Recent results in quarkonium production and decays

Peter M. Lewis | University of Hawai`i
on behalf of the BaBar and Belle Collaborations

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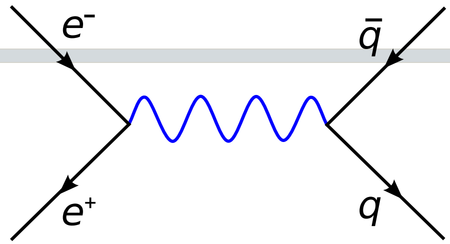
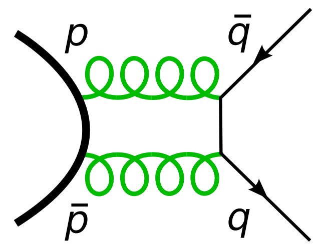
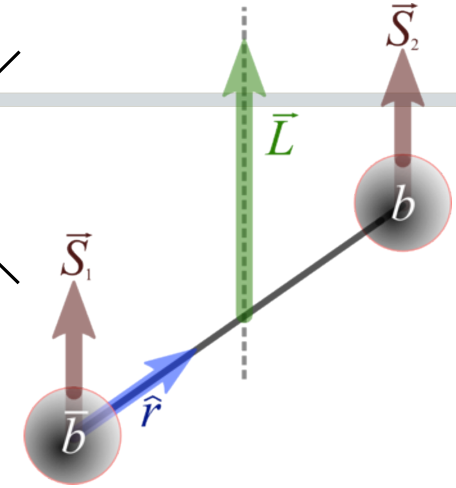
- Quarkonium
  - Charmonium
  - Bottomonium
- Spectroscopy and production
- Υ(5S)
- Decays
- Double charmonium production
- Outlook

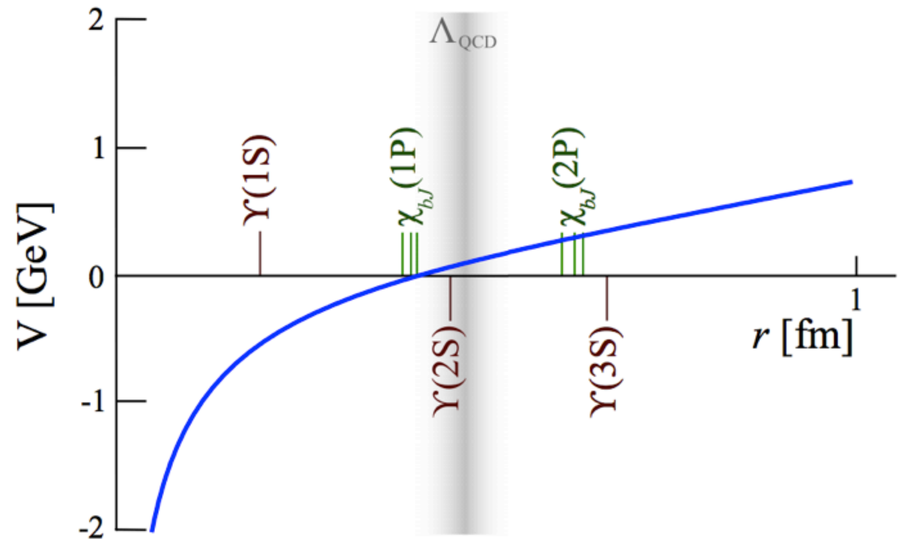
Quarkonium

- $c\bar{c}$ and $b\bar{b}$ bound states $n^{2S+1}L_J$
- Produced at *B*-factories via virtual photons and at hadron colliders via gluons
- Excellent features for probing QCD:
  - A rich array of stable bound states
  - High masses; simple nonrelativistic positronium-like potential models
  - Resolvable relativistic corrections
  - Spans transition region between confinement and asymptotic freedom
  - Transitions are soft and test non-perturbative QCD calculations
  - Below open-flavor thresholds, widths are narrow and radiative decays are competitive
- There's a great value in precision measurements of production and decays in heavy quarkonia [but you won't see me write "NP"]



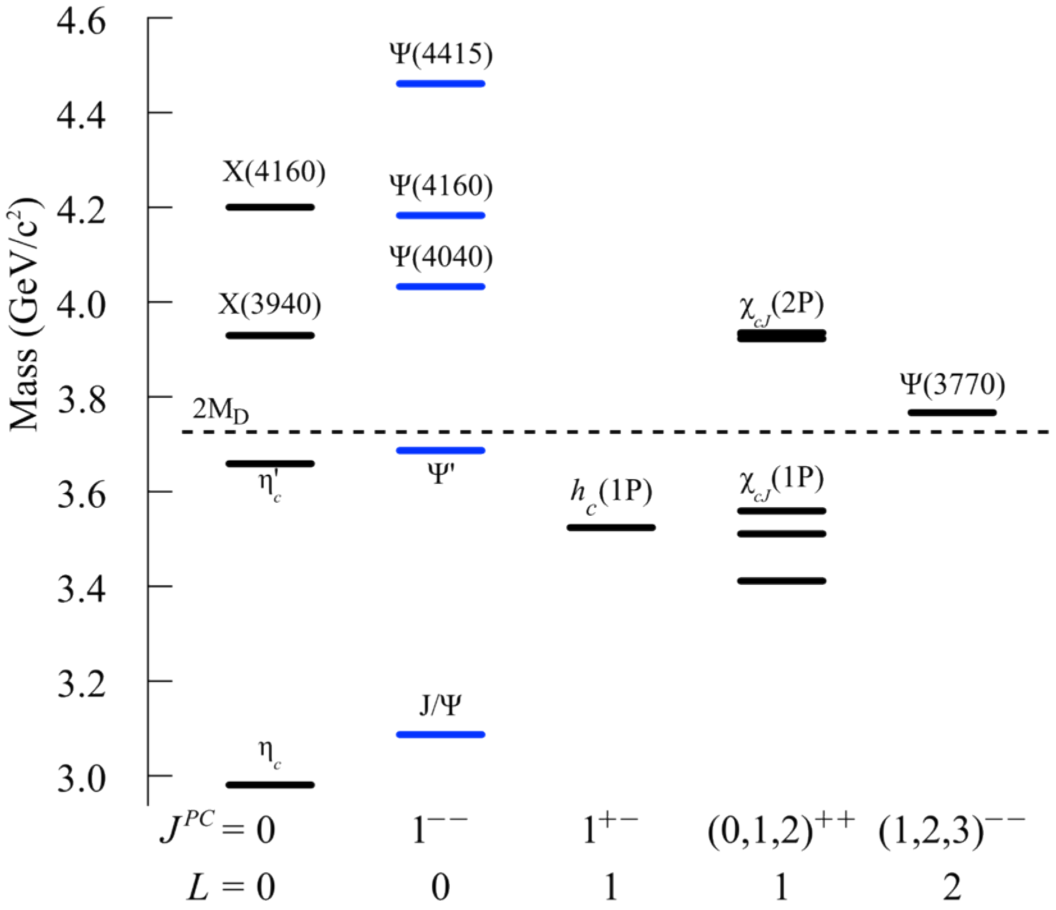






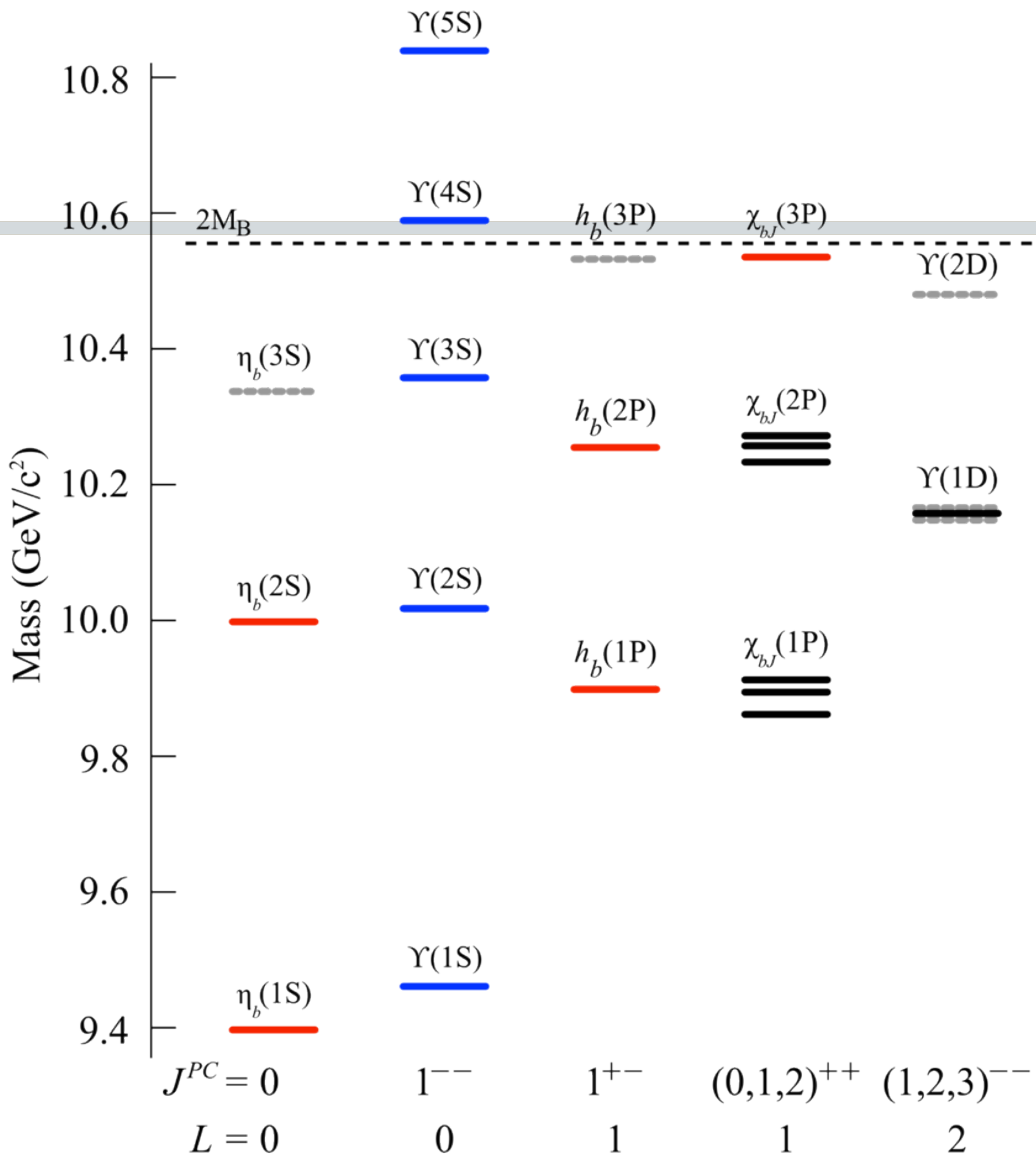
Charmonium

- [simplified view]
- **Blue**: producible in e^+e^- annihilation.



