Vector-like quarks and leptons, and dark matter

Aldo Deandrea
Université Lyon 1 & IUF

IRN Terascale

IPHC Strasbourg - May 31st 2018

Vector-Like fermions

- Unique window to test models (Xdim, composite, Little Higgs, SUSY, GUT). Both VL-Quarks and VL-Leptons are well motivated
- Reach at LHC substantial and now partially exploited
- Mixings with all the 3 SM generations can be important for quarks (production/decay) and "dangerous" for leptons
- VL-Fermions are not chiral but they do have chiral couplings to the SM fermions and the Higgs boson or Dark matter particles, L or R depending on their $SU(2)_W$ quantum numbers (more on this later)

Why "Vector-Like" matters

- Vector-like means couplings of the left and right components of the Dirac spinor to gauge bosons are the same. They have therefore both L and R charged current:

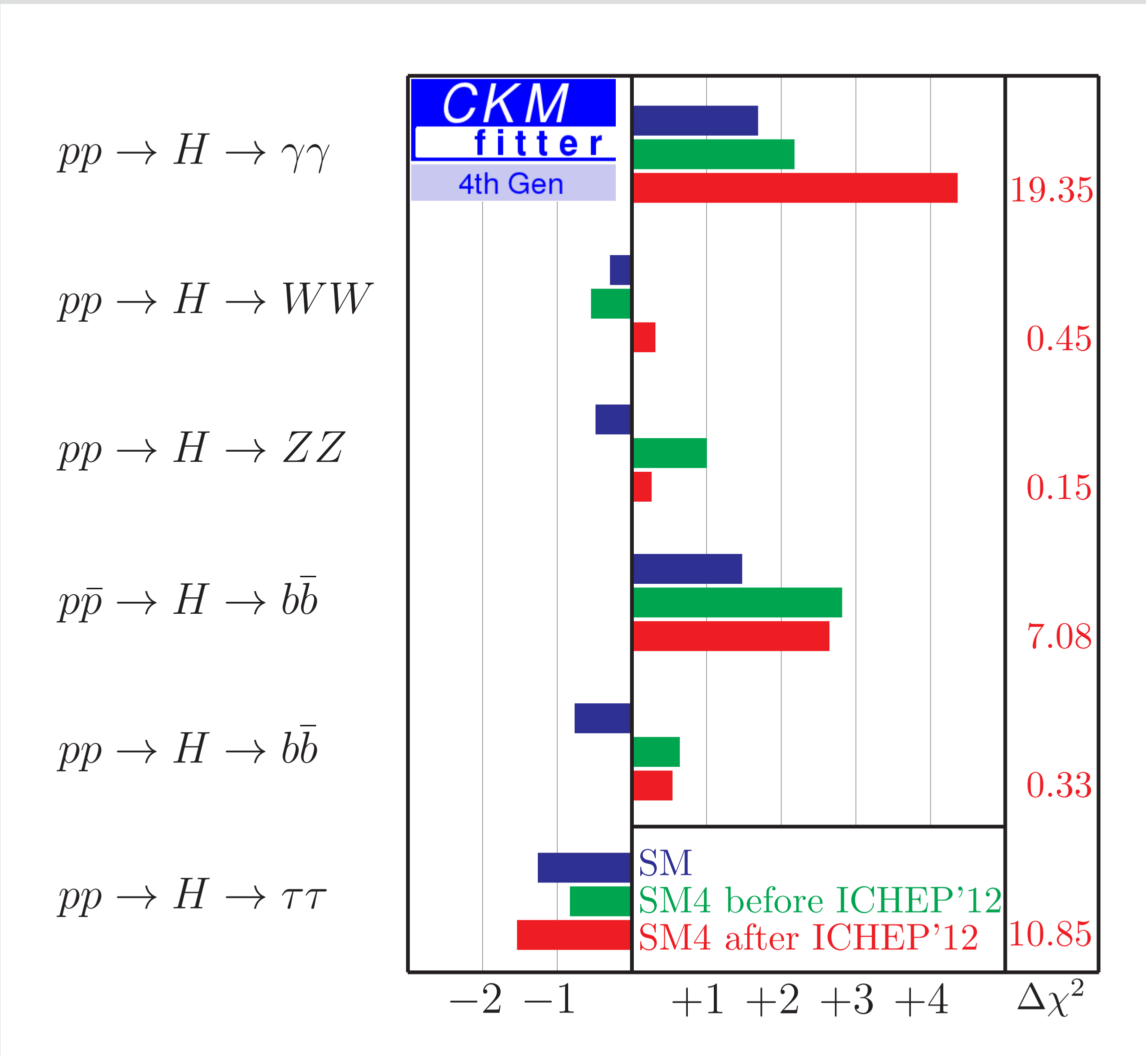
$$J^{\mu +} = J_L^{\mu +} + J_R^{\mu +} = \bar{u}_L \gamma^\mu d_L + \bar{u}_R \gamma^\mu d_R = \bar{u} \gamma^\mu d = V$$

For SM chiral quarks only L weak charged currents are present:

$$J^{\mu +} = J_L^{\mu +} + J_R^{\mu +} \quad \text{with} \quad \begin{cases} J_L^{\mu +} = \bar{u}_L \gamma^\mu d_L = \bar{u} \gamma^\mu (1-\gamma^5) d = V - A \\ J_R^{\mu +} = 0 \end{cases}$$

- Contrary to SM chiral fermions they are automatically anomaly-free
- Usual bounds for a 4-th chiral generation do not apply, in particular in Higgs physics, if you consider only one top-partner the ggh and γγh one loop vertices are not modified (when you mix the top with T, the state in the loop is just a rotation of t,T with the usual couplings)
- A gauge invariant mass term is present: $\mathcal{L}_M = -M\bar{\psi}\psi$

and vs Chiral 4th generation

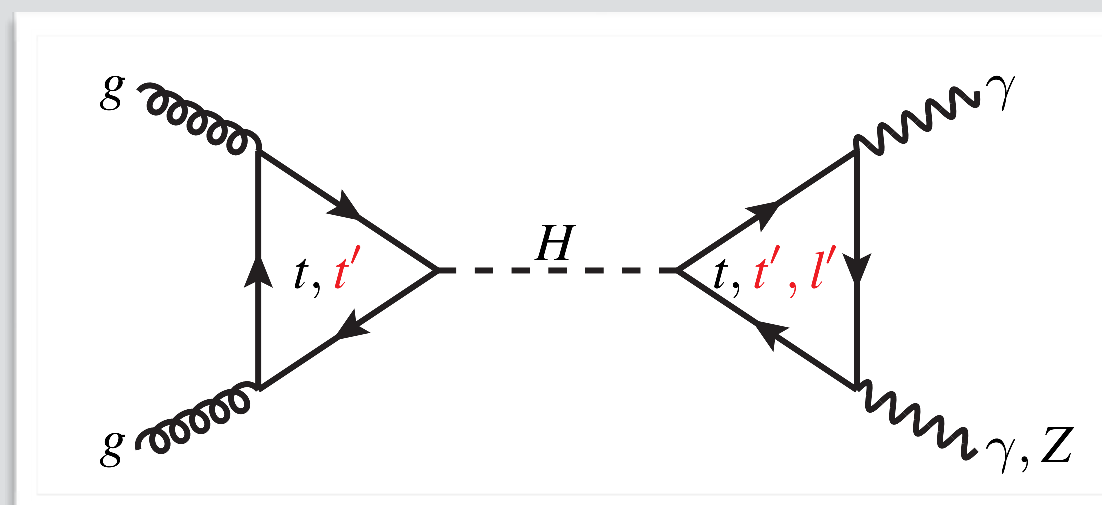


4th generation excluded
at more than 4 σ

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix} \quad \begin{pmatrix} t' \\ b' \end{pmatrix}$$

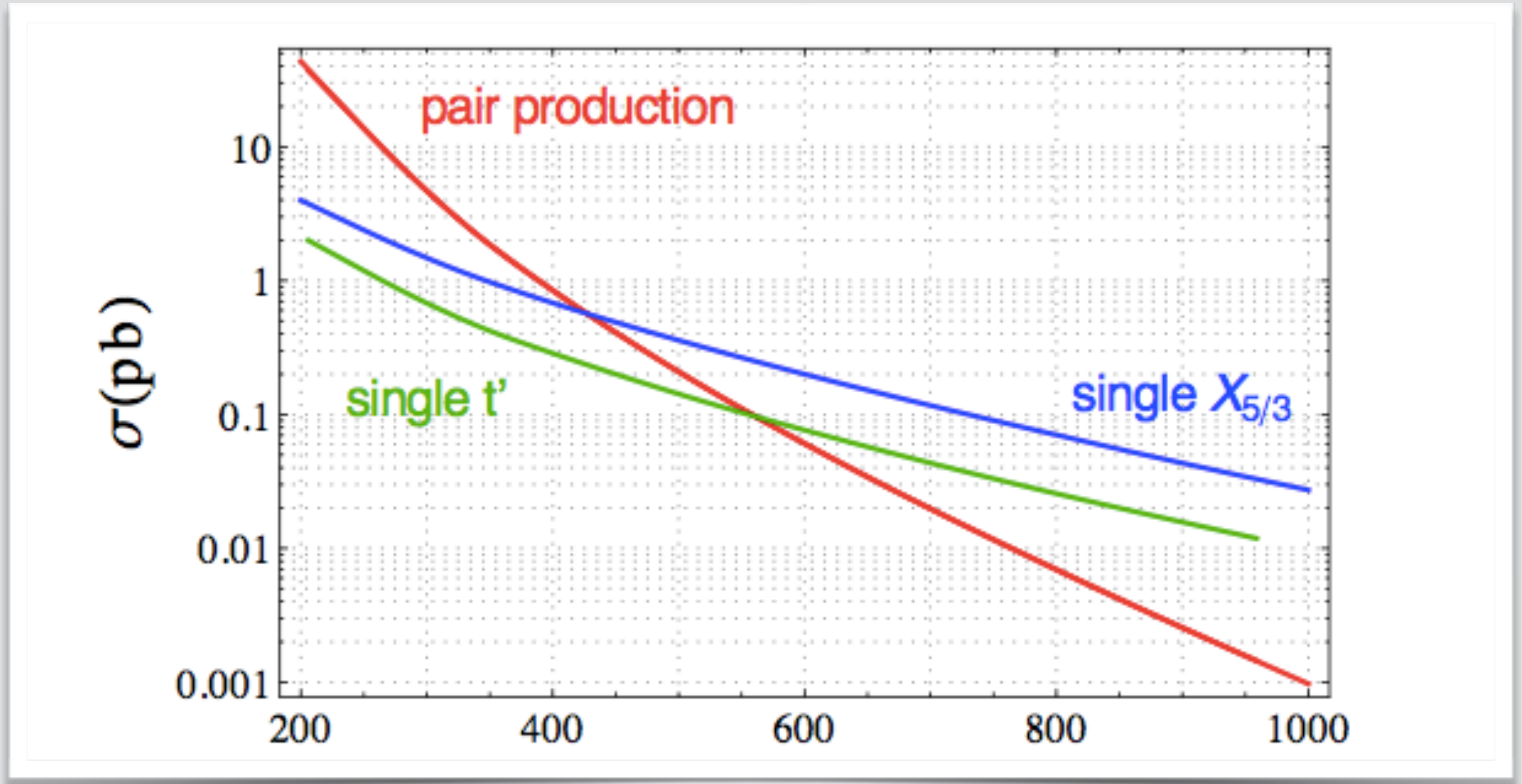
$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \quad \begin{pmatrix} \nu' \\ l' \end{pmatrix}$$

