SM challenges and BSM opportunities in rare B decays in the light of recent data

Sebastian Jäger

University of Sussex

Portoroz 2015
Wednesday 08 April 2015

largely based on work with J Martin Camalich
arXiv:1212.2263/JHEP1305(2013)043; arXiv:1412.3183; work in progress

Between you and dinner

Theory of B->V l l (etc) and why I like the heavy-quark expansion

New LHCb data, and how it likes the heavy-quark expansion

Clean null tests of the SM and right-handed current searches (no update with new data yet)

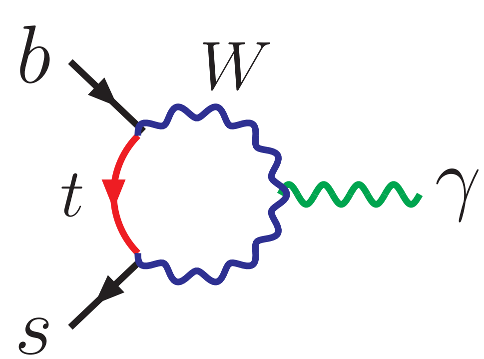
If the lord turns out to be not so subtle: Lepton universality violation

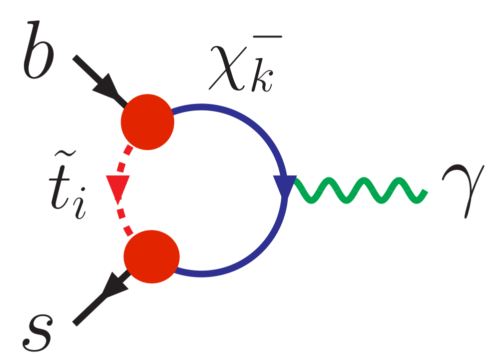
(You know the) motivation

- After the Higgs discovery, the naturalness problem is a reality. But even natural new physics may lie beyond the LHC energy reach. ATLAS & CMS may point to that.

- This puts precision Higgs and flavour at the centre of the quest for physics beyond the Standard Model

- Natural BSM models tend to have a flavour problem
  eg SUSY





new sources of flavour violation

$B \to K^{*}\gamma$, $K^{*}ll$
$B \to X_{s}\gamma$

- Unprecedented statistics & interesting results from LHCb, with Belle2 rapidly approaching

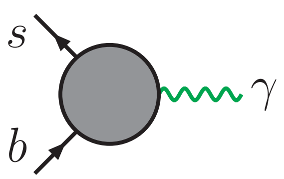
weak ΔB=ΔS=1 Hamiltonian

= EFT for ΔB=ΔS=1 transitions (up to dimension six)

$$\mathcal{H}_{\rm eff}^{\rm had} = \frac{4G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_p \left[C_1 Q_1^p + C_2 Q_2^p + \sum_{i=3\ldots6} C_i P_i + C_{8g} Q_{8g} \right]$$

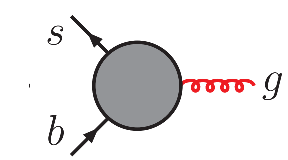
$$C_i \sim g_{\rm NP} \frac{m_W^2}{M_{\rm NP}^2}$$

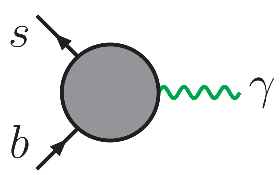
$$\mathcal{H}_{\rm eff}^{\rm sl} = -\frac{4G_F}{\sqrt{2}} \lambda_t \Big[C_7 Q_{7\gamma} + C_7' Q_{7\gamma}' + C_9 Q_{9V} + C_9' Q_{9V}' + C_{10} Q_{10A} + C_{10}' Q_{10A}' + C_S Q_S + C_S' Q_S' + C_P Q_P + C_P' Q_P' + C_T Q_T + C_T' Q_T' \Big].$$



$$\mathcal{O}_7 = \frac{e}{16\pi^2} \hat{m}_b \, \bar{s} \sigma_{\mu\nu} P_R F^{\mu\nu} b \,,$$

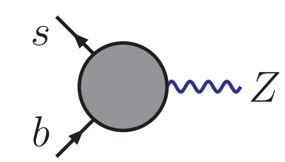
$$\mathcal{O}_8 = \frac{g_s}{16\pi^2} \hat{m}_b \, \bar{s} \sigma_{\mu\nu} P_R G^{\mu\nu} b \,,$$



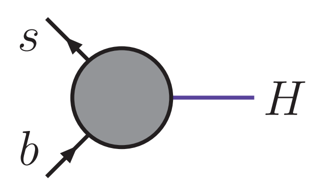


$$\mathcal{O}_V = \frac{\alpha_{\rm em}}{4\pi} (\bar{s} \gamma_\mu P_L b)(\bar{l} \gamma^\mu l) \,,$$

$$\mathcal{O}_A = \frac{\alpha_{\rm em}}{4\pi} (\bar{s} \gamma_\mu P_L b)(\bar{l} \gamma^\mu \gamma^5 l)_A$$



$$\mathcal{O}_S = \frac{\alpha_{\rm em}}{4\pi} \hat{m}_b (\bar{s} P_R b)(\bar{l} l) \,,$$



$$\mathcal{O}_P = \frac{\alpha_{\rm em}}{4\pi} \hat{m}_b (\bar{s} P_R b)(\bar{l} \gamma^5 l) \,,$$

$$\mathcal{O}_T = \frac{\alpha_{\rm em}}{4\pi} \hat{m}_b (\bar{s} \sigma_{\mu\nu} P_R b)(\bar{l} \sigma^{\mu\nu} P_R s) \,,$$

+ chirality-flipped operators with $P_R \leftrightarrow P_L$: suppressed in SM by m_s/m_b

look for observables sensitive to C_i's, specifically
those that are suppressed in the SM

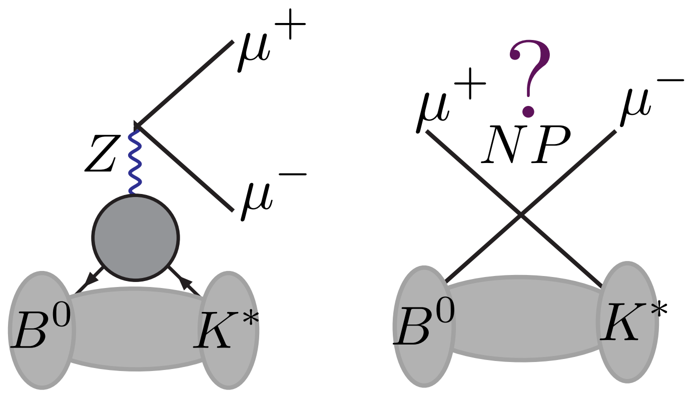
B->Vll decay

Two mechanisms to produce dilepton in & beyond SM

B->Vll decay

Two mechanisms to produce dilepton in & beyond SM

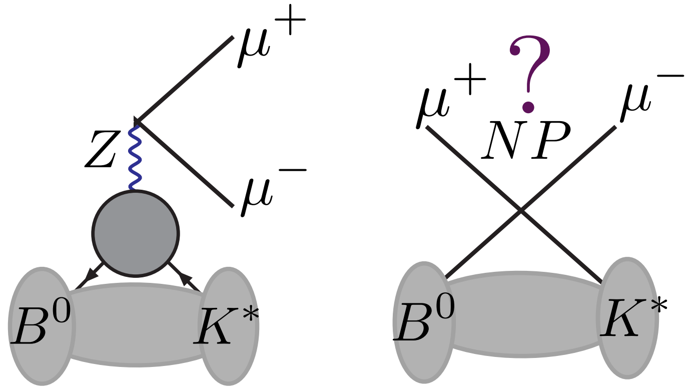
- via axial lepton current (in SM: Z, boxes)



B->VII decay

Two mechanisms to produce dilepton in & beyond SM

- via axial lepton current (in SM: Z, boxes)

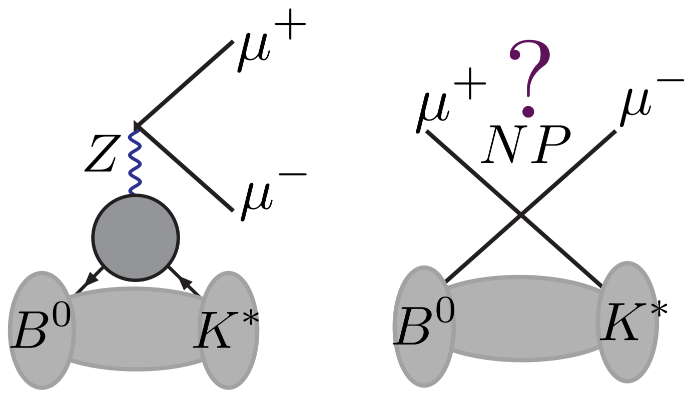


$$H_A(\lambda) \propto \tilde{V}_\lambda(q^2) C_{10} - V_{-\lambda}(q^2) C'_{10}$$

B->Vll decay

Two mechanisms to produce dilepton in & beyond SM

- via axial lepton current (in SM: Z, boxes)



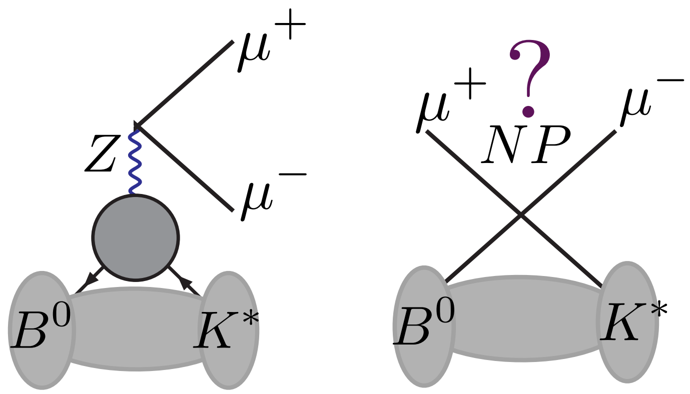
K* helicity

$$H_A(\lambda) \propto \tilde{V}_\lambda(q^2)C_{10} - V_{-\lambda}(q^2)C'_{10}$$

B->Vll decay

Two mechanisms to produce dilepton in & beyond SM

- via axial lepton current (in SM: Z, boxes)



K* helicity

$$H_A(\lambda) \propto \tilde{V}_\lambda(q^2) C_{10} - V_{-\lambda}(q^2) C'_{10}$$

one form factor (nonperturbative) per helicity

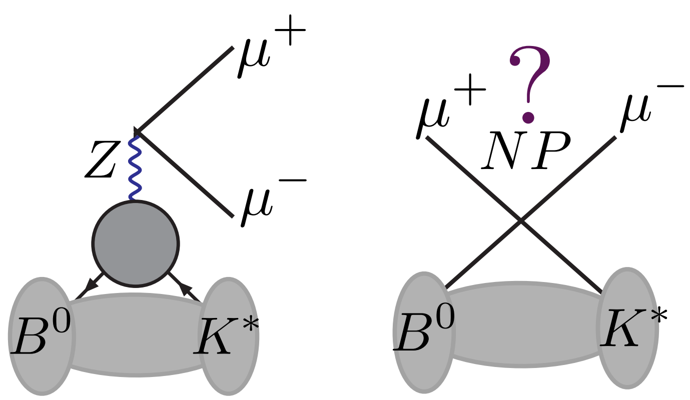
amplitudes factorize naively

[nb - one more amplitude if not neglecting lepton mass]

B->Vll decay

Two mechanisms to produce dilepton in & beyond SM

- via axial lepton current (in SM: Z, boxes)



K* helicity

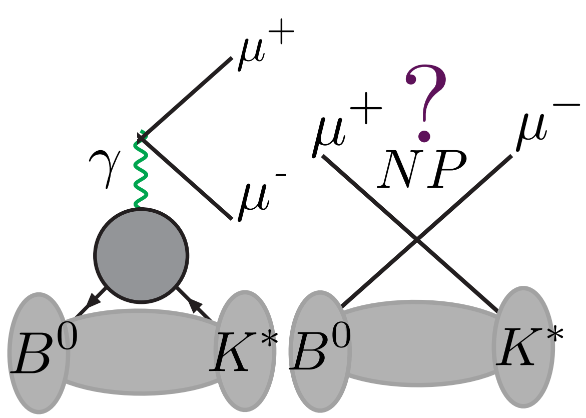
$$H_A(\lambda) \propto \tilde{V}_\lambda(q^2) C_{10} - V_{-\lambda}(q^2) C'_{10}$$

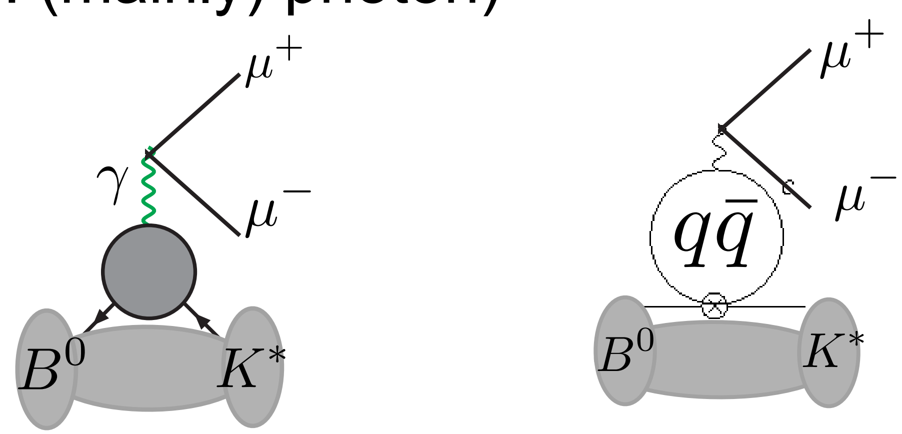
one form factor (nonperturbative) per helicity

amplitudes factorize naively

[nb - one more amplitude if not neglecting lepton mass]

- via vector lepton current (in SM: (mainly) photon)



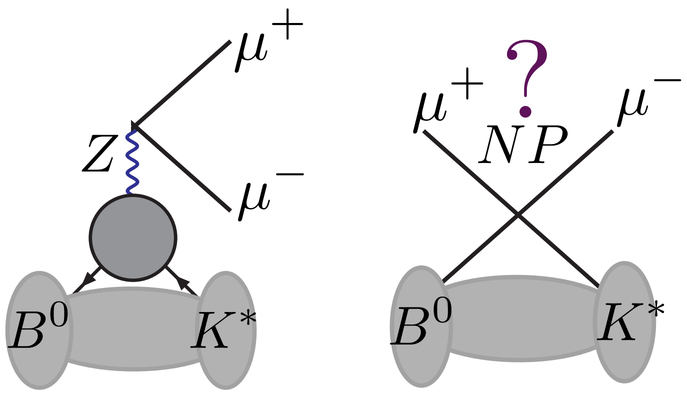


$$H_V(\lambda) \propto \tilde{V}_\lambda(q^2) C_9 - V_{-\lambda}(q^2) C'_9 + \frac{2\, m_b m_B}{q^2} \left(\tilde{T}_\lambda(q^2) C_7 - \tilde{T}_{-\lambda}(q^2) C'_7 \right) - \frac{16\, \pi^2 m_B^2}{q^2}\, h_\lambda(q^2)$$

B->Vll decay

Two mechanisms to produce dilepton in & beyond SM

- via axial lepton current (in SM: Z, boxes)



K* helicity

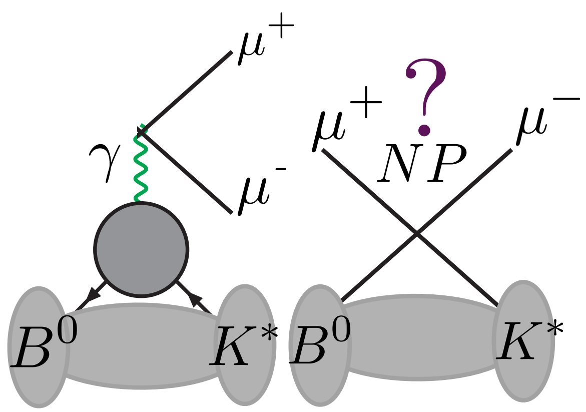
$$H_A(\lambda) \propto \tilde{V}_\lambda(q^2) C_{10} - V_{-\lambda}(q^2) C'_{10}$$

