Study of Bottomonia and Charmonia at Belle

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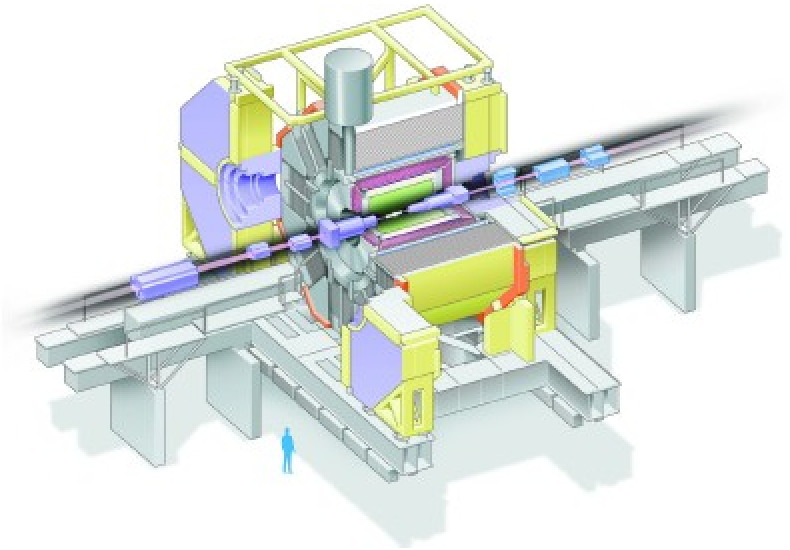
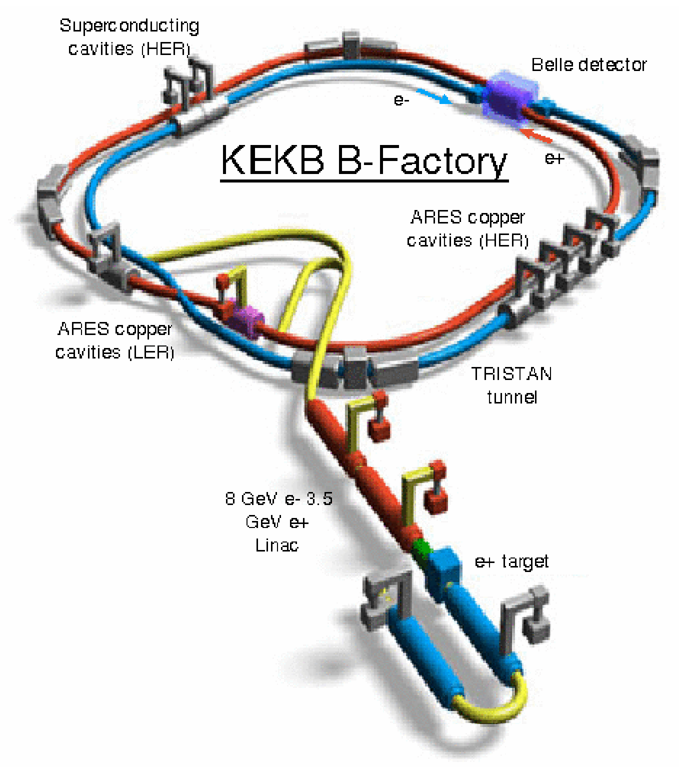
Outline

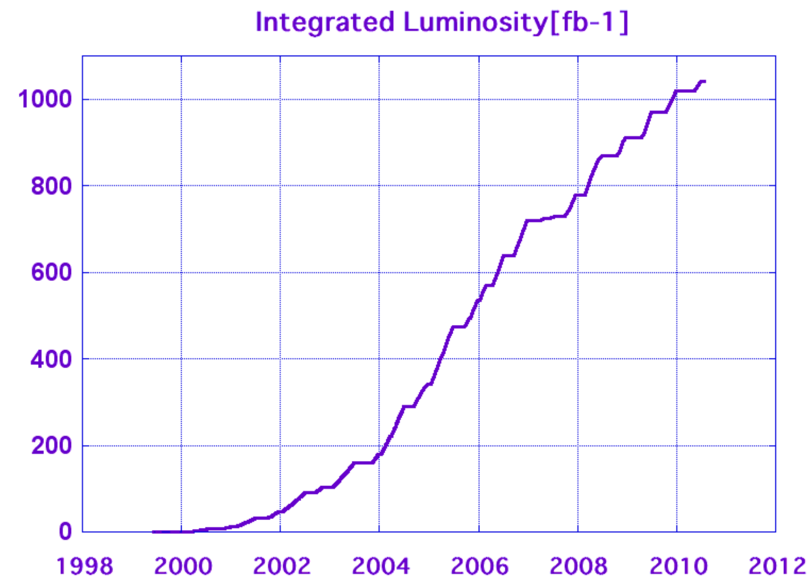
- Introduction
- Observation of $\chi_{c0}(2P)$ candidate in $e^+e^- \to J/\psi D\bar{D}$
- $\eta_c(1S)$, $\eta_c(2S)$ and $\eta\pi^+\pi^-$ production via two-photon collisions
- Search for $\Upsilon(1S,2S) \to Z_c^+ Z_c^{(\prime)-}$
- Search for light tetraquark states in $\Upsilon(1S,2S)$ decays
- Study of $\Upsilon(4S,5S)$ transitions to lower bottomonia via $\eta^{(\prime)}$

