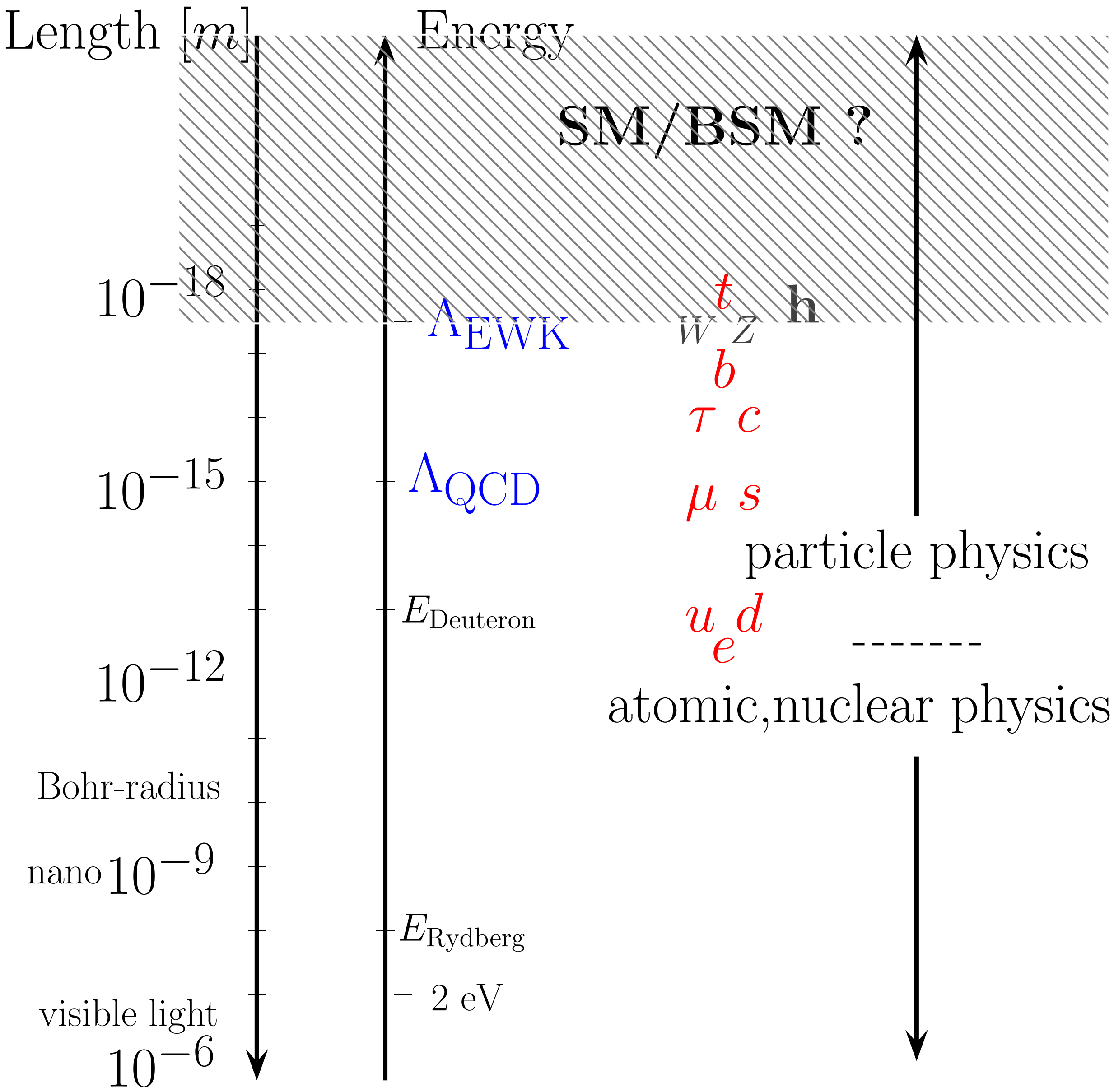
From flavor data to QCD and back:

rare decays 2014

Gudrun Hiller, Dortmund

based on works with Christian Hambrock, Stefan Schacht and Roman Zwicky, 1308.4379 [hep-ph], 1312.1923 [hep-ph]

Exploring Physics at Highest Energies



The Higgs-flavor arena

With observation of scalar boson with mass 126 GeV scalar new arena for flavor physics.

In SM, $f = q, l$:

– $hf\bar{f}'$ couplings are strictly flavor diagonal $\propto \delta_{ff'}$.

– $hf\bar{f}'$ couplings are strictly $\propto m_f$, $\mu(h \to \tau\tau)/\mu(h \to \mu\mu)|_{SM} = \frac{m_\tau^2}{m_\mu^2}$.

$\mu(h \to f\bar{f})$: signal strength

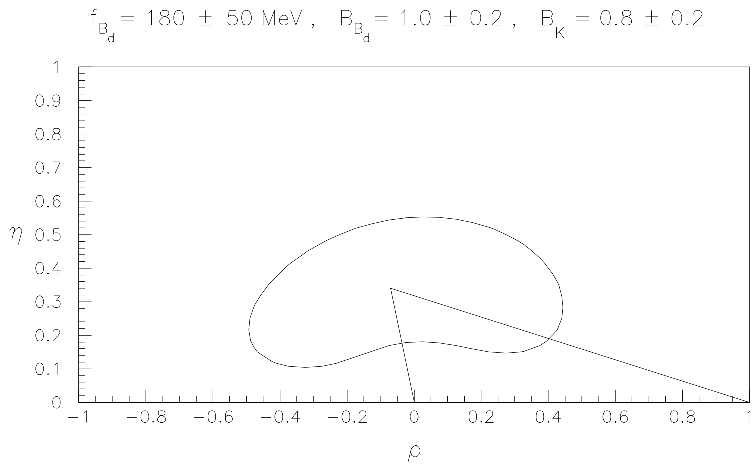
Already in 2 Higgs Doublet models, this doesnt have to be the case. Important test of SM and flavor physics. e.g. arXiv: :1302.3229,1304.6727

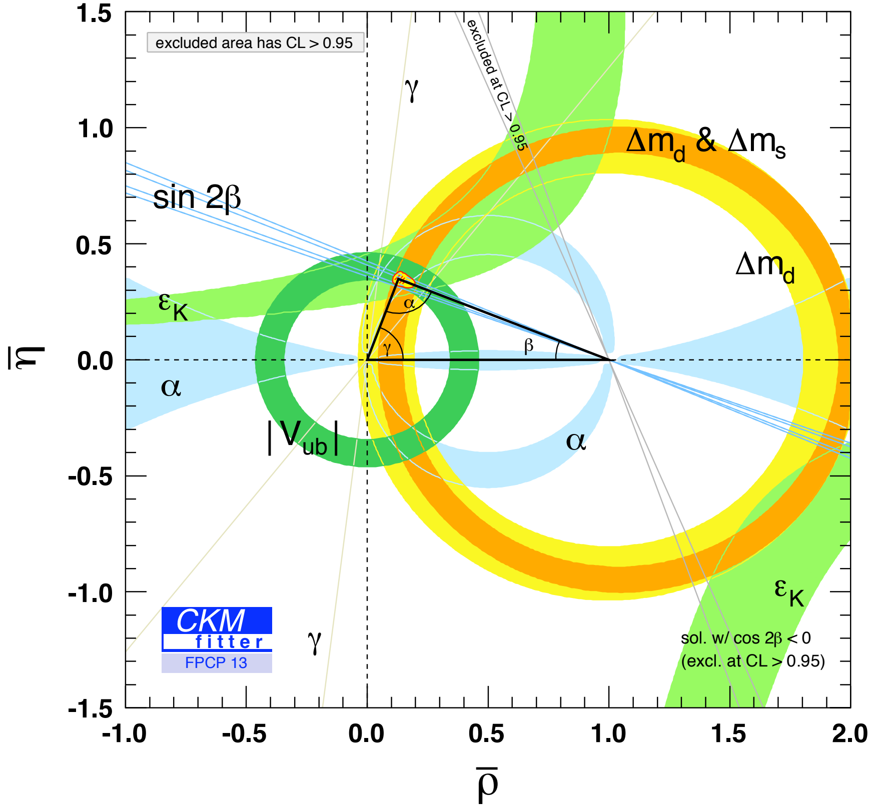
Aspen flavor workshop: ”Connecting Flavor Physics with Naturalness: from Theory to Experiment” ,

Aspen Center for Physics, R.Harnik, GH, G.Kribs,J.Zupan Colorado, June 22-July 20, 2014

SM tests with Quark flavor/CKM 1995 vs today

The CKM-picture of flavor and CP violation is currently consistent with all – and quite different – laboratory observations, although some tensions exist.





$$V_{CKM}V_{CKM}^{\dagger} = 1$$

Different sectors and different couplings presently probed:

$s \to d$: $K^0 - \bar{K}^0$, $K \to \pi\nu\bar{\nu}$

$c \to u$: $D^0 - \bar{D}^0$, ΔA_{CP}

$b \to d$: $B^0 - \bar{B}^0$, $B \to \rho\gamma$, $b \to d\gamma$, $B \to \pi\mu\mu$

$b \to s$: $B_s - \bar{B}_s$, $b \to s\gamma$, $B \to K_s\pi^0\gamma$, $b \to sll$, $B \to K^{(*)}ll$, $B_s \to \Phi ll$ (precision, angular analysis), $B_s \to \mu\mu$, $\Lambda_b \to \Lambda\mu\mu$

