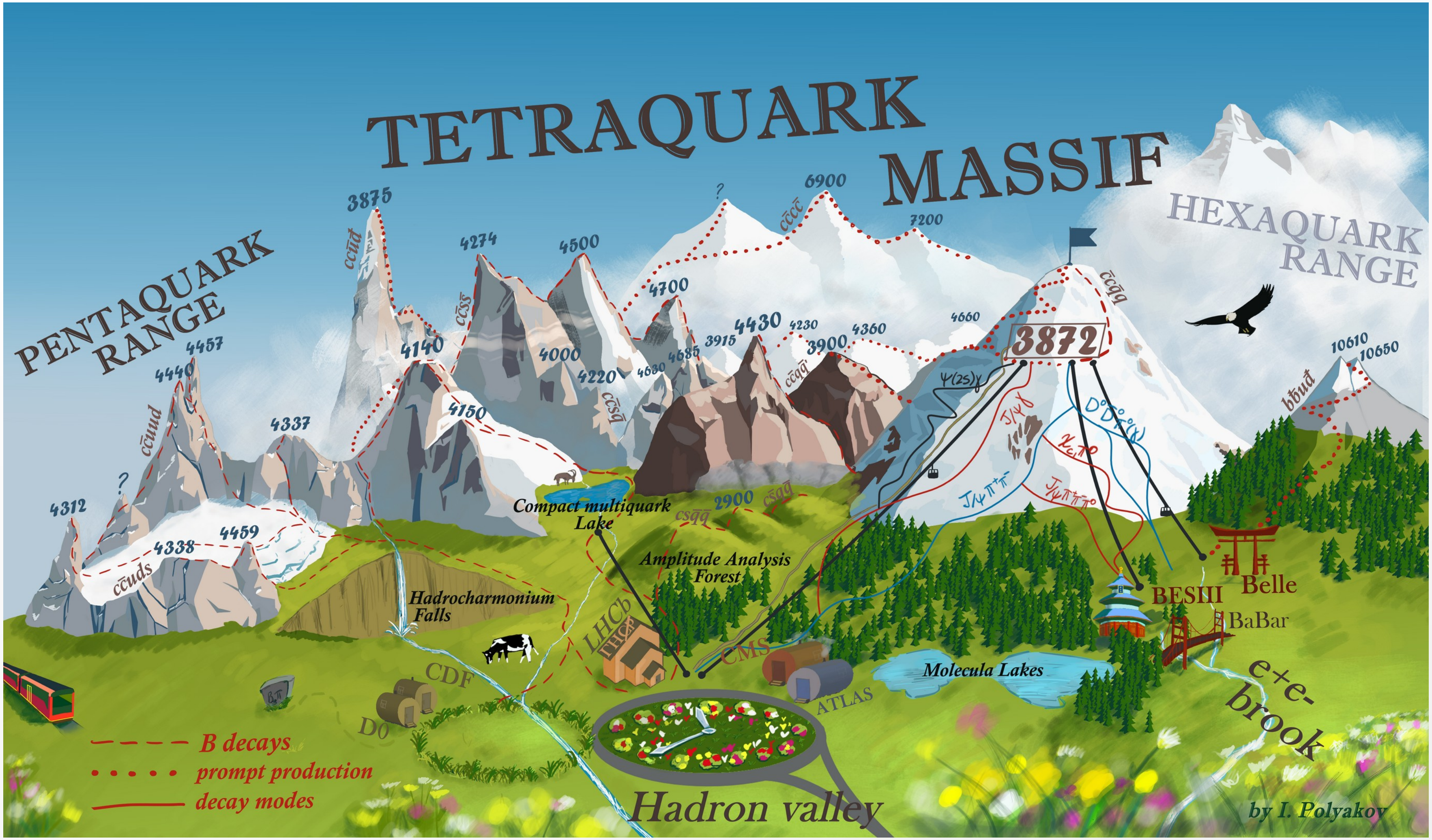
Spectroscopy in decays

overview with a focus on ~~LHCb~~ exotics



Ivan Polyakov

MANCHESTER 1824
The University of Manchester

GDR QCD, InF and Gluodynamics workshop, Orsay, 17 December 2024

Outlook

- History Message
- Conventional hadron spectroscopy
- Exotic hadron spectroscopy
  - Quick overview
  - Reflection
  - T_{cc} [$cc\bar{u}\bar{d}$]
  - Prospects
- Conclusion

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ANNUAL REVIEWS

Annual Review of Nuclear and Particle Science

Exotic Hadrons at LHCb

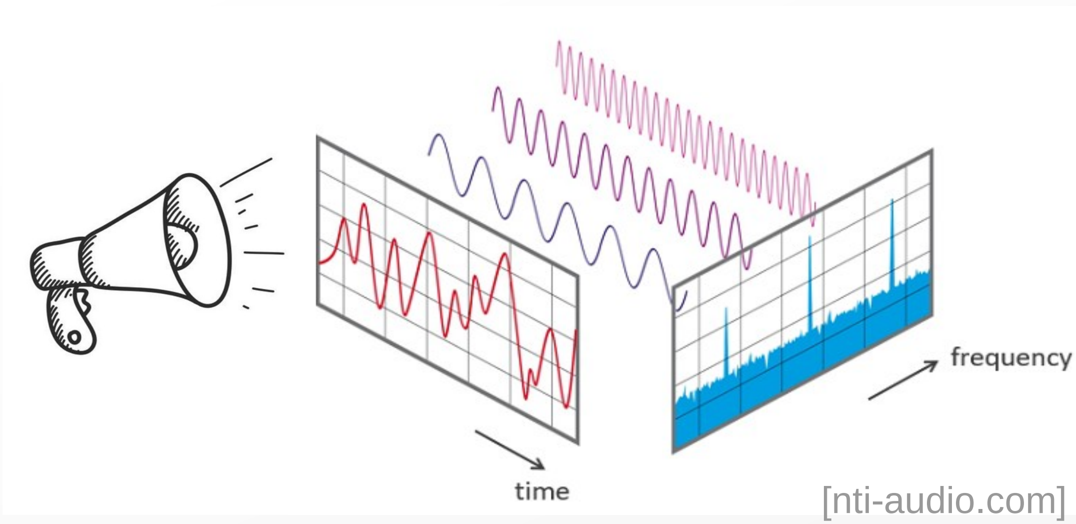
Daniel Johnson,[1] Ivan Polyakov,[2] Tomasz Skwarnicki,[3] and Mengzhen Wang[4]

arXiv:2410.06923

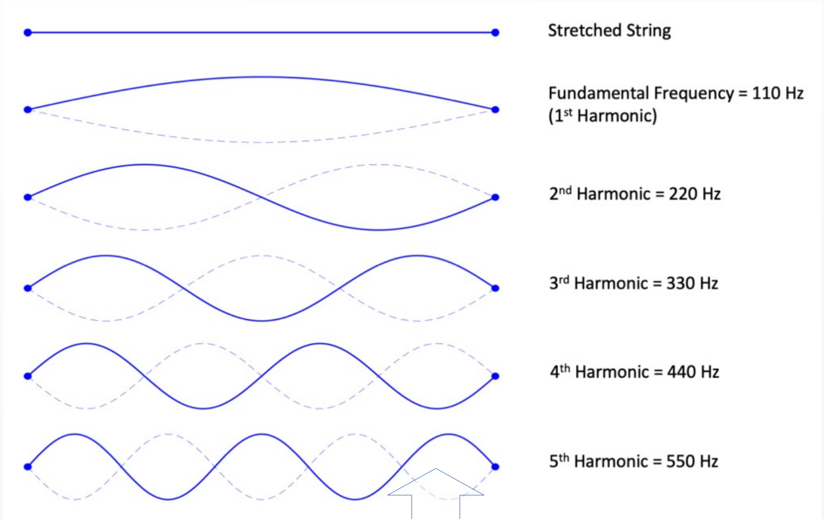
A Brief Guide to Exotic Hadrons

Nils Hüsken,[1] Elisabetta Spadaro Norella,[2] and Ivan Polyakov[3]

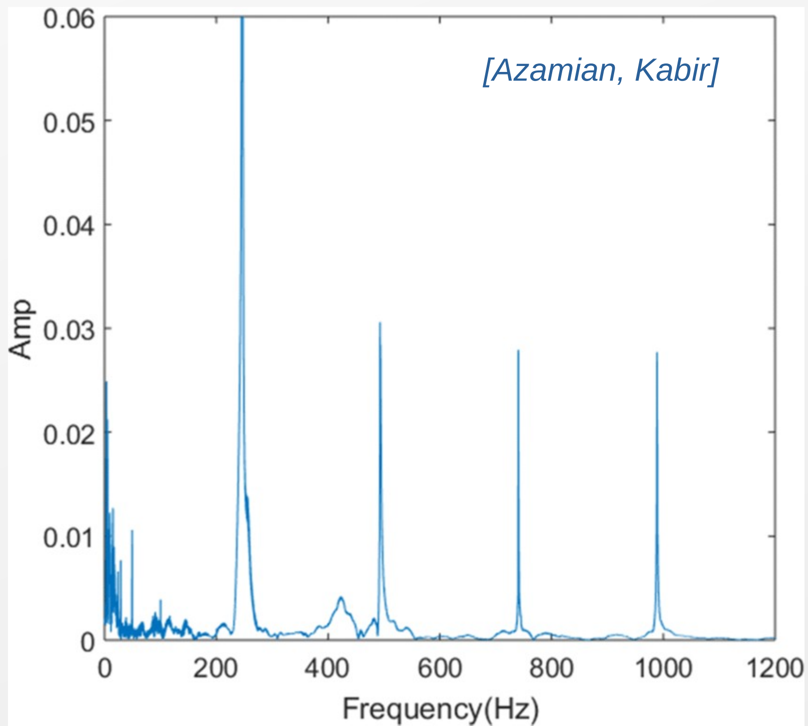
What is Spectroscopy?



[nti-audio.com]



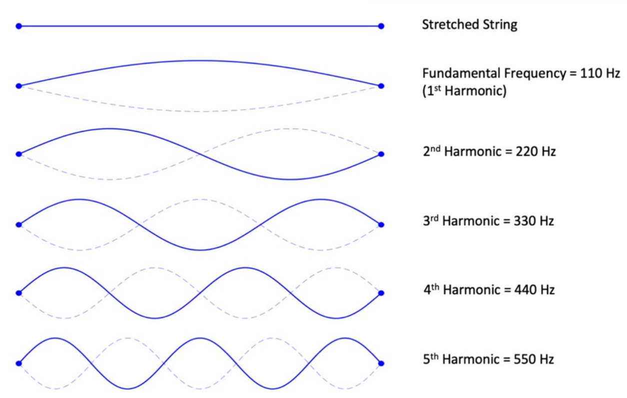
Spectra of piano note B3



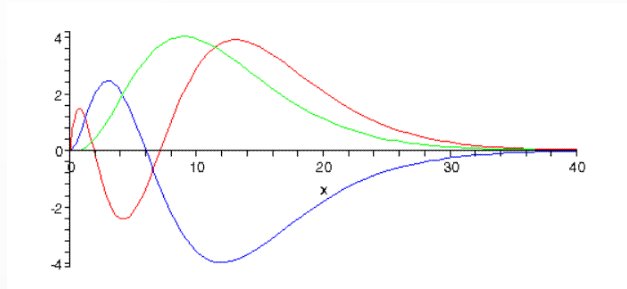
[Azamian, Kabir]

What is Spectroscopy?

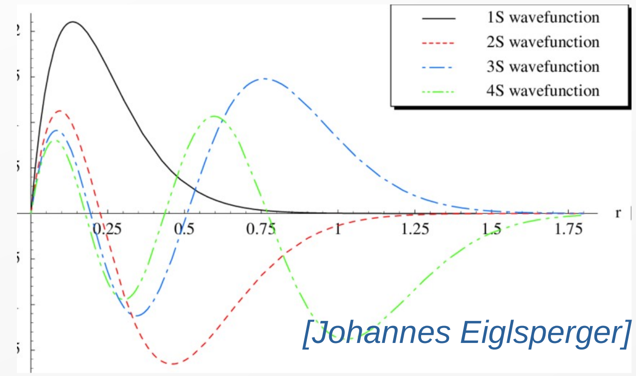
String oscillation harmonics



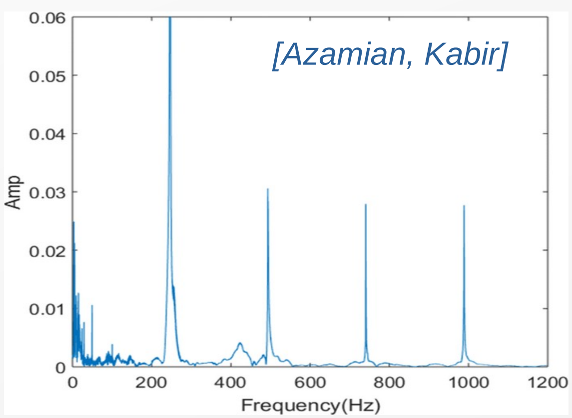
Radial wave functions of electron in Hydrogen atom



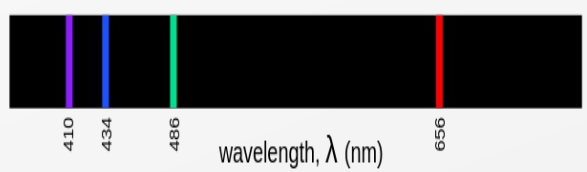
Radial wave functions of $b\bar{b}$ quark system



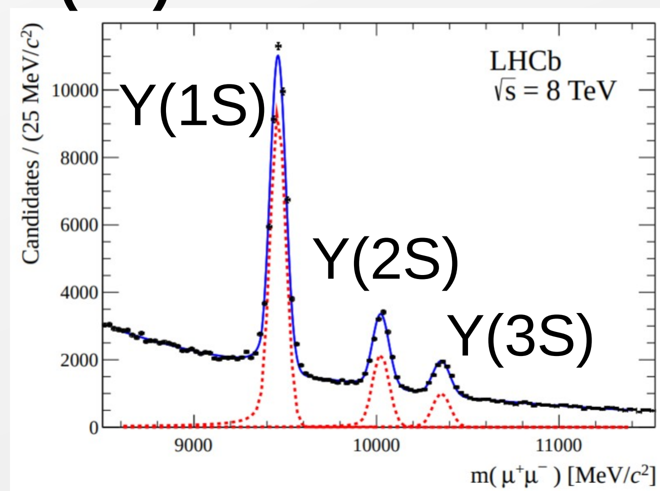
Spectra of piano note B3



Hydrogen emission spectrum

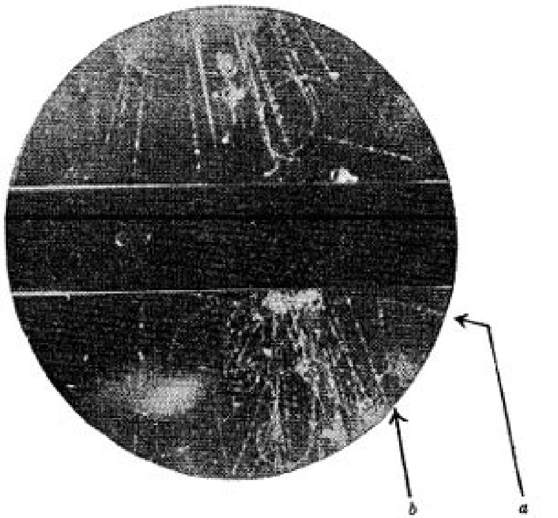


Mass spectra of Υ(nS) states

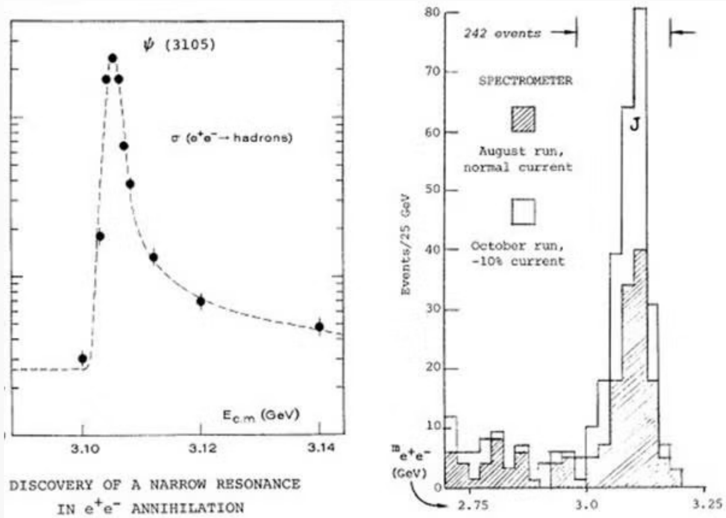


Why decays?

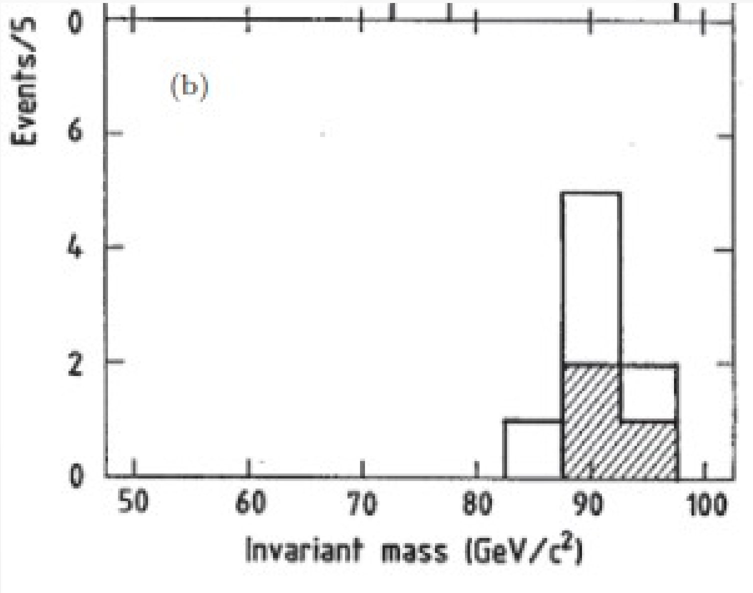
K → ππ in 1947



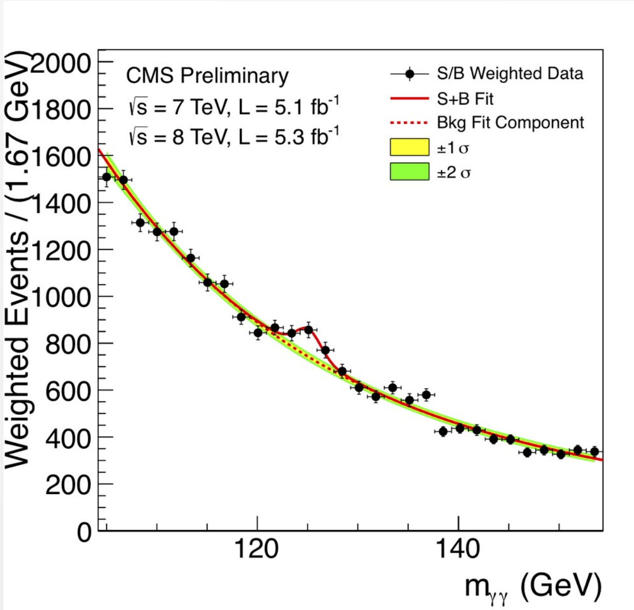
J/ψ → e⁻e⁺ in 1974



Z → e⁻e⁺ in 1983



H → γγ in 2012



Light (conventional) hadrons

$m_{u,d}$~ 2-5 MeV
m_s~ 100 MeV
Λ_{QCD} ~ 200 MeV

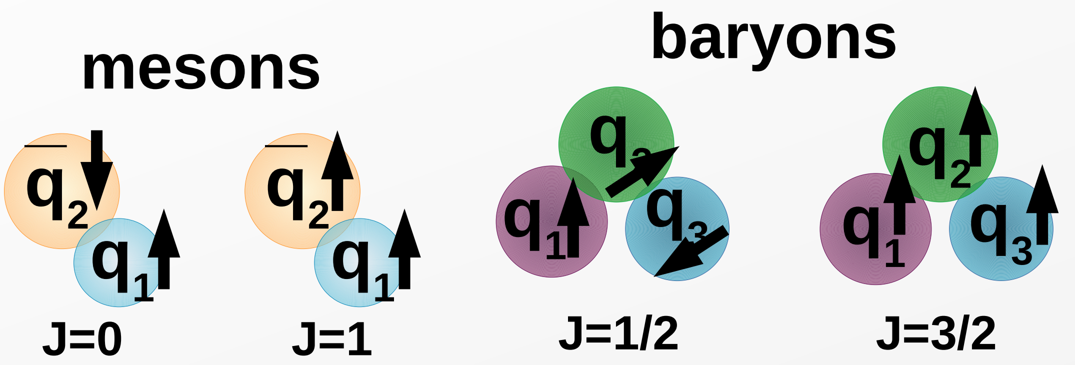
- Highly non-perturbative regime
- Extract effective parameters from ground states (1st harmonics)

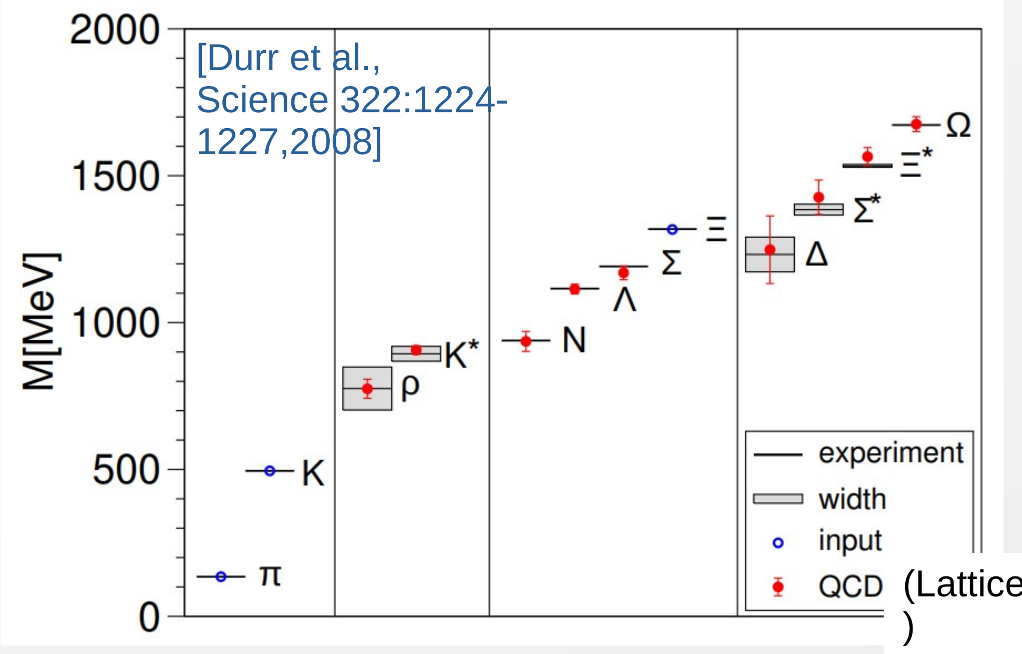
[Karliner&Rosner, PRD 90, 094007 (2014);
Gasiorowicz&Rosner, Am. J. Phys. 49 (1981) 954]

State (mass in MeV)	Spin	Expression for mass [24]	Predicted mass (MeV)
$\pi(138)$	0	$2m_q^m - 6b/(m_q^m)^2$	140
$\rho(775), \omega(782)$	1	$2m_q^m + 2b/(m_q^m)^2$	780
$K(496)$	0	$m_q^m + m_s^m - 6b/(m_q^m m_s^m)$	485
$K^*(894)$	1	$m_q^m + m_s^m + 2b/(m_q^m m_s^m)$	896
$\phi(1019)$	1	$2m_s^m + 2b/(m_s^m)^2$	1032

State (mass in MeV)	Spin	Expression for mass [24]	Predicted mass (MeV)
$N(939)$	1/2	$3m_q^b - 3a/(m_q^b)^2$	939
$\Delta(1232)$	3/2	$3m_q^b + 3a/(m_q^b)^2$	1239
$\Lambda(1116)$	1/2	$2m_q^b + m_s^b - 3a/(m_q^b)^2$	1114
$\Sigma(1193)$	1/2	$2m_q^b + m_s^b + a/(m_q^b)^2 - 4a/m_q^b m_s^b$	1179
$\Sigma(1385)$	3/2	$2m_q^b + m_s^b + a/(m_q^b)^2 + 2a/m_q^b m_s^b$	1381
$\Xi(1318)$	1/2	$2m_s^b + m_q^b + a/(m_s^b)^2 - 4a/m_q^b m_s^b$	1327
$\Xi(1530)$	3/2	$2m_s^b + m_q^b + a/(m_s^b)^2 + 2a/m_q^b m_s^b$	1529
$\Omega(1672)$	3/2	$3m_s^b + 3a/(m_s^b)^2$	1682

good description within 10 MeV!



