Interplay between inclusive and exclusive $b \to s\ell\ell$ decays

Enrico Lunghi
Indiana University

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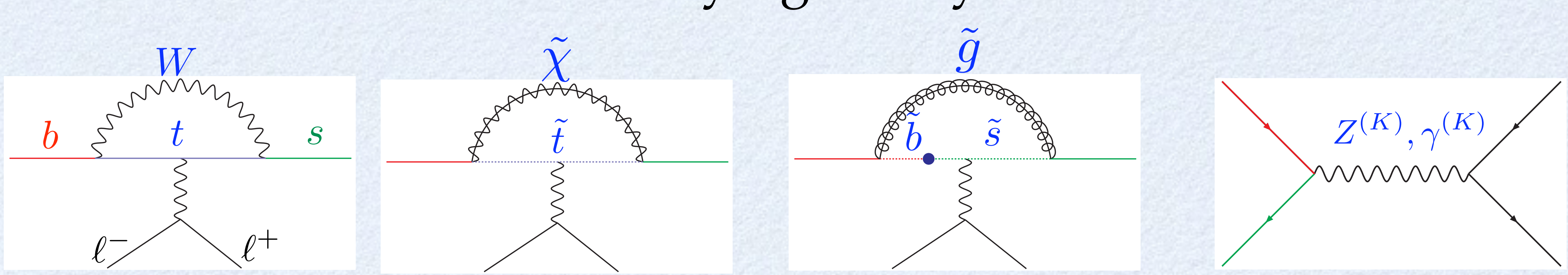
INTRODUCTION

- $b \to s\ell^+\ell^-$ transitions are sensitive to many extensions of the SM
- 3- and 4-body final states allow for a exhaustive study of the ***chiral structure*** of the underlying theory



- ***Theory***: amplitudes can be calculated in terms of elementary hadronic quantities up to power corrections
- ***Experiment***: decays studied at Fermilab (CDF), B-factories (Babar, Belle), LHCb and (in the future) at Belle-II
- *Results based on:*
  Huber, Hurth, EL, JHEP 1506 (2015) 176, arXiv:1503.04849
  Fermilab/MILC & EL, accepted for publication on PRL, arXiv:1507.01618
  Du, El-Khadra, Gottlieb, Kronfeld, Laiho, EL, Van de Water, Zhou, to appear today

Operators

Most relevant SM operators have very definite V-A chiral structure:

- Magnetic & chromo-magnetic

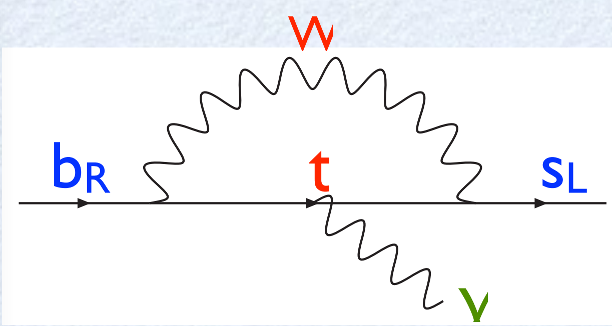
$$Q_7 = \frac{e}{16\pi^2} m_b (\bar{q}_L \sigma^{\mu\nu} b_R) F_{\mu\nu}$$

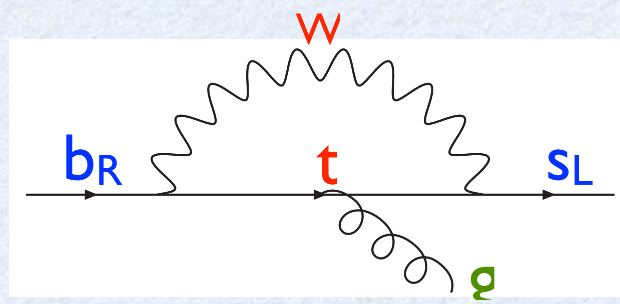
$$Q_8 = \frac{g}{16\pi^2} m_b (\bar{q}_L \sigma^{\mu\nu} T^a b_R) G^a_{\mu\nu}$$

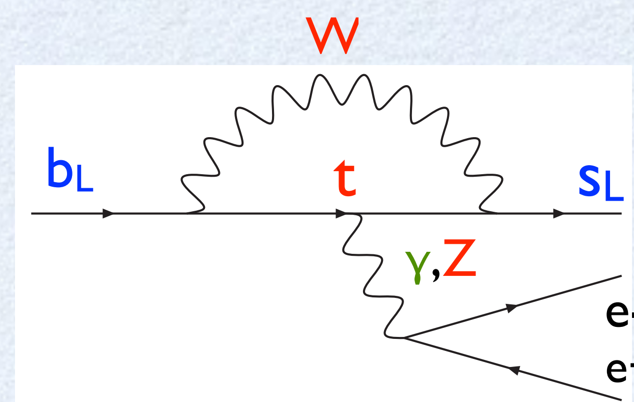
- Semileptonic

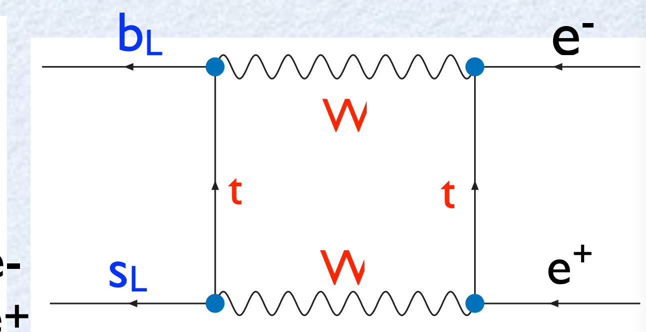
$$Q_9 = (\bar{q}_L \gamma_\mu b_L) \sum (\bar{\ell} \gamma^\mu \ell)$$

$$Q_{10} = (\bar{q}_L \gamma_\mu b_L) \sum (\bar{\ell} \gamma^\mu \gamma_5 \ell)$$









New physics can produce V+A, scalar and tensor structures:

$$Q'_7 = \frac{e}{16\pi^2} m_b [\bar{s}_R \sigma^{\mu\nu} b_L] F_{\mu\nu}$$

$$Q'_8 = \frac{g}{16\pi^2} m_b [\bar{s}_R \sigma^{\mu\nu} T^a b_L] G^a_{\mu\nu}$$

$$Q'_9 = [\bar{s}_R \gamma_\mu b_R][\bar{\ell} \gamma^\mu \ell]$$

$$Q'_{10} = [\bar{s}_R \gamma_\mu b_R][\bar{\ell} \gamma^\mu \gamma_5 \ell]$$

$$Q_S = [\bar{s}_L b_R][\bar{\ell}\bar{\ell}]$$

$$Q'_S = [\bar{s}_R b_L][\bar{\ell}\bar{\ell}]$$

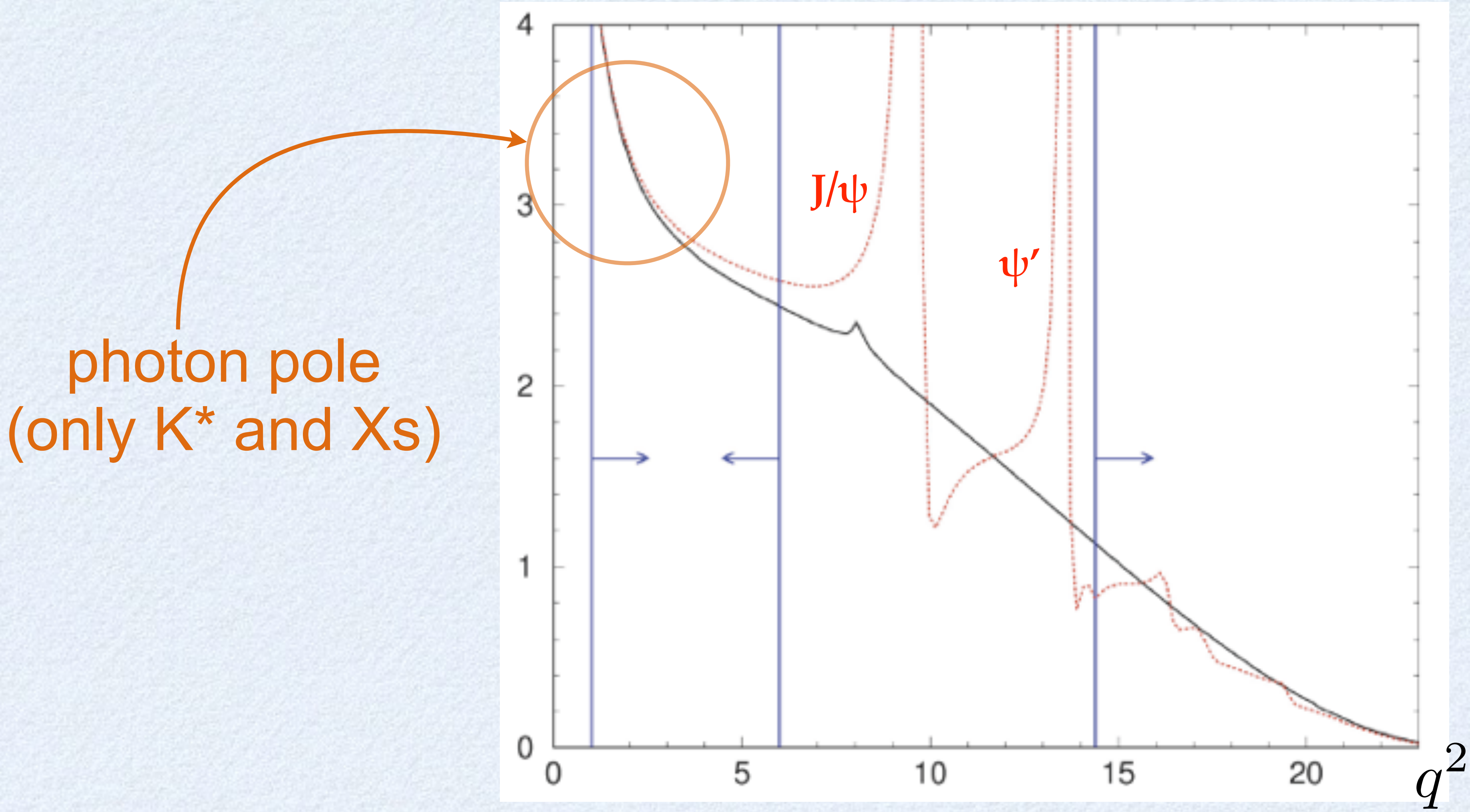
$$Q_P = [\bar{s}_L b_R][\bar{\ell} \gamma_5 \bar{\ell}]$$

$$Q'_P = [\bar{s}_R b_L][\bar{\ell} \gamma_5 \bar{\ell}]$$

$$Q_T = [\bar{s} \sigma_{\mu\nu} b][\bar{e}ll \sigma^{\mu\nu} \ell]$$

$$Q_{T5} = \frac{i}{2} \varepsilon^{\mu\nu\alpha\beta} [\bar{s} \sigma_{\mu\nu} b][\bar{\ell} \sigma_{\alpha\beta} \ell]$$

Typical Spectrum



- Intermediate charmonium resonances contribute via: $B \to (K, K^*, X_s)\ \psi_{\bar{c}c} \to (K, K^*, X_s)\ \ell^+\ell^-$
- Contributions of J$/\psi$ and ψ' have to be dropped
- Theory at low- and high-q² presents different challenges

Observables

- $B \to K\ell\ell$

$$\frac{d^2\Gamma^K}{dq^2\ d\cos\theta_\ell} = a + b\ \cos\theta_\ell + c\ \cos\theta_\ell^2$$

  - In the SM ***b*** is suppressed by the lepton mass

- $B \to X_s\ell\ell$

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

$$H_T \sim 2\hat{s}(1-\hat{s})^2\left[|C_9 + \frac{2}{\hat{s}}C_7|^2 + |C_{10}|^2\right] \qquad \hat{s} = q^2/m_b^2$$

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

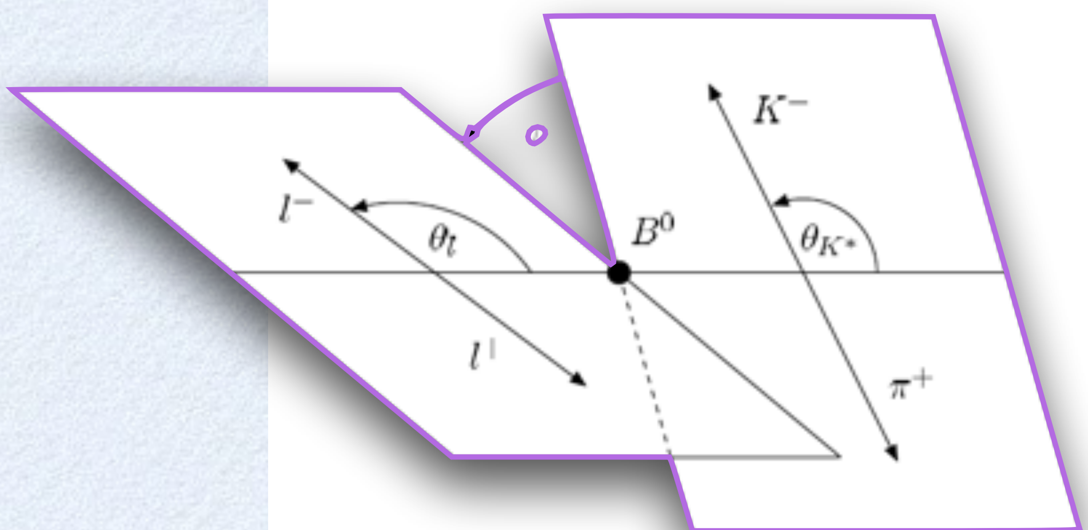
$$H_A \sim -4\hat{s}(1-\hat{s})^2\mathrm{Re}\left[C_{10}(C_9 + 2\frac{m_b^2}{q^2}C_7)\right]$$

  - In the SM H_A is not suppressed by the lepton mass
  - There are similar contributions from non-SM operators ***but there is no interference between V+A and V-A structures***

OBSERVABLES

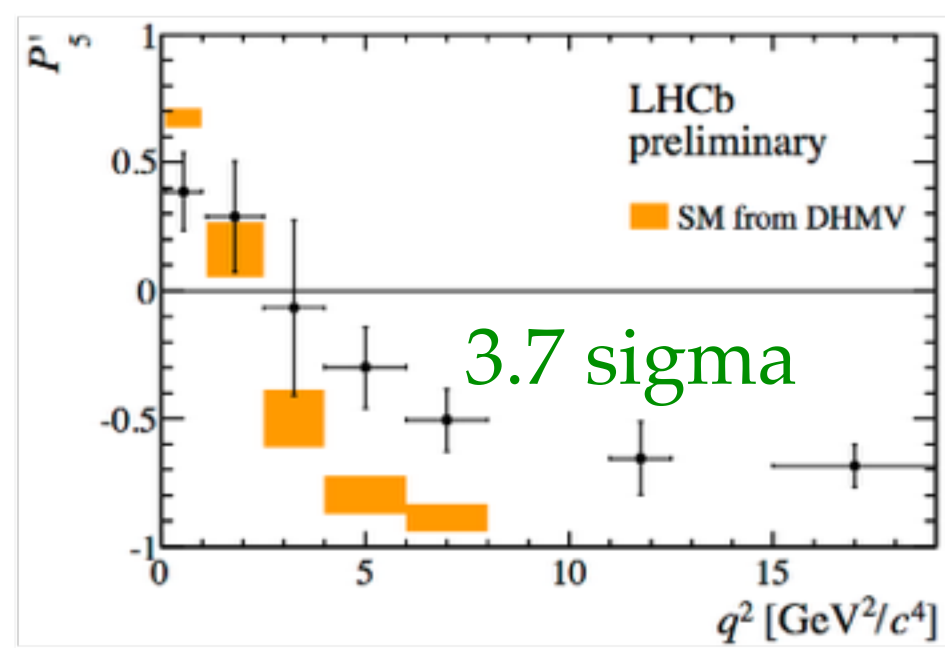
- $B \to K^* \ell\ell \to K\pi\ell\ell$

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}}\bigg|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$
$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$



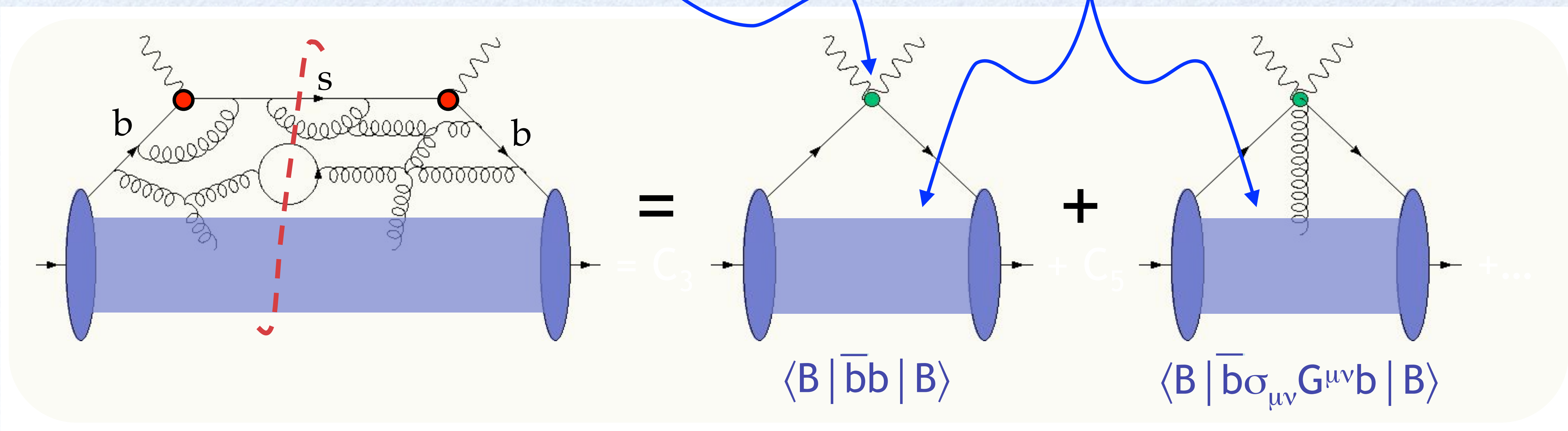
"clean ratios"

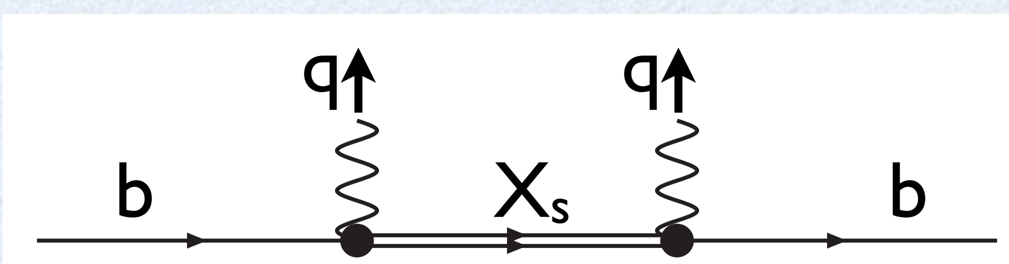
$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}}$$



THEORY: INCLUSIVE

$$\Gamma\left[\bar{B}\to X_s\ell^+\ell^-\right] = \Gamma\left[\bar{b}\to X_s\ell^+\ell^-\right] + O\left(\frac{\Lambda^2_{QCD}}{m_b^2}, \frac{\Lambda^3_{QCD}}{m_b^3}, \frac{\Lambda^2_{QCD}}{m_c^2}, \ldots\right)$$





$$\begin{aligned} p^2_{X_s} &= (p_b - q)^2 = m_b^2 + q^2 - 2m_b q_0 \\ &< m_b^2 + q^2 - 2m_b\sqrt{q^2} = \left(m_b - \sqrt{q^2}\right)^2 \end{aligned}$$

OPE is an expansion in $\Lambda_{QCD}/(m_b - \sqrt{q^2})$ and breaks down at $q^2 \sim m_b^2$

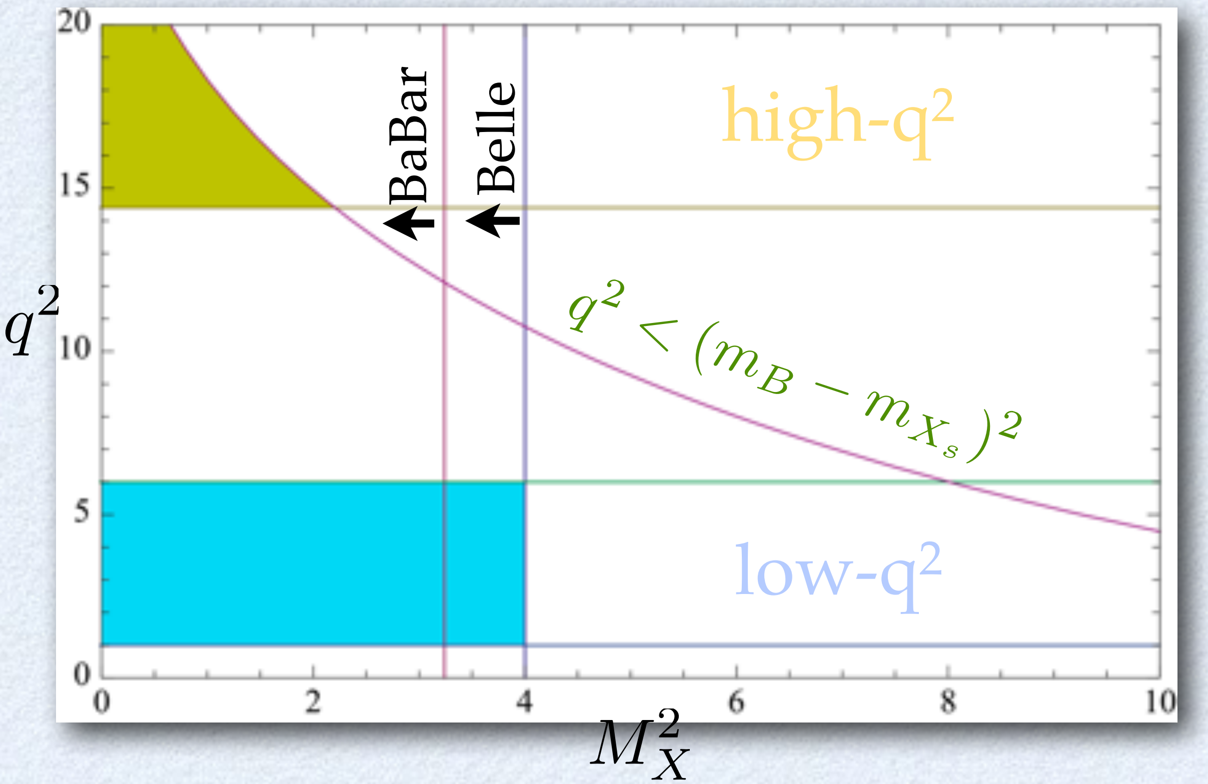
THEORY: INCLUSIVE

$$\Gamma\left[\bar{B} \to X_s \ell^+ \ell^-\right] = \Gamma\left[\bar{b} \to X_s \ell^+ \ell^-\right] + O\left(\frac{\Lambda^2_{QCD}}{m_b^2}, \frac{\Lambda^3_{QCD}}{m_b^3}, \frac{\Lambda^2_{QCD}}{m_c^2}, \ldots\right)$$

local OPE, optical theorem
quark-hadron duality

HQET

Phase space cuts introduce sensitivity to new scales, the rate becomes less inclusive and new non-perturbative effects appear



$M_{X_s} < [1.8, 2]$ GeV **cut to remove double semileptonic decay background**

- High-q² region unaffected
- **Experiments correct using Fermi motion model**
- SCET$_\mathrm{I}$ suggests cuts are universal (same for b→sll and b→ulν)

Effect of cc resonances can be included using data from ee→hadrons

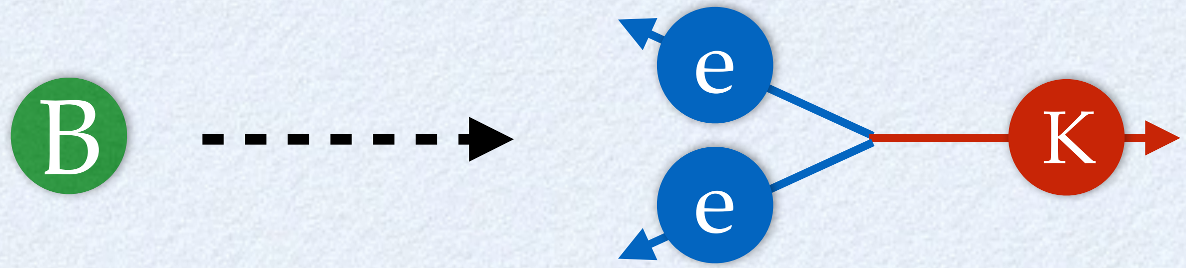
Theory: Exclusive (Low Q^2)

- The central problem is the calculation of matrix elements:

$$\langle K^{(*)}\ell\ell|O(y)|B\rangle \;\approx\; \langle K^{(*)}|T\; J_\mu^{\rm em}(x)\; O(y)|B\rangle$$

if O contains a leptonic current (i.e. $O_{7,9,10}$) the matrix elements reduces to a form factor

- At low-q^2 the $K^{(*)}$ recoils strongly:



- The large energy of the $K^{(*)}$ introduces three scales: m_b^2, Λm_b and Λ^2:

$$\langle K^{(*)}|T\; J_\mu^{\rm em}(x)\; O(y)|B\rangle \quad \sim \quad \boxed{\underbrace{C}_{m_b^2} \times [\underbrace{\text{Form Factor}}_{\Lambda^2} + \underbrace{\phi_B}_{\Lambda^2} \star \underbrace{J}_{\Lambda m_b} \star \underbrace{\phi_K}_{\Lambda^2}] + O\left(\frac{\Lambda}{m_b}\right)}$$

SCET$_{\rm II}$

Theory: exclusive (low q^2)

- For example, the B→Kll rate is given by:

$$\frac{d\Gamma}{dq^2} \sim \left| f_+(q^2)\, C_9^{\rm eff}(q^2) + \frac{2m_b}{m_B+m_K} f_T(q^2)\, C_7^{\rm eff}(q^2) \right.$$

$$\left. + \frac{2m_b}{m_B}\frac{\pi^2}{N_c}\frac{f_B f_K}{m_B}\sum_\pm \int \frac{d\omega}{\omega}\Phi_{B,\pm}(\omega)\int_0^1 du\,\Phi_K(u)\left[T_{P,\pm}^{(0)} + \tilde\alpha_s C_F\, T_{P,\pm}^{(\rm nf)}\right]\right|^2$$

$$+ \left| f_+(q^2)\, C_{10}\right|^2$$

- The form factor f_T can be expressed in terms of f_+ (it is now preferable to use directly the lattice determination of f_T):

$$\frac{m_B}{m_B+m_K} f_T = f_+ \left[1 + \tilde\alpha_s C_F\left(\log\frac{m_b^2}{\mu^2} + 2L\right)\right]$$

$$- \frac{\pi}{N_c}\frac{f_B f_K}{E}\alpha_s C_F \overbrace{\int \frac{d\omega}{\omega}\Phi_{B,+}(\omega)}^{\lambda_{B,+}^{-1}}\int_0^1 \frac{du}{\bar u}\,\Phi_K(u)$$

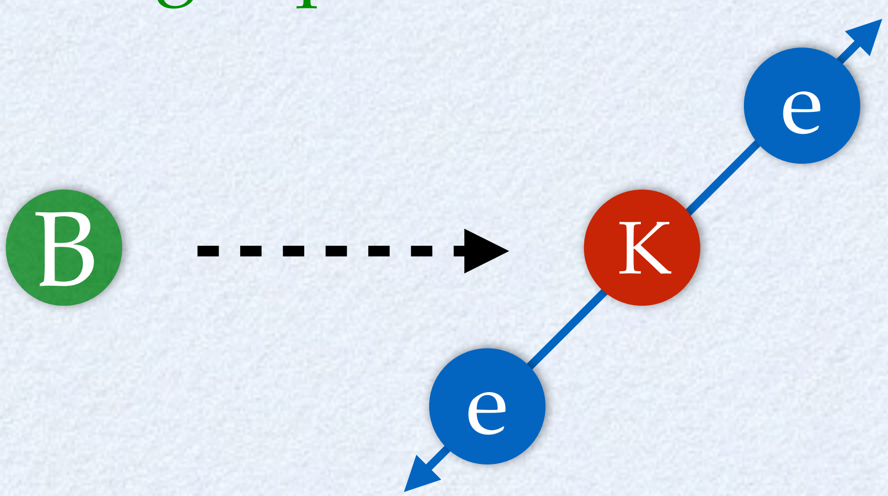
Theory: exclusive (high q^2)

