Mind the gap: exclusion limits and unconventional searches for leptoquarks

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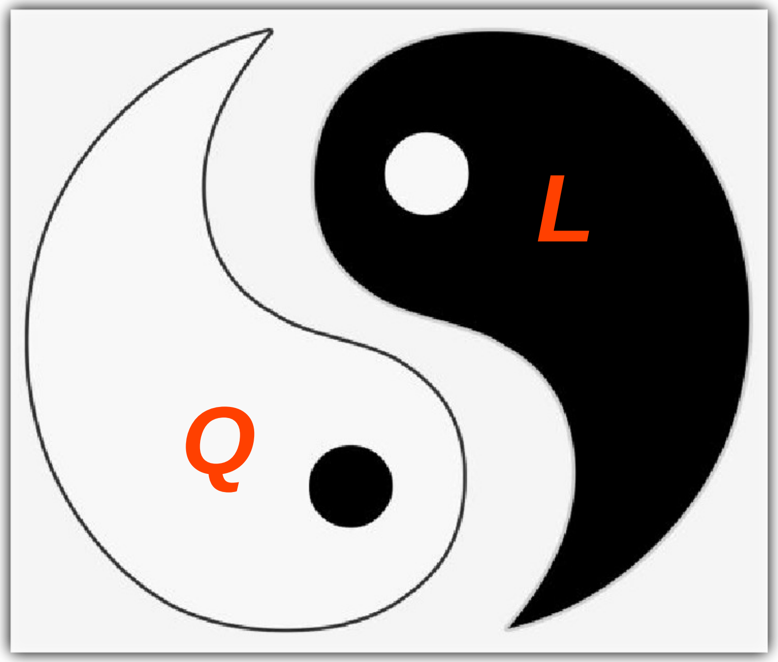
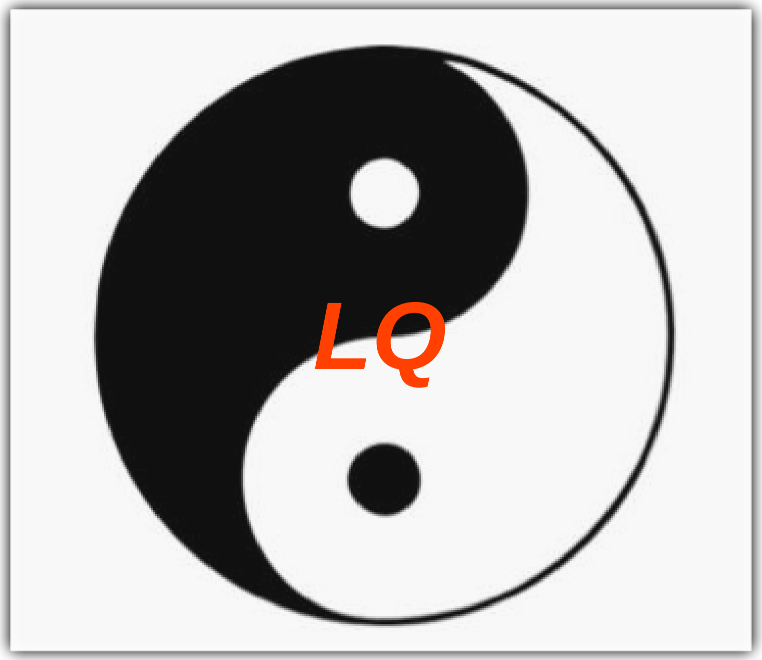
What are leptoquarks?





- Leptoquarks are color triplet spin-0 or spin-1 bosons (weak and hypercharged)
- Carry both lepton and baryon numbers; connector of lepton and quark sector
- Naturally appear in Pati-Salam models, GUT theories, flavour models, neutrino mass models, RPV SUSY models - squarks are leptoquarks etc.
- Bottom-up: scalar LQ can be added by hand; adding vector LQ is tricky – need to know the additional gauge structure

Leptoquark species

Leptoquark (Φ)	Spin	F	Colour	T_3	Q_{em}	$\lambda_L(lq)$	$\lambda_R(lq)$	$\lambda_L(\nu q)$
S_1	0	-2	$\bar{3}$	0	1/3	g_{1L}	g_{1R}	$-g_{1L}$
$\tilde{S}_1$	0	-2	$\bar{3}$	0	4/3	0	$\tilde{g}_{1R}$	0
				$+1$	4/3	$-\sqrt{2}g_{3L}$	0	0
S_3	0	-2	$\bar{3}$	0	1/3	$-g_{3L}$	0	$-g_{3L}$
				-1	$-2/3$	0	0	$\sqrt{2}g_{3L}$
				1/2	5/3	h_{2L}	h_{2R}	0
R_2	0	0	3					
				$-1/2$	2/3	0	$-h_{2R}$	h_{2L}
				1/2	2/3	$\tilde{h}_{2L}$	0	0
$\tilde{R}_2$	0	0	3					
				$-1/2$	$-1/3$	0	0	$\tilde{h}_{2L}$
				1/2	4/3	g_{2L}	g_{2R}	0
$V_{2\mu}$	1	-2	$\bar{3}$					
				$-1/2$	1/3	0	g_{2R}	g_{2L}
				1/2	1/3	$\tilde{g}_{2L}$	0	0
$\tilde{V}_{2\mu}$	1	-2	$\bar{3}$					
				$-1/2$	$-2/3$	0	0	$\tilde{g}_{2L}$
$U_{1\mu}$	1	0	3	0	2/3	h_{1L}	h_{1R}	h_{1L}
$\tilde{U}_{1\mu}$	1	0	3	0	5/3	0	$\tilde{h}_{1R}$	0
				$+1$	5/3	$\sqrt{2}h_{3L}$	0	0
$U_{3\mu}$	1	0	3	0	2/3	$-h_{3L}$	0	h_{3L}
				-1	$-1/3$	0	0	$\sqrt{2}h_{3L}$

Blumlein, Ruckl; PLB 304 (1993) 337-346

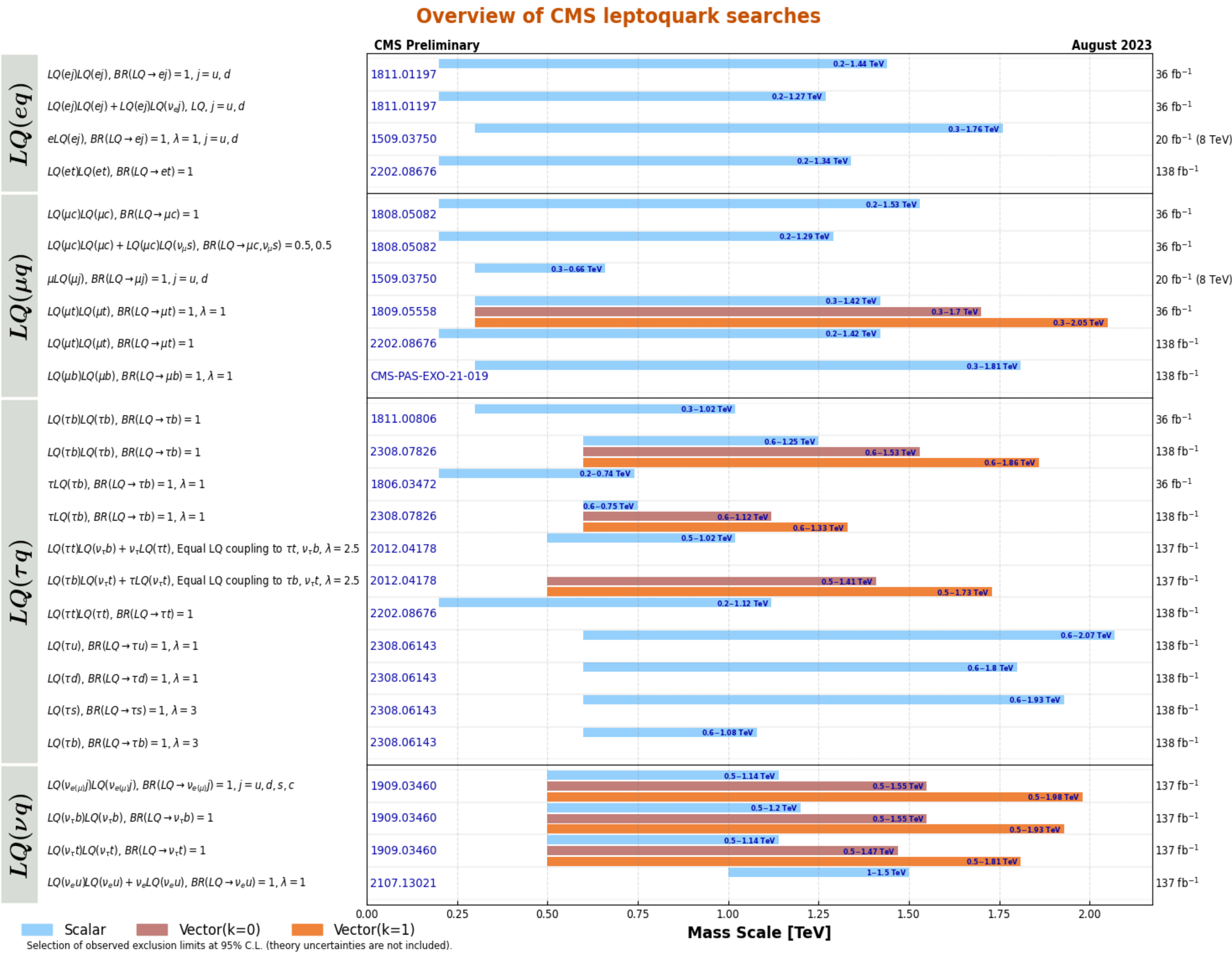
Why leptoquarks?

