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

$$\sqrt{\hat{s}} \ll \sqrt{s}$$

MuC

$$\sqrt{\hat{s}} \simeq \sqrt{s}$$

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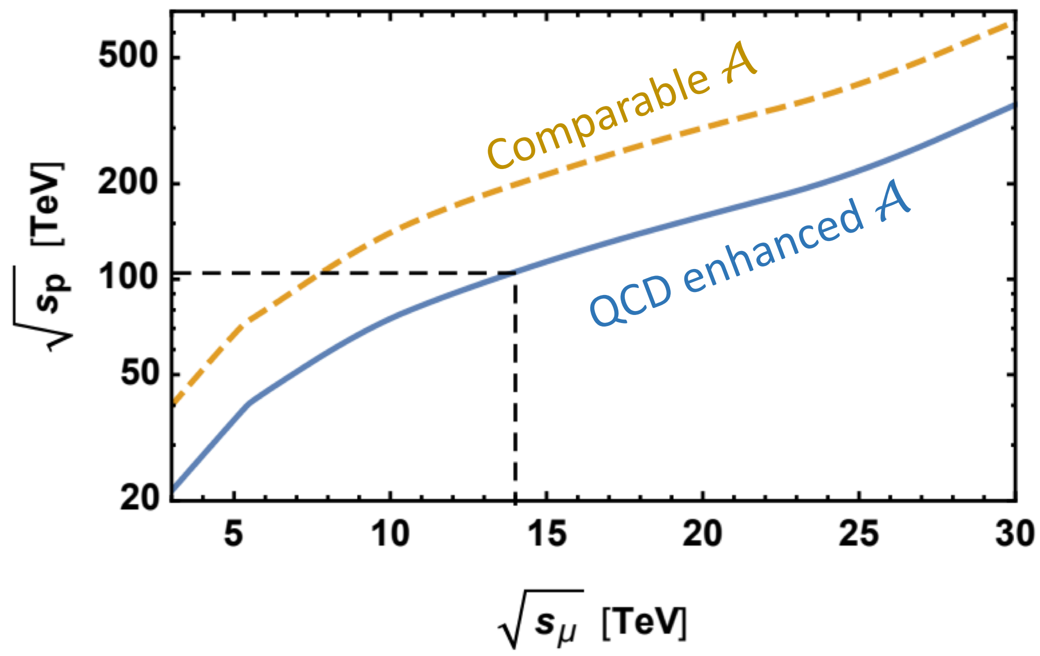
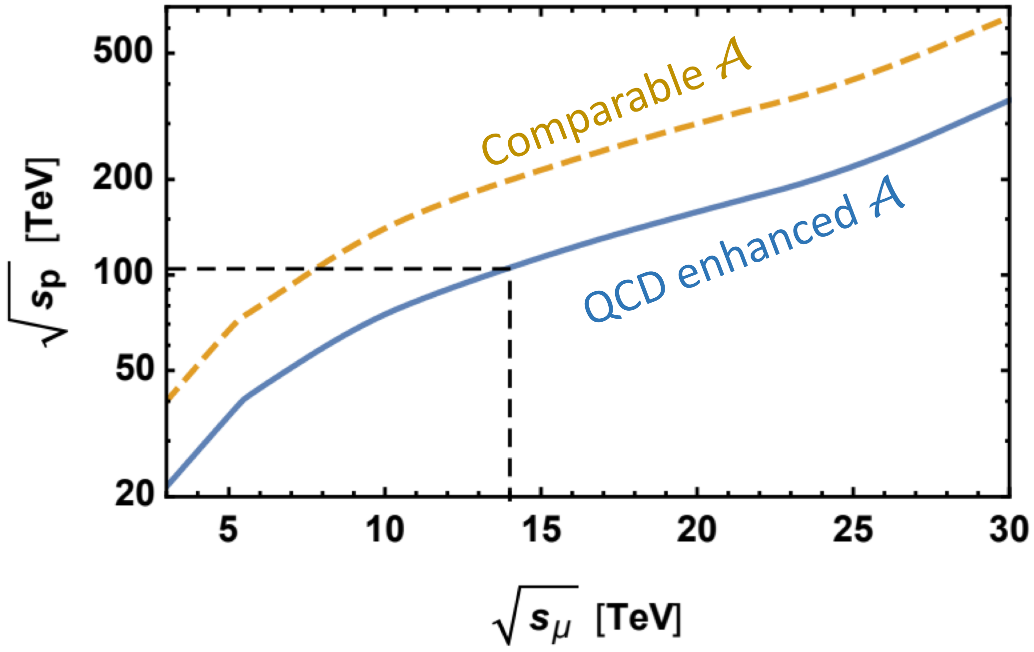