- The central problem is the calculation of matrix elements:

$$\langle K^{(*)}\ell\ell|O(y)|B\rangle \;\approx\; \langle K^{(*)}|T\; J_\mu^{\rm em}(x)\; O(y)|B\rangle$$

if O contains a leptonic current (i.e. $O_{7,9,10}$) the matrix elements reduces to a form factor (lattice, QCD sum rules)

- At high-q^2 the $K^{(*)}$ doesn't recoil:



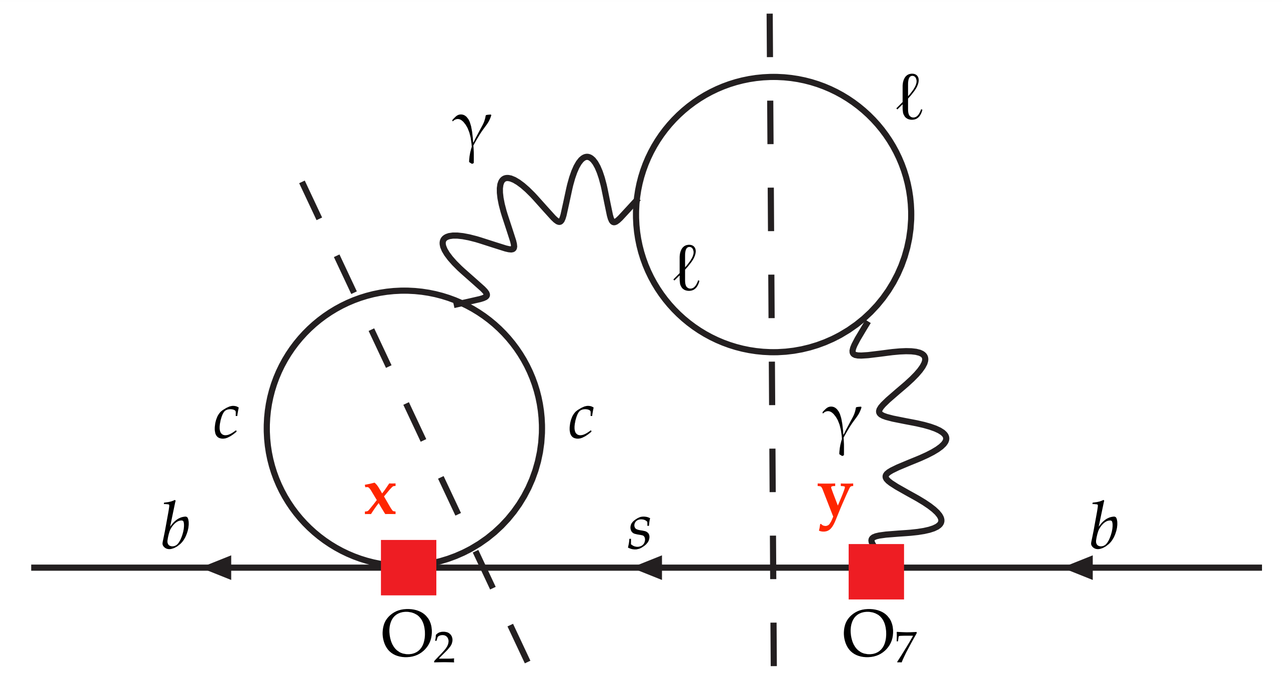
$$(x-y)^2 \sim \frac{1}{q^2} \sim \frac{1}{m_b^2}$$

Grinstein & Pirjol showed how to write a simple OPE in which **all matrix elements** are given in terms of calculable hard coefficients and **form factors** (up to power corrections)

THEORY: EXCLUSIVE (HIGH Q²)

- Note the difference between inclusive and exclusive (high-q²) OPE:

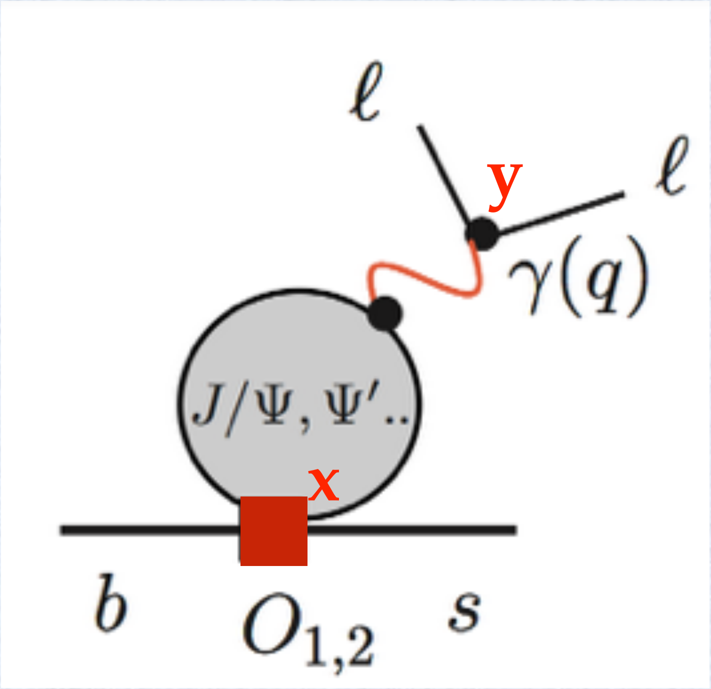
Inclusive



$$(x-y)^2 \sim \frac{1}{\left(m_b - \sqrt{q^2}\right)^2}$$

The breakdown of the OPE at very large q² is independent of the presence of resonant charm loops

Exclusive



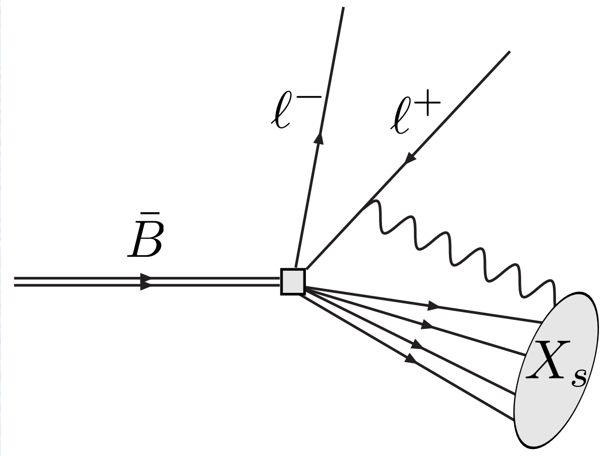
$$(x-y)^2 \gg \frac{1}{q^2}$$

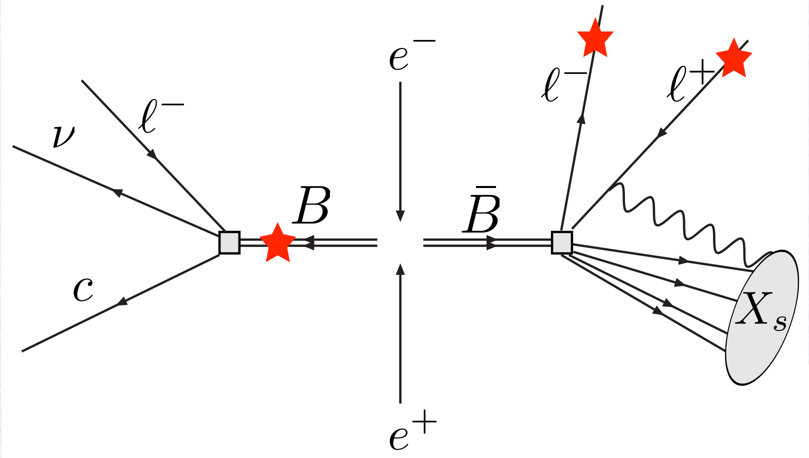
The presence of resonant charm loops jeopardize the OPE itself and one has to rely on quark-hadron duality

[Beylich, Buchalla, Feldmann]

Inclusive: QED radiation

- Photons emitted by the final state leptons (especially electrons) should be technically included in the Xs system:





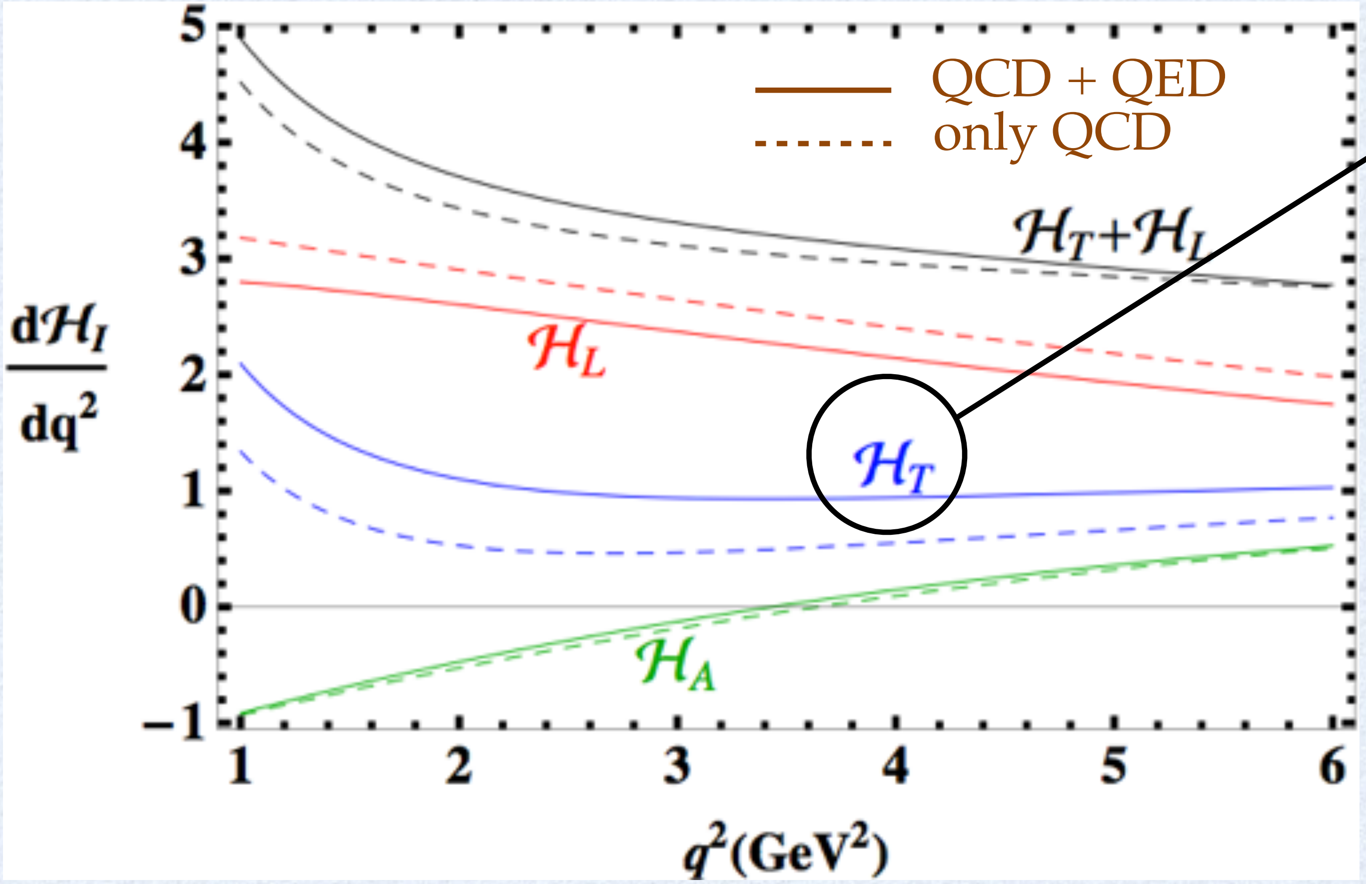
- **This implies very large α_{em} log(m_e/m_b) at low and high-q^2**
- The logs cancel in the total rate that is however inaccessible (resonances)
- ***At B-factories most but not all of these photons are included in the Xs system***
- Need Monte Carlo studies (EVTGEN+PHOTOS) to find the correction factor:

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

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

Inclusive: Results

- Impact of collinear photon radiation is huge on some observables
- Cross check with Monte Carlo study (EVTGEN + PHOTOS)



Shift on $\mathrm{H_T}$ is ~70%!

$\mathrm{H_T}$ is smaller than $\mathrm{H_L}$ ($\hat{s} \lesssim 0.3$):

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

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

	$q^2 \in [1,6]$ GeV^2			$q^2 \in [1,3.5]$ GeV^2			$q^2 \in [3.5,6]$ GeV^2		
	$\frac{O_{[1,6]}}{\mathcal{B}_{[1,6]}}$	$\frac{\Delta O_{[1,6]}}{\mathcal{B}_{[1,6]}}$	$\frac{\Delta O_{[1,6]}}{O_{[1,6]}}$	$\frac{O_{[1,3.5]}}{\mathcal{B}_{[1,6]}}$	$\frac{\Delta O_{[1,3.5]}}{\mathcal{B}_{[1,6]}}$	$\frac{\Delta O_{[1,3.5]}}{O_{[1,3.5]}}$	$\frac{O_{[3.5,6]}}{\mathcal{B}_{[1,6]}}$	$\frac{\Delta O_{[3.5,6]}}{\mathcal{B}_{[1,6]}}$	$\frac{\Delta O_{[3.5,6]}}{O_{[3.5,6]}}$
$\mathcal{B}$	100	5.1	5.1	54.6	3.7	6.8	45.4	1.4	3.1
$\mathcal{H}_T$	19.5	14.1	72.5	9.5	8.8	92.1	10.0	5.4	53.6
$\mathcal{H}_L$	80.0	-8.7	-10.9	44.7	-4.7	-10.6	35.3	-4.0	-11.3
$\mathcal{H}_A$	-3.3	1.4	-43.6	-7.2	0.8	-10.7	4.0	0.6	16.2

Inclusive: Results

	δ_{th}		R(μ/e)
$\mathcal{H}_T[1,6]_{\mu\mu} = (4.03 \pm 0.28) \cdot 10^{-7}$	±7%	$\mathcal{H}_T[1,6]_{ee} = (5.34 \pm 0.38) \cdot 10^{-7}$	0.75
$\mathcal{H}_L[1,6]_{\mu\mu} = (1.21 \pm 0.07) \cdot 10^{-6}$	±6%	$\mathcal{H}_L[1,6]_{ee} = (1.13 \pm 0.06) \cdot 10^{-6}$	1.07
$\mathcal{H}_A[1,3.5]_{\mu\mu} = (-1.10 \pm 0.05) \cdot 10^{-7}$	±5%	$\mathcal{H}_A[1,3.5]_{ee} = (-1.03 \pm 0.05) \cdot 10^{-7}$	1.07
$\mathcal{H}_A[3.5,6]_{\mu\mu} = (+0.67 \pm 0.12) \cdot 10^{-7}$	±18%	$\mathcal{H}_A[3.5,6]_{ee} = (+0.73 \pm 0.12) \cdot 10^{-7}$	0.92
$\mathcal{H}_3[1,6]_{\mu\mu} = (3.71 \pm 0.50) \cdot 10^{-9}$	±13%	$\mathcal{H}_3[1,6]_{ee} = (8.92 \pm 1.20) \cdot 10^{-9}$	0.42
$\mathcal{H}_4[1,6]_{\mu\mu} = (3.50 \pm 0.32) \cdot 10^{-9}$	±9%	$\mathcal{H}_4[1,6]_{ee} = (8.41 \pm 0.78) \cdot 10^{-9}$	0.42
$\mathcal{B}[1,6]_{\mu\mu} = (1.62 \pm 0.09) \cdot 10^{-7}$	±6%	$\mathcal{B}[1,6]_{ee} = (1.67 \pm 0.10) \cdot 10^{-7}$	0.97
$\mathcal{B}[> 14.4]_{\mu\mu} = (2.53 \pm 0.70) \cdot 10^{-7}$	±28%	$\mathcal{B}[> 14.4]_{ee} = (2.20 \pm 0.70) \cdot 10^{-7}$	1.15

- **Scale uncertainties dominate at low-q^2**
- **Power corrections and scale uncertainties dominate at high-q^2**
- Log-enhanced QED corrections at low and high q^2 are anticorrelated

Inclusive: Reducing errors at high-q^2

- Normalize the decay width to the semileptonic B→X_ulν rate with the ***same dilepton invariant mass cut:***

$$\mathcal{R}(s_0) = \frac{\displaystyle\int_{\hat{s}_0}^{1} \mathrm{d}\hat{s}\, \frac{\mathrm{d}\Gamma(\bar{B} \to X_s \ell^+ \ell^-)}{\mathrm{d}\hat{s}}}{\displaystyle\int_{\hat{s}_0}^{1} \mathrm{d}\hat{s}\, \frac{\mathrm{d}\Gamma(\bar{B}^0 \to X_u \ell \nu)}{\mathrm{d}\hat{s}}}$$

[Ligeti,Tackmann]

- ***Impact of*** $1/m_b^2$ ***and*** $1/m_b^3$ ***power corrections drastically reduced:***

$$\begin{aligned}\mathcal{R}(14.4)_{\mu\mu} =& (2.62 \pm 0.09_{\rm scale} \pm 0.03_{m_t} \pm 0.01_{C,m_c} \pm 0.01_{m_b} \pm 0.01_{\alpha_s} \pm 0.23_{\rm CKM} \\ & \pm 0.0002_{\lambda_2} \pm 0.09_{\rho_1} \pm 0.04_{f_u^0+f_s} \pm 0.12_{f_u^0-f_s}) \cdot 10^{-3} \\ =& (2.62 \pm 0.30) \cdot 10^{-3} \qquad [11\%]\end{aligned}$$

$$\begin{aligned}\mathcal{R}(14.4)_{ee} =& (2.25 \pm 0.12_{\rm scale} \pm 0.03_{m_t} \pm 0.02_{C,m_c} \pm 0.01_{m_b} \pm 0.01_{\alpha_s} \pm 0.20_{\rm CKM} \\ & \pm 0.02_{\lambda_2} \pm 0.14_{\rho_1} \pm 0.08_{f_u^0+f_s} \pm 0.12_{f_u^0-f_s}) \cdot 10^{-3} \\ =& (2.25 \pm 0.31) \cdot 10^{-3} \qquad [14\%]\end{aligned}$$

- ***The largest source of uncertainty is*** V_{ub}

Inclusive: Experimental Status

BaBar: 471×10^6 BB pairs (424 fb^{-1})
Belle: 152×10^6 BB pairs (140 fb^{-1})
[711 fb^{-1} on tape]

- World averages (Babar, Belle):

$$\mathrm{BR}^{\mathrm{exp}} = (1.58 \pm 0.37) \times 10^{-6} \qquad q^2 \in [1,6]$$

$$\mathrm{BR}^{\mathrm{exp}} = (0.48 \pm 0.10) \times 10^{-6} \qquad q^2 > 14.4$$

$$\overline{A}_{\mathrm{FB}}^{\mathrm{exp}} = \begin{cases} 0.34 \pm 0.24 & q^2 \in [0.2, 4.3] \\ 0.04 \pm 0.31 & q^2 \in [4.3, 7.3(8.1)] \end{cases}$$

$\delta_{\mathrm{exp}} \approx 23\%$
$\delta_{\mathrm{exp}} \approx 21\%$

non-optimal binning

- Theory:

$$\mathrm{BR}^{\mathrm{th}} = (1.65 \pm 0.10) \times 10^{-6} \qquad q^2 \in [1,6]$$

$$\mathrm{BR}^{\mathrm{th}} = (0.237 \pm 0.070) \times 10^{-6} \qquad q^2 > 14.4$$

$$\overline{A}_{\mathrm{FB}}^{\mathrm{th}} = \begin{cases} -0.077 \pm 0.006 & q^2 \in [0.2, 4.3] \\ 0.05 \pm 0.02 & q^2 \in [4.3, 7.3(8.1)] \end{cases}$$

$\delta_{\mathrm{th}} \approx 6\%$
$\delta_{\mathrm{th}} \approx 30\%$

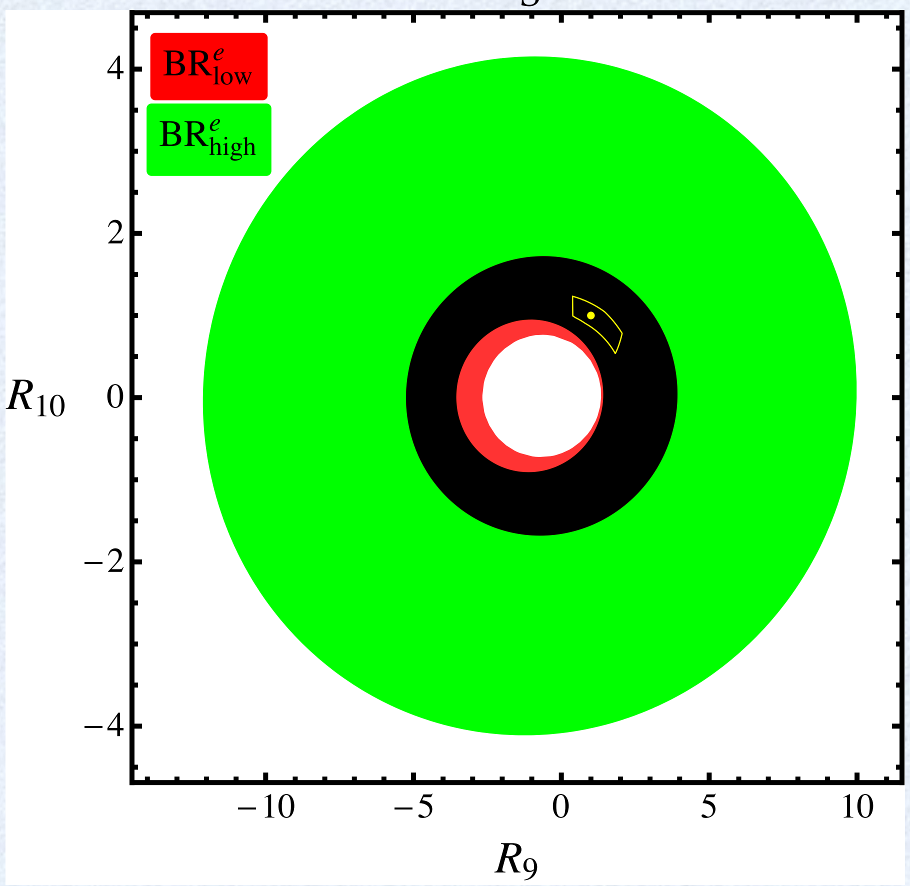
non-optimal binning

- $$\mathrm{BR} = H_T + H_L \qquad \overline{A}_{\mathrm{FB}} = \frac{3}{4}\frac{H_A}{H_T + H_L}$$

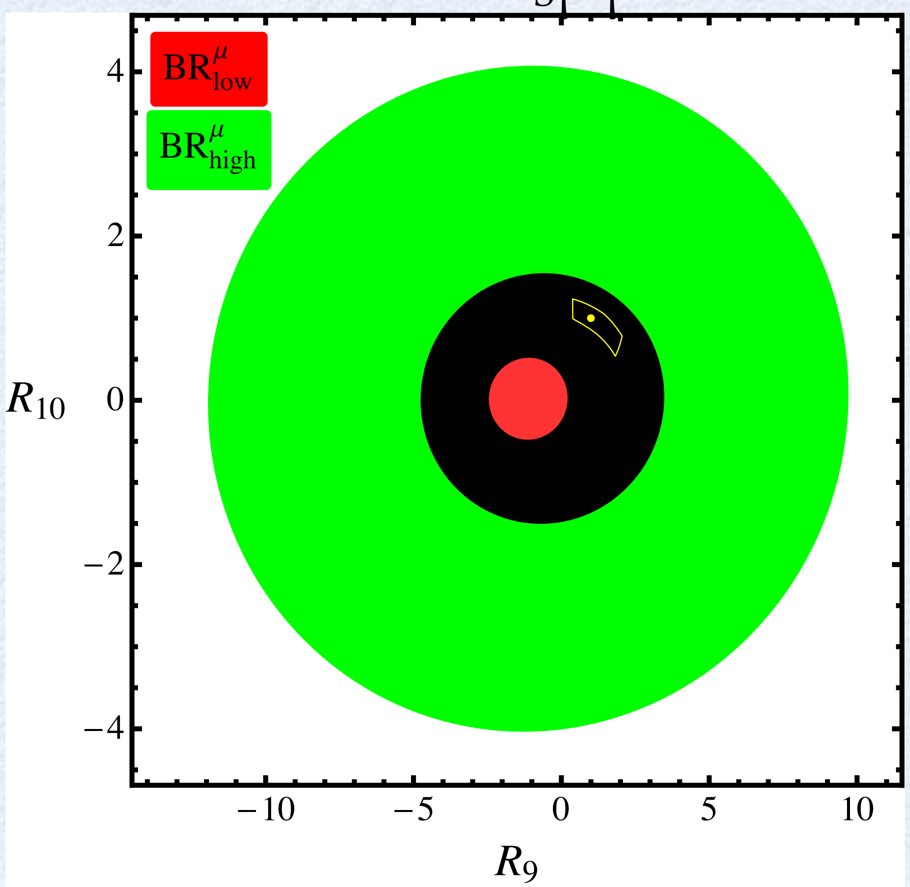
Inclusive: present constraints

- 95%CL constraints in the [R9,R10] plane ($R_i = C_i(\mu_0)/C_i^{\rm SM}(\mu_0)$):

