Observable effects of general new scalar particles

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in collaboration with **J. Blas**, **M. Pérez-Victoria** and

J. Santiago.

Based on *1507.00757*, *1412.8480* and *1307.5068.*

Outline

General new scalar sectors

Effective-field theory approach to the scalar sector

Constraints from the LHC

The Standard Model is very strong

Planck scale

valid up to

Renormalizable

Stable vacuum

Degrassi et al., 1205.6497

...

TeV scale

New **scalars** with renormalizable linear couplings to SM fields

Blas, **MC**, Pérez-Victoria, Santiago
1412.8480

Colorless Scalars	$\mathcal{S}$	$\mathcal{S}_1$	$\mathcal{S}_2$	φ	Ξ_0	Ξ_1	Θ_1	Θ_3
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,1)_2$	$(1,2)_{\frac{1}{2}}$	$(1,3)_0$	$(1,3)_1$	$(1,4)_{\frac{1}{2}}$	$(1,4)_{\frac{3}{2}}$

Colored Scalars	ω_1	ω_2	ω_4	Π_1	Π_7	ζ
Irrep	$(3,1)_{-\frac{1}{3}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{4}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$

Colored Scalars	Ω_1	Ω_2	Ω_4	Υ	Φ
Irrep	$(6,1)_{\frac{1}{3}}$	$(6,1)_{-\frac{2}{3}}$	$(6,1)_{\frac{4}{3}}$	$(6,3)_{\frac{1}{3}}$	$(8,2)_{\frac{1}{2}}$

Some examples: 2HDM, Higgs portal, exotic...

$$\boldsymbol{\varphi \sim (1,2)_{\frac{1}{2}}}$$

$$J_\varphi = (y^e_\varphi)_{ij}\ \overline{e^i_R} l^j_L + (y^d_\varphi)_{ij}\ \overline{d^i_R} q^j_L + (y^u_\varphi)_{ij}\ i\sigma_2 \overline{q^i_L}^T u^j_R$$

$$V_\varphi = \lambda_\varphi\ (\varphi^\dagger\phi)(\phi^\dagger\phi) + \text{h.c.}$$

$$\boldsymbol{\mathcal{S} \sim (1,1)_0}$$

$$V_\mathcal{S} = \kappa_\mathcal{S}\ \mathcal{S}\phi^\dagger\phi + \lambda_\mathcal{S}\ \mathcal{S}^2\phi^\dagger\phi + \kappa_{\mathcal{S}^3}\ \mathcal{S}^3$$

$$\boldsymbol{\zeta \sim (3,3)_{-\frac{1}{3}}}$$

$$J_\zeta = (y^{ql}_\zeta)_{ij}\ \overline{q^{c\,i}_L} i\sigma_2\sigma_a l^j_L + (y^{qq}_\zeta)_{ij}\ \varepsilon_{ABC}\ \overline{q^{i\,B}_L}\sigma_a i\sigma_2 q^{c\,j\,C}_L \qquad \left((y^{qq}_\zeta)_{ij} = -(y^{qq}_\zeta)_{ji}\right)$$

Phenomenological implications

Very sensitive to constraints from **flavor-violating** processes

Grinstein et al., 1108.4027

Leptoquarks constrained by LEP2 and LHC

Violation of **lepton and baryon numbers**

Wavefunction renormalization, $\Delta L_{H^3} = \frac{5}{6}\alpha_\phi \frac{v^3}{\Lambda^2} H^3 \;\; T = -\frac{\alpha_{\phi D}}{2\alpha_{em}} \frac{v^2}{\Lambda^2}$

Searches for di-jet (lepton, top, ...) resonances at the LHC

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Searches for di-jet (lepton, top, ...) resonances at the LHC

This motivates a different approach to the scalar sector

Use effective field theories

Effective Lagrangians and new physics

- All relevant degrees of freedom and symmetries are known (assume SM-like)
- Mass gap between EW and new physics scales
- Keep up to **dimension-six operators**

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{\alpha^{(5)}}{\Lambda}\mathcal{O}^{(5)} + \sum_i \frac{\alpha_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \cdots$$

New **scalars** with renormalizable linear couplings to SM fields

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Example: a second Higgs doublet, $\varphi \sim (1, \mathbf{2})_{\frac{1}{2}}$

