AdS/QCD predictions for semileptonic and rare B decays to ρ and K^* vector mesons.

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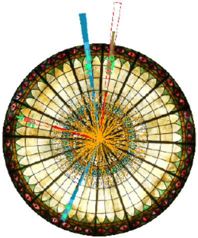
April 28, 2015

DIS 2015

XXIII International Workshop on
Deep-Inelastic Scattering and
Related Subjects

Dallas, Texas
April 27 – May 1, 2015



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 $B \to \rho \ell \bar{\nu}$ semileptonic decay
7. Predictions for $B \to K^* \mu^+ \mu^-$ decay
8. 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

- Experimentally favored especially in a hadronic environment like LHC.
- Theoretically challenging $\Rightarrow$ strong interactions, form factors
- Due to $m_B \gg \Lambda_{\mathrm{QCD}}$, 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 $b \to s\gamma$, $b \to s\ell\bar{\ell}$ transitions(Replace s with d for $b \to d(\gamma,\ \ell\bar{\ell})$ transition.:

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

$$\begin{aligned}
Q_1^p &= (\bar{s}p)_{V-A}(\bar{p}b)_{V-A} & Q_2^p &= (\bar{s}_i p_j)_{V-A}(\bar{p}_j b_i)_{V-A} \\
Q_3 &= (\bar{s}b)_{V-A}\sum_q (\bar{q}q)_{V-A} & Q_4 &= (\bar{s}_i b_j)_{V-A}\sum_q (\bar{q}_j q_i)_{V-A} \\
Q_5 &= (\bar{s}b)_{V-A}\sum_q (\bar{q}q)_{V+A} & Q_6 &= (\bar{s}_i b_j)_{V-A}\sum_q (\bar{q}_j q_i)_{V+A} \\
Q_7 &= \frac{e}{8\pi^2} m_b\, \bar{s}_i \sigma^{\mu\nu}(1+\gamma_5) b_i\, F_{\mu\nu} & Q_8 &= \frac{g}{8\pi^2} m_b\, \bar{s}_i \sigma^{\mu\nu}(1+\gamma_5) T^a_{ij} b_j\, G^a_{\mu\nu} \\
Q_9 &= \frac{e^2}{8\pi^2} \bar{s}\gamma^\mu(1-\gamma_5) b\, \bar{\ell}\gamma^\mu \ell & Q_{10} &= \frac{e^2}{8\pi^2} \bar{s}\gamma^\mu(1-\gamma_5) b\, \bar{\ell}\gamma^\mu \gamma_5 \ell
\end{aligned}$$

$B \to \rho$ transition form factors

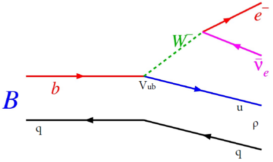
Form factors are defined as:

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

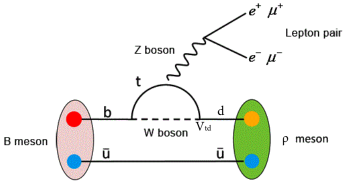
$$
\begin{aligned}
q_\nu\langle \rho(k,\varepsilon)|\bar{d}\sigma^{\mu\nu}(1-\gamma^5)b|B(p)\rangle &= 2T_1(q^2)\epsilon^{\mu\nu\rho\sigma}\varepsilon^*_\nu p_\rho k_\sigma \\
&- iT_2(q^2)[(\varepsilon^*\cdot q)(p+k)_\mu - \varepsilon^*_\mu(m_B^2-m_\rho^2)] \\
&- iT_3(q^2)(\varepsilon^*\cdot q)\left[\frac{q^2}{m_B^2-m_\rho^2}(p+k)_\mu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

Decay channel examples

Semileptonic $B \to \rho \ell \nu \Rightarrow V_{ub}$



Rare dileptonic $B \to \rho \ell \bar{\ell}$, $B \to \rho \gamma \Rightarrow V_{td}$ and possible new physics



