Power corrections to semileptonic penguin decays

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Semileptonic Penguin Decays

Based on

Huber,Hurth,Lunghi arXiv:1503.0449

Inclusive $B \to X_s \ell^+ \ell^-$: Complete angular analysis and a thorough study of collinear photons

Benzke,Fickinger,Hurth,Turczyk to appear

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

Hurth,Mahmoudi,Neshatpour arXiv:1603.00865

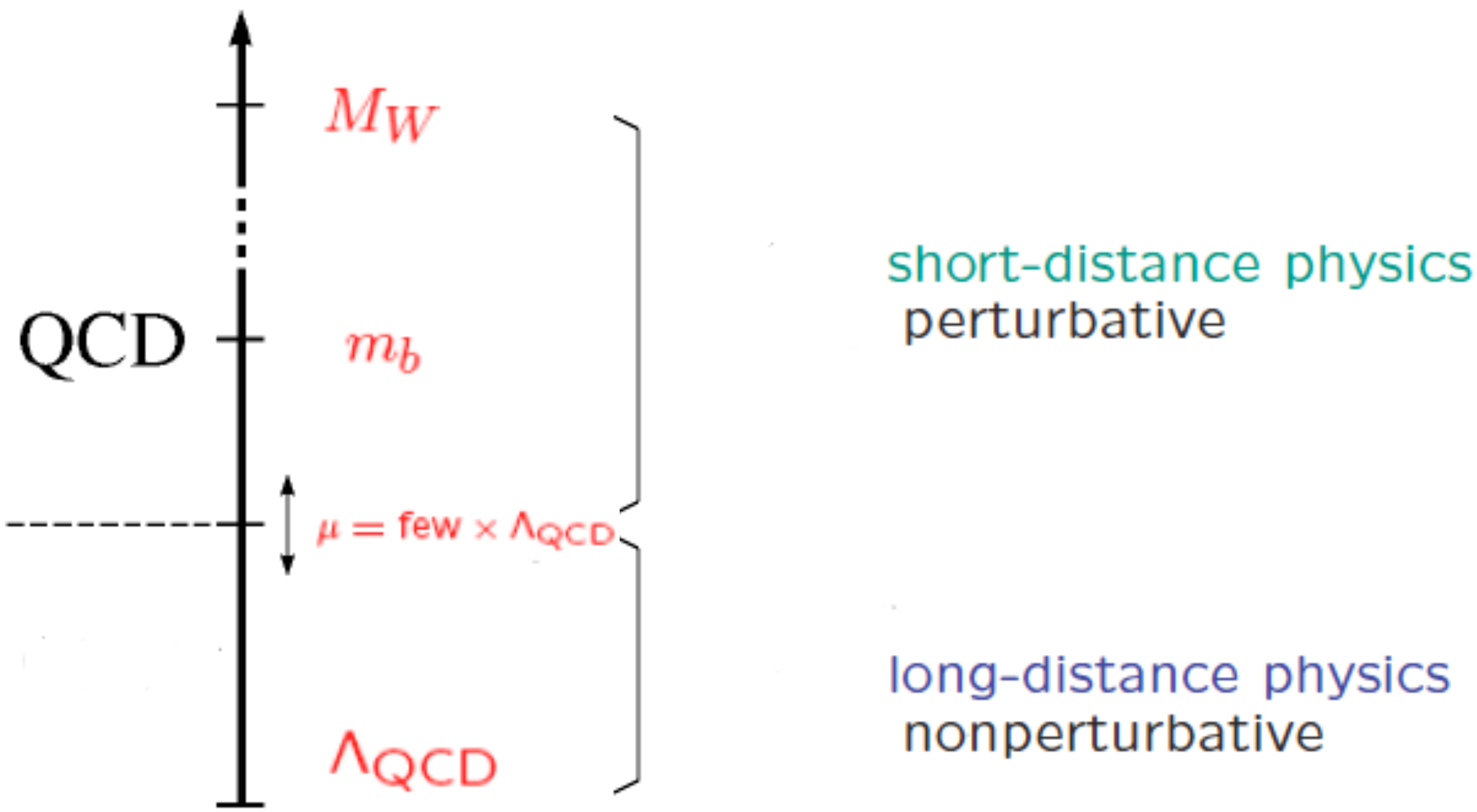
On the anomalies in the latest LHCb data

Motivation

- Radiative and semileptonic rare B decayse are highly sensitive probes for new physics
- Exclusive modes are experimentally easier (LHCb), but have larger theoretical uncertainties (issue of unknown power corrections !)
- Inclusive modes require Belle-II for full exploitation (complete angular analysis) but are theoretically very clean
- Inclusive modes allow for crosschecks of recent LHCb anomalies

Theoretical Tools

Theoretical tools for flavour precision observables



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 $\mathcal{O}_i(\mu = m_b)$?

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

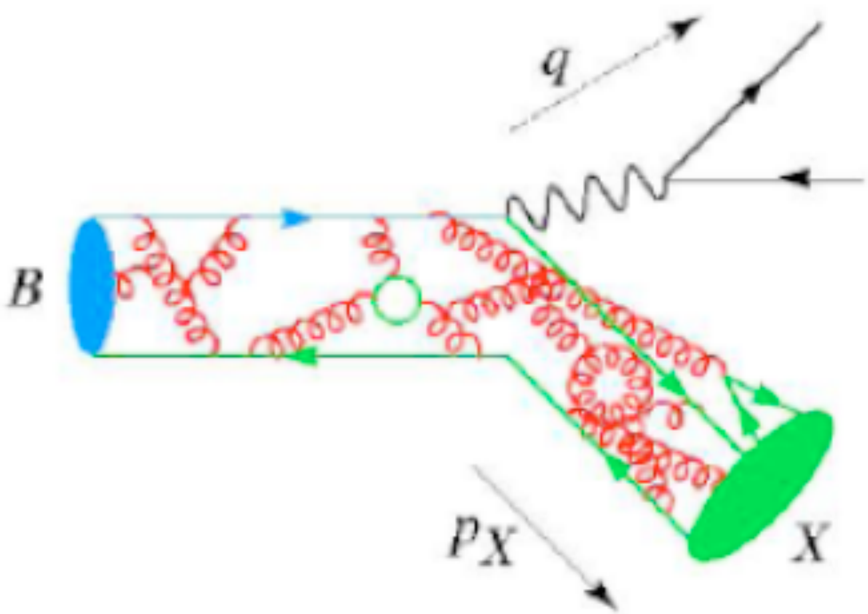
How to compute the hadronic matrix elements $\mathcal{O}_i(\mu = m_b)$?

Heavy mass expansion for inclusive modes:

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

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

Chay,Georgi,Grinstein 1990



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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,Fickinger,Hurth,Turczyk

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')

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"Full formfactor approach"

- we have factorizable and nonfactorizable power corrections
- using full QCD formfactors in the factorization formula takes factorizable power corrections into account automatically
- nonfactorizable contributions generated by four-quark and $\mathcal{O}_8$ operators

Altmannshofer et al., arXiv:0811.1214

Difference between exclusive and inclusive $b \to s\gamma, \ell\ell$ modes:

Inclusive

Λ^2/m_b^2 corrections can be calculated for the leading operators in the local OPE .

Λ/m_b corrections to the subleading operators correspond to nonlocal matrix elements and can be estimated !

Exclusive

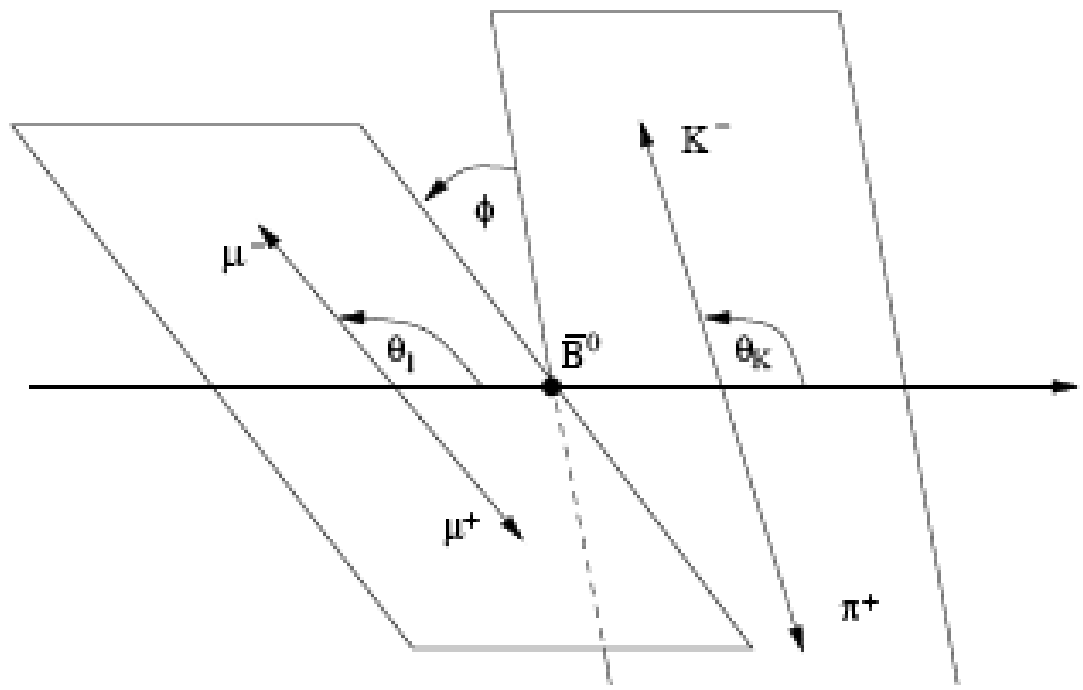
No theory of Λ/mb corrections at all within QCD factorization formula (in the low-q^2 region); these corrections can only be "guesstimated" !

The LHCb Anomalies

Differential decay rate of $B \to K^* \ell\ell$

Assuming the $\bar{K}^*$ to be on the mass shell, the decay $\bar{B}^0 \to \bar{K}^{*0}(\to K^-\pi^+)\ell^+\ell^-$ described by the lepton-pair invariant mass, s, and the three angles θ_l, θ_{K^*}, ϕ.

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi} J(q^2, \theta_l, \theta_K, \phi)$$



$$J(q^2, \theta_l, \theta_K, \phi) =$$

$$= J_{1s} \sin^2\theta_K + J_{1c} \cos^2\theta_K + (J_{2s} \sin^2\theta_K + J_{2c} \cos^2\theta_K) \cos 2\theta_l + J_3 \sin^2\theta_K \sin^2\theta_l \cos 2\phi$$
$$+ J_4 \sin 2\theta_K \sin 2\theta_l \cos\phi + J_5 \sin 2\theta_K \sin\theta_l \cos\phi + (J_{6s} \sin^2\theta_K + J_{6c} \cos^2\theta_K) \cos\theta_l$$
$$+ J_7 \sin 2\theta_K \sin\theta_l \sin\phi + J_8 \sin 2\theta_K \sin 2\theta_l \sin\phi + J_9 \sin^2\theta_K \sin^2\theta_l \sin 2\phi$$

Large number of independent angular obervables

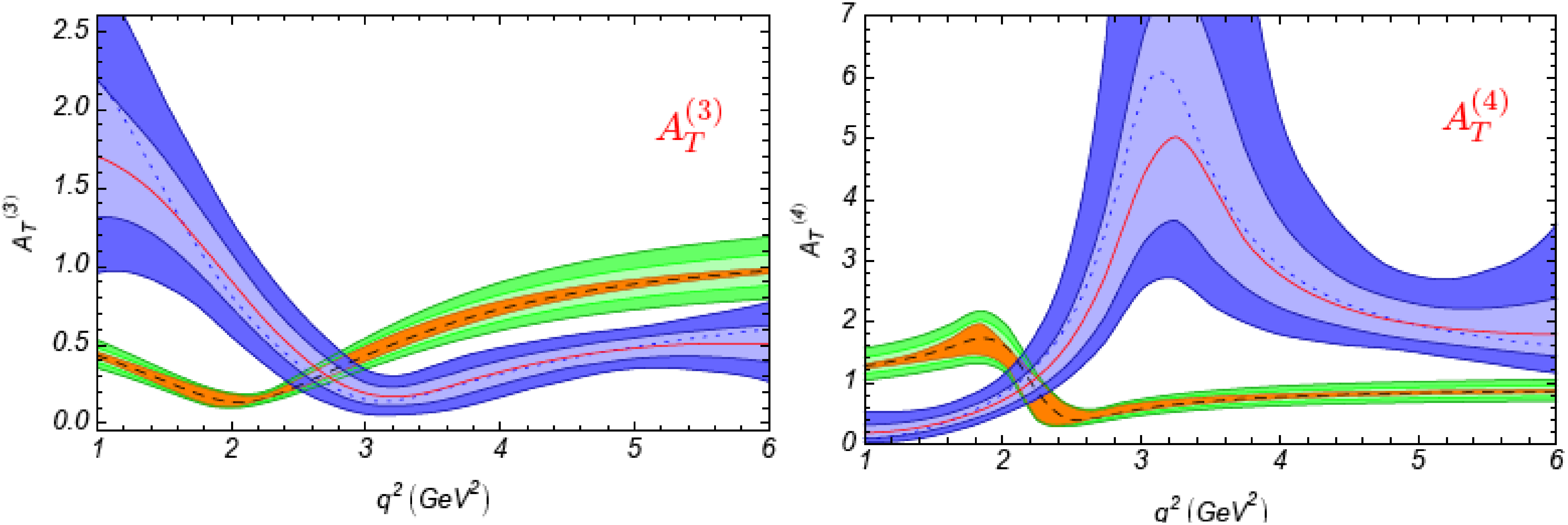
Previous predictions versus LHCb Monte Carlo (10 fb^1)

Egede,Hurth,Matias,Ramon,Reece,arXiv:0807.2589,arXiv:1005.0571

– unknown Λ/m_b power corrections

$A_{\perp,\|,0} = A^0_{\perp,\|,0}\left(1 + c_{\perp,\|,0}\right)$ vary c_i in a range of ±10% and also of ±5%

Guesstimate



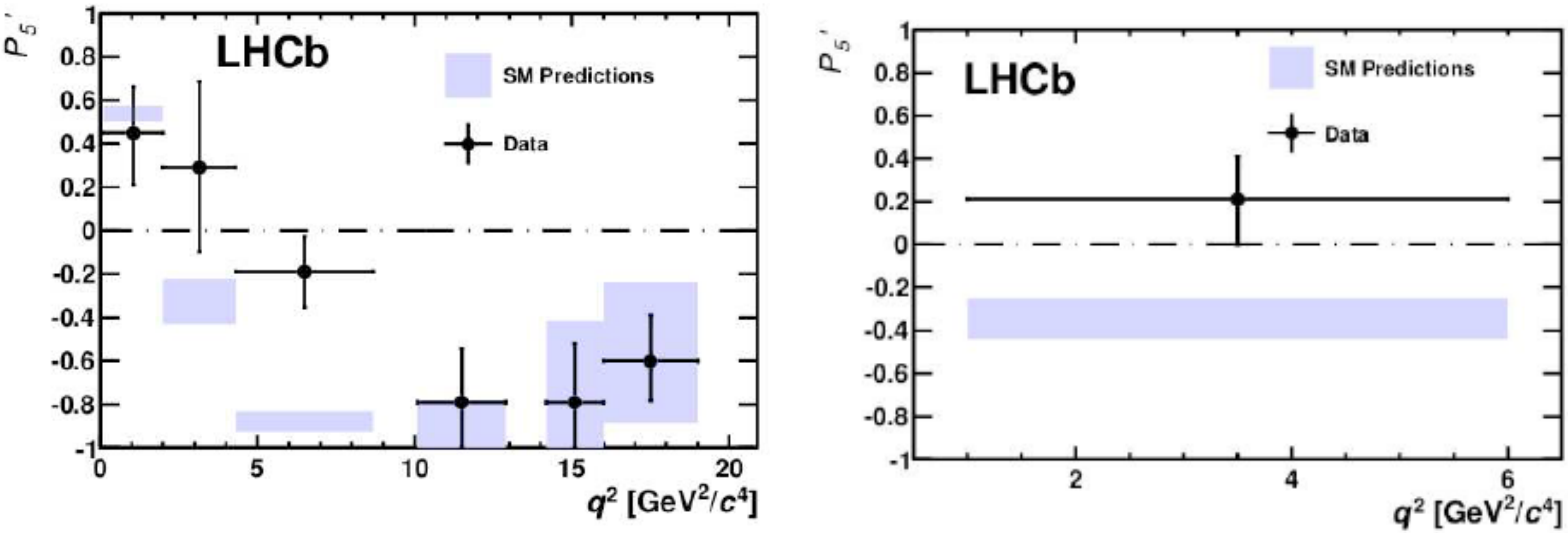
The experimental errors assuming SUSY scenario (b) with large-gluino mass and positive mass insertion, is compared to the theoretical errors assuming the SM.

