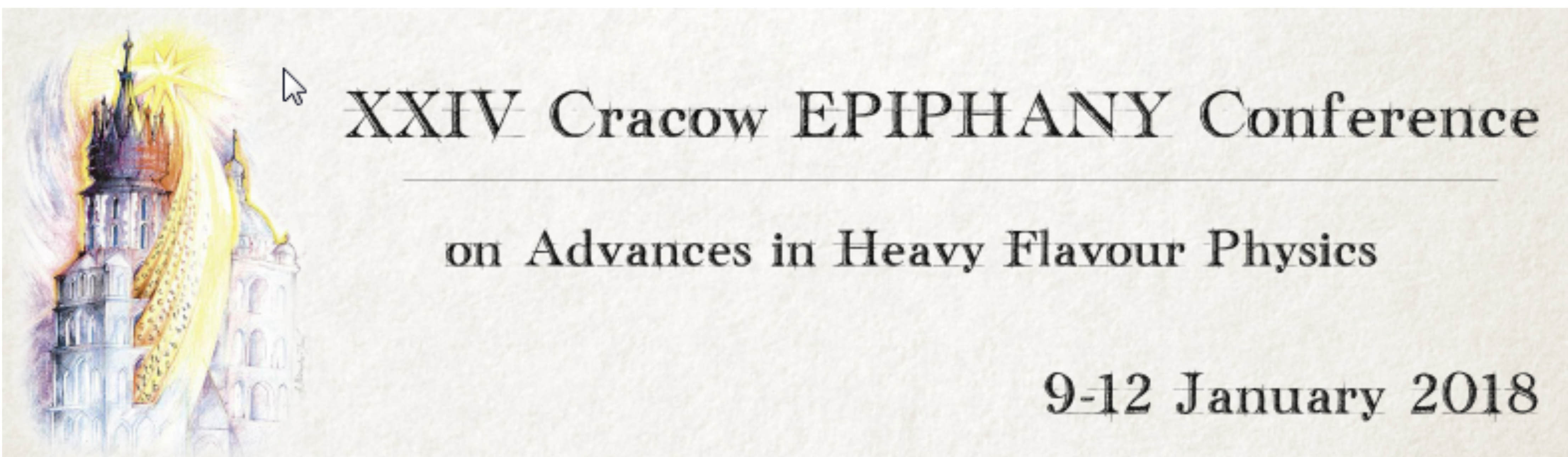
Inclusive Semi-leptonic Penguin Decays

Tobias Hurth, Johannes Gutenberg University Mainz



Motivation

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

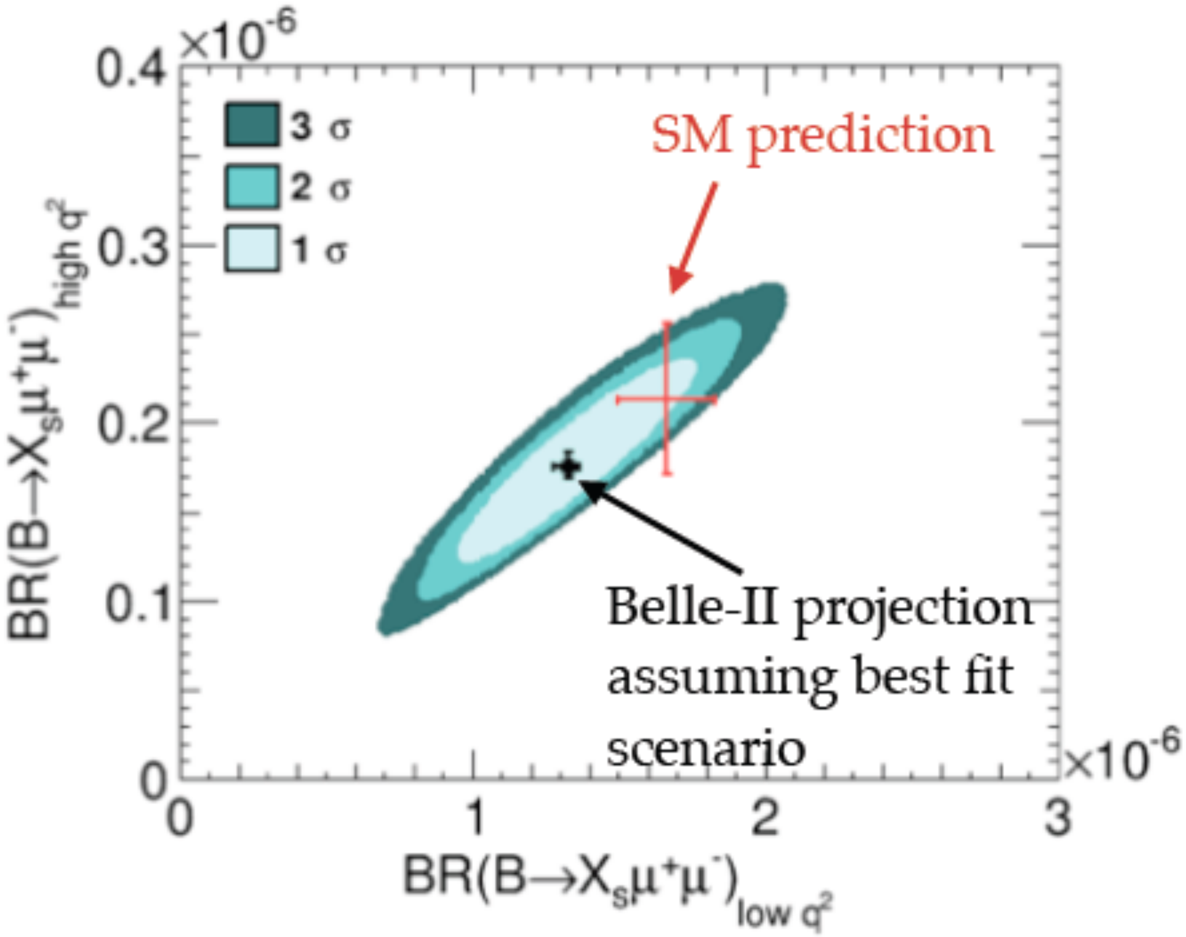
AFBn (%) (stat,syst)	0.7/ab	5/ab	50/ab
[1.0,3.5]	26 (26,2.7)	9.7 (9.7,1.3)	3.1 (3.1,0.5)
[3.5,6.0]	21 (21,2.7)	7.9 (7.9,1.3)	2.6 (2.6,0.5)
$\geq$ 14.4	19 (19,1.7)	7.3 (7.3,0.8)	2.4 (2.4,0.3)

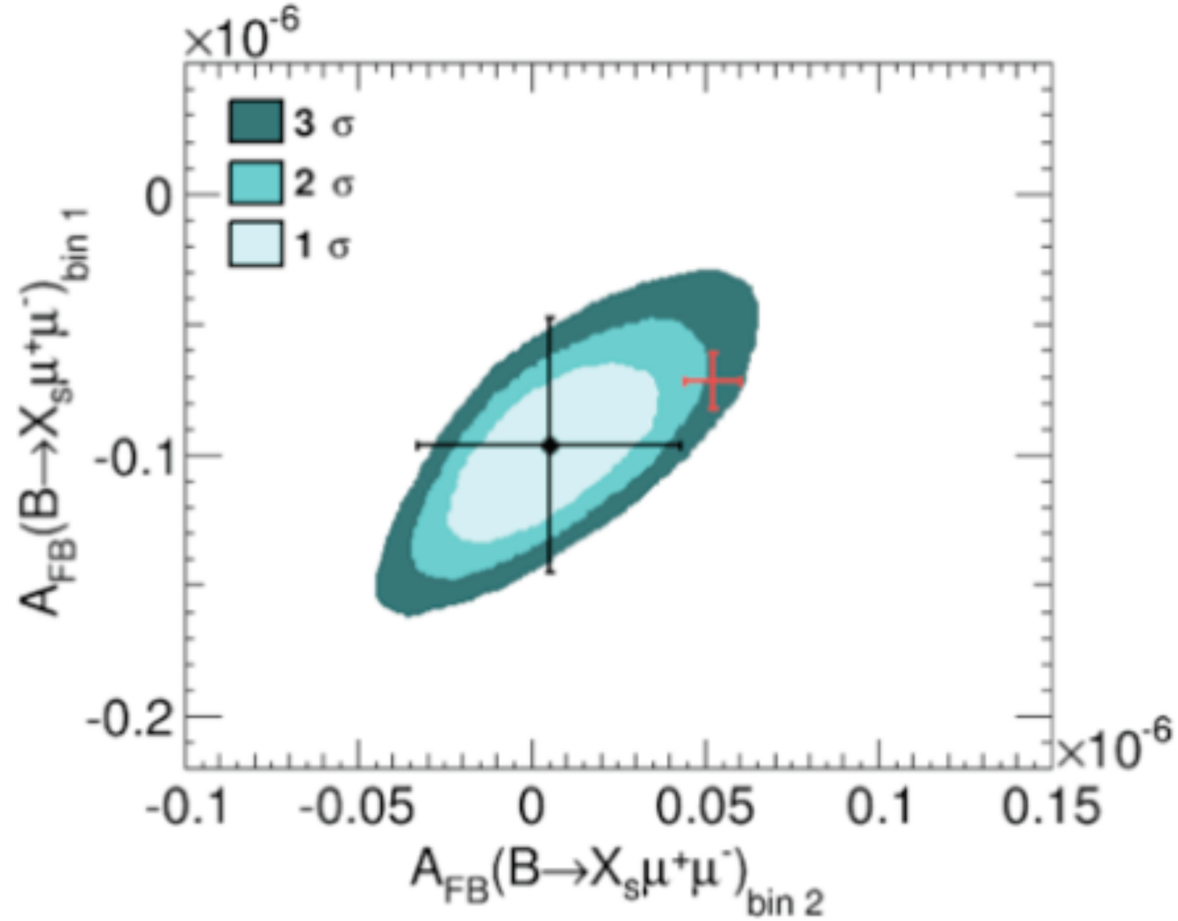
$B \to (\pi, \rho)\ell^+\ell^-$, semi-inclusive $\bar{B} \to X_d \ell^+ \ell^-$ at $50/ab$
(uncertainties like $\bar{B} \to X_s \ell^+ \ell^-$ at $0.7/ab$)

