Production and decay of Zb states

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Based on Phys. Rev. D 99, 034022,
Phys. Rev. D 102, 114037.

Collaborate with D.Y. Chen, F.K. Guo, and Takayuki Matsuki.

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Content

- Background of New hadron states

- Hadron loop effects on the production and decay process

  - $\Upsilon(5S,6S) \to Z_b^{(\prime)}\pi$
  - $Z_b^{(\prime)} \to \Upsilon(1D)\pi$
  - The role of $Z_b^{(\prime)}$ in $\Upsilon(5S) \to \Upsilon(1D)\pi^+\pi^-$

- Summary

The concept of the multiquarks was proposed at the birth of Quark Model, even before the advent of QCD

Phys.Lett. 8 (1964) 214-215

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

...

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) gives just the representations **1**, **8**, and **10** that have been observed, while

8419/TH.412
21 February 1964

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

II *)

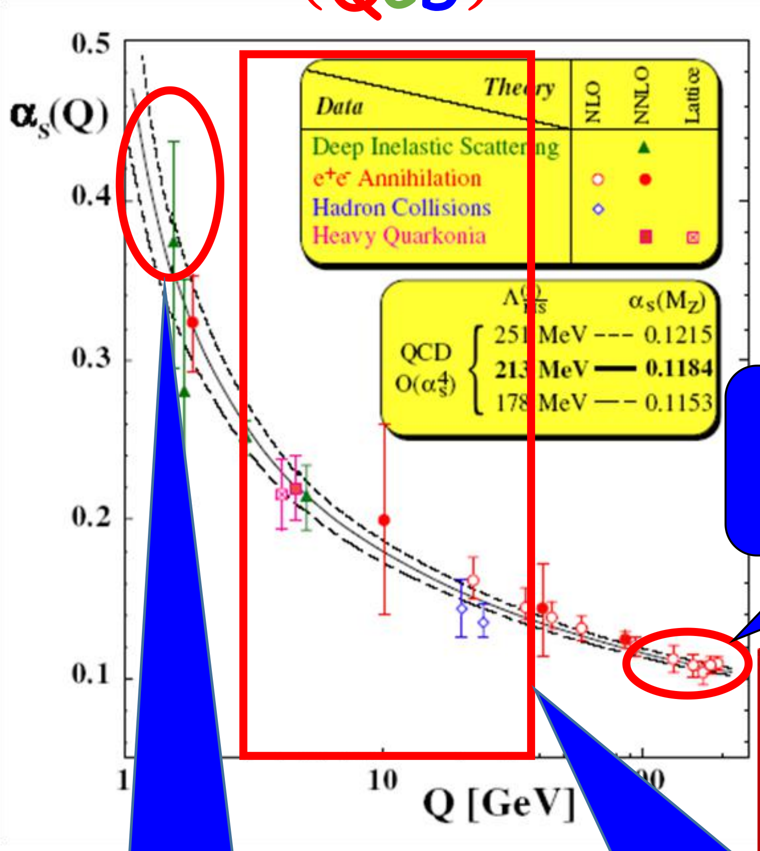
G. Zweig
CERN---Geneva

*) Version I is CERN preprint 8182/TH.401, Jan. 17, 1964.

...

6) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $AAAA\bar{A}$, $AAAAA\bar{A}\bar{A}$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $A\bar{A}$, $AA\bar{A}\bar{A}$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $A\bar{A}$ and AAA, that is, "deuces and treys".

Quantum ChromoDynamics (QCD)



Quark confinement

The interference between perturbation and non-perturbation becomes important in mid-energy area

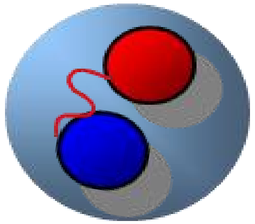
Asymptotic freedom

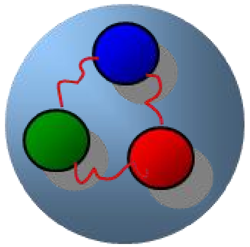
$$\alpha_s(Q^2) = \frac{4\pi}{\left(11 - \frac{2}{3}N_f\right) ln\left(\frac{Q^2}{\Lambda_{QCD}^2}\right)}$$

David J. Gross | H. David Politzer | Frank Wilczek

Normal hadron:

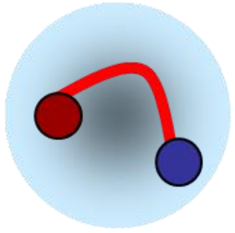
Meson





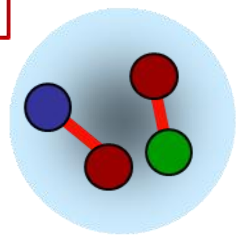
Baryon

QCD allows much richer hadron spectrum

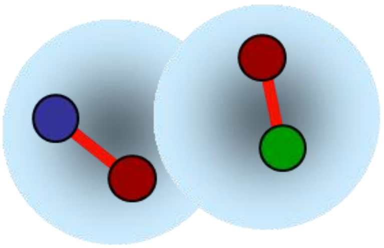


Hybrid

Glueballs

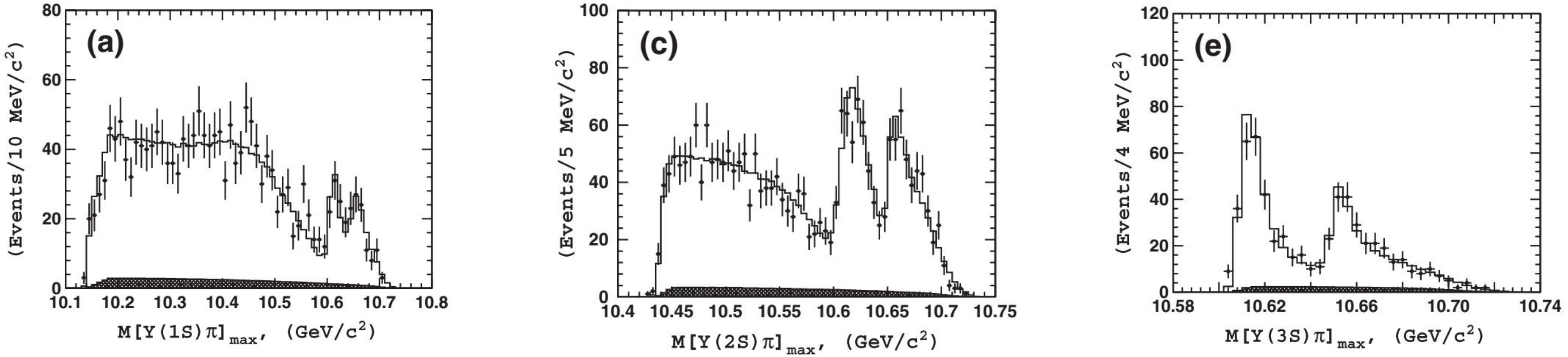


Tetraquarks

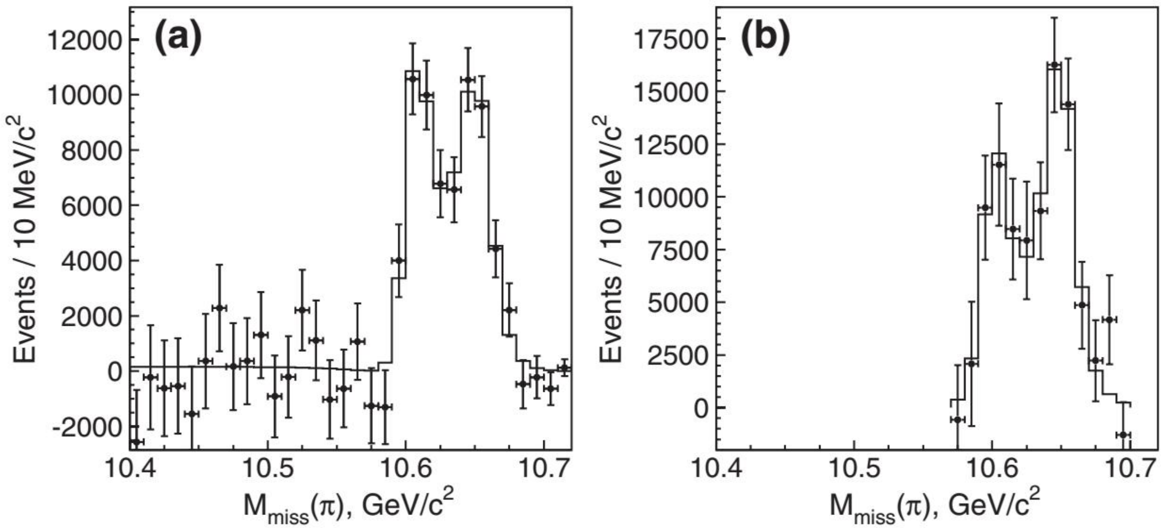


hadronic molecule

$Z_b(10610)$ and $Z_b(10650)$: Experimental information



$\Upsilon(5S) \rightarrow \Upsilon(nS)\,\pi^+\,\pi^-(n = 1, 2, 3)$

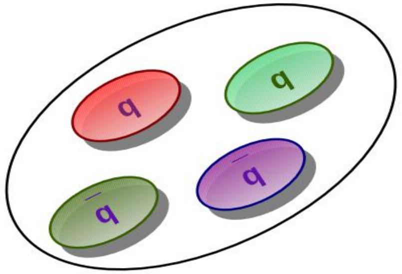


$\Upsilon(5S) \rightarrow\ h_b(mP)\pi^+\,\pi^-(m = 1, 2)$

PhysRevLett 108, 122001(2012)@Belle

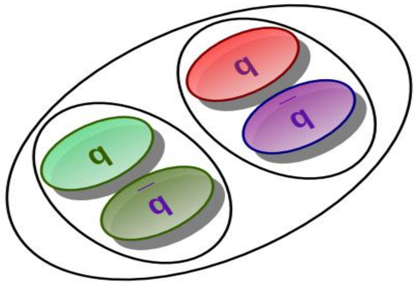
Structure of Z_b and Z'_b

Tetraquark



arXiv:1106.2284 (**chromomagnetic interaction**)
PRD **85**, 074014 (2012) (**QCD sum rules**)
PRD **85,054011** (2012) (**effective diquark-antidiquark Hamiltonian**)
Nucl. Phys. A **930**, 63 (2014) (**QCD sum rules**)
EPJC **76**, 356 (2016) (**diquark–antidiquark framework**)

Hadronic Molecule



Effective Lagrangian
J.Phys.G **40**, 015002 (2013)
PRD **89**, 074029 (2014)
PRD **87**, 034020 (2013)
PRD **96**, 014035 (2017)

QCD sum rules
EPJC **74**, 2891 (2014)
EPJC **74**, 2963 (2014)

Chiral quark model
J.Phys.G **40**, 015003 (2013)
J.Phys.G **39**, 105001 (2012)

Non-resonance explanation

ISPE mechanism

PRD **84**, 094003 (2011)
Chin. Phys. C**38**, 053102(2014)

Cusp effects

Europhys. Lett. **96**, 11002(2011)

Process $\Upsilon(5S, 6S) \rightarrow Z_b^{(\prime)}\pi$

Wu, Chen, Guo, Phys. Rev. D 99, 034022 (2019)

Branching ratio of $\Upsilon(5S) \to Z_b^{(\prime)}\pi$ from Exp.

