Phenomenological Study of the Nambu–Jona-Lasinio Composite Model at the LHC and HL-LHC

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SCALARS 2025
University of Warsaw
22–25 Sept 2025

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Content

Composite NJL Model

NJL Model (Y. Nambu and G. Jona-Lasinio) (1961)

Nambu-Jona-Lasinio (NJL) Four Fermion Interactions (SheSheng Xue) (2017)

- ❖ NJL-type interactions simplify non-perturbative aspects of strong interactions in Quantum Field Theory.
- ❖ Provides understanding of chiral symmetry breaking and hadron mass generation.
- ❖ Original model features a nonrenormalizable four-fermion interaction term in the Lagrangian.
- ❖ Adopted this because Well-defined QFT for SM Lagrangian requires a natural regularization (UV cutoff Λ_{cut}) where $\Lambda_{cut} \to 10^{19}\ GeV\ (planck\ scale)\ or\ 10^{16}\ GeV\ (GUT\ scale)$
- ❖ Implications for Beyond Standard Model Operators:

$$\sum_{f=1,2,3} G_{cut}[\overline{\psi_L}^f \psi_R{}^f \overline{\psi_R}^f \psi_L{}^f]_{Q_i=0,-1,\frac{2}{3},-\frac{1}{3}}. \quad where\ \ G_{cut} \propto \Lambda_{cut}{}^{-2}$$

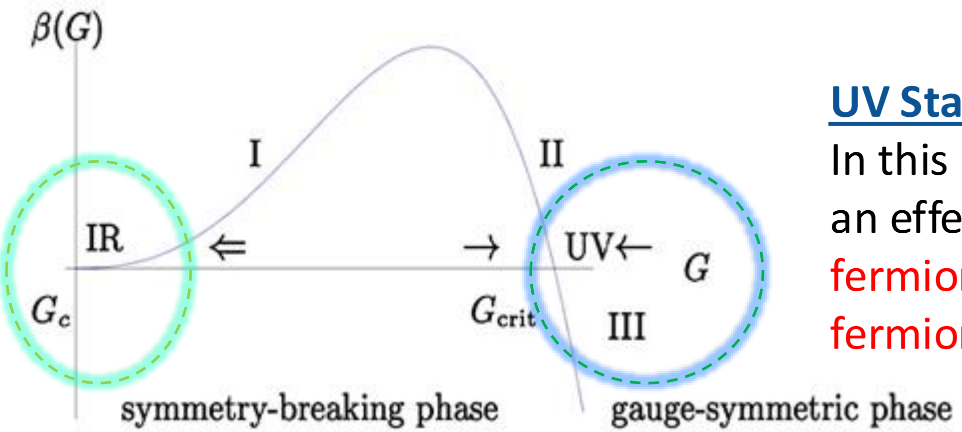
- ❖ Preserves not only the SM gauge symmetries and global fermion family symmetries but also the global symmetries for fermion-number conservations

IR-stable and UV-stable fixed points

❖By Analyzing the behavior of the **β-function** in terms of the four-fermion coupling (G).

IR Stable Fixed Point

The electroweak scale ($\upsilon \approx 246GeV$) where the low-energy SM is realized.