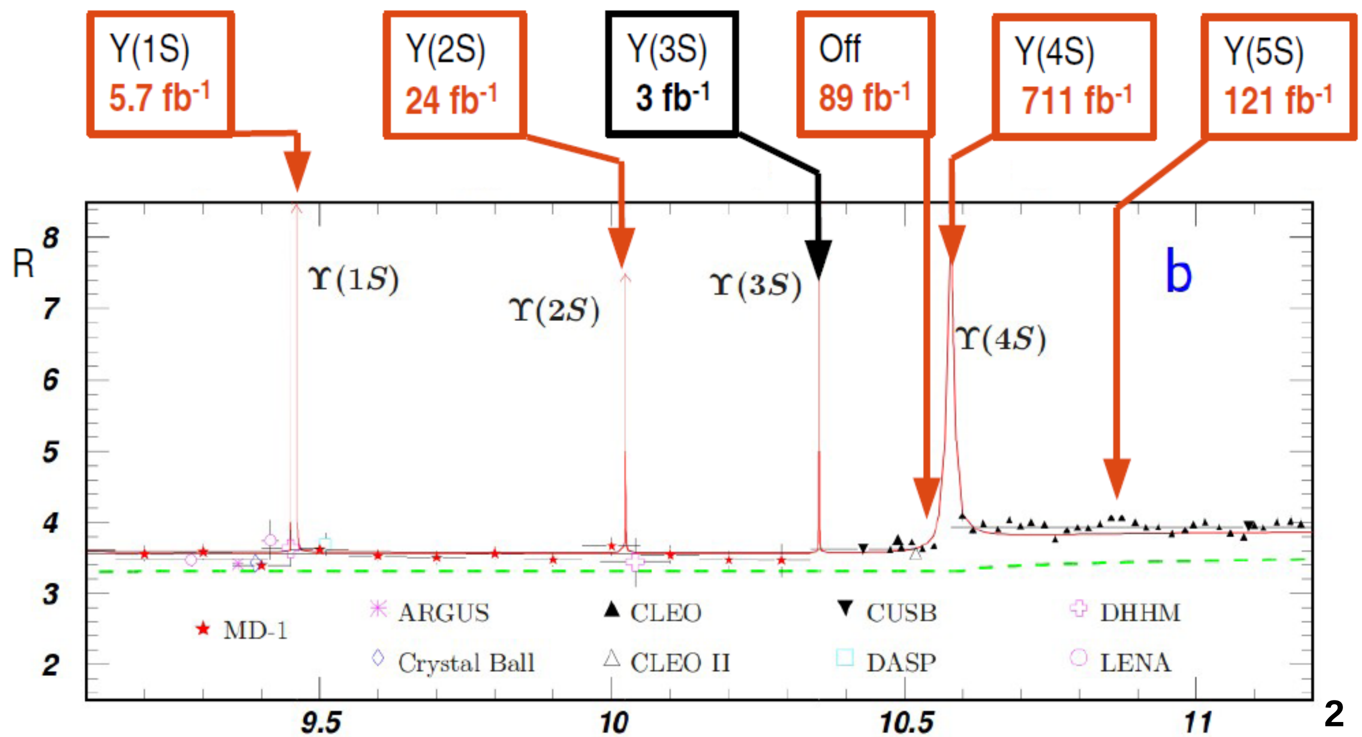
Summary

The Belle experiment









Observation of $\chi_{c0}(2P)$ in $e^+e^- \to J/\psi D\bar{D}$

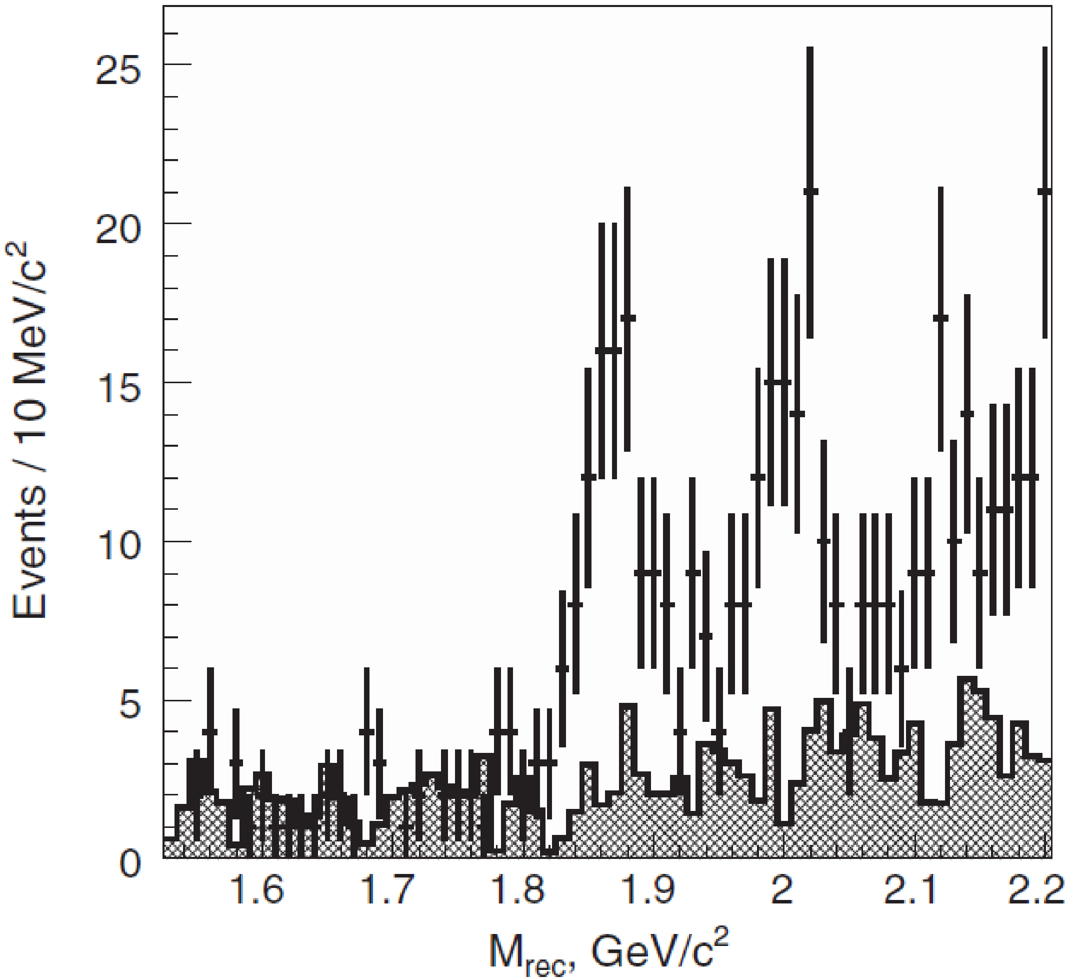
X(3915) was observed by the Belle in $B \to J/\psi\omega K$ decays. J^{PC} is measured to be 0^{++}. As a result, it was identified as the $\chi_{c0}(2P)$ in PDG 2014.

Doubts: expected main decay $\chi_{c0}(2P) \to D\bar{D}$ in an S-wave.

We search for $e^+e^- \to J/\psi\ \chi_{c0}(2P)$ with $\chi_{c0}(2P) \to D\bar{D}$

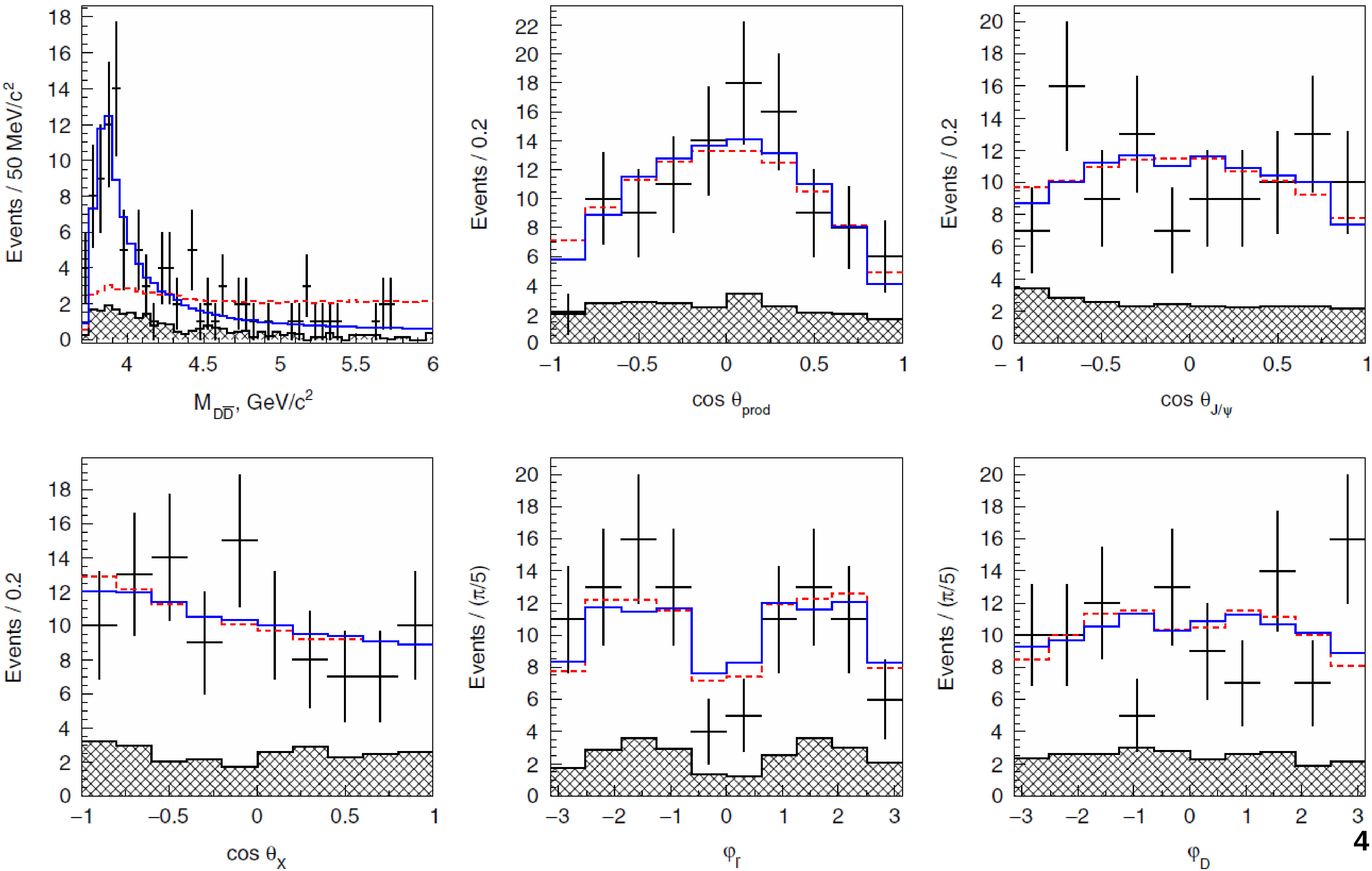
Only J/ψ and one of the D mesons are reconstructed; the other $\bar{D}$ meson is identified by the recoil mass of the $J/\psi D$ system.

- $D^+ \to K^0_S\pi^+$, $K^-\pi^+\pi^+$, $K^0_S\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^0$, and $K^0_S\pi^+\pi^+\pi^-$.
- $D^0 \to K^-\pi^+$, $K^0_S\pi^+\pi^-$, $K^-\pi^+\pi^0$, and $K^-\pi^+\pi^+\pi^-$.
- $J/\psi \to e^+e^-$, $\mu^+\mu^-$.



Phys.Rev.D95 112003(2017)

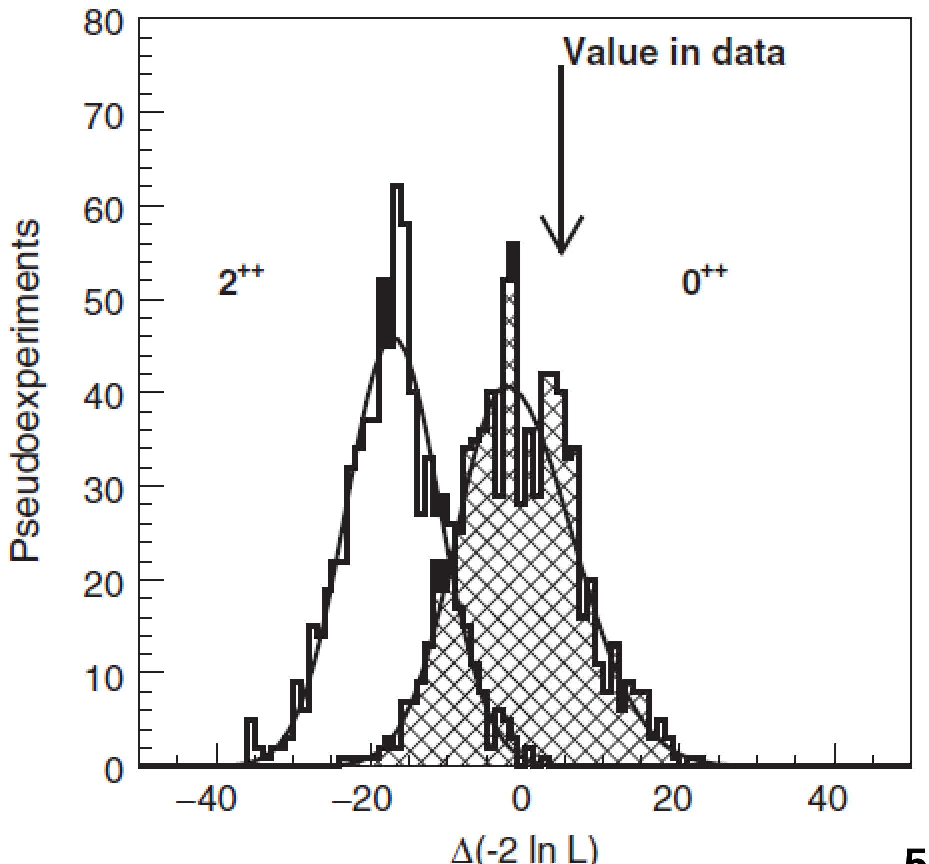
Observation of $\chi_{c0}(2P)$ in $e^+e^- \to J/\psi D\bar{D}$



Observation of $\chi_{c0}(2P)$ in $e^+e^- \to J/\psi D\bar{D}$

- A new charmoniumlike state, the X*(3860) is observed, with mass of $3862^{+26}_{-32}{}^{+40}_{-13}$ MeV/c^2, and width $201^{+154}_{-67}{}^{+88}_{-82}$ MeV.
- The J^{PC} 0^{++} is preferable, from 2^{++} at the level of 2.5σ.

- X*(3860) consistent with $\chi_c^0(2P)$ charmonium state hypotheses.
- The measured mass is close to potential model expectations for the $\chi_{c0}(2P)$.



