Corfu Summer Institute 2017
9 September 2017

Hidden sector explanation of B-decay & cosmic-ray anomalies

1702.00395 / Phys.Rev.D95, 095015

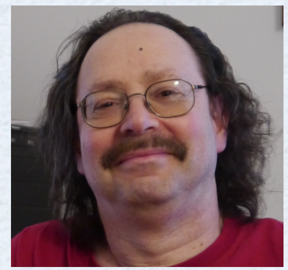
Ryoutaro Watanabe (U. Montréal)

with David London (U. Montréal),
James Cline, Jonathan Cornell (McGill U.)

[What I will explain today]

Z' can **simultaneously** explain

1. B anomaly




SM/data deviations in $b \to s\mu^+\mu^-$

2. Cosmic ray anomaly


AMS anti-proton excess

interpreted as **Dark Matter** annihilation

[Content]

constraint/prospect : $pp \to \mu^+\mu^-$

LHC bound

correlations

B physics

DM issue

anomaly : $b \to s\mu^+\mu^-$

constraint : $\bar{B}_s$–B_s mixing

$\nu N \to \nu N \mu^+\mu^-$

anomaly : antiproton excess

consistency : relic density

prospect : direct detections

[B anomaly]

Deviations from SM in $b \to s\mu^+\mu^-$

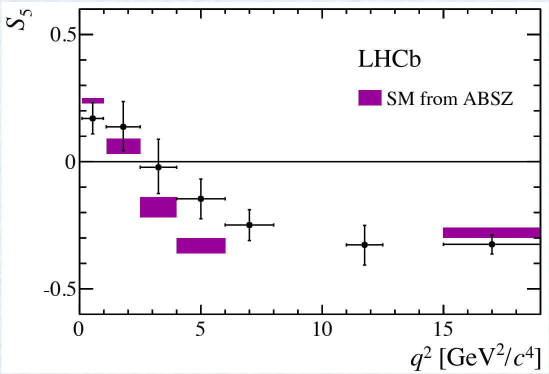
Obs. 1 $R_K = \Gamma(\bar{B} \to K\mu^+\mu^-) \Big/ \Gamma(\bar{B} \to K e^+ e^-)$

$$\mathrm{SM}: \quad 1 \pm \mathcal{O}(0.01)$$

$$\mathrm{LHCb}: \quad 0.745\,^{+0.090}_{-0.074} \pm 0.036$$

$\sim 2.6\,\sigma$ **1406.6482 (LHCb)**

Obs. 2 **Angular analyses of** $\bar{B} \to K^* \ell^+ \ell^-$



~100 observables.

Including all,

$\sim 4.0\,\sigma$

1308.1707 (LHCb)
1512.04442 (LHCb)
1604.04042 (Belle)

Obs. 3 **Angular analyses of** $\bar{B}_s \to \phi\, \ell^+ \ell^-$

$\sim 3.5\,\sigma$

1305.2168 (LHCb)
1506.08777 (LHCb)

[B anomaly : a solution]

The deviations can be explained by

New Physics in $b \to s\mu^+\mu^-$ **with the form of**

$$H_{\rm eff}^{\rm NP} = -\frac{\alpha G_F}{\sqrt{2}\pi} V_{tb} V_{ts}^* \left[\bar{s}\gamma^\mu P_L b\right] \left[\bar{\mu}\gamma^\mu (C_V + C_A \gamma^5)\mu\right]$$

Global fit to data suggests existence of NP

[1510.04239]

Point 1 : **with V - A current** $C_V = -C_A \sim -0.65 \quad \text{(best fit)}$

Point 2 : **only in muon sector**

Point 3 : **comparable with SM** $(C_V^{\rm SM} \simeq -C_A^{\rm SM} \simeq 0.94)$

[B anomaly : a model]

The simplest thought = Z' with left-handed current

$$\mathcal{L}_{Z'} = g_{bs} \, (\bar{s}\gamma^{\mu} P_L b) Z'_{\mu} + g_{\mu\mu} \, (\bar{\mu}\gamma^{\mu} P_L \mu) Z'_{\mu}$$

[B anomaly : a model]

The simplest thought = Z' with left-handed current

$$\mathcal{L}_{Z'} = g_{bs}\,(\bar{s}\gamma^{\mu}P_L b)\,Z'_{\mu} + g_{\mu\mu}\,(\bar{\mu}\gamma^{\mu}P_L\mu)\,Z'_{\mu}$$

To implement this interaction in a realistic model

- Z' **should be a new gauge boson (will get mass after symmetry broken)**
- **Interactions should respect the SM gauge invariance**

This work = U(1)' gauge

[B anomaly : $U(1)'$ model]

This work = U(1)' gauge (coupling = g', charge = Q)

$$\mathcal{L}_{U(1)'} = g' Q_q \left(\bar{q}_L \gamma^\mu q_L\right) Z'_\mu + g' Q_\ell \left(\bar{\ell}_L \gamma^\mu \ell_L\right) Z'_\mu$$

$$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad \ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \quad \text{are charged under } U(1)'$$

[B anomaly : $U(1)'$ model]

This work = U(1)' gauge (coupling = g', charge = Q)

$$\mathcal{L}_{U(1)'} = g' Q_q \left(\bar{q}_L \gamma^\mu q_L\right) Z'_\mu + g' Q_\ell \left(\bar{\ell}_L \gamma^\mu \ell_L\right) Z'_\mu$$

$$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad \ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \quad \text{are charged under } U(1)'$$

Structure of the couplings

- **3rd gene. quarks (tt, bb) and 2nd gene. leptons (μμ, νν) are charged**
- **b-s-Z' coupling is generated by a mixing of the quark field**

[B anomaly : $U(1)'$ model]

The minimum form to address the issues :

- **In the gauge basis**

$$\mathcal{L}_{U(1)'} = g_q\,(\bar{q}_L^3 \gamma^\mu q_L^3) Z'_\mu + g_\ell\,(\bar{\ell}_L^2 \gamma^\mu \ell_L^2) Z'_\mu$$

$$q_L^3 = \begin{pmatrix} t_L \\ b_L \end{pmatrix}, \qquad \ell_L^2 = \begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}, \qquad (g_f = g' Q_f)$$

[B anomaly : $U(1)'$ model]

The minimum form to address the issues :

- **In the gauge basis**

$$\mathcal{L}_{U(1)'} = g_q\,(\bar{q}_L^3 \gamma^\mu q_L^3) Z'_\mu + g_\ell\,(\bar{\ell}_L^2 \gamma^\mu \ell_L^2) Z'_\mu$$

$$q_L^3 = \begin{pmatrix} t_L \\ b_L \end{pmatrix}, \qquad \ell_L^2 = \begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}, \qquad (g_f = g' Q_f)$$

- **b-s coupling is obtained from a mixing in the mass eigen basis**

$$\begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}_{\text{gauge}} = D \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}_{\text{mass}}, \quad D \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_D & \sin\theta_D \\ 0 & -\sin\theta_D & \cos\theta_D \end{pmatrix}$$

- **For the other fermion fields, gauge eigenstates = mass eigenstates**

$[U(1)'$ model : processes$]$

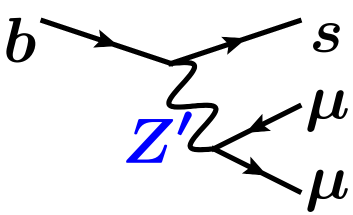
Allowed parameter space :

- **parameters**

$$\color{red}{g_q}\,, \qquad \color{red}{g_\ell}\,, \qquad \color{red}{\theta_D}\,, \qquad \text{and mass } (\color{red}{m_{Z'}})$$

- **relevant flavor constraints**

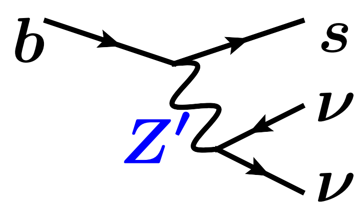
$\color{blue}{B \to K^{(*)}\mu^+\mu^-}$ **[1510.04239]**



Br, angles, distributions, etc.