- Anomalies: LQs are suitable and very popular candidates to explain B-meson decay anomalies, muon (g-2) anomalies
- Higgs physics: enhance the light-quark Yukawa couplings, flavour-violating decays of Higgs like $h \rightarrow \tau\mu$, enhanced di-Higgs production 2002.12571, 1508.01897, 2205.12210
- Dark matter: can act as a portal to dark matter (e.g., singlet fermion) 1807.06547, 1808.07844
- Strong production of uncolored particles: produce right-handed neutrinos, vectorlike leptons or vectorlike quarks 1708.06206, 2301.11889, 2312.09189
- GW+EWPT: give rise to strong first-order phase transition and can produce gravitational wave detectable in future experiments 2209.14605
- Vacuum stability: LQ can affect the vacuum stability of the SM 1609.03561

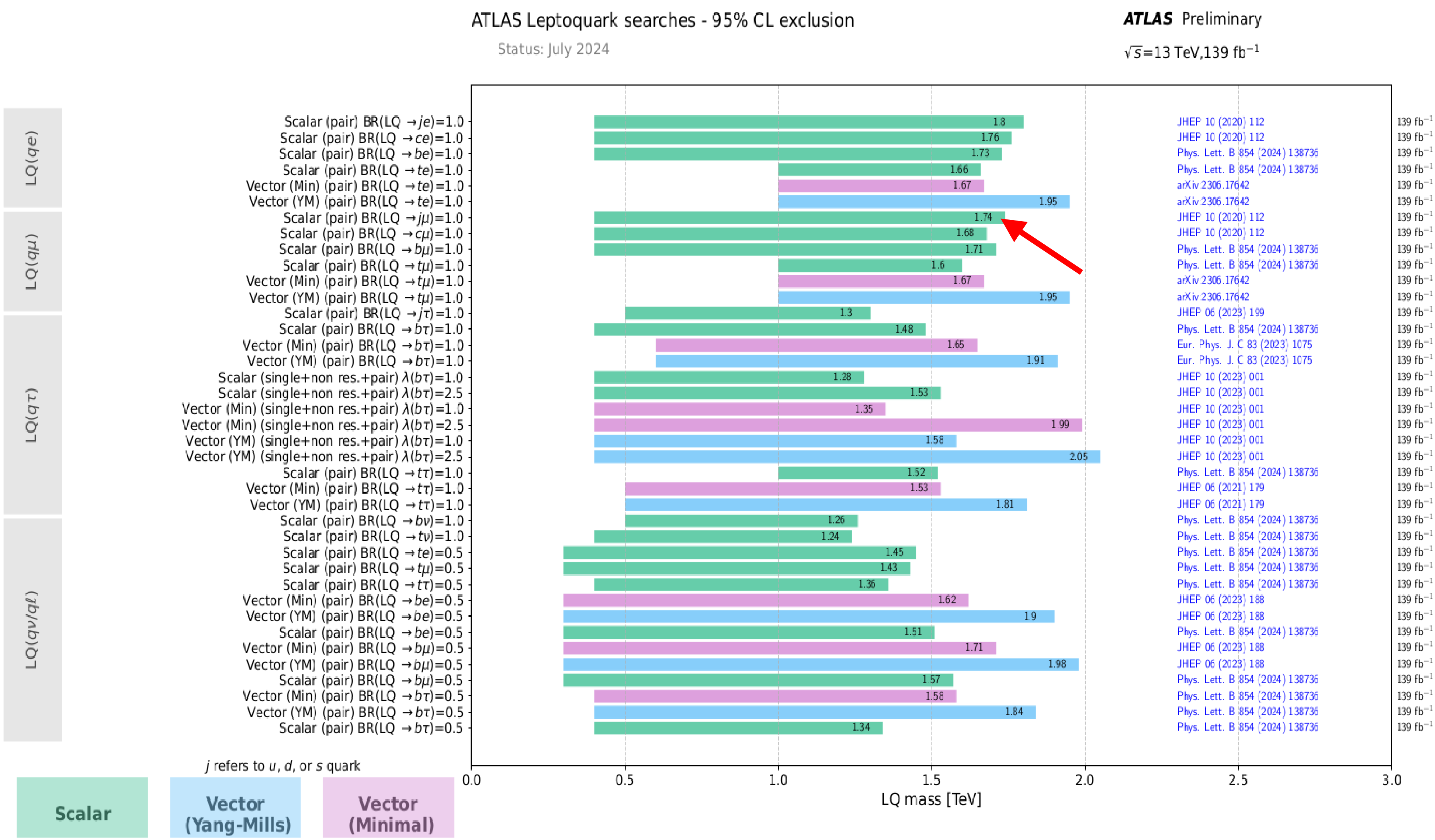
Questions will be anaswered

- Can we improve exclusion limits on LQ parameters (mass, BR, couplings)?
- What are the effects of weak and hypercharge of LQs on their exclusion limits?
- Non-observation of LQs - are LQs decaying to new “non-standard” decay modes?

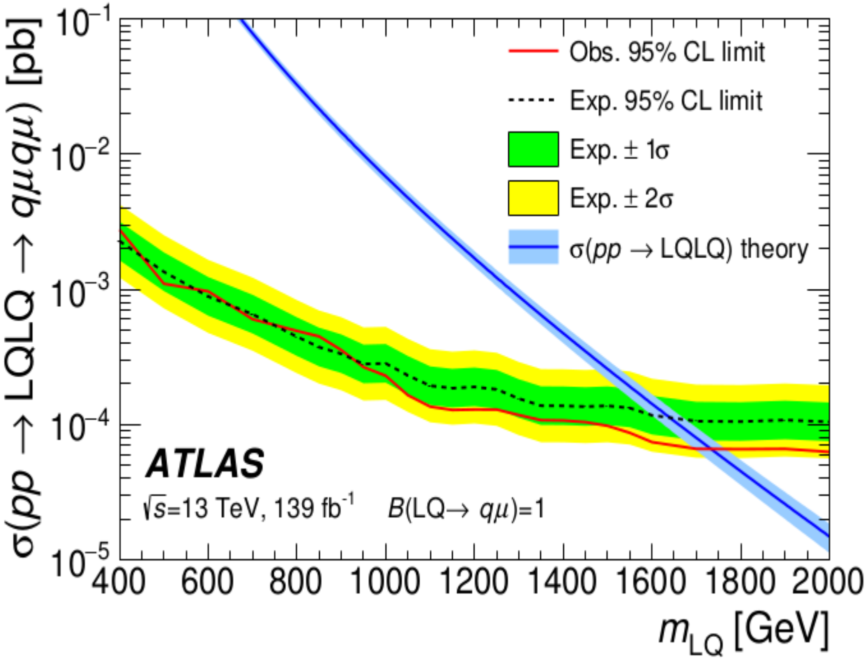
LQ mass limits from CMS

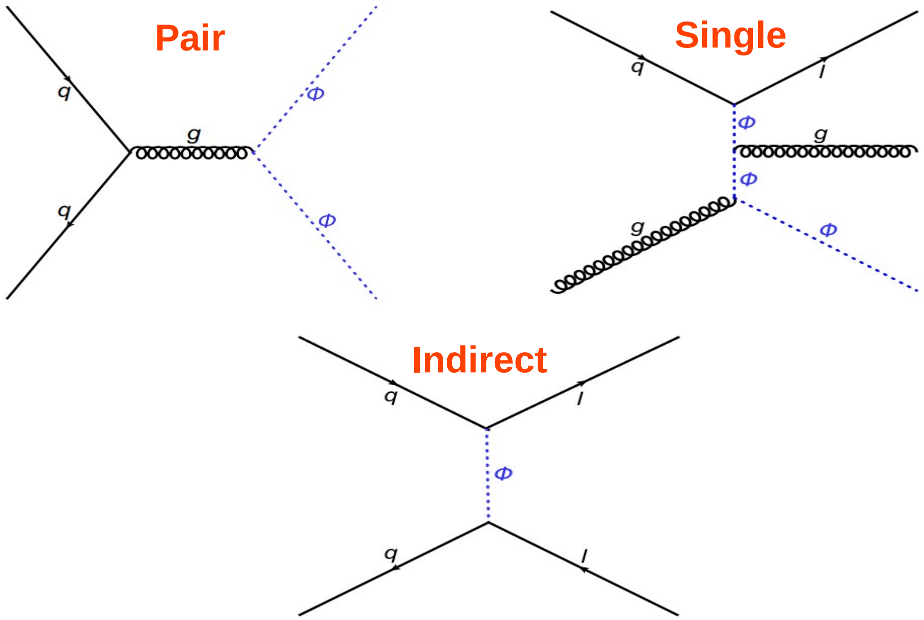


LQ mass limits from ATLAS



Coupling exclusion: dilepton-dijet data





$$\frac{\mathcal{N}_{\text{obs}}(M_{\ell_q})}{\mathcal{L}_{\text{exp}}} = \sigma_{\text{obs}}(M_{\ell_q}) \times \varepsilon_{\text{exp}}(M_{\ell_q})$$

$$= \sum_{i \in \text{topologies}} \sigma_i(M_{\ell_q}, \vec{y}) \times \beta_i(\vec{y}) \times \varepsilon_i(M_{\ell_q})$$

