Searching for New Physics at High-Energy Future Muon Colliders

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Snowmass Cross Frontier, EF-RF-TF RF1

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(2202.12302) S. Homiller, R. Mishra, M. Reece

What do we want from a future collider?

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Expand energy & intensity frontiers

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Develop complementary physics program to existing experiments

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Construction of a new collider

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Construction of a ~~new~~ μ collider

Muon Colliders (μC)

LHC (pp) μC

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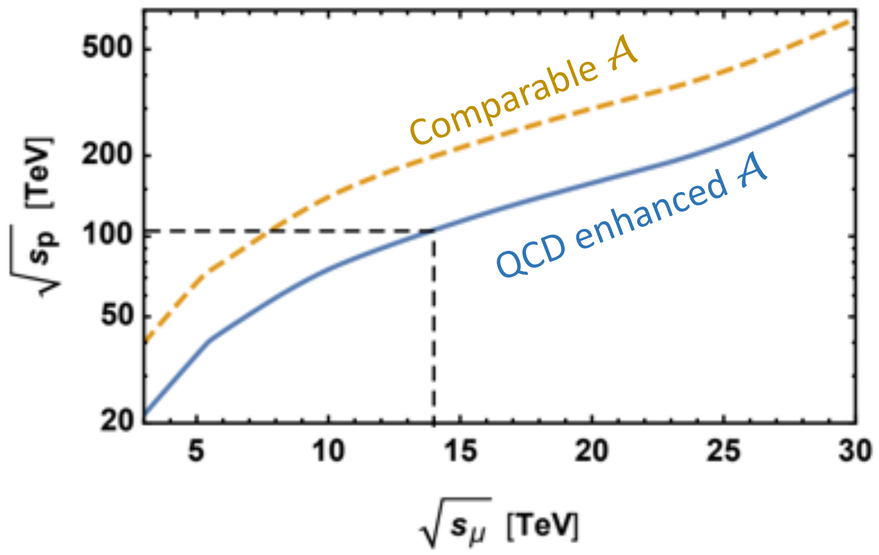
LHC (pp)

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

μC

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

1901.06150



Muon Colliders (μC)

LHC (pp)	μC
• $\sqrt{\hat{s}} \ll \sqrt{s}$	• $\sqrt{\hat{s}} \simeq \sqrt{s}$
• Color production	• Electroweak production

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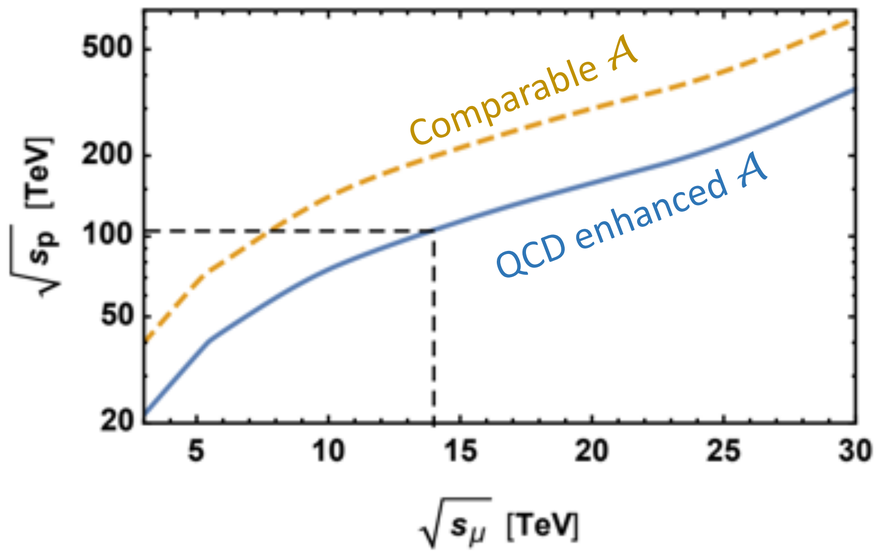

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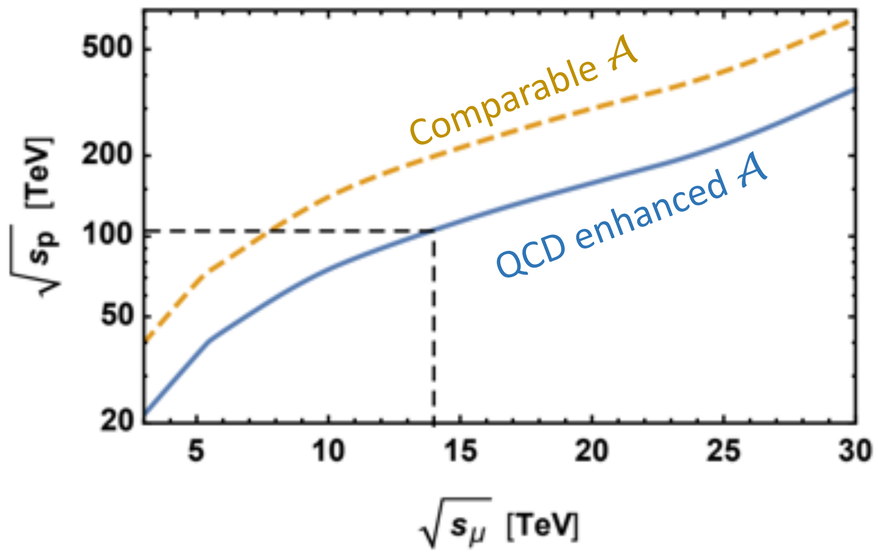

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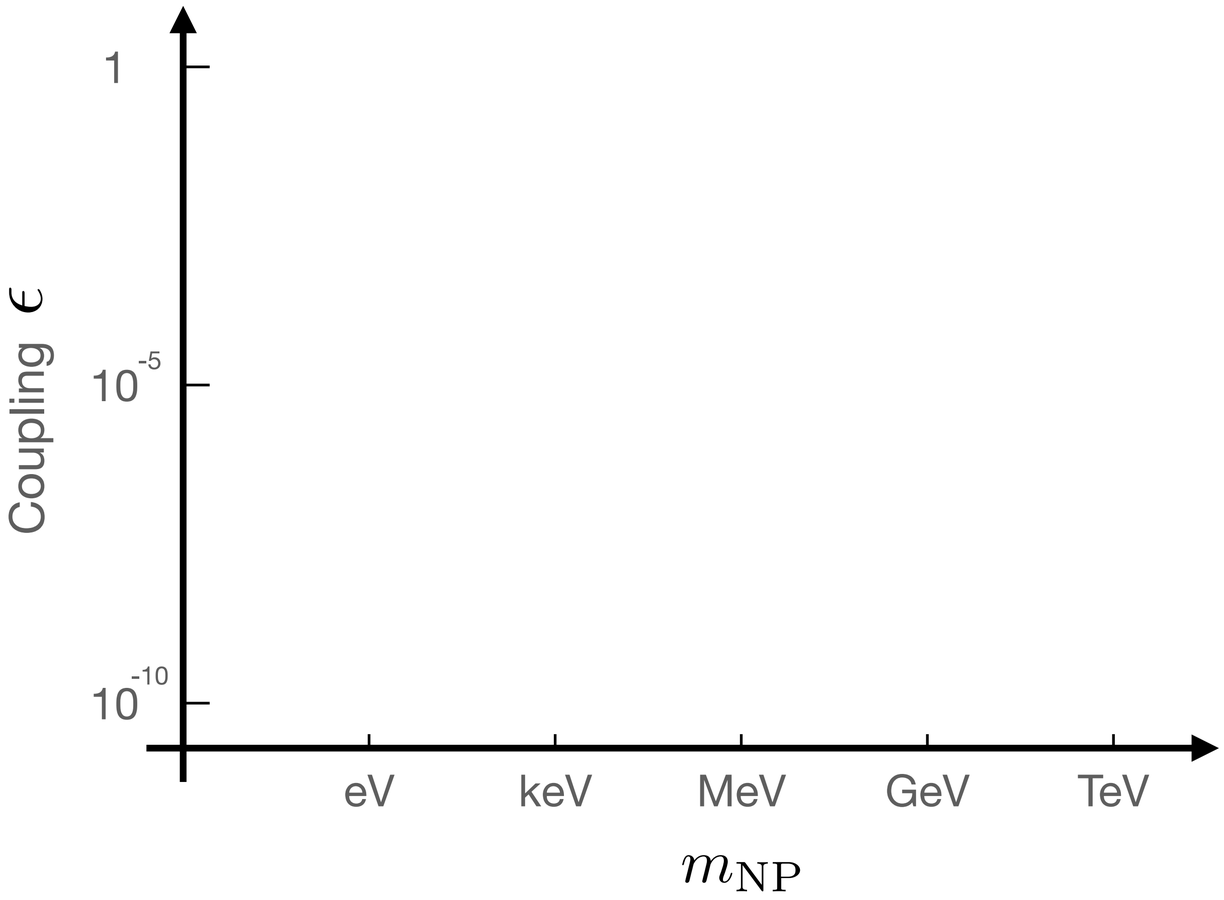
	• 2nd gen couplings	• 1st gen couplings

Future multi-TeV μC provides a complementary physics program



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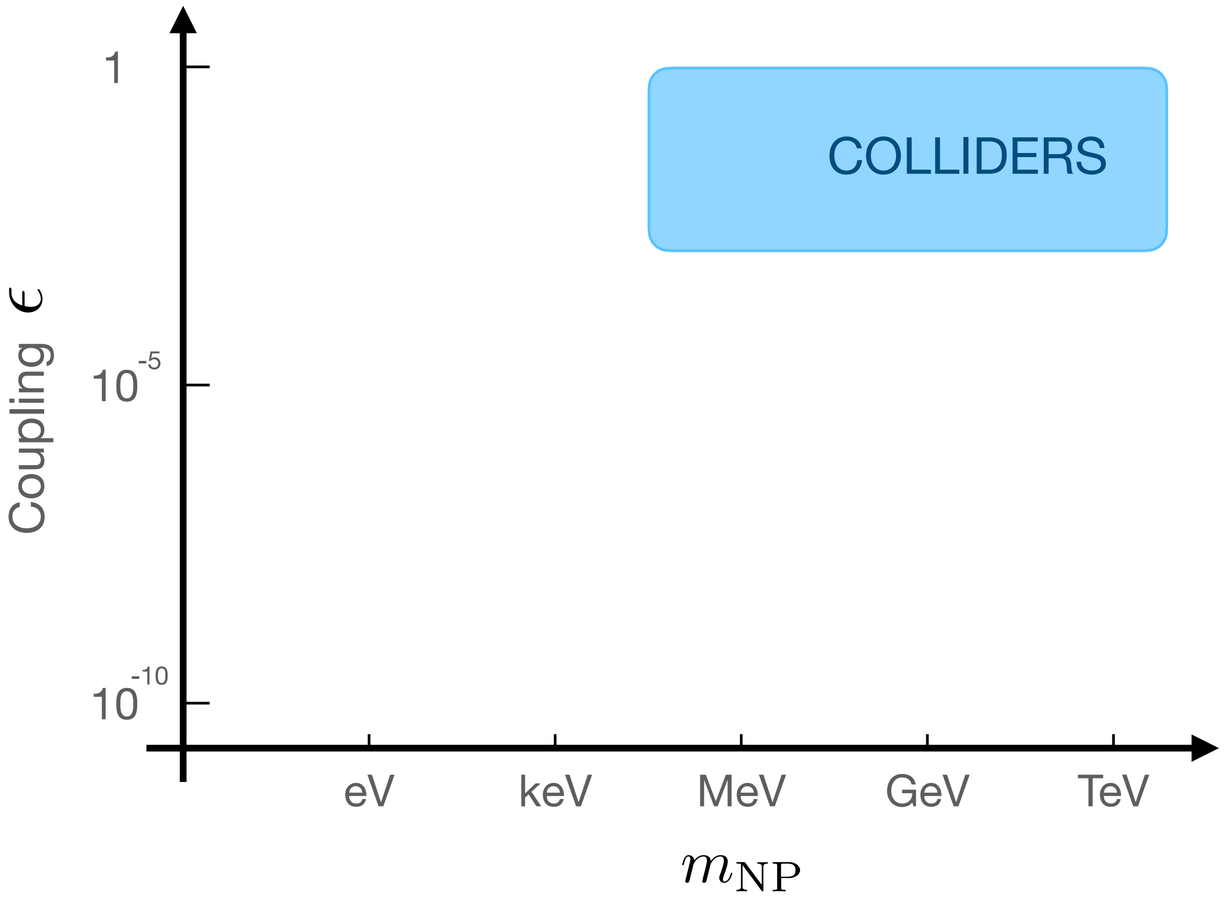

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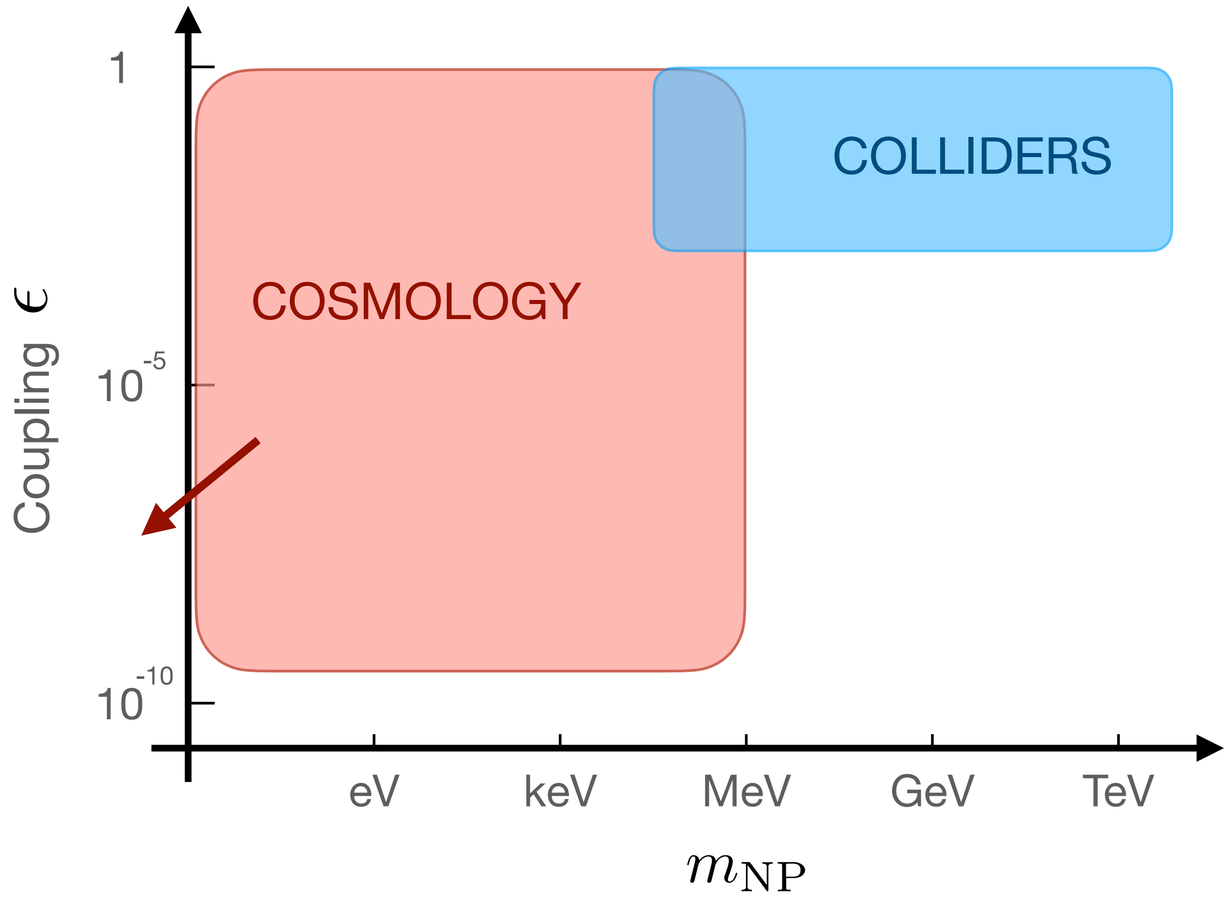