Bottomonium

- Open-flavor threshold is above Υ(3S) mass; more visible states
- Very high mass; nonrelativistic descriptions and mass eigenstates
- **Blue**: producible in e^+e^- annihilation.
- **Dotted**: not yet observed.
- **Red**: first observed 2008 or later (Υ(2,3S) data first available from Belle and BaBar plus commissioning of LHC)

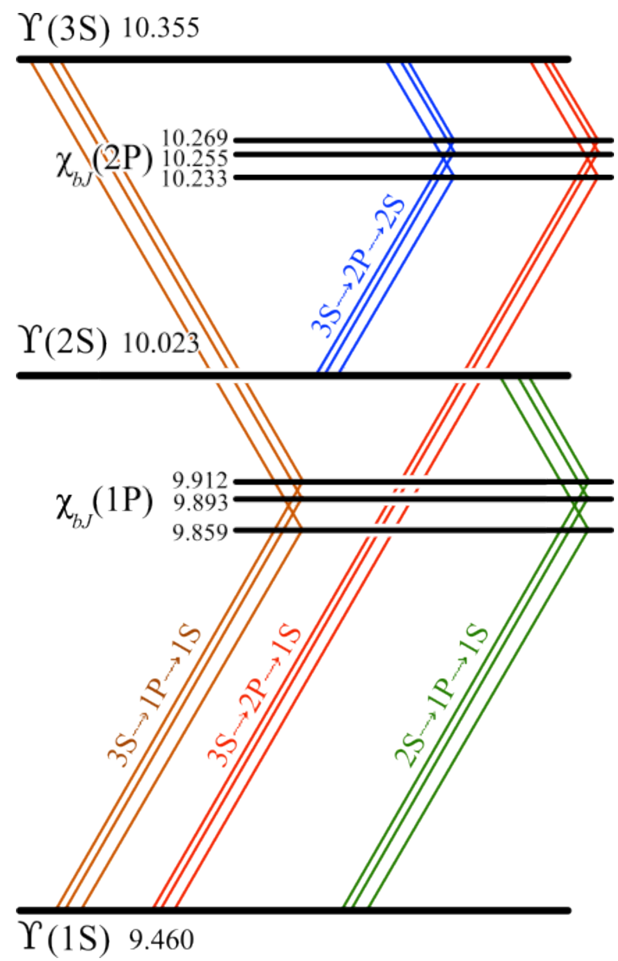


Spectroscopy and production

Radiative bottomonium spectroscopy at BaBar

PRD 90 112010 (2014)

- Comprehensive exclusive analysis of E1 radiative transitions involving the triplet *P* states using $(121\pm1)\times10^{6}$ Y(3S) and $(98\pm1)\times10^{6}$ Y(2S) mesons
- Final states: $\gamma\gamma\mu^{+}\mu^{-}$
- Two analysis techniques:
  - Calorimeter photons
  - One calorimeter plus one converted photon
- New beam background rejection using calorimeter timing
- Fit to the energy spectrum of the soft photon (calorimeter analysis) or hard photon (converted analysis) to obtain branching fractions
- Targeting particularly:
  - $\chi_{b0}(2P) \rightarrow \gamma\ Y(2S)$
  - $\chi_{b0}(2P) \rightarrow \gamma\ Y(1S)$
  - $\chi_{b0}(1P) \rightarrow \gamma\ Y(1S)$
  - $Y(3S) \rightarrow \gamma\ \chi_{b0}(1P)$
  - Fine mass splittings of $\chi_{bJ}(1,2P)$



NRQCD

PRD 90 112010 (2014)

- Expectation value of effective Hamiltonian in nonrelativistic QCD [NRQCD] gives χ_b masses:

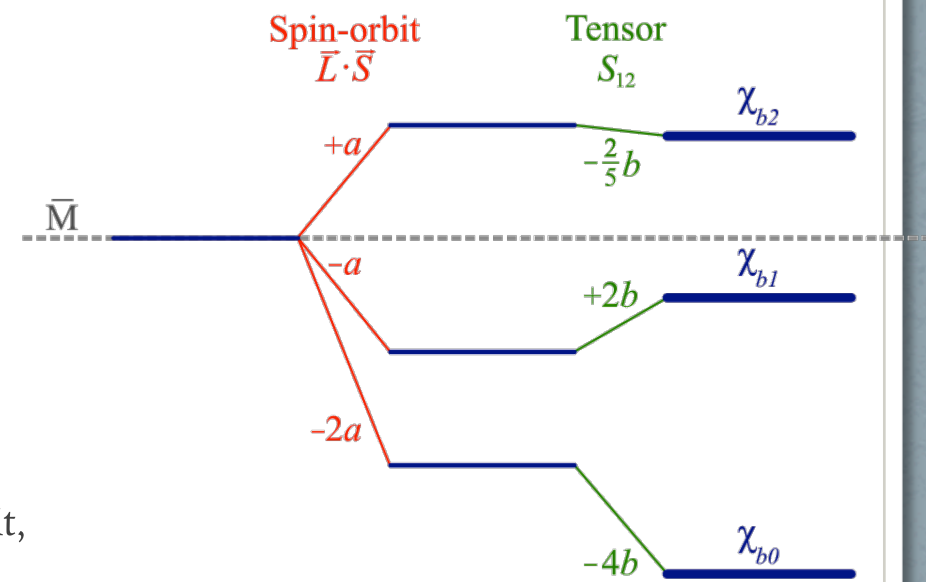
$$M_{nP(J)} = \overline{M_{nP}} + a\,\langle \mathbf{L}\cdot\mathbf{S}\rangle + b\,\langle S_{12}\rangle + c\,\langle \mathbf{S_1}\cdot\mathbf{S_2}\rangle$$

$$M_{nP(2)} = \overline{M_{nP}} + a - 2b/5,$$

$$M_{nP(1)} = \overline{M_{nP}} - a + 2b,$$

$$M_{nP(0)} = \overline{M_{nP}} - 2a - 4b,$$

- The coefficients a, b and c correspond to spin-orbit, tensor, and spin-spin interactions (c drops out)
- In the past, theorists have checked a and b against absolute masses, such as from the PDG
- But mass *splittings* can determine the parameters a and b with much lower systematic error (bottom right)
- As a “bonus,” this BaBar analysis provides high-precision measurements of a and b (also corresponding lattice coefficients)



$$a = \frac{1}{6}\left(\delta_0 - \frac{5}{2}\delta_2\right),$$

$$b = \frac{5}{72}\left(2\delta_0 + \delta_2\right).$$

$$\delta_0 = M_{nP(1)} - M_{nP(0)}$$

$$\delta_2 = M_{nP(1)} - M_{nP(2)}$$

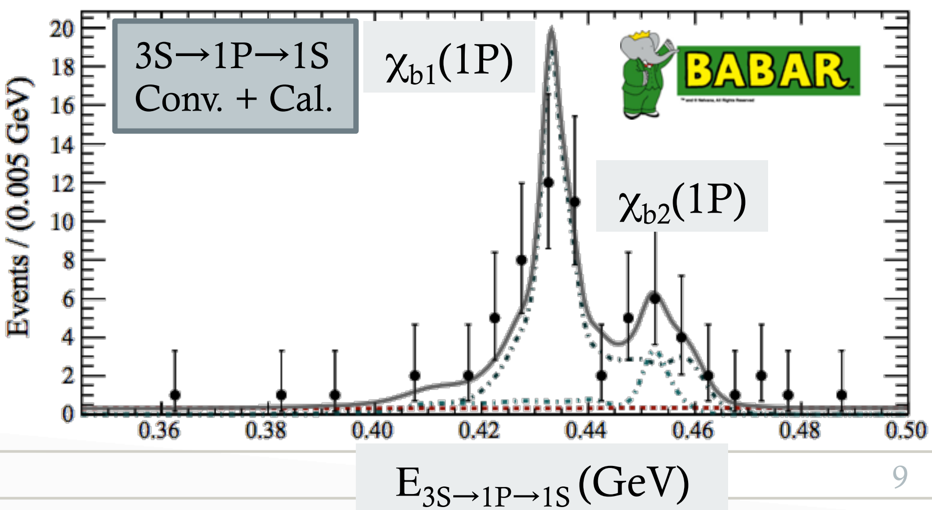
Radiative bottomonium spectroscopy at BaBar

