# Searching for Leptoquarks at Future Muon Colliders

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# The Future of Colliders

*How and where do we look for new physics?*

- LHC has enormous discovery potential
- Precision experiments

(1902.04222 CC w/ Y. Soreq, M. Strassler, J. Thaler, W. Xue)
(1810.07736 CC w/ Q. Lu, A. Parikh, Y. Nakai, M. Reece)

Expand energy frontier into $O(10)$ TeV

Construction of new colliders

# Muon Colliders (MuC)

Complementary probe into SM and BSM processes

LHC

MuC

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Complementary probe into SM and BSM processes

| LHC | MuC |
| --- | --- |
| $\sqrt{\hat{s}} \ll \sqrt{s}$ | $\sqrt{\hat{s}} \simeq \sqrt{s}$ |

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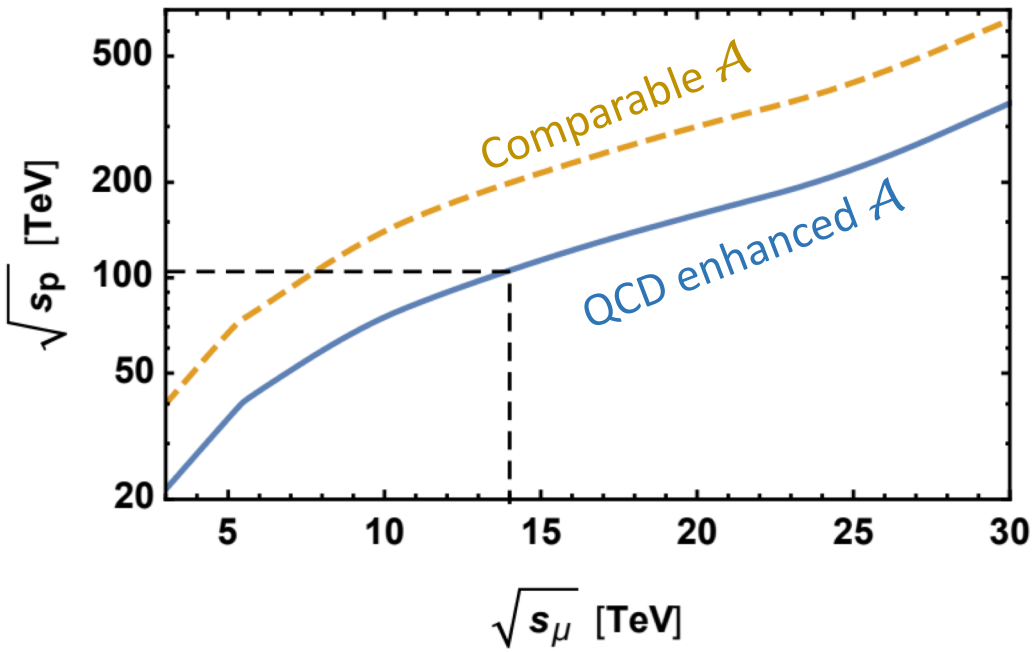

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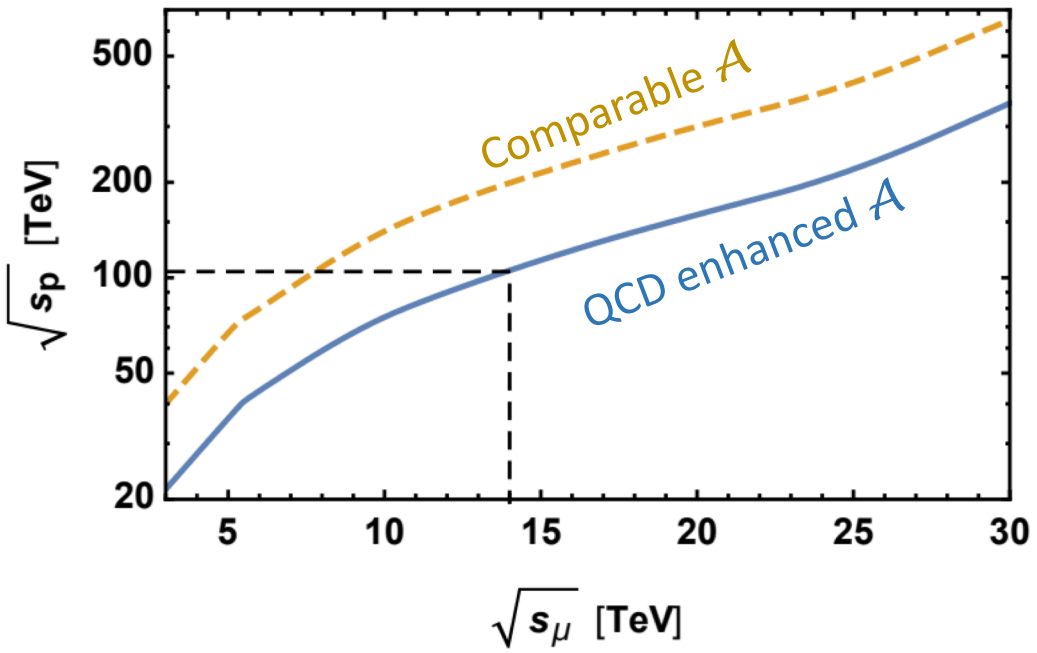

