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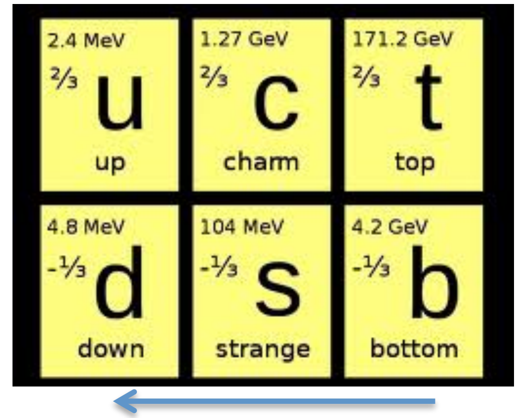
Predicting radiative B decays to vector mesons in holographic light-front QCD

Ruben Sandapen

DIS 2013, Marseille

Radiative B decays

$$B \rightarrow V + \gamma$$



Light vector mesons $V = \rho, K^{*}, \ldots$

- Driven by Flavor Changing Neutral Current (FCNC)
- Heavily suppressed at tree level in SM: rare decays
- Sensitive to New Physics that allows FCNC at tree level
- Very important to have reliable SM predictions to detect any New Physics

Theory of B decays

Bosch & Buchalla 2002

Effective Hamiltonian

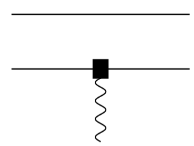
$$\mathrm{H}_{eff} = \frac{G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_p^{(s)} [C_1 Q_1^p + C_2 Q_2^p + \sum_{i=3..8} C_i Q_i]$$

QCD factorization (QCDF): matrix element factorizes to leading power in the heavy quark limit

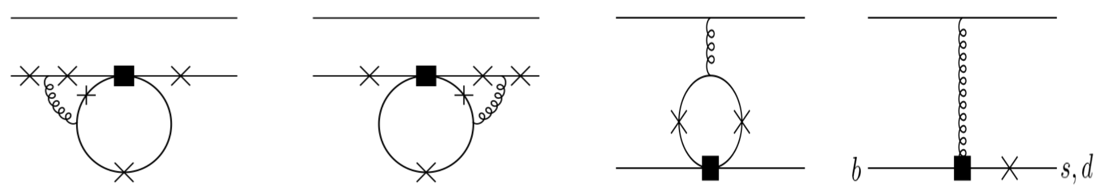
$$\left(\frac{\Lambda_{QCD}}{m_b}\right)^0 \qquad \langle V\gamma | Q_i | \overline{B} \rangle = F^{B\to V} T_i^I + \int_0^1 d\xi\, du T_i^{II}(\xi,u) \Phi_B(\xi) \phi_V(u)] \cdot e + \ldots$$

Twist-2 DA of vector meson

α_s^0



α_s^1



Predictive power of QCDF

The predictive power of QCDF is limited by

- ❑ Hadronic uncertainties encoded in non-perturbative form factors and the twist-2 DAs of the vector meson.

- ❑ Power corrections to the leading power amplitude (may involve higher twist-3 DAs)

Power corrections

Flavor Physics and CP Violation Conference, Taipei, 2008

Theory review of exclusive rare radiative decays

Ben D. Pecjak
DESY theory group, Hamburg, Germany

I briefly review the theory status of exclusive rare radiative decays.

- Computation of power corrections suffer from end-point divergences
- Occur with standard Sum-Rules DAs

6. Summary

Rare radiative $B \to V\gamma$ decays are of increasing interest as experimental measurements become more precise. QCD factorization and SCET have provided a theoretical framework which can be used to calculate observables for these decays to leading order in $1/m_b$. The perturbative hard-scattering kernels have been known at NLO in α_s for some time, and recently a set of NNLO results have been obtained for the operators Q_1, Q_7, and Q_8, although results for the four-quark operators Q_1 and Q_2 are not yet complete. The interesting observables such as isospin asymmetries and branching fractions in the $b \to d\gamma$ modes are sensitive to power corrections in $1/m_b$. Some of these have been estimated in the framework of light-cone sum rules, but a systematic treatment in SCET or QCD factorization is still missing due to the presence of endpoint divergences; a solution to this problem would be a much desired advance in this field.