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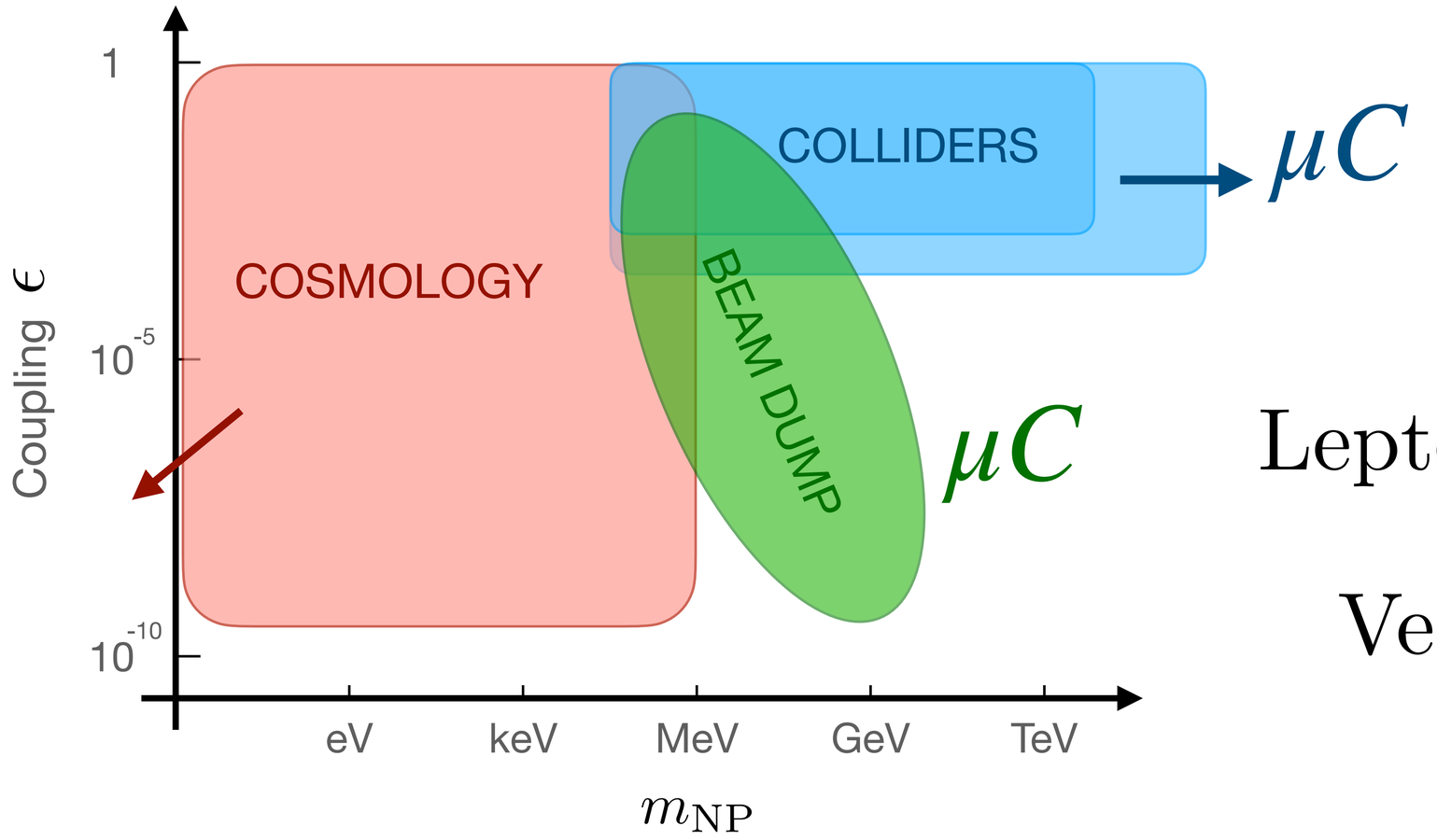

Leptoquarks @ Collider

Vector Bosons @ BD

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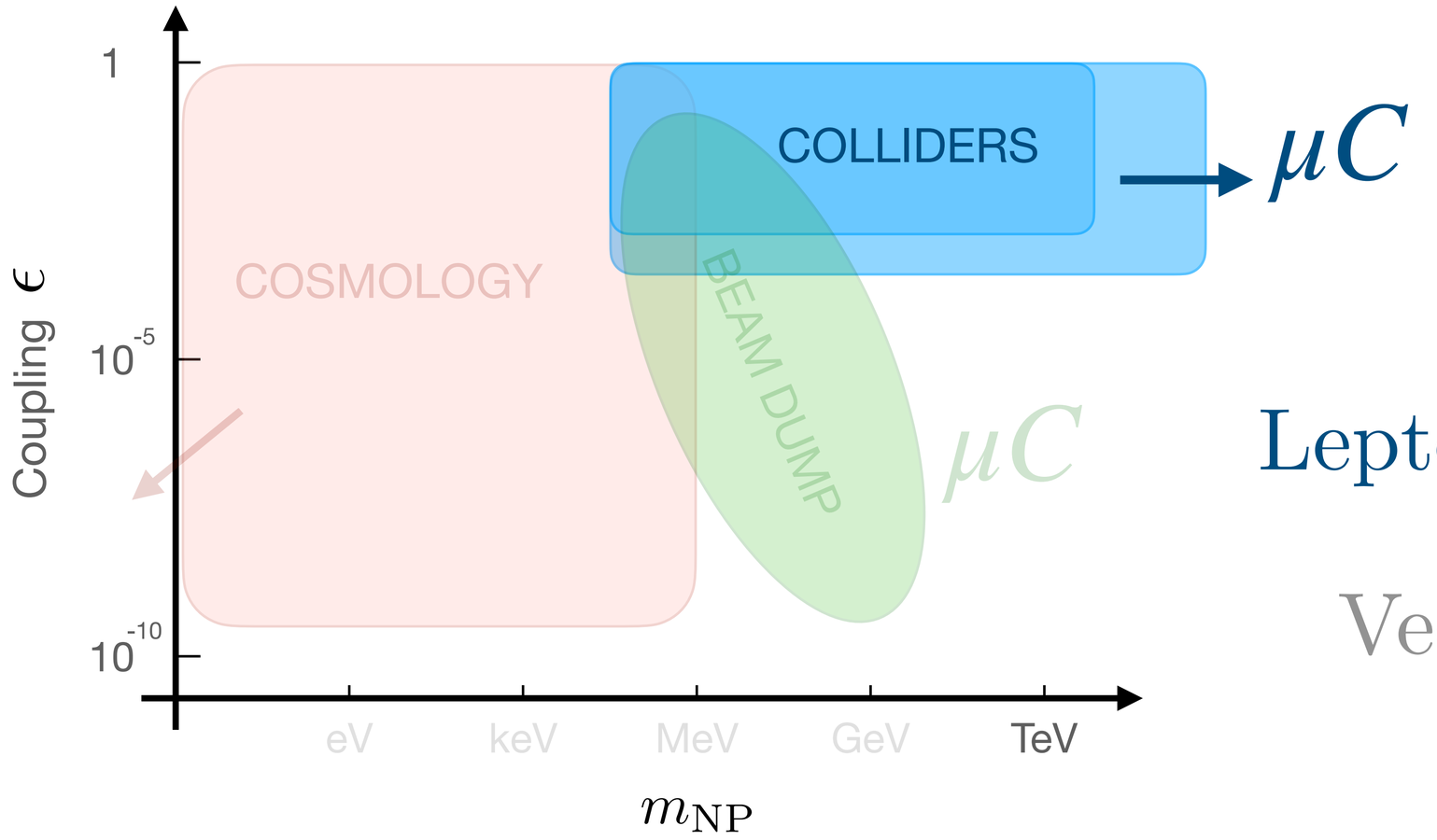

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Vector Bosons @ BD

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Leptoquarks @ μC explores complementary parameter space to existing experiments

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

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Minimal U_1 Leptoquark EFT

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

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

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First gen. couplings constrained by low energy experiments (1603.04993)

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Determines final states

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

$$m_{U_1} \in (1,50) \text{ TeV}$$

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Free parameter

$\sqrt{s} = 3$ TeV

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Final states of U_1 decay

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)	$(\beta_L^{32}, 0.1, 1)$

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Leptoquarks

Flavor observables

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

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]	$\beta_L^{33} \times \beta_L^{32}$	
$\mathrm{BR}\,(\tau \to \mu\phi)$	$< 8.4 \times 10^{-8}$	$\beta_L^{23} \times \beta_L^{22}$	
$\mathrm{BR}\,(D_s \to \mu\nu)$	$< 5.49 \times 10^{-3}$	$\beta_L^{22} \times \beta_L^{22}$	
$\mathrm{BR}\,(D_s \to \tau\nu)$	$< 5.48 \times 10^{-2}$	$\beta_L^{23} \times \beta_L^{23}$	
$\mathrm{BR}\,(B \to K\tau\mu)$	$< 2.8 \times 10^{-5}$	$\beta_L^{32} \times \beta_L^{23}$	$\beta_L^{33} \times \beta_L^{22}$
$\mathrm{BR}\,(B_s \to \tau\mu)$	$< 4.2 \times 10^{-5}$	$\beta_L^{32} \times \beta_L^{23}$	$\beta_L^{33} \times \beta_L^{22}$
$\mathrm{BR}\,(B_s \to \tau\tau)$	$< 2.1 \times 10^{-3}$	$\beta_L^{33} \times \beta_L^{23}$	

2103.16558

Leptoquarks

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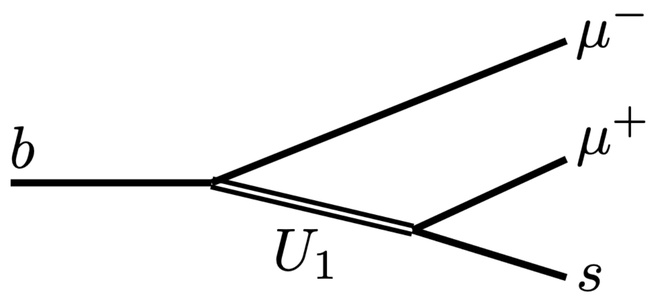

$$\frac{\beta_L^{22}\beta_L^{32}}{m_{U_1}^2} = 1.98 \times 10^{-3}\ \mathrm{TeV}^{-2}$$

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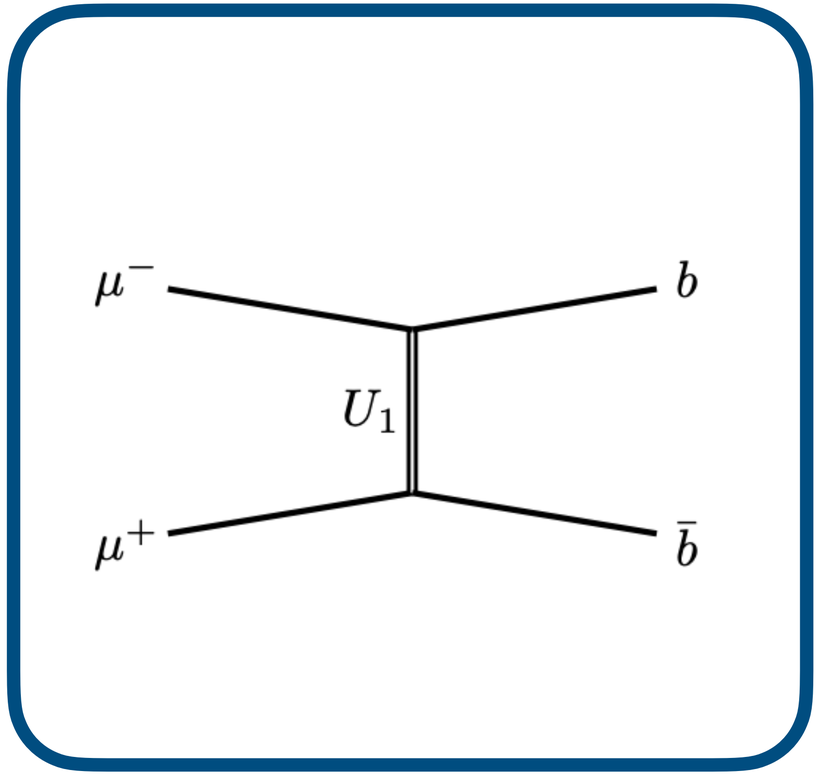
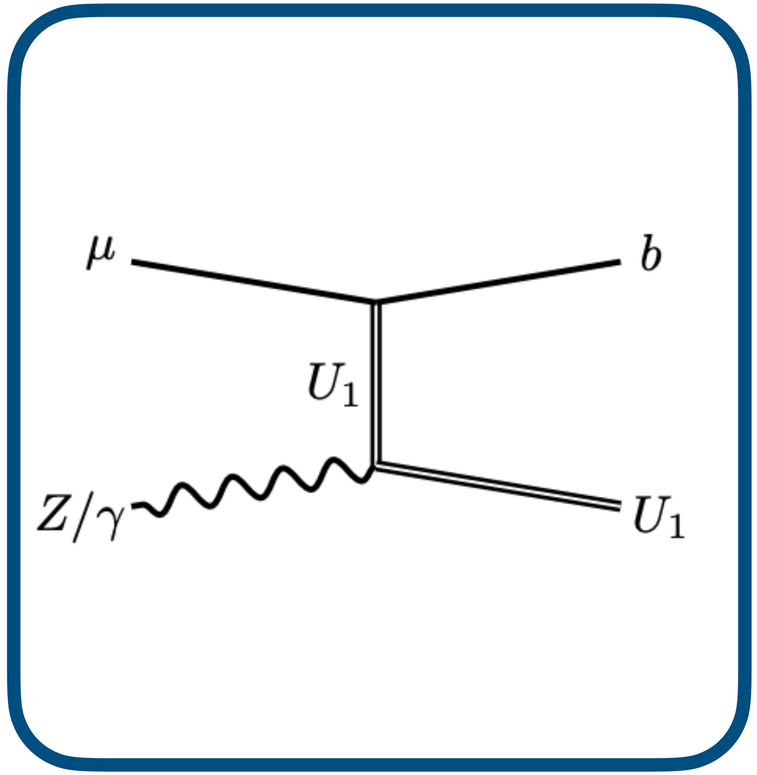
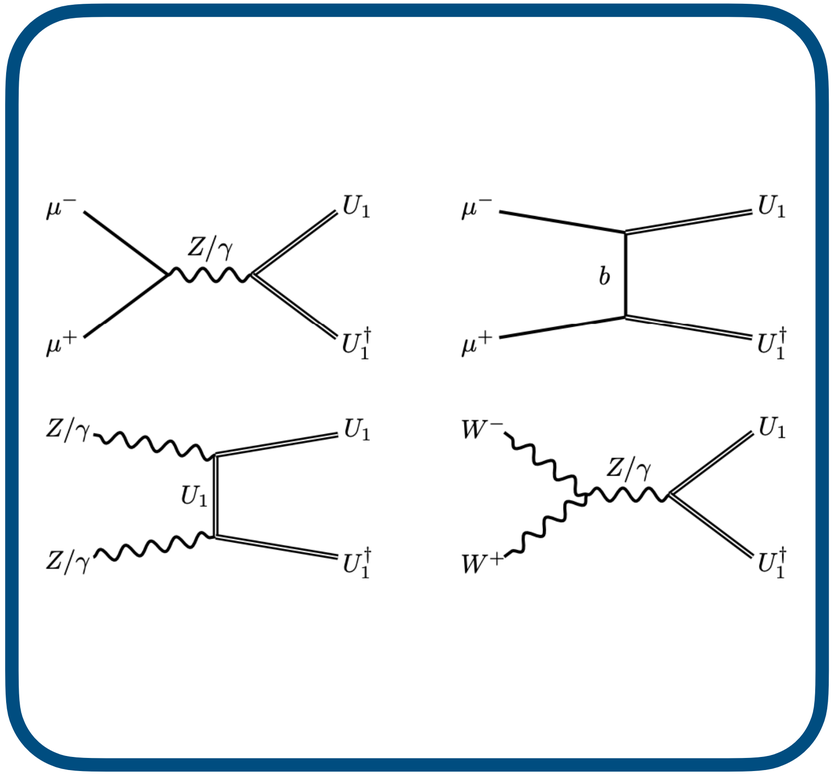
Production Modes