$t \to c, u$, $l \to l'$: not observed

$B \to K^*(\to K\pi)\mu\mu$, $Br \sim 10^{-7}$ angular distributions

LHCb collaboration ($1fb^{-1}$)
arXiv:1304.6325

Results

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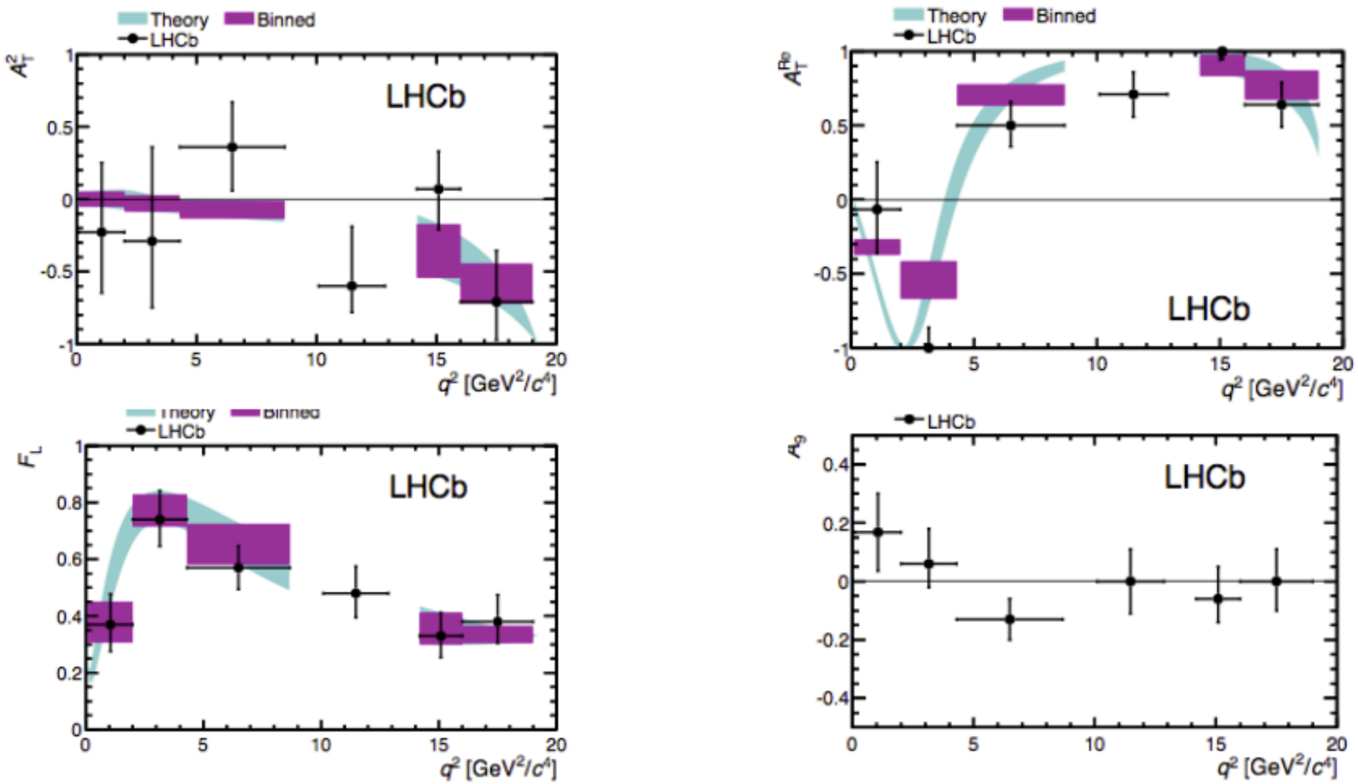
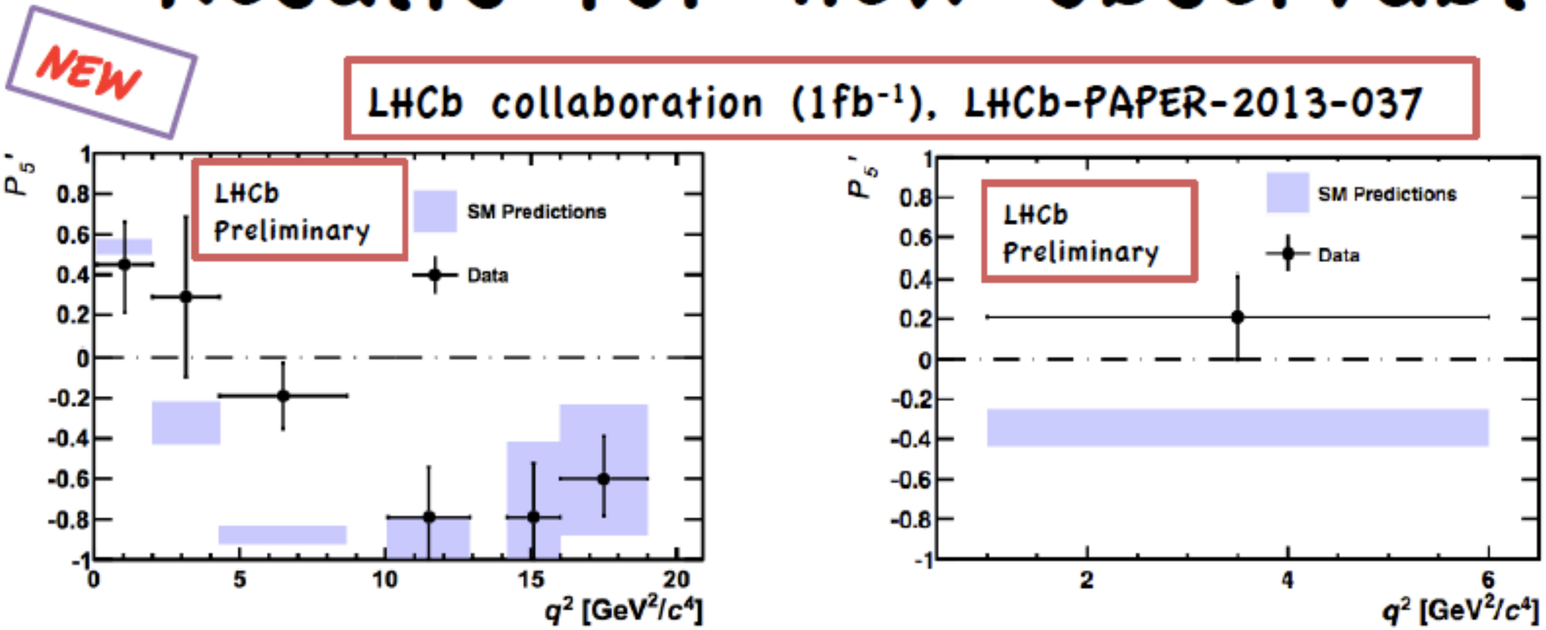


Good agreement with SM predictions
Bobeth-Hiller-Van Dyk (2011): Form-factor from Ball-Zwiky (2005):
Consistent with Matias et al.(2013)

18-24/07/2013 Nicola Serra - EPS 2013 10

$B \to K^*(\to K\pi)\mu\mu$, $Br \sim 10^{-7}$ angular distributions

Results for new observables



There are many more measurements on this mode, also from ATLAS and CMS. This is the one with a lot of discussions.

2013+: lots of data, and more to come. (LHCb run n, Belle II)

Sufficient control of hadronic physics vital for searches and interpretation.

contents of this talk:

1) Extracting form factor ratios from $B \to K^*$ data
2) Model-independent relations at & near the kinematic endpoint

$B \to K^* \mu^+ \mu^-$ data progress 2012 to 2013

2012:

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

2013:

	BaBar	CDF		LHCb			ATLAS	CMS
q^2	F_L	F_L	$A_T^{(2)}$	F_L	$A_T^{(2)}$	$^a\, P_4'$	F_L	F_L
bin1	$0.43^{+0.13}_{-0.16}$	$0.40^{+0.12}_{-0.12}$	$0.11^{+0.65}_{-0.65}$	$0.33^{+0.08}_{-0.08}$	$0.07^{+0.26}_{-0.28}$	$-0.18^{+0.54}_{-0.70}$	$0.28^{+0.16}_{-0.16}$	$0.53^{+0.12}_{-0.12}$
bin2	$0.55^{+0.15}_{-0.17}$	$0.19^{+0.14}_{-0.13}$	$-0.57^{+0.60}_{-0.57}$	$0.38^{+0.09}_{-0.08}$	$-0.71^{+0.36}_{-0.26}$	$0.70^{+0.44}_{-0.52}$	$0.35^{+0.08}_{-0.08}$	$0.44^{+0.08}_{-0.08}$

more experiments, more observables sensitive to form factors

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

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

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

$C^{L,R}$: 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 $\sim \alpha_s/m_b, C_7/(C_9 m_b)$

f_i: form factors

$C^{L,R}$ drops out in ratios:

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

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

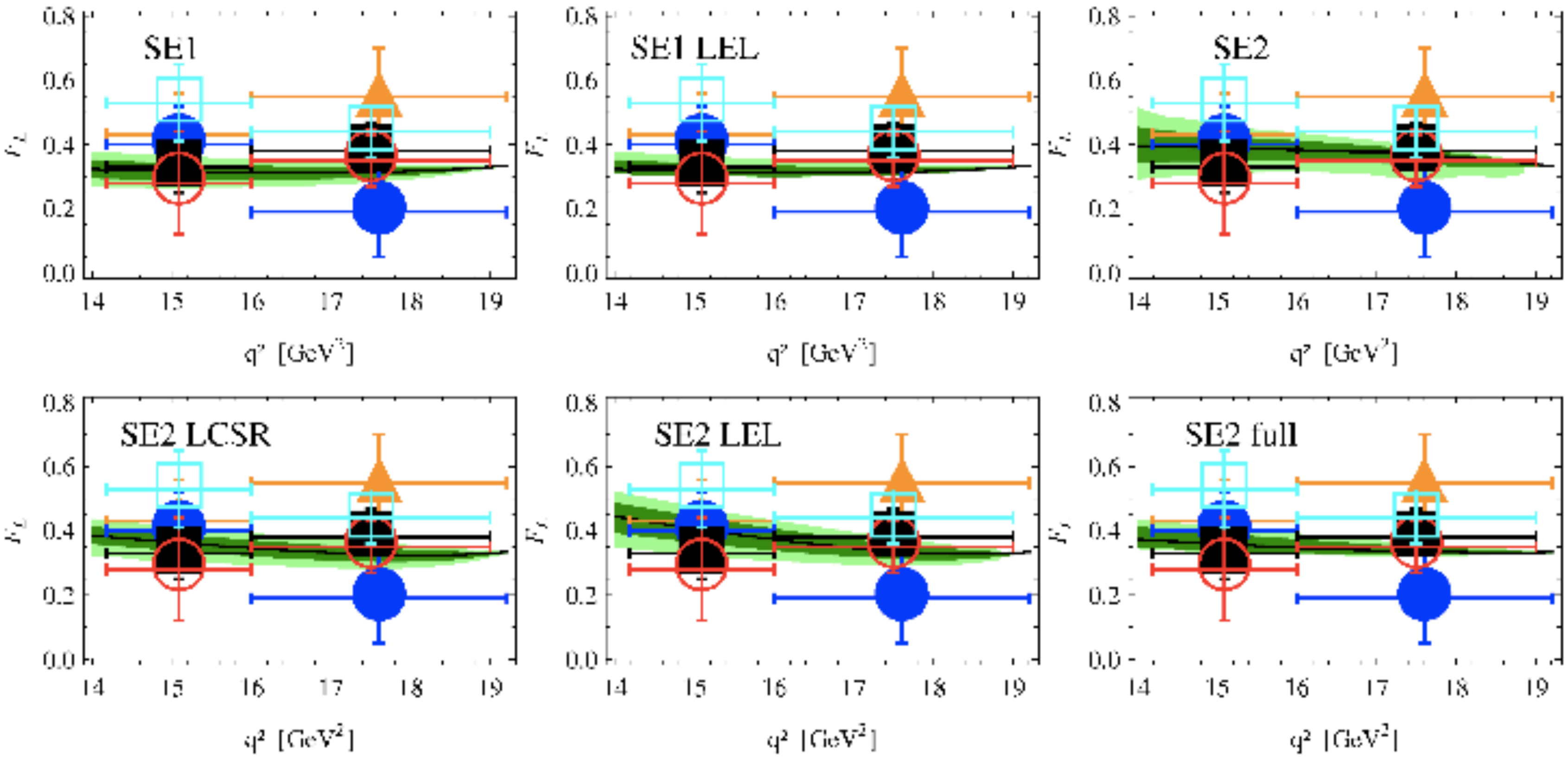
$$P_4'(q^2) = \frac{\sqrt{2} f_\parallel(q^2)}{\sqrt{f_\parallel^2(q^2) + f_\perp^2(q^2)}}$$

$*$ assuming only V-A operators

Advances in ... Extracting $B \to K^*$ form factors

Higher order Series Expansion; use theory input from low q^2: LCSR (sum rules) or $V(0)/A_1(0) = (m_B + m_{K^*})^2/(2m_B E_{K^*}) + \mathcal{O}(1/m_b) = 1.33 \pm 0.4$ (LEL)

F_L:



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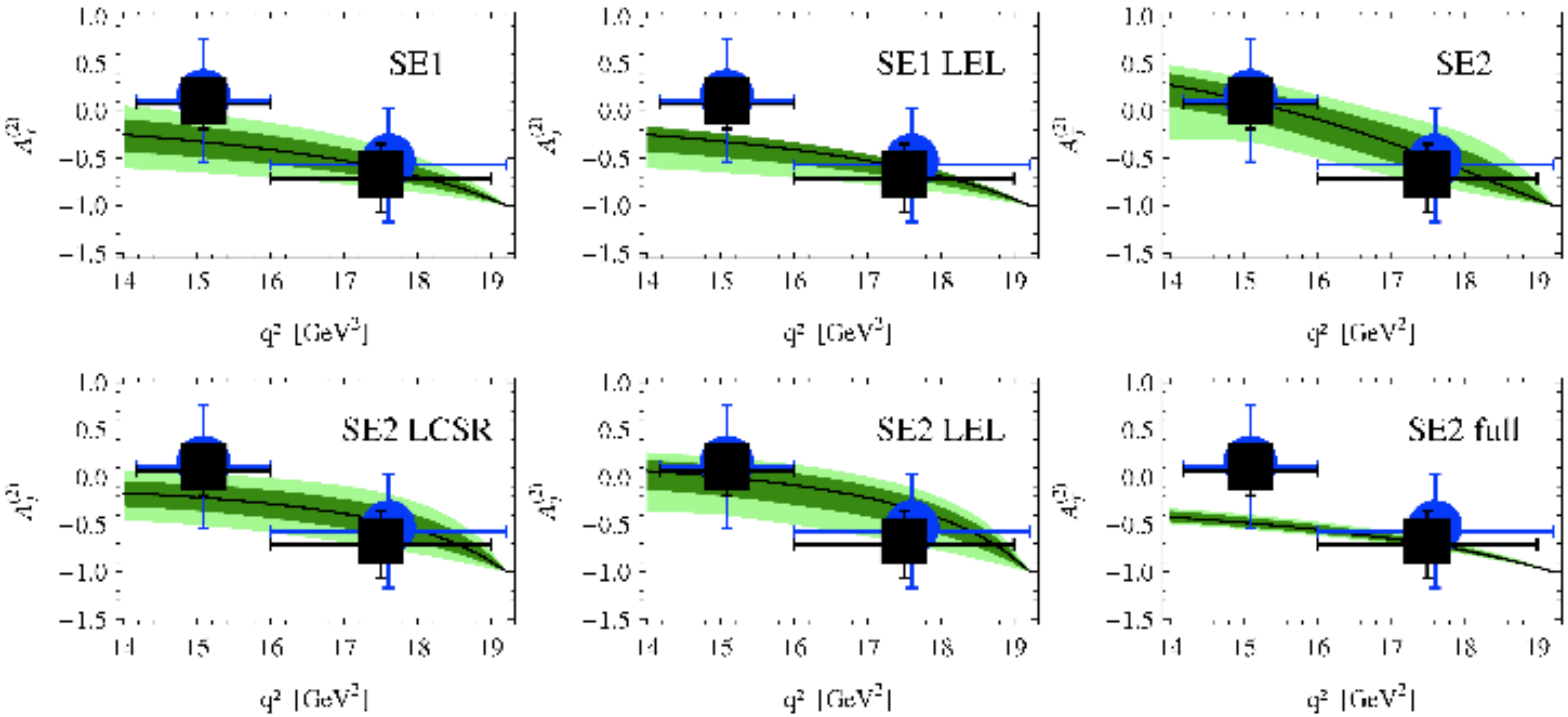
$A_T^{(2)}$:



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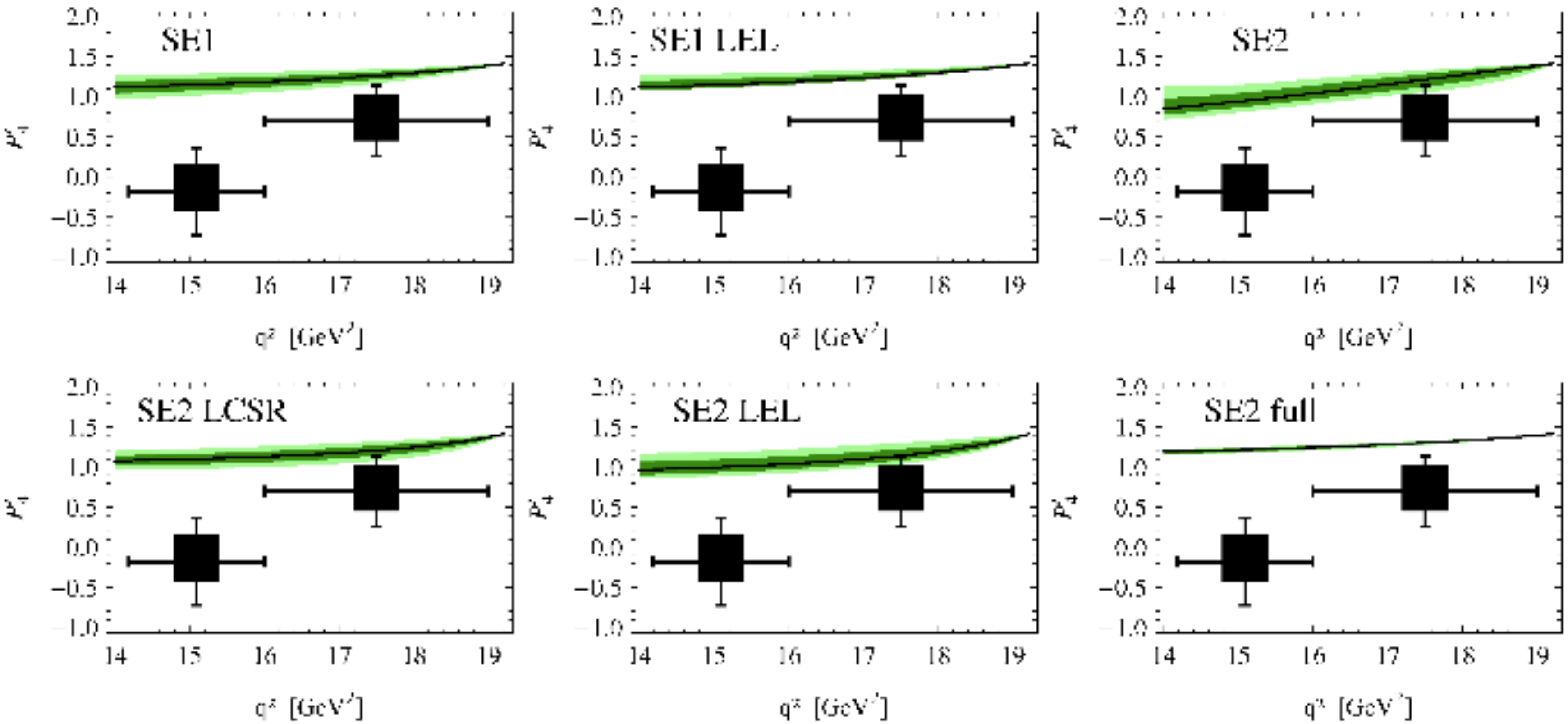
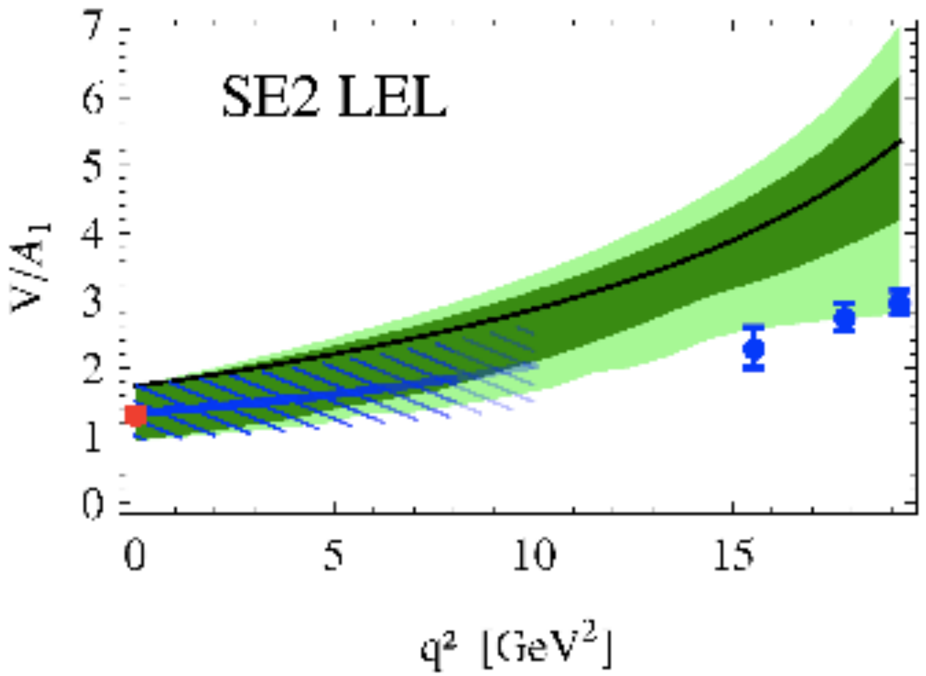
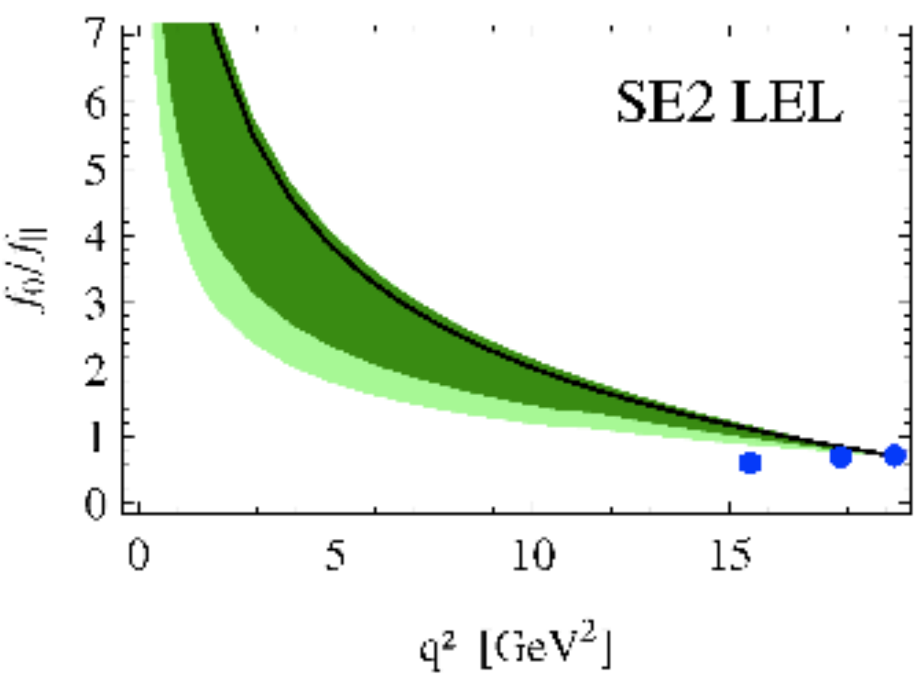


Advances in ... Extracting $B \to K^*$ form factors

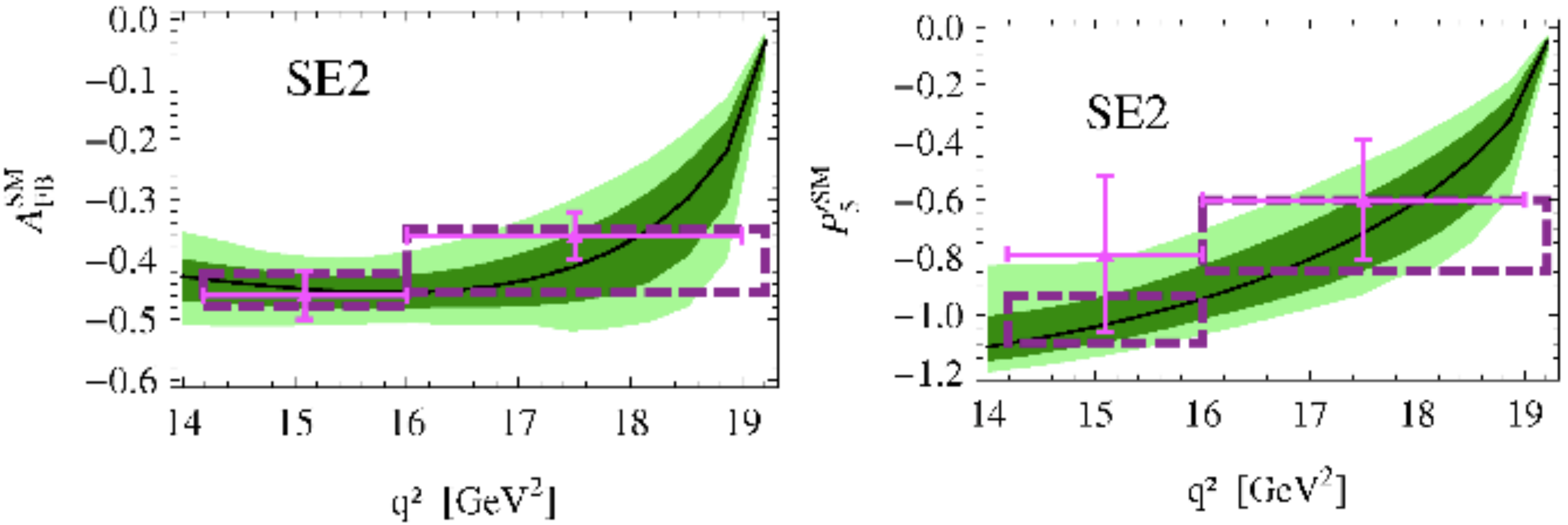




Predictivity at low q^2 is obtained from low q^2 input. (Required at higher order)

Data-extracted form factor ratios constitute benchmark for lattice form factor estimations at low recoil. Blue points: Wingate '13 et al

Advances in ... Extracting $B \to K^*$ form factors



SM predictions for A_{FB} and P_5' at low recoil (assuming $V - A$ currents). Good agreement with data in fits in both low recoil bins.

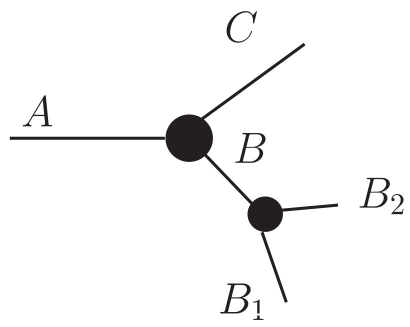
P_4' escapes explanation within factorizaton Altmannshofer, Straub '13, Hambrock, GH, Schacht, Zwicky '13, Beaujean, Bobeth, vanDyk '13, Descotes-Genon, Matias, Virto '13

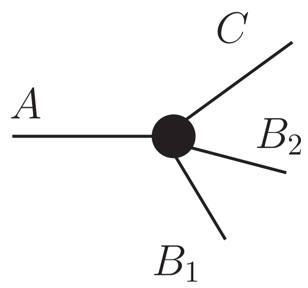
2) Model-independent relations at & near the kinematic endpoint

Introduction– endpoint kinematics and helicity

Consider particle decays

- $A \to B(\to B_1 B_2)C$ "sequential"
- $A \to B_1 B_2 C$ "from local operators", effective (weak) Hamiltonian





(Both types appear in weak flavor decays, e.g. $B \to K^{(*)}\ell^+\ell^-$ used to test the SM)

At zero recoil A at rest decays to C at rest, $\boldsymbol{p}_A = \boldsymbol{p}_C = 0$ and $\boldsymbol{p}_B \equiv \boldsymbol{p}_{B_1} + \boldsymbol{p}_{B_2} = 0$ (back-to-back). Assuming an unpolarized initial state, there is no preferred direction for $\boldsymbol{p}_{B_i}$. This implies relations among helicity amplitudes because of fewer lorentz invariants.