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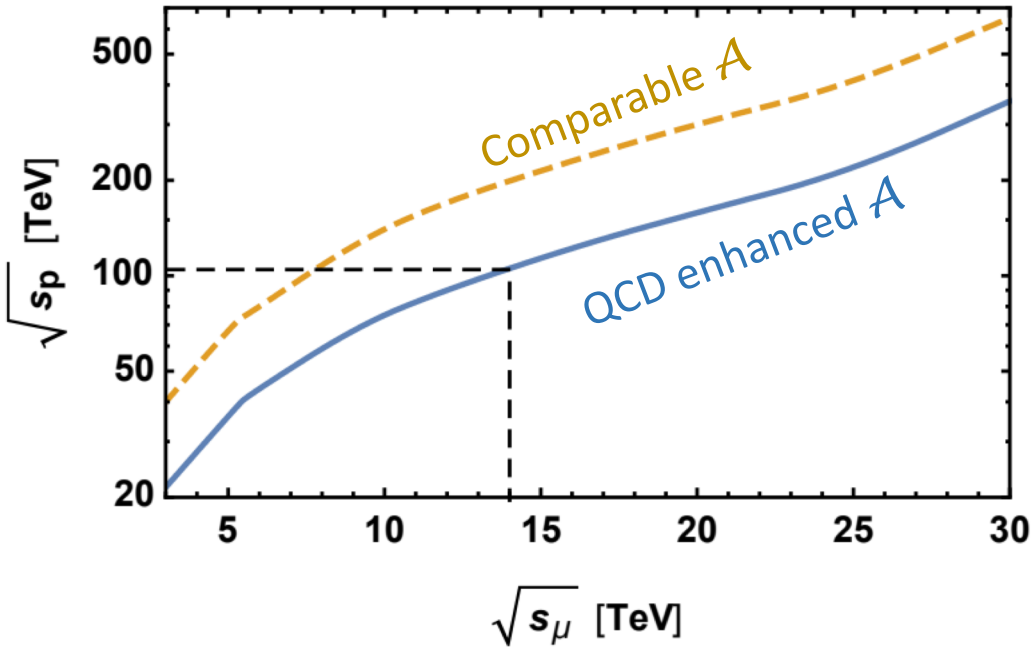

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Complementary probe into SM and BSM processes

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| | Second gen. couplings | First gen. couplings |

# Muon Colliders (MuC)

Future multi-TeV MuC provide a complementary and robust physics program

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Future multi-TeV MuC provide a complementary and robust physics program

The focus of this talk is a new physics scenario: vector leptoquarks

# Leptoquarks

$U_1 = (3, 1)_{2/3}$

Leptoquarks are motivated

- Emerges in Pati-Salam spectrum from GUT
- Address various flavor anomalies
- MuC explores complementary parameter space

# Leptoquarks

$U_1 = (3,1)_{2/3}$

Minimal $U_1$ Leptoquark EFT:

$$\mathcal{L}_{U_1} = -\frac{1}{2} {U_1}^{\dagger}_{\mu\nu} U_1^{\mu\nu} + m^2_{U_1} {U_1}^{\dagger}_{\mu} U_1^{\mu} - i g_s {U_1}^{\dagger}_{\mu} T^a U_{1\nu} G^{a\mu\nu}$$
$$- i g_Y \frac{2}{3} {U_1}^{\dagger}_{\mu} U_{1\nu} B^{\mu\nu} + \frac{g_U}{\sqrt{2}} U_1^{\mu} \left( \beta_L^{ij} \bar{Q}^i_L \gamma_\mu L^j_L + \text{ h.c.} \right)$$

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Production from $\mu^+ \mu^-$ collisions

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- Only include left-handed couplings
- Assuming $U_1$ is fundamental
- Additional $\beta^{ij}$ structure ansatz

# Leptoquarks

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$$\beta_R^{ij} = 0 \qquad \beta_L^{ij} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \beta_L^{22} & \beta_L^{23} \\ 0 & \beta_L^{32} & \beta_L^{33} \end{pmatrix}$$

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First gen. couplings constrained by low energy experiments

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First gen. couplings constrained by low energy experiments

Direct production

# Leptoquarks

$U_1 = (3,1)_{2/3}$

## Free Parameters of the Model

$$\beta_L^{ij} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \beta_L^{22} & \beta_L^{23} \\ 0 & \beta_L^{32} & \beta_L^{33} \end{pmatrix}$$

$$\sqrt{s} = 3,\ 14\ \text{TeV}$$

$$m_{\text{LQ}} \in (1, 50)\ \text{TeV}$$

| Scenarios | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| $(\beta_L^{22},\ \beta_L^{23},\ \beta_L^{33}) =$ | $(0,\ 0,\ 0)$ | $(\beta_L^{32},\ 0,\ 0)$ | $(0,\ 0.1,\ 1)$ | $(\beta_L^{32},\ 0.1,\ 1)$ |