Holographic AdS/QCD DAs offer a possibility to avoid end-point divergences

Phys. Rev. Lett. 102, 081601 (2009) [4 pages]

Light-Front Holography: A First Approximation to QCD

Abstract | References | Citing Articles (48)

Guy F. de Téramond[1] and Stanley J. Brodsky[2]
[1]Universidad de Costa Rica, San José, Costa Rica
[2]SLAC National Accelerator Laboratory, Stanford University, Stanford, California 94309, USA

Received 29 September 2008; published 24 February 2009

Starting from the Hamiltonian equation of motion in QCD, we identify an invariant light-front coordinate ζ which allows the separation of the dynamics of quark and gluon binding from the kinematics of constituent spin and internal orbital angular momentum. The result is a single-variable light-front Schrödinger equation for QCD which determines the eigenspectrum and the light-front wave functions of hadrons for general spin and orbital angular momentum. This light-front wave equation is equivalent to the equations of motion which describe the propagation of spin-J modes on anti–de Sitter (AdS) space.

URL: http://link.aps.org/doi/10.1103/PhysRevLett.102.081601
DOI: 10.1103/PhysRevLett.102.081601
PACS: 11.15.Tk, 12.38.Aw

A correspondence between light-front QCD in 4D and a string theory in 5D anti-de Sitter

A holographic light-front Schroedinger equation for mesons

- A relativistic QM equation for a meson in physical 4D spacetime which maps onto the classical wave equation for strings propagating in a modified 5D anti-de Sitter (AdS) space

$$\left(-\frac{d^2}{d\zeta^2}-\frac{1-4L^2}{4\zeta^2}+U(\zeta)\right)\Phi(\zeta)=M^2\Phi(\zeta) \qquad \zeta=\sqrt{z(1-z)}r$$

- Transverse distance in 4D maps onto fifth dimension in 5D AdS

$$\zeta \leftrightarrow z_5$$

- Angular momentum in 4D maps onto 5D mass times curvature radius of anti-de Sitter space

$$(m_5 R)^2 \leftrightarrow L^2-(J-2)^2$$

- Interacting potential in 4D driven by the geometry in fifth dimension of AdS

$$U(z_5)=\frac{1}{2}\varphi''(z_5)+\frac{1}{4}\varphi'(z_5)^2+\frac{2J-3}{2z_5}\varphi'(z_5)$$

AdS/QCD wavefunction for the ρ tested

PRL 109, 081601 (2012) PHYSICAL REVIEW LETTERS week ending 24 AUGUST 2012

AdS/QCD Holographic Wave Function for the ρ Meson and Diffractive ρ Meson Electroproduction

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(Received 5 April 2012; published 20 August 2012)

We show that anti–de Sitter/quantum chromodynamics generates predictions for the rate of diffractive ρ-meson electroproduction that are in agreement with data collected at the Hadron Electron Ring Accelerator electron–proton collider.

DOI: 10.1103/PhysRevLett.109.081601 PACS numbers: 11.25.Tq, 12.38.Aw, 12.38.−t, 13.60.Le

Introduction.—To date, 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 (see Refs. [1–4] and references therein). In this Letter, we demonstrate another success by showing that parameter-free AdS/QCD wave functions for the ρ meson lead to predictions for the rate of diffractive ρ meson production ($\gamma^* p \to \rho p$) that agree with the data collected at the Hadron Electron Ring Accelerator (HERA) ep collider.

In previous papers [5,6], we took a phenomenological approach and extracted the light-front wave functions of the ρ meson using the HERA data. We follow the same formalism here, except that we now use the AdS/QCD wave functions predicted in Refs. [7,8].