Four-Fermion Operators:

- **LLRR**

$$\frac{(\alpha_{le})_{ijkl}}{\Lambda^2} = -\frac{(y^e_\varphi)_{kj}(y^{e\,\dagger}_\varphi)_{il}}{2M^2_\varphi}$$

$$\frac{\left(\alpha^{(1)}_{qd}\right)_{ijkl}}{\Lambda^2} = -\frac{(y^d_\varphi)_{kj}(y^{d\,\dagger}_\varphi)_{il}}{6M^2_\varphi} \qquad \frac{\left(\alpha^{(8)}_{qd}\right)_{ijkl}}{\Lambda^2} = 6\frac{\left(\alpha^{(1)}_{qd}\right)_{ijkl}}{\Lambda^2}$$

$$\frac{\left(\alpha^{(1)}_{qu}\right)_{ijkl}}{\Lambda^2} = -\frac{(y^u_\varphi)_{il}(y^{u\,\dagger}_\varphi)_{kj}}{6M^2_\varphi} \qquad \frac{\left(\alpha^{(8)}_{qu}\right)_{ijkl}}{\Lambda^2} = 6\frac{\left(\alpha^{(1)}_{qu}\right)_{ijkl}}{\Lambda^2}$$

- **LRRL**

$$\frac{\left(\alpha_{ledq}\right)_{ijkl}}{\Lambda^2} = \frac{(y^d_\varphi)_{kl}(y^{e\,\dagger}_\varphi)_{ij}}{M^2_\varphi}$$

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Scalar-Fermion Operators

$$\frac{\left(\alpha_{e\phi}\right)_{ij}}{\Lambda^2} = \frac{\lambda_\varphi(y^{e\,\dagger}_\varphi)_{ij}}{M^2_\varphi}$$

$$\frac{\left(\alpha_{u\phi}\right)_{ij}}{\Lambda^2} = -\frac{\lambda^*_\varphi(y^u_\varphi)_{ij}}{M^2_\varphi} \qquad \frac{\left(\alpha_{d\phi}\right)_{ij}}{\Lambda^2} = \frac{\lambda_\varphi(y^{d\,\dagger}_\varphi)_{ij}}{M^2_\varphi}$$

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$$\frac{\alpha_\phi}{\Lambda^2} = 3\frac{|\lambda_\varphi|^2}{M^2_\varphi}$$

