QCD Sum Rule Study of Topped Mesons within Heavy Quark Effective Theory

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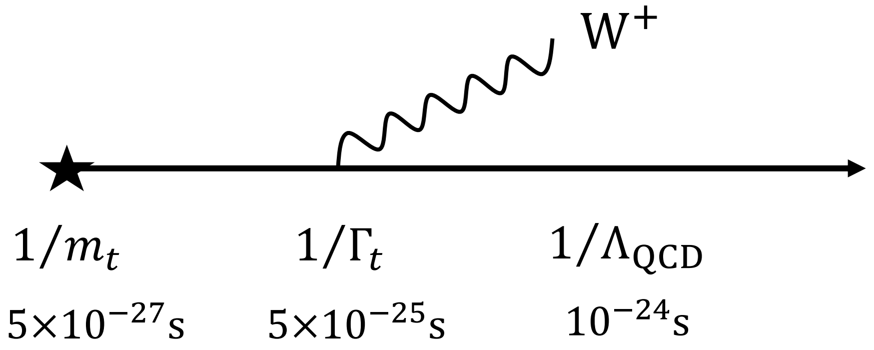
Content

01 Introduction

Specificity of Top Quark

- Large mass: ~ 173.57 GeV
- Extremely short lifetime: $\sim 5\times10^{-25}$ s



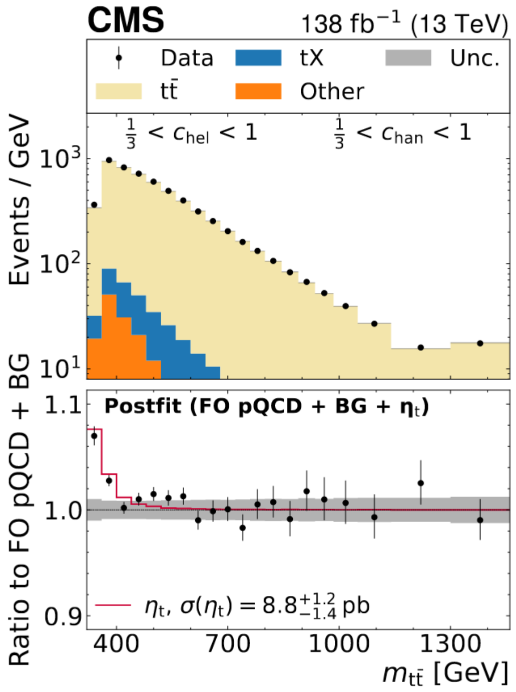


Fig.1 Discovery of Toponium.

The usual consensus is that **top quark cannot form bound states**

Discovery of Toponium $(t\bar{t})$

The CMS Collaboration recently reported an excess in the $t\bar{t}$ invariant mass spectrum near threshold.

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This discovery challenges the traditional views, initiating the exploration of an entirely new top-quark hadron spectrum.

01 Introduction

Top Hardons

- Toponium ($t\bar{t}$),
- **Single-top hadrons**
  - the topped mesons ($t\bar{q}$, with $\bar{q} = \bar{u}, \bar{d}, \bar{s}$),
  - the singly topped baryons (tqq, with $q = u, d, s$).
- …

Advantages of Single-top hadrons

Only one top quark undergoes weak decay, resulting in **longer lifetimes and narrower widths** that improve experimental accessibility.

Advantages of Topped Mesons

- Simpler quark content
- Cleaner final states
- More favorable production and reconstruction prospects.

02 Method

Heavy Quark Effective Theory

$m_t \gg \Lambda_{QCD}$ The top quark is treated as a static color source.

QCD Sum Rule

- The interpolating currents

$$J(x) = \bar{q}^a(x)\gamma_5 h_v^a(x),\ J_\mu(x) = \bar{q}^a(x)\gamma_\mu^t h_v^a(x)$$

- The two-point correlation function

$$\Pi_{\mu\nu}(\omega) = i\int d^4x\, e^{ik\cdot x}\langle 0|T\left[J_\mu(x)J_\nu^\dagger(0)\right]|0\rangle$$

- The sum rule equation are arrived as

$$\overline{\Lambda}(\omega_c,T) = \frac{1}{\Pi(\omega_c,T)}\cdot\frac{\partial\Pi(\omega_c,T)}{\partial(-2/T)},\ f^2(\omega_c,T) = \Pi(\omega_c,T)\cdot e^{2\overline{\Lambda}(\omega_c,T)/T}$$

