ΔM_s interplay with B-anomalies

10th International Workshop on the CKM Unitarity Triangle - 18.09.2018

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In collaboration with Matthew Kirk and Alexander Lenz
arXiv:1712.06572 + work in progress

Outline

1. ΔM_s in the SM [theoretical uncertainties]
    - Hadronic Matrix Element
    - V_{cb} dependence
2. Impact on B-anomalies
    - Neutral currents [Z', LQ]
    - Model building directions

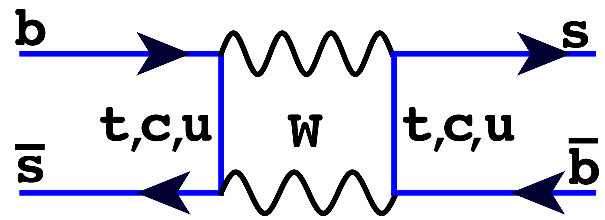
Part-I

ΔM_s in the SM

SM prediction [ingredients]

- $\Delta M_s \equiv M_H^s - M_L^s = 2\,|M_{12}^s|$

  [For a review see Lenz, Nierste hep-ph/0612167
  Artuso, Borissov, Lenz 1511.09466]



$$M_{12}^s = \frac{G_F^2}{12\pi^2} \lambda_t^2 M_W^2 S_0(x_t) B f_{B_s}^2 M_{B_s} \hat{\eta}_B$$

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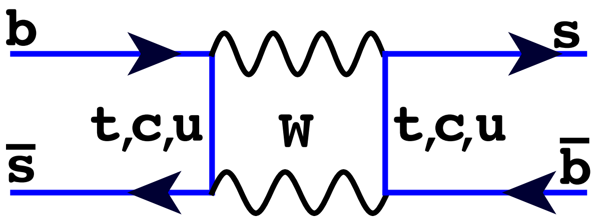

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★ Inami-Lim function $S_0(x_t = \bar{m}_t^2(\bar{m}_t)/M_W^2) \approx 2.368$ [Inami, Lim PTR65 (1981)]

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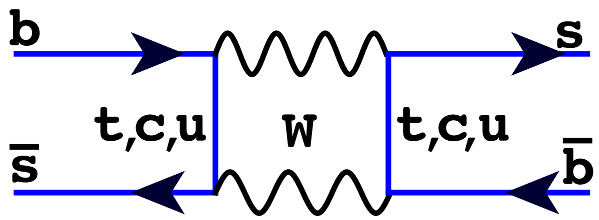

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★ Perturbative NLO QCD corrections $\hat{\eta}_B \approx 0.8379$ [Buras, Jamin, Weisz NPB347 (1990)]

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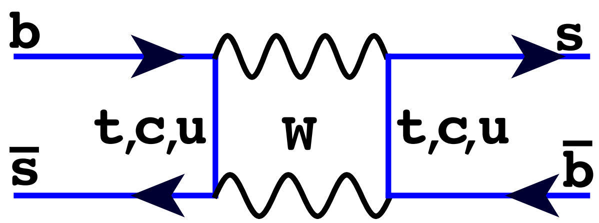

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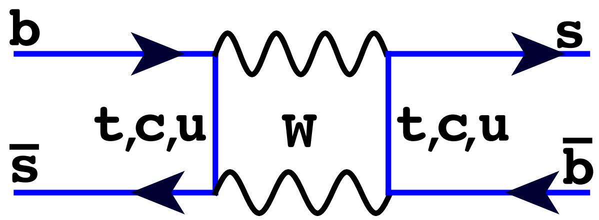
★ Hadronic matrix element (Lattice / HQET Sum Rules)

[See talks by
Andreas Kronfeld, Aida El-Khadra,
Thomas Mannel, Thomas Rauh]

$$\langle B_s^0|Q|\bar{B}_s^0\rangle = \frac{8}{3}M_{B_s}^2 f_{B_s}^2 B(\mu) \qquad Q = [\bar{s}\gamma_\mu(1-\gamma_5)b]\,[\bar{s}\gamma^\mu(1-\gamma_5)b]$$

$\hat{\eta}_B B \equiv \eta_B \hat{B}$ (Bhat renormalization scale and scheme independent)

SM prediction [ingredients]



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★ CKM elements

$\lambda_t \equiv V_{ts}^* V_{tb}$ ← V_{us} V_{cb} $|V_{ub}/V_{cb}|$ $\gamma_{\rm CKM}$

in terms of 4 inputs, assuming CKM unitarity
(not necessarily true in presence of NP)

Hadronic matrix element [Lattice]

[November 2017 web-update of Flavour Lattice Averaging Group (FLAG) 1607.00299]

S. Aoki et al., *Review of lattice results concerning low-energy particle physics*, 1607.00299

Collaboration	Ref.	N_f	publication status	continuum extrapolation	chiral extrapolation	finite volume	renormalization/matching	heavy-quark treatment	$f_{\mathrm{B_d}}\sqrt{\hat{B}_{\mathrm{B_d}}}$	$f_{\mathrm{B_s}}\sqrt{\hat{B}_{\mathrm{B_s}}}$	$\hat{B}_{\mathrm{B_d}}$	$\hat{B}_{\mathrm{B_s}}$
FNAL/MILC 16	[57]	2+1	A	★	○	★	○	✓	227.7(9.5)	274.6(8.4)	$1.38(12)(6)^{\odot}$	$1.443(88)(48)^{\odot}$
RBC/UKQCD 14A	[15]	2+1	A	○	○	○	○	✓	240(15)(33)	290(09)(40)	1.17(11)(24)	1.22(06)(19)
FNAL/MILC 11A	[56]	2+1	C	★	○	★	○	✓	$250(23)^{\dagger}$	$291(18)^{\dagger}$	–	–
HPQCD 09	[19]	2+1	A	○	$○^{\nabla}$	○	○	✓	$216(15)^{*}$	$266(18)^{*}$	$1.27(10)^{*}$	$1.33(6)^{*}$
HPQCD 06A	[58]	2+1	A	■	■	★	○	✓	–	281(21)	–	1.17(17)
ETM 13B	[9]	2	A	★	○	○	★	✓	216(6)(8)	262(6)(8)	1.30(5)(3)	1.32(5)(2)
ETM 12A, 12B	[24, 59]	2	C	★	○	○	★	✓	–	–	$1.32(8)^{\diamond}$	$1.36(8)^{\diamond}$

$^{\odot}$ PDG averages of decay constant f_{B^0} and f_{B_s} [2] are used to obtain these values.

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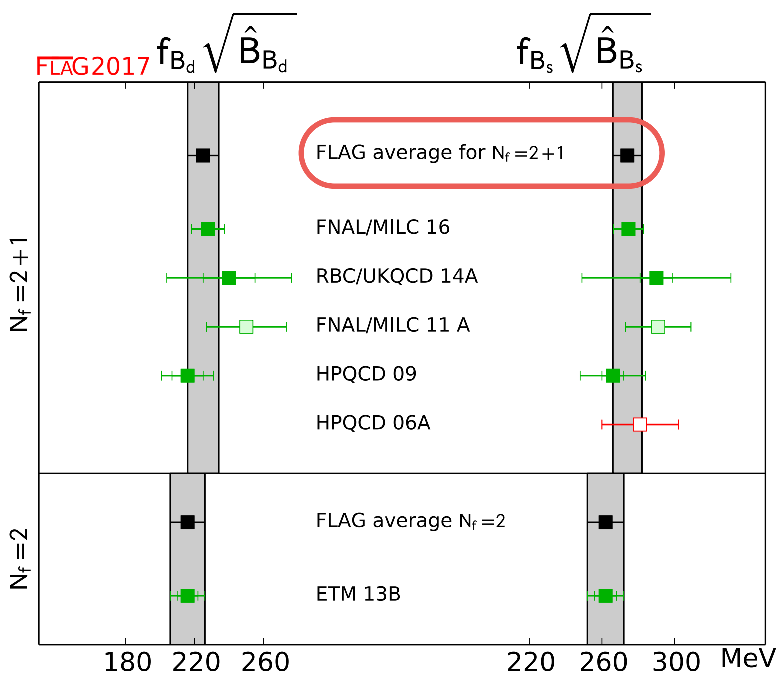

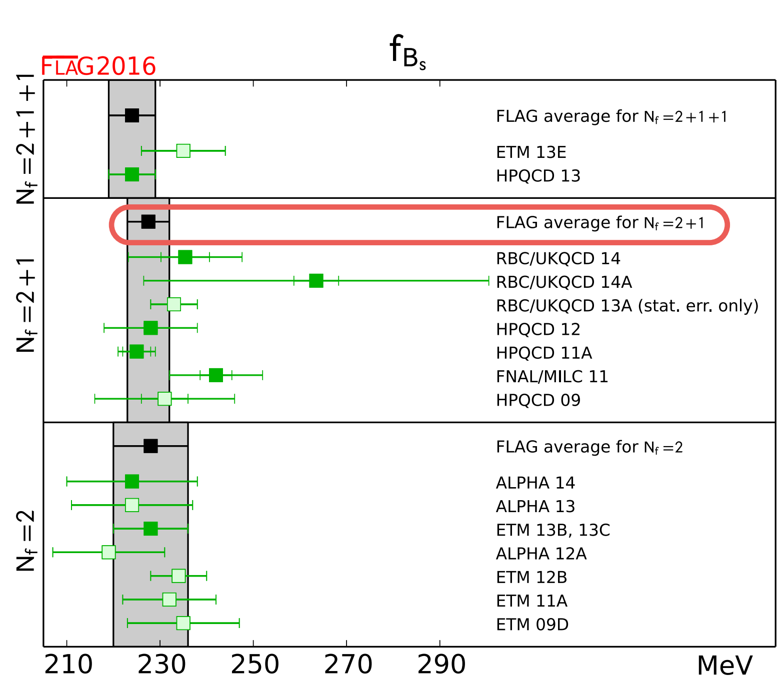

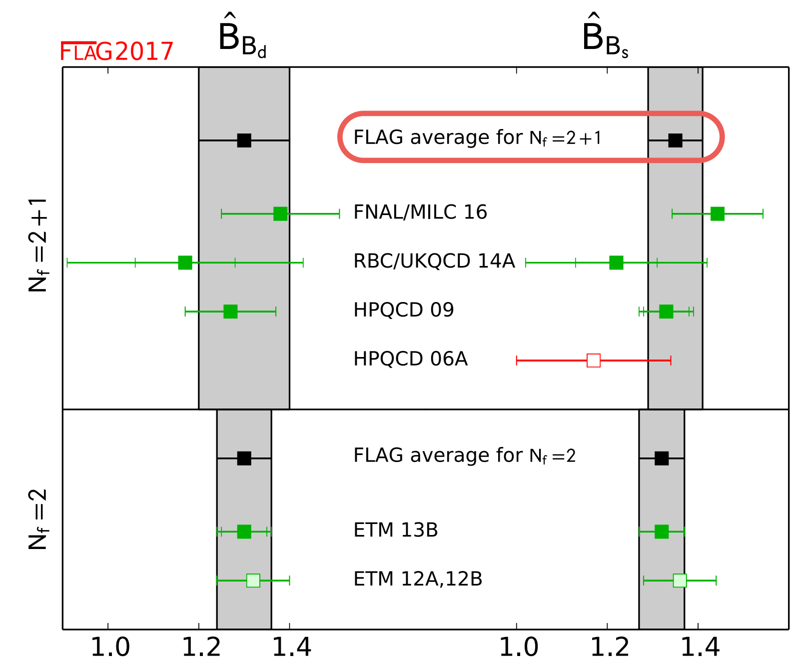

$$\left(f_{B_s}\sqrt{\hat{B}_{B_s}}\right)^{\rm FLAG17} = 274(8)\ \text{MeV}$$

$$(f_{B_s})^{\rm FLAG16}\left(\sqrt{\hat{B}_{B_s}}\right)^{\rm FLAG17} = 265(10)\ \text{MeV}^{*}$$

*Naive combination (does not include updated FNAL/MILC calculation of decay constant)

Hadronic matrix element [Lattice]

- FLAG17 + V_{cb} treatment (see next slide) implies a 1.8 σ discrepancy

$$\Delta M_s^{\rm SM} > \Delta M_s^{\rm exp} = (17.757 \pm 0.021)\ \text{ps}^{-1}$$ [HFLAV (CDF + LHCb) 1612.07233]

Source	$f_{B_s}\sqrt{\hat{B}}$	$\Delta M_s^{\rm SM}$
HPQCD14 [132]	(247 ± 12) MeV	$(16.2 \pm 1.7)\,\text{ps}^{-1}$
ETMC13 [133]	(262 ± 10) MeV	$(18.3 \pm 1.5)\,\text{ps}^{-1}$
HPQCD09 [134] = FLAG13 [135]	(266 ± 18) MeV	$(18.9 \pm 2.6)\,\text{ps}^{-1}$
FLAG17 [70]	$\mathbf{(274 \pm 8)}$ **MeV**	$\mathbf{(20.01 \pm 1.25)\,ps^{-1}}$
Fermilab16 [72]	(274.6 ± 8.8) MeV	$(20.1 \pm 1.5)\,\text{ps}^{-1}$
HQET-SR [77, 136]	(278^{+28}_{-24}) MeV	$(20.6^{+4.4}_{-3.4})\,\text{ps}^{-1}$
HPQCD06 [137]	(281 ± 20) MeV	$(21.0 \pm 3.0)\,\text{ps}^{-1}$
RBC/UKQCD14 [138]	(290 ± 20) MeV	$(22.4 \pm 3.4)\,\text{ps}^{-1}$
Fermilab11 [139]	(291 ± 18) MeV	$(22.6 \pm 2.8)\,\text{ps}^{-1}$

