Effective approaches to meson structure

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Outline

Part I: Effective Lagrangian approach

1. **Introductory remarks:** Charmonia & X, Y, Z mesons
2. **Hidden charm mesons as hadronic molecules:**
   - $Y(3940) = D^* \bar{D}^*$ and $Z^+(4430) = D^* \bar{D}_1$
3. **Theory**
   - Effective field theoretical approach for composite objects
4. **Selected radiative and hidden-charm decays**

Part II: AdS/CFT approach

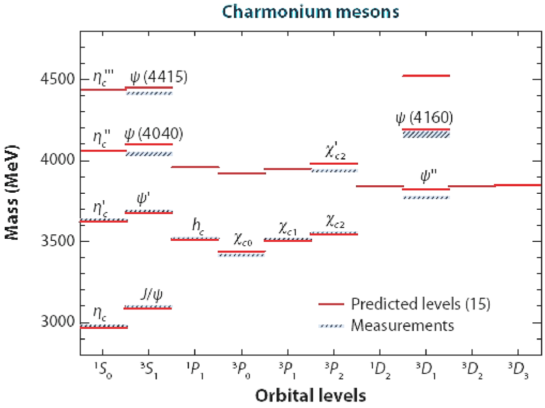
1. **Introduction of the method**
2. Computation of **meson mass spectrum**

Part I
Effective Lagrangian Approach

Together with:

Thomas Gutsche, Valery Lyubovitskij (Tübingen)
Mikhail A. Ivanov (Dubna), Jürgen G. Körner (Mainz)

$c\bar{c}$ meson spectrum



- mass spectrum predicted by potential models and lattice calculations
- good agreement with data below $D\bar{D}$ threshold
- well defined basis to study meson structure

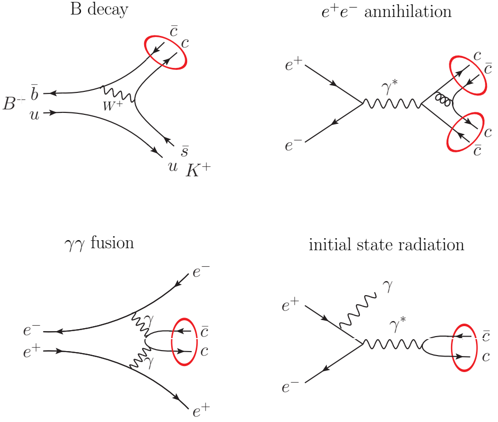
Fig. taken from Godfrey, Olsen, Annu. Rev. Nucl. Sci. 58, 51 (08)

Charmonium production mechanisms

B-factories BELLE, BaBar and CDF built to study B-physics

$\Rightarrow$ but also excellent environment for charmonium spectroscopy

Charmonium production:



Many new charmonium-like X, Y and Z mesons

State	M (MeV)	Γ (MeV)	J^{PC}	Decay Modes	Production Modes	Observed by:
$X(3872)$	3871.4 ± 0.6	< 2.3	1^{++}	$\pi^+\pi^- J/\psi$,$\gamma J/\psi$	$B \to KX(3872)$, $p\bar{p}$	Belle, CDF, D0, BaBar
$X(3875)$	3875.5 ± 1.5	$3.0^{+2.1}_{-1.7}$	?	$D^0\bar{D}^0\pi^0(\gamma)$	$B \to KX(3875)$	Belle, BaBar
$Z(3940)$	3929 ± 5	29 ± 10	2^{++}	$D\bar{D}$	$\gamma\gamma \to Z(3940)$	Belle
$X(3940)$	3942 ± 9	37 ± 17	J^{P+}	$D\bar{D}^*$	$e^+e^- \to J/\psi X(3940)$	Belle
$\mathbf{Y}(3940)$	3943 ± 17	87 ± 34	J^{P+}	$\omega J/\psi$	$B \to KY(3940)$	Belle, BaBar
$Y(4008)$	4008^{+82}_{-49}	226^{+97}_{-80}	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^-(ISR)	Belle
$\mathbf{Y}(4140)$	4130 ± 4.1	$11.7^{+12.0}_{-8.7}$	J^{P+}	$J/\psi\phi$	$B^+ \to K^+Y(4140)$	CDF
$X(4160)$	4156 ± 29	139^{+113}_{-65}	J^{P+}	$D^*\bar{D}^*$	$e^+e^- \to J/\psi X(4160)$	Belle
$Y(4260)$	4264 ± 12	83 ± 22	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^-(ISR)	BaBar, CLEO, Belle
$Y(4350)$	4361 ± 13	74 ± 18	1^{--}	$\pi^+\pi^-\psi'$	e^+e^-(ISR)	BaBar, Belle
$\mathbf{Z}^\pm(4430)$	4433 ± 5	45^{+35}_{-18}	?	$\pi^\pm\psi'$	$B \to KZ^\pm(4430)$	Belle
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$\pi^+\pi^-\psi'$	e^+e^-(ISR)	Belle