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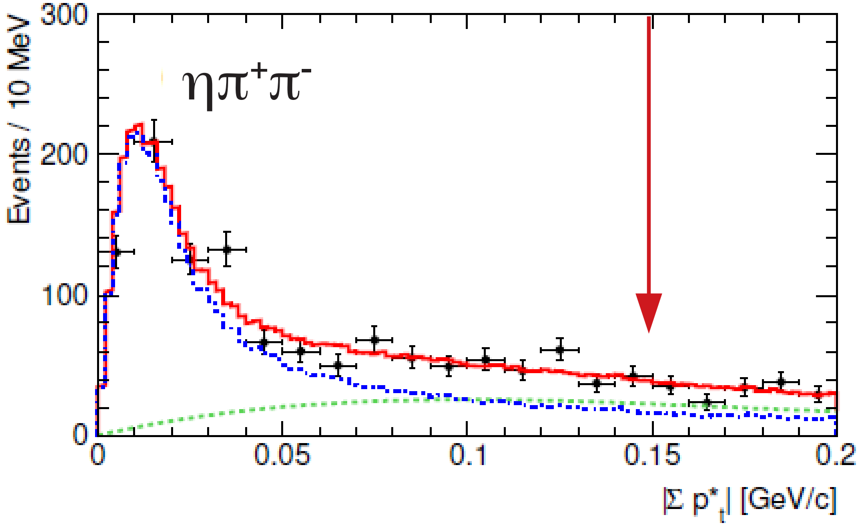
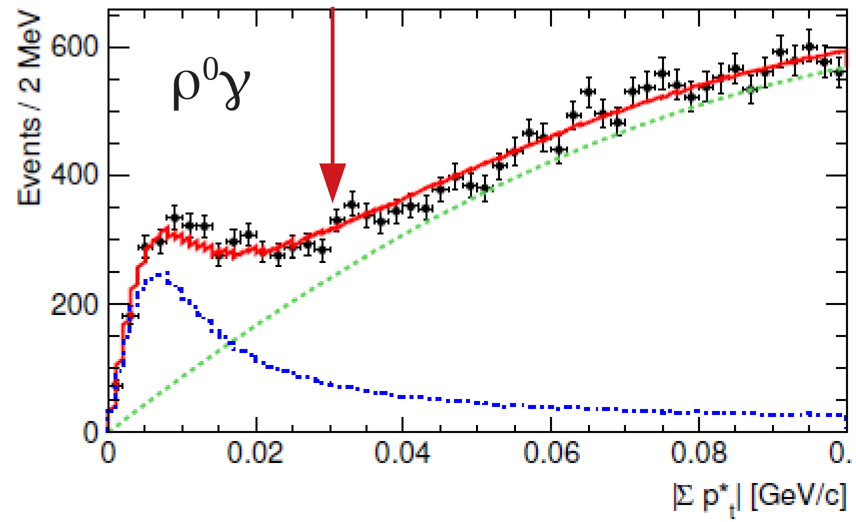
$\gamma\gamma \to \eta_c(1S)$, $\eta_c(2S)$ and $\eta' \pi^+\pi^-$

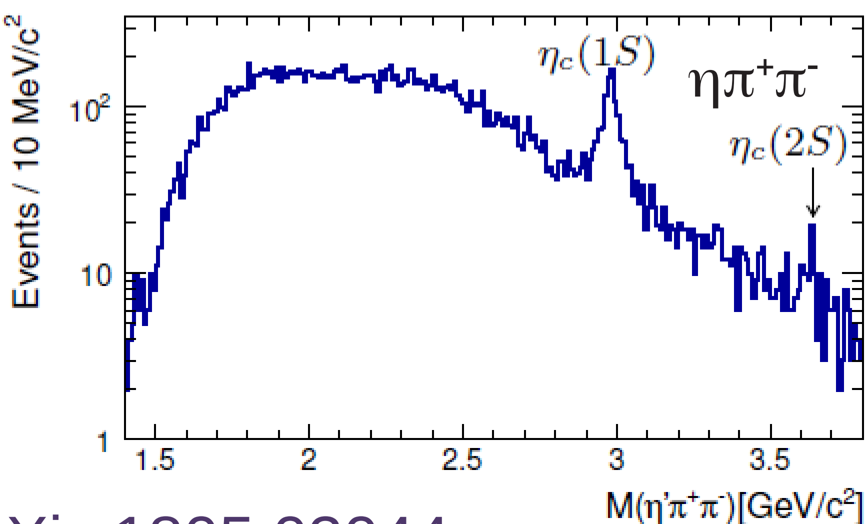
New

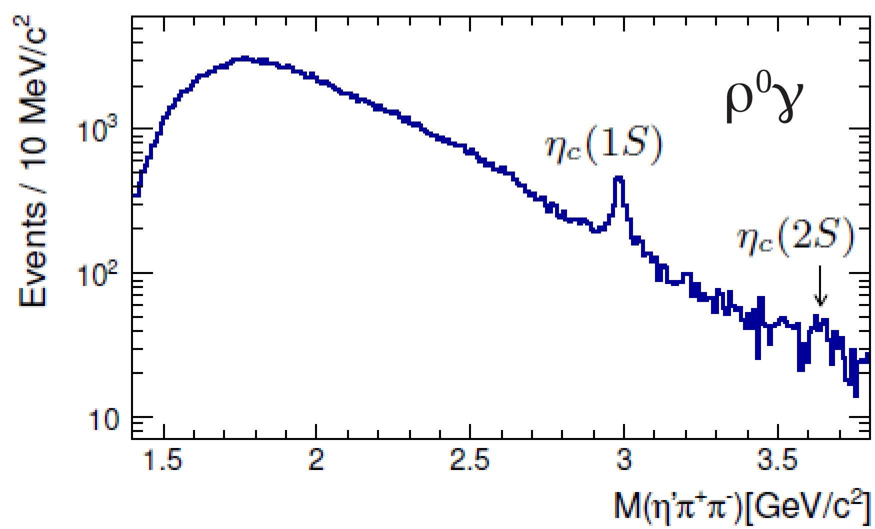
Motivation: improve measurement of $\eta_c(1S)$parameters, measure $\Gamma_{\gamma\gamma}$ for $\eta_c(2S)$

Reconstruction:$\gamma\gamma \to \eta_c(1S)$, $\eta_c(2S) \to \eta'\pi^+\pi^-$, $\eta' \to \eta\pi^+\pi^-$, $\rho^0\gamma$