from 1209.1101



Vector-Like Quarks

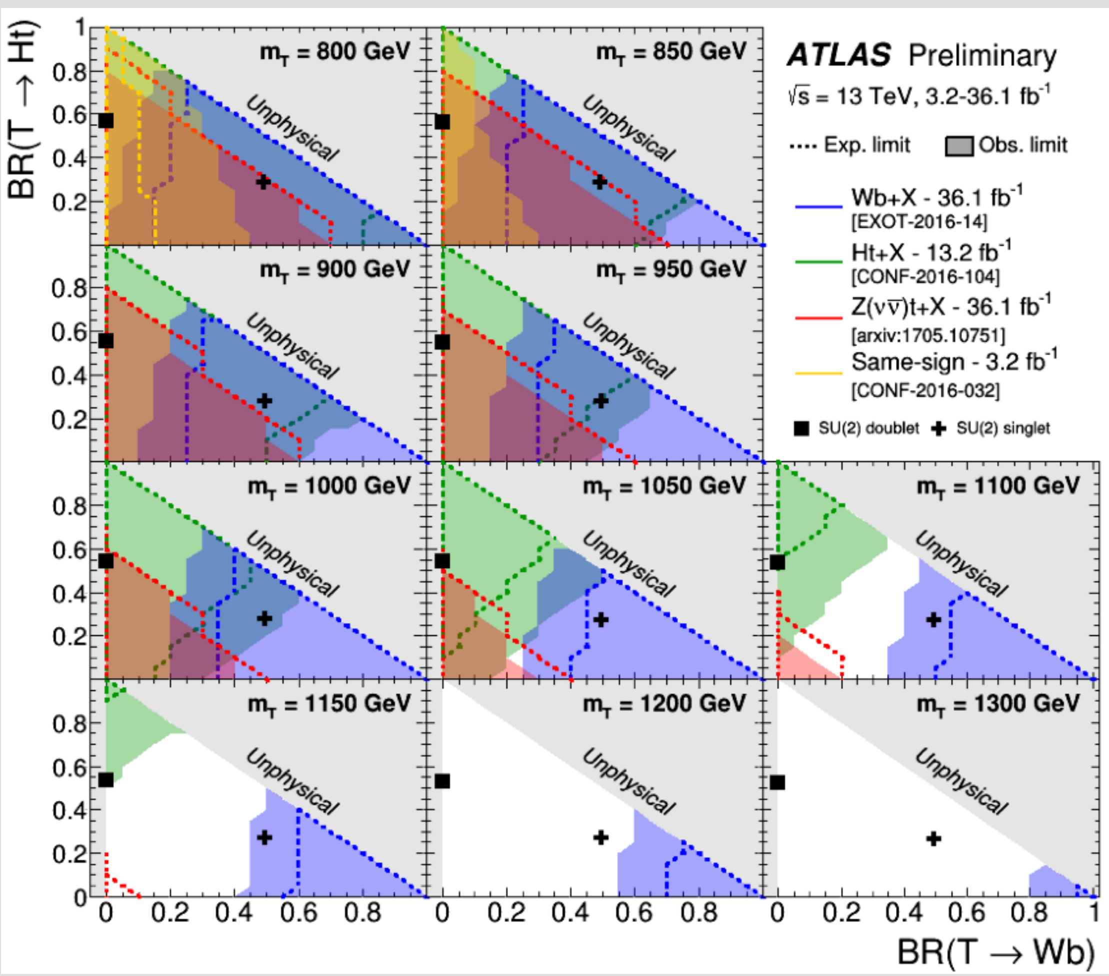
- For VLQs single production dominant with present mass bound at LHC (~1 TeV) but precise value model dependent
- Pair production almost model independent (mainly QCD)



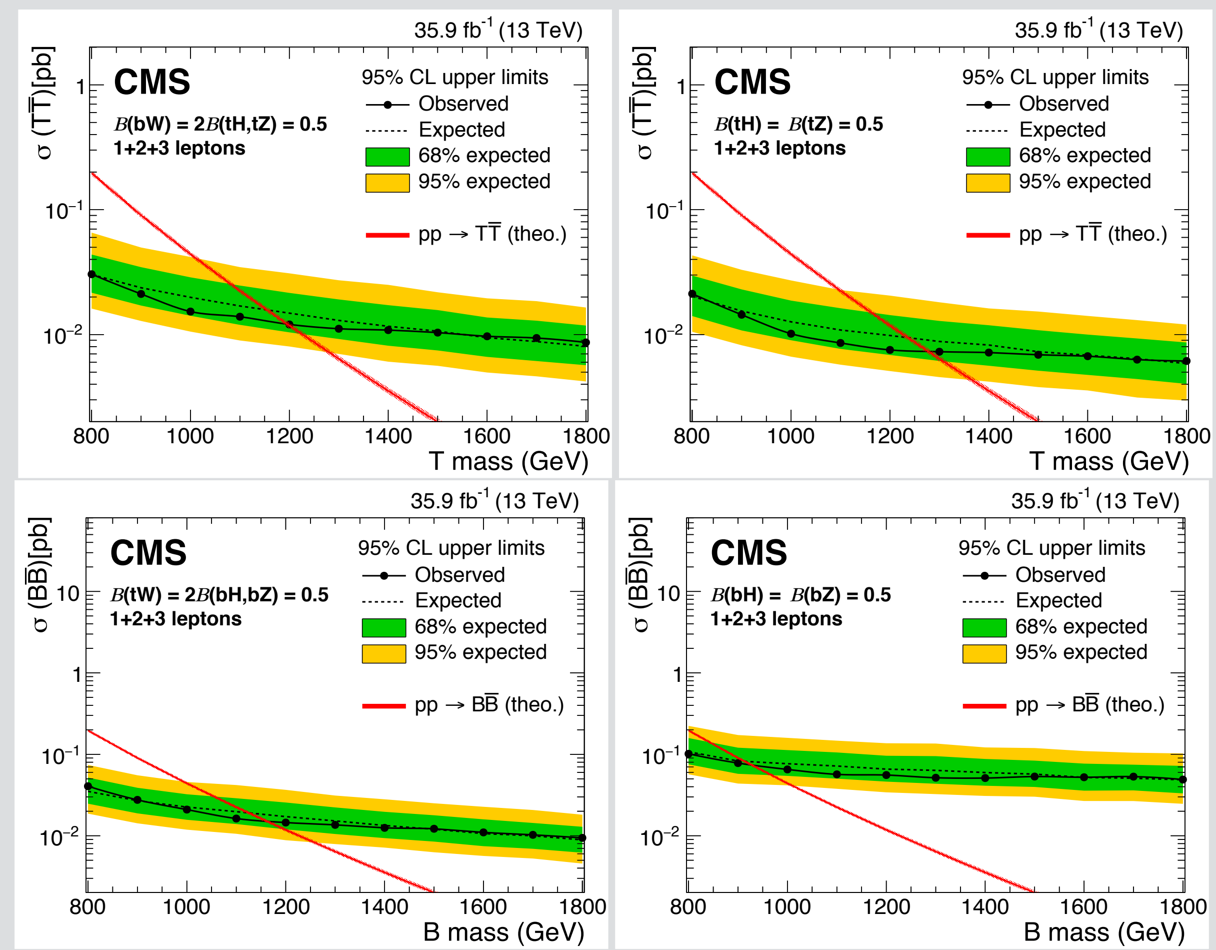
A.Deandrea - IRN Terascale

Sample recent bounds

- For VLQs assumptions on the decay channels and the couplings to the different SM generations may affect considerably the LHC bounds!



from ATLAS twiki



from CMS 1805.04758

A.Deandrea - IRN Terascale

Simplest multiplets (and SM quantum numbers)

