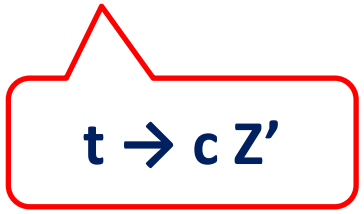
Z'-induced FCNC Decays of Top, Beauty and Strange Quarks



Masaya Kohda
(Chung Yuan Christian Univ., Taiwan)

Based on works with:

Kaori Fuyuto (Nagoya U.), Wei-Shu Hou (Nat'l Taiwan U.)
[PRL114, 171802, and work in progress]

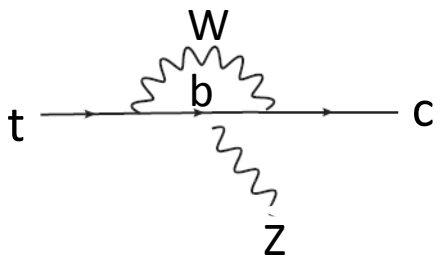
EPS HEP 2015 @ Vienna, July 24, 2015

Introduction

- Rare decays of top quark are good probes to see New Physics

1) Flavor Changing Neutral Current (FCNC) decays

ex.) $t \rightarrow c\,Z$, $t \rightarrow c\,h$



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  - Loop suppression
  - CKM suppression
  - GIM (perfectly works)

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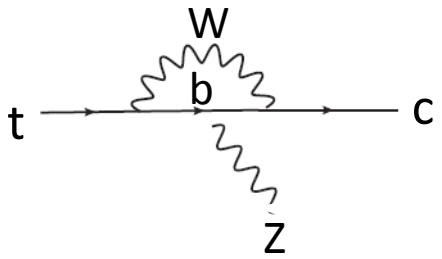

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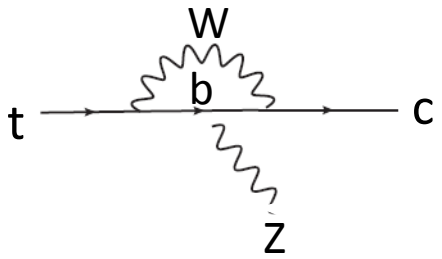

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3) New particle production in top FCNC decay

$t \rightarrow c\,Z'$ Z': new massive gauge boson

Hints from B physics

- b → s μ^+ μ^- transitions are being precisely measured at LHC
- Overall agreement with SM, but two tantalizing hints

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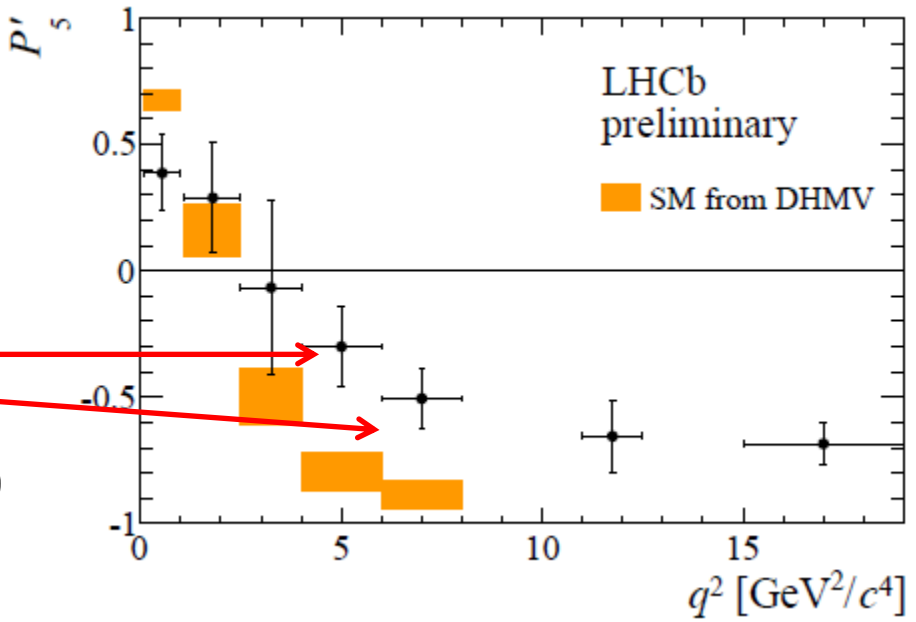
1) P_5' anomaly in $B^0 \to K^{*0} \mu^+ \mu^-$ decay angular distribution

LHCb, PRL 111, 191801 (2013) [1/fb]; LHCb-CONF-2015-002 [3/fb]

- P_5': a form-factor free observable made from angular coefficients
- measured spectrum: ($q^2 = m^2_{\mu\mu}$)



2.9σ tensions

--> 3.7σ tension (combo)

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2) Lepton flavor non-universality in $B^+ \to K^+ l^+ l^-$ (l = e, μ) decays

LHCb, PRL 113, 151601 (2014) [3/fb]

$$R_K = \frac{\Gamma(B^+ \to K^+ \mu^+ \mu^-)}{\Gamma(B^+ \to K^+ e^+ e^-)} = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{sys})$$

➢ 2.6σ deviation from SM: $R_K^{SM} = 1 + \mathcal{O}(\frac{m_\mu^2}{m_b^2})$

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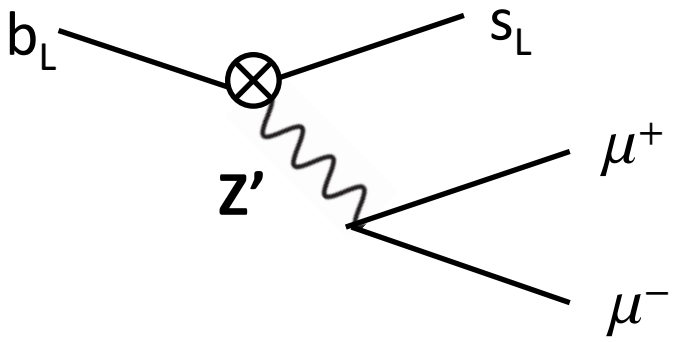
  LHCb, PRL 113, 151601 (2014) [3/fb]

- Both anomalies can be nicely explained by adding New Physics contribution to C_9 for muon, but not for electron
  - C_9: Wilson coefficient in $\mathcal{H}_{\rm eff} \supset C_9 (\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \mu)$
  - A global analysis tells: $\Delta C_9 \simeq -\frac{1}{(34\ \mathrm{TeV})^2}$ (~ -25% of SM)

  Altmannshofer and Straub, 1411.3161

A new muon-specific gauge boson Z’



$$m_{Z'} \gg m_b$$

$$\Delta C_9 \sim \frac{g_{bsZ'} g_{\mu\mu Z'}}{m^2_{Z'}}$$

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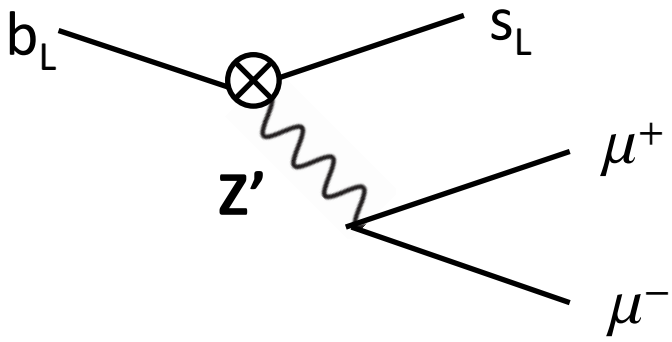

$$m_{Z'} \gg m_b \quad \Rightarrow \quad \Delta C_9 \sim \frac{g_{bsZ'} g_{\mu\mu Z'}}{m^2_{Z'}}$$

- A nice candidate is a Z’ boson of gauged $L_\mu - L_\tau$ symmetry (μ-number minus τ-number) **Altmannshofer et al., PRD89, 095033(2014)**
  - ➢ anomaly free **He, Joshi, Lew and Volkas, PRD43,22(1991)**

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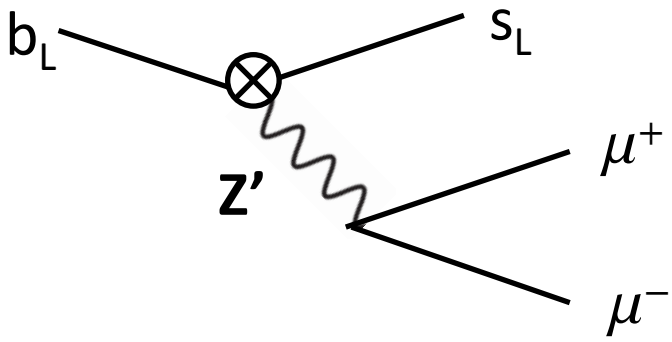

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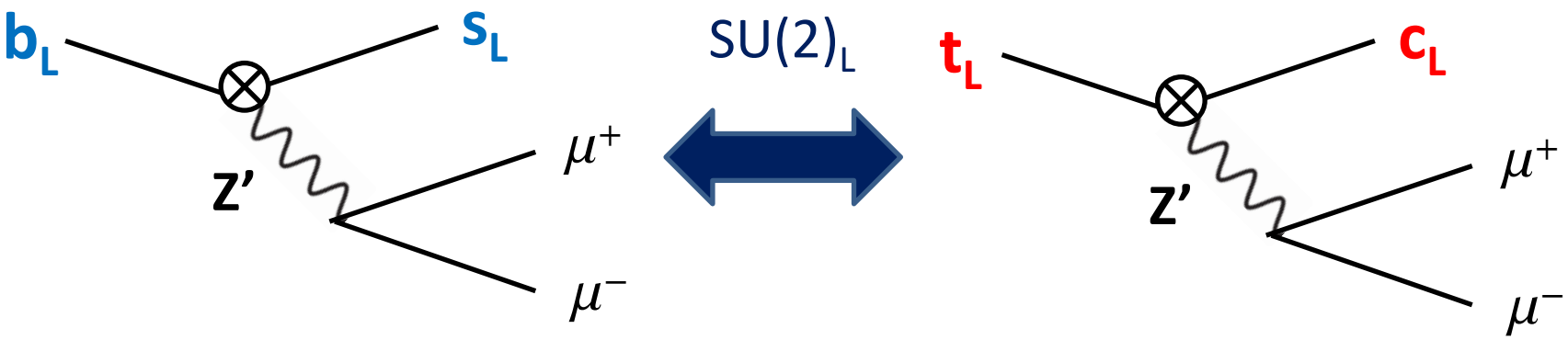
  - anomaly free **He, Joshi, Lew and Volkas, PRD43,22(1991)**
  - Z' may couple to b -> s current via higher dim. operator including U(1)' Higgs field Φ

$$\frac{i}{\Lambda^2}(\Phi^* \overleftrightarrow{D_\alpha} \Phi)(\bar{s}\gamma^\alpha P_L b) \quad \Rightarrow \quad -\frac{g' v_\Phi^2}{\Lambda^2} Z'_\alpha \bar{s}\gamma^\alpha P_L b$$

$$\langle \Phi \rangle = v_\Phi / \sqrt{2}$$

"b → s" to "t → c"

- Nonzero $b_L s_L Z'$ coupling implies nonzero $t_L c_L Z'$



- If $m_{Z'} < m_t - m_c$, the 2-body decay t → c Z' can happen!
  - ➢ This mass range is compatible with experimental data in the gauged $L_\mu - L_\tau$ model

Altmannshofer et al., PRD89, 095033(2014)

Plan of this talk

- Introduction
- The explicit mode for bsZ’ and tcZ’ couplings
- $t \to c\, Z'$ for $m_{Z'} >> m_b$ (motivated by P_5' and R_K)
- $t \to c\, Z'$ for $m_{Z'} << m_b$ (motivated by muon g-2)
- Discussion and summary

The model for bsZ' and tcZ' coupling

Altmannshofer, Gori, Pospelov and Yavin, PRD89, 095033(2014)

New matter fields

U(1)' Higgs	Vector-like quarks		
$\Phi : (\mathbf{1},\mathbf{1})_{\mathbf{0}}$	$Q : (\mathbf{3},\mathbf{2})_{+\mathbf{1/6}}$	$U : (\mathbf{3},\mathbf{1})_{+\mathbf{2/3}}$	$D : (\mathbf{3},\mathbf{1})_{-\mathbf{1/3}}$
$\mathcal{Q}_{U(1)'} =$ +1	+1	-1	-1

