Selected Results from Belle in the Bottomonium Region

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Outline

1. General
2. New state near 10750 MeV
3. Search for $e^+e^- \to \gamma\chi_{cJ},\ \gamma\eta_c$
4. Conclusions

General

- $\Upsilon(4S)$, $\Upsilon(10860)$, $\Upsilon(11020)$ have properties unexpected for pure $b\bar{b}$ bound states: much higher rate of transitions to lower bottomonia with emission of light hadrons, strong violation of HQSS
- Possible explanation – hadron loops, presence of $B_{(s)}^{(*)}\overline{B}_{(s)}^{(*)}$; in this approach $\Upsilon(10860), \Upsilon(11020)$ are $\Upsilon(5S)$ and $\Upsilon(6S)$ "dressed" by hadrons
- In the region of the $\Upsilon(4S,\ 5S,\ 6S)$ states the $\Upsilon(3D,\ 4D)$ are also predicted. In addition, exotic states are possible here
- Various final states have been studied in the $b\bar{b}$ region: $\Upsilon(nS)\pi^+\pi^-$, $h_b(nP)\pi^+\pi^-$, $\chi_{bJ}(1P)\pi^+\pi^-\pi^0$, $B_s^{(*)}\overline{B}_s^{(*)}$
- Electromagnetic quarkonium production is a good lab to test NRQCD predictions for the cross sections of radiative processes

A new structure near 10.75 GeV in $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ – I

Analysis is based on about 200 fb^{-1} collected at 28 c.m.energy points

Energy, MeV	Points	Luminosity, fb^{-1}
10520	1	60
10630-11020	21	20
$\Upsilon(10860)$ peak	6	121

$E_{\rm c.m.}$ calibration was performed with $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$

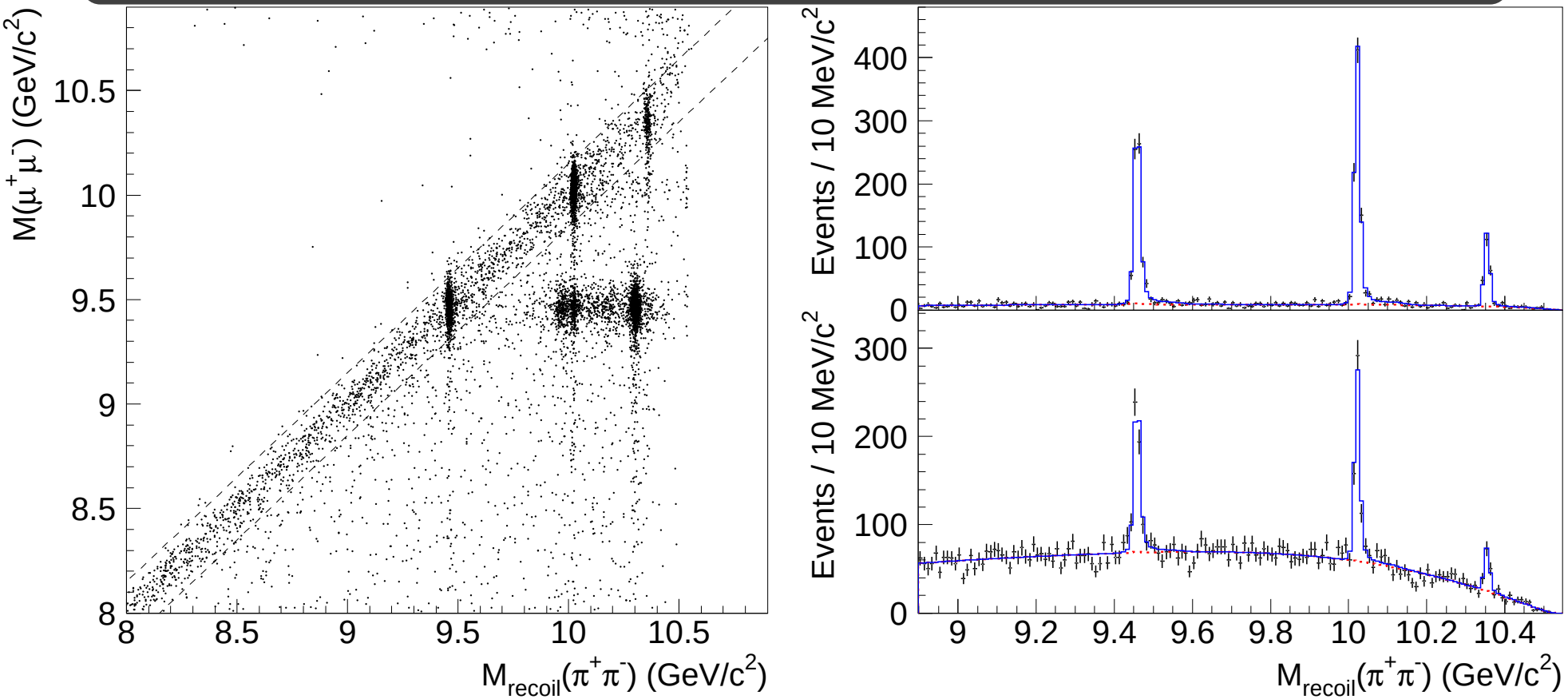
Events of $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ are selected, $\Upsilon(nS) \to e^+e^-,\ \mu^+\mu^-$, n=1,2,3

A special variable for selection and BG suppression is the recoil mass:

$$M_{\rm recoil}(\pi^+\pi^-) = \sqrt{(E_{\rm c.m.} - E_{\pi^+\pi^-})^2 - p^2_{\pi^+\pi^-}}$$

A. Abdesselam et al., arXiv:1905.05521

A new structure near 10.75 GeV in $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ – II

