The status of B anomalies after Moriond 2019

M. Fedele

based on arXiv:1512.07157 in collaboration with:

M. Ciuchini, E. Franco, S. Mishima, A. Paul, L. Silvestrini & M. Valli

on arXiv:1704.01737 and arXiv:1903.09632 in collaboration with:

M. Ciuchini, A. Coutinho, E. Franco, A. Paul, L. Silvestrini & M. Valli

and on arXiv:1904.05890 in collaboration with:

P. Arnan, F. Mescia and A. Crivellin

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Summary

- *Theoretical Framework*
- *Experimental anomalies*
- *Global fits*
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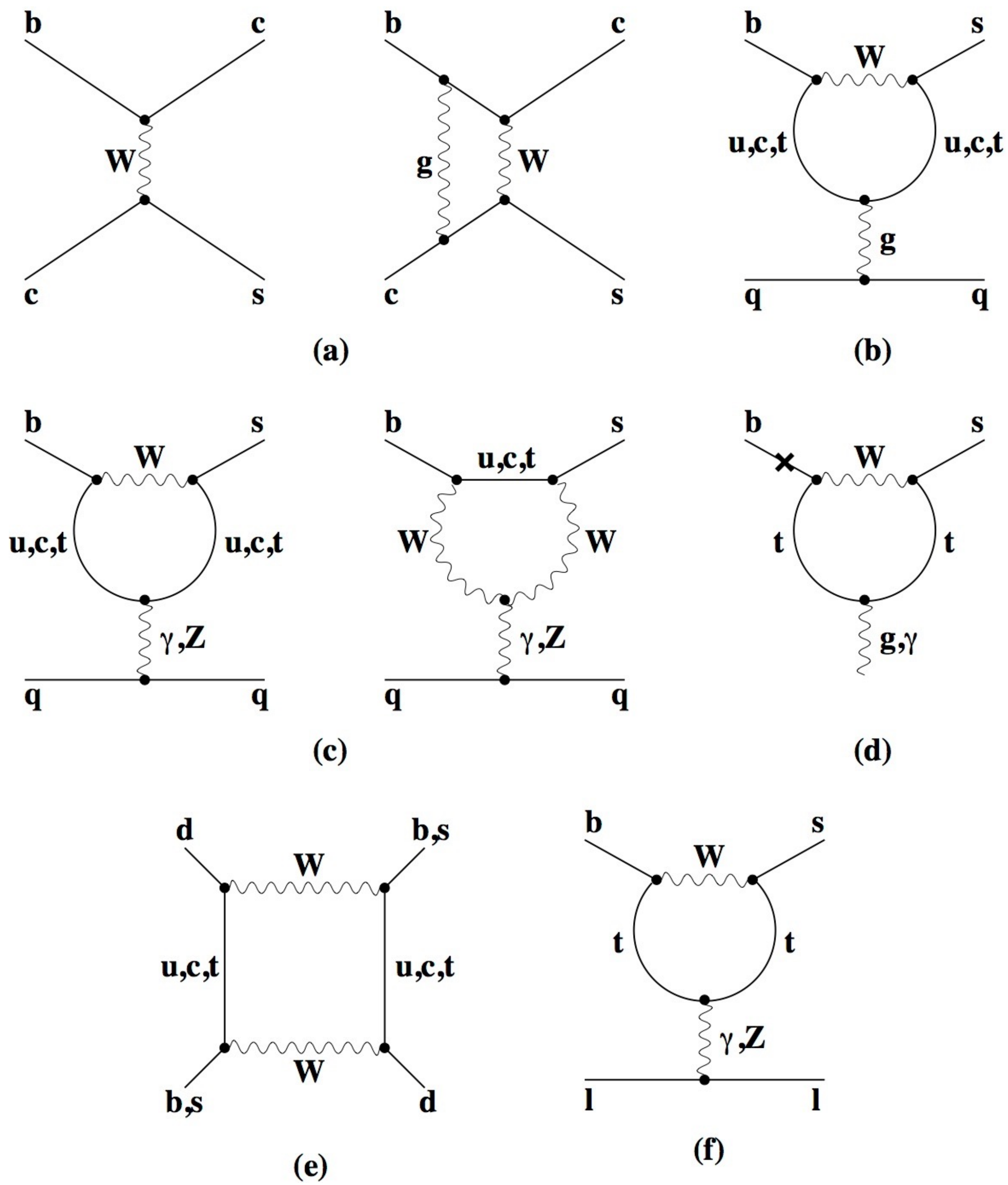
B Meson decays and the Quest for New Physics



- Absence of FCNC decays at tree-level in SM

$\Downarrow$

- Loop diagrams provide sizable contributions

$\Downarrow$

- New Physics processes might provide sizable contributions as well

The B → V(P)ll decay channel: the Hamiltonian

$$H_{eff}^{\Delta B=1} = H_{eff}^{had} + H_{eff}^{sl+\gamma}$$

$$H_{eff}^{had} = \frac{4G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_p \left[C_1 P_1^p + C_2 P_2^p + \sum_{i=3,\dots,6} C_i P_i + C_{8g} Q_{8g} \right]$$

$$H_{eff}^{sl+\gamma} = \frac{4G_F}{\sqrt{2}} \lambda_t \left[C_7^{(\prime)} Q_{7\gamma}^{(\prime)} + C_9^{(\prime)} Q_{9V}^{(\prime)} + C_{10}^{(\prime)} Q_{10A}^{(\prime)} + C_S^{(\prime)} Q_S^{(\prime)} + C_P^{(\prime)} Q_P^{(\prime)} \right]$$

$$\begin{aligned}
P_1^p &= (\bar{s}_L \gamma_\mu T^a p_L)(\bar{p}_L \gamma^\mu T^a b_L) \\
P_2^p &= (\bar{s}_L \gamma_\mu p_L)(\bar{p}_L \gamma^\mu b_L) \\
P_3 &= (\bar{s}_L \gamma_\mu b_L) \sum\nolimits_q (\bar{q} \gamma^\mu q) \\
P_4 &= (\bar{s}_L \gamma_\mu T^a b_L) \sum\nolimits_q (\bar{q} \gamma^\mu T^a q) \\
P_5 &= (\bar{s}_L \gamma_{\mu 1} \gamma_{\mu 2} \gamma_{\mu 3} b_L) \sum\nolimits_q (\bar{q} \gamma^{\mu 1} \gamma^{\mu 2} \gamma^{\mu 3} q) \\
P_6 &= (\bar{s}_L \gamma_{\mu 1} \gamma_{\mu 2} \gamma_{\mu 3} T^a b_L) \sum\nolimits_q (\bar{q} \gamma^{\mu 1} \gamma^{\mu 2} \gamma^{\mu 3} T^a q)
\end{aligned}$$

$$\begin{aligned}
Q_{7\gamma} &= \frac{e}{16\pi^2} \hat{m}_b \bar{s} \sigma_{\mu\nu} P_R F^{\mu\nu} b \\
Q_{8g} &= \frac{\gamma_s}{16\pi^2} \hat{m}_b \bar{s} \sigma_{\mu\nu} P_R G^{\mu\nu} b \\
Q_{9V} &= \frac{\alpha_{em}}{4\pi} (\bar{s} \gamma_\mu P_L b)(\bar{\ell} \gamma^\mu \ell) \\
Q_{10A} &= \frac{\alpha_{em}}{4\pi} (\bar{s} \gamma_\mu P_L b)(\bar{\ell} \gamma^\mu \gamma^5 \ell) \\
Q_S &= \frac{\alpha_{em}}{4\pi} \frac{\hat{m}_b}{m_W} (\bar{s} P_R b)(\bar{\ell} \ell) \\
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Matrix elements of quark currents from $Q_{7,9,10,S,P}$ naively factorize:

$$\mathcal{A} \sim \langle \ell^+ \ell^- | J_{\text{lep}} | 0 \rangle \langle V(P) | J_{had} | \overline{B} \rangle$$

Not possible for the hadronic Hamiltonian!

$$\tilde{h}_\lambda(q^2) \sim \epsilon_{\lambda,\mu} \int d^4x \, e^{iqx} \langle V(P) | T\{ J_{had}^{\mu,e.m.}(x) \mathcal{H}_{had}^{eff}(0) \} | B \rangle$$

The B → V(P)ll decay channel: the amplitudes

The amplitudes, in the helicity basis, are proportional to

$$
\begin{aligned}
H_\lambda^V(q^2) &\propto (C_9 - C_9')\tilde{V}_\lambda(q^2) + \frac{2m_b m_B}{q^2}(C_7 - C_7')\tilde{T}_\lambda(q^2) - 16\pi^2 \frac{m_B^2}{q^2}\tilde{h}_\lambda(q^2) \\
H_\lambda^A(q^2) &\propto (C_{10} - C_{10}')\tilde{V}_\lambda(q^2) \\
H^S(q^2) &\propto \frac{m_b}{m_W}(C_S - C_S')\tilde{S}(q^2) \\
H^P(q^2) &\propto \frac{m_b}{m_W}(C_P - C_P')\tilde{S}(q^2) + \frac{2m_\ell m_B}{q^2}(C_{10} - C_{10}')\left(1 + \frac{m_s}{m_b}\right)\tilde{S}(q^2)
\end{aligned}
$$

$$(\lambda = 0, \pm)$$

The main sources of uncertainties are coming from the form factors and from the hadronic parameters

The B → V(P)ll decay channel: the form factors

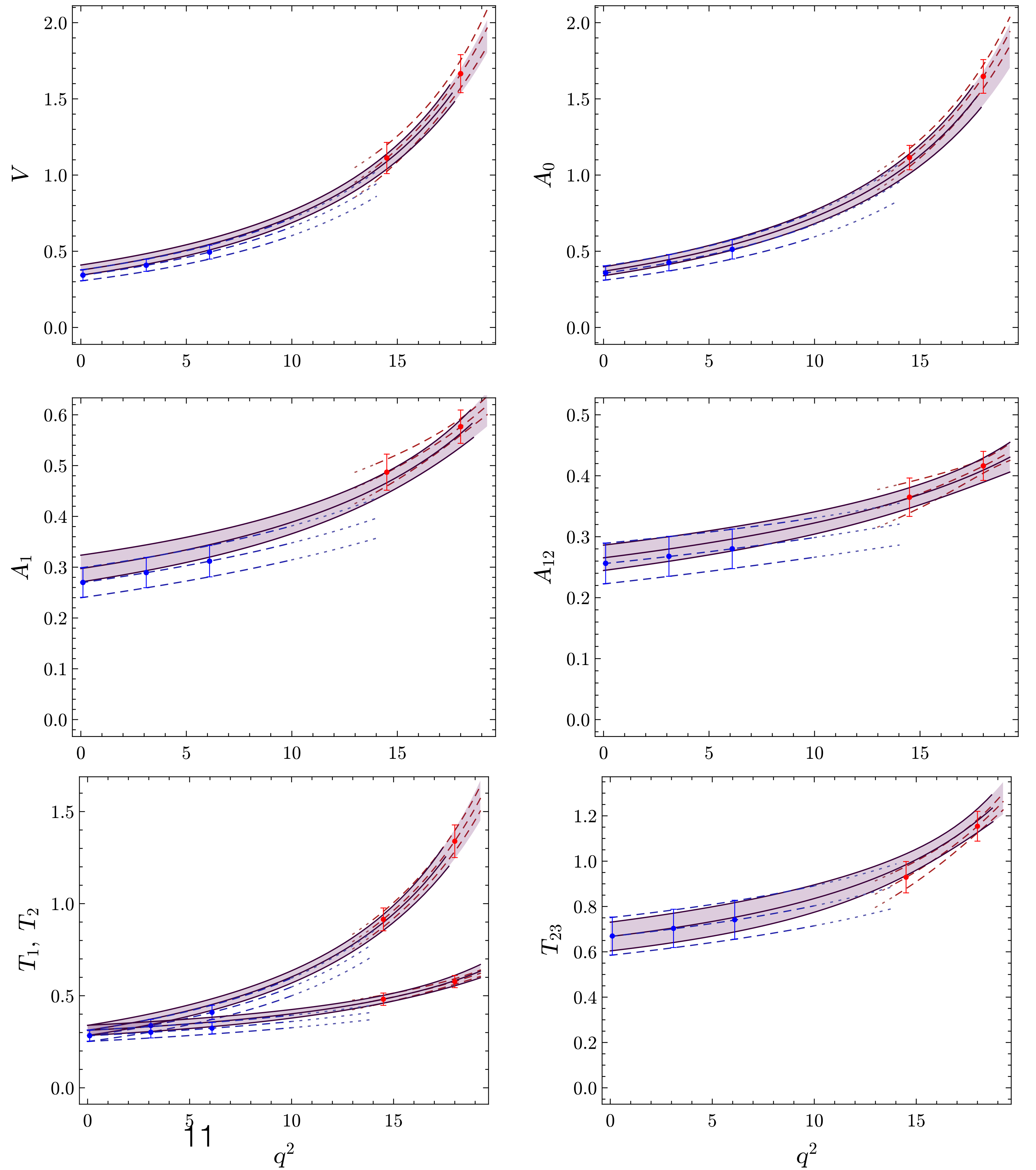
Low recoil region (Lattice, Pos Lattice2014 (2015) 372)

vs.

Large recoil region (LCSR, JHEP 08 (2016) 098)

⇓

Full form factors, together with the *correlation matrix*, have become a reliable option



The B → V(P)ll decay channel: the hadronic parameter

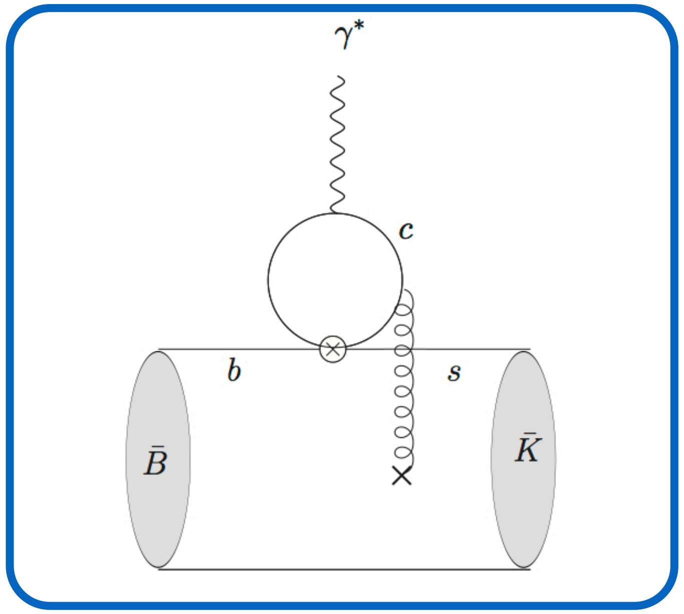
At first order in α_{em} we can get a contribution from current-current quark operators & QCD penguins

Loop suppressed amplitude, can be enhanced by non-perturbative QCD effects!

In particular, charm current-current insertion not further parametrically suppressed.

Soft gluon emission from cc-loop estimated for P = K and V = K* with LCSR + dispersion relation. **Sizable effect in K***

The charm-loop effect



⇒ Correlator expanded on the light-cone: **LCSR estimate based on small q^2** .

⇒ **Dispersion relation** in order **to extrapolate LCSR result** up to charm resonances.

⇒ **Single soft gluon approximation**: strictly valid only for $\mathbf{q^2 << 4 m^2_c}$!

A. Khodjamirian et al., **JHEP 1009 (2010) 089**

The B → V(P)ll decay channel: the hadronic parameter

Two more recent studies on the subject:

- Phenomenological model obtained as a sum of Breit-Wigner, resonance data to fix the parameters

T. Blake et al.,
EPJC 78 (2018) 6, 453

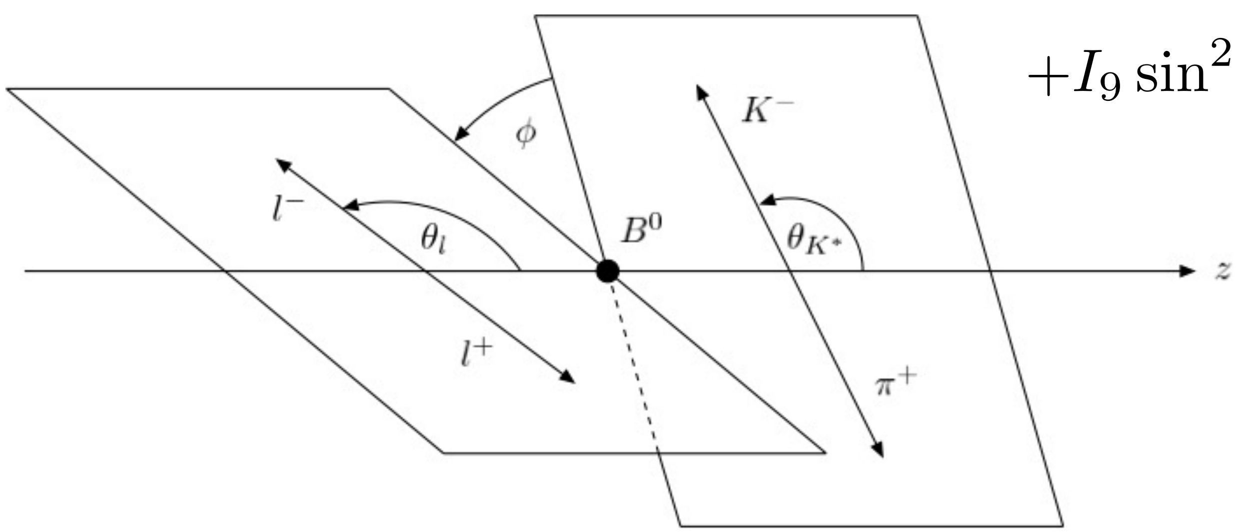
- Similar to JHEP09(2010)089, but with dispersion relation replaced by z-expansion, with coeffs. constrained by analicity and $B \to K^* \psi_n$ data

C. Bobeth et al.,
EPJC 78 (2018) 6, 451

Problem of multiple soft-gluon emission still open…

The B → V(P)ll decay channel: the kinematic distribution

$$\frac{d^{(4)}\Gamma}{dq^2 d(\cos\theta_\ell) d(\cos\theta_K) d\phi} = \frac{9}{32\pi}\Big(I_1^s \sin^2\theta_K + I_1^c \cos^2\theta_K + (I_2^s \sin^2\theta_K + I_2^c \cos^2\theta_K)\cos 2\theta_\ell$$
$$+ I_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + I_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi$$
$$+ I_5 \sin 2\theta_K \sin\theta_\ell \cos\phi + (I_6^s \sin^2\theta_K + I_6^c \cos^2\theta_K)\cos\theta_\ell$$
$$+ I_7 \sin 2\theta_K \sin\theta_\ell \sin\phi + I_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi$$
$$+ I_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi\Big).$$



$$\Sigma_i = \frac{I_i + \bar{I}_i}{2}$$

CP-Averaged

In the massless-lepton limit, 2 relations reduce the number of independent observables

$$\Sigma_{1c} = -\Sigma_{2c} \qquad \Sigma_{1s} = 3\Sigma_{2s}$$

The B $\to$ V(P)ll decay channel: the observables

The angular coefficients are functions of the helicity amplitudes, and the building blocks of the obs.

- BR

$$\Gamma' = \frac{1}{2}\frac{d\Gamma + d\bar{\Gamma}}{dq^2} = \Sigma_{1c} + 4\Sigma_{2s}$$

- 8 CP-Averaged angular observables

$$A_{FB} = -\frac{3\Sigma_{6s}}{4\Gamma'} \qquad F_L = \frac{\Sigma_{1c}}{\Gamma'}$$

$$S_{3,4,5,7,8,9} = \frac{\Sigma_{3,4,5,7,8,9}}{\Gamma'}$$

The B → V(P)ll decay channel: the observables

The angular coefficients are functions of the helicity amplitudes, and the building blocks of the obs.

- BR

$$\Gamma' = \frac{1}{2}\frac{d\Gamma + d\bar{\Gamma}}{dq^2} = \Sigma_{1c} + 4\Sigma_{2s}$$

- 8 CP-Averaged angular observables

$$P_1 = \frac{\Sigma_3}{2\Sigma_{2s}} \qquad P_2 = \frac{\Sigma_{6s}}{8\Sigma_{2s}} \qquad P_3 = -\frac{\Sigma_9}{4\Sigma_{2s}}$$

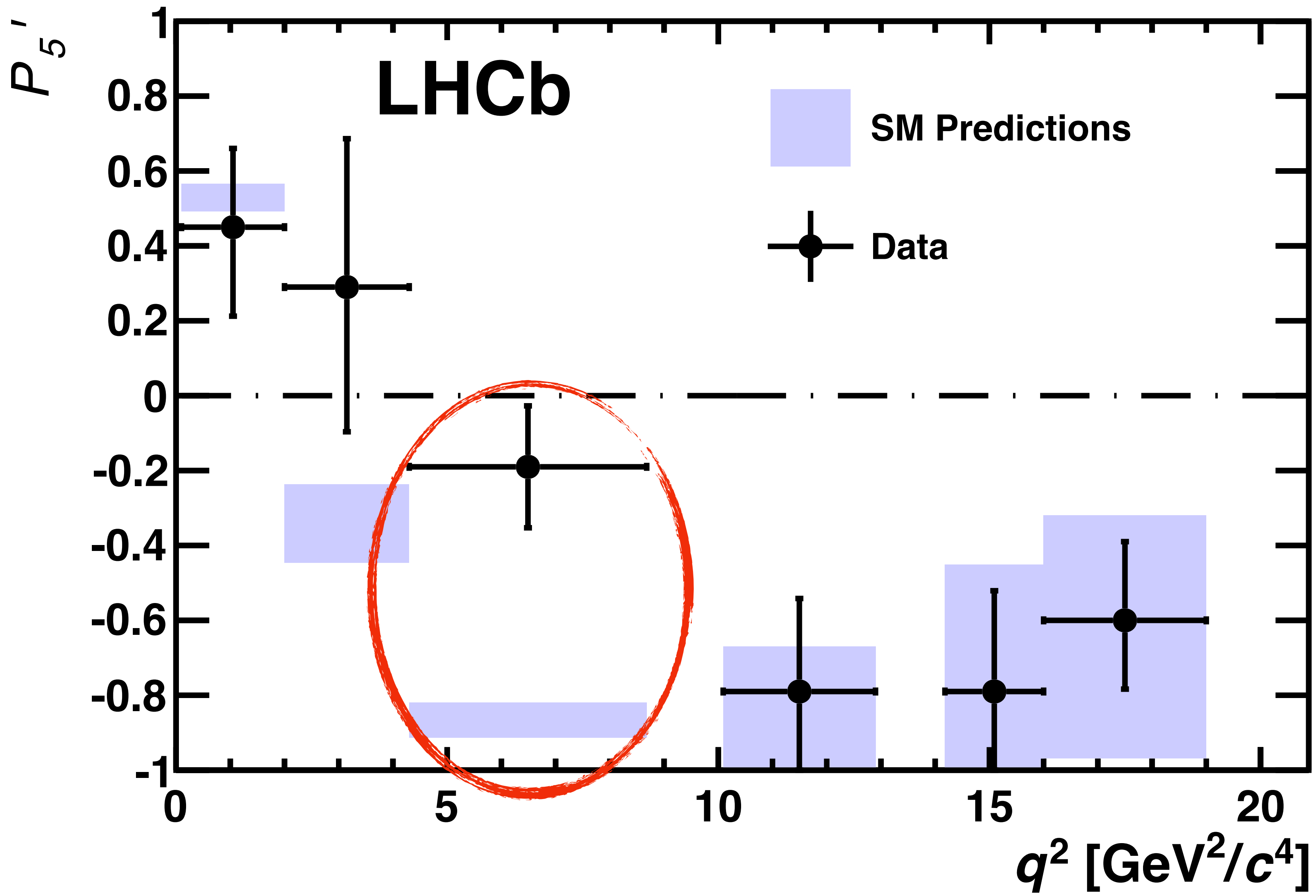
$$P_4' = \frac{\Sigma_4}{\sqrt{-\Sigma_{2s}\Sigma_{2c}}} \quad P_5' = \frac{\Sigma_5}{2\sqrt{-\Sigma_{2s}\Sigma_{2c}}} \quad P_6' = -\frac{\Sigma_7}{2\sqrt{-\Sigma_{2s}\Sigma_{2c}}} \quad P_8' = -\frac{\Sigma_8}{\sqrt{-\Sigma_{2s}\Sigma_{2c}}}$$

Summary

- *Theoretical Framework*
- *Experimental anomalies*
- *Global fits*
- *A possible solution*

Angular analysis of $B \to K^*\mu\mu$ (i)

INTRIGUING SET OF "ANOMALIES" IN DATA OF EXCLUSIVE B RARE DECAYS



PRL 111 (2013) 191801

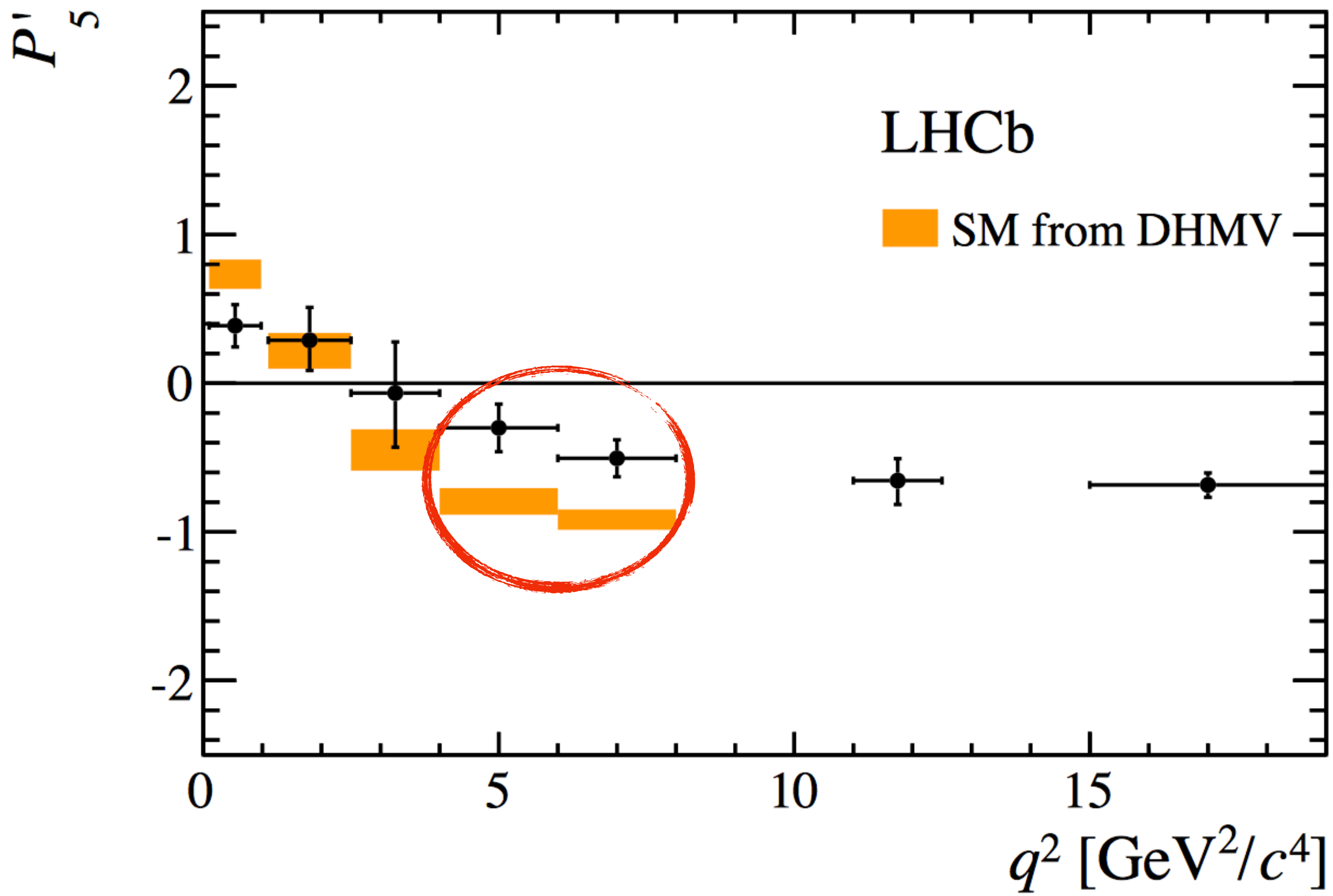
- LHCb (1fb^{-1}, mid-Run I)
- $4.30 < q^2 / \mathrm{GeV}^2 < 8.68$
- 3.7 σ

$$P_5' \equiv \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

Potential pollution from had. cont.