Table taken from Godfrey, arXiv:0910.3409

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- overpopulation of states
- untypical decay/production properties, ...

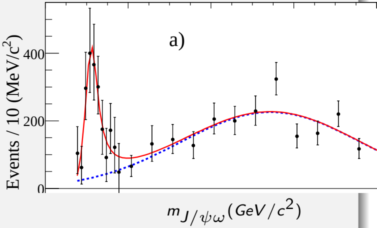
$Y(3940)$

$Y(3940)$ BELLE/BaBar (2005)

- $B \to Y(3940)K$ with $Y(3940) \to J/\psi\omega$
- $m_{Y(3940)} = 3914.6^{+3.8}_{-3.4}(\text{stat}) \pm 2(\text{syst})$ MeV,

  $\Gamma_{Y(3940)} = 34^{+12}_{-8}(stat) \pm 5(\text{syst})$ MeV
- resonance $X(3915)$ in $\gamma\gamma \to \omega J/\psi$ BELLE(09)

  $\to Y(3940)$?



$Z^+(4430)$

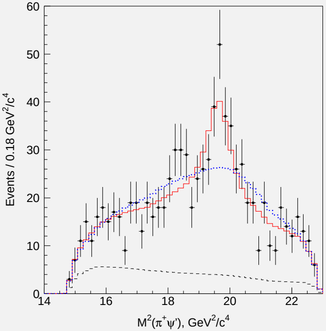
First detection of charged hidden-charm state

$Z^+(4430)$ BELLE (2008)

- $B \to Z^+(4430)K$
- $Z^+(4430) \to \pi^+\psi'$, $Z^+(4430) \not\to \pi^+\psi$
- $m_{Z^+(4430)} = 4443^{+15+19}_{-12-13}$ MeV,

  $\Gamma_{Z^+(4430)} = 107^{+86+74}_{-43-56}$ MeV
- not seen by BaBar but no contradiction.

$\Rightarrow$ needs confirmation by second experiment.



Further charged charmonium-like states in $B \to K\pi^+\chi_{c1}$:
$Z_1^+(4050)$, $Z_2^+(4250)$ (BELLE (08))

Y(3940) and Z^+(4430) - meson molecules

1. $m_{Y(3940)}$=3914.6 MeV, $D^*\bar{D}^*$-threshold ≈ 4014 MeV.

   interpretation as $\left|Y(3940)\right\rangle = \frac{1}{\sqrt{2}}\left(\left|D^{*+}D^{*-}\right\rangle + \left|D^{*0}\bar{D}^{*0}\right\rangle\right)$

   - quantum numbers (first estimate) $J^{PC} = 0^{++}, 2^{++}$

2. $m_{Z^+(4430)}$ ≈4430 MeV, $D^*\bar{D}_1(2420)$-threshold ≈ 4430 MeV.

   interpretation as $\left|Z^+(4430)\right\rangle = \frac{1}{\sqrt{2}}\left(\left|D^{*+}\overline{D_1^0}\right\rangle + \left|D_1^+\overline{D^{*0}}\right\rangle\right)$

   - $G-$parity positive state, $I^G(J^{PC}) = 1^+(0^{--}, 1^{--})$.