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[LDL, Kirk, Lenz 1712.06572]

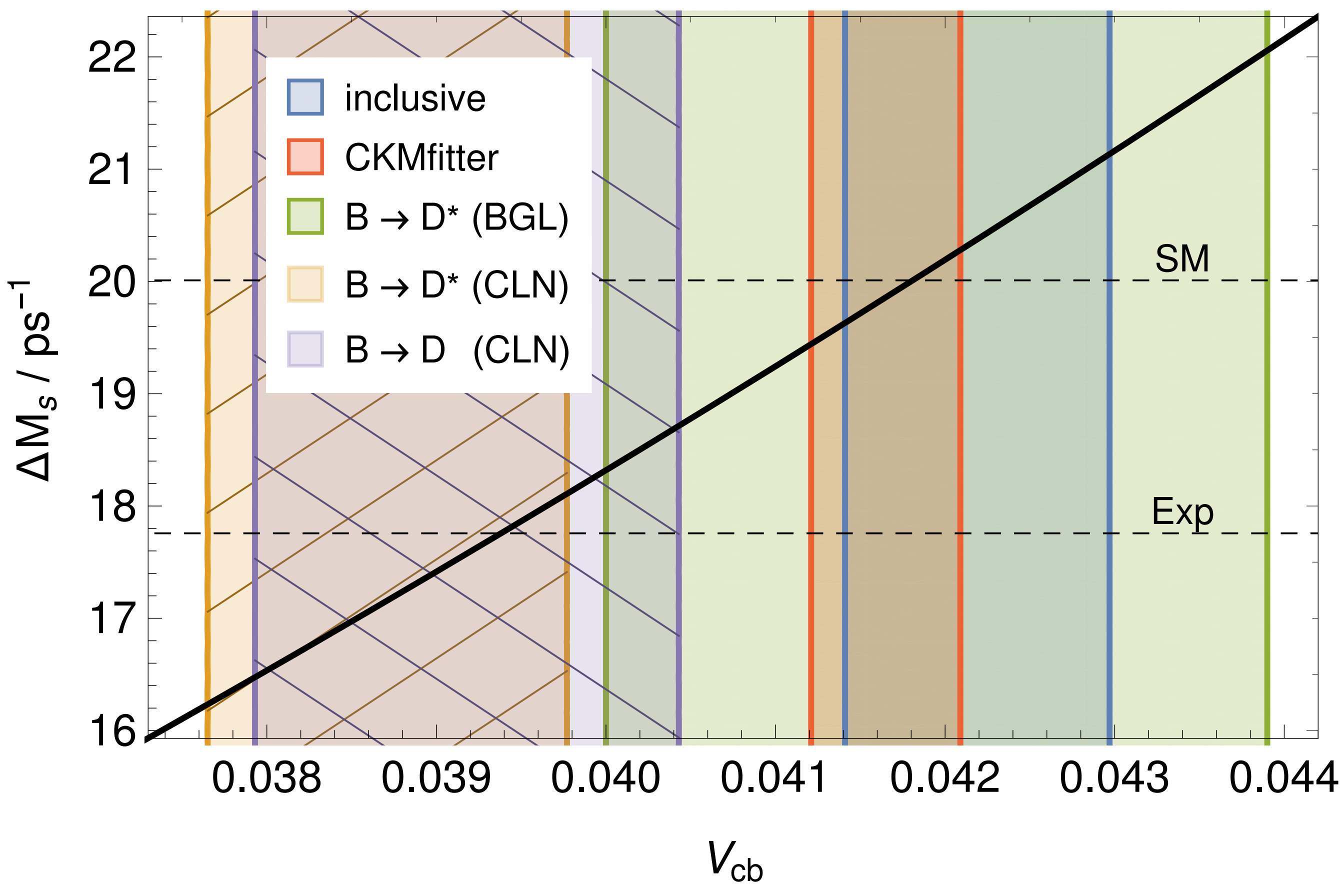
★ Lattice updates crucial to settle the issue !

V_{cb} dependence

- V_{cb} is the second most important ingredient for SM prediction

→ we use CKMfitter value* (consistent with inclusive determination)

[LDL, Kirk, Lenz 1712.06572]



$$\Delta M_s^{\text{SM, 2017}} = (20.01 \pm 1.25)\ \text{ps}^{-1}$$

$$\left[\Delta M_s^{\text{SM, 2017 (tree)}} = (19.9 \pm 1.5)\ \text{ps}^{-1}\right]$$

*Includes loop-mediated observables (potentially affected by NP)

Part-II

Impact on B-anomalies

ΔM_s vs. new physics (NP)

- As an example let's assume:

1. NP in purely V-A $\Delta B = 2$ operator (same matrix element as in the SM)

2. no NP pollution in the extraction of CKM elements

$$\Delta M_s^{\mathrm{Exp}} = 2\left|M_{12}^{\mathrm{SM}} + M_{12}^{\mathrm{NP}}\right| = \Delta M_s^{\mathrm{SM}}\left|1 + \frac{M_{12}^{\mathrm{NP}}}{M_{12}^{\mathrm{SM}}}\right|$$

ΔM_s vs. new physics (NP)

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$$\Delta M_s^{\rm Exp} = 2\left|M_{12}^{\rm SM} + M_{12}^{\rm NP}\right| = \Delta M_s^{\rm SM}\left|1 + \frac{M_{12}^{\rm NP}}{M_{12}^{\rm SM}}\right|$$

$$\frac{\Delta M_s^{\rm Exp}}{\Delta M_s^{\rm SM}} = \left|1 + \frac{\kappa}{\Lambda_{\rm NP}^2}\right| \quad \xrightarrow{\text{if } \kappa > 0} \quad \frac{\Lambda_{\rm NP}^{2017}}{\Lambda_{\rm NP}^{2015}} = \sqrt{\frac{\frac{\Delta M_s^{\rm Exp}}{(\Delta M_s^{\rm SM} - 2\delta\Delta M_s^{\rm SM})^{2015}} - 1}{\frac{\Delta M_s^{\rm Exp}}{(\Delta M_s^{\rm SM} - 2\delta\Delta M_s^{\rm SM})^{2017}} - 1}} \simeq 5 \qquad (2\,\sigma \text{ bound})$$

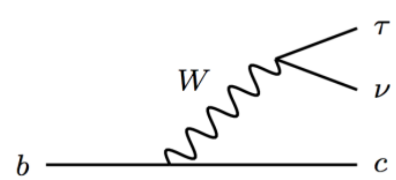
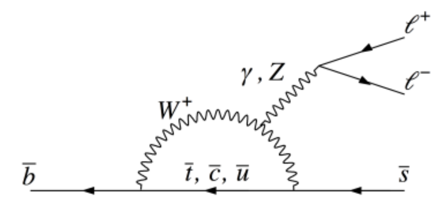
$\Delta M_s^{\rm SM,\,2015} = (18.3 \pm 2.7)\ {\rm ps}^{-1}$ [Artuso, Borissov, Lenz 1511.09466]

$\Delta M_s^{\rm SM,\,2017} = (20.01 \pm 1.25)\ {\rm ps}^{-1}$ [LDL, Kirk, Lenz 1712.06572]

$\Delta M_s^{\rm Exp} = (17.757 \pm 0.021)\ {\rm ps}^{-1}$ [HFLAV (CDF + LHCb) 1612.07233]

"B-anomalies"

- A seemingly coherent pattern of SM deviations building up since ~ 2012

<table>
<tr><th></th><th>$b \to c\tau\nu$

</th><th>$b \to s\mu\mu$

</th></tr>
<tr><td>Lepton Universality</td><td>$R(D), R(D^*),$
$R(J/\psi)$</td><td>$R(K), R(K^*)$</td></tr>
<tr><td>Angular Distributions</td><td></td><td>$B \to K^*\mu\mu \ (P_5')$</td></tr>
<tr><td>Differential BR
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$B_s \to \phi\mu\mu$
$\Lambda_b \to \Lambda\mu\mu$</td></tr>
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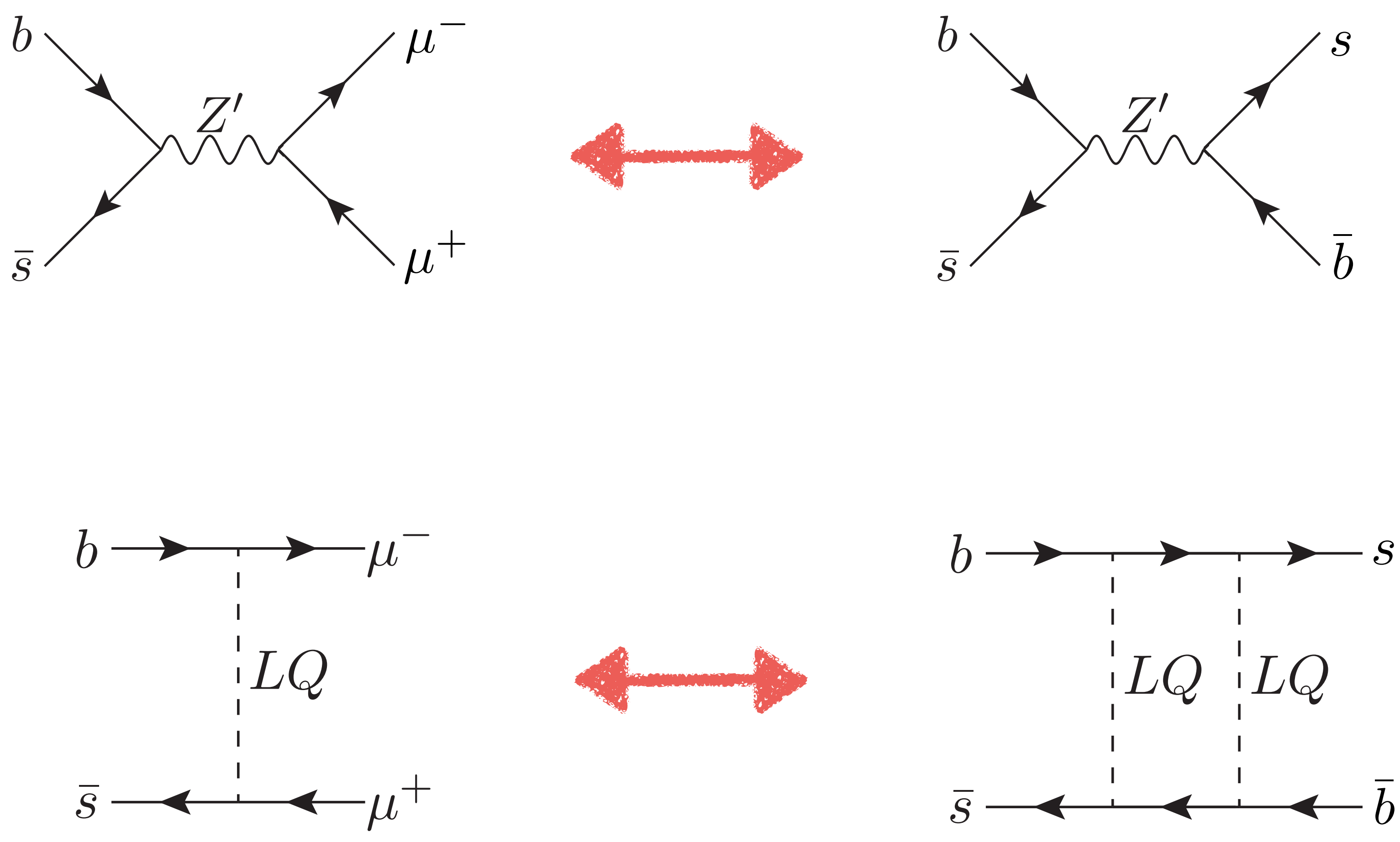
Neutral currents

