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BELLE

Study of $\chi_{bJ}(nP) \to \omega\Upsilon(1S)$ at Belle

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On behalf of the Belle Collaboration

Hadron 2021

U.S. DEPARTMENT OF ENERGY | Office of Science

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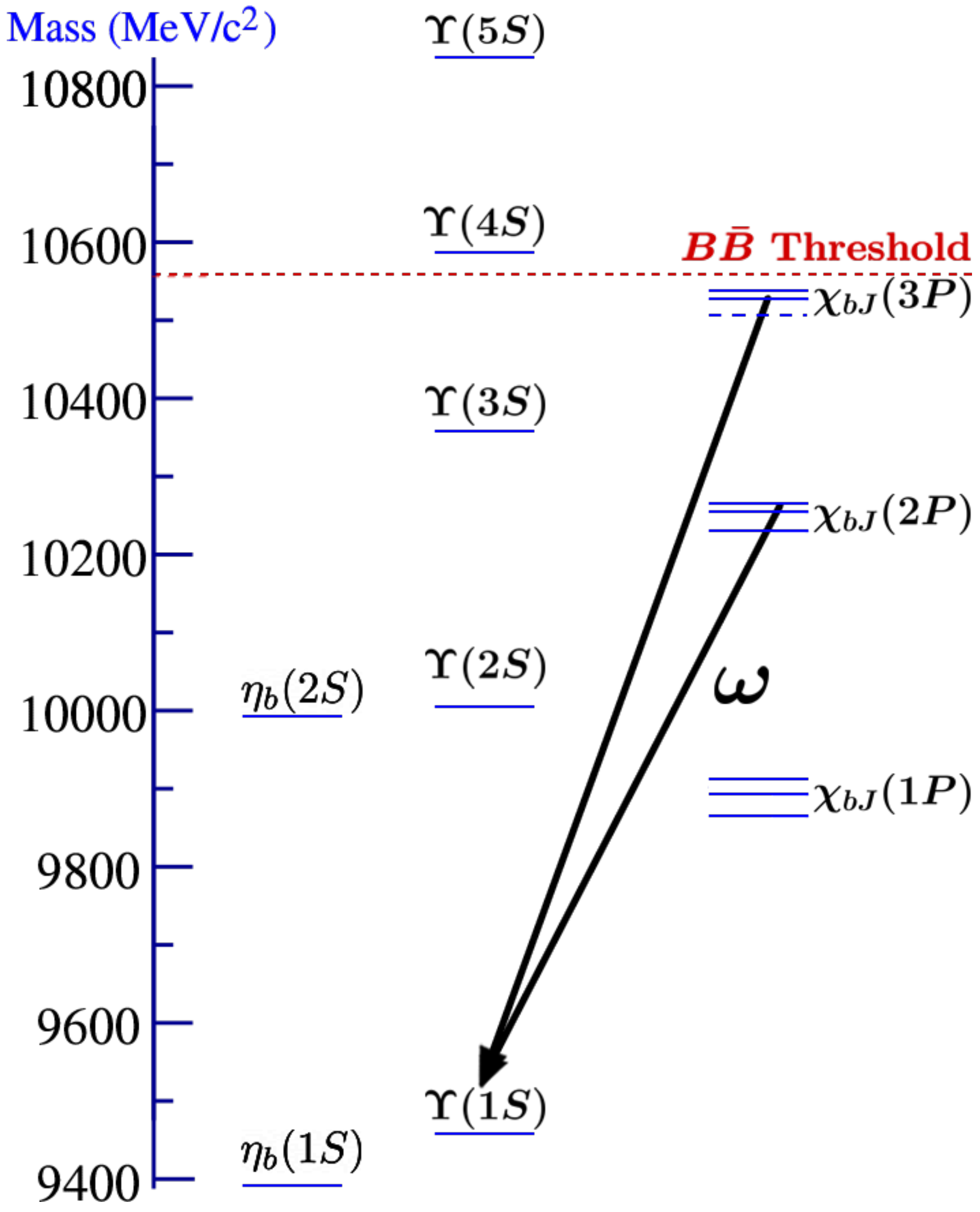
Overview

- Introduction
  - Belle
  - Bottomonium Spectroscopy
- Search for $\chi_{bJ}(nP) \to \omega\Upsilon(1S)$
  - Previous Measurement
  - Analysis Strategy
  - Event Selection and Background Suppression
  - Measurement of $\chi_{bJ}(2P)$ branching ratios
  - Search for $\chi_{bJ}(3P)$
- Summary

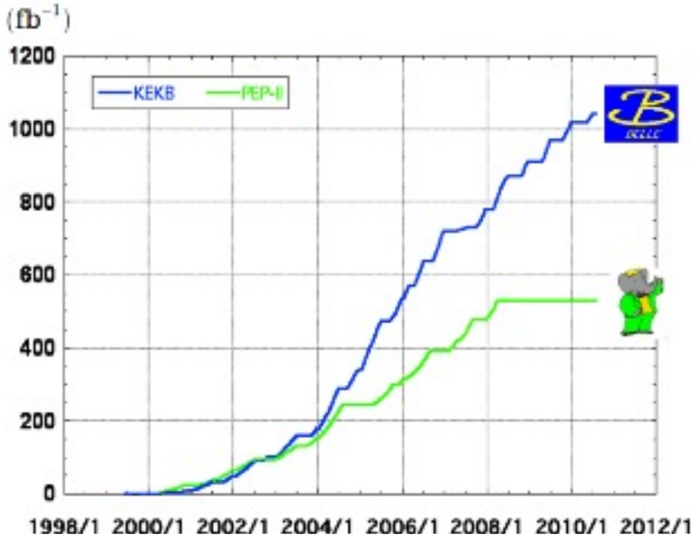


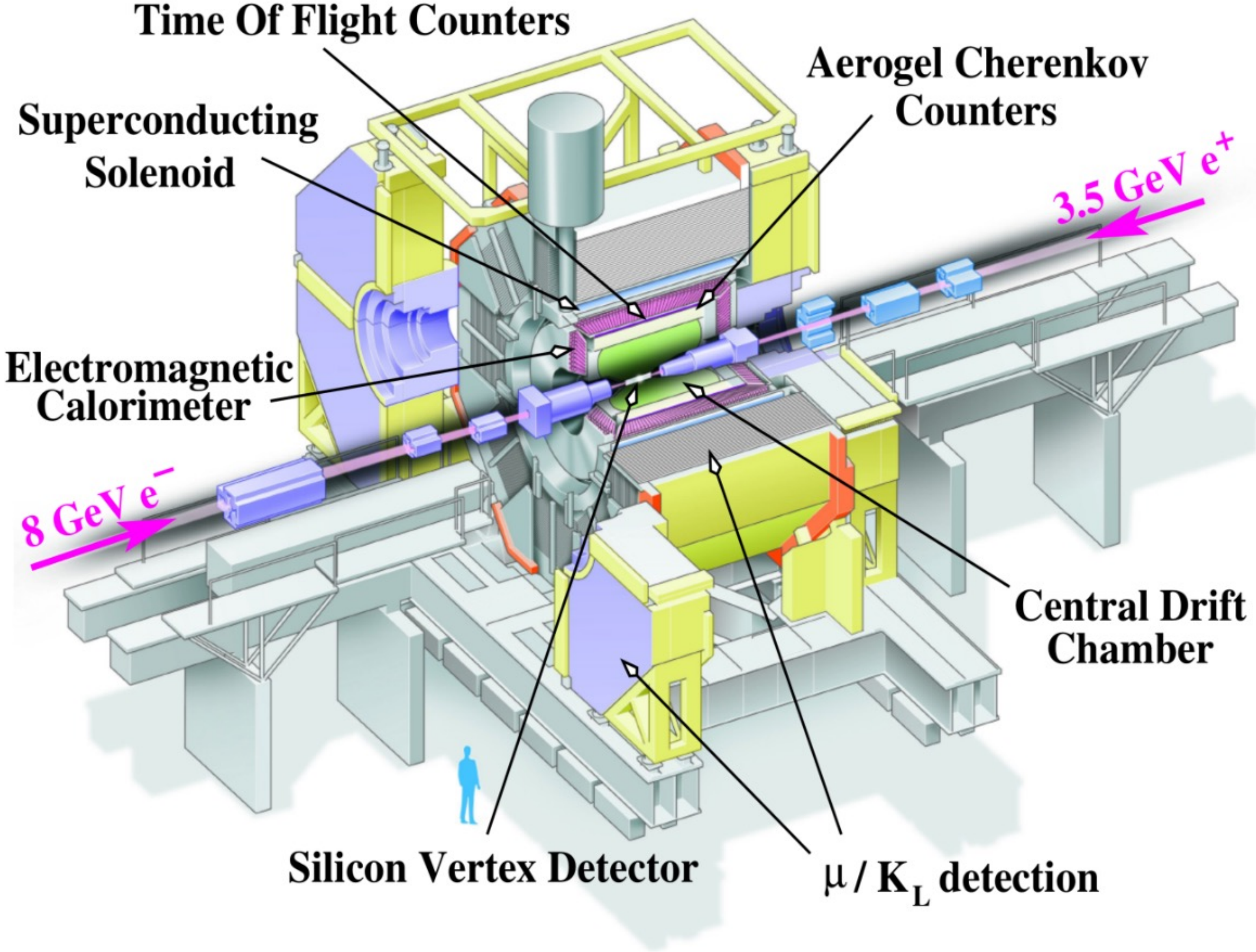
The Belle Experiment

- **Highlights**
  - KEK, Tsukuba, Japan
  - e^+e^- collider (KEKB)
    - ✓ **Operated at CM energies near $\Upsilon(nS)$ resonances of bottomonium**
  - Operation 1999-2010
  - Collected $\mathcal{L}\sim 1\ \mathrm{ab}^{-1}$
  - 500 members, 21 countries
  - More than 500 publications

We've Analyzed:

Resonance	Integrated Luminosity
$\Upsilon(1S)$	$6\ \mathrm{fb}^{-1}$
$\Upsilon(2S)$	$25\ \mathrm{fb}^{-1}$
→ $\Upsilon(3S)$	$3\ \mathrm{fb}^{-1}$
→ $\Upsilon(4S)$	$711\ \mathrm{fb}^{-1}$
$\Upsilon(5S)$	$121\ \mathrm{fb}^{-1}$