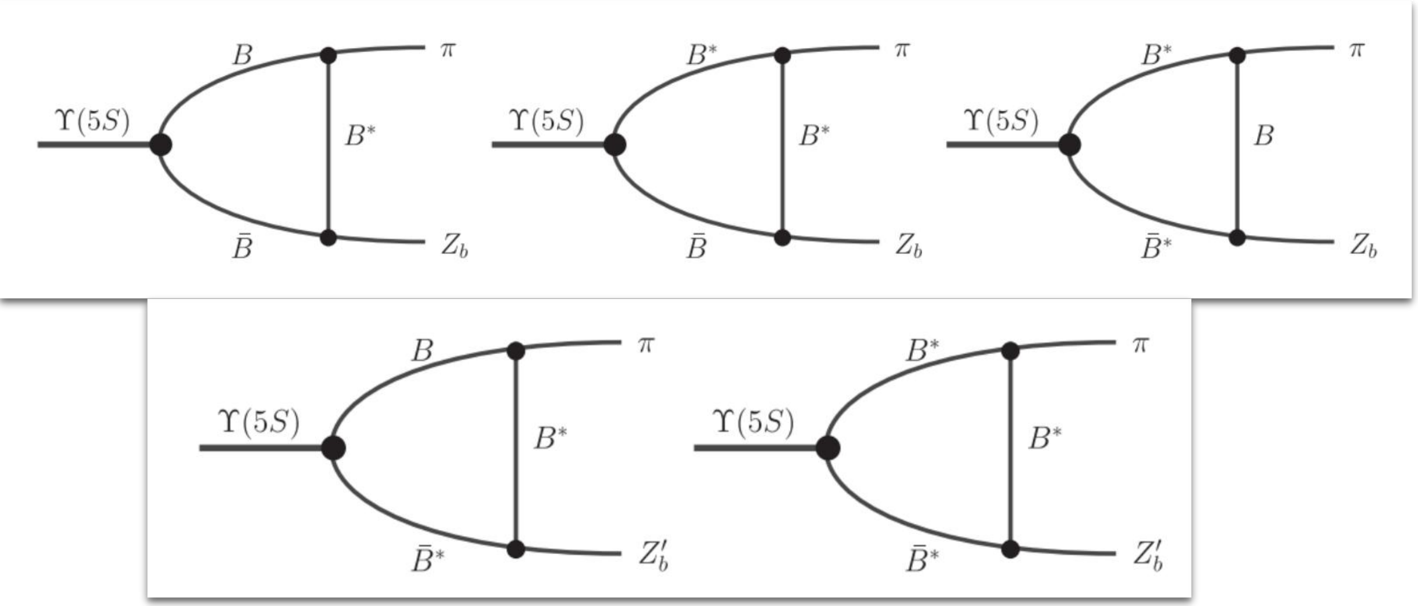
TABLE I: The experimental measurements of the related branching ratios, where $\mathcal{B}_{\Upsilon(5S)} = \mathcal{B}(\Upsilon(5S) \to (b\bar{b})\pi^+\pi^-)$, $\mathcal{B}_{Z_b^{(\prime)}} = \mathcal{B}(Z_b^{(\prime)} \to (b\bar{b})\pi)$ and $f_{Z_b^{(\prime)}}$ is the fractions of individual quasi-two-body channels contributions to $\Upsilon(5S) \to Z_b^{(\prime)\pm}\pi^\mp \to (b\bar{b})\pi^+\pi^-$, where $(b\bar{b})$ could be $\Upsilon(nS)$, $(n = 1,2,3)$ and $h_b(mP)$, $(m = 1,2)$. The branching ratios $\Upsilon(5S) \to Z_b^+\pi^-$ and $\Upsilon(5S) \to Z_b^{\prime+}\pi^-$ are estimated by the measured data.

	$\mathcal{B}_{\Upsilon(5S)}$ (10^{-3})	f_{Z_b} (%)	$f_{Z_b^\prime}$ (%)	$\mathcal{B}_{Z_b}$ (%)	$\mathcal{B}_{Z_b^\prime}$ (%)	$\mathcal{B}(\Upsilon(5S) \to Z_b^+\pi^-)$ (%)	$\mathcal{B}(\Upsilon(5S) \to Z_b^{\prime+}\pi^-)$ (%)
$\Upsilon(1S)$	5.3 ± 0.6	$2.54^{+0.86+0.13}_{-0.51-0.55}$	$1.04^{+0.65+0.07}_{-0.31-0.12}$	$0.54^{+0.16+0.11}_{-0.13-0.08}$	$0.17^{+0.07+0.03}_{-0.06-0.02}$	$1.25^{+0.63}_{-0.52}$	$1.62^{+1.26}_{-0.82}$
$\Upsilon(2S)$	7.8 ± 1.3	$19.6^{+3.5+1.9}_{-3.1-0.6}$	$5.77^{+1.44+0.27}_{-0.96-1.56}$	$3.62^{+0.76+0.79}_{-0.59-0.53}$	$1.39^{+0.48+0.34}_{-0.38-0.23}$	$2.11^{+0.84}_{-0.67}$	$1.62^{+0.84}_{-0.67}$
$\Upsilon(3S)$	$4.8^{+1.0}_{-1.7}$	$26.8^{+6.6}_{-3.9} \pm 1.5$	$11.0^{+4.2}_{-2.3} \pm 0.7$	$2.15^{+0.55+0.60}_{-0.42-0.43}$	$1.63^{+0.53+0.39}_{-0.42-0.28}$	$2.99^{+1.80}_{-1.42}$	$1.62^{+1.13}_{-0.84}$
$h_b(1P)$	$3.5^{+1.0}_{-1.3}$	$42.3^{+9.5+6.7}_{-12.7-0.8}$	$60.2^{+10.3+4.1}_{-12.7-3.8}$	$3.45^{+0.87+0.86}_{-0.71-0.63}$	$8.41^{+2.43+1.49}_{-2.12-1.06}$	$2.15^{+1.14}_{-1.18}$	$1.25^{+0.60}_{-0.73}$
$h_b(2P)$	$5.7^{+1.7}_{-2.1}$	$35.2^{+15.6+0.1}_{-0.4-13.4}$	$64.8^{+15.2+6.7}_{-11.4-15.5}$	$4.67^{+1.24+1.18}_{-1.00-0.89}$	$14.7^{+3.2+2.8}_{-2.8-2.3}$	$2.15^{+1.39}_{-1.41}$	$1.26^{+0.61}_{-0.60}$

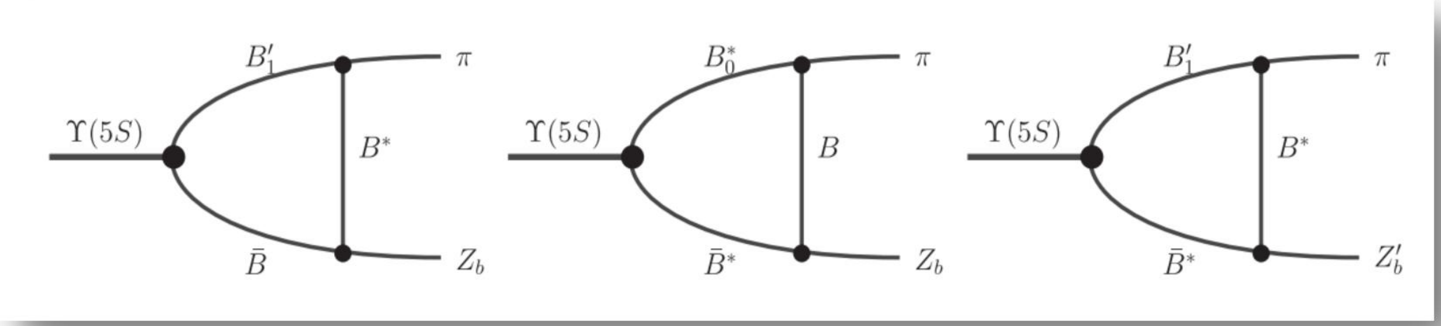
- The branching ratios from different channels are consistent with each other
- The branching ratios are of order of 10^{-2}

$$B_r(\Upsilon(5S) \to Z_b^{(\prime)}\pi) = \frac{f_{Z_b^{(\prime)}} B_{r\Upsilon(5S)}}{B_{rZ_b^{(\prime)}}}$$

