LEPTOQUARK TOOLBOX FOR PRECISION COLLIDER STUDIES*

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Heidelberg, Germany
September 20th, 2018

*I. D. and A. Greljo, arXiv:1801.07641.
I. D., S. Fajfer, A. Greljo, J. F. Kamenik, and N. Košnik, arXiv:1603.04993.
I. D., S. Fajfer, and A. Greljo, arXiv:1406.4831.

Supported in part by Croatian Science Foundation under the project 7118.

OUTLINE

- LEPTOQUARKS
- LEPTOQUARK PRODUCTION MECHANISMS
- LQ_NLO @ HepForge
- PHYSICS RESULTS
- OUTLOOK
- CONCLUSIONS

LEPTOQUARKS

q(uark)–ℓ(epton)–L(epto)Q(uark)

Leptoquark (LQ) is a colored field.

LEPTOQUARK $\equiv (SU(3),\ SU(2),\ U(1))$

SCALAR	VECTOR
$S_3 \equiv (\overline{\mathbf{3}}, \mathbf{3}, 1/3)$	$U_3 \equiv (\mathbf{3}, \mathbf{3}, 2/3)$
$R_2 \equiv (\mathbf{3}, \mathbf{2}, 7/6)$	$V_2 \equiv (\overline{\mathbf{3}}, \mathbf{2}, 5/6)$
$\tilde{R}_2 \equiv (\mathbf{3}, \mathbf{2}, 1/6)$	$\tilde{V}_2 \equiv (\overline{\mathbf{3}}, \mathbf{2}, -1/6)$
$\tilde{S}_1 \equiv (\overline{\mathbf{3}}, \mathbf{1}, 4/3)$	$\tilde{U}_1 \equiv (\mathbf{3}, \mathbf{1}, 5/3)$
$S_1 \equiv (\overline{\mathbf{3}}, \mathbf{1}, 1/3)$	$U_1 \equiv (\mathbf{3}, \mathbf{1}, 2/3)$

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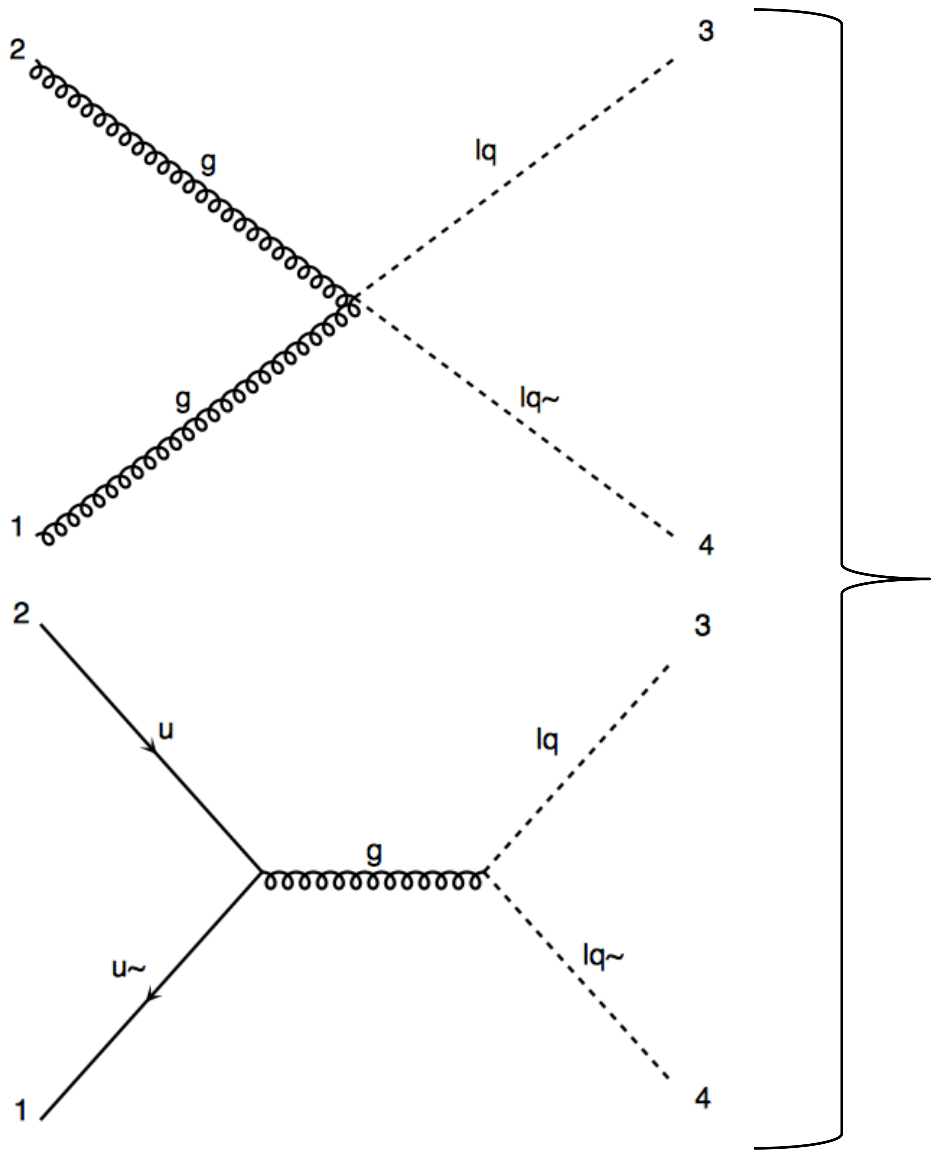
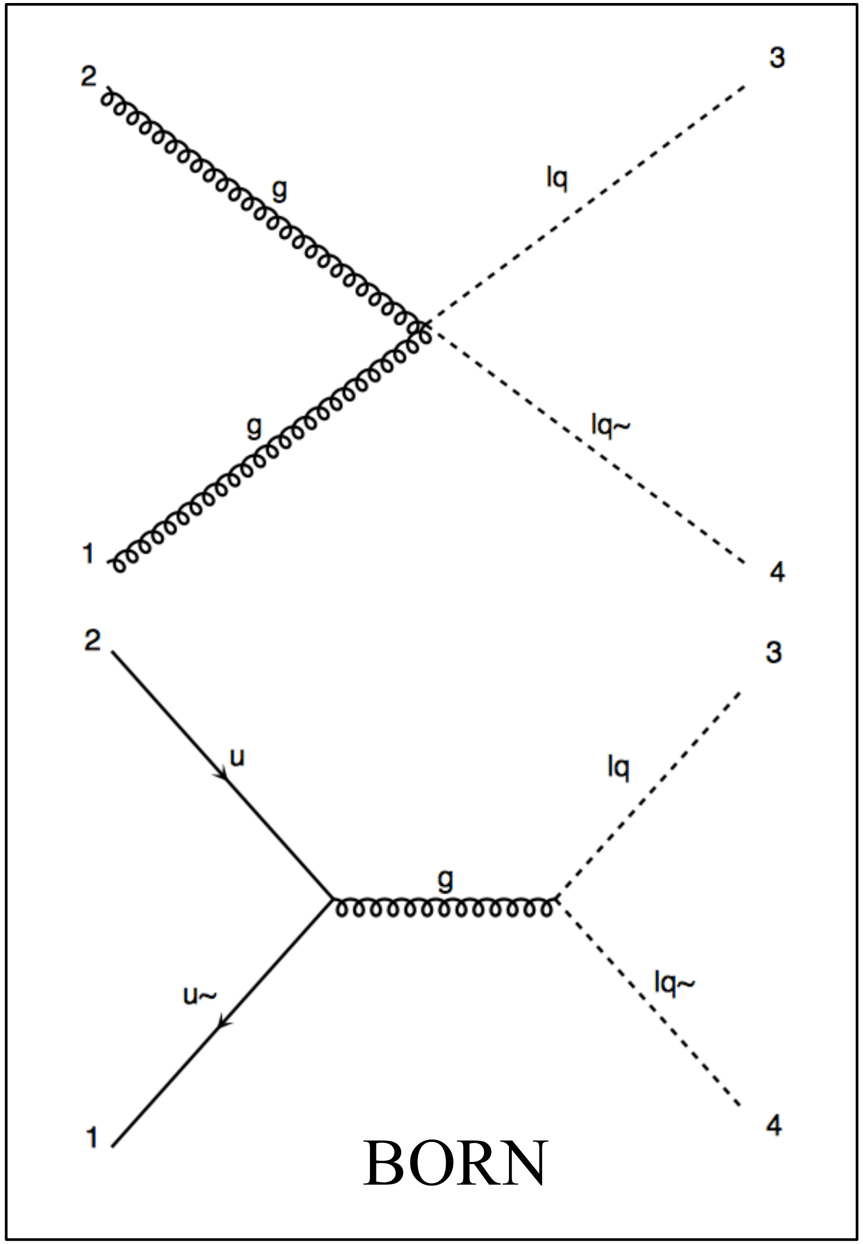
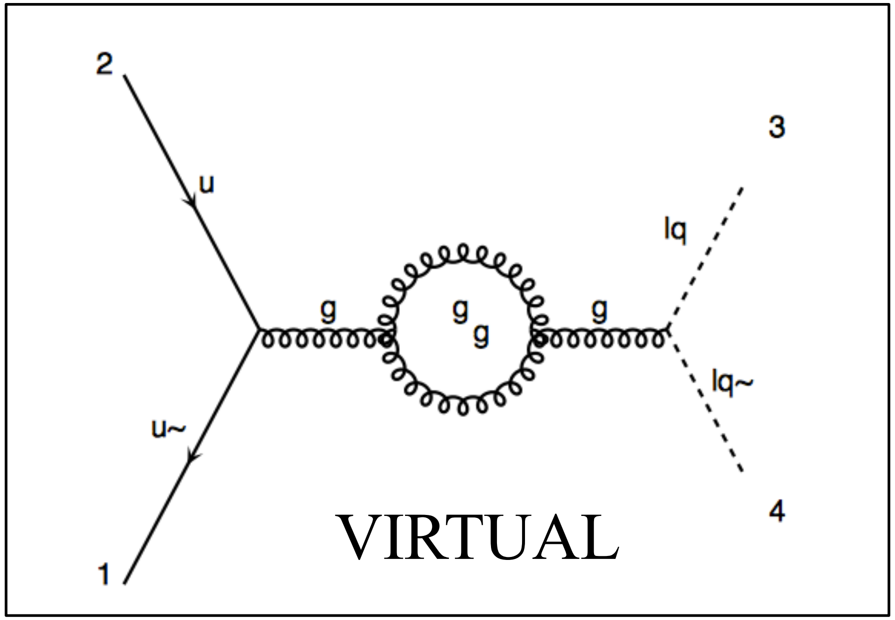
PAIR PRODUCTION OF LEPTOQUARKS @ LO