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





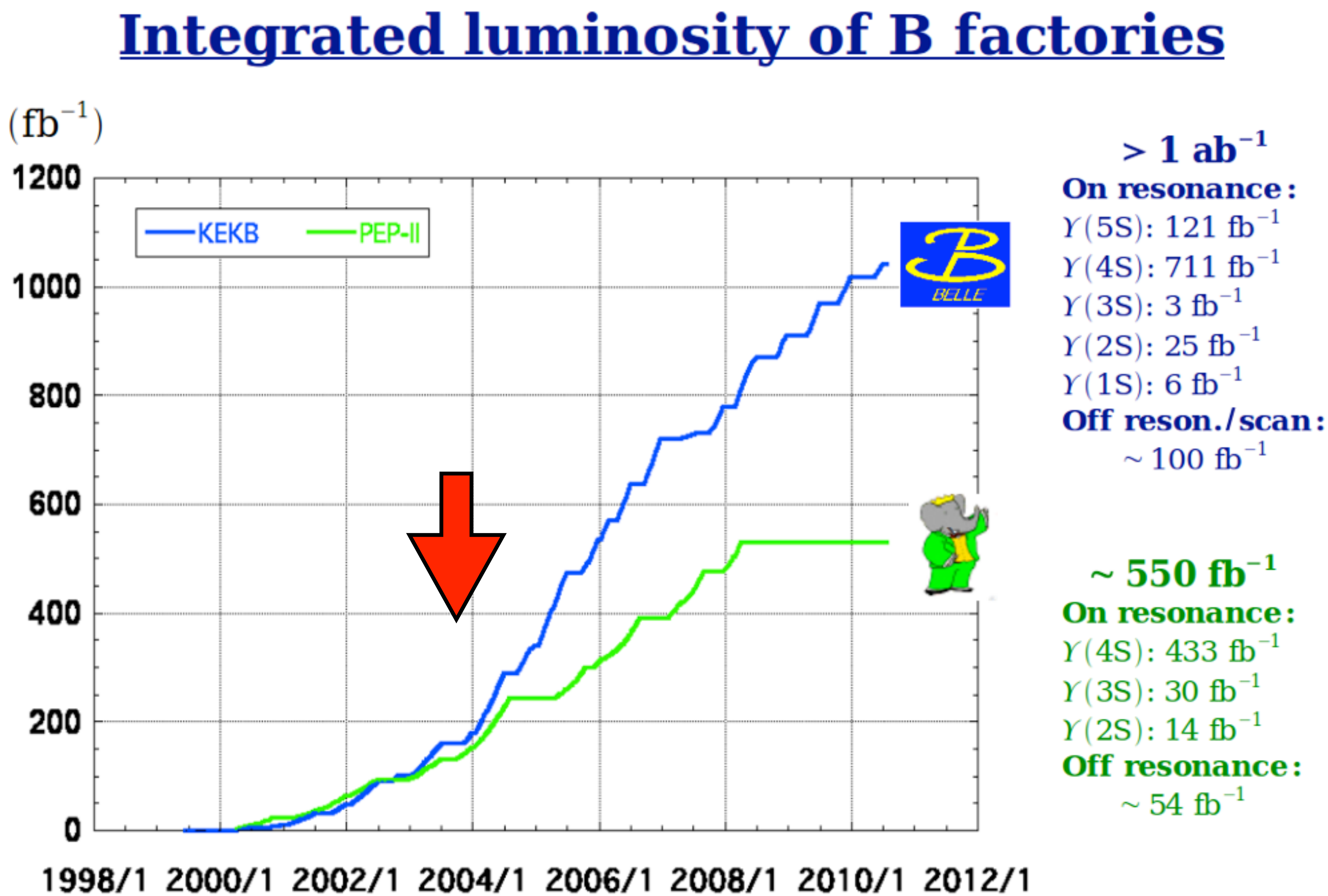
If NP then the effect of C_9 and C_9' are large enough to be checked at Belle-II with theoretically clean modes.

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

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)

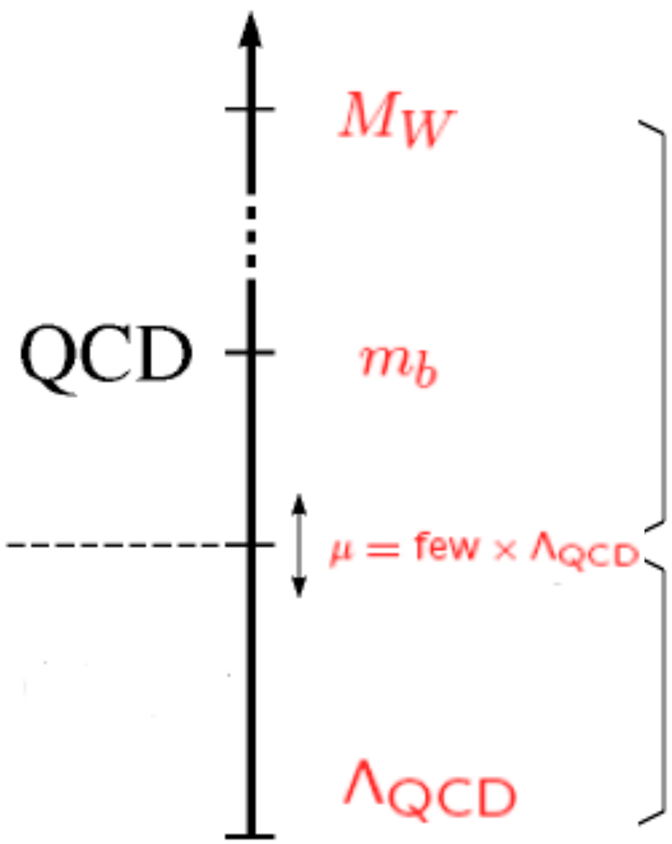


New Babar analysis on dilepton spectrum arXiv:1312.3664

New Belle analysis on AFB arXiv:1402.7134

Theoretical Tools

Theoretical tools for flavour precision observables



short-distance physics
perturbative

$log(m_b/M_W)$

long-distance physics
nonperturbative

Factorization theorems: separating long- and short-distance physics

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

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

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

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

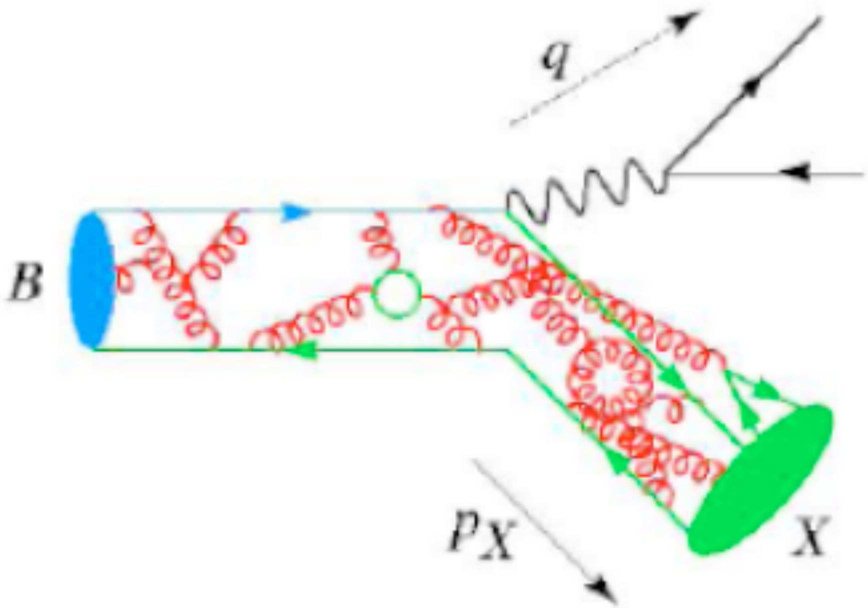
How to compute the hadronic matrix elements $\mathcal{O}_i(\mu = m_b)$?

Heavy mass expansion for inclusive modes:

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

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

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

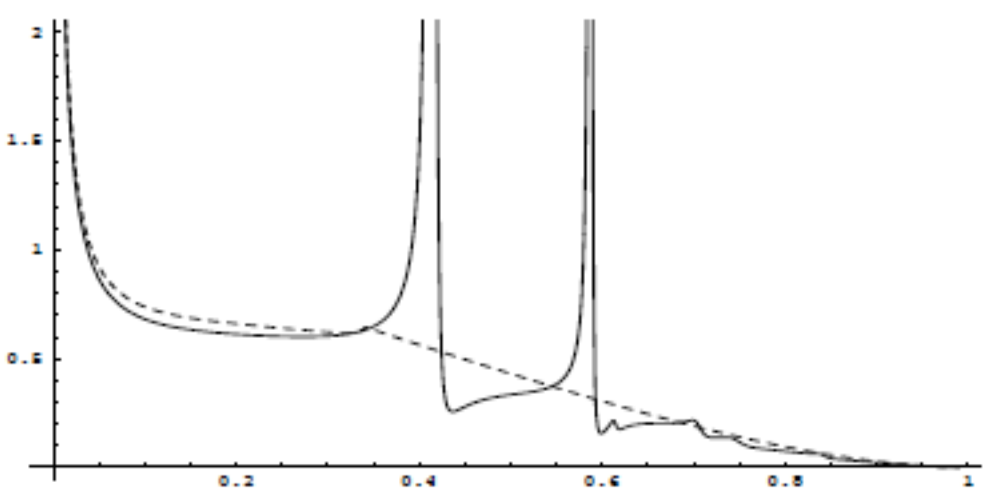
Analysis in $B \to X_s\ell\ell$ in this talk; Benzke,Fickinger,Hurth,Turczyk

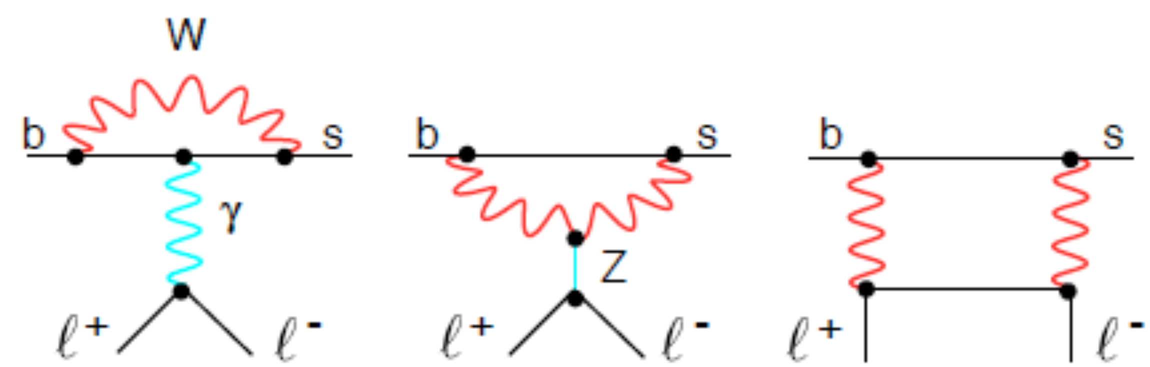
Perturbative contributions

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

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

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





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

- 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

- 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)

