B->K$^{(*)}$ l^+l^- at (very) low q^2 and new physics

Sebastian Jäger
University of Sussex

based on work with J Martin Camalich
arXiv:1212.2263 (JHEP) and to appear

ERC workshop “Effective field theories for collider physics, flavor phenomena and electroweak symmetry breaking
Schloss Waldthausen (Mainz/Budenheim), 12 November 2014

Outline

- $B \to K^* \mu^+ \mu^-$: observables and theoretical anatomy
- power corrections and so-called clean observables
- aim to provide a transparent discussion of theory errors from which some conclusions may follow
- both form-factor power corrections and long-distance effects of the hadronic weak hamiltonian
- Helicity hierarchies survive power corrections: Clean tests of the SM and sensitivity to right-handed dipoles
- Prospects

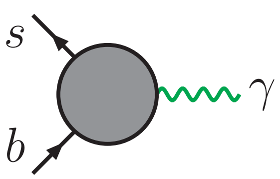
weak ΔB=ΔS=1 Hamiltonian

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

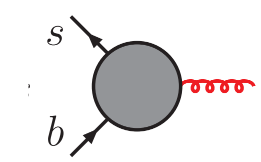
$$\mathcal{H}_{\rm eff}^{\rm had} = \frac{4G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_p \left[C_1 Q_1^p + C_2 Q_2^p + \sum_{i=3\ldots 6} C_i P_i + C_{8g} Q_{8g} \right]$$

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

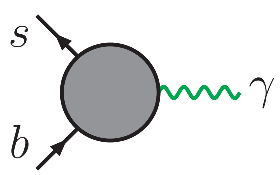
$$\mathcal{H}_{\rm eff}^{\rm sl} = -\frac{4G_F}{\sqrt{2}} \lambda_t \Big[C_7 Q_{7\gamma} + C_7' Q_{7\gamma}' + C_9 Q_{9V} + C_9' Q_{9V}' + C_{10} Q_{10A} + C_{10}' Q_{10A}' + C_S Q_S + C_S' Q_S' + C_P Q_P + C_P' Q_P' + C_T Q_T + C_T' Q_T' \Big].$$



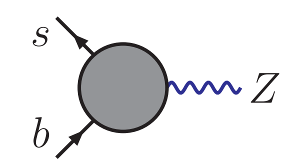
$$\mathcal{O}_7 = \frac{e}{16\pi^2} \hat{m}_b \, \bar{s} \sigma_{\mu\nu} P_R F^{\mu\nu} b \,,$$



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

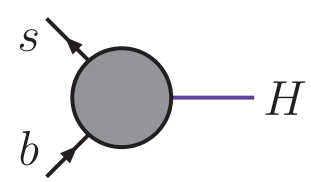


$$\mathcal{O}_V = \frac{\alpha_{\rm em}}{4\pi} (\bar{s} \gamma_\mu P_L b)(\bar{l} \gamma^\mu l) \,,$$



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

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



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

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

+ 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→K*l l: angular distribution

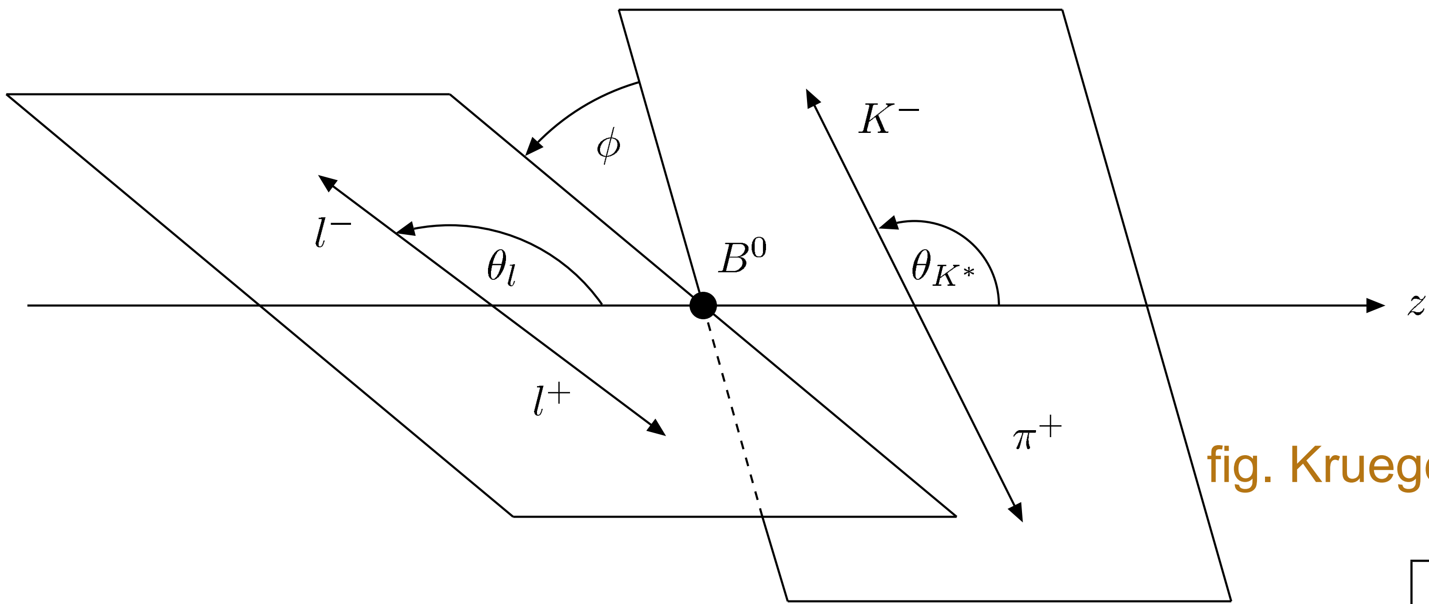


fig. Krueger, Matias 2002

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 the Wilson coefficients and the dilepton invariant mass q^2
and can be used to probe for new physics in various bins

Theoretical expressions for I_i quadratic functions of **helicity amplitudes**

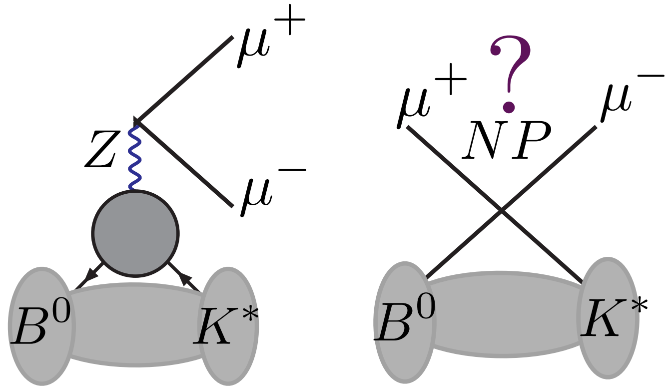
B->K*l^+ l^- helicity amplitudes

Two mechanisms to produce dilepton in & beyond SM

B->K*l+ l-   helicity amplitudes

Two mechanisms to produce dilepton in & beyond SM

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



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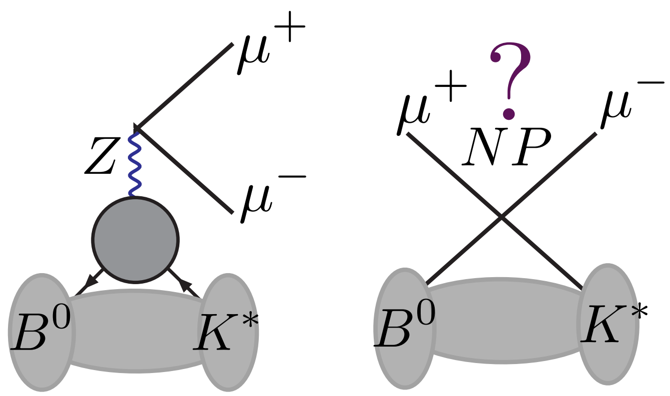

$$H_A(\lambda) \propto \tilde{V}_\lambda(q^2)C_{10} - V_{-\lambda}(q^2)C'_{10}$$

B->K*l+ l-   helicity amplitudes

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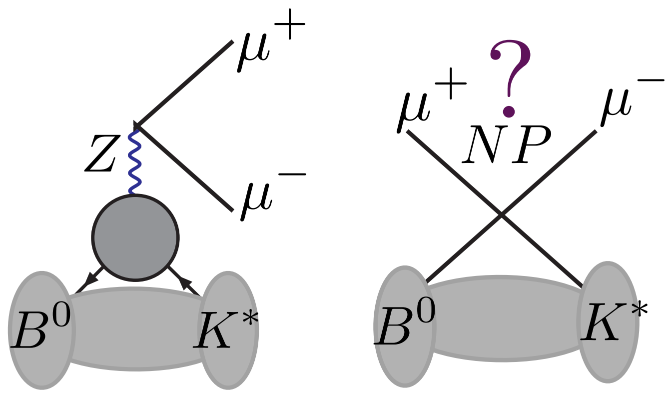

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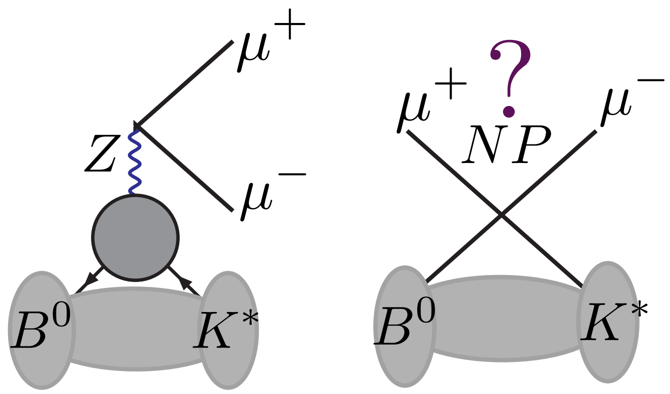

