Title: Searching for New Physics at Muon Colliders

Speakers: Cari Cesarotti

Series: Particle Physics

Date: July 06, 2021 - 1:00 PM

URL: https://pirsa.org/21070001

Abstract: A high energy muon collider complex can provide new and complementary discovery potential to the LHC or future hadron colliders. New spin-1 bosons are a motivated class of exotic new physics models. In particular leptoquarks, dark photons, and models have distinct production channels at hadron and lepton machines. We study a vector leptoquark model at a muon collider with ? s = 3, 14 TeV within a set of both UV and phenomenologically motivated flavor scenarios. We compute which production mechanism has the greatest reach for various values of the leptoquark mass and the coupling between leptoquark and Standard Model fermions. We find that we can probe leptoquark masses up to an order of magnitude beyond ? s with perturbative couplings. Additionally, we can also probe regions of parameter space unavailable to flavor experiments. In particular, all of the parameter space of interest to explain recent low-energy anomalies in B meson decays would be covered even by a ? s = 3 TeV collider. We also consider other applications of a muon collider complex in the hunt for new physics.

Zoom link: https://pitp.zoom.us/j/97081554839?pwd=bFBmdUExV0VSdm4vcm5iMTVtaTFrUT09

Searching for New Physics at Future Muon Colliders

Cari Cesarotti

Harvard University

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

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

The Future of Colliders

How and where do we look for new physics?

- LHC has enormous discovery potential
- Precision experiments
- Intensity frontier

(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

The Future of Colliders

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Expand energy frontier into $O(10)$ TeV

Construction of ~~new~~ μ colliders

Muon Colliders (MuC)

Complementary probe into SM and BSM processes

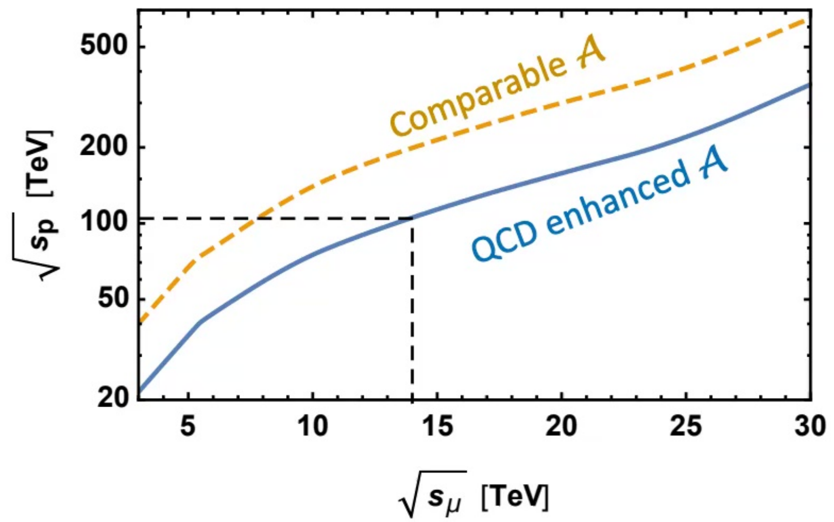
LHC MuC

Muon Colliders (MuC)

Complementary probe into SM and BSM processes

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

1901.06150



Muon Colliders (MuC)

Complementary probe into SM and BSM processes

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Hadronized final states	Small QCD Background

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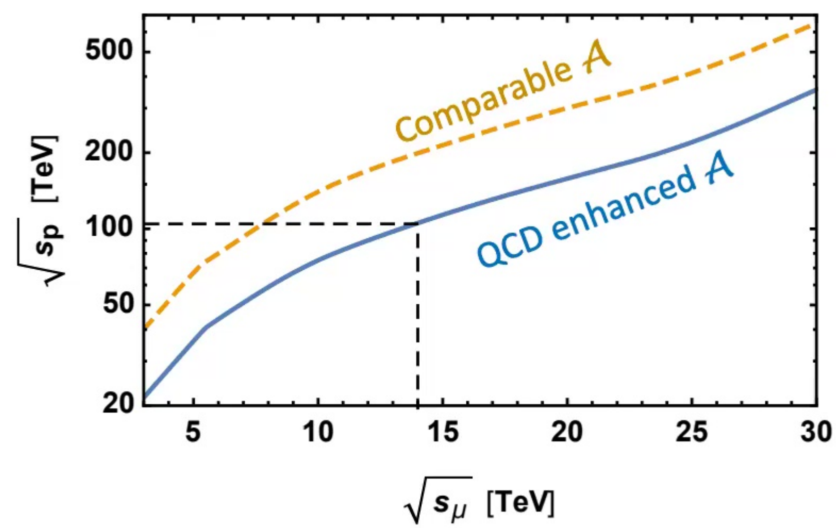

Muon Colliders (MuC)

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	Less synchrotron radiation	Synchrotron radiation

Muon Colliders (MuC)

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$\sqrt{\hat{s}} \ll \sqrt{s}$	$\sqrt{\hat{s}} \simeq \sqrt{s}$	
Color production	Electroweak production	
Hadronized final states	Small QCD Background	
	Less synchrotron radiation	Synchrotron radiation
	Second gen. couplings	First gen. couplings

Muon Colliders (MuC)

Excellent tool to study NP contributing to the g-2 anomaly

A Guaranteed Discovery at Future Muon Colliders

Rodolfo Capdevilla[a,b],* David Curtin[a],† Yonatan Kahn[c],‡ and Gordan Krnjaic[d§]

A No-Lose Theorem for Discovering the New Physics of $(g-2)_\mu$ at Muon Colliders

Rodolfo Capdevilla,[a,b] David Curtin,[a] Yonatan Kahn,[c,d] Gordan Krnjaic[e,f]

Muon Colliders (MuC)

Cons of MuC:

- Difficult to achieve high quality beam
- Muons decay, produce beam induced background

Muon Colliders (MuC)

Community effort to explore physics case of MuC

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]

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

Part I: Energy Frontier (2104.05720) P. Asadi, R. Capdevilla, S. Homiller

- Specific NP scenario: vector leptoquarks

Part II: Intensity Frontier *(Work in Progress)* S. Homiller, R. Mishra, M. Reece

- Auxiliary Experiments: muon beam dump

Muon Colliders (MuC)

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

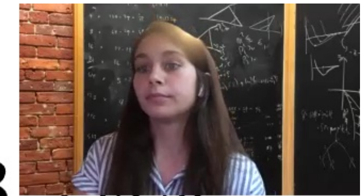
Part I: Energy Frontier

- Specific NP scenario: vector leptoquarks

Part II: Intensity Frontier

- Auxiliary Experiments: muon beam dump

Leptoquarks



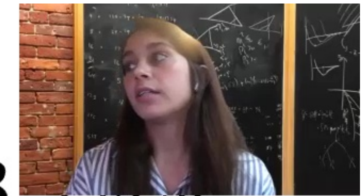
$$U_1 = (3, 1)_{2/3}$$

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:

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

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

Leptoquarks

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Direct production from $\mu^+ \mu^-$ collisions

Leptoquarks

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

Minimal U_1 Leptoquark EFT:

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

- 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

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

Minimal U_1 Leptoquark EFT:

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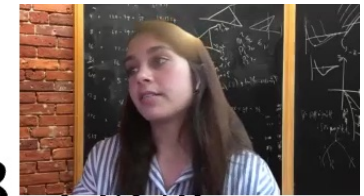
First gen. couplings constrained by low energy experiments (1603.04993)



Leptoquarks

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

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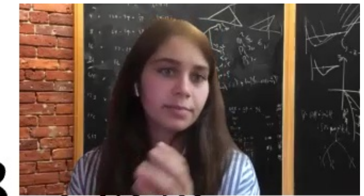
First gen. couplings constrained by low energy experiments (1603.04993)

Direct production

Leptoquarks

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



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

Relative strength determines final states

Leptoquarks

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

Free Parameters of the Model

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

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

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

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

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

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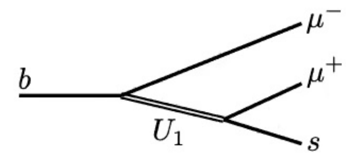
$\mathrm{BR}(B_s \to \tau\tau)$	$< 2.1 \times 10^{-3}$	$\beta_L^{33} \times \beta_L^{23}$

Low energy flavor observables

R_K anomaly:

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



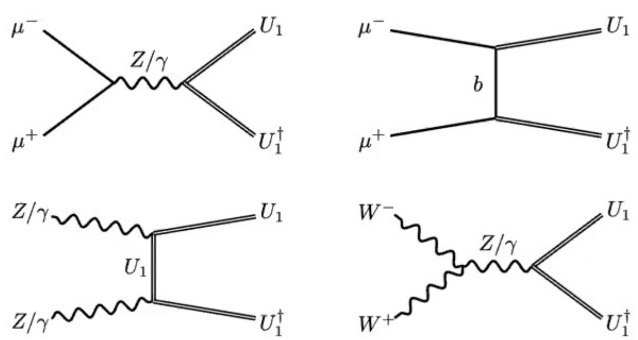
$$\frac{\beta_L^{22}\beta_L^{32}}{m_{\mathrm{LQ}}^2} = 1.98 \times 10^{-3}\ \mathrm{TeV}^{-2}$$

2103.16558

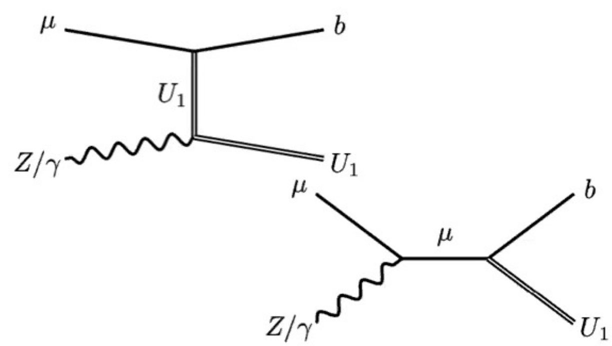
Leptoquarks

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

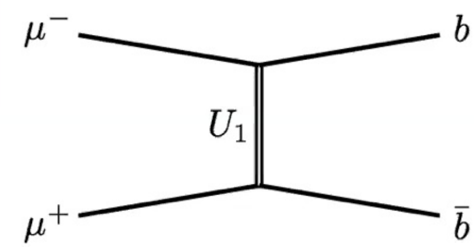
Production Modes



Pair Production



Single Production



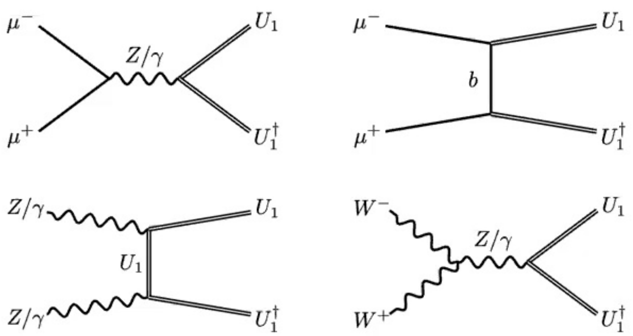
Drell-Yan†

Simulated with MG5

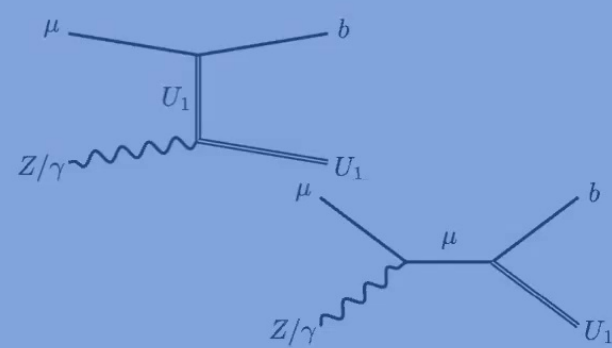
Leptoquarks

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

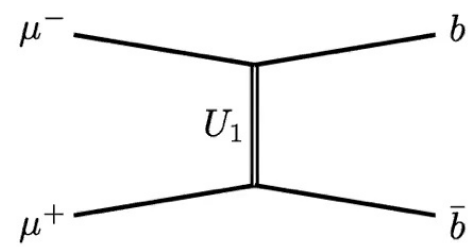
Production Modes



Pair Production



Single Production



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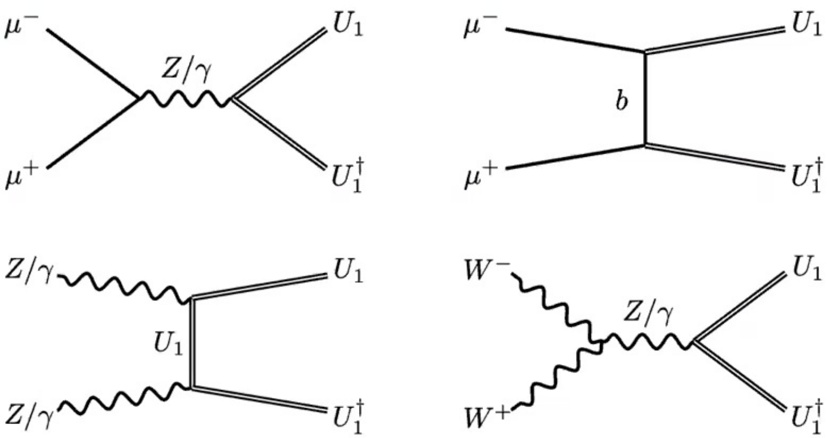
Leptoquarks

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

Pair Production



Final States

Scenario I, II:

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

Scenario III, IV:

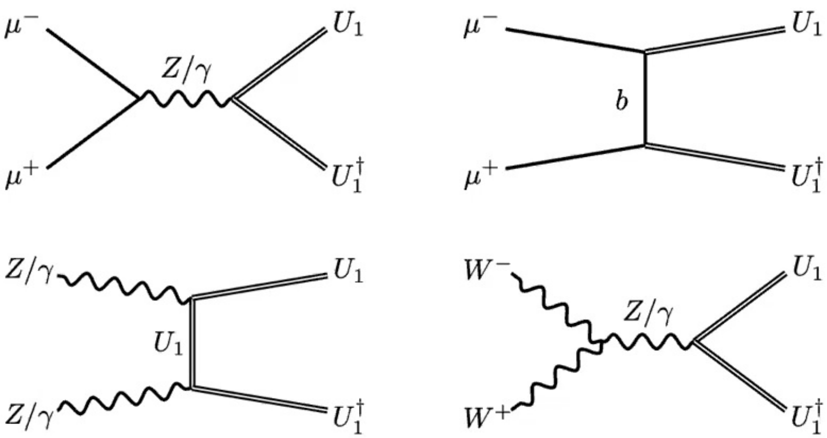
$$U_1 \to b\tau^+$$

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

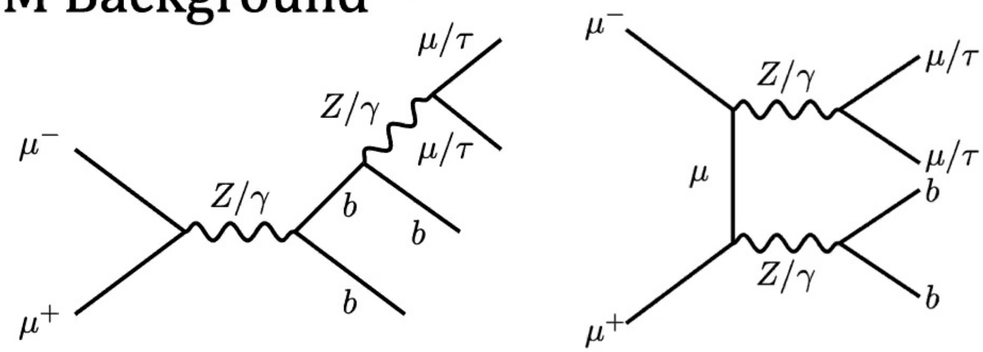
$$U_1 = (3, 1)_{2/3}$$

Pair Production



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

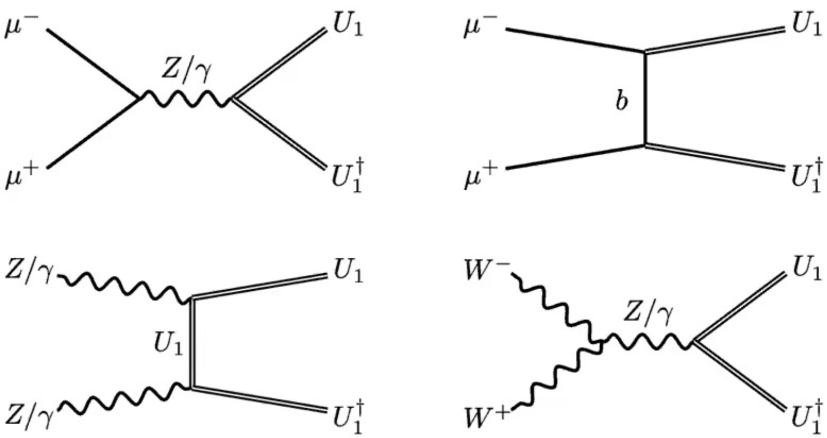
SM Background

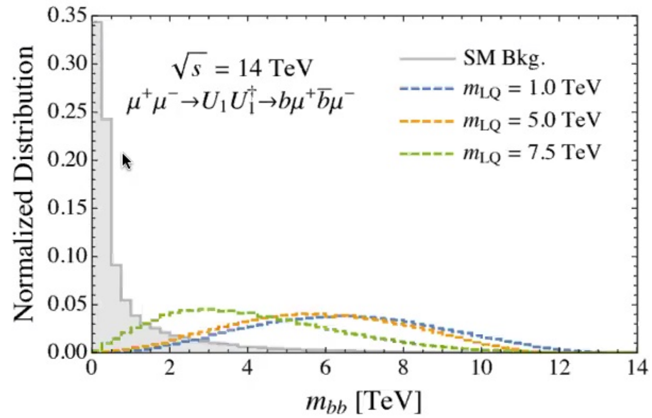


Leptoquarks

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

Pair Production

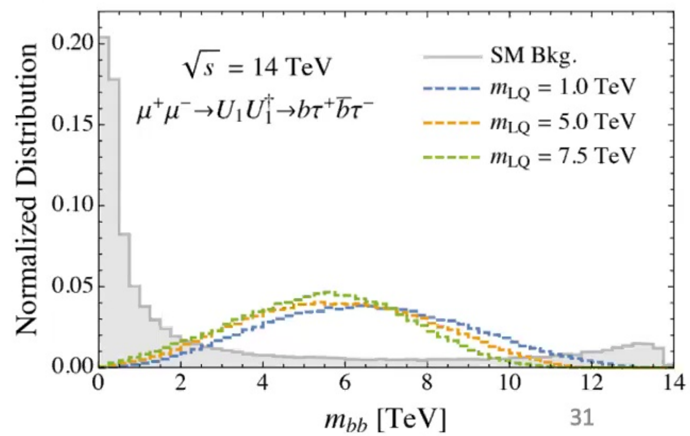




Mitigated by m_{bb} cut

$$m_{bb} > 0.5, 2 \text{ TeV}$$

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



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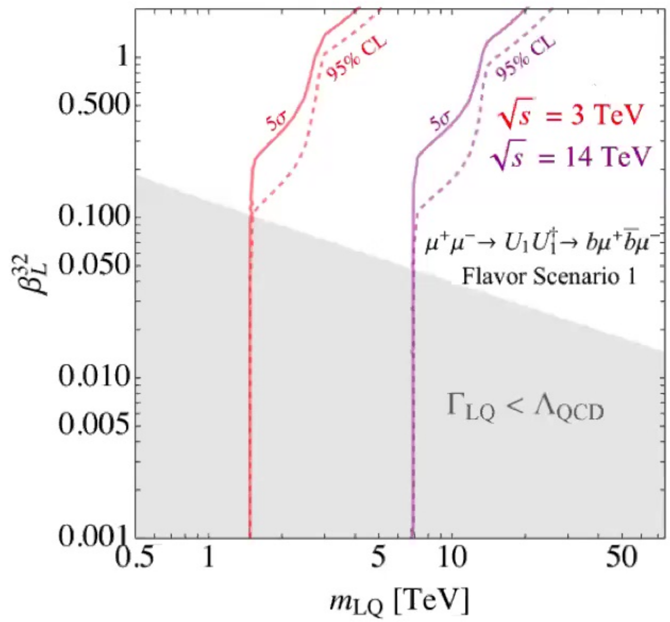
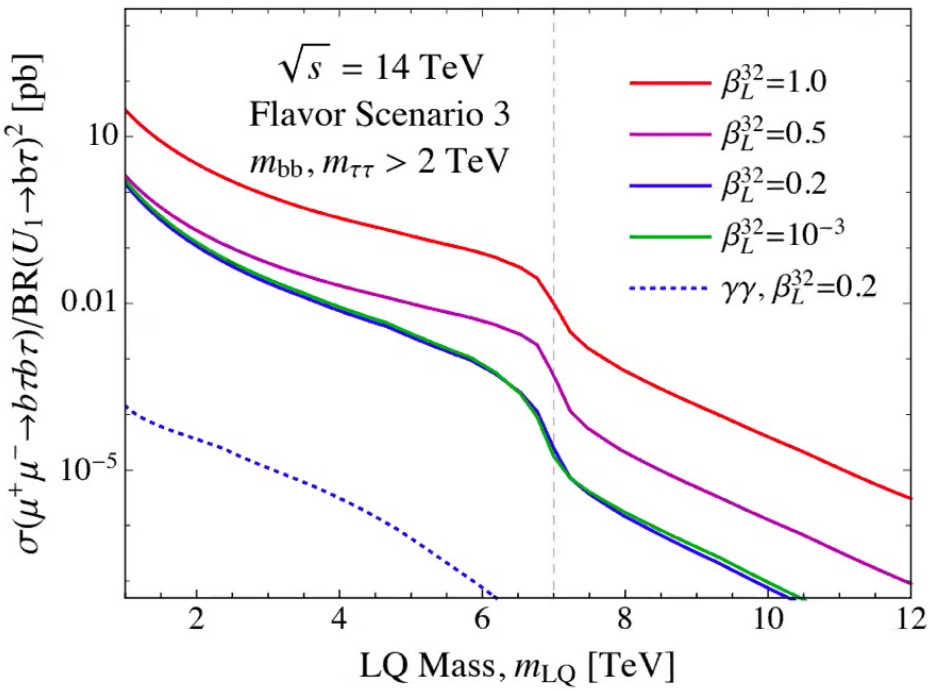
Leptoquarks

