$B \to K^{(*)}\mu^+\mu^-$ @ Low Recoil and Physics Implications

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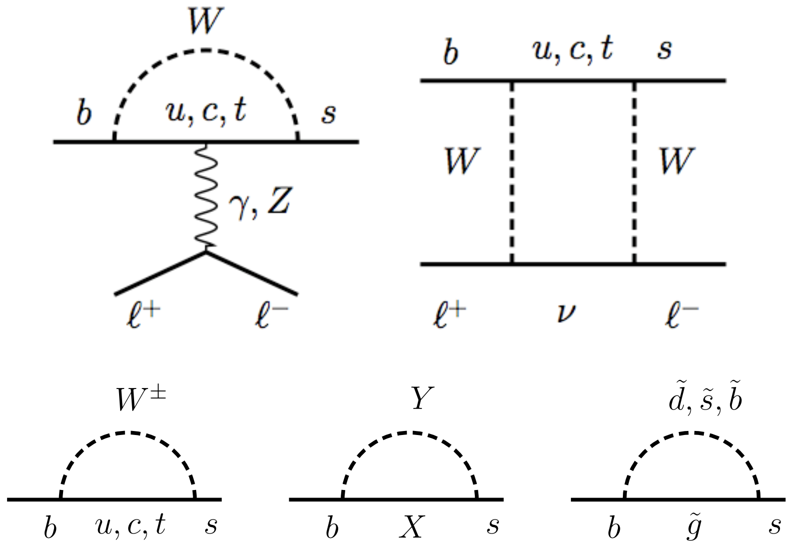
based on works with Christoph Bobeth, Danny van Dyk, Christian Hambrock, Stefan Schacht, Christian Wacker, Roman Zwicky

Exclusive semileptonic FCNC $b \to s\mu^+\mu^-$ decays

$\Delta F = 1$ FCNC; sensitive to flavor in and beyond the SM.

$Br_{\rm SM} \sim 10^{-6} - 10^{-7}$



observed (at SM level):

$B \to K^{(*)}\mu^+\mu^-$ BaBar, Belle, CDF 6.8 fb^{-1} and LHCb 1 fb^{-1} LHCb-CONF-2012-008

$B_s \to \Phi\mu^+\mu^-$ CDF 2011 1101.1028 [hep-ex] LHCb 2012 LHCb-CONF-2012-008

$\Lambda_b \to \Lambda\mu^+\mu^-$ CDF 2011 1107.3753 [hep-ex]

distributions measured. precision physics started.

$B \to K^{(*)} + 2$ **Leptons – Theory**

Different theory in both regions – binned data needed.

- Small dilepton mass $q^2 \leftrightarrow$ large hadronic recoil $E_{K^*} \gg \Lambda$
  QCD Factorization BBNS, Beneke, Feldmann, Seidel'01,04

- Large $q^2 \sim \mathcal{O}(m_b) \leftrightarrow$ low hadronic recoil $E_{K^*} \sim \Lambda$
  Operator product expansion in $1/m_b$ Grinstein,Pirjol '04, Beylich, Buchalla,Feldmann'11

THIS TALK:

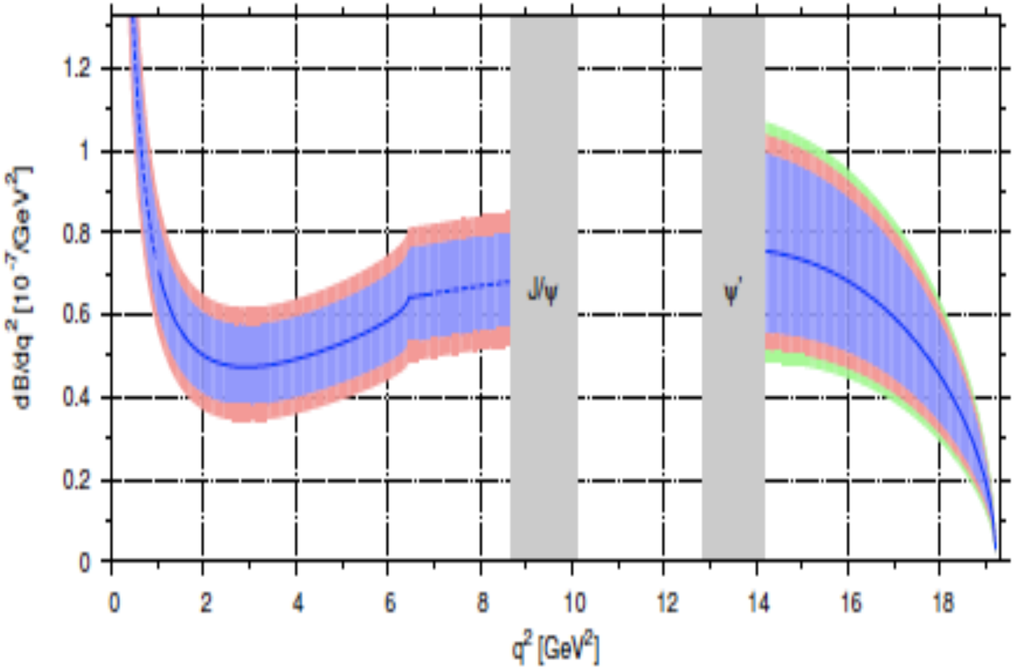
- Low recoil $B \to K^{(*)}\mu^+\mu^-$ predictions, pheno & implications