- Generic robust connection between neutral current anomalies and ΔM_s



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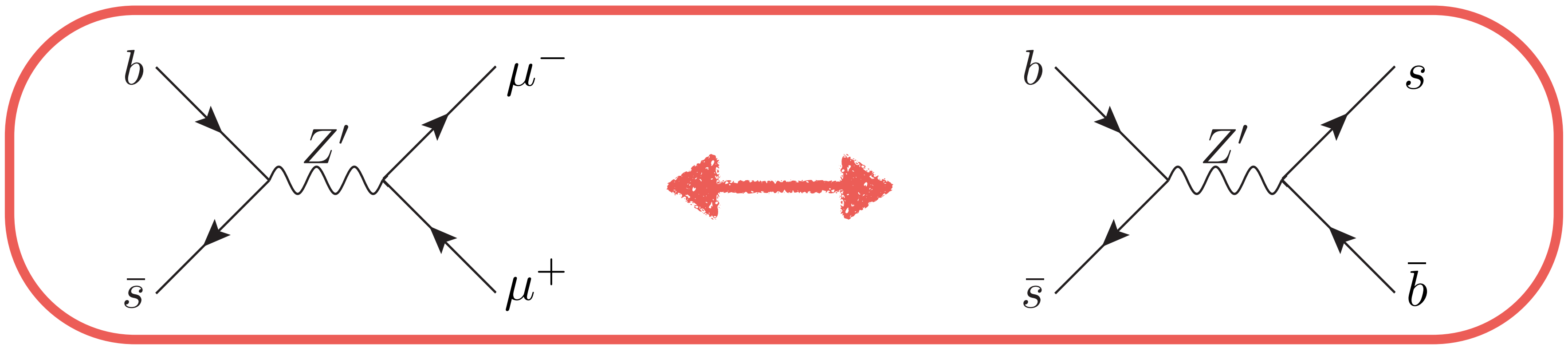
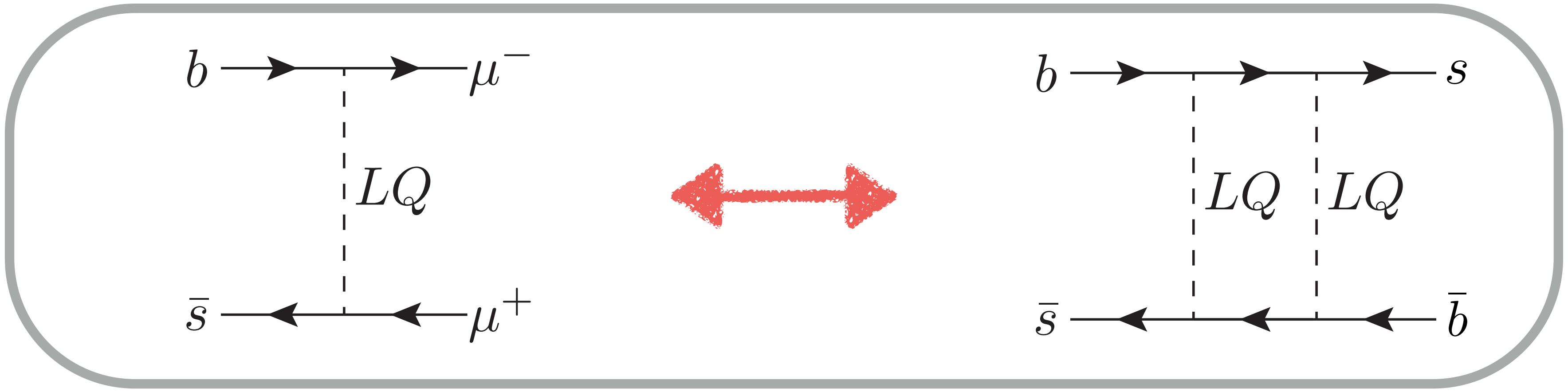




[See backup slides]

Neutral currents - Z'

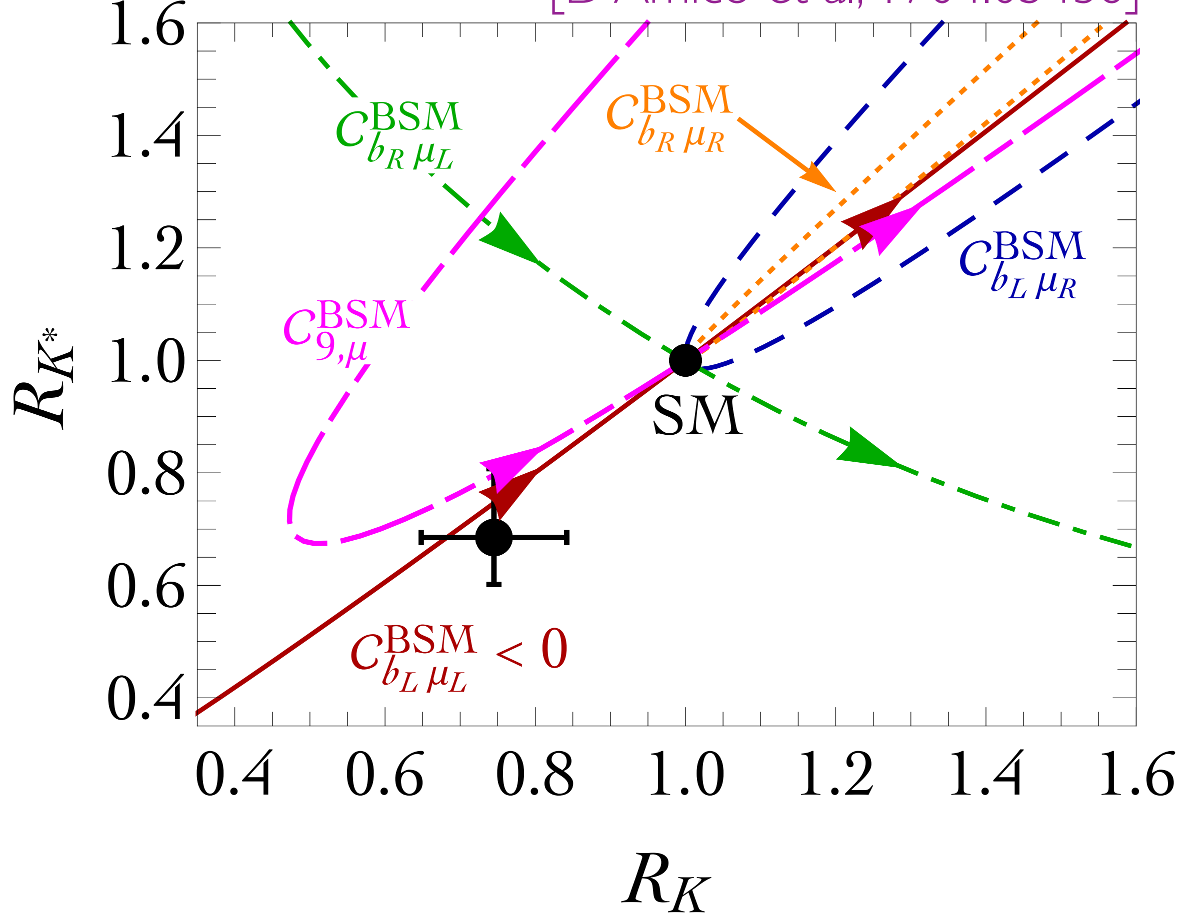
- Simplified Z' model with purely LH couplings

[For an anomaly-free UV completion see e.g. Alonso, Cox, Han, Yanagida 1705.03858]

$$\mathcal{L}_{Z'} = \frac{1}{2} M_{Z'}^2 (Z'_\mu)^2 + \left(\lambda_{ij}^Q \, \bar{d}_L^i \gamma^\mu d_L^j + \lambda_{\alpha\beta}^L \, \bar{\ell}_L^\alpha \gamma^\mu \ell_L^\beta \right) Z'_\mu$$

$$C_{b_L \mu_L}^{\rm BSM} = - \frac{\pi}{\sqrt{2} G_F M_{Z'}^2 \alpha} \left(\frac{\lambda_{bs}^Q \lambda_{\mu\mu}^L}{V_{tb} V_{ts}^*} \right)$$

[D'Amico et al, 1704.05438]



$$\mathcal{L}_{b \to s\mu\mu}^{\rm NP} \supset \frac{4 G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha}{4\pi} C_{b_L \mu_L}^{\rm BSM} \, [\bar{s}_L \gamma_\mu b_L] \, [\bar{\mu}_L \gamma^\mu \mu_L]$$

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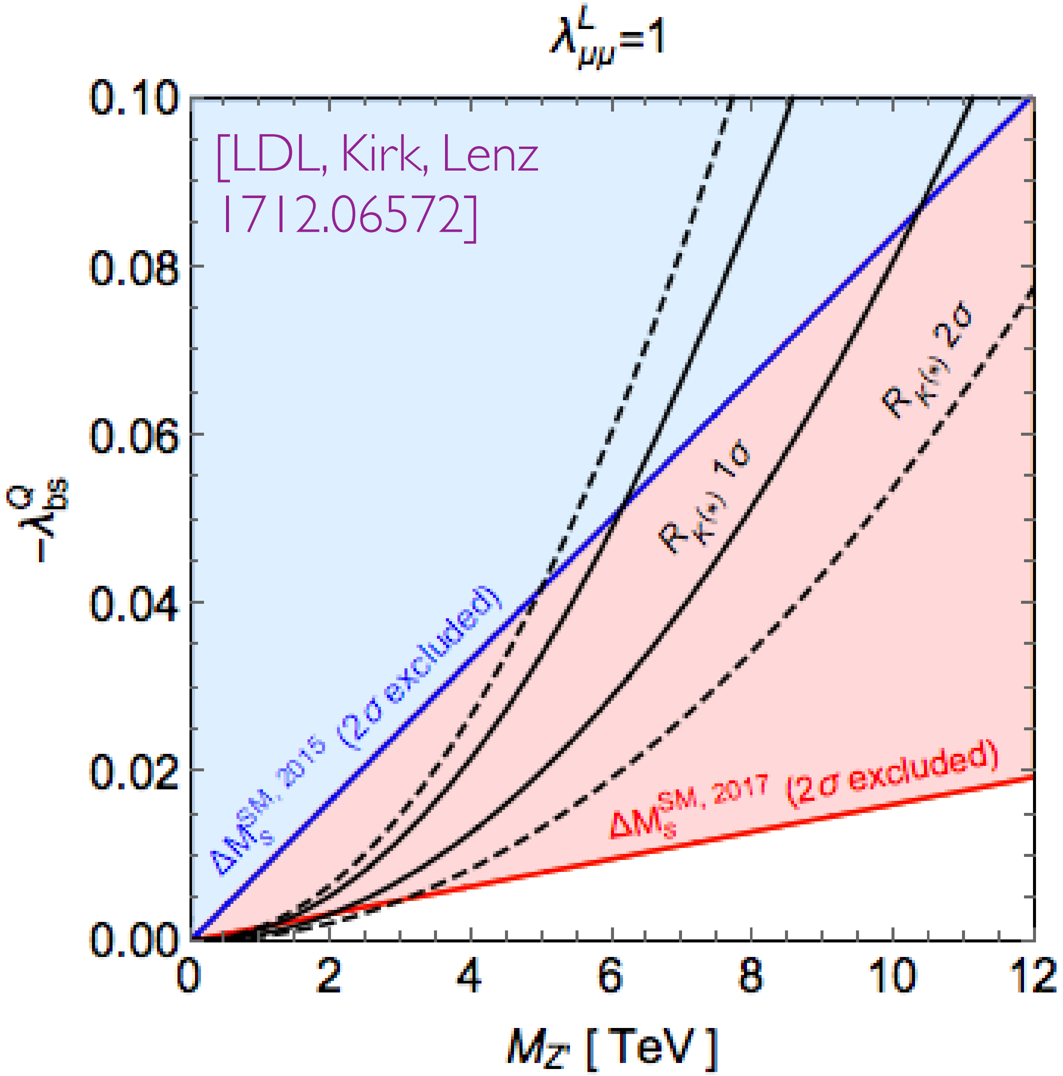


$$\mathcal{L}^{\rm NP}_{\Delta B=2} \supset -\frac{4 G_F}{\sqrt{2}} (V_{tb} V^*_{ts})^2\, C^{LL}_{bs} \left[\bar{s}_L \gamma_\mu b_L \right]^2$$

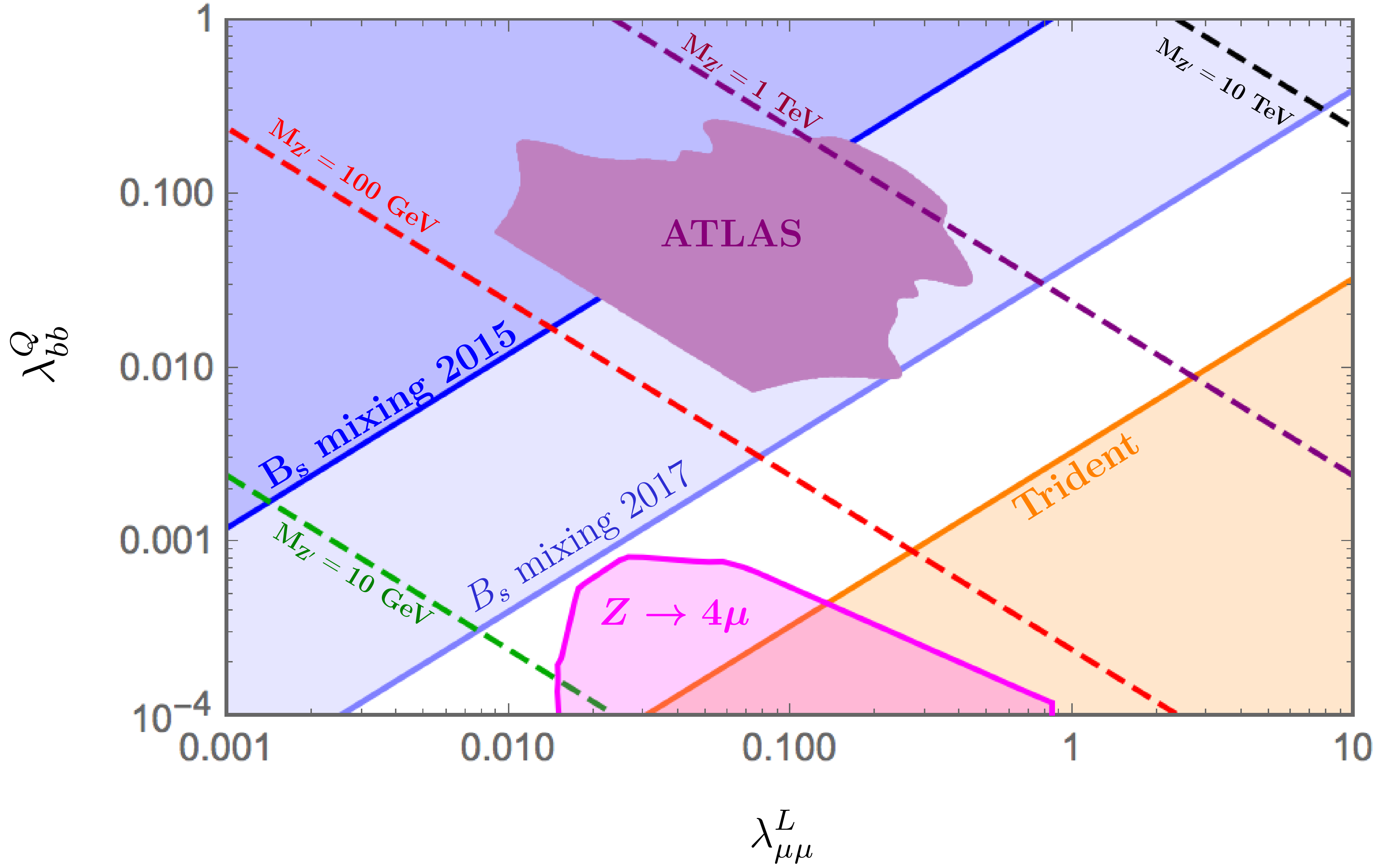
$$C^{LL}_{bs} = \frac{1}{4\sqrt{2} G_F M_{Z'}^2} \left(\frac{\lambda^Q_{bs}}{V_{tb} V^*_{ts}} \right)^2 > 0$$