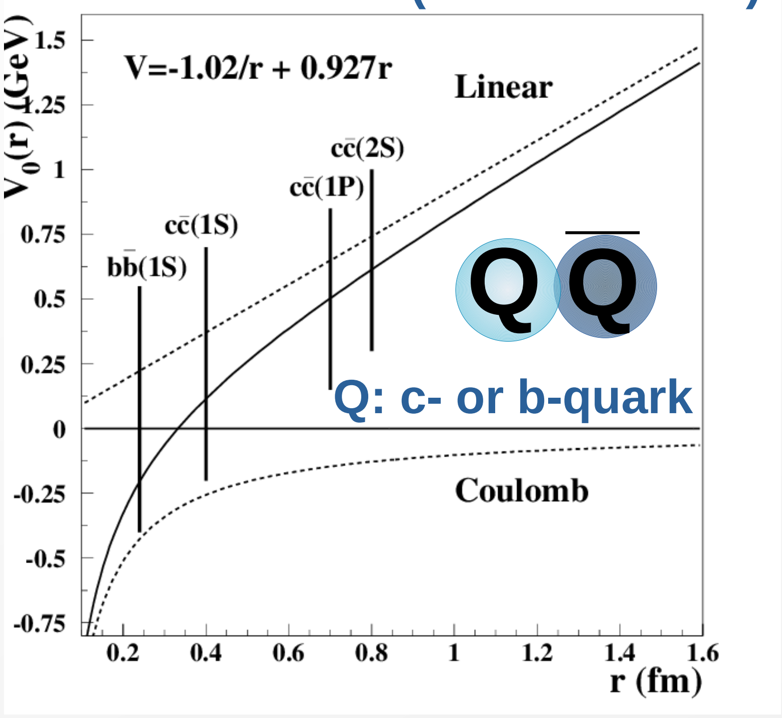


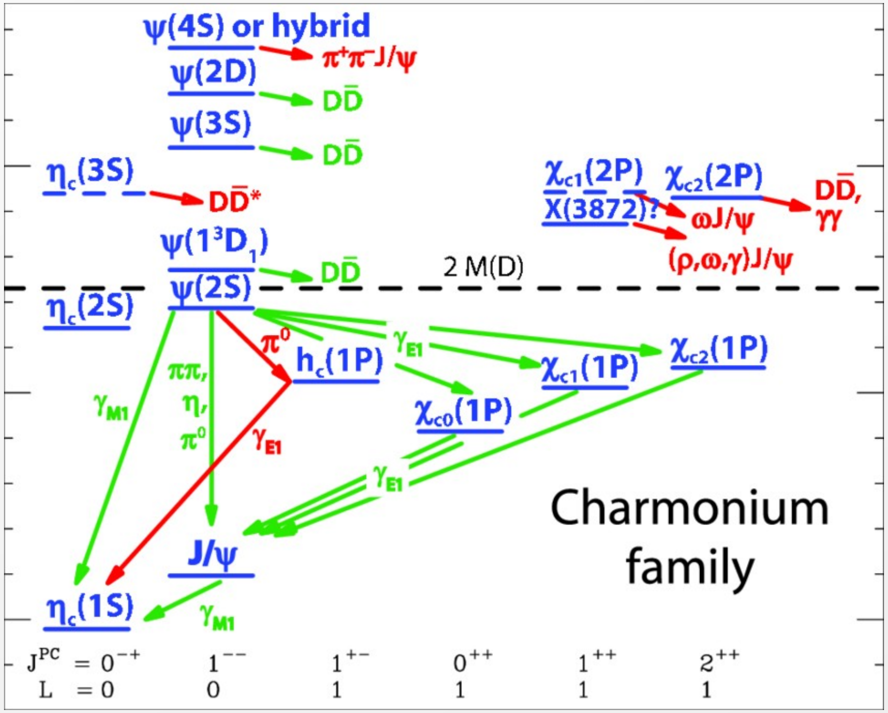
Quarkonia

- Heavy quarks → semi-perturbative regime
- Much clearer systems
- Great progress

$m_{u,d}$ ~ 2-5 MeV
m_s ~ 100 MeV
Λ_{QCD} ~ 200 MeV
m_c ~ 1300 MeV
m_b ~ 4200 MeV

Potential between two quarks (Cornell model)



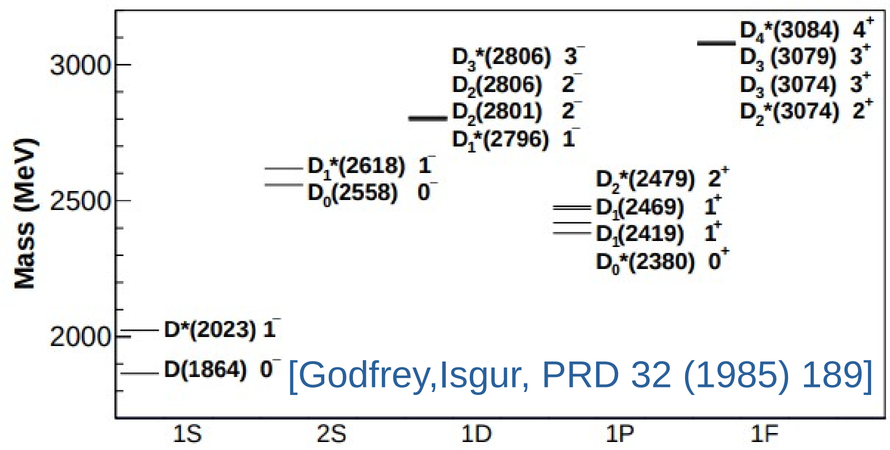


[Eichten, Godfrey, Mahlke, Rosner, Rev Mod Phys 80 (2007)]

Other Heavy hadrons

- Rich structure in $Q\bar{q}$ and Qqq' hadrons with heavy quarks
- One example: D^0 $[c\bar{u}]$ excitations

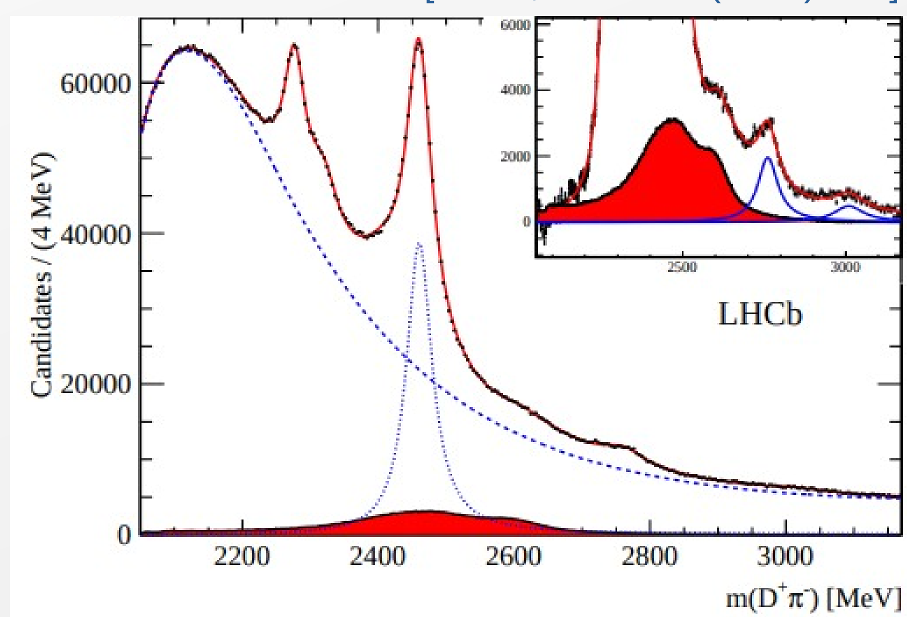
$m_{u,d} \sim$ 2-5 MeV
$m_s \sim$ 100 MeV
$\Lambda_{QCD} \sim$ 200 MeV
$m_c \sim$ 1300 MeV
$m_b \sim$ 4200 MeV



[Godfrey,Isgur, PRD 32 (1985) 189]

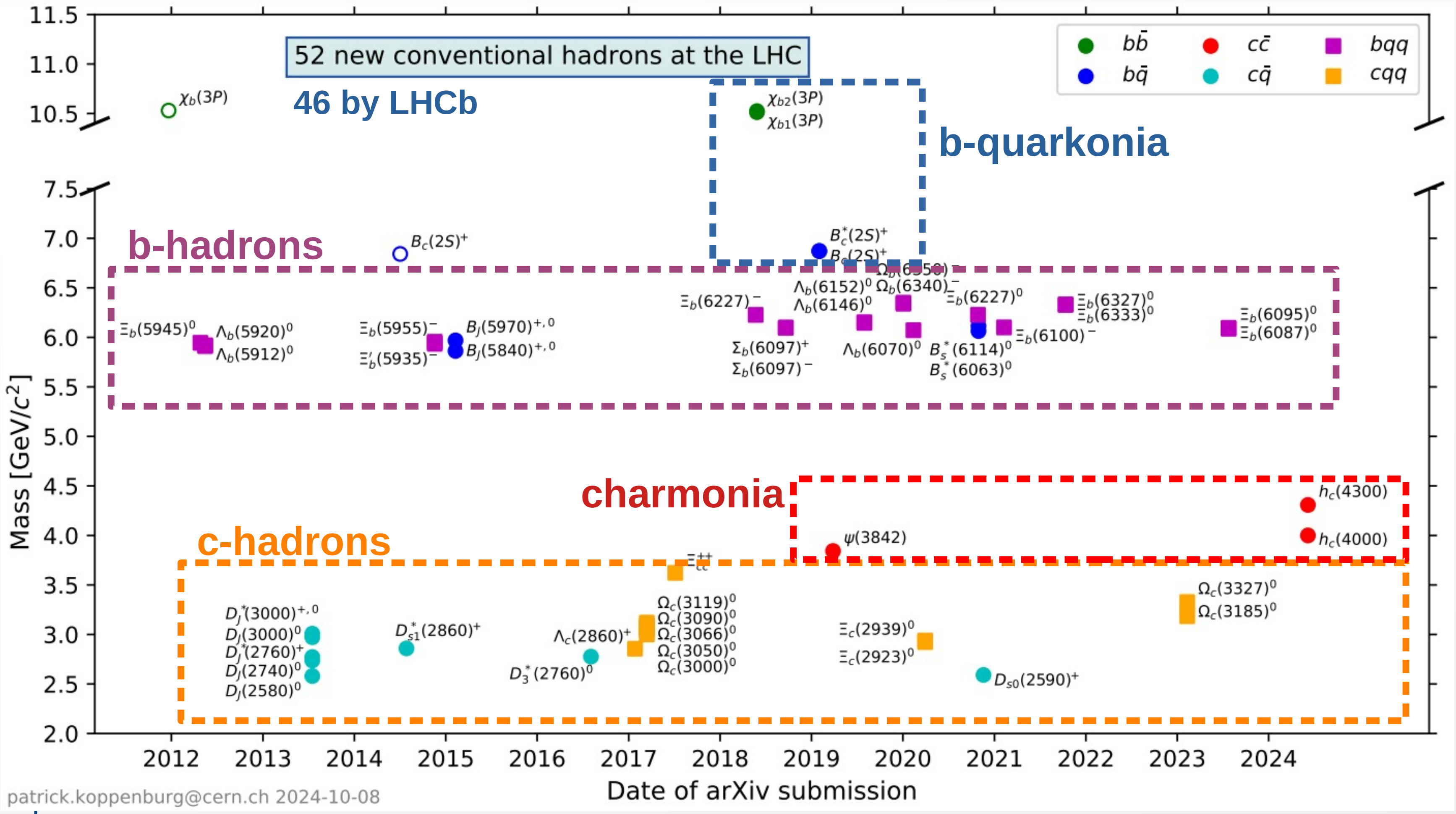
Resonance	Final state	Mass (MeV)
$D_1(2420)^0$	$D^{*+}\pi^-$	2419.6 ± 0.1 ± 0.7
$D_2^*(2460)^0$	$D^{*+}\pi^-$	2460.4 ± 0.4 ± 1.2
$D_J^*(2650)^0$	$D^{*+}\pi^-$	2649.2 ± 3.5 ± 3.5
$D_J^*(2760)^0$	$D^{*+}\pi^-$	2761.1 ± 5.1 ± 6.5
$D_J(2580)^0$	$D^{*+}\pi^-$	2579.5 ± 3.4 ± 5.5
$D_J(2740)^0$	$D^{*+}\pi^-$	2737.0 ± 3.5 ±11.2
$D_J(3000)^0$	$D^{*+}\pi^-$	2971.8 ± 8.7
$D_2^*(2460)^0$	$D^+\pi^-$	2460.4 ± 0.1 ± 0.1
$D_J^*(2760)^0$	$D^+\pi^-$	2760.1 ± 1.1 ± 3.7
$D_J^*(3000)^0$	$D^+\pi^-$	3008.1 ± 4.0
$D_2^*(2460)^+$	$D^0\pi^+$	2463.1 ± 0.2 ± 0.6
$D_J^*(2760)^+$	$D^0\pi^+$	2771.7 ± 1.7 ± 3.8
$D_J^*(3000)^+$	$D^0\pi^+$	3008.1 (fixed)

[LHCb, JHEP 09 (2013) 145]



Other Heavy hadrons

- Rich structure in $Q\bar{q}$ and Qqq' hadrons with heavy quarks
- Lots of results from the LHC (mainly by LHCb)



Conventional is not enough

- Progress limited by quark configurations studied

...

- 4/5/...-quark states **(exotic hadrons)** have been anticipated since 60’s

- No success in light sector
  - First candidates for tetraquarks in 90’s: $f_0(500)$, $K^*_0(800)$, … later $D^*_{sJ}(2317)$, ...
  - Pentaquark Θ^+ [uudd$\bar{s}$] in 2003

no clear conclusion reached due to large widths & theoretical ambiguities

Fazio, 2004 | Eidelman, Gutsche, Hanhart, Mitchell, Spanier, 2020 (PDG)

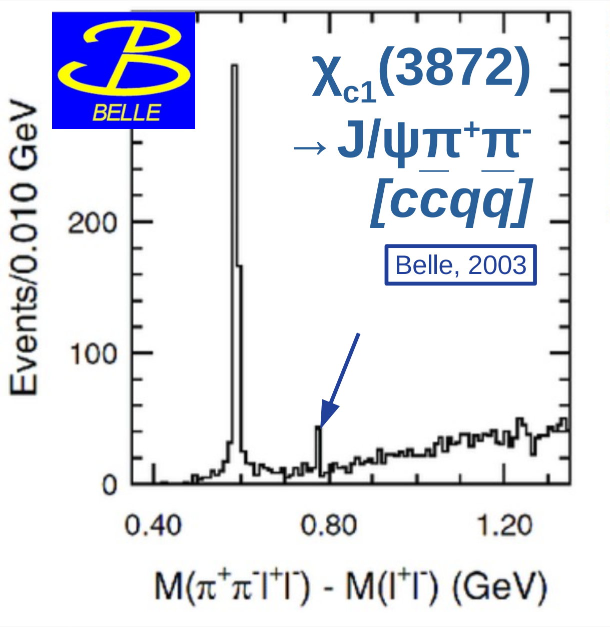
later shown to be false

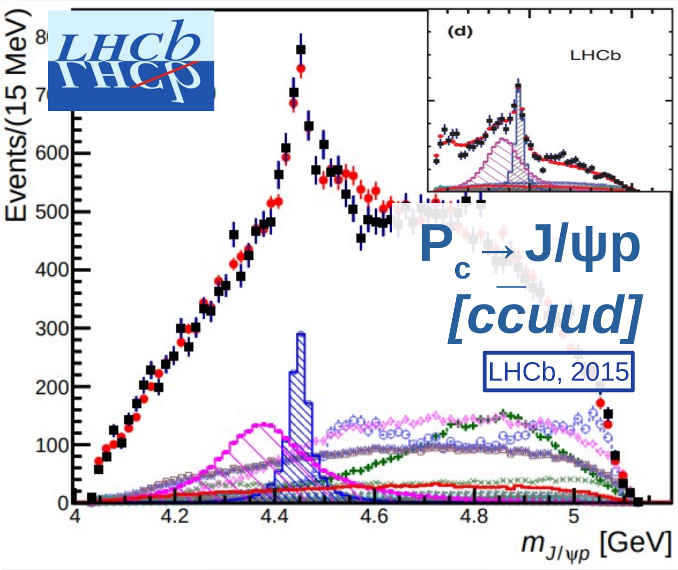
Trilling, 2006 (PDG)

First exotic hadrons

- First one uniquely identified as exotic was $\chi_{c1}(3872)$ discovered in heavy sector in 2003;
- First pentaquark in 2015 in heavy sector as well;

much smaller widths and clearer understanding of $c\bar{c}$ allowed to exclude conventional interpretations





50+ exotic hadron candidates

N. Hüsken, E. S. Norella, I. Polyakov

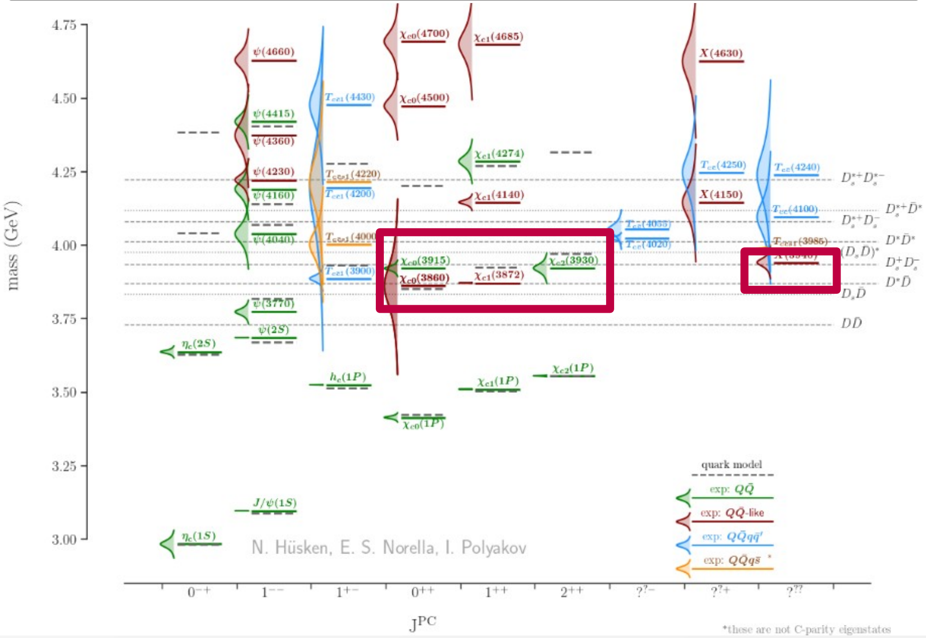
Table 2. All known exotic hadron candidates up to date. States we consider well-established are underscored.

