# Searching for New Physics at future Muon Colliders

**Cari Cesarotti, Harvard University**

**BSM PANDEMIC Seminar, December 7 2021**


(2104.05720) P. Asadi, R. Capdevilla, S. Homiller

*(Work in Progress)* S. Homiller, R. Mishra, M. Reece

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

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**Expand energy & intensity frontier**

**Construct new colliders**

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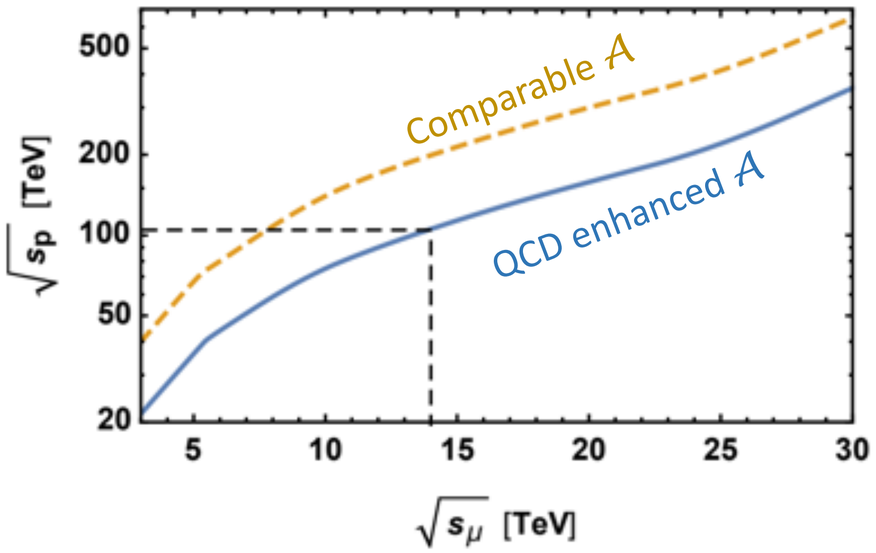
1901.06150



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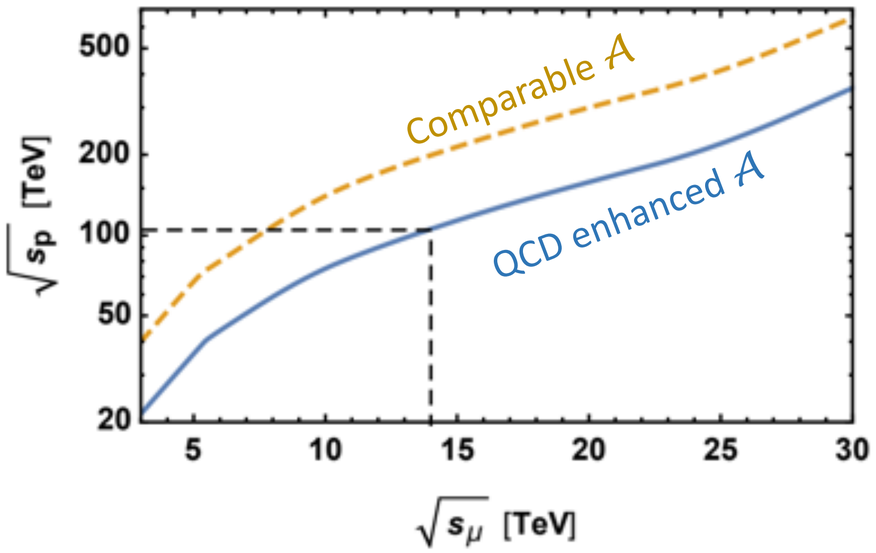

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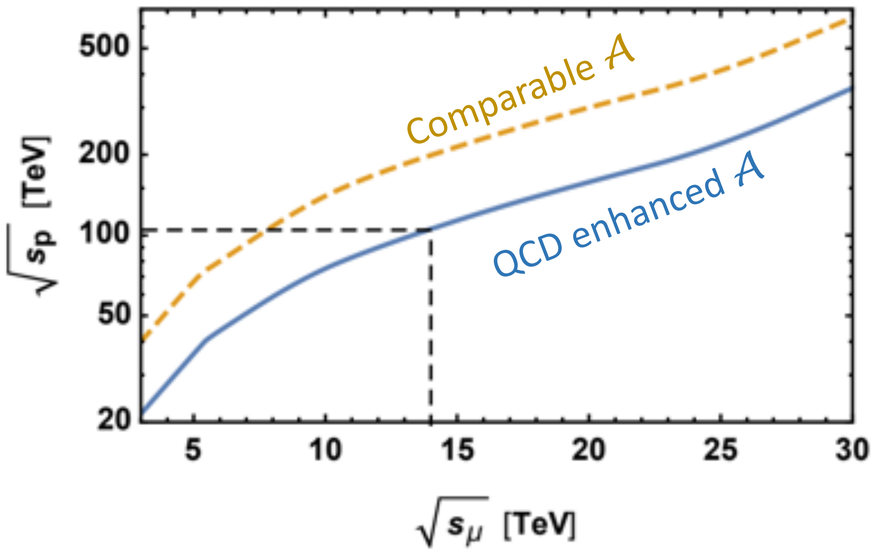

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$e^+e^-$

- Synchrotron radiation

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- $2^{nd}$ gen couplings

$e^+e^-$

- Synchrotron radiation
- $1^{st}$ gen couplings

# Muon Colliders ($\mu C$)

Community effort to explore physics case of $\mu C$

**The Muon Smasher's Guide**

Hind Al Ali[1], Nima Arkani-Hamed[2], Ian Banta[1], Sean Benevedes[1], Dario Buttazzo[3], Tianji Cai[1], Junyi Cheng[1], Timothy Cohen[4], Nathaniel Craig[1], Majid Ekhterachian[5], JiJi Fan[6], Matthew Forslund[7], Isabel Garcia Garcia[8], Samuel Homiller[9], Seth Koren[10], Giacomo Koszegi[1], Zhen Liu[5,11], Qianshu Lu[9], Kun-Feng Lyu[12], Alberto Mariotti[13], Amara McCune[1], Patrick Meade[7], Isobel Ojalvo[14], Umut Oktem[1], Diego Redigolo[15,16], Matthew Reece[9], Filippo Sala[17], Raman Sundrum[5], Dave Sutherland[18], Andrea Tesi[16,19], Timothy Trott[1], Chris Tully[14], Lian-Tao Wang[10], and Menghang Wang[1]

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Future multi-TeV $\mu C$ provides a complementary and robust physics program

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Part I: Energy Frontier

*Specific NP scenario: Leptoquarks*

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Part II: Intensity Frontier

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# Leptoquarks at $\mu C$

***Leptoquarks are motivated***

- Emerges in Pati-Salam spectrum from GUT
- Address various flavor anomalies
- $\mu C$ explores complementary parameter space

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

# Leptoquarks

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

Minimal $U_1$ Leptoquark EFT

$$\mathscr{L}_{U_1} \supset -\frac{1}{2} {U_1}^{\dagger}_{\mu\nu} U_1^{\mu\nu} + m^2_{U_1} {U_1}^{\dagger}_{\mu} U_1^{\mu} - i g_s {U_1}^{\dagger}_{\mu} T^a U_{a\nu} G^{a\,\mu\nu}$$

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

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*Direct production with $\mu C$*

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- Only including LH couplings
- Assuming $U_1$ is fundamental
- Additional $\beta_{ij}$ ansatz

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

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Relative strength determines final states

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

# Leptoquarks

Free parameters of the model

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

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

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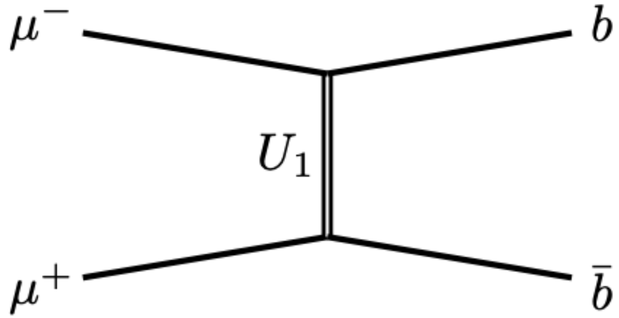
*Final states of $U_1$ decays*

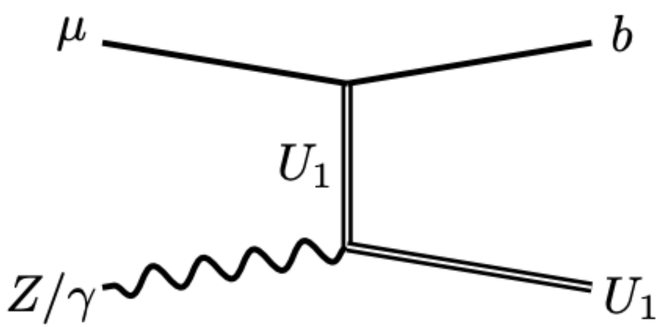
| Scenarios | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| $(\beta_L^{22}, \beta_L^{23}, \beta_L^{33})$ | $(0,\ 0,\ 0)$ | $(\beta_L^{32},\ 0,\ 0)$ | $(0,\ 0.1,\ 1)$ | $(\beta_L^{32},\ 0.1,\ 1)$ |

# Leptoquarks

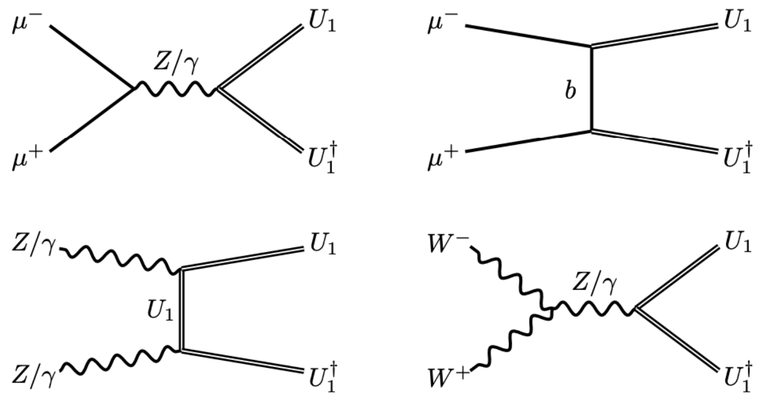
## *Production Modes*




Drell-Yan†




Single Production




Pair Production

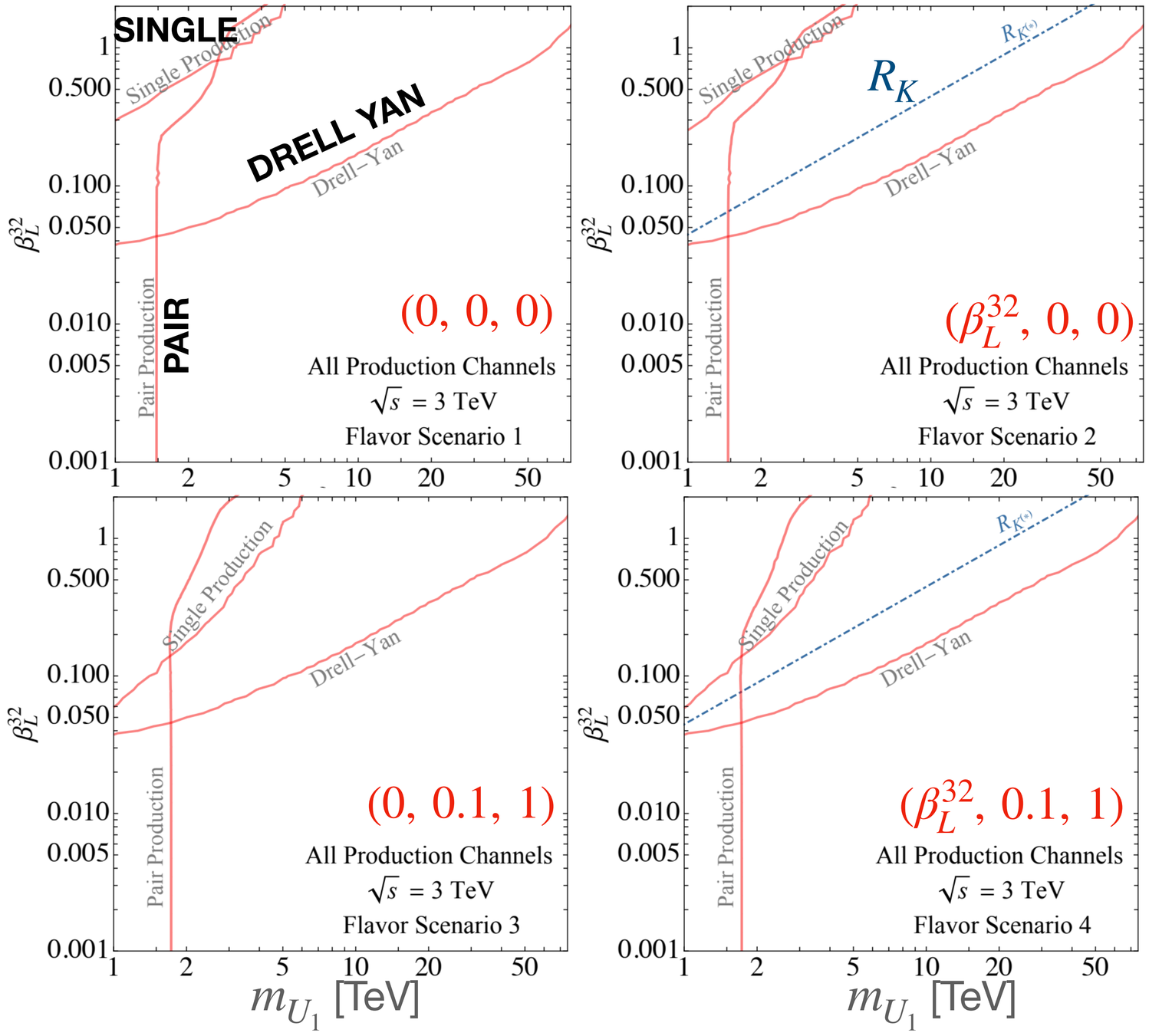
Simulated with MG5

# Leptoquarks

## $5\sigma$ confidence limits

## 3 TeV $\mu C$

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



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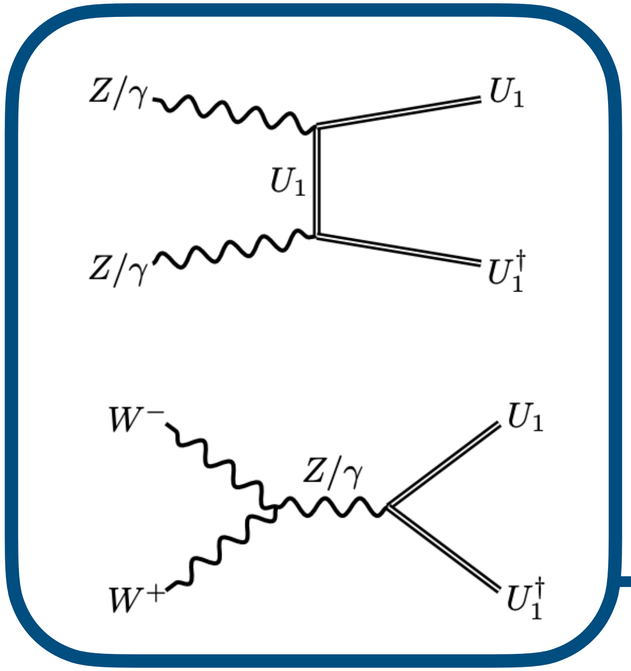


