Phenomenology of Composite Resonances

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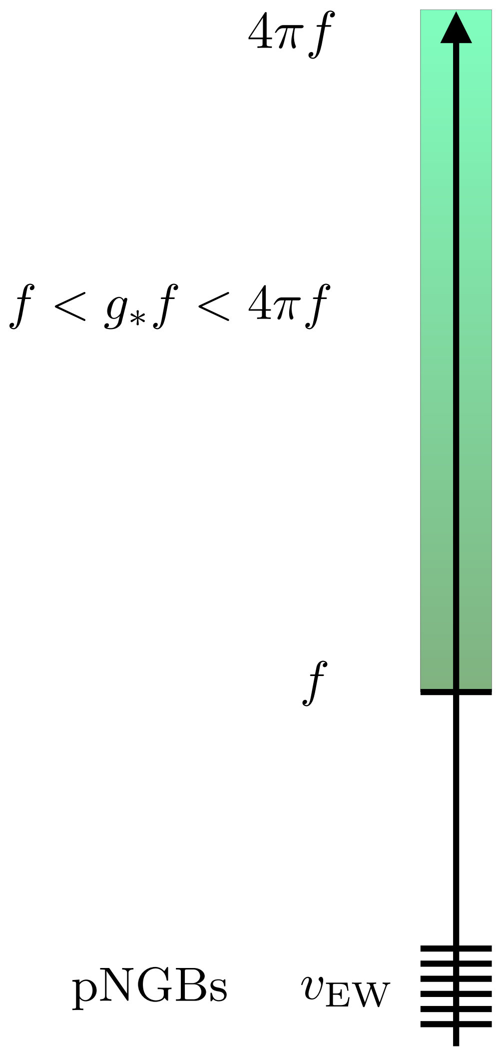
Composite Resonances



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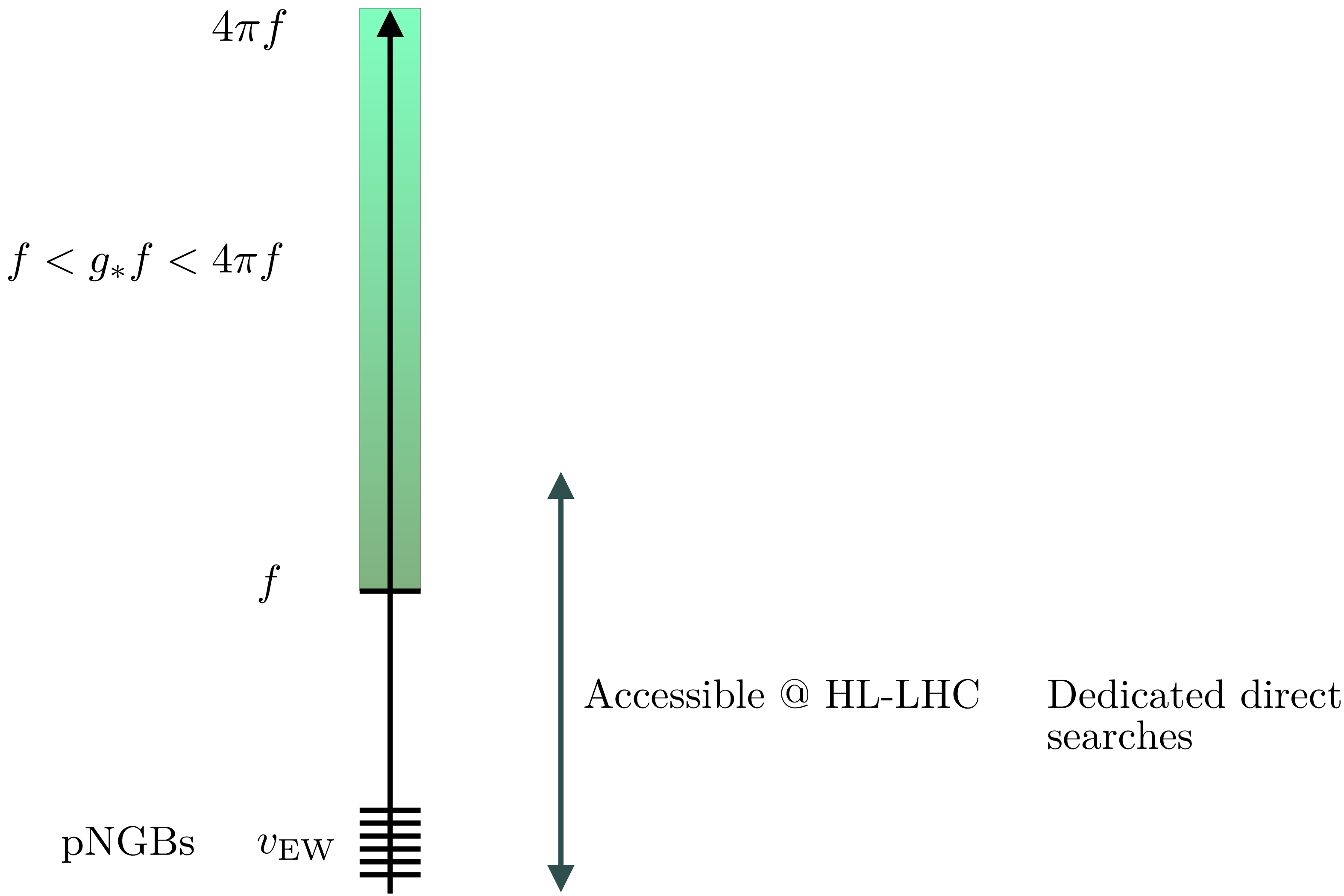

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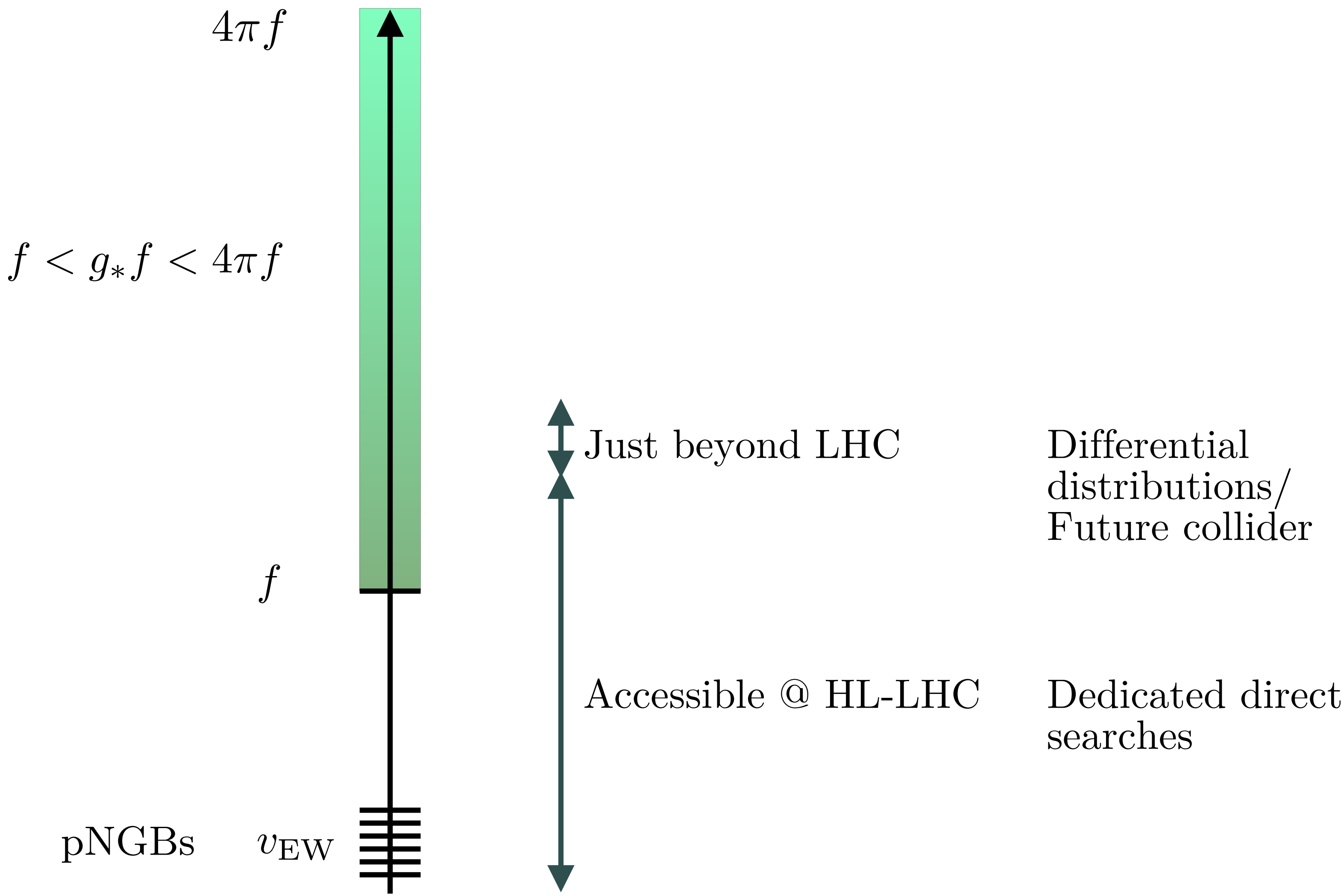

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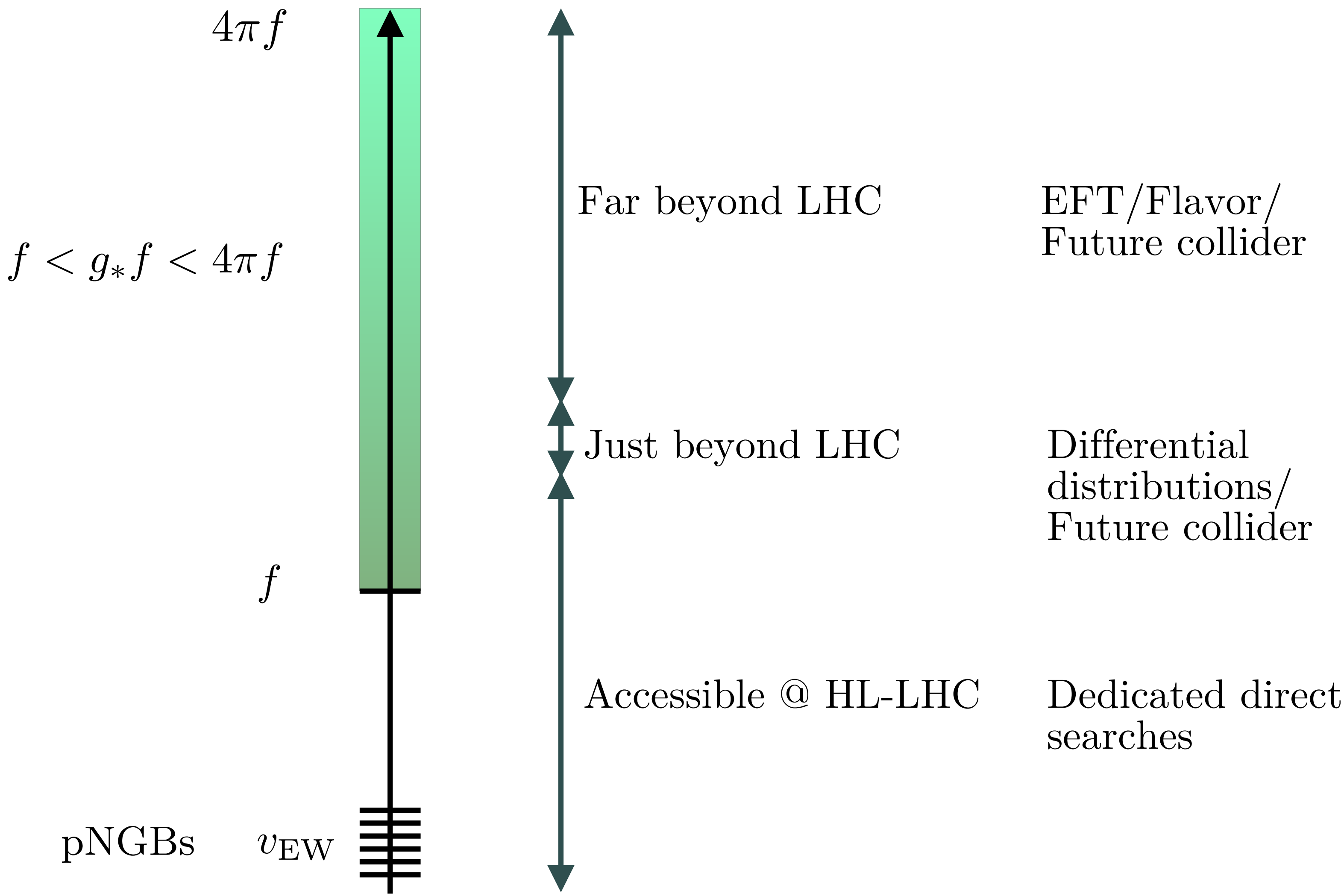


Composite Higgs: global symmetries

$$\left[\frac{G}{H}\right]_{\text{EW}} \times \left[\frac{G}{H}\right]_{\text{color}} \times U(1)$$

$\langle\psi\psi\rangle$

$\langle\chi\chi\rangle$

$$\frac{SU(4)}{Sp(4)} \quad \frac{SU(5)}{SO(5)} \quad \frac{SU(4)\times SU(4)}{SU(4)}$$

$$\frac{SU(6)}{Sp(6)} \quad \frac{SU(6)}{SO(6)} \quad \frac{SU(3)\times SU(3)}{SU(3)}$$

Composite Higgs: global symmetries

$$\left[\frac{G}{H}\right]_{\mathrm{EW}} \times \left[\frac{G}{H}\right]_{\mathrm{color}} \times U(1)$$

$\langle\psi\psi\rangle$ $\langle\chi\chi\rangle$

$$\frac{SU(4)}{Sp(4)} \quad \frac{SU(5)}{SO(5)} \quad \frac{SU(4)\times SU(4)}{SU(4)} \qquad \frac{SU(6)}{Sp(6)} \quad \frac{SU(6)}{SO(6)} \quad \frac{SU(3)\times SU(3)}{SU(3)}$$

$\mathbf{A}_2$ of $Sp(4) \to (1,1) + (2,2)$

$\mathbf{S}_2$ of $SO(5) \to (1,1) + (2,2) + (3,3)$

$\mathbf{Ad}$ of $SU(4)_D \to (1,1) + 2.(2,2) + (3,1) + (1,3)$

$\mathbf{A}_2$ of $Sp(6) \to 8 + 3 + \bar{3}$

$\mathbf{S}_2$ of $SO(6) \to 8 + 6 + \bar{6}$

$\mathbf{Ad}$ of $SU(3) \to 8$

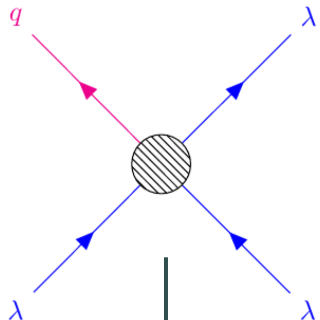
U(1) breaking gives an ALP

Coset	HC	ψ	χ	$-q_\chi/q_\psi$	Baryon	Name	Lattice
$\frac{SU(5)}{SO(5)} \times \frac{SU(6)}{SO(6)}$	SO(7)	$5 \times \mathbf{F}$	$6 \times \mathbf{Sp}$	5/6	$\psi\chi\chi$	M1	
	SO(9)			5/12		M2	
	SO(7)	$5 \times \mathbf{Sp}$	$6 \times \mathrm{F}$	5/6	$\psi\psi\chi$	M3	
	SO(9)			5/3		M4	
$\frac{SU(5)}{SO(5)} \times \frac{SU(6)}{Sp(6)}$	Sp(4)	$5 \times \mathbf{A}_2$	$6 \times \mathbf{F}$	5/3	$\psi\chi\chi$	M5	√
$\frac{SU(5)}{SO(5)} \times \frac{SU(3)^2}{SU(3)}$	SU(4)	$5 \times \mathbf{A}_2$	$3 \times (\mathbf{F}, \overline{\mathbf{F}})$	5/3	$\psi\chi\chi$	M6	√
	SO(10)	$5 \times \mathbf{F}$	$3 \times (\mathbf{Sp}, \overline{\mathbf{Sp}})$	5/12		M7	
$\frac{SU(4)}{Sp(4)} \times \frac{SU(6)}{SO(6)}$	Sp(4)	$4 \times \mathbf{F}$	$6 \times \mathbf{A}_2$	1/3	$\psi\psi\chi$	M8	√
	SO(11)	$4 \times \mathbf{Sp}$	$6 \times \mathbf{F}$	8/3		M9	
$\frac{SU(4)^2}{SU(4)} \times \frac{SU(6)}{SO(6)}$	SO(10)	$4 \times (\mathbf{Sp}, \overline{\mathbf{Sp}})$	$6 \times \mathbf{F}$	8/3	$\psi\psi\chi$	M10	
	SU(4)	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$6 \times \mathbf{A}_2$	2/3		M11	√
$\frac{SU(4)^2}{SU(4)} \times \frac{SU(3)^2}{SU(3)}$	SU(5)	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$3 \times (\mathbf{A}_2, \overline{\mathbf{A}_2})$	4/9	$\psi\psi\chi$	M12	