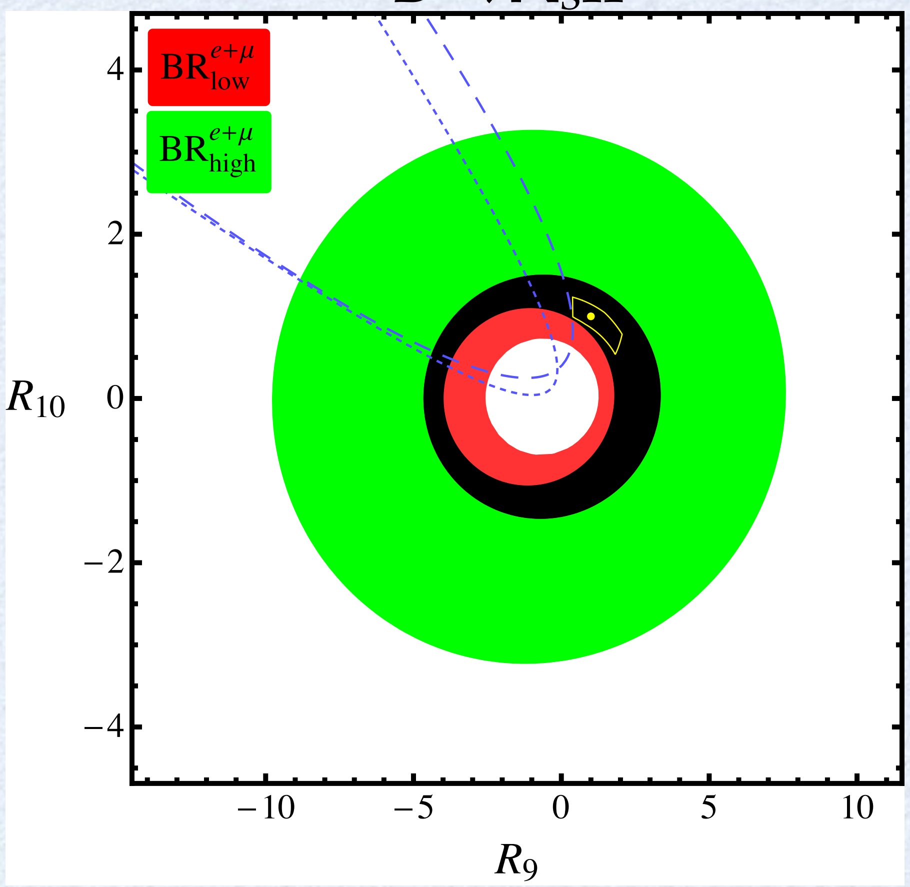
B→Xsee



B→Xsμμ



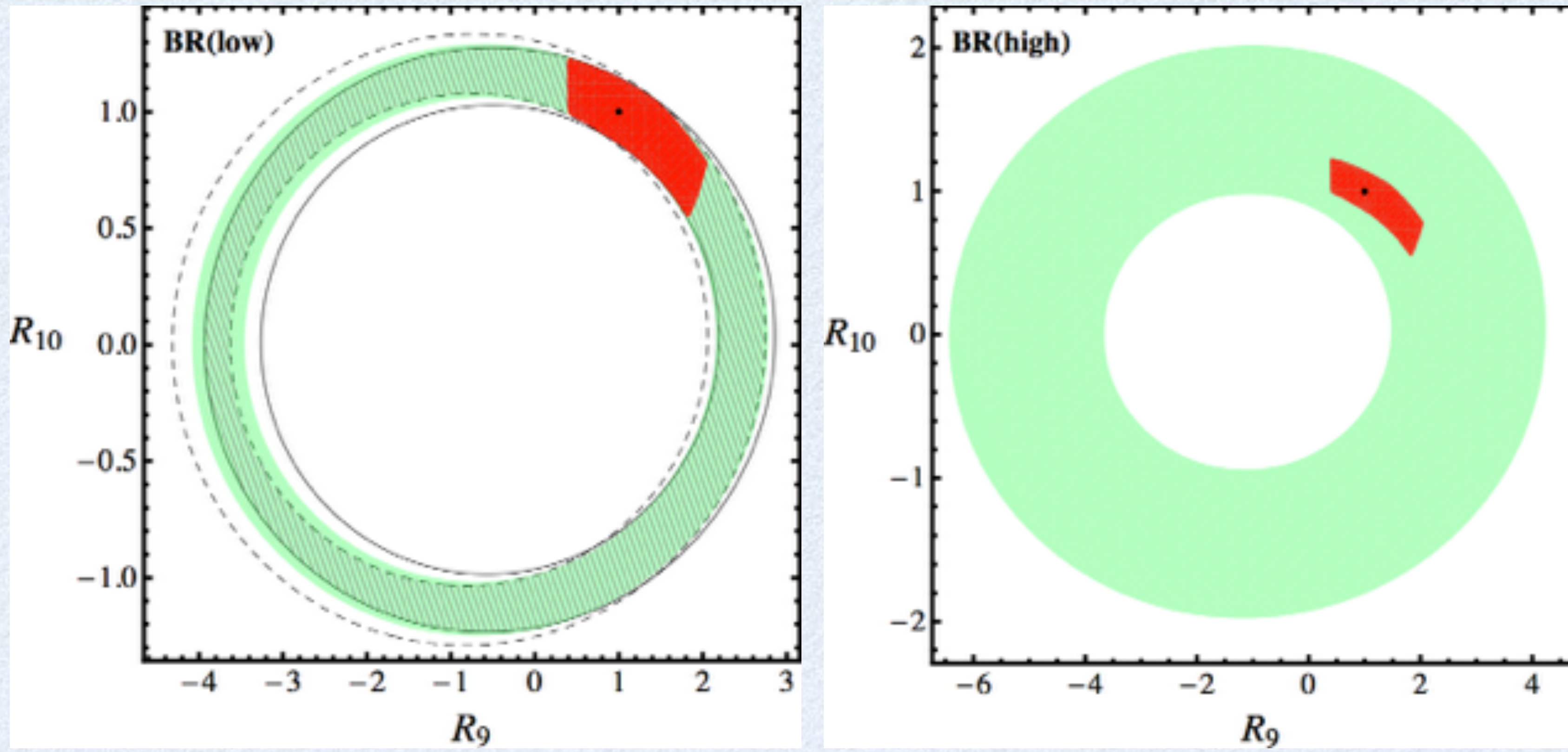
B→Xsll

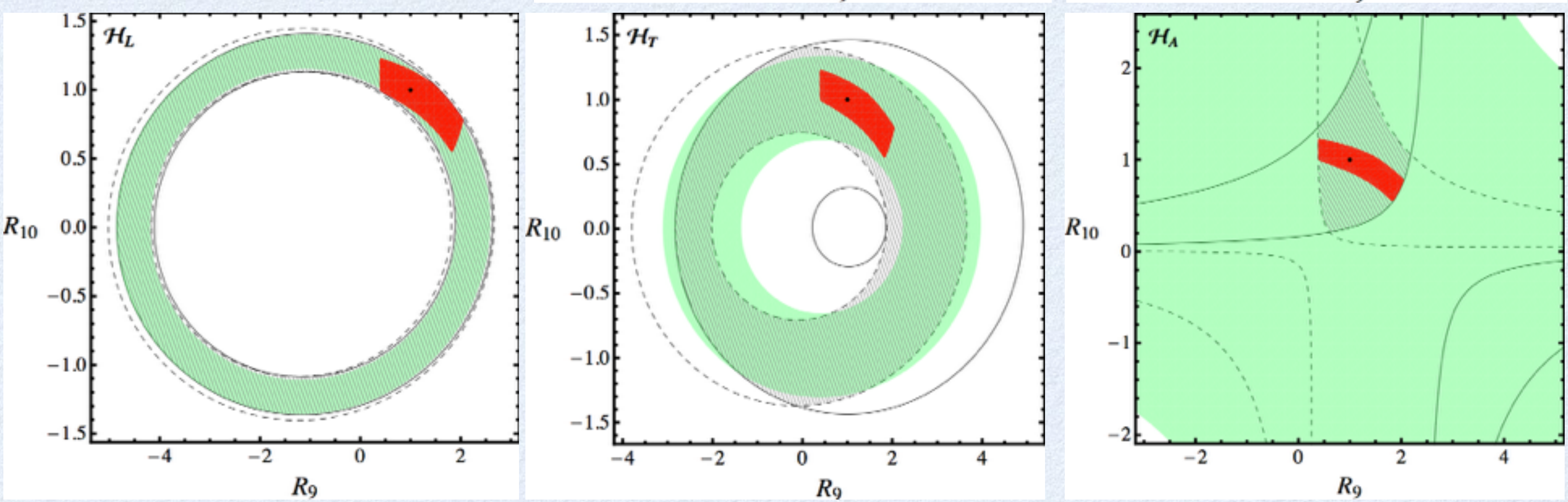


- Note that $C_9^{\rm SM}(\mu_0) = 1.61$ and $C_{10}^{\rm SM}(\mu_0) = -4.26$
- Best fits from the exclusive anomaly translate in R9 ~ 0.3 (for the single WC fit) or R9 ~ 0.65 and R10 ~ 0.9 (for the $C_9^{\rm NP} = -C_{10}^{\rm NP}$ scenario)

INCLUSIVE: PROJECTIONS

Projected reach with 50 ab^{-1} of integrated luminosity





Exclusive: Phenomenology

- No issues with photonic radiation (LHCb uses PHOTOS to reconstruct the original charged leptons)

- ***We focus on the $B \to K$ mode for which state-of-art calculations of all required form factors (f_+, f_T, f_0) are available***

[Bailey et al (Fermilab/MILC), arXiv: 1509.06235]

- Access to the form factors f_T and f_0 allows us to
(1) *eliminate perturbative and non-perturbative (power corrections) uncertainties associated with form factors relations*
(2) *take into account the scale dependence of f_T*

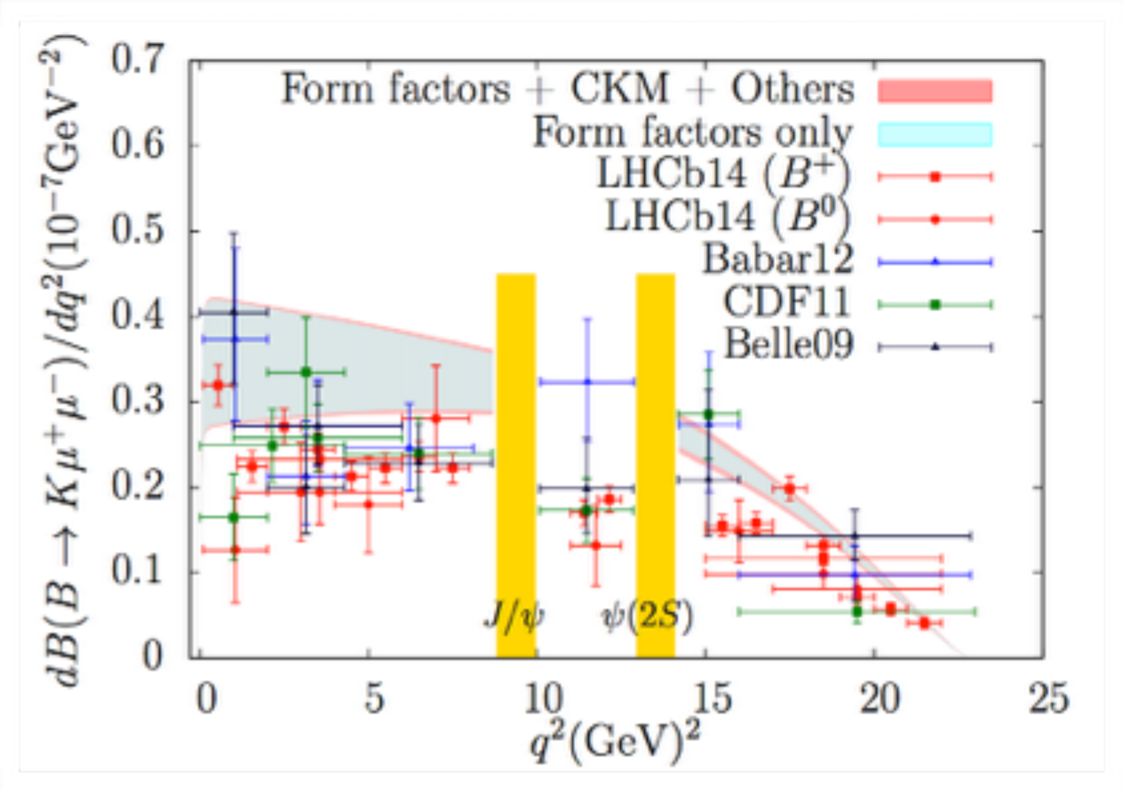
Exclusive: Phenomenology

- SM prediction (errors are CKM, FF, scale, rest):
  [Du, El-Khadra, Gottlieb, Kronfeld, Laiho, EL, Van de Water, Zhou, to appear today]

$$\Delta\mathcal{B}(B^+ \to K^+\mu^+\mu^-)^{\rm SM} \times 10^9 = \begin{cases} 174.7(9.5)(29.1)(3.2)(2.2), & 1.1\ \mathrm{GeV}^2 \le q^2 \le \ \ 6\ \mathrm{GeV}^2 \\ 106.8(5.8)(5.2)(1.7)(3.1), & 15\ \mathrm{GeV}^2 \le q^2 \le 22\ \mathrm{GeV}^2 \end{cases}$$

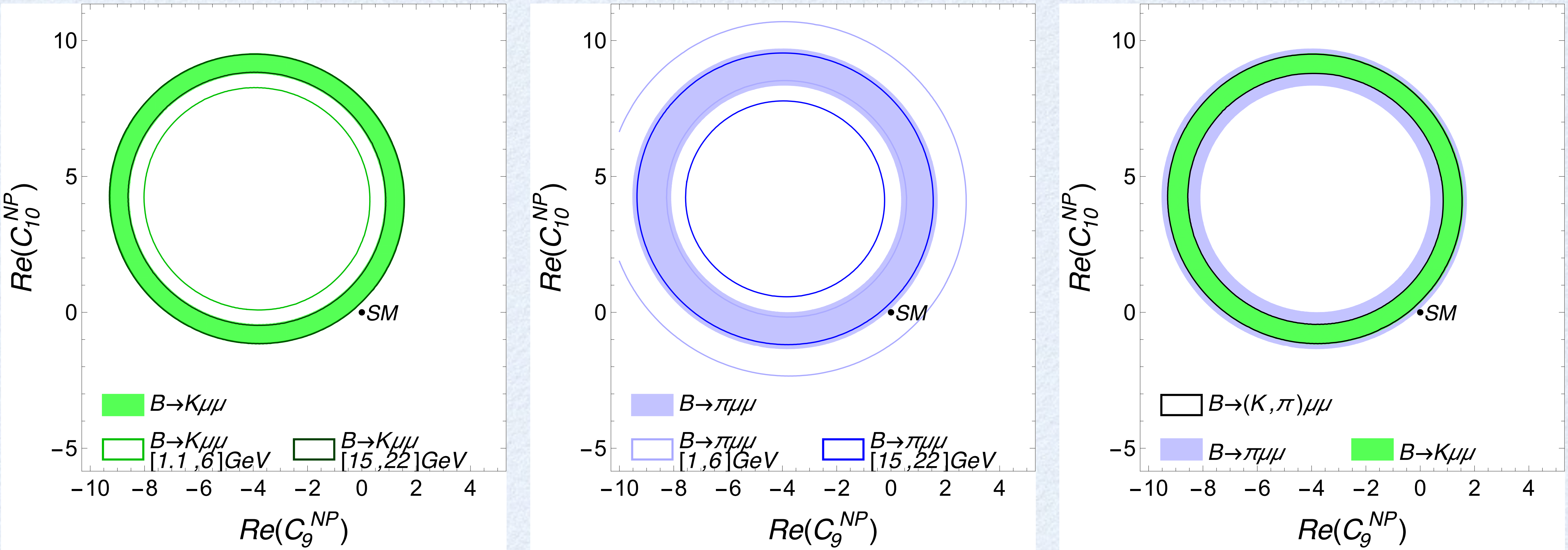
- Experimental results [LHCb, arXiv:1403.8044]:

$$\Delta\mathcal{B}(B^+ \to K^+\mu^+\mu^-)^{\rm exp} \times 10^9\ \mathrm{GeV}^2 = \begin{cases} 118.6(3.4)(5.9) & 1.1\ \mathrm{GeV}^2 \le q^2 \le \ \ 6\ \mathrm{GeV}^2 \\ 84.7(2.8)(4.2) & 15\ \mathrm{GeV}^2 \le q^2 \le 22\ \mathrm{GeV}^2 \end{cases}$$



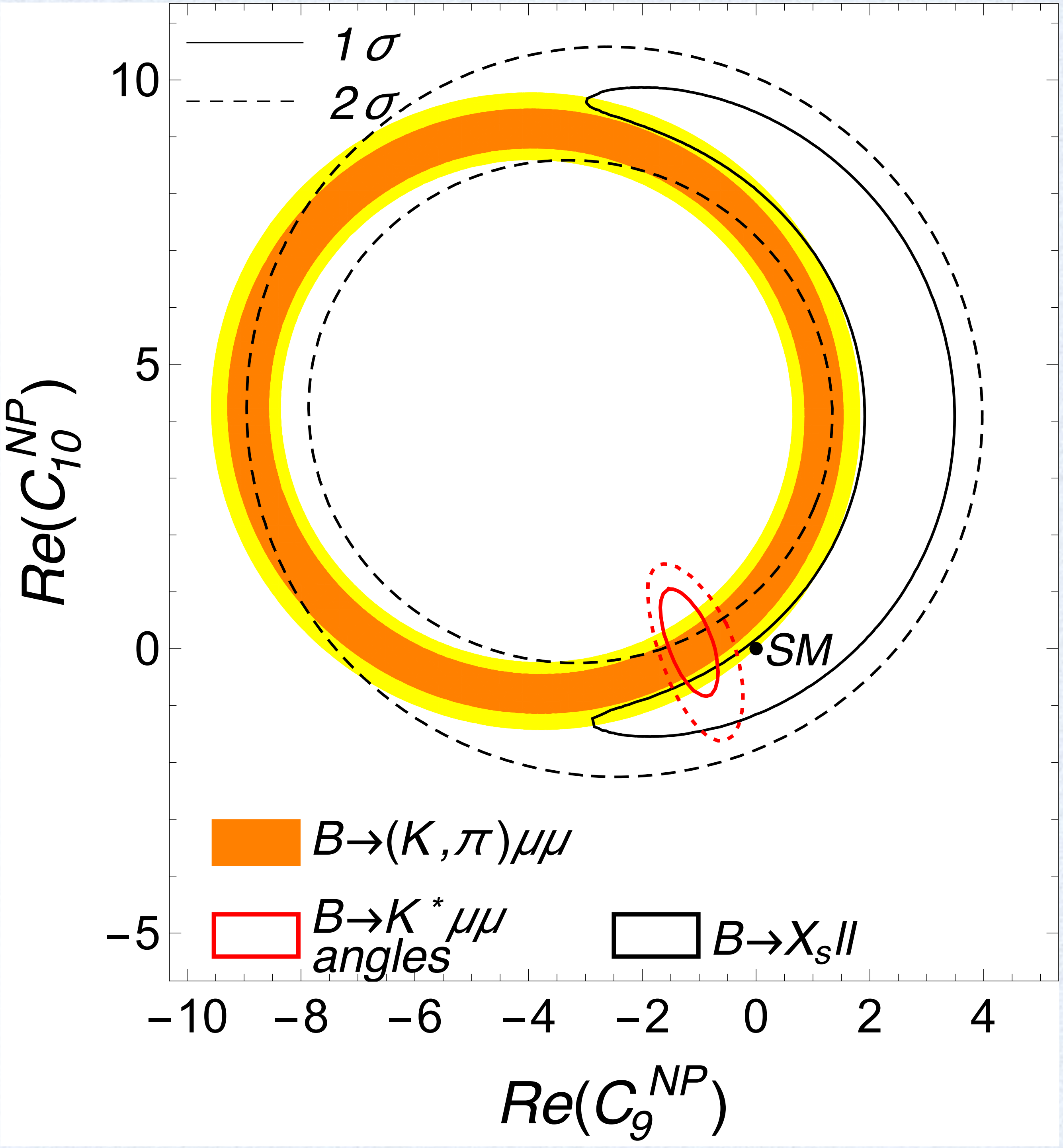
Exclusive: Phenomenology

- Constraints in the $[C_9, C_{10}]$ plane
- Include also constraints from $B \to \pi\mu\mu$ [Fermilab/MILC & EL, arXiv:1507.01618]



- Dominant constraint is $B^+ \to K^+\mu\mu$ at high-q^2
- Most relevant uncertainties are CKM and Form Factors!

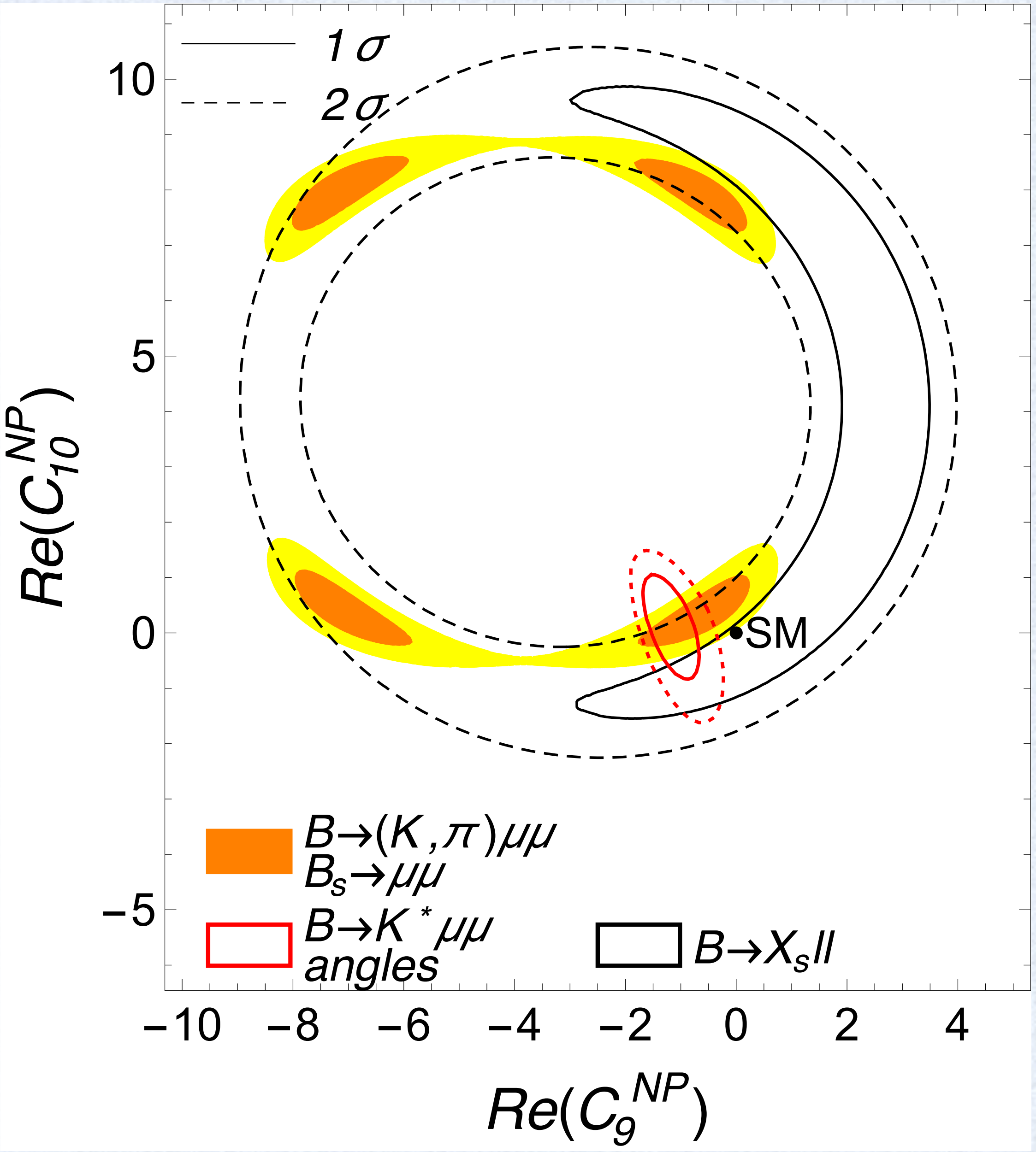
COMBINATION WITH INCLUSIVE

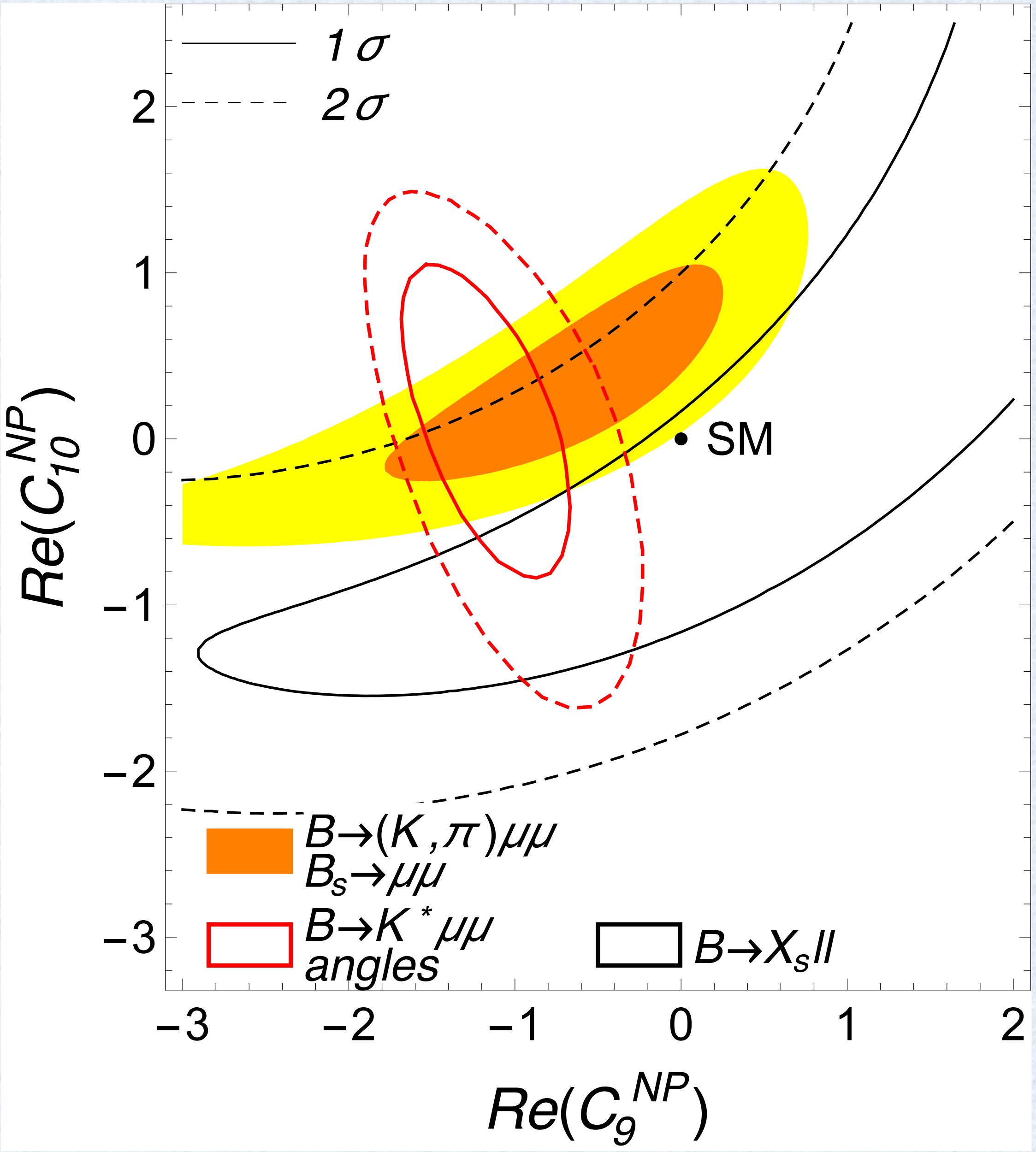


- Inclusive experimental uncertainties still very large
- Constraints from B→K*μμ angular observables is "orthogonal"
[Altmannshofer, Straub, arXiv:1503.06199]
- Without considering B→K*μμ , the tension is at the 2 sigma level

Exclusive: Phenomenology

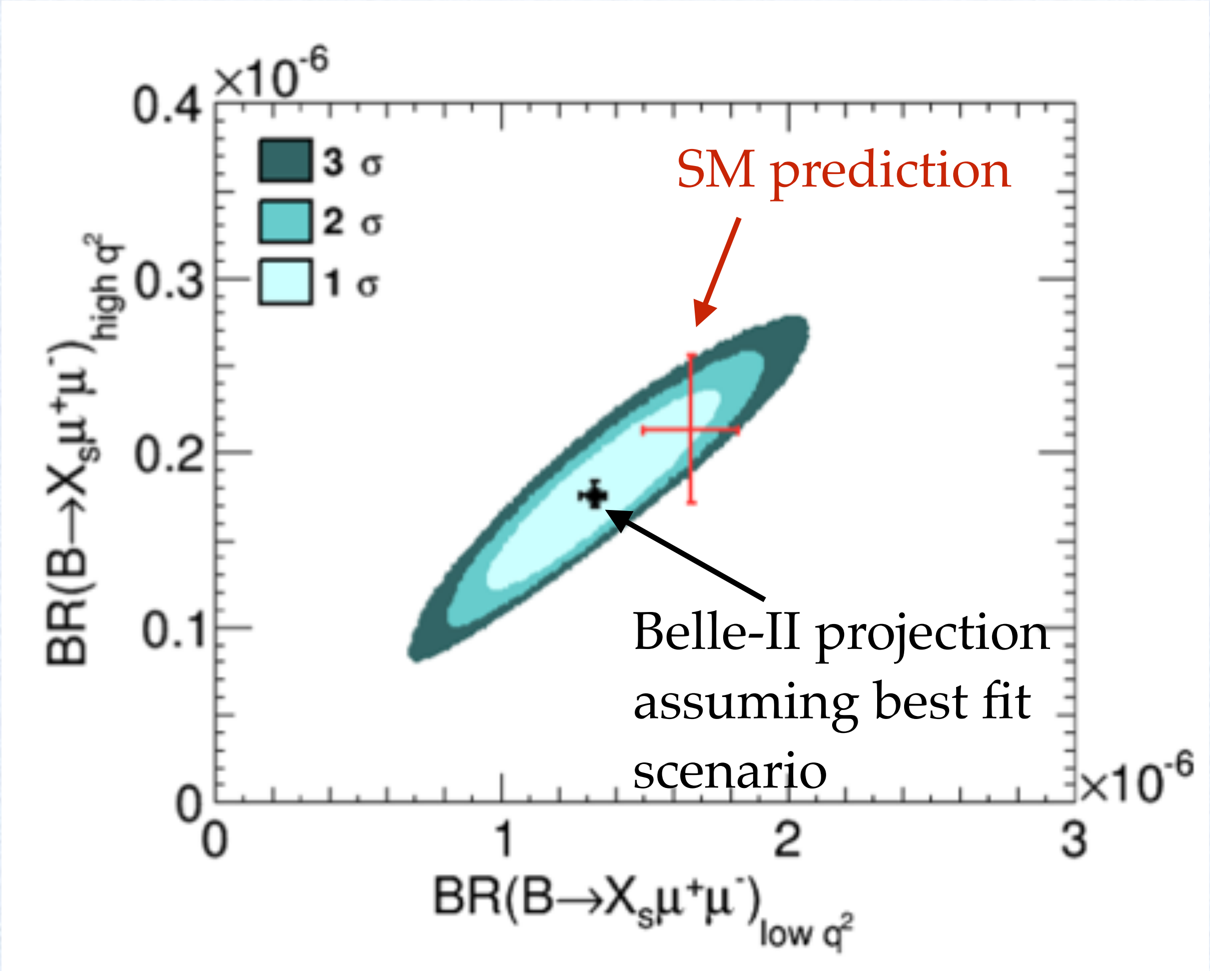
- With the inclusion of $B_s \to \mu\mu$ (only sensitive to C_{10}) the tension remains at the 2 sigma level