Binding of meson-meson systems

Y(3940)

- meson exchange potentials (Tornqvist (94), Liu *et al.* (09))
  $D^* \bar{D}^*$ bound by π exchange,
- dynamically generated (Oset *et al.* (09))
  $Y(3940)$ is mostly a $D^* \bar{D}^*$ bound state with $J^{PC} = 0^{++}$

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$Z^+(4430)$

- meson exchange potentials (Liu *et al.* (08))
  $D^*\bar{D}_1$ can form bound state by π, σ exchange ($J^P = 0^-$)
- OPE (Close et al. (10)) sufficient for $D^*\bar{D}_1$ binding with $J^P = 1^-$
- QCD sum rules (Lee et al. (08), Nielsen et al. (09))
  $D^*\bar{D}_1$ molecular structure with $J^P = 0^-$.

Effective Lagrangian approach

Hadronic molecule H as a bound state of mesons M_1 and M_2

- Aim: calculation of decay properties

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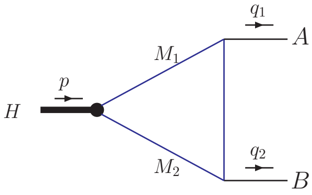

Decays of hadronic molecules:

Decay proceeds via constituent mesons M_1 & M_2

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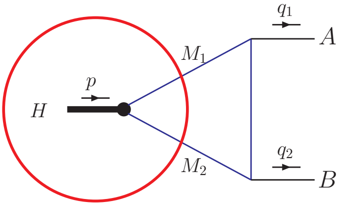

Decays of hadronic molecules:

Decay proceeds via
constituent mesons M_1 & M_2

1. finite size of hadronic molecule $\rightarrow$ form factors
2. determination of coupling constant g_H

Theoretical framework

Interaction of H with M_1 and M_2 characterized by effective Lagrangian:

$$\mathcal{L}_H(x) = g_H H(x) \int dy\, \Phi(y^2) M_1\left(x - \frac{y}{2}\right) M_2\left(x + \frac{y}{2}\right)$$

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1. Vertex function $\Phi(y^2)$ allows for finite size effects (distribution of constituents)

$$\Phi(y^2) = \int \frac{d^4k}{(2\pi)^4} e^{-iky} \widetilde{\Phi}(-k^2)$$

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Gaussian form in momentum space: $\widetilde{\Phi}(k_E^2) = \exp(-k_E^2/\Lambda^2)$

Size parameter Λ $\approx$ few GeV

Local limit (pointlike interaction): $\Lambda \to \infty$

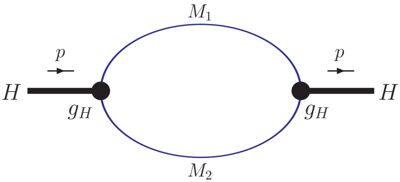
Compositeness/Weinberg condition

2. determination of the coupling constant g_H

Description of hadronic bound states based on compositeness condition[1]

$$Z_H = 1 - g_H^2 \tilde{\Pi}'(p^2)\Big|_{p^2=m_H^2} = 0 \, .$$

with the mass operator $g_H^2 \tilde{\Pi}(p^2)$



$$Z_H = \left|\left\langle H^{bare} \middle| H^{dressed} \right\rangle\right|^2 = 0$$

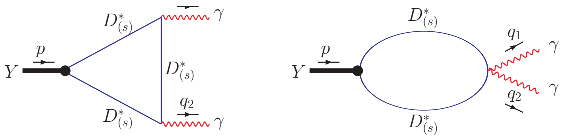
Coupling g_H finite and fixed self-consistently

[1] Weinberg, PR 130 (1963) 776; Salam, Nuov. Cim. 25 (1962) 224;...

