Critical insights into the near-threshold structures & production of the $X(3872)$ and its partners

Feng-Kun Guo

Helmholtz-Institut für Strahlen- und Kernphysik, Universität Bonn

The 10th International Workshop on Heavy Quarkonium

10-14 Nov. 2014, CERN

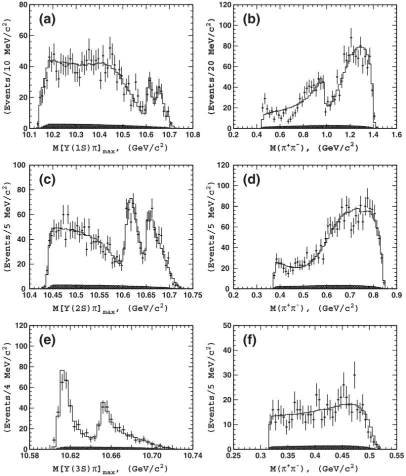
Based on:

FKG, C. Hanhart, Q. Wang, Q. Zhao, arXiv:1411.wxyz

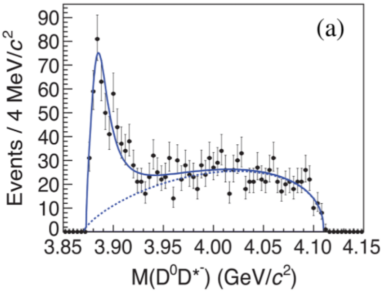
FKG, U.-G. Meißner, W. Wang, Commun.Theor.Phys. **61** (2014) 354 [arXiv:1308.0193]

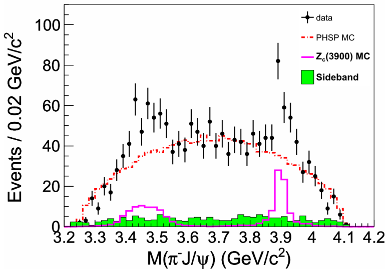
FKG, U.-G. Meißner, W. Wang, Z. Yang, Eur.Phys.J.C **74** (2014) 3063 [arXiv:1402.6236]

- Z_b states Belle (2011)



- Z_c states BESIII, Belle, Xiao et al (2013)





- ......

Two types of interpretations

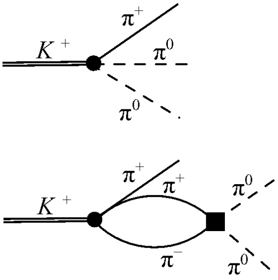
- Poles in the S-matrix: tetraquarks, hadronic molecules, …
- Cusp effects due to kinematical effect
- Can we distinguish them?
- There is always a cusp at the S-wave threshold, what does the strength of the cusp tell us?
  - ☞ well-known example of the cusp in $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$
  - ☞ the strength of the cusp is determined by the interaction strength!

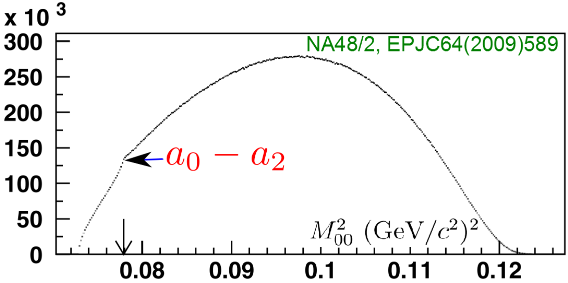
Meißner, Müller, Steininger (1997); Cabibbo (2004); Colangelo, Gasser, Kubis, Rusetsky (2006); …

Two types of interpretations

- Poles in the S-matrix: tetraquarks, hadronic molecules, ...
- Cusp effects due to kinematical effect
- Can we distinguish them?
- There is always a cusp at the S-wave threshold, what does the strength of the cusp tell us?
  - ☞ well-known example of the cusp in $K^\pm \to \pi^\pm\pi^0\pi^0$
  - ☞ the strength of the cusp is determined by the interaction strength!

