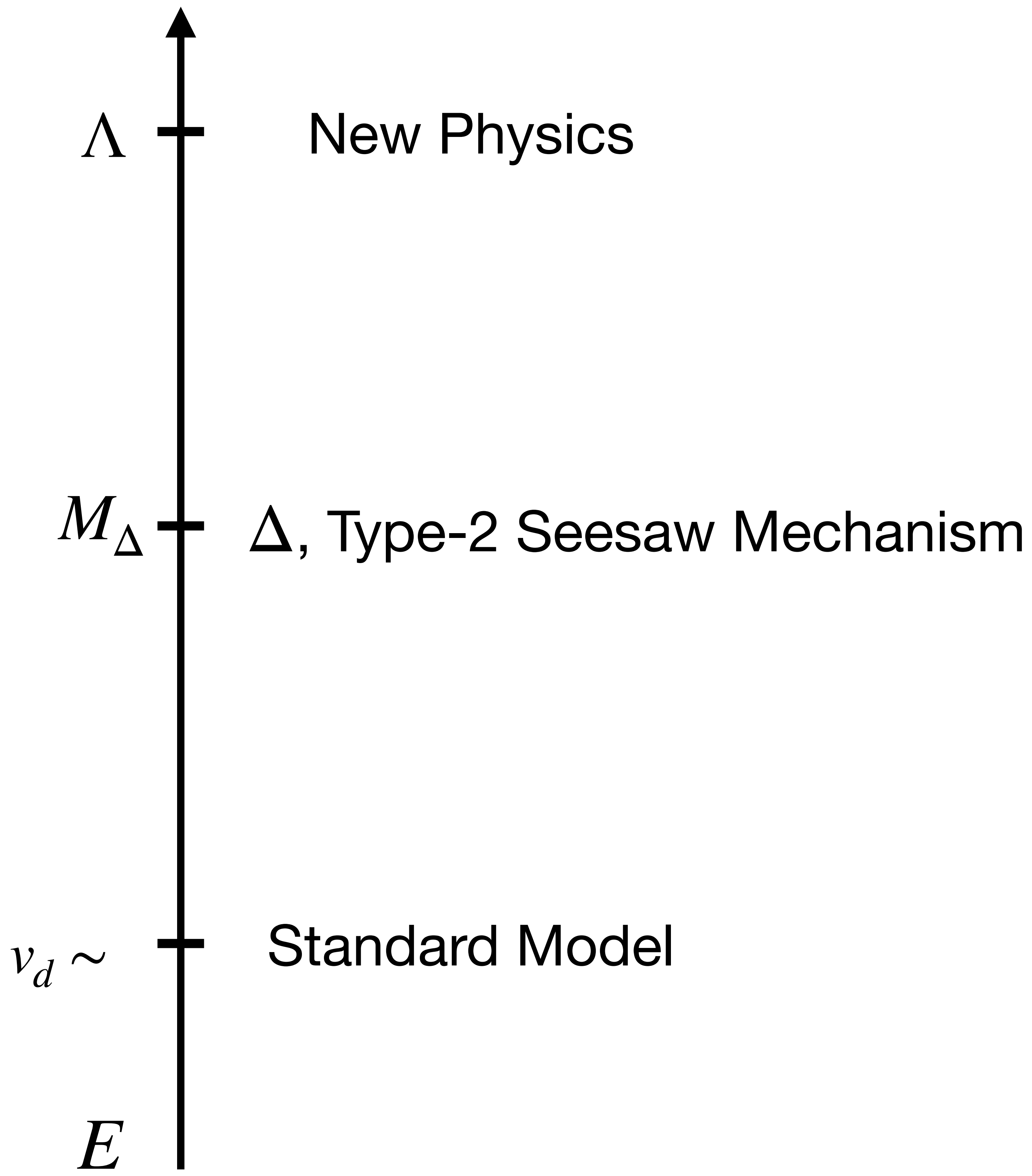


Even suppressing f_{ab} does not work, since other decays become relevant e.g. $H \to W^{\pm}W^{\mp}$

- And more: Strong-CP problem, flavour hierarchy problem, GUTs, quantum gravity…

- Phenomenologically testable at TeV scale.

Scales and EFT



- Consider $\Lambda \gg M_\Delta > \mathcal{O}(v_d)$ and a coupling of the NP to the SM + Δ. In this case we can "integrate out" the NP and work with an effective Lagrangian:

$$\mathscr{L}^{D\leq 6}_{\Delta EFT} = \mathscr{L}^{D\leq 4}_{\Delta} + \mathscr{L}^{D=5}_{\Delta EFT} + \mathscr{L}^{D=6}_{\Delta EFT} = \sum_i C_i(\mu)\,\mathcal{O}_i + \sum_j \frac{C_j^{(5)}(\mu)}{\Lambda}\,\mathcal{O}_j^{(5)} + \sum_k \frac{C_k^{(6)}(\mu)}{\Lambda^2}\,\mathcal{O}_k^{(6)}$$

- Where we allow the type-2 Lagrangian to have mass-dimension 6 terms. In other words, think it as SMEFT + Δ

- Inevitably we lose the "theoretically natural" mass range of the model.

The Basis

- At dimension 5 we obtain 7 different operators.
- Couplings to quarks do not appear at dimension 4. New ways of producing these particles at hadron colliders.
- The extended scalar sector is difficult to probe.
- Two $SU(2)_L$ doublets can be combined on a singlet and a triplet: $\bar{q}_p d_r \tilde{\varphi}$ and $\bar{q}_p d_r \tau^I \tilde{\varphi}$
- $\Delta \rightarrow U_L \Delta U_L^\dagger$ with $U_L = e^{i\alpha^j \frac{\tau^j}{2}}$

Fermions		Scalars	
$\mathcal{O}_{\Delta e}$	$(\overline{e_p^c} e_r)\mathrm{Tr}(\Delta\Delta)$	$\mathcal{O}^{(1)}_{\Delta^3\varphi^2}$	$\mathrm{Tr}(\Delta^\dagger\Delta)\varphi^\dagger\Delta\tilde{\varphi}$
$\mathcal{O}_{\Delta qd}$	$\bar{q}_p \Delta d_r \tilde{\varphi}$	$\mathcal{O}^{(3)}_{\Delta^3\varphi^2}$	$\varphi^\dagger\Delta\Delta^\dagger\Delta\tilde{\varphi}$
$\mathcal{O}_{\Delta le}$	$\bar{l}_p \Delta e_r \tilde{\varphi}$	$\mathcal{O}_{\varphi^4\Delta}$	$(\varphi^\dagger\Delta\tilde{\varphi})(\varphi^\dagger\varphi)$
$\mathcal{O}_{\Delta qu}$	$\varphi^\dagger\Delta\bar{u}_r q_p$		

The Basis

- 43 operators in this table.
- Again an extended scalar sector which is difficult to probe.
- Lower part of table almost identical to the Warsaw Basis.

Δ^6 and $\Delta^4 D^2$		$\Delta^4\varphi^2$ and $\Delta^2\varphi^4$		$\Delta^2\varphi^2 D^2$ and $\tilde{\varphi}^2\varphi^2\Delta^2$	
$\mathcal{O}^1_{\Delta}$	$[\mathrm{Tr}(\Delta^\dagger\Delta)]^3$	$\mathcal{O}^1_{\varphi\Delta}$	$\mathrm{Tr}(\Delta^\dagger\Delta)\,(\varphi^\dagger\varphi)^2$	$\mathcal{O}_{\Delta\Box\varphi}$	$\mathrm{Tr}(\Delta^\dagger\Delta)\,\Box\,(\varphi^\dagger\varphi)$
$\mathcal{O}^2_{\Delta}$	$\mathrm{Tr}(\Delta^\dagger\Delta)^2\,\mathrm{Tr}(\Delta^\dagger\Delta)$	$\mathcal{O}^2_{\varphi\Delta}$	$(\varphi^\dagger\Delta\Delta^\dagger\varphi)\,(\varphi^\dagger\varphi)$	$\mathcal{O}^1_{\Delta D\varphi}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)\mathrm{Tr}(\Delta^\dagger i\overleftrightarrow{D}^\mu\Delta)$
$\mathcal{O}^3_{\Delta}$	$\mathrm{Tr}\big(\Delta^\dagger\Delta\big)^3$	$\mathcal{O}^1_{\Delta\varphi}$	$\mathrm{Tr}(\Delta^\dagger\Delta)\,(\varphi^\dagger\Delta\Delta^\dagger\varphi)$	$\mathcal{O}^2_{\Delta D\varphi}$	$(D^\mu\varphi)^\dagger\Delta^\dagger\Delta D_\mu\varphi$
$\mathcal{O}_{\Delta\Box}$	$\mathrm{Tr}(\Delta^\dagger\Delta)\,\Box\,\mathrm{Tr}(\Delta^\dagger\Delta)$	$\mathcal{O}^2_{\Delta\varphi}$	$\mathrm{Tr}(\Delta^\dagger\Delta)^2\,(\varphi^\dagger\varphi)$	$\mathcal{O}^3_{\Delta D\varphi}$	$(\varphi^\dagger\overleftrightarrow{D}^{I\mu}\varphi)\mathrm{Tr}(\Delta^\dagger\overleftrightarrow{D}^I_\mu\Delta)$
$\mathcal{O}^1_{D\Delta}$	$\mathrm{Tr}(\Delta^\dagger D^\mu\Delta)^*\,\mathrm{Tr}\,(\Delta^\dagger D_\mu\Delta)$	$\mathcal{O}^3_{\Delta\varphi}$	$(\mathrm{Tr}\Delta^\dagger\Delta)^2\,(\varphi^\dagger\varphi)$	$\mathcal{O}^1_{\tilde{\varphi}\Delta}$	$(\varphi^\dagger\Delta\tilde{\varphi})\,(\varphi^\dagger\Delta\tilde{\varphi})$
$\mathcal{O}^2_{D\Delta}$	$\mathrm{Tr}[\Delta^\dagger\Delta\,\Box(\Delta^\dagger\Delta)]$	$\mathcal{O}^4_{\Delta\varphi}$	$\varphi^\dagger\Delta\Delta^\dagger\Delta\Delta^\dagger\varphi$	$\mathcal{O}^2_{\tilde{\varphi}\Delta}$	$(\tilde{\varphi}^\dagger\Delta\varphi)\,(\varphi^\dagger\Delta^\dagger\tilde{\varphi})$
$\Delta^2 X^2$		$\Delta^2\psi^2\varphi$		$\psi^2\Delta^2 D$	
$\mathcal{O}_{\Delta G}$	$\mathrm{Tr}(\Delta^\dagger\Delta)\,G^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}^{(1)}_{le\varphi}$	$\mathrm{Tr}(\Delta^\dagger\Delta)\,(\bar{l}_p e_r\varphi)$	$\mathcal{O}^{(1)}_{\Delta l}$	$\mathrm{Tr}(\Delta^\dagger i\overleftrightarrow{D}_\mu\Delta)\,(\bar{l}_p\gamma^\mu l_r)$
$\mathcal{O}_{\Delta\tilde{G}}$	$\mathrm{Tr}(\Delta^\dagger\Delta)\,\tilde{G}^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}^{(1)}_{qd\varphi}$	$\mathrm{Tr}(\Delta^\dagger\Delta)\,(\bar{q}_p d_r\varphi)$	$\mathcal{O}^{(3)}_{\Delta l}$	$\mathrm{Tr}(\Delta^\dagger i\overleftrightarrow{D}^I_\mu\Delta)\,(\bar{l}_p\tau^I\gamma^\mu l_r)$
$\mathcal{O}_{\Delta W}$	$\mathrm{Tr}(\Delta^\dagger\Delta)\,W^I_{\mu\nu}W^{I\mu\nu}$	$\mathcal{O}^{(1)}_{qu\varphi}$	$\mathrm{Tr}(\Delta^\dagger\Delta)\,(\bar{q}_p u_r\tilde{\varphi})$	$\mathcal{O}_{\Delta e}$	$\mathrm{Tr}(\Delta^\dagger i\overleftrightarrow{D}_\mu\Delta)\,(\bar{e}_p\gamma^\mu e_r)$
$\mathcal{O}_{\Delta\tilde{W}}$	$\mathrm{Tr}(\Delta^\dagger\Delta)\,\tilde{W}^I_{\mu\nu}W^{I\mu\nu}$	$\mathcal{O}^{(3)}_{le\varphi}$	$\bar{l}_p\Delta\Delta^\dagger e_r\varphi$	$\mathcal{O}^{(1)}_{\Delta q}$	$\mathrm{Tr}(\Delta^\dagger i\overleftrightarrow{D}_\mu\Delta)\,(\bar{q}_p\gamma^\mu q_r)$
$\mathcal{O}_{\Delta B}$	$\mathrm{Tr}(\Delta^\dagger\Delta)\,B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}^{(3)}_{qd\varphi}$	$\bar{q}_p\Delta\Delta^\dagger d_r\varphi$	$\mathcal{O}^{(3)}_{\Delta q}$	$\mathrm{Tr}(\Delta^\dagger i\overleftrightarrow{D}^I_\mu\Delta)\,(\bar{q}_p\tau^I\gamma^\mu q_r)$
$\mathcal{O}_{\Delta\tilde{B}}$	$\mathrm{Tr}(\Delta^\dagger\Delta)\,\tilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}^{(3)}_{qu\varphi}$	$\bar{q}_p\Delta\Delta^\dagger u_r\tilde{\varphi}$	$\mathcal{O}_{\Delta u}$	$\mathrm{Tr}(\Delta^\dagger i\overleftrightarrow{D}_\mu\Delta)\,(\bar{u}_p\gamma^\mu u_r)$
$\mathcal{O}_{\Delta WB}$	$\mathrm{Tr}(\Delta^\dagger\tau^I\Delta)\,W^I_{\mu\nu}B^{\mu\nu}$			$\mathcal{O}_{\Delta d}$	$\mathrm{Tr}(\Delta^\dagger i\overleftrightarrow{D}_\mu\Delta)\,(\bar{d}_p\gamma^\mu d_r)$
$\mathcal{O}_{\Delta\tilde{W}B}$	$\mathrm{Tr}(\Delta^\dagger\tau^I\Delta)\,\tilde{W}^I_{\mu\nu}B^{\mu\nu}$				
$\mathcal{O}_{\Delta WW}$	$\mathrm{Tr}(\Delta^\dagger\tau^I\Delta\tau^J)\,W^I_{\mu\nu}W^{J\mu\nu}$				
$\mathcal{O}_{\Delta\tilde{W}W}$	$\mathrm{Tr}(\Delta^\dagger\tau^I\Delta\tau^J)\,\tilde{W}^I_{\mu\nu}W^{J\mu\nu}$				

The Basis

- 7 Lepton number violating operators.
- These operators give contributions to lepton flavour violating processes, such as $\mu \to 3e$
- In total 57 new operators, 226 real parameters 179 complex phases = 405 number of parameters.

L-Violating	
$\mathcal{O}_{\Delta l}^{(1)}$	$\text{Tr}(\Delta^\dagger \Delta)\ (\bar{l}_p^c i\sigma^2 \Delta l_r)$
$\mathcal{O}_{\Delta l}^{(3)}$	$(\bar{l}_p^c i\sigma^2 \Delta\Delta^\dagger \Delta l_r)$
$\mathcal{O}_{\Delta\varphi l}^{1}$	$(\varphi^\dagger \varphi)\ (\bar{l}_p^c i\sigma^2 \Delta l_r)$
$\mathcal{O}_{\Delta\varphi l}^{2}$	$(l_p^T i\sigma^2 \varphi)\ C\ (\varphi^\dagger \Delta l_r)$
$\mathcal{O}_{l\Delta D}$	$\bar{l}_r^c i\sigma^2 \gamma^\mu e_r \Delta D_\mu \varphi$
$\mathcal{O}_{\Delta lB}$	$(\bar{l}_r^c i\sigma^2 \sigma^{\mu\nu} \Delta l_p)\ B_{\mu\nu}$
$\mathcal{O}_{\Delta lW}$	$(\bar{l}_r^c i\sigma^2 \sigma^{\mu\nu} \Delta \tau^I l_p)\ W_{\mu\nu}^I$

So, how can we constrain all these parameters?