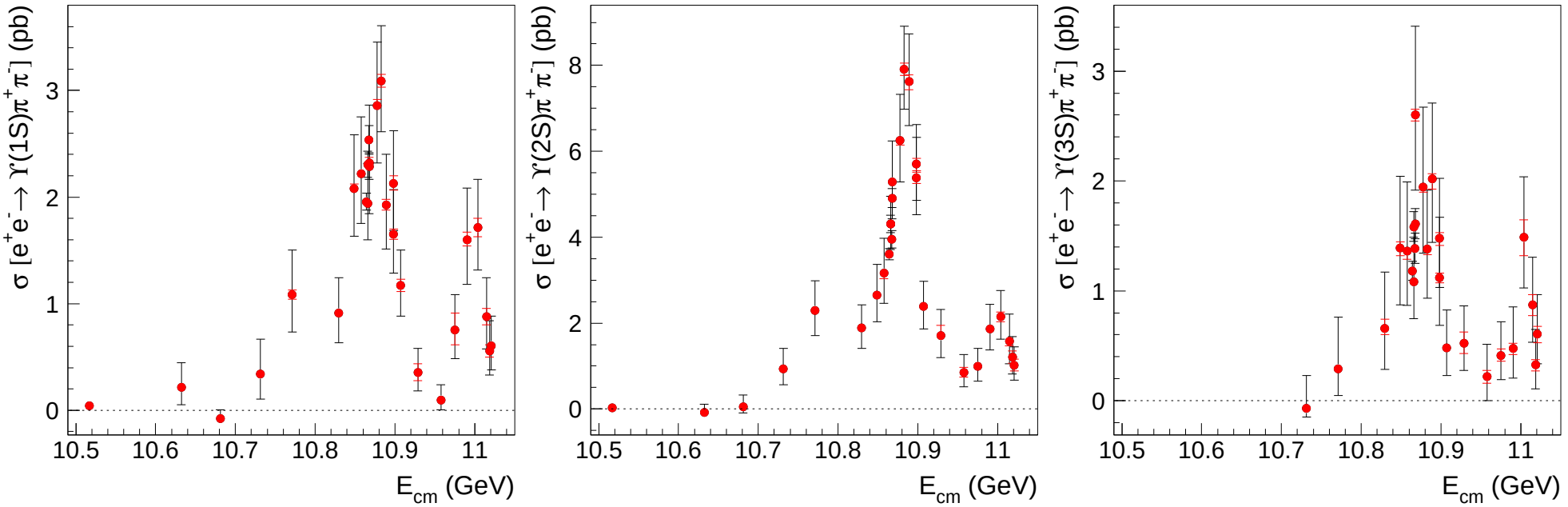


The fully reconstructed events (diagonal): $|M_{\rm recoil}(\pi^+\pi^-) - M(l^+l^-)|$ <150 MeV.

Two populated regions below the diagonal are due to transitions from the $\Upsilon(10860)$ to the $\Upsilon(2S, 3S)$ via ISR and light mesons

A. Abdesselam et al., arXiv:1905.05521

A new structure near 10.75 GeV in $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ – III

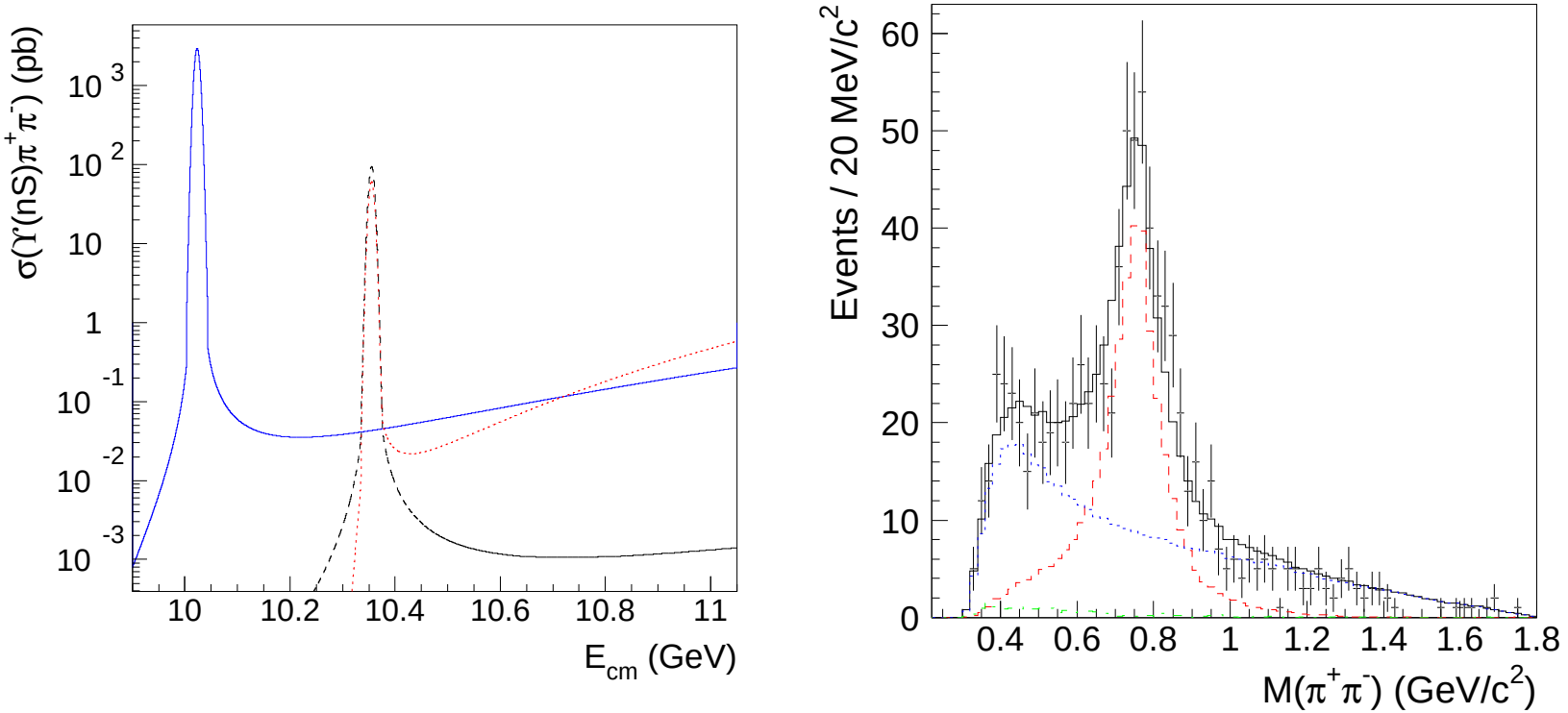


From the $M_{\rm recoil}(\pi^+\pi^-)$ fit the Born cross sections are obtained.