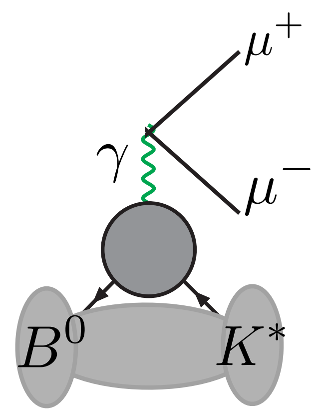
one form factor (nonperturbative) per helicity

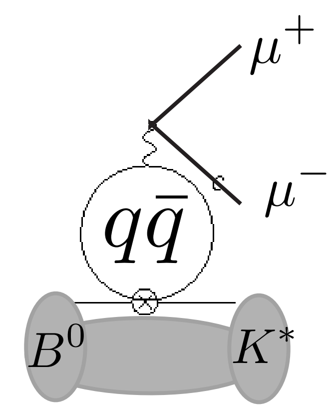
amplitudes factorize naively

[nb - one more amplitude if not neglecting lepton mass]

- via vector lepton current (in SM: (mainly) photon)







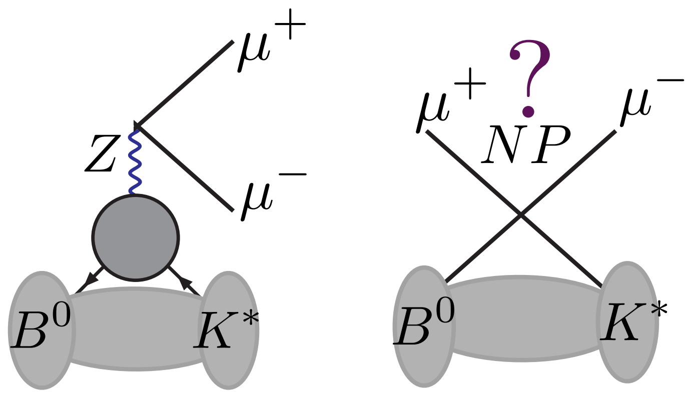
$$H_V(\lambda) \propto \tilde{V}_\lambda(q^2) C_9 - V_{-\lambda}(q^2) C'_9 + \frac{2\, m_b m_B}{q^2}\left(\tilde{T}_\lambda(q^2) C_7 - \tilde{T}_{-\lambda}(q^2) C'_7\right) - \frac{16\,\pi^2 m_B^2}{q^2} h_\lambda(q^2)$$

photon pole at q^2=0

B->VII decay

Two mechanisms to produce dilepton in & beyond SM

- via axial lepton current (in SM: Z, boxes)



K* helicity

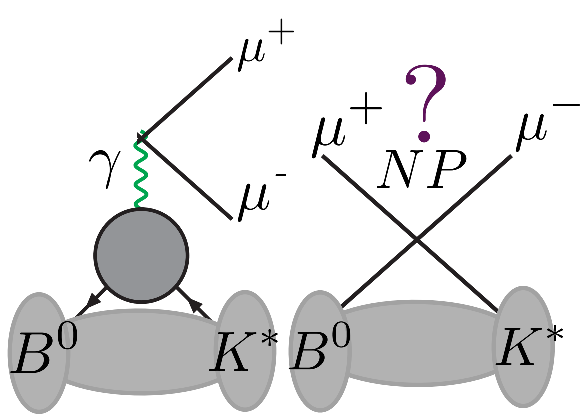
$$H_A(\lambda) \propto \tilde{V}_\lambda(q^2) C_{10} - V_{-\lambda}(q^2) C'_{10}$$

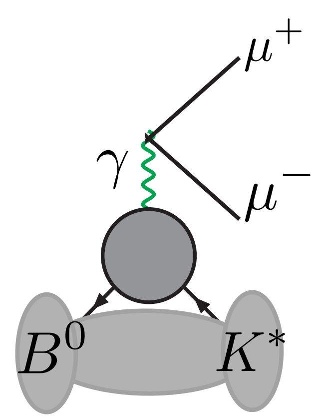
one form factor (nonperturbative) per helicity

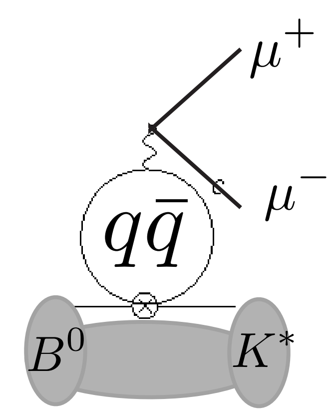
amplitudes factorize naively

[nb - one more amplitude if not neglecting lepton mass]

- via vector lepton current (in SM: (mainly) photon)







$$H_V(\lambda) \propto \tilde{V}_\lambda(q^2) C_9 - V_{-\lambda}(q^2) C'_9 + \frac{2\, m_b m_B}{q^2}\Big(\tilde{T}_\lambda(q^2) C_7 - \tilde{T}_{-\lambda}(q^2) C'_7\Big) - \frac{16\,\pi^2 m_B^2}{q^2} h_\lambda(q^2)$$

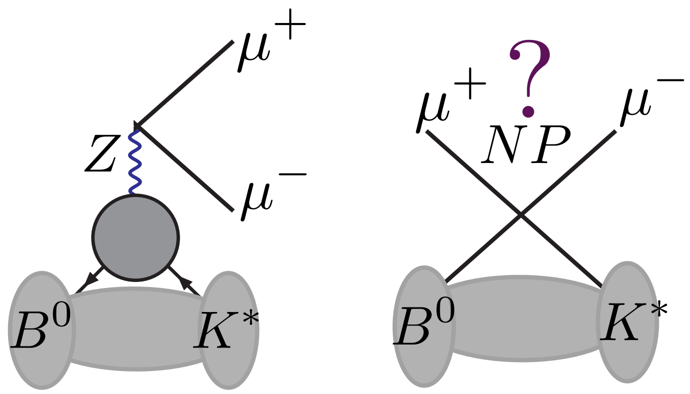
photon pole at $q^2=0$

nonlocal “quark loops”
do **not** factorize naively

B->Vll decay

Two mechanisms to produce dilepton in & beyond SM

- via axial lepton current (in SM: Z, boxes)



K* helicity

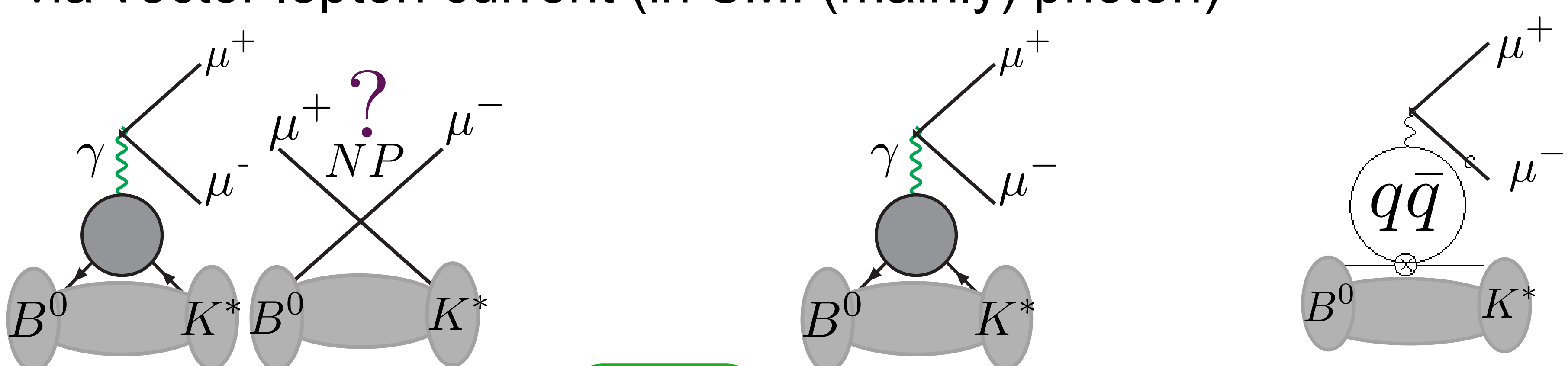
$$H_A(\lambda) \propto \tilde{V}_\lambda(q^2) C_{10} - V_{-\lambda}(q^2) C'_{10}$$

one form factor (nonperturbative) per helicity

amplitudes factorize naively

[nb - one more amplitude if not neglecting lepton mass]

- via vector lepton current (in SM: (mainly) photon)



$$H_V(\lambda) \propto \tilde{V}_\lambda(q^2) C_9 - V_{-\lambda}(q^2) C'_9 + \frac{2\, m_b m_B}{q^2}\left(\tilde{T}_\lambda(q^2) C_7 - \tilde{T}_{-\lambda}(q^2) C'_7\right) - \frac{16\,\pi^2 m_B^2}{q^2} h_\lambda(q^2)$$

photon pole at $q^2=0$

two form factors interfere for each helicity

nonlocal “quark loops”
do **not** factorize naively

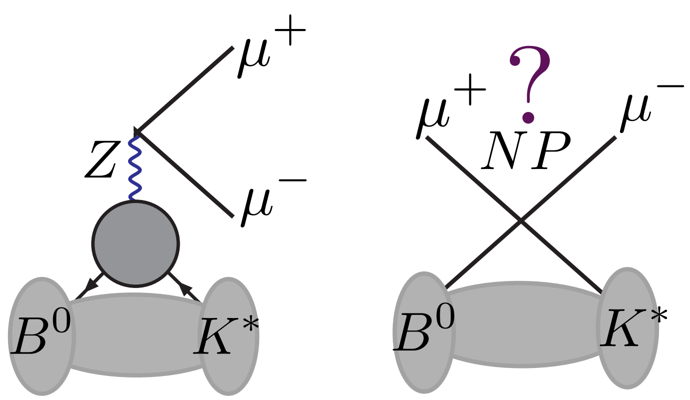
natural and transparent discussion in terms of 6 (7 if m_l != 0) helicity amplitudes

SJ, Martin Camalich 2012

B->Vll decay

Two mechanisms to produce dilepton in & beyond SM

- via axial lepton current (in SM: Z, boxes)



K* helicity

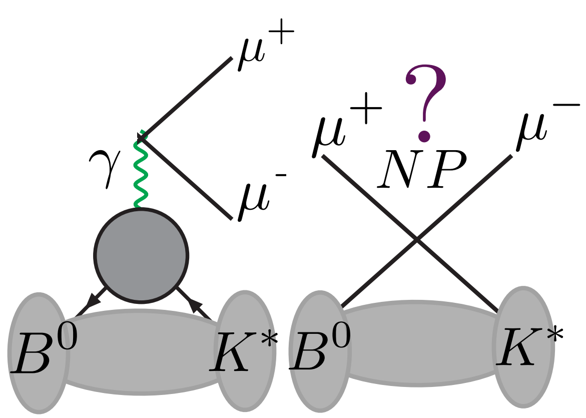
$$H_A(\lambda) \propto \tilde{V}_\lambda(q^2) C_{10} - V_{-\lambda}(q^2) C'_{10}$$

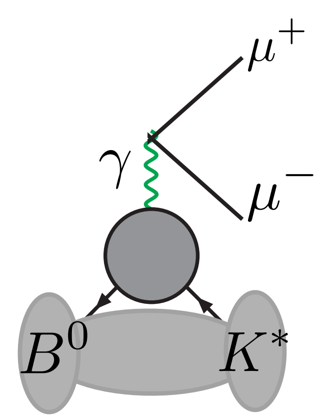
one form factor (nonperturbative) per helicity

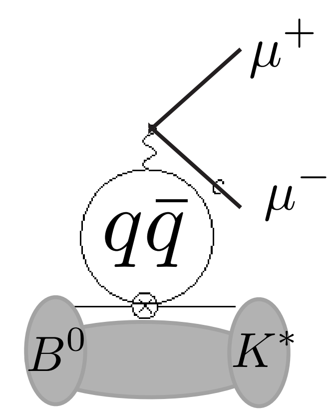
amplitudes factorize naively

[nb - one more amplitude if not neglecting lepton mass]

- via vector lepton current (in SM: (mainly) photon)







$$H_V(\lambda) \propto \tilde{V}_\lambda(q^2) C_9 - V_{-\lambda}(q^2) C'_9 + \frac{2\, m_b m_B}{q^2}\left(\tilde{T}_\lambda(q^2) C_7 - \tilde{T}_{-\lambda}(q^2) C'_7\right) - \frac{16\,\pi^2 m_B^2}{q^2} h_\lambda(q^2)$$

photon pole at q^2=0

two form factors interfere for each helicity

nonlocal "quark loops"
do **not** factorize naively

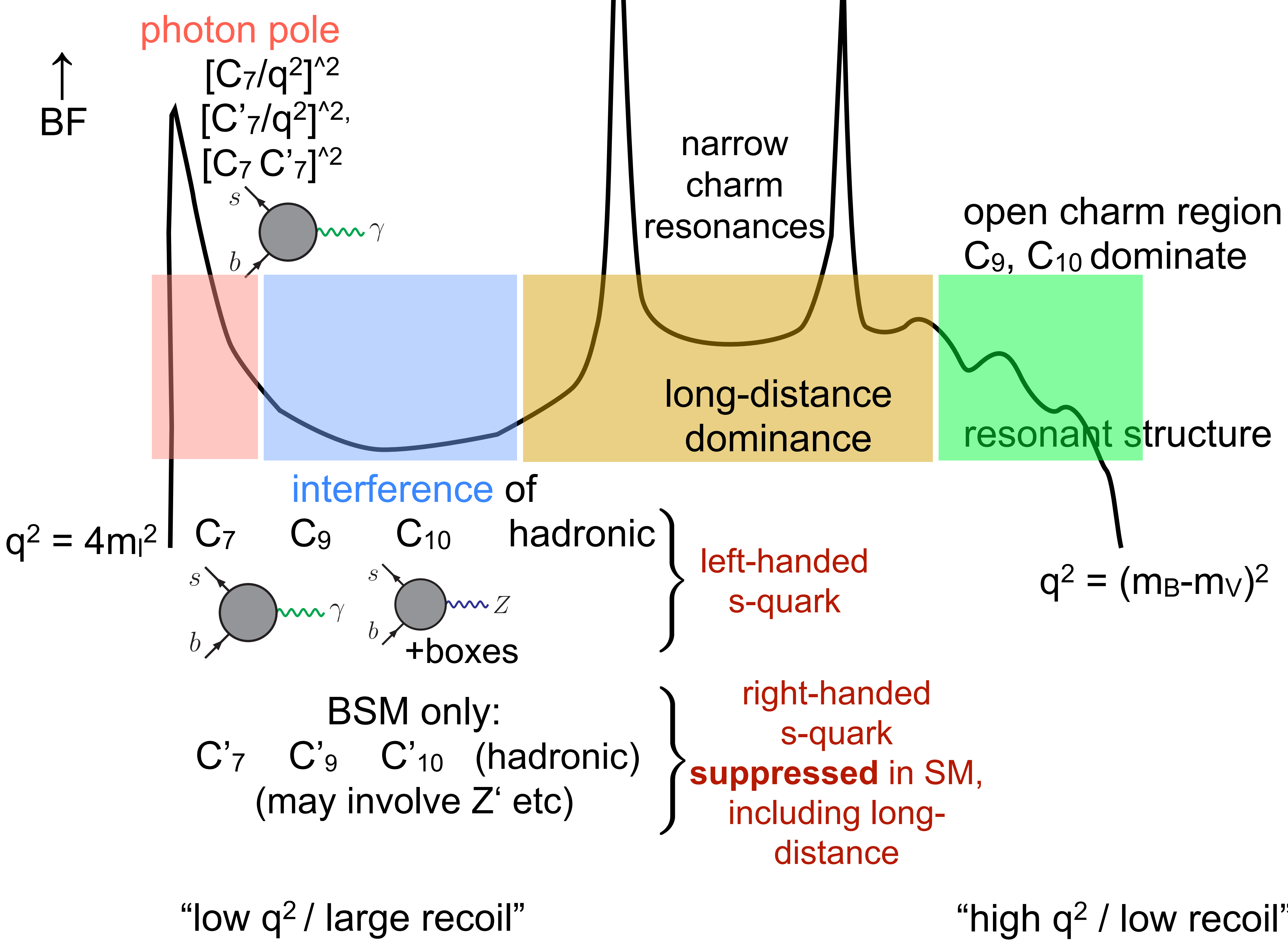
natural and transparent discussion in terms of 6 (7 if m_l != 0) helicity amplitudes

no tensor or scalar operators if $M_{NP} >> M_Z$ or NP SM singlet

SJ, Martin Camalich 2012

Alonso, Grinstein, Martin Camalich 2014

Rate: q^2 dependence (qualitative)



Form factors

Helicity amplitudes naturally involve helicity form factors

$$-im_B\tilde{V}_{L(R)\lambda}(q^2) = \langle M(\lambda)|\bar{s}\not{\epsilon}^*(\lambda)P_{L(R)}b|\bar{B}\rangle,$$
$$m_B^2\tilde{T}_{L(R)\lambda}(q^2) = \epsilon^{*\mu}(\lambda)q^\nu\langle M(\lambda)|\bar{s}\sigma_{\mu\nu}P_{R(L)}b|\bar{B}\rangle$$
$$im_B\tilde{S}_{L(R)}(q^2) = \langle M(\lambda=0)|\bar{s}P_{R(L)}b|\bar{B}\rangle.$$

~ Bharucha/Feldmann/Wick 2010

definitions here:
SJ, Martin Camalich 2012

- can be expressed as linear combinations of traditional "transversity" FFs, bringing in dependence on q^2 and meson masses - intransparent.
(However S is essentially A_0 in the traditional nomenclature.)