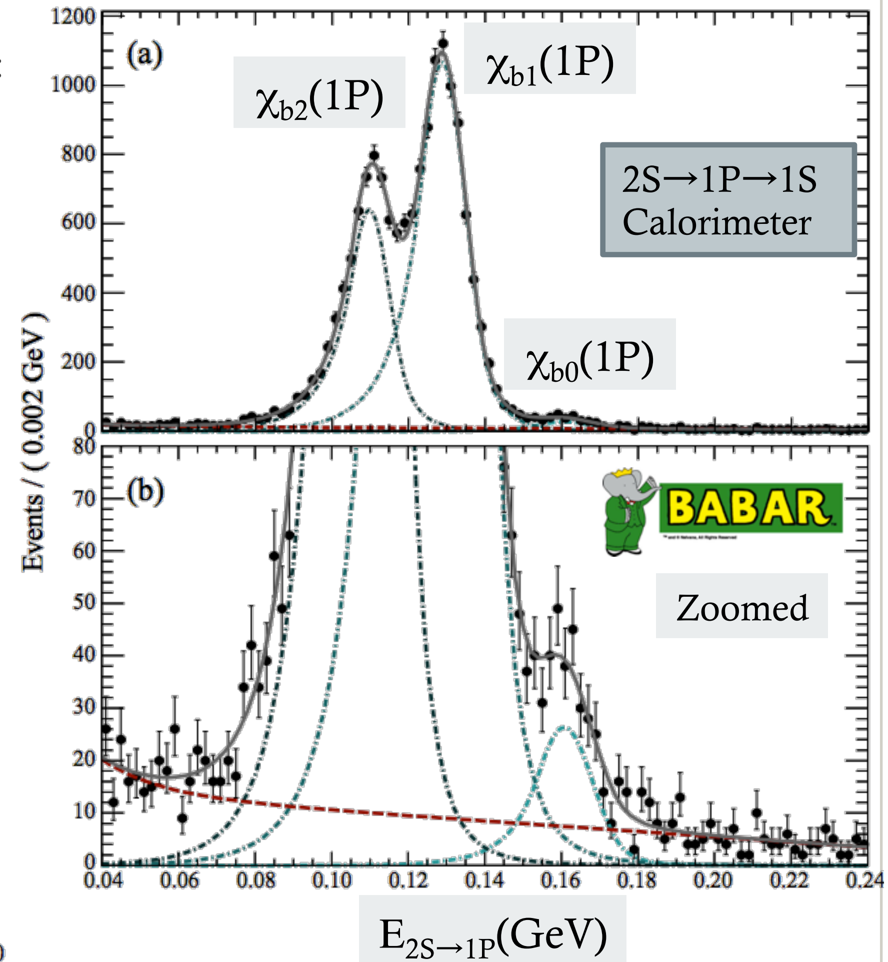
Results

PRD 90 112010 (2014)

- Best-yet observational significance for the transitions:
  - 8.9σ for $\chi_{b0}(1P) \to \gamma\, \Upsilon(1S)$
  - 5.9σ for $\chi_{b0}(2P) \to \gamma\, \Upsilon(2S)$
  - 2.1σ for $\chi_{b0}(2P) \to \gamma\, \Upsilon(1S)$
- $\mathcal{B}(\Upsilon(3S) \to \gamma\chi_{b1}(1P)) = 1.3^{+0.9}_{-0.8} \times 10^{-5}$
- Precision fine structure parameters for NRQCD:

a(MeV)	$1P$	13.34 ± 0.18
	$2P$	9.40 ± 0.31
b(MeV)	$1P$	3.19 ± 0.13
	$2P$	2.39 ± 0.25





χ_{bJ} production via converted photons at LHCb

arXiv:1409.1408
JHEP 1410 (2014) 88

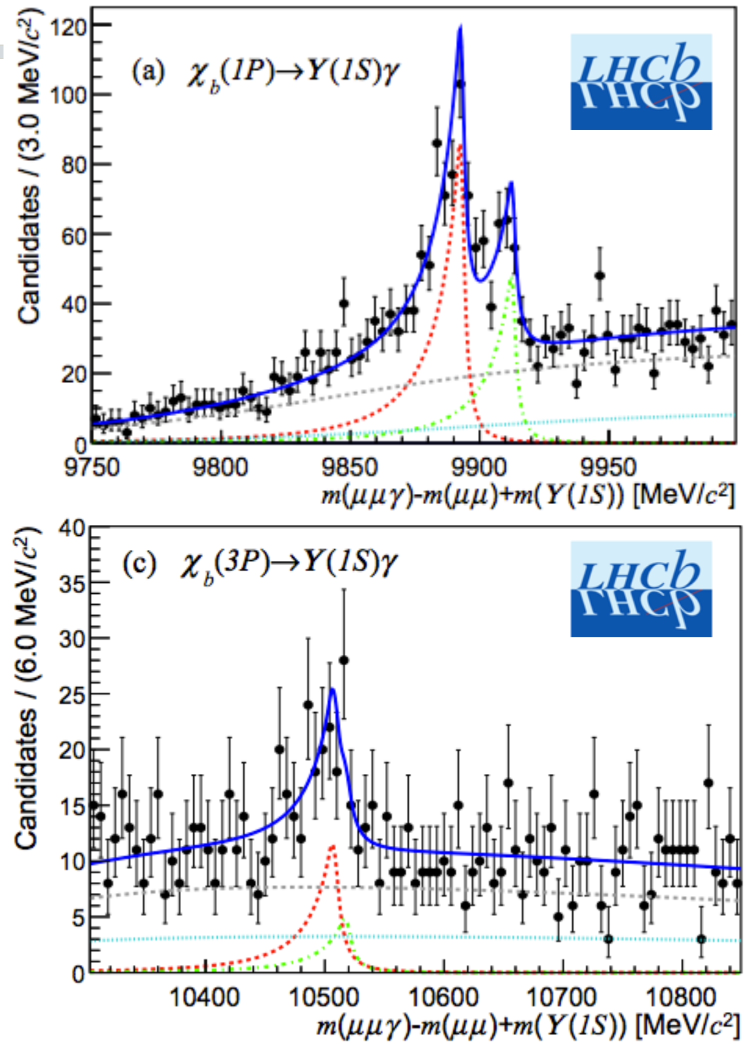
- Converted photon χ_{bJ} spectroscopy using 3.0 fb^{-1} at 7 and 8TeV, covering χ_{bJ} rapidity range 2.0-4.5
- $\chi_{bJ}(nP) \rightarrow \gamma \Upsilon(mS)$; $\Upsilon(mS) \rightarrow \mu^+\mu^-$, with γ converted to e^+e^- pair in detector material
  - Excellent resolution; χ_{bJ} mass splittings resolvable (except for 3P)
- Fit double Crystal Ball functions to J=1, 2 peaks
- Results (3.6σ significance for χ_{bJ}(3P) peak)

$$m(\chi_{b1}(3P)) = 10515.7^{+2.2}_{-3.9}(\text{stat})^{+1.5}_{-2.1}(\text{syst}) \text{ MeV}/c^2$$

$$\Delta m_{12}(1P) = 19.81 \pm 0.65(\text{stat}) \pm 0.20(\text{syst}) \text{ MeV}/c^2$$

$$\Delta m_{12}(2P) = 12.3 \pm 2.6(\text{stat}) \pm 0.6(\text{syst}) \text{ MeV}/c^2$$

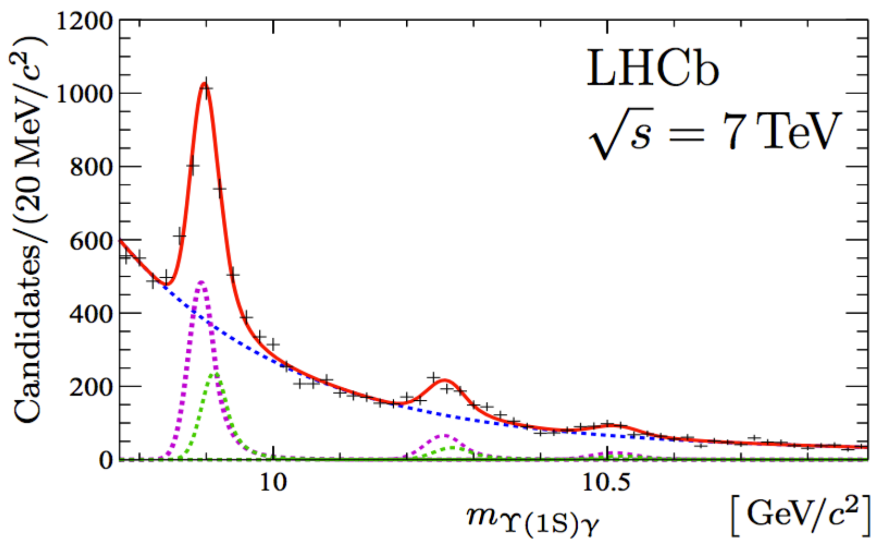
- Splittings consistent with BaBar results (previous slides):
  - Δm_{12}(1P)=19.01 ± 0.24 MeV/c^2
  - Δm_{12}(2P)=13.04 ± 0.26 MeV/c^2



arXiv:1407.7734
Eur. Phys. J. C 74 (2014) 3092.

Exclusive χ_b production at LHCb

- Same dataset; calorimeter photons, not converted
- Final state: μμγ
- A measurement of the fractio $\mathcal{R}^{\chi_b(mP)}_{\Upsilon(nS)}$ mesons originating from radiative decays of χ_b mesons
- Feed-down contribution from χ_b's helps interpretation of *S*-wave polarization
- Corrected mass distributions for selected χ_b candidates, below, decaying into Υ(1S)



Exclusive χ_b production at LHCb

arXiv:1407.7734
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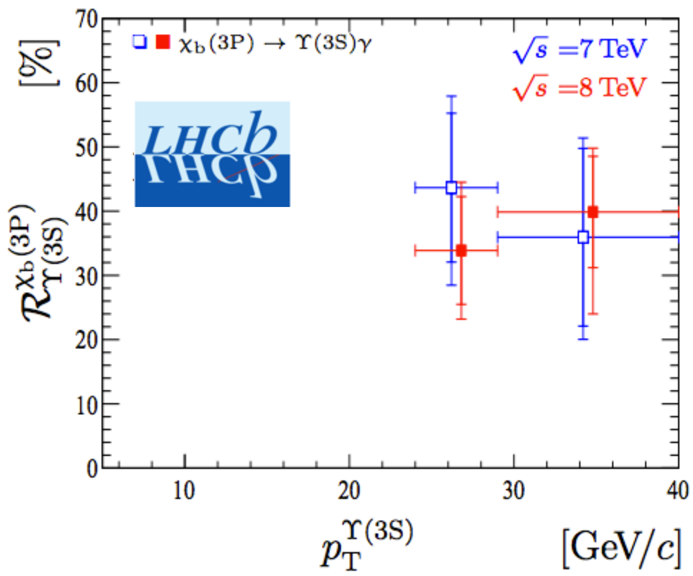
- Same dataset; calorimeter photons, not converted
- Final state: $\mu\mu\gamma$
- A measurement of the fractions of Υ mesons originating from radiative decays of χ_b mesons $\mathcal{R}^{\chi_b(mP)}_{\Upsilon(nS)}$
- Feed-down contribution from χ_b's helps interpretation of *S*-wave polarization
- Corrected mass distributions for selected χ_b candidates, right, decaying into Υ(1S), top, Υ(2S), middle and Υ(3S), bottom