Final state of $U_1$ decays

# Leptoquarks

$U_1 = (3, 1)_{2/3}$

| Observable | Experimental Bounds | Relevant Couplings |
|---|---|---|
| $R_{K^{(*)}}$ | $R_K = 0.846^{+0.044}_{-0.041}$ <br> $R_{K^*} = 0.685^{+0.113}_{-0.069} \pm 0.047$ [131, 132] | $\beta_L^{32} \times \beta_L^{22}$ |
| $\mathrm{BR}\,(B_s \to \mu\mu)$ | $3.09^{+0.48}_{-0.44} \times 10^{-9}$ [133–136] | $\beta_L^{32} \times \beta_L^{22}$ |
| $R_{D^{(*)}}$ | $R_D = 0.340 \pm 0.030$ <br> $R_{D^*} = 0.295 \pm 0.014$ [137] | $\beta_L^{33} \times \beta_L^{23}$ |
| $R_D^{\mu/e}$ | $0.995 \pm 0.022 \pm 0.039$ [138] | $\beta_L^{32} \times \beta_L^{22}$ |
| $\mathrm{BR}\,(\tau \to \mu\gamma)$ | $< 4.4 \times 10^{-8}$ [139] | $\beta_L^{33} \times \beta_L^{32}$ |
| $\mathrm{BR}\,(\tau \to \mu\phi)$ | $< 8.4 \times 10^{-8}$ | $\beta_L^{23} \times \beta_L^{22}$ |
| $\mathrm{BR}\,(D_s \to \mu\nu)$ | $< 5.49 \times 10^{-3}$ | $\beta_L^{22} \times \beta_L^{22}$ |
| $\mathrm{BR}\,(D_s \to \tau\nu)$ | $< 5.48 \times 10^{-2}$ | $\beta_L^{23} \times \beta_L^{23}$ |
| $\mathrm{BR}\,(B \to K\tau\mu)$ | $< 2.8 \times 10^{-5}$ | $\beta_L^{32} \times \beta_L^{23}$ \| $\beta_L^{33} \times \beta_L^{22}$ |
| $\mathrm{BR}\,(B_s \to \tau\mu)$ | $< 4.2 \times 10^{-5}$ | $\beta_L^{32} \times \beta_L^{23}$ \| $\beta_L^{33} \times \beta_L^{22}$ |
| $\mathrm{BR}\,(B_s \to \tau\tau)$ | $< 2.1 \times 10^{-3}$ | $\beta_L^{33} \times \beta_L^{23}$ |

Low energy flavor observables

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$$U_1 = (3,1)_{2/3}$$

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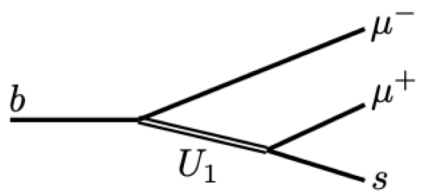
Low energy flavor observables

## $R_K$ anomaly:

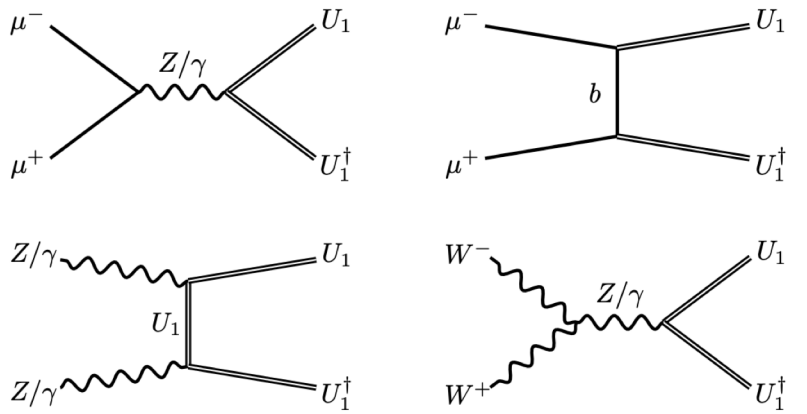



$$\frac{\beta_L^{22}\beta_L^{32}}{m_{\mathrm{LQ}}^2} = 1.98 \times 10^{-3}\ \mathrm{TeV}^{-2}$$