G Cacciapaglia, G Ferretti et. al. [1902.06890]

Spin-1/2 resonances

Partial compositeness: top-partners

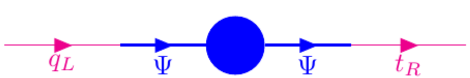


$$\sim \frac{c_{\rm UV}^2}{\Lambda_{\rm UV}^2} q\lambda^3 \qquad \Lambda_{\rm UV} \gg \Lambda_{\rm HC} \sim 4\pi f$$

$$\text{Vector}-\text{like quark}: \Psi \equiv \lambda^3$$

$$\sim c_{\rm UV}^2 \left(\frac{\Lambda_{\rm HC}}{\Lambda_{\rm UV}}\right)^{2-\gamma} \Lambda_{\rm HC} q\Psi \sim \kappa \Lambda_{\rm HC} q\Psi$$

EWSB



$$\propto \kappa_L \kappa_R v \sim 173 \text{ GeV}$$

Requirements:

- Nearly conformal dynamics above confinement scale
- **Large anomalous dimension** to reproduce top mass

- Physical states are mixture of elementary and composite degrees of freedom
- Top quark is more composite compared to lighter quarks

Examples

VLQ Review by SHIFT (in preparation)

Spin	Symbol	Quantum numbers $[SU(3)_c \times SU(2)_L]_{U(1)_Y}$	Components	Composite Higgs models $\frac{SO(5)}{SO(4)}$	$\frac{SU(4)}{Sp(4)}$	$\frac{SU(5)}{SO(5)}$	$\frac{SU(4)^2}{SU(4)}$
0	η	$(\mathbf{1},\mathbf{1})_\mathbf{0}$	η	–	✓	✓	✓
	Φ	$(\mathbf{1},\mathbf{2})_{\mathbf{1/2}}$	$\begin{pmatrix} \phi^\pm \\ \phi^0 \end{pmatrix}$	–	–	–	✓
	Δ	$(\mathbf{1},\mathbf{3})_\mathbf{0}$	$\begin{pmatrix} \Delta^0 & \Delta^+ \\ \Delta^- & \Delta^0 \end{pmatrix}$	–	–	✓	✓
	Σ	$(\mathbf{1},\mathbf{3})_\mathbf{1}$	$\begin{pmatrix} \Sigma^+ & \Sigma^{++} \\ \Sigma^0 & \Sigma^- \end{pmatrix}$	–	–	✓	–
1/2	$T_{2/3}$	$(\mathbf{3},\mathbf{1})_{\mathbf{2/3}}$	$T_{2/3}$	✓	✓	✓	✓
	$B_{-1/3}$	$(\mathbf{3},\mathbf{1})_{-\mathbf{1/3}}$	$B_{-1/3}$	✓	✓	✓	✓
	$\Psi_{2_{1/6}}$	$(\mathbf{3},\mathbf{2})_{\mathbf{1/6}}$	$(T_{2/3}, B_{-1/3})$	✓	✓	✓	✓
	$\Psi_{2_{7/6}}$	$(\mathbf{3},\mathbf{2})_{\mathbf{7/6}}$	$(X_{5/3}, T_{2/3})$	✓	✓	✓	✓
	$\Psi_{3_{-1/3}}$	$(\mathbf{3},\mathbf{3})_{-\mathbf{1/3}}$	$(T_{2/3}, B_{-1/3}, U_{-4/3})$	✓	–	✓	–
	$\Psi_{3_{2/3}}$	$(\mathbf{3},\mathbf{3})_{\mathbf{2/3}}$	$(X_{5/3}, T_{2/3}, B_{-1/3})$	✓	✓	✓	✓
	$\Psi_{3_{5/3}}$	$(\mathbf{3},\mathbf{3})_{\mathbf{5/3}}$	$(Y_{8/3}, X_{5/3}, T_{2/3})$	✓	–	✓	–

For fermions in higher SU(3) irreps: G Cacciapaglia, T Flacke, M Kunkel, W Porod [2112.00019]

Modelling resonances

- Model dependent chiral EFT: use global symmetries
- Simplified model: SU(3)xU(1) invariant Lagrangian
- Model independent EFT: Full SM invariant Lagrangian

Modelling resonances

Model dependent chiral EFT: use global symmetries

Simplified model: SU(3)xU(1) invariant Lagrangian

Model independent EFT: Full SM invariant Lagrangian

$$\mathcal{L}_{\rm pNGB} = \frac{f^2}{2}\mathrm{tr}\left[(D_\mu\Sigma)^\dagger(D^\mu\Sigma)\right]$$

$$\mathcal{L}_{\rm elem.} = \bar{q}_L iDq_L + \bar{t}_R iDt_R + \bar{b}_R iDb_R$$

$$\mathcal{L}_{\rm P.C.} = \kappa_L f\bar{\hat{q}}_L\Sigma\Psi_R + \kappa_R f\bar{\Psi}_L\Sigma\hat{t}_R$$

$$\mathcal{L} = \mathcal{L}_{\rm pNGB} + \mathcal{L}_{\rm anom.} + \mathcal{L}_{\rm elem.} + \mathcal{L}_{\Psi^2} + \mathcal{L}_{\rm P.C.} - V_{\rm pot.}$$

$$\mathcal{L}_{WZW} = \frac{i\,\dim(\psi)}{48\pi^2}\int\left(dAAdUU^\dagger + AdAdUU^\dagger + ...\right)$$

$$V_{\rm pot.} = B_m\mathrm{tr}\left[\epsilon^* U + \mathrm{h.c.}\right] + B_g\mathrm{tr}\left[g^2 T_L^a U T_L^{a*} U^\dagger\right] + ...$$

$$\mathcal{L}_{\Psi^2} = \mathrm{tr}\left[\bar{\Psi} iD\Psi\right] - M\mathrm{tr}\left[\bar{\Psi}\Psi\right] + \lambda\mathrm{tr}\left[\bar{\Psi}\partial\Sigma\Psi\right]$$

Ingredients : $\quad$ pNGB matrix(Σ), VLQ irrep(Ψ), Quark embeddings($\hat{q}_L, \hat{t}_R, \hat{b}_R$)

Modelling resonances

Model dependent chiral EFT: use global symmetries

Simplified model: SU(3)xU(1) invariant Lagrangian

Model independent EFT: Full SM invariant Lagrangian

$$\mathcal{L}_{Q^2+S^2} = \bar{Q}\left(iD - m_Q\right)Q + \left(|D_\mu S|^2 - m_S^2|S|^2\right)$$

$$\mathcal{L}_Q = \left[\kappa^W_{T,L}\bar{T}_{2/3}W^+P_L b + \kappa^W_{X,L}\bar{X}_{5/3}W^+P_L t + ...\right] + \left[\kappa^Z_{T,L}\bar{T}_{2/3}ZP_L t + ...\right] + h\left[\kappa^h_{T,L}\bar{T}_{2/3}P_L t + ...\right]$$

$$\mathcal{L}_{\rm NP} = \mathcal{L}_{Q^2+S^2} + \mathcal{L}_Q + \mathcal{L}_S$$

$$\mathcal{L}_S = S^0\left[\lambda^{S^0}_{t,L}\bar{t}P_L t + \lambda^{S^0}_{b,L}\bar{b}P_L b + \kappa^{S^0}_{T,L}\bar{T}_{2/3}P_L t + \kappa^{S^0}_{TT,L}\bar{T}_{2/3}P_L T_{2/3} + ...\right] + S^{++}\left[\kappa^{S^{++}}_{X,L}\bar{X}_{5/3}P_L b + ...\right]$$
$$+S^+\left[\lambda^{S^+}_L\bar{t}P_L b + \kappa^{S^+}_{X,L}\bar{X}_{5/3}P_L t + \kappa^{S^+}_{T,L}\bar{T}_{2/3}P_L b + \kappa^{S^+}_{XT,L}\bar{X}_{5/3}P_L T_{2/3} + ...\right]$$

All coupling strengths are free parameters

Modelling resonances

Model dependent chiral EFT: use global symmetries

Simplified model: SU(3)xU(1) invariant Lagrangian

Model independent EFT: Full SM invariant Lagrangian

$$\mathcal{L}_{NP}^{\leq 4} = \bar{\Psi}(iD - m_\Psi)\Psi + |D_\mu S|^2 - V(S,H) + \lambda \bar{\Psi} f + y_H \bar{\Psi} f H + y_S \bar{\Psi} f S + \tilde{y}_S \bar{\Psi}\Psi S + \text{h.c.}$$

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{NP}^{\leq 4} + \mathcal{L}_{NP}^{5} + \ldots \, .$$

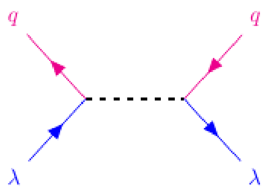
Coupling order fixed

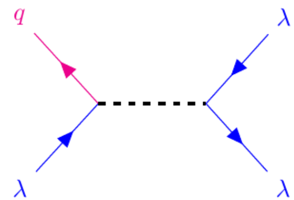
Full SM mutiplets considered

Bridge between concrete models and simplified models

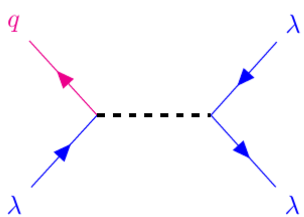
Ψ + SM fields	Ψ + S + SM fields
$\bar{\Psi}\sigma^{\mu\nu}\Psi X_{\mu\nu}$	$\bar{\Psi} f H S$
$\bar{\Psi}\sigma^{\mu\nu} f X_{\mu\nu}$	$\bar{\Psi} f S^2$
$\bar{\Psi} f H^2$	$\bar{\Psi}\Psi S^2$
$\bar{\Psi}\Psi H^2$	

Spectra of Top-partners



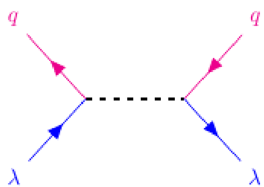


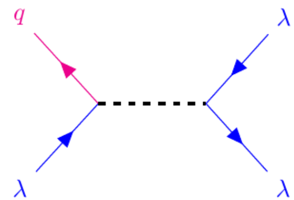
$$\begin{pmatrix} \bar{u}_L^1 \\ \bar{u}_L^2 \\ \bar{u}_L^3 \\ \hline \bar{T}_L^1 \\ \cdot \\ \cdot \\ \cdot \\ \bar{T}_L^n \end{pmatrix}^T \left(\begin{array}{c|c} y^{ij}_{3\times 3} v & \kappa_L^i f \mathcal{F}_L(\frac{v}{f}) \\ \hline \kappa_R^j f \mathcal{F}_R(\frac{v}{f}) & M \mathbb{1}_n \end{array}\right) \begin{pmatrix} u_R^1 \\ u_R^2 \\ u_R^3 \\ \hline T_R^1 \\ \cdot \\ \cdot \\ \cdot \\ T_R^n \end{pmatrix}$$



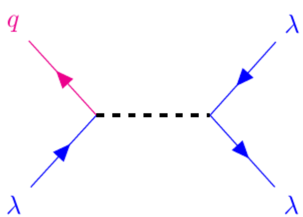
$$m_{1,2} \sim yv \qquad m_3 \sim \frac{\kappa_L \kappa_R f v}{M} + yv \gg yv$$

Spectra of Top-partners





$$\begin{pmatrix} \bar{u}_L^1 \\ \bar{u}_L^2 \\ \bar{u}_L^3 \\ \hline \bar{T}_L^1 \\ \cdot \\ \cdot \\ \cdot \\ \bar{T}_L^n \end{pmatrix}^T \left(\begin{array}{c|c} y^{ij}_{3\times 3} v & \kappa_L^i f \mathcal{F}_L(\frac{v}{f}) \\ \hline \kappa_R^j f \mathcal{F}_R(\frac{v}{f}) & M \mathbb{1}_n \end{array} \right) \begin{pmatrix} u_R^1 \\ u_R^2 \\ u_R^3 \\ \hline T_R^1 \\ \cdot \\ \cdot \\ \cdot \\ T_R^n \end{pmatrix}$$



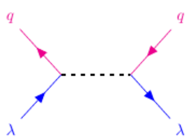
- n-2 degenerate VLQs with mass M
- 2 heavy:

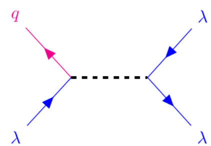
$$\frac{\Delta M}{M} \sim \frac{\kappa^2 f^2}{M^2} \text{ or, } \frac{\kappa^2 v^2}{M^2}$$

- Mixing of lighter generation of quarks with the VLQs are negligibly small

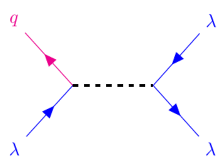
$$m_{1,2} \sim yv \qquad m_3 \sim \frac{\kappa_L \kappa_R f v}{M} + yv \gg yv$$

Spectra of Top-partners



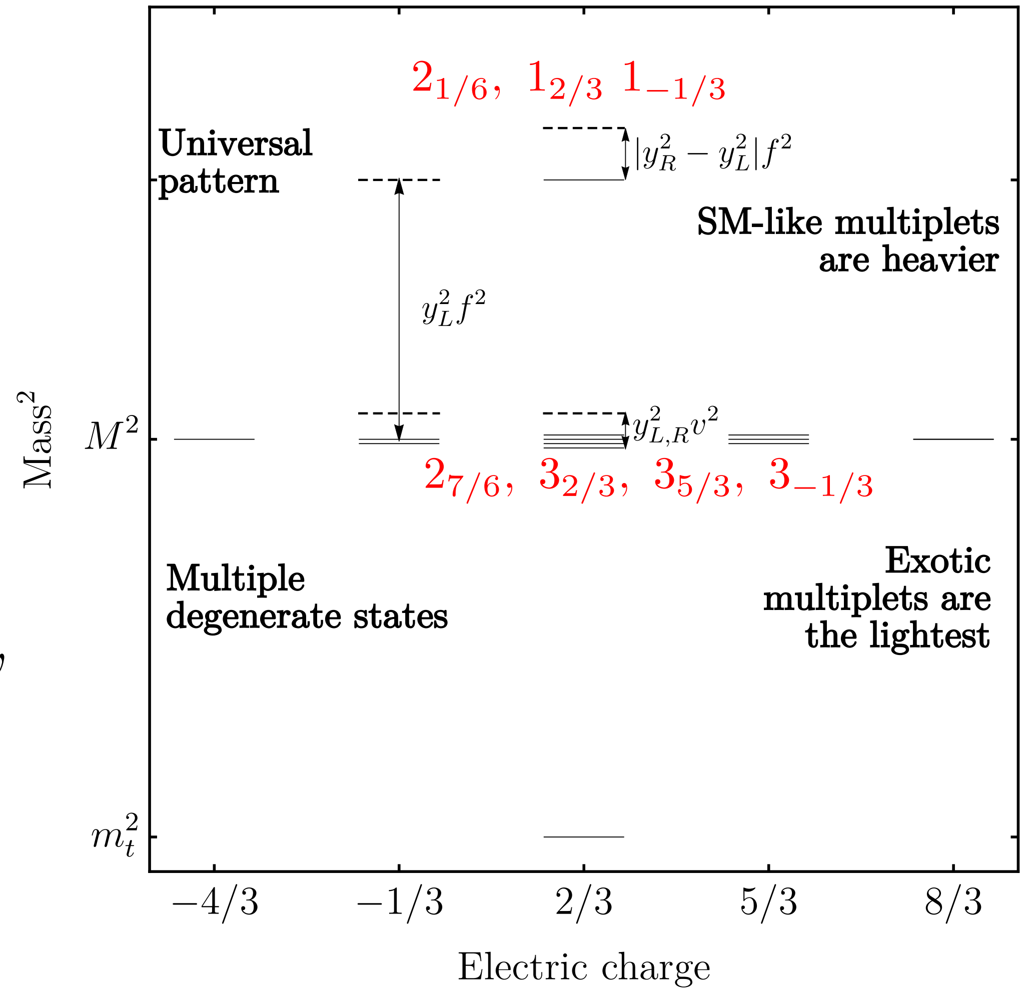


$$\left(\begin{array}{c} \bar{u}_L^1 \\ \bar{u}_L^2 \\ \bar{u}_L^3 \\ \hline \bar{T}_L^1 \\ \vdots \\ \bar{T}_L^n \end{array}\right)^T \left(\begin{array}{c|c} y^{ij}_{3\times 3} v & \kappa_L^i f \mathcal{F}_L(\frac{v}{f}) \\ \hline \kappa_R^j f \mathcal{F}_R(\frac{v}{f}) & M \mathbb{1}_n \end{array}\right) \left(\begin{array}{c} u_R^1 \\ u_R^2 \\ u_R^3 \\ \hline T_R^1 \\ \vdots \\ T_R^n \end{array}\right)$$