Category			States / Candidates
Meson-like (incl. tetraquarks)	Hidden Charm	$I = 0$	χ−like: $\underline{\chi_{c1}(3872)}$, $\chi_{c0}(3860)$, $\underline{\chi_{c0}(3915)}$, $\underline{\chi_{c2}(3930)}$, $X(3940)$
			ψ−like: $\underline{\psi(4230)}$, $\underline{\psi(4360)}$, $\psi(4660)$
			with $s\bar{s}$: $\underline{\chi_{c1}(4140)}$, $\underline{\chi_{c1}(4274)}$, $\chi_{c1}(4685)$, $\underline{\chi_{c1}(4500)}$, $\chi_{c1}(4700)$ $X(4150)$, $X(4630)$, $X(4740)$
		$I = 1/2$	$T_{c\bar{c}s}(3985)^-$, $T_{c\bar{c}s1}(4000)^{-/0}$, $T_{c\bar{c}s1}(4220)^-$
		$I = 1$	seen in e^+e^-: $\underline{T_{c\bar{c}1}(3900)^{+/0}}$, $\underline{T_{c\bar{c}}(4020)^+}$, $T_{c\bar{c}}(4055)^+$
			seen in B decays: $T_{c\bar{c}}(4050)^+$, $T_{c\bar{c}}(4100)^+$, $T_{c\bar{c}1}(4200)^+$, $T_{c\bar{c}}(4240)^+$, $T_{c\bar{c}}(4250)^+$, $\underline{T_{c\bar{c}1}(4430)^+}$
	Hidden Beauty	$I = 0$	$\Upsilon(10753)$, $\underline{\Upsilon(10860)}$, $\underline{\Upsilon(11020)}$
		$I = 1$	$\underline{T_{b\bar{b}1}(10610)^+}$, $\underline{T_{b\bar{b}1}(10650)^+}$
	Hidden Double Charm		$T_{c\bar{c}c\bar{c}}(6550)$, $\underline{T_{c\bar{c}c\bar{c}}(6900)}$, $T_{c\bar{c}c\bar{c}}(7290)$
	Open Single Charm		D_s^*-like: $\underline{D_{s0}^*(2317)^+}$, $\underline{D_{s1}(2460)^+}$
			$T_{cs/c\bar{s}}$: $T_{cs0}(2900)^0$, $T_{c\bar{s}0}(2900)^{0/++}$, $T_{cs1}(2900)^0$
	Open Double Charm		$T_{cc}(3875)^+$
Baryon-like (incl. pentaquarks)	Hidden Charm	$I = 1/2(3/2)$	$P_{c\bar{c}}(4312)^+$, $P_{c\bar{c}}(4440)^+$, $P_{c\bar{c}}(4457)^+$ $P_{c\bar{c}}(4380)^+$, $P_{c\bar{c}}(4337)^+$
		$I = 0(1)$	$P_{c\bar{c}s}(4458)^0$, $P_{c\bar{c}s}(4338)^0$

23 at the LHC, 21 of them by LHCb

Exotic charmonium

Category			States / Candidates
Meson-like (incl. tetraquarks)	Hidden Charm	$I=0$	χ−like: $\chi_{c1}(3872)$, $\chi_{c0}(3860)$, $\chi_{c0}(3915)$, $\chi_{c2}(3930)$, $X(3940)$
			ψ−like: $\psi(4230)$, $\psi(4360)$, $\psi(4660)$
			with $s\bar{s}$: $\chi_{c1}(4140)$, $\chi_{c1}(4274)$, $\chi_{c1}(4685)$, $\chi_{c1}(4500)$, $\chi_{c1}(4700)$ $X(4150)$, $X(4630)$, $X(4740)$
		$I=1/2$	$T_{c\bar{c}s}(3985)^-$, $T_{c\bar{c}s1}(4000)^{-/0}$, $T_{c\bar{c}s1}(4220)^-$
		$I=1$	seen in e^+e^-: $T_{c\bar{c}1}(3900)^{+/0}$, $T_{c\bar{c}}(4020)^+$, $T_{c\bar{c}}(4055)^+$
			seen in B decays: $T_{c\bar{c}}(4050)^+$, $T_{c\bar{c}}(4100)^+$, $T_{c\bar{c}1}(4200)^+$, $T_{c\bar{c}}(4240)^+$, $T_{c\bar{c}}(4250)^+$, $T_{c\bar{c}1}(4430)^+$
	Hidden Beauty	$I=0$	$\Upsilon(10753)$, $\Upsilon(10860)$, $\Upsilon(11020)$
		$I=1$	$T_{b\bar{b}1}(10610)^+$, $T_{b\bar{b}1}(10650)^+$
	Hidden Double Charm		$T_{c\bar{c}c\bar{c}}(6550)$, $T_{c\bar{c}c\bar{c}}(6900)$, $T_{c\bar{c}c\bar{c}}(7290)$
	Open Single Charm		D_s^*-like: $D_{s0}^*(2317)^+$, $D_{s1}(2460)^+$
			$T_{cs/c\bar{s}}$: $T_{cs0}(2900)^0$, $T_{c\bar{s}0}(2900)^{0/++}$, $T_{cs1}(2900)^0$
	Open Double Charm		$T_{cc}(3875)^+$
Baryon-like (incl. pentaquarks)	Hidden Charm	$I=1/2(3/2)$	$P_{c\bar{c}}(4312)^+$, $P_{c\bar{c}}(4440)^+$, $P_{c\bar{c}}(4457)^+$, $P_{c\bar{c}}(4380)^+$, $P_{c\bar{c}}(4337)^+$
		$I=0(1)$	$P_{c\bar{c}s}(4458)^0$, $P_{c\bar{c}s}(4338)^0$



χ_c-like *(aka X)*, >4 GeV

states:

- $I^G(J^{PC}) = 0^+(0^{++})$: $\chi_{c0}(3860)$, $\chi_{c0}(3915)$ *also known as* $X(3915)$
- $I^G(J^{PC}) = 0^+(2^{++})$: $\chi_{c2}(3930)$
- $I^G(J^{PC}) = ??(?^{??})$: $X(3940)$

minimal quark content: $[c\bar{c}]$, possibly $[c\bar{c}q\bar{q}]$

experiments: BaBar, Belle, BESIII, LHCb

production: $\gamma\gamma$-collisions and B-decays, e^+e^- / pp collisions

decay modes: $D\bar{D}$ (except $X(3940)$), $D^*\bar{D}$ ($X(3940)$), $\omega J/\psi$ ($\chi_{c0}(3915)$)

nearby thresholds: $D^*\bar{D}$, $D_s^+D_s^-$

characteristic widths: $\sim$200 MeV ($\chi_{c0}(3860)$) and 19-37 MeV ($\chi_{c0}(3915)$, $\chi_{c2}(3930)$, $X(394$

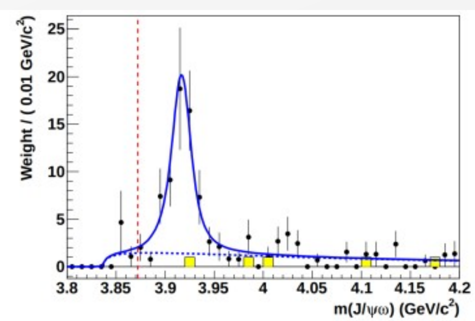
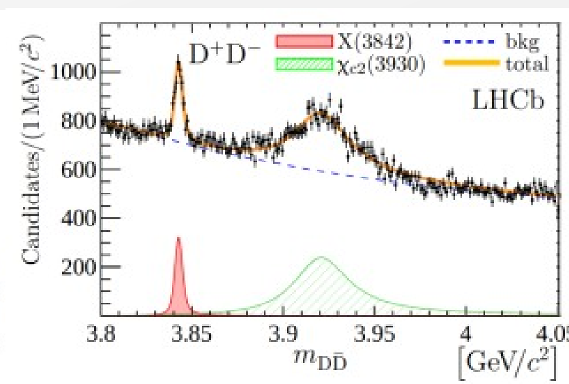
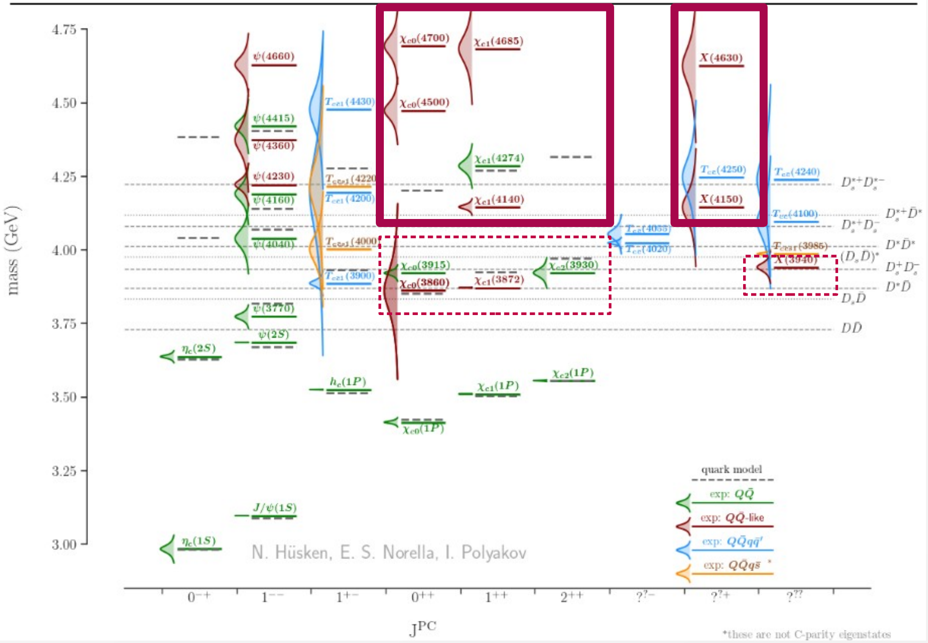


Fig. 5. $\chi_{c0}(3915) \to J/\psi\omega$ signal at BaBar [92]



Exotic charmonium

Category			States / Candidates
Meson-like (incl. tetraquarks)	Hidden Charm	$I=0$	$\chi-$like: $\chi_{c1}(3872)$, $\chi_{c0}(3860)$, $\chi_{c0}(3915)$, $\chi_{c2}(3930)$, $X(3940)$
			$\psi-$like: $\psi(4230)$, $\psi(4360)$, $\psi(4660)$
			with $s\bar{s}$: $\chi_{c1}(4140)$, $\chi_{c1}(4274)$, $\chi_{c1}(4685)$, $\chi_{c1}(4500)$, $\chi_{c1}(4700)$, $X(4150)$, $X(4630)$, $X(4740)$
		$I=1/2$	$T_{c\bar{c}\bar{s}}(3985)^-$, $T_{c\bar{c}s1}(4000)^{-/0}$, $T_{c\bar{c}s1}(4220)^-$
		$I=1$	seen in e^+e^-: $T_{c\bar{c}1}(3900)^{+/0}$, $T_{c\bar{c}}(4020)^+$, $T_{c\bar{c}}(4055)^+$
			seen in B decays: $T_{c\bar{c}}(4050)^+$, $T_{c\bar{c}}(4100)^+$, $T_{c\bar{c}1}(4200)^+$, $T_{c\bar{c}}(4240)^+$, $T_{c\bar{c}}(4250)^+$, $T_{c\bar{c}1}(4430)^+$
	Hidden Beauty	$I=0$	$\Upsilon(10753)$, $\Upsilon(10860)$, $\Upsilon(11020)$
		$I=1$	$T_{b\bar{b}1}(10610)^+$, $T_{b\bar{b}1}(10650)^+$
	Hidden Double Charm		$T_{c\bar{c}c\bar{c}}(6550)$, $T_{c\bar{c}c\bar{c}}(6900)$, $T_{c\bar{c}c\bar{c}}(7290)$
	Open Single Charm		D_s^*-like: $D_{s0}^*(2317)^+$, $D_{s1}(2460)^+$
			$T_{cs/c\bar{s}}$: $T_{cs0}(2900)^0$, $T_{c\bar{s}0}(2900)^{0/++}$, $T_{cs1}(2900)^0$
	Open Double Charm		$T_{cc}(3875)^+$
Baryon-like (incl. pentaquarks)	Hidden Charm	$I=1/2(3/2)$	$P_{c\bar{c}}(4312)^+$, $P_{c\bar{c}}(4440)^+$, $P_{c\bar{c}}(4457)^+$, $P_{c\bar{c}}(4380)^+$, $P_{c\bar{c}}(4337)^+$
		$I=0(1)$	$P_{c\bar{c}s}(4458)^0$, $P_{c\bar{c}s}(4338)^0$



χ_c-like *(aka X)*, >4 GeV
(with $s\bar{s}$ pair?)

states:

- $I(J^{PC}) = 0(0^{++})$: $\chi_{c0}(4500)$, $\chi_{c0}(4700)$
- $I(J^{PC}) = 0(1^{++})$: $\chi_{c1}(4140)$, $\chi_{c1}(4274)$, $\chi_{c1}(4685)$

  also known as $X(4140)$, $Y(4140)$, ...
- $I(J^{PC}) = 0(?^{?+})$: $X(4150)$, $X(4630)$, $X(4740)$

  also known as $X(4160)$

minimal quark content: $[c\bar{c}]$, more likely $[c\bar{c}q\bar{q}]$ or $[c\bar{c}s\bar{s}]$

experiments: CDF, CMS, D0, BaBar, LHCb, Belle

production: $B^+ \to J/\psi\phi K^+$, ...

decay modes: $J/\psi\phi$, $D^*\bar{D}^*$ ($X(4150)$)

nearby threshold: $D_s\bar{D}_s^*$, $D_s^*\bar{D}_s^*$

characteristic widths: 51-174 MeV[h]

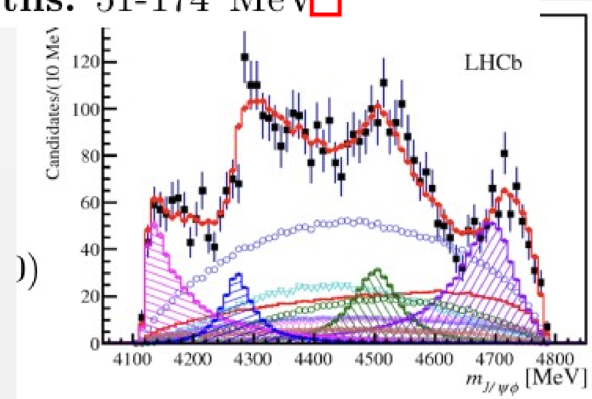
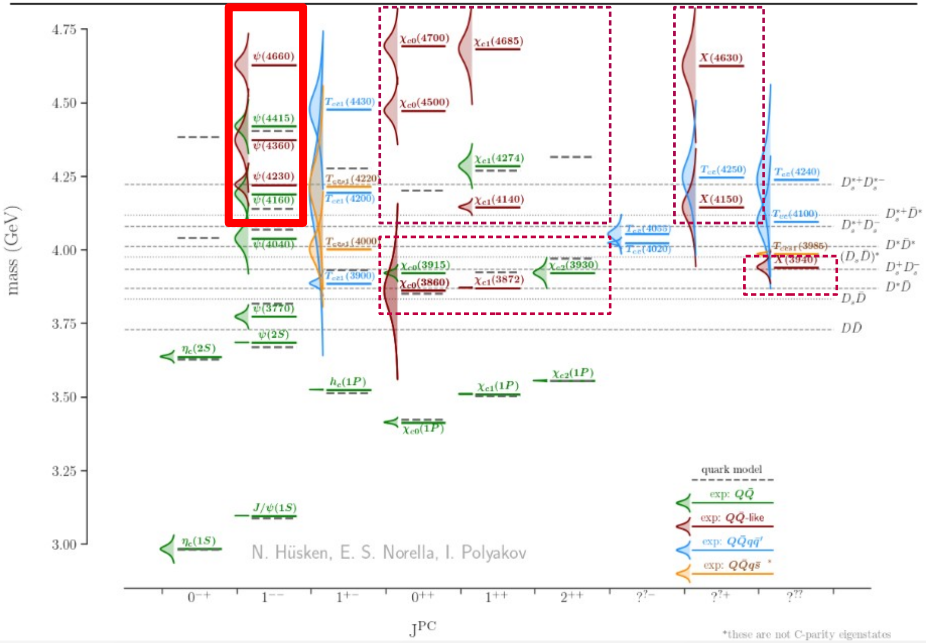


Fig. 9. Resonances in $J/\psi\phi$ at LHCb [116]

Exotic charmonium

Category			States / Candidates
Meson-like (incl. tetraquarks)	Hidden Charm	$I=0$	$\chi-$like: $\chi_{c1}(3872)$, $\chi_{c0}(3860)$, $\chi_{c0}(3915)$, $\chi_{c2}(3930)$, $X(3940)$
			$\psi-$like: $\psi(4230)$, $\psi(4360)$, $\psi(4660)$
			with $s\bar{s}$: $\chi_{c1}(4140)$, $\chi_{c1}(4274)$, $\chi_{c1}(4685)$, $\chi_{c1}(4500)$, $\chi_{c1}(4700)$ $X(4150)$, $X(4630)$, $X(4740)$
		$I=1/2$	$T_{c\bar{c}s}(3985)^-$, $T_{c\bar{c}s1}(4000)^{-/0}$, $T_{c\bar{c}s1}(4220)^-$
		$I=1$	seen in e^+e^-: $T_{c\bar{c}1}(3900)^{+/0}$, $T_{c\bar{c}}(4020)^+$, $T_{c\bar{c}}(4055)^+$
			seen in B decays: $T_{c\bar{c}}(4050)^+$, $T_{c\bar{c}}(4100)^+$, $T_{c\bar{c}1}(4200)^+$, $T_{c\bar{c}}(4240)^+$, $T_{c\bar{c}}(4250)^+$, $T_{c\bar{c}1}(4430)^+$
	Hidden Beauty	$I=0$	$\Upsilon(10753)$, $\Upsilon(10860)$, $\Upsilon(11020)$
		$I=1$	$T_{b\bar{b}1}(10610)^+$, $T_{b\bar{b}1}(10650)^+$
	Hidden Double Charm		$T_{c\bar{c}c\bar{c}}(6550)$, $T_{c\bar{c}c\bar{c}}(6900)$, $T_{c\bar{c}c\bar{c}}(7290)$
	Open Single Charm		D_s^*-like: $D_{s0}^*(2317)^+$, $D_{s1}(2460)^+$
			$T_{cs/c\bar{s}}$: $T_{cs0}(2900)^0$, $T_{c\bar{s}0}(2900)^{0/++}$, $T_{cs1}(2900)^0$
	Open Double Charm		$T_{cc}(3875)^+$
Baryon-like (incl. pentaquarks)	Hidden Charm	$I=1/2(3/2)$	$P_{c\bar{c}}(4312)^+$, $P_{c\bar{c}}(4440)^+$, $P_{c\bar{c}}(4457)^+$, $P_{c\bar{c}}(4380)^+$, $P_{c\bar{c}}(4337)^+$
		$I=0(1)$	$P_{c\bar{c}s}(4458)^0$, $P_{c\bar{c}s}(4338)^0$



ψ-like *(aka Y)*

states: $\psi(4230)$, $\psi(4360)$, $\psi(4660)$

also known as $Y(4230)$, $\psi(4260)$, $Y(4360)$, …

quantum numbers: $I^G(J^{PC}) = 0^-(1^{--})$

minimal quark content: $[c\bar{c}]$,

possibly $[c\bar{c}q\bar{q}]$ or $[c\bar{c}g]$

experiments: BaBar, CLEO, Belle, BESIII,

possibly D0

production: e^+e^- annihilation,

possibly b-decays ($\psi(4230)$)

decay modes: $\pi\pi J/\psi$, $\pi\pi\psi(2S)$, $\pi\pi h_c$

$\eta^{(\prime)}J/\psi$, KKJ/ψ, $3\pi\eta_c$, $\omega\chi_{c0}$, $\gamma\chi_{c1}(3872)$, …

$\mu\mu$, $D^*\bar{D}\pi$, $D\bar{D}\pi\pi$, ...

nearby threshold: $D_1\bar{D}$

characteristic widths: 48-118 MeV

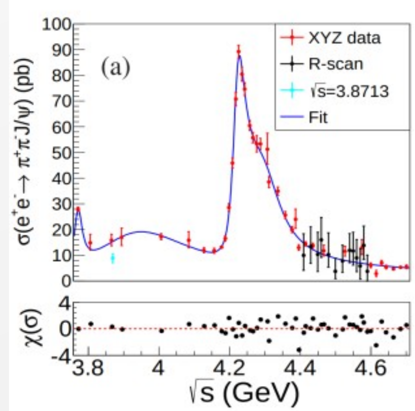
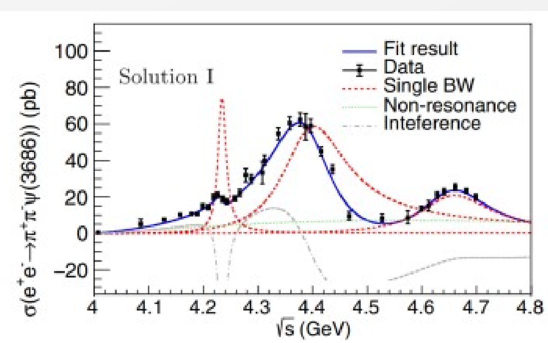