	Pair production			Single production			Indirect production			Indirect interference		
Mass (S_1) (TeV)	σ_{PP} (fb)	ε_{PP}	$\mathcal{N}_{\text{PP}}$	σ_{SP} (fb)	ε_{SP}	$\mathcal{N}_{\text{SP}}$	σ_{IP} (fb)	ε_{IP}	$\mathcal{N}_{\text{IP}}$	σ_{II} (fb)	ε_{II}	$\mathcal{N}_{\text{II}}$
1.5	1.4×10^{-1}	0.42	8.2	8.4	0.17	198.5	32.0	0.018	111.2	−275.0	0.007	−267.6
2.5	6.9×10^{-4}	0.32	3.1×10^{-2}	5.4×10^{-1}	0.13	9.8	5.4	0.018	13.4	−102.0	0.007	−99.2
4.0	4.6×10^{-7}	0.30	2.0×10^{-5}	3.4×10^{-2}	0.20	0.7	1.0	0.028	3.7	−40.2	0.010	−55.9

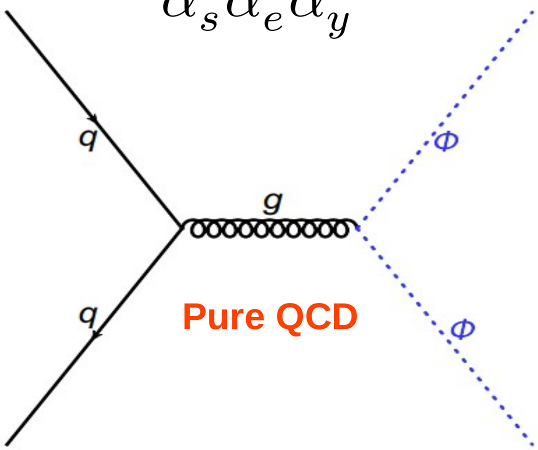
A. Bhaskar, A. Das, TM, S. Mitra, R. Sharma; PRD 109, 055018 (2024)

Pair production: different orders

$$D_\mu = \partial_\mu - i g_s \frac{\lambda^a}{2} G^a_\mu - i g \frac{\sigma^k}{2} W^k_\mu - i g' Y B_\mu$$

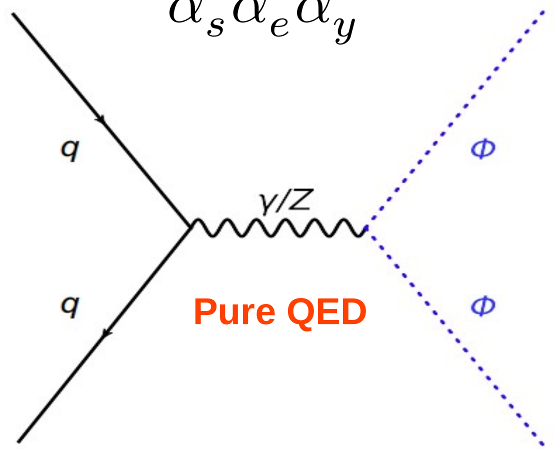
$$\alpha_s = \frac{g_s^2}{4\pi}; \quad \alpha_e = \frac{e^2}{4\pi}; \quad \alpha_y = \frac{y^2}{4\pi}$$

$$\alpha_s^2 \alpha_e^0 \alpha_y^0$$



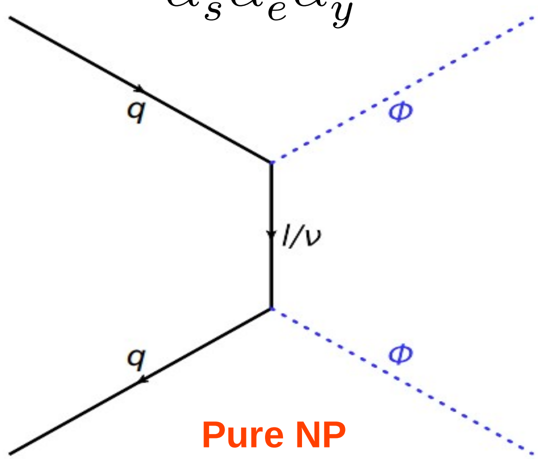
Pure QCD

$$\alpha_s^0 \alpha_e^2 \alpha_y^0$$



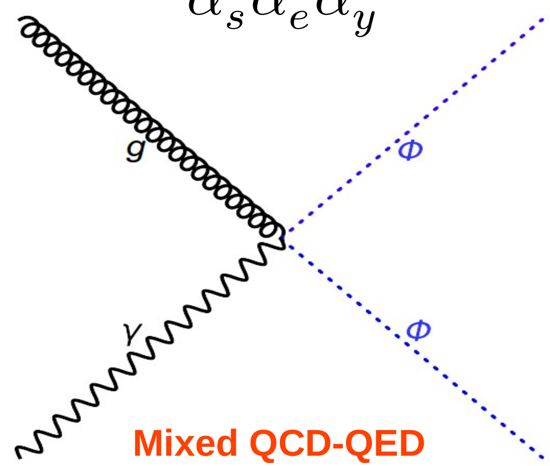
Pure QED

$$\alpha_s^0 \alpha_e^0 \alpha_y^2$$



Pure NP

$$\alpha_s^1 \alpha_e^1 \alpha_y^0$$



Mixed QCD-QED

Mass exclusion: effects of QED

A. Bhaskar, A. Das, TM, S. Mitra, R. Sharma; PRD 109, 055018 (2024)

Model	QCD	QCD + QED
$S_1(y^{LL}_{10,12})$	1418	1423
$S_1(y^{RR}_{10,12})$	1733	1741
$\tilde{S}_1(y^{RR}_{11,12})$	1733	1854
$R_2(y^{LR}_{20,12})$	1852	2012
$R_2(y^{RL}_{20,12})$	1733	1917
$\tilde{R}_2(y^{RL}_{21,12})$	1733	1767
$S_3(y^{LL}_{30,12})$	1772	1882

Mass exclusion: effects of QED

Model	QCD	QCD + QED
$S_1(y^{LL}_{10,12})$	1418	1423
$S_1(y^{RR}_{10,12})$	1733	1741
$\tilde{S}_1(y^{RR}_{11,12})$	1733	
$R_2(y^{LR}_{20,12})$	1852	
$R_2(y^{RL}_{20,12})$	1733	
$\tilde{R}_2(y^{RL}_{21,12})$	1733	
$S_3(y^{LL}_{30,12})$	1772	

Model	QCD	QCD+QED
$U_1(x^{LL}_{10,12})$	1746	1806
$U_1(x^{RR}_{10,12})$	1989	2056
$\tilde{U}_1(y^{RR}_{11,12})$	1989	2319
$V_2(x^{LR}_{20,12})$	2091	2275
$V_2(x^{RL}_{20,12})$	1979	2217
$\tilde{V}_2(x^{RL}_{21,12})$	1979	2010
$U_3(x^{LL}_{30,12})$	2027	2337

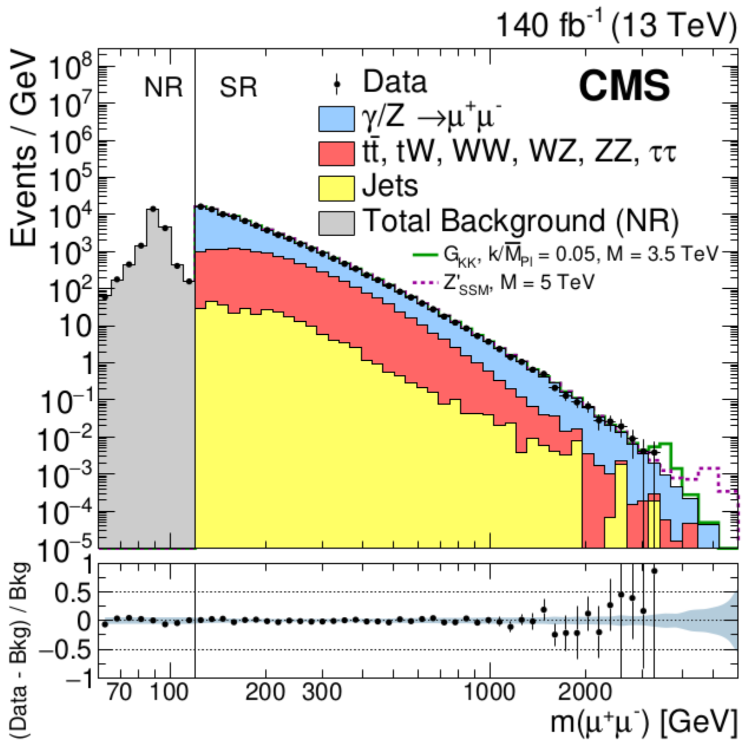
Mass exclusion: effects of QED

Model	QCD	QCD + QED
$S_1(y^{LL}_{10,12})$	1418	1423
$S_1(y^{RR}_{10,12})$	1733	1741
$\tilde{S}_1(y^{RR}_{11,12})$	1733	[illegible]
$R_2(y^{LR}_{20,12})$	1852	[illegible]
$R_2(y^{RL}_{20,12})$	1733	[illegible]
$\tilde{R}_2(y^{RL}_{21,12})$	1733	[illegible]
$S_3(y^{LL}_{30,12})$	1772	[illegible]