- Q mixes with SM quarks via

$$\mathcal{L}_{\text{int}} \supset Y_{Qq_i}\Phi\bar{Q}_R q_{iL}$$

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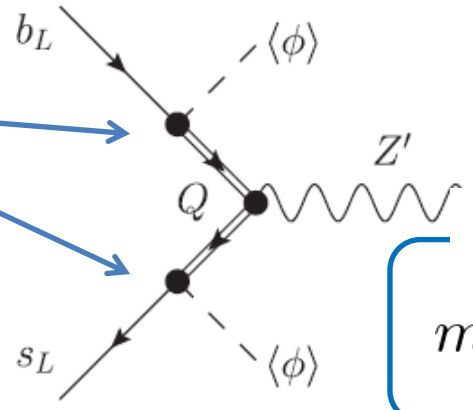

$$\Delta C_9 \simeq \frac{Y^*_{Qs}Y_{Qb}}{2m_Q^2}$$

P_5' & R_K anomalies

$$m_Q \simeq 24\ \text{TeV} \times |Y_{Qb}Y^*_{Qs}|^{1/2}$$

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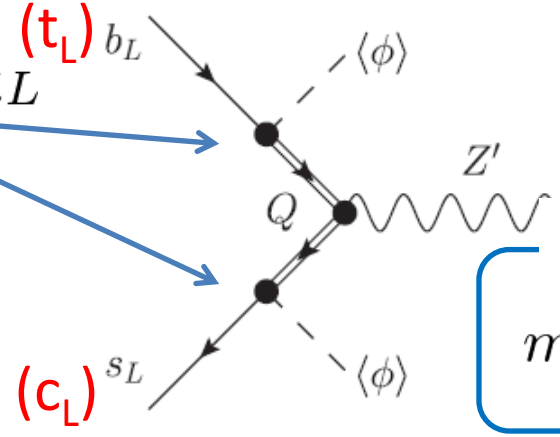

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Two major constraints on the model

$$540\,\mathrm{GeV} \lesssim v_\Phi = m_{Z'}/g' \lesssim 5.6\,\mathrm{TeV}$$

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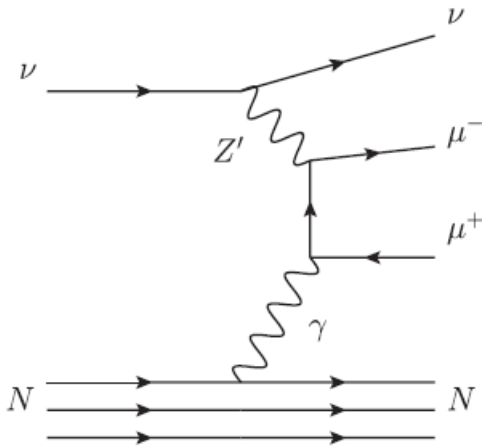
Altmannshofer, Gori, Pospelov and Yavin, PRL113, 091801(2014)



$$\propto \frac{g'^2}{m_{Z'}^2} = \frac{1}{v_\Phi^2}$$

CCFR experiment

PRL66, 3117 (1991)

$$v_\Phi \gtrsim 540\ \mathrm{GeV}$$

N.B.: $m_{Z'} \gtrsim 10\ \mathrm{GeV}$ is assumed

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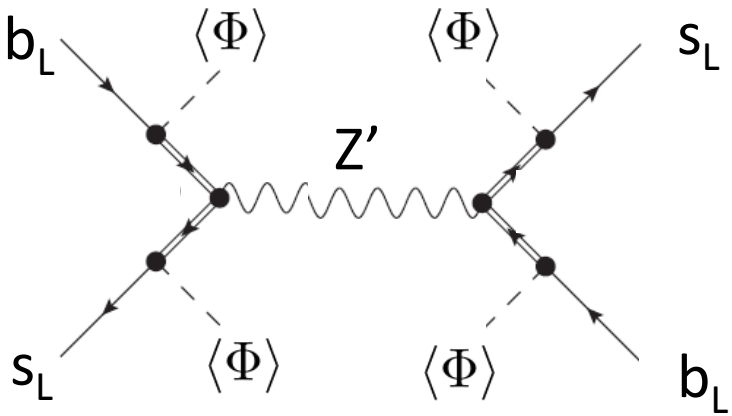
2) B_s mixing:

Altmannshofer et al. (2014); Crivellin et al. (2015)



$$\propto \frac{(Y_{Qs}^* Y_{Qb})^2}{m_Q^4} v_\Phi^2$$

P_5' & R_K anomalies

$$\frac{|Y_{Qs}^* Y_{Qb}|}{2m_Q^2} \simeq \frac{1}{(34\ \text{TeV})^2}$$

- Demanding NP effect < 15%

$$v_\Phi \lesssim 5.6\ \text{TeV}$$

Naïve experimental sensitivity for t → c Z'

- A similar process t → c Z(→ l^+l^-) was searched at LHC in

$$t\bar{t} \to qZ(\to \ell^+\ell^-) + bW(\to \ell\nu) \ \ (\ell = e, \mu, \tau)$$

- The 95% CL upper limits for t → q Z (q = c, u):
  - CMS (full Run1) **PRL112, 171802(2014)**

$$\mathcal{B}(t \to qZ) < 5 \times 10^{-4}$$

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- An advantage for t → c Z'(→ l^+l^-) search:

$$\mathcal{B}(Z' \to \ell^+\ell^-) \simeq 2/3 \quad \gg \quad \mathcal{B}(Z \to \ell^+\ell^-) \simeq 3 \times 3.4\% \simeq 10\%$$
$$(\text{for } m_{Z'} > 2m_\tau)$$

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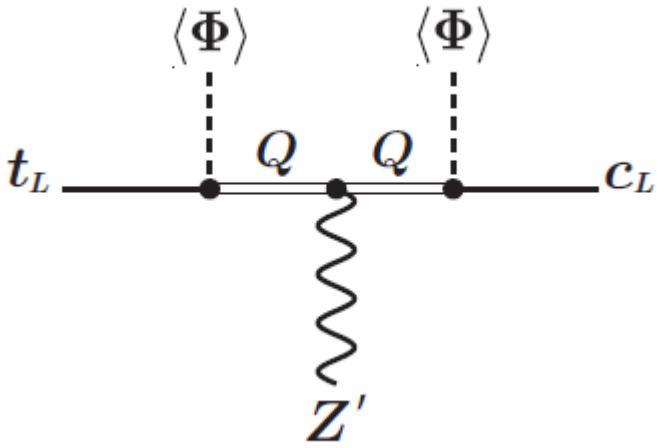
- Naïve expectation for CMS sensitivity on t → c Z'

$$\mathcal{B}(t \to cZ') \lesssim 8 \times 10^{-5} \quad \Rightarrow \quad \lesssim 2 \times 10^{-6}$$

t → c Z′ rate predicted by P_5' & R_K



$$\mathcal{B}(t \to cZ')_{\rm LH} \simeq \frac{(1-x')^2(1+2x')}{2(1-x_W)^2(1+2x_W)} \frac{|Y_{Qt}Y_{Qc}^*|^2}{4m_Q^4} v^2 v_\Phi^2$$

with $x' = \frac{m_{Z'}^2}{m_t^2}$ $x_W = \frac{m_W^2}{m_t^2}$

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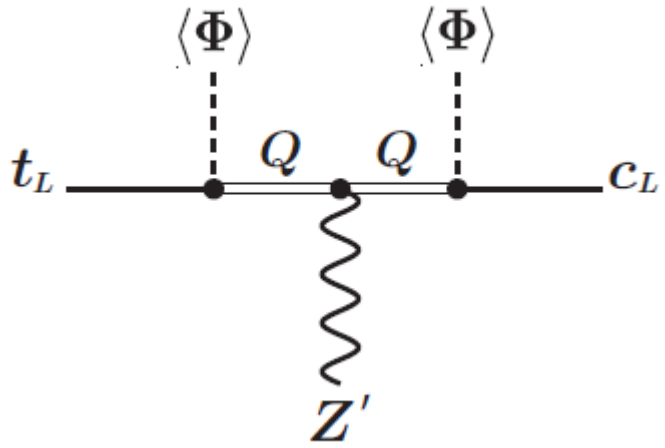

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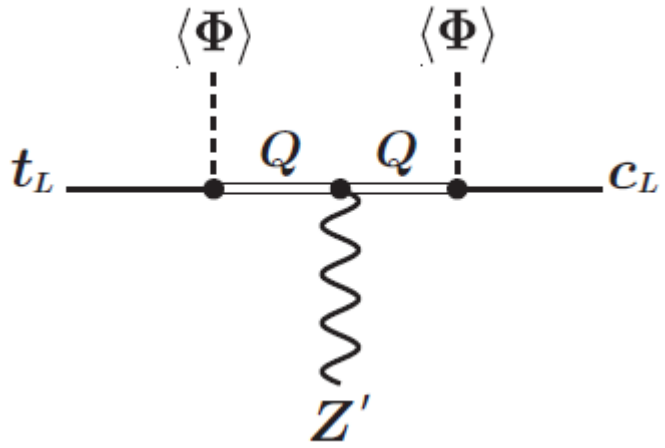

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with $x' = \dfrac{m_{Z'}^2}{m_t^2}$ $x_W = \dfrac{m_W^2}{m_t^2}$

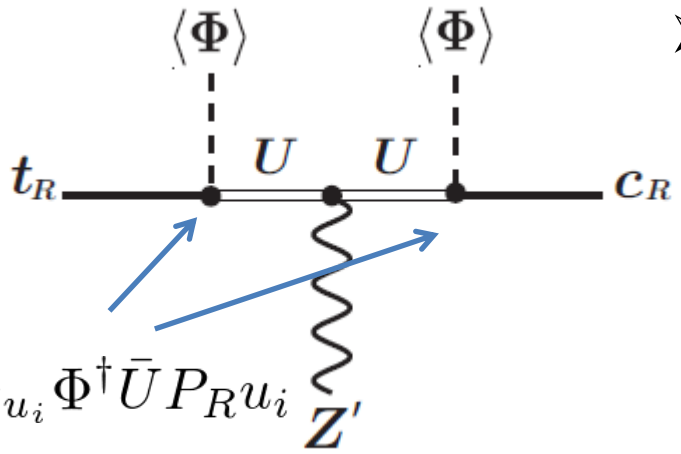
- Applying constraints on v_Φ,

$$0.8 \times 10^{-8} \lesssim \mathcal{B}(t \to cZ')_{\mathrm{LH}} \lesssim 0.8 \times 10^{-6}$$

slightly below CMS (300/fb)

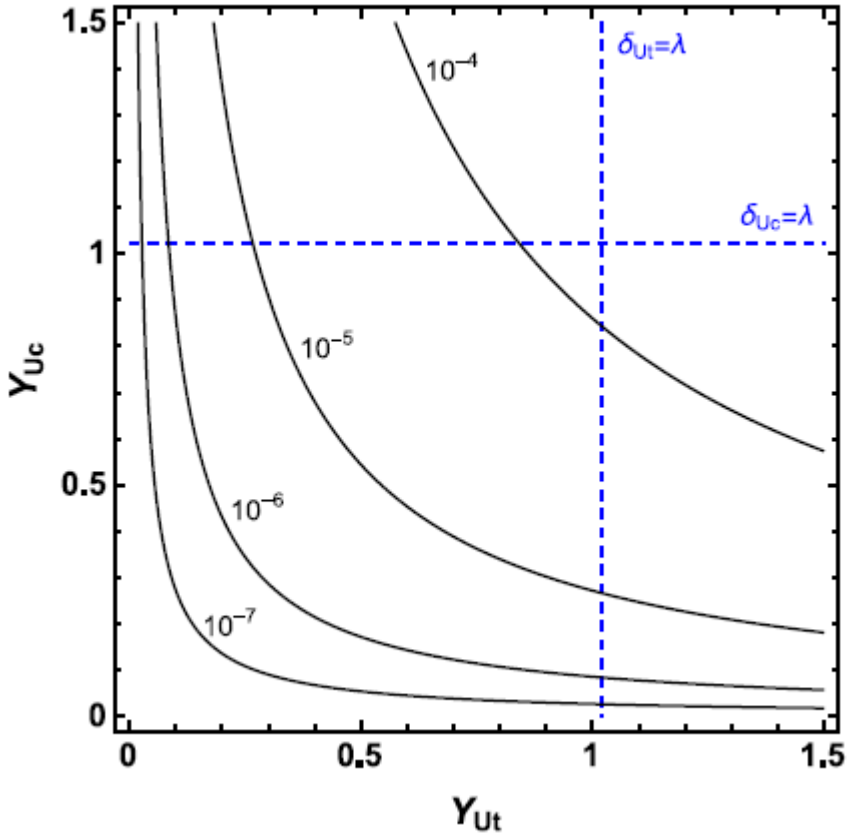
t → c Z’ via RH current

- Right-Handed tcZ’ coupling, mediated by SU(2) singlet quark U, is unconstrained by b → s data



$$\mathcal{L}_{\rm int} \supset Y_{U u_i} \Phi^\dagger \bar{U} P_R u_i$$

- BR(t → cZ’) contours for $m_{Z'}$ = 50 GeV, g’ = 0.064, v_Φ = 780 GeV, m_U = 2.5 TeV