Radiative decays $Y\ (D^*\bar{D}^*) \to \gamma\gamma$

1. minimal substitution $H^{\pm}\to(\partial^\mu \mp ieA^\mu)H^{\pm}$

$$\mathcal{L}_{\rm em}=eA_\alpha\left(g^{\alpha\nu}D^{*-}_\mu i\overleftrightarrow{\partial}^\mu D^{*+}_\nu+\mathrm{H.c}\right)+e^2D^{*-}_\mu D^{*+}_\nu\left(A^\mu A^\nu-g^{\mu\nu}A^\alpha A_\alpha\right).$$



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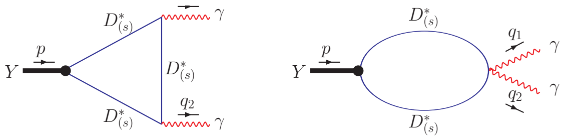
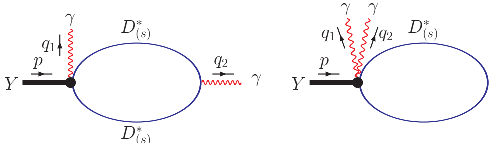


2. gauging the strong interaction Lagrangian with $H^{\pm}(y) \to e^{\mp ieI(y,x,P)} H^{\pm}(y)$, where $I(x,y,P) = \int_y^x dz_\mu A^\mu(z)$ (Terning (1991)).



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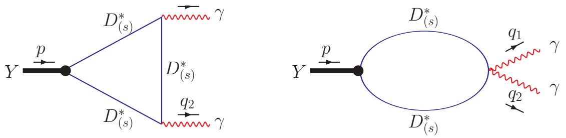

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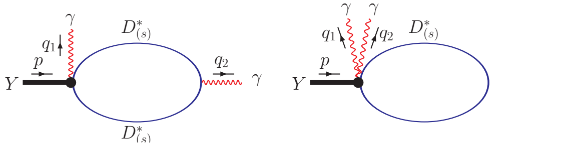


- two additional diagrams are generated
- necessary to guarantee full gauge invariance.

Results $Y(3940) \to \gamma\gamma$

$\mathbf{Y(3940) = D^*\bar{D}^*}$ $\Gamma_{Y(3940)} = 34^{+12}_{-8}(stat) \pm 5(syst)\ MeV$

- $\Gamma_{Y\to\gamma\gamma}$

effective Lagrangian approach [1]	0.33 keV
coupled channels [2]	0.09 keV

- resonance $X(3915)$ in $\gamma\gamma \to J/\psi\omega$ (BELLE (09)),

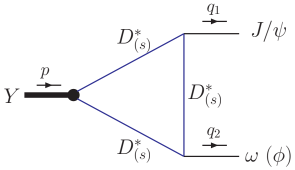
  $\to$ $X(3915)$ candidate for ($Y(3940)$?)

  $\Gamma(X(3915) \to \gamma\gamma)\mathcal{B}(X(3915) \to \omega J/\psi) = 61 \pm 17 \pm 8$ eV:

  $\Gamma(X(3915) \to \gamma\gamma) \approx 0.4$ keV same order of magnitude

[1] TB, T. Gutsche, V.E. Lyubovitskij, Phys. Rev. D 80, 054019 (2009)
[2] TB, R. Molina, E. Oset, arXiv:1010.0587.

Hidden-charm decay $Y \to J/\psi\omega$



Coupling to final states:

HHChPT Lagrangian (Wise (1992),Colangelo (2004)):

$$\mathcal{L}_{D^*D^*J_\psi} = ig_{D^*D^*J_\psi} J_\psi^\mu \left(D^{*\dagger}_{\mu i} \overleftrightarrow{\partial}_\nu D^{*\nu}_i + D^{*\dagger}_{\nu i} \overleftrightarrow{\partial}^\nu D^*_{\mu i} - D^{*\dagger\nu}_i \overleftrightarrow{\partial}_\mu D^*_{\nu i} \right),$$

$$\mathcal{L}_{D^*D^*V} = ig_{D^*D^*V} V^\mu_{ij} D^{*\dagger}_{\nu i} \overleftrightarrow{\partial}_\mu D^{*\nu}_j + 4if_{D^*D^*V} (\partial^\mu V^\nu_{ij} - \partial^\nu V^\mu_{ij}) D^*_{\mu i} D^{*\dagger\nu}_j$$

$V_{ij} = \mathrm{diag}\{\omega/\sqrt{2}, \omega/\sqrt{2}, \phi\}, D^* = (D^{*0}, D^{*+}, D^{*+}_s)$