Angular analysis of $B \to K^*\mu\mu$ *(ii)*

INTRIGUING SET OF "ANOMALIES" IN DATA OF EXCLUSIVE B RARE DECAYS



- LHCb (3fb^{-1}, end-Run I)
- $4.0 < q^2 / \text{GeV}^2 < 6.0$

  $6.0 < q^2 / \text{GeV}^2 < 8.0$
- 3.4 σ

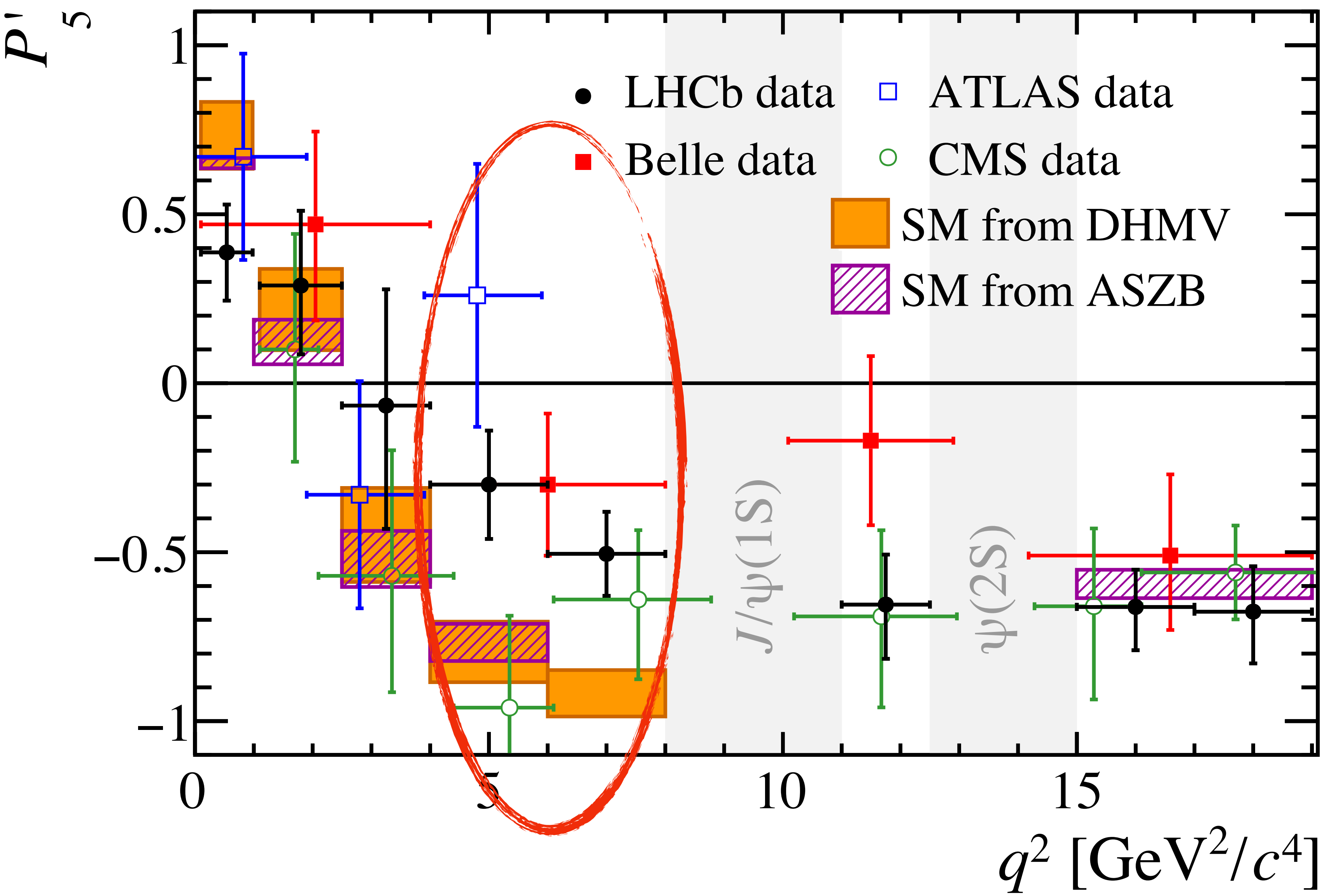
JHEP 02 (2016) 104

$$P'_5 \equiv \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

Potential pollution from had. cont.

Angular analysis of $B \to K^*\mu\mu$ (iii)

INTRIGUING SET OF "ANOMALIES" IN DATA OF EXCLUSIVE B RARE DECAYS



- ATLAS
- $4.0 < q^2$ / GeV$^2 < 6.0$
- 2.7 σ
- BELLE
- $4.0 < q^2$ / GeV$^2 < 8.0$
- 2.6 σ
- CMS
- No discrepancies!

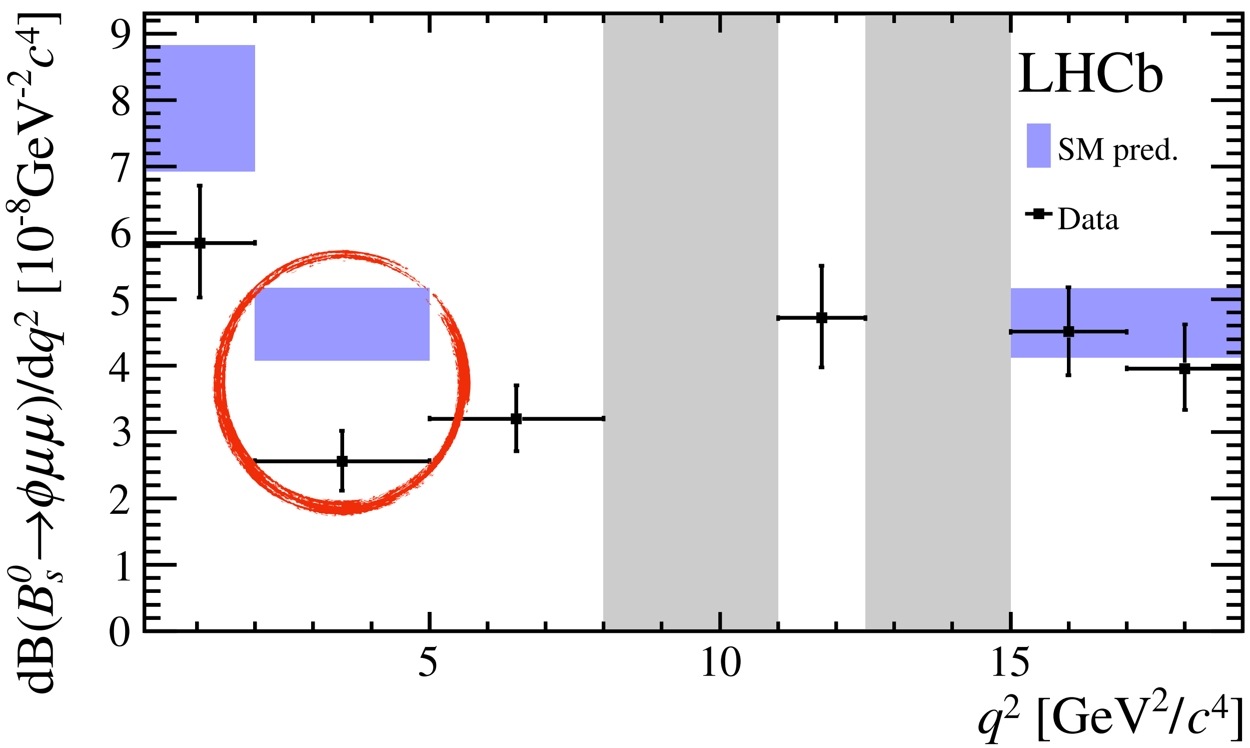
JHEP 02 (2016) 104 ATLAS-CONF-2017-023

PRL 118 (2017) 111801 CMS-PAS-BPD-15-008

Potential pollution from had. cont.

Branching Fractions of $B_s \to \phi\mu\mu$ and $B \to K\mu\mu$

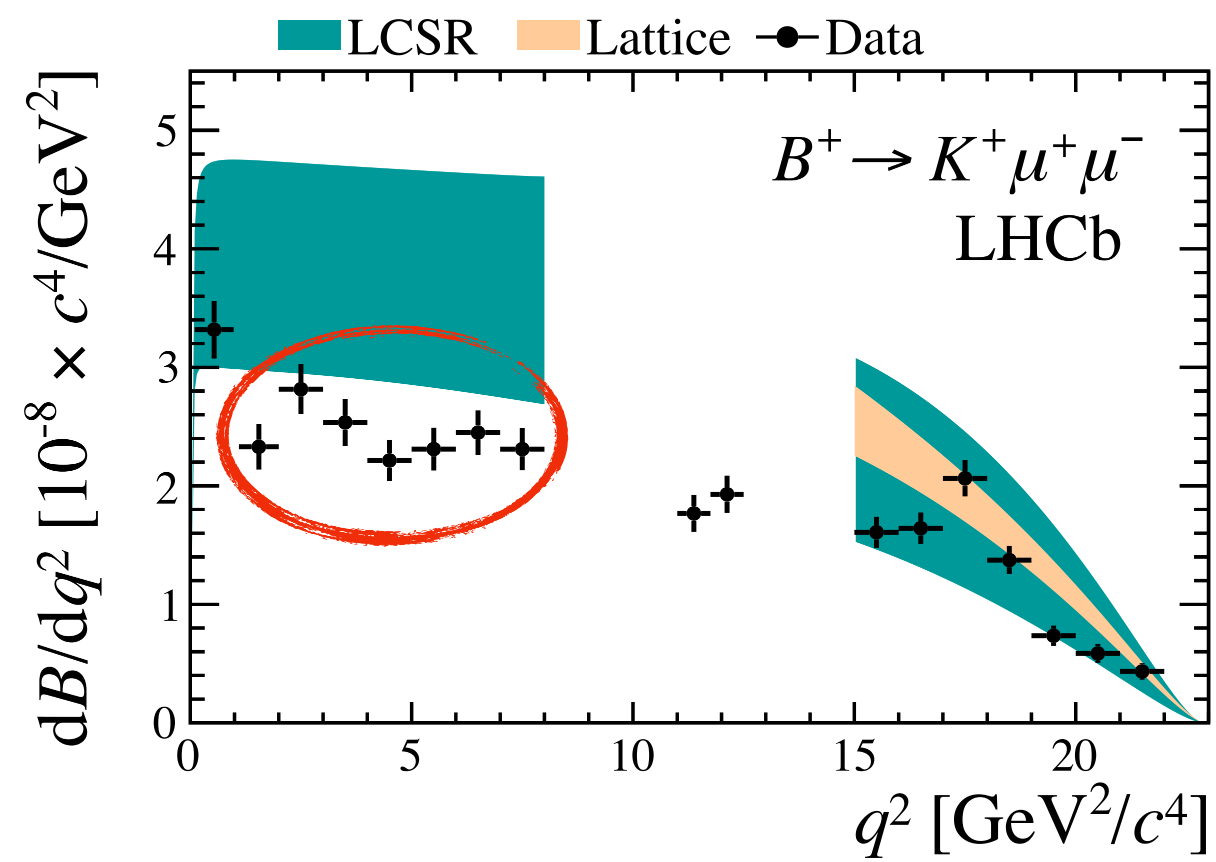
INTRIGUING SET OF "ANOMALIES" IN DATA OF EXCLUSIVE B RARE DECAYS



- 2.0 < q^2 / GeV^2 < 5.0
- 3.0 σ

JHEP 09 (2015) 179

Potential pollution from had. cont.



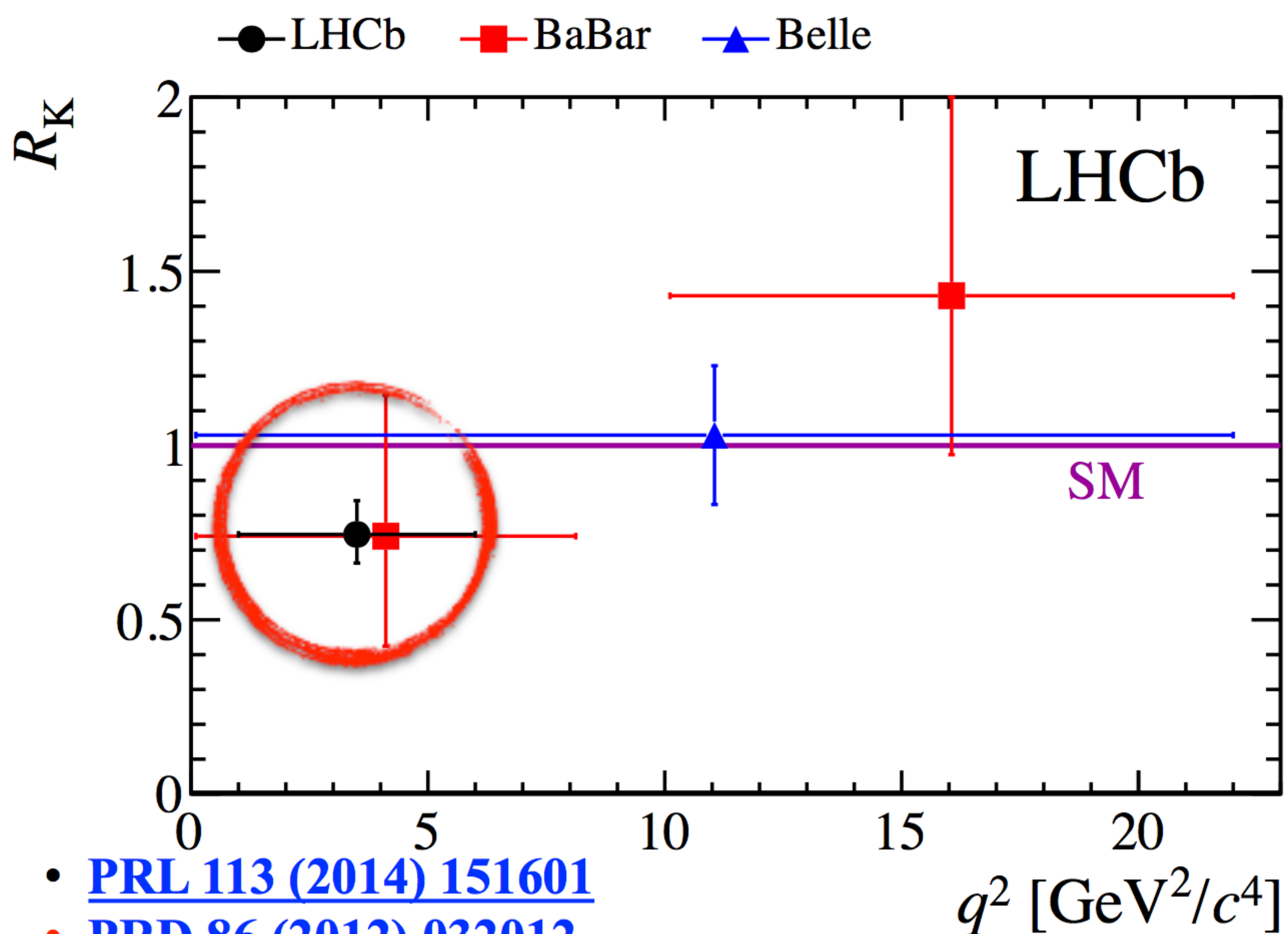
- Low q^2
- Consistently lower values

JHEP 06 (2014) 133

Pollution from had. cont. ~ negligible

Branching Fraction ratios: R_K

INTRIGUING SET OF "ANOMALIES" IN DATA OF EXCLUSIVE B RARE DECAYS



- PRL 113 (2014) 151601
- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

- LHCb
- $1.0 < q^2 / \mathrm{GeV}^2 < 6.0$
- 2.6 σ

No pollution from had. cont.

$R_{K^{(*)}} = Br(B \longrightarrow K^{(*)}\mu\mu) / Br(B \longrightarrow K^{(*)}ee)$

Branching Fraction ratios: R_{K^*}

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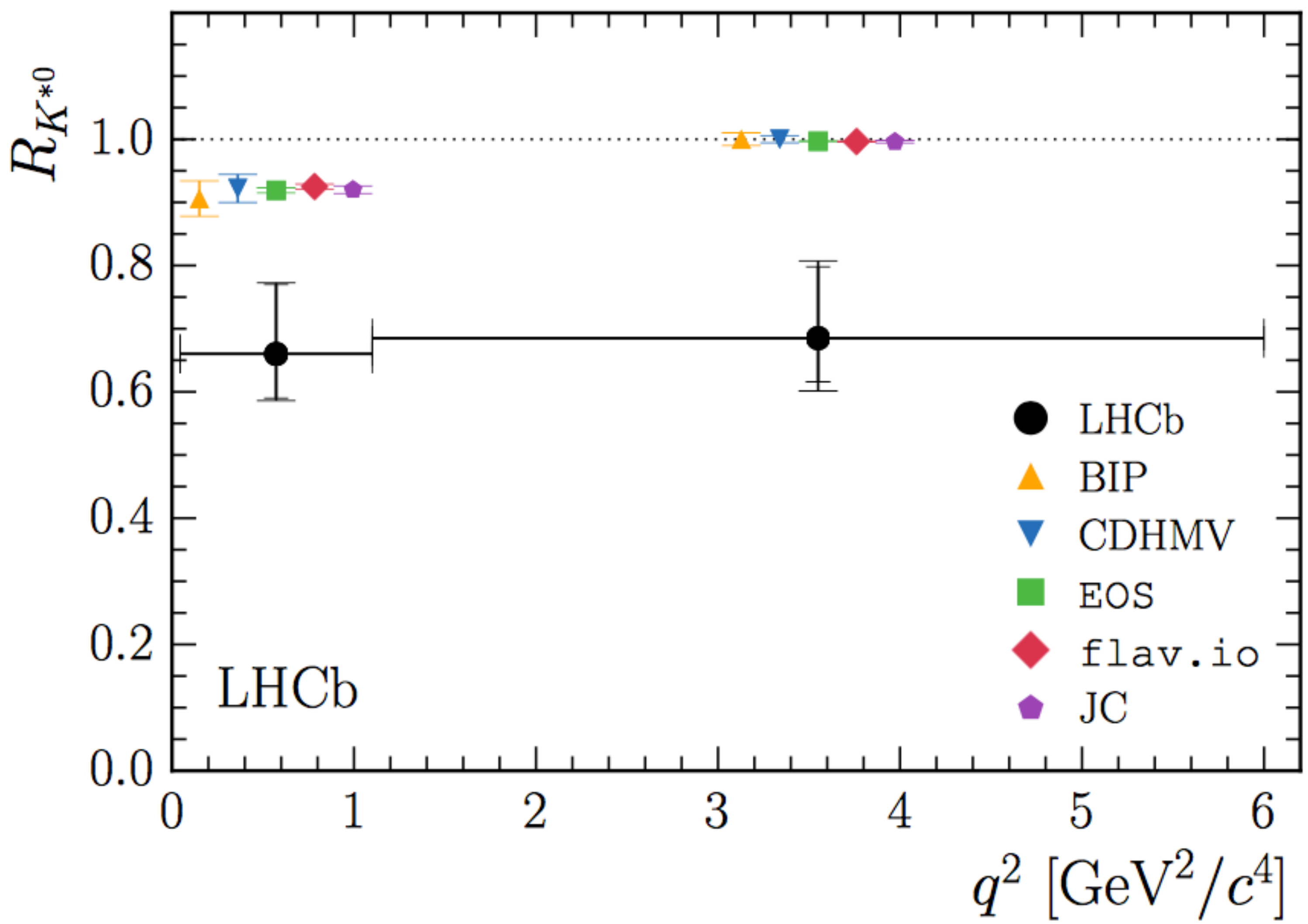

- LHCb
- $0.045 < q^2 / \text{GeV}^2 < 1.1$

  $1.1 < q^2 / \text{GeV}^2 < 6.0$
- 2.2 σ , 2.5 σ

JHEP 08 (2017) 055

No pollution from had. cont.

