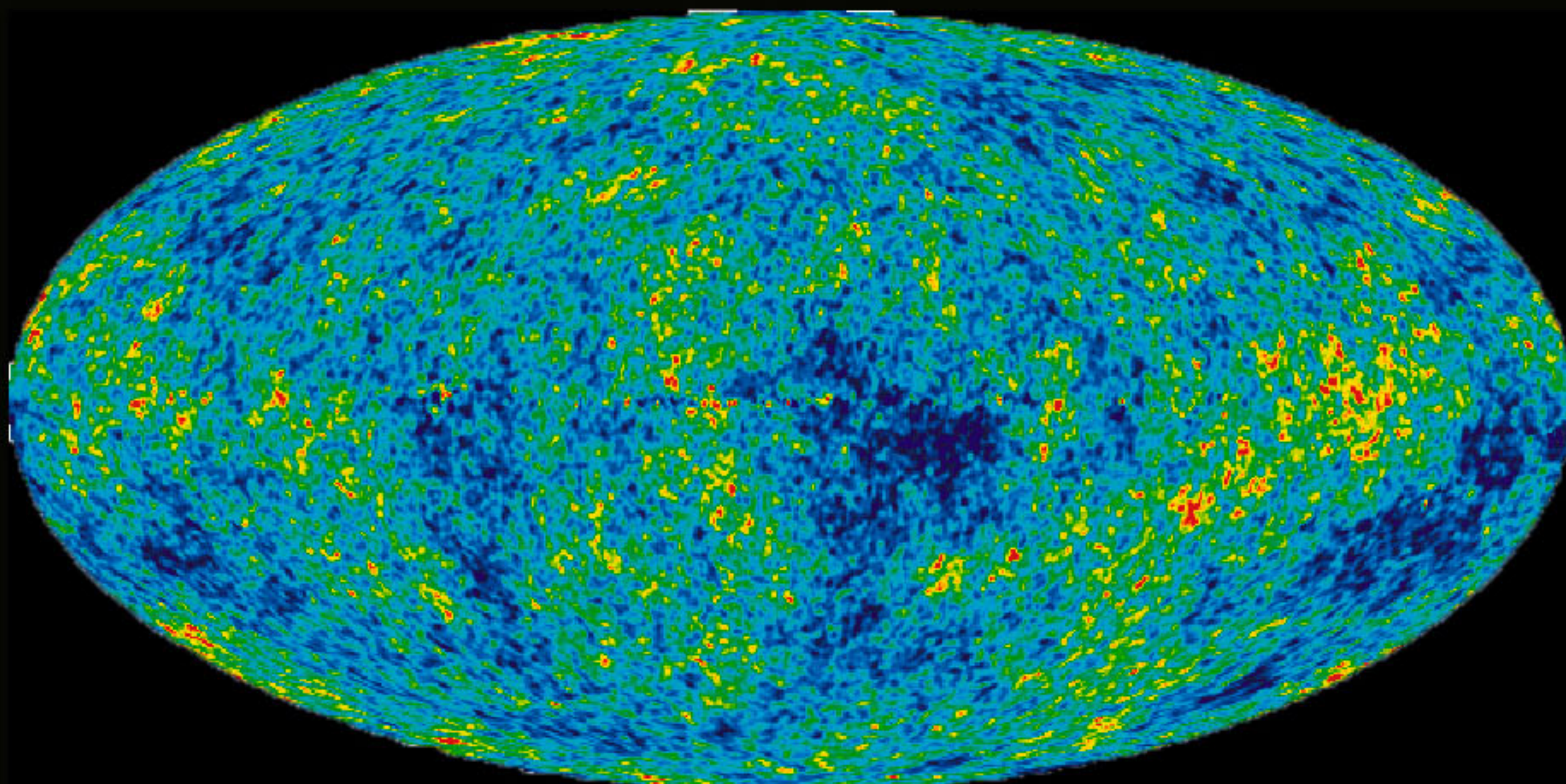
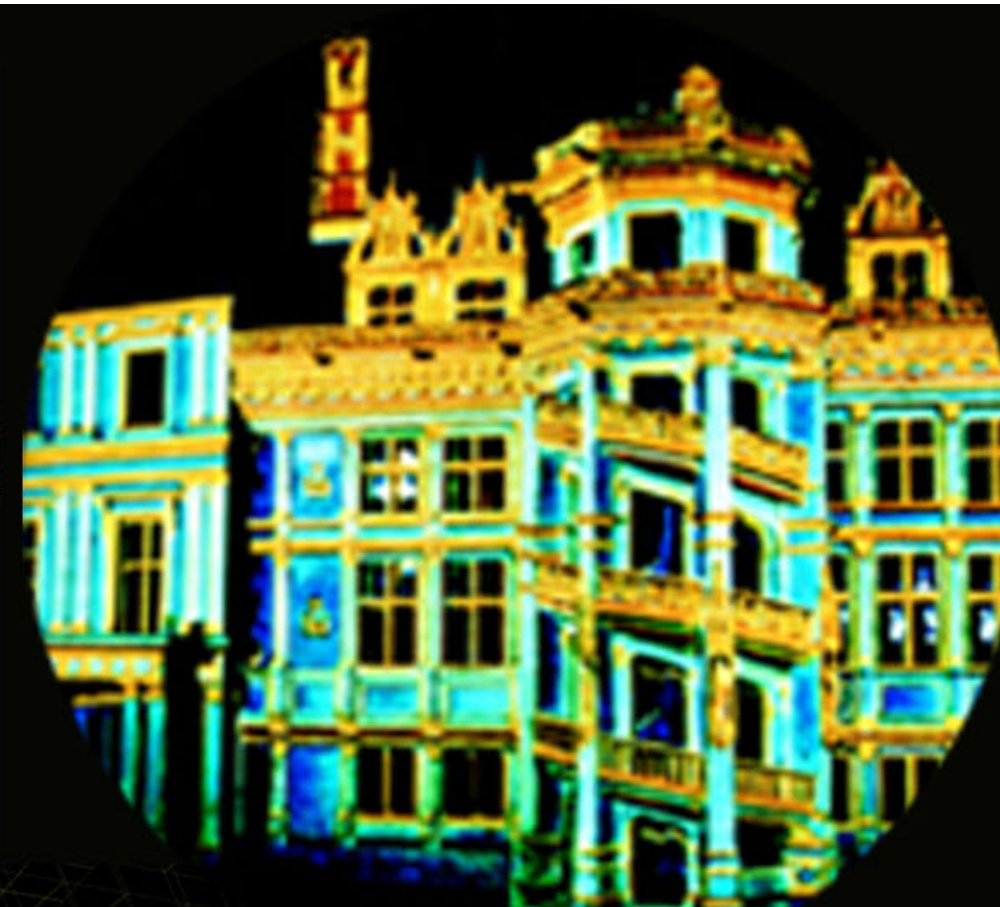
New Physics in Semi-leptonic Penguins ?

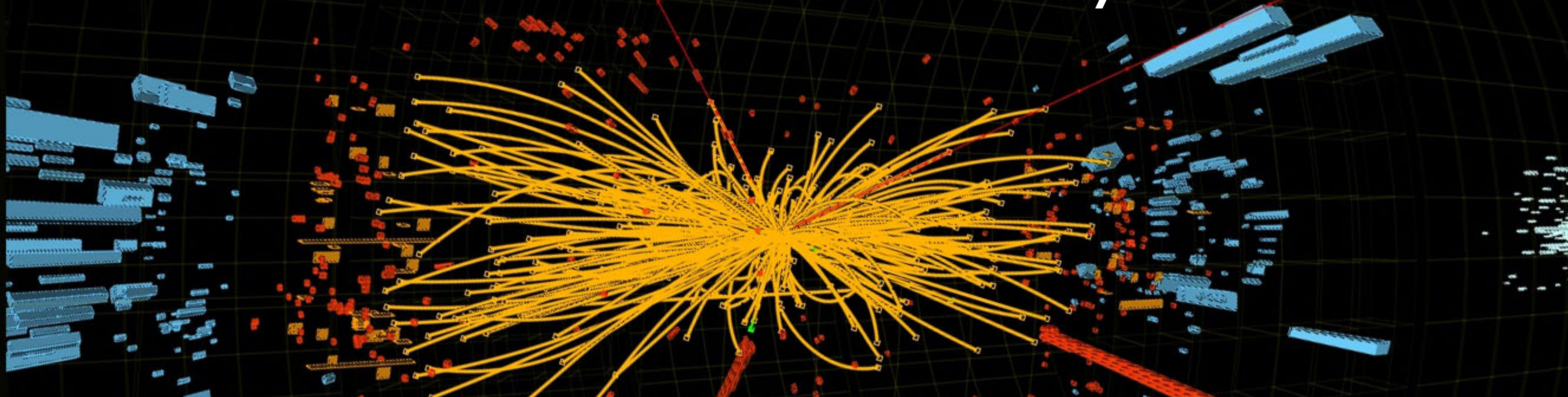
Tobias Hurth

Johannes Gutenberg University Mainz





31. Recontres des Blois: Particle Physics and Cosmology

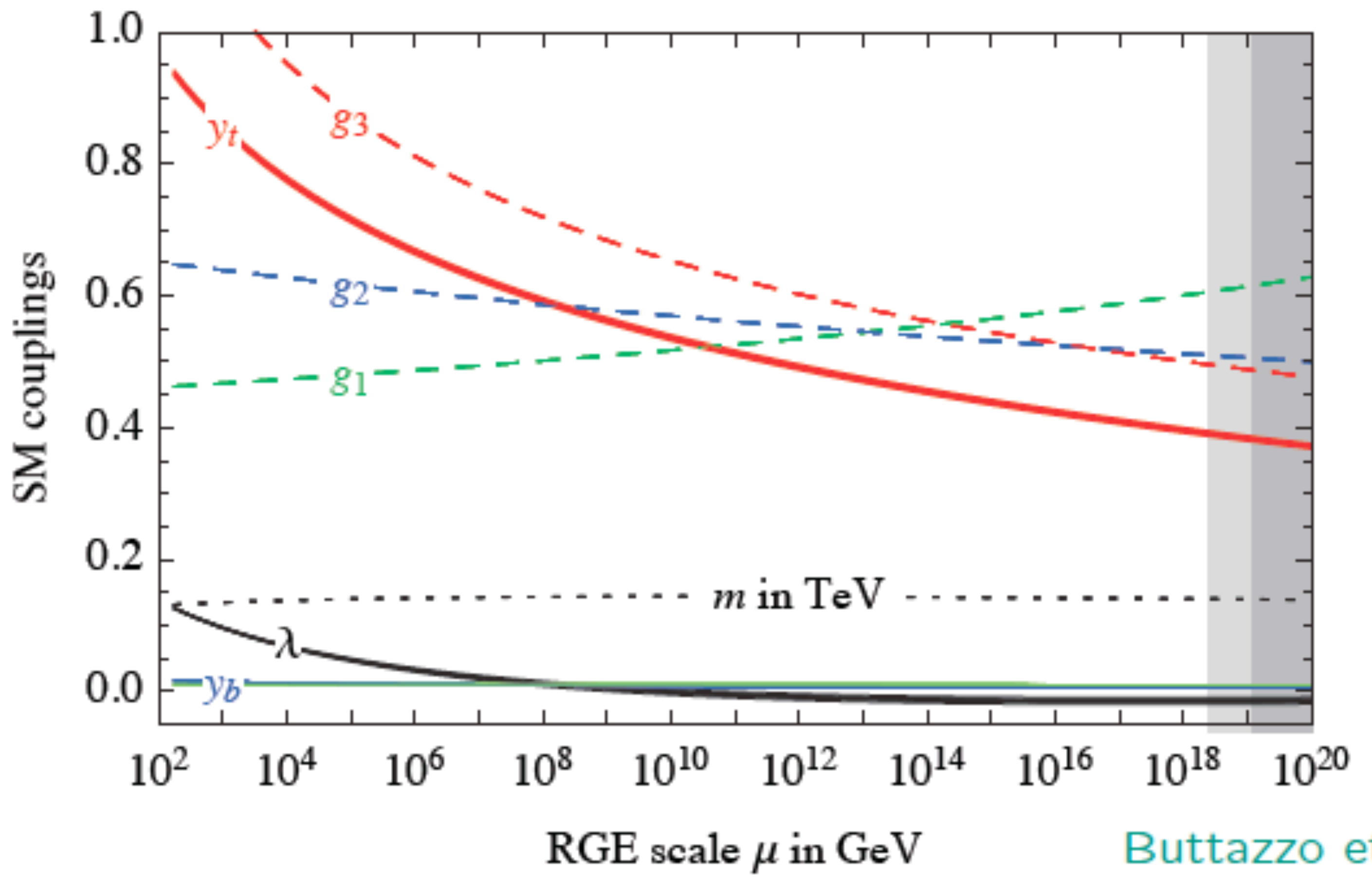


Prologue

Self-consistency of the SM

Do we need new physics beyond the SM ?

- It is possible to extend the validity of the SM up to the M_P as weakly coupled theory.



Buttazzo et al. arXiv:1307.3536

High-energy extrapolation shows that the Yukawa couplings, weak gauge couplings and the Higgs self coupling remain perturbative in the entire energy domain between the electroweak and Planck scale (no Landau poles !).

- Renormalizability implies no constraints on the free parameters of the SM Lagrangian.

Experimental evidence beyond SM

- Dark matter (visible matter accounts for only 4% of the Universe)
- Neutrino masses (Dirac or Majorana masses ?)
- Baryon asymmetry of the Universe (new sources of CP violation needed)

Caveat:

Answers perhaps wait at energy scales which we do not reach with present experiments.

Summary of experimental searches for New Physics

by Günther Dissertori (CMS)

$$\infty \times 0 = ?$$

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Infinite experimental measurements

No deviation from SM

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Infinite experimental measurements

No deviation from SM

There is still electroweak and flavour precision data to look for NP indirectly !

Indirect and direct discoveries

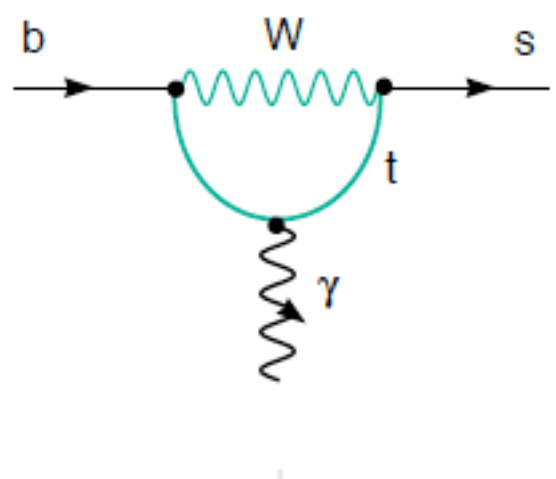
Particle	Indirect			Direct		
ν	β decay	Fermi	1932	Reactor ν-CC	Cowan, Reines	1956
W	β decay	Fermi	1932	$W\rightarrow e\nu$	UA1, UA2	1983
c	$K^0\rightarrow\mu\mu$	GIM	1970	J/ψ	Richter, Ting	1974
b	CPV $K^0\rightarrow\pi\pi$	CKM, 3rd gen	1964/	Υ	Ledermann	1977
Z	ν-NC	Gargamelle	1973	$Z\rightarrow e^+e^-$	UA1	1983
t	B mixing	ARGUS	1987	$t\rightarrow Wb$	D0, CDF	1995
H	e^+e^-	EW fit, LEP	2000	$H\rightarrow 4\mu/\gamma\gamma$	CMS, ATLAS	2012
?	**What's next ?**		?			?

