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

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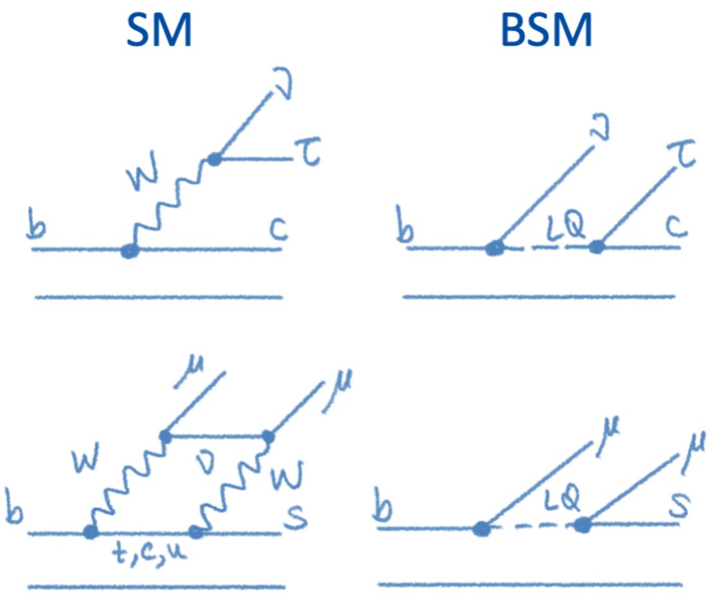
8th Young Researchers Workshop on "Physics Challenges in the LHC Era"

Content

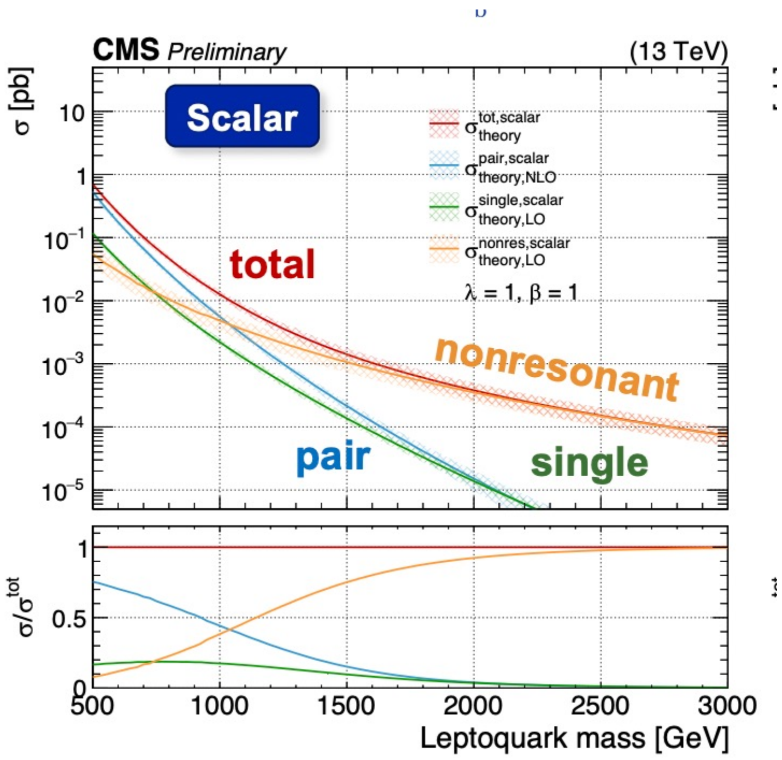
Introduction

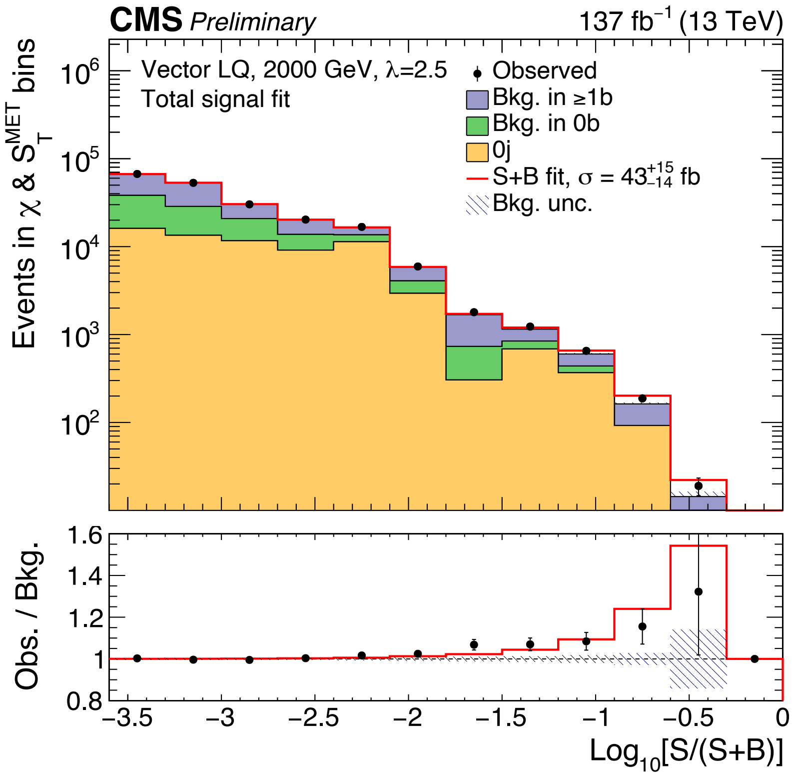
- The Standard Model (SM) is presently the benchmark theory.
- Unexplained phenomena (hierarchy problem, flavor problem, neutrino masses and mixing, etc…) forces us to go beyond-the-SM (BSM)
- **Leptoquarks** serve as a promising mediator for explaining anomalies in the BSM context.
  - UV completion of the theory
  - Anomalies involve leptons and quarks. $\Longrightarrow$ 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



Leptoquarks at High Energies

- ATLAS and CMS collaborations also explore Lepton flavor universality violation at the LHC.
- CMS observed excess with a significance of 3.4 standard deviations above the standard model expectation in the data in the Search for a third-generation leptoquark coupling to a τ lepton and a b quark CMS-PAS-EXO-19-016





CMS-PAS-EXO-19-016

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 $\Lambda_{cut} \rightarrow 10^{19}\ GeV\ (planck\ scale)\ or\ 10^{16}\ GeV\ (GUT\ scale)$
- Implications for Beyond Standard Model Operators:

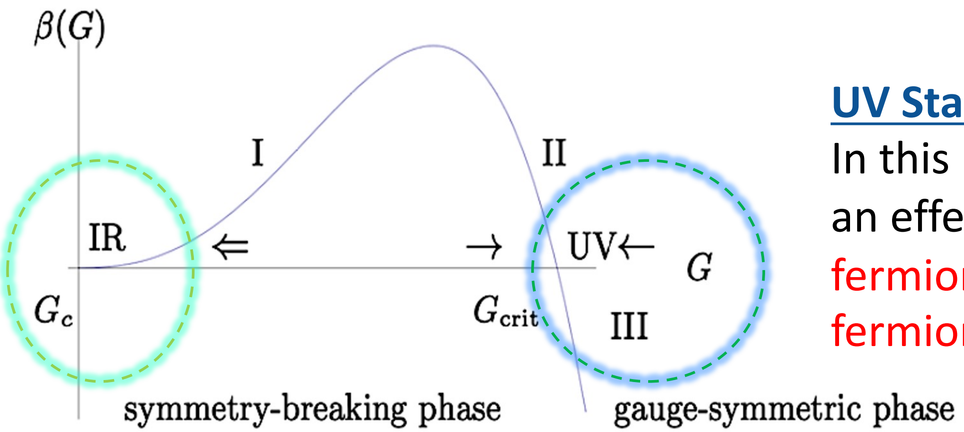
$$\sum_{f=1,2,3} G_{cut}[\overline{\psi_L}^f \psi_R{}^f \overline{\psi_R}^f \psi_L{}^f]_{Q_i=0,-1,\frac{2}{3},-\frac{1}{3}}. \quad where\ \ G_{cut} \propto \Lambda_{cut}{}^{-2}$$

- 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.

