

Malaphoric Z' Model

by
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$$b \rightarrow sl^+l^-$$

$B_3 - L_2$ model

Kinetic Mixing

BCA, Gubernari, 2409.06804



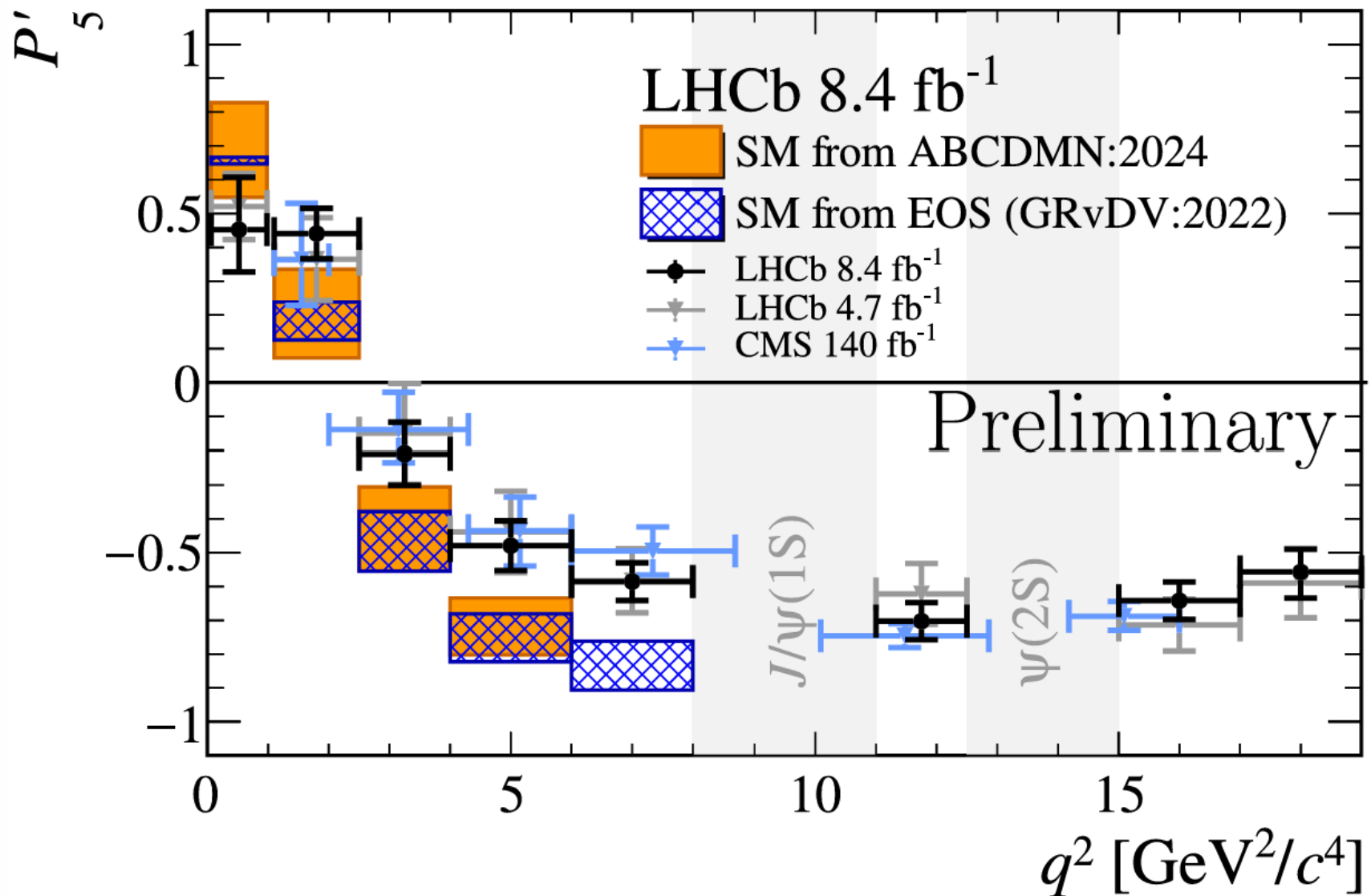


IPPP Benefits

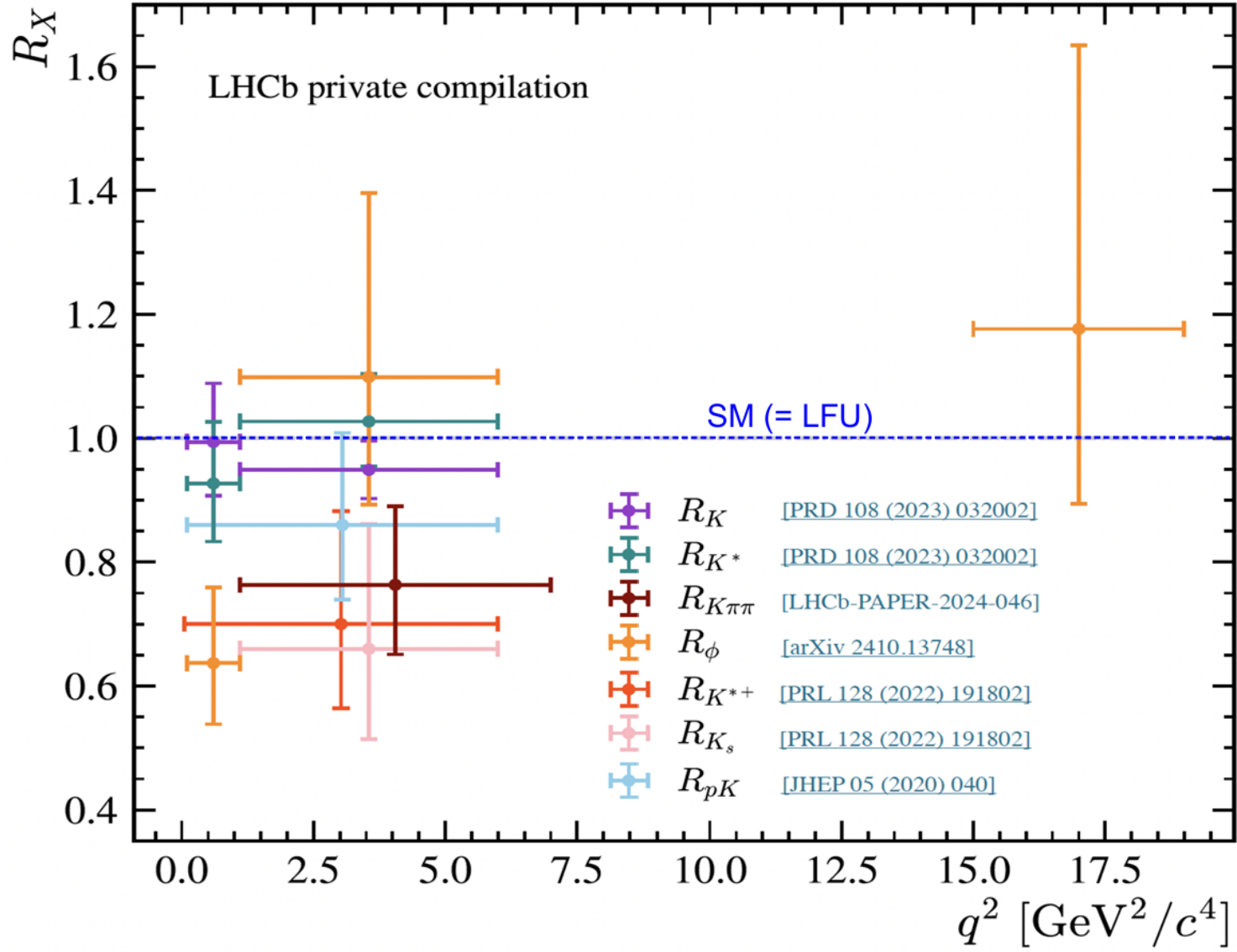
- 2005-2009 IPPP Steering Committee
- 2010-2011 IPPP Associateship
- 2004ish+ Annual Theory Meeting
- Sending students to YETI
- Thank you!



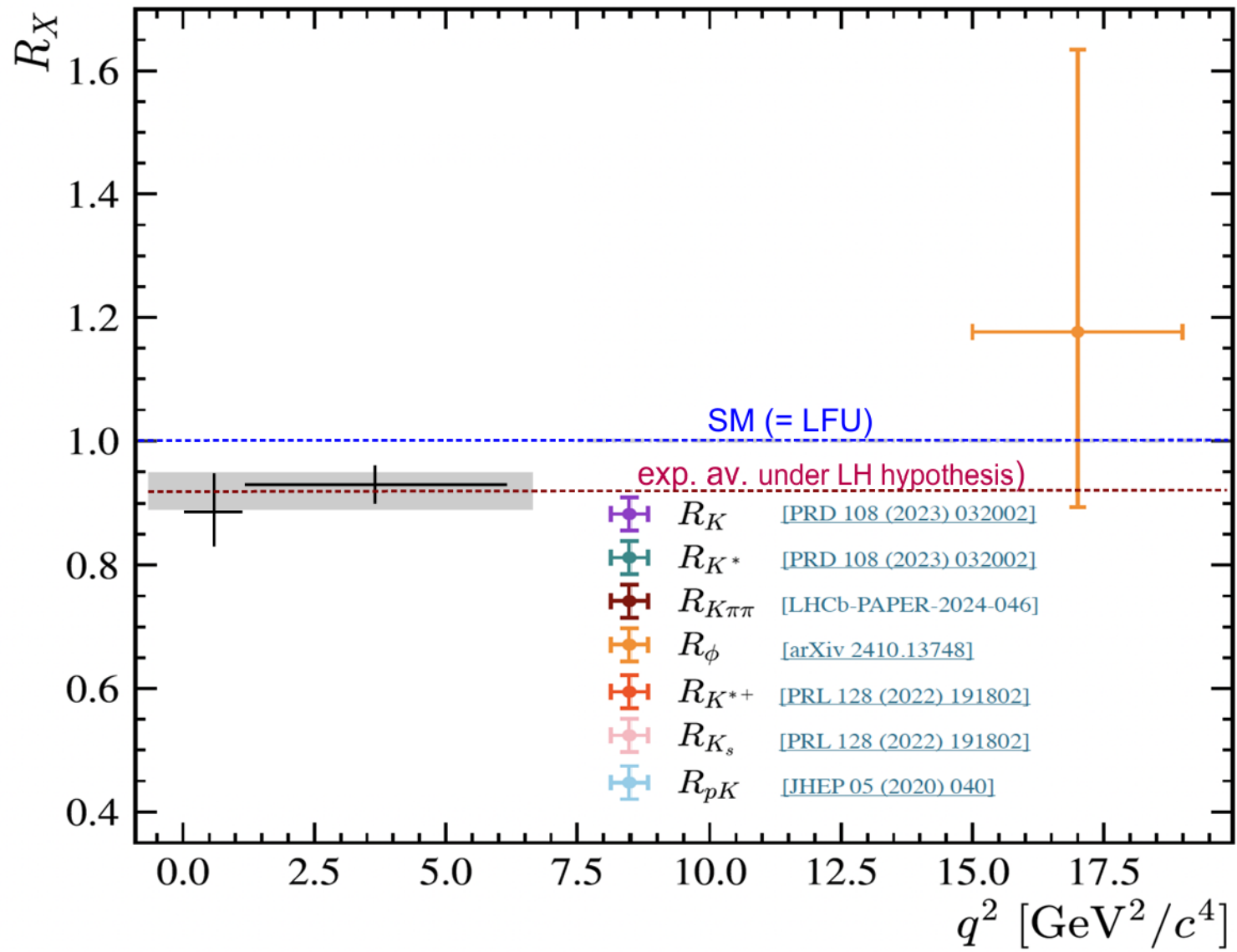
$$P'_5 = S_5 / \sqrt{F_L(1 - F_L)}$$



$$R_X = BR(B \rightarrow X\mu^+\mu^-)/BR(B \rightarrow Xe^+e^-)$$



Thanks to G Isidori



$B_3 - L_2$ model

SM-singlet scalar ‘flavon’ θ

Additional $U(1)_X$ gauge symmetry broken by $\langle \theta \rangle \sim \text{TeV} \Rightarrow M_X = g_X X_\theta \langle \theta \rangle \sim \mathcal{O}(\text{TeV})$

SM+ $3\nu_R$ fermion content

Zero charges for first two generations of quark

$X = B_3 - L_2$ postdicts some small CKM¹;
 $X_\mu \leftrightarrow$ propagating Z'

¹Bonilla *et al*, 1705.00915;
2009.02197 (*simplified EFT*)

Alonso *et al* 1705.03858,

BCA

Some Family Structure

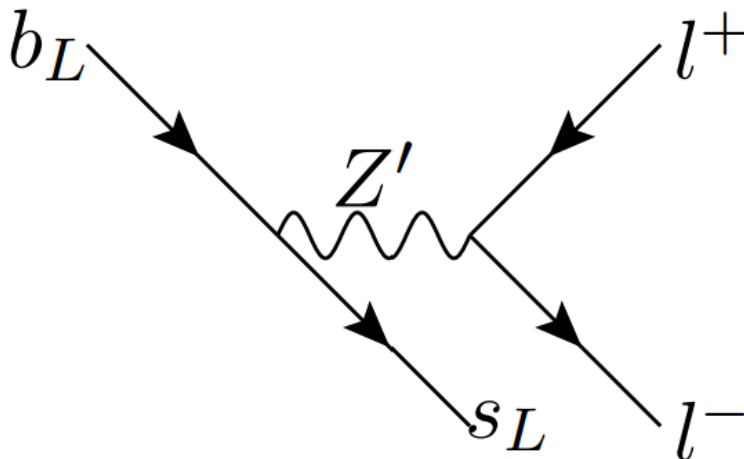
$$Y_u \sim \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & \times \end{pmatrix}, \quad Y_d \sim \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & \times \end{pmatrix},$$

Postdicts CKM angles $|V_{cb}|$, $|V_{ub}|$, $|V_{ts}|$,
 $|V_{td}|$ to be small

Important X Couplings

$$g_{Z'} \left[(\overline{d_L} \ \overline{s_L} \ \overline{b_L}) \begin{pmatrix} 0 & 0 & 0 \\ 0 & \sin^2 \theta_{sb} & \frac{1}{2} \sin 2\theta_{sb} \\ 0 & \frac{1}{2} \sin 2\theta_{sb} & \cos^2 \theta_{sb} \end{pmatrix} \not{X} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} \right.$$

$$\left. - (\overline{e} \ \overline{\mu} \ \overline{\tau}) \begin{pmatrix} 0 & 0 & 0 \\ 0 & \mathbf{3} & 0 \\ 0 & 0 & 0 \end{pmatrix} \not{X} \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix} \right]$$



– LFU Violating? $C_9 \neq 0$

Kinetic Mixing

BCA, Gubernari 2409.06804

This will induce a **family independent** component to the Z' couplings

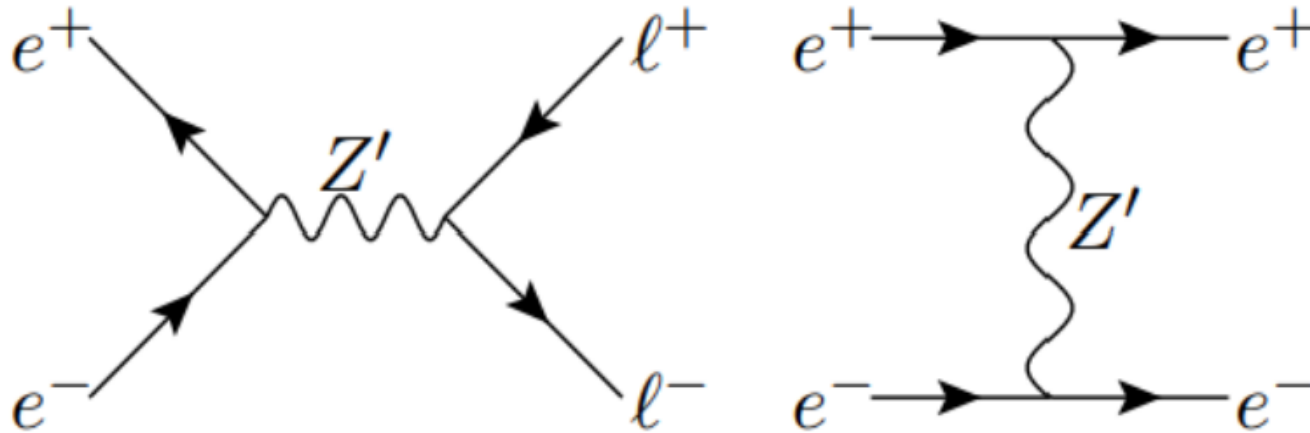
$$J^\mu = g_X \sum_{\psi'} X_{\psi'} \bar{\psi}' \gamma^\mu \psi',$$

$$j_\mu = ig' Y_H [H^\dagger D_\mu H - (D_\mu H)^\dagger H] + g' \sum_{\psi'} Y_\psi \bar{\psi}' \gamma_\mu \psi'.$$

$$\mathcal{L}_{XB} = -\frac{\epsilon}{2} B_{\mu\nu} X^{\mu\nu} - X_\mu J^\mu - B_\mu j^\mu.$$

LEP constraints

BCA, Mullin, 2306.08669



SMEFT contributions: C_{ee}^{11ii} , C_{ll}^{11ii} , C_{le}^{1ii1}

Code into flavio (cf Falkowski, Mimouni 1511.07434): 148 LEP2 bins, σ , A_{FB}

Global Fit

Observables: 306 quarks, 31 EWPOs, 148 LEP2, 24 LFU

$$\hat{\epsilon} := \epsilon \frac{3 \text{ TeV}}{M_X}, \quad \hat{g}_X := g_X \frac{3 \text{ TeV}}{M_X}.$$

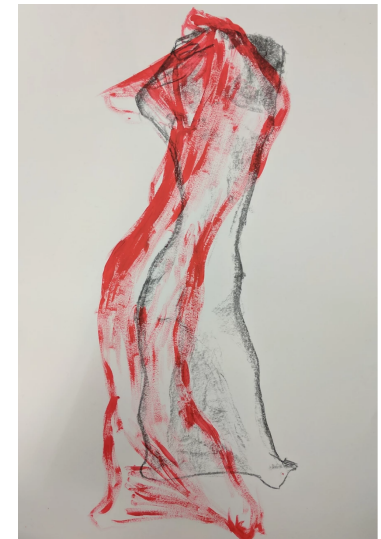
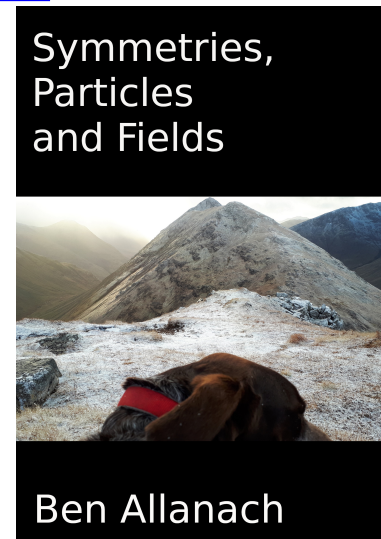
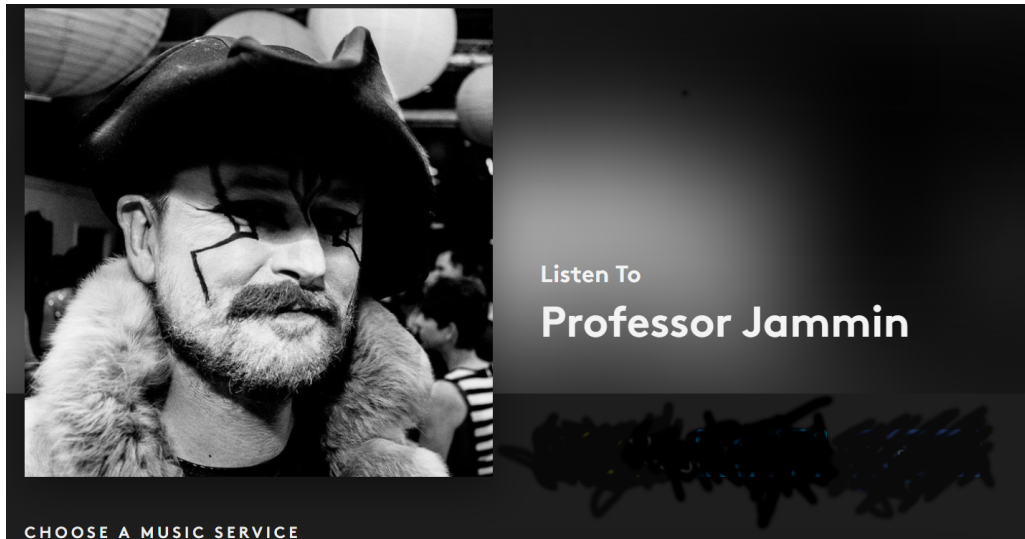
$\hat{\epsilon}$	$\hat{g}_X$	θ_{sb}	$\Delta\chi^2_{\text{quarks}}$	$\Delta\chi^2_{\text{EWPO}}$	$\Delta\chi^2_{\text{LEP2}}$	$\Delta\chi^2_{\text{LFU}}$	$\Delta\chi^2_{\text{global}}$
0	0.082	-0.11	36.2	0.0	0.00	-3.8	32.8
-0.86	0.048	-0.19	40.1	-0.4	-0.02	0.8	40.1

Epilogue

Calculated SMEFT coefficients for kinetically-mixed Z' models cf Dawson, Forslund, Schnubel 2404.01375

Improves fit of $B_3 - L_2$ model.

Links to my [music](#), [book \(18€\)](#) and [Quantum Selves art](#):



UV Completion

The $B_3 - L_2$ model with kinetic mixing is approximately physically equivalent to an unmixed model with

$$X := B_3 - L_2 + \alpha Y$$

where $\alpha \in \mathbb{Q}$ is chosen appropriately.

smelli

Aebischer, Kumar, Stangl, Straub, 1810.

Input: SMEFT coefficients C_i/Λ^2 .