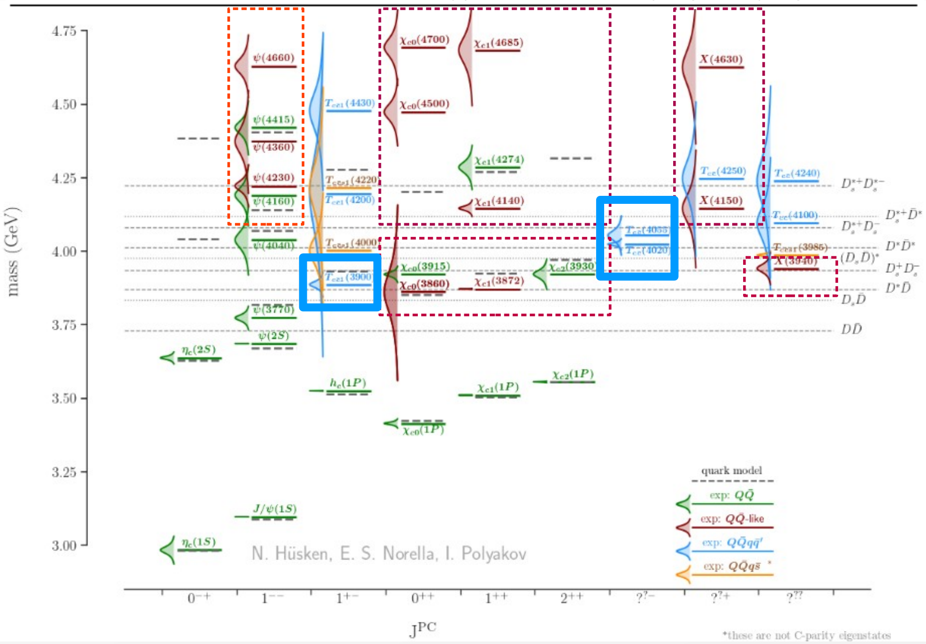
Fig. 7. $e^+e^- \to \pi^+\pi^- J/\psi$ cross-section at BESIII.[102]



$e^+e^- \to \pi^+\pi^-\psi(2S)$ (right) cross-sect

Exotic charmonium

Category			States / Candidates
Meson-like (incl. tetraquarks)	Hidden Charm	$I=0$	χ−like: $\chi_{c1}(3872)$, $\chi_{c0}(3860)$, $\chi_{c0}(3915)$, $\chi_{c2}(3930)$, $X(3940)$
			ψ−like: $\psi(4230)$, $\psi(4360)$, $\psi(4660)$
			with $s\bar{s}$: $\chi_{c1}(4140)$, $\chi_{c1}(4274)$, $\chi_{c1}(4685)$, $\chi_{c1}(4500)$, $\chi_{c1}(4700)$ $X(4150)$, $X(4630)$, $X(4740)$
		$I=1/2$	$T_{c\bar{c}s}(3985)^-$, $T_{c\bar{c}s1}(4000)^{-/0}$, $T_{c\bar{c}s1}(4220)^-$
		$I=1$	seen in e^+e^-: $T_{c\bar{c}1}(3900)^{+/0}$, $T_{c\bar{c}}(4020)^+$, $T_{c\bar{c}}(4055)^+$
			seen in B decays: $T_{c\bar{c}}(4050)^+$, $T_{c\bar{c}}(4100)^+$, $T_{c\bar{c}1}(4200)^+$, $T_{c\bar{c}}(4240)^+$, $T_{c\bar{c}}(4250)^+$, $T_{c\bar{c}1}(4430)^+$
	Hidden Beauty	$I=0$	$\Upsilon(10753)$, $\Upsilon(10860)$, $\Upsilon(11020)$
		$I=1$	$T_{b\bar{b}1}(10610)^+$, $T_{b\bar{b}1}(10650)^+$
	Hidden Double Charm		$T_{c\bar{c}c\bar{c}}(6550)$, $T_{c\bar{c}c\bar{c}}(6900)$, $T_{c\bar{c}c\bar{c}}(7290)$
	Open Single Charm		D_s^*-like: $D_{s0}^*(2317)^+$, $D_{s1}(2460)^+$
			$T_{cs/c\bar{s}}$: $T_{cs0}(2900)^0$, $T_{c\bar{s}0}(2900)^{0/++}$, $T_{cs1}(2900)^0$
	Open Double Charm		$T_{cc}(3875)^+$
Baryon-like (incl. pentaquarks)	Hidden Charm	$I=1/2(3/2)$	$P_{c\bar{c}}(4312)^+$, $P_{c\bar{c}}(4440)^+$, $P_{c\bar{c}}(4457)^+$ $P_{c\bar{c}}(4380)^+$, $P_{c\bar{c}}(4337)^+$
		$I=0(1)$	$P_{c\bar{c}s}(4458)^0$, $P_{c\bar{c}s}(4338)^0$



$T_{c\bar{c}}$ states (*aka Z_c*) seen in e^+e^- annihilation

states:

- $I^G(J^{PC}) = 1^+(1^{+-})$: $T_{c\bar{c}1}(3900)^{+/0}$
- $I^G(J^{PC}) = 1^+(?^{?-})$: $T_{c\bar{c}}(4020)^+$, $T_{c\bar{c}}(4055)^+$

minimal quark content: $[c\bar{c}q\bar{q}']$

experiments: Belle, BESIII, CLEO-c, D0

production: $e^+e^- \to T_{c\bar{c}}\pi$
possibly through $\psi(4230)/\psi(4360)$,
$T_{c\bar{c}1}(3900)$ potentially in $b \to J/\psi\pi^+\pi^- + X$

decay modes: $\pi J/\psi$, $D^*\bar{D}$ and
possibly $\rho\eta_c$ for $T_{c\bar{c}1}(3900)$,
$\pi^+ h_c(1P)$, $D^*\bar{D}^*$ for $T_{c\bar{c}}(4020)$,
$\pi^+\psi(2S)$ for $T_{c\bar{c}}(4055)$

nearby thresholds: $D^*\bar{D}$, $D^*\bar{D}^*$

characteristic widths: 13-45 MeV **in e^+e^-**

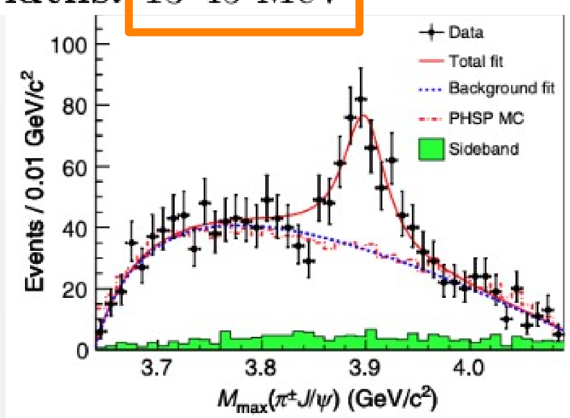
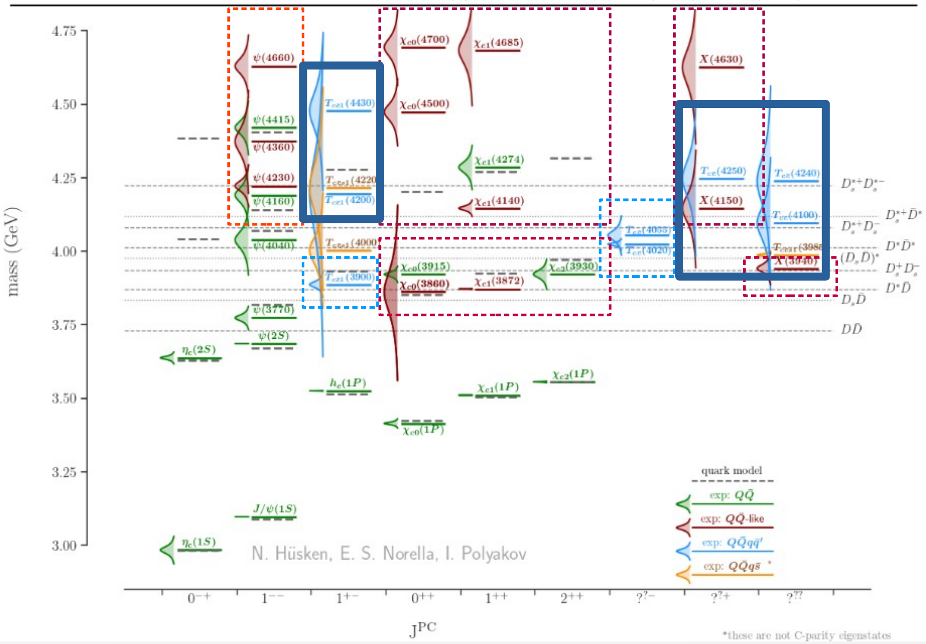


Fig. 11. $T_{c\bar{c}1}(3900)$ signal at BESIII [140]

Exotic charmonium

Category			States / Candidates
Meson-like (incl. tetraquarks)	Hidden Charm	$I=0$	χ−like: $\chi_{c1}(3872)$, $\chi_{c0}(3860)$, $\chi_{c0}(3915)$, $\chi_{c2}(3930)$, $X(3940)$
			ψ−like: $\psi(4230)$, $\psi(4360)$, $\psi(4660)$
			with $s\bar{s}$: $\chi_{c1}(4140)$, $\chi_{c1}(4274)$, $\chi_{c1}(4685)$, $\chi_{c1}(4500)$, $\chi_{c1}(4700)$ $X(4150)$, $X(4630)$, $X(4740)$
		$I=1/2$	$T_{c\bar{c}s}(3985)^-$, $T_{c\bar{c}s1}(4000)^{-/0}$, $T_{c\bar{c}s1}(4220)^-$
		$I=1$	seen in e^+e^-: $T_{c\bar{c}1}(3900)^{+/0}$, $T_{c\bar{c}}(4020)^+$, $T_{c\bar{c}}(4055)^+$
			seen in B decays: $T_{c\bar{c}}(4050)^+$, $T_{c\bar{c}}(4100)^+$, $T_{c\bar{c}1}(4200)^+$, $T_{c\bar{c}}(4240)^+$, $T_{c\bar{c}}(4250)^+$, $T_{c\bar{c}1}(4430)^+$
	Hidden Beauty	$I=0$	$\Upsilon(10753)$, $\Upsilon(10860)$, $\Upsilon(11020)$
		$I=1$	$T_{b\bar{b}1}(10610)^+$, $T_{b\bar{b}1}(10650)^+$
	Hidden Double Charm		$T_{c\bar{c}c\bar{c}}(6550)$, $T_{c\bar{c}c\bar{c}}(6900)$, $T_{c\bar{c}c\bar{c}}(7290)$
	Open Single Charm		D_s^*-like: $D_{s0}^*(2317)^+$, $D_{s1}(2460)^+$
			$T_{cs/c\bar{s}}$: $T_{cs0}(2900)^0$, $T_{c\bar{s}0}(2900)^{0/++}$, $T_{cs1}(2900)^0$
	Open Double Charm		$T_{cc}(3875)^+$
Baryon-like (incl. pentaquarks)	Hidden Charm	$I=1/2(3/2)$	$P_{c\bar{c}}(4312)^+$, $P_{c\bar{c}}(4440)^+$, $P_{c\bar{c}}(4457)^+$ $P_{c\bar{c}}(4380)^+$, $P_{c\bar{c}}(4337)^+$
		$I=0(1)$	$P_{c\bar{c}s}(4458)^0$, $P_{c\bar{c}s}(4338)^0$



$T_{c\bar{c}}$ states *(aka Z_c)*
seen in b-hadron decays

states:

- $I^G(J^{PC}) = 1^+(1^{+-})$: $T_{c\bar{c}1}(4200)^+$, $T_{c\bar{c}1}(4430)^+$
- $I^G(J^{PC}) = 1^+(?^{?-})$: $T_{c\bar{c}}(4240)^+$
  also known as $R_{c0}(4240)$, $Z_c(4240)$
- $I^G(J^{PC}) = 1^-(?^{?+})$: $T_{c\bar{c}}(4050)^+$, $T_{c\bar{c}}(4100)^+$, $T_{c\bar{c}}(4250)^+$

minimal quark content: $[c\bar{c}q\bar{q}']$

experiments: Belle, LHCb

production: $\bar{B}^0 \to (c\bar{c})\pi^+K^-$, where
$(c\bar{c}) = J/\psi,\ \psi(2S),\ \eta_c,\ \chi_{c1}$
$T_{c\bar{c}}(4200)$ also potentially in $\Lambda_b \to J/\psi\pi^-p$

decay modes: $J/\psi\pi^+$, $\psi(2S)\pi^+$, $\eta_c\pi^+$, $\chi_{c1}\pi^+$

nearby threshold: $D^*\bar{D}^*$

characteristic widths: 82-370 MeV

b-decays

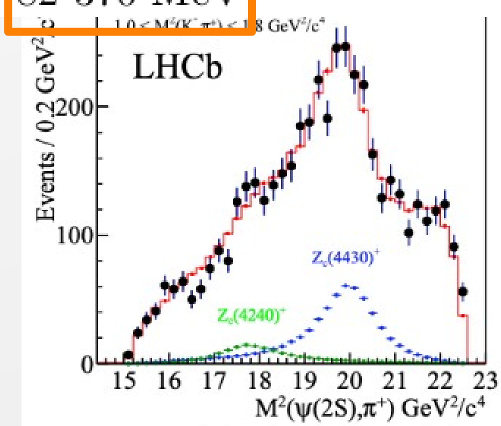
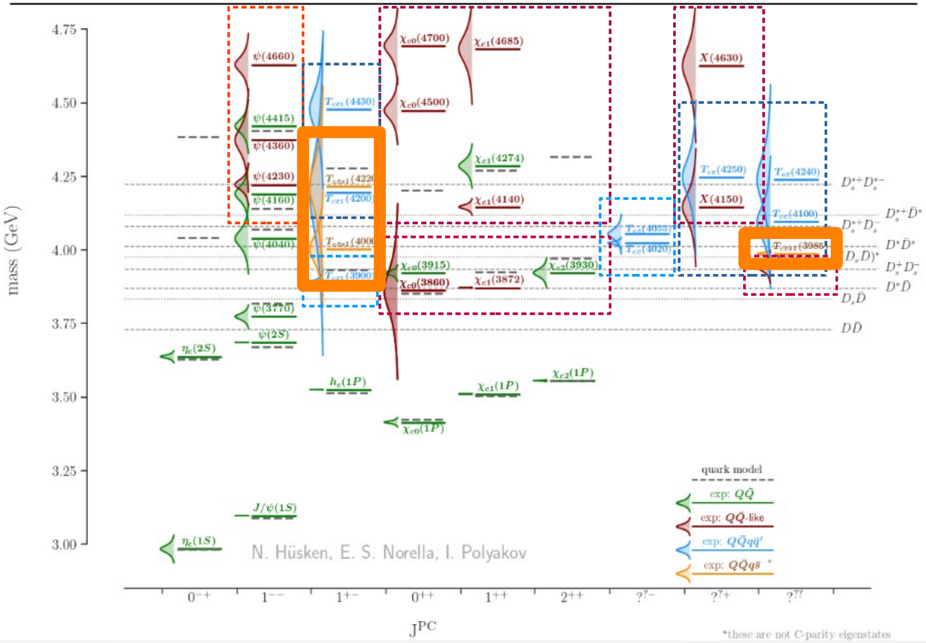


Fig. 12. $T_{c\bar{c}1}(4430)^+$ signal at LHCb.[162]

Exotic charmonium

Category			States / Candidates
Meson-like (incl. tetraquarks)	Hidden Charm	$I=0$	χ−like: $\chi_{c1}(3872)$, $\chi_{c0}(3860)$, $\chi_{c0}(3915)$, $\chi_{c2}(3930)$, $X(3940)$
			ψ−like: $\psi(4230)$, $\psi(4360)$, $\psi(4660)$
			with $s\bar{s}$: $\chi_{c1}(4140)$, $\chi_{c1}(4274)$, $\chi_{c1}(4685)$, $\chi_{c1}(4500)$, $\chi_{c1}(4700)$ $X(4150)$, $X(4630)$, $X(4740)$
		$I=1/2$	$T_{c\bar{c}s}(3985)^-$, $T_{c\bar{c}s1}(4000)^{-/0}$, $T_{c\bar{c}s1}(4220)^-$
		$I=1$	seen in e^+e^-: $T_{c\bar{c}1}(3900)^{+/0}$, $T_{c\bar{c}}(4020)^+$, $T_{c\bar{c}}(4055)^+$
			seen in B decays: $T_{c\bar{c}}(4050)^+$, $T_{c\bar{c}}(4100)^+$, $T_{c\bar{c}1}(4200)^+$, $T_{c\bar{c}}(4240)^+$, $T_{c\bar{c}}(4250)^+$, $T_{c\bar{c}1}(4430)^+$
	Hidden Beauty	$I=0$	$\Upsilon(10753)$, $\Upsilon(10860)$, $\Upsilon(11020)$
		$I=1$	$T_{b\bar{b}1}(10610)^+$, $T_{b\bar{b}1}(10650)^+$
	Hidden Double Charm		$T_{c\bar{c}c\bar{c}}(6550)$, $T_{c\bar{c}c\bar{c}}(6900)$, $T_{c\bar{c}c\bar{c}}(7290)$
	Open Single Charm		D_s^*-like: $D_{s0}^*(2317)^+$, $D_{s1}(2460)^+$
			$T_{cs/c\bar{s}}$: $T_{cs0}(2900)^0$, $T_{c\bar{s}0}(2900)^{0/++}$, $T_{cs1}(2900)^0$
	Open Double Charm		$T_{cc}(3875)^+$
Baryon-like (incl. pentaquarks)	Hidden Charm	$I=1/2(3/2)$	$P_{c\bar{c}}(4312)^+$, $P_{c\bar{c}}(4440)^+$, $P_{c\bar{c}}(4457)^+$, $P_{c\bar{c}}(4380)^+$, $P_{c\bar{c}}(4337)^+$
		$I=0(1)$	$P_{c\bar{c}s}(4458)^0$, $P_{c\bar{c}s}(4338)^0$



$T_{c\bar{c}s}$ states *(aka Z_{cs})*

states:

- $I(J^P) = \frac{1}{2}(?^?)$: $T_{c\bar{c}s}(3985)^{-/0}$
- $I(J^P) = \frac{1}{2}(1^+)$: $T_{c\bar{c}s1}(4000)^{-/0}$
- $I(J^P) = \frac{1}{2}(1^?)$: $T_{c\bar{c}s1}(4220)^-$

minimal quark content: $[c\bar{c}s\bar{q}]$

experiments: BESIII, LHCb

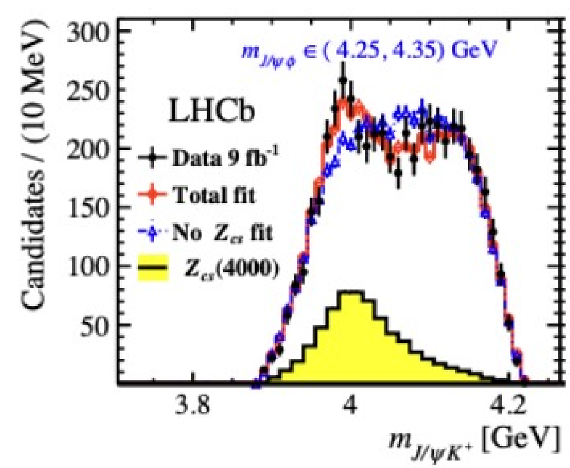
production: e^+e^- ($T_{c\bar{c}s}(3985)$),
$B^- \to J/\psi\phi K^-$ ($T_{c\bar{c}s1}(4000)$, $T_{c\bar{c}s1}(4220)$),
$B^0 \to J/\psi\phi K^0_S$ ($T_{c\bar{c}s1}(4000)$)

decay modes: $D_s^- D^{*+/0}/D_s^{*-}D^{+/0}$,
$J/\psi K^-$, $J/\psi K^0_S$

nearby thresholds: $D_s^- D^*$ **in e^+e^-** $D^{(*)+/0}$

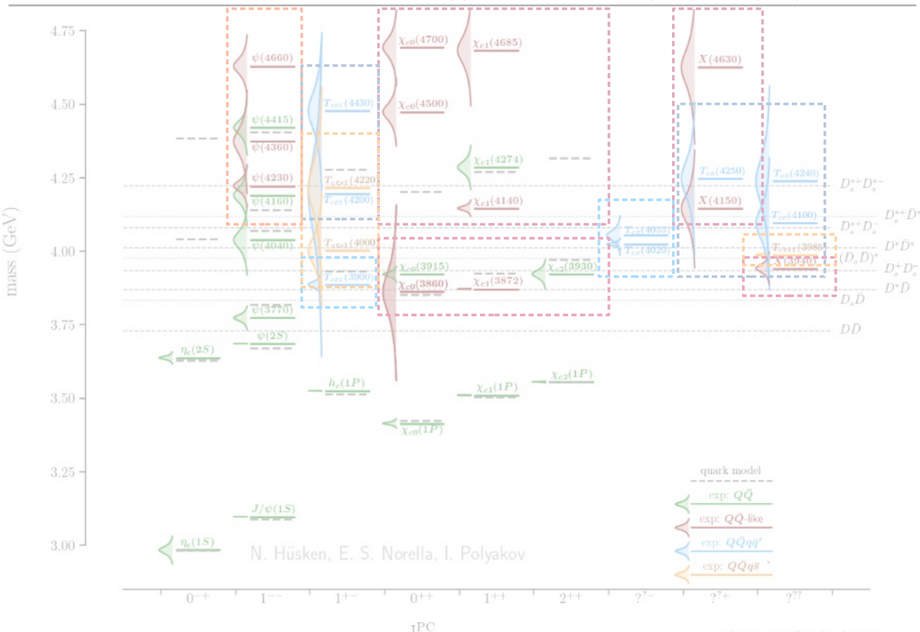
characteristic widths: **8-13 MeV** ($T_{c\bar{c}s}(3985)$),
130-233 MeV ($T_{c\bar{c}s1}(4000)$, $T_{c\bar{c}s1}(4220)$)

b-decays



Exotic charmonium

Category			States / Candidates
Meson-like (incl. tetraquarks)	Hidden Charm	$I=0$	χ−like: $\chi_{c1}(3872)$, $\chi_{c0}(3860)$, $\chi_{c0}(3915)$, $\chi_{c2}(3930)$, $X(3940)$
			ψ−like: $\psi(4230)$, $\psi(4360)$, $\psi(4660)$
			with $s\bar{s}$: $\chi_{c1}(4140)$, $\chi_{c1}(4274)$, $\chi_{c1}(4685)$, $\chi_{c1}(4500)$, $\chi_{c1}(4700)$ $X(4150)$, $X(4630)$, $X(4740)$
		$I=1/2$	$T_{c\bar{c}s}(3985)^-$, $T_{c\bar{c}s1}(4000)^{-/0}$, $T_{c\bar{c}s1}(4220)^-$
		$I=1$	seen in e^+e^-: $T_{c\bar{c}1}(3900)^{+/0}$, $T_{c\bar{c}}(4020)^+$, $T_{c\bar{c}}(4055)^+$
			seen in B decays: $T_{c\bar{c}}(4050)^+$, $T_{c\bar{c}}(4100)^+$, $T_{c\bar{c}1}(4200)^+$, $T_{c\bar{c}}(4240)^+$, $T_{c\bar{c}}(4250)^+$, $T_{c\bar{c}1}(4430)^+$
	Hidden Beauty	$I=0$	$\Upsilon(10753)$, $\Upsilon(10860)$, $\Upsilon(11020)$
		$I=1$	$T_{b\bar{b}1}(10610)^+$, $T_{b\bar{b}1}(10650)^+$
	Hidden Double Charm		$T_{c\bar{c}c\bar{c}}(6550)$, $T_{c\bar{c}c\bar{c}}(6900)$, $T_{c\bar{c}c\bar{c}}(7290)$
	Open Single Charm		D_s^*-like: $D_{s0}^*(2317)^+$, $D_{s1}(2460)^+$
			$T_{cs/c\bar{s}}$: $T_{cs0}(2900)^0$, $T_{c\bar{s}0}(2900)^{0/++}$, $T_{cs1}(2900)^0$
	Open Double Charm		$T_{cc}(3875)^+$
Baryon-like (incl. pentaquarks)	Hidden Charm	$I=1/2(3/2)$	$P_{c\bar{c}}(4312)^+$, $P_{c\bar{c}}(4440)^+$, $P_{c\bar{c}}(4457)^+$ $P_{c\bar{c}}(4380)^+$, $P_{c\bar{c}}(4337)^+$
		$I=0(1)$	$P_{c\bar{c}s}(4458)^0$, $P_{c\bar{c}s}(4338)^0$