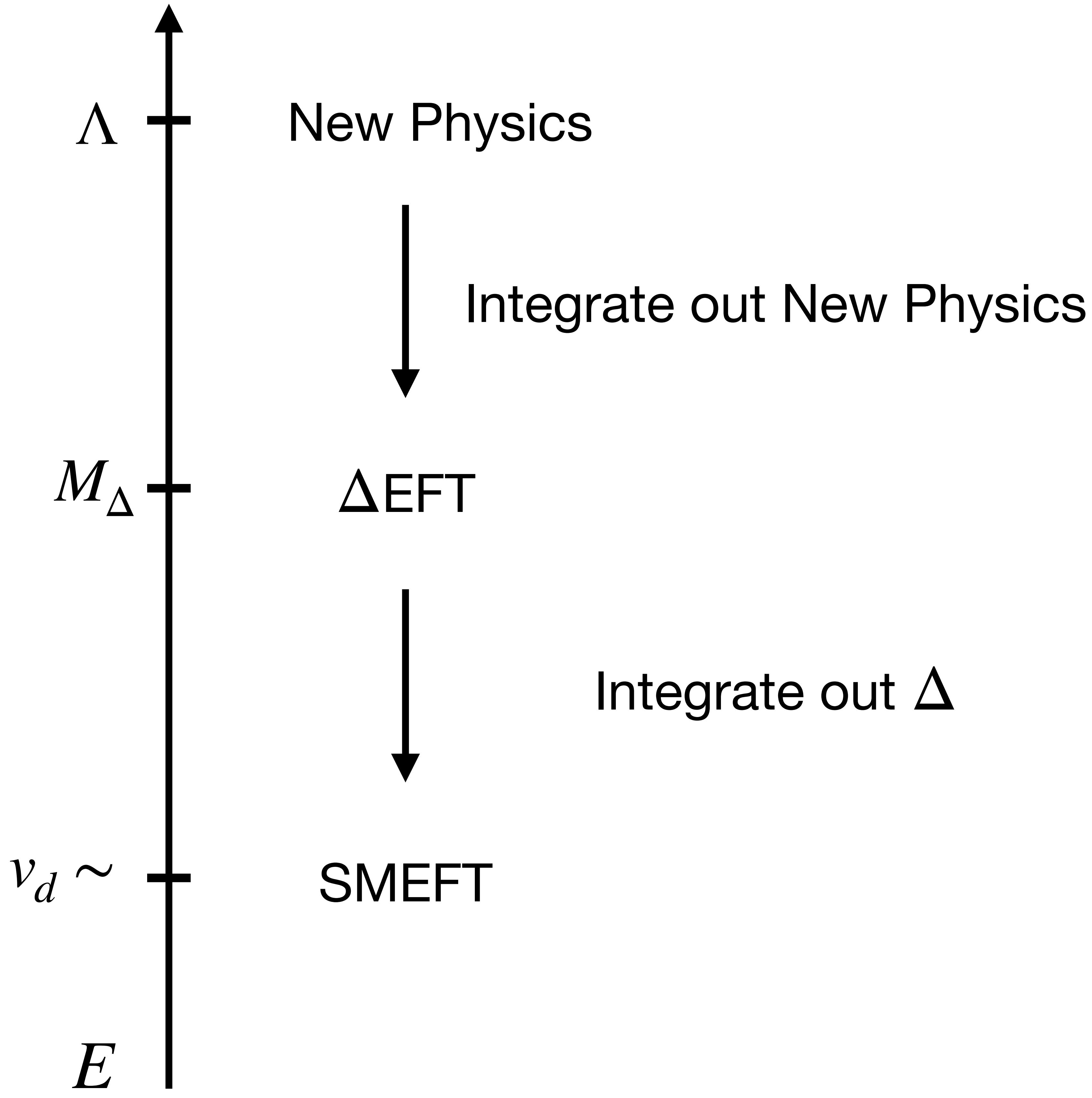
- The triplet has not been observed → integrate out the triplet
- EWPO are modified by this basis → Constraints from LEP
- $H^{\pm\pm}$ has a signature of 2 same-charge leptons → LHC searches

Summary

- The type-2 seesaw mechanism introduces a complex triplet. After SSB a Majorana neutrino mass-term is produced: $\frac{1}{2}m^{\nu}_{ab}\overline{\nu}^{c}_{a}\nu_{b}$ with $m^{\nu}_{ab} = \sqrt{2}f_{ab}v_{t} \sim 0.1$eV
- The vev is naturally small if the mass of the triplet is large: $v_t \simeq \frac{\mu v_d^2}{\sqrt{2}M^2}$
- f_{ab} is also the coupling of the decay $H^{++} \to l^+l^+$ lower vev stronger coupling.
- The type-2 seesaw mechanism at a "natural" mass scale, would (naively) imply a hierarchy problem of the Higgs. Other questions of the SM remain open.
- This motivates the extension of the type-2 seesaw mechanism with higher dimensional operators induced by some new physics at a scale $\Lambda \gg M_{\Delta}$
- This basis includes a large amount of new operators, including an enlarged scalar sector difficult to probe, new operators that affect EWPO and direct couplings of the triplet field to quarks, which does not happen at dimension 4.

Phenomenology

Below the mass scale



- The ΔEFT is defined at energies above the mass of the triplet. If we assume we work at energies below that mass we can also integrate the triplet.
- In the process of integrating out include dimension 5 operators.
- Then, work with SMEFT:
  - Only observed fields.
  - Large amounts of data available.
  - Many of the SMEFT contributions to observables already computed.
  - Matching has already been done at tree level: arXiv:1711.10391

The Matching

- We obtain 9 operators of the Warsaw basis.
- Not all operators are well constrained
- Typically Weinberg operator is not included due to LFV.

$$\mathcal{O}_5 = (\tilde{\varphi}^\dagger l_p^c)^T(\tilde{\varphi}^\dagger l_r)$$

$$\mathcal{O}_{\varphi\Box} = (\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi) \qquad \mathcal{O}_{ll} = (\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma_\mu l_t)$$

$$\mathcal{O}_{\varphi D} = (\varphi^\dagger D_\mu\varphi)^*(\varphi^\dagger D_\mu\varphi) \qquad \mathcal{O}_{u\varphi} = (\varphi^\dagger\varphi)(\bar{q}_p u_r\tilde{\varphi})$$

$$\lambda' = \left(\lambda - 4\frac{|\mu|^2}{M^2} + 8\frac{|\mu|^2 m_\varphi^2}{M^4}\right) \qquad (C_5)_{rp} = -\frac{\mu f_{rp}}{M^2} \qquad C_{\varphi D} = 2\frac{|\mu|^2}{M^4}$$

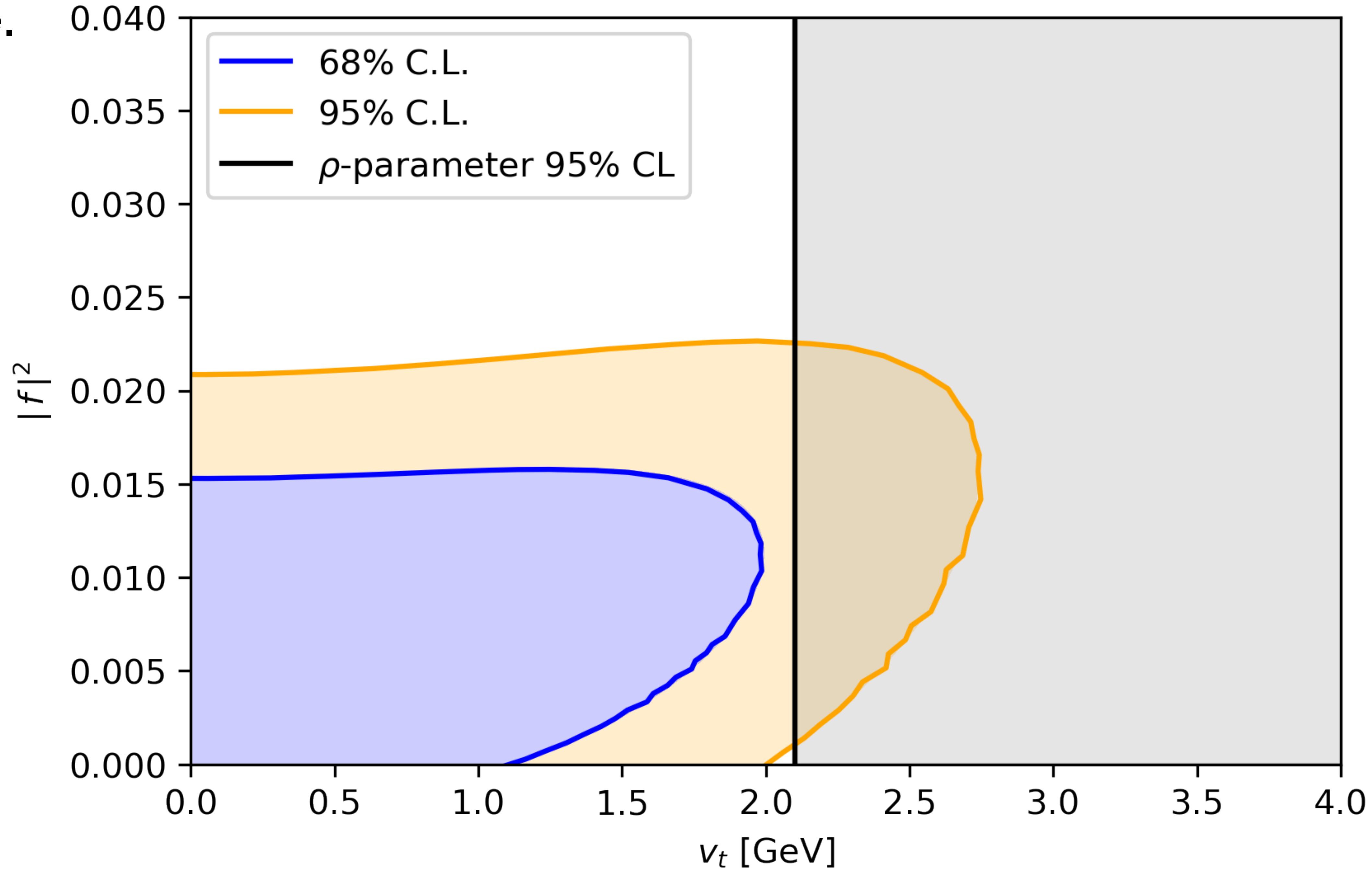
$$C_{\varphi\Box} = \frac{|\mu|^2}{M^4} \qquad C_\varphi = -\frac{|\mu|^2}{M^4}\left(\lambda_1 + \lambda_4 - \lambda\right) + \frac{2}{\Lambda}\frac{Re(\mu C_{\varphi^4\Delta})}{M^2} \qquad (C_{ll})_{rpst} = \frac{f_{rp}f_{st}^*}{2M^2}$$

$$(C_{e\varphi})_{rp} = \frac{|\mu|^2}{M^4}y_{rp}^{e*} + \frac{1}{\Lambda}\frac{\mu}{M^2}(C_{\Delta le})_{rp} \qquad (C_{d\varphi})_{rp} = \frac{|\mu|^2}{M^4}y_{rp}^{d*} + \frac{1}{\Lambda}\frac{\mu}{M^2}(C_{\Delta qd})_{rp} \qquad (C_{u\varphi})_{rp} = \frac{|\mu|^2}{M^4}y_{rp}^{u*} + \frac{1}{\Lambda}\frac{\mu^*}{M^2}(C_{\Delta qu})_{rp}^*$$

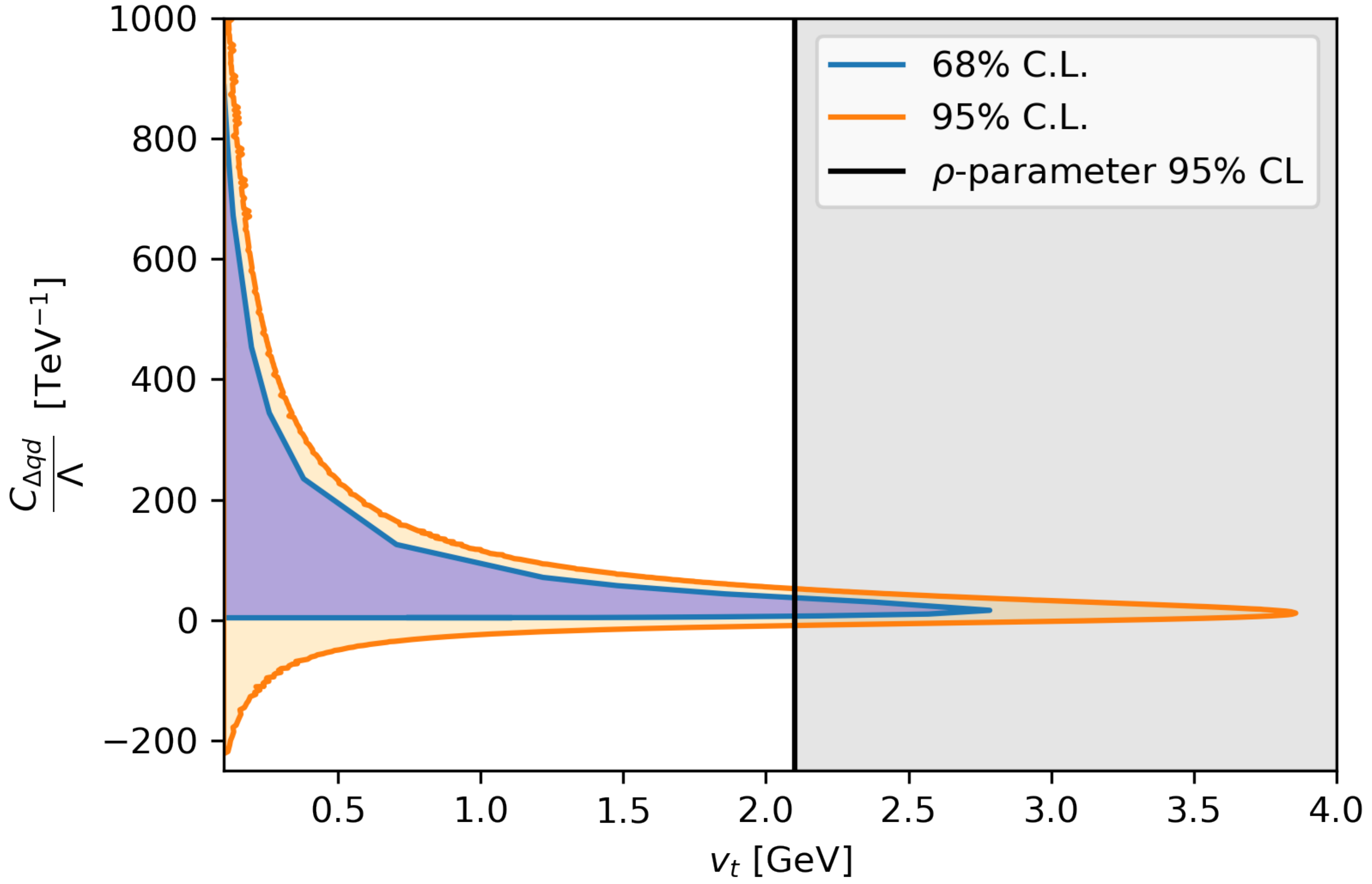
Constraints Below the Mass Scale

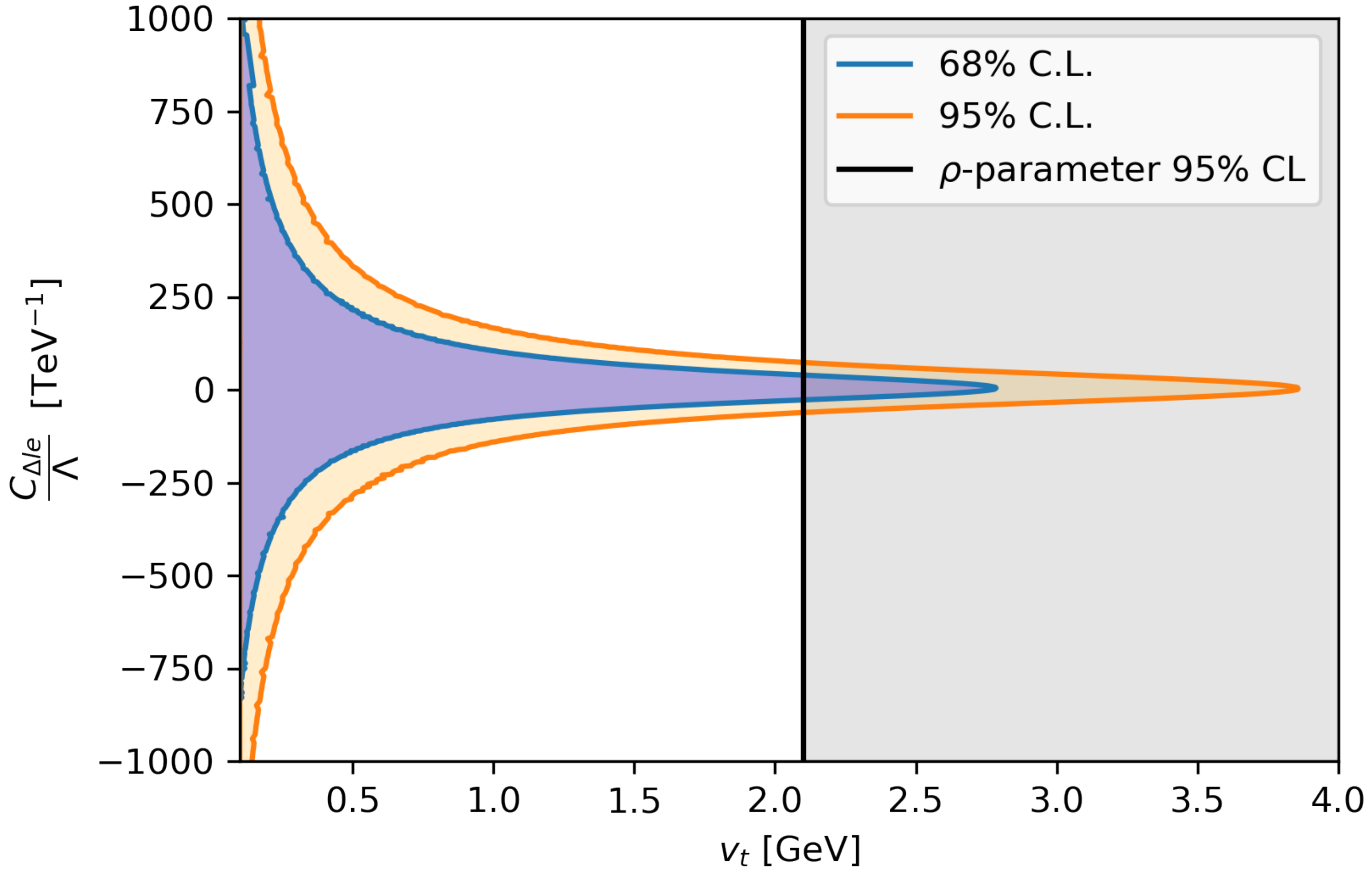
- Typically these analysis are made using χ^2 functions: $\chi^2 = (y - \mu(C))^T V^{-1}(y - \mu(C))$
- Some groups make available their χ^2 functions, for global analysis: J. Ellis, *et al.* arXiv:1803.03252
- Which includes: EWPO (most of them from LEP), LHC run 1 & 2 signal strengths…
- We can use $v_t \simeq \frac{\mu v_d^2}{\sqrt{2}M^2}$ and write the constraints in $v_t - C_i$ plane.