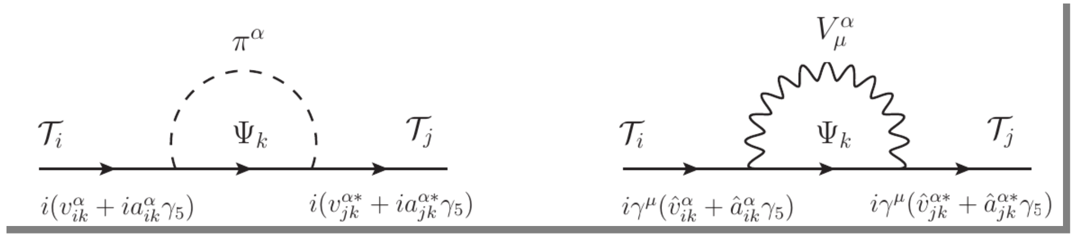


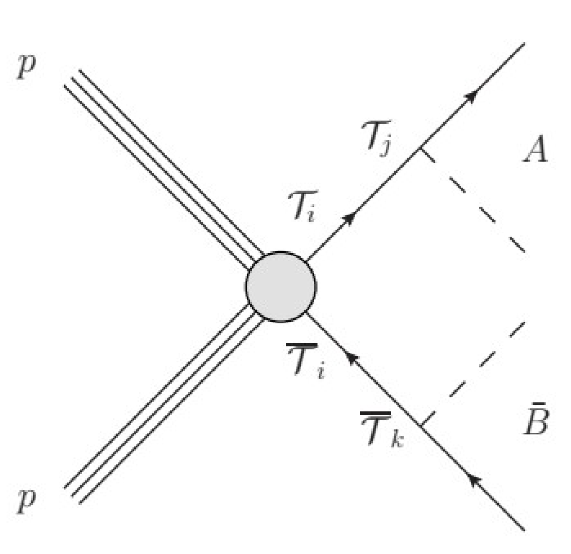
$$m_{1,2} \sim yv \qquad m_3 \sim \frac{\kappa_L \kappa_R f v}{M} + yv \gg yv$$

- One-loop mass splitting and off-diagonal self-energy



- Degenerate states are the lightest with off-diagonal terms in self energy
- One loop mass-splitting can be comparable to the decay widths





Interesting quantum interference problem between channels for a pair production process

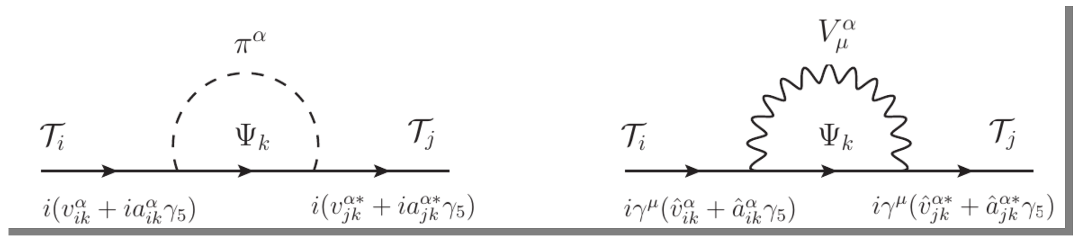
$$\sigma(pp \to \mathcal{T}\overline{\mathcal{T}} \to A\bar{B}) \overset{\text{NWA}}{=} N_{\mathcal{T}}\sigma(pp \to \mathcal{T}\overline{\mathcal{T}})\mathcal{BR}_2(\mathcal{T}\overline{\mathcal{T}} \to A\bar{B})$$

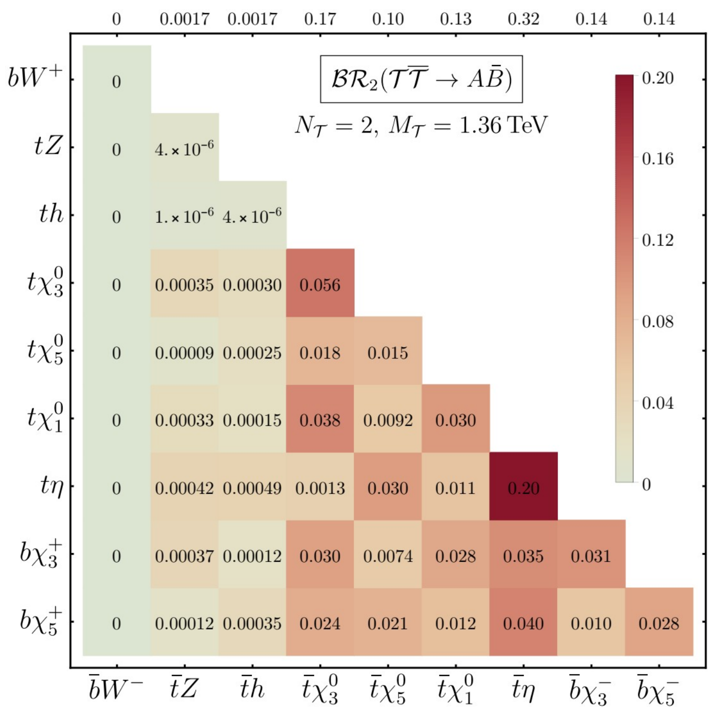
Non-trivial correlations between the two final states

$$\mathcal{BR}_2(\mathcal{T}\overline{\mathcal{T}} \to A\bar{B}) \neq \mathcal{BR}(\mathcal{T} \to A)\mathcal{BR}(\bar{\mathcal{T}} \to \bar{B})$$

Any applications in SM physics?

- Degenerate states are the lightest with off-diagonal terms in self energy
- One loop mass-splitting can be comparable to the decay widths





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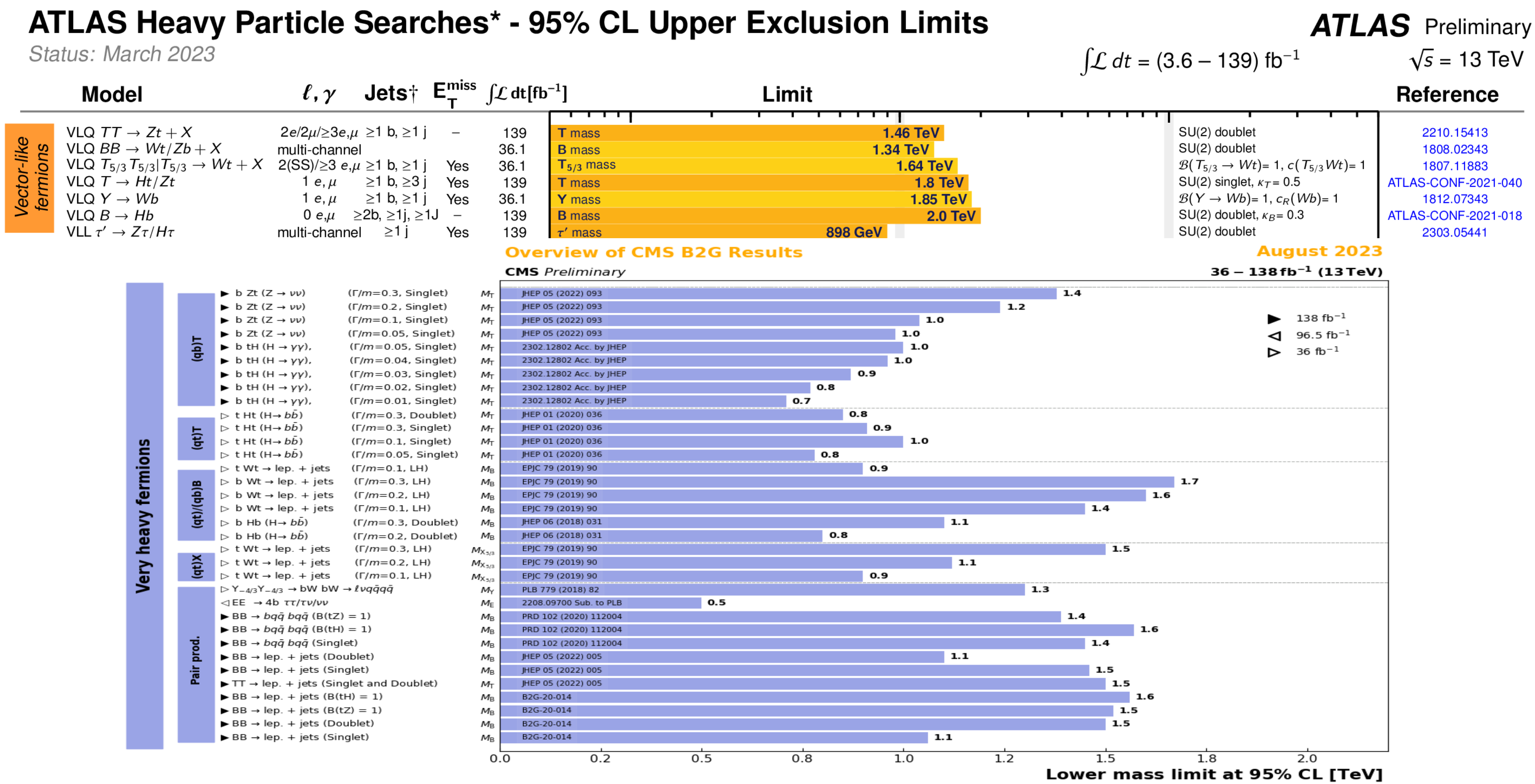
Any applications in SM physics?

Vector-like quark searches at LHC



- Limits on VLQ mass ~ **1.5 TeV**
- Caveats: simplified model (often with single VLQ), **purely SM decays of VLQs**

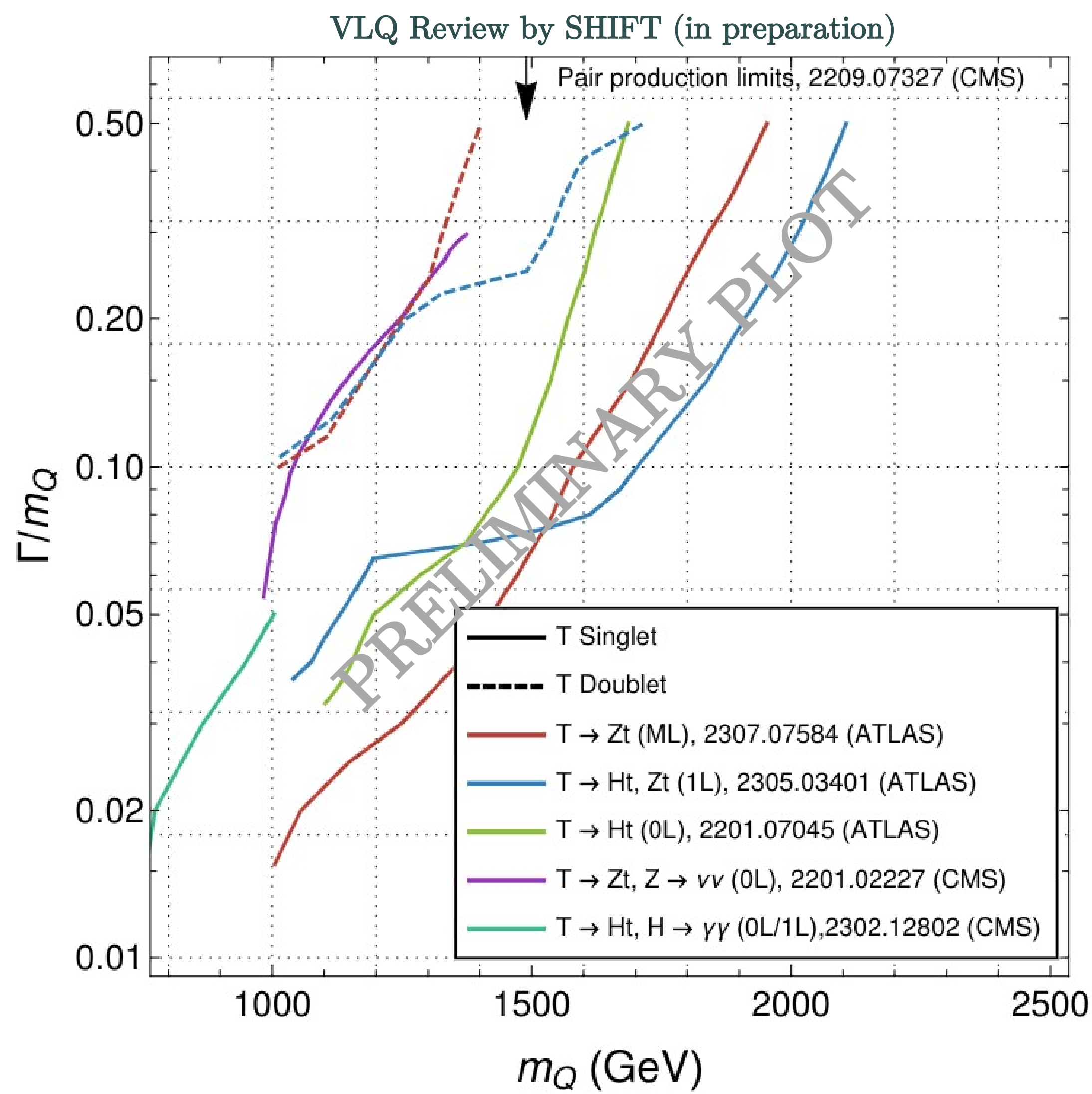
Single production of VLQs

- Limits from single production:

  Cross-section proportional to coupling to SM particles

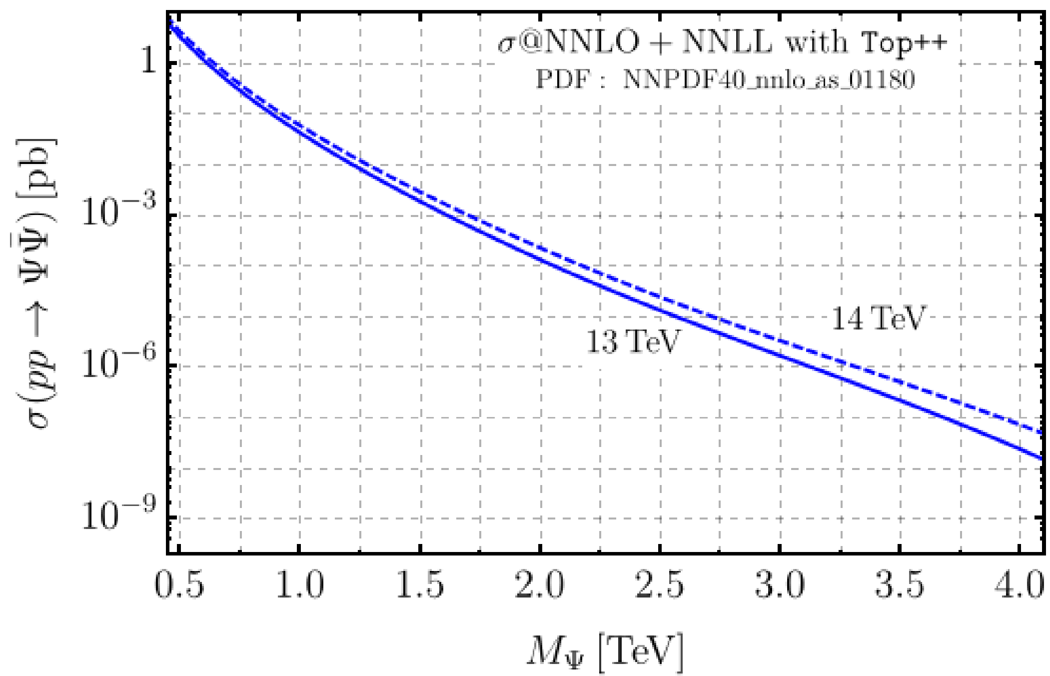
  Maximum sensitivity for large width

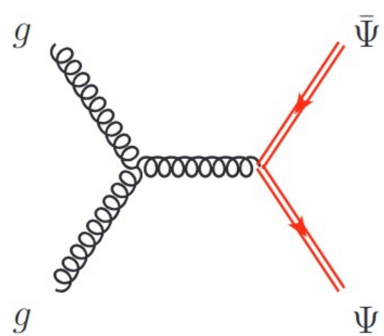
- Pair production: limited by energy at high mass, Single production: sensitive at large width



VLQ production

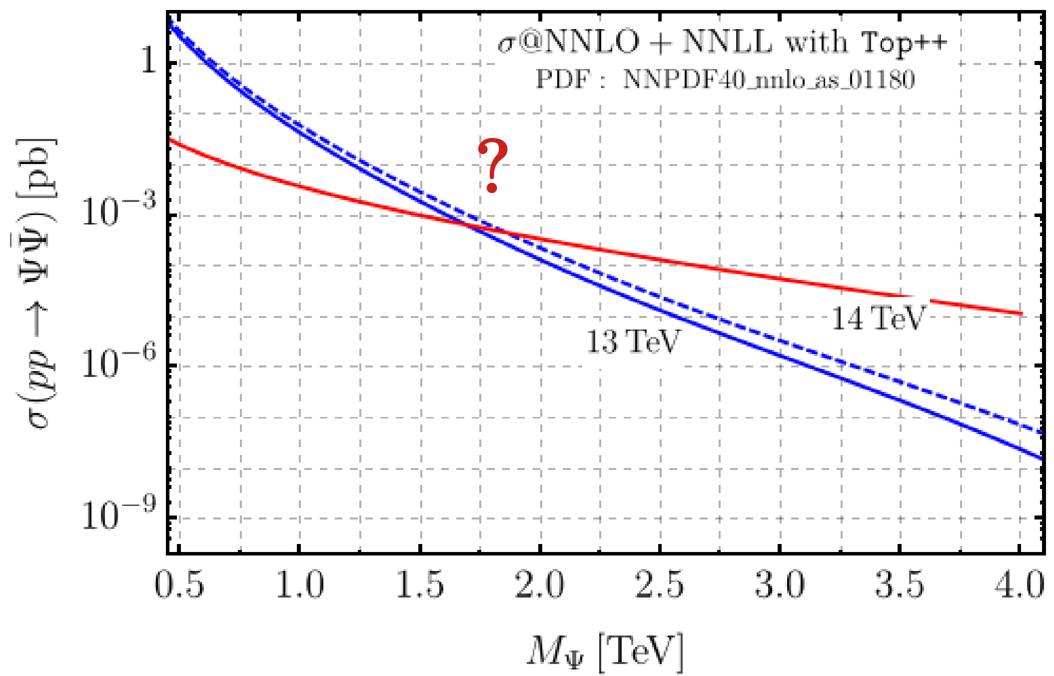
- Pair production:
  - driven by QCD,
  - σ depends on VLQ mass (NWA)

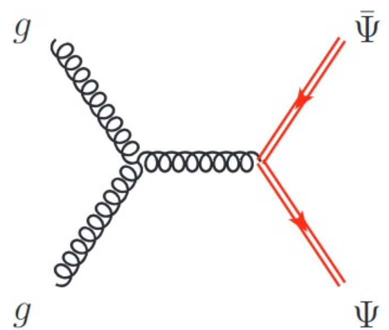


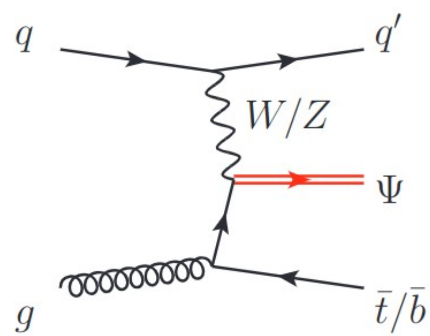


VLQ production

- Pair production:
  - driven by QCD,
  - σ depends on VLQ mass (NWA)
- Single production:
  - σ proportional to couplings of VLQs with SM particles
  - **where is the crossing?**

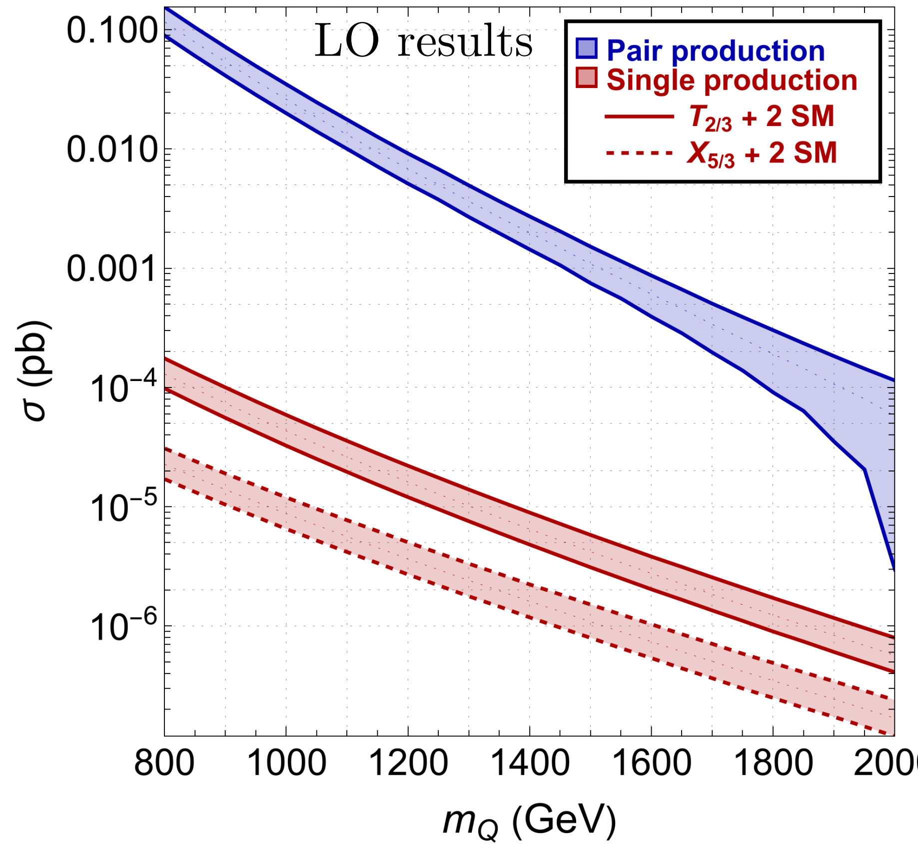






Pair production – still important?

- Single production is suppressed if:
  - Narrow width
  - VLQ couplings with SM particles are forbidden/ suppressed
- Example: **Composite Higgs motivated VLQ triplet with Y=5/3**
- $Q_{3_{5/3}} = (Y_{8/3}, X_{5/3}, T_{2/3})$



AB, V Ellajosyula, L Panizzi, [2311.17877]

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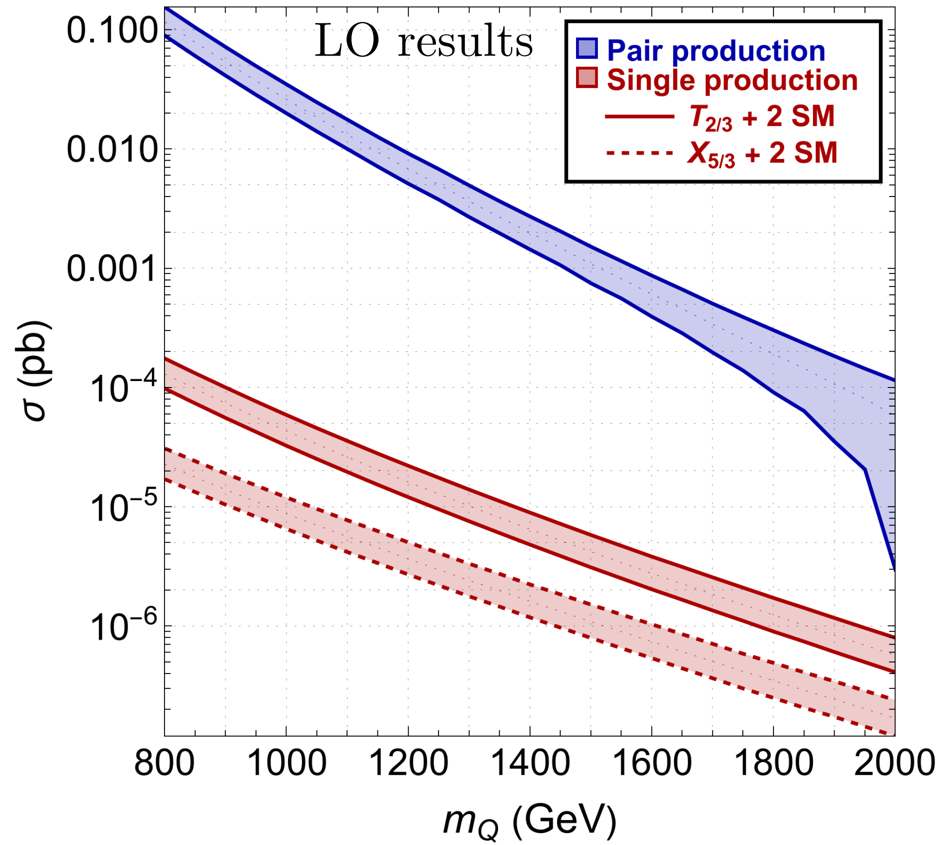
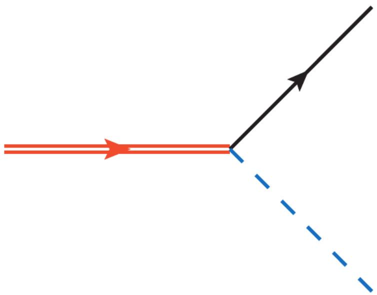
  - VLQ couplings with SM particles are forbidden/ suppressed
- Example: **Composite Higgs motivated VLQ triplet with Y=5/3**
- $Q_{3_{5/3}} = (Y_{8/3}, X_{5/3}, T_{2/3})$

Pair production is necessary: exploit the multiplet structure to gain in signal σ



AB, V Ellajosyula, L Panizzi, [2311.17877]

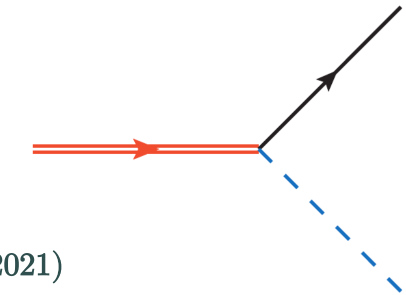
Decays to exotics



VLQ	SM Decays	BSM Decays
$U_{-4/3}$	bW^-	bS^-, tS^{--}
$B_{-1/3}$	tW^-, bh, bZ	tS^-, bS^0
$T_{2/3}$	th, tZ, bW^+	tS^0, bS^+
$X_{5/3}$	tW^+	tS^+, bS^{++}
$Y_{8/3}$	tW^+W^+	tS^{++}

Scalar	Final state	Condtions
S^0	$t\bar{t}$	$m_S > 2m_t$
S^0	$b\bar{b}$	$m_S < 2m_t$
S^0	$\gamma\gamma$, $Z\gamma$, W^+W^-, ZZ	Fermiophobic
$S^\pm$	$t\bar{b}$	$m_S > m_t + m_b$
$S^\pm$	$W^\pm\gamma$, $W^\pm Z$	Fermiophobic
$S^{\pm\pm}$	$t\bar{b}W^\pm$	$m_S > m_t + m_b + M_W$
$S^{\pm\pm}$	$W^\pm W^\pm$	Fermiophobic

Decays to exotics



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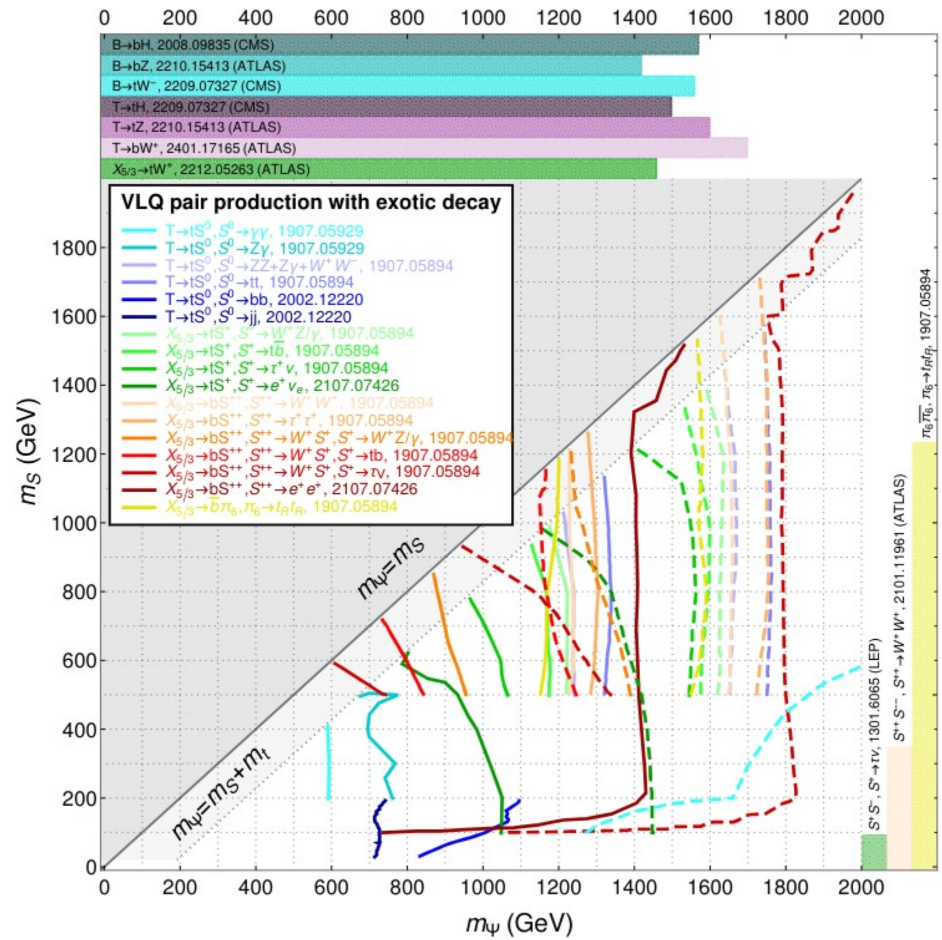
S^0	$\gamma\gamma$, $Z\gamma$, W^+W^-, ZZ	Fermiophobic
$S^\pm$	$t\bar{b}$	$m_S > m_t + m_b$
$S^\pm$	$W^\pm\gamma$, $W^\pm Z$	Fermiophobic
$S^{\pm\pm}$	$t\bar{b}W^\pm$	$m_S > m_t + m_b + M_W$
$S^{\pm\pm}$	$W^\pm W^\pm$	Fermiophobic