Light cone sum rules

Z. Phys. C 63, 437–454 (1994)

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

A. Ali[1,*], V.M. Braun [2,**], H. Simma[3]

[1]Theory Division, CERN, CH-1211 Geneva 23, Switzerland
[2]Max-Planck-Institut für Physik-Werner-Heisenberg-Institut – D-80805, Munich, Germany
[3]Deutsches Elektronen Synchrotron DESY, D-22603 Hamburg, Germany

Received: 19 January 1994

Light cone sum rules: Form factors obtained from distribution amplitudes

$$\frac{f_B m_B^2}{m_b + m_q} 2T_1(0) e^{-(m_B^2 - m_b^2)/t} =$$

$$= \int_0^1 du \frac{1}{u} \exp\left[-\frac{\bar{u}}{t}\left(\frac{m_b^2}{u} + m_\rho^2\right)\right] \theta\left[s_0 - \frac{m_b^2}{u} - \bar{u} m_\rho^2\right] \left\{ m_b f_\rho^\perp \phi_\perp(u) \right.$$

$$\left. + u m_\rho f_\rho g_\perp^{(v)}(u) + \frac{m_b^2 - u^2 m_\rho^2 + ut}{4ut} m_\rho f_\rho g_\perp^{(a)}(u) \right\}$$

For $q^2 \neq 0$

$$\frac{f_B m_B^2}{m_b + m_q} 2T_1(q^2) e^{-(m_B^2 - m_b^2)/t} =$$

$$= \int_0^1 du \frac{1}{u} \exp\left[-\frac{\bar{u}}{t}\left(\frac{m_b^2 - q^2}{u} + m_\rho^2\right)\right] \theta\left[s_0 - \frac{m_b^2 - \bar{u} q^2}{u} - \bar{u} m_\rho^2\right] \left\{ m_b f_\rho^\perp \phi_\perp(u) \right.$$

$$\left. + u m_\rho f_\rho g_\perp^{(v)}(u) + \frac{m_b^2 + q^2 - u^2 m_\rho^2 + ut}{4ut} m_\rho f_\rho g_\perp^{(a)}(u) \right\}$$

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 $A^+ = 0$,

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

$$+ f_\rho M_\rho \left(\epsilon^\mu - P^\mu \frac{\epsilon\cdot x}{P^+x^-}\right) \int_0^1 \mathrm{d}u\, e^{-iuP^+x^-} g_\rho^{\perp(v)}(u,\mu)$$

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

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

Vector meson's polarization vectors ϵ are chosen as

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

Light cone distribution amplitudes

Distribution amplitudes are normalized:

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

$x^- \to 0$ limit: usual definitions of f_ρ and $f_\rho^\perp$ are recovered:

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

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

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 anti-de 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:

$$\phi(x,\zeta) = \mathcal{N}\frac{\kappa}{\sqrt{\pi}}\sqrt{x(1-x)}\exp\left(-\frac{\kappa^2\zeta^2}{2}\right)\exp\left(-\frac{m_f^2}{2\kappa^2 x(1-x)}\right) ,$$

$\mathcal{N}$ is fixed by normalization condition once spin wavefunction is included.
$\zeta = \sqrt{x(1-x)}r$
$x \Rightarrow$ the light-front longitudinal momentum fraction of the quark
$r \Rightarrow$ the quark-antiquark transverse separation
Application to diffractive ρ production produces very promising results.
J. Forshaw and R. Sandapen PRL 109, 081601 (2012)