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form factor (nonperturbative)

amplitudes factorize naively

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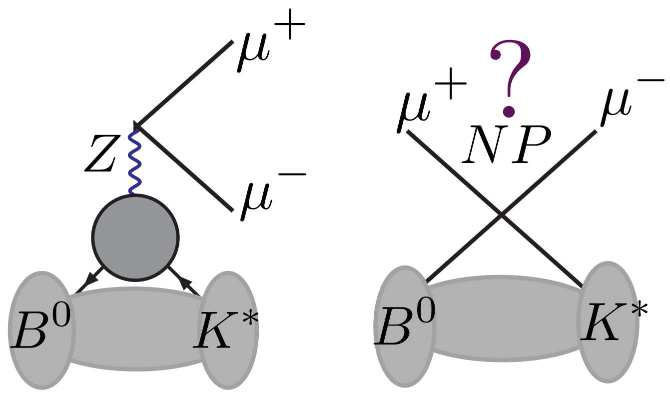

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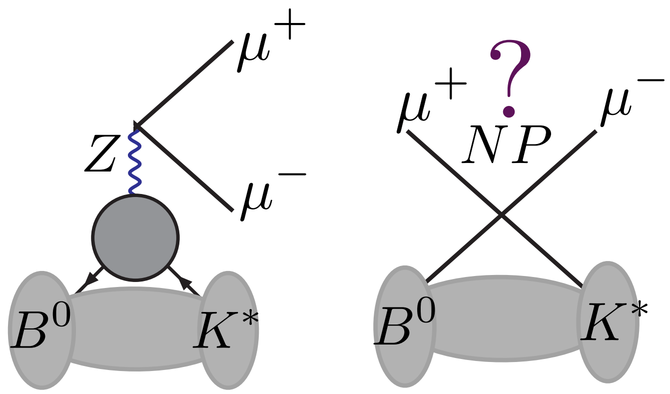

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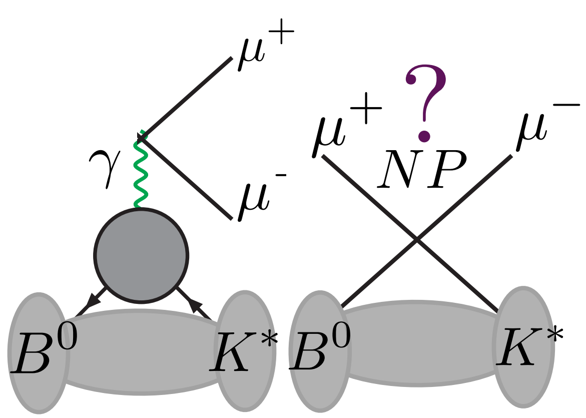

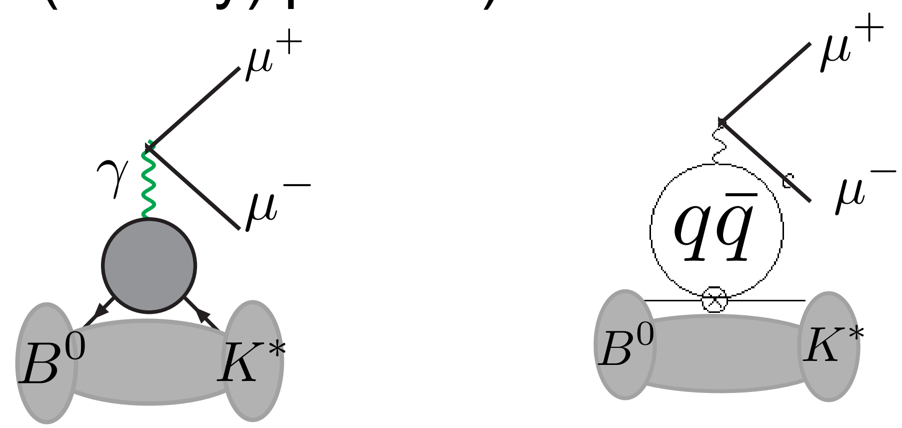

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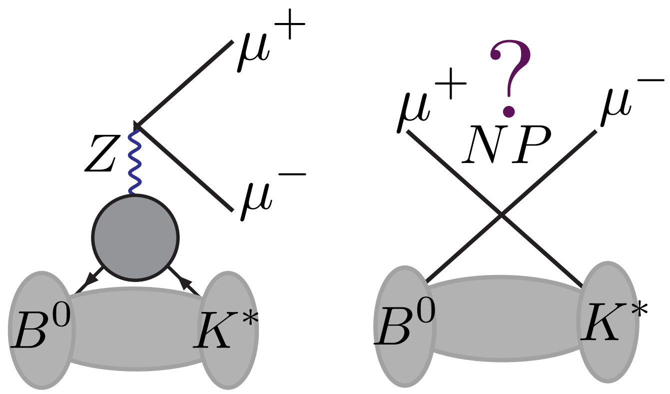

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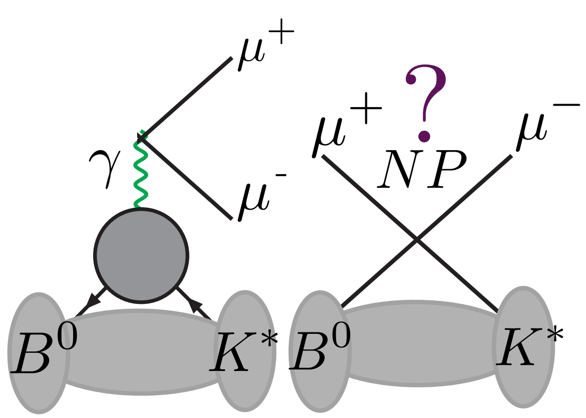

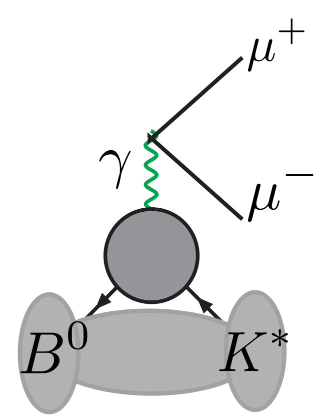

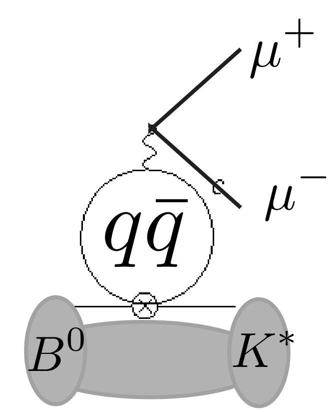

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photon pole at $q^2=0$

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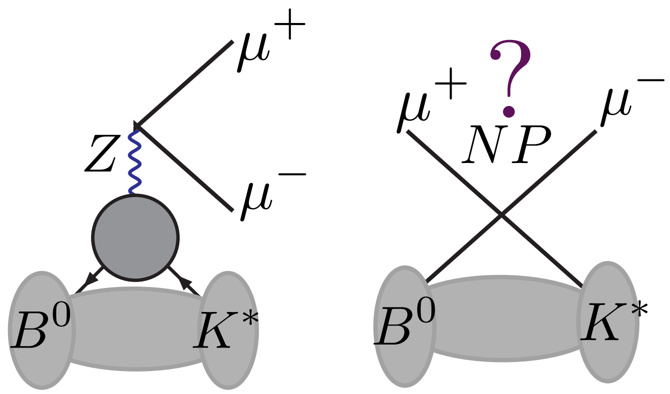

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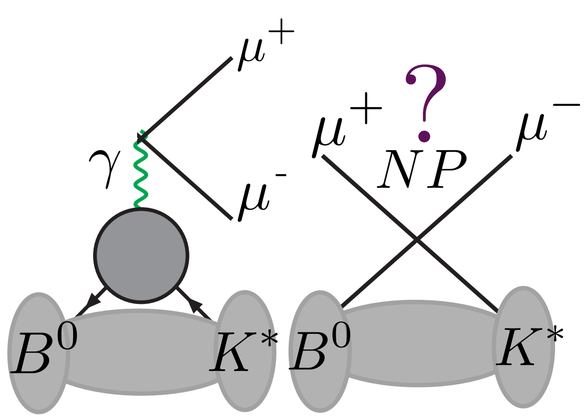

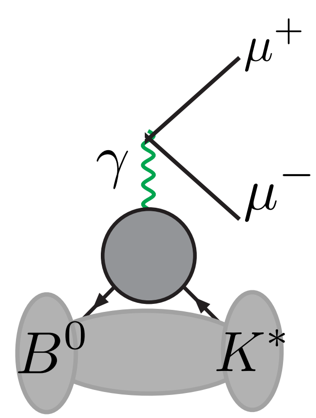

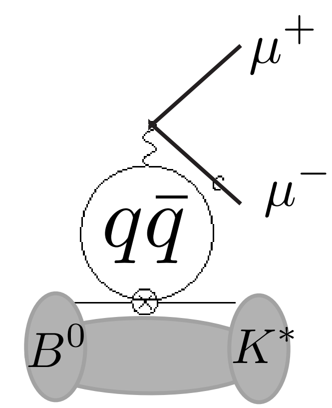

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photon pole at $q^2=0$

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

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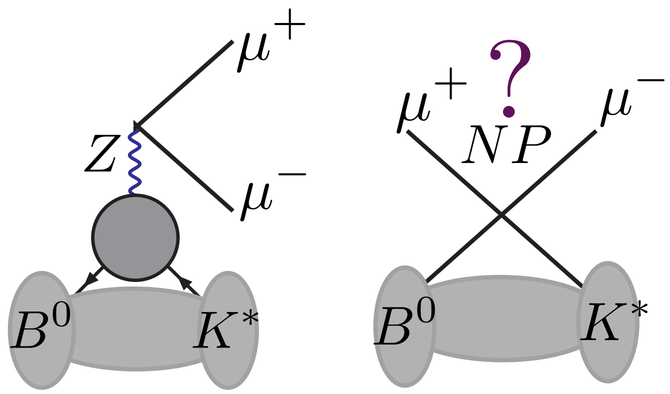