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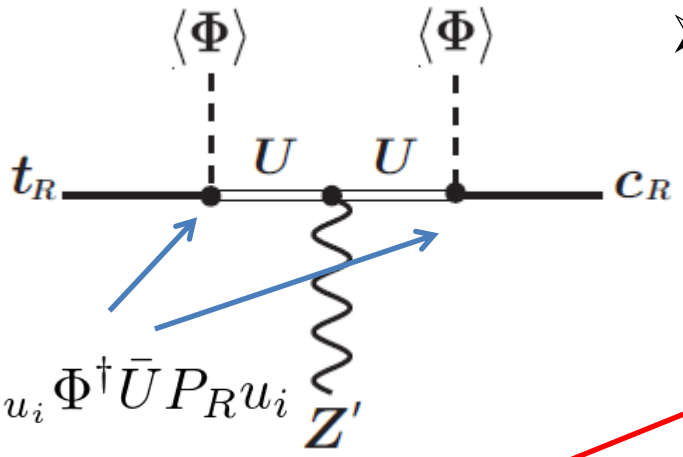

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- BR(t → c Z’) ~ 10^{-4} is possible, but not more to keep small mixing angle for U-t and U-c

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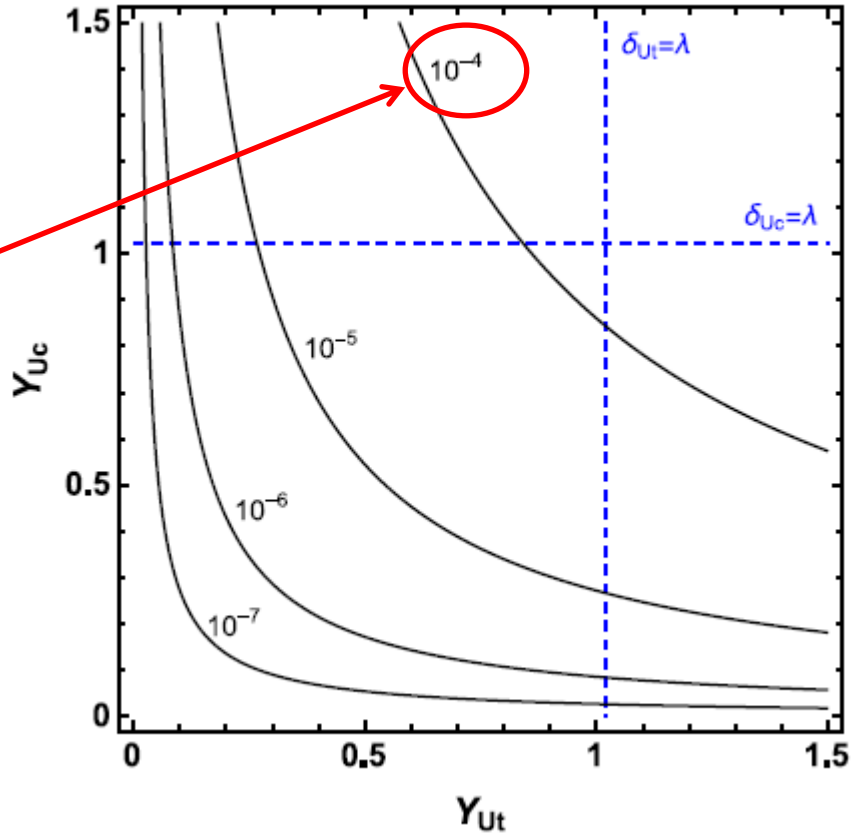

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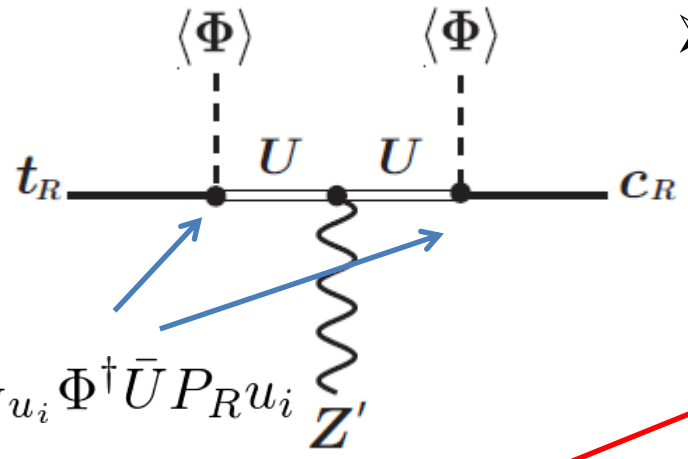

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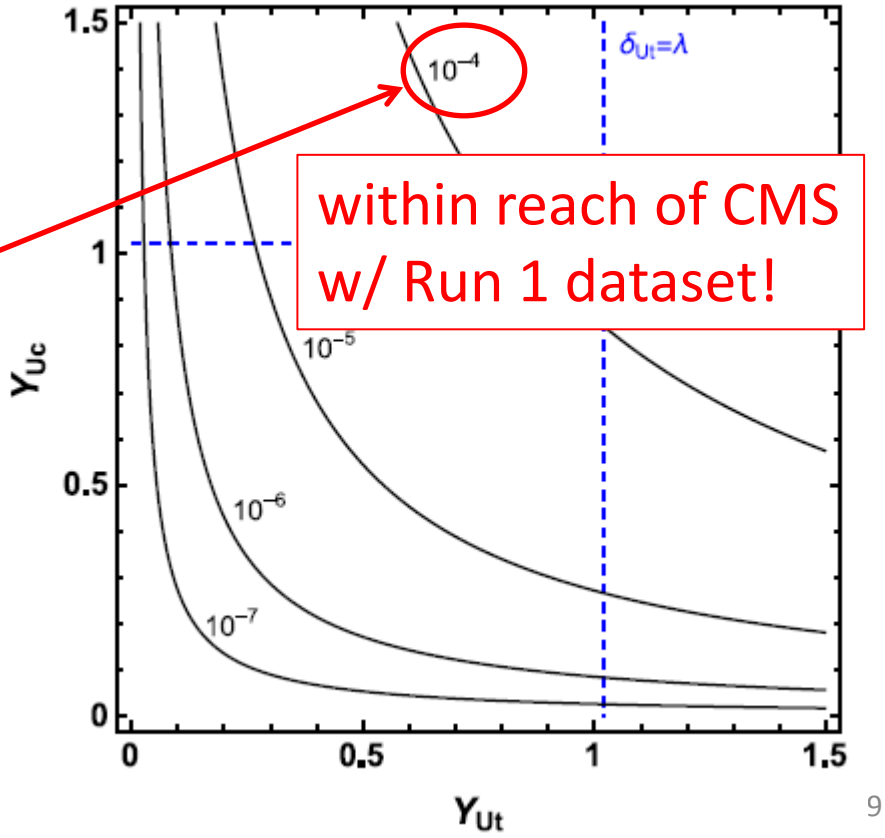
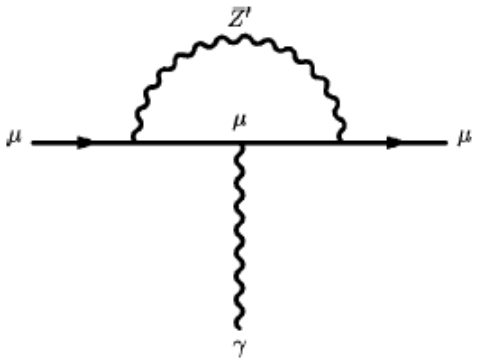


What if the Z’ is extremely light?

$m_{Z'} << m_b$

- Cannot explain P_5' and R_K anomalies
- But, motivated by the muon g-2 anomaly

Baek, Deshpande, He and Ko (2001)



What if the Z' is extremely light?

$m_{Z'} << m_b$

- Cannot explain P_5' and R_K anomalies
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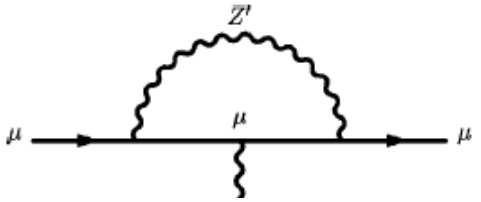
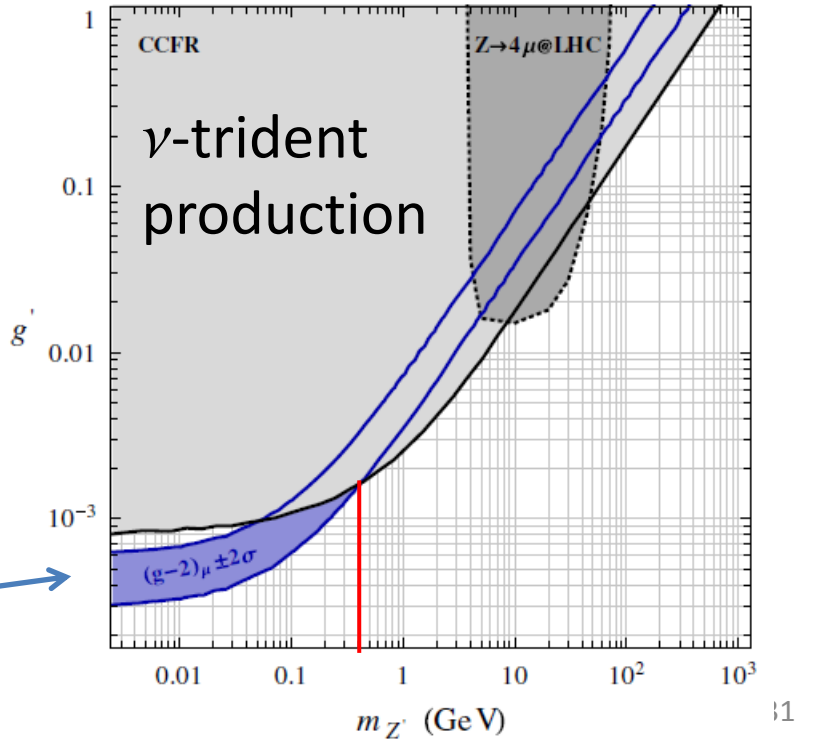


- The Z' can explain the anomaly only if $m_{Z'} \lesssim 400\ \mathrm{MeV}$

Altmannshofer et al., PRL113, 091801(2014)



favored by $(g-2)_\mu$

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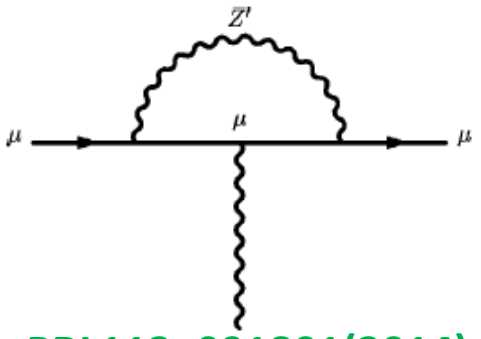