Meißner, Müller, Steininger (1997); Cabibbo (2004); Colangelo, Gasser, Kubis, Rusetsky (2006); ...



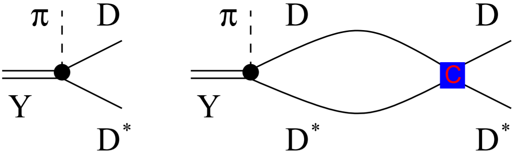


$Z_c(3900)$ as an example (I)

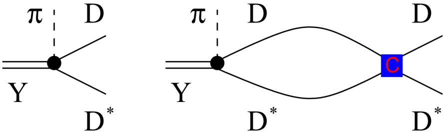
- Logic:
  first, fit to data with the one-loop expression which contains a cusp;
  then, try to understand the implications of the resulting values of the parameters
- Example: $Y(4260) \to D\bar{D}^*\pi$:

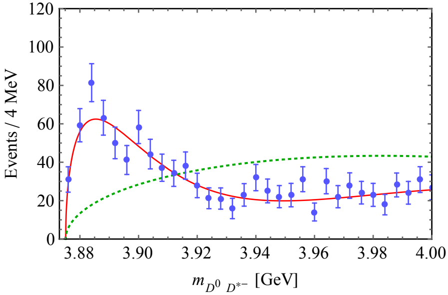
$$\mathcal{A}_{\text{1-loop}} = g_Y \left[1 - C\,G(\Lambda)\right]$$

regularize the loop with a Gaussian form factor with a cutoff Λ
three parameters: g_Y, C, Λ



$Z_c(3900)$ as an example (II)



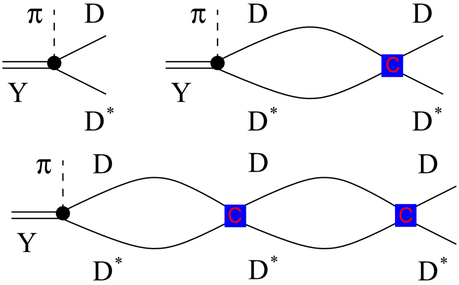


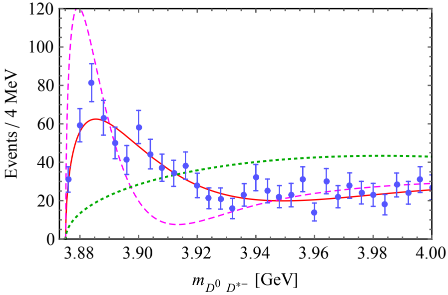
- If we use $g_Y\,[1 - C\,G(\Lambda)]$ as the full amplitude, this means we have implicitly assumed that the $D\bar{D}^*$ interaction is perturbative
- The two-loop contribution is large $\Rightarrow$ nonperturbative

  Resumming all the bubbles by $\dfrac{g_Y}{1 + C\,G(\Lambda)}$

  with the parameters determined from the 1-loop fit gives a bound state pole very close to the threshold

$Z_c(3900)$ as an example (II)

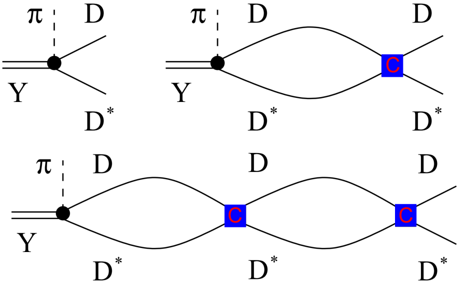


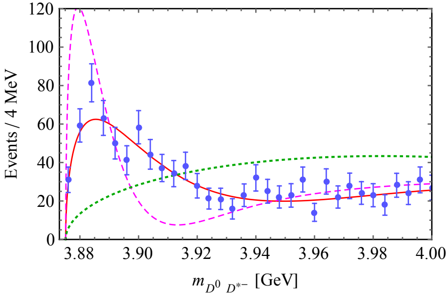


- If we use $g_Y\,[1 - C\,G(\Lambda)]$ as the full amplitude, this means we have implicitly assumed that the $D\bar{D}^*$ interaction is perturbative
- The two-loop contribution is large $\Rightarrow$ nonperturbative