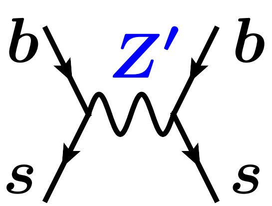
~100 observables

$B \to K^{(*)}\nu\bar{\nu}$ **[1409.4557]**



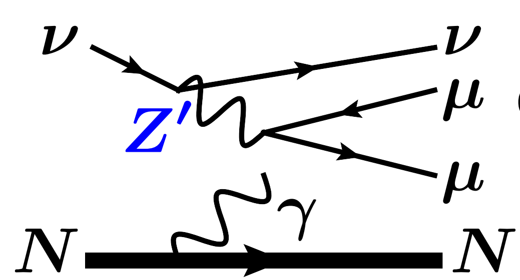
Branching ratio (upper limit)

B_s-$\bar{B}_s$ mixing **[PDG 2016]**



Mass difference of Bs

$N\nu \to N\nu\mu^+\mu^-$ **[1609.04026]**



Cross section

[$U(1)'$ model : processes]

Allowed parameter space :

- **parameters**

$$g_q\,,\qquad g_\ell\,,\qquad \theta_D\,,\qquad \text{and mass } (m_{Z'})$$

- **relevant flavor constraints**

Process	Observable	Constraint on
$b \to s\mu^+\mu^-$	global fit ($\sim$ 100 observables)	$g_q g_\ell \sin\theta_D \cos\theta_D m_{Z'}^{-2}$
$b \to s\nu\bar{\nu}$	branching ratio (upper limit)	$g_q g_\ell \sin\theta_D \cos\theta_D m_{Z'}^{-2}$
$\bar{B}_s^0$-B_s^0 mixing	mass difference (ΔM_s)	$g_q^2 \sin\theta_D \cos\theta_D m_{Z'}^{-2}$
$\nu N \to \nu N \mu^+\mu^-$	production cross section	$g_\ell^2 m_{Z'}^{-2}$

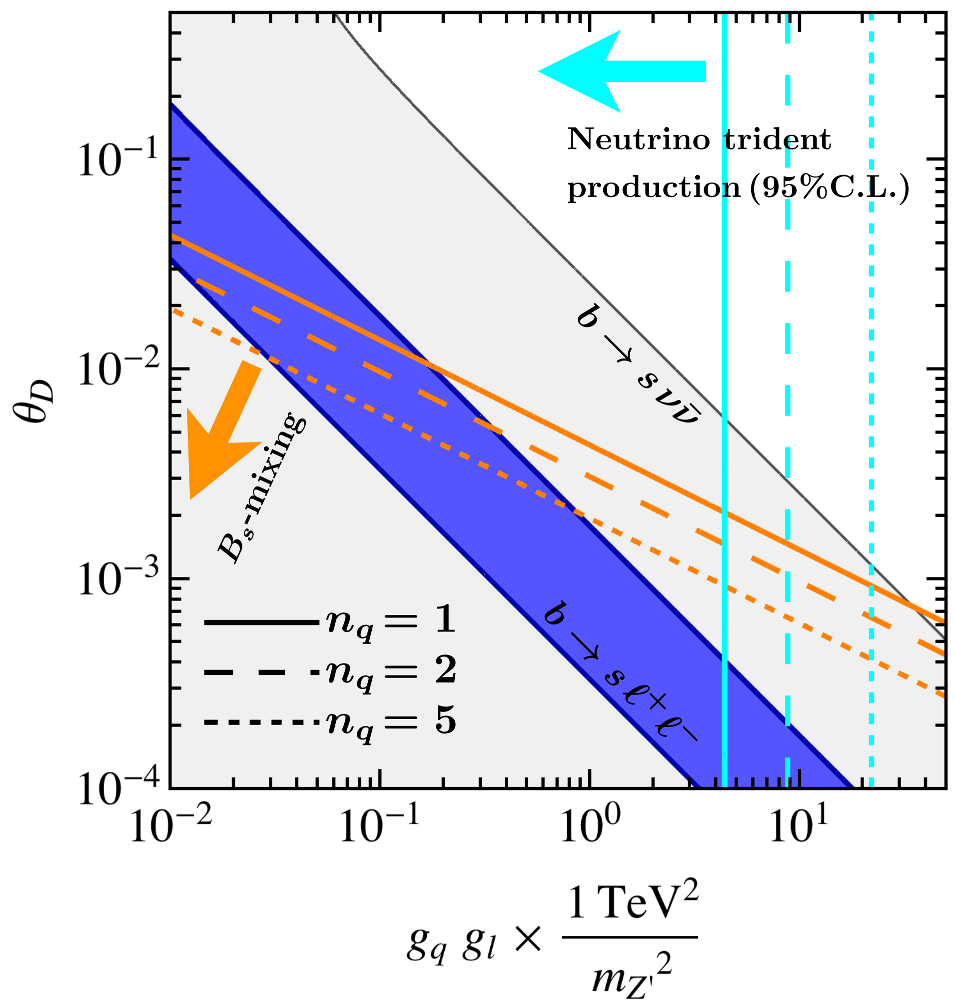
- **we define ratio of the couplings: "hierarchy of the couplings"**

$$n_q \equiv \frac{g_q}{g_\ell}$$

(ex) $n_q > 1 \;\Rightarrow\; g_q > g_\ell$

[$U(1)'$ model : constraints]