The AdS/QCD wavefunction.—Brodsky and de Téramond have recently shown that, in what they call a first semiclassical approximation to light-front QCD [9], the meson wave function can be written in the following factorized form

$$\phi(x, \zeta, \varphi) = \frac{\Phi(\zeta)}{\sqrt{2\pi\zeta}} f(x) e^{iL\varphi} \quad (1)$$

where L is the orbital quantum number and $\zeta = \sqrt{x(1-x)}b$ (x is the light-front longitudinal momentum fraction of the quark, and b is the quark-antiquark transverse separation). The function $\Phi(\zeta)$ satisfies a Schrödinger-like wave equation

$$U(\zeta) = \kappa^4 \zeta^2 + 2\kappa^2 (J-1). \quad (3)$$

This potential encodes the confinement dynamics of QCD, and the challenge remains to derive it from first-principles QCD.

Solving Eq. (2) with this potential results in eigenvalues

$$M^2 = 4\kappa^2 (n + J/2 + L/2), \quad (4)$$

which reproduces the correct meson mass spectrum. In particular, it predicts a massless pion ($S = 0$, $n = 0$, $L = 0$) and $M_\rho^2 = 2\kappa^2$ for the ρ meson ($S = 1$, $n = 0$, $L = 0$). The corresponding eigenfunctions are [11]

$$\Phi(\zeta) = \kappa\sqrt{2\zeta}\exp\left(-\frac{\kappa^2\zeta^2}{2}\right). \quad (5)$$

It remains to specify the function $f(x)$ in Eq. (1). This can be done by comparing the expressions for the pion electromagnetic form factor obtained in the light-front formalism and in AdS space [7], and it results in

$$f(x) = \mathcal{N}\sqrt{x(1-x)}. \quad (6)$$

The resulting wave function is thus

$$\phi(x, \zeta) = \mathcal{N}\frac{\kappa}{\sqrt{\pi}}\sqrt{x(1-x)}\exp\left(-\frac{\kappa^2\zeta^2}{2}\right), \quad (7)$$

where $\mathcal{N}$ is a normalization constant. Assuming the meson is dominated by its leading $q\bar{q}$ Fock component, $\mathcal{N}$ is fixed by

Successful predictions for diffractive ρ production

In collaboration with J.R. Forshaw (Manchester U)

See talk by RS in WG2 at 15h tomorrow

Distribution Amplitudes are related to AdS/QCD light-front wavefunctions

We are then able to deduce that

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

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

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

and

$$\frac{\mathrm{d}g_\rho^{\perp(a)}}{\mathrm{d}z}(z,\mu) = \frac{\sqrt{2}N_c}{\pi f_\rho M_\rho}\int \mathrm{d}r\ \mu J_1(\mu r)(1-2z)[m_f^2 - \nabla_r^2]\frac{\phi_T(r,z)}{z^2(1-z)^2}\,. \qquad (51)$$

M. Ahmady & RS
PRD 87 (2013) 054013

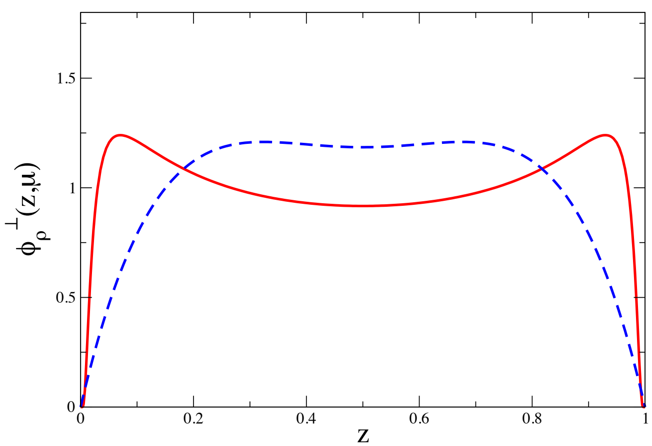
Also
J. R. Forshaw & RS
JHEP 1110 (2011) 093

Earlier: S. Brodsky & G. Lepage (1980)