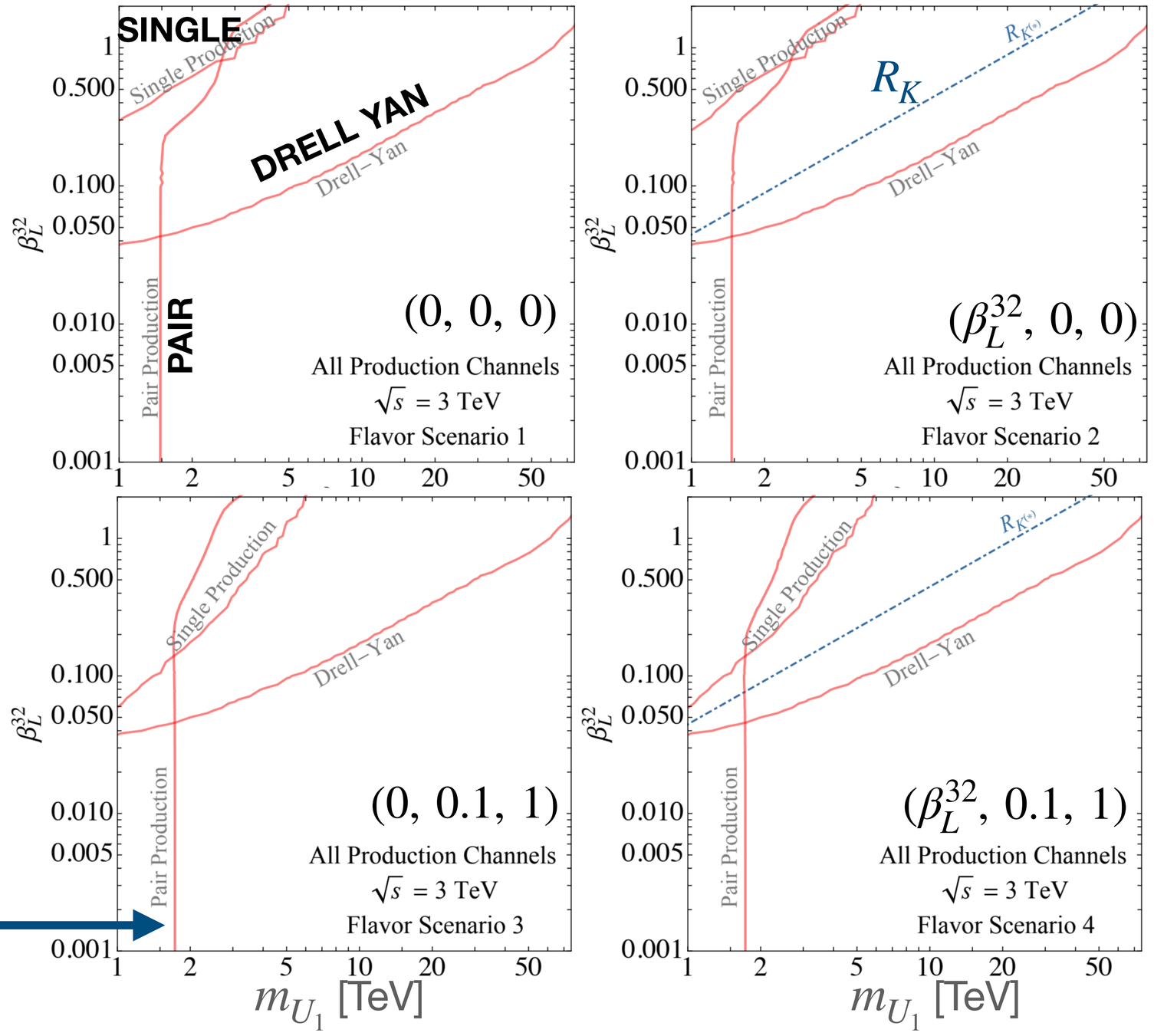

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## 3 TeV $\mu C$

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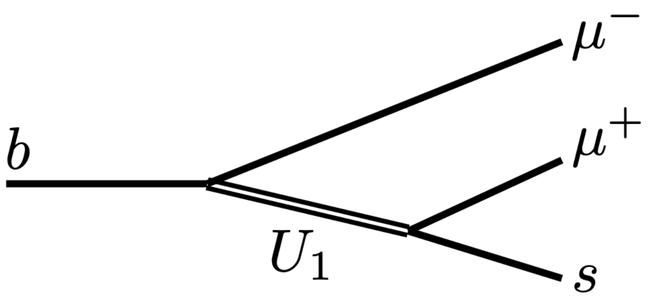
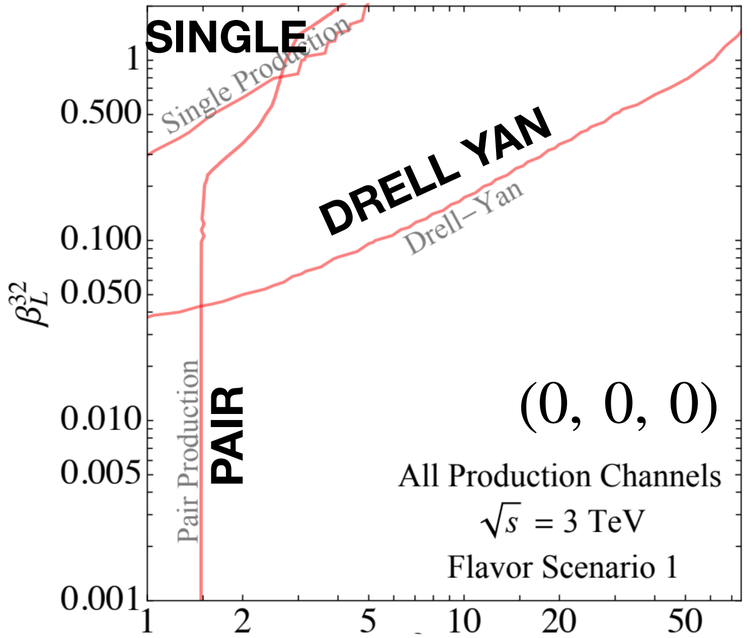
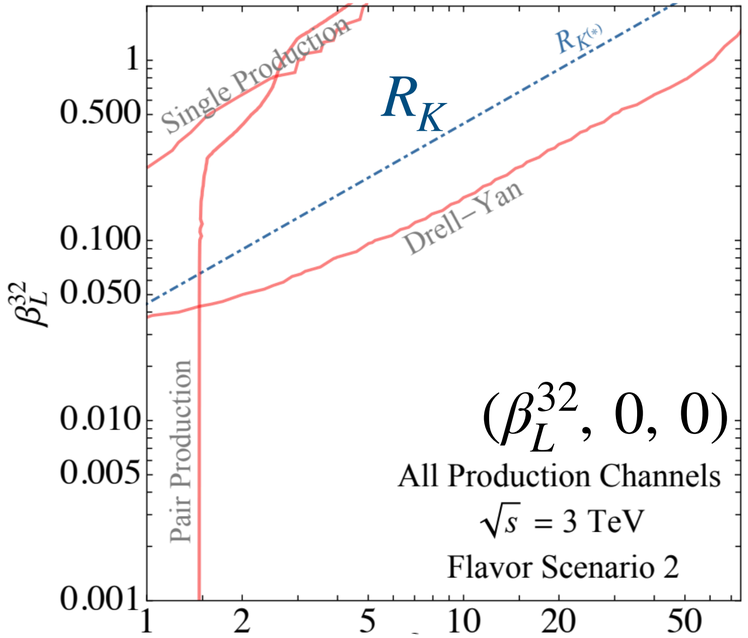
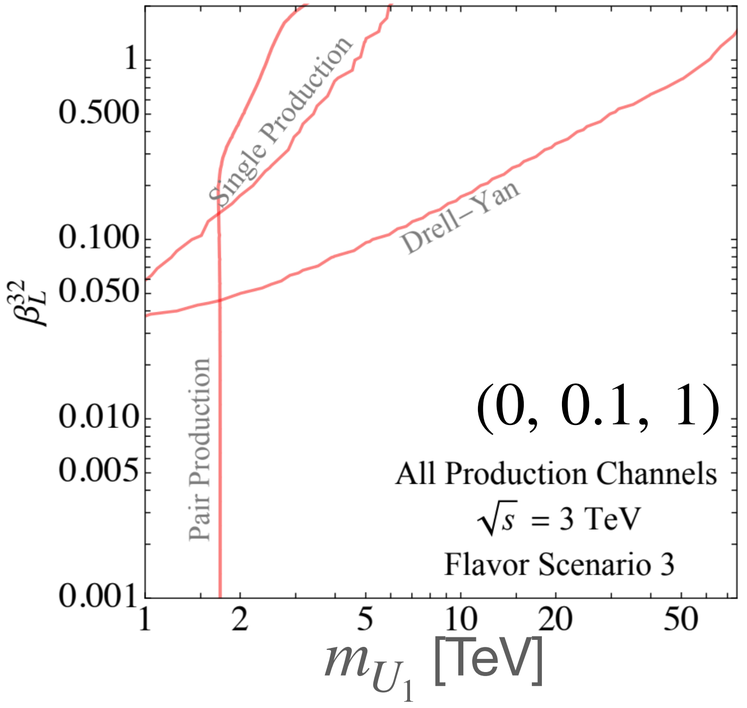
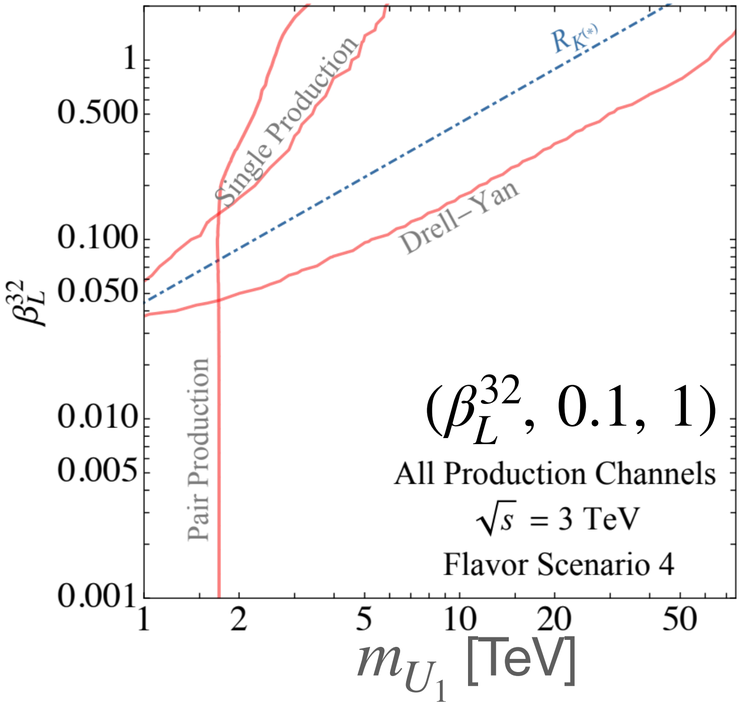
$$R_K = \frac{B \to K e^+ e^-}{B \to K \mu^+ \mu^-}$$