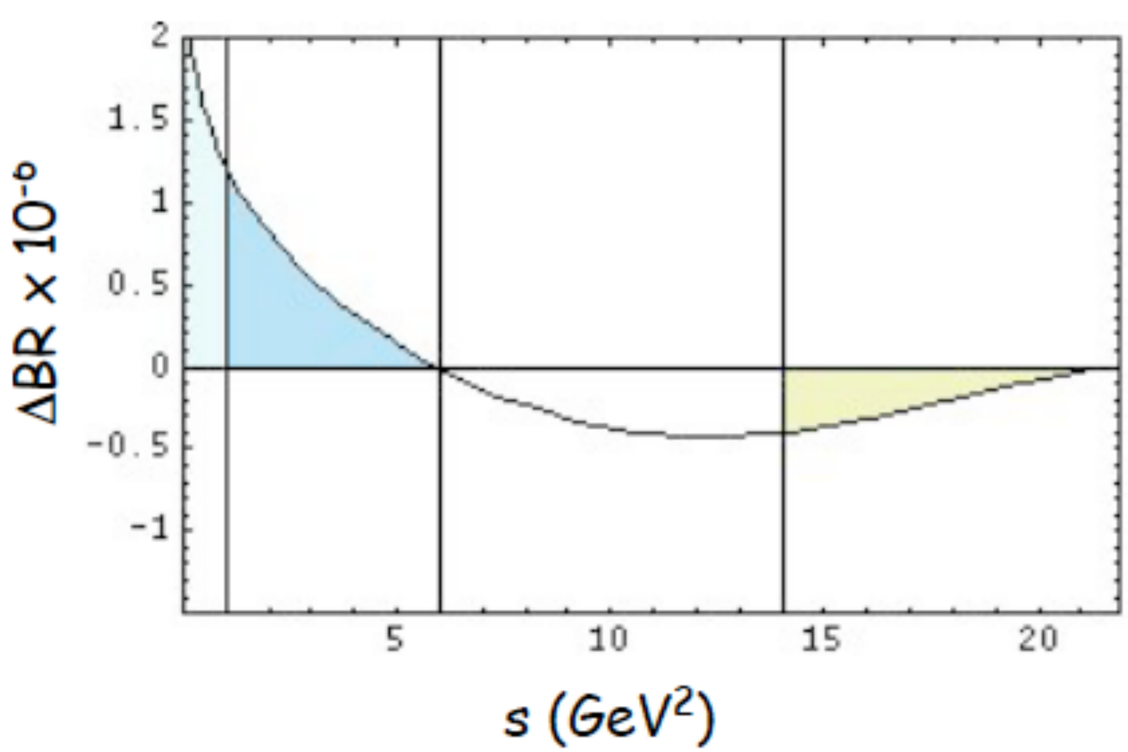
$$A_{FB}(q_0^2) = 0 \quad \text{for} \quad q_0^2 \sim C_7/C_9 \quad q_0^2 = (3.90 \pm 0.25) GeV^2$$

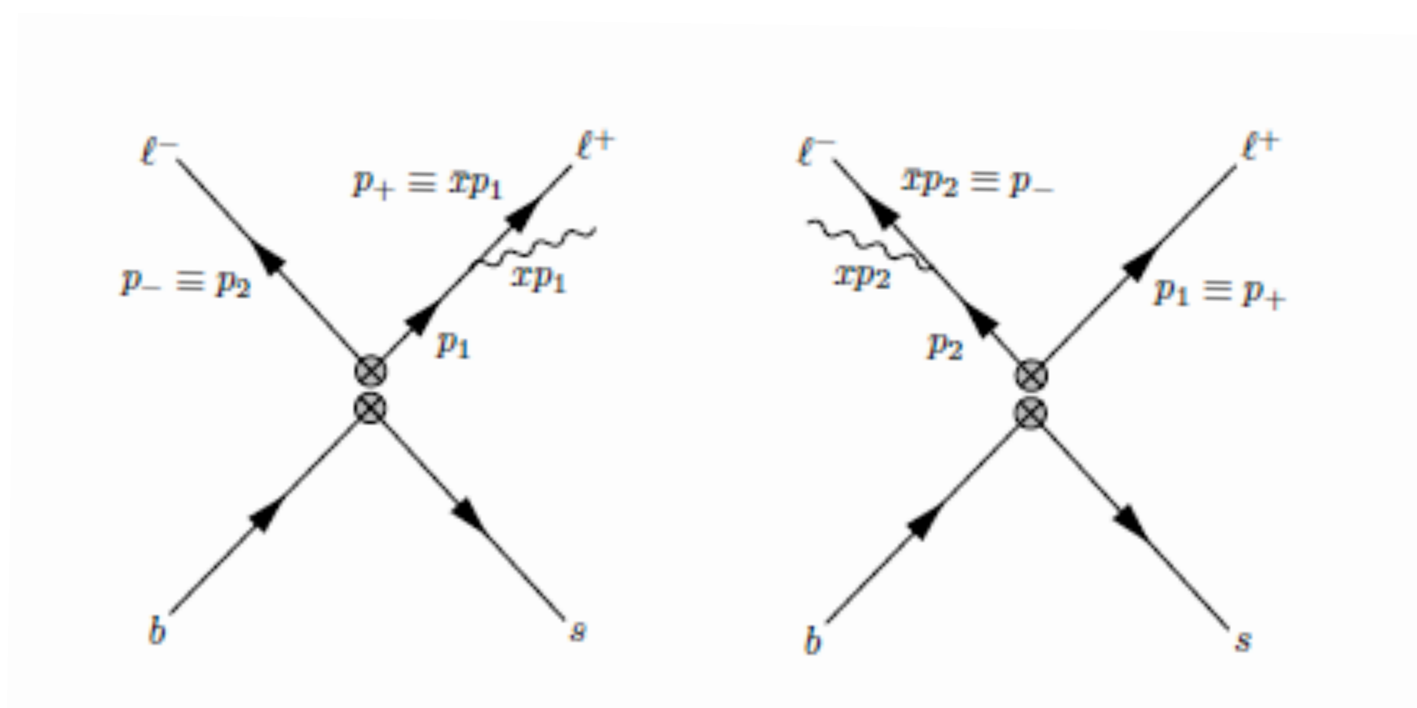
- Electromagnetic corrections in high-q^2 and for A_{FB}

  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 suppressed in low-q^2 window

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

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

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

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

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

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

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

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

Huber,Hurth,Lunghi, arXiv:1503.04849

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

- 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 !

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

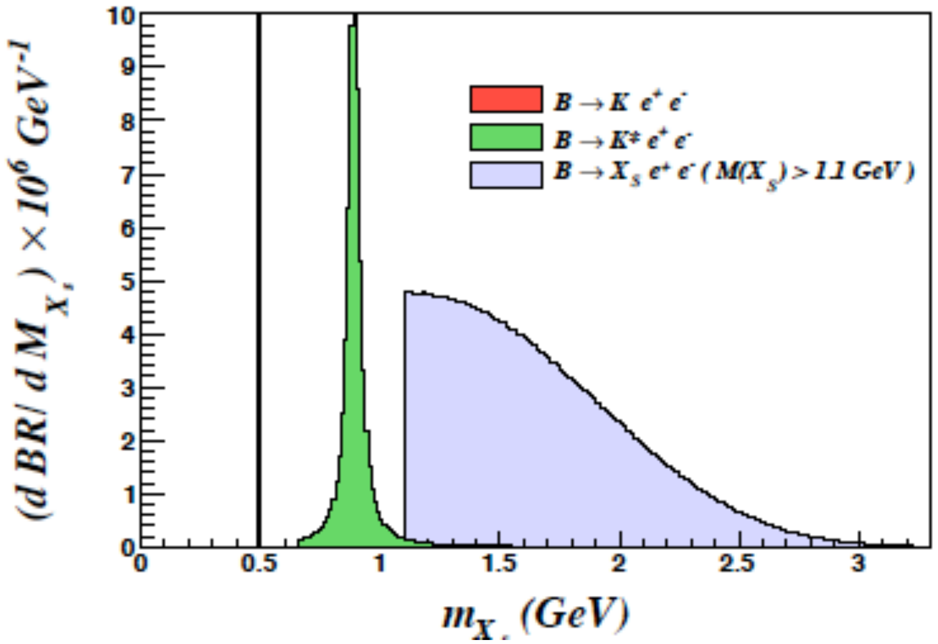
Monte Carlo analysis

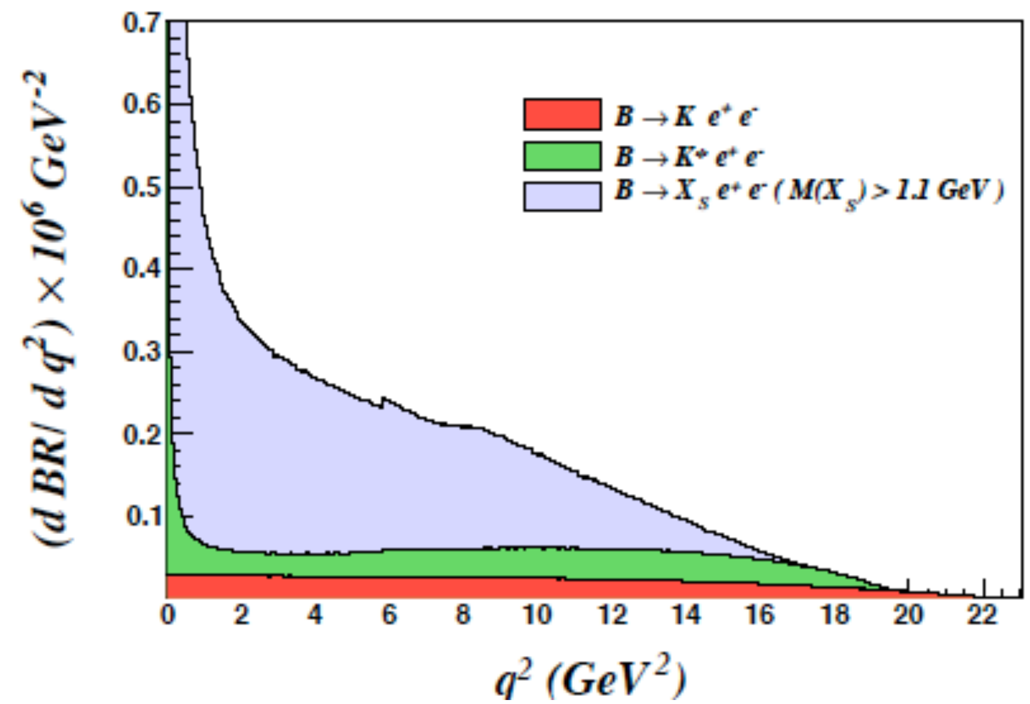
Huber, Hurth, Lunghi, arXiv:1503.04849

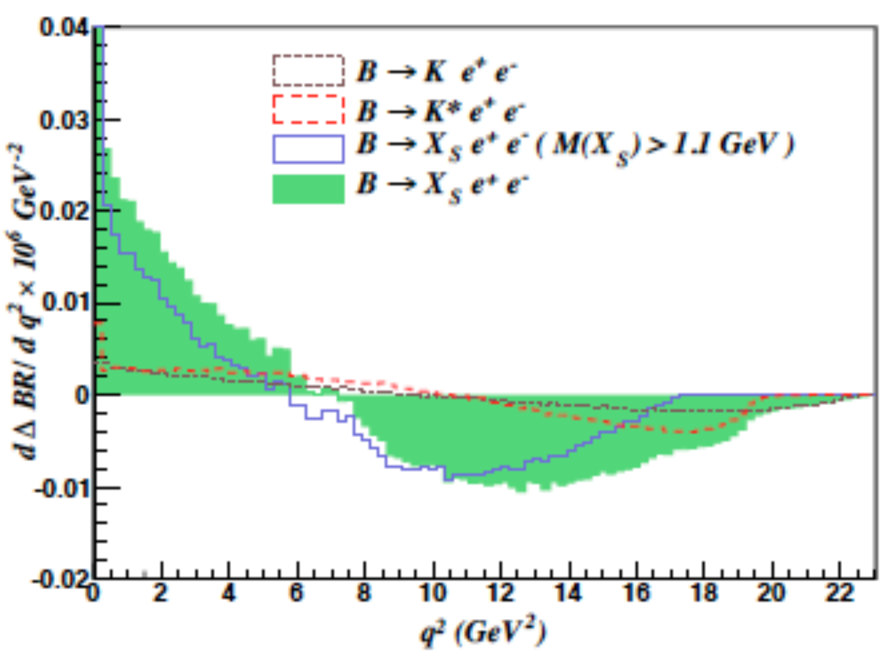
(event generator EVTGEN, hadronization JETSET, EM radiation PHOTOS)