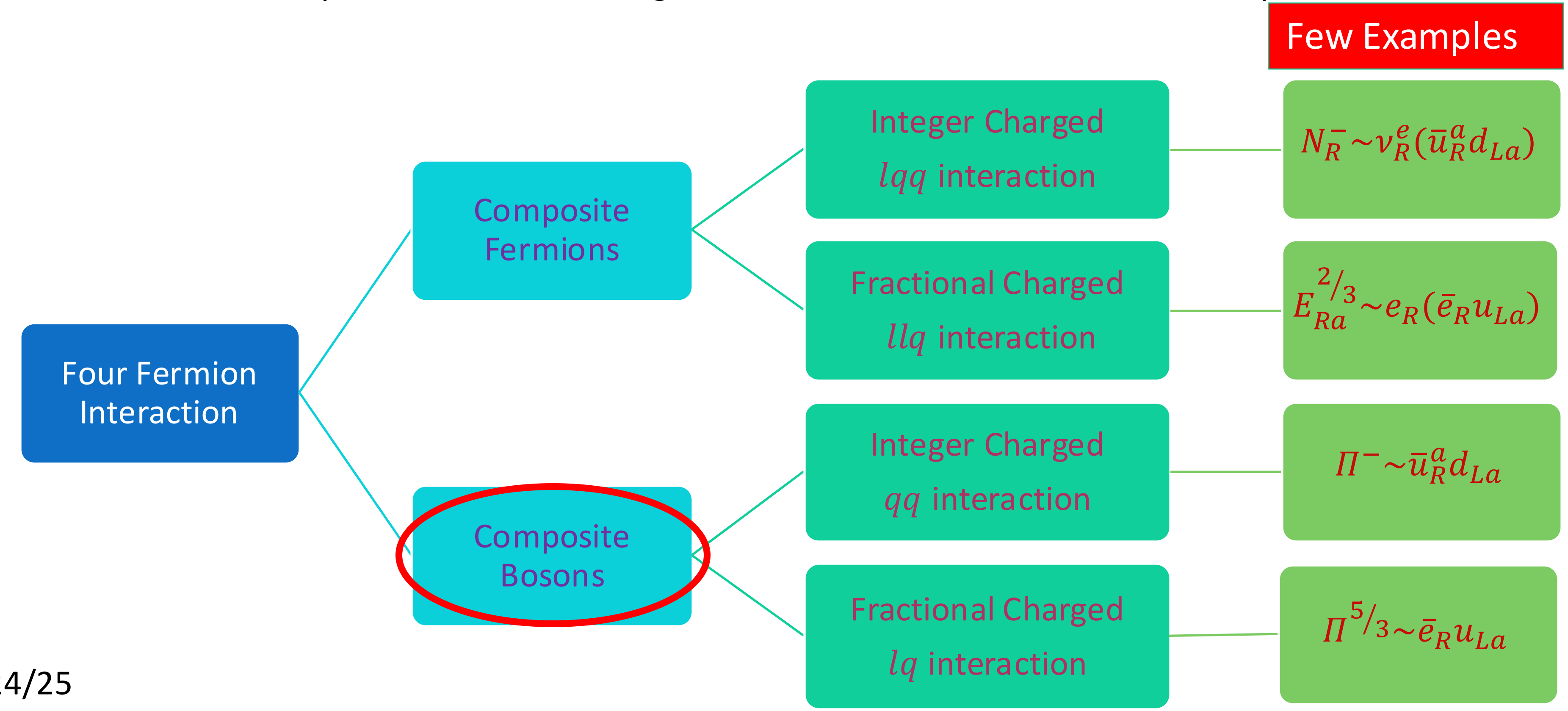
UV Stable Fixed Point

In this UV domain at high energies, it realizes an effective theory of composite bosons and fermions composed by SM elementary fermions, also preserves SM symmetries.

- ❖ G_c → weak critical coupling of NJL dynamics
- ❖ G_{crit} → a potential UV-stable fixed point
- ❖ Section "I" (Positive Increase)
- ❖ Section "II" (Positive Decrease)
- ❖ Section "III" (Negative/ UV-Domain)

Spectrum of Composite Particles

- Out of Four Fermion Interactions, we can delineate two primary categories, each of which is subsequently subdivided.
- Colorless Composite Particles are gauge invariant under the Electroweak part of SM i.e. $SU(2)_L \times U(1)_Y$
- In total we have 8 composite Bosons, 16 Right-handed and 16 Left-handed Composite Fermions.



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Searching for Exclusive Leptoquarks with the Nambu-Jona-Lasinio Composite Model at the LHC and HL-LHC

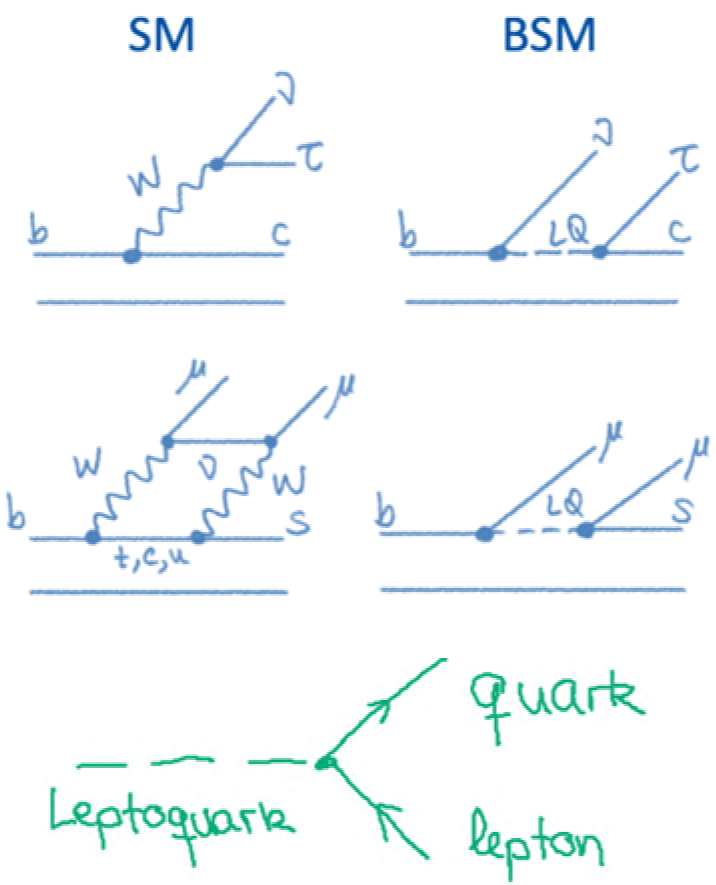
(https://link.springer.com/article/10.1007/JHEP08(2024)176)

Authors: **S. Ajmal**, J. T. Gaglione, F. Romeo, A. Gurrola, O.Panella, M. Presilla, H. Sun, and S. S. Xue

The LQ part of the model published on the official website of Feynrules
https://feynrules.irmp.ucl.ac.be/wiki/NJLComposite

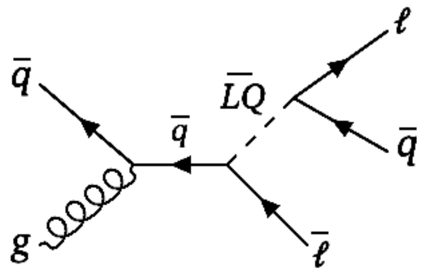
Introduction

- ❖ **Leptoquarks** serve as a promising mediator for explaining anomalies in the BSM context.
  - ❖UV completion of the theory
  - ❖Anomalies involve leptons and quarks. ⟹ Favored BSM: Leptoquark models
  - ❖Numerous models have been proposed which includes LQ’s
    - ❖GUT SU(5), Pati-Salam SU(4), RPV SUSY…
  - ❖Exploring LQ’s in different model and with some New production modes
  - ❖ATLAS and CMS collaborations also explore Lepton flavor universality violation at the LHC. (Ref)