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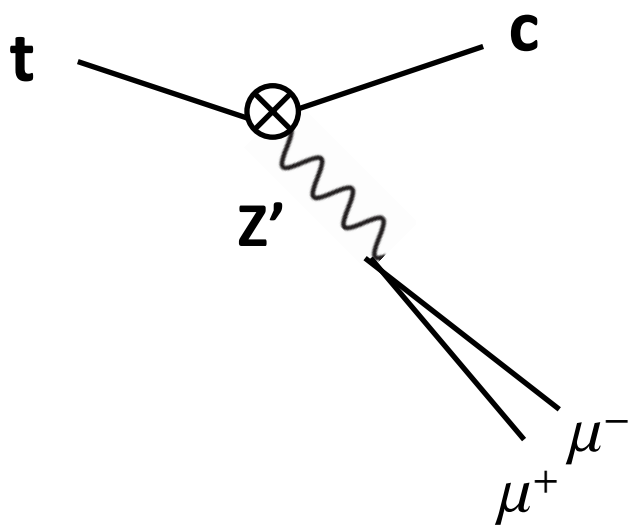
- The Z' can explain the anomaly only if

$$m_{Z'} \lesssim 400\ \mathrm{MeV}$$

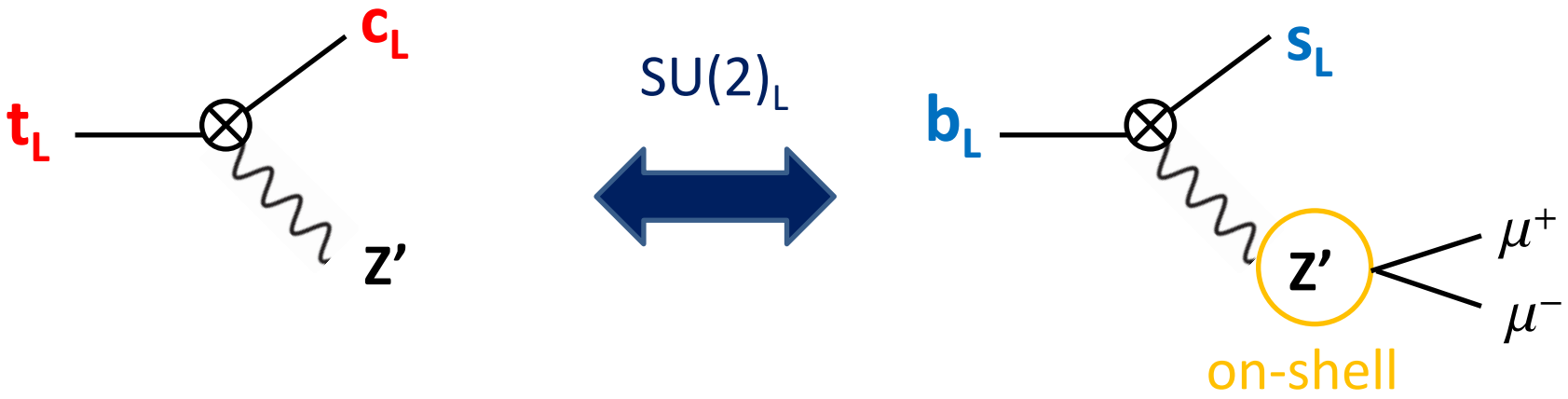
Altmannshofer et al., PRL113, 091801(2014)

- Striking collider signature: muon pairs from t → c Z' are collimated



Muon g-2 motivated t → c Z' via LH current

- For the light Z', left-handed **tcZ'** coupling is strongly constrained, as b → s $\mu^+\mu^-$ goes through the 2-body decay b → s Z' (→ $\mu^+\mu^-$), with on-shell Z', and LH bsZ' coupling is tightly bounded



- B-factories and LHCb data imply

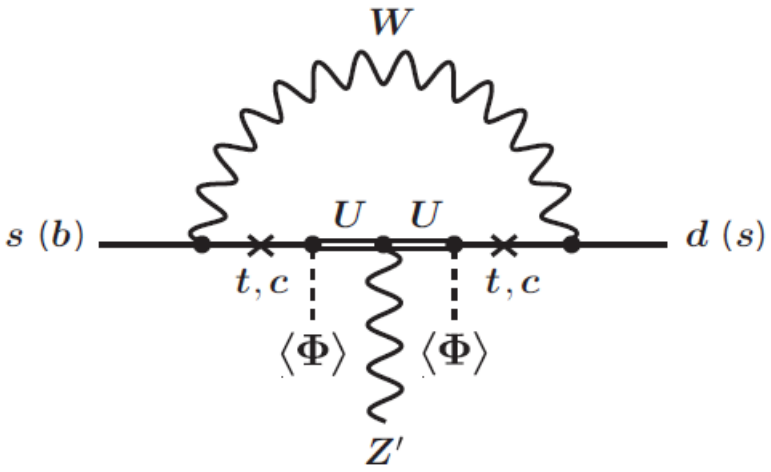
$$\mathcal{B}(t \to cZ')_{\rm LH} \lesssim 2 \times 10^{-14}$$ <- far below CMS (300/fb)

Fuyuto, Hou and MK, in preparation

Muon g-2 motivated t → c Z' via RH current

Fuyuto, Hou and MK, arXiv:1412.4397

- For the light Z', the right-handed tcZ' coupling is also constrained by meson decays
- At one-loop, U-t and U-c mixing induces effective bsZ'/sdZ' coupling



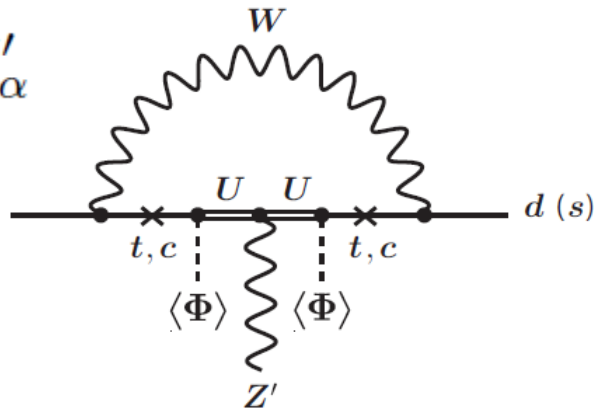
- The loop suppression is compensated by the two-body enhancement in the B and K decays, e.g., B → K Z'(→ $\mu\mu$)

Loop-induced bsZ'/sdZ' couplings

- Some assumptions:
  - For simplicity, the mixings with Q, D quarks are turned off
  - U-u mixing is also turned off to satisfy D-meson mixing/decay constraints

- Loop induced bsZ' coupling: $g_{sb}\bar{s}_L\gamma^\alpha b_L Z'_\alpha$

$$g_{sb} = \frac{g' v_\Phi^2}{32\pi^2 v^2}\left[c_{cc} f_{cc} + (c_{tc} + c_{ct}) f_{ct} + c_{tt} f_{tt}\right]$$



$$\text{with } c_{ij} = V_{ib} V_{js}^* Y_{Ui} Y_{Uj}^* m_i m_j / m_U^2$$

$$\begin{cases} f_{ct} \simeq 1 + \log\dfrac{m_U^2}{m_t^2} + \dfrac{3m_W^2}{m_t^2 - m_W^2}\log\dfrac{m_t^2}{m_W^2}, \quad f_{tt} \simeq \dfrac{3m_W^2}{m_t^2 - m_W^2}\left(1 - \dfrac{m_W^2}{m_t^2 - m_W^2}\log\dfrac{m_t^2}{m_W^2}\right) + \log\dfrac{m_U^2}{m_t^2}, \\ f_{cc} \text{ is obtained by } m_c^2 \ll m_W^2 \end{cases}$$

Relevant measurements for b → s Z' & s → d Z'

Bottom FCNC decays

[mass range]

- Binned $B^+ \to K^+ \mu^+\mu^-$ spectrum by LHCb (1/fb, 7 TeV) **JHEP1302.105** $m_{Z'} \gtrsim 224\ \mathrm{MeV}$

N.B.: Full Run1 results by LHCb cover only the half of $(g-2)_\mu$ region ($m_{Z'} > 316$ MeV) **JHEP1406.133**

- $B^+ \to K^* X(\to \mu^+\mu^-)$ search by Belle **PRL105, 091801(2010)** $m_{Z'} \in (212, 300)\ \mathrm{MeV}$
- Binned $B \to K^{(*)} \nu\nu$ search by BaBar **PRD87, 112005(2013)** $m_{Z'} \geq 0$

Strange FCNC decays

- Binned $K^+ \to \pi^+ \mu^+\mu^-$ spectrum by NA48/2 **PLB697, 107(2011)** $m_{Z'} \in (211, 354)\ \mathrm{MeV}$
- $K_L \to \pi^0 \mu^+\mu^-$ search by KTeV **PRL84, 5279(2000)** $m_{Z'} \in (211, 350)\ \mathrm{MeV}$
- $K^+ \to \pi^+ X\ (\to \nu\nu)$ search by E949 **PRD79, 092004(2009)** $m_{Z'} \in (0, 125)$ or $(150, 260)\ \mathrm{MeV}$
- $K_L \to \pi^0 \nu\nu$ search by E391a **PRD81, 072004(2010)** $m_{Z'} \lesssim 363\ \mathrm{MeV}$

Relevant measurements for b → s Z' & s → d Z'

Bottom FCNC decays [mass range]

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JHEP1406.133

- $B^+ \to K^* X(-$ MeV
- Binned B →

- Z' with mass around m_π can evade K^+ decay experiments, while it is sensed by K_L decay
- This leads to the apparent violation of Grossman-Nir bound

  Fuyuto, Hou and MK, PRL114, 171802
- See talk by W.-S. Hou in flavor session (7/24, 11:50~)

Strange FC

- Binned $K^+ \to$ MeV
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Constraint from $B^+ \to K^+ \mu^+ \mu^-$

- Z' would show up as a spike in $q^2 = m_{\mu\mu}^2$ distribution
- 1 fb^{-1} result of LHCb probes down to

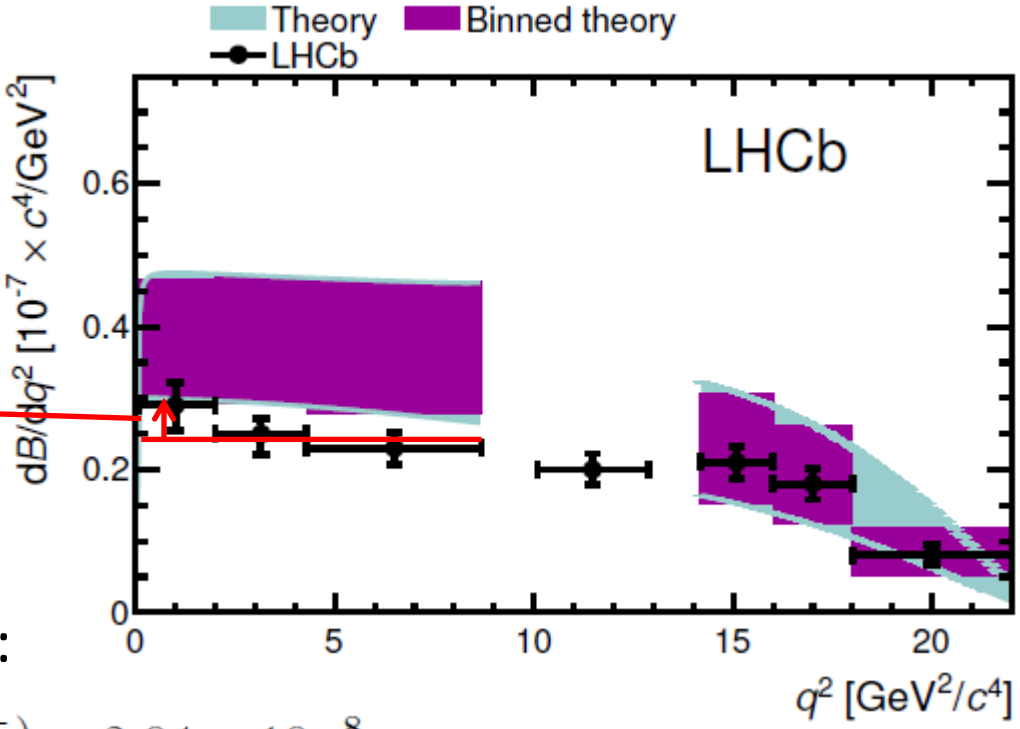
$$q^2 > 0.05\,\mathrm{GeV}^2 \simeq (224\,\mathrm{MeV})^2$$ **JHEP 02 (2013) 105**

target range

$$q^2 \in (0.05, 2.00)\ \mathrm{GeV}^2$$

$$m_{Z'} \in (224,\ 1414)\ \mathrm{MeV}$$

$$\Delta\mathcal{B}(B^+ \to K^+\mu^+\mu^-) = (0.86 \pm 0.59) \times 10^{-8}$$



- We obtain 2σ upper limit:

$$\mathcal{B}(B^+ \to K^+ Z')\mathcal{B}(Z' \to \mu^+\mu^-) < 2.04 \times 10^{-8}$$