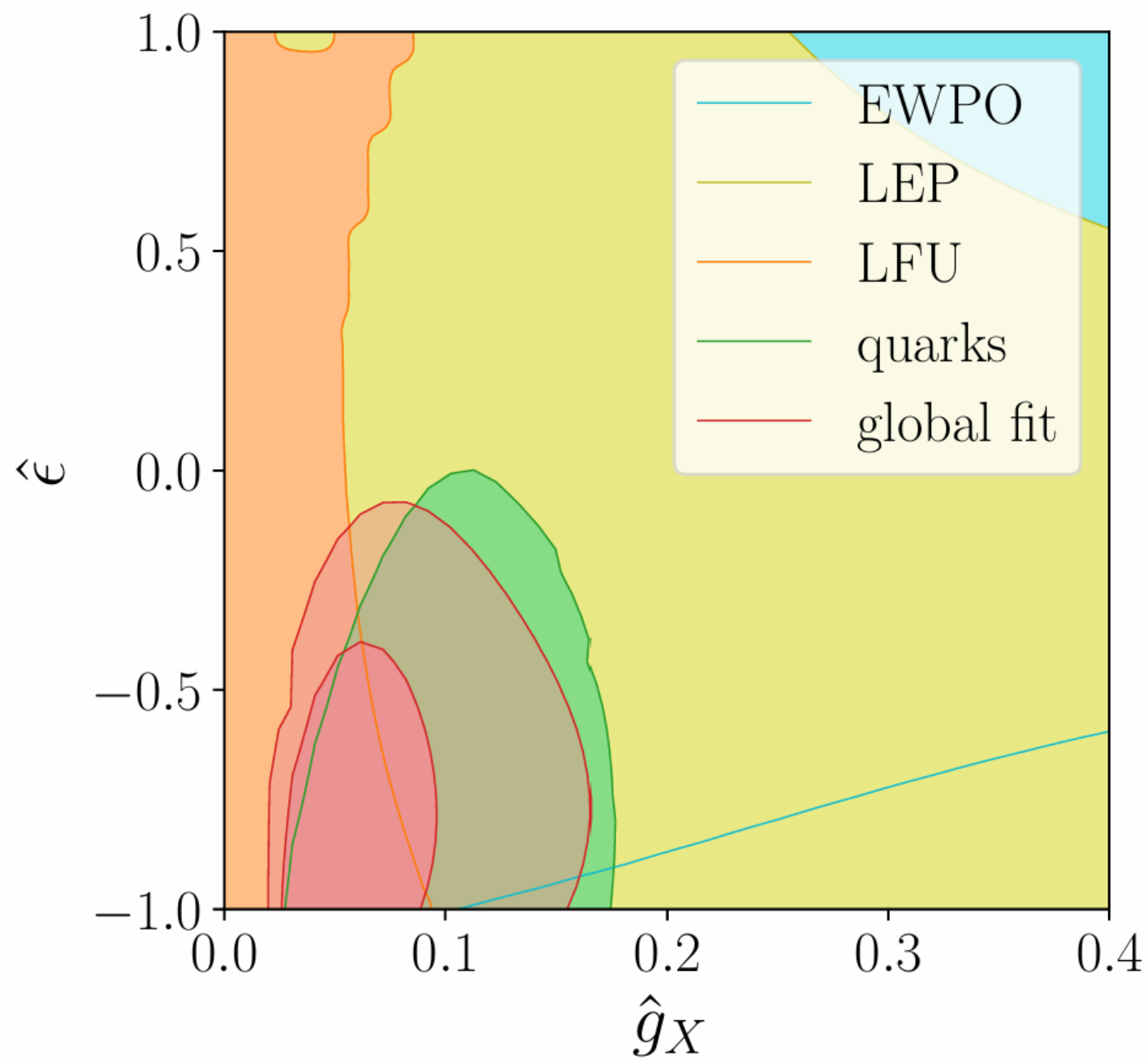
Output: χ^2

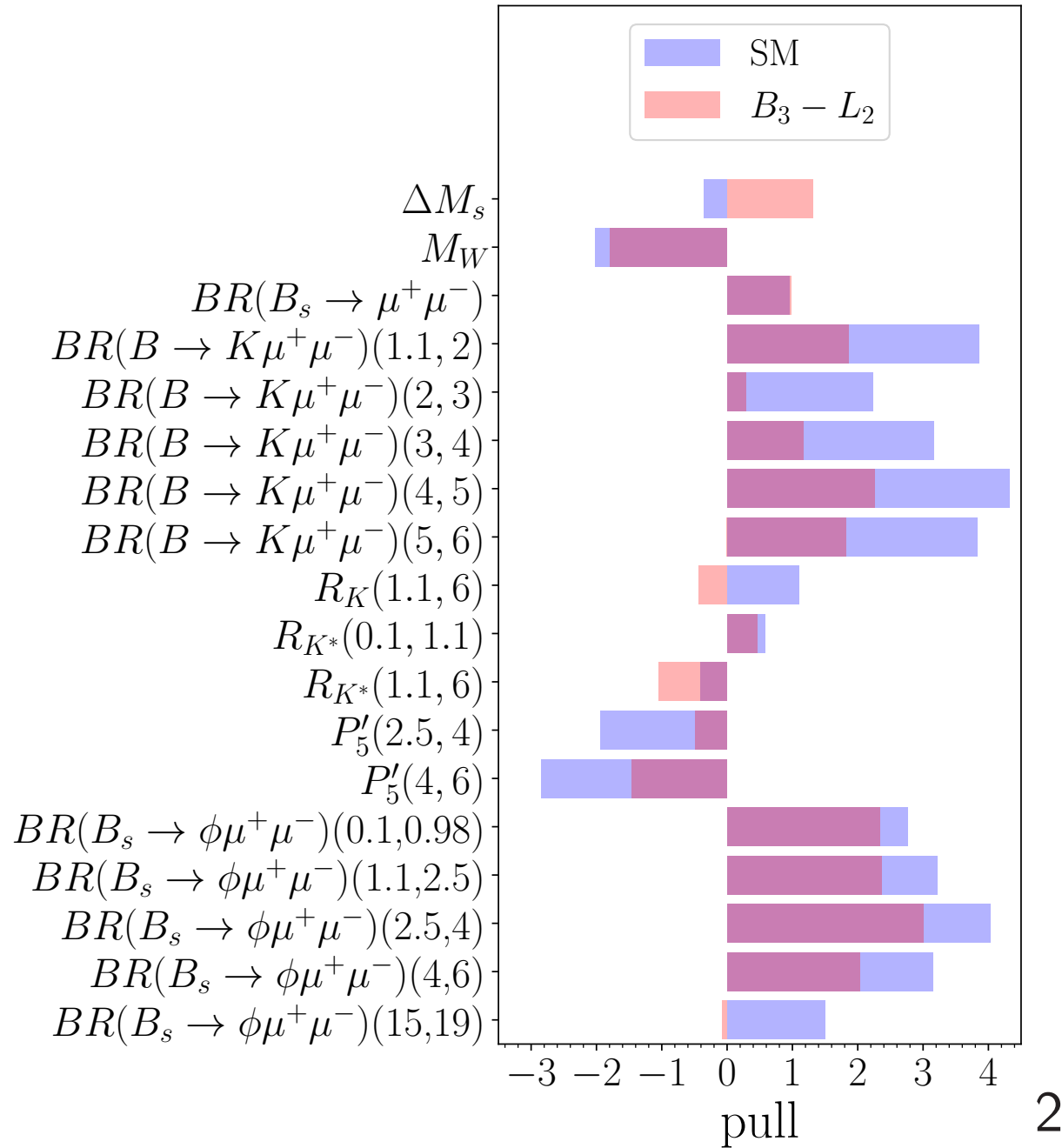
Hundreds of B —observables

31 EWPOs

Integrate out heavy X_μ

$$\begin{aligned}\mathcal{L}_6 &= -\frac{1}{2M_X^2} J_\mu J^\mu - \frac{\epsilon}{M_X^2} (\partial_\nu B^{\mu\nu}) J_\mu \\ &\quad - \frac{\epsilon^2}{2M_X^2} (\partial_\nu B^{\mu\nu}) (\partial^\rho B_{\mu\rho}) \\ &= -\frac{1}{2M_X^2} (J_\mu - \epsilon j_\mu) (J^\mu - \epsilon j^\mu)\end{aligned}$$

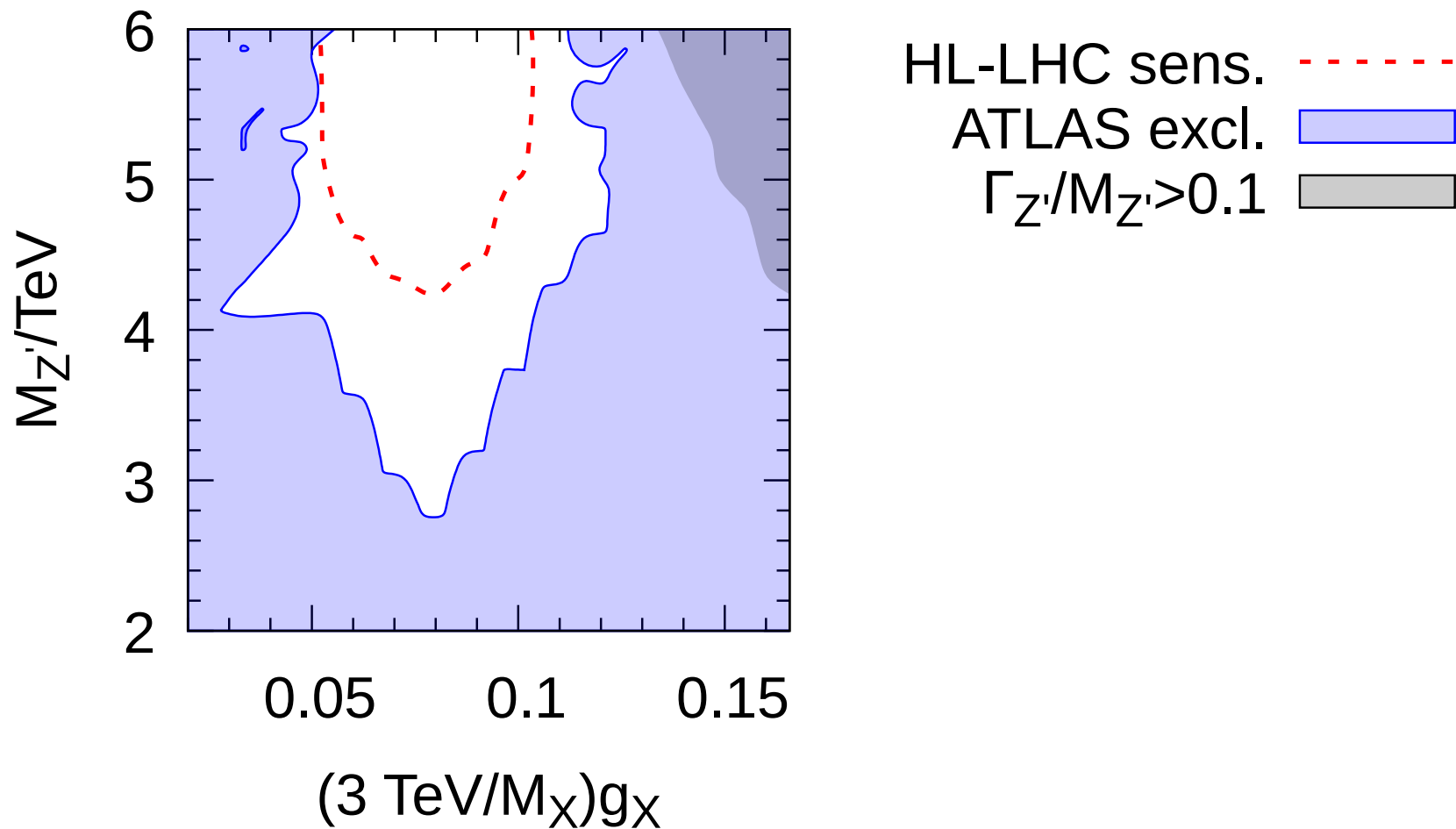




2

²pull=(theory-expt cntrl value)/error at best-fit point

BCA, 2412.01956



l^+l^- **ATLAS 13 TeV 139 fb⁻¹**

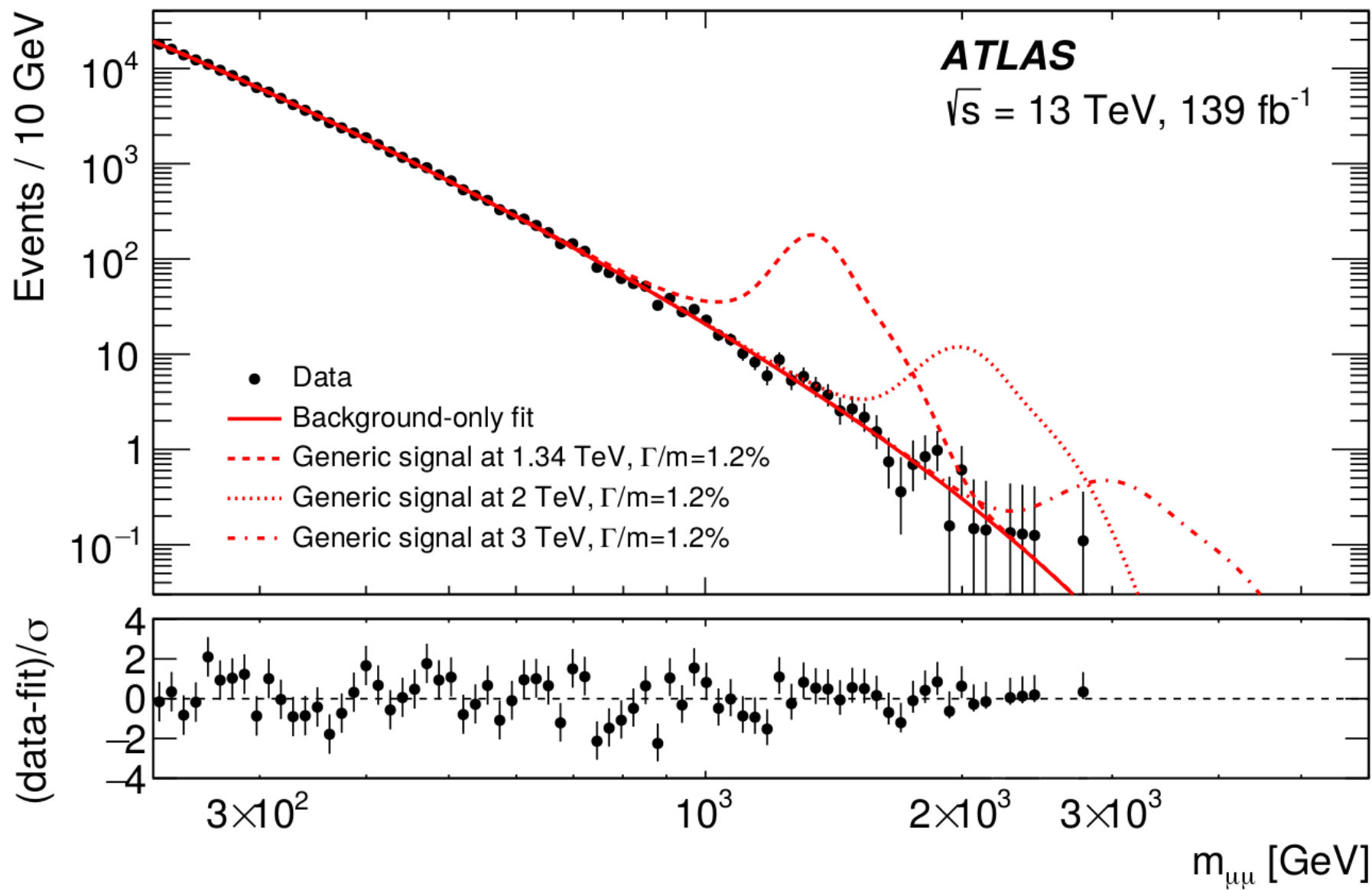
e.g. 2 track-based isolated μ , $p_T > 30$ GeV with reconstructed vertex.³ Only keep pair with highest $(|p_{T_1}| + |p_{T_2}|)$.

$$m_{\mu_1\mu_2}^2 = (p_1^\mu + p_2^\mu) (p_{1\mu} + p_{2\mu})$$

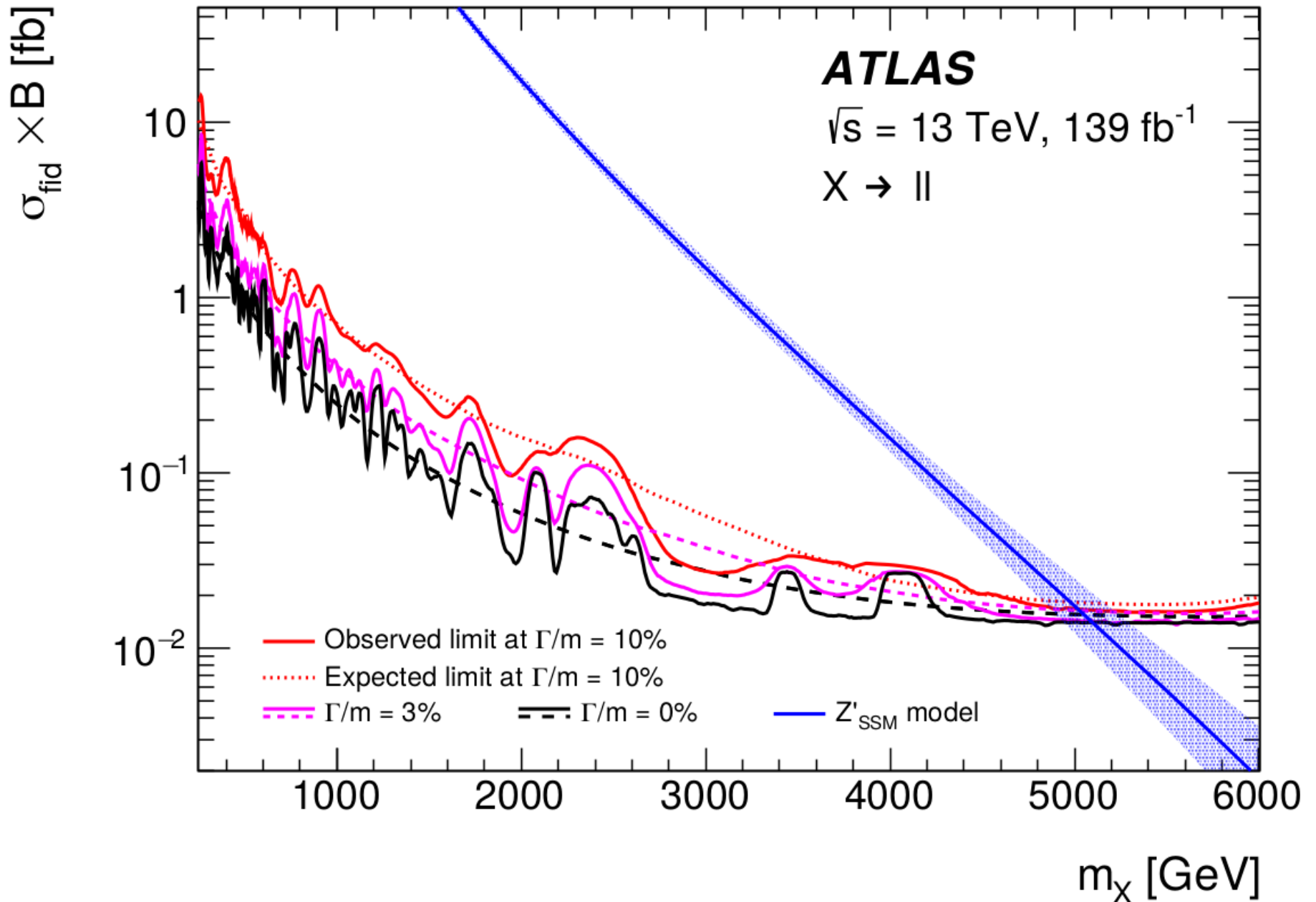
CMS also has a similar analysis⁴

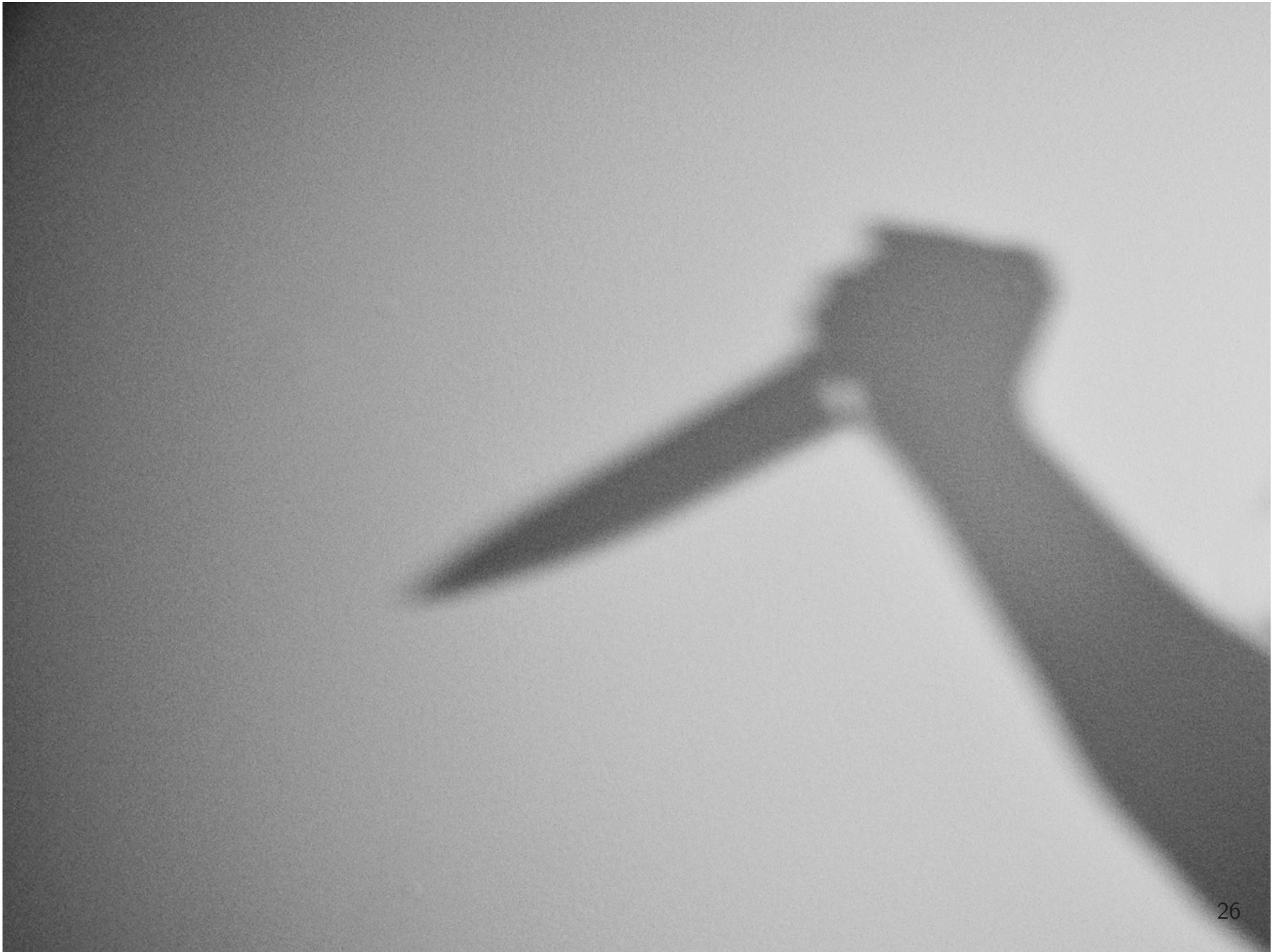
³ATLAS, 1903.06248

⁴CMS, 2103.02708

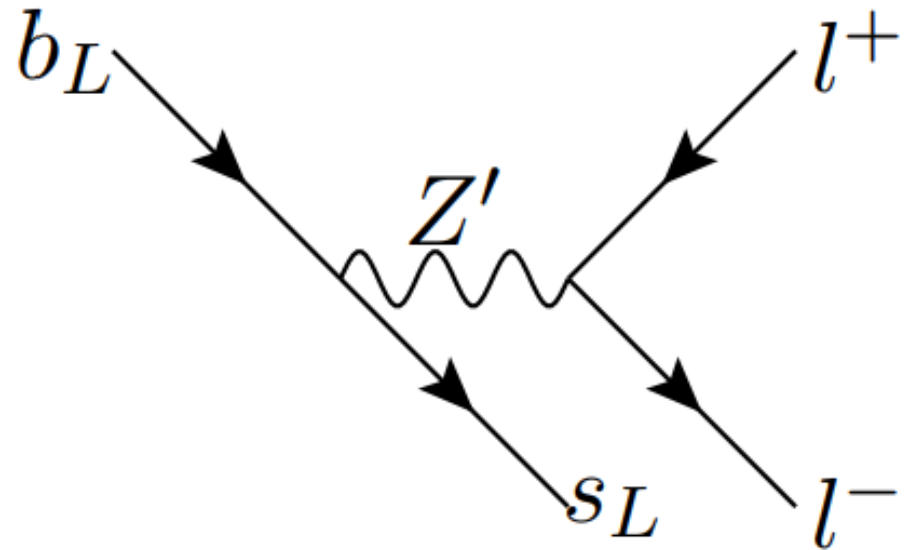
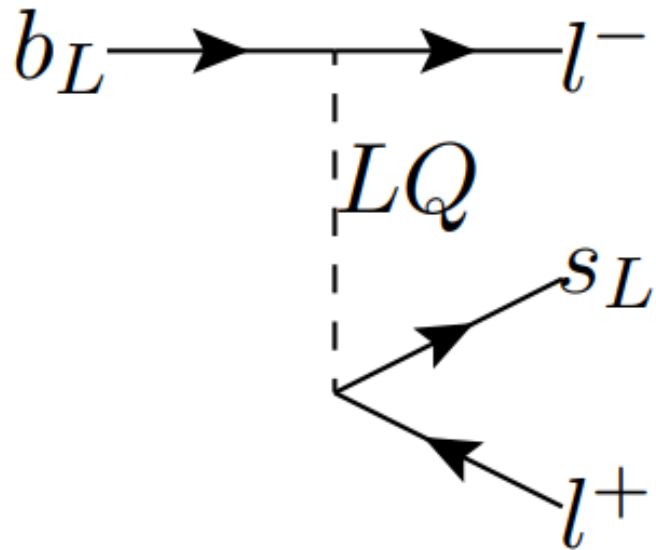


ATLAS l^+l^- limits





Tree-level Explanations



Interferes with Standard Model process

Vector-like Z' option leaves $BR(B_s \rightarrow \mu^+ \mu^-)$ unchanged

smelli

Aebischer, Kumar, Stangl, Straub, 1810.