Clear $\Upsilon(10860)$ and $\Upsilon(11020)$ peaks are seen, also a structure at 10.75 GeV

A. Abdesselam et al., arXiv:1905.05521

A new structure near 10.75 GeV in $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ - IV



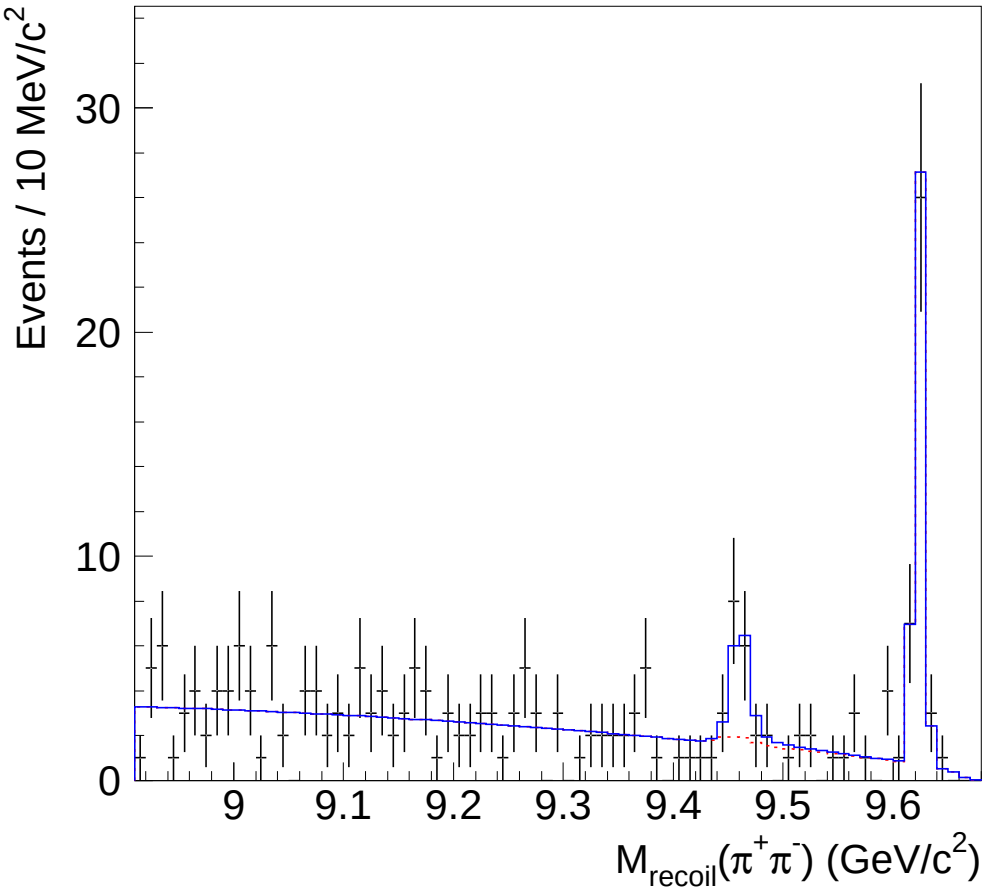
At $E_{\rm c.m.}$=10.52 GeV $\sigma(\Upsilon(1S)\pi^+\pi^-) = 40^{+21}_{-19}$ fb and $\sigma(\Upsilon(2S)\pi^+\pi^-) = 25^{+29}_{-25}$ fb,
consistent with the expectations for the $\Upsilon(2S, 3S)$ tails

In $\pi\pi$ transitions $\mathcal{M}^2 \propto M^2(\pi^+\pi^-)$, explains rather large σ's

The dominant BG comes from QED - $\mu^+\mu^-\pi^+\pi^-$

A. Abdesselam et al., arXiv:1905.05521

A new structure near 10.75 GeV in $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ - V