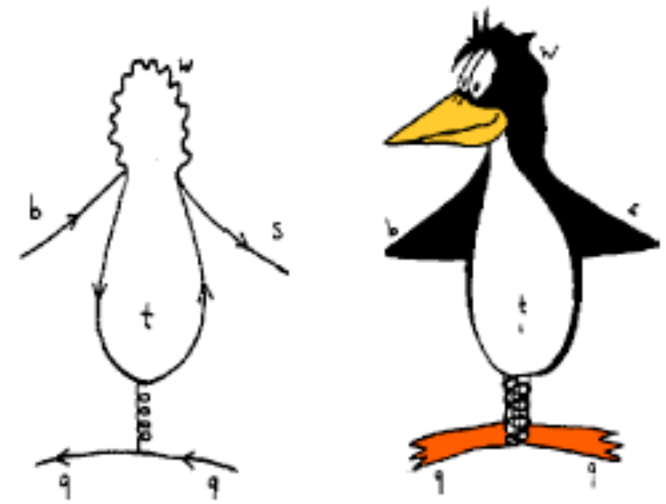
N. Tuning, ICHEP 2018

The indirect discovery very often was before the direct one, but the glory was reserved for the direct discoveries….

Indirect exploration of higher scales via flavour

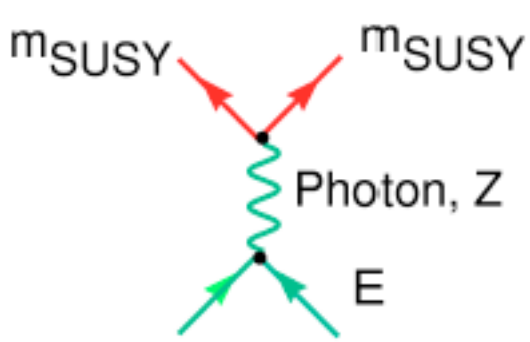
- Flavour changing neutral currrent processes like $b \to s\gamma$ or $b \to s\ell^+\ell^-$ directly probe the SM at the one-loop level.



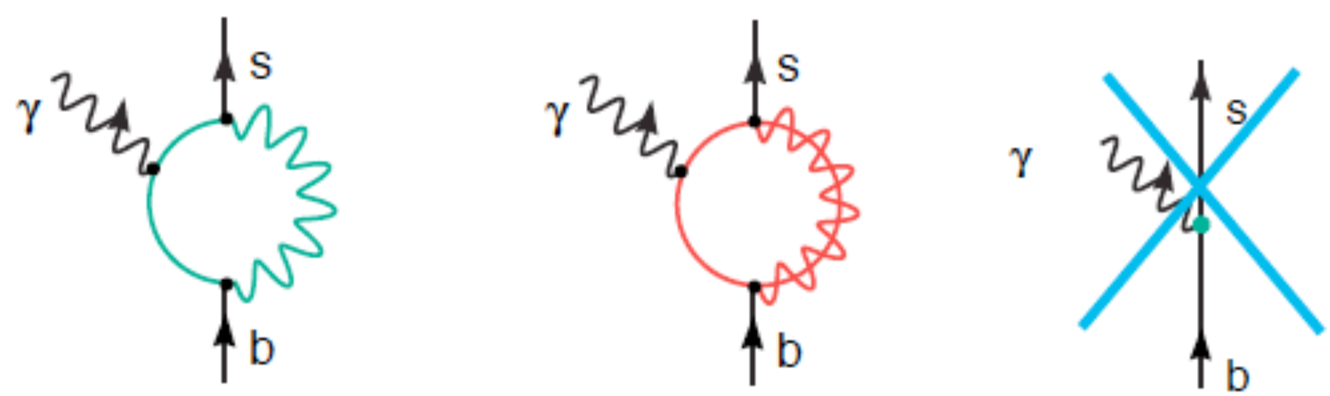


- Indirect search strategy for new degrees of freedom beyond the SM

Direct:



Indirect:



- High sensitivity for 'New Physics' ($\leftrightarrow$ elektroweak precision data, 10% $\leftrightarrow$ 0.1%)

Ambiguity of new physics scale from flavour data:

$$(C^i_{\mathsf{SM}}/M_W + C^i_{\mathsf{NP}}/\Lambda_{\mathsf{NP}}) \times \mathcal{O}_i$$

Minimal flavour violation as solution of NP flavour problem

Ambiguity of new physics scale from flavour data:

$$(C^i_{\mathrm{SM}}/M_W + C^i_{\mathrm{NP}}/\Lambda_{\mathrm{NP}}) \times \mathcal{O}_i$$

$$M(B_d\text{-}\bar{B}_d) \sim \frac{(V_{tb}^* V_{td})^2}{16\,\pi^2 M_W^2} + c_{NP}\frac{1}{\Lambda^2}$$

contribution of the new heavy degrees of freedom

c_{NP}:

- ~ 1 — tree/strong + generic flavour → $\Lambda \gtrsim 2\times10^4$ TeV [K]
- $\sim 1/(16\,\pi^2)$ — loop + generic flavour → $\Lambda \gtrsim 2\times10^3$ TeV [K]
- $\sim (V_{ti}^* V_{tj})^2$ — tree/strong + MFV → $\Lambda \gtrsim 5$ TeV [K & B_d]
- $\sim (V_{ti}^* V_{tj})^2/(16\,\pi^2)$ — loop + MFV → $\Lambda \gtrsim 0.5$ TeV [K & B_d]

Courtesy of Gino Isidori

Minimal flavour violation as solution of NP flavour problem

Ambiguity of new physics scale from flavour data:

$$\left(C^i_{\rm SM}/M_W + C^i_{\rm NP}/\Lambda_{\rm NP}\right) \times \mathcal{O}_i$$

$$M(B_d\text{-}\bar{B}_d) \sim \frac{(V_{tb}{}^* V_{td})^2}{16\,\pi^2 M_w{}^2} + c_{\rm NP}\frac{1}{\Lambda^2}$$

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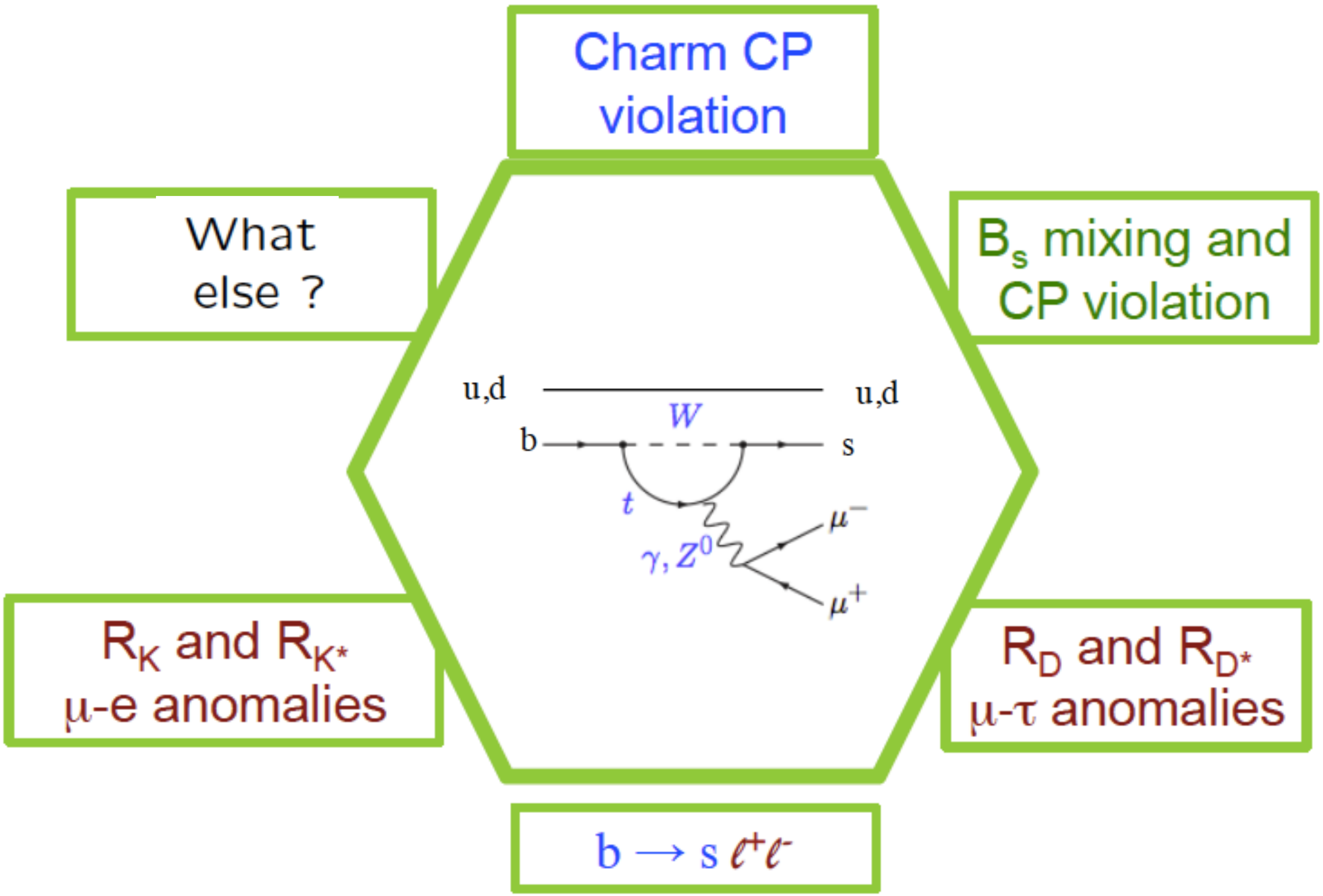
- $\sim (V_{ti}{}^* V_{tj})^2/(16\,\pi^2)$ — loop + MFV → $\Lambda \gtrsim 0.5$ TeV [K & B_d]

Courtesy of Gino Isidori

Non-minmal flavour structures are still compatible with the data !

Present status of tensions in flavour physics



Colour code: no anomaly seen; needs TH understanding; needs more data

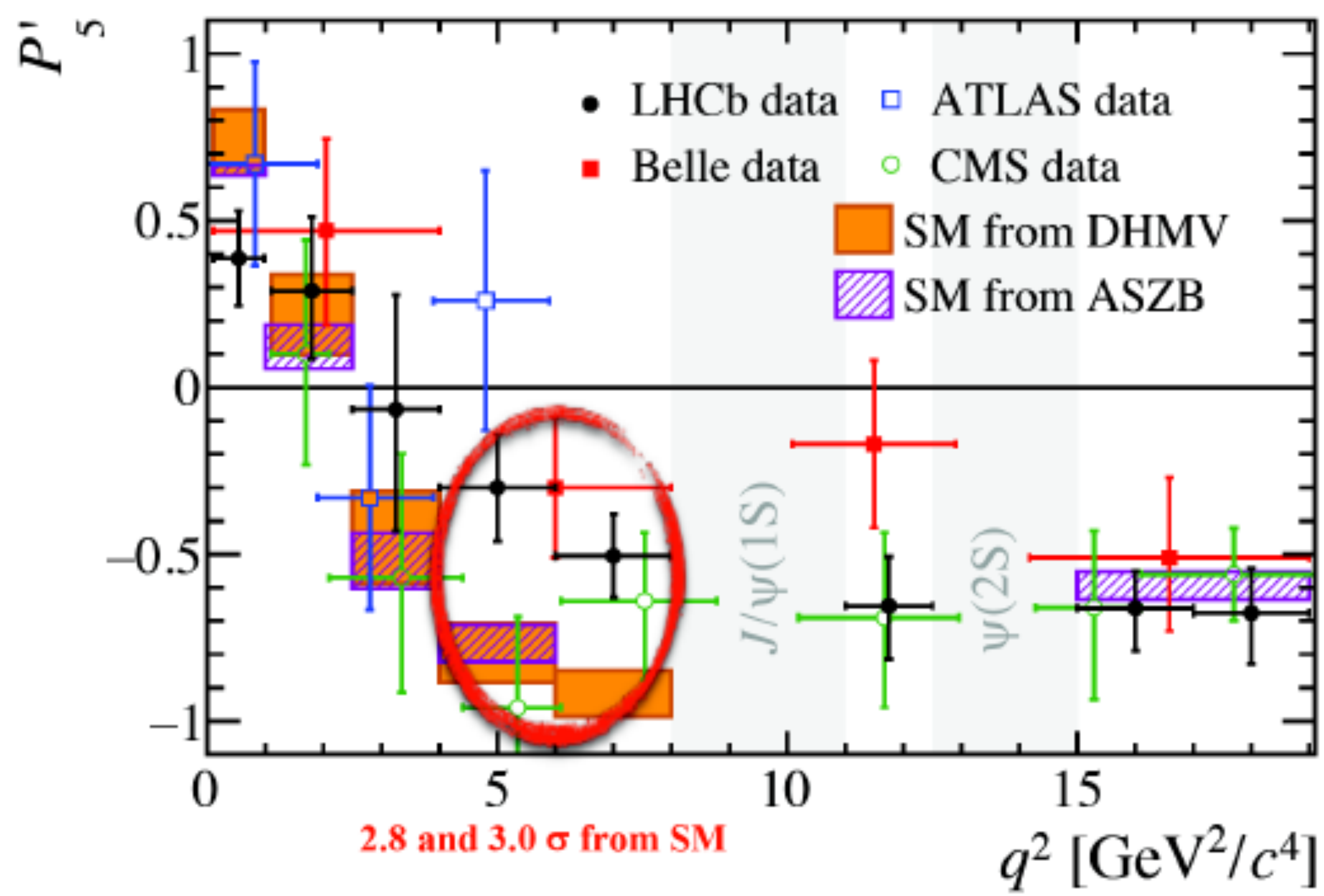
Courtesy of Johannes Albrecht

The b > s Anomalies

Anomalies in $B \to K^*\mu^+\mu^-$ angular observables, in particular P'_5 ; S_5

Long standing anomaly **2-3σ**:

- 2013 (1 fb^{-1}): disagreement with the SM for P_2 and P'_5 (PRL 111, 191801 (2013))
- March 2015 (3 fb^{-1}): confirmation of the deviations (LHCb-CONF-2015-002)
- Dec. 2015: 2 analysis methods, both show the deviations (JHEP 1602, 104 (2016))



LHCb, JHEP 02 (2016) 104; Belle, PRL 118 (2017); ATLAS, ATLAS-CONF-2017-023; CMS, CMS-PAS-BPH-15-008

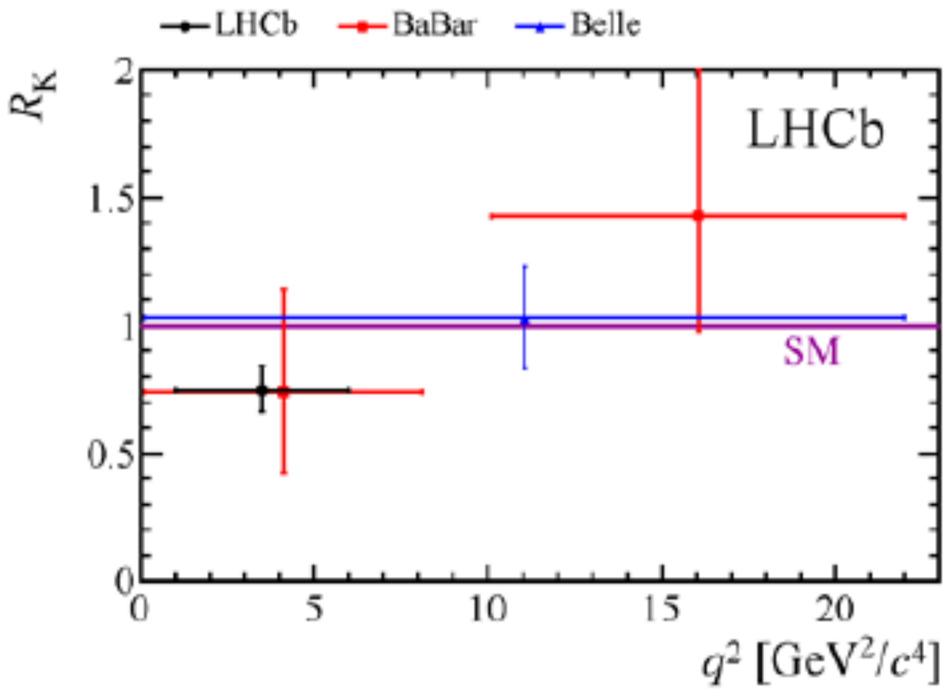
- Also measured by ATLAS, CMS and Belle

New Physics or underestimated hadronic uncertainties

(form factors, power corrections) ?