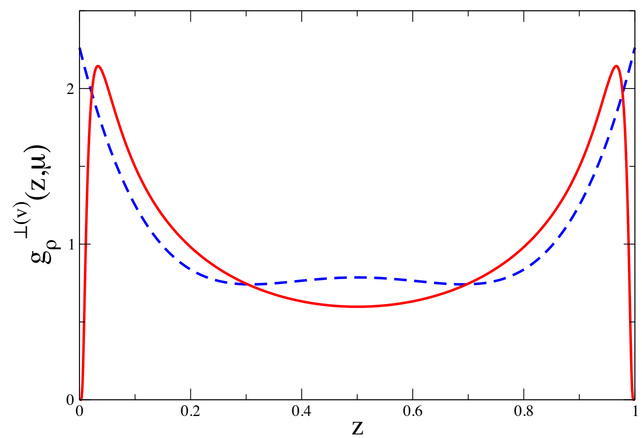
4 DAs: Twist-2 (long & trans), Twist-3(vector & axial vector)

Comparing AdS/QCD to Sum Rules

Twist-2 DA



Twist-3 DA

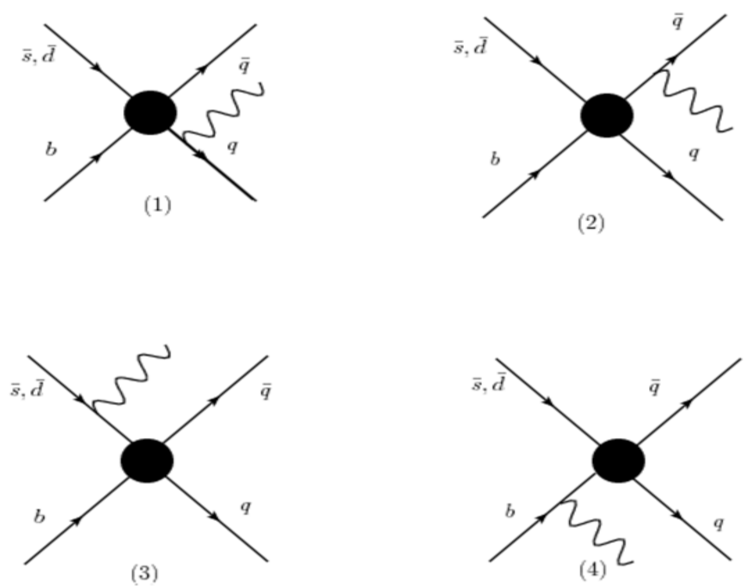


- Different end-point behavior for the (transverse) twist-2 and (vector) twist-3 DAs
- The transverse twist-2 DA enters the computation of the leading power decay amplitude
- The vector twist-3 DA enters the computation of some power corrections to the leading amplitude

Annihilation power corrections

M. Ahmady & RS
PRD 2013

- Two divergent integrals from diagram (1) and (2) with twist-3 SR DA
- No divergence with twist-3 AdS/QCD DA



Integral	SR	AdS/QCD
$I_{1(s)}^{\text{tw3}}(\mu)$	∞	0.237(0.229)
$I_{2(s)}^{\text{tw3}}(\mu)$	∞	0.036(0.034)

Branching ratio

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PRD 2013

$$Br(B \to V\gamma) = \frac{\Gamma(B \to V\gamma)}{\Gamma_{tot}}$$

Branching ratio $(\times 10^{-7})$ **for** $\bar{B}^{\circ} \to \rho^{\circ}\gamma$

DA	Accuracy	SR	AdS/QCD	PDG	Belle	BaBar
tw2 + tw3	Lead.(α_s^1) + Anni.$[\alpha_s^0, (1/m_b)^2]$		7.67	8.6 ± 1.5	$7.8 \pm^{1.7}_{1.6} \pm^{0.9}_{1.0}$	$9.7 \pm^{2.4}_{2.2} \pm^{0.6}_{0.6}$
tw2	Lead.(α_s^1) + Anni.$[\alpha_s^0, (1/m_b)]$	7.86	7.65			
tw2	Leading (α_s^1)	7.87	7.68			
None	Leading (α_s^0)	4.76	4.76			

- Power corrections are numerically small
- Divergence problem has no practical consequence when computing BR
- But it is a conceptual problem

Branching ratio for a very rare decay

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PRD 2013

$$\bar{B}_s^0 \rightarrow \rho + \gamma$$

- This decay proceeds only via annihilation
- AdS/QCD prediction for Branching Ratio is 5.5×10^{-10}
- Likely to be enhanced by New Physics
- Can it be investigated at LHCb ?