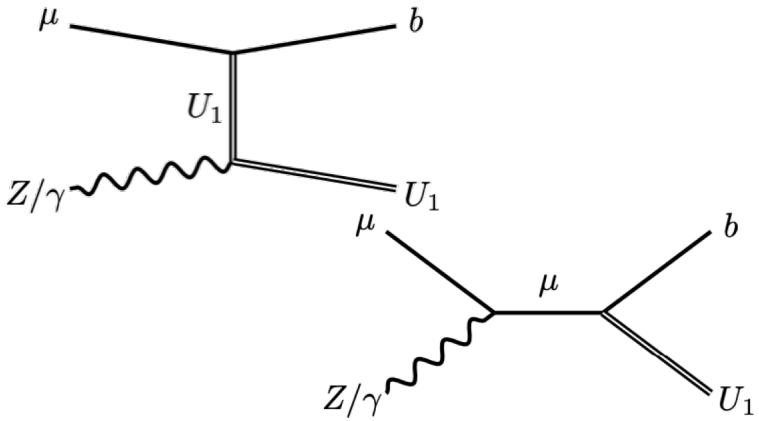
# Leptoquarks

$U_1 = (3, 1)_{2/3}$

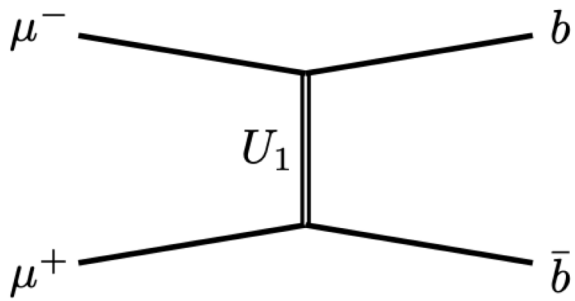
## Production Modes




Pair Production




Single Production




Drell-Yan†

Simulated with MG5

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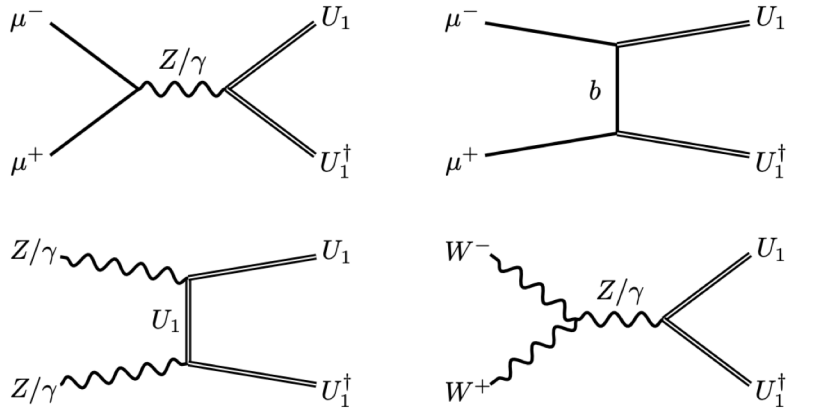


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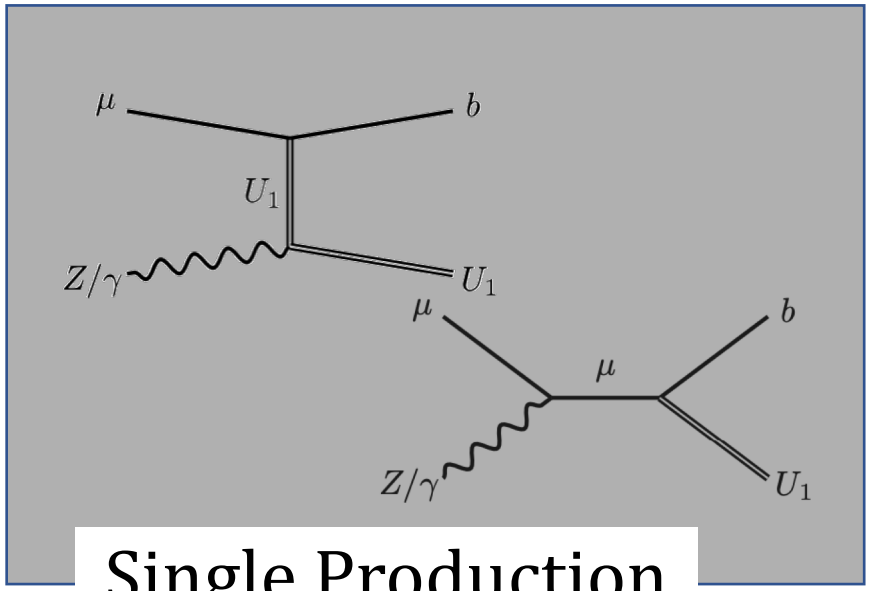


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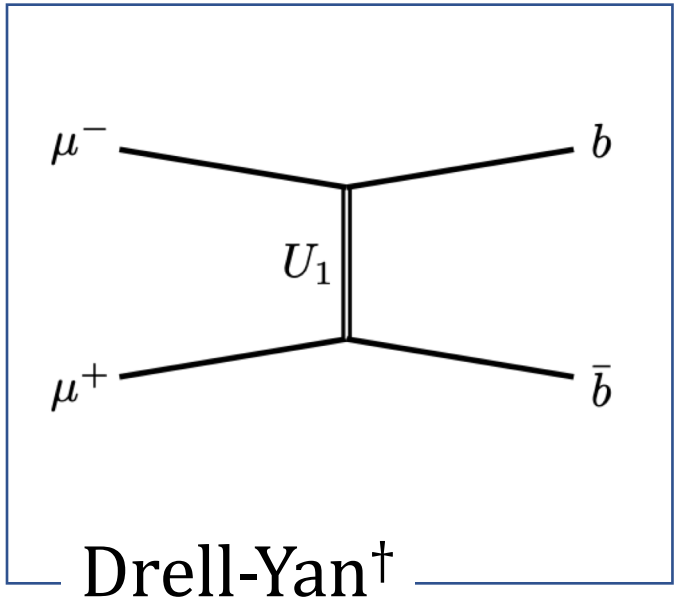