Muon Colliders (MuC)

Complementary probe into SM and BSM processes

1901.06150

LHC	MuC
$\sqrt{\hat{s}} \ll \sqrt{s}$	$\sqrt{\hat{s}} \simeq \sqrt{s}$
Color production	Electroweak production



Muon Colliders (MuC)

Complementary probe into SM and BSM processes

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Color production	Electroweak production
Hadronized final states	Small QCD Background

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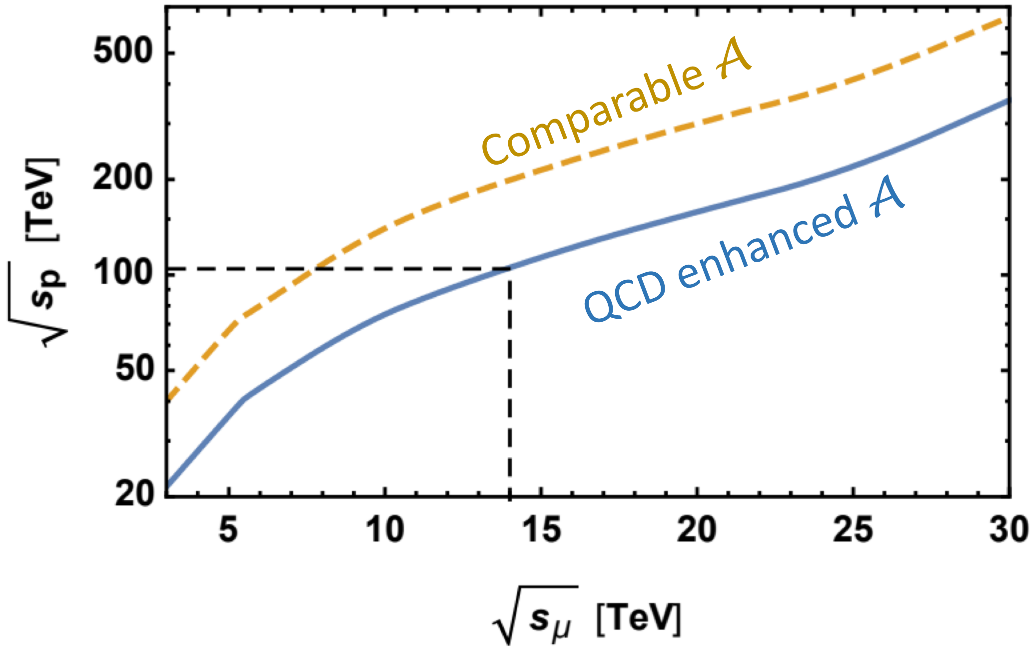

Muon Colliders (MuC)

Complementary probe into SM and BSM processes

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	Less synchrotron radiation	Synchrotron radiation

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Color production	Electroweak production	
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	Less synchrotron radiation	Synchrotron radiation
	Second gen. couplings	First gen. couplings

Muon Colliders (MuC)

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

Muon Colliders (MuC)

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 (1712.01368)
- Address various flavor anomalies
- MuC explores complementary parameter space

Leptoquarks

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

Minimal U_1 Leptoquark EFT:

$$\mathcal{L}_{U_1} = -\frac{1}{2}U_1{}^{\dagger}_{\mu\nu}U_1^{\mu\nu} + m_{U_1}^2 U_1{}^{\dagger}_{\mu}U_1^{\mu} - ig_s U_1{}^{\dagger}_{\mu}T^a U_{1\nu}G^{a\mu\nu}$$
$$-ig_Y\frac{2}{3}U_1{}^{\dagger}_{\mu}U_{1\nu}B^{\mu\nu} + \frac{g_U}{\sqrt{2}}U_1^{\mu}\left(\beta_L^{ij}\bar{Q}_L^i\gamma_\mu L_L^j + \text{ h.c.}\right)$$

Leptoquarks

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

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

Leptoquarks

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

Minimal U_1 Leptoquark EFT:

$$\mathcal{L}_{U_1} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left(\beta_L^{ij} \bar{Q}_L^i \gamma_\mu L_L^j + \text{ h.c.} \right)$$

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

Leptoquarks

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First gen. couplings constrained by low energy experiments

Leptoquarks

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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