Using only dimension 4 operators →

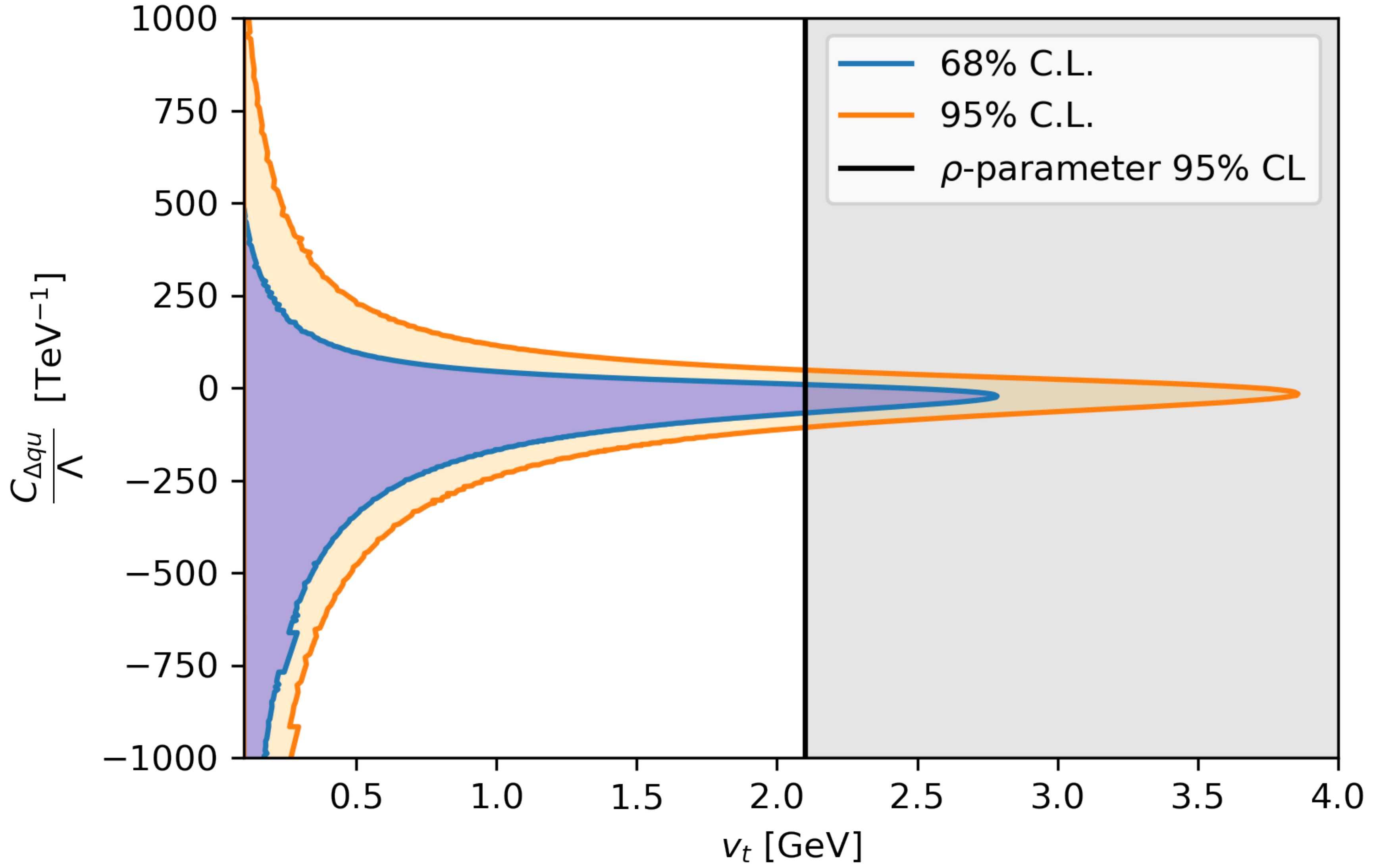


Constraints Below the Mass Scale





$$C_{d\varphi} \sim \frac{v_t}{\Lambda} C_{\Delta qd}$$



$$(\varphi^\dagger\varphi)(\bar{l}e\varphi)$$

- Higgs couplings to fermions are poorly constrained at LHC with current data.
- The vacuum expectation value of the triplet is constrained to small values, allowing for larger values of Wilson Coefficients.

Electroweak Precision Observables

- It is known in the SMEFT that dimension 6 operators modify Electroweak Observables.
- G_F is defined as a the 4-fermion vector - vector interaction:

$$\frac{4\hat{G}_F}{\sqrt{2}}(\bar{\nu}_\mu\gamma_\mu P_L\mu)(\bar{e}\gamma^\mu P_L\nu_e) \longrightarrow \hat{G}_F = \frac{1}{\sqrt{2}\bar{v}^2} - \frac{1}{\sqrt{2}}C_{ll} + \sqrt{2}C^{(3)}_{\varphi l}$$

- ΔEFT also contributes to these kind of observables. $\hat{G}_F = \frac{1}{\sqrt{2}\bar{v}^2} - \frac{1}{\sqrt{2}}C_{ll} + \sqrt{2}\left(C^{(3)}_{\varphi l} + \frac{v_t^2}{\bar{v}^2}C^{(3)}_{\Delta l}\right)$

- Other parameters that are modified: $g,\ g',\ \sin\theta_w,\ M_W,\ g^f_V,\ g^f_A,\ g^f_W$ with $f = \{u,\ d,\ e\}$
- Remark: One must always introduce three input parameters $\{G_F,\ M_Z,\ \alpha_{ew}\}$

Electroweak Precision Observables

Δ^6 and $\Delta^4 D^2$		$\Delta^4\varphi^2$ and $\Delta^2\varphi^4$		$\Delta^2\varphi^2 D^2$ and $\tilde{\varphi}^2\varphi^2\Delta^2$	
$\mathcal{O}^1_{\Delta}$	$[\mathrm{Tr}(\Delta^\dagger\Delta)]^3$	$\mathcal{O}^1_{\varphi\Delta}$	$\mathrm{Tr}(\Delta^\dagger\Delta)\,(\varphi^\dagger\varphi)^2$	$\mathcal{O}_{\Delta\Box\varphi}$	$\mathrm{Tr}(\Delta^\dagger\Delta)\,\Box\,(\varphi^\dagger\varphi)$
$\mathcal{O}^2_{\Delta}$	$\mathrm{Tr}(\Delta^\dagger\Delta)^2\,\mathrm{Tr}(\Delta^\dagger\Delta)$	$\mathcal{O}^2_{\varphi\Delta}$	$(\varphi^\dagger\Delta\Delta^\dagger\varphi)\,(\varphi^\dagger\varphi)$	$\mathcal{O}^1_{\Delta D\varphi}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)\mathrm{Tr}(\Delta^\dagger i\overleftrightarrow{D}^\mu\Delta)$
$\mathcal{O}^3_{\Delta}$	$\mathrm{Tr}\big(\Delta^\dagger\Delta\big)^3$	$\mathcal{O}^1_{\Delta\varphi}$	$\mathrm{Tr}(\Delta^\dagger\Delta)\,(\varphi^\dagger\Delta\Delta^\dagger\varphi)$	$\mathcal{O}^2_{\Delta D\varphi}$	$(D^\mu\varphi)^\dagger\Delta^\dagger\Delta D^\mu\varphi$
$\mathcal{O}_{\Delta\Box}$	$\mathrm{Tr}(\Delta^\dagger\Delta)\,\Box\,\mathrm{Tr}(\Delta^\dagger\Delta)$	$\mathcal{O}^2_{\Delta\varphi}$	$\mathrm{Tr}(\Delta^\dagger\Delta)^2\,(\varphi^\dagger\varphi)$	$\mathcal{O}^3_{\Delta D\varphi}$	$(\varphi^\dagger\overleftrightarrow{D}^{I\mu}\varphi)\mathrm{Tr}(\Delta^\dagger\overleftrightarrow{D}^I_\mu\Delta)$
$\mathcal{O}^1_{D\Delta}$	$\mathrm{Tr}(\Delta^\dagger D^\mu\Delta)^*\,\mathrm{Tr}\,(\Delta^\dagger D_\mu\Delta)$	$\mathcal{O}^3_{\Delta\varphi}$	$(\mathrm{Tr}\Delta^\dagger\Delta)^2\,(\varphi^\dagger\varphi)$	$\mathcal{O}^1_{\tilde{\varphi}\Delta}$	$(\varphi^\dagger\Delta\varphi)\,(\varphi^\dagger\Delta\varphi)$
$\mathcal{O}^2_{D\Delta}$	$\mathrm{Tr}[\Delta^\dagger\Delta\,\Box(\Delta^\dagger\Delta)]$	$\mathcal{O}^4_{\Delta\varphi}$	$\varphi^\dagger\Delta\Delta^\dagger\Delta\Delta^\dagger\varphi$	$\mathcal{O}^2_{\tilde{\varphi}\Delta}$	$(\tilde{\varphi}^\dagger\Delta\varphi)\,(\varphi^\dagger\Delta^\dagger\tilde{\varphi})$
$\Delta^2 X^2$		$\Delta^2\psi^2\varphi$		$\psi^2\Delta^2 D$	
$\mathcal{O}_{\Delta G}$	$\mathrm{Tr}(\Delta^\dagger\Delta)\,G^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}^{(1)}_{le\varphi}$	$\mathrm{Tr}(\Delta^\dagger\Delta)\,(\bar{l}_p e_r\varphi)$	$\mathcal{O}^{(1)}_{\Delta l}$	$\mathrm{Tr}(\Delta^\dagger i\overleftrightarrow{D}_\mu\Delta)\,(\bar{l}_p\gamma^\mu l_r)$
$\mathcal{O}_{\Delta\tilde{G}}$	$\mathrm{Tr}(\Delta^\dagger\Delta)\,\tilde{G}^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}^{(1)}_{qd\varphi}$	$\mathrm{Tr}(\Delta^\dagger\Delta)\,(\bar{q}_p d_r\varphi)$	$\mathcal{O}^{(3)}_{\Delta l}$	$\mathrm{Tr}(\Delta^\dagger i\overleftrightarrow{D}^I_\mu\Delta)\,(\bar{l}_p\tau^I\gamma^\mu l_r)$
$\mathcal{O}_{\Delta W}$	$\mathrm{Tr}(\Delta^\dagger\Delta)\,W^I_{\mu\nu}W^{I\mu\nu}$	$\mathcal{O}^{(1)}_{qu\varphi}$	$\mathrm{Tr}(\Delta^\dagger\Delta)\,(\bar{q}_p u_r\tilde{\varphi})$	$\mathcal{O}_{\Delta e}$	$\mathrm{Tr}(\Delta^\dagger i\overleftrightarrow{D}_\mu\Delta)\,(\bar{e}_p\gamma^\mu e_r)$
$\mathcal{O}_{\Delta\tilde{W}}$	$\mathrm{Tr}(\Delta^\dagger\Delta)\,\tilde{W}^I_{\mu\nu}W^{I\mu\nu}$	$\mathcal{O}^{(3)}_{le\varphi}$	$\bar{l}_p\Delta\Delta^\dagger e_r\varphi$	$\mathcal{O}^{(1)}_{\Delta q}$	$\mathrm{Tr}(\Delta^\dagger i\overleftrightarrow{D}_\mu\Delta)\,(\bar{q}_p\gamma^\mu q_r)$
$\mathcal{O}_{\Delta B}$	$\mathrm{Tr}(\Delta^\dagger\Delta)\,B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}^{(3)}_{qd\varphi}$	$\bar{q}_p\Delta\Delta^\dagger d_r\varphi$	$\mathcal{O}^{(3)}_{\Delta q}$	$\mathrm{Tr}(\Delta^\dagger i\overleftrightarrow{D}^I_\mu\Delta)\,(\bar{q}_p\tau^I\gamma^\mu q_r)$
$\mathcal{O}_{\Delta\tilde{B}}$	$\mathrm{Tr}(\Delta^\dagger\Delta)\,\tilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}^{(3)}_{qu\varphi}$	$\bar{q}_p\Delta\Delta^\dagger u_r\tilde{\varphi}$	$\mathcal{O}_{\Delta u}$	$\mathrm{Tr}(\Delta^\dagger i\overleftrightarrow{D}_\mu\Delta)\,(\bar{u}_p\gamma^\mu u_r)$
$\mathcal{O}_{\Delta WB}$	$\mathrm{Tr}(\Delta^\dagger\tau^I\Delta)\,W^I_{\mu\nu}B^{\mu\nu}$			$\mathcal{O}_{\Delta d}$	$\mathrm{Tr}(\Delta^\dagger i\overleftrightarrow{D}_\mu\Delta)\,(\bar{d}_p\gamma^\mu d_r)$
$\mathcal{O}_{\Delta\tilde{W}B}$	$\mathrm{Tr}(\Delta^\dagger\tau^I\Delta)\,\tilde{W}^I_{\mu\nu}B^{\mu\nu}$				
$\mathcal{O}_{\Delta WW}$	$\mathrm{Tr}(\Delta^\dagger\tau^I\Delta\tau^J)\,W^I_{\mu\nu}W^{J\mu\nu}$				
$\mathcal{O}_{\Delta\tilde{W}W}$	$\mathrm{Tr}(\Delta^\dagger\tau^I\Delta\tau^J)\,\tilde{W}^I_{\mu\nu}W^{J\mu\nu}$				

Contributions to the mass of the gauge bosons

$$C'_{D\Delta} \equiv \frac{1}{2}C^1_{\Delta D} + 4\left(C^2_{\Delta D} + C^3_{\Delta D}\right)$$