(assuming real couplings)

Global view on Z' par. space

- Simplified Z' model with purely LH couplings (assuming $\lambda^Q_{bs} = \lambda^Q_{bb} V_{ts}$)

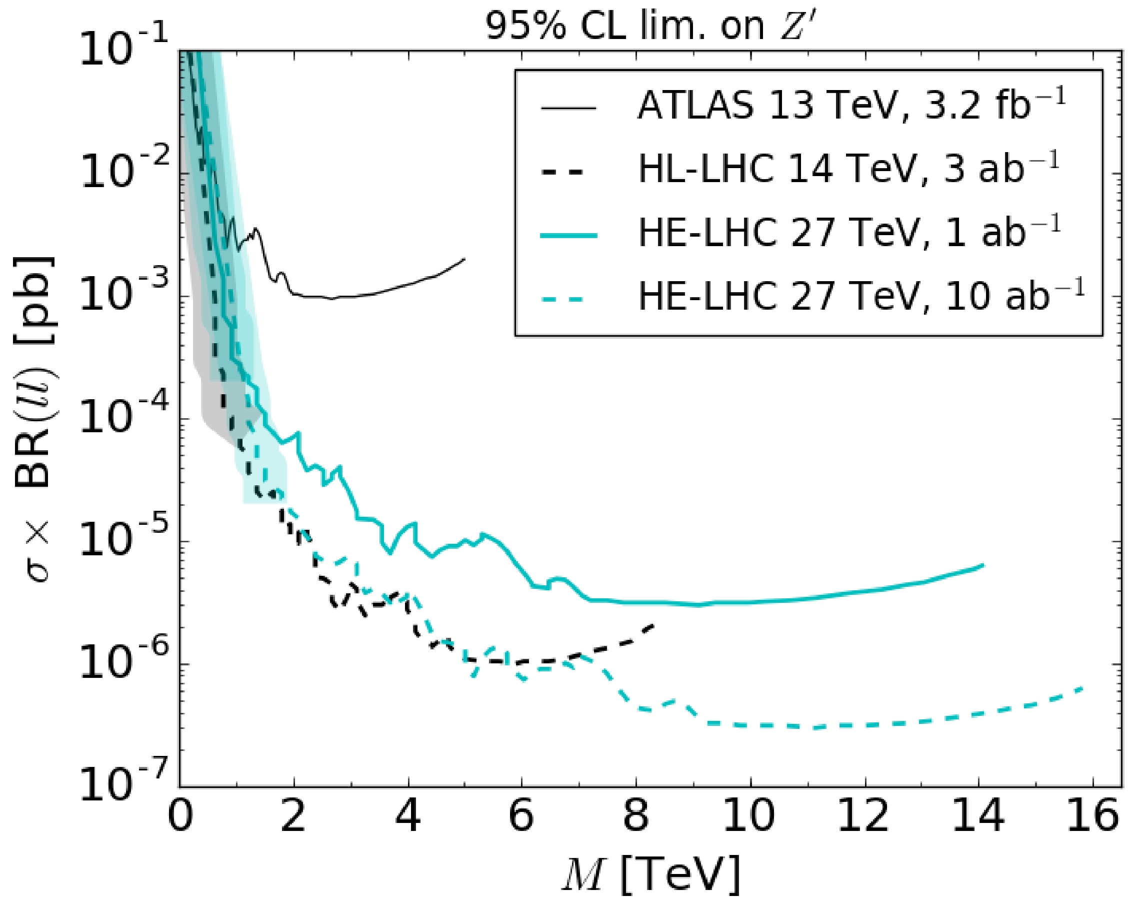
[Falkowski, King, Perdomo, Pierre 1803.04430]

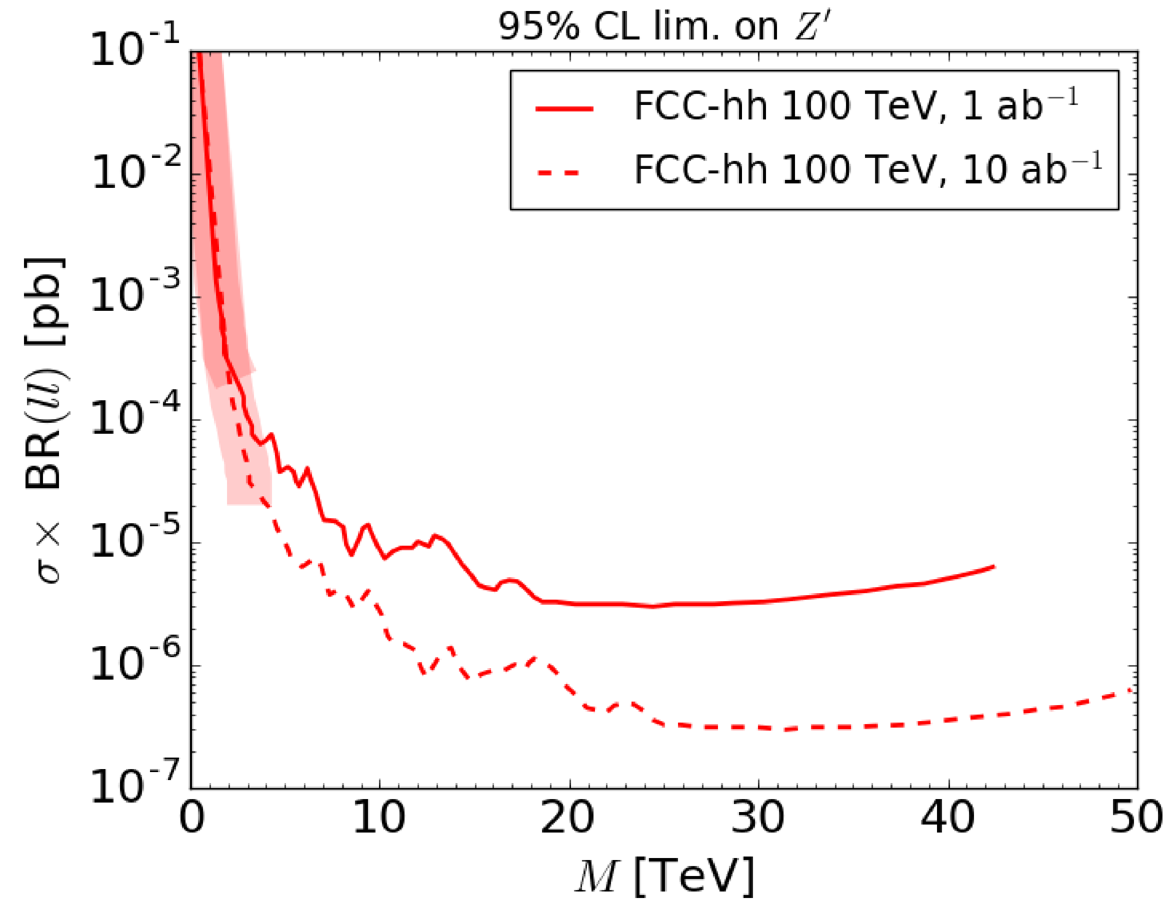


Z’ at future colliders

- Pessimistic scenario: only bs and mumu couplings fixed by anomaly $\frac{g_L^{bs} g_L^{\mu\mu}}{M_{Z'}^2} = \frac{1}{(31 \text{ TeV})^2}$

- Projected sensitivities of di-muons resonance searches [Allanach, Gripaios, You, 1710.06363]





[See also talk by Allanach]

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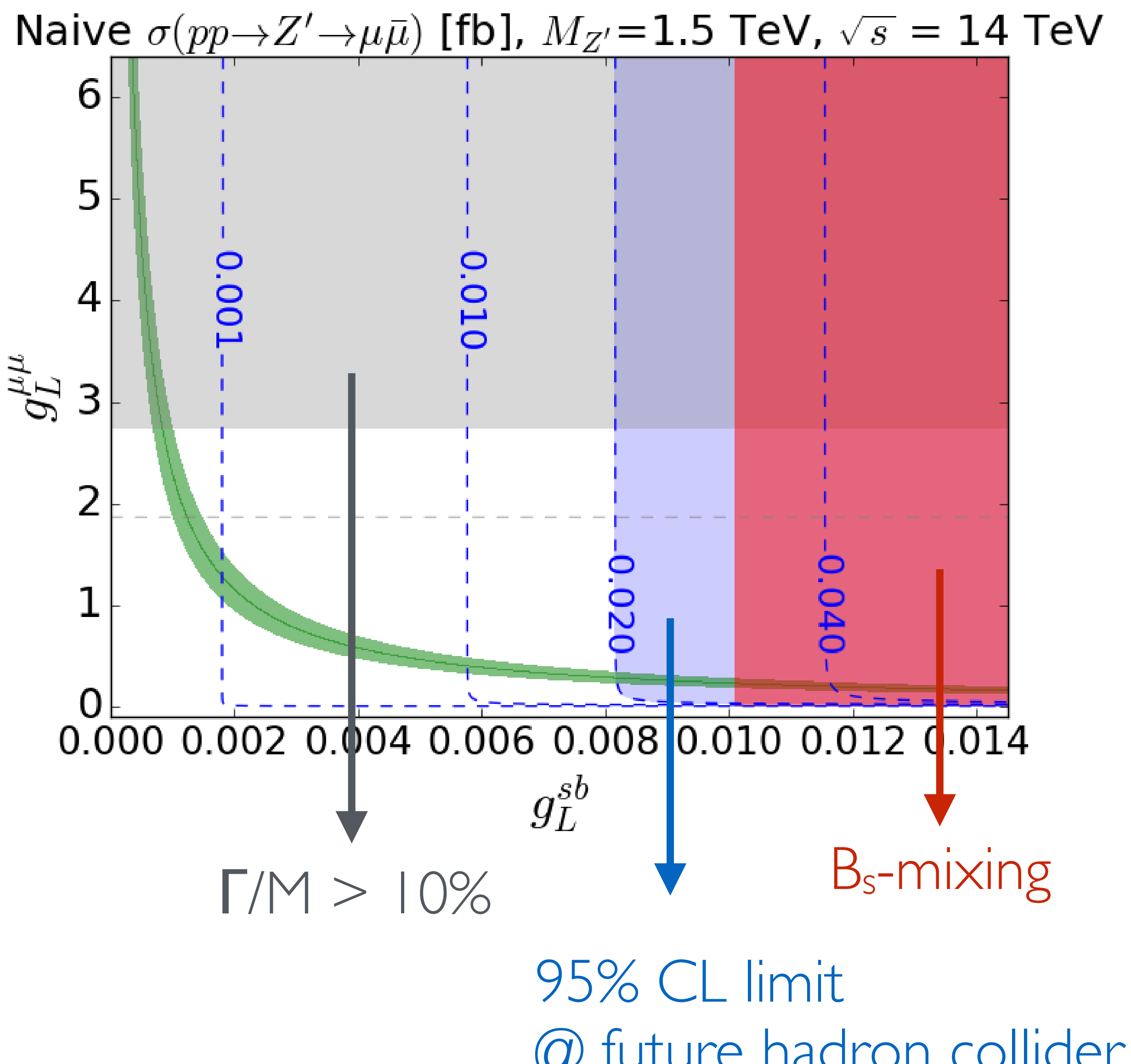

