Theory of the Inclusive Decays $\bar{B} \to X_{s,d}\ell\ell$

Tobias Hurth Johannes Gutenberg University Mainz

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

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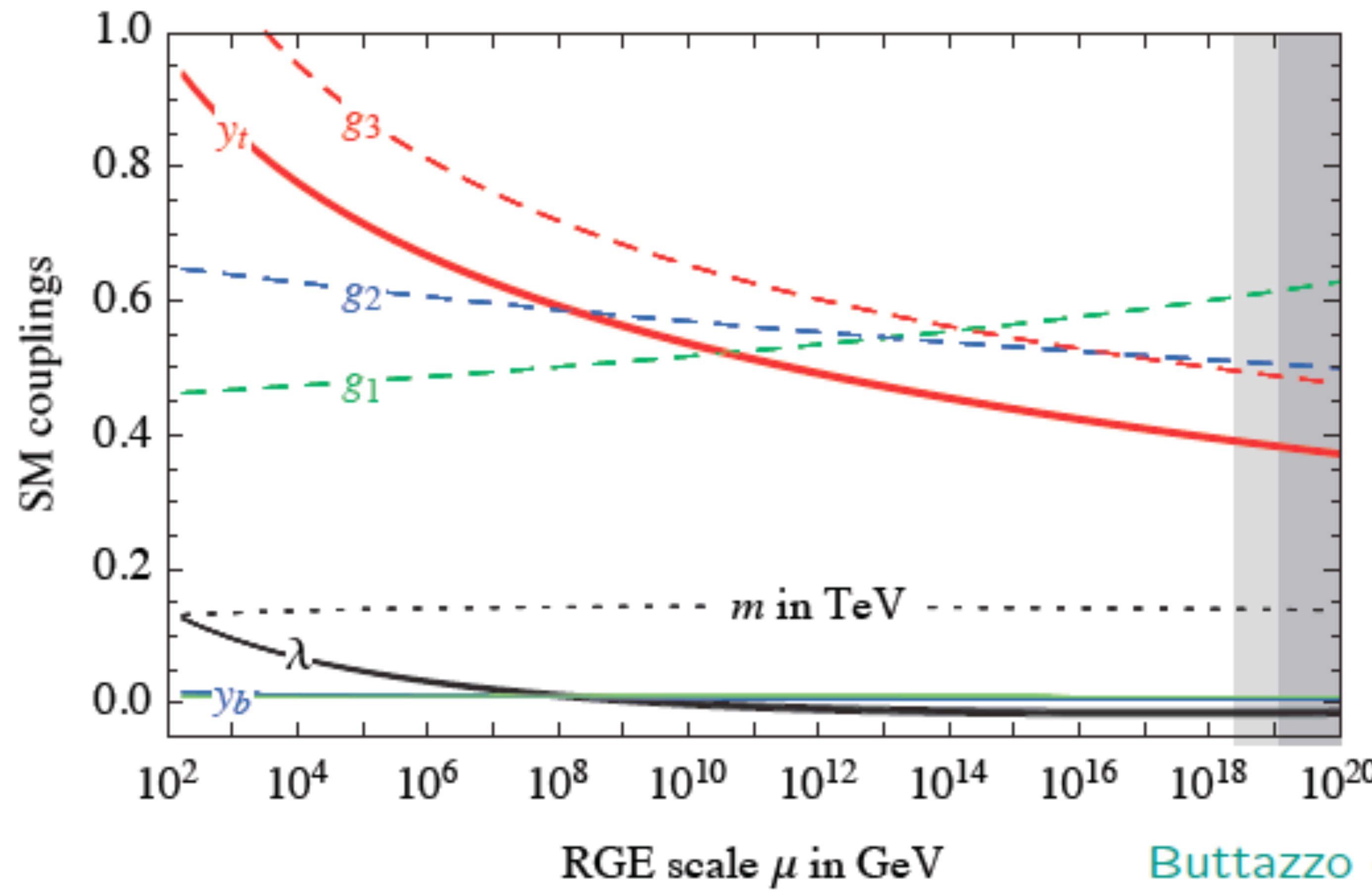
Prologue

Self-consistency of the SM

Do we need new physics beyond the SM ?

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



Buttazzo et al. arXiv:1307.3536

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

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

Experimental evidence beyond SM

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

Caveat:

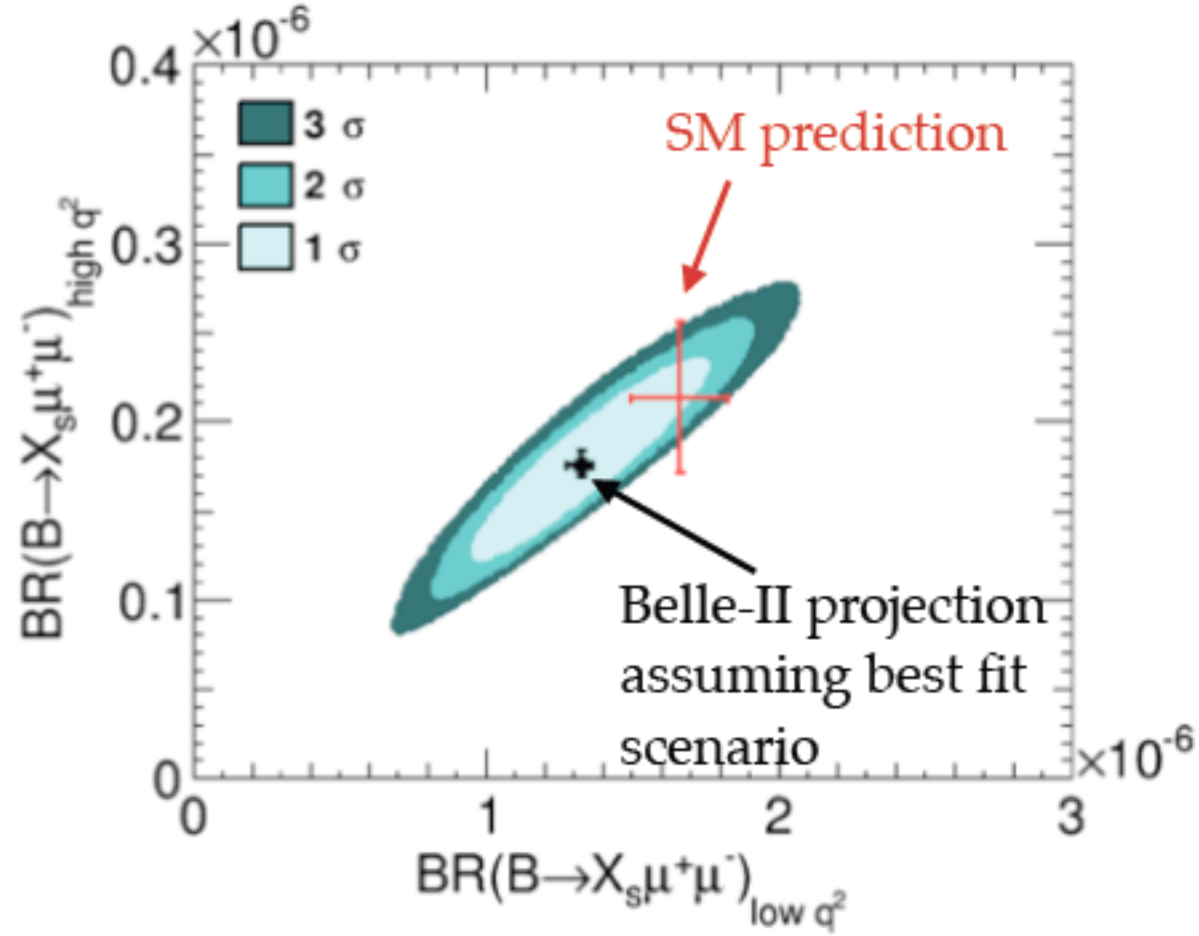
Answers perhaps wait at energy scales which we do not reach with present experiments.

Motivation: “From Flavour to New Physics”

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.

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

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

Arby,Hurth,Mahmoudi,Neshatpour arXiv: 1806.02791

20 Wilson coefficients sensitive to NP: $C_7, C_8, C_9^\ell, C_{10}^\ell, C_{Q_1}^\ell, C_{Q_2}^\ell$

$\to$ 10 independent WC (considering $\ell = e, \mu$) + 10 primed

Set of WC	Nr. parameters	$\chi^2_{\rm min}$	Pull$_{\rm SM}$	Improvement
SM	0	118.8	-	-
C_9^μ	1	85.1	5.8σ	5.8σ
$C_9^{(e,\mu)}$	2	83.9	5.6σ	1.1σ
$C_7, C_8, C_9^{(e,\mu)}, C_{10}^{(e,\mu)}$	6	81.2	4.8σ	0.5σ
All non-primed WC	10 (8)	81.0	$4.1\,(4.5)\sigma$	$0.0\,(0.1)\sigma$
All WC (incl. primed)	20 (16)	70.2	$3.6\,(4.1)\sigma$	$0.9\,(1.2)\sigma$

- No real improvement in the fits when going beyond the C_9^μ case
- Pull with the SM decreases when all WC are varied

NP significance of 5.8σ in C_9^μ

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

NP significance of 4.1σ in the global fit based on the assumption of 10% error for power corrections

Belle-II Extrapolations

Akimasa Ishikawa, B2TiP

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

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

Error of Normalized Forward-Backward-Asymmetry

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

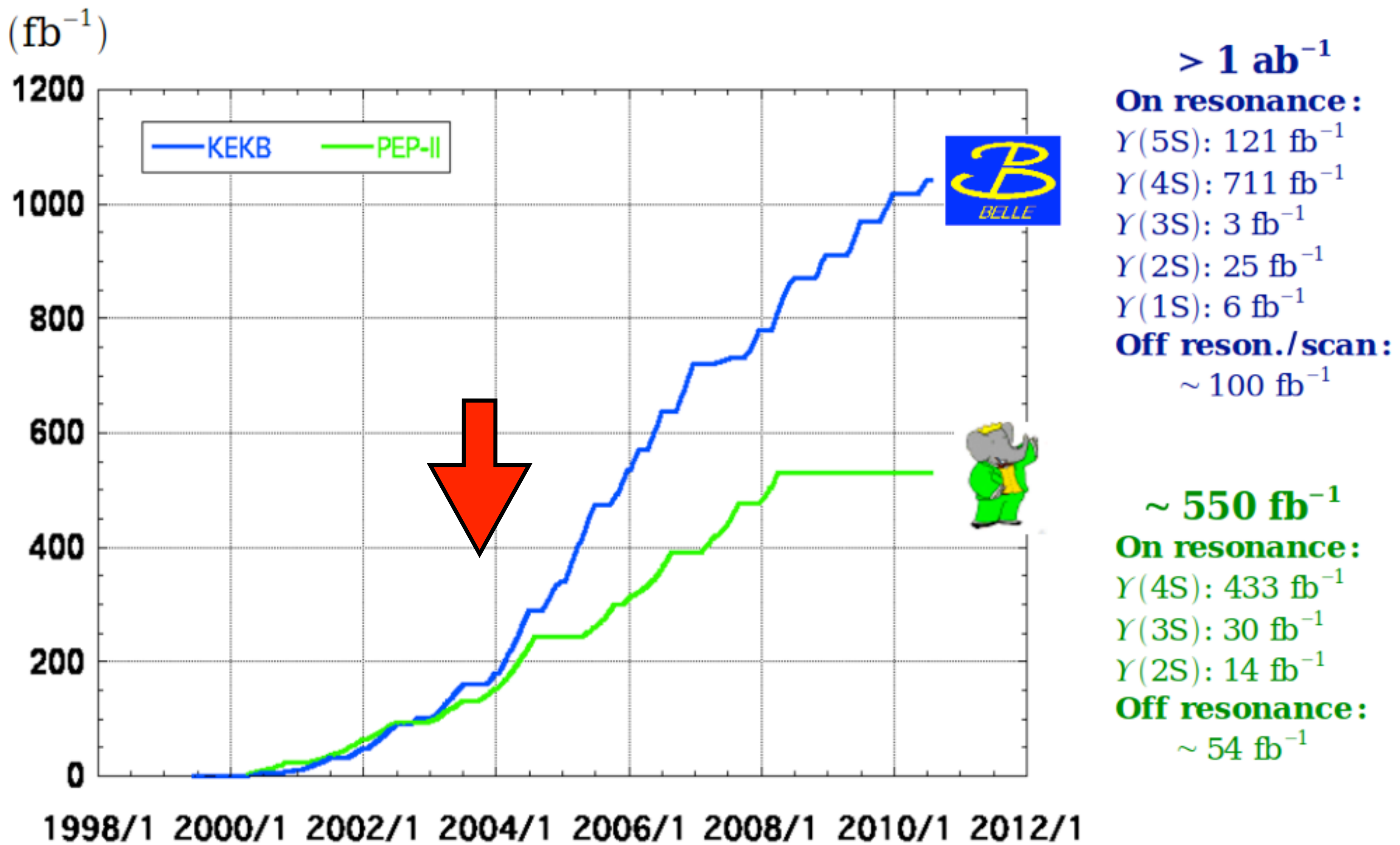
$B \to (\pi, \rho)\ell^+\ell^-$, semi-inclusive $\bar{B} \to X_d \ell^+ \ell^-$ at 50/ab
(uncertainties like $\bar{B} \to X_s \ell^+ \ell^-$ at 0.7/ab)