[2203.07270] (Snowmass 2021)



$$pp \to T_{2/3}\bar{T}_{2/3} \to (tS^0) + X \to (t\gamma\gamma) + X$$

Di-photon signal for a specific model: EW Coset : $SU(5)/SO(5)$

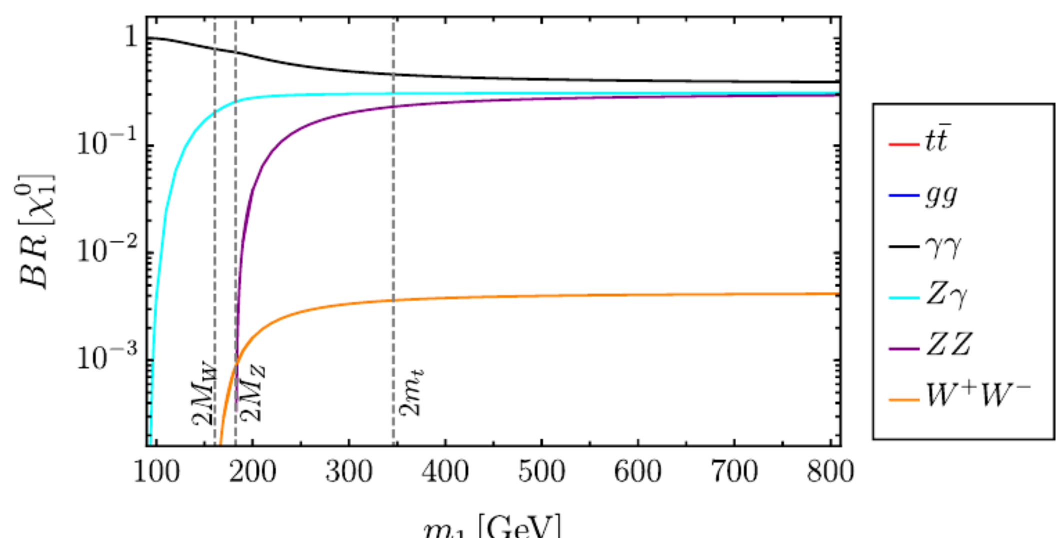
EW pNGBs: $\mathbf{14} \to (\mathbf{3},\mathbf{3}) + (\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{1}) \to \mathbf{3}_{\pm 1} + \mathbf{3}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{1}_0$

VLQs (top-partners): $\Psi \equiv \mathbf{10}_{\frac{2}{3}} \to (\mathbf{2},\mathbf{2})_{\frac{2}{3}} + (\mathbf{3},\mathbf{1})_{\frac{2}{3}} + (\mathbf{1},\mathbf{3})_{\frac{2}{3}} \to \mathbf{2}_{\frac{1}{6}} + \mathbf{2}_{\frac{7}{6}} + \mathbf{3}_{\frac{2}{3}} + \mathbf{1}_{-\frac{1}{3}} + \mathbf{1}_{\frac{2}{3}} + \mathbf{1}_{\frac{5}{3}}$

$$\sigma\,(pp \to (t/\bar{t}\gamma\gamma) + X) \sim 2.4 \text{ fb}, \;\; M = 1.35 \text{ TeV}$$

More inclusive cross-sections involving diphoton (resonant / non-resonant) can go upto around 10 fb

[Ongoing ATLAS search]



AB, D B Franzosi, G Ferretti, JHEP 03 (2022) 200

More Exotics: Model with triplets

$$Q = \left(Y_{8/3}, X_{5/3}, T_{2/3}\right) : \; \mathbf{3}_{5/3} \qquad\qquad S = \left(S^{++}, S^{+}, S^{0}\right) : \; \mathbf{3}_{1}$$

Coset (G/H)	VLQ (irrep under H)	pNGB (irrep under H)
$\frac{SO(5)}{SO(4)} \times U(1)_X$	$\mathbf{9}_{2/3} \to (\mathbf{3},\mathbf{3})_{2/3} \to \mathbf{3}_{-1/3} + \mathbf{3}_{2/3} + \mathbf{3}_{5/3}$	$\mathbf{4} \to (\mathbf{2},\mathbf{2}) \to \mathbf{2}_{\pm 1/2}$
$\frac{SU(5)}{SO(5)} \times U(1)_X$	$\mathbf{14}_{2/3} \to (\mathbf{1},\mathbf{1})_{2/3} + (\mathbf{2},\mathbf{2})_{2/3} + (\mathbf{3},\mathbf{3})_{2/3}$ $\to \mathbf{1}_{2/3} + \mathbf{2}_{1/6} + \mathbf{2}_{7/6} + \mathbf{3}_{-1/3} + \mathbf{3}_{2/3} + \mathbf{3}_{5/3}$	$\mathbf{14} \to (\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2}) + (\mathbf{3},\mathbf{3})$ $\to \mathbf{1}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{3}_0 + \mathbf{3}_{\pm 1}$

More Exotics: Model with triplets

$$Q = \left(Y_{8/3}, X_{5/3}, T_{2/3}\right) : \ 3_{5/3} \qquad\qquad S = \left(S^{++}, S^{+}, S^{0}\right) : \ 3_{1}$$

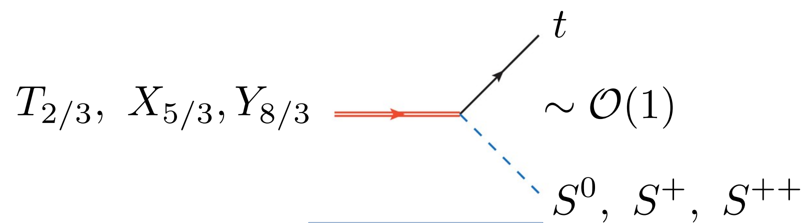
- VLQs are **nearly degenerate** as mixing with SM quarks are sub-leading
- One-loop mass splitting for VLQs ~ 50 GeV (considering QCD and QED contributions)
- **Scalar triplet does not receive vev** in accordance with EWPT
- Partial compositeness: **couplings with 3rd gen quarks only**
- Mimics SO(5)/SO(4) model when $m_Q \ll m_S$ and SU(5)/SO(5) if $m_Q \gg m_S$

Model independent EFT

$$\mathcal{L}_{\mathrm{NP}}^{d\leq 4} = |D_\mu S|^2 - m_S^2|S|^2 + \bar{Q}\left(iD\!\!\!/ - m_Q\right)Q + \lambda_R \bar{Q}_L S t_R + \mathrm{h.c.}$$

$$\mathcal{L}_{\mathrm{NP}}^{d=5} = \frac{\tilde{y}_t}{\Lambda}\bar{q}_L S^\dagger H t_R + \frac{\tilde{y}_b}{\Lambda}\bar{q}_L S H^c b_R + \frac{\tilde{\lambda}_1}{\Lambda} H^\dagger i\tau^2 \bar{Q}_L H^* t_R + \frac{\tilde{\lambda}_2}{\Lambda}\bar{q}_L S^\dagger Q_R H^c + \mathrm{h.c.}$$

Model independent EFT



$$\mathcal{L}_{\rm NP}^{d\leq 4} = |D_\mu S|^2 - m_S^2 |S|^2 + \bar{Q}\left(i\not{D} - m_Q\right) Q + \lambda_R \bar{Q}_L S t_R + \text{h.c.}$$

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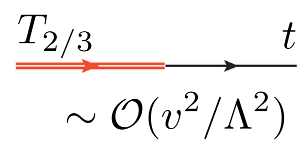
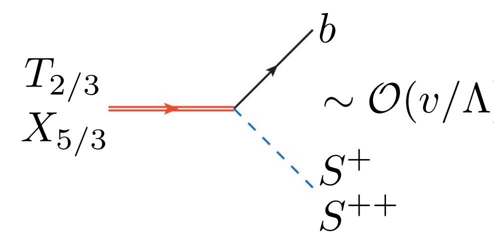
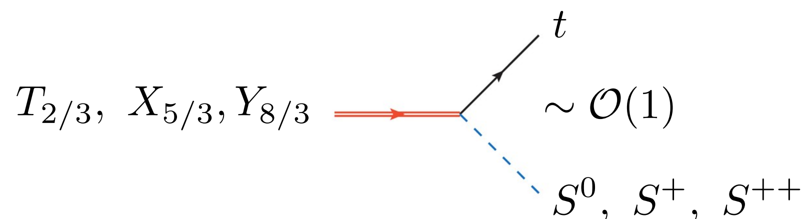




SM decays are subleading due to suppressed mixing

Model independent EFT



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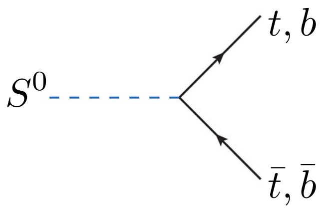

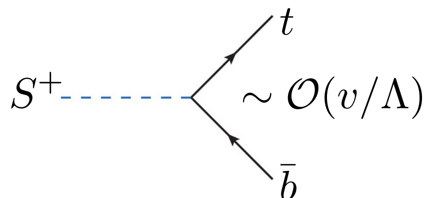

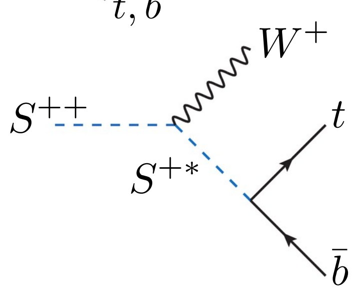

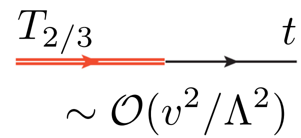

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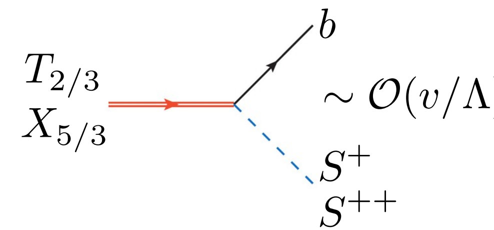
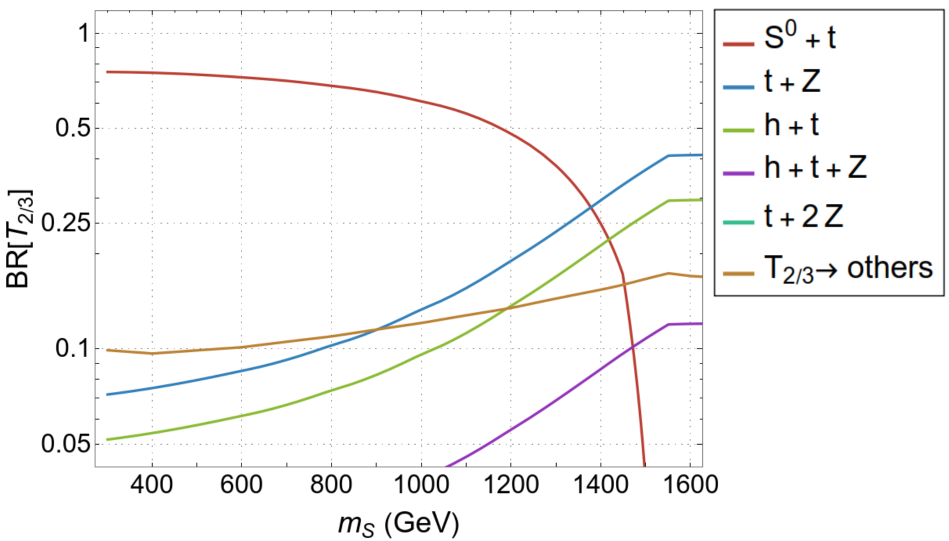
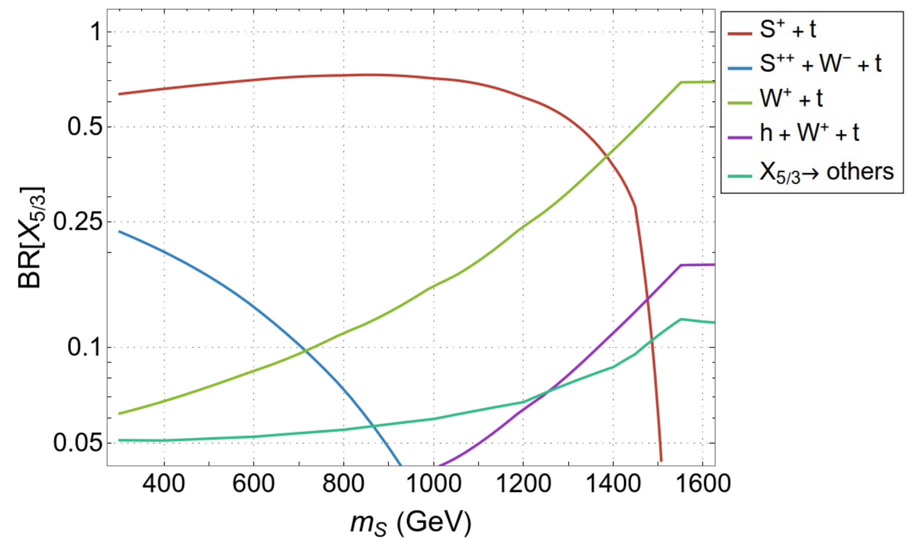
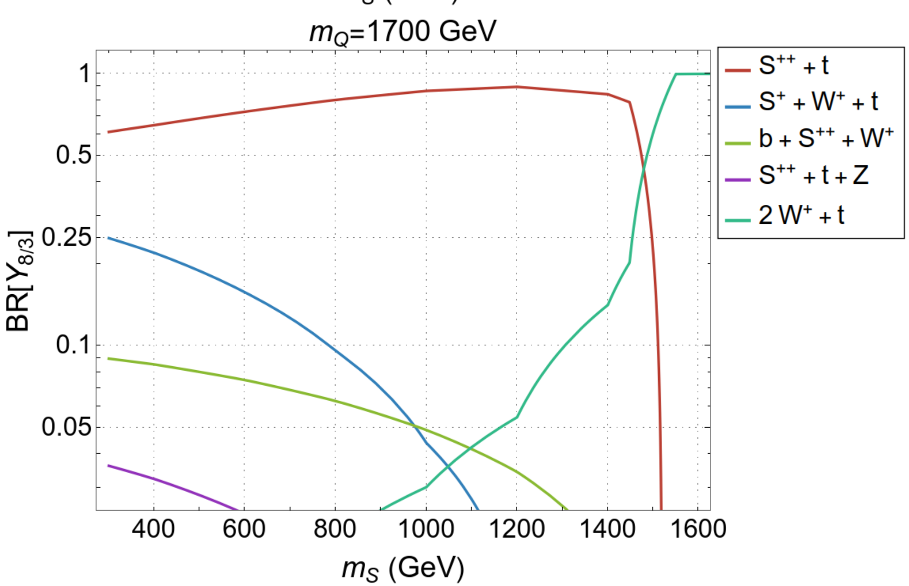


VLQ decays and branching ratios







$m_Q > m_S + m_t$: BSM decays dominate

$m_Q < m_S + m_t$: SM decays dominate

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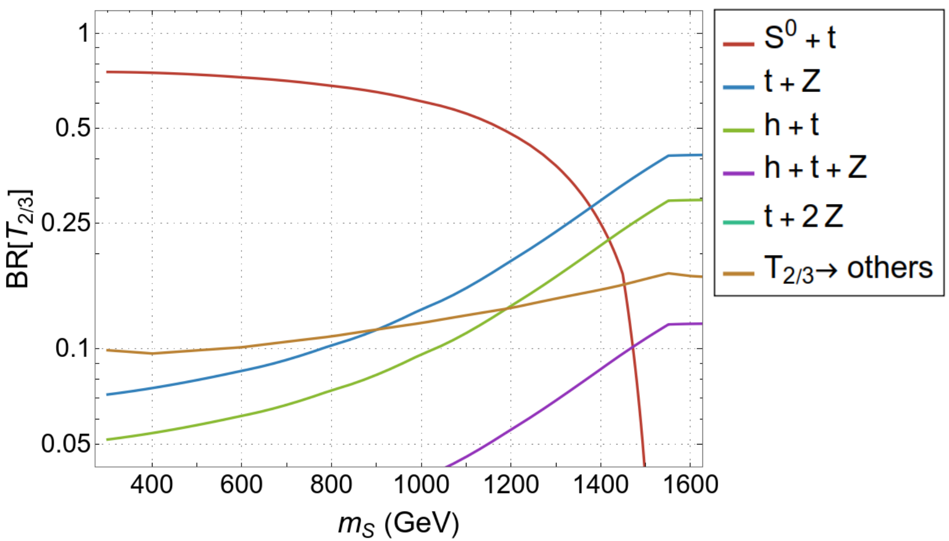