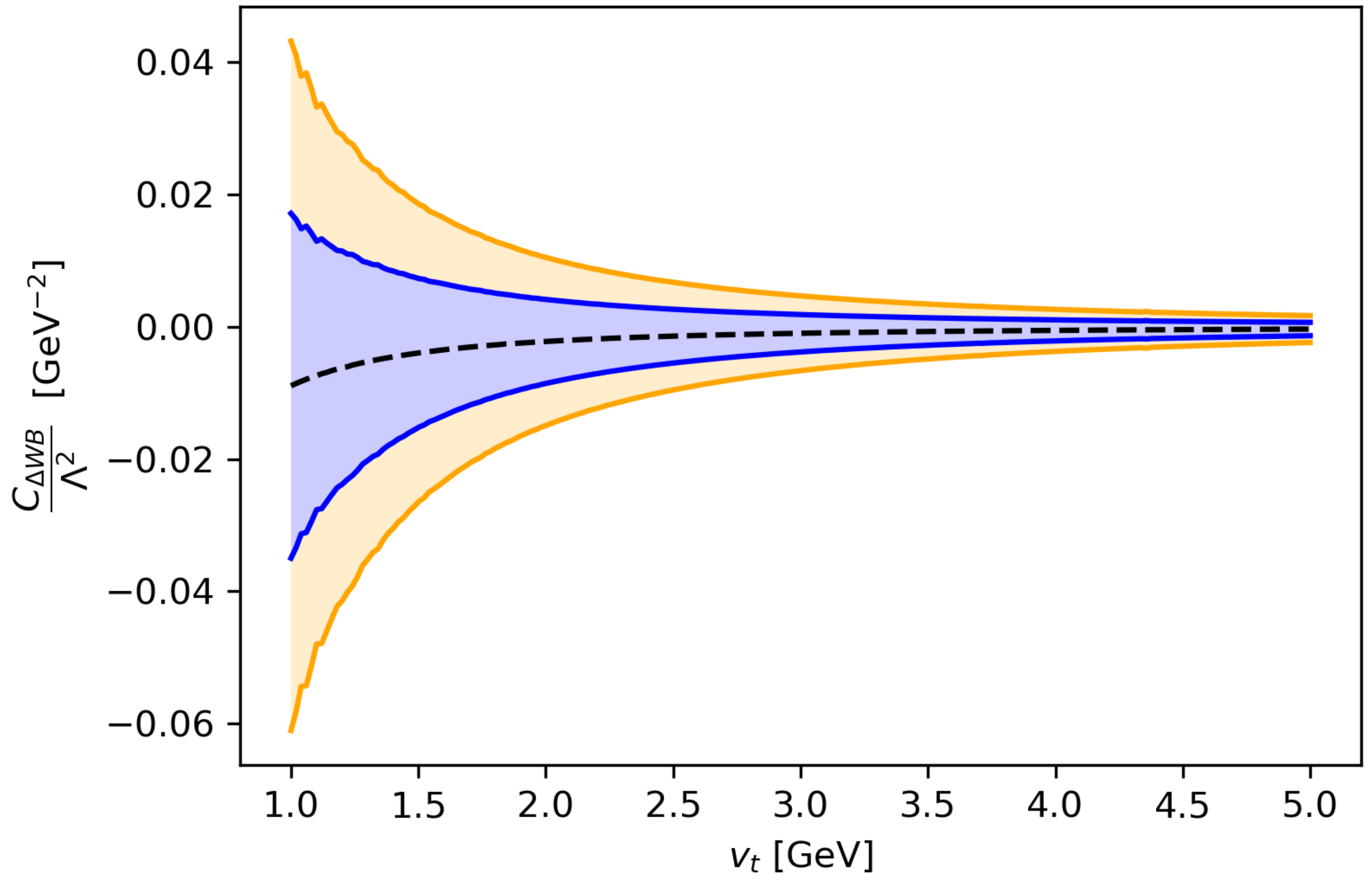
Modified Z and W boson couplings

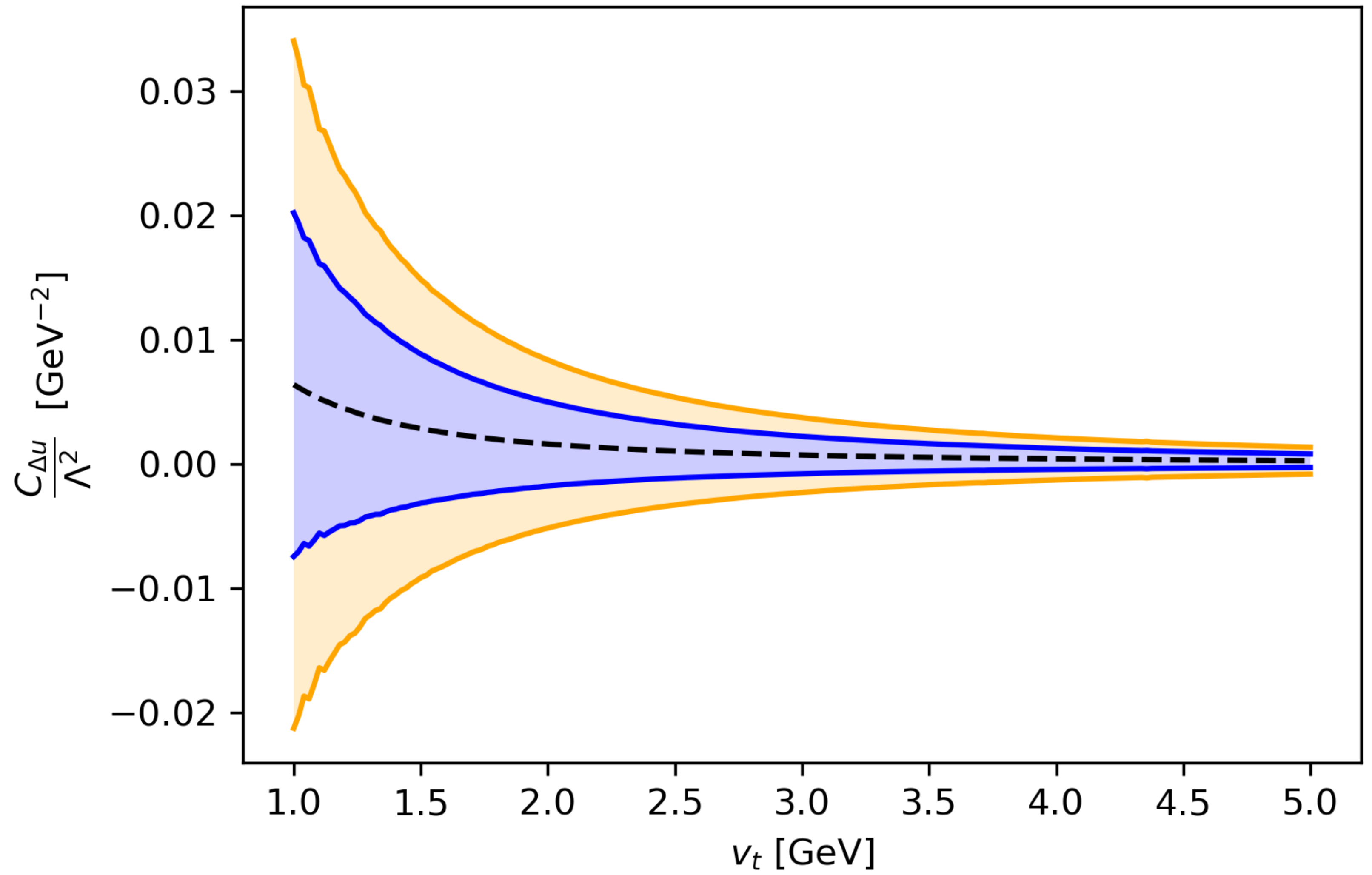
$$\sim C_{\Delta\psi} v_t^2 Z_\mu \bar{\psi}\gamma^\mu\psi$$

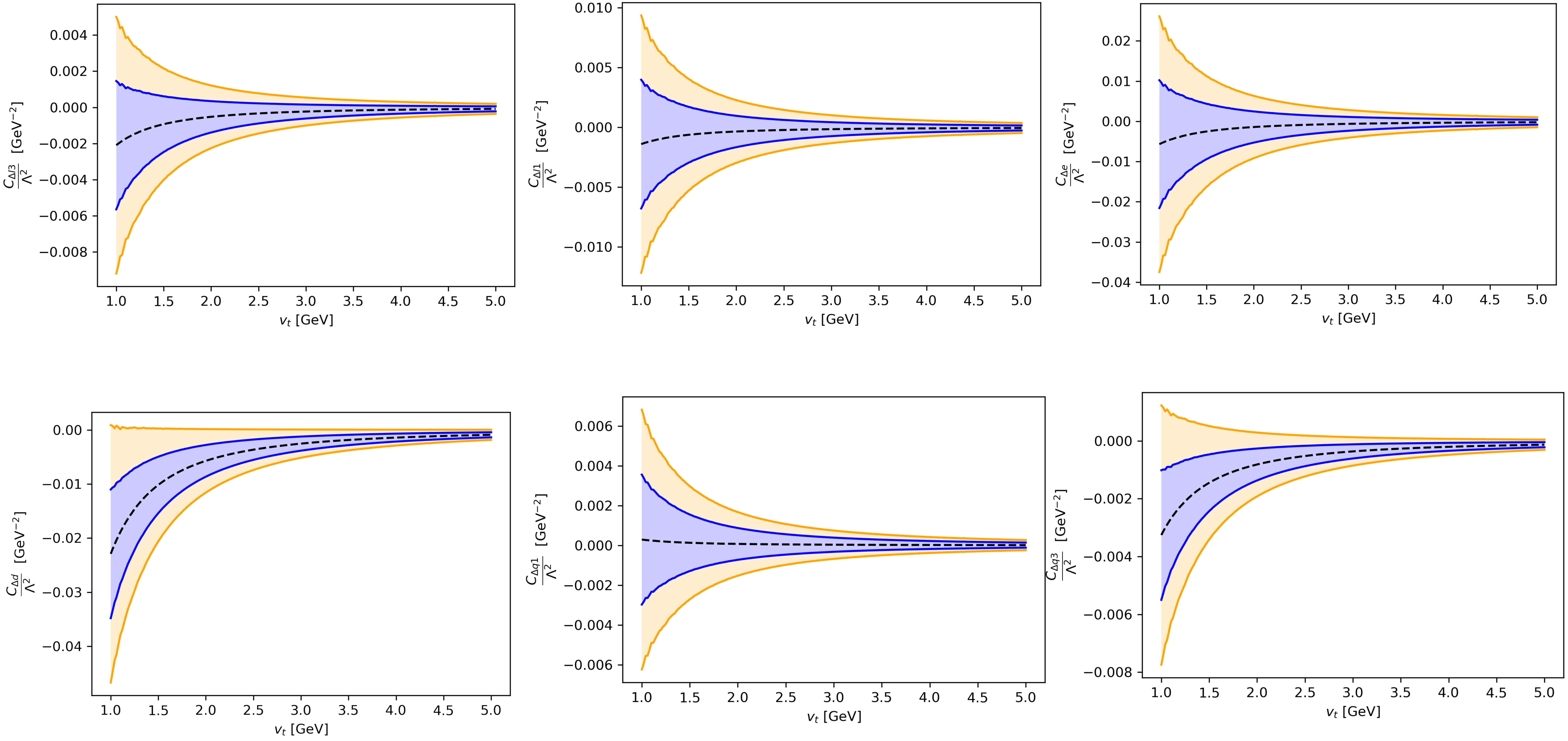
This adds another mixing term between gauge bosons, modifies $\sin\theta_w$

Electroweak Precision Observables

Observable	Measurement	SM prediction
Γ_Z [GeV]	2.4952 ± 0.0023	2.4943 ± 0.0005
σ^0_{had} [nb]	41.540 ± 0.037	41.488 ± 0.006
R^0_l	20.767 ± 0.025	20.752 ± 0.005
$A^{0,l}_{FB}$	0.0171 ± 0.0010	0.0171 ± 0.00009
A_l (P_τ)	0.1465 ± 0.0033	0.1470 ± 0.0004
A_l (SLD)	0.1513 ± 0.0021	0.1470 ± 0.0004
R^0_b	0.21629 ± 0.00066	0.2158 ± 0.00015
R^0_c	0.1721 ± 0.0030	0.17223 ± 0.00005
$A^{0,b}_{FB}$	0.0992 ± 0.0016	0.1031 ± 0.0003
$A^{0,c}_{FB}$	0.0707 ± 0.0035	0.0736 ± 0.0002
A_b	0.923 ± 0.020	0.9347
A_c	0.670 ± 0.027	0.6678 ± 0.0002
M_W [GeV]	80.387 ± 0.016	80.361 ± 0.006
M_W [GeV]	80.370 ± 0.016	80.361 ± 0.006
Γ_W [GeV]	2.085 ± 0.042	2.0896 ± 0.0008
$BR(W \to l\nu)$	0.1086 ± 0.0009	0.10832 ± 0.00005
$BR(W \to$ hadrons$)$	0.6741 ± 0.0027	0.6752 ± 0.0004






$\frac{C_{\Delta l3}}{\Lambda^2}$ [GeV^{-2}]
0.004
0.002
0.000
−0.002
−0.004
−0.006
−0.008
v_t [GeV]
$\frac{C_{\Delta l1}}{\Lambda^2}$ [GeV^{-2}]
0.010
0.005
0.000
−0.005
−0.010
v_t [GeV]
$\frac{C_{\Delta e}}{\Lambda^2}$ [GeV^{-2}]
0.02
0.01
0.00
−0.01
−0.02
−0.03
−0.04
v_t [GeV]
$\frac{C_{\Delta d}}{\Lambda^2}$ [GeV^{-2}]
0.00
−0.01
−0.02
−0.03
−0.04
v_t [GeV]
$\frac{C_{\Delta q1}}{\Lambda^2}$ [GeV^{-2}]
0.006
0.004
0.002
0.000
−0.002
−0.004
−0.006
v_t [GeV]
$\frac{C_{\Delta q3}}{\Lambda^2}$ [GeV^{-2}]
0.000
−0.002
−0.004
−0.006
−0.008
v_t [GeV]
1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0

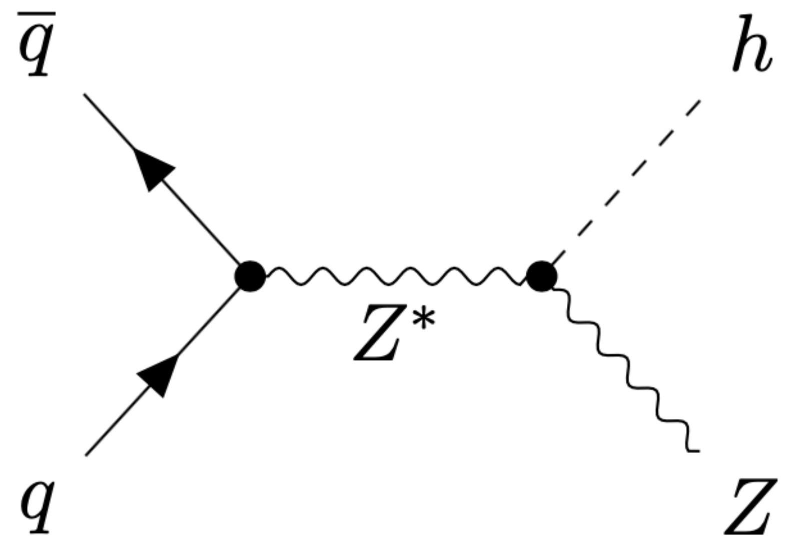
Electroweak Precision Observables

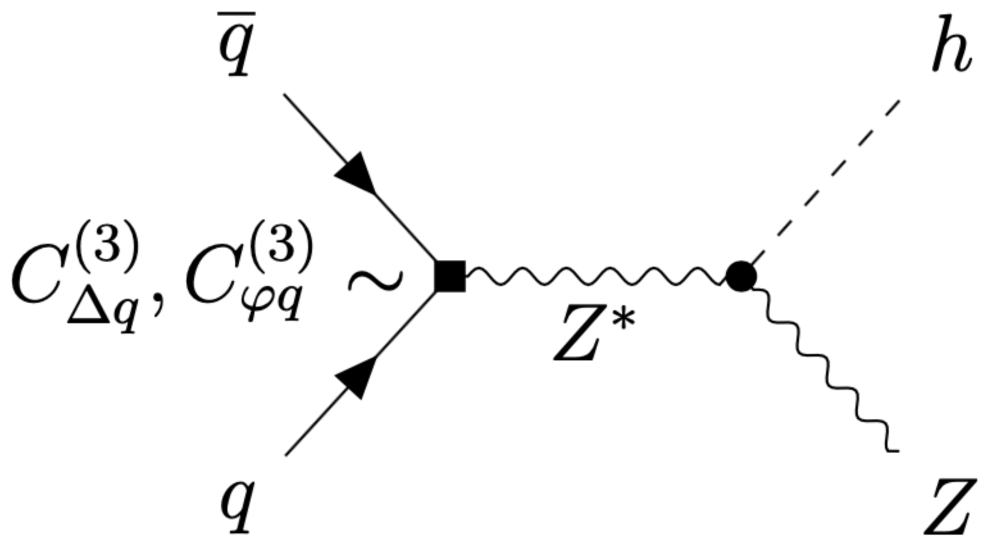
- SMEFT Couplings should also be taken into account.

- Always same combination of parameters, cannot be distinguished by only EW precision data.

