Rare semileptonic b-decays

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Outline

- Introduction to $b \to s\bar{\ell}\ell$ decays
  - Effective Theory (EFT) of $|\Delta B| = |\Delta S| = 1$ decays
- Observables in angular analyses
  - $B \to K^*\bar{\ell}\ell$ and $B \to K\bar{\ell}\ell$
- Theory of exclusive $b \to s\bar{\ell}\ell$ decays
  - $1/m_b$ expansions at low & high-q^2
  - Phenomenology
- Model-indep. Fits & New Physics Models

Introduction to $b \to s\bar{\ell}\ell$ decays

B-Hadron decays are a Multi-scale problem ...

... with hierarchical interaction scales

electroweak IA	$\gg$	ext. mom'a in B restframe	$\gg$	QCD-bound state effects
$M_W \approx 80$ GeV $M_Z \approx 91$ GeV		$M_B \approx 5$ GeV		$\Lambda_{\rm QCD} \approx 0.5$ GeV

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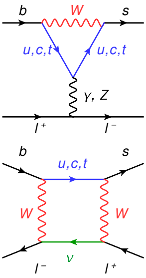
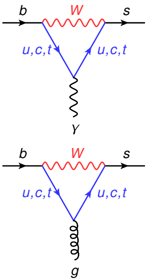
$$\mathcal{L}_{\text{eff}} \sim G_F\, V_{\text{CKM}} \times \Big[\sum_{9,10} C_i^{\ell\bar{\ell}}\, \mathcal{O}_i^{\ell\bar{\ell}} + \sum_{7\gamma,\,8g} C_i\, \mathcal{O}_i + \text{CC} + (\text{QCD \& QED-peng}) \Big]$$

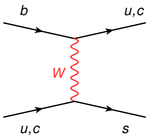
semi-leptonic



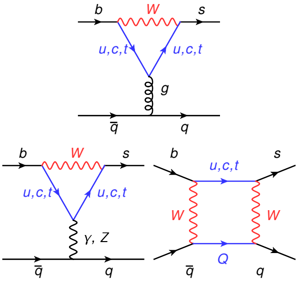
electro- & chromo-mgn



charged current



QCD & QED -penguin



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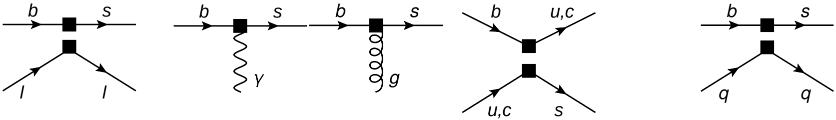
semi-leptonic | electro- & chromo-mgn | charged current | QCD & QED -penguin

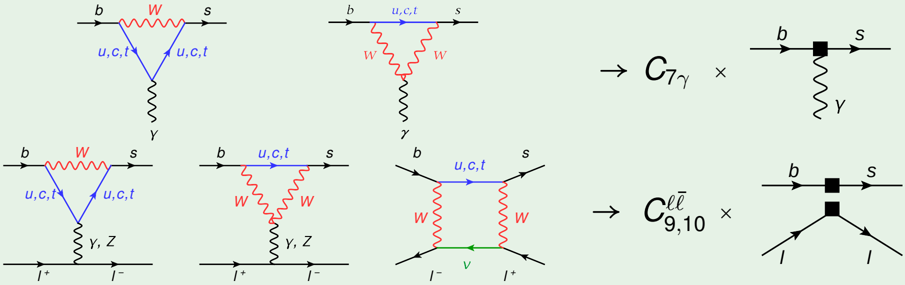


C_i = Wilson coefficients: contains short-dist. pmr's (heavy masses $M_t, \ldots$ – CKM factored out) and leading logarithmic QCD-corrections to all orders in α_s

$\Rightarrow$ in SM known up to next-to-next-to-leading order

$\mathcal{O}_i$ = higher-dim. operators: flavour-changing coupling of light quarks

Most important operators in the SM (Standard Model) for $b \to s + (\gamma, \bar{\ell}\ell)$



$$\mathcal{O}_{7\gamma} \propto m_b[\bar{s}\,\sigma^{\mu\nu} P_R\, b]F_{\mu\nu}, \qquad \mathcal{O}_{9(10)}^{\ell\bar{\ell}} \propto [\bar{s}\,\gamma^{\mu} P_L\, b][\bar{\ell}\,\gamma_{\mu}(\gamma_5)\,\ell]$$

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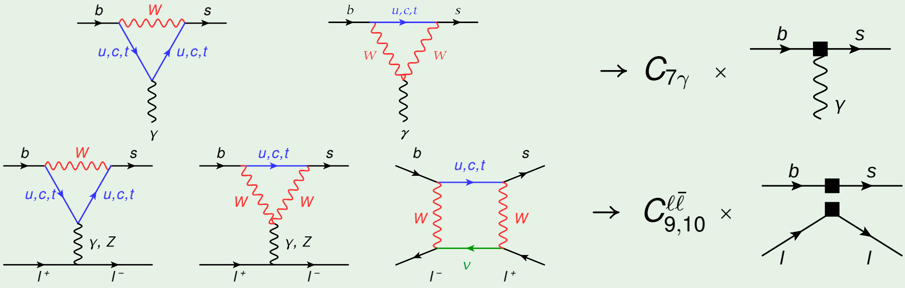

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and other contributions from

CC op's	$b \to s + \overline{U}U \;\; (U = u, c)$
QCD peng op's	$b \to s + \overline{Q}Q \;\; (Q = u, d, s, c, b)$
chromo-mgn op	$b \to s + gluon$

⇒ induce backgrounds

$$b \to s + (\overline{Q}Q) \to s + \bar{\ell}\ell$$

vetoed in exp's for $Q = c$: J/ψ and ψ'

$b \to s + (\gamma, \bar{\ell}\ell)$ operators beyond the SM ...

... frequently considered in model-(in)dependent searches

SM' = χ-flipped SM analogues ($P_L \leftrightarrow P_R$)

$$\mathcal{O}_{7'\gamma} \propto m_b[\bar{s}\,\sigma_{\mu\nu} P_L\, b]F^{\mu\nu}, \qquad \mathcal{O}^{\ell\bar{\ell}}_{9'(10')} \propto [\bar{s}\,\gamma^\mu P_R\, b][\bar{\ell}\,\gamma_\mu(\gamma_5)\,\ell]$$

S + P = scalar + pseudoscalar

$$\mathcal{O}^{\ell\bar{\ell}}_{S(S')} \propto [\bar{s}\,P_{R(L)}\,b][\bar{\ell}\,\ell], \qquad \mathcal{O}^{\ell\bar{\ell}}_{P(P')} \propto [\bar{s}\,P_{R(L)}\,b][\bar{\ell}\,\gamma_5\,\ell]$$

T + T5 = tensor

$$\mathcal{O}^{\ell\bar{\ell}}_{T} \propto [\bar{s}\,\sigma_{\mu\nu}\,b][\bar{\ell}\,\sigma^{\mu\nu}\,\ell], \qquad \mathcal{O}^{\ell\bar{\ell}}_{T5} \propto \frac{i}{2}\,\varepsilon^{\mu\nu\alpha\beta}[\bar{s}\,\sigma_{\mu\nu}\,b][\bar{\ell}\,\sigma_{\alpha\beta}\,\ell]$$

new Dirac-structures beyond SM:

SM'	=	right-handed currents
S + P	=	scalar-exchange & box-type diagrams
T + T5	=	box-type diagrams, Fierzed scalar tree exchange

Extension of EFT beyond the SM . . .

$$\mathcal{L}_{\rm eff}(\mu_b) = \mathcal{L}_{\rm QED\times QCD}(u, d, s, c, b, e, \mu, \tau, ???)$$

$$+ \frac{4G_F}{\sqrt{2}} V_{\rm CKM} \sum_{\rm SM} (C_i + \Delta C_i)\mathcal{O}_i + \sum_{\rm NP} C_j \mathcal{O}_j(???)$$

ΔC_i	=	NP contributions to SM C_i
$\sum_{\rm NP} C_j \mathcal{O}_j$	=	NP operators (e.g. $C'_{7,9,10}$, $C^{(\prime)}_{S,P}$, . . .)
???	=	additional light degrees of freedom ($\Leftarrow$ usually not pursued)

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model-*dep.* 1) decoupling of new heavy particles @ NP scale: $\mu_{NP} \gtrsim M_W$

2) RG-running to lower scale $\mu_b \sim m_b$ (potentially tower of EFT's)

C_i are correlated $\Rightarrow$ depend on fundamental parameters

model-*indep.* extending SM EFT-Lagrangian $\to$ new C_j

C_j are UN-correlated free parameters

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Observables

in angular analyses

Experimental data: $b \to s(d)\,\bar{\ell}\ell$ – number of events

# of evts	BaBar 2012 471 M $\bar{B}B$	Belle 2009 605 fb^{-1}	CDF 2011 9.6 fb^{-1}	LHCb 2011 (+2012) 1 (+2) fb^{-1}	CMS 2011 (+2012) 5 (+20) fb^{-1}	ATLAS 2011 5 fb^{-1}
$B^0 \to K^{*0}\,\bar{\ell}\ell$	$137 \pm 44^\dagger$	$247 \pm 54^\dagger$	288 ± 20	2361 ± 56	415 ± 70	426 ± 94
$B^+ \to K^{*+}\bar{\ell}\ell$			24 ± 6	162 ± 16		
$B^+ \to K^+\bar{\ell}\ell$	$153 \pm 41^\dagger$	$162 \pm 38^\dagger$	319 ± 23	4746 ± 81	not yet	not yet
$B^0 \to K^0_S\,\bar{\ell}\ell$			32 ± 8	176 ± 17		
$B_s \to \phi\,\bar{\ell}\ell$			62 ± 9	174 ± 15		
$B_s \to \bar{\mu}\mu$				emerging	emerging	limit
$\Lambda_b \to \Lambda\,\bar{\ell}\ell$			51 ± 7	78 ± 12		
$B^+ \to \pi^+\,\bar{\ell}\ell$		limit		25 ± 7		
$B_d \to \bar{\mu}\mu$			limit	limit	limit	limit

- CP-averaged results
- J/ψ and ψ' q^2-regions vetoed
- † unknown mixture of B^0 and $B^\pm$
- $\ell = \mu$ for CDF, LHCb, CMS, ATLAS

Babar arXiv:1204.3933 + 1205.2201
Belle arXiv:0904.0770
CDF arXiv:1107.3753 + 1108.0695 + Public Note 10894
LHCb arXiv:1205.3422 + 1209.4284 + 1210.2645 + 1210.4492 + 1304.6325 + 1305.2168 + 1306.2577 + 1307.5024 + 1307.7595 + 1308.1340 + 1308.1707 + 1403.8044 + 1403.8045 + 1406.6482
CMS arXiv:1307.5025 + 1308.3409
ATLAS ATLAS-CONF-2013-038

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Outlook / Prospects

Belle reprocessed all data 711 fb^{-1} $\to$ no final analysis yet!