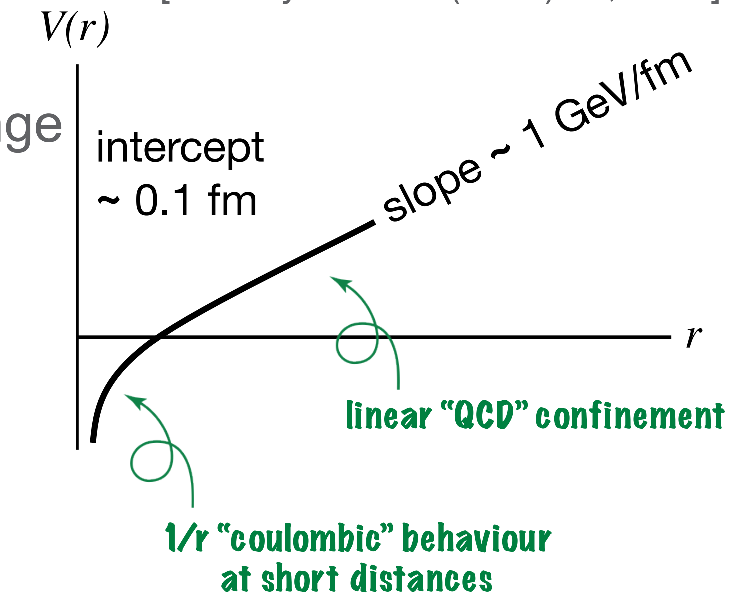
Bottomonium Spectroscopy

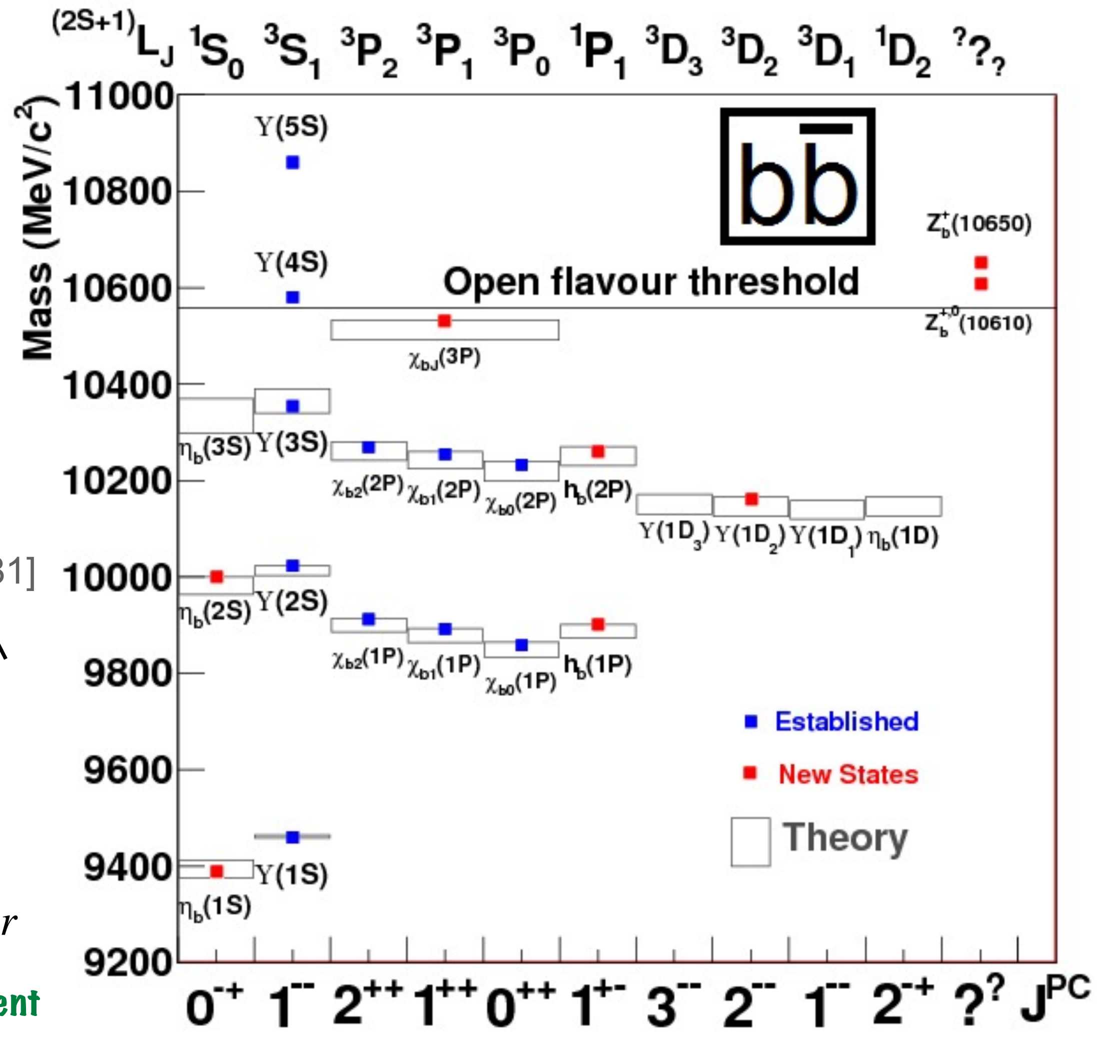
- **Bound state of bottom quark/anti-quark $(b\bar{b})$**
  - Analogous to hydrogen/positronium (e^+e^-)
  - Large constituent quark mass → nonrelativistic
  - Unique tool for study of low energy QCD
- **Theoretical description**
  - **Phenomological approach: Potential Models**

[Eur.Phys.J.C 74 (2014) 10, 2981]

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \cdots$$

    - ✓ Based on single-gluon exchange
    - ✓ Great Success!
  - **Modern approaches:**
    - ✓ Effective Field Theories
    - ✓ Lattice QCD
  -

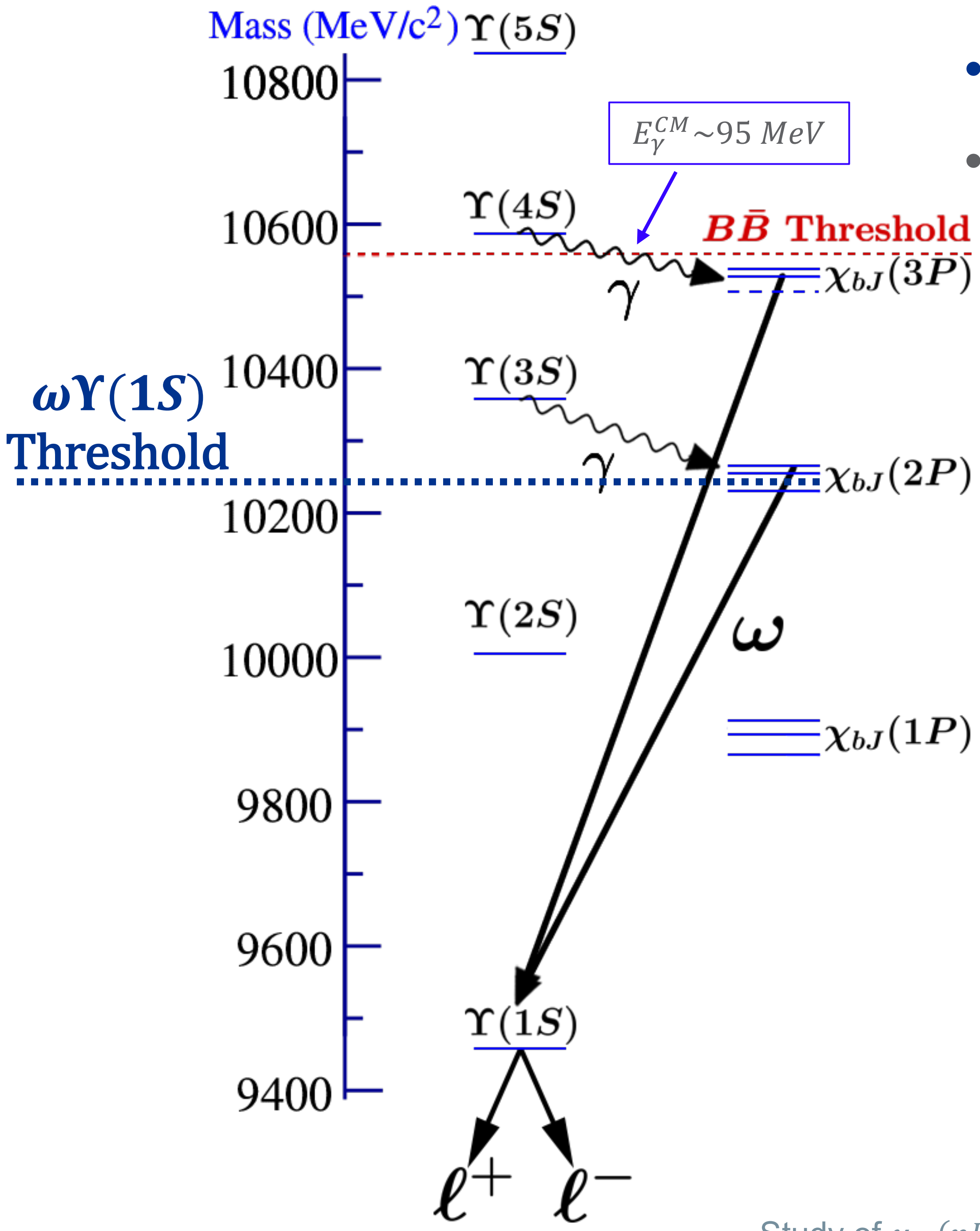




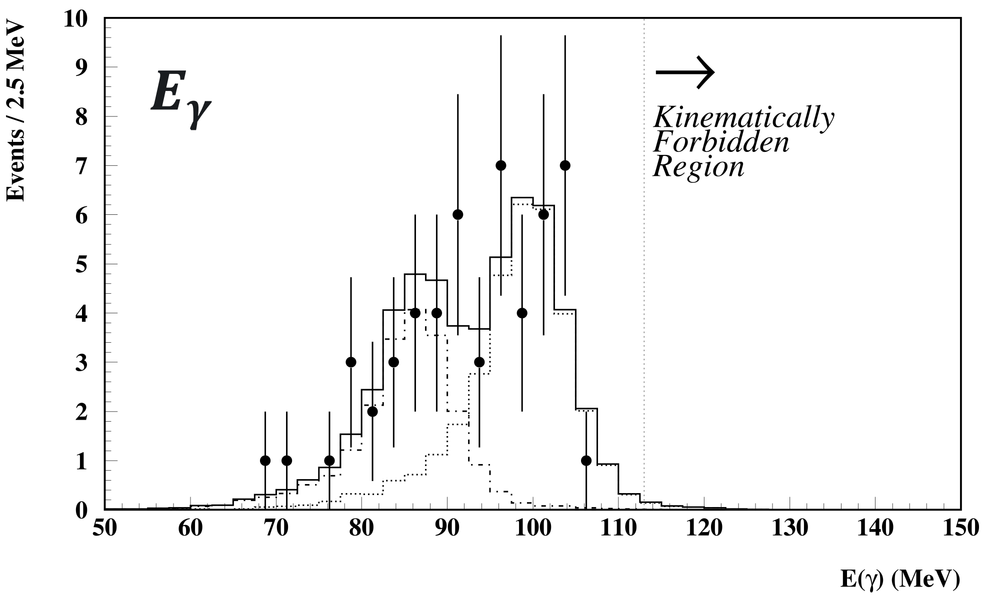
[Eur.Phys.J.C **74** (2014) 3026]

- Many (successful) predictions of spectroscopic properties:
  - ✓ Masses/Widths, Quantum Numbers, Production/Decay Mechanisms/Rates

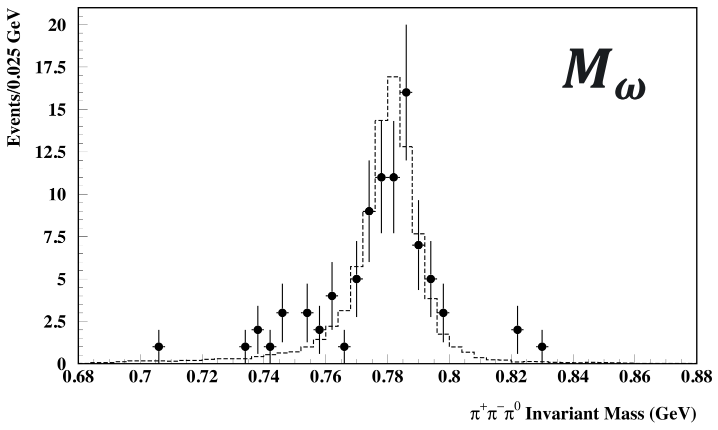
Previous Measurement & Analysis Strategy



- **$\chi_{b1,2}(2P)$ and $\chi_{b(0),1,2}(3P)$ states are kinematically accessible**
- **$\chi_{bJ}(2P) \to \omega\Upsilon(1S)$ Discovered by CLEO** [Phys.Rev.Lett. 92 (2004) 222002]
  - Analyzed about 6×10^6 $\Upsilon(3S)$ decays



Channel	Branching Fraction
J=1	$\left(1.63^{+0.35+0.12}_{-0.31-0.11}\right)$ %
J=2	$\left(1.10^{+0.32+0.08}_{-0.28-0.07}\right)$ %



- **We reconstruct the exclusive final state:**

$$\chi_{bJ} \to \omega[\Upsilon(1S)] \to \pi^+\pi^-\pi^0[\ell^+\ell^-]$$

- We analyze a sample of $(28.0 \pm 1.0)\times10^6$ $\Upsilon(3S)$ mesons collected near the $\Upsilon(3S)$ and $\Upsilon(4S)$ resonances.