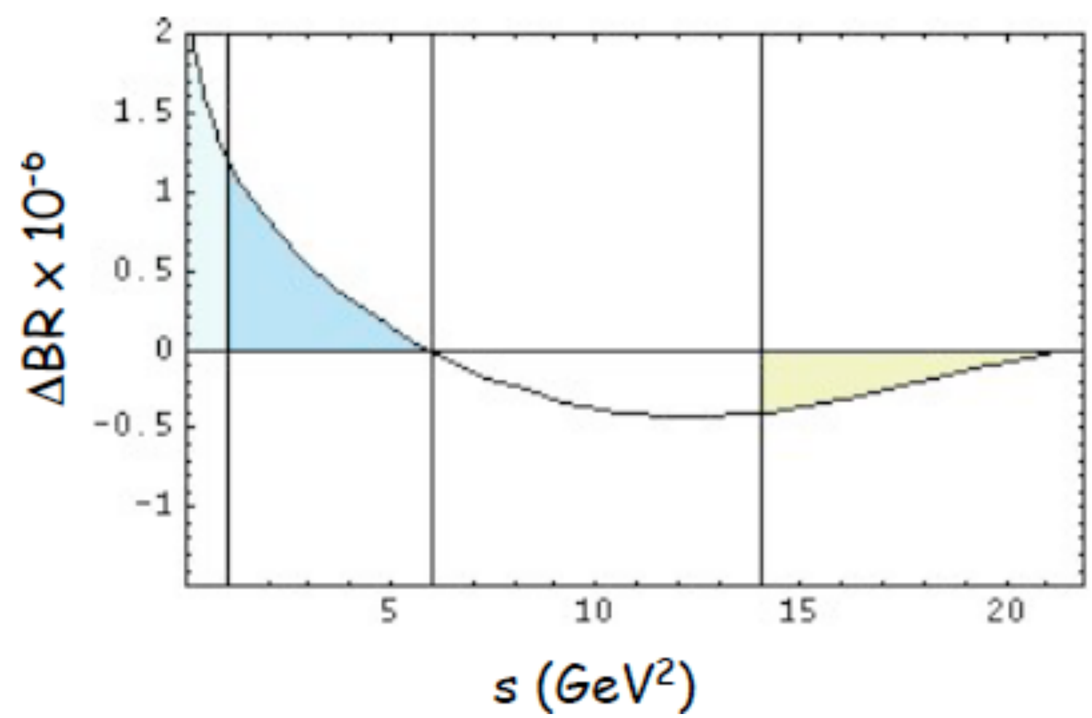
$$\frac{\left[\mathcal{B}_{ee}^{\text{low}}\right]_{q=p_{e^+}+p_{e^-}+p_{\gamma_{\text{coll}}}}}{\left[\mathcal{B}_{ee}^{\text{low}}\right]_{q=p_{e^+}+p_{e^-}}}-1=1.65\%$$

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









Theory predictions

Huber,Hurth,Lunghi, arXiv:1503.04849

Results

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

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

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

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

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

good agreement with SM

Huber,Hurth,Lunghi, arXiv:1503.04849

Results

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

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

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

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

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

2σ higher than SM

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

(but perfect agreement if we use their prescriptions)

Further refinement

Huber,Hurth,Lunghi, arXiv:1503.04849

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

Ligeti,Tackmann arXiv:0707.1694

Theory prediction for ratio

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

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

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

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

Huber,Hurth,Lunghi, arXiv:1503.04849

Further results in units of 10^{-6}

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

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

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

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

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

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

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

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

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

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

New physics sensitivity

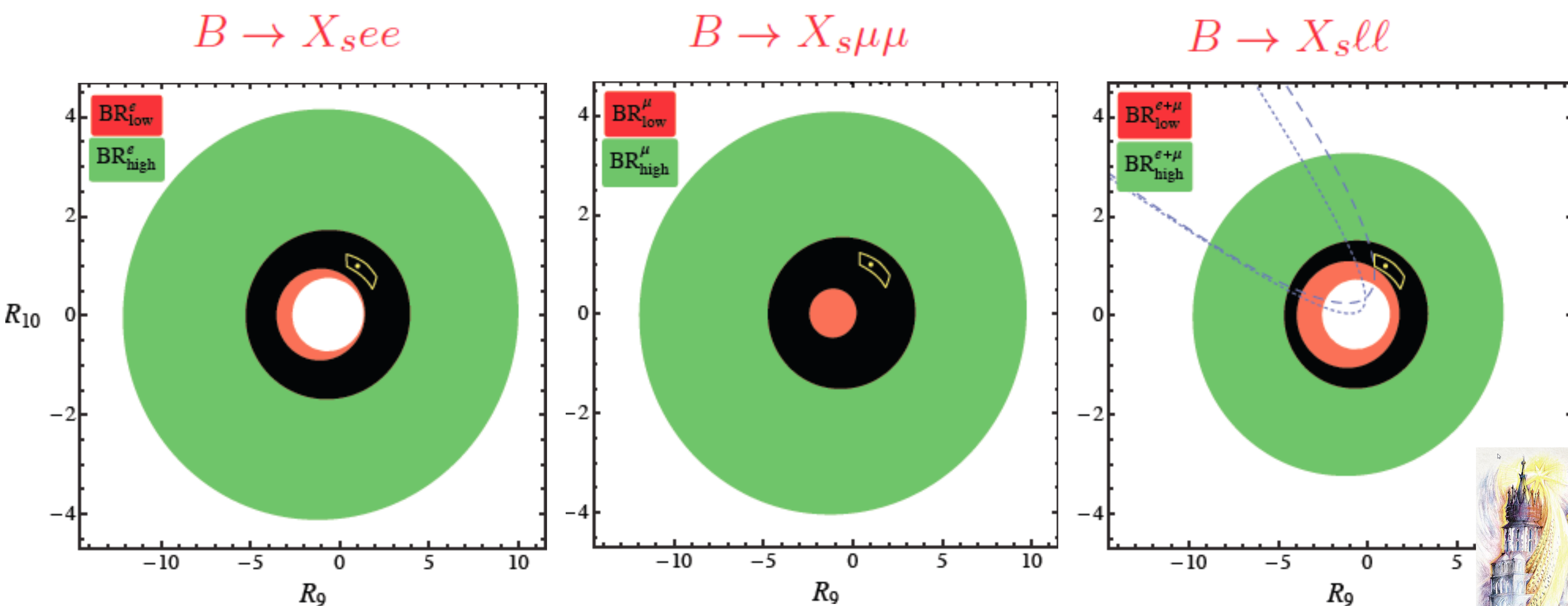
Huber,Hurth,Lunghi, arXiv:1503.04849

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)

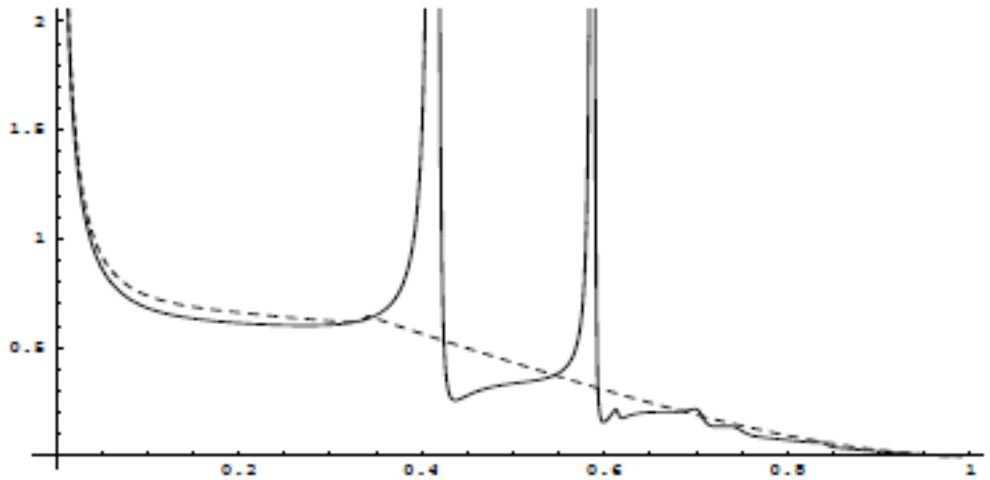
that we will obtain at 95% C.L. from $50ab^{-1}$ data at Belle-II
(yellow)

