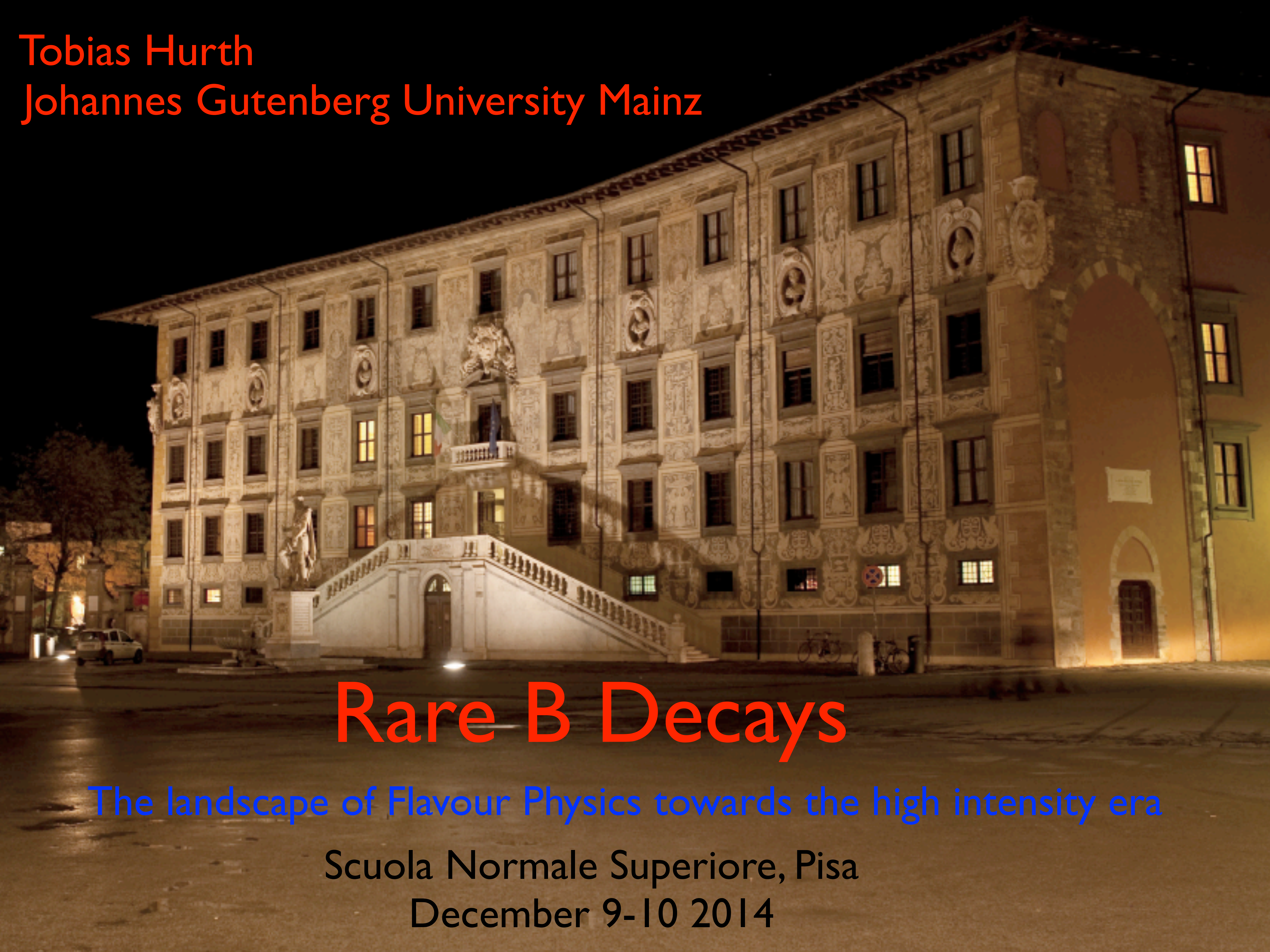


Tobias Hurth
Johannes Gutenberg University Mainz

Rare B Decays

The landscape of Flavour Physics towards the high intensity era

Scuola Normale Superiore, Pisa
December 9-10 2014

- Implications of the latest measurement of $B_s \to \mu\mu$

- Radiative and semileptonic penguin decays

  - Inclusive $B \to X_s \ell^+ \ell^-$
  - Exclusive $B \to K^* \ell^+ \ell^-$
  - Signs for lepton non-universality
  - Correlations between $b \to s\ell\ell$ and $b \to s\nu\bar{\nu}$

- **No guiding principle in the flavour sector**

$$\mathcal{L}_{SM} = \mathcal{L}_{Gauge}(A_i, \psi_i) + \mathcal{L}_{Higgs}(\Phi, \psi_i, v)$$

$|V_{us}| \approx 0.2, |V_{cb}| \approx 0.04, |V_{ub}| \approx 0.004$ versus $g_s \approx 1, g \approx 0.6, g' \approx 0.3$

  - Approximate symmetries (Froggatt -Nielsen)
  - Geometry in extra dimensions (Randall-Sundrum)

- **Ambiguity of new physics scale from flavour data**

$$\mathcal{L} = \mathcal{L}_{Gauge} + \mathcal{L}_{Higgs} + \sum_i \frac{c_i^{New}}{\Lambda_{\rm NP}} \mathcal{O}_i^{(5)} + \ldots$$

Implications of the latest measurements of $B_s \to \mu\mu$

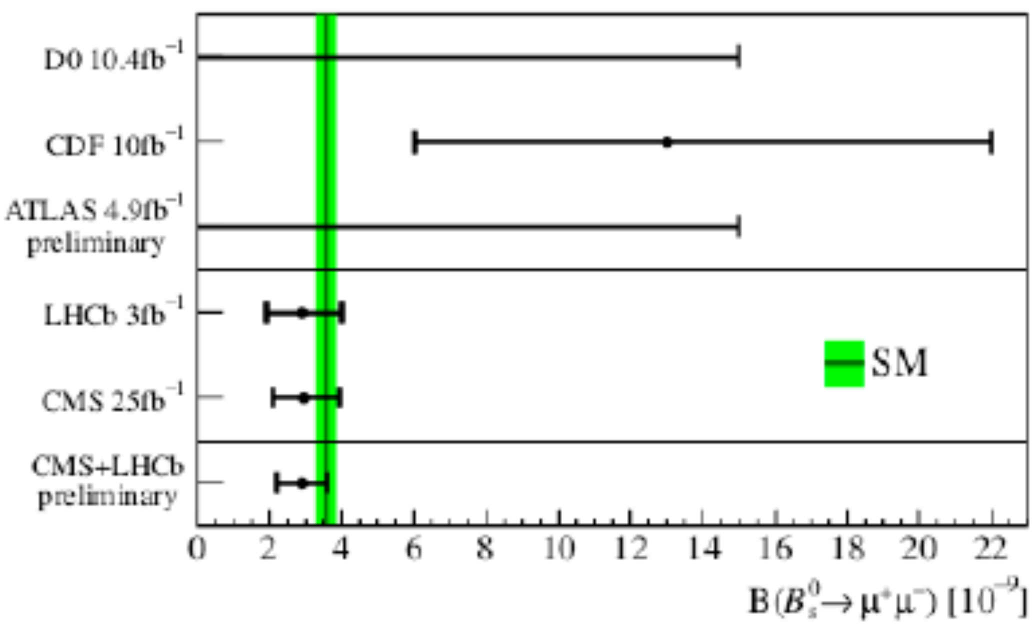
Implications of the latest measurements of $B_s \to \mu\mu$

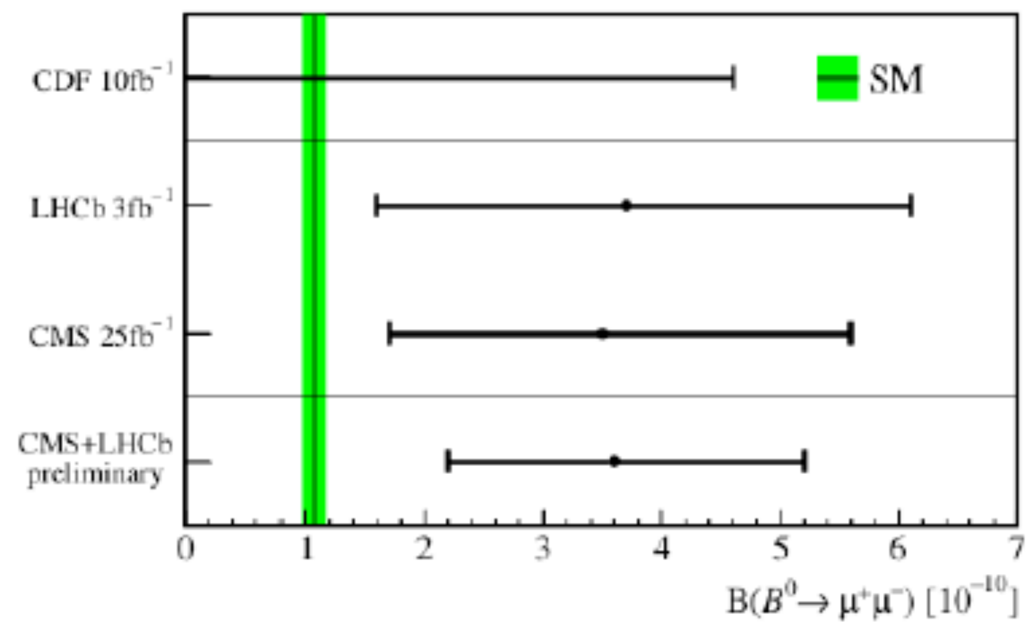
new @ EPS2013

Observation:

$$\mathrm{BR}(B_s \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$

$$\mathrm{BR}(B^0 \to \mu^+\mu^-) = 3.6^{+1.6}_{-1.4} \times 10^{-10}$$





LHCb-CONF-2013-012, CMS-PAS-BPH-13-007

Recent theory effort to eliminate perturbative uncertainties of 7%

NLO QCD corrections — Buchalla,Buras 1999, Misiak, Urban1999

→ NNLO QCD corrections — Hermann,Misiak,Steinhauser arXiv:1311.1347

Leading-m_t NLO electroweak corrections — Buchalla,Buras 1998

→ NLO electroweak corrections — Bobeth,Gorbahn.Stamou arXiv:1311.1348

Experiment versus Theory

$$\overline{\mathcal{B}}_{s\mu}{}^{\rm exp} = (2.9 \pm 0.7) \times 10^{-9}$$
$$\overline{\mathcal{B}}_{s\mu}{}^{\rm th} = (3.65 \pm 0.23) \times 10^{-9}$$

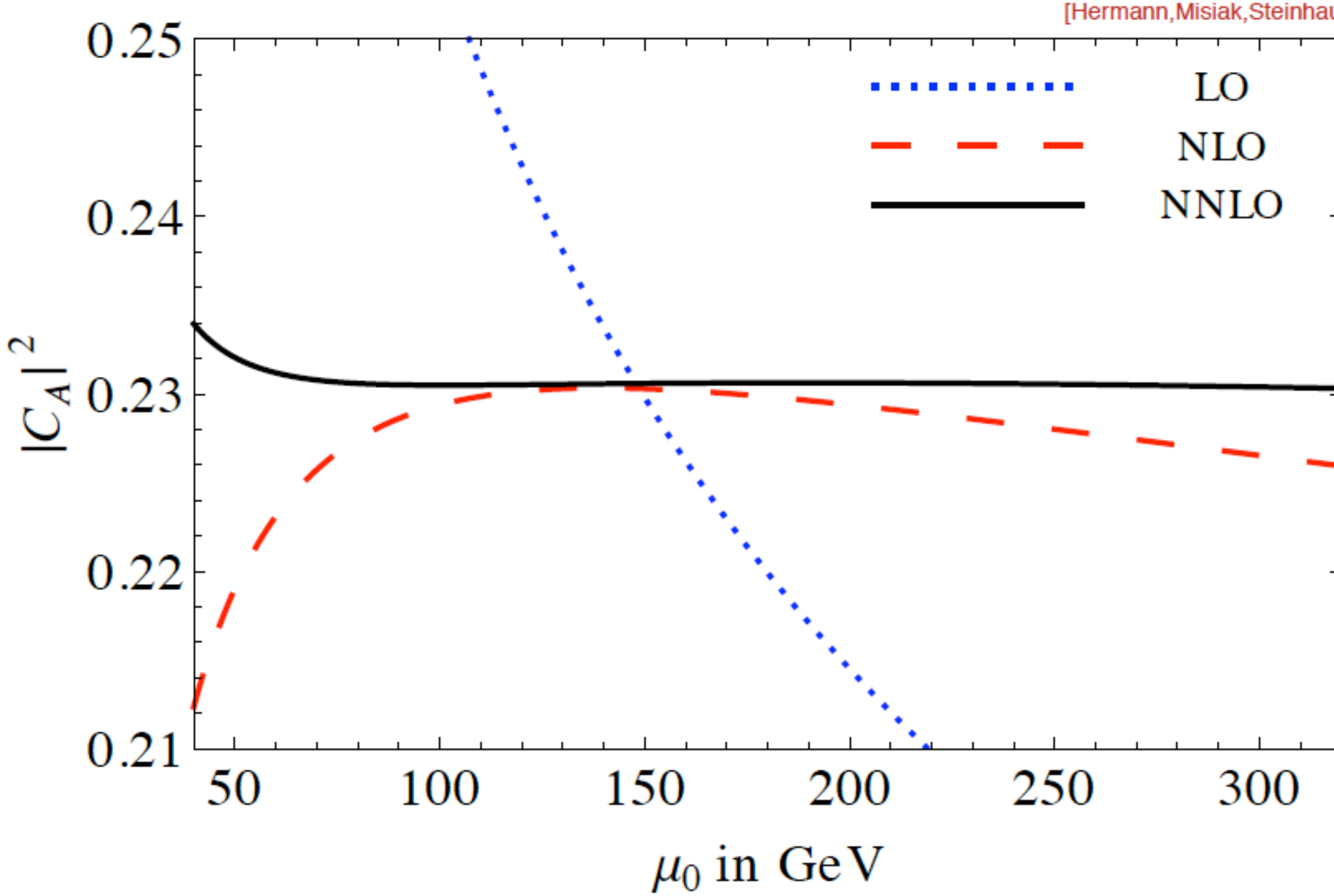
$$\overline{\mathcal{B}}_{d\mu}{}^{\rm exp} = (3.6^{+1.6}_{-1.4}) \times 10^{-10}$$
$$\overline{\mathcal{B}}_{d\mu}{}^{\rm th} = (1.06 \pm 0.09) \times 10^{-10}$$

Error budget:

	f_{B_s}	CKM	τ_H^s	M_t	α_s	other param.	non-param.	$\sum$
$\overline{\mathcal{B}}_{s\ell}$	4.0%	4.3%	1.3%	1.6%	0.1%	$<$ 0.1%	1.5%	6.4%

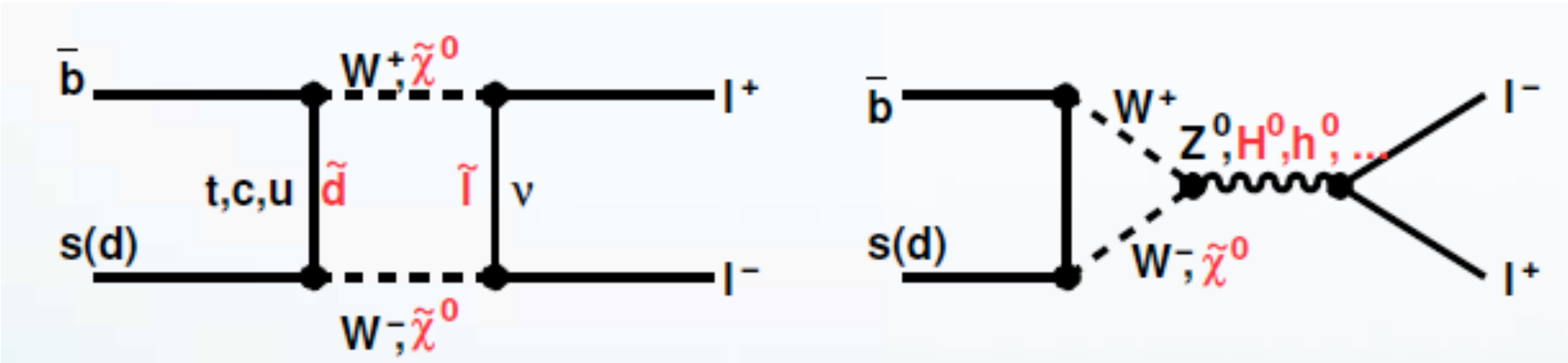
Scale dependence:

[Hermann,Misiak,Steinhauser'13]