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

Low energy flavor observables

Observable	Experimental Bounds	Relevant Couplings	
$R_{K^{(*)}}$	$R_K = 0.846^{+0.044}_{-0.041}$ $R_{K^*} = 0.685^{+0.113}_{-0.069} \pm 0.047$ [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]	$\beta_L^{32} \times \beta_L^{22}$	
$R_{D^{(*)}}$	$R_D = 0.340 \pm 0.030$ $R_{D^*} = 0.295 \pm 0.014$ [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]	$\beta_L^{33} \times \beta_L^{32}$	
$\mathrm{BR}\,(\tau \to \mu\phi)$	$< 8.4 \times 10^{-8}$	$\beta_L^{23} \times \beta_L^{22}$	
$\mathrm{BR}\,(D_s \to \mu\nu)$	$< 5.49 \times 10^{-3}$	$\beta_L^{22} \times \beta_L^{22}$	
$\mathrm{BR}\,(D_s \to \tau\nu)$	$< 5.48 \times 10^{-2}$	$\beta_L^{23} \times \beta_L^{23}$	
$\mathrm{BR}\,(B \to K\tau\mu)$	$< 2.8 \times 10^{-5}$	$\beta_L^{32} \times \beta_L^{23}$	$\beta_L^{33} \times \beta_L^{22}$
$\mathrm{BR}\,(B_s \to \tau\mu)$	$< 4.2 \times 10^{-5}$	$\beta_L^{32} \times \beta_L^{23}$	$\beta_L^{33} \times \beta_L^{22}$
$\mathrm{BR}\,(B_s \to \tau\tau)$	$< 2.1 \times 10^{-3}$	$\beta_L^{33} \times \beta_L^{23}$	

Leptoquarks

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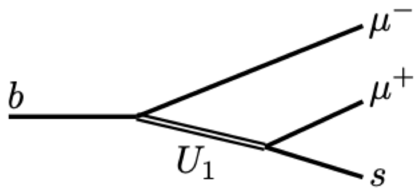
Low energy flavor observables

R_K anomaly:

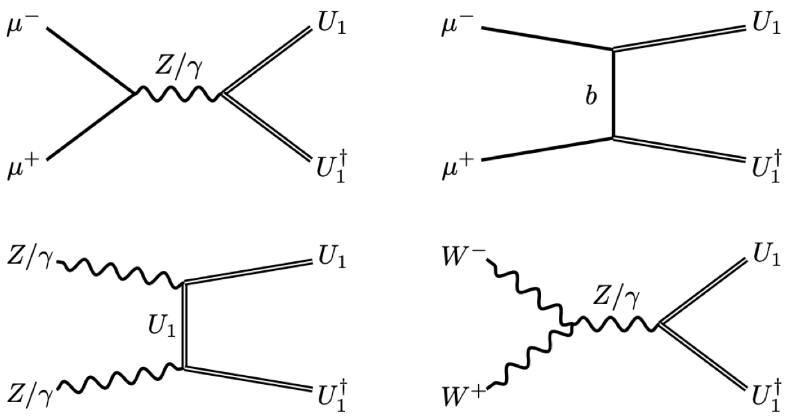


$$\frac{\beta_L^{22}\beta_L^{32}}{m_{\mathrm{LQ}}^2} = 1.98 \times 10^{-3}\ \mathrm{TeV}^{-2}$$