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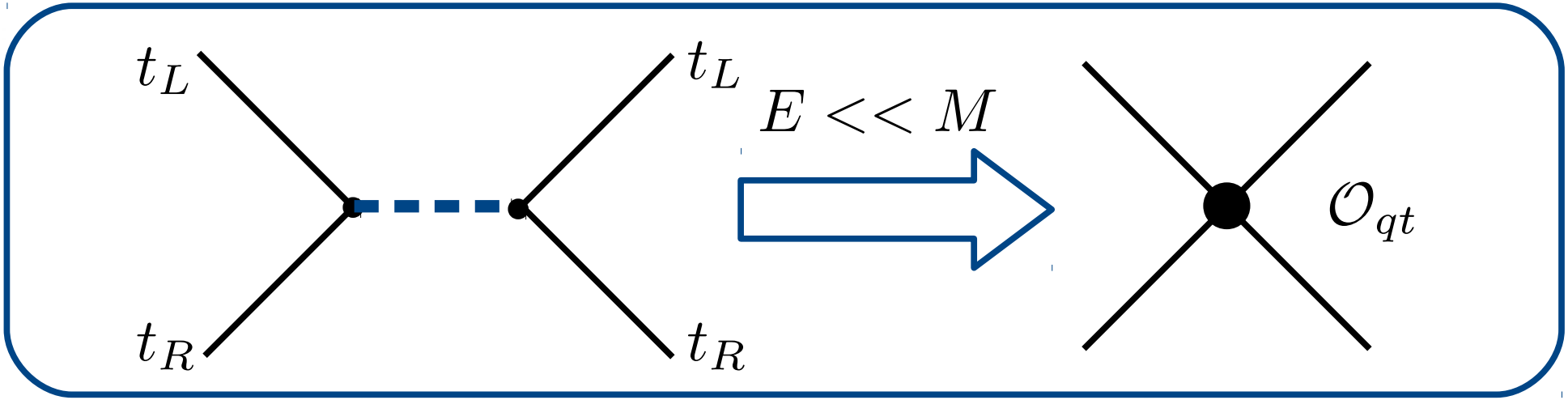
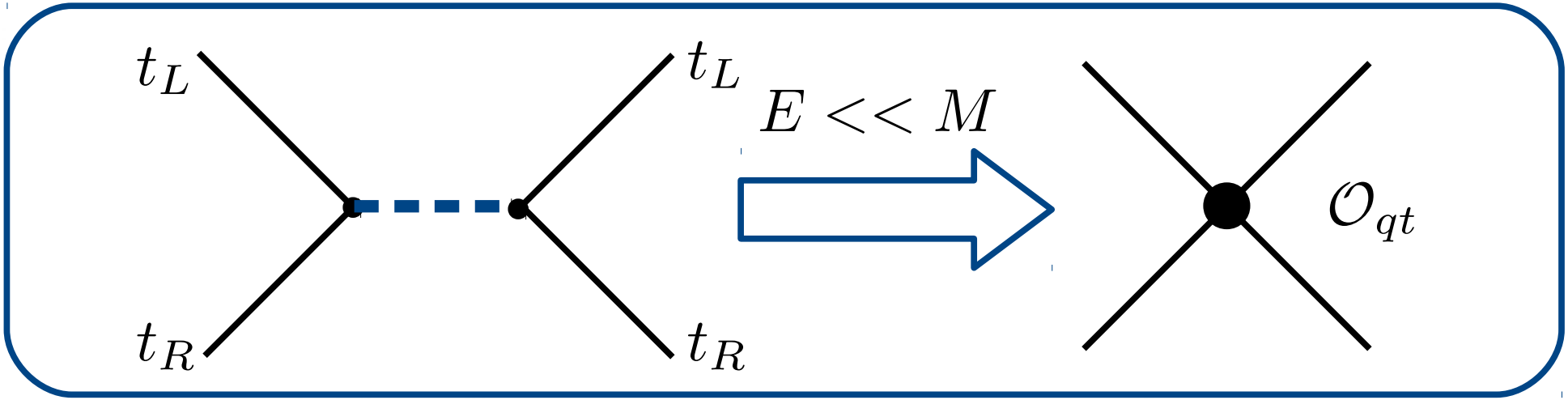
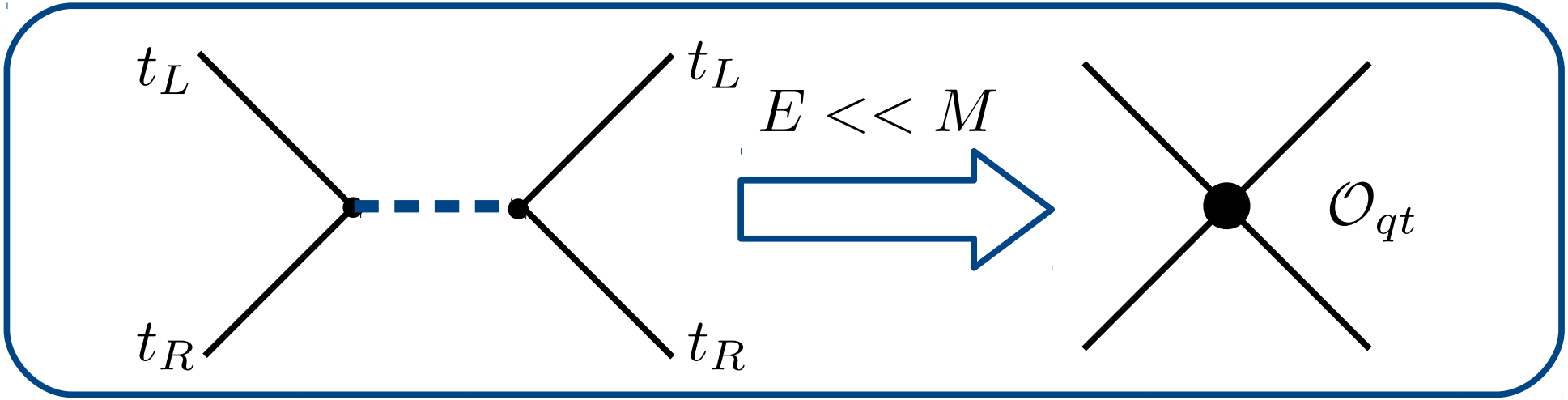

t_L
t_R
t_L
t_R
$E << M$
$\mathcal{O}_{qt}$



Running from the new physics scale **down to the electroweak scale**

$$c_{\phi q}^{(1),(3)} \sim \frac{N_c y_t^2}{16\pi^2} c_{qt}^{(1)} \log \frac{\Lambda}{v}$$