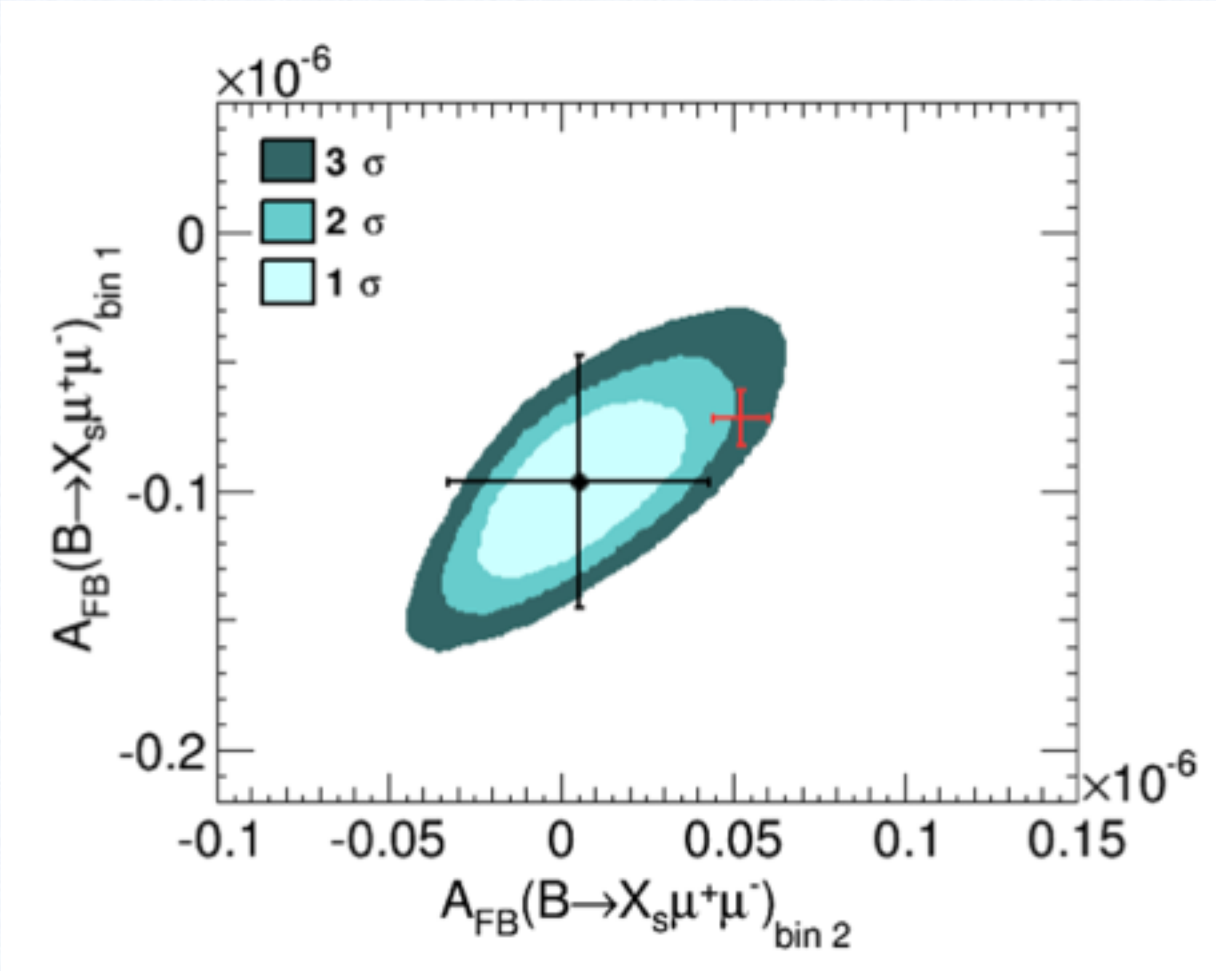




INCLUSIVE/EXCLUSIVE INTERPLAY

- The effects on C_9 and C_9' are large enough to be easily checked at Belle II with inclusive decays (free of most uncertainties that plague the exclusive modes)





[Hurth, Mahmoudi 1411.2786]

BACKUP SLIDES

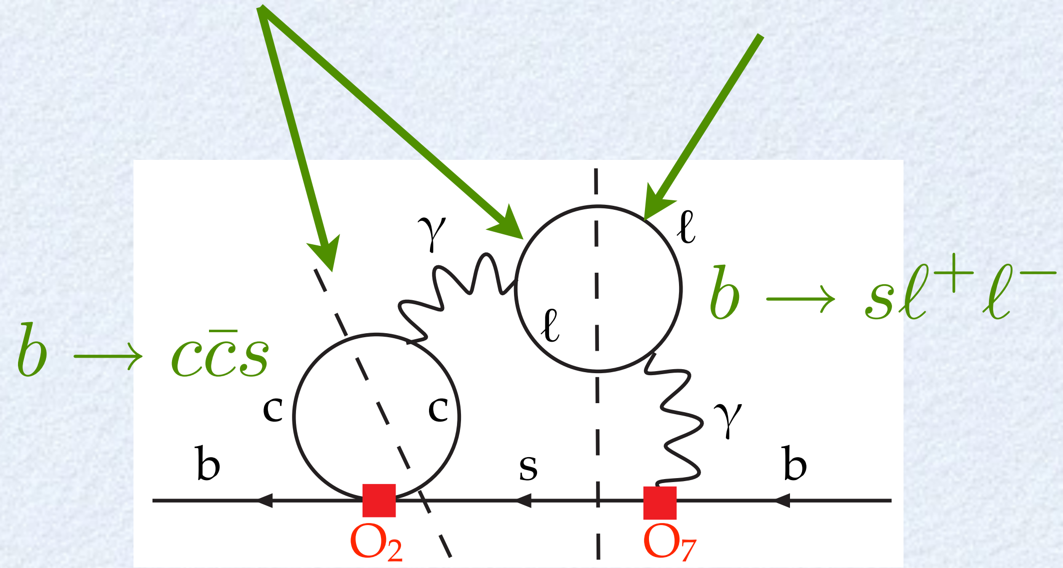
Inclusive: charmonium troubles

- Optical theorem: [Beneke, Buchalla, Neubert, Sachrajda]

$$\mathrm{Im}\left[\sum_{ij}\langle\bar{B}|T\,Q_i(0)\,Q_j(x)|\bar{B}\rangle\right]\sim\Gamma(\bar{B}\to X_s)\neq\Gamma(\bar{B}\to X_s\ell^+\ell^-)$$

$$\Gamma(\bar{B}\to X_s)\sim 10^{-4}$$

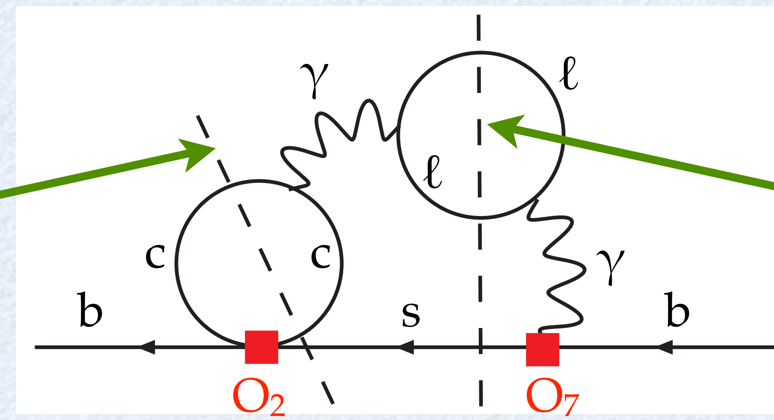
$$\Gamma(\bar{B}\to X_s\ell^+\ell^-)\sim 10^{-6}$$



1. This is **not a violation of quark-hadron duality** (that in the inclusive is related to the integral over the real states in the Xs system)
2. The **OPE itself is perfectly fine** and it breaks down only at large q^2
3. **For q^2 ~ m_{cc} the diagram is controlled by resonant long distance contributions** (think about the hadronic contribution to $(g-2)_\mu$)
4. The problem is that we are not including diagrams corresponding to open charm and hadronic decays of the charmonium resonances

Inclusive: Charmonium Troubles

$b \to c\bar{c}s$

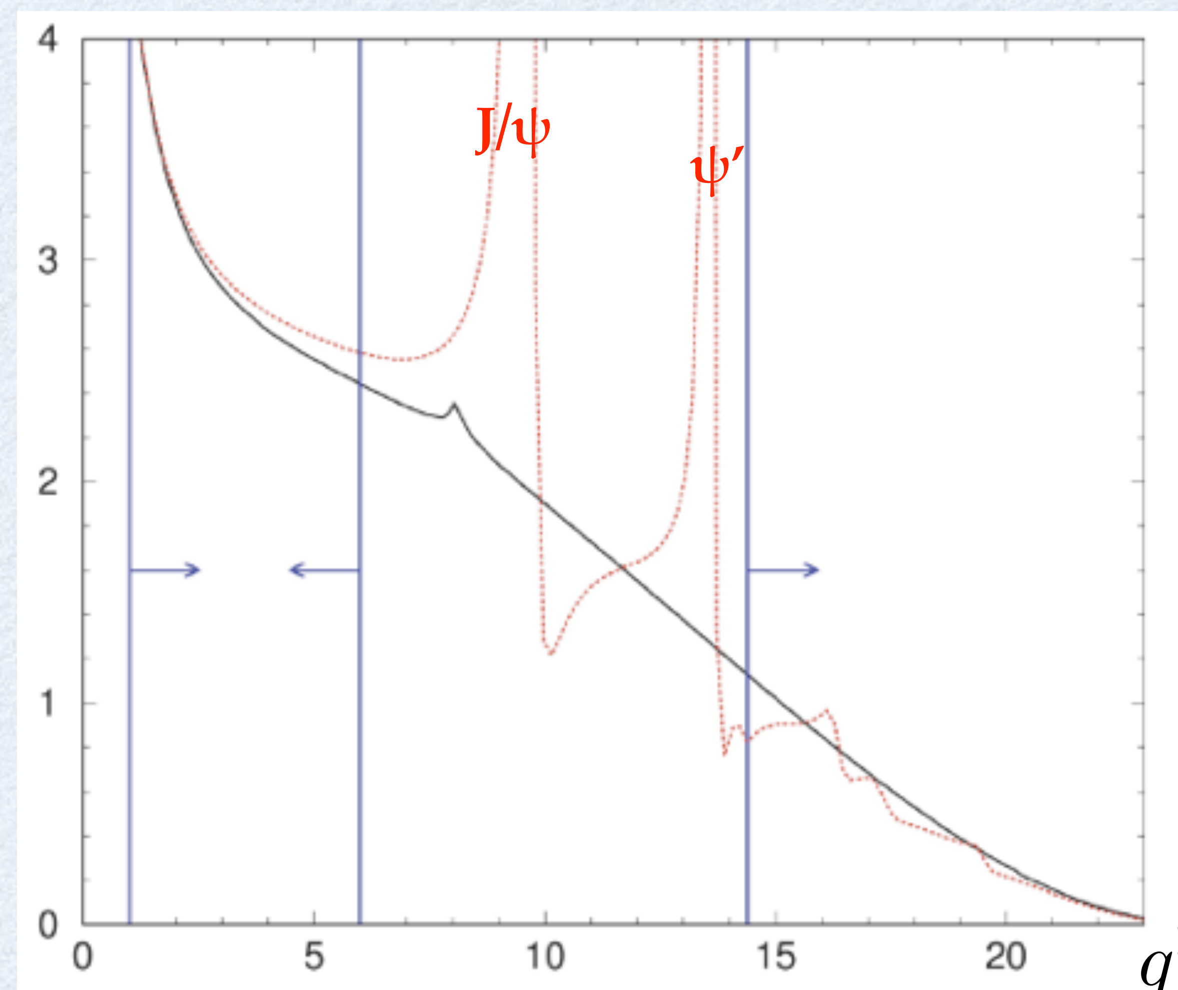


$b \to s\ell^+\ell^-$

- Three regions:
  - $0.04\ \mathrm{GeV}^2 < q^2 < 1\ \mathrm{GeV}^2$
  - ***$1\ \mathrm{GeV}^2 < q^2 < 6\ \mathrm{GeV}^2$***
  - ***$q^2 > 14.4\ \mathrm{GeV}^2$***

  dominated by the photon pole ($b \to s\gamma$)

- Resonances model using data:
  - ★ Krüger-Sehgal (e+e- data)
  - ★ Breit-Wigner ansatz (old approach)



q^2

$$\Gamma(\bar{B} \to X_s) \sim 10^{-4}$$

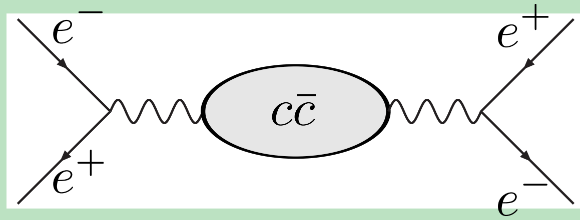
$$\Gamma(\bar{B} \to X_s \ell^+\ell^-) \sim 10^{-6}$$

Inclusive: Charmonium troubles

- Kruger-Sehgal mechanism:

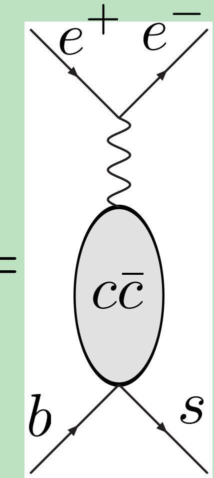
$$R^{c\bar{c}}_{\rm had} = \frac{\sigma(e^+e^- \to c\bar{c}\text{ hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

$$=$$



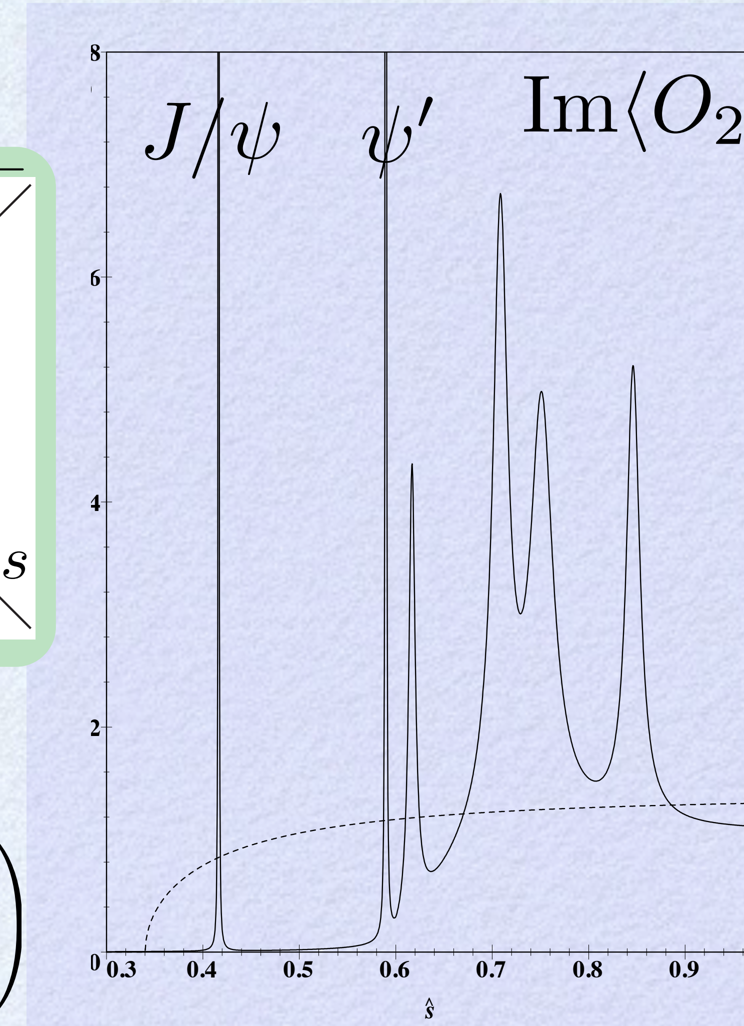
$$\Longleftrightarrow$$

$$\langle O_2 \rangle =$$



$$\mathrm{Im}\langle O_2\rangle \to \langle O_9\rangle_{\rm tree}\left(\frac{\pi}{3}R^{c\bar{c}}_{\rm had}(\hat{s})\right)$$

$$\mathrm{Re}\langle O_2\rangle \to \langle O_9\rangle_{\rm tree}\left(-\frac{8}{9}\log m_c/m_b - \frac{4}{9} + \frac{\hat{s}}{3}P\int_{4\hat{m}_D^2}^{\infty}\frac{R^{c\bar{c}}_{\rm had}(\hat{s}')}{\hat{s}'(\hat{s}'-\hat{s})}d\hat{s}'\right)$$



- Alternatively use a Breit-Wigner ansatz to parametrize <O$_2$>

$$Y_{\rm amm}(\hat{s}) = Y_{\rm pert}(\hat{s}) + \frac{3\pi}{\alpha^2}C^{(0)}\sum_{V_i=\psi(1s),\ldots,\psi(6s)}\kappa_i\frac{\Gamma(V_i\to\ell^+\ell^-)\,m_{V_i}}{{m_{V_i}}^2 - \hat{s}\,{m_B}^2 - i m_{V_i}\Gamma_{V_i}}$$

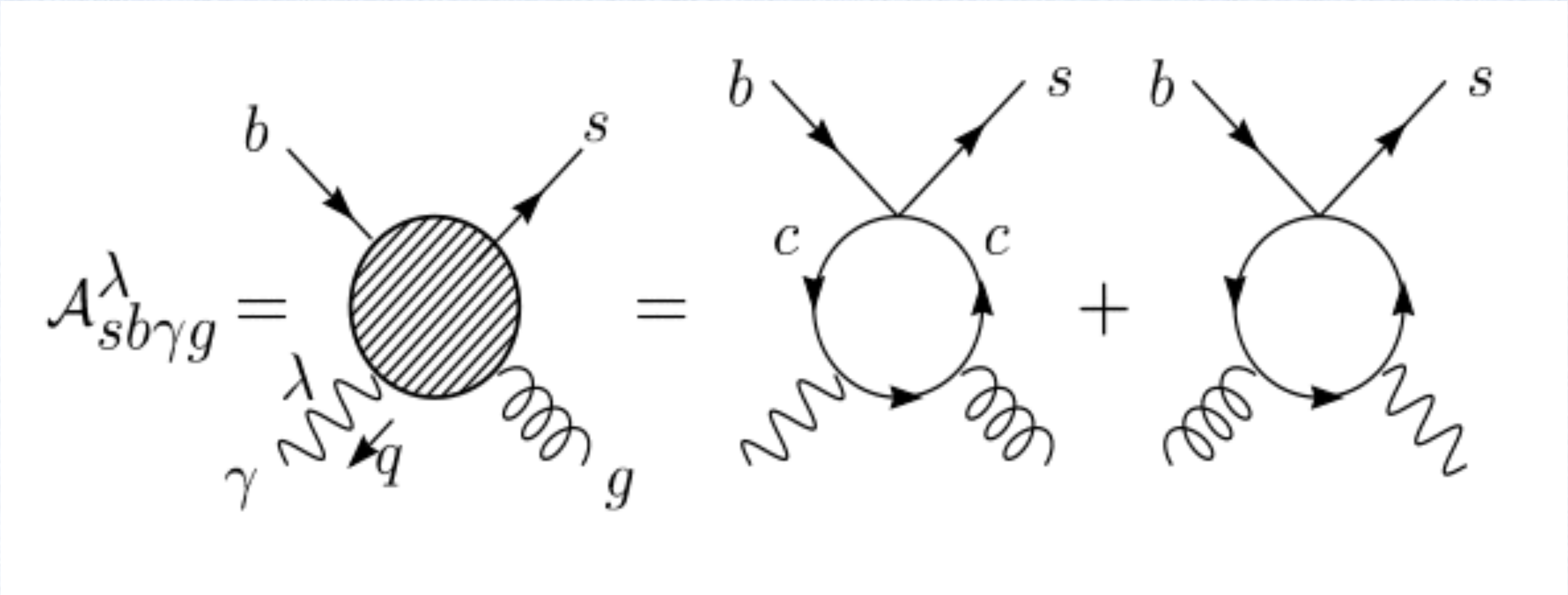
Fudge factors

- The impact in the low q^2 region is +1.8%, in the high q^2 region is -10%
- Historically $\kappa_i \approx 2$. Using NNLO Wilson coefficients one finds $\kappa_i \approx 1$

[Bobeth, Hiller, van Dyk]

Inclusive: Charmonium troubles

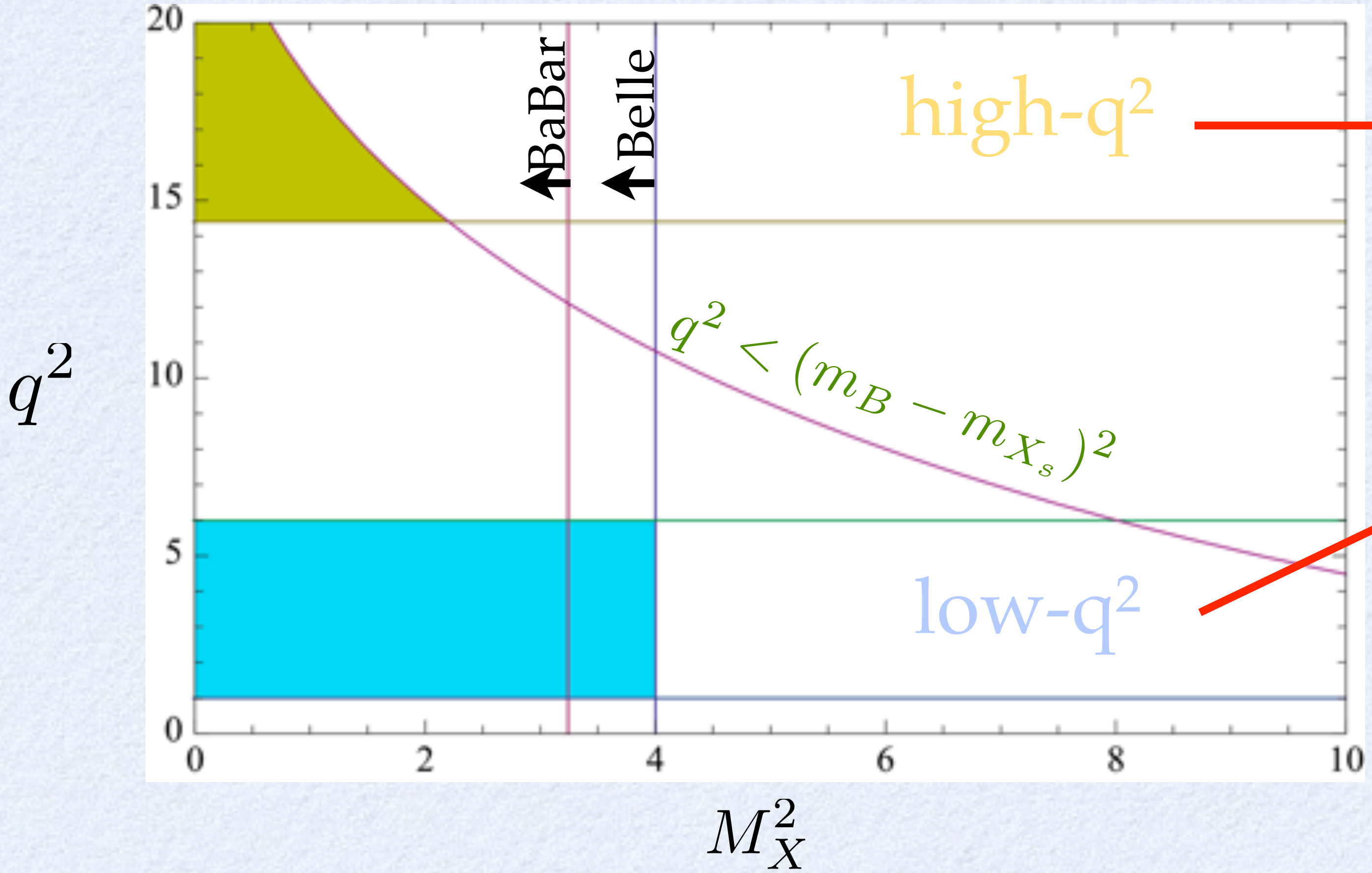
- The KS mechanism captures the long distance contribution that corresponds to cc pair in color singlet state (J/ψ)
- The color octet contribution is non-resonant, is captured by Λ^2/m_c^2 power corrections



and yields a local contribution proportional to $\langle \bar{B}|\bar{b}\sigma_{\mu\nu}G^{\mu\nu}b|\bar{B}\rangle \sim \lambda_2$

Inclusive: X_s cut

- MX cuts required to suppress the $b \to c\, l^- \nu \to s\, l^- l^+ \nu\, \nu$ background



unaffected

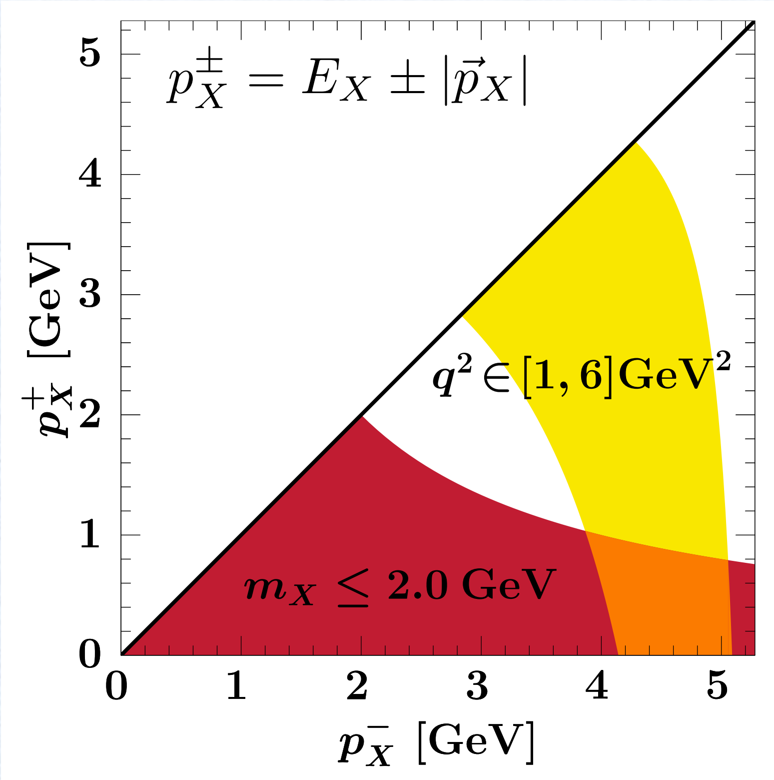
parton level at LO:
$M_{Xs} = m_s$
bremsstrahlung:
$m_s < M_{Xs} < m_b$
non-perturbative effects:
phase space (M_B-$m_b = \Lambda$)
Fermi motion [Ali, Hiller]

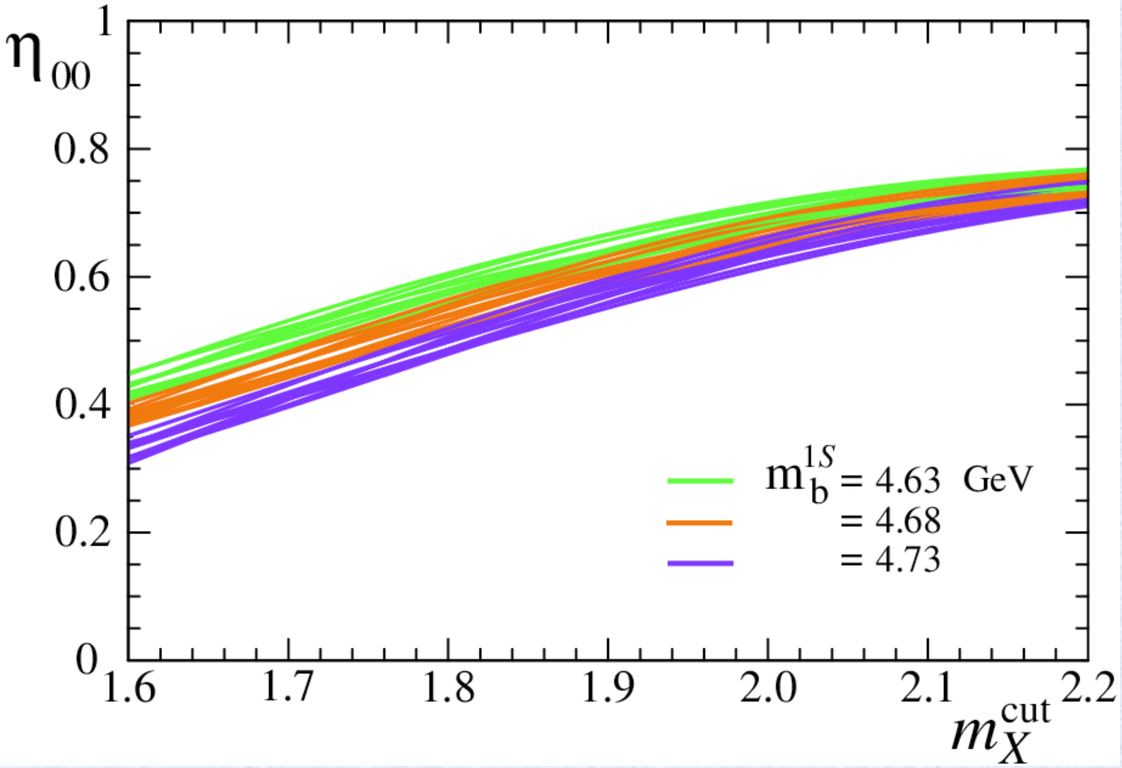
- Correction factor added in experimental results