Event Selection & Background Suppression

Final State Particle Selection Criteria

- At least 4 tracks with $|dr| < 0.5$ cm, $|dz| < 2.0$ cm
- At least 2 isolated clusters in ECL that do not match with a track.

Hard Tracks (Leptons)

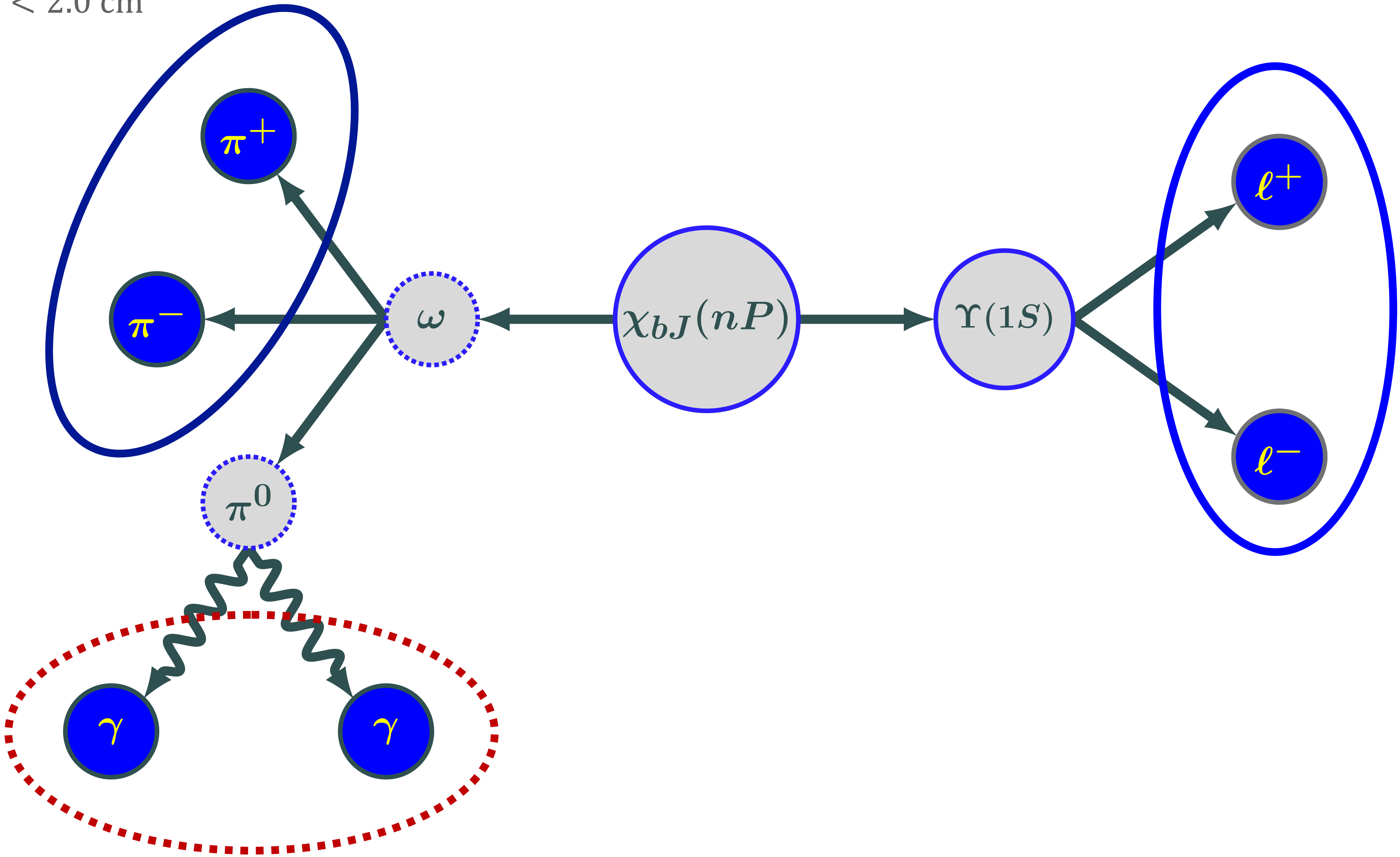
- $p_{\ell}^{CM} > 4.0$ GeV
- $M(\ell^+\ell^-) \in [9.0, 9.8]$ GeV
- Require exactly 1 di-lepton
- MuonID > 0.2 or eID > 0.2 (only in $\Upsilon(4S)$ Dataset)

Soft Tracks (Pions)

- $p_{\pi}^{CM} < 0.45$ GeV
- $cos(\psi_{\pi\pi}) < 0.95$
- Require exactly 1 di-pion

π^0 Candidates

- $p_{\gamma\gamma}^{CM} \in [0.08, 0.43]$ GeV
- $M_{\gamma\gamma} \in [0.11, 0.15]$ GeV
- **Retain π^0 with smallest mass fit χ^2**



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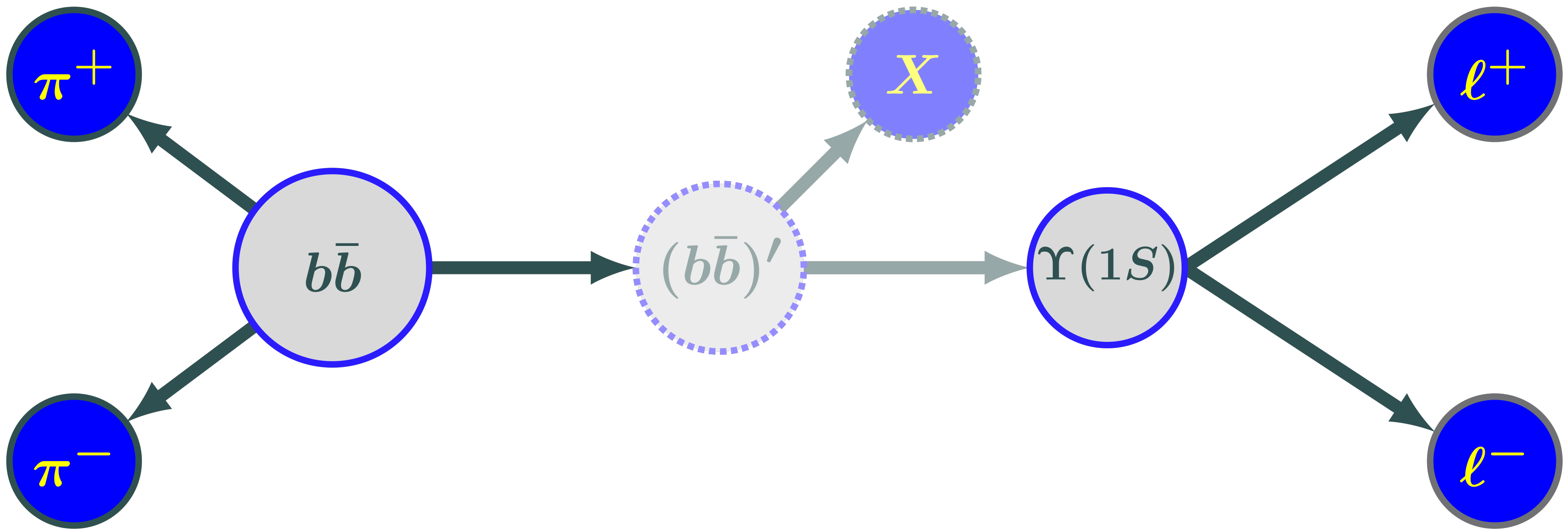
- **Retain π^0 with smallest mass fit χ^2**

To Veto Resonant $b\bar{b}$ Transitions, we define:

$$\Delta M_{\pi\pi} = M(\pi^+\pi^-\ell^+\ell^-) - M(\ell^+\ell^-) + M(\Upsilon(1S))$$



→ **$\Delta M_{\pi\pi}$ is sharply peaked for resonant di-pion transitions with a resolution of ~ 2 MeV.**

Event Selection & Background Suppression

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- **Retain π^0 with smallest mass fit χ^2**

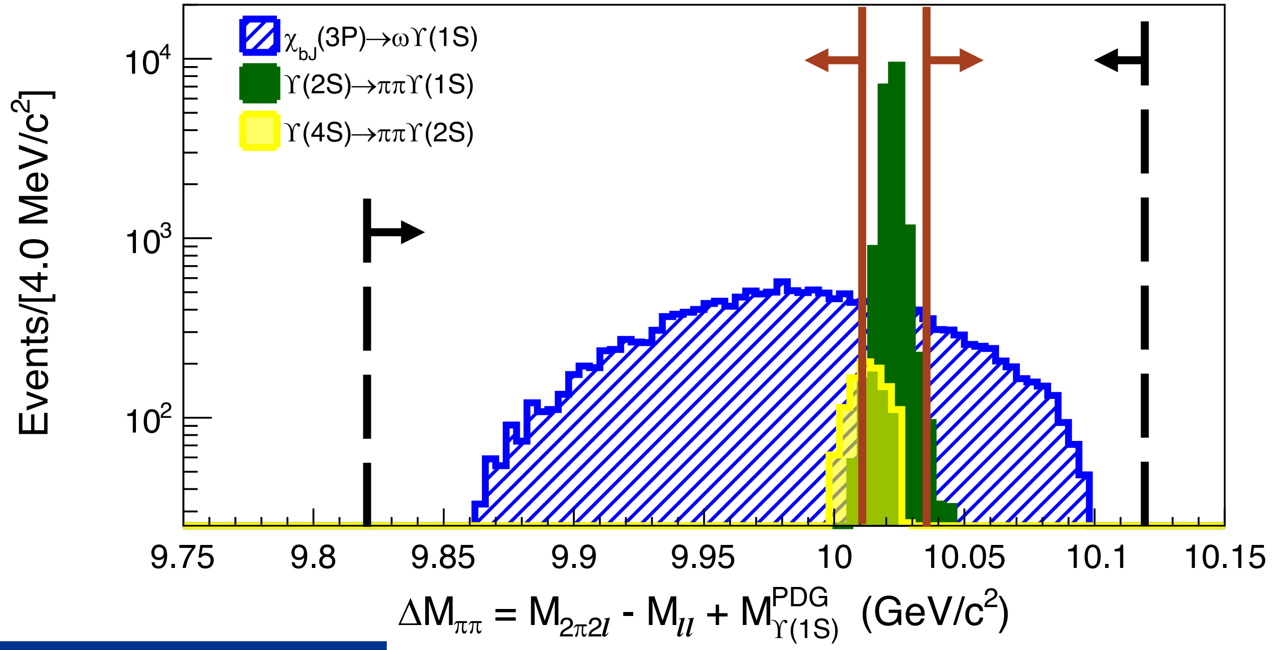
Resonant $b\bar{b} \to \pi^+\pi^- b\bar{b}'$ Veto