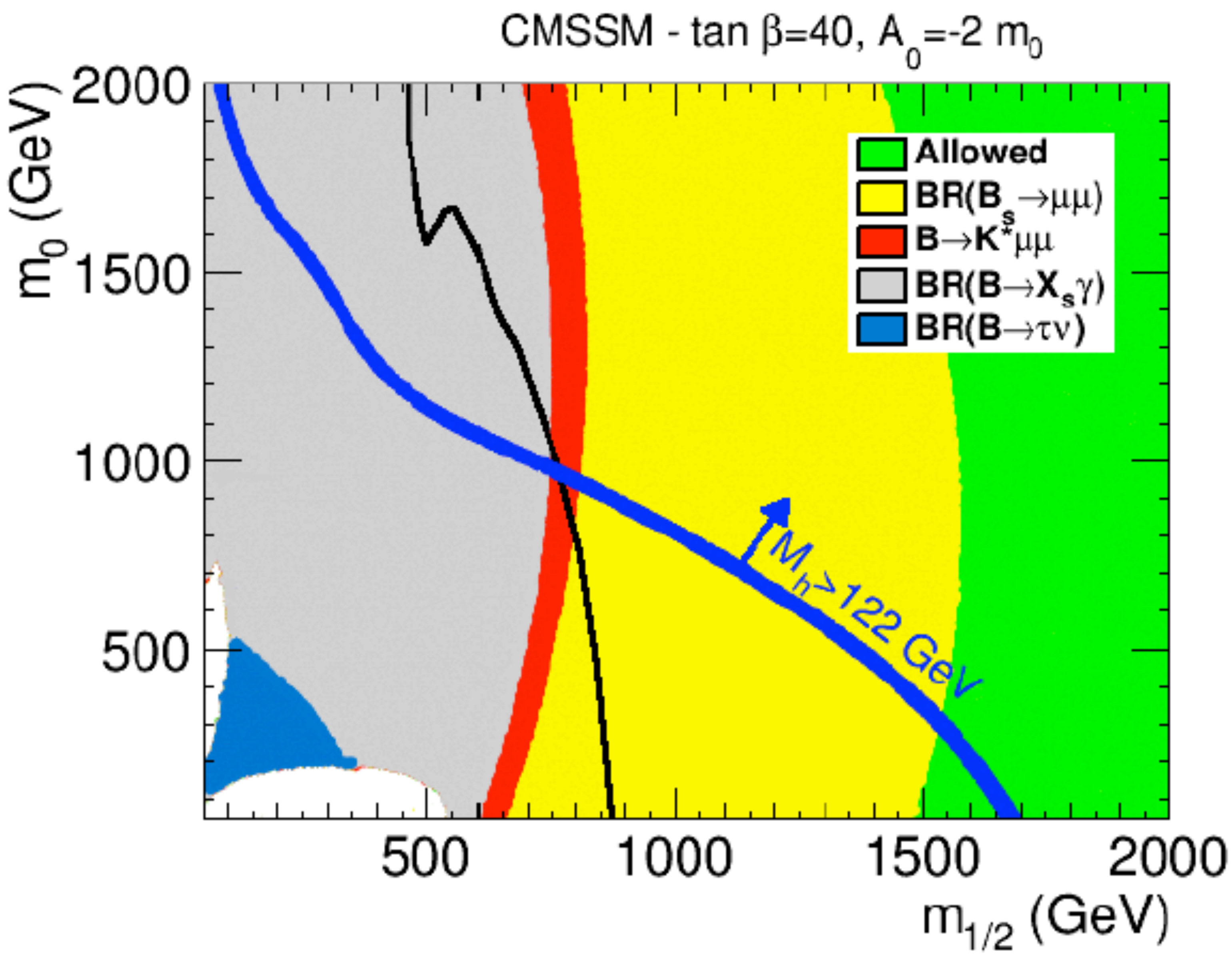
Implications of the latest measurements of $B_s \to \mu\mu$

$$A_{\mathsf{SM}} \sim m_\mu / m_b \Leftrightarrow A_{H^0,A^0} \sim \tan^3 \beta$$



Constraints on CMMSM

Mahmoudi,Neshatpour,Virto arXiv:1401.2145



Black line correponds to direct search: ATLAS with $20.3 fb^{-1}$

Constraints on CMMSM

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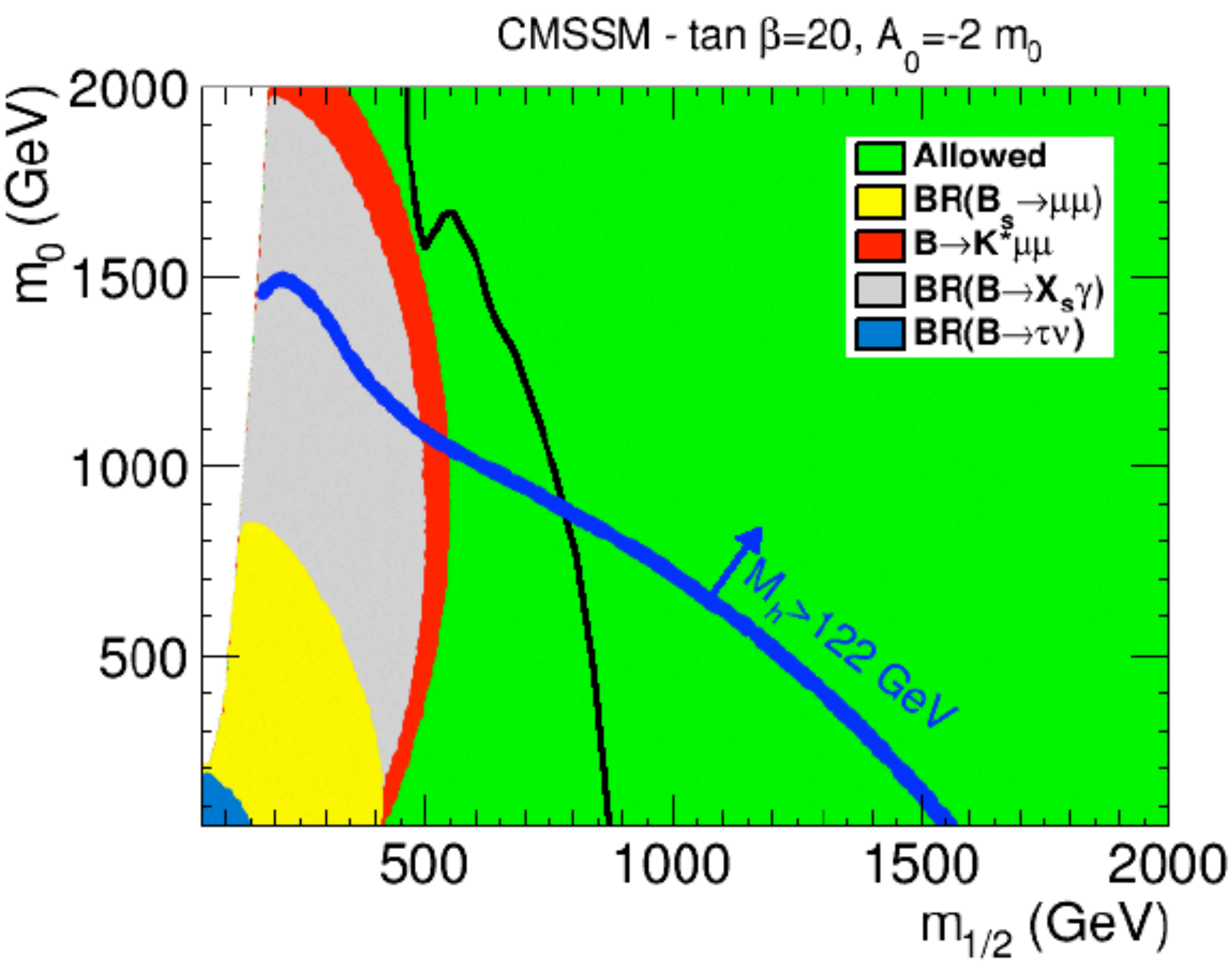
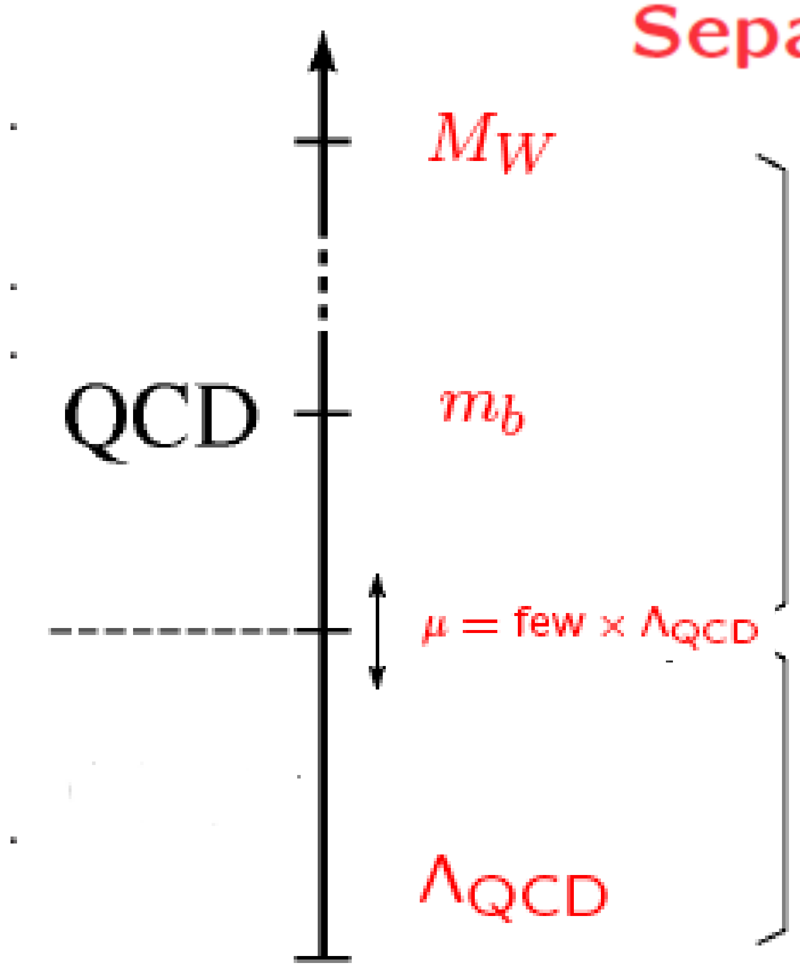


Black line correponds to direct search: ATLAS with $20.3 fb^{-1}$

Radiative and semileptonic penguin decays

Separation of new physics and hadronic effects



short-distance physics
perturbative

long-distance physics
nonperturbative

Operator product expansion: Factorization of short- and long-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 $\mathcal{O}_i(\mu = m_b)$?

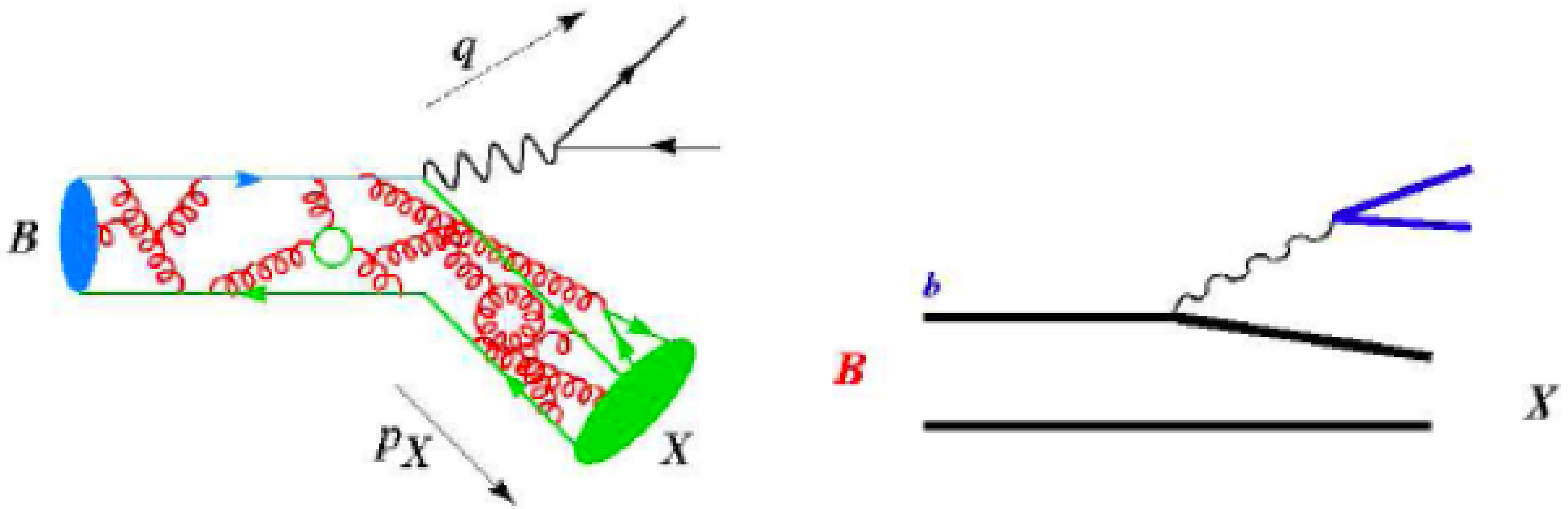
How to compute the hadronic matrix elements $\mathcal{O}_i(\mu = m_b)$?

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

- Heavy mass expansion for inclusive modes:

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

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



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

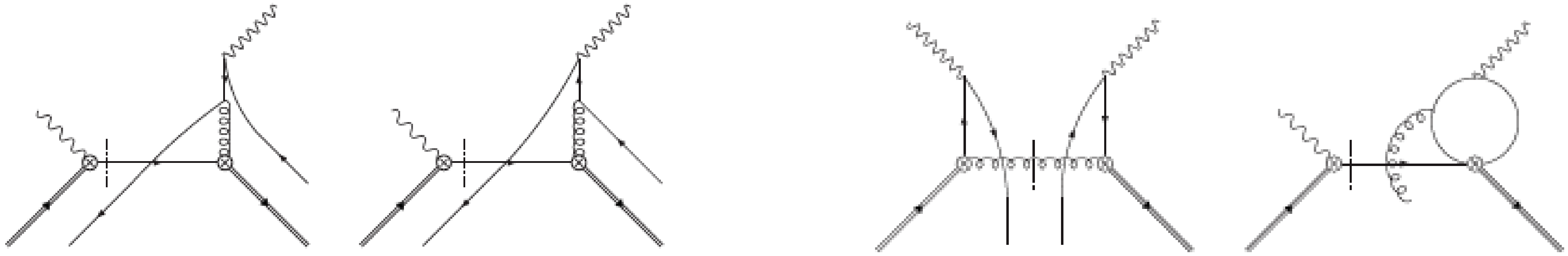
An old story:

- If one goes beyond the leading operator ($\mathcal{O}_7$, $\mathcal{O}_9$):
  breakdown of local expansion

A dedicated analysis:

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

Benzke,Lee,Neubert,Paz,arXiv:1003.5012

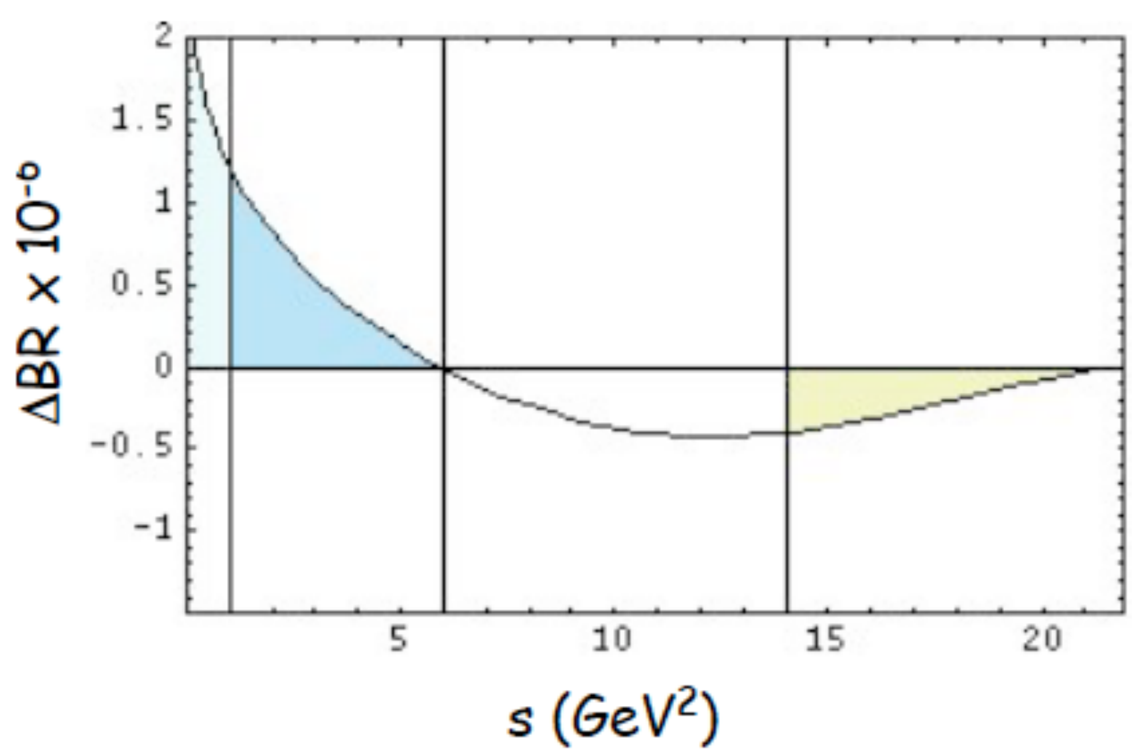


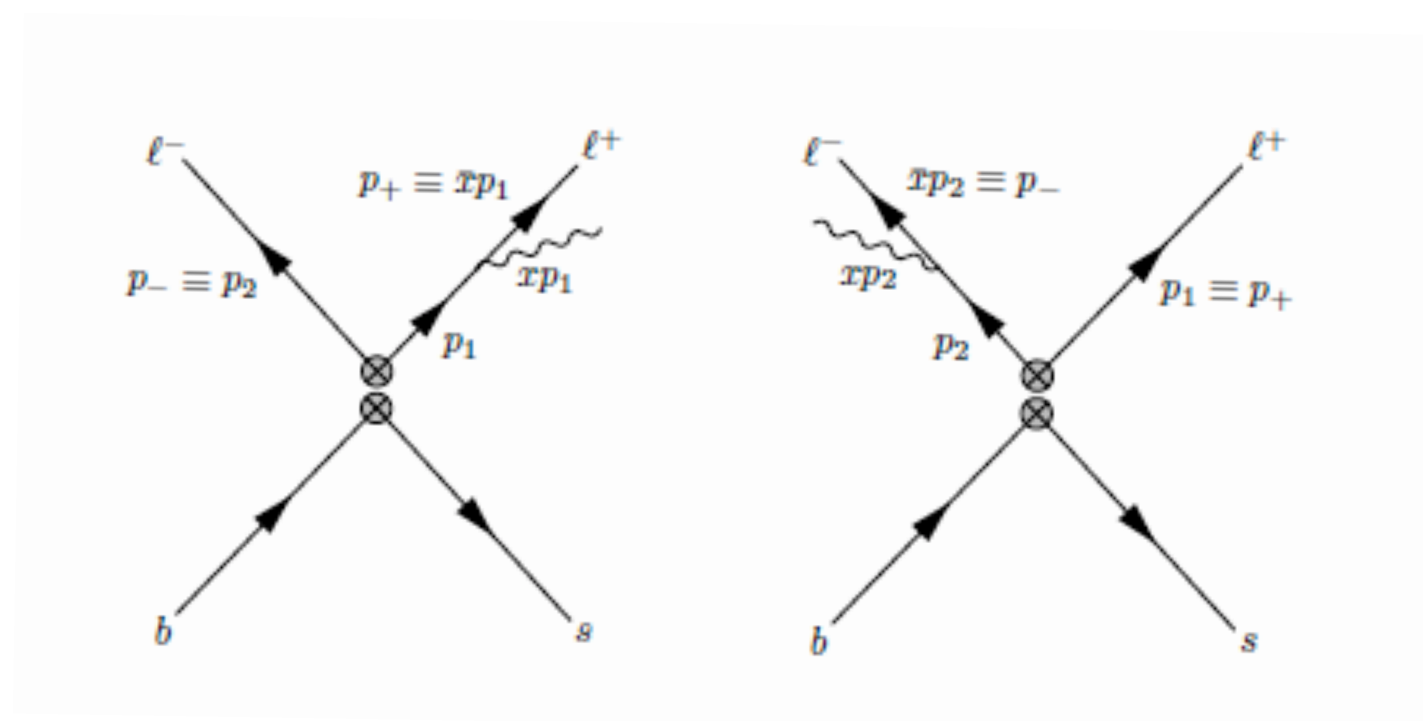
Latest improvements of inclusive $\bar{B} \to X_s \ell^+ \ell^-$

