Spectroscopy of Charmed Hadrons

Facing the Latest Experimental Results with the Theory

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Presentation Outline

My thesis in brief

The core of my thesis consisted in the calculations, within the framework of heavy chiral perturbation theory, of branching fraction ratios of a recently observed excited D meson, the $D_2^*(3000)$, aimed at its classification.

Structure of the presentation

1. **Why?** → Recent experimental findings in hadron spectroscopy.

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4. **What's the point?** → Identification of the $D_2^*(3000)$.
5. **So What?** → Conclusions and perspectives.

Advances in Hadron Spectroscopy

Bird-eye view

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Exotic spectroscopy

- Supernumerary states (es. $X(3872)$, $Y(4260)$, ...).
- Charged quarkoniumlike states (es. $Z(4430)^+$, $Z(4200)^+$, ...).
- Pentaquark states ($P_c(4380)^+$, $P_c(4450)^+$).

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Ordinary spectroscopy

- Heavy baryons
- Heavy mesons ← *The subject of my thesis!*

Advances in Hadron Spectroscopy

Charmed Mesons: Latest Observations

Leading role: B-factories (Belle, BaBar), LHCb

Latest observations:

2010 (BaBar), 2013 (LHCb) and **2016 (LHCb)** ← Observation of the $D_2^*(3000)$!

Resonance	mass (MeV)	Γ (MeV)	J^P
$D(2550)^0$	$2539.4 \pm 4.5 \pm 6.8$	$130 \pm 12 \pm 13$	0^-
$D^*(2600)^0$	$2608.7 \pm 2.4 \pm 2.5$	$93 \pm 6 \pm 13$	natural
$D^*(2600)^\pm$	$2621.3 \pm 3.7 \pm 4.2$	93 (fixed)	natural
$D(2750)^0$	$2752.4 \pm 1.7 \pm 2.7$	$71 \pm 6 \pm 11$	
$D^*(2760)^0$	$2763.3 \pm 2.3 \pm 2.3$	$60.9 \pm 5.1 \pm 3.6$	natural
$D^*(2760)^\pm$	$2769.7 \pm 3.8 \pm 1.5$	60.9 (fixed)	natural

BaBar (2010)

Resonance	mass (MeV)	Γ (MeV)	J^P
$D_J(2580)^0$	$2579.5 \pm 3.4 \pm 5.5$	$177.5 \pm 17.7 \pm 46.0$	unnatural
$D_J^*(2650)^0$	$2649.2 \pm 3.5 \pm 3.5$	$140.2 \pm 17.1 \pm 18.6$	natural
$D_J(2740)^0$	$2737.0 \pm 3.5 \pm 11.2$	$73.2 \pm 13.4 \pm 25.0$	unnatural
$D_J^*(2760)^0$	$2761.1 \pm 5.1 \pm 6.5$	$74.4 \pm 4.3 \pm 37.0$	natural
$D_J^*(2760)^0$	$2760.1 \pm 1.1 \pm 3.7$	$74.4 \pm 3.4 \pm 19.1$	natural
$D_J^*(2760)^\pm$	$2771.7 \pm 1.7 \pm 3.8$	$66.7 \pm 6.6 \pm 10.5$	natural
$D_J(3000)^0$	2971.8 ± 8.7	188.1 ± 44.8	unnatural
$D_J^*(3000)^0$	3008.1 ± 4.0	110.5 ± 11.5	natural
$D_J^*(3000)^\pm$	3008.1 (fixed)	110.5 (fixed)	natural

LHCb (2013)

Resonance	mass (MeV)	Γ (MeV)	J^P
$D_1^*(2680)^0$	$2681.1 \pm 5.6 \pm 4.9 \pm 13.1$	$186.7 \pm 8.5 \pm 8.6 \pm 8.2$	1^-
$D_3^*(2760)^0$	$2775.5 \pm 4.5 \pm 4.5 \pm 4.7$	$95.3 \pm 9.6 \pm 7.9 \pm 33.1$	3^-
$D_2^*(3000)^0$	$3214 \pm 29 \pm 33 \pm 36$	$186 \pm 39 \pm 34 \pm 63$	2^+

LHCb (2016)

The Theoretical Framework

It is unclear how to describe analytically relativistic bound systems in quantum field theories.