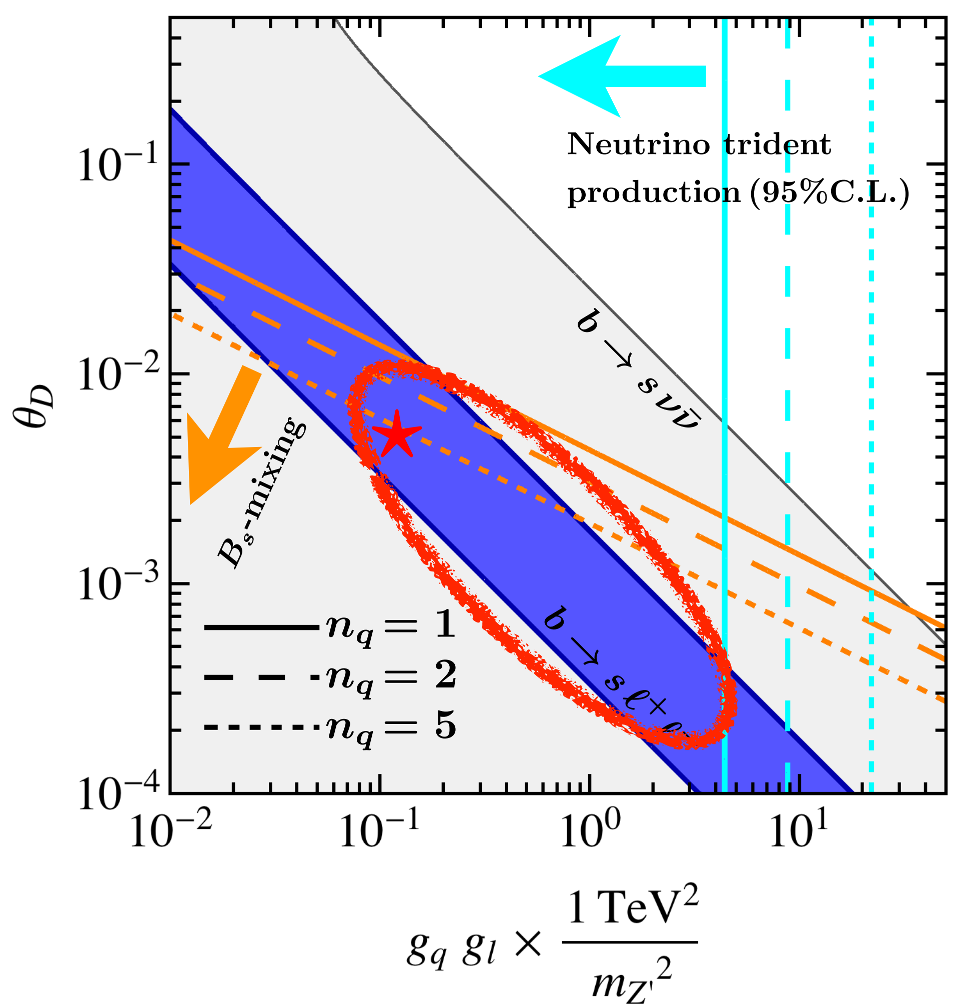
Space on $\left(g_q\, g_\ell\, m_{Z'}^{-2}\ ,\ \theta_D\right)$ for several choices of $n_q \equiv \dfrac{g_q}{g_\ell}$



- **Region in** [blue box] **explains the $b \to s\mu^+\mu^-$ anomaly**
- **A small mixing in limited range is only allowed**

[$U(1)'$ model : constraints]

Space on $\left(g_q\, g_\ell\, m_{Z'}^{-2}\,,\ \theta_D\right)$ **for several choices of** $n_q \equiv \dfrac{g_q}{g_\ell}$



- **Region in [blue box] explains the $b \to s\mu^+\mu^-$ anomaly**
- **Region in [red ellipse] satisfies all the flavor constraints**
- **The reference point (★)**

$$\theta_D = 0.005$$

$$g_q g_\ell / m_{Z'}^2 = 0.12/\mathrm{TeV}^2$$

- **A small mixing in limited range is only allowed**

[$U(1)'$ model : summary]

Reference point ★

$$g_q \equiv n_\ell \, g_\ell \simeq 0.35\sqrt{n_\ell}\left(\frac{m_{Z'}}{1\,\mathrm{TeV}}\right)$$

(Just keep this in mind)

Next point

- **introduction of Dark Matter to our model**
- **DM solution to Cosmic Ray anomaly**
- **Correlation between B and CR anomalies**

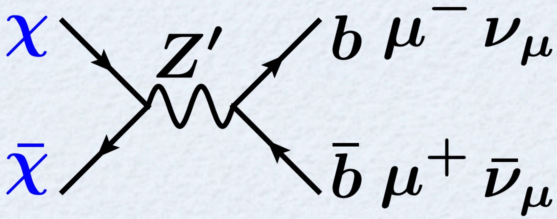
[$U(1)'$ model : dark matter]

Z' as a mediator of Dark Matter :

- We can easily introduce (Dirac) DM into our model

$$\mathcal{L}_{U(1)'} = g_q\,(\bar{q}_L^3 \gamma^\mu q_L^3) Z'_\mu + g_\ell\,(\bar{\ell}_L^2 \gamma^\mu \ell_L^2) Z'_\mu + g_\chi\,(\bar{\chi}\gamma^\mu \chi) Z'_\mu$$

- DM annihilation channel



$$\langle \sigma v \rangle = \frac{g_\chi^2 (3g_q^2 + 2g_\ell^2)}{2\pi} \left(\frac{m_\chi^2}{m_{Z'}^4} \right)$$

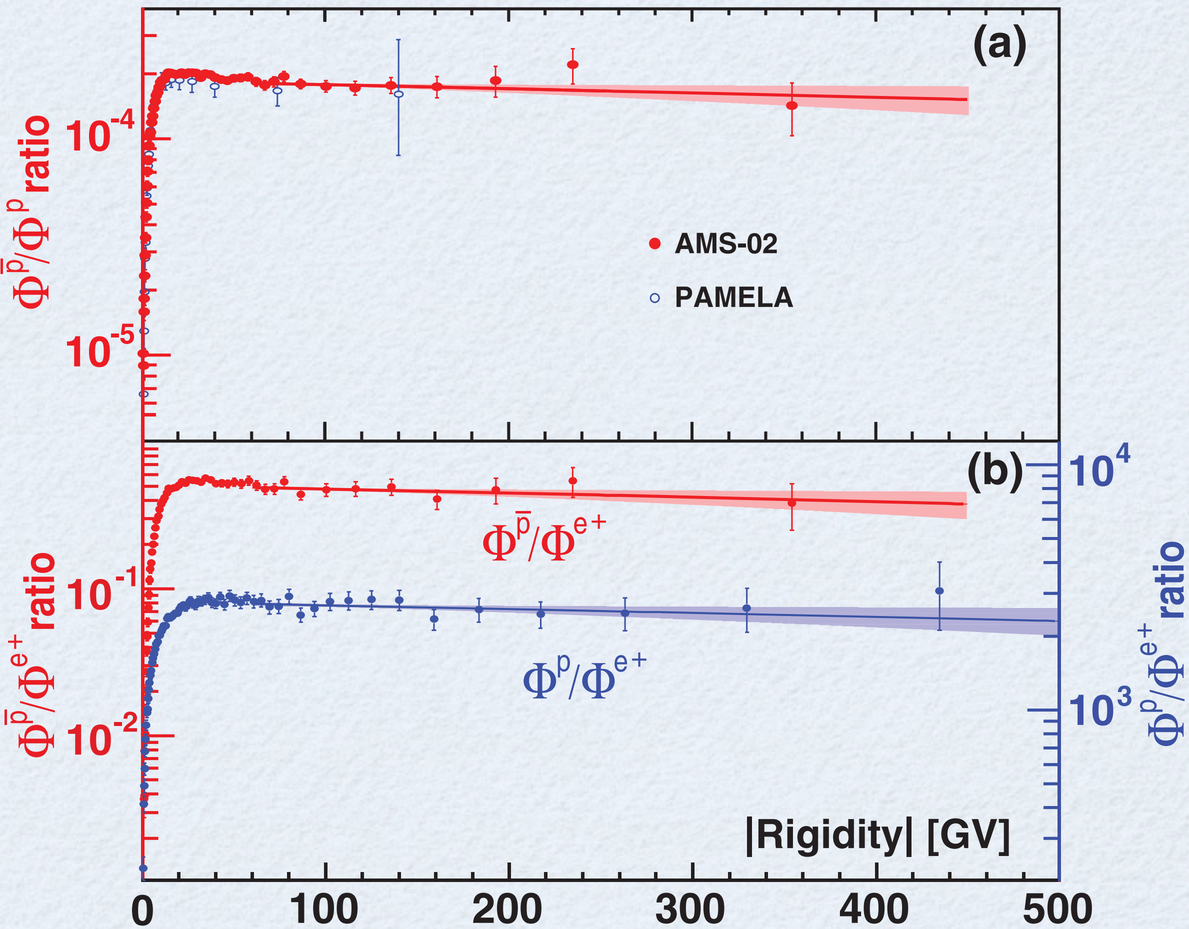
So, what can we play with this?