Experiment

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

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

Integrated luminosity of B factories

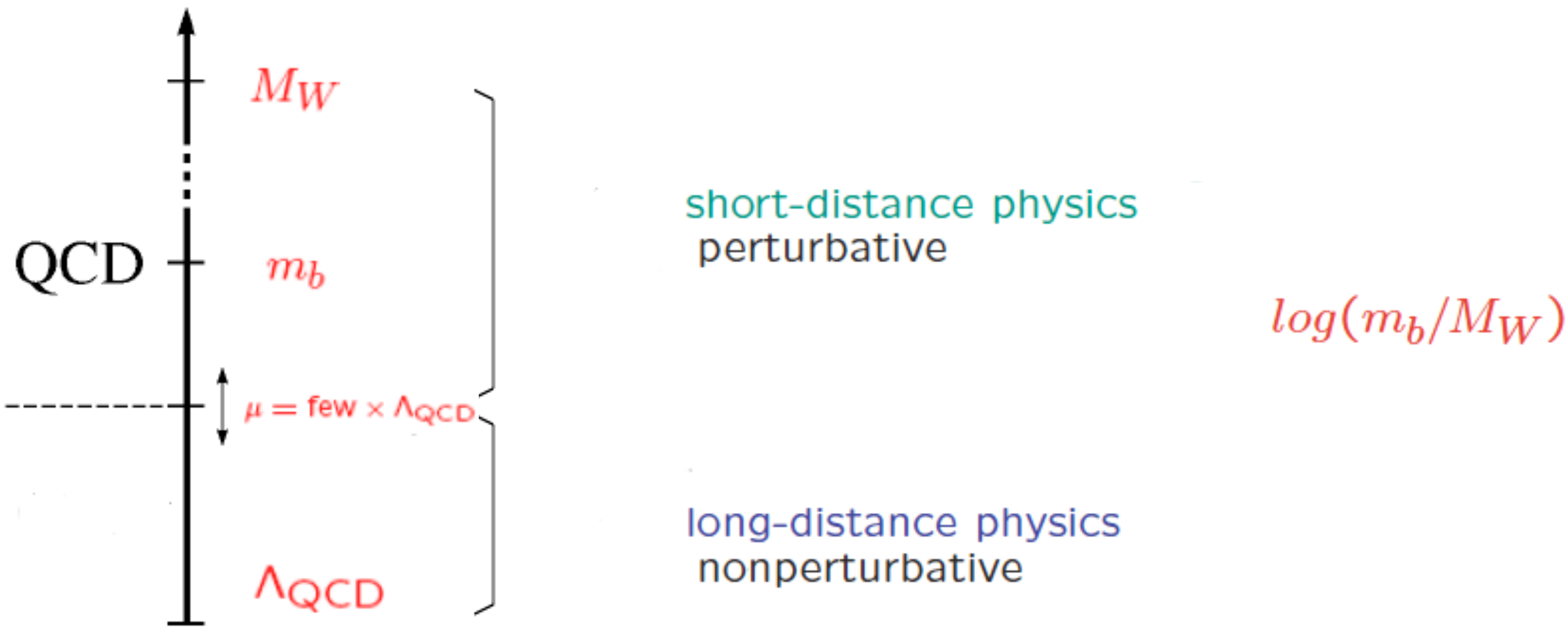


New Babar analysis on dilepton spectrum arXiv:1312.3664

New Belle analysis on AFB arXiv:1402.7134

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 $B \to X_s\ell^+\ell^-$

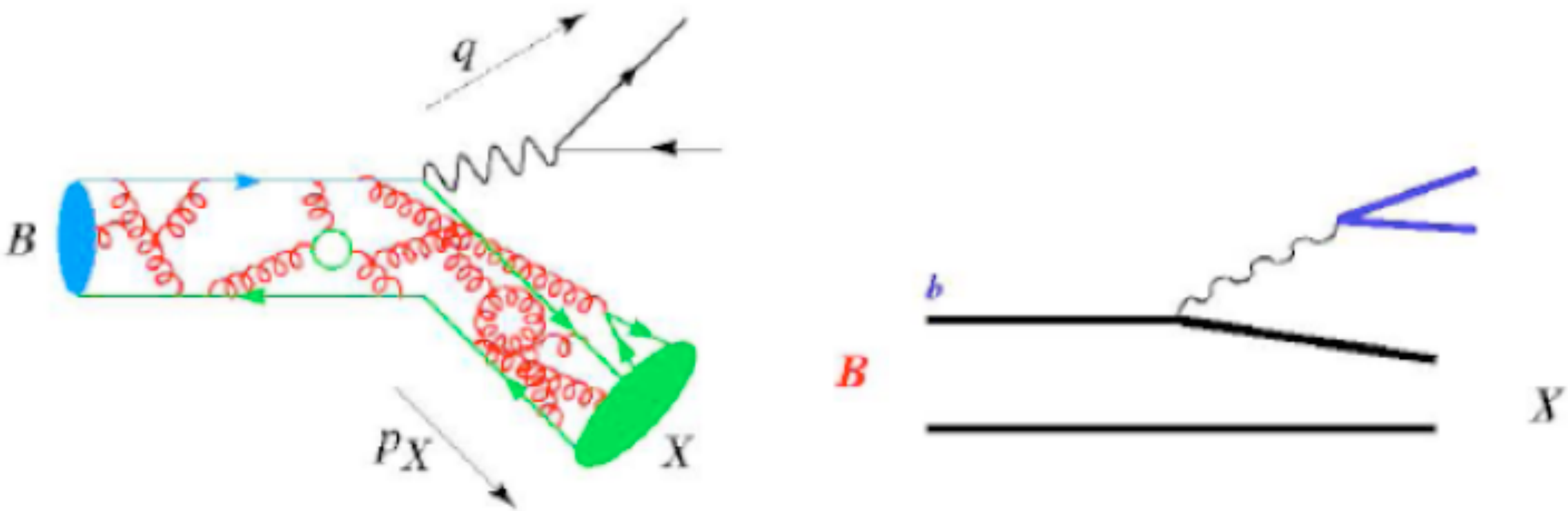
How to compute the hadronic matrix elements $\mathcal{O}_i(\mu = m_b)$?

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



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

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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

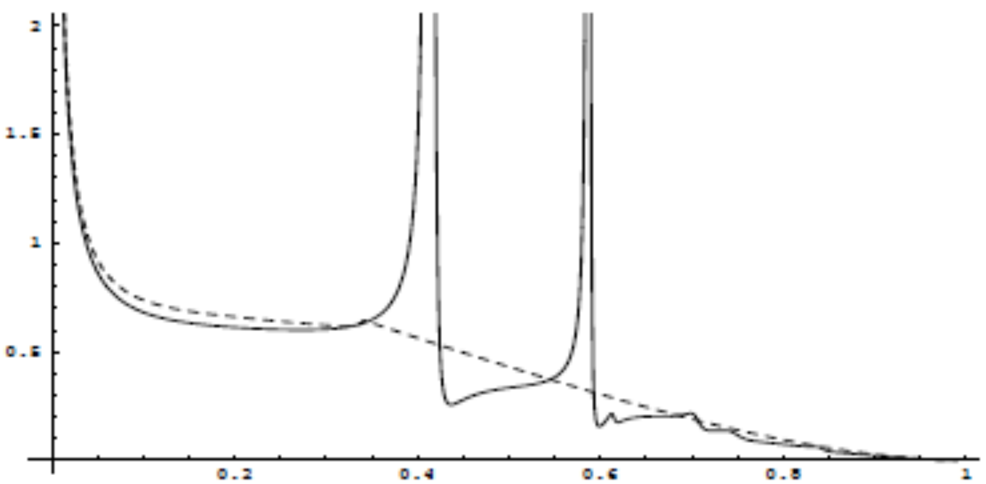
Analysis in $B \to X_s\ell\ell$ in this talk; Benzke,Fickinger,Hurth,Turczyk

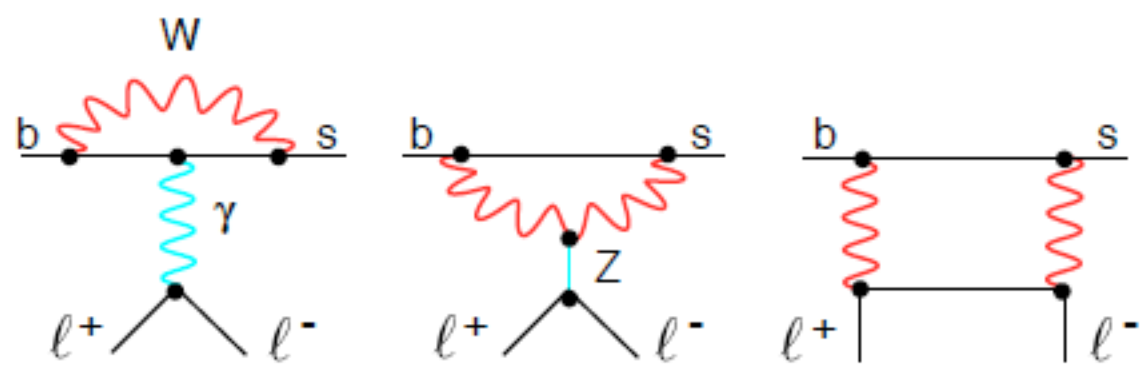
Perturbative contributions

Review of previous calculations for $B \to X_s\ell\ell$

- On-shell-$c\bar{c}$-resonances $\Rightarrow$ cuts in dilepton 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

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





$\hat{s} = q^2/m_b^2$

- NNLL prediction of $\bar{B} \to X_s\ell^+\ell^-$: dilepton mass spectrum
  Asatryan,Asatrian,Greub, Walker,hep-ph/0204341
  Ghinculov,Hurth,Isidori,Yao,hep-ph/0312128

$$BR(\bar{B} \to X_s\ell^+\ell^-)_{Cut:\ q^2\in[1GeV^2,6GeV^2]} = (1.63 \pm 0.20) \times 10^{-6}$$

$$BR(\bar{B} \to X_s l^+ l^-)_{Cut:\ q^2>14.4GeV^2} = (4.04 \pm 0.78) \times 10^{-7}$$

NNLL QCD corrections $q^2 \in [1GeV^2, 6GeV^2]$

central value: -14%, perturbative error: $13\% \to 6.5\%$

- Further refinements:
  - Completing NNLL QCD corrections:
    Mixing into $\mathcal{O}_9$ ($+1\%$), NNLL matrixelement of $\mathcal{O}_9$ (-4%)
  - NLL QED two-loop corrections to Wilson coefficients
    -1.5% shift for $\alpha_{em}(\mu = m_b)$, -8.5% for $\alpha_{em}(\mu = m_W)$
    Bobeth,Gambino,Gprbahn,Haisch,hep-ph/0312090
  - QED two-loop corrections to matrix elements
    Large collinear logarithm $Log(m_b/m_\ell)$ which survive intregration if a restricted part of the dilepton mass spectrum is considered
    $+2\%$ effect in the low-q^2 region for muons, for the electrons the effect depends on the experimental cut parameters
    Huber,Lunghi,Misiak,Wyler,hep-ph/0512066
    Huber,Hurth,Lunghi,Nucl.Phys.B802(2008)40
- NNLL prediction of $\bar{B} \to X_s \ell^+ \ell^-$: forward-backward-asymmetry (FBA)
  Asatrian,Bieri,Greub,Hovhannisyan,hep-ph/0209006
  Ghinculov,Hurth,Isidori,Yao,hep-ph/0208088,hep-ph/0312128

$$A_{\rm FB} \equiv \frac{1}{\Gamma_{semilep}} \left(\int_0^1 d(\cos\theta) \frac{d^2\Gamma}{dq^2 d\cos\theta} - \int_{-1}^0 d(\cos\theta) \frac{d^2\Gamma}{dq^2 d\cos\theta} \right)$$

(θ angle between ℓ^+ and B momenta in dilepton CMS)

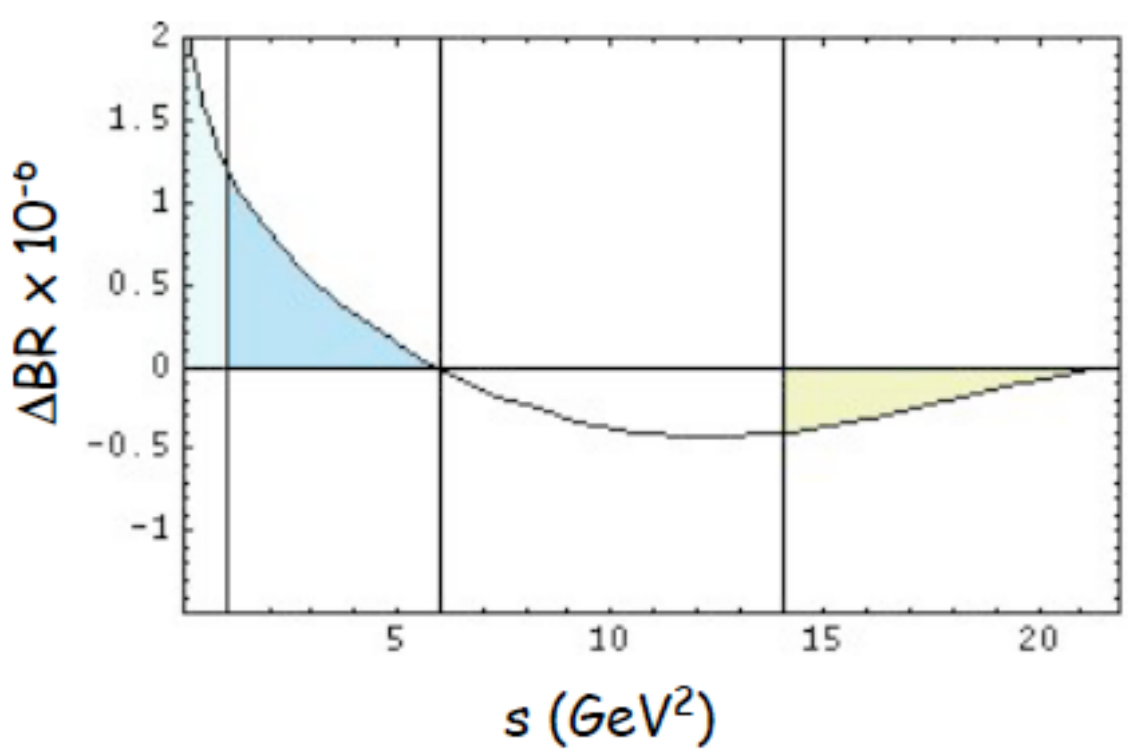
$$A_{FB}(q_0^2) = 0 \quad \text{for} \quad q_0^2 \sim C_7/C_9 \quad q_0^2 = (3.90 \pm 0.25) GeV^2$$