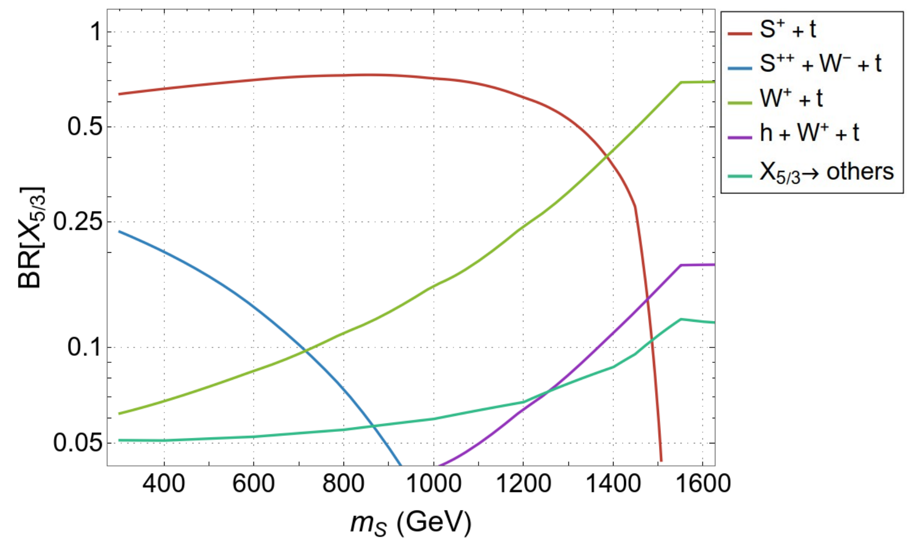

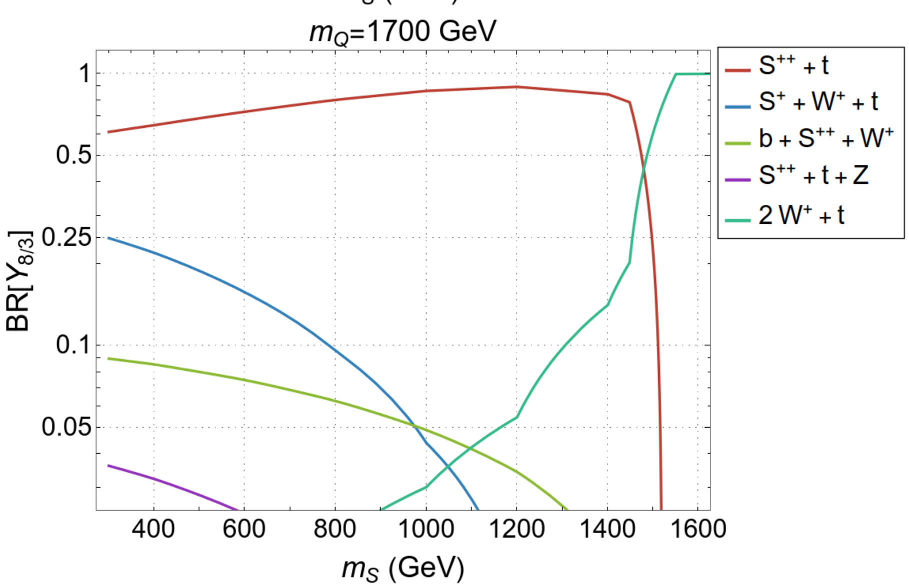

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$m_Q < m_S + m_t$: SM decays dominate

$$BR(S^0 \to t\bar{t}) \sim BR(S^0 \to b\bar{b}) \sim 50\%$$

$$BR(S^+ \to t\bar{b}) \sim 100\%$$

$$BR(S^{++} \to t\bar{b}W^+) \sim 100\%$$

Limits @ LHC Run 2

- Limits obtained with searches implemented in MadAnalysis5
- Most sensitive searches are **4top + SSL and multilepton** search by CMS
- Dedicated VLQ searches may improve the limits

Searches	Kinematics	SR	N_l	N_{OSSF}	N_b	N_j
1908.06463 CMS 4t + SSL	$H_T^j > 300$ GeV $\not{p}_T > 50$ GeV	SR7	2 same-sign	–	3	≥ 8
		SR8	2 same-sign	–	≥ 4	≥ 5
1911.04968 CMS multi-lepton	$M_{\text{OSSF}} > 106$ GeV $L_T + \not{E}_T \in [875, 1000]$ GeV	3L above-Z	3	1	–	–

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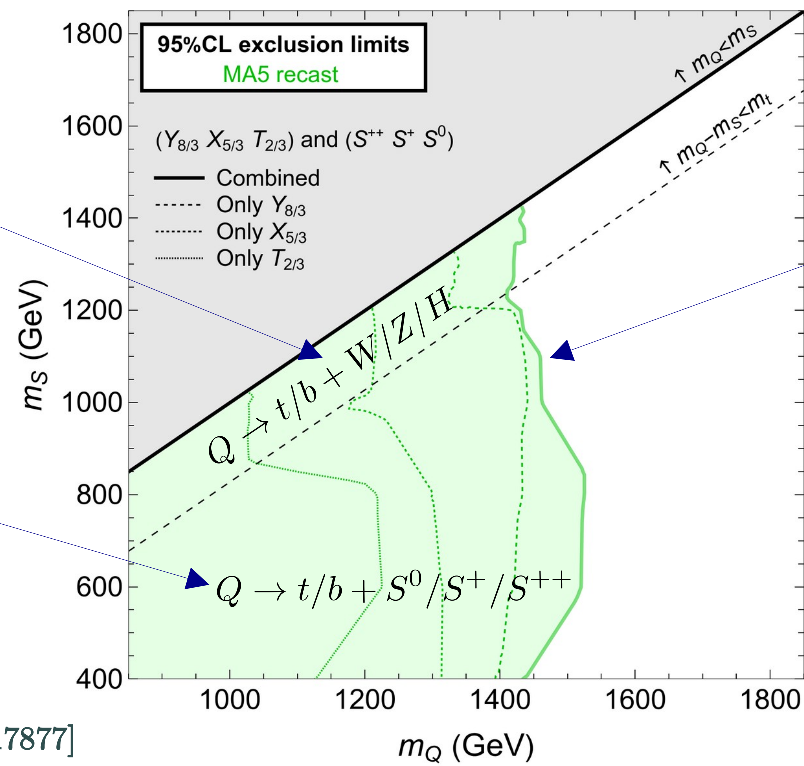

Stronger limits with full multiplet

How to improve in Run 3?

AB, V Ellajosyula, L Panizzi, [2311.17877]

Final state characterization

- We select two benchmark points allowed by current limits:

$$m_Q = 1700\ \text{GeV} \gg m_S = 600\ \text{GeV (SRL)} \qquad m_Q = 1700\ \text{GeV}, m_S = 1600\ \text{GeV (SRS)}$$

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- For SRL: (BSM decays dominate)

VLQ pair	No. of b-jets, $W^{\pm}$ from VLQ decay N_b	N_{W^+}	N_{W^-}	Contributing decays	Product of BRs
$Y_{8/3} + \bar{Y}_{8/3}$	6	3	3	$Y_{8/3} \to t + S^{++}$ $\to t + W^+ + S^+$ $\to b + W^+ + S^{++}$	$> 92\%$
$X_{5/3} + \bar{X}_{5/3}$	6	2	2	$X_{5/3} \to t + S^+$	$> 50\%$
	6	3	3	$X_{5/3} \to t + S^+$ $\to t + W^- + S^{++}$	$> 18\%$
	4	2	2	$X_{5/3} \to t + S^+$ $\to t + W^+$	$> 12\%$
$T_{2/3} + \bar{T}_{2/3}$	6	3	3	$T_{2/3} \to t + (S^0 \to t\bar{t})$	$> 9\%$
	6	< 3	< 3	$T_{2/3} \to t + S^0$ $\to t + (Z \to b\bar{b})$ $\to t + (h \to b\bar{b})$	$> 53\%$
	4	≥ 1	≥ 1	$T_{2/3} \to t + S^0$ $\to t + Z$ $\to t + h$	$> 11\%$

- Same sign leptons
- Multiple jets
- Multiple b-jets

Proposed signal region

SR	(m_Q, m_S) GeV	N_{SSL}	N_j	N_b	$p_T(l_0)$	m_{eff}
SRL	(1700,600)	≥ 1	≥ 3	≥ 2	–	≥ 2100 GeV or ≥ 2300 GeV
SRS	(1700,1600)			≥ 1	≥ 170 GeV	

- Choice of SR:
  - **maximize signal from full multiplet**
    - Multiplicity cuts (NSSL, Nj, Nb)
  - **reject background efficiently**
    - Kinematic cuts (meff)

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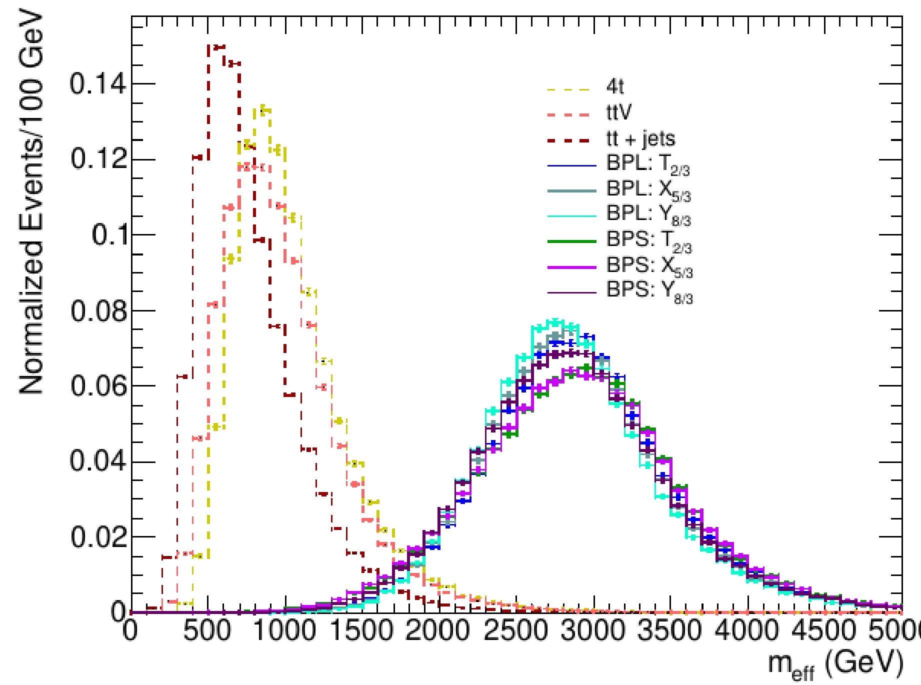
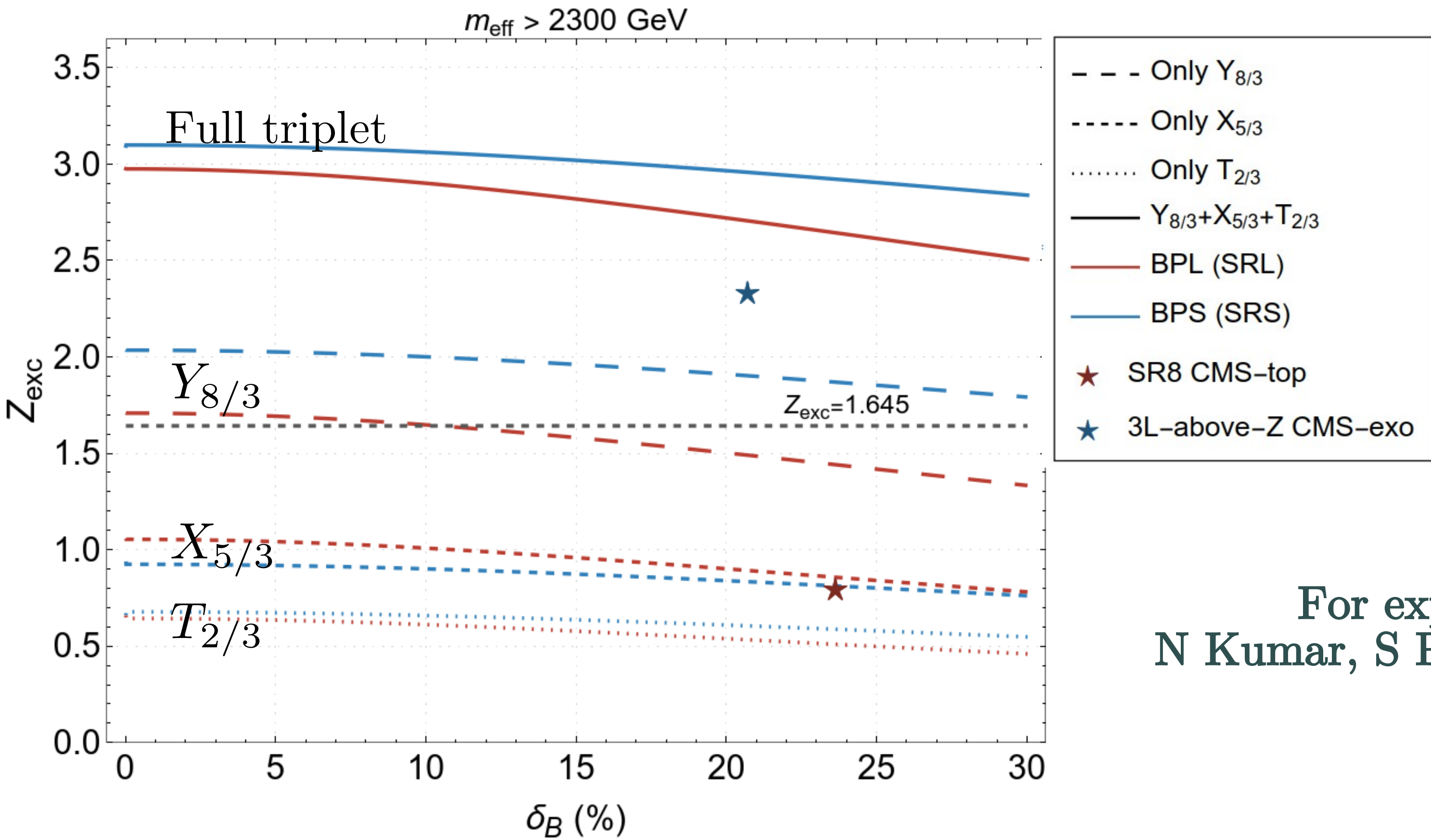
- Choice of SR:
  - **maximize signal from full multiplet**
    - Multiplicity cuts (NSSL, Nj, Nb)
  - **reject background efficiently**
    - Kinematic cuts (meff)
- Major backgrounds:
  - $4t,\ t\bar{t}V + \leq 2j,\ t\bar{t} + \leq 3j,\ t\bar{t}b\bar{b},\ VVV$
- Scope for further optimization: machine learning?
- Background modelling near tail of distributions