Two types of Meson loop contribution



$$\Upsilon(5S) \rightarrow B^{(*)}\bar{B}^{(*)} \rightarrow Z_b^{(\prime)}\,\pi$$



$$\Upsilon(5S) \rightarrow B_1'\bar{B}^{(*)}/B_0^*\bar{B}^* \rightarrow Z_b^{(\prime)}\,\pi$$

- meson loop contributions are evaluated in hadron level
- interactions are described by effective Lagrangians
- effective Lagrangians are constructed based on heavy quark symmetry & chiral symmetry

$$\mathcal{L} = i\frac{g_1}{2}\mathrm{Tr}[\Upsilon^\dagger H_a \vec{\sigma}\cdot \overleftrightarrow{\partial} \bar{H}_a] + \mathrm{H.c.}$$

$$\mathcal{L} = g_2 \mathrm{Tr}[\Upsilon^\dagger S_a \bar{H}_a + \Upsilon^\dagger H_a \bar{S}_a] + \mathrm{H.c}$$

$$\mathcal{L} = z' \varepsilon^{ijk} \bar{V}^{\dagger i} Z'^j V^{\dagger k} + z[\bar{V}^{\dagger i} Z^i P^\dagger - \bar{P}^\dagger Z^i V^{\dagger i}] + \mathrm{H.c.}$$

$$\mathcal{L} = -\frac{g}{2}\mathrm{Tr}[H_a^\dagger H_b \vec{\sigma}\cdot \vec{u}_{ba}]$$

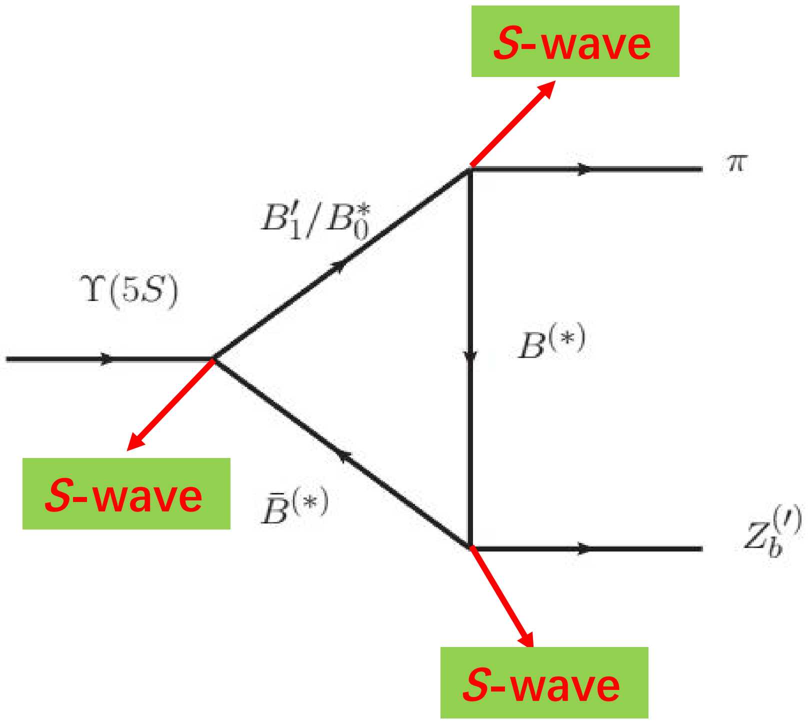
$$\mathcal{L} = i\frac{h}{2}\mathrm{Tr}[H_a^\dagger S_b u_{ba}^0] + \mathrm{H.c.}$$

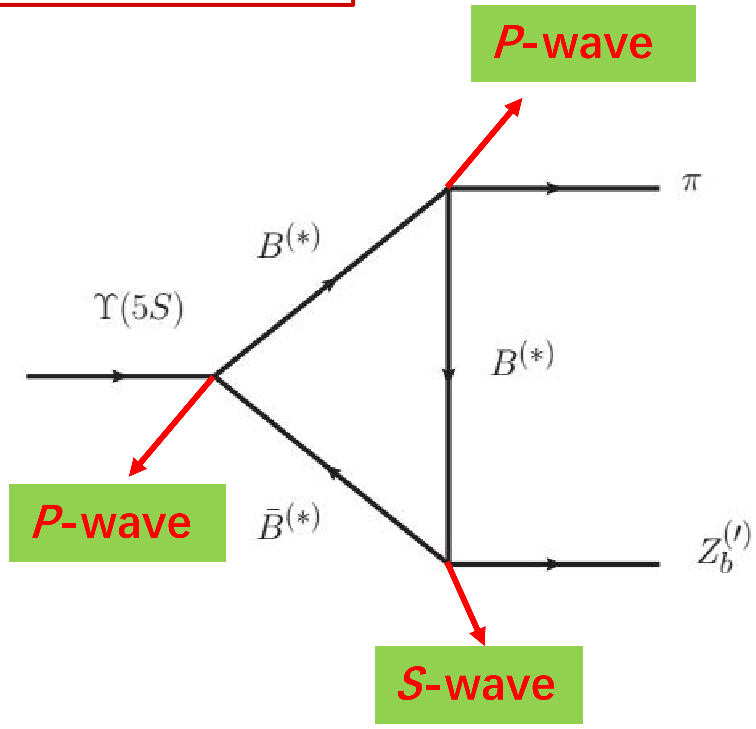
Power counting rule

$v_A = 0.12 \sim 0.14$

$v_B = 0.05 \sim 0.07$

→ Nonrelativistic





$$\mathcal{A}_B \sim N_B \frac{v_B^5 E_\pi}{(v_B^2)^3 m_B} = N_B \frac{E_\pi}{v_B m_B},$$

The ratio of two types meson loop?