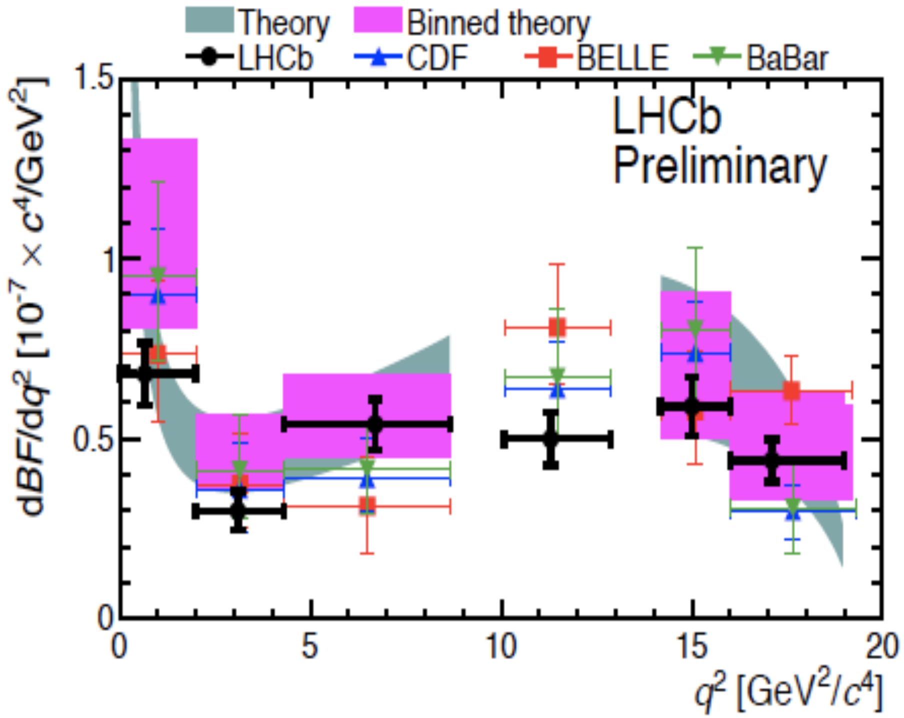
  Bobeth,GH, vanDyk, Wacker '10,11,12

- Extractions of hadronic form factor ratios at low recoil from data

  GH, Hambrock '12, and in preparation together with Schacht, Zwicky

Situation: Dilepton Mass Spectrum in $B \to K^* \mu^+ \mu^-$





left-hand Fig. from 1006.5013 [hep-ph] Blue band: form factor uncertainties, red: $1/m_b$ right-hand Fig. from LHCb-CONF-2012-008

Biggest source of theory uncertainty: the $B \to K^*$ form factors.