$P_{c\bar{c}}$ states *(aka P_c)*

states: $P_{c\bar{c}}(4312)^+$, $P_{c\bar{c}}(4440)^+$, $P_{c\bar{c}}(4457)^+$, $P_{c\bar{c}}(4380)^+$, $P_{c\bar{c}}(4337)^+$

minimal quark content: $[c\bar{c}uud]$

experiments: LHCb

production: $\Lambda_b \to J/\psi p K^-$, likely $\Lambda_b \to J/\psi p \pi^-$ ($P_{c\bar{c}}(4440|4457)$), $B_s^0 \to J/\psi p \bar{p}$ ($P_{c\bar{c}}(4337)$)

decay modes: $J/\psi p$

nearby threshold: $\Sigma_c^+ \bar{D}^{(*)0}$

characteristic widths: 10-30 MeV and ∼205 MeV ($P_{c\bar{c}}(4380)$)

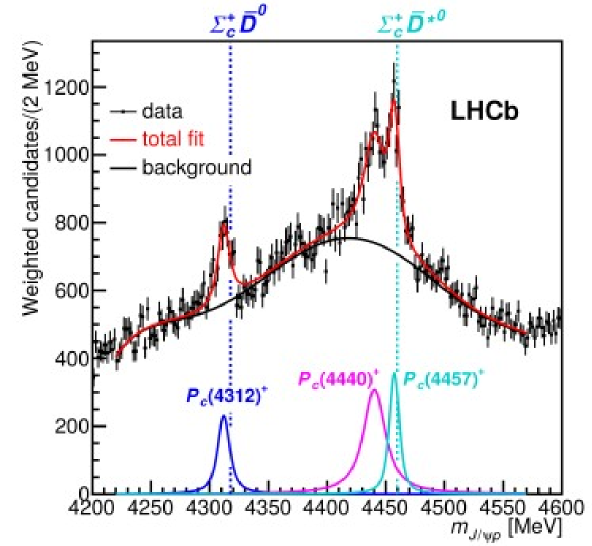
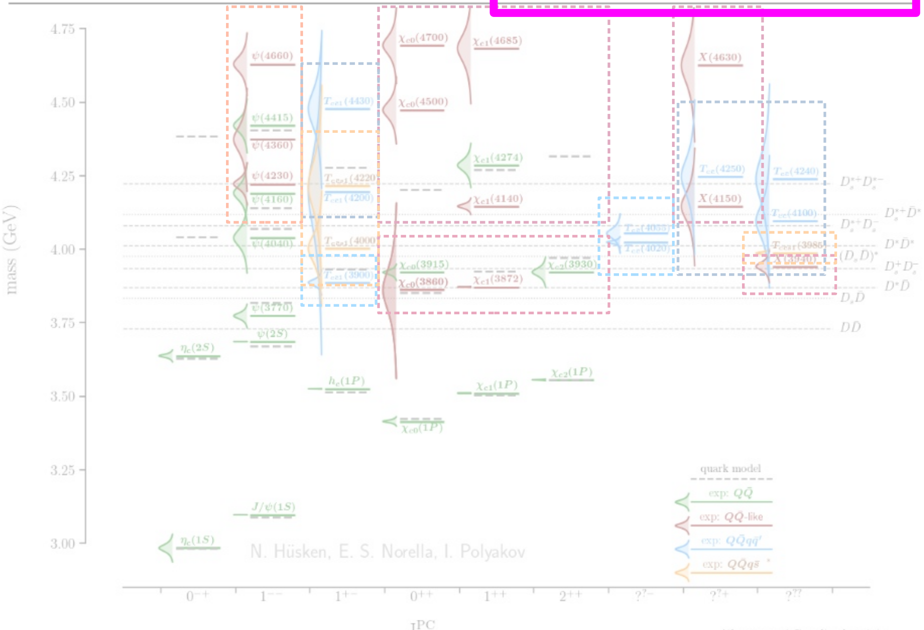


Figure 19: $P_{c\bar{c}}$ states in $\Lambda_b \to J/\psi p K^-$ at LHCb [240].

Exotic charmonium

Category			States / Candidates
Meson-like (incl. tetraquarks)	Hidden Charm	$I=0$	$\chi-$like: $\chi_{c1}(3872)$, $\chi_{c0}(3860)$, $\chi_{c0}(3915)$, $\chi_{c2}(3930)$, $X(3940)$
			$\psi-$like: $\psi(4230)$, $\psi(4360)$, $\psi(4660)$
			with $s\bar{s}$: $\chi_{c1}(4140)$, $\chi_{c1}(4274)$, $\chi_{c1}(4685)$, $\chi_{c1}(4500)$, $\chi_{c1}(4700)$ $X(4150)$, $X(4630)$, $X(4740)$
		$I=1/2$	$T_{c\bar{c}s}(3985)^-$, $T_{c\bar{c}s1}(4000)^{-/0}$, $T_{c\bar{c}s1}(4220)^-$
		$I=1$	seen in e^+e^-: $T_{c\bar{c}1}(3900)^{+/0}$, $T_{c\bar{c}}(4020)^+$, $T_{c\bar{c}}(4055)^+$
			seen in B decays: $T_{c\bar{c}}(4050)^+$, $T_{c\bar{c}}(4100)^+$, $T_{c\bar{c}1}(4200)^+$, $T_{c\bar{c}}(4240)^+$, $T_{c\bar{c}}(4250)^+$, $T_{c\bar{c}1}(4430)^+$
	Hidden Beauty	$I=0$	$\Upsilon(10753)$, $\Upsilon(10860)$, $\Upsilon(11020)$
		$I=1$	$T_{b\bar{b}1}(10610)^+$, $T_{b\bar{b}1}(10650)^+$
	Hidden Double Charm		$T_{c\bar{c}c\bar{c}}(6550)$, $T_{c\bar{c}c\bar{c}}(6900)$, $T_{c\bar{c}c\bar{c}}(7290)$
	Open Single Charm		D_s^*-like: $D_{s0}^*(2317)^+$, $D_{s1}(2460)^+$
			$T_{cs/c\bar{s}}$: $T_{cs0}(2900)^0$, $T_{c\bar{s}0}(2900)^{0/++}$, $T_{cs1}(2900)^0$
	Open Double Charm		$T_{cc}(3875)^+$
Baryon-like (incl. pentaquarks)	Hidden Charm	$I=1/2(3/2)$	$P_{c\bar{c}}(4312)^+$, $P_{c\bar{c}}(4440)^+$, $P_{c\bar{c}}(4457)^+$ $P_{c\bar{c}}(4380)^+$, $P_{c\bar{c}}(4337)^+$
		$I=0(1)$	$P_{c\bar{c}s}(4458)^0$, $P_{c\bar{c}s}(4338)^0$



$P_{c\bar{c}s}$ states (aka P_{cs})

states:

- $I(J^P) = 0(1/2^-)$: $P_{c\bar{c}s}(4338)^0$
- $I(J^P) = 0(?)$: $P_{c\bar{c}s}(4458)^0$

minimal quark content: $[c\bar{c}uds]$

experiments: LHCb

production: $B^- \to J/\psi\Lambda\bar{p}$ ($P_{c\bar{c}s}(4338)$), $\Xi_b \to J/\psi\Lambda K^-$ ($P_{c\bar{c}s}(4458)$)

decay modes: $J/\psi\Lambda$

nearby thresholds: $\Xi_c^+ D^-$, $\Xi_c^0 \bar{D}^{*0}$

characteristic widths: 7-17 MeV

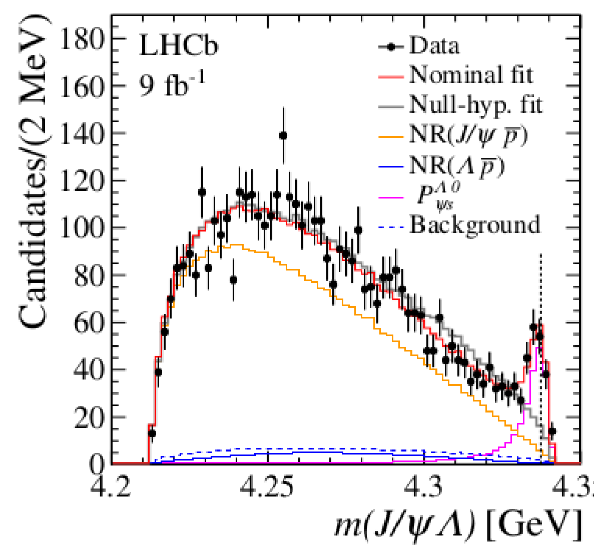


Figure 20: Discovery of the $P_{c\bar{c}s}(4338)^0$ at LHCb [254].

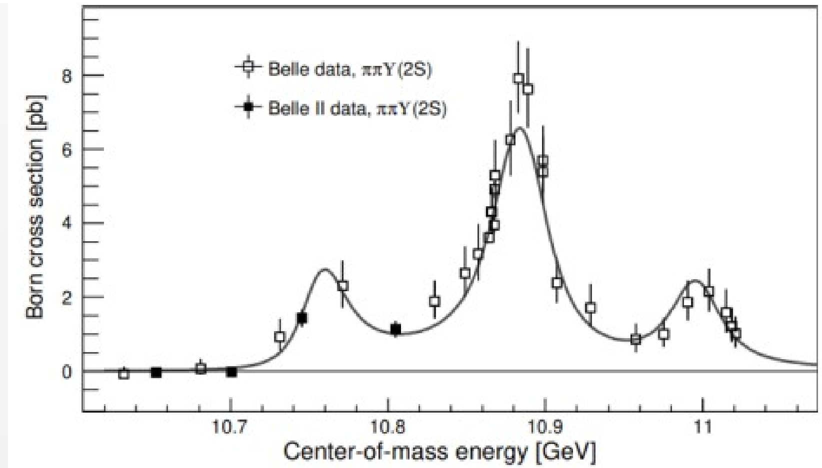
Exotic bottomonium

Category			States / Candidates
Meson-like (incl. tetraquarks)	Hidden Charm	$I=0$	χ−like: $\chi_{c1}(3872)$, $\chi_{c0}(3860)$, $\chi_{c0}(3915)$, $\chi_{c2}(3930)$, $X(3940)$
			ψ−like: $\psi(4230)$, $\psi(4360)$, $\psi(4660)$
			with $s\bar{s}$: $\chi_{c1}(4140)$, $\chi_{c1}(4274)$, $\chi_{c1}(4685)$, $\chi_{c1}(4500)$, $\chi_{c1}(4700)$ $X(4150)$, $X(4630)$, $X(4740)$
		$I=1/2$	$T_{c\bar{c}\bar{s}}(3985)^-$, $T_{c\bar{c}\bar{s}1}(4000)^{-/0}$, $T_{c\bar{c}\bar{s}1}(4220)^-$
		$I=1$	seen in e^+e^-: $T_{c\bar{c}1}(3900)^{+/0}$, $T_{c\bar{c}}(4020)^+$, $T_{c\bar{c}}(4055)^+$
			seen in B decays: $T_{c\bar{c}}(4050)^+$, $T_{c\bar{c}}(4100)^+$, $T_{c\bar{c}1}(4200)^+$, $T_{c\bar{c}}(4240)^+$, $T_{c\bar{c}}(4250)^+$, $T_{c\bar{c}1}(4430)^+$
	Hidden Beauty	$I=0$	$\Upsilon(10753)$, $\Upsilon(10860)$, $\Upsilon(11020)$
		$I=1$	$T_{b\bar{b}1}(10610)^+$, $T_{b\bar{b}1}(10650)^+$
	Hidden Double Charm		$T_{c\bar{c}c\bar{c}}(6550)$, $T_{c\bar{c}c\bar{c}}(6900)$, $T_{c\bar{c}c\bar{c}}(7290)$
	Open Single Charm		D_s^*-like: $D_{s0}^*(2317)^+$, $D_{s1}(2460)^+$
			$T_{cs/c\bar{s}}$: $T_{cs0}(2900)^0$, $T_{c\bar{s}0}(2900)^{0/++}$, $T_{cs1}(2900)^0$
	Open Double Charm		$T_{cc}(3875)^+$
Baryon-like (incl. pentaquarks)	Hidden Charm	$I=1/2(3/2)$	$P_{c\bar{c}}(4312)^+$, $P_{c\bar{c}}(4440)^+$, $P_{c\bar{c}}(4457)^+$ $P_{c\bar{c}}(4380)^+$, $P_{c\bar{c}}(4337)^+$
		$I=0(1)$	$P_{c\bar{c}s}(4458)^0$, $P_{c\bar{c}s}(4338)^0$

Υ-like

states: $\Upsilon(10753)$, $\Upsilon(10860)$, $\Upsilon(11020)$
also known as $\Upsilon(5S)$, $\Upsilon(6S)$

quantum numbers: $I^G(J^{PC}) = 0^-(1^{--})$
minimal quark content: $[b\bar{b}]$, possibly $[b\bar{b}q\bar{q}]$ or $[b\bar{b}g]$
experiments: CUSB, CLEO, BaBar, Belle, Belle II
production: e^+e^- annihilation
decay modes: all in $\pi^+\pi^-\Upsilon(nS)$ $(n=1,2,3)$,
also $\omega\chi_{b1,2}(1P)$ for $\Upsilon(10753)$ (and possibly $\Upsilon(10860)$),
$\pi^+\pi^-h_b(nP)$ $(n=1,2)$, and possibly $\pi^+\pi^-\pi^0\chi_{b1,2}(1P)$
nearby thresholds: $B_s\bar{B}_s$, $B_s\bar{B}_s^*$, $B_s^*\bar{B}_s^*$
characteristic widths: 24-37 MeV



analog to ψ-like states from charmonia sector

Exotic bottomonium

Category			States / Candidates
Meson-like (incl. tetraquarks)	Hidden Charm	$I = 0$	χ−like: $\chi_{c1}(3872)$, $\chi_{c0}(3860)$, $\chi_{c0}(3915)$, $\chi_{c2}(3930)$, $X(3940)$
			ψ−like: $\psi(4230)$, $\psi(4360)$, $\psi(4660)$
			with $s\bar{s}$: $\chi_{c1}(4140)$, $\chi_{c1}(4274)$, $\chi_{c1}(4685)$, $\chi_{c1}(4500)$, $\chi_{c1}(4700)$ $X(4150)$, $X(4630)$, $X(4740)$
		$I = 1/2$	$T_{c\bar{c}s}(3985)^-$, $T_{c\bar{c}s1}(4000)^{-/0}$, $T_{c\bar{c}s1}(4220)^-$
		$I = 1$	seen in e^+e^-: $T_{c\bar{c}1}(3900)^{+/0}$, $T_{c\bar{c}}(4020)^+$, $T_{c\bar{c}}(4055)^+$
			seen in B decays: $T_{c\bar{c}}(4050)^+$, $T_{c\bar{c}}(4100)^+$, $T_{c\bar{c}1}(4200)^+$, $T_{c\bar{c}}(4240)^+$, $T_{c\bar{c}}(4250)^+$, $T_{c\bar{c}1}(4430)^+$
	Hidden Beauty	$I = 0$	$\Upsilon(10753)$, $\Upsilon(10860)$, $\Upsilon(11020)$
		$I = 1$	$T_{b\bar{b}1}(10610)^+$, $T_{b\bar{b}1}(10650)^+$
	Hidden Double Charm		$T_{c\bar{c}c\bar{c}}(6550)$, $T_{c\bar{c}c\bar{c}}(6900)$, $T_{c\bar{c}c\bar{c}}(7290)$
	Open Single Charm		D_s^*-like: $D_{s0}^*(2317)^+$, $D_{s1}(2460)^+$
			$T_{cs/c\bar{s}}$: $T_{cs0}(2900)^0$, $T_{c\bar{s}0}(2900)^{0/++}$, $T_{cs1}(2900)^0$
	Open Double Charm		$T_{cc}(3875)^+$
Baryon-like (incl. pentaquarks)	Hidden Charm	$I = 1/2(3/2)$	$P_{c\bar{c}}(4312)^+$, $P_{c\bar{c}}(4440)^+$, $P_{c\bar{c}}(4457)^+$ $P_{c\bar{c}}(4380)^+$, $P_{c\bar{c}}(4337)^+$
		$I = 0(1)$	$P_{c\bar{c}s}(4458)^0$, $P_{c\bar{c}s}(4338)^0$

$T_{b\bar{b}}$ states *(aka Z_b)*

states: $T_{b\bar{b}1}(10610)^+$, $T_{b\bar{b}1}(10650)^+$

also known as $Z_b(10610)^+$, ... *or* $T^b_{\Upsilon 1}$, ... *or* $X(10610)$, ...

quantum numbers: $I^G(J^{PC}) = 1^+(1^{+-})$

minimal quark content: $[b\bar{b}u\bar{d}]$

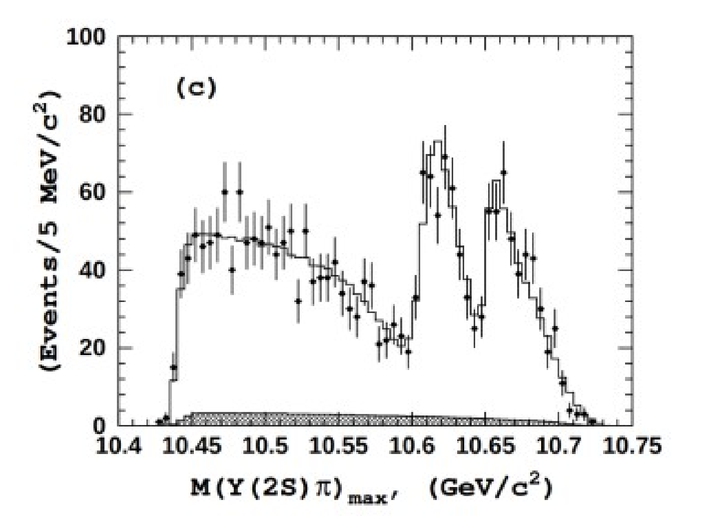
experiments: Belle

production: $e^+e^- \to T^{\pm}_{b\bar{b}}\pi^-$ around the $\Upsilon(10860)$ and $\Upsilon(11020)$

decay modes: $\pi\Upsilon(nS)$ $(n = 1, 2, 3)$, $\pi h_b(nP)$ $(n = 1, 2)$, $B^*\bar{B}$ $(T_{b\bar{b}1}(10610))$, $B^*\bar{B}^*$ $(T_{b\bar{b}1}(10650))$

nearby thresholds: $B^*\bar{B}$, $B^*\bar{B}^*$

characteristic widths: 11.5-18.4 MeV



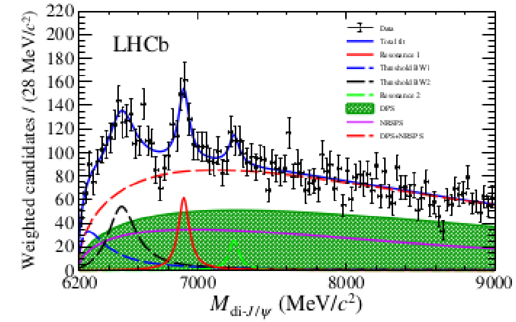
analog to $T_{c\bar{c}}$ states from charmonia sector