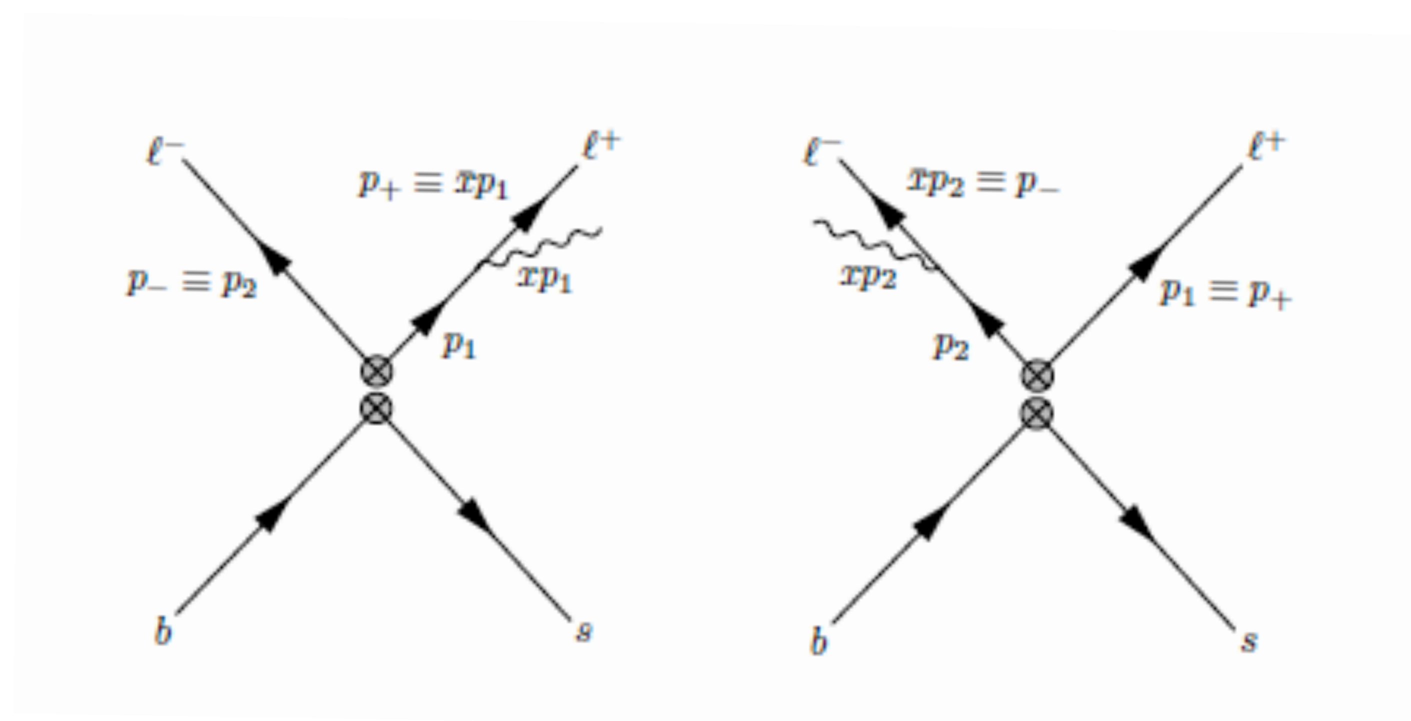
- Electromagnetic corrections in high-q^2 and for A_{FB}

  Huber,Hurth,Lunghi,Nucl.Phys.B802(2008)40

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

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





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

Huber,Hurth,Lunghi, arXiv:1503.04849

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

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

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

- Dependence on Wilson coefficients

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

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

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

H_T suppressed in low-q^2 window

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

Lee,Ligeti,Stewart, Tackmann hep-ph/0612156

New physics sensitivity

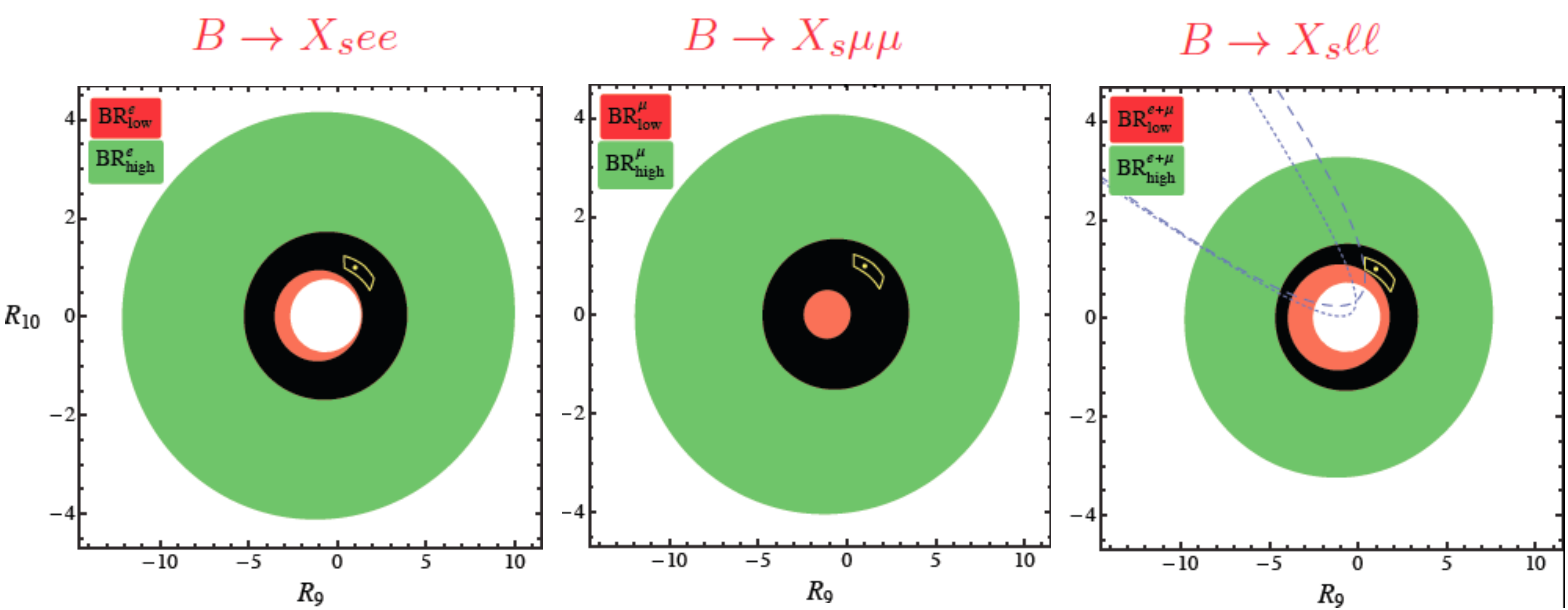
Huber,Hurth,Lunghi, arXiv:1503.04849

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

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

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

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



Cuts in the dilepton and hadronic mass spectra

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

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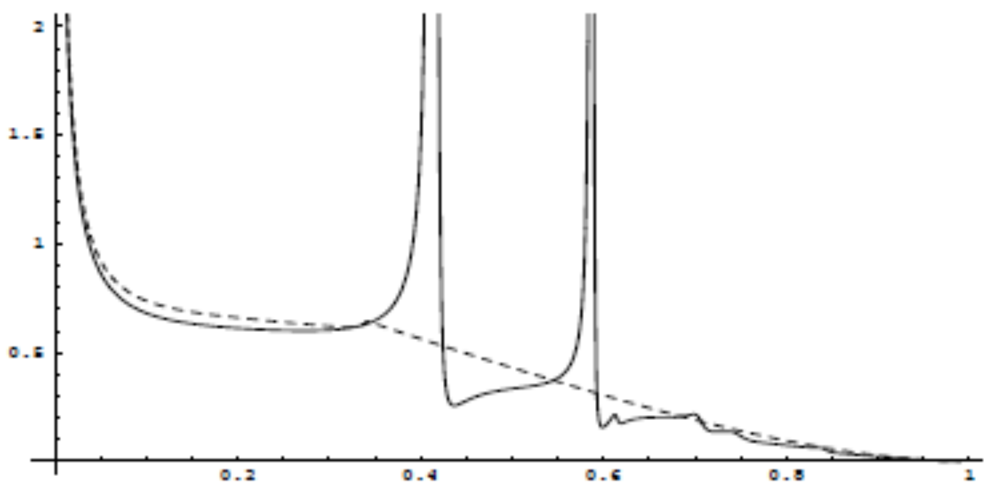
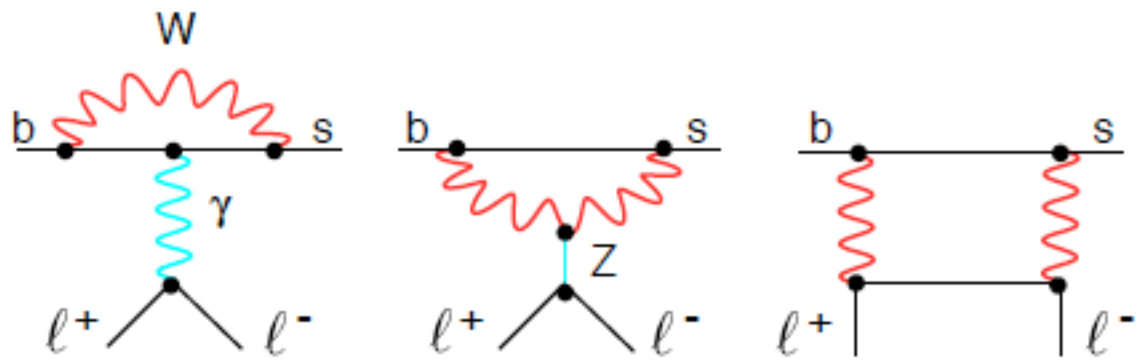




- Hadronic invariant-mass cut is imposed in order to eliminate the background like $b \to c\,(\to se^+\nu)e^-\bar{\nu} = b \to se^+e^- +$ missing energy
  - ∗ Babar,Belle: $m_X < 1.8\,\text{or}\,2.0GeV$
  - ∗ high-q^2 region not affected by this cut
  - ∗ kinematics: X_s is jetlike and $m_X^2 \leq m_b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

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

Nonlocal subleading contributions

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

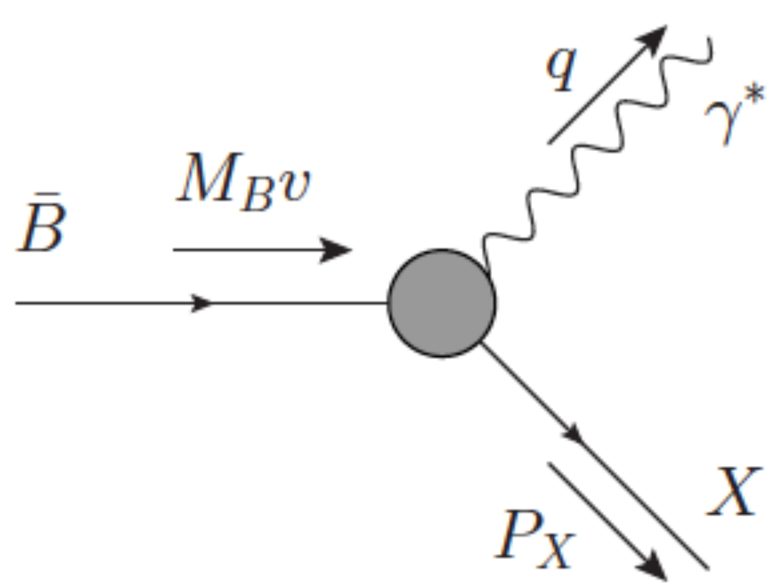
Benzke,Hurth,Turczyk, arXiv:1705.10366

Hadronic cut

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

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

Multiscale problem → SCET



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

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

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

Kinematics

B meson rest frame

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

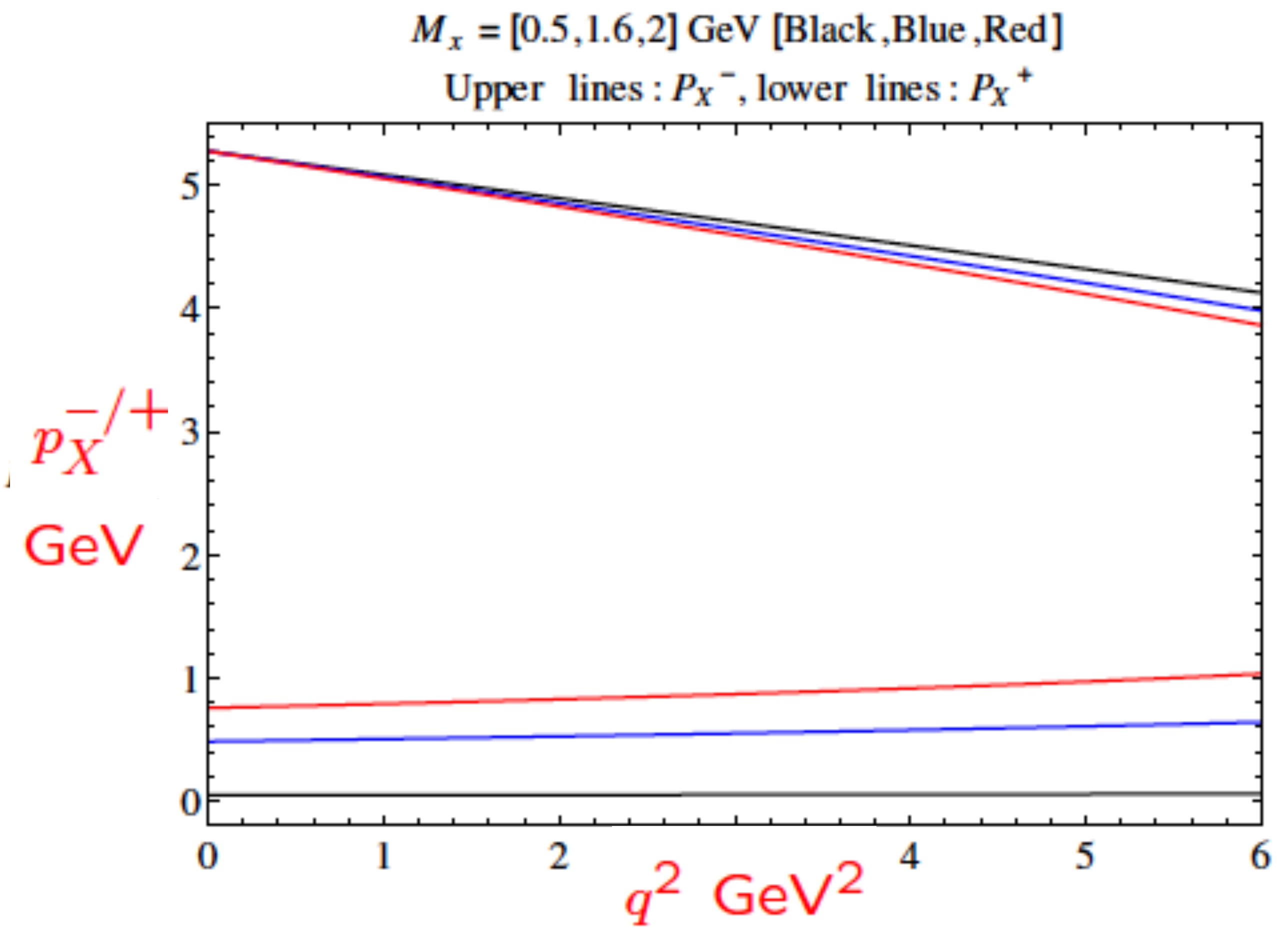
X_s system is jet-like with $E_X \sim m_B$ and $m_X^2 \ll E_X^2$