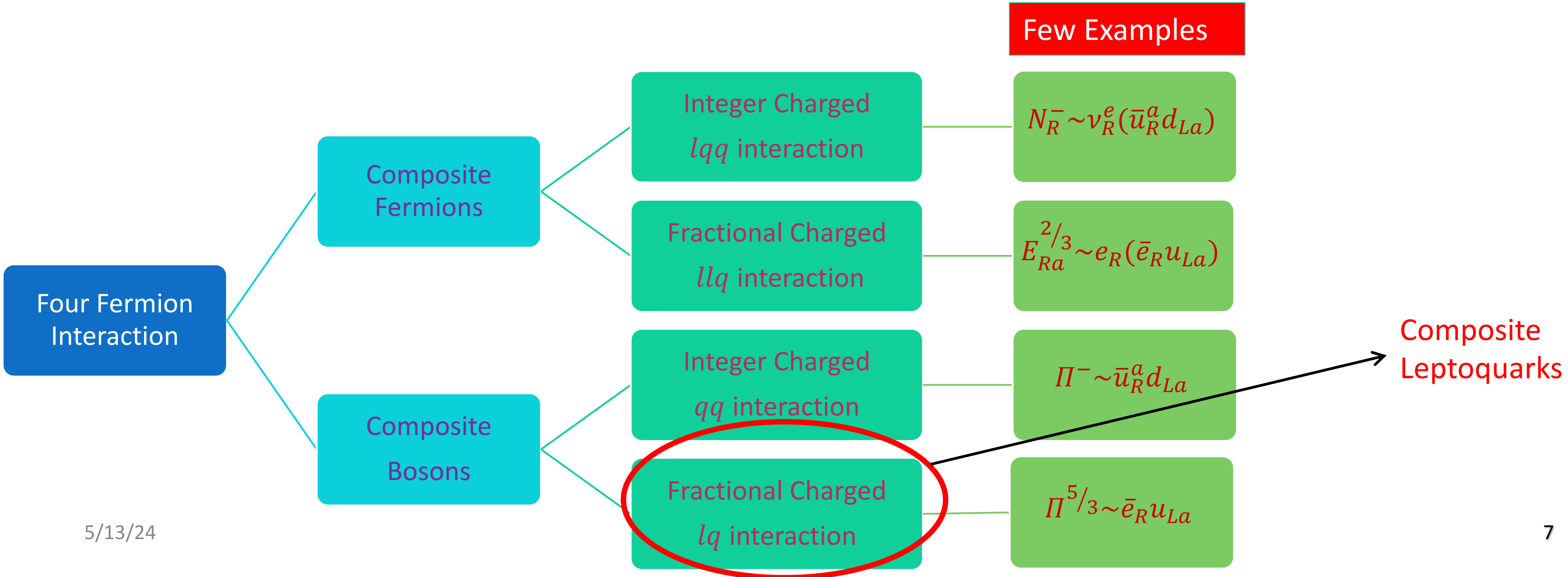


UV Stable Fixed Point
In this UV domain at high energies, it realizes an effective theory of composite bosons and fermions composed by SM elementary fermions, also preserves SM symmetries.

- ❖ 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.



Composite Leptoquarks

- There are four type of Leptoquarks, their CI Lagrangians are given.
- Table Below Contains the list of Composite Bosons LQ and their respective Quantum numbers.
- Interactions implemented with 5 Flavour scheme in Feynrules[Ref]
- Universal Feynrules output (UFO) for the use Monte Carlo generator: **MadGraph**

$$\mathcal{L}_{\mathrm{CI}}^{\Pi_a^{-5/3}} = g_Y(\bar{e}_R u_{La})\Pi_a^{-5/3} + \mathrm{h.c.},$$

$$\mathcal{L}_{\mathrm{CI}}^{\Pi_a^{1/3}} = g_Y(\bar{\nu}_R^e d_{La})\Pi_a^{1/3} + \mathrm{h.c.},$$

$$\mathcal{L}_{\mathrm{CI}}^{\Pi_{u_a}^{-2/3}} = g_Y(\bar{\nu}_R^e u_{La})\Pi_{u_a}^{-2/3} + \mathrm{h.c.},$$

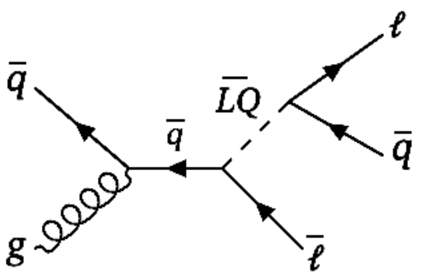
$$\mathcal{L}_{\mathrm{CI}}^{\Pi_{d_a}^{-2/3}} = g_Y(\bar{e}_R d_{La})\Pi_{d_a}^{-2/3} + \mathrm{h.c.},$$

where $g_Y = (F_\Pi/\Lambda)^2$.

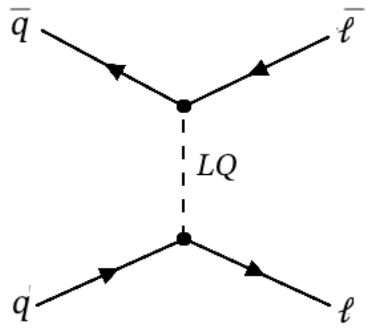
LQ Composite bosons Π_a^Q	constituents	charge $Q_i = Y + t_{3L}^i$	$SU_L(2)$ 3-isospin t_{3L}^i	$U_Y(1)$-hypercharge Y
$\Pi_a^{+5/3}$	$(\bar{e}_R u_{La})$	$+5/3$	$1/2$	$7/6$
$\Pi_a^{-1/3}$	$(\bar{\nu}_R^e d_{La})$	$-1/3$	$-1/2$	$1/6$
$\Pi_{u_a}^{2/3}$	$(\bar{\nu}_R^e u_{La})$	$2/3$	$1/2$	$1/6$
$\Pi_{d_a}^{2/3}$	$(\bar{e}_R d_{La})$	$2/3$	$-1/2$	$7/6$