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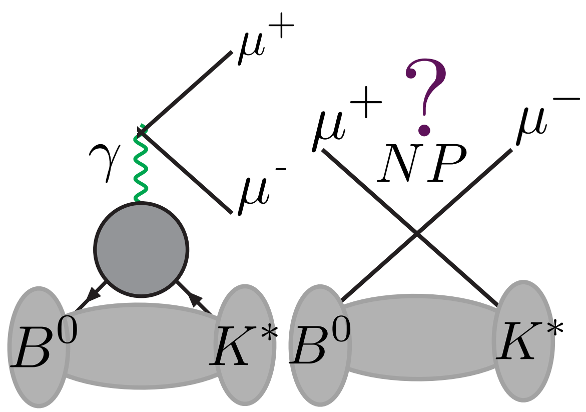

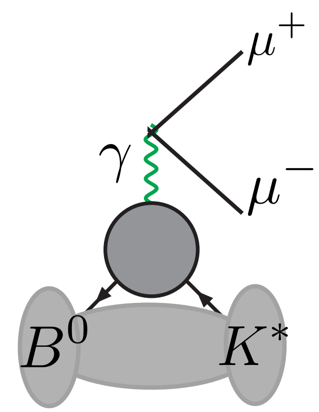

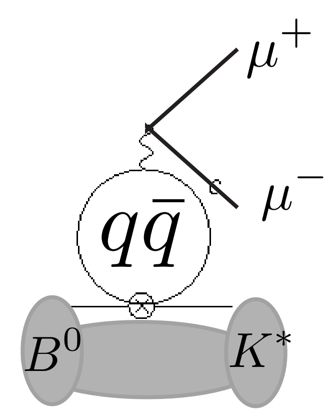

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photon pole at q^2=0

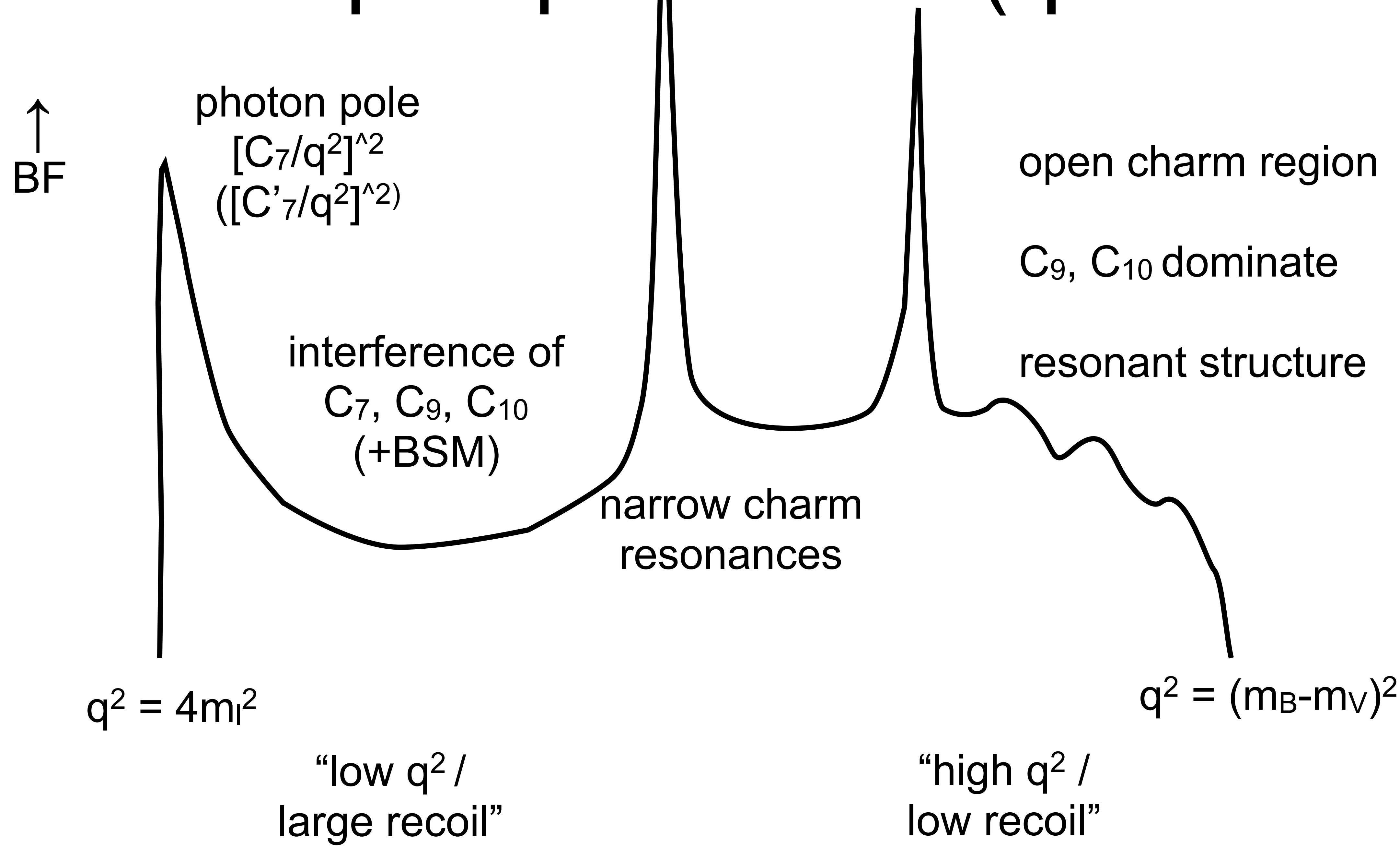
nonlocal “quark loops”
do **not** factorize naively

only corrections:

- higher orders in electromagnetism
- finite-width effects (would need dealing with K pi final state)

no tensor or scalar operators if M_{NP} >> M_Z Alonso, Grinstein, Martin Camalich 2014

Rate: q^2 dependence (qualitative)



Note - artist’s impression only.
LHCb has not yet published sufficiently fine binning to show the resonant features
[open charm resonances are however visible in published B->K l l data]

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 et al 2010

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

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

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

Heavy-quark limit and corrections

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

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

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)

$V_+^\infty(0) = 0$ $\quad T_+^\infty(0)=0$

$V_-^\infty(0) = T_-^\infty(0)$

$V_0^\infty(0) = T_0^\infty(0)$

from heavy-quark/ large energy symmetry

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

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

hence

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

[SJ @ LHCb 2013, Aspen 2014, ...]

- **"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)

“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
destructive interference 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}

LHCb anomaly

- PRL **111,** 191801 (2013) PHYSICAL REVIEW LETTERS week ending 8 NOVEMBER 2013

Measurement of Form-Factor-Independent Observables in the Decay $B^0 \to K^{*0}\mu^+\mu^-$

R. Aaij *et al.**
(LHCb Collaboration)
(Received 9 August 2013; published 4 November 2013)

We present a measurement of form-factor-independent angular observables in the decay $B^0 \to K^*(892)^0\mu^+\mu^-$. The analysis is based on a data sample corresponding to an integrated luminosity of 1.0 fb^{-1}, collected by the LHCb experiment in pp collisions at a center-of-mass energy of 7 TeV. Four observables are measured in six bins of the dimuon invariant mass squared q^2 in the range $0.1 < q^2 < 19.0\ \text{GeV}^2/c^4$. Agreement with recent theoretical predictions of the standard model is found for 23 of the 24 measurements. A local discrepancy, corresponding to 3.7 Gaussian standard deviations is observed in one q^2 bin for one of the observables. Considering the 24 measurements as independent, the probability to observe such a discrepancy, or larger, in one is 0.5%.

DOI: 10.1103/PhysRevLett.111.191801 PACS numbers: 13.20.He, 11.30.Rd, 12.60.−i

Descotes-Genon, Matias, Virto e PRD 88,074002 claim 3.9 *global*

further model-independent fits: Altmannshofer&Straub; Beaujean, Bobeth, van Dyk

interpretation in NP models: Altmannshofer&Straub, Gauld,Goertz,Haisch;
Buras&Girrbach; Buras, DeFazio, Girrbach; ...

LHCb anomaly

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PRL **111,** 191801 (2013) PHYSICAL REVIEW LETTERS week ending 8 NOVEMBER 2013

Measurement of Form-Factor-Independent Observables in the Decay $B^0 \to K^{*0}\mu^+\mu^-$

R. Aaij *et al.**
(LHCb Collaboration)

(Received 9 August 2013; published 4 November 2013)

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BSM physics?

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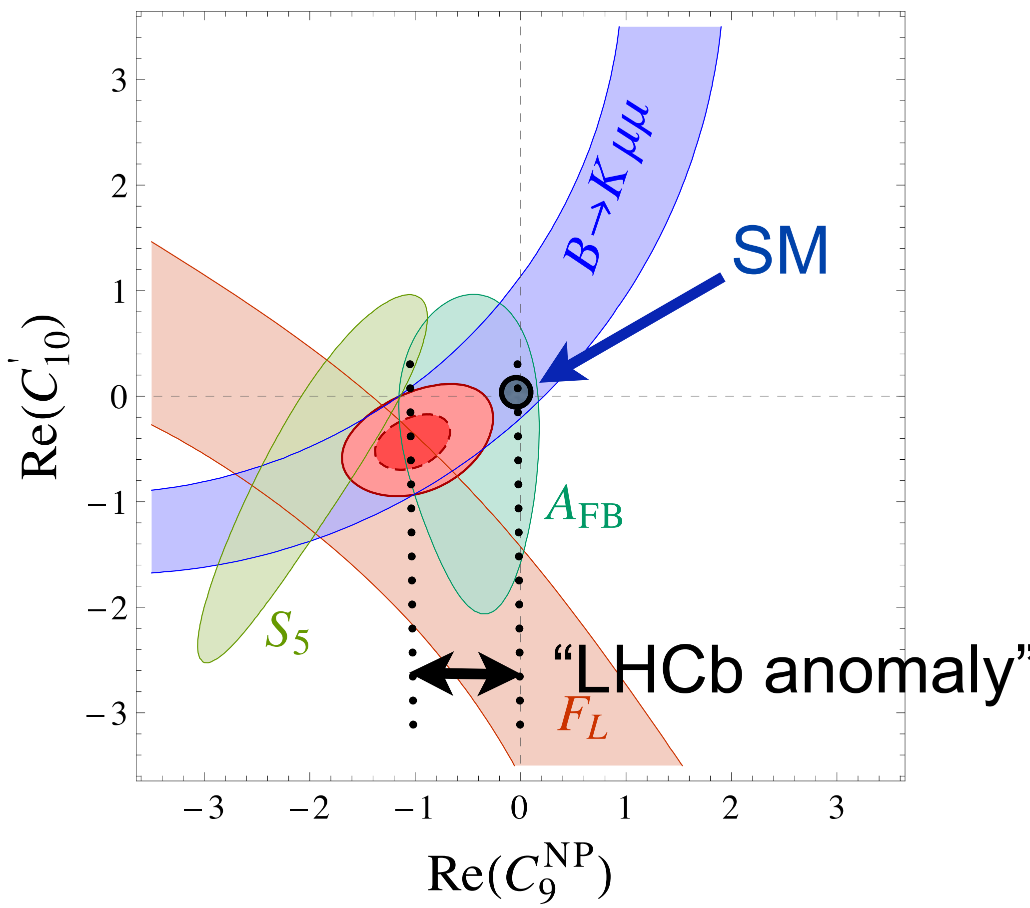
BSM physics?
Or not quite form-factor independent?