Lepton flavour universality in $B^+ \to K^+\ell^+\ell^-$

- June 2014 (3 fb^{-1}): measurement of R_K in the [1-6] GeV^2 bin (PRL 113, 151601 (2014)): **2.6σ** tension in [1-6] GeV^2 bin
- SM prediction very accurate (leading corrections from QED, giving rise to large logarithms involving the ratio $m_B/m_{\mu,e}$)



BaBar, PRD 86 (2012) 032012; Belle, PRL 103 (2009) 171801

$$R_K = BR(B^+ \to K^+\mu^+\mu^-)/BR(B^+ \to K^+e^+e^-)$$

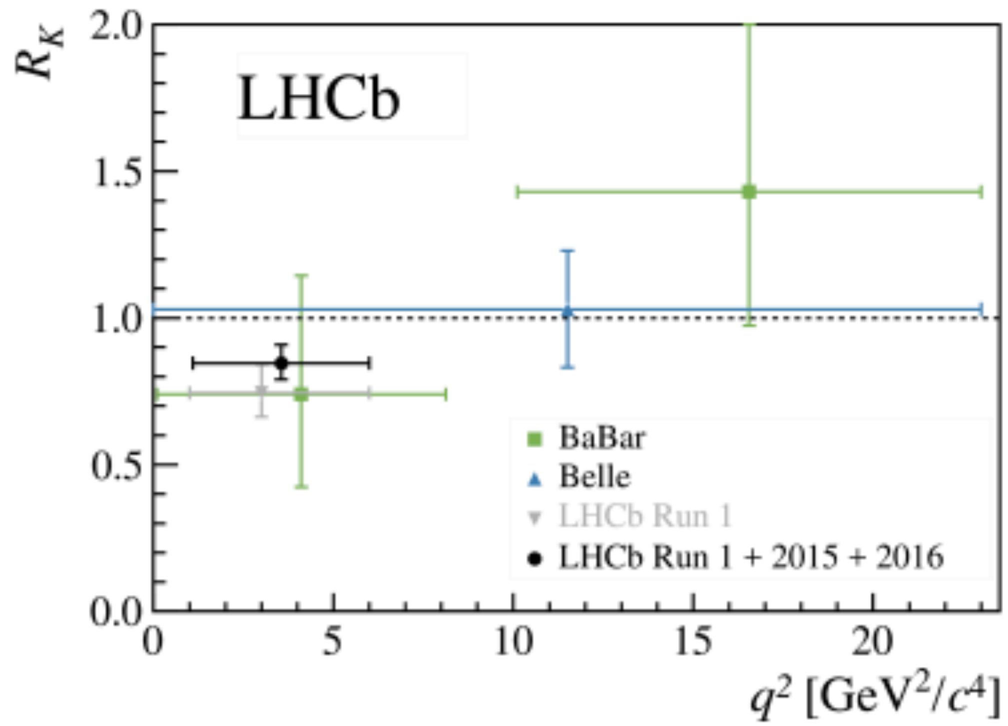
$$R_K^{\text{exp}} = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$$

$$R_K^{\text{SM}} = 1.0006 \pm 0.0004$$

Bordone, Isidori, Pattori, arXiv:1605.07633

Would be a spectacular fall of the SM !

New results: Lepton flavour universality in $B^+ \to K^+\ell^+\ell^-$



Run 1 (PRL 113, 151601 (2014)):

$$R_K([1.1, 6.0]\,\mathrm{GeV}^2) = 0.717^{+0.083+0.017}_{-0.071-0.016}$$

Run 2 (arXiv:1903.09252):

$$R_K([1.1, 6.0]\,\mathrm{GeV}^2) = 0.928^{+0.089+0.020}_{-0.076-0.017}$$

$$R_K^{\mathrm{SM}} = 1.0006 \pm 0.0004$$

Bordone, Isidori, Pattori, Eur.Phys.J. C76 (2016) 8, 440

Combined result (arXiv:1903.09252):

$$R_K([1.1, 6.0]\,\mathrm{GeV}^2) = 0.846^{+0.060+0.016}_{-0.054-0.014}$$

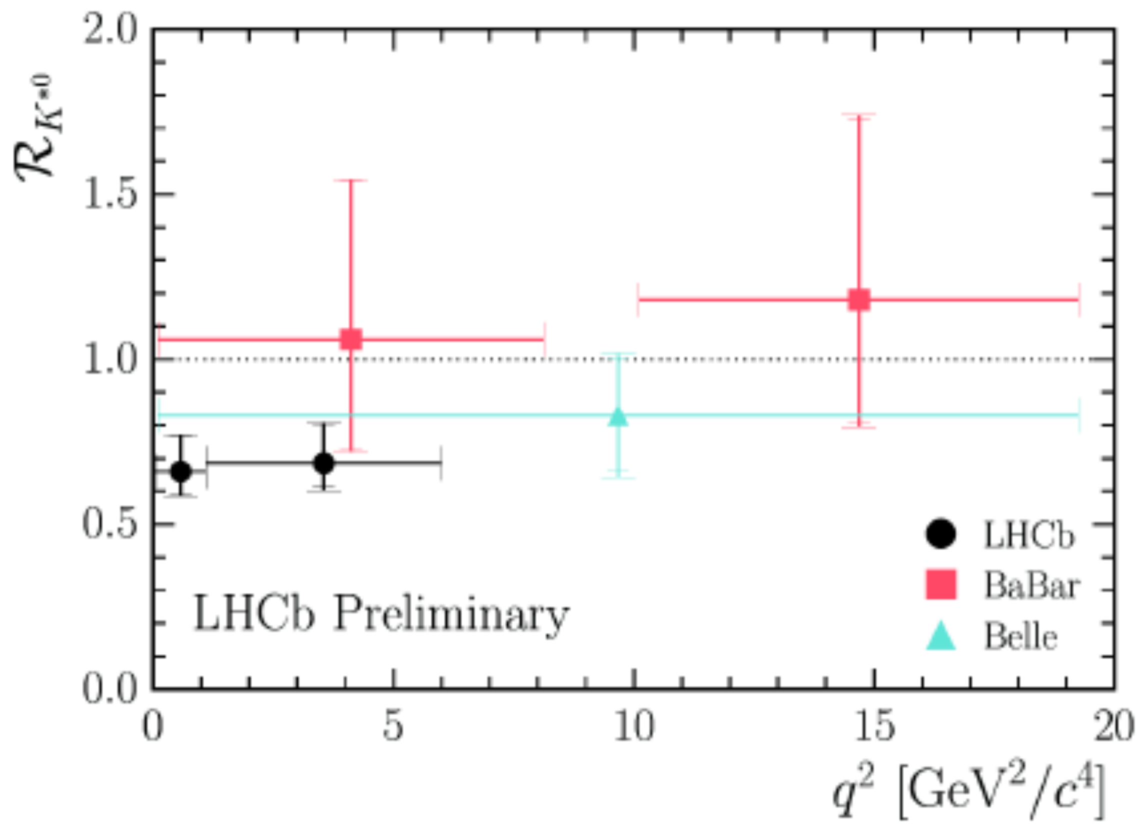
Central value is now closer to the SM prediction, but the tension is still 2.5σ due to the smaller uncertainty of the new measurement.

Lepton flavour universality in $B^0 \to K^{*0}\ell^+\ell^-$

- LHCb measurement (April 2017): **JHEP 1602, 104 (2016)**

$$R_{K^*} = BR(B^0 \to K^{*0}\mu^+\mu^-)/BR(B^0 \to K^{*0}e^+e^-)$$

- Two q^2 regions: [0.045-1.1] and [1.1-6.0] GeV^2



BaBar, PRD 86 (2012) 032012; Belle, PRL 103 (2009) 171801

$$R_{K^*}^{\mathrm{exp,bin1}} = 0.660^{+0.110}_{-0.070}(\mathrm{stat}) \pm 0.024(\mathrm{syst})$$

$$R_{K^*}^{\mathrm{exp,bin2}} = 0.685^{+0.113}_{-0.069}(\mathrm{stat}) \pm 0.047(\mathrm{syst})$$

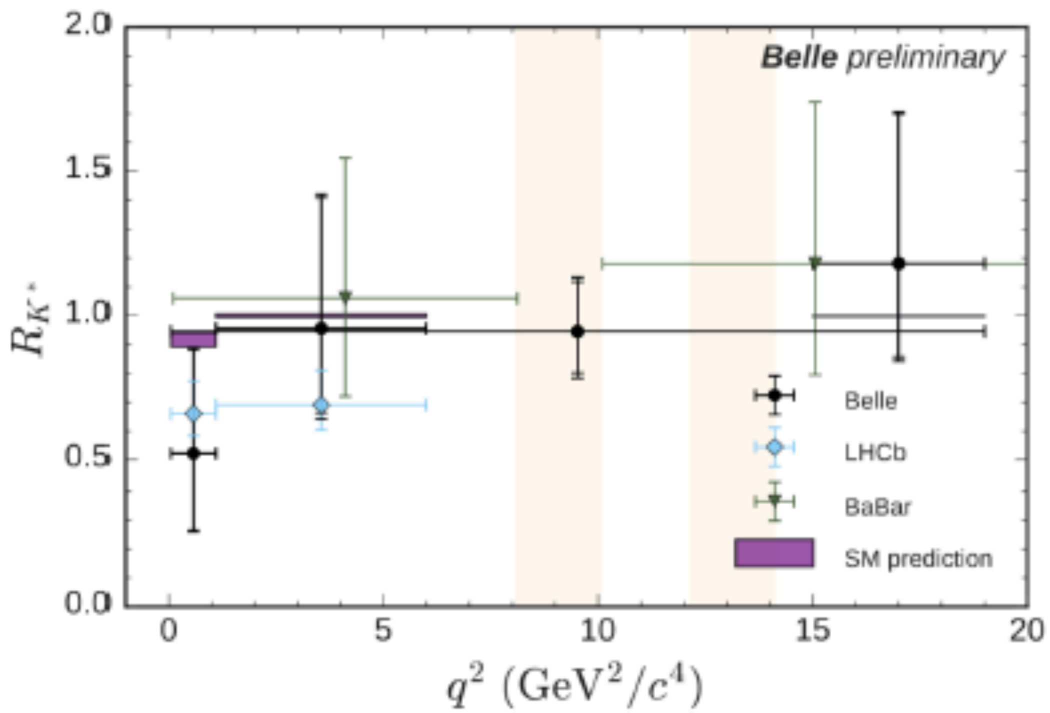
$$R_{K^*}^{\mathrm{SM,bin1}} = 0.906 \pm 0.020_{\mathrm{QED}} \pm 0.020_{\mathrm{FF}}$$

$$R_{K^*}^{\mathrm{SM,bin2}} = 1.000 \pm 0.010_{\mathrm{QED}}$$

Bordone, Isidori, Pattori, arXiv:1605.07633

2.2-2.5σ tension with the SM predictions in each bin

New results: Lepton flavour universality in $B^0 \to K^{*0}\ell^+\ell^-$



LHCb (JHEP 08 (2017) 055):

$$R_{K^*}([0.045, 1.1]\,\mathrm{GeV}^2) = 0.660^{+0.110}_{-0.070} \pm 0.024$$

$$R_{K^*}([1.1, 6]\,\mathrm{GeV}^2) = 0.685^{+0.113}_{-0.069} \pm 0.047$$

Belle (arXiv:1904.02440):

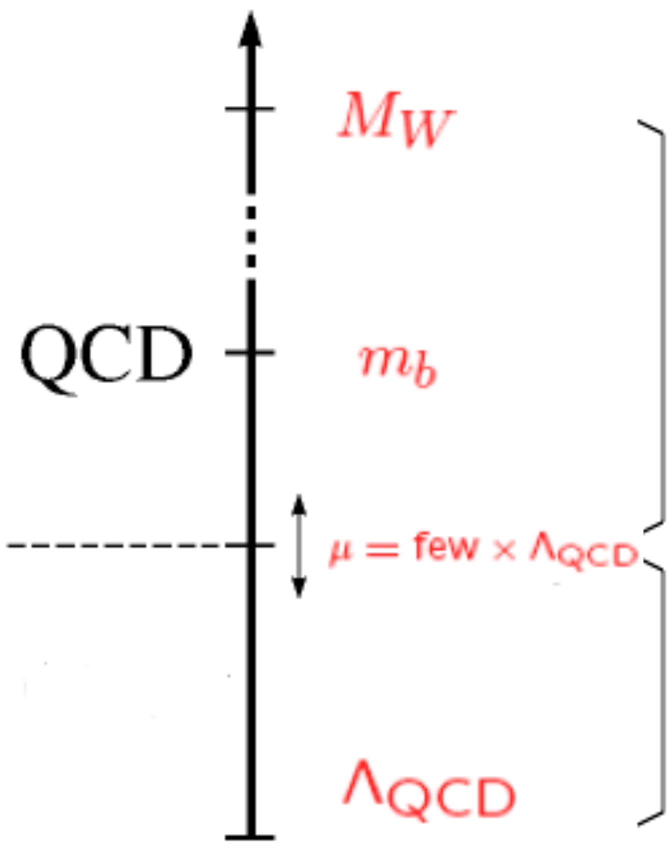
$$R_{K^*}([0.045, 1.1]\,\mathrm{GeV}^2) = 0.52^{+0.36}_{-0.26} \pm 0.05, \quad R_{K^*}([1.1, 6.0]\,\mathrm{GeV}^2) = 0.96^{+0.45}_{-0.29} \pm 0.11,$$

$$R_{K^*}([0.1, 8]\,\mathrm{GeV}^2) = 0.90^{+0.27}_{-0.21} \pm 0.10, \quad R_{K^*}([15, 19]\,\mathrm{GeV}^2) = 1.18^{+0.52}_{-0.32} \pm 0.10.$$

The very low-q^2 bin has a tension with the SM prediction slightly more than 1σ, while the other bins are all well in agreement with the SM at the 1σ-level.