Production modes

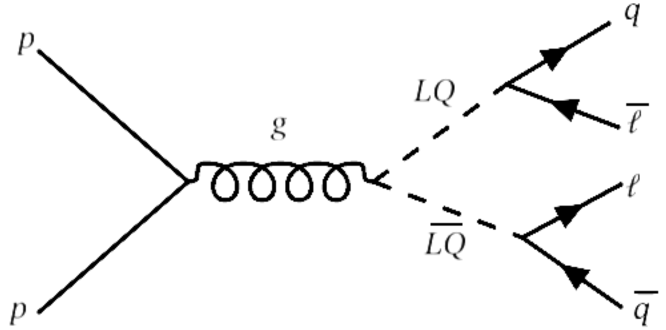
Mostly Explored Production modes



Single LQ Production

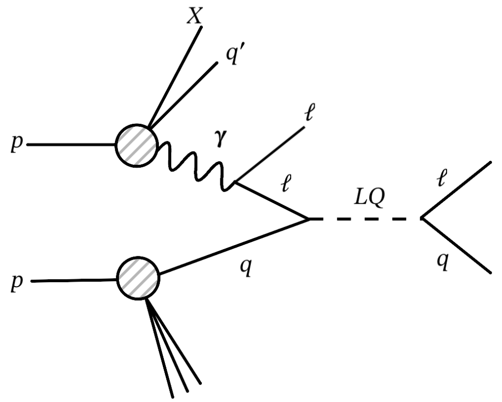


Off-shell Production

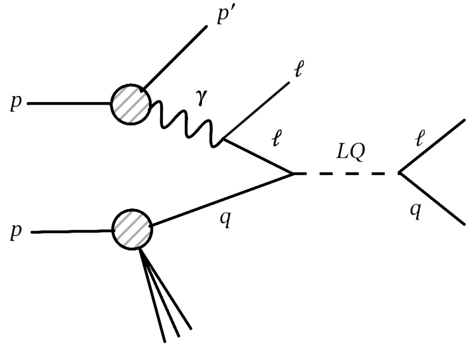


Pair LQ Production

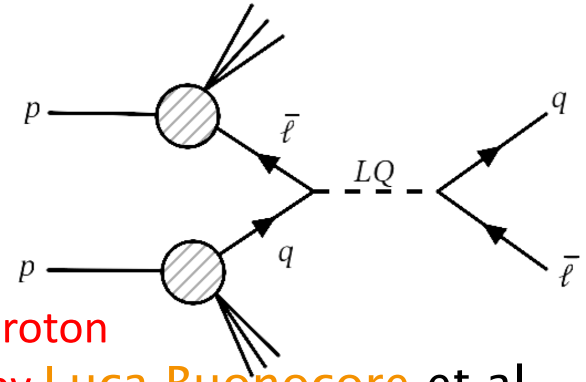
Recently Explored Production modes



Inelastic LQ Production



Elastic LQ Production



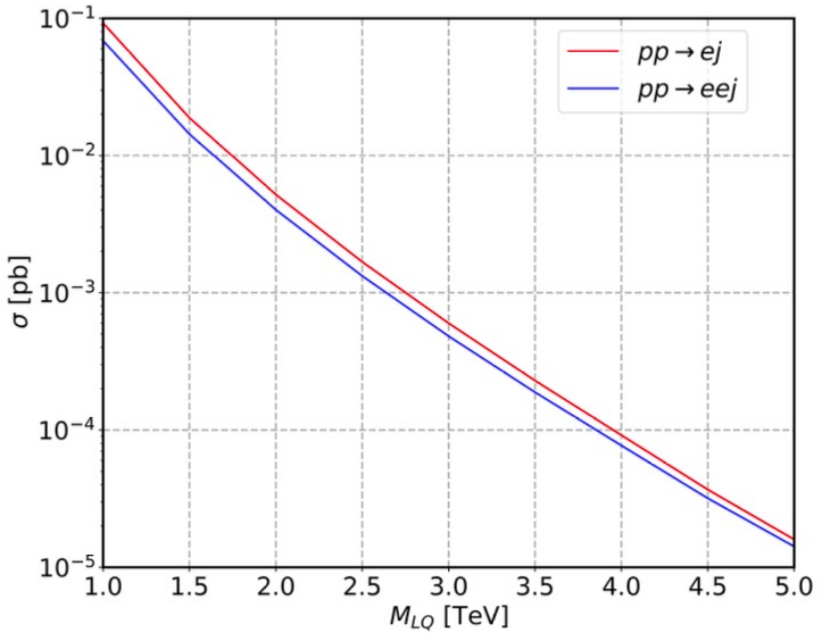
Single Production
Leptons coming from Proton

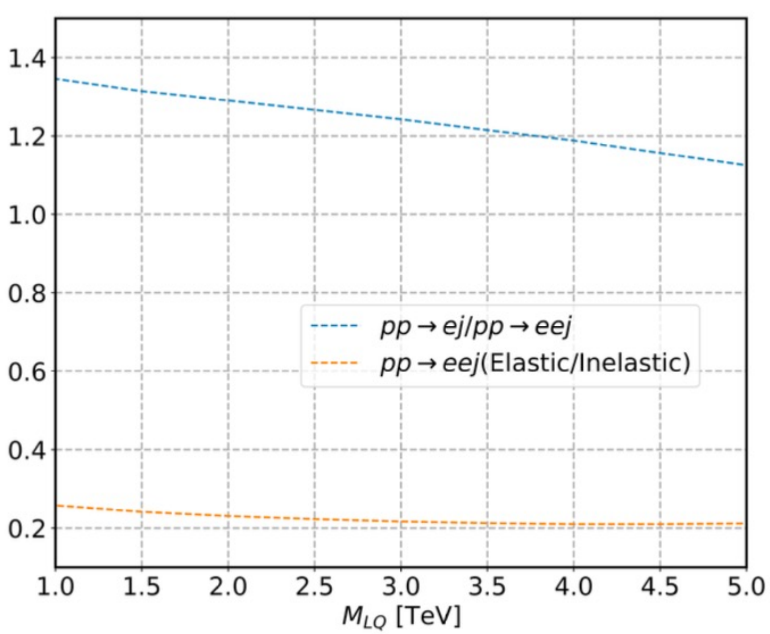
Leptons in the Proton by Luca Buonocore et al.
JHEP 08 (2020)019
(https://link.springer.com/article/10.1007/JHEP08(2020)019)

Lepton vs Photon Initiated Processes

- $pp \rightarrow e^+j$ (lepton initiated process) Lepton in proton PDF, LUXlep
- $pp \rightarrow e^+e^-J$ (photon initiated process) LUX PDF
- Comparison of $pp \rightarrow e^+e^-J$ elastic + inelastic part with $pp \rightarrow e^+j$
- LUXPDF doesn't gives separate contribution
- Chose different partonic distribution function
  i.e., MRST2004qed_proton with ID 20463

Implementation in Madgraph

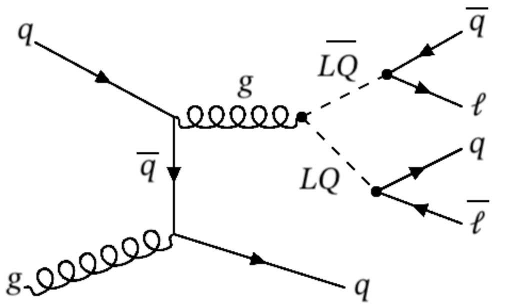


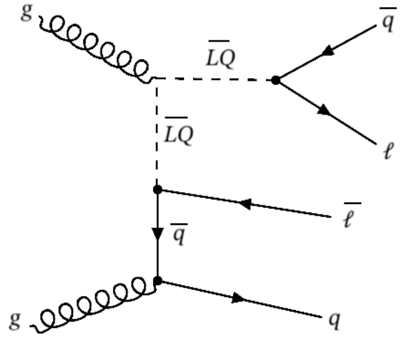


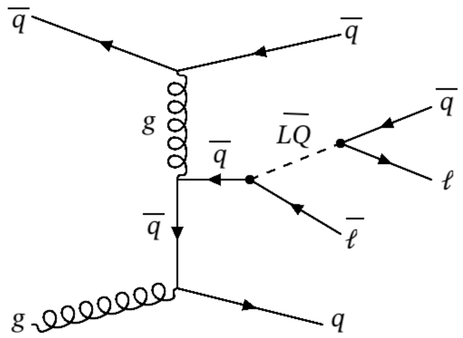
Coupling $g_y = 1$ and mass range is $0 - 5$ TeV

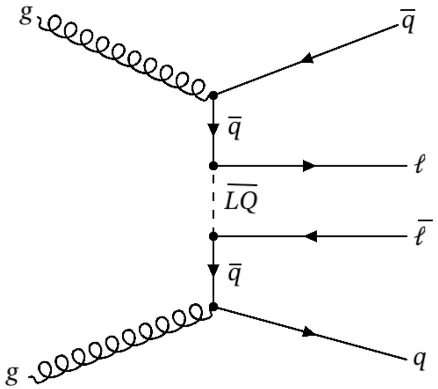
New Production Modes

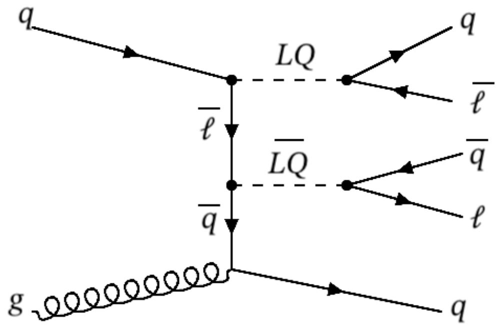
- ❖ $p\ p$ collisions containing quarks and gluon
- ❖ $p\ p$ collisions also contain radiating Photons
- ❖ For Monte Carlo Signal Production
  - $p\ p > \mu^{+}\mu^{-}(0 - 3\ jets)$
  - $p\ p > \mu^{+}\mu^{-}j, p =\ \gamma\ , quarks$
- ❖ This includes all possible contributions.