Helicity amplitudes $A \rightarrow (B_1 B_2)(\beta) C(\gamma)$

Decay amplitude in product form:

$$\mathcal{A}(A \rightarrow (B_1 B_2) C) = (B_1 B_2)_{\mu_1 .. \mu_X} \times C^{\mu_1 .. \mu_X}_{A \rightarrow B}(p_A^2, p_B^2, p_C^2)$$

Use completeness relation for polarization vectors $\omega(\lambda_r)$; λ: helicity ($\bar{\lambda} = -\lambda$)

$$\sum_{\lambda,\lambda' \in \{t,\pm,0\}} \omega^\mu(\lambda) \omega^{*\nu}(\lambda') G_{\lambda\lambda'} = g^{\mu\nu} \ , \quad G_{\lambda\lambda'} = \mathrm{diag}(1,-1,-1,-1)$$

Here for spin(A)$= 0$ and spin(C)$= 1$:

$$\mathcal{A}(A \rightarrow (B_1 B_2) C) = H_{\lambda_{B_1} .. \lambda_{B_X}, \lambda_C} (B_1 B_2)_{\lambda_{B'_1} .. \lambda_{B'_X}} G^{\lambda_{B_1} \lambda_{B'_1}} .. G^{\lambda_{B_X} \lambda_{B'_X}}$$

with helicity amplitudes H $\qquad C^{\alpha\mu_1 .. \mu_X} \gamma^*_\alpha(\lambda_C) \equiv C^{\mu_1 .. \mu_X}$

$$H_{\lambda_{B_1} .. \lambda_{B_X}, \lambda_C} = C^{\alpha\mu_1 .. \mu_X} \gamma^*_\alpha(\lambda_C) \beta^*_{\mu_1}(\lambda_{B_1}) .. \beta^*_{\mu_X}(\lambda_{B_X})$$

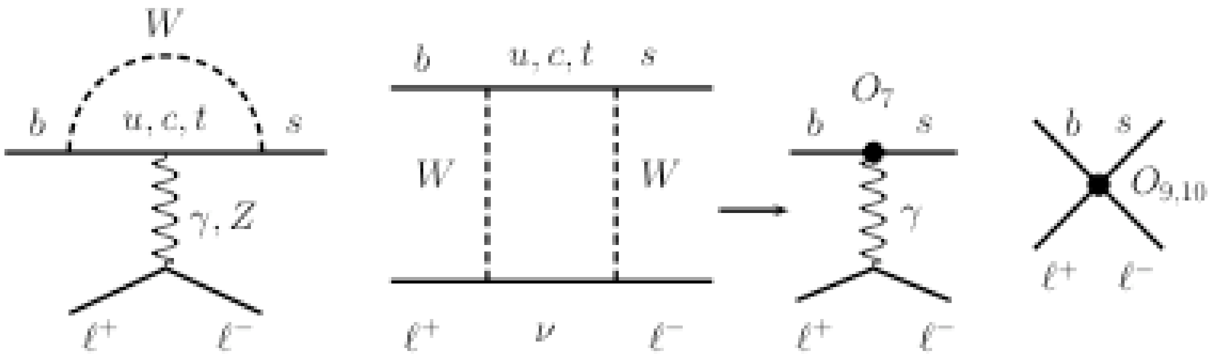
$$(B_1 B_2)_{\lambda_{B'_1} .. \lambda_{B'_X}} = (B_1 B_2)^{\mu_1 .. \mu_X} \beta_{\mu_1}(\lambda_{B_1}) .. \beta_{\mu_X}(\lambda_{B_X})$$

Notation for $\lambda_A = 0$ by helicity conservation $\lambda_A = \sum_{i=1}^{X} \lambda_{B_i} + \bar{\lambda}_C$:

$$H_{\lambda_{B_1} .. \lambda_{B_X}, \lambda_C} \rightarrow H_{\lambda_{B_1} .. \lambda_{B_X}}$$

Weak decays induced by effective Hamiltonians

$$\mathcal{H}_{\text{eff}} = -4\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i(\mu) O_i(\mu).$$



complete dim 6 basis for $|\Delta F| = 1$ transitions:

$$O_{S(P)} = \bar{s}_L b\, \bar{\ell}(\gamma_5)\ell\ , \quad O_{V(A)} = \bar{s}_L \gamma^\mu b\, \bar{\ell}\gamma_\mu(\gamma_5)\ell \ \ (\propto O_{9(10)})\ ,$$
$$O_{\mathcal{T}} = \bar{s}_L \sigma^{\mu\nu} b\, \bar{\ell}\sigma_{\mu\nu}\ell\ , \quad O' = O|_{s_L \to s_R}$$

”sequential” contributions with photons can be absorbed because S,P,V,A,T algebra closes. It follows $X \leq 2$. X: number of completeness relation insertions.

example1: S,P operators ($X = 0$): ansatz: $H_{S,P} = \gamma^*_\alpha(\lambda_C)\Gamma^\alpha$, $\lambda_C = 0$.

For lorentz vector Γ^α use available 4-momenta.

Endpoint kinematics in A-cms:

$$p_A = p_B + p_C, \;\; p_B = ((p_B)_0, 0, 0, 0), \;\; p_C = ((p_C)_0, 0, 0, 0)$$

At endpoint all 4-momenta are parallel, and since $p_C \cdot \gamma(\lambda_C) = 0$ the scalar product always vanishes.

$$H_{S,P} = 0.$$

Helicity symmetries at zero recoil

example 2: V,A operators ($X = 1$): $H_{\lambda_B} = \gamma^*_\alpha(\lambda_C)\beta^*_\mu(\lambda_B)\Gamma^{\alpha\mu}$, $\lambda_C = \lambda_B$

Use polarization vectors of B-(pseudo-) particle:

$\beta(0) = (0,0,0,(p_B)_0)/\sqrt{p_B^2}, \quad \beta(t) = p_B/\sqrt{p_B^2},$

$\gamma(0) = (0,0,0,(p_C)_0)/\sqrt{p_C^2}, \quad \gamma(\pm) = \beta(\mp) = (0,\mp 1, i, 0)/\sqrt{2}$

$$\beta(\lambda_B)\cdot\gamma(\lambda_C) = \begin{cases} 1 & \lambda_B = \bar{\lambda}_C = \pm \\ -1 & \lambda_B = \lambda_C = 0 \\ 0 & \text{otherwise} \end{cases}$$

$\Gamma^{\alpha\mu} = c\cdot\beta^\alpha(\lambda_B = \lambda_C)\beta^\mu(\lambda_B)$ is non-zero unless $\lambda_B = t$, and

$H_0 = -H_+ = -H_-$, $H_t = 0$; transversity basis $H_{\parallel(\perp)} \equiv \frac{1}{\sqrt{2}}(H_+ \pm H_-)$

$$H_\parallel = -\sqrt{2}H_0\,,\; H_\perp = 0.$$

for tensor amplitudes ($X = 2$), see arXiv:1312.1923 [hep-ph]

Summary, Generalizations

The endpoint relations ...

– are based on kinematics i.e. lorentz invariance only, hence independent of dynamics (approximation/BSM). (the ones we derived are for dim 6 basis.)

– hold exactly as long as decay is in endpoint configuration. For hadronic decays the relations are equally observable unless inelastic events are too frequent. E.g. $B \to V\Lambda\bar{\Lambda}$, $B \to Vp\bar{p}$, $B \to V\pi\pi$ ...

– in particular, hold beyond the low recoil OPE for $B \to K^{(*)}\ell^+\ell^-$ in $1/Q$, $Q = \{m_b, \sqrt{p_B^2}\}$ Grinstein,Pirjol '04, Beylich, Buchalla,Feldmann'11

– are generalizable to other spins and to more multi-particle final states, e.g. $S \to$ Spin 2 $+\ell\ell$

$$H_{\bar{2}} \,:\, H_{\bar{1}} \,:\, H_0 \,:\, H_1 \,:\, H_2 = 0 : 1 : \tfrac{-2}{\sqrt{3}} : 1 : 0 \,.$$

In SM+SM' basis (V,A operators and flipped ones only) the effective Wilson coefficients $C^{\text{eff}}_{\pm}(q^2) \equiv C^{\text{eff}}(q^2) \pm C^{\text{eff}\prime}(q^2)$ are independent of the polarization Bobeth,GH,van Dyk'12 (and as they should in agreement with endpoint relations)

$$B \to V\ell\ell: \quad H_{0,\|} = C^{\text{eff}}_{-}(q^2) f_{0,\|}(q^2)\,, \quad H_{\perp} = C^{\text{eff}}_{+}(q^2) f_{\perp}(q^2)\,,$$

$$B \to P\ell\ell: \quad H = C^{\text{eff}}_{+}(q^2) f(q^2)$$

$f_i, i = 0, \perp, \|$ (f) : usual $B \to V$ ($B \to P$) form factors

Parameterize corrections to the lowest order OPE results as

$f_\lambda(q^2) \to f_\lambda(q^2)(1 + \epsilon_\lambda(q^2))\,, \quad \epsilon_\lambda(q^2) = \mathcal{O}(\alpha_s/m_b, [\mathcal{C}_7/\mathcal{C}_9]/m_b)$ $\lambda = 0, \pm 1$

The endpoint relations imply degeneracy at endpoint

$\epsilon_\lambda(q^2_{\text{max}}) \equiv \epsilon\,, \quad \lambda = 0, \pm 1, \|, \perp$ with the endpoint relations already enforced by $f_{\|}(q^2_{\text{max}}) = \sqrt{2} f_0(q^2_{\text{max}})$, $f_{\perp}(q^2_{\text{max}}) = 0$. "There are no true non-factorizable contributions ($1/m_b$, resonances,..) at zero recoil."

Full $B \to K^*(\to K\pi)\ell\ell$ angular distribution

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

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

$J_i = J_i(q^2) = (H_j H_k^*)$ are bilinears of helicity/transversity amplitudes.