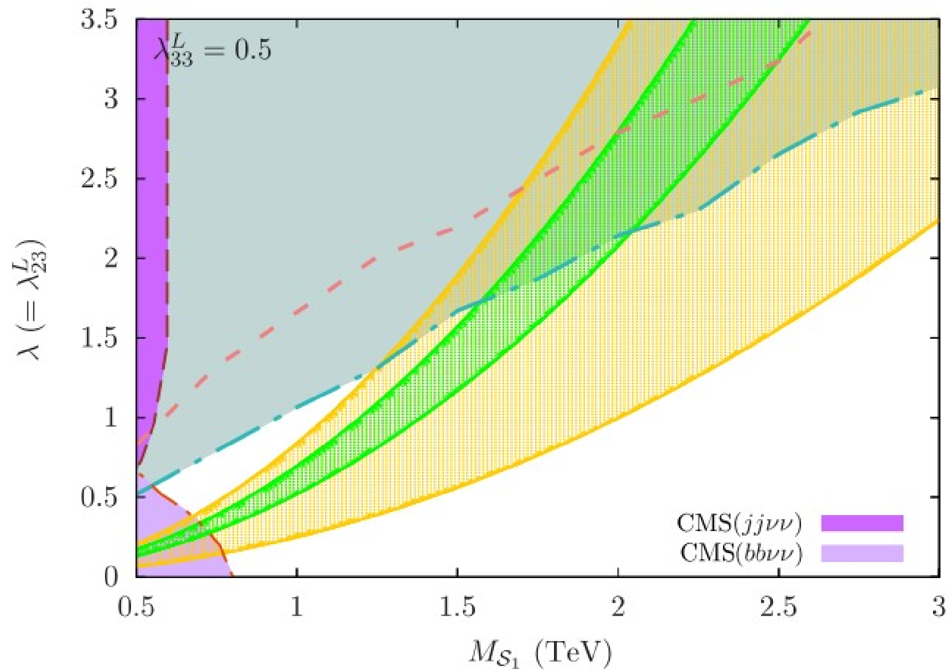
Model	QCD	QCD+QED
$U_1(x^{LL}_{10,12})$	1746	1806
$U_1(x^{RR}_{10,12})$	1989	2056
$\tilde{U}_1(y^{RR}_{11,12})$	1989	2319
$V_2(x^{LR}_{20,12})$	2091	[illegible]
$V_2(x^{RL}_{20,12})$	1979	[illegible]
$\tilde{V}_2(x^{RL}_{21,12})$	1979	[illegible]
$U_3(x^{LL}_{30,12})$	2027	[illegible]

Model	QCD	QCD+QED
$U_1(x^{LL}_{10,12})$	2038	2051
$U_1(x^{RR}_{10,12})$	2276	2295
$\tilde{U}_1(y^{RR}_{11,12})$	2278	2410
$V_2(x^{LR}_{20,12})$	2383	2451
$V_2(x^{RL}_{20,12})$	2279	2360
$\tilde{V}_2(x^{RL}_{21,12})$	2278	2283
$U_3(x^{LL}_{30,12})$	2310	2436

Coupling exclusion: high-pT dilepton tail

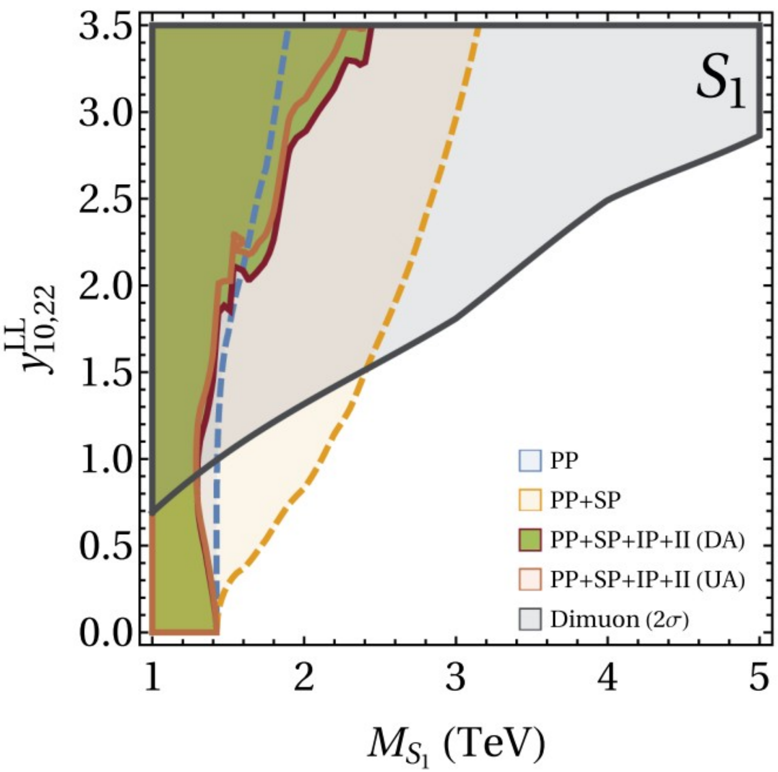


$$\chi^2(M_{LQ},\vec{\lambda}) = \sum_{\ell\ell=ee,\mu\mu,\tau\tau} \chi^2_{\ell}(M_{LQ},\vec{\lambda}) = \sum_{\ell\ell}\sum_{b\in \text{bins}} \left(\frac{\mathcal{N}^b_{\text{Theory}}(M_{LQ},\vec{\lambda}) - \mathcal{N}^b_{\text{Data}}}{\Delta\mathcal{N}^b}\right)^2\Bigg|_{\ell\ell}$$



TM, S. Mitra, S. Raz; PRD 99, 055028 (2019)