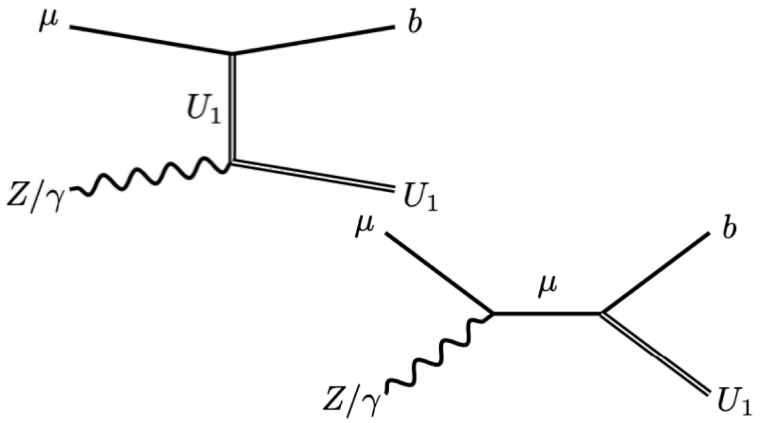
Leptoquarks

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

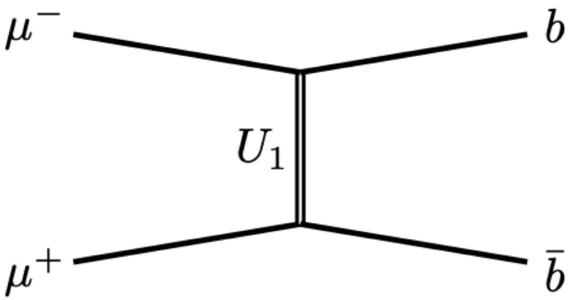
Production Modes



Pair Production



Single Production



Drell-Yan†

Simulated with MG5

Leptoquarks

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

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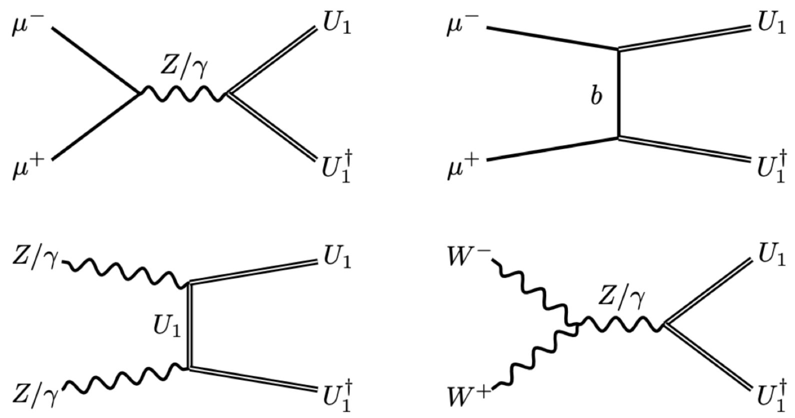

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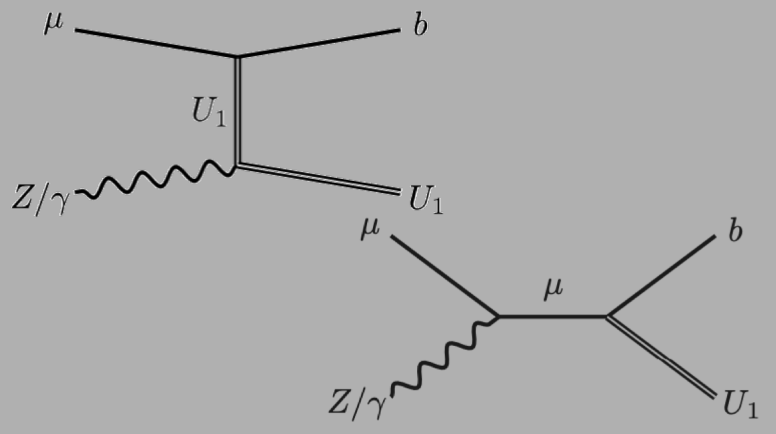

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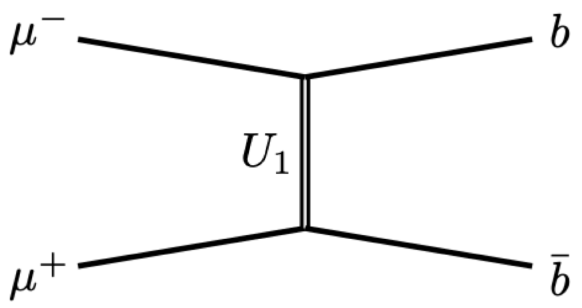