Θ_l: angle between l^- and $\bar{B}$ in dilepton CMS

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

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

Endpoint relations imply that the J_i are not independent:

$$J_{2s}(q^2_{\max}) = -J_{2c}(q^2_{\max})/2\,, \quad J_{1s}(q^2_{\max}) - J_{2s}(q^2_{\max})/3 = J_{1c}(q^2_{\max}) - J_{2c}(q^2_{\max})/3\,,$$

$$J_3(q^2_{\max}) = -J_4(q^2_{\max})\,, \qquad J_{2c}(q^2_{\max}) = J_3(q^2_{\max})\,, \quad J_{5,6s,6c,7,8,9}(q^2_{\max}) = 0\,.$$

Endpoint relations for uniangular distributions

From the endpoint relation we obtain (in full dim 6 basis) isotropic uniangular distributions

$$\frac{d^2\Gamma}{d\cos\Theta_\ell dq^2} \Big/ \left(\frac{d\Gamma}{dq^2}\right) = \kappa\kappa_\ell \left(\left(J_{1s} + \frac{J_{1c}}{2}\right) + \left(J_{6s} + \frac{J_{6c}}{2}\right)\cos\Theta_\ell + \left(J_{2s} + \frac{J_{2c}}{2}\right)\cos 2\Theta_\ell\right) \Big/ \left(\frac{d\Gamma}{dq^2}\right) \to \frac{1}{2}$$

$$\frac{d^2\Gamma}{d\cos\Theta_K dq^2} \Big/ \left(\frac{d\Gamma}{dq^2}\right) = \kappa\kappa_\ell \frac{3}{2} \left(\left(J_{1s} - \frac{J_{2s}}{3}\right)\sin^2\Theta_K + \left(J_{1c} - \frac{J_{2c}}{3}\right)\cos^2\Theta_K\right) \Big/ \left(\frac{d\Gamma}{dq^2}\right) \to \frac{1}{2}$$

The uniangular distribution in φ is not isotropic in general.

$\frac{d^2\Gamma}{d\varphi dq^2} / \left(\frac{d\Gamma}{dq^2}\right) = \frac{1}{2\pi}\left(1 + r_\varphi \cos 2\varphi\right)$, $r_\varphi \equiv \frac{-8J_{2s}}{9(J_{1s} - 1/3 J_{2s})}$ This is to be expected since φ is the angle between the two decay planes which has no special rôle at the kinematic endpoint. In SM + SM' operator basis ($O_{V(A)}$ and primed only) one obtains $r_\varphi^{V,A} = -1/3 + \mathcal{O}(m_\ell^2/m_b^2)$.

r_φ is modified i.e. sensitive to tensor contributions. see arXiv:1312.1923 [hep-ph] for formulae

Endpoint relations for key observables

(hold in full dim 6 basis)

longitudinal K^* polarization fraction:

$$F_L(q^2_{\rm max}) = \kappa\kappa_\ell \left(J_{1c} - \tfrac{1}{3} J_{2c}\right) / \left(\frac{d\Gamma}{dq^2}\right) = \frac{1}{3}$$

forward-backward asymmetry $A_{\rm FB}(q^2_{\rm max}) = \kappa\kappa_\ell \left(J_{6s} + \frac{J_{6c}}{2}\right) / \left(\frac{d\Gamma}{dq^2}\right) = 0$

transverse asymmetry $A_T^{(2)}(q^2_{\rm max}) = J_3/(2J_{2s}) = -1$

CP-(A)symmetries $A^{(D)}_{5,6,7,8,9}(q^2_{\rm max}) = 0, \;\; S_{5,6,7,8,9}(q^2_{\rm max}) = 0$

$$P'_{5,6,8}(q^2_{\rm max}) = 0\,, \qquad P'_4(q^2_{\rm max}) = \sqrt{2}$$

low recoil observables:

$$|H_T^{(1)}(q^2_{\rm max})| = 1\,, \quad H_T^{(1b)}(q^2_{\rm max}) = 1\,, \quad \frac{H_T^{(2)}(q^2_{\rm max})}{H_T^{(3)}(q^2_{\rm max})} = 1\,, \quad \frac{H_T^{(4)}(q^2_{\rm max})}{H_T^{(5)}(q^2_{\rm max})} = 1$$

observables from Krüger, Matias '05, Bobeth,GH,Piranishvili '08, Altmannshofer et al '08, Descotes-Genon et al '12, Bobeth,GH,van Dyk,10,12

Semileptonic B, D decays to vectors

Besides $B \to K^* \ell\ell$, the helicity relations apply to the rare decays

$$B \to \rho(\to \pi\pi)\ell^+\ell^-, \quad B_s \to \varphi(\to KK)\ell^+\ell^-, \quad B_s \to K^*(\to K\pi)\ell^+\ell^-,$$
$$B_c \to D_s^*(\to D_s\pi^0)\ell^+\ell^-, \quad B_c \to D^*(\to D\pi)\ell^+\ell^-,$$
$$D \to \rho(\to \pi\pi)\ell^+\ell^-, \quad D_s \to K^*(\to K\pi)\ell^+\ell^- \,,$$

as well as lepton flavor violating ones $S \to V\ell^+\ell'^-$, where $\ell \neq \ell'$, dineutrino-modes and charged current decays $S \to V(\to P_1P_2)\ell\nu$:

$$B \to D^*(\to D\pi)\ell\nu, \quad B_s \to D_s^*(\to D_s\pi^0)\ell\nu, \quad B_s \to K^*(\to K\pi)\ell\nu, \quad B \to \rho(\to \pi\pi)\ell\nu \,,$$
$$B_c \to \psi(3770)(\to DD)\ell\nu, \quad B_c \to D^*(\to D\pi)\ell\nu,$$
$$D \to \rho(\to \pi\pi)\ell\nu, \quad D_{(s)} \to K^*(\to K\pi)\ell\nu \,, \quad D_s \to \varphi(\to KK)\ell\nu \,.$$

Near zero recoil: the κ-expansion

$\kappa = |\boldsymbol{p_B}| = |\boldsymbol{p_C}| = \sqrt{\frac{\lambda(p_A^2, p_B^2, p_C^2)}{4p_A^2}}$ measures the distance away from the kinematic endpoint $\kappa = 0$.

Exploit parity to expand helicity amplitudes in κ, using $C_\pm \equiv C \pm C'$

H	H_t	$H_{0,\parallel}$	$H_\perp$	$H_{0,\parallel}^{\mathcal{T}_t}$	$H_\perp^{\mathcal{T}_t}$	$H_{0,\parallel}^{\mathcal{T}}$	$H_\perp^{\mathcal{T}}$
C_-	C_-	C_-	C_+	C_-	C_+	C_+	C_-
$\kappa + ..$	$\kappa + ..$	$\kappa^0 + ..$	$\kappa + ..$	$\kappa^0 + ..$	$\kappa + ..$	$\kappa^0 + ..$	$\kappa + ..$

Higher order corrections are at (relative) $\mathcal{O}(\kappa^2)$, e.g.

$$H_\parallel^x = -\sqrt{2} H_0^x = a_\parallel^x + \mathcal{O}(\kappa^2)\ , \quad H_\perp^x = a_\perp^x \kappa + \mathcal{O}(\kappa^3)\ , \quad x = L, R$$

$\kappa^2/q^2 \leq 0.06$ for $B \to K^* \ell\ell$ at low recoil.

Relations at endpoint and slope/ pheno

	F_L	S_3	$^a P'_4$	$^b P'_5/A_{\rm FB}$	$^b S_8/S_9$	$^a A_{\rm FB}$	P'_5	$^a S_8$	S_9
endp.	$1/3$	-1/3	$\sqrt{2}$	$\sqrt{2}$	$-1/2$	$\hat{R}\kappa$	$\sqrt{2}\hat{R}\kappa$	$1/3\hat{I}\kappa$	$-2/3\hat{I}\kappa$
$B \to K^*$	0.38 ± 0.04	-0.22 $\pm$ 0.09	$0.70^{+0.44}_{-0.52}$	1.63 ± 0.57	-0.5 ± 2.2	-0.36 ± 0.04	$-0.60^{+0.21}_{-0.18}$	-0.03 ± 0.12	$0.06^{+0.11}_{-0.10}$
$B_s \to \varphi$	$0.16^{+0.18}_{-0.12}$	$0.19^{+0.30}_{-0.31}$	–	–	–	–	–	–	–

Table 1: Endpoint predictions vs. world average in the available endpoint-bin $q^2 \in [16, 19]\,{\rm GeV}^2$ (LHC-experiments) or otherwise $q^2 \in [16\,{\rm GeV}^2, q^2_{\rm max}]$. $S_3 = 1/2(1-F_L)A_T^{(2)}$. $\hat{R} = R/|A|^2$, $\hat{I} = I/|A|^2$. For slope assume SM+SM' basis and $m_l = 0$.

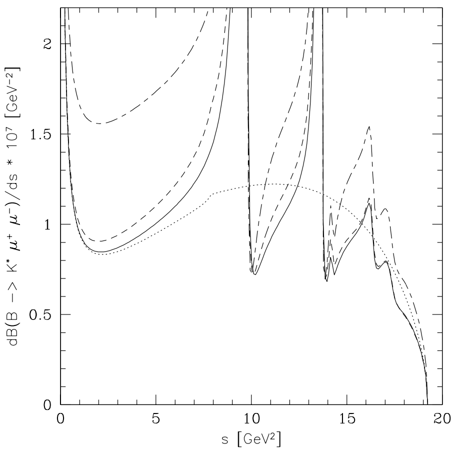
$|A|^2 \equiv |a_\parallel^L|^2 + |a_\parallel^R|^2$, $R \equiv {\rm Re}[a_\parallel^L a_\perp^{L*} - a_\parallel^R a_\perp^{R*}]$, $I \equiv {\rm Im}[a_\parallel^L a_\perp^{L*} + a_\parallel^R a_\perp^{R*}]$

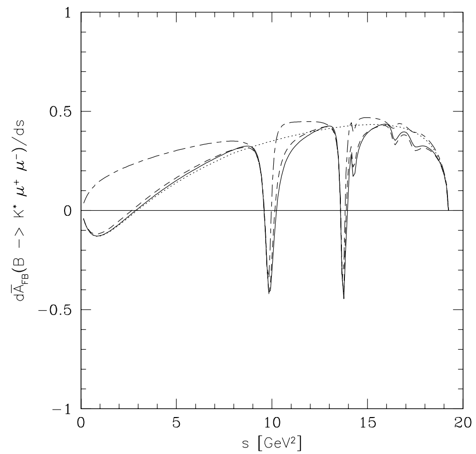
Fit: $\hat{R} = (-0.67 \pm 0.07)\,{\rm GeV}^{-1}$, $\hat{I} = (-0.17 \pm 0.27)\,{\rm GeV}^{-1}$,
$\hat{I}/\hat{R} = 0.25 \pm 0.40$

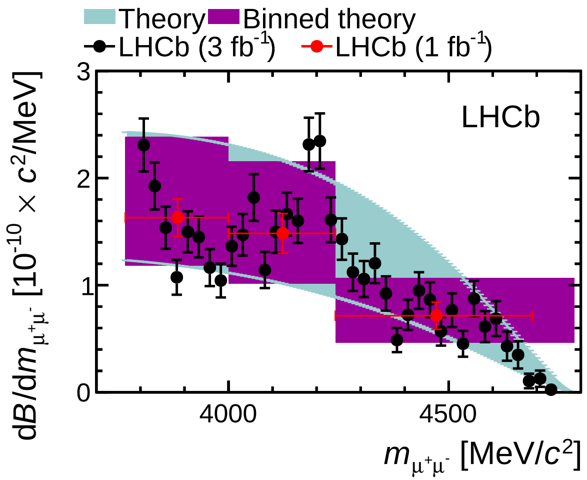
SM: $\hat{R}_{\rm SM} = (-0.73^{+0.12}_{-0.13})\,{\rm GeV}^{-1}$ Bobeth,GH,van Dyk '12 $\hat{I}_{\rm SM} \simeq 0$.
SM +SM' fit agrees with SM. The endpoint predictions ($\kappa = 0$) are consistent within 2 σ with data in the endpoint bin.