The isospin asymmetry

Work in progress with
M. Ahmady (Mount Allison U)

- Branching ratios are

$$Br(B \to K^* \gamma) = \frac{\Gamma(B \to K^* \gamma)}{\Gamma_{tot}}$$

- ➢ sensitive to hadronic uncertainties
- ➢ but less sensitive to power corrections

- Isospin asymmetry is

$$\Delta_{0-} \equiv \frac{\Gamma(\bar{B}^0 \to \bar{K}^{*0}\gamma) - \Gamma(B^- \to K^{*-}\gamma)}{\Gamma(\bar{B}^0 \to \bar{K}^{*0}\gamma) + \Gamma(B^- \to K^{*-}\gamma)}$$

- ➢ less sensitive to hadronic uncertainties
- ➢ but is a power correction

❑ Crucial to deal with the divergence problem when predicting the isospin asymmetry

Branching ratio for K*

Branching ratio	BABAR	BELLE	CLEO	PDG
$\mathcal{B}(B^0 \to K^{*0}\gamma) \times 10^6$	$44.7 \pm 1.0 \pm 1.6$	$45.5^{+7.2}_{-6.8} \pm 3.4$	$40.1 \pm 2.1 \pm 1.7$	43.3 ± 1.5
$\mathcal{B}(B^+ \to K^{*+}\gamma) \times 10^6$	$42.2 \pm 1.4 \pm 1.6$	$42.5 \pm 3.1 \pm 2.4$	$37.6^{+8.9}_{-8.3} \pm 2.8$	42.1 ± 1.8
$\Delta_{0-}(B \to K^*\gamma)$	$6.6 \pm 2.1 \pm 2.2$	$1.2 \pm 4.4 \pm 2.6$		5.2 ± 2.6

Our AdS/QCD for the branching ratio is 44.8×10^{-6} in agreement with the SR prediction and data

Isospin asymmetry for K*

Preliminary

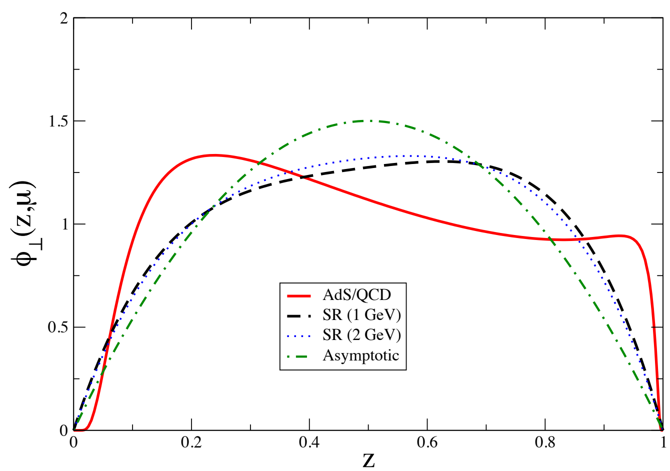
$$F_\perp = \int_0^1 \mathrm{d}z \frac{\phi_\perp(z)}{3(1-z)}$$

$$G_\perp(s_c) = \int_0^1 \mathrm{d}z \frac{\phi_\perp(z)}{3(1-z)} G(s_c, \bar{z})$$

$$H_\perp(s_c) = \int_0^1 \mathrm{d}z \left(g_\perp^{(v)} - \frac{1}{4}\frac{\mathrm{d}g_\perp^{(a)}}{\mathrm{d}z} \right) G(s_c, \bar{z})$$

$$X_\perp = \int_0^1 \mathrm{d}z \phi_\perp(z) \left(\frac{1+\bar{z}}{3\bar{z}^2} \right)$$