$R_{K^{(*)}} = Br(B \longrightarrow K^{(*)}\mu\mu) \,/\, Br(B \longrightarrow K^{(*)}ee)$

R_K & R_{K^*} After Moriond 2019

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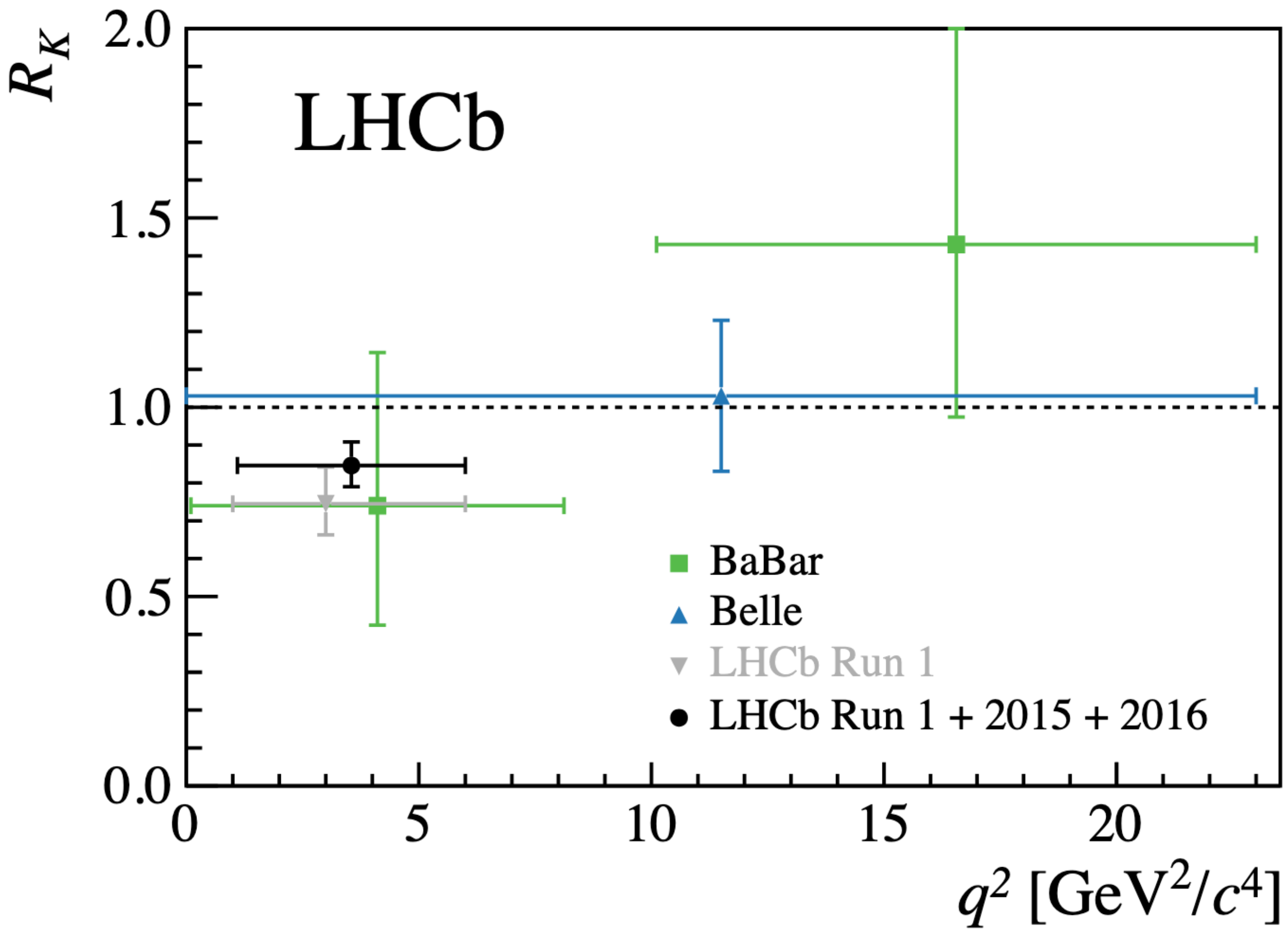

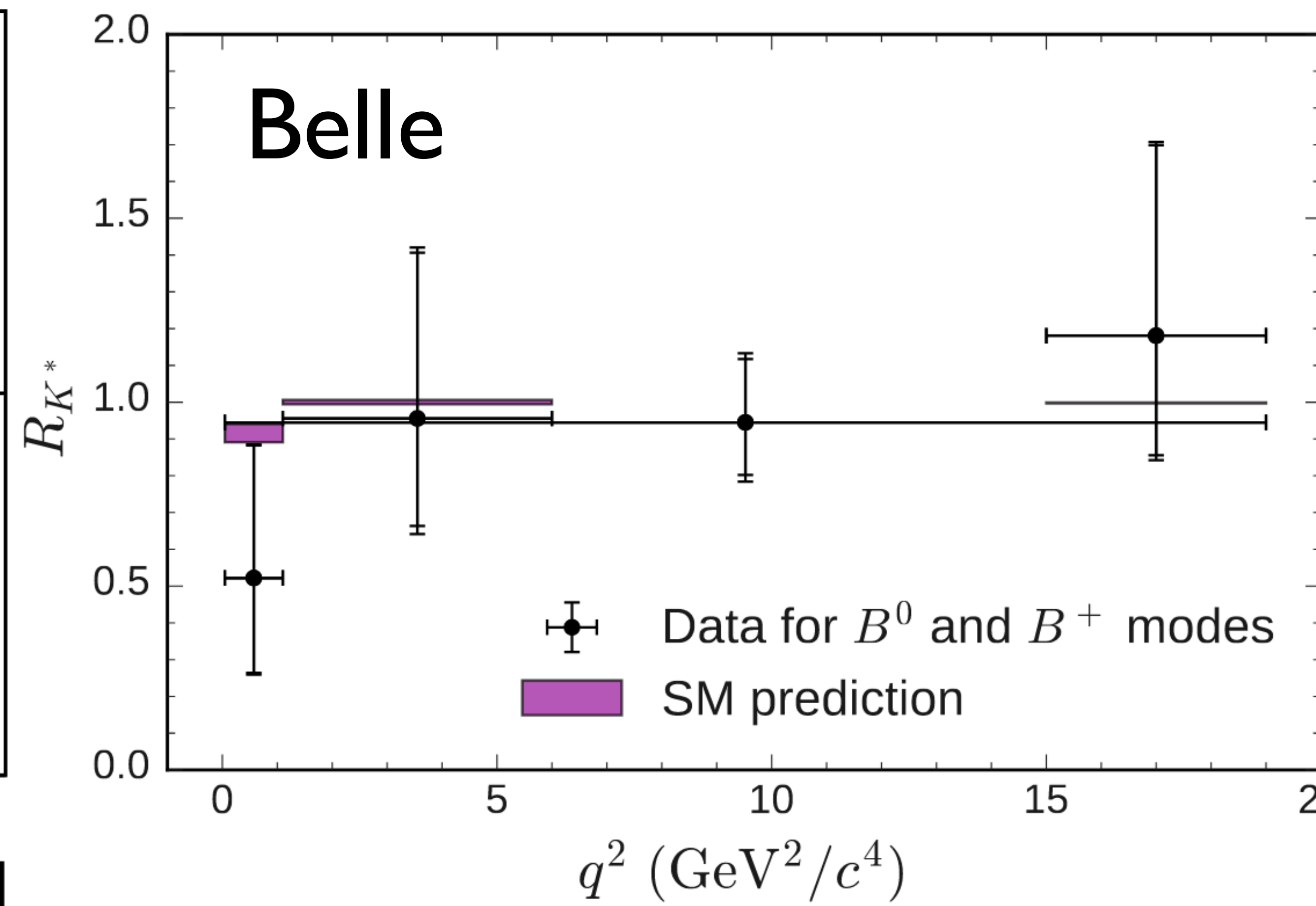

No pollution from had. cont.

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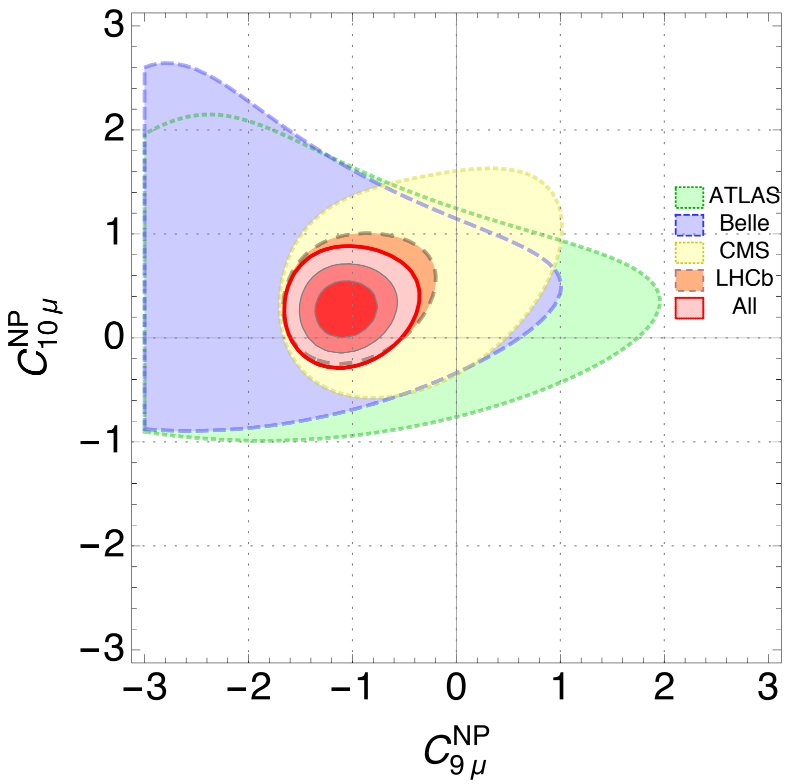
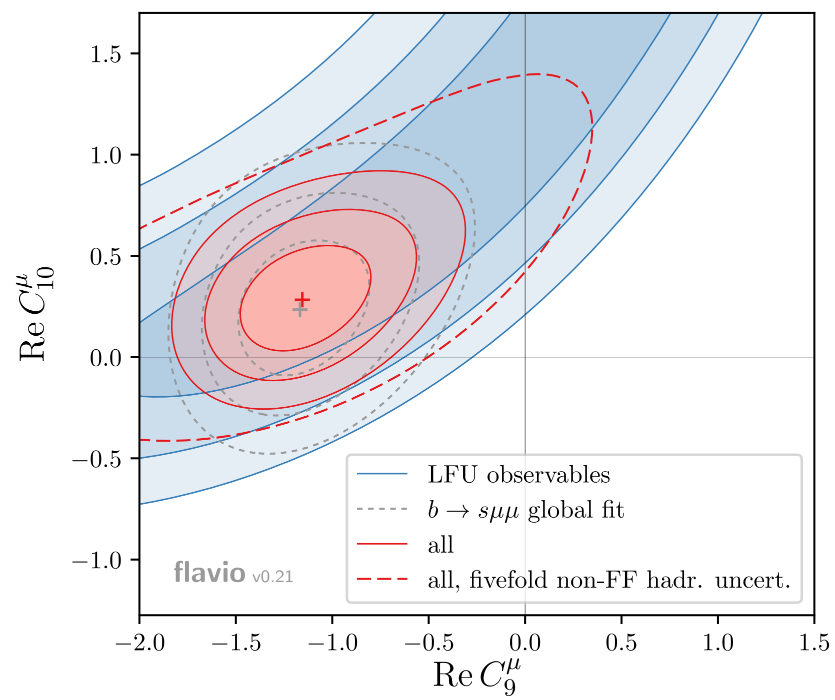
A fascinating solution: C9μ

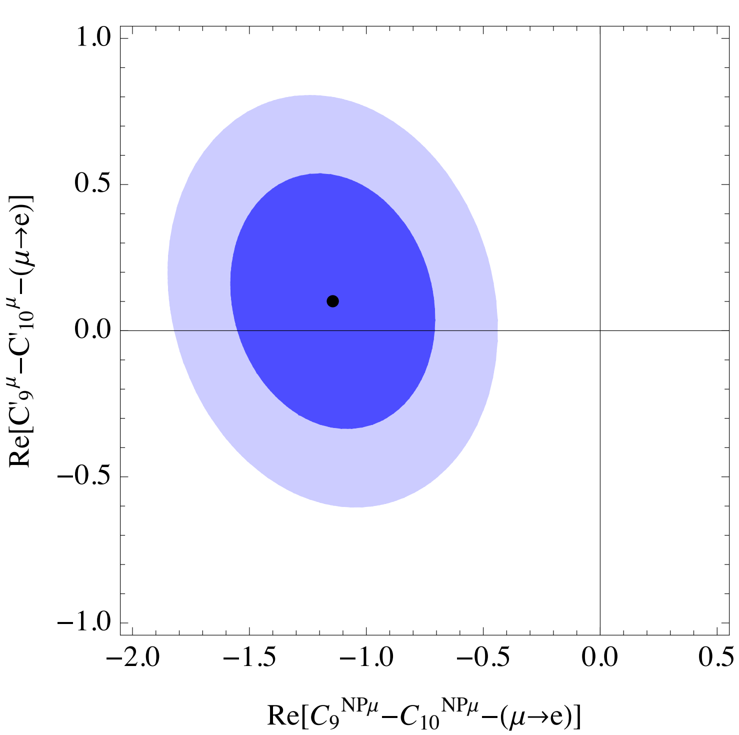
It is possible to explain everything simply requiring NP effect in C9μ



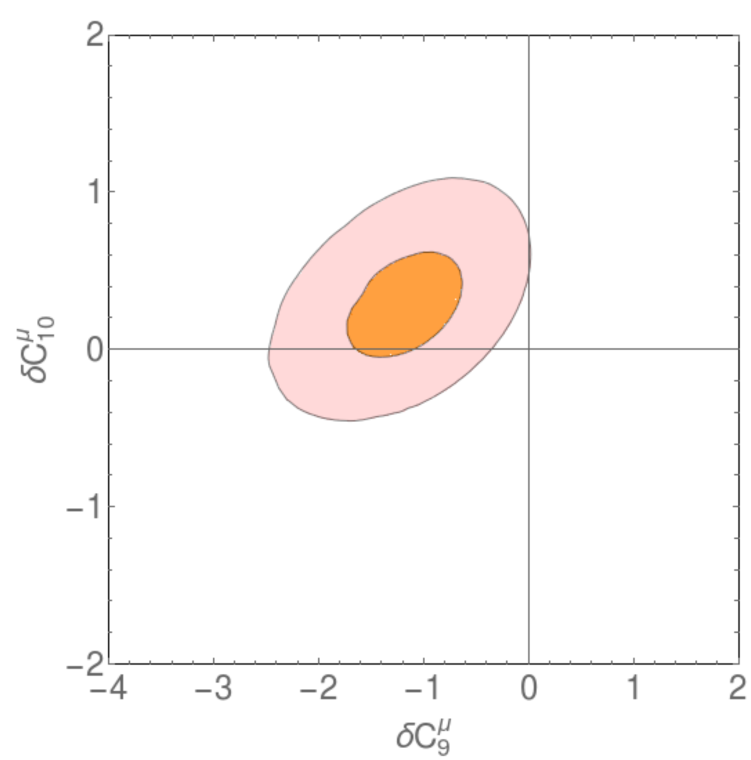
JHEP 01 (2018) 093



Phys. Rev. D96 (2017) 055008



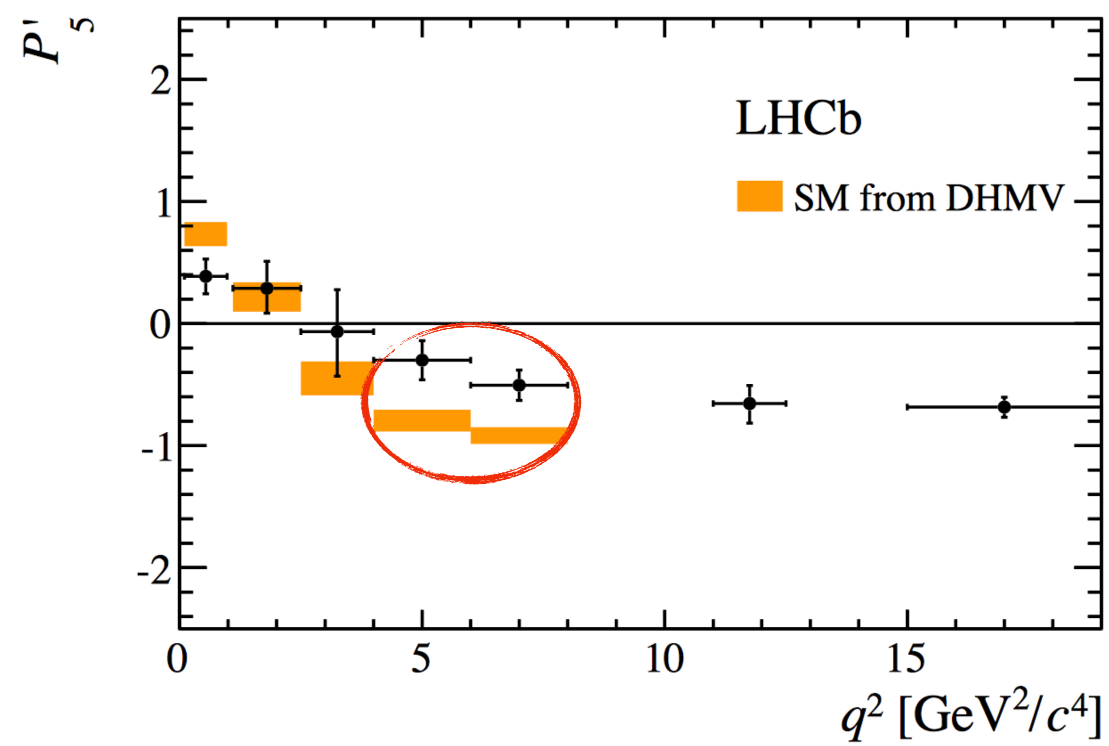
Phys. Rev. D96 (2017) 035003



Phys. Rev. D96 (2017) 093006

Yet another analysis: why?

The first analysis addressing the *B* —> *K**$\mu\mu$ angular anomaly where performed employing the **LCSR estimate** for the hadronic contribution



Single soft gluon approximation: strictly valid only for $\mathbf{q^2 << 4 m^2_c}$!

⇒ First analysis of the *B* —> *K**$\mu\mu$ decay channel only, aiming to extract the hadronic contribution from data and compare it with LCSR estimate

⇒ Global fit of the *b* —> *s* anomalies, without forgetting what we learnt from the previous analysis

Parameterizing the hadronic contribution

$$H_\lambda^V(q^2) \propto C_9 \tilde{V}_\lambda(q^2) + \frac{2 m_b m_B}{q^2} C_7 \tilde{T}_\lambda(q^2) - 16\pi^2 \frac{m_B^2}{q^2} \tilde{h}_\lambda(q^2)$$

$$H_\lambda^A(q^2) \propto C_{10} \tilde{V}_\lambda(q^2)\,, \qquad H^P(q^2) \propto \frac{2 m_\ell m_B}{q^2} C_{10} \left(1 + \frac{m_s}{m_b}\right) \tilde{S}(q^2)$$

We parameterized the hadronic contribution in order to have a term that cannot be reinterpreted as a NP contribution

$$\tilde{h}_\lambda(q^2) = \sum_i \tilde{h}_\lambda^{(i)} \left(\frac{q^2}{GeV^2}\right)^i \qquad \begin{array}{l} i = 0 \;\leftrightarrow\; C_7^{NP} \\ i = 1 \;\leftrightarrow\; C_9^{NP} \end{array}$$

OBS: $i = 2$ **gives a potential discriminator** (q^2 dependence in FFs being fairly mild).

—> hadronic effects may show important dependence on q^2 and on helicity as well

Ciuchini, MF, Franco, Mishima, Paul, Silvestrini, Valli (1512.07157)

The SM analysis, PDD vs. PMD

EXPERIMENTAL WEIGHTS :

$$F_L, A_{FB}, S_{3,4,5,7,8,9}$$

correlated in each bin of q^2

$$\mathcal{B}(B \to K^* \mu\mu)$$

$$\mathcal{B}(B \to K^* \gamma)$$

$$\mathcal{B}(B \to K^* ee), F_L, P_{1,2,3}$$

THEORY WEIGHTS :

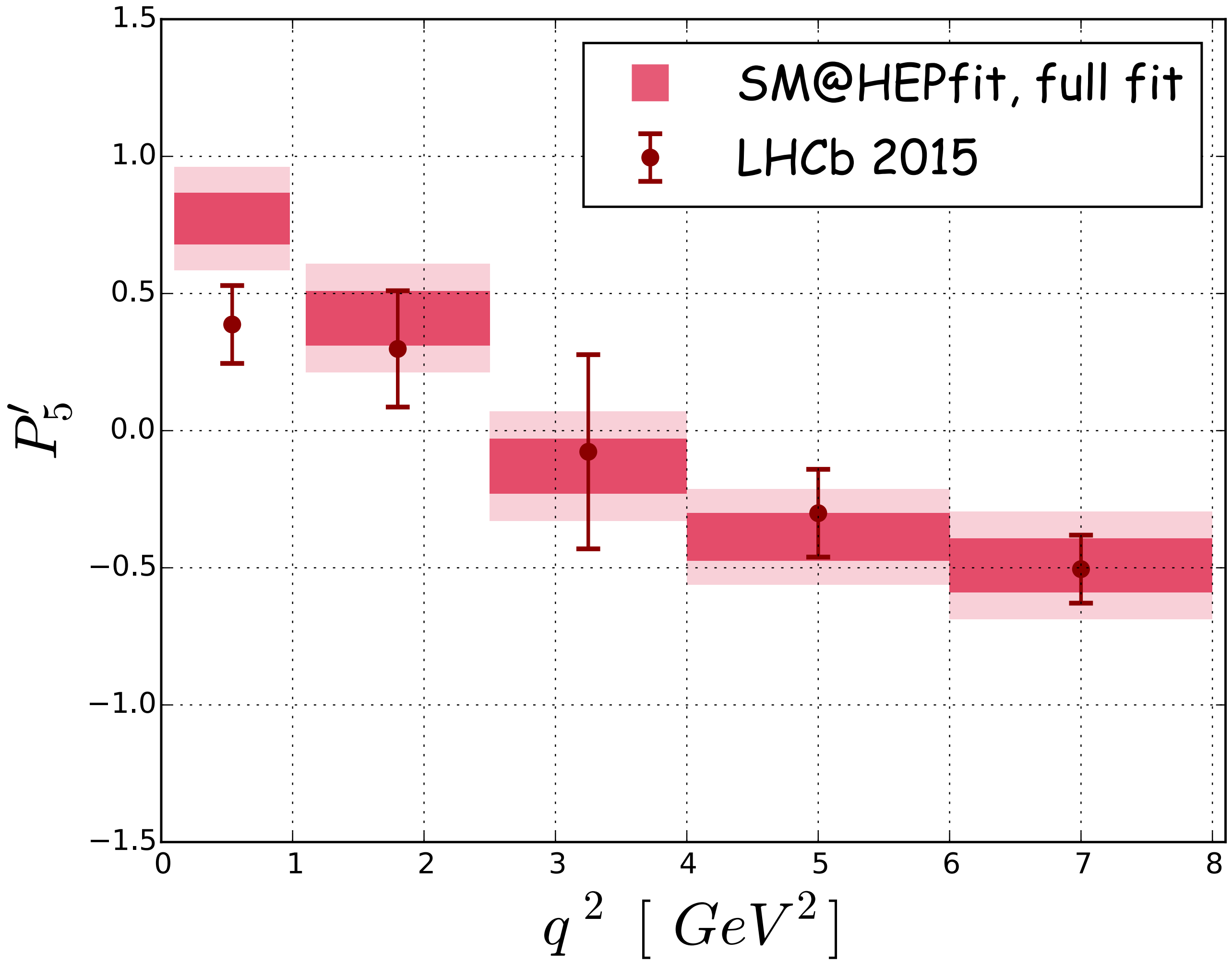
LCSR FFs with correlation matrix for low q^2 region only

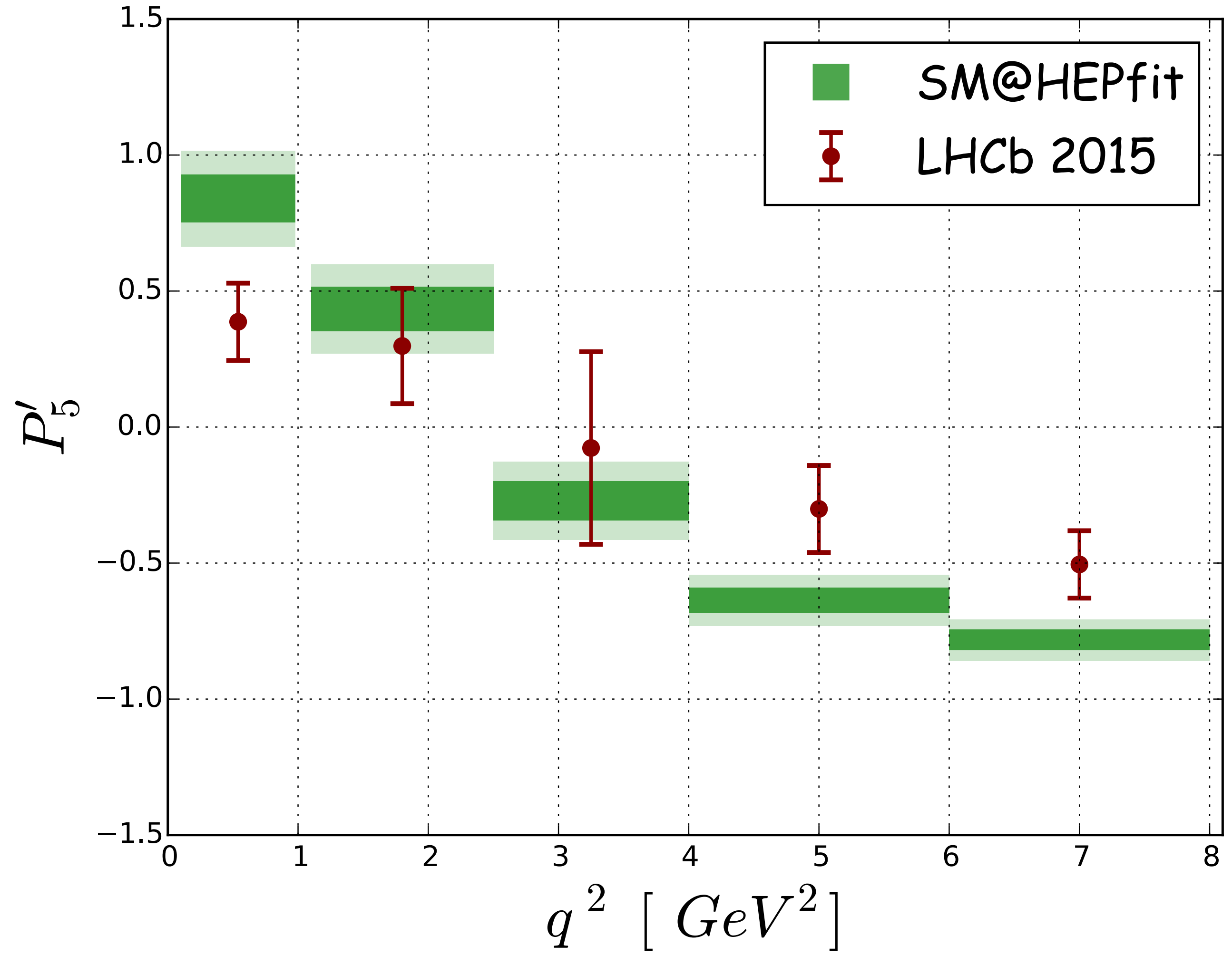
Amplitude helicity suppression at kinematical endpoint

JHEP 09(2010)089 *constraint* → only for $q^2 \lesssim 1\ \mathrm{GeV}^2$ (PDD)
→ for "all" q^2 (PMD)

Ciuchini, MF, Franco, Mishima, Paul, Silvestrini, Valli (1512.07157)

The SM analysis, PDD vs. PMD





No anomalies in P'_5 …!