Beyond existing NNLL QCD precision electromagnetic corrections were calculated: Huber,Hurth,Lunghi,Nucl.Phys.B802(2008)40 and work in progress

Corrections to matrix elements lead to large collinear $Log(m_b/m_\ell)$

$$\delta \mathrm{BR}(B \to X_s \mu^+ \mu^-) = \begin{cases} (+2.0\%) & \text{low } q^2 \\ (-6.8\%) & \text{high } q^2 \end{cases} \quad \delta \mathrm{BR}(B \to X_s e^+ e^-) = \begin{cases} (+5.2\%) & \text{low } q^2 \\ (-17.6\%) & \text{high } q^2 \end{cases}$$



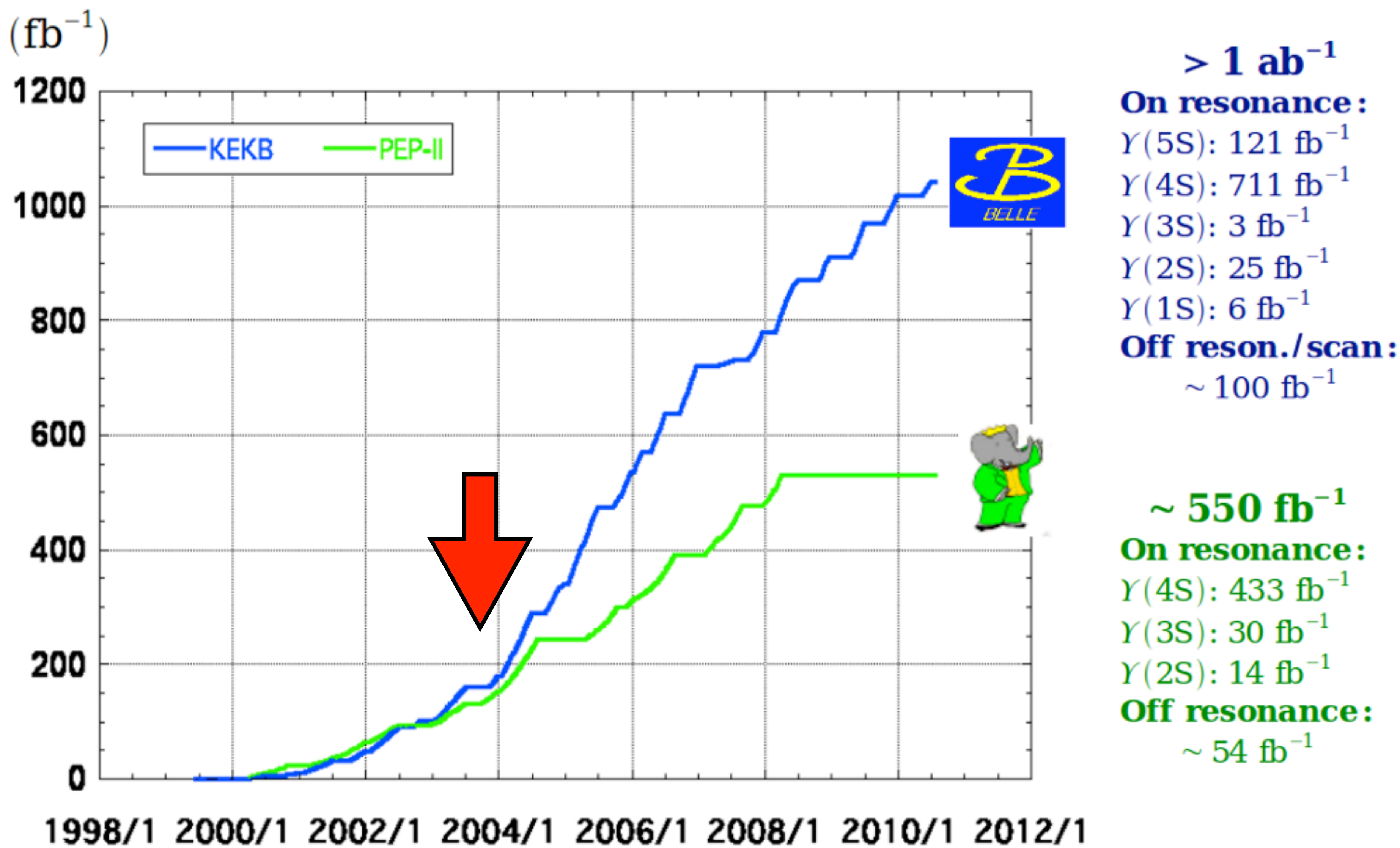


Until very recently:

'Latest' Babar and Belle measurements of inclusive $\mathcal{B}(b \to s\ell\ell)$

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)



Two new analyses from the B factories:

New Babar analysis on dilepton spectrum arXiv:1312.3664

New Belle analysis on AFB arXiv:1402.7134

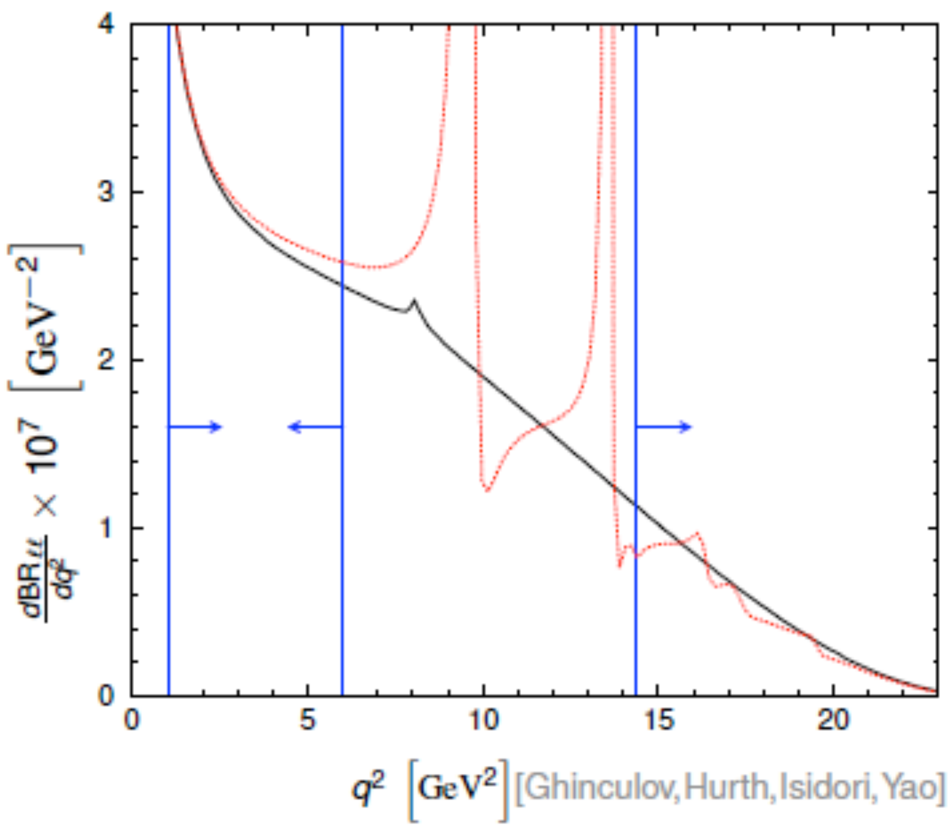
Forthcoming theory analysis including all three independent angular observables ($z = cos\theta$)

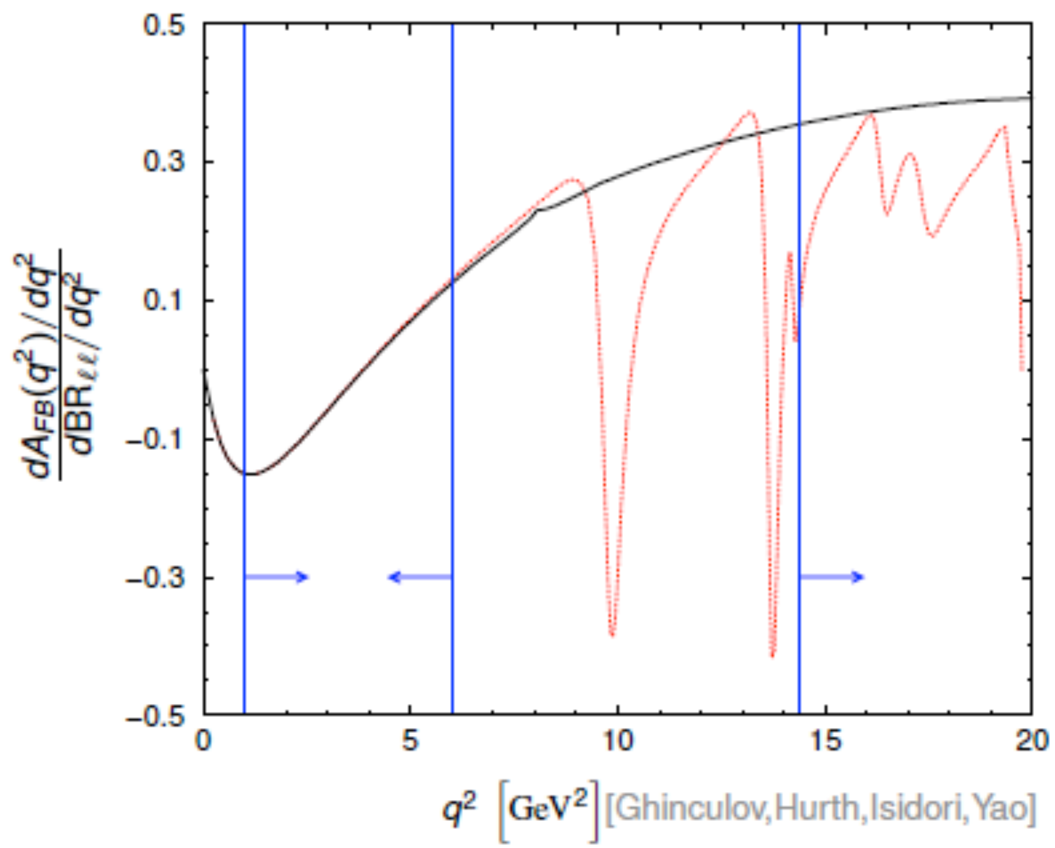
Huber, Hurth, Lunghi

- Observables

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

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





Low-q^2 region: $1\,\mathrm{GeV}^2 < q^2 < 6\,\mathrm{GeV}^2$ High-q^2 region: $q^2 > 14.4\,\mathrm{GeV}^2$

Forthcoming theory analysis including all three independent angular observables ($z = cos\theta$)

Huber, Hurth, Lunghi

- 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_T suppressed in low-q^2 window

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

- Devide low-q^2 bin in two bins (zero of H_A in low-q^2)

- Most important input parameters

$$m_b^{1S} = (4.691 \pm 0.037)\mathrm{GeV}\,, \qquad \overline{m}_c(\overline{m}_c) = (1.275 \pm 0.025)\mathrm{GeV}$$

$$|V_{ts}^* V_{tb}/V_{cb}|^2 = 0.9621 \pm 0.0027\,, \qquad BR^{exp.}_{b\to c\,e\,\nu} = (10.51 \pm 0.13)\,\%$$

- Perturbative expansion (NNLO QCD + NLO QED) α_s $\kappa = \alpha_{\mathrm{em}}/\alpha_s$

$$\begin{aligned} A &= \kappa\left[A_{LO} + \alpha_s A_{NLO} + \alpha_s^2 A_{NNLO} + \mathcal{O}(\alpha_s^3)\right] \\ &+ \kappa^2\left[A_{LO}^{em} + \alpha_s A_{NLO}^{em} + \alpha_s^2 A_{NNLO}^{em} + \mathcal{O}(\alpha_s^3)\right] + \mathcal{O}(\kappa^3) \end{aligned}$$

Forthcoming theory analysis including all three independent angular observables ($z = cos\theta$)

Huber,Hurth,Lunghi

- 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

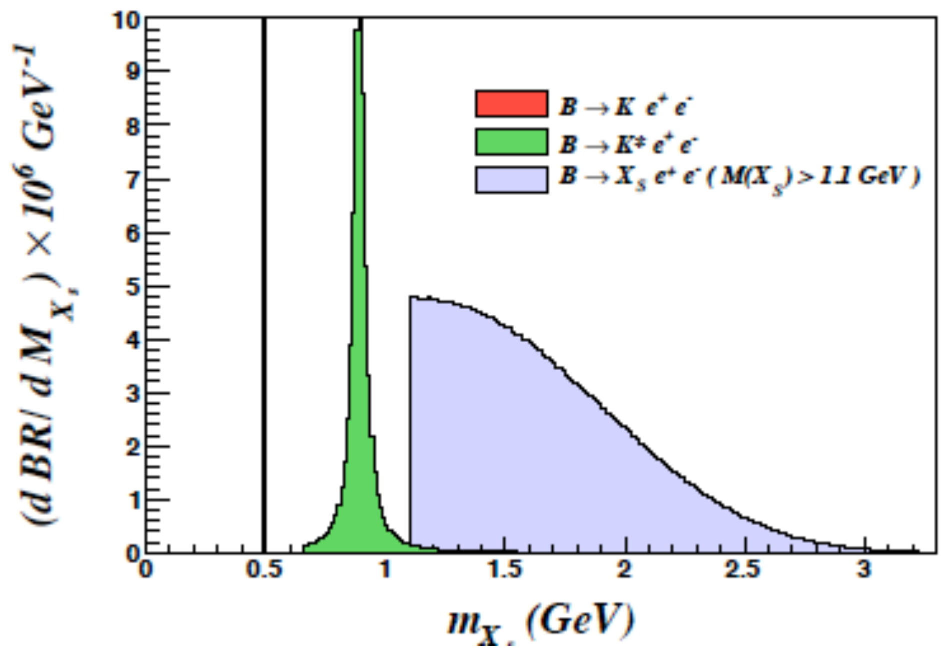
$$\frac{\left[\mathcal{B}_{ee}^{\rm low}\right]_{q=p_{e^+}+p_{e^-}+p_{\gamma_{\rm coll}}}}{\left[\mathcal{B}_{ee}^{\rm low}\right]_{q=p_{e^+}+p_{e^-}}} - 1 = 1.65\% \qquad \frac{\left[\mathcal{B}_{ee}^{\rm high}\right]_{q=p_{e^+}+p_{e^-}+p_{\gamma_{\rm coll}}}}{\left[\mathcal{B}_{ee}^{\rm high}\right]_{q=p_{e^+}+p_{e^-}}}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

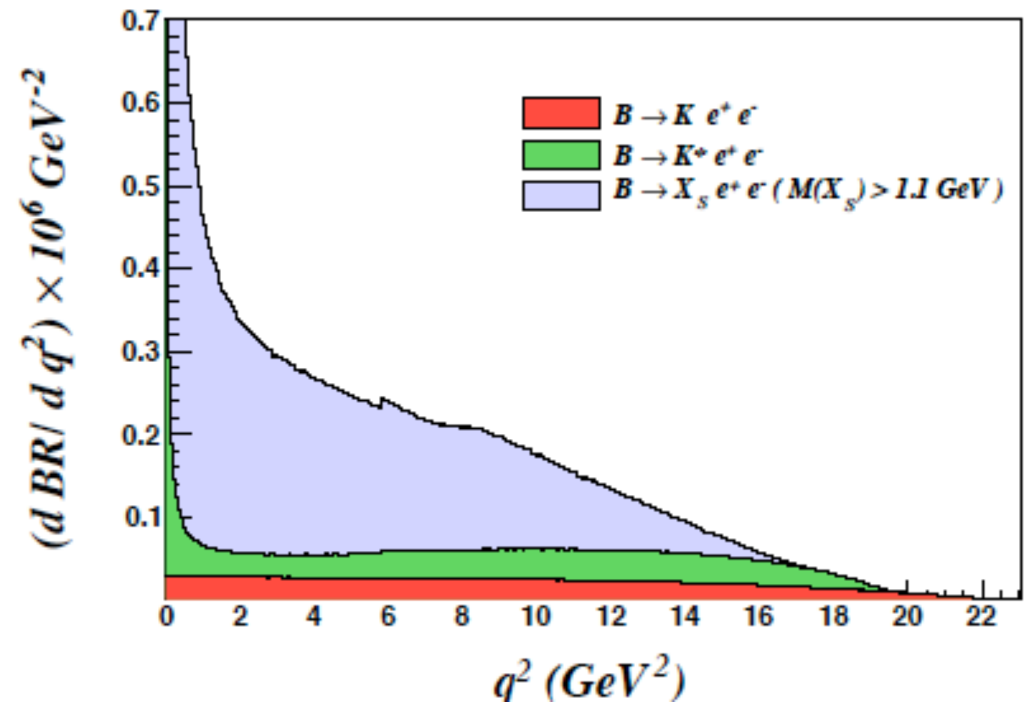
Forthcoming theory analysis including all three independent angular observables ($z = cos\theta$)