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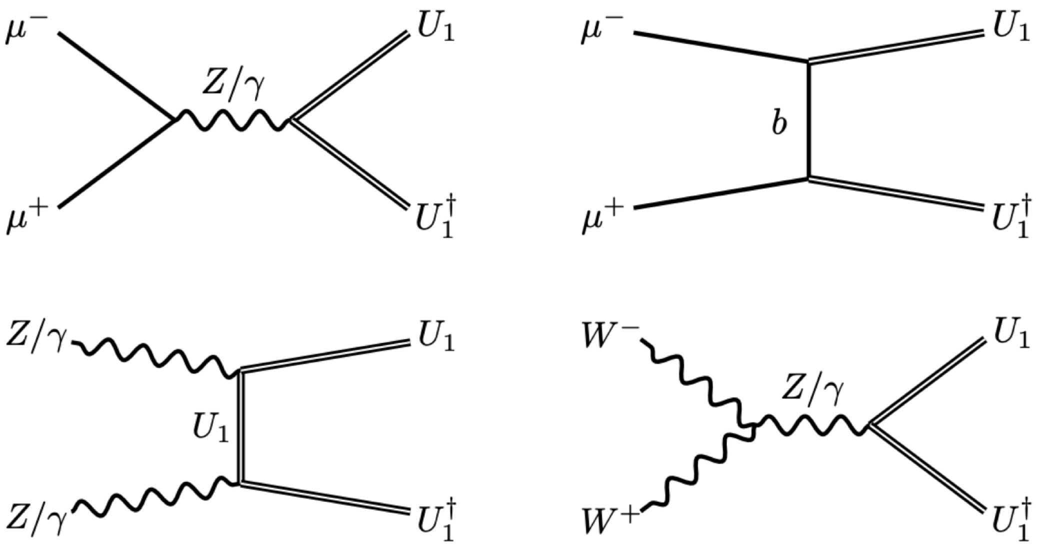
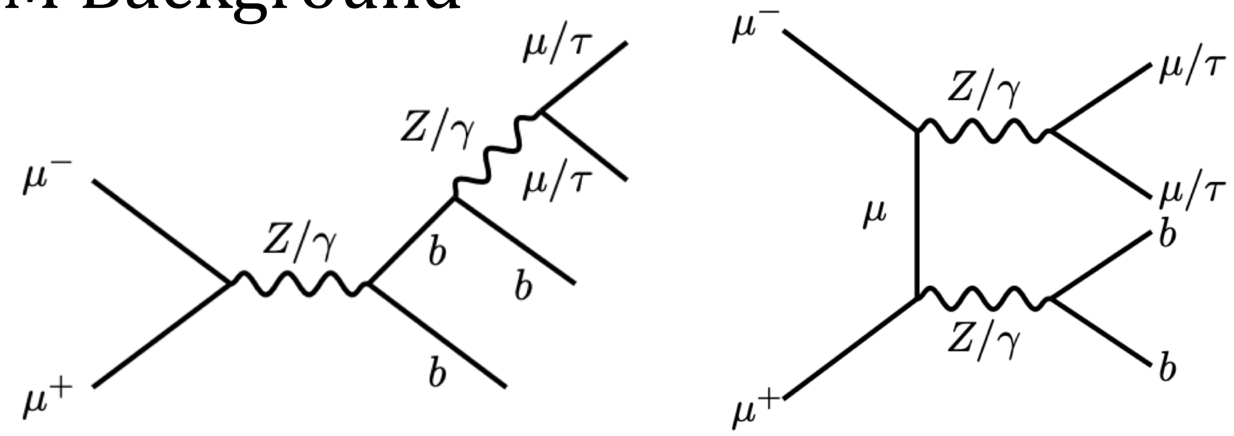


$$U_1 \to \begin{cases} b\mu^+ \\ b\tau^+ \end{cases}$$

SM Background



Leptoquarks

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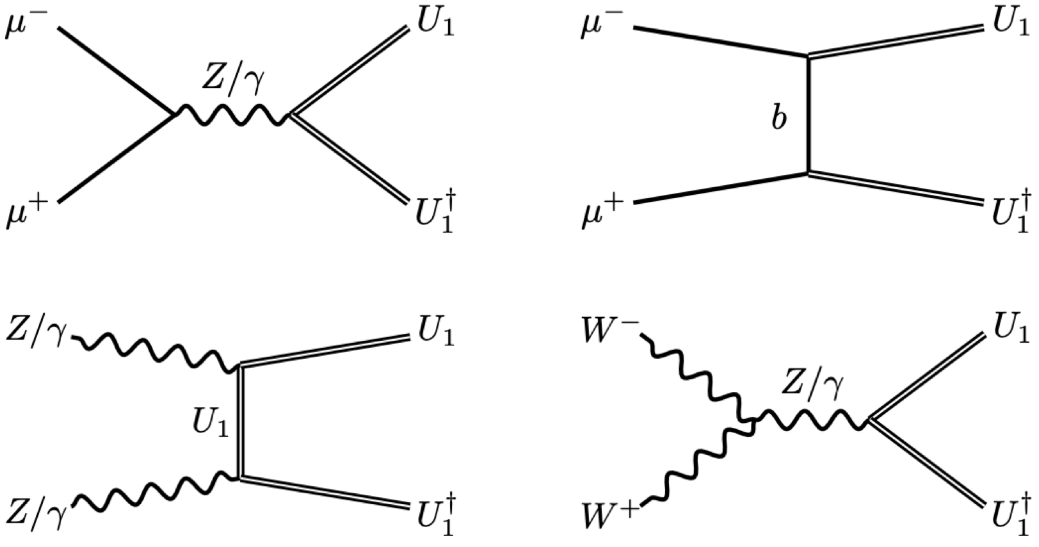