LHCb $\sim$ 2 fb^{-1} from 2012 to be analysed and $\gtrsim$ 8 fb^{-1} by the end of 2018

ATLAS / CMS $\sim$ 20 fb^{-1} from 2012 to be analysed

Belle II expects about (10-15) K events $B \to K^*\bar{\ell}\ell$ ($\gtrsim$ 2020) [Bevan arXiv:1110.3901]

Angular analysis of $\overline{B} \to \overline{K}^* [\to \overline{K}\pi] + \bar{\ell}\ell$

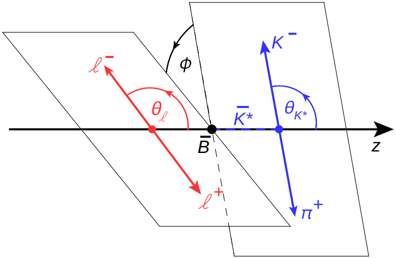
4-body decay with on-shell $\overline{K}^*$ (vector)

1) $q^2 = m^2_{\bar{\ell}\ell} = (p_\ell + p_{\bar{\ell}})^2 = (p_{\bar{B}} - p_{\bar{K}^*})^2$

2) $\cos\theta_\ell$ with $\theta_\ell \angle (\vec{p}_{\bar{B}}, \vec{p}_\ell)$ in $(\bar{\ell}\ell)$ – c.m. system

3) $\cos\theta_K$ with $\theta_K \angle (\vec{p}_{\bar{B}}, \vec{p}_{\bar{K}})$ in $(\bar{K}\pi)$ – c.m. system

4) $\phi \angle (\vec{p}_{\bar{K}} \times \vec{p}_\pi, \vec{p}_{\bar{\ell}} \times \vec{p}_\ell)$ in B-RF



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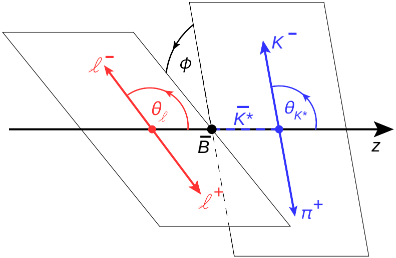

$J_i(q^2)$ = "Angular Observables"

$$\frac{32\pi}{9} \frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = J_{1s} \sin^2\theta_K + J_{1c} \cos^2\theta_K + (J_{2s} \sin^2\theta_K + J_{2c} \cos^2\theta_K) \cos 2\theta_\ell$$

$$+ J_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + J_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi + J_5 \sin 2\theta_K \sin\theta_\ell \cos\phi$$

$$+ (J_{6s} \sin^2\theta_K + J_{6c} \cos^2\theta_K) \cos\theta_\ell + J_7 \sin 2\theta_K \sin\theta_\ell \sin\phi$$

$$+ J_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi + J_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi$$

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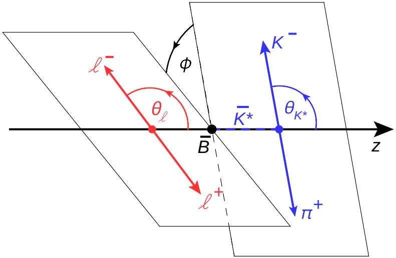

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$\Rightarrow$ "$2 \times (12 + 12) = 48$" if measured separately: A) decay + CP-conj and B) for $\ell = e, \mu$

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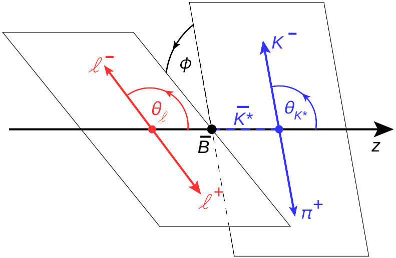

$\Rightarrow$ CP-averaged and CP-asymmetric angular observables

$$S_i = \frac{J_i + \bar{J}_i}{\Gamma + \bar{\Gamma}}, \qquad A_i = \frac{J_i - \bar{J}_i}{\Gamma + \bar{\Gamma}},$$

[Krüger/Sehgal/Sinha/Sinha hep-ph/9907386]
[Altmannshofer et al. arXiv:0811.1214]

CP-conj. decay $B^0 \to K^{*0}(\to K^+\pi^-)\ell^+\ell^-$: $d^4\bar{\Gamma}$ from $d^4\Gamma$ by replacing

$$\text{CP-even} : J_{1,2,3,4,7} \longrightarrow +\bar{J}_{1,2,3,4,7}[\delta_W \to -\delta_W]$$

$$\text{CP-odd} : J_{5,6,8,9} \longrightarrow -\bar{J}_{5,6,8,9}[\delta_W \to -\delta_W]$$

with weak phases δ_W conjugated

"Optimized observables" in $B \to K^* \bar{\ell}\ell$

Idea: reduce form factor (FF) sensitivity by combination (usually ratios) of angular obs's J_i

$\Rightarrow$ guided by large energy limit @ low-q^2 and Isgur-Wise @ high-q^2 FF-relations

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@ low q^2 = large recoil

$$A_T^{(2)} = P_1 = \frac{J_3}{2\,J_{2s}}, \qquad A_T^{(\mathrm{re})} = 2\,P_2 = \frac{J_{6s}}{4\,J_{2s}}, \qquad A_T^{(\mathrm{im})} = -2\,P_3 = \frac{J_9}{2\,J_{2s}},$$

$$P'_4 = \frac{J_4}{\sqrt{-J_{2c}J_{2s}}}, \qquad P'_5 = \frac{J_5/2}{\sqrt{-J_{2c}J_{2s}}}, \qquad P'_6 = \frac{-J_7/2}{\sqrt{-J_{2c}J_{2s}}}, \qquad P'_8 = \frac{-J_8}{\sqrt{-J_{2c}J_{2s}}},$$

$$A_T^{(3)} = \sqrt{\frac{(2\,J_4)^2 + J_7^2}{-2\,J_{2c}\,(2\,J_{2s} + J_3)}}, \qquad A_T^{(4)} = \sqrt{\frac{J_5^2 + (2\,J_8)^2}{(2\,J_4)^2 + J_7^2}}$$

[Krüger/Matias hep-ph/0502060, Egede/Hurth/Matias/Ramon/Reece arXiv:0807.2589 + 1005.0571]

[Becirevic/Schneider arXiv:1106.3283]

[Matias/Mescia/Ramon/Virto arXiv:1202.4266]

[Descotes-Genon/Matias/Ramon/Virto arXiv:1207.2753]

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⇒ guided by large energy limit @ low-q^2 and Isgur-Wise @ high-q^2 FF-relations

@ high q^2 = low recoil

$$H_T^{(1)} = P_4 = \frac{\sqrt{2} J_4}{\sqrt{-J_{2c}(2J_{2s} - J_3)}},$$

$$H_T^{(2)} = P_5 = \frac{J_5/\sqrt{2}}{\sqrt{-J_{2c}(2J_{2s} + J_3)}}, \qquad H_T^{(3)} = \frac{J_{6s}/2}{\sqrt{(2J_{2s})^2 - (J_3)^2}},$$

$$H_T^{(4)} = Q = \frac{\sqrt{2} J_8}{\sqrt{-J_{2c}(2J_{2s} + J_3)}}, \qquad H_T^{(5)} = \frac{-J_9}{\sqrt{(2J_{2s})^2 - (J_3)^2}},$$

$$\frac{A_9}{A_{\rm FB}} = \frac{J_9}{J_{6s}}, \qquad \text{and} \qquad \frac{J_8}{J_5}$$

[CB/Hiller/van Dyk arXiv:1006.5013]
[Matias/Mescia/Ramon/Virto arXiv:1202.4266]
[CB/Hiller/van Dyk arXiv:1212.2321]

Angular analysis and “real life”

When aiming at precision measurements in $B \to K^*(\to K\pi)\bar{\ell}\ell$ (P-wave config)

- inclusion of resonant and non-resonant $K\pi$ (in S-wave config) important in experiments

  $\Rightarrow$ additional contributions to angular distribution

  $\Rightarrow$ $P-$ and $S-$wave can be disentangled in angular analysis

  $\Rightarrow$ taken into account by LHCb and CMS

  [Lu/Wang arXiv:1111.1513, Becirevic/Tayduganov 1207.4004, Blake/Egede/Shires 1210.5279, Matias 1209.1525]

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Extended angular analysis

- $B \to K\pi\bar{\ell}\ell$ off-resonance ($m^2_{K\pi} \neq m^2_{K^*}$) at high-$q^2$ [Das/Hiller/Jung/Shires arXiv:1406.6681]

$$\frac{d^4\Gamma}{dq^2 d\cos\theta_\ell d\cos\theta_K d\phi} \longrightarrow \frac{d^5\Gamma}{dm^2_{K\pi} dq^2 d\cos\theta_\ell d\cos\theta_K d\phi}$$

  - $\Rightarrow$ include contributions from $S-$, $P-$, and $D-$wave
  - $\Rightarrow$ provide access to further combinations of Wilson coefficients
  - $\Rightarrow$ probe strong phase differences with resonant contribution
  - $\Rightarrow$ analogously for $B_s \to \bar{K}K\bar{\ell}\ell$

- complementary constraints from angular analysis of $\Lambda_b \to \Lambda\bar{\ell}\ell$

[Böer/Feldmann/van Dyk talk FLASY 2014]

Angular analysis of $B \to K \bar{\ell}\ell$

Besides $d\Gamma/dq^2$, two more obs's measured LHCb 3/fb arXiv:1403.8045

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell} = \frac{F_H}{2} + A_{\rm FB}\cos\theta_\ell + \frac{3}{4}[1 - F_H]\sin^2\theta_\ell$$

In the SM:

- $F_H \sim m_\ell^2/q^2$ tiny for $\ell = e, \mu$ and reduced FF uncertainties @ low- & high-q^2
  CB/Hiller/Piranishvili arXiv:0709.4174, CB/Hiller/van Dyk/Wacker arXiv:1111.2558
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Beyond SM: test scalar & tensor operators CB/Hiller/Piranishvili arXiv:0709.4174

- $F_H \sim |C_T|^2 + |C_{T5}|^2 + \mathcal{O}(m_\ell)$
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Lepton-flavour violating (LFV) effects: generalise $C_i \to C_i^\ell$!!!