$g_{D^*D^*J/\psi} \approx 3.69, \quad g_{D^*D^*V} \approx 4.61, \quad f_{D^*D^*V} \approx 8.00$

Results $Y(3940) \to J/\psi\omega$

Y(3940) $\Gamma_{Y(3940)} = 34^{+12}_{-8}(stat) \pm 5(syst)\ MeV$

- $\Gamma_{Y \to J/\psi\omega}$

Molina, Oset (09)	(dyn. generated)	1.52 MeV
our result	(HM)	5.47 MeV

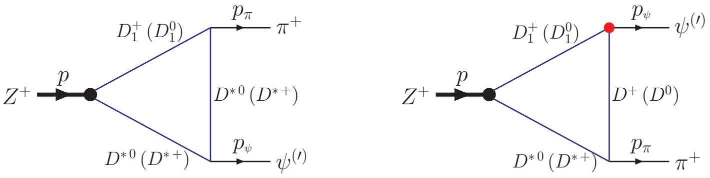
- $\mathcal{B}(B^+ \to Y(3940)K^+)\mathcal{B}(Y(3940) \to J/\psi\omega) = (7.1 \pm 1.3 \pm 3.2) \cdot 10^{-5}$

  leads to: $\Gamma_{Y \to J/\psi\omega}$ of a few MeV

  at least order of magnitude higher than $c\bar{c}$ estimates (keV scale)

TB, T. Gutsche, V.E. Lyubovitskij, Phys. Rev. D 80, 054019 (2009)

Hidden-charm decays $Z^+ \to \pi^+ \psi^{(\prime)}$



Couplings:

- $g_{D_1 D^* \pi}$=0.49 GeV^{-1} fixed by $\Gamma(D_1 \to D^{*+}\pi^-) \approx 20$ MeV
- $g_{D^* D^* J/\psi} = 8$, $g_{D^* D^* \psi'}/g_{D^* D^* \psi} = 1.67$ (HHChPT)
- $g_{D^* D\pi} = 17.9$ from corresponding decay
- $r_1 = g_{D_1 D\psi}/g_{D_1 D^* \pi} \approx 0.4 \pm 0.2$ from coupled channels
- $r_2 = g_{D_1 D\psi'}/g_{D_1 D\psi} \approx 2 \pm 1$ ($^3P_0$ quark model).

Results $Z^+ \to \pi^+\psi^{(\prime)}$

$\mathbf{Z}^+$(4430) $\Gamma_{Z^+(4430)} = 107^{+86+74}_{-43-56}\ MeV$

- $Z^+ \to \pi^+\psi', \quad Z^+ \not\to \pi^+\psi \quad \Rightarrow \quad \mathcal{B}\frac{Z^+\to\pi^+\psi'}{Z^+\to\pi^+\psi} >> 1$
- $\mathcal{B}(B \to Z^+K)\mathcal{B}(Z^+ \to \psi'\pi^+) = (4.1 \pm 1.0 \pm 1.4) \cdot 10^{-5}$ (BELLE(09))
  $\Rightarrow\ \Gamma(Z^+ \to \pi^+\psi') > 1$ MeV.

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  $\Rightarrow \Gamma(Z^+ \to \pi^+\psi') > 1$ MeV.
- Our result

$r_1 = \frac{g_{D_1 D\psi}}{g_{D_1 D^*\pi}}$	$\Gamma_{Z\to\pi\psi'}$ [MeV] $r_2 = 2$	$r_2 = 3$	$R = \Gamma_{Z\to\pi\psi'}/\Gamma_{Z\to\pi\psi}$ $r_2 = 2$	$r_2 = 3$
0.4	2.9	6.9	3.6	8.6
0.6	6.9	16.2	3.0	7.0

$$r_2 = \frac{g_{D_1 D\psi'}}{g_{D_1 D\psi}} = 1 - 3$$

TB, T. Gutsche, V.E. Lyubovitskij, Phys.Rev. D 82, 054025 (2010)

Part II
AdS/CFT

Together with:

Thomas Gutsche, Valery Lyubovitskij (Tübingen)
Ivan Schmidt, Alfredo Vega (Valparaiso, Chile)