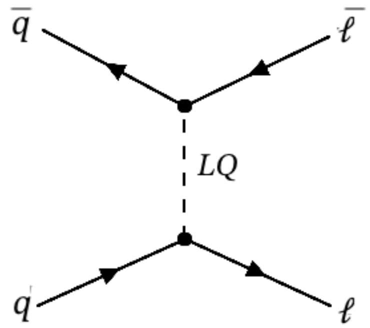


Classical Production modes

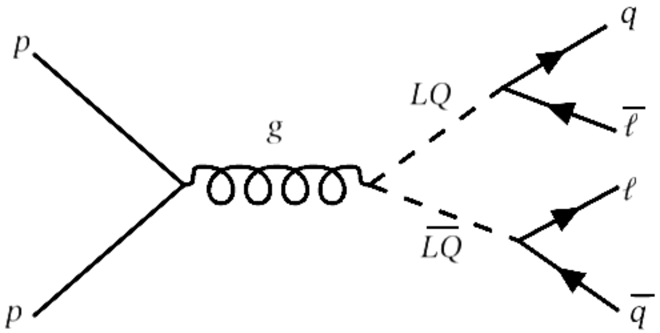
Mostly Explored Production modes



Single LQ Production

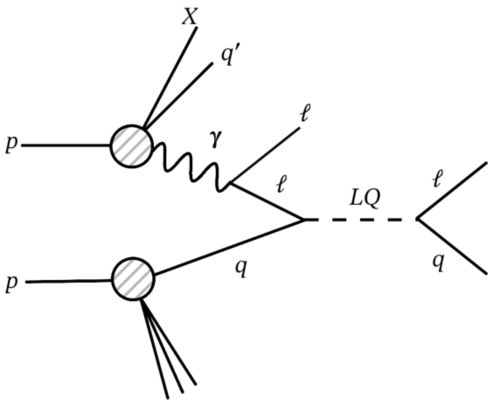


Off-shell Production

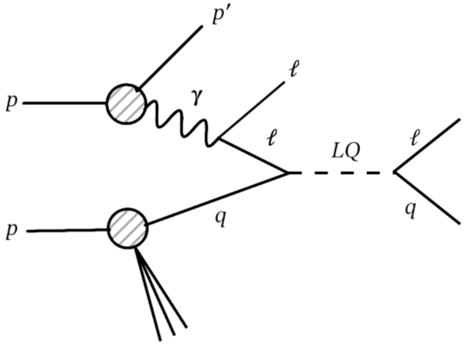


Pair LQ Production

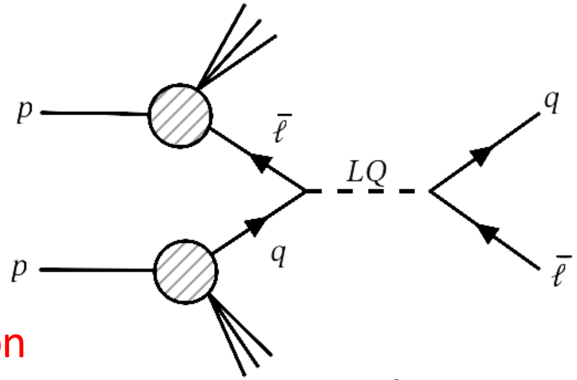
Recently Explored Production modes



Inelastic LQ Production



Elastic LQ Production



Single Production

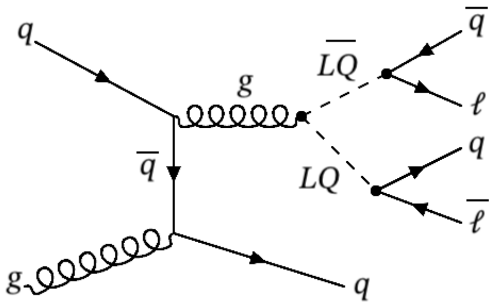
Leptons coming from Proton

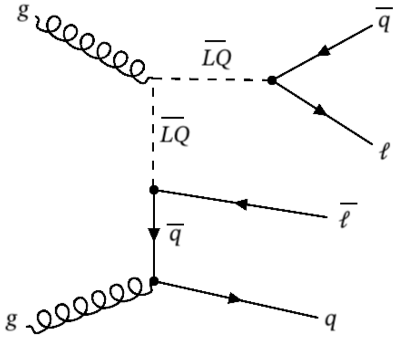
Leptons in the Proton by Luca Buonocore et al.

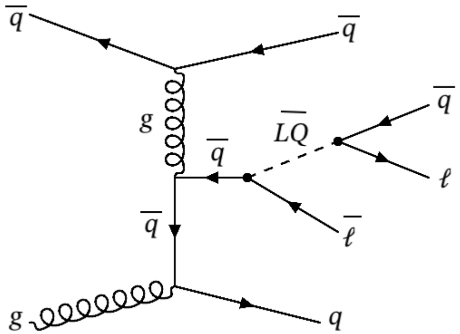
JHEP 08 (2020)019

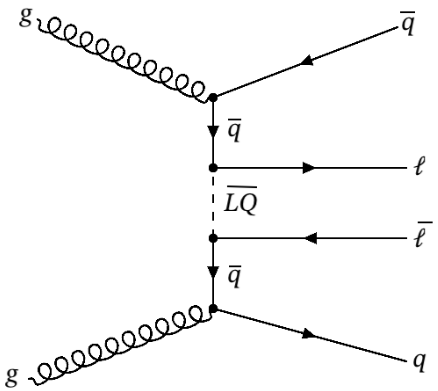
New Production Modes

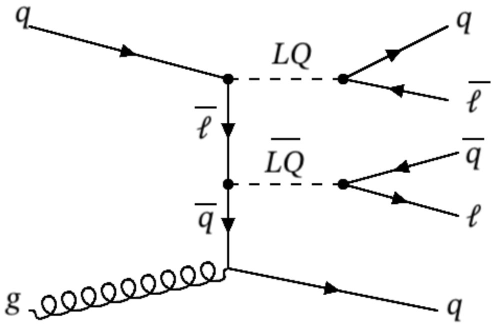
- $p\,p$ collisions containing quarks and gluon
- $p\,p$ collisions also contain radiating Photons
- For Monte Carlo Signal Production via MadGraph
  - $p\,p > \mu^{+}\mu^{-}(0-3\,jets)$
  - $p\,p > \mu^{+}\mu^{-}j, p = \gamma\,, quarks$
- This includes all possible contributions.