Integral	SR	AdS/QCD
$X_\perp$	∞	26.9
$F_\perp$	1.14	1.38
$G_\perp$	$2.55 + 0.43i$	$2.89 + 0.30i$
$H_\perp$	$2.48 + 0.50i$	$2.12 + 0.21i$



No diverging integral with AdS/QCD DA

Our prediction: $\Delta_{0-} = 4.6\%$

Particle Data Group: $\Delta_{0-} = (5.2 \pm 2.6)\%$

Conclusions

- Computed observables in radiative B decays to vector mesons (ρ,K*) using new AdS/QCD DAs for the vector mesons

- Agreement with data for branching ratios and isospin asymmetry

- Agreement with Sum Rules DAs for leading power predictions but avoids end-point divergences for power-suppressed contributions

Acknowledgements

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- Financial support from Universite de Moncton and Mount Allison University

Back up slide 1

Definition of DAs

Distribution Amplitudes parameterize the operator product expansion of vacuum-to-meson transition matrix elements of quark-antiquark non-local gauge invariant operators at light-like separations. At equal light-front time $x^+ = 0$ and in the light-front gauge $A^+ = 0$, we have [4, 5]

$$\begin{aligned} \langle 0|\bar{q}(0)\gamma^\mu q(x^-)|\rho(P,\lambda)\rangle \; &= \; f_\rho M_\rho \frac{e_\lambda \cdot x}{P^+ x^-} P^\mu \int_0^1 \mathrm{d}u \, e^{-iuP^+x^-} \phi_\rho^\parallel(u,\mu) \\ &+ \; f_\rho M_\rho \left(e_\lambda^\mu - P^\mu \frac{e_\lambda \cdot x}{P^+ x^-} \right) \int_0^1 \mathrm{d}u \, e^{-iuP^+x^-} g_\rho^{\perp(v)}(u,\mu) \; , \end{aligned} \tag{27}$$

$$\langle 0|\bar{q}(0)[\gamma^\mu,\gamma^\nu] q(x^-)|\rho(P,\lambda)\rangle = 2 f_\rho^\perp (e_\lambda^\mu P^\nu - e_\lambda^\nu P^\mu) \int_0^1 \mathrm{d}u \, e^{-iuP^+x^-} \phi_\rho^\perp(u,\mu) \tag{28}$$

and

$$\langle 0|\bar{q}(0)\gamma^\mu \gamma^5 q(x^-)|\rho(P,\lambda)\rangle = -\frac{1}{4} \epsilon^\mu_{\nu\rho\sigma} e_\lambda^\nu P^\rho x^\sigma f_\rho M_\rho \int_0^1 \mathrm{d}u \, e^{-iuP^+x^-} g_\rho^{\perp(a)}(u,\mu) \tag{29}$$

for the vector, tensor and axial-vector current respectively. The polarization vectors e_λ are