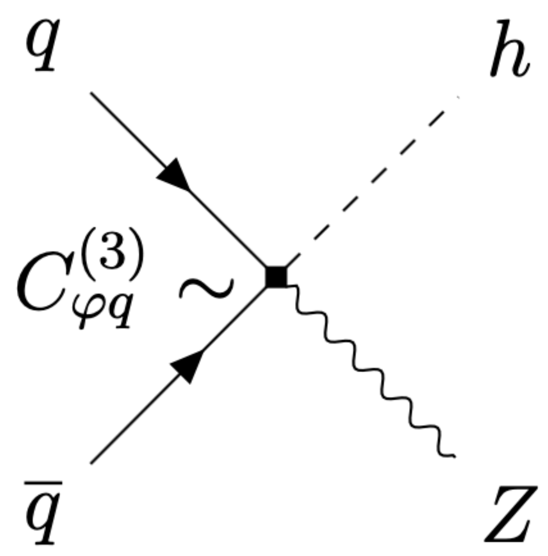
$$\delta g_V^u = \delta g_Z\, g_V^{u,SM} + \frac{v_t^2}{2}\left(C_{\Delta q}^{(3)} - C_{\Delta q}^{(1)} - C_{\Delta u}\right) + \frac{v_d^2}{4}\left(C_{\varphi q}^{(3)} - C_{\varphi q}^{(1)} - C_{\varphi u}\right) - \frac{2}{3}\delta s_{\hat{\theta}}^2$$

- Introduce orthogonal measurements with a different combination of the operators.

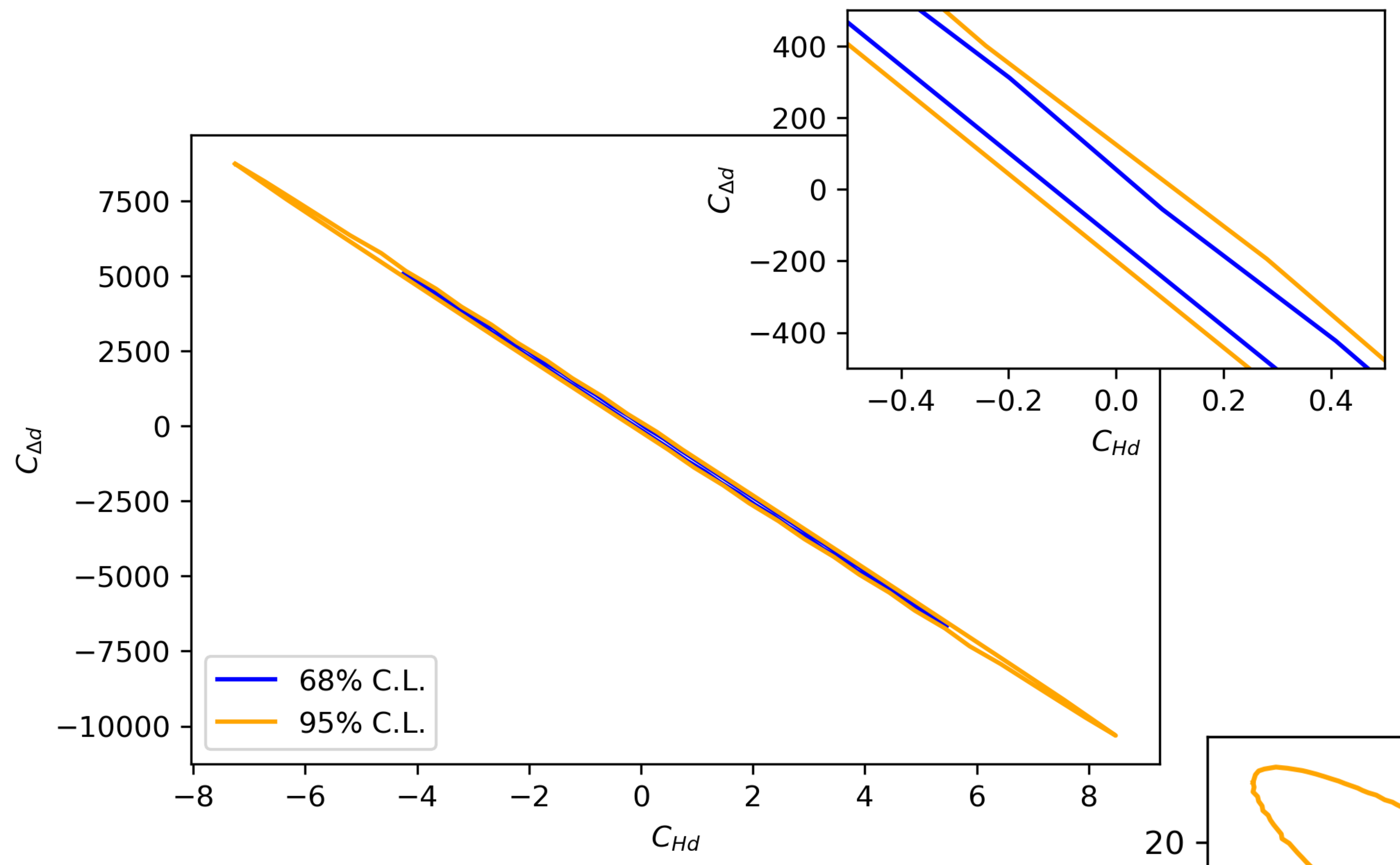


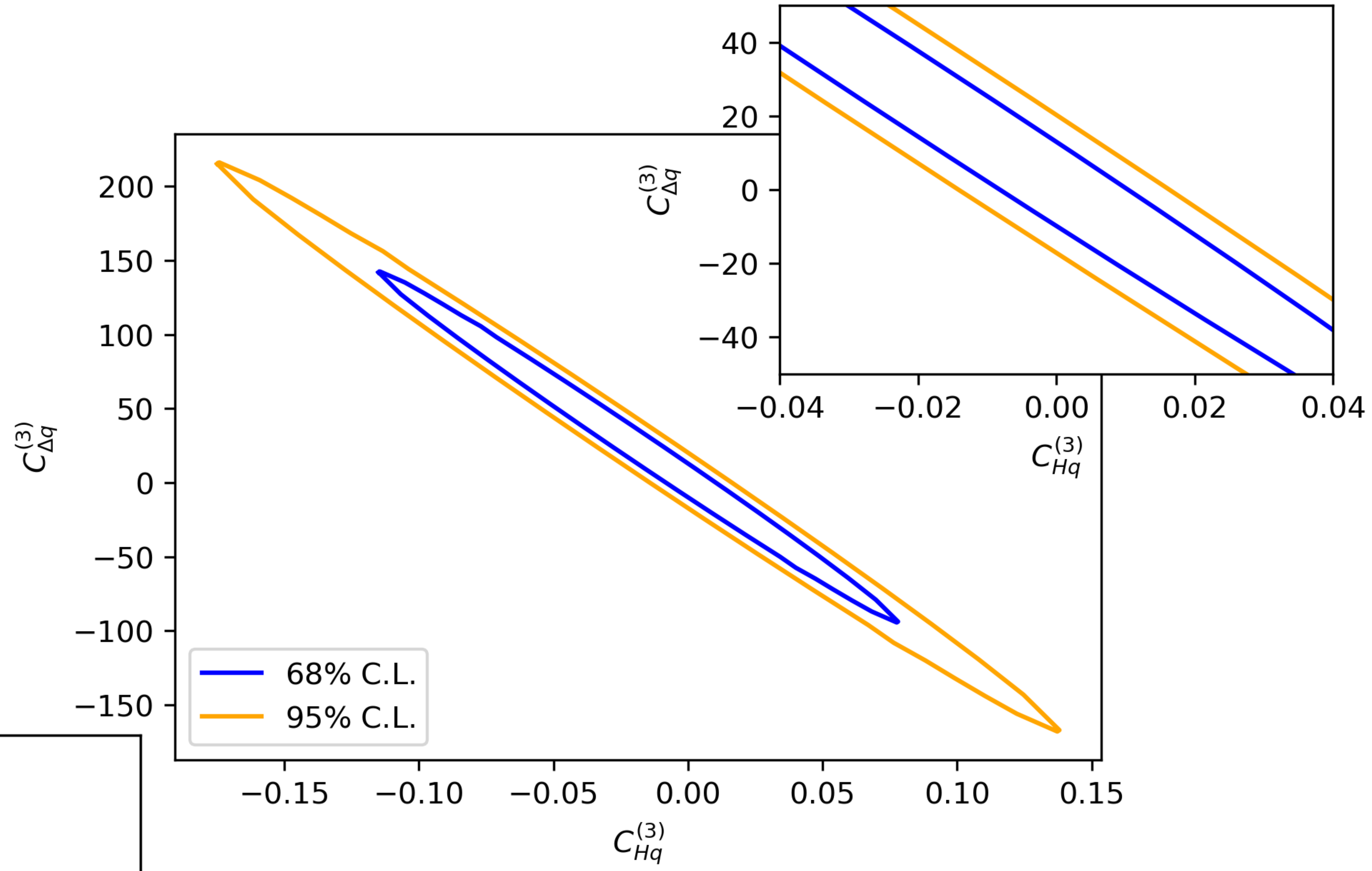


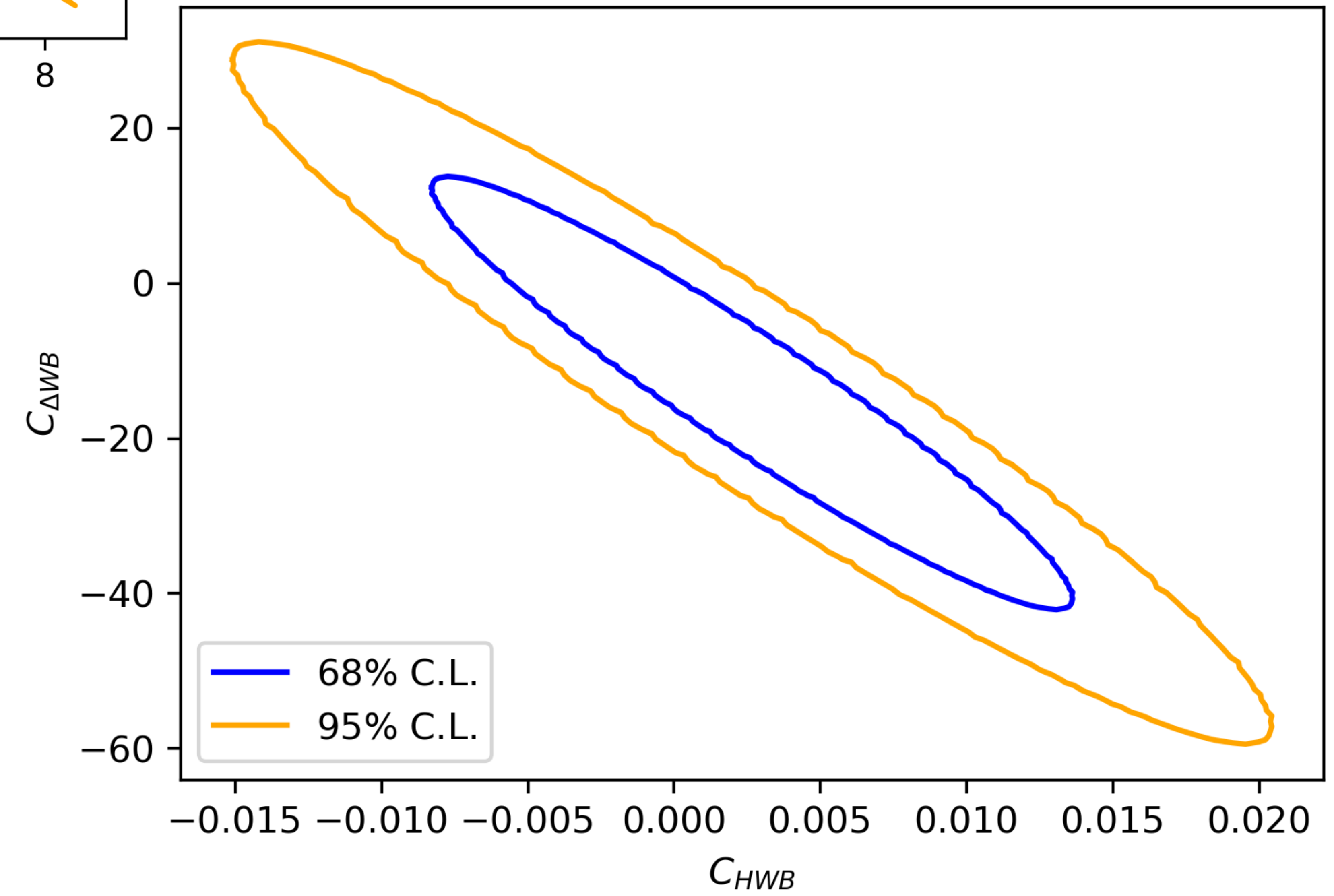
$$\mathcal{O}_{\varphi q}^{(3)} = (\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}\tau^I \gamma^\mu q)$$