Opportunity: Angular Analysis $B \to K^*(\to K\pi)\mu^+\mu^-$

$$d\Gamma^4 \sim J dq^2 d\cos\Theta_l d\cos\Theta_{K^*} d\Phi$$ Krüger, Sehgal,Sinha, Sinha hep-ph/9907386

$$\begin{aligned} J(q^2,\theta_l,\theta_{K^*},\phi) = {} & J_1^s \sin^2\theta_{K^*} + J_1^c \cos^2\theta_{K^*} + (J_2^s \sin^2\theta_{K^*} + J_2^c \cos^2\theta_{K^*})\cos 2\theta_l \\ & + J_3 \sin^2\theta_{K^*} \sin^2\theta_l \cos 2\phi + J_4 \sin 2\theta_{K^*} \sin 2\theta_l \cos\phi + J_5 \sin 2\theta_{K^*} \sin\theta_l \cos\phi \\ & + J_6 \sin^2\theta_{K^*} \cos\theta_l + J_7 \sin 2\theta_{K^*} \sin\theta_l \sin\phi \\ & + J_8 \sin 2\theta_{K^*} \sin 2\theta_l \sin\phi + J_9 \sin^2\theta_{K^*} \sin^2\theta_l \sin 2\phi, \qquad (2.3) \end{aligned}$$

Θ_l: angle between l^- and $\bar{B}$ in dilepton CMS (warning: different conventions in literature)

Θ_{K^*}: angle between K and $\bar{B}$ in K^*-CMS

Φ: angle between normals of the $K\pi$ and l^+l^- plane

complex structure, plenty of observables, not all need full $\mathrm{d}^4\Gamma$.

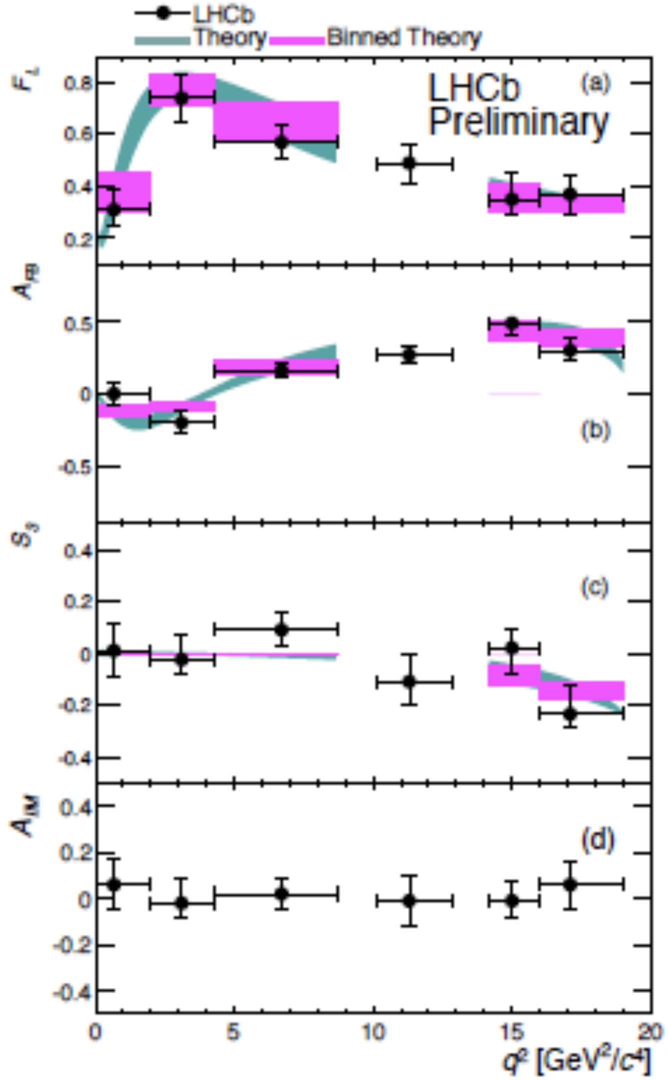
$\Gamma \sim J_1 - J_2/3$, $A_{\mathrm{FB}} \sim J_6$, $A_T^{(2)} \sim J_3$ Krüger, Matias hep-ph/0502060

With full $\Delta B = 1$ dimension six operators: Bobeth et al, 1212.2321 [hep-ph]