- **directly relevant** to B->V l l including the LHCb anomaly in particular, **V_-/T_- determines of the zero crossing of both A_{FB} and of S_5/P_5', as far as form factors are concerned**

(Burdman; Beneke/Feldmann/Seidel)
SJ, Martin Camalich 2012,2014, this talk and WIP

- helicity+ vanishes at q^2=0, in particular

$$T_+(q^2=0)=0$$

implying several clean null tests of the SM

Burdman, Hiller 2000
SJ, Martin Camalich 2012

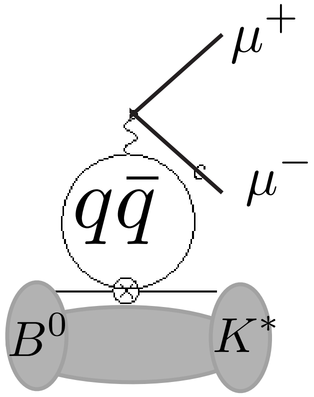
difficult to calculate - lattice cannot cover small q^2 (plus other issues)
best shot: light-cone sum rules with continuum subtractions

see previous talks

Vector amplitude: nonlocal term

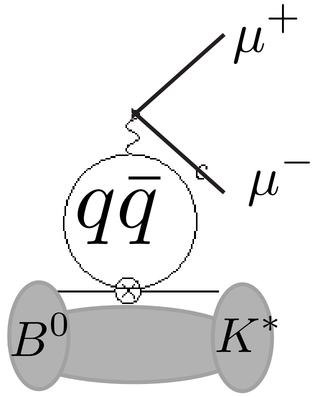
Vector amplitude: nonlocal term

$$H_V(\lambda) \propto \tilde{V}_\lambda(q^2) C_9 - V_{-\lambda}(q^2) C_9' + \frac{2\, m_b m_B}{q^2}\left(\tilde{T}_\lambda(q^2) C_7 - \tilde{T}_{-\lambda}(q^2) C_7'\right) - \frac{16\,\pi^2 m_B^2}{q^2}\, h_\lambda(q^2)$$



Vector amplitude: nonlocal term

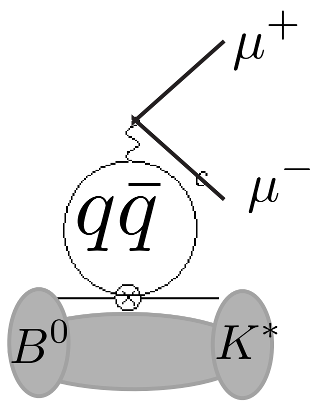
$$H_V(\lambda) \propto \tilde{V}_\lambda(q^2) C_9 - V_{-\lambda}(q^2) C_9' + \frac{2\, m_b m_B}{q^2}\left(\tilde{T}_\lambda(q^2) C_7 - \tilde{T}_{-\lambda}(q^2) C_7'\right) - \frac{16\,\pi^2 m_B^2}{q^2}\, h_\lambda(q^2)$$



+ strong interactions!

Vector amplitude: nonlocal term

$$H_V(\lambda) \propto \tilde{V}_\lambda(q^2)C_9 - V_{-\lambda}(q^2)C_9' + \frac{2\,m_b m_B}{q^2}\left(\tilde{T}_\lambda(q^2)C_7 - \tilde{T}_{-\lambda}(q^2)C_7'\right) - \frac{16\,\pi^2 m_B^2}{q^2}\,h_\lambda(q^2)$$



+ strong interactions!

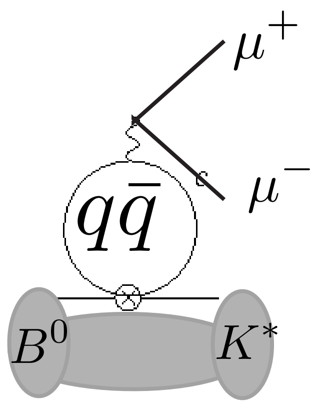
more properly:

$$\frac{e^2}{q^2}L_V^\mu a_\mu^{\rm had} = -i\frac{e^2}{q^2}\int d^4x e^{-iq\cdot x}\langle \ell^+\ell^-|j_\mu^{\rm em,lept}(x)|0\rangle \int d^4y\, e^{iq\cdot y}\langle M|j^{\rm em,had,\mu}(y)\mathcal{H}_{\rm eff}^{\rm had}(0)|\bar{B}\rangle$$

$$h_\lambda \equiv \frac{i}{m_B^2}\epsilon^{\mu *}(\lambda)a_\mu^{\rm had}$$

Vector amplitude: nonlocal term

$$H_V(\lambda) \propto \tilde{V}_\lambda(q^2)C_9 - V_{-\lambda}(q^2)C_9' + \frac{2\,m_b m_B}{q^2}\left(\tilde{T}_\lambda(q^2)C_7 - \tilde{T}_{-\lambda}(q^2)C_7'\right) - \frac{16\,\pi^2 m_B^2}{q^2}\,h_\lambda(q^2)$$



+ strong interactions!

more properly:

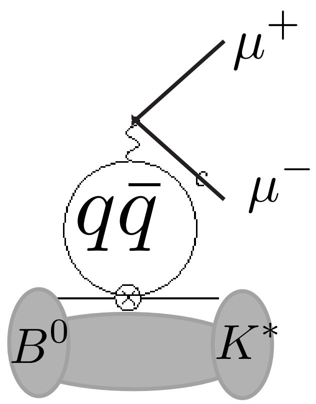
$$\frac{e^2}{q^2}L_V^\mu a_\mu^{\text{had}} = -i\frac{e^2}{q^2}\int d^4x e^{-iq\cdot x}\langle \ell^+\ell^-|j_\mu^{\text{em,lept}}(x)|0\rangle \int d^4y\, e^{iq\cdot y}\langle M|j^{\text{em,had},\mu}(y)\mathcal{H}_{\text{eff}}^{\text{had}}(0)|\bar{B}\rangle$$

$$h_\lambda \equiv \frac{i}{m_B^2}\epsilon^{\mu *}(\lambda)a_\mu^{\text{had}}$$

nonlocal, nonperturbative, large normalisation ($V_{cb}^* V_{cs}\ C_2$)

Vector amplitude: nonlocal term

$$H_V(\lambda) \propto \tilde{V}_\lambda(q^2)C_9 - V_{-\lambda}(q^2)C_9' + \frac{2\,m_b m_B}{q^2}\left(\tilde{T}_\lambda(q^2)C_7 - \tilde{T}_{-\lambda}(q^2)C_7'\right) - \frac{16\,\pi^2 m_B^2}{q^2}\,h_\lambda(q^2)$$



+ strong interactions!

more properly:

$$\frac{e^2}{q^2}L_V^\mu a_\mu^{\rm had} = -i\frac{e^2}{q^2}\int d^4x e^{-iq\cdot x}\langle \ell^+\ell^-|j_\mu^{\rm em,lept}(x)|0\rangle \int d^4y\, e^{iq\cdot y}\langle M|j^{\rm em,had,\mu}(y)\mathcal{H}_{\rm eff}^{\rm had}(0)|\bar{B}\rangle$$

$$h_\lambda \equiv \frac{i}{m_B^2}\epsilon^{\mu *}(\lambda)a_\mu^{\rm had}$$

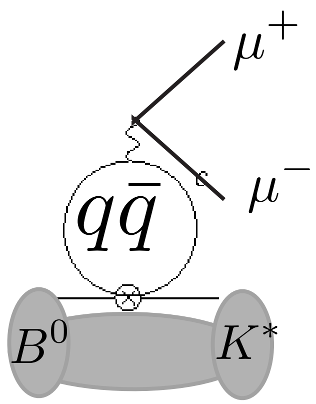
nonlocal, nonperturbative, large normalisation (V_{cb}^* V_{cs} C_2)

traditional “ad hoc fix” : $C_9 \to C_9 + Y(q^2) = C_9^{\rm eff}(q^2)$,
$C_7 \to C_7^{\rm eff}$

“taking into account the charm loop”

Vector amplitude: nonlocal term

$$H_V(\lambda) \propto \tilde{V}_\lambda(q^2) C_9 - V_{-\lambda}(q^2) C_9' + \frac{2\, m_b m_B}{q^2} \left(\tilde{T}_\lambda(q^2) C_7 - \tilde{T}_{-\lambda}(q^2) C_7' \right) - \frac{16\,\pi^2 m_B^2}{q^2} h_\lambda(q^2)$$



+ strong interactions!

more properly:

$$\frac{e^2}{q^2} L_V^\mu a_\mu^{\rm had} = -i \frac{e^2}{q^2} \int d^4x e^{-iq\cdot x} \langle \ell^+\ell^- | j_\mu^{\rm em,lept}(x) | 0 \rangle \int d^4y\, e^{iq\cdot y} \langle M | j^{\rm em,had,\mu}(y) \mathcal{H}_{\rm eff}^{\rm had}(0) | \bar{B} \rangle$$

$$h_\lambda \equiv \frac{i}{m_B^2} \epsilon^{\mu *}(\lambda) a_\mu^{\rm had}$$

nonlocal, nonperturbative, large normalisation ($V_{cb}^* V_{cs}$ C_2)

traditional "ad hoc fix" : C_9 -> $C_9 + Y(q^2) = C_9^{eff}(q^2)$, C_7 -> C_7^{eff} "taking into account the charm loop"

- * for C_7^{eff} this seems ok at lowest order (pure UV effect; scheme independence)
- * for C_9^{eff} amounts to factorisation of scales ~ m_b (, m_c , q^2) and Λ (soft QCD)
- * not justified in large-N limit (broken already at leading logarithmic order)
- * what about QCD corrections?
- * not a priori clear whether this even gets one closer to the true result!

only known justification is a heavy-quark expansion in Λ/m_b (just like inclusive decay is treated !)

Beneke, Feldmann, Seidel 2001, 2004

Nonlocal term - another look

traditional “ad hoc fix” : $C_9 \to C_9 + Y(q^2) = C_9^{eff}(q^2)$, $C_7 \to C_7^{eff}$

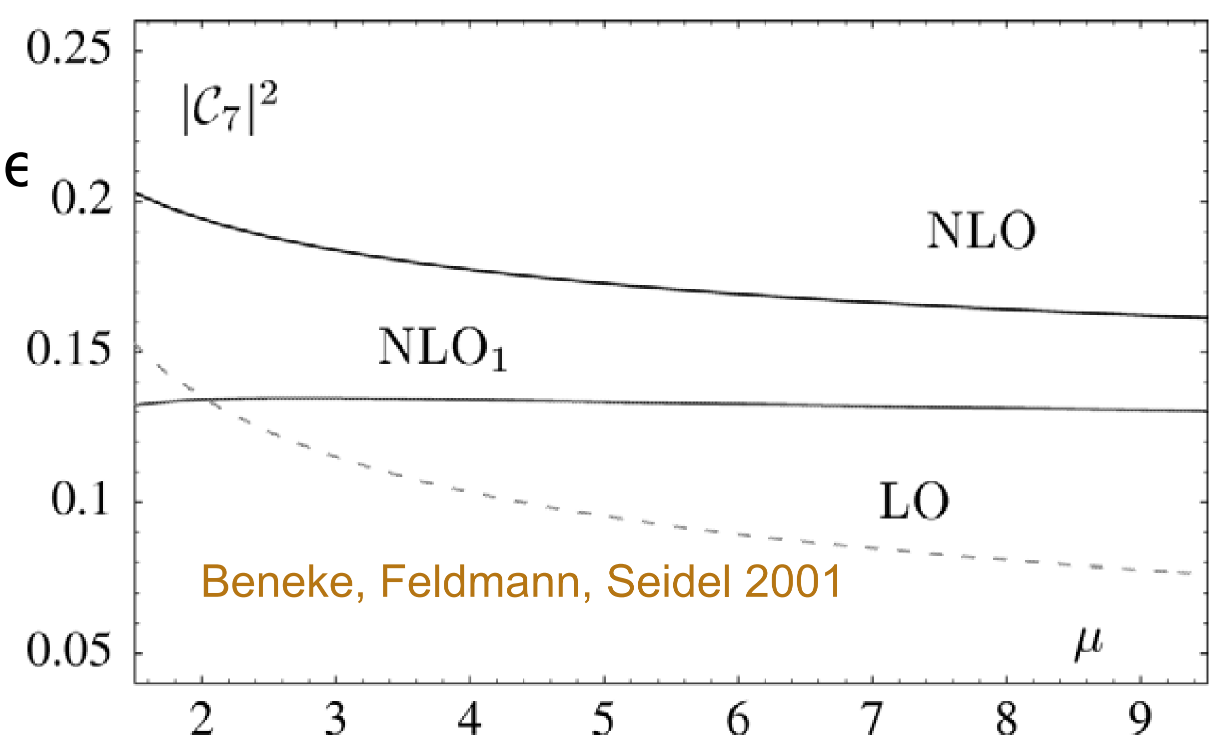
dominant effect: charm loop, proportional to ($z = 4\, m_c^2/q^2$)

$$-\frac{4}{9}\left(\ln\frac{m_q^2}{\mu^2} - \frac{2}{3} - z\right) - \frac{4}{9}(2+z)\sqrt{|z-1|}\begin{cases}\arctan\dfrac{1}{\sqrt{z-1}}, & z>1,\\ \ln\dfrac{1+\sqrt{1-z}}{\sqrt{z}} - \dfrac{i\pi}{2}, & z\leqslant 1\end{cases}$$

$$C_9^{\rm eff} = \begin{cases} 4.18|_{C_9} + (0.22+0.05i)|_Y & (m_c = m_c^{\rm pole} = 1.7{\rm GeV}) \\ 4.18|_{C_9} + (0.40+0.05i)|_Y & (m_c = m_c^{\overline{\rm MS}} = 1.2{\rm GeV}). \end{cases}$$

ie a 5% mass scheme ambiguity

separately, one has a residual scale ambiguity of order 30% at the level of the decay amplitude