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The approaches used in hadron spectroscopy so far:

1. Potential models (i.e. Schroedinger eq. with *ad hoc* potentials)
2. QCD effective theories ← *The one used in my thesis!*

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Effective theories leverage symmetries emerging from QCD in well defined limits.

The Theoretical Framework

Heavy Quark Symmetries

Heavy quarks

Quarks within hadrons exchange gluons with $p \approx \Lambda_{\mathrm{QCD}} = 200\,\mathbf{MeV} \approx 1\,\mathbf{fm}^{-1}$.

Quarks with $m_Q \gg \Lambda_{\mathrm{QCD}}$ referred to as heavy (c, b). ← t bound states unobserved!

QCD Lagrangian for Heavy Quarks (HQ)

$$\mathcal{L}_{\mathrm{QCD}} = \overline{Q}\left(i\not{D} - m_Q\right) Q \qquad D_\mu = \partial_\mu - igA_\mu^a T^a \qquad Q\text{: HQ field}$$

HQ limit $m_Q \to \infty$

$$\mathcal{L}_{\mathrm{QCD}} = \overline{h}_v\; iv^\mu D_\mu\; h_v + \frac{1}{2m_Q}\overline{h}_v (iD_\perp)^2 h_v + \frac{g}{4m_Q}\overline{h}_v \sigma_{\alpha\beta} G^{\alpha\beta} h_v + \mathcal{O}\left(\frac{1}{m_Q^2}\right)$$

$$h_v(x) = e^{im_Q v_\mu x^\mu}\frac{1+\not{v}}{2}Q(x) \qquad \leftarrow \text{positive energy component of } Q$$

The HQET Lagrangian

$$\mathcal{L}_{\mathrm{HQET}} \equiv \overline{h}_v\; iv^\mu D_\mu\; h_v$$

In heavy hadrons the heavy quark decouples:
HQ spin and flavour symmetries.

There is an analogy with atomic spectroscopy (HQ $\leftrightarrow$ nuclei):

Analogy with non-relativistic electrodynamics

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There is an analogy with atomic spectroscopy (HQ $\leftrightarrow$ nuclei):

- HQ spin decoupling → hyperfine splitting is small
- HQ flavour irrelevant → different isotopes have the same chemistry

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For heavy mesons, in the exact HQ limit

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- Properties of beauty mesons related to those of charmed ones.
- Mesons differing only for the orientation of the heavy quark spin expected to be degenerate.
- Heavy quark spin $\vec{S}_Q$ and total angular momentum of the light degrees of freedom $\vec{S}_\ell$ separately conserved.

The Theoretical Framework

HQET Classification of Heavy Mesons

HQET doublets

$$\vec{S}_\ell = \vec{L} + \vec{S}_q$$

$$\vec{J} = \vec{S}_\ell + \vec{S}_Q$$

$$P = (-1)^{L+1}$$

n : radial quantum number

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- Heavy mesons classified in doublets with given n and S_ℓ^P.
- In each doublet there are two states with $J^P = (S_\ell \pm 1/2)^P$.
- For each n, a state with assigned J^P can belong to two possible doublets with $S_\ell^P = (J \pm 1/2)^P$ (except for 0^-).

HQET doublets

$$\left.\begin{array}{l}\left.\begin{array}{l}\left.\begin{array}{l}P,\ J^P=0^-\\ P^*,\ J^P=1^-\end{array}\right\} H,\ S_\ell^P=1/2^-\end{array}\right\} L=0\\[2em] \left.\begin{array}{l}\left.\begin{array}{l}P_0^*,\ J^P=0^+\\ P_1',\ J^P=1^+\end{array}\right\} S,\ S_\ell^P=1/2^+\\ \left.\begin{array}{l}P_1,\ J^P=1^+\\ P_2^*,\ J^P=2^+\end{array}\right\} T,\ S_\ell^P=3/2^+\end{array}\right\} L=1\\[2em] \qquad\qquad\vdots\end{array}\right\} n=1,\ \ldots$$