- $\Delta M_{\pi\pi} \in [9.83, 10.12]$ GeV

To Veto

$$\Upsilon(2S) \to \pi^+\pi^- \Upsilon(1S)$$

We Optimize FOM $= \frac{S}{\sqrt{S+B}}$



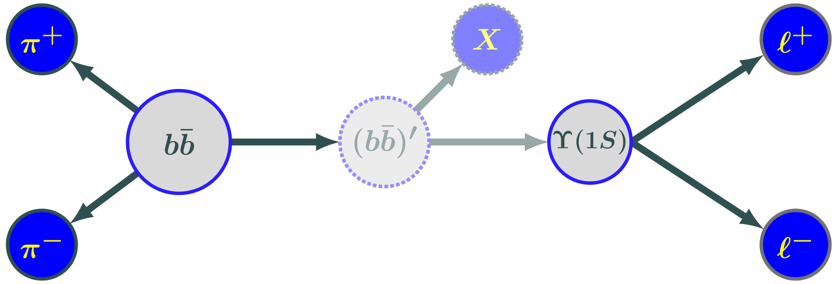
$\Upsilon(3S)$ and off-Resonance $\Upsilon(4S)$ Datasets

$$\Delta M_{\pi\pi} \notin (10.017, 10.029) \text{ GeV}$$

On Resonance $\Upsilon(4S)$ Dataset

$$\Delta M_{\pi\pi} \notin (10.014, 10.030) \text{ GeV}$$

$$\Delta M_{\pi\pi} = M(\pi^+\pi^-\ell^+\ell^-) - M(\ell^+\ell^-) + M(\Upsilon(1S))$$

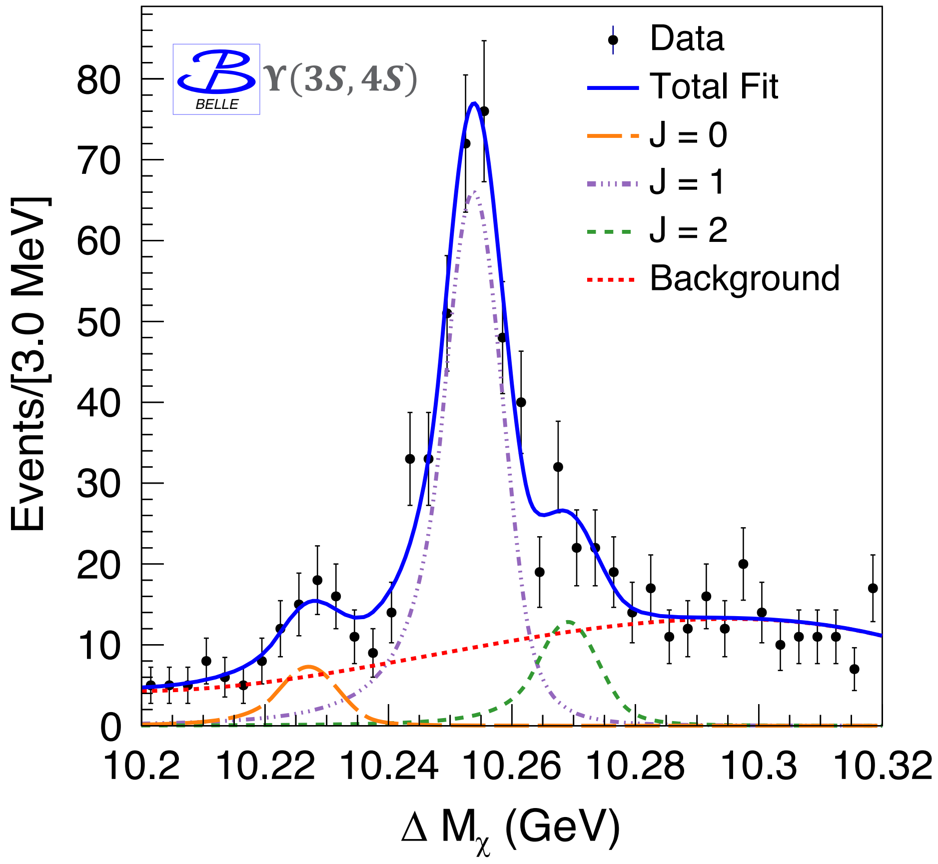


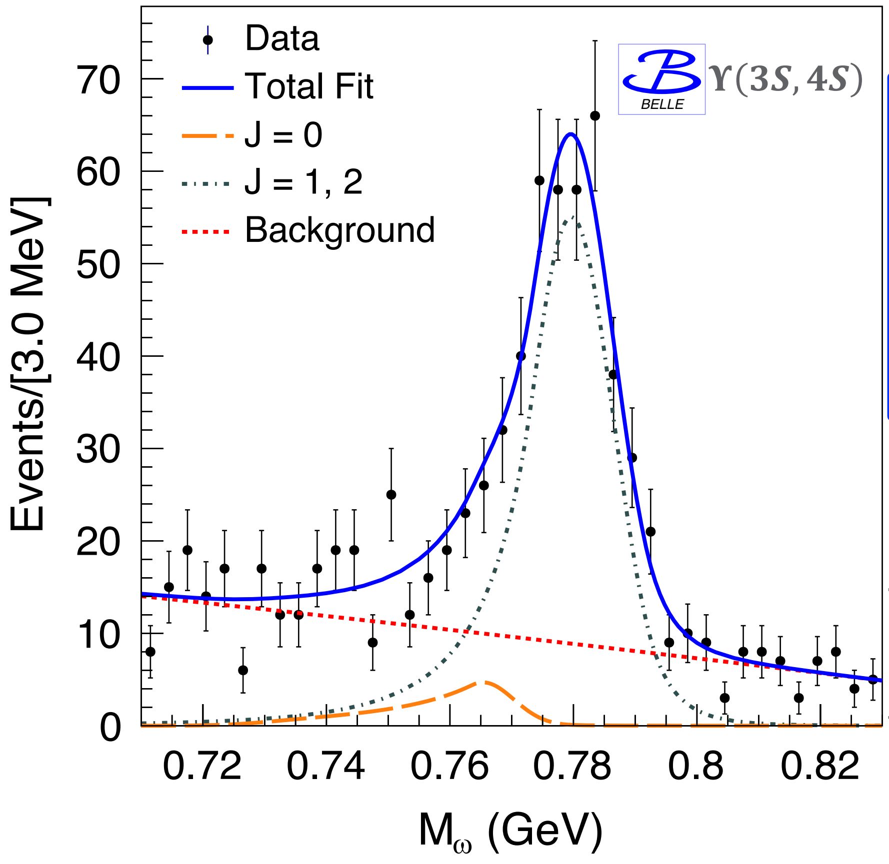
Fit to Data

- **Signals are extracted with a simultaneous fit to M_ω and:**

$$\Delta M_\chi = M(\pi^0\pi^+\pi^-\ell^+\ell^-) - M(\ell^+\ell^-) + M(\Upsilon(1S))$$

- **ΔM_χ is narrowly peaked at the $\chi_{bJ}(nP)$ masses (resolution: $4.5 - 6.0$ MeV)**
- We analyze **$3\ \mathrm{fb}^{-1}$** and **$513\ \mathrm{fb}^{-1}$** of (available) data collected near the **$\Upsilon(3S)$** and **$\Upsilon(4S)$**, respectively, as well as **$56\ \mathrm{fb}^{-1}$** of data collected about 60 MeV **below the $\Upsilon(4S)$**.
  - Corresponds to $(28.0 \pm 1.0)\times 10^6$ $\Upsilon(3S)$ initial states produced directly or via ISR.





Results

Channel	Signal Yield	Significance (σ)
$J = 0$	$33.1^{+11.1}_{-10.8}$	3.2
$J = 1$	309 ± 24	15.0
$J = 2$	62 ± 16	3.9

Signals: Double-Sided Crystal Ball (DSCB)
→ $J = 0$ in M_ω is DSCB×sigmoid

Backgrounds: cubic and quadratic polynomials in ΔM_χ and M_ω, respectively.

Calculation of Branching Fractions

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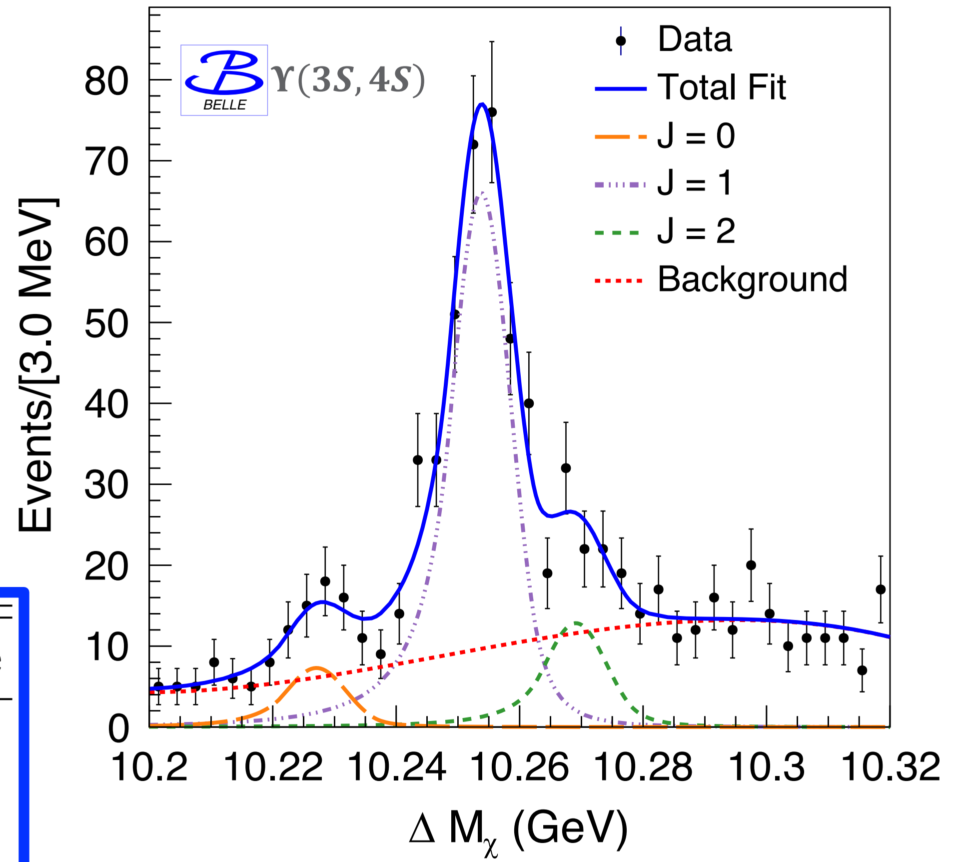
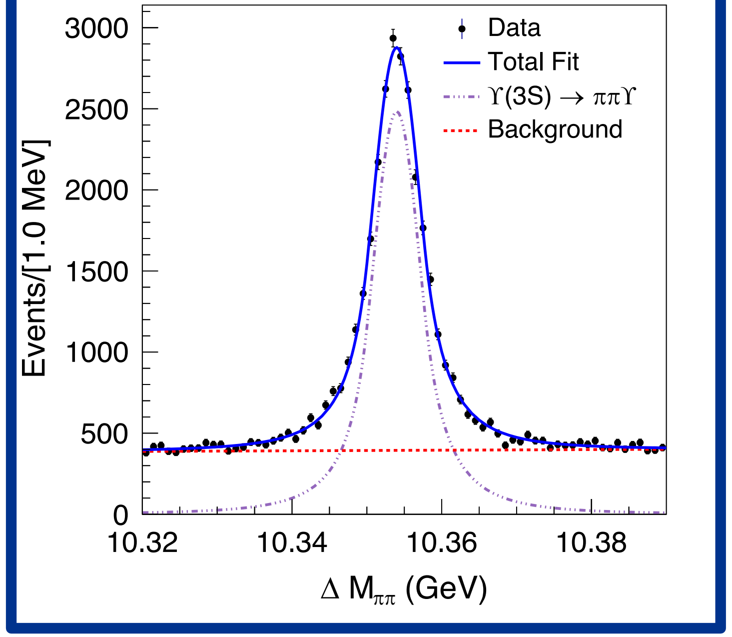
– $\Upsilon(3S)$ Population –
$(28.0 \pm 1.0) \cdot 10^6$