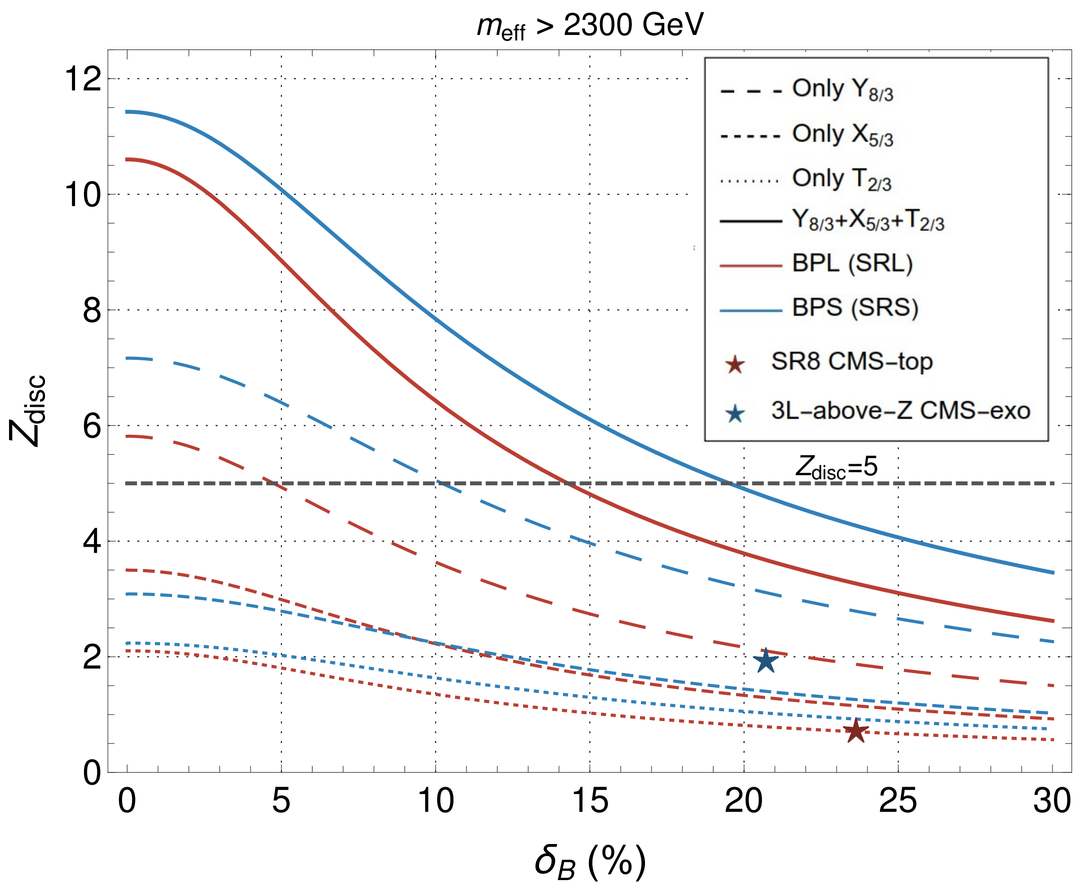
Sensitivity @ Run 3



For expressions of Z:
N Kumar, S P Martin, [1510.03456]

- Exclusion with fairly large systematic uncertainties when **full multiplet** is considered
- **Proposed SRs perform better** than 300/fb projections of most sensitive SRs from recast

HL-LHC Prospects



- Pushing for discovery: if **entire multiplet** contributes to the SR (<20% systematics)
- Introducing mass-split ~ 50 GeV for VLQs does not alter the conclusions significantly

Feynrules implementation

Fields	Spin	$SU(3)_c$	$U(1)_{\text{em}}$
S_i^0	0	$\mathbf{1}$	0
$S_i^\pm$	0	$\mathbf{1}$	±1
$S_i^{\pm\pm}$	0	$\mathbf{1}$	±2
$U_{-4/3}$	1/2	$\mathbf{3}$	$-4/3$
B	1/2	$\mathbf{3}$	$-1/3$
T	1/2	$\mathbf{3}$	2/3
$X_{5/3}$	1/2	$\mathbf{3}$	5/3
$Y_{8/3}$	1/2	$\mathbf{3}$	8/3

Features:

1. Generic particle content
2. Modular structure: switch off unwanted parts
3. Suitable for NLO (QCD) simulation
4. Non-SM decays of VLQs included
5. Available on Feynrules webpage (NLO section)

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{QQV} + \mathcal{L}_{QqV} + \mathcal{L}_{QQS} + \mathcal{L}_{QqfS} + \mathcal{L}_{qqS} + \mathcal{L}_{SSV} + \mathcal{L}_{SSVV} + \mathcal{L}_{SVV}$$

Vector like quarks + exotic pNGBs: https://feynrules.irmp.ucl.ac.be/wiki/NLOModels

AB, D B Franzosi, G Cacciapaglia et. al. [2203.07270] (Snowmass 2021)

All simulation banners are available on arxiv: 2311.17877

Summary

- Planning time for Run 3 and beyond: what are the priorities?
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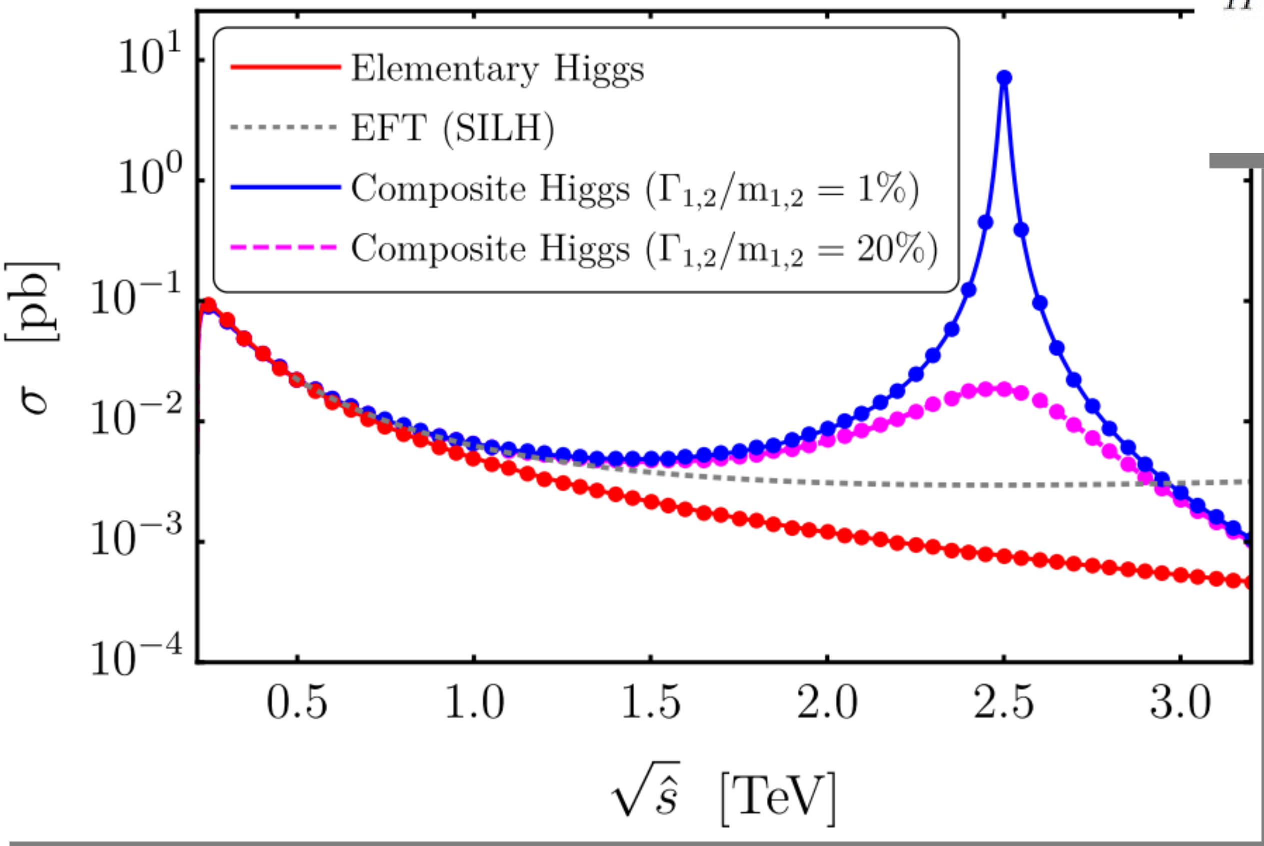
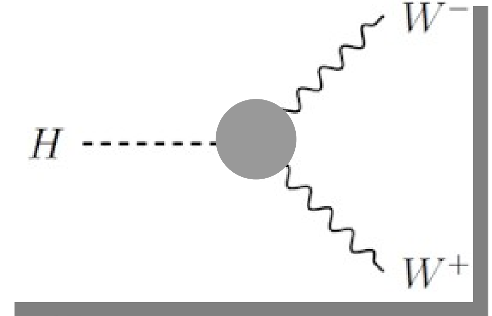
BACKUP





$$g_V^{\rm SM}\frac{\Pi_V^{\mu\nu}(p_1,p_2)}{f^2}hV_\mu(p_1)V_\nu(p_2)$$

$pp \to Z^* \to Zh \to l^+l^-b\bar{b}$

AB, S Dasgupta, T S Ray [2105.01093]

Simplified Lagrangian and couplings

$$\mathcal{L}_{Q^2+S^2} = \bar{Q}\left(i\not{D} - m_Q\right)Q + \left(|D_\mu S|^2 - m_S^2|S|^2\right),$$

$$\mathcal{L}_Q = \frac{e}{\sqrt{2}s_W}\left[\kappa^W_{T,L}\bar{T}_{2/3}\not{W}^+P_Lb + \kappa^W_{X,L}\bar{X}_{5/3}\not{W}^+P_Lt + L \leftrightarrow R\right] + \text{h.c.}$$
$$+ \frac{e}{s_Wc_W}\left[\kappa^Z_{T,L}\bar{T}_{2/3}\not{Z}P_Lt + L \leftrightarrow R\right] + \text{h.c.} + h\left[\kappa^h_{T,L}\bar{T}_{2/3}P_Lt + L \leftrightarrow R\right] + \text{h.c.}$$

$$\mathcal{L}_S = S^0\left[\lambda^{S^0}_{t,L}\bar{t}P_Lt + \lambda^{S^0}_{b,L}\bar{b}P_Lb + \kappa^{S^0}_{T,L}\bar{T}_{2/3}P_Lt + \kappa^{S^0}_{TT,L}\bar{T}_{2/3}P_LT_{2/3} + L \leftrightarrow R\right] + \text{h.c.}$$
$$+ S^{++}\left[\kappa^{S^{++}}_{Y,L}\bar{Y}_{8/3}P_Lt + \kappa^{S^{++}}_{X,L}\bar{X}_{5/3}P_Lb + \kappa^{S^{++}}_{YT,L}\bar{Y}_{8/3}P_LT_{2/3} + L \leftrightarrow R\right] + \text{h.c.}$$
$$+ S^+\left[\lambda^{S^+}_L\bar{t}P_Lb + \kappa^{S^+}_{X,L}\bar{X}_{5/3}P_Lt + \kappa^{S^+}_{T,L}\bar{T}_{2/3}P_Lb + \kappa^{S^+}_{XT,L}\bar{X}_{5/3}P_LT_{2/3}\right.$$
$$\left.+\kappa^{S^+}_{YX,L}\bar{Y}_{8/3}P_LX_{5/3} + L \leftrightarrow R\right] + \text{h.c.}$$

Simplified Lagrangian and couplings

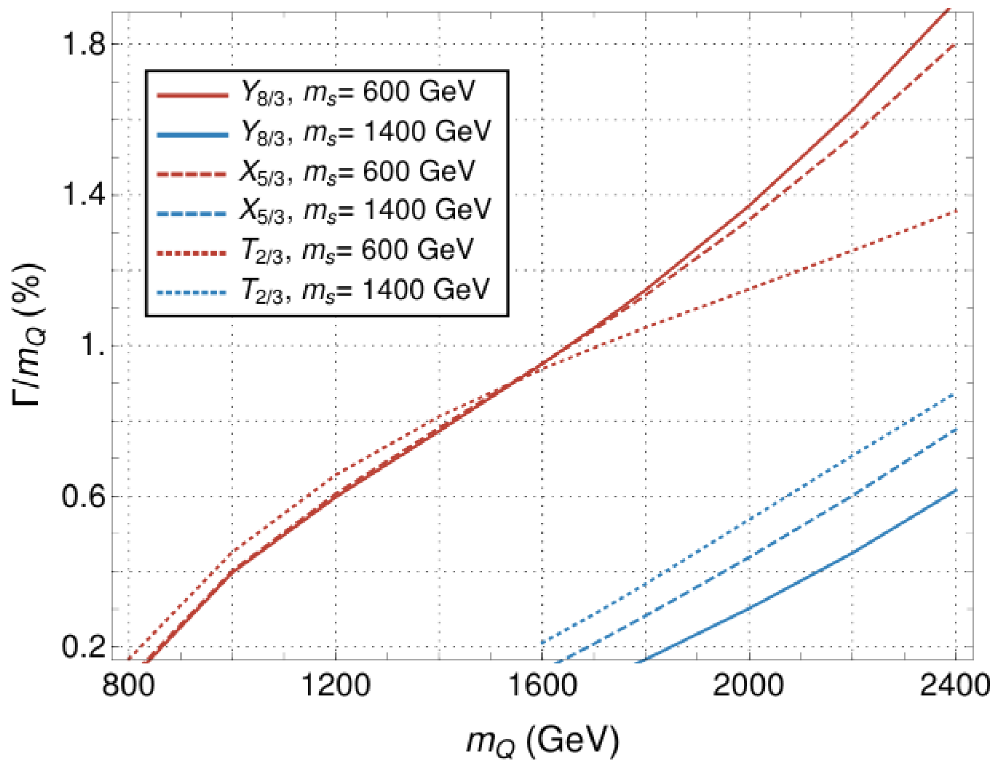
$\lambda_L^{S^+}$	$\lambda_R^{S^+}$	$\lambda_{t,L}^{S^0}$	$\lambda_{t,R}^{S^0}$	$\lambda_{b,L}^{S^0}$	$\lambda_{b,R}^{S^0}$	$\kappa_{X,L}^{S^+}$	$\kappa_{X,R}^{S^+}$
-0.123	0.123	0.174	0	0	0.174	-0.087	1

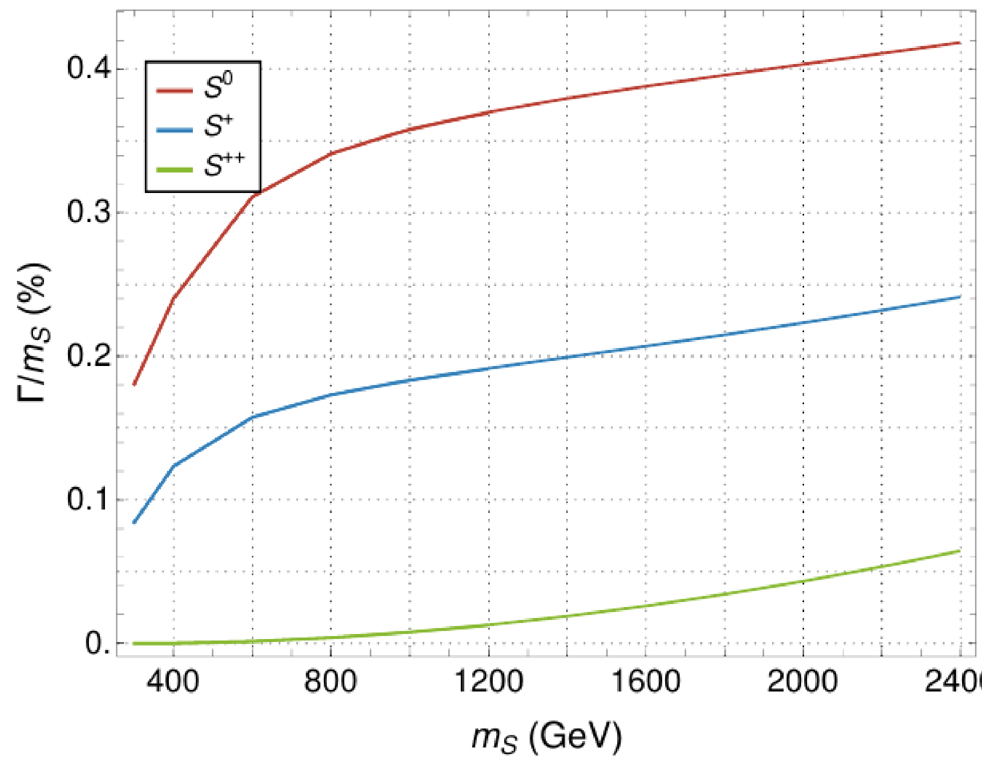
$\kappa_{T,L}^{S^+}$	$\kappa_{T,R}^{S^+}$	$\kappa_{Y,L}^{S^{++}}$	$\kappa_{Y,R}^{S^{++}}$	$\kappa_{X,L}^{S^{++}}$	$\kappa_{X,R}^{S^{++}}$	$\kappa_{T,L}^{S^0}$	$\kappa_{T,R}^{S^0}$
0.123	0	0	1	0.123	0	-0.174	1