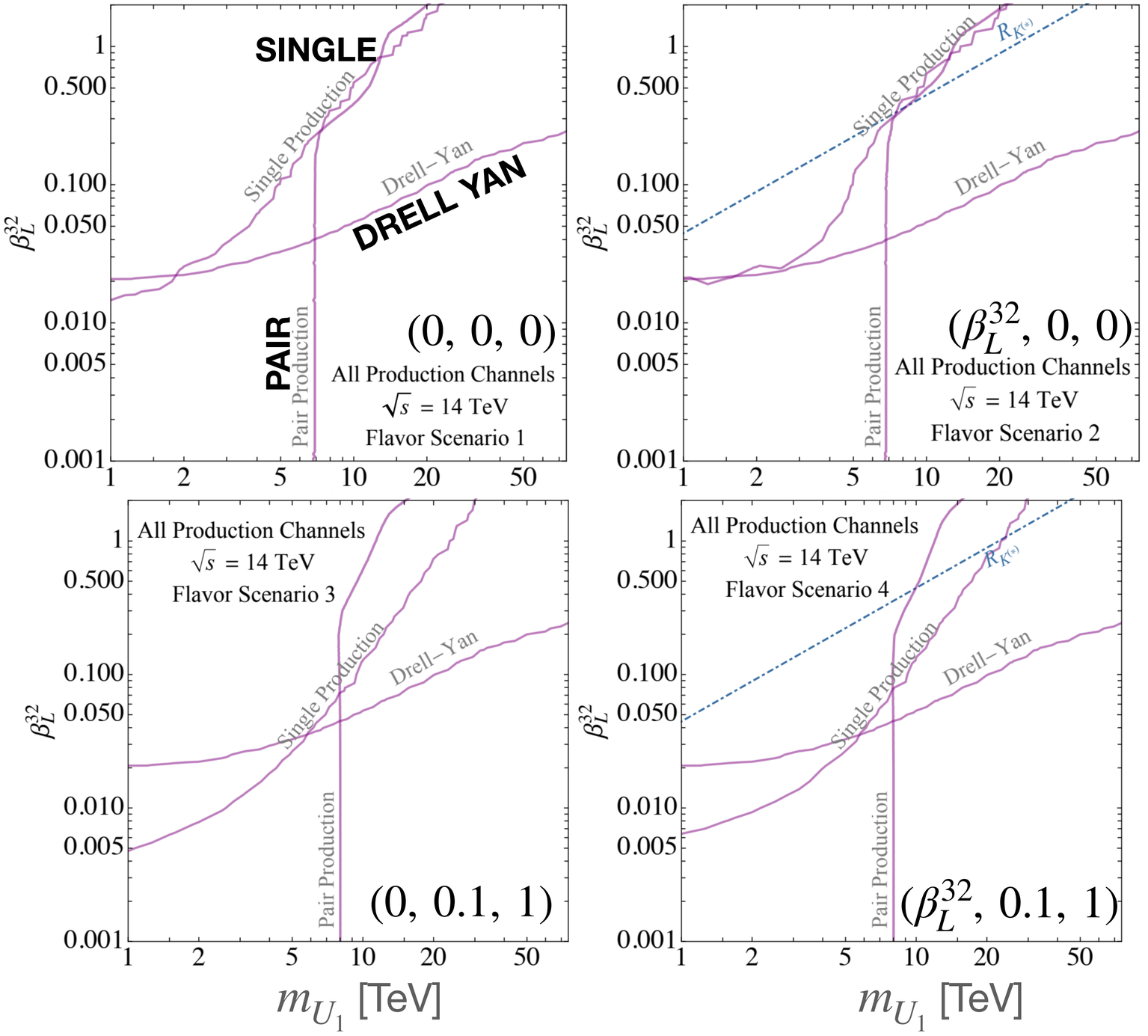



# Leptoquarks

## $5\sigma$ confidence limits

## 14 TeV $\mu C$

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



# Leptoquarks

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

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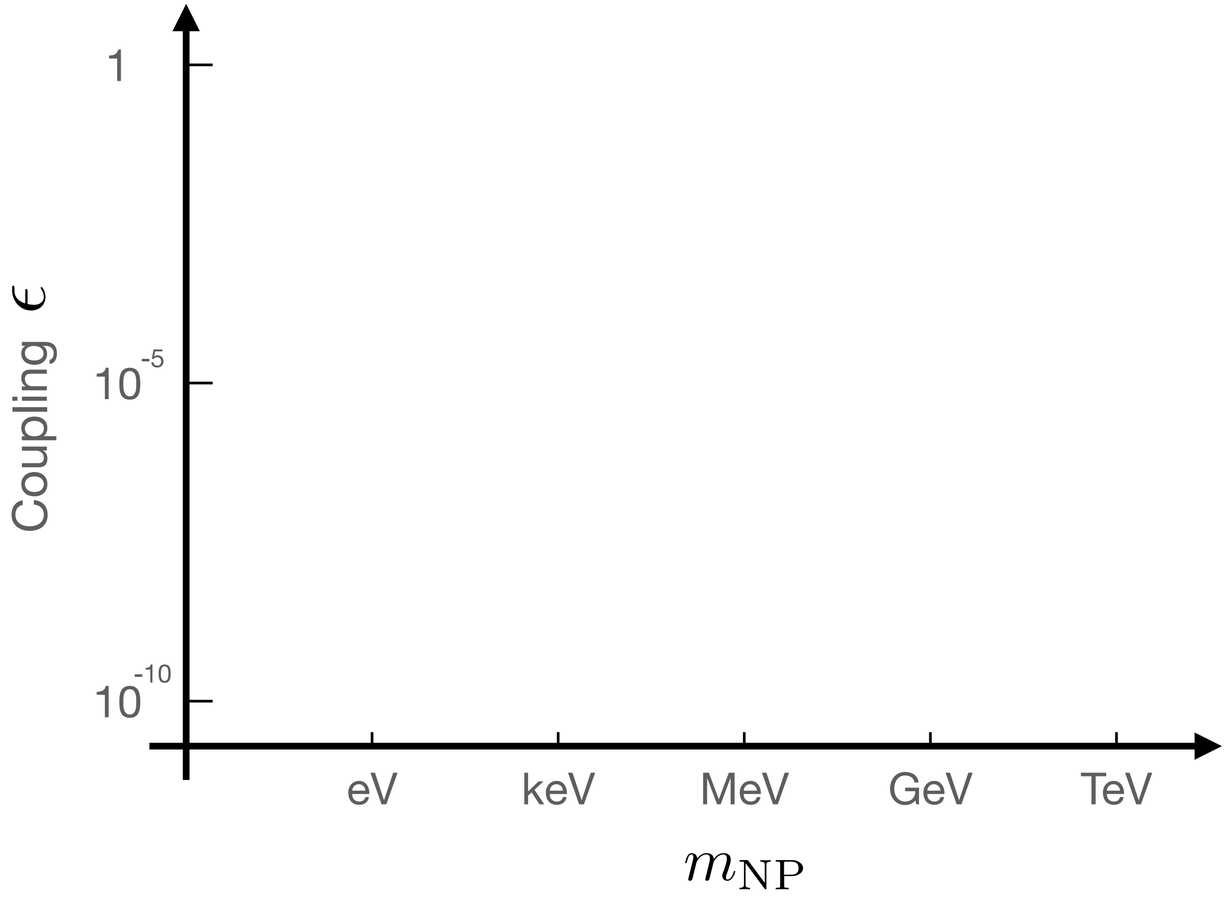
# Searching for Physics Beyond the SM

***How do we effectively explore parameter space?***



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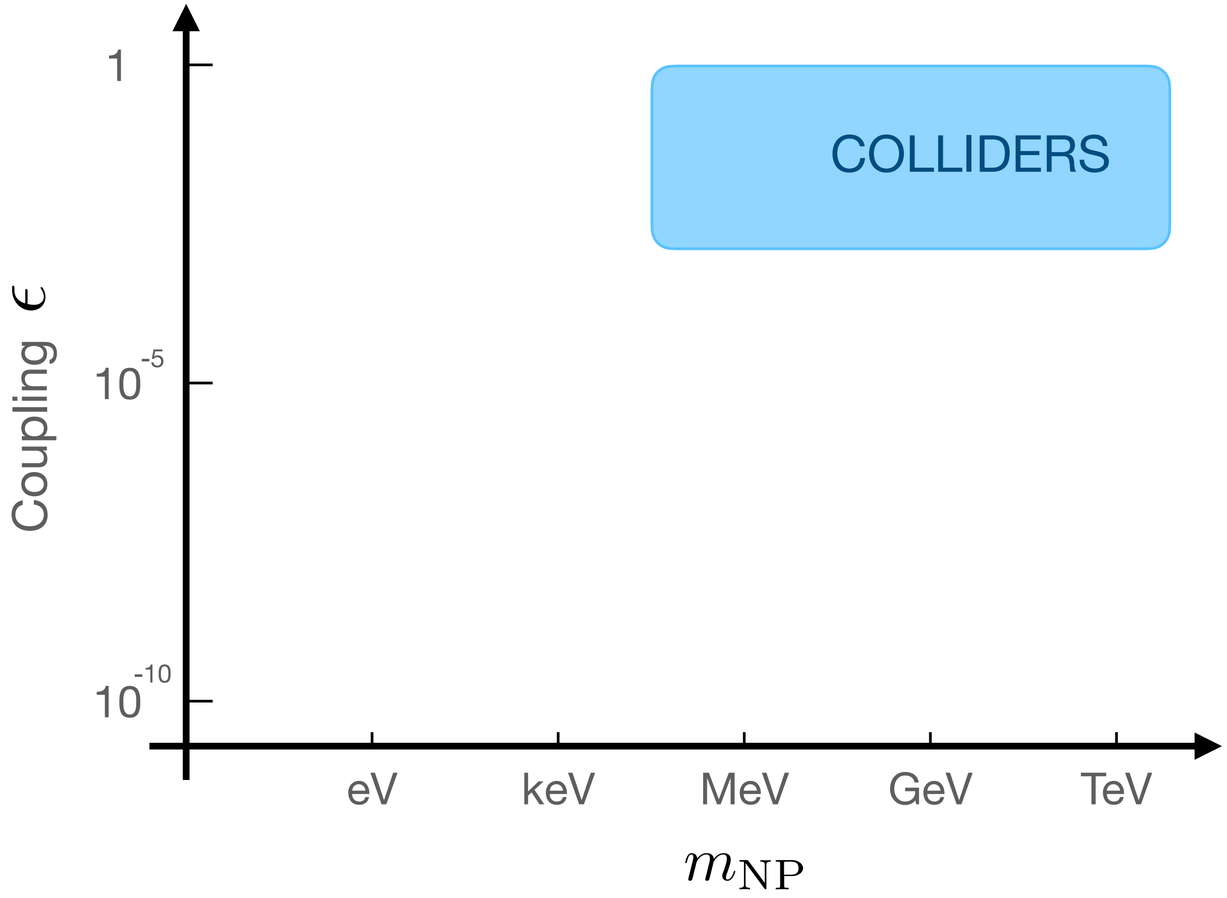

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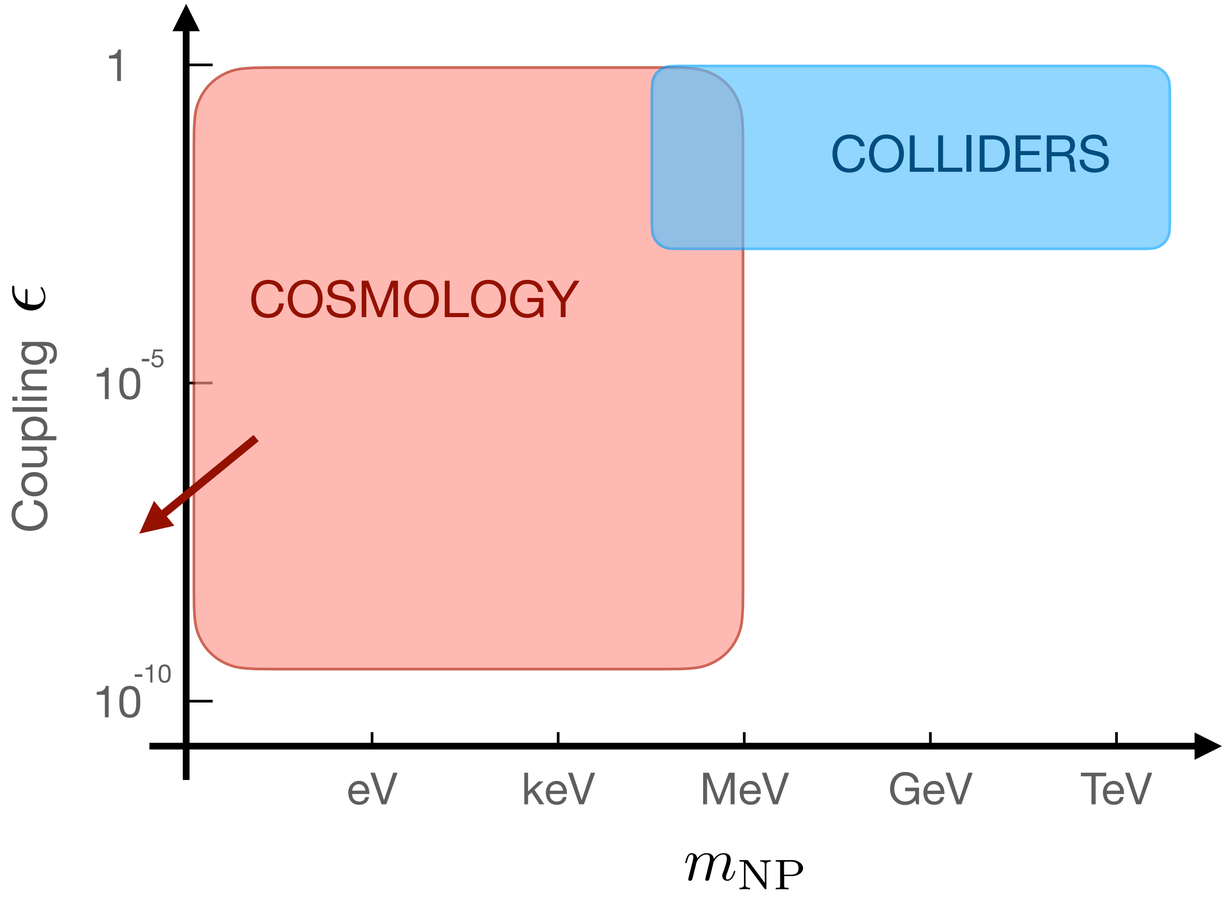

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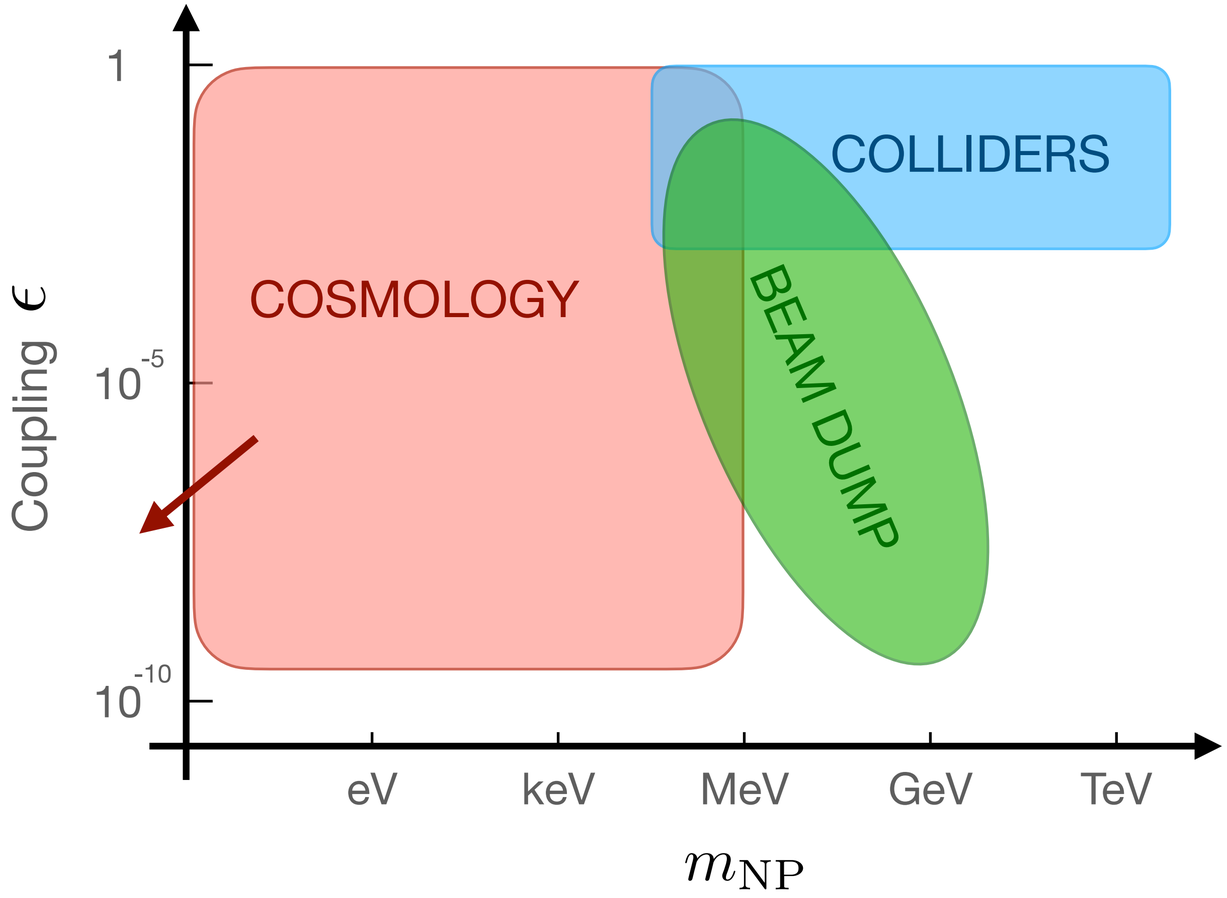