This was the dream in 2008

see also Altmannshofer et al.,arXiv:0811.1214; Bobeth et al.,arXiv:0805.2525

First measurements of new angular observables LHCb arXiv:1308.1707

SM predictions Descotes-Genon, Hurth, Matias, Virto arXiv:1303.5794



LHCb Anomaly

a statistical fluctuation, an underestimation

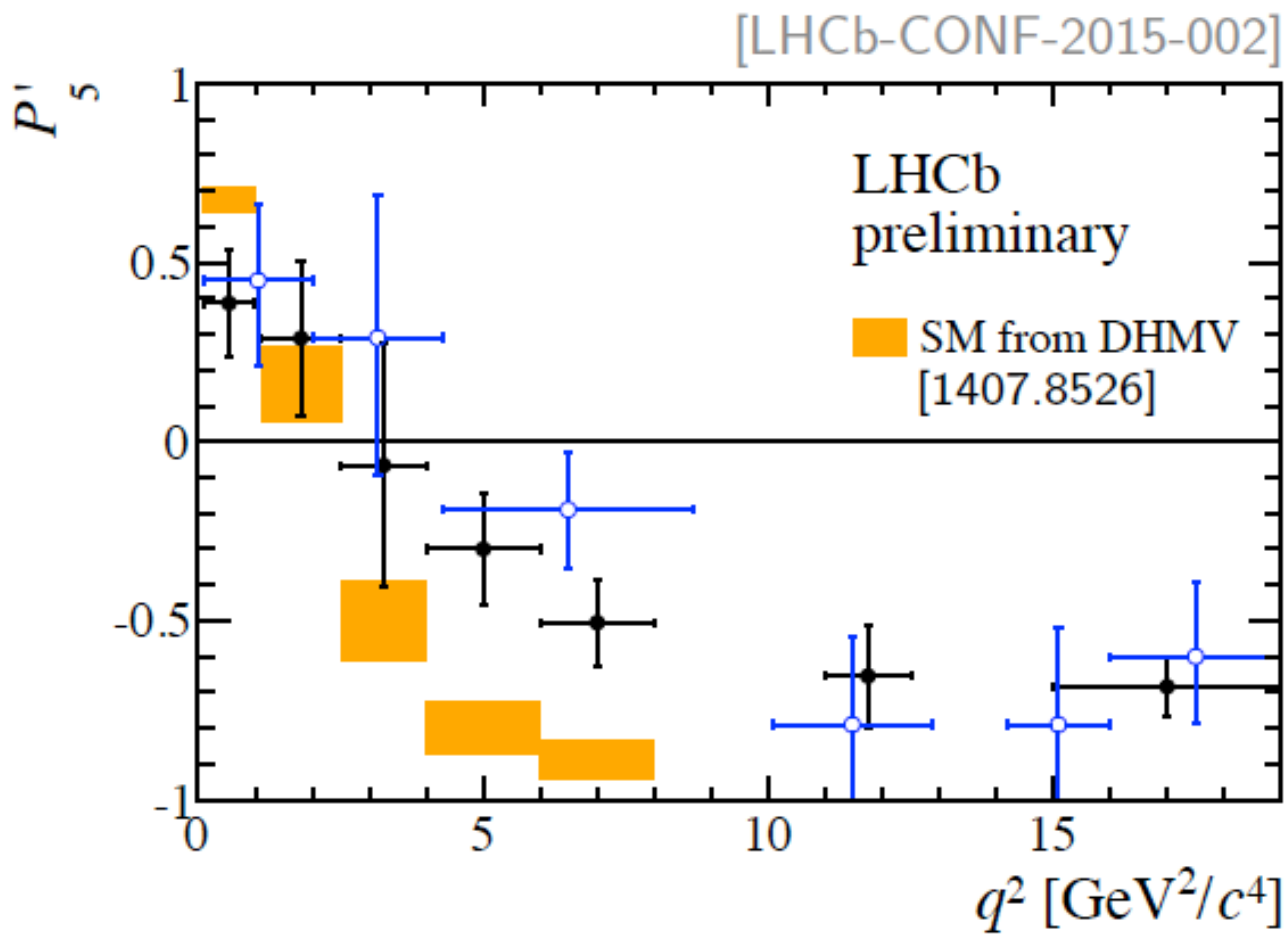
of Λ/m_b corrections or new physics in C_9 ?

$C_7 \quad (B \to X_s\gamma)$ $\qquad$ $C_{10} \quad (B \to \mu^+\mu^-)$

$O_7^{(\prime)} \propto m_b\, \bar{s}\sigma_{\mu\nu}P_{R(L)}b\, F^{\mu\nu}$ $\quad$ $O_9^{(\prime)} \propto \bar{s}\gamma^\mu P_{L(R)}\, \bar{\ell}\gamma_\mu\ell$ $\quad$ $O_{10}^{(\prime)} \propto \bar{s}\gamma^\mu P_{L(R)}\, \bar{\ell}\gamma_\mu\gamma_5\ell$

Update of LHCb at Moriond 2015

LHCb arXiv:1512.04442



$3\,fb^{-1}$

- Tension seen in P_5' in [PRL 111, 191801 (2013)] confirmed
- $[4.0, 6.0]$ and $[6.0, 8.0]\,\mathrm{GeV}^2/c^4$ show deviations of 2.9σ each
- Naive combination results in a significance of 3.7σ
- Compatible with $1\,fb^{-1}$ measurement

Sign for lepton non-universality ?

LHCb; arXiv:1406.6482

$$R_K \equiv \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} = 0.745^{+0.090}_{-0.074}\,(\mathrm{stat}) \pm 0.036\,(\mathrm{syst})$$

2.6σ deviation from SM

- NP tensor or scalar contribution difficult, sign for tension in C_9^μ

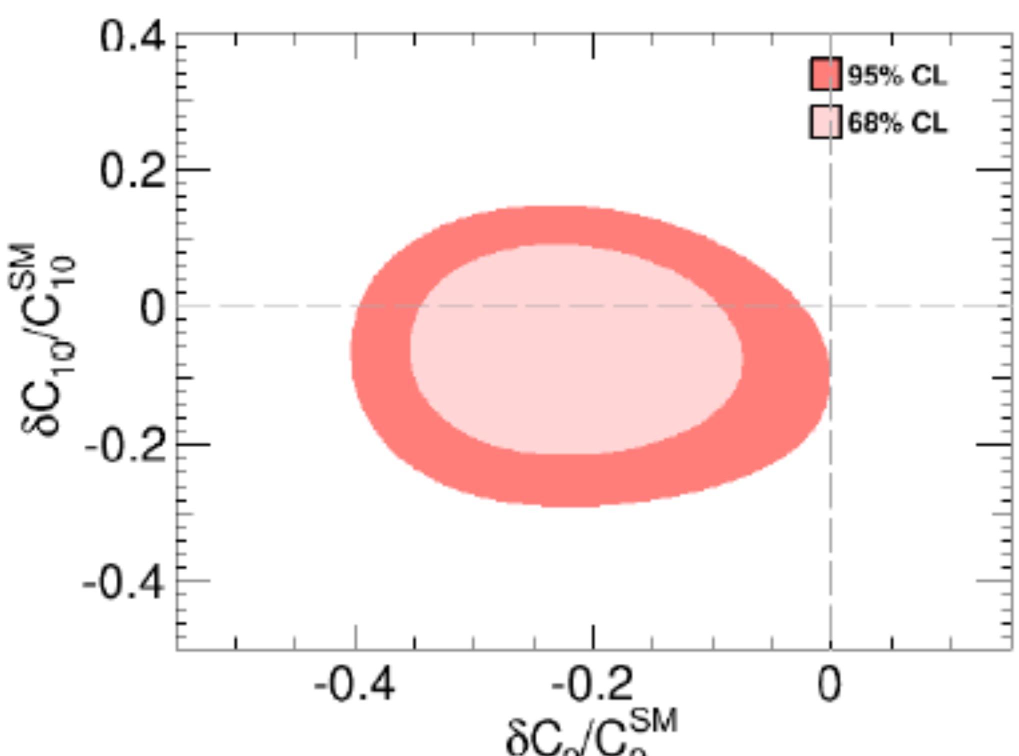
  Alonso,Camalich,Grinstein, arXiv:1407.7044

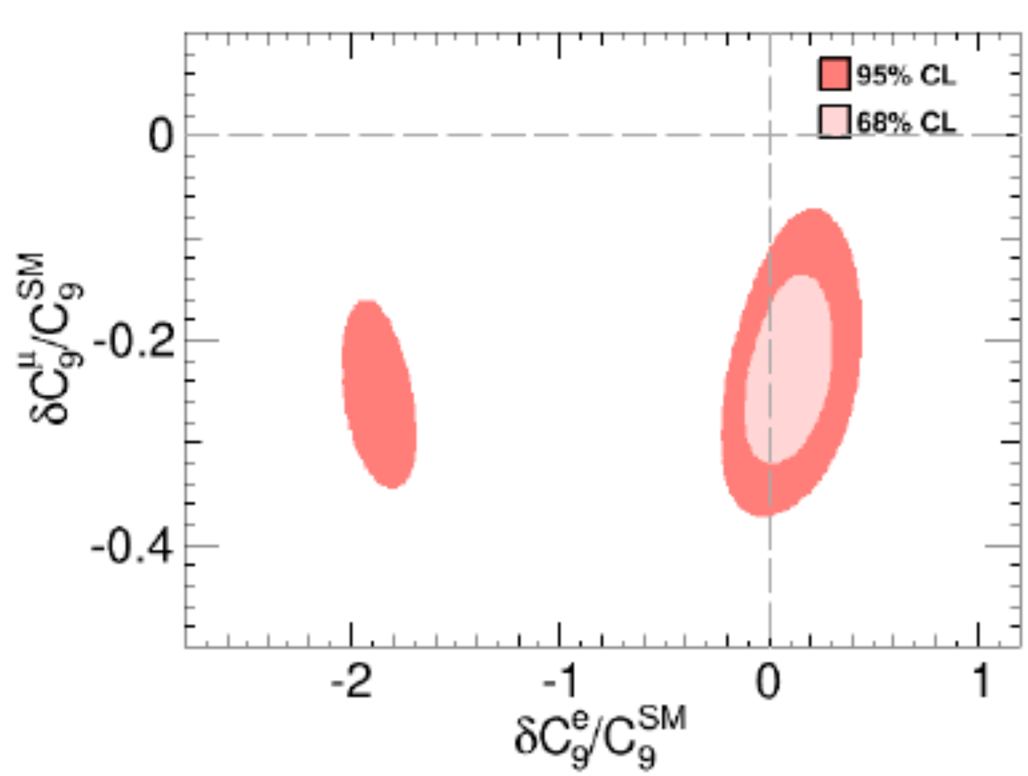
- Theoretically rather clean, cannot explained by power corrections

- Electromagnetic corrections are taken into account

Global fits to the $b \to s\ell\ell$ data

Hurth,Mahmoudi,Neshatpour,arXiv:1410.4545



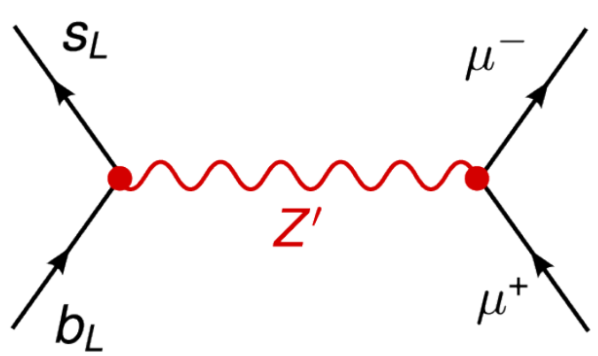


New physics explanations (1σ solutions)

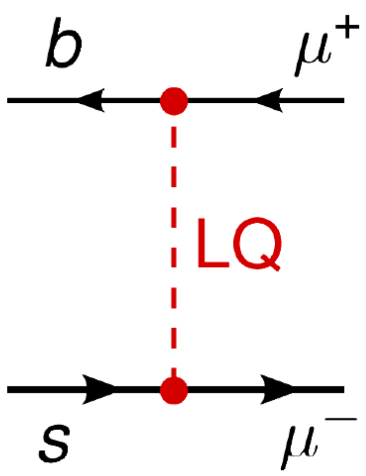
Difficult to generate $\delta C_9 = -1$ at loop level (MSSM with MFV)

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)
...

Bauer, Neubert arXiv:1511.01900

Model explaining all anomalies by one leptoquark

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

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

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

  2.6σ deviation from $\mu - e$ universality

- $(g-2)_\mu$

Bauer, Neubert arXiv:1511.01900

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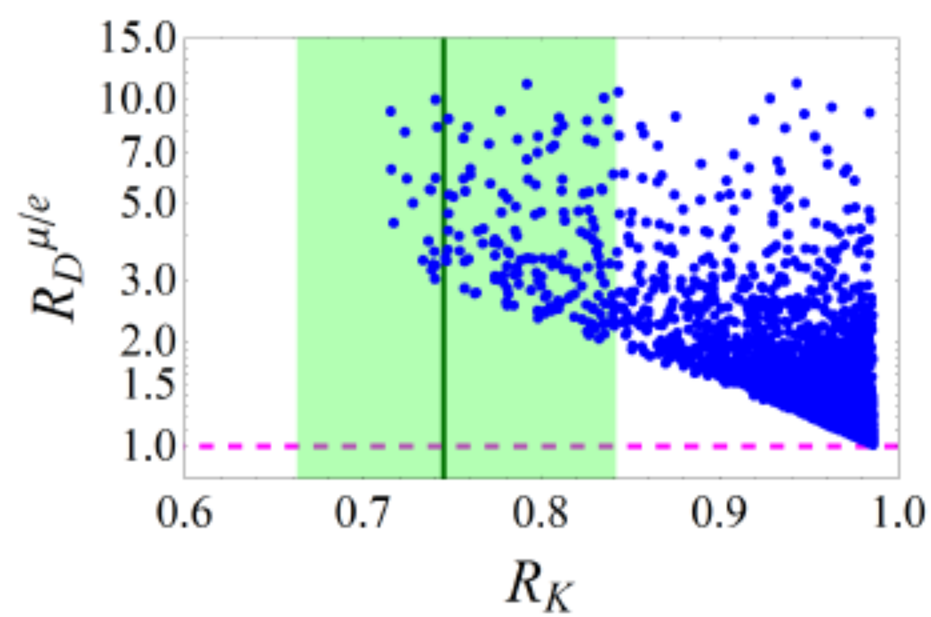
Problem with $R_D^{\mu/e}$?

Becirevic et al. arXiv:1608.07583



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.