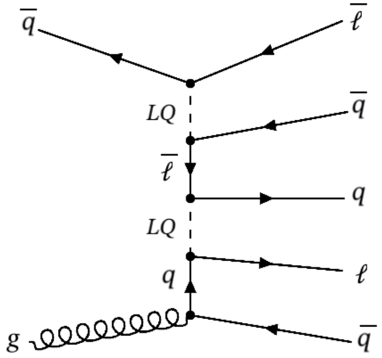






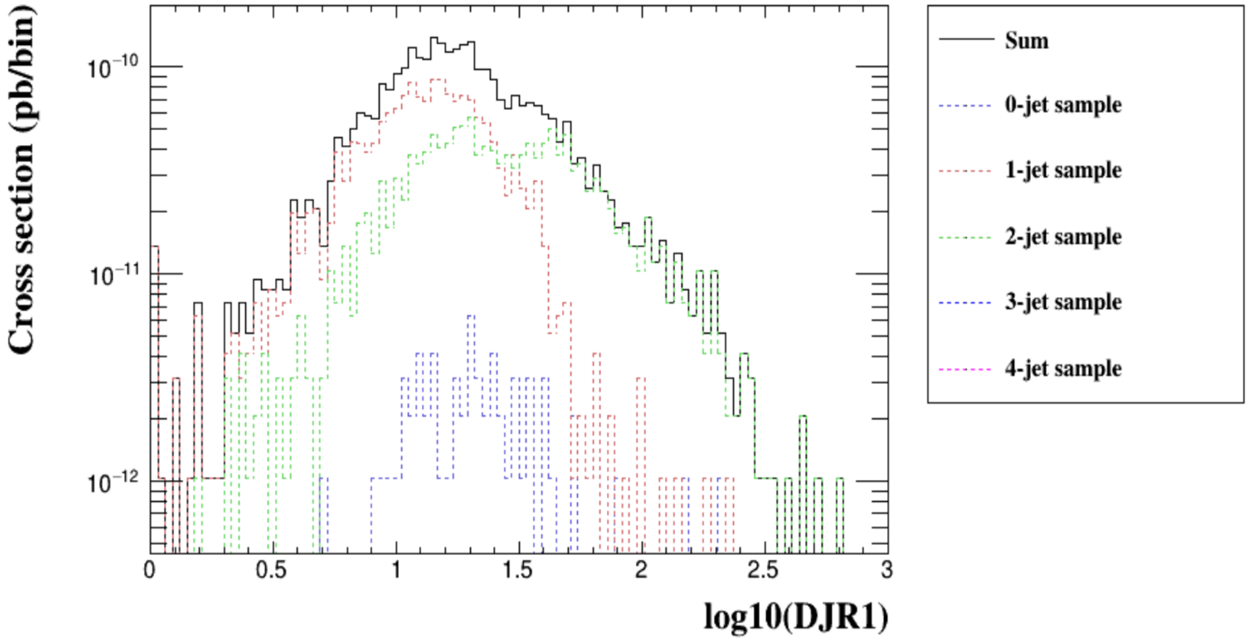






Jet Merging

- We employ the matrix element-parton shower matching technique known as **MLM merging,** first presented by Michelangelo L. Mangano, Mauro Moretti and others in 2007 (https://iopscience.iop.org/article/10.1088/1126-6708/2007/01/013)
- We adopt a matching scale of Qcut set at 30 GeV.



The final jets after parton-shower evolution and jet clustering are matched to the original partons. The event is accepted if a reasonable match is found, and rejected if not.

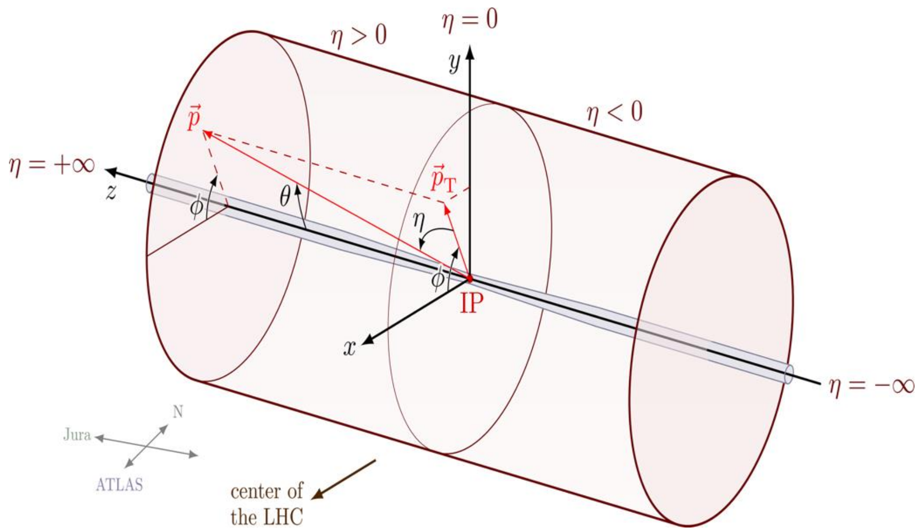
Search Strategy

- The signal sample consists of $p\,p > l^+l^-(0-3\;jets)$ and $p\,p > l^+l^-j, p = \gamma\,, quarks$.
- Parameter space sampling
  - 1000 to 30000 GeV for mass points
  - $g_y = \left(\frac{F_\Pi}{\Lambda}\right)^2$ = 0.5, 1.0,1.5, 2.0, 2.5
- To simulate the detector response, we utilize the Delphes-3.5.0 framework
- Backgrounds are selected: **Single and Pair top production, WJ, VV and Drell-Yan.**
- Event selection criteria include two leptons with pT > 20 GeV, |η| < 2.5, and invariant lepton pair mass > 120 GeV, missing transverse energy < 50 GeV, and no b quark-originating jets.
- Jets require pT > 20 GeV, pseudorapidity |η| < 5 and spatial separation from leptons (ΔR > 0.4)