Validity of κ-expansion: $c\bar{c}$-resonances

$B \to K^{(*)}\ell^+\ell^-$ decays receive contributions from $c\bar{c}$-resonances







Ali,Ball,Handoko,GH '99, LHCB-PAPER-2013-039 How much are RATIOS affected?

$$H_i^V = F_i^V(q^2)(1 + L^{\text{fac,c}}(q^2) + L_i^{\text{n-fac,c}}(q^2) + ...)\,, \quad H_i^A = F_i^A(q^2)(1 + ...)\,, \quad i = \perp, \parallel, 0\,,$$

Leading (factorizable) $c\bar{c}$ effects $L^{\text{fac,c}}(q^2)$ drop out in observables of type $(H_i^L H_j^{L*} + H_i^R A_j^{R*})/(H_l^L H_k^{L*} + H_l^R H_k^{R*})$ such as F_L, $A_T^{(2)}$ and P_4'.

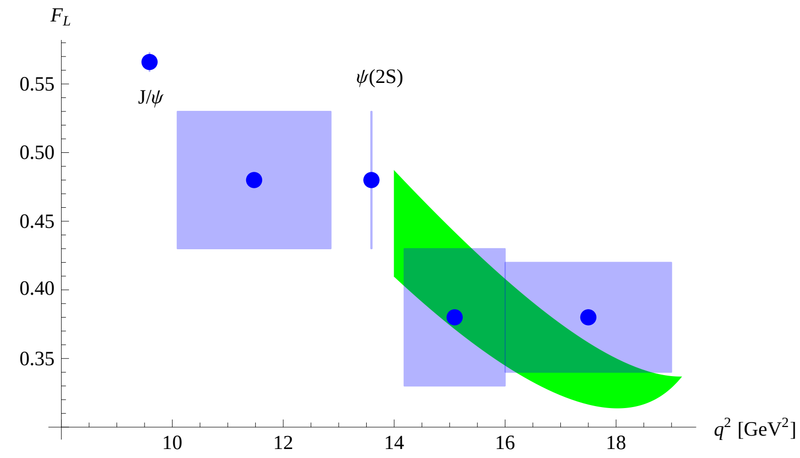
Validity of κ-expansion: $c\bar{c}$-resonances

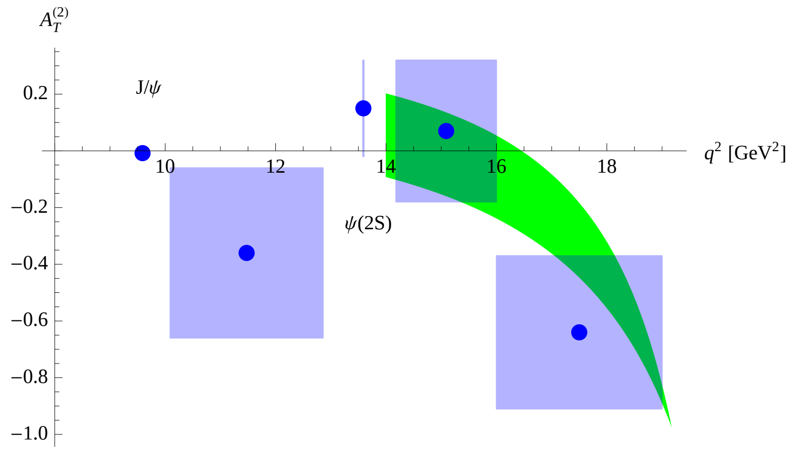
$$F_L \equiv \frac{|H_0^L|^2 + |H_0^R|^2}{\sum_{X=L,R}(|H_0^X|^2 + |H_\perp^X|^2 + |H_\parallel^X|^2)}\,, \tag{1}$$

$$A_T^{(2)} \equiv \frac{|H_\perp^L|^2 + |H_\perp^R|^2 - (|H_\parallel^L|^2 + |H_\parallel^R|^2)}{|H_\perp^L|^2 + |H_\perp^R|^2 + |H_\parallel^L|^2 + |H_\parallel^R|^2}\,, \tag{2}$$

$$P_4' \equiv \frac{\sqrt{2}\mathrm{Re}(H_0^L H_\parallel^{L*} + H_0^R H_\parallel^{R*})}{\sqrt{(|H_\perp^L|^2 + |H_\perp^R|^2 + |H_\parallel^L|^2 + |H_\parallel^R|^2)(|H_0^L|^2 + |H_0^R|^2)}}\,, \tag{3}$$

Low recoil OPE and $c\bar{c}$-resonances





boxes: $B \to K^* \ell^+ \ell^-$ data off $c\bar{c}$, points: $B \to K^* \ell^+ \ell^-$ data on $c\bar{c}$

bands: leading OPE within the SM basis Hambrock,GH, Schacht,Zwicky'13

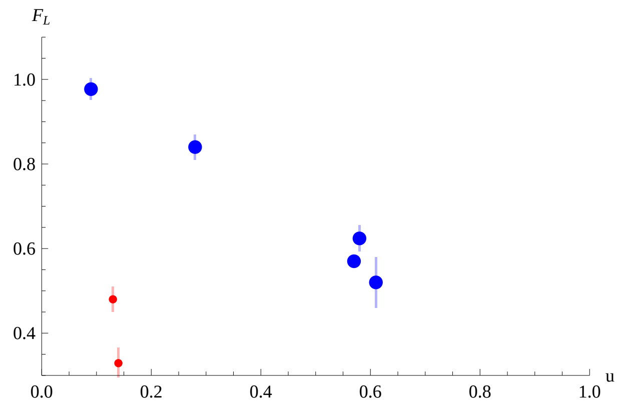
Overall consistency with data suggest non-factorizable $c\bar{c}$-effects subdominant in ratios at low recoil.

Near endpoint predictions $S \to V_1 V_2$

introduce $u \equiv ((m_{V_1} + m_{V_2})/m_S)^2$; "endpoint": $u = 1$

$B \to V_1 V_2$	$B^0 \to D_s^{*+} D^{*-}$	$B^0 \to J/\Psi K^{*0}$	$B^0 \to D^{*+} D^{*-}$	$B^0 \to D_s^{*+} \rho^-$	$B^0 \to \rho^+ \rho^-$
u	0.61	0.58	0.57	0.28	0.09
F_L (PDG)	0.52 ± 0.06	0.570 ± 0.008	0.624 ± 0.031	0.84 ± 0.03	0.977 ± 0.026

Table 2: Examples that illustrate $F_L|_{u=1} = 1/3$ and $F_L|_{u \to 0} \to 1$.



red points: penguin decays ($B \to \varphi K^*, B_s \to \varphi\varphi$)

closer to endpoint in charm:

$D \to V_1V_2$	$\rho\rho$	K^*K^*	$K^*\rho$	$\varphi\rho$	φK^*
$u(D_0, D_\pm)$	0.68	0.92	0.80	0.92	–
$u(D_s)$	0.61	0.83	0.72	0.83	0.95

Table 3: u-values for $D \to V_1V_2$ decays. The columns (rows) correspond to final (initial) states.

Low recoil parameterizations

κ-expansion for amplitude parameterizations and fits:

$$-\sqrt{2}H_0^x = \sqrt{q^2_{\rm max}/q^2}(a_0^x + b_0^x\kappa^2 + \frac{c_0}{q^2} + ..)(1 + \sum_r \Delta_0^{(r)}(q^2)) \ , \quad x = L, R \ ,$$

$$H_\perp^x = \kappa(a_\perp^x + b_\perp^x\kappa^2 + \frac{c_\perp}{q^2} + ..)(1 + \sum_r \Delta_\perp^{(r)}(q^2)) \ ,$$

$$H_\parallel^x = (a_\parallel^x + b_\parallel^x\kappa^2 + \frac{c_\parallel}{q^2} + ..)(1 + \sum_r \Delta_\parallel^{(r)}(q^2)) \ ,$$

endpoint relations: $a_0^x = a_\parallel^x \ , \quad c_0 = c_\parallel \ , \quad \Delta_0^{(r)}(q^2_{\rm max}) = \Delta_\parallel^{(r)}(q^2_{\rm max})$

$\Delta_0^{(r)}(q^2) \neq \Delta_\parallel^{(r)}(q^2)$ if non-factorizable

Summary

- There is plenty to be gained with high statistics flavor data: Besides more precise measurements the backgrounds can be controlled better (exp +th). Eg, form factor ratios can be extracted and compared with non-pertubative predictions.
- Exact endpoint relations fix distributions of many decay modes without* dynamical assumptions.

  *if indeed in endpoint configuration and visible if inelasticities not overwhelming.
- Useful to control backgrounds (th and exp) and guide experimental analyses.