BSM interpretation

Global fits to (mostly) B->K* l l angular distribution.



Altmannshofer, Straub 2013

[also Descotes-Genon, Matias, Virto 2013;
Beaujean, Bobeth, van Dyk 2013, ...]

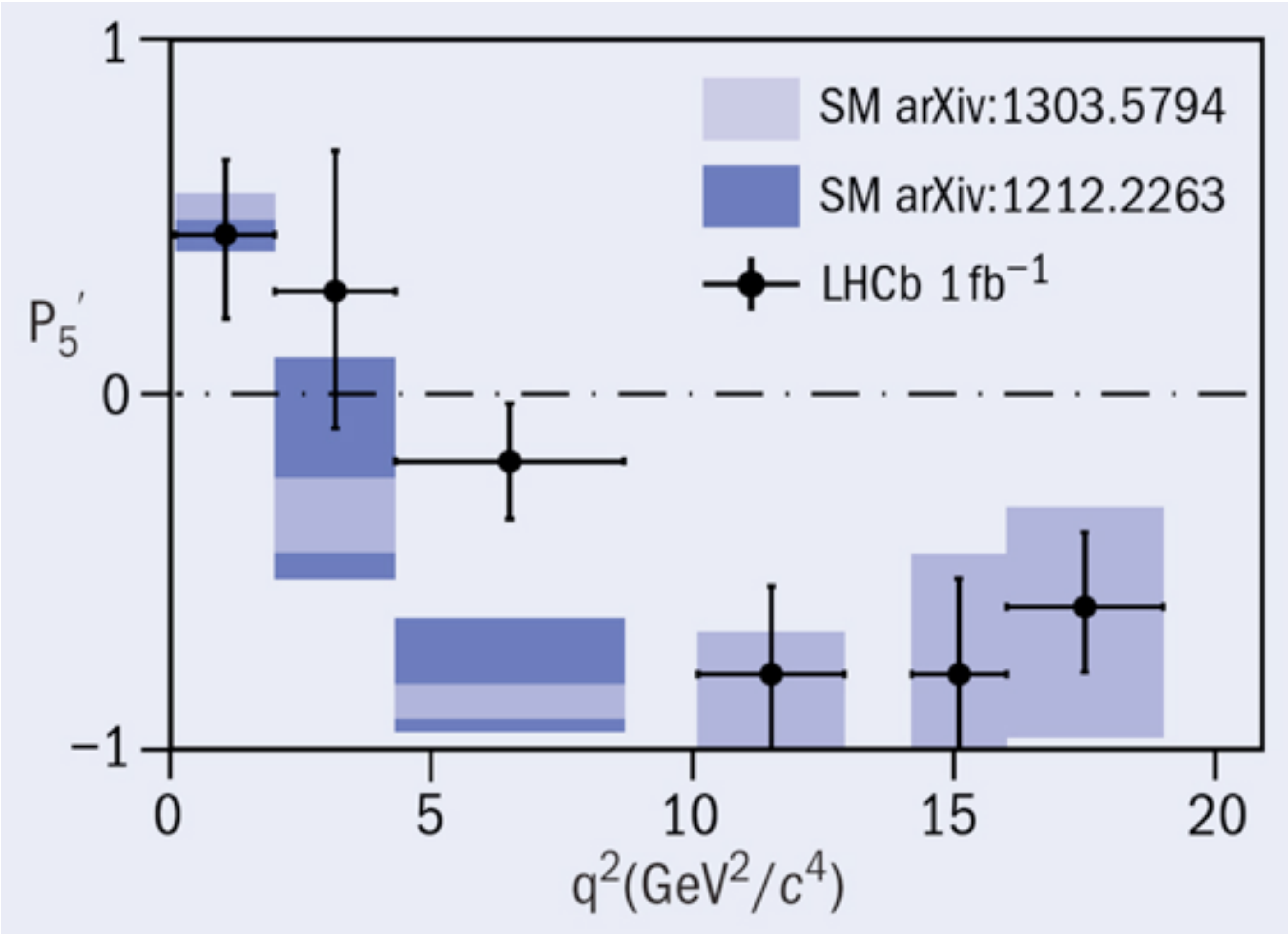
Tension with SM, driven largely but not solely
by a single bin of a single angular coefficient (S_5 ~ P_5')

(Essentially same form factor input as employed in LHCb
significance estimate.)

P_5' "anomaly"

$$\langle P_5' \rangle = \frac{\langle \beta(\mathrm{Re}[(H_V^- - H_V^+)H_A^{0*} + (H_A^- - H_A^+)H_V^{0*})\rangle}{\sqrt{\langle \beta^2|H_V^0|^2 + |H_A^0|^2)\rangle\langle \beta^2(|H_V^+|^2 + |H_V^-|^2 + |H_A^+|^2 + |H_A^-|^2)\rangle}}$$

CERN Courier, December 2013



Descotes-Genon, Matias, Virto [DMV]

SJ, J Martin Camalich (4.3..8.68 bin is actually a private update, not stated in paper)

* Significance of the effect depends strongly on treatment of theory uncertainties!

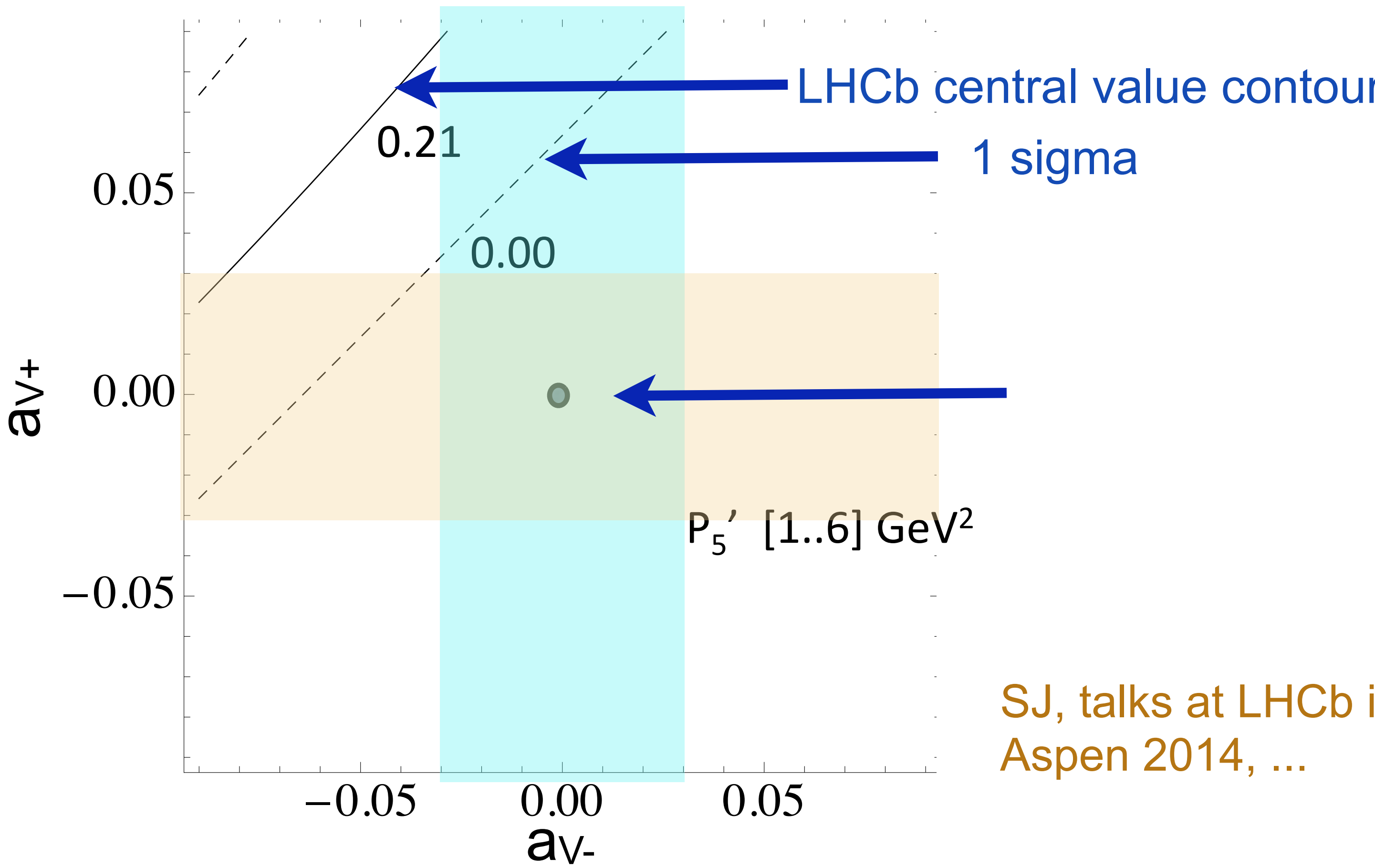
* The most significant effect occurs in a bin extending well above the perturbative charm threshold, outside the range of validity of the theory framework

P_5' power-correction dependence

plot in plane of two form factor power correction parameters

relating to V_+ and V_-, respectively

(there are 10 power-correction parameters to order q^2/m_B^2)



SJ, talks at LHCb implications 10/2013, Aspen 2014, ...