	SM	Singlets	Doublets	Triplets
	$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$	(t') (b')	$\begin{pmatrix} X \\ t' \end{pmatrix} \begin{pmatrix} t' \\ b' \end{pmatrix} \begin{pmatrix} b' \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ t' \\ b' \end{pmatrix} \begin{pmatrix} t' \\ b' \\ Y \end{pmatrix}$
$SU(2)_L$	2	1	2	3
$U(1)_Y$	$q_L = 1/6$ $u_R = 2/3$ $d_R = -1/3$	2/3 -1/3	1/6 7/6 -5/6	2/3 -1/3
$\mathcal{L}_Y$	$-\frac{y_u^i v}{\sqrt{2}} \bar{u}_L^i u_R^i$ $-\frac{y_d^i v}{\sqrt{2}} \bar{d}_L^i V_{CKM}^{i,j} d_R^j$	$-\frac{\lambda_u^i v}{\sqrt{2}} \bar{u}_L^i U_R$ $-\frac{\lambda_d^i v}{\sqrt{2}} \bar{d}_L^i D_R$	$-\frac{\lambda_u^i v}{\sqrt{2}} U_L u_R^i$ $-\frac{\lambda_d^i v}{\sqrt{2}} D_L d_R^i$	$-\frac{\lambda_i v}{\sqrt{2}} \bar{u}_L^i U_R$ $-\lambda_i v \bar{d}_L^i D_R$
$\mathcal{L}_m$		$-M\bar{\psi}\psi$ (gauge invariant since vector-like)		
Free parameters		4 $M + 3 \times \lambda^i$	4 or 7 $M + 3\lambda_u^i + 3\lambda_d^i$	4 $M + 3 \times \lambda^i$

Simplified Mixing effects (t-T sector only)

- Yukawa coupling generates a mixing between the new state(s) and the SM ones

- Type 1 : singlet and triplets couple to SM L-doublet
  - Singlet ψ = (1, 2/3) = U : only a top partner is present
  - triplet ψ = (3, 2/3) = {X, U, D} , the new fermion contains a partner for both top and bottom, plus X with charge 5/3
  - triplet ψ = (3, −1/3) = {U, D, Y} , the new fermions are a partner for both top and bottom, plus Y with charge −4/3

$$\mathcal{L}_{\text{mass}} = -\frac{y_u v}{\sqrt{2}} \bar{u}_L u_R - x\, \bar{u}_L U_R - M\, \bar{U}_L U_R + h.c.$$

$$\begin{pmatrix} \cos\theta_u^L & -\sin\theta_u^L \\ \sin\theta_u^L & \cos\theta_u^L \end{pmatrix} \begin{pmatrix} \frac{y_u v}{\sqrt{2}} & x \\ 0 & M \end{pmatrix} \begin{pmatrix} \cos\theta_u^R & \sin\theta_u^R \\ -\sin\theta_u^R & \cos\theta_u^R \end{pmatrix}$$

Simplified Mixing effects (t-T sector only)

- Type 2 : new doublets couple to SM R-singlet
- SM doublet case ψ = (2, 1/6) = {U, D} , the vector-like fermions are a top and bottom partners
- non-SM doublets ψ = (2, 7/ 6) = {X, U} , the vector-like fermions are a top partner and a fermion X with charge 5/3
- non-SM doublets ψ = (2, -5/ 6) = {D,Y} , the vector-like fermions are a bottom partner and a fermion Y with charge -4/3

$$\mathcal{L}_{\rm mass} = -\frac{y_u v}{\sqrt{2}} \bar{u}_L u_R - x \bar{U}_L u_R - M \bar{U}_L U_R + h.c.$$

$$\begin{pmatrix} \cos\theta_u^L & -\sin\theta_u^L \\ \sin\theta_u^L & \cos\theta_u^L \end{pmatrix} \begin{pmatrix} \frac{y_u v}{\sqrt{2}} & 0 \\ x & M \end{pmatrix} \begin{pmatrix} \cos\theta_u^R & \sin\theta_u^R \\ -\sin\theta_u^R & \cos\theta_u^R \end{pmatrix}$$

Mixing 1VLQ (doublet) with the 3 SM generations

$$M_u = \begin{pmatrix} \tilde{m}_u & & & \\ & \tilde{m}_c & & \\ & & \tilde{m}_t & \\ x_1 & x_2 & x_3 & M \end{pmatrix} = V_L \cdot \begin{pmatrix} m_u & & & \\ & m_c & & \\ & & m_t & \\ & & & M \end{pmatrix} \cdot V_R^\dagger$$

$$V_L \implies M_u \cdot M_u^\dagger = \begin{pmatrix} \tilde{m}_u^2 & & & x_1^* \tilde{m}_u^2 \\ & \tilde{m}_c^2 & & x_2^* \tilde{m}_c^2 \\ & & \tilde{m}_t^2 & x_3 \tilde{m}_t^2 \\ x_1 \tilde{m}_u & x_2 \tilde{m}_c & x_3 \tilde{m}_t & |x_1|^2 + |x_2|^2 + x_3^2 + M^2 \end{pmatrix}$$

$m_q \propto \tilde{m}_q$

mixing is suppressed by quark masses

$$V_R \implies M_u^\dagger \cdot M_u = \begin{pmatrix} \tilde{m}_u^2 + |x_1|^2 & x_1^* x_2 & x_1^* x_3 & x_1^* M \\ x_2^* x_1 & \tilde{m}_c^2 + |x_2|^2 & x_2^* x_3 & x_2^* M \\ x_3 x_1 & x_3 x_2 & \tilde{m}_t^2 + x_3^2 & x_3 M \\ x_1 M & x_2 M & x_3 M & M^2 \end{pmatrix}$$

mixing in the right sector present also for $\tilde{m}_q \to 0$

flavour constraints for q_R are relevant

Mixing with more VL multiplets

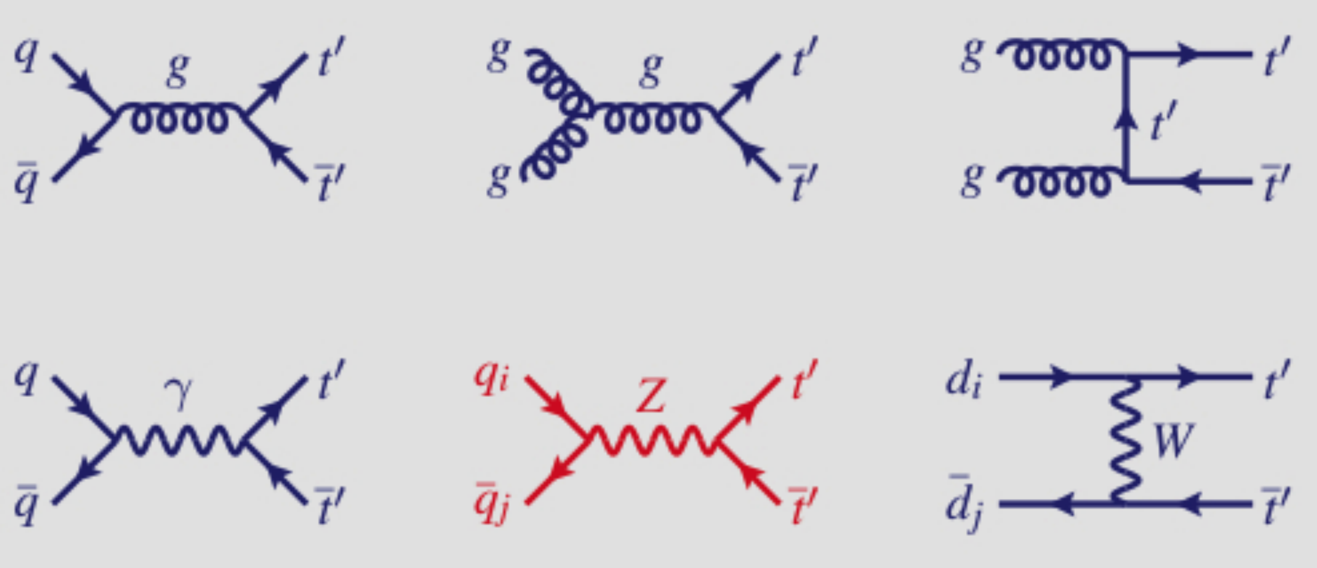
1305.4172 M.Buchkremer et al.

integer isospin multiplets

$$
\mathcal{L}_{\text{mass}} = \bar{q}_L \cdot \left(\begin{array}{ccc|ccc|ccc}
\mu_1 & 0 & 0 & 0 & \dots & 0 & x_{1,n_d+4} & \dots & x_{1,N} \\
0 & \mu_2 & 0 & 0 & \dots & 0 & x_{2,n_d+4} & \dots & x_{2,N} \\
0 & 0 & \mu_3 & 0 & \dots & 0 & x_{3,n_d+4} & \dots & x_{3,N} \\
\hline
y_{4,1} & y_{4,2} & y_{4,3} & M_4 & 0 & 0 & & & \\
\vdots & \vdots & \vdots & 0 & \ddots & 0 & & \omega_{\alpha\beta} & \\
y_{n_d+3,1} & y_{n_d+3,2} & y_{n_d+3,3} & 0 & 0 & M_{n_d+3} & & & \\
\hline
0 & 0 & 0 & & & & M_{n_d+4} & 0 & 0 \\
\vdots & \vdots & \vdots & & \omega'_{\alpha\beta} & & 0 & \ddots & 0 \\
0 & 0 & 0 & & & & 0 & 0 & M_N
\end{array}\right) \cdot q_R + h.c.
$$