Electroweak Precision Observables

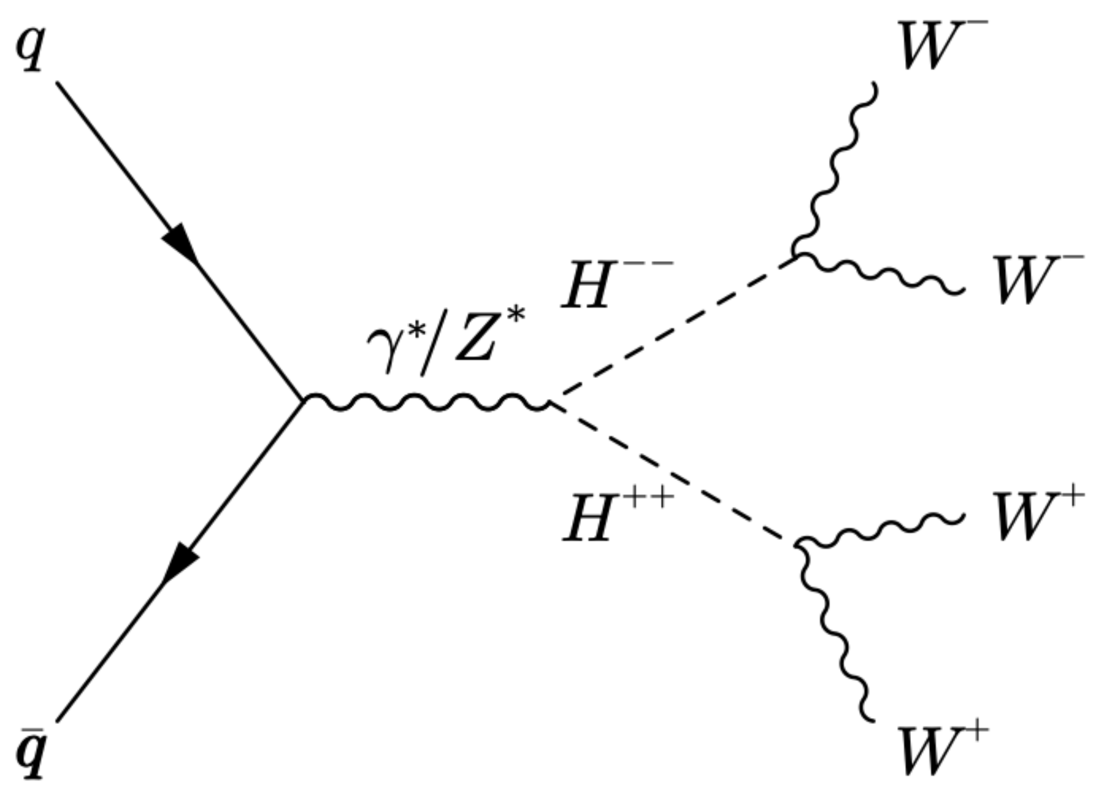


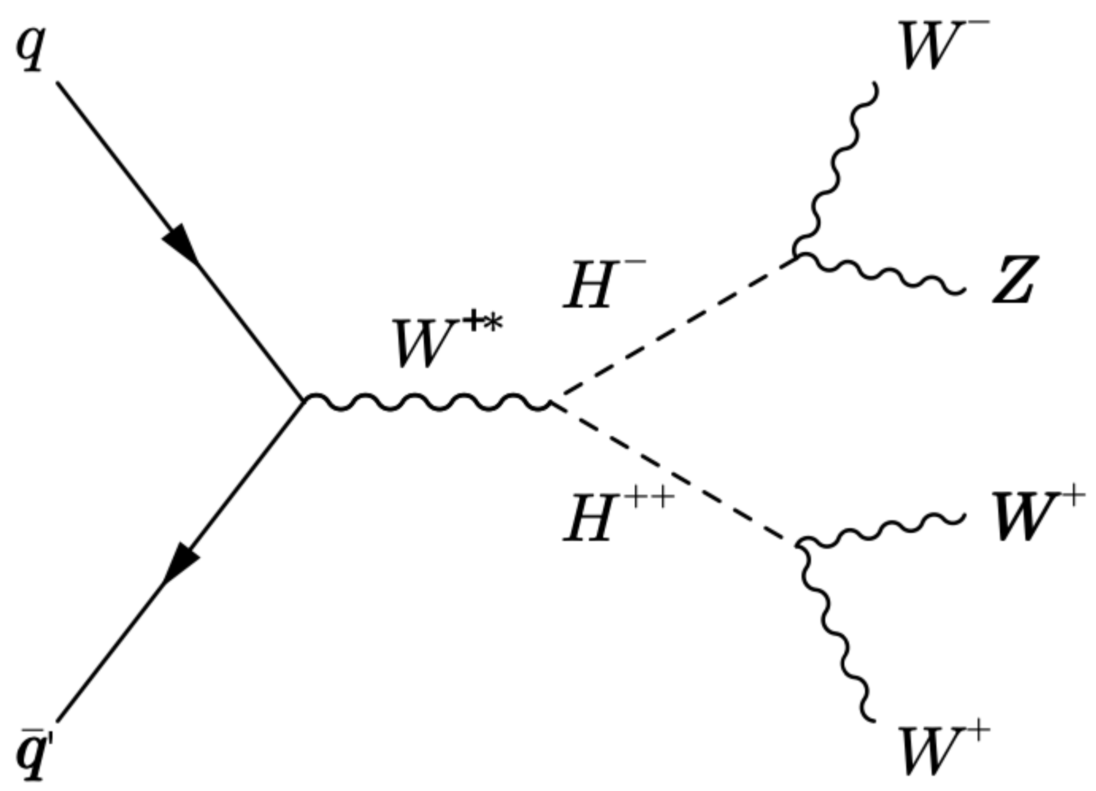


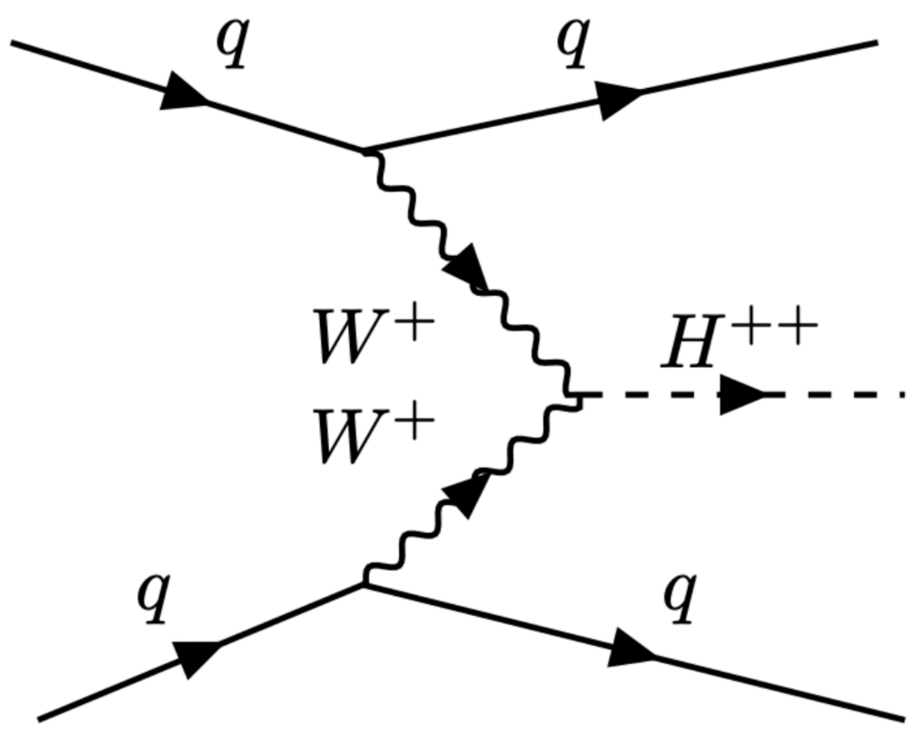


Phenomenology at LHC

- Type-2 Seesaw mechanism is typically searched in colliders by observing the decaying signature of $H^{++} \to l^+\ l^+,\ W^+\ W^+$
- However there are only a couple of ways to produce them at LHC:

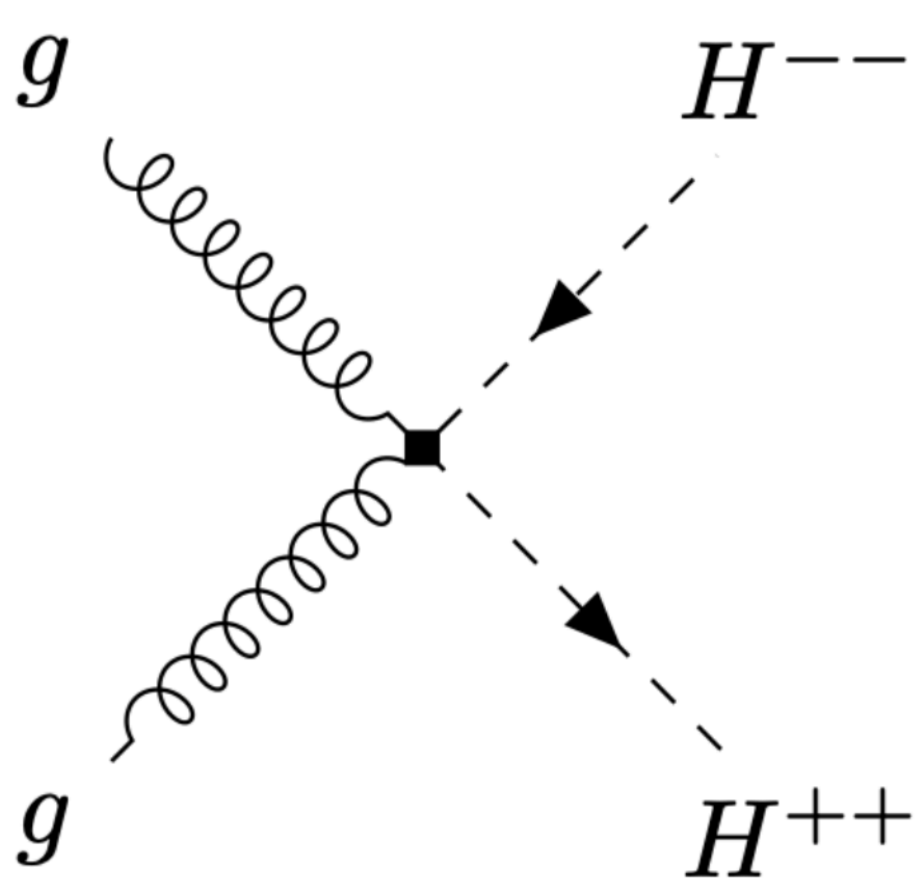


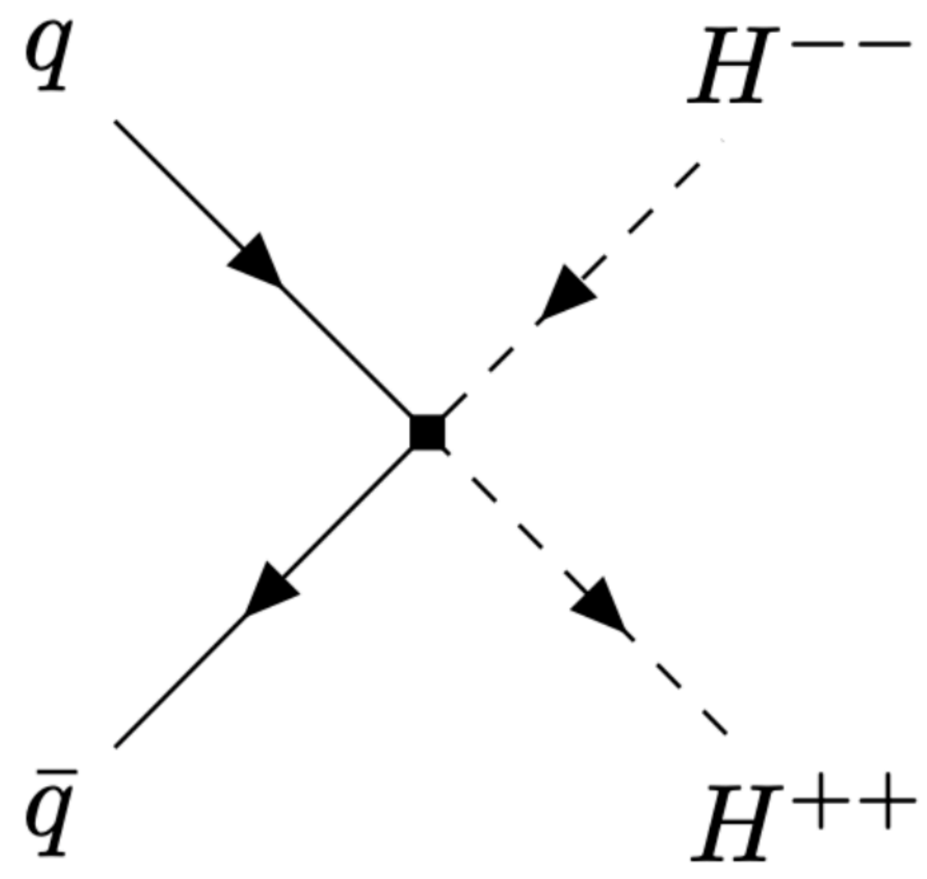


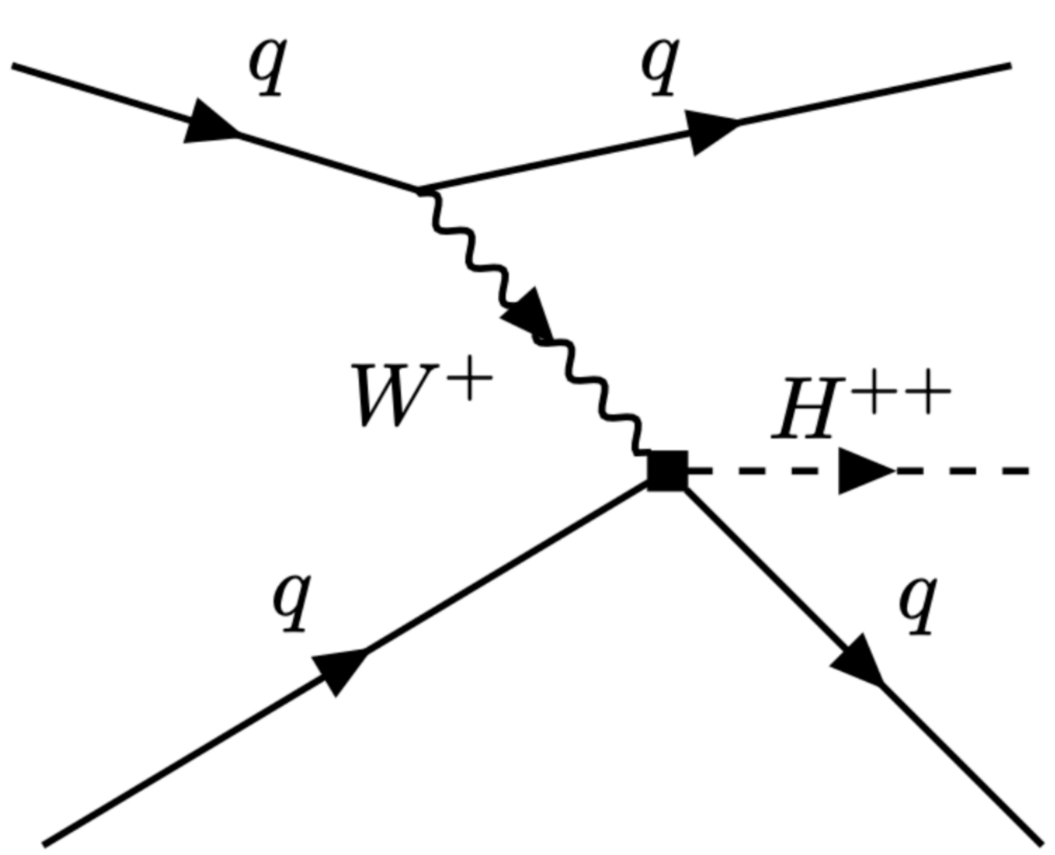


Phenomenology at LHC

- Now with this basis more production channels are added:
- Direct couplings to quarks and gluons.