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2}$$

- Events are normalized

$$n = \frac{\sigma \mathcal{L}_{int} N_{sel}}{N_{gen}} \quad \text{where} \quad \mathcal{L}_{int} = 300 fb^{-1}$$

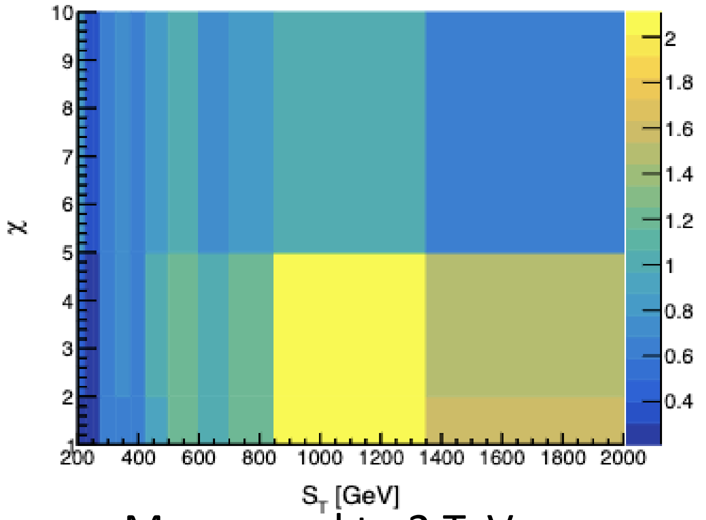


Histograms (μc)

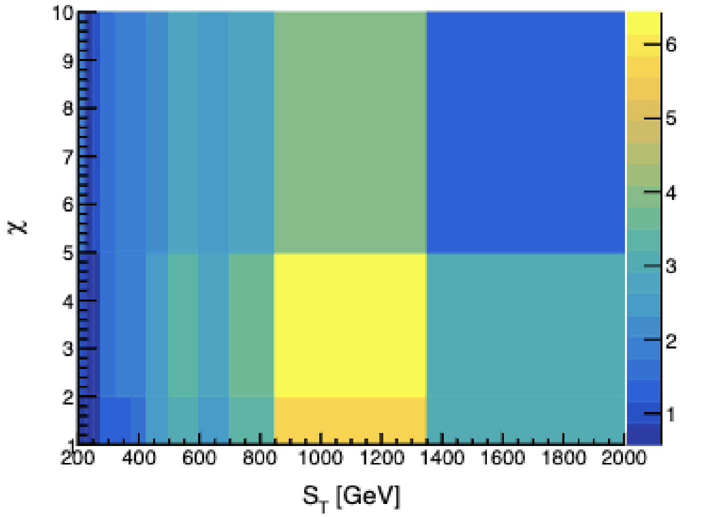
<u>Discriminating varaibles</u>

- ❖ $\chi = e^{\eta_1 - \eta_2}$ *and* η_1, η_2 are the pseudorapidities of the two *leptons*
- ❖ S_T is defined as the sum of the scalar p_T of the leptons and jets.

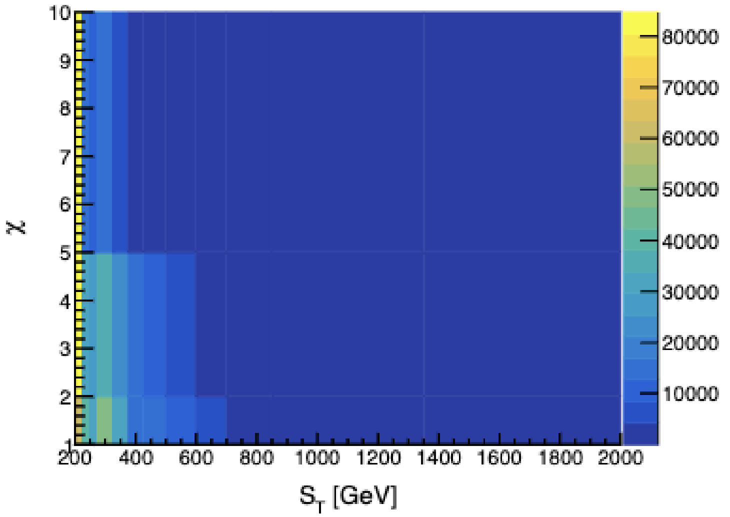
$$S_T = \sum_{leptons} p_T + \sum_{jets} p_T$$



Mass equal to 2 TeV
coupling of 1.0



Mass equal to 4 TeV
Coupling of 2.5



The SM background

Sensitivity Results

- Significance is computed via CMS Combine Tool by feeding the histograms of the discriminating variables for $pp + \gamma p$
- Expected significance by profile-binned likelihood statistical test

$$-2\ln\left(\frac{\mathcal{L}(data|r = 0, \theta_0)}{\mathcal{L}(data|r = \hat{r}, \theta_0)}\right)$$