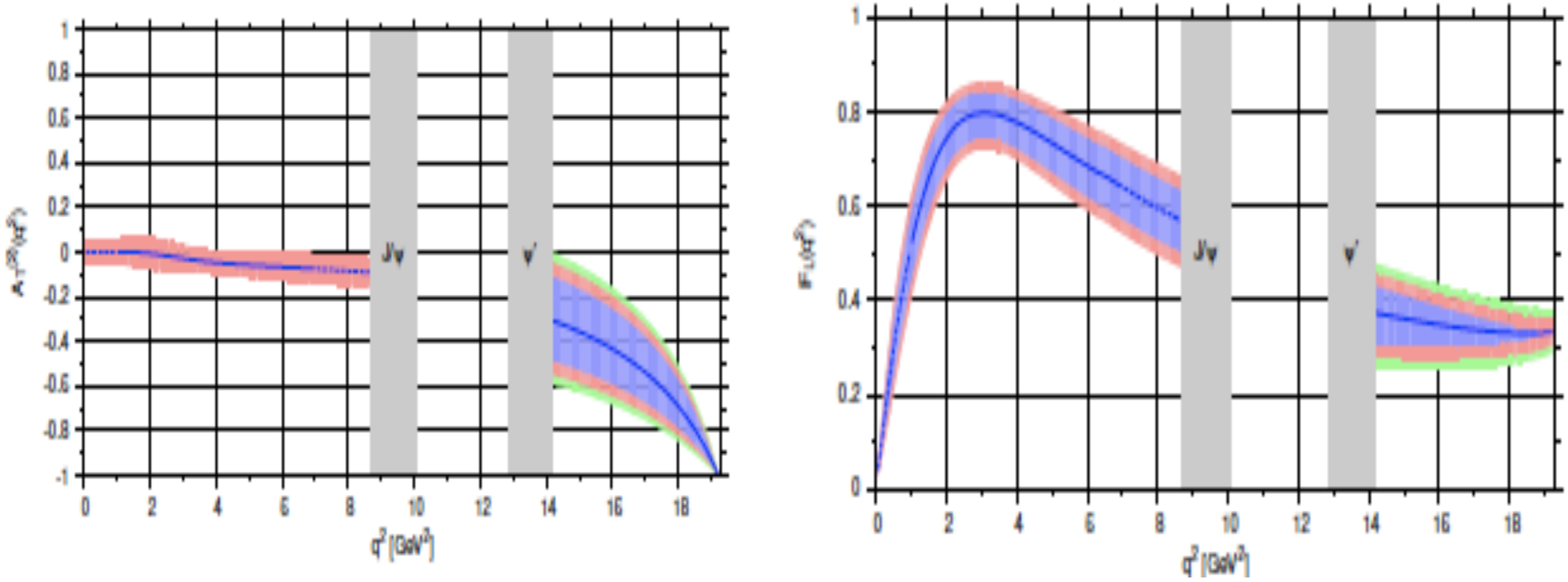
Angular distributions available 2012

$B^0 \to K^{*0}\mu^+\mu^-$ Angular Analysis Results

- 4D fit to 3 angles and mass
- Larger data sample enables measurements of S_3 and $A_{\rm IM}$
- Error bars include systematic uncertainties
- Data points at average q^2 of signal candidates in data
- These are the most precise measurements to-date [preliminary]
- The results are consistent with the SM prediction [1]



A_T^2 and F_L in $B \to K^* \mu^+ \mu^-$



Figs. from 1006.5013 [hep-ph] Blue band: form factor uncertainties, red: $1/m_b$ $A_T^{(2)} = 2S_3/(1-F_L)$

F_L: fraction of longitudinally polarized K^*

$A_T^{(2)}$: transverse Asymmetry; Null test of SM at low q^2

Both probe form factor ratios at low recoil! pollution from BSM right-handed currents can be controlled by e.g. $A_T^{(2)}$@large recoil; currently $\lesssim 30$ % Bobeth et al '12

A_T^2 and F_L in $B \to K^* \mu^+ \mu^-$ data 2012

	BaBar	CDF		LHCb	
q^2 [GeV^2]	F_L	F_L	$A_T^{(2)}$	F_L	$A_T^{(2)}$
$[14.18, 16]$	$0.43^{+0.13}_{-0.16}$	$0.40^{+0.12}_{-0.12}$	$0.11^{+0.65}_{-0.65}$	$0.35^{+0.10}_{-0.06}$	$0.06^{+0.24}_{-0.29}$
$[16, 19.xx]$	$0.55^{+0.15}_{-0.17}$	$0.19^{+0.14}_{-0.13}$	$-0.57^{+0.60}_{-0.57}$	$0.37^{+0.07}_{-0.08}$	$-0.75^{+0.35}_{-0.20}$