semi-integer isospin multiplets

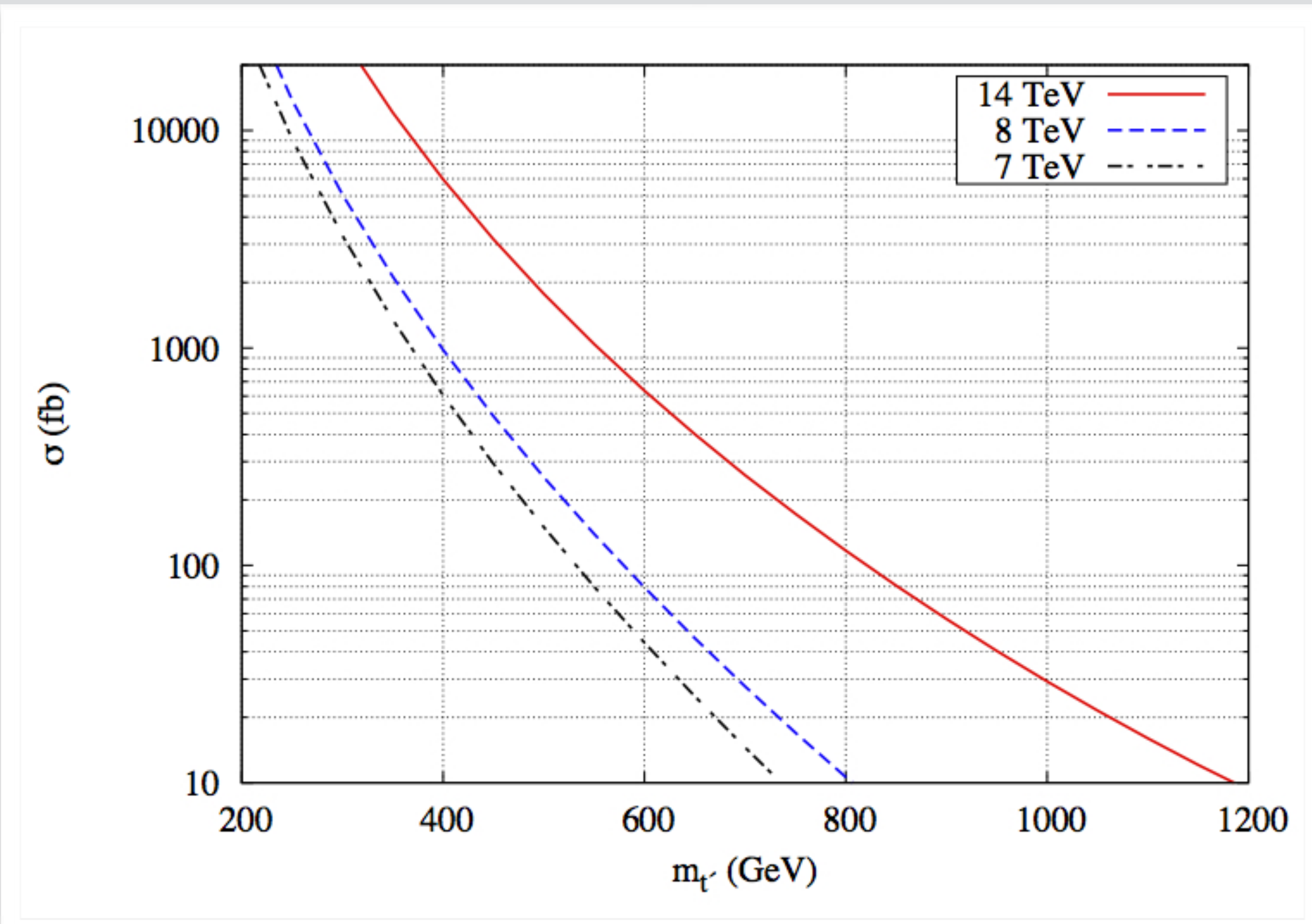
Pair production



Purely QCD diagrams
(dominant contribution)

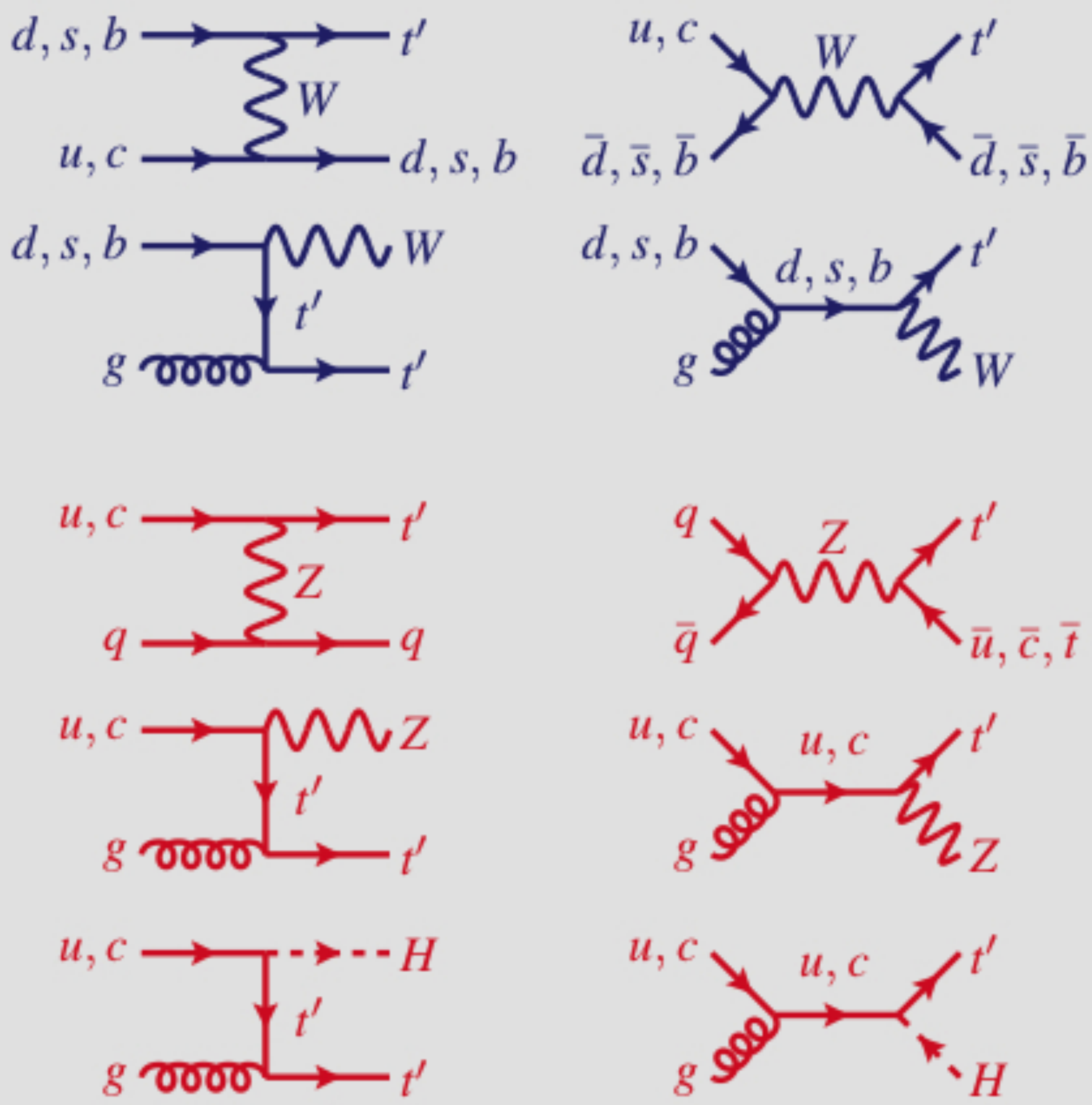
Purely EW diagrams

“new” FCNC channel,
but suppressed wrt to
QCD



Pair production for t’
of the non-SM doublet
pp → t' t @ LHC

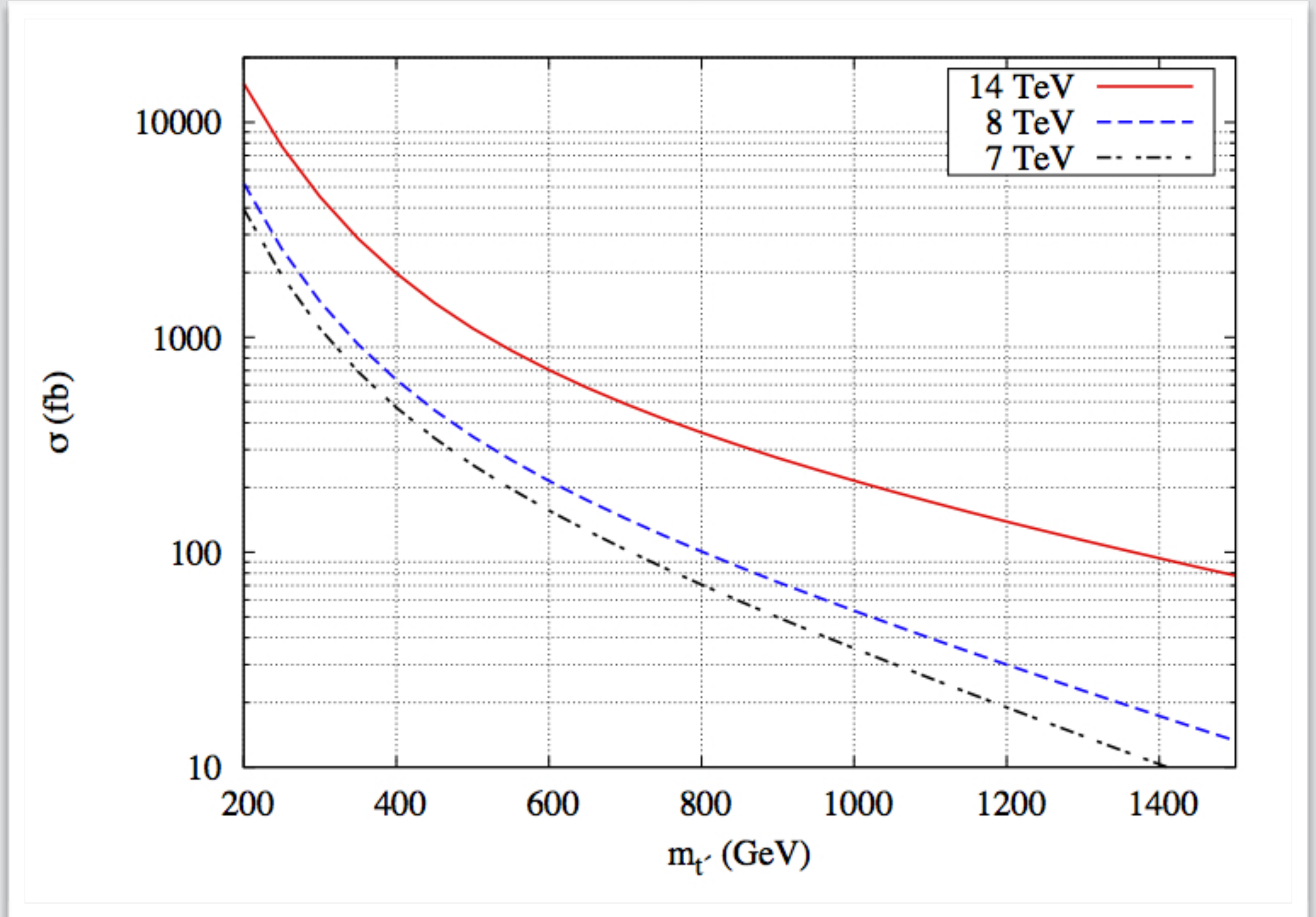
Single production



Charged current channels are suppressed in $(X \;\; t')$ doublet, non-suppressed in singlet and triplets