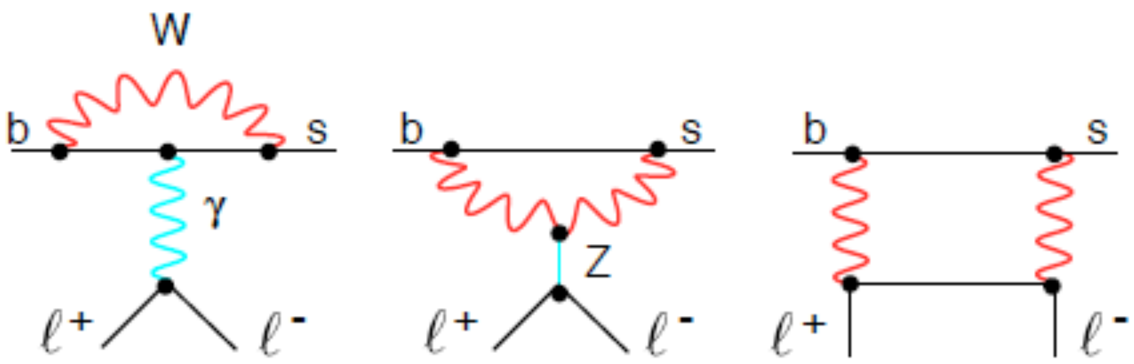


Cuts in the dilepton and hadronic mass spectra

- 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

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





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

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

Nonlocal subleading contributions

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

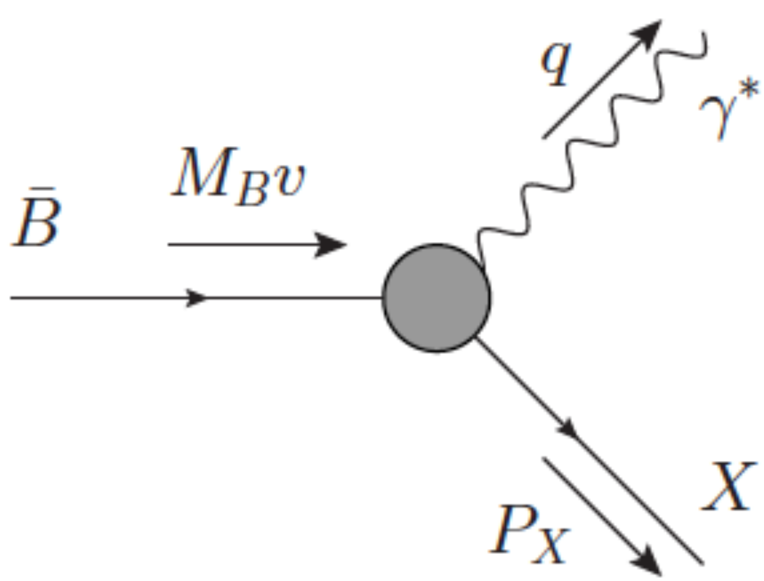
Benzke,Hurth,Turczyk, arXiv:1705.10366

Hadronic cut

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

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

Multiscale problem $\to$ SCET



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

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

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

Kinematics

B meson rest frame

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

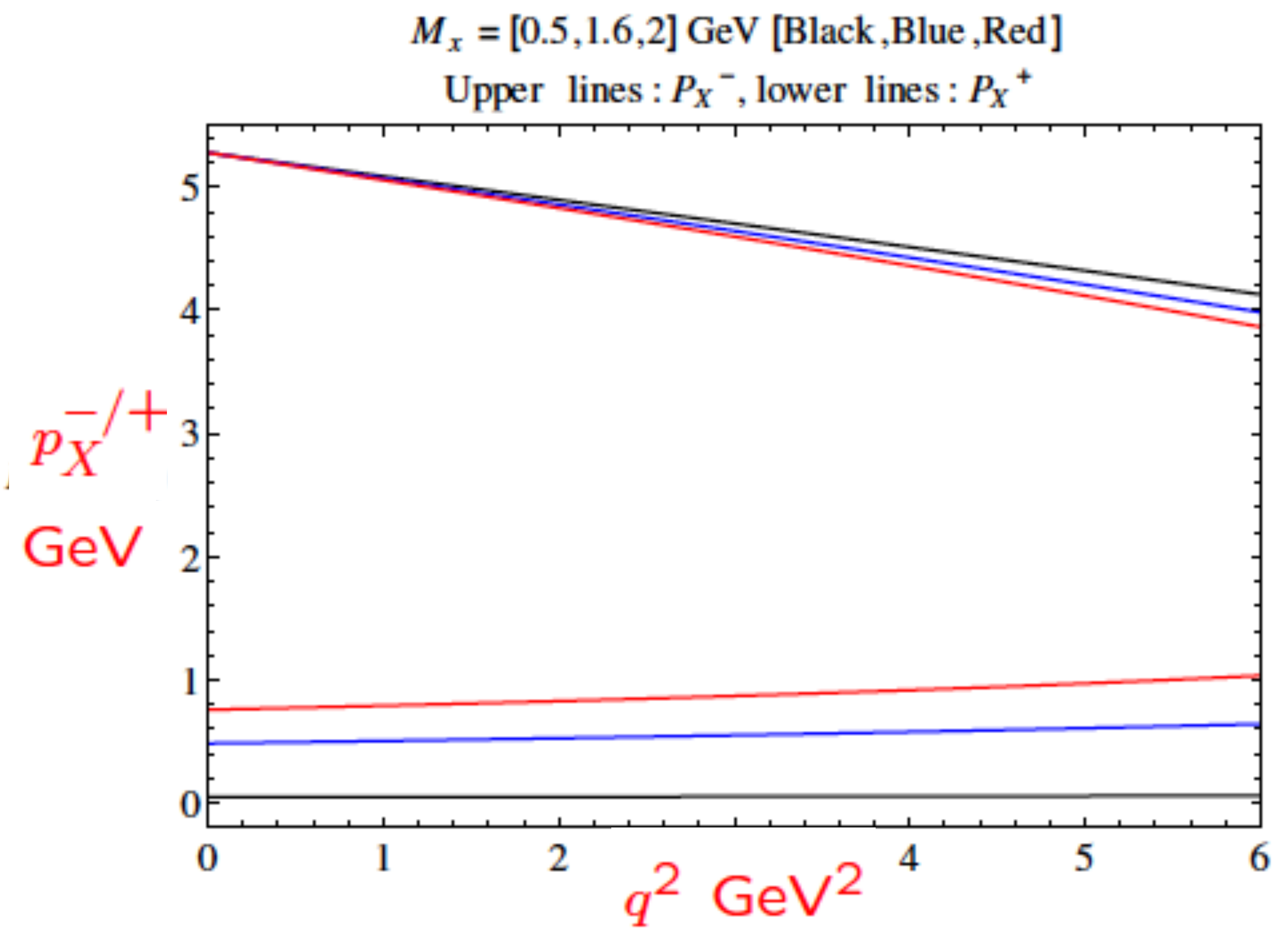
X_s system is jet-like with $E_X \sim m_B$ and $m_X^2 \ll E_X^2$

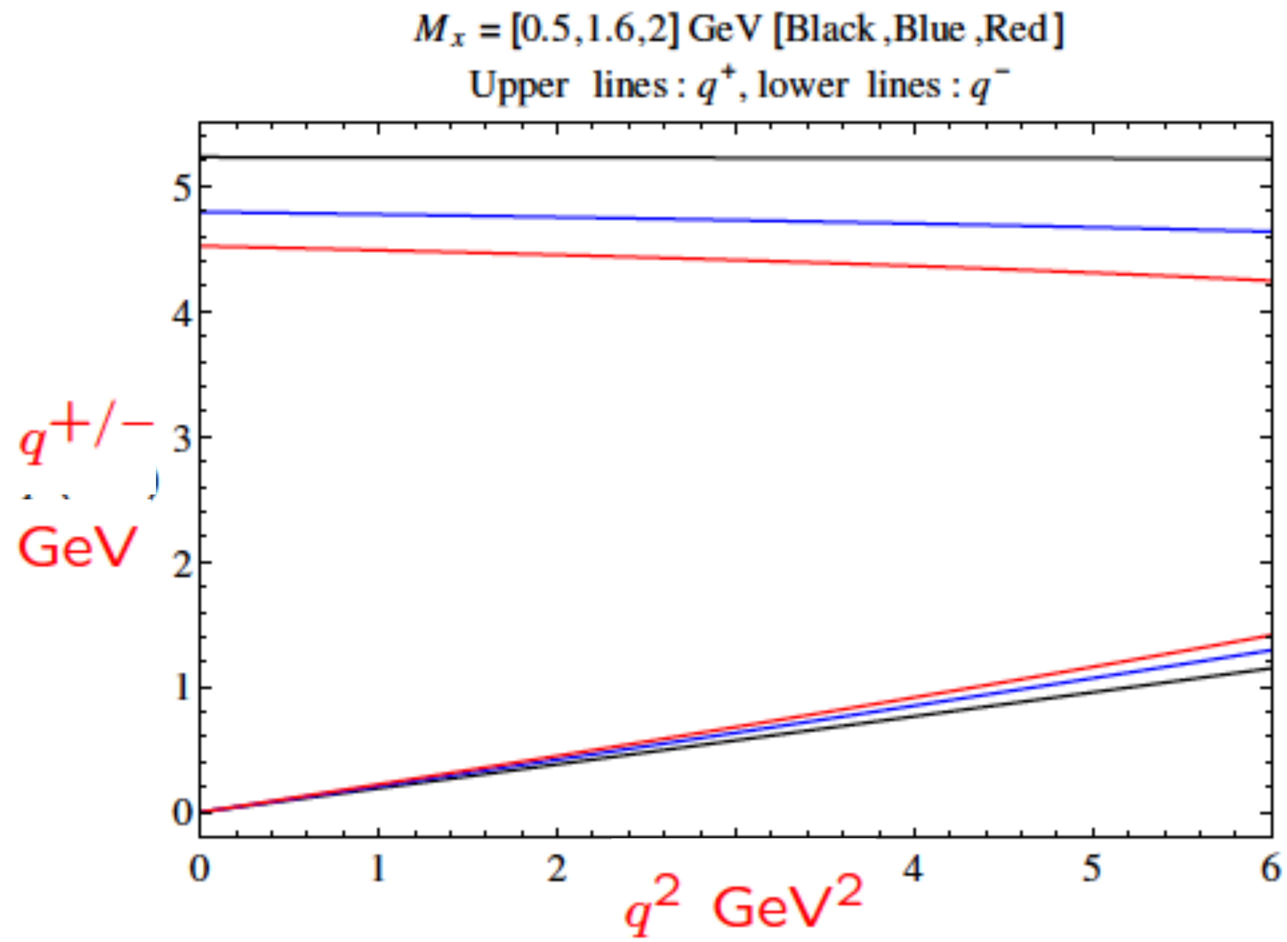
two light-cone components $\qquad p_X^- p_X^+ = m_X^2$

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

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

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





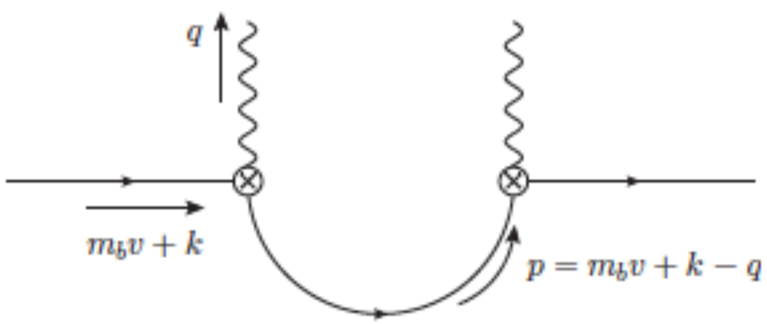
For $q^2 < 6GeV^2$ the scaling of np_X and $\bar{n}p_X$ implies $\bar{n}q$ is of order λ, means q anti-hard-collinear (just kinematics).

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 $m_X^2 \sim \lambda$:



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

Resummation of leading contributions into a shape function.

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

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

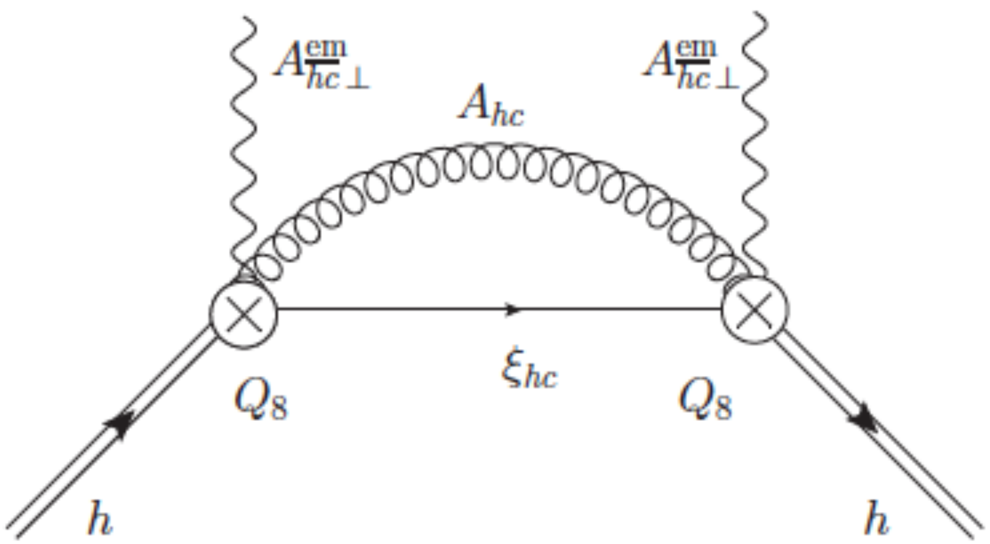
The hard function H and the jet function J are perturbative quantities.