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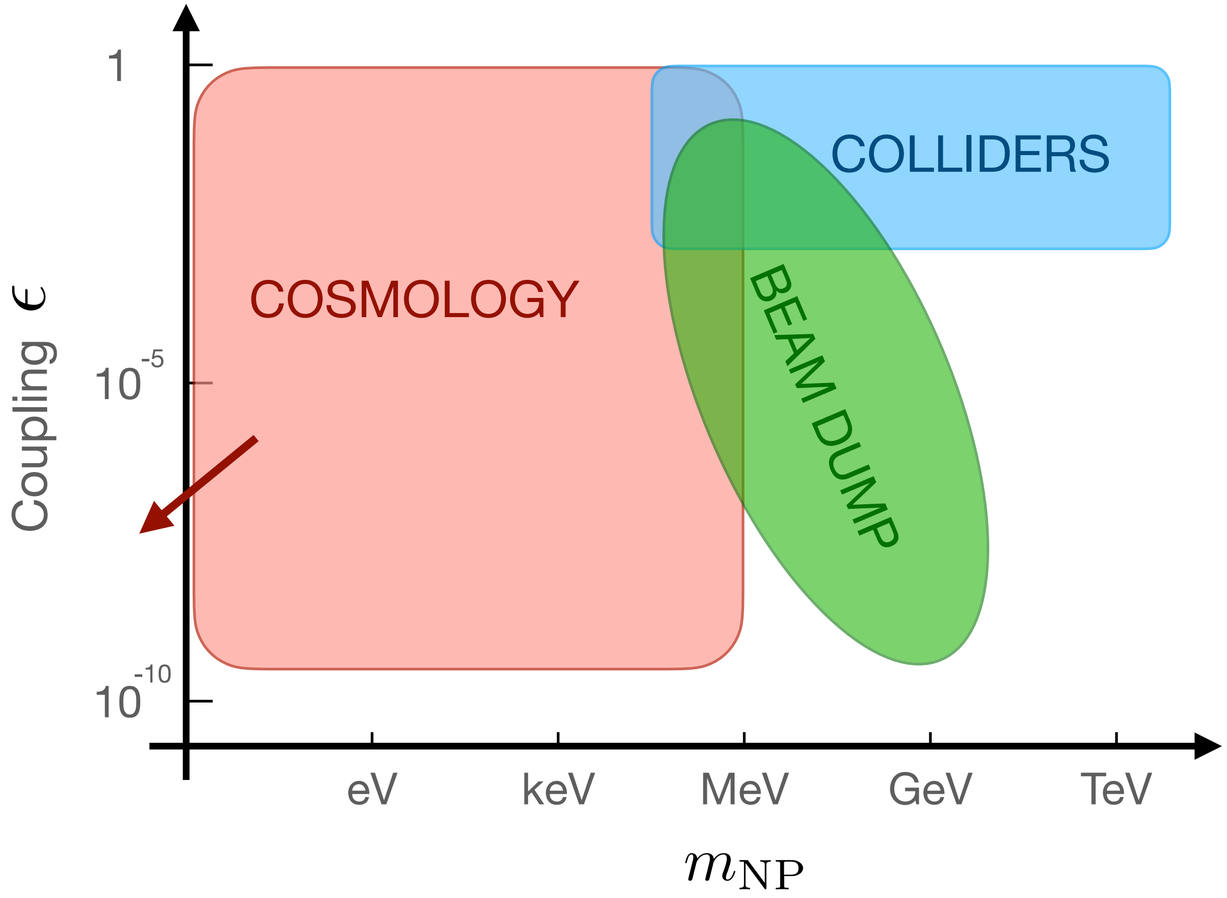
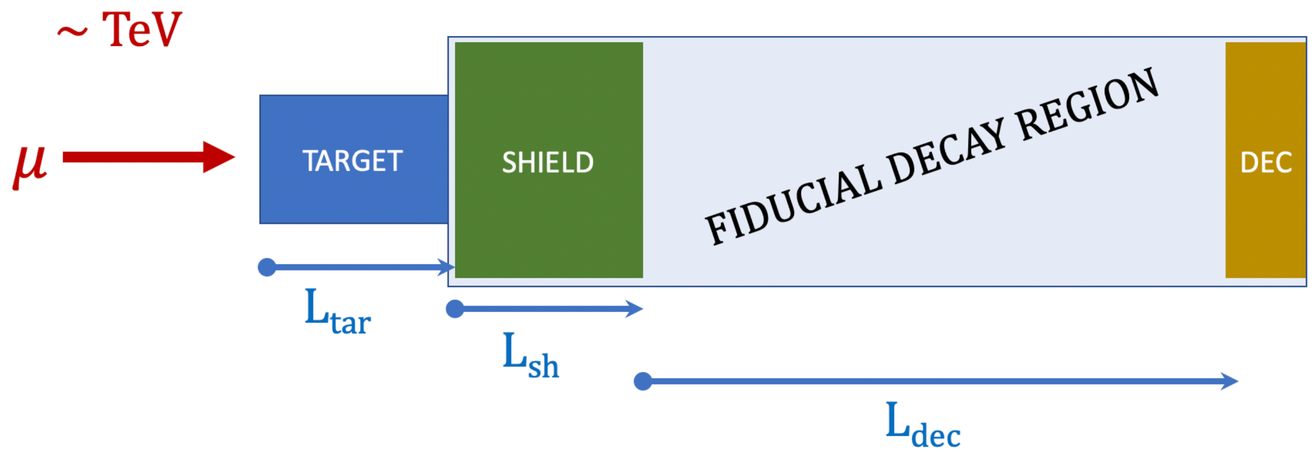



If we build a $\mu C$, we should consider a beam dump!

# Muon Beam Dump ($\mu$BD)

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

Can probe NP scenarios with:



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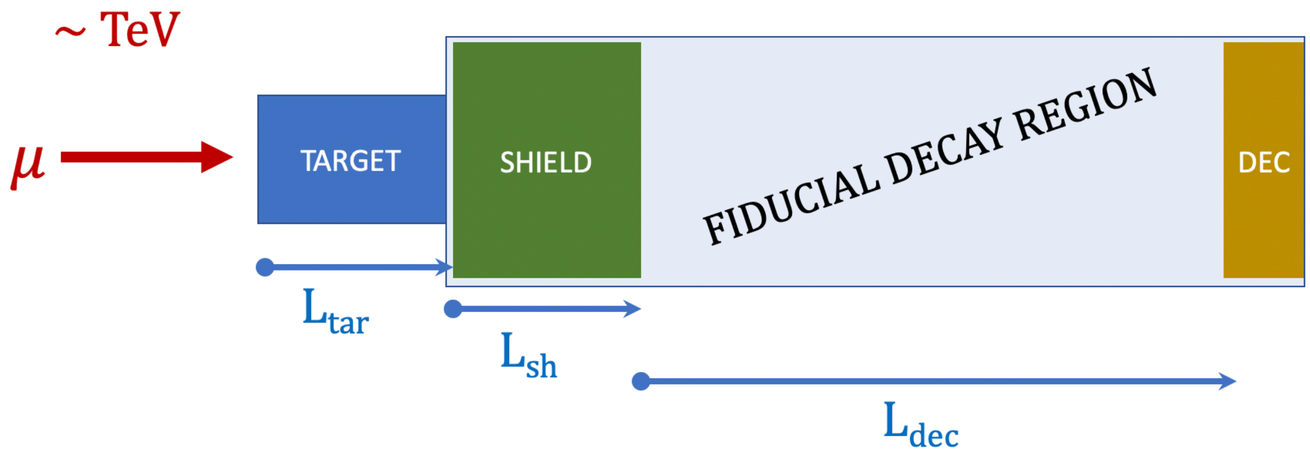

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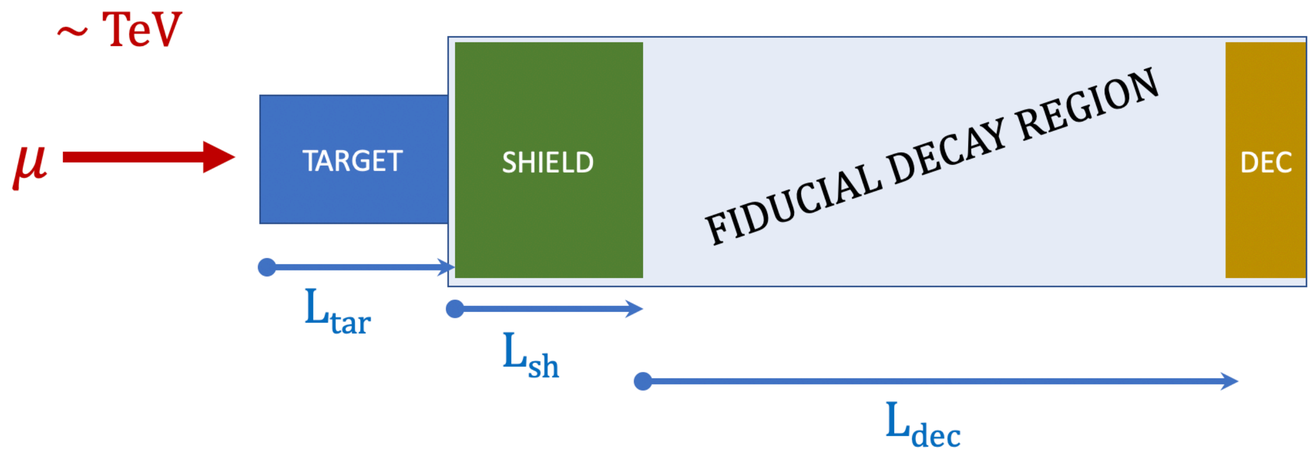

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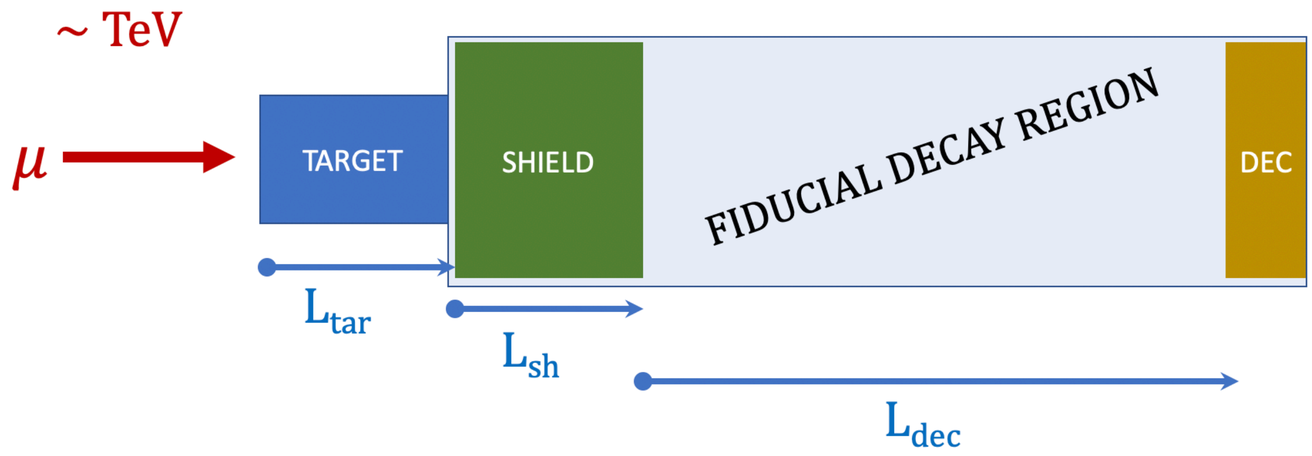
- Masses ~ 100 GeV



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***Work in Progress***

Search for vector or scalar new physics signals at muon beam dump

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

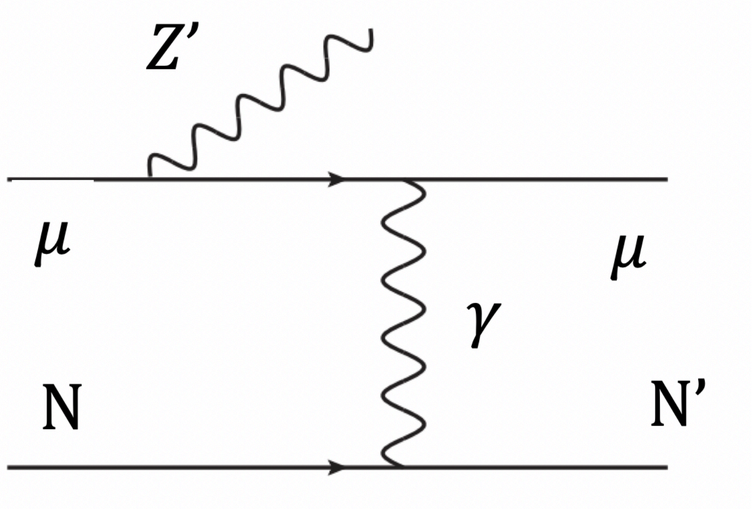
$$m_{NP} \sim 10 \text{ MeV} - 10 \text{ GeV}$$

This talk: vector scenarios

# Muon Beam Dump ($\mu$BD)

## Vector NP (Z') Scenarios

$$\mathscr{L}_V \supset \mathscr{L}_{SM} - \frac{1}{4} Z'^{\mu\nu} Z'_{\mu\nu} + \frac{1}{2} m_{Z'}^2 Z'^{\mu} Z'_{\mu} - i g Z'_{\mu} \sum_{l \in e,\mu,\tau} \left( Q_l \bar{l} \gamma^{\mu} l + Q'_l \bar{\nu}_l \gamma^{\mu} \nu_l \right)$$



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Dark Photon

- $Q'_l = 0$
- $Q_l = 1$
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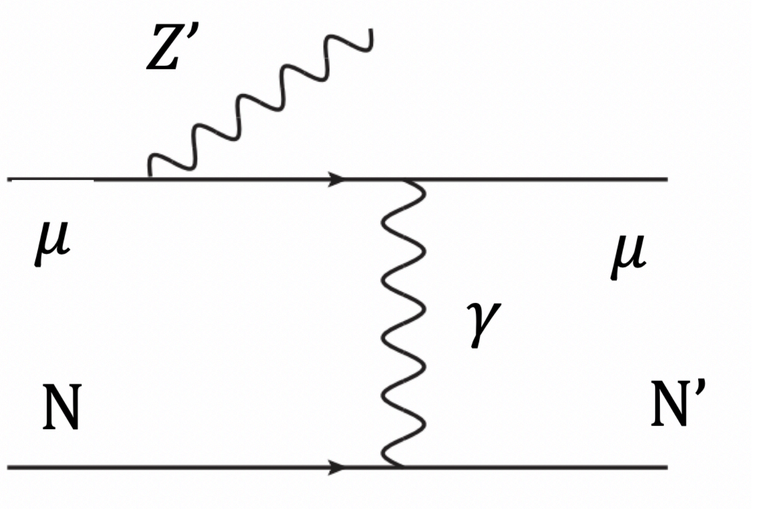
  + quarks