Huber,Hurth,Lunghi

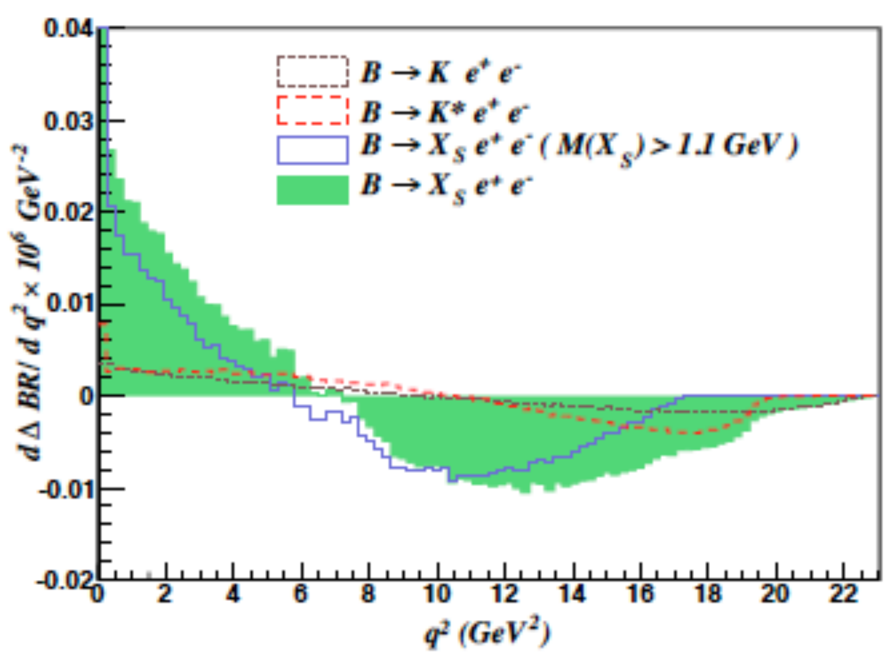
Monte Carlo analysis

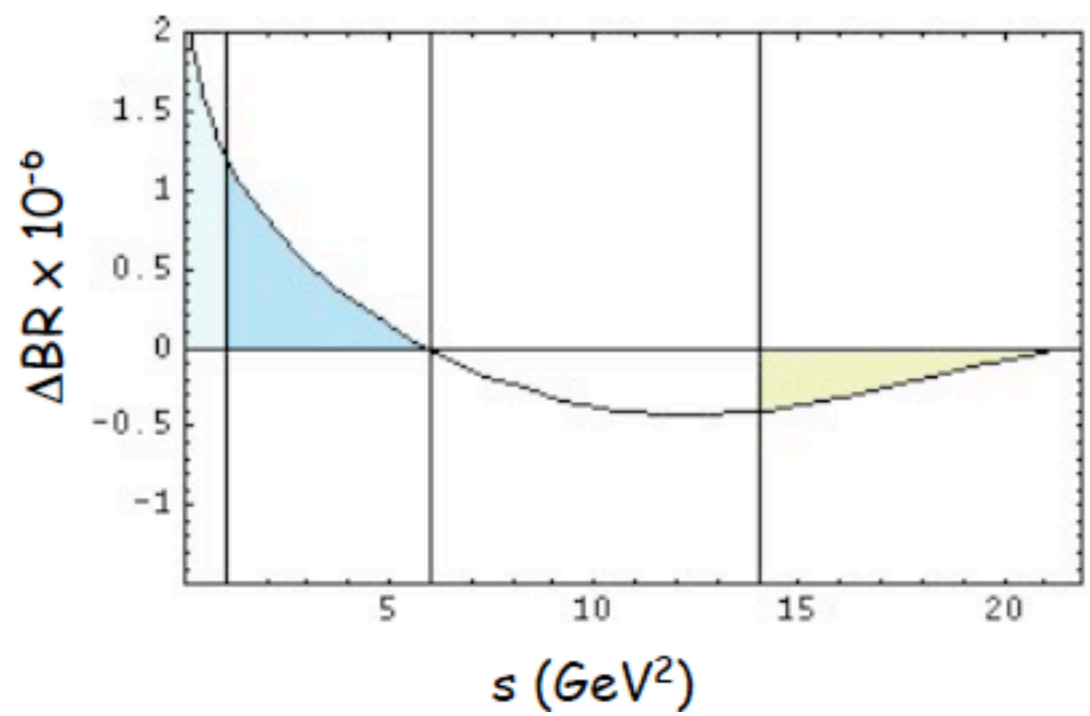
(event generator EVTGEN, hadronization JETSET, EM radiation PHOTOS)





Validation of MC analysis (without Photos)





Forthcoming theory analysis including all three independent angular observables ($z = cos\theta$)

Huber,Hurth,Lunghi

Results

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

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

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

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

Forthcoming theory analysis including all three independent angular observables ($z = cos\theta$) Huber,Hurth,Lunghi

Results

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

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

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

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

Comparison with $B \to K^* \ell\ell$ data >>>

Further refinement

- 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 (preliminary)

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

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

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

Forthcoming theory analysis including all three independent angular observables ($z = cos\theta$)

Huber,Hurth,Lunghi

Further results in units of 10^{-6} (preliminary)

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

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

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

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

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

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

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

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

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

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

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

Exclusive modes $B \to K^* \gamma$ or $B \to K^* \ell^+ \ell^-$

Naive approach:

Parametrize the hadronic matrix elements in terms of form factors

Exclusive modes $B \to K^*\gamma$ or $B \to K^*\ell^+\ell^-$

QCD-improved factorization: BBNS 1999

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

Existence of 'non-factorizable' strong interaction effects

which do *not* correspond to form factors

Exclusive modes $B \to K^*\gamma$ or $B \to K^*\ell^+\ell^-$

QCD-improved factorization: BBNS 1999

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

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

– Relations between formfactors in large-energy limit Charles et al. 1998

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

Phenomenologically highly relevant issue

general strategy of LHCb to look at ratios of exclusive modes

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

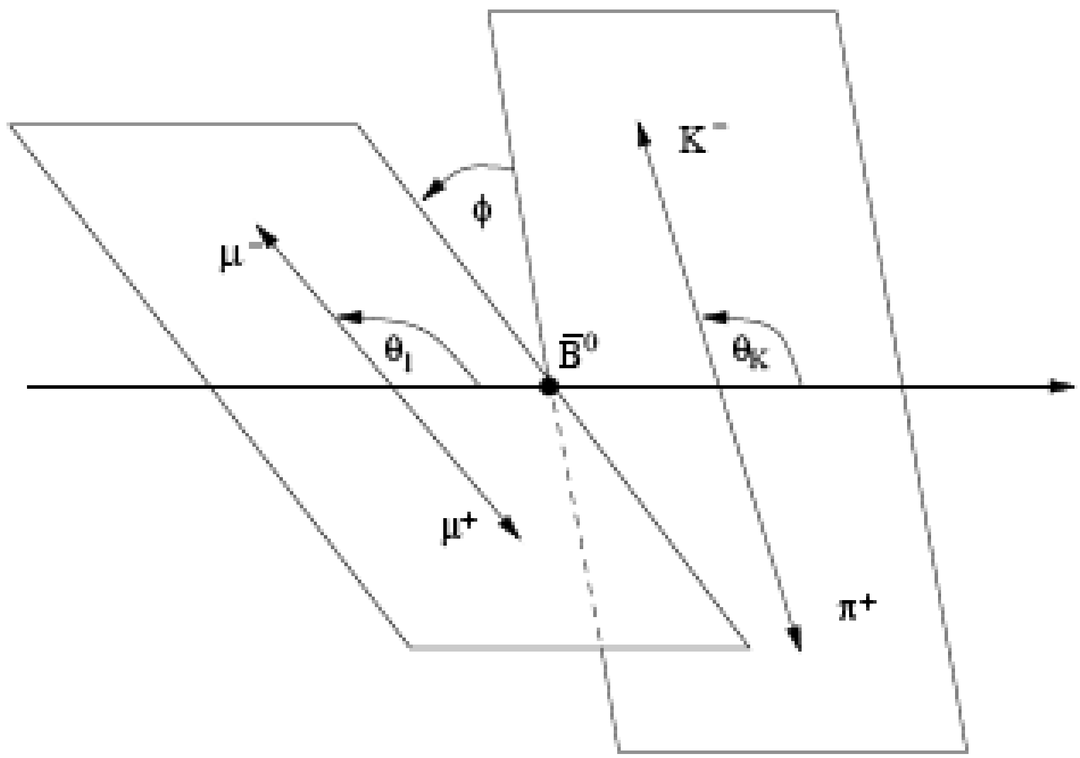
see also Altmannshofer et al.,arXiv:0811.1214; Bobeth et al.,arXiv:0805.2525

Kinematics

- 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.

After summing over the spins of the final particles:

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



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

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

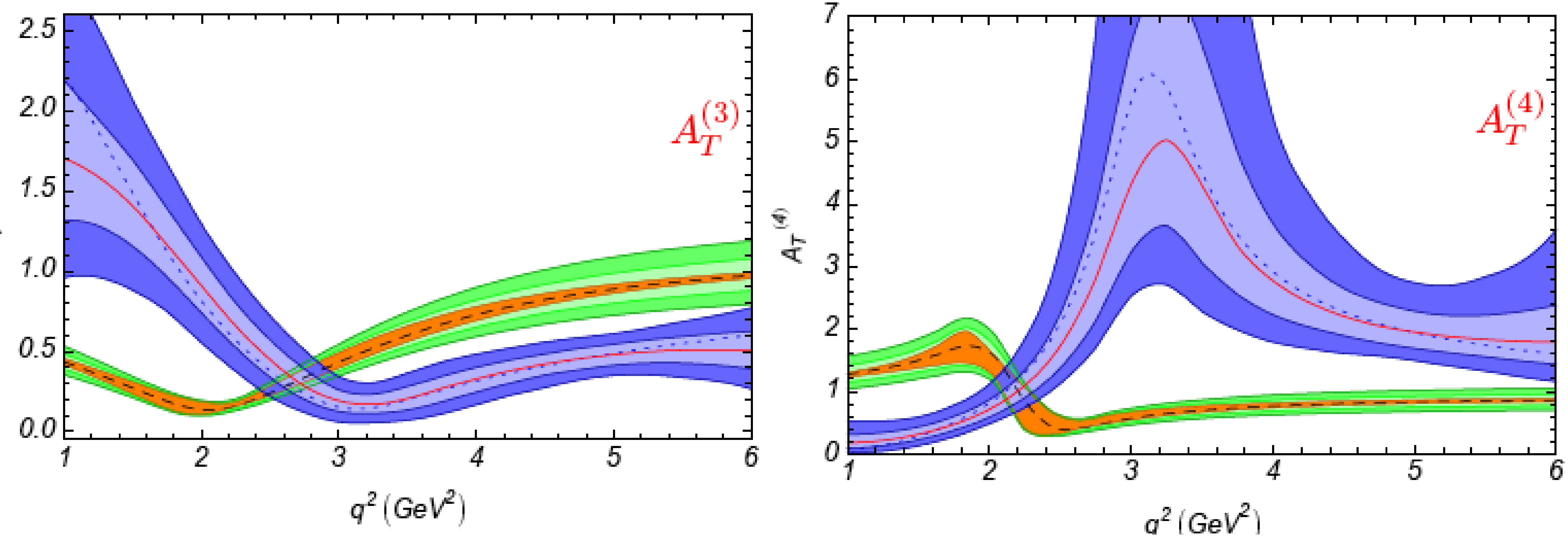
$$J_i = J_i(A_{\perp L/R}, A_{\parallel L/R}, A_{0L/R}) \qquad A_{\perp,\parallel} = (H_{+1} \mp H_{-1})/\sqrt{2}, \quad A_0 = H_0$$

Careful design of theoretical clean angular observables

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

– Dependence of soft form factors, $\xi_\perp$ and $\xi_\parallel$, to be minimized !
  form factors should cancel out exactly at LO, best for all s
– unknown Λ/m_b power corrections

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



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

Careful design of theoretical clean angular observables

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

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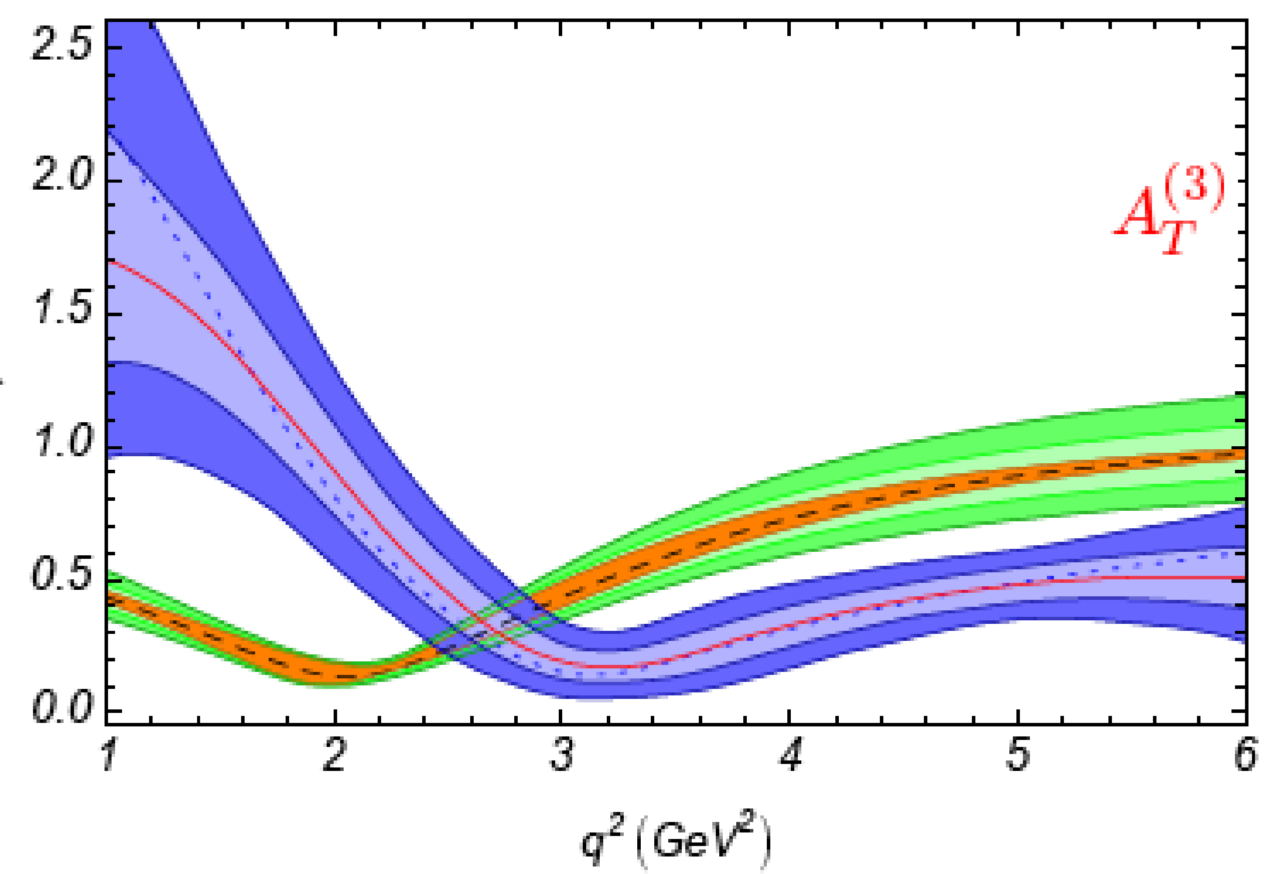
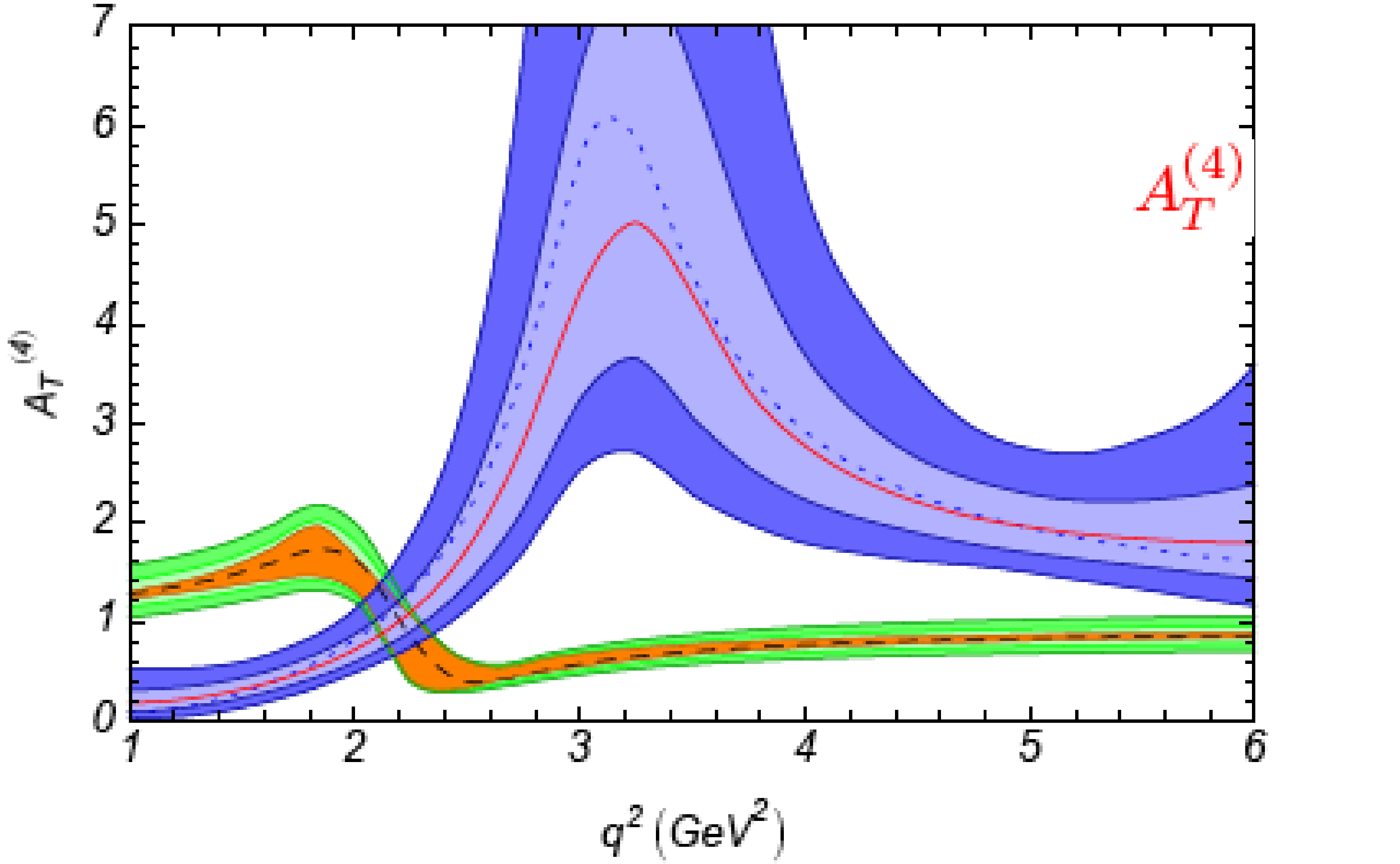