Anomaly strikes back in P'_5 …!

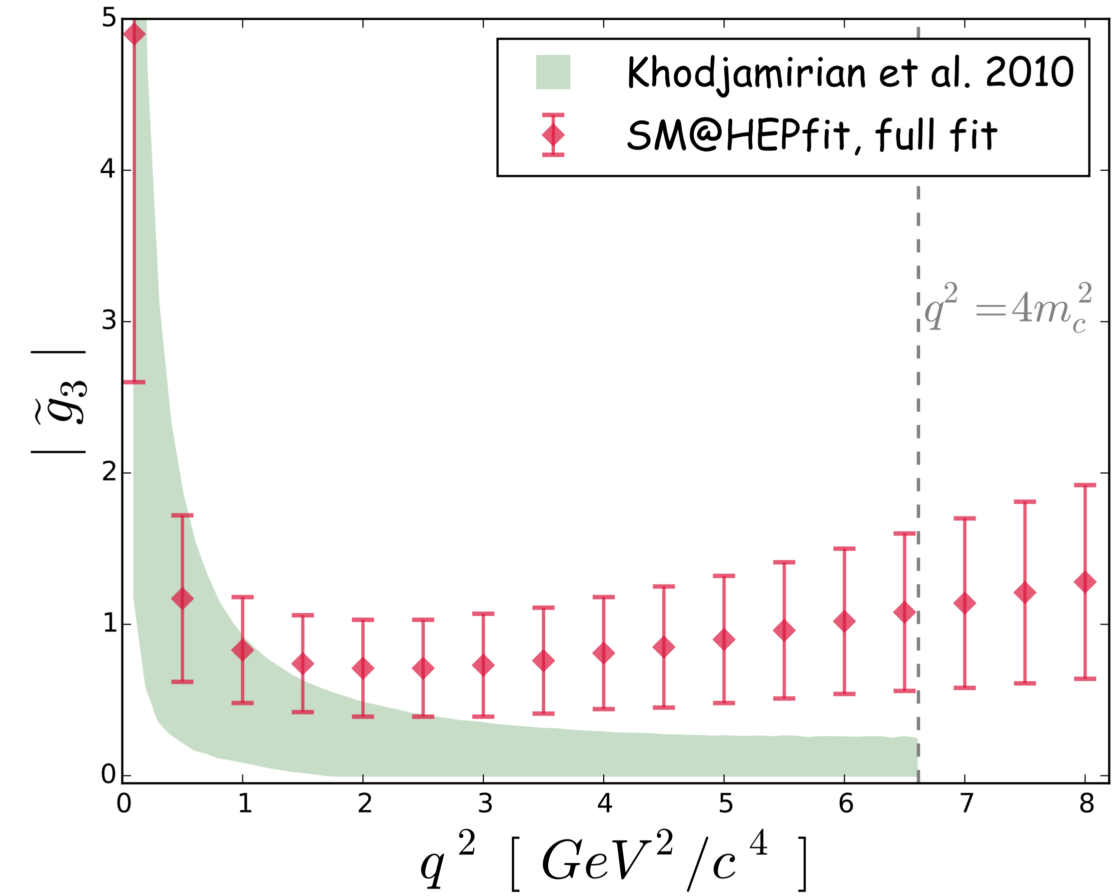
All other obs in agreement with exp data

Ciuchini, MF, Franco, Mishima, Paul, Silvestrini, Valli (1512.07157)

EXTRACTING THE NON-PERTURBATIVE HADRONIC CONTRIBUTION

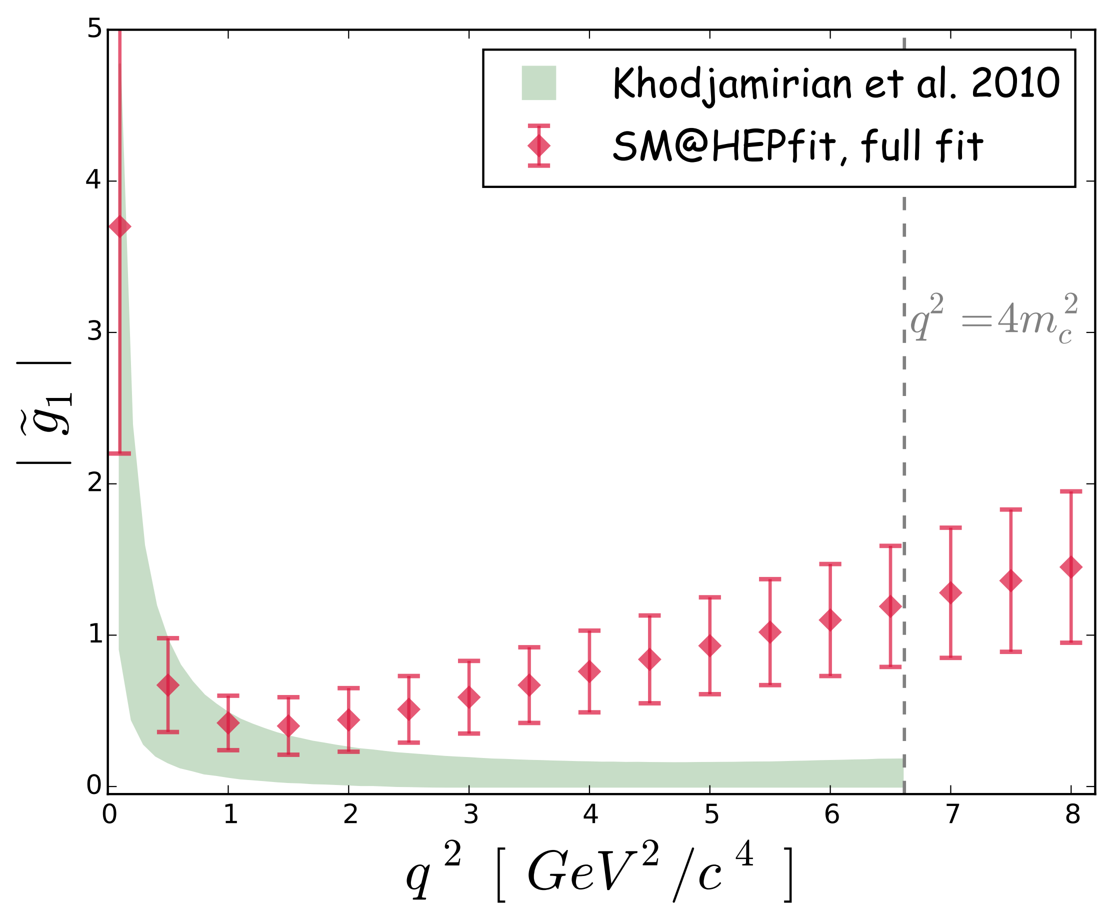
$$\tilde{g} \equiv \Delta C_9^{(\text{non pert.})}/(2C_1)$$

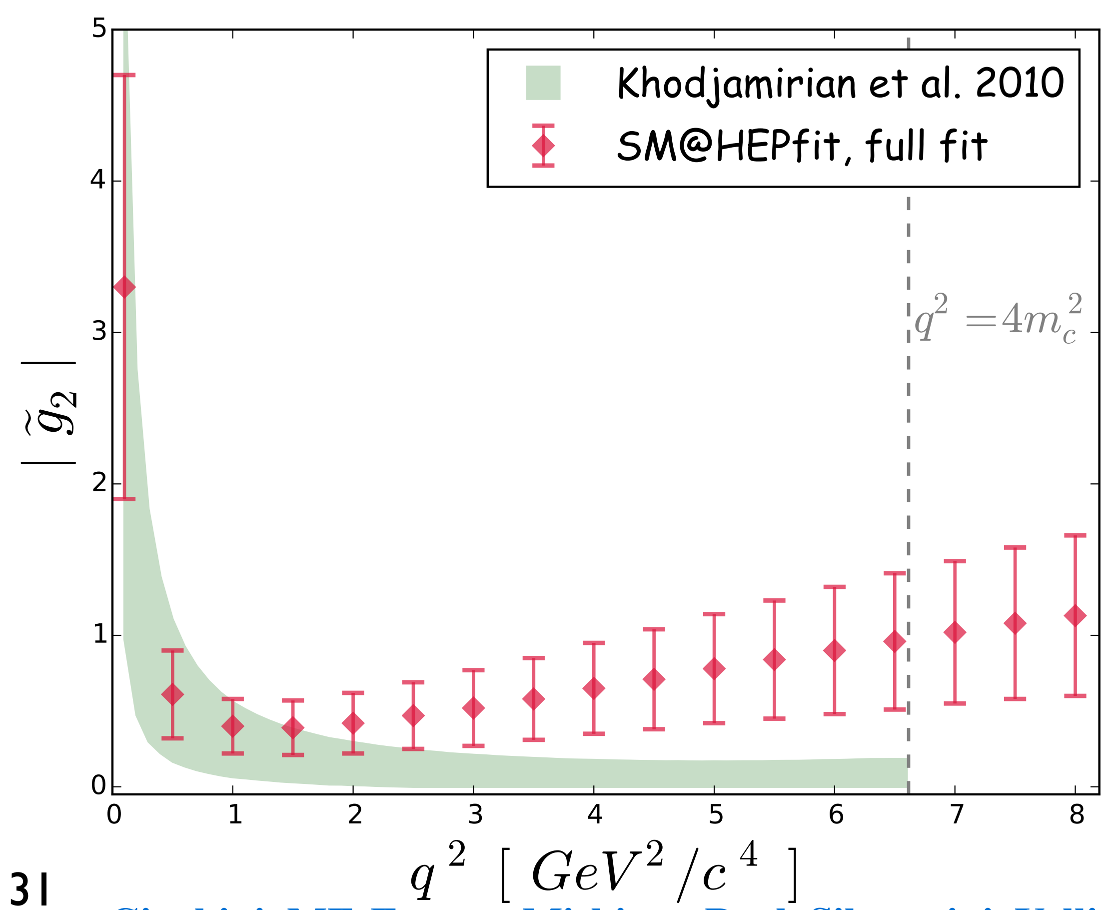
see *arXiv:1006.4945*



DISCLAIMER

NP contribution in C_7 and/or C_9 cannot reproduce such a q^2 behaviour

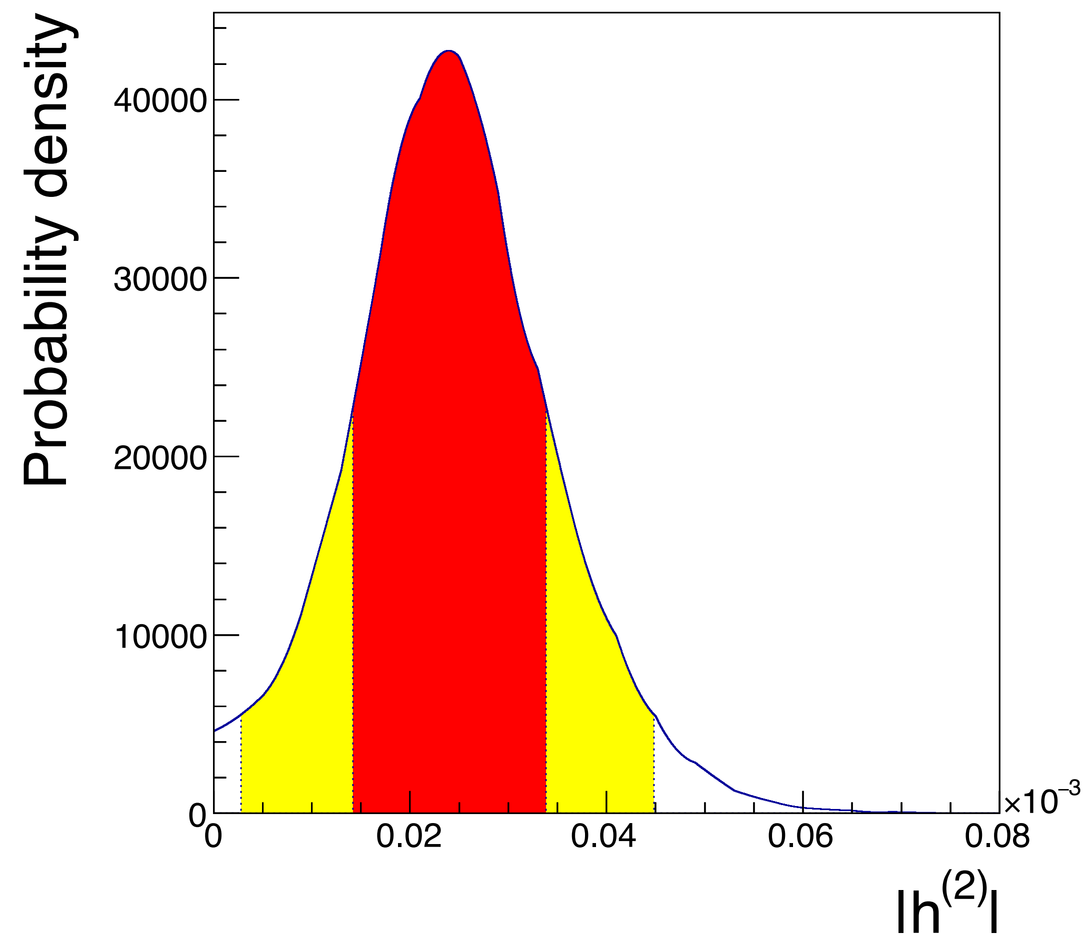




Ciuchini, MF, Franco, Mishima, Paul, Silvestrini, Valli (1512.07157)

RESULTS FOR THE HADRONIC PARAMETERS h_λ

Parameter	Absolute value	Phase (rad)
$h_0^{(0)}$	$(5.7 \pm 2.0) \cdot 10^{-4}$	3.57 ± 0.55
$h_0^{(1)}$	$(2.3 \pm 1.6) \cdot 10^{-4}$	0.1 ± 1.1
$h_0^{(2)}$	$(2.8 \pm 2.1) \cdot 10^{-5}$	-0.2 ± 1.7
$h_+^{(0)}$	$(7.9 \pm 6.9) \cdot 10^{-6}$	0.1 ± 1.7
$h_+^{(1)}$	$(3.8 \pm 2.8) \cdot 10^{-5}$	-0.7 ± 1.9
$h_+^{(2)}$	$(1.4 \pm 1.0) \cdot 10^{-5}$	3.5 ± 1.6
$h_-^{(0)}$	$(5.4 \pm 2.2) \cdot 10^{-5}$	3.2 ± 1.4
$h_-^{(1)}$	$(5.2 \pm 3.8) \cdot 10^{-5}$	0.0 ± 1.7
$h_-^{(2)}$	$(2.5 \pm 1.0) \cdot 10^{-5}$	0.09 ± 0.77



$|h_-^{(2)}|$ *differs from zero* **at more than 95.45% probability,**
thus **disfavouring** *the interpretation of the hadronic correction as* **NP contributions in C_7 and/or C_9**

Ciuchini, MF, Franco, Mishima, Paul, Silvestrini, Valli (1512.07157)

Time for a $b \to s$ global analysis

- Once we add the ratios in the analysis, it is not possible for the hadronic contributions to account for all the anomalies

- Interesting interplay between hadronic contribution and NP effects

- Is NP in the muon channel the only viable scenario?

Set of measurements included in our global analysis

LHCb	$F_L, A_{FB}, S_{3,4,5,7,8,9}$	JHEP 1611 (2016) 047
	i.e. available angular info for $K^{(*)}, \phi$ modes	JHEP 1602 (2016) 104
	$\mathcal{B}(B \to K^{(*)}\ell\ell, \gamma)$	JHEP 1509 (2015) 179
		JHEP 1504 (2015) 064
	$\mathcal{B}(B_s \to \phi\,\mu\mu, \gamma)$	Nucl.Phys. B867 (2013) 1-18
	$R_{K,[1,6]}, R_{K^*,[0.045,1.1],[1.1,6]}$	PRL 113 (2014) 151601 arXiv:1705.05802
ATLAS	$F_L, A_{FB}, S_{3,4,5,7,8}$	ATLAS-CONF-2017-023
CMS	$P_1, P_5', F_L, A_{FB}, \mathcal{B}(B \to K^*\mu\mu)$	CMS-PAS-BPH-15-008 twiki.cern/…/CMSPublic/…
Belle	$P'_{5\,(\mu,e)}$	PRL 118 (2017) 111801

We use data in the large recoil region only, i.e. where anomalies show up.

We always take into account theory/experimental correlations when provided.

LHCb, HFLAV	$\mathcal{B}(B_s \to \mu\mu), \mathcal{B}(B \to X_s\gamma)$	LHCB-PAPER-2017-001 FERMILAB-PUB-16-611-ND

Global fits before Moriond 2019

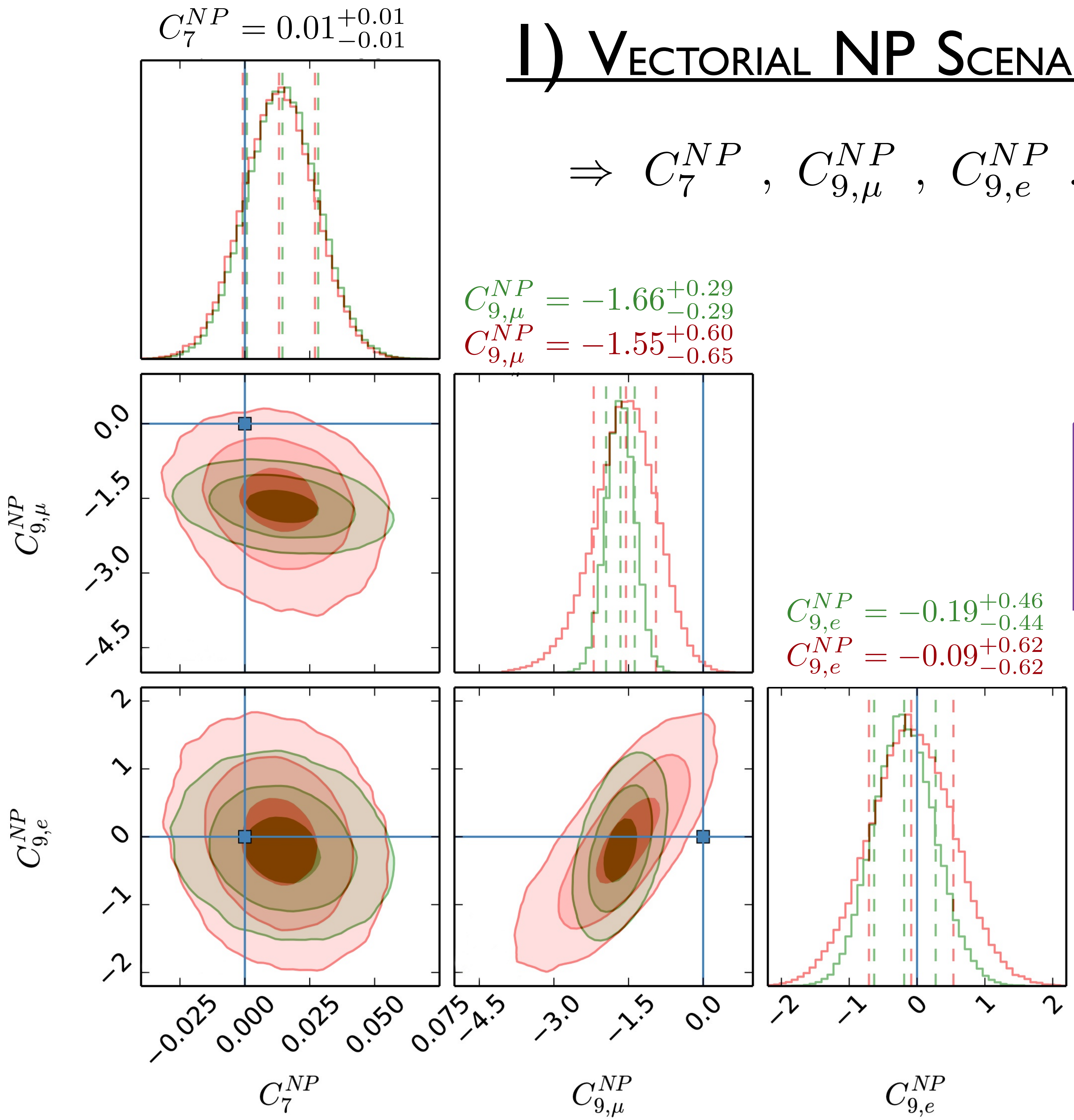
I) Vectorial NP Scenario

$$\Rightarrow \; C_7^{NP} \;,\; C_{9,\mu}^{NP} \;,\; C_{9,e}^{NP} \;.$$

dashed lines in 1D histograms
16th, 50th, 84th percentiles

2D joint probability density
1,2,3 σ contours (darker to lighter)

blue lines and blue square
SM limit of NP Wilson coeffs



Significance of NP affected by non-factorizable QCD power corrections !

PDD approach

PMD approach

Ciuchini, Coutinho, MF, Franco, Paul, Silvestrini, Valli (1704.05447)

Global fits before Moriond 2019

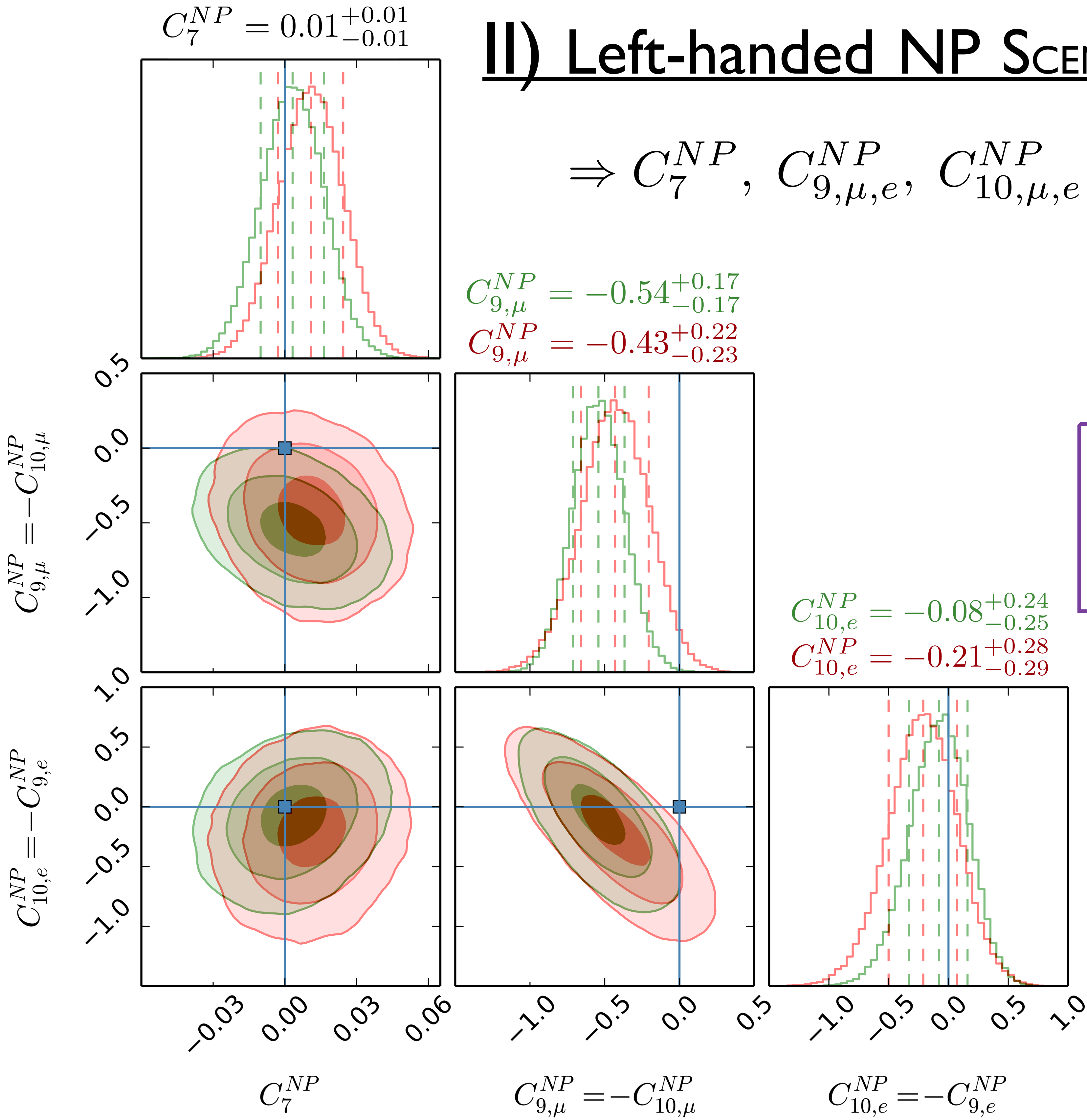
II) Left-handed NP Scenario

$$\Rightarrow C_7^{NP},\ C_{9,\mu,e}^{NP},\ C_{10,\mu,e}^{NP}$$

dashed lines in 1D histograms
16th, 50th, 84th percentiles

2D joint probability density
1,2,3 σ contours (darker to lighter)

blue lines and blue square
SM limit of NP Wilson coeffs



Significance of NP affected by non-factorizable QCD power corrections !