Coupling exclusion: scalar LQ



A. Bhaskar, A. Das, TM, S. Mitra, R. Sharma; PRD 109, 055018 (2024)

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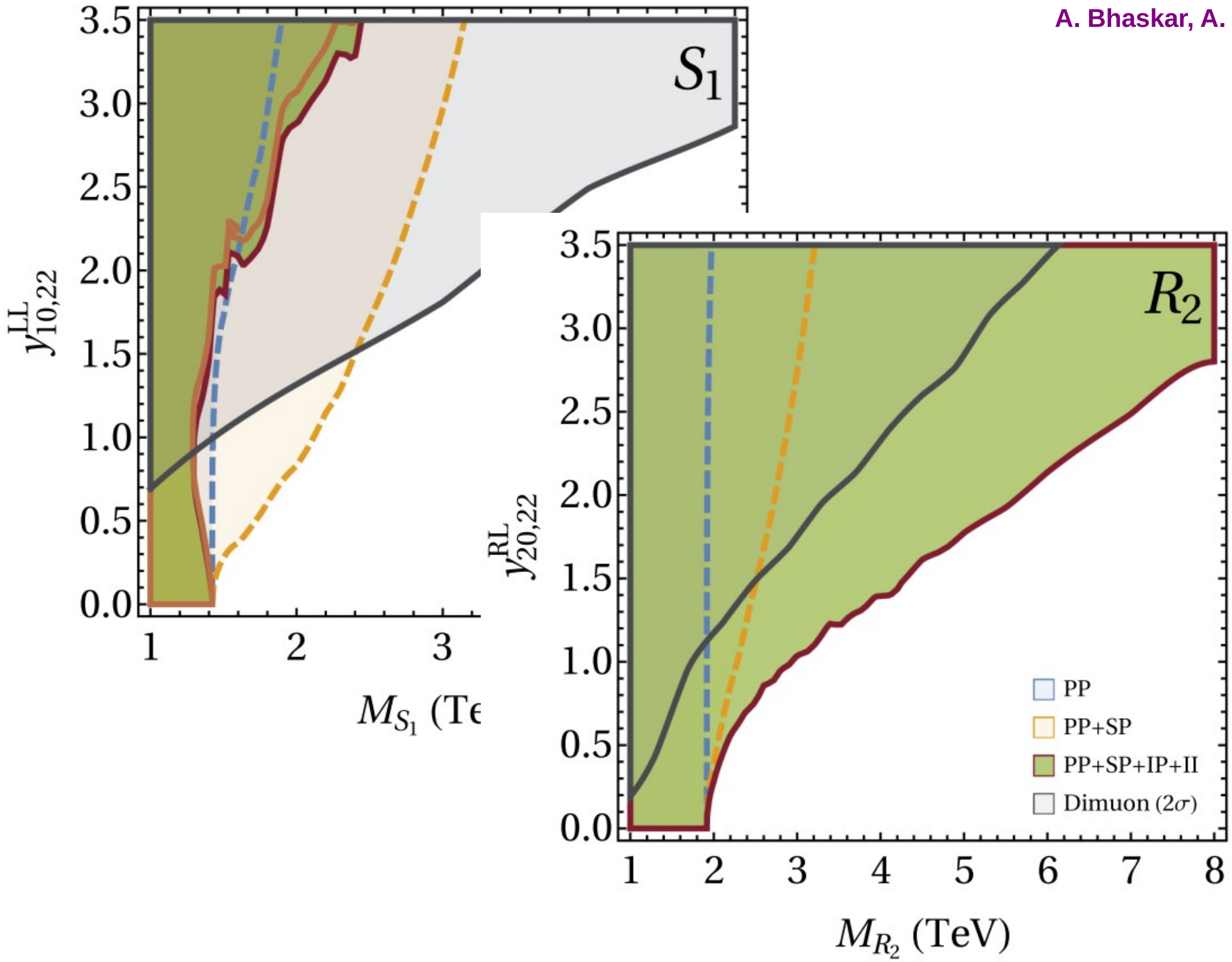
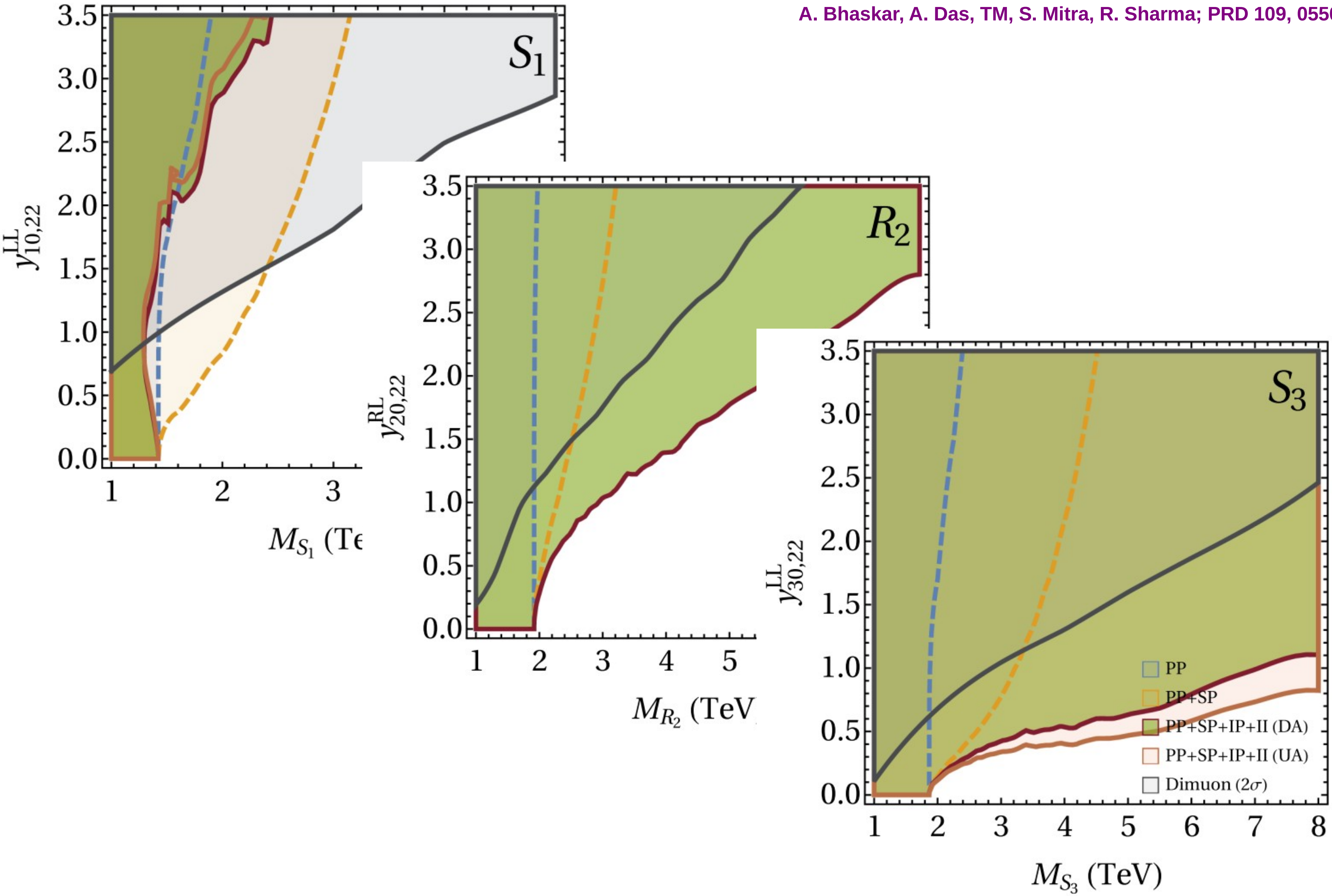
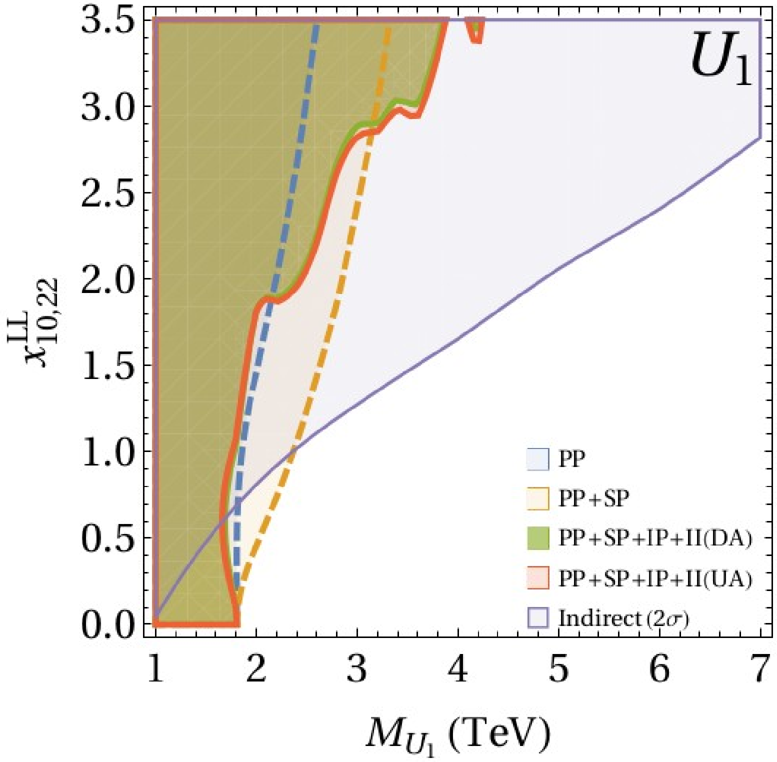