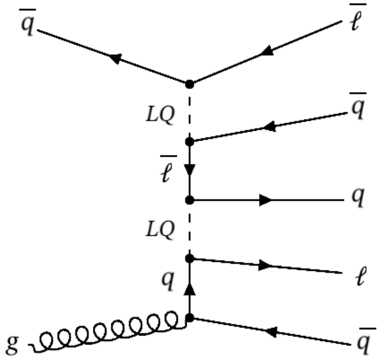






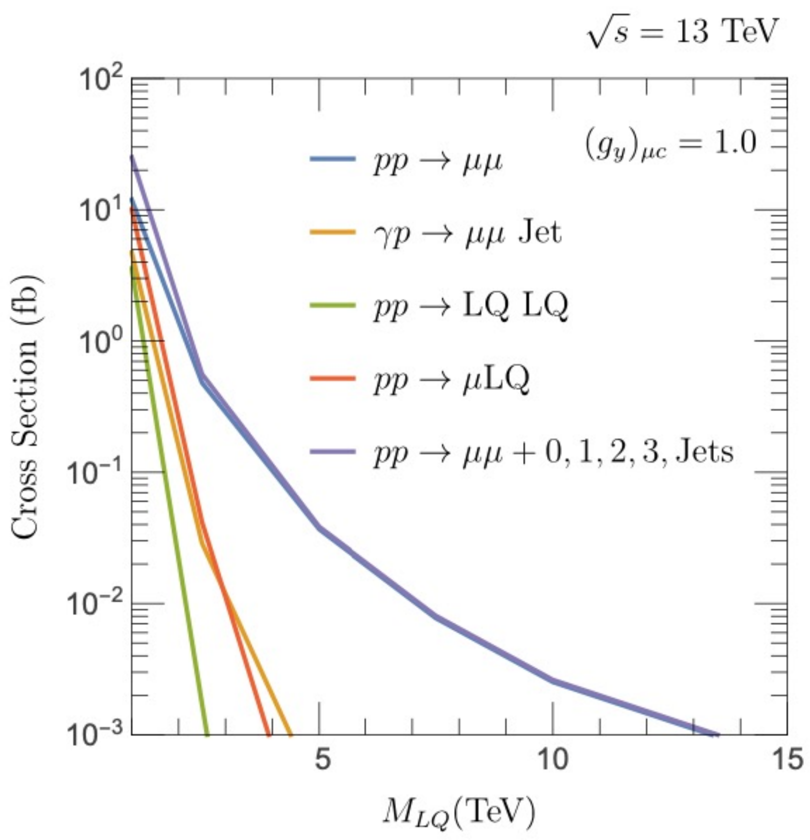


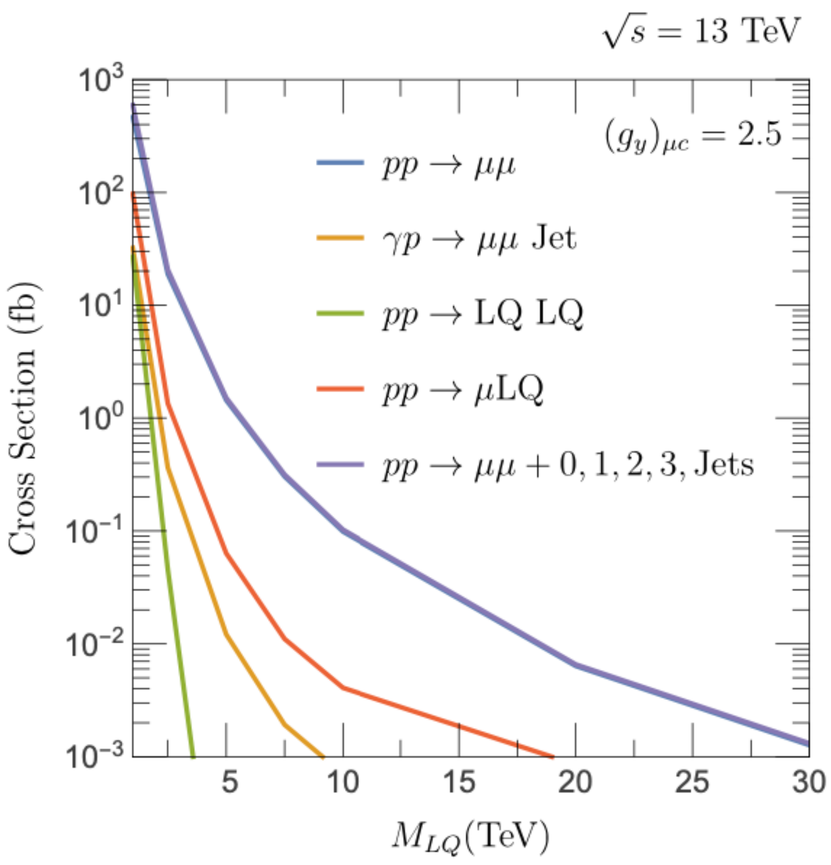




Cross Section studies (2nd Gen)

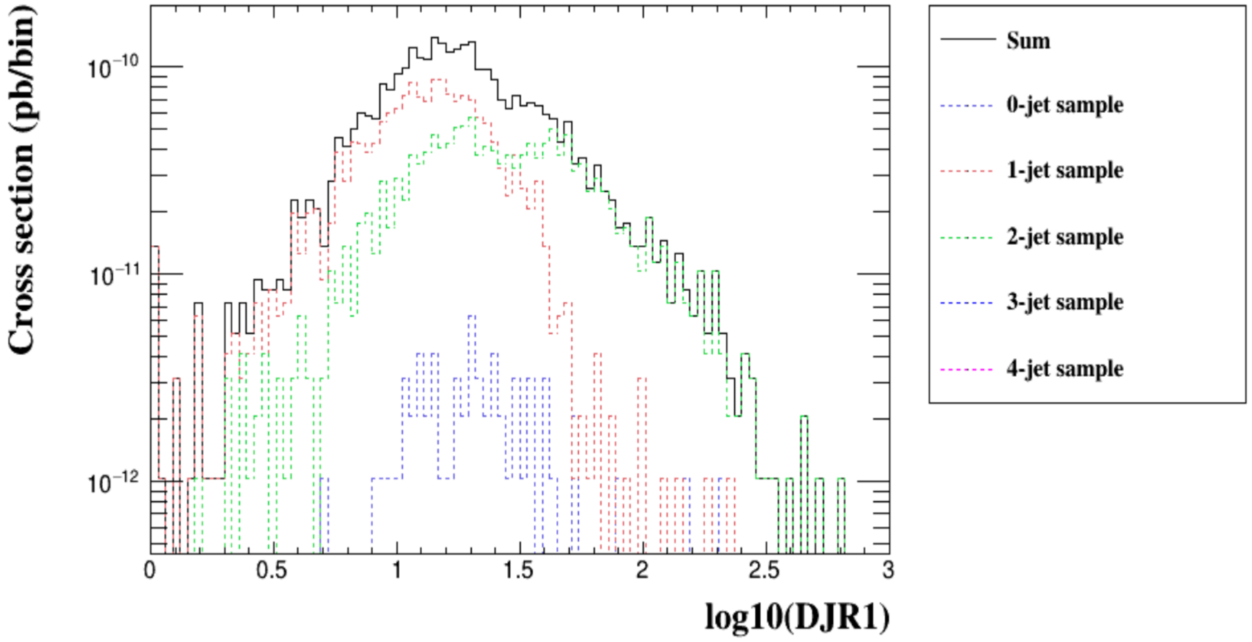
- Cross-section vs mass plots for comparison for different processes for left plot coupling equals 1 , right plot coupling equals 2.5
- Plot contains
  - Pair , single and off-shell production for second generation
  - $pp \to \mu^+\mu^- 0123j$
  - $pp \to \mu^+\mu^- J$ (p contains photon, , Inelastic contribution)





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.