Optimised basis of clean (formfactor-independent) observables: P_i Descotes-Genon, Hurth, Matias, Virto arXiv:1303.5794

Definition of P_5'

$$n_\parallel = \begin{pmatrix} A_\parallel^L \\ A_\parallel^{R*} \end{pmatrix}, \quad n_\perp = \begin{pmatrix} A_\perp^L \\ -A_\perp^{R*} \end{pmatrix}, \quad n_0 = \begin{pmatrix} A_0^L \\ A_0^{R*} \end{pmatrix}$$

$$P_1 = \frac{|n_\perp|^2 - |n_\parallel|^2}{|n_\perp|^2 + |n_\parallel|^2} = \frac{J_3}{2J_{2s}} ,$$

$$P_2 = \frac{\mathrm{Re}(n_\perp^\dagger n_\parallel)}{|n_\parallel|^2 + |n_\perp|^2} = \beta_\ell \frac{J_{6s}}{8J_{2s}} ,$$

$$P_3 = \frac{\mathrm{Im}(n_\perp^\dagger n_\parallel)}{|n_\parallel|^2 + |n_\perp|^2} = -\frac{J_9}{4J_{2s}} ,$$

$$P_4 = \frac{\mathrm{Re}(n_0^\dagger n_\parallel)}{\sqrt{|n_\parallel|^2 |n_0|^2}} = \frac{\sqrt{2} J_4}{\sqrt{-J_{2c}(2J_{2s} - J_3)}} ,$$

$$P_5 = \frac{\mathrm{Re}(n_0^\dagger n_\perp)}{\sqrt{|n_\perp|^2 |n_0|^2}} = \frac{\beta_\ell J_5}{\sqrt{-2J_{2c}(2J_{2s} + J_3)}} ,$$

$$P_6 = \frac{\mathrm{Im}(n_0^\dagger n_\parallel)}{\sqrt{|n_\parallel|^2 |n_0|^2}} = -\frac{\beta_\ell J_7}{\sqrt{-2J_{2c}(2J_{2s} - J_3)}} ,$$

Redefinition:

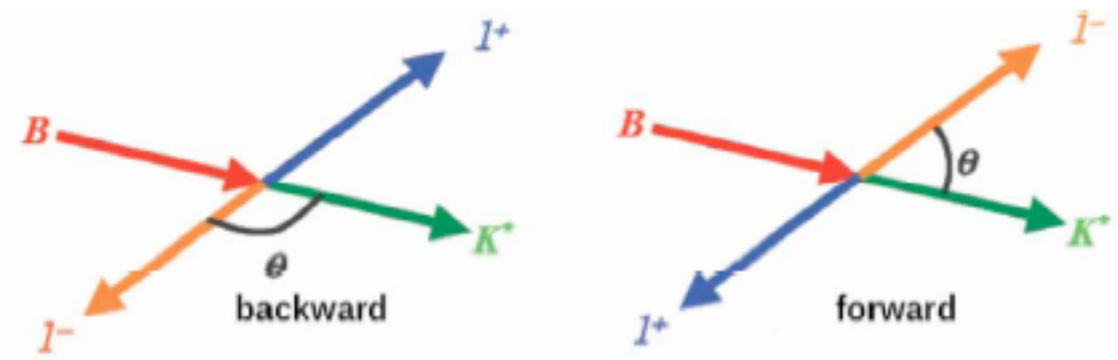
$$P_4' \equiv P_4 \sqrt{1 - P_1} = \frac{J_4}{\sqrt{-J_{2c} J_{2s}}}$$

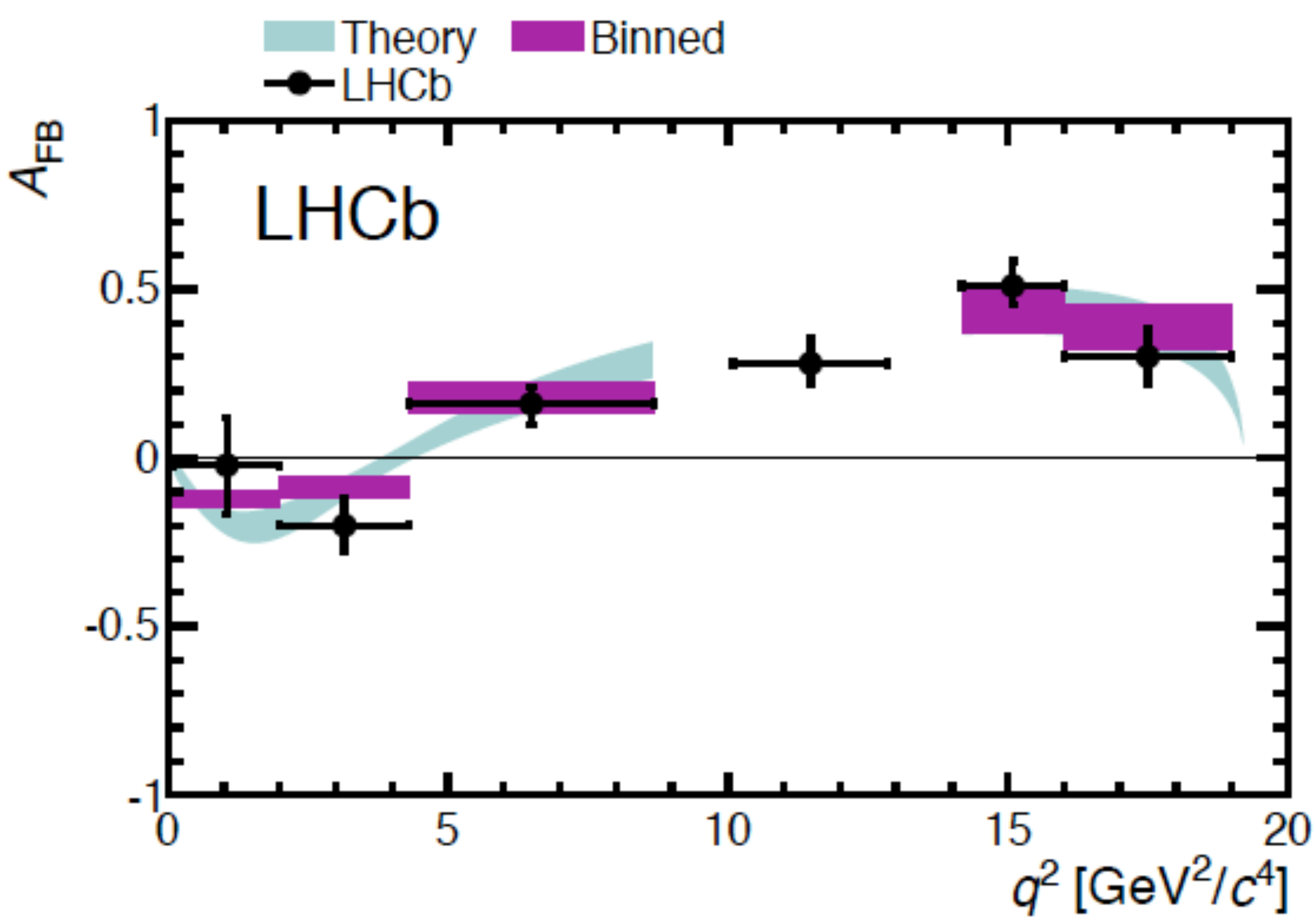
$$P_5' \equiv P_5 \sqrt{1 + P_1} = \frac{J_5}{2\sqrt{-J_{2c} J_{2s}}}$$

$$P_6' \equiv P_6 \sqrt{1 - P_1} = -\frac{J_7}{2\sqrt{-J_{2c} J_{2s}}}$$

Measurements of forward-backward asymmetry in $B \to K^*\mu^+\mu^-$

$$A_{FB}\left(s = m^2_{\mu^+\mu^-}\right) = \frac{N_F - N_B}{N_F + N_B}$$





Excellent agreement with SM at current level of precision.

However:

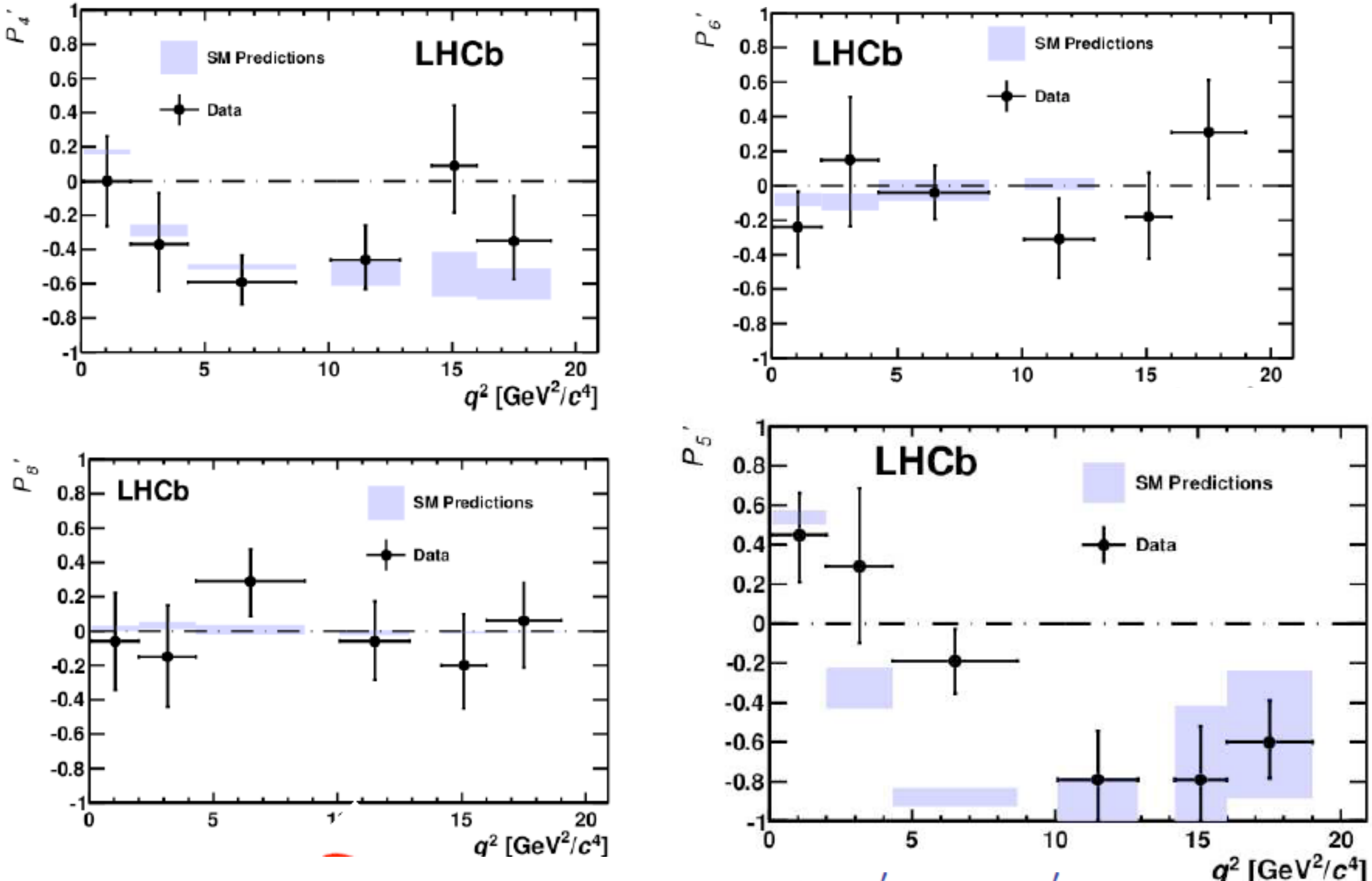
Many more angular observables in $B \to K^*\mu\mu$ to be measured, more sensitive to NP than AFB.

New flavour structures needed !

LHCb arXiv:1304.6325

First measurements of new angular observables

LHCb arXiv:1308.1707

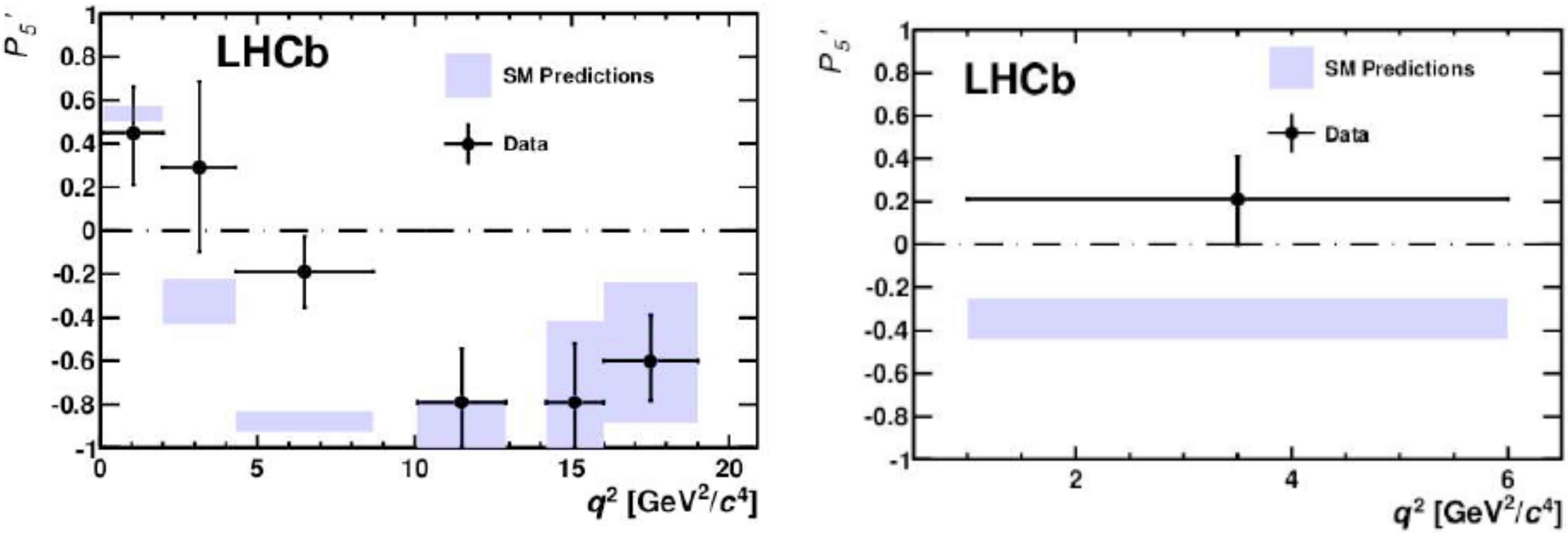


Good agreement with SM in P_4', P_6' and P_8',

but a 4.0σ deviation in the third bin in P_5'

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

First measurements of new angular observables LHCb arXiv:1308.1707



LHCb Anomaly

a statistical fluctuation, an underestimation of Λ/m_b corrections or new physics in C_9 ?

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

LHCb Anomaly

Hurth, Mahmoudi arXiv:1312.5276,1411.2786

- **Power corrections:** No strict theory: $A_i' = A_i(1 + C_i)$, $|C_i|$ 10%

  3% on the observable level: 4.0σ

  More realistic: 10% on the observable level: 3.6σ

  Dimensional estimate, some soft arguments

  Assume 30% : 2.2σ

  Descotes,Matias,Virto arXiv:1307.5683

- **Validity of QCDf and of perturbative description of charm loops:** $[1GeV^2, 6GeV^2]$,
  but local bin is $q^2 \in [4.3, 8.63]GeV^2$

- **Issue of charm loops** Khodjamirian et al. arXiv:1006.4945

  Only soft gluon (but no spectator) contributions included yet

- **Analysis of factorizable power corrections**

Descotes,Hofer,Matias,Virto,arXiv:1407.8526

$$A_2(q^2) = \frac{m_B}{m_B - m_{K^*}} \left[\xi_\perp(q^2) - \xi_\|(q^2)\right] + \Delta A_2^{\alpha_s}(q^2) + \Delta A_2^{\Lambda}(q^2)\,,$$

$$A_0(q^2) = \frac{E}{m_{K^*}}\,\xi_\|(q^2) + \Delta A_0^{\alpha_s}(q^2) + \Delta A_0^{\Lambda}(q^2)\,, \qquad \xi_\|^{(2)}(q^2) \equiv \frac{m_{K^*}}{E} A_0(q^2)$$

Only central value of power corrections fixed

Present error (without knowing the correlations)
in the LCSR calculation of formfactors too large

Nonfactorizable power corrections still open

- **Analysis of factorizable power corrections**

Descotes,Hofer,Matias,Virto,arXiv:1407.8526

$$A_2(q^2) = \frac{m_B}{m_B - m_{K^*}} \left[\xi_\perp(q^2) - \xi_\parallel(q^2)\right] + \Delta A_2^{\alpha_s}(q^2) + \Delta A_2^{\Lambda}(q^2)\,,$$

$$A_0(q^2) = \frac{E}{m_{K^*}}\,\xi_\parallel(q^2) + \Delta A_0^{\alpha_s}(q^2) + \Delta A_0^{\Lambda}(q^2)\,, \qquad \xi_\parallel^{(2)}(q^2) \equiv \frac{m_{K^*}}{E} A_0(q^2)$$

Only central value of power corrections fixed

Present error (without knowing the correlations)
in the LCSR calculation of formfactors too large