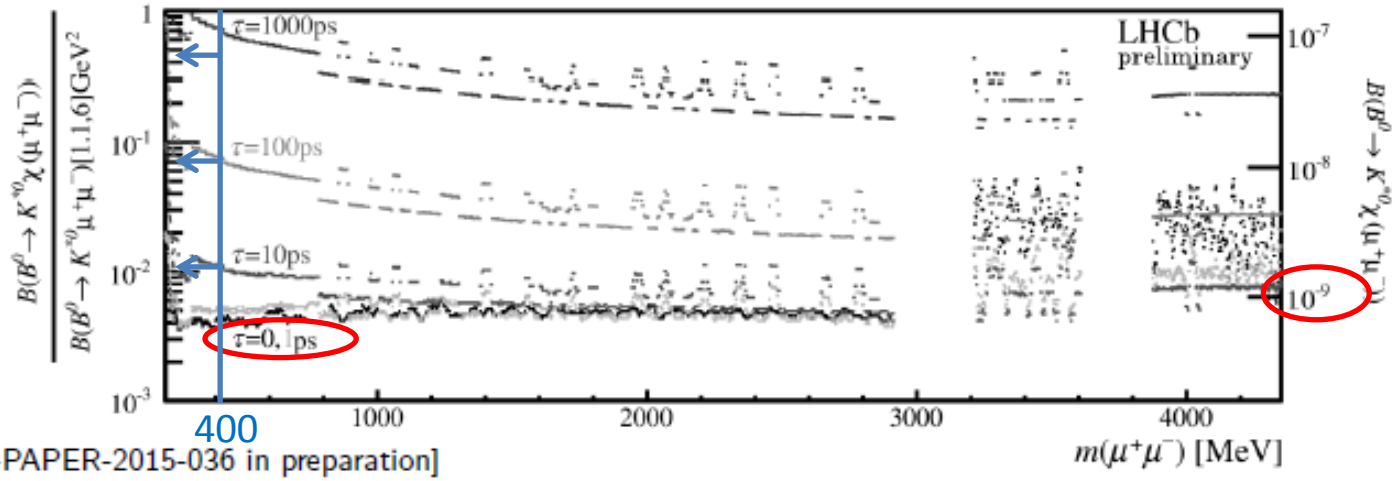
$B^0 \to K^{*0} \chi(\to \mu\mu)$ search by LHCb

Talk by A. Mauri in this conference

Exclusion limit

No deviation from the background only hypothesis is observed

- We set a 95% CL upper limit as function of mass and lifetime of the new particle (in the LHCb accessible range)
- The new particle is assumed to be a scalar
- Lower lifetimes have better limit due to higher reconstruction efficiency



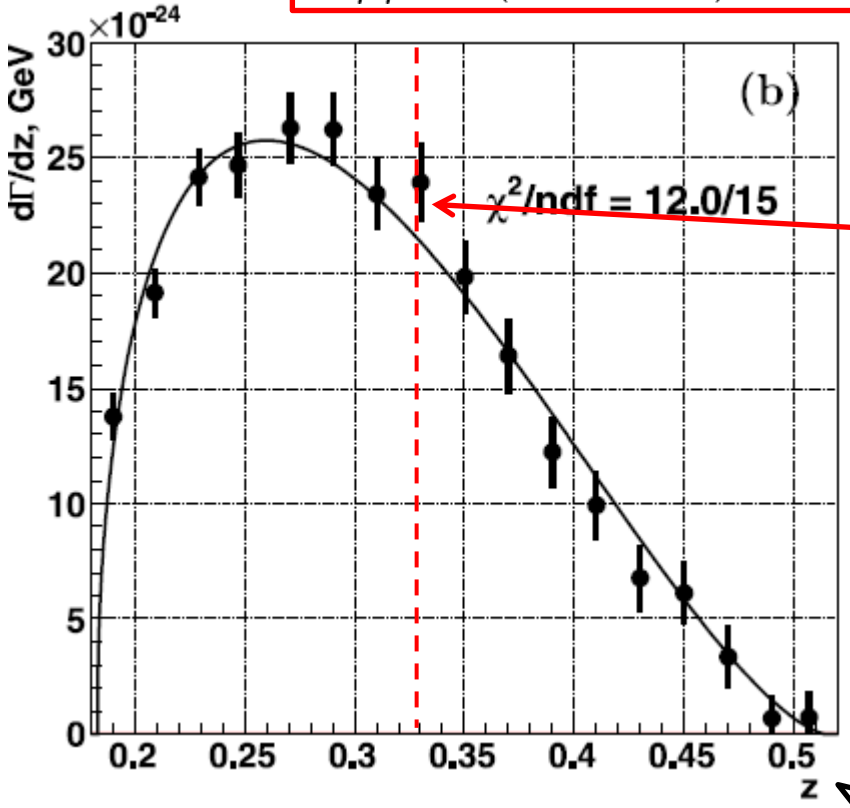
[LHCb-PAPER-2015-036 in preparation]

Constraint from $K^+ \to \pi^+ \mu^+ \mu^-$

- NA48/2@CERN SPS: most precise single measurement

$m_{\mu\mu} \in (279, 288)\ \mathrm{MeV}$

PLB697, 107(2011)



- take most tolerant case

$$\Delta\mathcal{B}(K^+ \to \pi^+\mu^+\mu-) \simeq (9.4 \pm 5.6) \times 10^{-10}$$

- We obtain 2σ upper limit:

$$\mathcal{B}(K^+ \to \pi^+ Z')\mathcal{B}(Z' \to \mu^+\mu^-) < 2.1 \times 10^{-9}$$

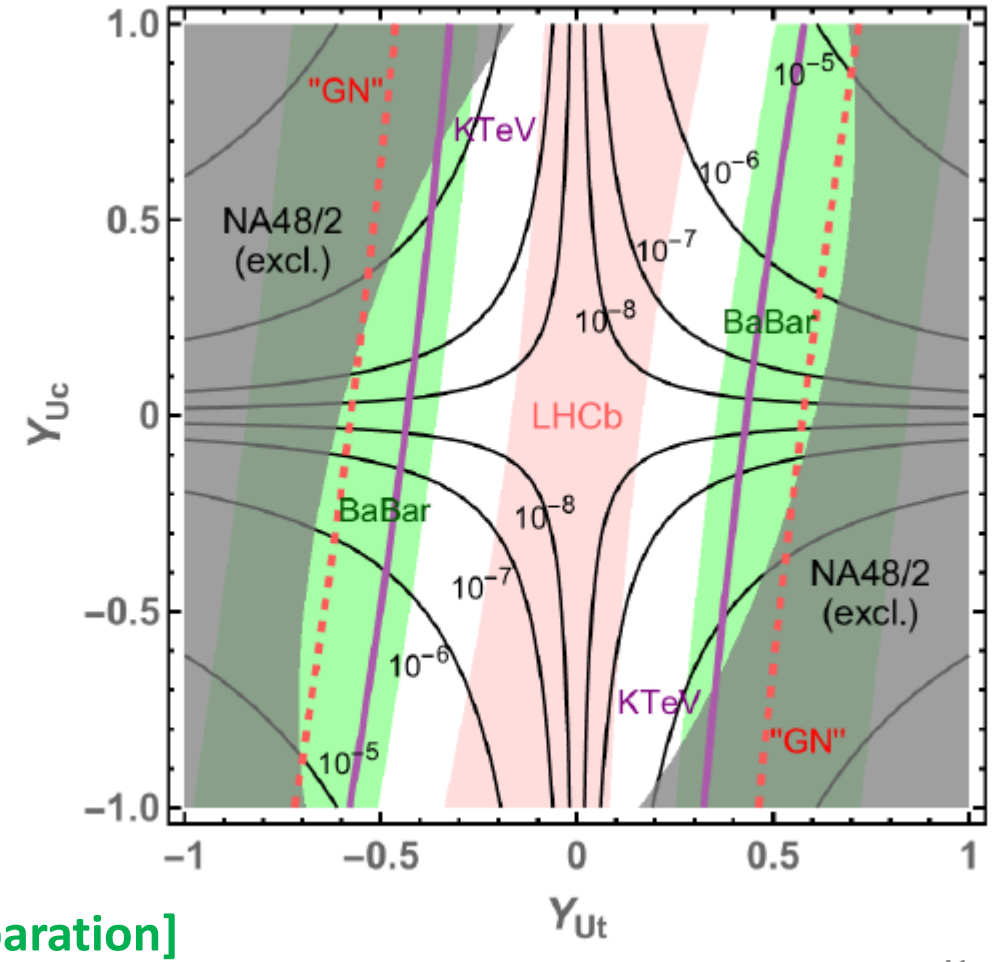
$z \equiv q^2/m^2_{K^+}$

- fit by linear form factor $W(z) = G_F M_K^2 f_0(1 + \delta z)$

Constraints on Y_{Ut} and Y_{Uc}

$Y_{Uu_i}\Phi^\dagger \bar{U} P_R u_i$

Benchmark $m_{Z'} = 285\ \mathrm{MeV},\ g' = 1.3 \times 10^{-3},\ m_U = 2\ \mathrm{TeV}$



[Fuyuto, Hou and MK, in preparation]

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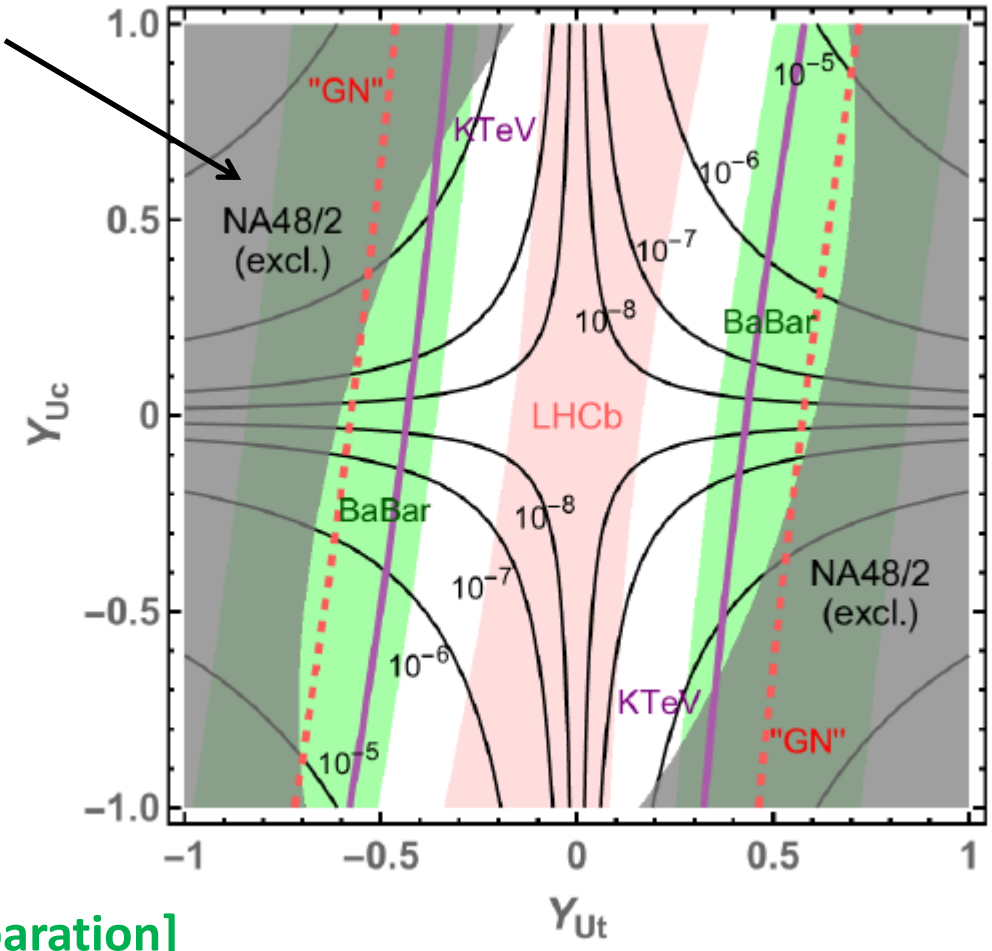
Excluded by $K^+ \to \pi^+ \mu^+ \mu^-$ at 2σ