~ +/- 0.03 for either power correction parameter corresponds to a 10% power correction & is sufficient to bring data in agreement with SM theory

Drawing conclusions based on this observable requires **sufficient accuracy on the form factor calculations** (not even considering nonfactorizable effects). DMV and most other phenomenology employs one of two light-cone-sum rule calculations.

This conclusion relies solely on the functional dependence of P_5' and holds **irrespectively** of statistical treatments, assumptions on soft form factors at q^2=0, etc.

Fitting the power-correction parameters?

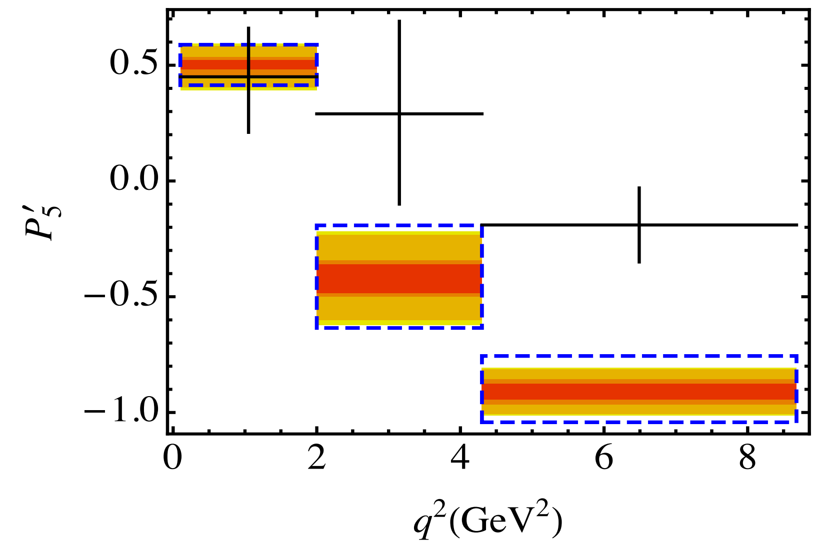
Dedicated analysis employing same power correction model

Descotes-Genon, Hofer, Matias, Virto arXiv:1407.8526

* identify a different set of 2 QCD form factors, claiming this reduces sensitivity of P_5' to power correction parameters

* **fit the power-correction parameters to two different light-cone sum rule calculations**

-> Again obtain small theory uncertainties

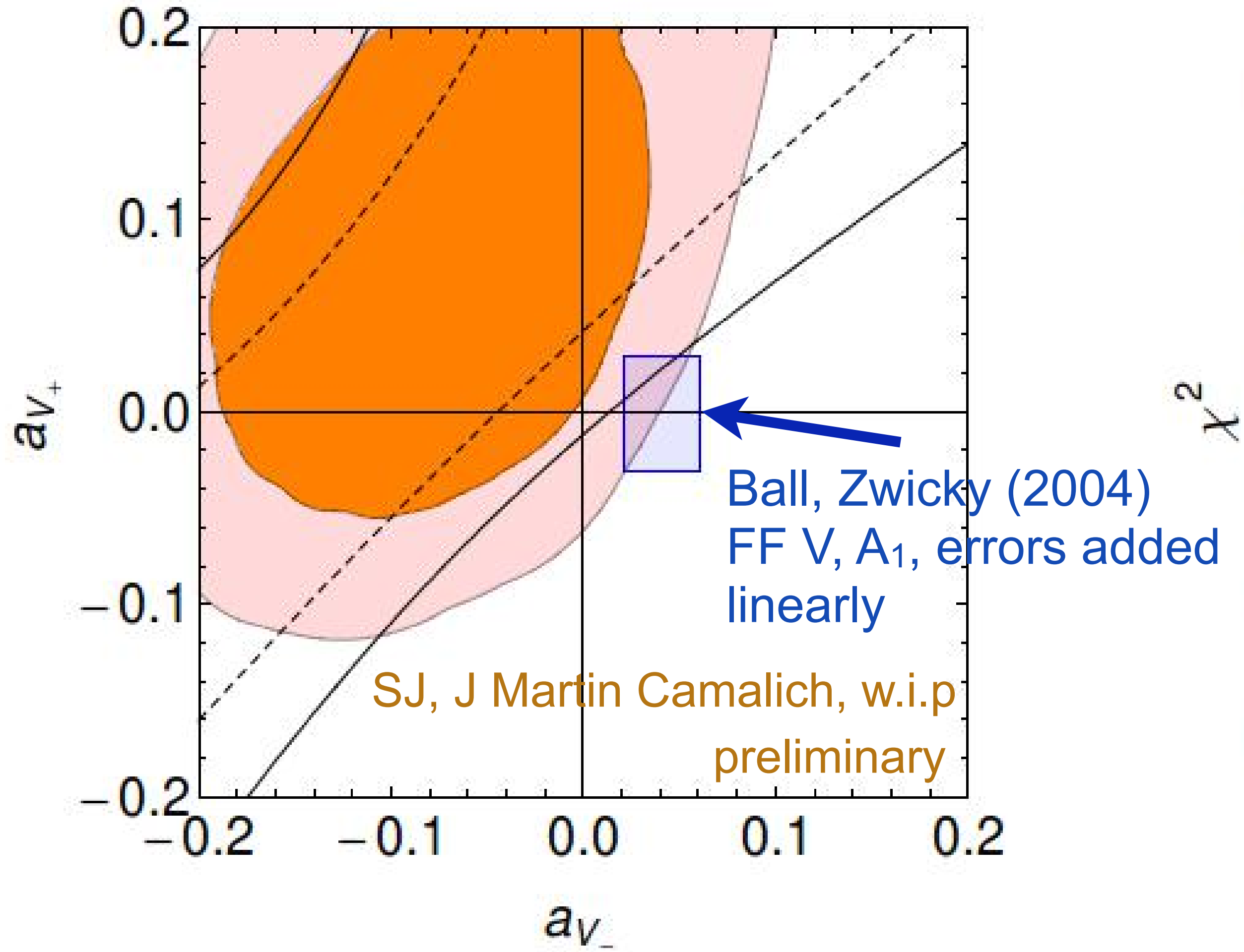


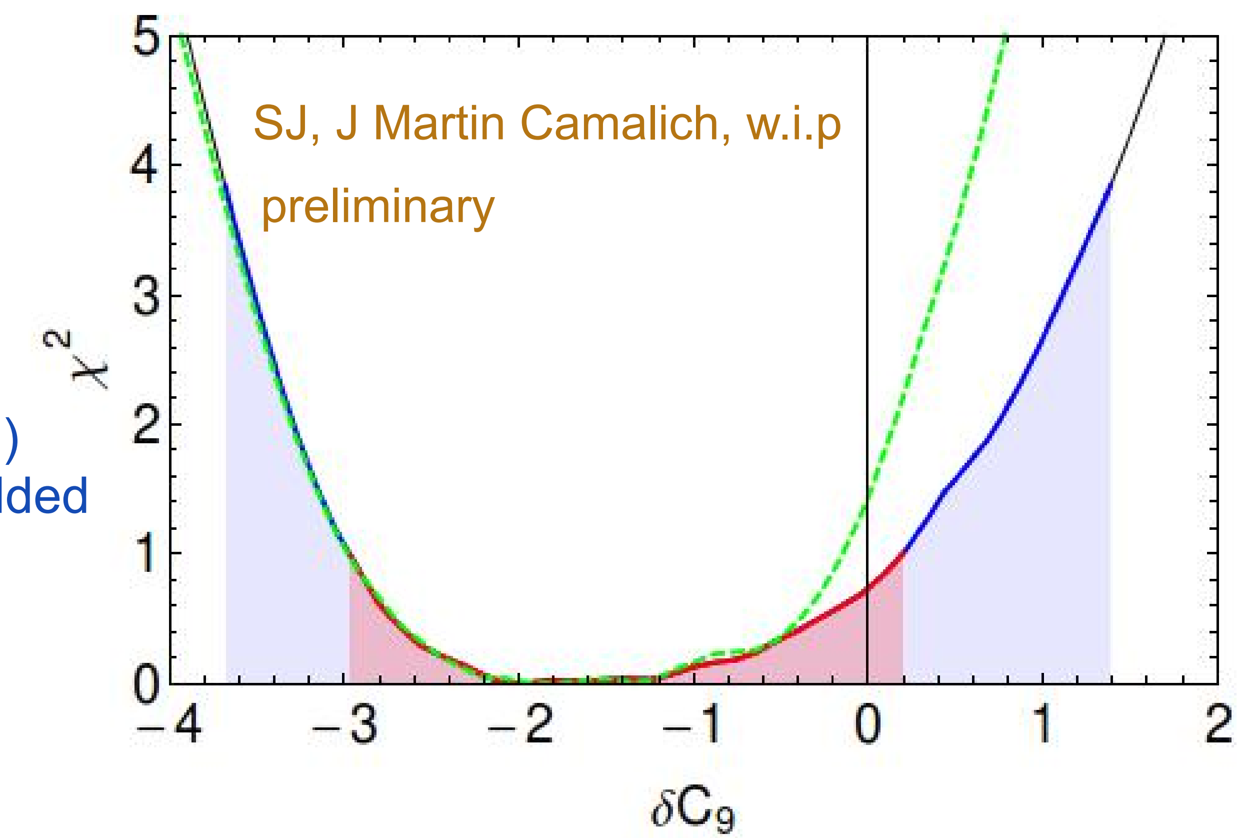
$\langle P_5' \rangle_{[1,6]}$	$-0.412^{+0.042+0.026+0.096+0.014}_{-0.070-0.045-0.089-0.017}$	$-0.416^{+0.039+0.000+0.083+0.014}_{-0.064-0.000-0.086-0.017}$

- Can LCSR be trusted to the required level of <10% accuracy? Parton/hadron duality model, ...