Take ratios of observables for $\ell = \mu$ over $\ell = e$ (or $\ell = \tau$) Krüger/Hiller hep-ph/0310219

$\Rightarrow$ FF's cancel in SM up to $\mathcal{O}(m_\ell^4/q^4)$ @ low-q^2 CB/Hiller/Piranishvili arXiv:0709.4174

$$R_M^{[q^2_{\rm min},\, q^2_{\rm max}]} = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2 \frac{d\Gamma[B \to M \bar{\mu}\mu]}{dq^2}}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2 \frac{d\Gamma[B \to M \bar{e}e]}{dq^2}}$$

for $M = K, K^*, X_s$

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for $M = K, K^*, X_s$

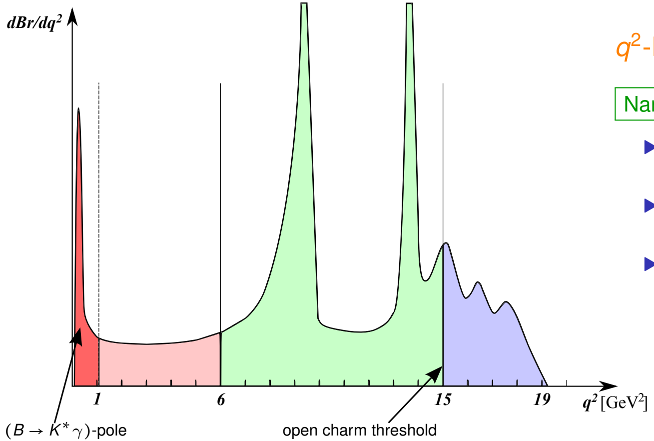
Recent measurement of

$R_K^{[1,6]} = 0.745^{+0.090}_{-0.074} \pm 0.036$ LHCb 3/fb arXiv:1406.6482

deviates by 2.6σ from SM

$R_{K,\rm SM}^{[1,6]} = 1.0008 \pm 0.0004$ Bouchard et al. arxiv:1303.0434

Theory of exclusive $b \to s \bar{\ell}\ell$ decays



q^2-Regions in $B \to K^* \bar{\ell}\ell$

Narrow resonances

- dominated by charged-cur. (tree-level) op's
- not sensitive to new physics in $b \to s\bar{\ell}\ell$
- nonperturbative predictions via: dispersion relations + $B \to K^*(\bar{c}c)$ data

Large Recoil (low-q^2)

- very low-q^2 ($\lesssim 1$ GeV^2) dominated by $\mathcal{O}_7$
- low-q^2 ($[1, 6]$ GeV^2) dominated by $\mathcal{O}_{9,10}$
- 1) QCD factorization or SCET
  2) LCSR
  3) non-local OPE of $\bar{c}c$-tails

Low Recoil (high-q^2)

- dominated by $\mathcal{O}_{9,10}$
- HQET + OPE $\Rightarrow$ theory only for sufficiently large q^2-integrated obs's

Theory at large and low recoil

$\lambda \equiv \Lambda_{\rm QCD}/m_b \lesssim 0.15$

"Naive factorization" works for $O_i \sim [\bar{s}\Gamma_i b][\bar{\ell}\Gamma'_i \ell] \Rightarrow$ FF's F_i $\big(i = 9^{(\prime)}, 10^{(\prime)}, S^{(\prime)}, P^{(\prime)}, T/T5\big)$

$$\mathcal{A}_i^{L/R} \propto (F_i + \mathrm{SL}_{FF,i})(C_9^{\rm eff} \mp C_{10}) + (F'_i + \mathrm{SL}_{FF',i})C_7^{\rm eff} + \mathrm{SL}_{Amp,i} + \mathcal{A}_{\bar{c}c} \qquad i = L, \perp, \parallel$$

1) $\mathrm{SL}_{FF^{(\prime)}} \sim \lambda$: subleading corrections from FF-relations
   $\Rightarrow$ absent when not using FF-relations [Altmannshofer et al. arXiv:0811.1214]
2) SL_{Amp} : subleading corrections from $1/m_b$ expansions to amplitude
3) $\mathcal{A}_{\bar{c}c}$: contributions from $\bar{c}c$ resonances

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Large recoil

- large energy $E_{K^*} \sim m_b$: hard-scattering of spectator in QCDF/SCET
- $\mathrm{SL}_{Amp} \sim \lambda$: some known in QCDF [Matias/Feldmann hep-ph/0212158, Beneke/Feldmann/Seidel hep-ph0412400]
  also LCSR [(Dimou)/Lyon/Zwicky arXiv:(1212.2242)1305.4797]
  $\Rightarrow$ numerical contribution below λ
- $\mathcal{A}_{\bar{c}c}$ become important for $q^2 \gtrsim 6$ GeV^2 [Khodjamirian/Mannel/Pivovarov/Wang arXiv:1006.4945]

Low recoil

- large $q^2 \sim m_b$: local OPE of 4-quark operators, accounts for $\mathcal{A}_{\bar{c}c}$ [Buchalla/Isidori hep-ph/9801456]
- $\mathrm{SL}_{FF} \sim \lambda\, C_7/C_9 \approx 0.02$ with $C_7/C_9 \approx 0.1$
- $\mathrm{SL}_{Amp} \sim \alpha_s \lambda \approx 0.05$ [Grinstein/Pirjol hep-ph/0404250]
- duality violation of OPE $\lesssim$ few % [Beylich/Buchalla/Feldmann arxiv:1101.5188]

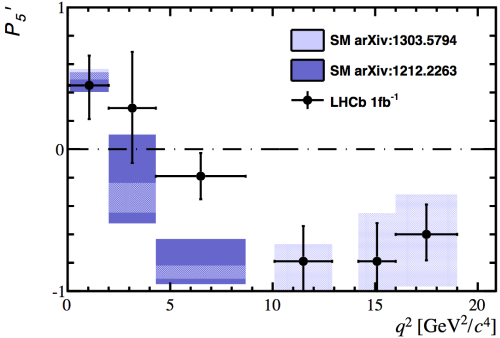
P'_5 & subleading corrections

3.7σ local tension in $P'_{5,\, q^2 \in [4.3,\, 8.7]}$

2.5σ local tension in $P'_{5,\, q^2 \in [1.0,\, 6.0]}$

comparing LHCb arXiv:1308.1707 with theory: Descotes-Genon/Hurth/Matias/Virto arXiv:1303.5794

$\Rightarrow$ Two “recipes” used to estimate subleading crr’s (mainly for SL_{FF})



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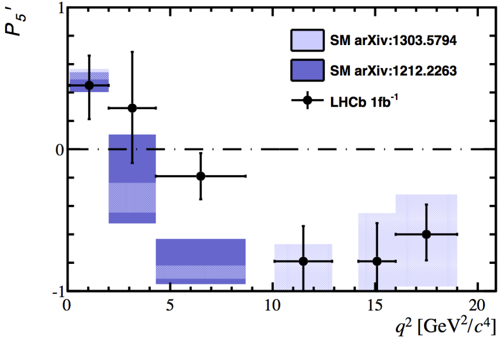

I) Egede/Hurth/Matias/Ramon/Reece arXiv:0807.2589

Introduce rescaling factor ζ for each transversity ampl.

$$A^{L/R}_{L,\perp,\parallel} \longrightarrow \zeta^{L/R}_{L,\perp,\parallel} \times A_{L,\perp,\parallel} \qquad\qquad 1 - \frac{\Lambda_{\rm QCD}}{m_b} \lesssim \zeta \lesssim 1 + \frac{\Lambda_{\rm QCD}}{m_b}$$

⇒ mimic subleading crr's from A) FF relations and B) $1/m_b$ contr. to ampl.