- weakest at $m_{Z'}$ = 285 MeV



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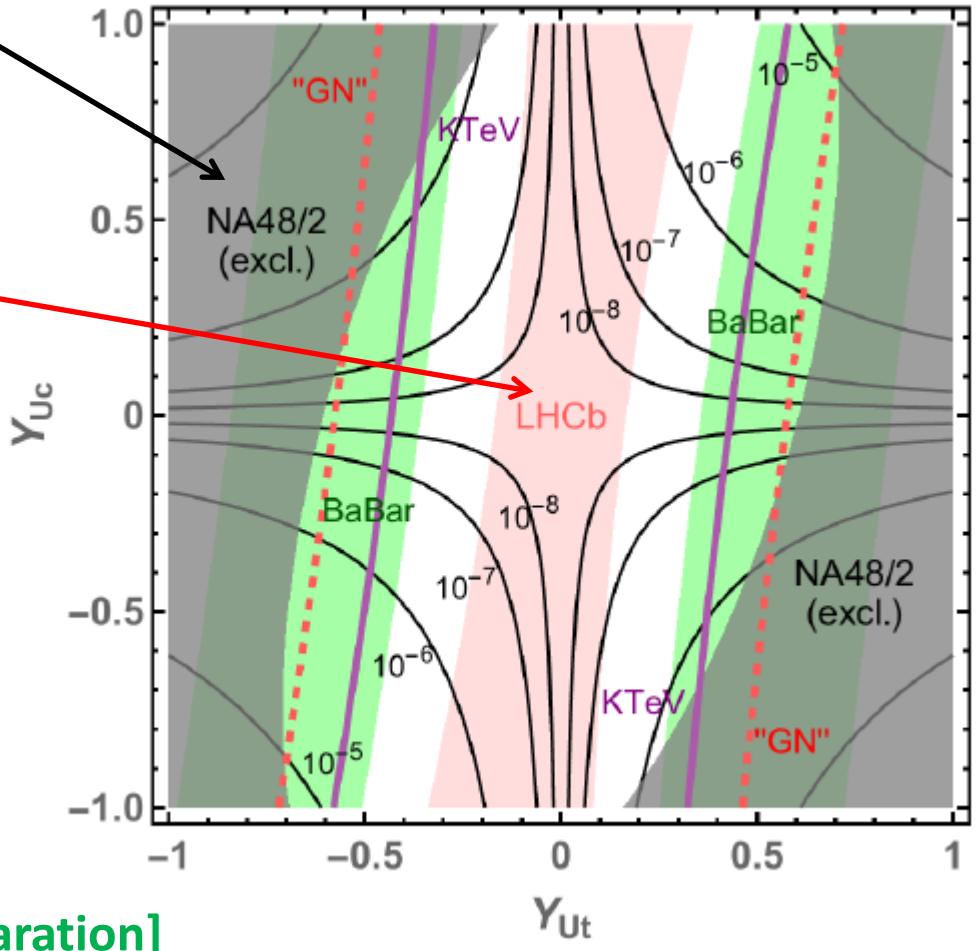
Allowed by $B^+ \to K^+\mu^+\mu^-$ at 2σ



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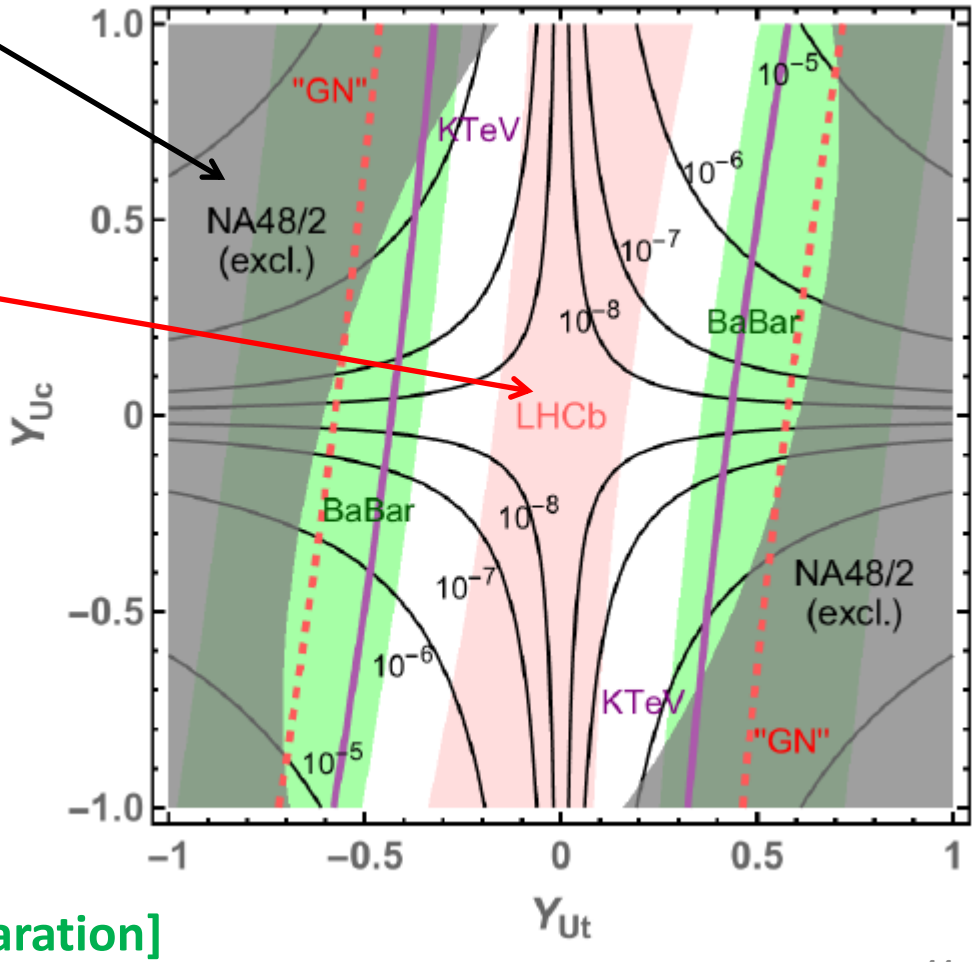


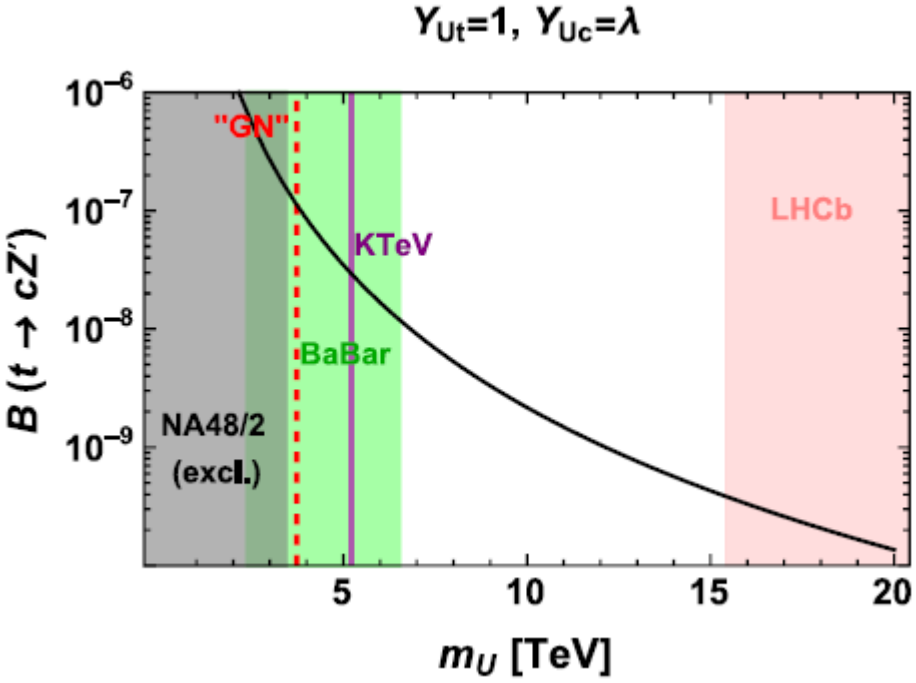
- More sensitive to Y_{Ut} than Y_{Uc}, due to chiral factor m_t/m_c in the loop-induced bsZ'/sdZ' coupling
- BR(t → c Z') contours are shown by solid-black lines

[Fuyuto, Hou and MK, in preparation]

RH-current induced t → c Z' rates

Fuyuto, Hou and MK, in preparation

(1) Normal Yukawa hierarchy



- $B^+ \to K^+ \mu\mu$ data pushes down to BR(t → c Z') < 10^{-9}

-> far below sensitivity of CMS (300/fb)

RH-current induced t → c Z' rates

Fuyuto, Hou and MK, in preparation

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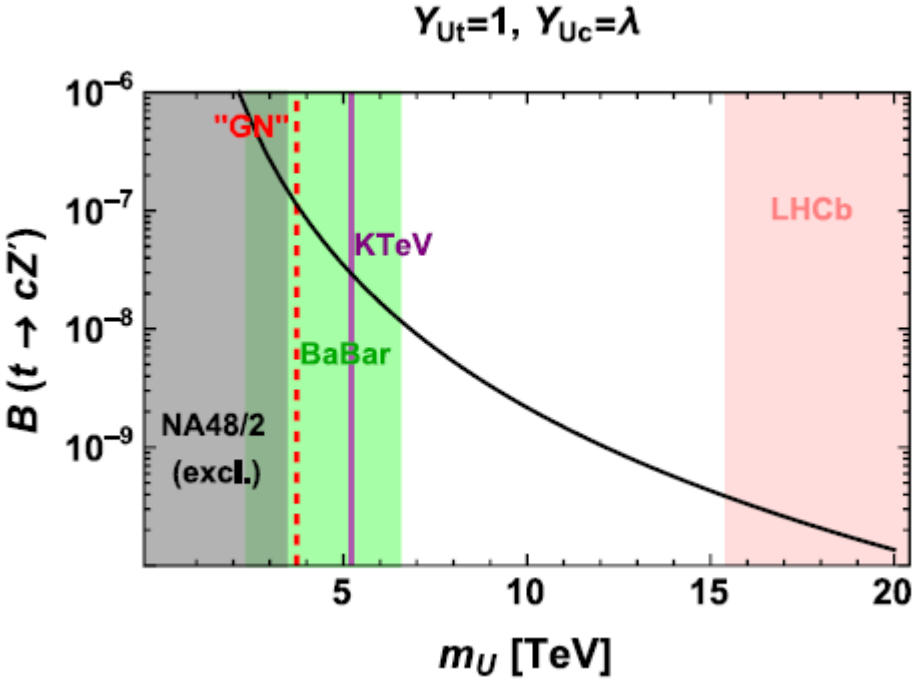
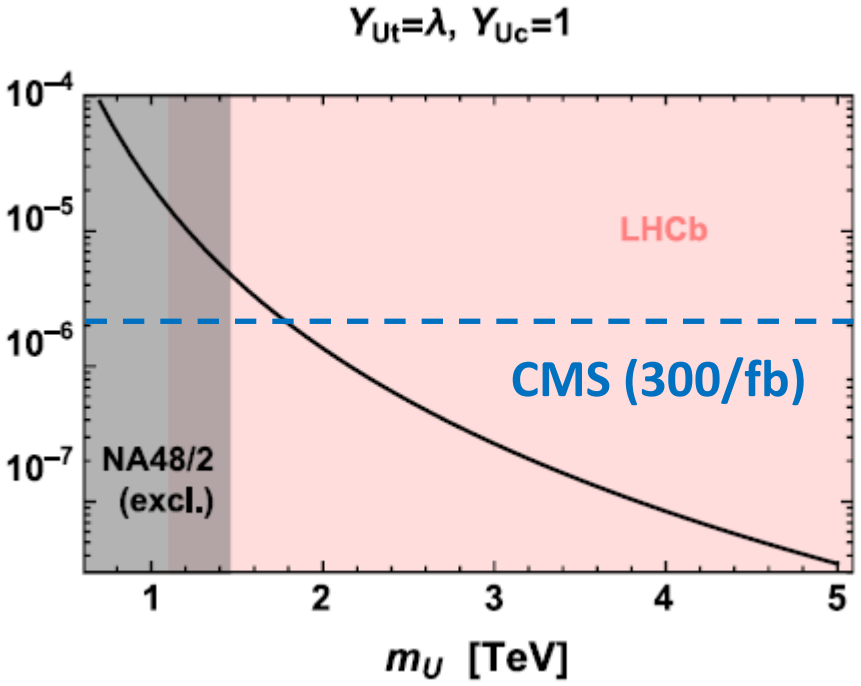


(2) Flipped Yukawa hierarchy



- $B^+ \to K^+ \mu\mu$ data pushes down to BR(t → c Z') < 10^{-9}

-> far below sensitivity of CMS (300/fb)