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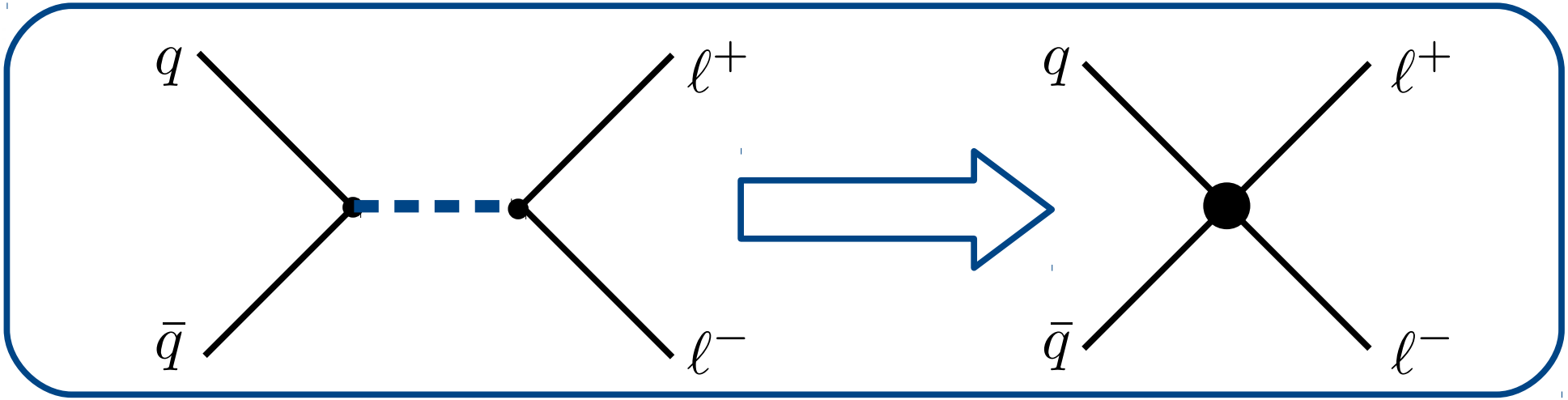
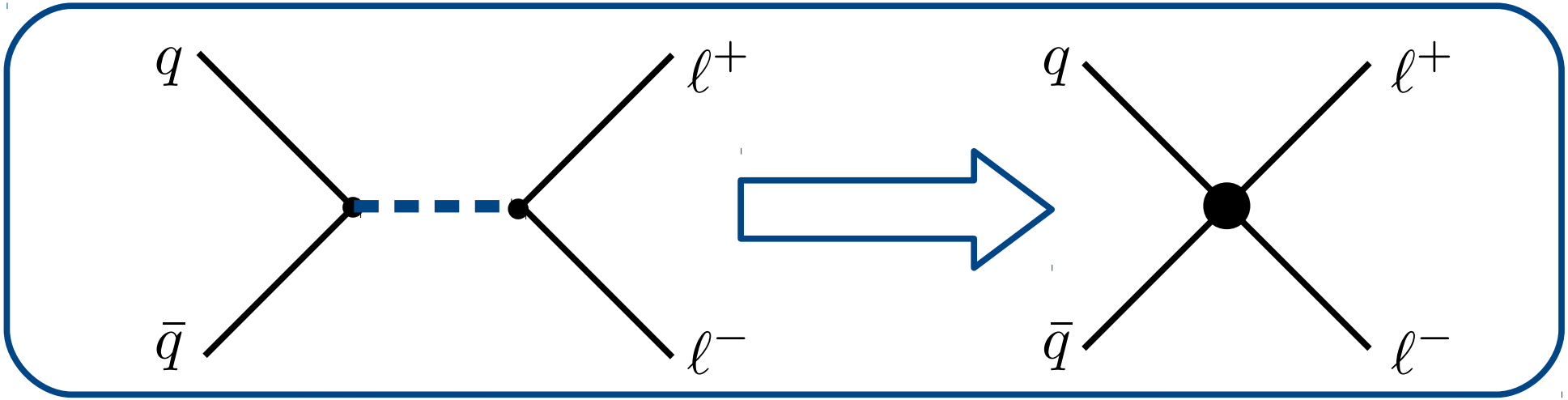
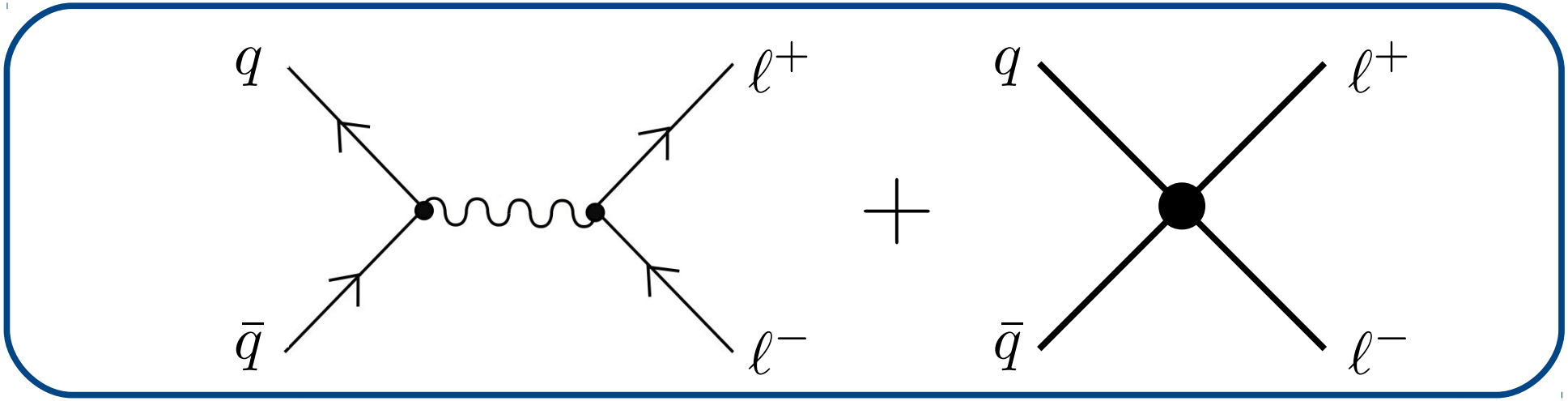