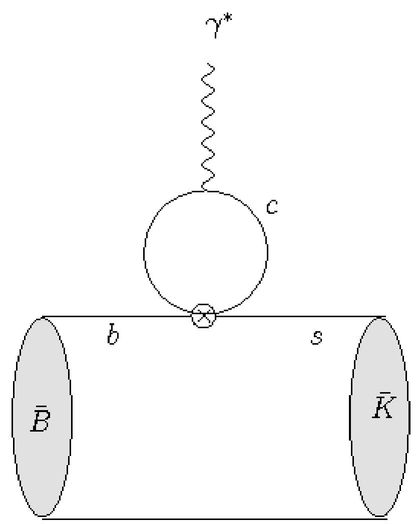


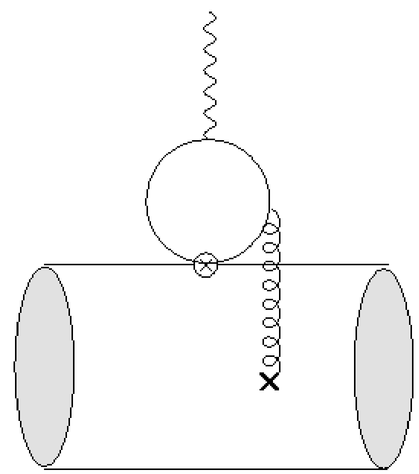
Beneke, Feldmann, Seidel 2001

resolved in the heavy-quark expansion (to leading power)

Beneke, Feldmann, Seidel 2001, 2004

Nonlocal terms:heavy-quark expansion





leading-power: factorises into perturbative kernels, form factors, LCDA's (including hard/hard-collinear gluon corrections to all orders)

α_s^0 : $C_7 \rightarrow C_7^{eff}$
$C_9 \rightarrow C_9^{eff}(q^2)$
+ 1 annihilation diagram
α_s^1 : further corrections to $C_7^{eff}(q^2)$ and $C_9^{eff}(q^2)$

(convergent) convolutions of hard-scattering kernels with meson light cone-distribution amplitudes
Beneke, Feldmann, Seidel 2001

state-of-the-art in phenomenology

unambigous (save for parametric uncertainties)

at subleading powers: breakdown of factorisation

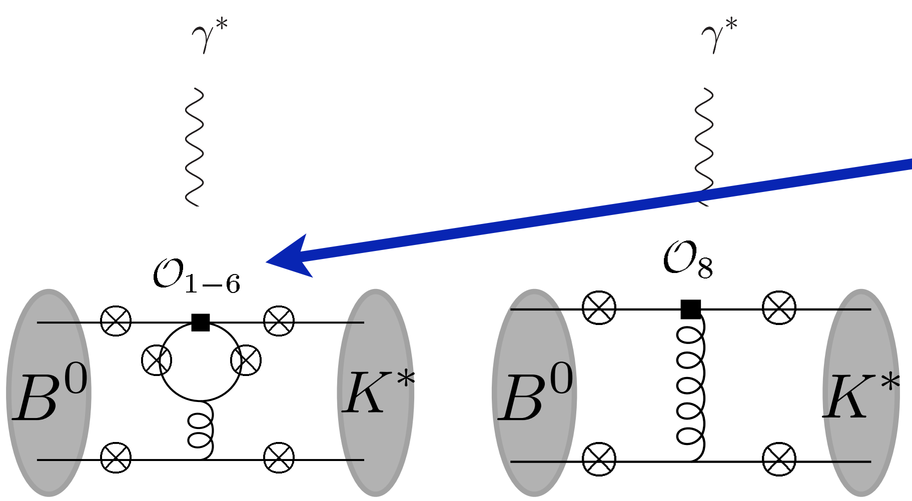
some contributions have been estimated as end-point divergent convolutions with a cut-off Kagan&Neubert 2001, Feldmann&Matias 2002

can perform light-cone OPE of charm loop & estimate resulting (nonlocal) operator matrix elements

Khodjamirian et al 2010

effective shifts of helicity amplitudes as large as ~10%

New effect: spectator scattering



includes Q_1^c, Q_2^c - large Wilson coefficients

+ annihilation (+ "vertex corrections")

Beneke, Feldmann, Seidel 2001

leading-power: everything factorises into perturbative kernels, form factors, meson light-cone distribution amplitudes (including hard/hard-collinear gluon corrections to all orders)

$$h_\lambda = \int_0^1 du \phi_K^*(u) T(u, \alpha_s) + \mathcal{O}(\Lambda/m_b)$$

- leading power in the heavy quark limit - same as the vertex corrections going into C_7^{eff}, C_9^{eff}

Form factor relations

Once one accepts the heavy-quark limit as necessary evil (?) for dealing with the nonleptonic Hamiltonian ("charm loops" etc) one takes note that it also predicts simple relations between the (helicity) form factors, for instance:

Charles et al 1999
Beneke, Feldmann 2000
...

$$\frac{T_-(q^2)}{V_-(q^2)} = 1 + \frac{\alpha_s}{4\pi} C_F \left[\ln \frac{m_b^2}{\mu^2} - L \right] + \frac{\alpha_s}{4\pi} C_F \frac{1}{2} \frac{\Delta F_\perp}{V_-}$$

where

$$L = -\frac{2E}{m_B - 2E} \ln \frac{2E}{m_B}$$

"vertex" correction: no new parameter

"spectator scattering": mainly dependent on B meson LCDA but a_s suppressed

Eliminates form factor dependence from some observables (eg P_2') almost completely, up to power corrections

Descotes-Genon, Hofer, Matias, Virto

(earlier: Egede et al; Becirevic and Schneider; Bobeth et al, ...)

Heavy-quark limit and corrections

At most 1-2% over entire 0..6 GeV^2 range -> ignore

$$F(q^2) = F^\infty(q^2) + a_F + b_F q^2/m_B^2 + \mathcal{O}([q^2/m_B^2]^2)$$

heavy quark limit

Power corrections - parameterise

$$F^\infty(q^2) = F^\infty(0)/(1-q^2/m_B^2)^p + \Delta_F(\alpha_s; q^2)$$

(Charles et al)

(Beneke, Feldmann)

q^2 dependence in heavy-quark limit not known (model by a power p, and/or a pole model)

$V_+^\infty(0) = 0$ $T_+^\infty(0)=0$
$V_-^\infty(0) = T_-^\infty(0)$
$V_0^\infty(0) = T_0^\infty(0)$

from heavy-quark/ large energy symmetry

Corrections are calculable in terms of perturbation theory, decay constants, light cone distribution amplitudes

$V_+^\infty(q^2) = 0$ $T_+^\infty(q^2)=0$

hence

$$T_+(q^2) = \mathcal{O}(q^2) \times \mathcal{O}(\Lambda/m_b)$$
$$V_+(q^2) = \mathcal{O}(\Lambda/m_b).$$

- **"naively factorizing" part of the helicity amplitudes $H_{V,A}^+$ strongly suppressed** as a consequence of chiral SM weak interactions
- We see the suppression is **particularly strong** near low-q^2 endpoint
- Form factor relations imply reduced uncertainties in suitable observables

Burdman, Hiller 1999 (quark picture)

Beneke, Feldmann, Seidel 2001 (QCDF)

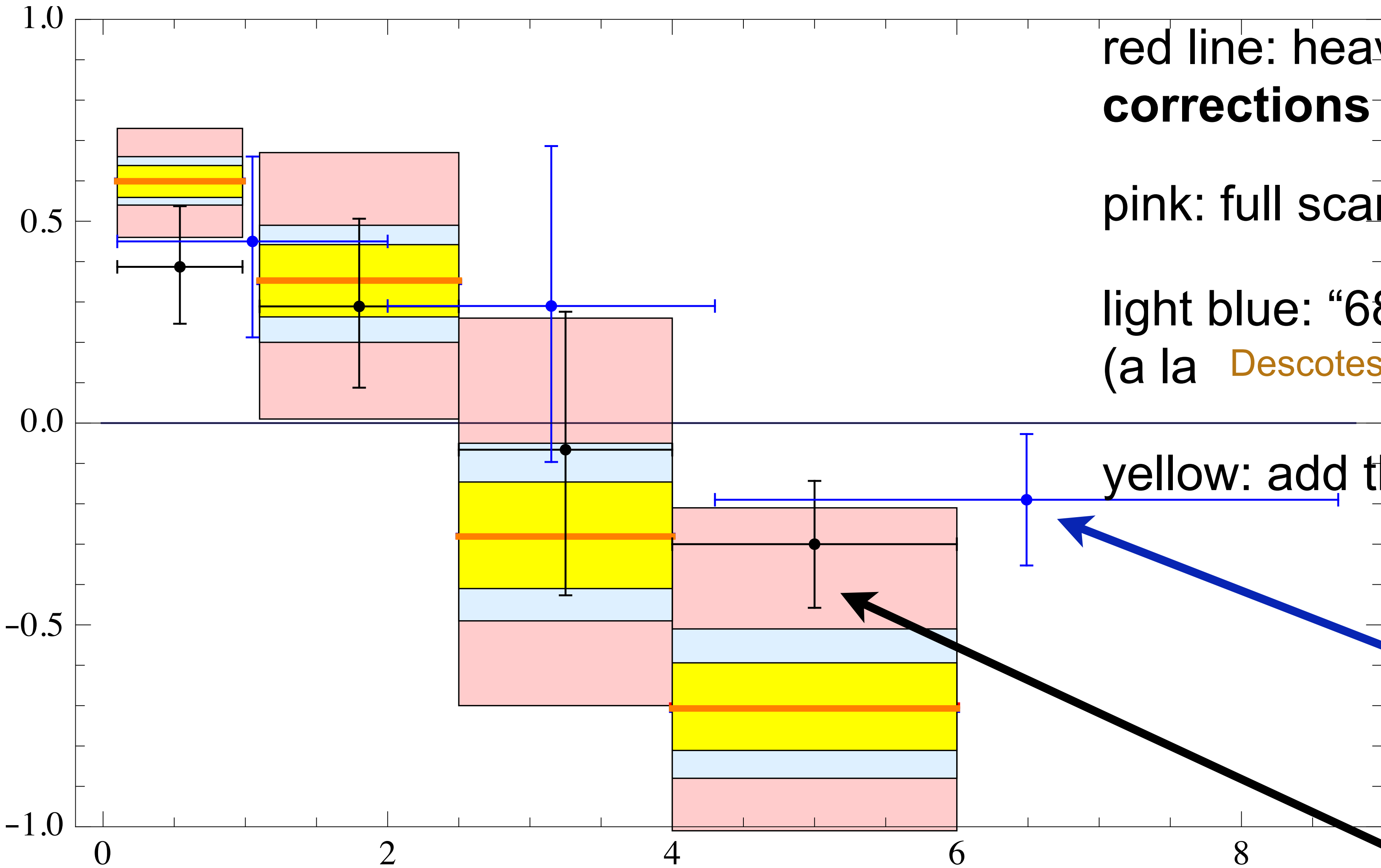
Angular distribution phenomenology

methodology as in SJ and Martin Camalich 2012, 2014, parameter ranges as in 1412.3183

in particular, model all FF power correction parameters as 10% relative corrections, and employ a similar parameterisation of long-distance corrections to the three vector helicity amplitudes (taking into account helicity+ suppression as justified in above papers)

very preliminary, W.I.P

Angular observable P_5' SJ, Martin Camalich, preliminary



red line: heavy-quark limit, **no power corrections**

pink: full scan over all theory errors

light blue: “68% Gaussian” theory error (a la Descotes-Genon, Hofer, Matias, Virto)

yellow: add theory errors in quadrature

LHCb 2013 (1 fb^{-1})

LHCb Moriond 2015 (3 fb^{-1})

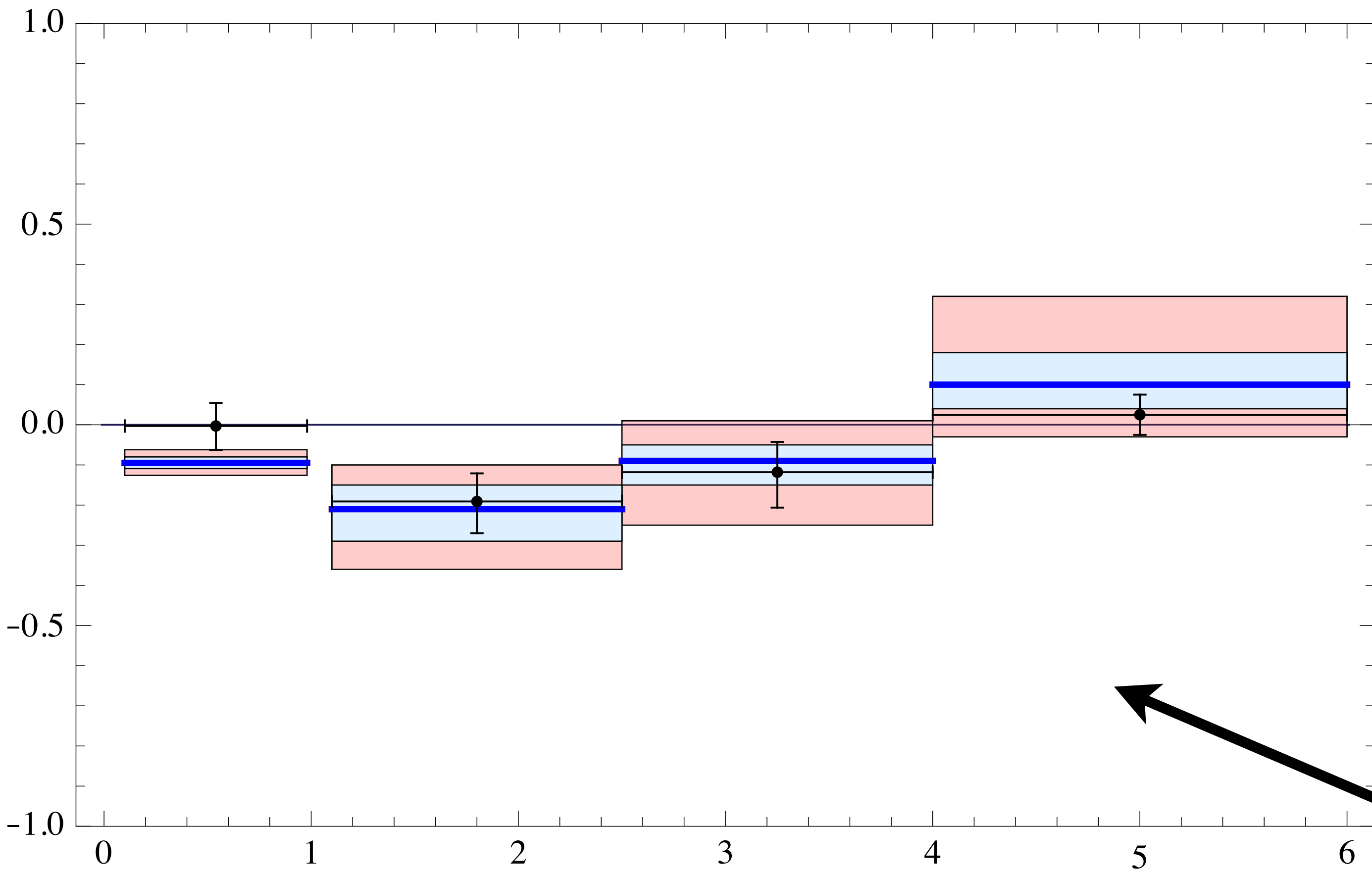
Pure heavy-quark limit (!) describes data surprisingly well.