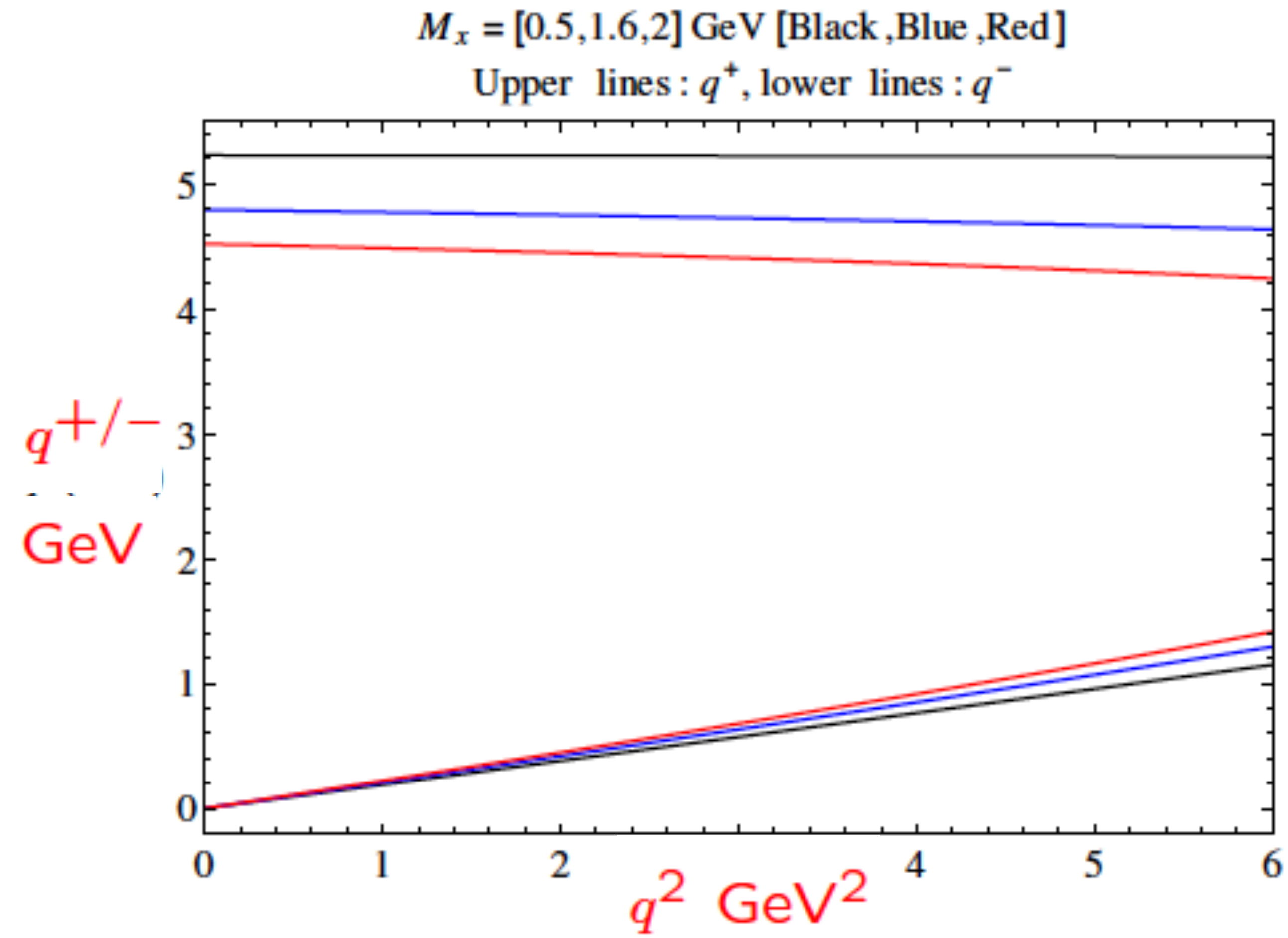
two light-cone components $\qquad p_X^- p_X^+ = m_X^2$

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

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

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





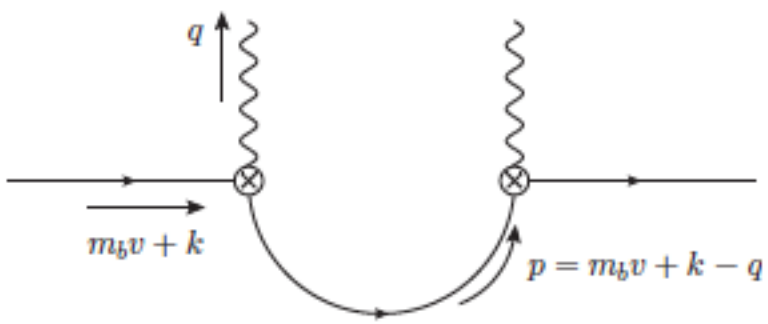
For $q^2 < 6GeV^2$ the scaling of np_X and $\bar{n}p_X$ implies $\bar{n}q$ is of order λ, means q anti-hard-collinear (just kinematics).

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

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

Shapefunction region

Local OPE breaks down for $m_X^2 \sim \lambda$:



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

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

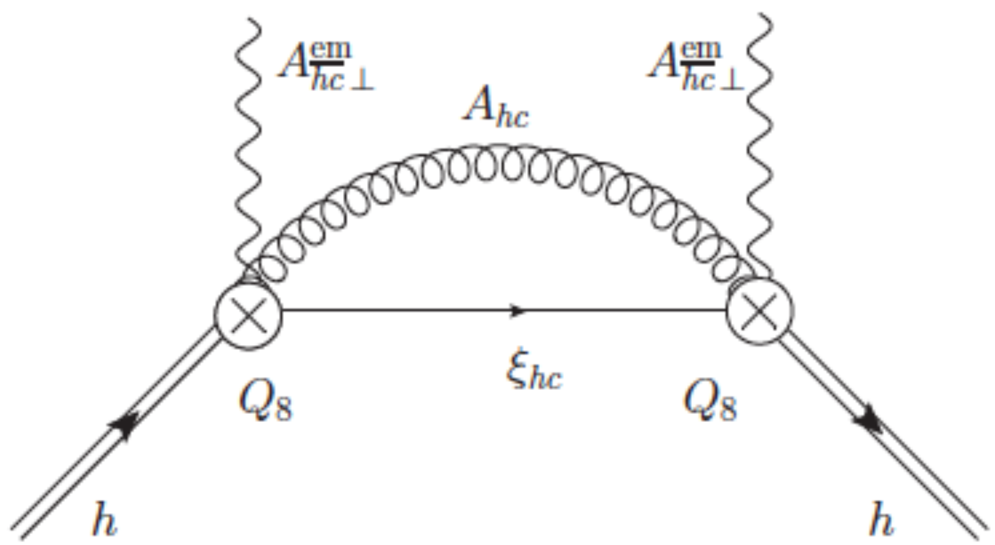
The hard function H and the jet function J are perturbative quantities.

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

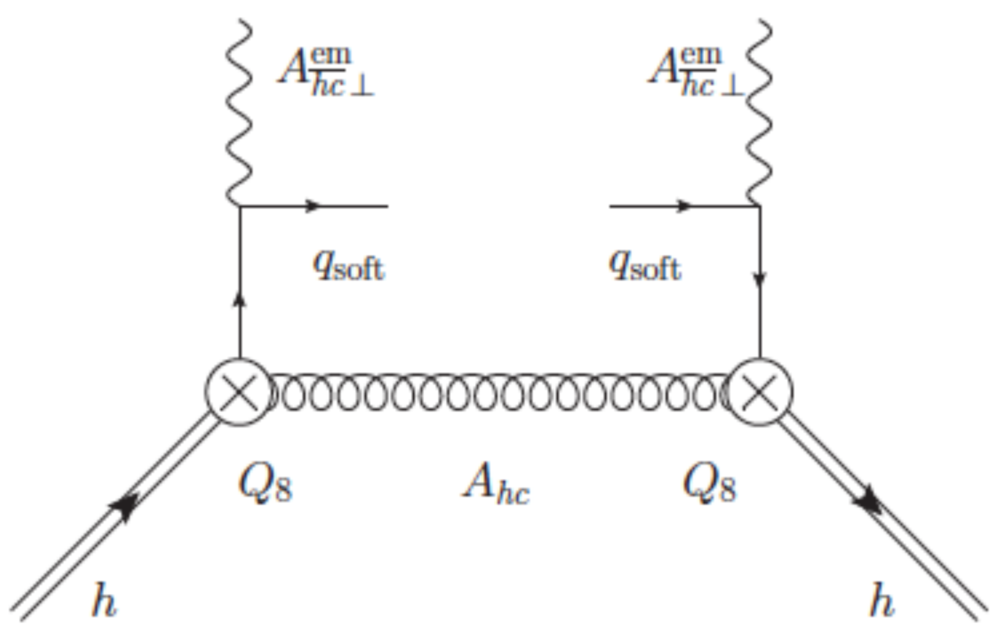
Example of **direct** photon contribution which factorizes $d\Gamma \sim H \cdot j \otimes S$



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

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

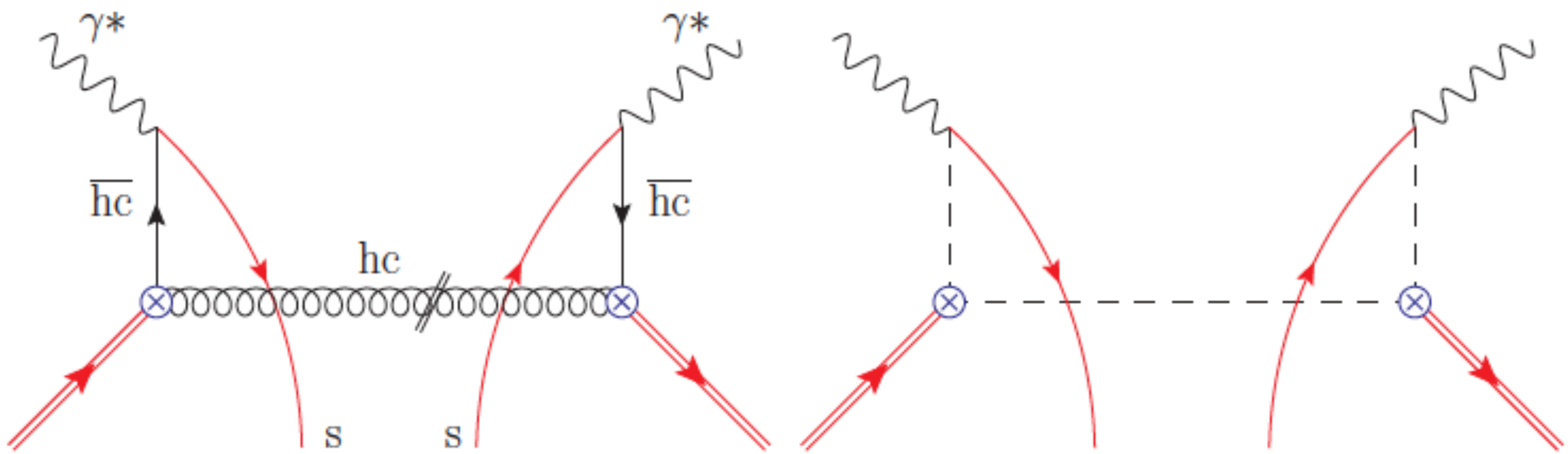
$d\Gamma \sim H \cdot J \otimes s \otimes \bar{J} \otimes \bar{J}$



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

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

Interference of Q_8 and Q_8



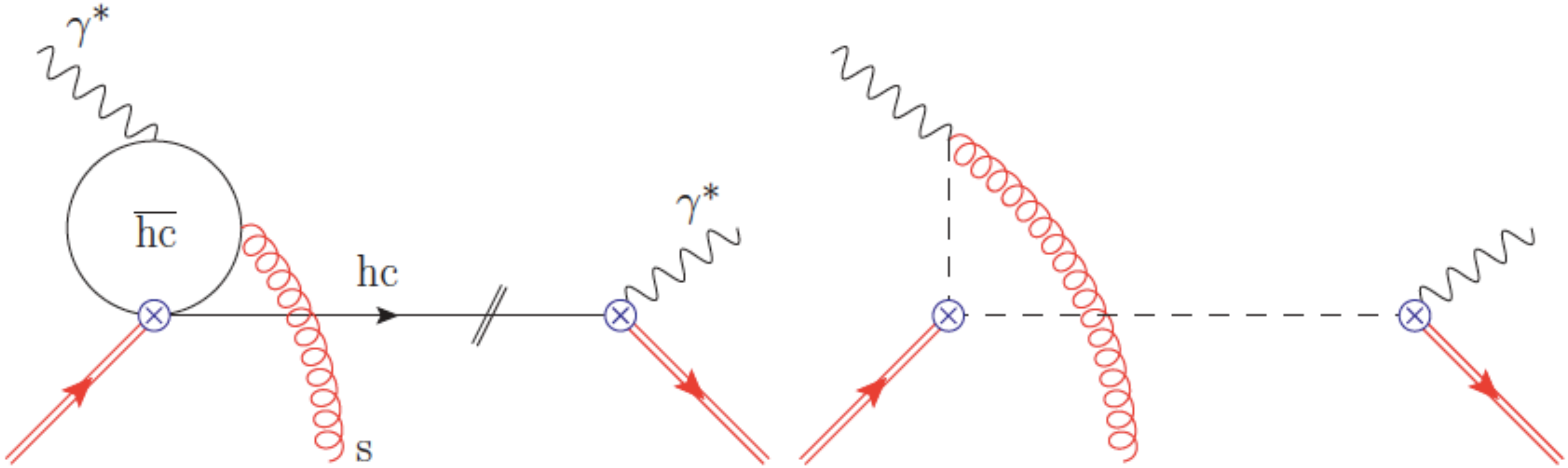
$$\frac{d\Gamma^{\rm res}}{dn\cdot q\, d\bar{n}\cdot q} \sim \frac{e_s^2\alpha_s}{m_b}\int d\omega\, \delta(\omega+p_+)\int \frac{d\omega_1}{\omega_1+\bar{n}\cdot q+i\varepsilon}\int \frac{d\omega_2}{\omega_2+\bar{n}\cdot q-i\varepsilon} g_{88}(\omega,\omega_1,\omega_2)$$