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

Pair Production

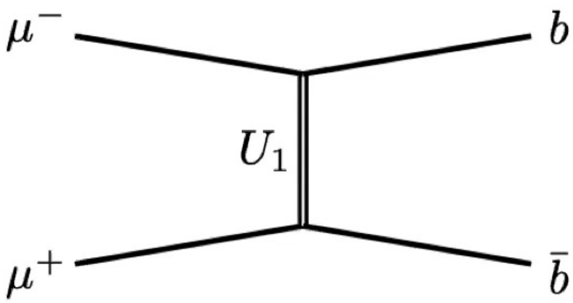




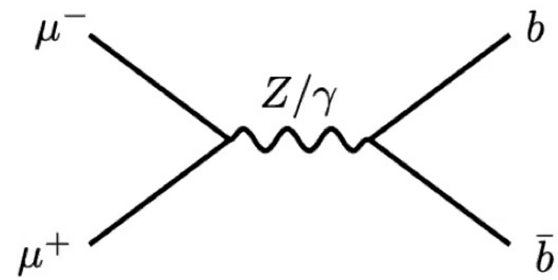
Leptoquarks

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

Drell-Yan



SM Background



Leptoquarks

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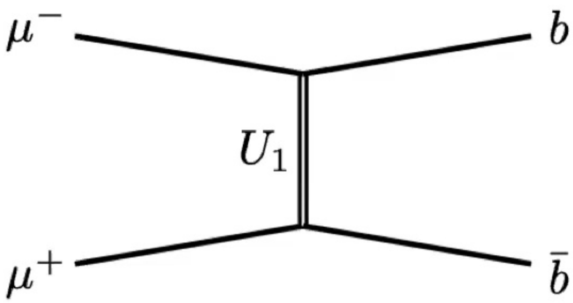
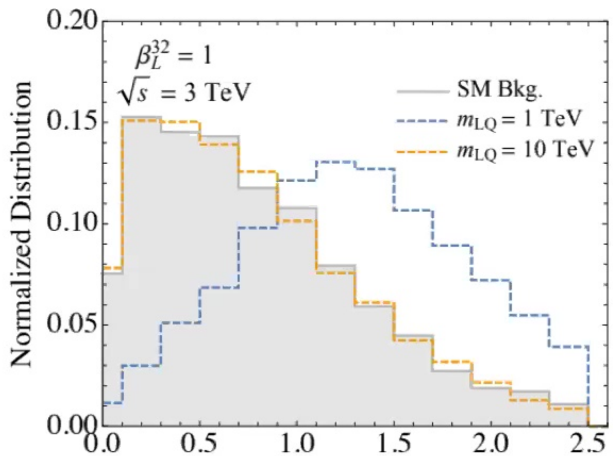
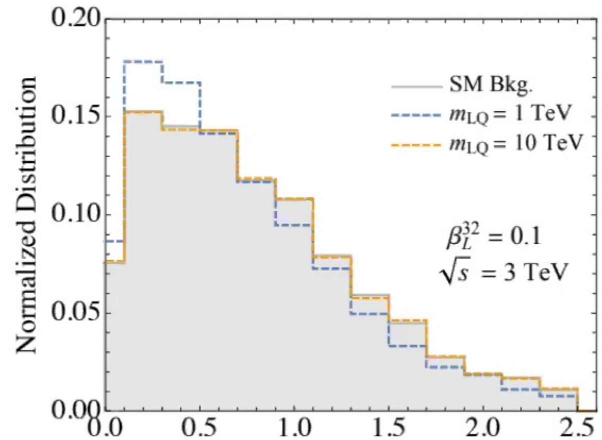
Drell-Yan