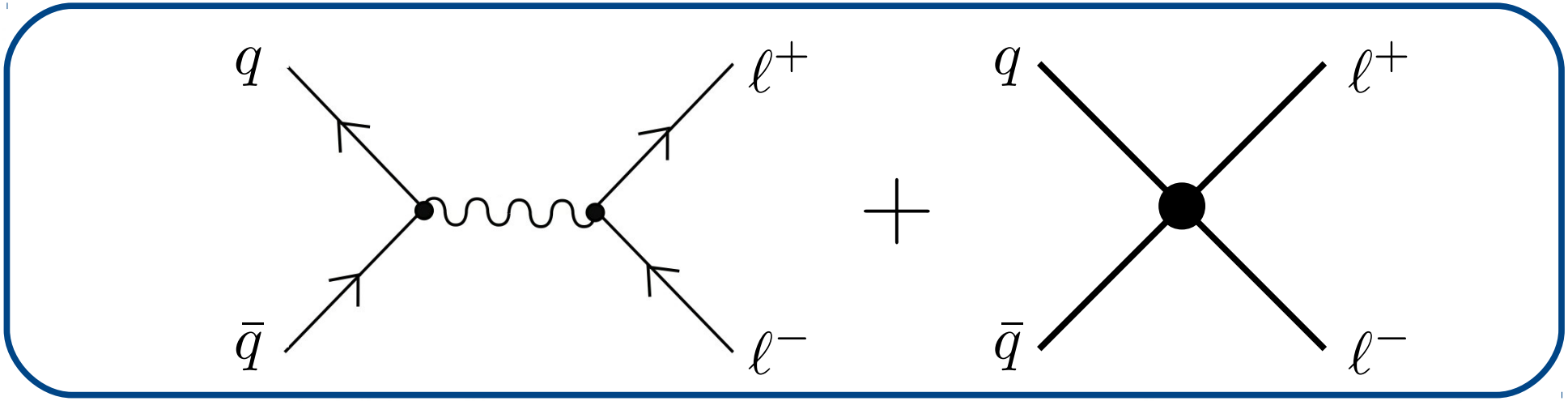
It translates into **constraints** on the new scale **of order TeV** for couplings of order 1