Theoretical Tools

Theoretical tools for flavour precision observables



short-distance physics
perturbative

long-distance physics
nonperturbative

Factorization theorems: separating long- and short-distance physics

- Electroweak effective Hamiltonian: $H_{eff} = -\frac{4G_F}{\sqrt{2}} \sum C_i(\mu, M_{heavy})\ \mathcal{O}_i(\mu)$

- $\mu^2 \approx M_{New}^2 >> M_W^2$: 'new physics' effects: $C_i^{SM}(M_W) + C_i^{New}(M_W)$

How to compute the hadronic matrix elements $\mathcal{O}_i(\mu = m_b)$?

Exclusive modes $B \to K^{(*)}\ell\ell$

QCD-improved factorization: BBNS 1999

$$\mathcal{T}_a^{(i)} = C_a^{(i)}\xi_a + \phi_B \otimes T_a^{(i)} \otimes \phi_{a,K^*} + O(\Lambda/m_b)$$

(Soft-collinear effective theory)

– Separation of perturbative hard kernels from process-independent nonperturbative functions like form factors

– Relations between formfactors in large-energy limit

– Limitation: insufficient information on power-suppressed Λ/m_b terms (breakdown of factorization: 'endpoint divergences')

The significance of the anomalies depends on the assumptions made for the unknown power corrections!

(This does not affect R_K and R_K^* of course, but does affect combined fits!)

Model independent Analysis

Hurth, Mahmoudi, Martinez Santos, Neshatpour arXiv: 1705.06274

Arby,Hurth,Mahmoudi,Neshatpour arXiv: 1806.02791

Arby,Hurth,Mahmoudi,Martinez-Santos,Neshatpour, arXiv:1904.08399

Model-independent global fits to $b \to s$ data

Relevant operators: $\mathcal{O}_7, \mathcal{O}_8, \mathcal{O}'_{9\mu,e}, \mathcal{O}'_{10\mu.e}$

Scan over the values of δC_i: $C_i(\mu) = C_i^{\rm SM} + \delta C_i$

More than 100 observables included

Experimental and theoretical correlations considered

Several groups doing global fits.

Fits to the data including R_{K^*} of 2017

Capdevilla et al. arXix:1704.05340
Geng et al. arXiv:1704.05446
Altmannshofer et al. arXiv:1704.05435
D'Amico et al. arXiv:1704.05438
Ciuchini et al. arXiv:1704.05447
Hiller, Nisandzic arXiv:1704.05444
Hurth et al. arXiv:1705.06274

Fits to the data after Moriond 2019

Alguero et al. arXiv:1903.09578
Aebischer et al. arXiv:1903.10434
Ciuchini et al. arXiv:1903.09632
Arby et al. arXiv:1904.08399

Separate NP fits with a single operator

	All observables except R_K, R_{K^*} ($\chi^2_{\rm SM} = 100.2$)		
	b.f. value	$\chi^2_{\rm min}$	$\mathrm{Pull}_{\rm SM}$
δC_9	-1.00 ± 0.20	82.5	4.2σ
δC_9^μ	-1.03 ± 0.20	80.3	4.5σ
δC_9^e	0.72 ± 0.58	98.9	1.1σ
δC_{10}	0.25 ± 0.23	98.9	1.1σ
δC_{10}^μ	0.32 ± 0.22	98.0	1.5σ
δC_{10}^e	-0.56 ± 0.50	99.1	1.0σ
$\delta C_{\rm LL}^\mu$	-0.48 ± 0.15	89.1	3.3σ
$\delta C_{\rm LL}^e$	0.33 ± 0.29	99.0	1.1σ

	Only R_K, R_{K^*} ($\chi^2_{\rm SM} = 16.9$)		
	b.f. value	$\chi^2_{\rm min}$	$\mathrm{Pull}_{\rm SM}$
δC_9	-2.04 ± 5.93	16.8	0.3σ
δC_9^μ	-0.74 ± 0.28	8.4	2.9σ
δC_9^e	0.79 ± 0.29	7.7	3.0σ
δC_{10}	4.10 ± 11.87	16.7	0.5σ
δC_{10}^μ	0.77 ± 0.26	6.1	3.3σ
δC_{10}^e	-0.78 ± 0.27	6.0	3.3σ
$\delta C_{\rm LL}^\mu$	-0.37 ± 0.12	7.0	3.1σ
$\delta C_{\rm LL}^e$	0.41 ± 0.15	6.8	3.2σ

$\delta C_{\rm LL}^\ell$ basis corresponds to $\delta C_9^\ell = -\delta C_{10}^\ell$.

Reduced NP significance of the ratios compared to before

NP analyses of the two sets of observables are less coherent than often stated, especially regarding the coefficients $C_{10}^{\mu,e}$.

Separate NP fits with a single operator

All observables except $R_K, R_{K^*}, B_{s,d} \to \mu^+\mu^-$ ($\chi^2_{\rm SM} = 99.7$)			
	b.f. value	$\chi^2_{\rm min}$	$\rm Pull_{SM}$
δC_9	-1.03 ± 0.20	81.0	4.3σ
δC_9^μ	-1.05 ± 0.19	78.8	4.6σ
δC_9^e	0.72 ± 0.58	98.5	1.1σ
δC_{10}	0.27 ± 0.28	98.7	1.0σ
δC_{10}^μ	0.38 ± 0.28	97.7	1.4σ
δC_{10}^e	-0.56 ± 0.50	98.7	1.0σ
$\delta C_{\rm LL}^\mu$	-0.50 ± 0.16	88.8	3.3σ
$\delta C_{\rm LL}^e$	0.33 ± 0.29	98.6	1.1σ

Only $R_K, R_{K^*}, B_{s,d} \to \mu^+\mu^-$ ($\chi^2_{\rm SM} = 19.0$)			
	b.f. value	$\chi^2_{\rm min}$	$\rm Pull_{SM}$
δC_9	-2.04 ± 5.93	18.9	0.3σ
δC_9^μ	-0.74 ± 0.28	10.6	2.9σ
δC_9^e	0.79 ± 0.29	9.9	3.0σ
δC_{10}	0.43 ± 0.32	17.0	1.4σ
δC_{10}^μ	0.65 ± 0.20	6.9	3.5σ
δC_{10}^e	-0.78 ± 0.27	8.2	3.3σ
$\delta C_{\rm LL}^\mu$	-0.37 ± 0.11	7.2	3.4σ
$\delta C_{\rm LL}^e$	0.41 ± 0.15	9.0	3.2σ

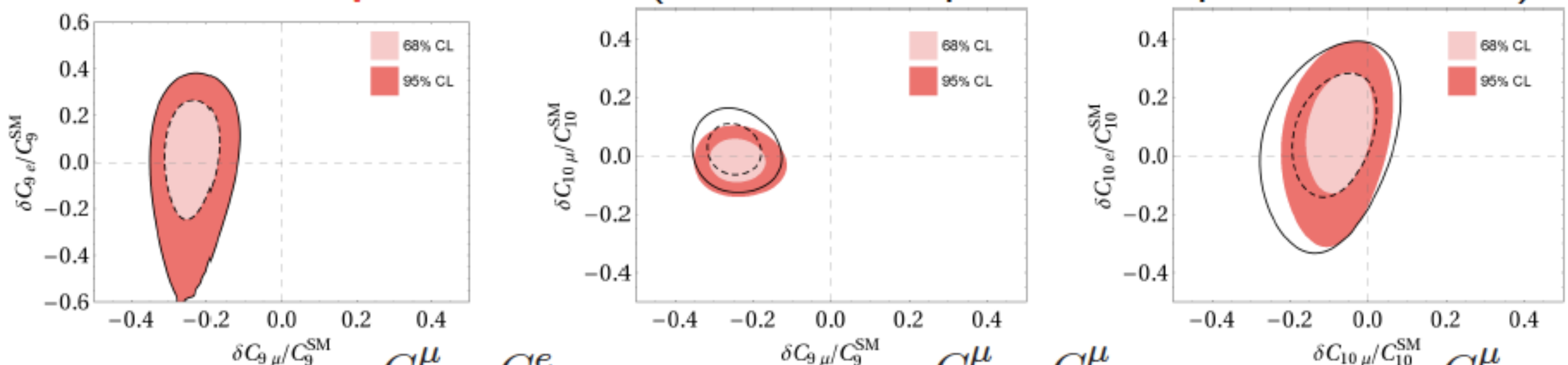
$\delta C_{\rm LL}^\ell$ basis corresponds to $\delta C_9^\ell = -\delta C_{10}^\ell$.

Within the one-operator fits, $B_{s,d} \to \mu^+\mu^-$ do not play a major role!

The new $\mathrm{BR}(B_s \to \mu^+\mu^-)$ shows a tension of 1.5σ with the SM prediction, which suggests the same direction for C_{10}^μ as it is preferred by the $R_{K^{(*)}}$ fit.

Separate NP fits with two operators

All observables except R_K and R_{K^*} (with the assumption of 10% power corrections)



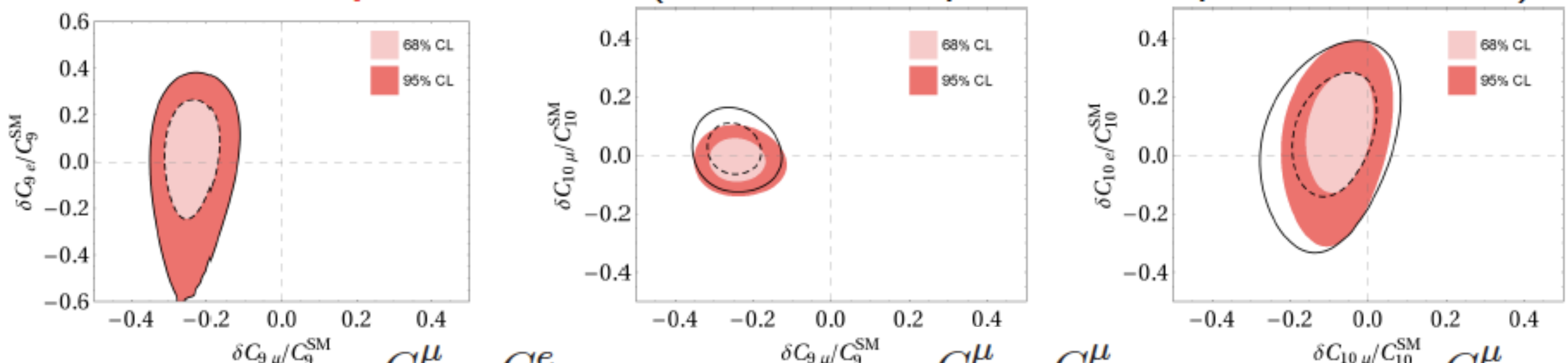
$C_9^\mu - C_9^e$ | $C_9^\mu - C_{10}^\mu$ | $C_{10}^\mu - C_{10}^e$

Pull: 4.1σ | 4.1σ | 1.1σ

[Black contours: without BR($B_{s,d} \to \mu^+\mu^-$)]

Separate NP fits with two operators

All observables except R_K and R_{K^*} (with the assumption of 10% power corrections)

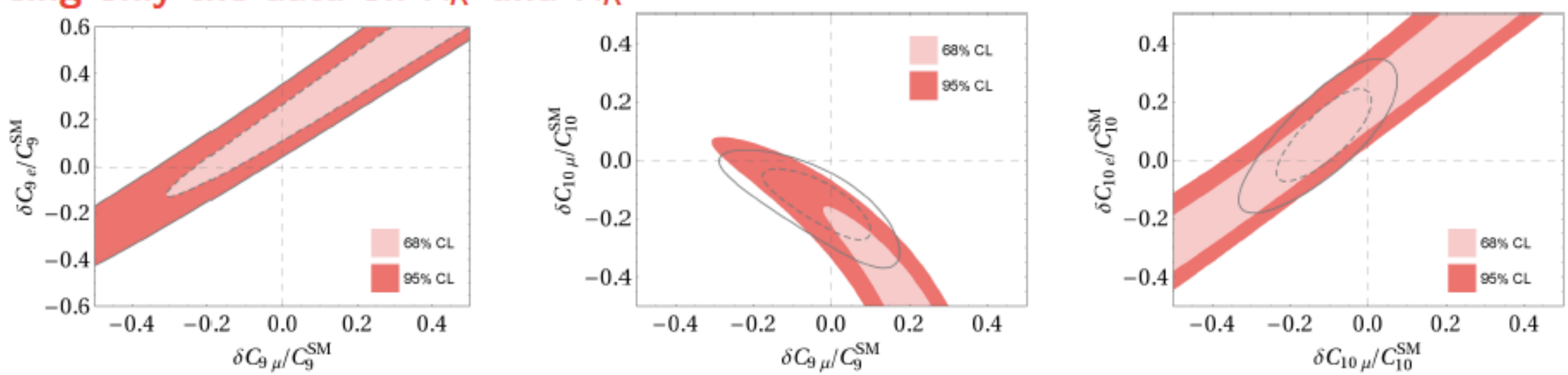


$C_9^\mu - C_9^e$ $\quad$ $C_9^\mu - C_{10}^\mu$ $\quad$ $C_{10}^\mu - C_{10}^e$

Pull: $\quad 4.1\sigma \quad 4.1\sigma \quad 1.1\sigma$

[Black contours: without BR($B_{s,d} \to \mu^+\mu^-$)]

Using only the data on R_K and R_{K^*}



Pull: $\quad 3.1\sigma \quad 3.2\sigma \quad 3.1\sigma$

[Gray contours: with BR($B_{s,d} \to \mu^+\mu^-$)]

The two sets are compatible at least at the 2 σ level

Using <u>all</u> the relevant data on $b \to s$ transitions:

assuming 10% error for the power corrections

All observables ($\chi^2_{\rm SM} = 117.03$)			
	b.f. value	$\chi^2_{\rm min}$	$\mathrm{Pull}_{\rm SM}$
δC_9	-1.01 ± 0.20	99.2	4.2σ
δC_9^μ	-0.93 ± 0.17	89.4	5.3σ
δC_9^e	0.78 ± 0.26	106.6	3.2σ
δC_{10}	0.25 ± 0.23	115.7	1.1σ
δC_{10}^μ	0.53 ± 0.17	105.8	3.3σ
δC_{10}^e	-0.73 ± 0.23	105.2	3.4σ
$\delta C_{\rm LL}^\mu$	-0.41 ± 0.10	96.6	4.5σ
$\delta C_{\rm LL}^e$	0.40 ± 0.13	105.8	3.3σ

The NP significance is reduced by at least 0.5σ compared to before.