- Reminder: bin in plot extends above pert. charm threshold

Anomaly significance





all angular observables
low-q^2 only [1..6 GeV^2]

all other theory errors profiled

setting either power correction parameter to zero [by soft form factor redefinition] does not seem to help!

all angular observables
low-q^2 only [1..6 GeV^2]

profile likelihood ("Rfit" theory error treatment a la CKMfitter)

significance below 1 sigma

Clean SM Null Tests & RH dipoles

Extending to BSM Wilson coefficients, have

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

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

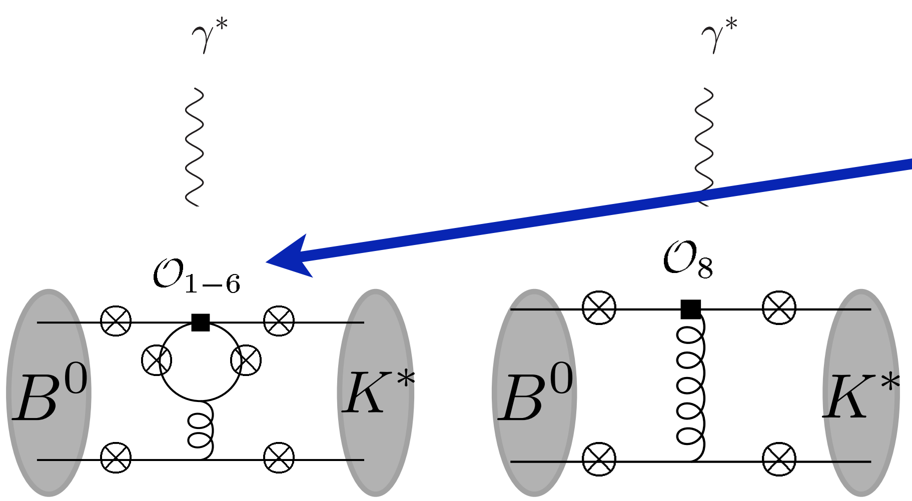
$$P_1 \equiv \frac{I_3 + \bar{I}_3}{2(I_{2s} + \bar{I}_{2s})} = \frac{-2\,\mathrm{Re}(H_V^+ H_V^{-*} + H_A^+ H_A^{-*})}{|H_V^+|^2 + |H_V^-|^2 + |H_A^+|^2 + |H_A^-|^2} \approx 2\frac{\mathrm{Re}(C_7 C_7'^*)}{|C_7|^2 + |C_7'|^2}$$

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

- **double** suppression $T_+(q^2) = \mathcal{O}(q^2/m_B^2) \times \mathcal{O}(\Lambda/m_b)$

- What is the fate of the helicity hierarchy in the nonlocal term?
  Crucial question for sensitivity to C_7'

Nonlocal terms (hadronic hamiltonian)



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

+ "vertex corrections" + annihilation

Beneke, Feldmann, Seidel 2001

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

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

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

α_s^1 : (convergent) convolutions of hard- scattering kernels with meson LCDA

unambigous (save for parametric uncertainties)
state-of-the-art in phenomenology

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

LCSR computation finds effective shifts of transversity amplitudes as large as ~10%

Khodjamirian et al 2010

Digression: relation to B->K*γ

$$\mathcal{A}(\bar{B} \to V(\lambda)\gamma(\lambda)) = \lim_{q^2\to 0} \frac{q^2}{e} H_V(q^2 = 0; \lambda)$$ exact (LSZ)

$$= \frac{iNm_B^2}{e} \left[\frac{2\hat{m}_b}{m_B} (C_7 \tilde{T}_\lambda(0) - C_7' \tilde{T}_{-\lambda})(0) - 16\pi^2 h_\lambda(q^2 = 0) \right]$$

(only λ=+/- 1)

same amplitudes as in B->Kll incuding all long-distance details

$$S_{K^*\gamma} = 2\,\frac{\mathrm{Im}(e^{-i\phi_d} H_V^+(0) H_V^{-*}(0))}{|H_V^+(0)|^2 + |H_V^-(0)|^2} \approx 2\,\frac{\mathrm{Im}(e^{-i\phi_d} C_7 C_7'^*)}{|C_7|^2 + |C_7'|^2}$$

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

~ 10% — Grinstein, Grossman, Ligeti, Pirjol 2004 (SCET)

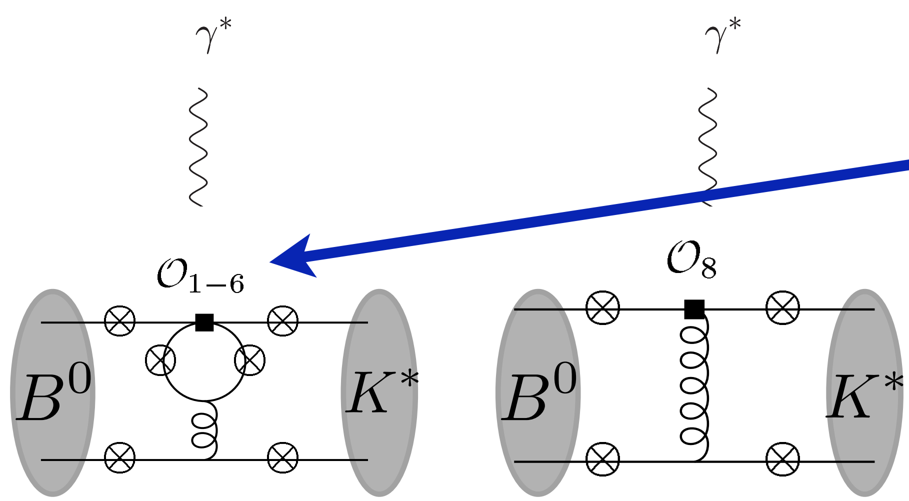
few percent — Ball, Jones, Zwicky 2006 (LCSR)
also Muheim, Xie, Zwicky 2008 (refer to unpub LCSR)

- understand differences

- clarify relation/double counting with heavy-quark limit

- important for fate of clean null tests!

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:

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

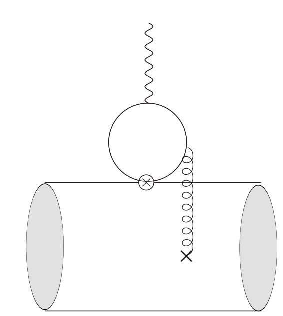
1) power corrections from: (i) higher-twist 2-particle LCDA; (ii) multi-particle LCDA, and from soft endpoint region (iii)

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

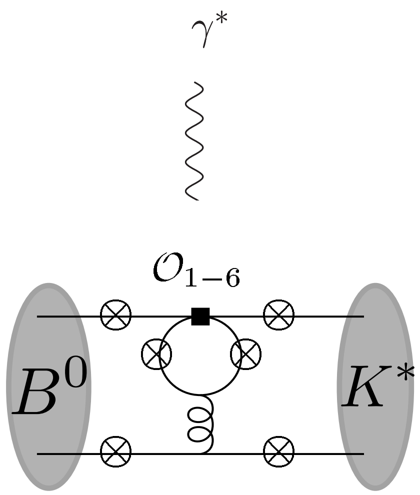
Kagan&Neubert 2001, Feldmann&Matias 2002

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"



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

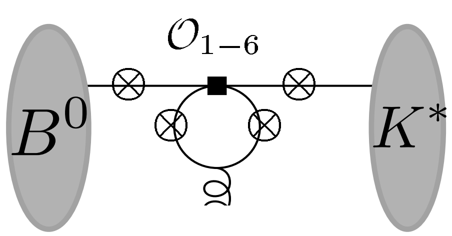
Q_1^c, Q_2^c insertions with hard-collinear gluon(s):

cannot generate soft gluon (in B rest frame)

consider λ=+ (left-handed strange quark) with two-particle LCDA

multi-particle LCDA contributions suppressed by extra α_s

From collinear factorisation viewpoint this represents the endpoint region, which is known to give a power-suppressed contribution



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 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 2010

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

Helicity hierarchies survive!

- LCSR helicity amplitudes

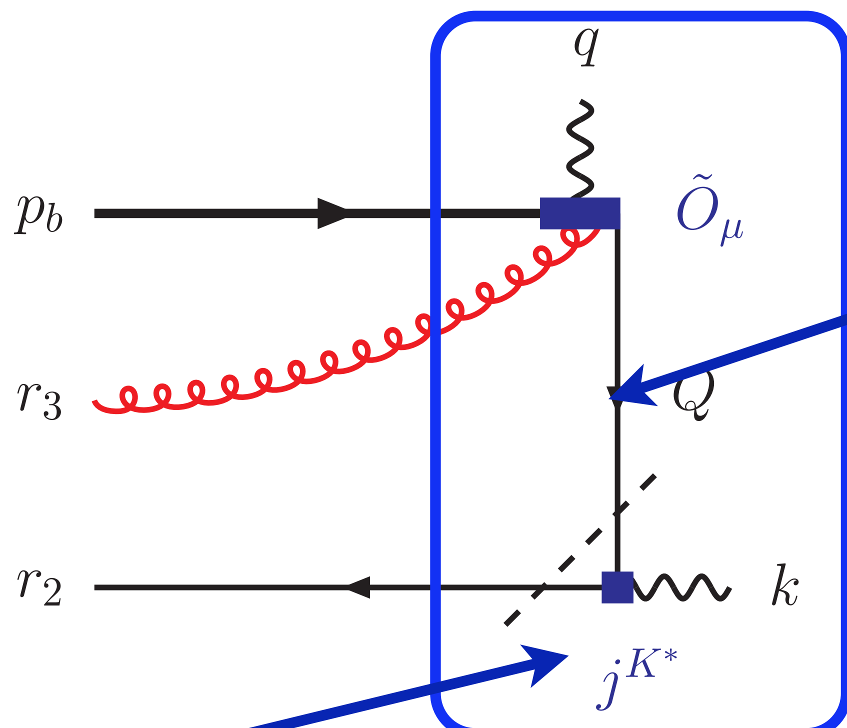
SJ, Martin Camalich 2012
(also for helicity-+ form factors!)