  Resumming all the bubbles by $$\frac{g_Y}{1 + C\,G(\Lambda)}$$

  with the parameters determined from the 1-loop fit gives a bound state pole very close to the threshold



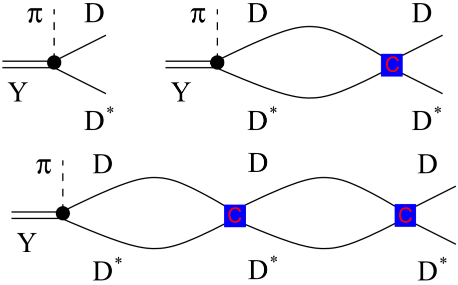


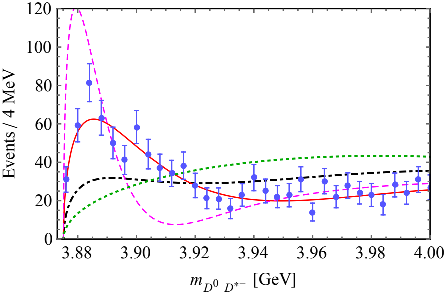
- If we use $g_Y\,[1 - C\,G(\Lambda)]$ as the full amplitude, this means we have implicitly assumed that the $D\bar{D}^*$ interaction is perturbative
- The two-loop contribution is large $\Rightarrow$ nonperturbative

  Resumming all the bubbles by $$\frac{g_Y}{1 + C\,G(\Lambda)}$$

  with the parameters determined from the 1-loop fit gives a bound state pole very close to the threshold

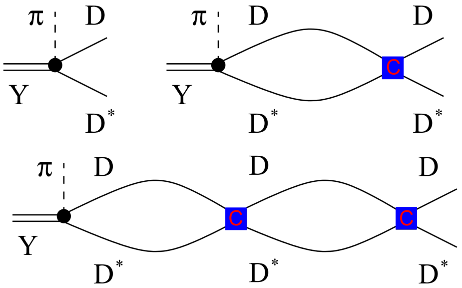
$Z_c(3900)$ as an example (II)

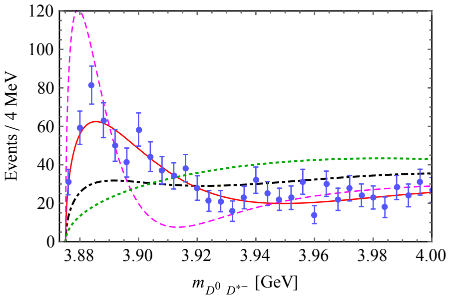




- If we use $g_Y\ [1 - C\,G(\Lambda)]$ as the full amplitude, this means we have implicitly assumed that the $D\bar{D}^*$ interaction is perturbative
- If we require the interaction to be perturbative, we need $C\,G_{\text{th}}(\Lambda) \ll 1$
  Black curve: up to 1 loop with $C\,G_{\text{th}}(\Lambda) = 1/2$, no pronounced peak any more
- Conclusion: When the cusp is a pronounced peak in the elastic channel as those observed structures, the interaction will be nonperturbative and there will be a pole (bound state, virtual state or resonance).

$Z_c(3900)$ as an example (II)





- If we use $g_Y\ [1 - C\,G(\Lambda)]$ as the full amplitude, this means we have implicitly assumed that the $D\bar{D}^*$ interaction is perturbative
- If we require the interaction to be perturbative, we need $C\,G_{\text{th}}(\Lambda) \ll 1$
  Black curve: up to 1 loop with $C\,G_{\text{th}}(\Lambda) = 1/2$, no pronounced peak any more
- Conclusion: When the cusp is a pronounced peak in the elastic channel as those observed structures, the interaction will be nonperturbative and there will be a pole (bound state, virtual state or resonance).