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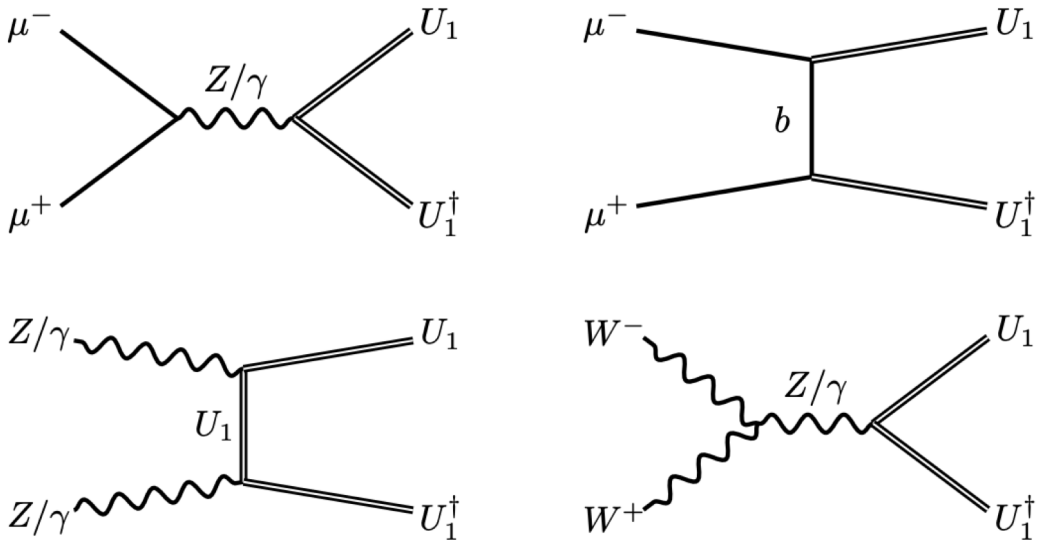
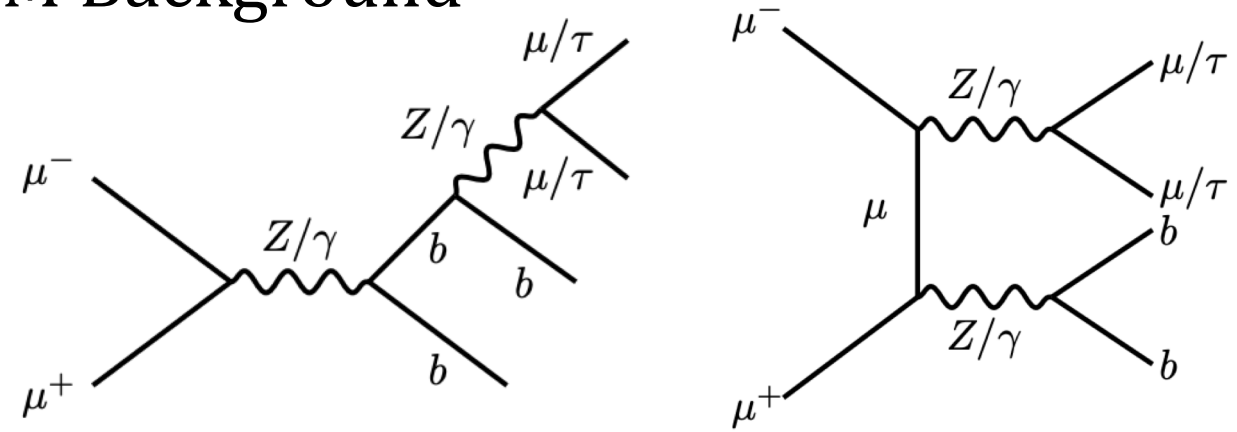



$$U_1 \to \begin{cases} b\mu^+ \\ b\tau^+ \end{cases}$$

SM Background



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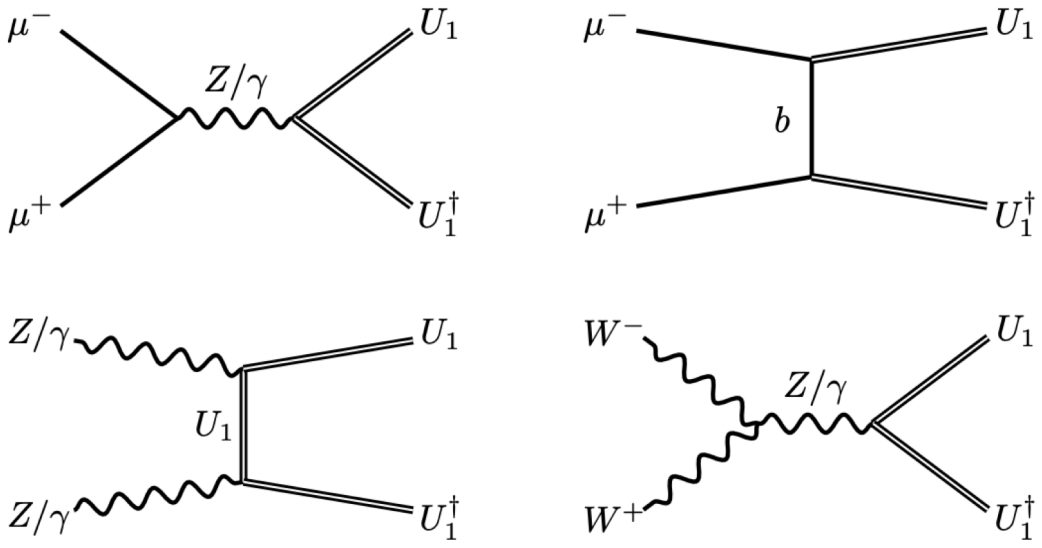