Input: SMEFT coefficients C_i/Λ^2 .

Output: χ^2

Hundreds of B —observables

31 EWPOs

SMEFT

Parameterises heavy new physics effects

$$\mathcal{L} = \mathcal{L}_{4D} + \sum_{d=5} \sum_i \frac{C_i}{\Lambda^{d-4}} \mathcal{O}.$$

Assumptions:

All BSM fields have mass scale $\Lambda \gg$ scale of observables.

Higgs doublet linearly realises EWSB

Important term

2499 $d = 6$ terms

$$\mathcal{L} = \dots + \frac{(C_{lq}^{(1)})^{2223}}{\Lambda^2} (\overline{L}_2 \gamma_\alpha L_2) (\overline{Q}_2 \gamma^\alpha Q_3)$$

mediates $b \rightarrow s \mu^+ \mu^-$ transitions.

Here, from integrating Z' out:

$$\frac{(C_{lq}^{(1)})^{2223}}{\Lambda^2} = \frac{-3 \sin 2\theta_{sb} g_X^2}{M_X}$$

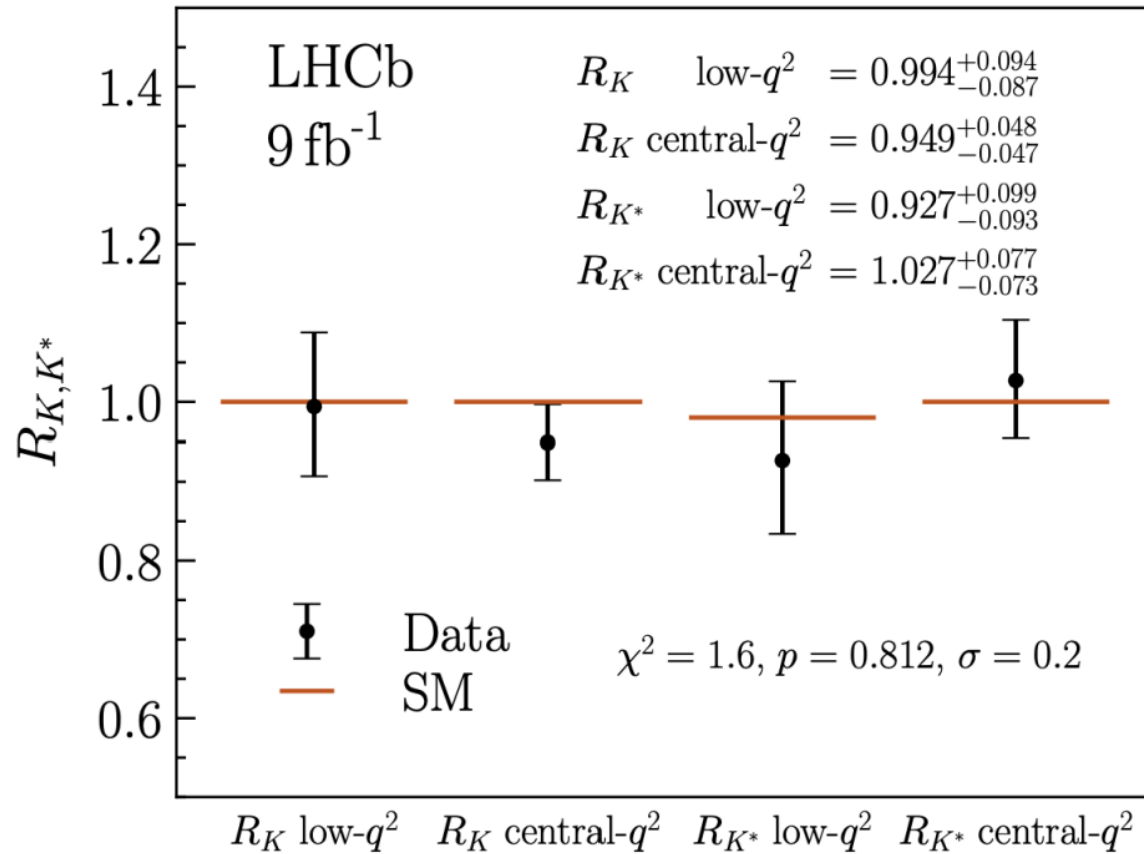
SMEFT WCs / (g_X^2/M_X^2)

BCA, Davighi, 2211.11766

WC	value	WC	value
C_{ll}^{2222}	$-\frac{9}{2}$	$(C_{lq}^{(1)})^{22ij}$	$3\Lambda_{\Xi ij}^{(d_L)}$
$(C_{qq}^{(1)})^{ijkl}$	$\Lambda_{\Xi ij}^{(d_L)} \Lambda_{\Xi kl}^{(d_L)} \frac{\delta_{ik}\delta_{jl}-2}{2}$	C_{ee}^{2222}	$-\frac{9}{2}$
C_{uu}^{3333}	$-\frac{1}{2}$	C_{dd}^{3333}	$-\frac{1}{2}$
C_{eu}^{2233}	3	C_{ed}^{2233}	3
$(C_{ud}^{(1)})^{3333}$	-1	C_{le}^{2222}	-9
C_{lu}^{2233}	3	C_{ld}^{2233}	3
C_{qe}^{ij22}	$3\Lambda_{\Xi ij}^{(d_L)}$	$(C_{qu}^{(1)})^{ij33}$	$-\Lambda_{\Xi ij}^{(d_L)}$
$(C_{qd}^{(1)})^{ij33}$	$-\Lambda_{\Xi ij}^{(d_L)}$		

| wilson | flavio | smelli > output

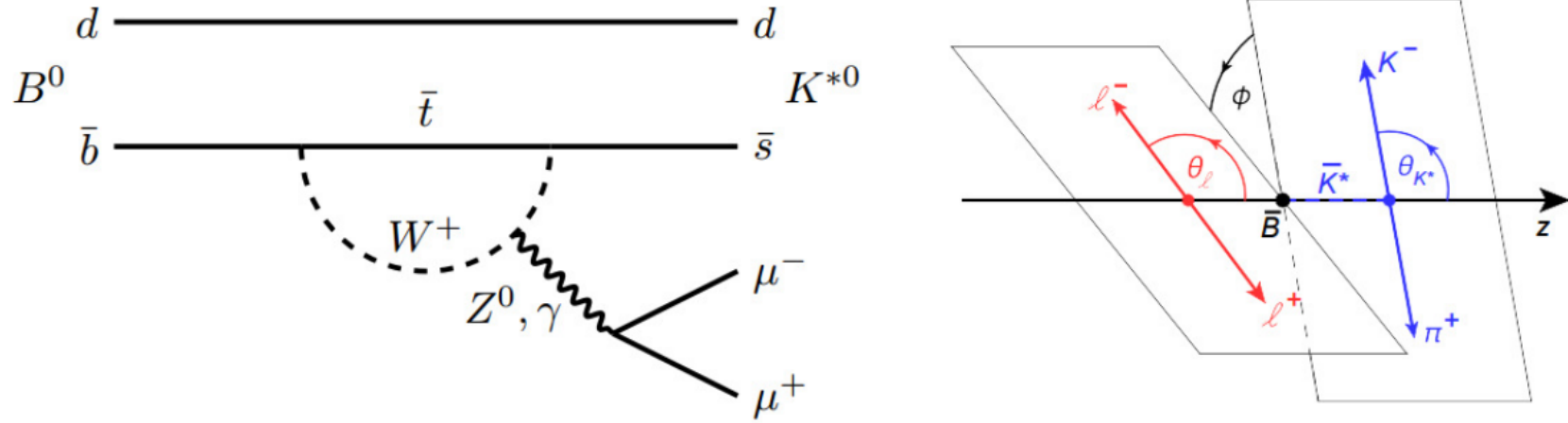
LHCb 2212.09152



$$R_X(q^2) = \frac{BR(B \rightarrow X \mu^+ \mu^-)}{BR(B \rightarrow X e^+ e^-)}(q^2)$$



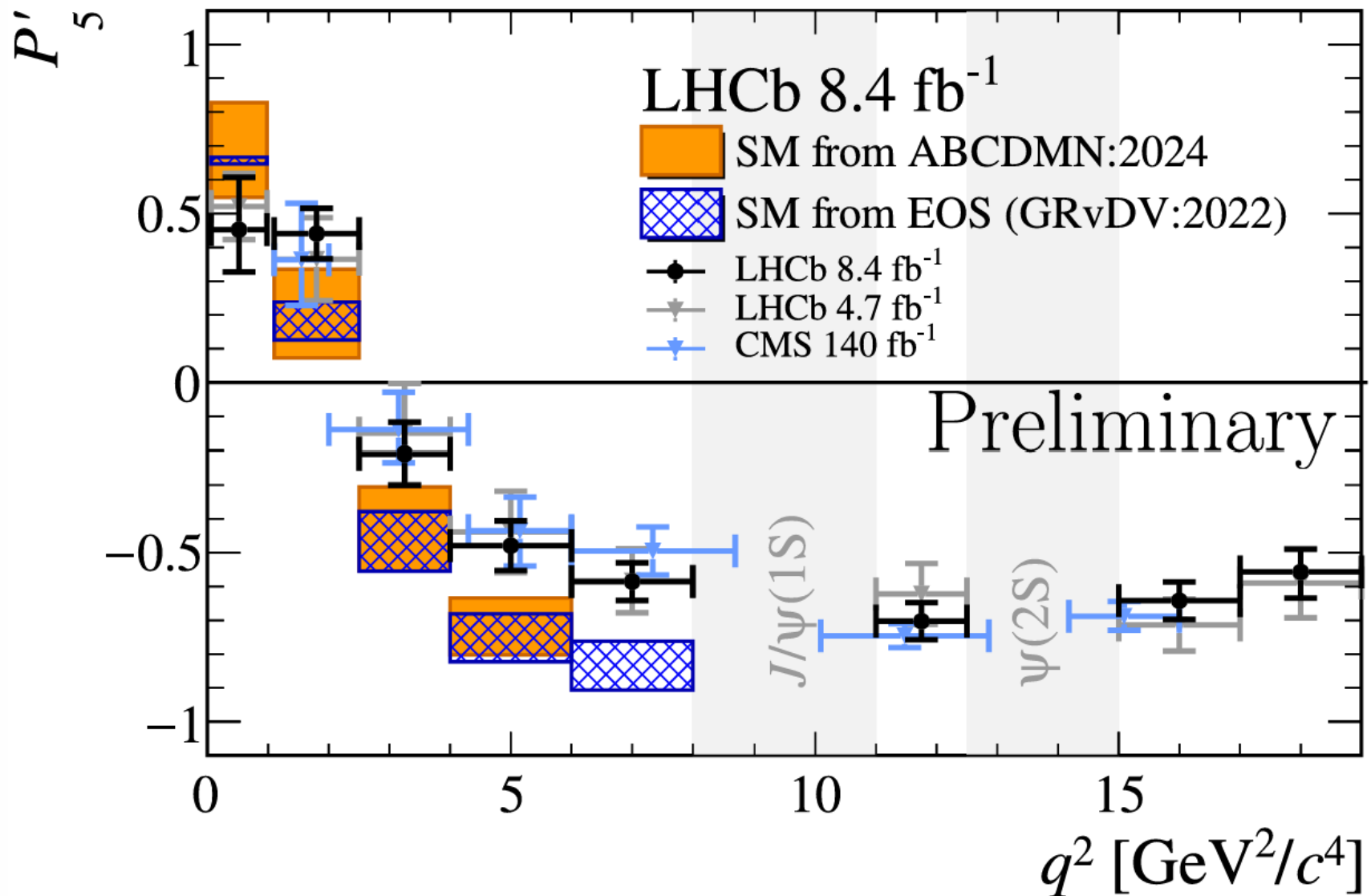
$$B^0 \rightarrow K^{*0}(\rightarrow K^+\pi^-)\mu^+\mu^-$$



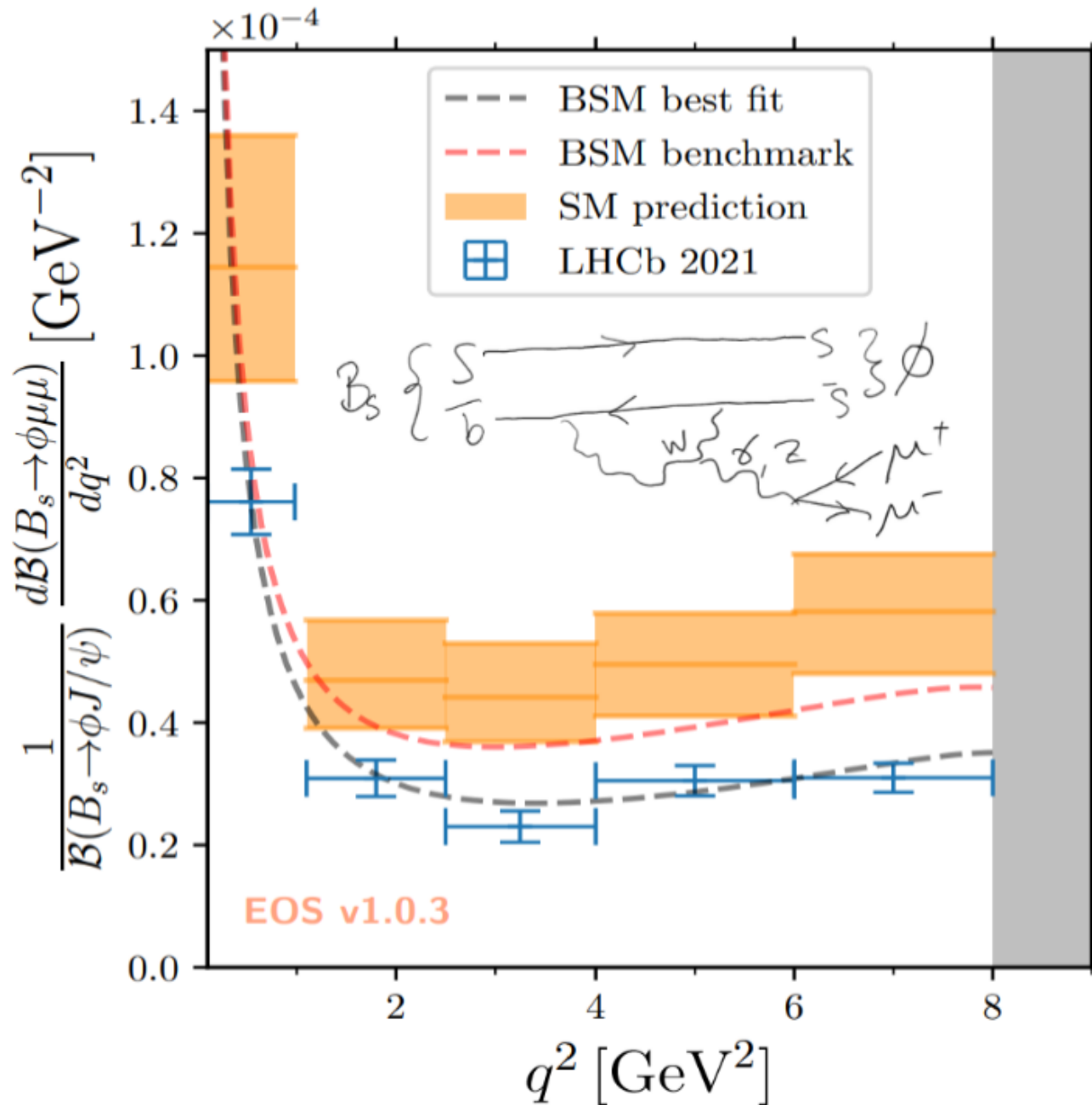
Decay fully described by three helicity angles $\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$ and $q^2 = m_{\mu\mu}^2$

$$\begin{aligned} \frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^3(\Gamma + \bar{\Gamma})}{d\vec{\Omega}} &= \frac{9}{32\pi} \left[\frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4}(1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell \right. \\ &\quad - F_L \cos^2 \theta_K \cos 2\theta_\ell + S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi \\ &\quad + S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + S_5 \sin 2\theta_K \sin \theta_\ell \cos \phi \\ &\quad + \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_\ell + S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi \\ &\quad \left. + S_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right] \end{aligned}$$

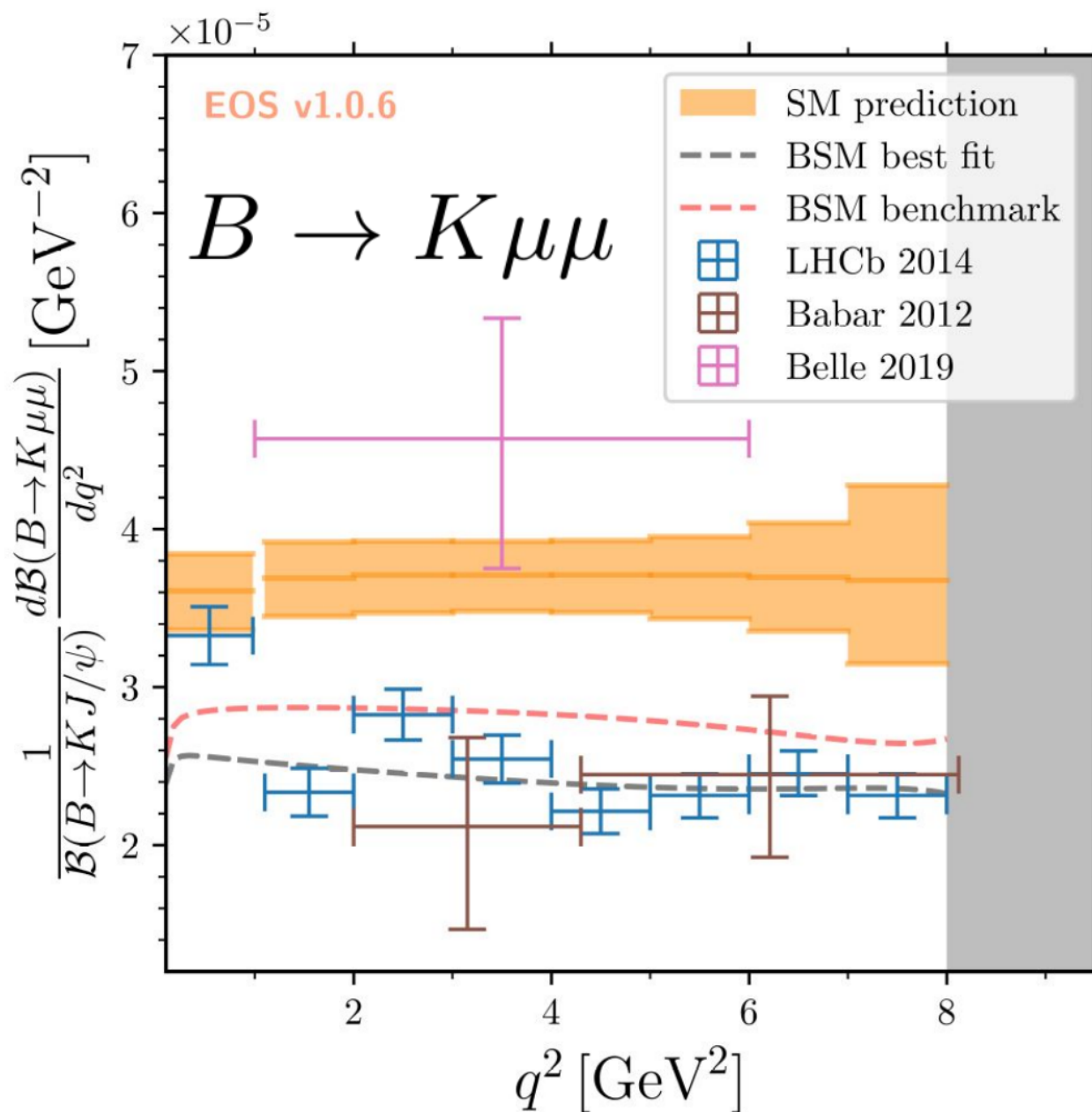
$$P'_5 = S_5 / \sqrt{F_L(1 - F_L)}$$



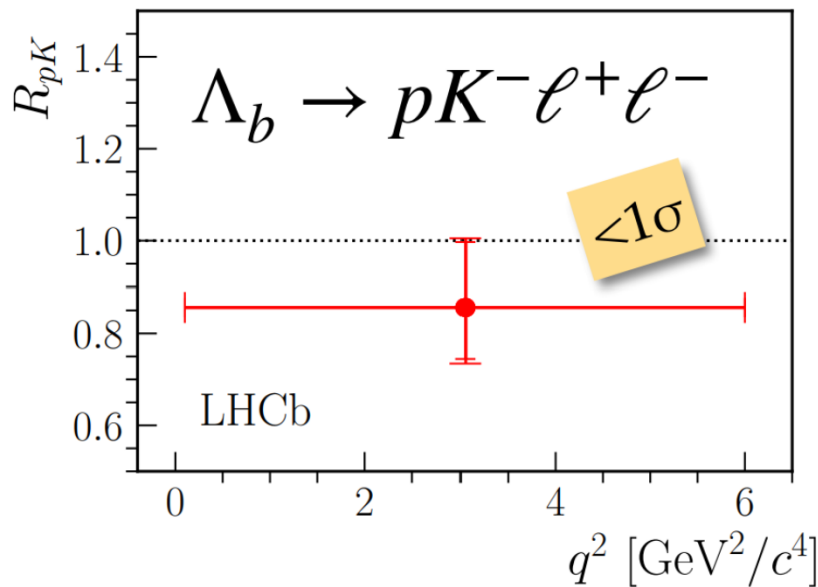
$$B_s \rightarrow \phi \mu^+ \mu^- : \phi = (s\bar{s})$$