Results:

- **A first observation of the χ_b(3P) →Υ(3S) transition**
- $\mathcal{R}^{\chi_b(3P)}_{\Upsilon(3S)}$ is **large**; feed-down may not be negligible, as is often assumed when comparing with theory
- 3P mass comparable to conversions analysis:
  - $m(\chi_{b1}(3P)) = 10511.3 \pm 1.7 \pm 2.5$ MeV/c^2

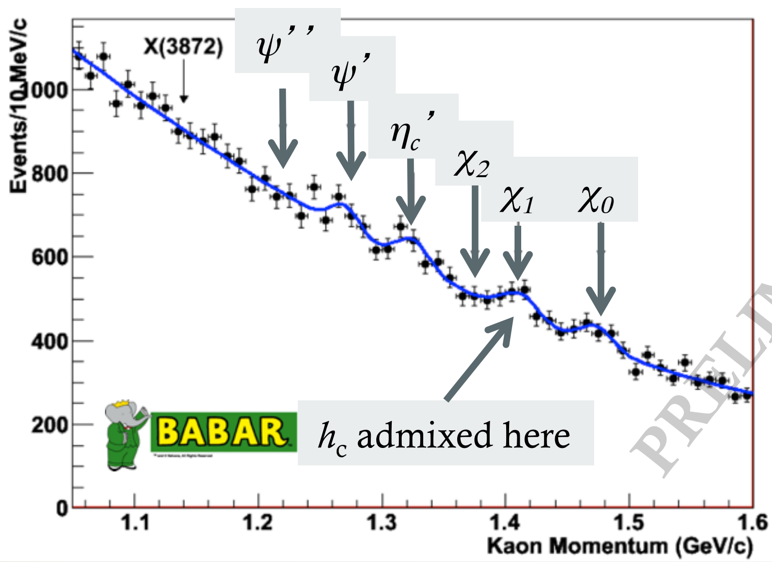


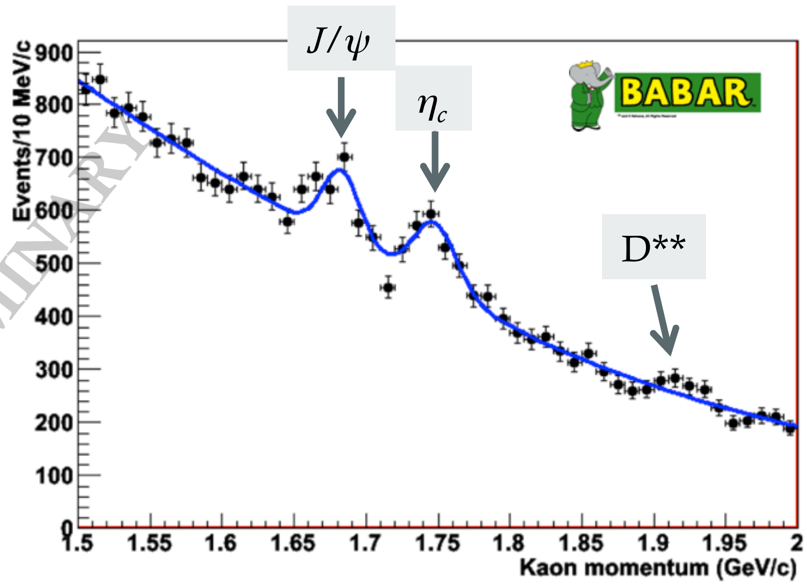
[Preliminary] Update on inclusive charmonium production in $B^{\pm}$ decays

Not yet on arXiv

- Two-body decays $B^{\pm} \to X_{cc} + K^{\pm}$
  - 424 fb^{-1} (210 fb^{-1} in original study)
  - X_{cc} state has large available phase space; charmonia are produced with roughly equal rate
  - Direct measurement of branching fractions $\mathcal{B}(B^{\pm} \to X_{cc} + K^{\pm})$
  - Range increased from previous analysis

- Inclusive approach
  - Tag one B
  - Boost into COM frame of the second B
  - Look at kaon momentum in that frame
    - Continuous background
    - Monochromatic peaks from decays to charmonium

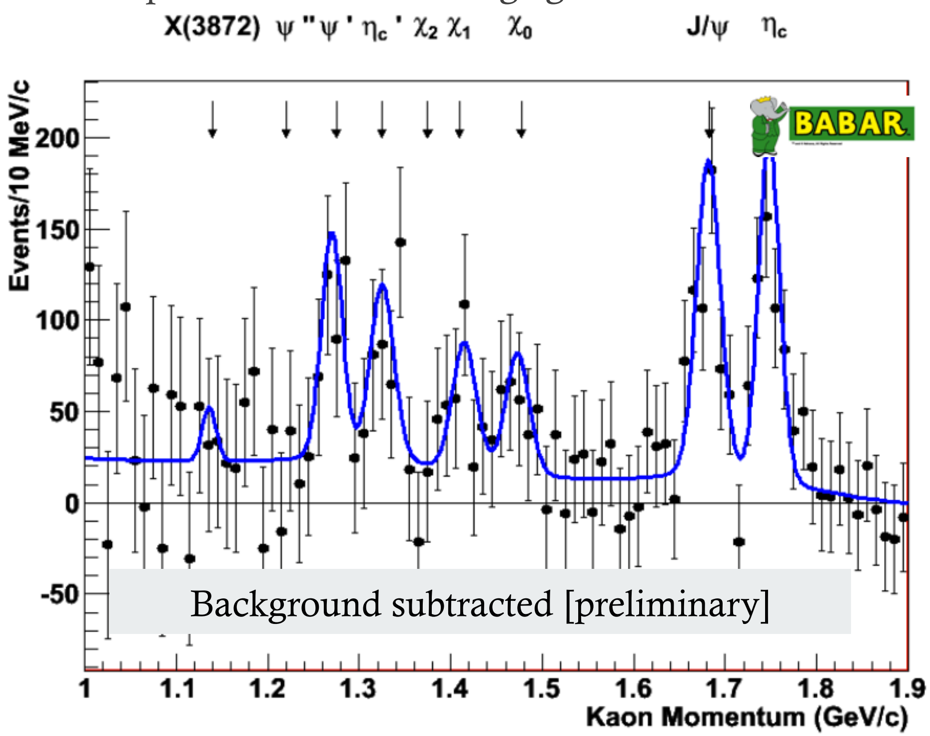




[Preliminary] Update on inclusive charmonium production in $B^{\pm}$ decays

Not yet on arXiv

- Results
  - An improvement in $\mathcal{B}(B^{\pm}\rightarrow X_{cc}+K^{\pm})$ for all channels (right)
  - Null results for search of momentum spectrum of $K^{\pm}$ recoiling against B^0



Particle	Yield	Peak Position	Width	BF(10^{-4})
J/ψ	516±67			9.6±1.2(sta)±0.8(sys)
η_c	655±77	2982±5	<43	13.3±1.8(stat)±0.4(sys)±0.3(ref)
χ_{c0}	218±76			4.4±0.9
χ_{c1}	192±35			7.0±1.3(stat)±1.0(sys)
χ_{c2}	0±32			<1.2
η_c (2S)	283±94	3632±0.007	<33	6.0±2.1(stat)±0.4(sys)
ψ'	293±90			6.2±2(stat)±0.6(sys)
$\psi(3770)$	0±49			<2.0
X(3872)	75±81			1.4±1.5 or < 4.4

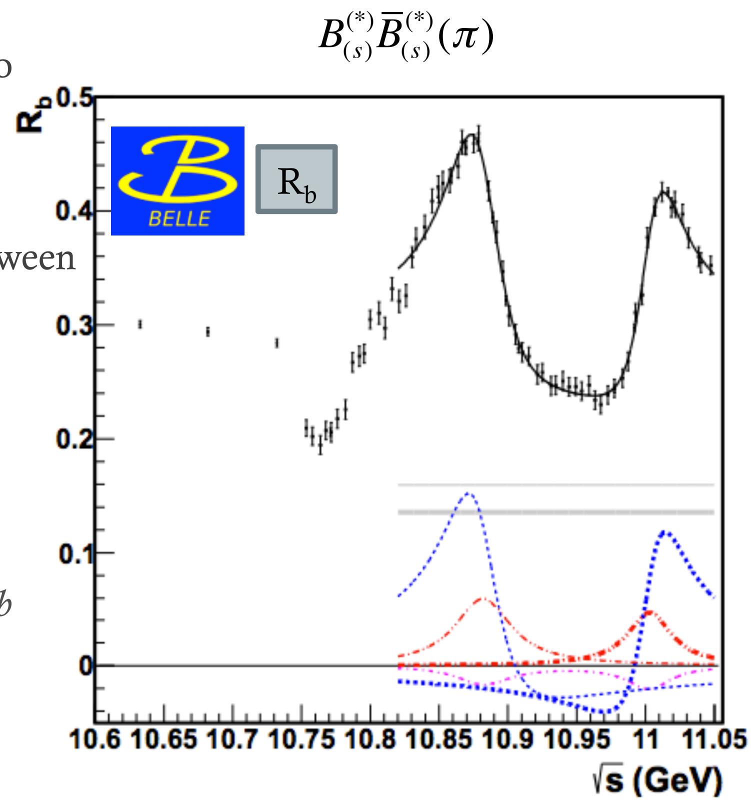
PRELIMINARY

Υ(5S)

Relative rates of strong transitions from the "Y(5S)" resonance at Belle

Measurements of $\sigma(e^+e^- \to Y(nS)\pi^+\pi^-)$ and $\sigma(e^+e^- \to bb)$ in the Y(10860) and Y(11020) resonance region
arXiv:1501.01137
Sub. to PRL