[CR anomaly]

AMS-02 antiproton observation

- **Precise measurement of antiproton flux in cosmic rays at ISS**

Phys. Rev. Lett. 117.091103



[CR anomaly : DM interpretation]

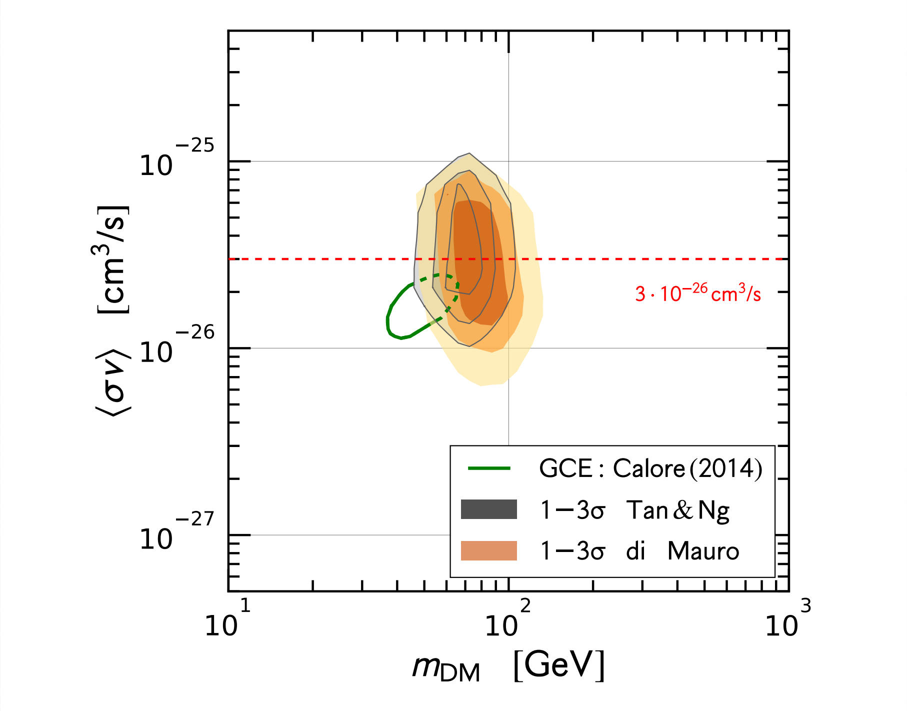
AMS-02 antiproton observation

- Recent studies for re-fit to AMS data taking DM into account suggest

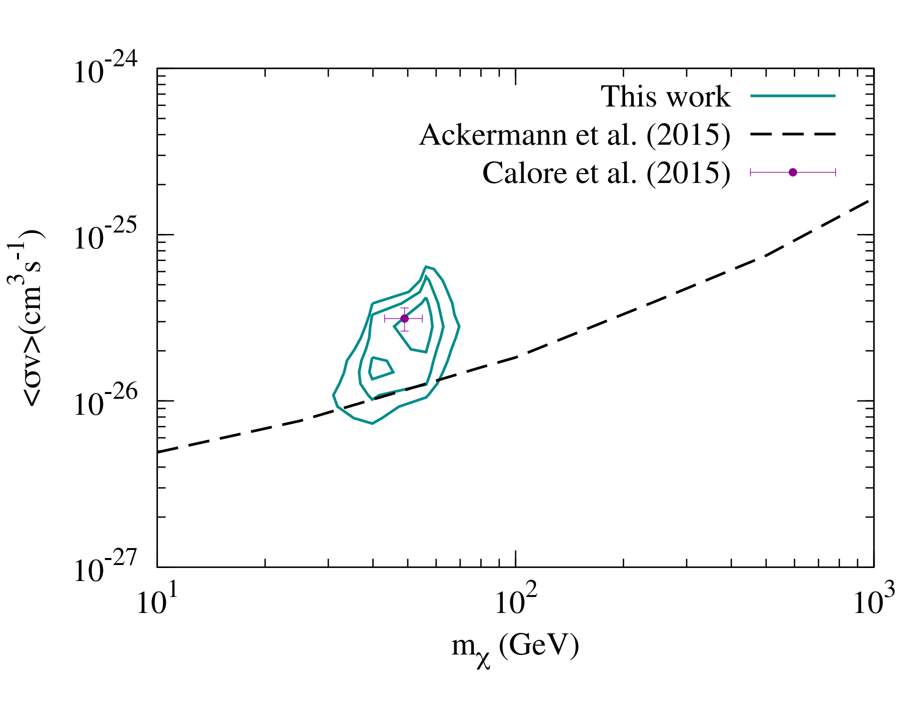
$\chi\bar{\chi} \to b\bar{b}$ is favored when

$m_\chi \sim 70\,\mathrm{GeV}$ and $\langle \sigma v \rangle \sim$ Relic density

Phys.Rev.Lett. 118.191102



Phys.Rev.Lett.118.191101



[CR anomaly : DM solution]

Implication with respect to our model

- [Relic density] + [DM favored by AMS-02 data]

$$\langle \sigma v \rangle = \frac{g_\chi^2 (3g_q^2 + 2g_\ell^2)}{2\pi} \left(\frac{(70\,\mathrm{GeV})^2}{m_{Z'}^4} \right) \simeq 4.4 \times 10^{-26}\,\mathrm{cm}^3/s$$

- DM solution in our model

$$g_\chi \equiv n_\chi g_q \simeq 1.09 \sqrt{n_\chi} \left(\frac{m_{Z'}}{1\,\mathrm{TeV}} \right)$$

[CR anomaly : DM solution]

Implication with respect to our model

- [Relic density] + [DM favored by AMS-02 data]

$$\langle \sigma v \rangle = \frac{g_\chi^2 (3 g_q^2 + 2 g_\ell^2)}{2\pi} \left(\frac{(70\,\mathrm{GeV})^2}{m_{Z'}^4} \right) \simeq 4.4 \times 10^{-26}\,\mathrm{cm}^3/s$$

($\chi\bar{\chi} \to b\bar{b}$ dominated)

- DM solution in our model

$$g_\chi \equiv n_\chi g_q \simeq 1.09 \sqrt{n_\chi} \left(\frac{m_{Z'}}{1\,\mathrm{TeV}} \right)$$

[CR anomaly : DM solution]

Implication with respect to our model

- [Relic density] + [DM favored by AMS-02 data]

$$\langle \sigma v \rangle = \frac{g_\chi^2 (3 g_q^2 + 2\cancel{g_\ell^2})}{2\pi} \left(\frac{(70\,\mathrm{GeV})^2}{m_{Z'}^4} \right) \simeq 4.4 \times 10^{-26}\,\mathrm{cm}^3/s$$

($\chi\bar{\chi} \to b\bar{b}$ dominated) (AMS-02 data favored)

- DM solution in our model

$$g_\chi \equiv n_\chi g_q \simeq 1.09 \sqrt{n_\chi} \left(\frac{m_{Z'}}{1\,\mathrm{TeV}} \right)$$

[CR anomaly : DM solution]

Implication with respect to our model

- [Relic density] + [DM favored by AMS-02 data]

$$\langle \sigma v \rangle = \frac{g_\chi^2 (3 g_q^2 + 2 g_\ell^2)}{2\pi} \left(\frac{(70\,\mathrm{GeV})^2}{m_{Z'}^4} \right) \simeq 4.4 \times 10^{-26}\,\mathrm{cm}^3/s$$