Nonfactorizable power corrections still open

- **Suggestions beyond guessing numbers**

Direct calculation of QCD formfactors including correlations

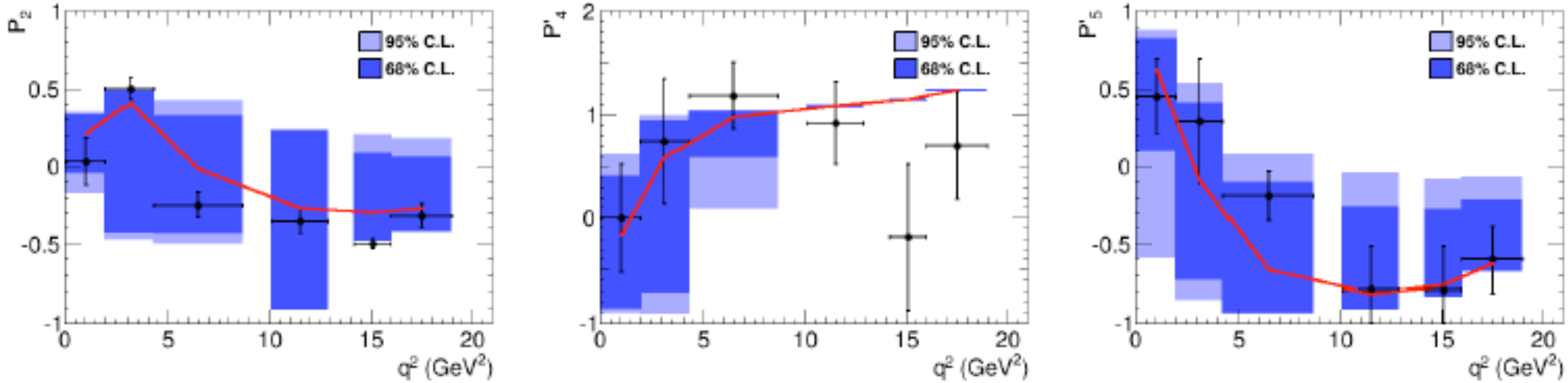
see Altmannshofer et al.,arXiv:0811.1214

Methods used in an analysis of $B \to K\ell\ell$

Kjodjamirian,Mannel,Wang,arXiv:1211.0234

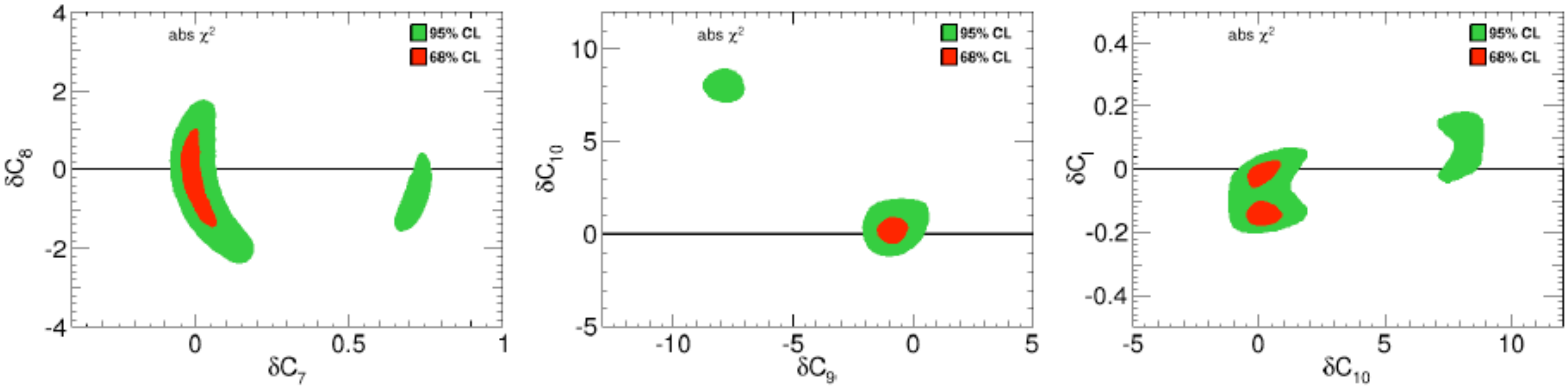
Kjodjamirian et al.,arXiv:1006.4945

- **If new physics (negative C_9 and less significant nontrivial C'_9) then it is compatible with the hypothesis of Minimal Flavour Violation**

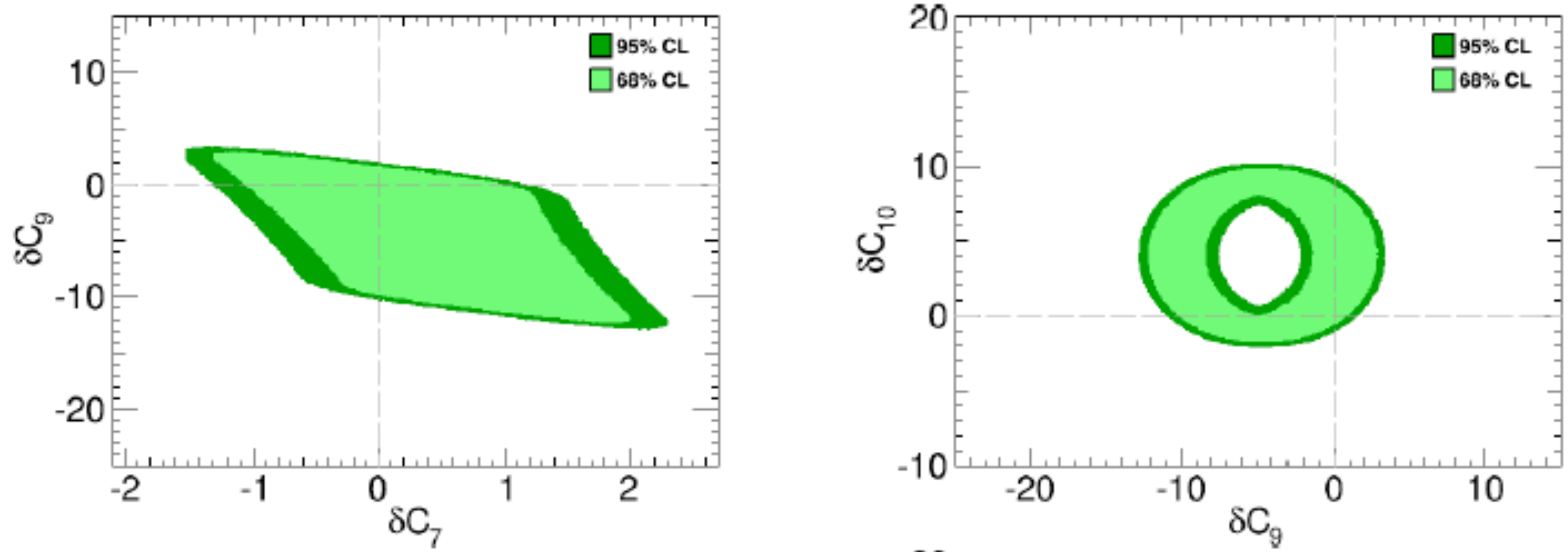


MFV predictions for P_2, P'_4, and P'_5

- **Global fit to the NP contributions δC_i in the MFV effective theory** **(Update)**

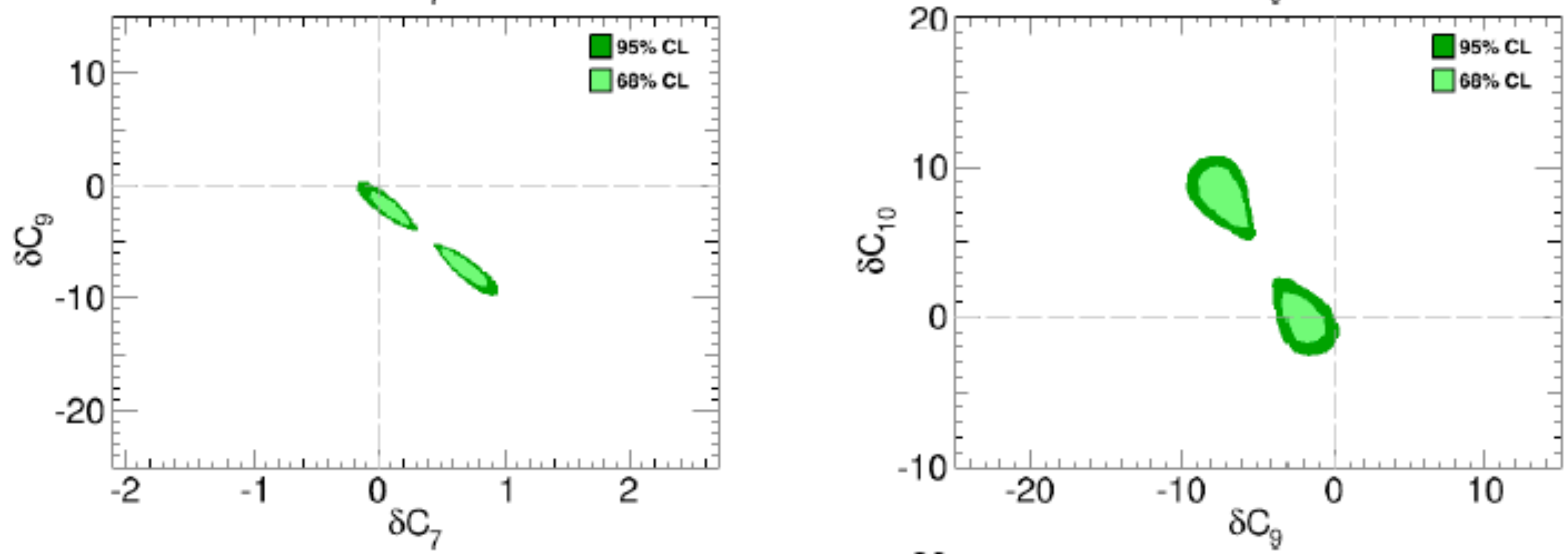


• Crosscheck with Inclusive mode (Update)



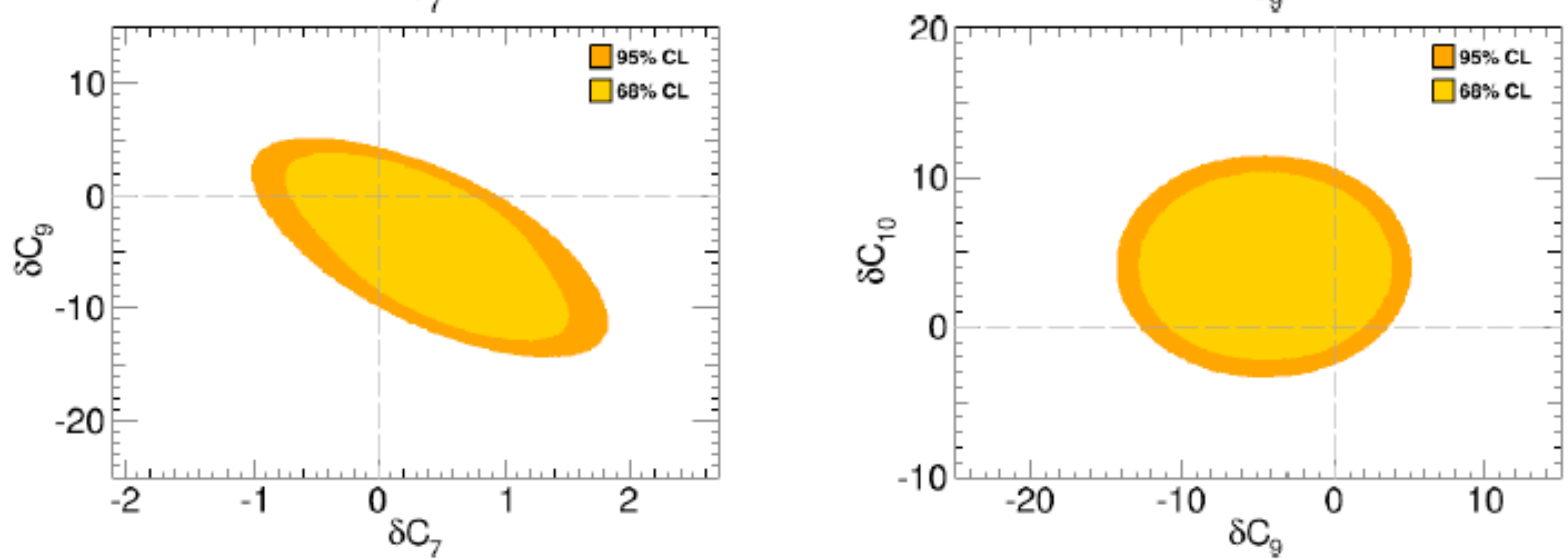
Exclusive observables

$(B \to K\mu^+\mu^-)$



Exclusive observables

$(B \to K^*\mu^+\mu^-)$

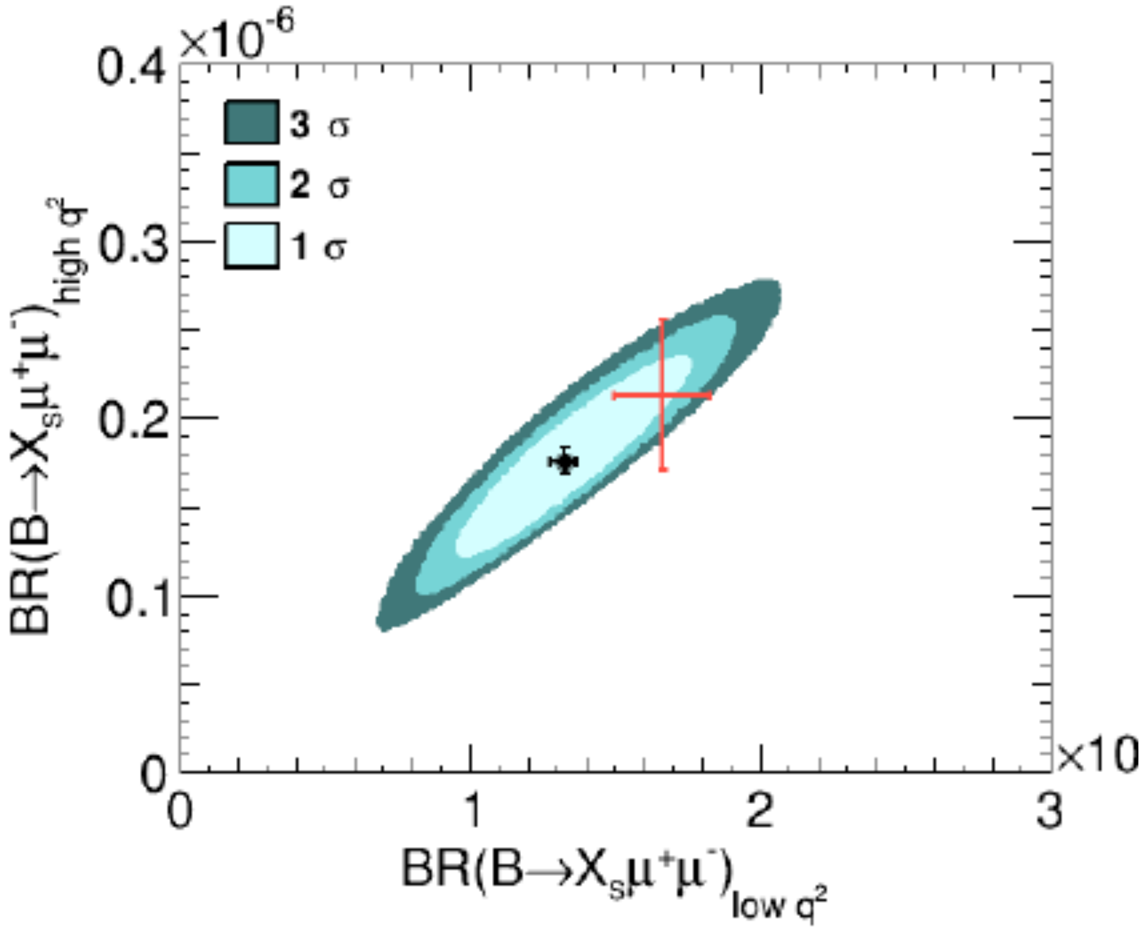


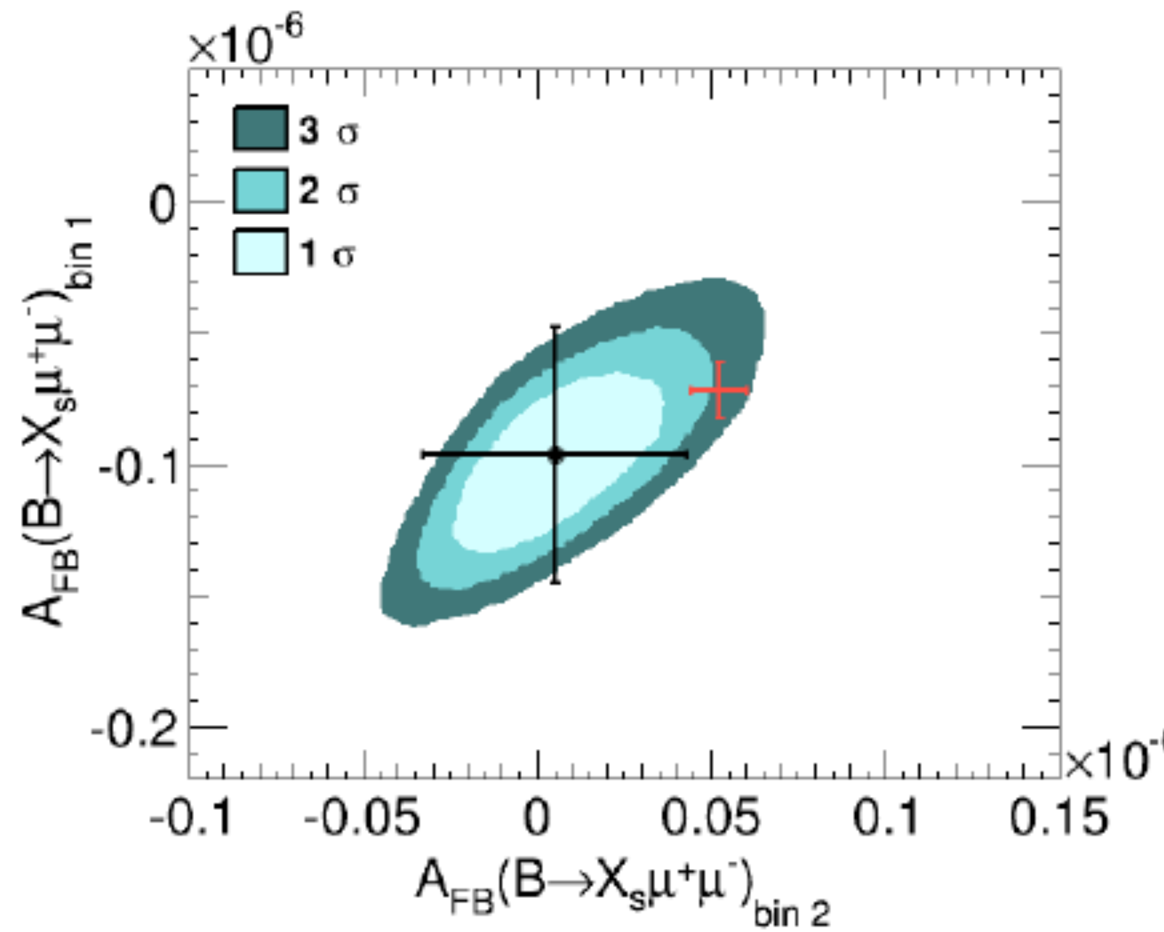
Inclusive observables

- **Future opportunities:** **(Update)**

  LHCb upgrade: $5 fb^{-1}$ to $50 fb^{-1}$

  Super-B Factory Belle-II: $50 ab^{-1}$





- **New physics explanations**
  - "The usual suspects, such as the MSSM, warped extra dimension scenarios, or models with partial compositeness, cannot accommodate the observed deviations ....."