Others

Category			States / Candidates
Meson-like (incl. tetraquarks)	Hidden Charm	$I=0$	$\chi-$like: $\chi_{c1}(3872)$, $\chi_{c0}(3860)$, $\chi_{c0}(3915)$, $\chi_{c2}(3930)$, $X(3940)$
			$\psi-$like: $\psi(4230)$, $\psi(4360)$, $\psi(4660)$
			with $s\bar{s}$: $\chi_{c1}(4140)$, $\chi_{c1}(4274)$, $\chi_{c1}(4685)$, $\chi_{c1}(4500)$, $\chi_{c1}(4700)$ $X(4150)$, $X(4630)$, $X(4740)$
		$I=1/2$	$T_{c\bar{c}s}(3985)^-$, $T_{c\bar{c}s1}(4000)^{-/0}$, $T_{c\bar{c}s1}(4220)^-$
		$I=1$	seen in e^+e^-: $T_{c\bar{c}1}(3900)^{+/0}$, $T_{c\bar{c}}(4020)^+$, $T_{c\bar{c}}(4055)^+$
			seen in B decays: $T_{c\bar{c}}(4050)^+$, $T_{c\bar{c}}(4100)^+$, $T_{c\bar{c}1}(4200)^+$, $T_{c\bar{c}}(4240)^+$, $T_{c\bar{c}}(4250)^+$, $T_{c\bar{c}1}(4430)$
	Hidden Beauty	$I=0$	$\Upsilon(10753)$, $\Upsilon(10860)$, $\Upsilon(11020)$
		$I=1$	$T_{b\bar{b}1}(10610)^+$, $T_{b\bar{b}1}(10650)^+$
	Hidden Double Charm		$T_{c\bar{c}c\bar{c}}(6550)$, $T_{c\bar{c}c\bar{c}}(6900)$, $T_{c\bar{c}c\bar{c}}(7290)$
	Open Single Charm		D_s^*-like: $D_{s0}^*(2317)^+$, $D_{s1}(2460)^+$
			$T_{cs/c\bar{s}}$: $T_{cs0}(2900)^0$, $T_{c\bar{s}0}(2900)^{0/++}$, $T_{cs1}(2900)^0$
	Open Double Charm		$T_{cc}(3875)^+$
Baryon-like (incl. pentaquarks)	Hidden Charm	$I=1/2(3/2)$	$P_{c\bar{c}}(4312)^+$, $P_{c\bar{c}}(4440)^+$, $P_{c\bar{c}}(4457)^+$ $P_{c\bar{c}}(4380)^+$, $P_{c\bar{c}}(4337)^+$
		$I=0(1)$	$P_{c\bar{c}s}(4458)^0$, $P_{c\bar{c}s}(4338)^0$

$T_{c\bar{c}c\bar{c}}$ states

states: $T_{c\bar{c}c\bar{c}}(6550)^0$, $T_{c\bar{c}c\bar{c}}(6900)^0$, $T_{c\bar{c}c\bar{c}}(7290)^0$
quantum numbers: $I^G(J^{PC}) = 0^+(?^{?+})$
minimal quark content: $[c\bar{c}c\bar{c}]$
experiments: LHCb, ATLAS, CMS
decay modes: $J/\psi J/\psi$
characteristic widths: 80-191 MeV

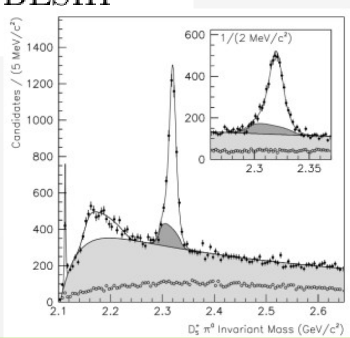


$D_{s0/1}^*$ states

states:

- $I(J^P) = 0(0^+)$: $D_{s0}^*(2317)^+$
- $I(J^P) = 0(1^+)$: $D_{s1}(2460)^+$

minimal quark content: $[c\bar{s}]$, or possibly $[c\bar{s}q\bar{q}]$
experiments: BaBar, CLEO, Belle, BESIII
characteristic widths: < 3.8 MeV



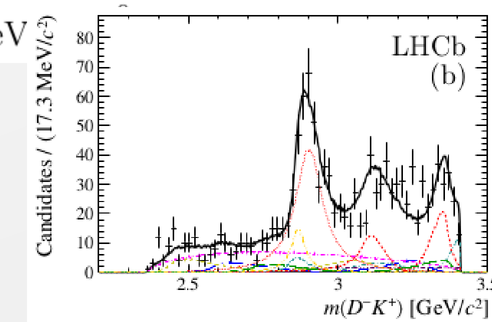
$T_{cs/c\bar{s}}$ states

states:

- $I(J^P) = ?(0^+)$: $T_{cs0}(2900)^0$, $T_{c\bar{s}0}(2900)^0$, $T_{c\bar{s}0}(2900)^{++}$
- $I(J^P) = ?(1^-)$: $T_{cs1}(2900)^0$

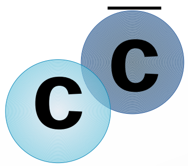
also known as $T_{cs0}^*(2870)^0$, $T_{cs1}^*(2900)^0$, … *or* $X_0(2900)$, $X_1(2900)$, …

minimal quark content: $[cs\bar{q}\bar{q}']$, $[c\bar{s}q\bar{q}']$
experiments: LHCb
characteristic widths: 57-136 MeV



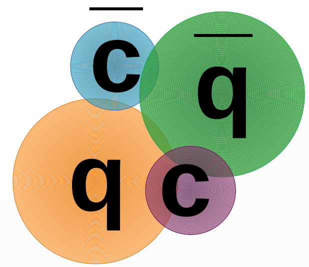
Theory models

** see references in Appendix*



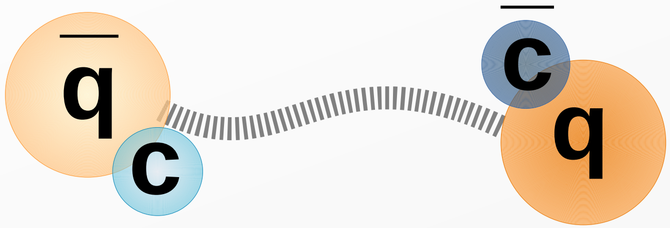
charmonium

Barnes, Godfrey, Swanson; Eichten, Lane, Quigg; Suzuki; ...



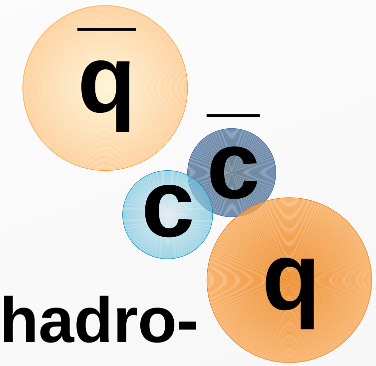
compact tetraquark

Maiani, Piccini, Polosa, Riquer; Matheus, Narison, Nielsen, Richard; ...



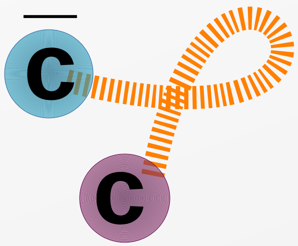
$D\bar{D}^*$ molecula

Braaten, Kusunoki; Swanson; Wong; Tornquist; ...



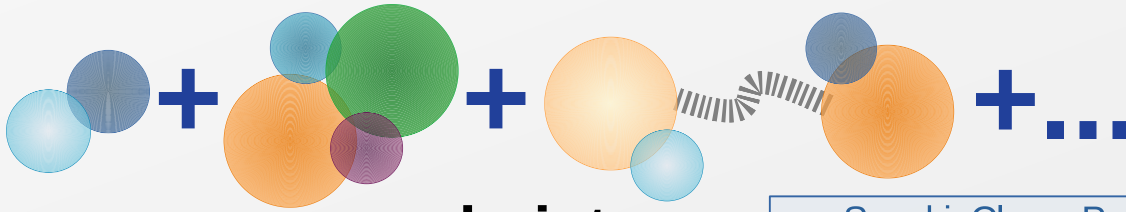
hadro-charmonium

Dubynskiy, Voloshin; ...



hybrid

Close, Godfrey; Li; ...



admixture

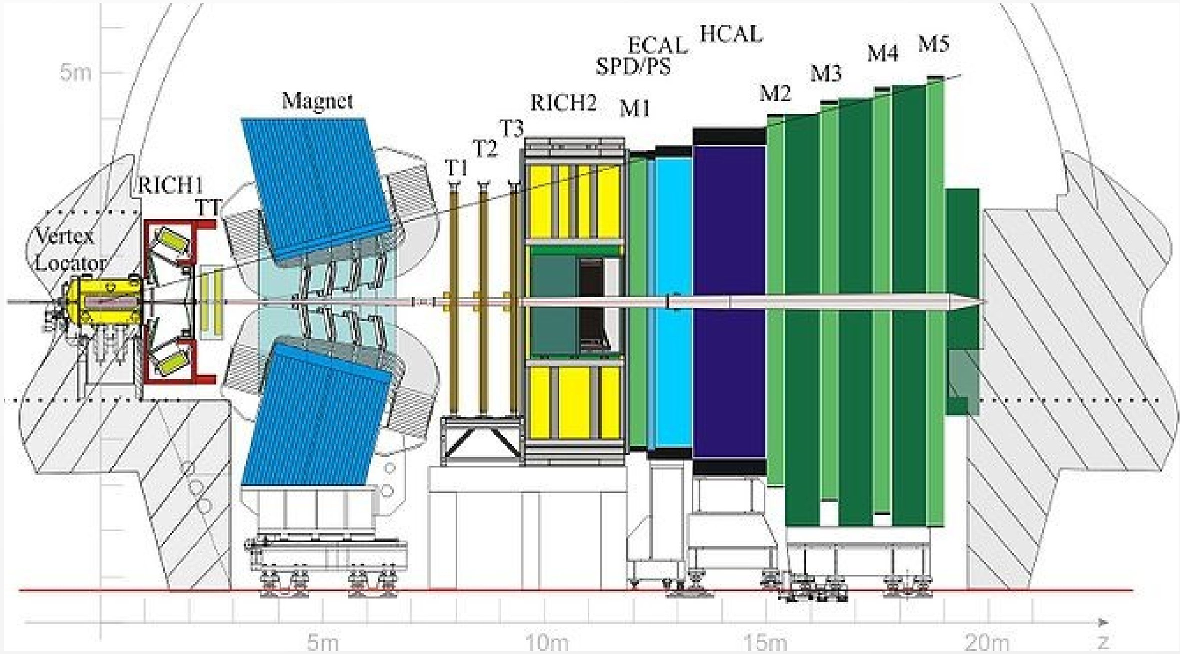
Suzuki; Close, Page; Dong, Faessler, Gutsche, Lyubovitskij; ...

Success of LHCb

- LHCb discovered:
  48 out of 52 conventional hadrons discovered at LHC
  21 out of all ~50 exotic hadrons known to date

- High b/c quark production rate

JINST 3 (2008) S08005



- Optimized for b/c-hadron detection
  - Excellent decay time resolution
  - Excellent momentum resolution
  - Excellent particle identification

- Data collected
  - Run1: 1+2 fb^{-1} at 7 and 8 TeV
  - Run2: 6 fb^{-1} at 13 TeV
  - Run3: expect 15 fb^{-1} at 13.6 TeV

LHCb perspective

- Access $c\bar{c}$-like exotic hadrons in b-hadron decays via:
  - $B \to \psi$ + hadrons, $\psi = J/\psi, \psi(2S), \eta_c, \chi_{cJ}(1P)$
  - since 2020 also in $B \to D\bar{D}$ + hadrons

- **Γ = 1-20 MeV**
  peak in 1D fit

  $\chi_{c1}(3872), \chi_{c2}(3930)$, ...
  $P_{c\bar{c}}, P_{c\bar{c}s}$

  - f ~ 0.1-1%
  - Robust, no info on J^{PC}
  - only selected states

- **Γ = 50-500 MeV**
  4D-7D amplitude analysis

  $\chi_c \to J/\psi\phi$, $T_{c\bar{c}} \to (c\bar{c})\pi$, $T_{c\bar{c}s} \to J/\psi K$, ...

  - f ~ 1-10%,
  - (often) gives J^{PC}
  - get's harder to control interference and coupled channels effects

see more on narrow vs wide states in backup

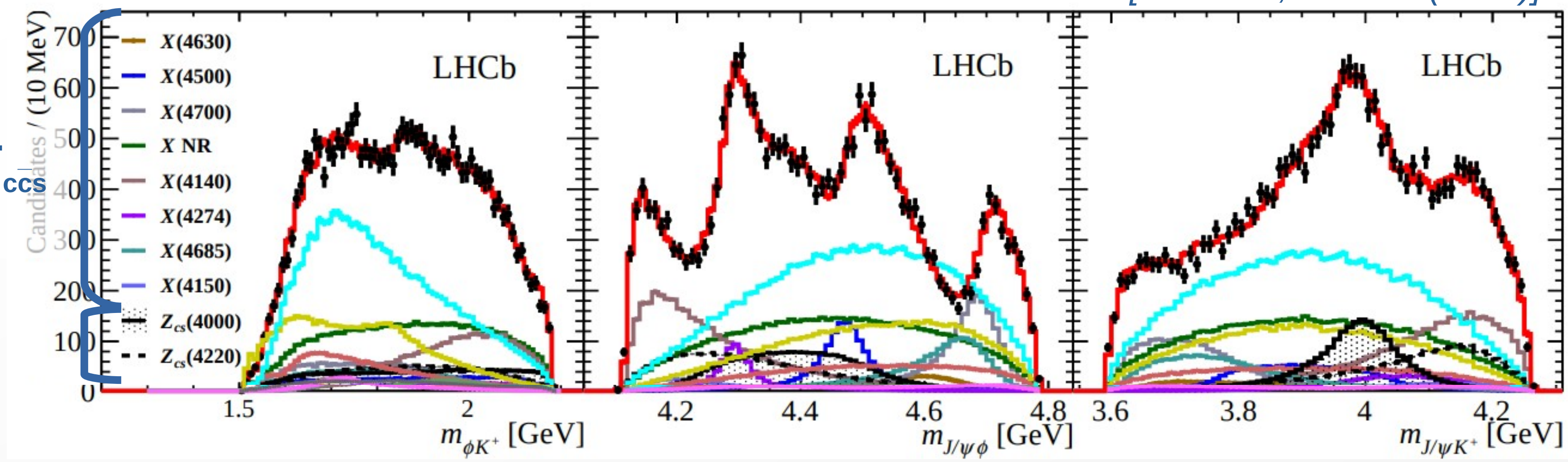
- A guaranteed observation of 10+ more states with
  - increase in statistics and
  - access to new decay channels

Problem of wide states

- Hard to measure

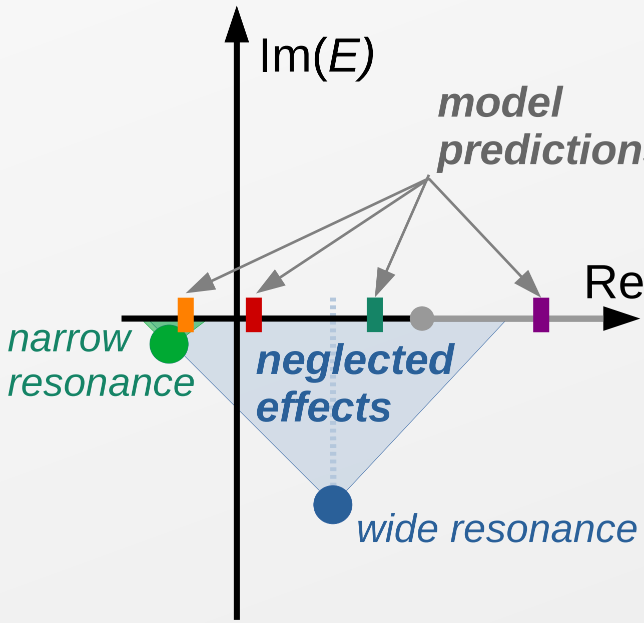
[PRL 127, 082001 (2021)]

8 $T_{c\bar{c}}$ + 2 $T_{cc\bar{s}}$ states



- Hard to interpret

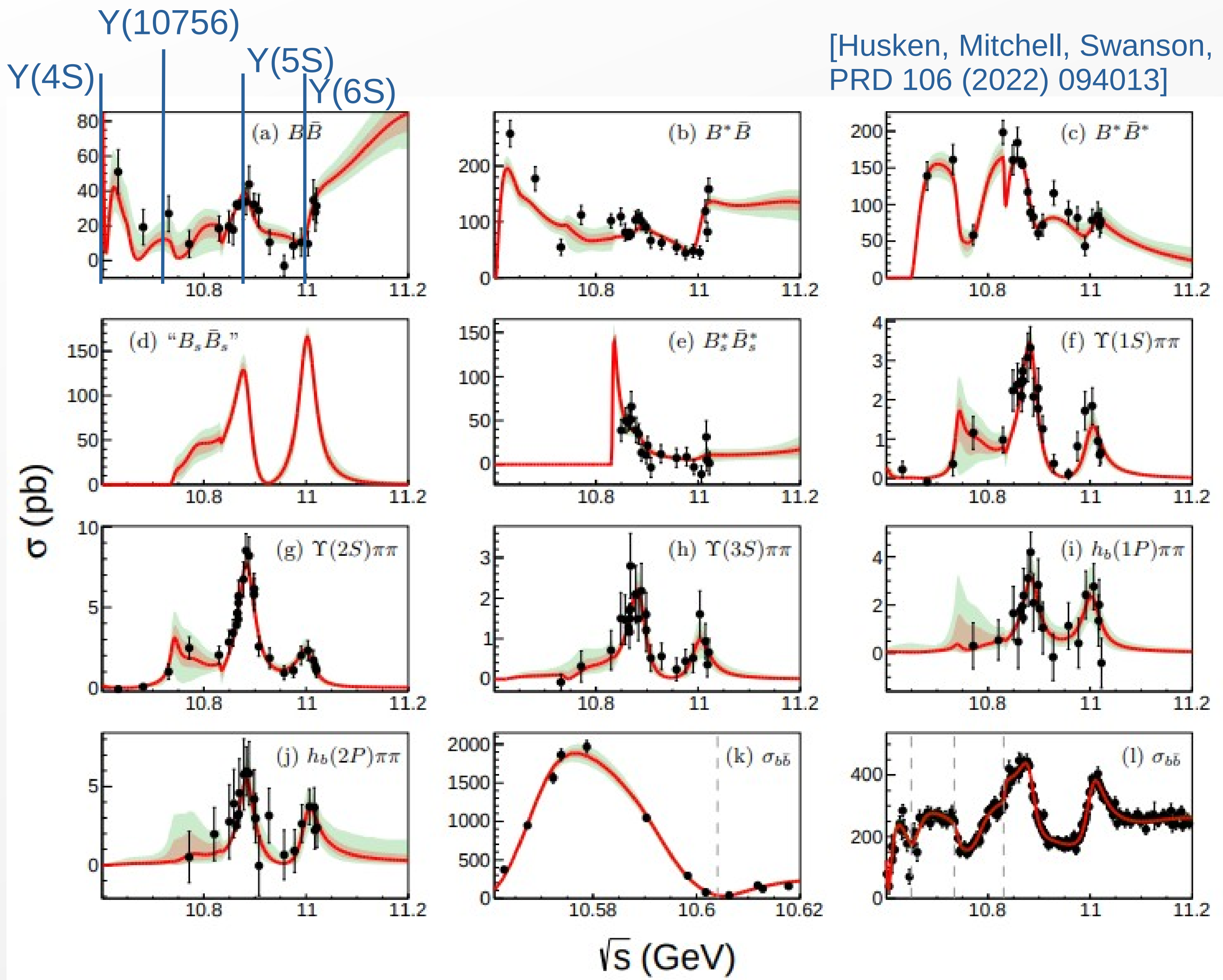
pole position of a resonance



- Coupled channels make troubles for both

Coupled channels

- K-matrix analysis of e^+e^- annihilation in the Bottomonium Region
- Model with 4 vector states



- Complex interplay between different resonances, channels and thresholds
- High standart hard to achieve in other cases