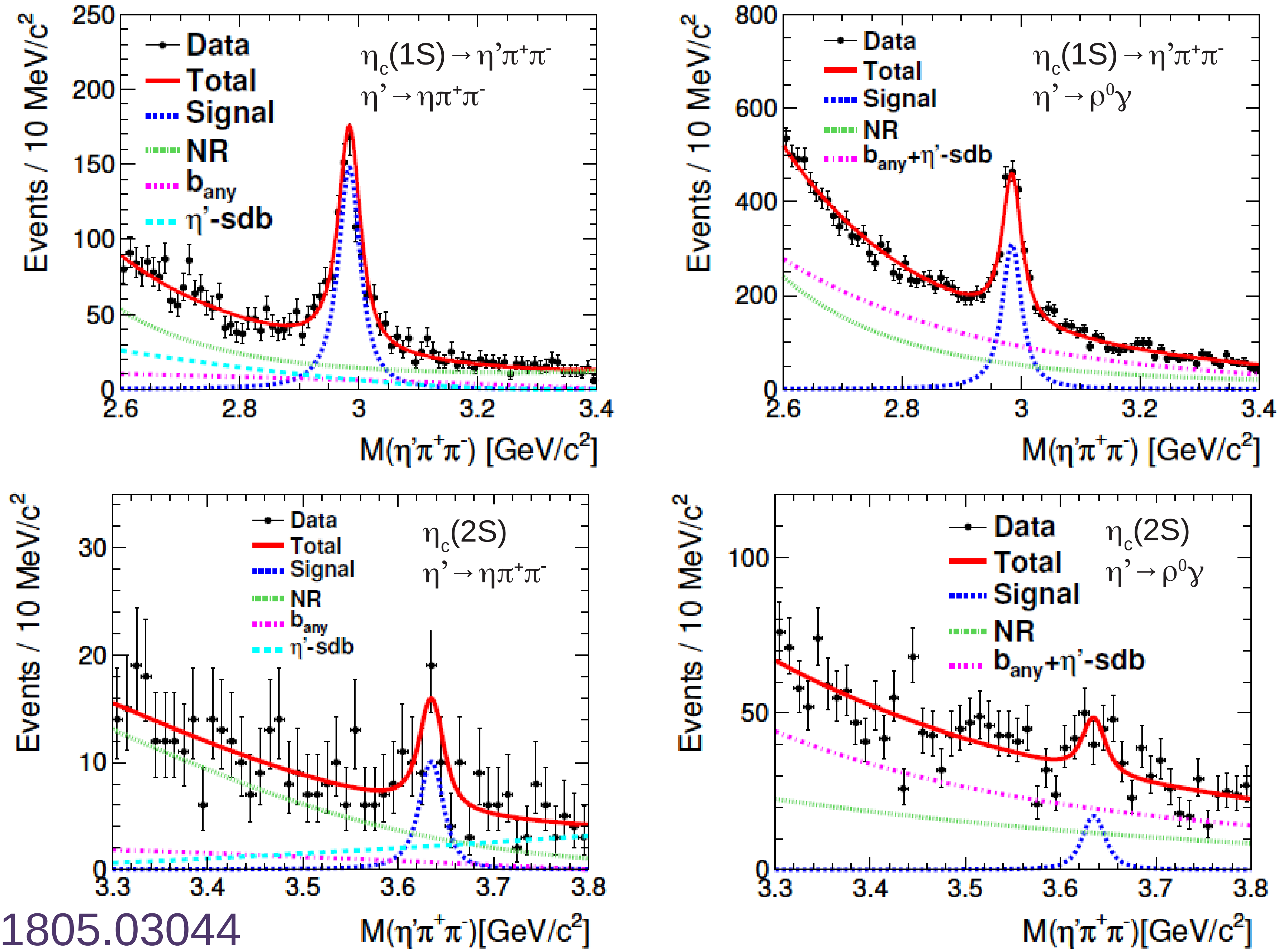






arXiv:1805.03044

$\gamma\gamma \to \eta_c(1S)$, $\eta_c(2S)$ and $\eta' \pi^+\pi^-$



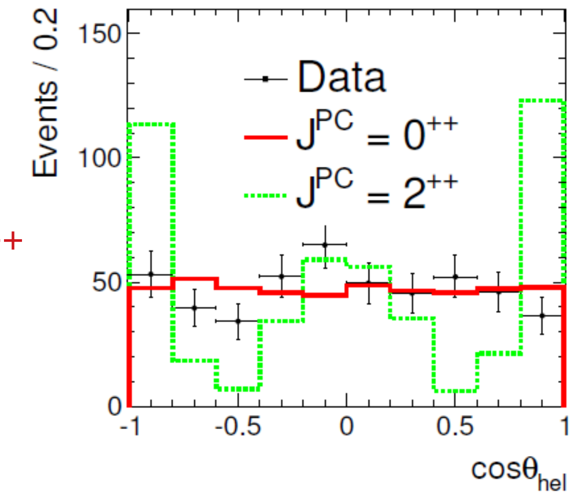
arXiv:1805.03044

New

$\gamma\gamma \to \eta_c(1S)$, $\eta_c(2S)$ and $\eta' \pi^+\pi^-$

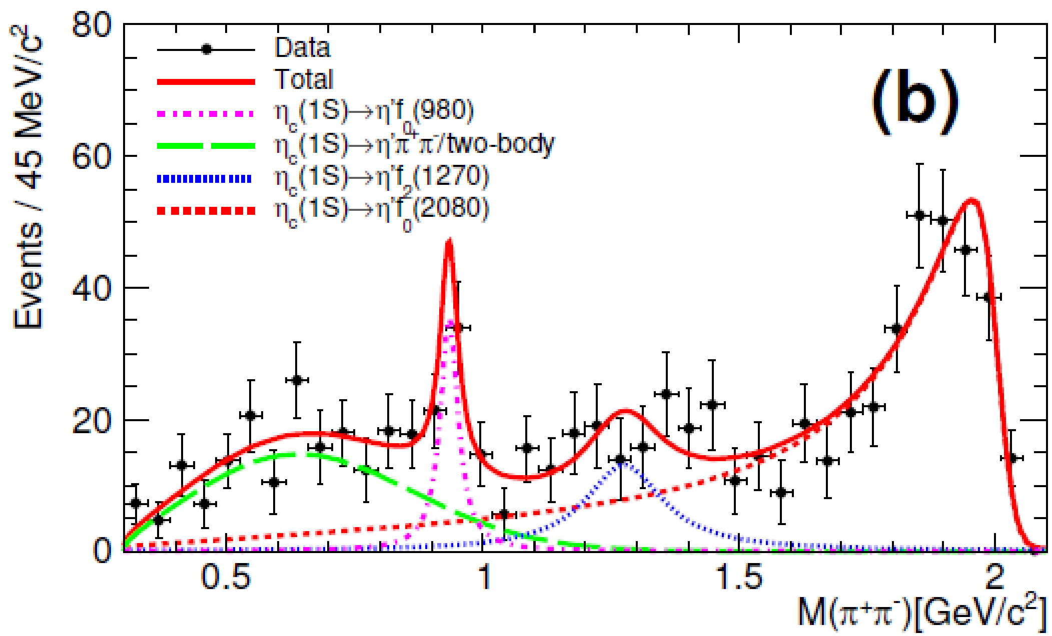
	$\eta_c(1S)$		$\eta_c(2S)$	
	$\gamma\rho$	$\eta\pi^+\pi^-$	$\gamma\rho$	$\eta\pi^+\pi^-$
n_s	1728^{+69}_{-68}	945^{+38}_{-37}	65^{+14}_{-13}	41^{+9}_{-8}
M (MeV/c^2)	$2984.6 \pm 0.7 \pm 2.2$		$3635.1 \pm 3.7 \pm 2.9$	
Γ (MeV)	$30.8^{+2.3}_{-2.2} \pm 2.5$		11.3 [fixed]	
$\Gamma_{\gamma\gamma}\mathcal{B}$ (eV)	$65.4 \pm 2.6 \pm 6.9$		$5.6^{+1.2}_{-1.1} \pm 1.1$	

J^{PC} is 0^{++}



First observation of
$\eta_c(2S) \to \eta'\pi^+\pi^-$

New decay mode
$\eta_c(1S) \to \eta' \; f^0(2080)$
$f^0(2080) \to \pi^+\pi^-$



arXiv:1805.03044

Search for $e^+e^- \rightarrow Z_c^+ Z_c^-$

New

Reconstruct only one Z_c:

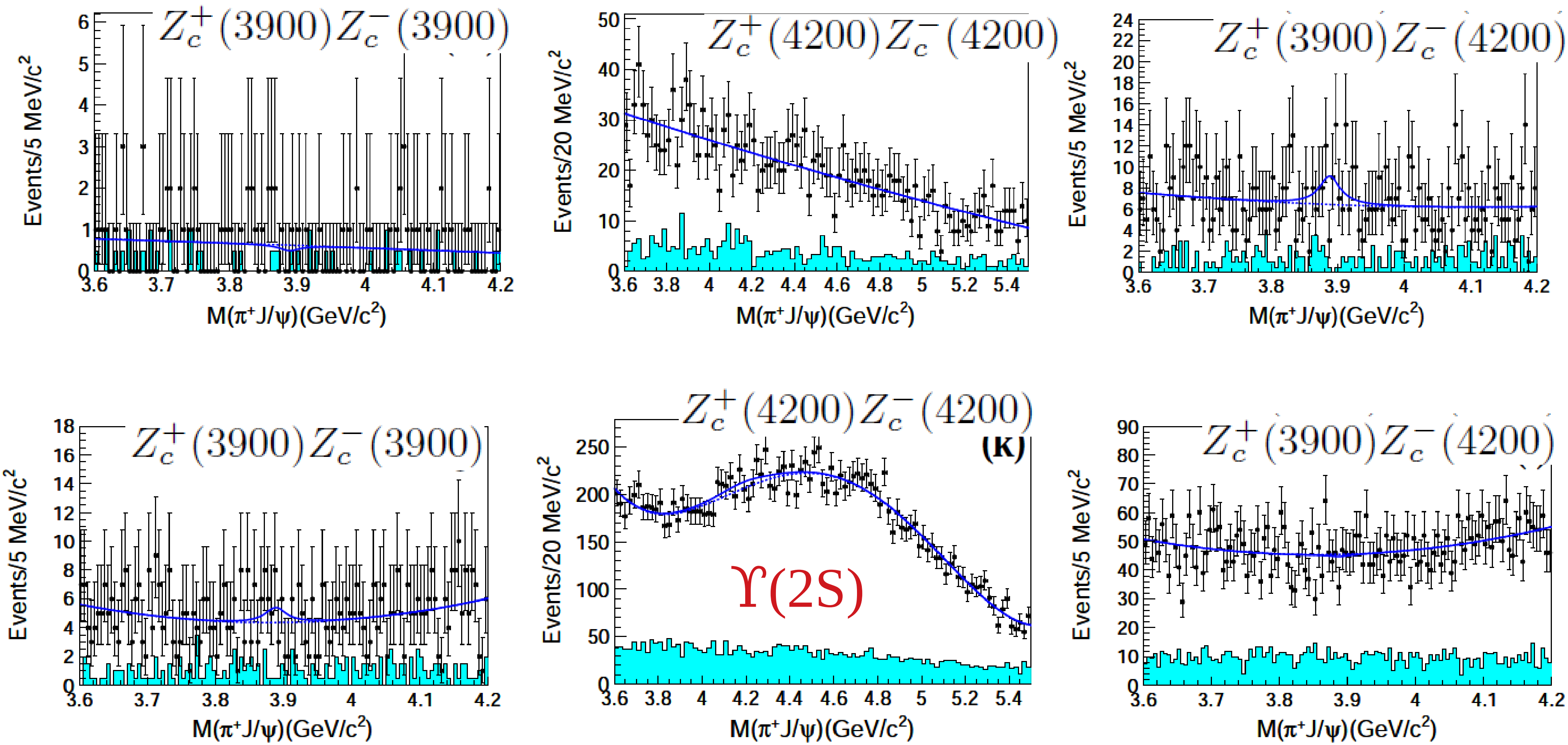
$Z_c^+(3900)$, $Z_c^+(3900)$ → $\pi^+ J/\psi$,

$Z_c^+(4050)$, $Z_c^+(4250)$ → $\pi^+ \chi_{c1}(1P)$,

$Z_c^+(4050)$, $Z_c^+(4430)$ → $\pi^+ \psi(2S)$

Then check recoil mass for other Z_c.