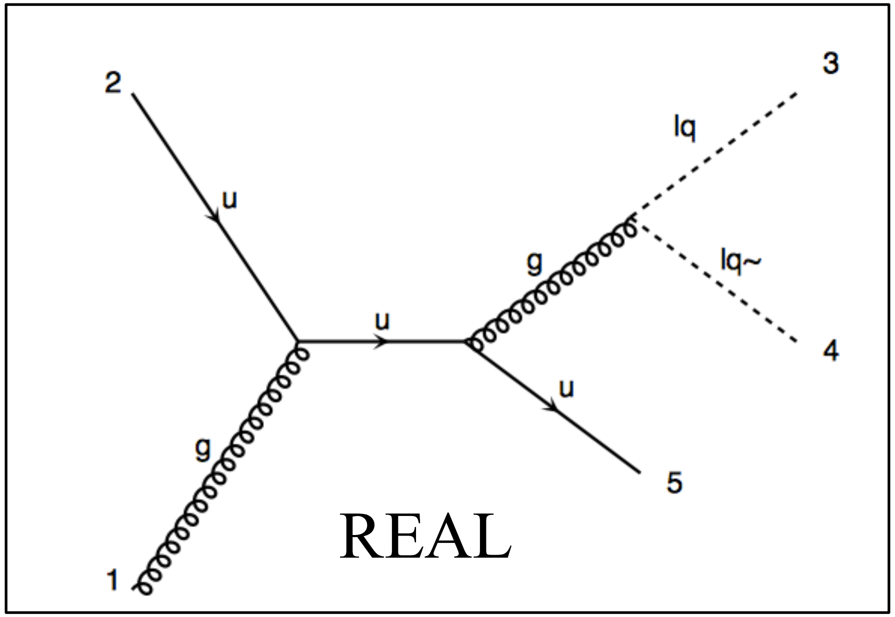


LEADING ORDER (LO)
FEYNMAN DIAGRAMS

PAIR PRODUCTION OF LEPTOQUARKS @ NLO







NEXT-TO-LEADING ORDER CALCULATIONS

M. Kramer, T. Plehn, M. Spira, and P. M. Zerwas, hep-ph/0411038.

T. Mandal, S. Mitra, and S. Seth, arXiv:1506.07369.

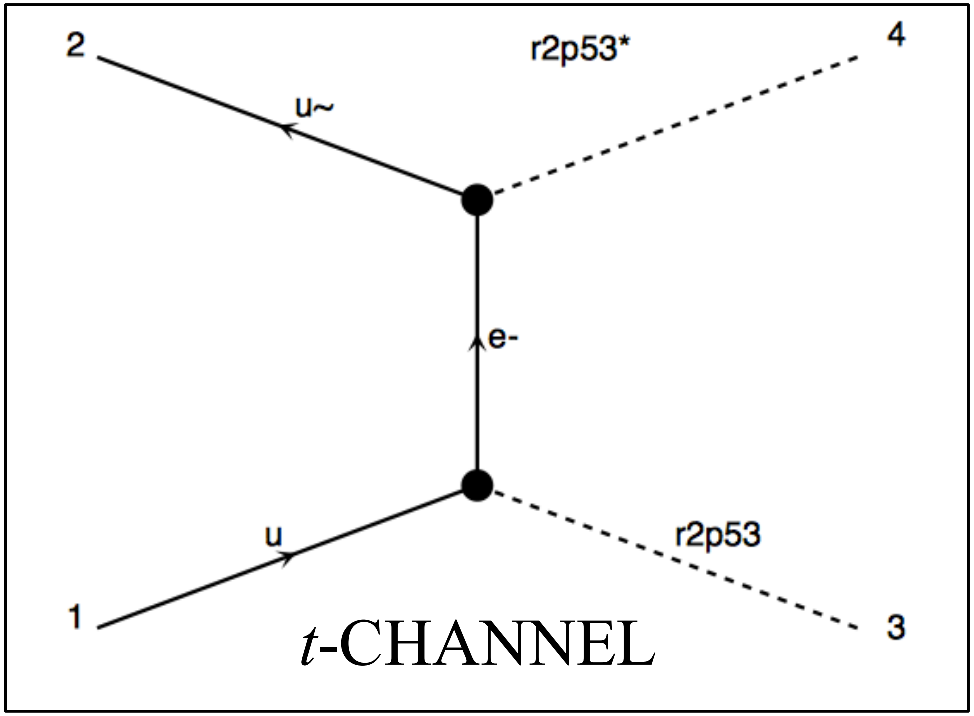
LEPTOQUARK PAIR PRODUCTION

https://web.physik.rwth-aachen.de/service/wiki/bin/view/Main/LeptoquarkProduction

PDFs: CTEQ6L1 (LO) & CTEQ6.6M (NLO)