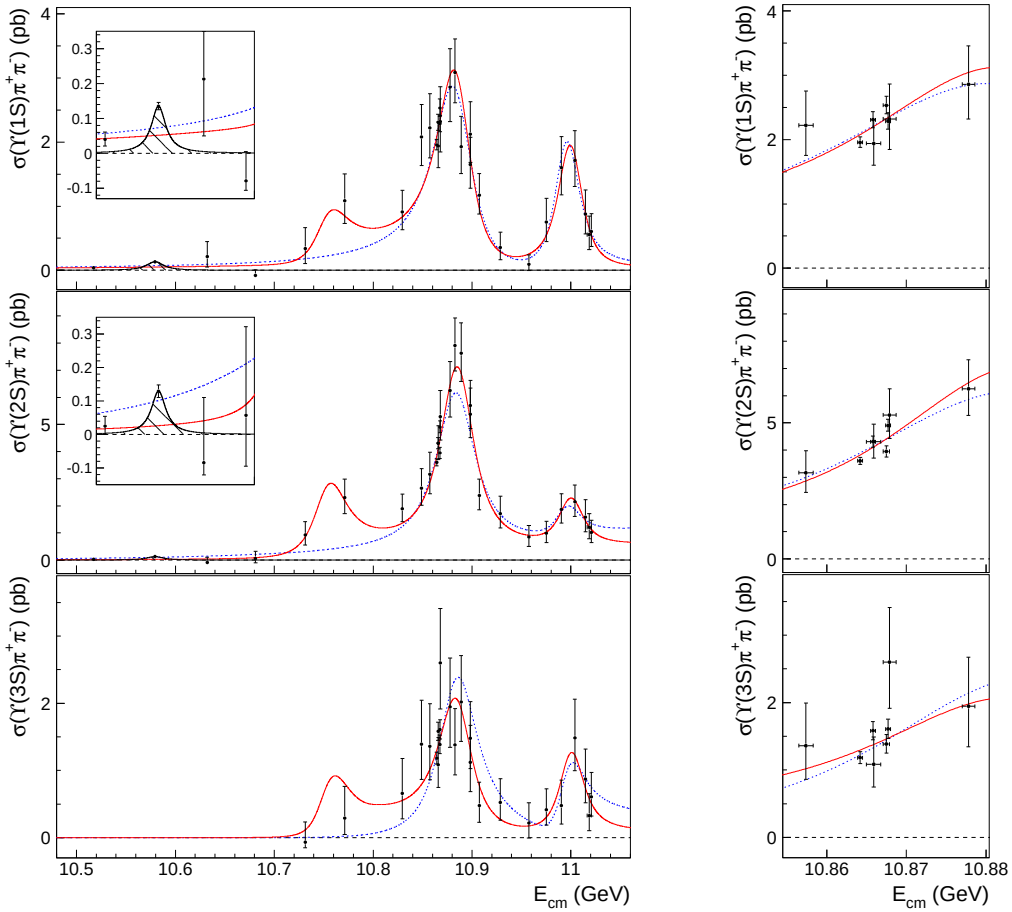


$M(\pi^+\pi^-) > 0.85$ GeV suppresses the QED background $\mu^+\mu^-\pi^+\pi^-$

Clear evidence for the $\Upsilon(1S)\pi^+\pi^-$ (3.6σ)

A. Abdesselam et al., arXiv:1905.05521

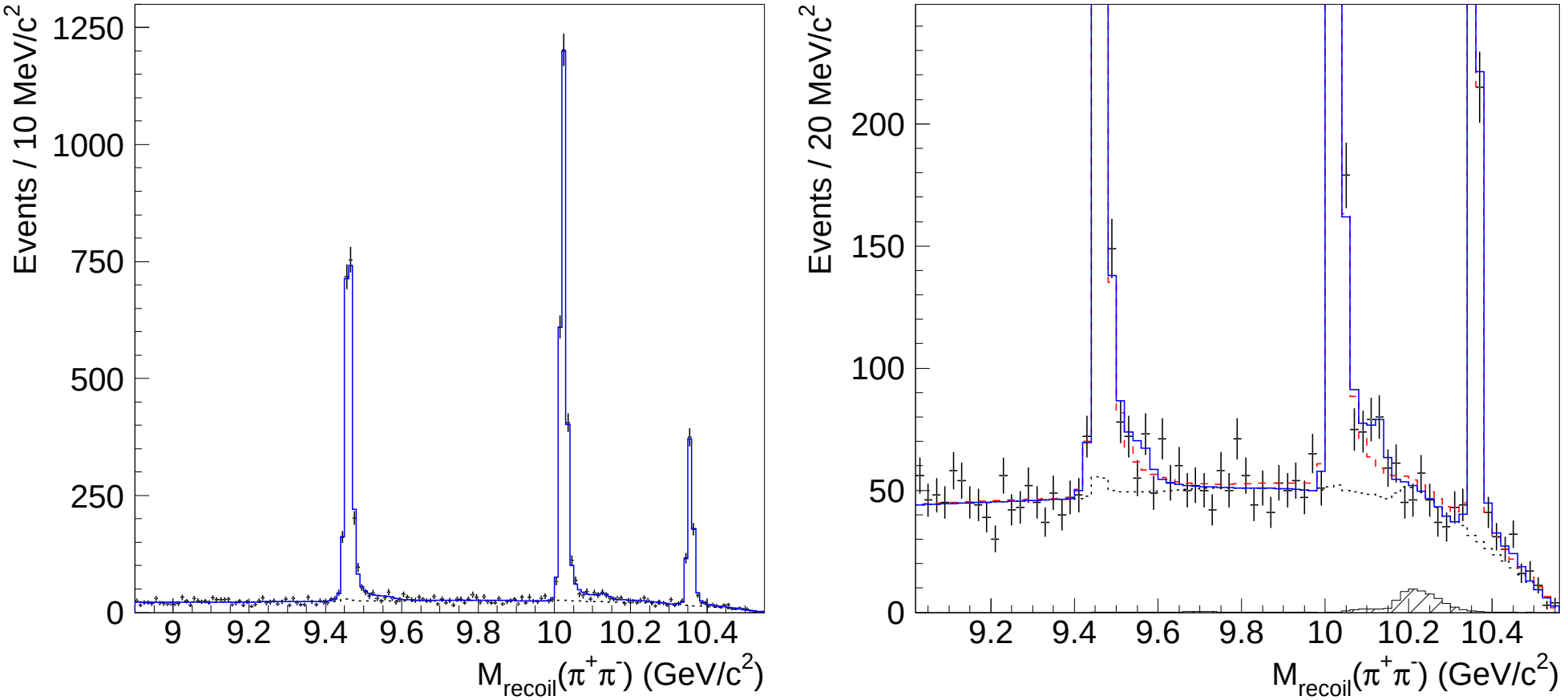
A new structure near 10.75 GeV in $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ – VI



The fit of the $\sigma(\Upsilon(nS))$ and $M_{\rm recoil}(\pi^+\pi^-)$ includes
the $\Upsilon(10860)$, $\Upsilon(11020)$, the new structure and the $\Upsilon(2S, 3S)$ tails

A. Abdesselam et al., arXiv:1905.05521

A new structure near 10.75 GeV in $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ – VII



$M_{\rm recoil}(\pi^+\pi^-)$ for $\mu^+\mu^-\pi^+\pi^-$ events at the $\Upsilon(10860)$ peak

A. Abdesselam et al., arXiv:1905.05521

A new structure near 10.75 GeV in $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ – VIII

Measured masses and widths

State	$\Upsilon(10860)$	$\Upsilon(11020)$	New structure
M, MeV	$10885.3 \pm 1.5\,^{+2.2}_{-0.9}$	$11000.0^{+4.0\ +1.0}_{-4.5\ -1.3}$	$10752.7 \pm 5.9\,^{+0.7}_{-1.1}$
Γ, MeV	$36.6^{+4.5\ +0.5}_{-3.9\ -1.1}$	$23.8^{+8.0\ +0.7}_{-6.8\ -1.8}$	$35.5^{+17.6\ +3.9}_{-11.3\ -3.3}$