Benefits of $B \to K^*$ at low recoil

At low hadronic recoil transversity amplitudes $A_i^{L,R}$, $i = \perp, ||, 0$ related:

$$A_i^{L,R} \propto C^{L,R} f_i$$

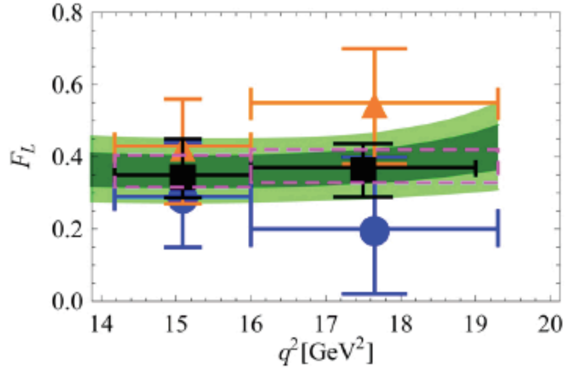
$C^{L,R}$: universal short-dist.-physics; $C^{L,R} = (C_9^{\text{eff}} \mp C_{10}) + \kappa \frac{2\hat{m}_b}{\hat{s}} C_7^{\text{eff}}$

$1/m_b$- corrections parametrically suppressed $\sim \alpha_s/m_b, C_7/C_9 1/m_b$

f_i: form factors

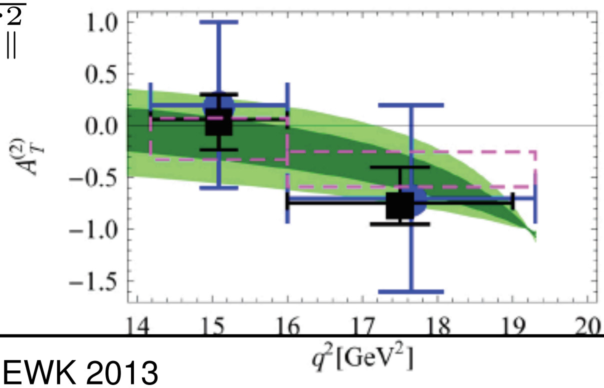
$C^{L,R}$ drops

out in ratios:



$$F_L = \frac{|A_0^L|^2 + |A_0^R|^2}{\sum_{X=L,R}(|A_0^X|^2 + |A_\perp^X|^2 + |A_\parallel^X|^2)} = \frac{f_0^2}{f_0^2 + f_\perp^2 + f_\parallel^2}$$

$$A_T^{(2)} = \frac{|A_\perp^L|^2 + |A_\perp^R|^2 - |A_\parallel^L|^2 - |A_\parallel^R|^2}{|A_\perp^L|^2 + |A_\perp^R|^2 + |A_\parallel^L|^2 + |A_\parallel^R|^2} = \frac{f_\perp^2 - f_\parallel^2}{f_\perp^2 + f_\parallel^2}$$