Partners of hadronic molecules of heavy hadrons

- Heavy quark symmetry for hadronic molecules: see the talk by J. Nieves
  ☞ in the heavy quark limit, the interaction potential between heavy hadrons is independent of the spin and flavor of heavy quarks
  ☞ heavy hadronic molecules have spin partners, and could have flavor partners
- For spin partners, the mass splitting should be approximately the same as their constituents

  Examples of candidates of hadronic molecules:

$$
\begin{aligned}
M_{D_{s1}(2460)} - M_{D_{s0}^*(2317)} &\approx M_{D^*} - M_D \\
M_{Z_b(10650)} - M_{Z_b(10610)} &\approx M_{B^*} - M_B \\
M_{Z_c(4020)} - M_{Z_c(3900)} &\approx M_{D^*} - M_D
\end{aligned}
$$

Partners of the $X(3872)$

- Spin partner X_2:
  - ☞ $X(3872)$ [1^{++}] should have a spin partner with $J^{PC} = 2^{++}$ with

$$M_{X_2} \approx M_{X(3872)} + M_{D^*} - M_D \approx 4012 \text{ MeV}$$

  - ☞ main decay channels are OZI allowed but in a D-wave: $D\bar{D}$ and $D\bar{D}^*/\bar{D}D^*$

- Flavor "analogue" X_b:
  - ☞ X_b has a much larger binding energy than that of the $X(3872)$
  - ☞ isospin $I = 0$, and isospin breaking effects should be small:

$$M_B + M_{B^*} - M_{X_b} \gg M_{B^0} - M_{B^\pm} = (0.32 \pm 0.06) \text{ MeV},$$

$$M_{X_b} - M_{\Upsilon(1S)} - M_{\omega/\rho} \gtrsim 300 \text{ MeV}$$

$\Rightarrow$ $\mathcal{B}(X_b \to \Upsilon(1S)\pi\pi) \sim 10^{-2}$, better to search for it in

$$\Upsilon\pi^+\pi^-\pi^0,\ \Upsilon(nS)\gamma \text{ and } \chi_{bJ}\pi^+\pi^-$$

  - ☞ its spin partner X_{b2}: $M_{X_{b2}} \approx M_{X_b} + 45$ MeV, $X_{b2} \to B\bar{B}$ (D-wave)

Partners of the $X(3872)$

- Spin partner X_2:
  ☞ $X(3872)$ [1^{++}] should have a spin partner with $J^{PC} = 2^{++}$ with

$$M_{X_2} \approx M_{X(3872)} + M_{D^*} - M_D \approx 4012 \text{ MeV}$$

  ☞ main decay channels are OZI allowed but in a D-wave:
  $D\bar{D}$ and $D\bar{D}^*/\bar{D}D^*$

- Flavor "analogue" X_b:
  ☞ X_b has a much larger binding energy than that of the $X(3872)$
  ☞ isospin $I = 0$, and isospin breaking effects should be small:

$$M_B + M_{B^*} - M_{X_b} \gg M_{B^0} - M_{B^\pm} = (0.32 \pm 0.06) \text{ MeV},$$

$$M_{X_b} - M_{\Upsilon(1S)} - M_{\omega/\rho} \gtrsim 300 \text{ MeV}$$

  $\Rightarrow$ $\mathcal{B}(X_b \to \Upsilon(1S)\pi\pi) \sim 10^{-2}$, better to search for it in

$$\Upsilon\pi^+\pi^-\pi^0,\ \Upsilon(nS)\gamma \text{ and } \chi_{bJ}\pi^+\pi^-$$