Global fit to 108 $b \to s$ observable with 20 operators

Considering only one or two Wilson coefficients may not give the full picture!

A generic set of Wilson coefficients:

$$\text{complex } C_7, C_8, C_9^\ell, C_{10}^\ell, C_S^\ell, C_P^\ell + \text{primed coefficients}$$

The available observables are mainly insensitive to the imaginary parts, one can limit the set to

$$\text{real } C_7, C_8, C_9^\ell, C_{10}^\ell, C_S^\ell, C_P^\ell + \text{primed coefficients}$$

corresponding to 20 degrees of freedom.

Some of the coefficients may have only weak effects on the observables, and affect the number of dof without affecting the χ^2, acting as *spurious* degrees of freedom.

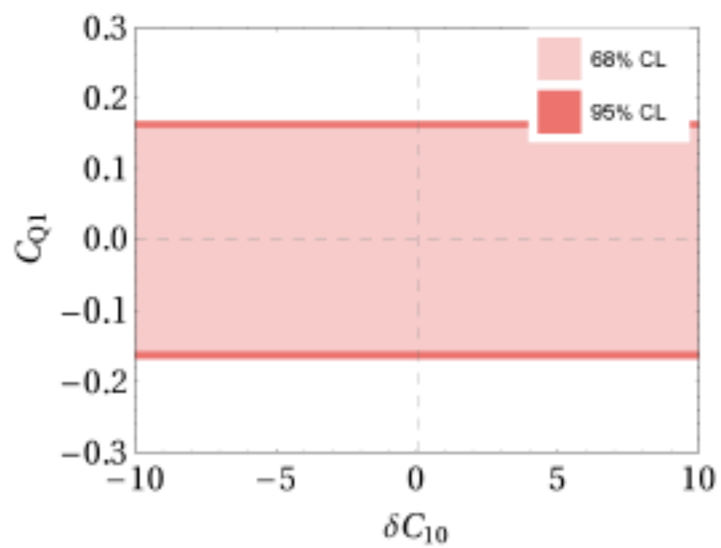
Effective degrees of freedom (e-dof): degrees of freedom minus the parameters δC_i only weakly affecting the χ^2, defined such as

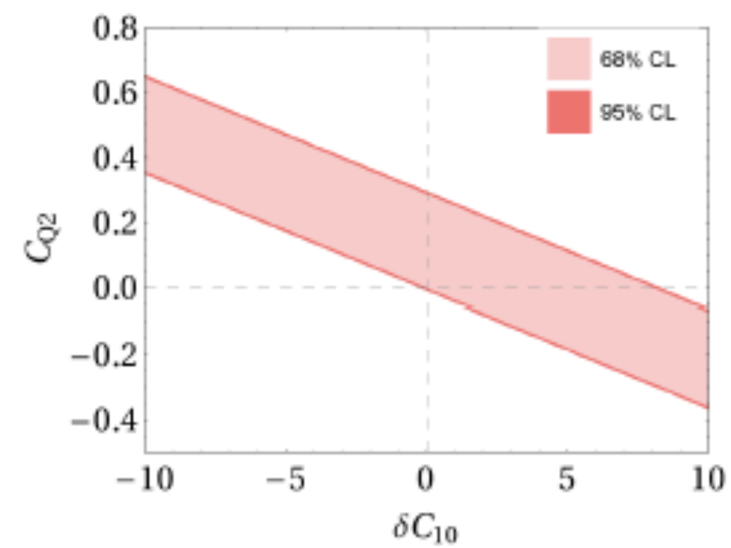
$$|\chi^2(\delta C_i = 1) - \chi^2(\delta C_i = 0)| < 1$$

$C_{S,P}$ are usually assumed to be highly constrained by $\text{BR}(B_s \to \mu^+\mu^-)$

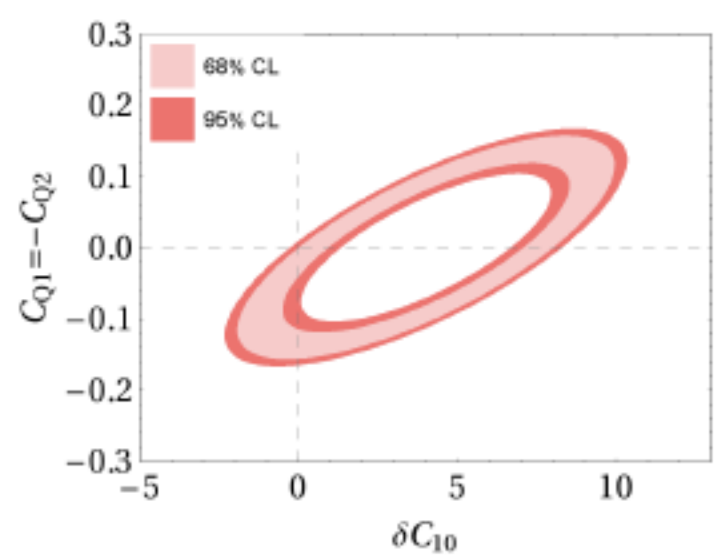
$\to$ not considered in the global fits   Not quite true!

Imposing $\text{BR}(B_s \to \mu^+\mu^-)$, if C_S and C_P independent, there exists a degeneracy between C_{10} and C_P so that large values for C_P are possible





Even if $C_S = -C_P$, allowing for small variations of $C_{S,P}$ alleviates the constraints from $B_s \to \mu^+\mu^-$ on C_{10}



Global fit to 108 $b \to s$ observable with 20 operators

Set: real C_7, C_8, C_9^ℓ, C_{10}^ℓ, C_S^ℓ, C_P^ℓ + primed coefficients (20 (16) degrees of freedom)

All observables with $\chi^2_{\rm SM} = 117.03$ ($\chi^2_{\rm min} = 71.96$; $\mathrm{Pull}_{\rm SM} = 3.3\ (3.8)\sigma$)			
δC_7		δC_8	
-0.01 ± 0.04		0.82 ± 0.72	
$\delta C_7'$		$\delta C_8'$	
0.01 ± 0.03		-1.65 ± 0.47	
δC_9^μ	δC_9^e	δC_{10}^μ	δC_{10}^e
-1.37 ± 0.25	-6.55 ± 2.37	-0.11 ± 0.27	2.34 ± 3.11
$\delta C_9'^\mu$	$\delta C_9'^e$	$\delta C_{10}'^\mu$	$\delta C_{10}'^e$
0.23 ± 0.62	0.75 ± 2.82	-0.16 ± 0.36	1.67 ± 3.05
$C_{Q_1}^\mu$	$C_{Q_1}^e$	$C_{Q_2}^\mu$	$C_{Q_2}^e$
-0.01 ± 0.09	undetermined	-0.05 ± 0.19	undetermined
$C_{Q_1}'^\mu$	$C_{Q_1}'^e$	$C_{Q_2}'^\mu$	$C_{Q_2}'^e$
0.13 ± 0.09	undetermined	-0.18 ± 0.20	undetermined

16 effective degrees of freedom ($C^{e(\prime)}_{Q_{1/2}}$ taken out)

NP significance 3.8 σ in the global fit

based on the assumption of 10% error for power corrections

Hadronic uncertainties

Crosscheck with $R_{\mu,e}$ ratios

Hurth, Mahmoudi, Martinez Santos, Neshatpour arXiv: 1705.06274

- R_K and R_{K^*} ratios are theoretically very clean
- The tensions cannot be explained by hadronic uncertainties

NP in the ratios would indirectly confirm the NP interpretation of the anomalies in the angular observables (if there is a coherent picture)

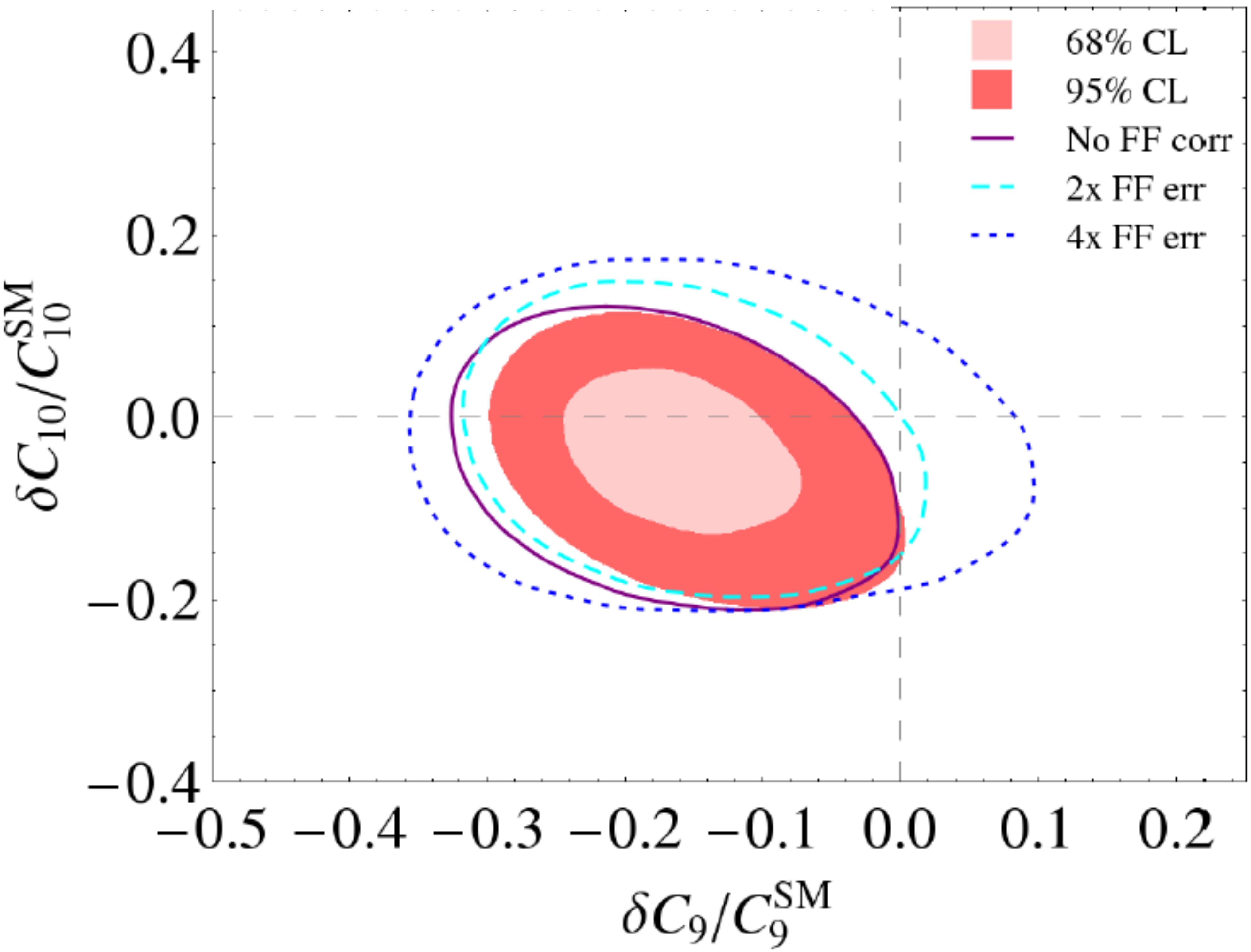
Calculations beyond guessing numbers

Methods offered in the analysis of $B \to K\ell^+\ell^-$ to calculate power corrections Kjodjamirian et al. arXIv: 1211.0234, also 1006.4945

Crosschecking errors and correlations of formfactor calculation in Zwicky et al. arXiv: 1503.0553 by independent LCSR analysis

Most recently: Estimate of power corrections based on analyticity structure Bobeth et al. arXiv:1707.07305 -

Fits assuming different form factor uncertainties



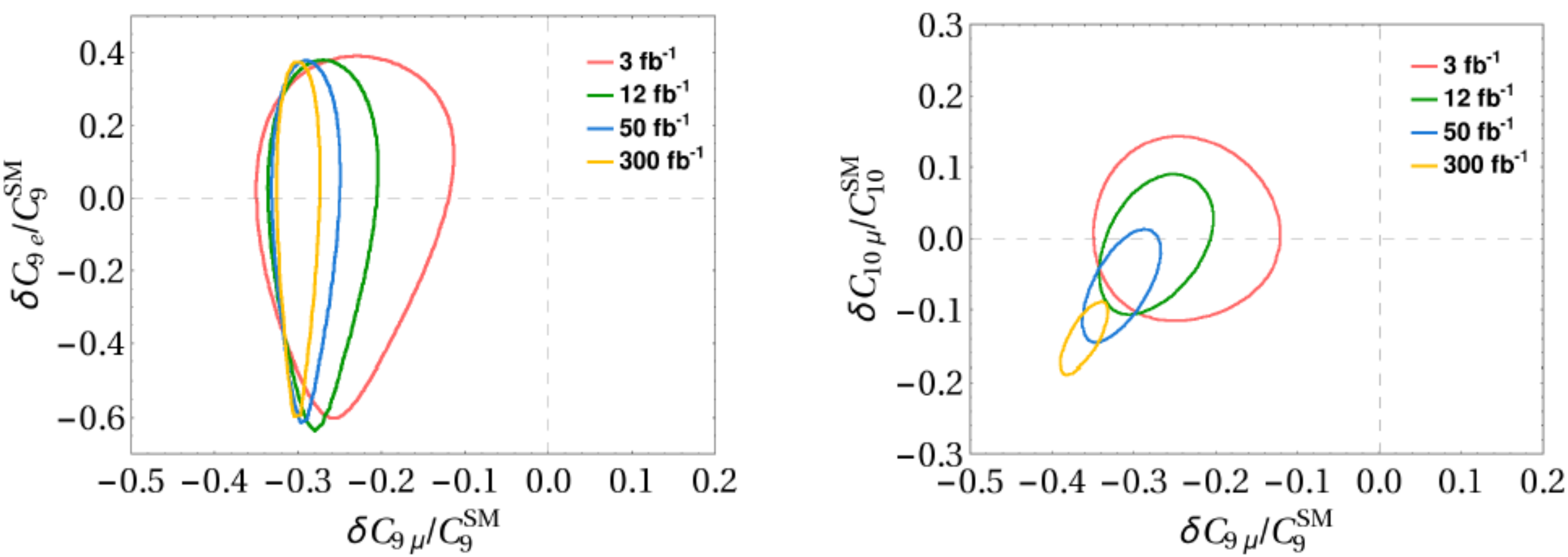
The size of the form factor errors has a crucial role in constraining the allowed region (LCSR-calculation Zwicky et al. arXiv:1503.0553)

Future LHCb prospects for the angular observables

Hurth, Mahmoudi, Martinez Santos, Neshatpour arXiv: 1705.06274

Global fits using the angular observables only (NO theoretically clean R ratios)

Considering several luminosities, assuming the current central values



LHCb upgrade will be able to distinguish between NP and hadronic effects within the angular observables – even without any theoretical progress

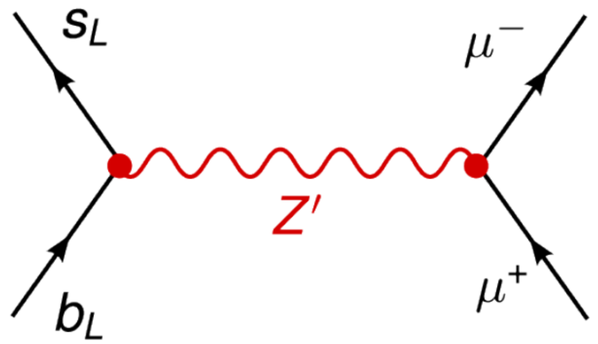
Simplified Models

New physics explanations (1σ solutions)

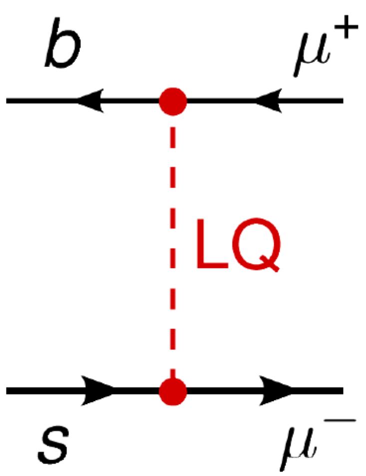
Difficult to generate $\delta C_9 = -1$ at loop level (MSSM with MFV)

Various models under discussion (tree level contributions):

Z' bosons



Leptoquarks



Altmannshofer, Straub arXiv:1308.1501
Gauld, Goertz, Haisch arXiv:1308.1959;1310.1082
Buras,De Fazio,Girrbach arXiv:1311.6729
Altmannshofer,Gori,Pospelov,Yavin arXiv:1403.1269
...