Coupling exclusion: scalar LQ

A. Bhaskar, A. Das, TM, S. Mitra, R. Sharma; PRD 109, 055018 (2024)

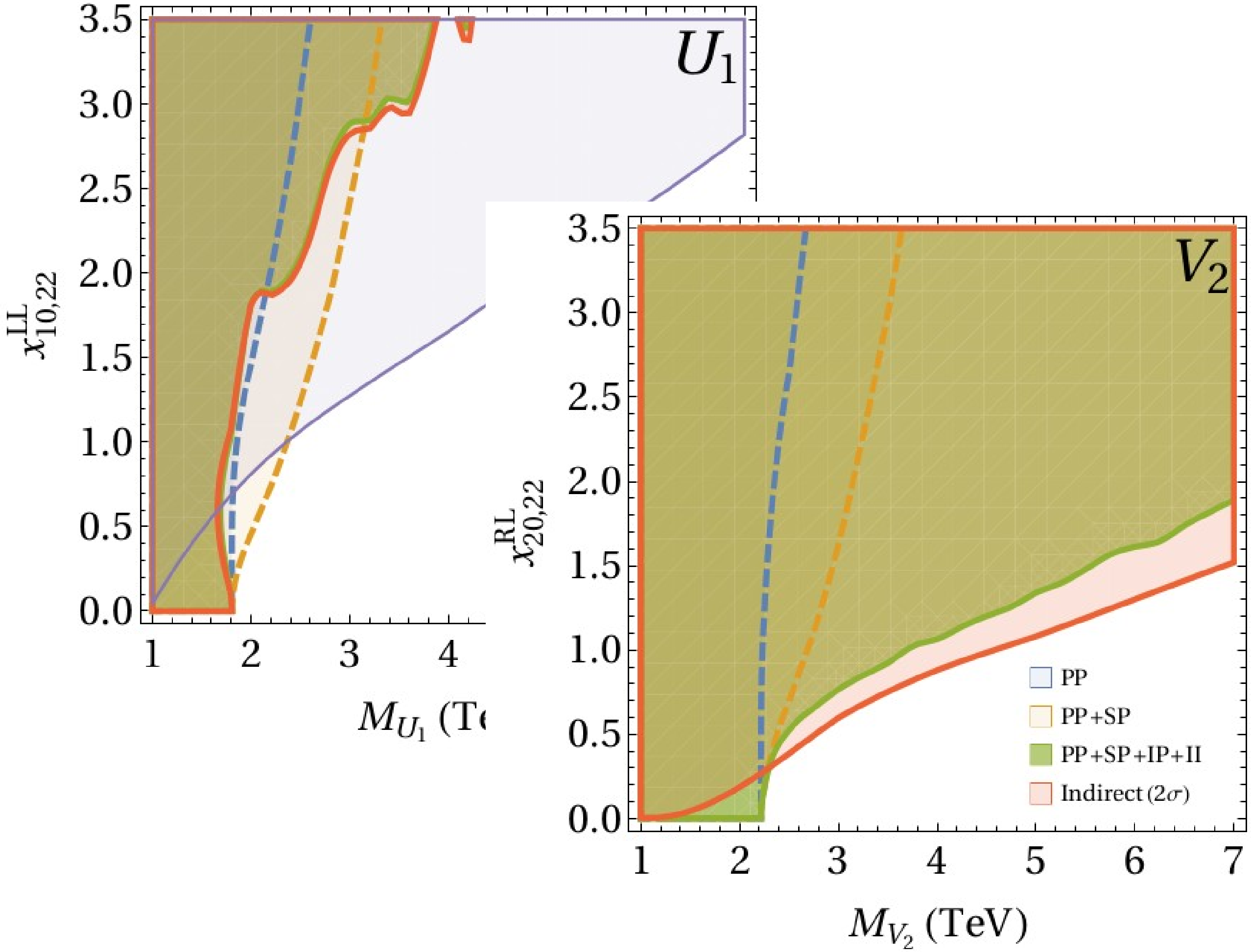


Coupling exclusion: vector LQ



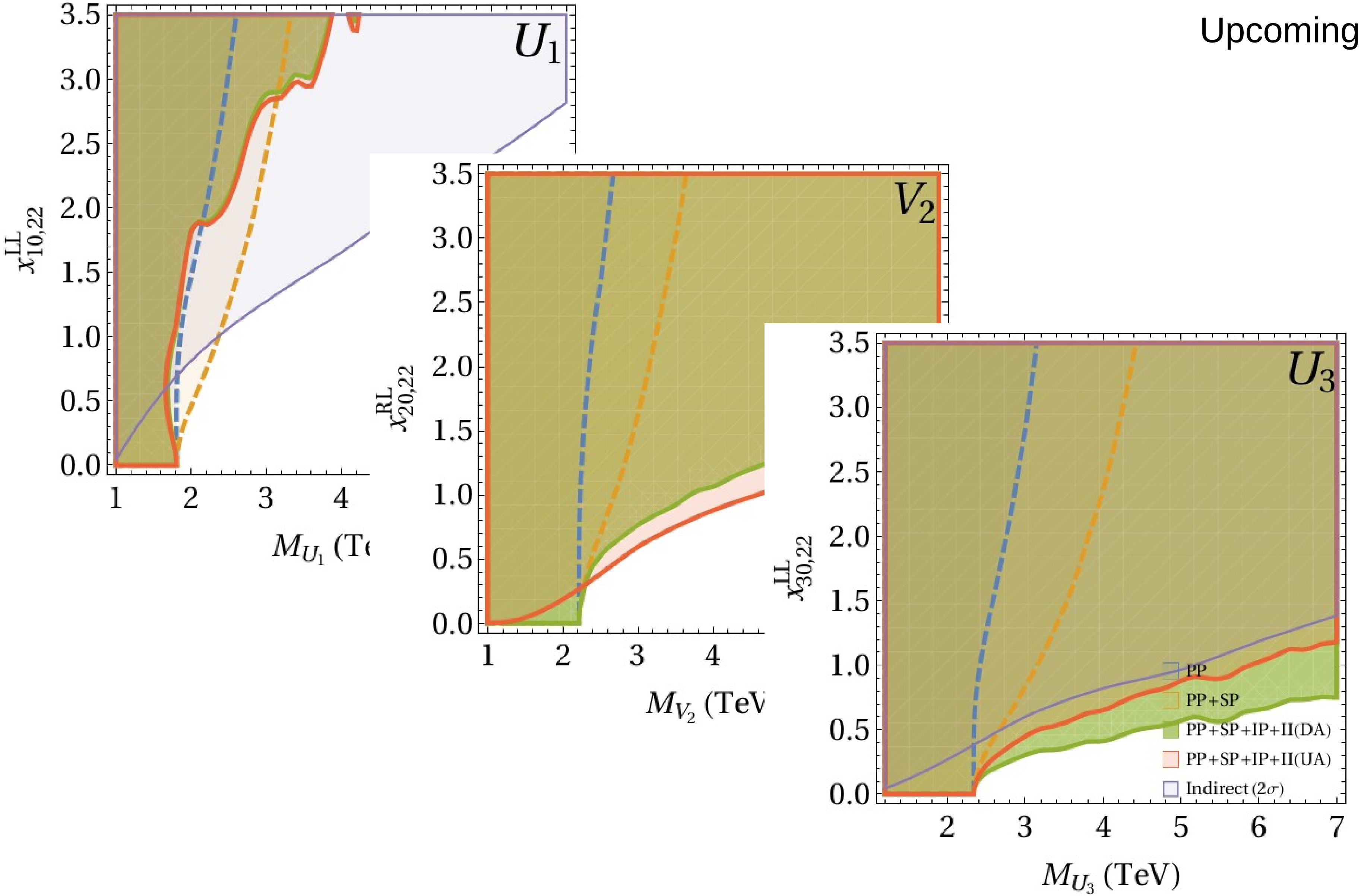
Upcoming...

Coupling exclusion: vector LQ



Upcoming...

Coupling exclusion: vector LQ



Upcoming...

TooLQit: PROJECT LEPTOQUARK

- Complete LO FeynRules model files for all scalar and vector LQ species; NLO FR model files are under progress; Available here: **https://github.com/rsrchtsm/LQ_Models**
- Introduced uniform naming convention, FeynRules notations, Monte-Carlo codes

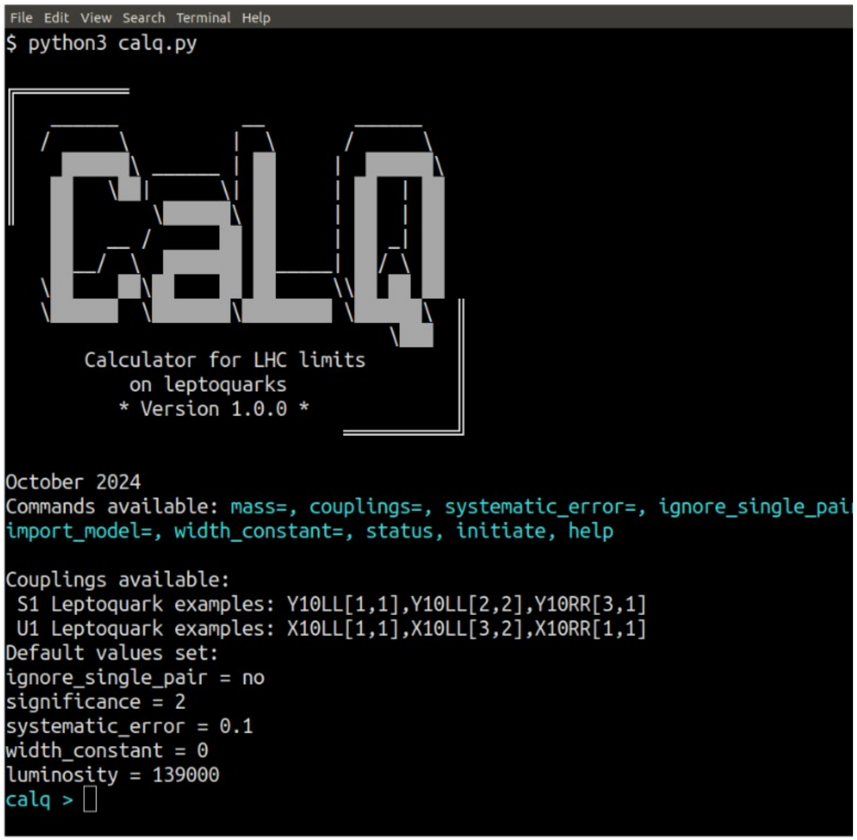
LQ types	FR notation	Monte Carlo codes
$S_1(\mathbf{3},\mathbf{1},\frac{1}{3})$	s101	4200011
$\widetilde{S}_1(\overline{\mathbf{3}},\mathbf{1},\frac{4}{3})$	s114	4200114
$S_3(\overline{\mathbf{3}},\mathbf{3},\frac{1}{3})$	s304, s301, s302	4200034, 4200031, 4200032
$R_2(\mathbf{3},\mathbf{2},\frac{7}{6})$	r205, r202	4200025, 4200022
$\widetilde{R}_2(\mathbf{3},\mathbf{2},\frac{1}{6})$	r212, r211	4200122, 4200121
$\overline{S}_1(\mathbf{3},\mathbf{1},-\frac{2}{3})$	s122	4210212
$U_1(\mathbf{3},\mathbf{1},\frac{2}{3})$	u102	4210012
$\widetilde{U}_1(\mathbf{3},\mathbf{1},\frac{5}{3})$	u115	4210015
$U_3(\mathbf{3},\mathbf{3},\frac{2}{3})$	u305, u302, u301	4210035, 4210032, 4210031
$V_2(\overline{\mathbf{3}},\mathbf{2},\frac{5}{6})$	v201, v204	4210021, 4210024
$\widetilde{V}_2(\overline{\mathbf{3}},\mathbf{2},-\frac{1}{6})$	v212, v211	4210122, 4210121
$\overline{U}_1(\mathbf{3},\mathbf{1},-\frac{1}{3})$	u121	4210211

