The forward-backward asymmetry in $B \to K^* \mu^+ \mu^-$

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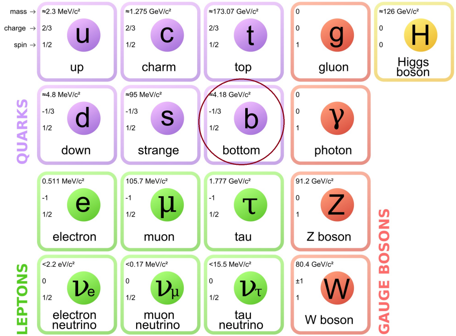
Overview

1. The importance of B physics
2. Exclusive decays and form factors
3. Light cone sum rules
4. Light cone distribution amplitudes
5. AdS/QCD holographic light front wavefunction for hadronic bound states
6. Predictions for $B \to K^*$ transitions
7. Summary and outlook

Focus on B mesons



- $m_b \gg \Lambda_{\mathrm{QCD}} \Rightarrow$ simplifies dealing with the strong force.
- Provides many diverse decay channels and associated observables
- Sensitivity to new physics

Exclusive B decays

$B \to K^* \mu^- \mu^+ \Rightarrow$ Exclusive rare decay to K^*
$B \to X_s \mu^+ \mu^- \Rightarrow$ Inclusive rare decay to final states containing an s-quark

The focus of this talk is on exclusive decays.

- Experimentally favored especially in a hadronic environment like LHC.
- Theoretically challenging $\Rightarrow$ strong interactions, form factors
- Due to $m_B \gg \Lambda_{\rm QCD}$, in certain kinematical regions, the number of form factors is reduced.
- Look for observables which are not very sensitive to form factors

Effective Hamiltonian

-The effective Hamiltonian for $b \to s$ transitions:

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \sum_{p=u,c} V_{ps}^* V_{pb} \left[C_1 Q_1^p + C_2 Q_2^p + \sum_{i=3,\ldots,10} C_i Q_i \right]$$

$C_i, \; i = 1..10$ are the Wilson coefficients

$$Q_1^p = (\bar{s}p)_{V-A}(\bar{p}b)_{V-A} \qquad Q_2^p = (\bar{s}_i p_j)_{V-A}(\bar{p}_j b_i)_{V-A}$$

$$Q_3 = (\bar{s}b)_{V-A} \sum_q (\bar{q}q)_{V-A} \qquad Q_4 = (\bar{s}_i b_j)_{V-A} \sum_q (\bar{q}_j q_i)_{V-A}$$

$$Q_5 = (\bar{s}b)_{V-A} \sum_q (\bar{q}q)_{V+A} \qquad Q_6 = (\bar{s}_i b_j)_{V-A} \sum_q (\bar{q}_j q_i)_{V+A}$$

$$Q_7 = \frac{e}{8\pi^2} m_b \, \bar{s}_i \sigma^{\mu\nu} (1+\gamma_5) b_i \, F_{\mu\nu} \quad Q_8 = \frac{g}{8\pi^2} m_b \, \bar{s}_i \sigma^{\mu\nu} (1+\gamma_5) T_{ij}^a b_j \, G_{\mu\nu}^a$$

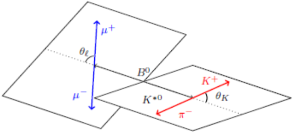
$$Q_9 = \frac{e^2}{8\pi^2} \bar{s}\gamma^\mu (1-\gamma_5) b \, \bar{\ell}\gamma^\mu \ell \qquad Q_{10} = \frac{e^2}{8\pi^2} \bar{s}\gamma^\mu (1-\gamma_5) b \, \bar{\ell}\gamma^\mu \gamma_5 \ell$$

New physics effects

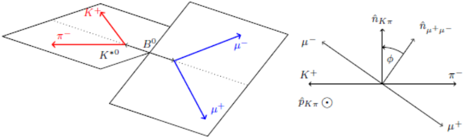
In most scenarios, new physics do not change the structure of the effective operators but only make additional contributions to the Wilson coefficients, i.e.