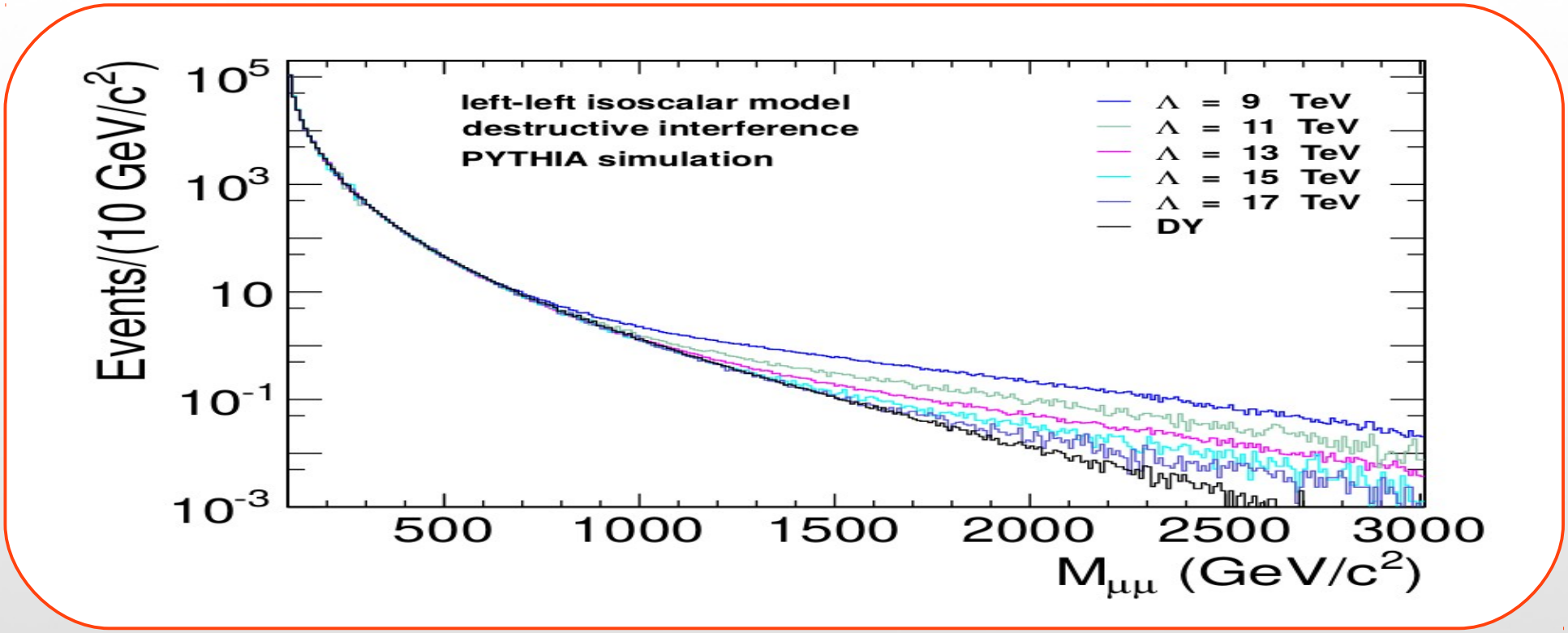

q
$\bar{q}$
ℓ^+
ℓ^-
q
$\bar{q}$
ℓ^+
ℓ^-

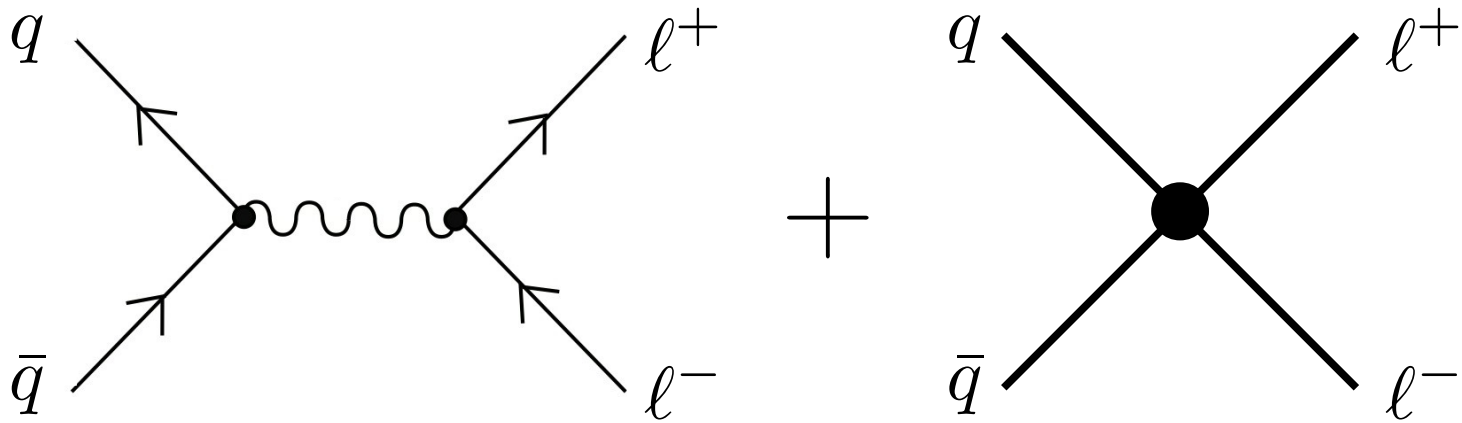


$$
\begin{aligned}
\mathcal{O}_{lq}^{(1)} &= (\bar{l}\gamma^\mu l)(\bar{q}\gamma_\mu q), & \mathcal{O}_{lq}^{(3)} &= (\bar{l}\sigma_I\gamma^\mu l)(\bar{q}\sigma_I\gamma_\mu q),\\
\mathcal{O}_{eu} &= (\bar{e}\gamma^\mu e)(\bar{u}\gamma_\mu u), & \mathcal{O}_{ed} &= (\bar{e}\gamma^\mu e)(\bar{d}\gamma_\mu d),\\
\mathcal{O}_{lu} &= (\bar{l}\gamma^\mu l)(\bar{u}\gamma_\mu u), & \mathcal{O}_{ld} &= (\bar{l}\gamma^\mu l)(\bar{d}\gamma_\mu d),\\
\mathcal{O}_{qe} &= (\bar{q}\gamma^\mu q)(\bar{e}\gamma_\mu e), & \mathcal{O}_{qde} &= (\bar{l}e)(\bar{d}q),\\