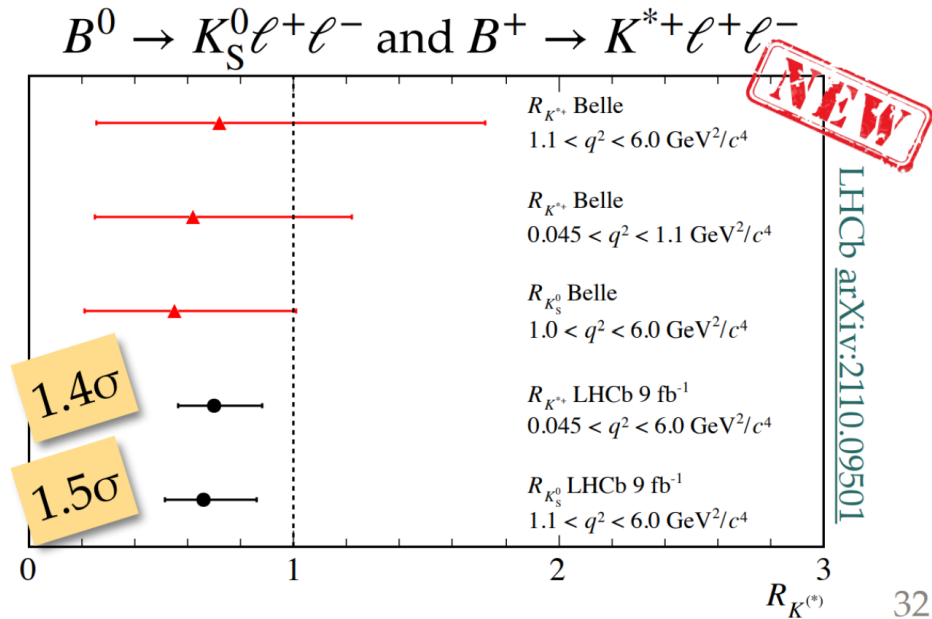
$$BR(B \rightarrow K \mu^+ \mu^-)$$



Other LFU



LHCb, JHEP 05 (2020) 040



32

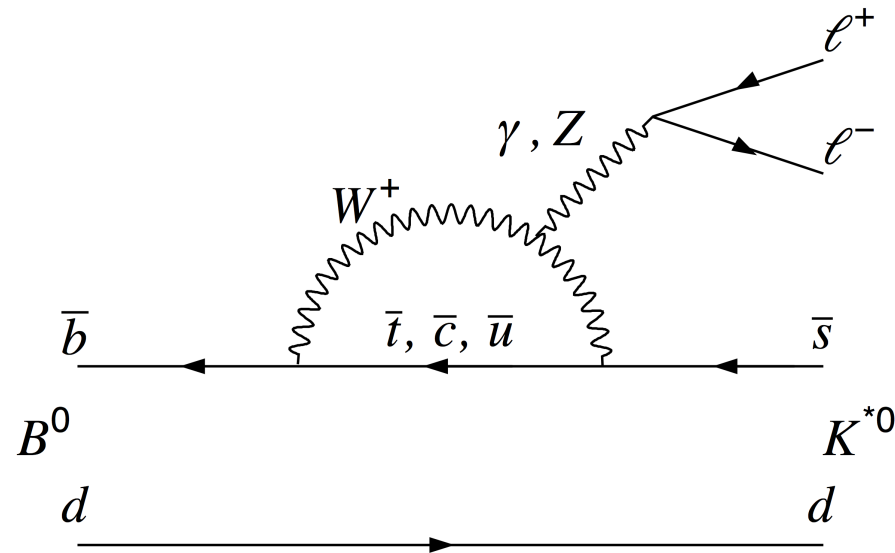
$$B_s \rightarrow \phi \ell^+ \ell^-,$$

$$B \rightarrow \pi \ell^+ \ell^-,$$

$$B \rightarrow K \pi^+ \pi^- \ell^+ \ell^-, \dots \text{ to come}$$

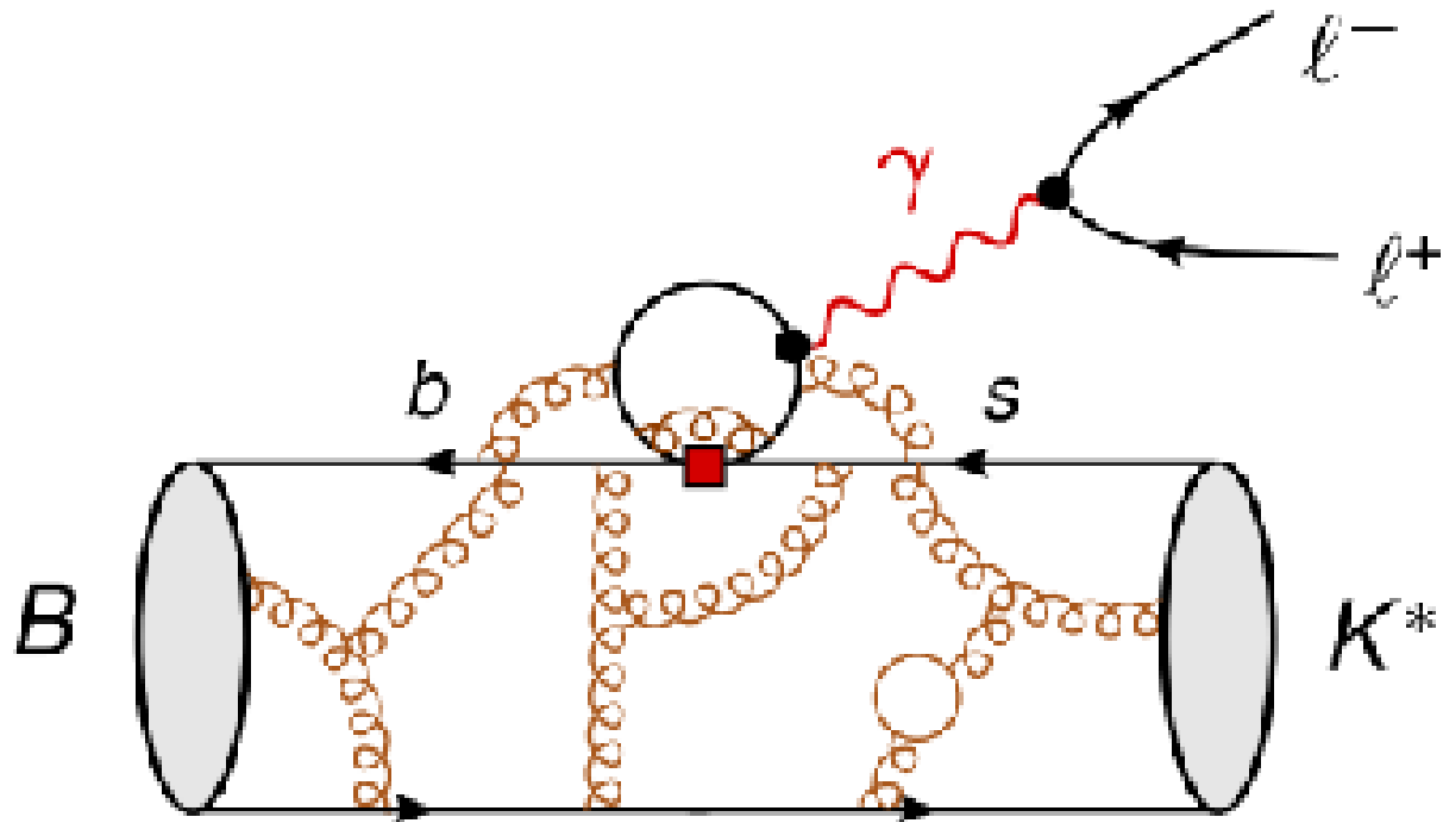
$b \rightarrow sl^+l^-$ in Standard Model

BR $\sim \mathcal{O}(10^{-6})$: loop+EW+CKM



$$R_{K^*} = \frac{BR(B \rightarrow K^* \mu^+ \mu^-)}{BR(B \rightarrow K^* e^+ e^-)} = 1.00$$

Form Factors



Predicting $B \rightarrow M \ell^+ \ell^-$: FFs

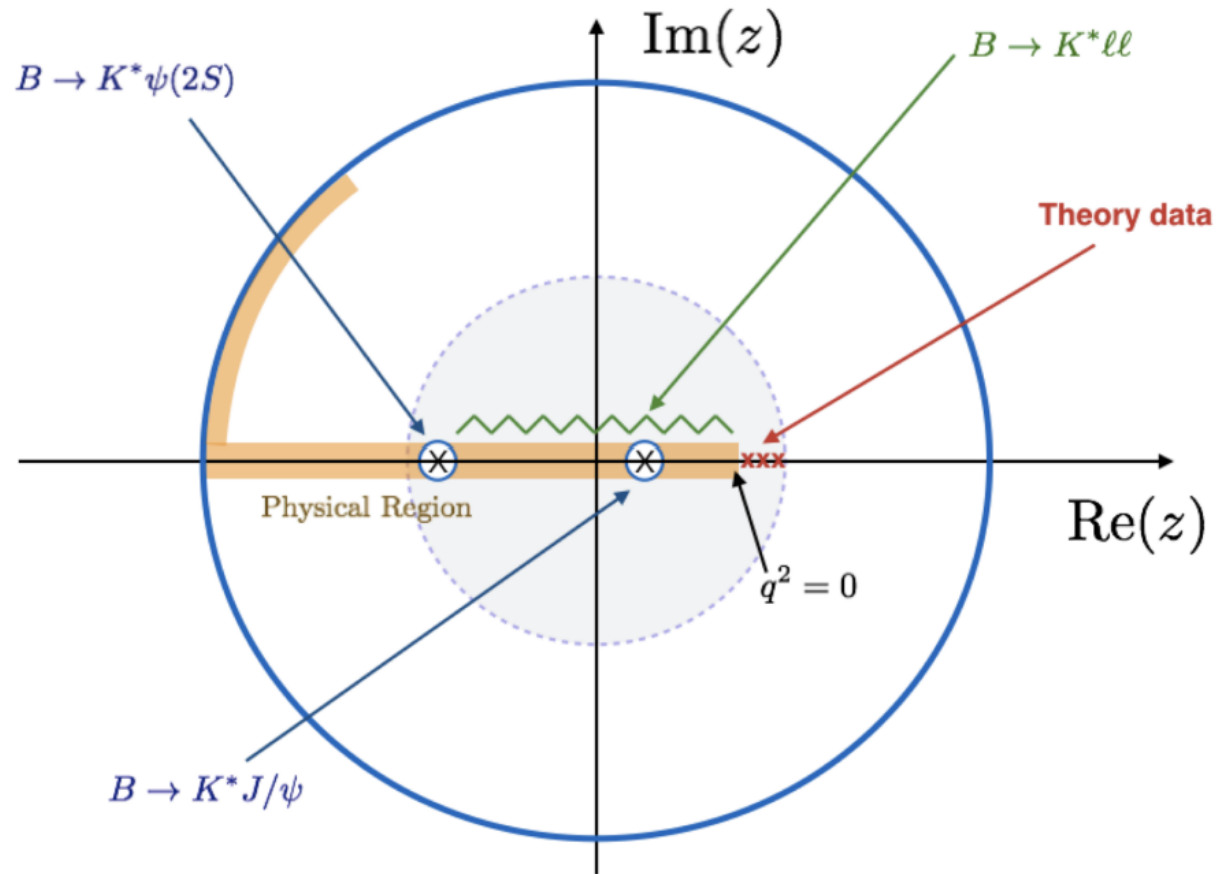
$$\mathcal{A} = \text{local} + \text{non-local}$$

local: interpolate lattice at high $q^2 = m_{\ell\ell}^2$ and LCSR at low q^2 .

non-local: no lattice. Most use QCD factorisation: perturbative charm loop+ad-hoc

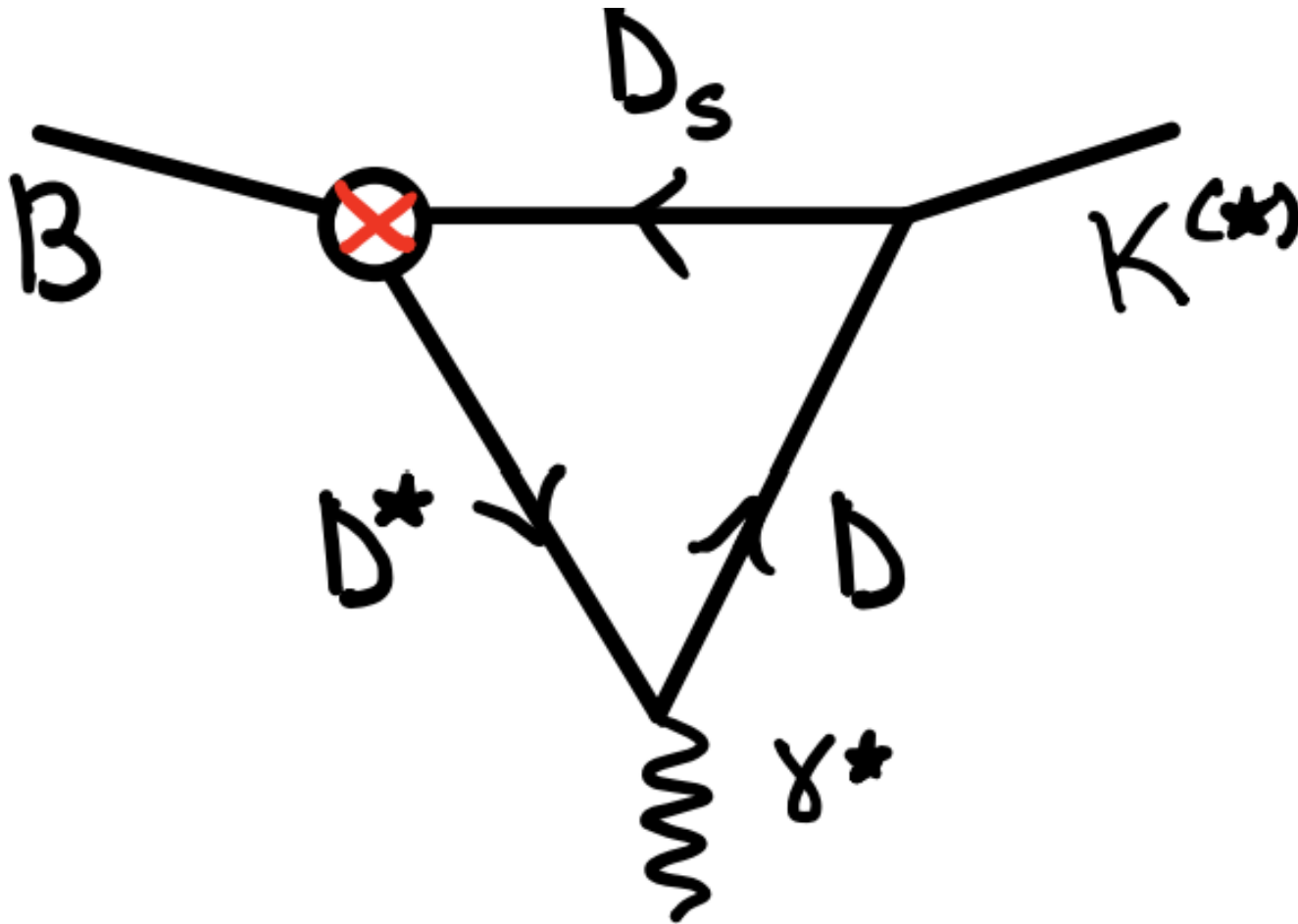
EOS approach: interpolate $q^2 < 0$ LCOPE and measurements of BRs/angular dists at $q^2 = M_{J/\psi}^2$.

$$q^2 \rightarrow z(q^2), \quad |z| < 1$$



$$C_9^{LD} \propto \sum_n a_n z^n \quad 1707.07305 \text{ truncation } 2205.03797$$

Caveat Emptor



2212.10516

Backup

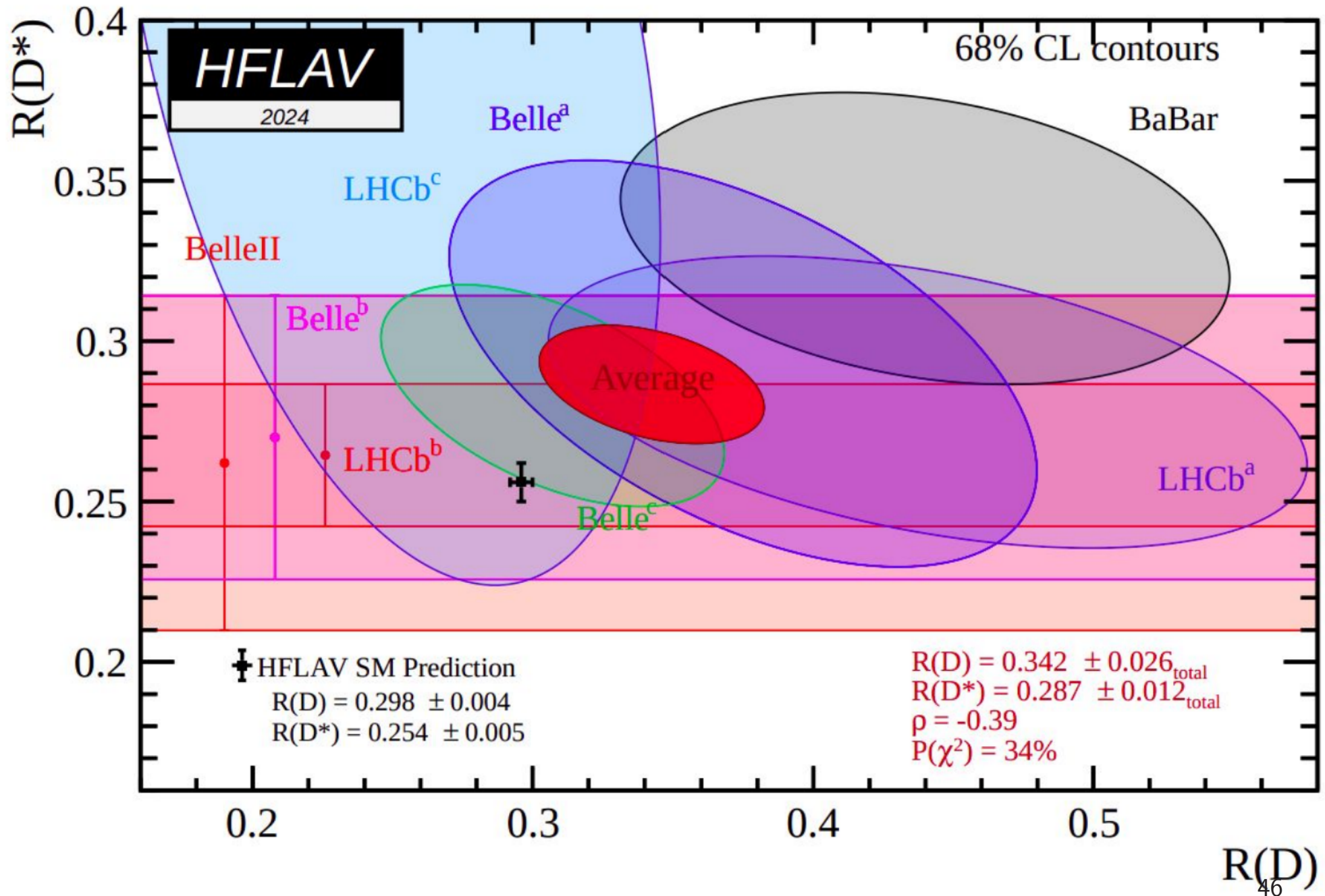
Ultra-violet completion?