Drell-Yan†



Single Production



Pair Production

Simulated with MG5

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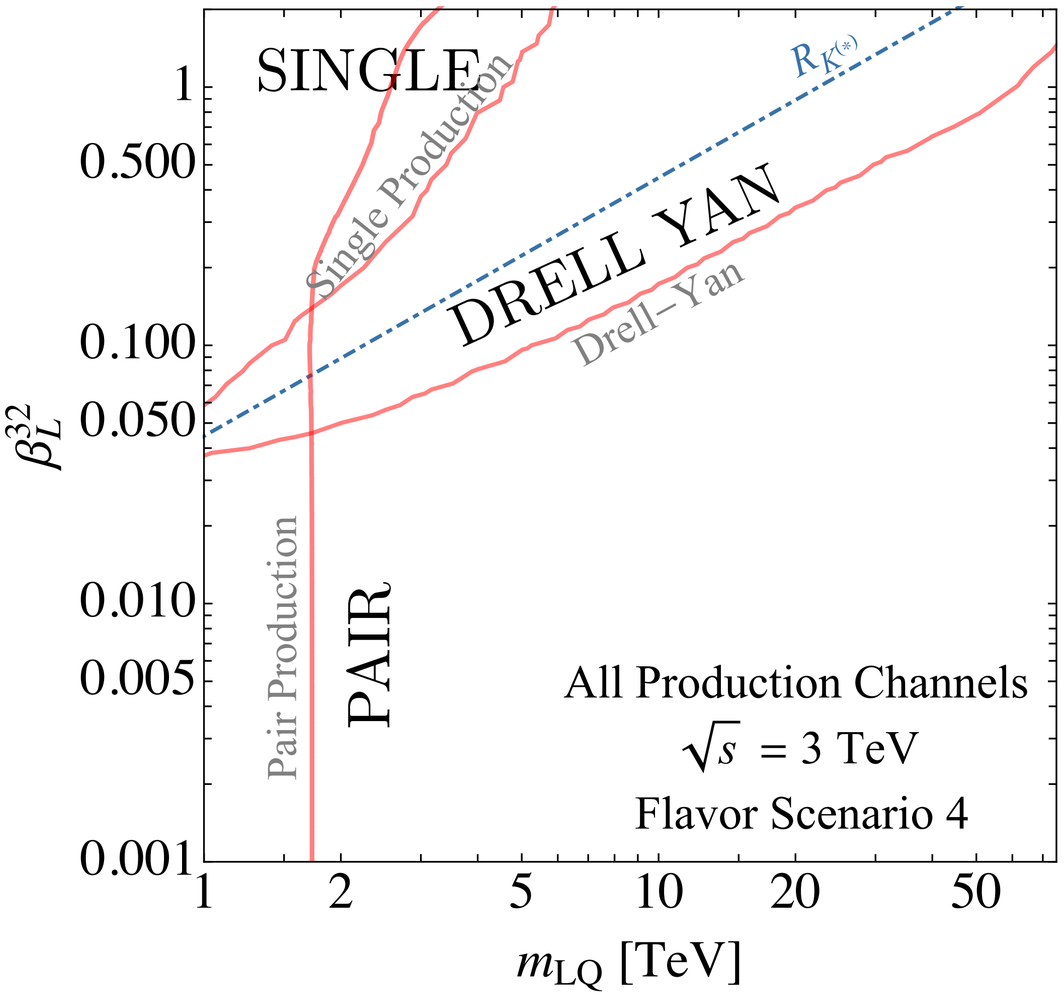
Leptoquarks

5σ confidence limits

3 TeV μC

$$\left(\beta_L^{22}, \beta_L^{23}, \beta_L^{33}\right) = (\beta_L^{32}, 0.1, 1)$$



m_{U_1} [TeV]

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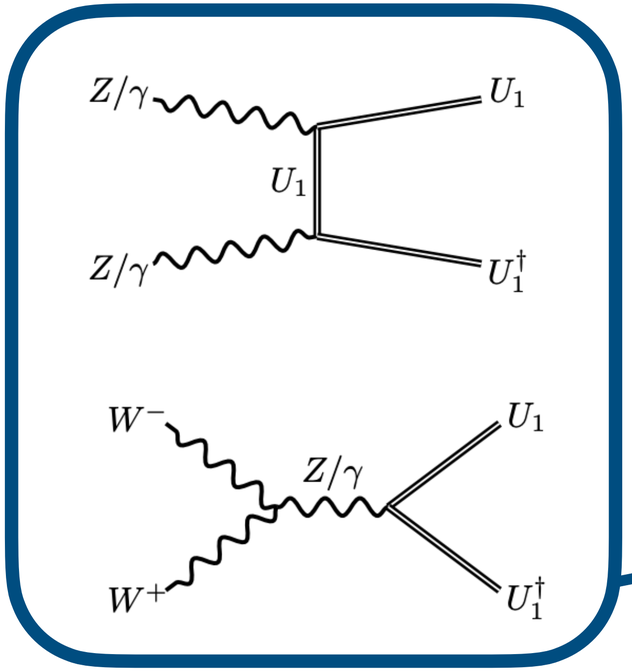

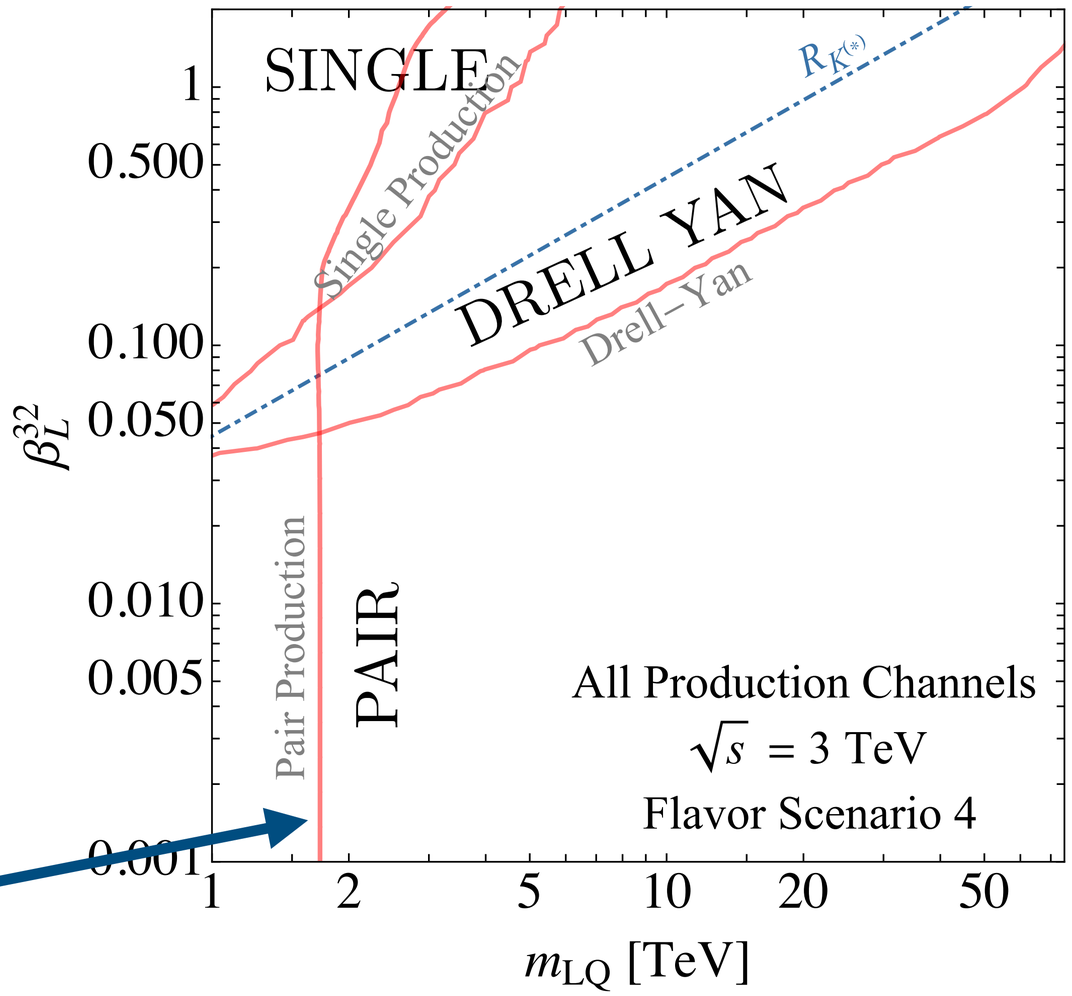

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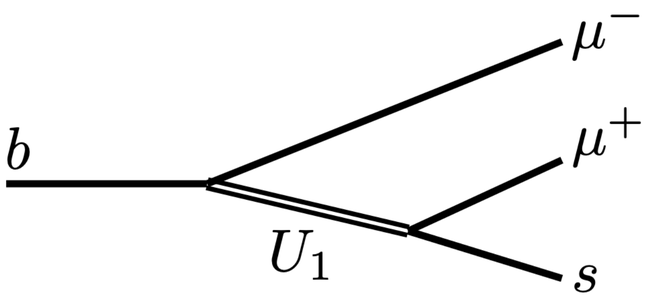

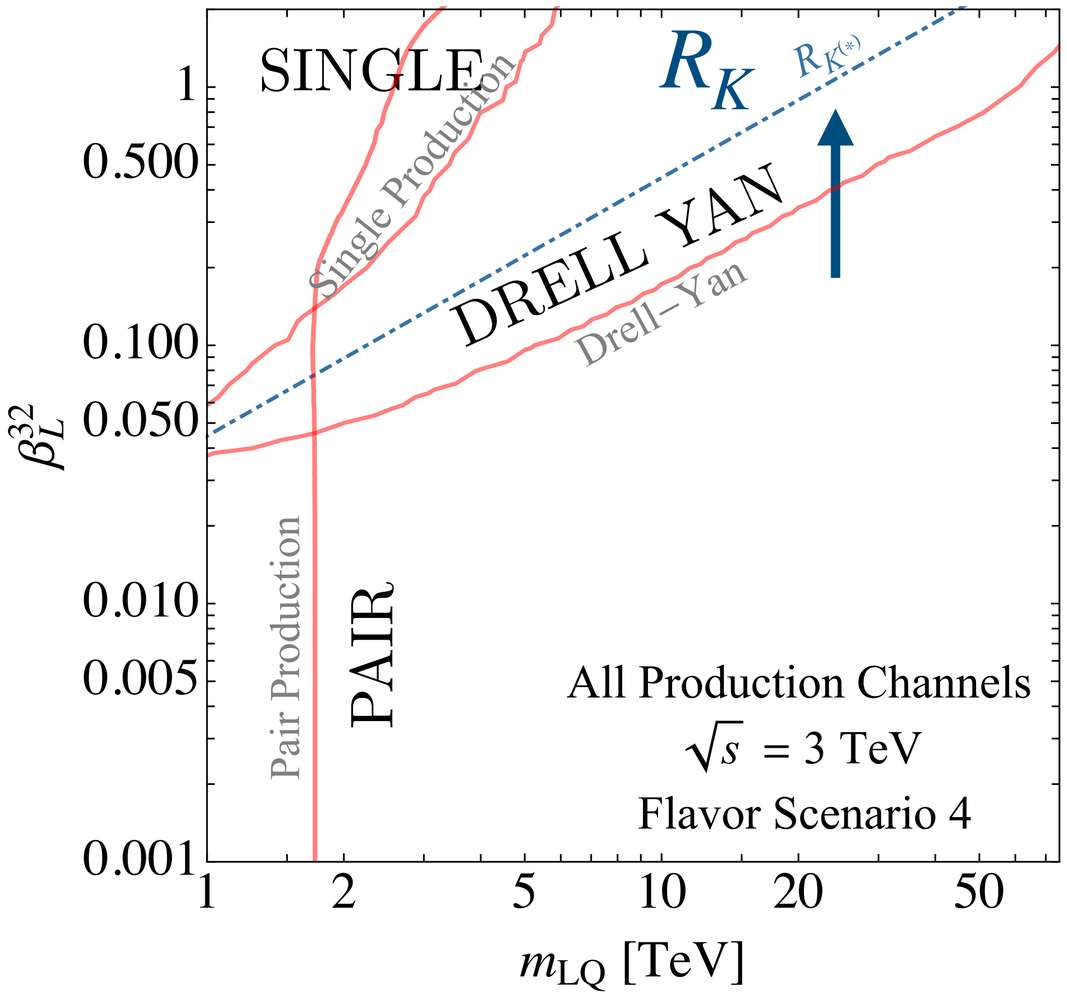

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Leptoquarks

5σ confidence limits

3 TeV μC

$(\beta_L^{22}, \beta_L^{23}, \beta_L^{33})$

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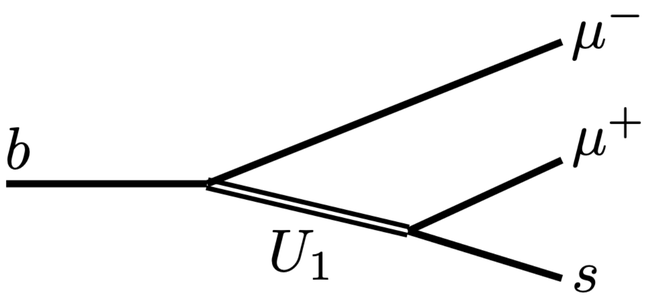
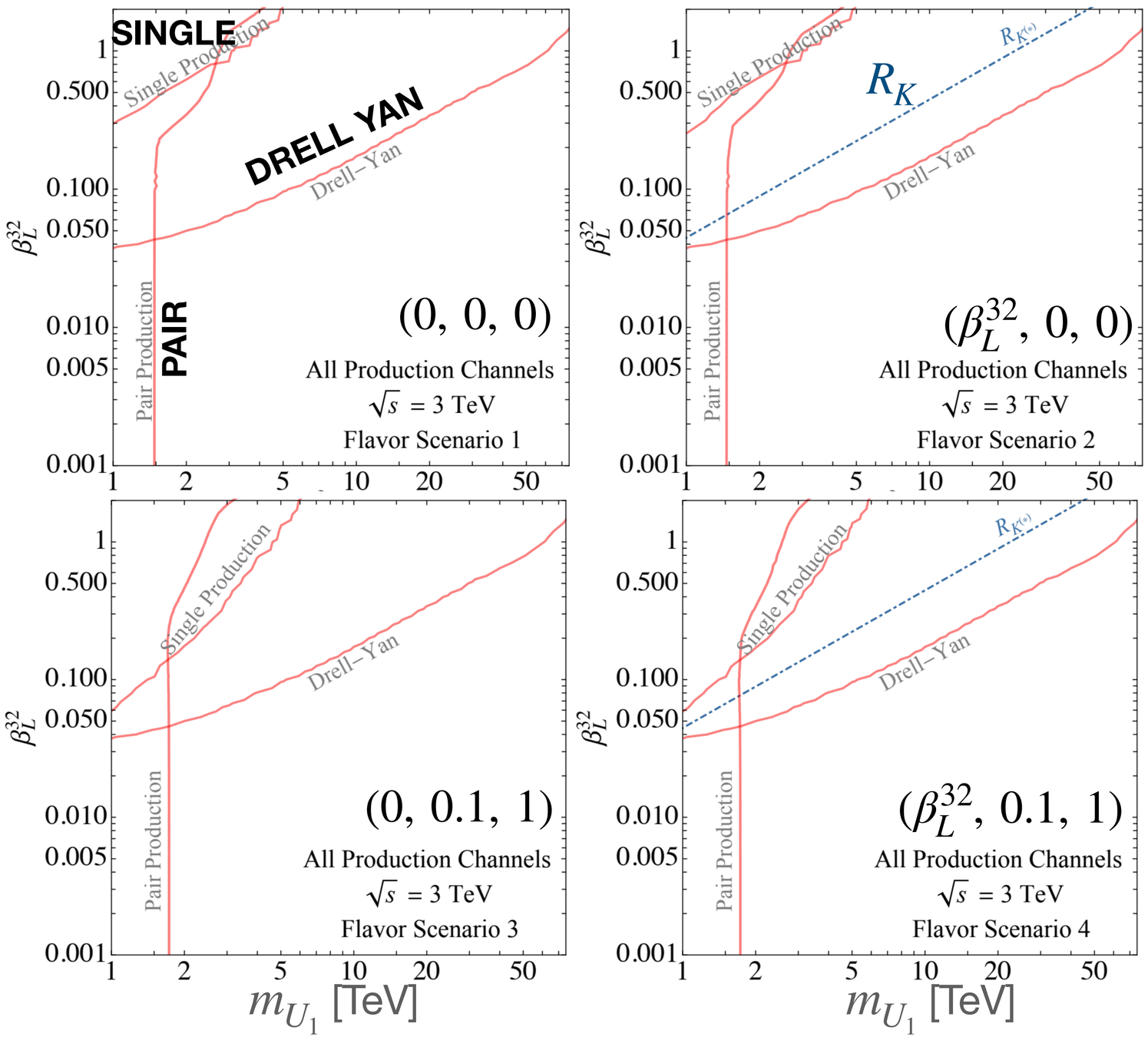