$$C_i = C_i^{\mathrm{SM}} + C_i^{\mathrm{NP}}$$

Look for observables which are most sensitive to C_i^{NP}



(a) θ_K and θ_ℓ definitions for the B^0 decay



(b) ϕ definition for the B^0 decay

$B \to K^*$ transition form factors

Form factors are defined as:

$$\begin{aligned}\langle K^*(k,\varepsilon)|\bar{q}\gamma^\mu(1-\gamma^5)b|B(p)\rangle &= \frac{2iV(q^2)}{m_B+m_{K^*}}\epsilon^{\mu\nu\rho\sigma}\varepsilon^*_\nu k_\rho p_\sigma - 2m_{K^*}A_0(q^2)\frac{\varepsilon^*\cdot q}{q^2}q^\mu \\ &- (m_B+m_{K^*})A_1(q^2)\left(\varepsilon^{\mu *}-\frac{\varepsilon^*\cdot q q^\mu}{q^2}\right) \\ &+ A_2(q^2)\frac{\varepsilon^*\cdot q}{m_B+m_{K^*}}\left[(p+k)^\mu - \frac{m_B^2-m_{K^*}^2}{q^2}q^\mu\right]\end{aligned}$$

$$\begin{aligned}q_\nu\langle K^*(k,\varepsilon)|\bar{d}\sigma^{\mu\nu}(1-\gamma^5)b|B(p)\rangle &= 2T_1(q^2)\epsilon^{\mu\nu\rho\sigma}\varepsilon^*_\nu p_\rho k_\sigma \\ &- iT_2(q^2)[(\varepsilon^*\cdot q)(p+k)_\mu - \varepsilon^*_\mu(m_B^2-m_{K^*}^2)] \\ &- iT_3(q^2)(\varepsilon^*\cdot q)\left[\frac{q^2}{m_B^2-m_{K^*}^2}(p+k)_\mu - q_\mu\right]\end{aligned}$$

Light cone sum rules

Z. Phys. C 63, 437–454 (1994)

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Exclusive radiative *B*-decays in the light-cone QCD sum rule approach

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Light cone sum rules: Form factors obtained from distribution amplitudes

As an example, the form factor T_1 is given as the following in terms of twist 2 and 3 DAs

$$T_1(q^2) = \frac{1}{4}\left(\frac{m_b}{f_B m_B^2}\right)\exp\left(\frac{m_B^2}{M^2}\right)\int_\delta^1 \frac{\mathrm{d}u}{u}\exp\left(-\frac{m_b^2 + p^2 u\bar{u} - q^2\bar{u}}{uM^2}\right)\left\{m_b f_{K^*}^{\perp}\phi_{\perp}(u) + f_{K^*} m_{K^*}\left[\Phi_{\parallel}(u) + u g_{\perp}^{(v)}(u) + \frac{g_{\perp}^{(a)}(u)}{4} + \frac{(m_b^2 + q^2 - p^2 u^2) g_{\perp}^{a}(u)}{4uM^2}\right]\right\}$$

$\delta = (m_b^2 - q^2)/(s_0^B - q^2)$
The Borel parameter $M_B^2 = 8\ \mathrm{GeV}^2$
The continuum threshold $s_0^B = 36\ \mathrm{GeV}^2$
The quark mass $m_b = 4.8$ GeV

Light cone distribution amplitudes

Light cone coordinates: $x^\mu = (x^+, x^-, x_\perp)$, where $x^\pm = x^0 \pm x^3$ and $x_\perp$ any combinations of x_1 and x_2.
At equal light-front time $x^+ = 0$ and in the light-front gauge $A^+ = 0$,

$$\langle 0|\bar{q}(0)\gamma^\mu q(x^-)|K^*(P,\epsilon)\rangle = f_{K^*} M_{K^*} \frac{\epsilon \cdot x}{P^+ x^-} P^\mu \int_0^1 \mathrm{d}u \, e^{-iuP^+x^-} \phi_{K^*}^{\parallel}(u,\mu) + f_{K^*} M_{K^*} \left(\epsilon^\mu - P^\mu \frac{\epsilon \cdot x}{P^+ x^-}\right) \int_0^1 \mathrm{d}u \, e^{-iuP^+x^-} g_{K^*}^{\perp(v)}(u,\mu)$$