This model is *equivalent* to
 $SU(3) \times SU(2) \times U(1)_Y \times U(1)_{X_1}$
without kinetic mixing and

$$X_1 := B_3 - L_2 + \alpha Y,$$

where $\alpha \in \mathbb{Q}$.

$$R_{D^{(*)}} = BR(B \rightarrow D^{(*)}\tau\nu)/BR(B \rightarrow D^{(*)}\ell\nu_\ell): \text{ } \mathbf{3.2\sigma}$$



$$R_{D^{(*)}}$$

$$R_{D^{(*)}} = \frac{BR(B \rightarrow D^{(*)} \tau \nu)}{BR(B \rightarrow D^{(*)} l \nu)}$$

b
 $\textcolor{red}{W}, H^+, W'$
 λ_1

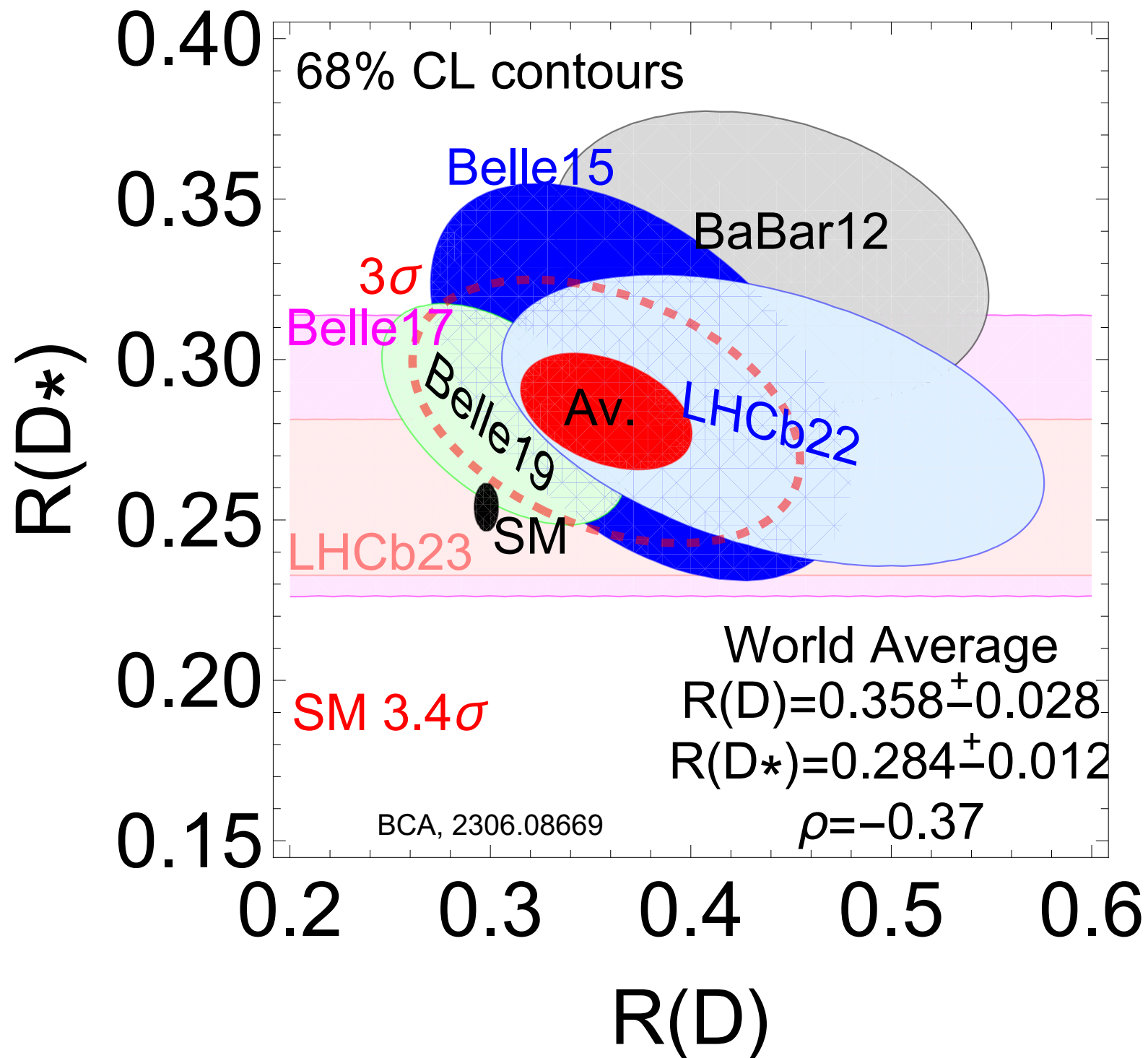
c
 τ

b
 LQ
 λ_1

τ
 c
 $\bar{\nu}$

Changed object; rerun axon help

$$\mathcal{L}_{WET} = -\frac{2\lambda_1\lambda_2}{M^2} (\bar{c}\gamma^\mu P_L \nu) (\bar{\tau}\gamma_\mu P_L b) + H.c.$$



2022 Measurement

Using BaBar data (not official BaBar analysis)
and *semi-leptonic* tag: (2012 used *hadronic*)

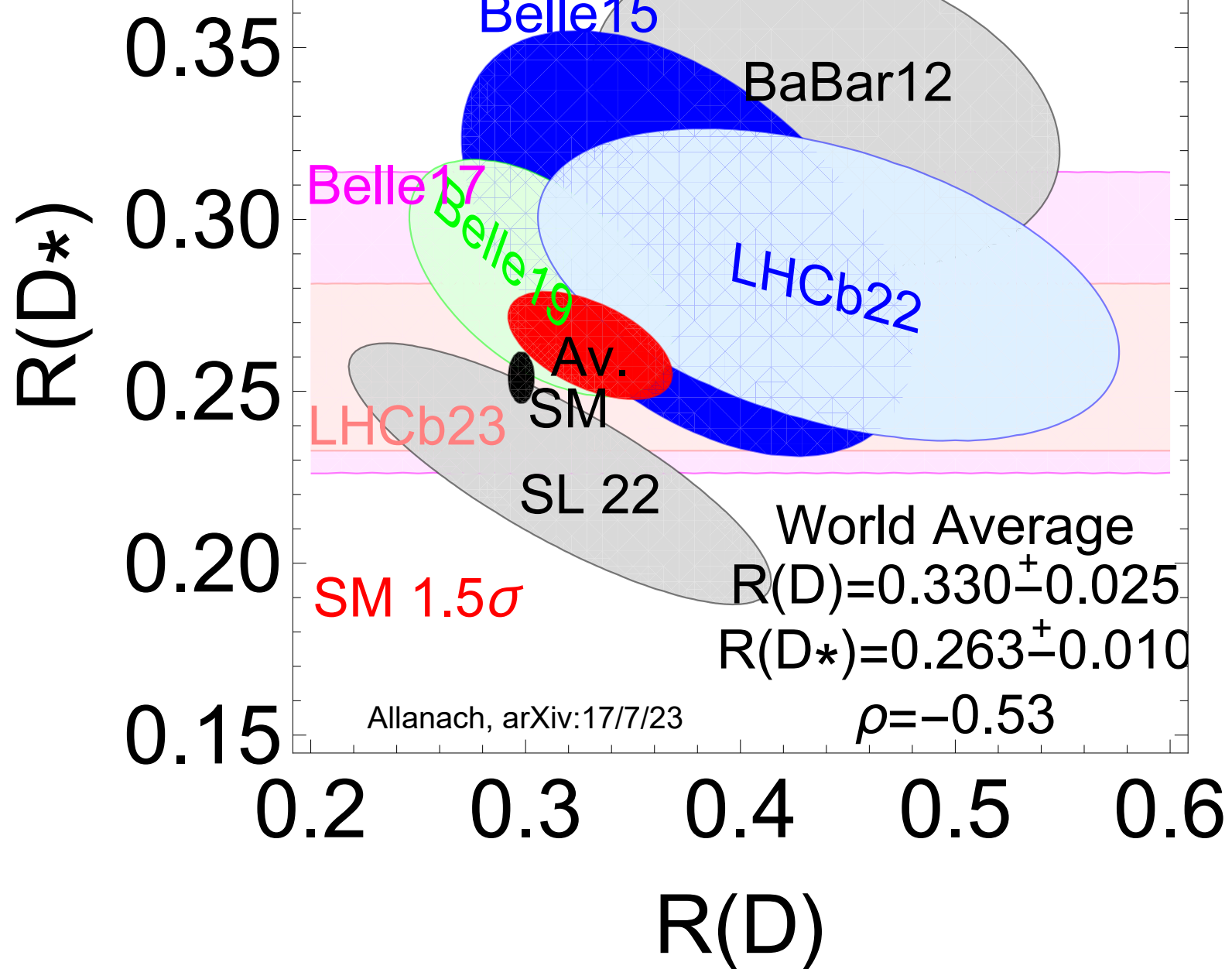
$$R(D) = 0.316 \pm 0.062 \pm 0.019$$

$$R(D^*) = 0.226 \pm 0.022 \pm 0.012$$

$$\rho = -0.82$$

Yunxuan Li, *Search for Beyond Standard Model Physics at BaBar*, (2022), Caltech Ph.D. thesis

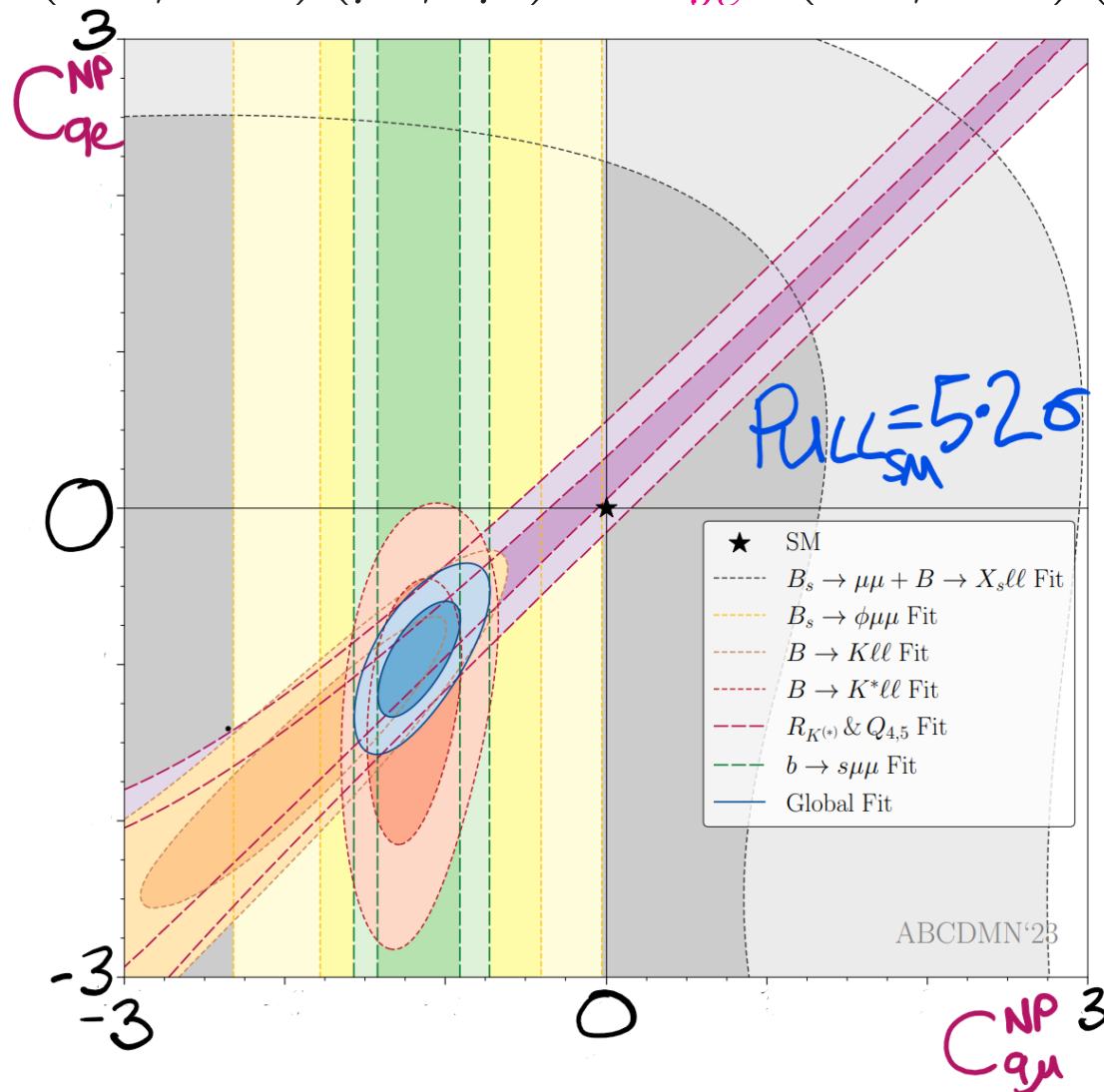
<https://resolver.caltech.edu/CaltechTHESIS:05232022-144829107>

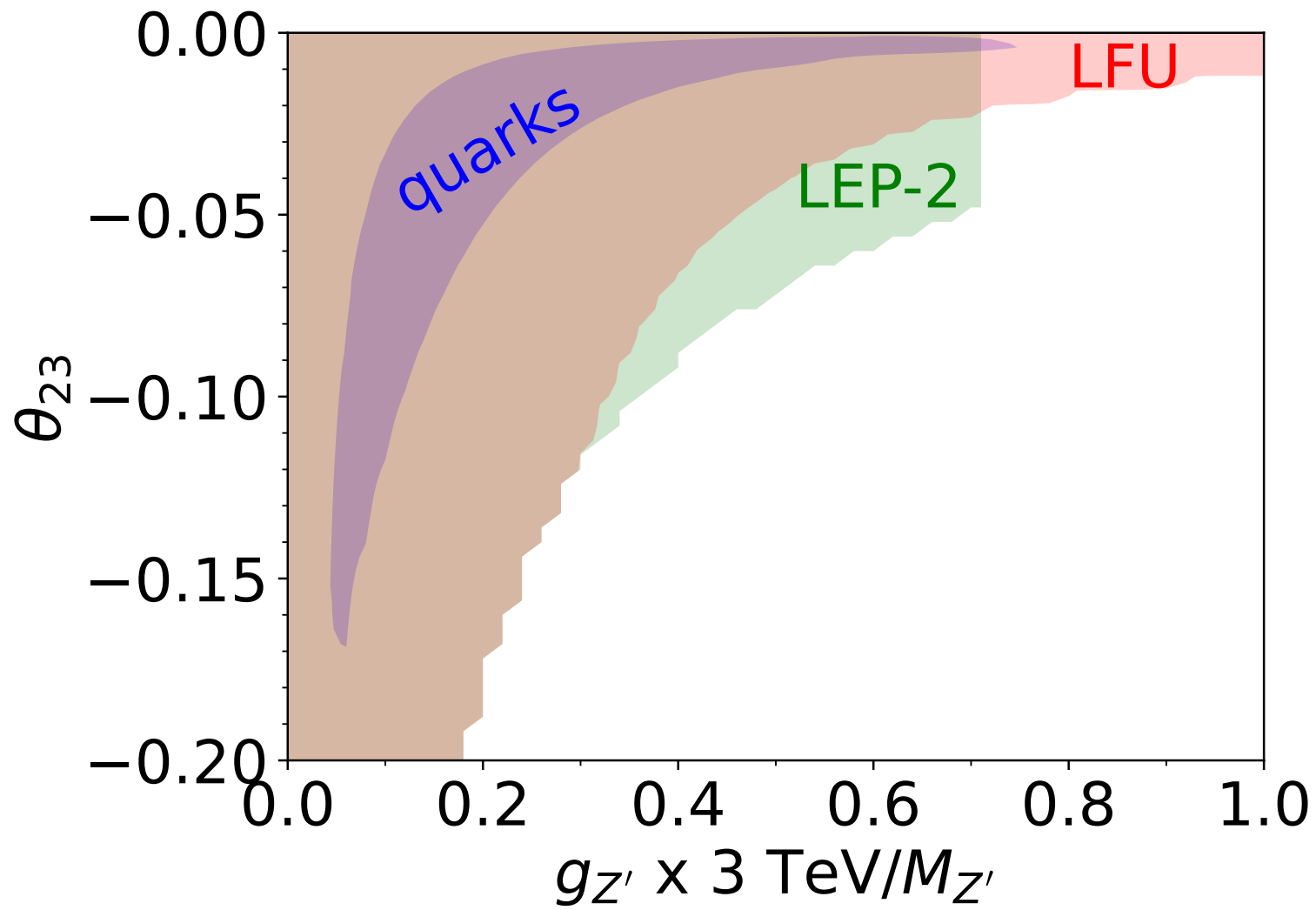


μ/e Neutral Current Fits

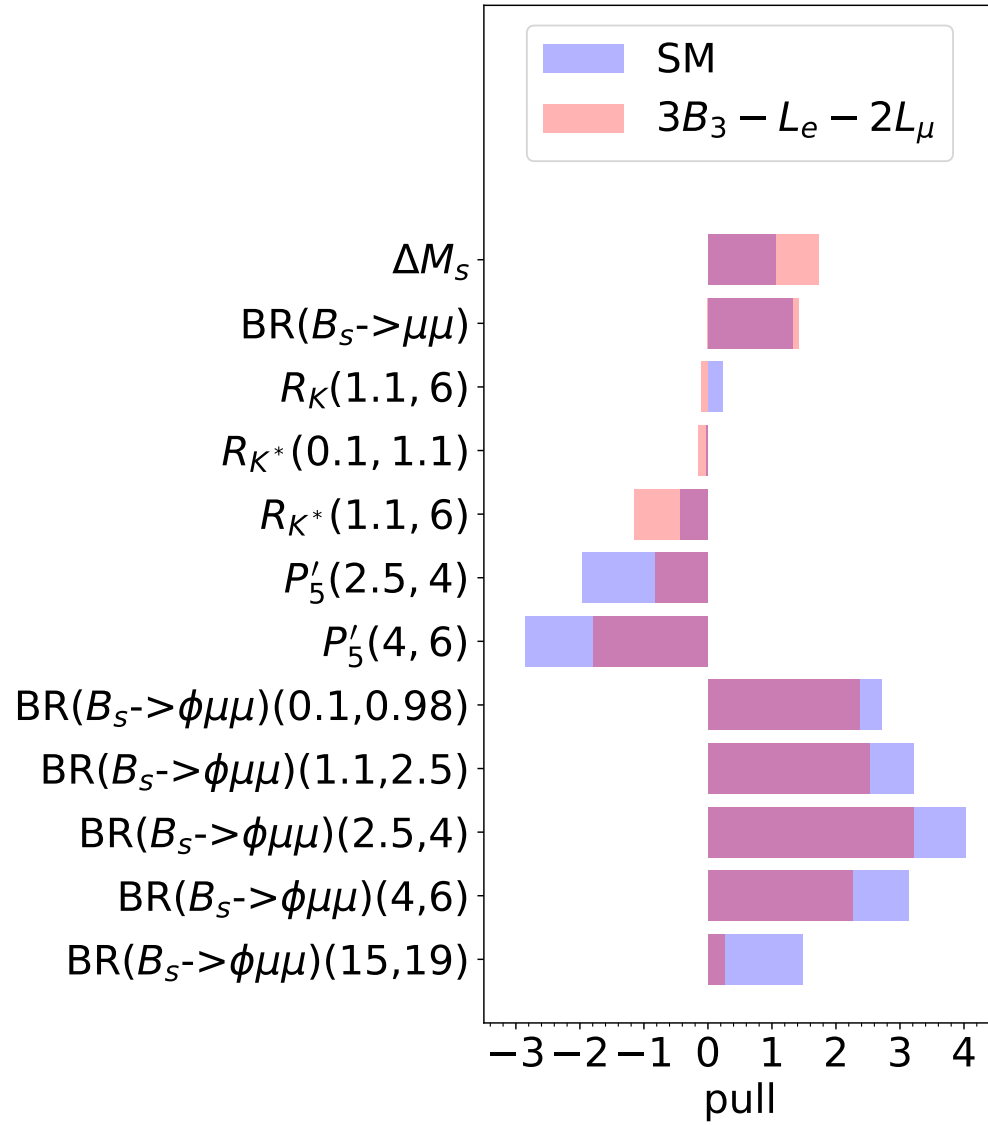
Alguero et al, 2304.07330

$$\mathcal{L} = N[C_{9\mu}^{NP}(\bar{b}_L\gamma^\alpha s_L)(\bar{\mu}\gamma_\alpha\mu) + C_{9e}^{NP}(\bar{b}_L\gamma^\alpha s_L)(\bar{e}\gamma_\alpha e)] + H.c.$$



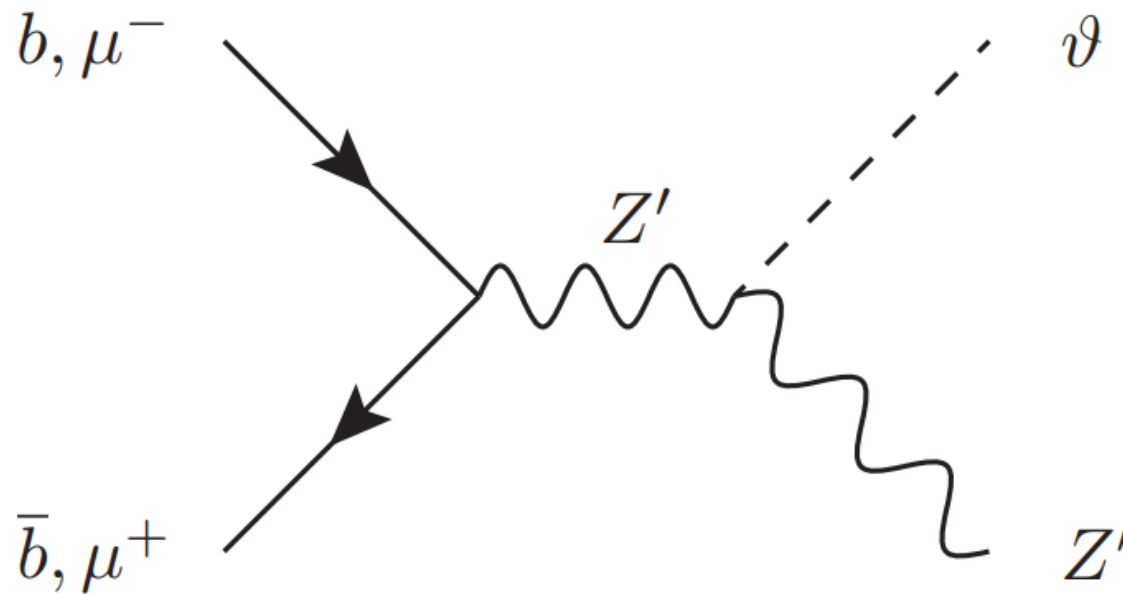


BCA, Mullin, 2306.08669



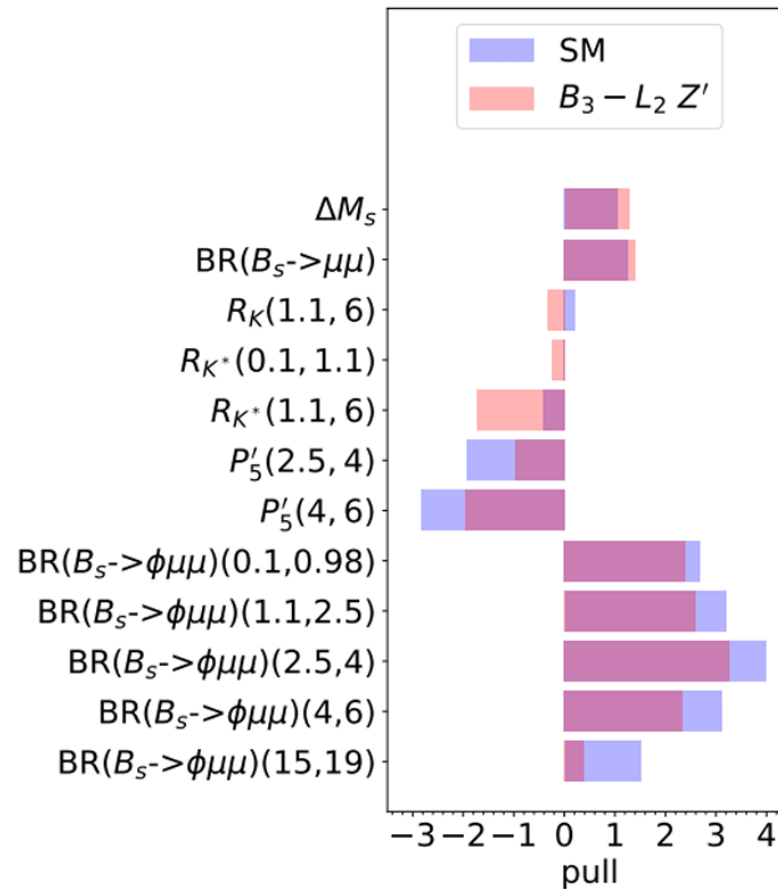
Flavonstrahlung

Models of Z' ilk possess $\mathcal{L} = \lambda H H^\dagger \theta \theta^\dagger \Rightarrow$ a *flavonstrahlung* signature:

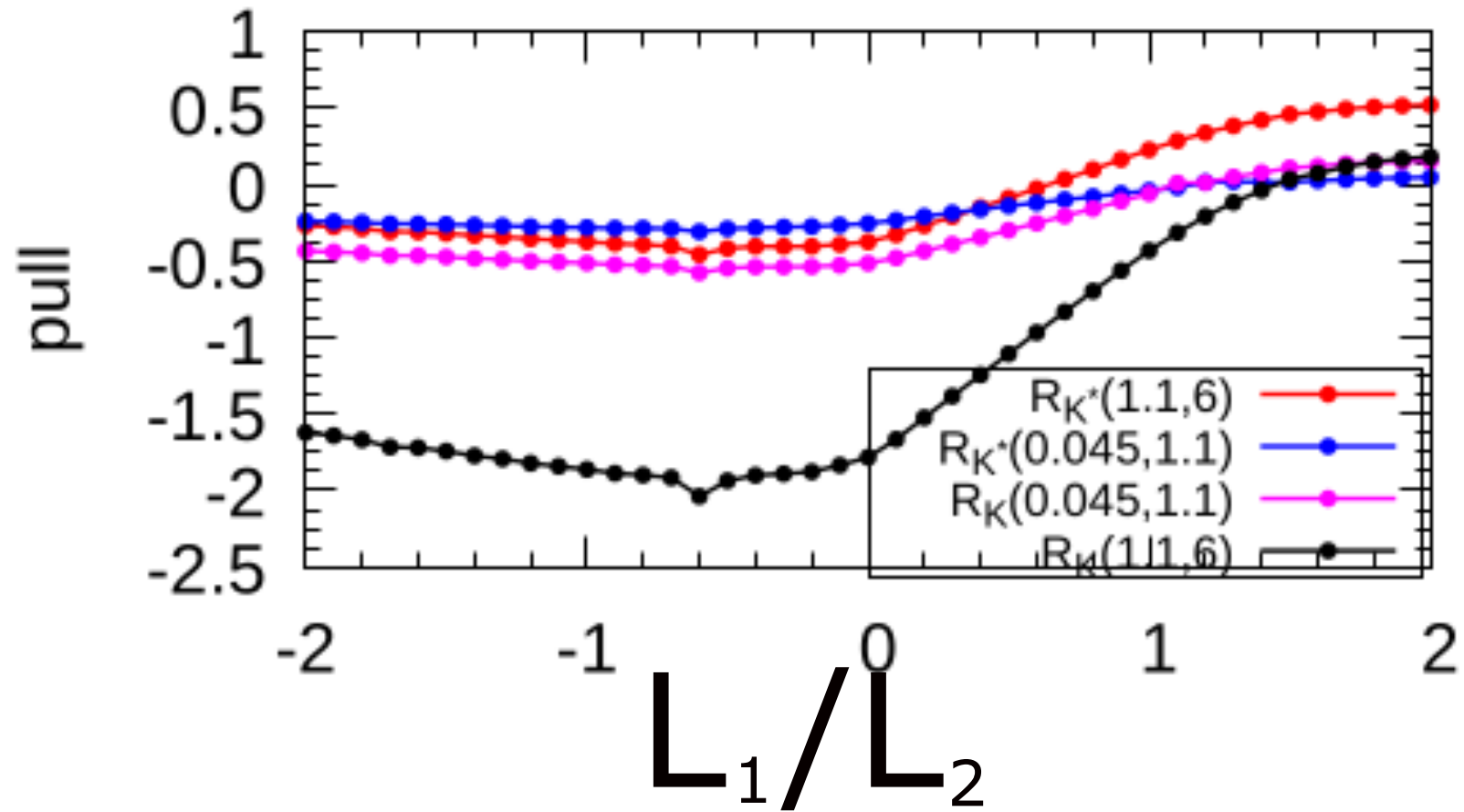


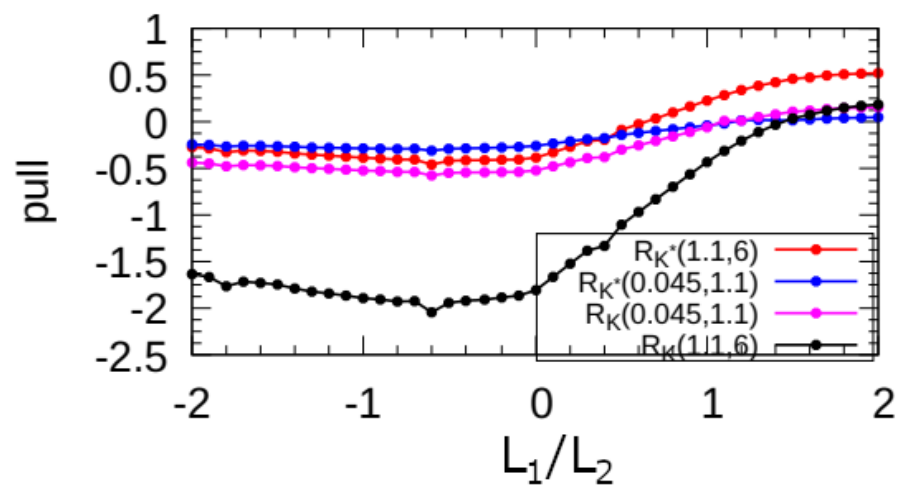
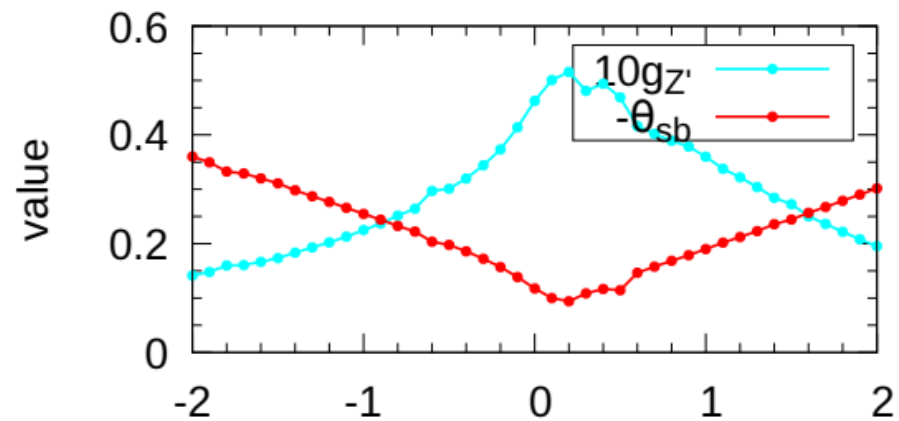
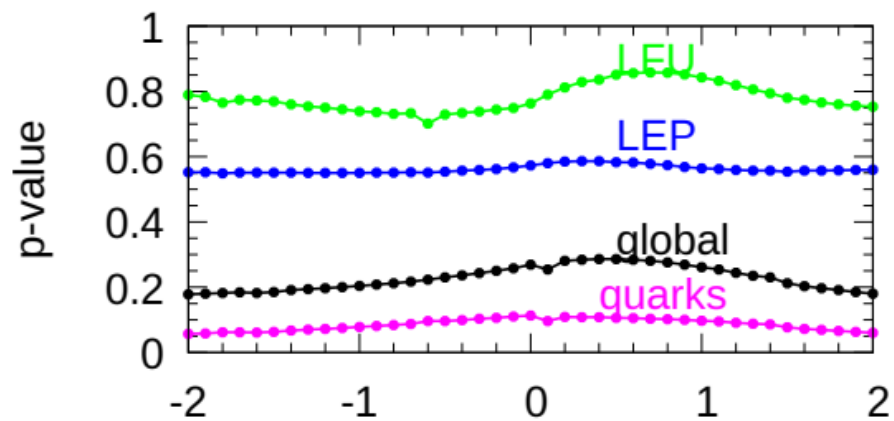
BCA, 2009.02197; **BCA, Loisa, 2212.07440**

$$\text{Pull} = (\text{theory} - \text{exp}) / \text{error}$$



BCA, Davighi, 2211.11766

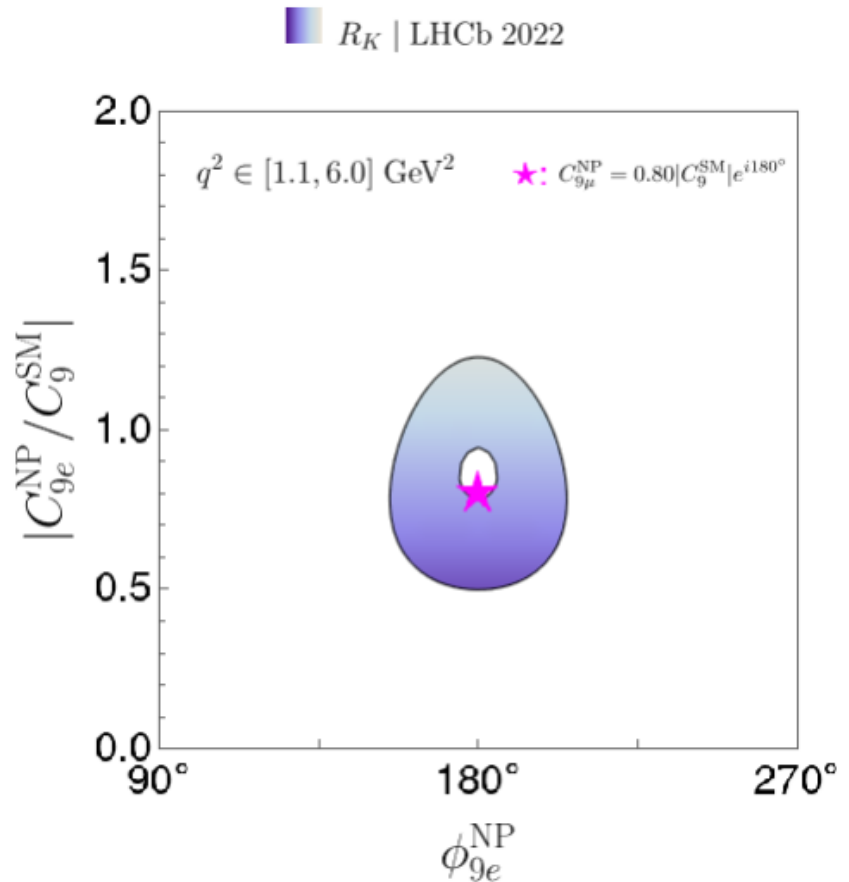
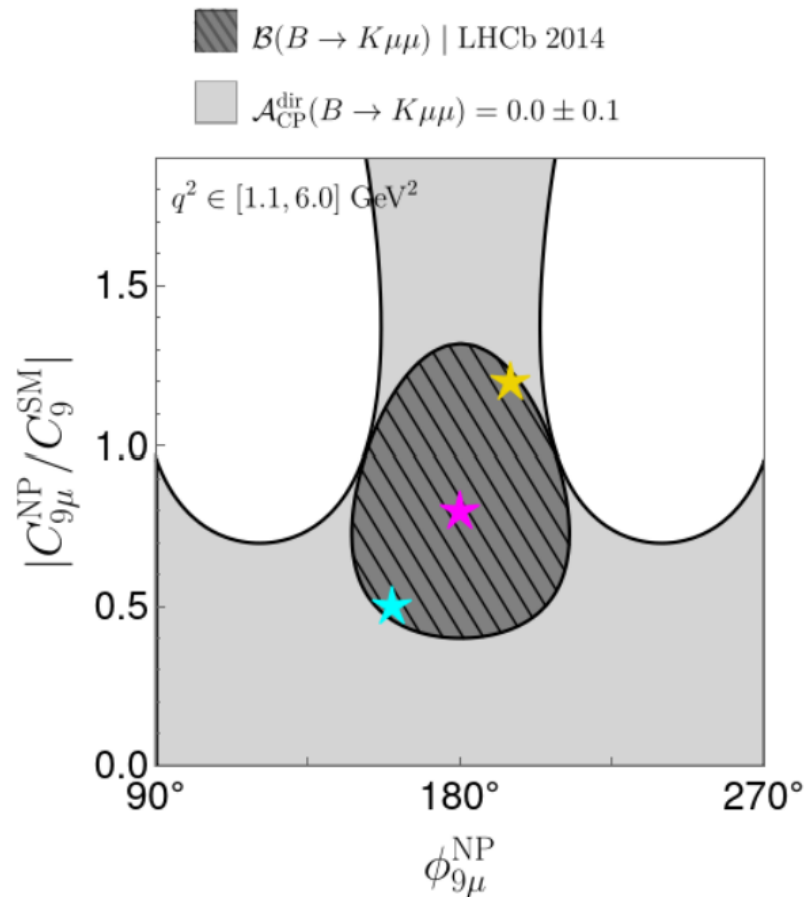




$e \neq \mu$ allowed

Fleischer, Malami, Rehult, Keri Vos, 2303.08764; $C_{9\ell}^{NP} = |C_{9\ell}^{NP}|e^{i\phi_{9\ell}^{NP}}$

$$\mathcal{L} = N(\bar{b}_L \gamma^\alpha s_L) [\textcolor{violet}{C}_{9\mu}^{NP}(\bar{\mu} \gamma_\alpha \mu) + \textcolor{violet}{C}_{9e}^{NP}(\bar{e} \gamma_\alpha e)] + H.c.$$



Anomaly cancellation

Need to pick X charges for fermions consistent with QFT anomaly cancellation.

$$X = 3B_3 - (X_e L_e + X_\mu L_\mu + [3 - X_e - X_\mu] L_\tau)$$

works (proof in 2306.08669).

Trident Neutrino Process

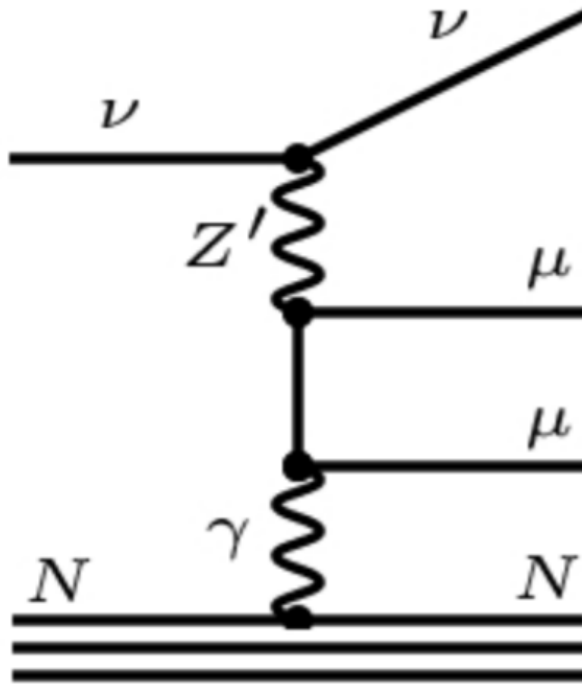
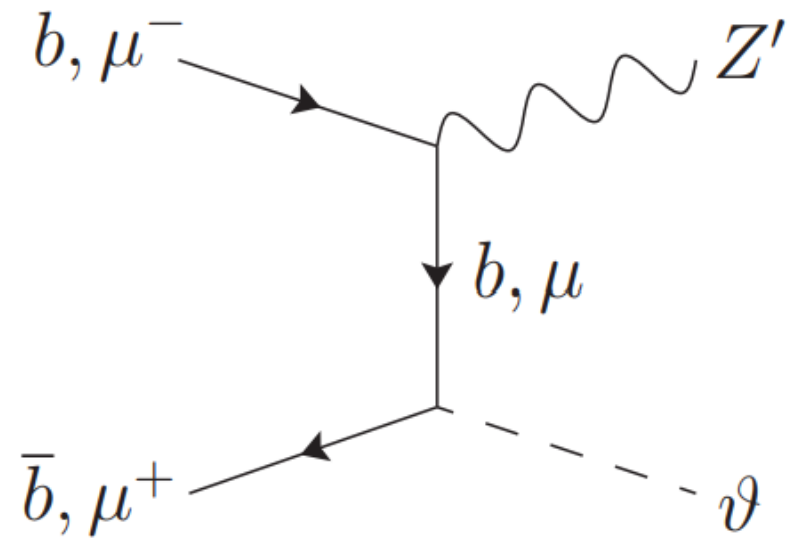
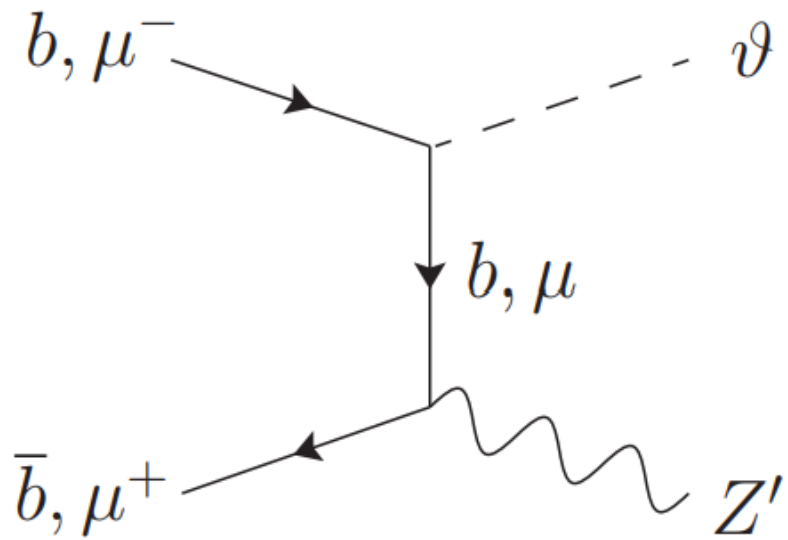
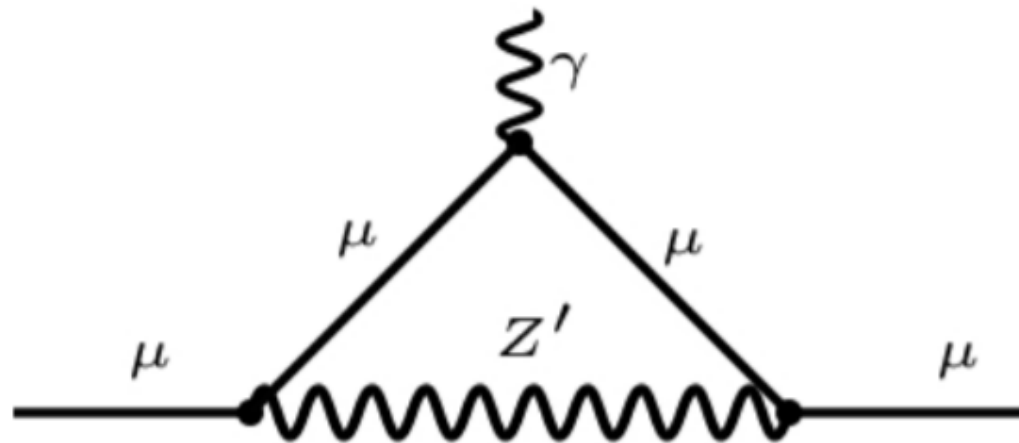
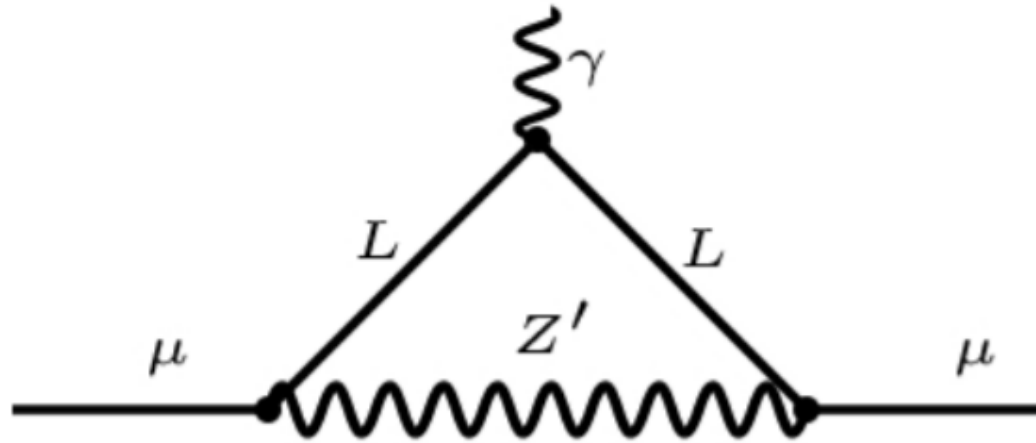


FIG. 10. Neutrino trident process that leads to constraints on the Z^μ coupling strength to neutrinos-muons, namely $M_{Z'}/g_{\nu\mu} \gtrsim 750$ GeV.

t -channel



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



$H\vartheta$ potential

$$\begin{aligned} V &= -\mu^2 H^\dagger H + \lambda_H (H^\dagger H)^2 - \mu_\theta^2 \theta^* \theta + \\ &\quad \lambda_\theta (\theta^* \theta)^2 + \lambda_{\theta H} \theta^* \theta H^\dagger H \\ &= -\frac{1}{2} \begin{pmatrix} h' & \vartheta' \end{pmatrix} M^2 \begin{pmatrix} h' \\ \vartheta' \end{pmatrix} + \dots \end{aligned}$$

$$M^2 = \begin{pmatrix} 2\lambda_H v_H^2 & \lambda_{\theta H} v_H v_\theta \\ \lambda_{\theta H} v_H v_\theta & 2\lambda_\theta v_\theta^2 \end{pmatrix}$$