$$\mathcal{B}\left(\chi_{bJ}(2P) \to \omega \Upsilon(1S)\right)$$

$$= \frac{N_J}{N_{\pi\pi\Upsilon}} \frac{\epsilon_{\pi\pi\Upsilon}}{\epsilon_J} \frac{\mathcal{B}\left(\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)\right)}{\mathcal{B}\left(\Upsilon(3S) \to \gamma\chi_{bJ}(2P)\right)\mathcal{B}\left(\omega \to \pi^+\pi^-\pi^0\right)\mathcal{B}\left(\pi^0 \to \gamma\gamma\right)}$$

$\pi\pi\Upsilon$ denotes quantities from $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$ (Normalization Channel)



Results

Channel	$\mathcal{B}(\chi_{bJ}(2P) \to \omega\Upsilon(1S))$	Significance
$J=0$	$\left(0.56^{+0.19}_{-0.18} \pm 0.08\right)\%$	3.2σ
$J=1$	$\left(2.38 \pm 0.19^{+0.23}_{-0.24}\right)\%$	15.0σ
$J=2$	$\left(0.46 \pm 0.12^{+0.06}_{-0.07}\right)\%$	3.9σ

Constitutes 1st Confirmation Measurement

- No sign of $\Upsilon(4S) \to \gamma\chi_{bJ}(2P)$
- Consider production mechanism to be $\Upsilon(3S) \to \gamma\chi_{bJ}(2P)$

Compare with PDG

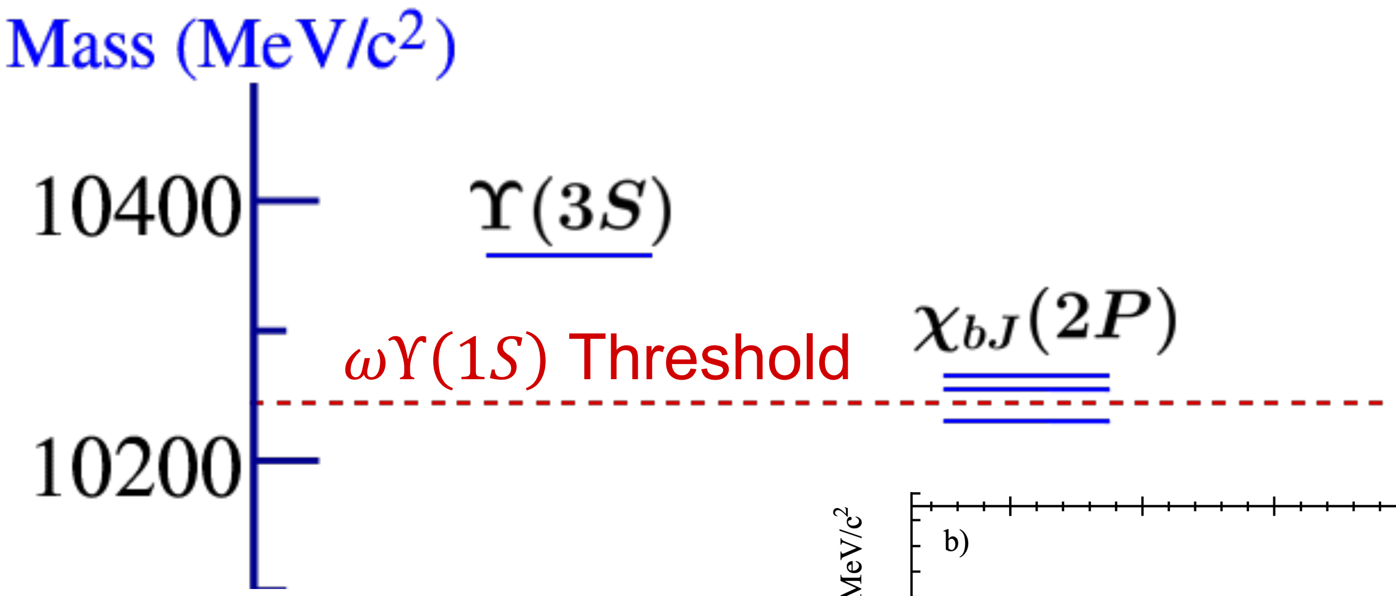
Channel	Branching Fraction	Consistency
J=1	$\left(1.63^{+0.35+0.12}_{-0.31-0.11}\right)\%$	-1.9σ
J=2	$\left(1.10^{+0.32+0.08}_{-0.28-0.07}\right)\%$	$+2.0\sigma$

Discussion of Results

- Naïvely, there is **insufficient phase space** for the $\chi_{b0}(2P) \rightarrow \omega\Upsilon(1S)$ transition:

$$\boldsymbol{\Delta_0 = M_{\chi_{b0}(2P)} - M_{\Upsilon(1S)} - M_\omega}$$
$$\boldsymbol{= -10.5\ \mathrm{MeV}}$$

- **The $\chi_{b0}(2P)$ is a wide state, $\Gamma_{\chi_{b0}} \gg \Gamma_{\chi_{b1,2}}$**
  → $\Gamma_{\chi_{b0}} = 2.6\ \mathrm{MeV}$ [PhysRevD.92.054034]
- **The ω is a wide state, $\Gamma_\omega = 8.68\ MeV$** [PDG]

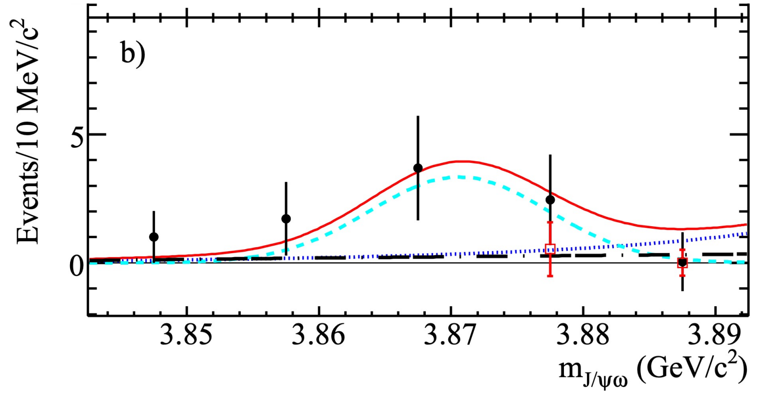


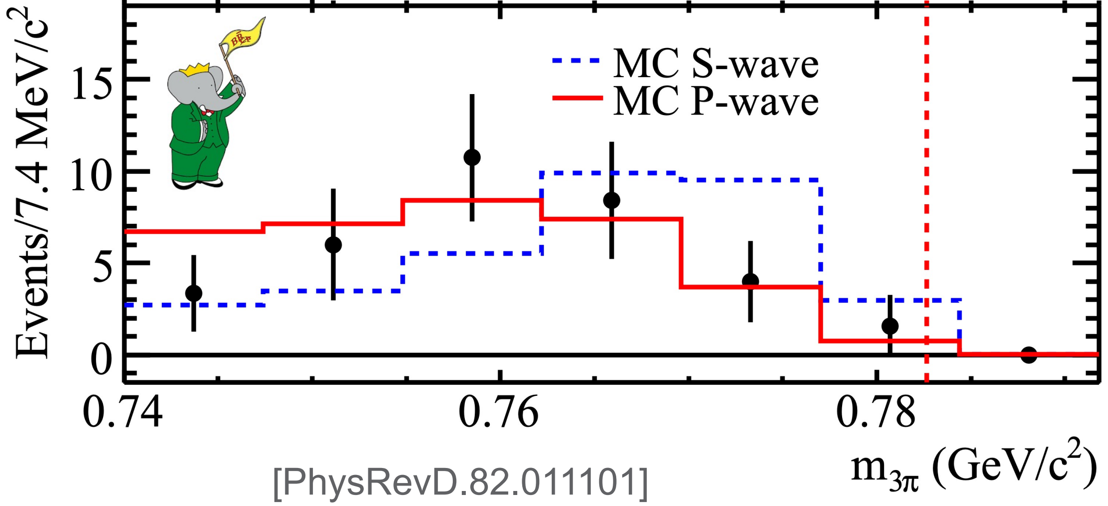
Analogous $\omega J/\psi$ Threshold in $c\bar{c}$ Sector

$$\chi_{c1}(3872) \rightarrow \omega J/\psi$$

- $\chi_{c1}(3872)$ **lies 8 MeV below threshold**
- $\Gamma(X(3872)) < 1.2\ \mathrm{MeV}$ (Belle 1107.0163)
- Evidence from Belle and BaBar ($< 5\sigma$)
- BES III recently observed transition (5.7σ)
  - 2019 – [PhysRevLett.122.232002]
  - Employ PHSP to model $X \rightarrow \omega\, J/\psi$