η_b

Bin in η

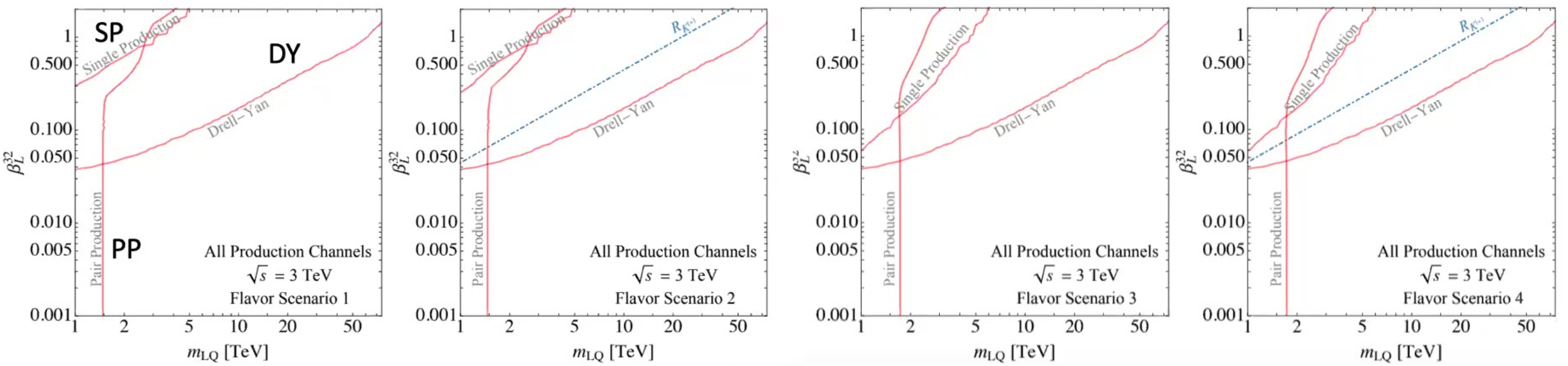


η_b

Leptoquarks

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

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

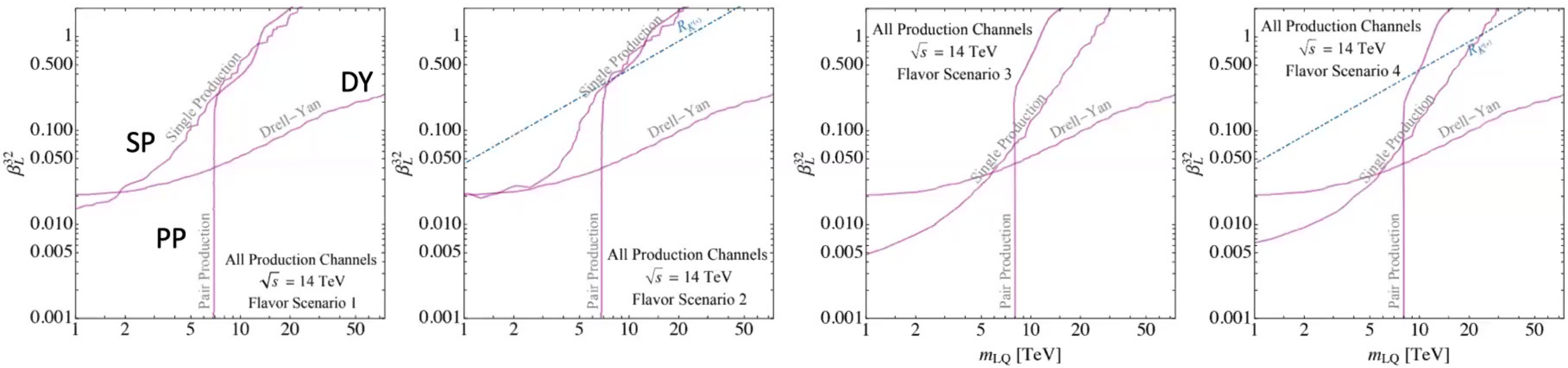


Scenarios	1	2	3	4
$(\beta_L^{22},\ \beta_L^{23},\ \beta_L^{33}) =$	$(0,\ 0,\ 0)$	$(\beta_L^{32},\ 0,\ 0)$	$(0,\ 0.1,\ 1)$	$(\beta_L^{32},\ 0.1,\ 1)$

Leptoquarks

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

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



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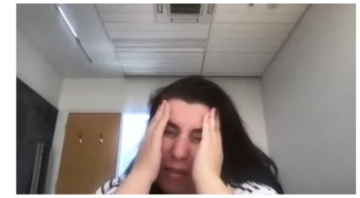


Leptoquarks

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

Muon Colliders (MuC)

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

Part I: Energy Frontier

- Specific NP scenario: vector leptoquarks

Part II: Intensity Frontier

- Auxiliary Experiments: muon beam dump

Muon Beam Dump (MuBD)

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

Can probe NP scenarios with
- Very weak couplings
- Couplings to 2^{nd} gen. leptons
- Masses ~ 100 GeV

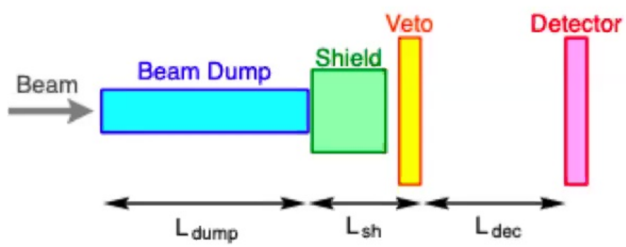
Muon Beam Dump (MuBD)

Rich literature in proposed electron beam dumps

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 colliders:

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)]

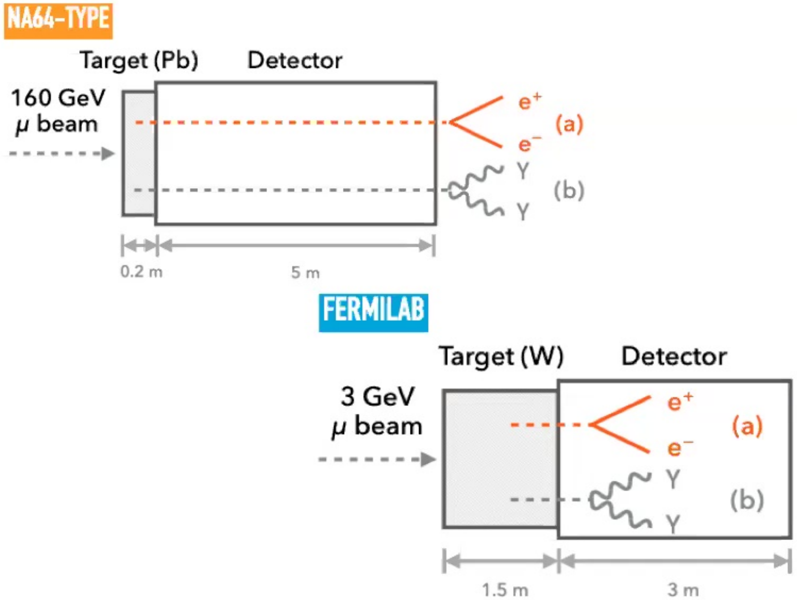
Muon Beam Dump (MuBD)

Proposed beam dump at Fermilab & NA64

Muon Beam Experiments to Probe the Dark Sector

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

- 3, 160 GeV muon beams
- Light scalars ($m_S < 2\ m_\mu$)
- Address g-2 anomaly
- 10^{12} - 10^{14} μOT



Muon Beam Dump (MuBD)

Work in progress with SH, RM, MR at Harvard:

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

Muon Beam Dump (MuBD)

Vector NP Scenarios

$$\mathcal{L}_{\rm V} = \mathcal{L}_{\rm SM} - \frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu} + \frac{1}{2}m^2_{Z'}Z'^{\mu}Z'_{\mu} - \sum_{l\in e,\mu,\tau} ig\left(Q_l\bar{l}\gamma^{\mu}Z'_{\mu}l + Q'_l\bar{\nu}_l\gamma^{\mu}Z'_{\mu}\nu_l\right)$$