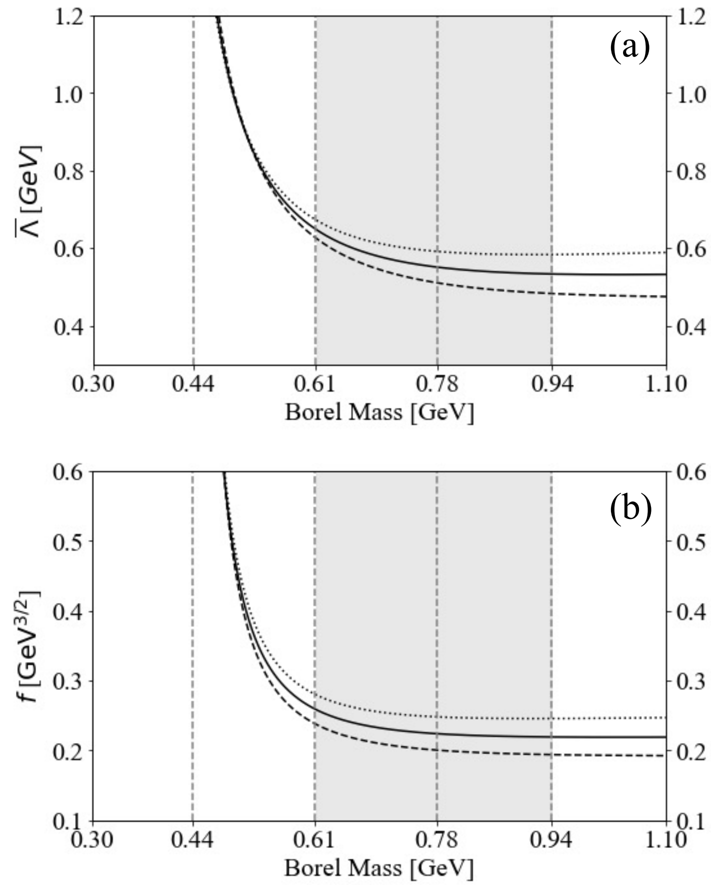

Fig.2 Variations of (a) the residual mass $\overline{\Lambda}$ and (b) the decay constant f with respect to the Borel mass T

02 Method

$$\bar{\Lambda}(\omega_c,T) = \frac{1}{\Pi(\omega_c,T)} \cdot \frac{\partial \Pi(\omega_c,T)}{\partial(-2/T)},\ f^2(\omega_c,T) = \Pi(\omega_c,T) \cdot e^{2\bar{\Lambda}(\omega_c,T)/T}$$

Two free parameters: the threshold value ω_c and the Borel mass T.

QCD Sum Rule Criteria

- The convergence of OPE $\leq 20\%$
- the pole contribution $\geq 40\%$
- the Borel stability condition

$\mathcal{O}(1/m_Q)$ corrections

We extend our analysis to incorporate $\mathcal{O}(1/m_Q)$ corrections to evaluate the mass correction δm. Finally, the mass of the ground-state $T_s^{\star}$meson is given by