Interlude: covariant representation of states

$$L = 0 \left\{ \quad H = \frac{1+\not{v}}{2}\left(P^{*}{}_{\mu}\gamma^{\mu} - P\gamma^{5}\right) \right.$$

$$L = 1 \left\{ \begin{array}{l} S = \dfrac{1+\not{v}}{2}\left(P_{1}'{}_{\mu}\gamma^{\mu}\gamma^{5} - P_{0}^{*}\right) \\ T^{\mu} = \dfrac{1+\not{v}}{2}\left(P_{2}^{*}{}^{\mu}{}_{\nu}\gamma^{\nu} - P_{1\,\nu}\sqrt{\dfrac{3}{2}}\gamma^{5}\left(\eta^{\mu\nu} - \dfrac{1}{3}\gamma^{\nu}\left(\gamma^{\mu} - v^{\mu}\right)\right)\right) \end{array} \right.$$

$$L = 2 \left\{ \begin{array}{l} X^{\mu} = \dfrac{1+\not{v}}{2}\left(P_{2}{}^{\mu}{}_{\nu}\gamma^{\nu}\gamma^{5} - P_{1}^{*\prime}{}_{\nu}\sqrt{\dfrac{3}{2}}\left(\eta^{\mu\nu} - \dfrac{1}{3}\gamma^{\nu}\left(\gamma^{\mu} + v^{\mu}\right)\right)\right) \\ X'^{\mu\nu} = \dfrac{1+\not{v}}{2}\left(P_{3}^{*}{}^{\mu\nu}{}_{\rho}\gamma^{\rho} - P_{2}'{}_{\alpha\beta}\sqrt{\dfrac{5}{3}}\gamma^{5}\left(\eta^{\mu\alpha}\eta^{\nu\beta} - \dfrac{1}{5}\gamma^{\alpha}\eta^{\nu\beta}\left(\gamma^{\mu} - v^{\mu}\right) - \dfrac{1}{5}\gamma^{\beta}\eta^{\mu\alpha}\left(\gamma^{\nu} - v^{\nu}\right)\right)\right) \end{array} \right.$$

$$L = 3 \left\{ \begin{array}{l} F^{\mu\nu} = \dfrac{1+\not{v}}{2}\left(P_{3}{}^{\mu\nu}{}_{\rho}\gamma^{\rho}\gamma^{5} - P_{2}^{*\prime}{}_{\alpha\beta}\sqrt{\dfrac{5}{3}}\left(\eta^{\mu\alpha}\eta^{\nu\beta} - \dfrac{1}{5}\gamma^{\alpha}\eta^{\nu\beta}\left(\gamma^{\mu} + v^{\mu}\right) - \dfrac{1}{5}\gamma^{\beta}\eta^{\mu\alpha}\left(\gamma^{\nu} + v^{\nu}\right)\right)\right) \\ \vdots \end{array} \right.$$

First radial excitations ($n = 2$) will be marked with a tilde.

Classification of observed states

			$c\bar{q}$			$c\bar{s}$	
Doublet	J^P	$n=1$	$n=2$	$n=3$	$n=1$	$n=2$	$n=3$
H	0^-	$D(1869)$	$D(2550)^\star$		$D_s(1968)$		
H	1^-	$D^*(2010)$	$D^*(2600)^\star$	$D_1^*(2680)^\star$	$D_s^*(2112)$	$D_{s1}^*(2700)$	$D_{s1}^*(2860)^\star$
S	0^+	$D_0^*(2400)$			$D_{s0}^*(2317)$		
S	1^+	$D_1'(2430)$	$D(3000)^\star$		$D_{s1}'(2460)$	$D_{sJ}(3040)^\star$	
T	1^+	$D_1(2420)$	$D(3000)^\star$		$D_{s1}(2536)$	$D_{sJ}(3040)^\star$	
T	2^+	$D_2^*(2460)$	$D_2^*(3000)^\star$		$D_{s2}^*(2573)$		
X	1^-	$D_1^*(2680)^\star$			$D_{s1}^*(2860)^\star$		
X	2^-						
X'	2^-	$D(2750)^\star$					
X'	3^-	$D_3^*(2760)$			$D_{s3}^*(2860)$		
F	2^+	$D_2^*(3000)^\star$					
F	3^+						

States with uncertain identification are indicated with $\star$.

The Theoretical Framework

Chiral Symmetry

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In the limit $m_q \to 0$, the relevant part of the QCD Lagrangian

$$\mathcal{L}_{\text{QCD}} = \overline{q}\left(i\not{D} - m_q\right) q$$

can be written as

$$\mathcal{L}_{\text{QCD}} = q_L i\not{D} q_L + q_R i\not{D} q_R \ ,$$

where q_L and q_R are the left and right chiral components of q.

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where q_L and q_R are the left and right chiral components of q.