Dark Photon

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

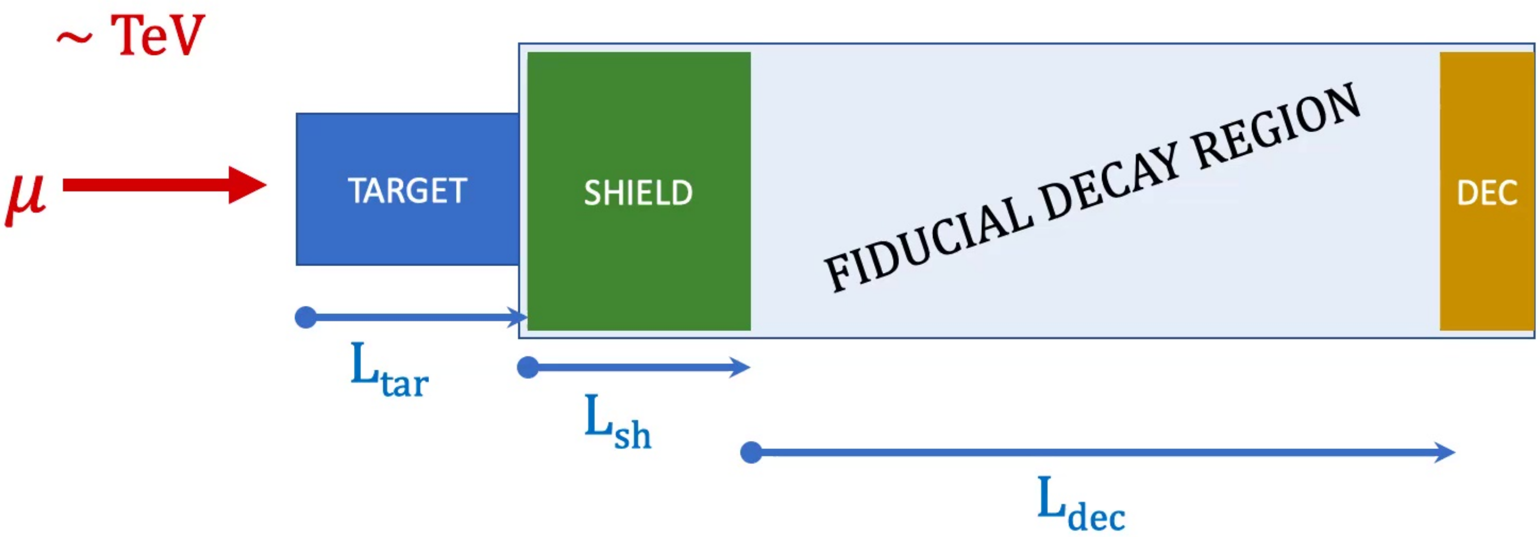
+ quarks

$\mathbf{L_{\mu}}$-$\mathbf{L_{\tau}}$

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

Muon Beam Dump (MuBD)

Experimental set up



Muon Beam Dump (MuBD)

Vector NP Scenarios

$$\mathcal{L}_{\rm V} = \mathcal{L}_{\rm SM} - \frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \frac{1}{2} m_{Z'}^2 Z'^{\mu} Z'_{\mu} - \sum_{l \in e,\mu,\tau} ig \left(Q_l \bar{l} \gamma^\mu Z'_\mu l + Q'_l \bar{\nu}_l \gamma^\mu Z'_\mu \nu_l \right)$$

Dark Photon Lifetime

$$\Gamma_{Z'} \sim m_{Z'} \epsilon^2 \alpha_{EM}$$

$$l_0 = \gamma\tau = \frac{E_{Z'}}{m_{Z'} \Gamma_{Z'}}$$

$$l_0 \approx \left(\frac{10^{-6}}{\epsilon} \right)^2 \left(\frac{\rm GeV}{m_{Z'}} \right)^2 \cdot 10 \text{ m}$$

Muon Beam Dump (MuBD)

To compute number of signal events

$$\frac{dN}{dxdz} = N_\mu \frac{N_0 X_0}{A} \int_{E_{Z'}}^{E_0} dE_1 \int_0^T dt I(E_1; E_0, t) \left(\frac{E_0}{E_1} \frac{d\sigma}{dx'} \right) \Bigg|_{x'=\frac{E'_A}{E_1}} \frac{dP(z - \frac{X_0}{\rho} t)}{dz}$$

Muon Beam Dump (MuBD)

To compute number of signal events

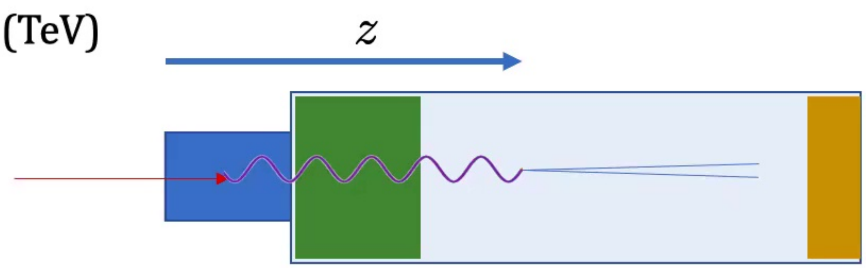
Target material — Beam energy distribution — Probability of Z' decay at z

$$\frac{dN}{dxdz} = N_\mu \boxed{\frac{N_0 X_0}{A}} \int_{E_{Z'}}^{E_0} dE_1 \int_0^T \boxed{dt I(E_1; E_0, t)} \left(\frac{E_0}{E_1}\frac{d\sigma}{dx'}\right)\Bigg|_{x'=\frac{E'_A}{E_1}} \frac{dP(z-\frac{X_0}{\rho}t)}{dz}$$

Production cross section

$x \equiv E_{Z'}/E_0$

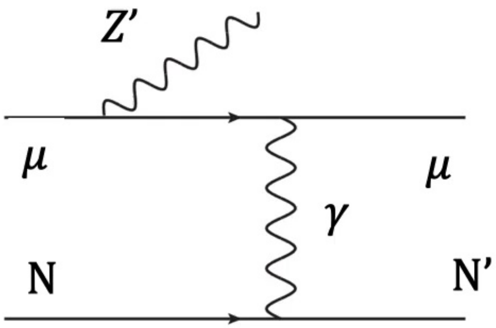
E_0: Beam energy (TeV)



$$\frac{dP(z)}{dz} = \frac{1}{l_0} e^{-z/l_0}$$

Muon Beam Dump (MuBD)

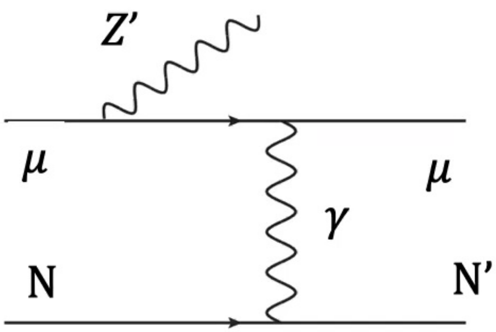
Production cross section is from photon exchange process

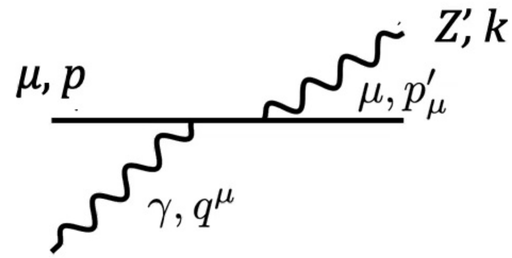


$$\frac{d\sigma(2 \to 3)}{dx}$$

Muon Beam Dump (MuBD)

Production cross section is from photon exchange process





$$\frac{d\sigma(2\to 3)}{dx} \xrightarrow{\text{Weizsäcker-Williams}} \left(\frac{\alpha\chi}{\pi}\right)\left(\frac{E_0 x \beta_{Z'}}{1-x}\right)\frac{d\sigma(p+q\to p'+k)}{d(p\cdot k)}\bigg|_{t=t_{\min}}$$