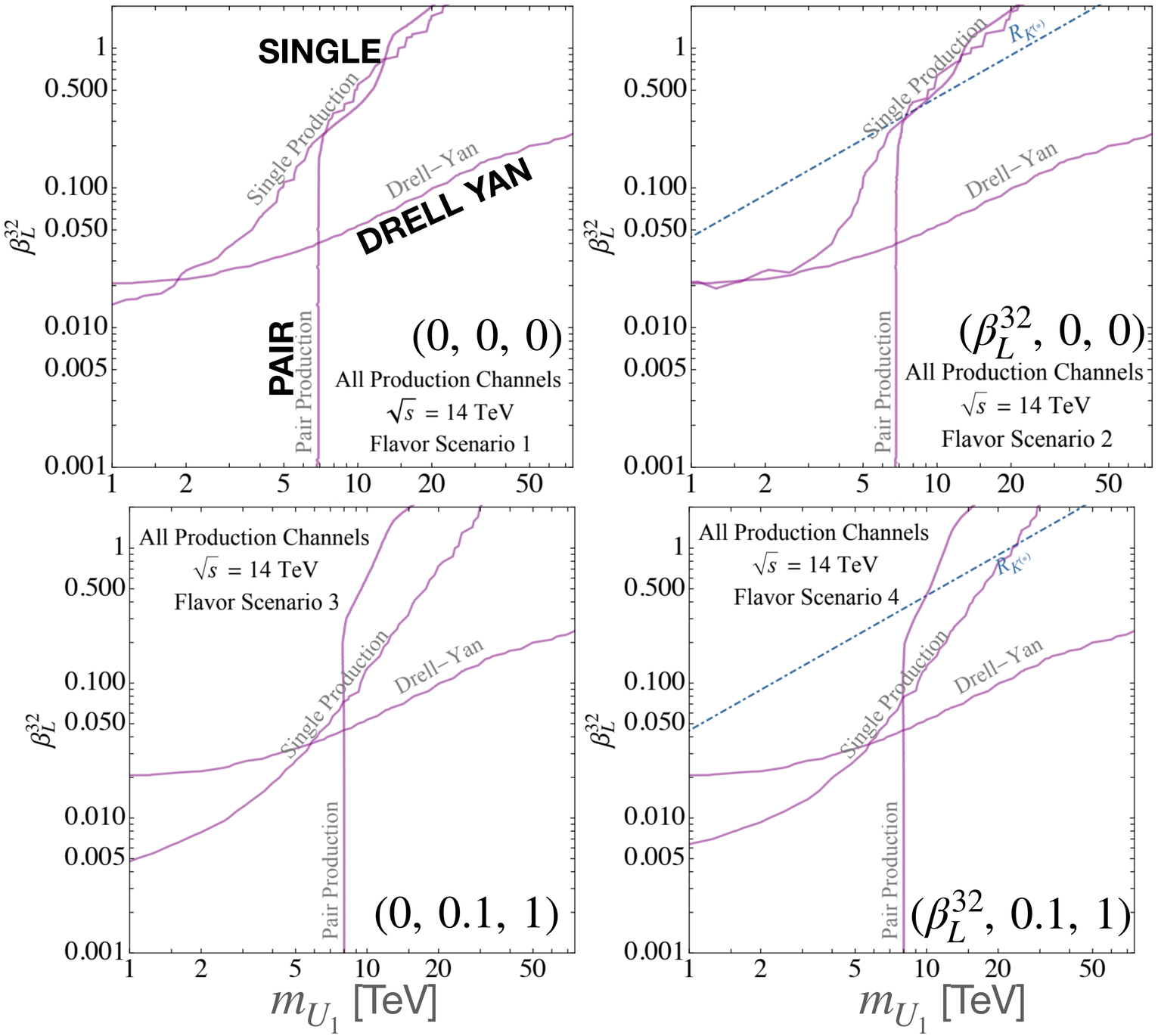


Leptoquarks

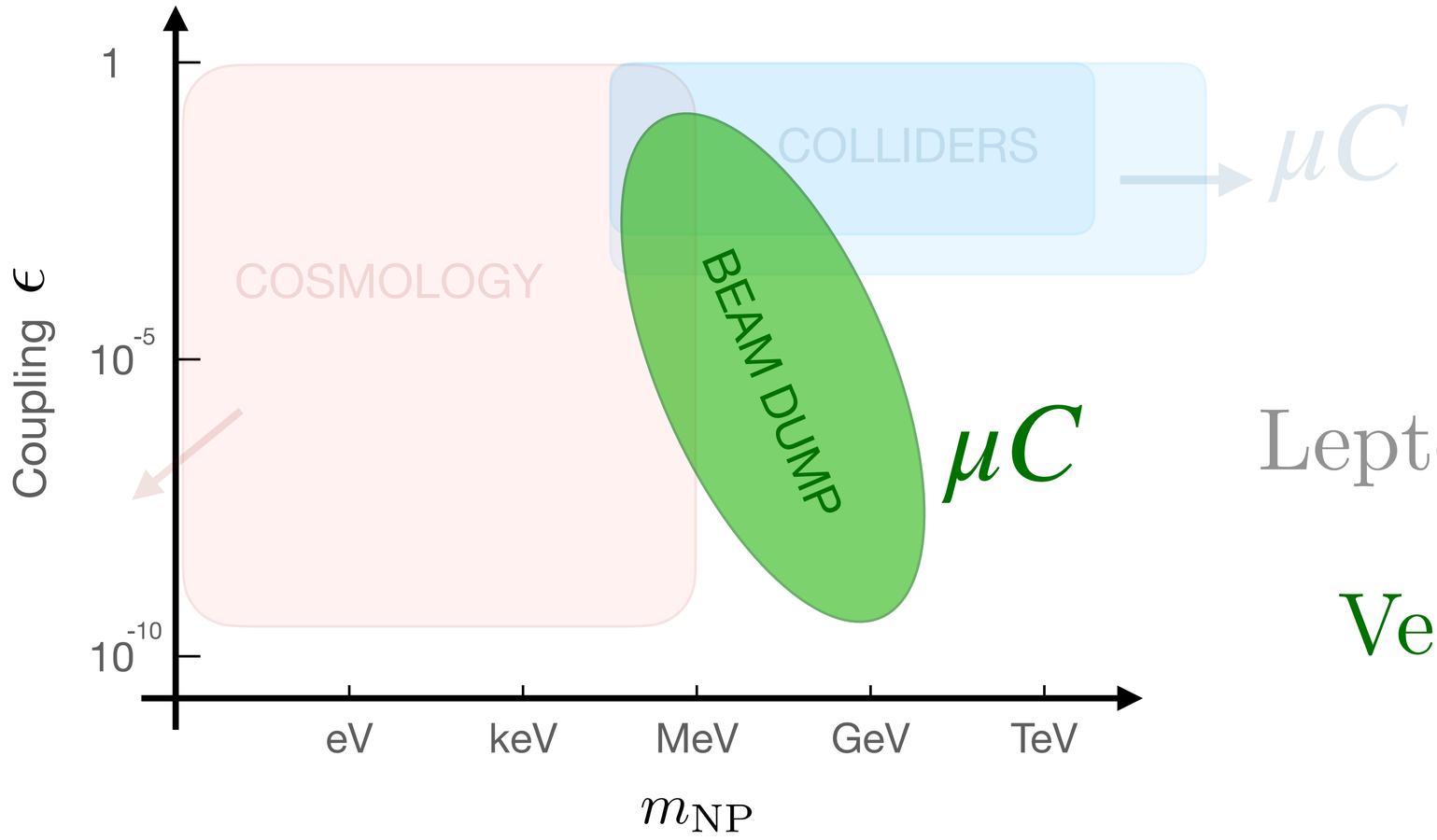
5σ confidence limits

14 TeV μC

$(\beta_L^{22}, \beta_L^{23}, \beta_L^{33})$



Future multi-TeV μC provides a complementary physics program



Leptoquarks @ Collider

Vector Bosons @ BD

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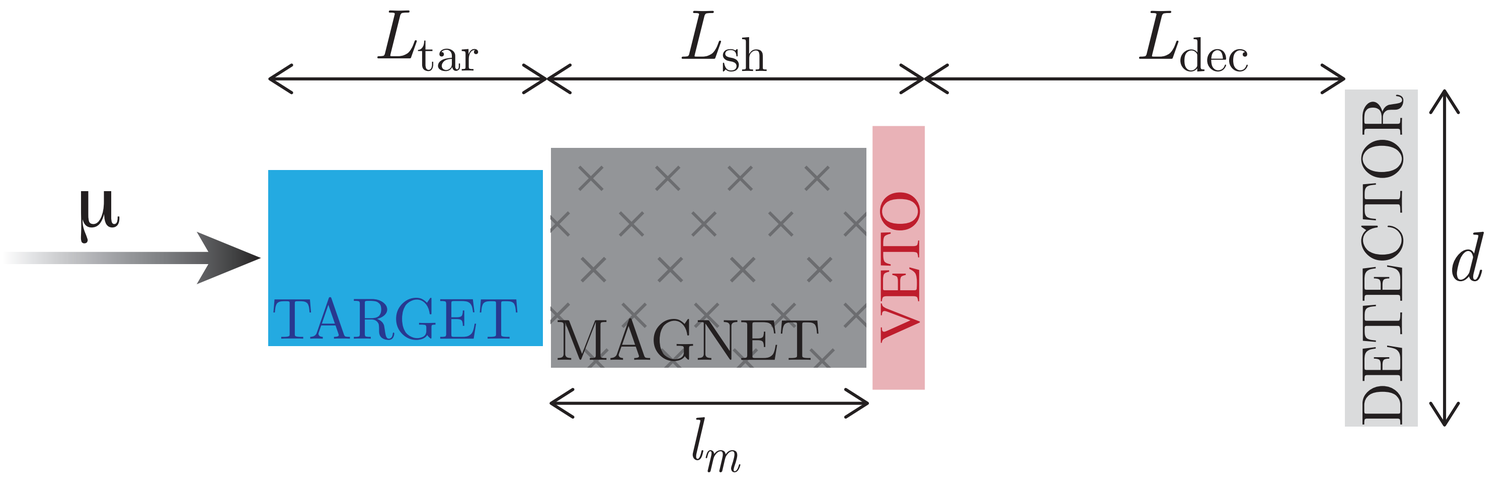
A beam dump experiment at the μC allows us to push into both the energy and the intensity frontier



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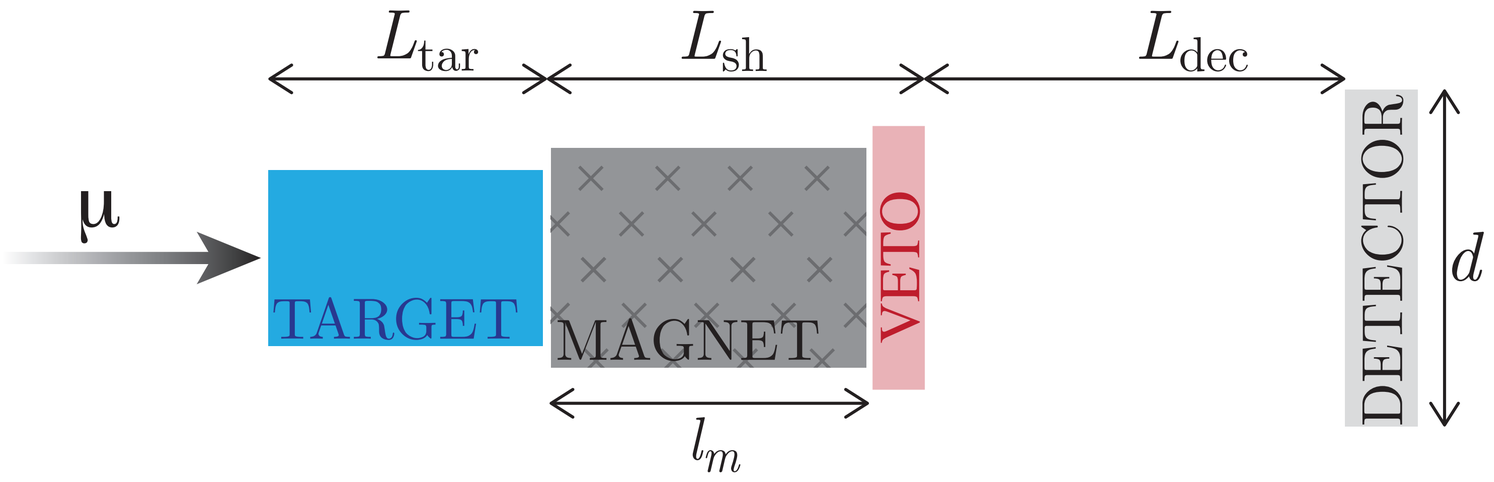
A beam dump experiment at the μC allows us to push into both the energy and the intensity frontier

Can probe NP scenarios with:



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Can probe NP scenarios with:

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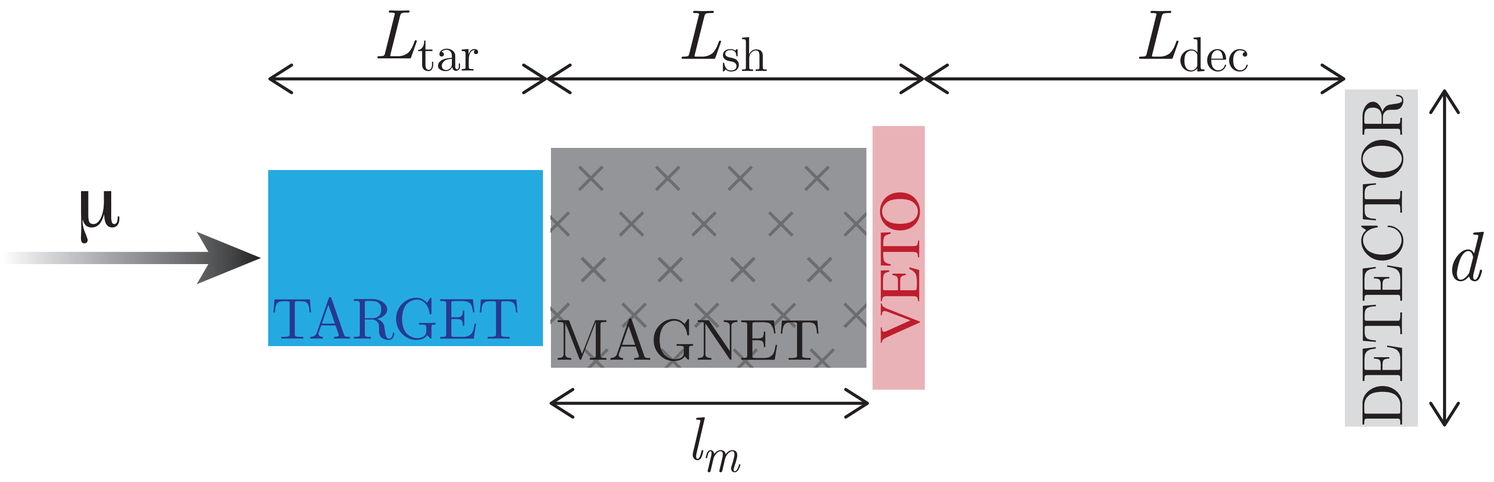