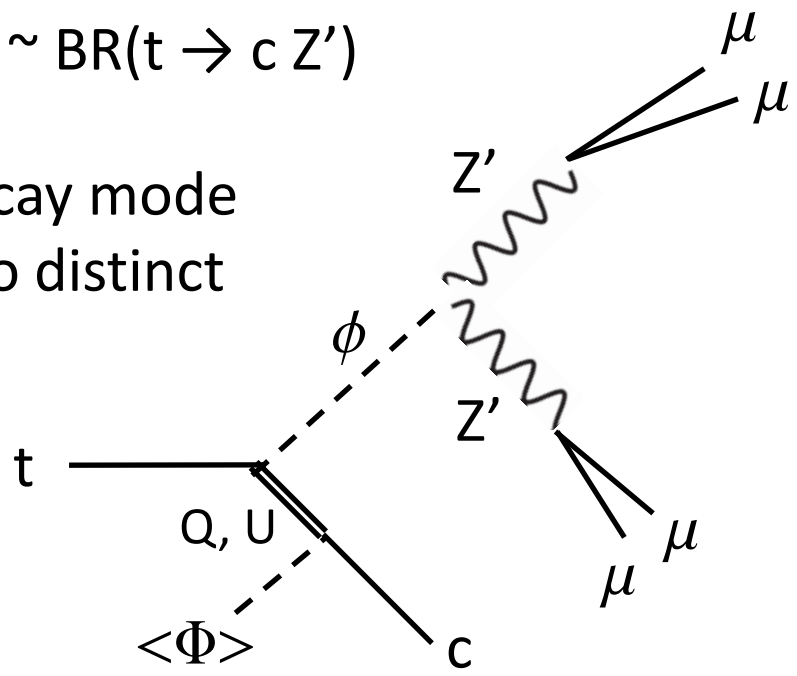
- $K^+ \to \pi^+ \mu\mu$ data imposes BR(t → c Z') < 10^{-5}

-> CMS (300/fb) sensitivity is barely attained

Discussion: t → c ϕ

Hou and MK, in preparation

- The model predicts FCNC couplings with U(1)' Higgs ϕ
- This leads to t → c ϕ → c Z' Z' → c + 4μ
- For m_ϕ, $m_{Z'}$ << m_t, BR(t → c ϕ) ~ BR(t → c Z')
- If ϕ is lighter than top, this decay mode may be more promising due to distinct signature



Summary

- We studied allowed ranges for the t → c Z' rate based on a gauged L_μ - L_τ model

- 2 scenarios are considered

	B(t → c Z') range
(1) Heavy Z': $m_b << m_{Z'}$ (< m_t - m_c) motivated by P_5' & R_K anomalies	< 10^{-3}
(2) Light Z': $m_{Z'}$ < 400 MeV motivated by muon g-2 anomaly	< 10^{-9} (normal) < 10^{-5} (flipped)

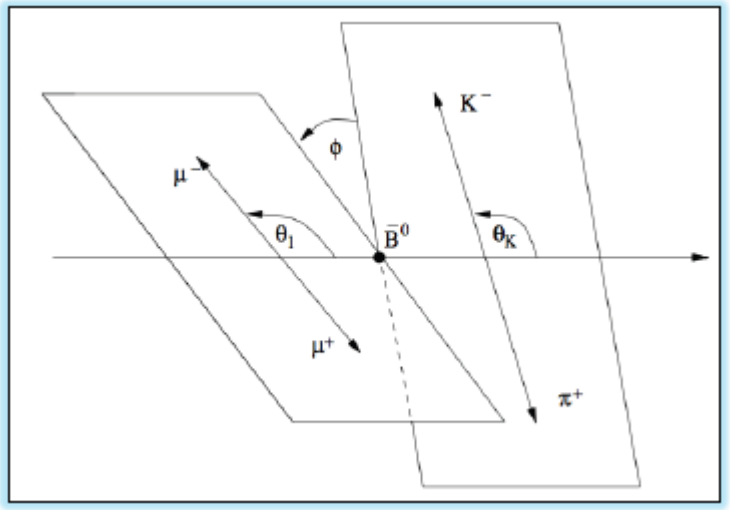
  - Within reach of CMS with Run 1 dataset!
  - Seemingly beyond reach of near future LHC in most parts of the parameter space

Back Up Slides

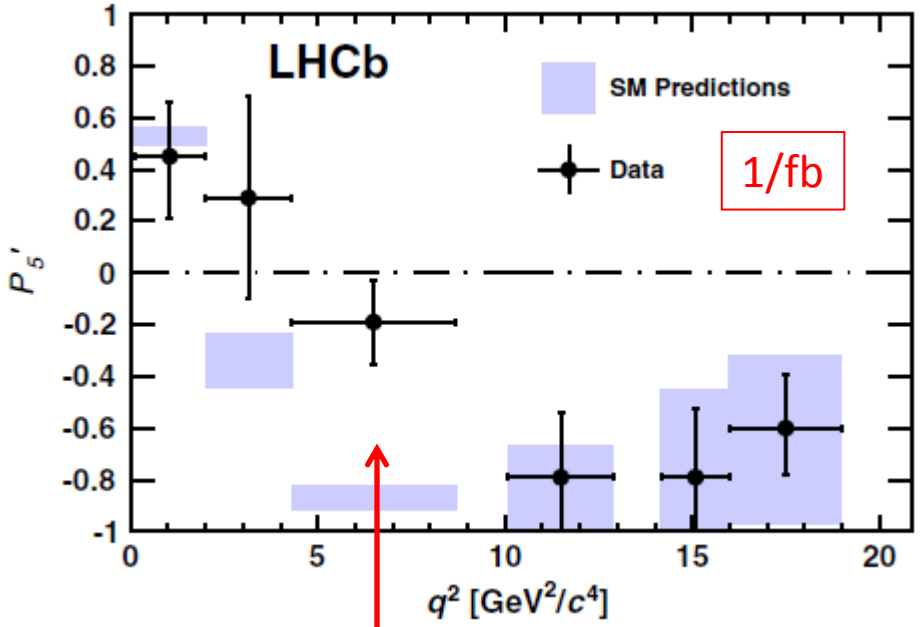
Some hints of NP in b → s transitions

- P_5' anomaly in angular distribution of

  B → K*(→$K^+\pi^-$) $\mu^+\mu^-$



LHCb, PRL 111, 191801 (2013)



3.7σ discrepancy

* 2.5σ in better controlled 1 - 6 GeV^2

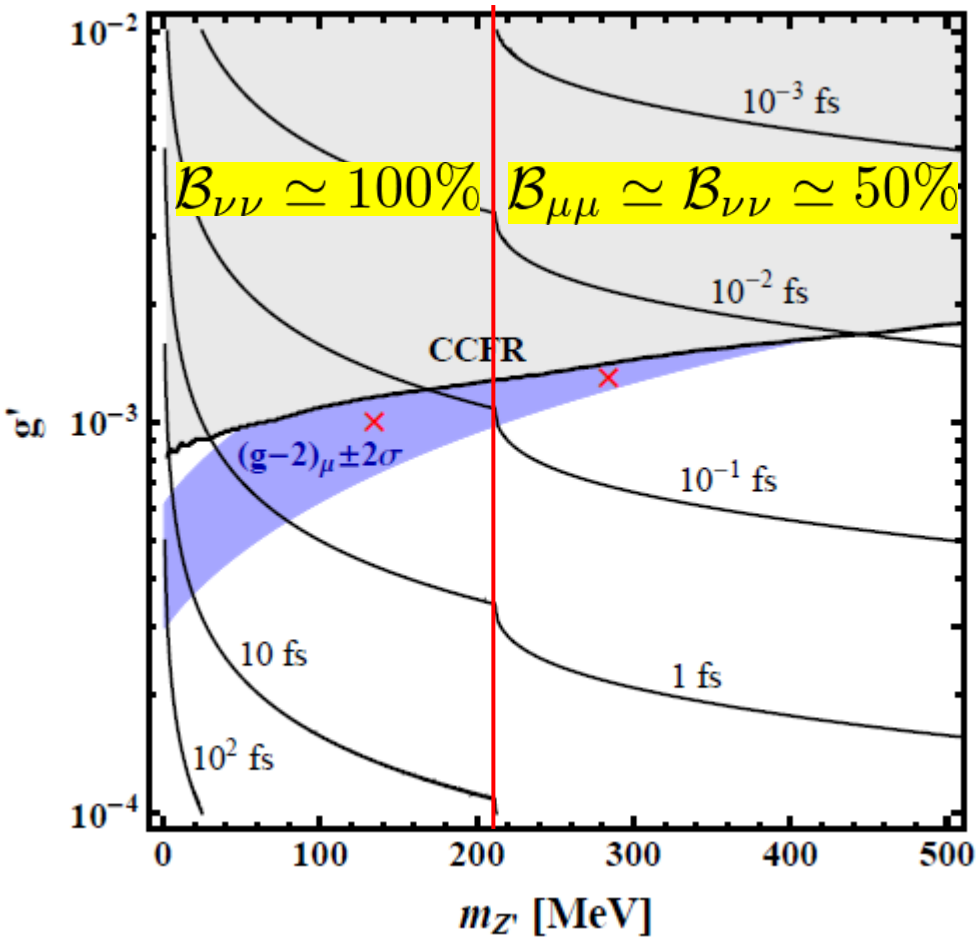
$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell d\cos\theta_K d\phi dq^2}$$

$$= \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi$$
$$+ S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big],$$

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

Lifetime and BR for light Z', motivated by $(g-2)_\mu$

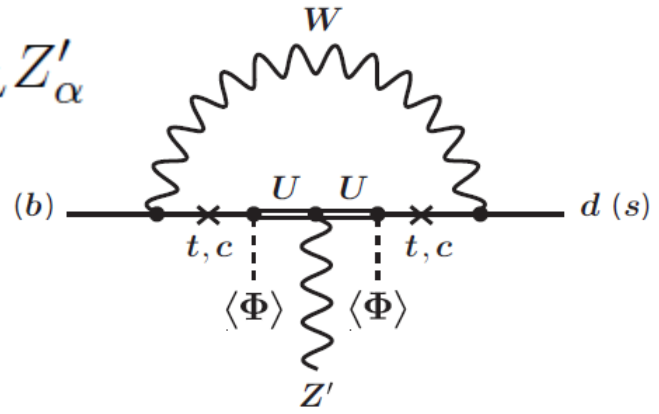
K. Fuyuto, W.-S. Hou, MK, in preparation



b → s Z' formulas

Fuyuto, Hou and MK, arXiv:1412.4397

- Loop induced bsZ' coupling: $g_{sb}\bar{s}_L\gamma^\alpha b_L Z'_\alpha$



$$g_{sb} = \frac{g' v_\Phi^2}{32\pi^2 v^2}\left[c_{cc} f_{cc} + (c_{tc} + c_{ct}) f_{ct} + c_{tt} f_{tt}\right]$$

$$\text{with } c_{ij} = V_{ib} V_{js}^* Y_{Ui} Y_{Uj}^* m_i m_j / m_U^2$$

$$\begin{cases} f_{ct} \simeq 1 + \log\dfrac{m_U^2}{m_t^2} + \dfrac{3m_W^2}{m_t^2 - m_W^2}\log\dfrac{m_t^2}{m_W^2}, \quad f_{tt} \simeq \dfrac{3m_W^2}{m_t^2 - m_W^2}\left(1 - \dfrac{m_W^2}{m_t^2 - m_W^2}\log\dfrac{m_t^2}{m_W^2}\right) + \log\dfrac{m_U^2}{m_t^2}, \\ f_{cc} \text{ is obtained by } m_c^2 \ll m_W^2 \end{cases}$$

- B → K Z' branching ratio (similar for Kaon decays):

$$\mathcal{B}(\bar{B} \to \bar{K} Z') = \tau_B \frac{|g_{sb}|^2}{64\pi}\frac{m_B^3}{m_{Z'}^2}\lambda^{3/2}\left(1, \frac{m_K^2}{m_B^2}, \frac{m_{Z'}^2}{m_B^2}\right)\left[f_+^{B\to K}(m_{Z'}^2)\right]^2$$