CODE: Fortran 77

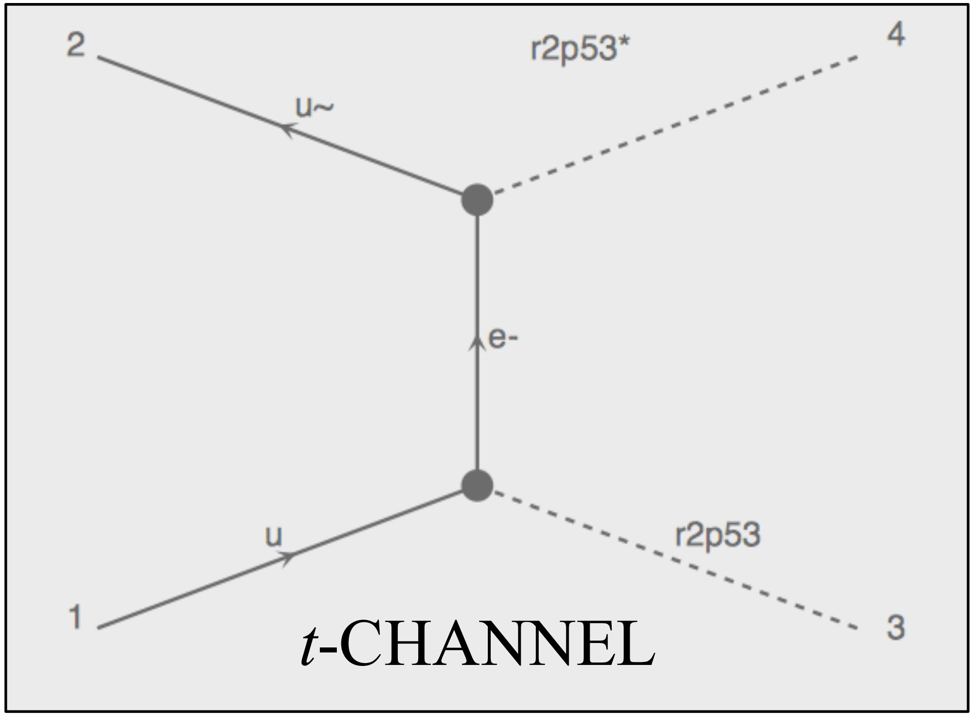
PAIR PRODUCTION OF LEPTOQUARKS



● = YUKAWA COUPLING

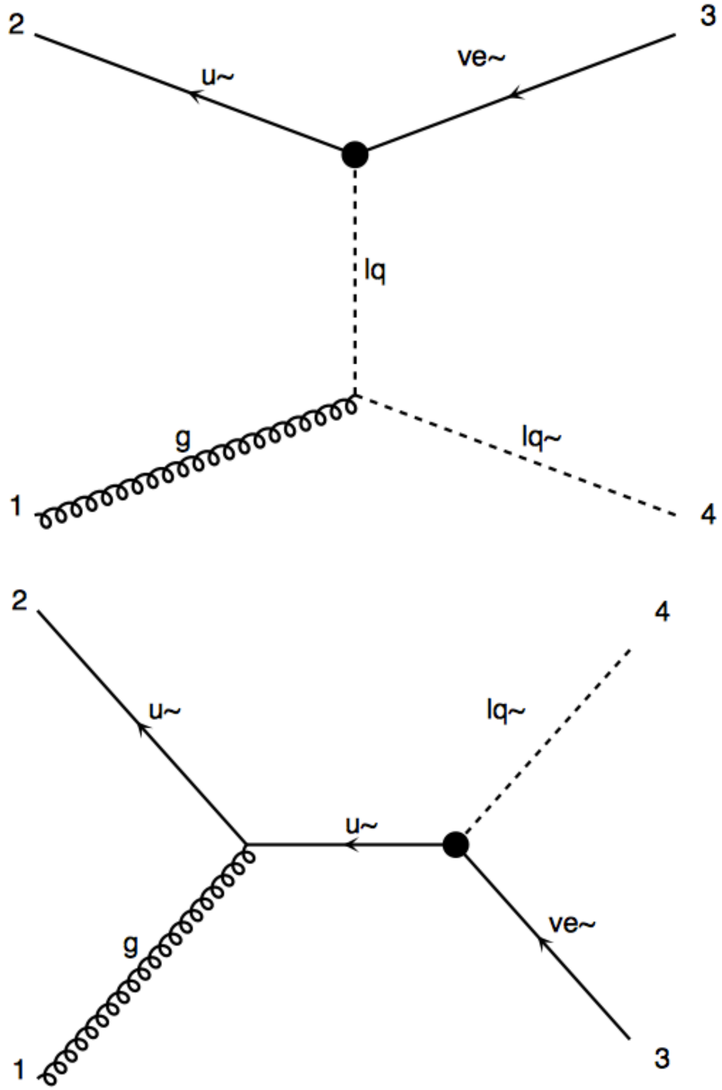
I. D., S. Fajfer, and A. Greljo, arXiv:1406.4831.

PAIR PRODUCTION OF LEPTOQUARKS



$$\sigma_{\text{pair}} = f(\alpha_s, m_{\text{LQ}})$$

SINGLE LEPTOQUARK + LEPTON PRODUCTION

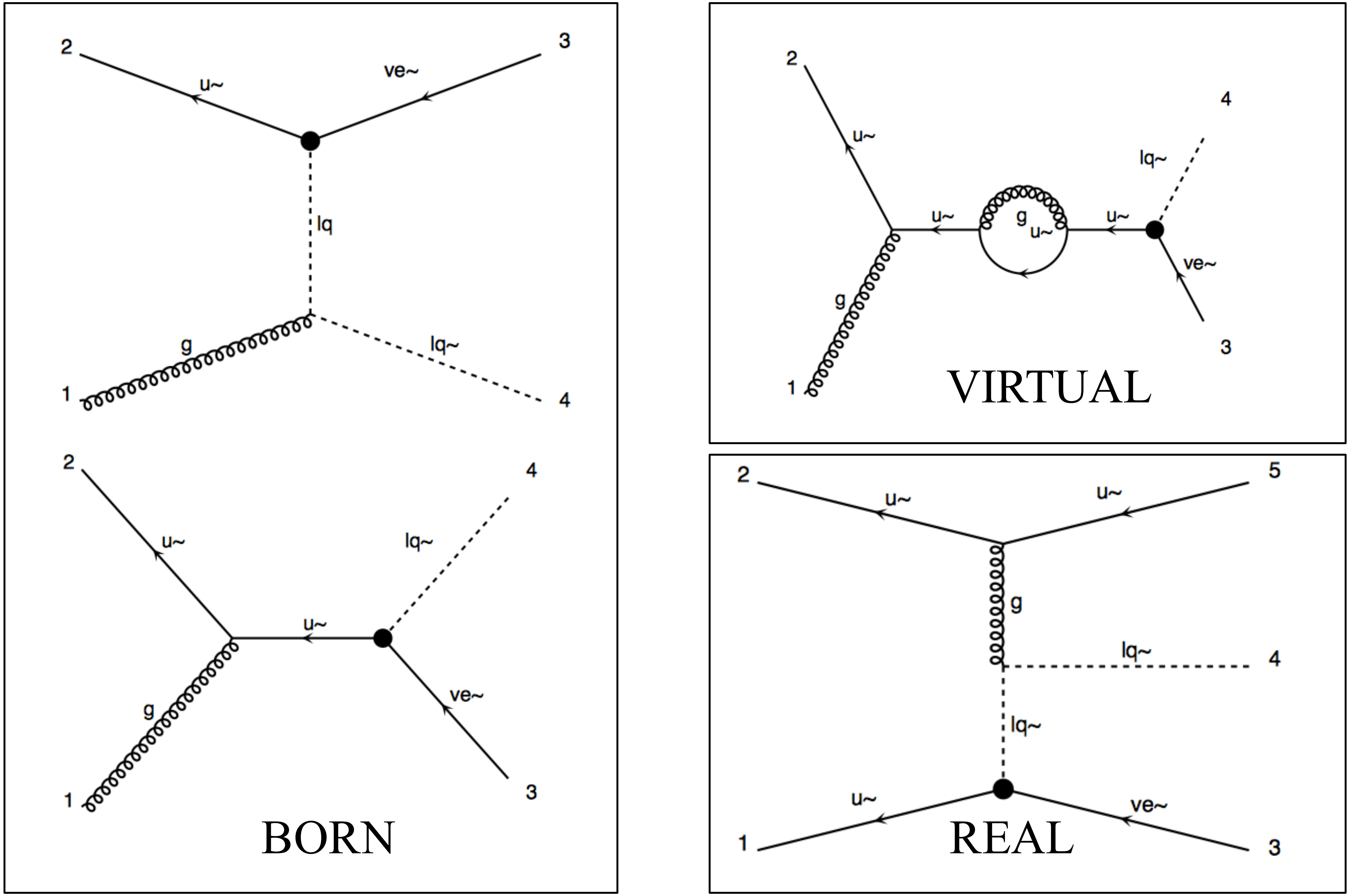


$y_{q\ell}$ $(q$–ℓ–LQ$)$

● = YUKAWA COUPLING ($y_{q\ell}$)

LEADING ORDER (LO)
FEYNMAN DIAGRAMS

SINGLE LEPTOQUARK + LEPTON PRODUCTION



NEXT-TO-LEADING ORDER CALCULATIONS

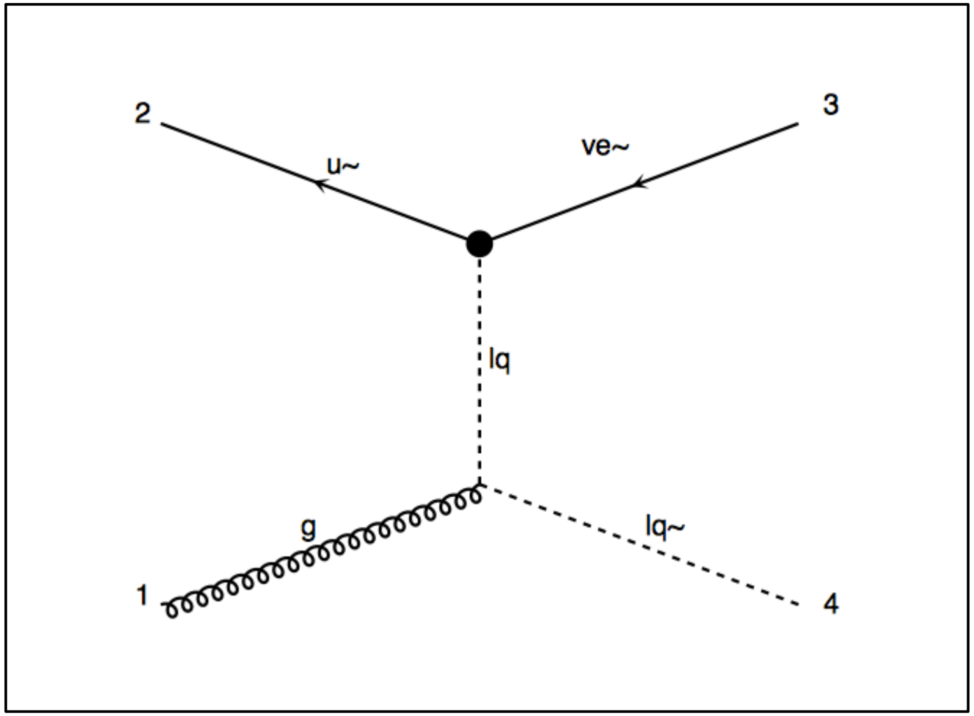
A. Alves, O. Eboli and T. Plehn, hep-ph/0211441.