Summary

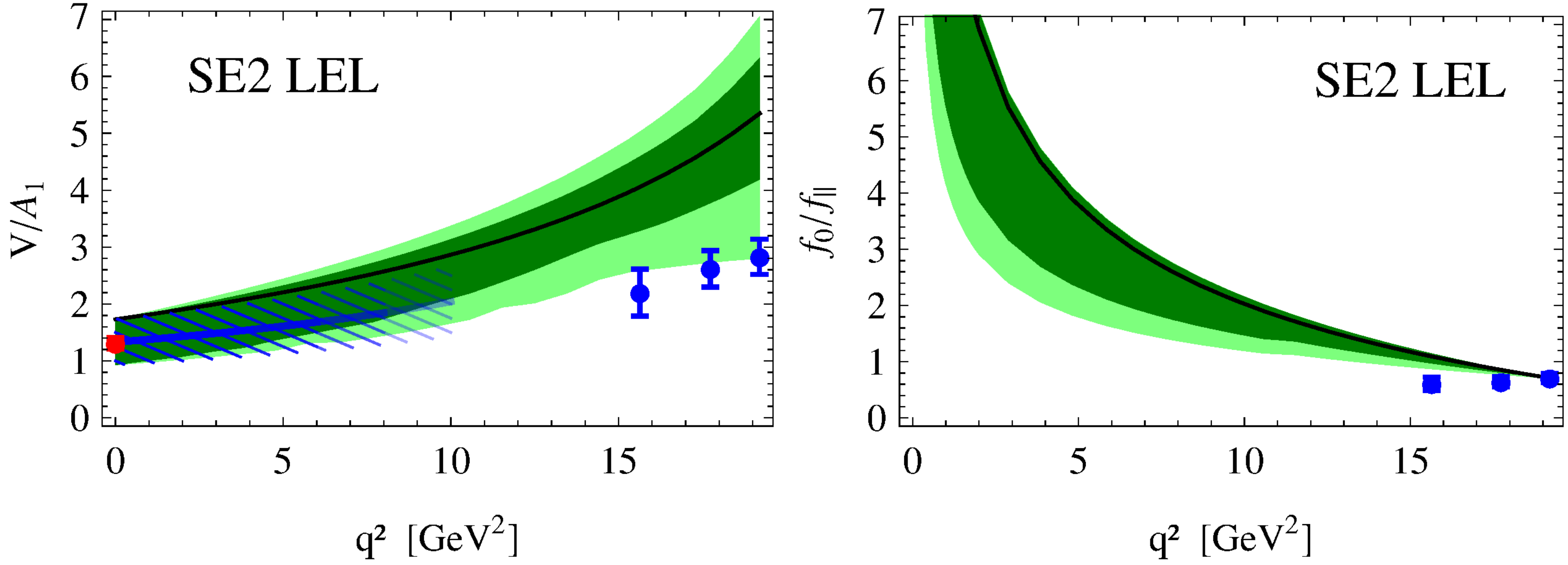
breakdown data 2013: $F_L(q^2_{\rm max})=1/3,\ A_T^{(2)}(q^2_{\rm max})=-1,\ P'_4(q^2_{\rm max})=\sqrt{2}$

	BaBar	CDF		LHCb			ATLAS	CMS
q^2	F_L	F_L	$A_T^{(2)}$	F_L	$A_T^{(2)}$	${}^a\,P'_4$	F_L	F_L
$[14.18, 16]$	$0.43^{+0.13}_{-0.16}$	$0.40^{+0.12}_{-0.12}$	$0.11^{+0.65}_{-0.65}$	$0.33^{+0.08}_{-0.08}$	$0.07^{+0.26}_{-0.28}$	$-0.18^{+0.54}_{-0.70}$	$0.28^{+0.16}_{-0.16}$	$0.53^{+0.12}_{-0.12}$
$[16, 19.xx]$	$0.55^{+0.15}_{-0.17}$	$0.19^{+0.14}_{-0.13}$	$-0.57^{+0.60}_{-0.57}$	$0.38^{+0.09}_{-0.08}$	$-0.71^{+0.36}_{-0.26}$	$0.70^{+0.44}_{-0.52}$	$0.35^{+0.08}_{-0.08}$	$0.44^{+0.08}_{-0.08}$

- BSM can be searched for e.g. with i) angular distribution $d\Gamma/d\varphi$ ii) slope/κ-expansion ($A_{\rm FB}, P'_5$, ...).

- $c\bar{c}$-resonance contributions: i) non-factorizable ones vanish at endpoint ii) factorizable ones drop out in certain ratios at low recoil $\rightarrow$ form factor extractions (SM basis) work Hambrock, GH '12, Hambrock, GH, Schacht, Zwicky '13

Summary



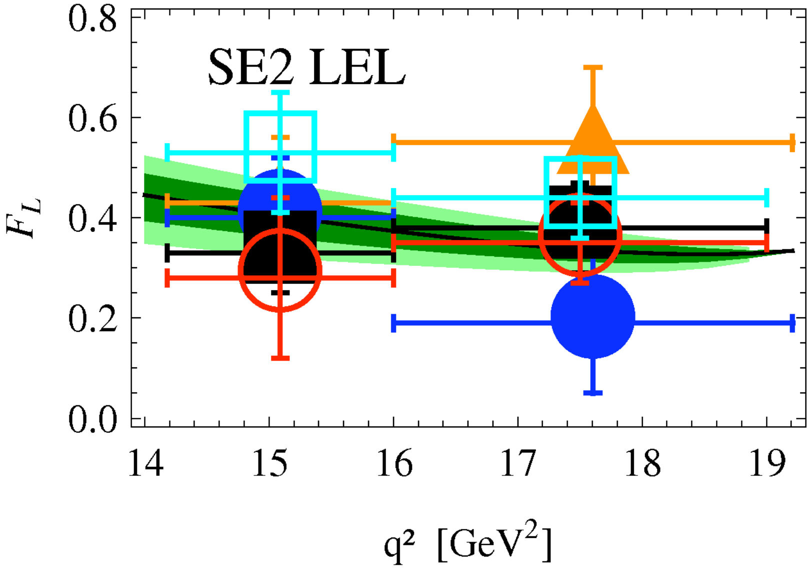
figs from 1308.4379 ;

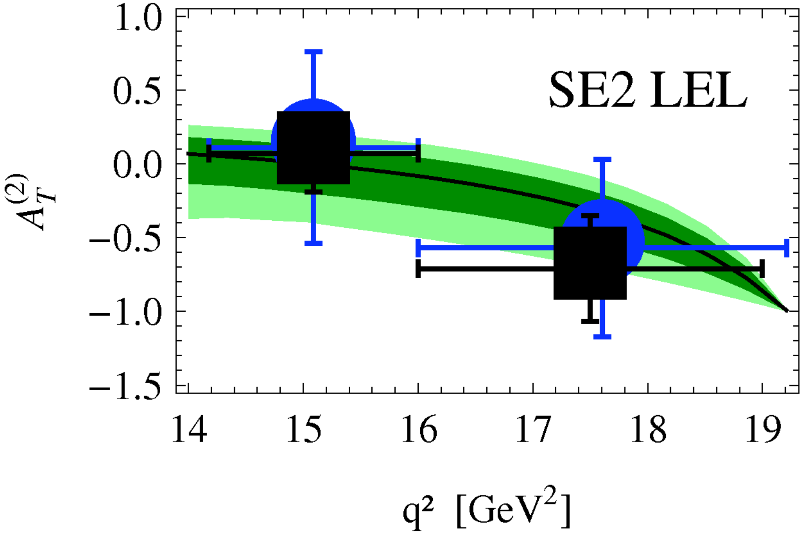
blue points: lattice Wingate et al '13, blue shaded: LEL (input at $q^2 = 0$), red: LCSR

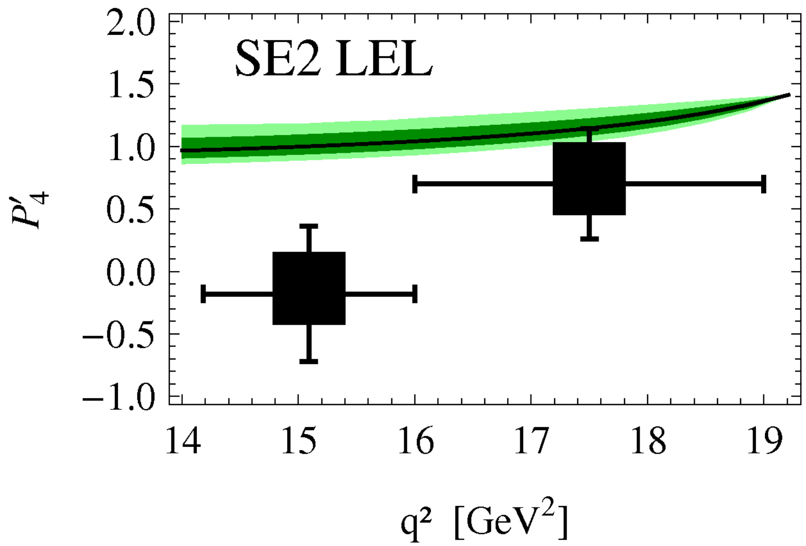
iii) low recoil data suggest non-fac $c\bar{c}$ effects subdominant in ratios.

- P_4' escapes explanation within factorizaton Altmannshofer, Straub '13, Hambrock, GH, Schacht, Zwicky '13, Beaujean, Bobeth, vanDyk '13, Descotes-Genon, Matias, Virto '13

Summary







figs from 1308.4379 black boxes: LHCb $1\,\mathrm{fb}^{-1}$

- Current rare decay data are in agreement with the SM, although there are interesting puzzles related to the $B \to K^* \mu\mu$ angular distribution, which may point to "NP". (New Physics, Non-Perturbative Physics).

- There is much more data to come. In the near future, for instance LHCb's 3 fb^{-1} data.

STAY TUNED