# Muon Beam Dump ($\mu$BD)

## Vector NP (Z') Scenarios

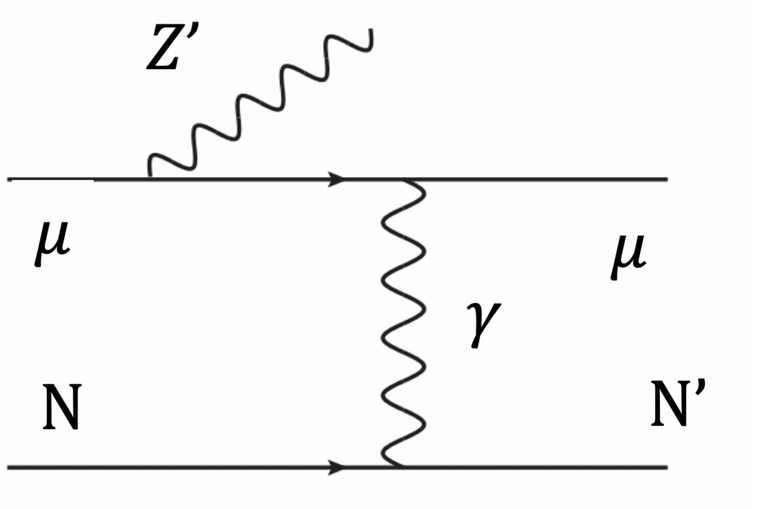
$$\mathscr{L}_V \supset \mathscr{L}_{SM} - \frac{1}{4} Z'^{\mu\nu} Z'_{\mu\nu} + \frac{1}{2} m_{Z'}^2 Z'^{\mu} Z'_{\mu} - i g Z'_{\mu} \sum_{l \in e,\mu,\tau} \left( Q_l \bar{l} \gamma^{\mu} l + Q'_l \bar{\nu}_l \gamma^{\mu} \nu_l \right)$$

Dark Photon

- $Q'_l = 0$
- $Q_l = 1$
- $g = \epsilon e$
  + quarks

$$L_\mu - L_\tau$$

- $Q'_{\mu(\tau)} = \pm 1$
- $Q_{\mu(\tau)} = \pm 1$
- $Q_e = Q'_e = 0$



# Muon Beam Dump ($\mu$BD)

## Experimental Setup

*Can we probe interesting parameter space with a realistic experimental set up?*

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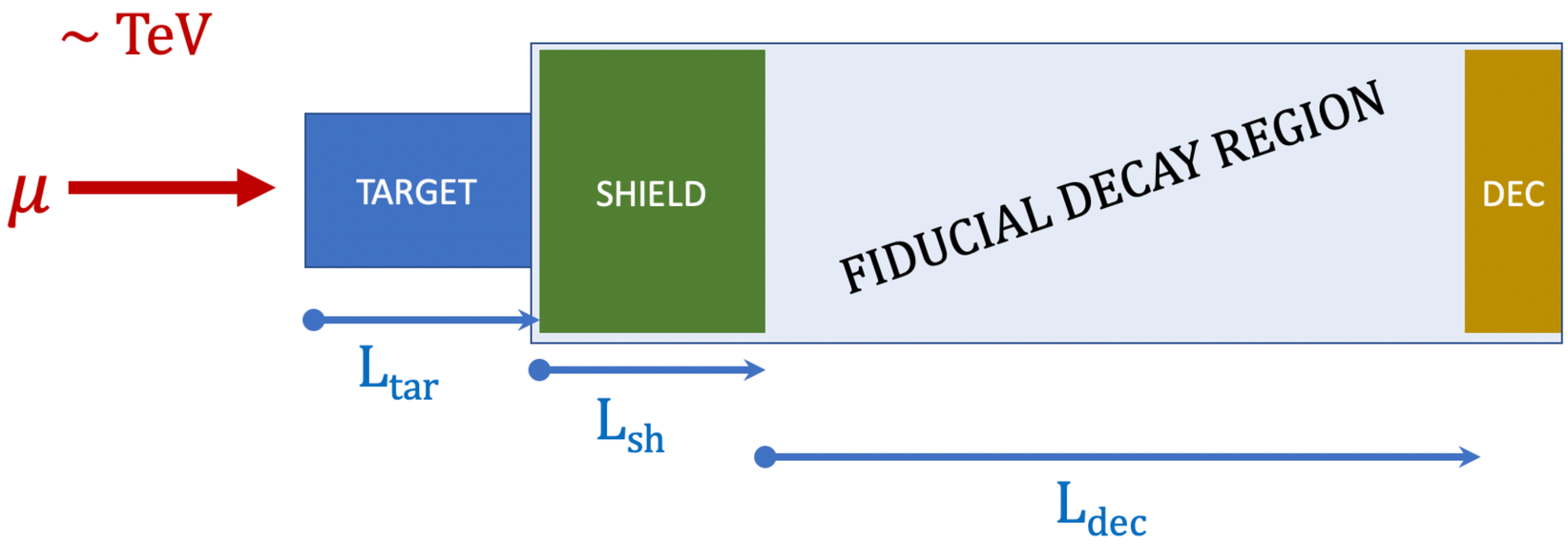
$$l_0 \approx \left(\frac{E_0}{\text{TeV}}\right)\left(\frac{10^{-7}}{\epsilon}\right)^2\left(\frac{10\ \text{GeV}}{m_{Z'}}\right)^2 \cdot\ 10\ \text{m}$$

# Muon Beam Dump ($\mu$BD)

## Experimental Setup



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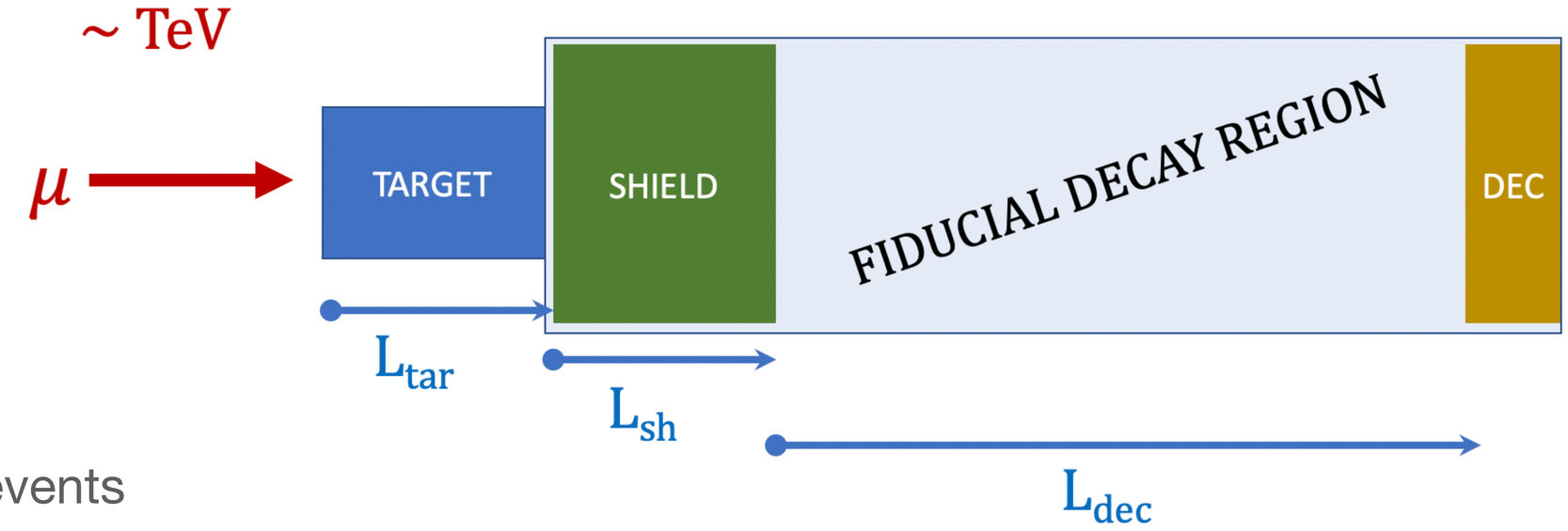
## Experimental Setup




$$l_0 = \gamma\tau = \frac{xE_0}{m_{Z'}\Gamma}$$

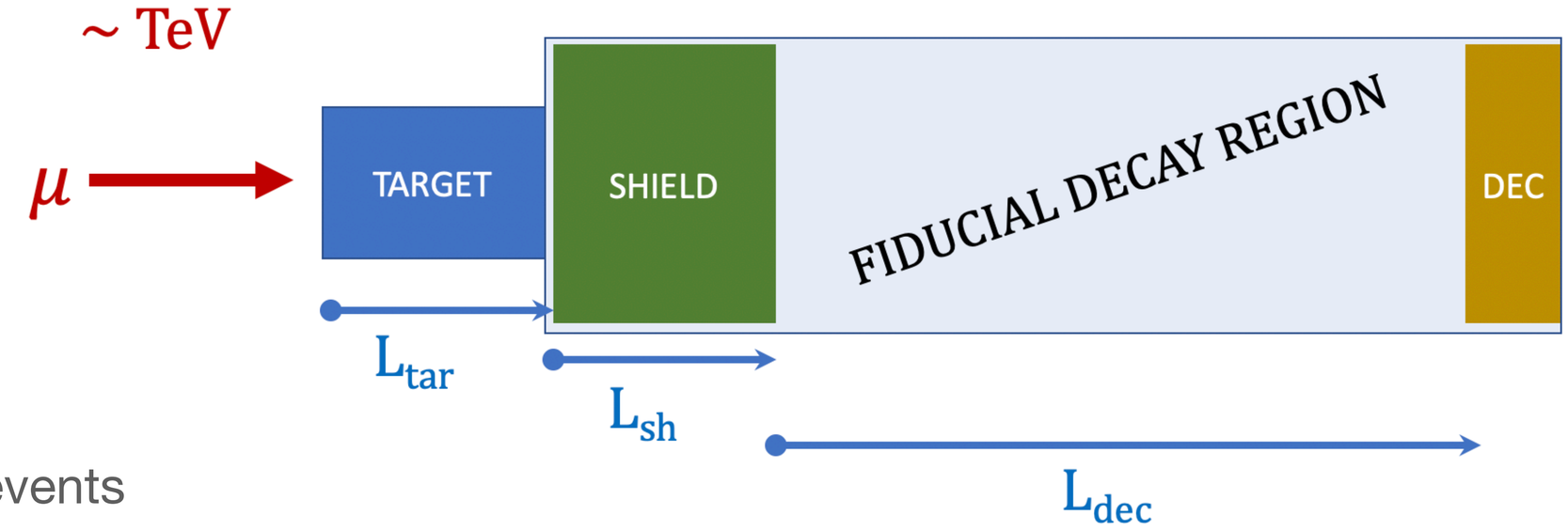
N - signal events

$x$ - $\dfrac{E_{Z'}}{E_0}$

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

# Muon Beam Dump ($\mu$BD)

## Experimental Setup

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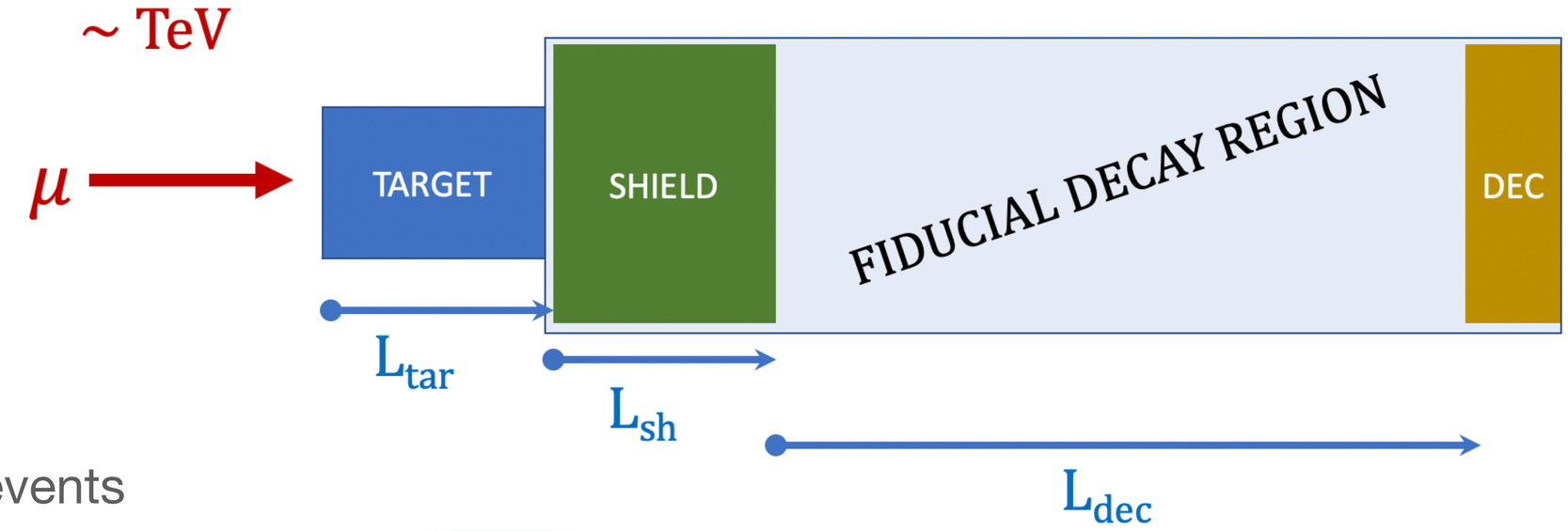
Muons on target ( $\sim 10^{20}$)

# Muon Beam Dump ($\mu$BD)

## Experimental Setup

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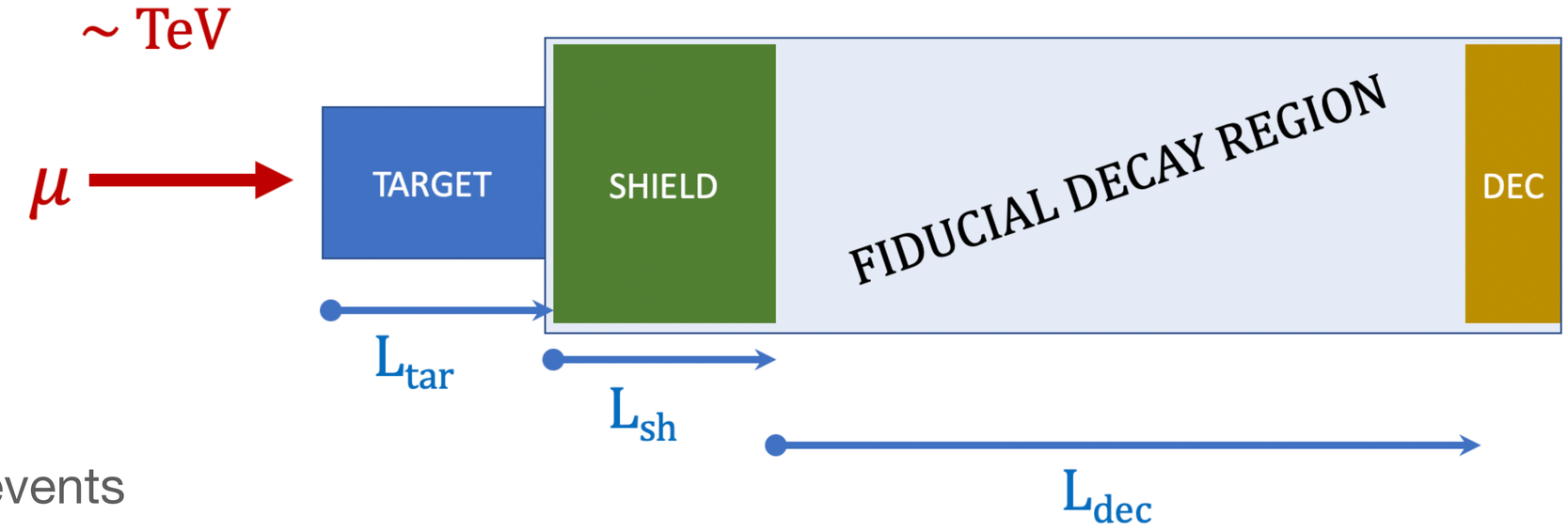
Target material details