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

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

Calculation at subleading power

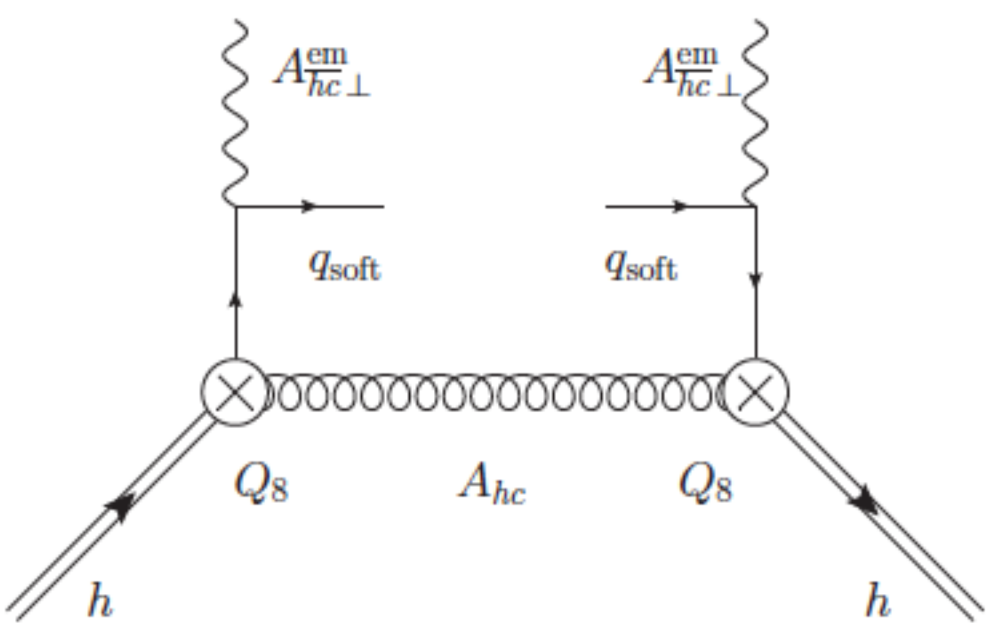
Example of **direct** photon contribution which factorizes $d\Gamma \sim H \cdot j \otimes S$



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

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

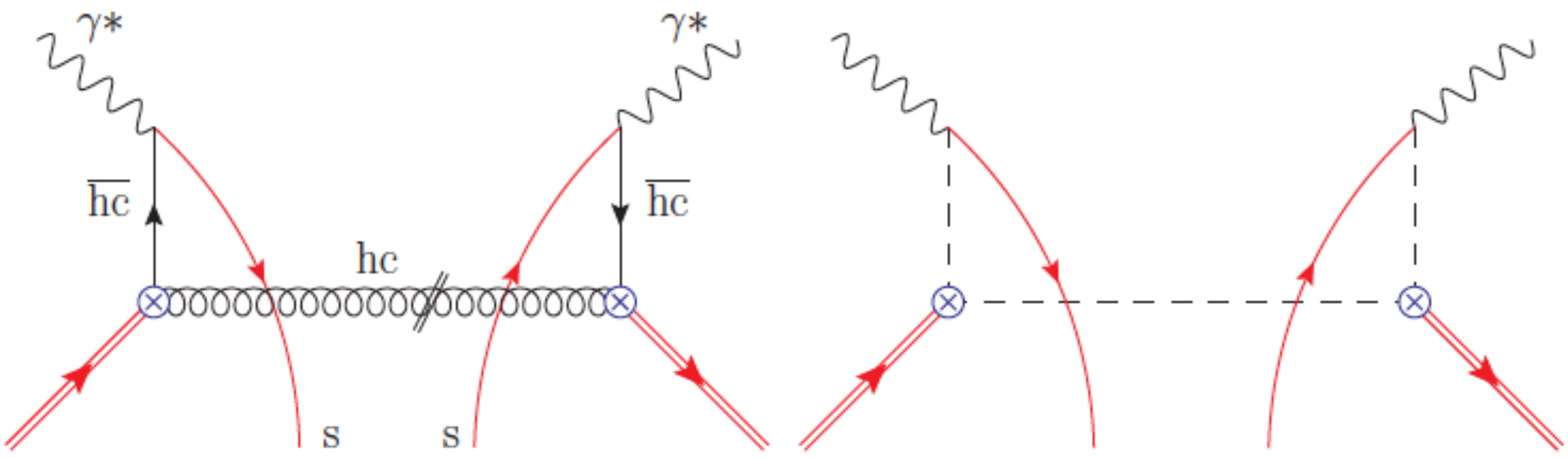
$d\Gamma \sim H \cdot J \otimes s \otimes \bar{J} \otimes \bar{J}$



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

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

Interference of Q_8 and Q_8



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

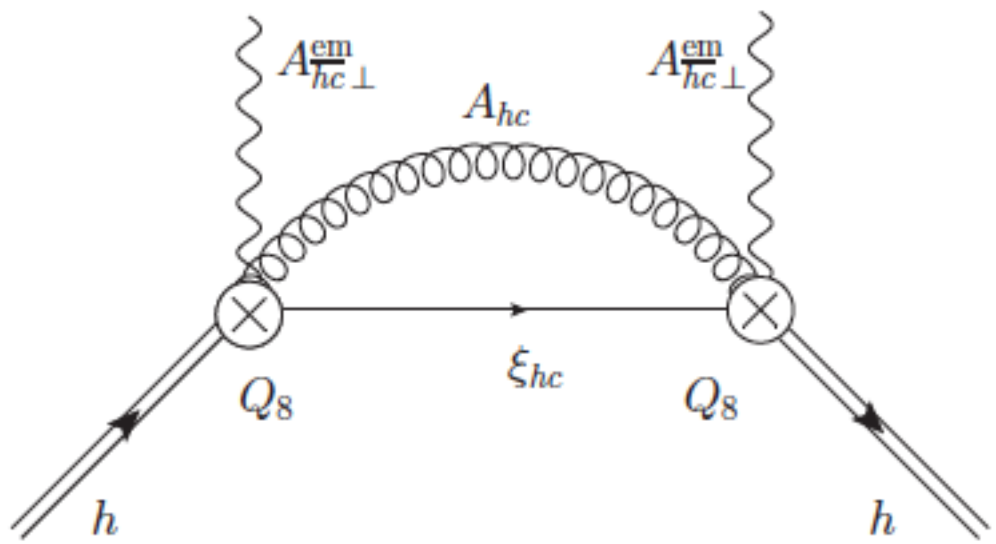
$$g_{88}(\omega,\omega_1,\omega_2) = \frac{1}{M_B}\langle\bar B|\bar h(\mathbf{tn})\dots s(\mathbf{tn}+\mathbf{u\bar n})\bar s(\mathbf{r\bar n})\dots h(\mathbf{0})|\bar B\rangle_{\rm F.T.}$$

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

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

Calculation at subleading power

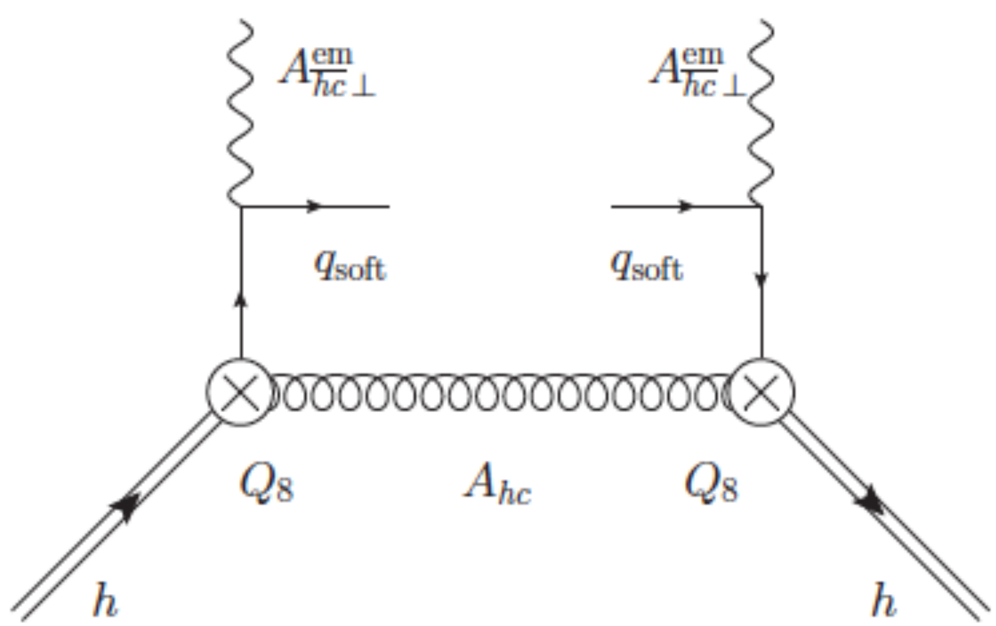
Example of **direct** photon contribution which factorizes $d\Gamma \sim H \cdot j \otimes S$



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

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

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



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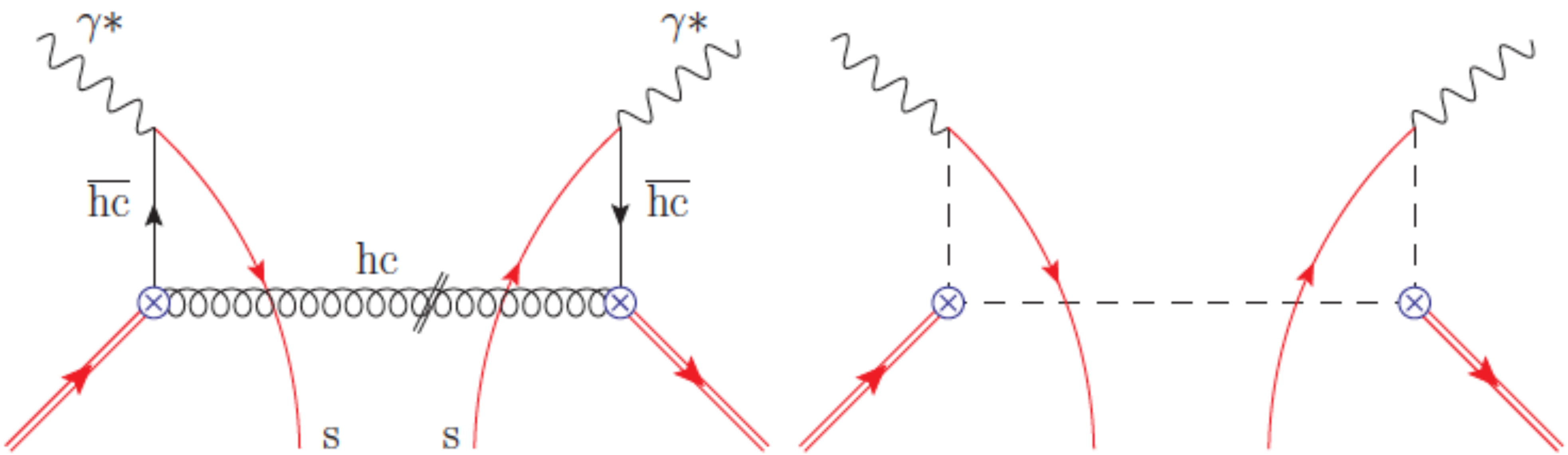
Interference of Q_8 and Q_8