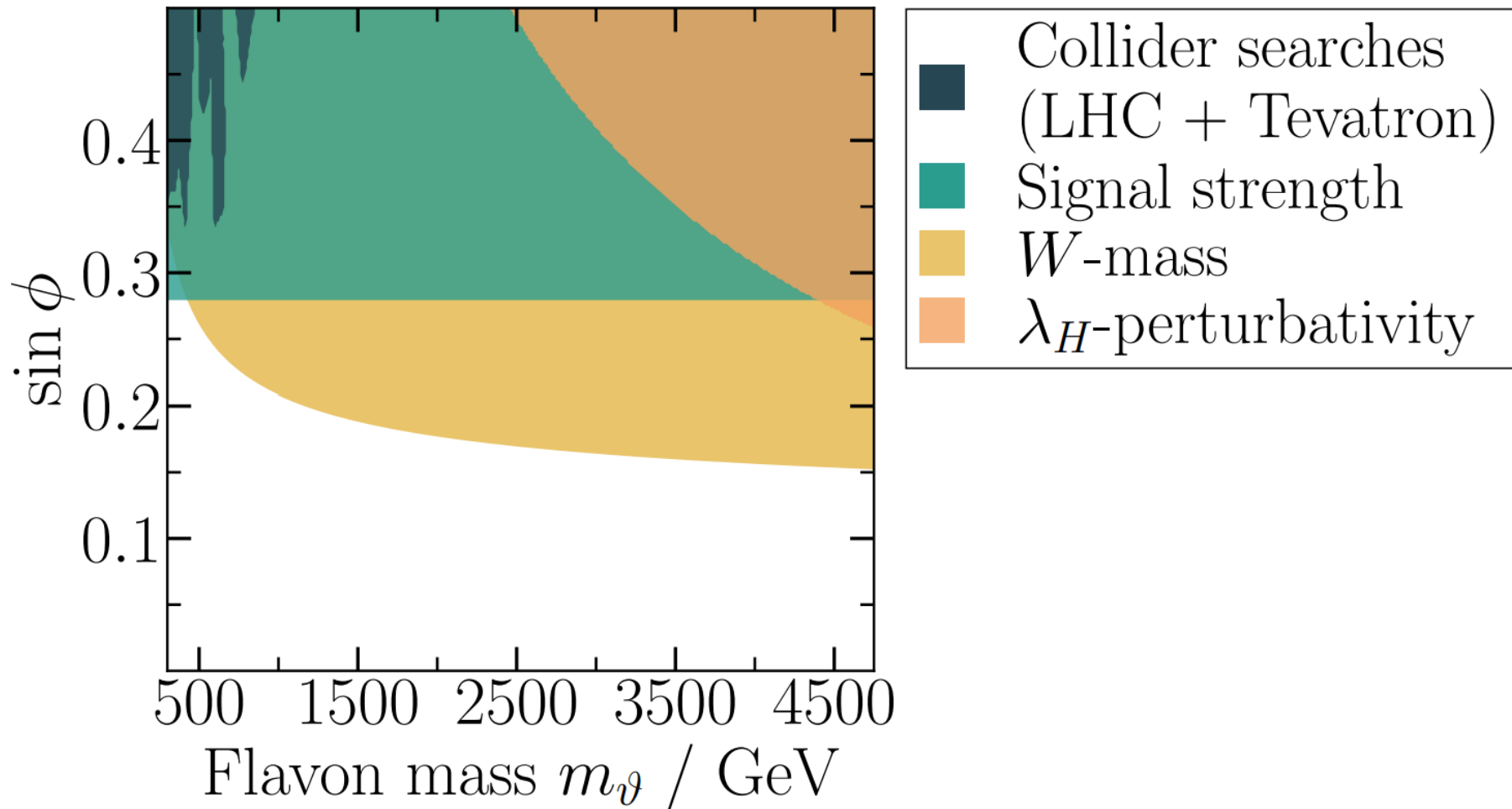
$H\vartheta$ mixing

$$\begin{pmatrix} h \\ \vartheta \end{pmatrix} = \begin{pmatrix} \cos \phi & -\sin \phi \\ \sin \phi & \cos \phi \end{pmatrix} \begin{pmatrix} h' \\ \vartheta' \end{pmatrix}$$
$$\sin 2\phi = \frac{2\lambda_{\theta H} v_h v_{\theta}}{m_{\vartheta}^2 - m_h^2}. \quad (-9)$$

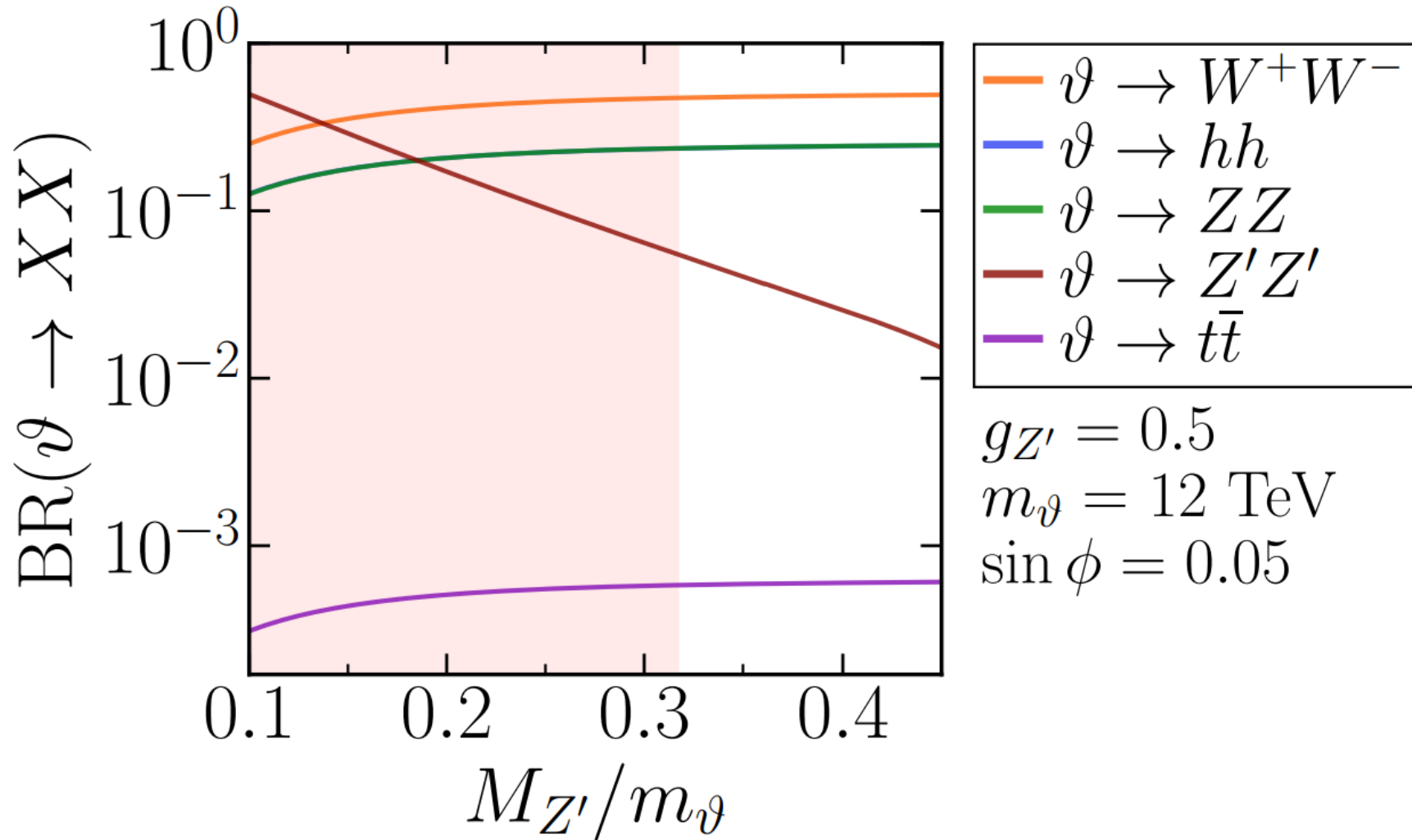
Three parameters: $v_{\theta} = M_{Z'}/g_{Z'}$, m_{ϑ} and ϕ .

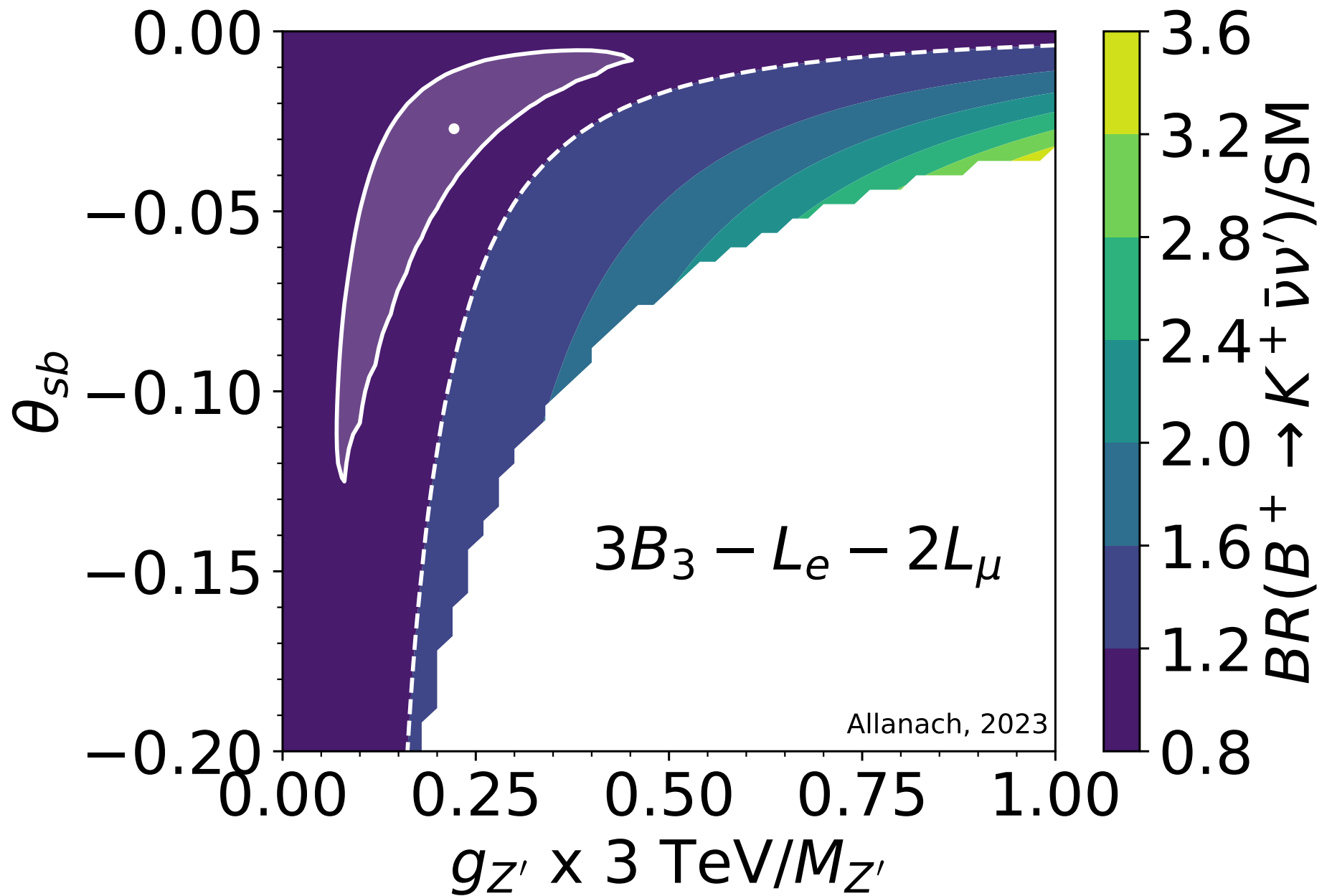
Higgs Signal Strength

BCA, Loisa, 2212.07440

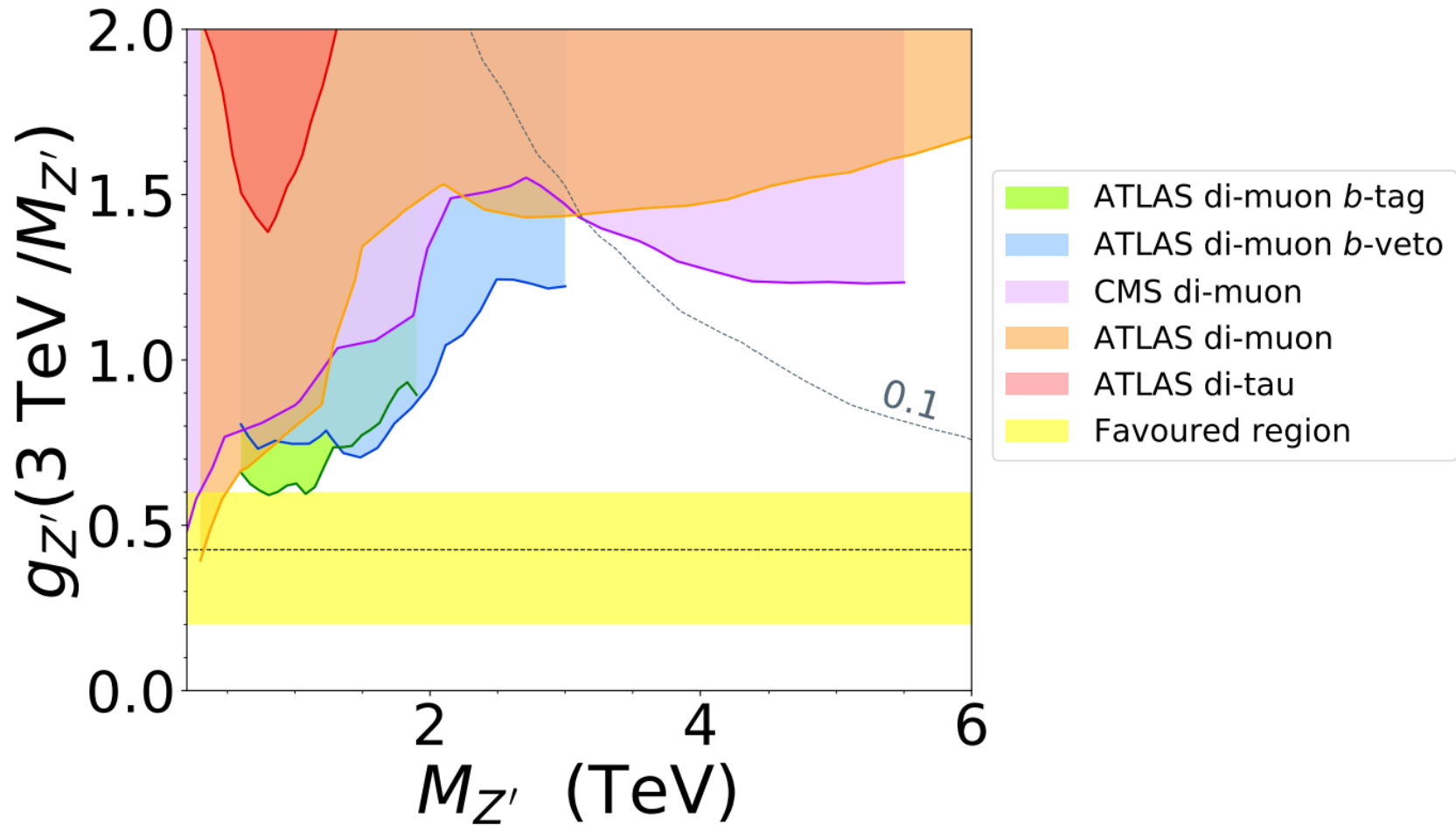


ϑ BRs

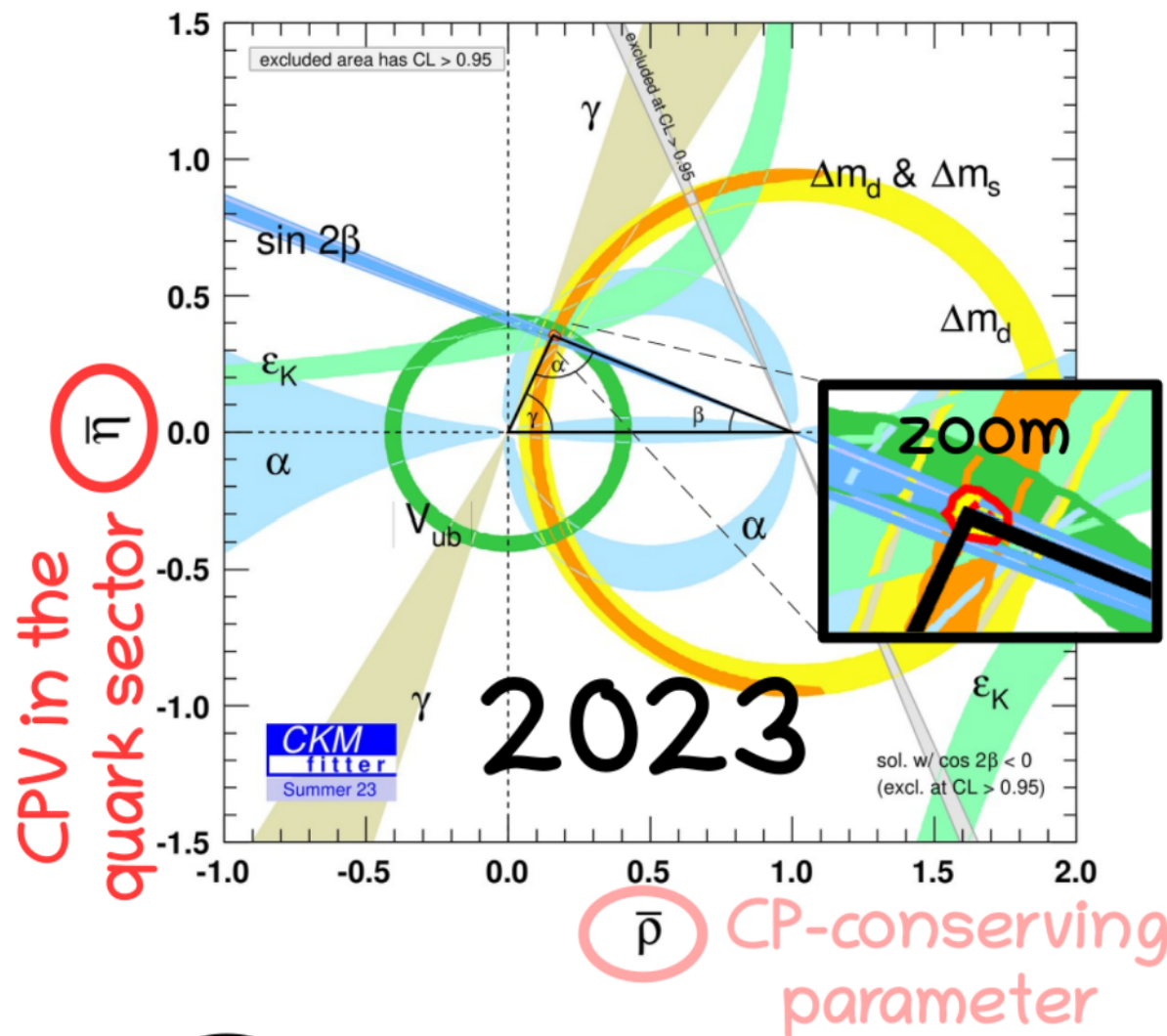


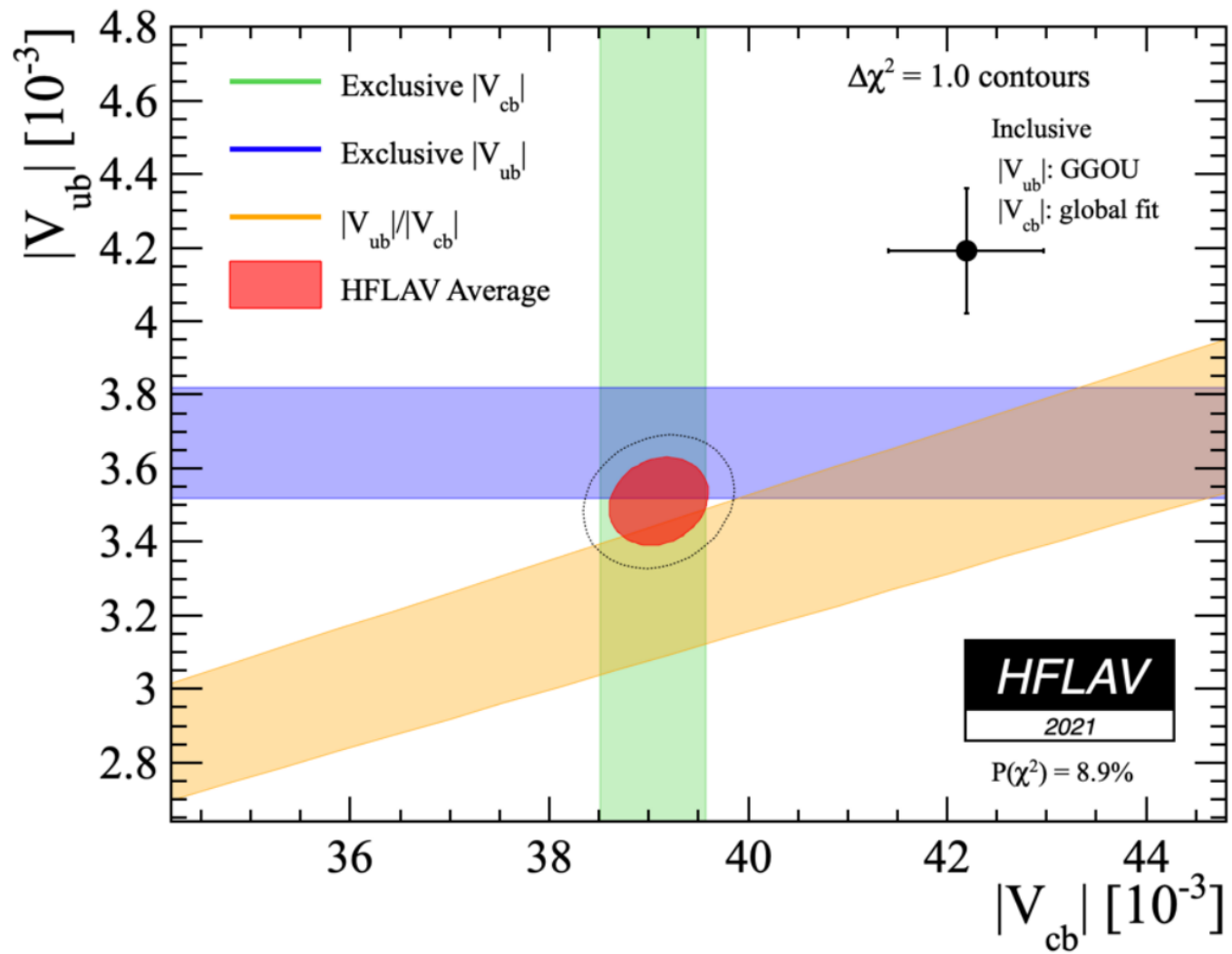


Z' Searches⁵



⁵BCA, Banks, 2111.06691

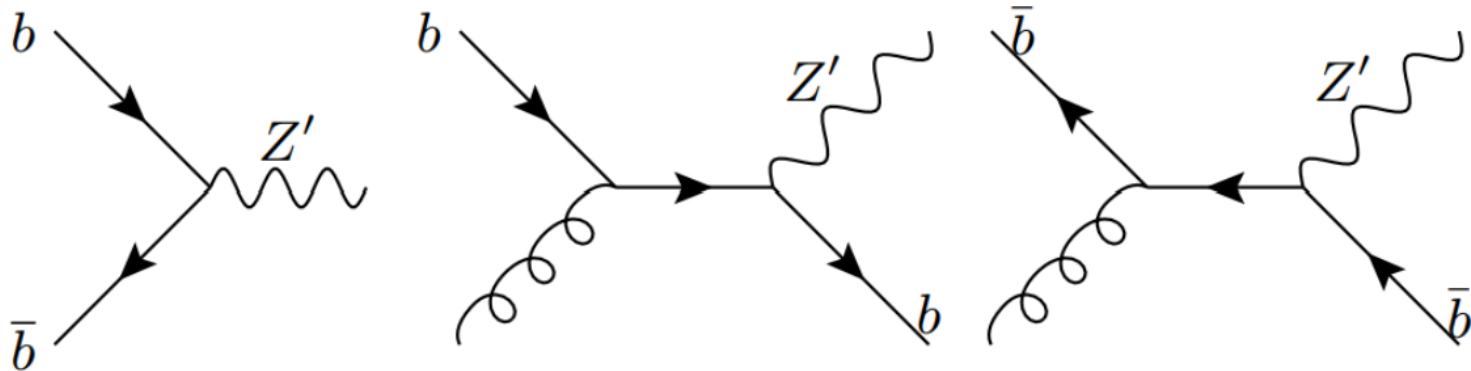




Z' Decay Modes

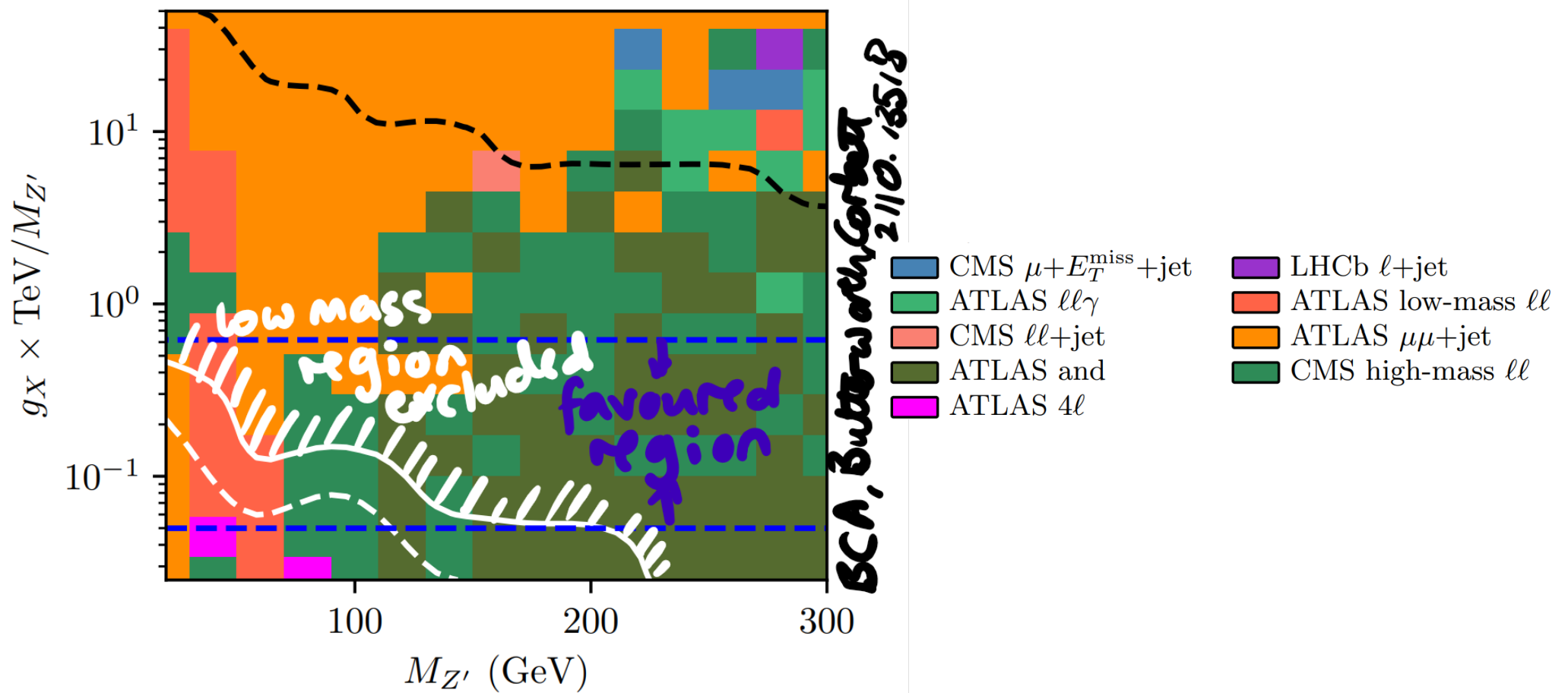
Mode	BR	Mode	BR	Mode	BR
$t\bar{t}$	0.15	$b\bar{b}$	0.15	$\nu\bar{\nu}'$	0.23
$\mu^+\mu^-$	0.37	e^+e^-	0.09		