Studies based on the latest LHCb data:

Decsotes-Genon,Hofer,Matias,Virto arXiv:1510.04239

Ciuchini,Fedele,Franco,Mishima,Paul,Silvestrini,Valli arXiv:1512.07157

Hurth,Mahmoudi,Neshatpour arXiv:1603.00865

Previous studies:

Beaujean,Bobeth,Jahn arXiv:1508.01526

Altmannshofer,Straub arXiv:1503.06199,1411.3161

Hurth,Mahmoudi,Neshatpour arXiv:1410.4545

Hurth,Mahmoudi,Neshatpour arXiv:1603.00865

Fit results for one operator

Using full QCD formfactors (Zwicky et al. arXiv:1503.0553)

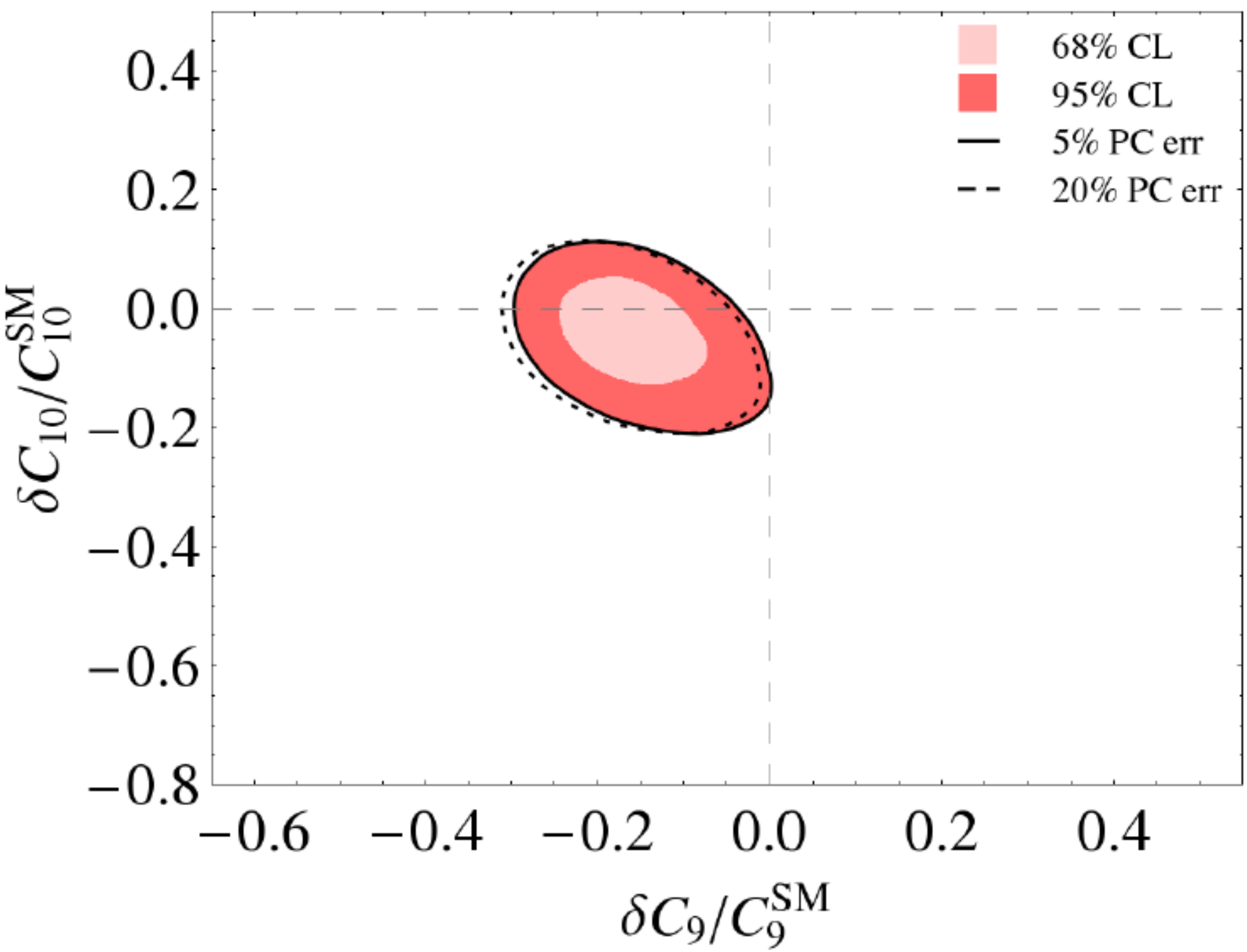
Assuming 10% power correction errors (on amplitude level)

	b.f. value	$\chi^2_{\rm min}$	Pull$_{\rm SM}$	68% C.L.	95% C.L.
$\delta C_9/C_9^{\rm SM}$	-0.18	123.8	3.0σ	$[-0.25, -0.09]$	$[-0.30, -0.03]$
$\delta C_9'/C_9^{\rm SM}$	$+0.03$	131.9	1.0σ	$[-0.05, +0.12]$	$[-0.11, +0.18]$
$\delta C_{10}/C_{10}^{\rm SM}$	-0.12	129.2	1.9σ	$[-0.23, -0.02]$	$[-0.31, +0.04]$
$\delta C_9^{\mu}/C_9^{\rm SM}$	-0.21	115.5	4.2σ	$[-0.27, -0.13]$	$[-0.32, -0.08]$
$\delta C_9^{e}/C_9^{\rm SM}$	$+0.25$	124.3	2.9σ	$[+0.11, +0.36]$	$[+0.03, +0.46]$

Allowing for lepton non-universality improves the fit !

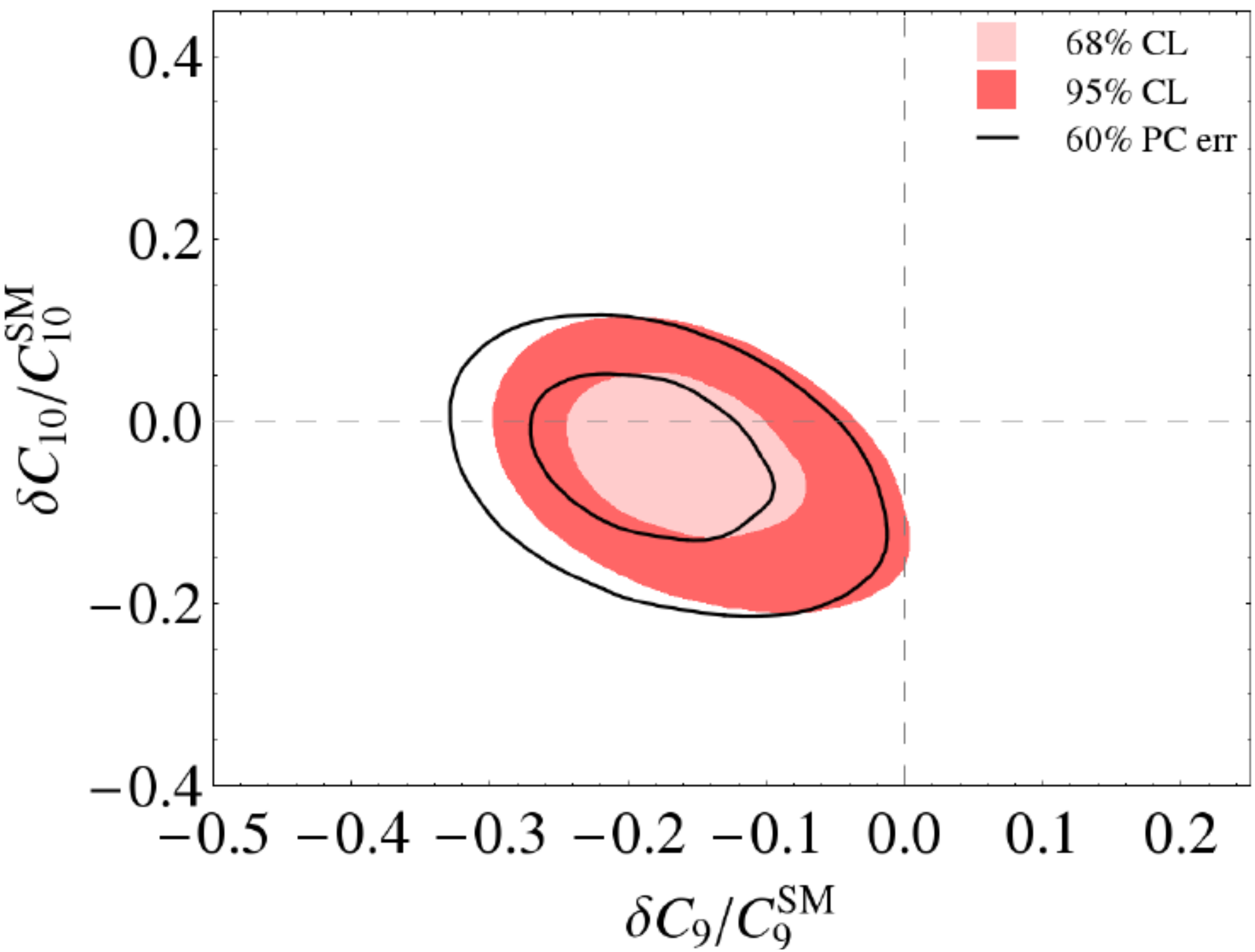
Fit results for two operators

$\{C_9, C_{10}\}$



Hurth,Mahmoudi,Neshatpour arXiv:1603.00865

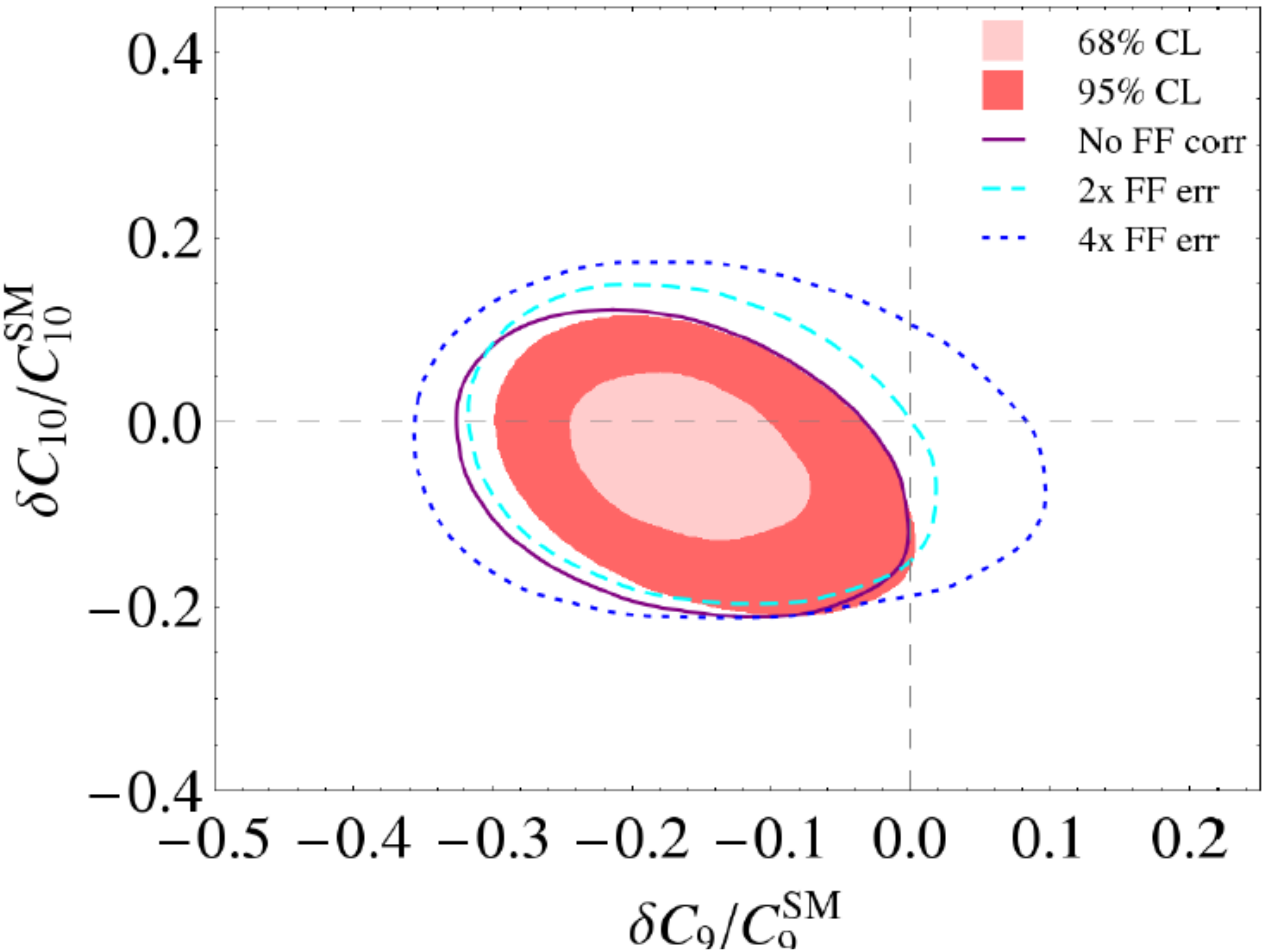
Assumption of 60% power correction error (on the amplitude level)



The assumption on the power correction errors have a rather mild impact on the constraints of the allowed region

Hurth,Mahmoudi,Neshatpour arXiv:1603.00865

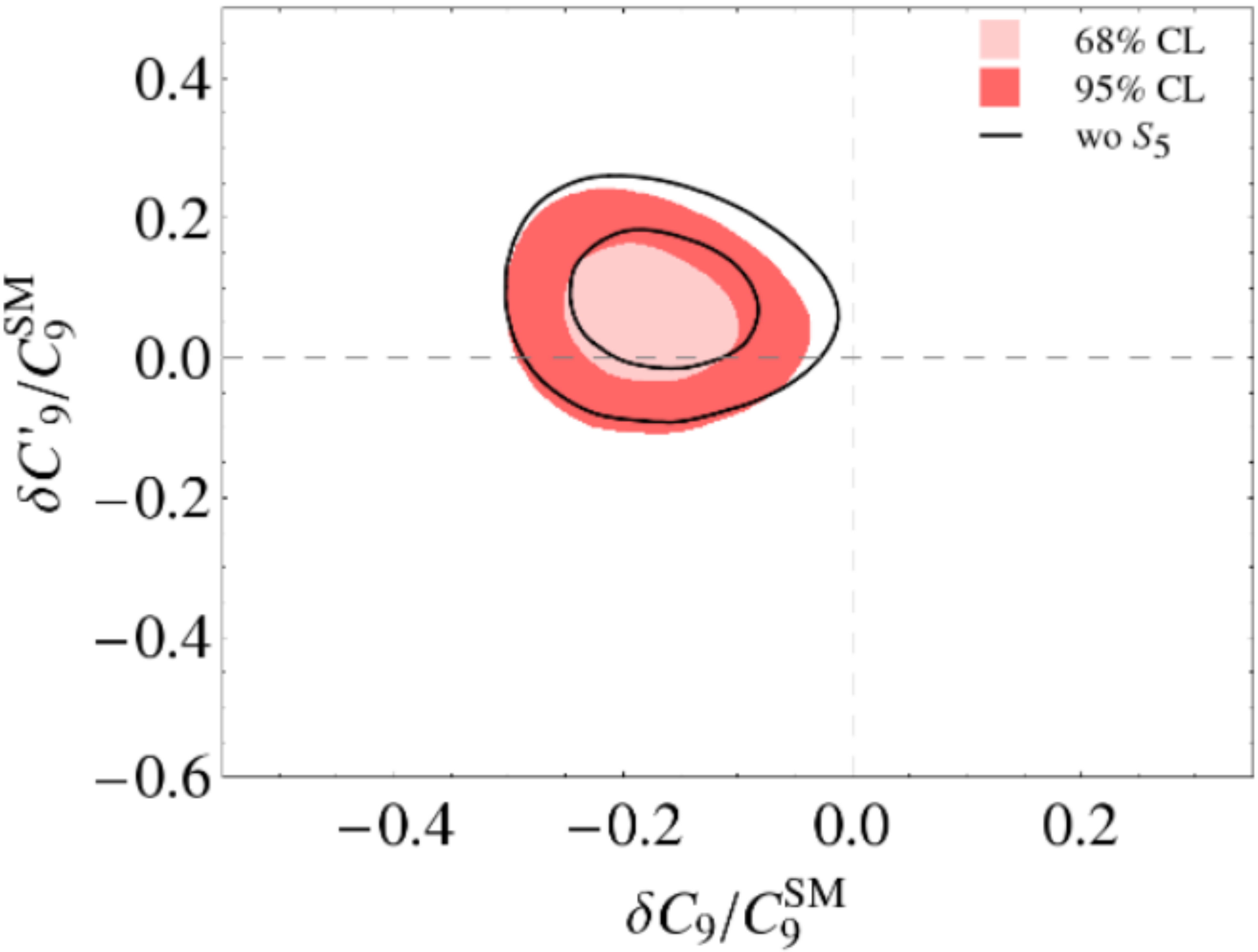
Fits assuming different form factor uncertainties