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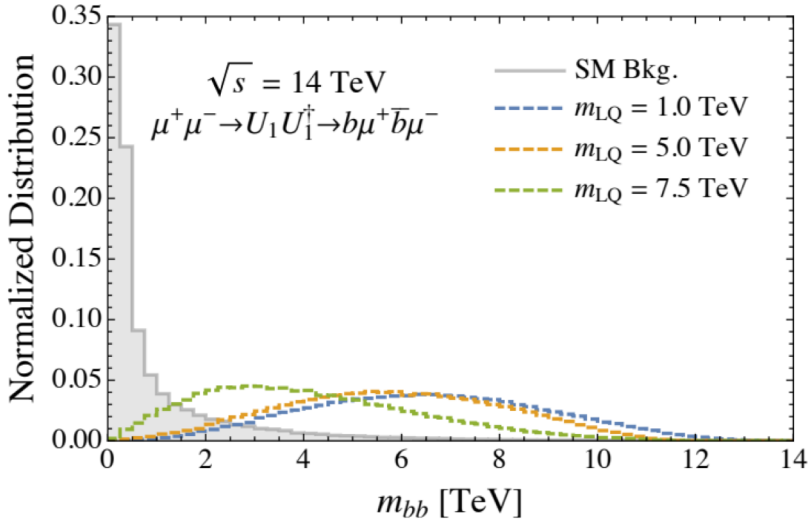
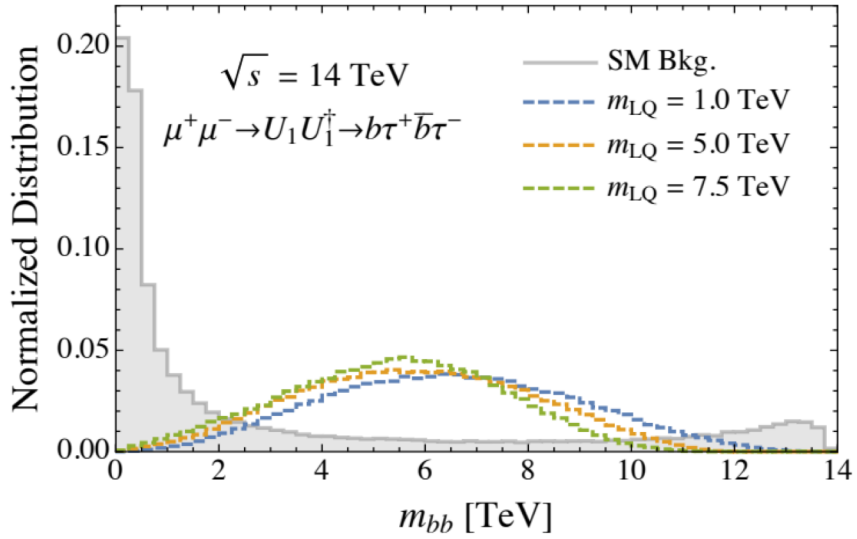



Mitigated by $m_{bb}$ cut



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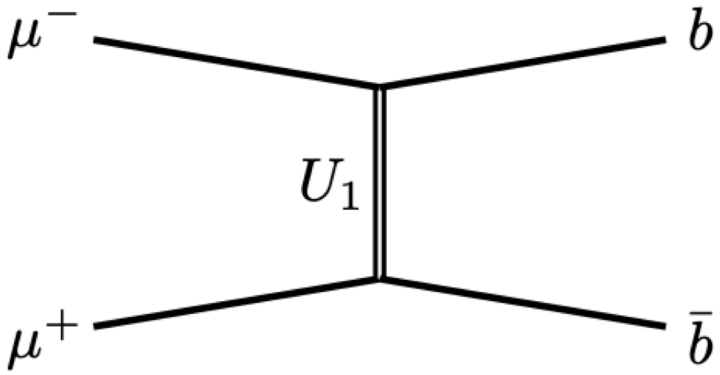
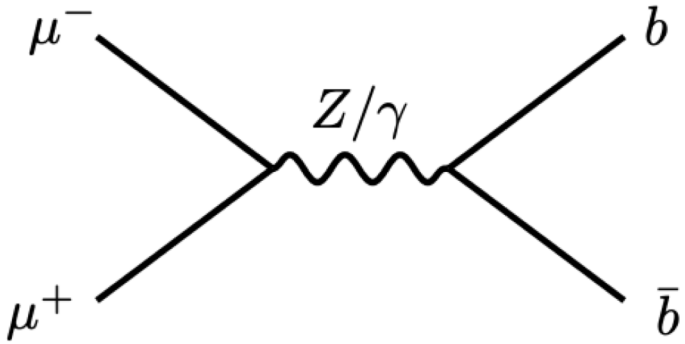
$U_1 = (3, 1)_{2/3}$