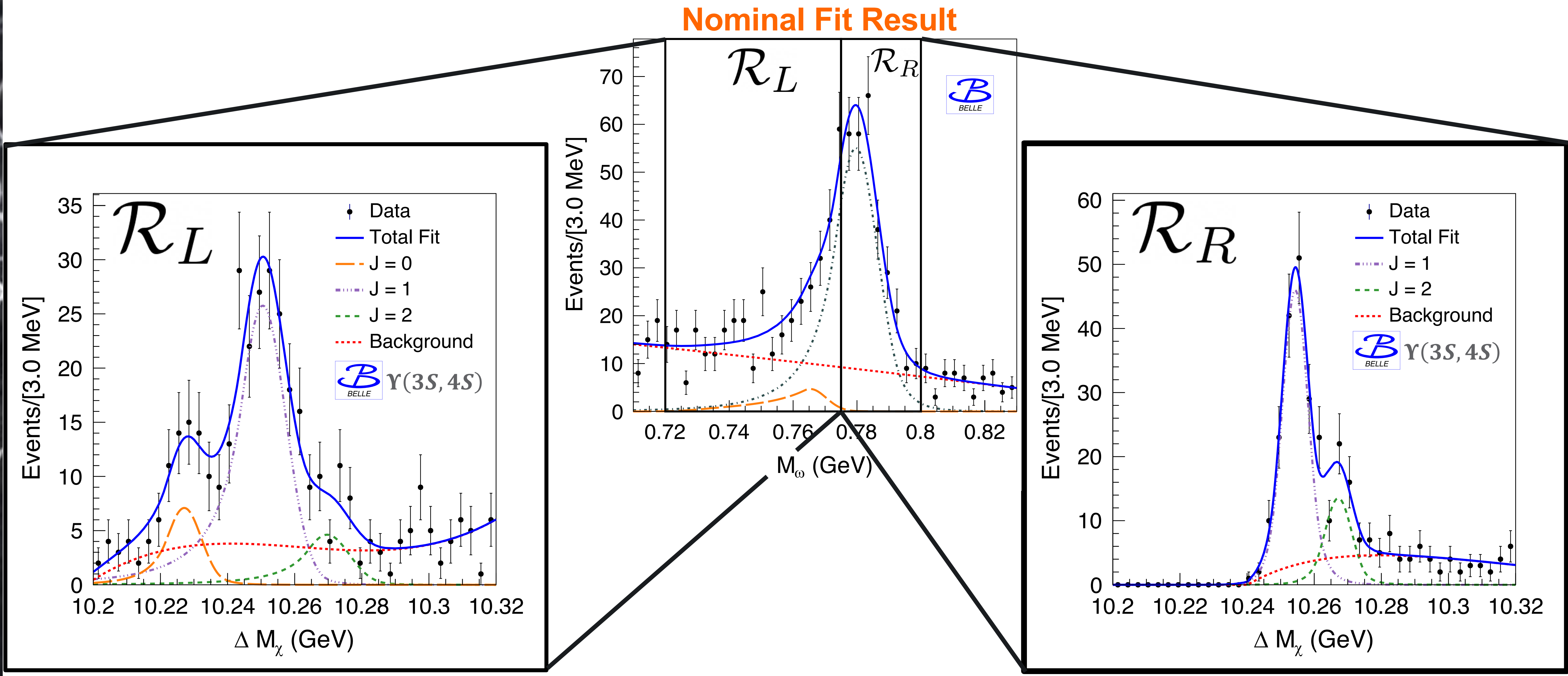
Plot with $m(\omega J/\psi)$ in the $\chi_{c1}(3872)$ Signal Region





[PhysRevD.82.011101]

Cross Check: Fits to ΔM_χ for Separate Regions in M_ω



Cascade Branching Ratio

In QCD Multipole Expansion (QCDME), the heavy quark spin decouples from the partial width $\Gamma\left(\chi_{bJ}(2P) \to \omega\Upsilon(1S)\right)$

Voloshin Calculates: [Mod. Phys. Lett. A18 (2003) 1067]

$$r_{2/1}^{QCDME} = \frac{\mathcal{B}\left(\Upsilon(3S) \to \gamma\chi_{b2}(2P) \to \gamma\omega\Upsilon(1S)\right)}{\mathcal{B}\left(\Upsilon(3S) \to \gamma\chi_{b1}(2P) \to \gamma\omega\Upsilon(1S)\right)}$$

$$= \frac{\Gamma(\Upsilon(3S) \to \gamma\chi_{b2}(2P))\,\Gamma(\chi_{b2}(2P) \to \omega\Upsilon(1S))\,\Gamma(\chi_{b1}(2P))}{\Gamma(\Upsilon(3S) \to \gamma\chi_{b1}(2P))\,\Gamma(\chi_{b1}(2P) \to \omega\Upsilon(1S))\,\Gamma(\chi_{b2}(2P))}$$

Estimated as average of $\mathcal{B}\left(\chi_{bJ}(2P) \to \gamma\Upsilon(mS)\right)$ for $m = 1, 2$

$$\begin{cases} 0.6359 \pm 0.1003, & m = 1 \\ 0.4179 \pm 0.0714, & m = 2 \end{cases}$$

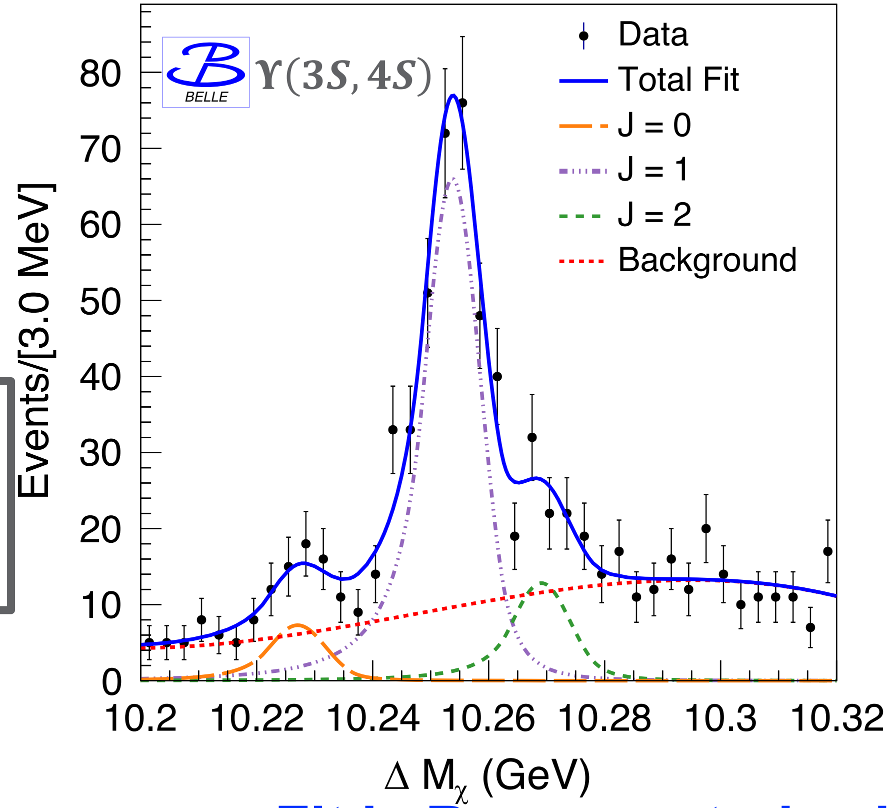
$$\Gamma\left(\Upsilon(3S) \to \chi_{bJ}(2P)\right) \approx (2J+1)k_\gamma^3$$

Ratio of S-wave Phase Space Factors $\sqrt{\frac{\Delta_2}{\Delta_1}}$

$$\Delta_J = M\left(\chi_{bJ}(2P)\right) - M\left(\Upsilon(1S)\right) - M(\omega)$$

Using current world averages we calculate

$$r_{2/1}^{QCDME} = 0.77 \pm 0.16$$



Fit is Reparameterized:

$$r_{2/1} = P_{J/1} \times \frac{\epsilon_1}{\epsilon_J}$$

$$\frac{N_J}{N_1}$$

RESULT

$$r_{0/1} = 0.110^{+0.037}_{-0.036} \pm 0.010$$

$$r_{2/1} = 0.200^{+0.062}_{-0.058}\,{}^{+0.009}_{-0.017}$$

3.3σ tension with QCDME

Search for $\chi_{bJ}(3P) \to \omega\Upsilon(1S)$
Event Selection Revisited

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Final State Particle Selection Criteria

- At least 4 tracks with $|dr| < 0.5$ cm, $|dz| < 2.0$ cm
- At least 2 isolated clusters in ECL that do not match with a track.

Hard Tracks (Leptons)

- $p_\ell^{CM} > 4.0$ GeV
- $M(\ell^+\ell^-) \in [9.0, 9.8]$ GeV
- Require exactly 1 di-lepton
- MuonID > 0.2 or eID > 0.2 (only in $\Upsilon(4S)$ Dataset)

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- $p_\pi^{CM} < 0.45$ GeV
- $cos(\psi_{\pi\pi}) < 0.95$
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π^0 Candidates

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- **Retain π^0 with smallest mass fit χ^2**

Resonant $b\bar{b} \to \pi^+\pi^- b\bar{b}'$ Veto

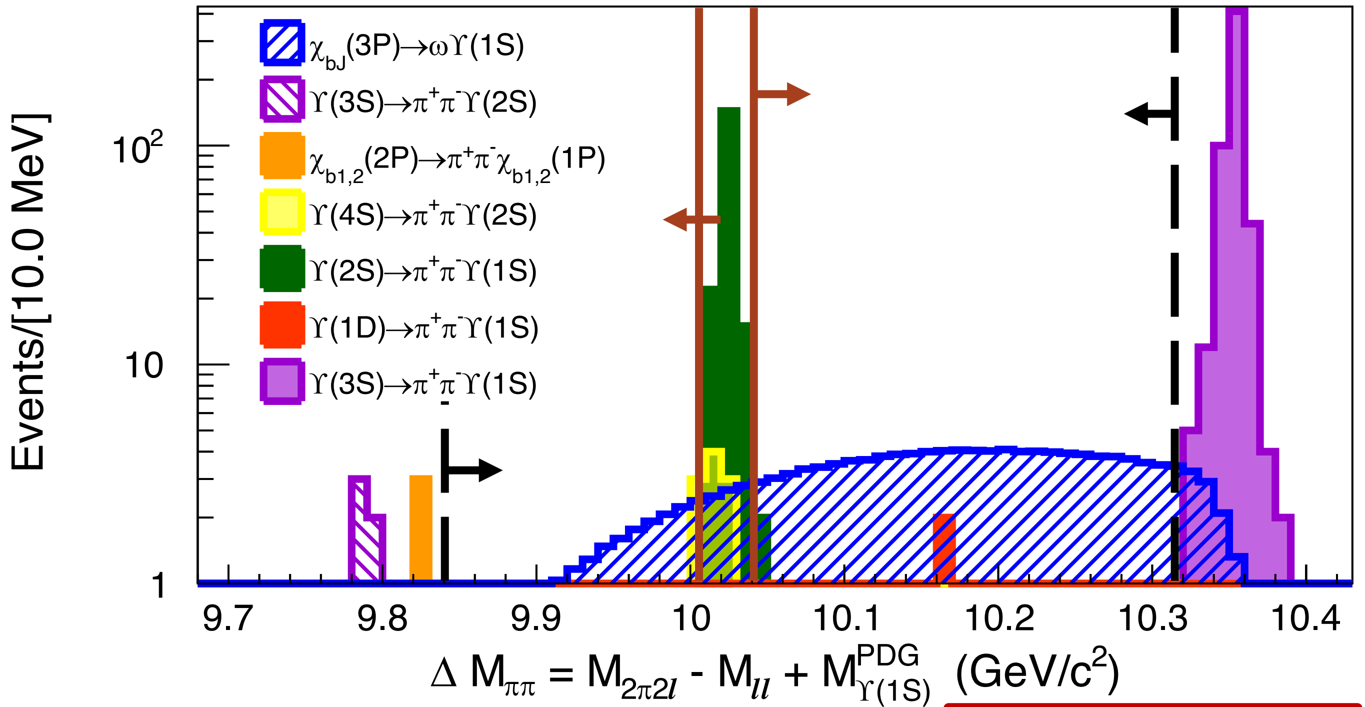
- $\Delta M_{\pi\pi} \notin (10.014, 10.030)$ GeV
- $\mathbf{\Delta M_{\pi\pi} < 10.32}$ **GeV**