Holographic approach to hadronic matter

Light front holography approach based on AdS/CFT correspondence

AdS: Anti de Sitter space ('Strings')

CFT: Conformal field theory ('hadronic world'), (here conformal=scale invariant)

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AdS: Anti de Sitter space ('Strings')

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- application of string theory to physical observables.
- semi classical approximation to QCD

Holographic approach to hadronic matter

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Aim of the model:

- Description of hadrons in terms of quarks and gluons
- Computation of hadron properties
- Mass spectrum
- Decay constants and widths

Basic blocks of the Framework

AdS/CFT correspondence

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AdS/CFT correspondence

String-Theory in
Anti-de-Sitter space (AdS)

5 dimensions

(4 space-time coordinates x,
plus one holographic variable z)

String mode $\Phi(z)$
holographic variable z

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Conformal Field Theory (CFT) in Physical Space-Time

(3+1) dimensions

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Physical states
Light front wave functions $\Psi(\zeta)$
impact variable ζ

ζ=extension of hadron

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Matching
$\Leftrightarrow$

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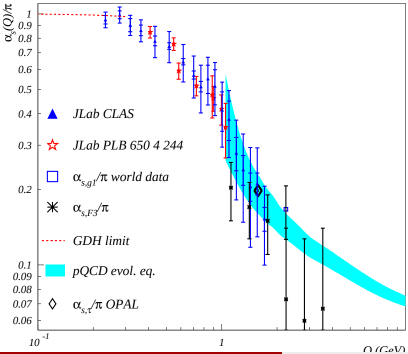
Brodsky, de Teramond, Phys. Rev. D 77, 056007 (2008)

Conformal field theory (CFT)

Why can we use a conformal (scale invariant) theory?

- The strong coupling $\alpha_S(Q^2)$ is **not** scale invariant.
- However, it is assumed that $\alpha_S(Q^2)$ becomes big but slowly varying at large distances $\rightarrow$ conformal window
- existence of an IR fixed point



Deur et al. (2008)

AdS-Space

AdS_5-space

- 5-dim. space with negative curvature and conformal symmetry.
- Metric: $ds^2 = \frac{R^2}{z^2}(\eta^{lm} dx_l dx_m - dz^2)$,

  $\eta^{lm} = diag(1, -1, -1, -1)$

  R: radius
- invariant with respect to $x \to \lambda x$ and $z \to \lambda z$.

  $\to$ scale transformations in z can be matched to physical space-time.

- **Action of string**

  $S_\Phi = \frac{(-1)^J}{2} \int d^4x dz \sqrt{g}\, e^{-\phi(z)} \left(\partial_I \Phi_J \partial_I \Phi_J - \mu^2 \Phi_J \Phi_J\right),$

  J: total spin,

  $\phi(z) = \kappa^2 z^2$: Dilaton field

- **Ansatz for string:** plain wave along the Poincaré coordinates and profile function in the holographic variable $\Phi(x, z) = e^{-iPx}\Phi(z)$

- **Equation of motion** of string mode:

  $\left(-\frac{d^2}{dz^2} - \frac{1-4L^2}{4z^2} + U(z)\right)\Phi(z) = \mathcal{M}^2\Phi(z),$

  $U(z) = \kappa^4 z^2 + 2\kappa^2(J-1)$ due to dilaton field.

Matching procedure

Electromagnetic form factor of the pion in light-front formalism

$$F(Q^2) = 2\pi \int\limits_0^1 dx \frac{1-x}{x} \int\limits_0^\infty d\zeta \zeta J_0\left(\zeta Q \sqrt{\frac{1-x}{x}}\right) \widetilde{\rho}(x,\zeta)$$

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comparing both expressions:

$z = \zeta$ $\Rightarrow$ holographic variable $\equiv$ impact variable

$$\widetilde{\rho}(x,\zeta) = \frac{x}{1-x} \frac{\left|\Phi(\zeta)\right|^2}{2\pi\zeta}$$

Brodsky, de Teramond, Phys. Rev. D 77, 056007 (2008)