J. B. Hammett and D. A. Ross, arXiv:1501.06719.

T. Mandal, S. Mitra and S. Seth, arXiv:1503.04689.

SINGLE LEPTOQUARK PRODUCTION

SINGLE LEPTOQUARK + LEPTON PRODUCTION



$$\sigma^q_{\text{single}} = y^2_{q\ell}\, g_q(\alpha_s, m_{\text{LQ}})$$

$$q = u, d, s, c, b$$

LQ_NLO TOOLBOX PROJECT

LQ_NLO contains Universal FeynRules Output (UFO) model file directories for all scalar leptoquarks (S_3, $\tilde{R}_2$, R_2, S_1, $\tilde{S}_1$) and one vector leptoquark (U_1^{μ}) to be used with MADGRAPH5_AMC@NLO.

We use the NLOCT package (version 1.02)* together with FEYNARTS (version 3.9)◉ to generate the relevant UV and R2 counterterms at one-loop level in QCD for the NLO simulations.

We assume the Standard Model + one leptoquark scenario and impose the conservation of both baryon (B) and lepton (L) numbers.

*C. Degrande,, arXiv:1406.3030.

◉T. Hahn, hep-ph/0012260.

WHERE DOES LQ_NLO EXCEL?

M. Kramer, T. Plehn, M. Spira, and P. M. Zerwas, hep-ph/0411038.

T. Mandal, S. Mitra, and S. Seth, arXiv:1506.07369.

LEPTOQUARK PAIR PRODUCTION

A. Alves, O. Eboli and T. Plehn, hep-ph/0211441.

J. B. Hammett and D. A. Ross, arXiv:1501.06719.

T. Mandal, S. Mitra and S. Seth, arXiv:1503.04689.

SINGLE LEPTOQUARK PRODUCTION

LQ_NLO TOOLBOX @ HepForge

https://www.hepforge.org

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HEPForge (2018)

HEPForge is a development environment for high energy physics software projects.

Some of the benefits offered by HEPForge are:

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- Developer Mailing Lists
- Bug Tracker
- Wiki and Documentation system

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LQ_NLO TOOLBOX @ HepForge

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-

- **likedm** Likelihood calculator of dark matter detection
- **lilith** A tool for constraining new physics from Higgs measurements
- **lool** Leading Order One-Loop Integrals
- **loopsim** Method to generate unitarity-based approximations to loop contributions
- **lqnlo** Leptoquark toolbox for precision collider studies
- **lusifer**
- **manet** Implementation for NVIDIA GPUs of a statistical two-sample comparison test known as the energy test
- **matrix**
- **matthew4hep**
- **mbtools** Tools for evaluating Mellin-Barnes integrals

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https://lqnlo.hepforge.org

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LQ_NLO

LQ_NLO is a leptoquark toolbox for precision collider studies. It contains Universal FeynRules Output (UFO) model file directories for all scalar leptoquarks and one vector leptoquark to be used with MADGRAPH5_AMC@NLO. It also contains original FeynRules model files to allow for reusability and customisation. The main features of these UFO models and associated physics results are summarised in **arXiv:1801.07641**.

Please acknowledge **arXiv:1801.07641** if you use the LQ_NLO material.

VERSIONS

LQ_NLO-0.0.1 (upload date 11/2/2018)

DESCRIPTION

LQ_NLO provides both the leading order (LO) and next-to-leading order (NLO) UFO model files to be used with MADGRAPH5_AMC@NLO. We describe the content of the latest LQ_NLO version, i.e., LQ_NLO-0.0.1, briefly in what follows.

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LQ_NLO TOOLBOX @ HepForge

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lqnlo Downloads

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Directory: /

Type	File Name	File Size
ZIP	LQ_NLO-0.0.1.zip	*0,76 MB*

$R_2 \equiv (\mathbf{3}, \mathbf{2}, 7/6)$

LQ_NLO TOOLBOX .fr MODEL SAMPLE

$$R_2 \equiv (\mathbf{3}, \mathbf{2}, 7/6)$$

$$\mathcal{L} \supset -\, y_{2\,ij}^{RL} \bar{u}_R^i R_2^a \epsilon^{ab} L_L^{j,b}$$

LQ_NLO TOOLBOX .fr MODEL SAMPLE

```
S[200] == {
ClassName          -> R2p53,
Mass               -> {MR2, Internal},
Width              -> {WR253, Internal},
SelfConjugate      -> False,
PropagatorLabel    -> "R253",
PropagatorType     -> D,
PropagatorArrow    -> None,
QuantumNumbers     -> {Q -> 5/3, LeptonNumber -> -1},
Indices            -> {Index[Colour]},
ParticleName       -> "R2p53",
AntiParticleName -> "R2p53*",
FullName           -> "R53"
},

S[201] == {
ClassName          -> R2p23,
Mass               -> {MR2, Internal},
Width              -> {WR223, Internal},
SelfConjugate      -> False,
PropagatorLabel    -> "R2p23",
```

LQ_NLO TOOLBOX .fr MODEL SAMPLE

```
WR253 == {
   ParameterType -> Internal,
   Value         -> (MR2*(Abs[yRL[1,1]]^2 + Abs[yRL[1,2]]^2 + Abs[yRL[1,3]]^2
                       + Abs[yRL[2,1]]^2 + Abs[yRL[2,2]]^2 + Abs[yRL[2,3]]^2
                       + Abs[CKM[1,1]*yLR[1,1]+CKM[1,2]*yLR[1,2]]^2
                       + Abs[CKM[2,1]*yLR[1,1]+CKM[2,2]*yLR[1,2]]^2
                       + Abs[CKM[1,1]*yLR[2,1]+CKM[1,2]*yLR[2,2]]^2
                       + Abs[CKM[2,1]*yLR[2,1]+CKM[2,2]*yLR[2,2]]^2
                       + Abs[CKM[1,1]*yLR[3,1]+CKM[1,2]*yLR[3,2]]^2
                       + Abs[CKM[2,1]*yLR[3,1]+CKM[2,2]*yLR[3,2]]^2)
                      + (Abs[yRL[3,1]]^2 + Abs[yRL[3,2]]^2 + Abs[yRL[3,3]]^2
                       + Abs[yLR[1,3]]^2 + Abs[yLR[2,3]]^2 + Abs[yLR[3,3]]^2)*(MR2^2-
ymt^2)^2/MR2^3)/(16*Pi)
         },
```

PHYSICS RESULTS

$$\mathcal{L} \supset \left(-y_{q\ell}\, \bar{q} P_{L,R} \ell\, \Phi + \text{h.c.}\right)$$

DECAY WIDTH:

$$\Gamma(\Phi \to q\ell) = \frac{|y_{q\ell}|^2 m_{\rm LQ}}{16\pi} \underbrace{\left(1 + \left(\frac{9}{2} - \frac{4\pi^2}{9}\right)\frac{\alpha_s}{\pi}\right)}_{1.0043}{}^{*}$$

*T. Plehn, H. Spiesberger, M. Spira, and P. M. Zerwas, hep-ph/9703433.

PHYSICS RESULTS

p p @ 14 TeV: PDF4LHC15*

m_{LQ} (TeV)	σ^{pair} (pb)	$\sigma_u^{\mathrm{single}}$ (pb)	$\sigma_d^{\mathrm{single}}$ (pb)
0.2	$75.1^{+12.3\%+2.6\%}_{-12.1\%-2.6\%}$	$130.^{+7.1\%+1.6\%}_{-6.2\%-1.6\%}$	$86.8^{+7.3\%+2.2\%}_{-6.2\%-2.2\%}$
0.4	$2.25^{+11.5\%+4.0\%}_{-12.5\%-4.0\%}$	$8.68^{+7.6\%+1.4\%}_{-7.0\%-1.4\%}$	$5.23^{+7.3\%+2.2\%}_{-6.9\%-2.2\%}$
0.6	$0.222^{+11.1\%+5.2\%}_{-12.7\%-5.2\%}$	$1.54^{+7.3\%+1.6\%}_{-7.2\%-1.6\%}$	$0.864^{+7.4\%+2.3\%}_{-7.3\%-2.3\%}$
0.8	$0.037^{+10.9\%+6.4\%}_{-12.9\%-6.4\%}$	$0.414^{+7.7\%+2.0\%}_{-7.6\%-2.0\%}$	$0.218^{+7.8\%+2.5\%}_{-7.8\%-2.5\%}$
1.0	$0.00787^{+11.5\%+7.7\%}_{-13.4\%-7.7\%}$	$0.138^{+7.5\%+2.3\%}_{-7.7\%-2.3\%}$	$0.0686^{+8.0\%+2.7\%}_{-8.1\%-2.7\%}$
1.2	$0.00204^{+11.5\%+9.1\%}_{-13.6\%-9.1\%}$	$0.0535^{+8.0\%+2.6\%}_{-8.2\%-2.6\%}$	$0.0256^{+8.2\%+2.9\%}_{-8.5\%-2.9\%}$
1.4	$0.000574^{+12.1\%+10.8\%}_{-14.0\%-10.8\%}$	$0.023^{+8.2\%+3.0\%}_{-8.5\%-3.0\%}$	$0.0105^{+8.6\%+3.3\%}_{-8.8\%-3.3\%}$
1.6	$0.000177^{+12.1\%+12.5\%}_{-14.2\%-12.5\%}$	$0.0107^{+8.4\%+3.3\%}_{-8.7\%-3.3\%}$	$0.00466^{+8.8\%+3.6\%}_{-9.1\%-3.6\%}$
1.8	$0.0000585^{+13.2\%+14.7\%}_{-14.9\%-14.7\%}$	$0.00518^{+8.6\%+3.7\%}_{-9.0\%-3.7\%}$	$0.00219^{+9.3\%+4.1\%}_{-9.5\%-4.1\%}$
2.0	$0.0000193^{+13.3\%+17.0\%}_{-15.1\%-17.0\%}$	$0.00267^{+9.1\%+4.2\%}_{-9.4\%-4.2\%}$	$0.00108^{+9.5\%+4.6\%}_{-9.7\%-4.6\%}$
2.2	$(6.72 \times 10^{-6})^{+14.1\%+19.9\%}_{-15.6\%-19.9\%}$	$0.0014^{+9.3\%+4.6\%}_{-9.6\%-4.6\%}$	$0.000548^{+9.7\%+5.1\%}_{-9.9\%-5.1\%}$
2.4	$(2.33 \times 10^{-6})^{+14.5\%+23.8\%}_{-15.9\%-23.8\%}$	$0.00077^{+9.6\%+5.1\%}_{-9.8\%-5.1\%}$	$0.000288^{+10.1\%+5.7\%}_{-10.3\%-5.7\%}$
2.6	$(8.2 \times 10^{-7})^{+15.1\%+29.0\%}_{-16.3\%-29.0\%}$	$0.000427^{+9.5\%+5.7\%}_{-9.9\%-5.7\%}$	$0.000156^{+10.3\%+6.4\%}_{-10.4\%-6.4\%}$
2.8	$(2.87 \times 10^{-7})^{+15.3\%+37.7\%}_{-16.5\%-37.7\%}$	$0.000241^{+10.0\%+6.2\%}_{-10.3\%-6.2\%}$	$0.0000851^{+10.6\%+7.1\%}_{-10.8\%-7.1\%}$
3.0	$(1.02 \times 10^{-7})^{+15.8\%+52.5\%}_{-16.6\%-52.5\%}$	$0.000139^{+10.4\%+6.8\%}_{-10.5\%-6.8\%}$	$0.0000477^{+10.9\%+7.9\%}_{-11.0\%-7.9\%}$