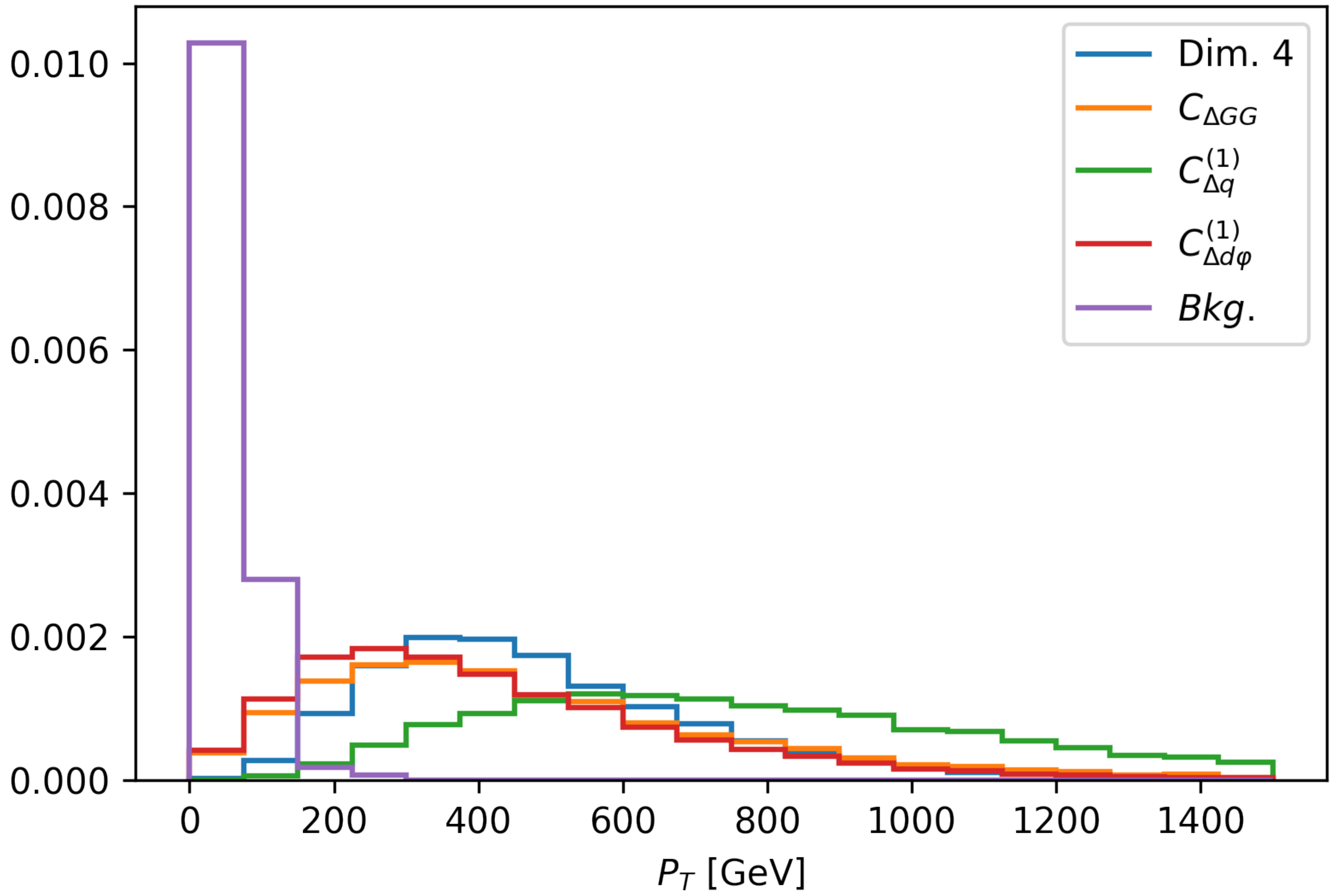
Phenomenology at LHC

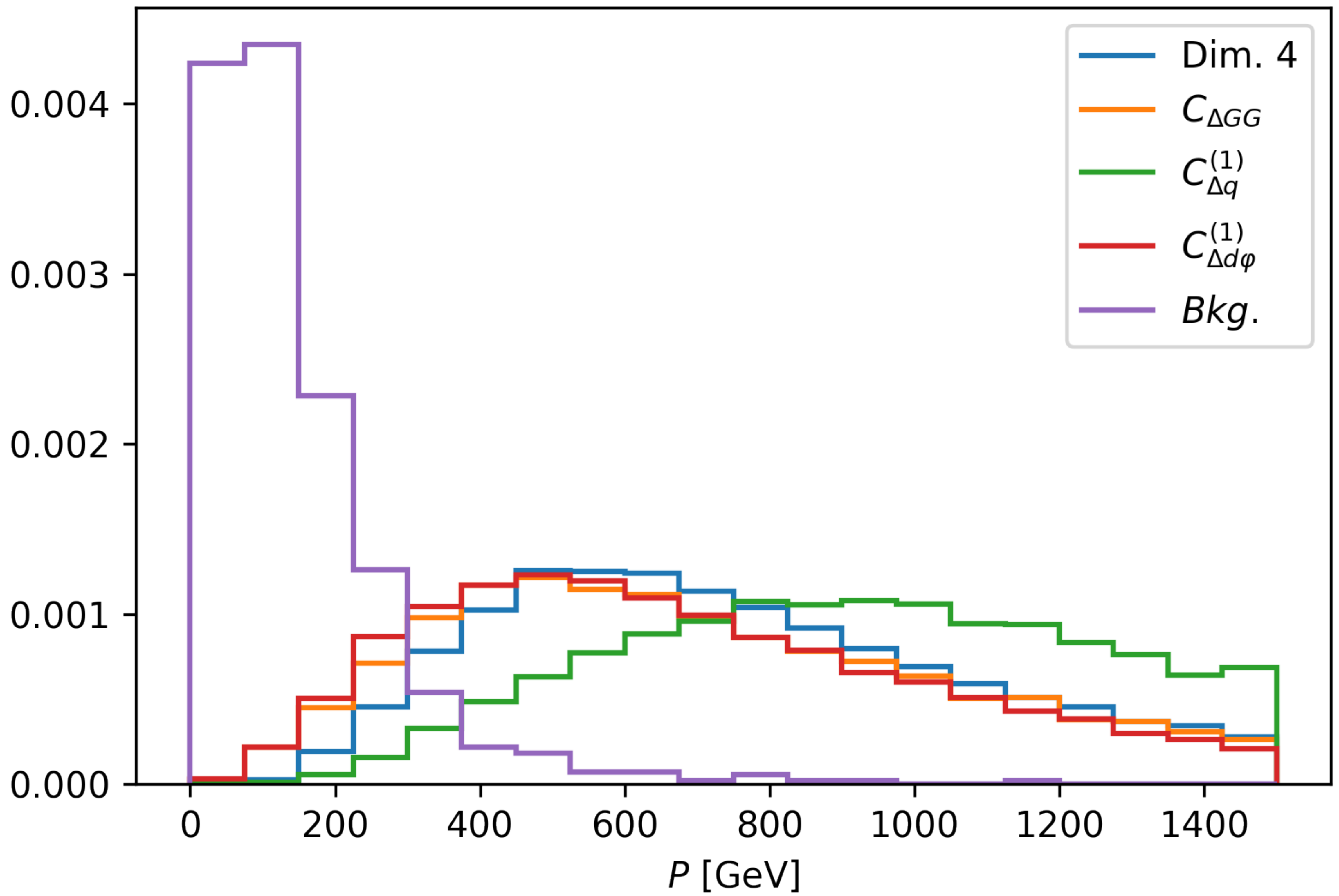
$$\mathcal{O}_{\Delta G} = Tr(\Delta^\dagger \Delta)\, G^A_{\mu\nu} G^{A\mu\nu}$$

$$\mathcal{O}^{(1)}_{\Delta q} = Tr(\Delta^\dagger i \overleftrightarrow{D}_\mu \Delta)\, (\bar{q}_p \gamma^\mu q_r)$$

$$\mathcal{O}^{(1)}_{\Delta d\varphi} = Tr(\Delta^\dagger \Delta)\, (\bar{q}_p d_r \varphi)$$

- New kinematic distributions: $p\, p \to H^{++}\, H^{--} \to l^+ l^+ l^- l^-$



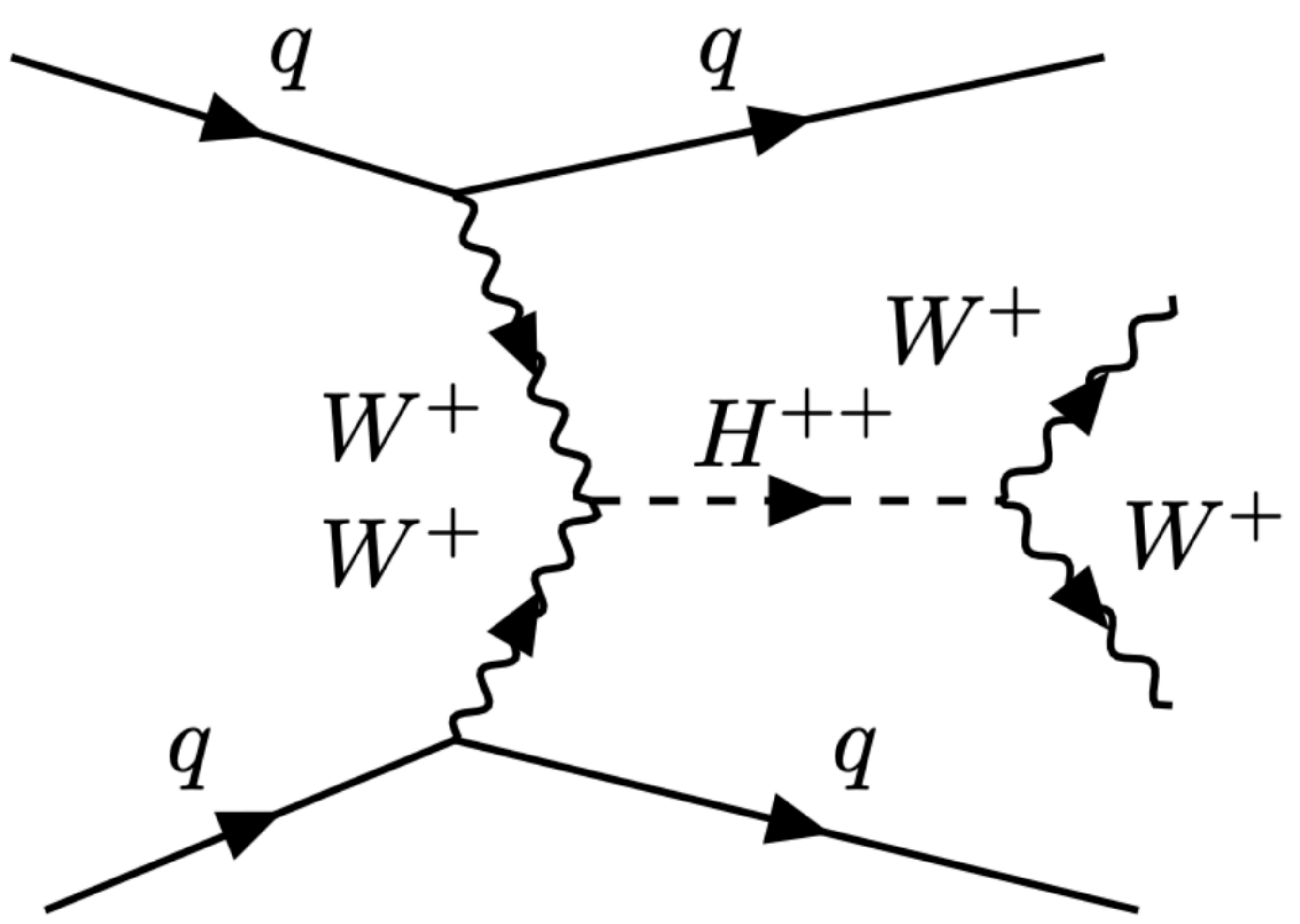


Phenomenology at LHC

- To put constraints we take the latest analysis by CMS on charged Higgs (2021). [2104.04762v2]
- To put constraints we need to reproduce CMS analysis (since our basis modifies kinematic distributions).
- CMS looks at decays of $H \to W^+ \, W^+$, which is dominant at larger v_t
- The operators in our basis that contribute to this process are:

$$\mathcal{O}_{\Delta WB} = Tr(\Delta^\dagger \tau^I \Delta) W^I_{\mu\nu} B^{\mu\nu}$$

$$\mathcal{O}_{\Delta WW} = Tr(\Delta^\dagger \tau^I \Delta \tau^J)\, W^I_{\mu\nu} W^{J\mu\nu}$$



- We also add another operator:

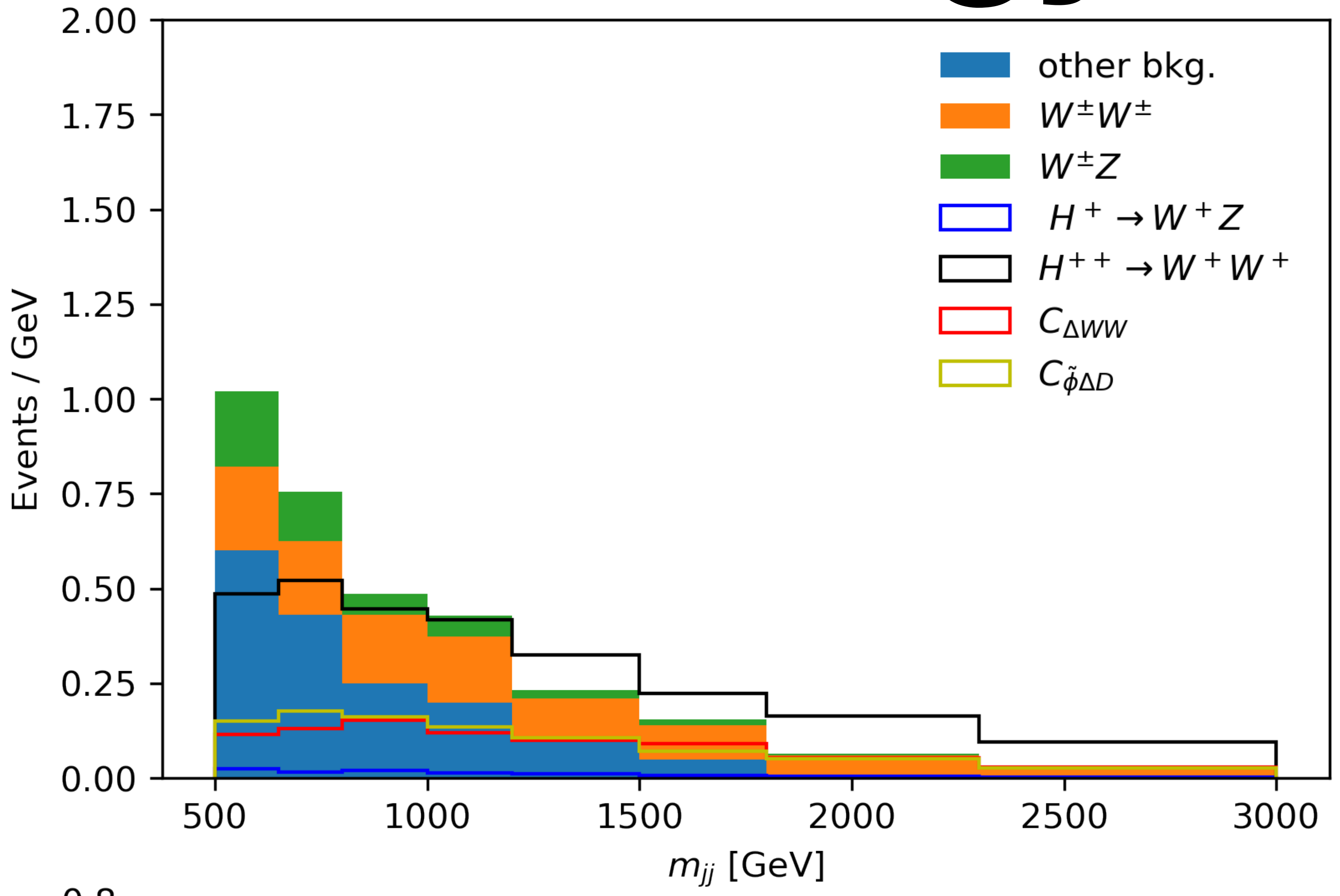
$$\mathcal{O}_{\tilde{\varphi}\Delta D} = (D_\mu \varphi)^\dagger \Delta D^\mu \tilde{\varphi}$$

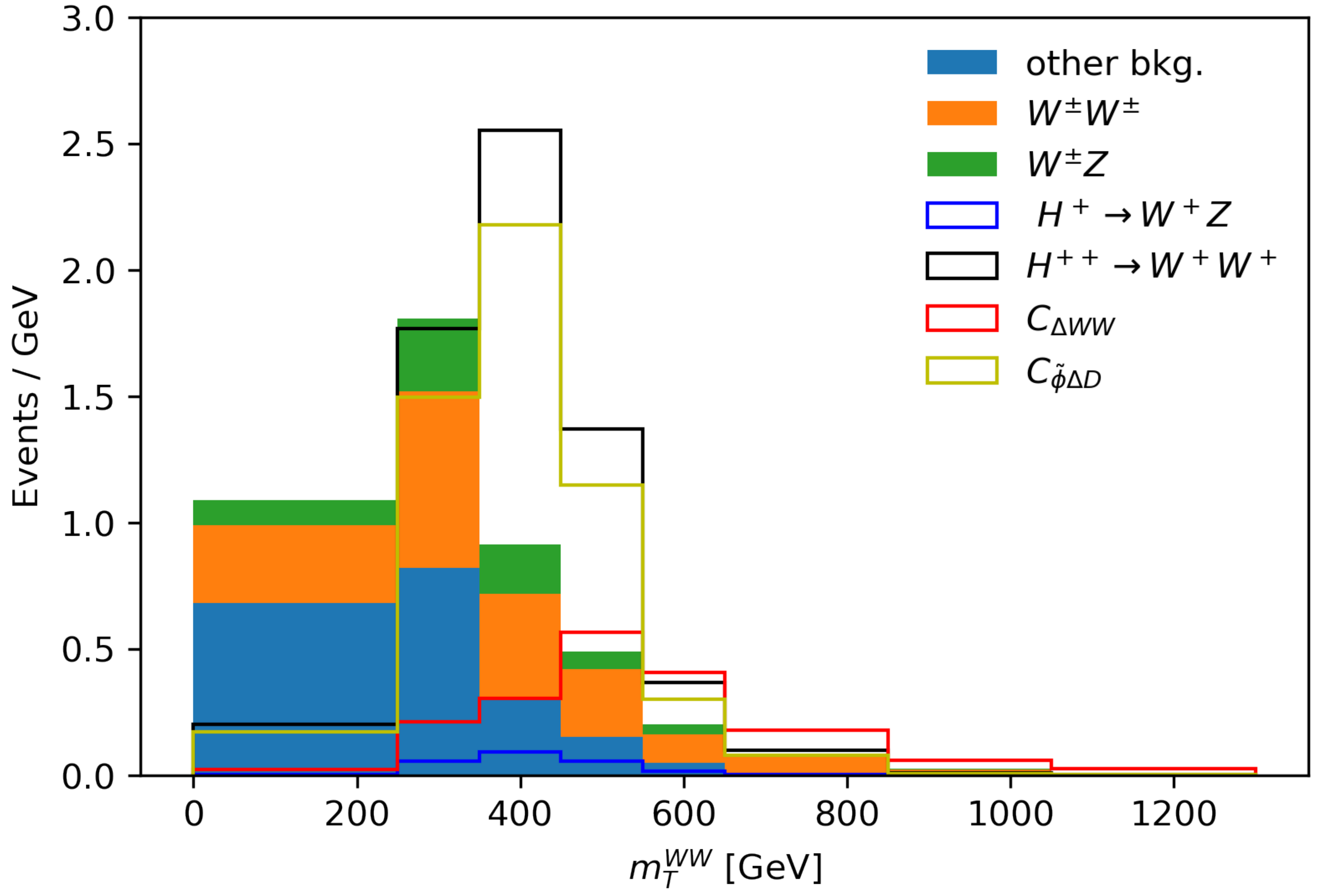
Phenomenology at LHC

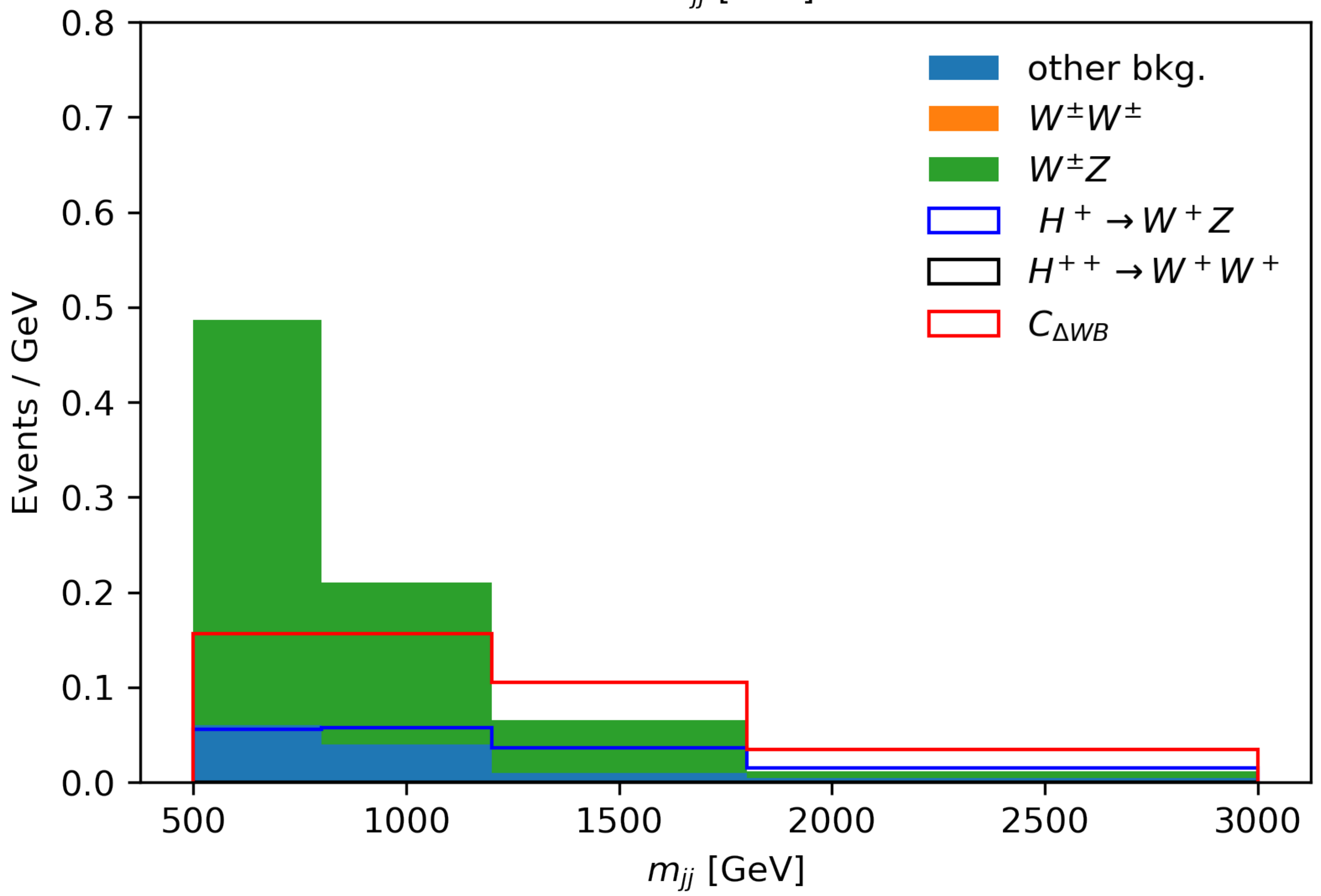
- To reproduce CMS analysis one must:
  - Implement the model in Feynrules
  - Generate the relevant processes
  - Hadronize the final quark states with Pythia8
  - Run a (fast) detector simulator Delphes 3
  - Run an analysis with mad analysis5 applying all the cuts.