⇒ can account for q^2-dep.: introduce ζ for each q^2-bin

⇒ used in most analysis/fits

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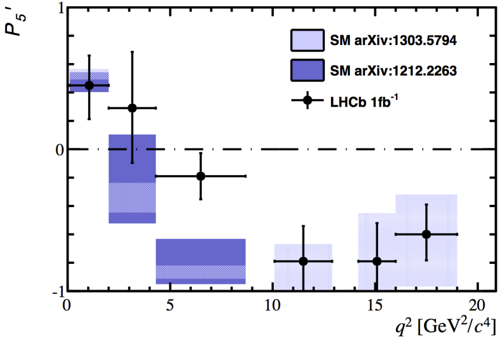

II) Jäger/Martin-Camalich arXiv:1212.2263

Keep track of subleadig crr.'s to FF-relations (ξ_j = universal FF)

$$FF_i \propto \xi_j + \alpha_s \Delta FF_i + a_i + b_i \frac{q^2}{m_B^2} + \ldots$$

with a_i, b_i from spread of nonperturbative FF-calculations (LCSR, quark models ...)

a_i, b_i are $\sim \Lambda_{\rm QCD}/m_b$ and ΔFF_i QCD crr's [Beneke/Feldmann hep-ph/0008255]

III) preliminary Hofer/Matias talk ICHEP 2014

Update of method II)

⇒ find smaller subleading FF corrections, contrary to II)

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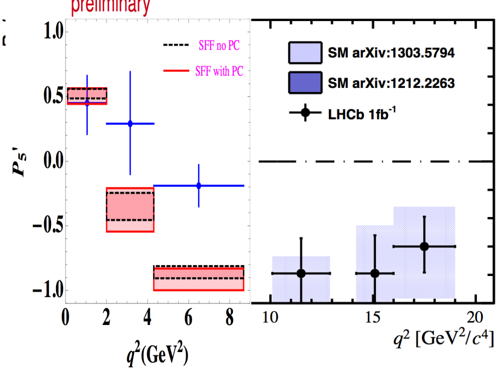

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High-q^2 $\bar{c}c$-resonances in $B^+ \to K^+ \bar{\mu}\mu$

[Lyon/Zwicky arXiv:1406.0566]

factorization assumption for $B \to K + \Psi(nS)(\to \bar{\ell}\ell)$:

$$\langle \Psi(nS)\, K | (\bar{c}\Gamma c)(\bar{s}\Gamma' b) | B \rangle \approx \langle \Psi(nS) | \bar{c}\Gamma c | 0 \rangle \otimes \langle K | \bar{s}\Gamma' b | B \rangle + \ldots \text{ nonfactorisable}$$

+ dispersion relations with BES II $\bar{e}e \to \bar{q}q$ data

+ comparison with LHCb 3 fb^{-1} of $B^+ \to K^+ \bar{\mu}\mu$ @ high-q^2

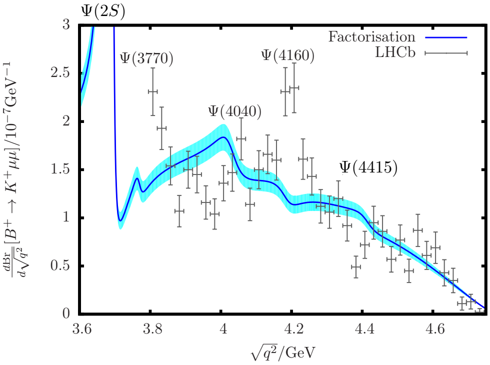
- factorization "badly fails" differentially in q^2
  - $\Rightarrow$ not unexpected, well-known from $B \to K\Psi(nS)$
  - $\Rightarrow$ "fudge factor" $\neq 1$
- does it invalidate the OPE ???

  this requires q^2-integration !!!
- investigate other $B \to M \bar{\ell}\ell$

  $M = K^*$ at LHCb

  $M = X_s$ (inclusive) at Belle II

  + including J/ψ and ψ'



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+ dispersion relations with BES II $\bar{e}e \to \bar{q}q$ data

+ comparison with LHCb 3 fb^{-1} of $B^+ \to K^+ \bar{\mu}\mu$ @ high-q^2

- a) no "fudge factor": $p = 0\%$

  various "generalisations of factorisable contributions"

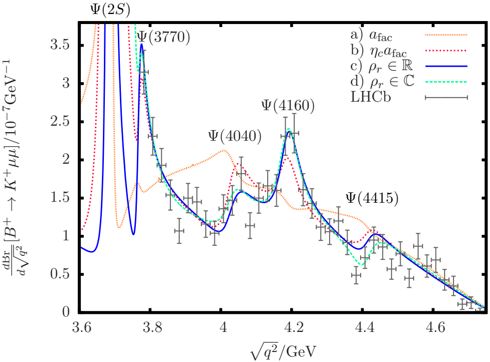
  b) fit "fudge factor" = −2.6: $p = 1.5\%$

  c), d) fit rel. factors of $\Psi(nS)$:
  $p = 12\%$ and $p = 20\%$

  ⇒ improve the combined fit of BES II and LHCb considerably

  (BES II data alone: $p = 44\%$)
- BUT can these parametrisations capture all features of non fact. contr.: Wilson coeffs. & q^2 ???
- can't be explained with NP in C_9

  ⇒ can ease tension in P_5'
  ⇒ NP in $b \to s\,\bar{c}c$?!



Model-independent Fits of $b \to s \bar{\ell}\ell$ decays

Recent “Global Fit’s” after EPS-HEP 2013 Conference

1) DGMV	=	Descotes-Genon/Matias/Virto	[arXiv:1307.5683 + 1311.3876]	χ^2-frequentist
2) AS	=	Altmannshofer/Straub	[arXiv:1308.1501]	χ^2-fit
3) BBvD	=	Beaujean/CB/van Dyk	[arXiv:1310.2478 (journal version)]	Bayesian
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Theory predictions

@ low q^2: $B \to K^* \bar{\ell}\ell$, $B \to K\bar{\ell}\ell$, $B \to K^*\gamma$

DGMV, AS, BBvD: based on QCDF [Beneke/Feldmann/Seidel hep-ph/0106067 + 0412400]

(HLMW only uses high-q^2 data)

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[Grinstein/Pirjol hep-ph/0404250; Beylich/Buchalla/Feldmann arXiv:1101.5118]

DGMV, AS, BBvD: LCSR $B \to K^*$ FF-results extrapolated from low q^2

HLMW, BBvD: use lattice $B \to K^*$ FF predictions [HLMW arXiv:1310.3722]

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Theory uncertainties

DGMV, AS, HLMW: combining theoretical and experimental uncertainties
$\Rightarrow$ included in likelihood

BBvD: most relevant parameters included in the fit as nuisance parameters

Which data is used?

q^2 Binning

	q^2-Bins [GeV^2]
lo	[1, 6]
LO	[0, 2] [2, 4.3] [4.3, 8.68]
hi	[14.18, 16] [16, 19]

DGMV: only LHCb data of $B \to K^* \bar{\ell}\ell$

AS, BBvD, HLMW:
use all available data from Belle, Babar, CDF, LHCb, CMS, ATLAS

decay	obs	DGMV	AS	BBvD	HLMW
$B \to X_s \gamma$	Br	✓	✓	✓	
	A_{CP}		✓		
$B \to K^* \gamma$	Br			✓	
	$S(C)$	✓	✓	✓ (✓)	
	A_I	✓			
$B_s \to \bar{\mu}\mu$	Br	✓	✓	✓	
$B \to X_s \bar{\ell}\ell$	Br	lo	lo+hi	lo	
$B \to K \bar{\ell}\ell$	Br		lo+hi	lo+hi	
$B \to K^* \bar{\ell}\ell$	Br		lo+hi	lo+hi	hi
	F_L		lo+hi	lo+hi	hi
	$A_{\rm FB}$	LO+hi	lo+hi	lo+hi†	hi
	$P_{1,2}$, $P'_{4,5,6}$	LO+hi		lo+hi†	
	P'_8	LO+hi			
	$S_{3,4,5}$		lo+hi		hi
	A_9		lo+hi		
$B_s \to \phi \bar{\ell}\ell$	Br, F_L, S_3				hi

† if P_2 is available then $A_{\rm FB}$ is not used: LHCb

DGMV "Only $B \to K^* \bar{\ell}\ell$ and only from LHCb"

with 3 q^2-bins @ low q^2

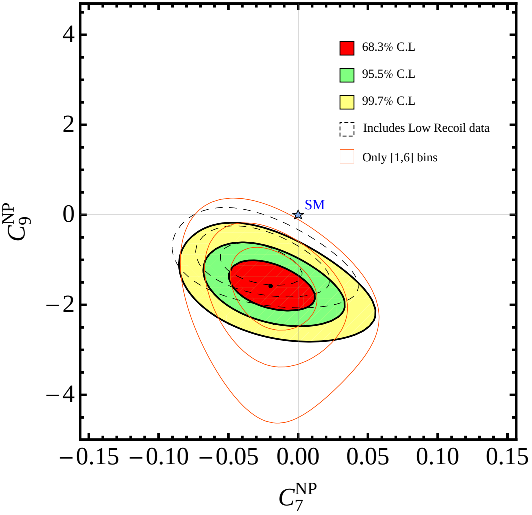
1) only low q^2:
$A_{\rm FB}$, P_2 and P_5' prefer:

$C_9^{NP} \approx -1.6$

2) adding high q^2:
due to $q^2 \in [14.18, 16.0]$ GeV^2 bin

$C_9^{NP} \approx -1.2$

3) only $C_7^{NP} \neq 0$ beneficial,
NO real need for $C_{7',9',10'}$,
however $C_{9'} < 0$ preferred



AS "Adding $B \to K\bar{\ell}\ell$ and other experiments"

$\Rightarrow$ 3 main tensions between data and SM:

A) F_L @ low q^2 (from Babar and ATLAS)

B) P_5'/S_5 @ low q^2

C) P_4'/S_4 @ high q^2
($\Leftarrow$ even not resolvable with $C_{7',9',10'} \neq 0$)

1) $C_{7,9}^{NP} \neq 0$ can reduce tension for F_L and S_5,
but not as good as:

2) C_9^{NP} with $C_{9'}$ (or $C_{10'}$)
$B \to K\bar{\ell}\ell$ requires $C_{9'} > 0$ (or $C_{10'} < 0$)

3) Fit does not improve much when allowing all $C_{i(')} \neq 0 \to$ best fit:

$$C_7^{NP} = -0.03, \quad C_9^{NP} = -0.9, \quad C_{10}^{NP} = -0.1,$$
$$C_{7'} = -0.11, \quad C_{9'} = +0.7, \quad C_{10'} = -0.2$$