FCNCs channels can be relevant in single production especially in the singlet t' and $(X \;\; t')$ doublet

Single production



Non-SM doublet single t' production cross section as function of the t' mass

General parameterisation (example with a t')

- T' will in general couple with Wq, Zq, hq
- it is more physical to consider observables (BRs, cross-sections) rather than Lagrangian parameters
- Neglect SM quark masses here (full case in the paper)

$$BR(T \to V q_i) = \frac{\kappa_V^2 |V_{L/R}^{4i}|^2 \Gamma_V^0}{\left(\sum_{j=1}^3 |V_{L/R}^{4j}|^2\right)\left(\sum_{V'=W,Z,H} \kappa_{V'}^2 \Gamma_{V'}^0\right)}$$

$$\zeta_i = \frac{|V_{L/R}^{4i}|^2}{\sum_{j=1}^3 |V_{L/R}^{4j}|^2}, \quad \sum_{i=1}^3 \zeta_i = 1,$$

$$\xi_V = \frac{\kappa_V^2 \Gamma_V^0}{\sum_{V'=W,Z,H} \kappa_{V'}^2 \Gamma_{V'}^0}, \quad \sum_{V=W,Z,H} \xi_V = 1;$$

$$BR(T \to V q_i) = \zeta_i \xi_V$$

$$\zeta_{jet} = \zeta_1 + \zeta_2 = 1 - \zeta_3$$

- Only 5 independent parameters, M, ξ_W, ξ_Z, ζ_{jet}, κ
- Choosing multiplet selects ξ_W, ξ_Z

A.Deandrea - IRN Terascale

General parameterisation

- Complete Lagrangian

$$\mathcal{L} = \kappa_T \left\{ \sqrt{\frac{\zeta_i \xi_W^T}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{T}_L W_\mu^+ \gamma^\mu d_L^i] + \sqrt{\frac{\zeta_i \xi_Z^T}{\Gamma_Z^0}} \frac{g}{2c_W} [\bar{T}_L Z_\mu \gamma^\mu u_L^i] - \sqrt{\frac{\zeta_i \xi_H^T}{\Gamma_H^0}} \frac{M}{v} [\bar{T}_R H u_L^i] - \sqrt{\frac{\zeta_3 \xi_H^T}{\Gamma_H^0}} \frac{m_t}{v} [\bar{T}_L H t_R] \right\}$$
$$+ \kappa_B \left\{ \sqrt{\frac{\zeta_i \xi_W^B}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{B}_L W_\mu^- \gamma^\mu u_L^i] + \sqrt{\frac{\zeta_i \xi_Z^B}{\Gamma_Z^0}} \frac{g}{2c_W} [\bar{B}_L Z_\mu \gamma^\mu d_L^i] - \sqrt{\frac{\zeta_i \xi_H^B}{\Gamma_H^0}} \frac{M}{v} [\bar{B}_R H d_L^i] \right\}$$
$$+ \kappa_X \left\{ \sqrt{\frac{\zeta_i}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{X}_L W_\mu^+ \gamma^\mu u_L^i] \right\} + \kappa_Y \left\{ \sqrt{\frac{\zeta_i}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{Y}_L W_\mu^- \gamma^\mu d_L^i] \right\} + h.c.\,,$$

- Parameters: Mass + 4 (for T and B) or + 2 (for X and Y)

NLO extension

Example with T, B, X, Y VLQs

$$\mathcal{L}_{\rm VLQ} = i\bar{Y}\not{D}Y - m_{Y}\bar{Y}Y + i\bar{B}\not{D}B - m_{B}\bar{B}B + i\bar{T}\not{D}T - m_{T}\bar{T}T + i\bar{X}\not{D}X - m_{X}\bar{X}X$$
$$- h\left[\bar{B}\left(\hat{\kappa}_L^B P_L + \hat{\kappa}_R^B P_R\right)q_d + \bar{T}\left(\hat{\kappa}_L^T P_L + \hat{\kappa}_R^T P_R\right)q_u + \text{h.c.}\right]$$
$$+ \frac{g}{2c_W}\left[\bar{B}\not{Z}\left(\tilde{\kappa}_L^B P_L + \tilde{\kappa}_R^B P_R\right)q_d + \bar{T}\not{Z}\left(\tilde{\kappa}_L^T P_L + \tilde{\kappa}_R^T P_R\right)q_u + \text{h.c.}\right]$$
$$+ \frac{\sqrt{2}g}{2}\left[\bar{Y}\not{W}\left(\kappa_L^Y P_L + \kappa_R^Y P_R\right)q_d + \bar{B}\not{W}\left(\kappa_L^B P_L + \kappa_R^B P_R\right)q_u + \text{h.c.}\right]$$
$$+ \frac{\sqrt{2}g}{2}\left[\bar{T}\not{W}\left(\kappa_L^T P_L + \kappa_R^T P_R\right)q_d + \bar{X}\not{W}\left(\kappa_L^X P_L + \kappa_R^X P_R\right)q_u + \text{h.c.}\right]$$

similar to the previous, one more parameter to satisfy the renormalisation conditions

see Fuks & Shao (EPJC'17); Cacciapaglia, Cai, Carvalho, AD, Flacke, Fuks, Majumder & Shao (*in prep.*)

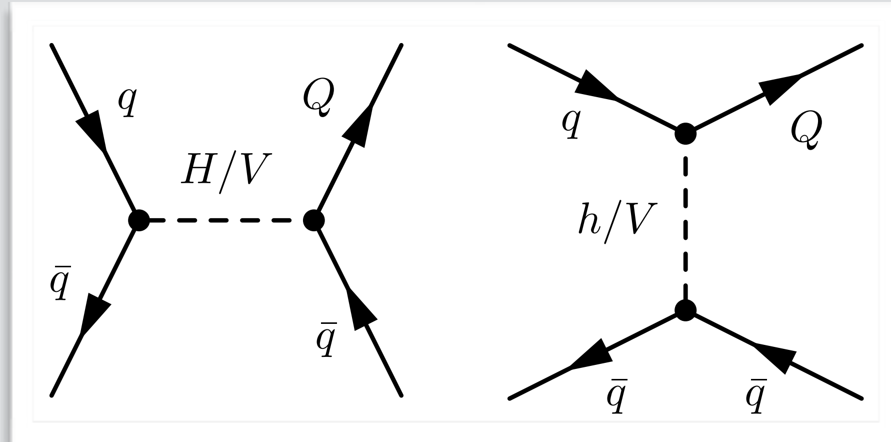
Pair production at 13 TeV

m_T [GeV]	Scenario	$\sigma_{\rm LO}$ [pb]	$\sigma_{\rm NLO}$ [pb]
400	QCD	$(7.069\ 10^{0})^{+32.0\%\,+2.7\%}_{-22.6\%\,-2.7\%}$	$(1.004\ 10^{1})^{+9.4\%\,+2.5\%}_{-11.3\%\,-2.5\%}$
	TH1	$(7.022\ 10^{0})^{+30.2\%\,+1.2\%}_{-23.8\%\,-4.1\%}$	$(9.980\ 10^{0})^{+8.0\%\,+1.2\%}_{-12.5\%\,-3.8\%}$
800	QCD	$(1.261\ 10^{-1})^{+33.2\%\,+3.8\%}_{-23.2\%\,-3.8\%}$	$(1.733\ 10^{-1})^{+8.5\%\,+4.4\%}_{-11.1\%\,-4.4\%}$
	TH1	$(1.244\ 10^{-1})^{+18.8\%\,+7.3\%}_{-31.2\%\,-14.0\%}$	$(1.702\ 10^{-1})^{+2.3\%\,+6.0\%}_{-20.0\%\,-13.9\%}$
1200	QCD	$(7.685\ 10^{-3})^{+34.0\%\,+5.8\%}_{-23.7\%\,-5.8\%}$	$(1.061\ 10^{-2})^{+8.8\%\,+5.8\%}_{-11.4\%\,-5.8\%}$
	TH1	$(1.053\ 10^{-2})^{+1.7\%\,+18.4\%}_{-36.7\%\,-25.8\%}$	$(1.372\ 10^{-2})^{+16.6\%\,+18.2\%}_{-29.0\%\,-25.8\%}$
1600	QCD	$(7.477\ 10^{-4})^{+34.9\%\,+8.5\%}_{-24.2\%\,-8.5\%}$	$(1.030\ 10^{-3})^{+9.0\%\,+8.6\%}_{-11.6\%\,-8.6\%}$
	TH1	$(3.395\ 10^{-3})^{+3.3\%\,+13.3\%}_{-27.0\%\,-19.9\%}$	$(4.117\ 10^{-3})^{+14.6\%\,+14.4\%}_{-21.8\%\,-20.9\%}$
2000	QCD	$(8.980\ 10^{-5})^{+35.5\%\,+18.3\%}_{-24.5\%\,-18.3\%}$	$(1.260\ 10^{-4})^{+8.7\%\,+17.8\%}_{-11.7\%\,-17.8\%}$
	TH1	$(1.563\ 10^{-3})^{+4.2\%\,+5.4\%}_{-20.0\%\,-13.0\%}$	$(1.960\ 10^{-3})^{+6.3\%\,+6.0\%}_{-14.0\%\,-13.6\%}$