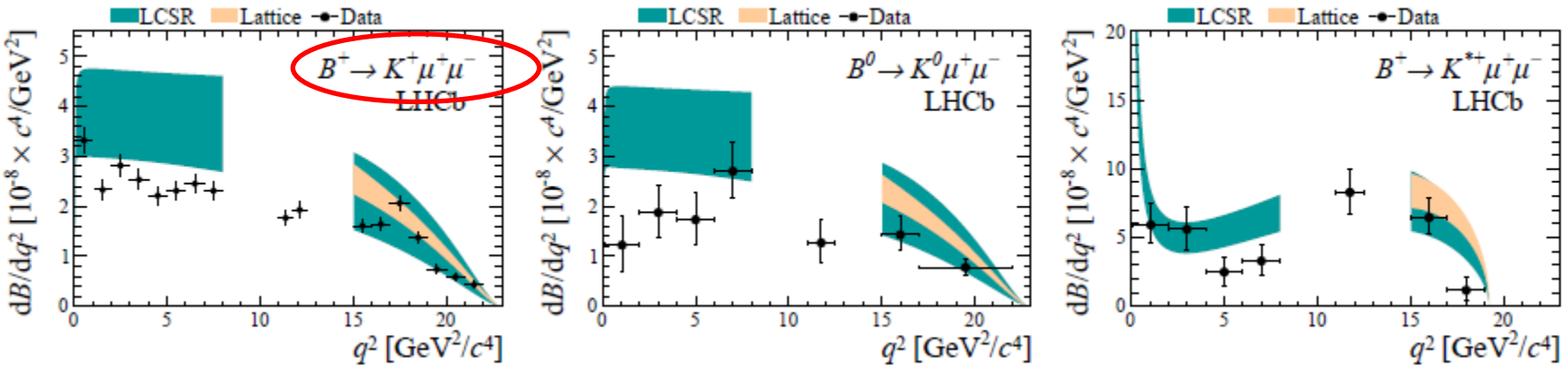
$$\text{where } \lambda(x,y,z) \equiv x^2 + y^2 + z^2 - 2(xy + xz + yz)$$

$f_+^{B\to K}$: B → K form factor Ball and Zwicky, PRD71, 014015(2005)

Constraint from B → K $\mu^+\mu^-$

- Z' would show up as a spike in $q^2 = m_{\mu\mu}{}^2$ distribution
- 3 fb^{-1} results by LHCb **JHEP 06 (2014) 133**

$$q^2 \lesssim 0.16\ \mathrm{GeV}^2$$

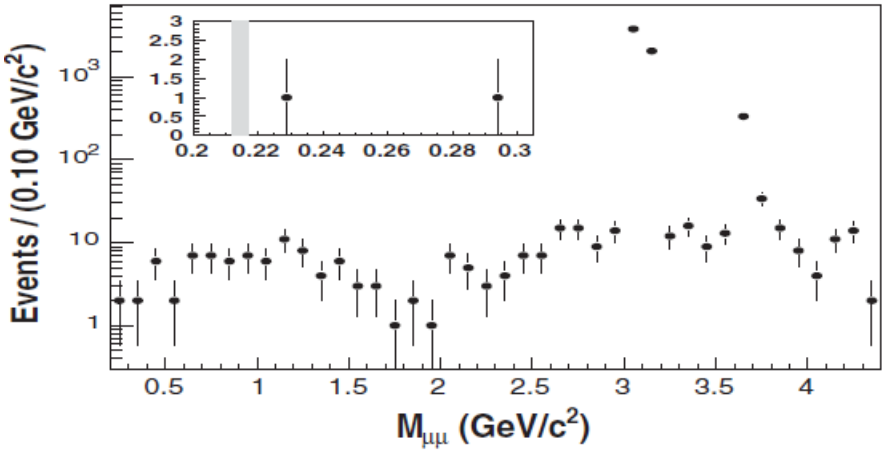


- ➢ best place to search Z'
- ➢ less statistics
- ➢ photon peak pollution

- However, LHCb sets the cut $q^2 > 0.1\ \mathrm{GeV}^2 \simeq (316\ \mathrm{MeV})^2$

  => This constraint can be avoided if $m_{Z'} < 316$ MeV

Belle's search for B → K*X (→ $\mu^+\mu^-$)



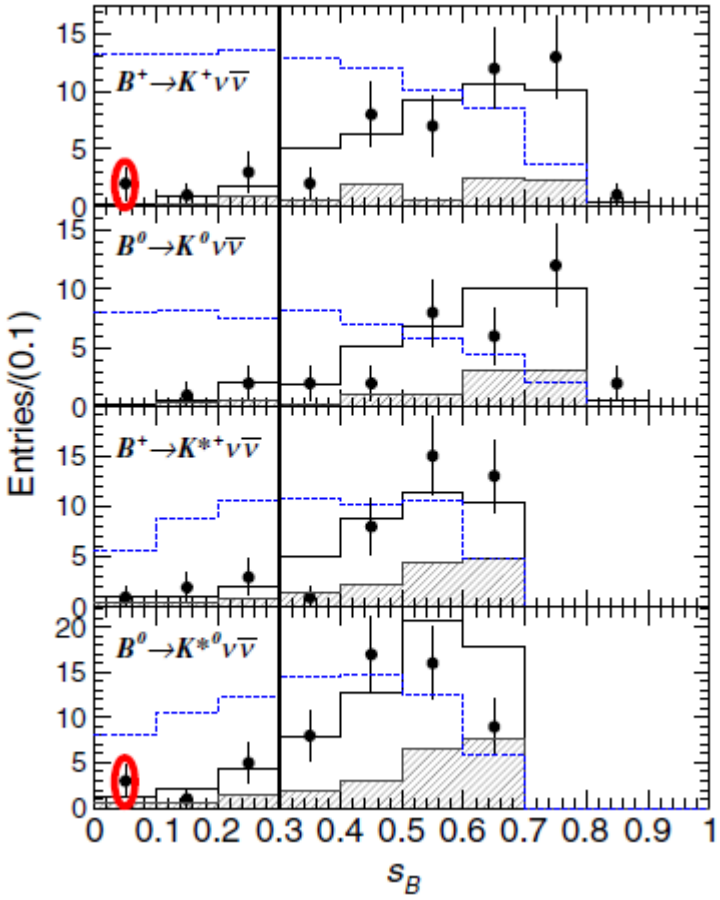
PRL105, 091801(2010)

$M_{\mu\mu}$ (MeV/c^2)	$B^0 \to K^{*0}X,\ K^{*0} \to K^+\pi^-,\ X \to \mu^+\mu^-$				
	N_{obs}	N_{bg}	ϵ	S_{90}	U.L. (10^{-8})
212.0	0	$0.03^{+0.01}_{-0.01}$ $(0.03^{+0.01}_{-0.01})$	23.8 (23.7)	2.43 (2.43)	2.34 (2.34)
214.3	0	$0.13^{+0.04}_{-0.03}$ $(0.13^{+0.04}_{-0.03})$	23.6 (23.5)	2.33 (2.33)	2.26 (2.27)
220.0	0	$0.13^{+0.02}_{-0.02}$ $(0.13^{+0.02}_{-0.02})$	23.0 (22.9)	2.33 (2.33)	2.31 (2.33)
230.0	1	$0.24^{+0.02}_{-0.02}$ $(0.25^{+0.02}_{-0.02})$	21.4 (21.4)	4.09 (4.12)	4.37 (4.40)
240.0	0	$0.38^{+0.02}_{-0.02}$ $(0.39^{+0.02}_{-0.02})$	20.0 (20.0)	2.09 (2.09)	2.40 (2.39)
250.0	0	$0.51^{+0.01}_{-0.01}$ $(0.51^{+0.01}_{-0.01})$	18.0 (18.4)	1.92 (1.94)	2.43 (2.41)
260.0	0	$0.63^{+0.01}_{-0.01}$ $(0.63^{+0.01}_{-0.01})$	16.5 (17.2)	1.83 (1.83)	2.54 (2.43)
270.0	0	$0.75^{+0.02}_{-0.02}$ $(0.75^{+0.02}_{-0.02})$	15.4 (16.4)	1.76 (1.76)	2.61 (2.45)
280.0	0	$0.69^{+0.03}_{-0.03}$ $(0.86^{+0.04}_{-0.04})$	14.6 (15.8)	1.78 (1.69)	2.78 (2.45)
290.0	1	$0.98^{+0.06}_{-0.06}$ $(0.97^{+0.06}_{-0.06})$	14.0 (15.5)	3.35 (3.37)	5.47 (4.99)
300.0	1	$1.08^{+0.08}_{-0.08}$ $(1.08^{+0.08}_{-0.08})$	13.6 (15.1)	3.28 (3.28)	5.53 (4.97)

<-- 90%CL upper limit

Constraint from B → K $\nu\,\nu$

- Belle & BaBar's sensitivities are ~ 10 x BR(SM)
- BaBar's result is sensitive to low mass Z' **PRD87, 112005(2013)**



constraint on New Physics effect in 1st bin

$$s_B \equiv \frac{m^2_{\nu\nu}}{m^2_B} \in (0,\ 0.1) \quad m_{Z'} \in (0,\ 1670)\ \mathrm{MeV}$$

$$\Delta\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{(0,0.1)} = (0.35^{+0.60}_{-0.15}) \times 10^{-5}$$

$$\Delta\mathcal{B}(B^0 \to K^0\nu\bar{\nu})_{(0,0.1)} = (-0.2^{+1.8}_{-0.1}) \times 10^{-5}$$

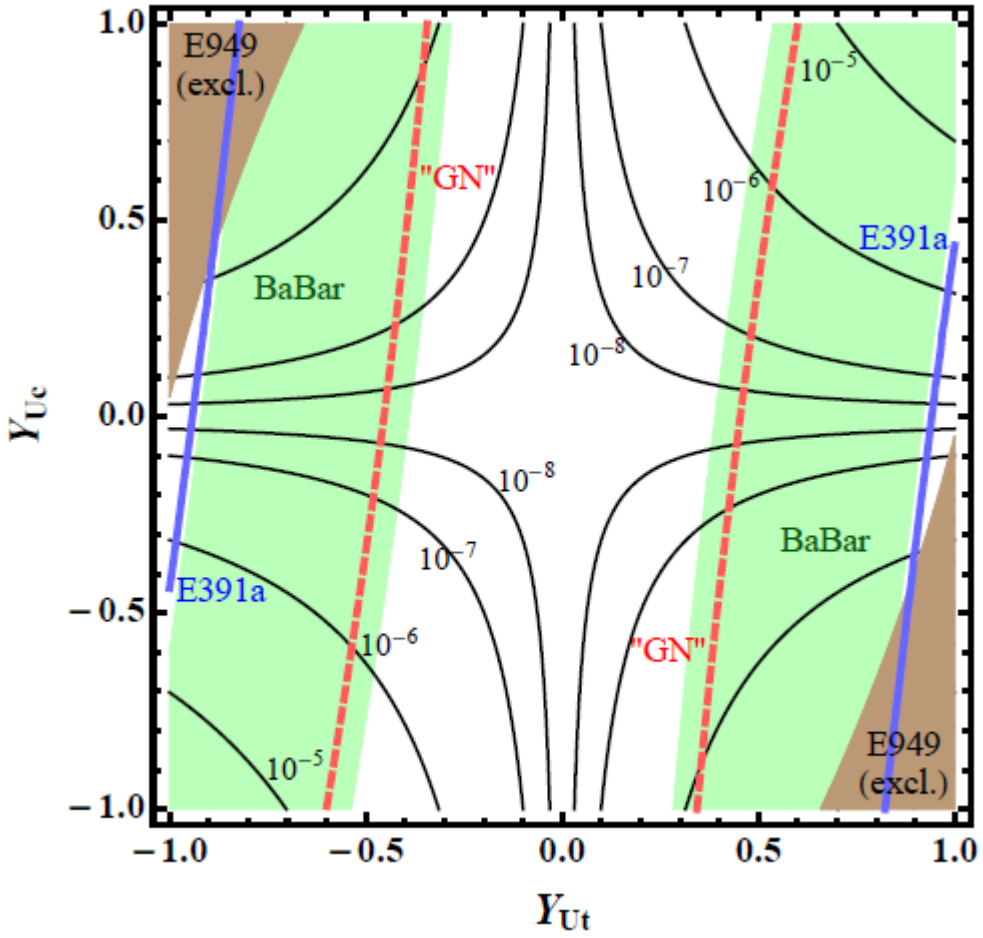
$$\Delta\mathcal{B}(B^+ \to K^{*+}\nu\bar{\nu})_{(0,0.1)} = (-0.1^{+1.9}_{-0.3}) \times 10^{-5}$$

$$\Delta\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu})_{(0,0.1)} = (1.1^{+1.9}_{-0.6}) \times 10^{-5}$$

N.B. These are supplied by genuine experiments

Allowed Region: $m_{Z'}$ = 135 MeV

$$g' = 10^{-3},\ v_\Phi = 135\,\mathrm{GeV},\ m_U = 2\,\mathrm{TeV}$$



- **E391a** set better limit than E949 in some region
- **"GN"** is usual GN bound, which should not be applied in this case

$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) \lesssim 1.4 \times 10^{-9}$$

- $K_L \to \pi^0 Z'$ can go beyond **"GN"** bound (favored by the **BaBar** data)