($\chi\bar{\chi} \to b\bar{b}$ dominated) (AMS-02 data favored) (Relic density)

- DM solution in our model

$$g_\chi \equiv n_\chi g_q \simeq 1.09 \sqrt{n_\chi} \left(\frac{m_{Z'}}{1\,\mathrm{TeV}} \right)$$

[CR anomaly : DM solution]

Implication with respect to our model

- [Relic density] + [DM favored by AMS-02 data]

$$\langle \sigma v \rangle = \frac{g_\chi^2 (3 g_q^2 + 2 g_\ell^2)}{2\pi} \left(\frac{(70\,\mathrm{GeV})^2}{m_{Z'}^4} \right) \simeq 4.4 \times 10^{-26}\,\mathrm{cm}^3/s$$

($\chi\bar{\chi} \to b\bar{b}$ **dominated**) **(AMS-02 data favored)** **(Relic density)**

- **DM solution in our model**

$$g_\chi \equiv n_\chi g_q \simeq 1.09 \sqrt{n_\chi} \left(\frac{m_{Z'}}{1\,\mathrm{TeV}} \right)$$

[B and CR anomalies]

Requirement

- **In terms of couplings**

$$B \text{ physics}: \quad g_q^2 \simeq 0.12\, n_q \times \left(\frac{m_{Z'}}{1\,\text{TeV}}\right)^2 \quad \text{for the point } \star$$

$$\text{Astrophysics}: \quad g_q^2 \simeq \frac{1.2}{n_\chi} \times \left(\frac{m_{Z'}}{1\,\text{TeV}}\right)^2 \quad \text{for } m_\chi = 70\,\text{GeV}$$

$$\boxed{n_\chi \cdot n_q \simeq 10} \qquad (\, g_\chi \equiv n_\chi g_q, \;\; g_q \equiv n_q g_\ell \,)$$

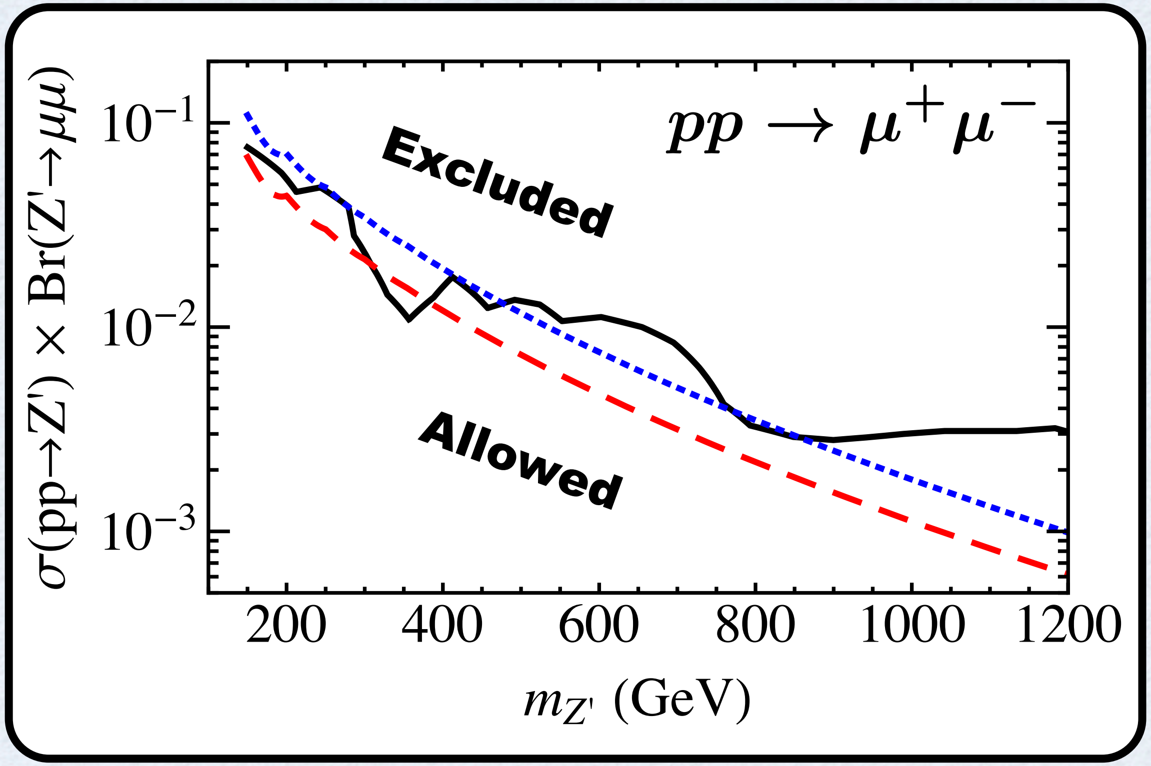
- **The DM re-fit to AMS data indicates** $\chi\bar{\chi} \to b\bar{b}$ **is dominant process**

  At least, $n_q > 1 \quad (g_q > g_\ell)$

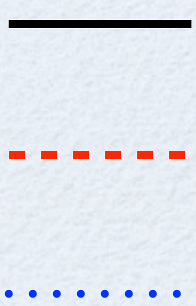
  Indeed, $n_q = 2 \quad (g_q = 2g_\ell)$ **is sufficient (86% of full bb case)**

[B and CR anomalies : LHC prospect]

Collider limit and prospect



[ATLAS-CONF-2016-045]



n_χ ↗ = $\mathrm{Br}(Z' \to \mu\mu)$ ↘

Z' mass ↗ **= couplings** ↗

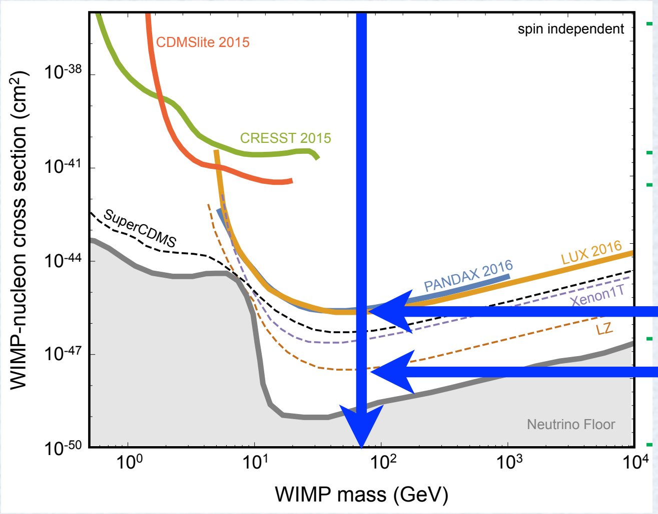
Hierarchical couplings are favored: $g_\chi > g_q > g_\ell$

Small Z' mass is (1) still viable
(2) rather favored

$m_{Z'} \sim 500\,\mathrm{GeV}$

[B and CR anomalies : DM prospect]

Current & future limits of DM direct detection



[Talk by M. Lisanti] 1612.01223 (PandaX-II)
1602.03489 (LUX)
1509.02910 (LZ)

Current $\sim 2\times 10^{-45}\mathrm{cm}^2$

Future $\sim 10^{-48}\mathrm{cm}^2$

DM-proton scattering in nucleon

- **Kinetic mixing (ε) of Z' and photon induces a contribution**
- **Our naive estimation obtains** $\sigma_p = \dfrac{(\epsilon e g_\chi m_p)^2}{\pi m_{Z'}^4} \lesssim 1.7\times 10^{-45}\mathrm{cm}^2$

sufficiently detectable in near future

[Summary]