Within errors there appears to be no significant discrepancy

Cannot support LHCb claim of 2.9 sigma effect in the 4..6 GeV^2 bin

Forward-backward asymmetry

SJ, Martin Camalich, preliminary



red line: heavy-quark limit, **no power corrections**

pink: full scan over all theory errors

light blue: “68% Gaussian” theory error (a la Descotes-Genon, Hofer, Matias, Virto)

LHCb 2013 (1 fb^{-1})

LHCb Moriond 2015 (3 fb^{-1})

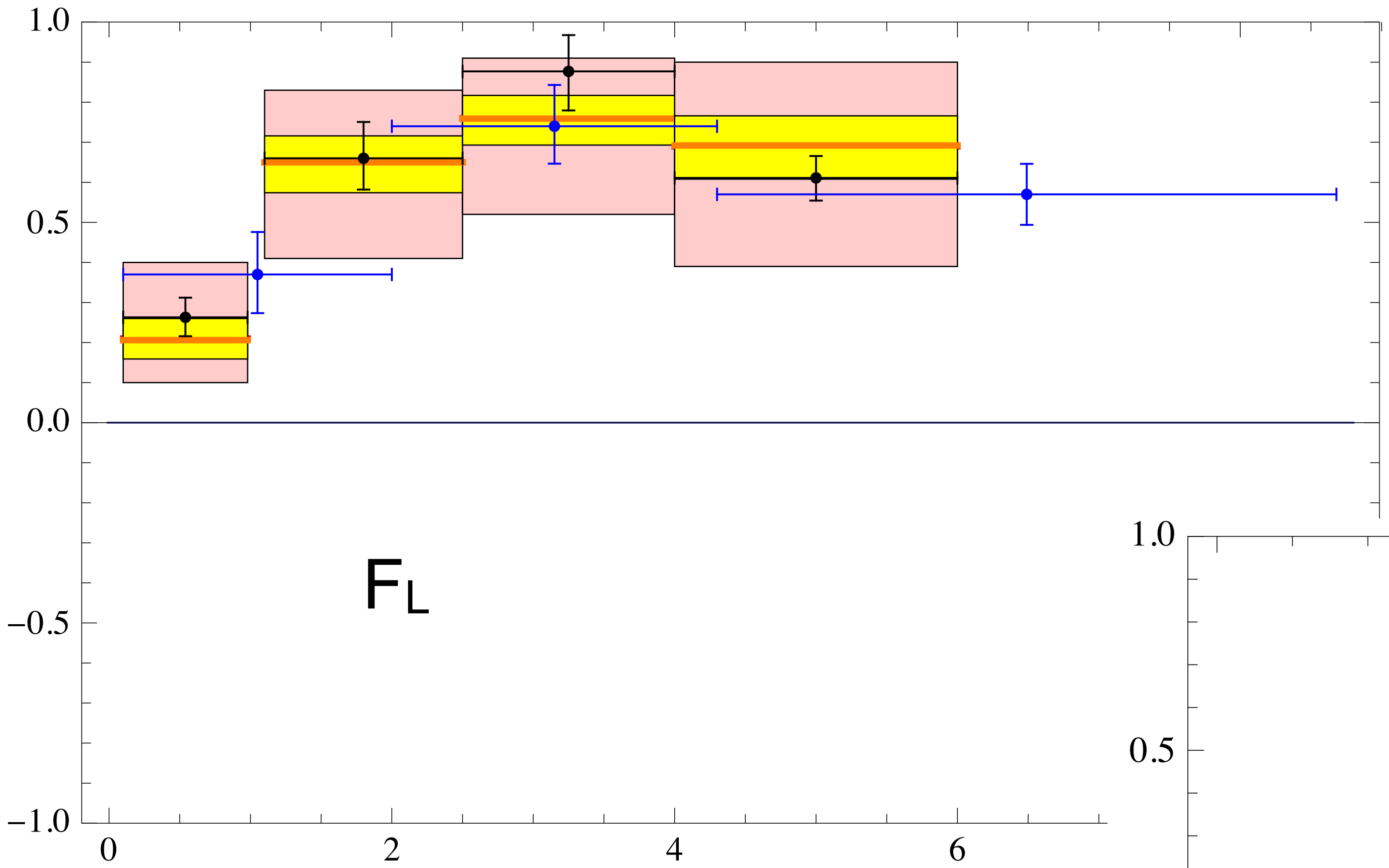
Pure heavy-quark limit (!) matches data. Even at central values nothing of significance.

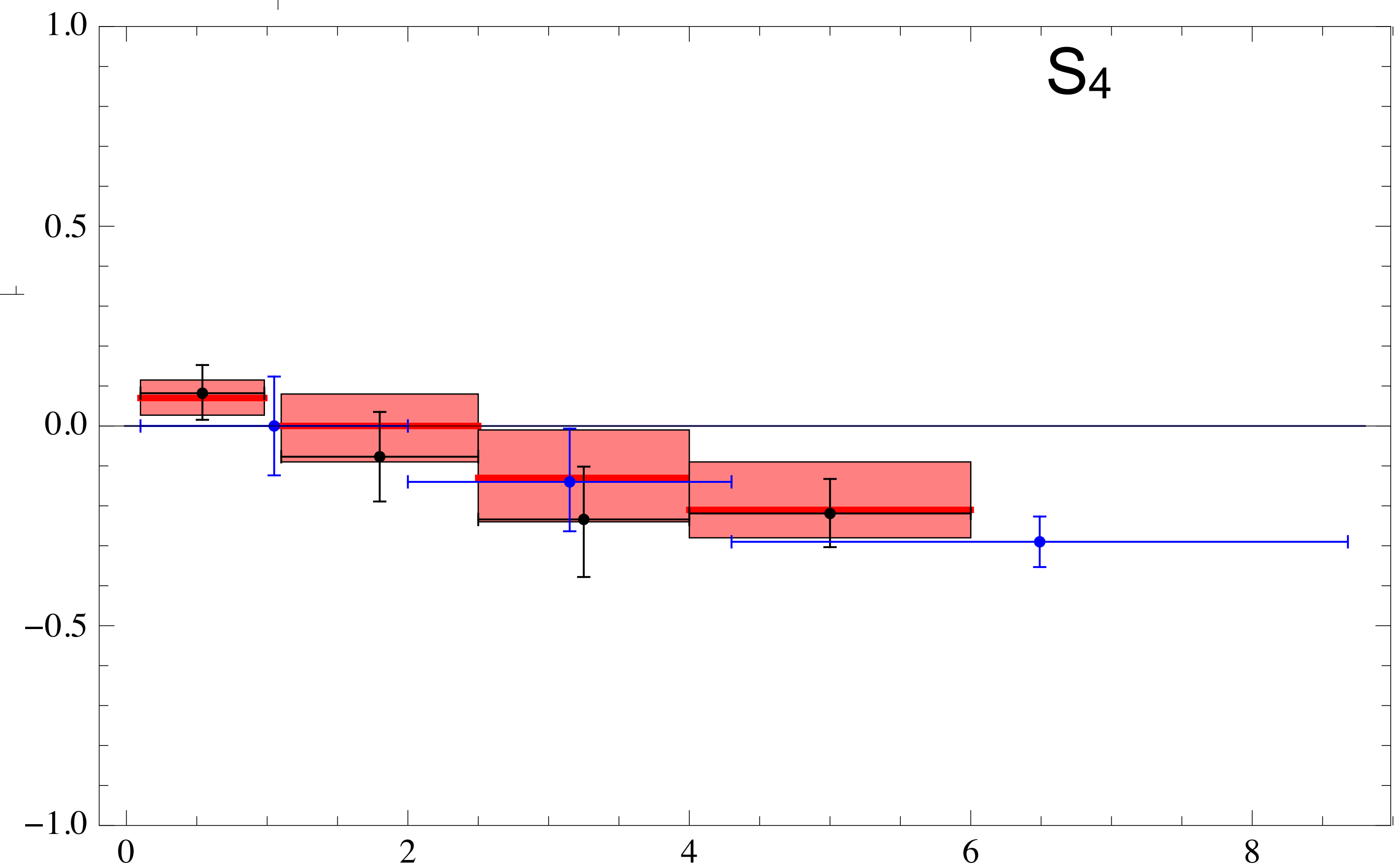
Data almost spot on our predictions -
cannot confirm systematic downward shift claimed by LHCb.

Similar conclusions F_L and S_4.

F_L and S_4

SJ, Martin Camalich, preliminary



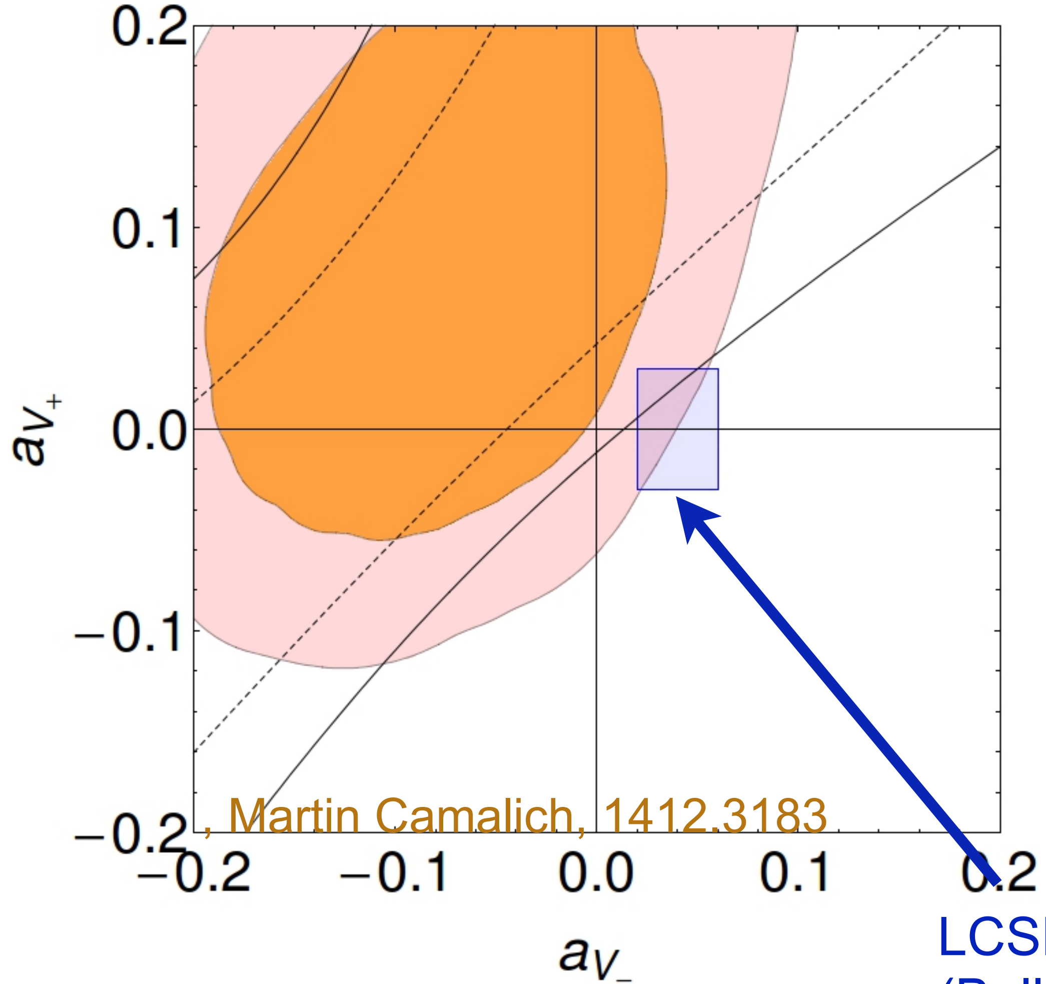


Same here.

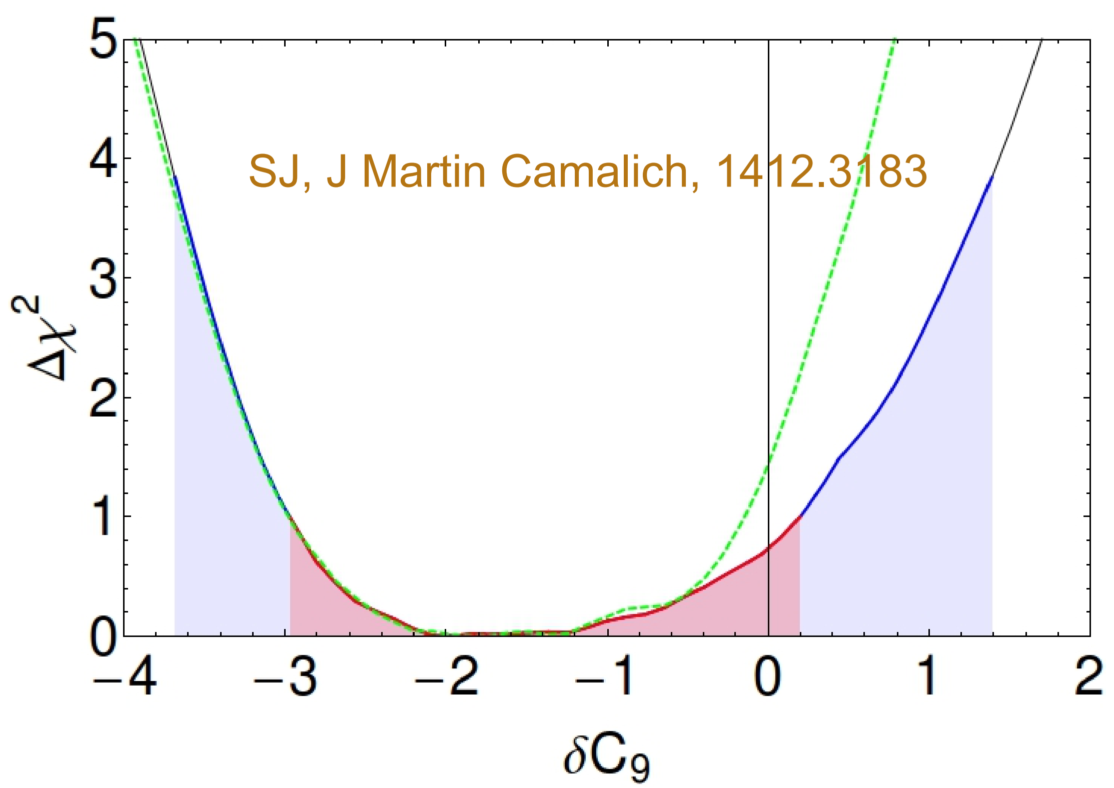
"Null tests" S_3 not yet analysed with new data; A_9 no update by LHCb yet

Discussion

work in progress SJ, Martin Camalich, to appear



LCSR form factors
(Ball,Zwicky)



awaiting update (and more) with new data

Brief digression

(from Star Trek, The Next Generation, final episode "All Good Things")

Synopsis of episode: *In his effort to save humanity, Picard must sacrifice himself and all those he loves…perhaps more than once. And if their sacrifice fails, all mankind is doomed.*

[from memory-beta.wikia.com]

(The anomaly turns out to be magnified by Picard's own efforts, who has been conned into all this as part of a mean test of humanity by superhuman beings.)

Today we are "only" talking about the Standard Model, and we all (?) would like to see it doomed. Nevertheless, it is possible that the LHCb anomaly is of our own making.

“Clean” angular observables

Useful to consider functions of the angular coefficients for which form factors drop out in the heavy quark limit if perturbative QCD corrections neglected.