    Gauld, Goertz, Haisch arXiv:1308.1959;1310.1082
    Altmannshofer, Straub arXiv:1308.1501

Coefficient	$1\,\sigma$	$2\,\sigma$	$3\,\sigma$
$\mathcal{C}_7^{\rm NP}$	$[-0.05, -0.01]$	$[-0.06, 0.01]$	$[-0.08, 0.03]$
$\mathcal{C}_9^{\rm NP}$	$[-1.6, -0.9]$	$[-1.8, -0.6]$	$[-2.1, -0.2]$
$\mathcal{C}_{10}^{\rm NP}$	$[-0.4, 1.0]$	$[-1.2, 2.0]$	$[-2.0, 3.0]$
$\mathcal{C}_{7'}^{\rm NP}$	$[-0.04, 0.02]$	$[-0.09, 0.06]$	$[-0.14, 0.10]$
$\mathcal{C}_{9'}^{\rm NP}$	$[-0.2, 0.8]$	$[-0.8, 1.4]$	$[-1.2, 1.8]$
$\mathcal{C}_{10'}^{\rm NP}$	$[-0.4, 0.4]$	$[-1.0, 0.8]$	$[-1.4, 1.2]$

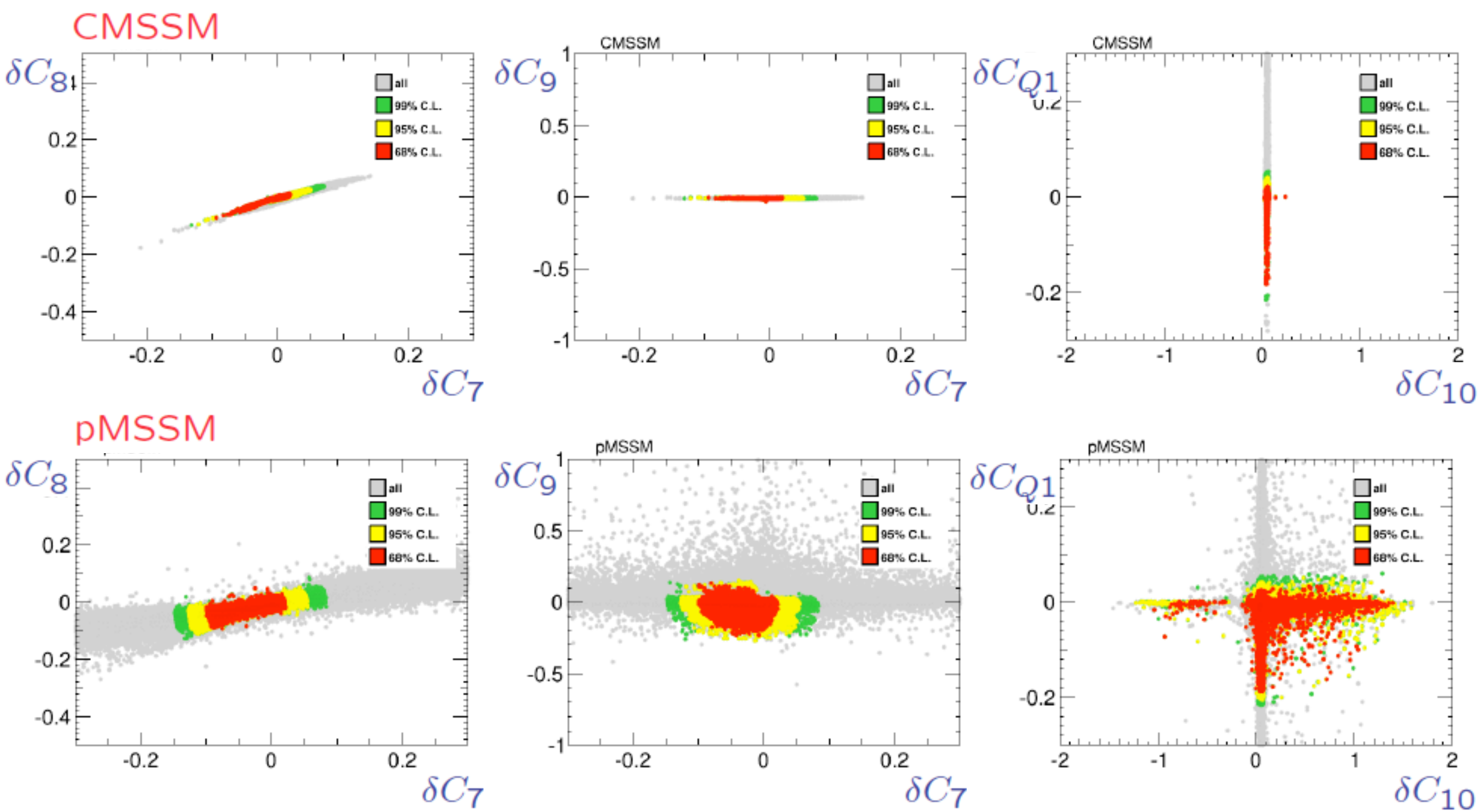
Model-independent analysis Descotes,Matias,Virto arXiv:1307.5683

- 1σ solutions: Z' -models (331-models....): only change C_9

  Descotes,Matias,Virto arXiv:1307.5683
  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

- SUSY are compatible with the anomaly at the 2σ level

  Overall fit at the 1σ level   Mahmoudi, Neshatpour, Virto arXiv:1401.2145



Let us wait for the new LHCb analysis based on the $3fb^{-1}$ data set !

Signs for lepton non-universality ?

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

LHCb; arXiv:1406.6482

2.6σ deviation from SM

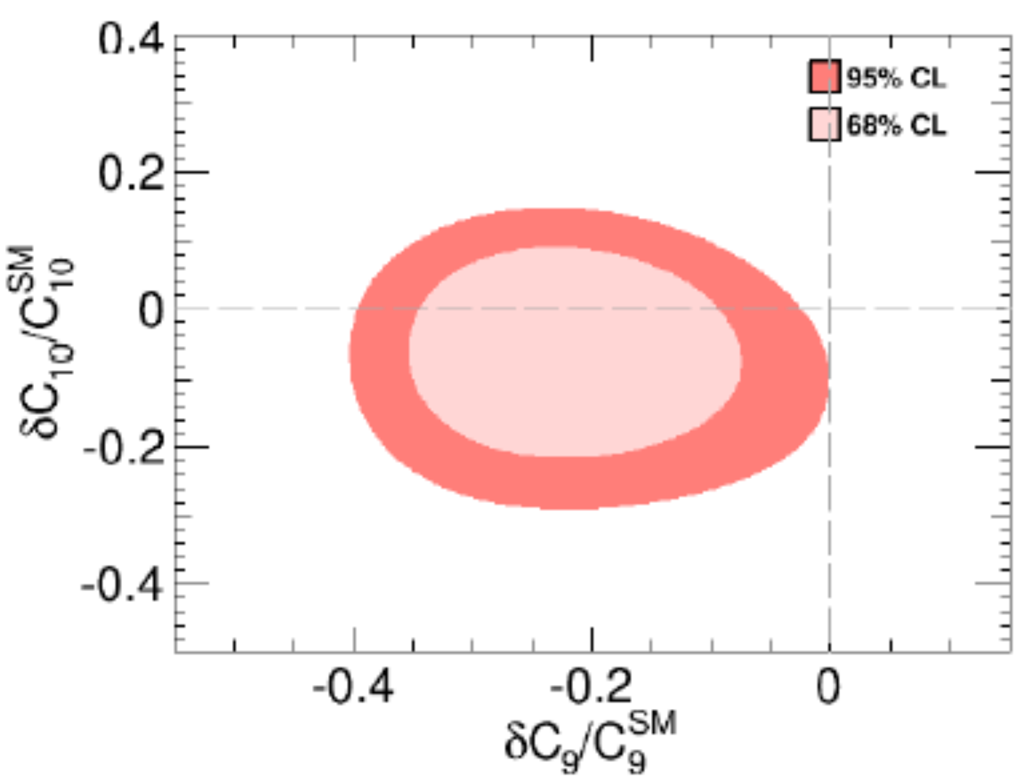
Hiller,Schmaltz; Ghosh et al.; Biswas et al.; Straub et al.;Hurth et al.;Glashow et al.

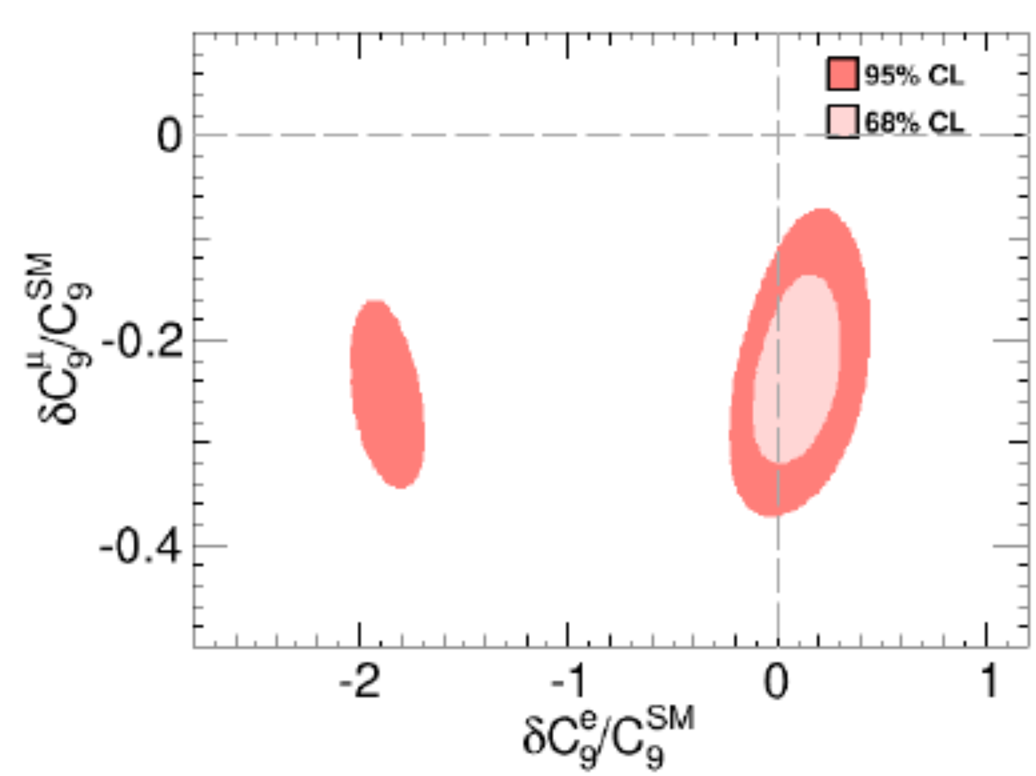
Global fits to the $b \to s\ell\ell$ data

Hurth,Mahmoudi,Neshatpour,arXiv:1410.4545

Fit results for two operators

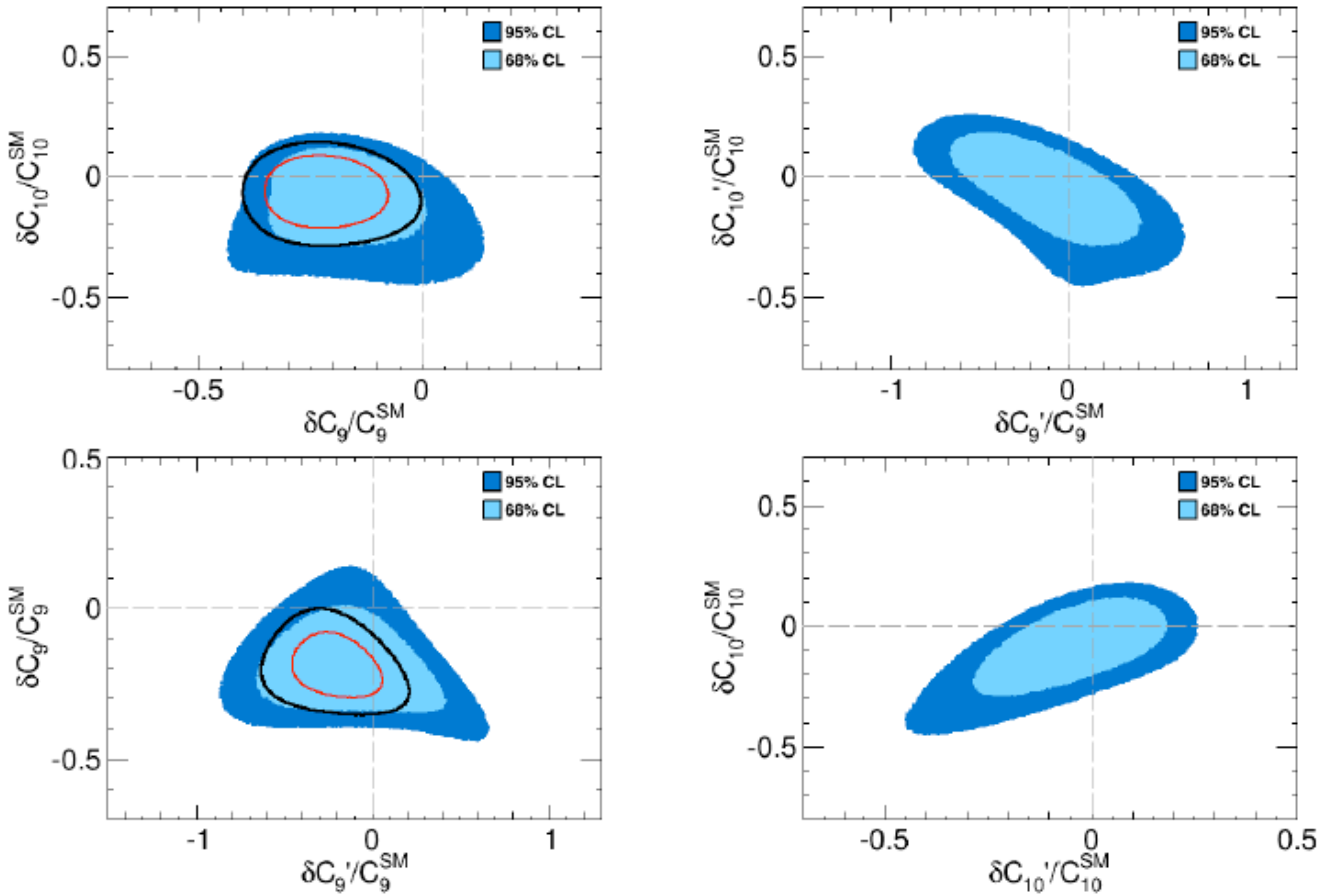
Tensors, scalars difficult, sign for tension in C_9^μ





Fit results for four operators $\{C_9, C_9', C_{10}, C_{10}'\}$

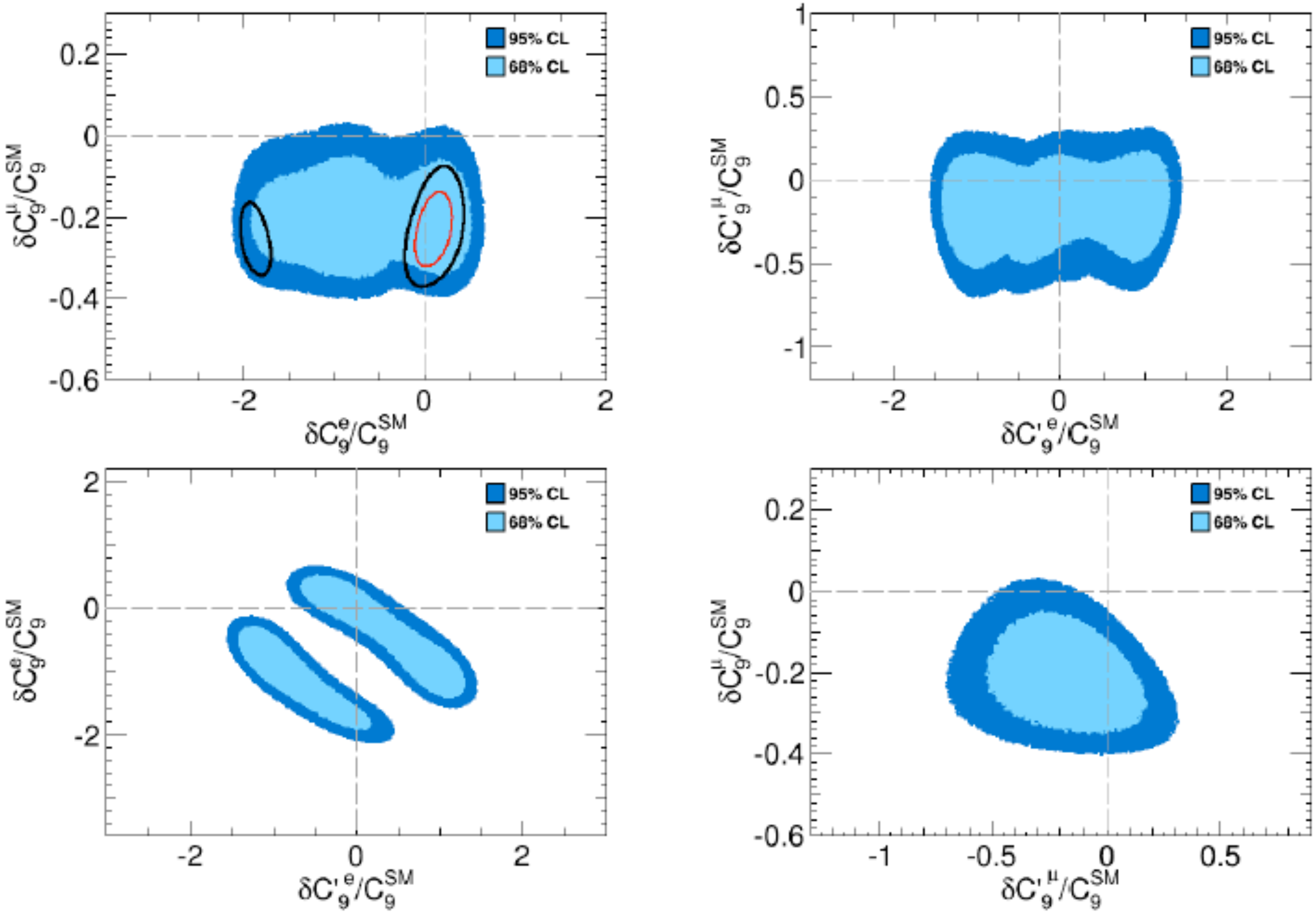
Larger new physics contributions are allowed within 1σ



		$\{C_9, C_9'\}$	$\{C_9, C_{10}\}$	$\{C_9, C_9', C_{10}, C_{10}'\}$
Best fit point:	χ^2 :	52 (52)	52 (52)	51 (50)

Adding $C_{10}^{(\prime)}$ or primed operators does not improve the fit !