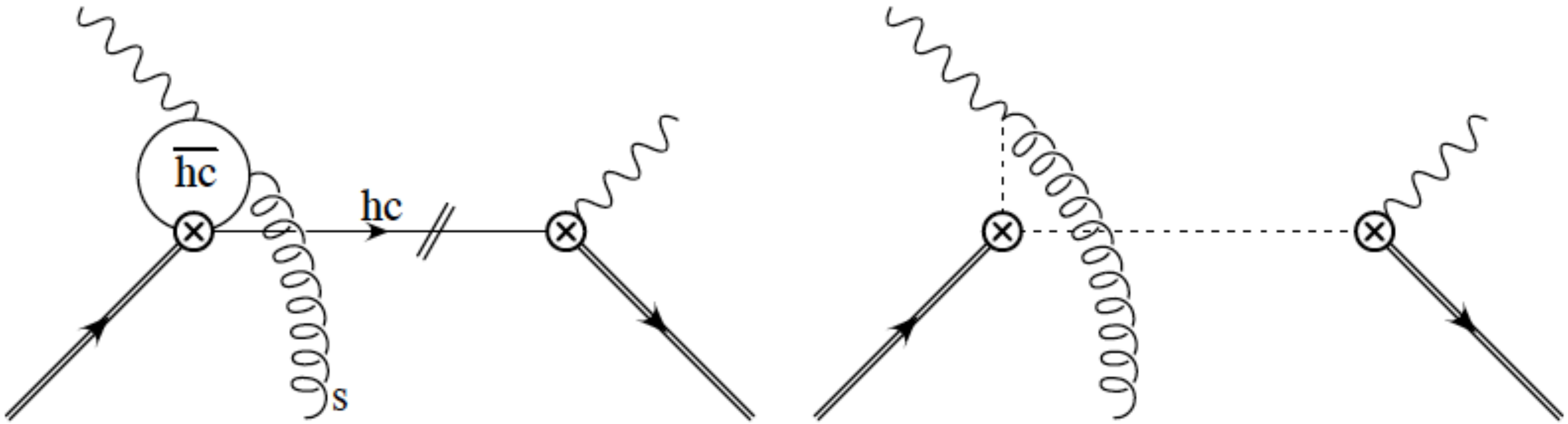
$$\frac{d\Gamma^{\rm res}}{dn\cdot q\, d\bar{n}\cdot q} \sim \frac{e_s^2\alpha_s}{m_b}\int d\omega\, \delta(\omega+p_+)\int \frac{d\omega_1}{\omega_1+\bar{n}\cdot q+i\varepsilon}\int\frac{d\omega_2}{\omega_2+\bar{n}\cdot q-i\varepsilon}\, g_{88}(\omega,\omega_1,\omega_2)$$

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

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



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

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

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

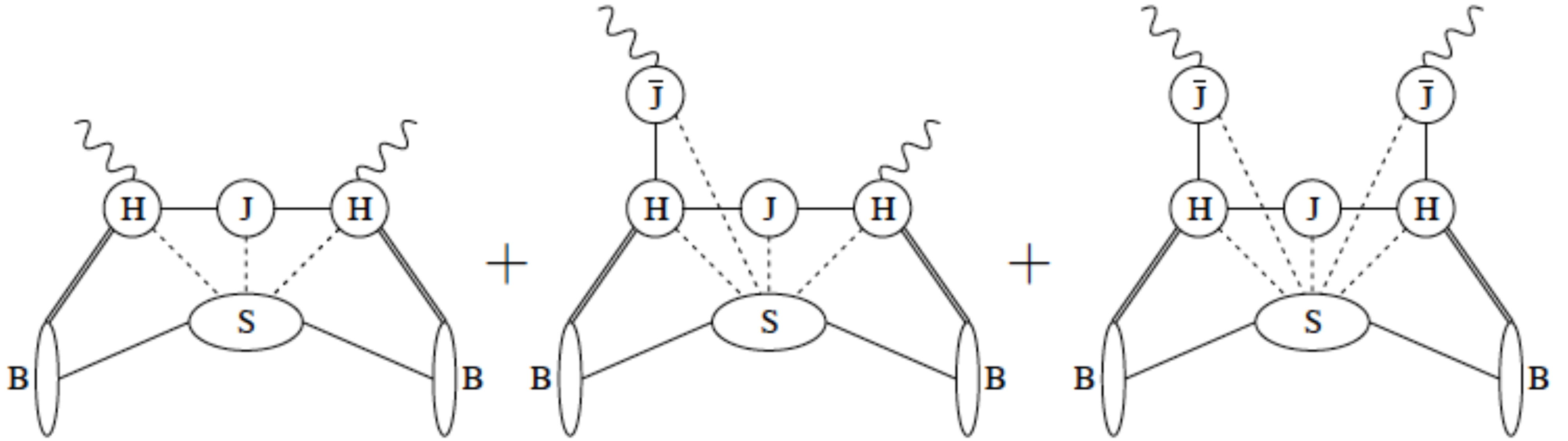
$$g_{17}(\omega,\omega_1)=\int\frac{dr}{2\pi}e^{-i\omega_1 r}\int\frac{dt}{2\pi}e^{-i\omega t}\frac{1}{M_B}\langle\bar{B}|\bar{h}(\mathbf{tn})\ldots G_s^{\alpha\beta}(\mathbf{r\bar{n}})\ldots h(\mathbf{0})|\bar{B}\rangle$$

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

Factorization formula

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

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



Factorization formula

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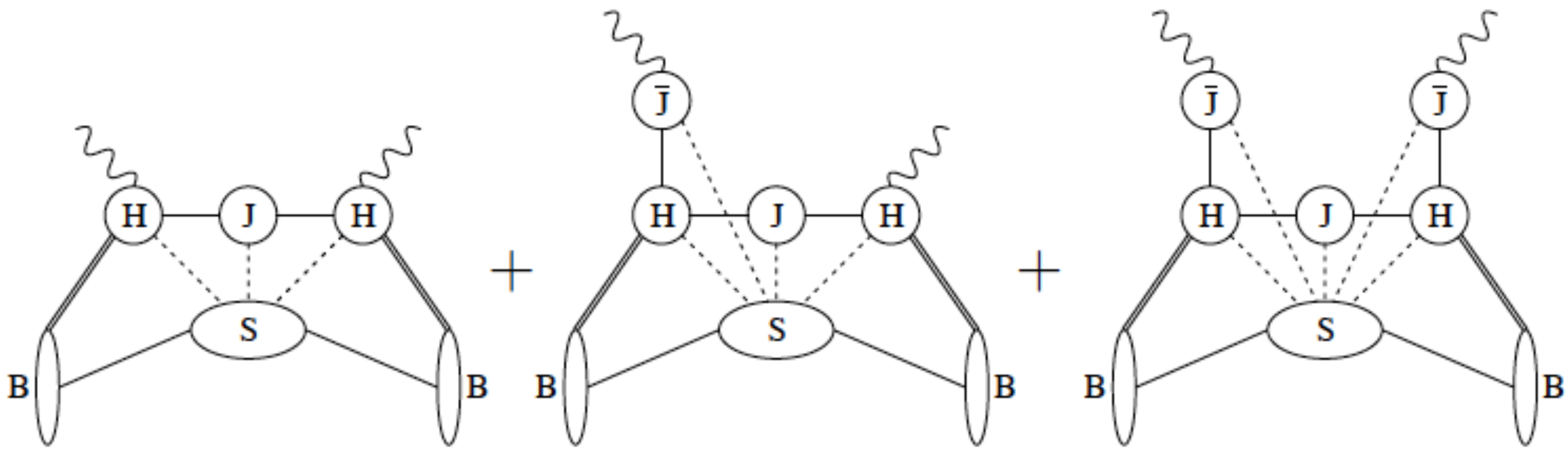
$$+ \frac{1}{m_b} \sum H \cdot J \otimes s_i \otimes \bar{J} + \frac{1}{m_b} \sum H \cdot J \otimes s_i \otimes \bar{J} \otimes \bar{J} + \mathcal{O}\left(\frac{1}{m_b^2}\right)$$



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.

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

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Final result

$$\mathcal{F}_{17} \in [-0.5, +3.4]\,\%, \quad \mathcal{F}_{78} \in [-0.2, -0.1]\,\%, \quad \mathcal{F}_{88} \in [0, 0.5]\,\%$$

(normalized to OPE result)

$$\mathcal{F}_{1/m_b} \in [-0.7, +3.8]$$

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

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 $H_T(q^2)$.

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

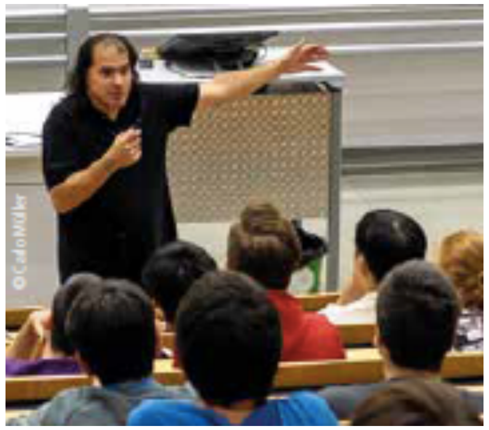
- Phenomenological analysis to NNLO QCD and NLO QED for all angular observables available

- 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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Jens Erler **UNAM**, Mikhail Gorshteyn, Hubert Spiesberger **JGU**
April 23 - May 4, 2018

Modern Techniques for CFT and AdS
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call for proposals 2019:
deadline 31.1.2018

Extra

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 ($s_{\rm min} \approx 0.6$): Ghinculov,Hurth,Isidori,Yao,hep-ph/0312128