- Systematic uncertainties have been added in terms of nuisance parameters for $r = \hat{r}$ and $r = 0$
- COM energy is 13 TeV and Luminosity is $300fb^{-1}$ and then scaled to $140fb^{-1}$ and $3000fb^{-1}$

Uncertainty Source	**Signal** (%)	**Backgrounds**(%)
PDF	2.8	3.0
Pileup	0.2	1.0
Jet Energy Resolution	0.1	1.7
Lepton Energy Resolution	0.2	5.3
Jet Energy Scale	0.5	0.9
Lepton Energy Scale	1.5	2.5
Leptonic Reconstruction efficiency	3.0	3.0
Leptonic Identification efficiency	1.3	0.3
Trigger	1.1	1.4

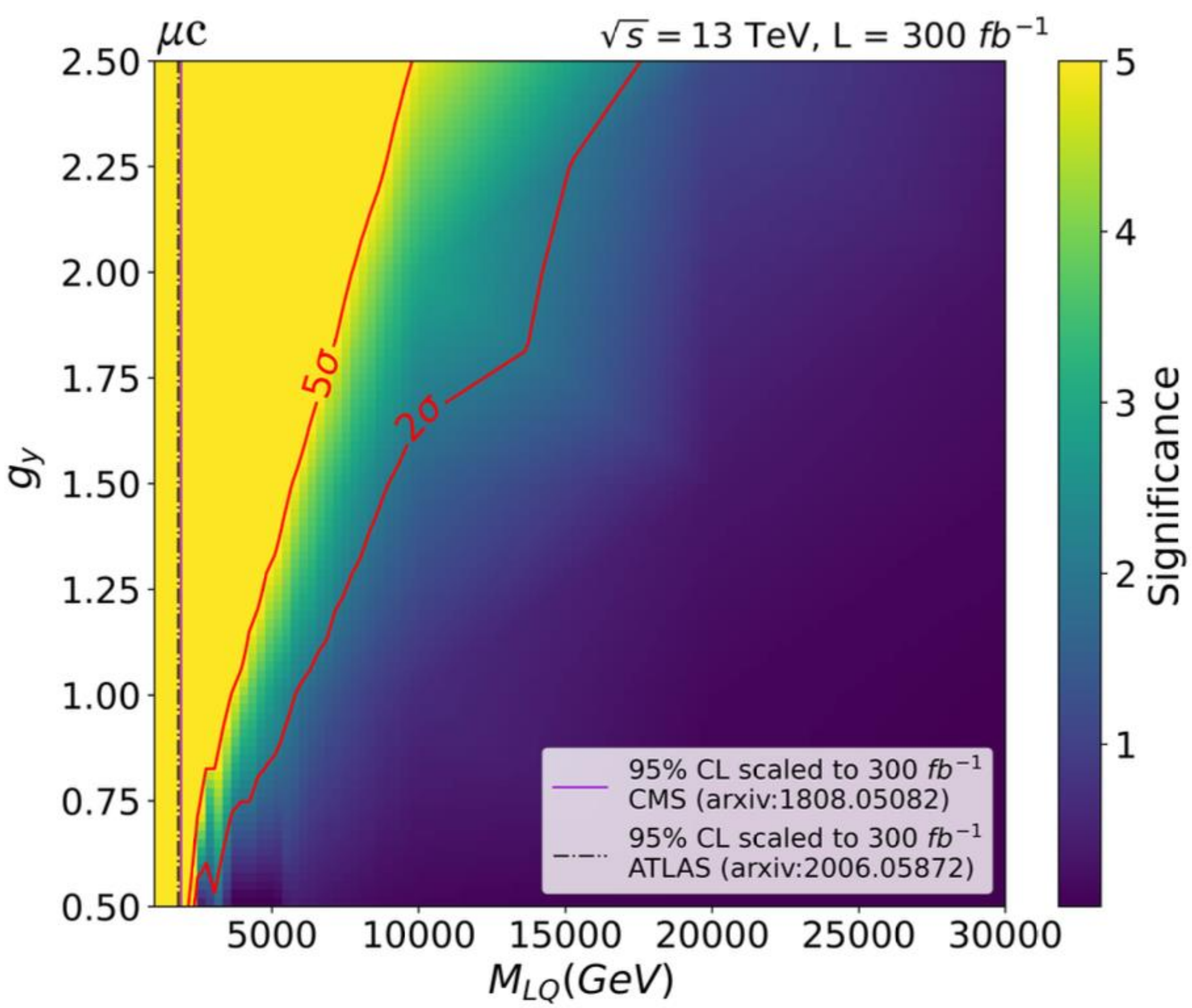
Followed the same prescriptions used in the published LQ searches https://arxiv.org/abs/1808.05082

Sensitivity Results for $300\ fb^{-1}$

Signal significance in the plane of the coupling μc and the mass of the LQ using $pp + \gamma p$ events at $\sqrt{s} = 13\ TeV$ expected for $300\ fb^{-1}$. We showed 5 and 2 σ levels, while the vertical lines show the most recent exclusion limits results at 95% CL from a search for LQs from