\mathcal{O}_{lq\epsilon} &= (\bar{l}e)\epsilon(\bar{q}^T u), & \mathcal{O}_{ql\epsilon} &= (\bar{q}e)\epsilon(\bar{l}^T u),
\end{aligned}
$$


q
ℓ^+
$\bar{q}$
ℓ^-
$+$
q
ℓ^+
$\bar{q}$
ℓ^-


q
ℓ^+
$\bar{q}$
ℓ^-
+
q
ℓ^+
$\bar{q}$
ℓ^-


left-left isoscalar model
destructive interference
PYTHIA simulation
Λ = 9 TeV
Λ = 11 TeV
Λ = 13 TeV
Λ = 15 TeV
Λ = 17 TeV
DY
Events/(10 GeV/c²)
10⁵
10³
10
10⁻¹
10⁻³
500
1000
1500
2000
2500
3000
M_μμ (GeV/c²)



Search for Contact Interactions in Dilepton Mass Spectra in pp Collisions at $\sqrt{s} = 8\,\text{TeV}$

The CMS Collaboration

$$\frac{d\sigma^{\text{CI/DY}}}{dM} = \frac{d\sigma^{\text{DY}}}{dM} - \frac{\eta_{LL}}{\Lambda^2}\mathcal{I}(M) + \frac{\eta_{LL}^2}{\Lambda^4}\mathcal{C}(M)$$