- Framework: Fermi motion, SCET

Inclusive: X_s cut

- New idea: use SCET to describe the X_s system





$$p_X^+ \ll p_X^- \Longrightarrow m_X^2 \ll E_X^2$$

X_S is a hard-collinear mode:

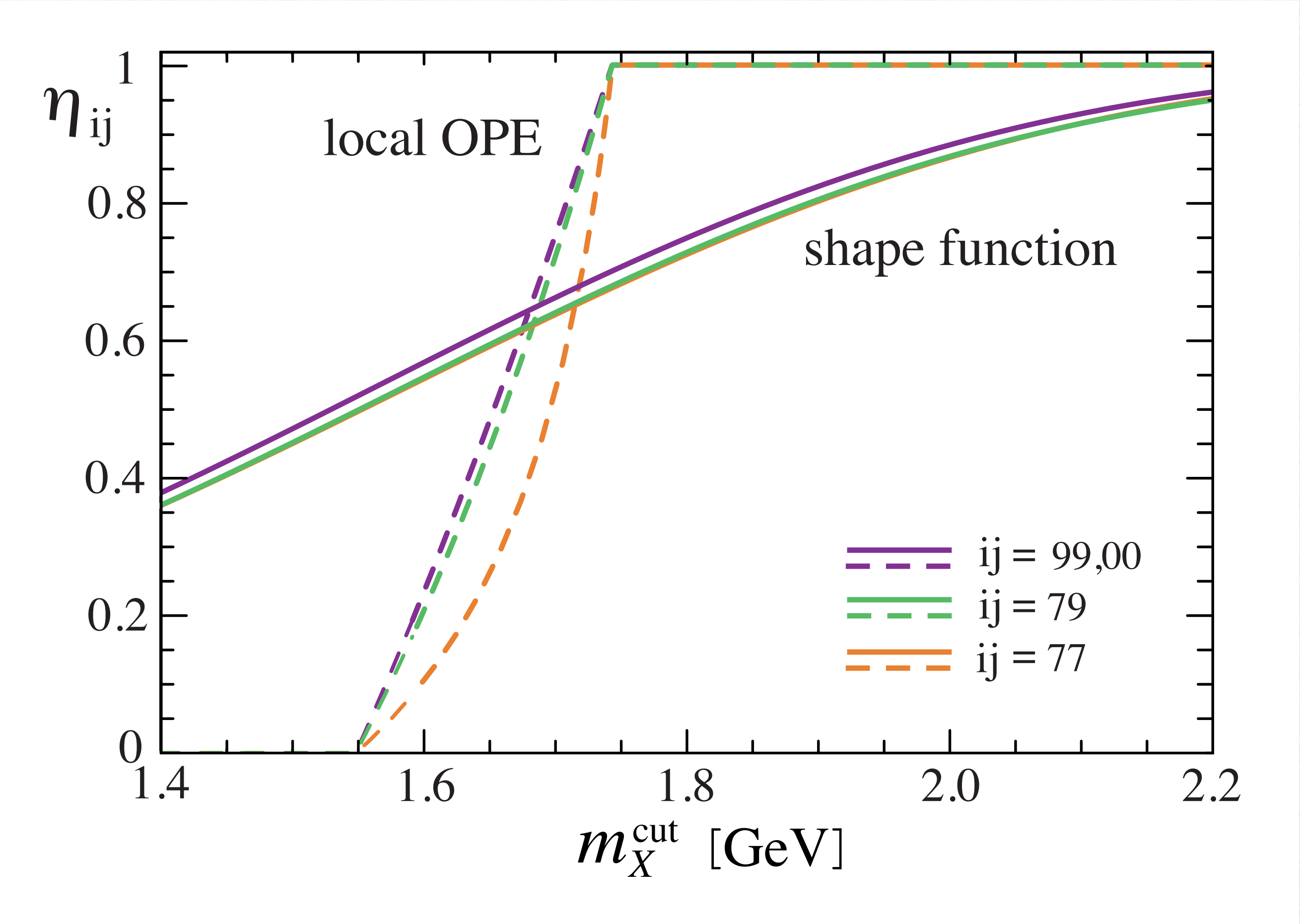
$$\Lambda^2 \ll p_{X_s}^2 \sim \Lambda m_b \ll m_b^2$$

$$\eta_{ij} = \frac{\displaystyle\int_{1\,\mathrm{GeV}^2}^{6\,\mathrm{GeV}^2} \mathrm{d}q^2 \int_0^{m_X^{\mathrm{cut}}} \mathrm{d}m_X^2 \, \frac{\mathrm{d}\Gamma_{ij}}{\mathrm{d}q^2\,\mathrm{d}m_X^2}}{\displaystyle\int_{1\,\mathrm{GeV}^2}^{6\,\mathrm{GeV}^2} \mathrm{d}q^2 \, \frac{\mathrm{d}\Gamma_{ij}}{\mathrm{d}q^2}}$$

ij: C_9^2 and C_{10}^2, C_7C_9, C_7^2

Inclusive: X_s cut

- At leading power and at order α_s, these corrections are a universal multiplicative factor:



- Reduce non-perturbative effects by considering: [Lee, Ligeti, Stewart, Tackmann]

$\Gamma^{\rm cut}(B \to X_s \ell^+ \ell^-)/\Gamma^{\rm cut}(B \to X_u \ell \bar{\nu})$ *[same M_X cut]*

Inclusive: High-q^2

$$\Gamma\left[\bar{B}\to X_s\ell^+\ell^-\right] = \Gamma\left[\bar{b}\to X_s\ell^+\ell^-\right] + O\left(\frac{\Lambda_{QCD}^2}{m_b^2}, \frac{\Lambda_{QCD}^3}{m_b^3}, \frac{\Lambda_{QCD}^2}{m_c^2}, \ldots\right)$$

local OPE, optical theorem
quark-hadron duality

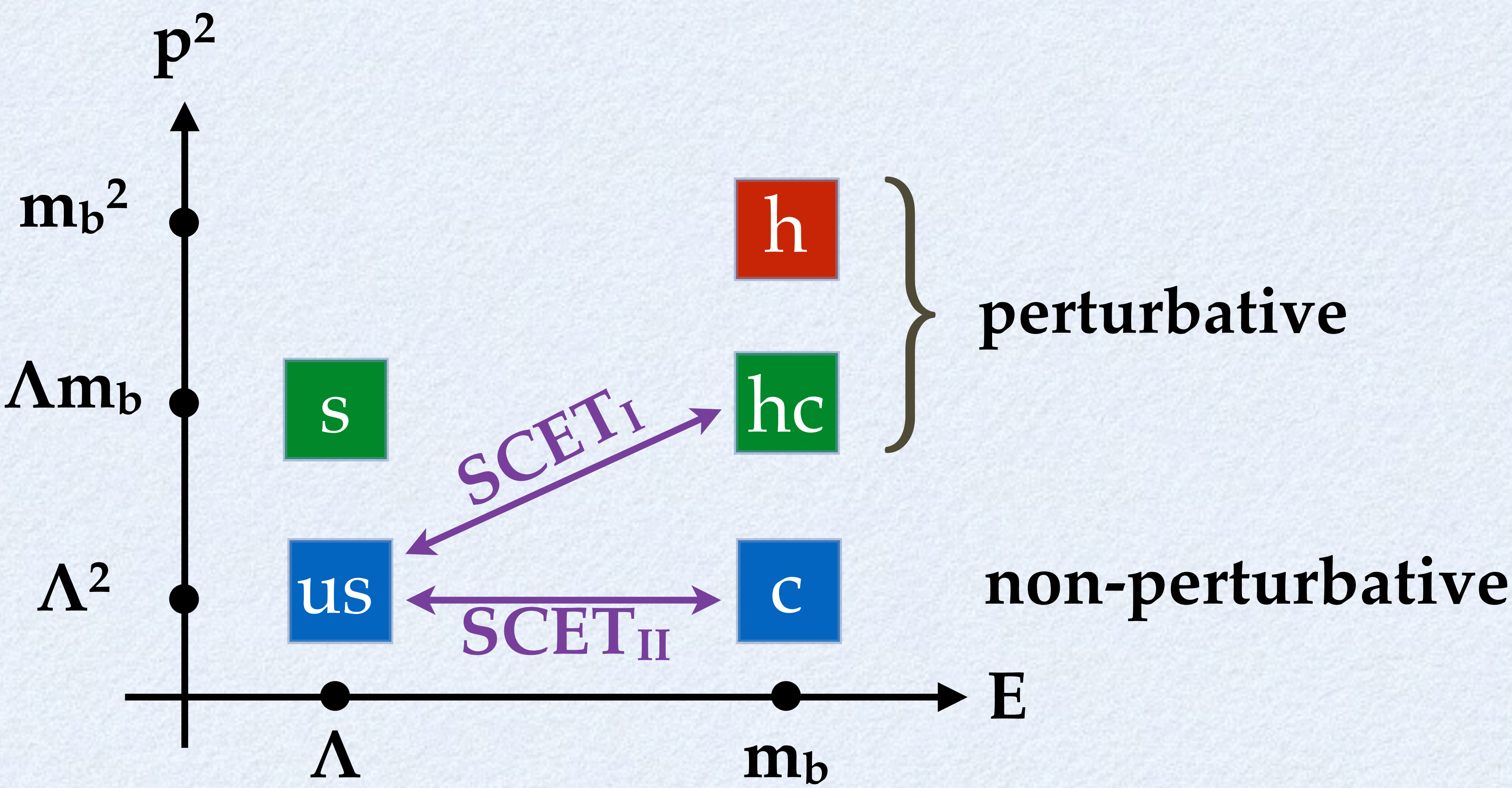
HQET

- Low-q^2: theory in excellent shape
- High-q^2: the OPE starts to break down and only integrated quantities are reliable
  - mismatch between partonic and hadronic phase space
  - power corrections are larger
  - higher charmonium resonances must be integrated over
  - things improve dramatically by normalizing the rate to the semileptonic rate with the same q^2 cut [Ligeti et al.]

$$\mathcal{R}(s_0) = \int_{s_0}^{1} \mathrm{d}\hat{s}\, \frac{\mathrm{d}\Gamma(\bar{B}\to X_s\ell^+\ell^-)}{\mathrm{d}\hat{s}} \Big/ \int_{s_0}^{1} \mathrm{d}\hat{s}\, \frac{\mathrm{d}\Gamma(\bar{B}^0\to X_u\ell\nu)}{\mathrm{d}\hat{s}}$$

Exclusive: Low Q^2

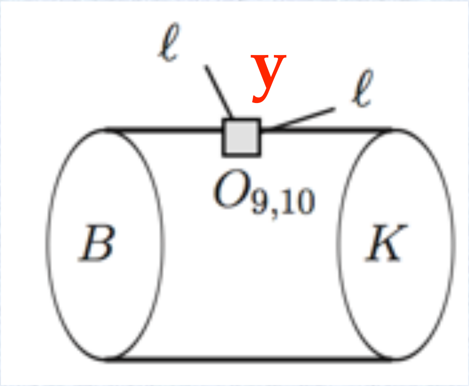
- **Soft Collinear Effective Theory**



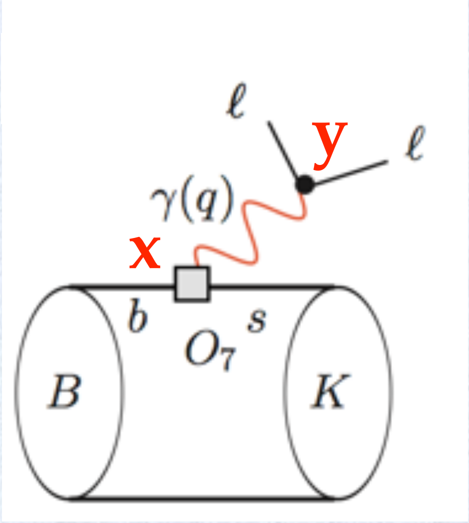
- us-hc factorization is rock solid (inclusive modes, collider physics)
- us-c factorization is more problematic (exclusive modes) because both collinear and ultrasoft modes have $p^2 \sim \Lambda^2$ and sometimes they don't factorize (zero-bin, messenger modes …)

Theory: Exclusive (high q^2)

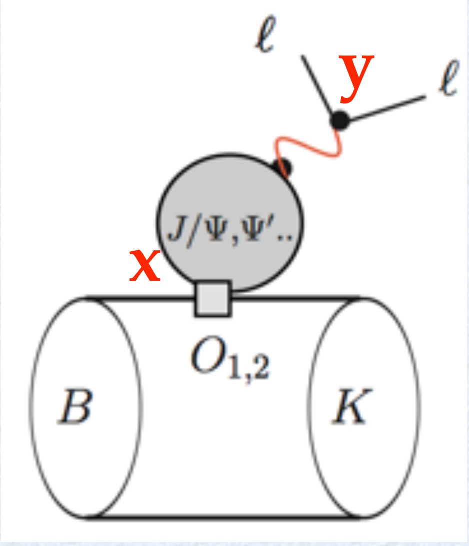
- b→sll matrix elements are controlled by the large q^2



$$\langle K^{(*)}|O_{9,10}(y)|B\rangle \sim f_+(q^2)$$ local



$$\langle K^{(*)}|TJ^\mu(x)O_7(y)|B\rangle \sim \frac{1}{q^2}f_T(q^2)$$ local

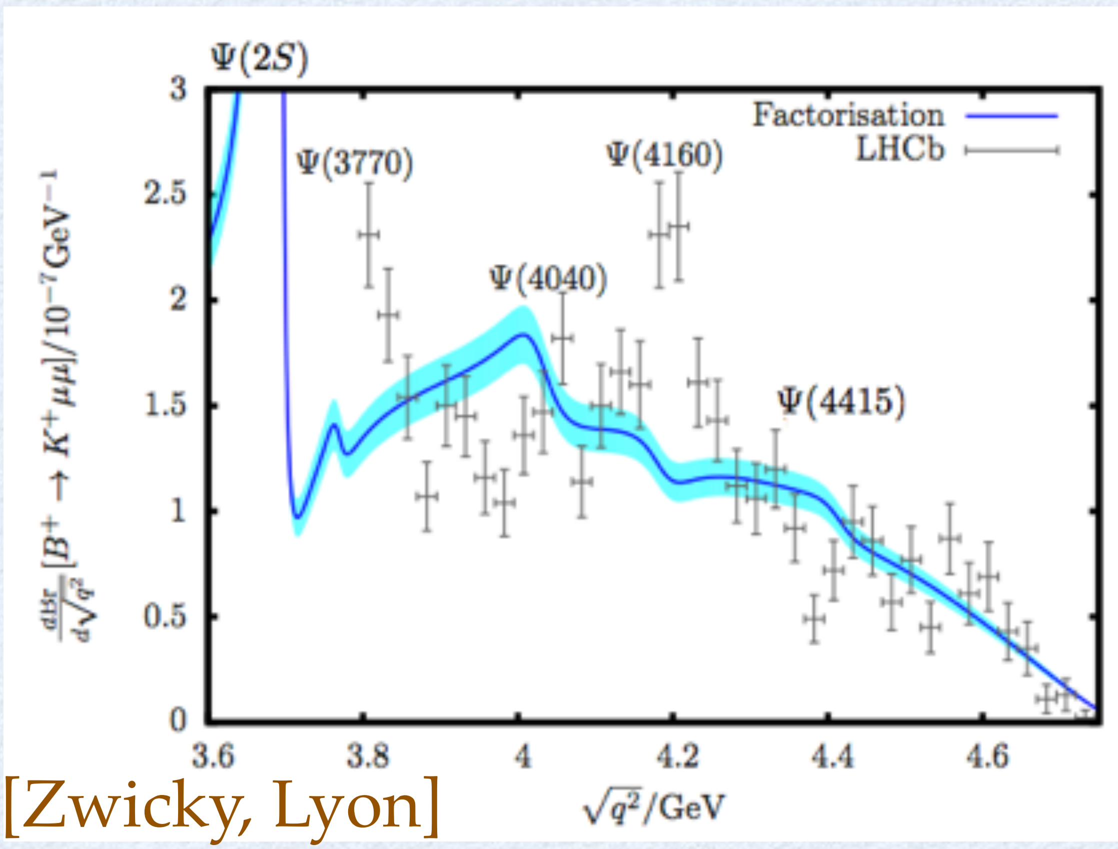


$$\langle K^{(*)}|TJ^\mu(x)O_{1,2}(y)|B\rangle \sim h(q^2)\ f_+(q^2)$$ highly non-local

Does this signal a breakdown of the OPE?

THEORY: EXCLUSIVE (HIGH Q^2)

- Does the KS mechanism to include resonant effects work?
- For $B \to Kll$ these attempts seem to fail:



[Zwicky, Lyon]

Experimental and theoretical valley and peaks do not match

Beylich, Buchalla and Feldmann argue that integrating over the high-q^2 region and invoking quark-hadron duality yields accurate predictions

- What is going on? Apparently this seems to be a failure of QCD factorization in describing the hadronic $B \to \psi_{cc} K$ process (i.e. color octet contributions might be important)
- Will this persists for the K^* and Xs modes?
  Apparently not [Bobeth, Hiller, van Dyk]

Inclusive: definition of observables

- At leading order in QED and at all orders in QCD, the double differential width is a quadratic polynomial: Γ~a cos²θ+b cosθ+c.
- Γ receives non polynomial log-enhanced QED corrections
- Best strategy: **measure individual observables (BR, A_{FB}) and use Legendre polynomial as projectors**

$$\boxed{H_I(q^2) = \int_{-1}^{+1} \frac{d^2\Gamma}{dq^2 dz} W_I(z) dz}$$

$$W_T = \frac{2}{3} P_0(z) + \frac{10}{3} P_2(z), \qquad \boxed{W_3 = P_3(z)}$$

$$W_L = \frac{1}{3} P_0(z) - \frac{10}{3} P_2(z), \qquad \boxed{W_4 = P_4(z)}$$

$$W_A = \frac{4}{3}\text{sign}(z).$$

new observables

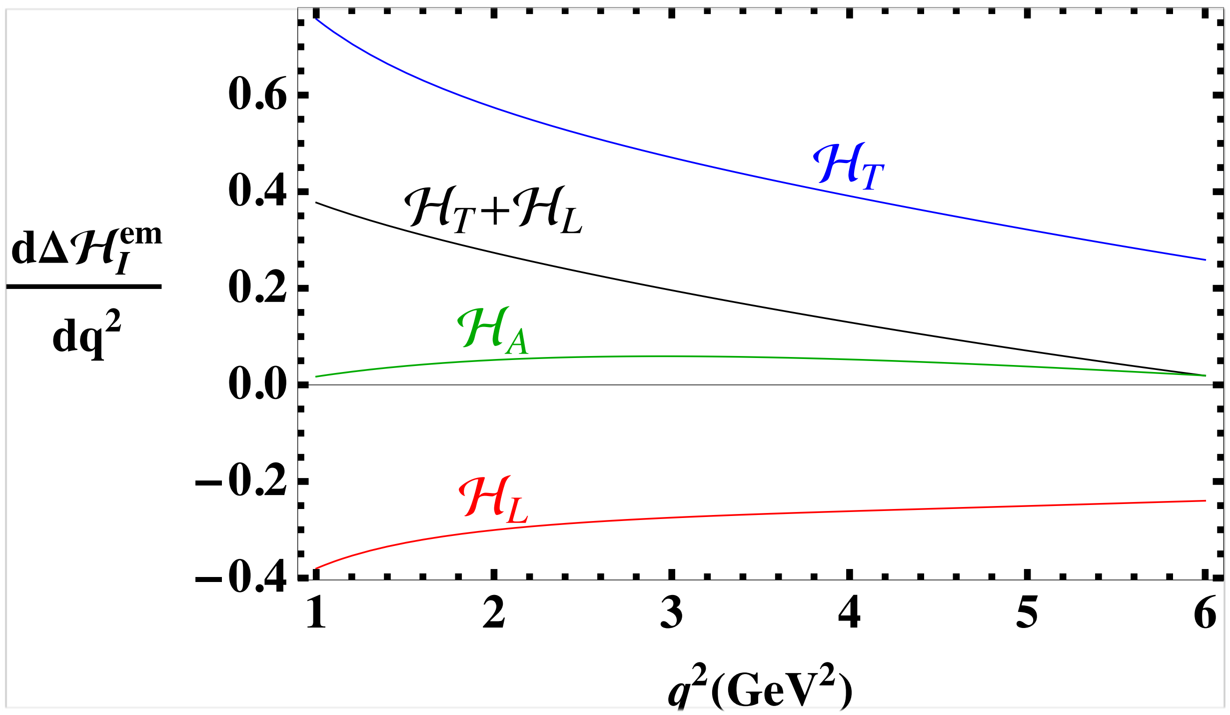
$$\frac{d\Gamma}{dq^2} = \int_{-1}^{+1} \frac{d^2\Gamma}{dq^2 dz} dz = H_T + H_L$$

$$\frac{dA_{\rm FB}}{dq^2} = \int_{-1}^{+1} \frac{d^2\Gamma}{dq^2 dz} \text{sign}(z) dz = \frac{3}{4} H_A$$

$$\frac{d\bar{A}_{\rm FB}}{dq^2} = \frac{\int_{-1}^{+1} \frac{d^2\Gamma}{dq^2 dz} \text{sign} dz}{\int_{-1}^{+1} \frac{d^2\Gamma}{dq^2 dz} dz} = \frac{3}{4} \frac{H_A}{H_T + H_L}$$

QED logs: size of the effect

- We calculated the effect of collinear photon radiation and found large effects on some observables

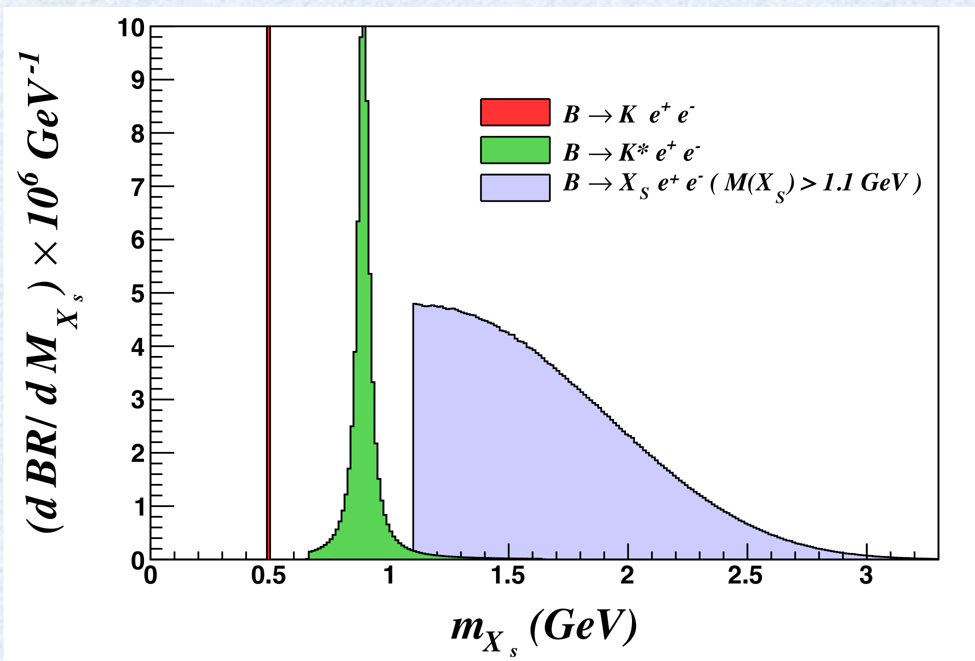


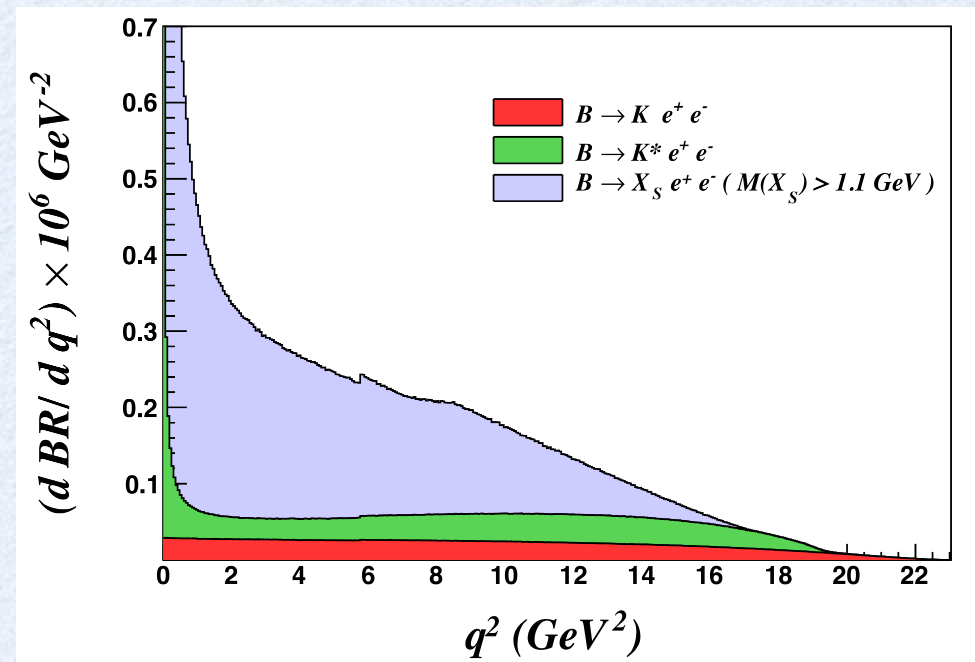
Size of QED contributions to the H_T and H_L is similar

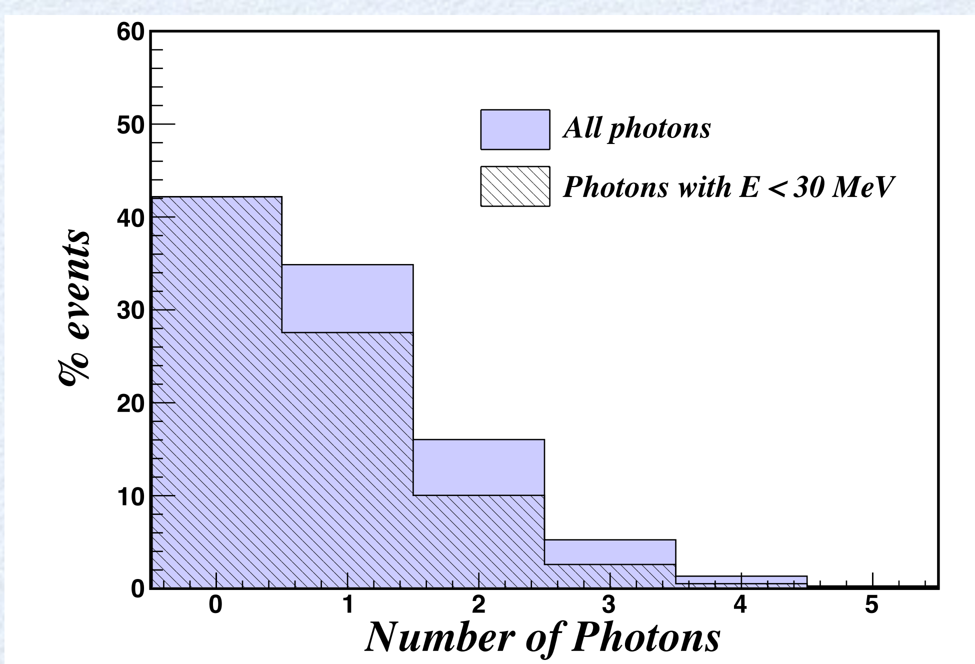
	$q^2 \in [1,6]$ GeV^2			$q^2 \in [1,3.5]$ GeV^2			$q^2 \in [3.5,6]$ GeV^2		
	$\frac{O_{[1,6]}}{\mathcal{B}_{[1,6]}}$	$\frac{\Delta O_{[1,6]}}{\mathcal{B}_{[1,6]}}$	$\frac{\Delta O_{[1,6]}}{O_{[1,6]}}$	$\frac{O_{[1,3.5]}}{\mathcal{B}_{[1,6]}}$	$\frac{\Delta O_{[1,3.5]}}{\mathcal{B}_{[1,6]}}$	$\frac{\Delta O_{[1,3.5]}}{O_{[1,3.5]}}$	$\frac{O_{[3.5,6]}}{\mathcal{B}_{[1,6]}}$	$\frac{\Delta O_{[3.5,6]}}{\mathcal{B}_{[1,6]}}$	$\frac{\Delta O_{[3.5,6]}}{O_{[3.5,6]}}$
$\mathcal{B}$	100	5.1	5.1	54.6	3.7	6.8	45.4	1.4	3.1
$\mathcal{H}_T$	19.5	14.1	72.5	9.5	8.8	92.1	10.0	5.4	53.6
$\mathcal{H}_L$	80.0	-8.7	-10.9	44.7	-4.7	-10.6	35.3	-4.0	-11.3
$\mathcal{H}_A$	-3.3	1.4	-43.6	-7.2	0.8	-10.7	4.0	0.6	16.2