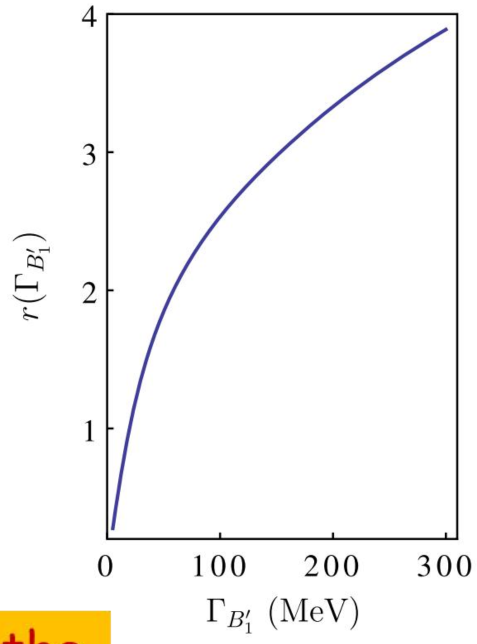
$$\mathcal{A}_A \sim N_A \frac{v_A^5 \vec{q}^{\,2}}{(v_A^2)^3 m_B^2} = N_A \frac{\vec{q}^{\,2}}{v_A m_B^2},$$

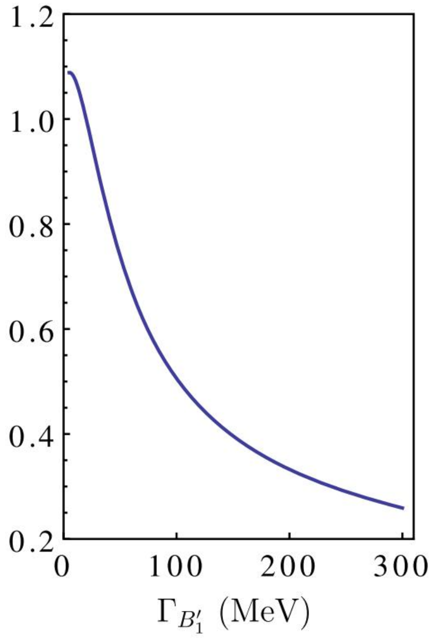
$$\frac{\mathcal{A}_B}{\mathcal{A}_A} \sim \frac{m_B E_\pi v_A}{\vec{q}^{\,2} v_B} = \mathcal{O}(30),$$

	$\mathcal{B}(\Upsilon(5S)\to Z_b^+\pi^-)$	$\mathcal{B}(\Upsilon(5S)\to Z_b'^+\pi^-)$	$\mathcal{B}(\Upsilon(6S)\to Z_b^+\pi^-)$	$\mathcal{B}(\Upsilon(6S)\to Z_b'^+\pi^-)$
$B^{(*)}\bar{B}^{(*)}$ Loops	6.1×10^{-4}	2.8×10^{-4}	4.1×10^{-4}	1.9×10^{-4}
$B_1'\bar{B}^{(*)}$ Loops	$9.5g_2^2$	$3.2g_2^2$	$17.3g_2'^2$	$8.3g_2'^2$

g_2 and g_2' cannot be determined using the available data at present

- The contributions from $B^{(*)}\bar{B}^{(*)}$ loops are two orders of magnitude smaller than the experimental data and can be neglected.
- The $B_1'\bar{B}^{(*)}/B_0^*\bar{B}^*$ meson loops show the possibility to be the dominant production mechanism.





Width effect

$$\mathcal{M}_{B_0^*} = \frac{1}{W_{B_0^*}} \int_{s_l}^{s_h} ds \rho_{B_0^*}(s) \bar{\mathcal{M}}_{B_0^*}(s)$$

$$\rho_{B_0^*}(s) = \frac{1}{\pi} \mathrm{Im} \frac{-1}{s - M_{B_0^*}^2 + iM_{B_0^*}\Gamma_{B_0^*}}$$

- ✓ The B_1' width depends on the coupling h
- ✓ The same coupling enters the $B_0^*B\pi$ and $B_1'B^*\pi$ vertices
- ✓ The B_1' width effect depends on their competition

Proportional to h^2

$$r(\Gamma_{B_1'}) \equiv \frac{\Gamma'_{(5S)}(\Gamma_{B_1'})}{\Gamma'_{(5S)}(\Gamma_{B_1'} = 20\text{ MeV})}$$

Process $Z_b^{(\prime)} \to \Upsilon(1D)\,\pi$

Wu, Chen, Matsuki. Phys. Rev. D 102, 114037 (2020)

	Yield, 10^3	Mass, MeV/c^2	Significance
$\Upsilon(1S)$	$104.9 \pm 5.8 \pm 3.0$	$9459.4 \pm 0.5 \pm 1.0$	18.1σ
$h_b(1P)$	$50.0 \pm 7.8^{+4.5}_{-9.1}$	$9898.2^{+1.1+1.0}_{-1.0-1.1}$	6.1σ
$3S \to 1S$	55 ± 19	9973.01	2.9σ
$\Upsilon(2S)$	$143.7 \pm 8.7 \pm 6.8$	$10\,022.2 \pm 0.4 \pm 1.0$	17.1σ
$\Upsilon(1D)$	22.4 ± 7.8	$10\,166.1 \pm 2.6$	2.4σ
$h_b(2P)$	$83.9 \pm 6.8^{+23.}_{-10.}$	$10\,259.8 \pm 0.6^{+1.4}_{-1.0}$	12.3σ
$2S \to 1S$	$151.3 \pm 9.7^{+9.0}_{-20.}$	$10\,304.6 \pm 0.6 \pm 1.0$	15.7σ
$\Upsilon(3S)$	$45.5 \pm 5.2 \pm 5.1$	$10\,356.7 \pm 0.9 \pm 1.1$	8.5σ

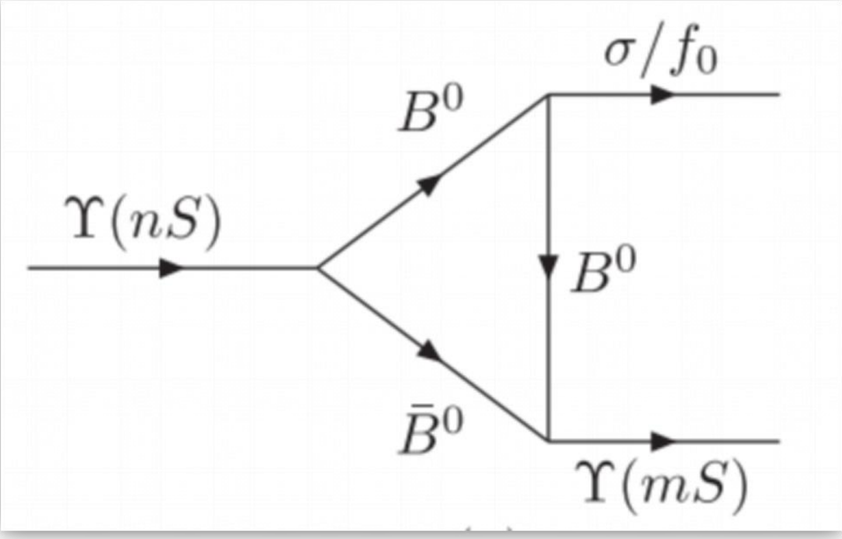
PhysRevLett 108, 032001(2012)@Belle

$$Br\,(\Upsilon(5S) \to \Upsilon(1S)\,\pi^+\,\pi^-) = (5.3 \pm 0.6) \times 10^{-3}$$

$$Br\,(\Upsilon(5S) \to \Upsilon(2S)\,\pi^+\,\pi^-) = (7.8 \pm 1.3) \times 10^{-3}$$