- What is "Y(5S)"?
  - Previous Belle results: rates for $Y(nS) \to \pi^+\pi^- Y(mS)$ are two orders of magnitude greater for n=5 than for n=2,3,4
  - Rate to $h_b(mP)$ states is anomalously high
  - "Y(5S)" is not exactly Y(5S)
- Use 121.4 fb^{-1} from Y(5S) mass plus 77 other scan points between 10.63 and 11.05 GeV ("Y(6S)")
- Compare cross sections to muon-pair Born cross section:
  - Open decays: $R_b = \sigma(e^+e^- \to b\bar{b})/\sigma^0_{\mu\mu}$
  - Transitions: $R_{Y\pi\pi} = \sigma(e^+e^- \to Y(nS)\pi^+\pi^-)/\sigma^0_{\mu\mu}$ (n=1,2,3)
- Fit resonances, coherent and incoherent continuum
- Results
  - R_b results are **paradoxical**, likely due to poorly modeled *bb* background; this method is suspect
  - (also no sign of 10.91 GeV tetraquark candidate)



Relative rates of strong transitions from the "Υ(5S)" resonance at Belle

Measurements of σ(e^+e^- →Υ(nS)$\pi^+\pi^-$) and σ(e^+e^- →bb) in the Υ(10860) and Υ(11020) resonance region
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- Compare cross sections to muon-pair Born cross section:
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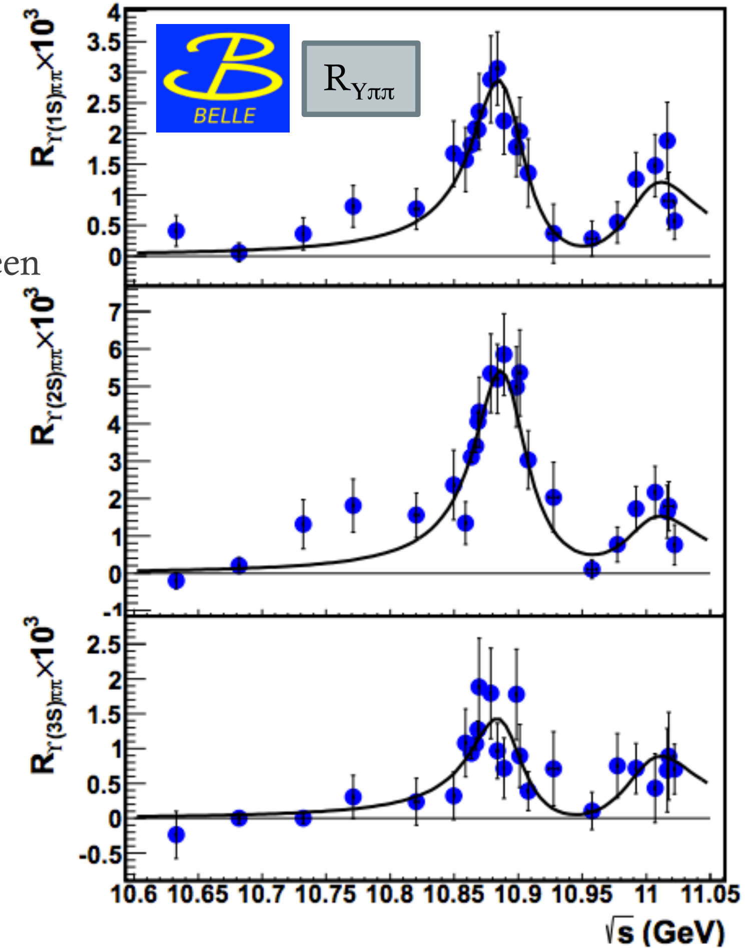
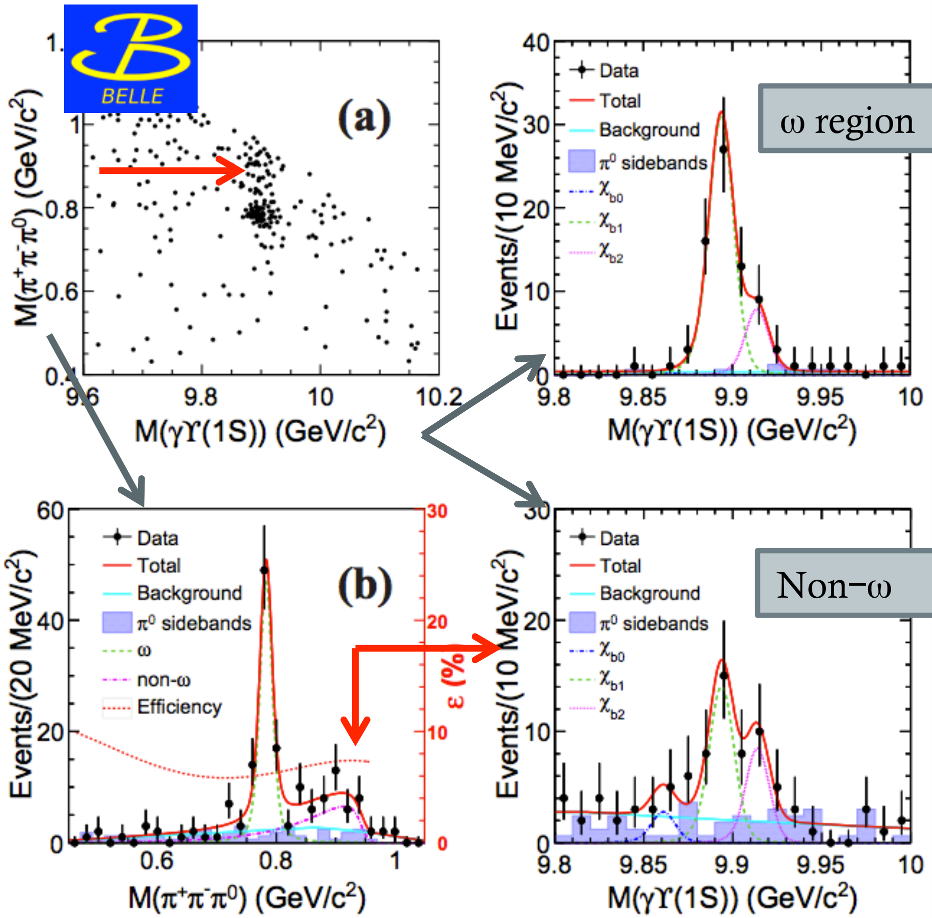
- Fit resonances, coherent and incoherent continuum
- Results
  - R_b results are **paradoxical**, likely due to poorly modeled *bb* background; this method is suspect
  - (also no sign of 10.91 GeV tetraquark candidate)
  - $R_{\Upsilon\pi\pi}$ is nearly free from *bb* continuum but lower statistics; **Υ(5S) is "essentially saturated" by bottomonium(-like) modes**
  - First measurements of $M_{\Upsilon(6S)}$ and $\Gamma_{\Upsilon(6S)}$ and relative phase $\phi_{\Upsilon(6S)}$-$\phi_{\Upsilon(5S)}$, using $R_{\Upsilon\pi\pi}$



Exclusive hadronic transitions from the "Y(5S)" resonance

Observation of e+e- → π+π- π0 χ bJ and search for Xb → ω Y(1S) at √s ~ 10.867 GeV
PRL 113, 142001 (2014)

- A different approach to probing Y(5S)
  - Look at $\pi^+\pi^-\pi^0\chi_{bJ}$ in Y(5S) run (118 fb^{-1} at $\sqrt{s}$= 10.867 GeV)
  - Select χ_{bJ} from γl^+l^- (μ or e)
  - Look for ω resonance in $\pi^+\pi^-\pi^0$ invariant mass spectrum
- Results and implications:
  - Clear χ_{bJ} peaks for J=1,2 from both ω resonance and non-resonance signals
  - Results also show **an accumulation of non-ω events (red arrows)**
  - Since preliminary results were released last summer there has been a lot of theoretical interest; the "Y(5S)" remains weird



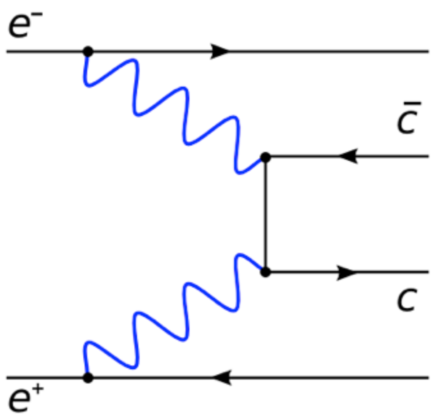
Decays

[Preliminary] Dalitz plot analysis of $\eta_c \to K\bar{K}\pi$ in two-photon interactions

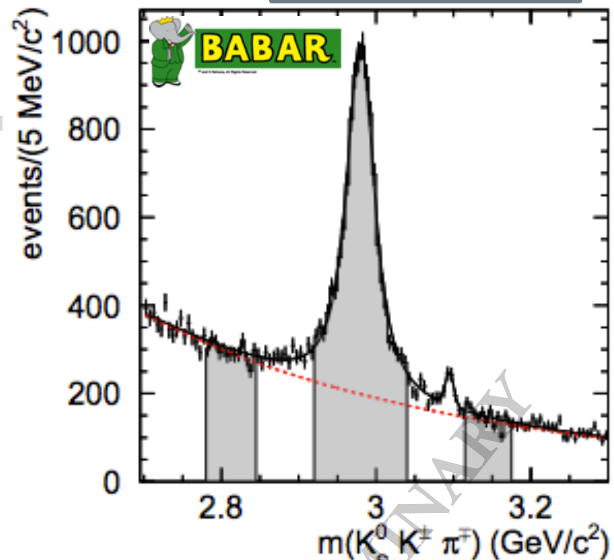
Not yet on arXiv

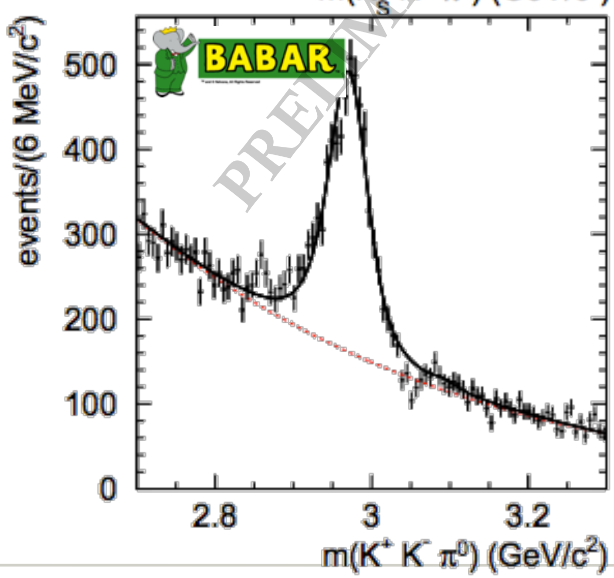
- A model-independent measurement of mass-dependent $K\pi$ amplitude and phase
- Dalitz plot analysis
  - Using 519 fb^{-1} at and around Υ(2,3,4S) resonances
  - Select η_c produced in two-photon interactions, with e^+e^- unrecovered:

$$\gamma\gamma \to K_S^0 K^\pm \pi^\mp$$
$$\gamma\gamma \to K^+ K^- \pi^0$$



- Model-Independent Partial Wave Analysis
  - Use $K\pi$ S-wave as reference (amplitude 1, phase 0)
  - $K\pi$ mass spectrum divided into 30 60 MeV intervals