Root of the problem

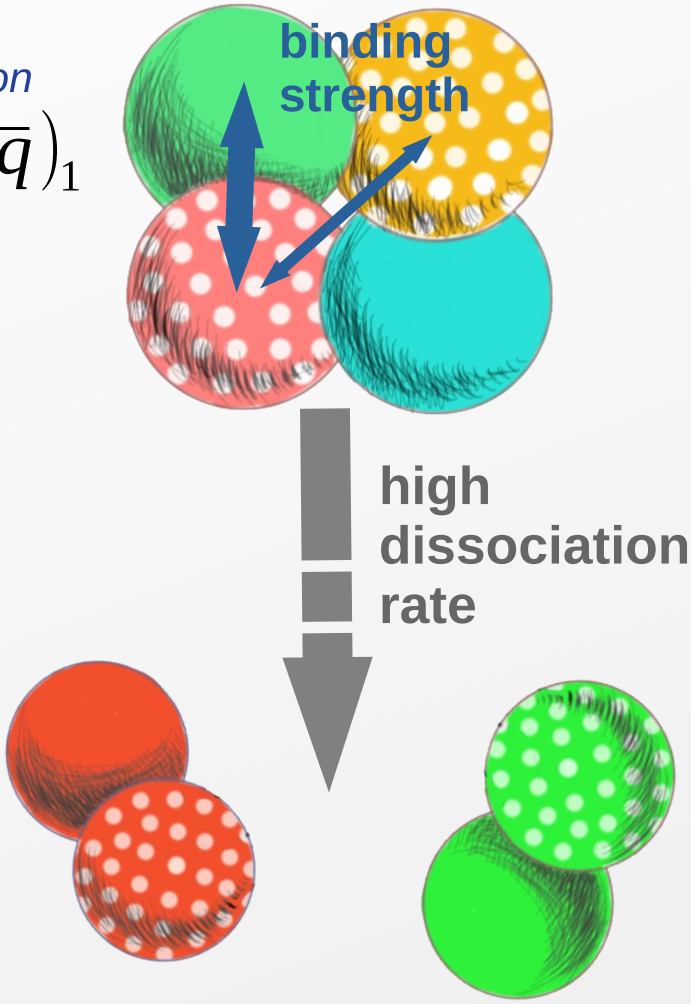
- Interaction potential between quarks

color of quarks

$$V(q_i q_j) \sim \frac{\lambda_i}{2}\frac{\lambda_j}{2} \Rightarrow V(qq)_{3^*} = \frac{1}{2} V(q\bar{q})_1$$

interaction between quarks — *diquark* — *meson*

→ grouping on $q\bar{q}$ and $q\bar{q}$ is often prefered



- Typical exotic hadron: $[Q\bar{Q}q\bar{q}']$, $[Q\bar{Q}qq'q'']$

  - has many channels to decay to or couple

  - hard to measure & interpret

- Need states where it doesn’t happen

T_{cc} $[cc\bar{u}\bar{d}]$

- Discovery of 2021: signal in $D^0D^0\pi^+$ just below D^0D^{*+} threshold
- Model as $T_{cc}^+ \to D^0D^{*+}(\to D\pi)$ for $I(J^P)$ of T_{cc} as $0(1^+)$

  in this model width defined by $\Gamma(D^{*+})$ and δm

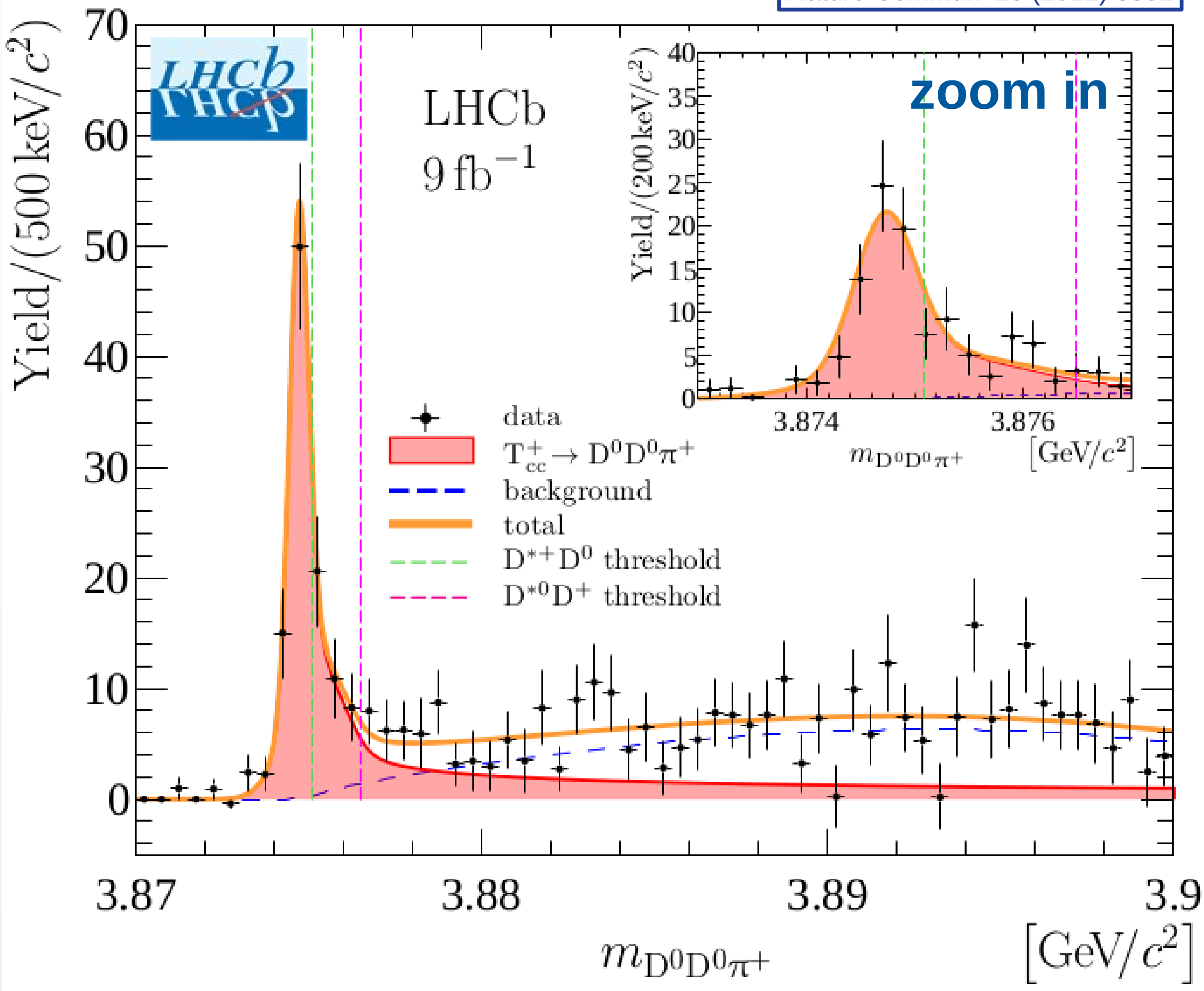
- Results:

$$\delta m_{\text{pole}} = -360 \pm 40^{+4}_{-0}\ \text{keV}/c^2\,,$$
$$\Gamma_{\text{pole}} = 48 \pm 2^{+0}_{-14}\ \text{keV}\,,$$

- 20x more narrow than $\chi_{c1}(3872)$ and 1000x than all other exotics

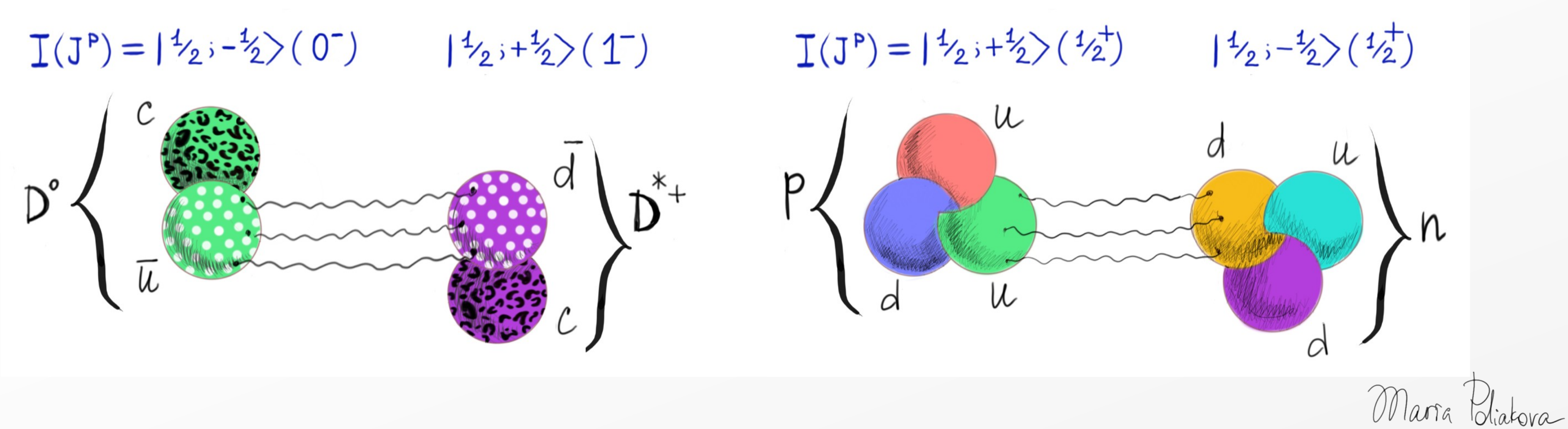
Nature Phys. 18 (2022) 751

Nature Commun. 13 (2022) 3351

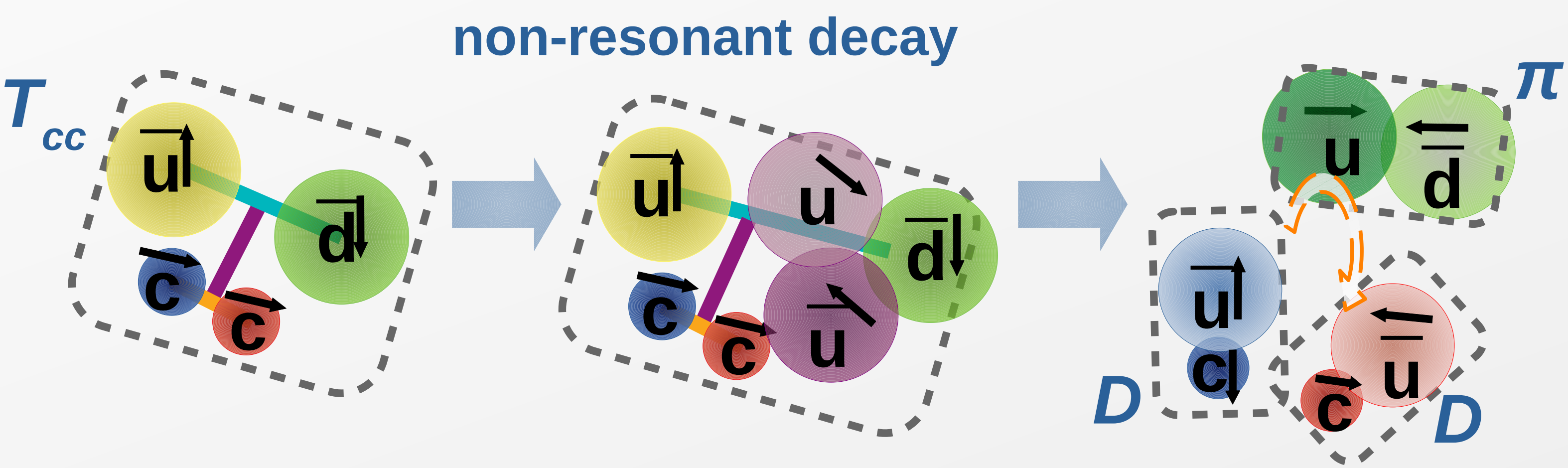


T_{cc} as (is) molecula

- Compare DD* molecula to deuteron (pn)



- Now should probe compact component

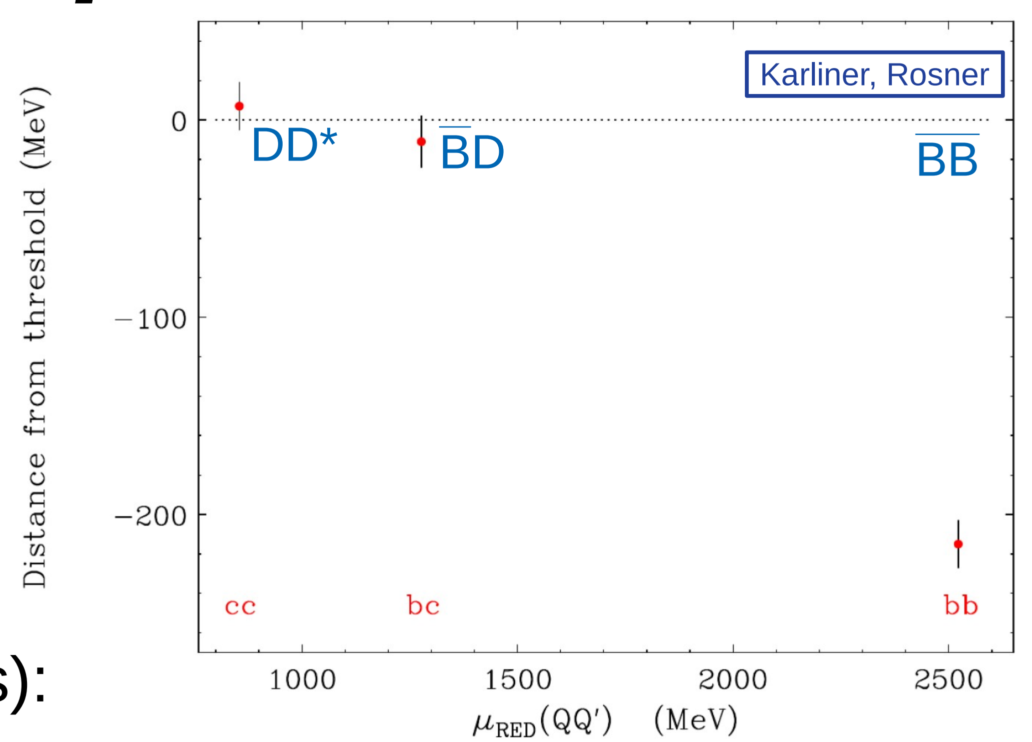


Other doubly-heavy states, $[bb\bar{u}\bar{d}]$

- The T_{cc} below DD* threshold supports predictions for long-lived T_{bb} ***$[bb][\overline{ud}]$***

  Semay, SIlvestre-Brac, 1994
  Janc, Rosina, 2003
  Bicudo et al, 2015
  Karliner, Rosner, 2017
  Francis et al., 2017
  Junnarkar, Mathur, Padmanath, 2018

  … and many more



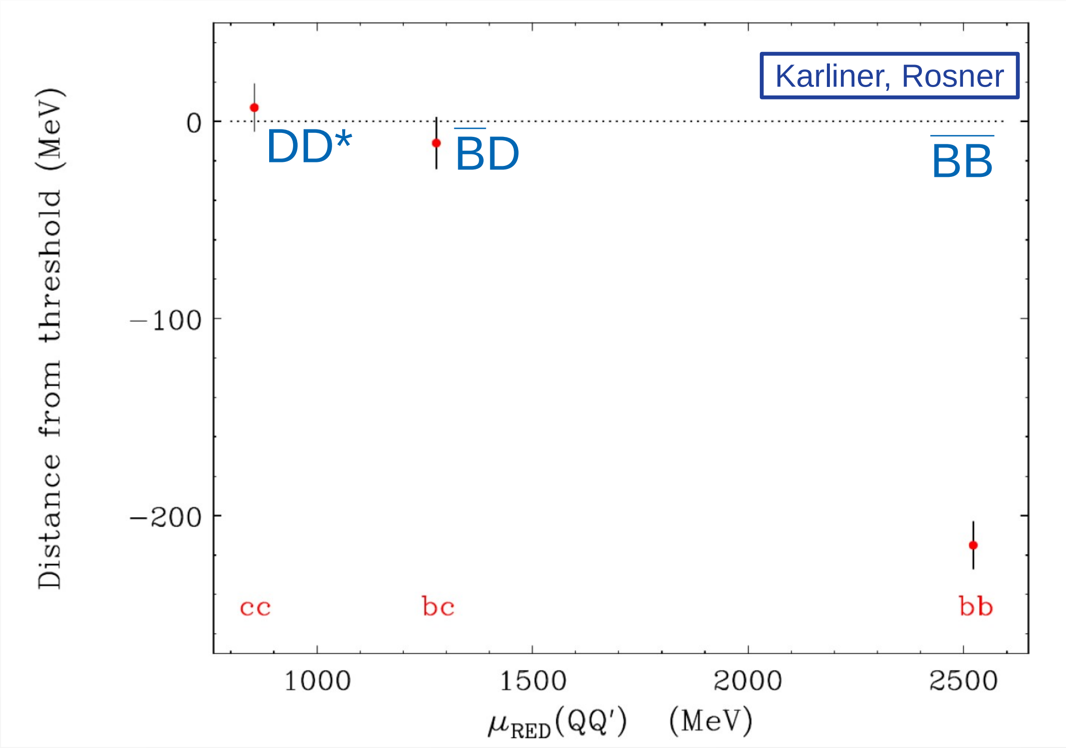
- Suppressed wrt to T_{cc} (150 events):
  - $b\bar{b}b\bar{b}$ production: 1.5%
  - BR($b \to D\pi/\mu$): $(0.1\text{-}1\%)^2$

  → expect yields of only ~10^{-2} even in 2040

Other doubly-heavy states, $[bc\bar{u}\bar{d}]$

- T_{bc} ***[bc][$\overline{ud}$]*** may be below $\bar{B}D$ threshold by O(10) MeV

  Karliner, Rosner, 2017 | Semay, SIlvestre-Brac, 1994 | Carames, Vijande, Valcarce, 2019 | Meng et al., 2021



- Opposite expectations in some molecula models

  Li, Sun, Liu, Zhu, 2012 | Liu et al., 2019 | Hudspith et al., 2020

  … and many more

  Much more interesting!

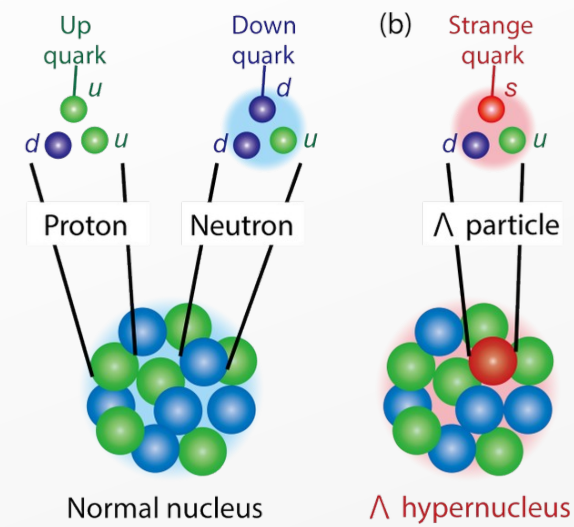
- Prospects for searches at pp (LHC/LHCb) :

  1-10 events per mode in Run3.

  real chances to find (if combining several modes)

Six-quark state with b/c quarks

- Hyper-nuclei with Λ(Σ/ΛΛ) are explored since 50's
- Long story of searches for stable ΛΛ di-baryon (H-[uuddss])… still not found, but not excluded *[see refs in backup]*



shall adding heavy hadrons give a breakthrough, again?

- Theory calculations on $\bar{Q}qqqq$ and Qqqqqq states since 1980's, may be loosely (2-10 MeV) bound and long-lived *[see refs in backup]*

easier to produce

harder to produce

H_{ss} [ssuudd] :	ΛΛ *2231 MeV*	$\Xi^0 n$ *2254 MeV*	may expect for LHCb:
H_{cs} [csuudd] :	$\Lambda_c\Lambda$ *3402 MeV*	$\Xi_c^+ n$ *3407 MeV*	$O(10^3\text{-}10^5)$
H_{bs} [bsuudd] :	$\Lambda_b\Lambda$ *6735 MeV*	$\Xi_b^0 n$ *6732 MeV*	O(10-1000)

Conclusion

- Exotic Hadron spectroscopy is a most promising way to advance understanding of non-perturbative QCD

- Great progress in last 20 years...

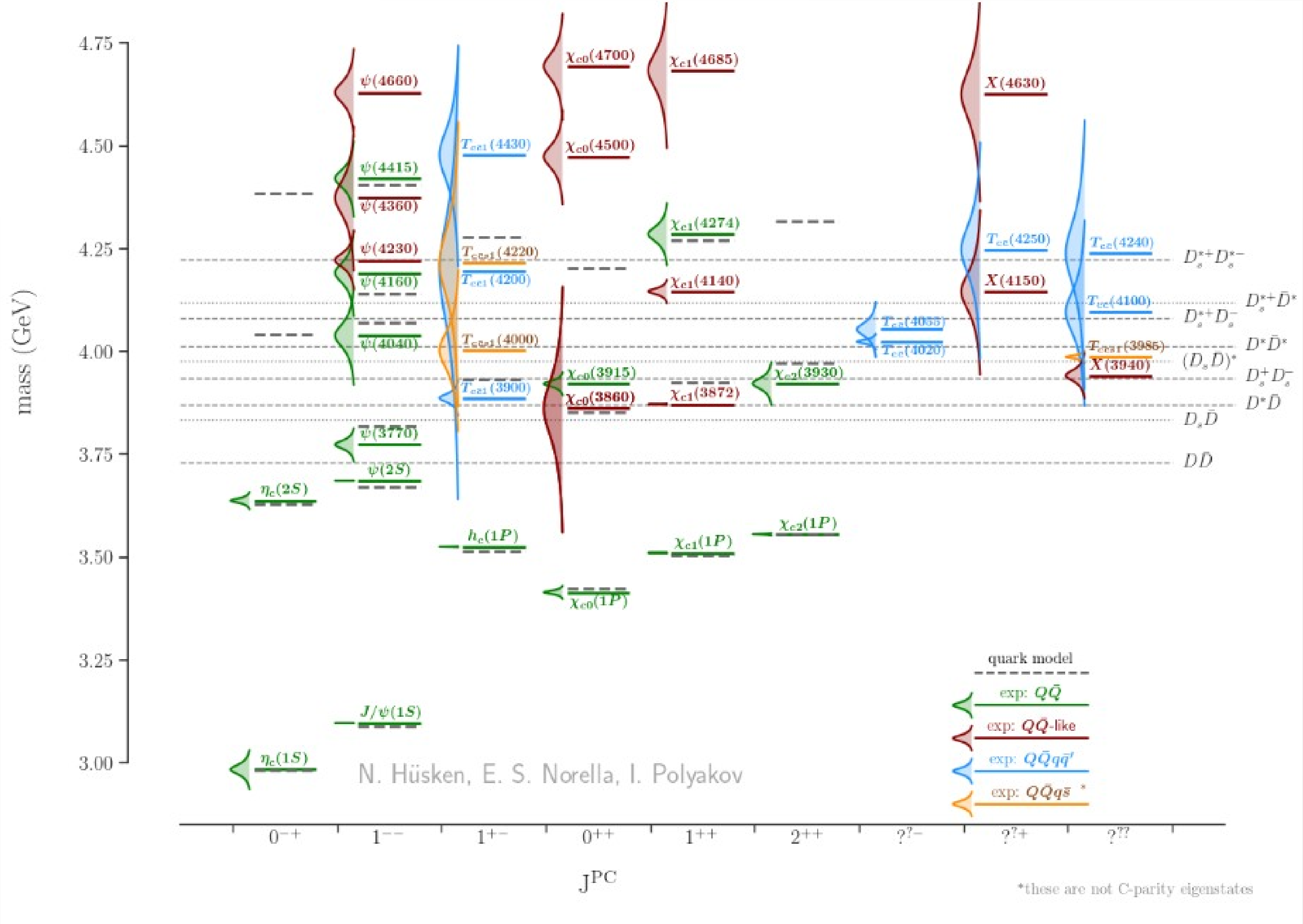
  … just discovering another one is no longer enough ...