Hiller, Schmaltz arXiv:1408.1627
Sahoo, Mohanta arXiv:1501.05193
Becirevic, Fajfer, Kosnik arXiv:1503.09024
Bauer, Neubert arXiv:1511.01900 (loop)
...

Model explaining all anomalies by one leptoquark

Bauer, Neubert arXiv:1511.01900

- $$R_{D^{(*)}}^{\tau/l} = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau\bar{\nu})/\mathcal{B}(\bar{B} \to D^{(*)}\tau\bar{\nu})_{SM}}{\mathcal{B}(\bar{B} \to D^{(*)}l\bar{\nu})/\mathcal{B}(\bar{B} \to D^{(*)}l\bar{\nu})_{SM}}$$

  3.9σ deviation from $\tau - \mu/e$ universality

- $$R_K^{\mu/e} = \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to Ke^+e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

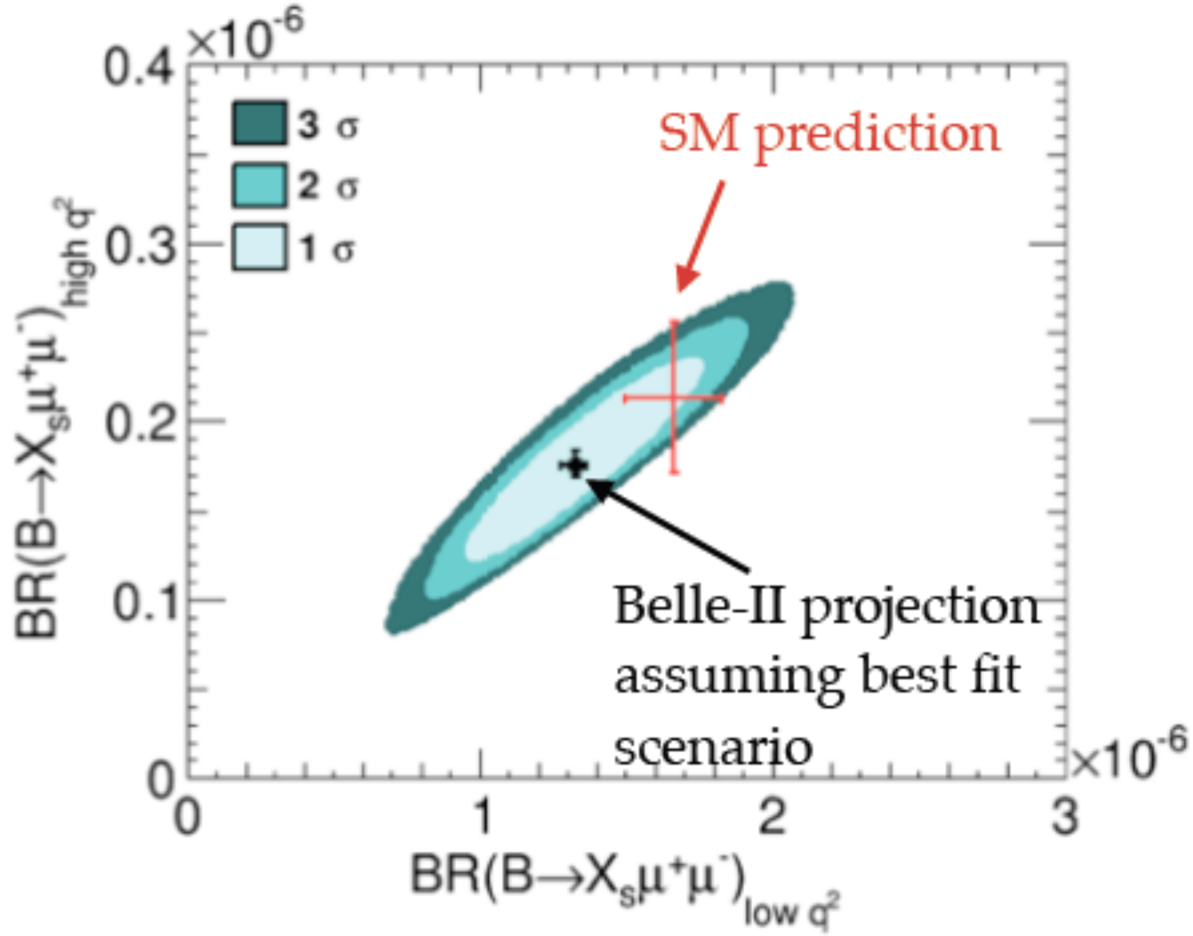
  2.6σ deviation from $\mu - e$ universality

- $(g-2)_\mu$

Inclusive semi-leptonic penguins

Crosscheck of LHCb anomalies with inclusive modes

Hurth,Mahmoudi,Neshatpour,arXiv:1410.4545



If NP then the effect of C_9 and C_9' are large enough to be checked at Belle-II with theoretically clean modes.

Hurth, Mahmoudi, arXiv:1312.5267 Experimental extrapolation by Kevin Flood

Belle-II Extrapolations

Akimasa Ishikawa, B2TiP

Error of Branching ratio $\bar{B} \to X_s \ell^+ \ell^-$

BF (%) (stat,syst)	0.7/ab	5/ab	50/ab
[1.0,3.5]	29 (26,12)	13 (9.7,8.0)	6.6 (3.1,5.8)
[3.5,6.0]	24 (21,12)	11 (7.9,8.0)	6.4 (2.6,5.8)
$\geq$ 14.4	23 (21,9)	10 (8.1,6.0)	4.7 (2.6,3.9)

Error of Normalized Forward-Backward-Asymmetry

AFBn (%) (stat,syst)	0.7/ab	5/ab	50/ab
[1.0,3.5]	26 (26,2.7)	9.7 (9.7,1.3)	3.1 (3.1,0.5)
[3.5,6.0]	21 (21,2.7)	7.9 (7.9,1.3)	2.6 (2.6,0.5)
$\geq$ 14.4	19 (19,1.7)	7.3 (7.3,0.8)	2.4 (2.4,0.3)

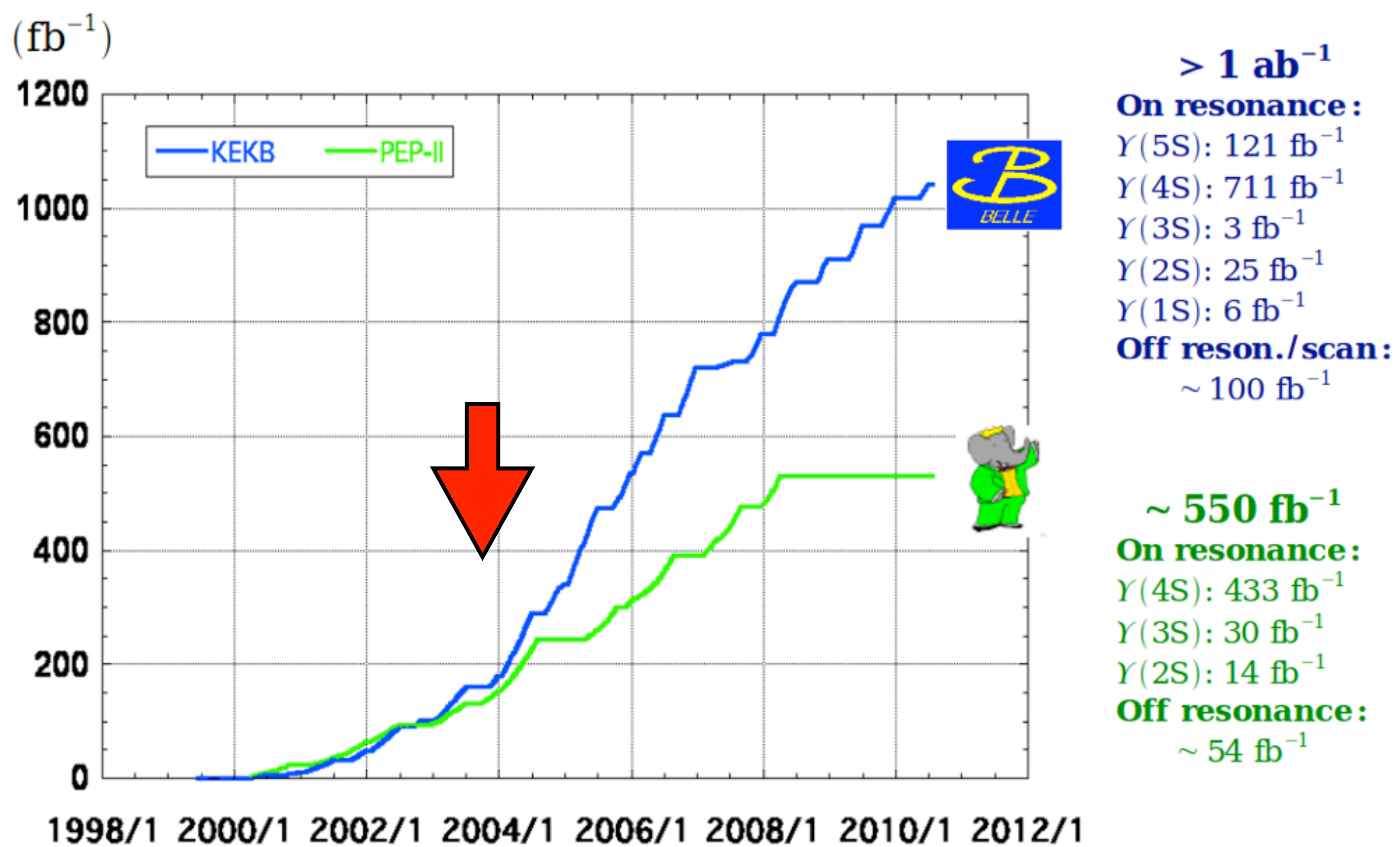
$B \to (\pi, \rho)\ell^+\ell^-$, semi-inclusive $\bar{B} \to X_d \ell^+ \ell^-$ at $50/ab$
(uncertainties like $\bar{B} \to X_s \ell^+ \ell^-$ at $0.7/ab$)

Experiment

- "Latest" Belle measurement of branching ratio is based on less than 30% of the total luminosity

Belle hep-ex/0503044 (!!!) (based $152 \times 10^6 B\bar{B}$ events)

Integrated luminosity of B factories



New Babar analysis on dilepton spectrum arXiv:1312.3664

New Belle analysis on AFB arXiv:1402.7134

Inclusive modes $B \to X_s\gamma$ and $B \to X_s\ell^+\ell^-$

How to compute the hadronic matrix elements $\mathcal{O}_i(\mu = m_b)$?

Heavy mass expansion for inclusive modes:

$$\Gamma(\bar{B} \to X_s\gamma) \stackrel{m_b\to\infty}{\longrightarrow} \Gamma(b \to X_s^{parton}\gamma)\,, \quad \Delta^{nonpert.} \sim \Lambda^2_{QCD}/m_b^2$$

No linear term Λ_{QCD}/m_b (perturbative contributions dominant)

An old story:

– If one goes beyond the leading operator ($\mathcal{O}_7$, $\mathcal{O}_9$):

breakdown of local expansion

A new dedicated analysis:

naive estimate of non-local matrix elements leads to 5% uncertainty.