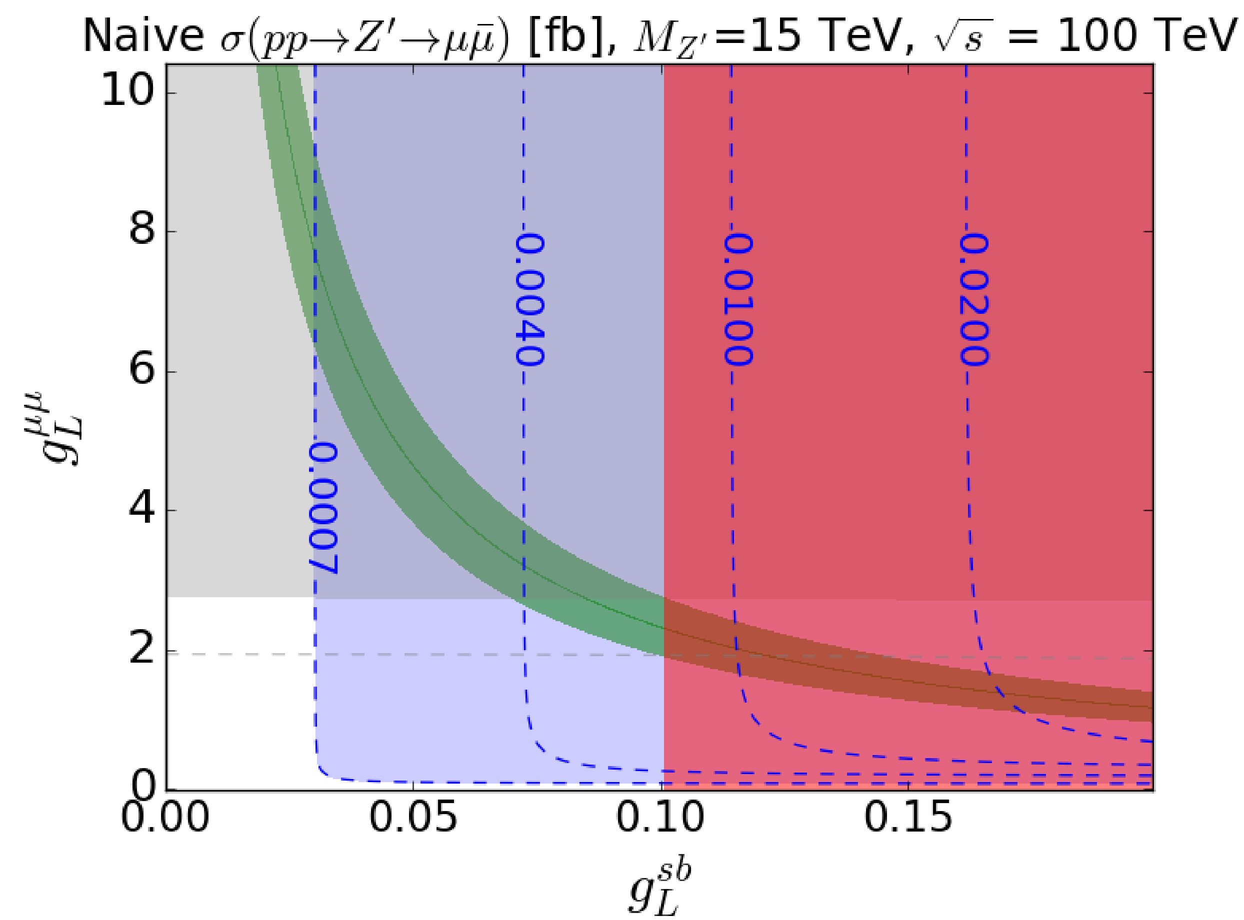

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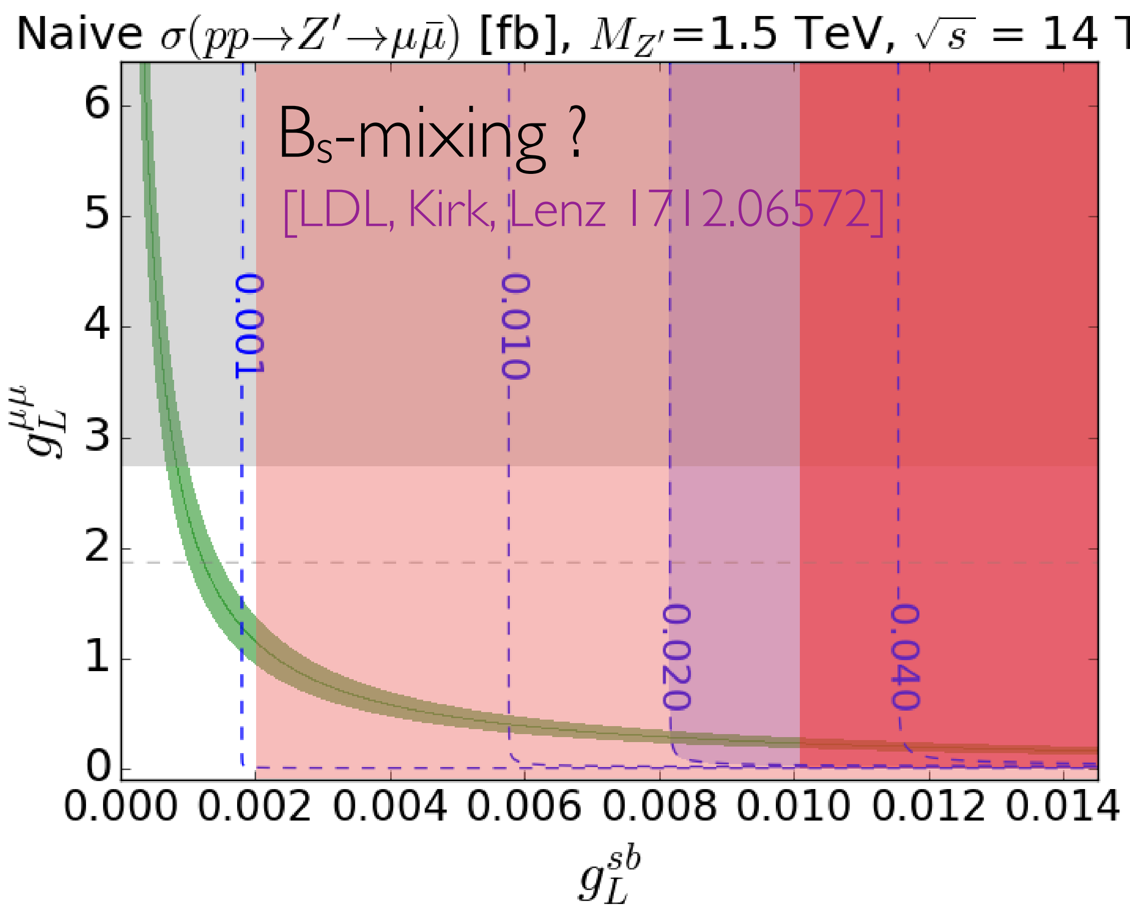
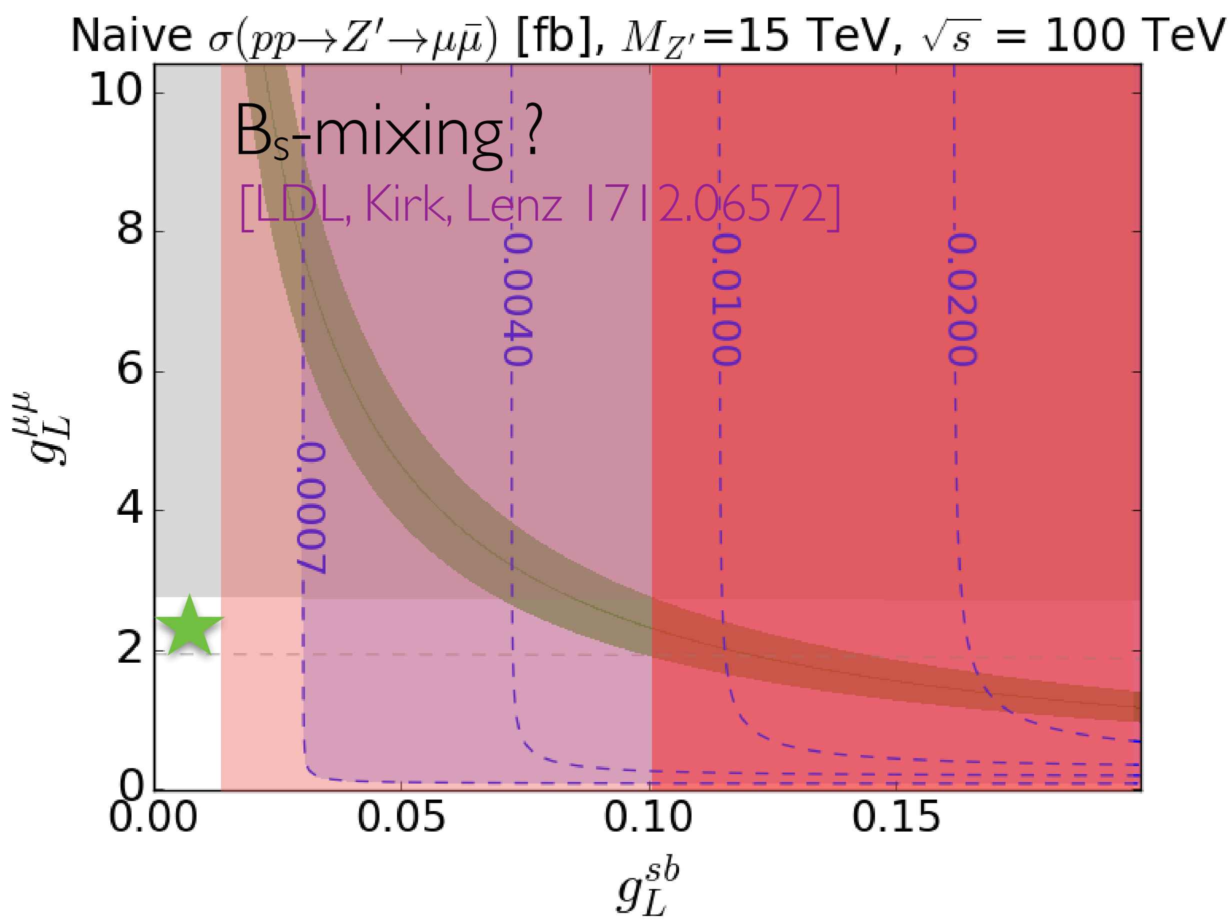




→ ΔM_s bound stronger than future colliders ?

[See also talk by Allanach]

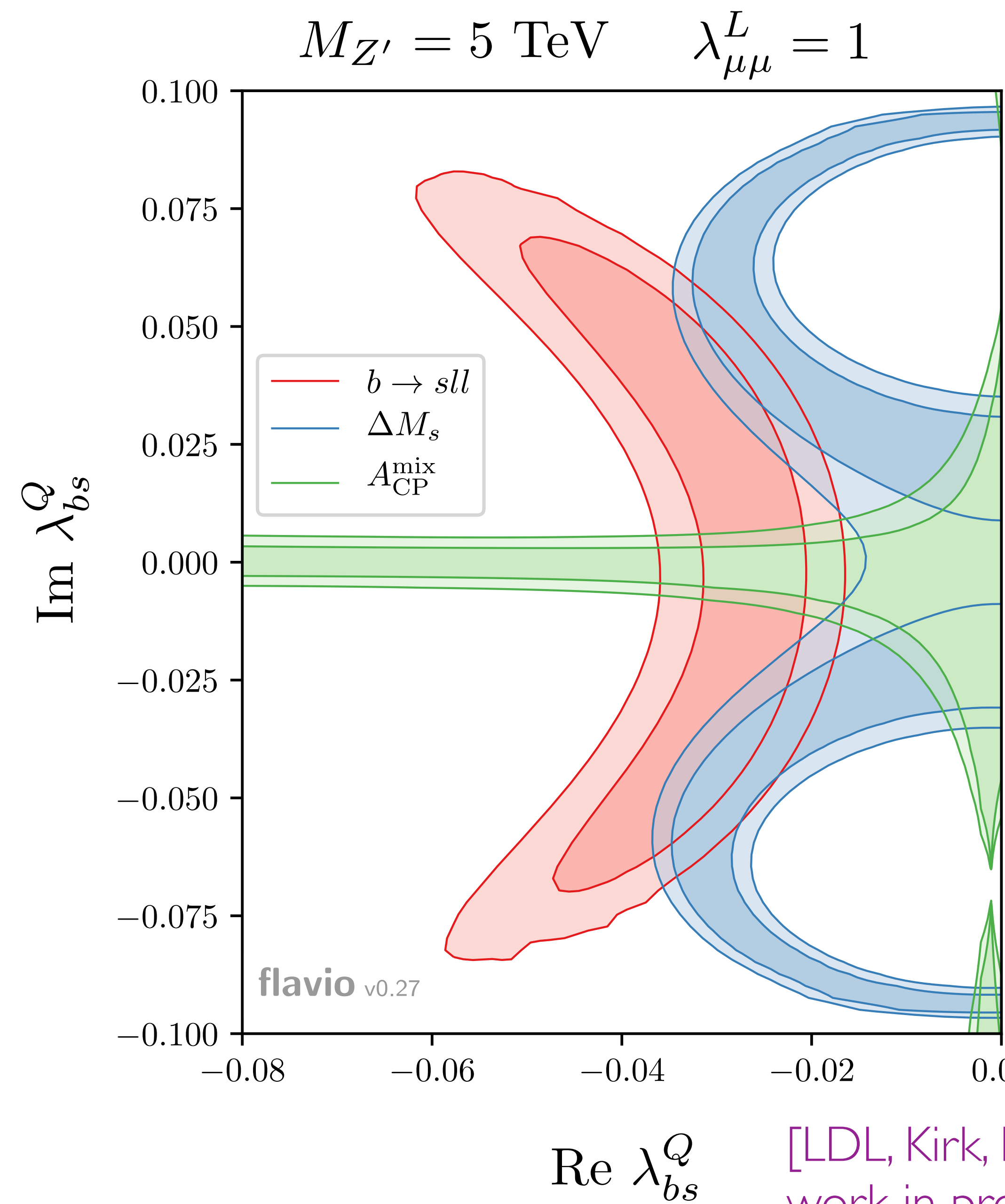
How to fit the ΔM$_s$ "discrepancy"