In any region of the phase space

$$\sigma = \sigma_{SM} + \frac{\alpha_1}{\Lambda^2} A_1 + ... + \frac{\alpha_N}{\Lambda^2} A_N$$
$$+ \frac{\alpha_1^2}{\Lambda^4} A_{11} + \cdots + \frac{\alpha_N^2}{\Lambda^4} A_{NN}$$
$$+ \frac{\alpha_1 \alpha_2}{\Lambda^4} A_{12} + \cdots + \frac{\alpha_{N-1} \alpha_N}{\Lambda^4} A_{NN-1}$$

But the actual number of independent coefficients is much smaller: no interference, reduced number of structures, ...

Actually, only five independent parameters

$$\sigma = \sigma^{\rm SM} + \frac{1}{\Lambda^2}\sum_{q=u,d} F^q(A_1^q + A_2^q) + \frac{1}{\Lambda^4}\sum_{q+u,d} G^q(B_1^q + B_2^q + 3B_3^q)$$

$$\begin{aligned}
A_1^u &= [e^2 Q_u Q_e + g_{u_L} g_{e_L}](\alpha_{lq}^{(1)} - \alpha_{lq}^{(3)}) + [e^2 Q_u Q_e + g_{u_R} g_{e_R}]\alpha_{eu}, \\
A_2^u &= [e^2 Q_u Q_e + g_{u_L} g_{e_R}]\alpha_{qe} + [e^2 Q_u Q_e + g_{u_R} g_{e_L}]\alpha_{lu}, \\
A_1^d &= [e^2 Q_d Q_e + g_{d_L} g_{e_L}](\alpha_{lq}^{(1)} + \alpha_{lq}^{(3)}) + [e^2 Q_d Q_e + g_{d_R} g_{e_R}]\alpha_{ed}, \\
A_2^d &= [e^2 Q_d Q_e + g_{d_L} g_{e_R}]\alpha_{qe} + [e^2 Q_d Q_e + g_{d_R} g_{e_L}]\alpha_{ld}, \\
B_1^u &= 4(\alpha_{lq}^{(1)} - \alpha_{lq}^{(3)})^2 + 4\alpha_{eu}^2 - 2{\rm Re}(\alpha_{lq\epsilon}\alpha_{ql\epsilon}^*), \\
B_2^u &= 4\alpha_{qe}^2 + 4\alpha_{lu}^2 + 2|\alpha_{ql\epsilon}|^2 + 2{\rm Re}(\alpha_{lq\epsilon}\alpha_{ql\epsilon}^*) \\
B_3^u &= 2|\alpha_{lq\epsilon}|^2 + 2{\rm Re}(\alpha_{lq\epsilon}\alpha_{ql\epsilon}^*), \\
B_1^d &= 4(\alpha_{lq}^{(1)} + \alpha_{lq}^{(3)})^2 + 4\alpha_{ed}^2, \\
B_2^d &= 4\alpha_{qe}^2 + 4\alpha_{ld}^2, \\
B_3^d &= 2|\alpha_{qde}|^2.
\end{aligned}$$

Coefficients for different observables

	$b_1(e)$	$b_2(e)$	$b_3(e)$	$b_4(e)$	$b_1(\mu)$	$b_2(\mu)$	$b_3(\mu)$	$b_4(\mu)$
$N_{\rm SM}$	32.6	4.68	0.60	8.72	37.0	5.38	0.74	9.44
F_1^u	2514	731	202	1324	2746	811	251	1410
F_1^d	1484	359	80.2	677	1590	481	93.6	775
G_1^u	346	203	116	404	376	219	134	415
G_1^d	200	106	46.1	199	219	118	53.0	207
$N_{\rm Obs}$	41	4	0	10	49	11	1	8

Only five for each observable → easy for exp. collaborations

Conclusions

- We have classified all possible new scalar particles that can have renormalizable linear couplings to SM fields

- This classification exhausts the list of heavy scalar particles that contribute at the tree level to the SM effective Lagrangian to dimension six

- Current constraints motivate an EFT approach to new physics in the scalar sector

- It is more worthwhile to provide observable-dependent coefficients than bounds for particular operators

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Thank you for your attention!