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

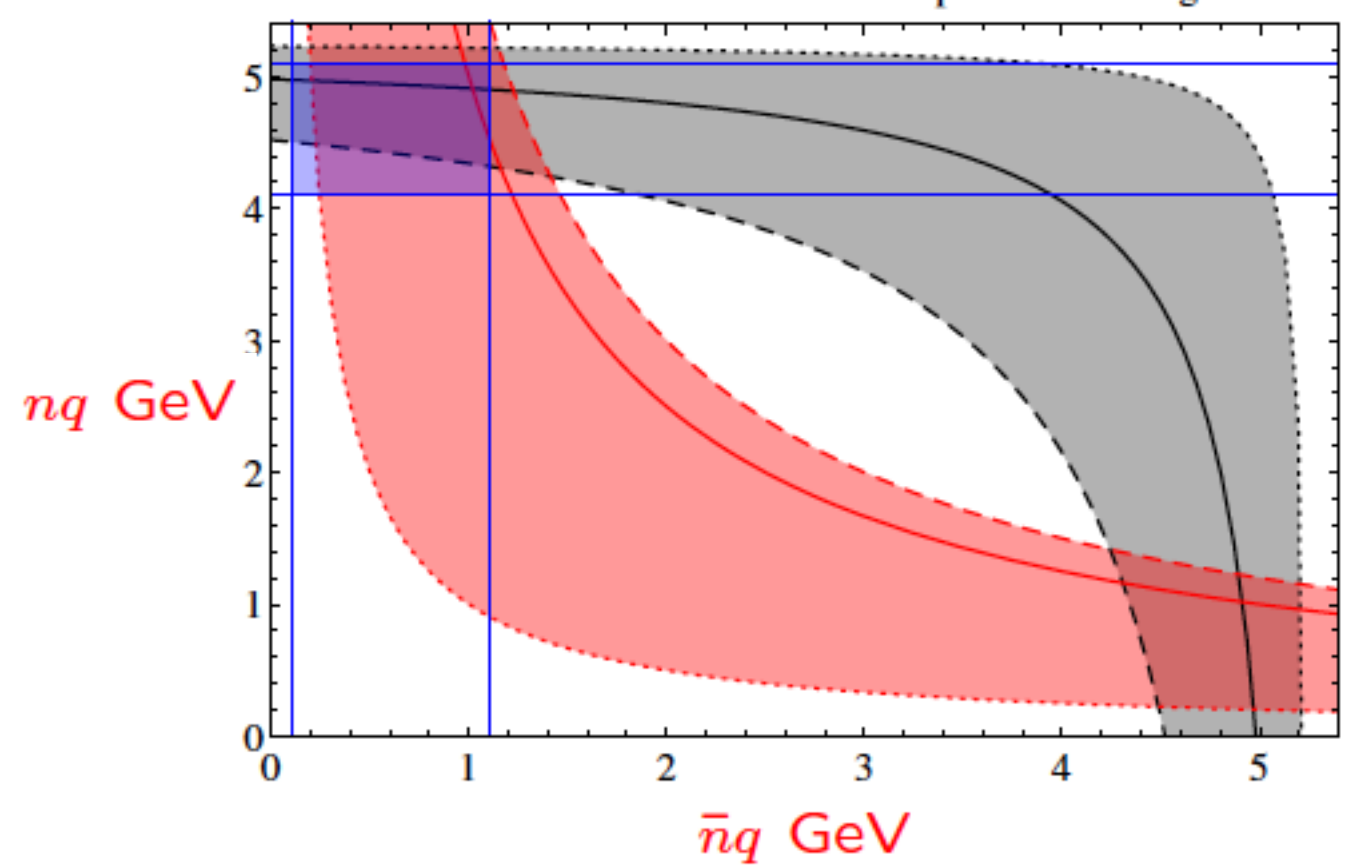
Alllowed regions

low-q^2

Red: q^2= [1,5,6] GeV^2 [Dotted , Solid ,Dashed]

Black: M_x = [0.495,1.25,2] GeV [Dotted , Solid , Dashed]

Blue : anti −hard −collinear component scaling

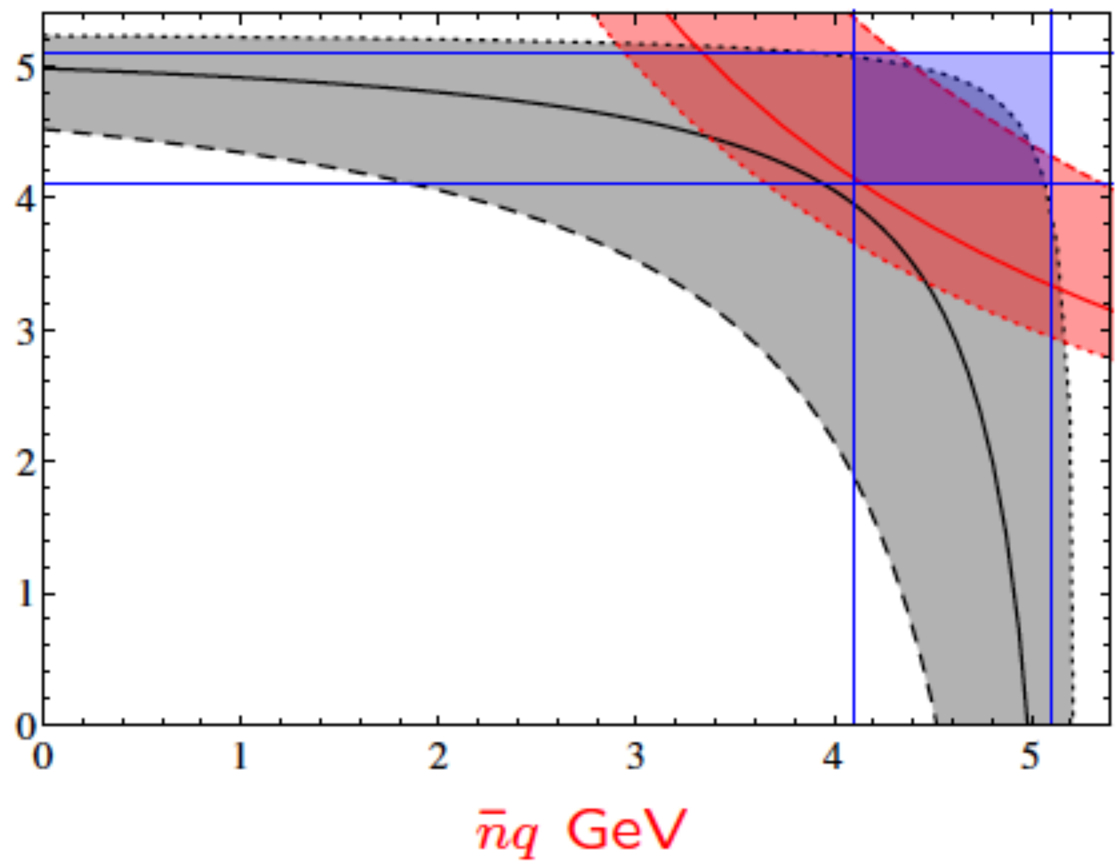


high-q^2

Red: q^2= [15,17,22] GeV^2 [Dotted , Solid , Dashed]

Black: M_x = [0.495,1.25,2] GeV [Dotted , Solid , Dashed]

Blue : hard component scaling



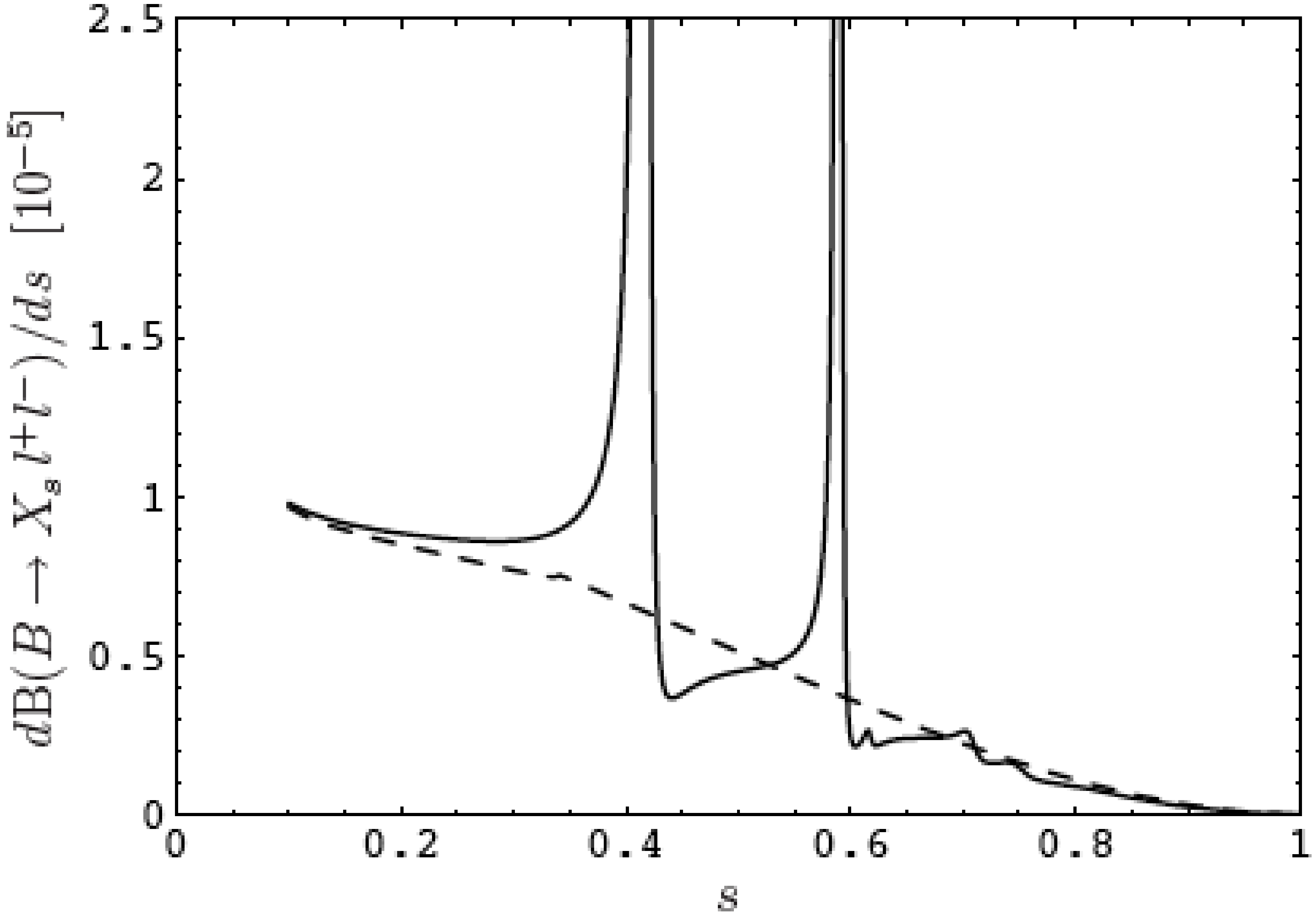
Scaling

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

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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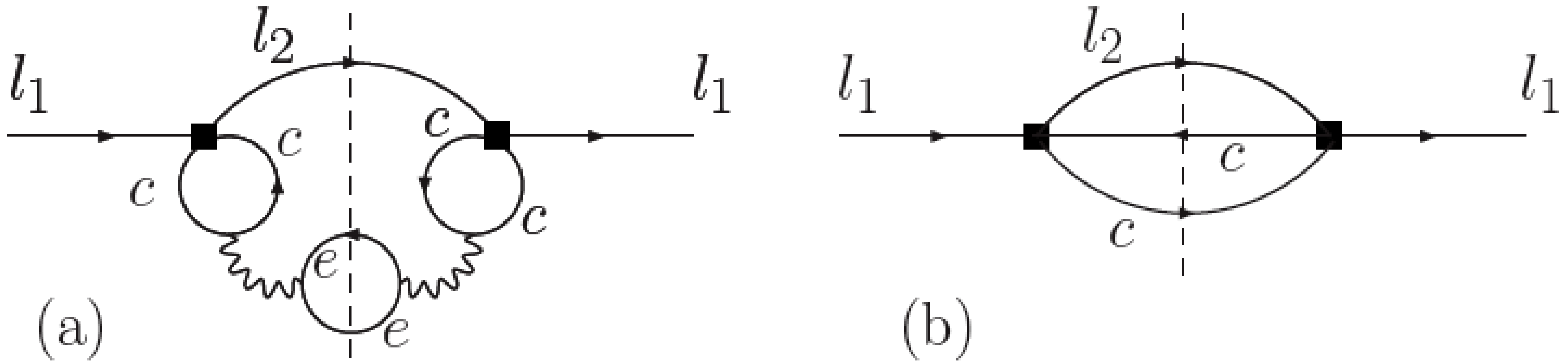

The rate $l_1 \to l_2 e^+ e^-$ (a) is connected to the integral over $|\Pi(q^2)|^2$ for which global duality is NOT expected to hold.

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