## Drell-Yan




SM Background



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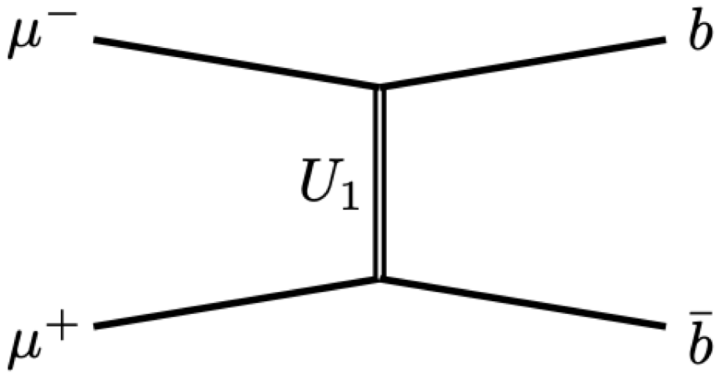
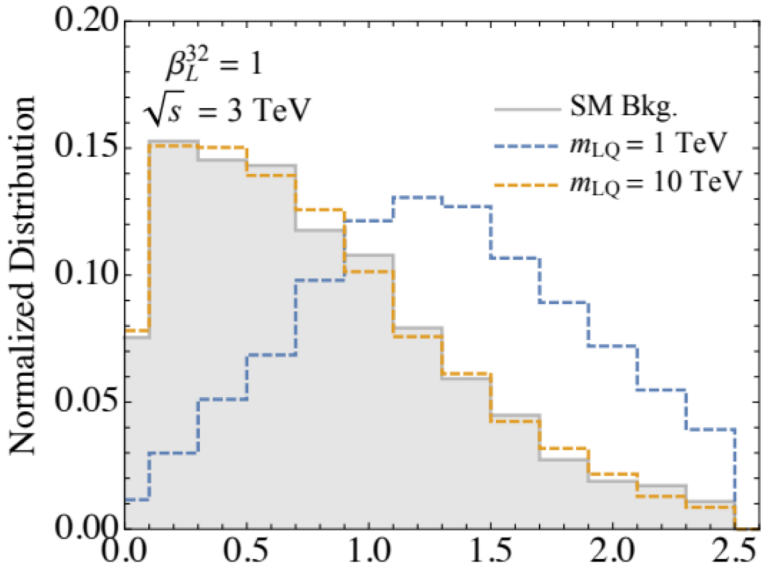
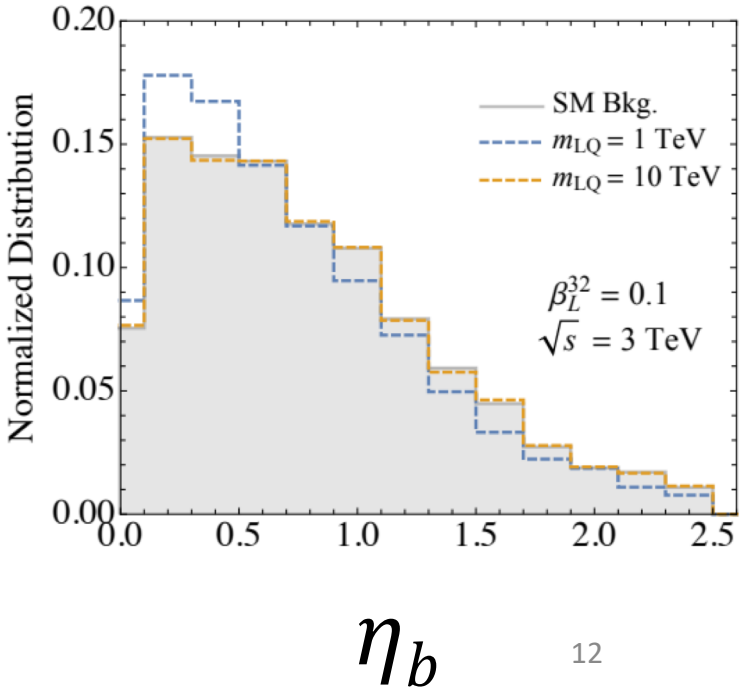