The fit: Born cross sections, the new structure, $\Upsilon(2S, 3S)$ tails and $\Gamma_f(s)$

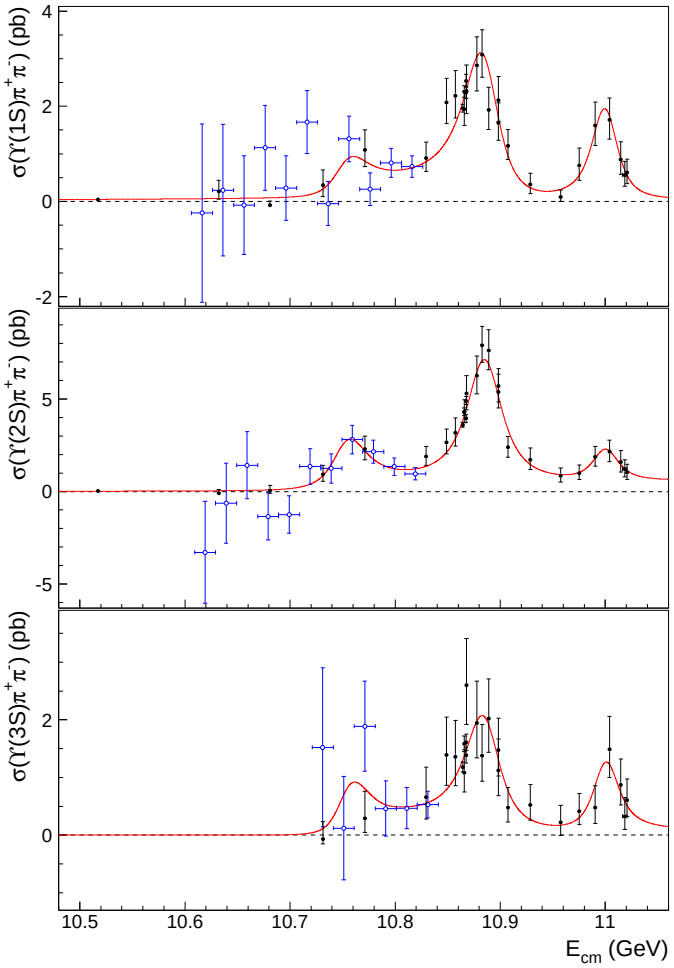
The range of $\Gamma_{ee}\mathcal{B}$ from multiple solutions in eV

State	$\Upsilon(10860)$	$\Upsilon(11020)$	New structure
$\Upsilon(1S)\pi^+\pi^-$	$0.75 - 1.43$	$0.38 - 0.54$	$0.12 - 0.47$
$\Upsilon(2S)\pi^+\pi^-$	$1.35 - 3.80$	$0.13 - 1.16$	$0.53 - 1.22$
$\Upsilon(3S)\pi^+\pi^-$	$0.43 - 1.03$	$0.17 - 0.49$	$0.21 - 0.26$

4 or 8 solutions are found for the sum of 3 or 4 Breit-Wigners

A. Abdesselam et al., arXiv:1905.05521

A new structure near 10.75 GeV in $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ – IX



Energy dependence of $\sigma(\Upsilon(nS))$ with visualized ISR

A. Abdesselam et al., arXiv:1905.05521

Search for $e^+e^- \to \gamma\chi_{cJ}$ and $e^+e^- \to \gamma\eta_c$ at Belle – I

The following data samples were used:

$\sqrt{s}$, GeV	10.52	10.58	10.867
$\int Ldt$, fb^{-1}	89.5	711.0	121.4

Reconstruction via the following decay channels:

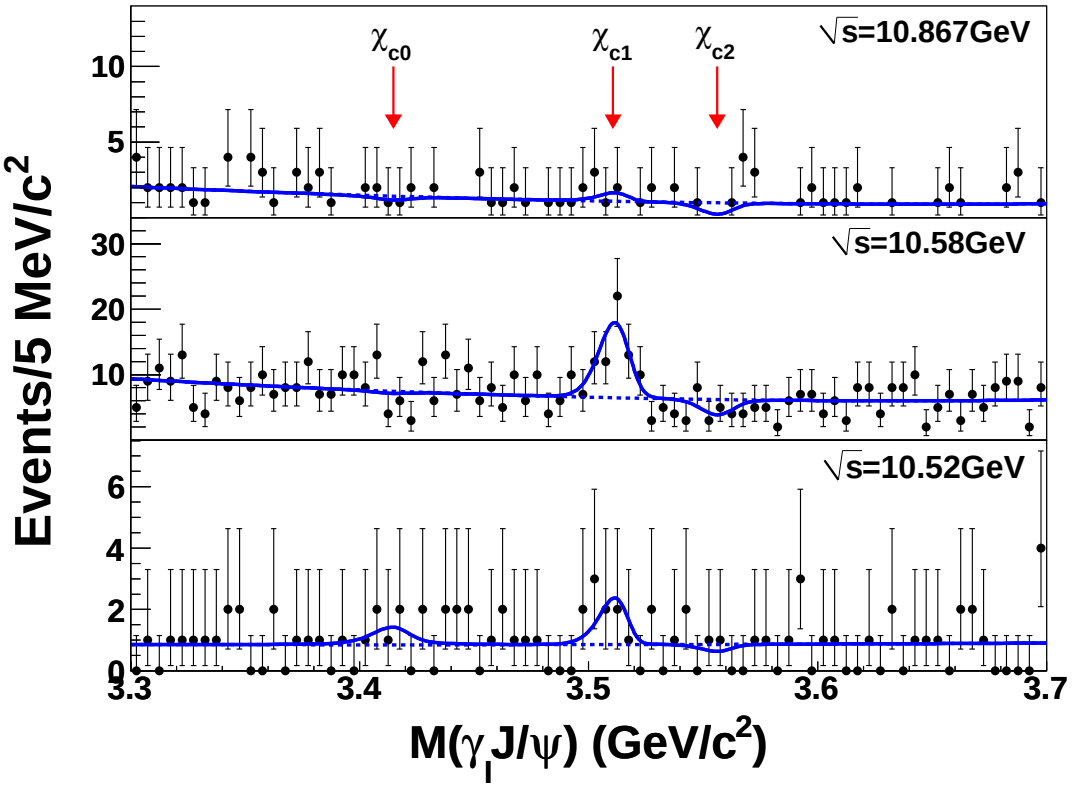
$\chi_{cJ} \to J/\psi\gamma$, $J/\psi \to \mu^+\mu^-$, $J = 0,\ 1,\ 2$