$\mathcal{L}_{\mathrm{QCD}}$ invariant for separate flavour rotations of $q_{L/R}$. ← QCD *Chiral symmetry*

Chiral symmetry is spontaneously broken

The light pseudoscalar mesons are the Goldstone bosons of this broken symmetry.

At low energies, dof of QCD are hadrons not quarks. ← Modelled as effective fields

Hadrons containing light quarks can be represented by effective fields with light-flavour indices.

$$\mathcal{M} = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \overline{K}^0 & -\sqrt{\frac{2}{3}}\eta \end{pmatrix}$$

Aim: describe interactions of heavy mesons with π, K and η.

The Theoretical Framework

Heavy Chiral Perturbation Theory

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- Describe transitions between doublets with emission of a light pseudoscalar.
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Notice: only decays to the fundamental doublet H considered

- Large available phase space.
- Easier reconstruction.

HChPT interaction Lagrangians

$$S_\ell = 1/2 \begin{cases} \mathcal{L}_{HH} = g\,\mathrm{Tr}\left(\overline{H}_a H_b \gamma_\mu \gamma^5 A^\mu_{ba}\right) \\ \mathcal{L}_{SH} = h\,\mathrm{Tr}\left(\overline{H}_a S_b \gamma_\mu \gamma^5 A^\mu_{ba}\right) + \text{h.c.} \end{cases}$$

$$S_\ell = 3/2 \begin{cases} \mathcal{L}_{TH} = \dfrac{h'}{\Lambda_\chi}\,\mathrm{Tr}\left(\overline{H}_a T^\mu_b \left(iD_\mu \not{A} + i\not{D} A_\mu\right)_{ba} \gamma^5\right) + \text{h.c.} \\ \mathcal{L}_{XH} = \dfrac{k'}{\Lambda_\chi}\,\mathrm{Tr}\left(\overline{H}_a X^\mu_b \left(iD_\mu \not{A} + i\not{D} A_\mu\right)_{ba} \gamma^5\right) + \text{h.c.} \end{cases}$$

$$S_\ell = 5/2 \begin{cases} \mathcal{L}_{X'H} = \dfrac{1}{\Lambda_\chi^2}\,\mathrm{Tr}\left(\overline{H}_a X'^{\mu\nu}_b \left(k_1 \left(D_\mu D_\nu A_\lambda + D_\nu D_\mu A_\lambda\right) + k_2 \left(D_\mu D_\lambda A_\nu + D_\nu D_\lambda A_\mu\right)\right)_{ba} \gamma^\lambda \gamma^5\right) + \text{h.c.} \\ \mathcal{L}_{FH} = \dfrac{1}{\Lambda_\chi^2}\,\mathrm{Tr}\left(\overline{H}_a F^{\mu\nu}_b \left(l_1 \left(D_\mu D_\nu A_\lambda + D_\nu D_\mu A_\lambda\right) + l_2 \left(D_\mu D_\lambda A_\nu + D_\nu D_\lambda A_\mu\right)\right)_{ba} \gamma^\lambda \gamma^5\right) + \text{h.c.} \end{cases}$$

$$A_\mu = \frac{1}{f_\pi} \partial_\mu \mathcal{M}$$

What's the use of HChPT?

Each HChPT Lagrangian term comes with its coupling constant. ← Low energy constants are not given by HChPT

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Predictions obtained are very sound, since do not rely on approximate models.

Classification of the $D_2^*(3000)$

Available assignments

LHCb PRD 94 (2016) 072001

Measured properties of the $D_2^*(3000)$

	mass (MeV)	Γ (MeV)	J^P
$D_2^*(3000)^0$	$3214 \pm 29 \pm 33 \pm 36$	$186 \pm 39 \pm 34 \pm 63$	2^+

→ Lowest available assignments

- $\tilde{T}$ doublet: $n = 1$, $L = 1$, $S_\ell^P = 3/2^+$
- F doublet: $n = 0$, $L = 3$, $S_\ell^P = 7/2^+$

Classification of the $D_2^*(3000)$

The Ratio R_π

Definition

$$R_\pi = \frac{\Gamma\left(D_2^*(3000)^0 \to D^{*+}\pi^-\right) + \Gamma\left(D_2^*(3000)^0 \to D^{*0}\pi^0\right)}{\Gamma\left(D_2^*(3000)^0 \to D^{+}\pi^-\right) + \Gamma\left(D_2^*(3000)^0 \to D^{0}\pi^0\right)}.$$

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Calculated values

$$R_\pi = \begin{cases} 0.40 \pm 0.01 & F \\ 1.06 \pm 0.03 & \tilde{T} \end{cases}$$

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Calculated values

$$R_\pi = \begin{cases} 0.40 \pm 0.01 & F \\ 1.06 \pm 0.03 & \tilde{T} \end{cases}$$

What does it mean?