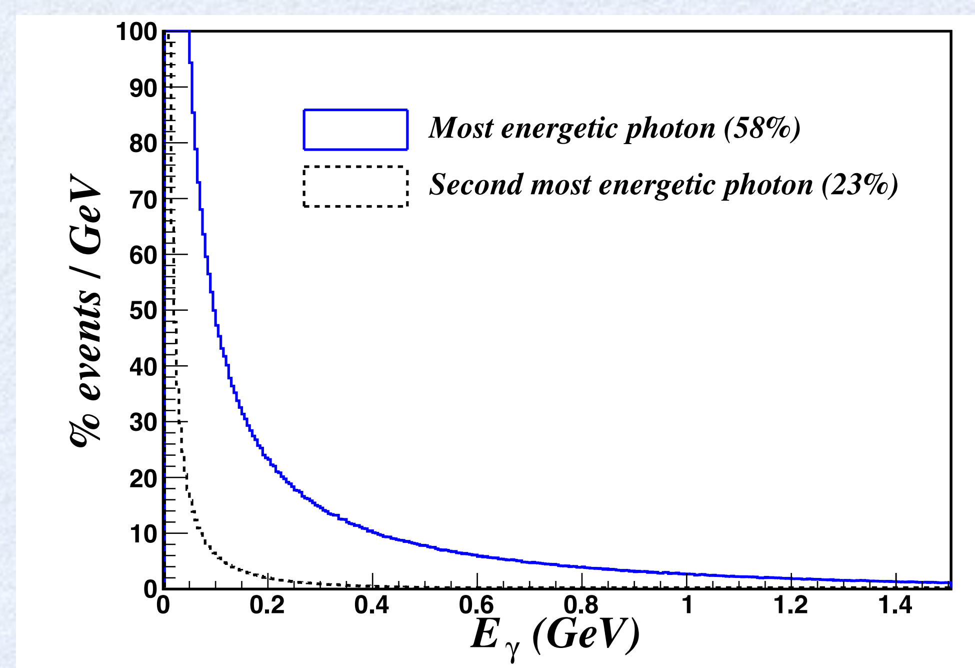
QED Logs: Monte Carlo

- EM effects have been calculated analytically and cross checked against Monte Carlo generated events (EVTGEN + PHOTOS)



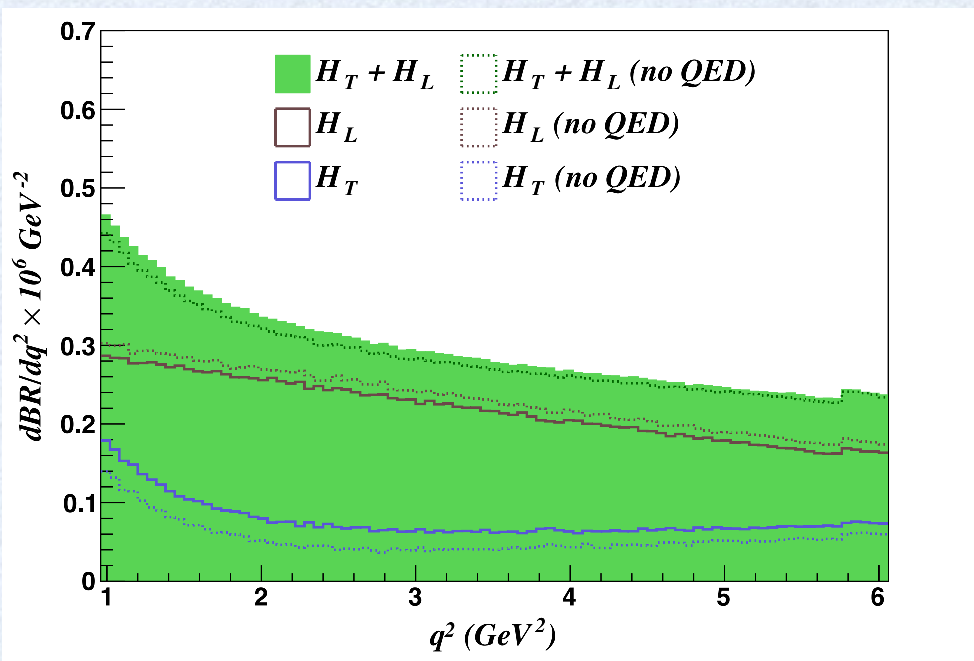


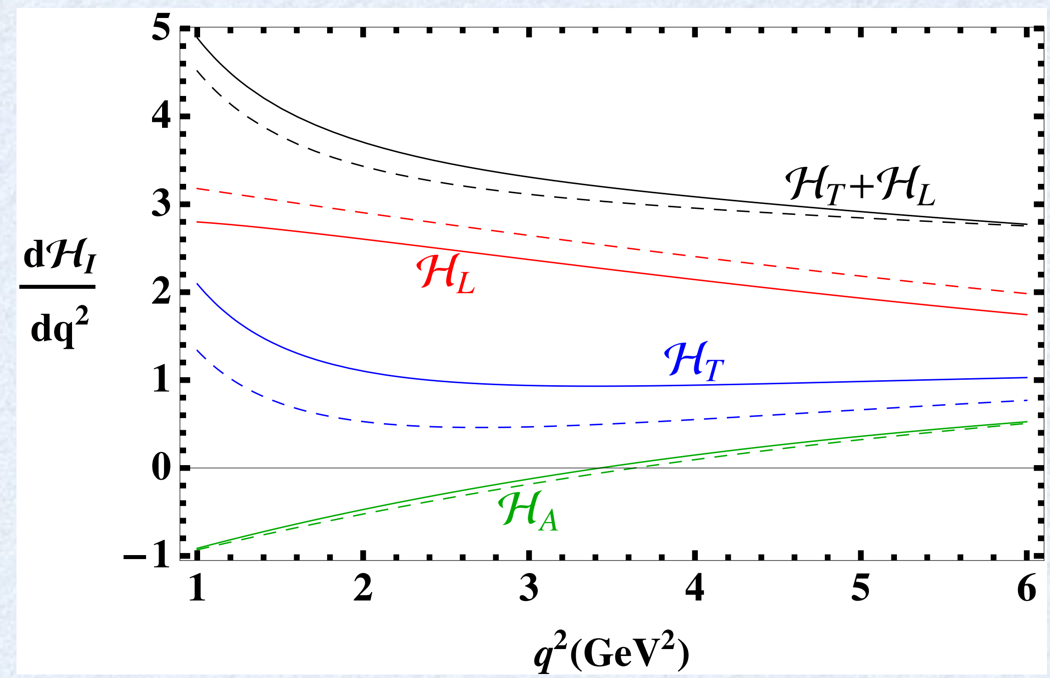


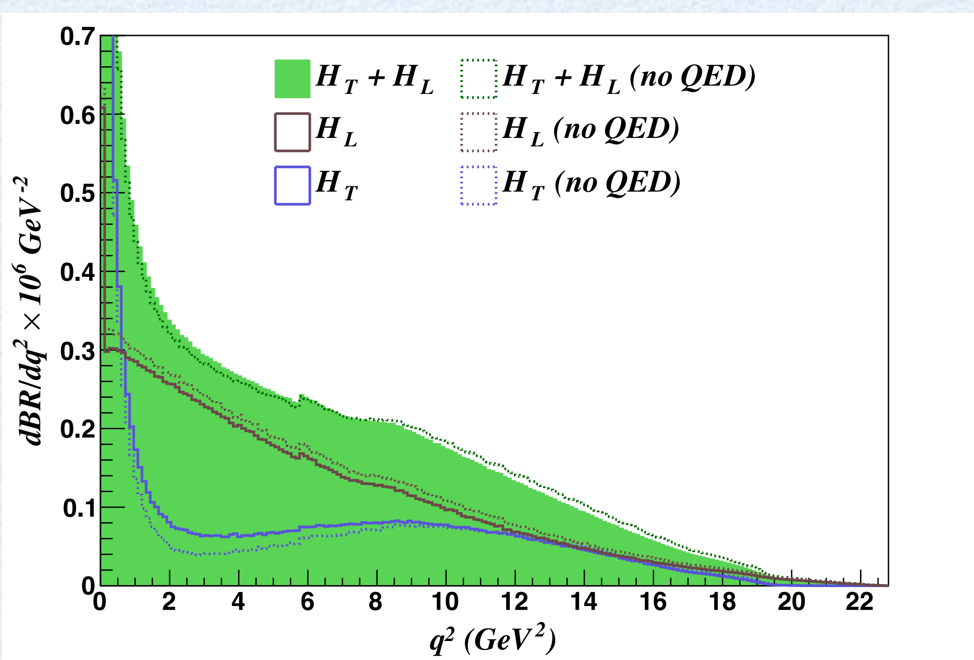


QED Logs: Monte Carlo

- The Monte Carlo study reproduces the main features of the analytical results







Monte Carlo:

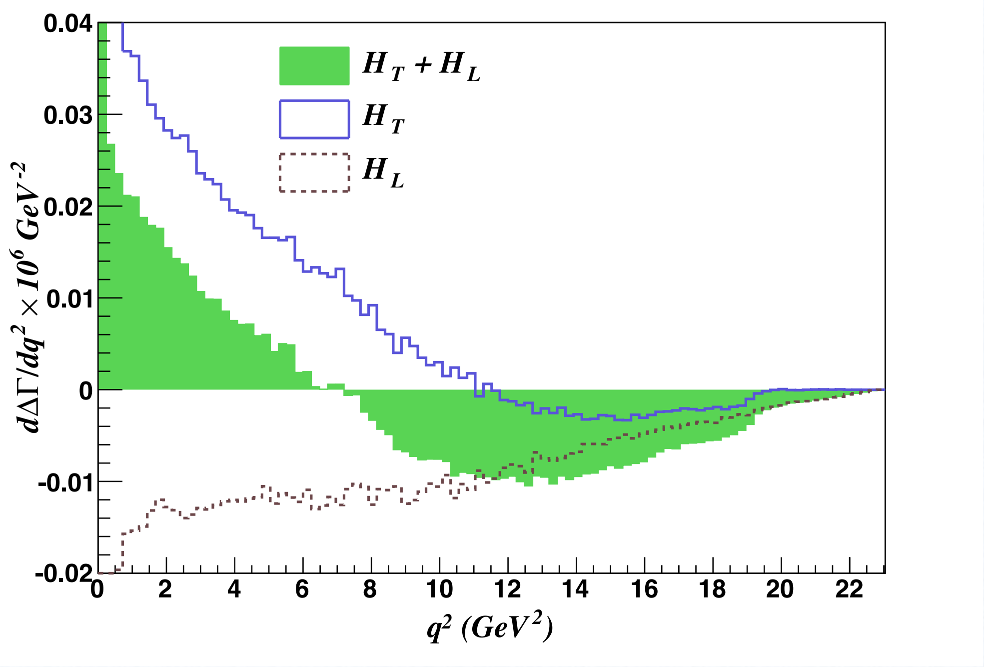
	$q^2 \in [1,6]$ GeV^2		
	$\frac{O_{[1,6]}}{\mathcal{B}_{[1,6]}}$	$\frac{\Delta O_{[1,6]}}{\mathcal{B}_{[1,6]}}$	$\frac{\Delta O_{[1,6]}}{O_{[1,6]}}$
$\mathcal{B}$	100	3.5	3.5
$\mathcal{H}_T$	19.0	8.0	43.0
$\mathcal{H}_L$	81.0	-4.5	-5.5

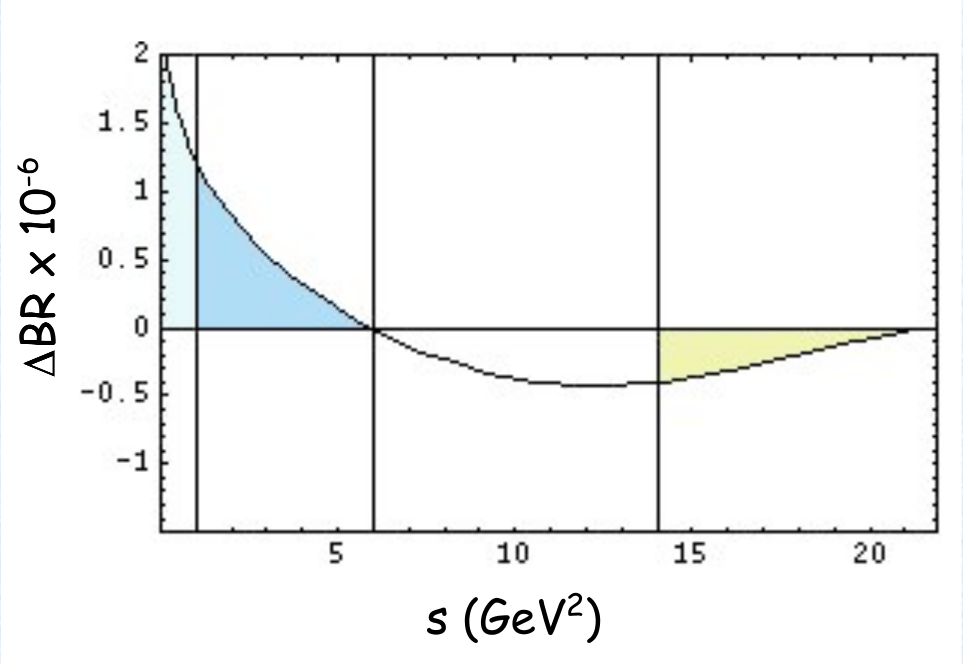
Analytical:

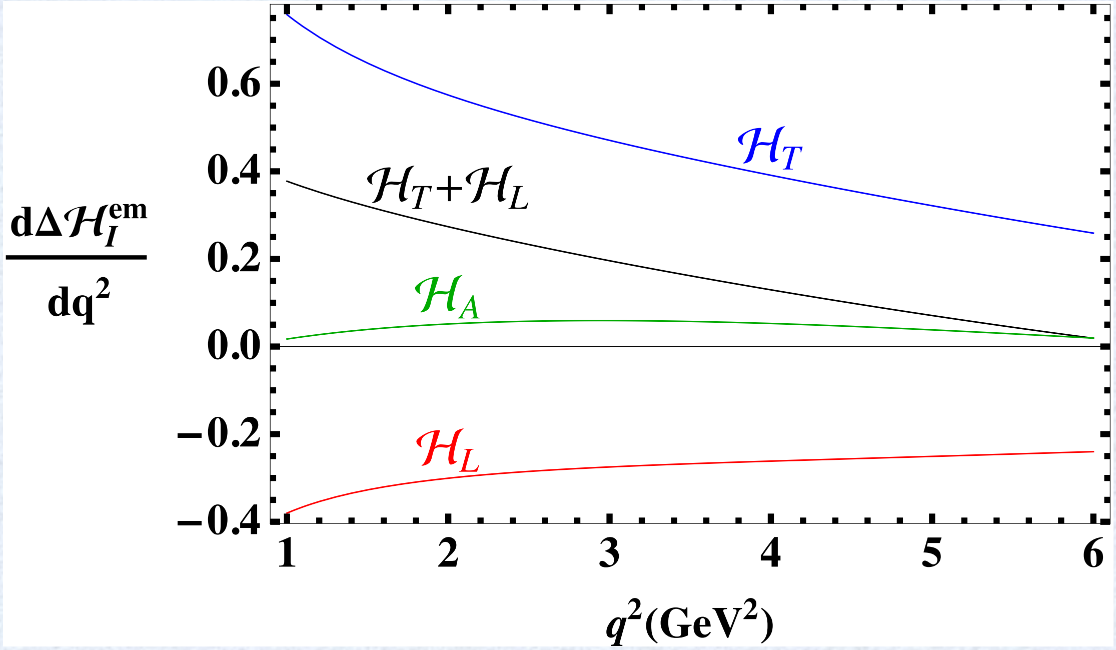
	$q^2 \in [1,6]$ GeV^2		
	$\frac{O_{[1,6]}}{\mathcal{B}_{[1,6]}}$	$\frac{\Delta O_{[1,6]}}{\mathcal{B}_{[1,6]}}$	$\frac{\Delta O_{[1,6]}}{O_{[1,6]}}$
$\mathcal{B}$	100	5.1	5.1
$\mathcal{H}_T$	19.5	14.1	72.5
$\mathcal{H}_L$	80.0	-8.7	-10.9

QED Logs: Monte Carlo

- The Monte Carlo study reproduces the main features of the analytical results

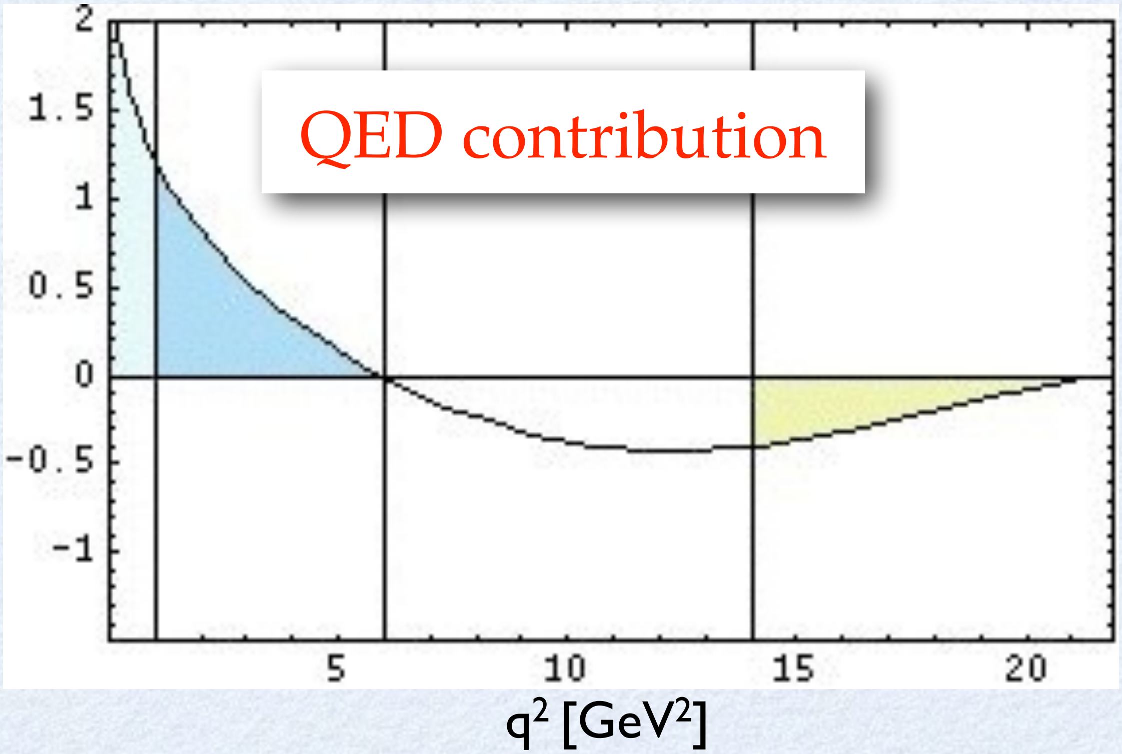






Inclusive: QED Logs

- The ***rate is proportional to*** $\alpha_{em}^2(\mu^2)$. Without QED corrections the scale μ is undetermined $\rightarrow \pm 4\%$ uncertainty
- Focus on corrections enhanced by large logarithms:
  - $\alpha_{\rm em} \log(m_W/m_b) \sim \alpha_{\rm em}/\alpha_s$ [WC, RG running] [Bobeth,Gambino,Gorbahn,Haisch]
  - $\alpha_{\rm em} \log(m_\ell/m_b)$ [Matrix Elements]
- The differential rate is not IR safe with respect to photon emission the results in the presence of a physical collinear logarithm, $\log(m_\ell/m_b)$



$$\text{virtual} = \frac{A_{\rm soft+collinear}}{\epsilon^2} + \frac{B_{\rm collinear} + B_{\rm soft}}{\epsilon} + C$$

$$\text{real} = -\frac{A_{\rm soft+collinear}}{\epsilon^2} - \frac{B'_{\rm collinear} + B_{\rm soft}}{\epsilon} + C'$$

$$\int dq^2 \left(B_{\rm collinear} - B'_{\rm collinear}\right) = 0$$

QED logs in R_K?

- Inclusive: at BaBar and Belle the Xs system is reconstructed as sum over exclusive final states. **Most of the photons are not recovered nor searched for**. The analysis is performed by letting them be part of the hadronic system: **$\log(m_{e,\mu}/m_b)$ is physical**.

- Exclusive: At LHCb the B meson are massively boosted and collinear photons can be extremely energetic. LHCb uses PHOTOS to put back into the leptons all soft/collinear emissions. This procedure is cross checked on $J/\psi \to (ee,\mu\mu)$.
There are no $\log(m_{e,\mu}/m_b)$ enhanced corrections.

- Given the not-so-great agreement between the analytic calculation and the MC simulation, LHCb is pursuing a data-driven approach to the reconstruction of missing photons

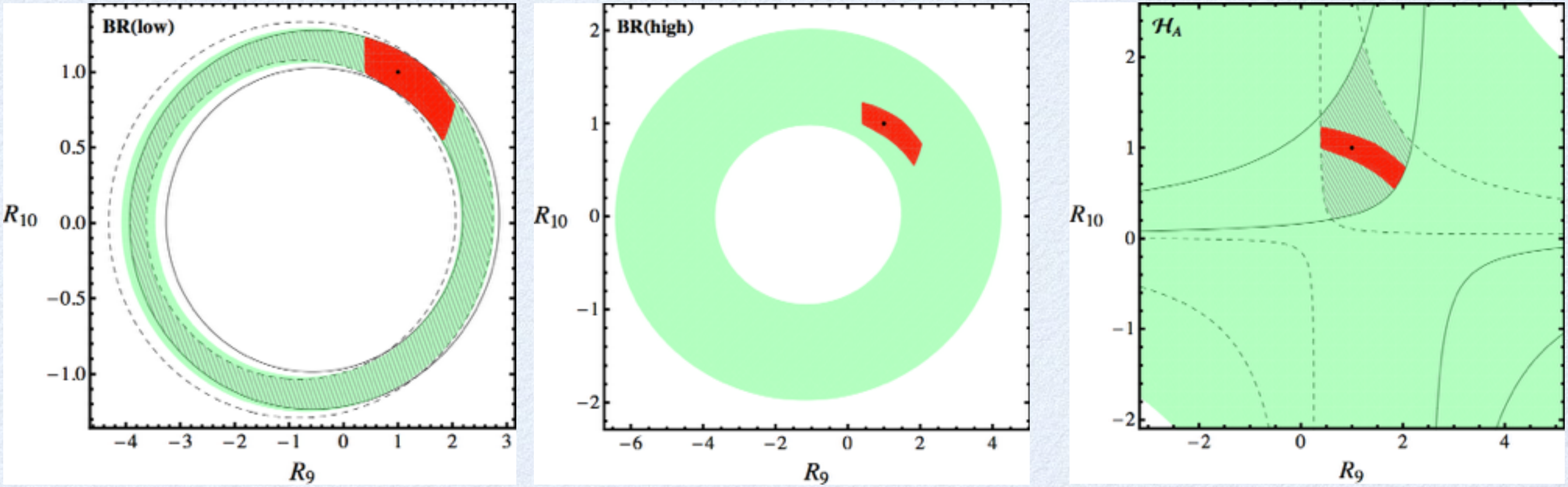
Inclusive: Projections

- Projected reach with 50 ab^{-1} of integrated luminosity

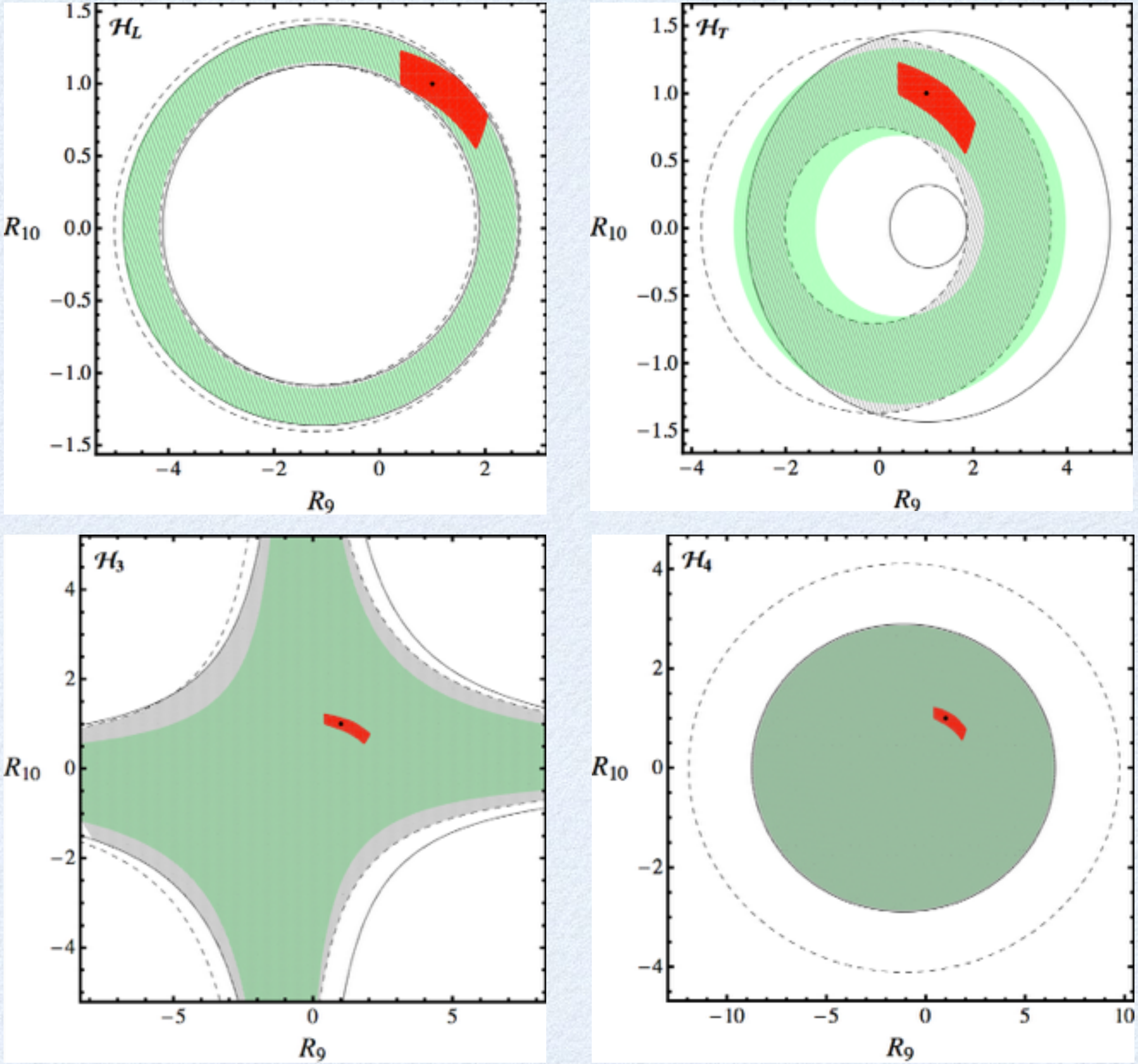
$$\mathcal{O}_{\rm exp} = \int \frac{d^2\mathcal{N}}{d\hat{s}dz} W[\hat{s}, z]\, d\hat{s}\, dz\ ,$$

$$\delta\mathcal{O}_{\rm exp} = \left[\int \frac{d^2\mathcal{N}}{d\hat{s}dz} W[\hat{s}, z]^2\, d\hat{s}\, dz\right]^{\frac{1}{2}}$$

	$[1, 3.5]$	$[3.5, 6]$	$[1, 6]$	> 14.4
$\mathcal{B}$	3.7 %	4.0 %	3.0 %	4.1%
$\mathcal{H}_T$	24 %	21 %	16 %	-
$\mathcal{H}_L$	5.8 %	6.8 %	4.6 %	-
$\mathcal{H}_A$	37 %	44 %	200 %	-
$\mathcal{H}_3$	240 %	180 %	150 %	-
$\mathcal{H}_4$	140 %	360 %	140 %	-