PhysRevD 98, 030001(2018)@PDG

$$Br(\Upsilon(5S) \to \Upsilon(1D)\pi^+\,\pi^-) \sim 1 \times 10^{-3}$$



PhysRevD 77, 074003(2008)

$\Upsilon(5S) \to \Upsilon(nS)\,\pi^+\pi^-$, $n = \{1, 2, 3\}$

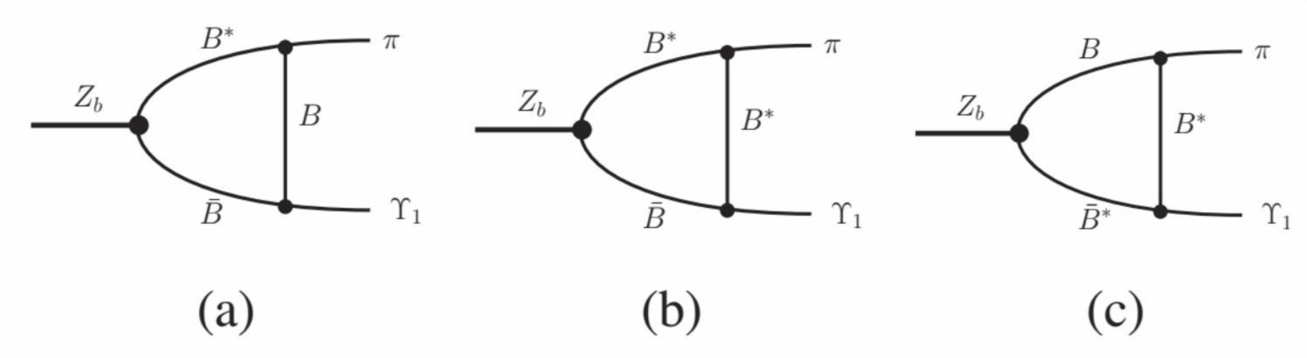
Could be well reproduced with meson loop effect

PhysRevD 84, 074006(2011)

Meson loop effect can not reproduce the dipion invariant mass spectrum and the helicity angle distributions simultaneously

Both the meson loop contributions and $Z_b^{(\prime)}$ are important in interpreting the anomalous widths

Conclusion: the most possible sources of the anomalous width of $\Upsilon(5S) \to \Upsilon(1D)\,\pi^+\,\pi^-$ are $Z_b^{(\prime)}$



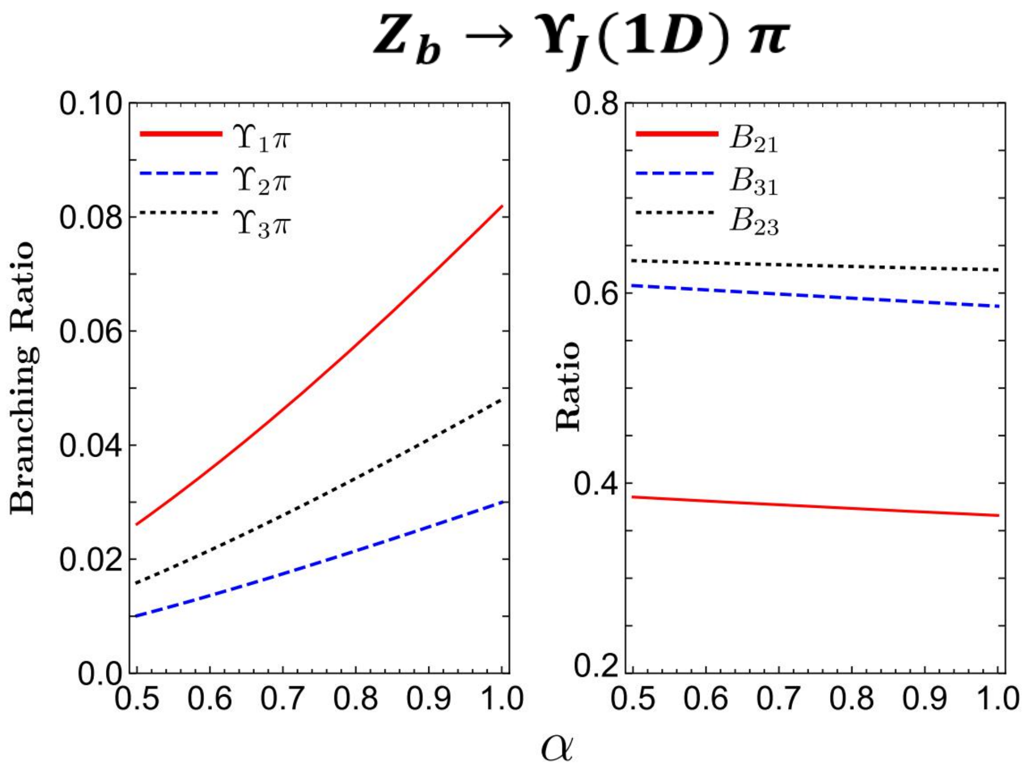
Monopole form

$$\mathcal{F}(q^2, m_q^2) = \frac{m_q^2 - \Lambda^2}{q^2 - \Lambda^2}$$

$$\Lambda = m_q + \alpha \Lambda_{QCD}$$

$$\mathcal{M}_{\text{tot}} = \mathcal{M}_a + \mathcal{M}_b + \mathcal{M}_c$$

$$\Gamma = \frac{1}{3}\frac{1}{32\pi^2}|\bar{\mathcal{M}}_{\text{tot}}|^2 \frac{|\vec{p}_1|}{m_0^2} d\Omega$$