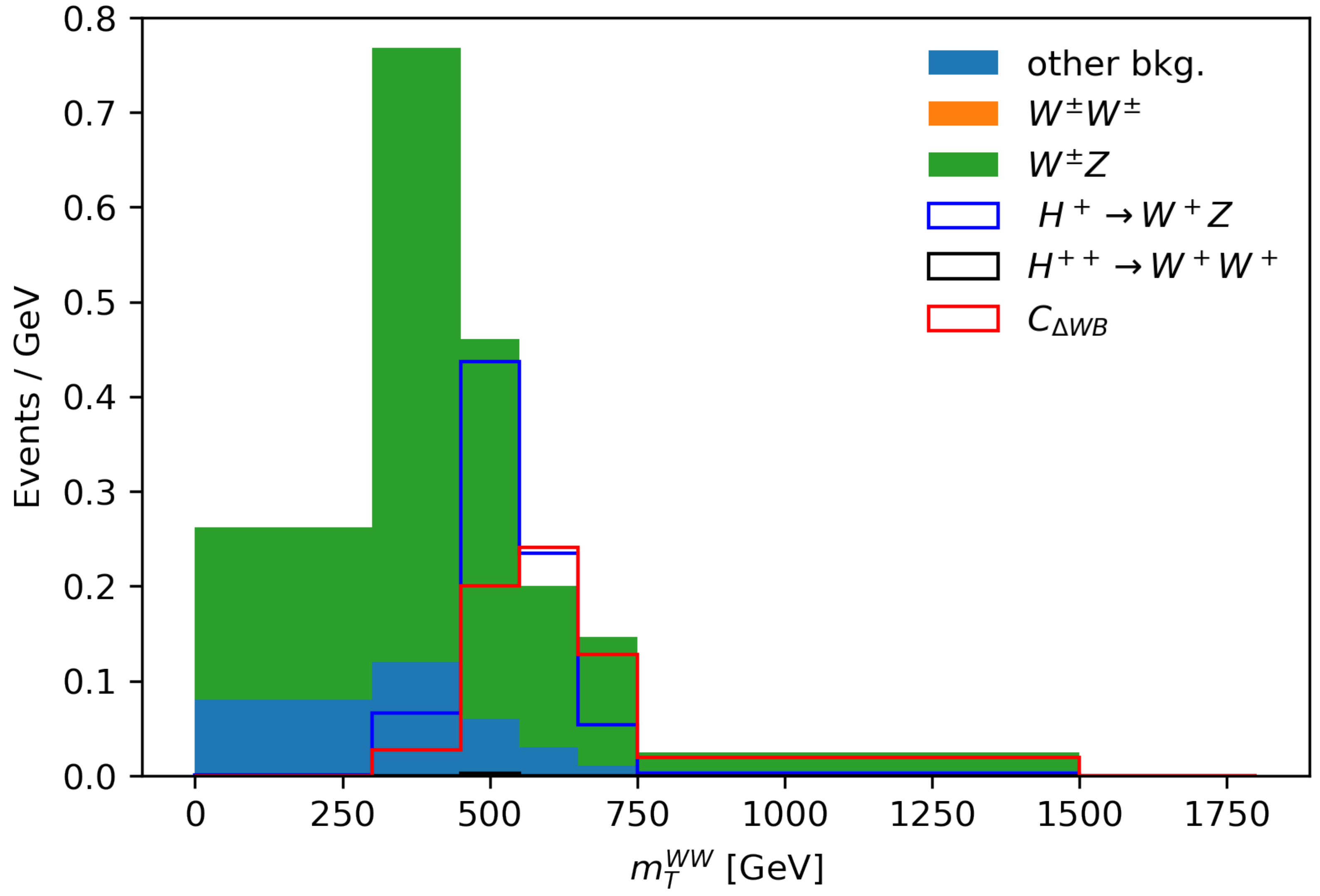
Variable	$W^{\pm}W^{\pm}$	$W^{\pm}Z$
Leptons	2 leptons, $p_T > 25/20$ GeV	3 leptons, $p_T > 25/10/20$ GeV
p_T^j	$> 50/30$ GeV	$> 50/30$
$\|m_{ll} - m_Z\|$	> 15 GeV (ee)	< 15 GeV
m_{ll}	> 20 GeV	–
m_{lll}	–	> 100 GeV
p_T^{miss}	> 30 GeV	> 30 GeV
b jet veto	Required	Required
τ_h veto	Required	Required
max(z_l^*)	< 0.75	< 1.0
m_{jj}	> 500 GeV	> 500 GeV
$\|\Delta\eta_{jj}\|$	> 2.5	> 2.5

Phenomenology at LHC

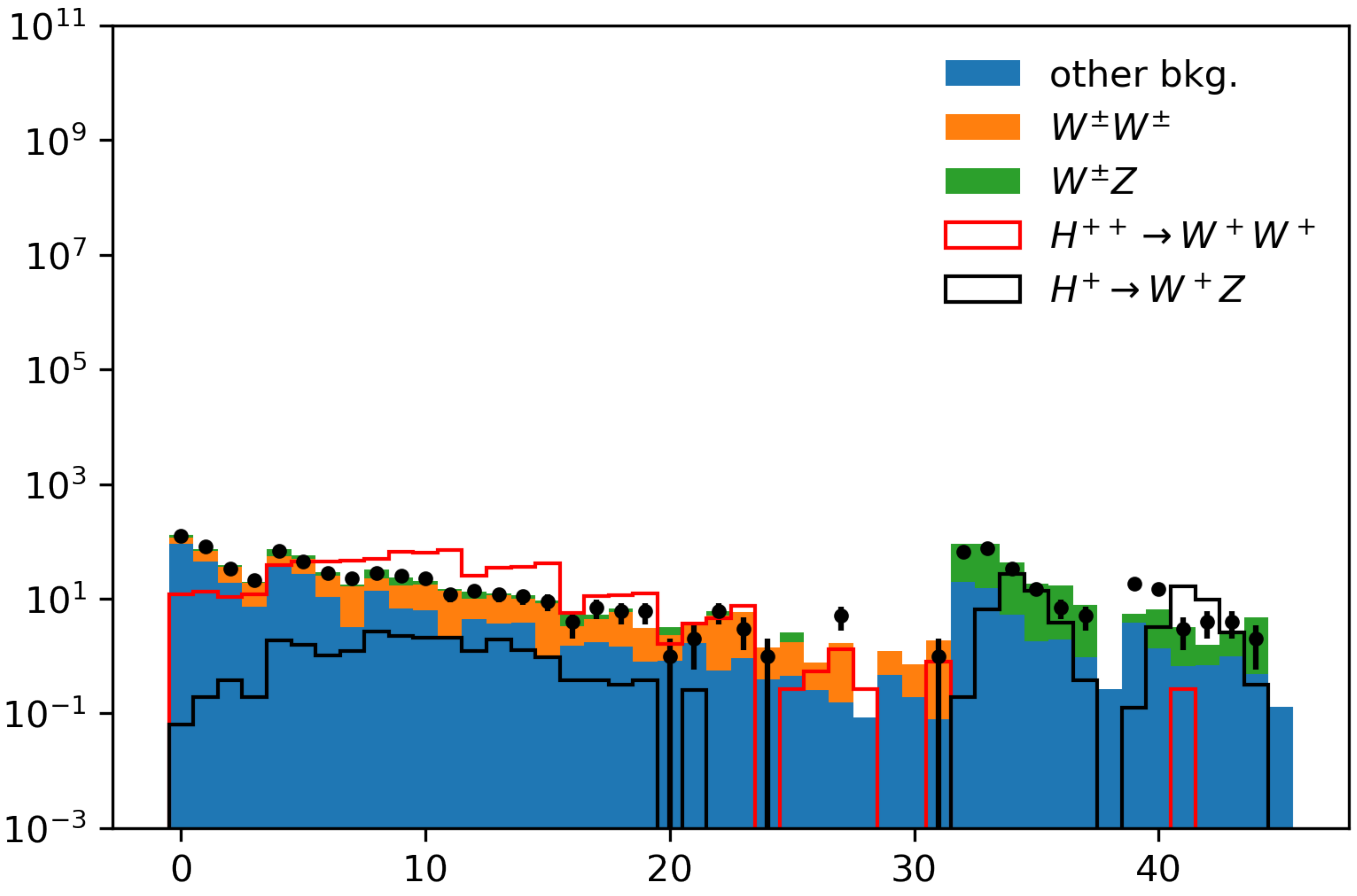


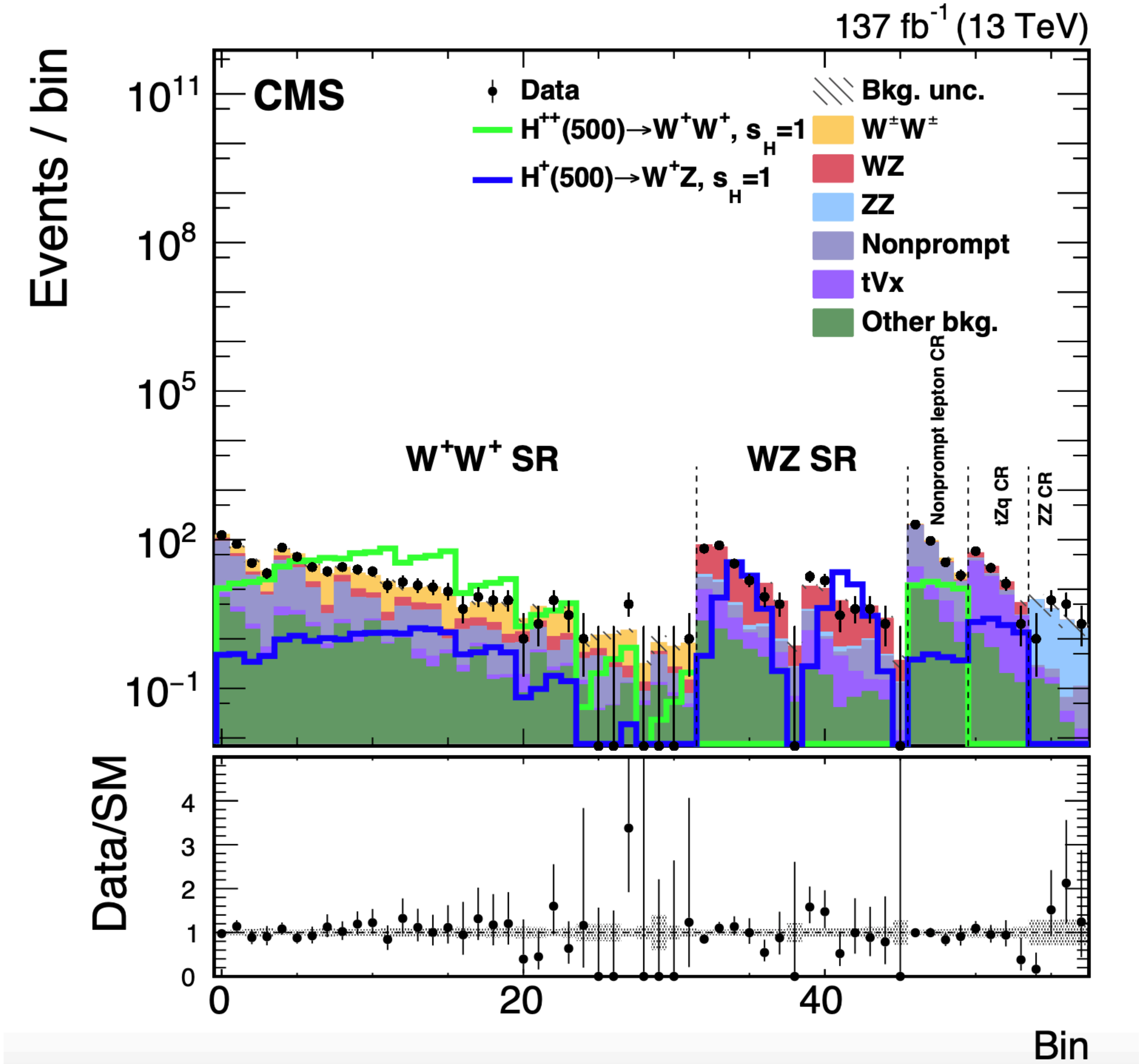






Phenomenology at LHC





Phenomenology at LHC

- By using a Poissonian distribution for each bin: $$L(\mu,\theta) = \prod_j^N \frac{(\mu s_j + b_j)^{n_j}}{n_j!} e^{-(\mu s_j + b_j)}$$

- It is possible to define a test statistic to find the values of μ for $CL_s = 95\,\%$

- And then find the values of the Wilson coefficients associated to that signal

	Operator	$CL_s = 95\%$
$v_t = 5$ GeV	$C_{\tilde{\varphi}\Delta D}/\Lambda$ [TeV^{-1}]	1.7
	$C_{\Delta WW}/\Lambda^2$ [TeV^{-2}]	27.8
	$C_{\Delta WB}/\Lambda^2$ [TeV^{-2}]	75.5
$v_t = 3$ GeV	$C_{\tilde{\varphi}\Delta D}/\Lambda$ [TeV^{-1}]	2.1
	$C_{\Delta WW}/\Lambda^2$ [TeV^{-2}]	49.3
	$C_{\Delta WB}/\Lambda^2$ [TeV^{-2}]	148.9

	Operator	$CL_s = 95\%$
$v_t = 5$ GeV	$C_{\tilde{\varphi}\Delta D}/\Lambda$ [TeV^{-1}]	2.1
	$C_{\Delta WW}/\Lambda^2$ [TeV^{-2}]	30.3
	$C_{\Delta WB}/\Lambda^2$ [TeV^{-2}]	96.9
$v_t = 3$ GeV	$C_{\tilde{\varphi}\Delta D}/\Lambda$ [TeV^{-1}]	4.1
	$C_{\Delta WW}/\Lambda^2$ [TeV^{-2}]	42.0
	$C_{\Delta WB}/\Lambda^2$ [TeV^{-2}]	145.9

Conclusions

- We have seen arguments that motivate an EFT expansion of the type-2 seesaw mechanism.
- We have built a basis of operators up to dimension 6 containing all possible couplings.
- Different ways of constraining these operators have been used:
    - Integrating out the triplet field, adding dimension 5 operators.
    - Through contribution to EWPO, which are constrained using LEP data.
    - We also showed how to distinguish SMEFT and ΔEFT.
    - We discussed new interactions relevant in the context of the LHC.
    - And found upper bounds for some parameters using CMS searches.

Thanks for your attention

and happy holidays!