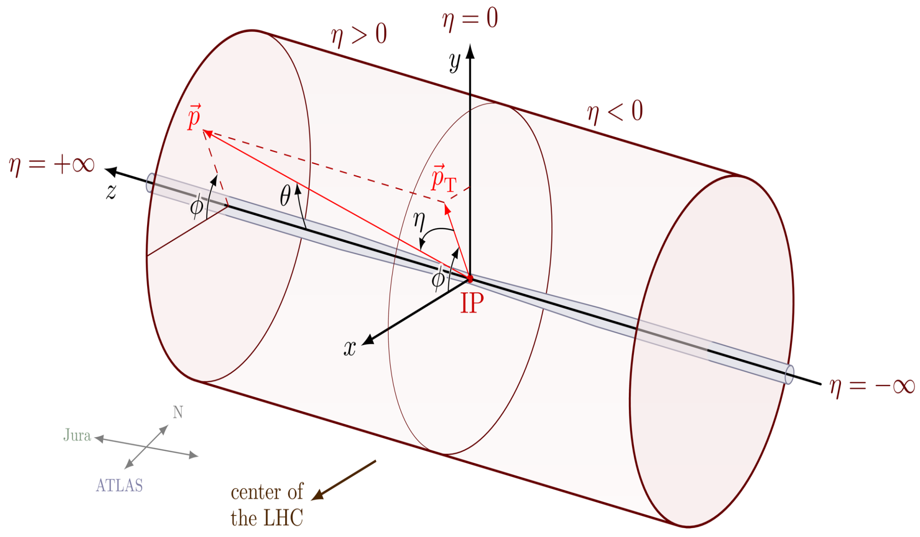
Search Strategy

- The signal 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

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

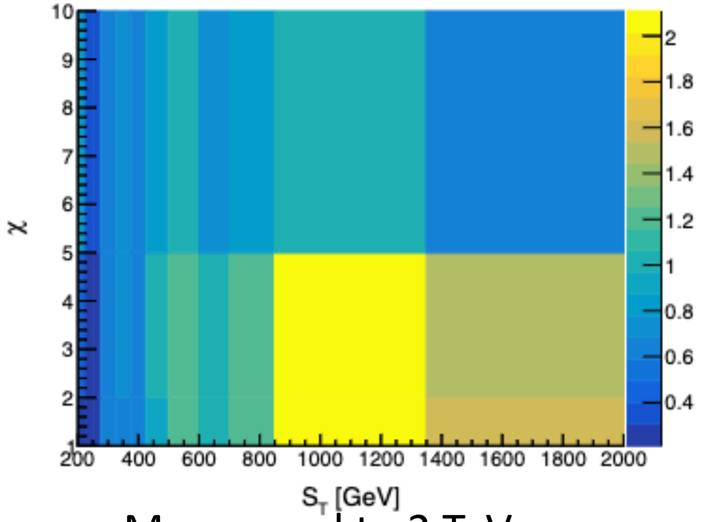


Histograms (μc)

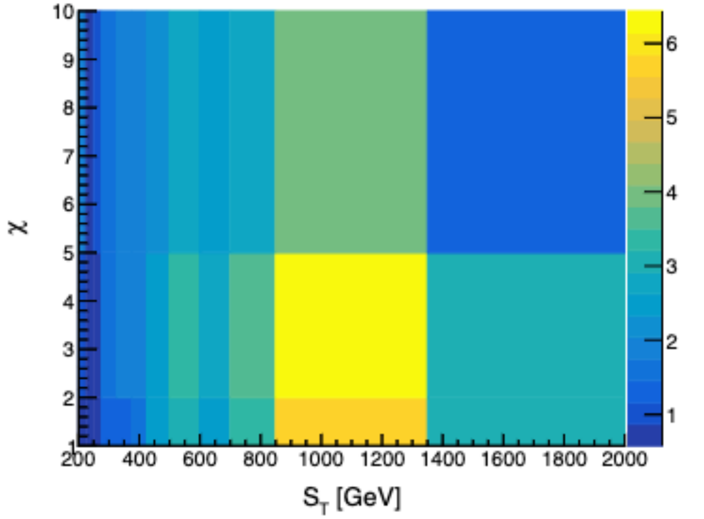
<u>Discriminating varaibles</u>

- $\chi = e^{\eta_1 - \eta_2}$ *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.

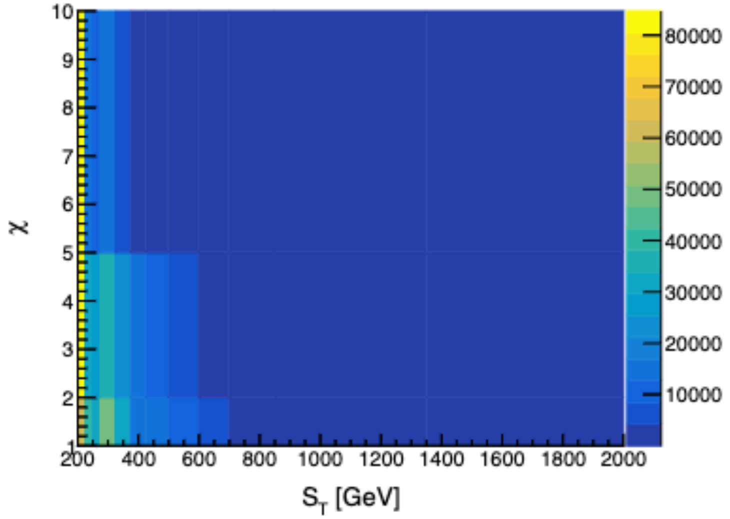
$$S_T = \sum_{leptons} p_T + \sum_{jets} p_T$$



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 $300 fb^{-1}$ and then scaled to $140 fb^{-1}$ and $3000 fb^{-1}$

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

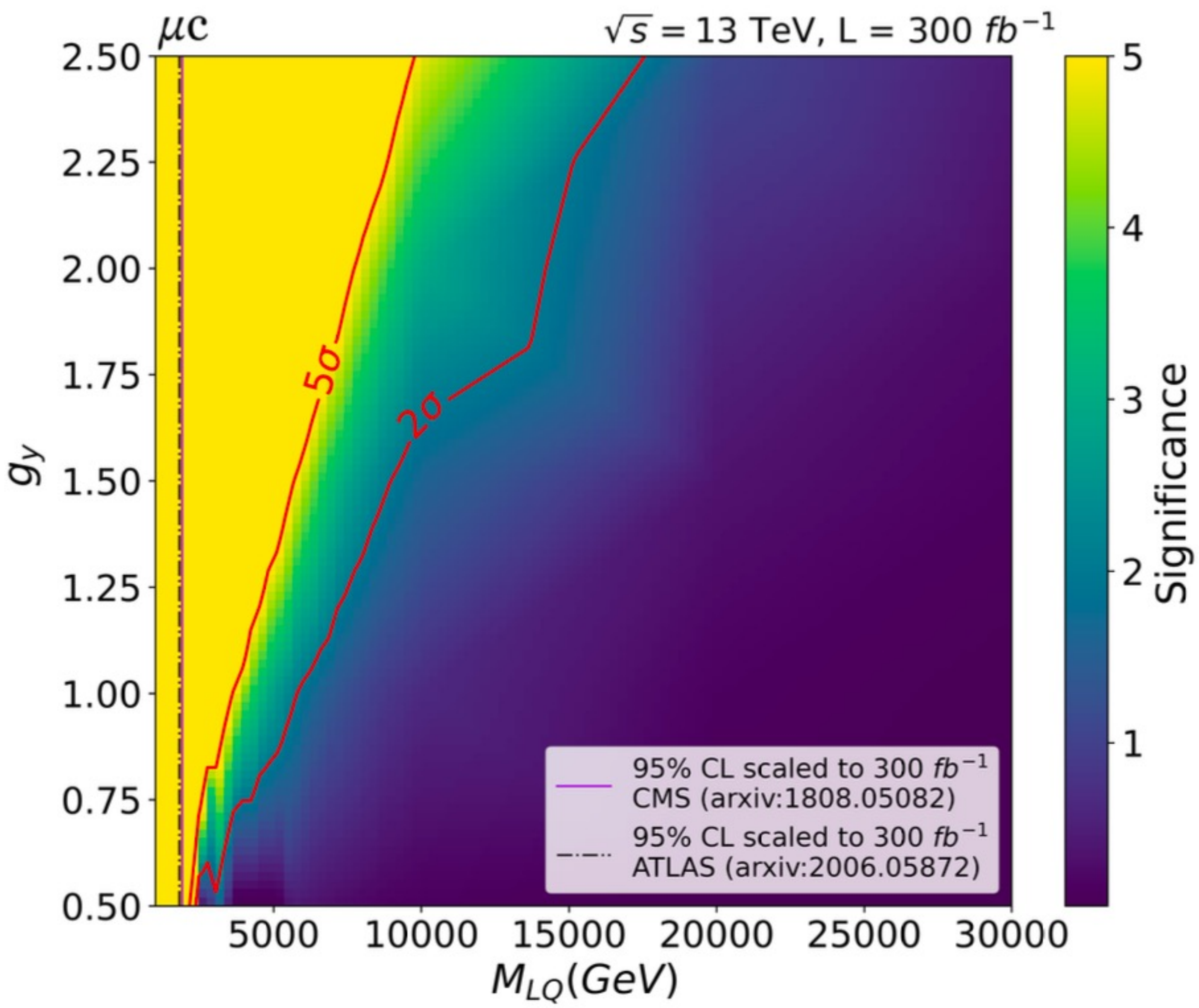
Followed the same prescriptions used in the published LQ searches
https://arxiv.org/abs/1808.05082