Additional Selections

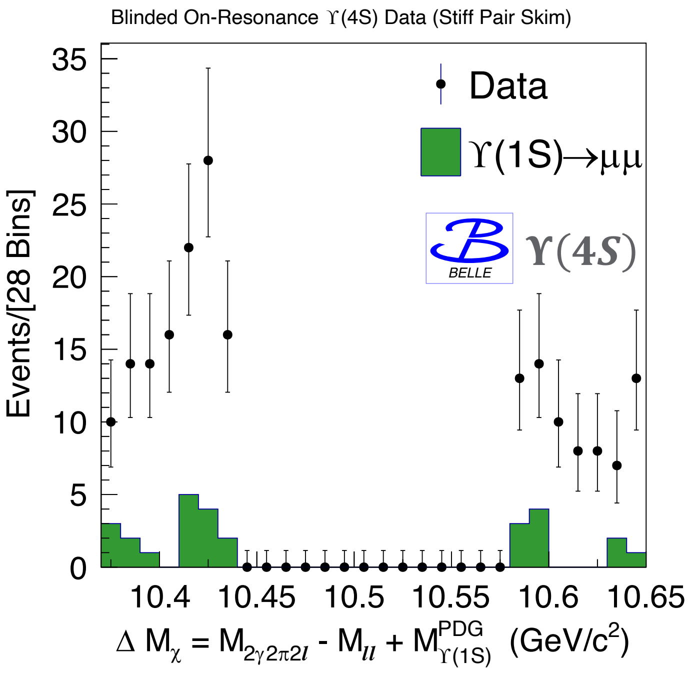
$\chi_{bJ}(3P)$ Continuum Veto

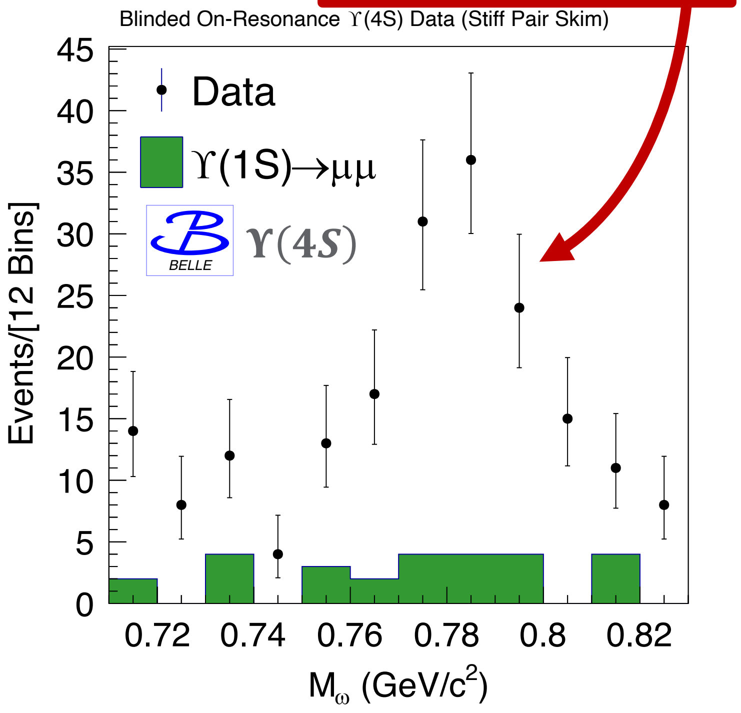
- MuID > 0.2 for leptons
- $M_{\ell\ell} \in [9.2, 9.6]$ GeV

Reject $\Upsilon(1S) \to e^+e^-$ to suppress large backgrounds



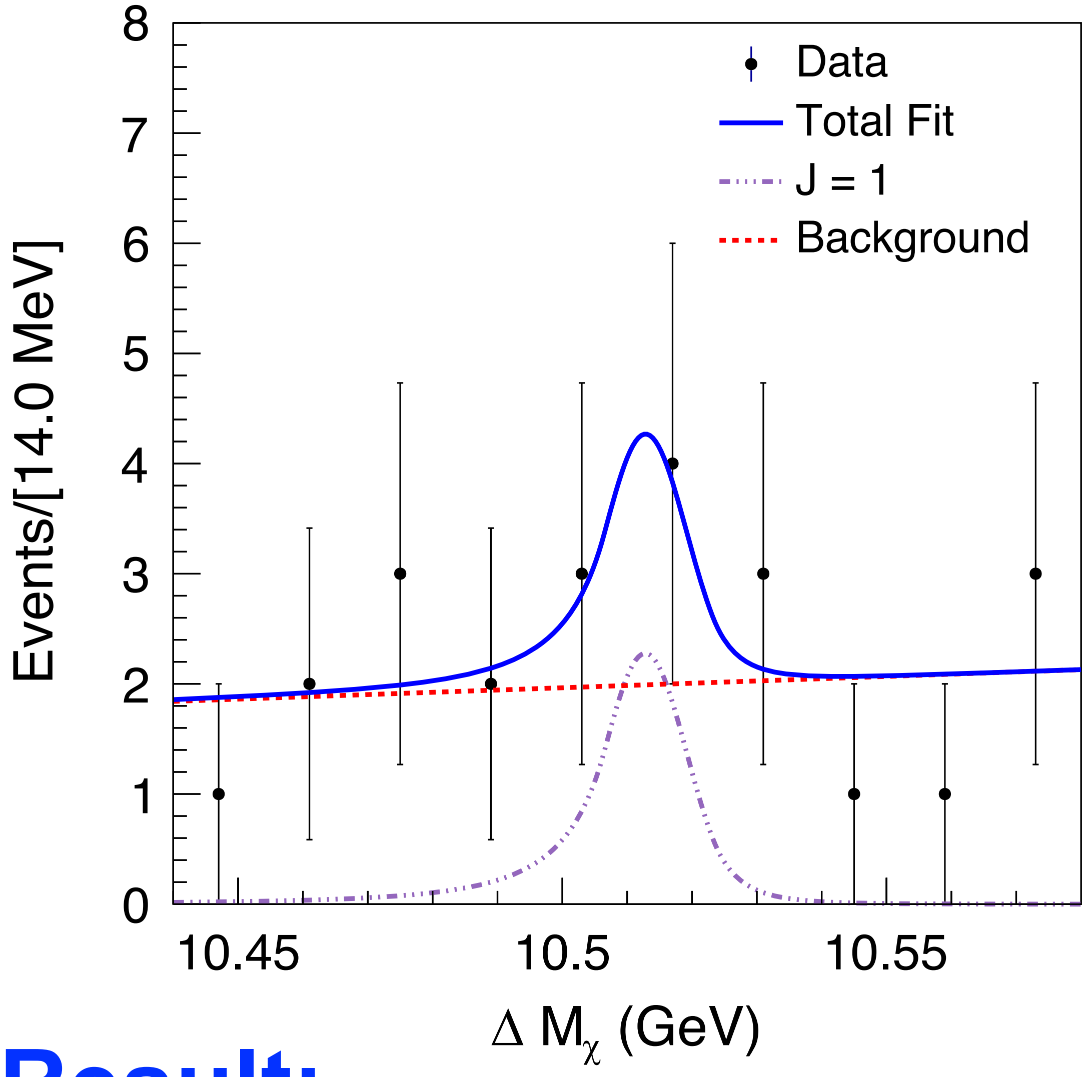
$e^+e^- \to h^+h^-\omega$





Search for $\chi_{bJ}(3P)$

$513\ \text{fb}^{-1}$ of **on-resonance $\Upsilon(4S)$ data analyzed**



[Phys.Rev.D 92 (2015) 5, 054034]

Initial state	Final state	M_f (GeV)	$\mathcal{M}$	Predicted Width (keV)	Predicted BR (%)	Width (keV)
$\Upsilon(4^3S_1)$	$\ell^+\ell^-$		0.459	0.39	1.8×10^{-3}	0.32 ± 0.04^a
10.579^a	ggg		0.459	15.1	0.0686	
	γgg		0.459	0.40	1.8×10^{-3}	
	$\gamma\gamma\gamma$		0.459	6.0×10^{-6}	2.7×10^{-8}	
	$\chi_{b2}(3^3P_2)\gamma$	10.528^d	-3.223	0.82	$3.7\times10^{-3}\%$	
	$\chi_{b1}(3^3P_1)\gamma$	10.516^d	-3.072	0.84	$3.8\times10^{-3}\%$	
	$\chi_{b0}(3^3P_0)\gamma$	10.500^d	-2.869	0.48	$2.2\times10^{-3}\%$	

Assume: $\mathcal{B}\left(\chi_{b1}(nP)\to\omega\Upsilon(1S)\right)$ is equivalent for $n=2,\ 3$

Estimate:

$$\mathcal{B}\left(\Upsilon(4S)\to\gamma\chi_{b1}(3P)\to\gamma\omega\Upsilon(1S)\right)\sim 8.4\times10^{-7}$$

Corresponding to ~1 event.

Signal Yield: $3.2^{+3.6}_{-2.8}$ events

With no significant signal is seen, an upper limit is set.

→ Convolute the profile likelihood with a Gaussian whose width is equal to the systematic uncertainty

→ Integrate the profile likelihood for non-negative yields.

Result:

$$\mathcal{B}\left(\Upsilon(4S)\to\gamma\chi_{b1}(3P)\to\gamma\omega\Upsilon(1S)\right)<1.4\times10^{-5}\ (90\%\ \text{CL})$$

Summary

- Belle remains productive in $Q\bar{Q}$ spectroscopy!
- We Present Results: [arXiv:TBD]
  - $\chi_{bJ}(2P)$ Branching Fraction Measurements:

Channel	$\mathcal{B}(\chi_{bJ}(2P) \to \omega\Upsilon(1S))$	Significance
$J=0$	$\left(0.56^{+0.19}_{-0.18} \pm 0.08\right)$ %	3.2σ
$J=1$	$\left(2.38 \pm 0.19^{+0.23}_{-0.24}\right)$ %	15.0σ
$J=2$	$\left(0.46 \pm 0.12^{+0.06}_{-0.07}\right)$ %	3.9σ

First Evidence of Sub-Threshold Decay!

First Confirmation of CLEO Discovery!

Consistent with CLEO at 2σ level

[Phys.Rev.Lett. 92 (2004) 222002]

  - Search for $\chi_{bJ}(3P)$ at Belle
    - ✓ Set an upper limit on the cascade branching fraction:

$$\mathcal{B}\left(\Upsilon(4S) \to \gamma\chi_{b1}(3P) \to \gamma\omega\Upsilon(1S)\right) < 1.4 \times 10^{-5} \; (90\% \text{ CL})$$

- The future is bright for Quarkonium at Belle and high luminosity Belle II

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Thank you

Systematic Uncertainties

TABLE IV: Summary of systematic efficiencies impacting the branching fraction measurements, reported in percent.