ATLAS (black dashed) upto 1.8 TeV

CMS (violet plain) upto 1.9 TeV

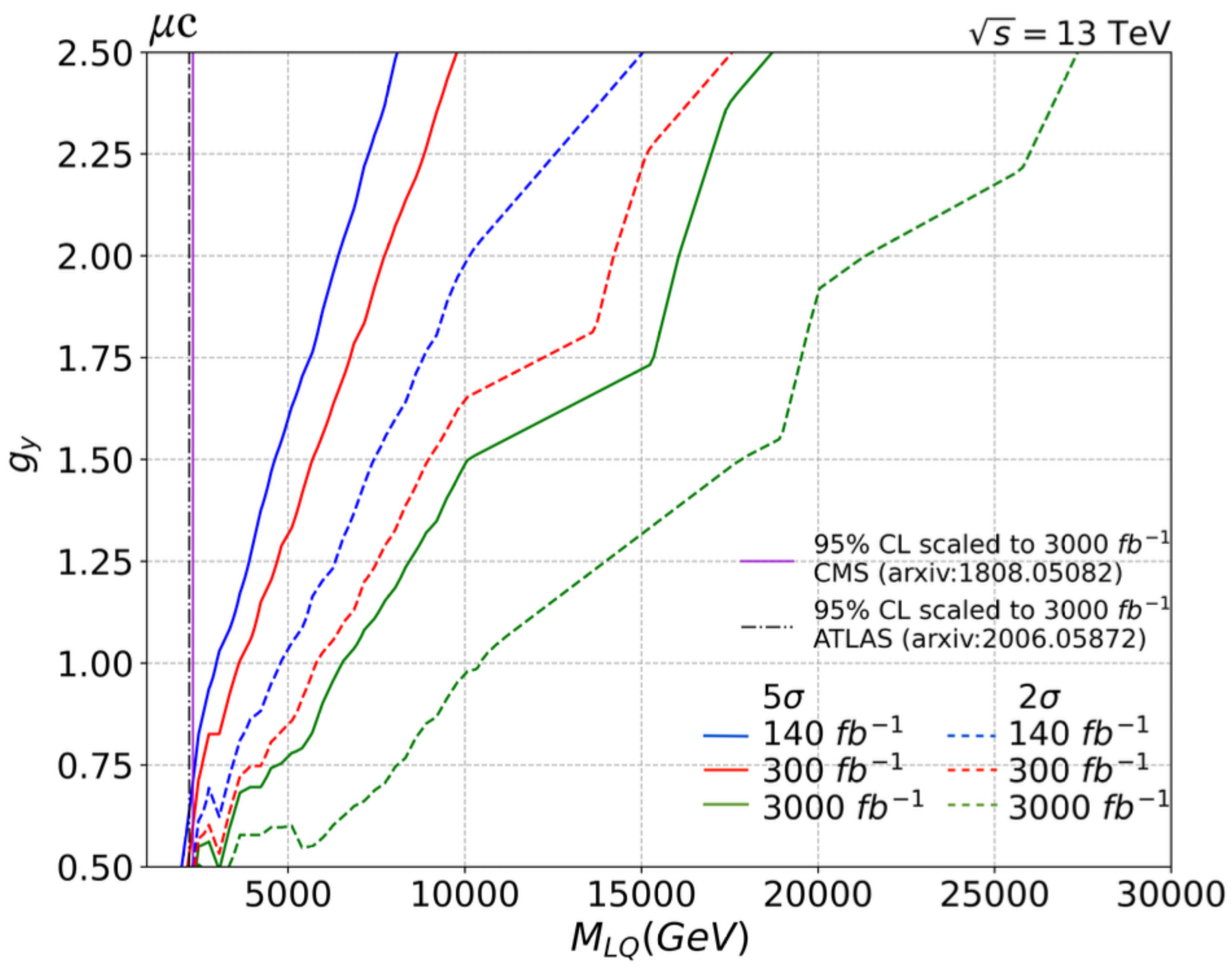


Sensitivity Results for $3000\ fb^{-1}$

Signal significance in the plane of the coupling μc and the mass of the LQ using $pp + \gamma p$ events at $\sqrt{s} = 13\ TeV$ expected for different luminosity scenarios . We showed 5 and 2 σ levels, while the vertical lines show the most recent exclusion limits results at 95% CL from a search for LQs from

ATLAS (black dashed) upto 2.2 TeV

CMS (violet plain) upto 2.3 TeV



Composite Bosons (On going study)

- There are 3 type of composite bosons, their CI Lagrangians are given.
- Table Below Contains the list of Composite Bosons and their respective Quantum numbers.
- Composite bosons are gauge invariant under the Electroweak part of SM. So, gauge interactions are calculated for the gauge group $SU(2)_L \times U(1)_Y$
- Gauge Interaction Lagrangian for Composite Bosons

$$\mathcal{L}_{\rm CI}^{\Pi^\pm} = g_{\rm Y}(\bar{d}_R^a u_{La})\Pi^- + \text{h.c.},$$
$$\mathcal{L}_{\rm CI}^{\Pi_{\rm d}^0} = g_{\rm Y}(\bar{d}_R^a d_{La})\Pi_d^0 + \text{h.c.},$$
$$\mathcal{L}_{\rm CI}^{\Pi_{\rm u}^0} = g_{\rm Y}(\bar{u}_R^a u_{La})\Pi_u^0 + \text{h.c.},$$

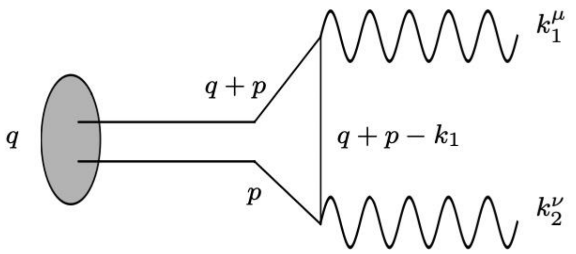
where $g_{\rm Y} = (F_\Pi/\Lambda)^2$.

