Study of Bottomonium Decays

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Belle II Summer School

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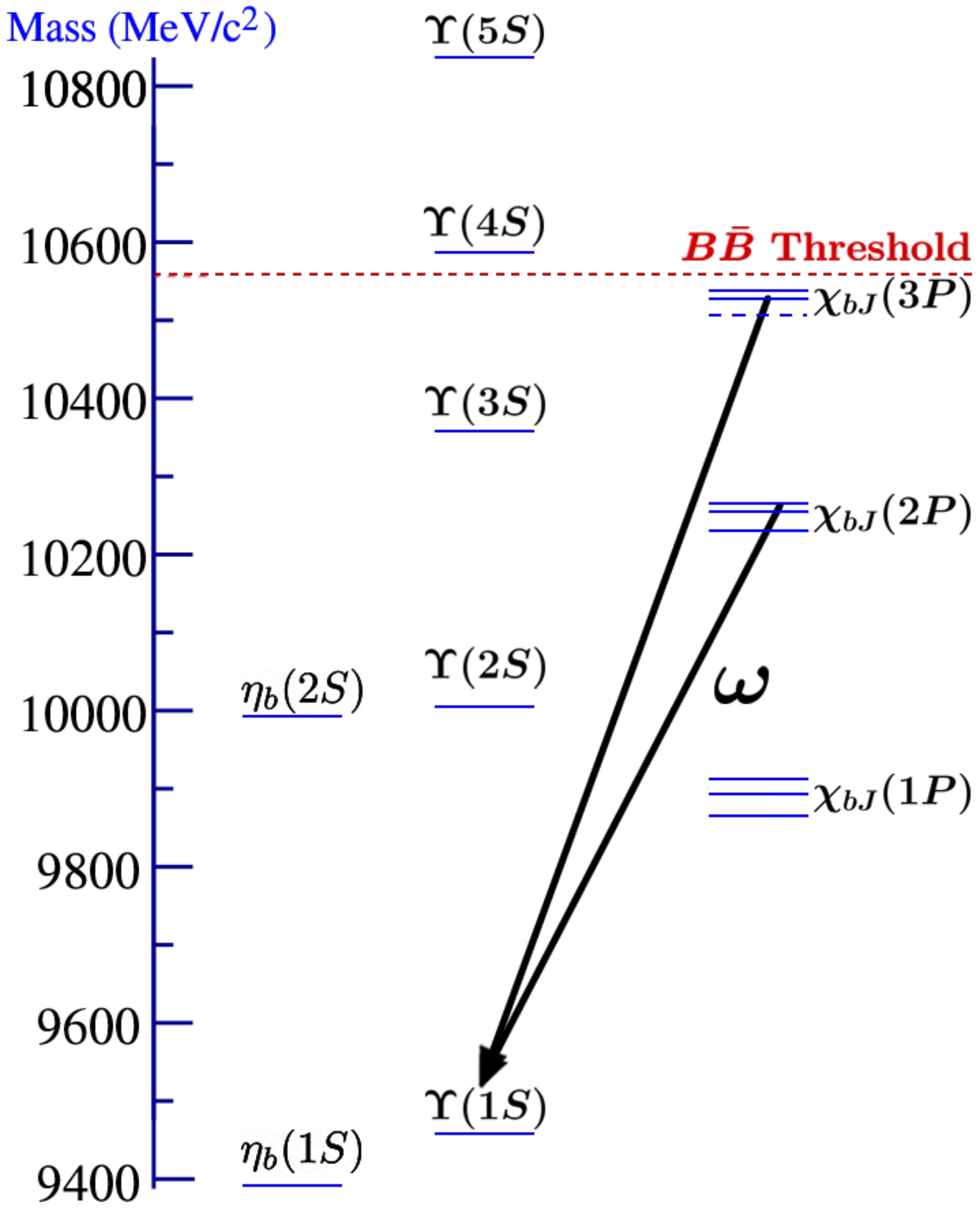
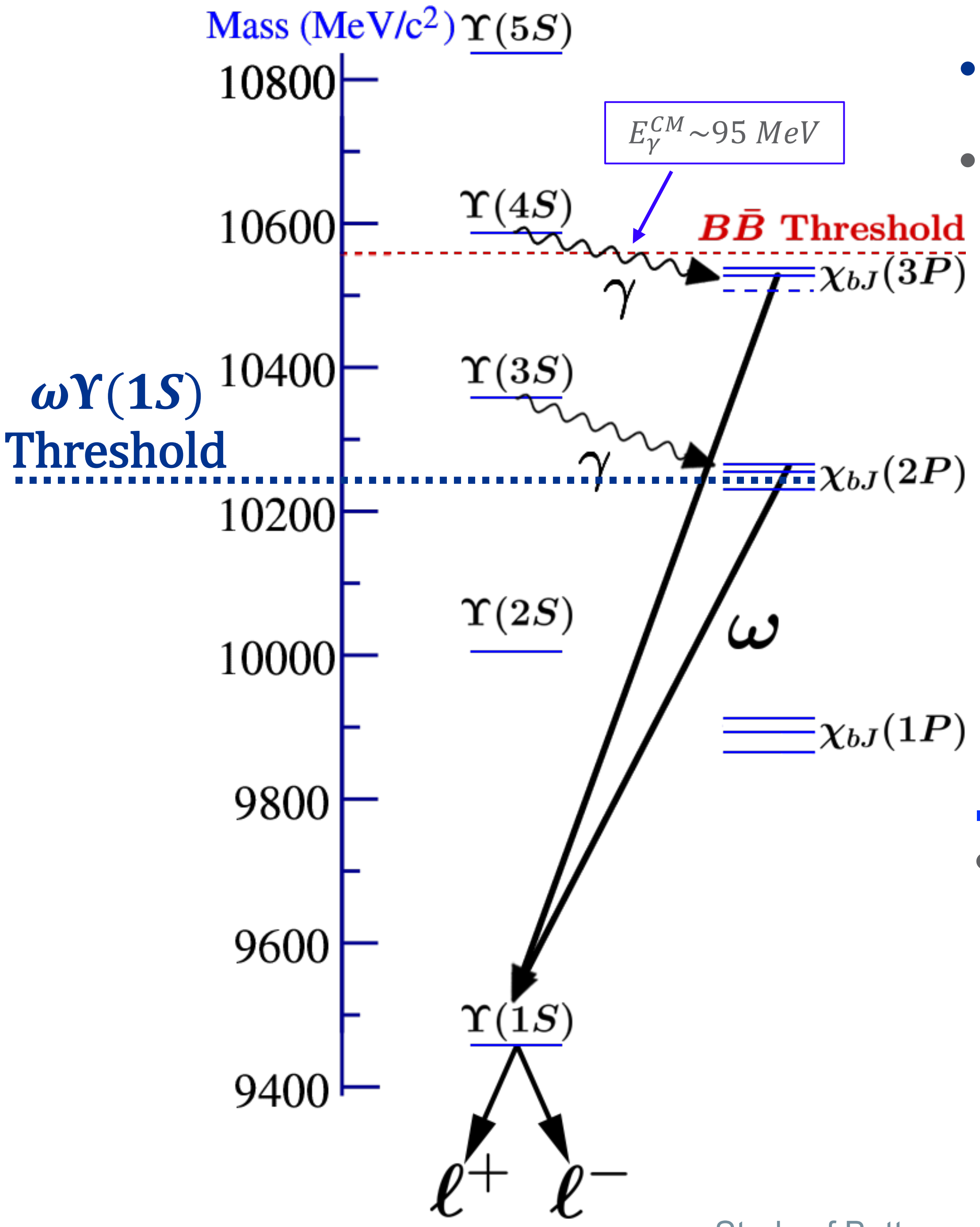
Overview