Source	$\mathcal{B}(\chi_{b0}(2P) \to \omega\Upsilon)$	$\mathcal{B}(\chi_{b1}(2P) \to \omega\Upsilon)$	$\mathcal{B}(\chi_{b2}(2P) \to \omega\Upsilon)$	$\mathcal{B}(\Upsilon(4S) \to \gamma\chi_{b1}(3P) \to \gamma\omega\Upsilon)$
Tracking	...	...	...	± 1.4
PID	...	...	...	± 1.1
π^0 reconstruction	± 1.7	± 1.7	± 1.7	± 3.3
Selection Efficiency	± 0.1	± 0.1	± 0.1	± 0.02
Signal Extraction	$^{+8.7}_{-8.8}$	$^{+1.1}_{-2.6}$	$^{+3.6}_{-7.9}$	$^{+10.1}_{-12.6}$
Number of $\Upsilon(4S)$	...	...	...	± 1.4
Number of $\Upsilon(3S)$	$^{+1.2}_{-1.1}$	$^{+1.2}_{-1.1}$	$^{+1.2}_{-1.1}$	...
External Branching Fractions	± 10.4	± 9.4	± 12.4	± 2.2
Total	$^{+14.1}_{-14.2}$	$^{+9.7}_{-10.0}$	$^{+13.1}_{-14.8}$	$^{+11.1}_{-13.4}$

Systematic Uncertainties

Channel	Fixed Parameters	Bkg Shape + Fit Window	Fitter Bias	Fit Procedure Systematic
$J = 0$	$^{+4.1\%}_{-3.9\%}$	$^{+6.9\%}_{-7.3\%}$	3.2%	$^{+8.7\%}_{-8.8\%}$
$J = 1$	$^{+0.6\%}_{-0.5\%}$	$^{+0.8\%}_{-2.5\%}$	0.4%	$^{+1.1\%}_{-2.6\%}$
$J = 2$	$^{+1.4\%}_{-1.3\%}$	$^{+1.4\%}_{-7.2\%}$	2.9%	$^{+3.6\%}_{-7.9\%}$

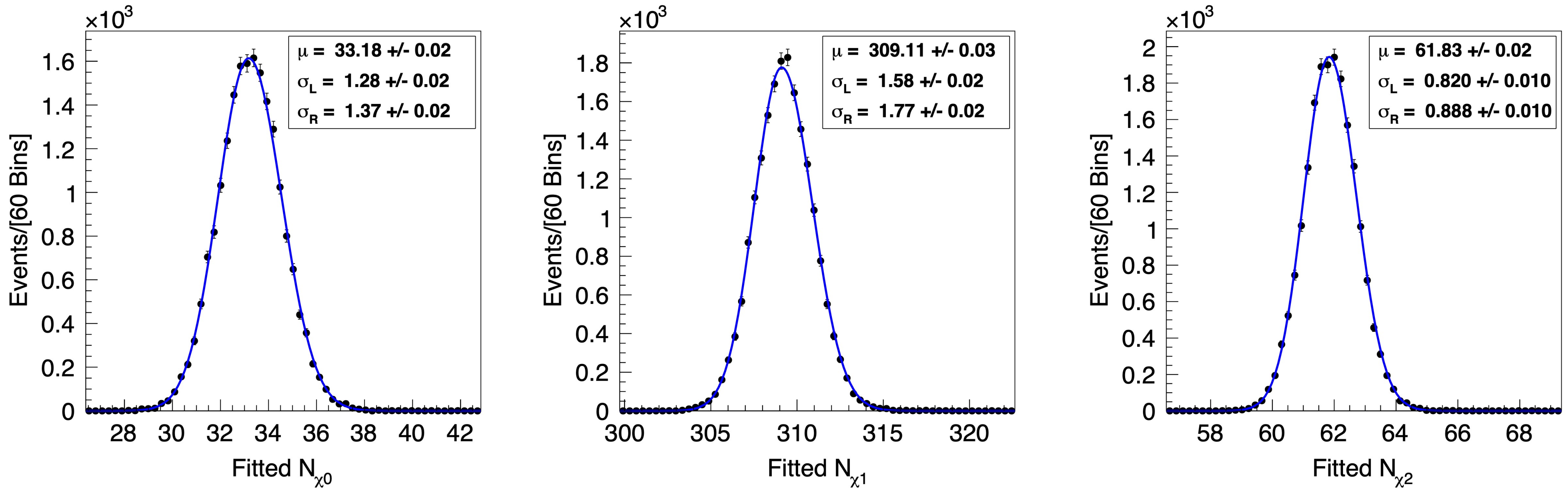

FIG. 81: The signal yield distribution for each decay of interest, obtained from 20,000 fits to data while the model parameters are varied according to the global covariance matrix.

Systematic Uncertainties

Channel	Fixed Parameters	Bkg Shape + Fit Window	Fitter Bias	Fit Procedure Systematic
$J = 0$	$^{+4.1\%}_{-3.9\%}$	$^{+6.9\%}_{-7.3\%}$	3.2%	$^{+8.7\%}_{-8.8\%}$
$J = 1$	$^{+0.6\%}_{-0.5\%}$	$^{+0.8\%}_{-2.5\%}$	0.4%	$^{+1.1\%}_{-2.6\%}$
$J = 2$	$^{+1.4\%}_{-1.3\%}$	$^{+1.4\%}_{-7.2\%}$	2.9%	$^{+3.6\%}_{-7.9\%}$

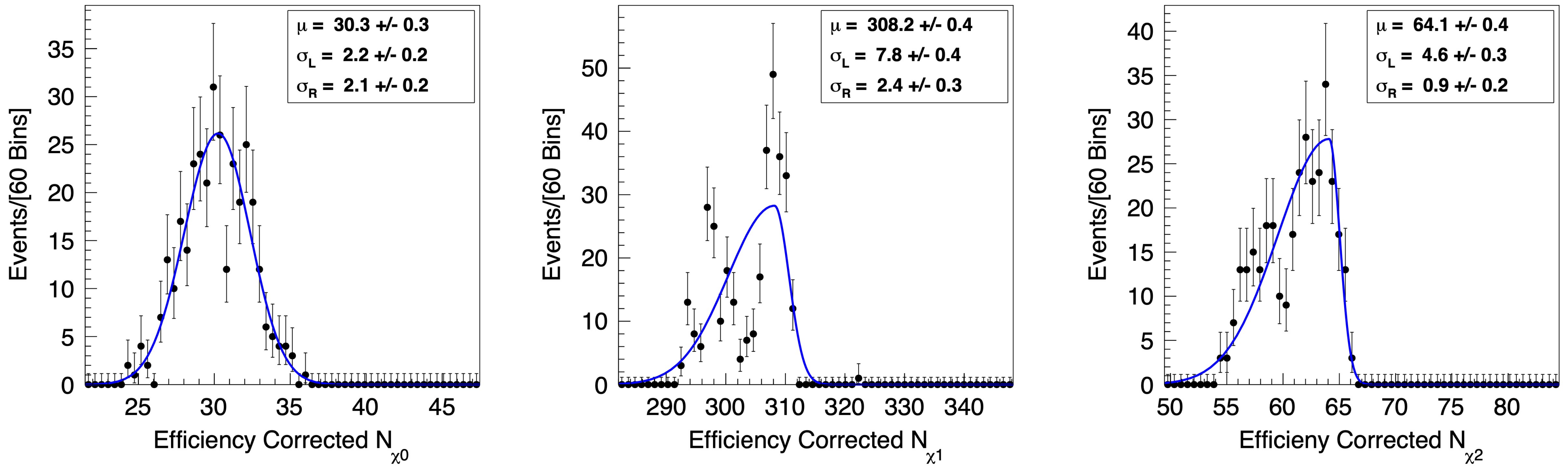

FIG. 82: Distributions of efficiency-corrected signal yields, obtained from fits to data with varied fit windows and background shapes.

Systematic Uncertainties

Channel	Fixed Parameters	Bkg Shape + Fit Window	Fitter Bias	Fit Procedure Systematic
$J = 0$	$^{+4.1\%}_{-3.9\%}$	$^{+6.9\%}_{-7.3\%}$	3.2%	$^{+8.7\%}_{-8.8\%}$
$J = 1$	$^{+0.6\%}_{-0.5\%}$	$^{+0.8\%}_{-2.5\%}$	0.4%	$^{+1.1\%}_{-2.6\%}$
$J = 2$	$^{+1.4\%}_{-1.3\%}$	$^{+1.4\%}_{-7.2\%}$	2.9%	$^{+3.6\%}_{-7.9\%}$

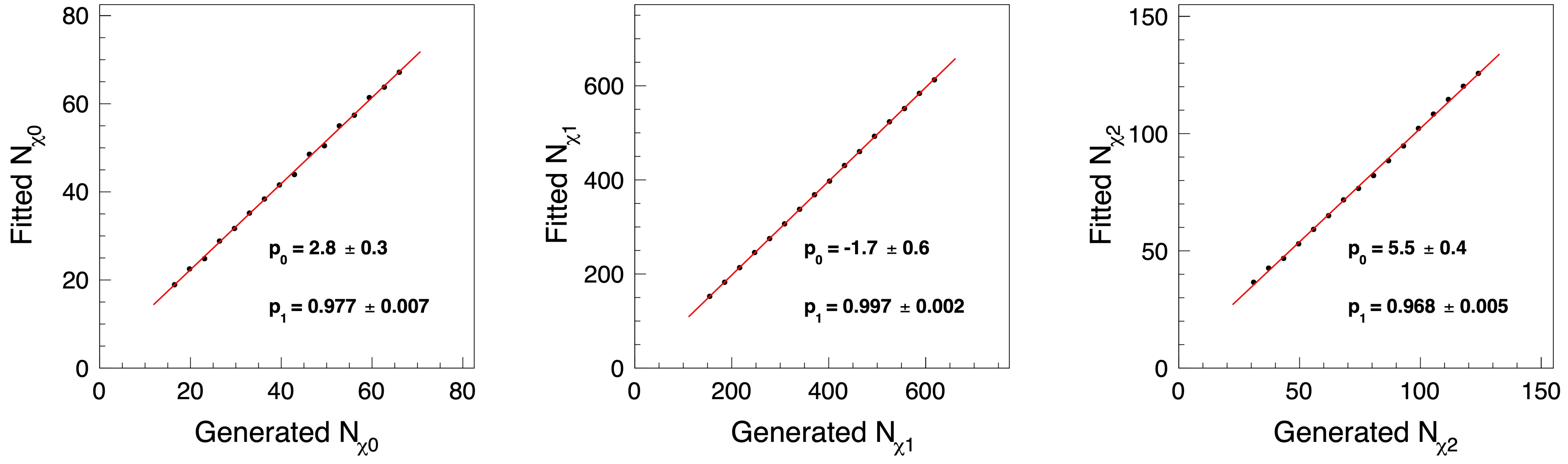

FIG. 83: Linearity test results of the $\chi_{b1}(2P) \to \omega\Upsilon(1S)$ fitter.