Sensitivity Results(2nd Gen) 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

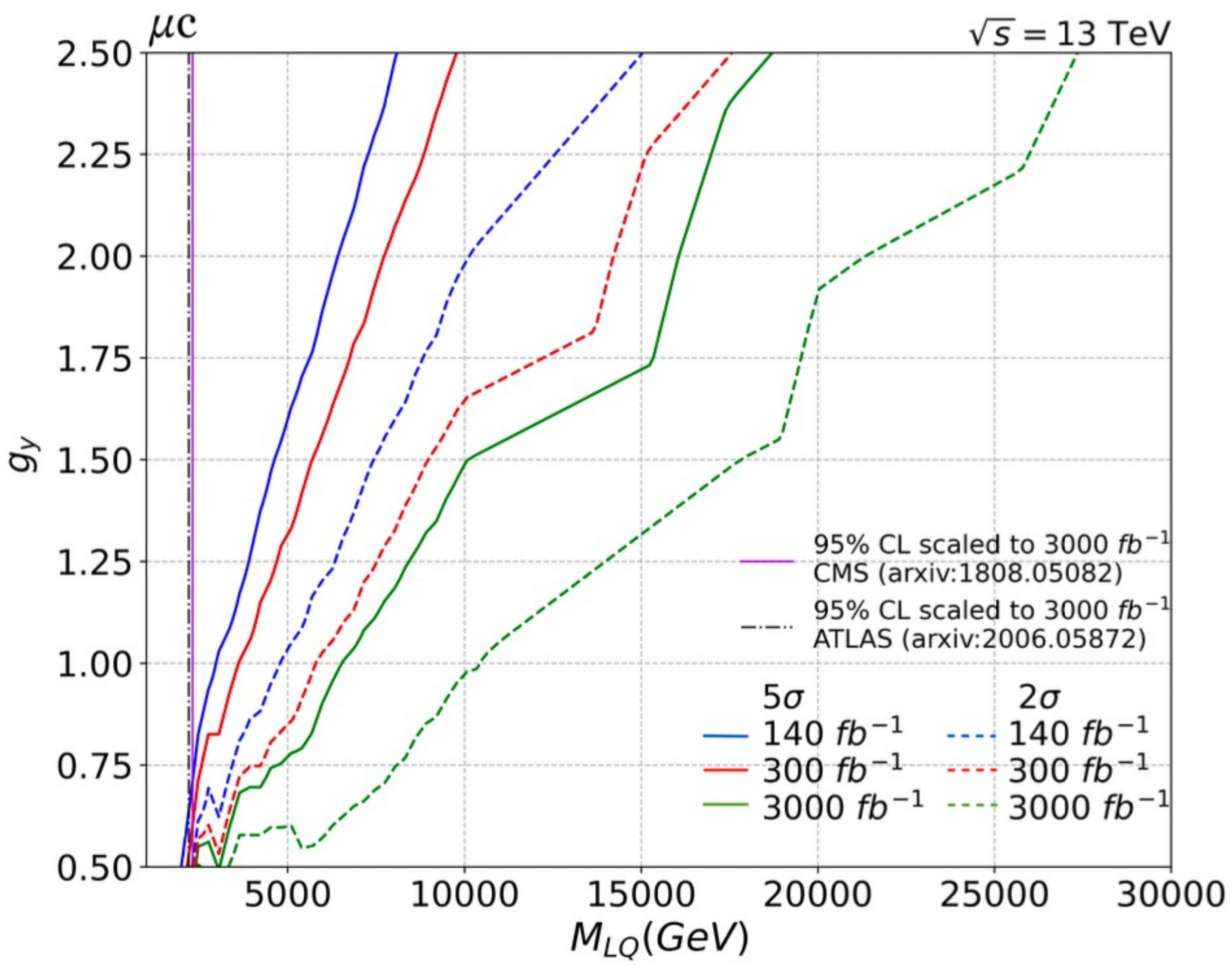


Sensitivity Results(2nd Gen) for $3000\ fb^{-1}$

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

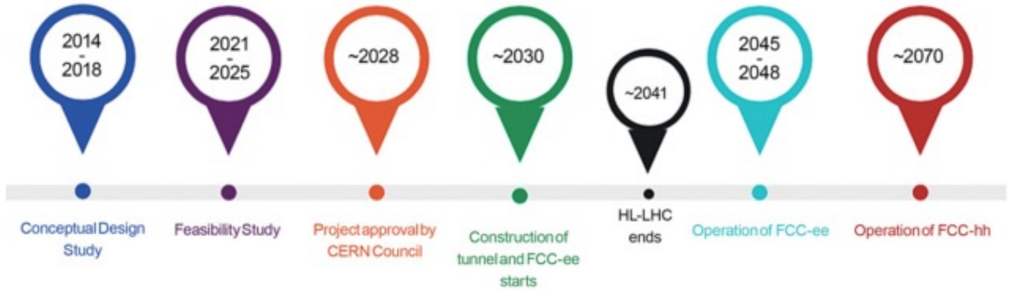


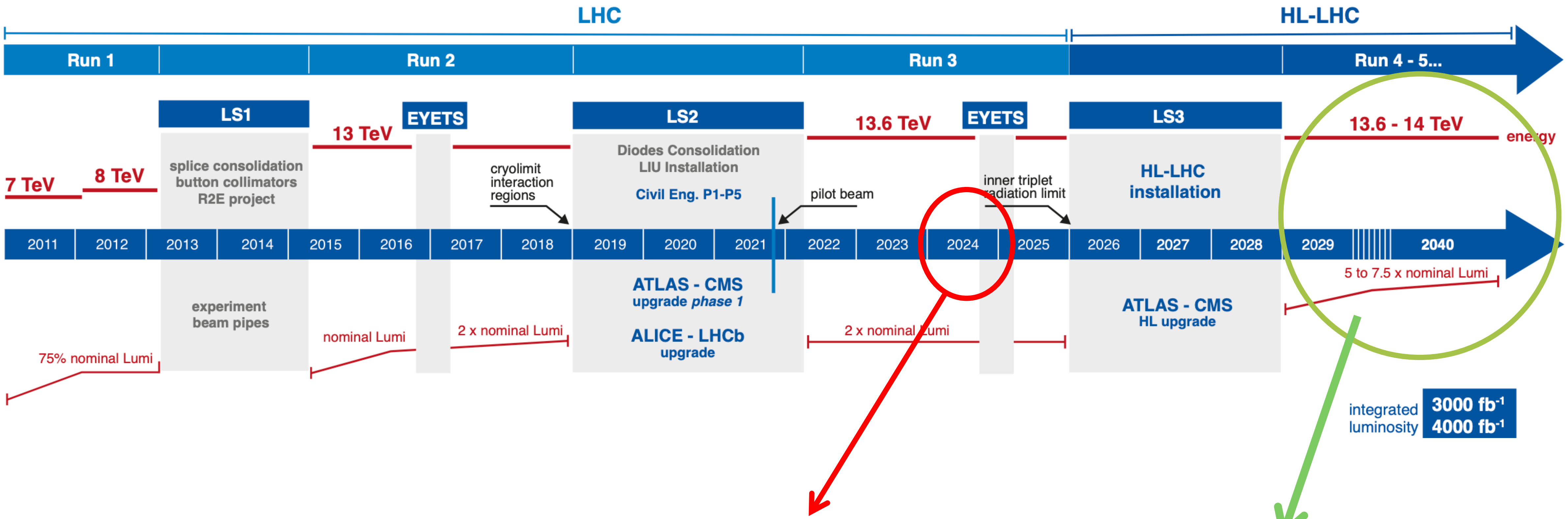
Summary

- For the first time, we have examined the impact on the sensitivity of the search for particles when they are produced in association with additional jets.
- We have found that several New Mechanisms are possible besides the classical pair, single, and Drell-Yan non-resonant LQ generation.
- Explored parameter space parameter to assess its impact on the outcomes
- Projected 2 and 5σ contours for different Luminosities, 3000 fb^{-1}, 300 fb^{-1}, and 140 fb^{-1}. For center-of-mass energy of 13 TeV.
- These findings hold particular relevance within the context of the BSM scenario.
- Work has been already available on arxiv: 2311.18472 [hep-ph]
- **The LQ part of the model published on the official website of Feynrules https://feynrules.irmp.ucl.ac.be/wiki/NJLComposite**

Thanks for giving me opportunity to speak and for Attention

LHC and Future Colliders





At HL_LHC energy will not be increased much but statistics will.

Composite NJL Model

- The Effective Four Fermion operators

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

- Preserves not only the SM gauge symmetries and global fermion family symmetries but also the global symmetries for fermion-number conservations
- Effective Lagrangian at Cutoff Λ_{cut}:
  - Massless SM fermion fields interact as gauge eigenstates of SM gauge symmetries.
  - Unique four-fermion coupling $\boldsymbol{G_{cut}}$ establishes exact global fermion-family $U_L(3) \times U_R(3)$ chiral symmetries.
- Converting gauge to mass eigenstates using a unitary matrix

$$\psi_L^f \rightarrow \mathcal{U}_L^f \psi_L^f; \qquad \psi_R^f \rightarrow \mathcal{U}_R^f \psi_R^f; \qquad \mathcal{U}_{L,R}^f \in \mathcal{U}_{L,R}^f(3)$$