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

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

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

Interference of Q_1 and Q_7



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

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

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

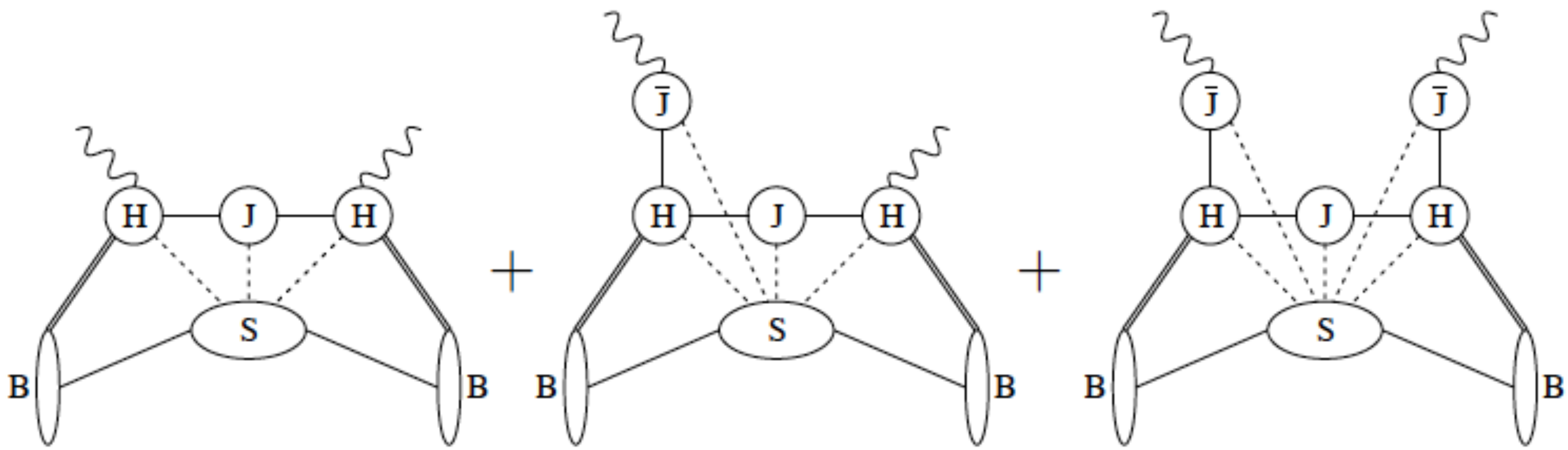
$$g_{17}(\omega,\omega_1)=\int\frac{dr}{2\pi}e^{-i\omega_1 r}\int\frac{dt}{2\pi}e^{-i\omega t}\frac{1}{M_B}\langle\bar{B}|\bar{h}(\mathbf{t n})\ldots G_s^{\alpha\beta}(\mathbf{r\bar{n}})\ldots h(0)|\bar{B}\rangle$$

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

Factorization formula

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

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



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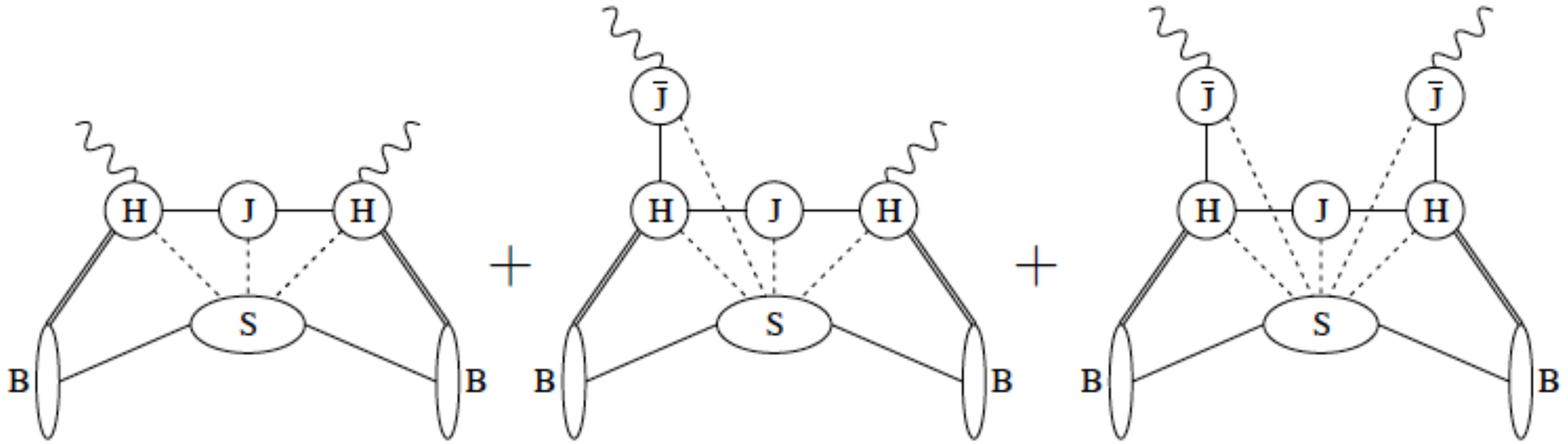
In the $m_X^2 \sim \lambda$ and $q^2 \sim \lambda$ region we have the following factorization formula

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



Subtlety in the Q_8 and Q_8 contribution: convolution integral is UV divergent

- This subtlety implies that there is no complete proof of the factorization formula.
- Nevertheless one shows that scale dependence of direct and resolved contribution cancel.
- No direct analogy to the problem of IR divergent convolution integrals in power-suppressed contributions to exclusive B decays.

Angular observables

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

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

$$d\Gamma(\bar{B} \to X_s \ell^+ \ell^-) \equiv d\Lambda_{\alpha\beta}\,W^{\alpha\beta}(v,q)\,,$$

$$d\Lambda_{\alpha\beta;1/m_b} = dn\cdot q\,d\bar{n}\cdot q\,dz\frac{\alpha}{128\pi^3}(1+z^2)\frac{n\cdot q}{\bar{n}\cdot q}g_{\perp,\alpha\beta}\,.$$

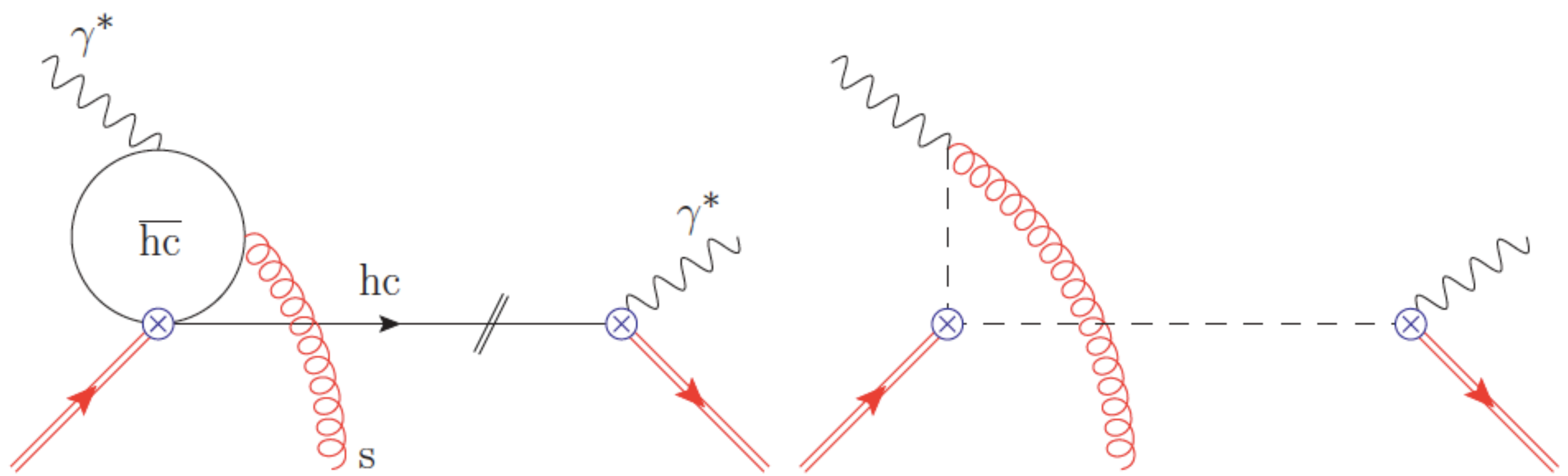
At $O(1/m_b)$ nonlocal powercorrections only to $H_T(q^2)$.

Numerical evaluation

Benzke,Hurth,Turczyk, arXiv:1705.10366

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

Numerical evaluation $\mathcal{O}_1^u - \mathcal{O}_{7\gamma}$



$$d\Gamma_{17} = \frac{1}{m_b}\,\mathrm{Re}\left[\hat{\Gamma}_{17}\frac{-(\lambda_t^q)^*\lambda_c^q}{|\lambda_t^q|^2}\right]\frac{\alpha}{24\pi^3}\,dn\cdot q d\bar{n}\cdot q\,\frac{(n{\cdot}q)^3}{\bar{n}{\cdot}q}$$

$$\times\mathrm{Re}\int d\omega\;\delta(\omega + m_b - n\cdot q)\int d\omega_1\frac{1}{\omega_1 + i\epsilon}$$

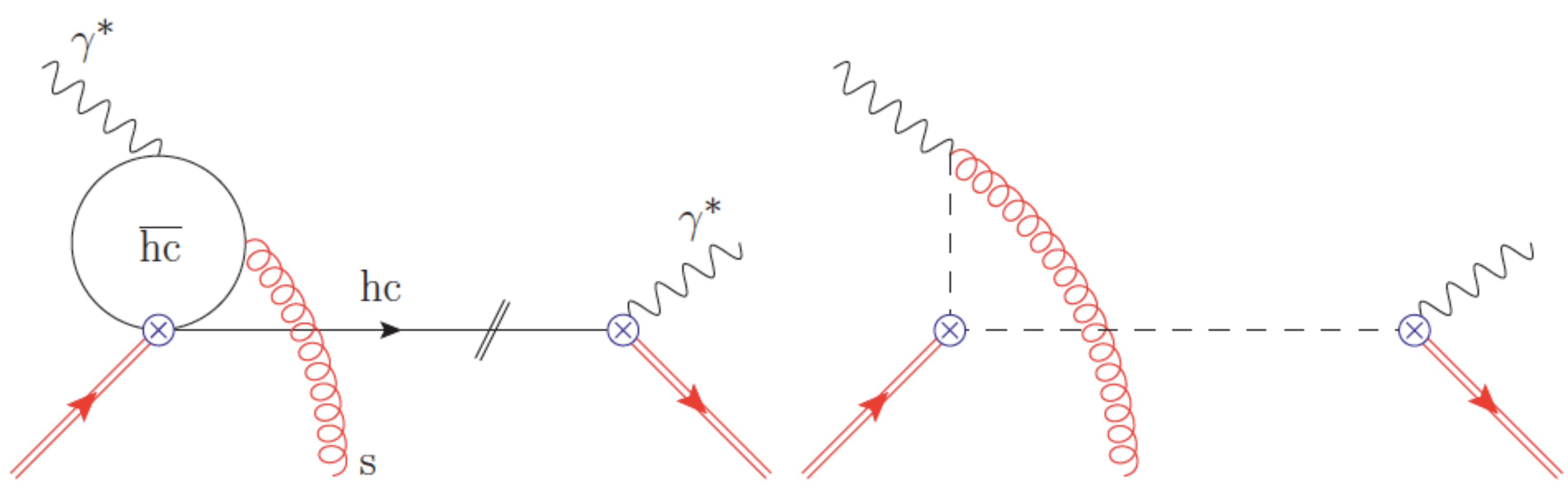
$$\times\frac{1}{\omega_1}\left[(\overline{n}\cdot q + \omega_1)\left(1 - F\left(\frac{m_c^2}{n{\cdot}q(\overline{n}{\cdot}q+\omega_1)}\right)\right) - \overline{n}\cdot q\left(1 - F\left(\frac{m_c^2}{n{\cdot}q\overline{n}{\cdot}q}\right)\right)\right.$$

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

$$g_{17}(\omega,\omega_1,\mu) = \int\frac{dr}{2\pi}\,e^{-i\omega_1 r}\int\frac{dt}{2\pi}\,e^{-i\omega t}$$

$$\times\frac{\langle\bar{B}|\left(\bar{h}S_n\right)(tn)\,\bar{n}\!\!\!/(1+\gamma_5)\left(S_n^\dagger S_{\bar{n}}\right)(0)\,i\gamma_\alpha^\perp\bar{n}_\beta\left(S_{\bar{n}}^\dagger\,gG_s^{\alpha\beta}S_{\bar{n}}\right)(r\bar{n})\left(S_{\bar{n}}^\dagger h\right)(0)|\bar{B}\rangle}{2M_B}$$

Numerical evaluation $\mathcal{O}_1^u - \mathcal{O}_{7\gamma}$



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

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$\mathcal{O}_1^u - \mathcal{O}_{7\gamma}$

- **Limit** $m_c\to m_u=0$

$$\times\frac{1}{\omega_1}\left[\;\omega_1\;\right]g_{17}(\omega,\omega_1,\mu)$$

$$g_{17}(\omega,\omega_1,\mu)=\int\frac{dr}{2\pi}\,e^{-i\omega_1 r}\int\frac{dt}{2\pi}\,e^{-i\omega t}$$

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Numerical evaluation $\mathcal{O}_1^u - \mathcal{O}_{7\gamma}$