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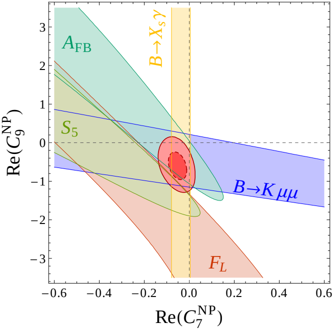

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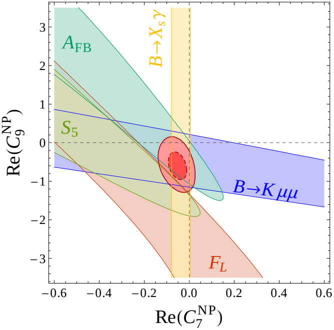
C) P_4'/S_4 @ high q^2
($\Leftarrow$ even not resolvable with $C_{7',9',10'} \neq 0$)

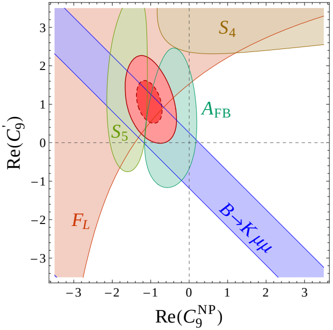
1) $C_{7,9}^{NP} \neq 0$ can reduce tension for F_L and S_5, but not as good as:

2) C_9^{NP} with $C_{9'}$ (or $C_{10'}$)
$B \to K\bar{\ell}\ell$ requires $C_{9'} > 0$ (or $C_{10'} < 0$)

3) Fit does not improve much when allowing all $C_{i(')} \neq 0 \to$ best fit:

$$C_7^{NP} = -0.03, \quad C_9^{NP} = -0.9, \quad C_{10}^{NP} = -0.1,$$
$$C_{7'} = -0.11, \quad C_{9'} = +0.7, \quad C_{10'} = -0.2$$





AS "Adding $B \to K\bar{\ell}\ell$ and other experiments"

$\Rightarrow$ 3 main tensions between data and SM:

A) F_L @ low q^2 (from Babar and ATLAS)

B) P_5'/S_5 @ low q^2

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($\Leftarrow$ even not resolvable with $C_{7',9',10'} \neq 0$)

1) $C_{7,9}^{NP} \neq 0$ can reduce tension for F_L and S_5, but not as good as:

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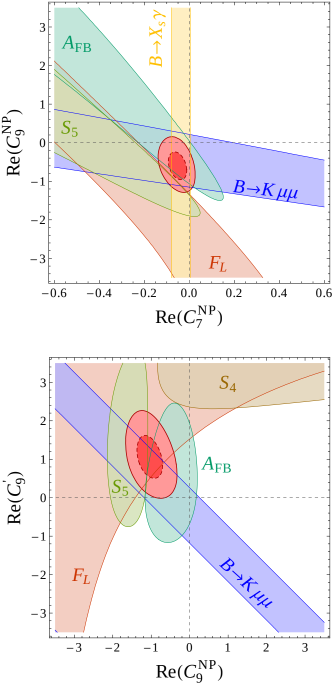


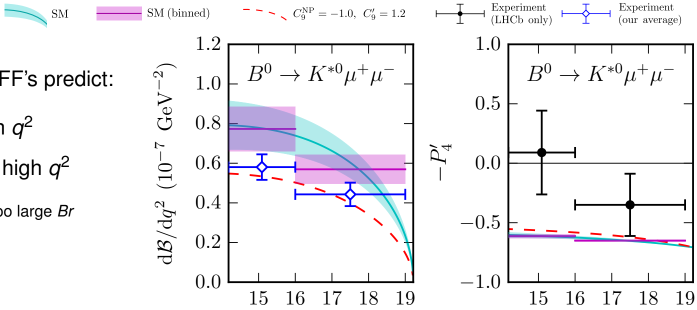
HLMW "Only $B \to K^* \bar{\ell}\ell$ @ high q^2" with $B \to K^*$ lattice FF's

⇒ $B \to K^*$ (and $B_s \to \phi$) FF's predict:

A) too large Br @ high q^2

B) too small P_4'/S_4 @ high q^2

also ($B_s \to \phi$) FF's predict too large Br



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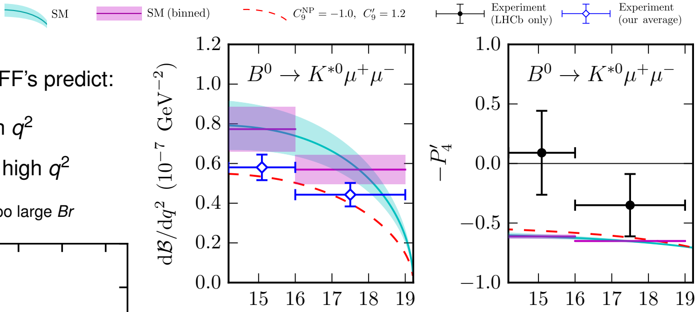

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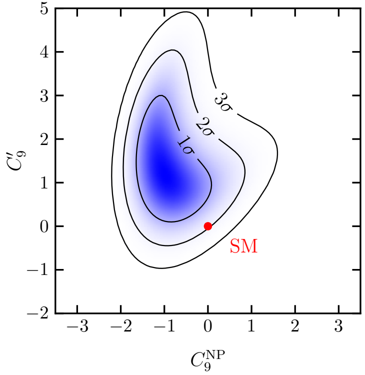

1) only high q^2 data of $B \to K^* \bar{\ell}\ell$ & $B_s \to \phi\bar{\ell}\ell$

2) consider only $C_9^{NP} - C_9'$ scenario

3) best fit point:

$C_9^{NP} = -1.0 \pm 0.6, \qquad C_{9'} = +1.2 \pm 1.0$

and only highest $q^2 \in [16, 19]$ GeV^2 bin:

$C_9^{NP} = -0.9 \pm 0.7, \qquad C_{9'} = +0.4 \pm 0.7$

BBvD “Fitting also all the nuisance parameters . . .”

A) . . . describing q^2-dependence of form factors

- $B \to K$: $2\times \to$ prior from LCSR + Lattice
- $B \to K^*$: $6\times \to$ prior from 1) LCSR (NO Lattice) OR 2) LCSR + Lattice

B) . . . of naive parametrisation of subleading corrections

- $B \to K$: $2\times$ @ low and high q^2
- $B \to K^*$: $6\times$ @ low q^2 and $3\times$ @ high q^2

priors: about 15%$\sim \Lambda_{\text{QCD}}/m_b$ of leading amplitude

C) CKM, quark masses, . . .

. . . in total 28 nuisance parameters

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- $B \to K^*$: 6× @ low q^2 and 3× @ high q^2

priors: about 15%$\sim \Lambda_{\rm QCD}/m_b$ of leading amplitude

C) CKM, quark masses, ...

... in total 28 nuisance parameters

Model-independent New Physics scenarios

Fits in the SM

1) SM = only nuisance parameters

and model-independent scenarios

2) $\text{SM}_{7,9,10}$ = $C^{NP}_{7,9,10} \neq 0$

3) SM+SM' = $C^{NP}_{7,9,10} \neq 0$ and $C_{7',9',10'} \neq 0$

4) $\text{SM+SM'}_{9,9'}$ = $C^{NP}_{9} \neq 0$ and $C_{9'} \neq 0$

Fitting nuisance parameters

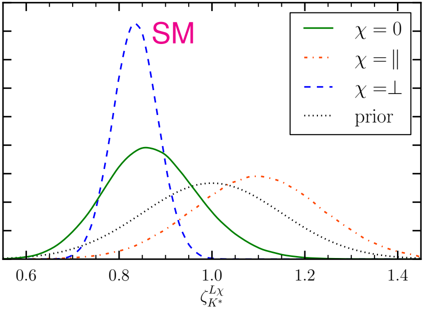
subleading corrections

⇒ in SM some subleading $B \to K^*$ corrections

$\sim -(15 - 20)\%$ for $\chi = \perp, 0$ @ low q^2

$\sim +10\%$ for $\chi = \parallel$

with gaussian priors of $1\sigma \sim \Lambda_{\rm QCD}/m_b \sim 15\%$



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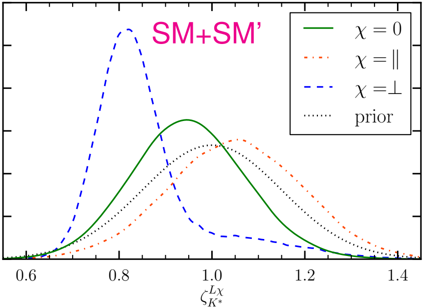
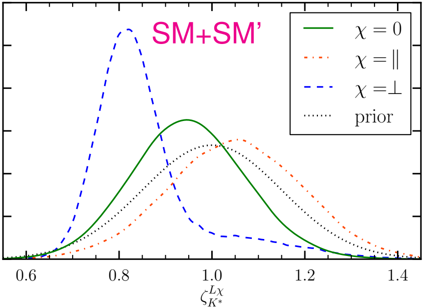


Fitting nuisance parameters



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$\Rightarrow$ relaxed in SM+SM', except $\zeta_{K^*}^{L\perp}$

$B \to K^*$ form factors

No lattice $B \to K^*$ in prior

$\Rightarrow$ data prefers higher FF's in SM+SM' than SM & $SM_{7,9,10}$

$\Rightarrow$ consistent with lattice results:

[Horgan/Liu/Meinel/Wingate arXiv:1310.3722]