Matching procedure - here Mesons

$\widetilde{\rho}(x,\zeta) = \frac{x}{1-x}\frac{\left|\Phi(\zeta)\right|^2}{2\pi\zeta}$, density for two parton system: $\widetilde{\rho}_{n=2}(x,\zeta) = \frac{\left|\widetilde{\Psi}(x,\zeta)\right|^2}{(1-x)^2}$

The hadron wave function characterized by the string mode:

$$\left|\Psi(x,\zeta)\right|^2 = x(1-x)\frac{\left|\Phi(\zeta)\right|^2}{2\pi\zeta}$$

- String mode $\Phi(z)$ can be directly mapped to the LFWF $\Psi(\zeta)$

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  ⇒ Full hadronic wave function is known
  ⇒ computation of meson properties and amplitudes

Improvement of the model

Inclusion of

- quark masses: $-\frac{d^2}{d\zeta^2} \to -\frac{d^2}{d\zeta^2} + m_{12}^2$, $m_{12}^2 = \frac{m_1^2}{x} + \frac{m_2^2}{1-x}$ in EoM
- one gluon exchange: $-\dfrac{64\alpha_s^2 m_1 m_2}{9(n+L+1)^2}$, $\alpha_s = 0.33 - 0.79$ flavor dependent
- hyperfine splitting: $+\dfrac{32\pi\alpha_s\beta_S v}{9\mu_{12}}$, $\beta = -3\,(S=0),\, 1\,(S=1)$

  $\mu_{12} = \frac{2m_1 m_2}{m_1+m_2}$, hyperfine-splitting parameter $v = 10^{-4}$ GeV^3.

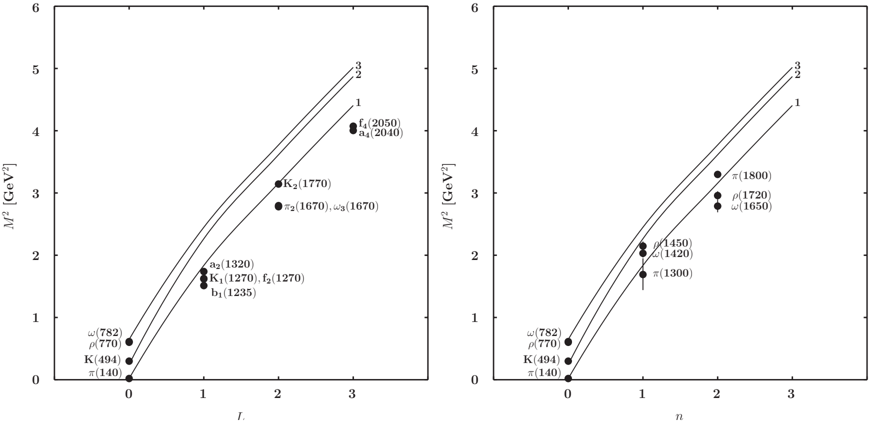
Mass spectrum:

$$\mathcal{M}_{nJ}^2 = 4\kappa^2\left(n + \frac{L+J}{2}\right) + \int_0^1 dx \left(\frac{m_1^2}{x} + \frac{m_2^2}{1-x}\right) N^2 e^{-\frac{m_{12}^2}{\kappa^2}} - \frac{64\alpha_s^2 m_1 m_2}{9(n+L+1)^2} + \frac{32\pi\alpha_s\beta_S v}{9\mu_{12}}.$$

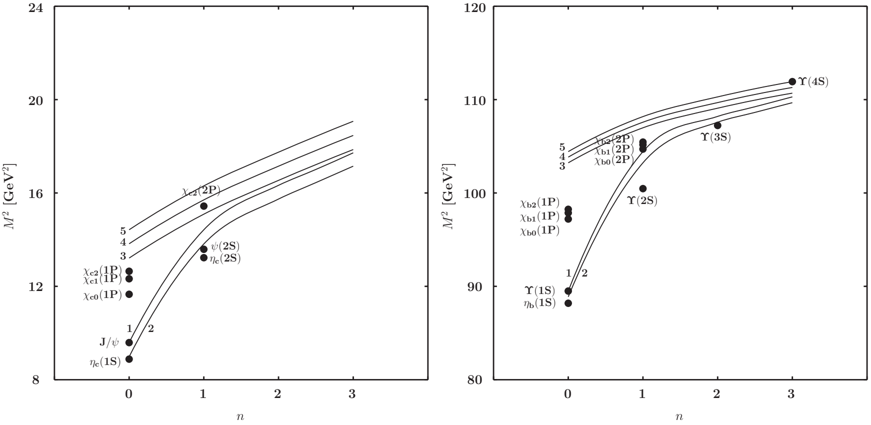
N normalization: $1 = \int_0^1 dx\, N^2 e^{-\frac{m_{12}^2}{\kappa^2}}$