- **Trace formalism of HQET:** $\int_{-\infty}^{\bar\Lambda} d\omega\, g_{17}(\omega,\omega_1,\mu) = \int_{-\infty}^{\bar\Lambda} d\omega\, (g_{17}(\omega,-\omega_1,\mu))^*$

$$d\Gamma_{17} = \frac{1}{m_b}\,\mathrm{Re}\left[\hat\Gamma_{17}\frac{-(\lambda_t^q)^*\lambda_c^q}{|\lambda_t^q|^2}\right]\frac{\alpha}{24\pi^3}\,dn\cdot q d\bar n\cdot q\,\frac{(n\cdot q)^3}{\bar n\cdot q}$$
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$$\times\frac{1}{\omega_1}\left[(\overline{n}\cdot q+\omega_1)\left(1-F\left(\frac{m_c^2}{n\cdot q(\overline{n}\cdot q+\omega_1)}\right)\right)-\overline{n}\cdot q\left(1-F\left(\frac{m_c^2}{n\cdot q\overline{n}\cdot q}\right)\right)\right.$$
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$\mathcal{O}_1^u - \mathcal{O}_{7\gamma}$

- **Limit** $m_c \to m_u = 0$

$$\times\frac{1}{\omega_1}\,[\;\omega_1\;]\;g_{17}(\omega,\omega_1,\mu)$$

Numerical evaluation $\mathcal{O}_1^u - \mathcal{O}_{7\gamma}$

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$\mathcal{O}_1^u - \mathcal{O}_{7\gamma}$

- **Limit** $m_c \to m_u = 0$

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Numerical evaluation $\mathcal{O}_1^u - \mathcal{O}_{7\gamma}$

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

$\mathcal{O}_1^u - \mathcal{O}_{7\gamma}$

- **Limit** $m_c \to m_u = 0$

$$\times\frac{1}{\omega_1}\,[\;\omega_1\;]\;g_{17}(\omega,\omega_1,\mu)$$

- **Integration of** ω_1**:**

Interference term $\mathcal{O}_1^u - \mathcal{O}_{7\gamma}$ vanishes within the integrated rate

Numerical evaluation $\mathcal{O}_1^c - \mathcal{O}_{7\gamma}$

$$\mathcal{F}_{17}^q = \frac{1}{m_b} \frac{C_1(\mu) C_{7\gamma}(\mu)}{C_{\rm OPE}} e_c \, {\rm Re}\left[\frac{-(\lambda_t^q)^* \lambda_c^q}{|\lambda_t^q|^2} \right] \int_{-\infty}^{+\infty} d\omega_1 \, J_{17}(q^2_{\rm min}, q^2_{\rm max}, \omega_1) \, h_{17}(\omega_1, \mu)$$

Numerical evaluation $\mathcal{O}_1^c - \mathcal{O}_{7\gamma}$

$$\mathcal{F}_{17}^q = \frac{1}{m_b}\frac{C_1(\mu)C_{7\gamma}(\mu)}{C_{\mathrm{OPE}}} e_c \,\mathrm{Re}\left[\frac{-(\lambda_t^q)^* \lambda_c^q}{|\lambda_t^q|^2}\right] \int_{-\infty}^{+\infty} d\omega_1 \, J_{17}(q^2_{\mathrm{min}}, q^2_{\mathrm{max}}, \omega_1)\, h_{17}(\omega_1, \mu)$$

$$h(\omega_1, \mu) := \int_{-\infty}^{\bar{\Lambda}} d\omega \, g_{17}(\omega, \omega_1, \mu)$$

Numerical evaluation $\mathcal{O}_1^c - \mathcal{O}_{7\gamma}$

$$\mathcal{F}_{17}^q = \frac{1}{m_b}\frac{C_1(\mu)C_{7\gamma}(\mu)}{C_{\text{OPE}}} e_c \,\text{Re}\left[\frac{-(\lambda_t^q)^*\lambda_c^q}{|\lambda_t^q|^2}\right] \int_{-\infty}^{+\infty} d\omega_1 \, J_{17}(q^2_{\text{min}}, q^2_{\text{max}}, \omega_1)\, h_{17}(\omega_1,\mu)$$

$$J_{17}(q^2_{\text{min}}, q^2_{\text{max}}, \omega_1) = \text{Re}\frac{1}{\omega_1 + i\epsilon}\int_{\frac{q^2_{\text{min}}}{M_B}}^{\frac{q^2_{\text{max}}}{M_B}} \frac{d\overline{n}\cdot q}{\overline{n}\cdot q}\frac{1}{\omega_1}$$

$$h(\omega_1,\mu) := \int_{-\infty}^{\bar{\Lambda}} d\omega\, g_{17}(\omega,\omega_1,\mu)$$

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

Numerical evaluation $\mathcal{O}_1^c - \mathcal{O}_{7\gamma}$

$$\mathcal{F}_{17}^q = \frac{1}{m_b} \frac{C_1(\mu) C_{7\gamma}(\mu)}{C_{\rm OPE}} e_c \, {\rm Re}\left[\frac{-(\lambda_t^q)^* \lambda_c^q}{|\lambda_t^q|^2}\right] \int_{-\infty}^{+\infty} d\omega_1 \, J_{17}(q^2_{\rm min}, q^2_{\rm max}, \omega_1) \, h_{17}(\omega_1, \mu)$$

$$J_{17}(q^2_{\rm min}, q^2_{\rm max}, \omega_1) = {\rm Re} \frac{1}{\omega_1 + i\epsilon} \int_{\frac{q^2_{\rm min}}{M_B}}^{\frac{q^2_{\rm max}}{M_B}} \frac{d\bar{n}\cdot q}{\bar{n}\cdot q} \frac{1}{\omega_1}$$

$$h(\omega_1, \mu) := \int_{-\infty}^{\bar{\Lambda}} d\omega \, g_{17}(\omega, \omega_1, \mu)$$

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

- One derives normalization of soft function: $\int_{-\infty}^{\infty} d\omega_1 h_{17}(\omega_1, \mu) = 2\,\lambda_2$
- h_{17} should not have any significant structure (maxima or zeros) outside the hadronic range
- Values of h_{17} should be within the hadronic range

- First trial for a model function for h_{17}, a Gaussian, fullfills all needed properties.

$$h_{17}(\omega_1) = \frac{2\lambda_2}{\sqrt{2\pi}\sigma} e^{-\frac{\omega_1^2}{2\sigma^2}}$$

$\sigma = 0.5\,\mathrm{GeV}$ as typical hadronic scale: $\mathcal{F}^s_{17\mathrm{exp}} \approx +1.6\,\%$

$\sigma = 0.1\,\mathrm{GeV}$: $\mathcal{F}^s_{17\mathrm{exp}} \approx +1.9\,\%$

However, convolution leads only to positive percentages !

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However, convolution leads only to positive percentages !

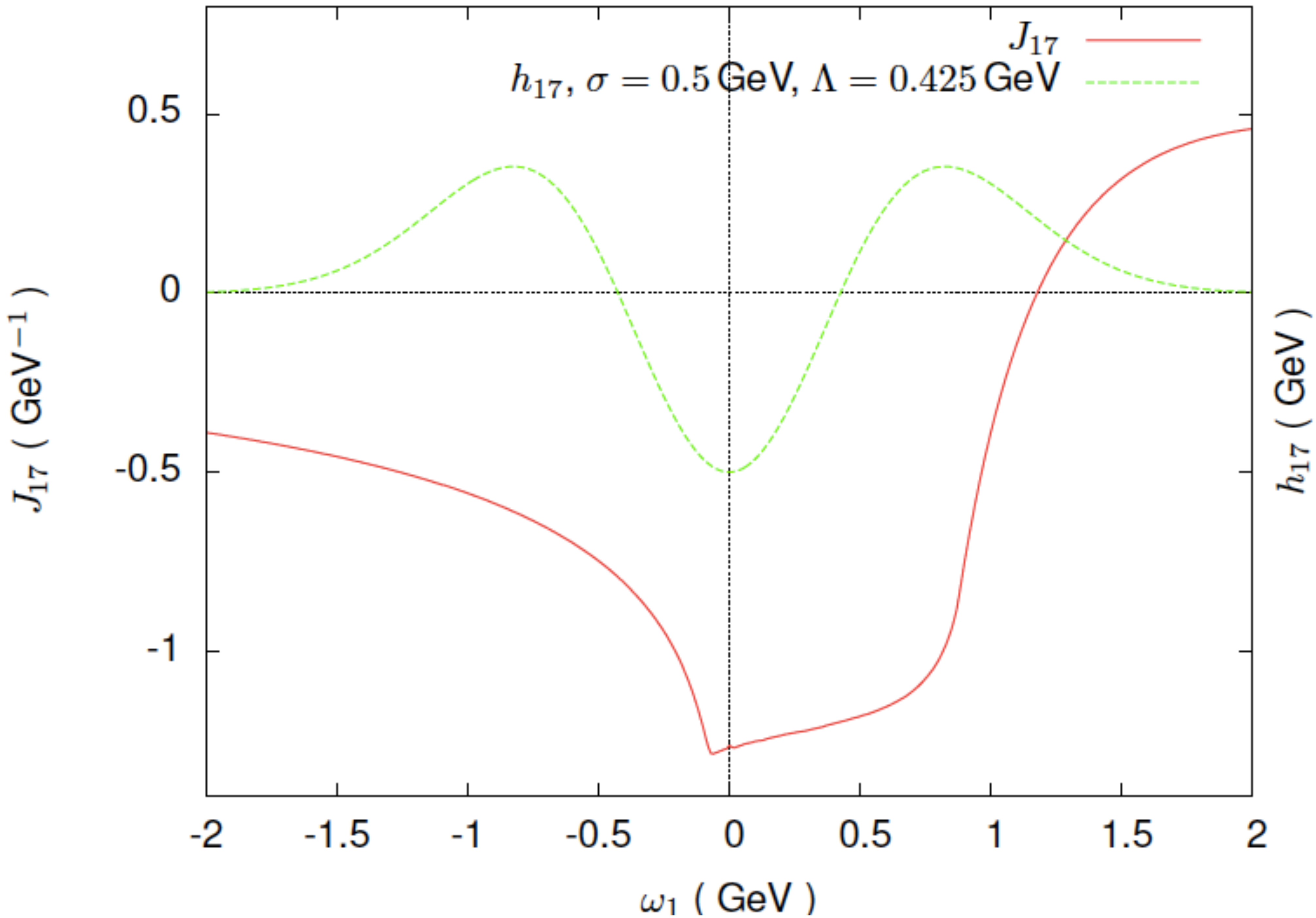
- More conservative estimate with $h_{17}(\omega_1) = \frac{2\lambda_2}{\sqrt{2\pi}\sigma} \frac{\omega_1^2 - \Lambda^2}{\sigma^2 - \Lambda^2} e^{-\frac{\omega_1^2}{2\sigma^2}}$

With Λ and σ of order Λ_{QCD} all general properties of h_{17} are fulfilled.

$\sigma = 0.5\,\mathrm{GeV};\ \Lambda = 0.425\,\mathrm{GeV}$: $\mathcal{F}^s_{17} = -0.5\%$

$\Lambda = 0.575\,\mathrm{GeV}$: $\mathcal{F}^s_{17} = +3.4\%$

$$\mathcal{F}^s_{17} \in [-0.5, +3.4]\,\%, \qquad \mathcal{F}^d_{17} \in [-0.6, +4.1]\,\%$$



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

- Relation to the Voloshin term: Voloshin 1997, Buchalla,Isidori,Rey 1997

We can rederive the leading Voloshin term under the following assumptions:

One starts with a narror enough Gaussian as shape function, so that one can expand the jet function around $\omega_1 = 0$ assuming $\Lambda_{\rm QCD} m_b/m_c^2$ to be small ($(m_b\omega_1)/m_c^2$ corresponds to $t = k \cdot q/m_c^2$ in Buchalla et al.):

$$[\ldots] = \omega_1^2 \bar{n}\cdot q \left[\frac{1}{2\bar{n}\cdot q^2} - \frac{2m_c^2}{\bar{n}\cdot q^2} \frac{1}{4m_c^2 - m_b \bar{n}\cdot q} \sqrt{\frac{4m_c^2 - m_b\bar{n}\cdot q}{m_b \bar{n}\cdot q}} \arctan \frac{1}{\sqrt{\frac{4m_c^2 - m_b\bar{n}\cdot q}{m_b\bar{n}\cdot q}}} \right]$$

$$= -\frac{m_b\omega_1^2}{12 m_c^2} F_{\rm V}(r)\,, \quad r = q^2/(4m_c^2)$$

However:

Voloshin term significantly underestimates the possible charm contributions.