Fuks & Shao (EPJC'17): example of T-Higgs-quark interaction, NNPDF 3.0

NLO increases σ and reduced scale uncertainty

Single production at 13 TeV



Example of VLQ-h-q interaction. Production in association with jets in setups with first and second quark generation mixings

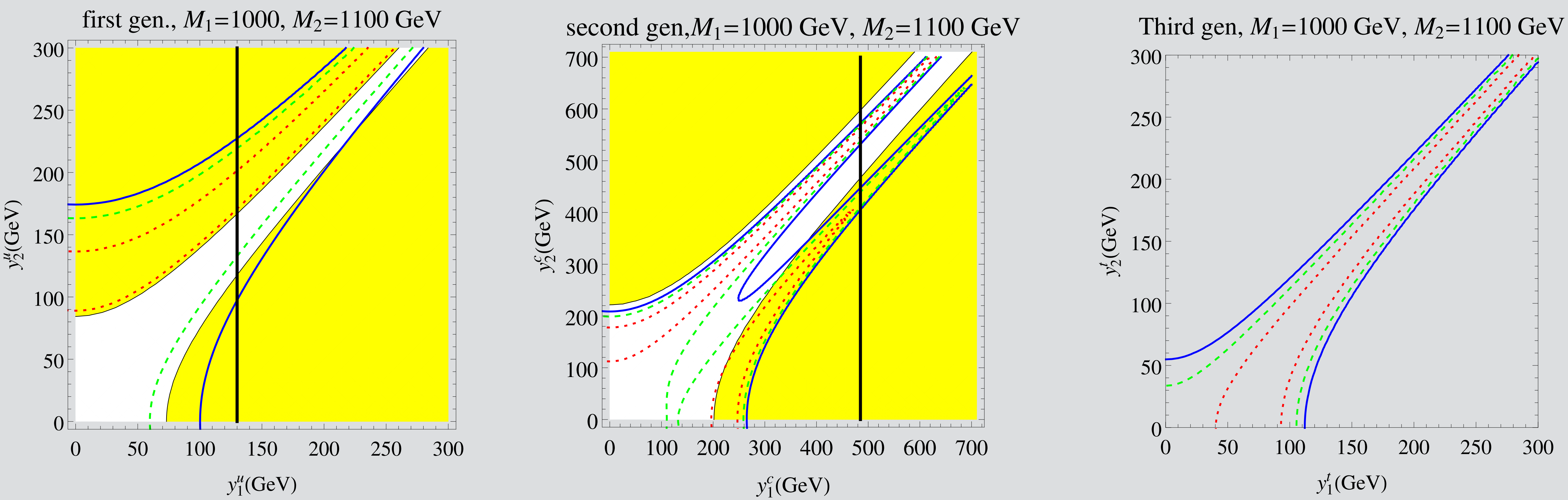
Rate almost unchanged here due to interplay with the PDFs.

1st and 2nd generation mixings with κ_1 =0.07 and κ_2 =0.2

Fuks & Shao (EPJC'17)

m_T [GeV]	Scenario	$\sigma_{\rm LO}$ [pb]	$\sigma_{\rm NLO}$ [pb]
400	**TZ1**	$(1.995\ 10^{0})^{+2.6\%+1.6\%}_{-2.7\%-1.6\%}$	$(1.987\ 10^{0})^{+0.8\%+1.7\%}_{-0.6\%-1.7\%}$
	TZ2	$(2.613\ 10^{0})^{+0.1\%+1.2\%}_{-1.0\%-1.2\%}$	$(2.685\ 10^{0})^{+1.1\%+1.2\%}_{-0.6\%-1.2\%}$
	TW1	$(1.541\ 10^{0})^{+3.4\%+2.4\%}_{-3.3\%-2.4\%}$	$(1.575\ 10^{0})^{+0.9\%+2.4\%}_{-0.2\%-2.4\%}$
	TW2	$(4.229\ 10^{0})^{+1.1\%+4.5\%}_{-1.5\%-4.5\%}$	$(4.392\ 10^{0})^{+1.1\%+4.4\%}_{-0.3\%-4.4\%}$
1200	**TZ1**	$(2.214\ 10^{-1})^{+8.2\%+1.9\%}_{-7.1\%-1.9\%}$	$(2.483\ 10^{-1})^{+1.4\%+2.0\%}_{-1.9\%-2.0\%}$
	TZ2	$(1.168\ 10^{-1})^{+5.6\%+3.2\%}_{-5.3\%-3.2\%}$	$(1.348\ 10^{-1})^{+1.6\%+2.9\%}_{-1.6\%-2.9\%}$
	TW1	$(1.572\ 10^{-1})^{+8.9\%+3.5\%}_{-7.6\%-3.5\%}$	$(1.812\ 10^{-1})^{+1.9\%+3.5\%}_{-2.4\%-3.5\%}$
	TW2	$(2.476\ 10^{-1})^{+7.3\%+12.0\%}_{-6.5\%-12.0\%}$	$(2.878\ 10^{-1})^{+2.0\%+11.3\%}_{-2.2\%-11.3\%}$
2000	**TZ1**	$(4.721\ 10^{-2})^{+10.9\%+2.4\%}_{-9.2\%\ -2.4\%}$	$(5.771\ 10^{-2})^{+2.9\%+2.4\%}_{-3.5\%-2.4\%}$
	TZ2	$(1.277\ 10^{-2})^{+8.7\%+7.0\%}_{-7.8\%-7.0\%}$	$(1.600\ 10^{-2})^{+3.0\%+6.6\%}_{-3.1\%-6.6\%}$
	TW1	$(3.105\ 10^{-2})^{+11.5\%+5.0\%}_{-9.7\%\ -5.0\%}$	$(3.899\ 10^{-2})^{+3.5\%+4.7\%}_{-4.0\%-4.7\%}$
	TW2	$(3.725\ 10^{-2})^{+10.1\%+24.7\%}_{-8.7\%\ -24.7\%}$	$(4.653\ 10^{-2})^{+3.2\%+23.1\%}_{-3.6\%-23.1\%}$

Interplay of VLQ multiplets



Tree level (yellow area is excluded at 3σ), EWPT (blue continuous line corresponds to the 3σ bound, green dashed to 2σ, red dotted to 1σ, the strip between the lines is allowed) and LHC single VLQ production bounds (vertical black line, excluded region on the right) in the case of mixing of two VLQ doublets with the first, second or third SM quark generation (KEK-TH-2024, paper to appear on ArXiv this week and 1502.00370).

Vector-Like Leptons

- VL-Leptons are present both in model building (GUT, Xdim...) and in simplified approaches for Dark matter
- A VL-Lepton family coupled to the SM leptons is constrained mainly by:
    - muon anomalous magnetic moment
    - electron, muon and tau left-right (and forward-backward) asymmetry in Z decay
    - Lepton flavour violation, lepton non-universality in B decays
    - Electroweak precision tests
- Mass bound for VL charged leptons > 100 GeV (LEP) but depends on decay modes assumptions
- VL-Leptons are also used in connection with Dark Matter in simplified models (and usually have the same new parity as the DM particle)

Focus on this case in the following

VLL and DM singlet

$$\mathcal{L}_1^S = \sum_{f=e,\mu,\tau} \left[\lambda_{11}^f \bar{E} P_R e_f + \lambda_{21}^f \left(\bar{N}\ \bar{E}\right) P_L \begin{pmatrix} \nu_f \\ e_f \end{pmatrix} \right] S_{DM}^0 + h.c.$$

$$\mathcal{L}_1^V = \sum_{f=e,\mu,\tau} \left[g_{11}^f \bar{E} \gamma_\mu P_R e_f + g_{21}^f \left(\bar{N}\ \bar{E}\right) \gamma_\mu P_L \begin{pmatrix} \nu_f \\ e_f \end{pmatrix} \right] V_{DM}^{0\mu} + h.c.$$

- VLL can be singlet or doublet of SU(2)w
- DM and VLL are both odd under a Z2 parity
- VLL couplings to SM fermions and DM are only L or R depending on the multiplet

VLL and DM doublet

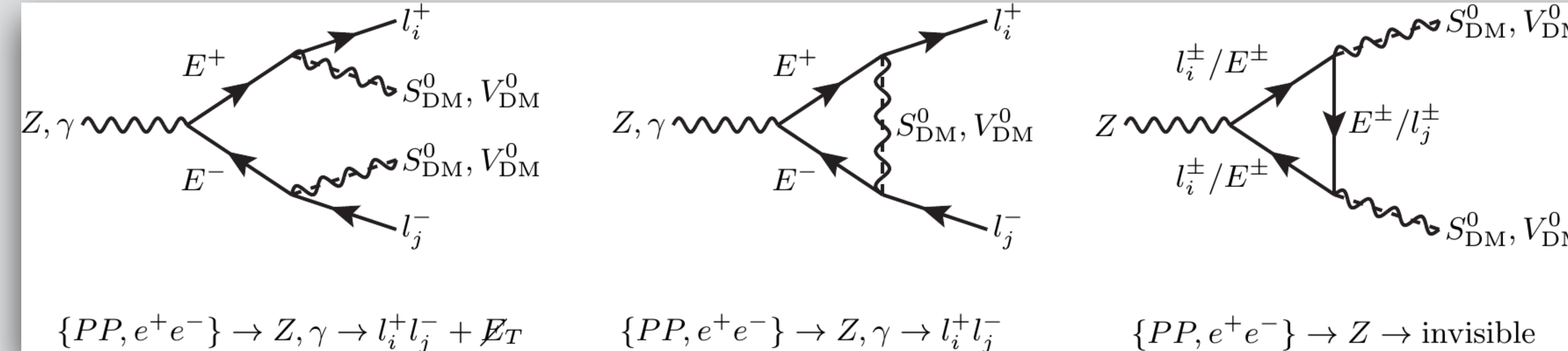
$$\mathcal{L}_2^S = \sum_{f=e,\mu,\tau} \left[\lambda_{12}^f \bar{E} P_L \begin{pmatrix} \nu_f \\ e_f \end{pmatrix} + \lambda_{22}^f \bar{\Psi}_{-1/2} P_R e_f \right] \Sigma_{\rm DM} + \left[(\lambda_{22}^f)' \bar{\Psi}_{-3/2} P_R e_f \right] \Sigma_{\rm DM}^c + h.c.$$