1) Complex couplings

$$C^{\mathrm{BSM}}_{b_L\mu_L} = -\frac{\pi}{\sqrt{2}G_F M^2_{Z'}\alpha}\left(\frac{\lambda^Q_{bs}\lambda^L_{\mu\mu}}{V_{tb}V^*_{ts}}\right)$$

$$\boxed{R_{K^{(*)}} \approx 1 + 2\,\mathrm{Re}\left(\frac{C^{\mathrm{BSM}}_{b_L\mu_L}}{C^{\mathrm{SM}}_{b_L\mu_L}}\right)}$$

Not strong dependence from Im part
(as long as we are in the linear regime)



[LDL, Kirk, Lenz, work in progress]

How to fit the ΔM$_s$ "discrepancy"

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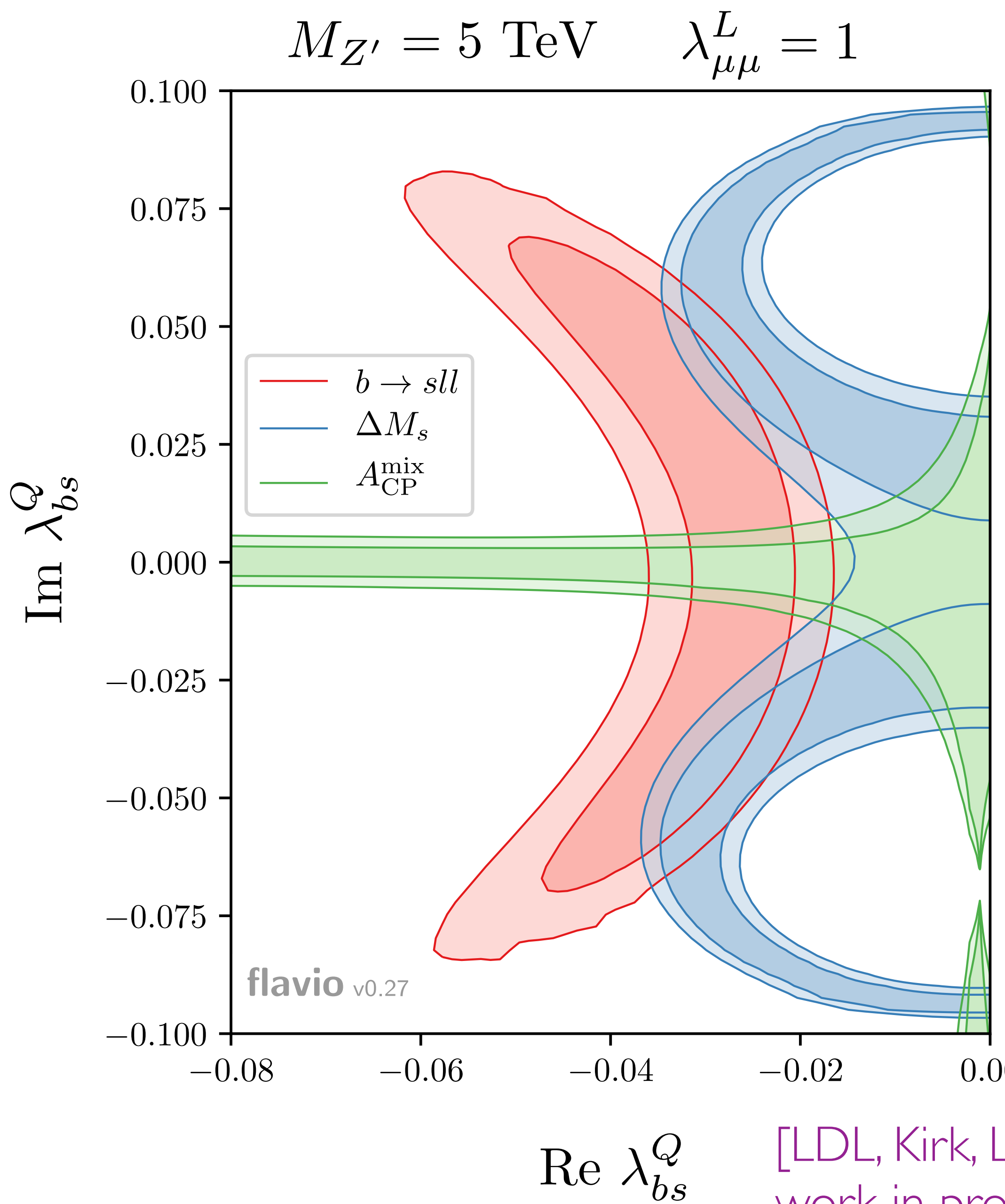
$$\frac{M_{12}^{\rm SM+NP}}{M_{12}^{\rm SM}} \equiv |\Delta|\, e^{i\phi_\Delta}$$

$$\boxed{\frac{\Delta M_s^{\rm Exp}}{\Delta M_s^{\rm SM}} = |\Delta| = \left|1 + \frac{C_{bs}^{LL}}{R_{\rm SM}^{\rm loop}}\right|}$$

Blue and Red regions have a 1σ overlap



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How to fit the ΔM_s "discrepancy"

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$$C^{\rm BSM}_{b_L \mu_L} = -\frac{\pi}{\sqrt{2} G_F M^2_{Z'} \alpha} \left(\frac{\lambda^Q_{bs} \lambda^L_{\mu\mu}}{V_{tb} V^*_{ts}} \right)$$

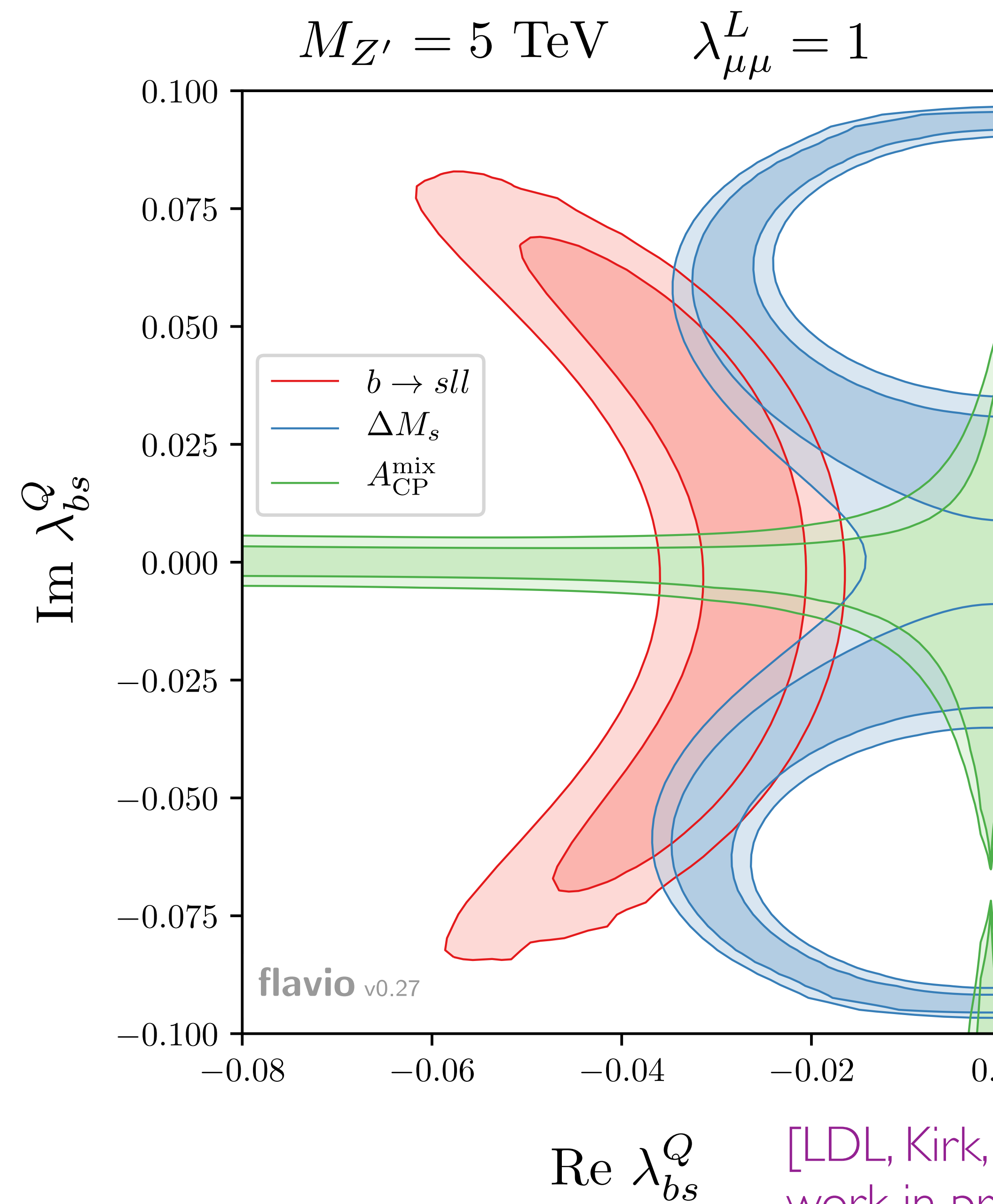
$$\frac{M_{12}^{\rm SM+NP}}{M_{12}^{\rm SM}} \equiv |\Delta| \, e^{i\phi_\Delta}$$

$$\phi_\Delta = {\rm Arg} \left(1 + \frac{C^{LL}_{bs}}{R^{\rm loop}_{\rm SM}} \right)$$

$$\boxed{A^{\rm mix}_{\rm CP}(B_s \to J/\psi \phi) = \sin \left(\phi_\Delta - 2\beta_s \right)}$$

$A^{\rm mix}_{\rm CP} = -0.021 \pm 0.031$ [HFLAV 1612.07233]

$\beta_s = 0.01852 \pm 0.00032$ [CKMFitter]



[LDL, Kirk, Lenz, work in progress]

CP violation in mixing <u>limits</u> imaginary part

How to fit the ΔM_s "discrepancy"

1) Complex couplings

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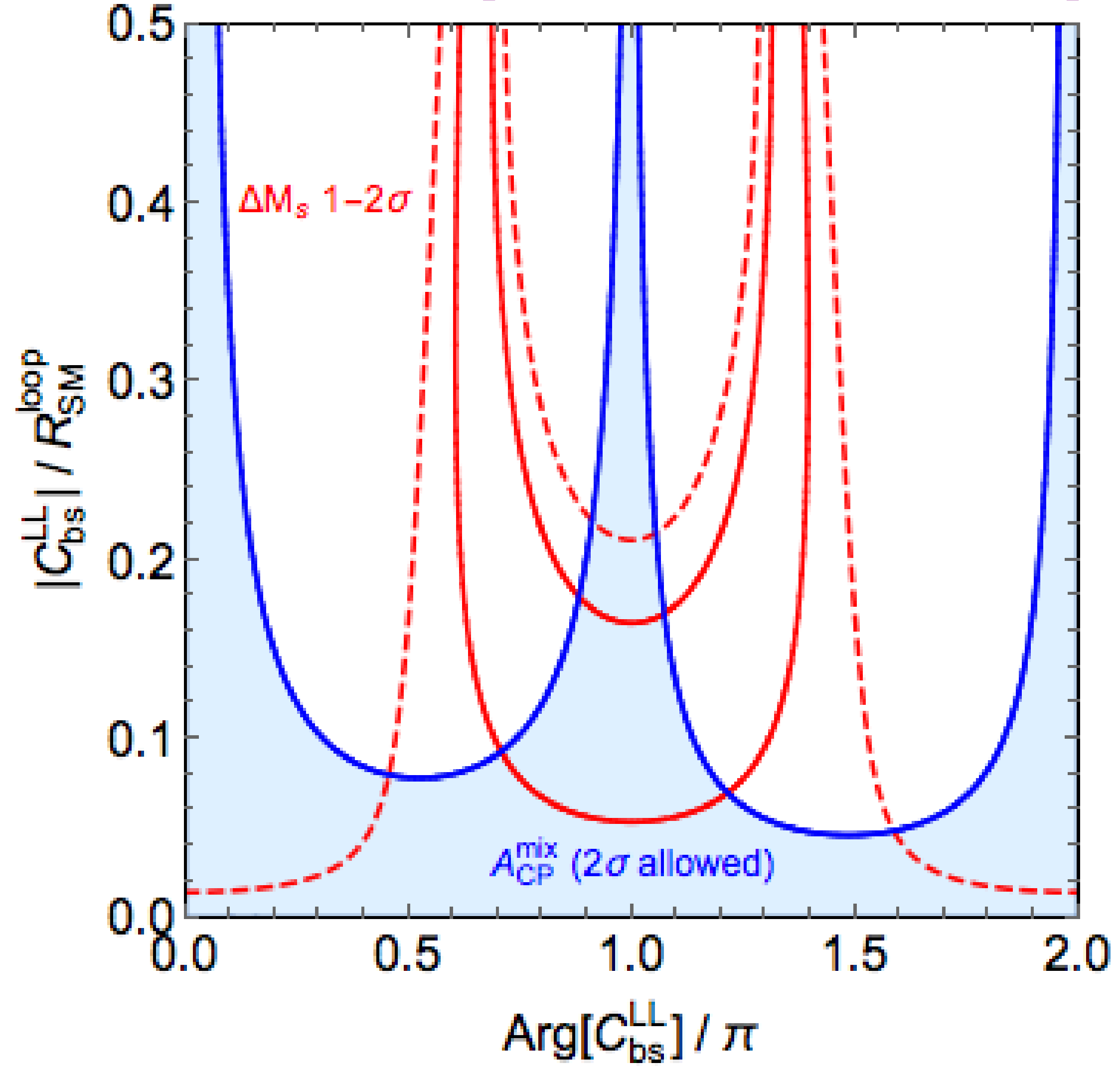
Need new phases close to maximal

$$\text{Arg}(\lambda_{bs}^Q) \sim \pi/2$$

not directly connected to $R(K^{(*)})$

[LDL, Kirk, Lenz 1712.06572]