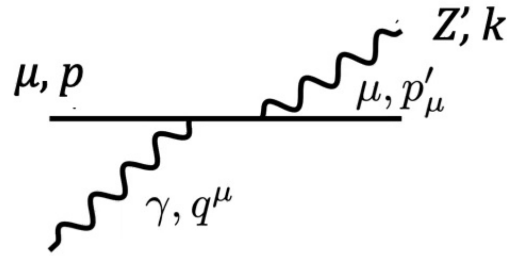
Muon Beam Dump (MuBD)

Weizsäcker-Williams is valid in the regime:

$$\theta_{Z'} \ll 1$$

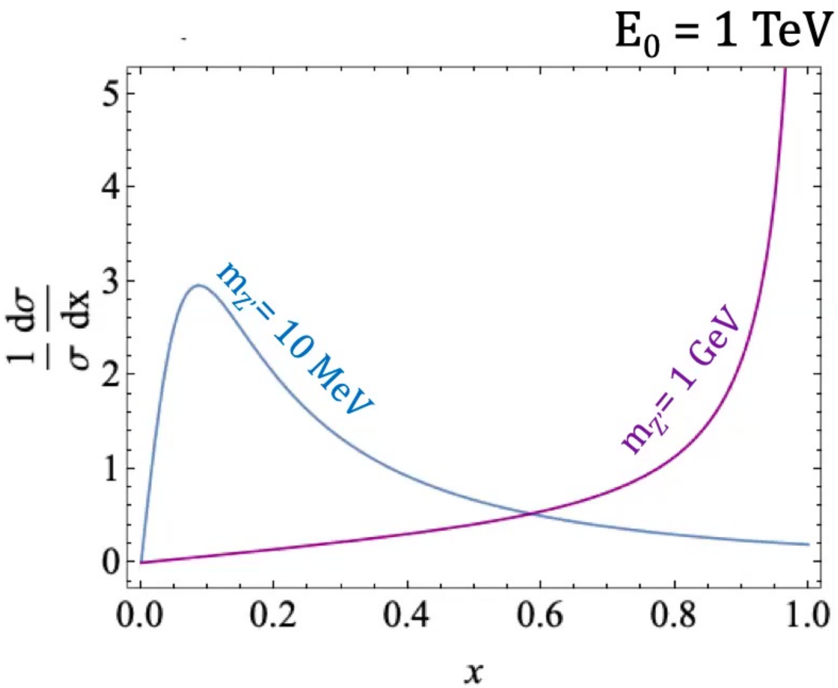
$$m_{Z'}/E_{Z'} \ll 1$$

$$m_\mu/E_0 \ll 1$$



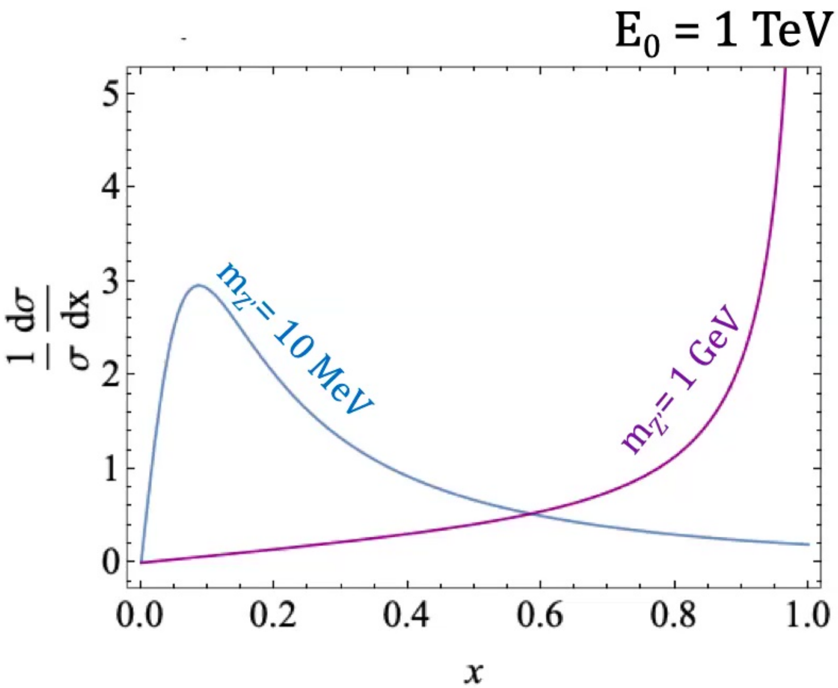
$$\frac{d\sigma(2 \to 3)}{dx} \longrightarrow \left(\frac{\alpha\chi}{\pi}\right)\left(\frac{E_0 x \beta_{Z'}}{1-x}\right) \frac{d\sigma(p+q \to p' + k)}{d(p \cdot k)}\bigg|_{t=t_{\min}}$$

Muon Beam Dump (MuBD)

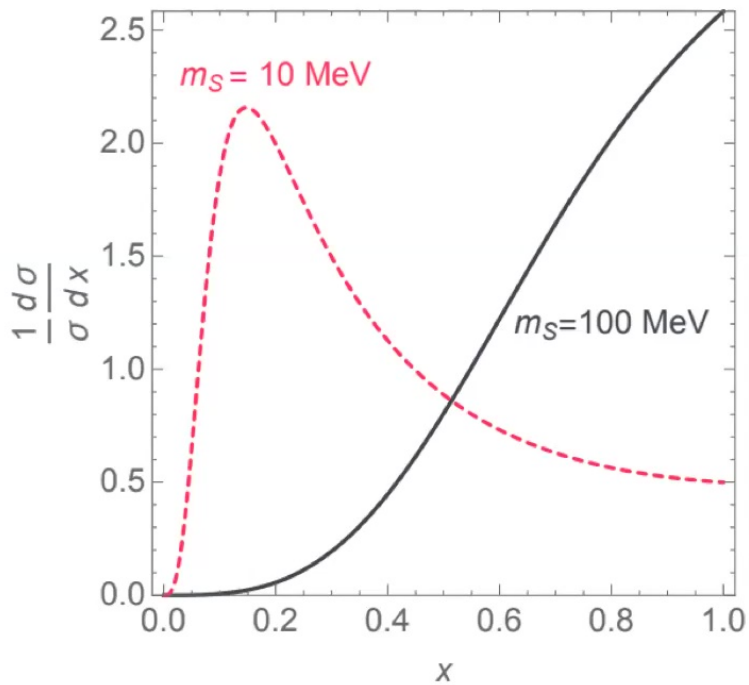


$$\frac{d\sigma}{dx} = \frac{8\chi\epsilon^2\alpha_{EM}^3\sqrt{1-m_{Z'}^2/E_0^2}}{m_{Z'}^2\frac{(1-x)}{x}+m_\mu^2 x}$$

Muon Beam Dump (MuBD)



1701.07437



Muon Beam Dump (MuBD)

New experimental challenge: muons are hard to stop

$$\frac{dE}{dx} = a(E) + b(E)E$$

b(E) parameterizes energy loss to radiation

$$X_0 = 1/b$$

Muon Beam Dump (MuBD)