pp Z' Production:



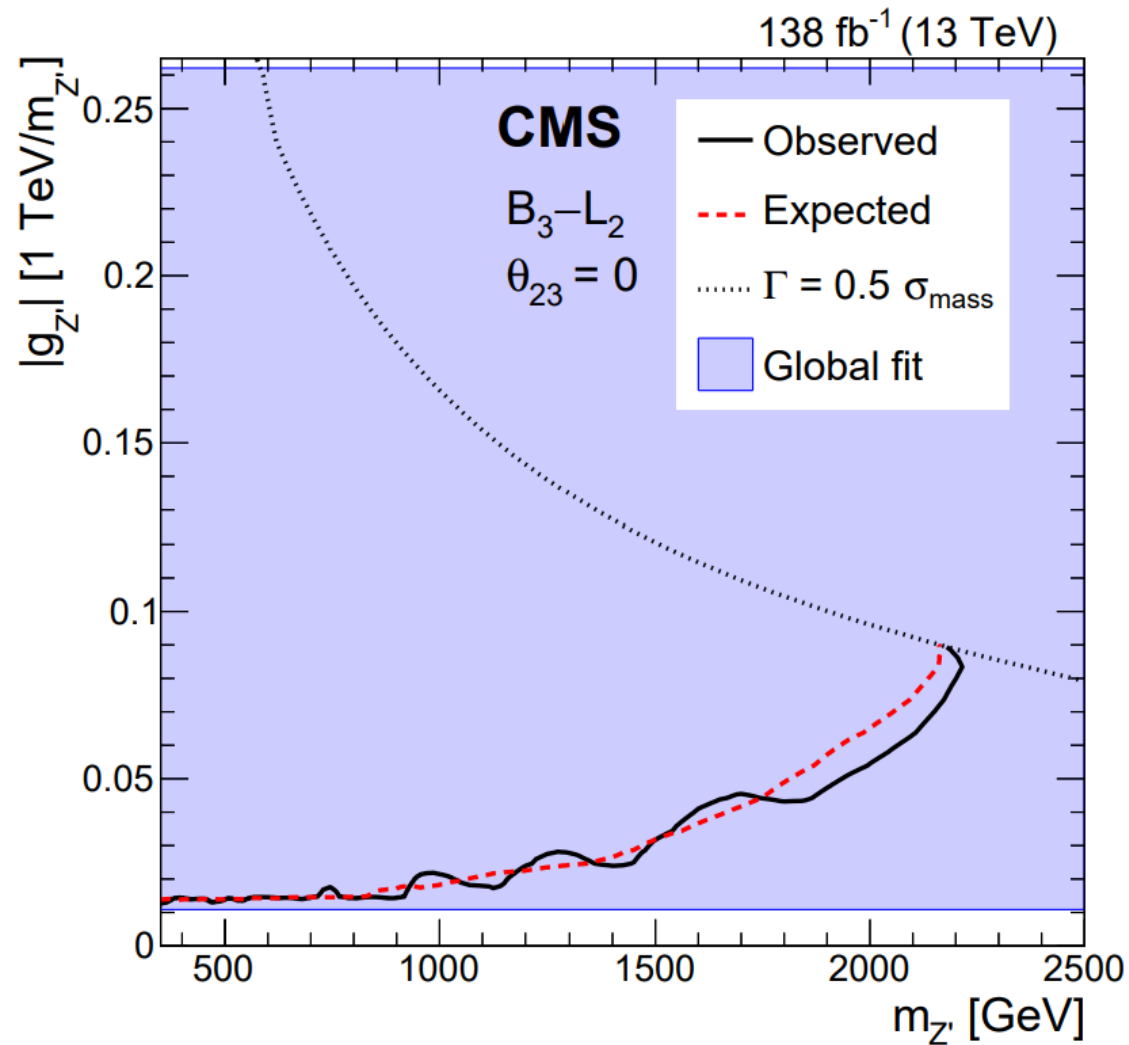
$$\sigma_{prod} \propto g_{Z'}^2 \cos^4 \theta_{sb} = g_{Z'}^2 (1 - 2\theta_{sb}^2 + \mathcal{O}(\theta_{sb}^4))$$

$B_3 - L_2$ model's $^6 Z'$

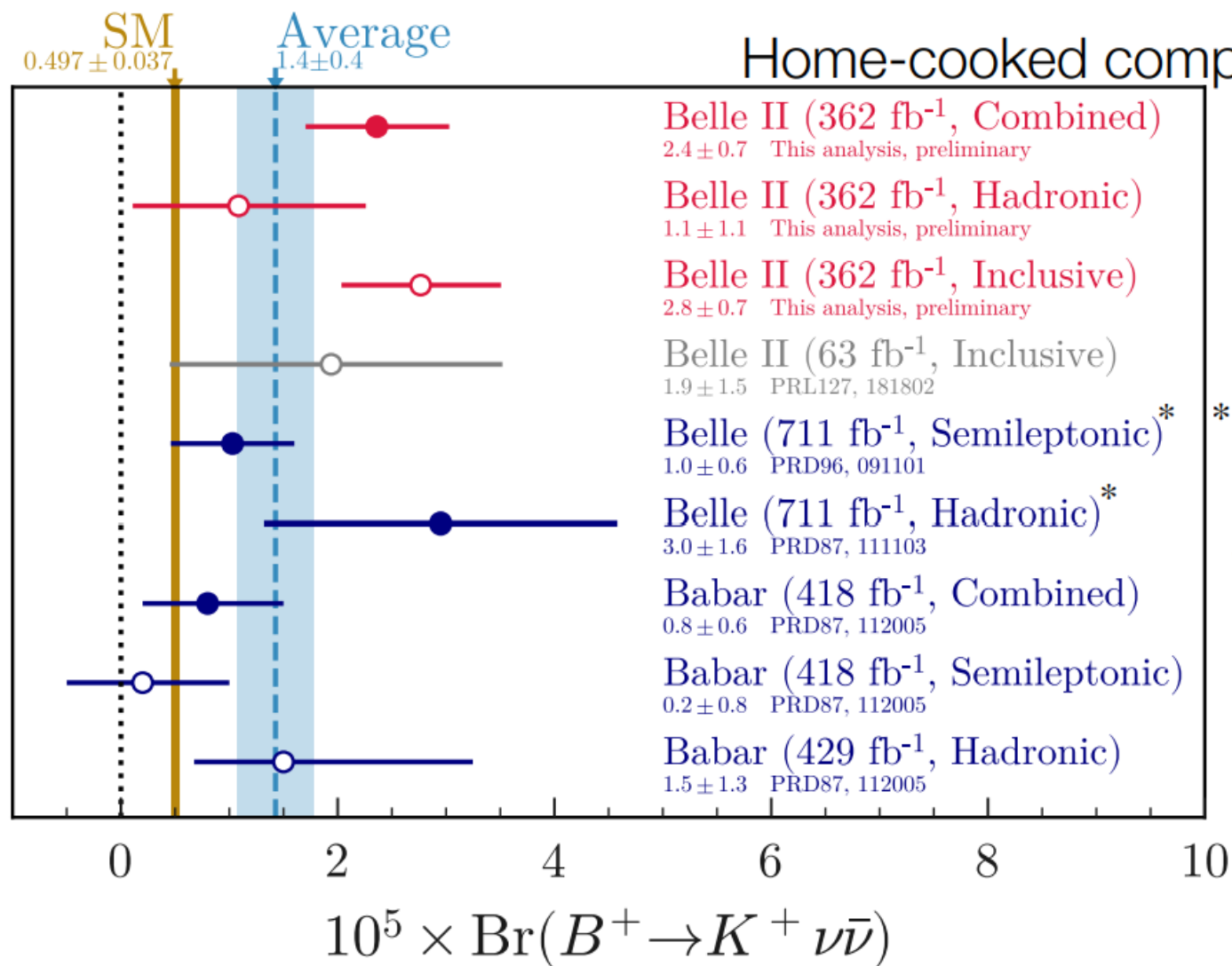


⁶Bonilla, Modak, Srivastava, Valle, 1705.00915; Alonso, Cox, Han, Yanagida 1705.03858

CMS $\mu^+\mu^-b$ 2307.08708

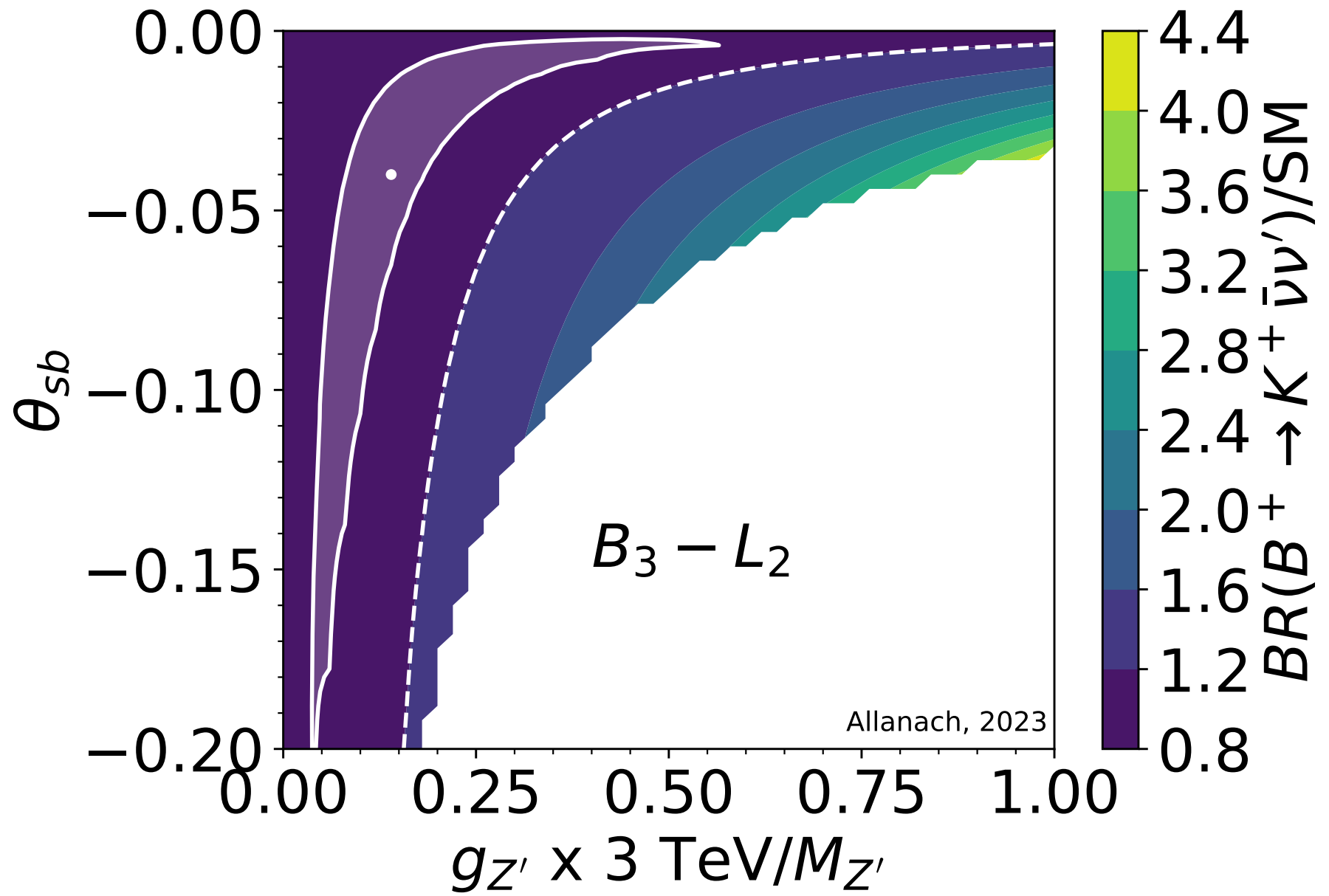


Home-cooked comparison

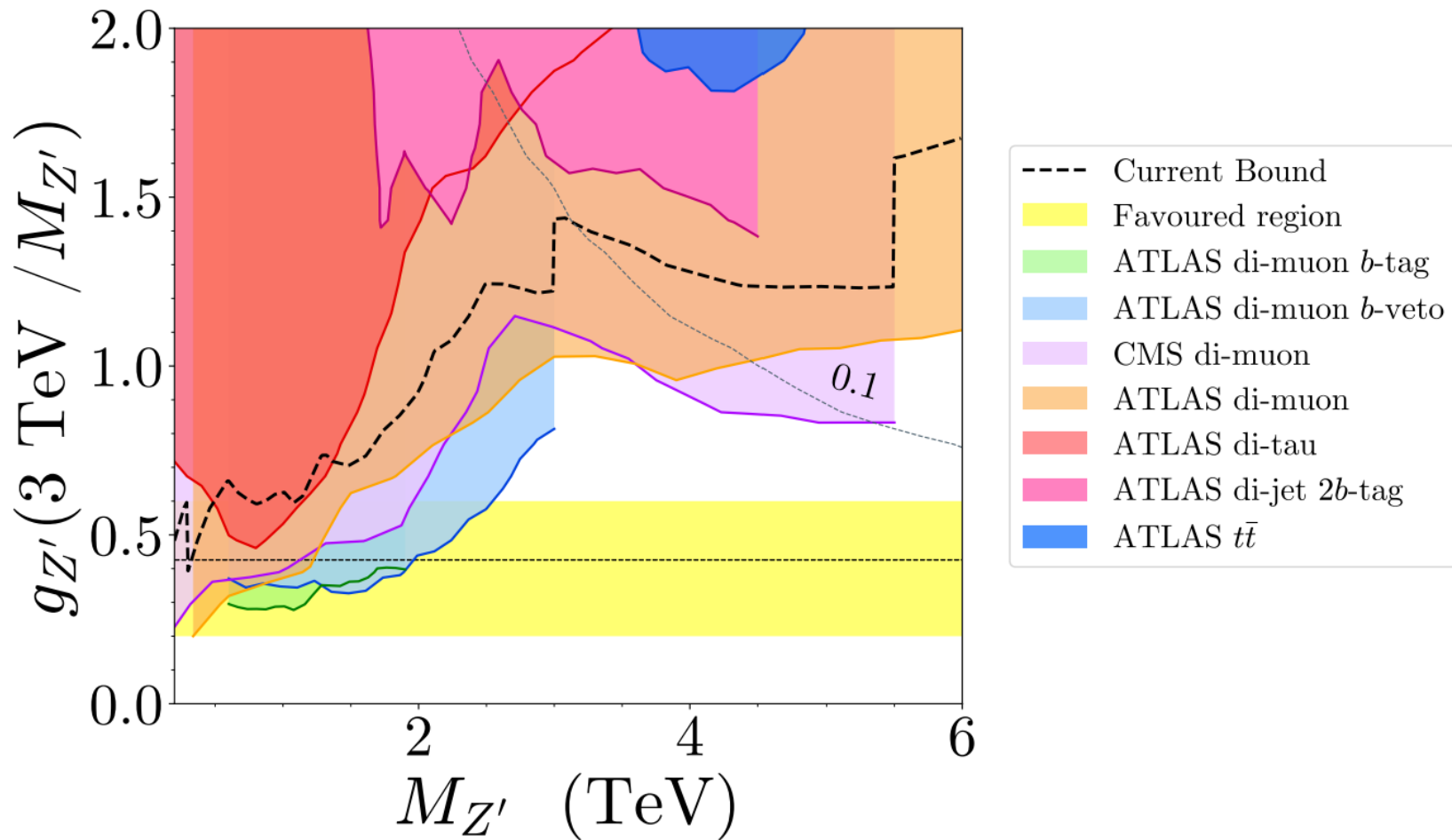


*Belle reports only upper limits.
We calculate BF ourselves

Overall compatibility is good $\chi^2/\text{ndf} = 4.3/4$

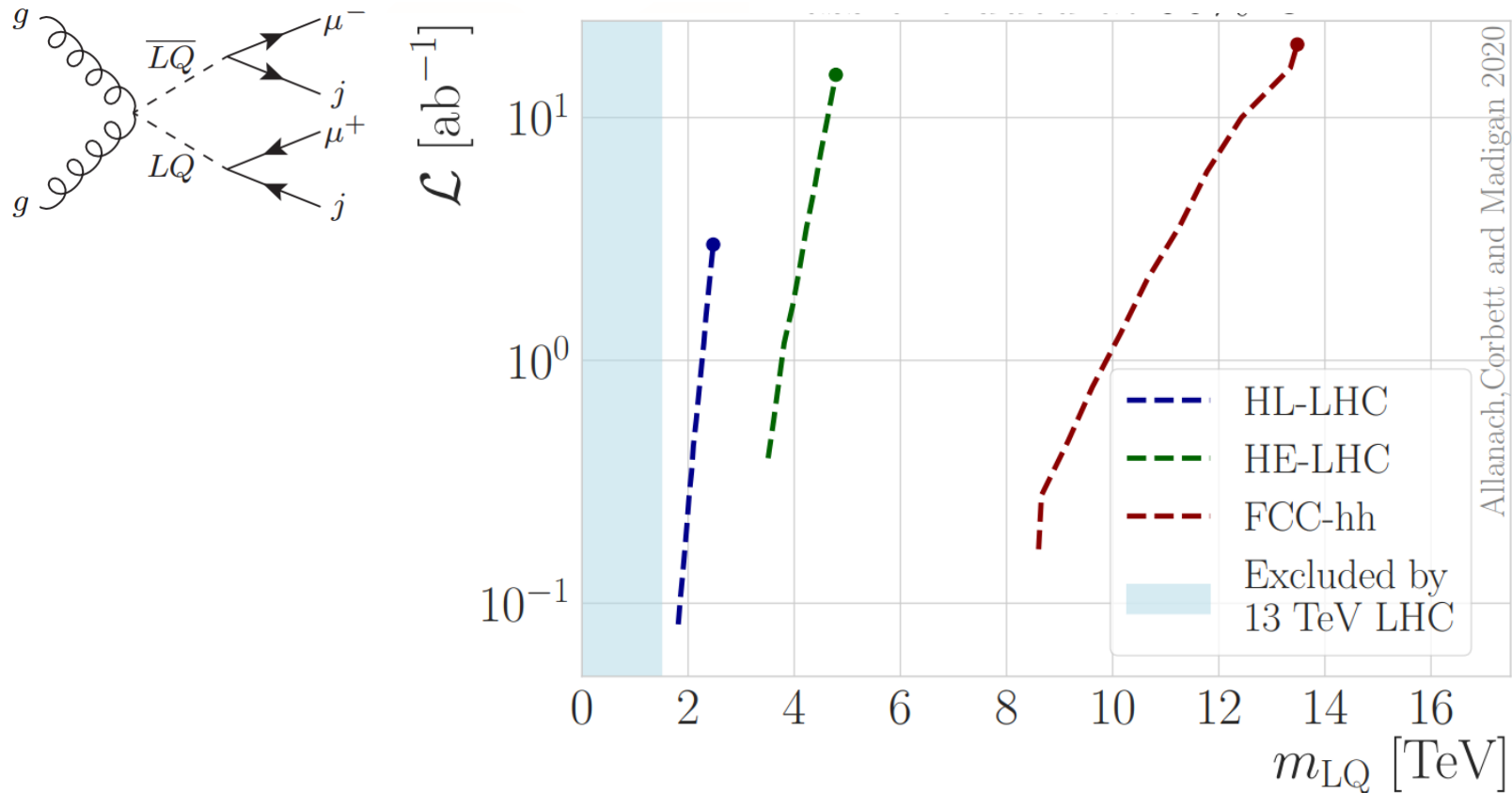


Y_3 HL-LHC sensitivity⁷



⁷BCA, Banks, 2111.06691

Scalar LQ^8 : eg $S_3 \sim (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$



⁸BCA, Corbett, Madigan, 1911.0445