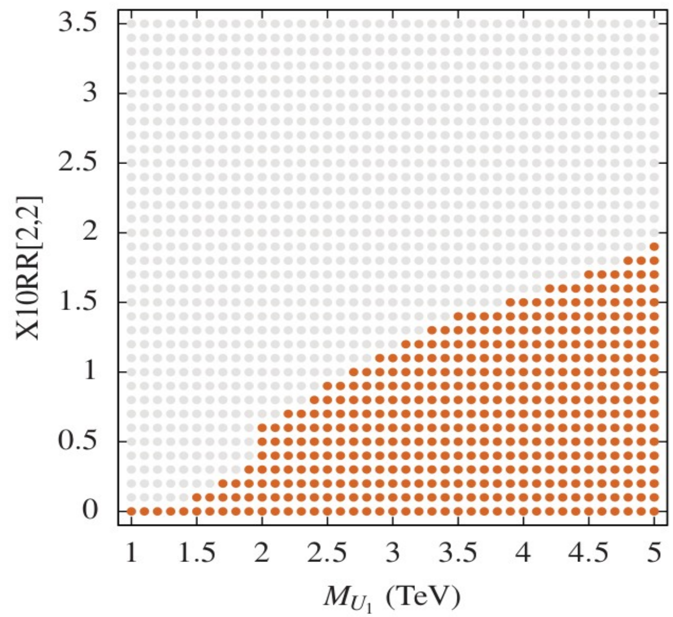
Project goals

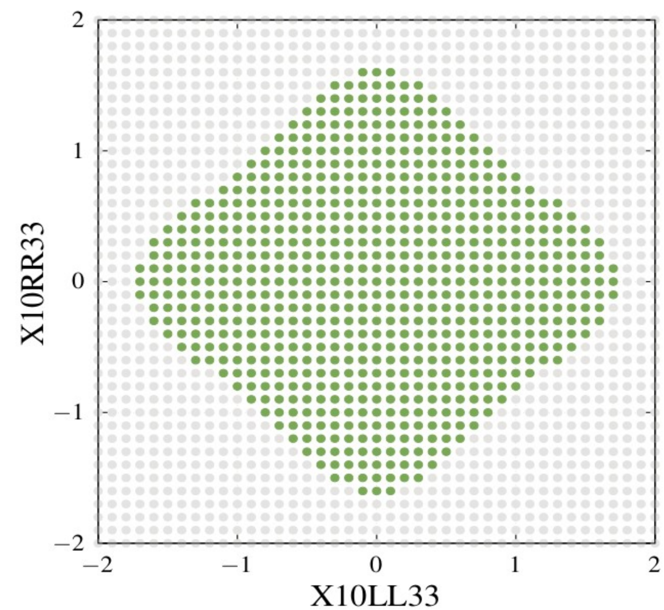
- Derive exclusion limits on masses and couplings of all LQ species
- LQ induced effective operators and constrain Wilson coefficients
- Propose new search strategies and improve using advanced methods
- LQ decaying to RHN, VLF – many interesting processes

Leptoquark calculator

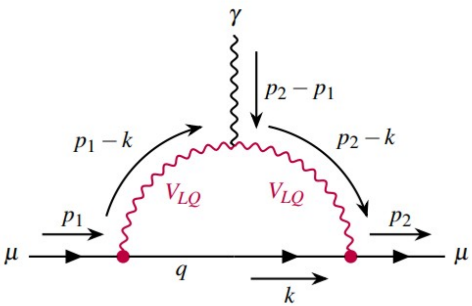
Upcoming...

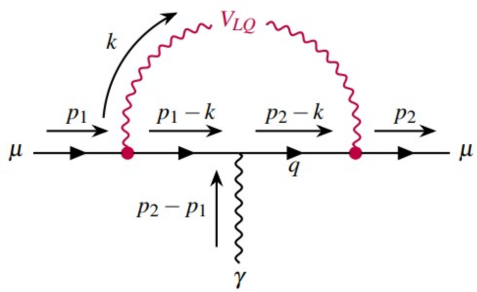


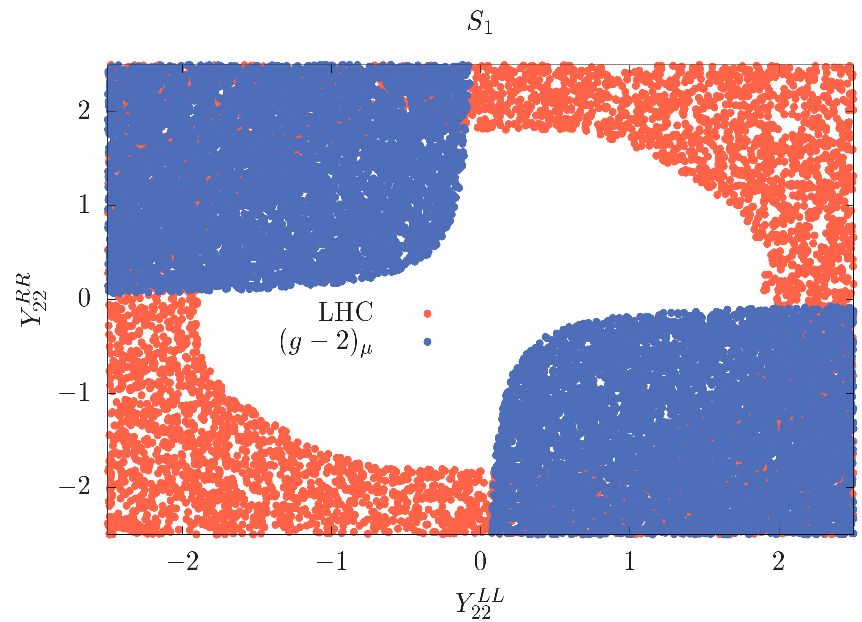




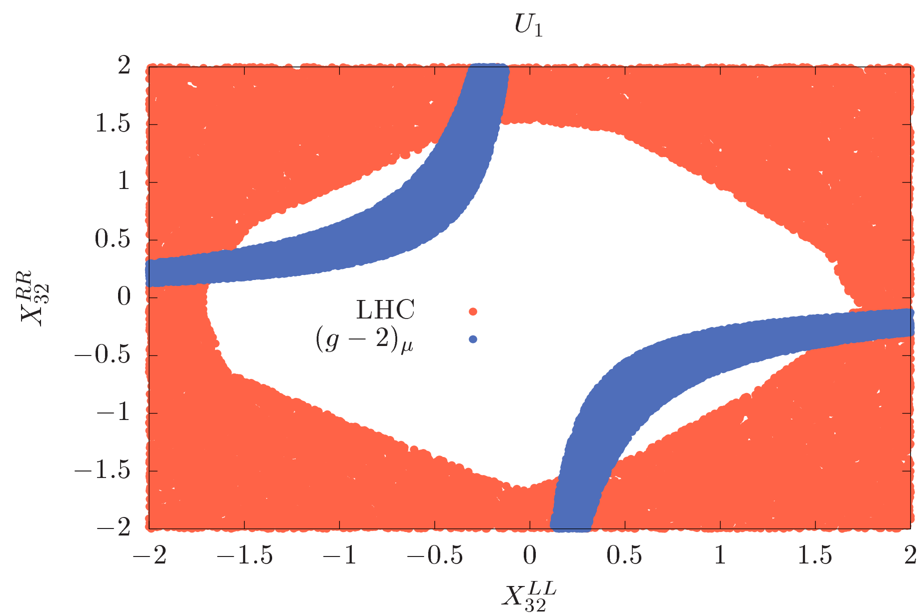
LHC limits and muon (g-2)