Light cone DAs in terms of LFWF

R. Sandapen, MA, PRD87.054013(2013)

$$\phi_\rho^{\parallel}(z,\mu) = \frac{N_c}{\pi f_\rho M_\rho} \int \mathrm{d}r \; \mu J_1(\mu r)[M_\rho^2 z(1-z) + m_f^2 - \nabla_r^2] \frac{\phi_L(r,z)}{z(1-z)} \; ,$$

$$\phi_\rho^{\perp}(z,\mu) = \frac{N_c m_f}{\pi f_\rho^{\perp}} \int \mathrm{d}r \; \mu J_1(\mu r) \frac{\phi_T(r,z)}{z(1-z)} \; ,$$

$$g_\rho^{\perp(v)}(z,\mu) = \frac{N_c}{2\pi f_\rho M_\rho} \int \mathrm{d}r \; \mu J_1(\mu r) \left[m_f^2 - (z^2 + (1-z)^2)\nabla_r^2 \right] \frac{\phi_T(r,z)}{z^2(1-z)^2}$$

$$\frac{\mathrm{d}g_\rho^{\perp(a)}}{\mathrm{d}z}(z,\mu) = \frac{\sqrt{2} N_c}{\pi f_\rho M_\rho} \int \mathrm{d}r \; \mu J_1(\mu r)(1-2z)[m_f^2 - \nabla_r^2] \frac{\phi_T(r,z)}{z^2(1-z)^2} \; .$$

$$f_\rho = \frac{N_c}{m_V \pi} \int_0^1 \mathrm{d}z \; [z(1-z) m_V^2 + m_{\bar{q}} m_q - \nabla_r^2] \frac{\phi_L(r,z)}{z(1-z)} \bigg|_{r=0}$$

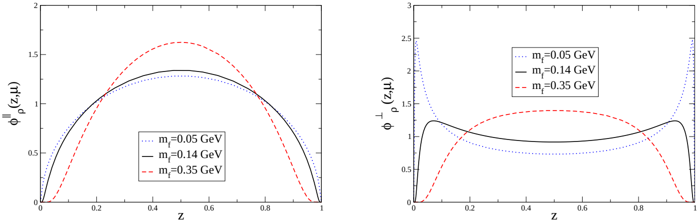
$$f_\rho^{\perp}(\mu) = \frac{N_c}{\pi} \int_0^1 \mathrm{d}z (m_q - z(m_q - m_{\bar{q}})) \int \mu J_1(\mu r) \frac{\phi_T(r,z)}{z(1-z)}$$

Decay constants f_ρ and $f_\rho^\perp$

Approach	Scale μ	f_ρ [MeV]	$f_\rho^\perp(\mu)$ [MeV]	$f_\rho^\perp(\mu)/f_\rho$
Experiment		220 ± 2		
AdS/QCD	~ 1 GeV	$214, 214, 202$	$36, 95, 152$	$0.17, 0.45, 0.75$
Sum Rules	2 GeV	206 ± 7	145 ± 8	0.70 ± 0.04
Lattice	2 GeV			0.72 ± 0.02
Lattice	2 GeV			0.742 ± 0.014

Table: AdS/QCD predictions for the decay constants of the ρ meson compared to sum rules, lattice predictions and experiment. The three AdS/QCD predictions are given for $m_f = 0.05, 0.14$ and 0.35 GeV respectively.

AdS/QCD DAs for ρ:sensitivity to quark mass

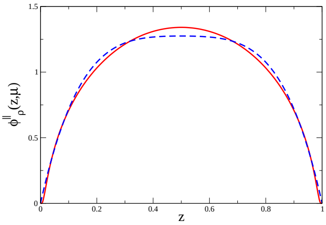


(a) Twist-2 DA for the longitudinally polarized ρ meson

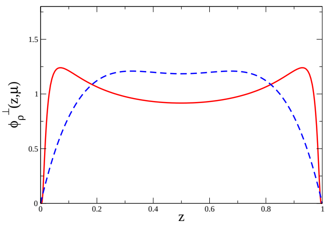
(b) Twist-2 DA for the transversely polarized ρ meson

Figure: Twist-2 DAs for the ρ meson for 3 different quark mass inputs.