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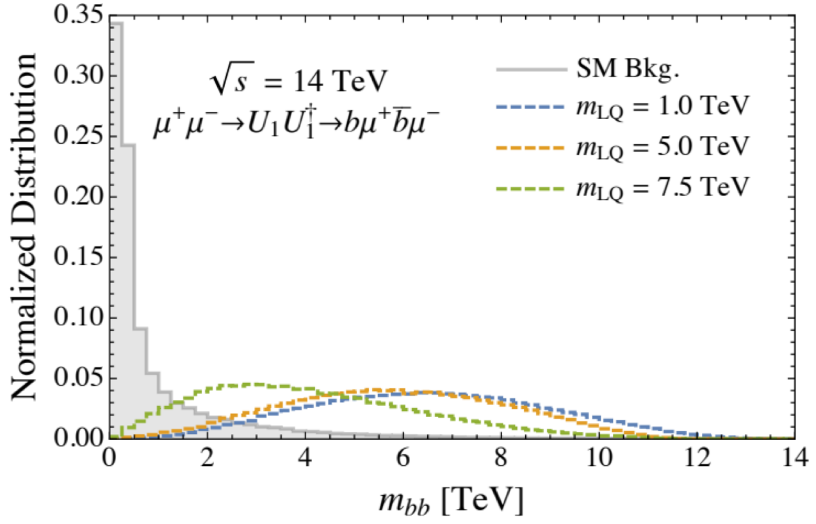
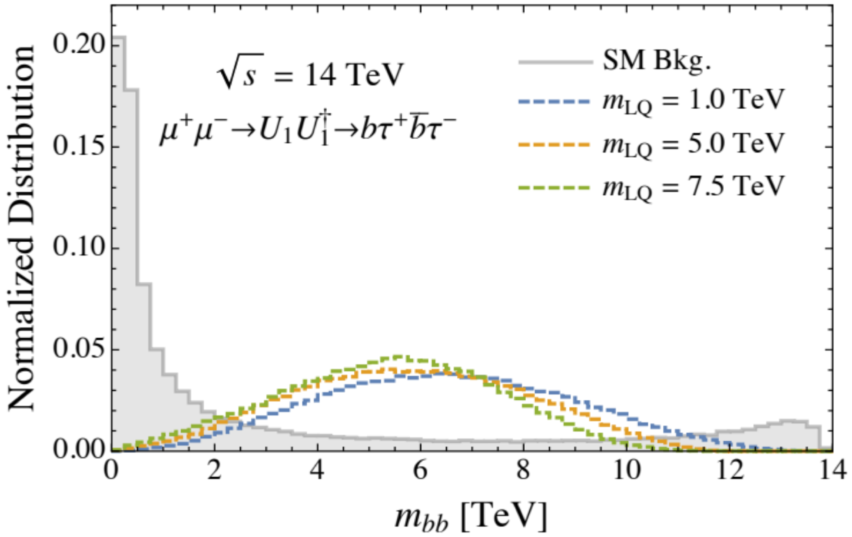


Mitigated by m_{bb} cut



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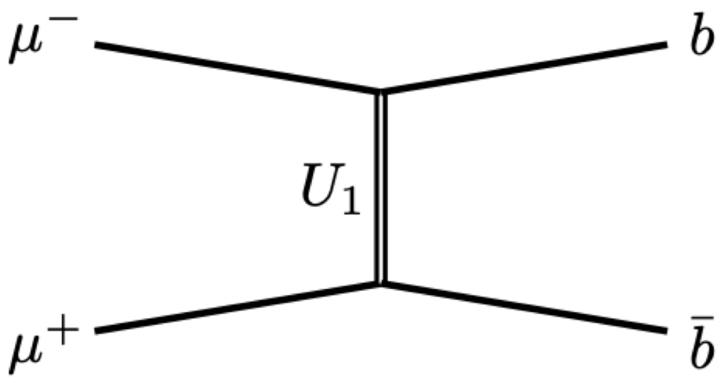
Drell-Yan