Z' can simultaneously explain

SM/data deviations in $b \to s\mu^+\mu^-$

AMS anti-proton excess
interpreted as Dark Matter annihilation

One viable scenario :

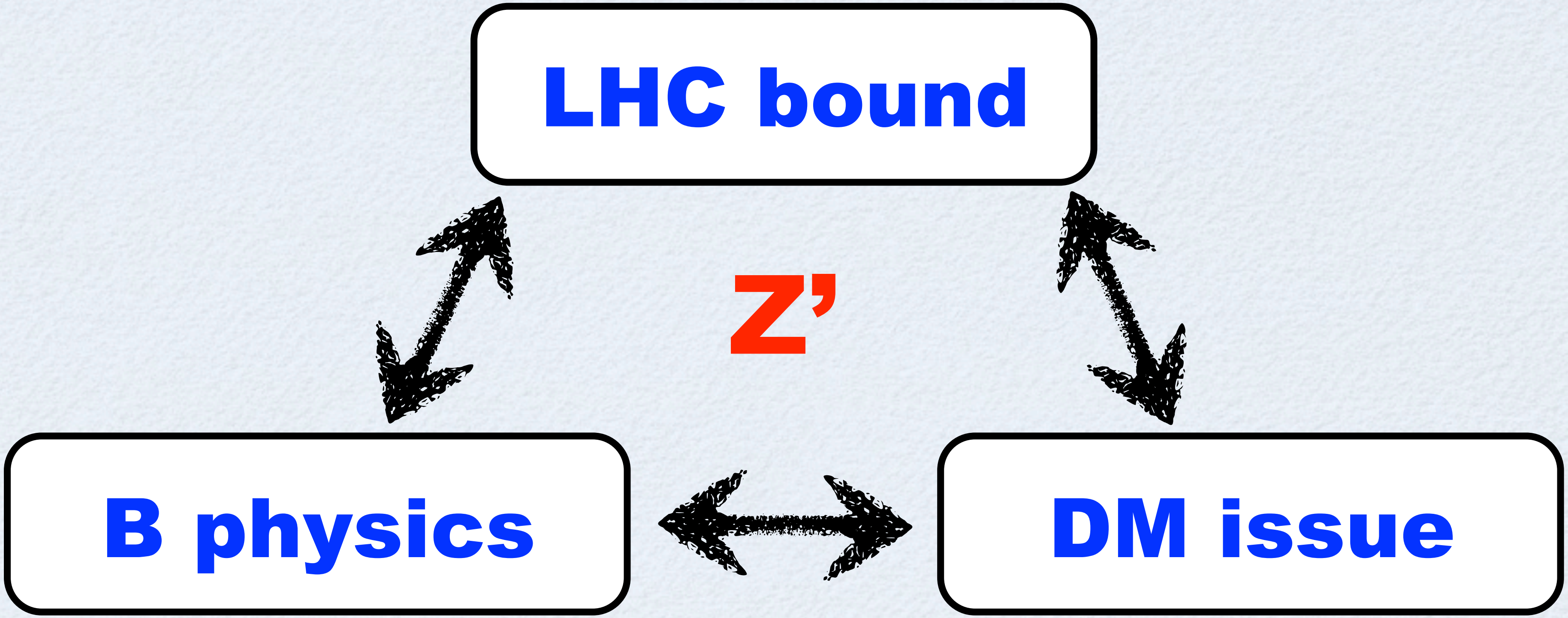
$$\mathcal{L}_{U(1)'} = g_q\,(\bar{q}_L^3\gamma^\mu q_L^3)Z'_\mu + g_\ell\,(\bar{\ell}_L^2\gamma^\mu \ell_L^2)Z'_\mu + g_\chi\,(\bar{\chi}\gamma^\mu\chi)Z'_\mu$$

with

$$g_\chi \simeq 5\,g_q,\quad g_q \simeq 2\,g_\ell, \qquad \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}_{\rm gauge} \simeq \begin{pmatrix} 1 & 0 & 0 \\ 0 & \sim 1 & 0.005 \\ 0 & -0.005 & \sim 1 \end{pmatrix} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}_{\rm mass}$$

[Summary]

constraint/prospect : $pp \to \mu^+\mu^-$



anomaly : $b \to s\mu^+\mu^-$
constraint : $\bar{B}_s$–B_s mixing
$\nu N \to \nu N \mu^+\mu^-$

anomaly : antiproton excess
consistency : relic density
prospect : direct detections

[Summary]

constraint/prospect : $pp \to \mu^+\mu^-$

LHC bound

Z'

B physics — explained

anomaly : $s\mu^+\mu^-$

constraint : $\bar{B}_s$–B_s mixing

$\nu N \to \nu N \mu^+\mu^-$

DM issue — explained

anomaly : roton excess

consistency : relic density

prospect : direct detections

[Summary]

constraint/pros

small Z' mass is
still viable / detectable

L bound

Z'

B physics

explained

anomaly : $s\mu^+\mu^-$

constraint : $\bar{B}_s$–B_s mixing

$\nu N \to \nu N \mu^+\mu^-$

DM issue

explained

anomaly : proto

consistency : rel

prospect : ions

detectable
in σ_p

Thank you!

[DM direct detection]

DM-nucleon scattering

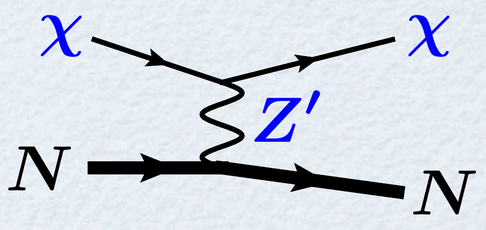
- **Coupling to up-quark is very much suppressed, but exists**

$$\mathcal{L}_{u\bar{u}Z'} = g_q X_{uu}(\bar{u}\gamma^\mu P_L u)Z'_\mu$$

$$X_{uu} \sim |V_{ub} - \theta_D V_{us}|^2 \sim 6 \times 10^{-6} \quad \text{for} \ \star$$

(no interaction of d-$\bar{d}$-Z')

- **Still, it gives rise to a contribution to** $\chi N \to \chi N$



$$\sigma_N = (1 + Z/A)^2 \frac{g_\chi^2 g_q^2 X_{uu}^2}{4\pi} \frac{m_n^2}{m_{Z'}^2}$$

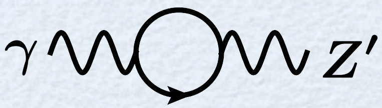
$$\simeq 2 \times 10^{-51} \text{cm}^2$$

keeping the conditions from B-physics & Astrophysics

for the $n_q = 2, \ n_\chi = 5$ **scenario and for xenon**

[DM direct detection]

Kinetic mixing of Z' & photon $\frac{\epsilon}{2} F^{\mu\nu} Z'_{\mu\nu}$



- **Natural size at one loop (for "marginal" point)**

  1. Log divergence at UV cancels only if $g_q = g_\ell$
  2. The present case is, however, $g_q > g_\ell$
  3. Possible solution is to introduce **heavy vector-like fermion (F)**
  4. In this case, contribution at the low energy is calculable

$$\epsilon \sim 0.04\, e\, g_q \quad (\text{for } m_F \sim 100\,\text{TeV and } g_q = 2g_\ell)$$