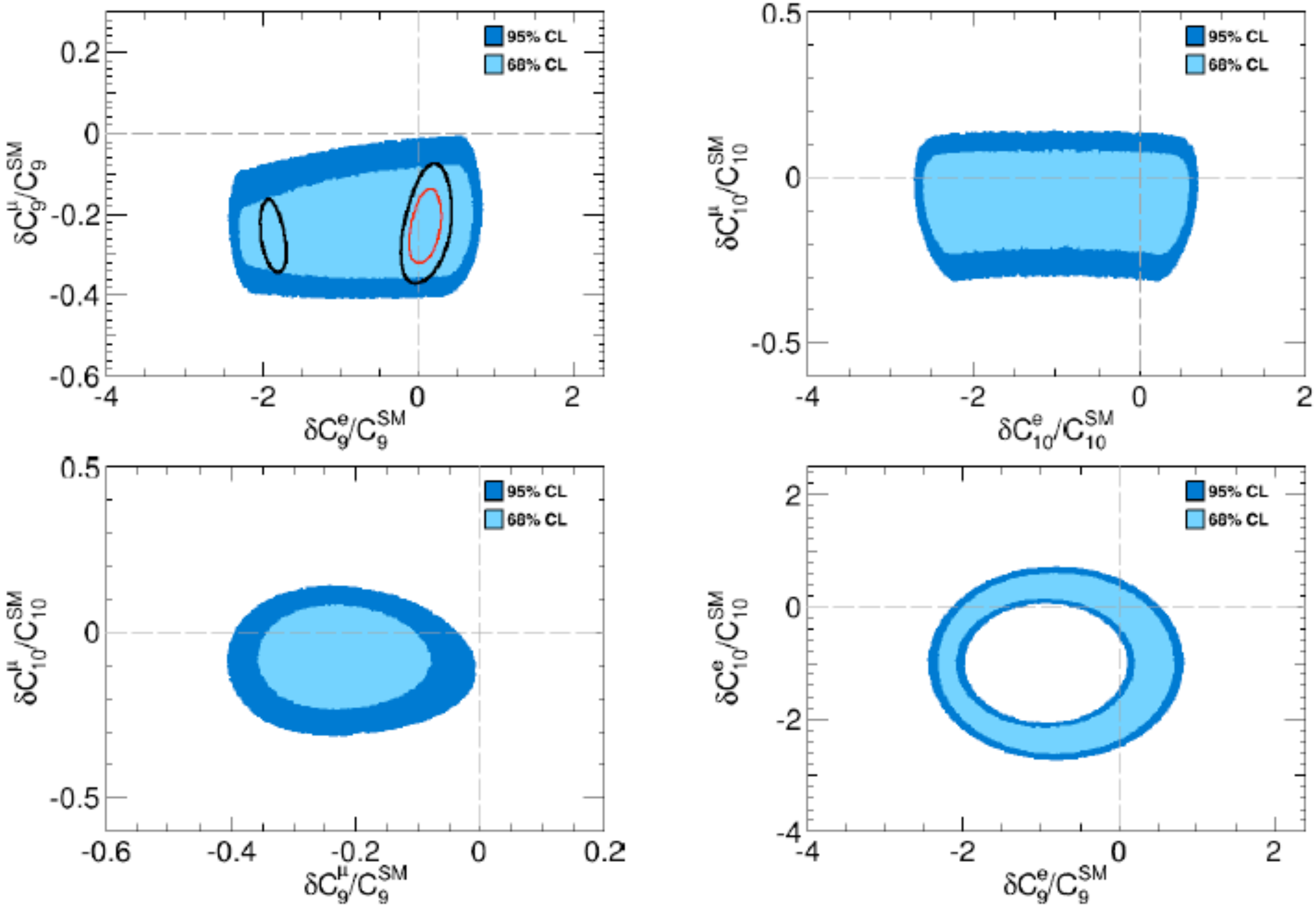
$\{C_9^\mu, C_9'^\mu, C_9^e, C_9'^e\}$ Larger new physics contributions are allowed within 1σ



	$\{C_9, C_9'\}$	$\{C_9^\mu, C_9'^\mu, C_9^e, C_9'^e\}$
Best fit point: χ^2 :	52 (52)	42 (50)

Fit improved by 2.6σ Assuming that this specific four-operator scenario is correct, the one with the two-operators is ruled out by 2.6σ

$\{C_9^\mu, C_9^e, C_{10}^\mu, C_{10}^e\}$ Larger new physics contributions are allowed within 1σ



	$\{C_9, C_{10}\}$	$\{C_9^\mu, C_9^e\}$.	$\{C_9^\mu, C_9^e, C_{10}^\mu, C_{10}^e\}$
χ^2 :	52 (52)	44 (52)	43 (50)

Again χ^2 favours the non-universal extension against the universal one

Correlations between $b \to s\ell\ell$ and $b \to s\nu\bar{\nu}$ Buras et al.,arXiv:1409.4557

Gauge-invariant effective theory:

$$Q_{Hq}^{(1)} = i(\bar{q}_L \gamma_\mu q_L)H^\dagger D^\mu H\,, \qquad Q_{ql}^{(1)} = (\bar{q}_L \gamma_\mu q_L)(\bar{l}_L \gamma^\mu l_L)\,,$$

$$Q_{Hq}^{(3)} = i(\bar{q}_L \gamma_\mu \tau^a q_L)H^\dagger D^\mu \tau_a H\,, \quad Q_{ql}^{(3)} = (\bar{q}_L \gamma_\mu \tau^a q_L)(\bar{l}_L \gamma^\mu \tau_a l_L)\,,$$

$$Q_{Hd} = i(\bar{d}_R \gamma_\mu d_R)H^\dagger D^\mu H\,, \qquad Q_{dl} = (\bar{d}_R \gamma_\mu d_R)(\bar{l}_L \gamma^\mu l_L)\,,$$

$$Q_{de} = (\bar{d}_R \gamma_\mu d_R)(\bar{e}_R \gamma^\mu e_R)\,, \qquad Q_{qe} = (\bar{q}_L \gamma_\mu q_L)(\bar{e}_R \gamma^\mu e_R)\,.$$

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Match on standard electroweak effective theory:

$$\mathcal{O}_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)}\, b)(\bar{\ell}\gamma^\mu \ell)\,, \qquad \mathcal{O}_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)}\, b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,.$$

$$\mathcal{O}_L = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L\, b)(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu)\,, \quad \mathcal{O}_R = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_R\, b)(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu)\,.$$

Correlations between $b \to s\ell\ell$ and $b \to s\nu\bar{\nu}$

Buras et al.,arXiv:1409.4557

Gauge-invariant effective theory:

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$$Q_{Hd} = i(\bar{d}_R \gamma_\mu d_R) H^\dagger D^\mu H\,, \qquad Q_{dl} = (\bar{d}_R \gamma_\mu d_R)(\bar{l}_L \gamma^\mu l_L)\,,$$

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$$C_L = C_L^{\rm SM} + \tilde{c}_{ql}^{(1)} - \tilde{c}_{ql}^{(3)} + \tilde{c}_Z\,, \qquad C_R = \tilde{c}_{dl} + \tilde{c}'_Z \qquad \tilde{c}_Z = \tfrac{1}{2}(\tilde{c}_{Hq}^{(1)} + \tilde{c}_{Hq}^{(3)})$$

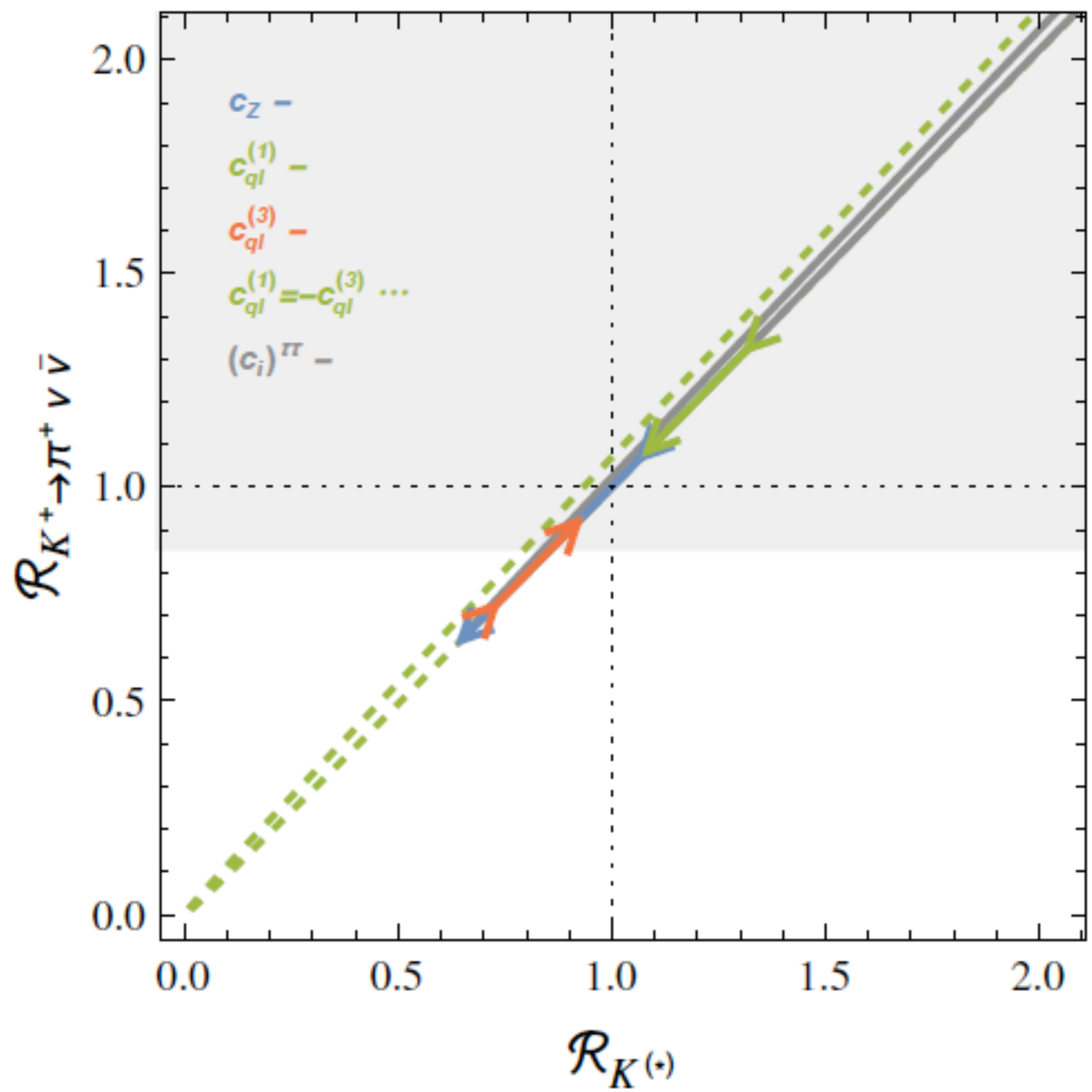
$$C_9 = C_9^{\rm SM} + \tilde{c}_{qe} + \tilde{c}_{ql}^{(1)} + \tilde{c}_{ql}^{(3)} - \zeta\,\tilde{c}_Z\,, \quad C'_9 = \tilde{c}_{de} + \tilde{c}_{dl} - \zeta\,\tilde{c}'_Z \qquad \tilde{c}'_Z = \tfrac{1}{2}\tilde{c}_{Hd}$$

$$C_{10} = C_{10}^{\rm SM} + \tilde{c}_{qe} - \tilde{c}_{ql}^{(1)} - \tilde{c}_{ql}^{(3)} + \tilde{c}_Z\,, \quad C'_{10} = \tilde{c}_{de} - \tilde{c}_{dl} + \tilde{c}'_Z \qquad \zeta = 1 - 4s_w^2 \approx 0.08$$

No model-independent correlations via gauge-invariant operators

MFV hypothesis

Buras et al.,arXiv:1409.4557

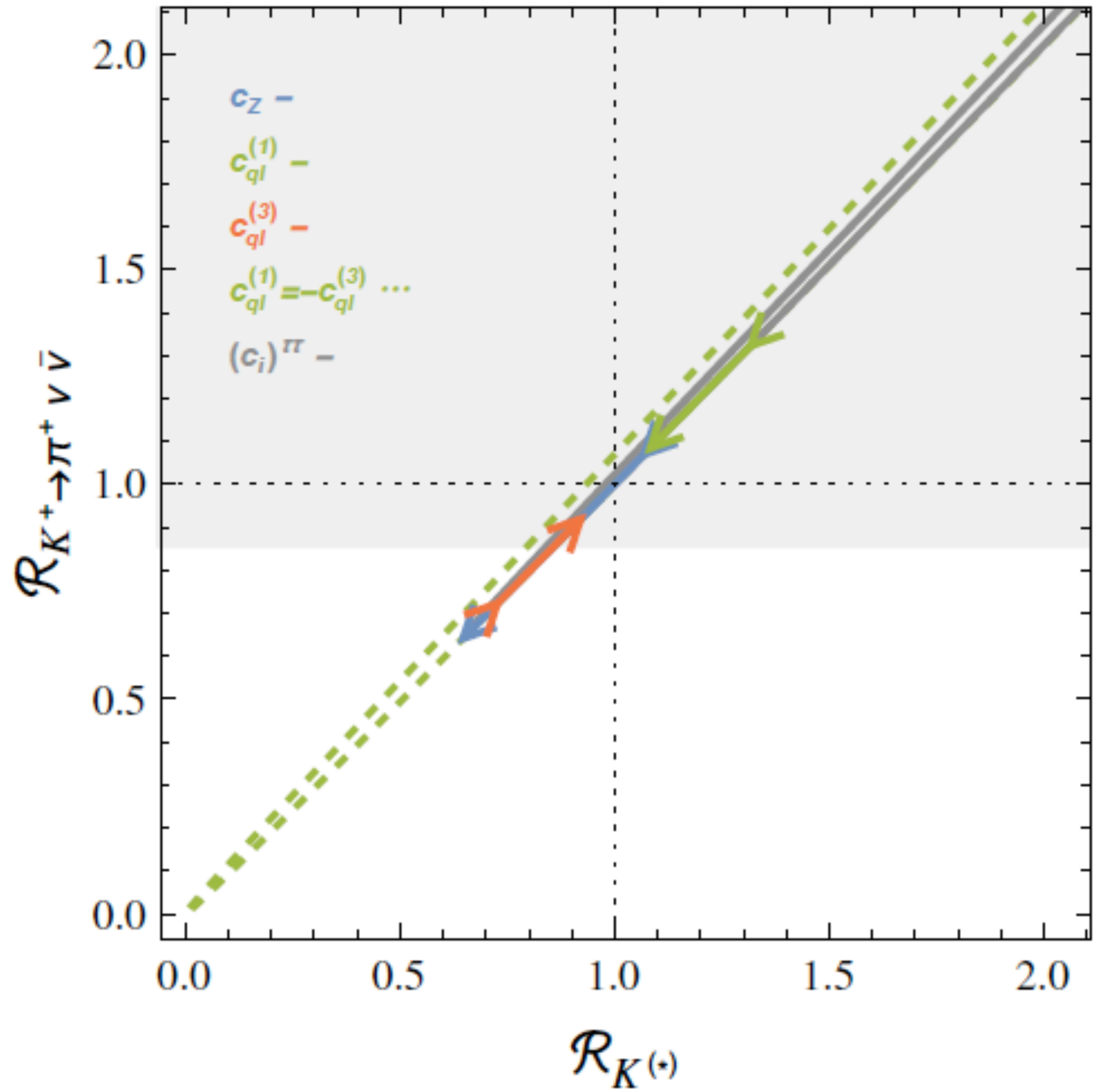


Separate variation: up to 30% deviation from SM possible

Impact of the Wilson coefficients of the SM-EFT on $B \to K^{(*)}\nu\bar{\nu}$ vs. $K^+ \to \pi^+\nu\bar{\nu}$, assuming MFV and LFU, varied within their 2σ ranges allowed by the global fit to $b \to s\mu\mu$ data. Blue: $\tilde{c}_Z$, green: $\tilde{c}_{ql}^{(1)}$, red: $\tilde{c}_{ql}^{(3)}$. The dashed green line shows the case $\tilde{c}_{ql}^{(1)} = -\tilde{c}_{ql}^{(3)}$,

MFV hypothesis

Buras et al.,arXiv:1409.4557



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Correlations exist if additional assumptions made:

i.e. NP only through flavour changing Z couplings: $\tilde{c}_Z$, $\tilde{c}'_Z$