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
- Contact Interactions and Gauge interactions are implemented for both. Next to leading order Interactions are there for Composite bosons
- 5 Flavour scheme is implemented.
- Universal Feynrules output (UFO) for the use Monte Carlo generator: **MadGraph**

```
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

Comparison to Other Models

- LQ part of the implementation is compared with well-known LQ model in CMS LQ UFO or $\tilde{R}_2 = (3, 2, 1/6)$

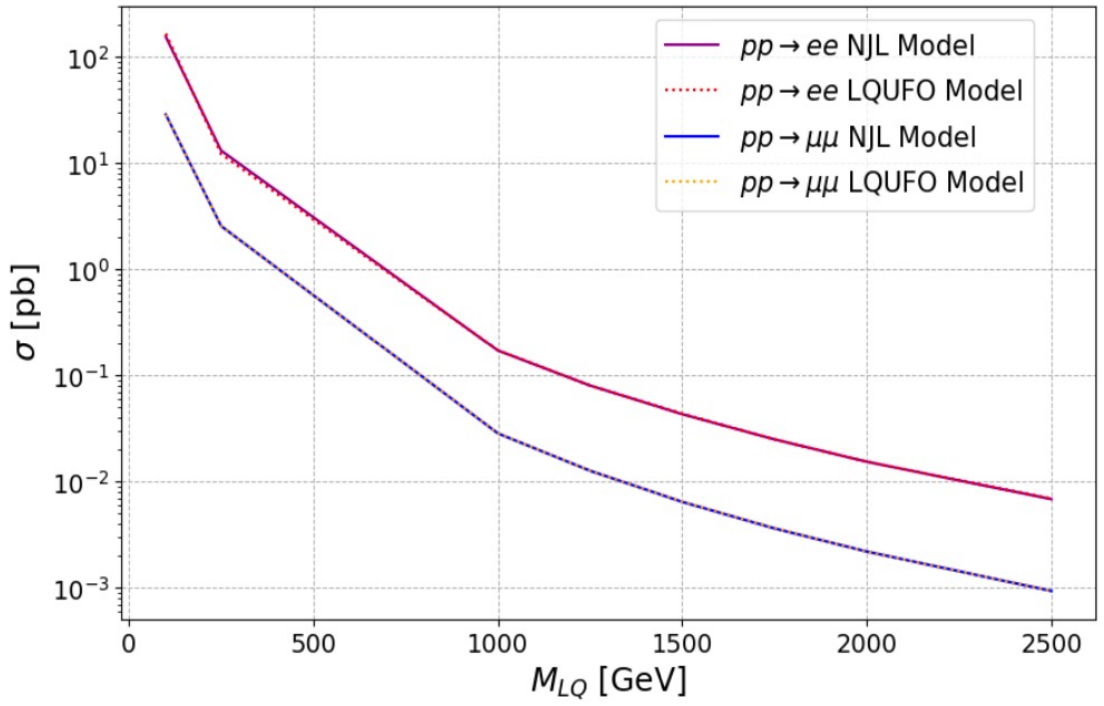
Process	Xsec in Composite NJL model(pb)	Xsec in LQ-UFO model(pb)
$pp \to LQLQ$	$0.005568 \pm 4.9 \times 10^{-06}$	$0.005561 \pm 4.92 \times 10^{-06}$
$pp \to eLQ$	$0.0369 \pm 2.9 \times 10^{-05}$	$0.0369 \pm 2.9 \times 10^{-05}$
$pp \to ee$	0.1294 ± 0.0001	0.1294 ± 0.00014

For Single pair and t channel production cross-section comparisons for LQ mass set to 1 TeV and coupling set to 1. Used (electron and down quark) for both models.

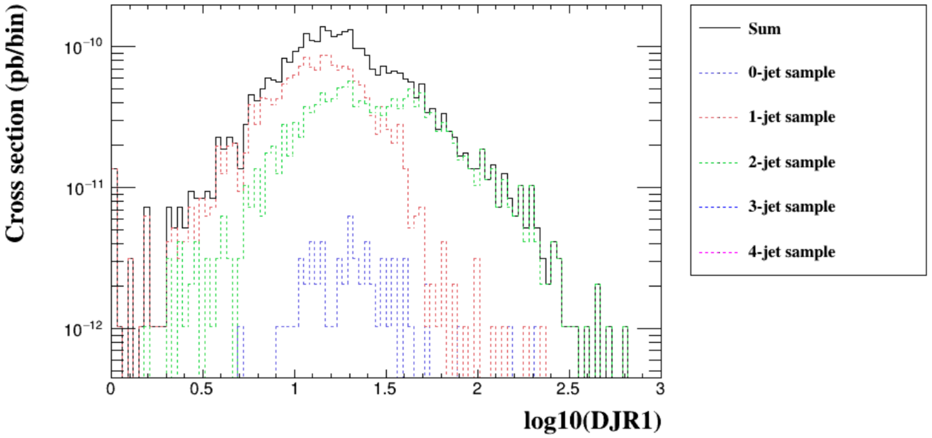
Comparison to Other Models

- Comparative analysis broadened to encompass e-d and μ-s couplings for t-channel production ($pp \rightarrow \ell^+\ell^-$).