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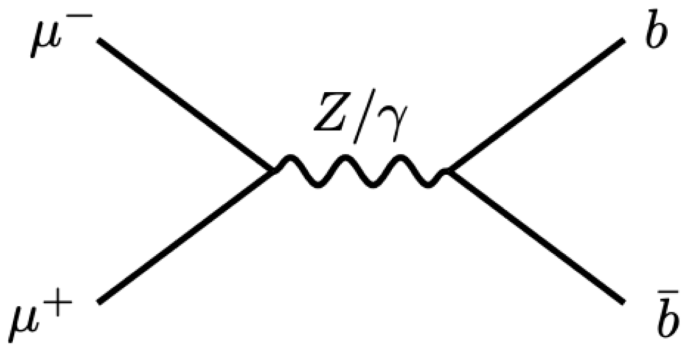

Leptoquarks

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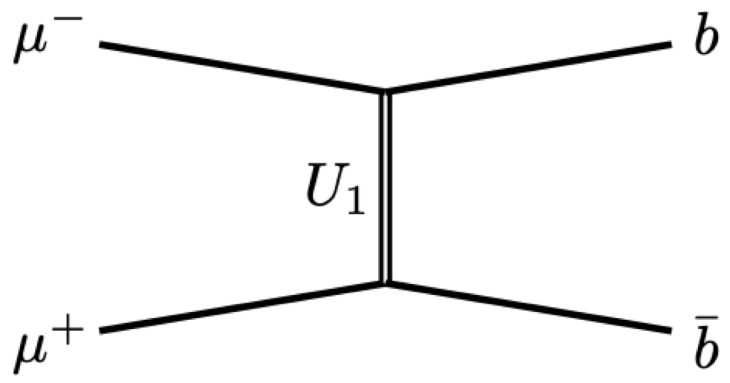
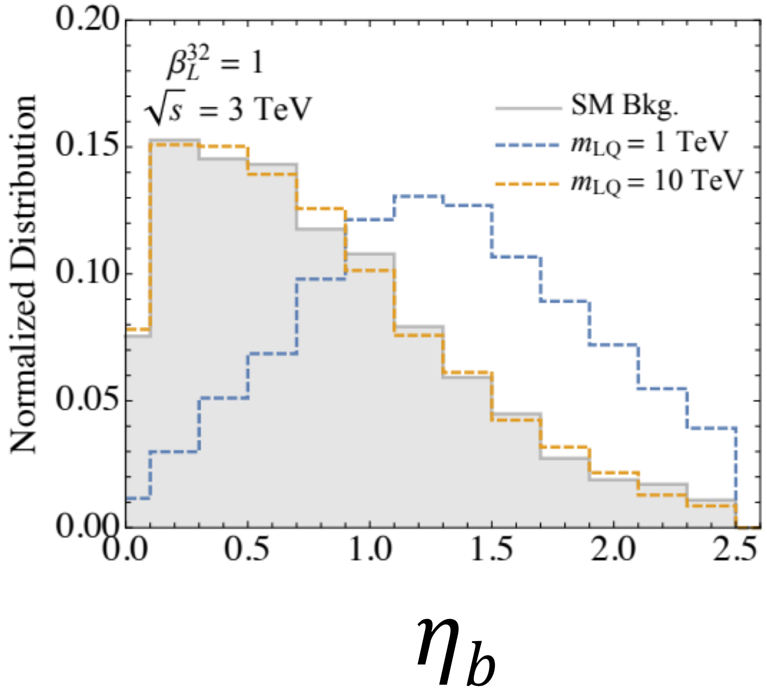
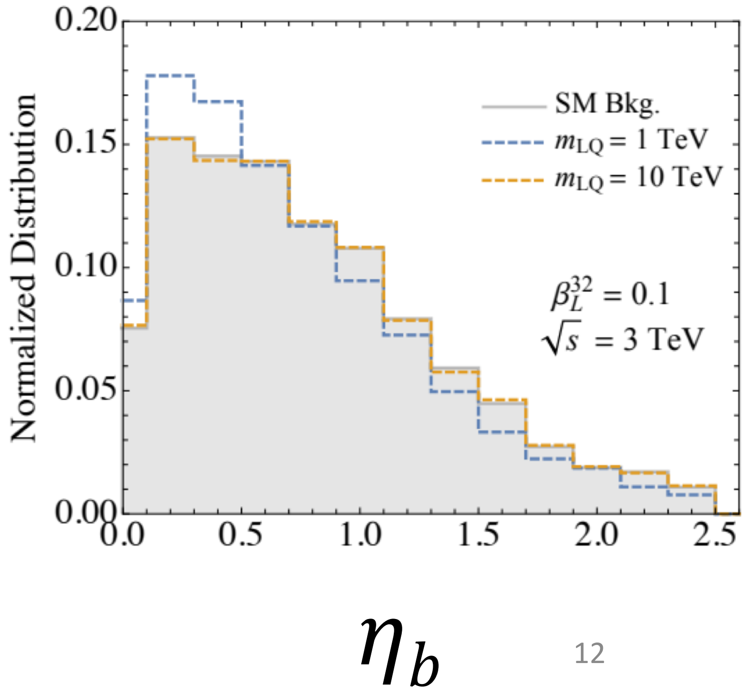
Drell-Yan