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

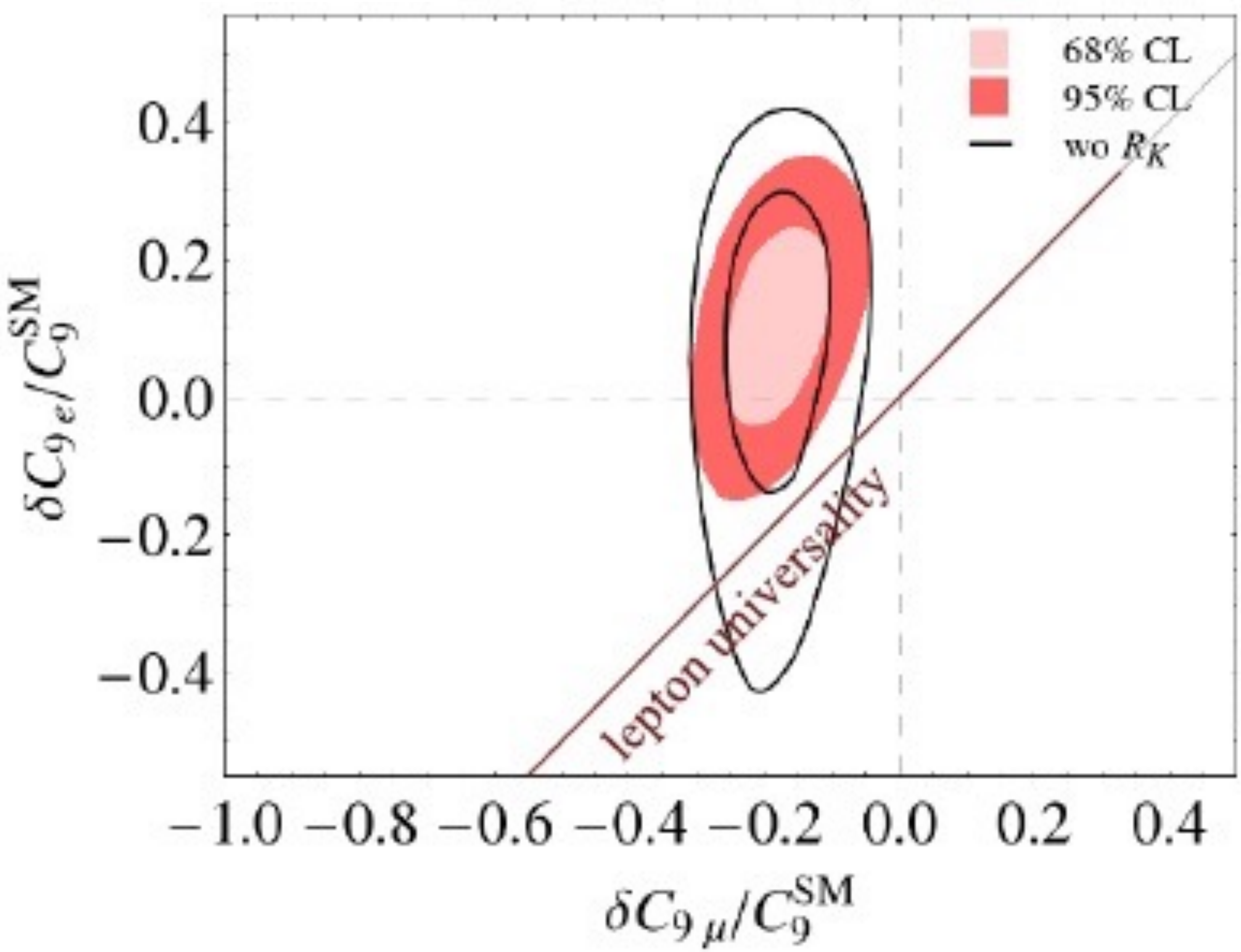
Hurth,Mahmoudi,Neshatpour arXiv:1603.00865

Omitting S_5 from the fit



S_5 is not the only observable which drives $\delta C_9/C_9^{\mathrm{SM}}$ to negative values

Removing R_K from the fit



R_K is the main player for the best fit value for $C_9^\mu - C_9^e$ which are in more than 2σ tension with lepton universality

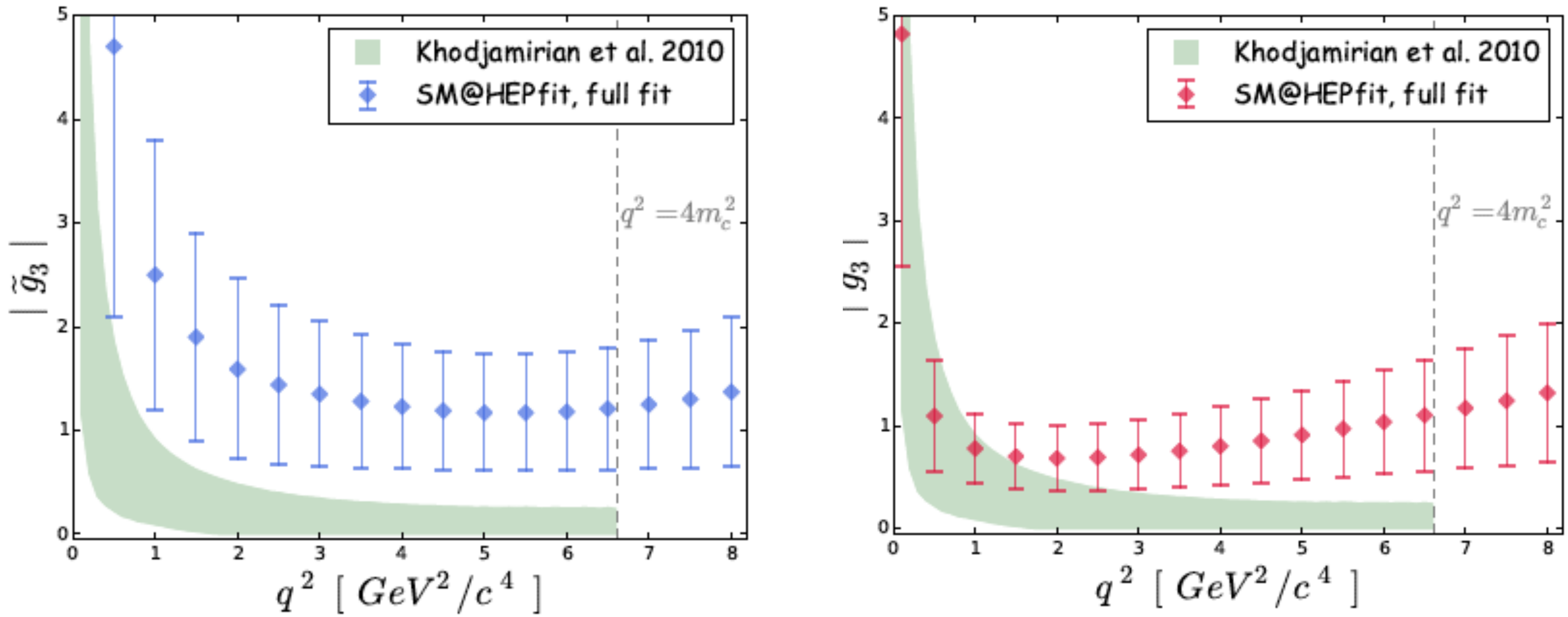
Strategy for the Future

Fit the unknown power corrections to the data

Ciuchini et al. arXiv:1512.07157

Leading SCET amplitude with general ansatz with 18 parameters for power corrections   Camalich,Jäger arXiv:1212.2263

Fit needs 20 – 50% power corrections (on the observable level)



No sign for q^2 dependence in the theory-independent fit

Significant q^2 dependence if power corrections are fixed at 1GeV via result of LCSR calculation   Kjodjamirian et al. arXiv:1211.0234

Significance of the LHCb anomalies depend on the assumptions on the power corrections

Ciuchini et al. (arXiv:1512.07157): Fit produces 20-50% nonfact. power corrections on the observable level in the critical bins.

Hurth et al. (arXiv:1603.00865): Assumption of 60% nonfact. power corrections on the amplitude level lead to 17-20 % on the observable level (S_3, S_4, S_5) only.

Calculations beyond guessing numbers

Any reasonable calculation is better than a fit!

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

Crosscheck of LHCb anomalies with various ratios $R(e/\mu)$

Hurth,Mahmoudi,Neshatpour arXiv:1603.00865

Altmannshofer,Straub arXiv:1503.06199

R_K is theoretically rather clean compared to LHCb anomalies and its tension with the SM cannot be explained by power corrections.

But both tensions might be healed by new physics in C_9^μ

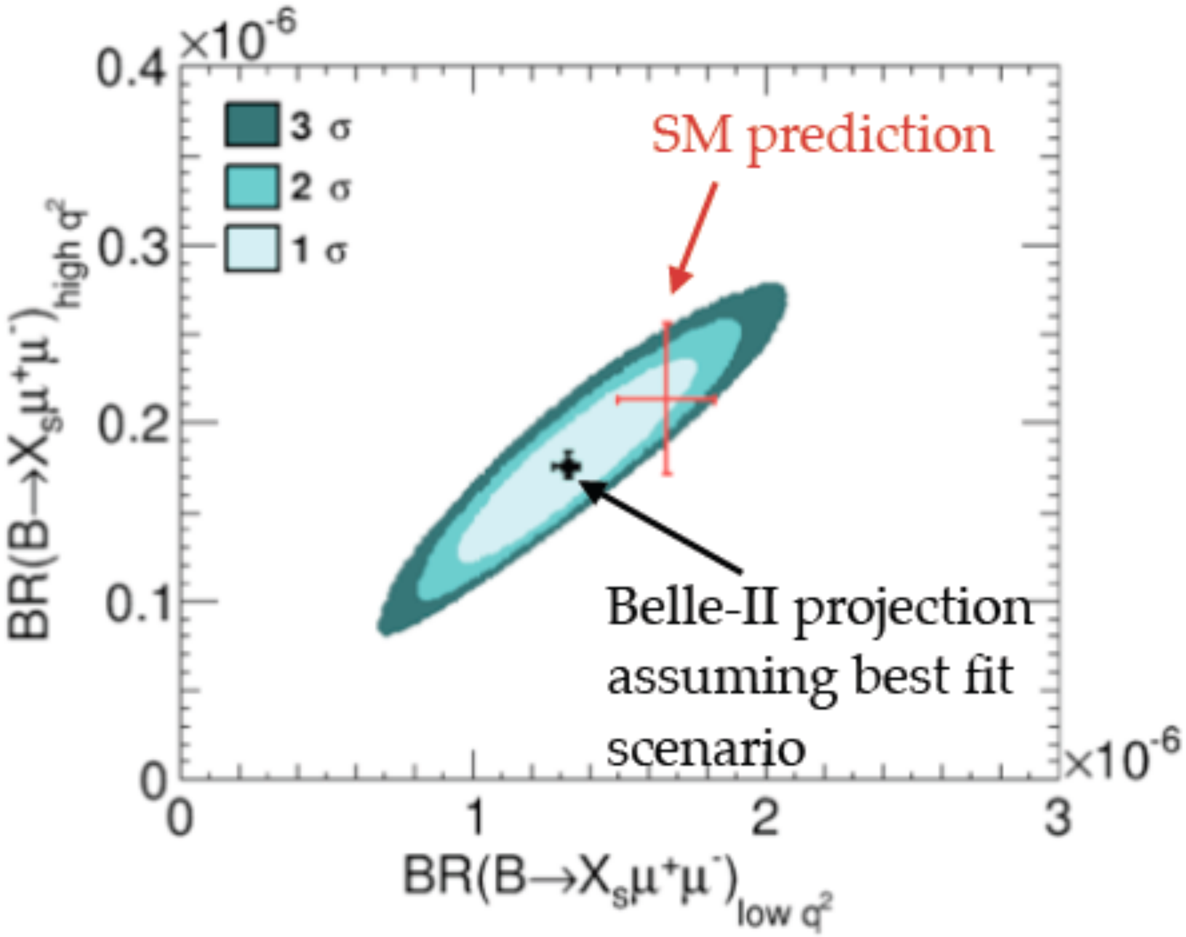
Observable	95% C.L. prediction
$\mathrm{BR}(B \to X_s\mu^+\mu^-)/\mathrm{BR}(B \to X_s e^+e^-)_{q^2\in[1,6](\mathrm{GeV})^2}$	$[0.61, 0.93]$
$\mathrm{BR}(B \to X_s\mu^+\mu^-)/\mathrm{BR}(B \to X_s e^+e^-)_{q^2>14.2(\mathrm{GeV})^2}$	$[0.68, 1.13]$
$\mathrm{BR}(B^0 \to K^{*0}\mu^+\mu^-)/\ \mathrm{BR}(B^0 \to K^{*0}e^+e^-)_{q^2\in[1,6](\mathrm{GeV})^2}$	$[0.65, 0.96]$
$\langle F_L(B^0 \to K^{*0}\mu^+\mu^-)\rangle/\langle F_L(B^0 \to K^{*0}e^+e^-)\rangle_{q^2\in[1,6](\mathrm{GeV})^2}$	$[0.85, 0.96]$
$\langle A_{FB}(B^0 \to K^{*0}\mu^+\mu^-)\rangle/\langle A_{FB}(B^0 \to K^{*0}e^+e^-)\rangle_{q^2\in[4,6](\mathrm{GeV})^2}$	$[-0.21, 0.71]$
$\langle S_5(B^0 \to K^{*0}\mu^+\mu^-)\rangle/\langle S_5(B^0 \to K^{*0}e^+e^-)\rangle_{q^2\in[4,6](\mathrm{GeV})^2}$	$[0.53, 0.92]$
$\mathrm{BR}(B^0 \to K^{*0}\mu^+\mu^-)/\ \mathrm{BR}(B^0 \to K^{*0}e^+e^-)_{q^2\in[15,19](\mathrm{GeV})^2}$	$[0.58, 0.95]$
$\langle F_L(B^0 \to K^{*0}\mu^+\mu^-)\rangle/\langle F_L(B^0 \to K^{*0}e^+e^-)\rangle_{q^2\in[15,19](\mathrm{GeV})^2}$	$[0.998, 0.999]$
$\langle A_{FB}(B^0 \to K^{*0}\mu^+\mu^-)\rangle/\langle A_{FB}(B^0 \to K^{*0}e^+e^-)\rangle_{q^2\in[15,19](\mathrm{GeV})^2}$	$[0.87, 1.01]$
$\langle S_5(B^0 \to K^{*0}\mu^+\mu^-)\rangle/\langle S_5(B^0 \to K^{*0}e^+e^-)\rangle_{q^2\in[15,19](\mathrm{GeV})^2}$	$[0.87, 1.01]$
$\mathrm{BR}(B^+ \to K^+\mu^+\mu^-)/\ \mathrm{BR}(B^+ \to K^+e^+e^-)_{q^2\in[1,6](\mathrm{GeV})^2}$	$[0.58, 0.95]$
$\mathrm{BR}(B^+ \to K^+\mu^+\mu^-)/\ \mathrm{BR}(B^+ \to K^+e^+e^-)_{q^2\in[15,22](\mathrm{GeV})^2}$	$[0.58, 0.95]$

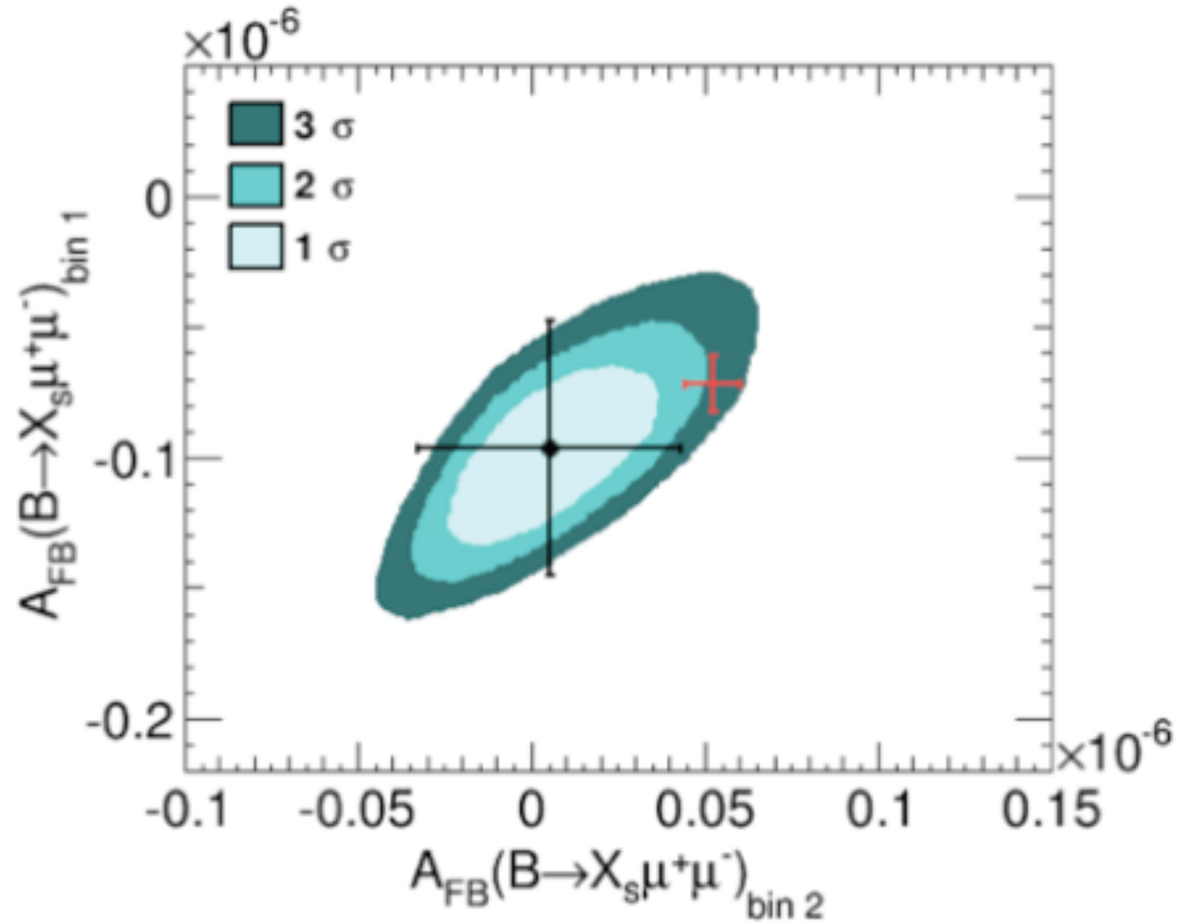
Table 3: Predicted ratios of observables with muons in the final state to electrons in the final state, considering the two operator fit within the $\{C_9^\mu, C_9^e\}$ set.