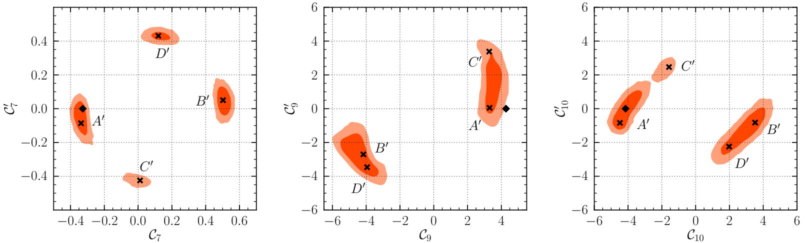
SM: lattice FF's too large for measured $Br[B \to K^* \bar{\ell}\ell]$ @ high q^2

	prior	SM	$SM_{7,9,10}$	SM+SM'
$V(0)$	$0.35^{+0.13}_{-0.08}$	$0.38^{+0.04}_{-0.02}$	$0.38^{+0.03}_{-0.03}$	$0.38^{+0.04}_{-0.03}$
$A_1(0)$	$0.27^{+0.09}_{-0.05}$	$0.24^{+0.03}_{-0.02}$	$0.24^{+0.03}_{-0.03}$	$0.28^{+0.04}_{-0.03}$
$A_2(0)$	$0.24^{+0.13}_{-0.07}$	$0.23^{+0.04}_{-0.04}$	$0.22^{+0.05}_{-0.04}$	$0.27^{+0.06}_{-0.05}$
	with lattice $B \to K^*$ in prior			
$V(0)$	$0.37^{+0.03}_{-0.02}$	$0.38^{+0.03}_{-0.02}$	$0.38^{+0.03}_{-0.02}$	$0.37^{+0.02}_{-0.02}$
$A_1(0)$	$0.29^{+0.03}_{-0.03}$	$0.26^{+0.02}_{-0.02}$	$0.26^{+0.03}_{-0.02}$	$0.28^{+0.03}_{-0.03}$
$A_2(0)$	$0.29^{+0.05}_{-0.05}$	$0.27^{+0.03}_{-0.04}$	$0.26^{+0.04}_{-0.03}$	$0.28^{+0.04}_{-0.03}$

Fitting effective couplings

(◆) = SM, (×) = best fit point

SM+SM'

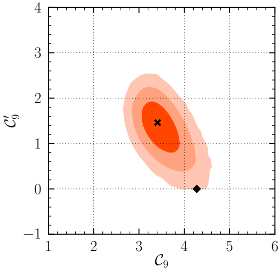


⇒ 4 solutions with posterior masses: A' = 39%, B' = 41%, C' = 5%, D' = 15%

with lattice $B \to K^*$ FF's: A' = 49%, B' = 31%, C' = 5%, D' = 15%

⇒ $\mathcal{C}_9^{\rm SM}$ at border of 2σ

All scenarios:
inclusion of lattice $B \to K^*$ yields only minor changes in $\mathcal{C}_i$



SM+SM'$_{9,9'}$

⇒ $\mathcal{C}_9^{\rm SM}$ at border of 2σ

⇒ $\mathcal{C}_{9'}^{\rm SM}$ at border of 3σ

Goodness of fit

$\Rightarrow$ In SM: 6 measurements (out of 92) with pull values $> 2\sigma$ @ best fit point:

Belle	:	$\langle Br \rangle_{[16,19]}$	$\rightarrow +2.6\sigma$			
BaBar	:	$\langle F_L \rangle_{[1,6]}$	$\rightarrow -3.5\sigma$			
LHCb	:	$\langle P'_4 \rangle_{[14,16]}$	$\rightarrow -2.4\sigma$	$\langle P'_5 \rangle_{[1,6]}$	$\rightarrow +2.1\sigma$	not yet published
ATLAS	:	$\langle A_{\rm FB} \rangle_{[16,19]}$	$\rightarrow +2.2\sigma$	$\langle F_L \rangle_{[1,6]}$	$\rightarrow -2.6\sigma$	

SM p values @ best fit point: 0.10 (and 0.04 with lattice $B \to K^*$ FF's)

excluding $\langle F_L \rangle_{[1,6]}$ from BaBar and ATLAS: 0.38 (and 0.30 with lattice $B \to K^*$ FF's)

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Model comparison of models M_1 and M_2 with priors $P(M_i)$ ($\leftarrow$ unknown!)

$$\frac{P(M_1|D)}{P(M_2|D)} = B(D|M_1, M_2)\frac{P(M_1)}{P(M_2)}$$

Bayes factor: $B(D|M_1, M_2) \equiv \dfrac{P(D|M_1)}{P(D|M_2)}$

!!! Models with more parameters are disfavored by larger prior volume,
unless they improve the fit substantially

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$B(D\|M_1, M_2)^\dagger$	$\text{SM}_{7,9,10}$: SM	SM+SM' : SM	$\text{SM+SM'}_{9,9'}$: SM
no lattice FF's	1 : 93	1 : 19	8 : 1
with lattice FF's	1 : 97	5 : 1	820 : 1

$\delta C_{7(')} \in [-0.2, 0.2]$

$\delta C_{9('),10(')} \in [-2, 2]$

† H. Jeffreys interpretation of $B(D|M_1, M_2)$ as strength of evidence in favour of M_2:

1:3 < barely worth mentioning, 1:10 < substantial, 1:30 < strong, 1:100 < very strong, > 1:100 decisive.

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!!! Models with more parameters are disfavored by larger prior volume, unless they improve the fit substantially

!!! Looks very interesting

⇒ waiting eagerly for LHCb update with 3 fb^{-1}, hopefully this year

⇒ updated analysis from BaBar, ATLAS, Belle would be also welcome

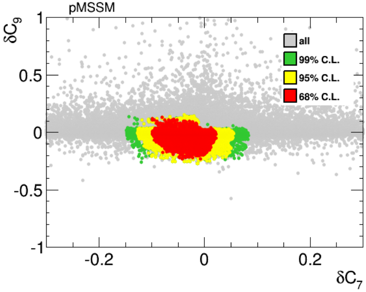
Constraints in the MSSM

In MSSM NO large $|C^{\text{NP}}_{9,9'}| \sim 1$ possible $\Rightarrow$ qualitative discussion [Altmannshofer/Straub arXiv:1308.1501]

Quantitative analysis for

CMSSM(5), NUHM(6), pMSSM(19)

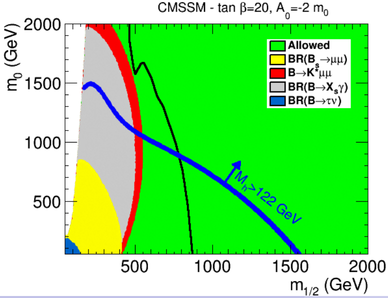
[Mahmoudi/Neshatpour/Virto arXiv:1401.2145]

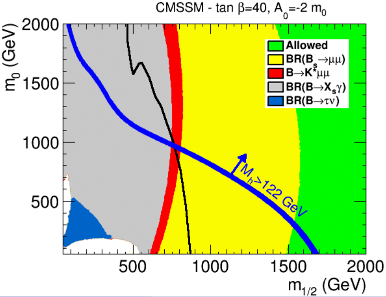


- even in pMSSM: $-0.3 \lesssim |C^{\text{NP}}_9| \lesssim 0.2$
- $B \to K^* \bar{\ell}\ell$ as constraining as $B \to X_s\gamma$ and/or $B_s \to \bar{\mu}\mu$, depending on NP parameters ⇒ example CMSSM

blue line: requiring $M_H > 122$ GeV

black line: direct searches ATLAS 20.3 fb^{-1}





Other studies

- Z, Z' models

  $\Rightarrow$ tree-FCNC most natural to accommodate NP in C_9 without changing C_{10}

  $\Rightarrow$ many particular models

  Gauld/Goetz/Haisch arxiv:1308.1959 & 1310.1082
  Buras/Girrbach arXiv:1309.2466 and Buras/De Fazio/Girrbach arXiv:13011.6729
  Altmannshofer/Gori/Pospelov/Yavin arXiv:1403.1269

- Partial compositeness models [Altmannshofer/Straub arXiv:1308.1501]

  $\Rightarrow$ NP in $C_{7,7'}$ possible

  $\Rightarrow$ large NP in $C_{9,9'}$ requires large degree of compositeness and cancellations for $C_{10,10'}$

  $\Rightarrow$ not clear whether viable once accounting for constraints on lepton sector

- Model-independent $b \to s\bar{b}b$ dim-6 operators [Datta/Duraisamy/Ghosh arXiv:1310.1937]

  $\Rightarrow$ $b \to s\bar{b}b$ dim-6 operators mix into $\mathcal{O}_{7,7',9,9'}$ but not $\mathcal{O}_{10,10'}$

Summary & Issues

Summary of model-independent fits

- 4 analyses (DGMV, AS, BBvD, HLMW) → many differences:
  1) choice of data
  2) choice of theory uncertainties (subleading, high q^2, FF's)

  ⇒ still: consistent picture in fits

- $B \to K^* \bar{\ell}\ell$ low-q^2 data prefers $C_9^{NP} < 0$, not only from P_5'
- $B \to K^* \bar{\ell}\ell$ high-q^2 data with $B \to K^*$ FF's prefers $C_9^{NP} < 0$ & $C_{9'} > 0$

- in combination with $B \to K \bar{\ell}\ell$ can drive $C_{9',10'} \neq 0$

- SM compatible with data for subleading crr's @ low $q^2 \neq 0$, but within $\Lambda_{\rm QCD}/m_b$ expectation

- Bayes factors shift prior probability in favour of SM+SM' with only $C_{9,9'}$ over SM
  !!! when using $B \to K^*$ lattice FF's even SM+SM' with $C_{7',9',10'}$ favoured over SM

"EOS = Flavour tool" by Beaujean/CB/van Dyk et al.
Download @ `http://project.het.physik.tu-dortmund.de/eos/`

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"Pessimistic" interpretation:

"Fits yield $C_9^{NP} \neq 0$ as a sign of nonunderstood QCD effects,
whereas C_{10} is free of them and therefore we find indeed $C_{10}^{NP} = 0$,
consistent with the SM prediction."

"EOS = Flavour tool" by Beaujean/CB/van Dyk et al.
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Issues ?!