- Varying couplings (1 for 1st generation, 1.5 for 2nd generation) over a mass range from 100 to 2500 GeV.
- Cross-sections obtained using our implemented model consistent within a 1% margin with LQ-UFO model.
- **The LQ part of the model published on the official website of Feynrules**

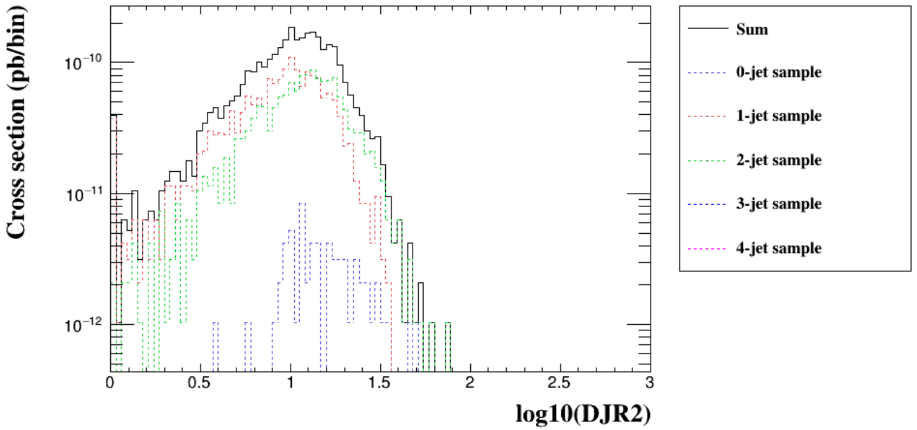
https://feynrules.irmp.ucl.ac.be/wiki/NJLComposite



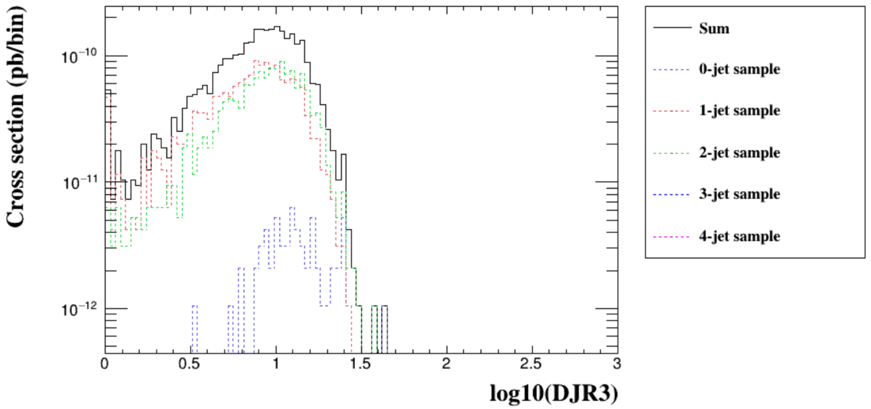
- The matching scale is adjusted at 30 GeV based on the specific variable characterizing the jet production.
- There is a distinct cut- off between 0- and 1-parton samples in DJR(0 → 1), signifying a critical threshold where the probability of transitioning from zero to one jet experiences a notable change and so on



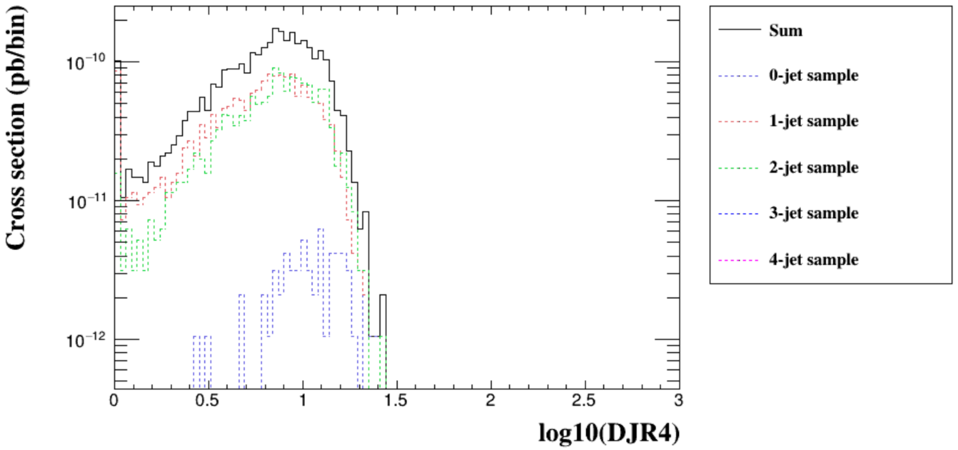
(a) DJR1 : 0 jet -> 1 jet



(b) DJR2 : 1 jet -> 2 jets



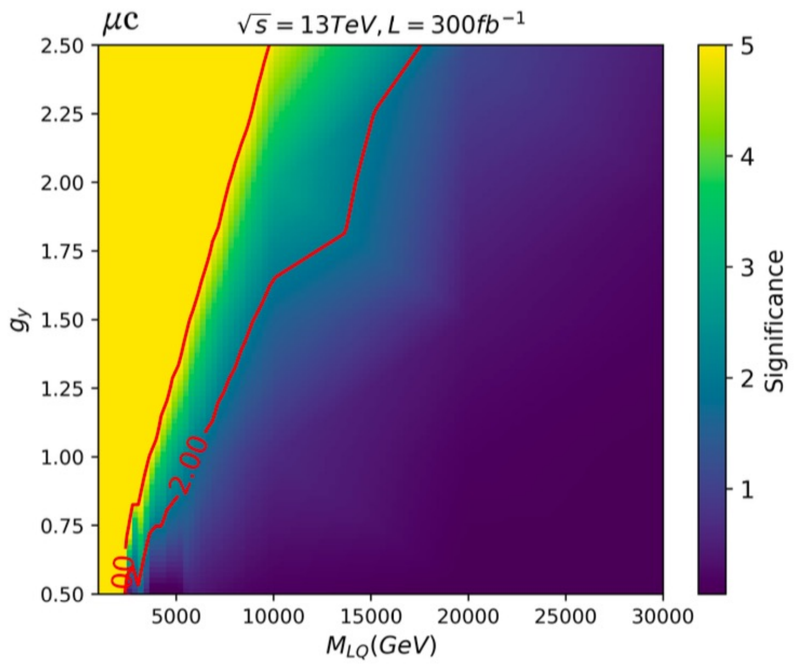
(c) DJR3 : 2 jets -> 3 jets

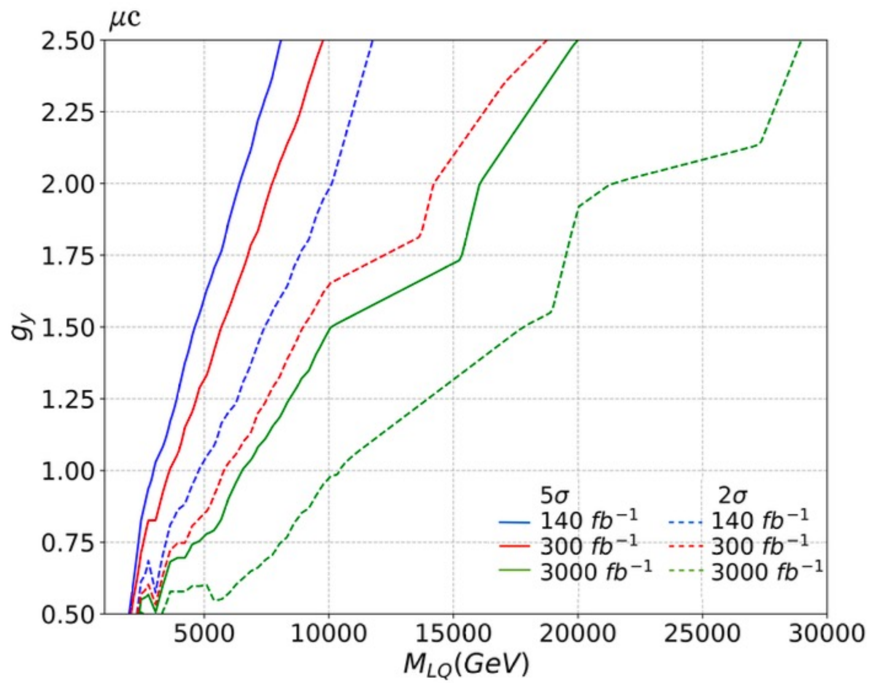


(d) DJR4 : 3 jets -> 4 jets

Sensitivity Results

2 and 5σ significance contours associated with the coupling of **μ c-quark**





At luminosity level 300 fb^{-1}(red) and COM at 13 TeV

At varying luminosity levels at 13 TeV, specifically, 3000 fb^{-1}(Green), 300 fb^{-1}(red), and 140 fb^{-1}(Blue).