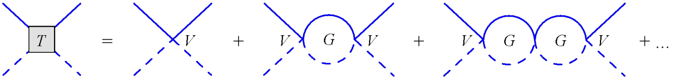
  ☞ its spin partner X_{b2}: $M_{X_{b2}} \approx M_{X_b} + 45$ MeV, $X_{b2} \to B\bar{B}$ (D-wave)

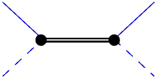
Our assumption for the production of hadronic molecules

- We assume that hadronic molecules are produced through the production of their constituent hadrons
- This means that the FSI between the heavy hadrons is essential

Artoisenet, Braaten, PRD81(2010)114018

- Hadronic molecules are poles of the T-matrix



around the pole $\sim$ 

- Production:

production of constituent hadrons

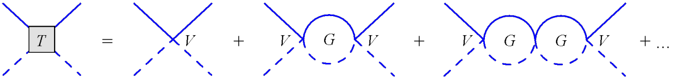
production of hadronic molecule

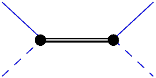
Our assumption for the production of hadronic molecules

- We assume that hadronic molecules are produced through the production of their constituent hadrons
- This means that the FSI between the heavy hadrons is essential

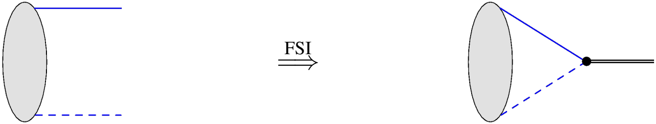
Artoisenet, Braaten, PRD81(2010)114018

- Hadronic molecules are poles of the T-matrix

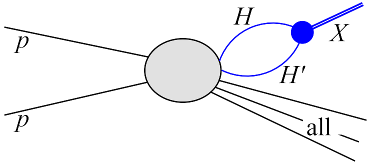


around the pole $\sim$ 

- Production:



production of constituent hadrons production of hadronic molecule

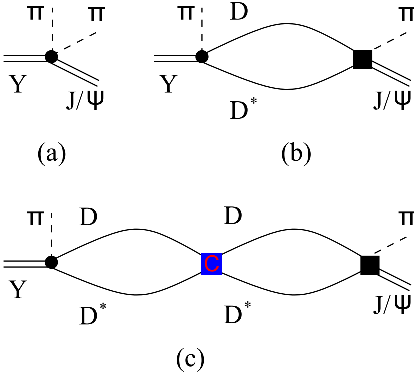


- Method: a simple extension of the method in Artoisenet, Braaten(2010) using Monte Carlo event generators (Pythia and Herwig) to generate heavy meson pairs, Bignamini et al (2009, 2010); Esposito et al (2013); Artoisenet, Braaten(2010, 2011) and incorporate the FSI using nonrelativistic EFT
- This is just an order-of-magnitude estimate
- The results for the $X(3872)$ are consistent with both CDF and CMS
- Predictions for inclusive production cross sections at LHC:
  - ☞ for X_b, X_{b2} and Z_b's: $\mathcal{O}(\text{nb})$
  - ☞ for X_{c2} and Z_c's: $\mathcal{O}(10\text{ nb}) \sim \mathcal{O}\left(10^2\text{ nb}\right)$

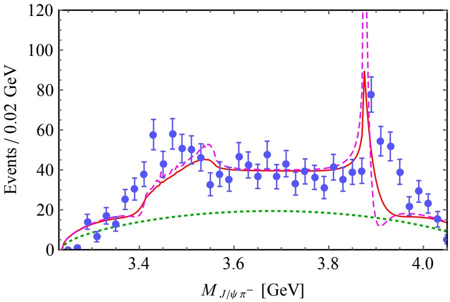
Conclusions

- A pronounced cusp in line shape of the elastic channel would suggest that the interaction is nonperturbative and there will be a pole
- The estimated production cross sections for the X and Z states indicate a large discovery potential at LHC