- **DM can then interact with proton in nucleon**

$$\sigma_p = \frac{(\epsilon e g_\chi m_p)^2}{\pi m_{Z'}^4} \sim 1.7 \times 10^{-45}\text{cm}^2$$

  1. Just below the bound from PandaX-II $1.8 \times 10^{-45}\text{cm}^2$
  2. Well above the expected reach of LZ experiment $\sim 10^{-47}\text{cm}^2$

sufficiently detectable in near future

[UV completion]

Simple example

- **Gaugeed flavor symmetries**

$$SU(3)_q \times SU(3)_u \times SU(3)_d \times SU(3)_\ell \times SU(3)_e \times O(3)_{\nu_R}$$

$$SU(3)_q \times SU(3)_\ell \to U(1)' \ \text{ at TeV scale}$$

- **Direction of U(1)'**

We assign U(1)' in a way that q^3 and ℓ^2 are charged under U(1)'

- **Some requirements (unimportant for today's topic)**

Scalar field that breaks U(1)' to get Z' mass

Chiral fermion(s) to ensure anomaly free

Cut-off scale (>100TeV for <1TeV Z' mass) due to running effect of g_χ

[UV completion]

Realization of U(1)’

- gives a prediction on hierarchy of coupling

arXiv:1704.08158

$$SU(3)_H \times U(1)_{B-L} \to U(1)'$$

$$n_q = 5/9\,, \quad n_\chi = ? \quad (\mathrm{DM} = \nu_R)$$

$$\theta_D \sim V_{tb} V_{ts}^*$$

arXiv:1706.08510

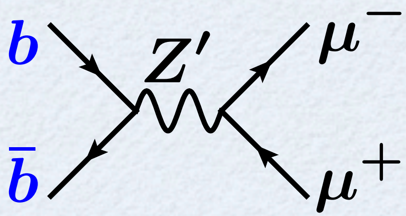
$$SU(3)_L \times SU(3)_R \to U(1)'$$

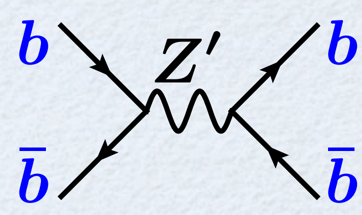
$$n_q = 4\,, \quad n_\chi = ? \quad (\mathrm{DM\ is\ not\ considered})$$

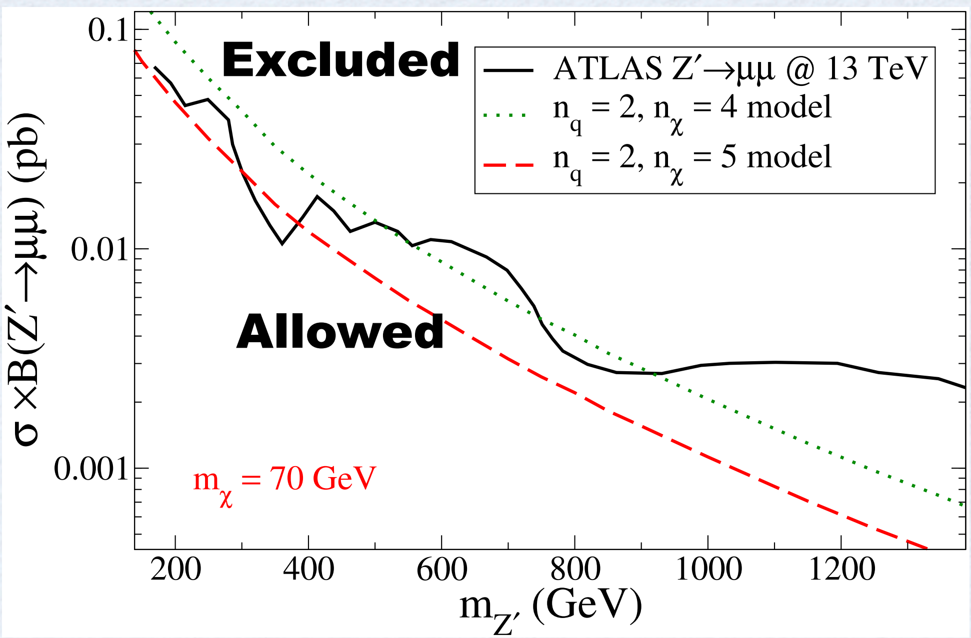
$$\theta_D \sim V_{tb} V_{ts}^*$$

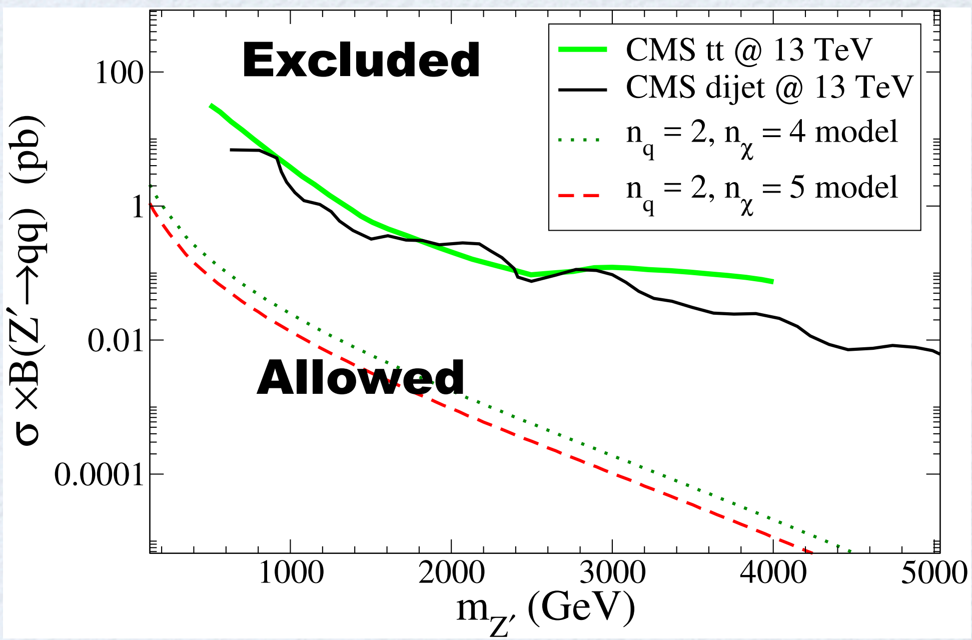
[LHC bound]

Two relevant analyses









[ATLAS-CONF-2016-045]