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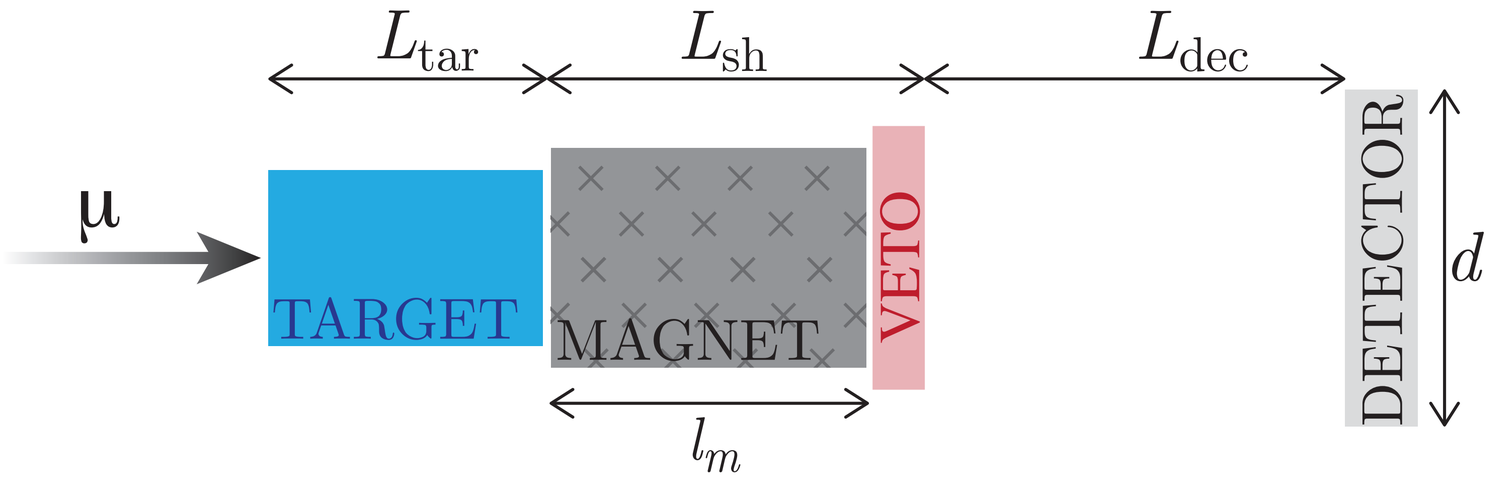
Can probe NP scenarios with:

- Very weak couplings
- Couplings to 2nd gen. leptons



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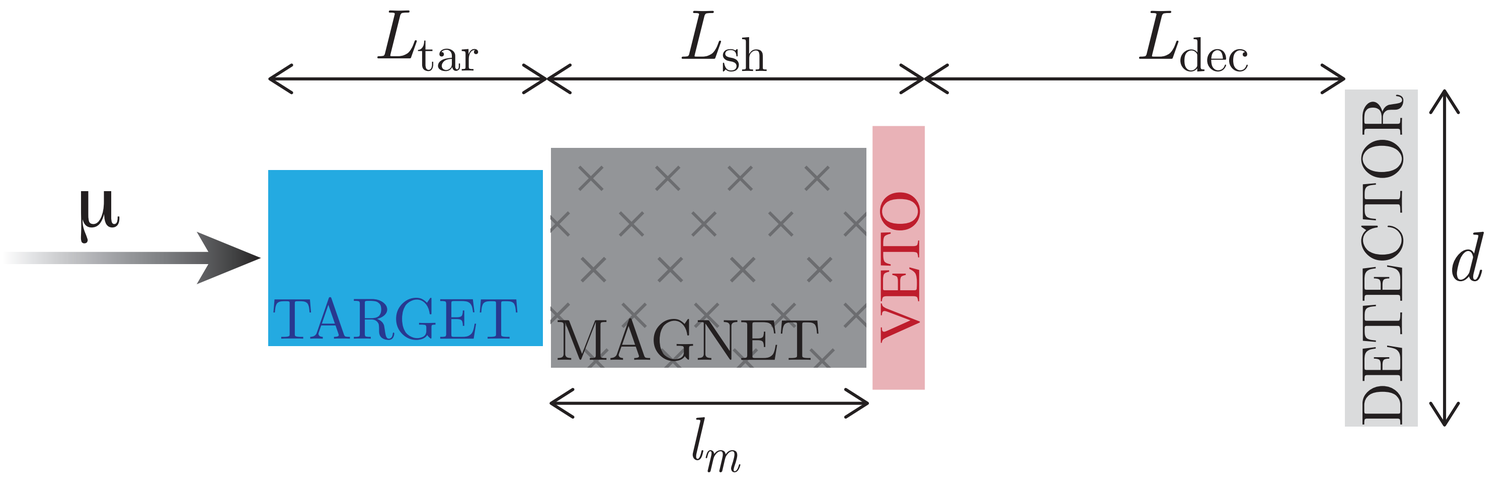
A beam dump experiment at the μC allows us to push into both the energy and the intensity frontier

Can probe NP scenarios with:

- Very weak couplings
- Couplings to 2nd gen. leptons
- Masses $\lesssim$ 100 GeV



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We search for vector new physics signals at μC beam dump

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$$\sqrt{s} \sim \text{ TeV}$$

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We consider 2 models:

- Dark Photon
- Gauged Flavor Symmetry $L_\mu - L_\tau$

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New physics Z' Scenarios

Dark Photon

$L_\mu - L_\tau$

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$$\mathscr{L}_V \supset -i\epsilon e Z'_\mu \sum_{l \in e,\mu,\tau} \bar{l}\gamma^\mu l$$

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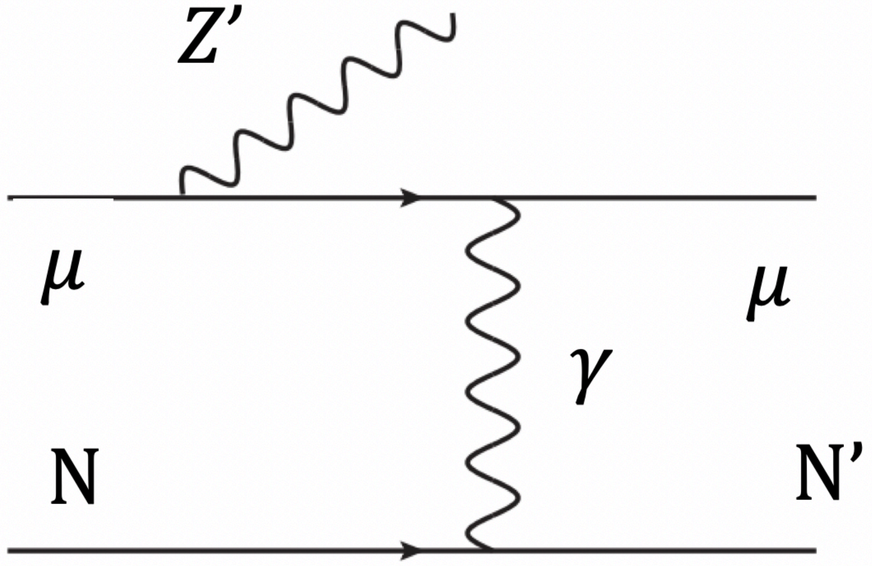

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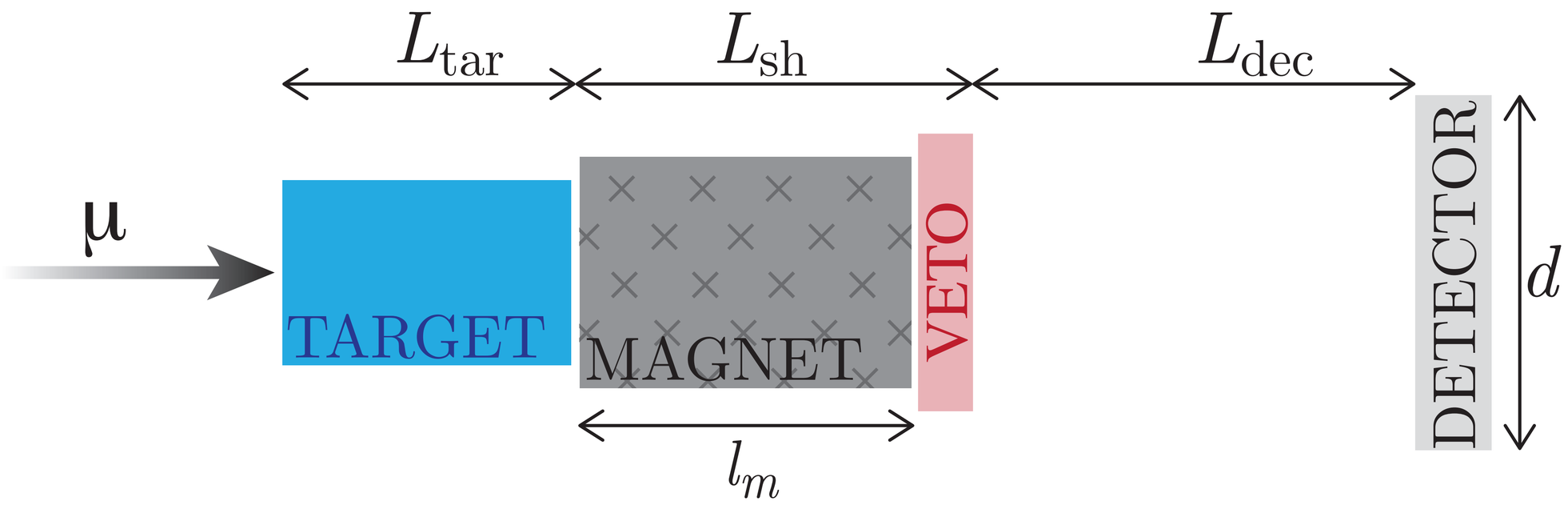
Beam Dump Setup



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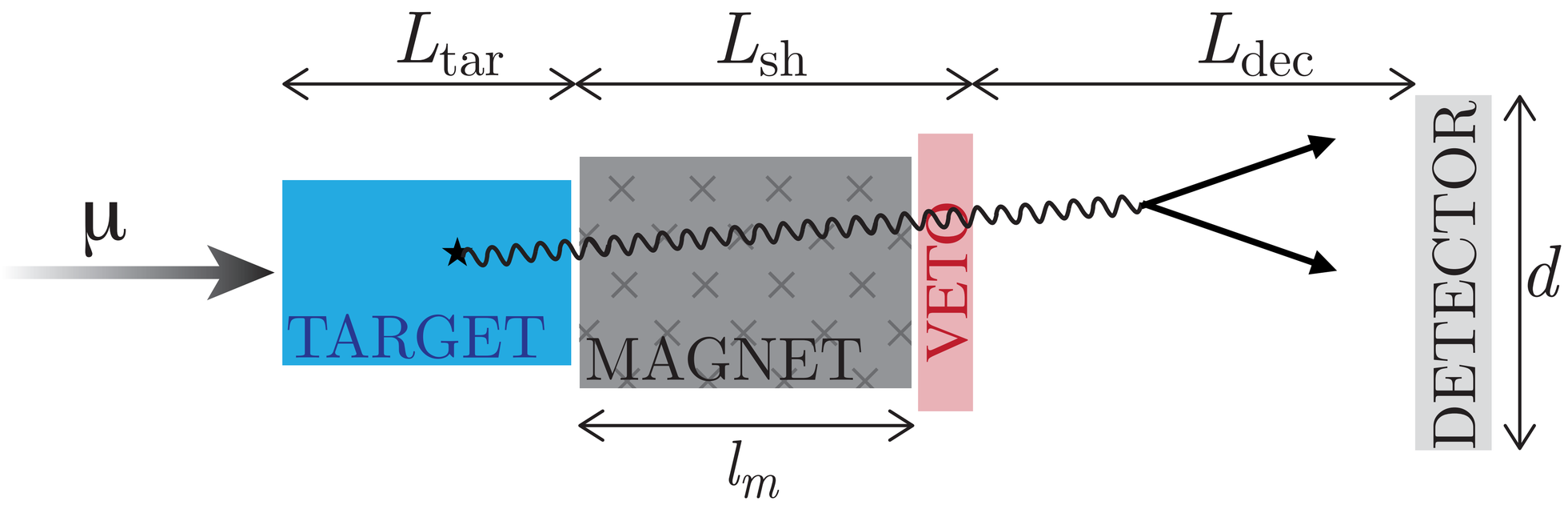

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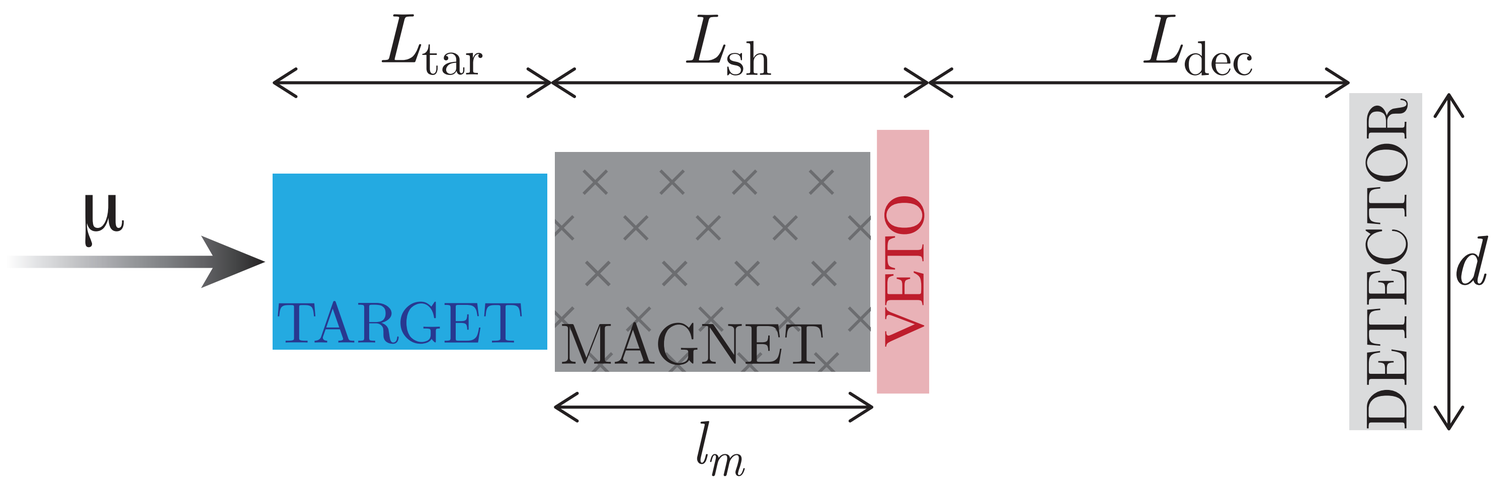
Number of signal events depends on l_0 and experiment geometry



2202.12302 CC, S. Homiller, R. Mishra, M. Reece

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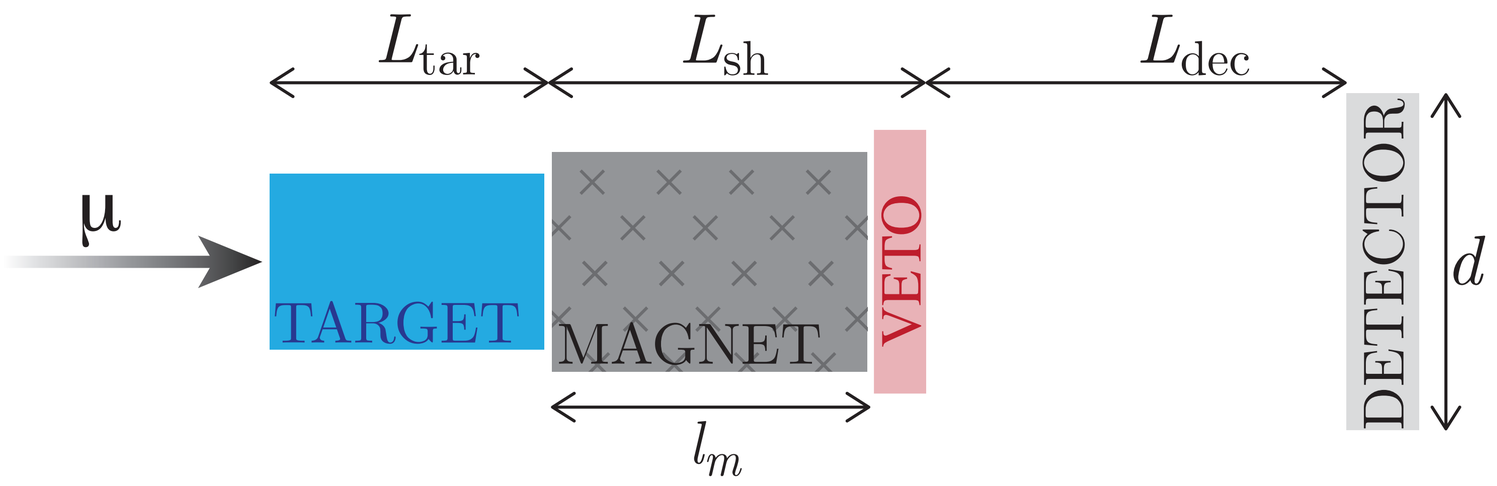
$$\frac{dN}{dx} = N_\mu \frac{N_0 \rho l_0}{A} \frac{d\sigma}{dx} \left(e^{L_{tar}/l_0} - 1\right) e^{-(L_{tar}+L_{sh})/l_0} \left(1 - e^{-L_{dec}/l_0}\right)$$