The ratio of branching ratios are model independent

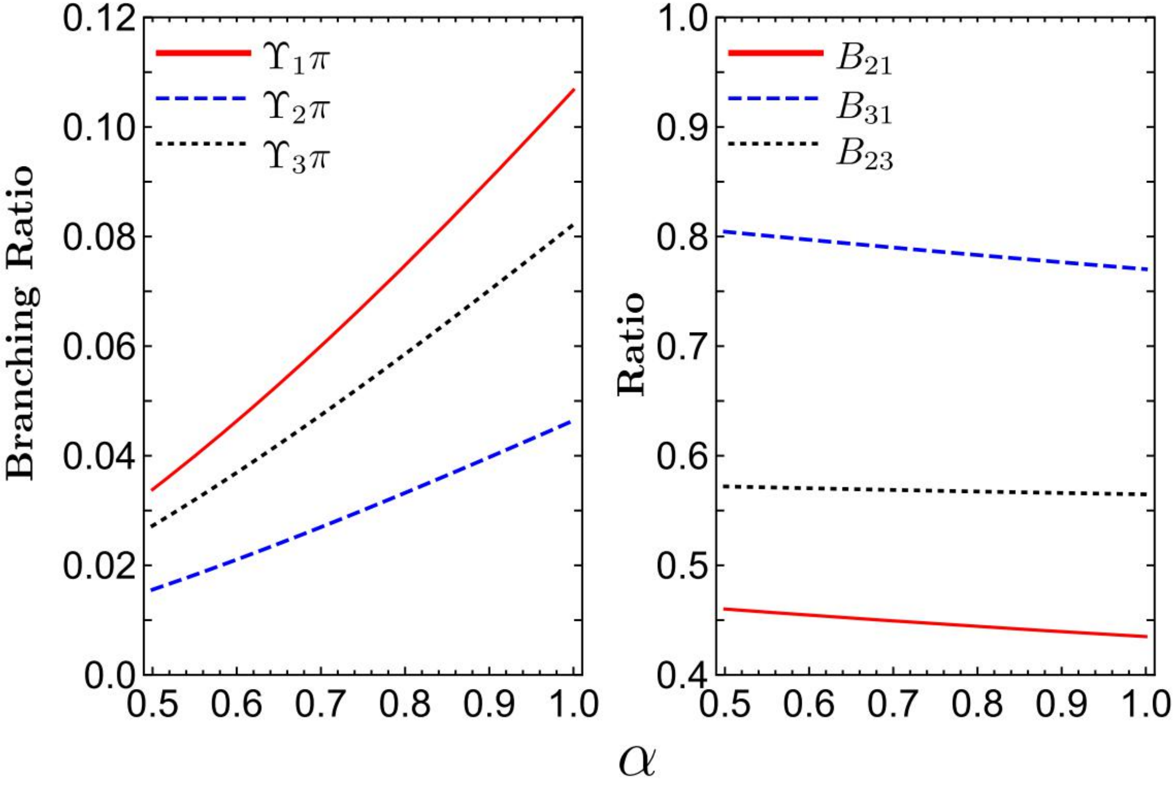
Form factors:

- **Internal structures** of the involved particles
- **Off shell effects**
- **Remove the divergence** of the loop integrals

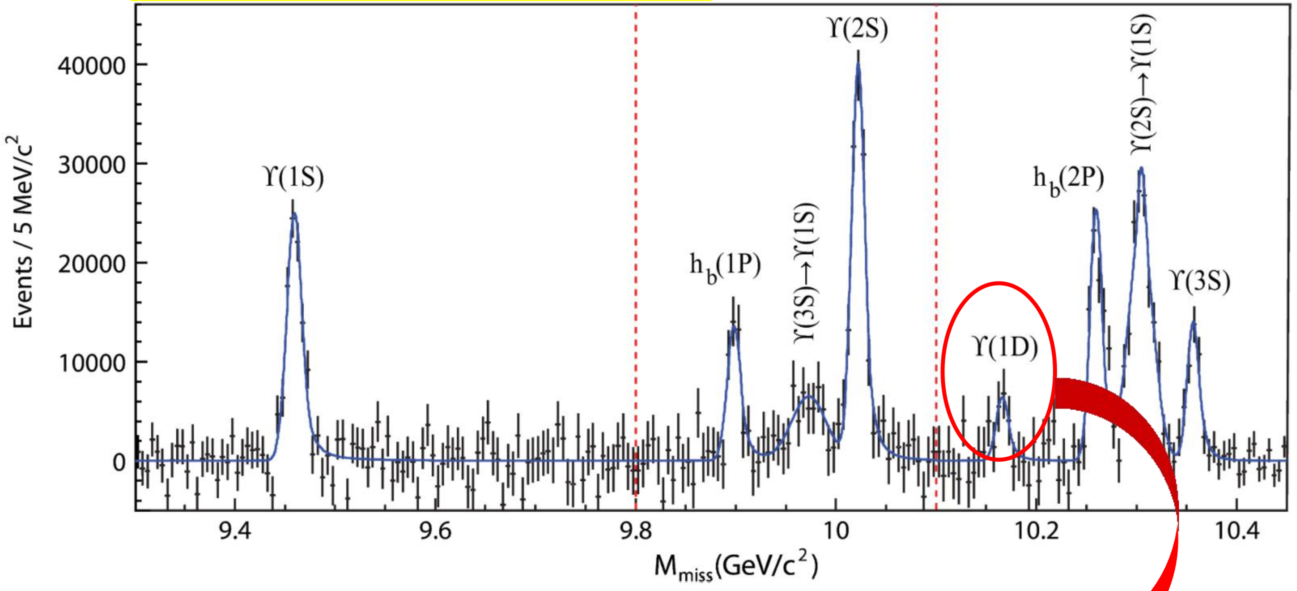
$$\mathcal{B}[Z_b \to \Upsilon_1\pi] = (2.62 - 8.19) \times 10^{-2},$$
$$\mathcal{B}[Z_b \to \Upsilon_2\pi] = (1.01 - 3) \times 10^{-2},$$
$$\mathcal{B}[Z_b \to \Upsilon_3\pi] = (1.59 - 4.8) \times 10^{-2},$$

$$B_{21} = 0.37 \sim 0.39$$
$$B_{31} = 0.59 \sim 0.61$$
$$B_{23} = 0.62 \sim 0.63$$