Perhaps with data:

- fluctuations in the data

  ⇒ new results will be available – hopefully within this year – from

  1) Belle (final reprocessed)
  2) LHCb (1 $\text{fb}^{-1} \to 3\ \text{fb}^{-1}$ missing for $B \to K^* \bar{\ell}\ell$)
  3) CMS and ATLAS (5 $\text{fb}^{-1} \to 25\ \text{fb}^{-1}$)
  4) Babar F_L, A_{FB} not yet published

- exact endpoint relations at $q^2 = q^2_{\text{max}}$ have to be fulfilled experimentally

  [Hiller/Zwicky arXiv:1312.1923]

- consistency checks among angular obs's in $B \to K^* \bar{\ell}\ell$ (in limit $m_\ell \to 0$)

  [Matias/Serra arXiv:1402.6855]

and/or the theory:

- theory @ high q^2

  1) local OPE is not reliable (even q^2-integrated OR large duality violation)

     ⇒ some predictions of OPE can be tested experimentally

     [CB/Hiller/van Dyk arXiv:1006.5013 + 1212.2321]

  2) q^2-binning in exp. data not yet optimal for OPE?
  3) $B \to K^*$ FFs from lattice too high and/or underestimated systematics?

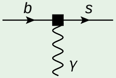
- theory @ low q^2

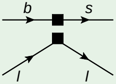
  1) for subleading corrections Λ_{QCD}/m_b (QCD factorization)
  2) large long-distance $\bar{c}c$ contributions

Backup Slides

Exclusive $B \to K^* (\to K\pi)\, \ell^+ \ell^-$

Hadronic amplitude $B \to K^* (\to K\pi)\, \ell^+ \ell^-$ — neglecting 4-quark operators

$\mathcal{M} = \langle K\pi|\;\; C_7 \times$ 

$+\;\; C_{9,10} \times$ 

$|B\rangle$

Exclusive $B \to K^* (\to K\pi)\, \ell^+\ell^-$

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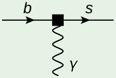
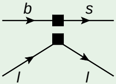
$$\mathcal{M} = \langle K\pi| \quad C_7 \times$$



$$+ \quad C_{9,10} \times$$



$$|B\rangle$$

$\mathcal{M}$ may expressed in terms of transversity amplitudes of K^* ($m_\ell = 0$)

. . . using narrow width approximation & intermediate K^* on-shell

⇒ "just" requires $B \to K^*$ form factors V, $A_{1,2}$, $T_{1,2,3}$:

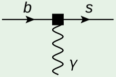
$$A_\perp^{L,R} \sim \sqrt{2\,\lambda}\left[(C_9 \mp C_{10})\frac{V}{M_B + M_{K^*}} + \frac{2\,m_b}{q^2} C_7\, T_1\right],$$

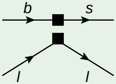
$$A_\parallel^{L,R} \sim -\sqrt{2}\,(M_B^2 - M_{K^*}^2)\left[(C_9 \mp C_{10})\frac{A_1}{M_B - M_{K^*}} + \frac{2\,m_b}{q^2} C_7\, T_2\right],$$

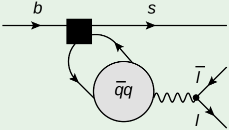
$$A_0^{L,R} \sim -\frac{1}{2\,M_{K^*}\sqrt{q^2}}\left\{(C_9 \mp C_{10})\Big[\ldots A_1 + \ldots A_2\Big] + 2\,m_b C_7\Big[\ldots T_2 + \ldots T_3\Big]\right\}$$

Exclusive $B \to K^* (\to K\pi)\, \ell^+ \ell^-$

Hadronic amplitude $B \to K^* (\to K\pi)\, \ell^+ \ell^-$ — including 4-quark operators

$\mathcal{M} = \langle K\pi | \quad C_7 \times$


$+ \quad C_{9,10} \times$


$+ \sum_i C_i \times$


$|B\rangle$

... but 4-Quark operators and $\mathcal{O}_{8g}$ have to be included

- current-current $b \to s + (\bar{u}u,\, \bar{c}c)$
- QCD-penguin operators $b \to s + \bar{q}q$ $(q = u, d, s, c, b)$

$\Rightarrow$ large peaking background around certain $q^2 = (M_{J/\psi})^2,\, (M_{\psi'})^2$:

$B \to K^{(*)} (\bar{q}q) \to K^{(*)} \bar{\ell}\ell$

Low-q^2 = Large Recoil

QCD Factorisation (QCDF)

[Beneke/Feldmann/Seidel hep-ph/0106067, hep-ph/0412400]

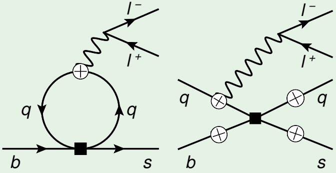
= (large recoil + heavy quark) limit [also Soft Collinear ET (SCET)]

$$\left\langle \bar{\ell}\ell\, K_a^* \left| H_{\text{eff}}^{(i)} \right| B \right\rangle \sim$$

$$C_a^{(i)} \times \xi_a + \phi_B \otimes T_a^{(i)} \otimes \phi_{a,K^*} + \mathcal{O}(\Lambda_{\text{QCD}}/m_b)$$

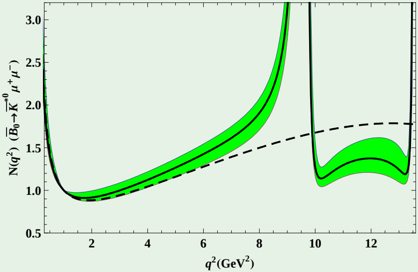
$C_a^{(i)}$, $T_a^{(i)}$: perturbative kernels in α_s ($a = \perp, \parallel$, $i = u, t$)

ϕ_B, ϕ_{a,K^*} : B– and K_a^*–distribution amplitudes



$c\bar{c}$-contributions

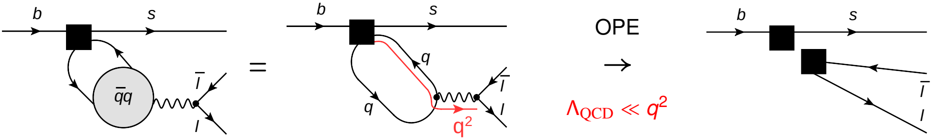
[Khodjamirian/Mannel/Pivovarov/Wang arXiv:1006.4945]



- OPE near light-cone incl. soft-gluon emission (non-local operator) for $q^2 \leq 4$ GeV^2 $\ll 4m_c^2$
- hadronic dispersion relation using measured $B \to K^{(*)}(\bar{c}c)$ amplitudes at $q^2 \geq 4$ GeV^2
- $B \to K^{(*)}$ form factors from LCSR
- up to (15-20) % in rate for $1 < q^2 < 6$ GeV^2

High-q^2 = Low Recoil

Hard momentum transfer $(q^2 \sim M_B^2)$ through $(\bar{q}q) \to \bar{\ell}\ell$ allows local OPE



$$\mathcal{M}[\bar{B} \to \bar{K}^* + \bar{\ell}\ell] \sim \frac{8\pi^2}{q^2} i \int d^4x\, e^{iq\cdot x} \langle \bar{K}^* | T\{\mathcal{L}^{\rm eff}(0), j_\mu^{\rm em}(x)\} | \bar{B}\rangle\, [\bar{\ell}\gamma^\mu \ell]$$

$$= \left(\sum_a \mathcal{C}_{3a} \mathcal{Q}_{3a}^\mu + \sum_b \mathcal{C}_{5b} \mathcal{Q}_{5b}^\mu + \sum_c \mathcal{C}_{6c} \mathcal{Q}_{6c}^\mu + \mathcal{O}(dim > 6) \right) [\bar{\ell}\gamma_\mu \ell]$$

Buchalla/Isidori hep-ph/9801456, Grinstein/Pirjol hep-ph/0404250, Beylich/Buchalla/Feldmann arXiv:1101.5118

Leading $dim = 3$ operators: $\langle \bar{K}^* | \mathcal{Q}_{3,a} | \bar{B}\rangle \sim$ usual $B \to K^*$ form factors $V, A_{0,1,2}, T_{1,2,3}$

$$\mathcal{Q}_{3,1}^\mu = \left(g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2} \right) [\bar{s}\gamma_\nu (1-\gamma_5) b] \quad \to \quad C_9 \to C_9^{\rm eff}, \quad (V, A_{1,2})$$

$$\mathcal{Q}_{3,2}^\mu = \frac{i m_b}{q^2} q_\nu \, [\bar{s}\sigma_{\nu\mu}(1+\gamma_5) b] \quad \to \quad C_7 \to C_7^{\rm eff}, \quad (T_{1,2,3})$$

High-q^2 = Low Recoil

[Beylich/Buchalla/Feldmann arXiv:1101.5118]

dim = 3	α_s matching corrections are also known
$m_s \neq 0$	2 additional *dim* = 3 operators, suppressed with $\alpha_s m_s / m_b \sim 0.5$ %, NO new form factors
dim = 4	absent
dim = 5	suppressed by $(\Lambda_{\rm QCD}/m_b)^2 \sim 2$ %, explicite estimate @ $q^2 = 15$ GeV^2: < 1%
dim = 6	suppressed by $(\Lambda_{\rm QCD}/m_b)^3 \sim 0.2$ % and small QCD-penguin's: $C_{3,4,5,6}$ spectator quark effects: from weak annihilation
beyond OPE	duality violating effects

- based on Shifman model for *c*-quark correlator + fit to recent BES data
- ± 2 % for integrated rate $q^2 > 15$ GeV^2

$\Rightarrow$ OPE of exclusive $B \to K^{(*)} \ell^+ \ell^-$ predicts small sub-leading contributions !!!