$\Upsilon(5S)$



arXiv:1805.02308

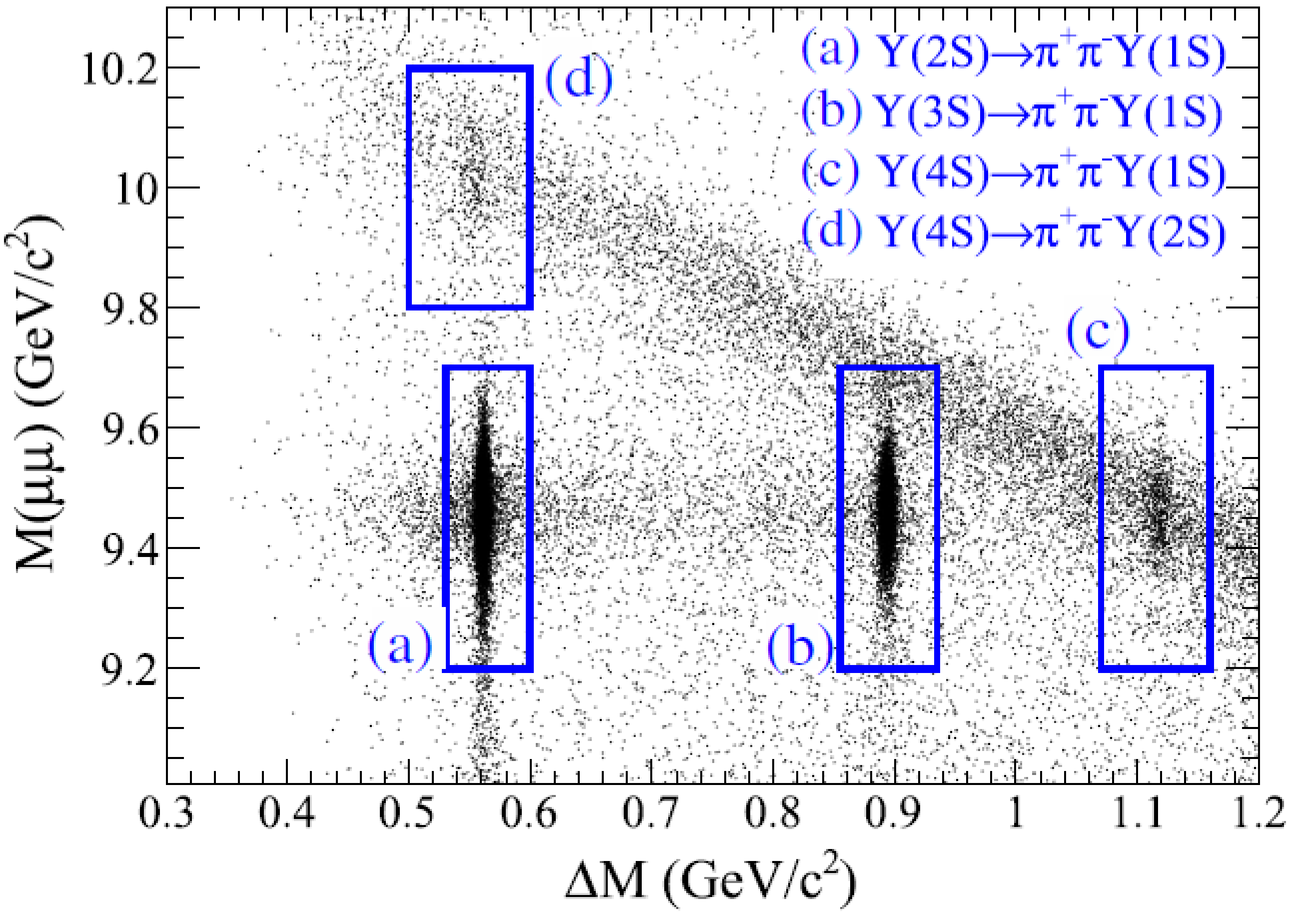
Search for $e^+e^- \to Z_c^+ Z_c^-$

Mode	$N^{\rm fit}$	$N^{\rm UL}$	ε (%)	Σ (σ)	$\sigma_{\rm syst}$ (%)	$\mathcal{B}(\Upsilon \to Z_c^+ Z_c^{(\prime)-}) \times \mathcal{B}(Z_c^+ \to \pi^+\chi_{c1}(1P)/\pi^+\psi(2S))$ (10^{-6})	$\mathcal{B}^{\rm UL}(\Upsilon \to Z_c^+ Z_c^{(\prime)-}) \times \mathcal{B}(Z_c^+ \to \pi^+\chi_{c1}(1P)/\pi^+\psi(2S))$ (10^{-6})
$\Upsilon(1S) \to Z_{c1}^+(4050)Z_{c1}^-(4050)$	-2.1 ± 7.2	13.1	21.6	-	41.3	-2.4 ± 8.1	15.8
$\Upsilon(1S) \to Z_{c2}^+(4250)Z_{c2}^-(4250)$	-8.3 ± 14.1	21.7	20.9	-	34.5	-9.7 ± 16.8	26.6
$\Upsilon(1S) \to Z_{c1}^+(4050)Z_{c2}^-(4250) + c.c.$	-1.3 ± 10.2	18.1	10.1	-	25.9	-3.1 ± 24.3	44.2
$\Upsilon(2S) \to Z_{c1}^+(4050)Z_{c1}^-(4050)$	2.9 ± 7.7	16.4	20.5	0.2	38.7	2.2 ± 5.9	13.5
$\Upsilon(2S) \to Z_{c2}^+(4250)Z_{c2}^-(4250)$	8.1 ± 15.8	32.6	19.2	0.5	34.0	6.6 ± 13.2	26.7
$\Upsilon(2S) \to Z_{c1}^+(4050)Z_{c2}^-(4250) + c.c.$	-6.3 ± 10.5	16.1	9.4	-	18.0	-10.5 ± 17.6	27.2
$\Upsilon(1S) \to Z_c^+(4050)Z_c^-(4050)$	6.7 ± 5.3	14.4	16.0	1.4	16.4	10.0 ± 8.1	23.3
$\Upsilon(1S) \to Z_c^+(4430)Z_c^-(4430)$	-1.5 ± 7.6	13.6	16.2	-	22.0	-2.2 ± 11.3	20.3
$\Upsilon(1S) \to Z_c^+(4050)Z_c^-(4430) + c.c.$	4.4 ± 5.7	14.3	7.7	0.8	28.8	13.6 ± 18.1	45.5
$\Upsilon(2S) \to Z_c^+(4050)Z_c^-(4050)$	-1.9 ± 6.4	10.8	15.1	-	16.1	-1.9 ± 6.6	11.1
$\Upsilon(2S) \to Z_c^+(4430)Z_c^-(4430)$	3.4 ± 9.6	20.0	15.3	0.3	17.8	3.4 ± 9.7	20.3
$\Upsilon(2S) \to Z_c^+(4050)Z_c^-(4430) + c.c.$	-4.9 ± 6.2	10.2	7.5	-	26.1	-10.1 ± 13.1	21.1

Mode	$\sqrt{s}$ (GeV)	$N^{\rm fit}$	$N^{\rm UL}$	ε (%)	Σ (σ)	$\sigma_{\rm syst}$ (%)	$\sigma \times \mathcal{B}(Z_c^+ \to \pi^+\chi_{c1}(1P)/\pi^+\psi(2S))$ (nb)	$\sigma^{\rm UL} \times \mathcal{B}(Z_c^+ \to \pi^+\chi_{c1}(1P)/\pi^+\psi(2S))$ (nb)
$e^+e^- \to Z_{c1}^+(4050)Z_{c1}^-(4050)$	10.52	1.2 ± 6.5	13.2	20.9	0.2	28.3	2.3 ± 12.4	25.0
$e^+e^- \to Z_{c2}^+(4250)Z_{c2}^-(4250)$	10.52	40.9 ± 16.8	65.1	19.4	2.6	32.9	83.9 ± 44.1	143.9
$e^+e^- \to Z_{c1}^+(4050)Z_{c2}^-(4250) + c.c.$	10.52	5.2 ± 10.4	21.5	9.5	0.5	33.0	21.7 ± 44.1	93.2
$e^+e^- \to Z_{c1}^+(4050)Z_{c1}^-(4050)$	10.58	4.1 ± 18.9	36.3	20.5	0.2	21.9	1.0 ± 4.6	8.8
$e^+e^- \to Z_{c2}^+(4250)Z_{c2}^-(4250)$	10.58	-35.2 ± 48.3	25.7	19.2	-	45.8	-9.0 ± 13.1	7.1
$e^+e^- \to Z_{c1}^+(4050)Z_{c2}^-(4250) + c.c.$	10.58	-18.0 ± 24.8	34.5	9.8	-	45.0	-9.1 ± 13.2	18.2
$e^+e^- \to Z_{c1}^+(4050)Z_{c1}^-(4050)$	10.867	8.6 ± 8.5	23.0	19.4	1.0	26.0	12.9 ± 13.2	35.7
$e^+e^- \to Z_{c2}^+(4250)Z_{c2}^-(4250)$	10.867	27.7 ± 16.1	49.5	18.5	1.7	27.0	43.6 ± 28.0	82.0
$e^+e^- \to Z_{c1}^+(4050)Z_{c2}^-(4250) + c.c.$	10.867	-17.5 ± 8.6	9.4	9.1	-	28.5	-55.7 ± 31.6	30.8
$e^+e^- \to Z_c^+(4050)Z_c^-(4050)$	10.52	9.4 ± 15.5	18.1	15.0	1.1	23.4	24.5 ± 40.8	47.7
$e^+e^- \to Z_c^+(4430)Z_c^-(4430)$	10.52	-9.7 ± 8.4	10.5	15.0	-	16.9	-25.3 ± 22.3	29.7
$e^+e^- \to Z_c^+(4050)Z_c^-(4430) + c.c.$	10.52	6.5 ± 7.2	18.7	7.5	0.9	17.3	33.9 ± 38.0	97.9
$e^+e^- \to Z_c^+(4050)Z_c^-(4050)$	10.58	7.7 ± 9.3	23.5	15.0	0.7	16.5	2.5 ± 3.0	7.6
$e^+e^- \to Z_c^+(4430)Z_c^-(4430)$	10.58	-60.5 ± 27.8	22.9	14.6	-	12.7	-20.1 ± 9.6	8.3
$e^+e^- \to Z_c^+(4050)Z_c^-(4430) + c.c.$	10.58	22.8 ± 17.2	48.5	7.3	1.3	19.5	15.1 ± 11.8	32.2
$e^+e^- \to Z_c^+(4050)Z_c^-(4050)$	10.867	-8.0 ± 3.4	5.2	14.2	-	20.8	-16.1 ± 7.6	10.8
$e^+e^- \to Z_c^+(4430)Z_c^-(4430)$	10.867	2.7 ± 8.2	16.7	14.0	0.3	22.1	5.5 ± 16.7	35.2
$e^+e^- \to Z_c^+(4050)Z_c^-(4430) + c.c.$	10.867	-3.7 ± 5.7	9.1	7.0	-	21.1	-15.1 ± 23.4	39.1

Study of η and dipion transitions in ϒ(4S) decays to lower bottomonia

Motivation: QCD multipole model predicts high suppression of bottomonia transitions via η due to spin flip of heavy quark. However tis is not cosistent with experimental data.