# Muon Beam Dump ($\mu$BD)

## Experimental Setup

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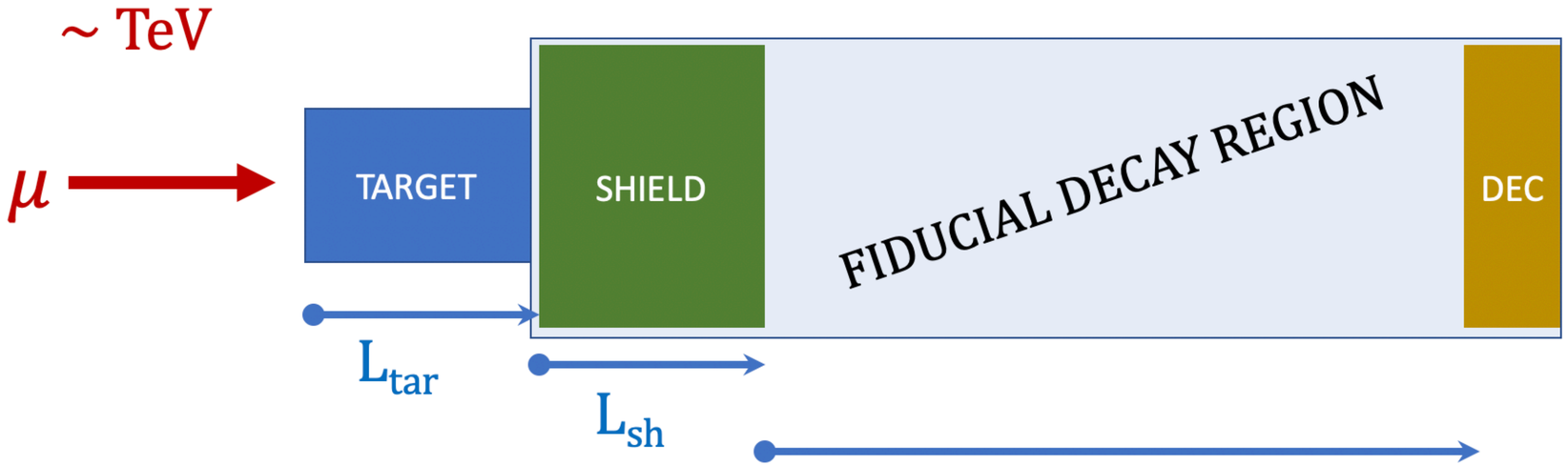
Differential cross section $(3 \to 2)$

# Muon Beam Dump ($\mu$BD)

## Experimental Setup




$$l_0 = \gamma\tau = \frac{xE_0}{m_{Z'}\Gamma}$$

N - signal events

$x$ - $\frac{E_{Z'}}{E_0}$

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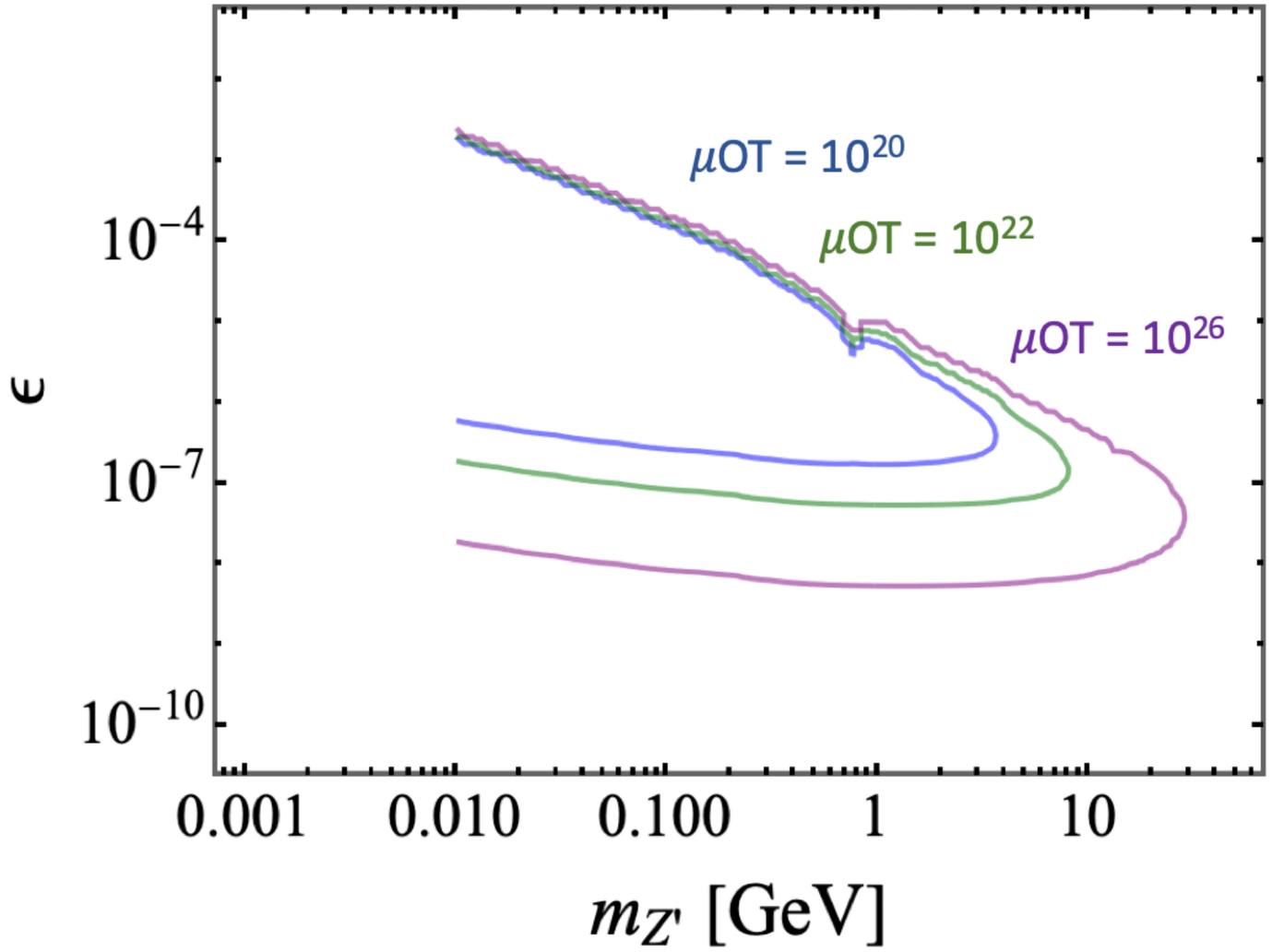
Balance of target, shield, fiducial volume

# Muon Beam Dump ($\mu$BD)

## Dark photon




Water target

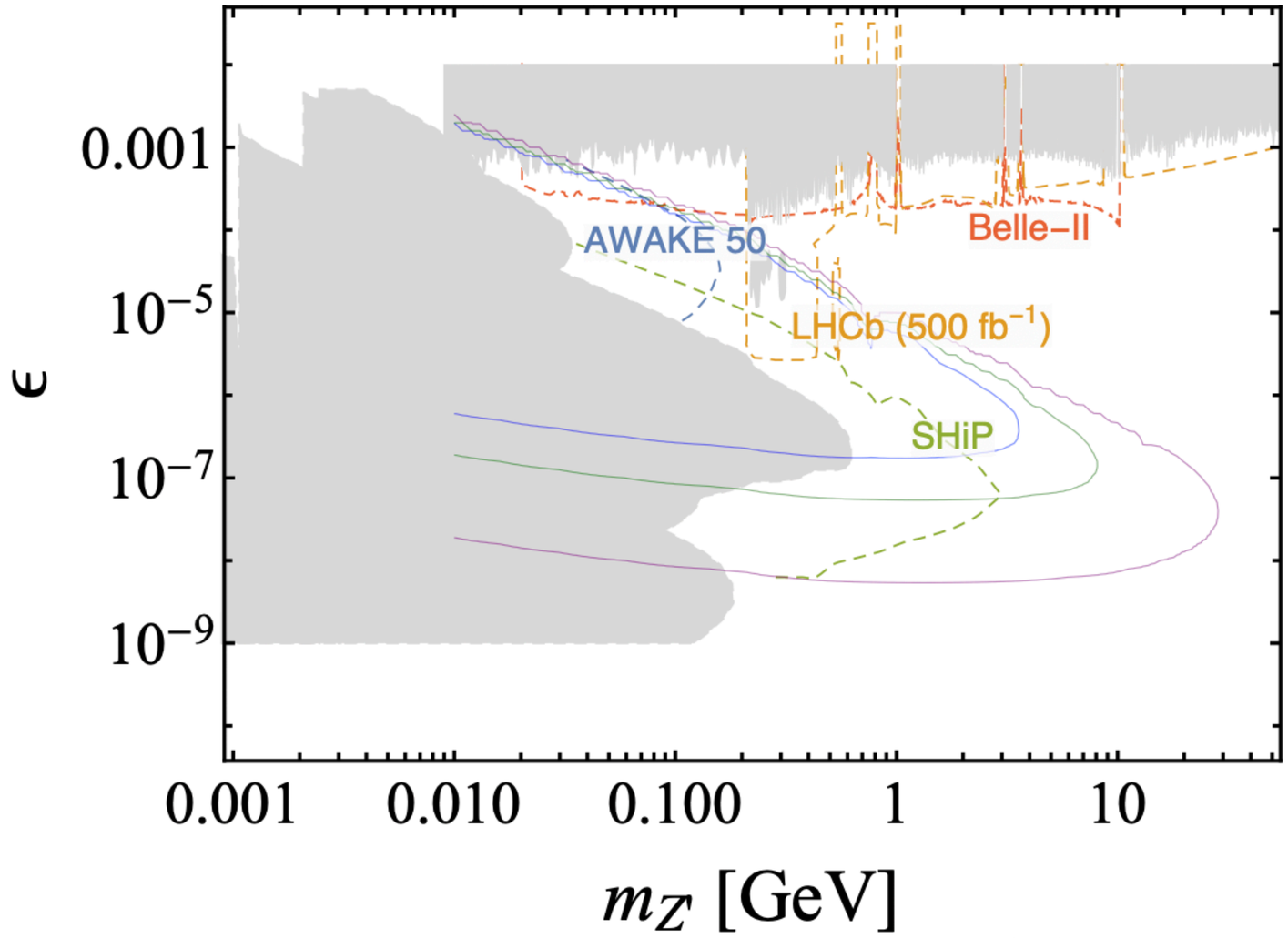
$L_{\text{tar}} = 10$ m

$L_{\text{sh}} = 10$ m

$L_{\text{dec}} = 100$ m

# Muon Beam Dump ($\mu$BD)

## Dark photon

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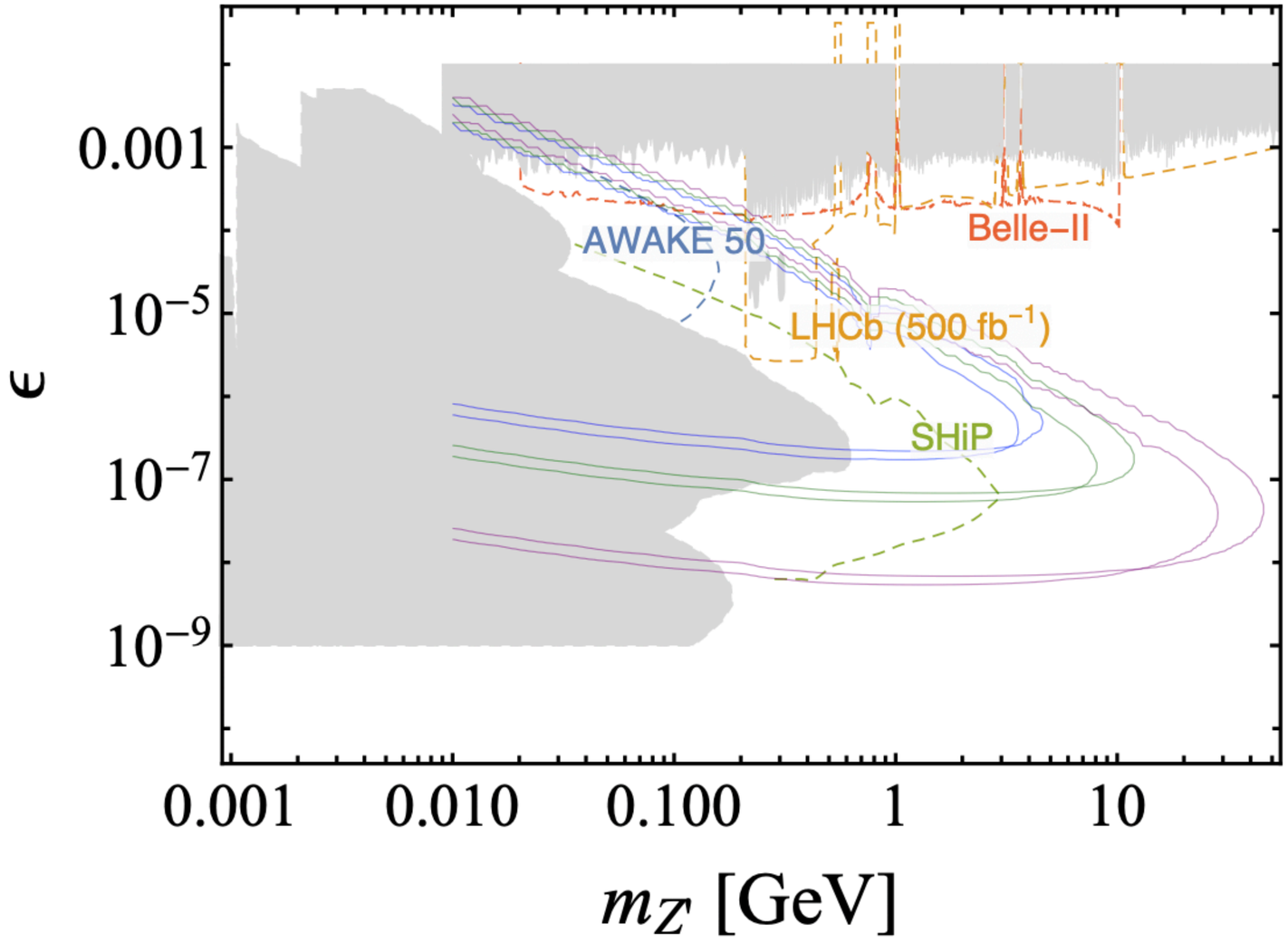