Inclusive: Projections



Exclusive: observables (K*)

- LHCb measured the complete angular distribution for the K* channel:

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}}\bigg|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$

$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$

$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$

$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$

$$+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$

$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}}.$$

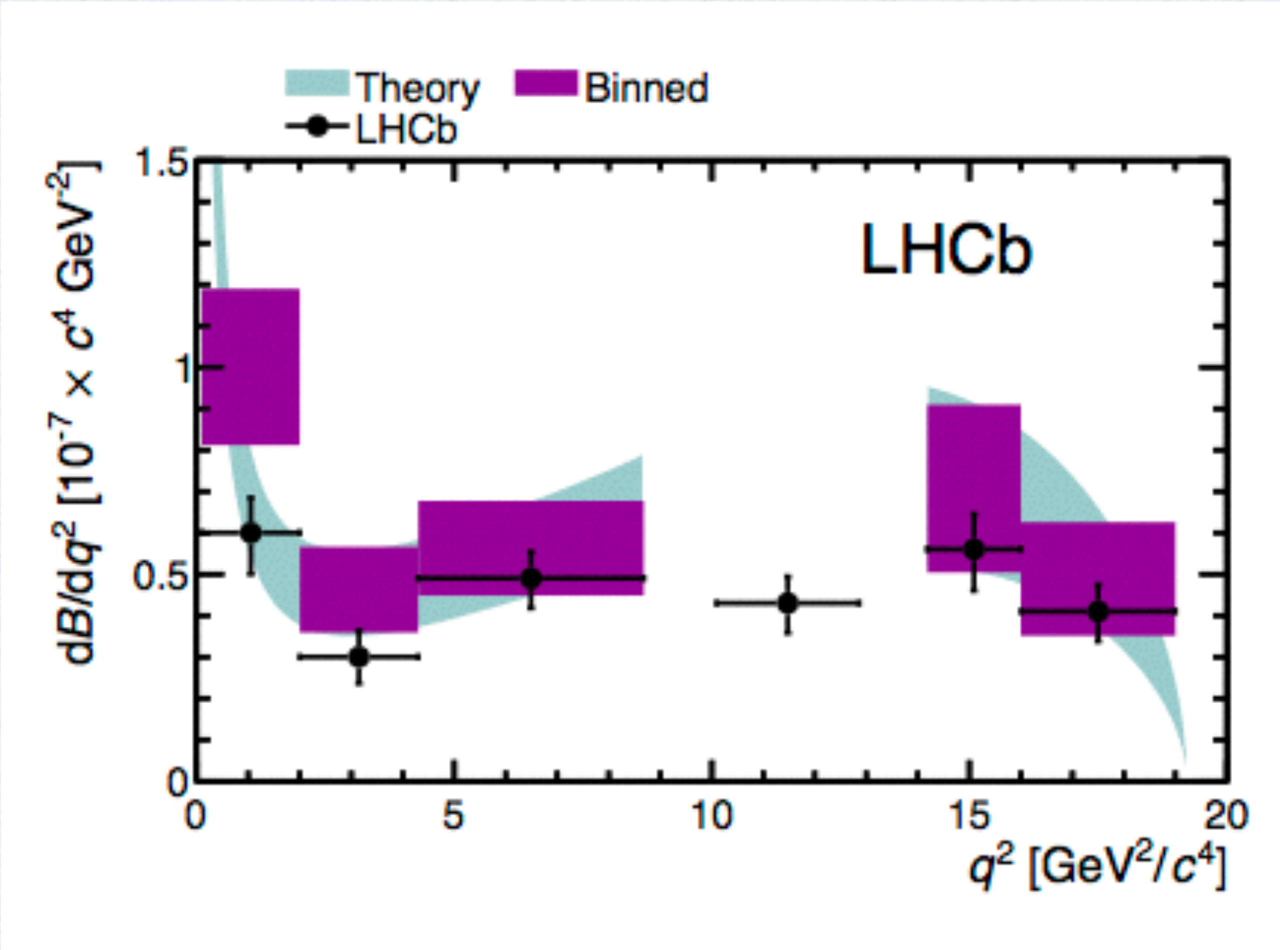
Exclusive: observables (K*)

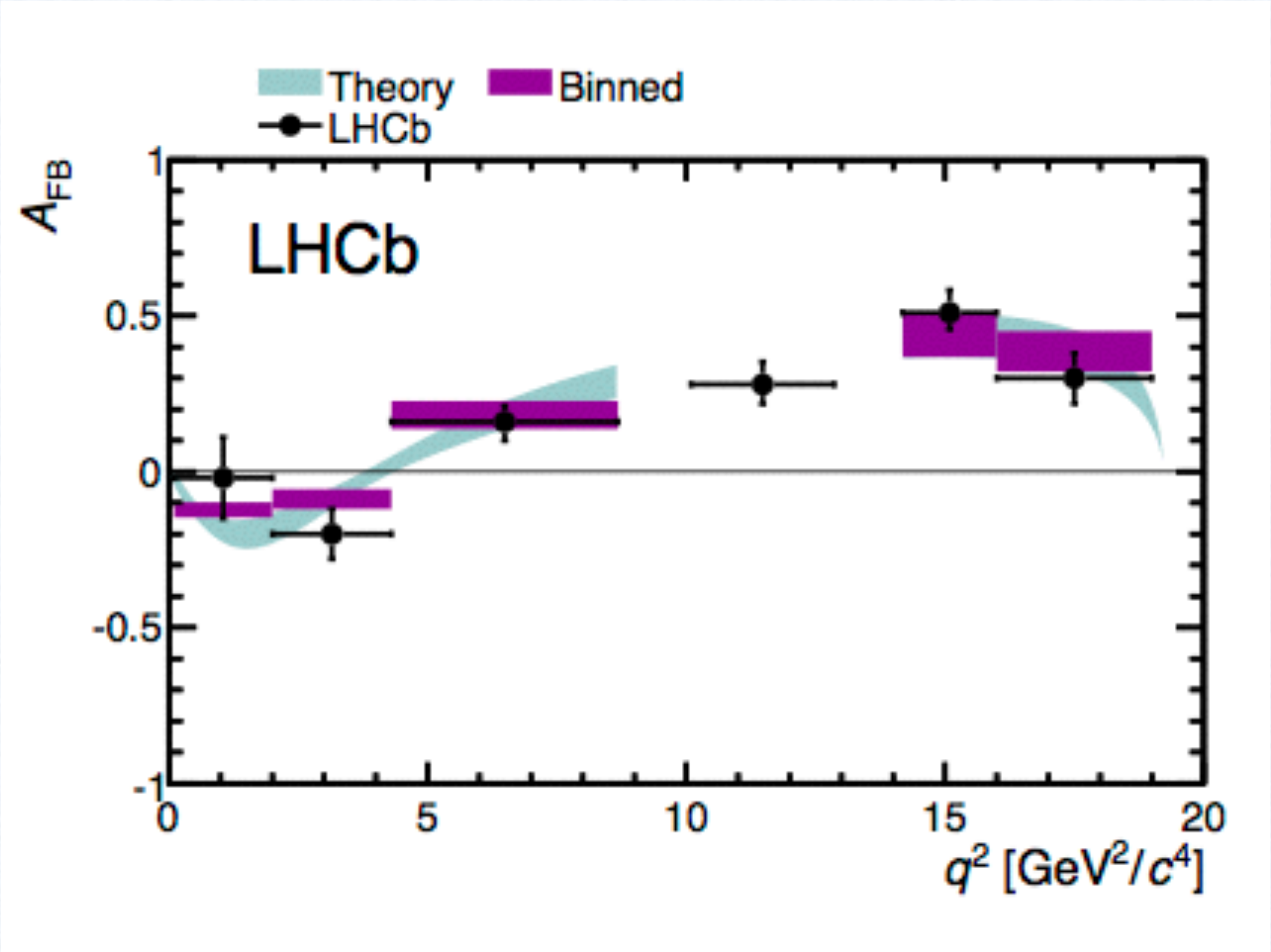
- All these observables are given by simple formulas in terms of helicity amplitudes:

$$
\begin{aligned}
A_{\perp}^{L,R} &= \sqrt{2} N m_B (1-\hat{s}) \left[(C_9^{\text{eff}} + C_9^{\text{eff}\prime}) \mp (C_{10} + C_{10}') + \frac{2\hat{m}_b}{\hat{s}} (C_7^{\text{eff}} + C_7^{\text{eff}\prime}) \right] \xi_{\perp}(E_{K^*}), \\
A_{\parallel}^{L,R} &= -\sqrt{2} N m_B (1-\hat{s}) \left[(C_9^{\text{eff}} - C_9^{\text{eff}\prime}) \mp (C_{10} - C_{10}') + \frac{2\hat{m}_b}{\hat{s}} (C_7^{\text{eff}} - C_7^{\text{eff}\prime}) \right] \xi_{\perp}(E_{K^*}) \\
A_{0}^{L,R} &= -\frac{N m_B (1-\hat{s})^2}{2\hat{m}_{K^*}\sqrt{\hat{s}}} \left[(C_9^{\text{eff}} - C_9^{\text{eff}\prime}) \mp (C_{10} - C_{10}') + 2\hat{m}_b (C_7^{\text{eff}} - C_7^{\text{eff}\prime}) \right] \xi_{\parallel}(E_{K^*}).
\end{aligned}
$$

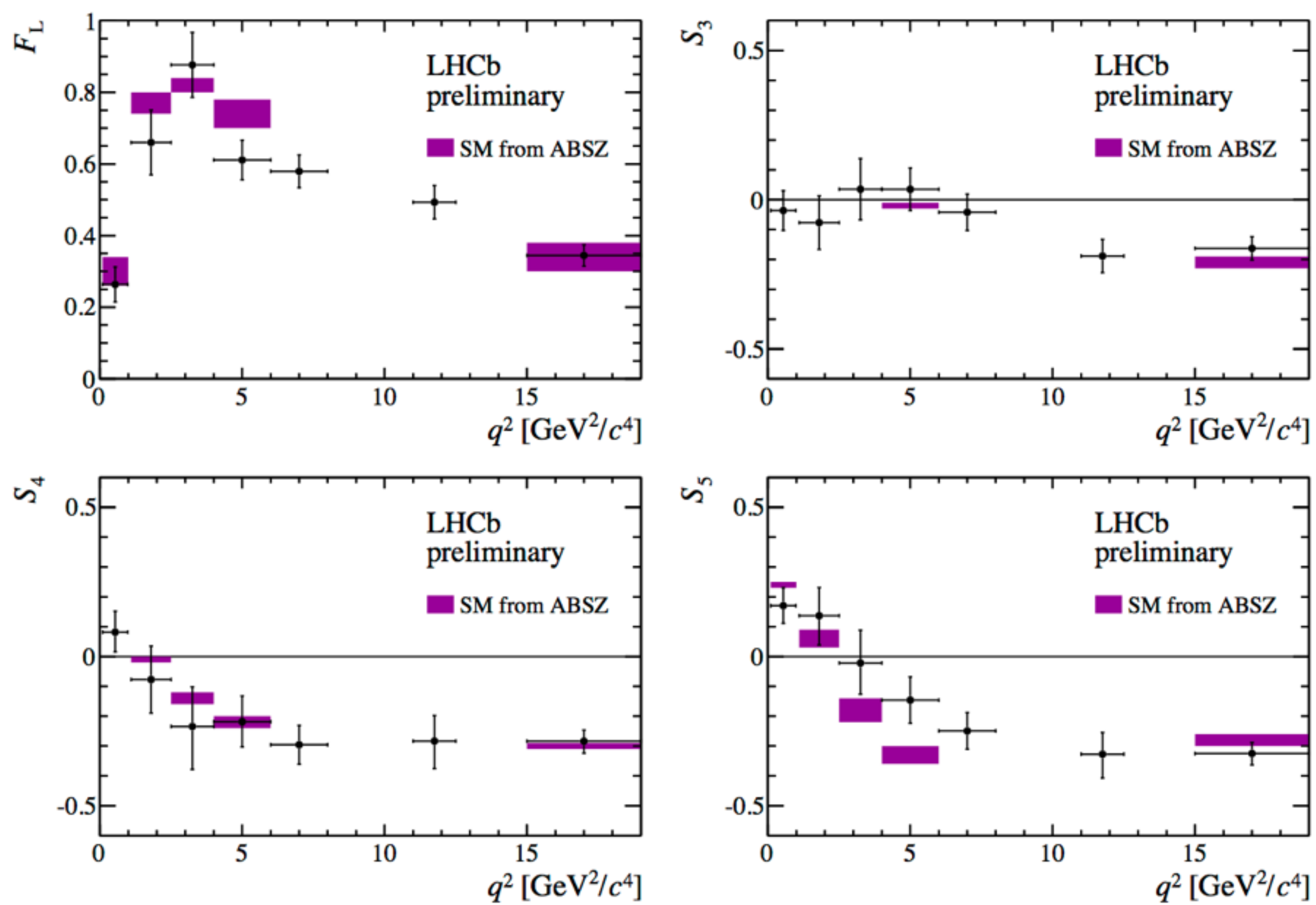
- These formulas hold at leading power and receive $O(\alpha_s)$ corrections (that are included in the numerics)

Exclusive: LHCb Results





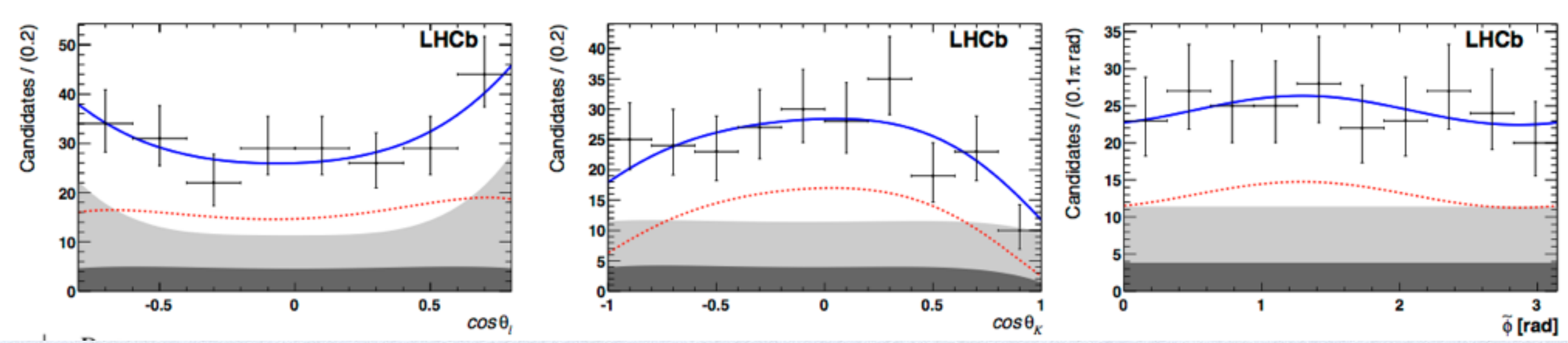
Exclusive: LHCb Results



Exclusive: LHCb Results

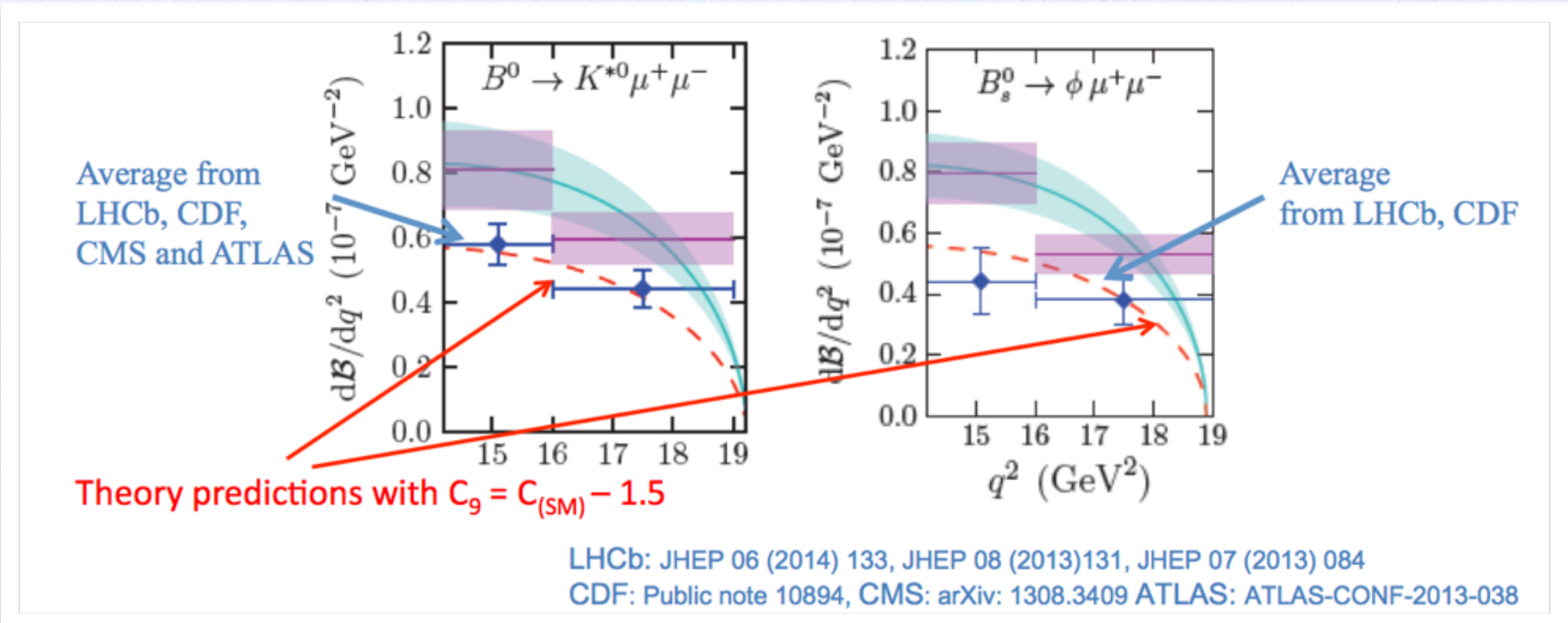
- Angular distributions in B→K*ll

Observable	Measurement	SM prediction[†]
F_{L}	$+0.16 \pm 0.06 \pm 0.03$	$+0.10^{+0.11}_{-0.05}$
$A_{\mathrm{T}}^{(2)}$	$-0.23 \pm 0.23 \pm 0.05$	$0.03^{+0.05}_{-0.04}$
$A_{\mathrm{T}}^{\mathrm{Re}}$	$+0.10 \pm 0.18 \pm 0.05$	$-0.15^{+0.04}_{-0.03}$
$A_{\mathrm{T}}^{\mathrm{Im}}$	$+0.14 \pm 0.22 \pm 0.05$	$(-0.2^{+1.2}_{-1.2}) \times 10^{-4}$



EXCLUSIVE: LHCB RESULTS

- Branching ratio at high-q^2



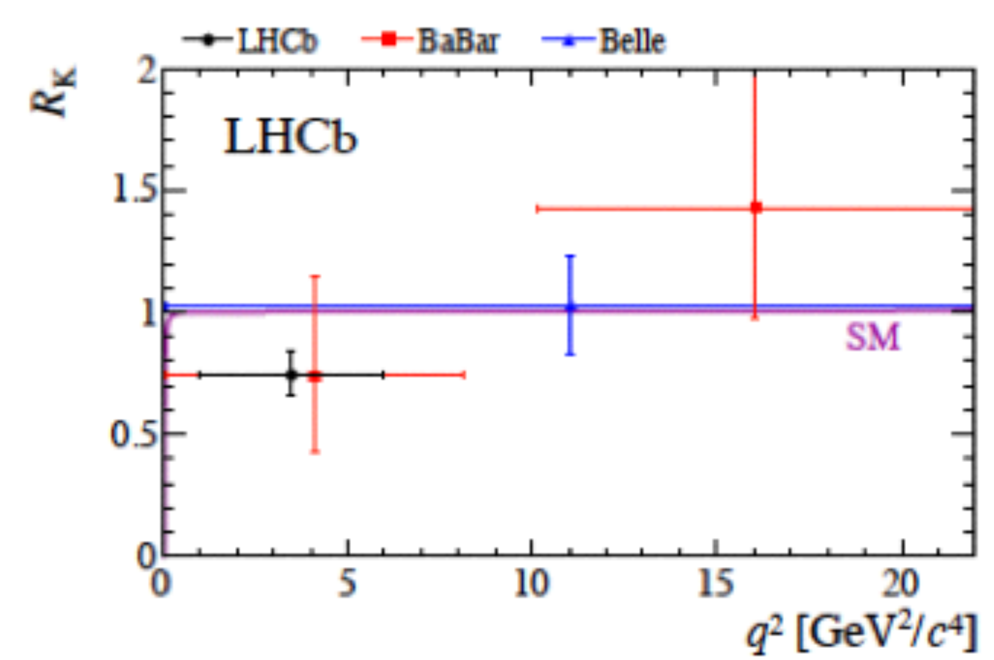
At high-q^2 the only sensible comparison is between rates integrated over a large enough range

Exclusive: LHCb Results

- Evidence for violation of lepton flavor universality?

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

- Experimentally the ratio is fairly clean (stat dominated)



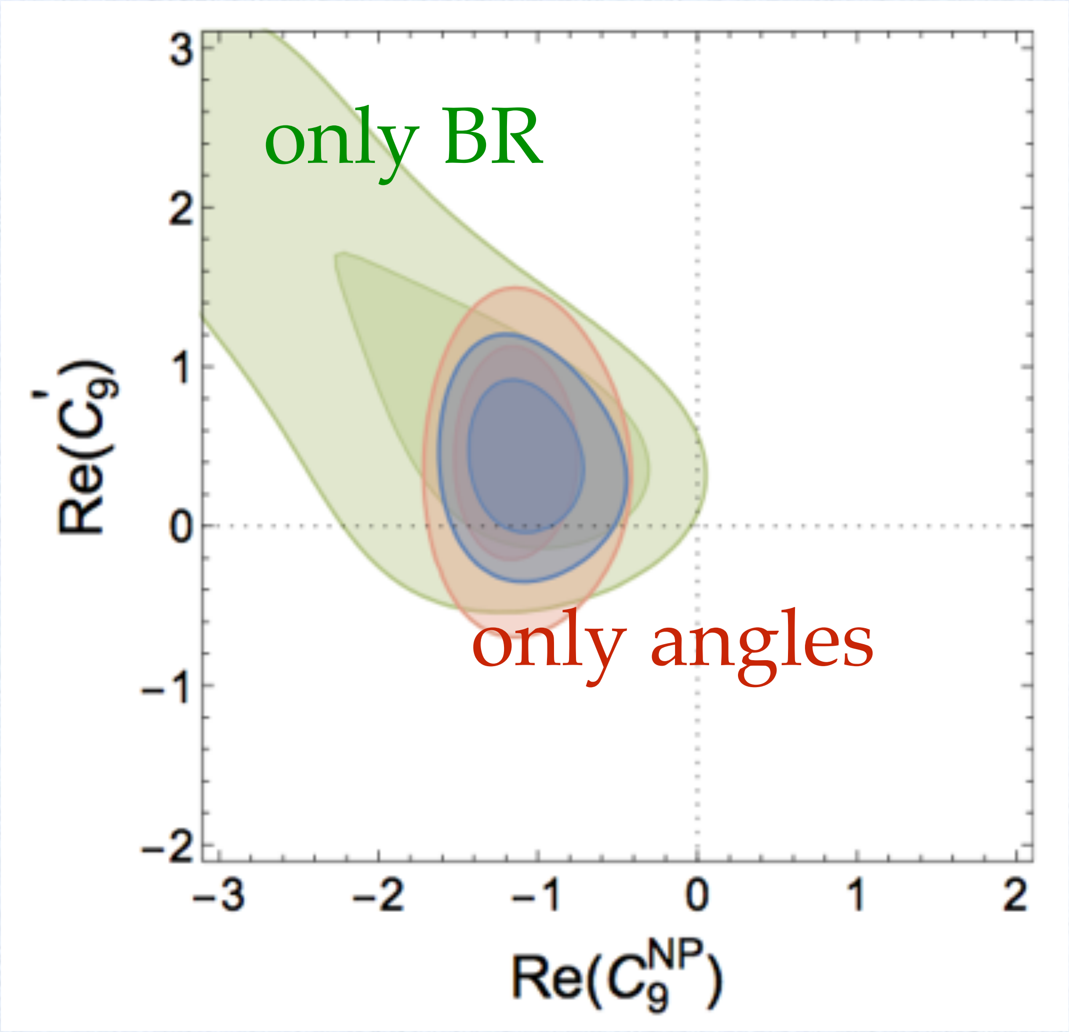
LHCb, PRL 113 (2014) 151601
Belle, PRL 103 (2009) 171801
Babar, PRD 86 (2012) 032012

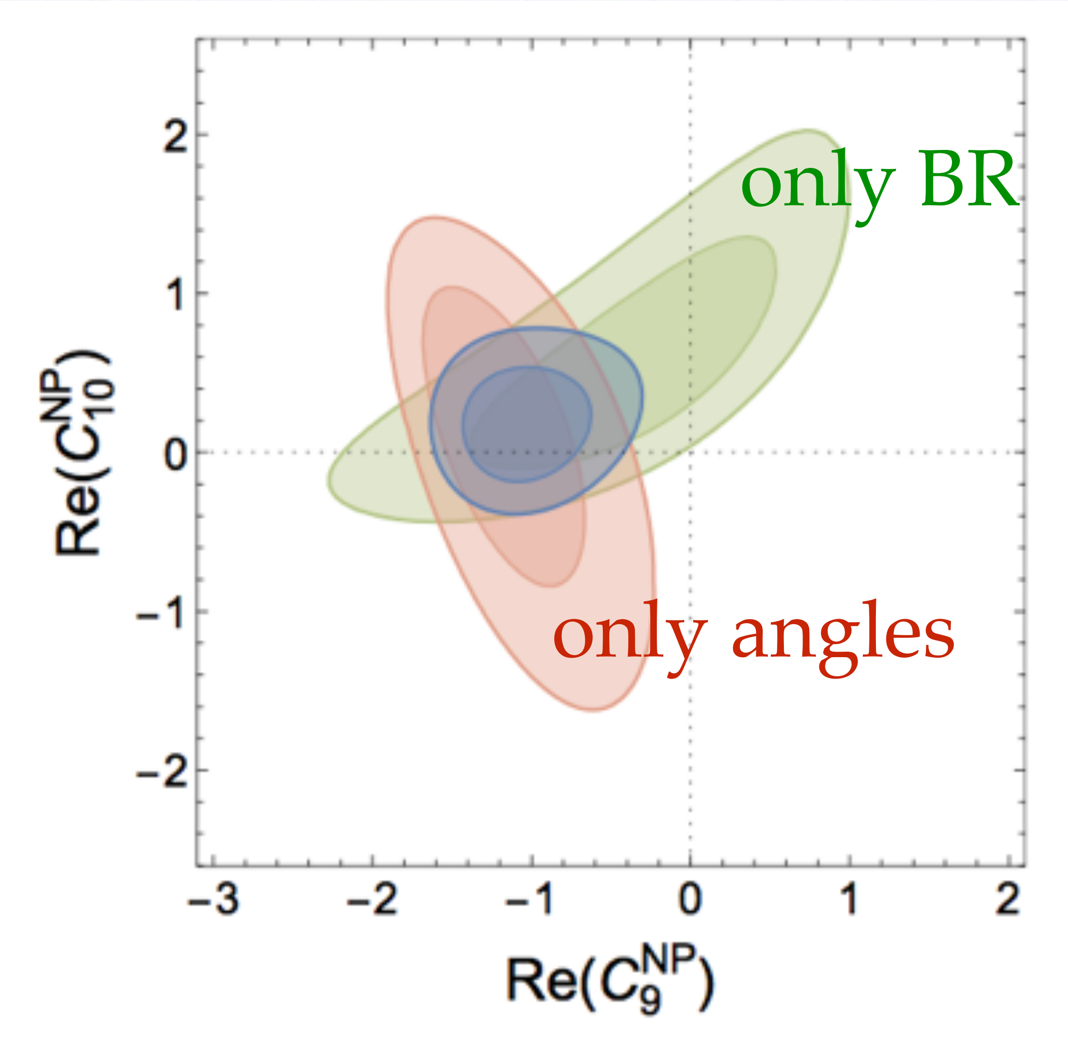
$$R_K = 0.745^{+0.090}_{-0.074}\,(\text{stat})\,^{+0.036}_{-0.036}\,(\text{syst})$$

$$R_K\,(\text{SM}) = 1.0003 \pm 0.0001$$

Wilson coefficients fits

- Deviations in P_5' seem to favor a negative shift in C_9 and a smaller positive contribution to C_9'