Final result

Benzke,Hurth,Turczyk, arXiv:1705.10366

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

(normalized to OPE result)

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

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

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

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

(work in progress)

Power corrections in the inclusive mode

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

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

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

(work in progress)

Summary

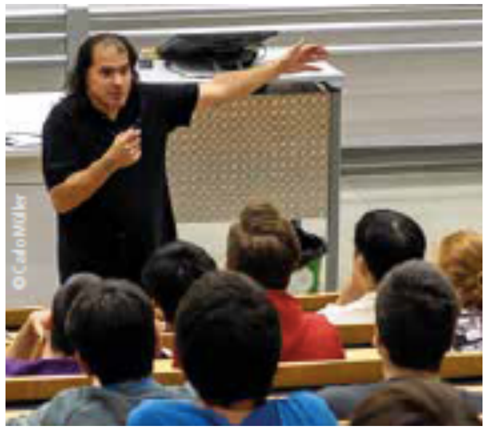
- Phenomenological analysis to NNLO QCD and NLO QED for all angular observables available

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

- Nonlocal power corrections are under control and calculated to $O(1/m_b)$

- Theory predictions for inclusive $\bar{B} \to X_d \ell^+ \ell^-$ (including QED and power corrections) will be soon available (work in progress)

- Inclusive $\bar{B} \to X_s \ell\ell$ has a complementary role in new physics search to $\bar{B} \to X_s \gamma$ and $B \to K^{(*)} \ell\ell$



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Probing Physics Beyond the SM with Precision
Ansgar Denner U Würzburg, Stefan Dittmaier U Freiburg,
Tilman Plehn Heidelberg U
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Bridging the Standard Model to New Physics with the Parity Violation Program at MESA
Jens Erler UNAM, Mikhail Gorshteyn, Hubert Spiesberger JGU
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Philip Candelas, Xenia de la Ossa, Andre Lukas U Oxford,
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The Evaluation of the Leading Hadronic Contribution to the Muon Anomalous Magnetic Moment
Carlo Carloni Calame INFN Pavia, Massimo Passera INFN Padua,
Luca Trentadue U Parma, Graziano Venanzoni INFN Pisa
February 19 - 23, 2018

Applied Newton-Cartan Geometry
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Cora Dvorkin Harvard, Silvia Galli IAP Paris,
Fabio Iocco ICTP-SAIFR, Federico Marinacci MIT
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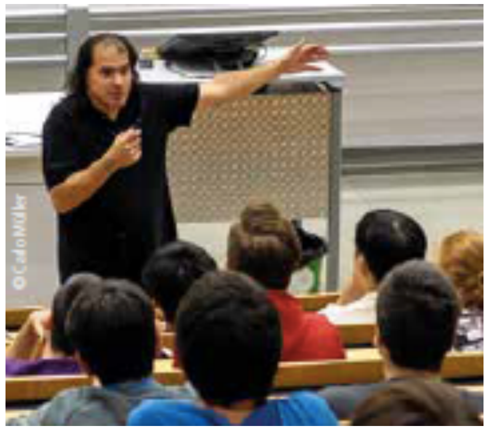

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…anzoni INFN Pisa

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… Chicago
…16, 2018

…allenges in Semileptonic B Decays
Paolo Gambino U Turin, Andreas Kronfeld Fermilab,
Marcello Rotondo INFN-LNF Frascati, Christoph Schwanda ÖAW Vienna
April 9 - 13, 2018

Tensions in the LCDM Paradigm
Cora Dvorkin Harvard, Silvia Galli IAP Paris,
Fabio Iocco ICTP-SAIFR, Federico Marinacci MIT
May 14 - 18, 2018

The Proton Radius Puzzle and Beyond
Richard Hill U Kentucky / Fermilab, Gil Paz Wayne State U, Randolf Pohl JGU
July 23 - 27, 2018

Scattering Amplitudes and Resonance Properties from Lattice QCD
Maxwell T. Hansen CERN, Sasa Prelovsek U Ljubljana / U Regensburg,
Steve Sharpe U Washington, Georg von Hippel, Hartmut Wittig JGU
August 27 - 31, 2018

Quantum Fields – From Fundamental Concepts to Phenomenological Questions
Astrid Eichhorn Heidelberg U, Roberto Percacci SISSA Trieste,
Frank Saueressig U Nijmegen
September 26 - 28, 2018

MITP SUMMER SCHOOL 2018

Johannes Henn, Matthias Neubert, Stefan Weinzierl, Felix Yu JGU
July 2018

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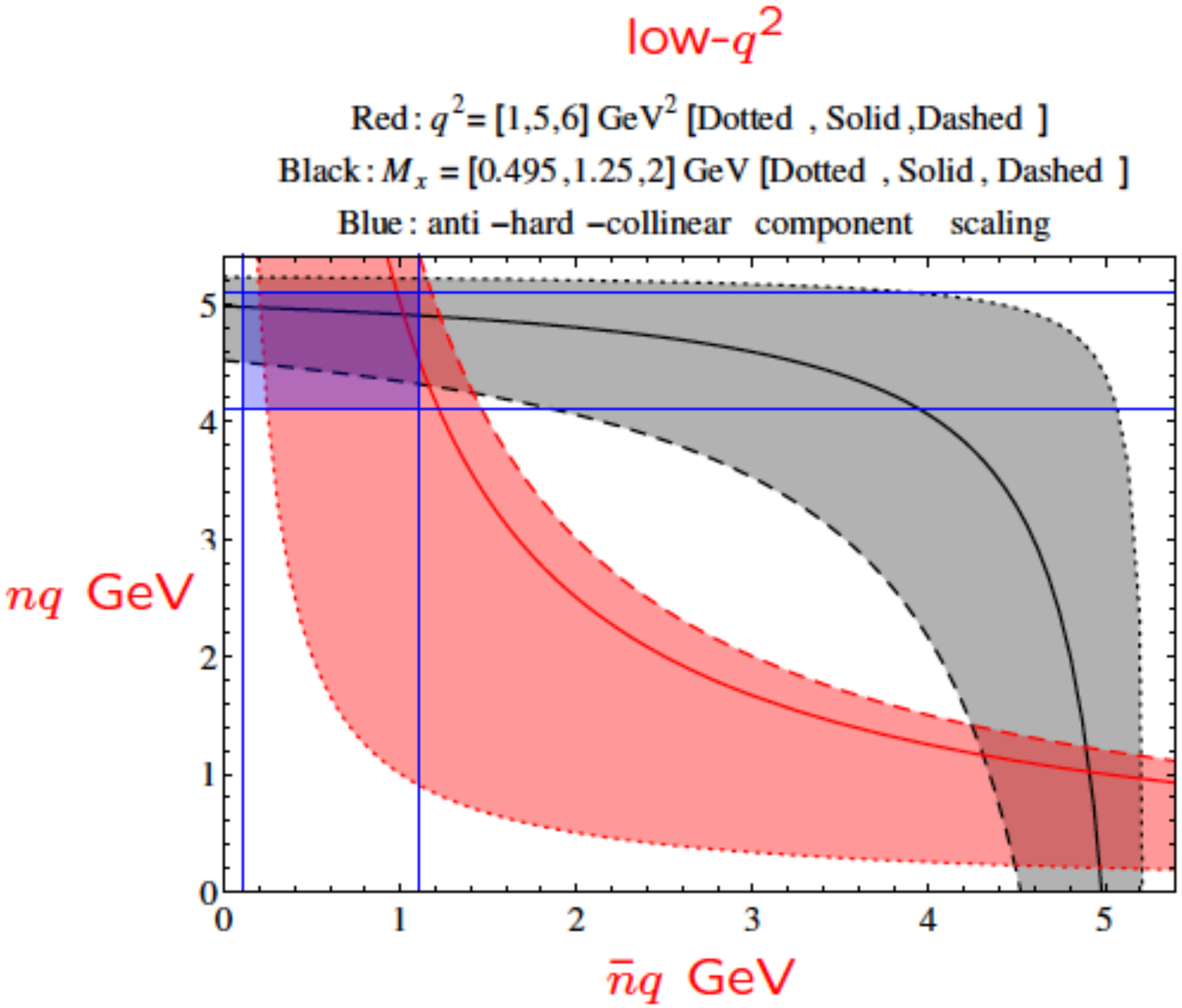
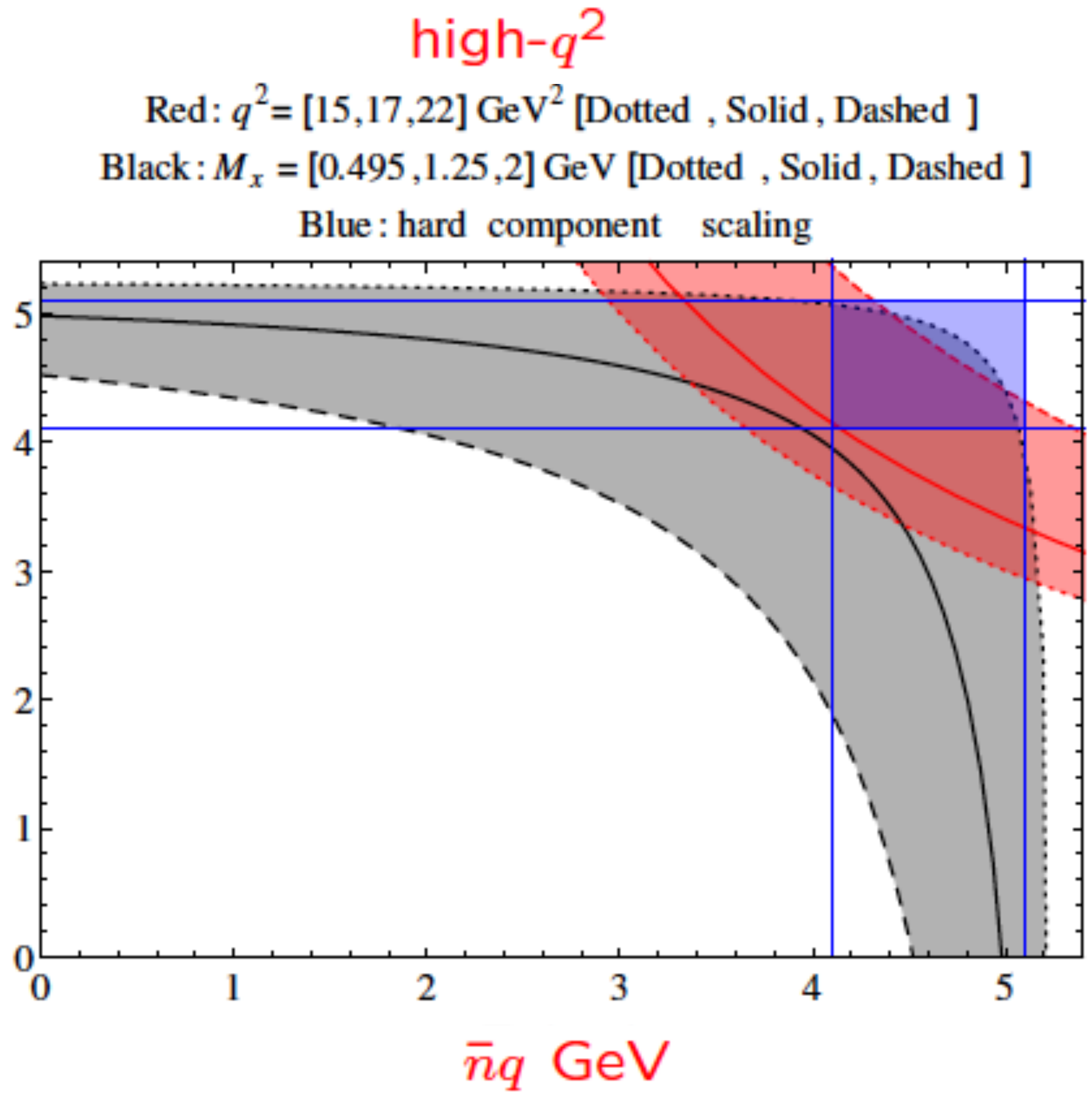
Extra

Alllowed regions





Scaling

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

Theory predictions

Huber,Hurth,Lunghi, arXiv:1503.04849

- 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 $\kappa = \alpha_{\rm em}/\alpha_s$

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

$$\mathrm{LO} = \alpha_{\rm em}/\alpha_s\,, \qquad \mathrm{NLO} = \alpha_{\rm em}\,, \qquad \mathrm{NNLO} = \alpha_{\rm em}\,\alpha_s$$

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LO = $\alpha_{\rm em}/\alpha_s$, NLO = $\alpha_{\rm em}$, NNLO = $\alpha_{\rm em}\,\alpha_s$

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

  Size of logs depend on experimental set-up

  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 !

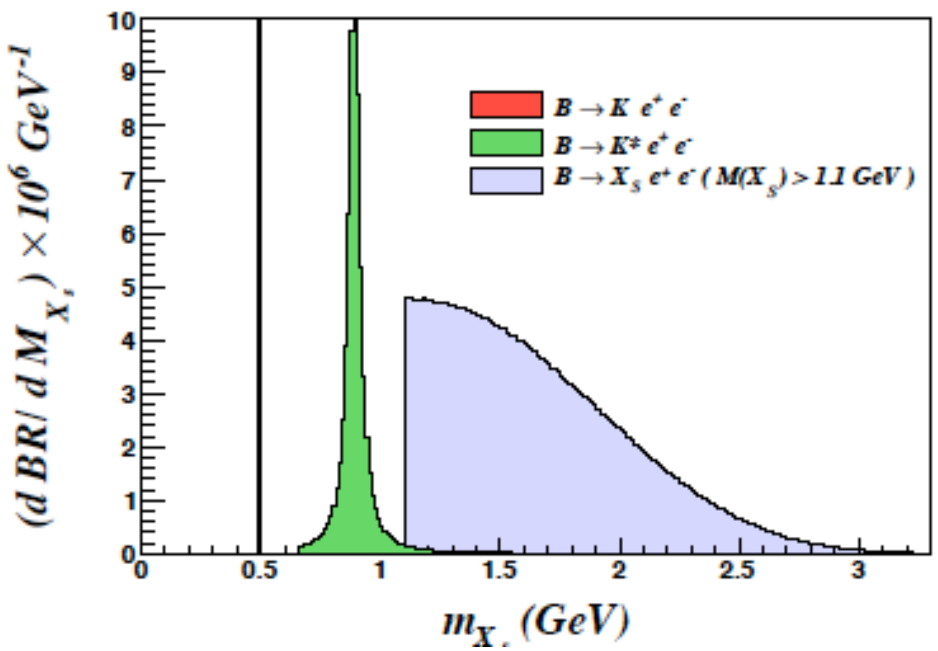
$$q^2 = (p_{\ell^+} + p_{\ell^-})^2 \quad \text{vs.} \quad q^2 = (p_{\ell^+} + p_{\ell^-} + p_{\gamma,\rm coll})^2$$