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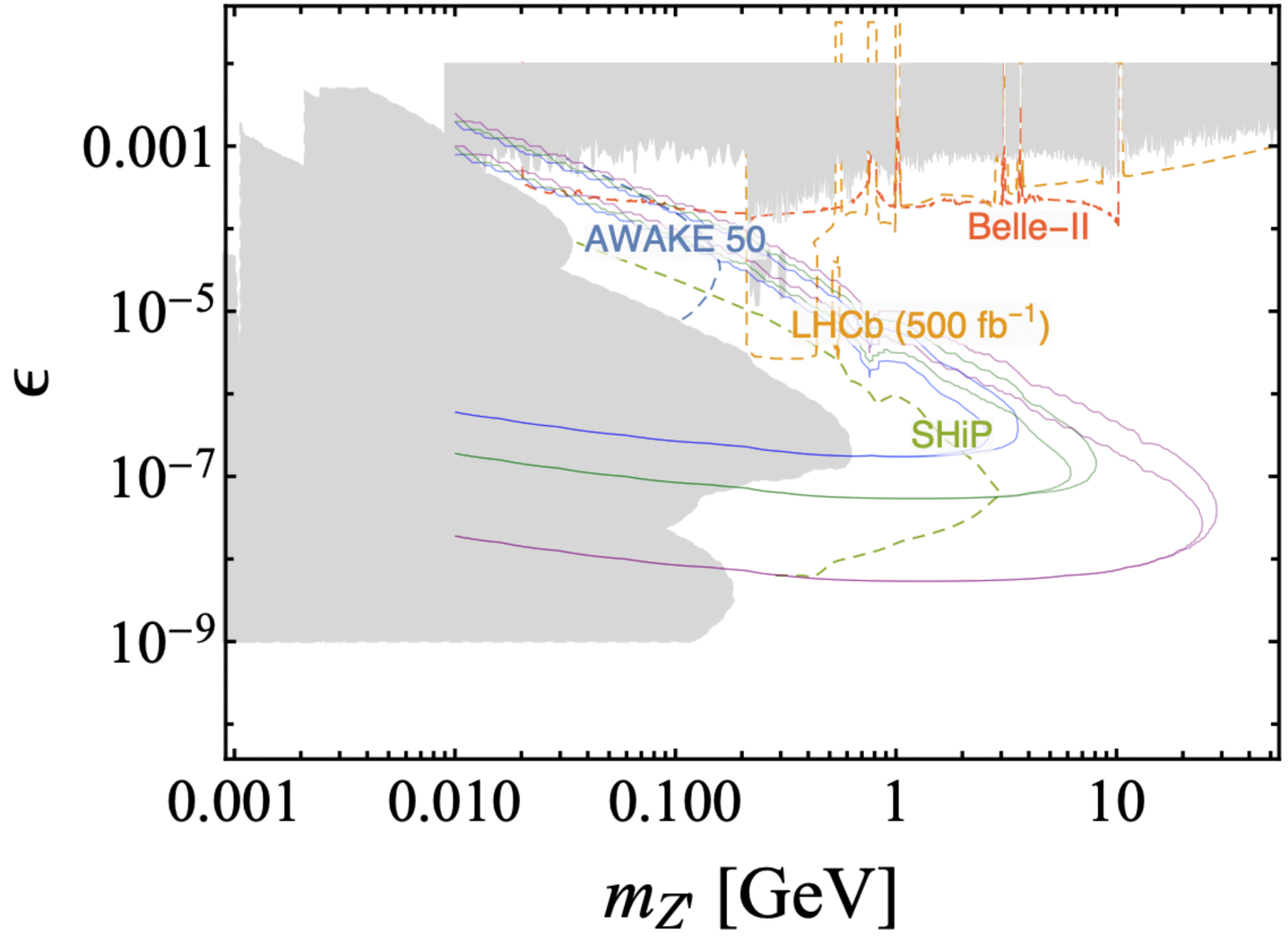
$\sqrt{s} = 3$ TeV $\rightarrow$ 10 TeV

# Muon Beam Dump ($\mu$BD)

## Dark photon




Water target

$L_{\text{tar}} = 10$ m

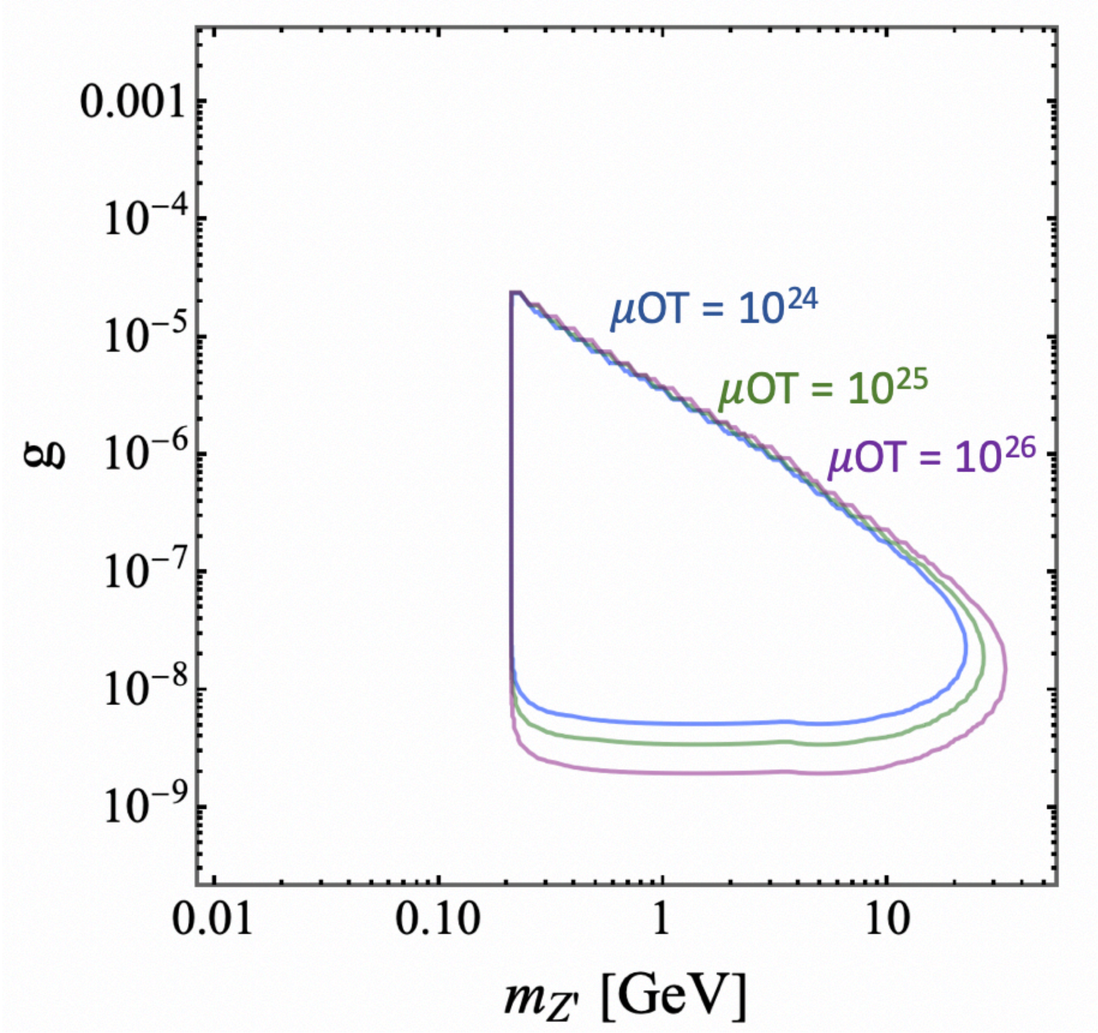
$L_{\text{sh}} = 10$ m

$L_{\text{dec}} = 100$ m

$L_{sh} = 10\ \text{m} \rightarrow 50\ \text{m}$

# Muon Beam Dump ($\mu$BD)

$L_\mu - L_\tau$

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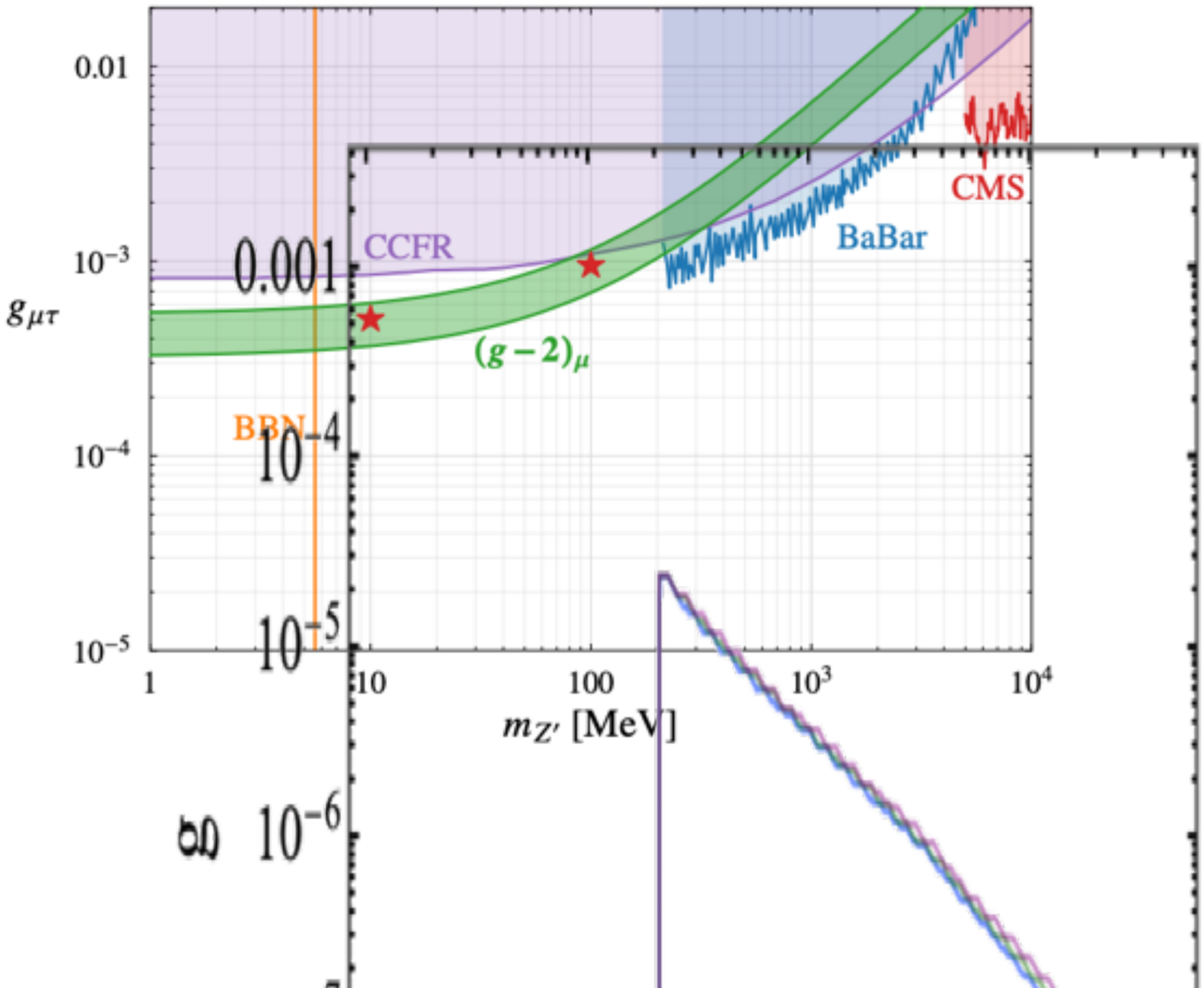


Water target

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$L_{\text{sh}} = 10$ m

$L_{\text{dec}} = 100$ m

# Conclusions & Outlook

Future multi-TeV $\mu C$ provide a complementary and robust physics program

Leptoquarks are a motivated and novel signal to consider at $\mu C$

We should take advantage of a TeV $\mu C$ to probe intensity frontier with a $\mu BD$

# Backups

# Leptoquarks

## *Flavor observables*

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

| Observable | Experimental Bounds | Relevant Couplings | |
|---|---|---|---|
| $R_{K^{(*)}}$ | $R_K = 0.846^{+0.044}_{-0.041}$<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] | $\beta_L^{33} \times \beta_L^{32}$ | |
| $\mathrm{BR}(\tau \to \mu\phi)$ | $< 8.4 \times 10^{-8}$ | $\beta_L^{23} \times \beta_L^{22}$ | |
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| $\mathrm{BR}(B \to K\tau\mu)$ | $< 2.8 \times 10^{-5}$ | $\beta_L^{32} \times \beta_L^{23}$ | $\beta_L^{33} \times \beta_L^{22}$ |
| $\mathrm{BR}(B_s \to \tau\mu)$ | $< 4.2 \times 10^{-5}$ | $\beta_L^{32} \times \beta_L^{23}$ | $\beta_L^{33} \times \beta_L^{22}$ |
| $\mathrm{BR}(B_s \to \tau\tau)$ | $< 2.1 \times 10^{-3}$ | $\beta_L^{33} \times \beta_L^{23}$ | |

2103.16558

# Leptoquarks

## *Flavor observables*

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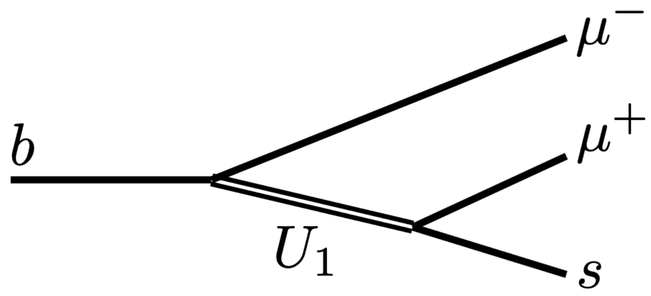
$$U_1 = (3,1)_{2/3}$$

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

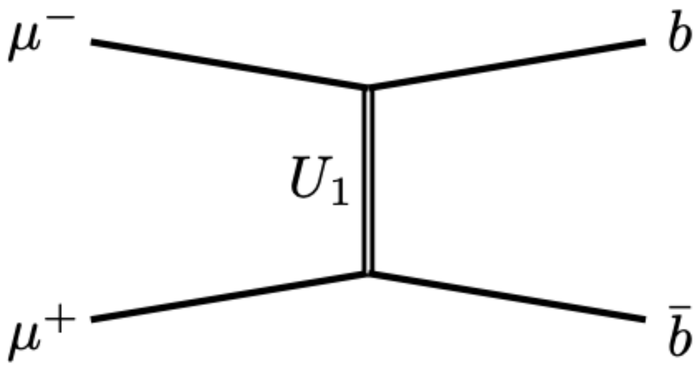



$$\frac{\beta_L^{22}\beta_L^{32}}{m_{U_1}^2} = 1.98 \times 10^{-3}\ \mathrm{TeV}^{-2}$$