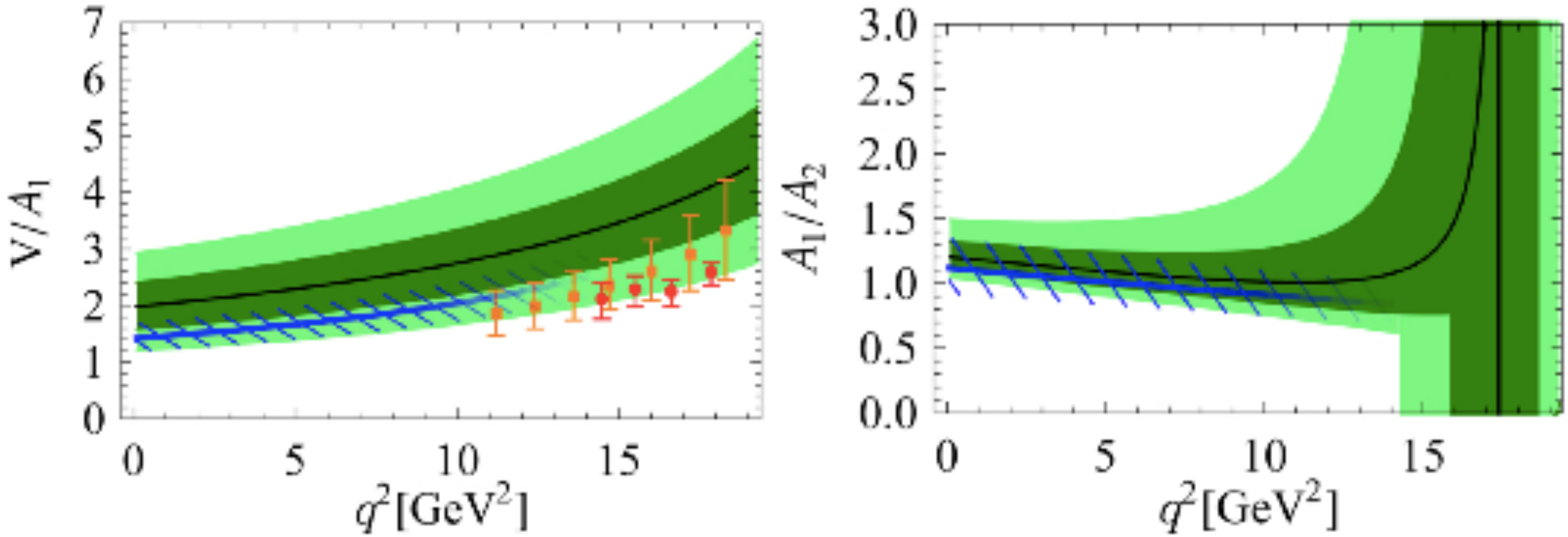


Extracting $B \to K^*$ form factors from data

Using series expansion

$$\hat{f}_i(t) = \frac{(\sqrt{-z(t,0)})^m (\sqrt{z(t,t_-)})^l}{B(t)\,\varphi_f(t)} \sum_k \alpha_{i,k}\, z^k(t)\,,$$

The best-fit results: $\alpha_\parallel/\alpha_\perp = 0.43^{+0.11}_{-0.08},\ \alpha_0/\alpha_\perp = 0.15^{+0.03}_{-0.02}$



Yellow, red points; lattice QCD; blue bands: QCD sum rules Ball, Zwicky '05: green bands: $1, 2\sigma$ fit 1204.4444 [hep-ph]

1. Its great to have (even more) data.

2. With (even one) more bins the sensitivity in the fits to the q^2-shape increases.

3. If you (lattice, sum rules,..) calculate form factors, please provide also ratios (with uncertainties).

4. Data-extracted form factor ratios constitute benchmarks for lattice form factor estimations at low recoil.

Exploiting $B \to K^* l^+ l^-$ at low recoil further

OPE in $1/Q$, $Q = \{m_b, \sqrt{q^2}\}$ by Grinstein, Pirjol '04 with heavy quark FF relations $T_{1,2,3} \leftrightarrow V, A_{1,2}$ leads to simply transversity structure with universal short-distance C and form factor coefficients f_i

$$A_i^{L,R} \sim C^{L,R} \cdot f_i$$

up to corrections of order $\alpha_s \Lambda / m_b$ and $(C_7/C_9)\Lambda/m_b$ (few percent).

Allows to design new observables which are Bobeth, GH,vanDyk 1006.5013, and '11,'12

– independent of form factors ($H_T^{(2,3,4,5)}$)

– independent of short-distance coefficients and test the form factors

– independent of either ones and test the theoretical low recoil framework $H_T^{(1)}$, $H_T^{(2)}/H_T^{(3)}$, $H_T^{(4)}/H_T^{(5)}$

Exploiting $B \to K^* l^+ l^-$ at low recoil further

$$H_T^{(1)} = \frac{\mathrm{Re}(A_0^L A_\parallel^{L*} + A_0^{R*} A_\parallel^R)}{\sqrt{\left(|A_0^L|^2 + |A_0^R|^2\right)\left(|A_\parallel^L|^2 + |A_\parallel^R|^2\right)}} = \frac{\sqrt{2} J_4}{\sqrt{-J_2^c\,(2J_2^s - J_3)}},$$

$$H_T^{(2)} = \frac{\mathrm{Re}(A_0^L A_\perp^{L*} - A_0^{R*} A_\perp^R)}{\sqrt{\left(|A_0^L|^2 + |A_0^R|^2\right)\left(|A_\perp^L|^2 + |A_\perp^R|^2\right)}} = \frac{\beta_l J_5}{\sqrt{-2J_2^c\,(2J_2^s + J_3)}},$$

$$H_T^{(3)} = \frac{\mathrm{Re}(A_\parallel^L A_\perp^{L*} - A_\parallel^{R*} A_\perp^R)}{\sqrt{\left(|A_\parallel^L|^2 + |A_\parallel^R|^2\right)\left(|A_\perp^L|^2 + |A_\perp^R|^2\right)}} = \frac{\beta_l J_6}{2\sqrt{(2J_2^s)^2 - J_3^2}}.$$