Benzke,Lee,Neubert,Paz,arXiv:1003.5012

Analysis in $B \to X_s\ell\ell$ in this talk; Benzke,Hurth,Turczyk, arXiv:1705.10366

Complete angular analysis of inclusive $B \to X_s \ell\ell$

Huber, Hurth, Lunghi, arXiv:1503.04849

- Phenomenological analysis to NNLO QCD and NLO QED for all angular observables

$$\frac{d^2\Gamma}{dq^2\,dz} = \frac{3}{8}\left[(1+z^2)\,H_T(q^2) + 2\,z\,H_A(q^2) + 2\,(1-z^2)\,H_L(q^2)\right] \qquad (z = \cos\theta_\ell)$$

$$\frac{d\Gamma}{dq^2} = H_T(q^2) + H_L(q^2) \qquad \frac{dA_{\rm FB}}{dq^2} = 3/4\,H_A(q^2)$$

- Dependence on Wilson coefficients

$$H_T(q^2) \propto 2s(1-s)^2\left[\left|C_9 + \frac{2}{s}\,C_7\right|^2 + |C_{10}|^2\right]$$

$$H_A(q^2) \propto -4s(1-s)^2\ \mathrm{Re}\left[C_{10}\left(C_9 + \frac{2}{s}\,C_7\right)\right]$$

$$H_L(q^2) \propto (1-s)^2\left[\left|C_9 + 2\,C_7\right|^2 + |C_{10}|^2\right]$$

- Electromagnetic effects due to energetic photons are large and calculated analytically and crosschecked against Monte Carlo generator events

New physics sensitivity

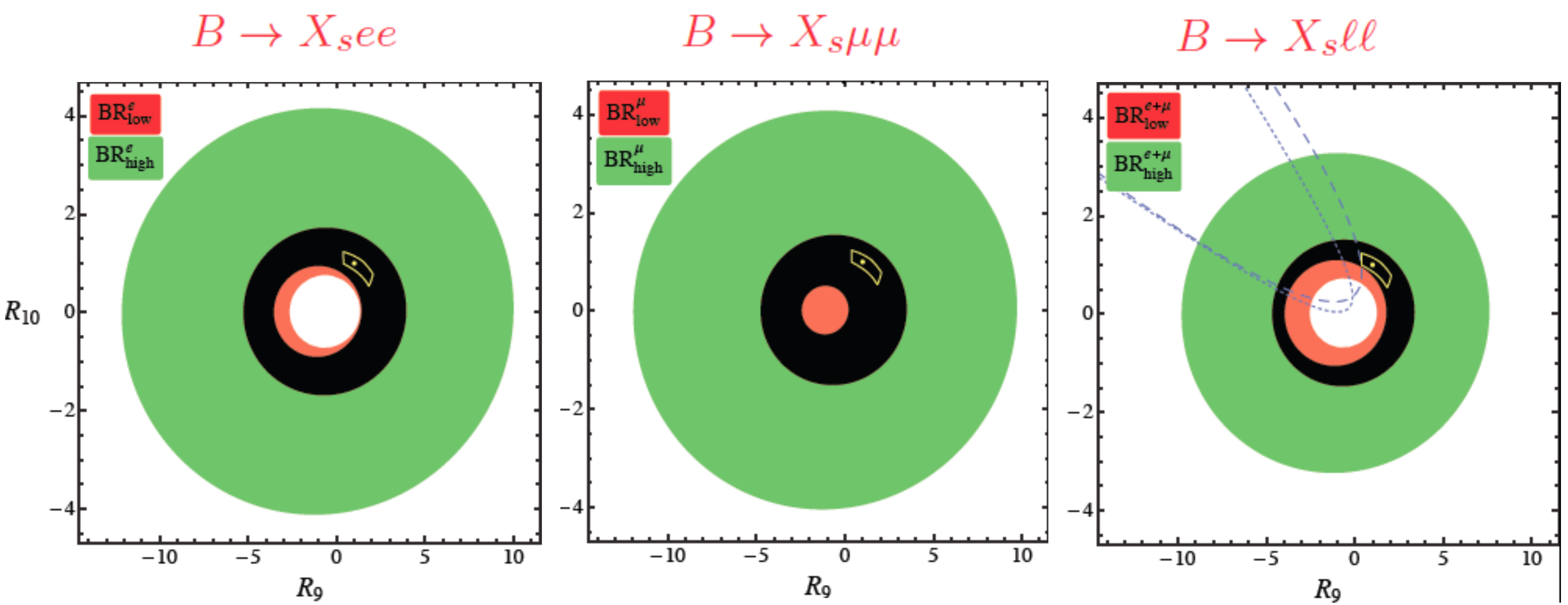
Huber,Hurth,Lunghi, arXiv:1503.04849

Constraints on Wilson coefficients C_9/C_9^{SM} and C_{10}/C_{10}^{SM}

$$R_i = \frac{C_i(\mu_0)}{C_i^{SM}(\mu_0)}$$

that we obtain at 95% C.L. from present experimental data (red low q^2, green high q^2)

that we will obtain at 95% C.L. from $50ab^{-1}$ data at Belle-II (yellow)



Cuts in the dilepton and hadronic mass spectra

- On-shell-$c\bar{c}$-resonances $\Rightarrow$ cuts in dlepton mass spectrum necessary :
  1GeV$^2 < q^2 <$ 6GeV^2 and 14.4GeV$^2 < q^2$ $\Rightarrow$ perturbative contributions dominant

- Hadronic invariant-mass cut is imposed in order to eliminate the background like $b \to c\,(\to se^+\nu)e^-\bar{\nu} = b \to se^+e^- +$ missing energy
  - Babar,Belle: $m_X <$ 1.8 or 2.0GeV
  - high-q^2 region not affected by this cut
  - kinematics: X_s is jetlike and $m_X^2 \leq m_b \Lambda_{QCD}$ $\Rightarrow$ shape function region
  - SCET analysis: universality of jet and shape functions found:
    the 10-30% reduction of the dilepton mass spectrum can be accurately computed using the $\bar{B} \to X_s\gamma$ shape function
    5% additional uncertainty for 2.0GeV cut due to subleading shape functions

Lee,Stewart hep-ph/0511334
Lee,Ligeti,Stewart,Tackmann hep-ph/0512191
Lee,Tackmann arXiv:0812.0001 (effect of subleading shape functions)
Bell,Beneke,Huber,Li arXiv:1007.3758 (NNLO matching QCD $\to$ SCET)

Nonlocal subleading contributions

Benzke,Hurth,Turczyk, arXiv:1705.10366

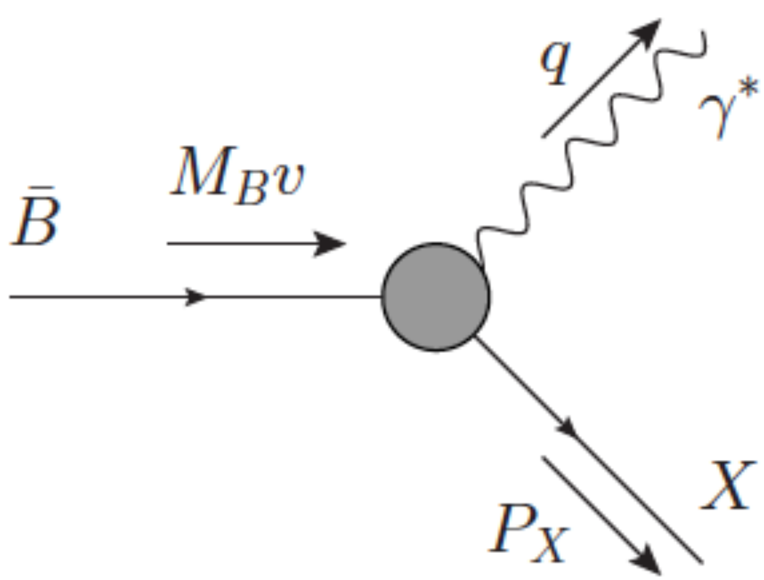
Subleading power factorization in $B \to X_s \ell^+ \ell^-$

Hadronic cut

Additional cut in X_s necessary to reduce background affects only low-q^2 region.

Hadronic invariant $m_X^2 < 1.8(2.0) GeV^2$

Multiscale problem $\to$ SCET



$$M_B^2 \sim m_b^2 \gg m_X^2 \sim \Lambda_{\rm QCD} m_b \gg \Lambda_{\rm QCD}^2$$

$$m_X^2 = P_X^2 = (M_B - n \cdot q)(M_B - \bar{n} \cdot q)$$

Scaling $\lambda = \Lambda_{\rm QCD} / m_b$

Kinematics

B meson rest frame

$$q = p_B - p_X \qquad 2\, m_B\, E_X = m_B^2 + M_X^2 - q^2$$

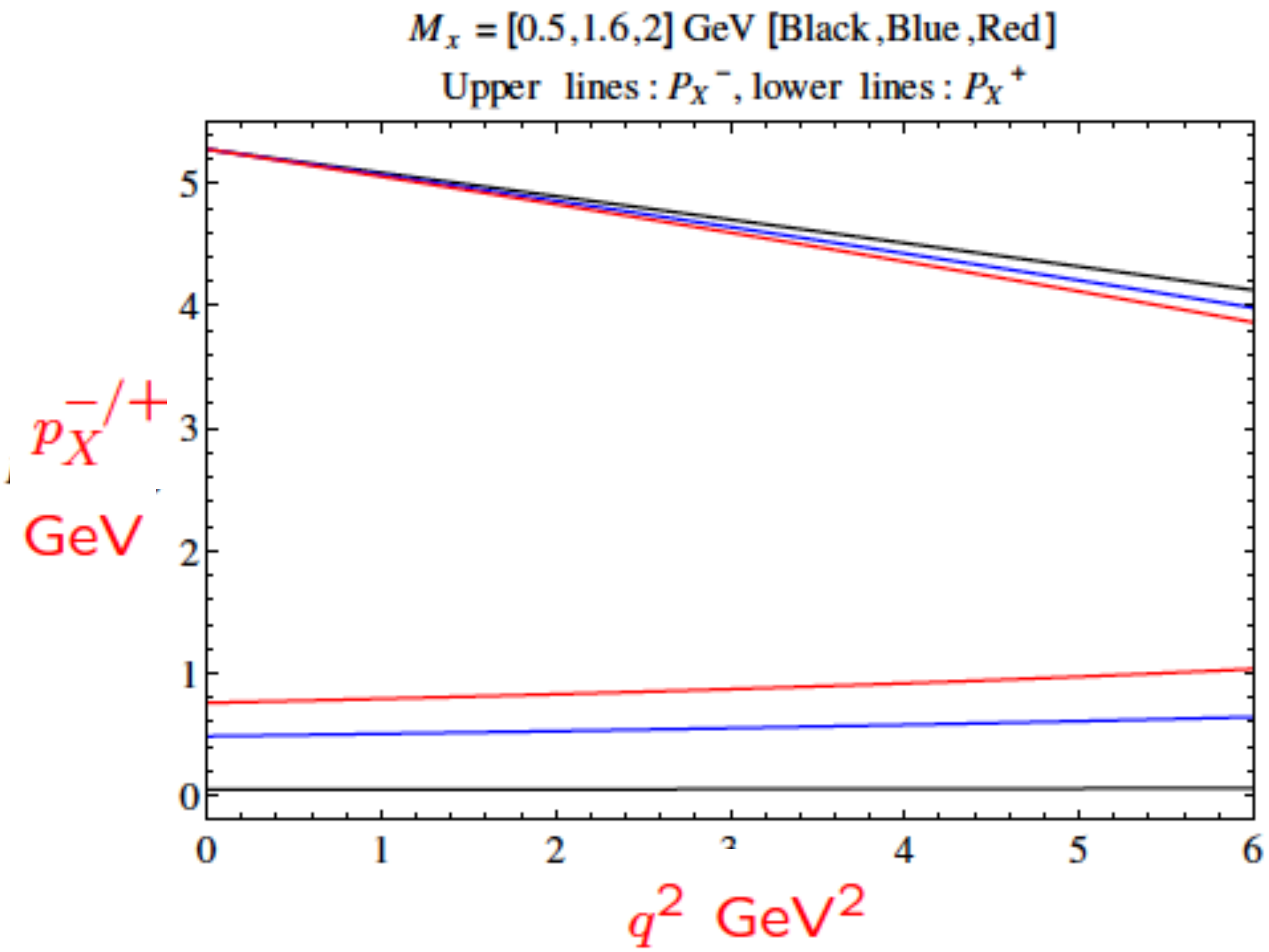
X_s system is jet-like with $E_X \sim m_B$ and $m_X^2 \ll E_X^2$

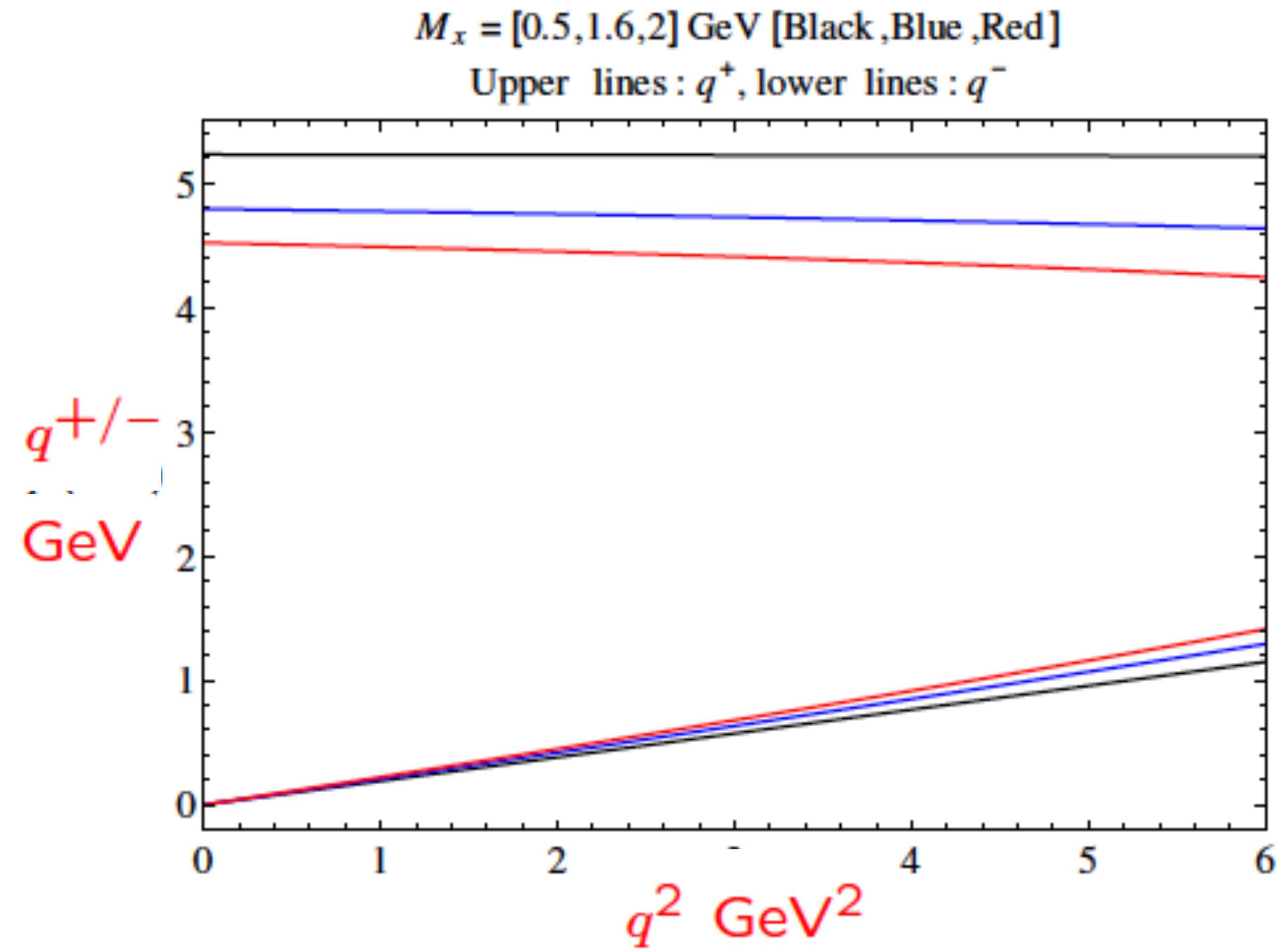
two light-cone components $\qquad p_X^- p_X^+ = m_X^2$

$$\bar{n} p_X = p_X^- = E_X + |\vec{p}_X| \sim \mathcal{O}(m_B)$$
$$n p_X = p_X^+ = E_X - |\vec{p}_X| \sim \mathcal{O}(\Lambda_{\mathrm{QCD}})$$

$$q^+ = nq = m_B - p_X^+ \qquad q^- = \bar{n} q = m_B - p_X^-$$

Scaling $\lambda = \Lambda_{\mathrm{QCD}}/m_b \qquad m_X^2 \sim \lambda \Rightarrow m_b - n \cdot q \sim \lambda$





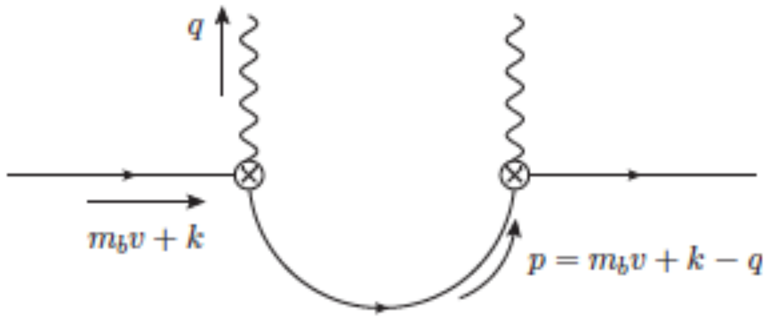
For $q^2 < 6GeV^2$ the scaling of np_X and $\bar{n}p_X$ implies $\bar{n}q$ is of order λ, means q anti-hard-collinear (just kinematics).