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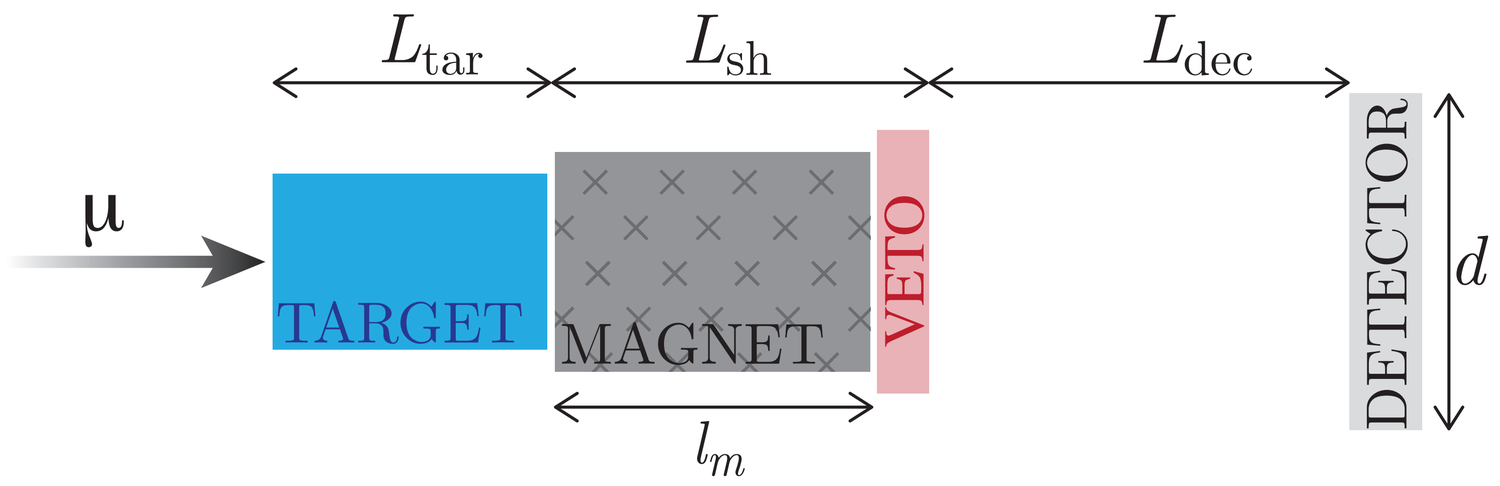
Signal events

$$x \equiv \frac{E_{Z'}}{E_{beam}}$$



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Number of μ

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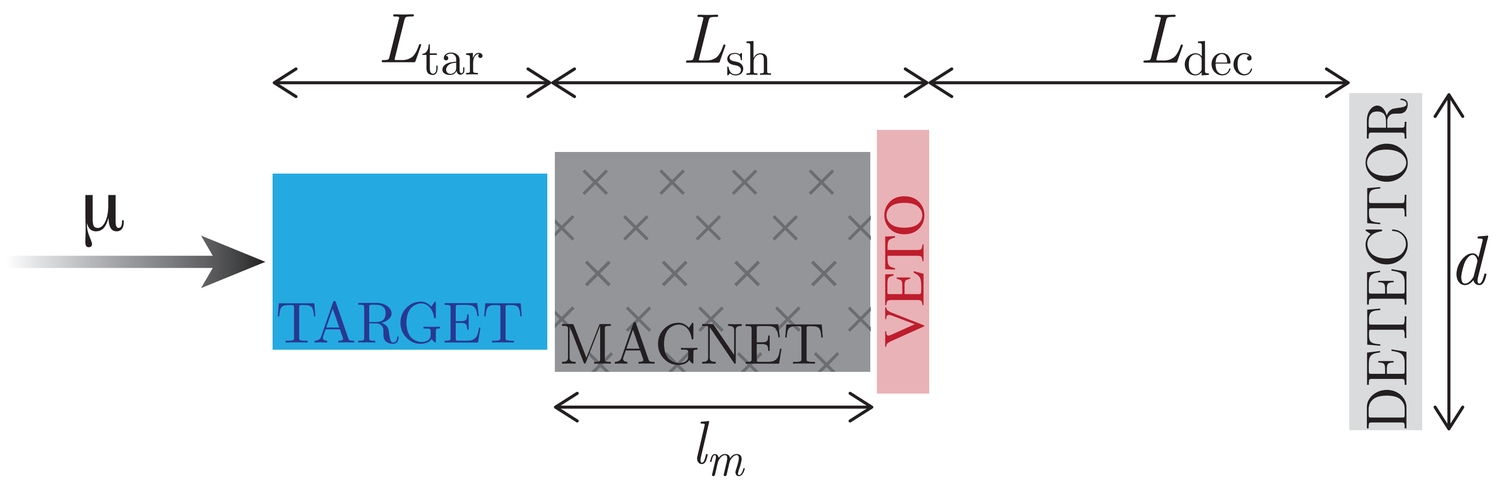

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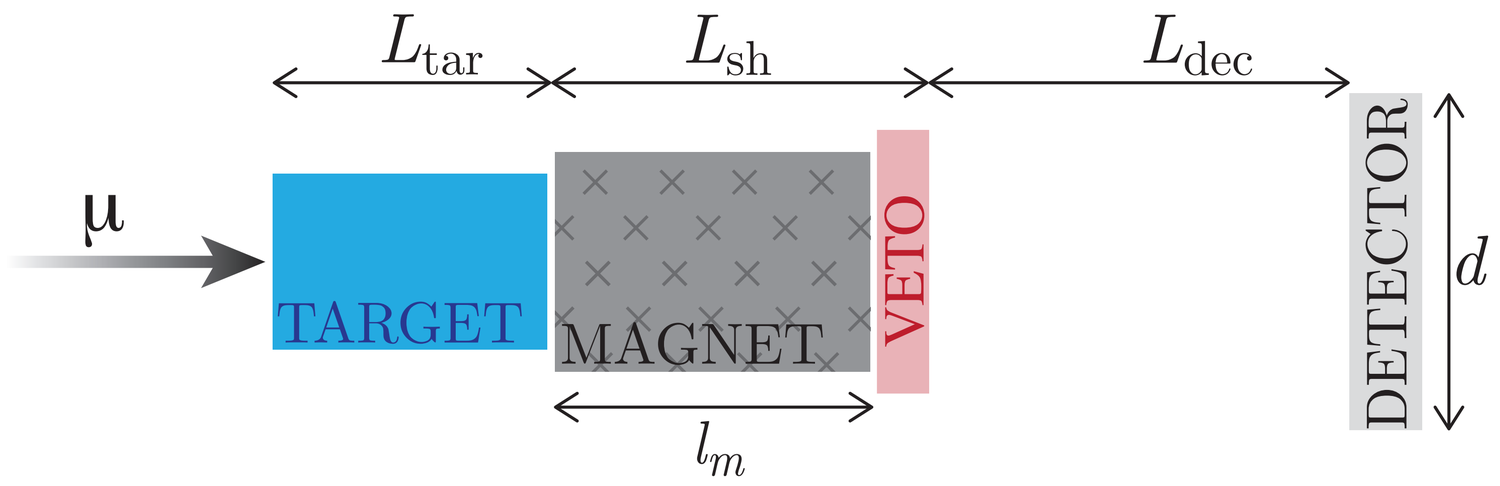
Detector material

$$x \equiv \frac{E_{Z'}}{E_{beam}}$$



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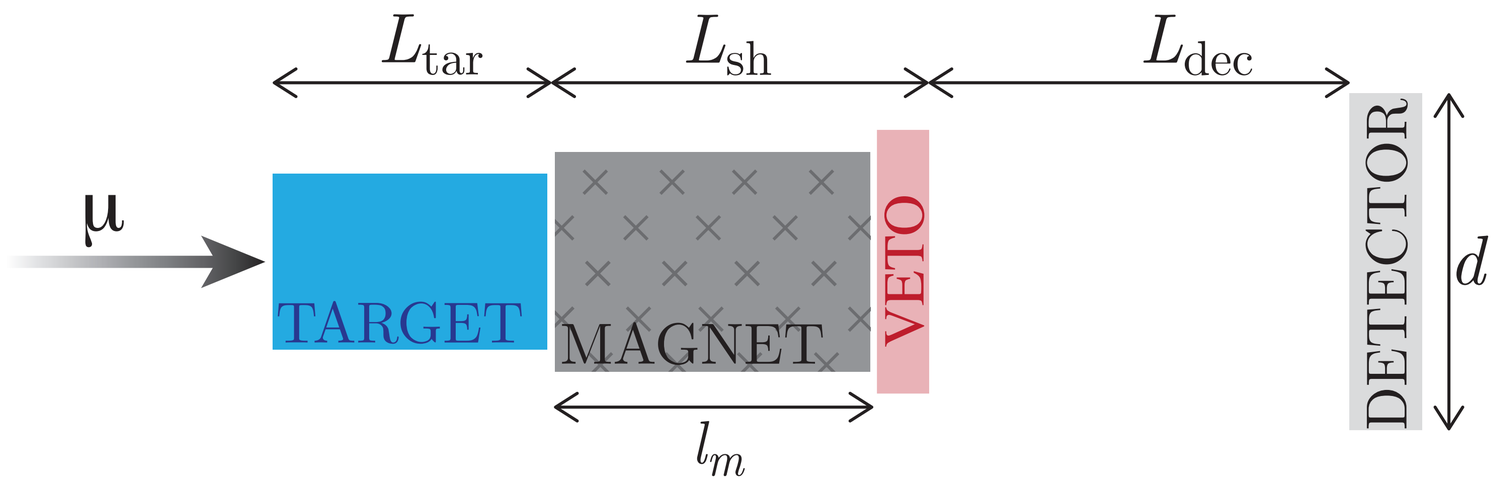
Production cross section

$$x \equiv \frac{E_{Z'}}{E_{beam}}$$



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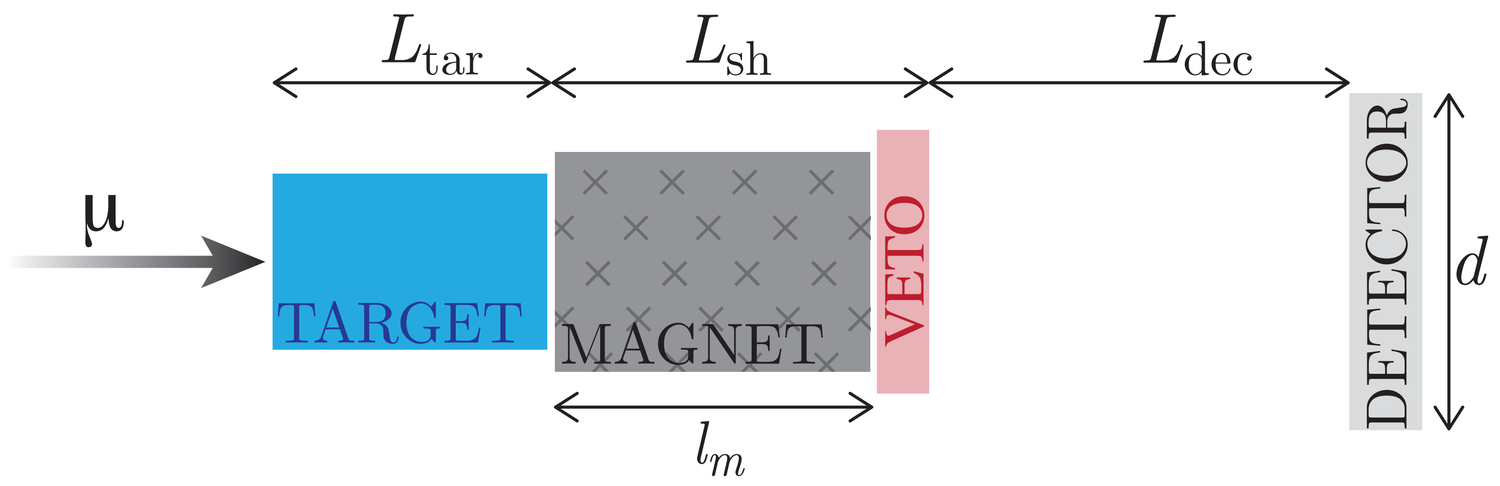
Probability of decay

$$x \equiv \frac{E_{Z'}}{E_{beam}}$$



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Dark Photon Reach

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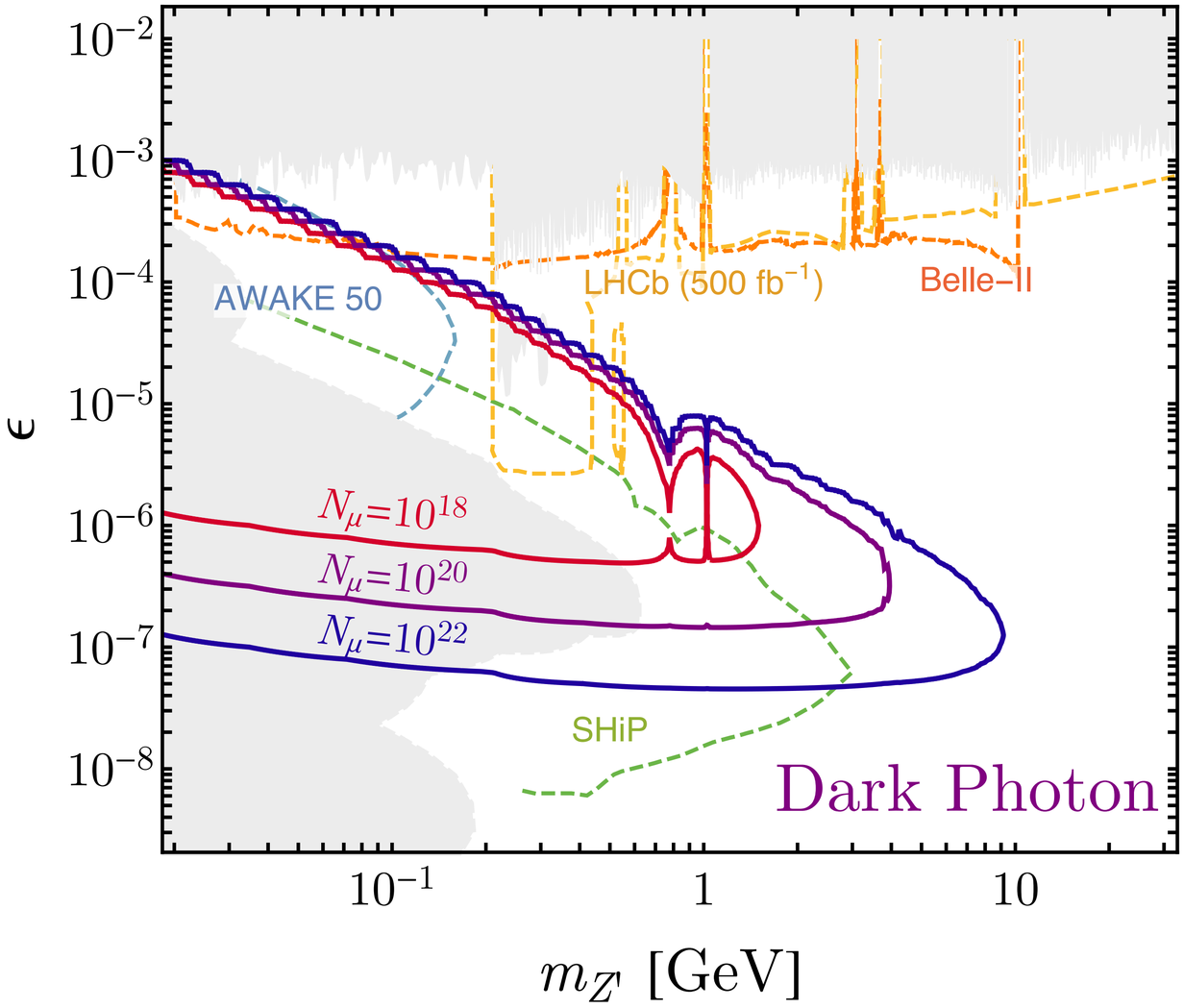