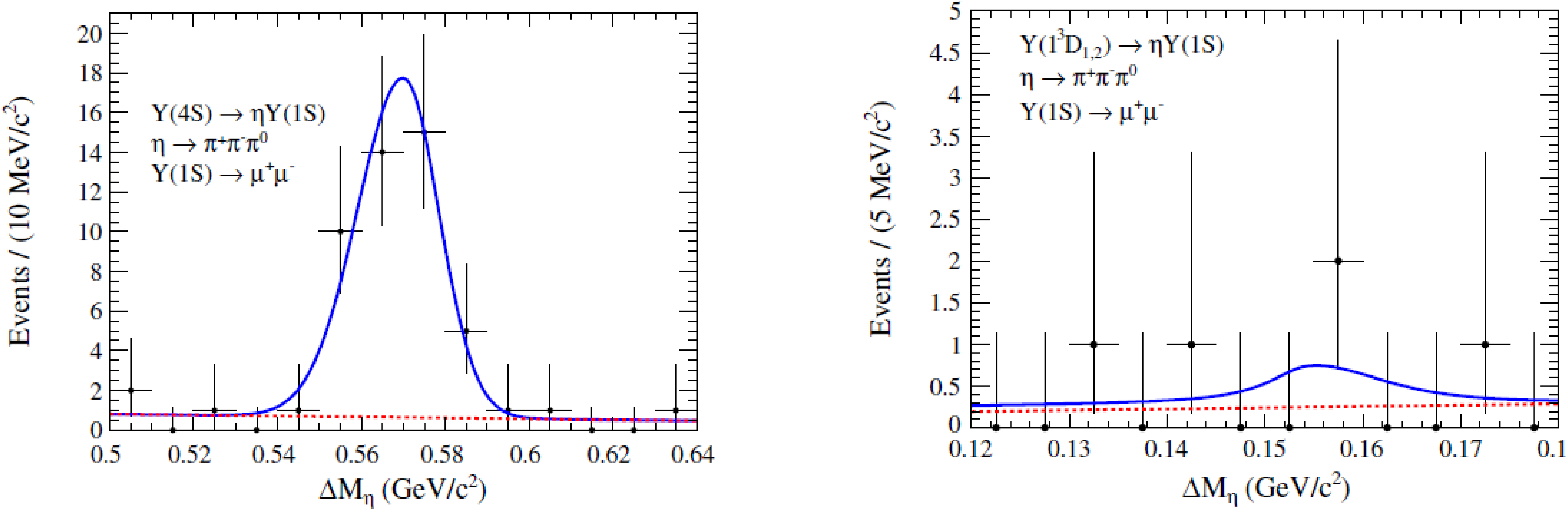
Final state: $\mu^+\mu^-\pi^+\pi^-$

Signal selection:
 $M(\mu^+\mu^-)$ and
$\Delta M = M(\mu^+\mu^-\pi^+\pi^-) - M(\mu^+\mu^-)$

$Br(\Upsilon(4S)\to\pi^+\pi^-\Upsilon(1S)) = (8.2 \pm 0.5 \pm 0.4)\times10^{-5}$
$Br(\Upsilon(4S)\to\pi^+\pi^-\Upsilon(2S)) = (7.9 \pm 1.0 \pm 0.4)\times10^{-5}$

Phys.Rev.D96 052005(2017)

Study of η and dipion transitions in Υ(4S) decays to lower bottomonia



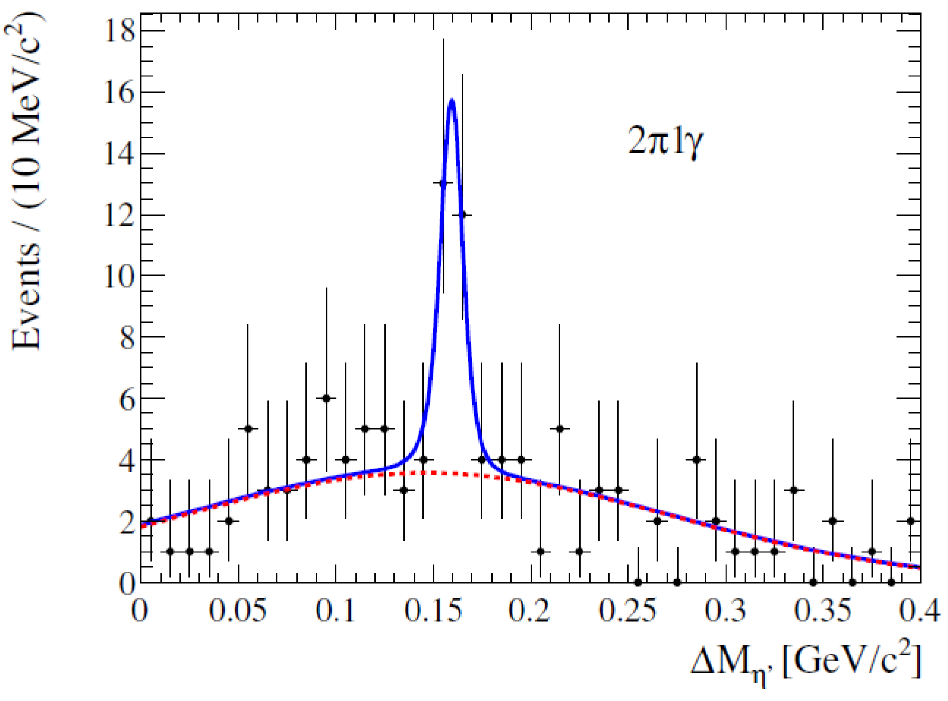
Measurement	Result	PDG value [17]
$\mathcal{B}(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S))$	$(8.2 \pm 0.5 \pm 0.4) \times 10^{-5}$	$(8.1 \pm 0.6) \times 10^{-5}$
$\mathcal{B}(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(2S))$	$(7.9 \pm 1.0 \pm 0.4) \times 10^{-5}$	$(8.6 \pm 1.3) \times 10^{-5}$
$\mathcal{B}(\Upsilon(4S) \to \eta\Upsilon(1S))$	$(1.70 \pm 0.23 \pm 0.08) \times 10^{-4}$	$(1.96 \pm 0.28) \times 10^{-4}$
$\mathcal{R}$ as in Eq. (1)	$2.07 \pm 0.30 \pm 0.11$	2.41 ± 0.42

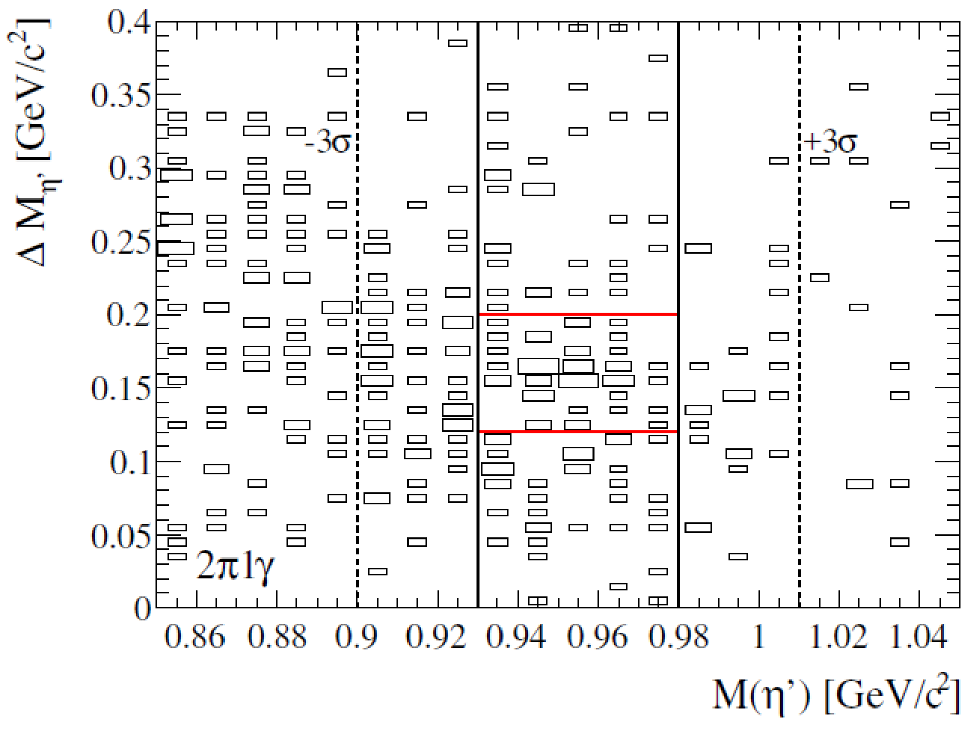
Phys.Rev.D96 52005(2017)

Observation of $\Upsilon(4S) \to \eta' \Upsilon(1S)$

- $Y(1S) \to \mu^+\mu^-$.
- $\eta' \to \eta\pi^+\pi^-$, $\rho^0\gamma$

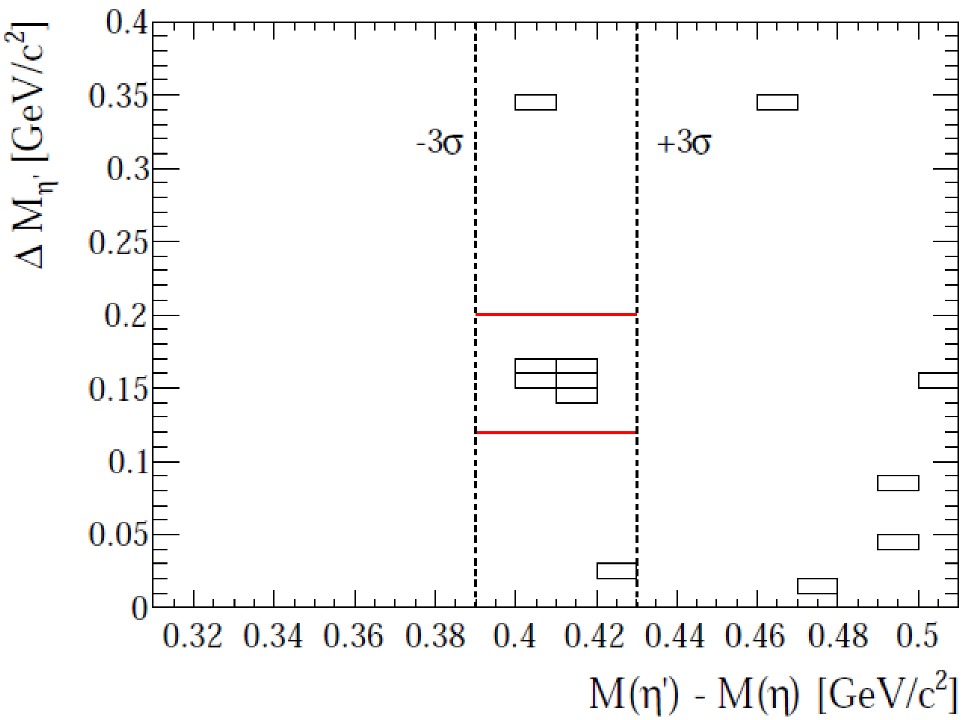
$$\Delta M_{\eta'} = M(\Upsilon(4S)) - M(\Upsilon(1S)) - M(\eta'),$$