$y_{q\ell} = 1$ (applies to the $\sigma_u^{\mathrm{single}}$ and $\sigma_d^{\mathrm{single}}$ columns)

*J. Butterworth *et al.*, arXiv:1510.03865.

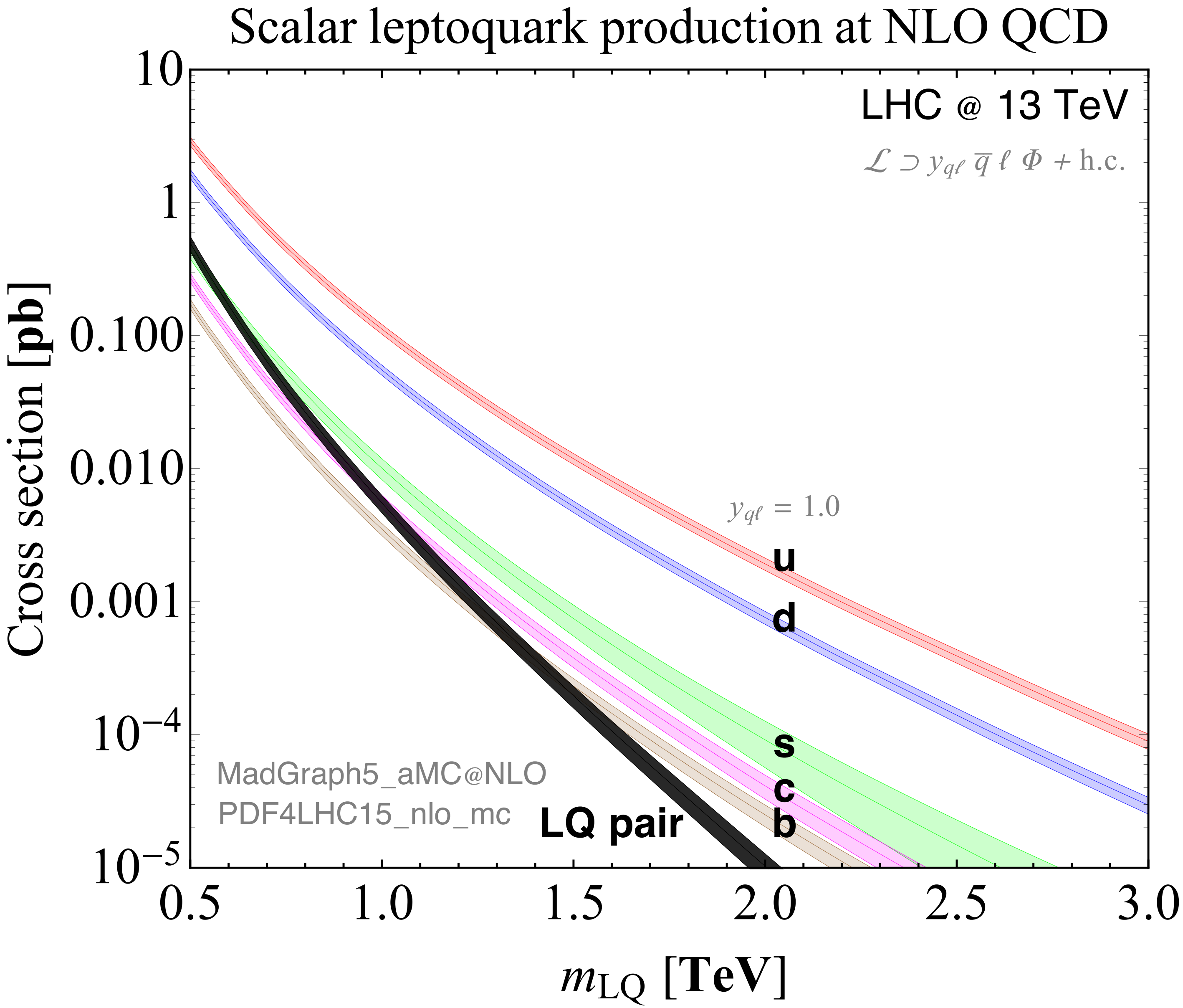
PHYSICS RESULTS

p p @ 14 TeV: PDF4LHC15

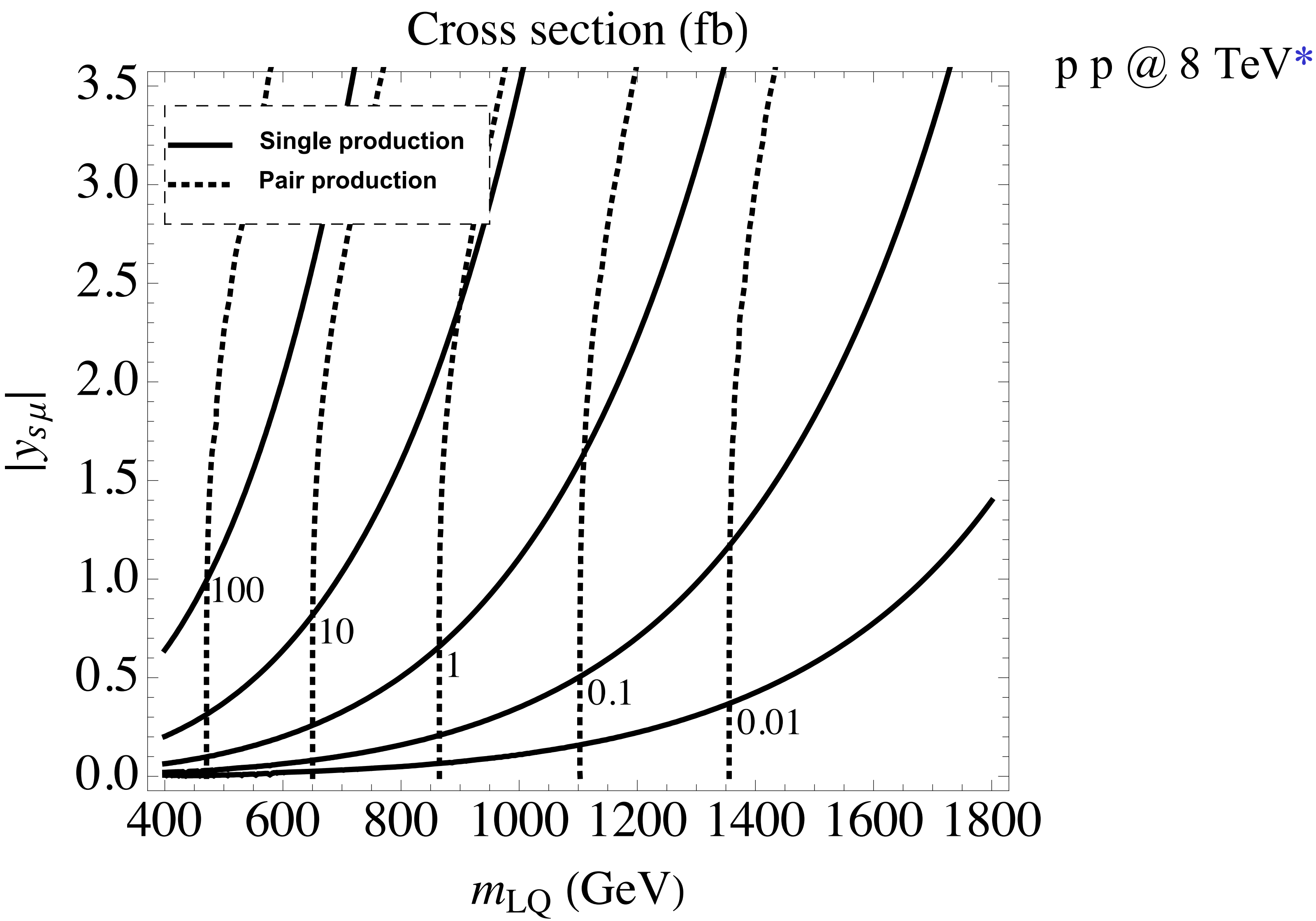
$m_{\rm LQ}$ (TeV)	$\sigma_s^{\rm single}$ (pb)	$\sigma_c^{\rm single}$ (pb)	$\sigma_b^{\rm single}$ (pb)
0.2	$33.1^{+7.4\%+8.3\%}_{-6.6\%-8.3\%}$	$23.2^{+8.3\%+3.1\%}_{-7.8\%-3.1\%}$	$14.7^{+9.4\%+4.2\%}_{-9.9\%-4.2\%}$
0.4	$1.57^{+6.3\%+9.7\%}_{-6.1\%-9.7\%}$	$1.04^{+6.2\%+4.4\%}_{-5.2\%-4.4\%}$	$0.653^{+7.2\%+5.2\%}_{-6.6\%-5.2\%}$
0.6	$0.216^{+6.8\%+11.2\%}_{-6.8\%-11.2\%}$	$0.135^{+5.9\%+5.6\%}_{-5.9\%-5.6\%}$	$0.085^{+6.2\%+6.2\%}_{-5.1\%-6.2\%}$
0.8	$0.0471^{+7.1\%+13.0\%}_{-7.3\%-13.0\%}$	$0.028^{+6.2\%+7.0\%}_{-6.4\%-7.0\%}$	$0.0175^{+5.2\%+7.2\%}_{-4.7\%-7.2\%}$
1.0	$0.0134^{+7.5\%+15.1\%}_{-7.7\%-15.1\%}$	$0.00757^{+6.7\%+8.4\%}_{-6.9\%-8.4\%}$	$0.00469^{+4.9\%+8.5\%}_{-5.1\%-8.5\%}$
1.2	$0.00442^{+7.8\%+17.7\%}_{-8.1\%-17.7\%}$	$0.00244^{+6.9\%+9.9\%}_{-7.2\%-9.9\%}$	$0.00149^{+5.0\%+9.7\%}_{-5.5\%-9.7\%}$
1.4	$0.00165^{+8.1\%+20.6\%}_{-8.4\%-20.6\%}$	$0.000868^{+7.2\%+11.6\%}_{-7.5\%-11.6\%}$	$0.000535^{+5.3\%+11.0\%}_{-5.9\%-11.0\%}$
1.6	$0.000676^{+8.4\%+24.4\%}_{-8.7\%-24.4\%}$	$0.000344^{+7.5\%+13.2\%}_{-7.9\%-13.2\%}$	$0.000211^{+5.5\%+12.6\%}_{-6.2\%-12.6\%}$
1.8	$0.000294^{+8.8\%+28.5\%}_{-9.1\%-28.5\%}$	$0.000144^{+7.7\%+15.0\%}_{-8.2\%-15.0\%}$	$0.0000884^{+5.8\%+14.2\%}_{-6.5\%-14.2\%}$
2.0	$0.000135^{+9.1\%+33.2\%}_{-9.4\%-33.2\%}$	$0.000064^{+7.7\%+16.8\%}_{-8.3\%-16.8\%}$	$0.0000388^{+6.0\%+15.8\%}_{-6.8\%-15.8\%}$
2.2	$0.0000653^{+9.3\%+38.5\%}_{-9.6\%-38.5\%}$	$0.0000293^{+8.3\%+18.9\%}_{-8.7\%-18.9\%}$	$0.0000179^{+6.4\%+17.6\%}_{-7.1\%-17.6\%}$
2.4	$0.0000327^{+9.4\%+44.1\%}_{-9.7\%-44.1\%}$	$0.000014^{+8.4\%+21.2\%}_{-8.9\%-21.2\%}$	$(8.38\times10^{-6})^{+6.7\%+19.7\%}_{-7.5\%-19.7\%}$
2.6	$0.0000167^{+9.7\%+50.6\%}_{-10.0\%-50.6\%}$	$(6.93\times10^{-6})^{+8.7\%+23.4\%}_{-9.2\%-23.4\%}$	$(4.13\times10^{-6})^{+7.1\%+21.8\%}_{-7.8\%-21.8\%}$
2.8	$(8.82\times10^{-6})^{+10.0\%+57.0\%}_{-10.2\%-57.0\%}$	$(3.47\times10^{-6})^{+9.1\%+25.9\%}_{-9.6\%-25.9\%}$	$(2.06\times10^{-6})^{+7.1\%+23.8\%}_{-7.9\%-23.8\%}$
3.0	$(4.79\times10^{-6})^{+10.3\%+63.8\%}_{-10.5\%-63.8\%}$	$(1.78\times10^{-6})^{+9.3\%+28.4\%}_{-9.8\%-28.4\%}$	$(1.05\times10^{-6})^{+7.5\%+26.4\%}_{-8.3\%-26.4\%}$