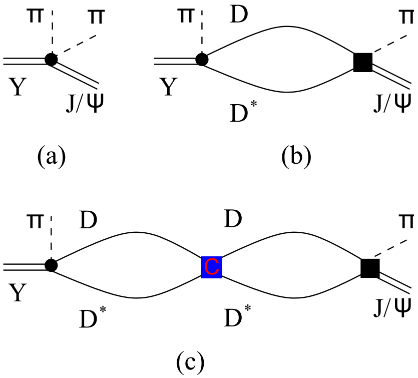
For $Y(4260) \to J/\psi\pi^+\pi^-$



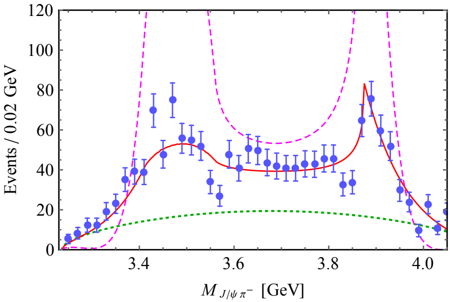
- Fit to the data with fixed Λ



For $Y(4260) \to J/\psi\pi^+\pi^-$



- Fit to the data with free Λ



Cross sections for the production of the $X(3872)$

Table 1 Integrated cross sections (in units of nb) for $pp/\bar{p} \to X(3872)$ compared with previous theoretical estimates [16,18] and experimental measurements by CDF [43] and CMS [6]. Results outside (inside) brackets are obtained using Herwig (Pythia). Kinematical cuts used are $p_T > 5$ GeV and $|y| < 1.2$ at Tevatron and $10\,\mathrm{GeV} < p_T < 50\,\mathrm{GeV}$ and $|y| < 0.6$ at LHC with $\sqrt{s} = 7$ TeV. We have converted the experimental data $\sigma(p\bar{p} \to X) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (3.1 \pm 0.7)$ nb [43] and $\sigma(pp \to X) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (1.06 \pm 0.11 \pm 0.15)$nb [6] into cross sections using $\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) \in [0.027, 0.083]$ as discussed in the text

$\sigma(pp/p\bar{p} \to X(3872))$	Reference [16]	Reference [18]	$\Lambda = 0.5$ GeV	$\Lambda = 1$ GeV	Experiment
Tevatron	<0.085	1.5–23	10 (7)	47 (33)	37–115 [43]
LHC7	–	45–100[a]	16 (7)	72 (32)	13–39 [6]

[a] Estimate based on non-relativistic QCD

Refs.:

[6] CMS, JHEP1304(2013)154

[16] C. Bignamini et al, PRL103(2009)162001

[18] P. Artoisenet, E. Braaten, PRD81(2010)114018

[43] CDF, IJMPA20(2005)3765

Table 2 Integrated cross sections (in units of nb) for the $pp/\bar{p} \to X_b$, and $pp/\bar{p} \to X_{b2}$ at the LHC and Tevatron. Results out of (in) brackets are obtained using Herwig (Pythia). The rapidity range $|y| < 2.5$ has been assumed for the LHC experiments (ATLAS and CMS) at 7, 8 and 14 TeV; for the Tevatron experiments (CDF and D0) at 1.96 TeV, we use $|y| < 0.6$; the rapidity range $2.0 < y < 4.5$ is used for the LHCb

X_b	$E_{X_b} = 24$ MeV ($\Lambda = 0.5$ GeV)	$E_{X_b} = 66$ MeV ($\Lambda = 1$ GeV)
Tevatron	0.08 (0.18)	0.61 (1.4)
LHC 7	1.5 (3.1)	12 (23)
LHCb 7	0.25 (0.49)	1.9 (3.7)
LHC 8	1.8 (3.6)	14 (27)
LHCb 8	0.3 (0.62)	2.2 (4.7)
LHC 14	3.2 (6.8)	24 (51)
LHCb 14	0.65 (1.3)	4.9 (9.7)