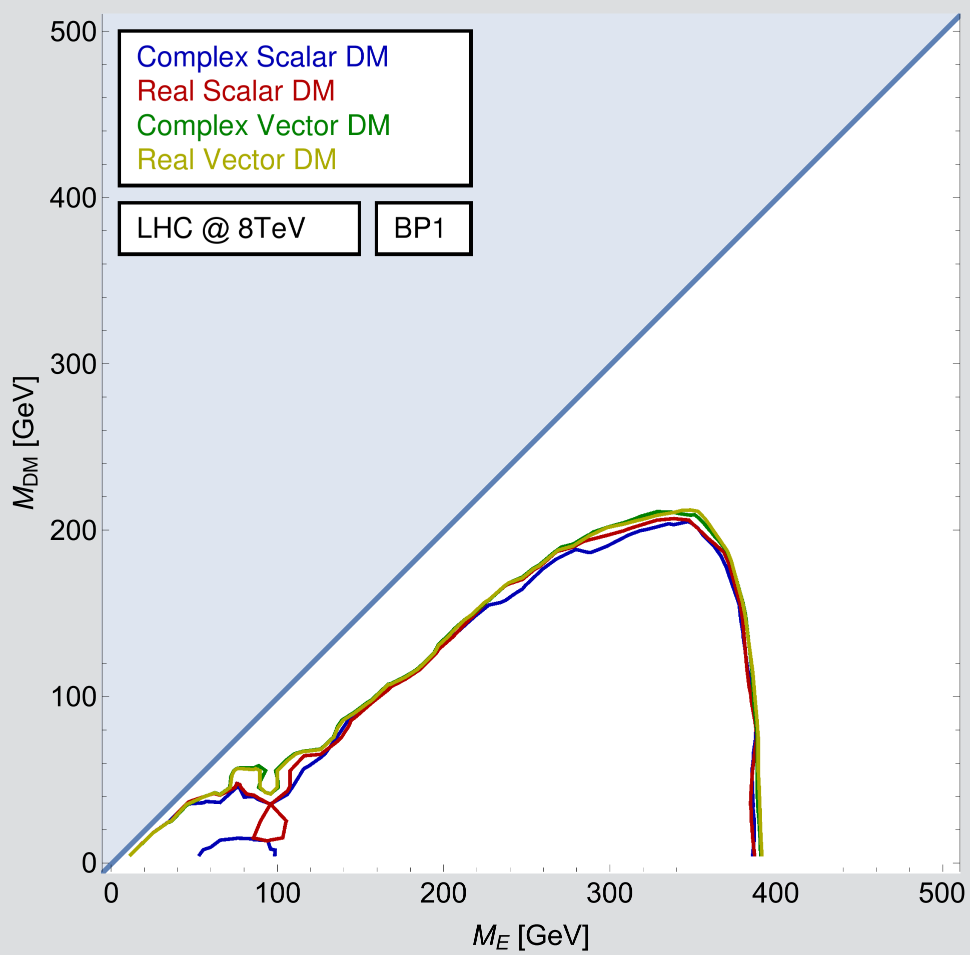
$$\mathcal{L}_2^V = \sum_{f=e,\mu,\tau} \left[g_{12}^f \bar{E} \gamma^\mu P_L \begin{pmatrix} \nu_f \\ e_f \end{pmatrix} + g_{22}^f \bar{\Psi}_{-1/2} \gamma_\mu P_R e_f \right] \mathcal{V}_{\rm DM}^\mu + \left[(g_{22}^f)' \bar{\Psi}_{-3/2} \gamma_\mu P_R e_f \right] \mathcal{V}_{\rm DM}^{c,\mu} + h.c.$$

- Gauge couplings of VLL depend on the representation (ex. coupling to W only for VLL doublet)

$$\begin{aligned}
\mathcal{L}_{AXL} &= -eA^\mu \bar{E} \gamma_\mu E \\
\mathcal{L}_{ZXL} &= Z^\mu \bar{E} \gamma_\mu \left(g_L^{ZEE} P_L + g_R^{ZEE} P_R \right) E + Z^\mu \bar{N} \gamma_\mu \left(g_L^{ZNN} P_L + g_R^{ZNN} P_R \right) N \\
\mathcal{L}_{WXL} &= W^{+\mu} \bar{N} \gamma_\mu \left(g_L^{WLN} P_L + g_R^{WLN} P_R \right) E + h.c
\end{aligned}$$

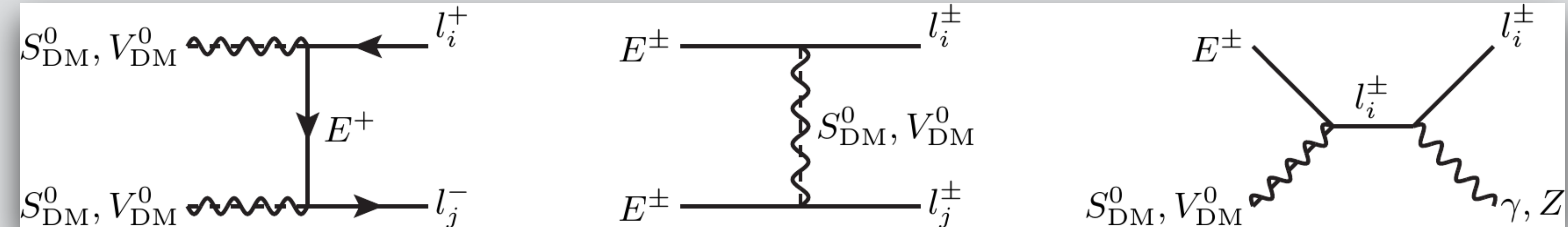
Collider signatures

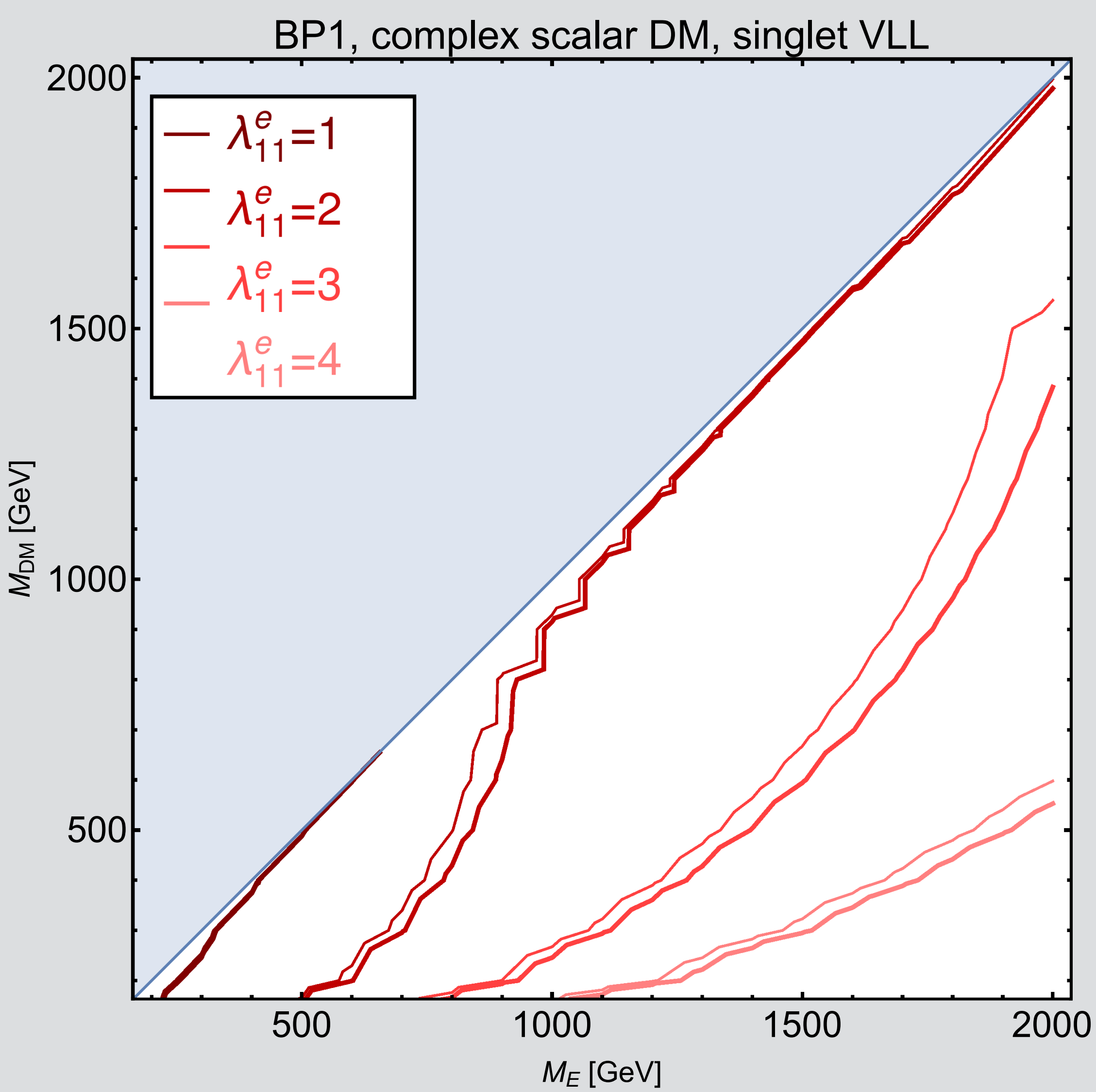




Sample bound of VL pair production with coupling to electrons only. 13 TeV bound is similar.