Back-up slide 2

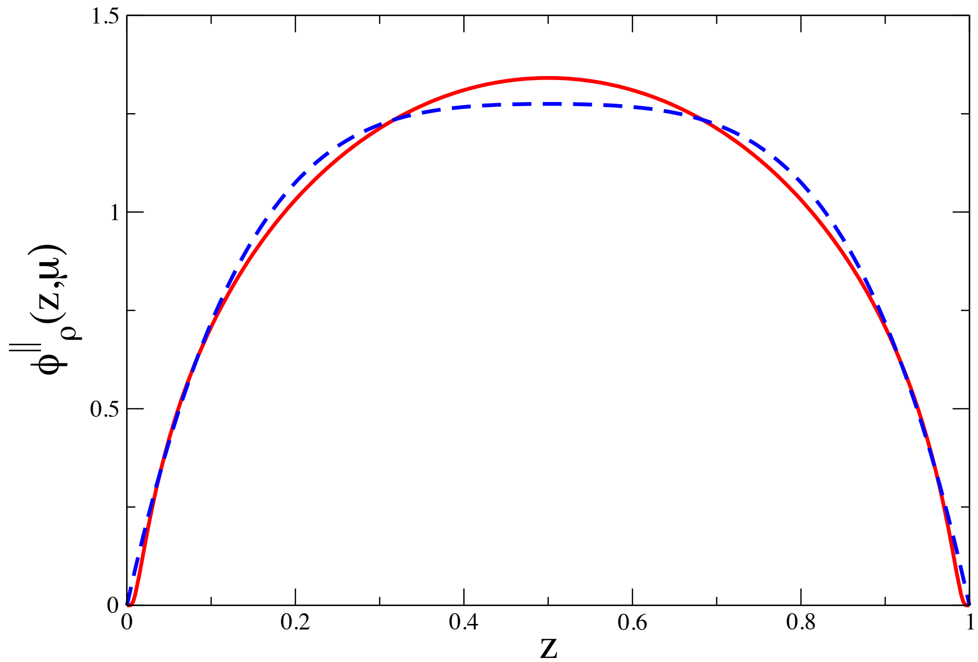
Explicit expressions for SR DAs for the ρ

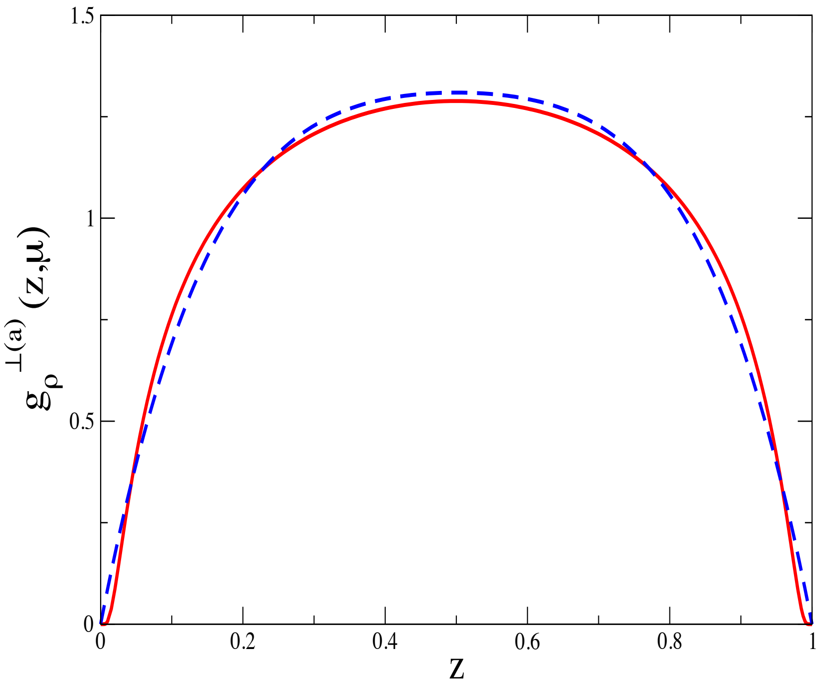
$$\phi_\rho^{\parallel,\perp}(z,\mu) = 6z(1-z)\left[1 + a_2^{\parallel,\perp}(\mu)\,\frac{3}{2}(5\xi^2-1)\right]$$

$$\begin{aligned} g_\rho^{\perp(v)}(z,\mu) \;=\; & \frac{3}{4}(1+\xi^2) + \left(\frac{3}{7}\,a_2^{\parallel}(\mu) + 5\zeta_3(\mu)\right)(3\xi^2-1) \\ & + \left[\frac{9}{112}\,a_2^{\parallel}(\mu) + \frac{15}{32}\,\omega_3^{\parallel}(\mu) - \frac{15}{64}\tilde{\omega}_3^{\parallel}(\mu)\right](3 - 30\xi^2 + 35\xi^4) \end{aligned}$$

Back-up slide 3

Longitudinal twist-2 DA and axial vector twist-3 DA: AdS/QCD Red, SR Blue





Back-up slide 4

Longitudinal twist-2 and vector twist-3 DAs for K*