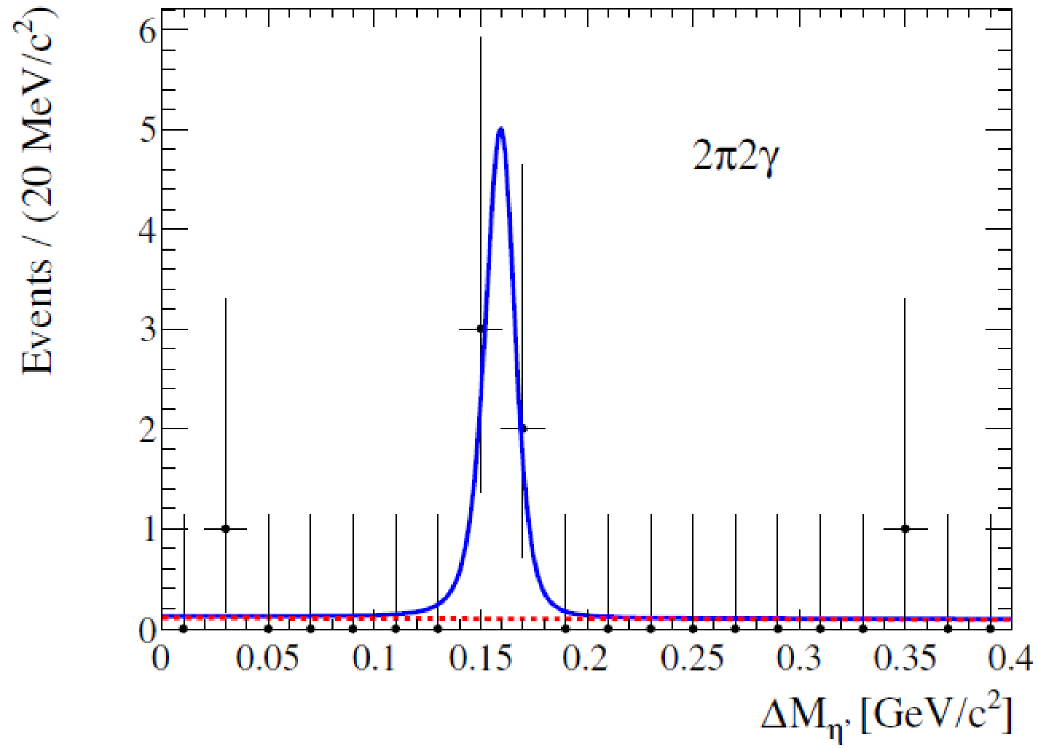




arXiv:1803.10303

Observation of $\Upsilon(4S) \to \eta' \Upsilon(1S)$





B(Y(4S)→ η' Y(1S)) = (3.43 ± 0.88 ± 0.21) 10^{-5}

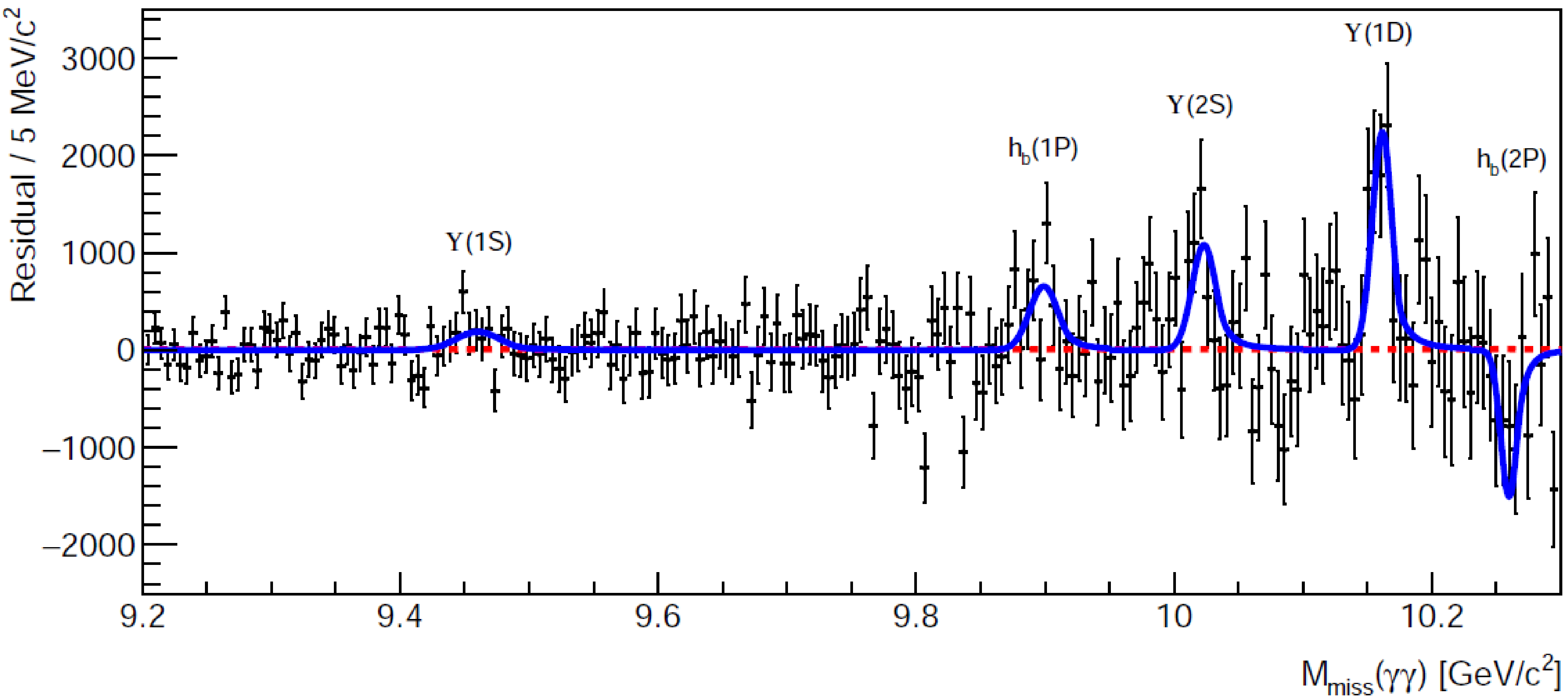
$$R_{\eta'/h} = \frac{\mathcal{B}(\Upsilon(4S) \to \eta' \Upsilon(1S))}{\mathcal{B}(\Upsilon(4S) \to h \Upsilon(1S))}$$

$$R_{\eta'/\eta} = 0.20 \pm 0.06$$

$$R_{\eta'/\pi^+\pi^-} = 0.42 \pm 0.11$$

arXiv:1803.10303

New Inclusive study $\Upsilon(5S) \to \eta\, b\bar{b}$



Process	Σ	$N_{\rm meas}[10^3]$	ϵ [%]	σ_v [pb]	$1+\delta_{\rm ISR}$	σ_B [pb]
$e^+e^- \to \eta\Upsilon(1S)$	1.5σ	1.7 ± 1.0	20.1	< 0.34	0.644 ± 0.007	< 0.49
$e^+e^- \to \eta h_b(1P)$	2.7σ	3.9 ± 1.5	22.2	< 0.52	0.644 ± 0.007	< 0.76
$e^+e^- \to \eta\Upsilon(2S)$	3.3σ	5.6 ± 1.6	16.5	$0.70 \pm 0.21 \pm 0.12$	0.644 ± 0.007	$1.02 \pm 0.30 \pm 0.17$
$e^+e^- \to \eta\Upsilon(1D)$	5.3σ	9.3 ± 1.8	17.2	$1.14 \pm 0.22 \pm 0.15$	0.643 ± 0.006	$1.64 \pm 0.31 \pm 0.21$
$e^+e^- \to \eta h_b(2P)$	–	-5.2 ± 3.6	16.7	< 0.44	0.636 ± 0.005	< 0.64