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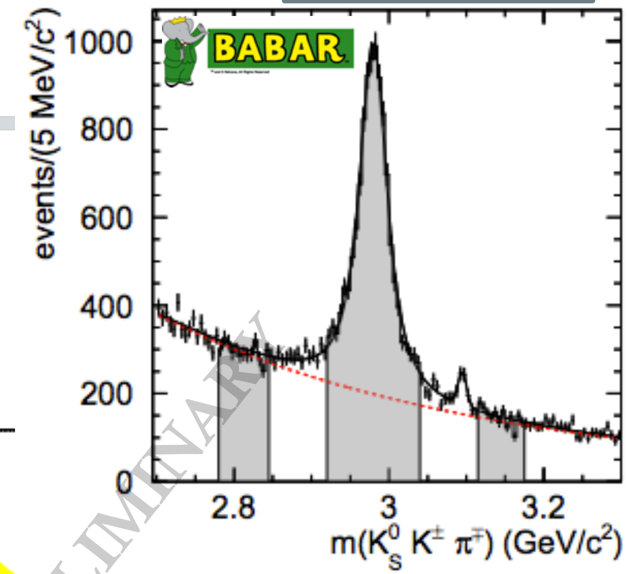

- A model-independent measurement of mass-dependent $K\pi$ amplitude and phase
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  - Using 519 fb^{-1} at and around Υ(2,3,4S) resonances
  - Select η_c produced in two-photon interactions, with e^+e^- unrecovered:

$$\gamma\gamma \to K^0_S K^\pm \pi^\mp$$

$$\gamma\gamma \to K^+ K^- \pi^0$$

- Model-Independent Partial Wave Analysis
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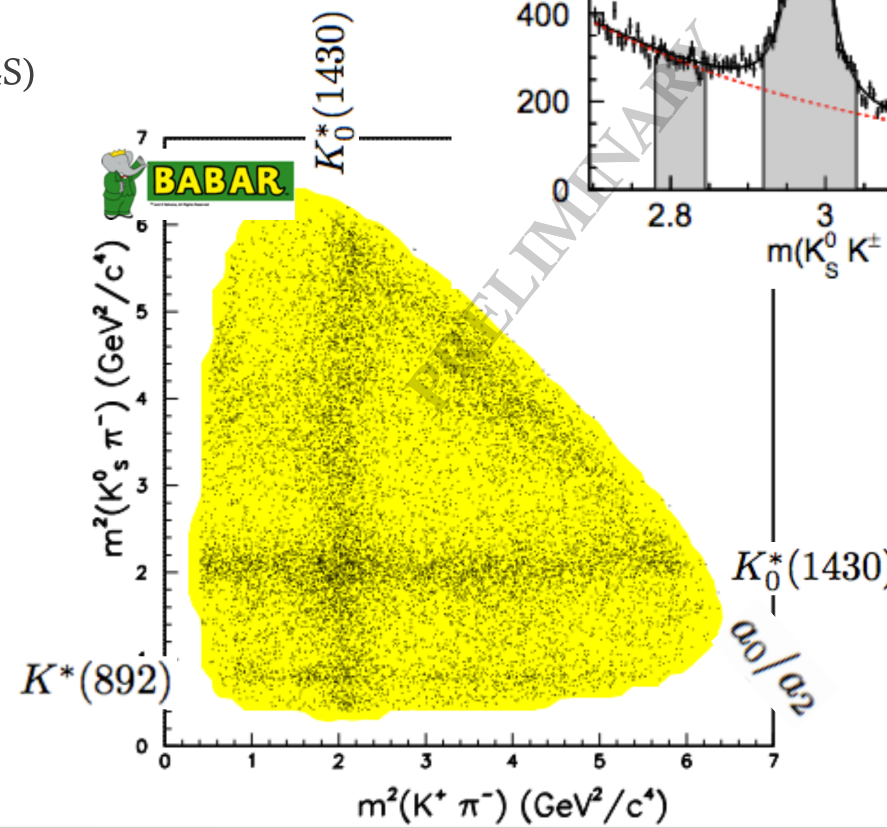

[Preliminary] Dalitz plot analysis of $\eta_c \to K\bar{K}\pi$ in two-photon interactions

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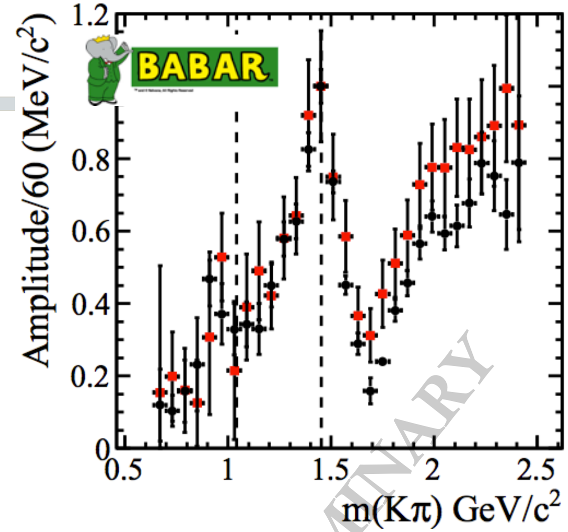
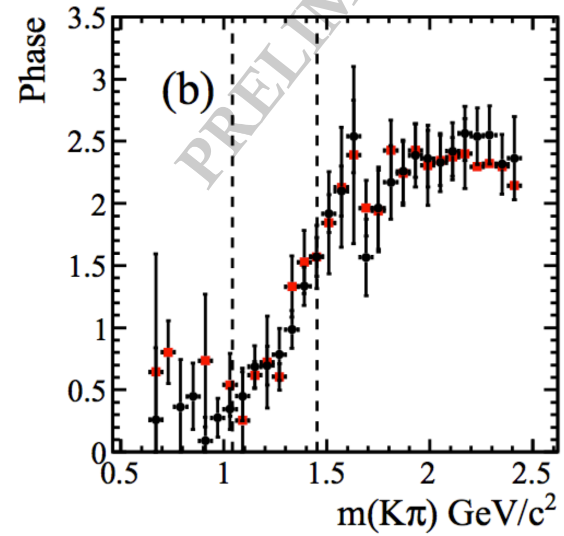


Results:

- Phase and amplitude for η_c agree for both modes (right)…
- …but amplitude strongly disagrees with E791 and LASS results
- The $K_0^*(1430)$ resonance dominates the $K\pi$ *S*-wave
- The broad structure around 1.95 GeV/c² indicates $K_0^*(1950)$ resonance
- **A new $a_0(1950)$ resonance is needed to fit the data in both modes**:
  - $m(a_0(1950))$ = 1931 ± 14 ± 22 MeV/c2
  - $\Gamma(a_0(1950))$ = 271 ± 22 ± 29 MeV
  - Statistical significance of 2.5σ and 4.0σ, including systematics
  - MIPWA results, below, with new $a_0(1950)$ resonance included