Crosscheck of LHCb anomalies with inclusive modes

Hurth,Mahmoudi,Neshatpour,arXiv:1410.4545

if SM deviations in R_K and P_5' persist until Belle-II





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

Inclusive modes

New physics sensitivity

Huber,Hurth,Lunghi, arXiv:1503.04849

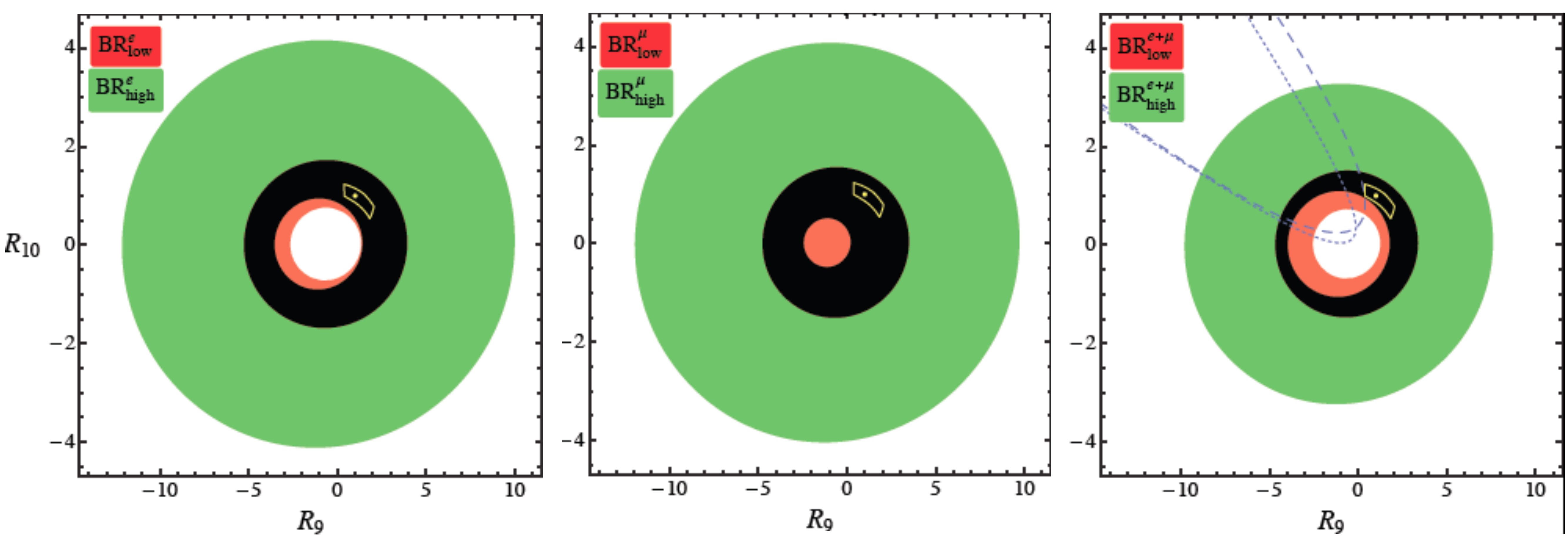
Constraints on Wilson coefficients C_9/C_9^{SM} and C_{10}/C_{10}^{SM}

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

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)

$B \to X_s ee$ $\qquad$ $B \to X_s \mu\mu$ $\qquad$ $B \to X_s \ell\ell$



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

Huber,Hurth,Lunghi, arXiv:1503.04849

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

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Huber,Hurth,Lunghi, arXiv:1503.04849

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

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

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

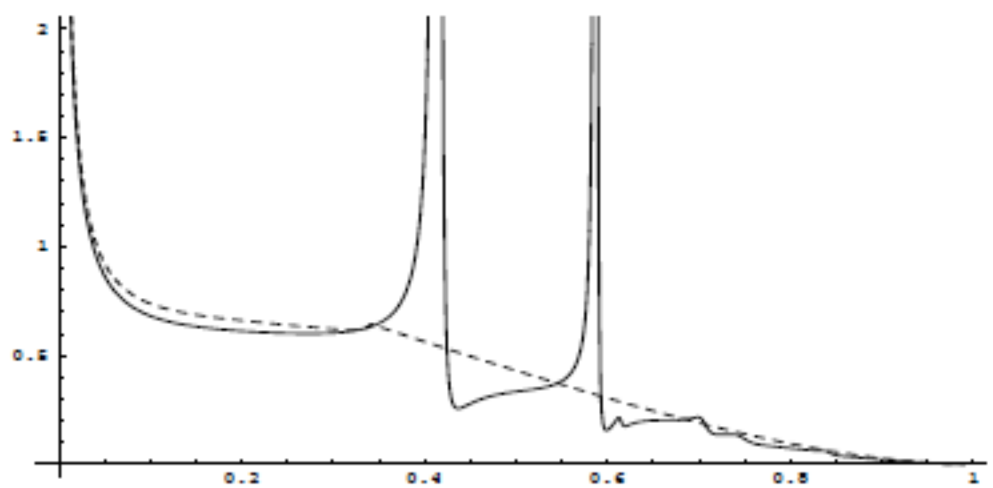
- Electromagnetic effects due to energetic photons are large and calculated analytically and crosschecked against Monte Carlo generator events

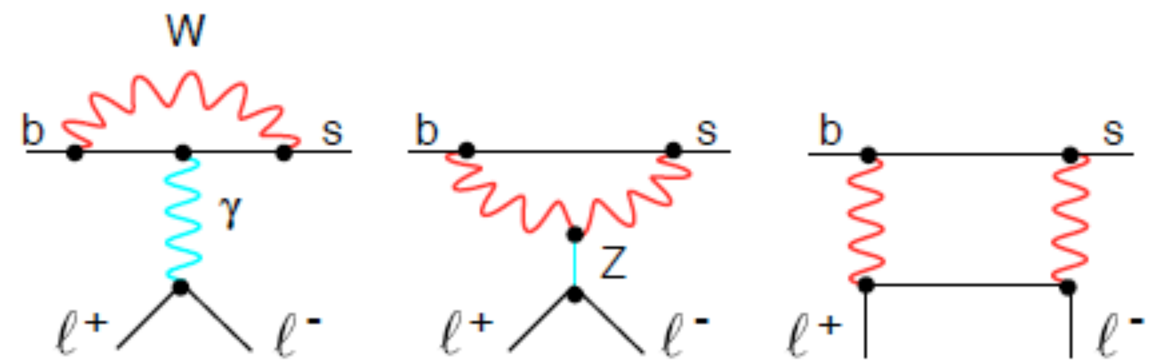
Large logs $log(mb/m_\ell)$ different for muon and electron !

Subleading contributions in $B \to X_s \ell^+ \ell^-$

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

$\frac{d}{d\hat{s}} BR(\bar{B} \to X_s l^+ l^-) \times 10^{-5}$





- 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 $2.0 GeV$
  - 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 $2.0 GeV$ 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)

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

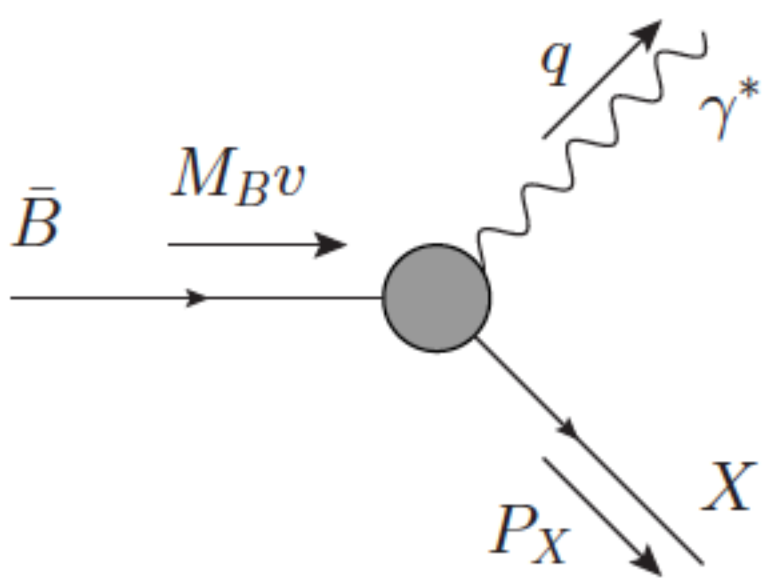
Benzke,Fickinger,Hurth,Turczyk, to appear

Hadronic cut

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

Hadronic invariant $m_X^2 < 1.8(2.0) GeV^2$, jet-like X_s $E_X \sim \mathcal{O}(m_b)$