Becirevic, Schneider 2011
Matias, Mescia, Ramon, Virto 2012
Descotes-Genon et al 2012
(also Krueger,Matias 2005; Egede et al 2008)

E.g.

neglecting strong phase differences
[tiny; take into account in numerics]

$$P_1 \equiv \frac{I_3 + \bar{I}_3}{2(I_{2s} + \bar{I}_{2s})} = \frac{-2\,\mathrm{Re}(H_V^+ H_V^{-*} + H_A^+ H_A^{-*})}{|H_V^+|^2 + |H_V^-|^2 + |H_A^+|^2 + |H_A^-|^2} = 0$$

$$P_3^{CP} \equiv -\frac{I_9 - \bar{I}_9}{4(I_{2s} + \bar{I}_{2s})} = -\frac{\mathrm{Im}(H_V^+ H_V^{-*} + H_A^+ H_A^{-*})}{|H_V^+|^2 + |H_V^-|^2 + |H_A^+|^2 + |H_A^-|^2} = 0$$

(Melikhov 1998)
Krueger, Matias 2002
Lunghi, Matias 2006
Becirevic, Schneider 2011

$$P_5' = \frac{\mathrm{Re}[(H_V^- - H_V^+)H_A^{0*} + (H_A^- - H_A^+)H_V^{0*}]}{\sqrt{(|H_V^0|^2 + |H_A^0|^2)(|H_V^+|^2 + |H_V^-|^2 + |H_A^+|^2 + |H_A^-|^2)}} = \frac{C_{10}\,(C_{9,\perp} + C_{9,\parallel})}{\sqrt{(C_{9,\parallel}^2 + C_{10}^2)(C_{9,\perp}^2 + C_{10}^2)}}$$

in SM, neglecting power corrections and pert. QCD corrections

where $$C_{9,\perp} = C_9^{\mathrm{eff}}(q^2) + \frac{2\, m_b\, m_B}{q^2}\, C_7^{\mathrm{eff}}$$

$$C_{9,\parallel} = C_9^{\mathrm{eff}}(q^2) + \frac{2\, m_b\, E}{q^2}\, C_7^{\mathrm{eff}}$$

C_7 and C_9 opposite sign
Interference maximal near zero-crossing
enhances vulnerability to anything that violates the large-energy form factor relations

much more relevant to P_5’ (and others) than to P_1 or P_3^{CP}

Power corrections: analytical

SJ, Martin Camalich 1412.3183

Compare

$$P_5' = P_5'|_\infty \Bigg(1 + \frac{a_{V_-} - a_{T_-}}{\xi_\perp} \frac{m_B}{|\vec{k}|} \frac{m_B^2}{q^2} C_7^{\rm e} \, \frac{C_{9,\perp}C_{9,\|} - C_{10}^2}{(C_{9,\perp}^2 + C_{10}^2)(C_{9,\perp} + C_{9,\|})}$$
$$+ \frac{a_{V_0} - a_{T_0}}{\xi_\|} 2\, C_7^{\rm e} \, \frac{C_{9,\perp}C_{9,\|} - C_{10}^2}{(C_{9,\|}^2 + C_{10}^2)(C_{9,\perp} + C_{9,\|})}$$
$$+ 8\pi^2 \frac{\tilde{h}_-}{\xi_\perp} \frac{m_B}{|\vec{k}|} \frac{m_B^2}{q^2} \frac{C_{9,\perp}C_{9,\|} - C_{10}^2}{C_{9,\perp} + C_{9,\|}} + \text{further terms} \Bigg) + \mathcal{O}(\Lambda^2/m_B^2)$$

(truncated after 3 out of 11 independent power-correction terms!)
also, dependence on soft form factors reappears at PC level

and

$$P_1 = \frac{1}{C_{9,\perp}^2 + C_{10}^2} \frac{m_B}{|\vec{k}|} \Bigg(- \frac{a_{T_+}}{\xi_\perp} \frac{2\, m_B^2}{q^2} C_7^{\rm eff} C_{9,\perp} - \frac{a_{V_+}}{\xi_\perp} (C_{9,\perp} C_9^{\rm eff} + C_{10}^2) - \frac{b_{T_+}}{\xi_\perp} 2 C_7^{\rm eff} C_{9,\perp}$$
$$- \frac{b_{V_+}}{\xi_\perp} \frac{q^2}{m_B^2} (C_{9,\perp} C_9^{\rm eff} + C_{10}^2) + 16\pi^2 \frac{h_+}{\xi_\perp} \frac{m_B^2}{q^2} C_{9,\perp} \Bigg) + \mathcal{O}(\Lambda^2/m_B^2).$$

(complete expression)

Further notice that a_{T+} vanishes as $q^2 \to 0$, h_+ helicity suppressed, and the other three terms lacks the photon pole.

Hence P_1 **much** cleaner than P_5', especially at very low q^2

Probing right-handed currents

Extending to BSM Wilson coefficients, have

neglecting strong phase differences
[tiny; take into account in numerics]

close to q^2 = 0 (photon
pole dominance)

$$P_1 \equiv \frac{I_3 + \bar{I}_3}{2(I_{2s} + \bar{I}_{2s})} = \frac{-2\,\mathrm{Re}(H_V^+ H_V^{-*} + H_A^+ H_A^{-*})}{|H_V^+|^2 + |H_V^-|^2 + |H_A^+|^2 + |H_A^-|^2} \approx 2\frac{\mathrm{Re}(C_7 C_7'^*)}{|C_7|^2 + |C_7'|^2}$$

$$P_3^{CP} \equiv -\frac{I_9 - \bar{I}_9}{4(I_{2s} + \bar{I}_{2s})} = -\frac{\mathrm{Im}(H_V^+ H_V^{-*} + H_A^+ H_A^{-*})}{|H_V^+|^2 + |H_V^-|^2 + |H_A^+|^2 + |H_A^-|^2} \approx \frac{\mathrm{Im}(C_7 C_7'^*)}{|C_7|^2 + |C_7'|^2}$$

- recall **double** suppression of T_+ at (very) low q^2

- extends to the long-distance contribution to H_V^+
(discussed in great detail in 1212.2264 and 1412.3183)

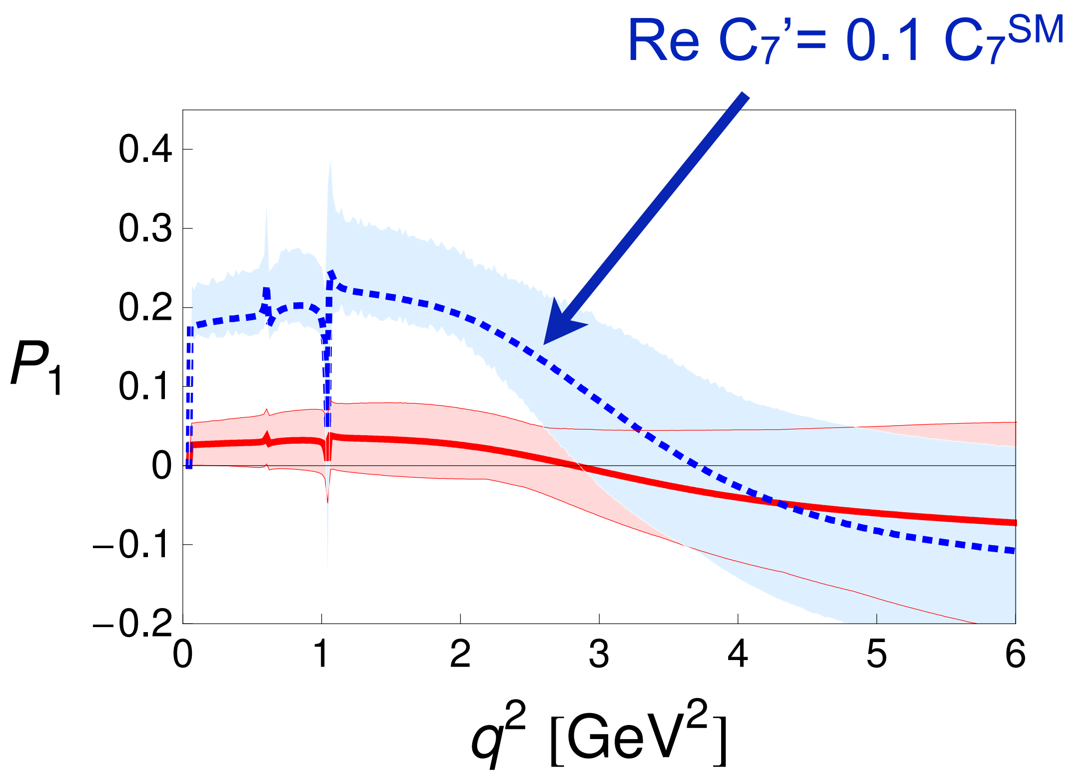
so very small nonperturbative QCD corrections to right-hand side

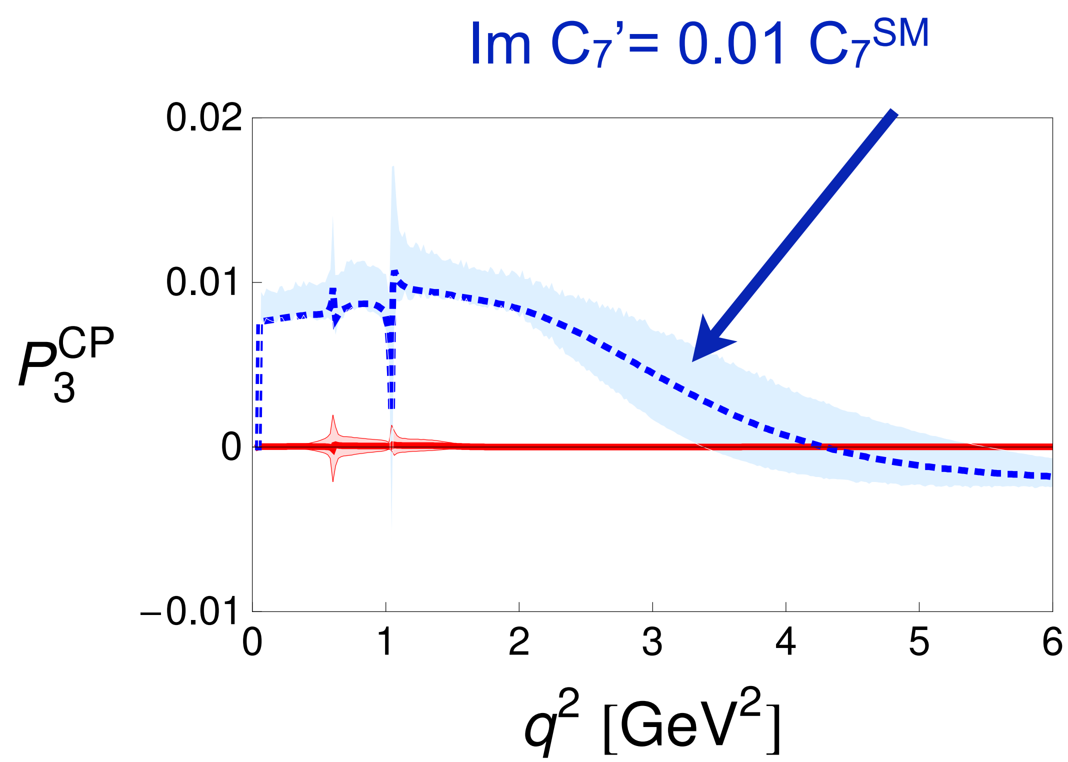
also, B->K* gamma is described in terms of the same λ=+/- 1
helicity amplitudes

$$\begin{aligned}\mathcal{A}(\bar{B} \to V(\lambda)\gamma(\lambda)) &= \lim_{q^2\to 0} \frac{q^2}{e} H_V(q^2 = 0; \lambda) \\ &= \frac{iN m_B^2}{e}\left[\frac{2\hat{m}_b}{m_B}(C_7 \tilde{T}_\lambda(0) - C_7' \tilde{T}_{-\lambda})(0) - 16\pi^2 h_\lambda(q^2 = 0)\right]\end{aligned}$$

exact (LSZ)

Sensitivity to C_7'(muonic mode)





SJ, Martin Camalich 2012

Two angular observables remain clean null tests of the SM in the presence of long-distance corrections

(theoretical limit on) sensitivity to Re C_7' at <10% (C_7^{SM}) level, to Im C_7' at <1%

sensitivity stems from $q^2 \in [0.1, 2]$ GeV^2

Predictions for electronic mode

$Br\ [10^{-8}]$	F_L	P_1	P_2	$P_3^{CP}\ [10^{-4}]$	P_4'	P_5'	P_6'	P_8'
26^{+12}_{-9}	$0.10^{+0.11}_{-0.05}$	$0.030^{+0.047}_{-0.044}$	$-0.073^{+0.020}_{-0.016}$	$0.1^{+0.6}_{-0.6}$	$0.18^{+0.06}_{-0.08}$	$0.55^{+0.11}_{-0.12}$	$0.06^{+0.07}_{-0.07}$	$0.01^{+0.09}_{-0.09}$

SJ, Martin Camalich
1412.3183

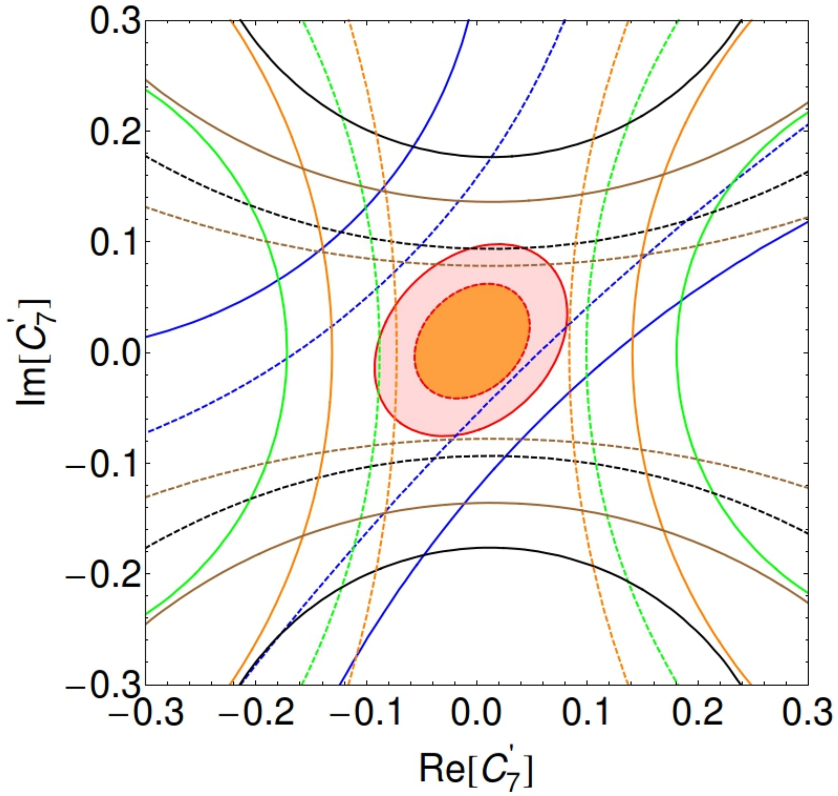
"Effective" bin $[0.0020^{+0.0008}_{-0.0008}, 1.12^{+0.06}_{-0.06}]$ to deal with acceptance issues (negligible impact on theory error)

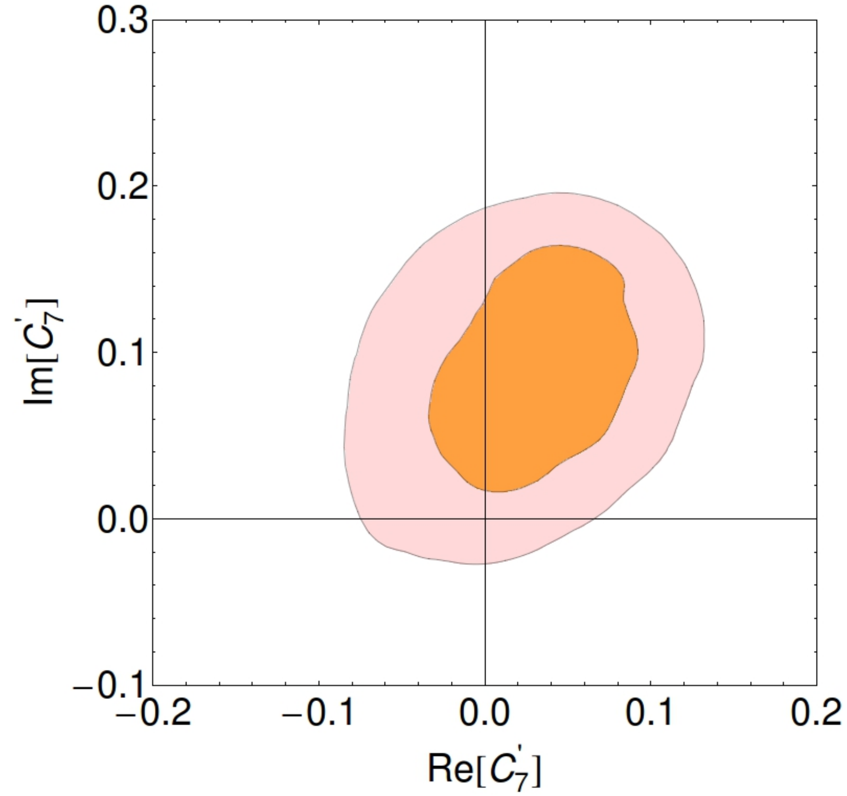
Theoretically even cleaner than muonic mode at very low q^2 as tensor form factor / photon pole dominates more

Boost in BR due to lower q^2_{min}

for C_7' sensitivity, offsets disadvantages at LHCb

Prospects





SJ, Martin Camalich
1412.3183

$$S \simeq \frac{2\mathrm{Im}(e^{-2i\beta} C_7 C_7')}{|C_7|^2+|C_7'|^2},$$

$$P_1 \simeq \frac{2\mathrm{Re}(C_7 C_7')}{|C_7|^2+|C_7'|^2},$$

$$P_3^{\mathrm{CP}} \simeq \frac{2\mathrm{Im}(C_7 C_7')}{|C_7|^2+|C_7'|^2}$$

Left: assuming $\sigma_{P_i} = 0.25$ for muons and electrons, no theory errors

Right: Profile likelihood for current data (1sigma and 95% CL)

excellent sensitivity to right-handed currents remains with conservative treatment of QCD uncertainties

awaiting update with new LHCb B->K*mu mu and B->K*e e angular data

What would a signal look like?