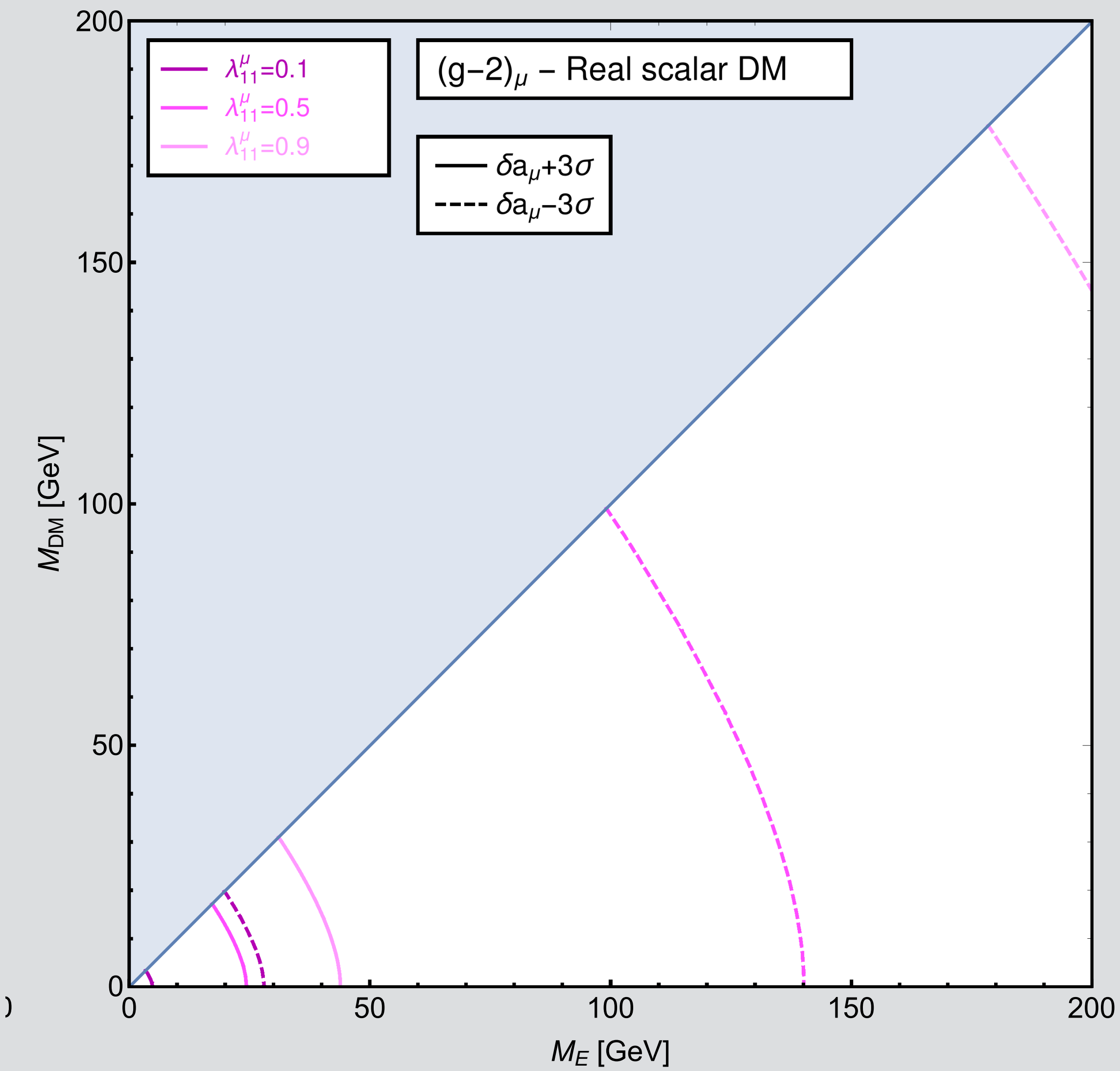
Relic density

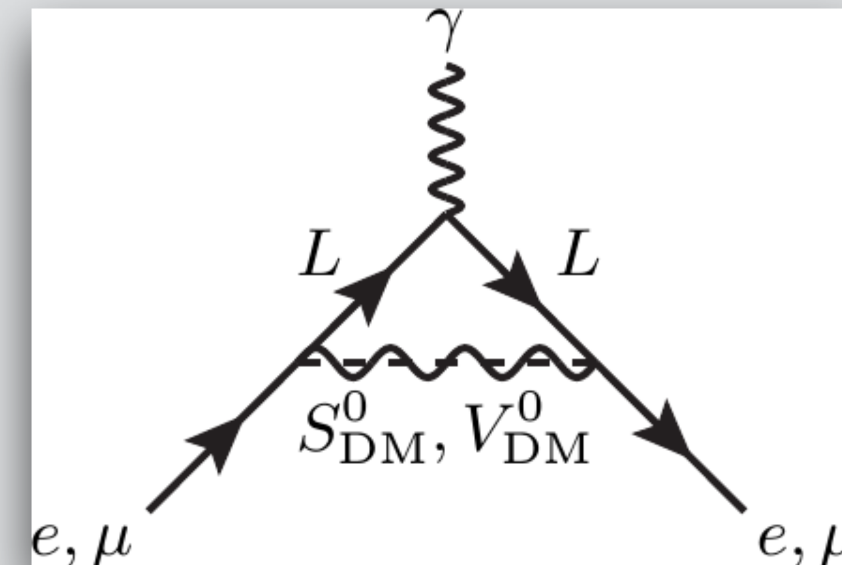




Sample relic density limit (excluded on the right of the thick line)

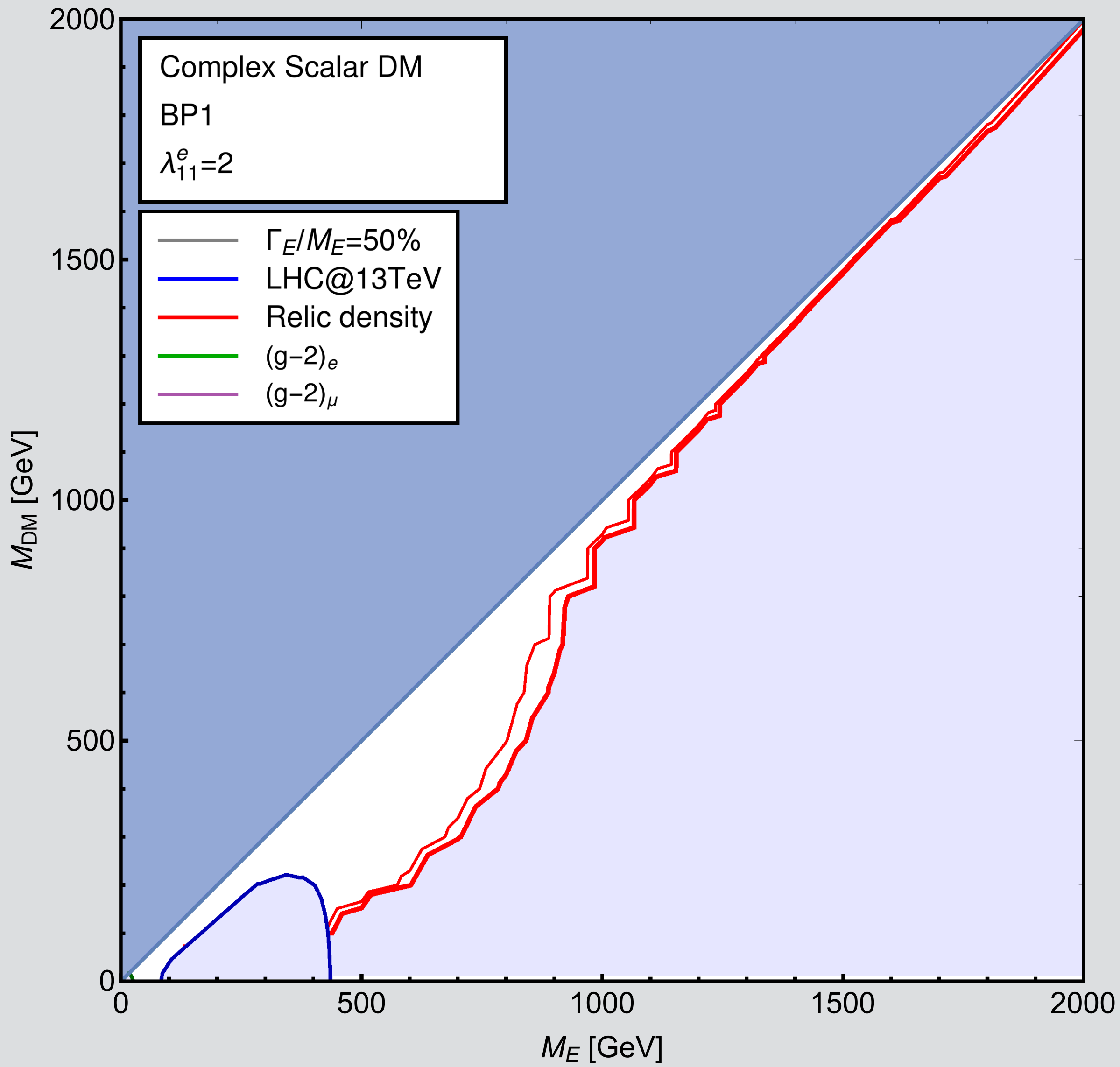
g-2 of the muon, electron





Allowed bands from g-2 for different coupling values in the M_E,M_{DM} plane.

Combined bounds



For coupling to electrons (BP1) a vectorial DM is excluded by the complementarity between $(g-2)_e$, which requires a coupling $g_{11} < 0.02$, and relic density, which requires a coupling $g_{11} > 0.3$. Scalar DM is allowed but constrained (white area). Similar situation for coupling to muons only (BP2). For details see 1801.02707

Conclusions

- Current limits with LHC data are in the TeV region in mass for VLQs (actual limit depends on the couplings and decay modes).
- In the realistic (for model building) case of more than 1 multiplet cancellations are present.
- VLL have mainly constraints from lower energy observables.
- DM and VLL, even in simplified models, allows to limit or exclude some cases using existing data.