PDD approach

PMD approach

Ciuchini, Coutinho, MF, Franco, Paul, Silvestrini, Valli (1704.05447)

Global fits before Moriond 2019

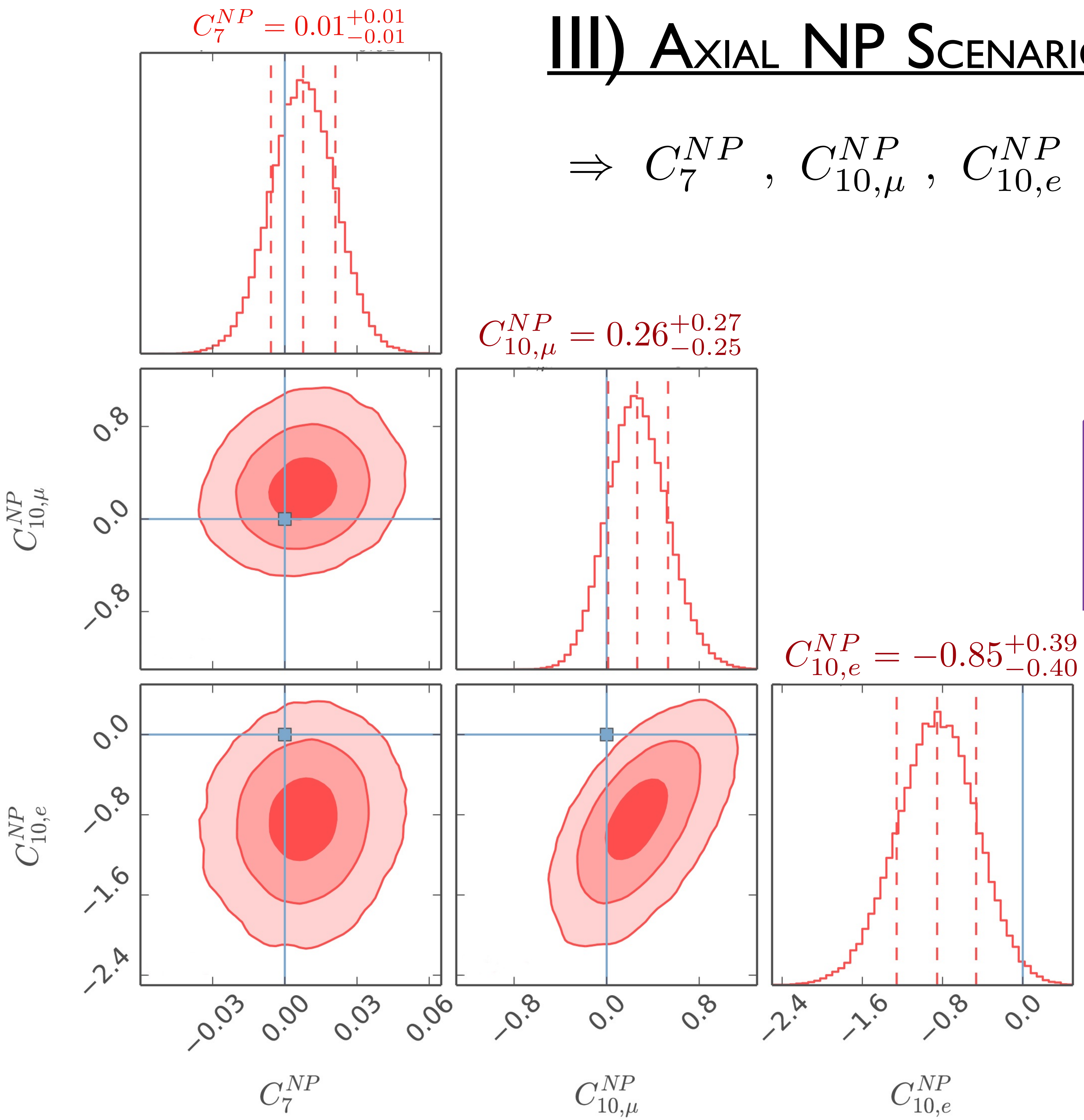
III) Axial NP Scenario

$$\Rightarrow \; C_7^{NP} \; , \; C_{10,\mu}^{NP} \; , \; C_{10,e}^{NP} \; .$$

dashed lines in 1D histograms
16th, 50th, 84th percentiles

2D joint probability density
1,2,3 σ contours (darker to lighter)

blue lines and blue square
SM limit of NP Wilson coeffs



Significance of NP affected by non-factorizable QCD power corrections !

PDD approach

No means to explain angular analysis in PMD

Ciuchini, Coutinho, MF, Franco, Paul, Silvestrini, Valli (1704.05447)

(Re)parameterizing the hadronic contribution

$$h_-(q^2) = -\frac{m_b}{8\pi^2 m_B}\widetilde{T}_{L-}(q^2)h_-^{(0)} - \frac{\widetilde{V}_{L-}(q^2)}{16\pi^2 m_B^2}h_-^{(1)}q^2 + h_-^{(2)}q^4 + \mathcal{O}(q^6)$$

$$h_+(q^2) = -\frac{m_b}{8\pi^2 m_B}\widetilde{T}_{L+}(q^2)h_-^{(0)} - \frac{\widetilde{V}_{L+}(q^2)}{16\pi^2 m_B^2}h_-^{(1)}q^2 + h_+^{(0)} + h_+^{(1)}q^2 + h_+^{(2)}q^4 + \mathcal{O}(q^6)$$

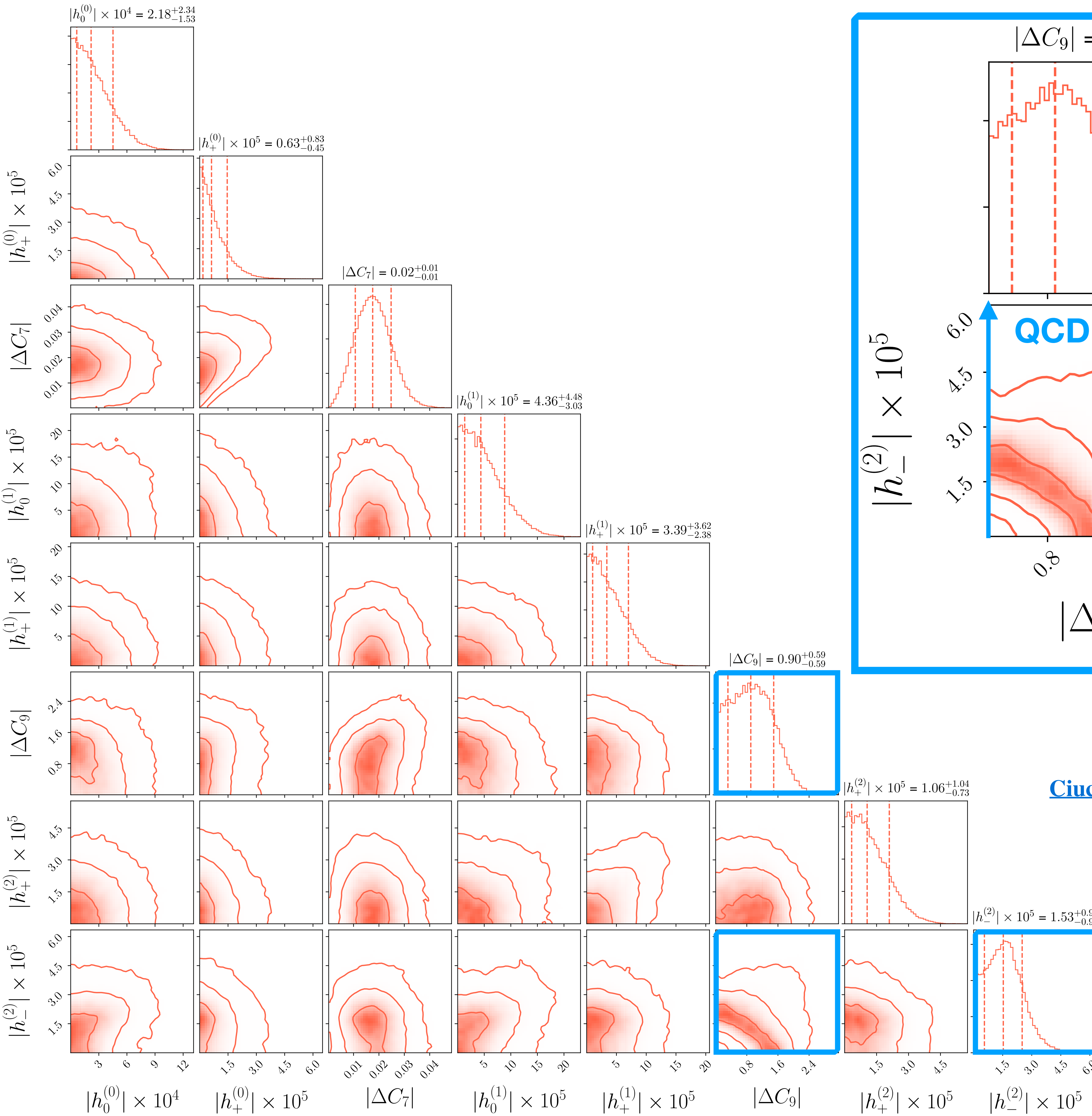
$$h_0(q^2) = -\frac{m_b}{8\pi^2 m_B}\widetilde{T}_{L0}(q^2)h_-^{(0)} - \frac{\widetilde{V}_{L0}(q^2)}{16\pi^2 m_B^2}h_-^{(1)}q^2 + h_0^{(0)}\sqrt{q^2} + h_0^{(1)}(q^2)^{\frac{3}{2}} + \mathcal{O}((q^2)^{\frac{5}{2}})$$

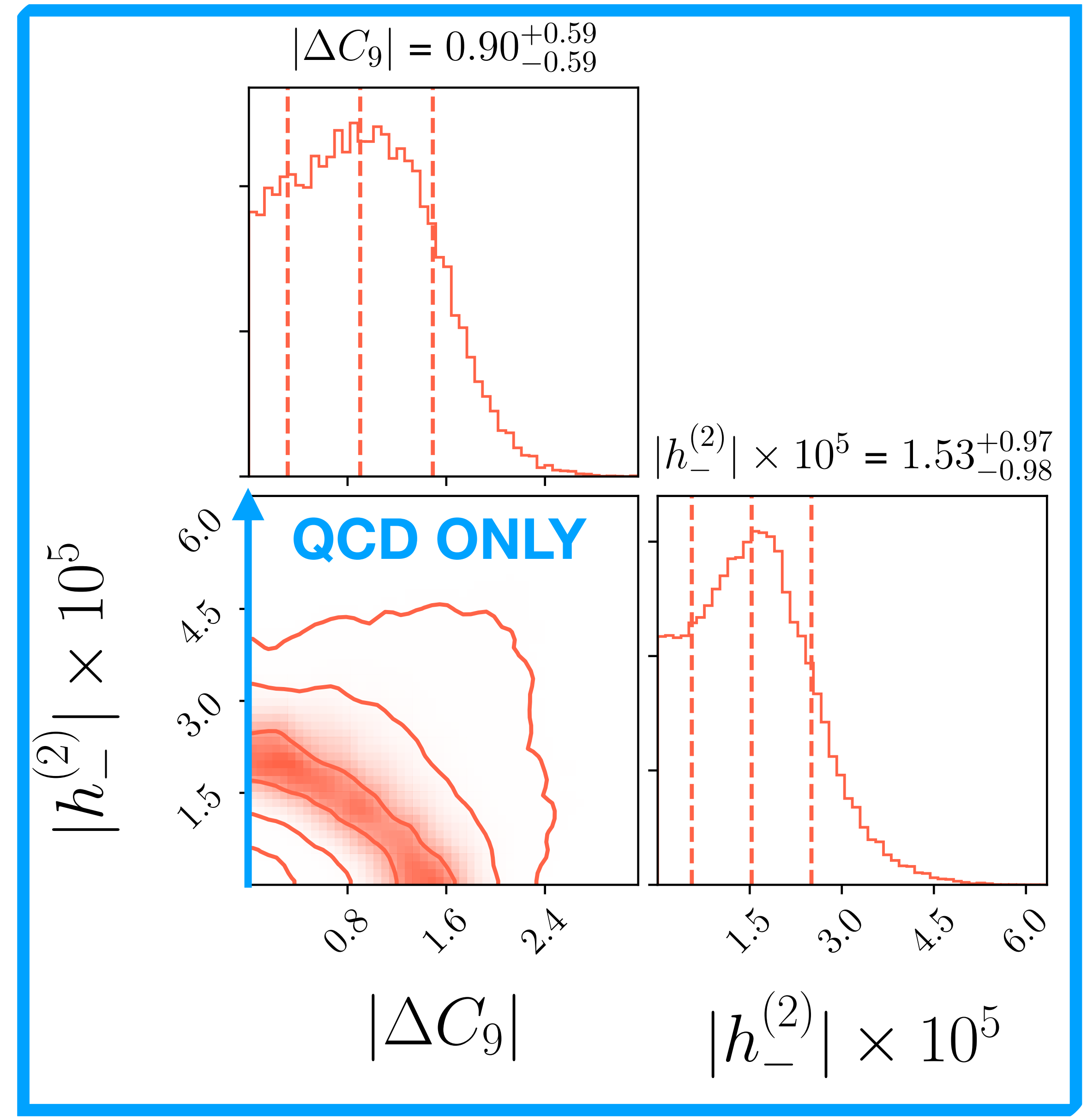
$$H_V^- \propto \left\{ \left(C_9^{\rm SM} + h_-^{(1)}\right)\widetilde{V}_{L-} + \frac{m_B^2}{q^2}\left[\frac{2m_b}{m_B}\left(C_7^{\rm SM} + h_-^{(0)}\right)\widetilde{T}_{L-} - 16\pi^2 h_-^{(2)}\, q^4\right]\right\}$$

$$H_V^+ \propto \left\{ \left(C_9^{\rm SM} + h_-^{(1)}\right)\widetilde{V}_{L+} + \frac{m_B^2}{q^2}\left[\frac{2m_b}{m_B}\left(C_7^{\rm SM} + h_-^{(0)}\right)\widetilde{T}_{L+} - 16\pi^2\left(h_+^{(0)} + h_+^{(1)}\, q^2 + h_+^{(2)}\, q^4\right)\right]\right\}$$

$$H_V^0 \propto \left\{ \left(C_9^{\rm SM} + h_-^{(1)}\right)\widetilde{V}_{L0} + \frac{m_B^2}{q^2}\left[\frac{2m_b}{m_B}\left(C_7^{\rm SM} + h_-^{(0)}\right)\widetilde{T}_{L0} - 16\pi^2\sqrt{q^2}\left(h_0^{(0)} + h_0^{(1)}\, q^2\right)\right]\right\}$$

Can be interpreted as LFU NP!

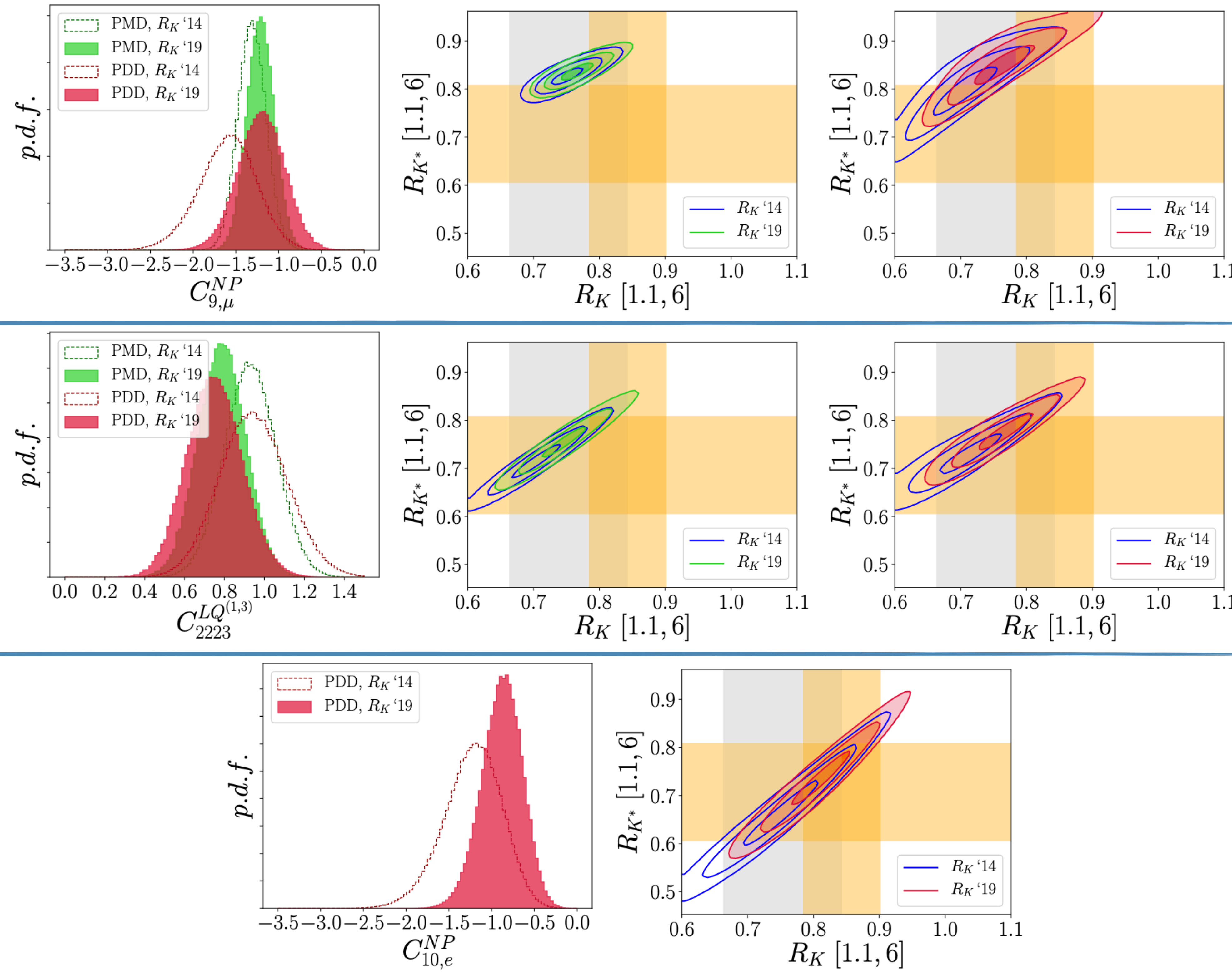




[Ciuchini, Coutinho, MF, Franco, Paul, Silvestrini, Valli (1809.03789)]

Global fits after Moriond 2019

Purely left-handed solutions are no longer preferred by data:

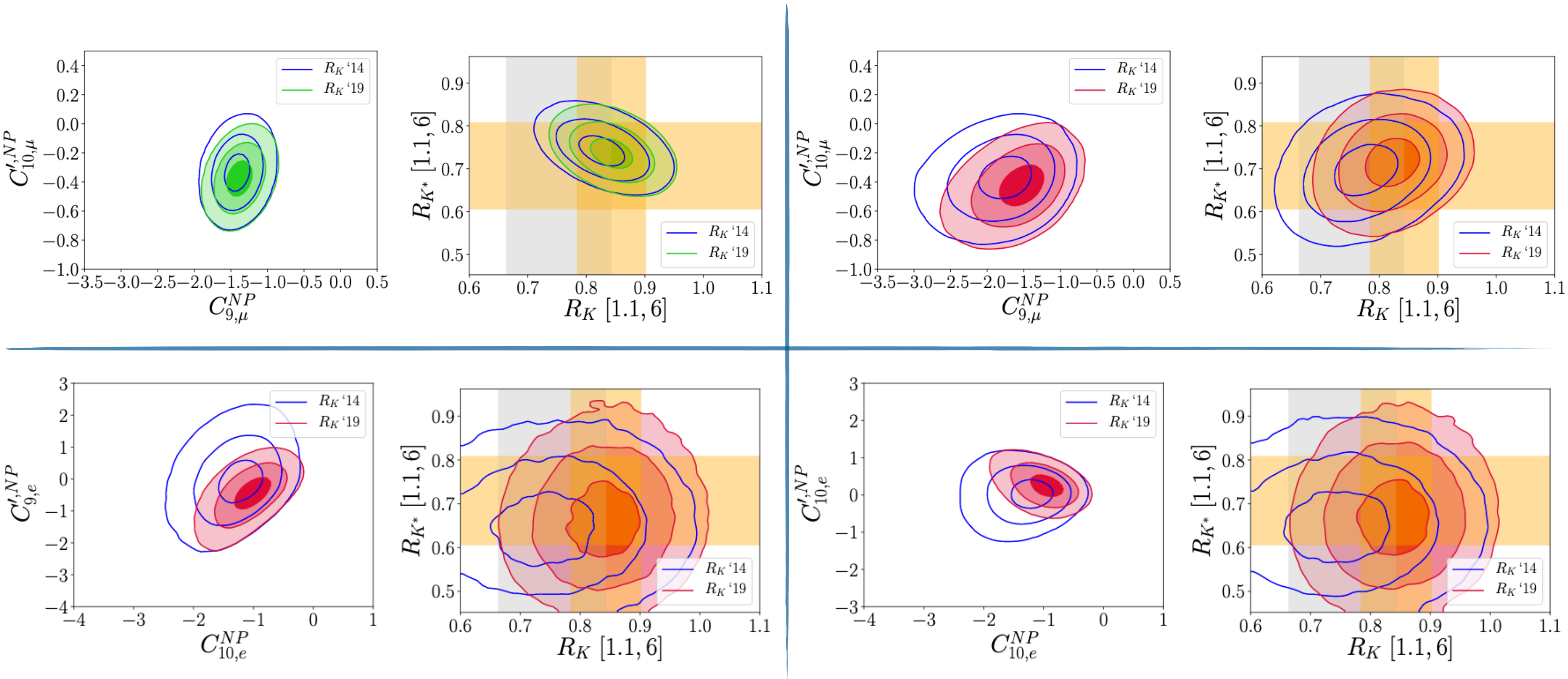


$$R_{K^*}[1.1,6]/R_K[1.1,6] \simeq 0.86 \pm 0.13$$

Ciuchini, Coutinho, MF, Franco, Paul, Silvestrini, Valli (1903.09632)

Global fits after Moriond 2019

The inclusion of right-handed currents better reproduce data!



$$R_K \propto C_i + C_i'$$

$$R_{K^*} \propto C_i - C_i'$$

$$R_{K^*}[1.1,6]/R_K[1.1,6] \simeq 0.86 \pm 0.13$$

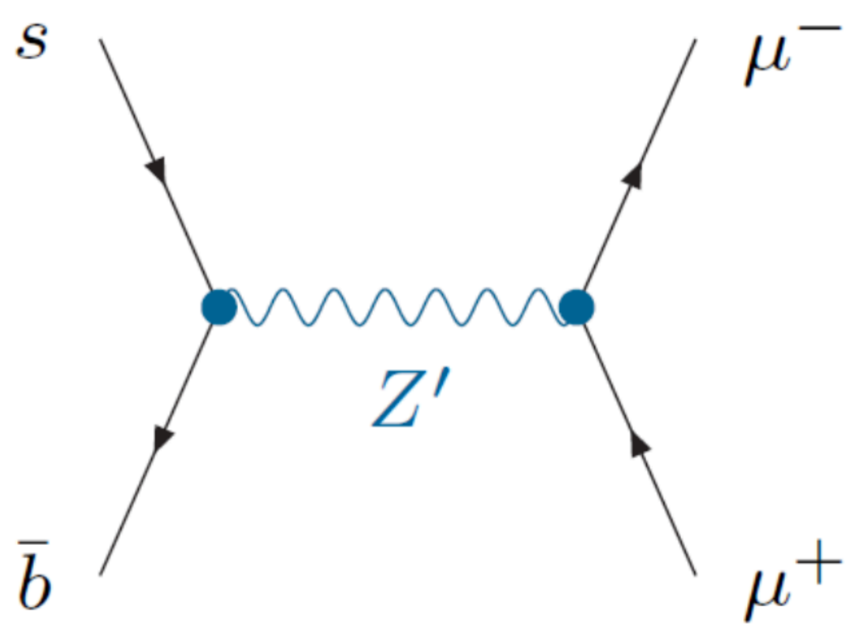
[Ciuchini, Coutinho, MF, Franco, Paul, Silvestrini, Valli (1903.09632)](https://arxiv.org/abs/1903.09632)