Interesting option:
in UV compete models of vector leptoquark ($R(K^{(*)})$ + $R(D^{(*)})$) extra Z'/G' states can naturally (compatibly with a U(2) spurion analysis) accommodate that

[Bordone, Cornella, Fuentes-Martin, Isidori 1805.09328]

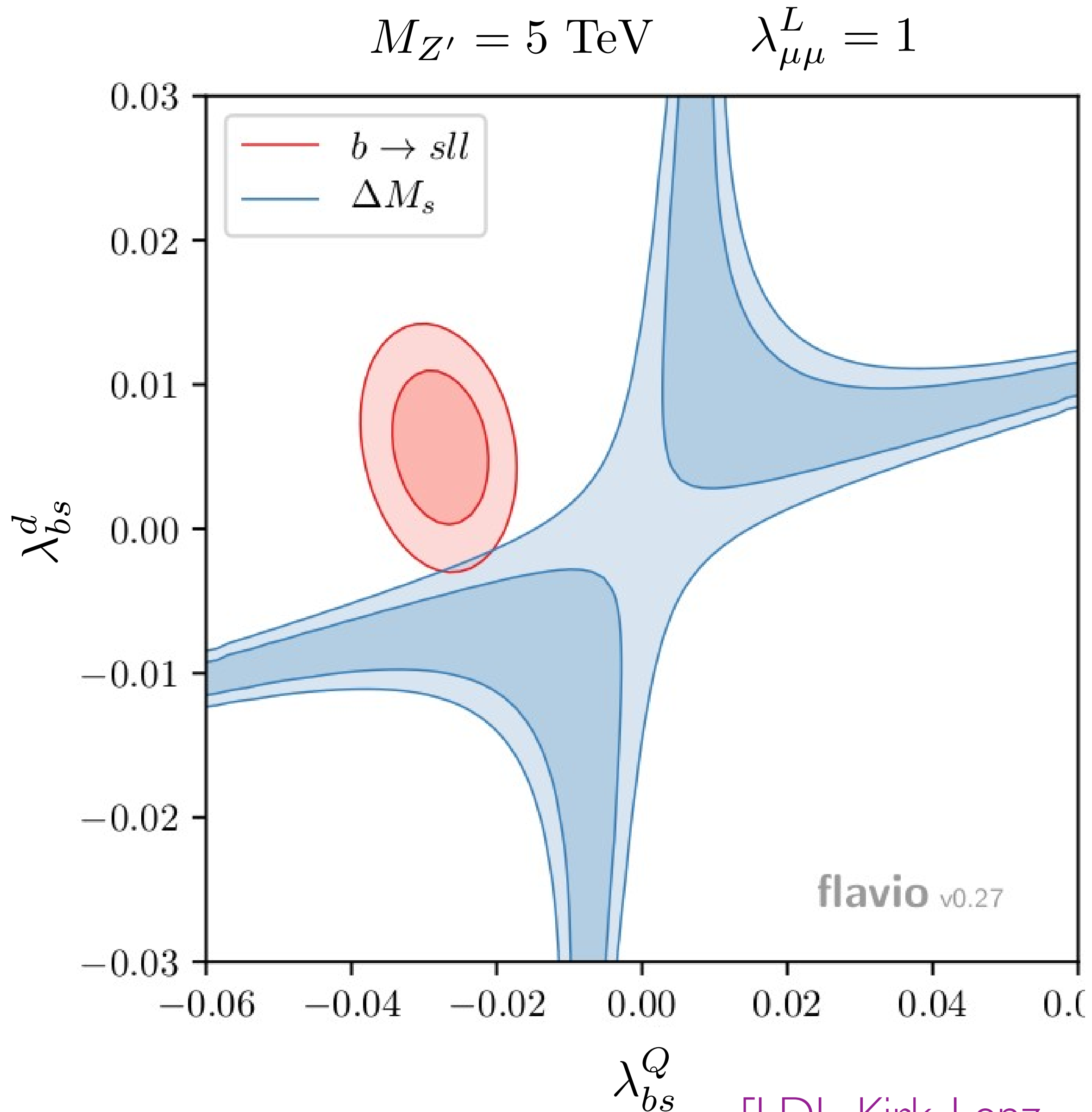
How to fit the ΔM$_s$ "discrepancy"

1) Complex couplings

2) RH currents contamination

$$\mathcal{L}_{Z'} \supset \tfrac{1}{2} M_{Z'}^2 (Z'_\mu)^2 + \left(\lambda^Q_{ij}\, \bar{d}^i_L \gamma^\mu d^j_L + \lambda^d_{ij}\, \bar{d}^i_R \gamma^\mu d^j_R \right) Z'_\mu$$

$$\mathcal{L}^{\rm eff}_{Z'} \supset -\frac{1}{2M_{Z'}^2} \Big[(\lambda^Q_{23})^2 \, (\bar{s}_L \gamma_\mu b_L)^2 + (\lambda^d_{23})^2 \, (\bar{s}_R \gamma_\mu b_R)^2 + 2\lambda^Q_{23}\lambda^d_{23} (\bar{s}_L \gamma_\mu b_L)(\bar{s}_R \gamma_\mu b_R) + \text{h.c.} \Big]$$



[LDL, Kirk, Lenz, work in progress]

How to fit the ΔM$_s$ "discrepancy"

1) Complex couplings

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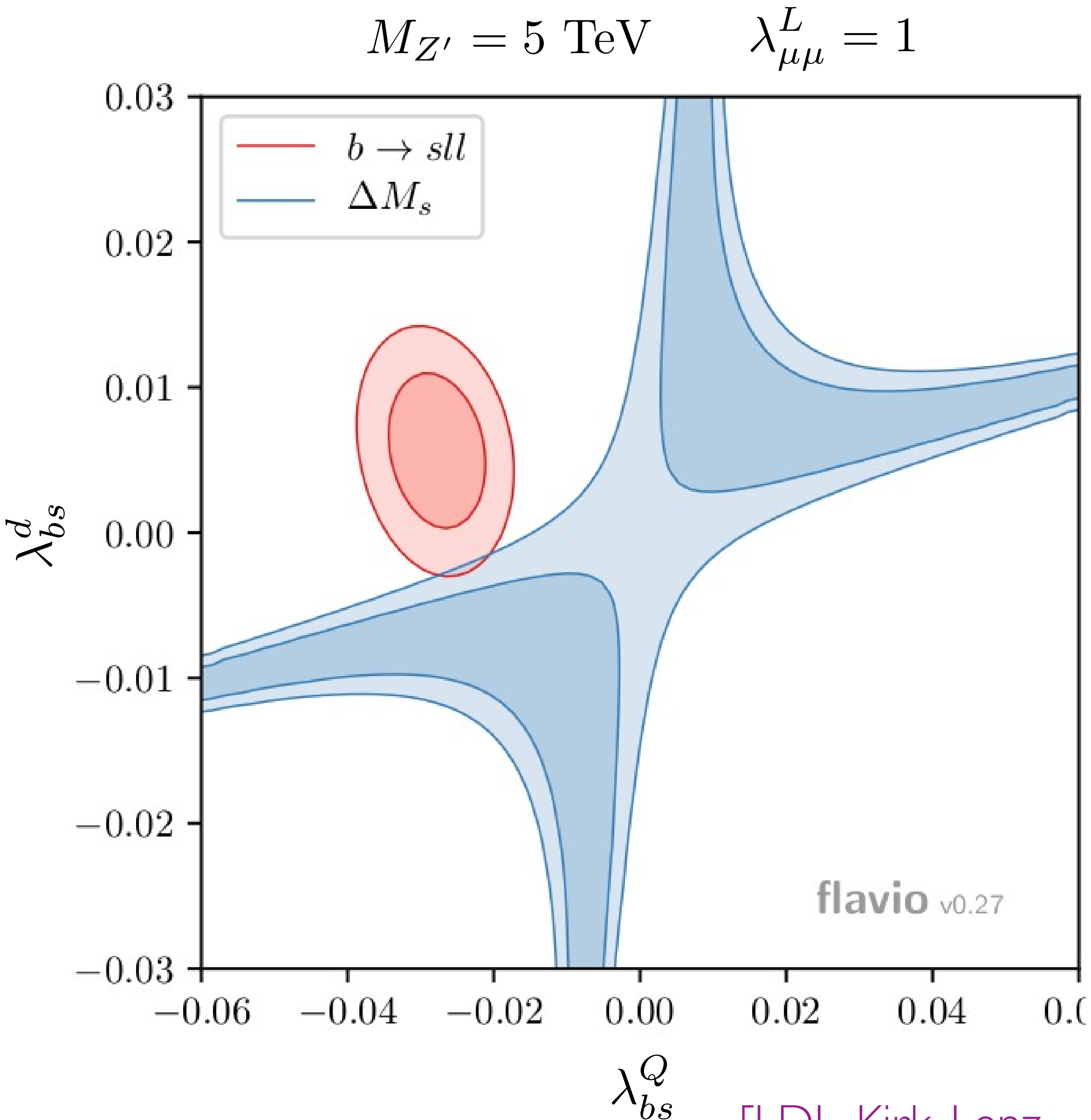
LR operator can have any sign
and gets RG enhanced

However RH quark currents worsen
the fit of neutral current anomalies



[LDL, Kirk, Lenz, work in progress]

Conclusions

1. ΔM_s is a powerful test of the SM

2. If new physics in $b \to s \ell \ell$ natural to expect a deviation in ΔM_s

→ Looking forward for Lattice / HQET-SR updates !

Backup slides

Input parameters

Parameter	Value	Reference
M_W	80.385(15) GeV	PDG 2017
G_F	$1.1663787(6)10^{-5}$ GeV^{-2}	PDG 2017
$\hbar$	$6.582119514(40)10^{-25}$ GeV s	PDG 2017
M_{B_s}	5.36689(19) GeV	PDG 2017
m_t	173.1(0.6) GeV	PDG 2017
$\bar{m}_t(\bar{m}_t)$	165.65(57) GeV	own evaluation
$\bar{m}_b(\bar{m}_b)$	4.203(25) GeV	NRSR
$\alpha_s(M_Z)$	0.1181(11)	PDG 2017
$\alpha_s(\overline{m}_b)$	0.2246(21)	own evaluation
$\Lambda^{(5)}$	0.2259(68) GeV	own evaluation
V_{us}	$0.22508^{+0.00030}_{-0.00028}$	CKMfitter
V_{cb}	$0.04181^{+0.00028}_{-0.00060}$	CKMfitter
$\lvert V_{ub}/V_{cb}\rvert$	0.0889(14)	CKMfitter
γ_{CKM}	$1.141^{+0.017}_{-0.020}$	CKMfitter
$f_{B_s}\sqrt{\hat{B}}$	274(8) MeV	FLAG

[LDL, Kirk, Lenz 1712.06572]

Error budget

ΔM_s^{SM}	This work	ABL 2015 [65]	LN 2011 [66]	LN 2006 [119]
Central Value	$20.01\,\mathrm{ps}^{-1}$	$18.3\,\mathrm{ps}^{-1}$	$17.3\,\mathrm{ps}^{-1}$	$19.3\,\mathrm{ps}^{-1}$
$\delta(f_{B_s}\sqrt{B})$	5.8%	13.9%	13.5%	34.1%
$\delta(V_{cb})$	2.1%	4.9%	3.4%	4.9%
$\delta(m_t)$	0.7%	0.7%	1.1%	1.8%
$\delta(\alpha_s)$	0.1%	0.1%	0.4%	2.0%
$\delta(\gamma_{\mathrm{CKM}})$	0.1%	0.1%	0.3%	1.0%
$\delta(\lvert V_{ub}/V_{cb}\rvert)$	$< 0.1\%$	0.1%	0.2%	0.5%
$\delta(\overline{m}_b)$	$< 0.1\%$	$< 0.1\%$	0.1%	$---$
$\sum \delta$	6.2%	14.8%	14.0%	34.6%