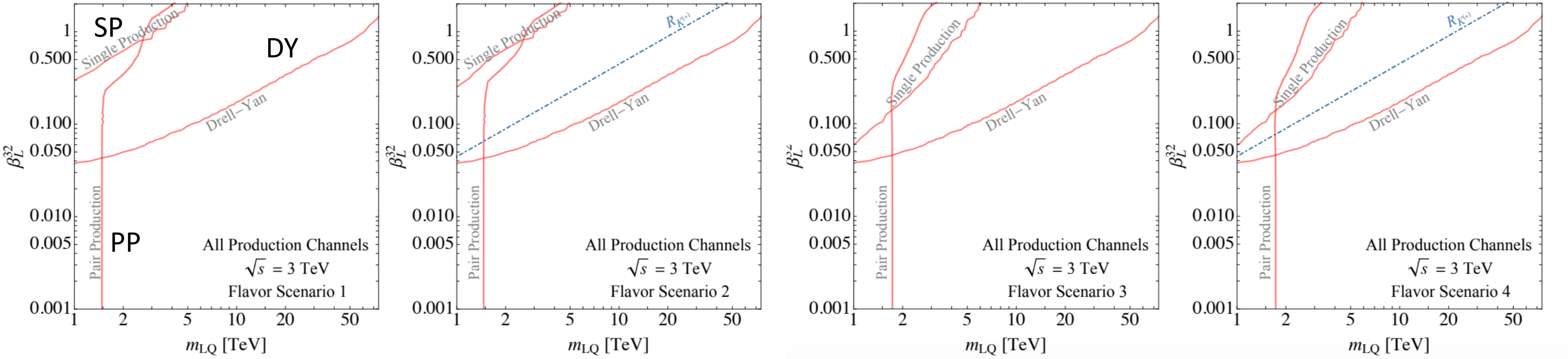
Bin in η



Leptoquarks

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

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



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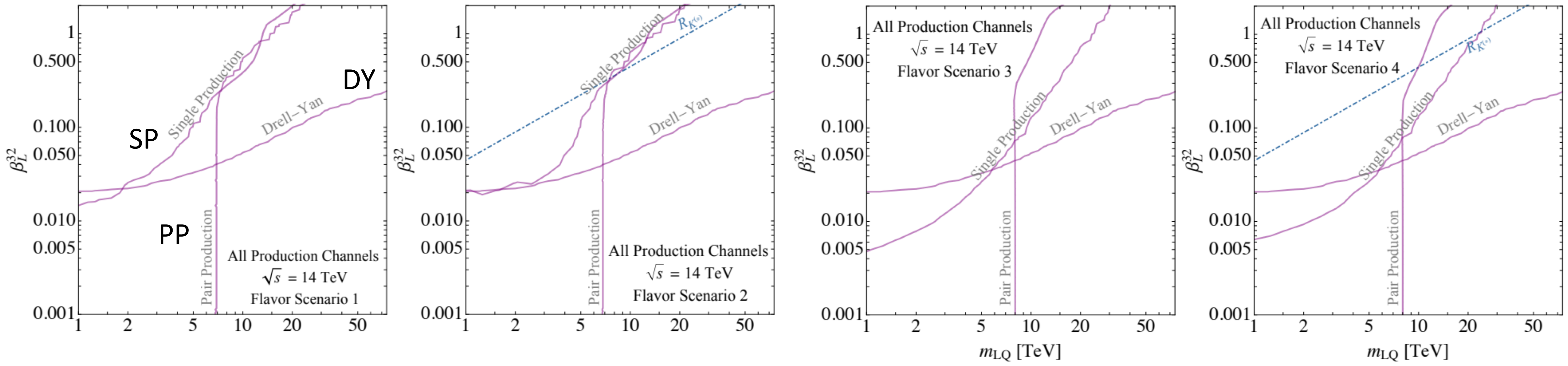
Leptoquarks

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

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



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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!