R_π very different in the two cases → Very good discriminator to identify $D_2^*(3000)$.

Classification of the $D_2^*(3000)$

Its Spin Partner

The two alternatives

Let D^{**} be the spin partner of the $D_2^*(3000)$.

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- If $D_2^*(3000)$ belongs to the $\tilde{T}$ doublet, the D^{**} has $J^P = 1^+$
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What about its mass?

In all the observed cases, in each doublet the mass splitting between the two spin partners ranges between $50\ \mathbf{MeV}$ and $100\ \mathbf{MeV}$ (larger for the one with higher spin).

Spin partner branching ratio

Definition

$$R'_\pi = \frac{\Gamma\left(D^{**0} \to D^{*+}\pi^-\right) + \Gamma\left(D^{**0} \to D^{*0}\pi^0\right)}{\Gamma\left(D_2^*(3000)^0 \to D^+\pi^-\right) + \Gamma\left(D_2^*(3000)^0 \to D^0\pi^0\right)}$$

- If $J^P(D^{**}) = 1^+$ → $m_{D^{**}} < m_{D_2^*(3000)}$
- If $J^P(D^{**}) = 3^+$ → $m_{D^{**}} > m_{D_2^*(3000)}$

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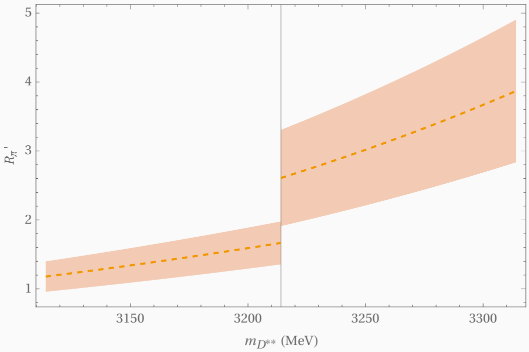
- If $J^P(D^{**}) = 1^+ \to m_{D^{**}} < m_{D_2^*(3000)}$
- If $J^P(D^{**}) = 3^+ \to m_{D^{**}} > m_{D_2^*(3000)}$

Parametric analysis



Classification of the $D_2^*(3000)$

Its Strange Partner

What about its mass?

In (almost) all observed states the strange partner has a mass difference of about $100\ \mathbf{MeV}$. ← *About the mass difference between the strange and up/down quarks*

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An Educated Guess

The strange partner of the $D_2^*(3000)$, namely the $D_{s2}^{*\prime}$, should have mass $\approx 3.3~\mathrm{GeV}$

The value $m(D_{s2}^{*\prime}) = 3313 \pm 62~\mathrm{MeV}$ is used.

Strange decays hierarchy

Definitions

$$R_K = \frac{\Gamma\left(D_{s2}^{*+} \to D^{*0} K^+\right) + \Gamma\left(D_{s2}^{*+} \to D^{*+} K_S\right)}{\Gamma\left(D_{s2}^{*+} \to D^0 K^+\right) + \Gamma\left(D_{s2}^{*+} \to D^+ K_S\right)}$$

$$R_\eta = \frac{\Gamma\left(D_{s2}^{*+} \to D_s^+ \eta\right)}{\Gamma\left(D_{s2}^{*+} \to D^0 K^+\right) + \Gamma\left(D_{s2}^{*+} \to D^+ K_S\right)}$$

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$$R_\eta^* = \frac{\Gamma(D_{s2}^{*+} \to D_s^{*+}\eta)}{\Gamma(D_{s2}^{*+} \to D^0K^+) + \Gamma(D_{s2}^{*+} \to D^+K_S)}$$

Calculated values

	$\tilde{T}$	F
R_K	1.02 ± 0.03	0.39 ± 0.02
R_η	0.31 ± 0.01	0.29 ± 0.01
R_η^*	0.29 ± 0.02	0.10 ± 0.01