$y_{q\ell} = 1$

PHYSICS RESULTS

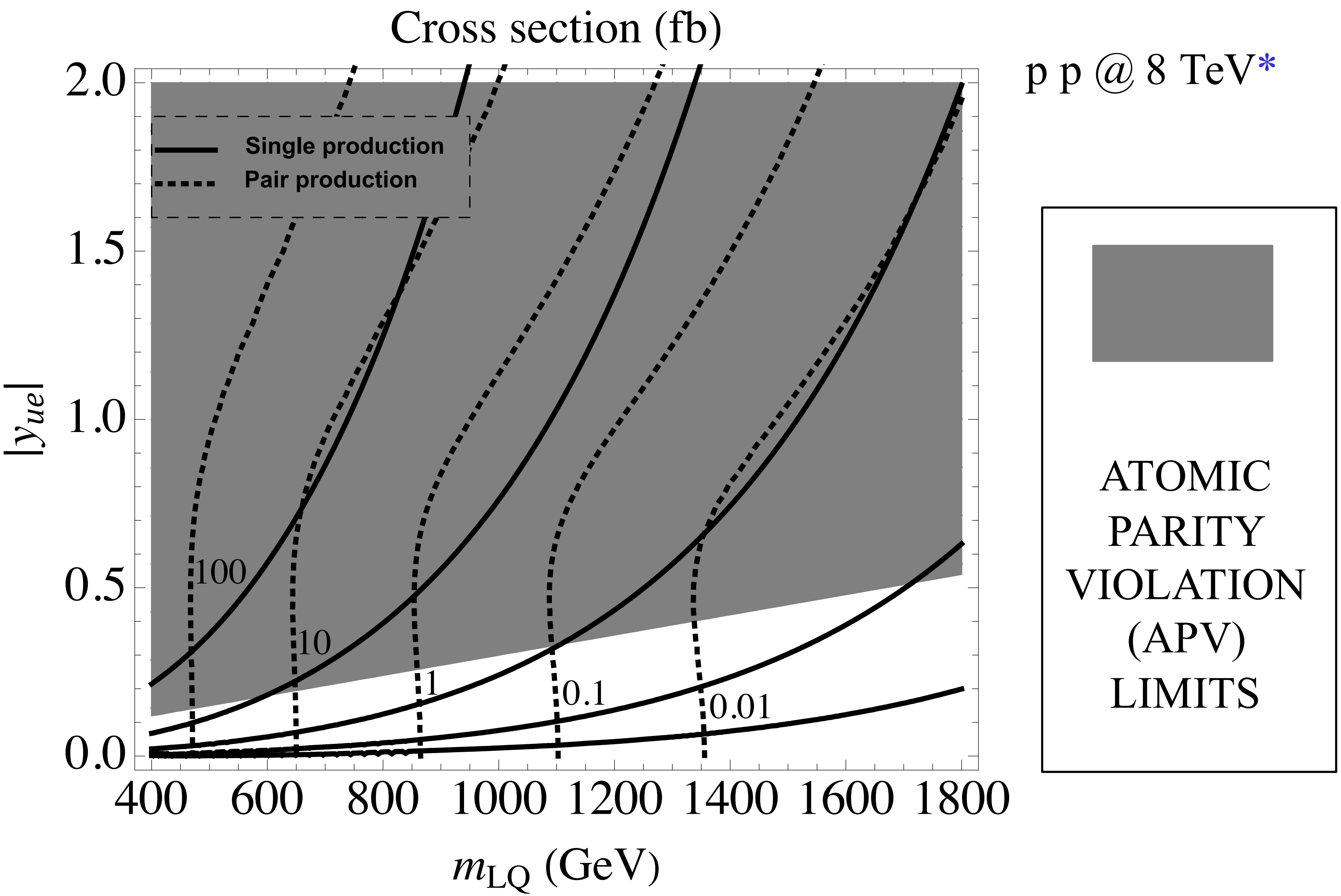


PHYSICS RESULTS



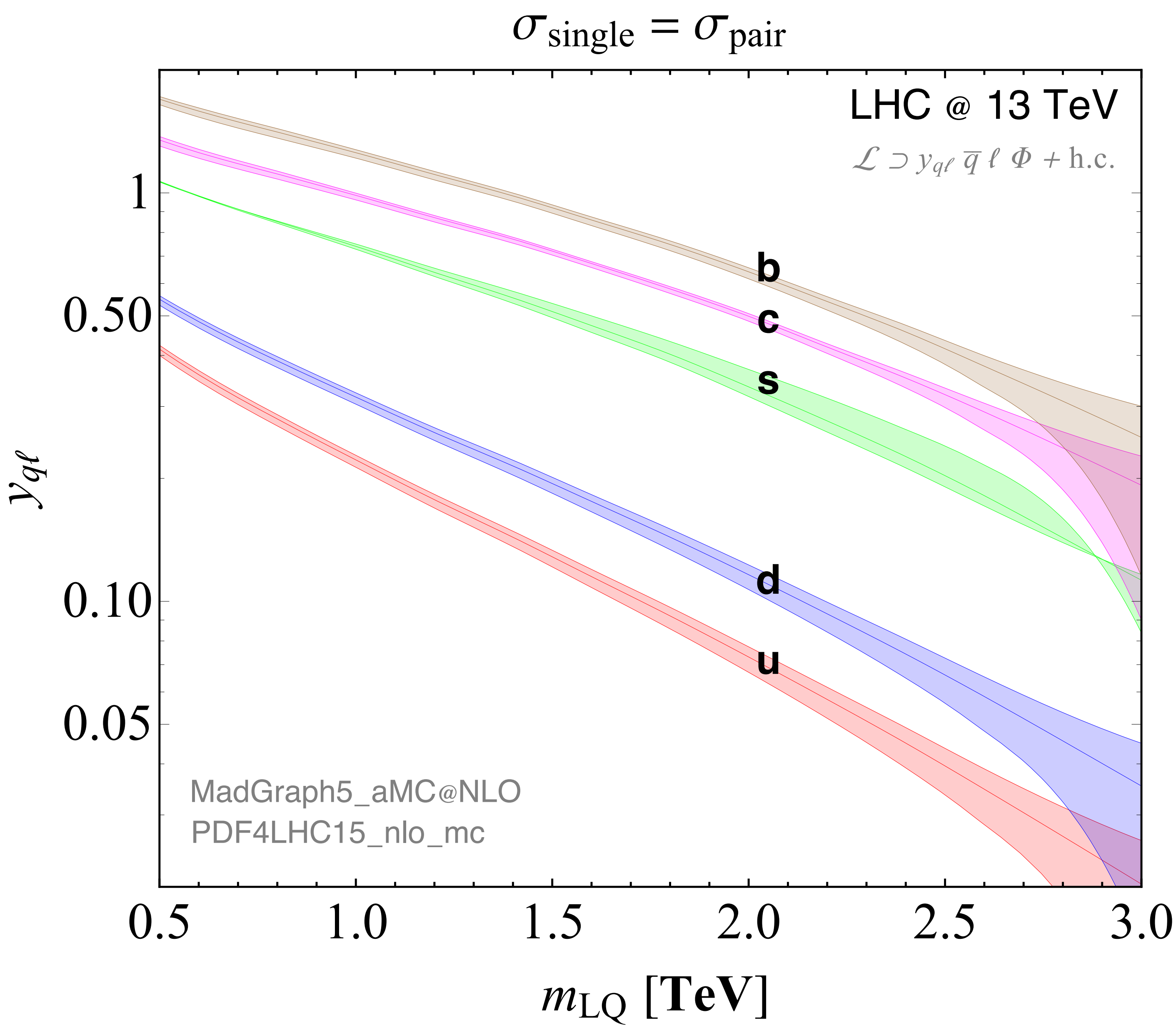
*I. D., S. Fajfer, and A. Greljo, arXiv:1406.4831.

PHYSICS RESULTS



*I. D., S. Fajfer, and A. Greljo, arXiv:1406.4831.

PHYSICS RESULTS



PHYSICS RESULTS

(VECTOR LEPTOQUARK)