SJ, Martin Camalich
1412.3183

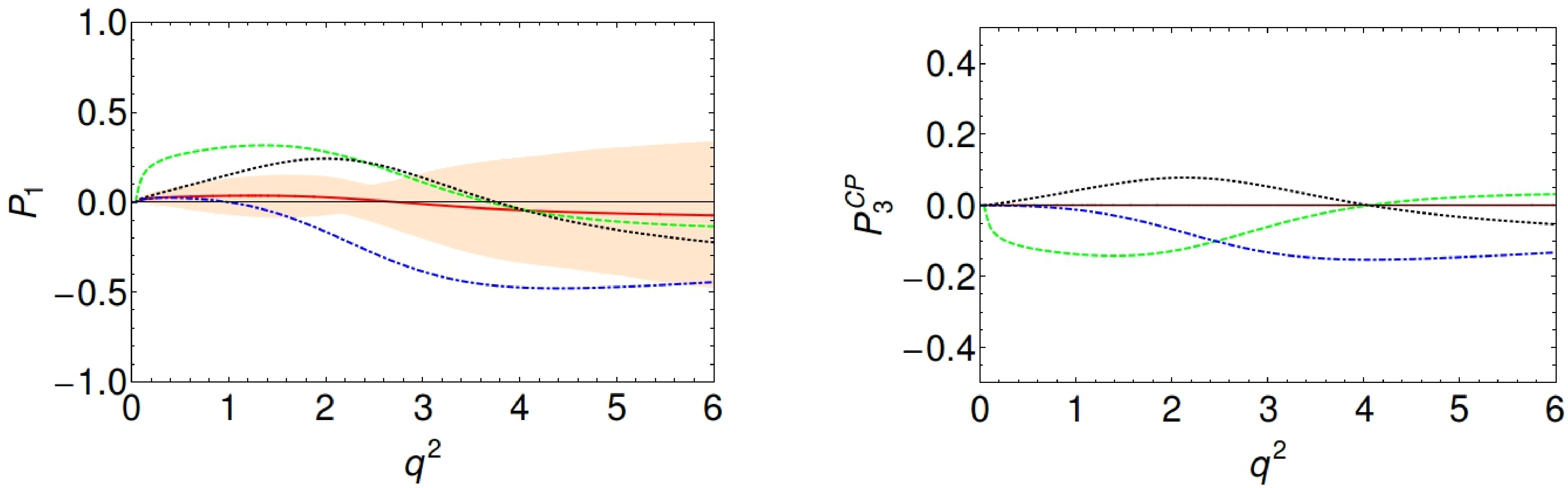
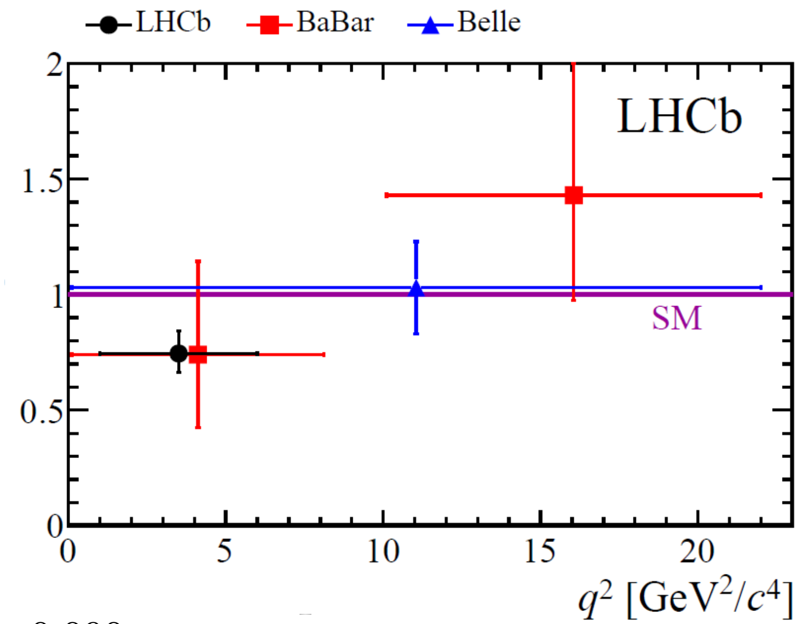


FIG. 7. Sensitivity of $P_1(q^2)$ and $P_3^{CP}(q^2)$ to right-handed quark currents. The SM predictions are the solid (red) lines and the theoretical uncertainty, represented by the band, is obtained taking the maximum spread of theoretical predictions. In the plot of $P_1(q^2)$ the NP scenarios correspond to $C_7' = -0.05$ (dashed green), $C_9' = -1$ (dotted black) and $C_{10}' = 1$ (dot-dashed blue). In the plot of $P_3^{CP}(q^2)$, we show $C_7' = -0.05$ (dashed green), $C_9' = -1$ (dotted black) and $C_{10}' = 1$ (dot-dashed blue). In the plot of $P_3^{CP}(q^2)$, we plot $C_7' = 0.05\,i$ (dashed green), $C_9' = -e^{i\frac{\pi}{4}}$ (dotted black) and $C_{10}' = e^{i\frac{\pi}{4}}$ (dot-dashed blue).

Different BSM explanations of the P_5' anomaly easily discriminated, key role played by region below 3 GeV^2 - safe distance from charm threshold

Lepton universality tests

$$R_K = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{\mathrm{d}\Gamma[B^+ \to K^+\mu^+\mu^-]}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{\mathrm{d}\Gamma[B^+ \to K^+e^+e^-]}{\mathrm{d}q^2}\mathrm{d}q^2}$$



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

A Shires, workshop Paris, June 2014
LHCb arXiv:1406.6482

* naively =1 in SM if lepton masses negligible (as seems the case for 1 GeV^2 lower cutoff)) Hiller, Krueger 2003

* a large effect !

* can be ascribed to a negative C_9^{NP} , for muons only
* scalar operators ruled out by B_s -> mu mu data

Alonso, Grinstein, Martin Camalich 2014
(also Hiller, Schmaltz; Ghosh, Nardecchia, Renner)
(also Altmannshofer and Straub)

* could be explained in terms of Z' or leptoquark models

(Altmannshofer et al; Hiller and Schmaltz; Gripaios et al)

Further LUV tests

SM predicts lepton universality to great accuracy. In particular, apart from lepton mass effects all helicity amplitudes coincide and hence, to our accuracy, the theory error on any LUV ratio or difference is zero.

Altmannshofer, Straub; Hiller, Schmaltz; SJ, Martin Camalich

Two particular classes of observables:

(1)
$$R_{K^*_X} = \frac{\mathcal{B}(B \to K^*_X \mu^+ \mu^-)}{\mathcal{B}(B \to K^*_X e^+ e^-)}. \qquad X = L,\, T$$

$$R_i = \frac{\langle \Sigma_i^\mu \rangle}{\langle \Sigma_i^e \rangle} \qquad \Sigma_i = \frac{I_i + \bar{I}_i}{2}$$

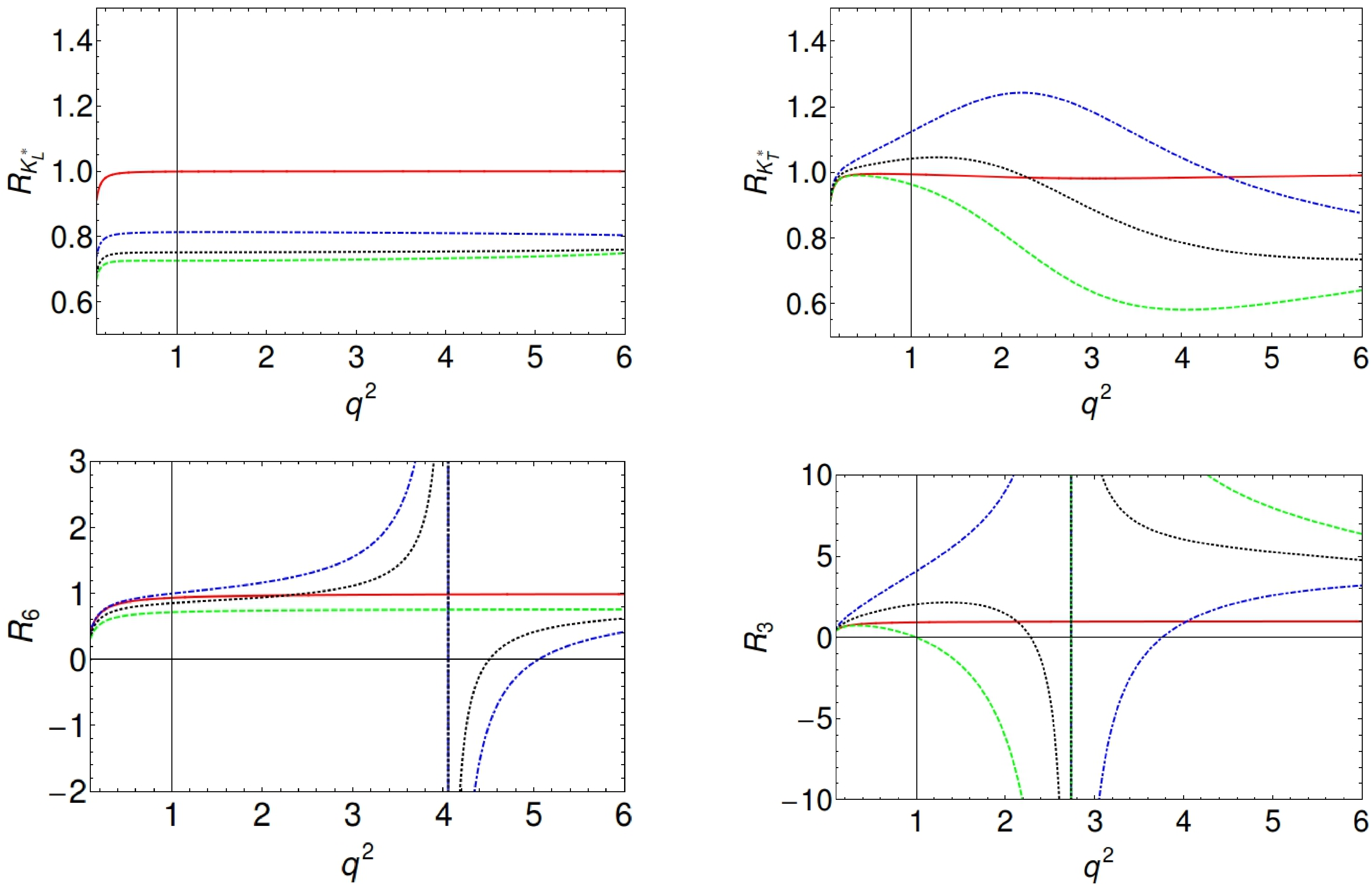
(2) lepton-flavour-dependence of position of zero-crossings

$$\Delta_0^i \equiv (q_0^2)_{I_i}^{(\mu)} - (q_0^2)_{I_i}^{(e)}$$

SJ, Martin Camalich 1412.3183

What would a signal look like?

SJ, Martin Camalich
1412.3183



Any observed deviation from one (R_i) or zero (Δ_0^i) would be a clear BSM signal

Different BSM explanations of the R_K discriminated

Conclusions

B->K*mu mu (and related decays) provide a very rich probe of BSM effects, with many different observables of varying theoretical cleanness

The pattern observed in the B->K* angular analysis (and to some degree) has been taken as evidence for a BSM contribution to C_9 by several groups.

In my view this is a premature conclusion - while a global fit may show a significant deviation, the bin-by-bin analysis of the most interesting observables shows no significant discrepancy, even with rather aggressive estimates of power corrections. Global analysis important.

Two angular observables provide an excellent sensitivity to right-handed new physics (particular right-handed dipoles C_7'). No deviation (yet).

A hint for lepton universality violation could be explained by various BSM models. New ratios of angular coefficients and shifts in zero-crossings can both confirm the effect and identify its origin.