Water target

$L_{\rm tar} = 10$ m

$L_{\rm sh} = 10$ m

$L_{\rm dec} = 100$ m

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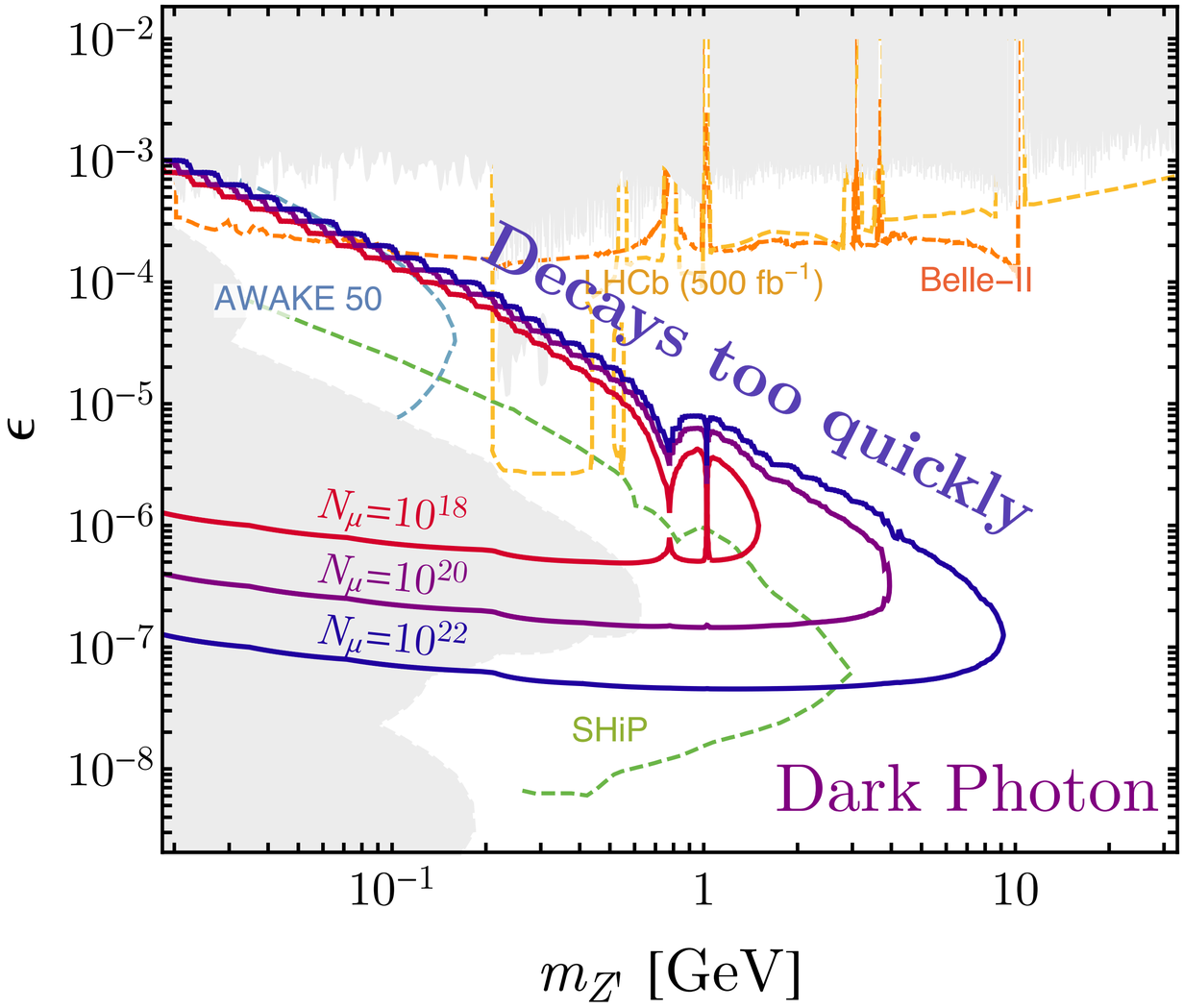

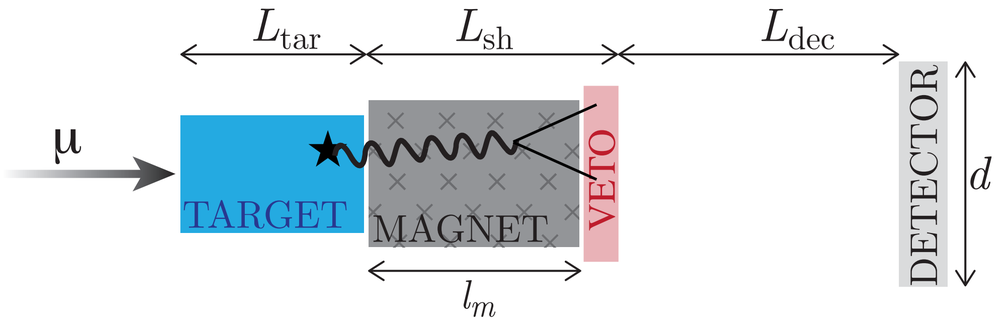

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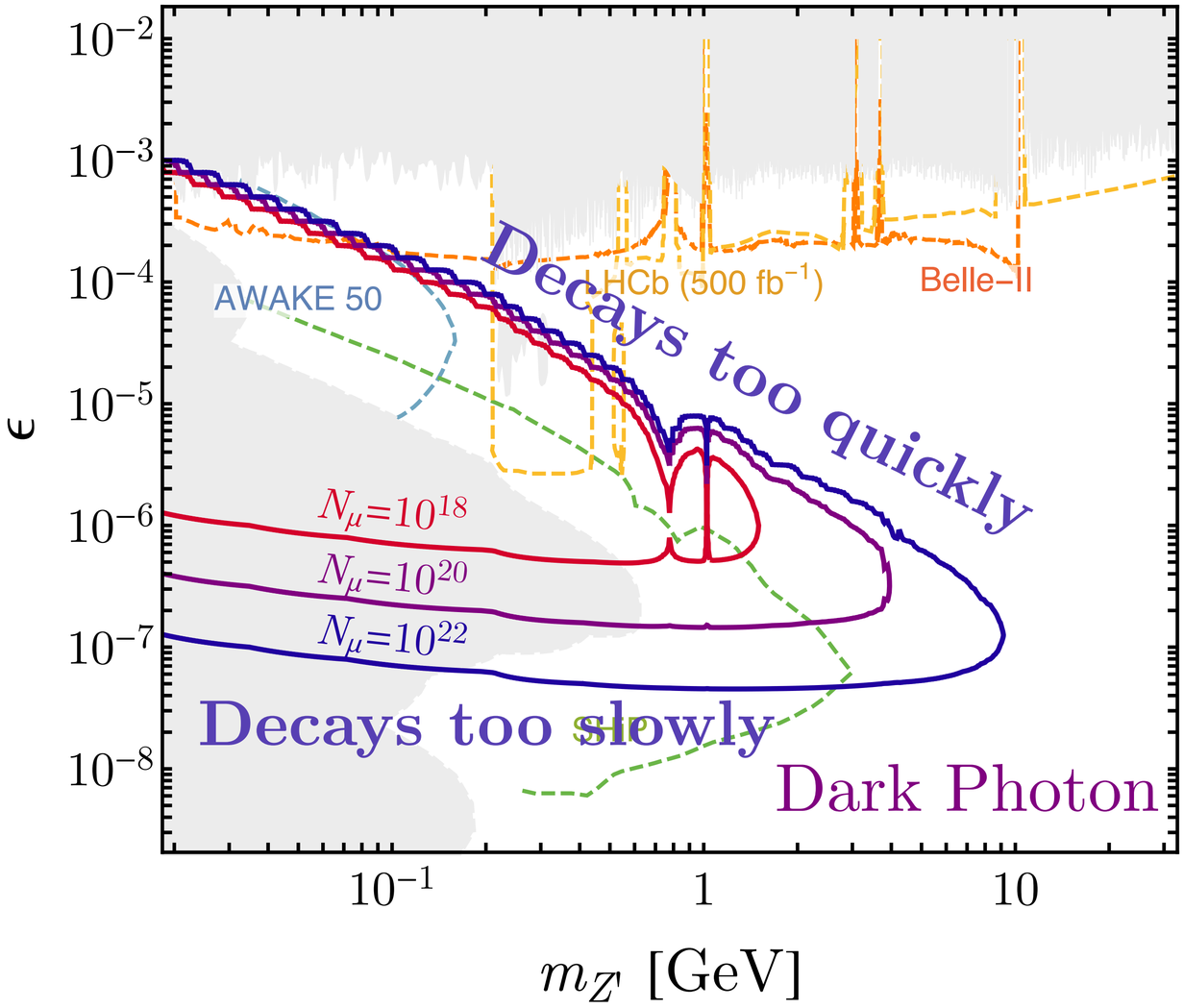

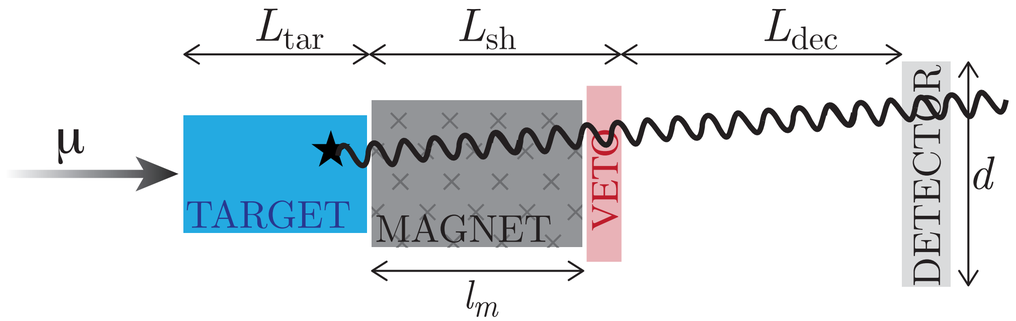

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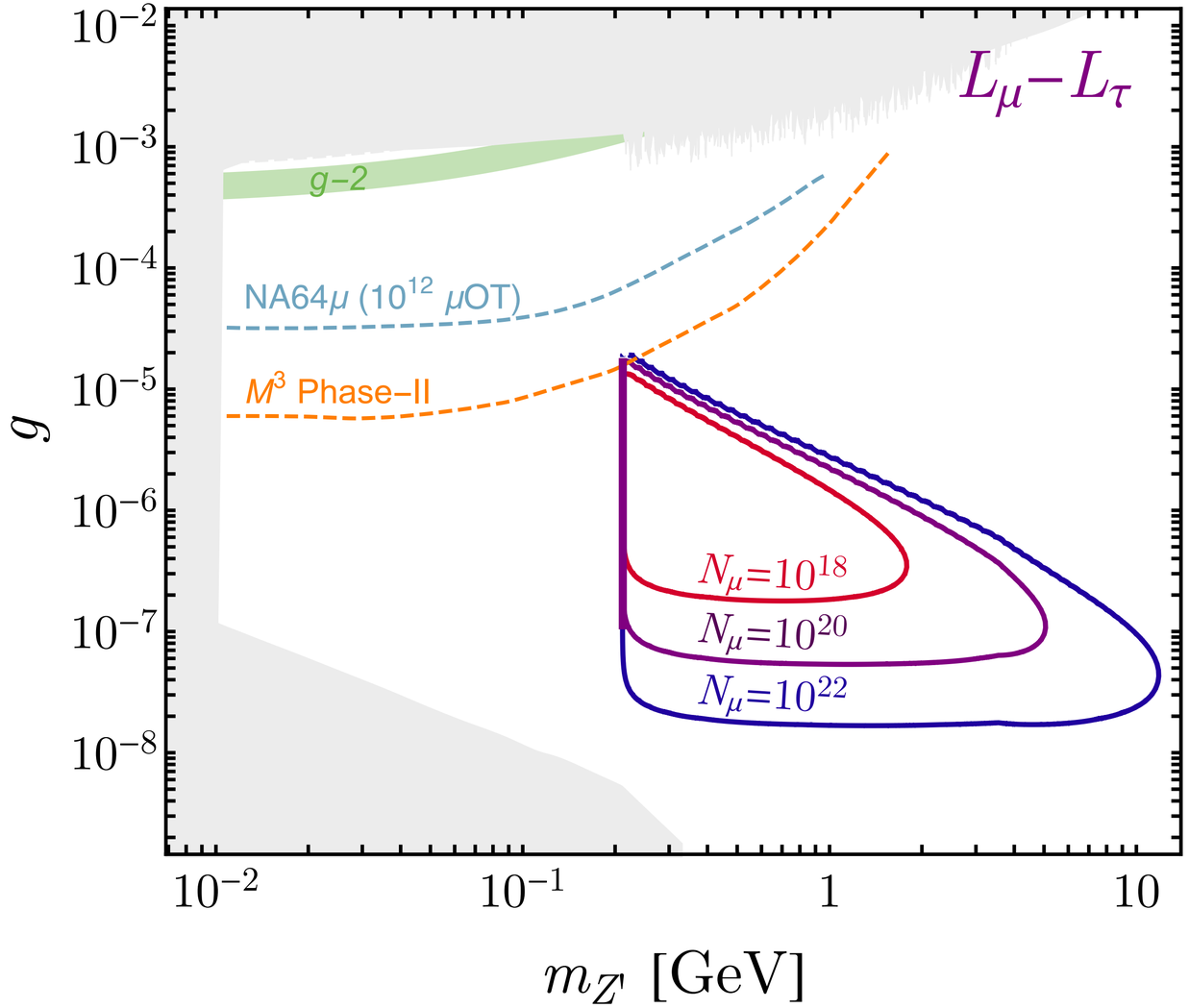

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Summary

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

2202.12302 CC, S. Homiller, R. Mishra, M. Reece

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Leptoquarks are a motivated and novel signal to consider at μC

We should take advantage of a TeV μC to probe intensity frontier with a μBD

Progress can be made in studies along the way

2104.05720 CC, P. Asadi, R Capdevilla, S. Homiller 2202.12302 CC, S. Homiller, R. Mishra, M. Reece

Backups

Leptoquarks

Flavor observables

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

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]	$\beta_L^{33} \times \beta_L^{32}$	
$\mathrm{BR}\,(\tau \to \mu\phi)$	$< 8.4 \times 10^{-8}$	$\beta_L^{23} \times \beta_L^{22}$	
$\mathrm{BR}\,(D_s \to \mu\nu)$	$< 5.49 \times 10^{-3}$	$\beta_L^{22} \times \beta_L^{22}$	
$\mathrm{BR}\,(D_s \to \tau\nu)$	$< 5.48 \times 10^{-2}$	$\beta_L^{23} \times \beta_L^{23}$	
$\mathrm{BR}\,(B \to K\tau\mu)$	$< 2.8 \times 10^{-5}$	$\beta_L^{32} \times \beta_L^{23}$	$\beta_L^{33} \times \beta_L^{22}$
$\mathrm{BR}\,(B_s \to \tau\mu)$	$< 4.2 \times 10^{-5}$	$\beta_L^{32} \times \beta_L^{23}$	$\beta_L^{33} \times \beta_L^{22}$
$\mathrm{BR}\,(B_s \to \tau\tau)$	$< 2.1 \times 10^{-3}$	$\beta_L^{33} \times \beta_L^{23}$	