$$\mathcal{L}_{\text{kinetic}}^{U_1} = -\frac{1}{2} U_{\mu\nu}^{\dagger} U_{\mu\nu} - i g_s \kappa \, U_{1\mu}^{\dagger} T^a U_{1\nu} G_{\mu\nu}^a + m_{U_1}^2 U_{1\mu}^{\dagger} U_{1\mu}$$

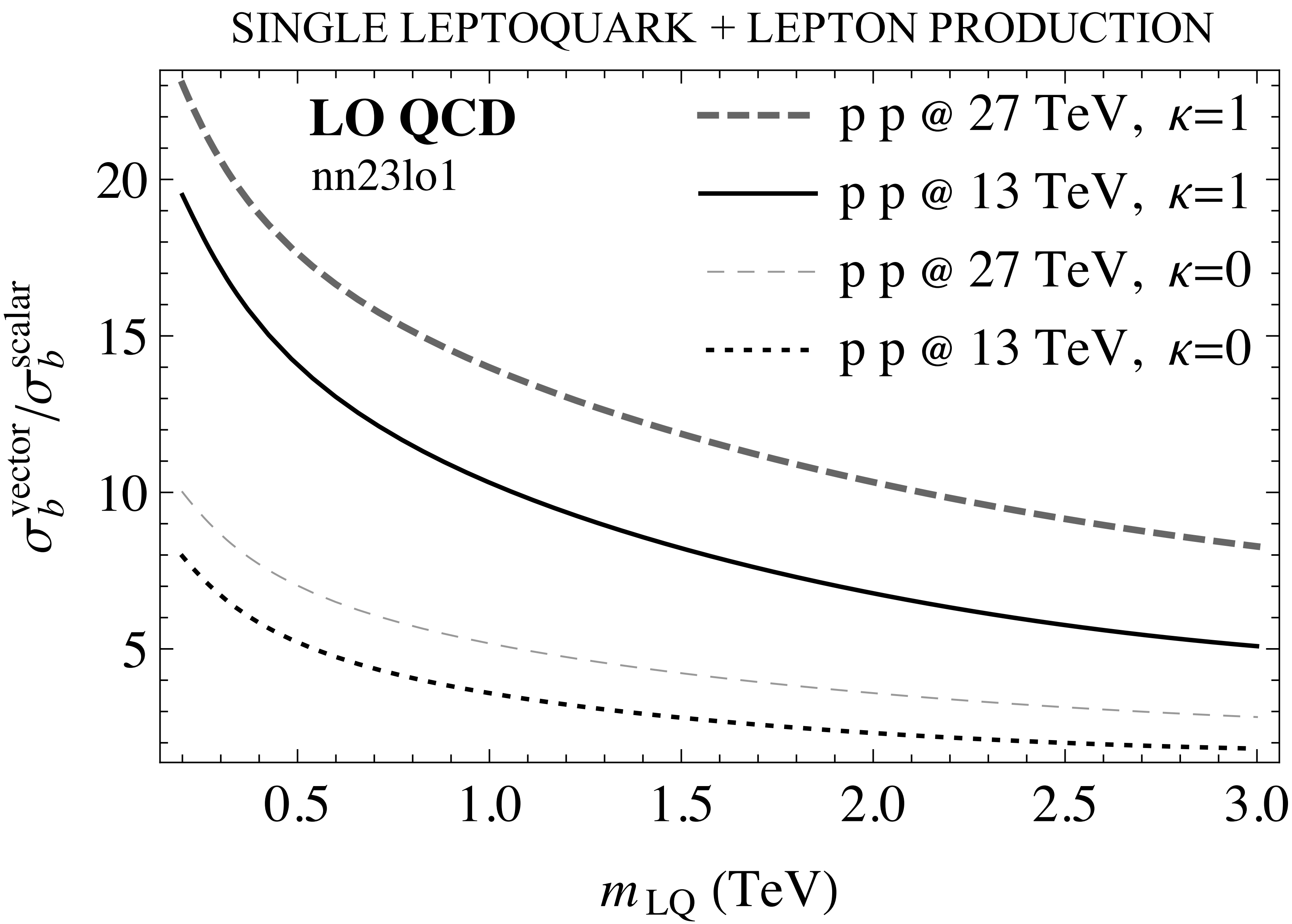
```
L4:= gbL vlq[mu,i] bbar[ss0,i].ta[ss2]
Ga[mu,ss0,ss1] ProjM[ss1,ss2] + gtL vlq[mu,i]
tbar[ss0,i].vt[ss2] Ga[mu,ss0,ss1] ProjM[ss1,ss2]
```

PHYSICS RESULTS
(VECTOR LEPTOQUARK)