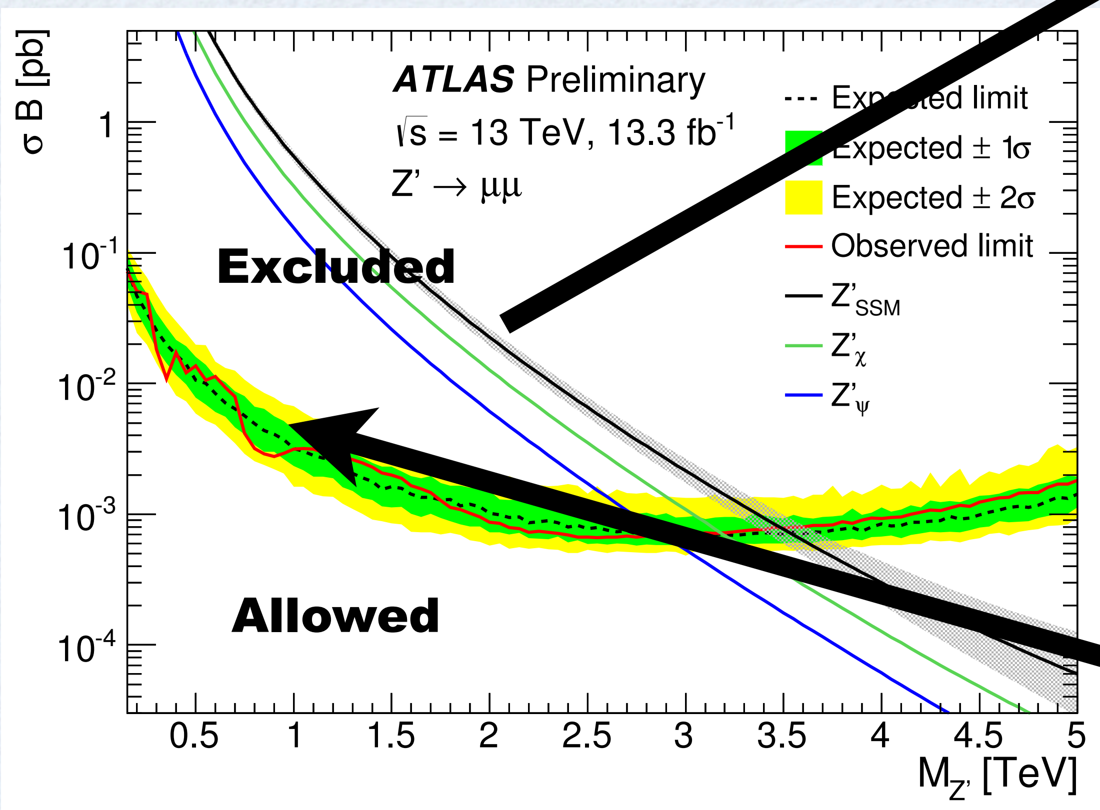
(also, CMS-PAS-EXO-16-031)

[arXiv:1611.03568]

[LHC bound]

Usual bound vs Our bound

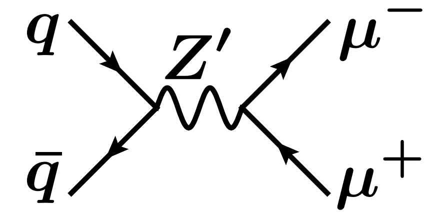
$pp \to \mu^+\mu^-$



[ATLAS-CONF-2016-045]

(also, CMS-PAS-EXO-16-031)

[Reference model]

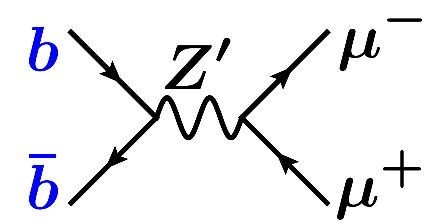


$$g_{\rm SM}\,(\bar{q}_L\gamma^\mu q_L)Z'_\mu$$

$$q = u, d, s, (c, b)$$

$$g_{\rm SM} = Z \text{ coupling}$$

[Our model]



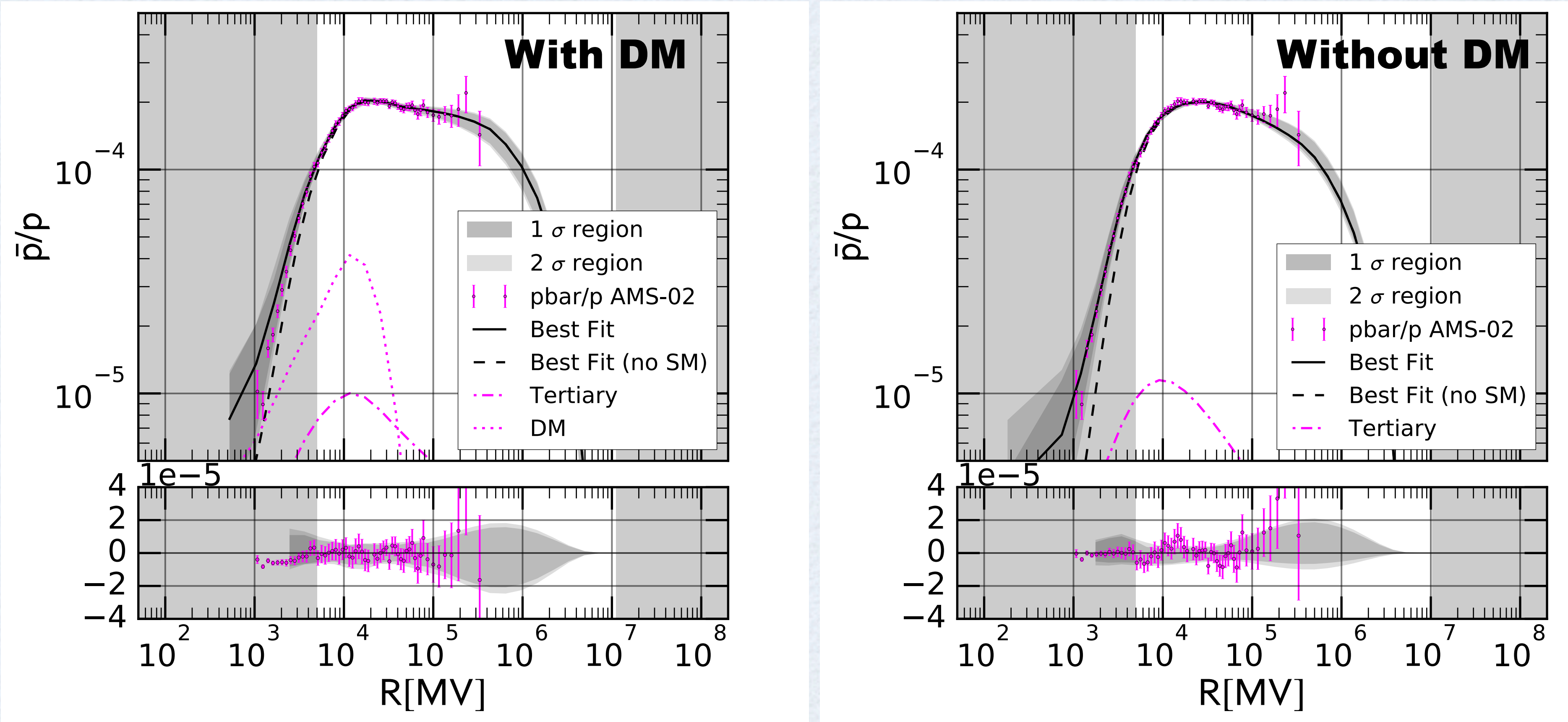
PDF suppressed

Smaller mass will be allowed

[Cosmic Ray anomaly]

AMS-02 antiproton observation

- **Fit including DM**



[arXiv:1610.03071]

[Cosmic Ray anomaly]

Conflict with dwarf spheroidal galaxies?

The most recent Fermi-LAT searches for emission from dark matter annihilation in dwarf spheroidal galaxies currently exclude cross sections of $\langle \sigma v \rangle > 1.9 \times 10^{-26}$ cm^3/s at 95% C.L. for 80 GeV DM annihilating to $b\bar{b}$ [53]. This is in tension with the cross sections suggested by the DM interpretation of the $\bar{p}$ excess. However, recent works [54, 55] have pointed out that the dark matter content of some of the dwarf spheroidals in the Fermi analysis may have been overestimated, resulting in a less stringent limit that can be compatible with DM explanations of cosmic ray excesses.

[arXiv:1504.02048]
[arXiv:1603.07721]