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

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

integrate out
(standard
LCSR step)

key: project out helicities
through interpolating current

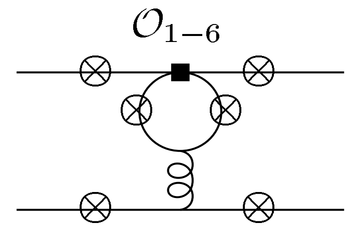
operator defining 3-particle
B-meson LCDA

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!

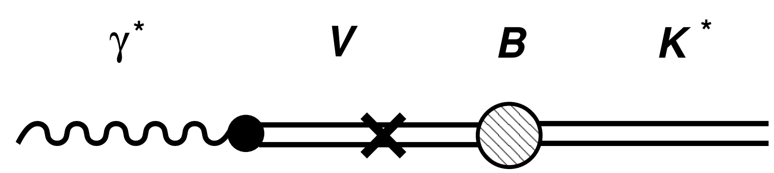
(different from somewhat analogous B -> X_s gamma case)

)

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

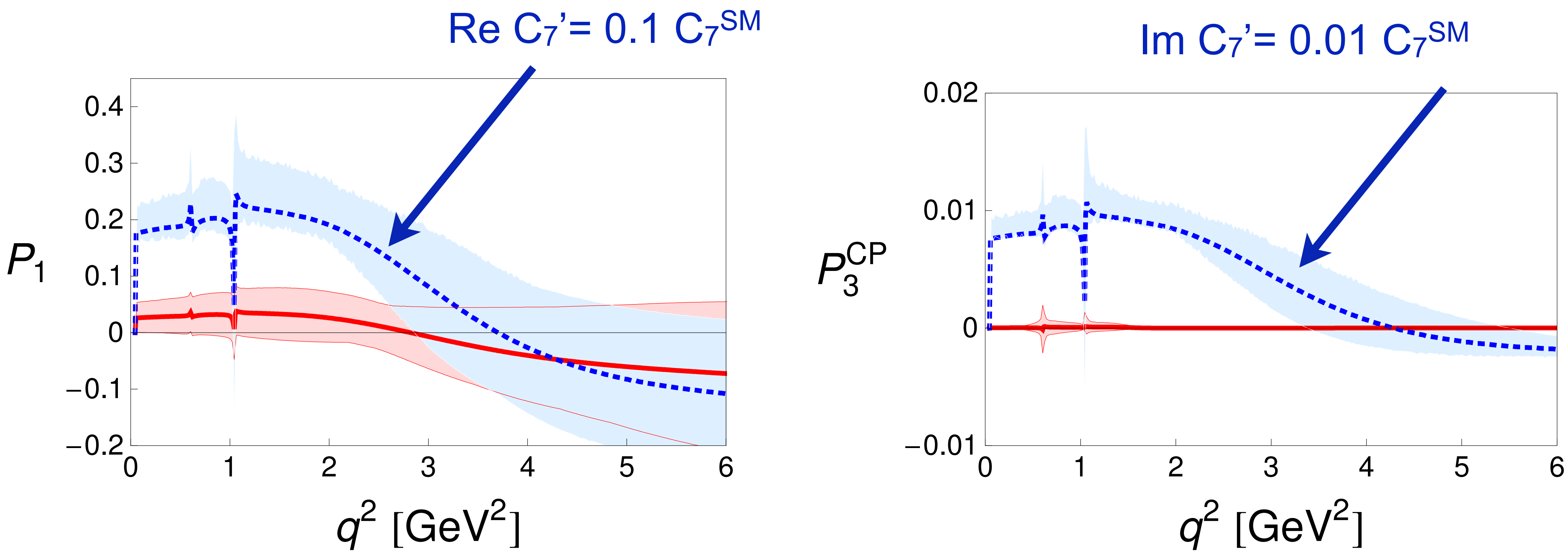


$$\tilde{a}_\mu^{\rm had,\,lq} = \int d^4x\, e^{-iq\cdot x} \sum_{P,P'} \langle 0|j_\mu^{\rm em,lq}(x)|P'\rangle\langle P'(x)|P(0)\rangle\langle \bar{K}^* P|\,\mathcal{H}_{\rm eff}^{\rm had}(0)|\bar{B}\rangle$$

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.

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

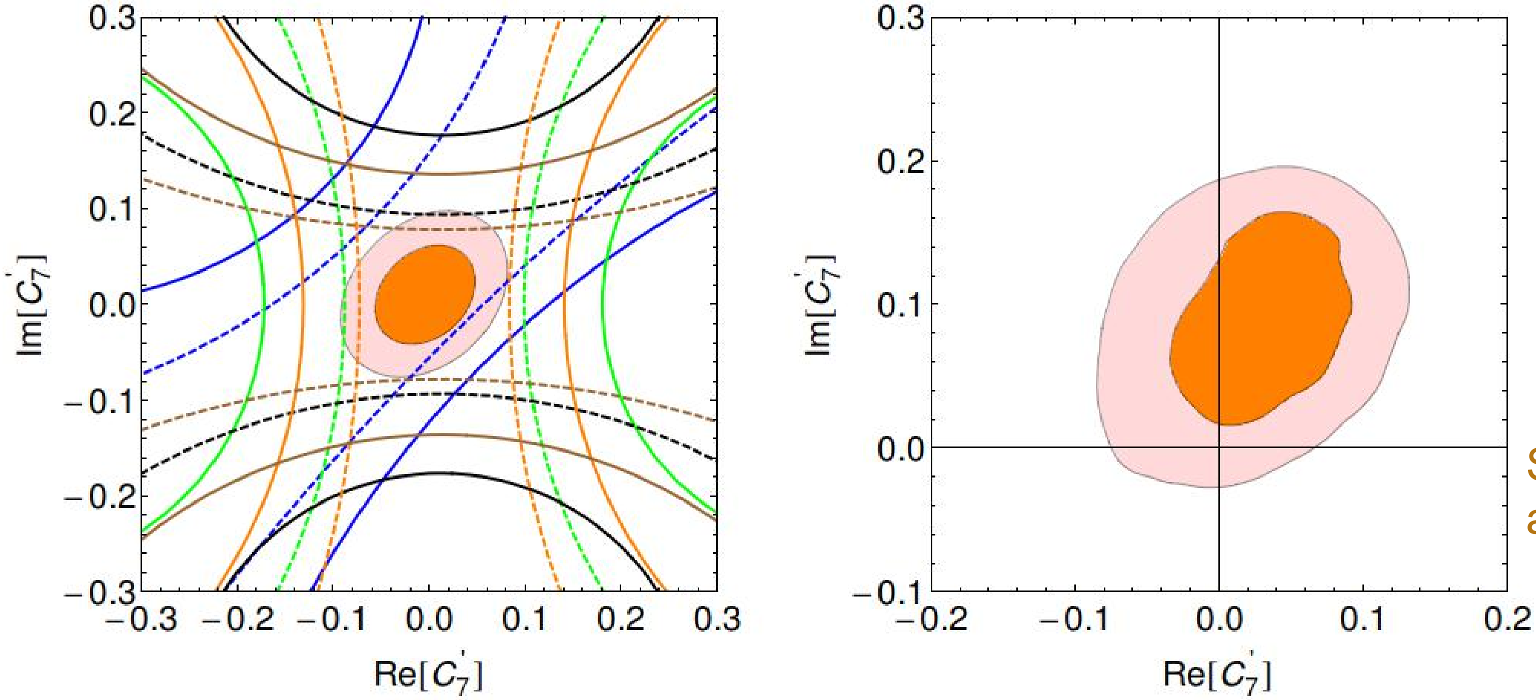
F_L	P_1	P_2	$P_3^{\rm CP}$ $[10^{-4}]$
$0.07^{+0.09}_{-0.04}$	$0.030^{+0.045}_{-0.041}$	$-0.054^{+0.015}_{-0.012}$	$0.1^{+0.7}_{-0.6}$

P_4'	P_5'	P_6'	P_8'
$0.18^{+0.06}_{-0.07}$	$0.52^{+0.10}_{-0.11}$	$0.05^{+0.07}_{-0.06}$	$0.01^{+0.08}_{-0.08}$

SJ, Martin Camalich to appear (preliminary)

- Theoretically even cleaner than muonic mode at very low q^2 as tensor form factor / photon pole dominates more
- Boost in BR: $BR^{e}_{[0.0004,\,1]} = 31^{+15}_{-11}\,10^{-8}$, $\quad BR^{\mu}_{[0.1,\,0.98]} = 9.5^{+5.2}_{-3.5}\,10^{-8}$
- Angular analysis in progress at LHCb
- Belle 2 well positioned to study this mode

Prospects



SJ, Martin Camalich to appear (preliminary)

$$S \simeq \frac{2\mathrm{Im}(e^{-2i\beta} C_7 C_7')}{|C_7|^2 + |C_7'|^2}, \quad P_1 \simeq \frac{2\mathrm{Re}(C_7 C_7')}{|C_7|^2 + |C_7'|^2}, \quad P_3^{\mathrm{CP}} \simeq \frac{2\mathrm{Im}(C_7 C_7')}{|C_7|^2 + |C_7'|^2}$$

- 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

Summary

Rich and growing set of measurements on b->s l l and related FCNC decays

Various anomalies (LHCb anomaly in P_5', but also hints of lepton flavour nonuniversality and in branching fraction data)

No single observable appears to be significant, and long-distance QCD effects may be an explanation. However, a consistent picture may be emerging.