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$$R_K = \frac{\Gamma\left(D_{s2}^{*+} \to D^{*0} K^+\right) + \Gamma\left(D_{s2}^{*+} \to D^{*+} K_S\right)}{\Gamma\left(D_{s2}^{*+} \to D^0 K^+\right) + \Gamma\left(D_{s2}^{*+} \to D^+ K_S\right)}$$

$$R_\eta = \frac{\Gamma\left(D_{s2}^{*+} \to D_s^+ \eta\right)}{\Gamma\left(D_{s2}^{*+} \to D^0 K^+\right) + \Gamma\left(D_{s2}^{*+} \to D^+ K_S\right)}$$

$$R_\eta^* = \frac{\Gamma\left(D_{s2}^{*+} \to D_s^{*+} \eta\right)}{\Gamma\left(D_{s2}^{*+} \to D^0 K^+\right) + \Gamma\left(D_{s2}^{*+} \to D^+ K_S\right)}$$

Calculated values

	$\tilde{T}$	F
R_K	1.02 ± 0.03	0.39 ± 0.02
R_η	0.31 ± 0.01	0.29 ± 0.01
R_η^*	0.29 ± 0.02	0.10 ± 0.01

What does it mean?

- Case $D_2^*(3000)$ belongs to $\tilde{T}$: $R_K \gg R_\eta \approx R_\eta^*$
- Case $D_2^*(3000)$ belongs to F: $R_K > R_\eta \gg R_\eta^*$

Conclusions and Perspectives

My thesis

What has been done?

- The whole observed spectrum of open-charm mesons has been presented and discussed.
- An original contribution aimed at the classification of the $D_2^*(3000)$ has been presented.

Summary of the Results for the Classification of the $D_2^*(3000)$

Case $D_2^*(3000)$ belongs to the F doublet

- $R_\pi = 0.40 \pm 0.01$.
- Spin partner: D_3^*, $J^P = 3^+$, ≈ 3.2–3.3 GeV.
- $R'_\pi = 3.60 \pm 1.60$.
- Strange partner: $R_K = 0.39 \pm 0.02 > R_\eta \gg R^*_\eta$.

Case $D_2^*(3000)$ belongs to the $\tilde{T}$ doublet

- $R_\pi = 1.06 \pm 0.03$.
- Spin partner: $\tilde{D}_1$, $J^P = 1^+$, ≈ 3.1–3.2 GeV.
- $R'_\pi = 1.50 \pm 0.60$.
- Strange partner: $R_K = 1.02 \pm 0.03 \gg R_\eta \approx R^*_\eta$.

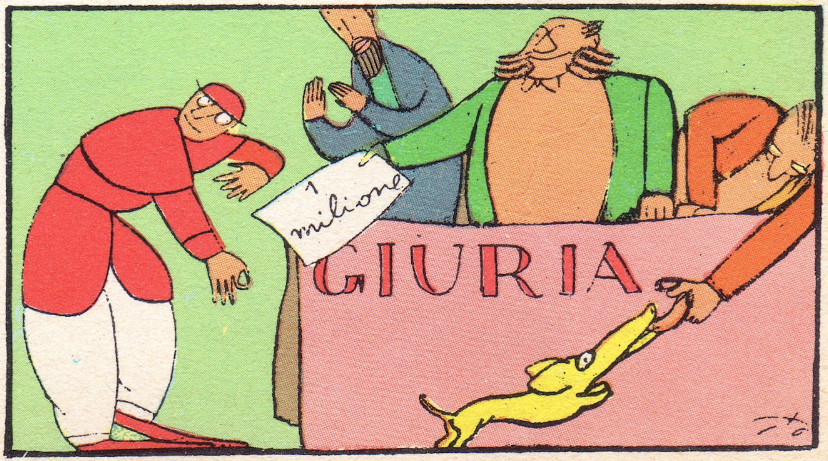
My thesis

What has been done?

- The whole observed spectrum of open-charm mesons has been presented and discussed.
- An original contribution aimed at the classification of the $D_2^*(3000)$ has been presented.

What could still be done?

- *Within the same framework*: decays to excited D mesons.
- *Needing and extension of the framework*: decays with light vector mesons in the final state (ρ, K^*, ω and ϕ).



A scappar Bonaventura
mostra diè di tal bravura,

che il giurì tutto dispone
che sia dato a lui il milione.

Q&A

He who knows does not speak; he who speaks does not know.

(Laozi, *Tao Te Ching*)