$\eta_c \to K^0_S K^\pm\pi^\mp,\ K^+K^-\pi^+\pi^-,\ 2(\pi^+\pi^-),\ 2(K^+K^-),\ 3(\pi^+\pi^-)$

The 5C (4C) kinematic fit was performed for $\chi_{cJ}\gamma$ ($\eta_c\gamma$)

S. Jia et al., Phys. Rev. D98, 092015 (2018)

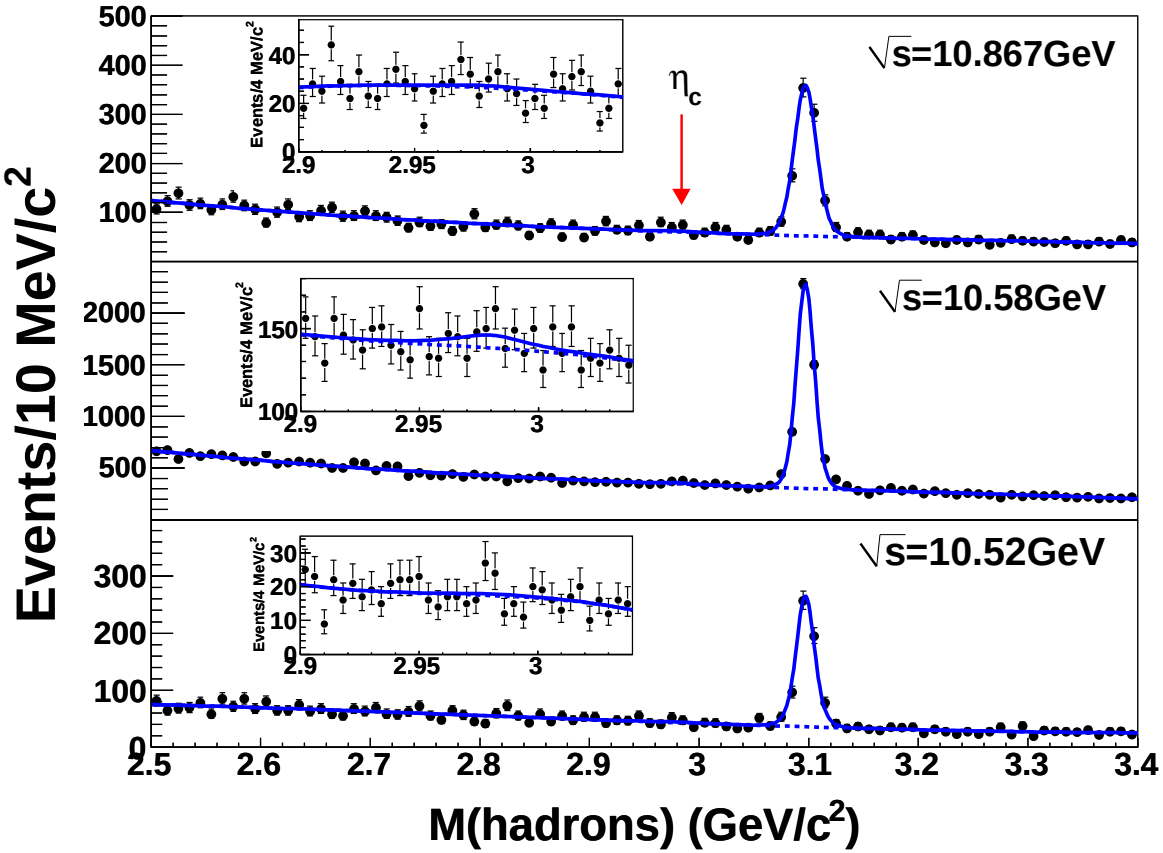
Search for $e^+e^- \to \gamma\chi_{cJ}$ and $e^+e^- \to \gamma\eta_c$ at Belle – II



A clear χ_{c1} signal (5.2σ) at $\Upsilon(4S)$, $\sigma = 17.3^{+4,2}_{-3.9} \pm 1.7$ fb

S. Jia et al., Phys. Rev. D98, 092015 (2018)

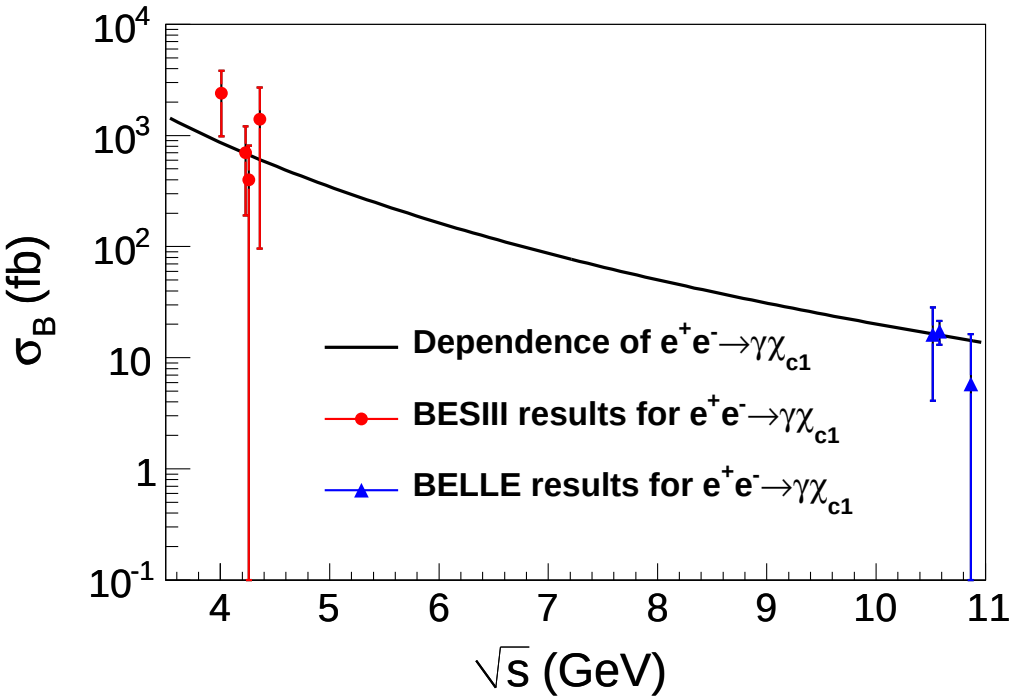
Search for $e^+e^- \to \gamma\chi_{cJ}$ and $e^+e^- \to \gamma\eta_c$ at Belle – III