Summary

- *Theoretical Framework*
- *Experimental anomalies*
- *Global fits*
- *A possible solution*

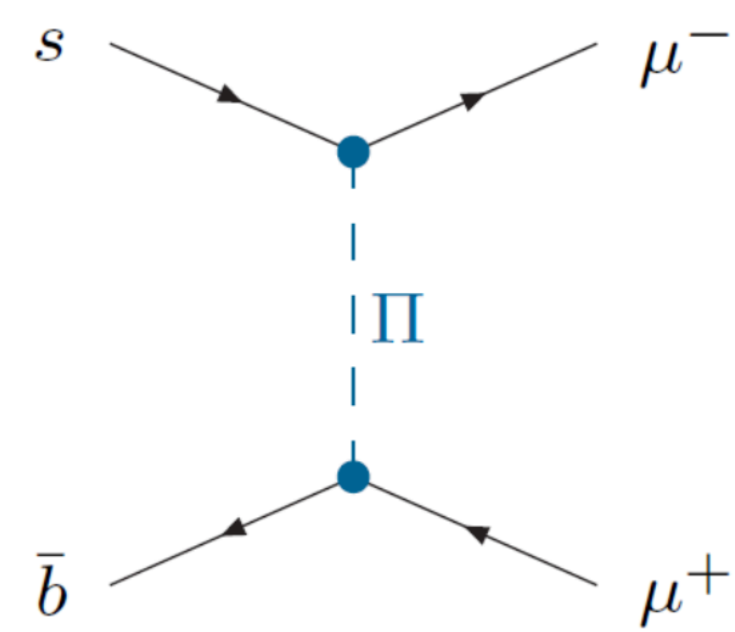
Tree-Level Models

Many possible solutions investigated so far involve tree-level NP



Z' models

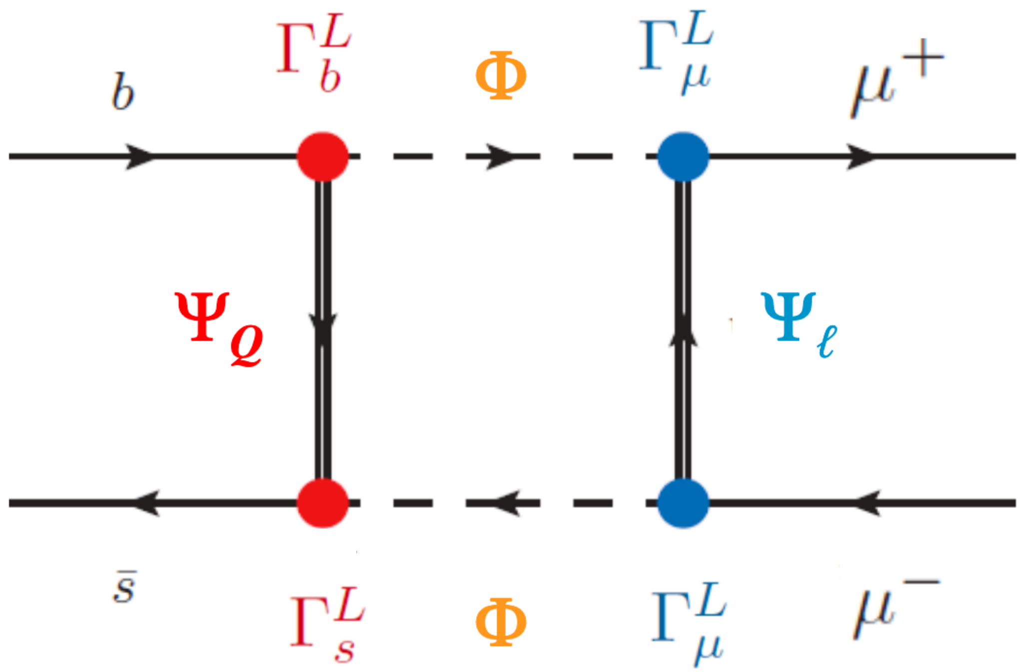
Allanach, Bordone, Buras, Crivellin, D'Ambrosio, De Fazio, Di Luzio, Falkowski, Fuentes-Martin, Gori, Isidori, Nierste, Vicente, …



Lepto-Quarks

Becirevic, Bordone, Crivellin, Di Luzio, Fajfer, Faroughy, Isidori, Kosnik, Marzocca, Sumensari, …

Loop Models

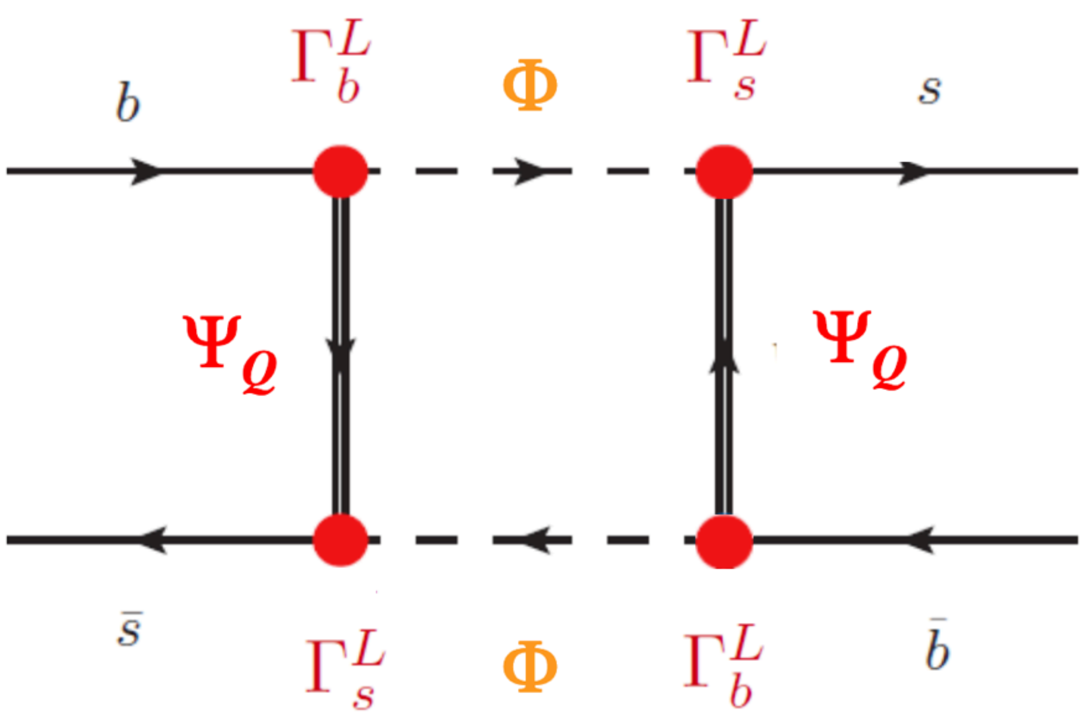


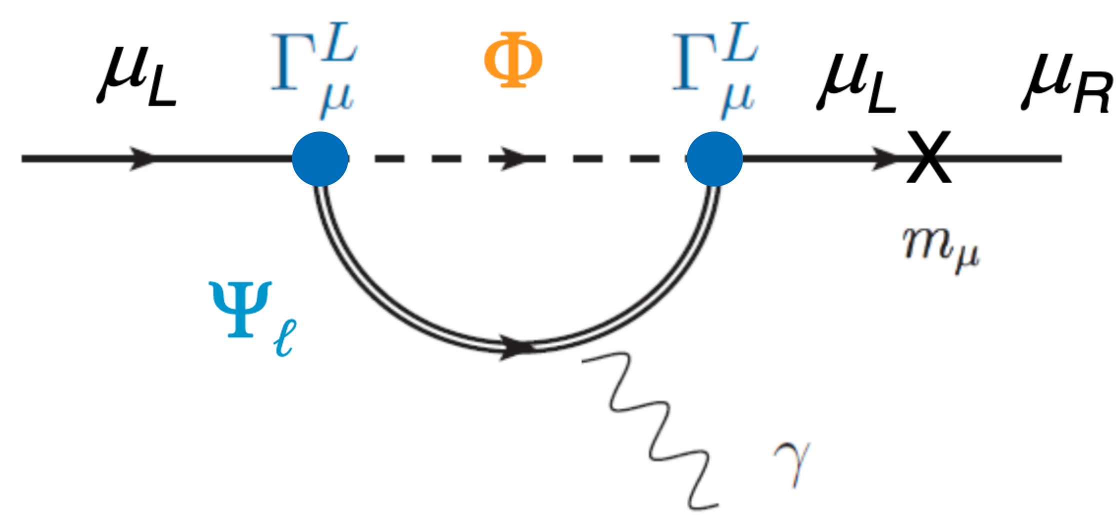
One scalar and 2 vector-like fermions (or vice versa)

$\Rightarrow$ C9 = -C10

Gripaios, Nardecchia, Renner '15
Arnan, Crivellin, Hofer, Mescia '16

Induces contributions to ΔMs and muon g-2





It is not possible to address everything with O(1) couplings and viable masses

Our Generic Loop Model

$$\mathcal{L}_{\text{int}} = \Big[\ \bar{\Psi}_A \left(L^b_{AM} P_L b + L^s_{AM} P_L s + L^\mu_{AM} P_L \mu \right) \Phi_M$$
$$+ \bar{\Psi}_A \left(R^b_{AM} P_R b + R^s_{AM} P_R s + R^\mu_{AM} P_R \mu \right) \Phi_M \Big] + \text{h.c.}$$

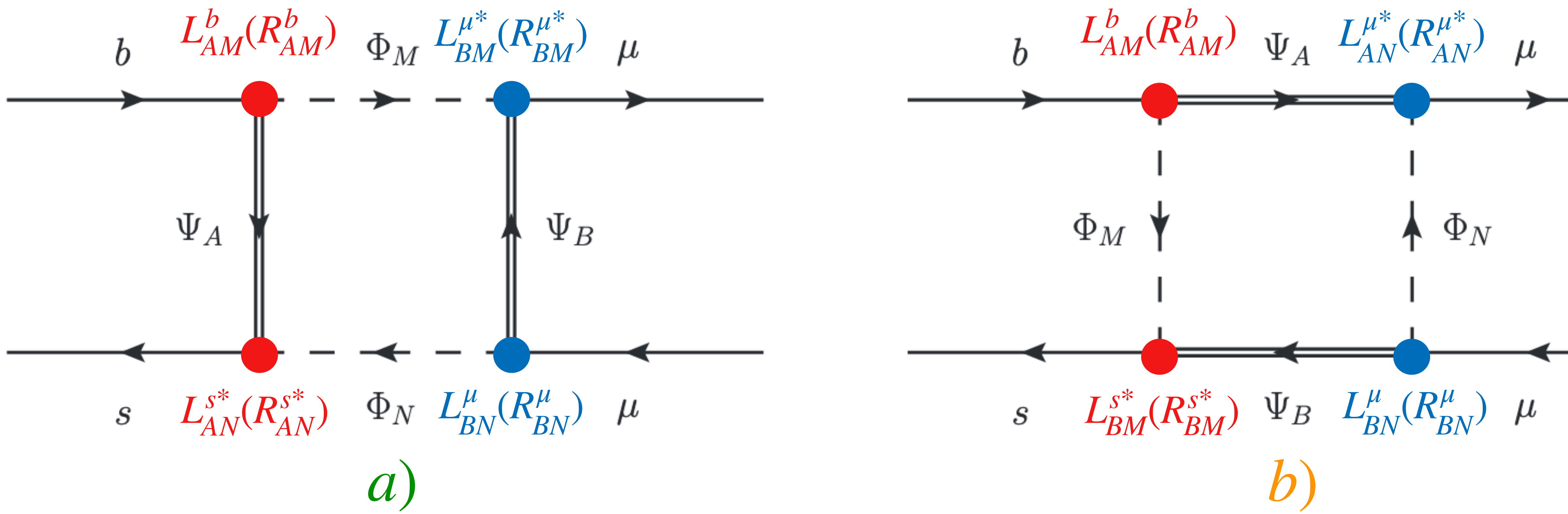
Ψ_A, Φ_M : Generic lists containing an arbitrary number of fields

$L^{b,s,\mu}_{AM}, R^{b,s,\mu}_{AM}$: Generic matrices in (A-M) space

- A and M also include implicitly SU(3) indices
- Non-vanishing entries of the coupling matrices ensure the preservation of colour and electric charge

Arnan, Crivellin, MF, Mescia (1904.05890)

$b \to s\mu\mu$



Two distinct solution, whether the fermion or the scalar is the NP field that couples to both quarks and leptons

$$x_{AM} \equiv (m_{\Psi_A}/m_{\Phi_M})^2$$

$$C_9^{\text{box},a)} = -\mathcal{N}\frac{\chi L_{AN}^{s*}L_{AM}^{b}}{32\pi\alpha_{\text{EM}}m_{\Phi_M}^2}\left[L_{BM}^{\mu*}L_{BN}^{\mu}+R_{BM}^{\mu*}R_{BN}^{\mu}\right]F(x_{AM},x_{BM},x_{NM})$$

$$C_{10}^{\text{box},a)} = \mathcal{N}\frac{\chi L_{AN}^{s*}L_{AM}^{b}}{32\pi\alpha_{\text{EM}}m_{\Phi_M}^2}\left[L_{BM}^{\mu*}L_{BN}^{\mu}-R_{BM}^{\mu*}R_{BN}^{\mu}\right]F(x_{AM},x_{BM},x_{NM})$$

$$C_{9(10)}^{\prime\text{box}} = \pm\, C_{9(10)}^{\text{box}}(L\leftrightarrow R)$$

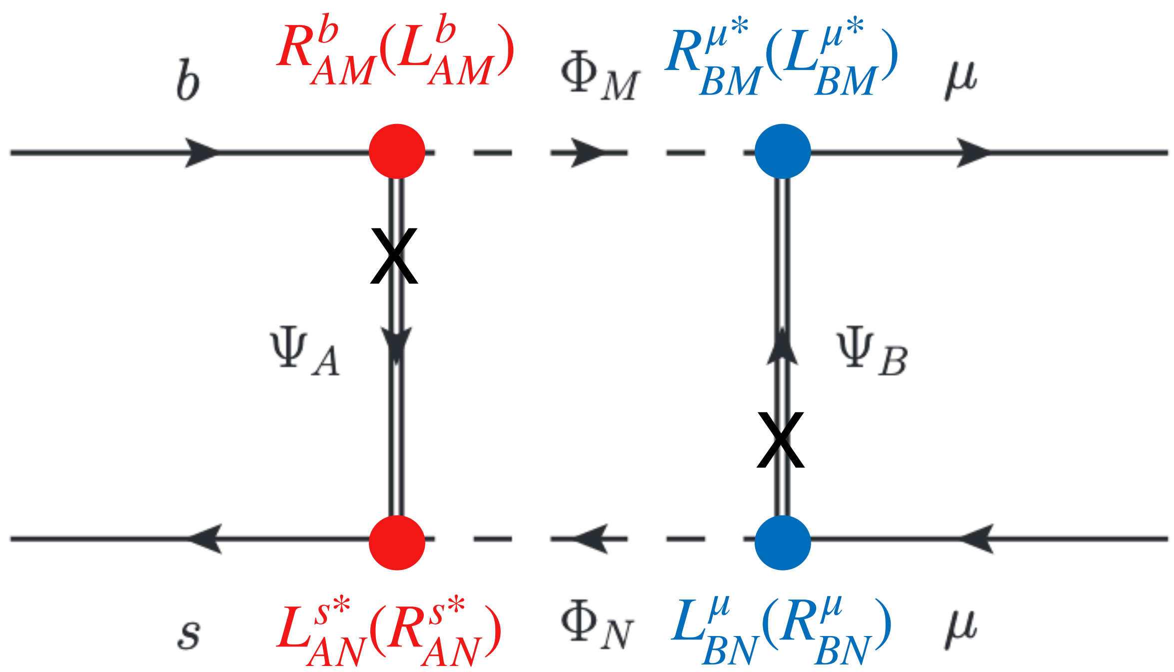
$$x_{NM} \equiv (m_{\Phi_N}/m_{\Phi_M})^2$$

$$C_9^{\text{box},b)} = -\mathcal{N}\frac{\chi L_{BM}^{s*}L_{AM}^{b}}{32\pi\alpha_{\text{EM}}m_{\Phi_M}^2}\left[L_{AN}^{\mu*}L_{BN}^{\mu}F(x_{AM},x_{BM},x_{NM})-R_{AN}^{\mu*}R_{BN}^{\mu}\frac{m_{\Psi_A}m_{\Psi_B}}{m_{\Phi_M}^2}G(x_{AM},x_{BM},x_{NM})\right]$$

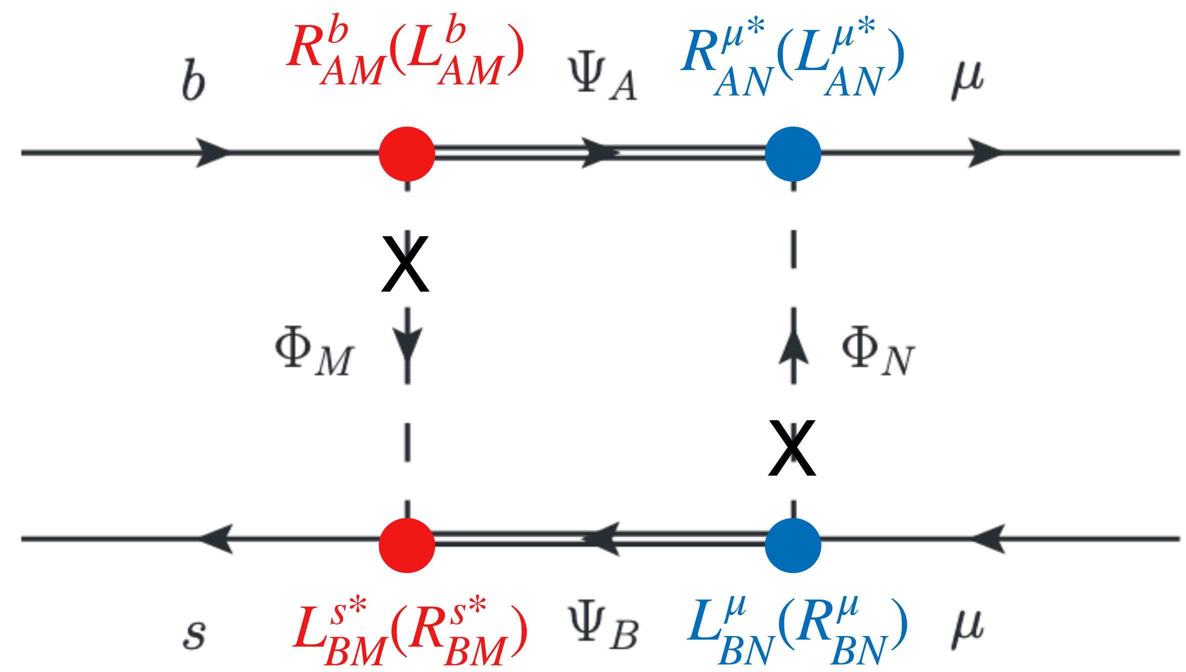
$$C_{10}^{\text{box},b)} = \mathcal{N}\frac{\chi L_{BM}^{s*}L_{AM}^{b}}{32\pi\alpha_{\text{EM}}m_{\Phi_M}^2}\left[L_{AN}^{\mu*}L_{BN}^{\mu}F(x_{AM},x_{BM},x_{NM})+R_{AN}^{\mu*}R_{BN}^{\mu}\frac{m_{\Psi_A}m_{\Psi_B}}{m_{\Phi_M}^2}G(x_{AM},x_{BM},x_{NM})\right]$$

Arnan, Crivellin, MF, Mescia (1904.05890)

b→sμμ



a)



b)

$$C_S^{\text{box},a)} = -\mathcal{N}\frac{\chi L^{s*}_{AN}R^b_{AM}}{16\pi\alpha_{\text{EM}}m^2_{\Phi_M}}\left[R^{\mu*}_{BM}L^{\mu}_{BN} + L^{\mu*}_{BM}R^{\mu}_{BN}\right]\frac{m_{\Psi_A}m_{\Psi_B}}{m^2_{\Phi_M}}G(x_{AM},x_{BM},x_{NM})$$

$$C_P^{\text{box},a)} = \mathcal{N}\frac{\chi L^{s*}_{AN}R^b_{AM}}{16\pi\alpha_{\text{EM}}m^2_{\Phi_M}}\left[R^{\mu*}_{BM}L^{\mu}_{BN} - L^{\mu*}_{BM}R^{\mu}_{BN}\right]\frac{m_{\Psi_A}m_{\Psi_B}}{m^2_{\Phi_M}}G(x_{AM},x_{BM},x_{NM})$$

$$C'^{\text{box}}_{S,T(P)} = \pm\, C^{\text{box}}_{S,T(P)}(L \leftrightarrow R)$$

$$C_S^{\text{box},b)} = \mathcal{N}\frac{\chi L^{s*}_{BM}R^b_{AM}}{16\pi\alpha_{\text{EM}}m^2_{\Phi_M}}\left[R^{\mu*}_{AN}L^{\mu}_{BN}F(x_{AM},x_{BM},x_{NM}) + L^{\mu*}_{AN}R^{\mu}_{BN}\frac{m_{\Psi_A}m_{\Psi_B}}{2m^2_{\Phi_M}}G(x_{AM},x_{BM},x_{NM})\right]$$

$$C_P^{\text{box},b)} = -\mathcal{N}\frac{\chi L^{s*}_{BM}R^b_{AM}}{16\pi\alpha_{\text{EM}}m^2_{\Phi_M}}\left[R^{\mu*}_{AN}L^{\mu}_{BN}F(x_{AM},x_{BM},x_{NM}) - L^{\mu*}_{AN}R^{\mu}_{BN}\frac{m_{\Psi_A}m_{\Psi_B}}{2m^2_{\Phi_M}}G(x_{AM},x_{BM},x_{NM})\right]$$

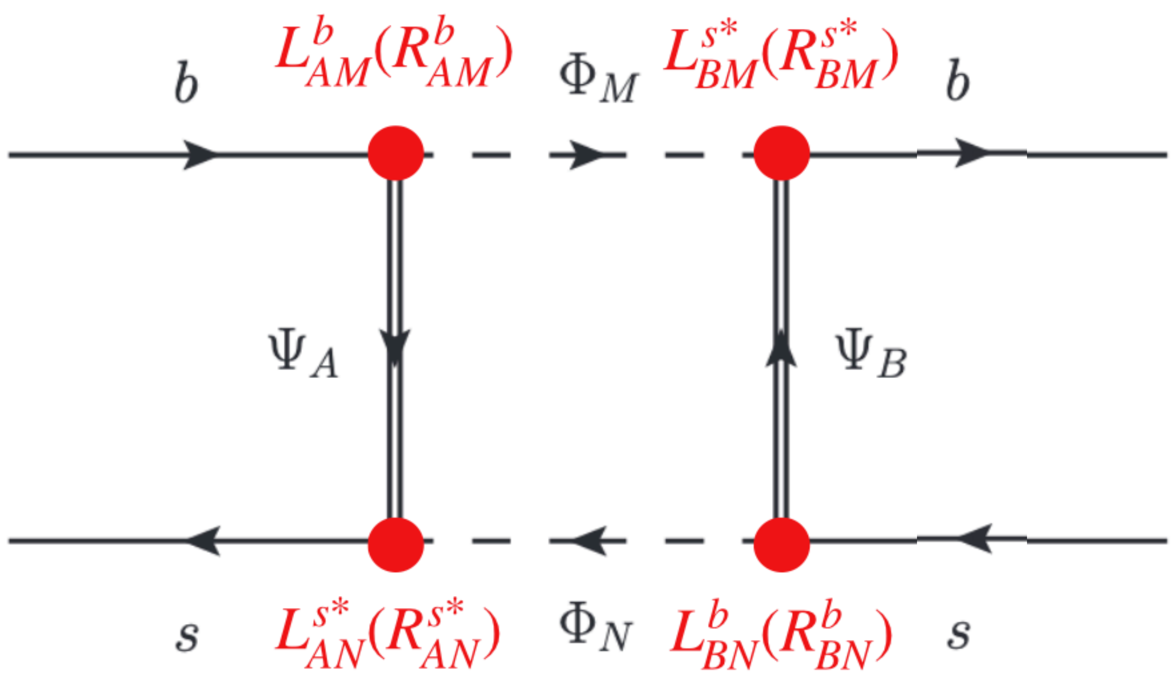
$$C_T^{\text{box},b)} = -\mathcal{N}\frac{\chi L^{s*}_{BM}R^b_{AM}L^{\mu*}_{AN}R^{\mu}_{BN}}{16\pi\alpha_{\text{EM}}m^2_{\Phi_M}}\frac{m_{\Psi_A}m_{\Psi_B}}{m^2_{\Phi_M}}G(x_{AM},x_{BM},x_{NM})$$