2103.16558

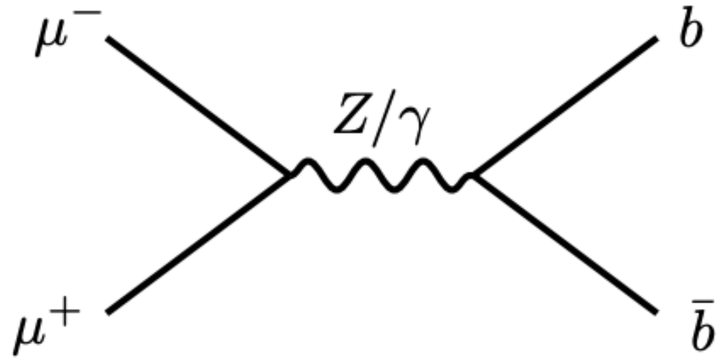
# Leptoquarks

## *Drell-Yan† Production*




*t-channel*

SM Background



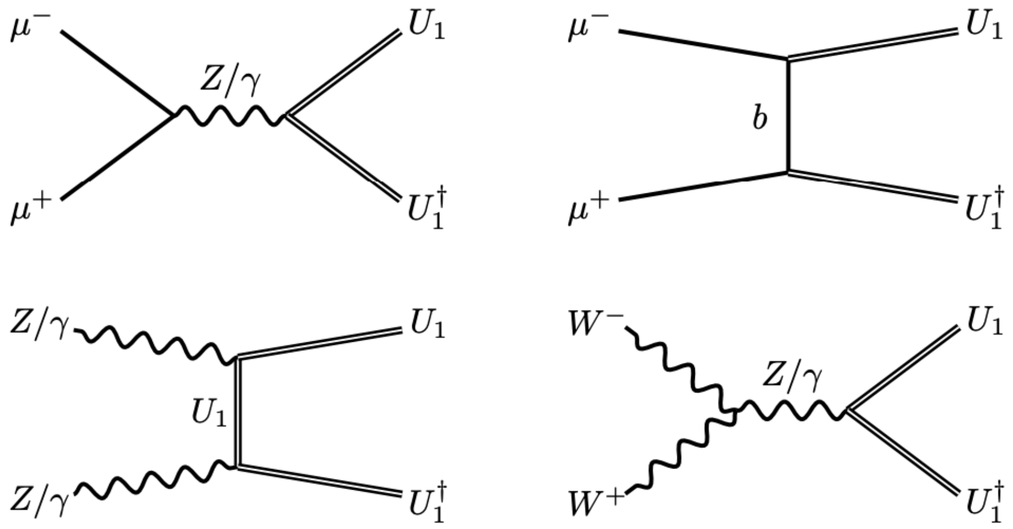

*s-channel*

Simulated with MG5

# Leptoquarks

## *Pair Production*

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




SM Background

Simulated with MG5

# Leptoquarks

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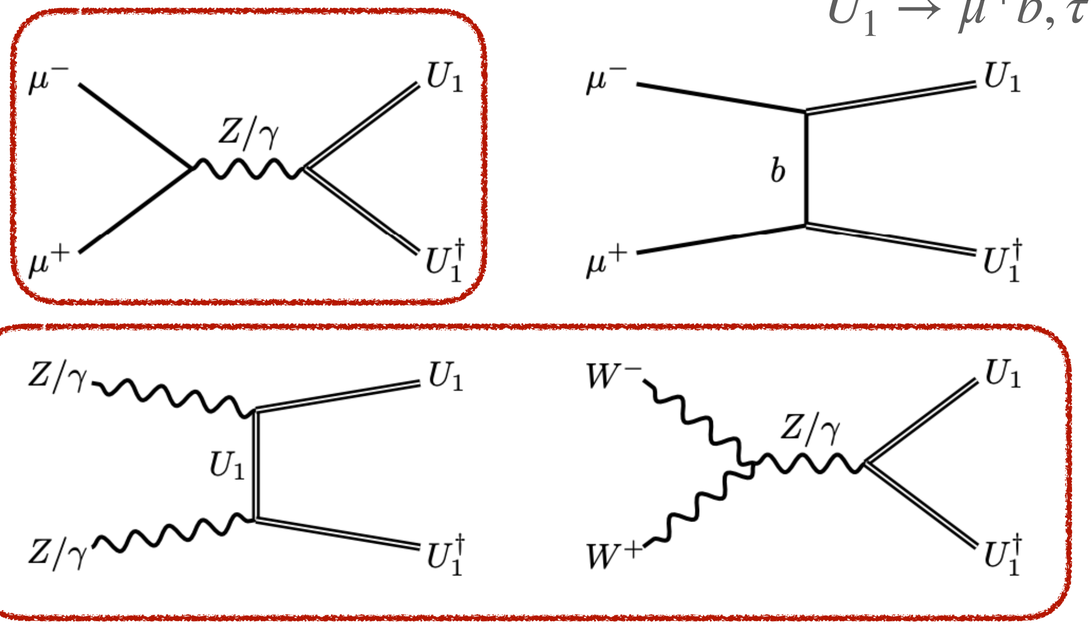


*No direct coupling to muons*

SM Background

Simulated with MG5

# Leptoquarks

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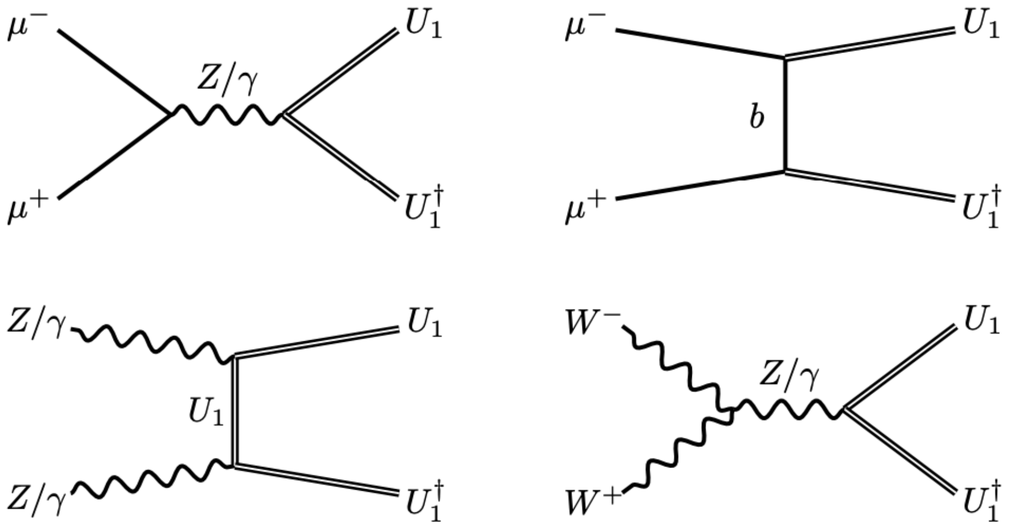
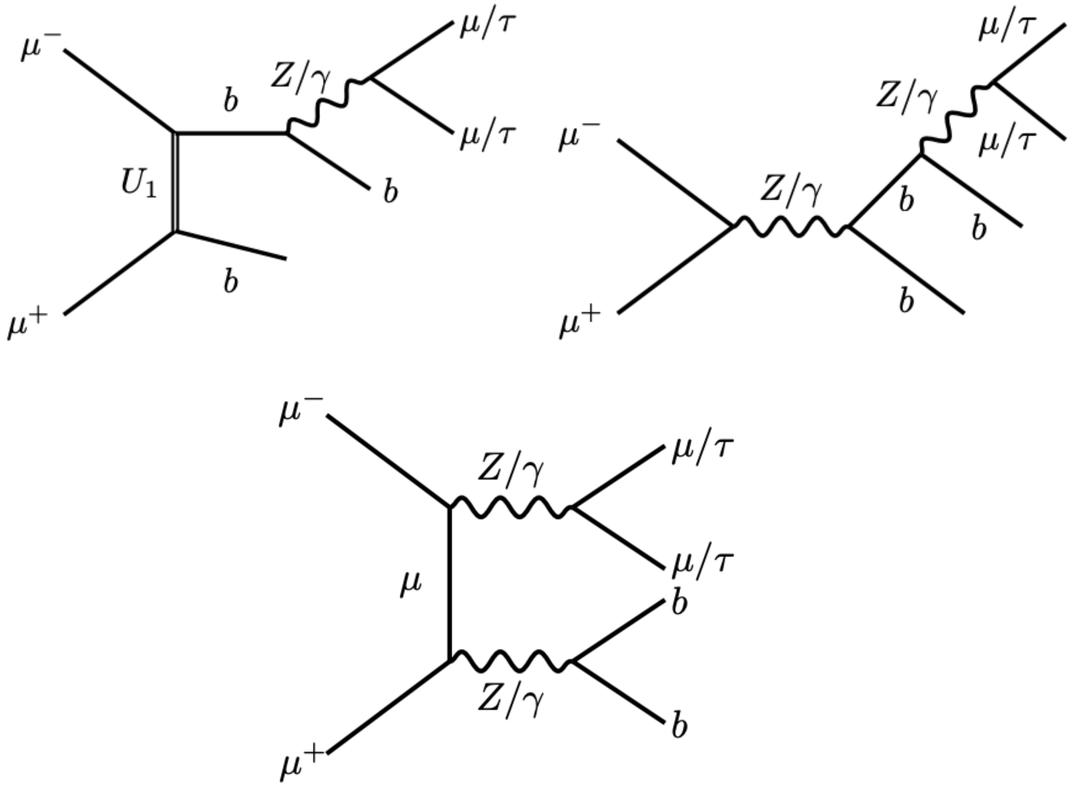
$U_1 \to \mu^+ b, \tau^+ b$




SM Background




Simulated with MG5

# Leptoquarks

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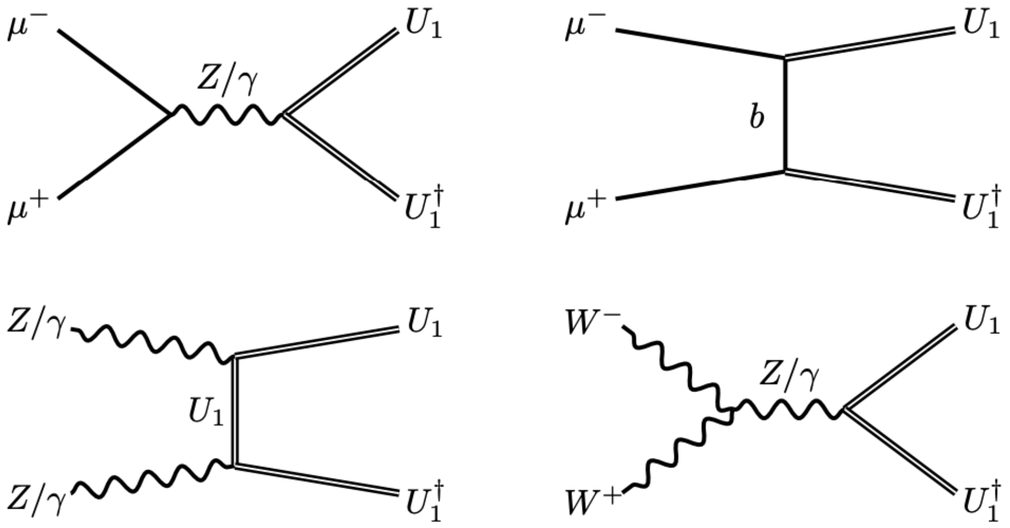
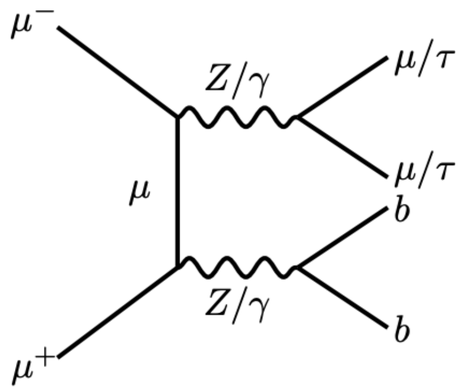
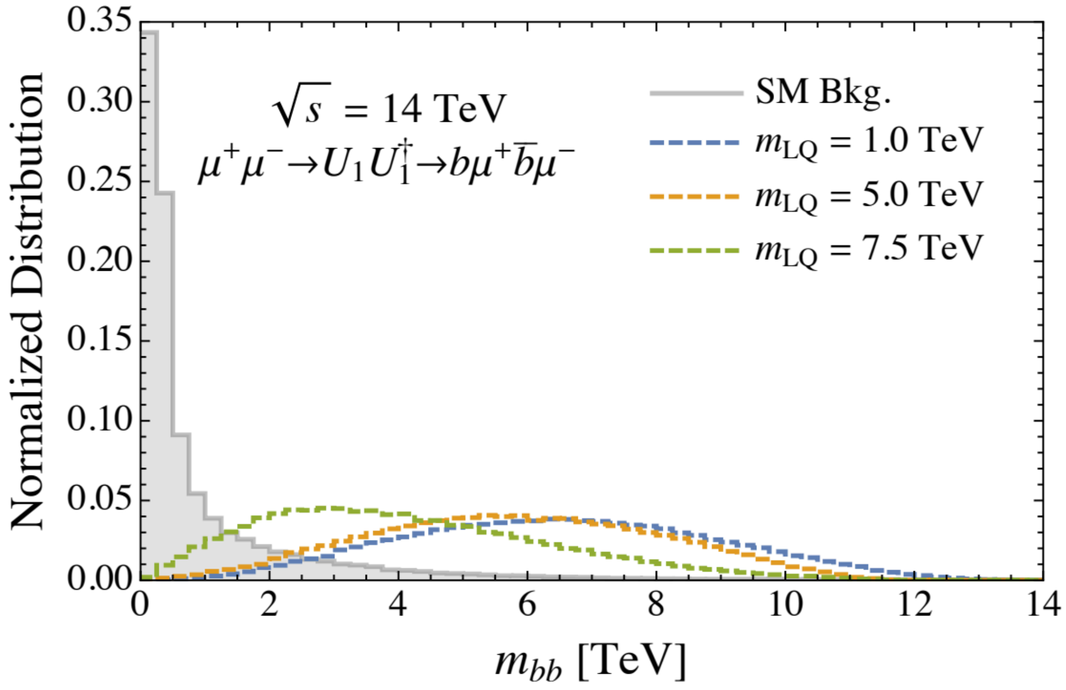



SM Background

Mitigated with $m_{bb}$ cut




Simulated with MG5

# Muon Beam Dump ($\mu$BD)

## *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 $\mu$

**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