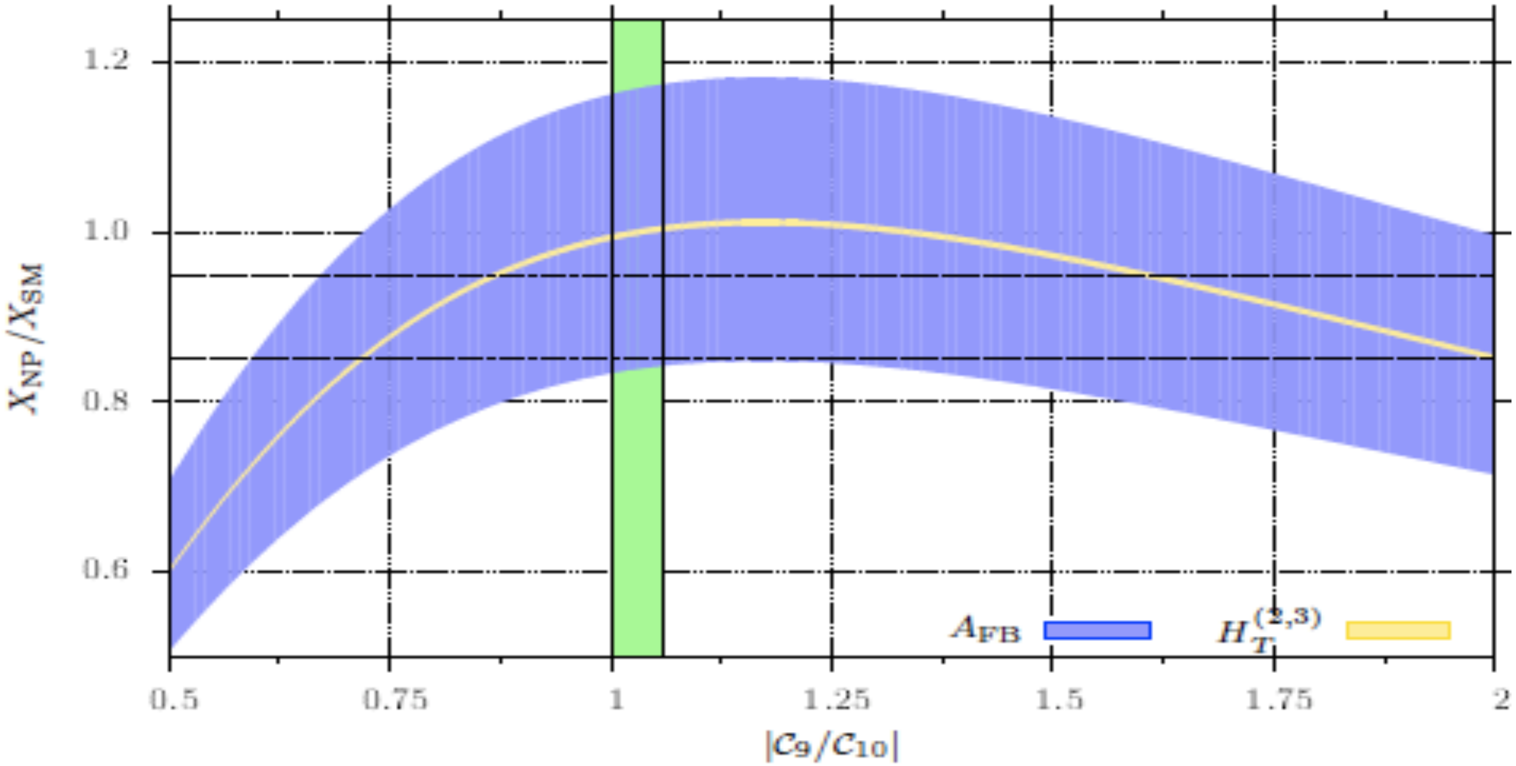
Low recoil Heavy-quark-OPE: $H_T^{(1)} = 1, \qquad H_T^{(2)}/H_T^{(3)} = 1.$

Extract them from the $B \to K^*(\to K\pi)\mu^+\mu^-$ angular distribution.