$\kappa_{T,L}^{h}$	$\kappa_{T,R}^{h}$	$\kappa_{T,L}^{W}$	$\kappa_{T,R}^{W}$	$\kappa_{X,L}^{W}$	$\kappa_{X,R}^{W}$	$\kappa_{T,L}^{Z}$	$\kappa_{T,R}^{Z}$
0.015	0.246	0	0	0	0.031	0	-0.043

$\kappa_{XT,L}^{S^+}$	$\kappa_{XT,R}^{S^+}$	$\kappa_{YX,L}^{S^+}$	$\kappa_{YX,R}^{S^+}$	$\kappa_{YT,L}^{S^{++}}$	$\kappa_{YT,R}^{S^{++}}$	$\kappa_{TT,L}^{S^0}$	$\kappa_{TT,R}^{S^0}$
0	0.022	0	0	0	-0.022	0	-0.022

Decay widths





Cross-sections and efficiencies

SR	Backgrounds	σ [fb]	$\epsilon(m_{\text{eff}} > 2100$ GeV$)$	$\epsilon(m_{\text{eff}} > 2300$ GeV$)$
SRL	$t\bar{t}V+\leq 2j$	838	1.20×10^{-4}	5.24×10^{-5}
SRS	(with $\sqrt{\hat{s}} \geq 1200$ GeV)		9.43×10^{-5}	3.24×10^{-5}
SRL	$4t$	5.32	3.20×10^{-4}	1.70×10^{-4}
SRS			2.00×10^{-4}	1.20×10^{-4}
BP/SR	**Signal**	**σ [fb]**	**$\epsilon(m_{\text{eff}} > 2100$ GeV$)$**	**$\epsilon(m_{\text{eff}} > 2300$ GeV$)$**
BPL/SRL	$Y_{8/3}$ pair	3.07	0.092	0.079
	$X_{5/3}$ pair	3.21	0.051	0.044
	$T_{2/3}$ pair	3.19	0.030	0.026
BPS/SRS	$Y_{8/3}$ pair	3.15	0.088	0.077
	$X_{5/3}$ pair	3.19	0.035	0.031
	$T_{2/3}$ pair	3.16	0.025	0.022

Exclusion / Discovery prospects

- Signal and background are governed by independent Poisson statistics
- Discovery significance: $H_{\text{data}} = H_{S+B},\ H_0 = H_B$

$$Z_{\text{disc}} = \sqrt{2}\left[(S+B)\ln\left(\frac{(S+B)(B+\sigma_B^2)}{B^2+(S+B)\sigma_B^2}\right) - \frac{B^2}{\sigma_B^2}\ln\left(1+\frac{\sigma_B^2 S}{B(B+\sigma_B^2)}\right)\right]^{1/2}$$

- Exclusion significance: $H_{\text{data}} = H_B,\ H_0 = H_{S+B}$

$$Z_{\text{exc}} = \left[2\left\{S - B\ln\left(\frac{B+S+x}{2B}\right) - \frac{B^2}{\sigma_B^2}\ln\left(\frac{B-S+x}{2B}\right)\right\} - (B+S-x)\left(1+\frac{B}{\sigma_B^2}\right)\right]^{1/2}$$

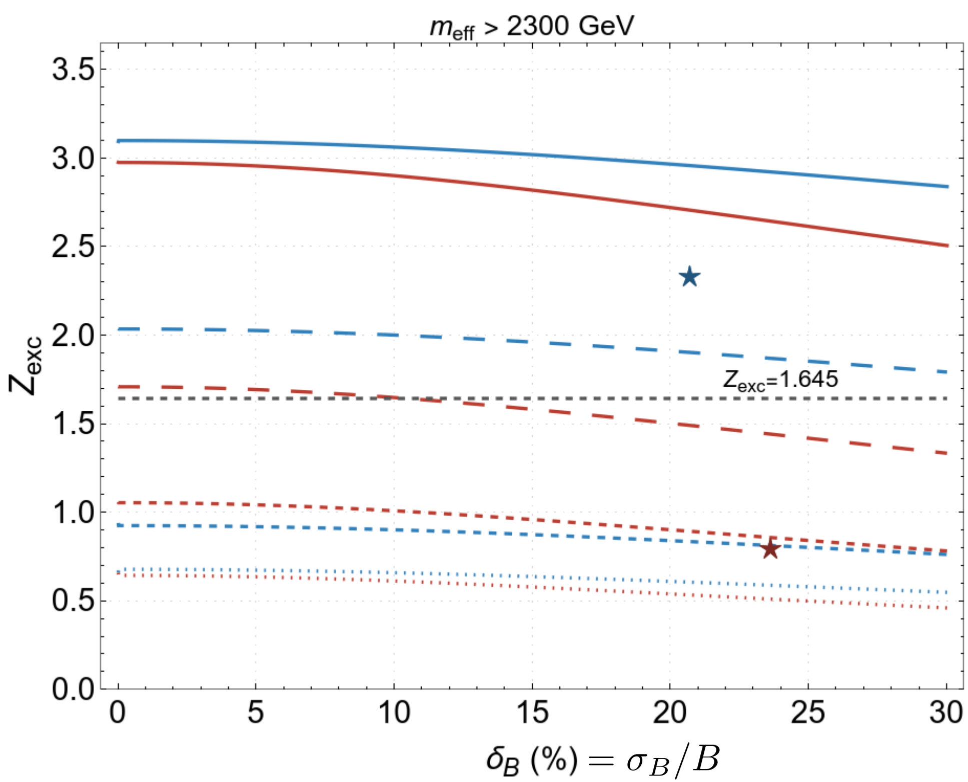
$$x \equiv \sqrt{(S+B)^2 - \frac{4SB\sigma_B^2}{B+\sigma_B^2}}$$

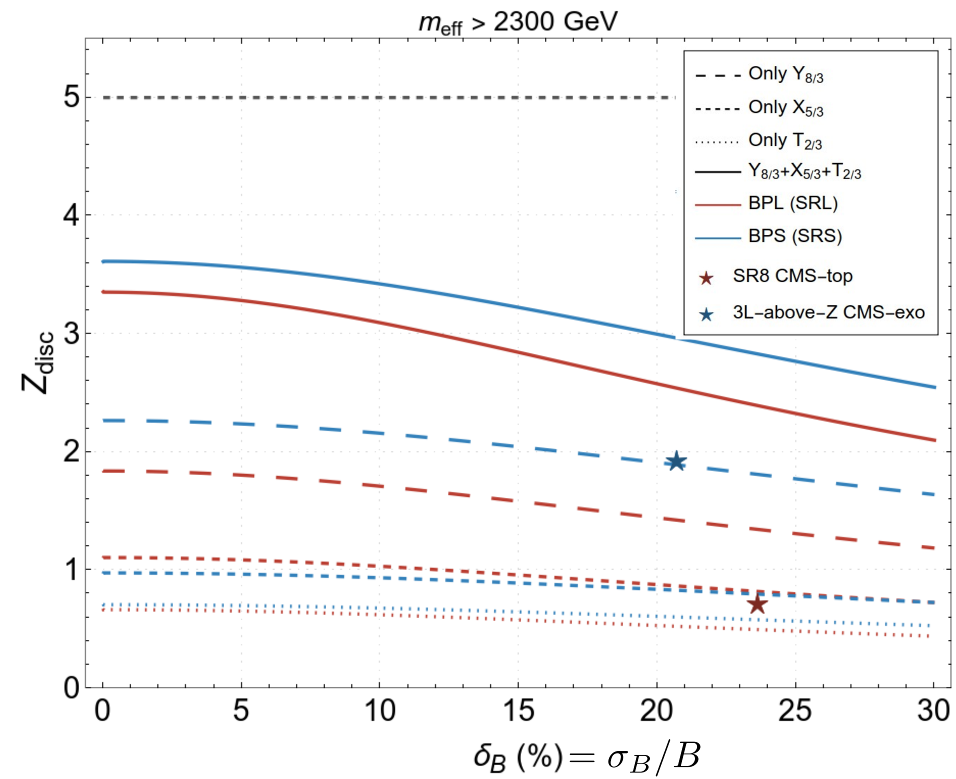
Discovery : $Z_{\text{disc}} > 5$

Exclusion : $Z_{\text{exc}} > 1.645$

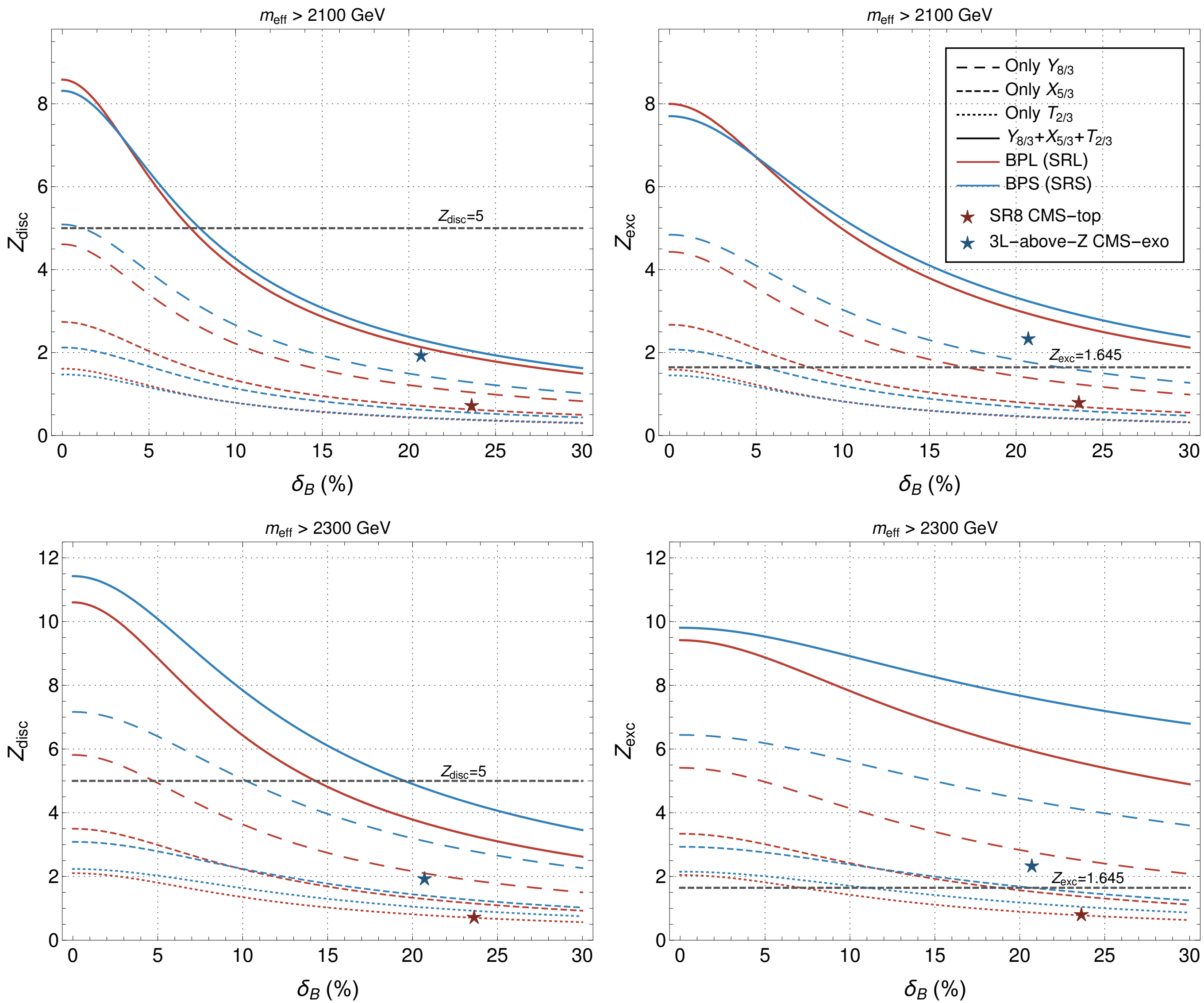
N Kumar, S P Martin, 1510.03456

Sensitivity @ Run 3



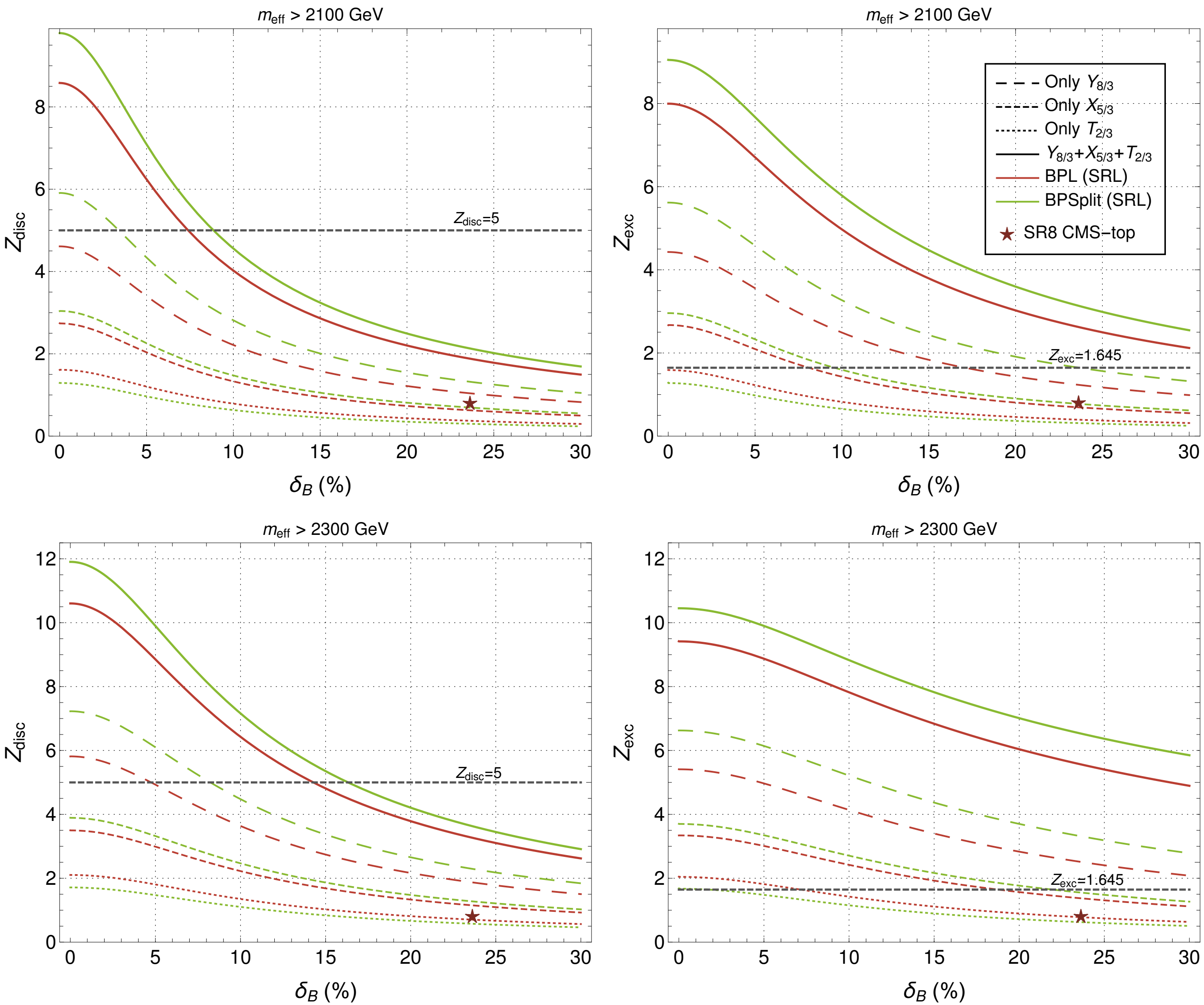


HL-LHC Prospects



- Discovery possible when entire multiplet contributes to the SR (<20% systematics)
- Exclusion possible for entire triplet even with >30% systematics
- SRL, SRS perform better than signal regions for most sensitive recast

Introducing mass-splitting



- Introducing mass-split ~50 GeV for VLQs does not alter the conclusions significantly