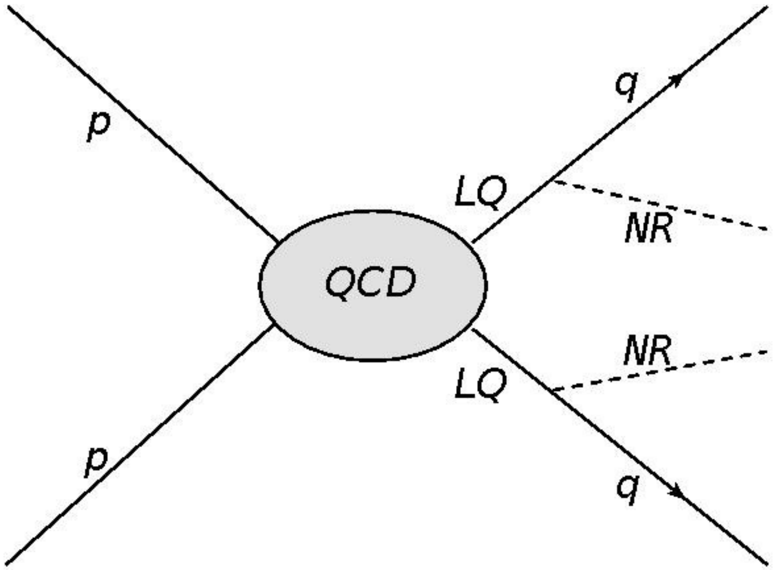




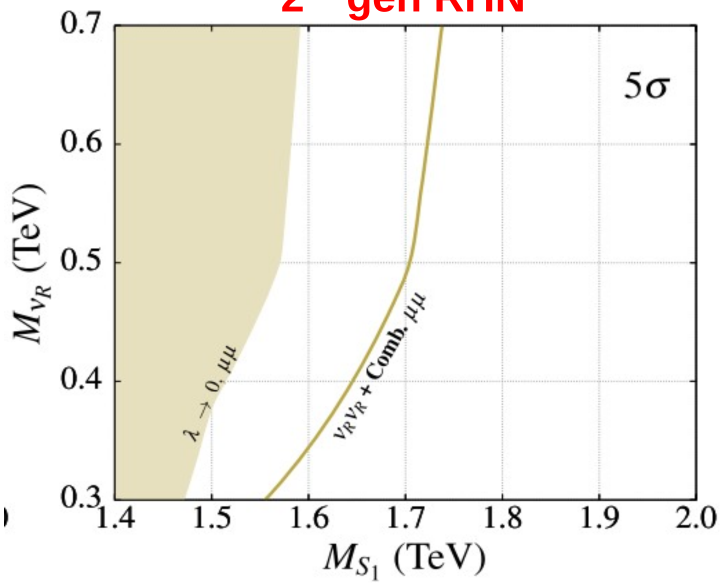
$$
\begin{aligned}
a_\ell = \frac{N_c}{16\pi^2}\sum_{i=1}^{3}\sum_{\alpha}^{L,R}\Bigg[& 2\mathrm{Re}(x_{i\ell}^{L\alpha} x_{i\ell}^{R\bar{\alpha}*})\frac{m_\ell m_{q_i}}{M_{\ell_q}^2}\Big\{2Q_q \\
& + Q_{\ell_q}\left((1-\kappa)\ln\left(\frac{\Lambda^2}{M_{\ell_q}^2}\right)+\frac{1-5\kappa_\alpha}{2}\right)\Big\} \\
& + (1-2\delta_{L\alpha})(|x_{i\ell}^{L\alpha}|^2+|x_{i\ell}^{R\bar{\alpha}}|^2)\frac{m_\ell^2}{M_{\ell_q}^2}\Big\{\frac{4}{3}Q_q \\
& + Q_{\ell_q}\left((1-\kappa_\alpha)\ln\left(\frac{\Lambda^2}{M_{\ell_q}^2}\right)-\frac{1+9\kappa_\alpha}{6}\right)\Big\} \\
& + 2\tilde{\kappa}_\alpha Q_{\ell_q}\mathrm{Im}(x_{i\ell}^{L\alpha} x_{i\ell}^{R\bar{\alpha}*})\frac{m_\ell m_{q_i}}{M_{\ell_q}^2}\left(\ln\frac{\Lambda^2}{M_{\ell_q}^2}-\frac{1}{2}\right)\Bigg]
\end{aligned}
$$



Leptoquark+RHN/VLF

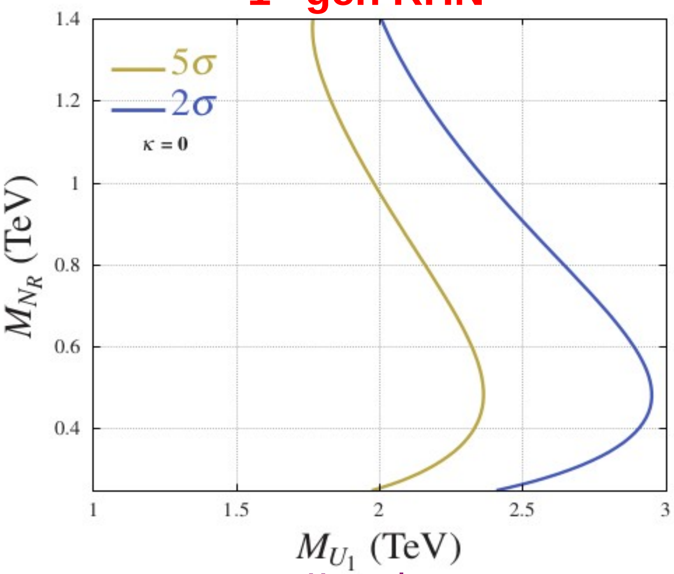


2nd gen RHN



A. Bhaskar et. al. PLB, 843, 138039, (2023)

1st gen RHN



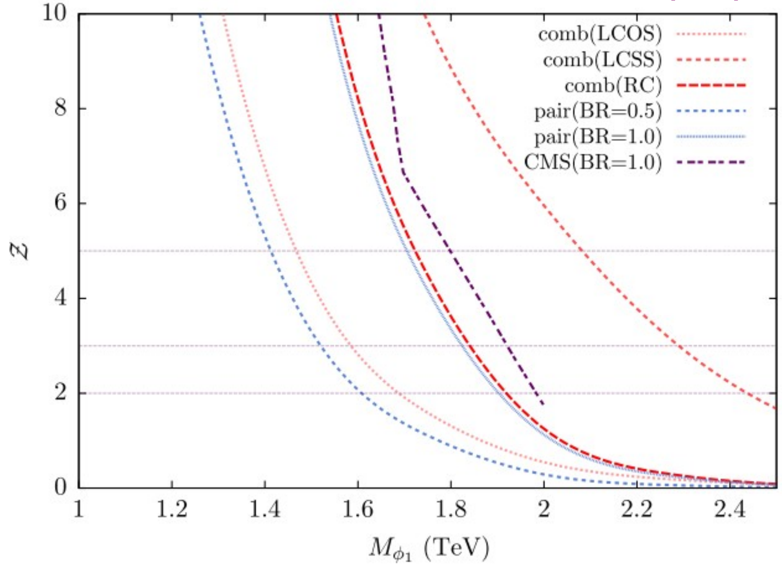
Upcoming...

Jet substructure and boosted top

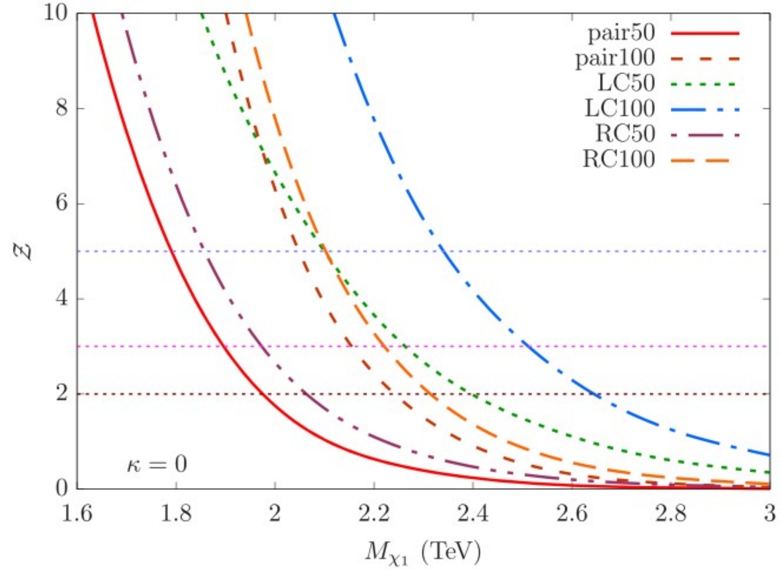
$$pp \to \ell_q \ell_q + \ell_q t\ell \to t\ell\ t\ell$$

Boosted tops+leptons; top-lepton resonance

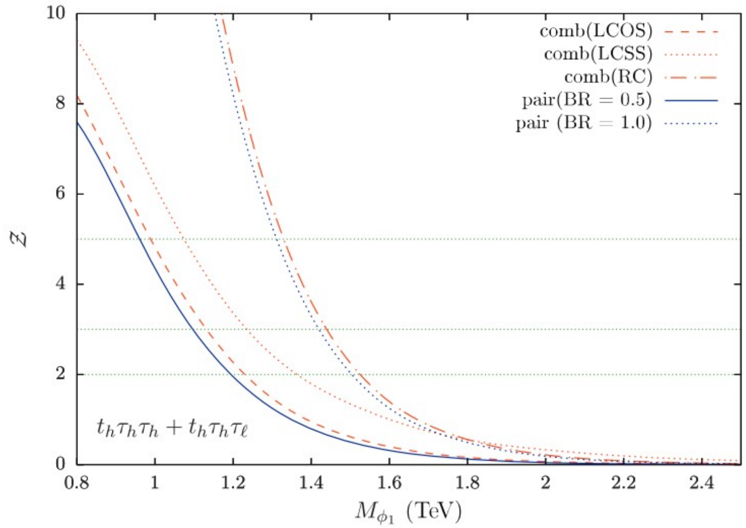
K. Chandak, TM, S. Mitra; PRD 100, 075019 (2019)



A. Bhaskar, TM, S. Mitra; PRD 101, 115015 (2020)



A. Bhaskar, TM, S. Mitra, M. Sharma; PRD 104, 075037 (2021)



Take away

- Improved exclusion limits on all leptoquark – mass, BR, couplings using dilepton-dijet data, high-pT dilepton tail data
- For the first time, we obtain the improved mass limit when QED effects are included
- Introduce a LQ limit calculator – can derive limits for any coupling of any LQ; can derive multicoupling limits
- Most likely LQ are decaying into new final states. Since we have not analyzed those possibilities, we might have missed them
- LQ signatures must be tiny and can also camouflage with background. Need advanced techniques like jet substructure/machine learning to find them out

THANK YOU