[LDL, Kirk, Lenz 1712.06572]

Scalar LQ

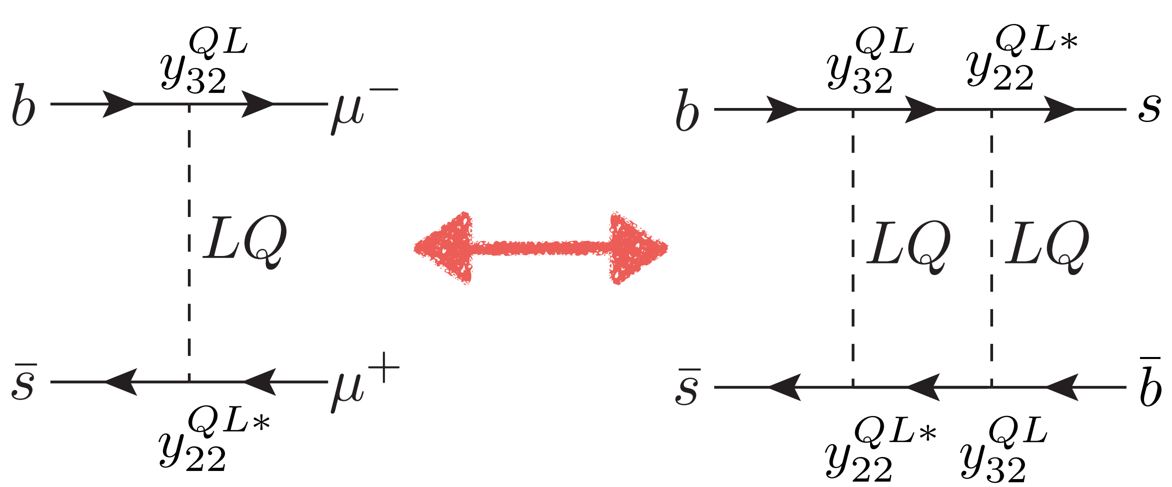
- $S_3 \sim (\bar{3}, 3, 1/3)$

$$\mathcal{L}_{S_3} = -M_{S_3}^2 |S_3^a|^2 + y_{i\alpha}^{QL} \overline{Q^c}^i (\epsilon \sigma^a) L^\alpha \, S_3^a$$

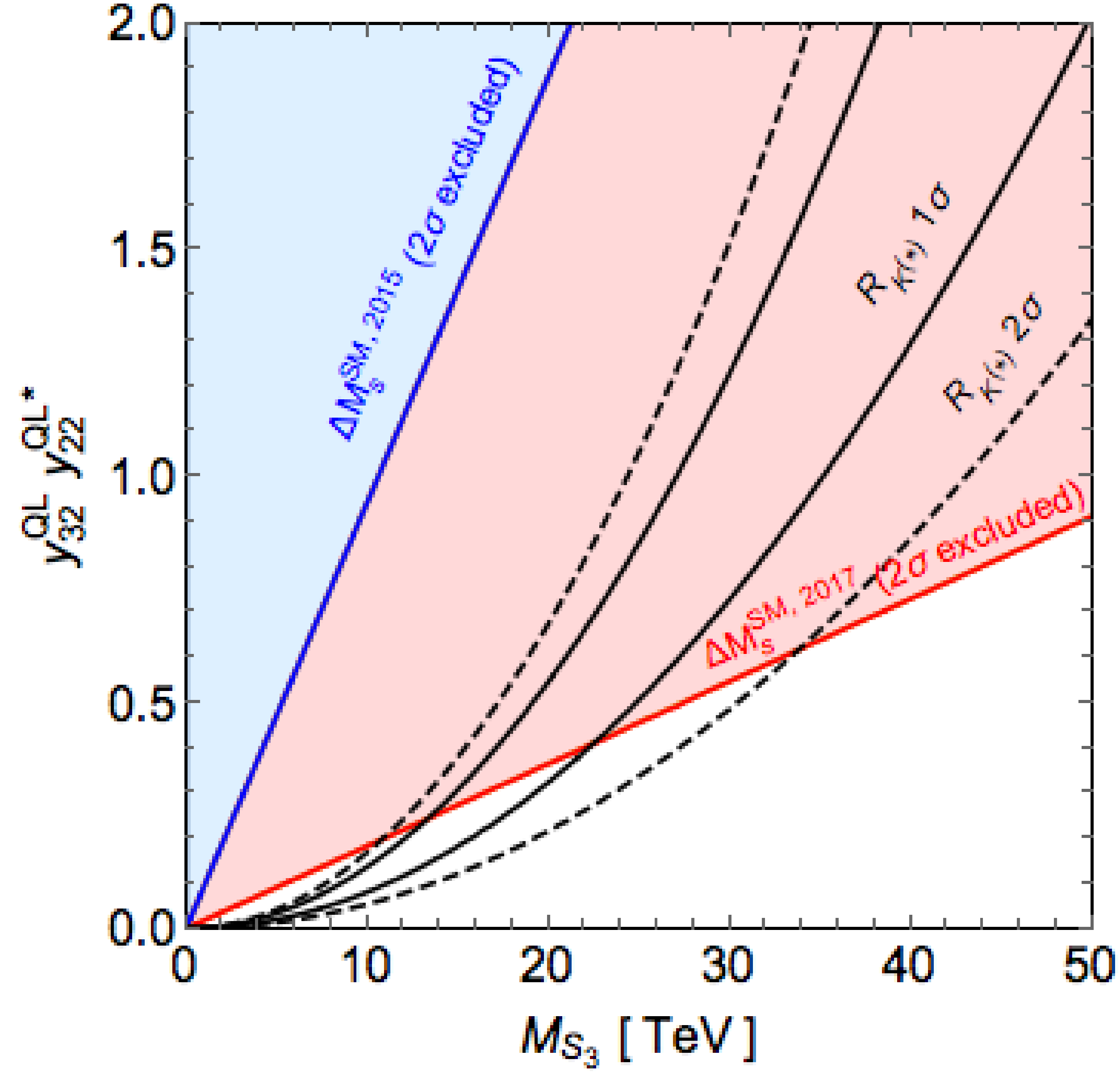
$$\delta C_9^\mu = -\delta C_{10}^\mu = \frac{\pi}{\sqrt{2} G_F M_{S_3}^2 \alpha} \left(\frac{y_{32}^{QL} y_{22}^{QL*}}{V_{tb} V_{ts}^*} \right)$$

$$C_{bs}^{LL} = \frac{1}{4\sqrt{2} G_F M_{S_3}^2} \frac{5}{64\pi^2} \left(\frac{y_{3\alpha}^{QL} y_{2\alpha}^{QL*}}{V_{tb} V_{ts}^*} \right)^2$$

Connection is "more direct" (compared to Z'), but bounds are weaker



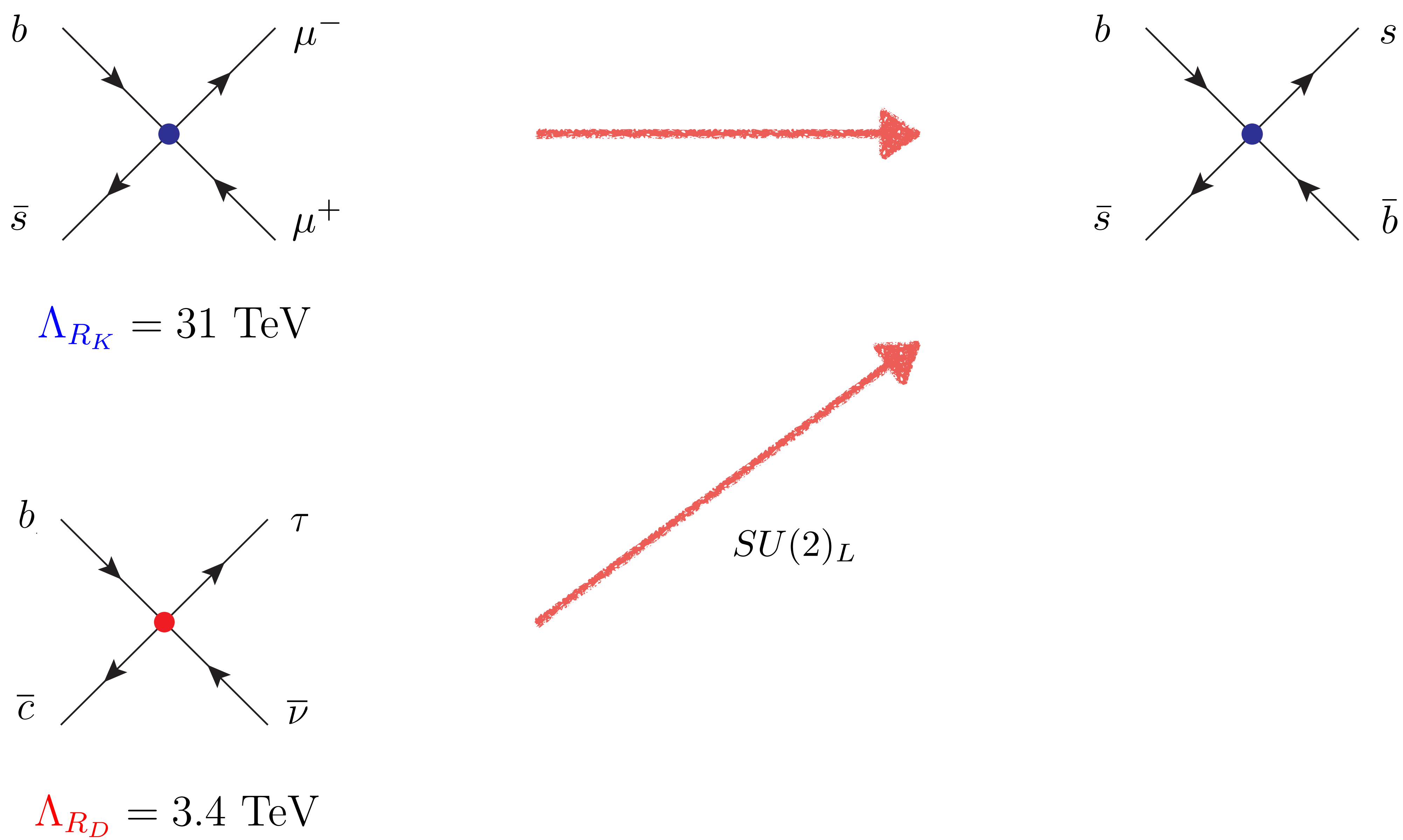
[LDL, Kirk, Lenz 1712.06572]



$M_{S_3} \gtrsim 900$ GeV [CMS 1703.03995]

Charged currents

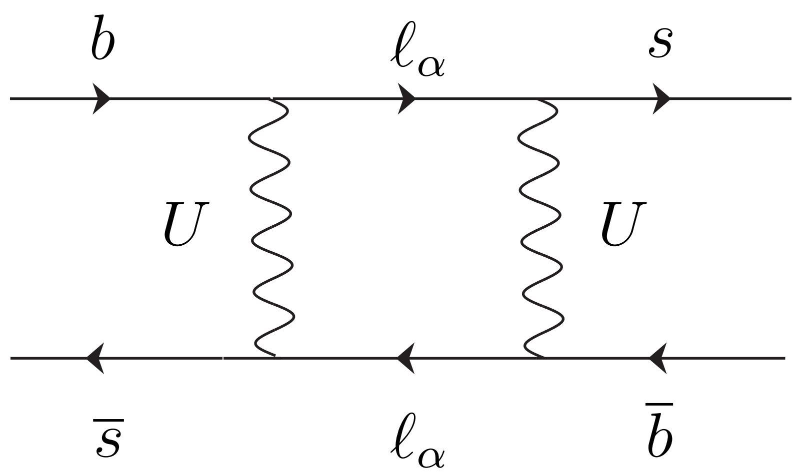
- Connection between R(D$^{(*)}$) and ΔM_s in presence of an $SU(2)_L$ triplet op.



Vector LQ [UV complete]

- FCNC @ 1-loop under control

[LDL, Fuentes-Martin, Greljo, Nardecchia, Renner 1808.00942]



$$\mathcal{H}_{\text{eff}}^{\text{NP}} = -\frac{g_4^4}{128\pi^2 m_U^2} \left(\bar{b}_L \gamma^\mu s_L\right) \left(\bar{b}_L \gamma_\mu s_L\right) \sum_{\alpha,\,\beta} \lambda_\alpha \lambda_\beta F(x_\alpha, x_\beta)$$

$$\lambda_\alpha = (\mathcal{V}^\dagger)^*_{\alpha b} \mathcal{V}^\dagger_{\alpha s} \qquad x_\alpha = m_\alpha^2 / M_U^2$$

$\sum_\alpha \lambda_\alpha = 0$ ensures cancellation of quadratic divergencies + GIM-like suppression

$F(x_\alpha, x_\beta) \simeq \cancel{1} + x_\alpha + x_\beta + \ldots$ → light lepton partners welcomed !

$C_{bs}^{LL} \sim \Delta R^2_{D^{(*)}} M_U^2$ → $C_{bs}^{LL} \sim \Delta R^2_{D^{(*)}} M_L^2$

↓

in absence of GIM protection

Vector LQ [UV complete]

- FCNC @ 1-loop under control

[LDL, Fuentes-Martin, Greljo, Nardecchia, Renner 1808.00942]