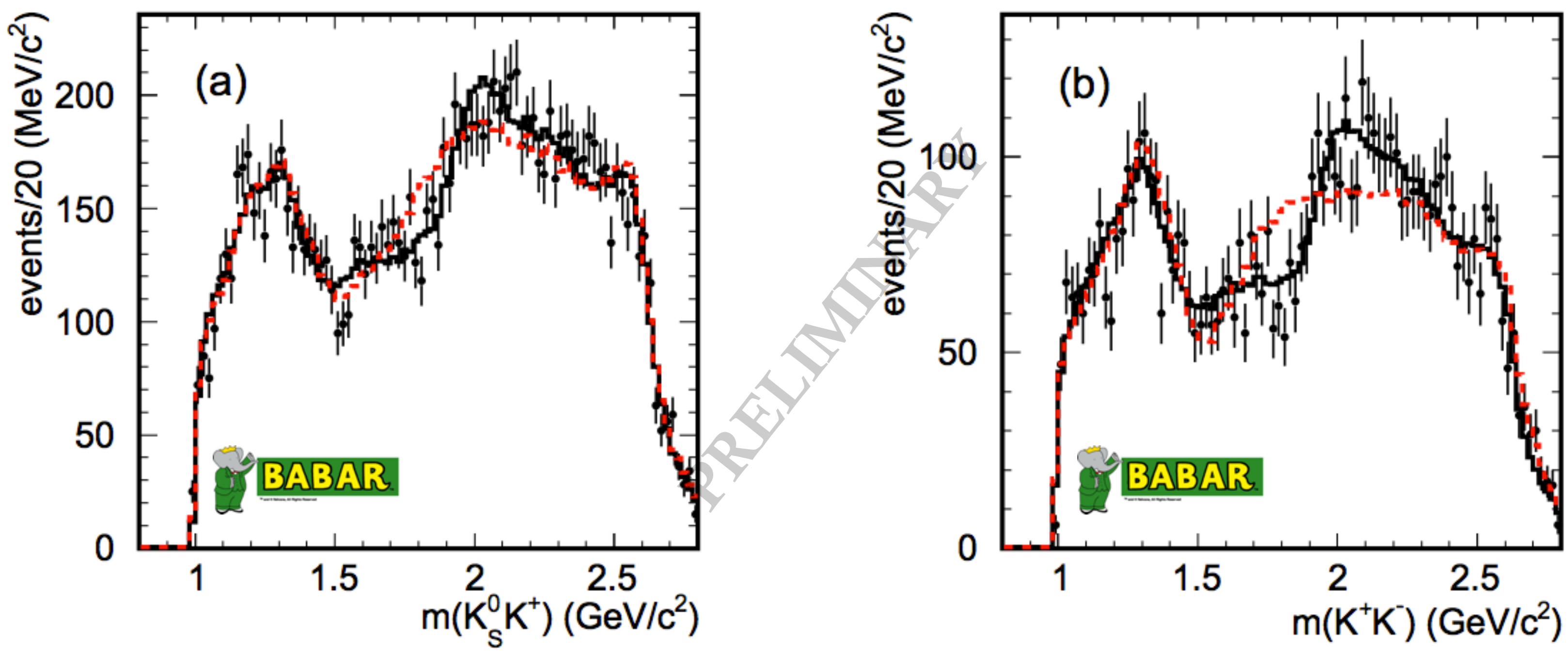
	$\eta_c \to K_S^0 K^\pm \pi^\mp$		$\eta_c \to K^+ K^- \pi^0$	
Amplitude	Fraction (%)	Phase	Fraction (%)	Phase
$(K\pi$ *S*-wave$)$ K	107.3 ± 2.6 ± 17.9	0.	125.5 ± 2.4 ± 4.2	0.
$a_0(980)\pi$	0.83 ± 0.46 ± 0.80	1.08 ± 0.18 ± 0.18	0.00 ± 0.03 ± 1.7	
$a_0(1450)\pi$	0.7 ± 0.2 ± 1.4	2.63 ± 0.13 ± 0.17	1.2 ± 0.4 ± 0.7	2.90 ± 0.12 ± 0.25
$a_0(1950)\pi$	3.1 ± 0.4 ± 1.2	−1.04 ± 0.08 ± 0.77	4.4 ± 0.8 ± 0.7	−1.45 ± 0.08 ± 0.27
$a_2(1320)\pi$	0.15 ± 0.06 ± 0.08	1.85 ± 0.20 ± 0.23	0.61 ± 0.23 ± 0.3	1.75 ± 0.23 ± 0.42
$K_2^*(1430)^0 K$	4.7 ± 0.9 ± 1.4	4.92 ± 0.05 ± 0.1	3.0 ± 0.8 ± 4.4	5.07 ± 0.09 ± 0.3
Total	116.8 ± 2.8		134.8 ± 2.7	
$-2\log\mathcal{L}$	−4314.2		−2339	
χ_2/N_{cells}	301/254=1.17		283.2/233=1.22	

[Preliminary] Dalitz plot analysis of $\eta_c \rightarrow K\bar{K}\pi$ in two-photon interactions

Not yet on arXiv

New $a_0(1950)$ resonance

- $K\bar{K}$ mass projections with MIPWA fit projections, below
- Fit quality is improved with (red) extra $a_0(1950) \rightarrow \bar{K}K$ resonance



[Preliminary] Dalitz plot analysis of $J/\psi \to \pi^+\pi^-\pi^0$ and $J/\psi \to K^+K^-\pi^0$ produced via e^+e^- annihilation with ISR

Not yet on arXiv

ISR production of charmonium in e^+e^- annihilations (γ_{ISR} not reconstructed):

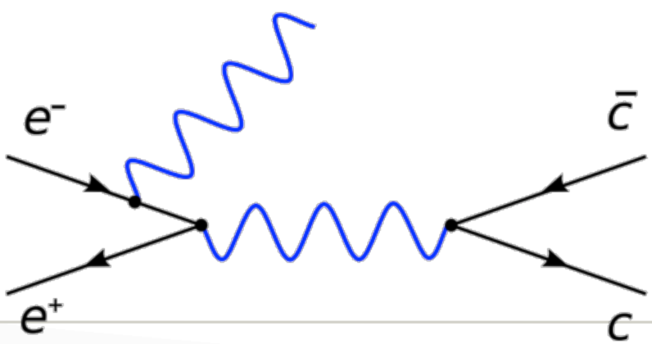
$$J/\psi \to \pi^+\pi^-\pi^0$$

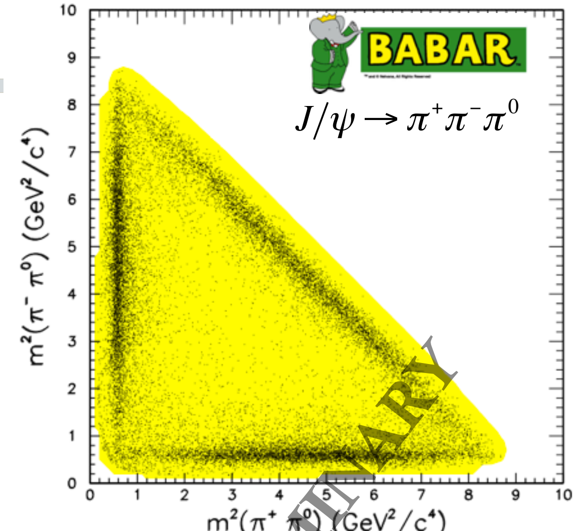
$$J/\psi \to K^+K^-\pi^0$$

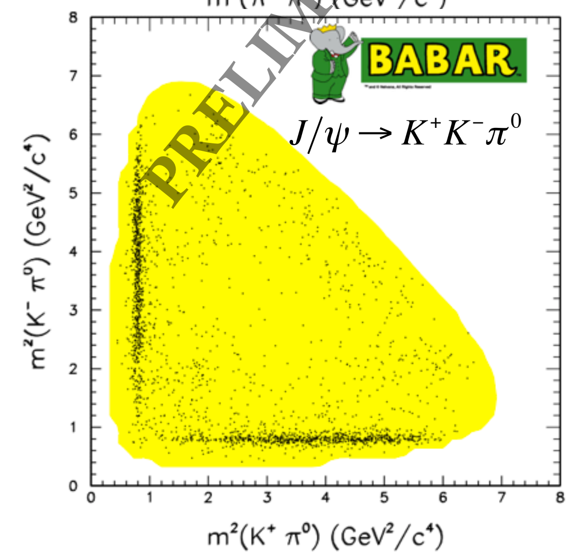
- 519 fb^{-1} at and near Υ(2,3,4S) resonances
- Measure branching fraction ratio:

$$\mathcal{R} = \frac{\mathcal{B}(J/\psi \to K^+K^-\pi^0)}{\mathcal{B}(J/\psi \to \pi^+\pi^-\pi^0)}$$

- Dalitz plots:
  - $J/\psi \to \pi^+\pi^-\pi^0$ (right top) is dominated by $\rho(770)\pi$ amplitudes
  - $J/\psi \to K^+K^-\pi^0$ (bottom) dominated by $K^*(892)K$ amplitude, with $\rho(1450)\pi^0$ contributions on diagonal







[Preliminary] Dalitz plot analysis of $J/\psi\to\pi^+\pi^-\pi^0$ and $J/\psi\to K^+K^-\pi^0$ produced via e^+e^- annihilation with ISR

Not yet on arXiv

Results:

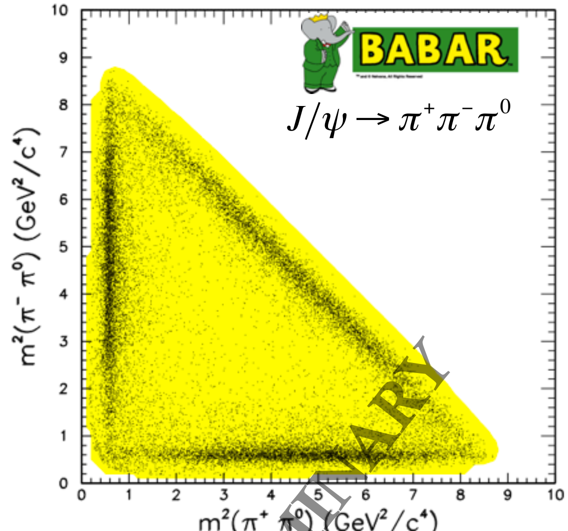
- $\mathcal{R} = 0.0929 \pm 0.002 \pm 0.002$
- $\rho(1450)$ visible in both channels, with $\mathcal{R}(\rho(1450)) = \mathcal{B}(\rho(1450) \to K^+K^-)/\mathcal{B}(\rho(1450) \to\pi^+\pi^-) = 0.190 \pm 0.042 \pm 0.049$
- Measured fractions for resonances contributing to the decays below:

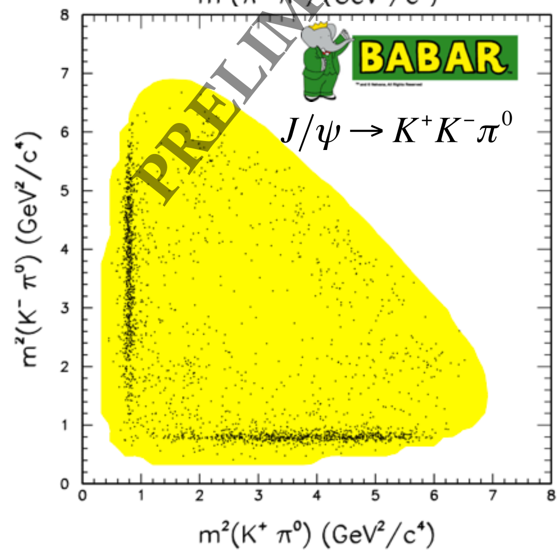
$J/\psi\to\pi^+\pi^-\pi^0$:

Final state	Isobar fraction %	Phase (radians)	Veneziano fraction %
$\rho(770)\pi$	119.0 ± 1.1 ± 3.3	0.	120.0 ± 1.9
$\rho(1460)\pi$	16.9 ± 2.0 ± 3.1	3.92 ± 0.05 ± 0.11	1.53 ± 0.13
$\rho(1700)\pi$	0.1 ± 0.1 ± 0.2	1.01 ± 0.35 ± 0.79	0.84 ± 0.08
$\rho(2150)\pi$	0.04 ± 0.05 ± 0.02	1.89 ± 0.30 ± 0.48	2.03 ± 0.17
$\rho_3(1690)\pi$			0.09 ± 0.02
Sum	136.0 ± 2.3 ± 4.3		124.5 ± 2.3
χ^2/ν	764/552		780/554

$J/\psi\to K^+K^-\pi^0$:

Final state	fraction %	phase
$K^*(892)K$	87.8 ± 2.0 ± 1.7	0.
$\rho(1450)^0\pi^0$	11.5 ± 2.1 ± 2.1	-2.81 ± 0.25 ± 0.36
$K^*(1410)K$	1.7 ± 0.7 ± 1.1	2.89 ± 0.35 ± 0.08
$K_2^*(1430)K$	3.8 ± 1.4 ± 0.5	-2.42 ± 0.22 ± 0.07
$\rho(1700)^0\pi^0$	0.9 ± 1.0 ± 0.6	1.06 ± 0.20 ± 0.7
Total	105.6 ± 3.4 ± 3.0	
$\chi^2/\nu = 94/92$		





Double charmonium production

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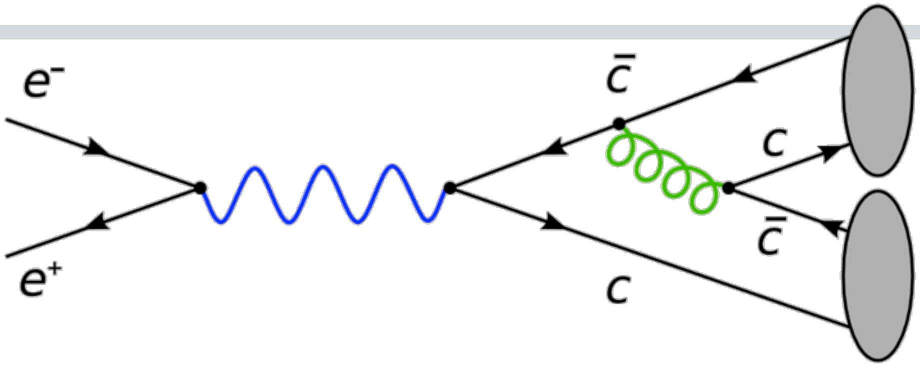
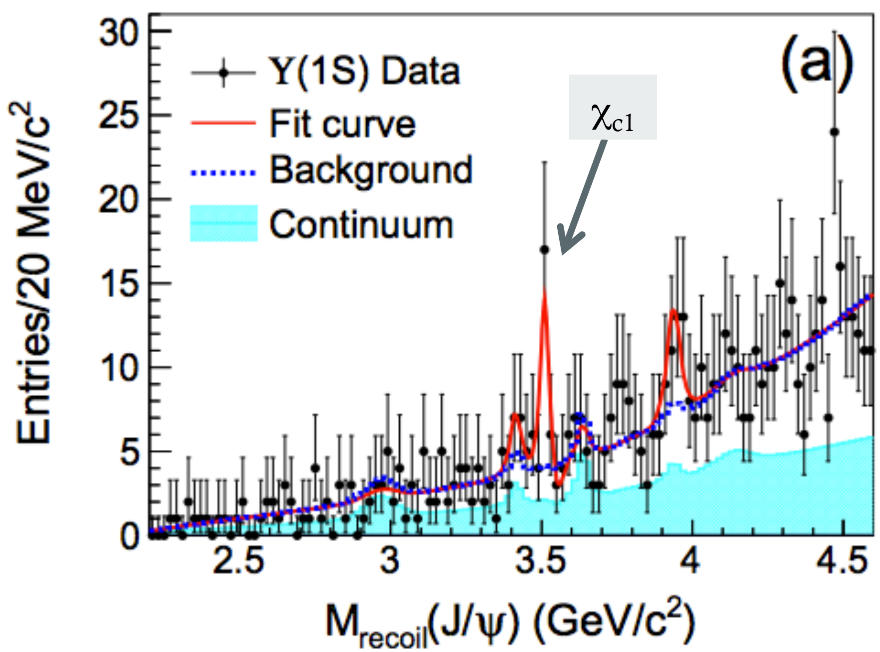
Exclusive double-charmonium production in Υ(1S) and Υ(2S) decays at Belle

PRD 90 112008 (2014)



- Double-charmonium production in e^+e^- annihilation exceeds leading-order NRQCD by an order of magnitude
- What about in bottomonium decay?
- Use Belle's Υ(1,2S) datasets (102×10^6, 158×10^6), look for:
  - $\Upsilon(1,2S) \to J/\psi\ (\psi(2S)) + X$
  - $X = \eta_c, \chi_{cJ}, \eta_c(2S), X(3940), X(4160)$
- Look at spectrum of mass recoiling against J/ψ ($\to\mu^+\mu^-$) or $\psi(2S)$ ($\to\mu^+\mu^-$ or $\to\pi^+\pi^- J/\psi$)
- Results:
  - Evidence for $\Upsilon(1S) \to J/\psi\ \chi_{c1}$
  - $\mathcal{B}(\Upsilon(1S) \to J/\psi\ \chi_{c1}) = (3.90 \pm 1.21(\text{stat.}) \pm 0.23(\text{syst.}))\times10^{-6}$
  - Significance of 4.6σ
  - All other signals <3σ
  - **All results consistent with NRQCD factorization approach**



Central exclusive production of double charmonium at LHCb

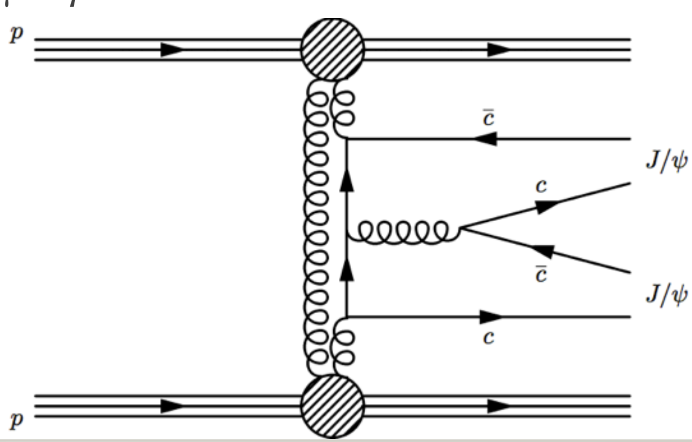
arXiv:1407.5973
J. Phys. G 41 (2014) 115002.

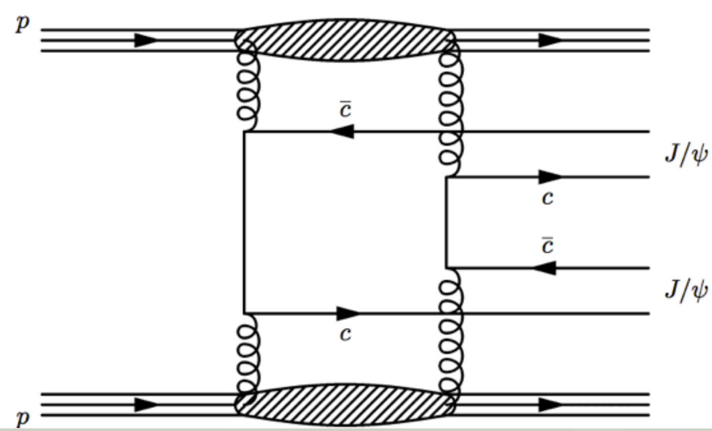
- A search for central exclusive production of charmonia: $pp \to pXp$, where X=$J/\psi\, J/\psi$, $J/\psi\, \psi(2S)$, $\psi(2S)\psi(2S)$, $\chi_{c0}\chi_{c0}$, $\chi_{c1}\chi_{c1}$, $\chi_{c2}\chi_{c2}$
- CEP production principally from **double pomeron exchange** (below)
- Sensitive to presence of additional particles (glueballs, tetraquarks, etc.)
- Exclusive reconstruction, 4μ+(0,1,2)γ:
  - J/ψ and $\psi(2S) \to \mu^+\mu^-$
  - $\chi_{cJ} \to \gamma\, J/\psi$

Results:

- **First observation of central exclusive production of pairs of charmonia**

$$\begin{aligned}
\sigma^{J/\psi\, J/\psi} &= 58 \pm 10(\text{stat}) \pm 6(\text{syst})\,\text{pb},\\
\sigma^{J/\psi\,\psi(2S)} &= 63^{+27}_{-18}(\text{stat}) \pm 10(\text{syst})\,\text{pb},\\
\sigma^{\psi(2S)\psi(2S)} &< 237\,\text{pb},\\
\sigma^{\chi_{c0}\chi_{c0}} &< 69\,\text{nb},\\
\sigma^{\chi_{c1}\chi_{c1}} &< 45\,\text{pb},\\
\sigma^{\chi_{c2}\chi_{c2}} &< 141\,\text{pb},
\end{aligned}$$





Outlook

It's still the "golden age" of heavy quarkonium physics

- **BaBar's** Υ(2,3S) and **Belle's** Υ(1,2,3,5S) datasets remain fruitful
- **BESIII** continues to be very active in quarkonium and especially exotics

The golden age will continue in the near future:

- **Belle II** will generate huge luminosity that will benefit quarkonium physics
  - At Υ(4S):
    - ISR production
    - $B \to$charmonium+X decays
    - Radiative decays with π-tagging: χ_b(3P), Υ(2D)…
  - Υ(1,2,3,5S) (please?):
    - Just 1 week at each would yield ~order of magnitude increased datasets
    - Υ(1D) J=0,2 states, "Υ(5S)" transitions, spin-flip transitions, etc. etc.
- Major upgrades at the **LHC** experiments for **Run 2** and beyond


Thank you!