No η_c signal, J/ψ signals are from ISR

S. Jia et al., Phys. Rev. D98, 092015 (2018)

Search for $e^+e^- \to \gamma\chi_{cJ}$ and $e^+e^- \to \gamma\eta_c$ at Belle – IV



Fit of Belle and BESIII data assuming $\sigma(s) \propto 1/s^n$:

$\sigma(e^+e^- \to \chi_{c1}\gamma) \propto s^{-(2.1^{+0.3}_{-0.4}\pm 0.3)}$

S. Jia et al. (Belle), Phys. Rev. D98, 092015 (2018)

M. Ablikim et al. (BESIII), Chin. Phys. C39, 041001 (2015)

Search for $e^+e^- \to \gamma\chi_{cJ}$ and $e^+e^- \to \gamma\eta_c$ at Belle – V

Theory (NRQCD factorization + relativistic corrections) in
N. Brambilla et al., Phys. Rev. D97. 096001 (2018)
gives for the cross section of the process in fb

Process	$e^+e^- \to \chi_{c0}\gamma$	$e^+e^- \to \chi_{c1}\gamma$	$e^+e^- \to \chi_{c2}\gamma$
Theory	1.3 ± 0.4	15.4 ± 6.7	4.7 ± 2.6
Belle	< 205.9	$17.3^{+4.2}_{-3.9} \pm 1.7$	< 5.7

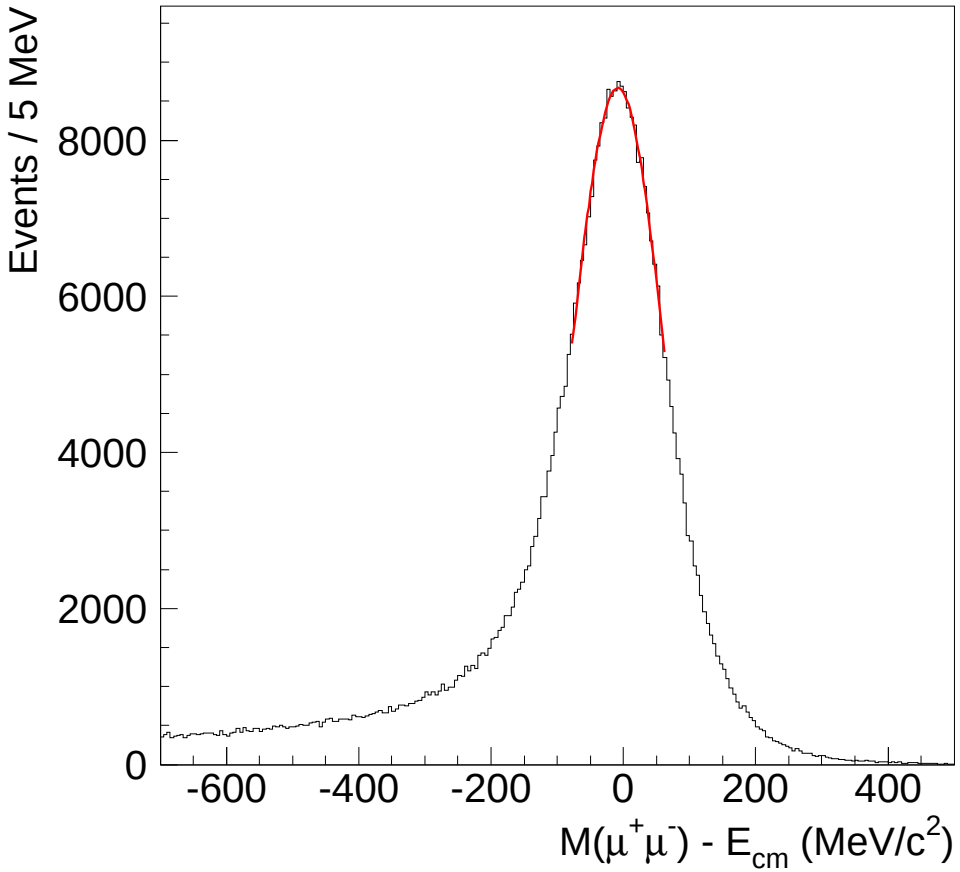
S. Jia et al. (Belle), Phys. Rev. D98, 092015 (2018)

Conclusions

- A new structure is observed in energy dependence of $\sigma(e^+e^- \to \Upsilon(nS)\pi^+\pi^-)$, n=1,2,3 ($6.7\sigma$)
- The parameters of $\Upsilon(10860)$ and $\Upsilon(11020)$ are improved
- Evidence is found for $\sigma(e^+e^- \to \Upsilon(1S)\pi^+\pi^-)$ at 10.52 GeV, cross sections and $M(\pi^+\pi^-)$ are consistent with the $\Upsilon(2S, 3S)$ tails, they will affect the $\mathcal{B}(\Upsilon(4S))$ measured at the $\Upsilon(4S)$ peak only
- More channels needed to clarify the nature of the new state: a resonance ($\Upsilon(3D)$ with enhanced $S-D$ mixing), an exotic state (compact tetraquark or hadrobottomonium), a non-resonant effect due to rescattering
- $e^+e^- \to \chi_{cJ}\gamma,\ \eta_c\gamma$ are studied at 10.52, 10.58 and 10.867 GeV
- A clear signal (5.2σ) is observed in $\chi_{c1}\gamma$ at 10.58 GeV
- Energy dependence of $\sigma(e^+e^- \to \chi_{c1}\gamma)$ is found from BESIII (4.009-4.36 GeV) to Belle (10.58 GeV) c.m.energies