AdS/QCD DAs for ρ:comparison to Sum Rules



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

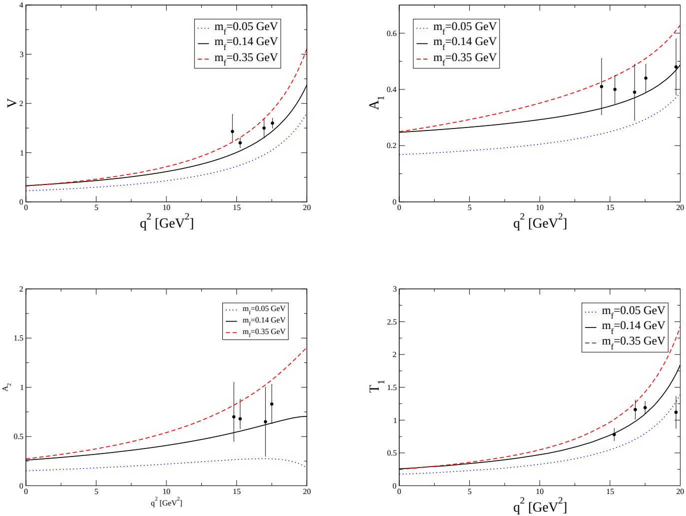


(b) Twist-2 DA for the transversely polarized ρ meson

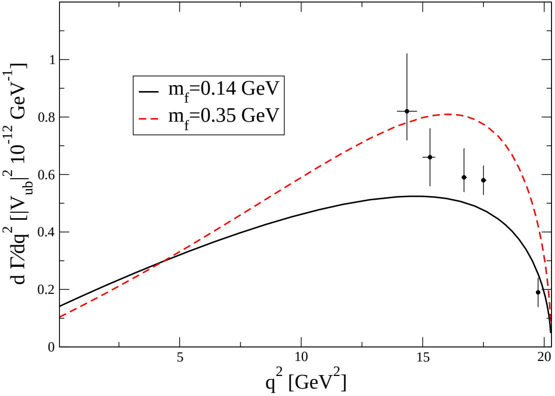
Figure: Twist-2 DAs for the ρ meson. Solid Red: AdS/QCD DA at $\mu \sim 1$ GeV; Dashed Blue: Sum Rules DA at $\mu = 2$ GeV.

AdS/QCD prediction for $B \to \rho$ transition form factors

R. Campbell, S. Lord, R. Sandapen, MA, PRD88.074031(2013)



Differential decay rate for semileptonic $B \to \rho\ell\nu$



(a) Differential decay rate for the semileptonic $B \to \rho\ell\bar{\nu}$ decay. The lattice data points are from UKQCD Collaboration.

Numerical predictions

BaBar collaboration has measured partial branching fractions in q^2 bins:PRD83, 032007 (2011)

$$\Delta B_{\text{low}} = \int_0^8 \frac{\mathrm{d}B}{\mathrm{d}\boldsymbol{q}^2}\mathrm{d}\boldsymbol{q}^2 = (0.564 \pm 0.166) \times 10^{-4}$$

$$\Delta B_{\text{mid}} = \int_8^{16} \frac{\mathrm{d}B}{\mathrm{d}\boldsymbol{q}^2}\mathrm{d}\boldsymbol{q}^2 = (0.912 \pm 0.147) \times 10^{-4}$$

$$\Delta B_{\text{high}} = \int_{16}^{20.3} \frac{\mathrm{d}B}{\mathrm{d}\boldsymbol{q}^2}\mathrm{d}\boldsymbol{q}^2 = (0.268 \pm 0.062) \times 10^{-4}$$

$$R_{\text{low}} = \frac{\Delta B_{\text{low}}}{\Delta B_{\text{mid}}} = 0.618 \pm 0.207$$

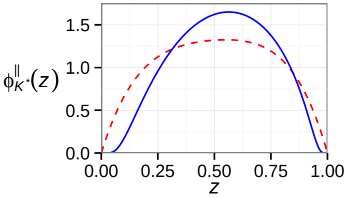
$$R_{\text{high}} = \frac{\Delta B_{\text{high}}}{\Delta B_{\text{mid}}} = 0.294 \pm 0.083$$