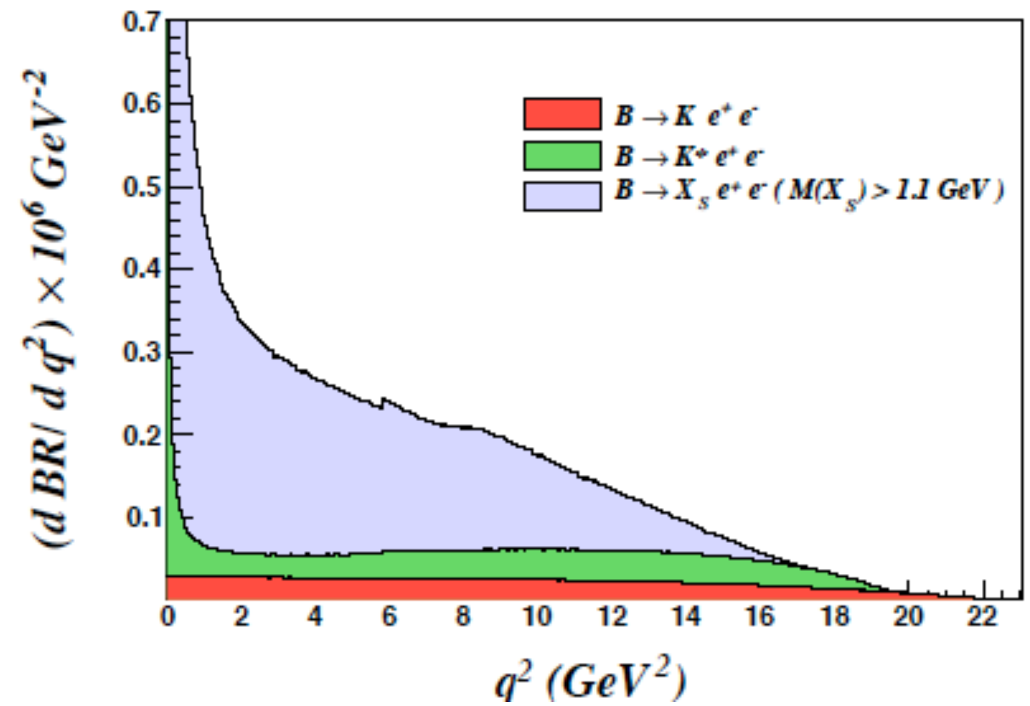
Monte Carlo analysis

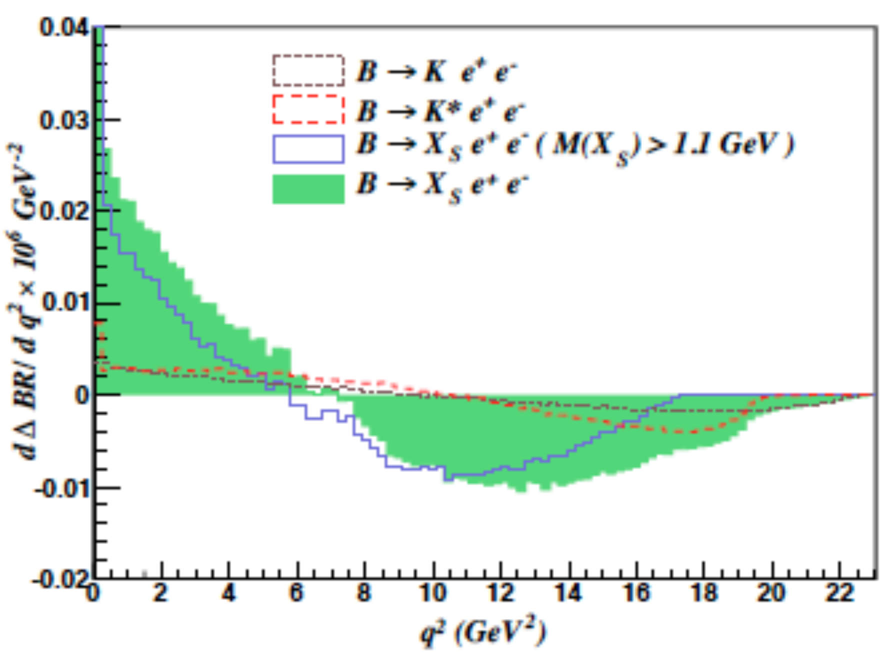
Huber,Hurth,Lunghi, arXiv:1503.04849

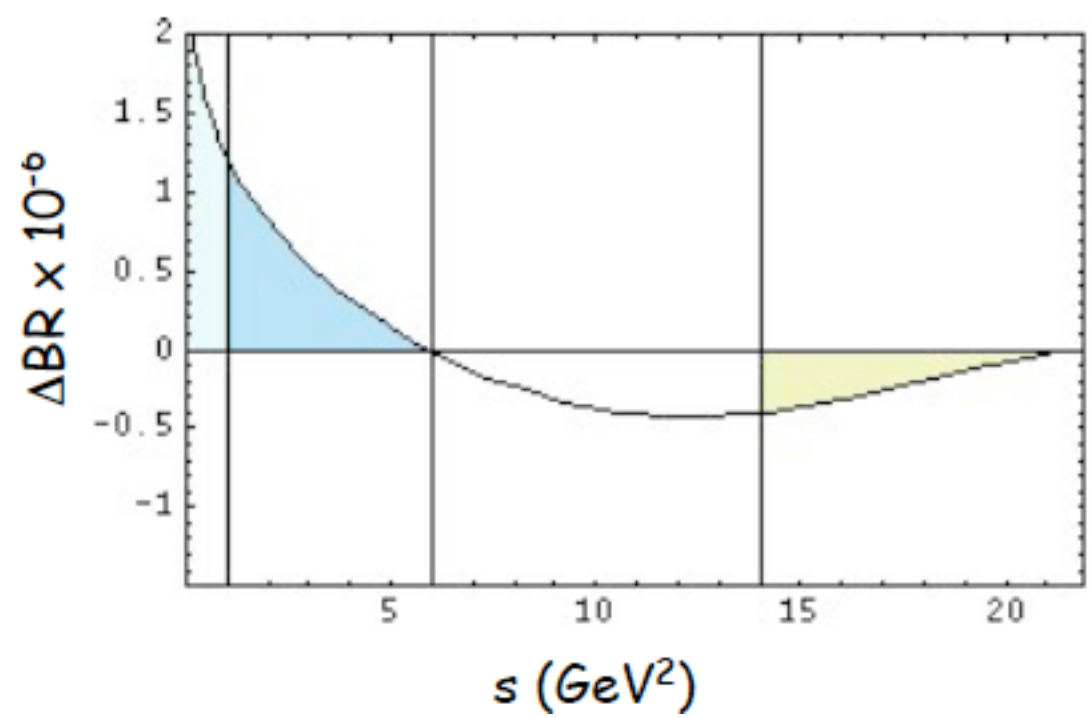
(event generator EVTGEN, hadronization JETSET, EM radiation PHOTOS)

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









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 results in units of 10^{-6}

$H_L[1,3.5]_{ee} = 0.64 \pm 0.03$	$H_L[1,3.5]_{\mu\mu} = 0.68 \pm 0.04$
$H_L[3.5,6]_{ee} = 0.50 \pm 0.03$	$H_L[3.5,6]_{\mu\mu} = 0.53 \pm 0.03$
$H_L[1,6]_{ee} = 1.13 \pm 0.06$	$H_L[1,6]_{\mu\mu} = 1.21 \pm 0.07$
$H_T[1,3.5]_{ee} = 0.29 \pm 0.02$	$H_T[1,3.5]_{\mu\mu} = 0.21 \pm 0.01$
$H_T[3.5,6]_{ee} = 0.24 \pm 0.02$	$H_T[3.5,6]_{\mu\mu} = 0.19 \pm 0.02$
$H_T[1,6]_{ee} = 0.53 \pm 0.04$	$H_T[1,6]_{\mu\mu} = 0.40 \pm 0.03$
$H_A[1,3.5]_{ee} = -0.103 \pm 0.005$	$H_A[1,3.5]_{\mu\mu} = -0.110 \pm 0.005$
$H_A[3.5,6]_{ee} = +0.073 \pm 0.012$	$H_A[3.5,6]_{\mu\mu} = +0.067 \pm 0.012$
$H_A[1,6]_{ee} = -0.029 \pm 0.016$	$H_A[1,6]_{\mu\mu} = -0.042 \pm 0.016$

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

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

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

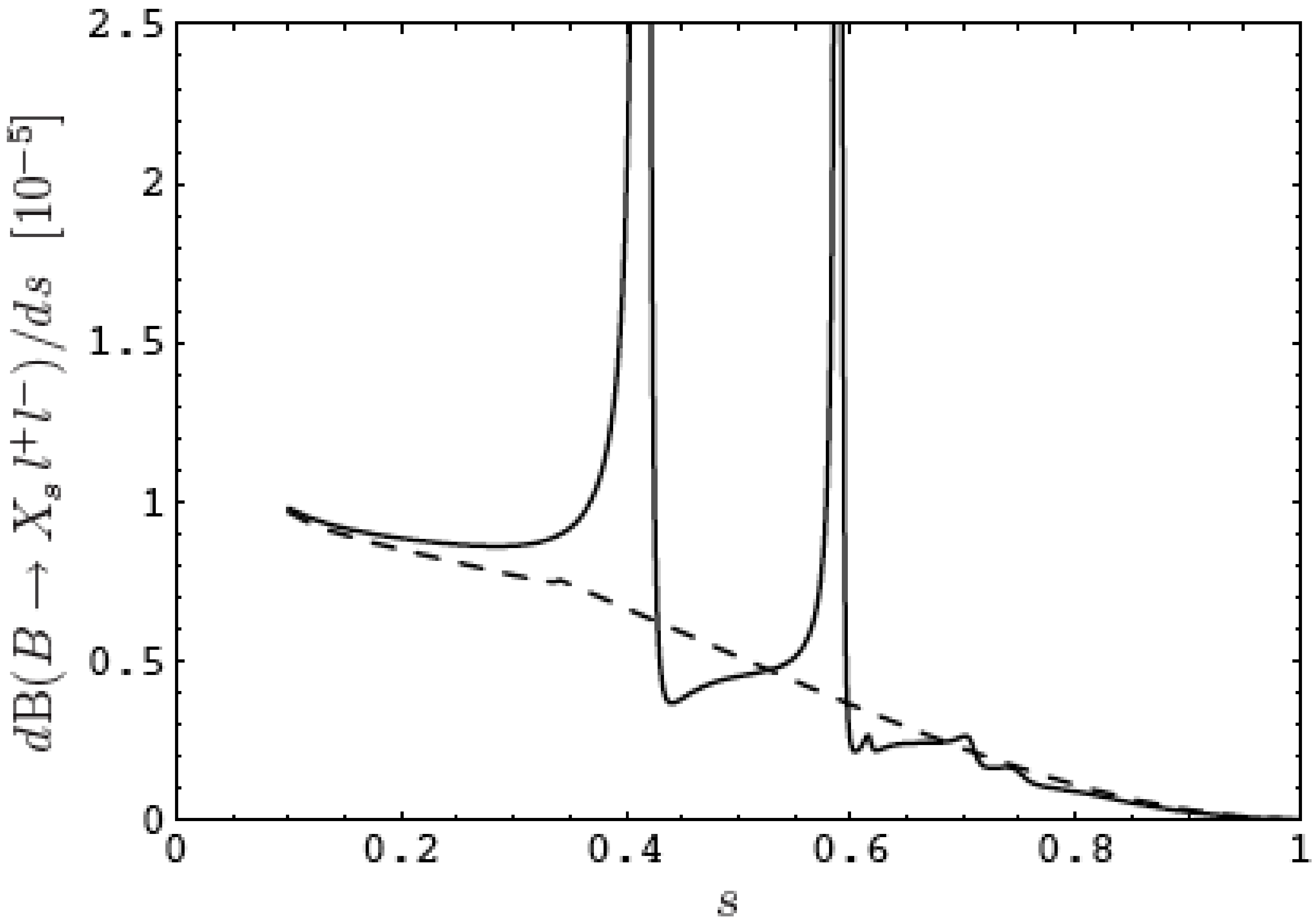
$$R(s_0)_{\mu\mu} = (2.62 \pm 0.30)\, 10^{-3}$$

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

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

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.



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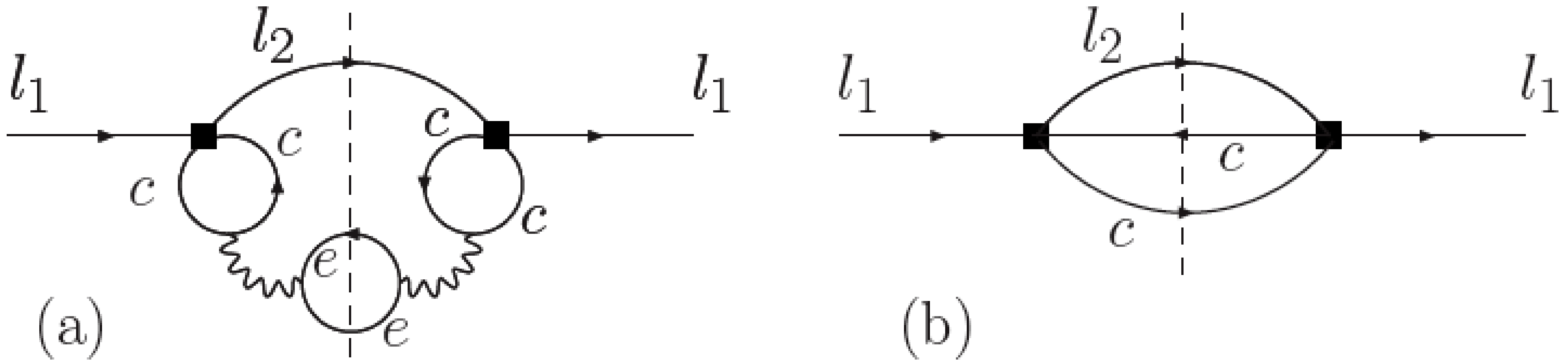

The rate $l_1 \to l_2 e^+ e^-$ (a) is connected to the integral over $|\Pi(q^2)|^2$ for which global duality is NOT expected to hold.

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

Subtlety in the high-q^2 region

Locally: breakdown of OPE in Λ_{QCD}/m_b in the high-s (q^2) endpoint
Partonic contribution vanishes in the limit $s \to 1$, while the $1/m_b^2$ corrections in $R(s)$ tend towards a nonzero value.

Theoretically: s-quark propagator in the correlator of OPE:

$$S_s(k) = \frac{\not k + i \not D}{k^2 + 2ik \cdot D - \not D \not D + i\varepsilon} \, .$$

Endpoint region of the q^2 spectrum in $\bar{B} \to X_s l^+ l^-$ different from endpoint region of the photon spectrum of $\bar{B} \to X_s \gamma$:
$q^2 \approx m_b^2 \approx M_B^2 \;\Rightarrow k \sim \Lambda, \quad k^2 \sim \Lambda^2 \;\Rightarrow$ complete breakdown of OPE
no partial all-orders resummation possible, shape-function irrelevant
Buchalla,isidori

Practically: for integrated high-s (q^2) spectrum one finds an effective expansion ($s_{\min} \approx 0.6$): Ghinculov,Hurth,Isidori,Yao,hep-ph/0312128

$$\int_{s_{\min}}^1 ds \; R(s) = \left[1 - \frac{1.6\lambda_2}{m_b^2(1-\sqrt{s_{\min}})^2} + \frac{1.8\rho_1 + 1.7 f_1}{m_b^3(1-\sqrt{s_{\min}})^3} \right] \times \int_{s_{\min}}^1 ds \;\; R(s)|_{m_b \to \infty}$$