$$\langle 0|\bar{q}(0)[\gamma^\mu, \gamma^\nu] q(x^-)|K^*(P,\epsilon)\rangle = 2 f_{K^*}^{\perp} (\epsilon^\mu P^\nu - \epsilon^\nu P^\mu) \int_0^1 \mathrm{d}u \, e^{-iuP^+x^-} \phi_{K^*}^{\perp}(u,\mu)$$

$$\langle 0|\bar{q}(0)\gamma^\mu \gamma^5 q(x^-)|K^*(P,\epsilon)\rangle = -\frac{1}{4} \epsilon^{\mu}_{\nu\rho\sigma} \epsilon^\nu P^{K^*} x^\sigma f_{K^*} M_{K^*} \int_0^1 \mathrm{d}u \, e^{-iuP^+x^-} g_{K^*}^{\perp(a)}(u,\mu)$$

Vector meson's polarization vectors ϵ are chosen as

$$\epsilon_L = \left(\frac{P^+}{M_{K^*}}, -\frac{M_{K^*}}{P^+}, 0_\perp\right) \quad \text{and} \quad \epsilon_{T(\pm)} = \frac{1}{\sqrt{2}}(0, 0, 1, \pm i)$$

Light cone distribution amplitudes

Distribution amplitudes are normalized:

$$\int_0^1 \mathrm{d}u\ \phi_{K^*}^{\perp,\parallel}(u,\mu) = \int_0^1 \mathrm{d}u\ g_{K^*}^{\perp(a,v)}(u,\mu) = 1$$

$x^- \to 0$ limit: usual definitions of f_{K^*} and $f_{K^*}^{\perp}$ are recovered:

$$\langle 0|\bar{q}(0)\gamma^\mu q(0)|K^*(P,\epsilon)\rangle = f_{K^*} M_{K^*} \epsilon^\mu$$

$$\langle 0|\bar{q}(0)[\gamma^\mu,\gamma^\nu]q(0)|K^*(P,\epsilon)\rangle = 2 f_{K^*}^{\perp}(\epsilon^\mu P^\nu - \epsilon^\nu P^\mu)$$

AdS/QCD holographic light front wavefunctions

G. F. de Teramond and S. J. Brodsky, PRL 102, 081601(2009).

The correspondence between string theory in five-dimensional antide Sitter (AdS)space and four-dimensional quantum chromodynamics (QCD) has enjoyed a number of successes.

The meson wavefunction in this model can be written as:

$$\phi_\lambda(z,\zeta) = \mathcal{N}_\lambda \frac{\kappa}{\sqrt{\pi}} \sqrt{z(1-z)} \exp\left(-\frac{\kappa^2\zeta^2}{2}\right) \exp\left\{-\left[\frac{m_s^2 - z(m_s^2 - m_{\bar{q}}^2)}{2\kappa^2 z(1-z)}\right]\right\}$$

$\mathcal{N}_\lambda$ is fixed by normalization condition once spin wavefunction is included.

$\zeta = \sqrt{x(1-x)}r$

$\kappa = m_{K^*}/\sqrt{2}$

$x \Rightarrow$ the light-front longitudinal momentum fraction of the quark

$r \Rightarrow$ the quark-antiquark transverse separation

Light cone DAs in terms of LFWF

R. Sandapen, MA PRD88.014042(2013)

$$\phi^{\parallel}_{K^*}(z,\mu) = \frac{N_c}{\pi f_{K^*} m_{K^*}} \int \mathrm{d}r \mu J_1(\mu r)[m^2_{K^*} z(1-z) + m_f m_s - \nabla^2_r] \frac{\phi_L(r,z)}{z(1-z)}$$

$$\phi^{\perp}_{K^*}(z,\mu) = \frac{N_c}{\pi f^{\perp}_{K^*}} \int \mathrm{d}r \mu J_1(\mu r)[m_s - z(m_s - m_{\bar{q}})] \frac{\phi_T(r,z)}{z(1-z)}$$