  … now need to focus on specific and simpler systems, like T_{cc}

- LHC (especially LHCb) has great prospects for this

Backup

Exotic charmonium



The $\chi_{c1}(3872)$ as example

N. Hüsken, E. S. Norella, I. Polyakov

4.2. *The $\chi_{c1}(3872)$* *(also known as $X(3872)$)*

MESON-LIKE/HIDDEN CHARM/ISOSCALAR

quantum numbers: $I^G(J^{PC}) = 0^+(1^{++})$

minimal quark content: $[c\bar{c}]$, more likely $[c\bar{c}(u\bar{u} + d\bar{d})]$

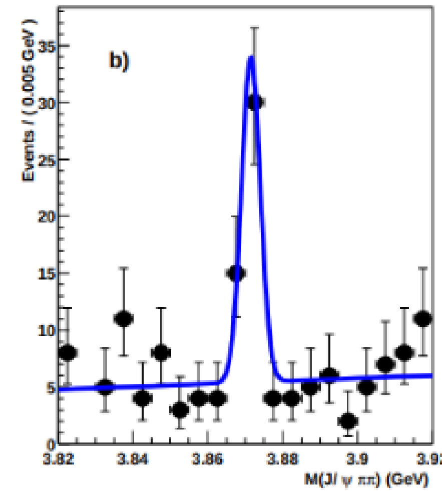
experiments: Belle, CDF, D0, BaBar, LHCb, CMS, ATLAS, BESIII (and potentially E705, COMPASS)

production: B^+, B^0, B_s^0 and Λ_b^0 decays, prompt pp, $p\bar{p}$, pPb (Pbp) and PbPb collisions, $e^+e^- \to \gamma\chi_{c1}(3872)$, $\omega\chi_{c1}(3872)$ potentially via ψ- or χ_c-like states

decay modes: $\pi^+\pi^- J/\psi$, $\omega J/\psi$, $D^{*0}\bar{D}^0$, $\pi^0\chi_{c1}(1P)$, $\gamma J/\psi$, $\gamma\psi(2S)$

nearby threshold: $D^{*0}\bar{D}^0$

width: 1.19 ± 0.21 MeV (in $\pi^+\pi^- J/\psi$ channel)

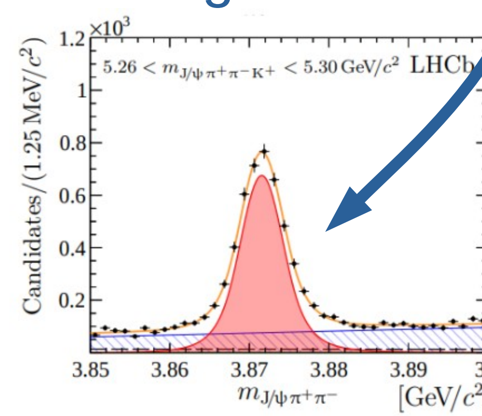


Belle, PRL 91 (2003) 262001

$36 \rightarrow 20\times10^3$ signal events

$m(\chi_{c1}(3872)) - m(D^0\bar{D}^{*0}) = -0.07 \pm 0.12$ MeV

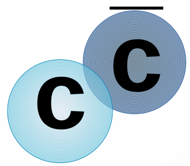
LHCb, JHEP 08 (2020) 123



LHCb, JHEP 08 (2020) 123

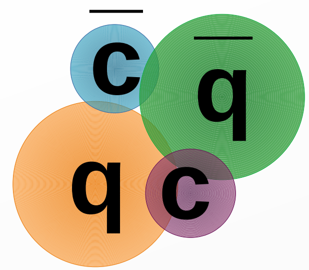
Theory models

** see references in Appendix*



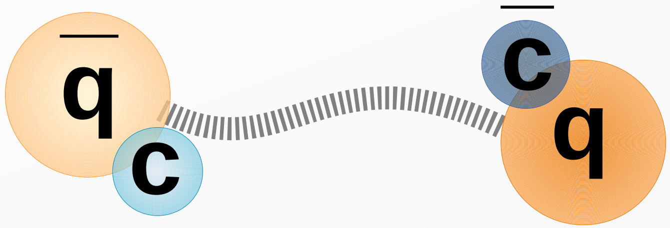
charmonium

Barnes, Godfrey, Swanson; Eichten, Lane, Quigg; Suzuki; ...



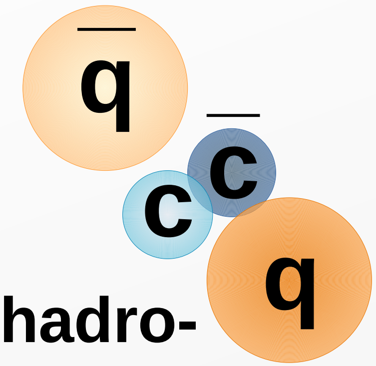
compact tetraquark

Maiani, Piccini, Polosa, Riquer; Matheus, Narison, Nielsen, Richard; ...



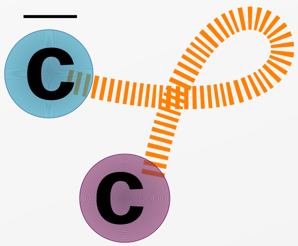
$D\bar{D}^*$ molecula

Braaten, Kusunoki; Swanson; Wong; Tornquist; ...



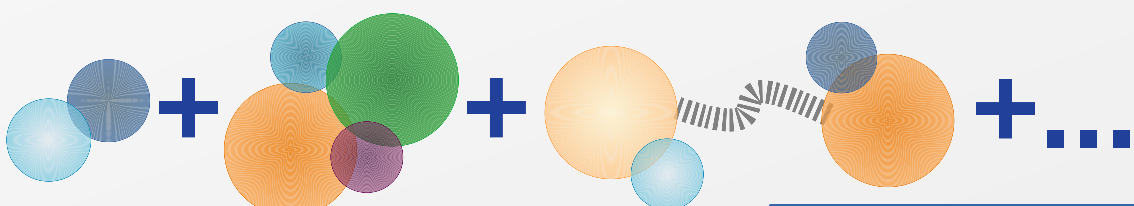
hadro-charmonium

Dubynskiy, Voloshin; ...



hybrid

Close, Godfrey; Li; ...



admixture

Suzuki; Close, Page; Dong, Faessler, Gutsche, Lyubovitskij; ...

Theory models (References)

charmonium

- Barnes, Godfrey, Swanson, Phys. Rev. D 69 (2004) 054008 & Phys. Rev. D 72 (2005) 054026;
- Eichten, Lane, Quigg, Phys. Rev. D69 (2004) 094019;
- Suzuki, Phys. Rev. D72 (2005) 606 114013;

compact tetraquark

- Maiani, Piccini, Polosa, Riquer, Phys. Rev. D71 (2005) 014028;
- Matheus, Narison, Nielsen, Richard, Phys. Rev. D75 (2007) 014005;

$D\bar{D}^*$ molecula

- Braaten, Kusunoki, Phys. Rev. D69 (2004) 074005;
- Swanson, Phys. Lett. B588 (2004) 189;
- Wong, Phys. Rev. C69 (2004) 055202;
- Tornquist, Phys. Lett. B590 (2004) 209;
- Hanhart, Kalashnikova, Kudryavtsev, Nefediev, Phys. Rev. D76 (2007) 034007

hadro-charmonium

- Dubynskiy, Voloshin, Phys. Lett. B666 (2008) 344;

hybrid

- Close, Godfrey, Phys. Lett. B574 (2003) 210;
- Li, Phys. Lett. B 605 (2005) 306;

admixture

- Suzuki, Phys. Rev. D72 (2005) 114013;
- Close, Page, Phys. Lett. B578 (2004) 119;
- Dong, Faessler, Gutsche, Lyubovitskij, J. Phys. G 38 (2011) 015001;

Wide and narrow states

- **Γ<20 MeV**
  peak in 1D fit

  - $\chi_{c1}(3872)$ and few other χ_c-like
  - $T_{c\bar{c}(s)}$ states from e^+e^-
  - $P_{c\bar{c}(s)}$
  - Υ and $T_{b\bar{b}}$ states
  - $D_{s0/1}{}^*$

- suppressed decays to
  J/ψ/Y+hadrons → moleculas?

[Marek Karliner,
CERN Courrier Nov 2024]

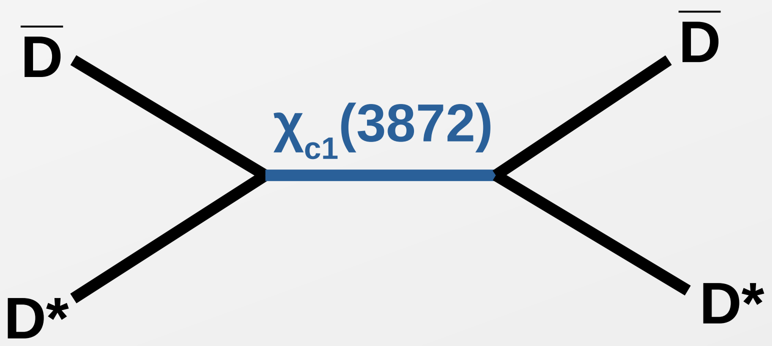
$\Sigma_c\bar{D}^*$ molecula

- **Γ = 50-500 MeV**
  often 4D-7D amplitude analysis

  - ψ-like, some χ_c-like, all $\chi_c \to J/\psi\phi$
  - $T_{c\bar{c}(s)}$ from b-decays
  - $T_{c\bar{c}c\bar{c}}$
  - $T_{cs/c\bar{s}}$

- lives less than its size/c;
  can structure at all be discussed?

  → SU(3) symmetries, EFT, ...



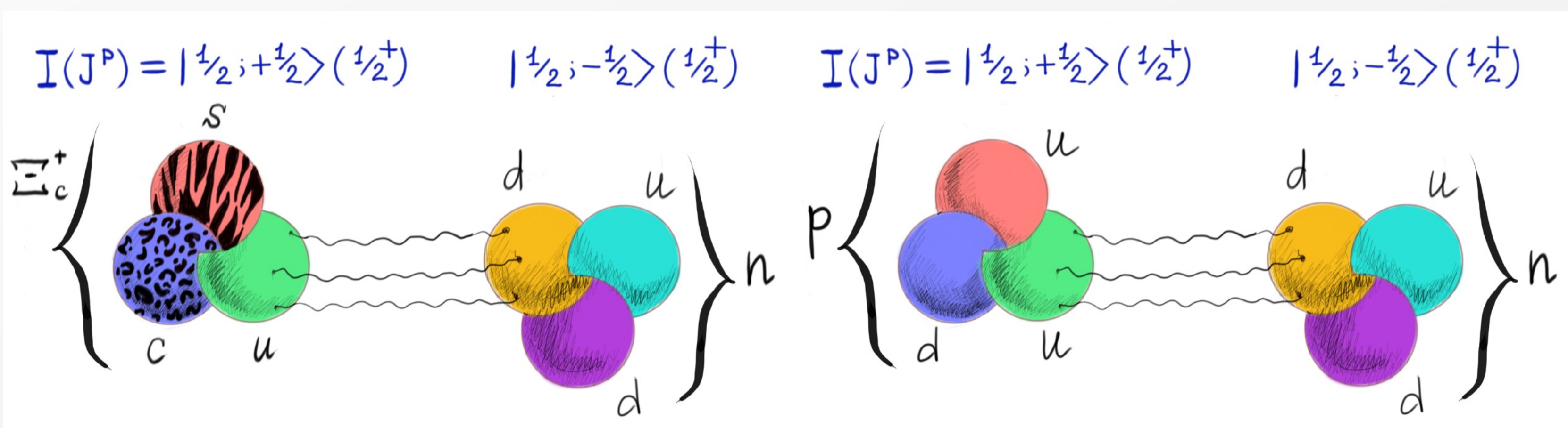
Similar moleculas with heavy quark

- $\bar{Q}qqqq$ and Qqqqqq are candidates for stable compact multiquarks since 1980s [Dover, Kahana, 1977] [Gignoux, Silvestre-Brac, Richard, 1987] [Lipkin, 1987]

- Arguments for both *instability* and *stability* can be found
  [Pepin, Stancu, 1998] [Park, Park, Lee, 2015] [Vijande et al., 2016] [Leandri, Silvestre-Brac, 1993, 1995] [Chow, 1995] [Wang et al., 1995] [Stancu, 1999] [Huang, Ping, Wang, 2014] [Park, Cho, Lee, 2018] [Meng, Wang, Zhu, 2020]

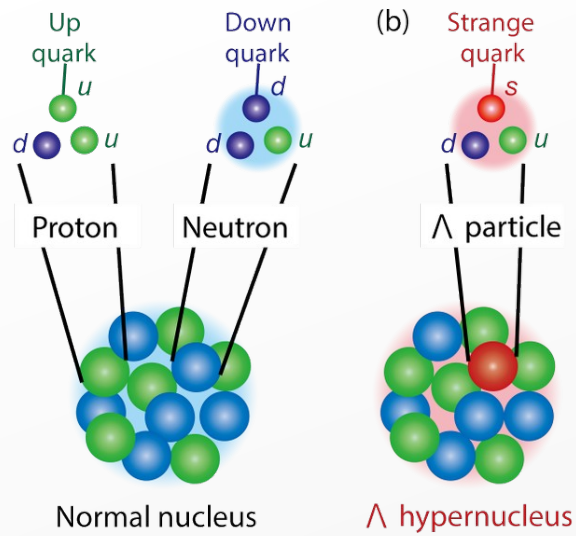
  Instability of compact-state → short-range repulsion for molecula?

- Molecula configurations may give ~2-20 MeV binding
  → long-lived states [Yamaguchi et al., 2011] [Huang, Ping, Wang, 2014]



Hypernuclei studies

- Hyper-nuclei with Λ(Σ/ΛΛ) are explored since 50's



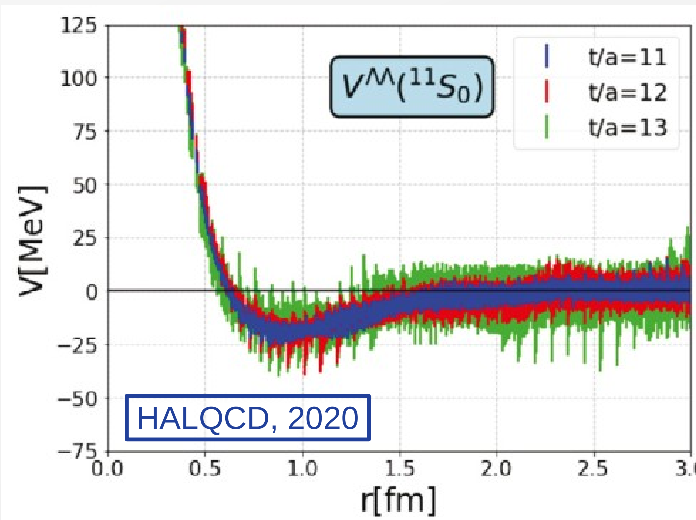
- ΛΛ in $_{\Lambda\Lambda}{}^{6}$He & $_{\Lambda\Lambda}{}^{10}$Be seem to provide extra binding (0.7-4.5 MeV)

Gal, Hungerford, Millener, 2016

Hypernucleus	Number of events	$B_\Lambda \pm \Delta B_\Lambda$ (MeV)
$^{3}_{\Lambda}$H	204	0.13 ± 0.05
$^{4}_{\Lambda}$H	155	2.04 ± 0.04
$^{4}_{\Lambda}$He	279	2.39 ± 0.03
$^{5}_{\Lambda}$He	1784	3.12 ± 0.02
$^{6}_{\Lambda}$He	31	4.18 ± 0.10
$^{7}_{\Lambda}$He	16	not averaged
$^{7}_{\Lambda}$Li	226	5.58 ± 0.03
$^{7}_{\Lambda}$Be	35	5.16 ± 0.08
$^{8}_{\Lambda}$He	6	7.16 ± 0.70
$^{8}_{\Lambda}$Li	787	6.80 ± 0.03
$^{8}_{\Lambda}$Be	68	6.84 ± 0.05
$^{9}_{\Lambda}$Li	8	8.50 ± 0.12
$^{9}_{\Lambda}$Be	222	6.71 ± 0.04
$^{9}_{\Lambda}$B	4	8.29 ± 0.18
$^{10}_{\Lambda}$Be	3	9.11 ± 0.22
$^{10}_{\Lambda}$B	10	8.89 ± 0.12
$^{11}_{\Lambda}$B	73	10.24 ± 0.05
$^{12}_{\Lambda}$B	87	11.37 ± 0.06
$^{12}_{\Lambda}$C	6	10.76 ± 0.19
$^{13}_{\Lambda}$C	6	11.69 ± 0.12
$^{14}_{\Lambda}$C	3	12.17 ± 0.33

- Stable ΛΛ di-baryon (***H-[uuddss]***) proposed in 1970s Jaffe, 1977 Hogaasen and Sorba, 1979

- Not found yet, but not excluded
  Chrien, 1998 Belle, 2013 ALICE, 2015
  STAR, 2015 BaBar, 2019



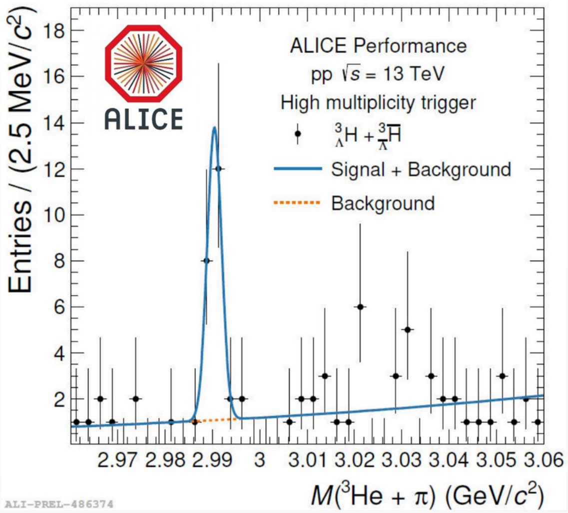
- Is attraction between ΛΛ strong enough to make bound state?

  $E_B(\Lambda\Lambda) = 3.2 \pm 2.6$ MeV ALICE, 2019

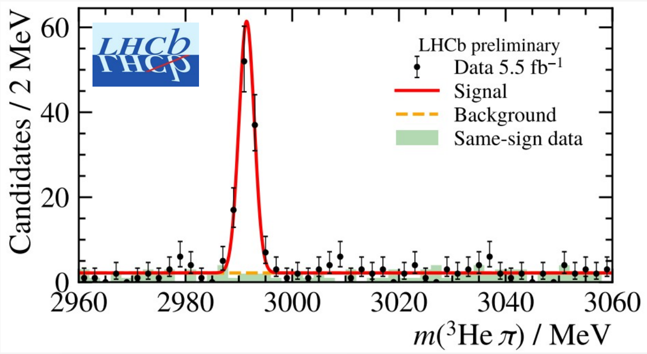
  $E_B(\Lambda\Lambda) < 0$ Kamiya et al., 2022

Experimental feasibility

- ALICE observed hypertriton [pnΛ] in both PbPb, pPb and pp collisions
  ALICE, 2021



- LHCb has observed hypertriton in pp
  LHCb-CONF-2023-002



- Higher prospects for hexaquarks (6-quark vs. 9)

- LHCb has searched for long-lived ***[$\bar{b}$udud] & [$\bar{b}$sudu]*** in J/ψpKπ & J/ψpϕ channels

  $\sigma^*BR(pp\rightarrow P_bX)/\sigma^*BR(pp\rightarrow \Lambda_b) < \sim 2 \times 10^{-3}$ LHCb, 2018

  compare to σ(d)/σ(p) ~ 1.5 x 10^{-3}

Expected Yields

- $\sigma(H_{b/c})/\sigma(\Lambda_{b/c})$ suppression is either
  - $\sigma(d)/\sigma(p) \sim 1.5x10^{-3}$
  - or $[\sigma(\Lambda_c)/\sigma(D)]^3 = [0.1\text{-}0.3]^3 = (0.1 – 2.7)\%$ LHCb, 2013
    $[\sigma(\Lambda_b)/\sigma(B)]^3 = [0.4]^3 = 6\%$ LHCb, 2012

- Additional 0.01-0.1 suppression from BRs x efficiency

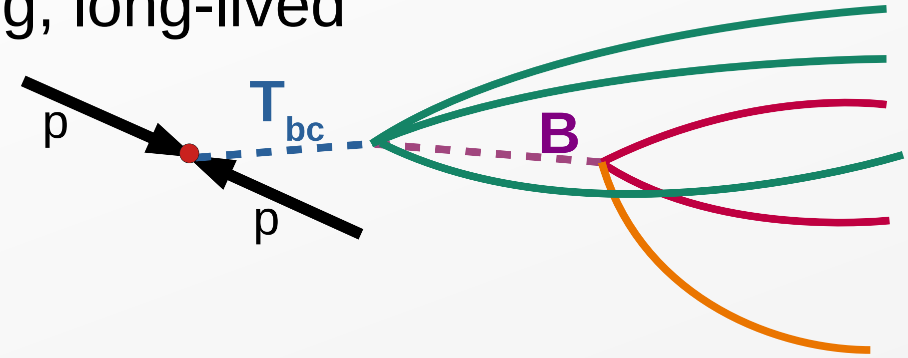
→ in Run3 expect $O(10^3\text{-}10^5)$ signal candidates for $H_{c(s)}$,
$O(10^1\text{-}10^3)$ for $H_{b(s)}$
$O(1\text{-}10)$ for H_{cc}

- High chances for observation / effective exclusion

The two cases of T_{bc}

- Having mass below/above $\bar{B}D$ threshold means very different signatures

  - $\delta m<0$: only weakly decaying, long-lived



  - $\delta m>0$: strongly decaying to $\bar{B}^0D^0$ & B^-D^+, short-lived