$$m_{T_s^\star} = m_t + \bar{\Lambda} + \delta m$$

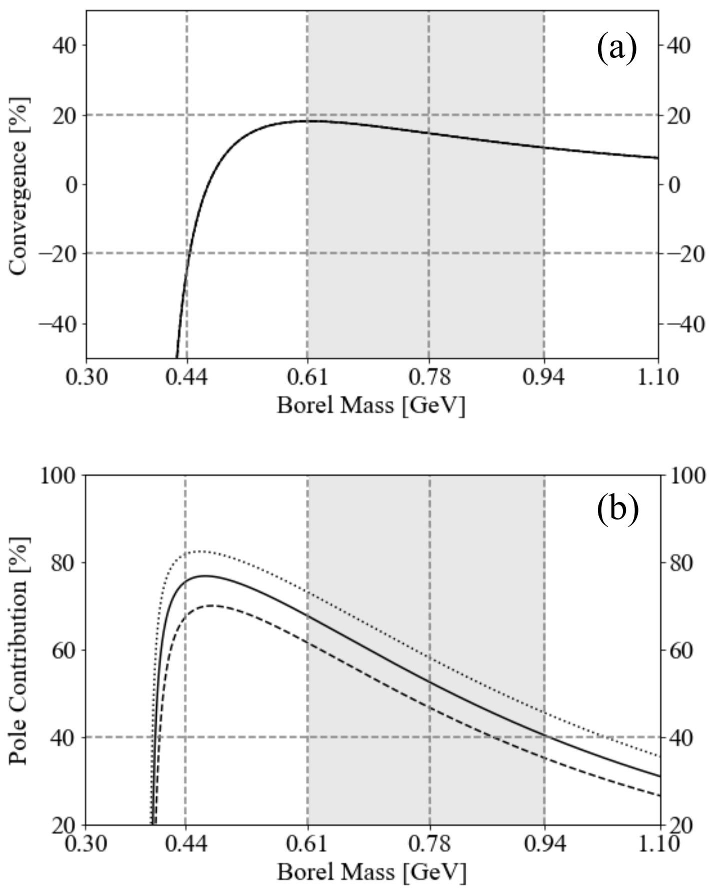

Fig.3 Variations of (a) the convergence parameter, (b) the pole contribution with respect to the Borel mass T

03 Results

Table 1. Parameters of ground-state topped mesons calculated using QCD sum rules within the HQET framework. The states $T^{(*)}$ and $T_s^{(*)}$ contain the quark contents $t\bar{q}(\bar{q}=\bar{u}/\bar{d})$ and $t\bar{s}$, respectively.

	ω_c (GeV)	Working region (GeV)	$\bar{\Lambda}$ (GeV)	Meson (J^P)	Mass (GeV)	Difference (MeV)	f ($\mathrm{GeV}^{3/2}$)	Decay channels
$T^{(*)}$	1.65	$0.79 \le T \le 0.89$	$0.46^{+0.07}_{-0.07}$	$T\ (0^-)$	$173.03^{+0.30}_{-0.30}$	$0.12^{+0.04}_{-0.04}$	$0.19^{+0.02}_{-0.02}$	$\Upsilon D^{(*)}$, $\bar{B}_c^{(*)}B^{(*)}$, $B_s^{(*)}D^{(*)}$, $D_s^{(*)}B^{(*)}$
				$T^*\ (1^-)$	$173.03^{+0.30}_{-0.30}$			
$T_s^{(*)}$	1.85	$0.61 \le T \le 0.94$	$0.55^{+0.12}_{-0.07}$	$T_s\ (0^-)$	$173.12^{+0.31}_{-0.30}$	$0.11^{+0.04}_{-0.04}$	$0.22^{+0.04}_{-0.03}$	$\Upsilon D_s^{(*)}$, $\bar{B}_c^{(*)}B_s^{(*)}$, $B_s^{(*)}D_s^{(*)}$
				$T_s^*\ (1^-)$	$173.12^{+0.31}_{-0.30}$			

- **Mass:** ~173.1GeV, approximately 0.5~0.6GeV above the top quark's pole mass.
- **Decay Channels:** weakly into a Υ meson and a charmed meson, as shown in Fig.4.

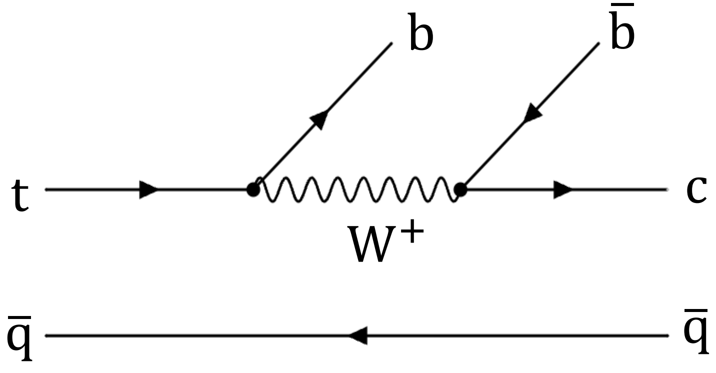

Fig.4 Feynman diagram of topped meson decay

04 Discussions and Conclusion

The Choice of Renormalization Scheme for m_t

$$m_t^{\overline{\mathrm{MS}}} = 162.5^{+2.1}_{-1.5}\ \mathrm{GeV}\,,$$

$$m_{T_s^*} = \boxed{m_t} + \boxed{\bar{\Lambda} + \delta m} \sim 1\ \mathrm{GeV} \qquad \sim 10\ \mathrm{GeV}$$

$$m_t^{\mathrm{pole}} = 172.57^{+0.29}_{-0.29}\ \mathrm{GeV}$$

- Due to the large mass of the top quark, its pole mass is closer to the mass of the bare quark.
- Once electroweak corrections are included, the $\overline{\mathrm{MS}}$ top-quark mass approaches the pole mass.

Conclusion

- This work presents the first application of QCD sum rules within the HQET framework to mesonic systems containing a top quark.
- A precise mass prediction of 173.1 GeV is given, along with clean experimental channels.

Thanks for your attention!

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