see TB, T. Gutsche, V.E. Lyubovitskij, I. Schmidt, A. Vega, Phys. Rev. D 82, 074022

Meson mass spectrum 1



Meson mass spectrum 2



Conclusions

Part I: Effective Lagrangian approach

- Covariant and gauge invariant QFT approach to hadronic bound states
- Study of decay properties of charmonium-like mesons $Y(3940)$ and $Z^{+}(4430)$
- Large hidden-charm decay widths can be explained by hadronic molecule interpretation.

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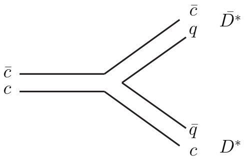
Part II: AdS/CFT

- Holographic model for strongly coupled QCD
- Computation of meson mass spectrum

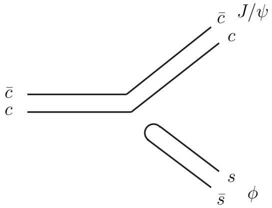
Decay pattern of Y

Why do the Y not fit in the $c\bar{c}$ scheme?

- $c\bar{c}$ decays to open charm modes dominant
- $(c\bar{c}) \to J/\psi\omega$ suppressed



open charm decay (OZI-allowed)



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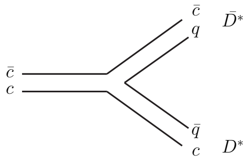

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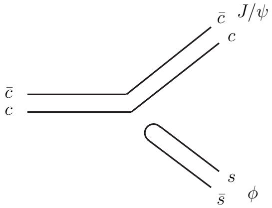
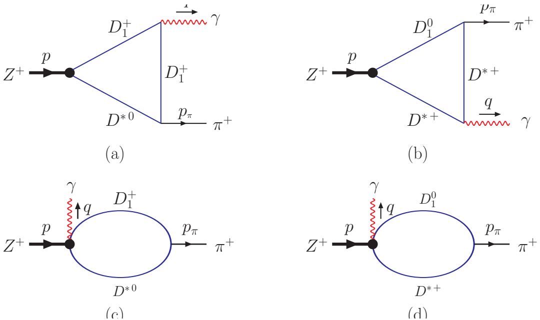


hidden charm decay (OZI-suppressed)

- Experiment: $Y \to J/\psi\omega > 1$ MeV
  (1 order of magnitude bigger than all charmonia!)

Radiative decay $Z^+(4430) \to \pi^+\gamma$



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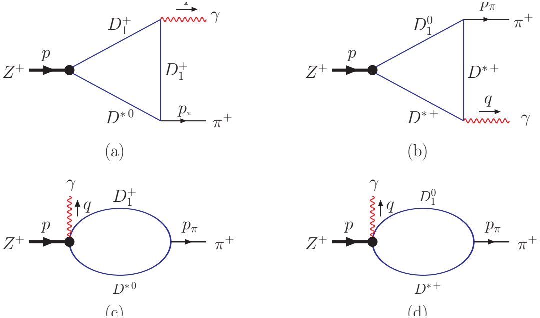

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$\mathbf{Z^+(4430)} = D^*\bar{D}_1$ $\Gamma_{Z^+(4430)} = 107^{+86+74}_{-43-56}$ MeV

$\Gamma_{Z^+\to\pi^+\gamma} \approx 0.3 - 0.8$ keV ($\epsilon = 1 - 10$ MeV) (for $J^P = 1^-$)