THANK YOU

BACKUP

B→K*l l: angular distribution

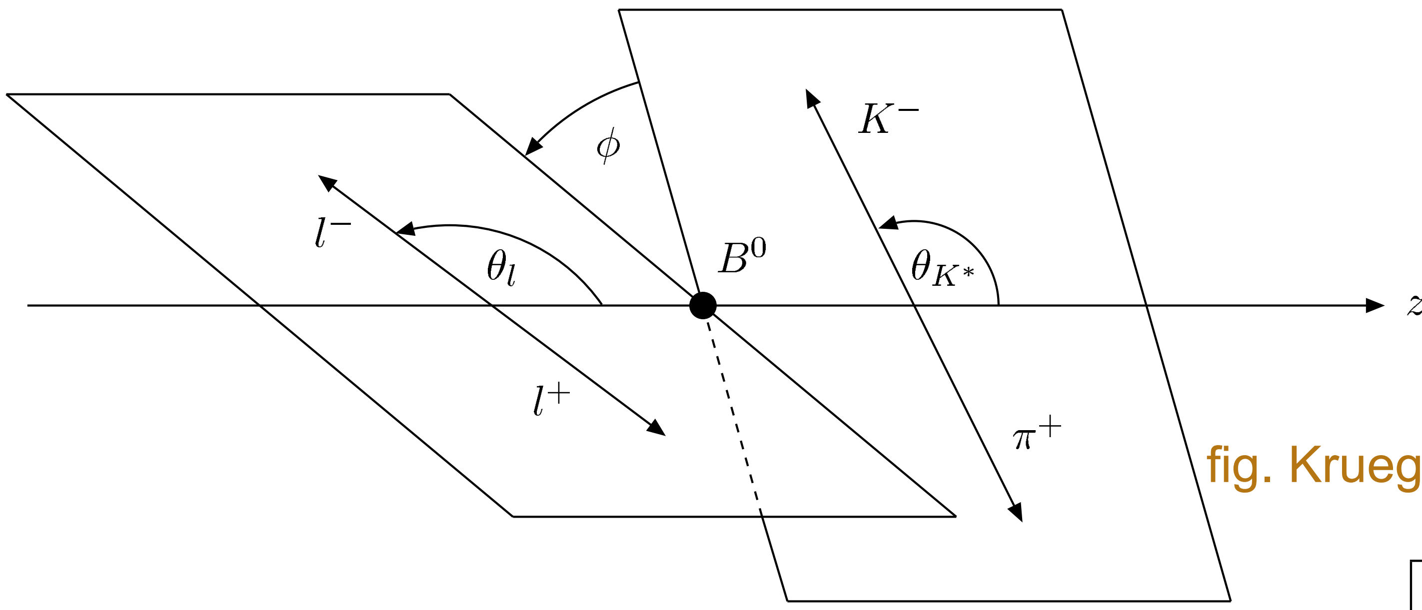


fig. Krueger, Matias 2002

θ_K in K* rest frame

θ_l in dilepton cm frame

ϕ boost-invariant (w.r.t. z axis)

Expt.	~# events
CDF	100 PRL106(2011)161801
BaBar	150 PRD86(2012)032012
Belle	200 PRL103(2009)171801
CMS	400 PLB727(2013)77
ATLAS	500 arXiv:1310.4213
LHCb (μ)	1000 (1 fb^{-1}) JHEP 1308 (2013) 131
LHCb (e)	128 ([0.0004, 1] GeV^2) M Borsato (LHCb)

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

$$\times \Big(I_1^s \sin^2\theta_k + I_1^c \cos^2\theta_k + (I_2^s \sin^2\theta_k + I_2^c \cos^2\theta_k)\cos 2\theta_l$$

$$+ I_3 \sin^2\theta_k \sin^2\theta_l \cos 2\phi + I_4 \sin 2\theta_k \sin 2\theta_l \cos\phi$$

$$+ I_5 \sin 2\theta_k \sin\theta_l \cos\phi + (I_6^s \sin^2\theta_k + I_6^c \cos^2\theta_K)\cos\theta_l$$

$$+ I_7 \sin 2\theta_k \sin\theta_l \sin\phi + I_8 \sin 2\theta_k \sin 2\theta_l \sin\phi + I_9 \sin^2\theta_k \sin^2\theta_l \sin 2\phi \Big)$$

Each angular coefficient is a function of **Wilson coefficients** incorporating the weak interactions and any BSM effects, and of the dilepton invariant mass q^2

This can be used to probe for new physics in various bins

Form factors

Helicity amplitudes naturally involve helicity form factors

$$-\, i m_B \tilde{V}_{L(R)\lambda}(q^2) = \langle M(\lambda)|\bar{s}\not{\epsilon}^*(\lambda) P_{L(R)} b|\bar{B}\rangle,$$
$$m_B^2 \tilde{T}_{L(R)\lambda}(q^2) = \epsilon^{*\mu}(\lambda) q^\nu \langle M(\lambda)|\bar{s}\sigma_{\mu\nu} P_{R(L)} b|\bar{B}\rangle$$
$$i m_B \tilde{S}_{L(R)}(q^2) = \langle M(\lambda=0)|\bar{s} P_{R(L)} b|\bar{B}\rangle.$$

~ Bharucha et al 2010

(& rescale helicity-0 form factors by kinematic factor.)
Can be expressed in terms of traditional "transversity" FFs

$$V_\pm(q^2) = \frac{1}{2}\left[\left(1+\frac{m_V}{m_B}\right) A_1(q^2) \mp \frac{\lambda^{1/2}}{m_B(m_B+m_V)} V(q^2)\right],$$
$$V_0(q^2) = \frac{1}{2 m_V \lambda^{1/2}(m_B+m_V)} \left[(m_B+m_V)^2(m_B^2-q^2-m_V^2) A_1(q^2) - \lambda A_2(q^2)\right]$$
$$T_\pm(q^2) = \frac{m_B^2-m_V^2}{2m_B^2} T_2(q^2) \mp \frac{\lambda^{1/2}}{2m_B^2} T_1(q^2),$$
$$T_0(q^2) = \frac{m_B}{2\, m_V \lambda^{1/2}}\left[(m_B^2+3m_V^2-q^2) T_2(q^2) - \frac{\lambda}{(m_B^2-m_V^2)} T_3(q^2)\right],$$
$$S(q^2) = A_0(q^2),$$

The form factors satisfy two exact relations:

$$T_+(q^2=0) = 0,$$
$$S(q^2=0) = V_0(0)$$

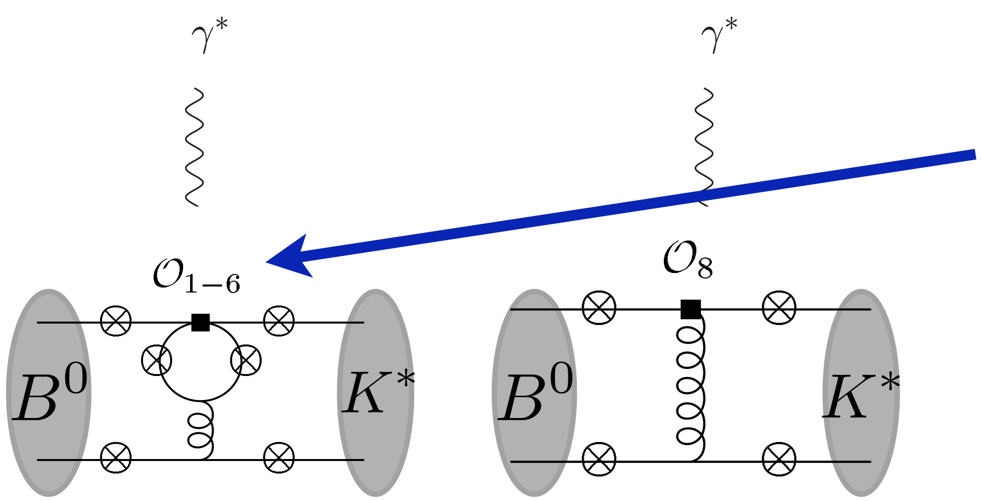
note - M can be multiparticle state. Eg for a two-pseudoscalar state

$$\tilde{V}_{L\lambda} = -\eta(-1)^L \tilde{V}_{R,-\lambda} \equiv \tilde{V}_\lambda,$$
$$\tilde{T}_{L\lambda} = -\eta(-1)^L \tilde{T}_{R,-\lambda} \equiv \tilde{T}_\lambda,$$
$$\tilde{S}_L = -\eta(-1)^L \tilde{S}_R \equiv \tilde{S},$$

L = angular momentum
η = intrinsic parity
+ invariant mass dependence

SJ, J Martin Camalich 2012

Nonlocal terms: power corrections



includes Q_1^c , Q_2^c - large Wilson coefficients

+ "vertex corrections" + annihilation

Beneke, Feldmann, Seidel 2001

subleading power: breakdown of factorisation. Schematically for Q_1^c, Q_2^c :

$$r_\lambda^c = \int_{\Lambda_h}^1 du \phi_K^*(u) T(u, \alpha_s) + r_{\lambda,\text{soft}}^c$$

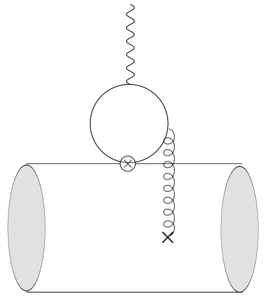
1) power corrections from: (i) higher-twist 2-particle LCDA; (ii) multi-particle LCDA, and from soft endpoint region (iii)

2) some endpoint-divergent contributions from hard-collinear gluon exchanges;

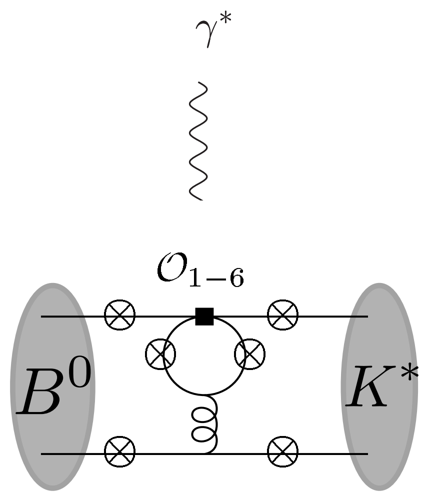
Kagan&Neubert 2001, Feldmann&Matias 2002

3) need to allow for "soft" remainder even if endpoint convergent: means only that endpoint region is power suppressed relative to "bulk" region!

4) In endpoint region hard-collinear gluon becomes soft



Long-distance "charm loop"

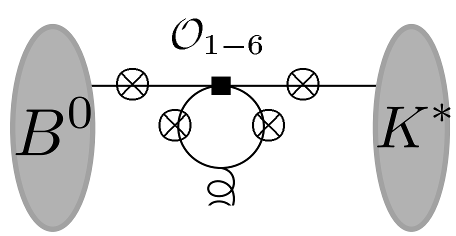


$$r^c_\lambda = \int_{\Lambda_h}^1 du \phi^*_K(u) T(u, \alpha_s) + r^c_{\lambda,\text{soft}}$$

Q_1^c, Q_2^c insertions with hard-collinear gluon(s):

cannot generate λ=+ (left-handed strange quark) with two-particle LCDA

multi-particle LCDA contributions suppressed by extra α_s



Q_1^c, Q_2^c insertions with soft gluon: can still integrate out charm, but not the gluons   Grinstein, Grossmann, Ligeti, Pirjol 2004

for single soft gluon the two gluon attachments to the charm line give

$$r^c_{\lambda,\text{soft}} = \epsilon^{\mu *}(\lambda) \langle M(k,\lambda) | \tilde{\mathcal{O}}_\mu | \bar{B} \rangle$$

where the light-cone operator (in notation of Khodjamirian, Mannel, Pivovarov, Wang 2010)

$$\tilde{\mathcal{O}}_\mu = \int d\omega I_{\mu\rho\alpha\beta}(q,\omega) \bar{s}_L \gamma^\rho \delta\Big(\omega - \frac{in_+ \cdot D}{2}\Big) \tilde{G}^{\alpha\beta} b_L$$

(corresponds to the two photon attachments to the charm loop, treating $\Lambda^2/(4\, m_c^2) \sim \Lambda/m_b$)

matrix element power counting: $\Lambda^2/(4\, m_c^2) \sim \Lambda/m_b$ per soft gluon   Khodjamirian et al 2010

power suppression as expected from heavy-quark power counting!
no double counting! - but 4 more photon attachments

Helicity hierarchies survive!

- LCSR helicity amplitudes

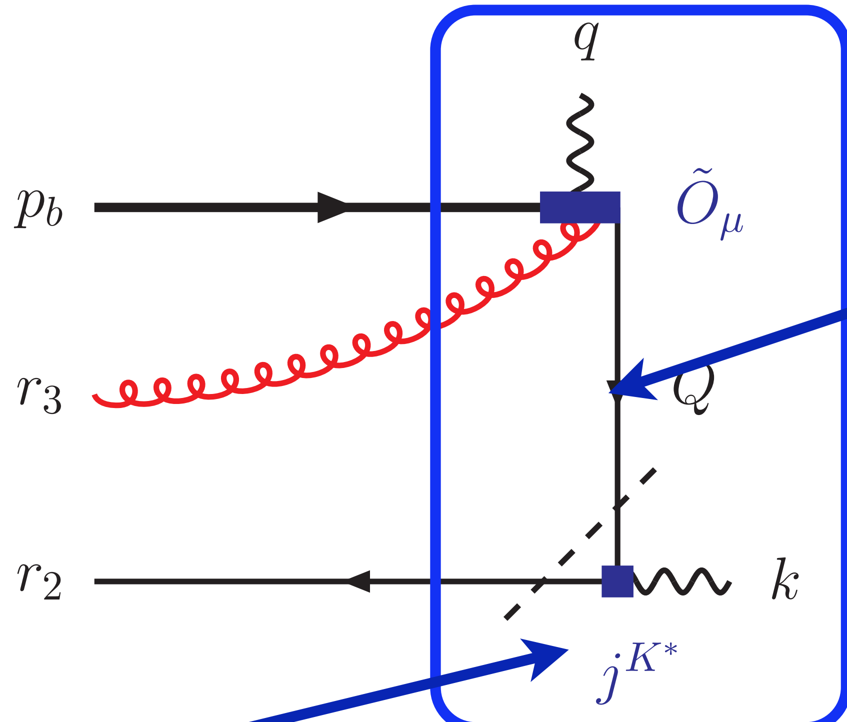
SJ, Martin Camalich 2012
(also for helicity-+ form factors!)

$$G_{h\lambda}(q^2;k^2) = -i\int d^4y e^{iky}\langle 0|T\{\epsilon^{\nu *}(\hat{z};\lambda) j_\nu^{K^*}(y)\epsilon^{\mu *}(-\hat{z};\lambda)\tilde{O}_\mu(0)\}|B\rangle$$

This has a hadronic representation containing the desired matrix elements

$$G_{h\lambda}(q^2;k^2) = \frac{f_{K^*\|}\, m_{K^*}}{m_{K^*}^2 - k^2}\langle K^*(\tilde{k};\lambda)|\epsilon^{\mu *}(-\hat{z};\lambda)\tilde{O}_\mu(0)|B\rangle \; + \text{continuum contributions.}$$

based on Khodjamirian et al 2010



for $k^2 \sim -1$ GeV^2
this line is hard-collinear
(numerically only - no heavy-quark expansion!)

integrate out
(standard
LCSR step)

operator defining 3-particle
B-meson LCDA

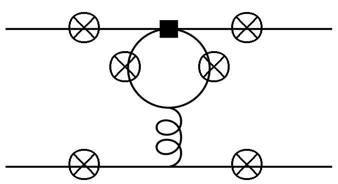
key: project out helicities
through interpolating current

vanishes for + helicity, up to higher power of Λ/m_b

SJ, Martin Camalich 2012

(

1) further photon attachments:



attachments to b or s quark quite local operator; simpler argument; again helicity hierarchy

attachments to spectator lines should give nonlocal operator product of [s G b] operator and light-quark part of em current.
However as photon always hard, soft-gluon exchange appears kinematically impossible (more detailed investigation desirable)

2) earlier estimates of **long-distance** effecs in $h_\lambda(0)$

SCET-based Grinstein, Grossman, Ligeti, Pirjol 2004

identify $SCET_I$ operator ~ $\tilde{O}_\mu$
only power counting estimate of matrix element, misses helicity hierarchy (cannot match onto $SCET_{II}$ b/c endpoint divergences)

LCSR-based Ball, Jones, Zwicky 2006 (also Muheim, Xie, Zwicky 2008)

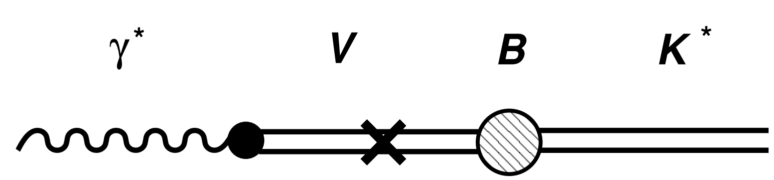
derive sum rule with external K* external (instead of B)
- does not single out the soft (endpoint) configuration
- moreover expand a light-cone operator in local operators; but the neglected higher-dimensional matrix elements scale like $m_B^2/(4\, m_c^2)$: not justified!
(different from somewhat analogous B -> X_s gamma case)

)

Light-quark contributions

Operators without charm have strong charm or CKM suppression; power corrections should be negligible.

However, they generate (mild) resonance structure even below the charm threshold, presumably “duality violation”
Presumably ρ,ω,φ most important; use vector meson dominance supplemented by heavy-quark limit B➔VK* amplitudes



$$\tilde{a}_\mu^{\rm had,\,lq} = \int d^4x\, e^{-iq\cdot x} \sum_{P,P'} \langle 0| j_\mu^{\rm em,lq}(x)|P'\rangle\langle P'(x)|P(0)\rangle\langle \bar{K}^* P|\, \mathcal{H}_{\rm eff}^{\rm had}(0)|\bar{B}\rangle$$

estimate **uncertainty** from difference between VMD model and the subset of heavy-quark limit diagrams corresponding to intermediate V states.

Helicity hierarchies in **hadronic** B decays prevent large uncertainties in H_V^+ from this source, too.