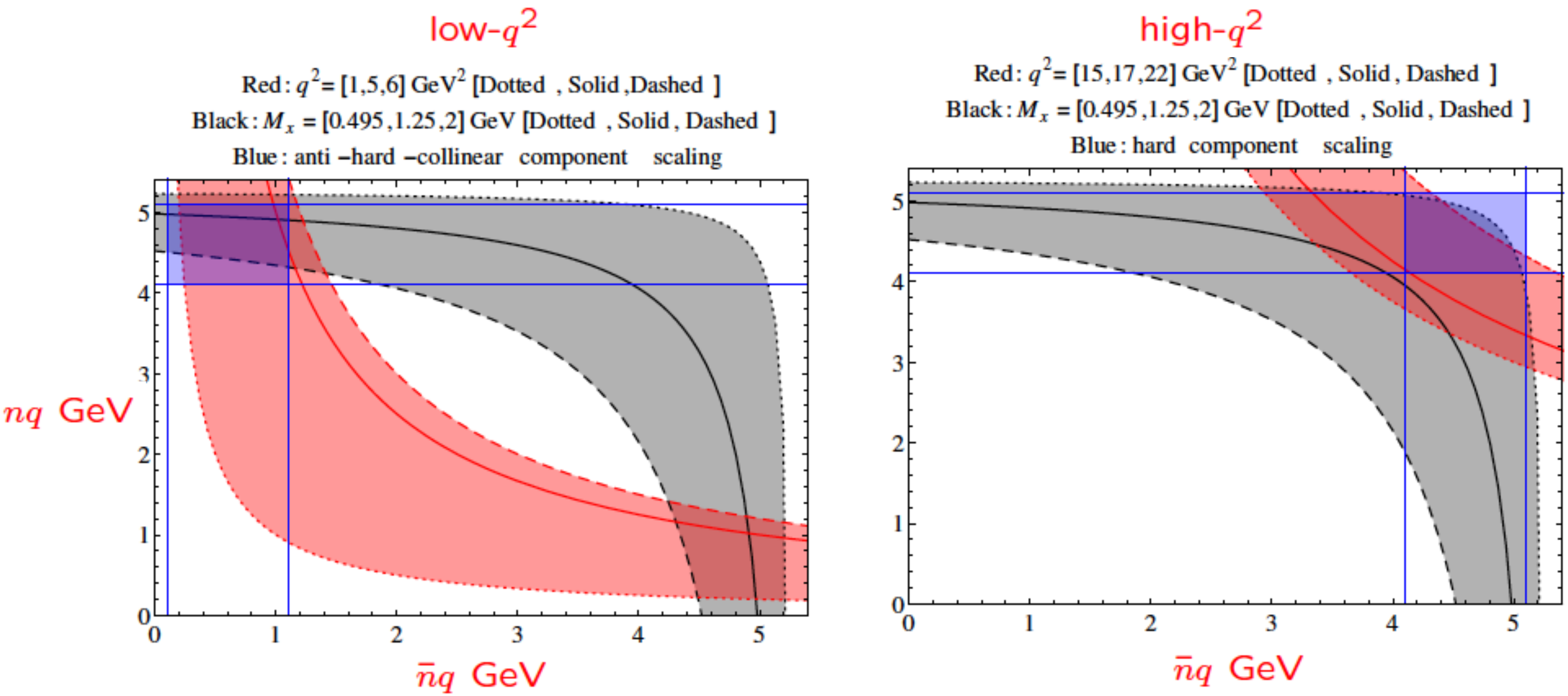
Multiscale problem $\to$ SCET



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

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

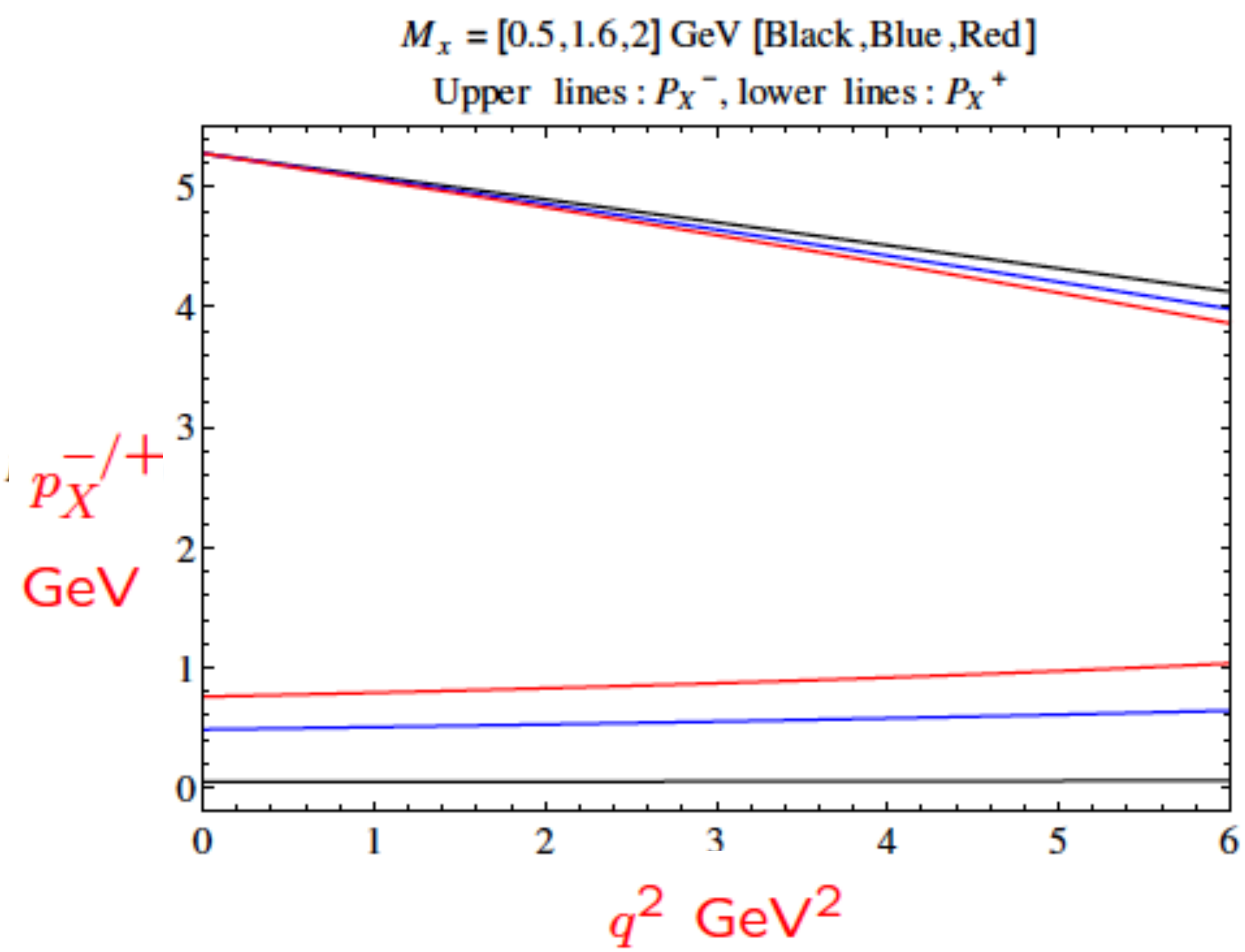
Alllowed regions

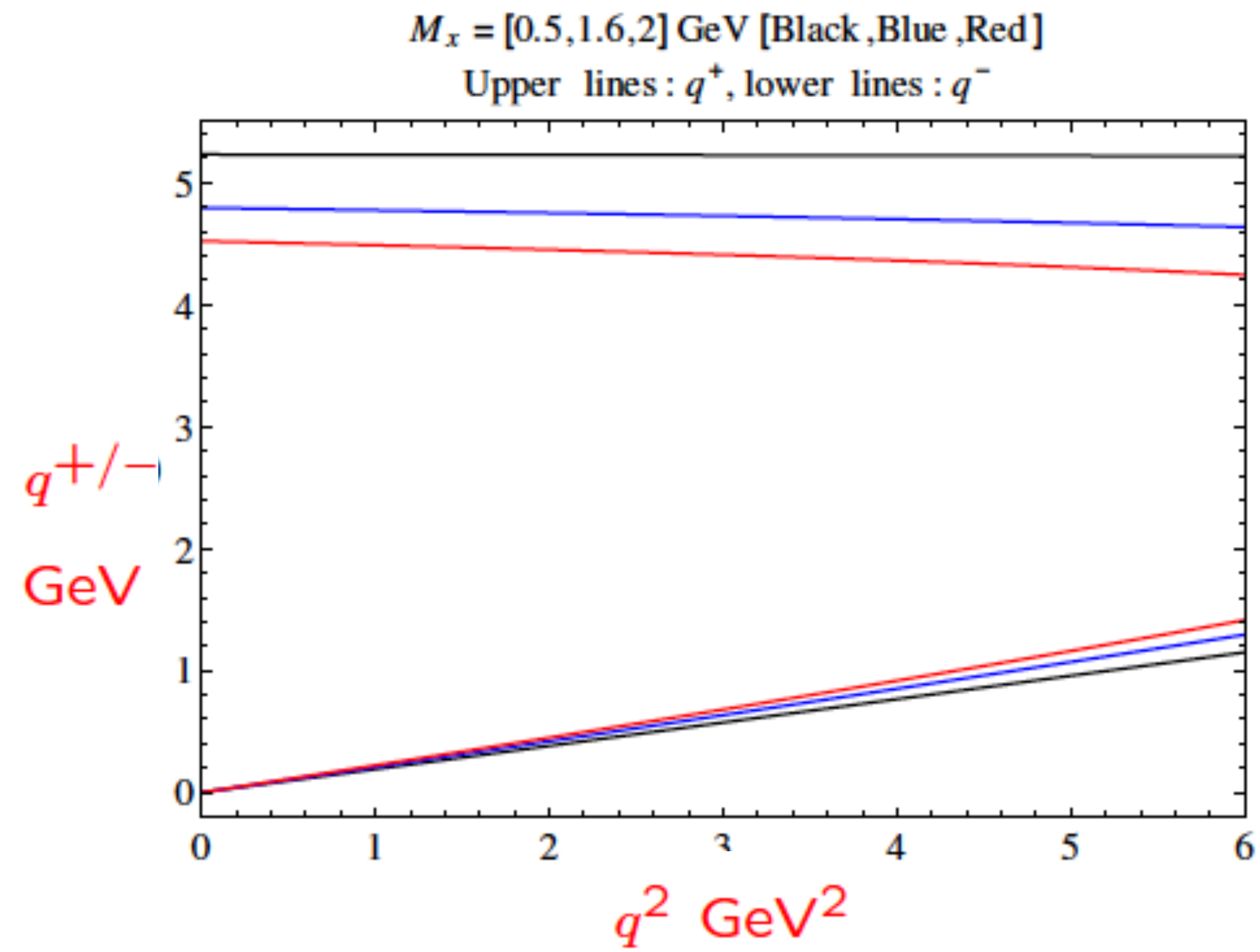


Scaling

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

Scaling





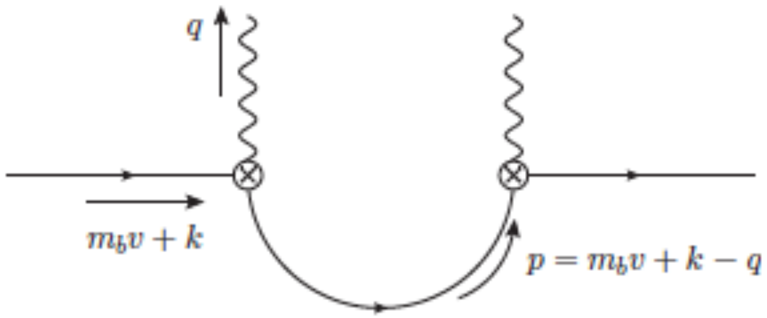
For $q^2 < 6GeV^2$ the scaling of np_X and $\bar{n}p_X$ implies $\bar{n}q$ is of order λ, means q anti-hard-collinear (just kinematics).

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 $m_X^2 \sim \lambda$:



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

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 $\quad d\Gamma \sim H \cdot J \otimes S$

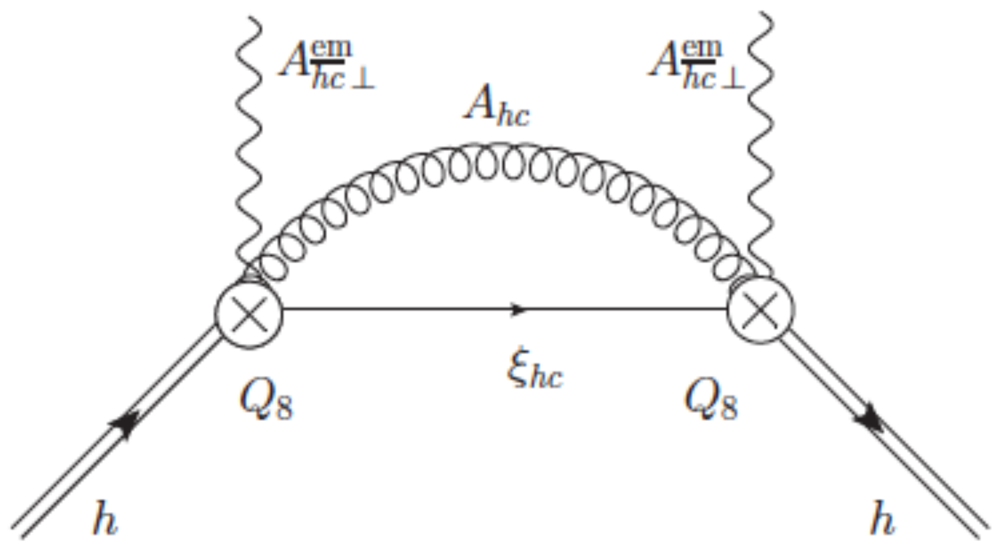
The hard function H and the jet function J are perturbative quantities.

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

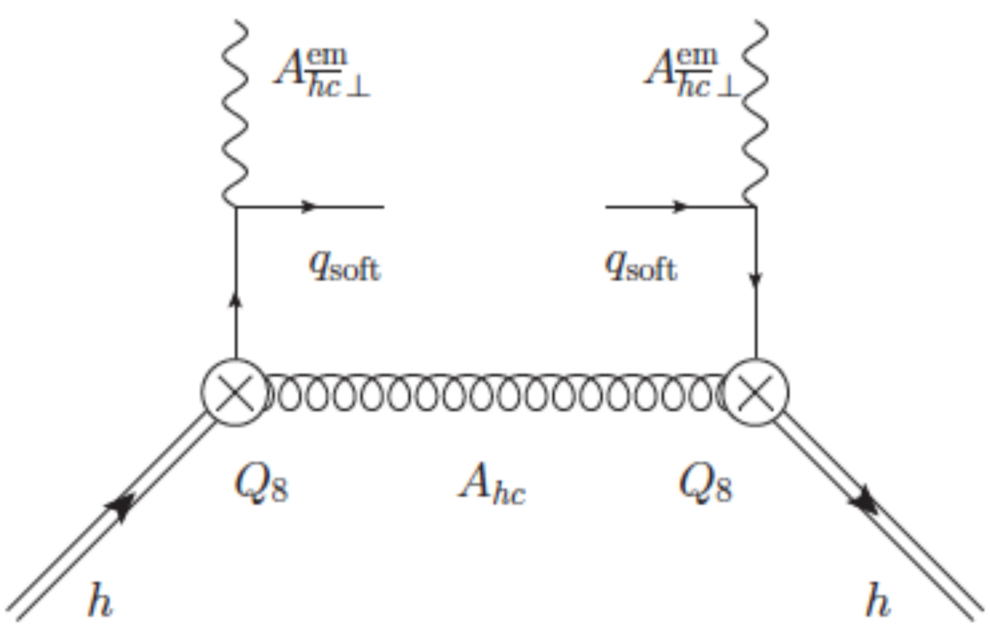
Example of **direct** photon contribution which factorizes $d\Gamma \sim H \cdot j \otimes S$



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

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

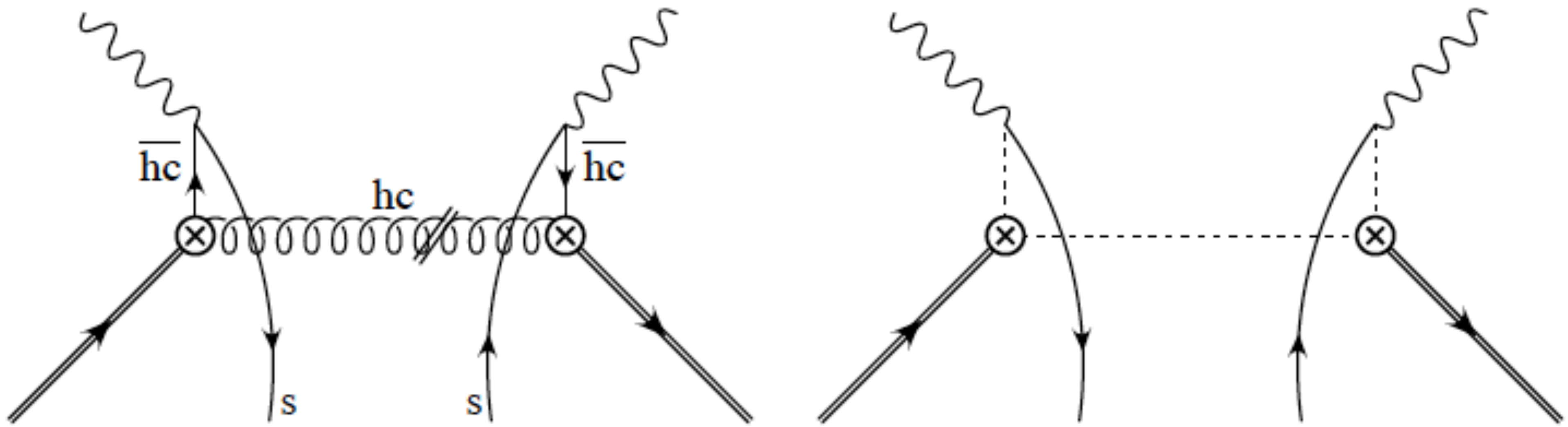
$d\Gamma \sim H \cdot J \otimes s \otimes \bar{J} \otimes \bar{J}$



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

Shape function is non-local in two light-cone directions.
It survives $M_X \rightarrow 1$ limit (irreducible uncertainty).

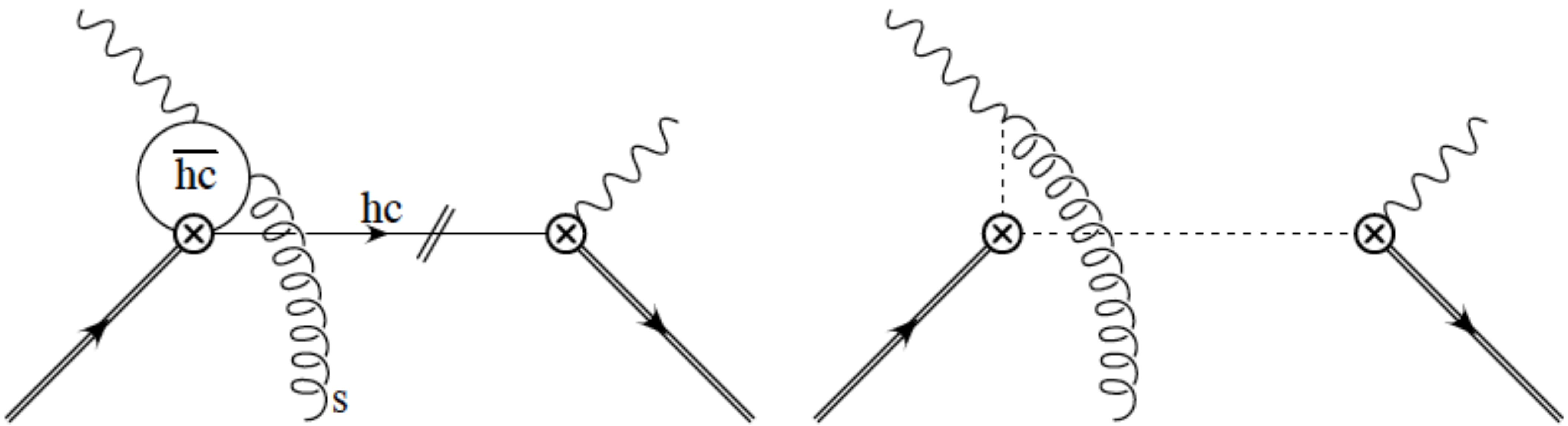
Interference of Q_8 and Q_8



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

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

Interference of Q_1 and Q_7



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

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

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

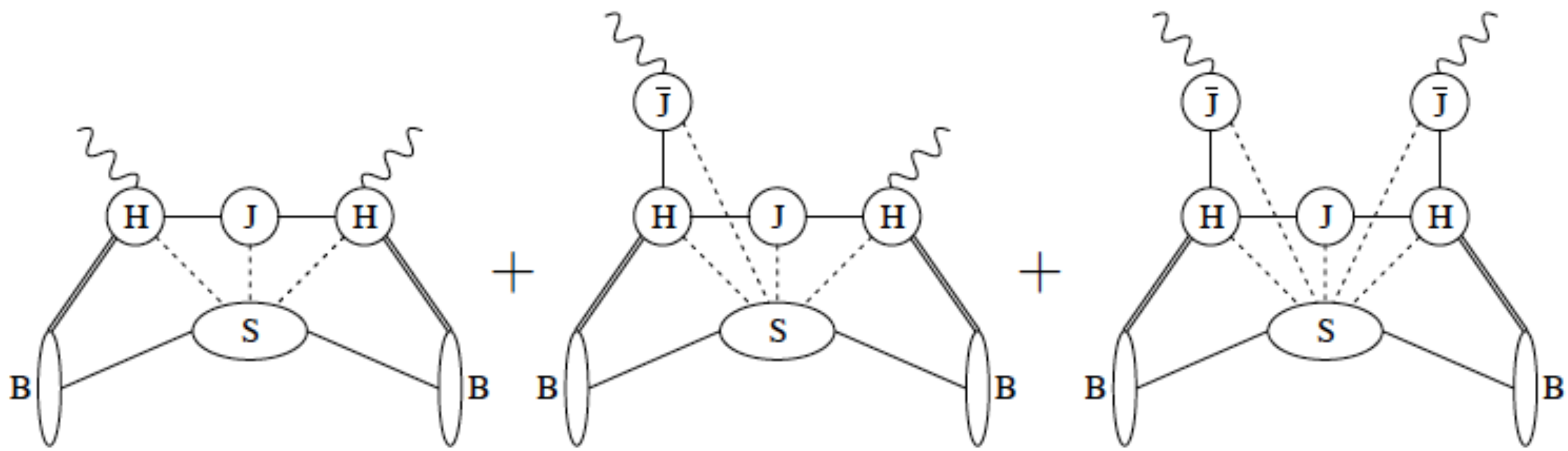
$$g_{17}(\omega,\omega_1)=\int\frac{dr}{2\pi}e^{-i\omega_1 r}\int\frac{dt}{2\pi}e^{-i\omega t}\frac{1}{M_B}\langle\bar{B}|\bar{h}(\mathbf{t}\mathbf{n})\ldots G_s^{\alpha\beta}(\mathbf{r}\bar{\mathbf{n}})\ldots h(\mathbf{0})|\bar{B}\rangle$$

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 $m_c < m_b$.