New experimental challenge: muons are hard to stop

$$\frac{dE}{dx} = a(E) + b(E)E$$

b(E) parameterizes energy loss to radiation

$$X_0 = 1/b$$

$$b_{\rm water}(E \sim {\rm TeV}) \sim 3 \times 10^{-6}\ {\rm cm}^2/{\rm g}$$

$$L = X_0/\rho_{\rm water} \approx 1\ {\rm km}$$

$$b_{\rm tungsten}(E \sim\ {\rm TeV}) \sim 15 \times 10^{-6} {\rm cm}^2/{\rm g}$$

$$L = X_0/\rho_{\rm tungsten} \approx 30\ {\rm m}$$

Muon Beam Dump (MuBD)

New experimental challenge: muons are hard to stop

$$\frac{dE}{dx} = a(E) + b(E)E$$

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$$b_{\text{tungsten}}(E \sim\ \text{TeV}) \sim 15 \times 10^{-6}\text{cm}^2/\text{g}$$

$$L = X_0/\rho_{\text{tungsten}} \approx 30\ \text{m}$$

$$L_e^{\text{water}} \sim 20\ \text{cm}$$

Muon Beam Dump (MuBD)

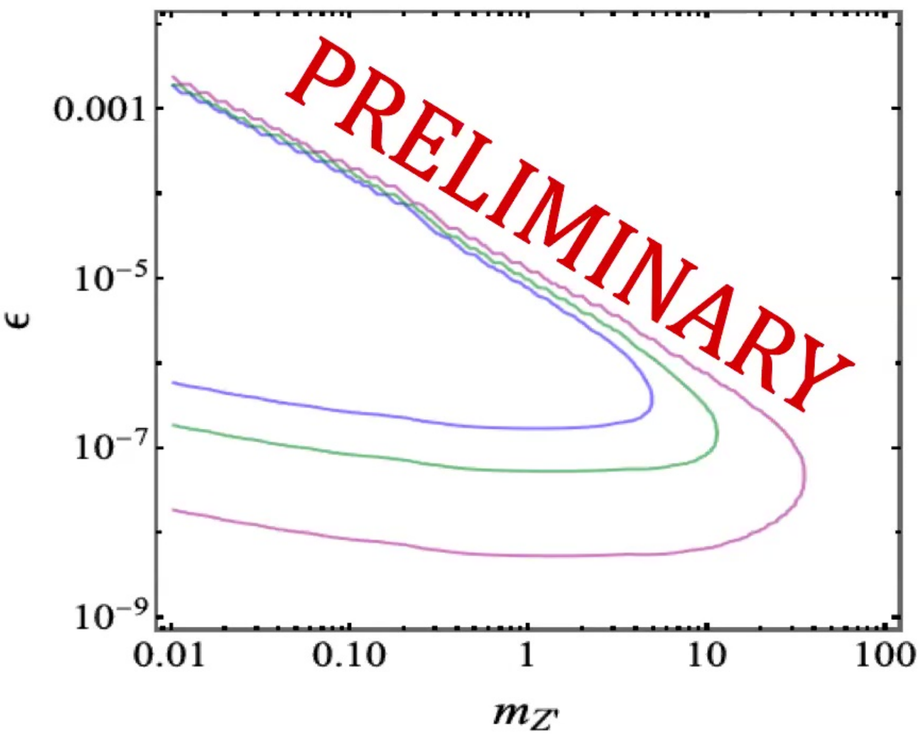
Experimental details*

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

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

** Very preliminary*

Muon Beam Dump (MuBD)



PRELIMINARY results:

Dark Photon model

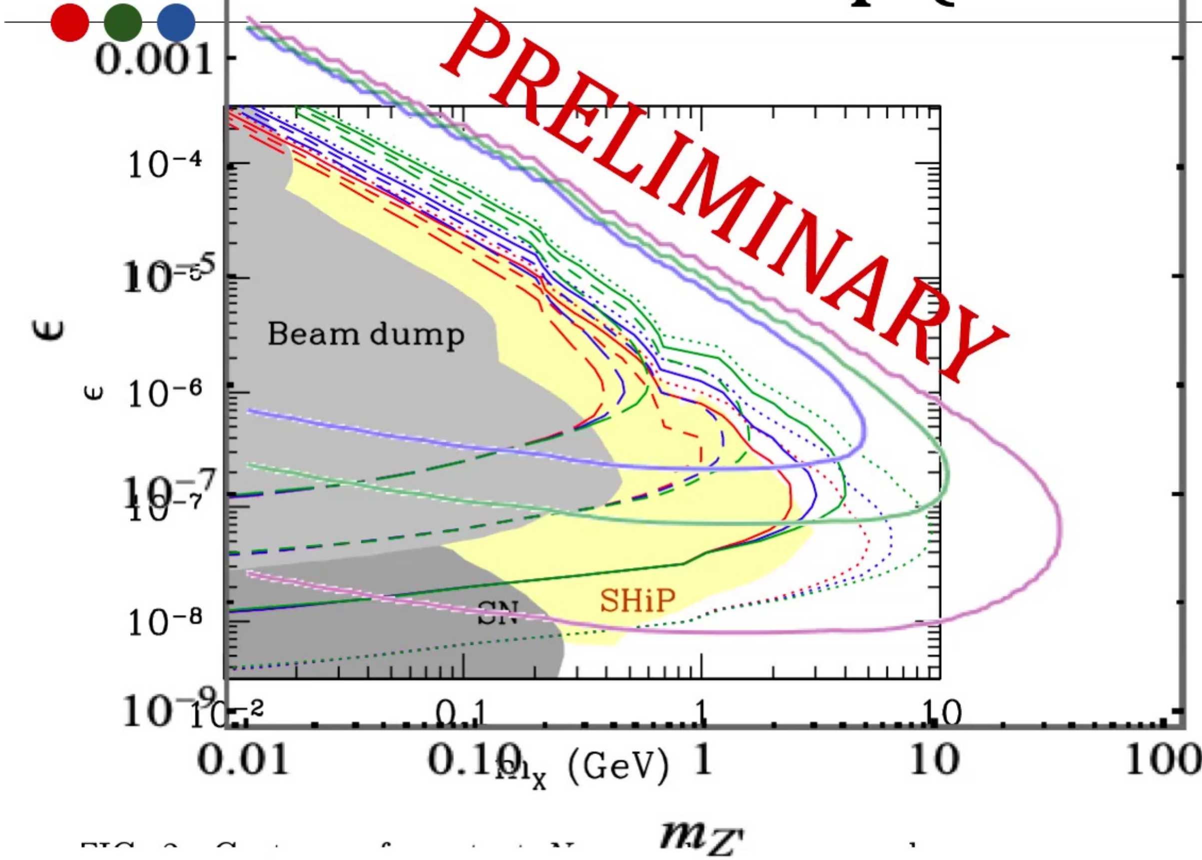
$\mu OT = 10^{20}$

$\mu OT = 10^{22}$

$\mu OT = 10^{26}$

N~10

Muon Beam Dump (MuBD)



PRELIMINARY results:

Dark Photon model

$\mu OT = 10^{20}$

$\mu OT = 10^{22}$

$\mu OT = 10^{26}$

N~10

Muon Beam Dump (MuBD)

On-going progress:

- Detector design / layout
- Different vector / scalar models
- Backgrounds

Muon Collider Complex

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

Leptoquarks are a motivated signal to consider at MuC

We should take advantage of a TeV MuC to probe intensity frontier with a MuBD