Composite bosons Π	constituents	charge $Q_i = Y + t_{3L}^i$	$SU_L(2)$ 3-isospin t_{3L}^i	$U_Y(1)$-hypercharge Y
Π^+	$(\bar{d}_R^a u_{La})$	$+1$	$1/2$	$1/2$
Π^-	$(\bar{u}_R^a d_{La})$	-1	$-1/2$	$-1/2$
Π_u^0	$(\bar{u}_R^a u_{La})$	0	$1/2$	$-1/2$
Π_d^0	$(\bar{d}_R^a d_{La})$	0	$-1/2$	$1/2$

Contact Interactions of Composite and Gauge Bosons

- In UV domain Composite bosons can decay into gauge bosons via contact interaction

$$\mathcal{L} = \frac{gg'N_c}{4\pi^2 F_\Pi}\epsilon_{\mu\nu\rho\sigma}\frac{1}{4}(F^{\rho\mu})(F'^{\sigma\nu})\Pi$$



- This Effective contact interaction is an axial anomaly vertex, as a result of a triangular quark loop and standard renormalization procedure in SM.
- Possible Decay channels

$$\Pi^0_{u,d} \rightarrow \gamma\gamma, \gamma Z^0, Z^0Z^0, W^+W^-$$

$$\Pi^\pm \rightarrow \gamma W^\pm, Z^0 W^\pm$$

- E.G for $\Pi^0_u \rightarrow \gamma\gamma$

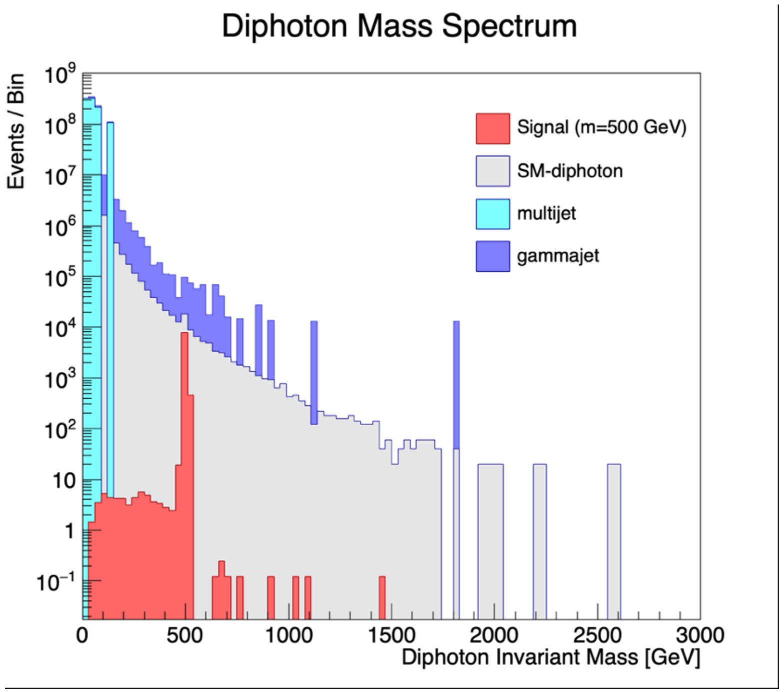
$$\Gamma = \left(\frac{4}{9}\right)^2 \left(\frac{\alpha N_c}{\pi F_\Pi}\right)^2 \frac{M_\Pi^3}{64\pi}$$

Parameters

- g, g' is the standard coupling of SM particles with gauge bosons
- $N_c = 3$ color factor
- F_Π is the decay constant of composite bosons
- M_Π is the mass of composite bosons

Phenomenological Studies

- For phenomenological aspects, Studying diphoton final state with MadAnalysis to set model limits.
- Initial plots for Diphoton invariant mass distribution with signal and backgrounds. With 0.1M events for signals and 1M for bkg, and mass of 500 GeV with coupling lambda 5 TeV, F_Pi = 0.2 TeV



Summary

- Major phenomenological analysis providing original results on the sensitivity of the LHC and HL-LHC to Scalar LQs.
- The analysis considers their production in association with additional jets for the first time. A comprehensive strategy is devised to capture all final state particles associated with lepto-quarks or originating from their decay.
- The assessment of statistical significance in ongoing and future LHC runs, with a specific emphasis on leptoquark couplings within 2nd generations, demonstrates superior sensitivity compared to current searches.
- Lastly, we discussed composite bosons quark-quark interactions.

Thanks

Implementation in Feynrules

- FeynRules is Mathematica Package [Ref]
- Composite Fermions Interactions were implemented before in article

Eur. Phys. J. C (2020) 80:309 by R. Leonardi, O. Panella, S.-S. Xue and others

- Extended the Implementation to
  - Composite Boson quark-quark
  - Composite Boson Lepton-quark
- 5 Flavour scheme is implemented.
- Universal Feynrules output (UFO) for the use Monte Carlo generator: **MadGraph**
- LQ Part: https://feynrules.irmp.ucl.ac.be/wiki/NJLComposite

```
Lcf := Lstarkin + HC[Llepqua + Llepqua1 + Llepqua2 + Llepqua3] + Llepqua + Llepqua1 + Llepqua2 + Llepqua3;
CheckHermiticity[Lcf, FlavorExpand → True];
vertices = FeynmanRules[Lcf];
FeynmanGauge = False;
GetKineticTerms[Lstarkin]
GetMassTerms[Lstarkin]
GetInteractionTerms[Lstarkin]
GetInteractionTerms[Llepqua + Llepqua1 + Llepqua2 + Llepqua3]
WriteUFO[LGauge, LFermions, LHiggs, LYukawa, LGhost, Lcf, FlavorExpand → True];
```

Data_Cards_LQ_Prodcution	coupling_update	last month
FR_NJL_3.2	version3.2	6 months ago
FR_NJL_3.3	update_of_July	3 months ago
FR_NJL_3.3LQ	update_september2022	last month
HN_FeynRules_model	update	9 months ago
NJL-Model_version_3.1	update_feb2022	8 months ago
Old version of model	updates	4 months ago
.DS_Store	..	4 months ago
README.md	september_update	last month

https://github.com/mpresill/compositeNJL