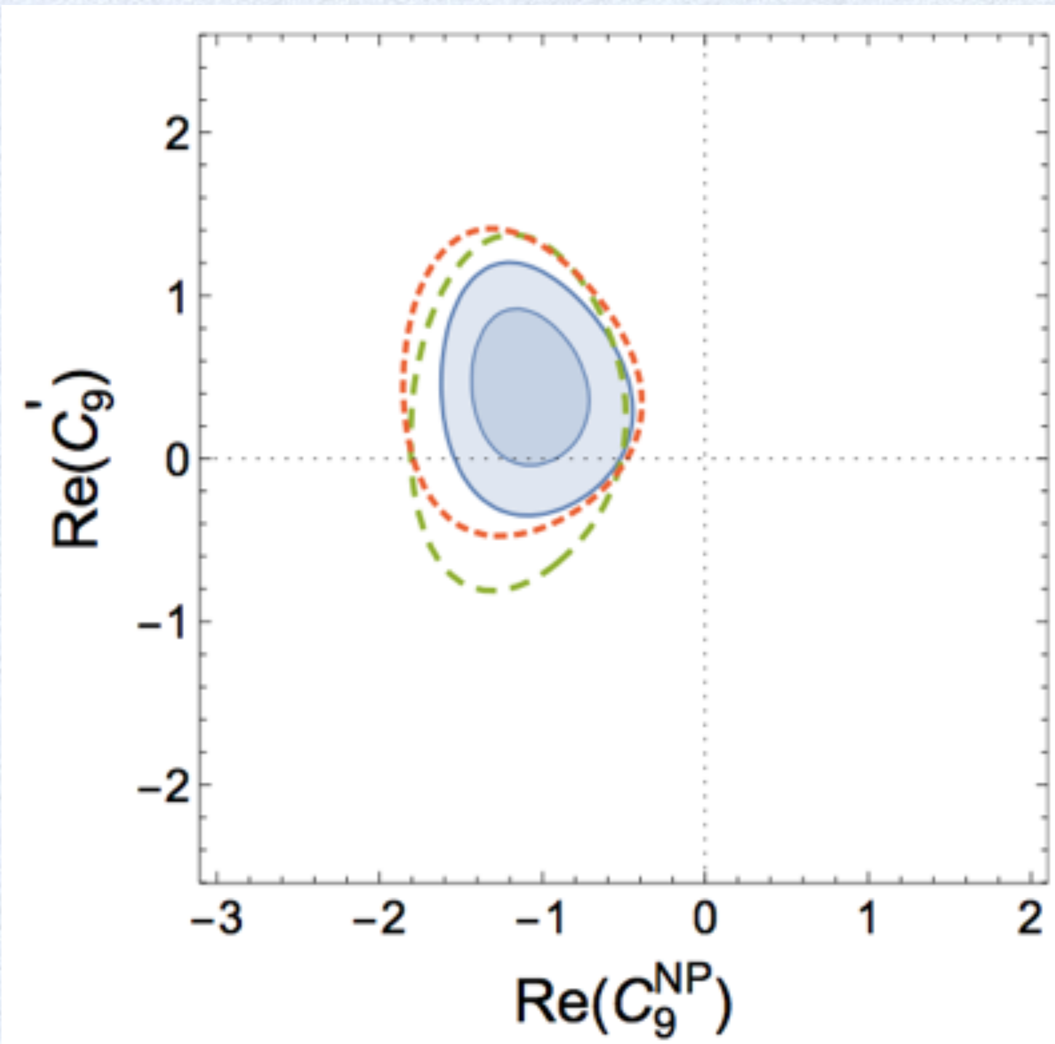


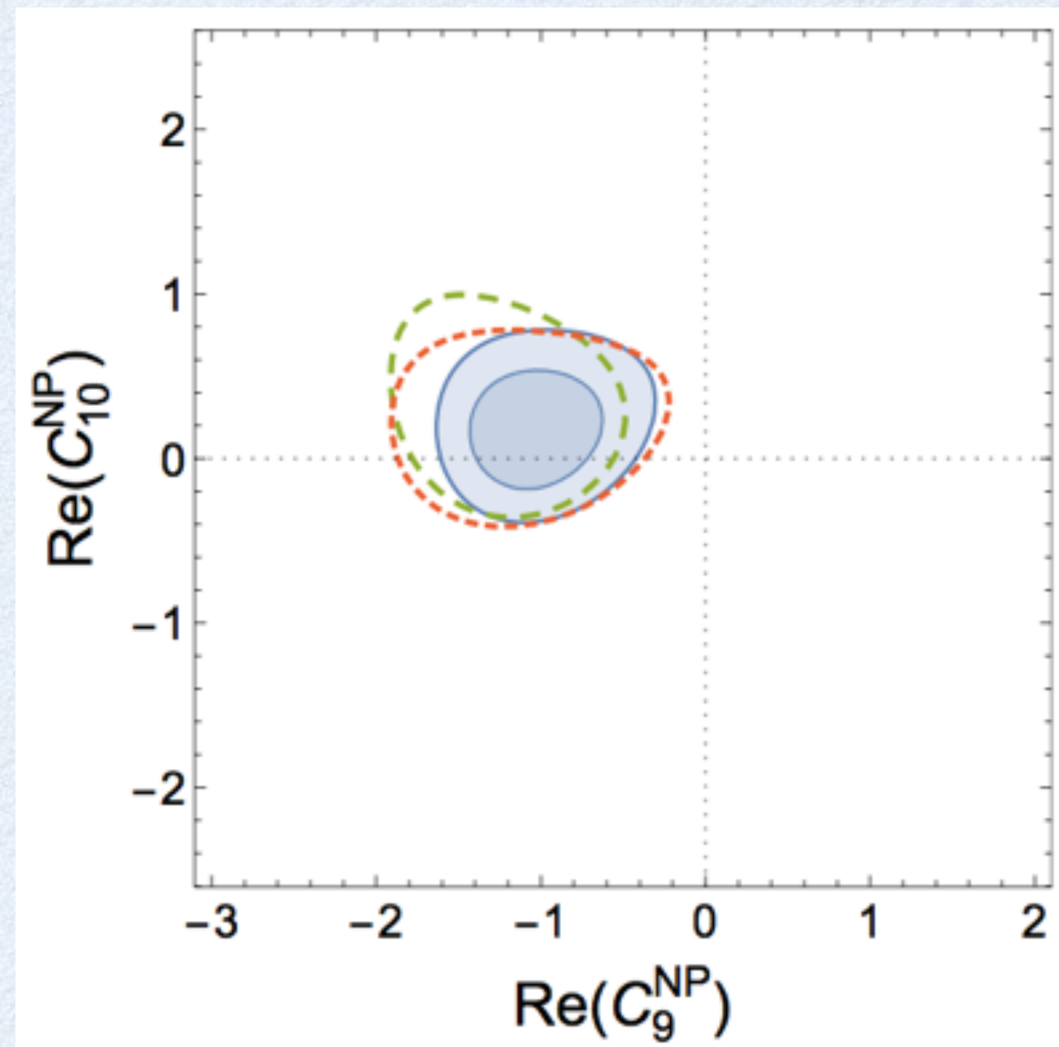
[Altmannshofer, Straub 1411.3161]

- BR data is compatible with the SM

Wilson coefficients fits

- Deviations in P_5' seem to favor a negative shift in C_9 and a smaller positive contribution to C_9'





[Altmannshofer, Straub 1411.3161]

- Dashed contours are obtained doubling some theory uncertainties (form factors, non-form factors)

Fit Results

Decay	obs.	q^2 bin	SM pred.	measurement		pull
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[2, 4.3]$	0.81 ± 0.02	0.26 ± 0.19	ATLAS	$+2.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[4, 6]$	0.74 ± 0.04	0.61 ± 0.06	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	S_5	$[4, 6]$	-0.33 ± 0.03	-0.15 ± 0.08	LHCb	-2.2
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P_5'	$[1.1, 6]$	-0.44 ± 0.08	-0.05 ± 0.11	LHCb	-2.9
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P_5'	$[4, 6]$	-0.77 ± 0.06	-0.30 ± 0.16	LHCb	-2.8
$B^- \to K^{*-}\mu^+\mu^-$	$10^7 \frac{dBR}{dq^2}$	$[4, 6]$	0.54 ± 0.08	0.26 ± 0.10	LHCb	$+2.1$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8 \frac{dBR}{dq^2}$	$[0.1, 2]$	2.71 ± 0.50	1.26 ± 0.56	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8 \frac{dBR}{dq^2}$	$[16, 23]$	0.93 ± 0.12	0.37 ± 0.22	CDF	$+2.2$
$B_s \to \phi\mu^+\mu^-$	$10^7 \frac{dBR}{dq^2}$	$[1, 6]$	0.48 ± 0.06	0.23 ± 0.05	LHCb	$+3.1$

[Altmannshofer, Straub 1411.3161]

χ^2_{SM} =125.8 for 91 measurements (p value 0.92 %)

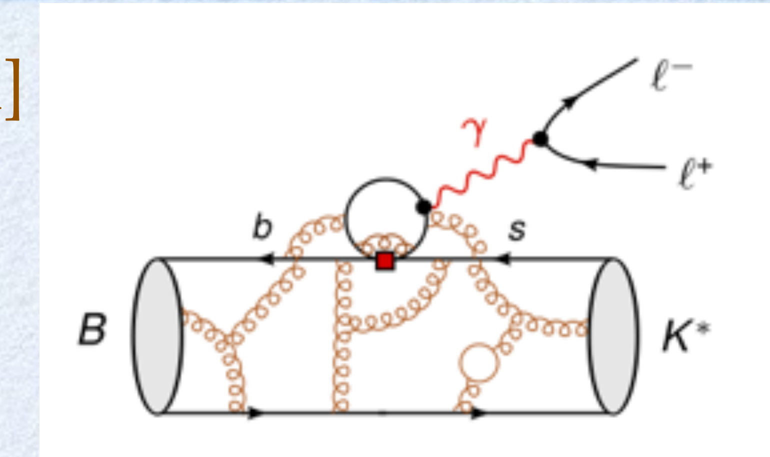
Fit Results

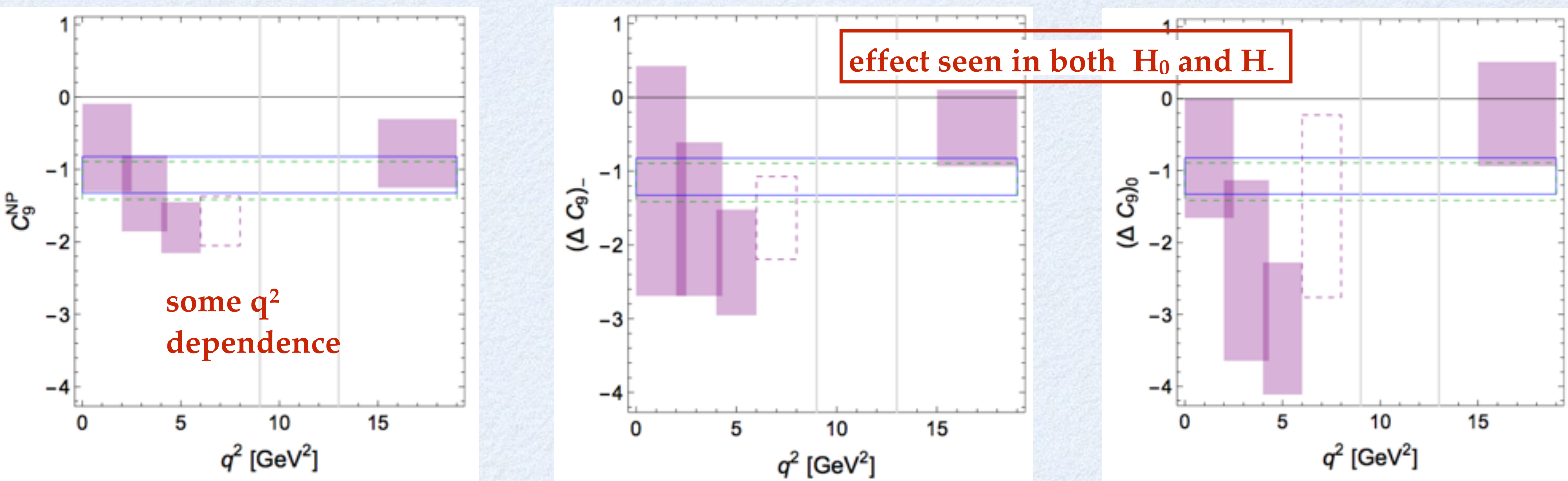
Coeff.	best fit	1σ	2σ	$\sqrt{\chi^2_{\text{b.f.}} - \chi^2_{\text{SM}}}$	p [%]
C_7^{NP}	-0.04	$[-0.07, -0.02]$	$[-0.10, 0.01]$	1.52	1.1
C_7'	0.00	$[-0.05, 0.06]$	$[-0.11, 0.11]$	0.05	0.8
C_9^{NP}	-1.12	$[-1.34, -0.88]$	$[-1.55, -0.63]$	4.33	10.6
C_9'	-0.04	$[-0.26, 0.18]$	$[-0.49, 0.40]$	0.18	0.8
C_{10}^{NP}	0.65	$[0.40, 0.91]$	$[0.17, 1.19]$	2.75	2.5
C_{10}'	-0.01	$[-0.19, 0.16]$	$[-0.36, 0.33]$	0.09	0.8
$C_9^{\text{NP}} = C_{10}^{\text{NP}}$	-0.20	$[-0.41, 0.05]$	$[-0.60, 0.33]$	0.82	0.8
$C_9^{\text{NP}} = -C_{10}^{\text{NP}}$	-0.57	$[-0.73, -0.41]$	$[-0.90, -0.27]$	3.88	6.8
$C_9' = C_{10}'$	-0.08	$[-0.33, 0.17]$	$[-0.58, 0.41]$	0.32	0.8
$C_9' = -C_{10}'$	-0.00	$[-0.11, 0.10]$	$[-0.22, 0.20]$	0.03	0.8

[Altmannshofer, Straub 1411.3161]

CHARMONIUM TROUBLES?

- Charm loops are included in C_9^{eff} using LCSR [Mannel et al]
- Issues in the calculation of charm effects could mimic NP in C_9 but effects should be:
  - q^2 dependent
  - lepton flavor universal
- What about resonant effects (tail of the J/ψ)?



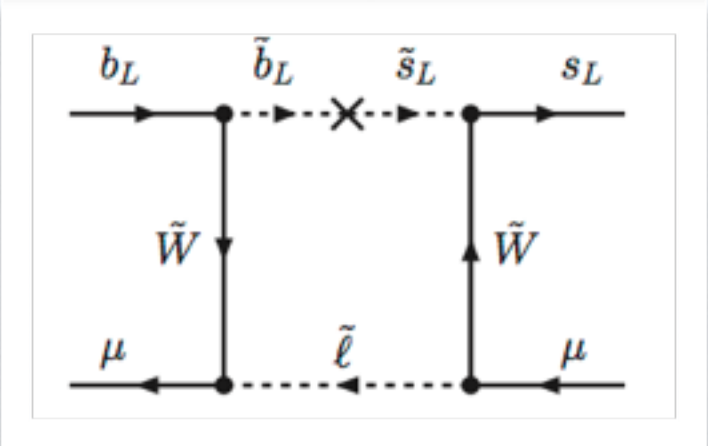


- In David [Straub]'s words: *"interesting hint or cruel coincidence?"*

[Altmannshofer, Straub 1411.3161]

NP interpretation

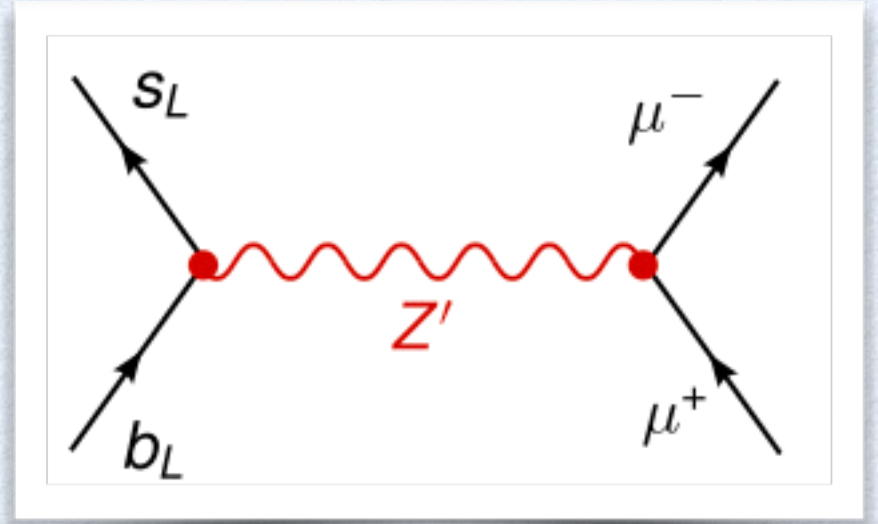
- The deviations in P_5' and R_K are **difficult to embed in NP models**
- Large contributions to C_9 or C_9' cannot be obtained in any minimal flavor violating MSSM and require additional flavor changing couplings (e.g. mass insertions in the 2-3 sector):



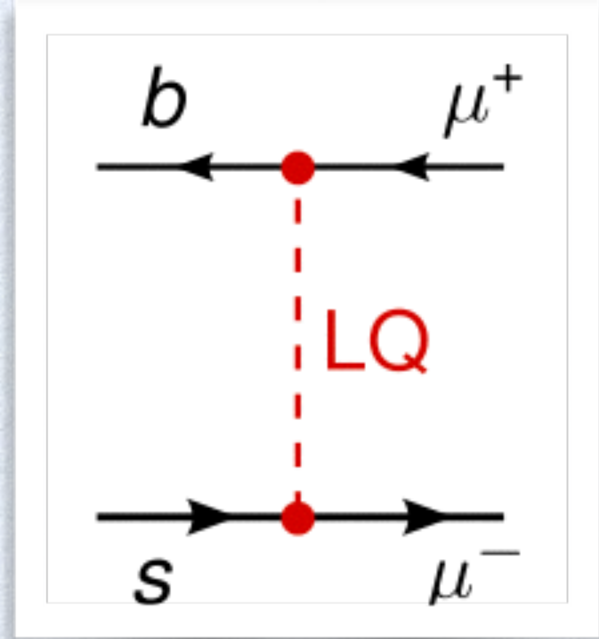
Z penguins can contribute to C10 but not to C9 because the Z current is mostly axial:

$$J^Z_\mu \propto (4s^2_W - 1)\bar{\ell}\gamma_\mu\ell + \bar{\ell}\gamma_\mu\gamma_5\ell$$

- FC Z′ models:

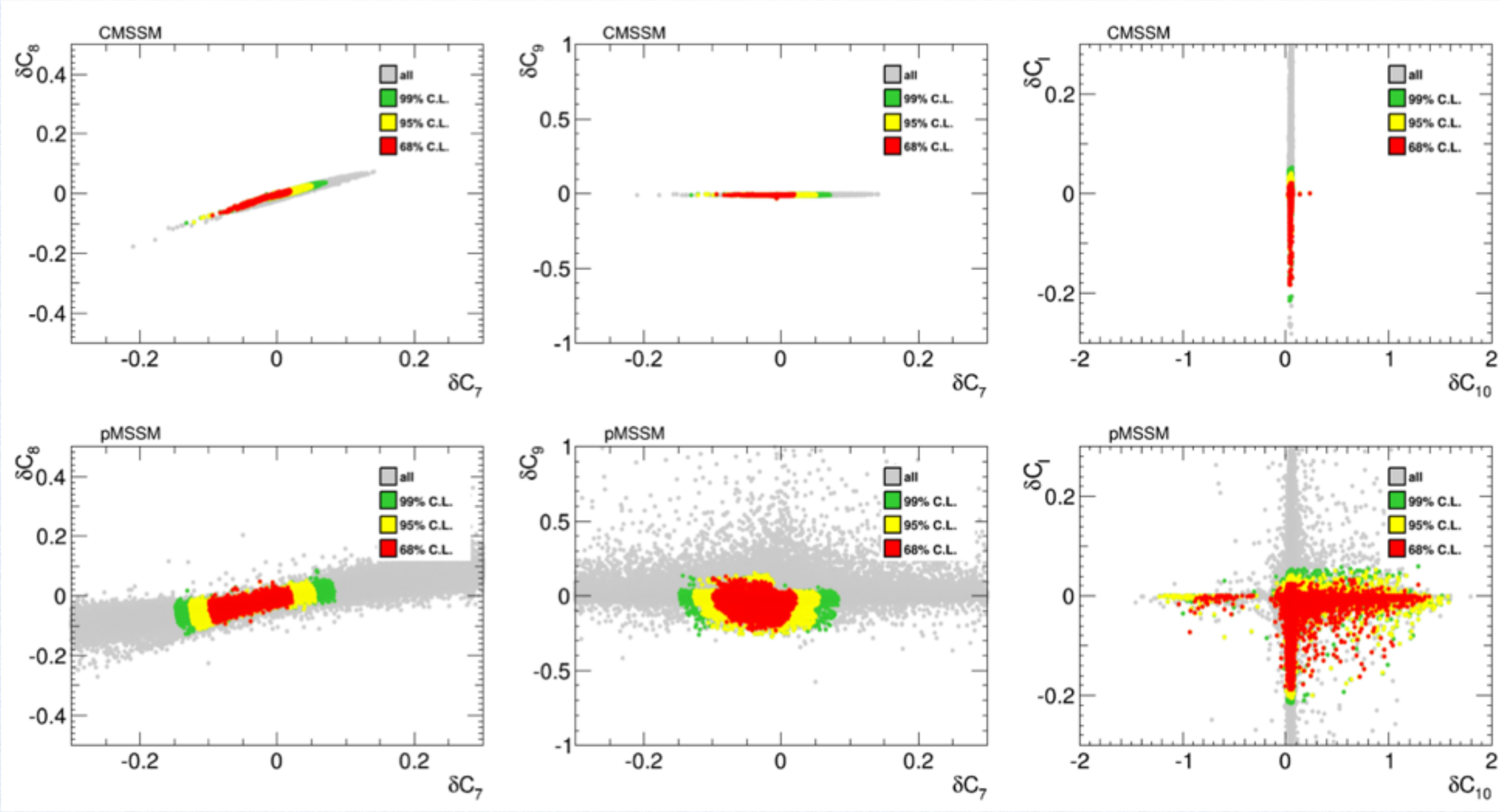


- Leptoquarks:



NP INTERPRETATION

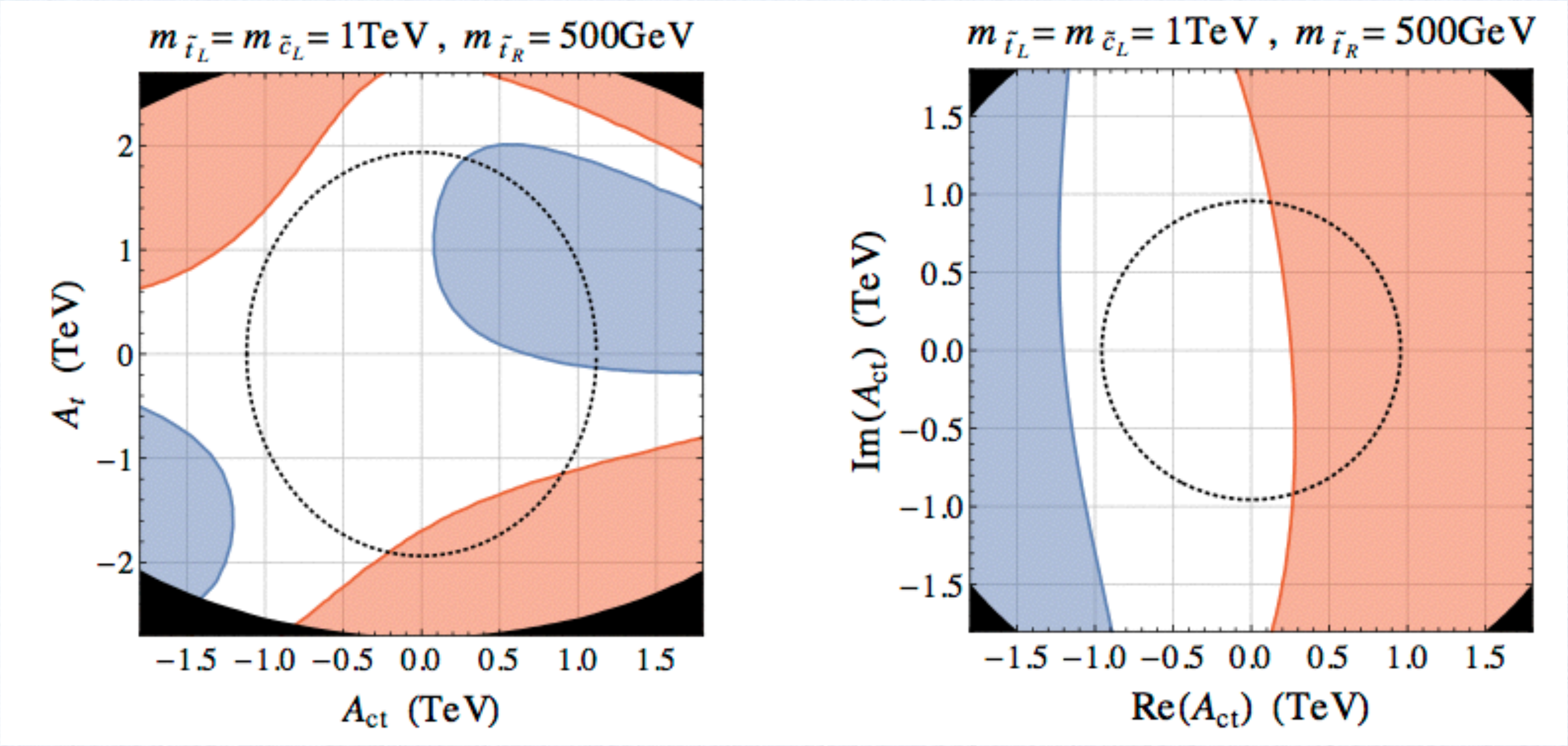
- No large effects on C_9 and C_9' are seen in the pMSSM



[Hurth, Mahmoudi 1411.2786]

NP interpretation

- Example: MSSM with mass insertions in the 2-3 sector (A_{ct}):



[Altmannshofer, Straub 1411.3161]

- Outside of the dashed circles: color/charge breaking minima
- Blue region: agreement with LHCb is "improved by more than one sigma"

INPUTS FOR B→SLL

$\alpha_s(M_z) = 0.1184 \pm 0.0007$	$m_e = 0.51099892$ MeV
$\alpha_e(M_z) = 1/127.918$	$m_\mu = 105.658369$ MeV
$s_W^2 \equiv \sin^2\theta_W = 0.2312$	$m_\tau = 1.77699$ GeV
$\lvert V_{ts}^* V_{tb}/V_{cb}\rvert^2 = 0.9621 \pm 0.0027$ [85]	$m_c(m_c) = (1.275 \pm 0.025)$ GeV
$\lvert V_{ts}^* V_{tb}/V_{ub}\rvert^2 = 130.5 \pm 11.6$ [85]	$m_b^{1S} = (4.691 \pm 0.037)$ GeV [86, 87]
$BR(B \to X_c e\bar{\nu})_{\rm exp} = 0.1051 \pm 0.0013$ [86]	$m_{t,\rm pole} = (173.5 \pm 1.0)$ GeV
$M_Z = 91.1876$ GeV	$m_B = 5.2794$ GeV
$M_W = 80.385$ GeV	$C = 0.574 \pm 0.019$ [71]
$\mu_b = 5^{+5}_{-2.5}$ GeV	$\mu_0 = 120^{+120}_{-60}$ GeV
$\lambda_2^{\rm eff} = (0.12 \pm 0.02)$ GeV^2	$\rho_1 = (0.06 \pm 0.06)$ GeV^3 [88]
$\lambda_1^{\rm eff} = (-0.362 \pm 0.067)$ GeV^2 [86, 87]	$f_u^0 + f_s = (0 \pm 0.2)$ GeV^3 [52]
$f_u^0 - f_s = (0 \pm 0.04)$ GeV^3 [52]	$f_u^\pm = (0 \pm 0.4)$ GeV^3 [52]

- Some references (inclusive):

  Misiak; Buras, Munz, Bobeth, Urban, Asatryan, Asatrian, Greub, Walker, Ghinculov, Hurth, Isidori, Yao, Gambino, Gorbahn, Haisch, Huber, Lunghi, Wyler, Lee, Ligeti, Stewart, Tackmann, …

- Some references (exclusive):

  Beneke, Feldmann, Seidel, Grinstein, Pirjol, Bobeth, Hiller, Dyk, Wacker, Piranishvili, Altmannshofer, Ball, Bharucha, Buras, Wick, Straub, Matias, Lunghi, Virto, Descotes-Genon, Hofer, Hurth, Mahmoudi, …