BUT, still missing $B \to K^{(*)}$ form factors @ high-q^2

for predictions of angular observables J_i

High-q^2: OPE + HQET

Framework developed by Grinstein/Pirjol hep-ph/0404250

1) OPE in $\Lambda_{\rm QCD}/Q$ with $Q = \{m_b, \sqrt{q^2}\}$ + matching on HQET + expansion in m_c

$$\mathcal{M}[\bar{B} \to \bar{K}^* + \bar{\ell}\ell] \sim \frac{8\pi}{q^2} \sum_{i=1}^{6} \mathcal{C}_i(\mu)\, \mathcal{T}_\alpha^{(i)}(q^2,\mu)\, [\bar{\ell}\gamma^\alpha \ell]$$

$$\mathcal{T}_\alpha^{(i)}(q^2,\mu) = i \int d^4x\, e^{iq\cdot x} \langle \bar{K}^* | T\{\mathcal{O}_i(0), j_\alpha^{\rm em}(x)\} | \bar{B}\rangle$$

$$= \sum_{k \geqslant -2} \sum_j C_{i,j}^{(k)} \langle \mathcal{Q}_{j,\alpha}^{(k)} \rangle$$

$\mathcal{Q}_{j,\alpha}^{(k)}$	power	$\mathcal{O}(\alpha_s)$
$\mathcal{Q}_{1,2}^{(-2)}$	1	$\alpha_s^0(Q)$
$\mathcal{Q}_{1-5}^{(-1)}$	$\Lambda_{\rm QCD}/Q$	$\alpha_s^1(Q)$
$\mathcal{Q}_{1,2}^{(0)}$	m_c^2/Q^2	$\alpha_s^0(Q)$
$\mathcal{Q}_{j>3}^{(0)}$	${\Lambda_{\rm QCD}}^2/Q^2$	$\alpha_s^0(Q)$
$\mathcal{Q}_{i}^{(2)}$	m_c^4/Q^4	$\alpha_s^0(Q)$

included,
unc. estimate by naive pwr cont.

2) HQET FF-relations at sub-leading order + α_s corrections in leading order

$$T_1(q^2) = \kappa\, V(q^2), \qquad T_2(q^2) = \kappa\, A_1(q^2), \qquad T_3(q^2) = \kappa\, A_2(q^2)\frac{M_B^2}{q^2},$$

$$\kappa = \left(1 + \frac{2D_0^{(v)}(\mu)}{C_0^{(v)}(\mu)}\right)\frac{m_b(\mu)}{M_B}$$

can express everything in terms of QCD FF's $V, A_{1,2}$ @ $\mathcal{O}(\alpha_s \Lambda_{\rm QCD}/Q)$!!!

Angular observables

$$J_i(q^2) \sim \{\text{Re, Im}\}\left[A_m^{L,R}\left(A_n^{L,R}\right)^*\right]$$

$$\sim \sum_a (C_a F_a) \sum_b (C_b F_b)^*$$

$A_m^{L,R}$ ... K^*-transversity amplitudes $m = \perp, \parallel, 0$

C_a ... short-distance coefficients

F_a ... form factors

Angular observables

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simplify when using form factor relations:

low K^* recoil limit: $E_{K^*} \sim M_{K^*} \sim \Lambda_{\mathrm{QCD}}$ [Isgur/Wise PLB232 (1989) 113, PLB237 (1990) 527]

$$T_1 \approx V, \qquad T_2 \approx A_1, \qquad T_3 \approx A_2 \frac{M_B^2}{q^2}$$

large K^* recoil limit: $E_{K^*} \sim M_B$ [Charles et al. hep-ph/9812358, Beneke/Feldmann hep-ph/0008255]

$$\xi_\perp \equiv \frac{M_B}{M_B + M_{K^*}} V \approx \frac{M_B + M_{K^*}}{2E_{K^*}} A_1 \approx T_1 \approx \frac{M_B}{2E_{K^*}} T_2$$

$$\xi_\| \equiv \frac{M_B + M_{K^*}}{2E_{K^*}} A_1 - \frac{M_B - M_{K^*}}{M_{K^*}} A_2 \approx \frac{M_B}{2E_{K^*}} T_2 - T_3$$

Sub-leading corrections to TransAmp's

$\lambda = \Lambda_{\mathrm{QCD}}/m_b \sim 0.15$

Low hadronic recoil

$$A_i^{L,R} \sim C^{L,R} \times f_i \qquad\qquad C^{L,R} = (C_9 \mp C_{10}) + \kappa \frac{2m_b^2}{q^2} C_7,$$

1 SD-coefficient $C^{L,R}$ and 3 FF's f_i ($i = \perp, \parallel, 0$)

$$f_\perp = \frac{\sqrt{2\hat{\lambda}}}{1 + \hat{M}_{K^*}} V, \qquad f_\parallel = \sqrt{2}\,(1 + \hat{M}_{K^*})\, A_1, \qquad f_0 = \frac{(1 - \hat{s} - \hat{M}_{K^*}^2)(1 + \hat{M}_{K^*})^2 A_1 - \hat{\lambda}\, A_2}{2\,\hat{M}_{K^*}\,(1 + \hat{M}_{K^*})\sqrt{\hat{s}}}$$

("helicity FF's" [Bharucha/Feldmann/Wick arXiv:1004.3249])

Low hadronic recoil

FF symmetry breaking

$$A_i^{L,R} \sim C^{L,R} \times f_i + C_7 \times \mathcal{O}(\lambda, \alpha_s)$$

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$C_7^{\rm SM} \approx -0.3, \; C_9^{\rm SM} \approx 4.2, \; C_{10}^{\rm SM} \approx -4.2$

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FF symmetry breaking OPE

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$\Rightarrow$ small, apart from possible duality violations

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Large hadronic recoil

$$A_{\perp,\parallel}^{L,R} \sim \pm C_\perp^{L,R} \times \xi_\perp + \mathcal{O}(\alpha_s, \lambda), \qquad A_0^{L,R} \sim C_\parallel^{L,R} \times \xi_\parallel + \mathcal{O}(\alpha_s, \lambda)$$

2 SD-coefficients $C_{\perp,\parallel}^{L,R}$ and 2 FF's $\xi_{\perp,\parallel}$

$$C_\perp^{L,R} = (C_9 \mp C_{10}) + \frac{2m_b M_B}{q^2} C_7, \qquad C_\parallel^{L,R} = (C_9 \mp C_{10}) + \frac{2\,m_b}{M_B} C_7,$$

Sub-leading corrections to TransAmp's

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Large hadronic recoil

$\Rightarrow$ limited, end-point-divergences at $\mathcal{O}(\lambda)$

$$A_{\perp,\parallel}^{L,R} \sim \pm C_\perp^{L,R} \times \xi_\perp + \mathcal{O}(\alpha_s, \lambda), \qquad A_0^{L,R} \sim C_\parallel^{L,R} \times \xi_\parallel + \mathcal{O}(\alpha_s, \lambda)$$

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“Global Fit” = combination of $b \to s + (\gamma, \bar{\ell}\ell)$ observables

Parameters of interest

$\vec{\theta} = C_i$ (Wilson coeff’s)

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Nuisance parameters

$\vec{\nu}$

1) process-specific

form factors & decay const's,
LCDA pmr's,
sub-leading Λ/m_b,
renormalization scales: $\mu_{b,0}$

2) general

quark masses, CKM, . . .

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Observables

1) observables

$$O(\vec{\theta}, \vec{\nu})$$

depend usually on sub-set of $\vec{\theta}$ and $\vec{\nu}$

2) experimental data for each observable

$$\text{pdf}(O = o)$$

$\Rightarrow$ probability distribution of values o

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Fit strategies: 1) Put theory uncertainties in likelihood:

$$\chi^2 = \sum \frac{(O_{\rm ex} - O_{\rm th})^2}{\sigma_{\rm ex}^2 + \sigma_{\rm th}^2}$$

- sample $\vec{\theta}$-space (grid, Markov Chain, importance sampling...)
- theory uncertainties of O_i at each $(\vec{\theta})_i$: vary $\vec{\nu}$ within some ranges $\Rightarrow \sigma_{\rm th}(O[(\vec{\theta})_i])$
- use Frequentist or Bayesian method $\Rightarrow$ 68 & 95 % (CL or CR) regions of $\vec{\theta}$

"Global Fit" = combination of $b \to s + (\gamma, \bar{\ell}\ell)$ observables

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depend usually on sub-set of $\vec{\theta}$ and $\vec{\nu}$

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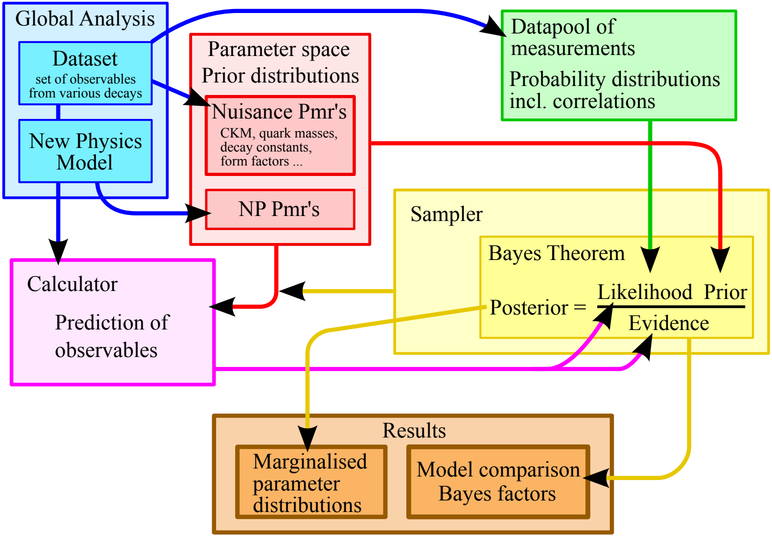
Fit strategies: 2) Fit also nuisance parameters:

- sample $(\vec{\theta} \times \vec{\nu})$-space (grid, Markov Chain, importance sampling...)
- accounts for theory uncertainties by fitting also $(\vec{\nu})_i$
- use Frequentist or Bayesian method $\Rightarrow$ 68 & 95 % (CL or CR) regions of $\vec{\theta}$ and $\vec{\nu}$

Workflow of global data analysis implemented in EOS . . .



Newly developed Sampler: Population Monte Carlo (PMC) initialised with Markov Chain samples

$\Rightarrow$ highly parallelizable !