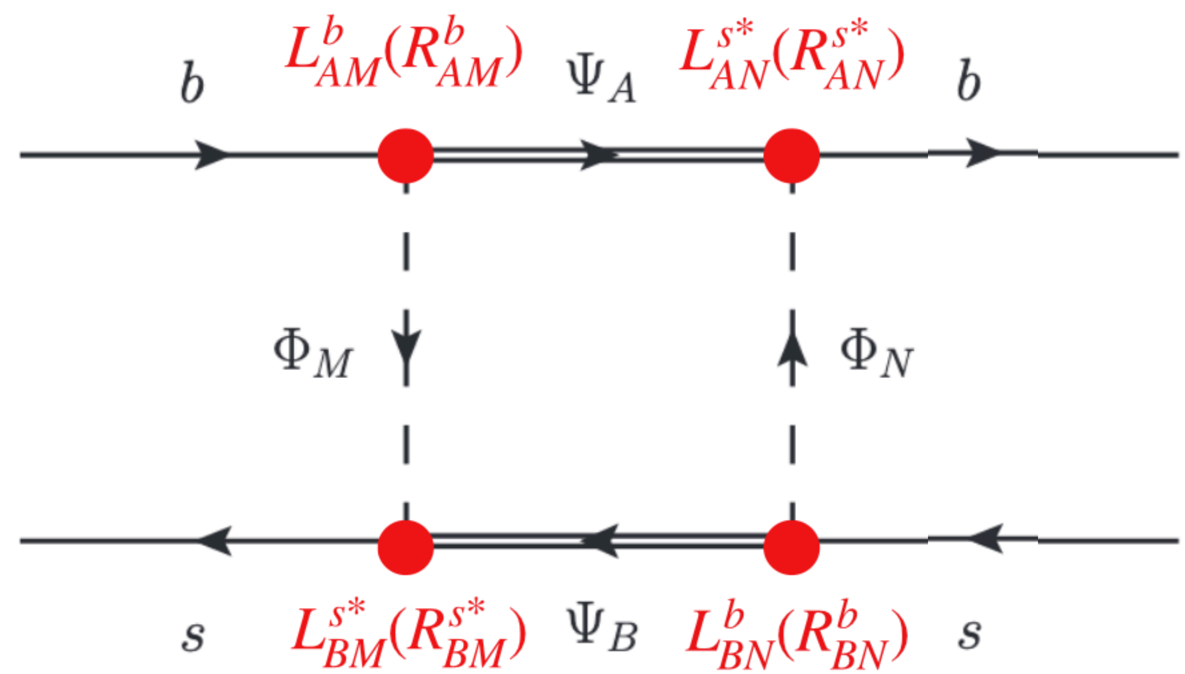
Additional WC appear only in the presence of additional SU(2) breaking effects

(phenomenologically suppressed)

Arnan, Crivellin, MF, Mescia (1904.05890)

ΔMs





Both diagrams appear, independently on b→s*μμ*, since no leptons are involved in this channel

$$C_1 = (\chi_{BB} + \tilde{\chi}_{BB}) \frac{L^{s*}_{AN} L^b_{AM} L^{s*}_{BM} L^b_{BN}}{128\pi^2 m^2_{\Phi_M}} F(x_{AM}, x_{BM}, x_{NM}) \,,$$

$$C_2 = \chi_{BB} \frac{R^{s*}_{AN} L^b_{AM} R^{s*}_{BM} L^b_{BN}}{64\pi^2 m^2_{\Phi_M}} \frac{m_{\Psi_A} m_{\Psi_B}}{m^2_{\Phi_M}} G(x_{AM}, x_{BM}, x_{NM}) \,,$$

$$C_3 = \tilde{\chi}_{BB} \frac{R^{s*}_{AN} L^b_{AM} R^{s*}_{BM} L^b_{BN}}{64\pi^2 m^2_{\Phi_M}} \frac{m_{\Psi_A} m_{\Psi_B}}{m^2_{\Phi_M}} G(x_{AM}, x_{BM}, x_{NM}) \,,$$

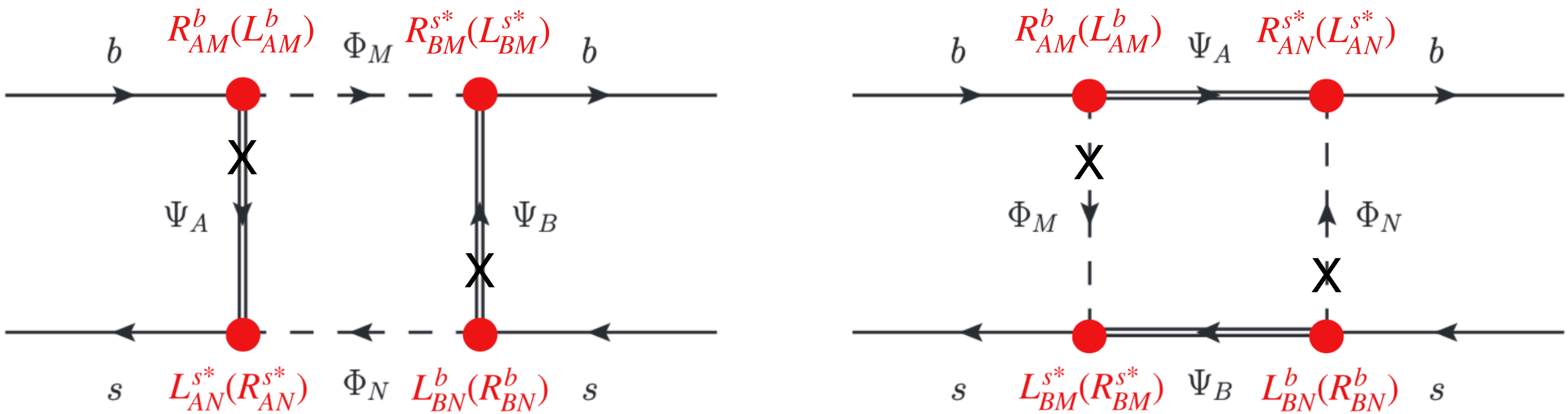
$$\widetilde{C}_{1,2,3} = C_{1,2,3}\,(L \leftrightarrow R)$$

$$C_4 = \chi_{BB} \frac{R^{s*}_{AN} L^b_{AM} L^{s*}_{BM} R^b_{BN}}{32\pi^2 m^2_{\Phi_M}} \frac{m_{\Psi_A} m_{\Psi_B}}{m^2_{\Phi_M}} G(x_{AM}, x_{BM}, x_{NM}) - \tilde{\chi}_{BB} \frac{R^{s*}_{AN} R^b_{AM} L^{s*}_{BM} L^b_{BN}}{32\pi^2 m^2_{\Phi_M}} F(x_{AM}, x_{BM}, x_{NM}) \,,$$

$$C_5 = \tilde{\chi}_{BB} \frac{R^{s*}_{AN} L^b_{AM} L^{s*}_{BM} R^b_{BN}}{32\pi^2 m^2_{\Phi_M}} \frac{m_{\Psi_A} m_{\Psi_B}}{m^2_{\Phi_M}} G(x_{AM}, x_{BM}, x_{NM}) - \chi_{BB} \frac{R^{s*}_{AN} R^b_{AM} L^{s*}_{BM} L^b_{BN}}{32\pi^2 m^2_{\Phi_M}} F(x_{AM}, x_{BM}, x_{NM}) \,,$$

Arnan, Crivellin, MF, Mescia (1904.05890)

ΔMs



Both diagrams appear, independently on b→s*μμ*, since no leptons are involved in this channel

$$C_1 = (\chi_{BB} + \tilde{\chi}_{BB}) \frac{L^{s*}_{AN} L^b_{AM} L^{s*}_{BM} L^b_{BN}}{128\pi^2 m^2_{\Phi_M}} F(x_{AM}, x_{BM}, x_{NM}) \; ,$$

$$C_2 = \chi_{BB} \frac{R^{s*}_{AN} L^b_{AM} R^{s*}_{BM} L^b_{BN}}{64\pi^2 m^2_{\Phi_M}} \frac{m_{\Psi_A} m_{\Psi_B}}{m^2_{\Phi_M}} G(x_{AM}, x_{BM}, x_{NM}) \; ,$$

$$C_3 = \tilde{\chi}_{BB} \frac{R^{s*}_{AN} L^b_{AM} R^{s*}_{BM} L^b_{BN}}{64\pi^2 m^2_{\Phi_M}} \frac{m_{\Psi_A} m_{\Psi_B}}{m^2_{\Phi_M}} G(x_{AM}, x_{BM}, x_{NM}) \; ,$$

$$\widetilde{C}_{1,2,3} = C_{1,2,3} \, (L \leftrightarrow R)$$

$$C_4 = \chi_{BB} \frac{R^{s*}_{AN} L^b_{AM} L^{s*}_{BM} R^b_{BN}}{32\pi^2 m^2_{\Phi_M}} \frac{m_{\Psi_A} m_{\Psi_B}}{m^2_{\Phi_M}} G(x_{AM}, x_{BM}, x_{NM}) - \tilde{\chi}_{BB} \frac{R^{s*}_{AN} R^b_{AM} L^{s*}_{BM} L^b_{BN}}{32\pi^2 m^2_{\Phi_M}} F(x_{AM}, x_{BM}, x_{NM}) \; ,$$

$$C_5 = \tilde{\chi}_{BB} \frac{R^{s*}_{AN} L^b_{AM} L^{s*}_{BM} R^b_{BN}}{32\pi^2 m^2_{\Phi_M}} \frac{m_{\Psi_A} m_{\Psi_B}}{m^2_{\Phi_M}} G(x_{AM}, x_{BM}, x_{NM}) - \chi_{BB} \frac{R^{s*}_{AN} R^b_{AM} L^{s*}_{BM} L^b_{BN}}{32\pi^2 m^2_{\Phi_M}} F(x_{AM}, x_{BM}, x_{NM}) \; ,$$

Additional contributions to WC appear in the presence of additional SU(2) breaking effects

Arnan, Crivellin, MF, Mescia (1904.05890)

ΔMs

$$C_1 = (\chi_{BB} + \tilde{\chi}_{BB}) \frac{L^{s*}_{AN} L^b_{AM} L^{s*}_{BM} L^b_{BN}}{128\pi^2 m^2_{\Phi_M}} F(x_{AM}, x_{BM}, x_{NM}) \,,$$

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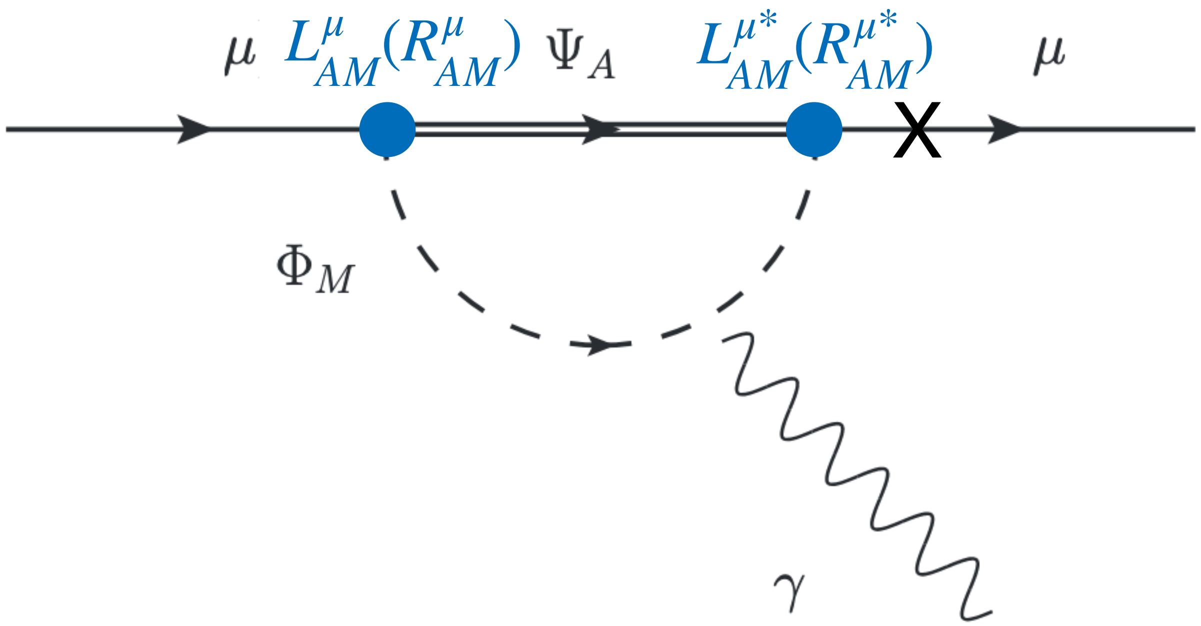
$$\frac{\Delta M_s^{\rm exp}}{\Delta M_s^{\rm SM}} = \left| 1 + \sum_{i,j=1}^{3} R_i(\mu_b) \frac{\eta_{ij}(\mu_b, \mu_H)}{C_1^{\rm SM}(\mu_b)} \left(C_j + \widetilde{C}_j \right) + \sum_{i,j=4}^{5} R_i(\mu_b) \frac{\eta_{ij}(\mu_b, \mu_H)}{C_1^{\rm SM}(\mu_b)} C_j \right|$$
$$= \left| 1 + \frac{0.8\,(C_1 + \widetilde{C}_1) - 1.9\,(C_2 + \widetilde{C}_2) + 0.5\,(C_3 + \widetilde{C}_3) + 5.2\,C_4 + 1.9\,C_5}{C_1^{\rm SM}(\mu_b)} \right|$$

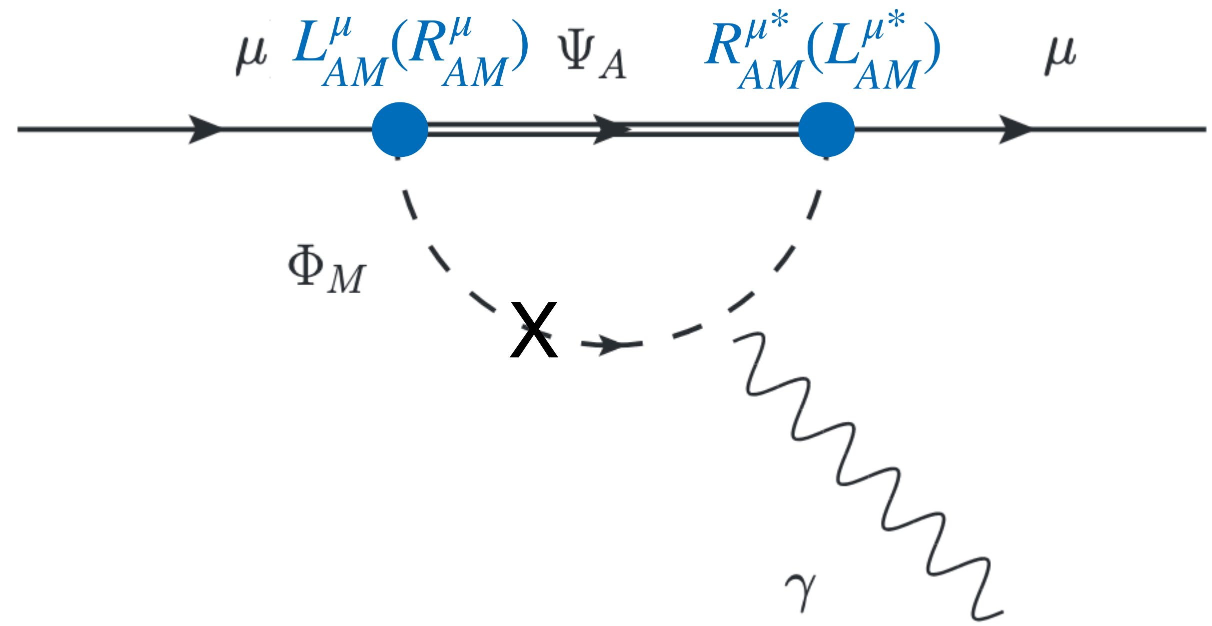
$R_i(\mu_b)$: ratios of matrix elements

μ_H: heavy scale, set at 1 TeV

Arnan, Crivellin, MF, Mescia (1904.05890)

g-2





$$\Delta a_\mu = \frac{\chi_{a_\mu} m_\mu^2}{8\pi^2 m_{\Phi_M}^2} \Big[\left(L^{\mu*}_{AM} L^{\mu}_{AM} + R^{\mu*}_{AM} R^{\mu}_{AM} \right) \left(Q_{\Phi_M} \widetilde{F}_7\left(x_{AM}\right) - Q_{\Psi_A} F_7\left(x_{AM}\right) \right) + \left(L^{\mu*}_{AM} R^{\mu}_{AM} + R^{\mu*}_{AM} L^{\mu}_{AM} \right) \frac{2 m_{\Psi_A}}{m_\mu} \left(Q_{\Phi_M} \widetilde{G}_7\left(x_{AM}\right) - Q_{\Psi_A} G_7\left(x_{AM}\right) \right) \Big]$$

Additional term induced by SU(2) breaking, and chirally enhanced

Arnan, Crivellin, MF, Mescia (1904.05890)

Positive features of the model

- b→$s\mu\mu$

  Presence of primed operator is allowed

- ΔM_S

  Interference b/w C1 and C4/C5 helps to relax bounds on couplings

- g-2

  Additional chiral. enhanced term helps to account for deviation

Arnan, Crivellin, MF, Mescia (1904.05890)

4th Generation Model

$$L^{4\text{th}} = \sum_i \left(\Gamma^L_{q_i}\bar\Psi_q P_L q_i + \Gamma^L_{\ell_i}\bar\Psi_\ell P_L \ell_i + \Gamma^R_{u_i}\bar\Psi_u P_R u_i + \Gamma^R_{d_i}\bar\Psi_d P_R d_i + \Gamma^R_{e_i}\bar\Psi_e P_R e_i\right)\Phi + \text{h.c.}$$
$$+ \sum_{C=L,R}\left(\lambda^U_C\bar\Psi_q P_C \tilde h \Psi_u + \lambda^D_C\bar\Psi_q P_C h\Psi_d + \lambda^E_C \bar\Psi_\ell P_C h \Psi_e\right) + \text{h.c.}$$
$$+ \sum_{F=q,\ell,u,d,e} M_F \bar\Psi_F \Psi_F + \kappa\, h^\dagger h\,\Phi^\dagger\Phi + m^2_\Phi \Phi^\dagger\Phi$$

We start writing down the most general Lagrangian before EWSB including a 4th vector-like generation and a neutral scalar

	$SU(3)$	$SU(2)$	$U(1)$	$U'(1)$
Ψ_q	3	2	1/6	Z
Ψ_u	3	1	2/3	Z
Ψ_d	3	1	$-1/3$	Z
Ψ_ℓ	1	2	$-1/2$	Z
Ψ_e	1	1	-1	Z
Φ	1	1	0	$-Z$

NB. We work in the basis with diagonal down-type quarks

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$$+ \sum_{C=L,R} \left(\lambda^U_C \bar{\Psi}_q P_C \tilde{h} \Psi_u + \lambda^D_C \bar{\Psi}_q P_C h \Psi_d + \lambda^E_C \bar{\Psi}_\ell P_C h \Psi_e\right) + \text{h.c.}$$

$$+ \sum_{F=q,\ell,u,d,e} M_F \bar{\Psi}_F \Psi_F + \kappa\, h^\dagger h\, \Phi^\dagger \Phi + m^2_\Phi \Phi^\dagger \Phi$$

What is the minimal subset of couplings we can consider?

Arnan, Crivellin, MF, Mescia (1904.05890)

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$$+ \sum_{C=L,R}\left(\lambda^U_C \bar{\Psi}_q P_C \tilde{h}\Psi_u + \lambda^D_C \bar{\Psi}_q P_C h \Psi_d + \lambda^E_C \bar{\Psi}_\ell P_C h \Psi_e\right) + \mathrm{h.c.}$$

$$+ \sum_{F=q,\ell,u,d,e} M_F \bar{\Psi}_F \Psi_F + \kappa\, h^\dagger h\, \Phi^\dagger \Phi + m^2_\Phi \Phi^\dagger \Phi$$

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- B anomalies only constrain couplings to d-type (b,s) and leptons (μ)

Arnan, Crivellin, MF, Mescia (1904.05890)

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$$+ \sum_{F=q,\ell,u,d,e} M_F \bar{\Psi}_F \Psi_F + \kappa\, h^\dagger h\, \Phi^\dagger \Phi + m^2_\Phi \Phi^\dagger \Phi$$

What is the minimal subset of couplings we can consider?

- B anomalies only constrain couplings to d-type (b,s) and leptons (μ)
- We consider negligible SU(2) breaking for down-type quarks (constrained by the phenomenological un-relevant scalar/tensor operators)

Arnan, Crivellin, MF, Mescia (1904.05890)

4th Generation Model

$$L^{4\text{th}} = \sum_i \left(\Gamma^L_{q_i}\bar{\Psi}_q P_L q_i + \Gamma^L_{\ell_i}\bar{\Psi}_\ell P_L \ell_i + \Gamma^R_{u_i}\bar{\Psi}_u P_R u_i + \Gamma^R_{d_i}\bar{\Psi}_d P_R d_i + \Gamma^R_{e_i}\bar{\Psi}_e P_R e_i\right)\Phi + \text{h.c.}$$

$$+ \sum_{C=L,R}\left(\lambda^U_C\bar{\Psi}_q P_C\tilde{h}\Psi_u + \lambda^D_C\bar{\Psi}_q P_C h\Psi_d + \lambda^E_C\bar{\Psi}_\ell P_C h\Psi_e\right) + \text{h.c.}$$

$$+ \sum_{F=q,\ell,u,d,e} M_F\bar{\Psi}_F\Psi_F + \kappa\, h^\dagger h\Phi^\dagger\Phi + m^2_\Phi\Phi^\dagger\Phi$$

What is the minimal subset of couplings we can consider?

- B anomalies only constrain couplings to d-type (b,s) and leptons (μ)
- We consider negligible SU(2) breaking for down-type quarks (constrained by the phenomenological un-relevant scalar/tensor operators)
- The Higgs portal coupling is relevant only in expanded models (e.g. DM)

Arnan, Crivellin, MF, Mescia (1904.05890)

4th Generation Model

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$$+ \sum_{C=L,R}\left(\lambda^U_C\bar\Psi_q P_C\tilde h\Psi_u + \lambda^D_C\bar\Psi_q P_C h\Psi_d + \lambda^E_C\bar\Psi_\ell P_C h\Psi_e\right) + \text{h.c.}$$

$$+ \sum_{F=q,\ell,u,d,e} M_F\bar\Psi_F\Psi_F + \kappa h^\dagger h\Phi^\dagger\Phi + m^2_\Phi\Phi^\dagger\Phi$$

We need to diagonalise the lepton sector!