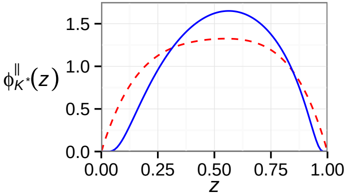
$$g^{\perp(v)}_{K^*}(z,\mu) = \frac{N_c}{2\pi f_{K^*} M_{K^*}} \int \mathrm{d}r \mu J_1(\mu r) \left[(m_s - z(m_s - m_{\bar{q}}))^2 - (z^2 + (1-z)^2)\nabla^2_r\right] \frac{\phi^T_{K^*}(r,z)}{z^2(1-z)^2}$$

$$\frac{\mathrm{d}g^{\perp(a)}_{K^*}}{\mathrm{d}z}(z,\mu) = \frac{\sqrt{2}N_c}{\pi \tilde{f}_{K^*} M_{K^*}} \int \mathrm{d}r \mu J_1(\mu r)[(1-2z)(m_s^2 - \nabla^2_r) + z^2(m_s + m_{\bar{q}})(m_s - m_{\bar{q}})] \frac{\phi^T_{K^*}(r,z)}{z^2(1-z)^2}$$

$$f_{K^*} = \frac{N_c}{m_{K^*}\pi} \int_0^1 \mathrm{d}z \, [z(1-z)m^2_{K^*} + m_{\bar{q}} m_s - \nabla^2_r] \frac{\phi_L(r,z)}{z(1-z)}\bigg|_{r=0}$$

$$f^{\perp}_{K^*}(\mu) = \frac{N_c}{\pi} \int_0^1 \mathrm{d}z (m_s - z(m_s - m_{\bar{q}})) \int \mu J_1(\mu r) \frac{\phi_T(r,z)}{z(1-z)}$$

AdS/QCD DAs for K^*:comparison to Sum Rules



(a) Twist-2 DA for the longitudinally polarized ρ meson

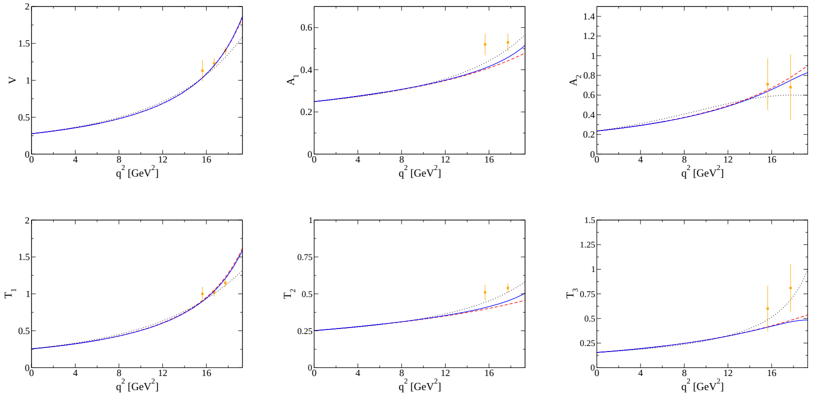
(b) Twist-2 DA for the transversely polarized ρ meson

Figure: Twist-2 DAs for the K^* meson. Solid Blue: AdS/QCD DA; Dashed Red: Sum Rules DA.