Results for the production of the X_{b2} and X_{c2}

X_{b2}	$E_{X_{b2}} = 24$ MeV ($\Lambda = 0.5$ GeV)	$E_{X_{b2}} = 66$ MeV ($\Lambda = 1$ GeV)
Tevatron	0.05 (0.13)	0.36 (1.0)
LHC 7	0.92 (2.3)	6.9 (17)
LHCb 7	0.14 (0.36)	1.1 (2.7)
LHC 8	1.1 (2.7)	8.1 (20)
LHCb 8	0.19 (0.46)	1.4 (3.5)
LHC 14	1.9 (5.0)	15 (37)
LHCb 14	0.38 (0.96)	2.9 (7.2)
X_{c2}	$E_{X_{c2}} = 4.8$ MeV ($\Lambda = 0.5$ GeV)	$E_{X_{c2}} = 5.6$ MeV ($\Lambda = 1$ GeV)
Tevatron	4.4 (3.0)	22 (15)
LHC 7	66 (44)	327 (216)
LHCb 7	14 (8.5)	71 (42)
LHC 8	74 (52)	369 (256)
LHCb 8	17 (10)	83 (50)
LHC 14	135 (90)	672 (446)
LHCb 14	35 (19)	174 (92)

Updated results for the production of the Z_c states

$Z_{c(3900)}$	$E_{Z_{c(3900)}} = 5.$ MeV($\Lambda = 0.5$ GeV)	$E_{Z_{c(3900)}} = 39$ MeV($\Lambda = 1$ GeV)
Tevatron	4.5(5.6)	59(74)
LHC 7	77(88)	1028(1162)
LHCb 7	14(16)	182(216)
LHC 8	91(100)	1209(1321)
LHCb 8	17(20)	221(264)
LHC 14	158(175)	2102(2326)
LHCb 14	35(37)	462(486)

$Z_{c(4020)}$	$E_{Z_{c(4020)}} = 4.2$ MeV($\Lambda = 0.5$ GeV)	$E_{Z_{c(4020)}} = 34$ MeV($\Lambda = 1$ GeV)
Tevatron	3.4(3.9)	46(53)
LHC 7	57(61)	777(831)
LHCb 7	11(11)	145(153)
LHC 8	67(70)	906(953)
LHCb 8	12(13)	168(183)
LHC 14	120(122)	1626(1656)
LHCb 14	26(27)	358(363)

Updated results for the production of the Z_b states

$Z_{b(10610)}$	$E_{Z_{b(10610)}} = 2.\ \text{MeV}(\Lambda = 0.5\ \text{GeV})$	$E_{Z_{b(10610)}} = 2.\ \text{MeV}(\Lambda = 1\ \text{GeV})$
Tevatron	0.05(0.09)	0.24(0.43)
LHC 7	0.94(1.6)	4.4(7.3)
LHCb 7	0.15(0.24)	0.7(1.1)
LHC 8	1.1(1.8)	5.4(8.7)
LHCb 8	0.18(0.28)	0.84(1.3)
LHC 14	2.1(3.4)	10(16)
LHCb 14	0.38(0.59)	1.8(2.8)
$Z_{b(10650)}$	$E_{Z_{b(10650)}} = 2.\ \text{MeV}(\Lambda = 0.5\ \text{GeV})$	$E_{Z_{b(10650)}} = 2.1\ \text{MeV}(\Lambda = 1\ \text{GeV})$
Tevatron	0.02(0.07)	0.11(0.32)
LHC 7	0.45(1.2)	2.1(5.5)
LHCb 7	0.07(0.18)	0.34(0.87)
LHC 8	0.54(1.4)	2.6(6.6)
LHCb 8	0.09(0.22)	0.41(1.)
LHC 14	1.(2.5)	4.9(12)
LHCb 14	0.2(0.46)	0.96(2.2)