Factorization formula

In the $m_X^2 \sim \lambda$ and $q^2 \sim \lambda$ region we have the following factorization formula

$$d\Gamma \sim H \cdot J \otimes S + \frac{1}{m_b} \sum H \cdot j_i \otimes S + \frac{1}{m_b} \sum H \cdot J \otimes s_i + \frac{1}{m_b} \sum H \cdot J \otimes s_i \otimes \bar{J} + \frac{1}{m_b} \sum H \cdot J \otimes s_i \otimes \bar{J} \otimes \bar{J} + \mathcal{O}\left(\frac{1}{m_b^2}\right)$$



Numerical evaluation (work in progress)

Similar subleading shape functions as in $B \to X_s \gamma$

Use vacuum insertion approximation, PT invariance,....

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.

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

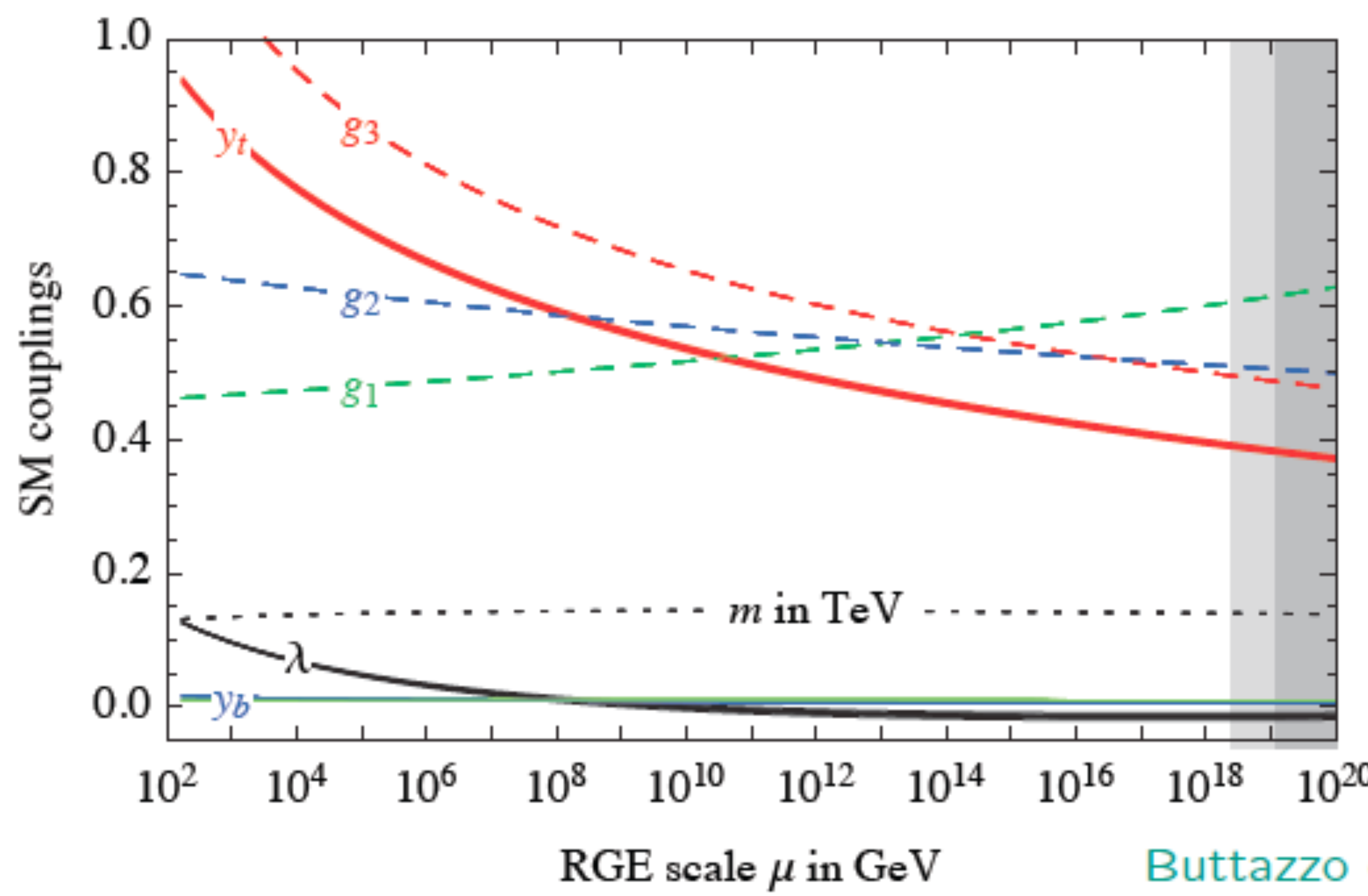
(work in progress)

Epilogue

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)

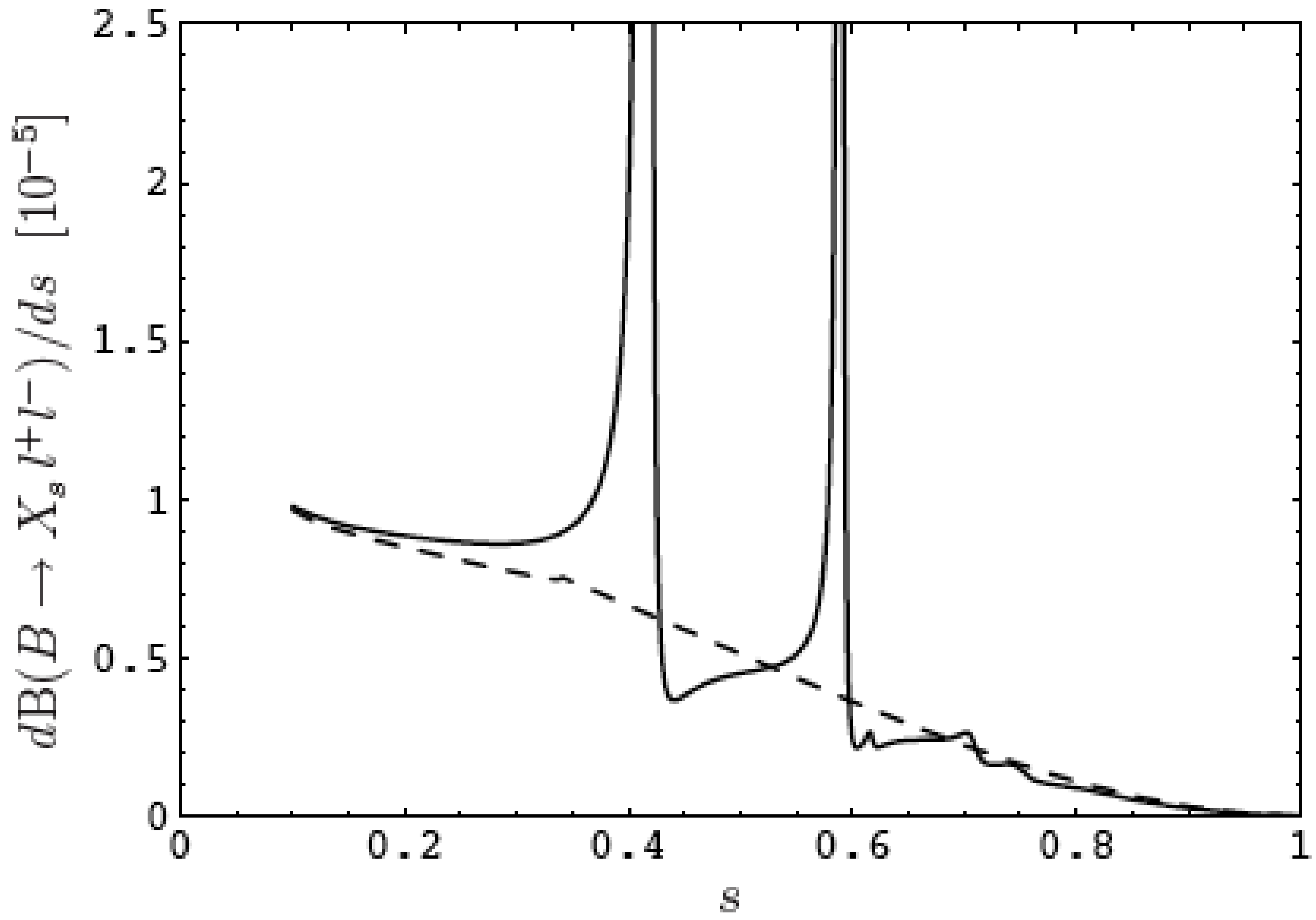
Caveat:

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

Extra

Quark-hadron duality violated in $\bar{B} \to X_s \ell^+ \ell^-$? BBNS, arXiv:0902.4446

Within integrated branching ratio the resonances J/ψ and ψ' exceed the perturbative contributions by two orders of magnitude.



Quark-hadron duality violated in $\bar{B} \to X_s \ell^+ \ell^-$?

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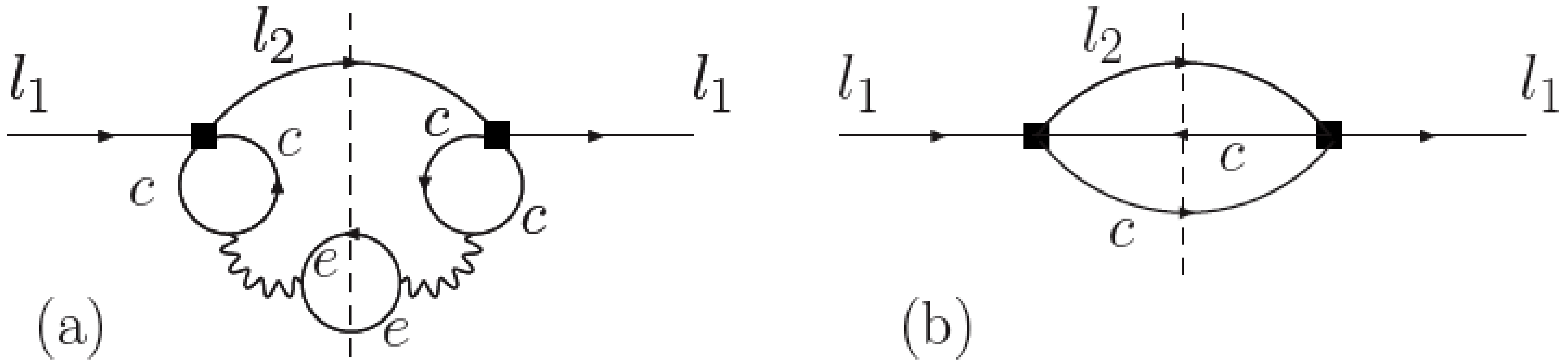


The rate $l_1 \to l_2 e^+ e^-$ (a) is connected to the integral over $|\Pi(q^2)|^2$ for which global duality is NOT expected to hold.

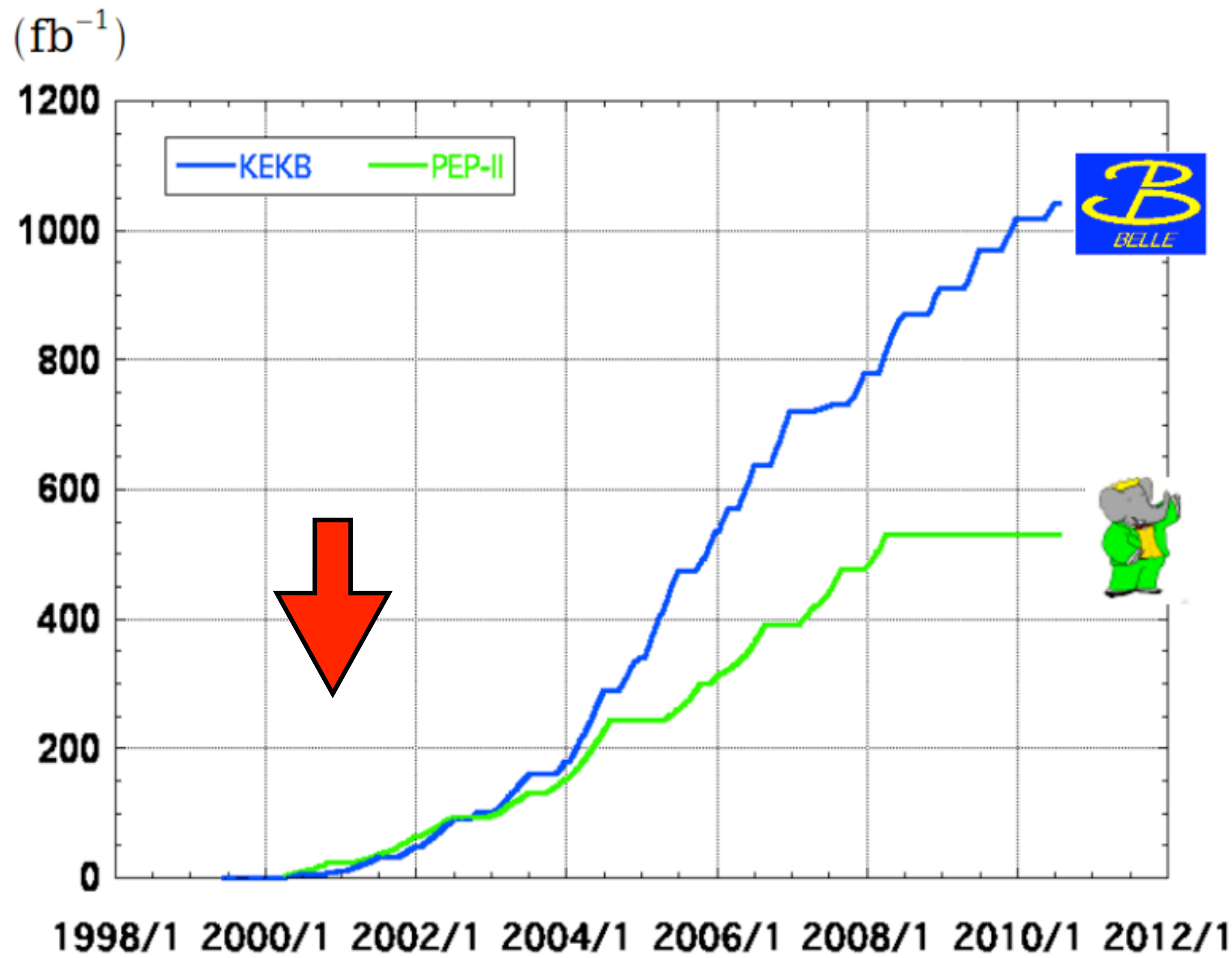
In contrast the inclusive hadronic rate $l_1 \to l_2 X$ (b) corresponds to the imaginary part of the correlator $\Pi(q^2)$.