However, helicity hierarchies remain intact for robust treatment of long-distance/power corrections, preserving two null-test observables in $B \to K^* \mu^+ \mu^-$

Precision probes of right-handed dipole transitions (and other coefficients) possible - good LHCb, and presumably Belle 2, prospects

かたじけない

BACKUP

Exclusive decays at the LHC

Experimental landscape dominated by LHCb, for exam[le in semileptonic modes alone:

channel	$\mathcal{L}^{int}$ (fb^{-1})	Publication
$d\mathcal{B}/dq^2$ $B \to K^{*+}\mu^+\mu^-$	3	[1403.8044]
$d\mathcal{B}/dq^2$ $B \to K^0\mu^+\mu^-$	3	[1403.8044]
$d\mathcal{B}/dq^2$ $B \to K^+\mu^+\mu^-$	3	[1403.8044]
$d\mathcal{B}/dq^2$ $B^0 \to K^{*0}\mu^+\mu^-$	1	[JHEP08(2013)131]
$d\mathcal{B}/dq^2$ $B_s^0 \to \phi\mu^+\mu^-$	1	[JHEP07(2013)084]
$d\mathcal{B}/dq^2$ $\Lambda_b \to \Lambda\mu^+\mu^-$	1	[PLB725(2013)25]
$\mathcal{B}$ $B^0 \to K^{*0}e^+e^-$	1	[JHEP05(2013)159]
$\mathcal{B}$ $B^+ \to \pi^+\mu^+\mu^-$	1	[JHEP12(2012)125]
A_I $B \to K^{(*)}\mu^+\mu^-$	3	[1403.8044]
A_{CP} $B^+ \to K^+\mu^+\mu^-$	1	[PRL111,151801(2013)]
A_{CP} $B^0 \to K^{*0}\mu^+\mu^-$	1	[PRL110,031801(2013)]
Angular $B^+ \to K^+\mu^+\mu^-$	3	[JHEP05(2014)082],[PRL111,112003(2013)]
Angular $B^0 \to K^0\mu^+\mu^-$	3	[JHEP05(2014)082]
Angular $B^0 \to K^{*0}\mu^+\mu^-$	1	[JHEP08(2013)131],[PRL111,191801(2013)]
Angular $B_s^0 \to \phi\mu^+\mu^-$	1	[JHEP07(2013)084]

K Petridis (LHCb), b->s workshop, Paris, June 2014

Updates and new analyses expected based on full 3 fb^{-1} data set
5-7 fb^{-1} expected during run II

Some results also from ATLAS, CMS

Angular coefficients

$$
\begin{aligned}
I_1^c &= F\left\{\frac{1}{2}\left(|H_V^0|^2+|H_A^0|^2\right)+4|H_P|^2+\frac{2m_\ell^2}{q^2}\left(|H_V^0|^2-|H_A^0|^2\right)+4\beta^2|H_S|^2\right\},\\
I_1^s &= F\left\{\frac{\beta^2+2}{8}\left(|H_V^+|^2+|H_V^-|^2+(V\to A)\right)+\frac{m_\ell^2}{q^2}\left(|H_V^+|^2+|H_V^-|^2-(V\to A)\right)\right\}\\
I_2^c &= -F\,\frac{\beta^2}{2}\left(|H_V^0|^2+|H_A^0|^2\right),\\
I_2^s &= F\,\frac{\beta^2}{8}\left(|H_V^+|^2+|H_V^-|^2\right)+(V\to A),\\
I_3 &= -\frac{F}{2}\mathrm{Re}\left[H_V^+(H_V^-)^*\right]+(V\to A),\\
I_4 &= F\,\frac{\beta^2}{4}\mathrm{Re}\left[\left(H_V^-+H_V^+\right)\left(H_V^0\right)^*\right]+(V\to A),\\
I_5 &= F\left\{\frac{\beta}{2}\mathrm{Re}\left[\left(H_V^--H_V^+\right)\left(H_A^0\right)^*\right]+(V\leftrightarrow A)-\frac{2\,\beta\,m_\ell}{\sqrt{q^2}}\mathrm{Re}\left[H_S^*(H_V^++H_V^-)\right]\right\}\\
I_6^s &= F\beta\,\mathrm{Re}\left[H_V^-(H_A^-)^*-H_V^+(H_A^+)^*\right],\\
I_6^c &= 8F\frac{\beta\,m_\ell}{\sqrt{q^2}}\mathrm{Re}\left[H_S^*H_V^0\right],\\
I_7 &= F\left\{\frac{\beta}{2}\,\mathrm{Im}\left[\left(H_A^++H_A^-\right)\left(H_V^0\right)^*+(V\leftrightarrow A)\right]-\frac{2\,\beta\,m_\ell}{\sqrt{q^2}}\,\mathrm{Im}\left[H_S^*(H_V^--H_V^+)\right]\right\},\\
I_8 &= F\,\frac{\beta^2}{4}\mathrm{Im}\left[(H_V^--H_V^+)(H_V^0)^*\right]+(V\to A),\\
I_9 &= F\,\frac{\beta^2}{2}\mathrm{Im}\left[H_V^+(H_V^-)^*\right]+(V\to A),
\end{aligned}
$$

strongly suppressed in SM
good sensitivity to NP with
different chirality structure
(“right-handed currents”)

suppression of I_3,I_9 due to
suppression of +-amplitudes
must quantify corrections

SJ, J Martin Camalich 2012

Helicity amplitudes

decompose amplitude in lepton currents & “dilepton helicity”

$$\mathcal{A} = -\sum_{\lambda=\pm1,0} \mathcal{L}_V(\lambda)H_V(\lambda) - \sum_{\lambda=\pm1,0} \mathcal{L}_A(\lambda)H_A(\lambda) + L_S H_S + L_P H_P$$
$$- \sum_{\lambda=\pm1,0} \mathcal{L}_{TL}(\lambda)H_{TL}(\lambda) - \sum_{\lambda=\pm1,0} \mathcal{L}_{TR}(\lambda)H_{TR}(\lambda),$$

polarisation vectors for dilepton

$$\mathcal{L}_V(\lambda) = \epsilon_\mu(\lambda) L_V^\mu\,,$$
$$\mathcal{L}_A(\lambda) = \epsilon_\mu(\lambda) L_A^\mu\,,$$
$$\mathcal{L}_{TL}(\lambda) = \epsilon_\mu(\lambda) L_{TL}^\mu\,,$$
$$\mathcal{L}_{TR}(\lambda) = \epsilon_\mu(\lambda) L_{TR}^\mu\,,$$
$$\mathcal{L}_S = L_S$$
$$\mathcal{L}_P = L_P$$

$$L_V^\mu = \langle \ell^+\ell^- | \bar{l}\gamma^\mu l | 0\rangle, \qquad L_A^\mu = \langle \ell^+\ell^- | \bar{l}\gamma^\mu\gamma^5 l | 0\rangle,$$
$$L_S = \langle \ell^+\ell^- | \bar{l} l | 0\rangle, \qquad L_P = \langle \ell^+\ell^- | \bar{l}\gamma^5 l | 0\rangle,$$
$$L_{TL}^\mu = \frac{i}{\sqrt{q^2}}\langle \ell^+\ell^- | q_\nu \bar{l}\sigma^{\mu\nu} P_L l | 0\rangle, \qquad L_{TR}^\mu = \frac{i}{\sqrt{q^2}}\langle \ell^+\ell^- | q_\nu \bar{l}\sigma^{\mu\nu} P_R l | 0\rangle$$

most of the literature employs transversity amplitudes

$$A_{\parallel L(R)} = \frac{1}{\sqrt{2}}(H_{+1,L(R)} + H_{-1,L(R)}), \qquad A_{\perp L(R)} = \frac{1}{\sqrt{2}}(H_{+1,L(R)} - H_{-1,L(R)})$$
$$H_{\lambda L/R} = i\sqrt{f}\,\frac{1}{2}(H_V(\lambda) \mp H_A(\lambda)), \qquad A_t = i\,\frac{\sqrt{q^2}}{2m_\ell}\sqrt{f}\,H_P, \qquad A_S = -i\,\sqrt{f}\,H_S$$

Helicity amplitude definitions

Helicity amplitudes are expressed in terms of Wilson coefficients, form-factors and a nonlocal operator product

$$
\begin{aligned}
H_A(\lambda) &= N(C_{10A}\tilde{V}_{L\lambda} + C'_{10A}\tilde{V}_{R\lambda}), \\
H_{TR}(\lambda) &= N\frac{4\,\hat{m}_b\,m_B}{m_W\sqrt{q^2}}\,C_T\tilde{T}_{L\lambda}, \\
H_{TL}(\lambda) &= N\frac{4\,\hat{m}_b\,m_B}{m_W\sqrt{q^2}}\,C'_T\tilde{T}_{R\lambda}, \\
H_S &= -N\frac{\hat{m}_b}{m_W}(C_S\tilde{S}_L + C'_S\tilde{S}_R), \\
H_P &= -N\Big\{\frac{\hat{m}_b}{m_W}(C_P\tilde{S}_L + C'_P\tilde{S}_R) \\
&\quad + \frac{2\,m_l\hat{m}_b}{q^2}\Big[C_{10A}\Big(\tilde{S}_L - \frac{m_s}{m_b}\tilde{S}_R\Big) + C'_{10A}\Big(\tilde{S}_R - \frac{m_s}{m_b}\tilde{S}_L\Big)\Big]\Big\}
\end{aligned}
$$

11 helicity amplitudes factorize naively (into form factors and Wilson coefficients)

$$
H_V(\lambda) = N\Big\{C_{9V}\tilde{V}_{L\lambda} + C'_{9V}\tilde{V}_{R\lambda} - \frac{m_B^2}{q^2}\Big[\frac{2\,\hat{m}_b}{m_B}(C_{7\gamma}\tilde{T}_{L\lambda} + C'_{7\gamma}\tilde{T}_{R\lambda}) - 16\pi^2 h_\lambda\Big]\Big\}
$$

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

(only) 3 helicity amplitudes are sensitive to non-(naively-)factorizing long-distance physics

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

Form factors and non-factorizable contributions control theory errors