Below EWSB:

$$L^{4\text{th}}_{\text{mass}} = \begin{pmatrix}\bar\Psi_{\ell,2}\\ \bar\Psi_e\end{pmatrix}^T \begin{pmatrix} M_\ell & \sqrt{2}v\lambda^E_R \\ \sqrt{2}v\lambda^{E*}_L & M_e\end{pmatrix} P_L \begin{pmatrix}\Psi_{\ell,2}\\ \Psi_e\end{pmatrix} \Rightarrow$$

$$P_L\begin{pmatrix}\Psi_{\ell,2}\\ \Psi_e\end{pmatrix}_I \to W^{E_L}_{IJ}\Psi^{E_L}_J$$

$$\begin{pmatrix}\bar\Psi_{\ell,2}\\ \bar\Psi_e\end{pmatrix}^T_I P_L \to \bar\Psi^{E_R}_J W^{E_R}_{IJ}$$

Arnan, Crivellin, MF, Mescia (1904.05890)

4th Generation Model

$$L^{4\text{th}} = \sum_{i} \left(\Gamma^L_{q_i}\bar{\Psi}_q P_L q_i + \Gamma^L_{\ell_i}\bar{\Psi}_\ell P_L \ell_i + \Gamma^R_{u_i}\bar{\Psi}_u P_R u_i + \Gamma^R_{d_i}\bar{\Psi}_d P_R d_i + \Gamma^R_{e_i}\bar{\Psi}_e P_R e_i\right)\Phi + \text{h.c.}$$

$$P_L \begin{pmatrix}\Psi_{\ell,2}\\ \Psi_e\end{pmatrix}_I \to W^{E_L}_{IJ}\Psi^{E_L}_J$$

$$\begin{pmatrix}\bar{\Psi}_{\ell,2}\\ \bar{\Psi}_e\end{pmatrix}^T_I P_L \to \bar{\Psi}^{E_R}_J W^{E_R}_{IJ}$$

$$P_L \begin{pmatrix}\Psi_{q,2}\\ \Psi_d\end{pmatrix}_I \to \delta_{IJ}\Psi^{D_L}_J$$

$$\begin{pmatrix}\bar{\Psi}_{q,2}\\ \bar{\Psi}_d\end{pmatrix}^T_I P_L \to \bar{\Psi}^{D_R}_J \delta_{IJ}$$

$$L^{4\text{th}}_{\text{int}} = \left(L^b_1\bar{\Psi}^D_1 P_L b + L^s_1\bar{\Psi}^D_1 P_L s + L^\mu_I\bar{\Psi}^E_I P_L \mu\right)\Phi + \left(R^b_2\bar{\Psi}^D_1 P_R b + R^s_2\bar{\Psi}^D_1 P_R s + R^\mu_I\bar{\Psi}^E_I P_R \mu\right)\Phi$$

$$L^s_1 = \Gamma^L_s\,, \qquad L^b_1 = \Gamma^L_b\,, \qquad R^s_2 = \Gamma^R_s\,, \qquad R^b_2 = \Gamma^R_b\,,$$

$$L^\mu_1 = \Gamma^L_\mu \cos\theta_L\,, \qquad L^\mu_2 = -\Gamma^L_\mu \sin\theta_L\,, \qquad R^\mu_1 = \Gamma^R_\mu \sin\theta_R\,, \qquad R^\mu_2 = \Gamma^R_\mu \cos\theta_R$$

[Arnan, Crivellin, MF, Mescia (1904.05890)]

4th Generation Model - WC

$$\Gamma^L \equiv L_1^b L_1^{s*}\,, \qquad \Gamma^R \equiv R_2^b R_2^{s*}$$

- $b \to s\mu\mu$

$$C_9^{\text{box}} = -\mathcal{N}\frac{\Gamma^L}{32\pi\alpha_{\text{EM}} m_\Phi^2}\left(|\Gamma_\mu^L|^2 + |\Gamma_\mu^R|^2\right) F(x_D, x_E)$$

$$C_{10}^{\text{box}} = \mathcal{N}\frac{\Gamma^L}{32\pi\alpha_{\text{EM}} m_\Phi^2}\left(|\Gamma_\mu^L|^2 - |\Gamma_\mu^R|^2\right) F(x_D, x_E)$$

$$C_{9(10)}^{\prime\text{box}} = \pm\, C_{9(10)}^{\text{box}}(L \leftrightarrow R)$$

- ΔM_S

$$C_1 = \frac{|\Gamma^L|^2}{128\pi^2 m_\Phi^2} F(x_D)\,, \quad C_5 = -\frac{\Gamma^L\Gamma^R}{32\pi^2 m_\Phi^2} F(x_D)\,, \quad \tilde{C}_1 = \frac{|\Gamma^R|^2}{128\pi^2 m_\Phi^2} F(x_D)$$

- g-2

$$\lambda_R^E = -\lambda_L^E \equiv \lambda^E$$

$$\Delta a_\mu = \frac{m_\mu^2}{8\pi^2 m_\Phi^2}\left[\left(|\Gamma_\mu^L|^2 + |\Gamma_\mu^R|^2\right) F_7(x_E) + \frac{8}{\sqrt{2}}\frac{v\,\lambda^E}{m_\mu}\Gamma_\mu^L\Gamma_\mu^R G_7(x_E)\right]$$

$$|\Gamma_\mu^L| = 1.5\,, \qquad |\Gamma_\mu^R| = 1.4\,, \qquad \lambda^E = 0.0015\,, \qquad \Gamma^L = -1.0\,, \qquad \Gamma^R = -0.12$$

$m_\phi = m_E = 450$ GeV $\qquad m_D = 3.15$ TeV

Arnan, Crivellin, MF, Mescia (1904.05890)

D-Dbar mixing

$$\Gamma^L \equiv L_1^b L_1^{s*}\,, \qquad \Gamma^R \equiv R_2^b R_2^{s*}$$

$$L^{4\mathrm{th}} = \sum_i \left(\Gamma_{q_i}^L \bar\Psi_q P_L q_i + \Gamma_{\ell_i}^L \bar\Psi_\ell P_L \ell_i + \Gamma_{u_i}^R \bar\Psi_u P_R u_i + \Gamma_{d_i}^R \bar\Psi_d P_R d_i + \Gamma_{e_i}^R \bar\Psi_e P_R e_i\right)\Phi + \mathrm{h.c.}$$

SU(2) + CKM $\Downarrow$

$$L_1^u = V_{us}^*\,\Gamma_s^L + V_{ub}^*\,\Gamma_b^L\,, \qquad L_1^c = V_{cs}^*\,\Gamma_s^L + V_{cb}^*\,\Gamma_b^L$$

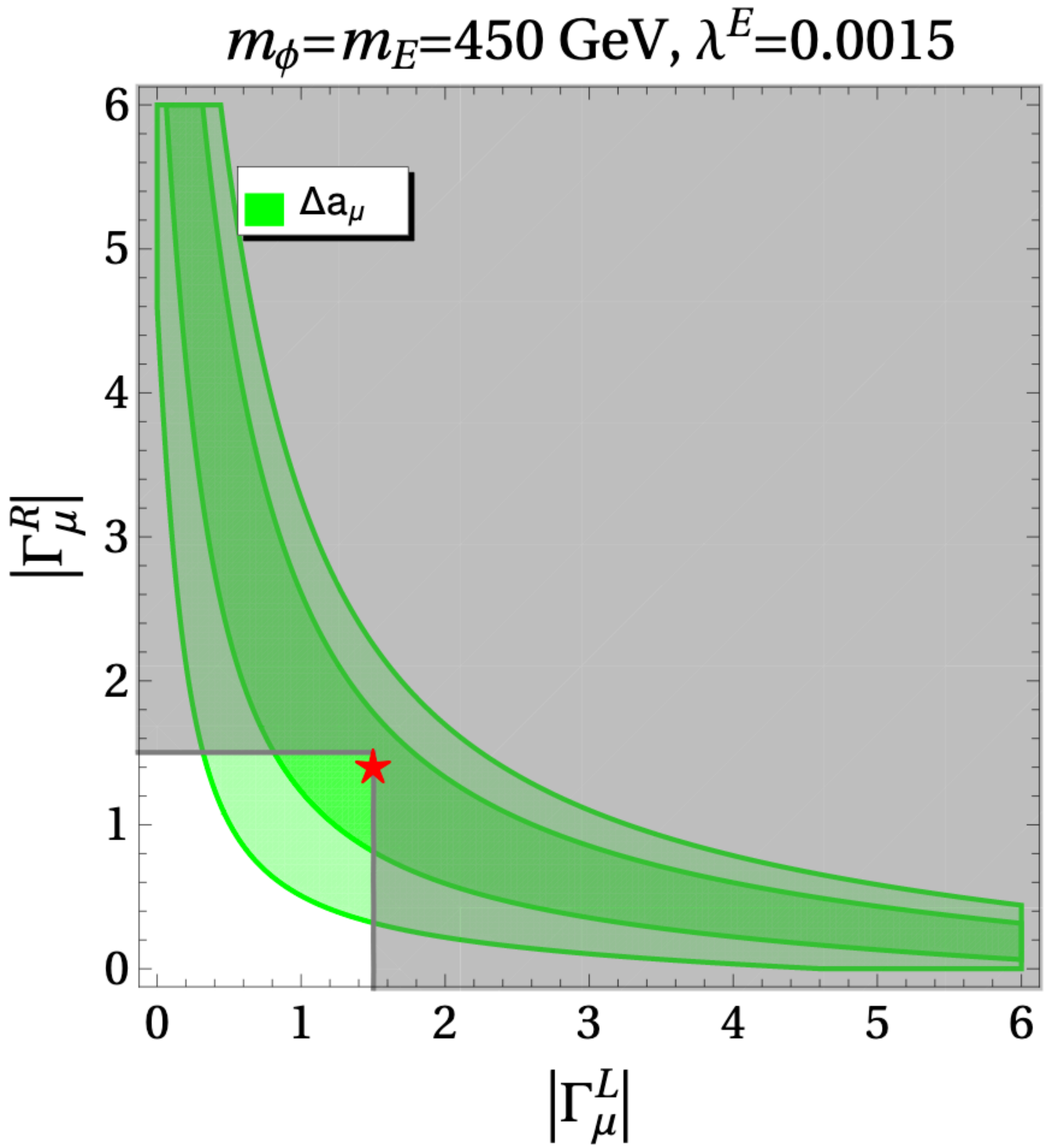
Only the product of down-type coupling is constrained

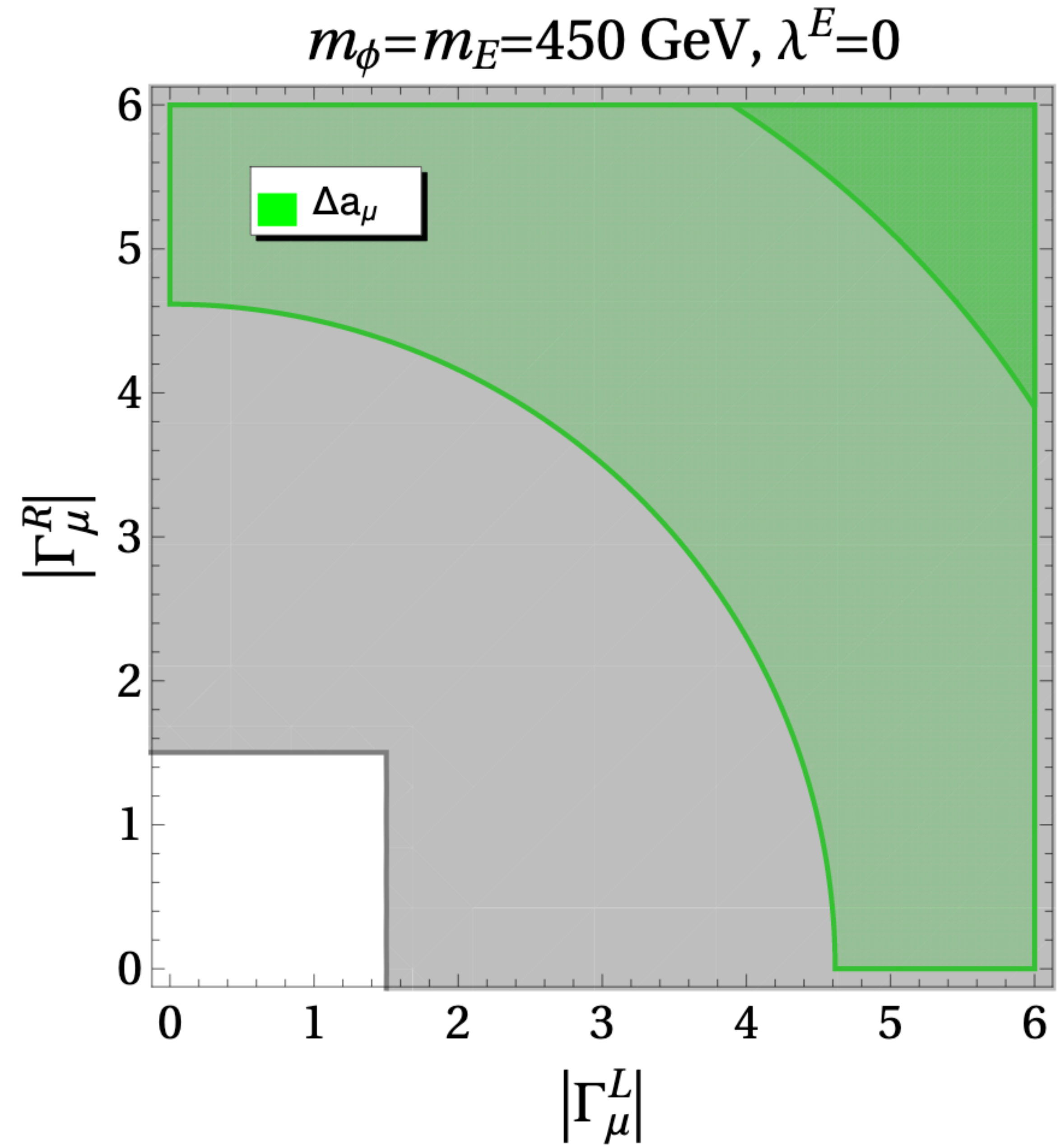
$$\Downarrow$$

$\Gamma_b^L \gg \Gamma_s^L$ implies negligible effects due to CKM suppressions

Arnan, Crivellin, MF, Mescia (1904.05890)

Fit g-2

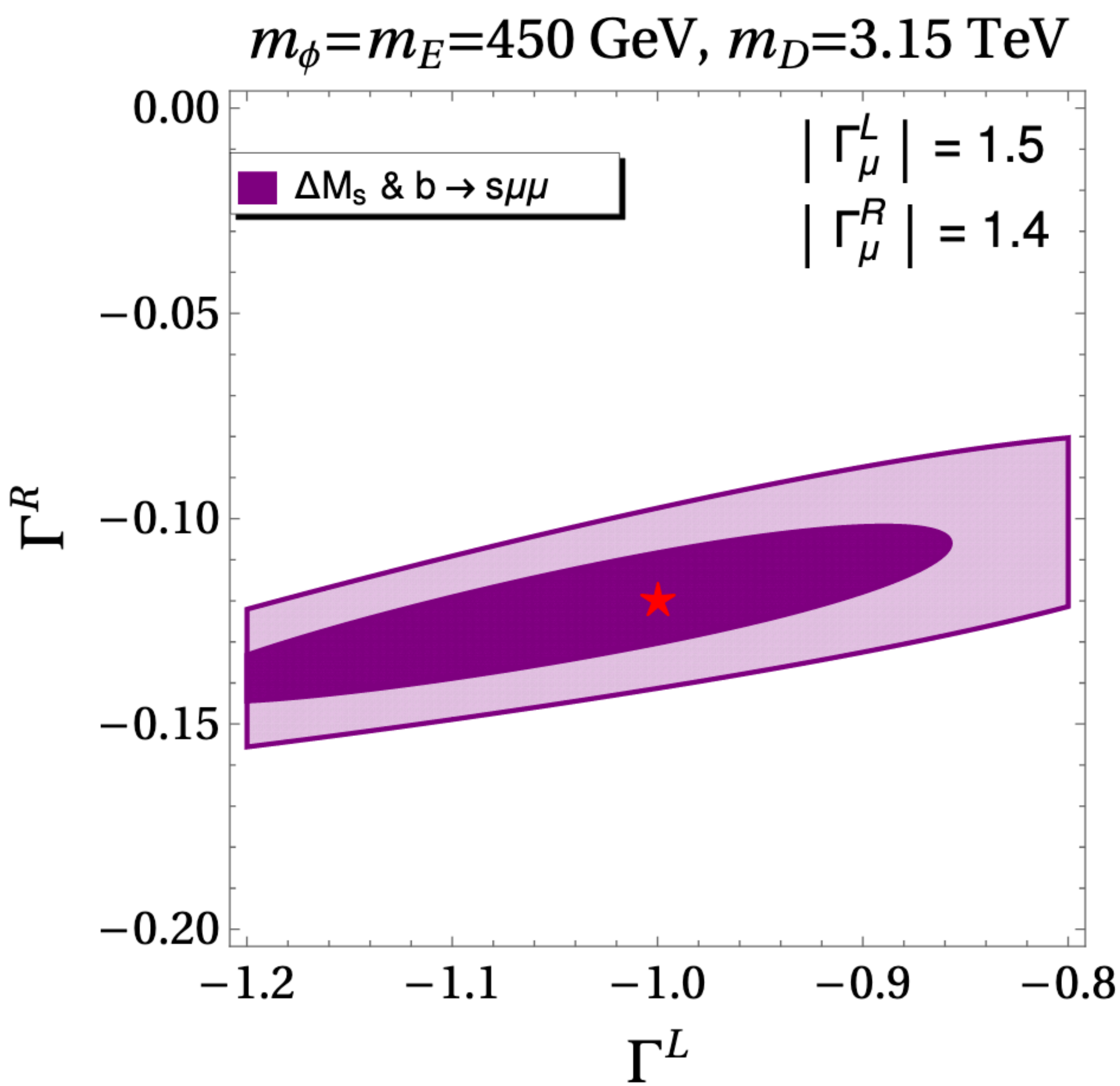


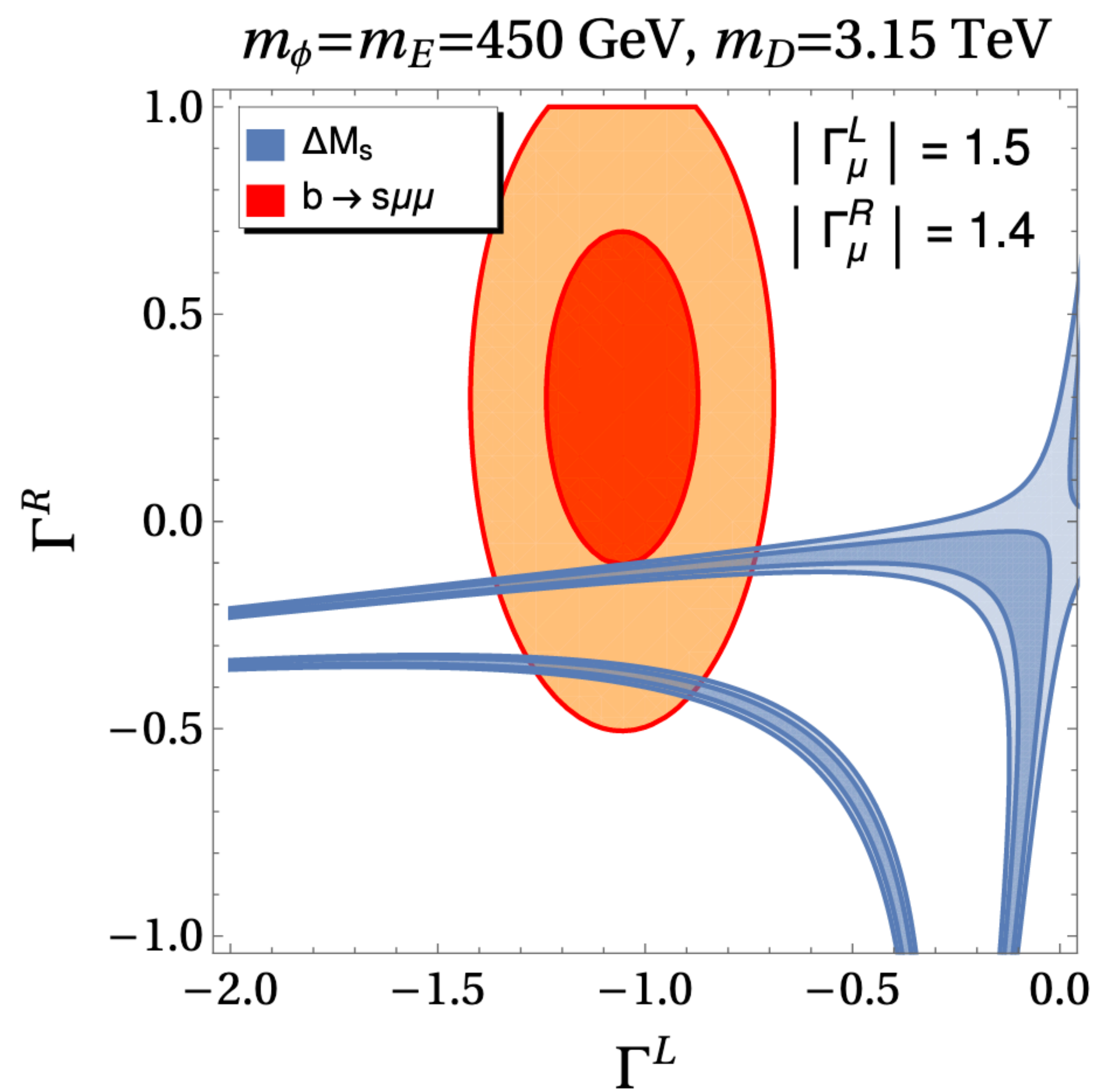


Right-handed coupling and SU(2) breaking both fundamental!

Arnan, Crivellin, MF, Mescia (1904.05890)

Fit B decays

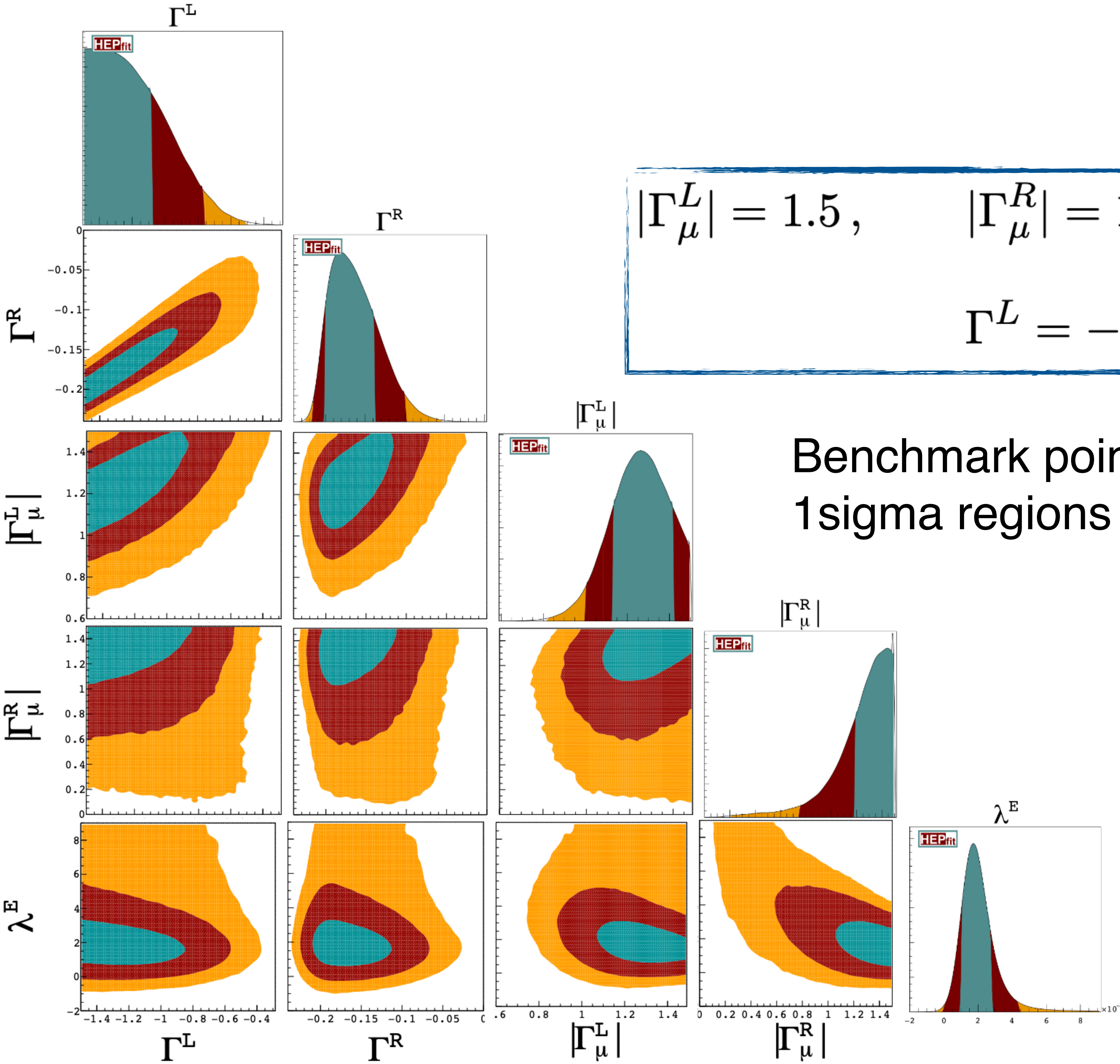




Right-handed coupling fundamental!

Arnan, Crivellin, MF, Mescia (1904.05890)

Global Fit



$$|\Gamma^L_\mu| = 1.5\,, \qquad |\Gamma^R_\mu| = 1.4\,, \qquad \lambda^E = 0.0015$$

$$\Gamma^L = -1.0\,, \qquad \Gamma^R = -0.12$$

Benchmark point, compatible with all 1sigma regions of combined pdf

Arnan, Crivellin, MF, Mescia (1904.05890)

Conclusions - i

- Hadronic contributions are important in B to V ll amplitude.
  —> present estimate of "charm-loop effect" limited to $q^2 << 4m^2_c$.

- Unknown QCD power corrections may also mimic NP effects.
  —> hard to call for NP in standalone study of $K^*\mu\mu$ angular obs!

Evidence for q^2 dependence beyond the first order in a power expansion in q^2 of the hadronic correlator

$$\tilde{h}_\lambda(q^2) \sim \epsilon_{\lambda,\mu} \int d^4x\, e^{iqx} \langle \overline{V}(\overline{P})| T\{J^{\mu,e.m.}_{had}(x)\mathcal{H}^{eff}_{had}(0)\}|\overline{B}\rangle$$

may definitely discriminate genuine NP effects with the advent of more data from LHCb / Belle2.

- $R_{K^{(*)}}$ anomalies (if not stat fluke/exp issue) undoubtedly require NP, both in left handed and right handed currents

A conservative approach to hadronic effects in b —> s ll global fits impacts significances + leaves room for different NP interpretations of current data.

Conclusions - ii

- We have provided analytical formulae for studying B anomalies, BBbar mixing and g-2 in the context of general loop models

- We have investigated the additional effects provided by right-handed couplings and additional SU(2) breaking effects

- We have investigated the phenomenology in a specific model, i.e. 4th generations of vector-like fermions + neutral scalar, and addressed all the above anomalies with viable masses and O(1) couplings

- The neutral scalar is a viable (stable) DM candidate, which however require a further detailed analysis still to be addressed