- "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)

Babar hep-ex/0404006 (!!!) (based $89 \times 10^6 B\bar{B}$ events)

Integrated luminosity of B factories



$> 1\ ab^{-1}$

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

$\sim 100\ fb^{-1}$

$\sim 550\ fb^{-1}$

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

$\Upsilon(3S)$: 30 fb^{-1}

$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

$\sim 54\ fb^{-1}$

Two new analyses from the B factories:

New Babar analysis on dilepton spectrum arXiv:1312.3664

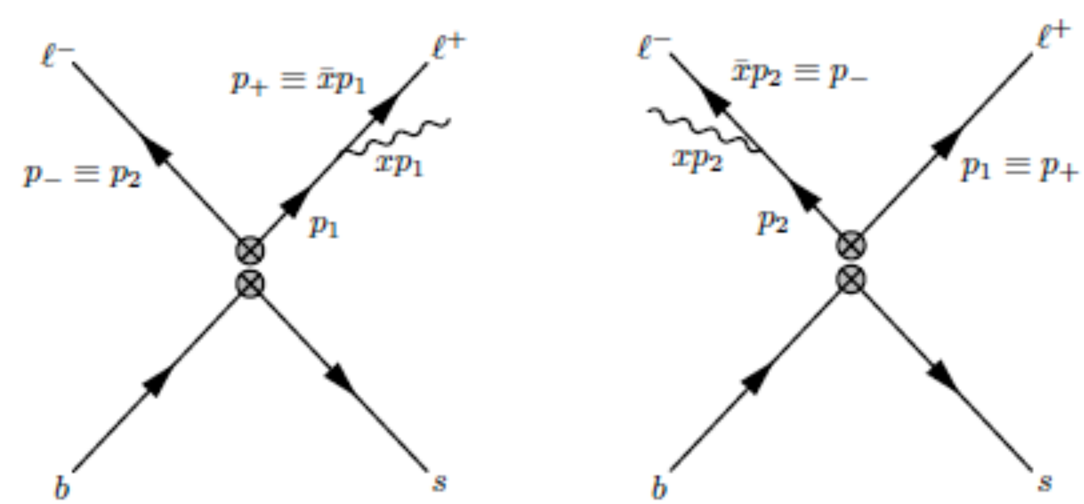
New Belle analysis on AFB arXiv:1402.7134

Huber,Hurth,Lunghi, arXiv:1503.04849

- Collinear Photons give rise to log-enhanced QED corrections $\alpha_{\rm em} \log(m_b^2/m_\ell^2)$
- Higher powers of z in double differential decay width
  - Definition of H_i ? Sensitivity for QED observables ?

We use Legendre poynomials for H_T and H_L and $Sign(z)$ for H_A

We can construct QED sensitive observables (vanish in absence of QED) by Legendre projectors $P_3(z)$ or $P_4(z)$: 10^{-8}



Huber,Hurth,Lunghi, arXiv:1503.04849

- Collinear Photons give rise to log-enhanced QED corrections $\alpha_{\rm em} \log(m_b^2/m_\ell^2)$
- Higher powers of z in double differential decay width
  - Definition of H_i ? Sensitivity for QED observables ?
- Size of logs depend on experimental set-up

$$q^2 = (p_{\ell^+} + p_{\ell^-})^2 \quad \text{vs.} \quad q^2 = (p_{\ell^+} + p_{\ell^-} + p_{\gamma,\rm coll})^2$$

  - We assume no photons are included in the definition of q^2 (di-muon channel at Babar/Belle, di-electron at Belle)
  - Babar's di-electron channel: Photons that are emitted in a cone of 35 mrad angular opening are included in q^2

  Monte Carlo techniques needed to estimate this effect

$$\frac{\left[\mathcal{B}_{ee}^{\rm low}\right]_{q=p_{e^+}+p_{e^-}+p_{\gamma_{\rm coll}}}}{\left[\mathcal{B}_{ee}^{\rm low}\right]_{q=p_{e^+}+p_{e^-}}} - 1 = 1.65\% \qquad \frac{\left[\mathcal{B}_{ee}^{\rm high}\right]_{q=p_{e^+}+p_{e^-}+p_{\gamma_{\rm coll}}}}{\left[\mathcal{B}_{ee}^{\rm high}\right]_{q=p_{e^+}+p_{e^-}}} - 1 = 6.8\%$$

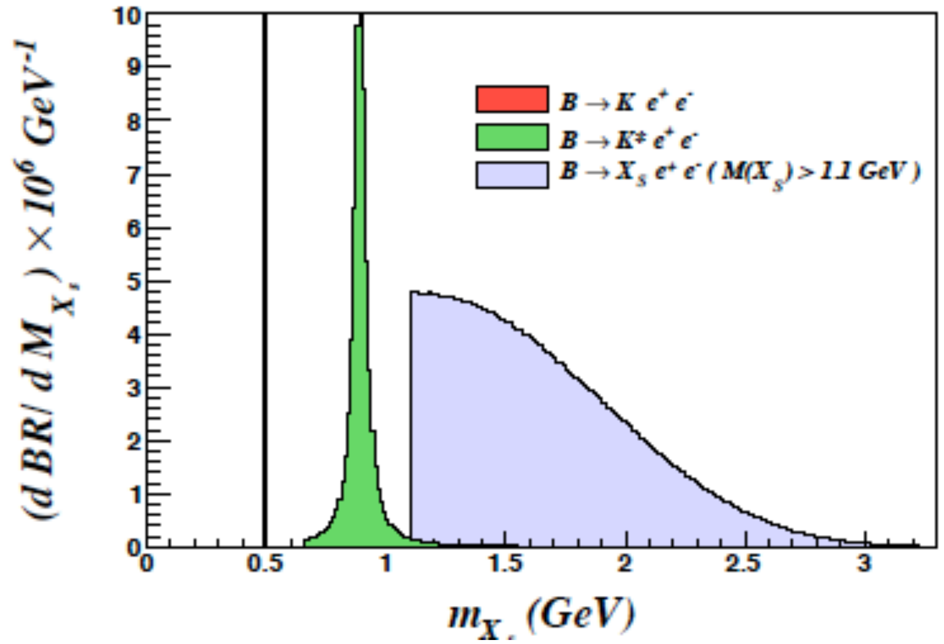
Monte Carlo analysis

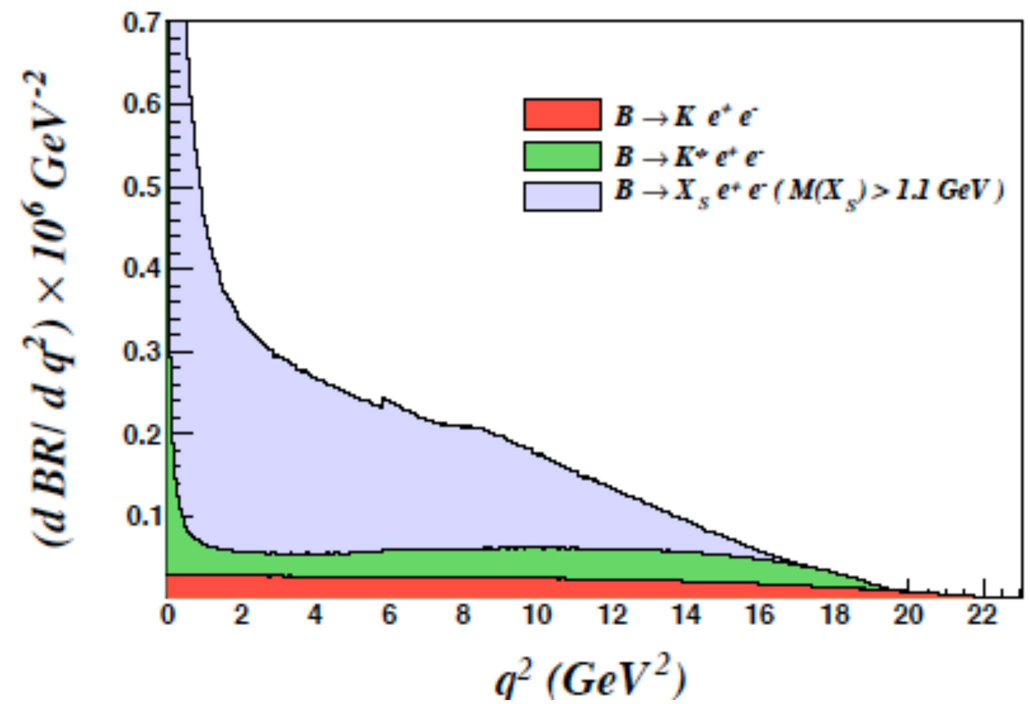
Huber,Hurth,Lunghi, arXiv:1503.04849

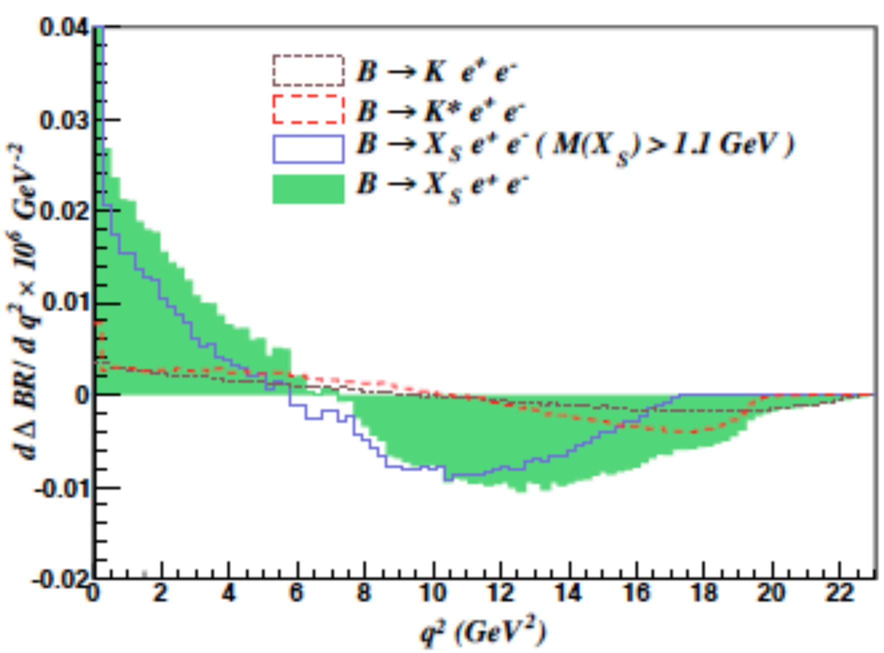
(event generator EVTGEN, hadronization JETSET, EM radiation PHOTOS)

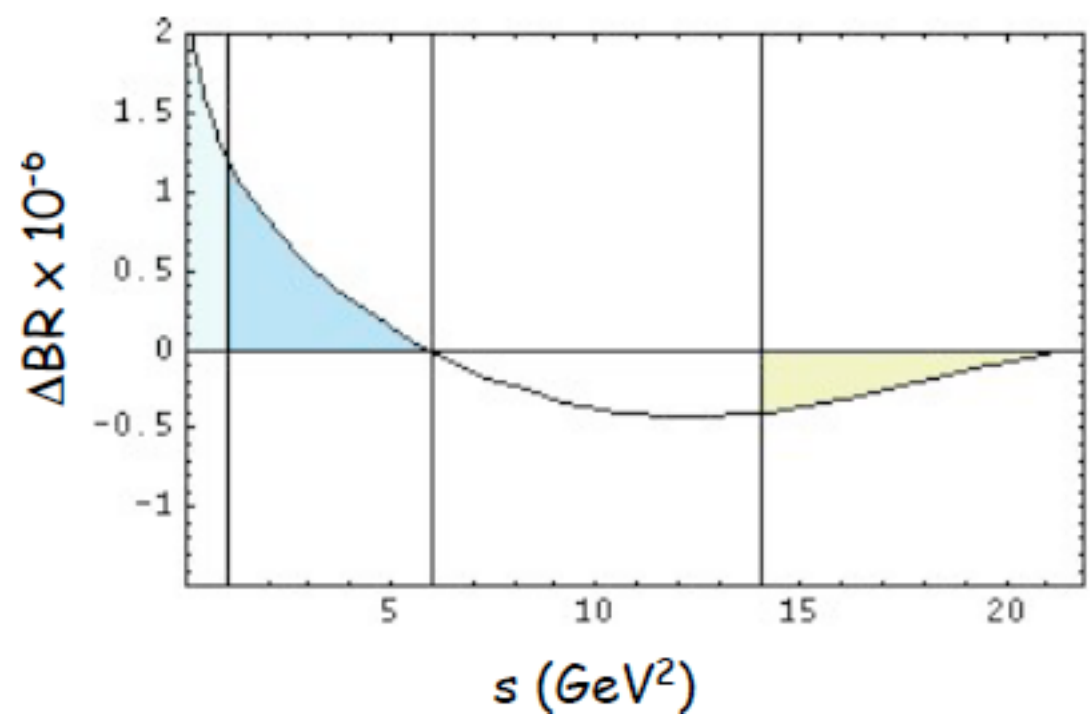
$$\frac{\left[\mathcal{B}_{ee}^{\rm low}\right]_{q=p_{e^+}+p_{e^-}+p_{\gamma_{\rm coll}}}}{\left[\mathcal{B}_{ee}^{\rm low}\right]_{q=p_{e^+}+p_{e^-}}} - 1 = 1.65\%$$

$$\frac{\left[\mathcal{B}_{ee}^{\rm high}\right]_{q=p_{e^+}+p_{e^-}+p_{\gamma_{\rm coll}}}}{\left[\mathcal{B}_{ee}^{\rm high}\right]_{q=p_{e^+}+p_{e^-}}} - 1 = 6.8\%$$









Huber,Hurth,Lunghi, arXiv:1503.04849

Results

Low-q^2 $(1GeV^2 < q^2 < 6GeV^2)$

$BR(B \to X_s ee) = (1.67 \pm 0.10)\, 10^{-6}$

$BR(B \to X_s \mu\mu) = (1.62 \pm 0.09)\, 10^{-6}$

Babar:$BR(B \to X_s \ell\ell) =$

$= (1.60\ (+0.41 - 0.39)_{stat}(+0.17 - 0.13)_{syst}(\pm 0.18)_{mod})\, 10^{-6}$

good agreement with SM

Huber,Hurth,Lunghi, arXiv:1503.04849

Results

High-q^2, Theory: $q^2 > 14.4 GeV^2$, Babar: $q^2 > 14.2 GeV^2$

$$BR(B \to X_s ee) = (0.220 \pm 0.070)\, 10^{-6}$$

$$BR(B \to X_s \mu\mu) = (0.253 \pm 0.070)\, 10^{-6}$$

Babar: $BR(B \to X_s \ell\ell) =$

$$(0.57\ (+0.16 - 0.15)_{stat} (+0.03 - 0.02)_{syst})\, 10^{-6}$$

2σ higher than SM

Significant higher values predicted in Greub et al. due to missing power and QED corrections and different cut Greub,Pilipp,Schupbach,arXiv:0810.4077

(but perfect agreement if we use their prescriptions)

Further refinement

Huber,Hurth,Lunghi, arXiv:1503.04849

Normalization to semileptonic $B \to X_u \ell \nu$ decay rate with the same cut reduces the impact of $1/m_b$ corrections in the high-q^2 region significantly.

Ligeti,Tackmann arXiv:0707.1694

Theory prediction for ratio

$$R(s_0)_{ee} = (2.25 \pm 0.31)\, 10^{-3}$$

$$R(s_0)_{\mu\mu} = (2.62 \pm 0.30)\, 10^{-3}$$

Largest source of error are CKM elements (V_{ub})

Note: Additional $O(5\%)$ uncertainty due to nonlocal power corrections $O(\alpha_s \Lambda / m_b)$

Further results in units of 10^{-6}

$$H_L[1,3.5]_{ee} = 0.64 \pm 0.03 \qquad H_L[1,3.5]_{\mu\mu} = 0.68 \pm 0.04$$

$$H_L[3.5,6]_{ee} = 0.50 \pm 0.03 \qquad H_L[3.5,6]_{\mu\mu} = 0.53 \pm 0.03$$

$$H_L[1,6]_{ee} = 1.13 \pm 0.06 \qquad H_L[1,6]_{\mu\mu} = 1.21 \pm 0.07$$

$$H_T[1,3.5]_{ee} = 0.29 \pm 0.02 \qquad H_T[1,3.5]_{\mu\mu} = 0.21 \pm 0.01$$

$$H_T[3.5,6]_{ee} = 0.24 \pm 0.02 \qquad H_T[3.5,6]_{\mu\mu} = 0.19 \pm 0.02$$

$$H_T[1,6]_{ee} = 0.53 \pm 0.04 \qquad H_T[1,6]_{\mu\mu} = 0.40 \pm 0.03$$

$$H_A[1,3.5]_{ee} = -0.103 \pm 0.005 \qquad H_A[1,3.5]_{\mu\mu} = -0.110 \pm 0.005$$

$$H_A[3.5,6]_{ee} = +0.073 \pm 0.012 \qquad H_A[3.5,6]_{\mu\mu} = +0.067 \pm 0.012$$

$$H_A[1,6]_{ee} = -0.029 \pm 0.016 \qquad H_A[1,6]_{\mu\mu} = -0.042 \pm 0.016$$

Total error $\mathcal{O}(5-8\%)$. Still dominated by scale uncertainty.