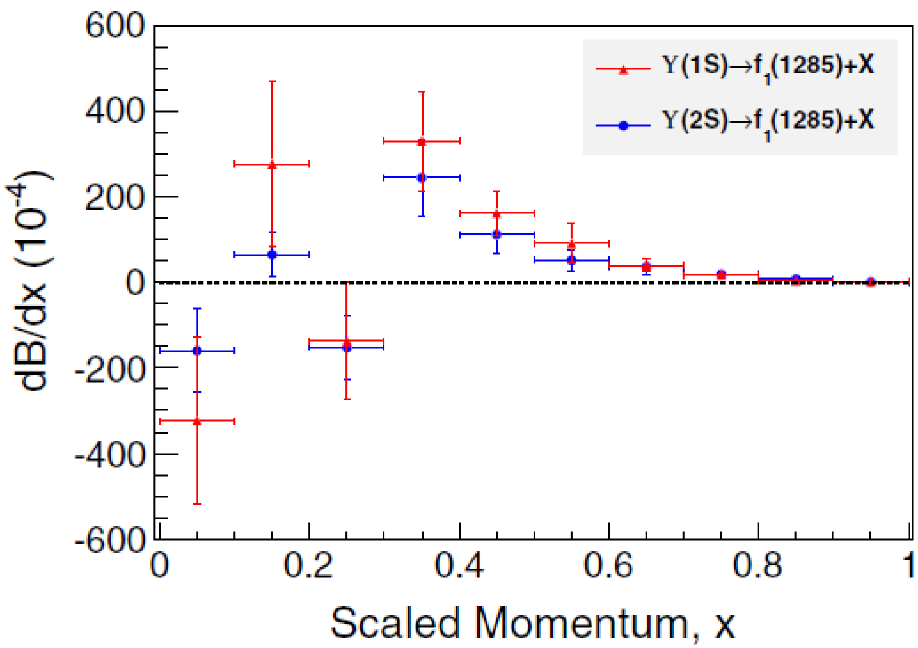
arXiv:1803.03225

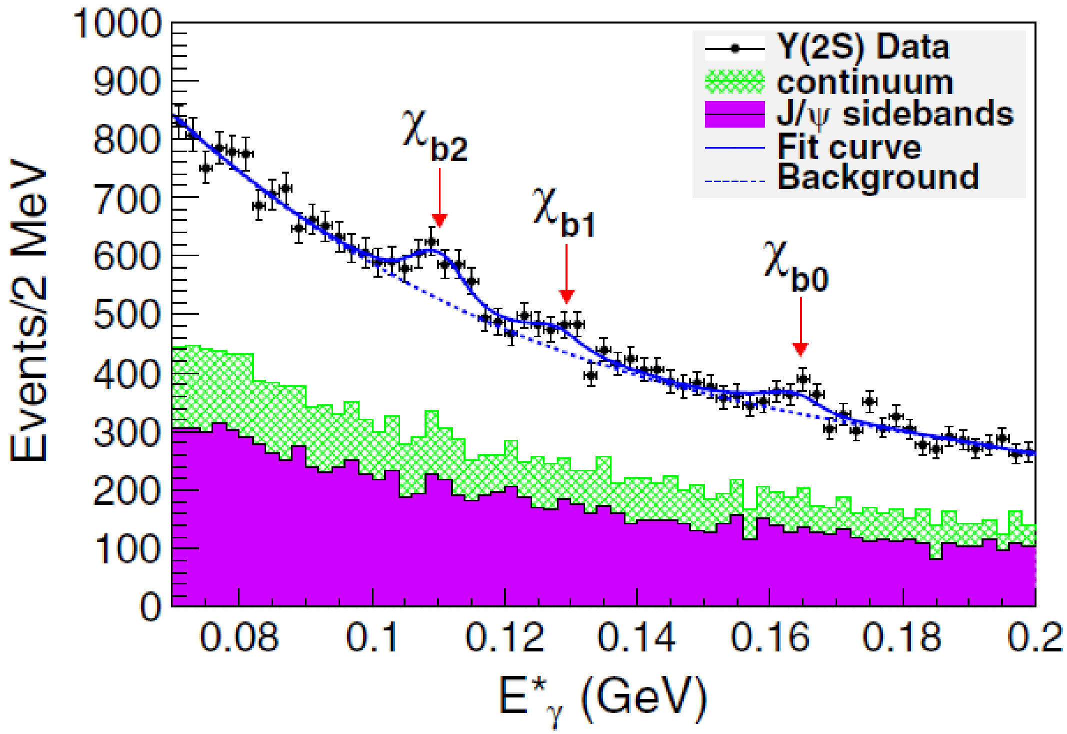
Search for light tetraquark states in $\Upsilon(1S,2S)$ decays

- The Dalitz analysis of the decay $D^0 \to \pi^+\pi^-\pi^0$ indicates the existence of exotic state decaying into a $\rho\pi$ final state with J^{PC} 0^{--}, at a mass of 1865 MeV/c^2, can not be explained as $q\bar{q}$
- Search for $J^{PC} = 0^{--}$ and 1^{+-} teraqurk states X_{tetra} in

  $\Upsilon(1S,2S)$ decays to χ_{c1} X_{tetra} and $f_1(1285)$ X_{tetra}

  χ_{b1} decays to J/ψ X_{tetra} and ω X_{tetra}.





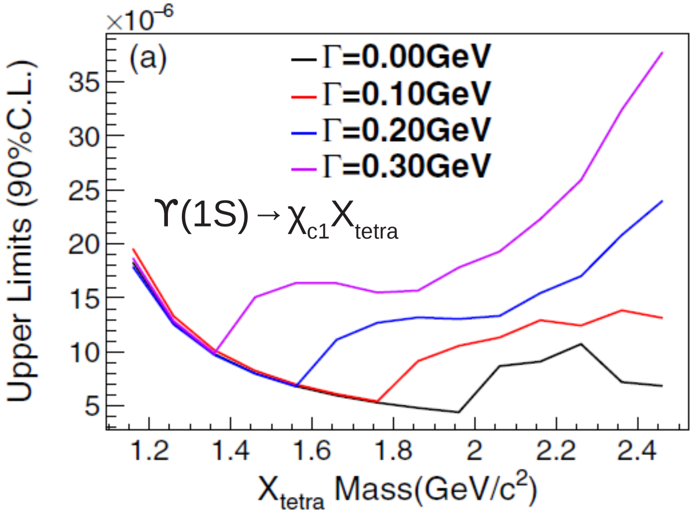
$B(\Upsilon(1S) \to f_1(1285)$ anything$) = (46\pm28\pm13)\ 10^{-4}$, $B(\Upsilon(2S) \to f_1(1285)$ anything$) = (22\pm15\pm6.3)\ 10^{-4}$,

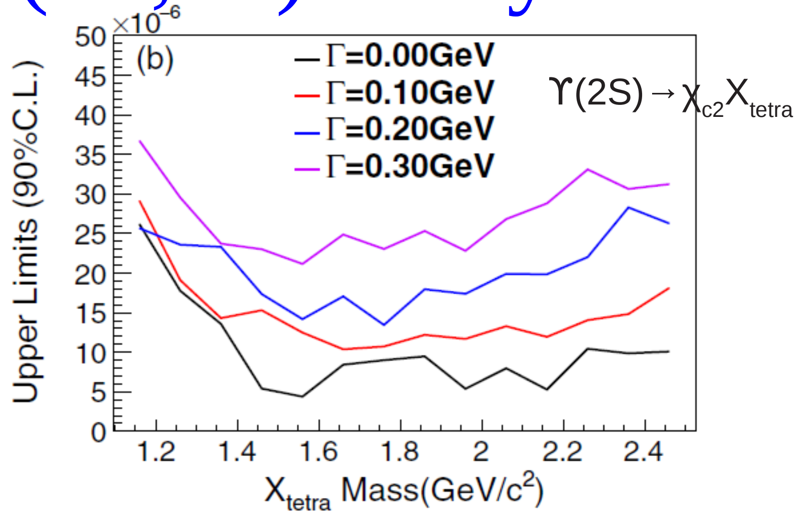
$B(\chi_{b2} \to J/\psi$ anything$) = (15 \pm 3.4 \pm 2.2)\ 10^{-4}$, $B(\chi_{b2} \to \omega$ anything$) = (490 \pm 130 \pm 60)\ 10^{-4}$,

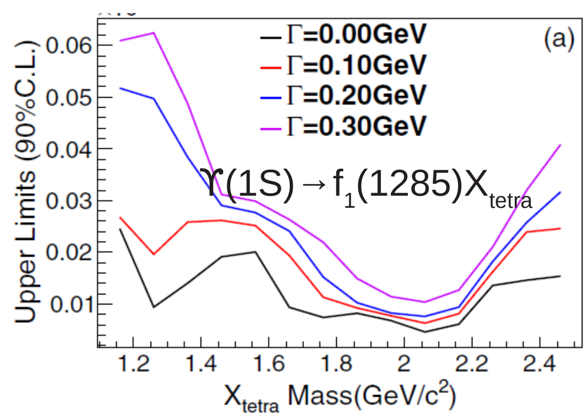
$B(\chi_{b0} \to J/\psi$ anything$) < 23\ 10^{-4}$ 90% CL, $B(\chi_{b1} \to J/\psi$ anything$) < 11\ 10^{-4}$ 90% CL

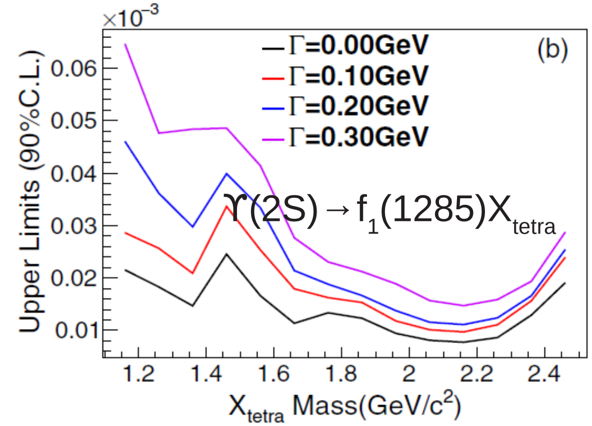
Phys.Rev.D96 112002 (2017)

Search for light tetraquark states in $\Upsilon(1S,2S)$ decays

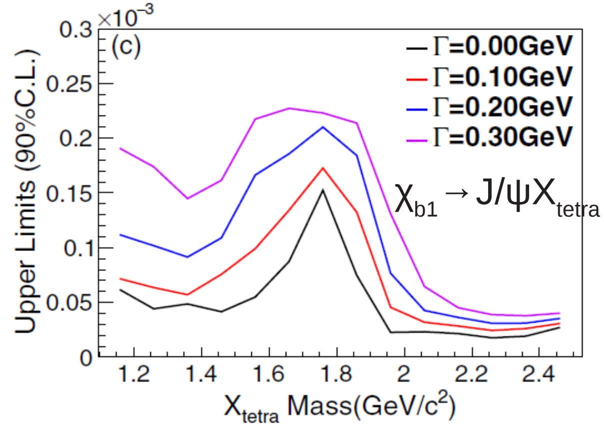


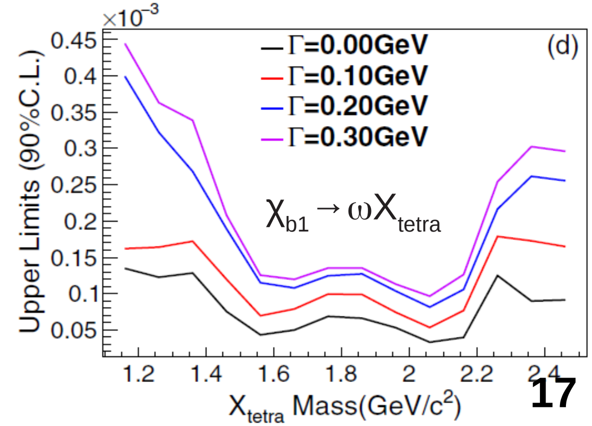






No teraqurk states X_{tetra} have been found





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Summary

- Observation of charmonium-like state $X^{*}(3860)$, consistent with $\chi_{c0}(2P)$
- **New** Measurement of $\eta_c(1S,2S)$ and $\eta\,\pi^{+}\pi^{-}$ production via two-photon collisions.
- **New** First observation of $\eta_c(2S) \to \eta' \pi^{+}\pi^{-}$ and $\eta_c(1S) \to \eta' f_0(2080) \to \eta' \pi^{+}\pi^{-}$
- No signal have been found for $e^{+}e^{-} \to Z_c^{+} Z_c^{-}$
- **New** Measurement of branching fraction $\Upsilon(4S) \to \eta\, \Upsilon(1S)$
- **New** Observation of $\Upsilon(4S) \to \eta'\, \Upsilon(1S)$
- Observation of $\Upsilon(5S) \to \eta\, \Upsilon(1D)$ decays in inclusive study
- No light tetraquark states have been found in $\Upsilon(1S,2S)$ decays

- More exciting results are going to come from Belle II.