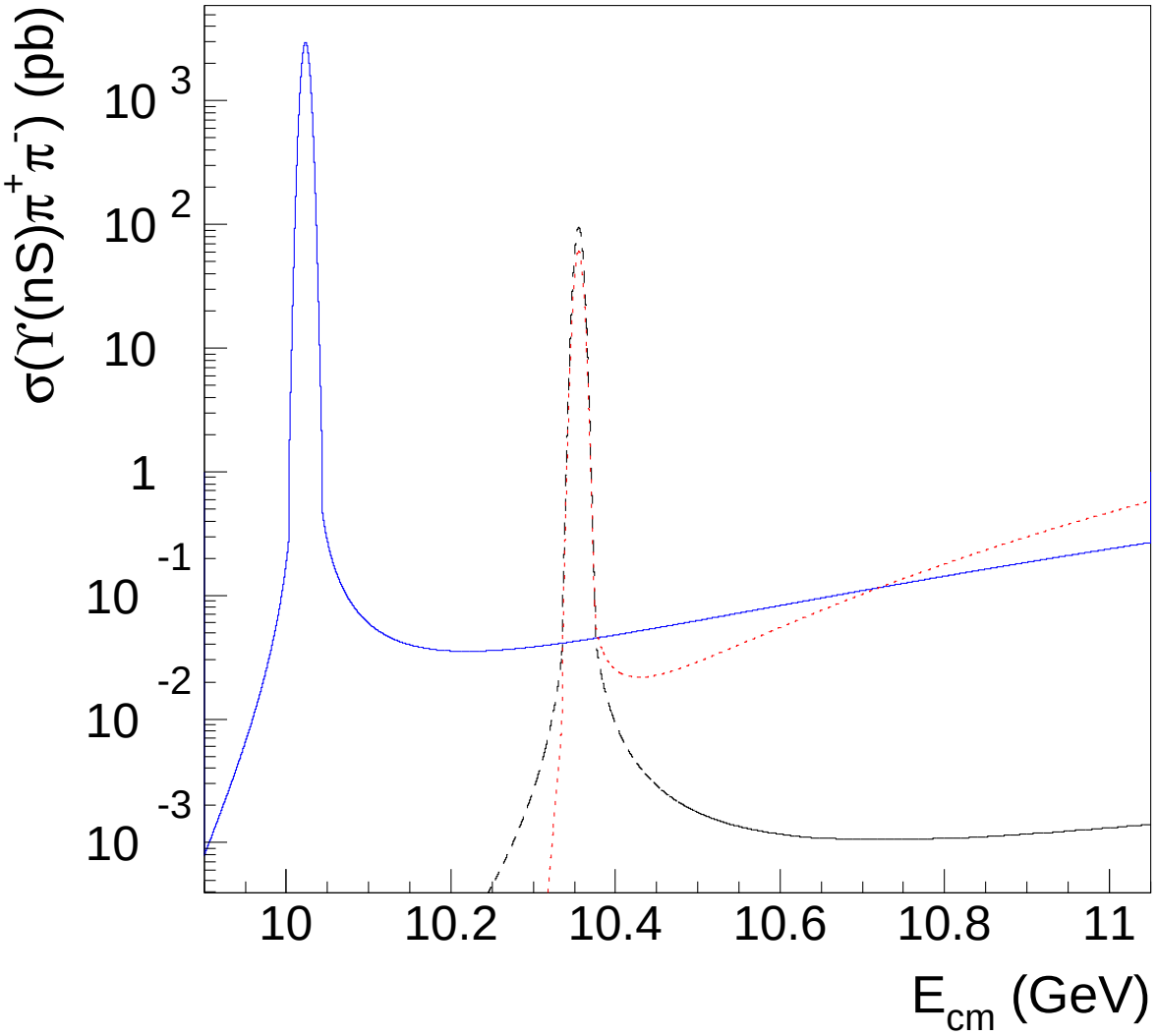
Backup Slides

A new structure near 10.75 GeV in $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$



A. Abdesselam et al., arXiv:1905.05521

A new structure near 10.75 GeV in $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$



A. Abdesselam et al., arXiv:1905.05521

A new structure near 10.75 GeV in $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$

	$M_{\Upsilon(10860)}$	$\Gamma_{\Upsilon(10860)}$	$M_{\Upsilon(11020)}$	$\Gamma_{\Upsilon(11020)}$	$M_{\rm new}$	$\Gamma_{\rm new}$
$\Upsilon_{\rm new}$ param.	$^{+0.0}_{-0.8}$	$^{+0.0}_{-0.4}$	$^{+0.0}_{-0.7}$	$^{+0.0}_{-0.6}$	–	–
$\Upsilon(10860)$ param.	$^{+2.2}_{-0.0}$	$^{+0.5}_{-0.0}$	$^{+0.3}_{-0.0}$	± 0.0	$^{+0.0}_{-0.1}$	$^{+0.0}_{-0.1}$
$\Upsilon_{\rm new}$, $\Upsilon(11020)$ mod.	$^{+0.1}_{-0.4}$	± 0.2	$^{+0.7}_{-0.8}$	$^{+0.7}_{-0.5}$	$^{+0.6}_{-0.0}$	$^{+3.1}_{-0.6}$
$\Upsilon(2S,3S)$ tails	$^{+0.2}_{-0.3}$	$^{+0.0}_{-1.0}$	$^{+0.6}_{-0.7}$	$^{+0.0}_{-1.6}$	$^{+0.4}_{-1.1}$	$^{+2.3}_{-3.2}$
Total	$^{+2.2}_{-0.9}$	$^{+0.5}_{-1.1}$	$^{+1.0}_{-1.3}$	$^{+0.7}_{-1.8}$	$^{+0.7}_{-1.1}$	$^{+3.9}_{-3.3}$