$Z_b' \to \Upsilon_J(1D)\,\pi$



PhysRevLett 108, 032001(2012)@Belle



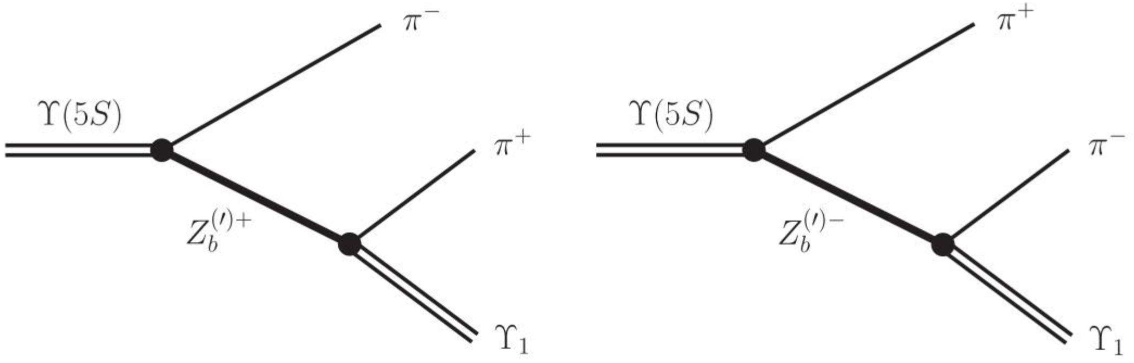
$\mathbf{\Upsilon_1(1D)}$

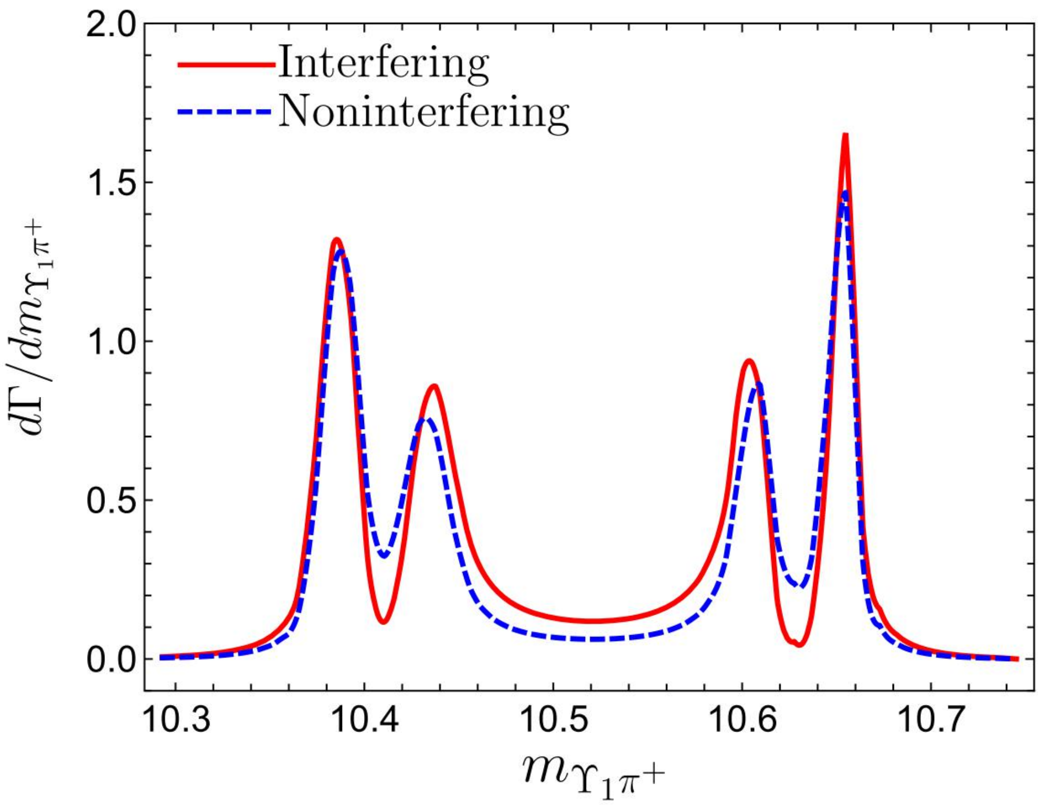
$$\mathcal{B}[Z_b' \to \Upsilon_1\pi] = (3.38 - 10.67) \times 10^{-2},$$
$$\mathcal{B}[Z_b' \to \Upsilon_2\pi] = (1.56 - 4.64) \times 10^{-2},$$
$$\mathcal{B}[Z_b' \to \Upsilon_3\pi] = (2.72 - 8.22) \times 10^{-2},$$

$$B_{21} = 0.43 \sim 0.46,$$
$$B_{31} = 0.77 \sim 0.80,$$
$$B_{23} = 0.56 \sim 0.57,$$

- The branching ratios of $Z_b^{(\prime)} \to \Upsilon(1D)\,\pi$ should be of order 10^{-2}
- The ratio of branching ratios could be an important test of the present estimation.

The role of $Z_b^{(\prime)}$ in $\Upsilon(5S) \to \Upsilon(1D)\pi^+\pi^-$





Consider the case without the interference as a good approximation

$$\mathcal{B}(\Upsilon(5S)\to\Upsilon_J(1D)\pi^+\pi^-) \simeq 2(\mathcal{B}(\Upsilon(5S)\to Z_b^+\pi^-)\times\mathcal{B}(Z_b^+\to\Upsilon_J(1D)\pi^+) + \mathcal{B}(\Upsilon(5S)\to Z_b'^+\pi^-)\times\mathcal{B}(Z_b'^+\to\Upsilon_J(1D)\pi^+))$$

$$\mathrm{Br}\left(\Upsilon(5S)\to Z_b^{(\prime)}\pi\right) = 1.0\%$$

$$\mathcal{B}[\Upsilon(5S)\to\Upsilon_1(1D)\pi^+\pi^-)] \sim (1.2-3.7)\times 10^{-3}$$

$$\mathcal{B}[\Upsilon(5S)\to\Upsilon_2(1D)\pi^+\pi^-)] \sim (0.5-1.5)\times 10^{-3}$$

$$\mathcal{B}[\Upsilon(5S)\to\Upsilon_3(1D)\pi^+\pi^-)] \sim (0.8-2.6)\times 10^{-3}$$

Consistent with the experimental measurement by the Belle collaboration in order of magnitude

Summary

- Hadron loop is an effective description for non-perturbative aspect of QCD;
- The dominant source of the anomalous decay widths of $\Upsilon(5S) \to \Upsilon(1D)\, \pi^+ \pi^-$ should be $Z_b^{(\prime)}$;
- The loops with one bottom meson being the broad B_0^* or B_1' resonance could provide the dominant contributions to the $\Upsilon(5S) \to Z_b^{(\prime)}\, \pi$;

Thanks for your attention!