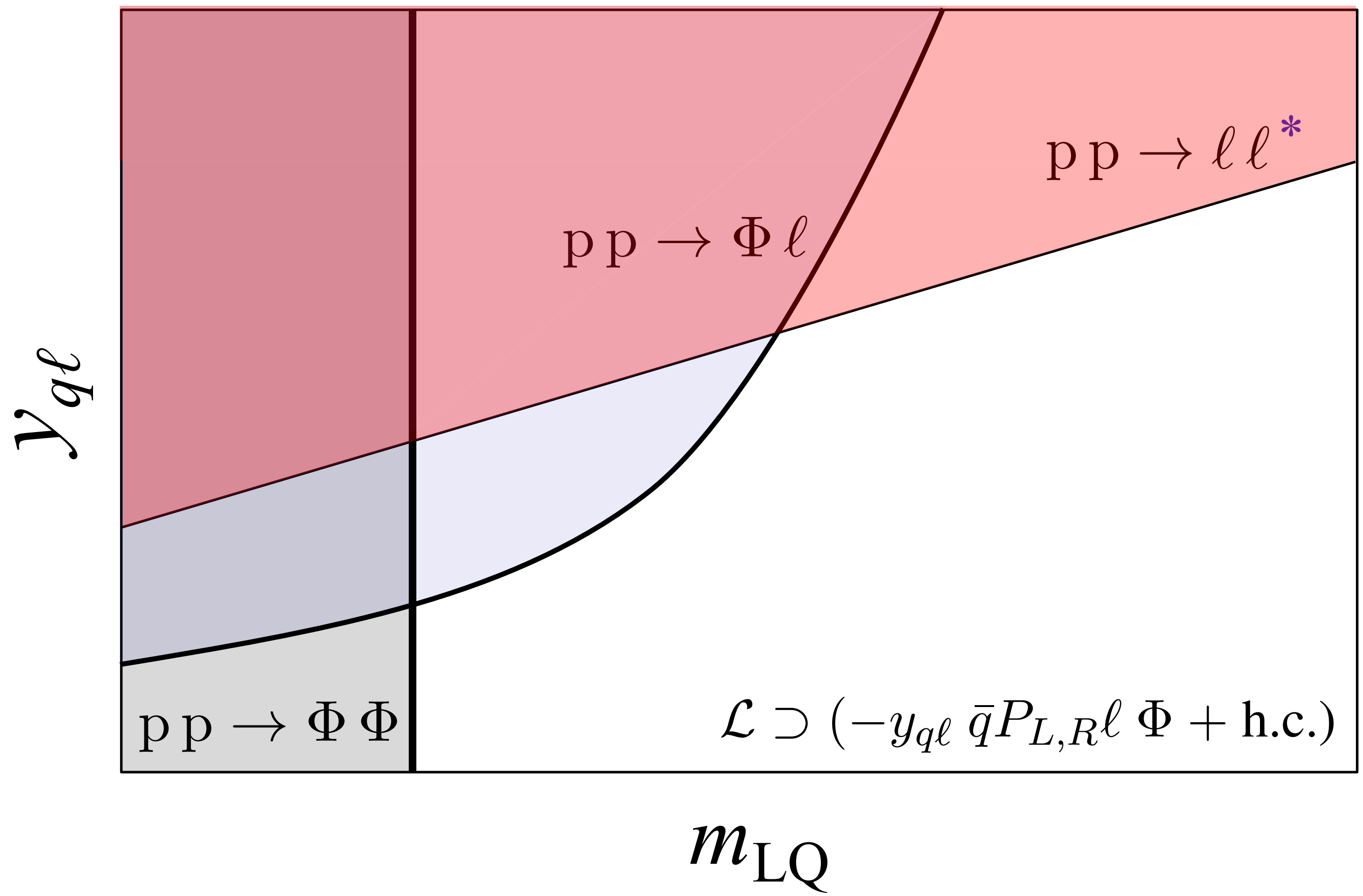
$$\mathcal{L}^{U_1}_{\text{kinetic}} = -\frac{1}{2} U^{\dagger}_{\mu\nu} U_{\mu\nu} - i g_s \kappa \, U^{\dagger}_{1\mu} T^a U_{1\nu} G^a_{\mu\nu} + m^2_{U_1} U^{\dagger}_{1\mu} U_{1\mu}$$

```
L4:= gbL vlq[mu,i] bbar[ss0,i].ta[ss2]
Ga[mu,ss0,ss1] ProjM[ss1,ss2] + gtL vlq[mu,i]
tbar[ss0,i].vt[ss2] Ga[mu,ss0,ss1] ProjM[ss1,ss2]
```

PHYSICS RESULTS
(VECTOR VS. SCALAR LEPTOQUARK)

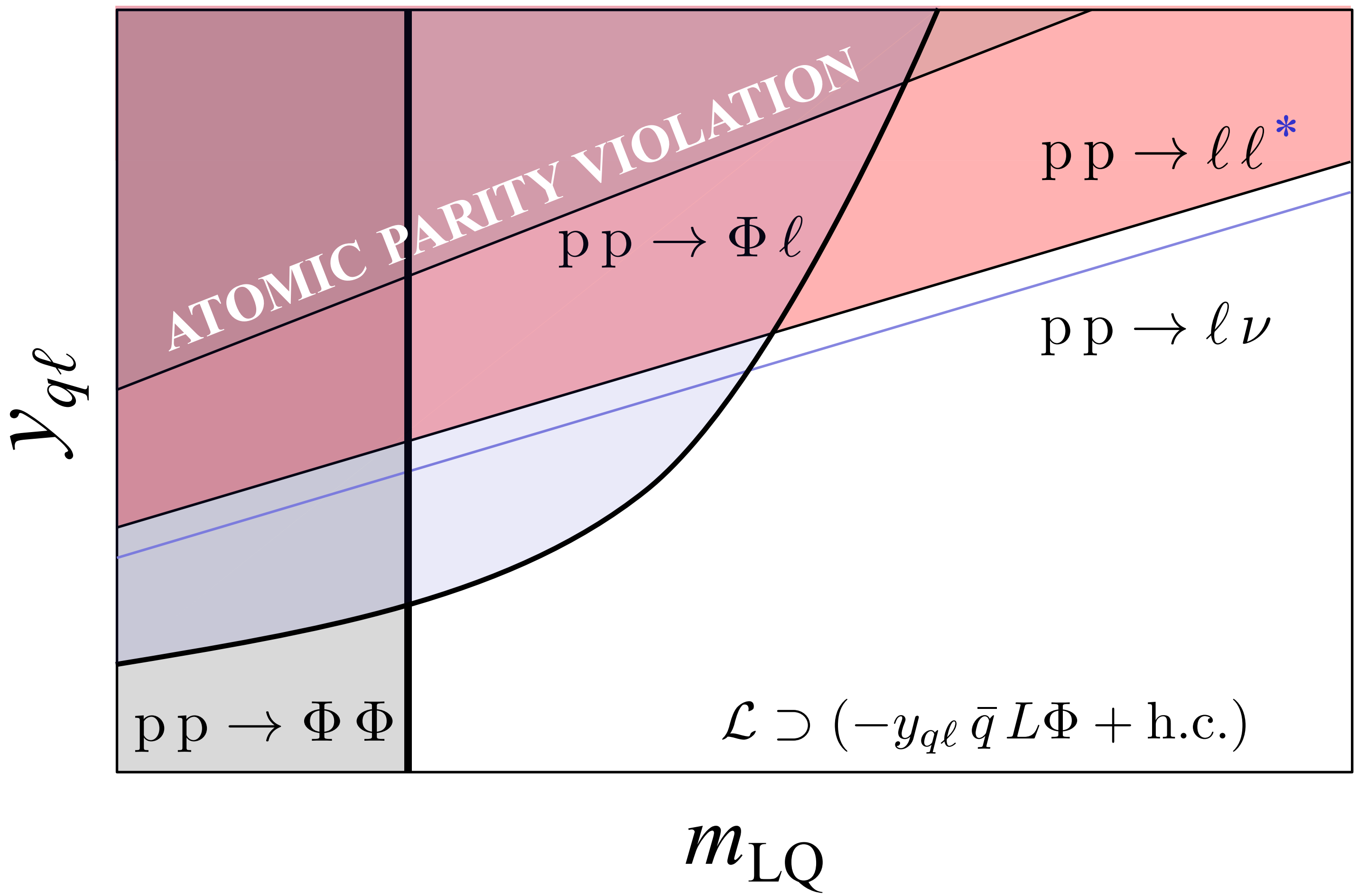


OUTLOOK



*D. A. Faroughy, A. Greljo, and J. F. Kamenik, arXiv:1609.07138.
A. Greljo and D. Marzocca, arXiv:1704.09015.

OUTLOOK



*S. Bansal *et al.*, arXiv:1806.02370.

CONCLUSIONS

We address the need for an up-to-date Monte Carlo event generator output that can be used for the current and future experimental searches and search recasts concerning scalar and vector leptoquarks.

Pair production of the leptoquarks can be taken to be purely QCD driven.

Single leptoquark + lepton production cross section scales with the square of the relevant Yukawa coupling. It further depends on the quark flavor and the leptoquark mass.

Universal Feynrules Output (UFO) model file directories to be used with MADGRAPH5_AMC@NLO for the LO and NLO simulations can be found at LQ_NLO @ HepForge.

THANK YOU

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