AdS/QCD prediction for $B \to K^*$ transition form factors

R. Campbell, S. Lord, R. Sandapen, MA, PRD89.074021(2014)

Lattice points ⇒ R. Horgan, Z. Liu, S. Meinel, M. Wingate PRD89.094501(2014)



Two-parameter fit for the form factors

The values of a and b are obtained by fitting

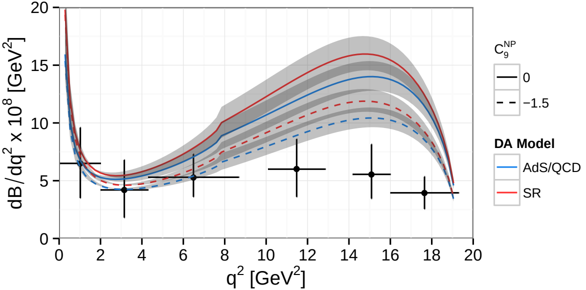
$$F(q^2) = \frac{F(0)}{1 - a(q^2/m_B^2) + b(q^4/m_B^4)}$$

to both the AdS/QCD predictions for low-to-intermediate q^2 and the lattice data at high q^2.

F	$F(0)$	a	b
A_0	0.285	1.314	0.160
A_1	0.249	0.537	-0.403
A_2	0.235	1.895	1.453
V	0.277	1.783	0.840
T_1	0.255	1.750	0.842
T_2	0.251	0.555	-0.379
T_3	0.155	1.208	-0.030

Differential decay rate for semileptonic $B \to K^* \mu^+ \mu^-$

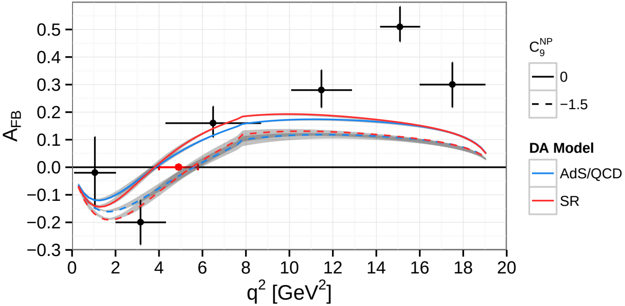
The data points are obtained by averaging LHCb data for dileptonic B^+ and B° decays. The dashed curves are the result of shifting the Wilson coefficient C_9 by -1.5. The grey band represents the uncertainty due to scale dependence.



Forward-Backward asymmetry in dileptonic $B \to K^* \mu^+ \mu^-$

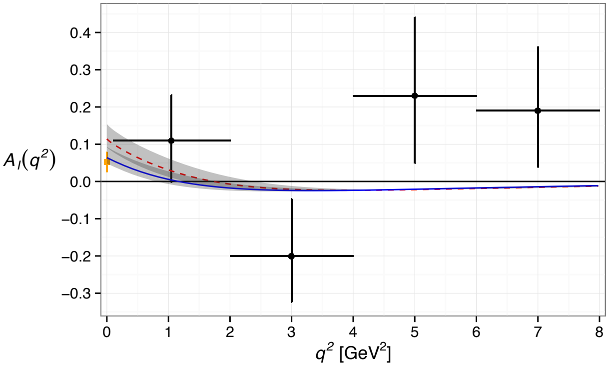
$$\frac{dA_{\rm FB}}{dq^2} \equiv \frac{1}{d\Gamma/dq^2}\left(\int_0^1 d(\cos\theta_\ell)\,\frac{d^2\Gamma}{dq^2 d\cos\theta_\ell} - \int_{-1}^0 d(\cos\theta_\ell)\,\frac{d^2\Gamma}{dq^2 d\cos\theta_\ell}\right) \quad (1)$$

The data points are from LHCb. The dashed curves are the result of shifting the Wilson coefficient C_9 by -1.5. The grey band represents the uncertainty due to scale dependence.



S. Lord, R. Sandapen, MA, PRD90.074010(2014)

The data points are from LHCb. The dashed red curve is the prediction of the QCD sum rules. The grey band represents the uncertainty due to scale dependence.



Summary and outlook

- AdS/QCD LFWF is used to obtain K^* DAs.
- DAs are essential ingredients for the calculation of the $B \to K^*$ transition form factors via LCSR.
- The predictions for rare dileptonic B decays to K^* are presented.
- AdS/QCD prediction for diffractive ϕ production will motivate its application to $B \to \phi$ transitions.
- It would be interesting to look into the AdS/QCD predictions for $B \to \pi, K$.