2103.16558

Leptoquarks

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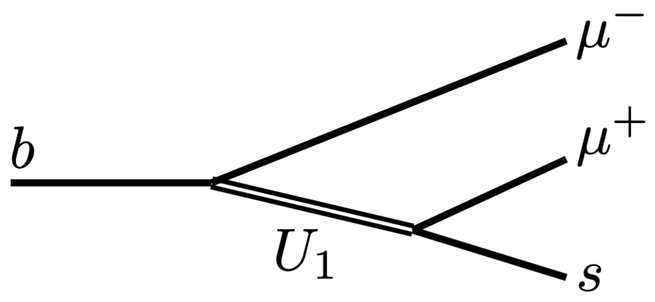
$$U_1 = (3,1)_{2/3}$$

$$R_K = \frac{B \to K e^+ e^-}{B \to K \mu^+ \mu^-}$$

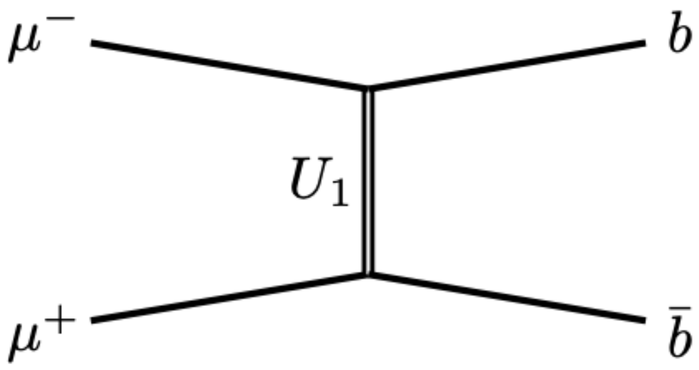


$$\frac{\beta_L^{22}\beta_L^{32}}{m_{U_1}^2} = 1.98 \times 10^{-3}\ \mathrm{TeV}^{-2}$$

2103.16558

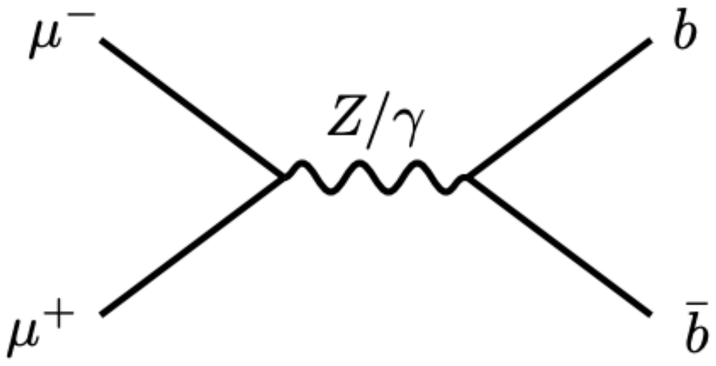
Leptoquarks

Drell-Yan† Production



t-channel

SM Background



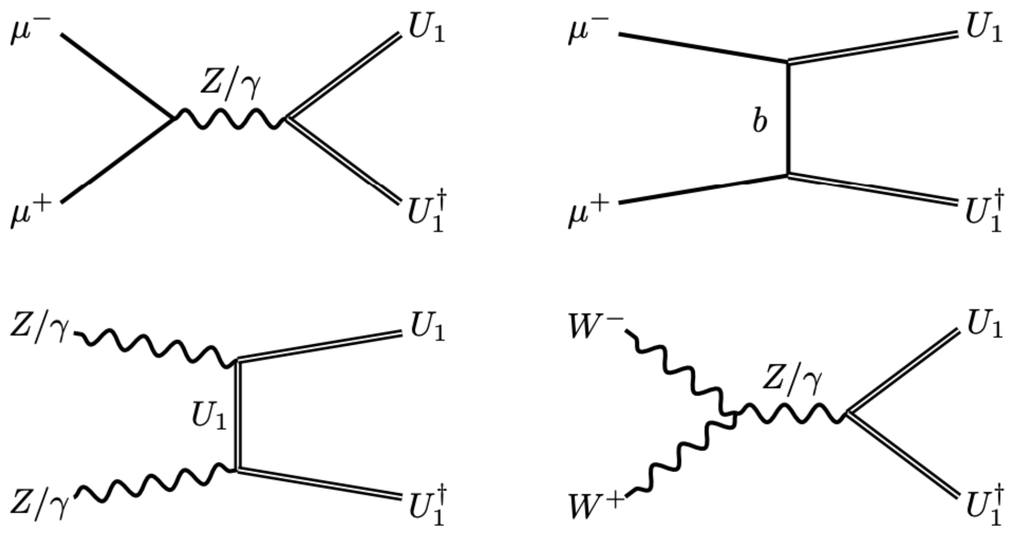
s-channel

Simulated with MG5

Leptoquarks

Pair Production

$U_1 \to \mu^+ b, \tau^+ b$



SM Background

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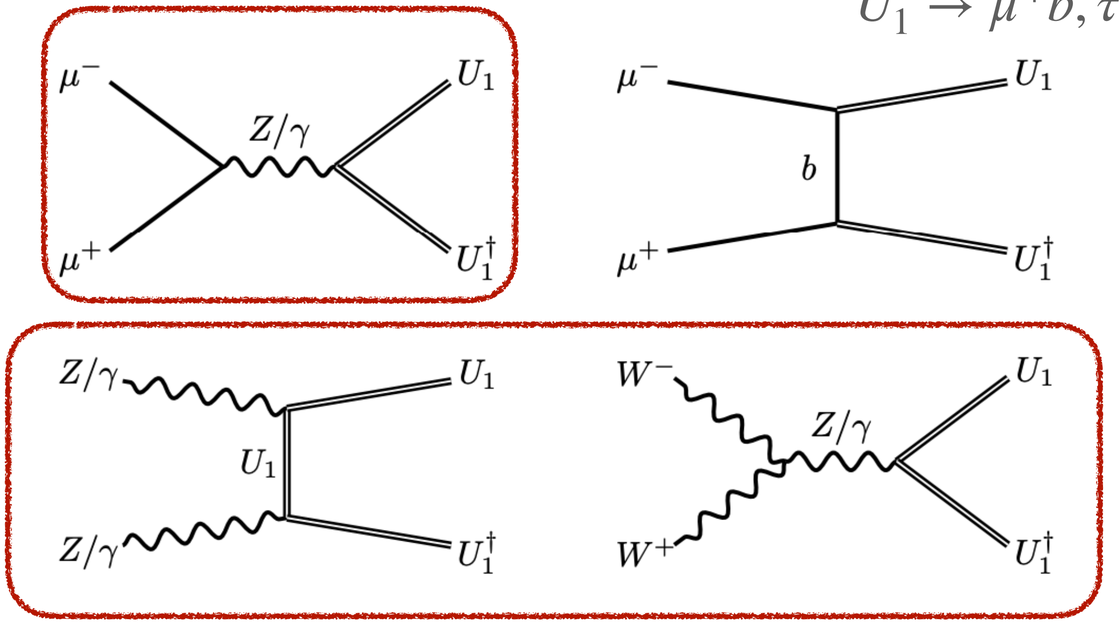

No direct coupling to muons

SM Background

Simulated with MG5

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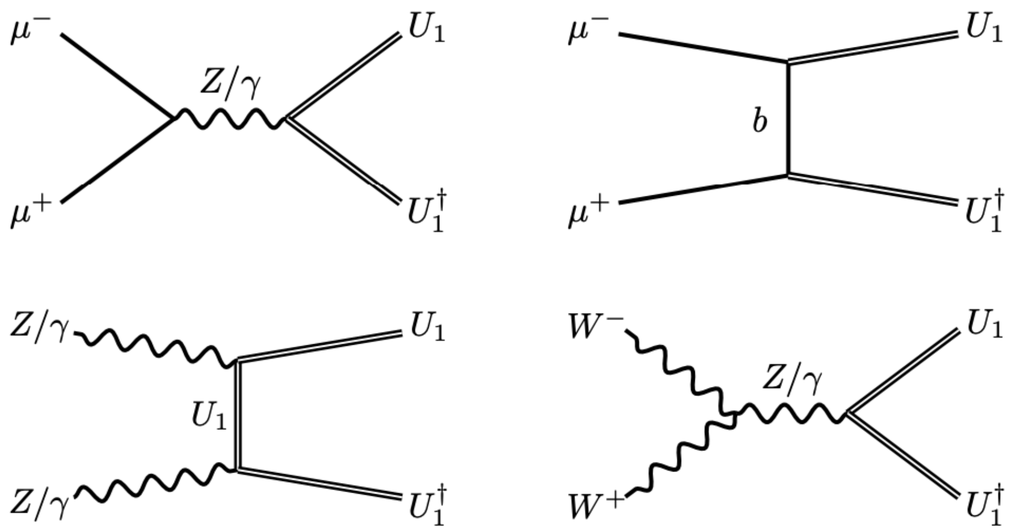

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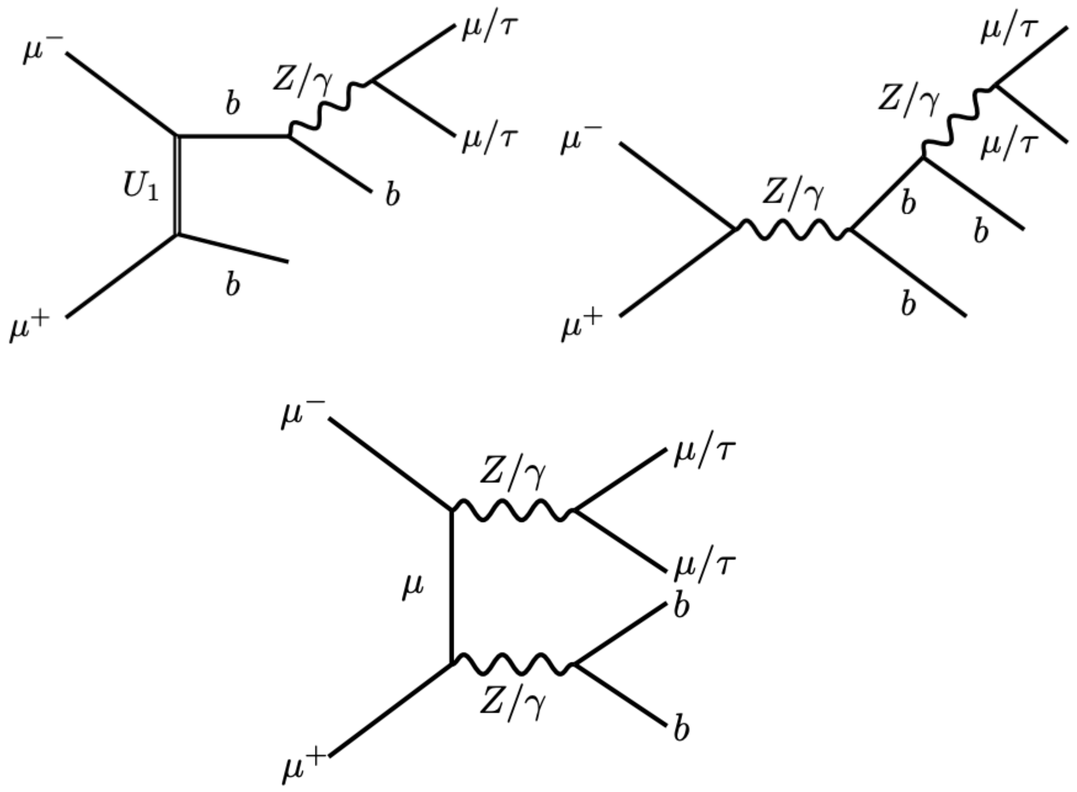

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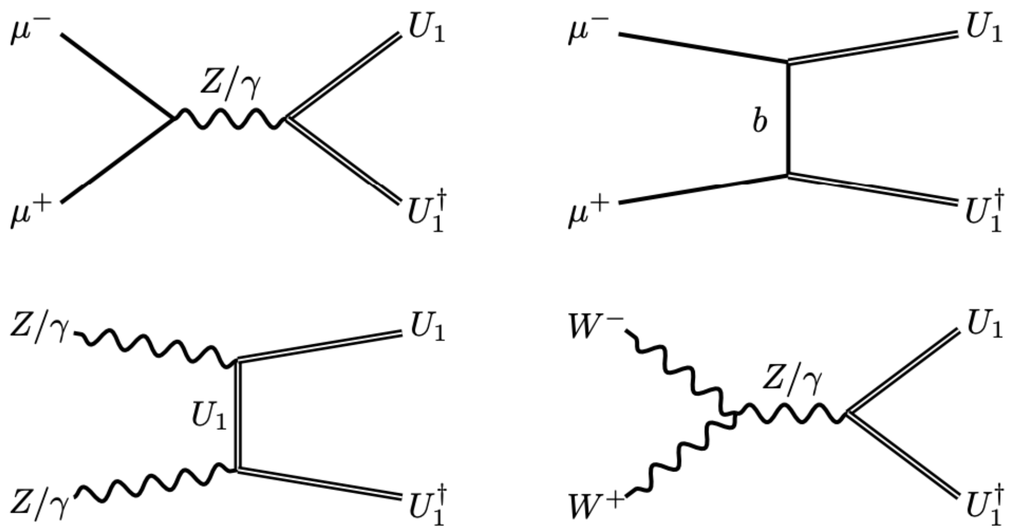
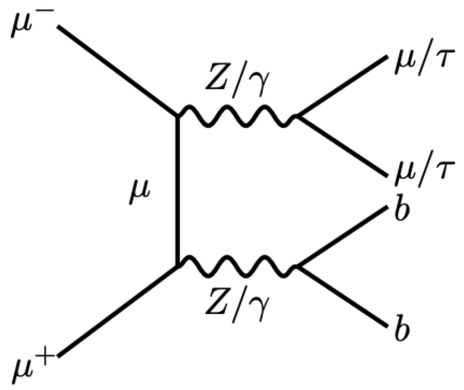
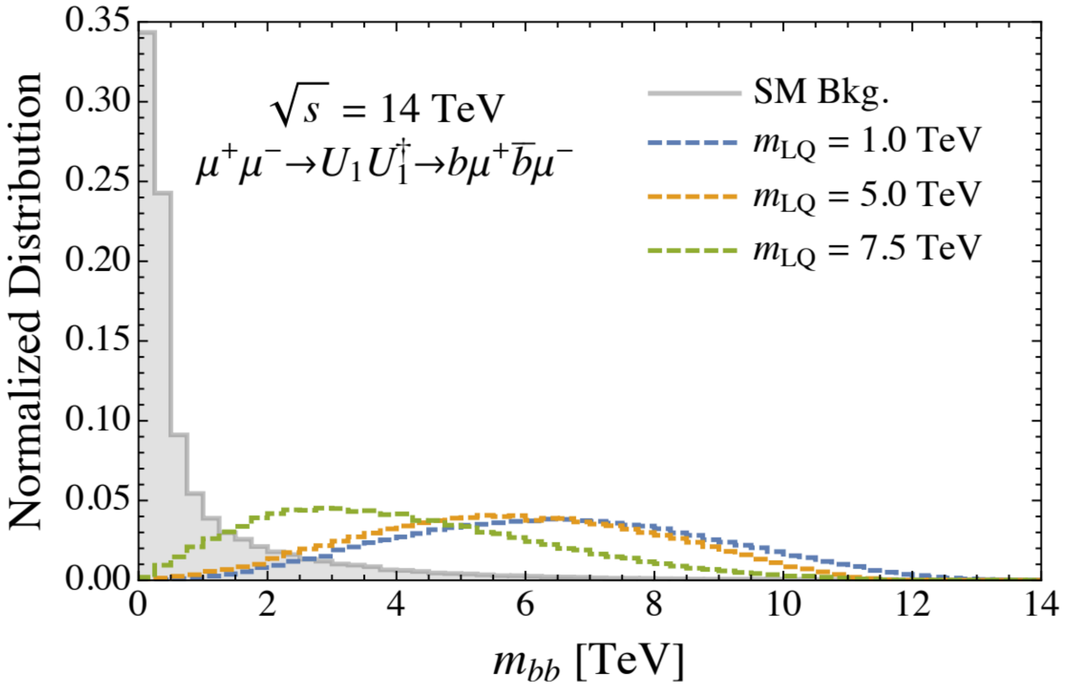


SM Background

Mitigated with m_{bb} cut





Simulated with MG5

Muon Beam Dump (μBD)

Existing BD literature

At existing experiments

New Fixed-Target Experiments to Search for Dark Gauge Forces

James D. Bjorken,[1] Rouven Essig,[1] Philip Schuster,[1] and Natalia Toro[2]

At future experiments

Beam Dump Experiment at Future Electron-Positron Colliders

Shinya Kanemura[(a)], Takeo Moroi[(b)], Tomohiko Tanabe[(c)]

Leptophilic Gauge Bosons at ILC Beam Dump Experiment

Kento Asai[(a,b)], Takeo Moroi[(a)] and Atsuya Niki[(a)]

With μ

Muon Beam Experiments to Probe the Dark Sector

Chien-Yi Chen,[1,2,*] Maxim Pospelov,[1,2,†] and Yi-Ming Zhong[3,‡]

- 160 GeV, 3 GeV
- Light scalars