Stewart and Lee assume $\bar{n}q$ to be order 1, means q is hard.

This problematic assumption implies a different matching of SCET/QCD.

Shapefunction region

Local OPE breaks down for $m_X^2 \sim \lambda \Rightarrow m_b - n \cdot q \sim \lambda$



$$\frac{1}{(m_b v+k-q)^2} = \frac{1}{m_b - n\cdot q}\left(1 - \frac{n\cdot k}{m_b - n\cdot q} + \ldots\right)\frac{1}{m_b - \bar{n}\cdot q}$$

Resummation of leading contributions into a shape function.

(scaling of $\bar{n}q$ does not matter here; zero in case of $B \to X_s\gamma$)

Factorization theorem $d\Gamma \sim H \cdot J \otimes S$

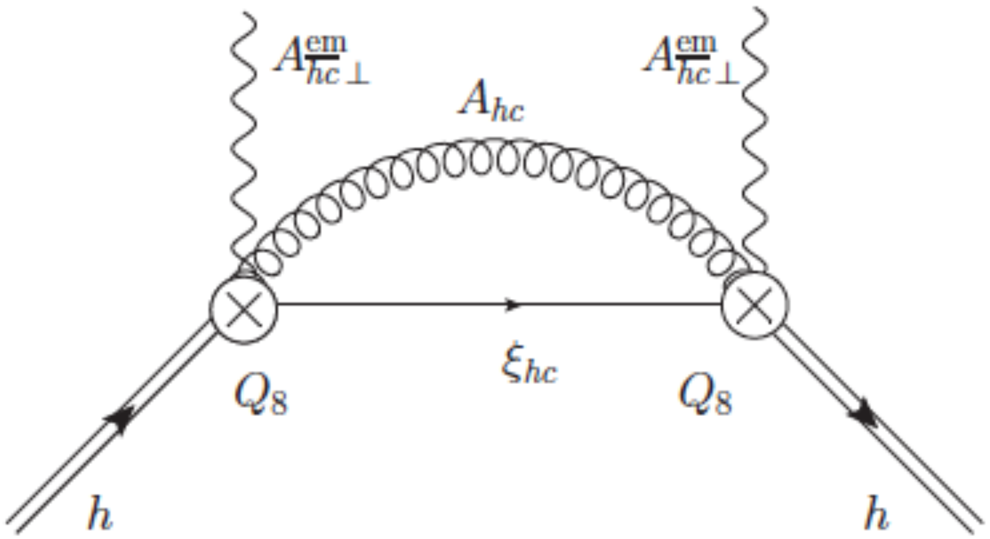
The hard function H and the jet function J are perturbative quantities.

The shape function S is a non-perturbative non-local HQET matrix element.

(universality of the shape function, uncertainties due to subleading shape functions)

Calculation at subleading power

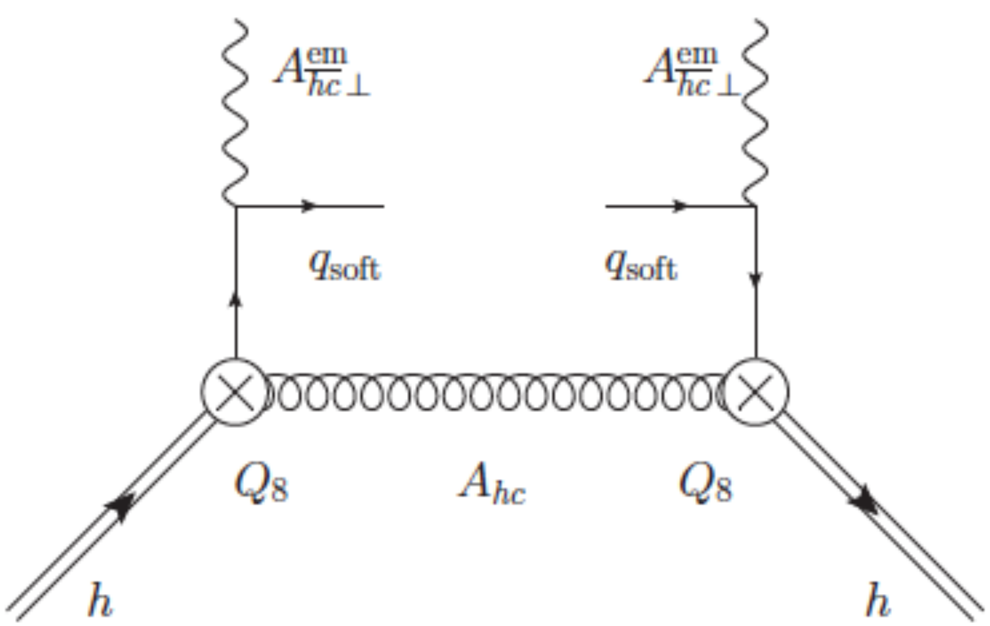
Example of **direct** photon contribution which factorizes $d\Gamma \sim H \cdot j \otimes S$



$\rightarrow \frac{\alpha_s}{m_b}$ in low m_X^2 region

Example of **resolved** photon contribution (double-resolved) which factorizes

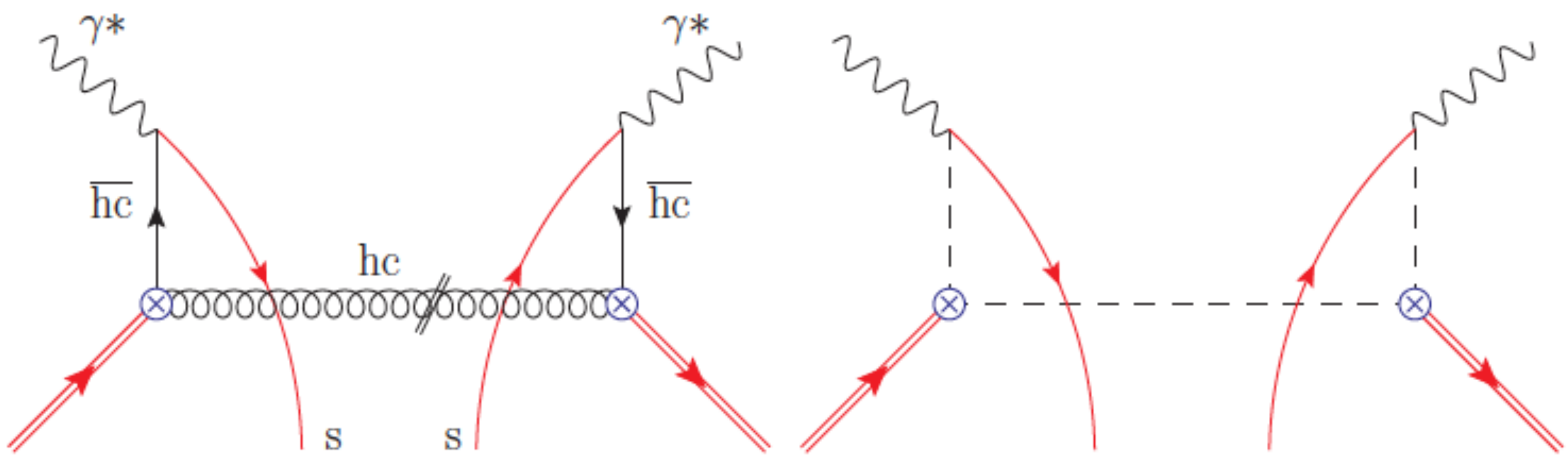
$d\Gamma \sim H \cdot J \otimes s \otimes \bar{J} \otimes \bar{J}$



$\rightarrow \frac{\Lambda}{m_b}$

In the resolved contributions the photon couples to light partons instead of connecting directly to the effective weak-interaction vertex.

Interference of Q_8 and Q_8



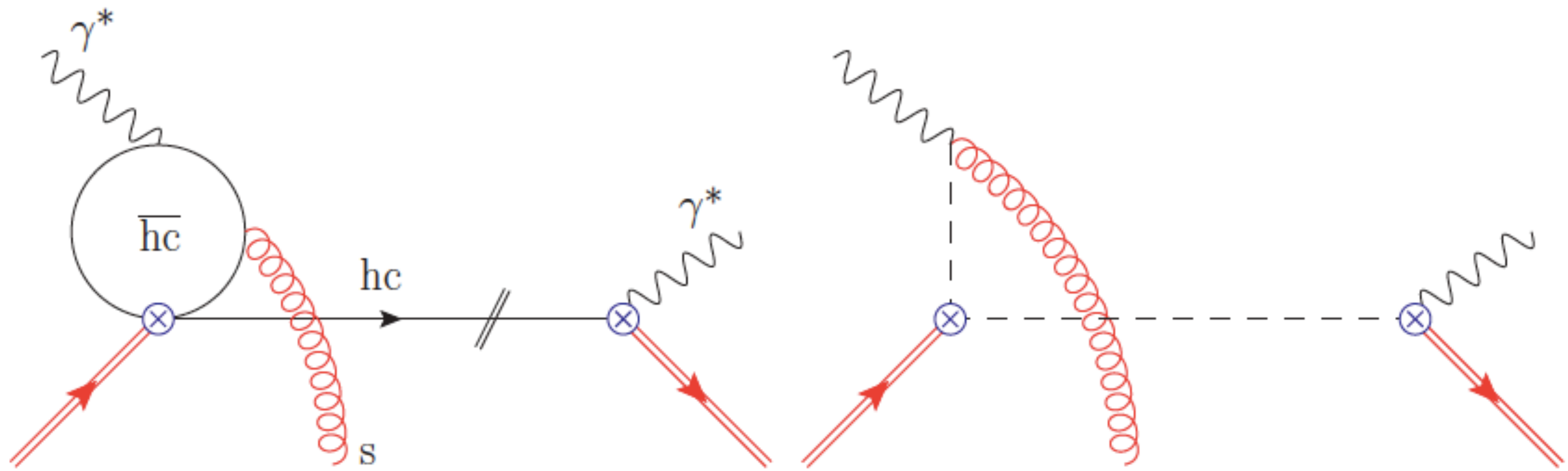
$$\frac{d\Gamma^{\mathrm{res}}}{dn\cdot q\, d\bar{n}\cdot q} \sim \frac{e_s^2\alpha_s}{m_b}\int d\omega\,\delta(\omega+p_+)\int\frac{d\omega_1}{\omega_1+\bar{n}\cdot q+i\varepsilon}\int\frac{d\omega_2}{\omega_2+\bar{n}\cdot q-i\varepsilon}g_{88}(\omega,\omega_1,\omega_2)$$

$$g_{88}(\omega,\omega_1,\omega_2) = \frac{1}{M_B}\langle\bar{B}|\bar{h}(\mathbf{tn})\ldots s(\mathbf{tn}+\mathbf{u\bar{n}})\bar{s}(\mathbf{r\bar{n}})\ldots h(\mathbf{0})|\bar{B}\rangle_{\mathrm{F.T.}}$$

Shape function is non-local in two light-cone directions.

It survives $M_X \to 1$ limit (irreducible uncertainty).

Interference of Q_1 and Q_7



$$\frac{d\Gamma^{\rm res}}{dn\cdot q\, d\bar{n}\cdot q} \sim \frac{1}{m_b}\int d\omega\, \delta(\omega+p_+)\int \frac{d\omega_1}{\omega_1+i\varepsilon}$$

$$\frac{1}{\omega_1}\Bigg[\bar{n}\cdot q\left(F\left(\frac{m_c^2}{n\cdot q\bar{n}\cdot q}\right)-1\right)-(\bar{n}\cdot q+\omega_1)\left(F\left(\frac{m_c^2}{n\cdot q(\bar{n}\cdot q+\omega_1)}\right)-1\right)$$

$$+\bar{n}\cdot q\left(G\left(\frac{m_c^2}{n\cdot q\bar{n}\cdot q}\right)-G\left(\frac{m_c^2}{n\cdot q(\bar{n}\cdot q+\omega_1)}\right)\right)\Bigg] g_{17}(\omega,\omega_1)$$

$$g_{17}(\omega,\omega_1)=\int\frac{dr}{2\pi}e^{-i\omega_1 r}\int\frac{dt}{2\pi}e^{-i\omega t}\frac{1}{M_B}\langle\bar{B}|\bar{h}(\mathbf{t}\mathbf{n})\ldots G_s^{\alpha\beta}(\mathbf{r}\bar{\mathbf{n}})\ldots h(0)|\bar{B}\rangle$$

Expansion for $m_c \sim m_b$ leads to Voloshin term in the total rate $(-\lambda_2/m_c^2)$, the terms stays non-local for $m_c < m_b$.

Numerical evaluation

Benzke,Hurth,Turczyk, arXiv:1705.10366

- Subleading shape functions of resolved contributions similar to $b \to s\gamma$
- Use explicit defintion to determine properties:
  * PT invariance: soft functions are real
  * Moments of g_{17} related to HQET parameters
  * Vacuum insertion approximation relates g_{78} to the B meson LCDA
- Perform convolution integrals with model functions

Final result

Benzke,Hurth,Turczyk, arXiv:1705.10366

Our final estimates of the resolved contributions to the leading order:

(normalized to OPE result)

$$\mathcal{F}_{17}^{s} \in [-0.5, +3.4]\,\%,\;\; \mathcal{F}_{17}^{d} \in [-0.6, +4.1]\,\%,$$

$$\mathcal{F}_{78}^{d,s} \in [-0.2, -0.1]\,\%,\;\; \mathcal{F}_{88}^{d,s} \in [0, 0.5]\,\%$$

$$\mathcal{F}_{1/m_b}^{d} \in [-0.8, +4.5]\,,\;\; \mathcal{F}_{1/m_b}^{s} \in [-0.7, +3.8]$$

$\mathcal{F}_{19}$: $O(1/m_b^2)$ but $|C_{9/10}| \sim 13|C_{7\gamma}|$

(work in progress)

Power corrections in the inclusive mode

- For q anti-hard-collinear we have identified a new type of subleading power corrections.
- In the resolved contributions the photon couples to light partons instead of connecting directly to the effective weak-interaction vertex.
- They constitute an irreducible uncertainty because they survive the $M_X \to 1$ limit.
- If q was hard then these resolved contributions would not exist

Nonlocal power corrections of $O(1/m_b^2)$ numerically relevant

M_X cut effects in the low-q^2 region with q^2 anti-hard-collinear

(work in progress)