Our predictions for $m_f = 0.14, 0.35$:

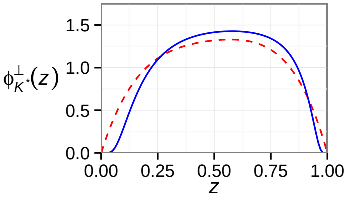
$$R_{\text{low}} = 0.580, 0.424$$
$$R_{\text{high}} = 0.427, 0.503$$

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

R. Sandapen, MA PRD88.014042(2013)



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

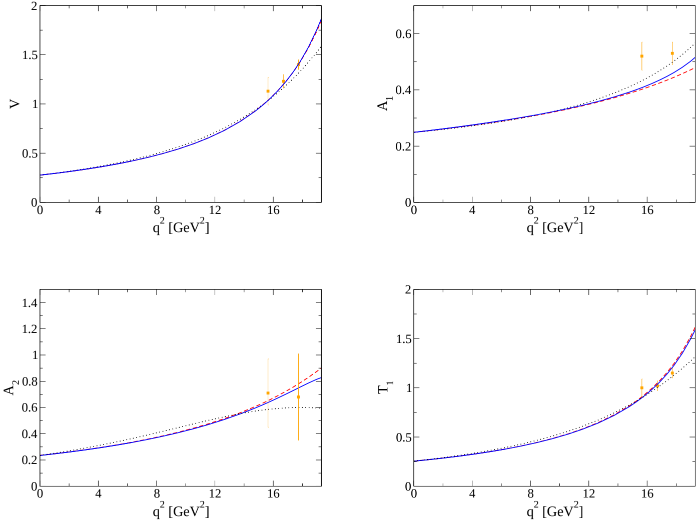


(c) Twist-2 DA for the transversely polarized ρ meson

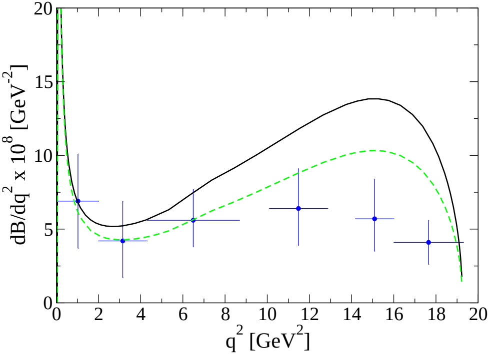
Figure: Twist-2 DAs for the K^* meson. Solid Blue: AdS/QCD DA; Dashed Red: Sum Rules DA.

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

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



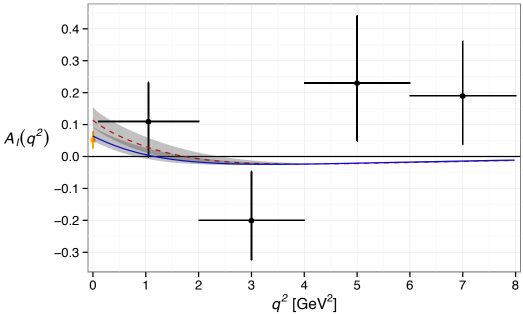
Differential decay rate for dileptonic $B \to K^* \mu^+ \mu^-$



(a) Differential decay rate for the semileptonic $B \to K^* \mu^+ \mu^-$ decay. The data points are obtained by averaging LHCb data for dileptonic B^+ and B° decays. The dashed green curve is the result of shifting the Wilson coefficient C_9.

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

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



(b) Isospin asymmetry in $B \to K^* \mu^+ \mu^-$ decay vs dileptonic invariant mass. The data points are from LHCb. The dashed red curve is the prediction of the QCD sum rules.

Summary and outlook

- AdS/QCD LFWF is used to obtain ρ and K^* DAs.
- DAs are essential ingredients for the calculation of the $B \to \rho, K^*$ transition form factors via LCSR.
- The predictions for rare semileptonic and dileptonic B decays to ρ and 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 $B \to \pi, K$.