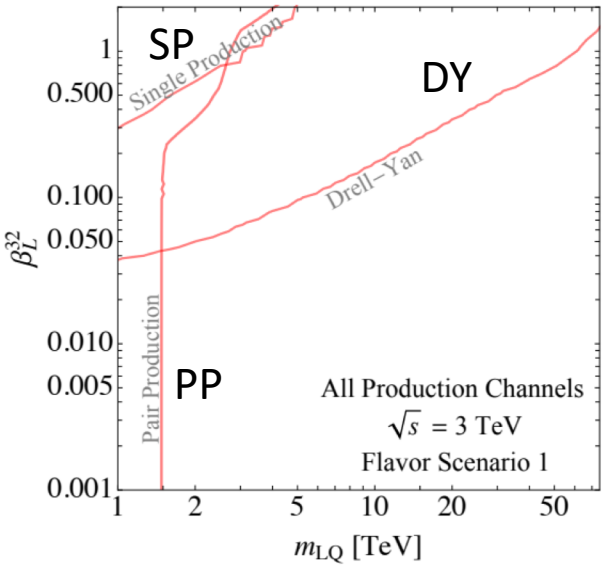

Bin in $\eta$

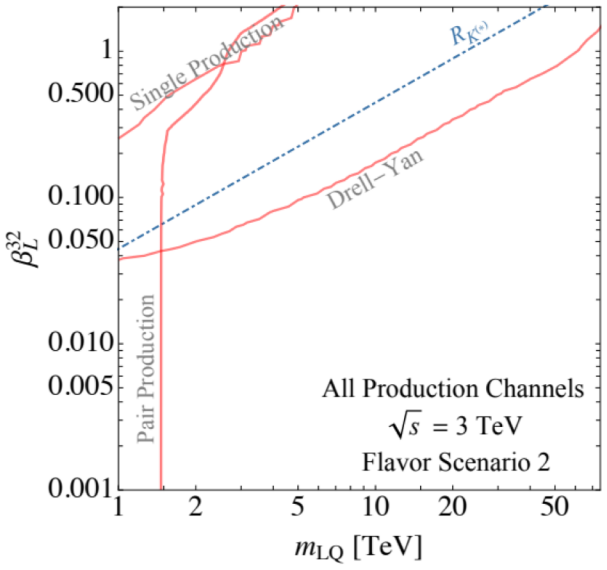


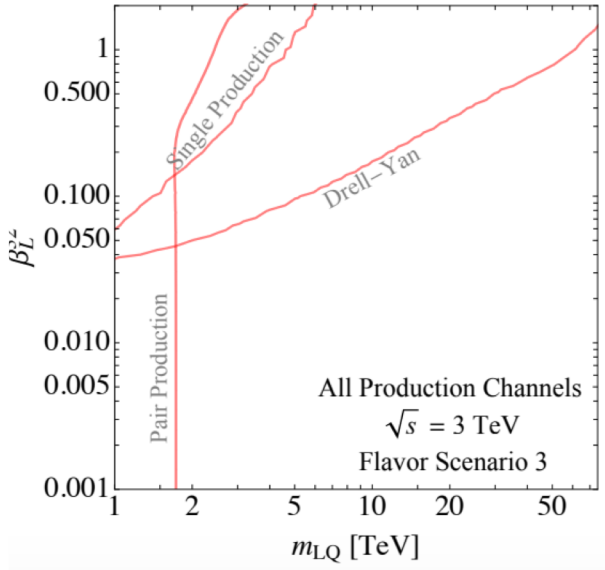
# Leptoquarks

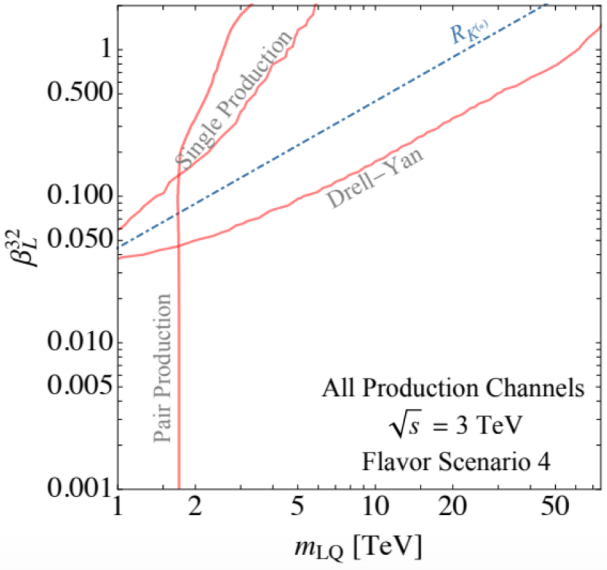
$U_1 = (3,1)_{2/3}$

$$\sqrt{s} = 3 \text{ TeV}, \; L = 1 \text{ ab}^{-1}$$



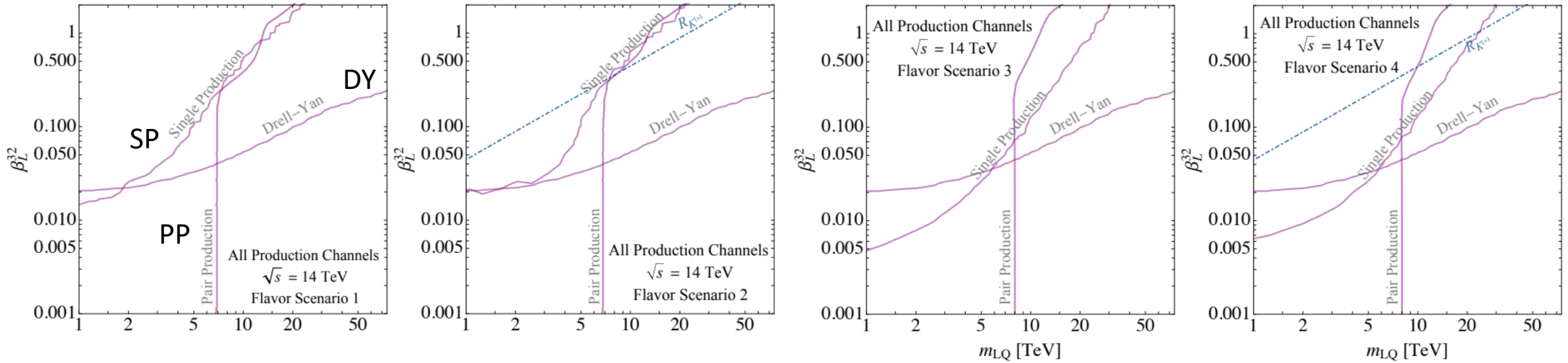




| Scenarios | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| $(\beta_L^{22},\ \beta_L^{23},\ \beta_L^{33}) =$ | $(0,\ 0,\ 0)$ | $(\beta_L^{32},\ 0,\ 0)$ | $(0,\ 0.1,\ 1)$ | $(\beta_L^{32},\ 0.1,\ 1)$ |

# Leptoquarks

$U_1 = (3, 1)_{2/3}$

$$\sqrt{s} = 14 \text{ TeV}, \; L = 20 \text{ ab}^{-1}$$

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# Conclusions

Future MuC can probe complementary parameter space to LHC

Leptoquarks are a motivated model to consider

Parameter space of leptoquark models that resolve current anomalies within reach!