Further Benefits of $B \to K^* l^+ l^-$ at low recoil: BSM

Reach in low recoil-integrated observables vs Wilson coefficients

C_9/C_{10}



green: SM; blue: A_{FB} (f_i-dependent) gold: $H_T^{(2)}$ (f_i-free)

Fig from 1212.2321

Further Benefits of $B \to K^* l^+ l^-$ at low recoil: BSM-CP

Reach in low recoil-integrated CP-asymmetries vs Wilson coefficients C'_{10}

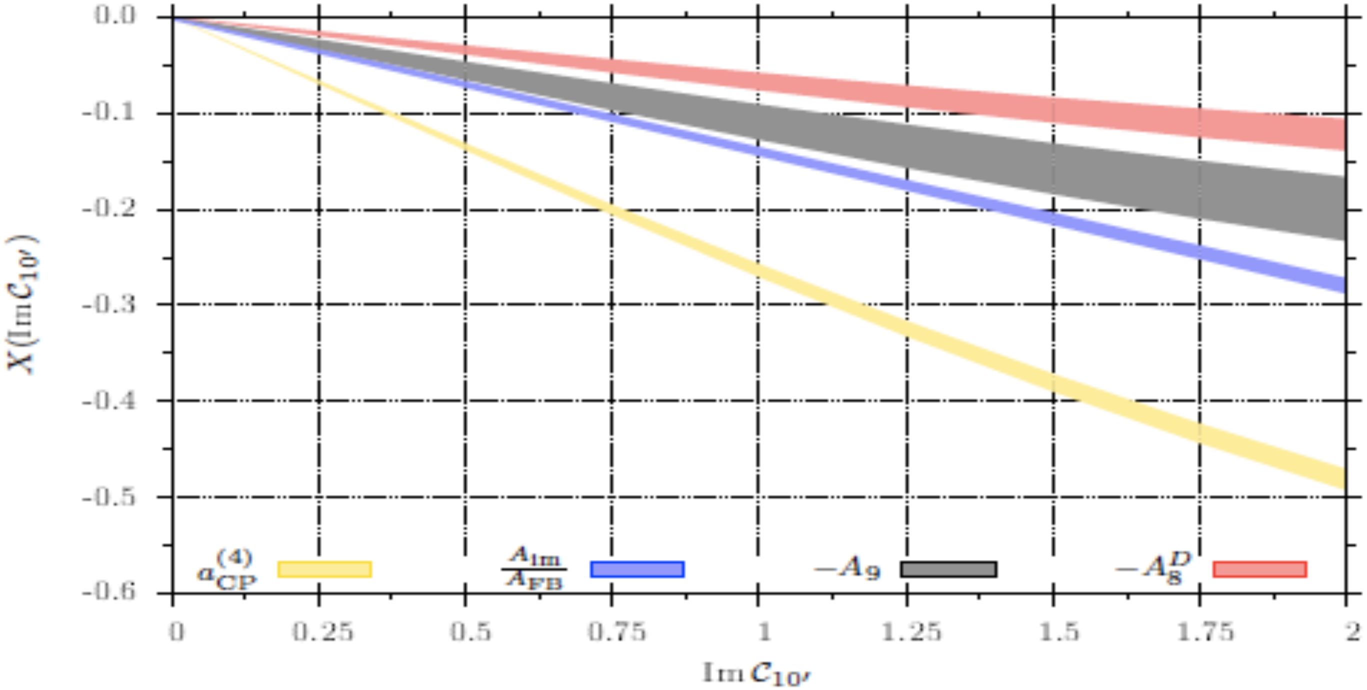


Fig from 1212.2321

gold: CP-asymmetry of $H_T^{(4)}$; blue $A_{im}/A_{FB} = J_9/J_{2s} \sim H_T^{(5)}/H_T^{(3)}$: both f_i-free; other two $A_{8,9}$ not

Summary

- It is fantastic to witness great advances in FCNC b-decays and respective tests of SM and BSM physics. After observing exclusive $b \to sll$ modes, first results of basic decay distributions and asymmetries are now available by several experiments. More involved and designed ones are accessible by angular analysis, promising for LHCb and Tevatron with muons; opportunity for electrons and neutrinos, also inclusive modes and if feasible taus, for super flavor factory.
- Lots of recent TH focus on angular distribution and their exploitation.
- New developments at low hadronic recoil in theory pheno+lattice greatly support exploitation of todays and tomorrows data.

- The large number of complementary observables accessible with $b \to s$ decays allows us to map out precisely the flavor structure at the TeV-scale.

$\ast$ It's fun to have data!