- Introduction
  - Modes of Interest
  - Previous Measurement
  - Datasets & $\Upsilon(3S)$ Population
- Search for $\chi_{bJ}(nP) \rightarrow \omega\Upsilon(1S)$
  - Analysis Strategy
  - Event Selection and Background Suppression
  - Fitter & improved J=0 signal shape
  - Branching Fraction Measurement
    - ✓ Cross check of tail shapes
  - Search for $\chi_{bJ}(3P) \rightarrow \omega\Upsilon(1S)$
- Summary



Previous Measurement & Analysis Strategy

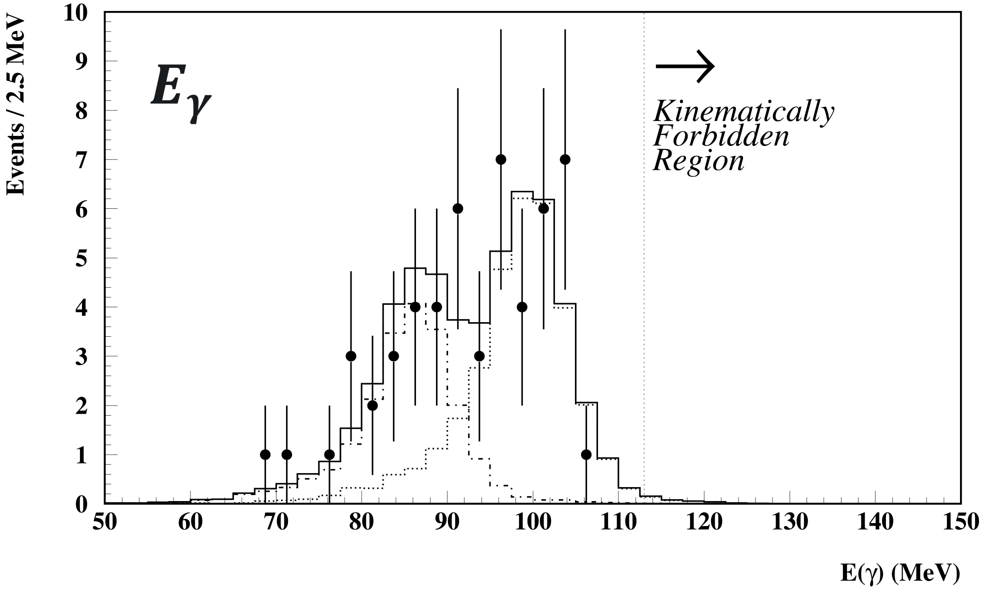


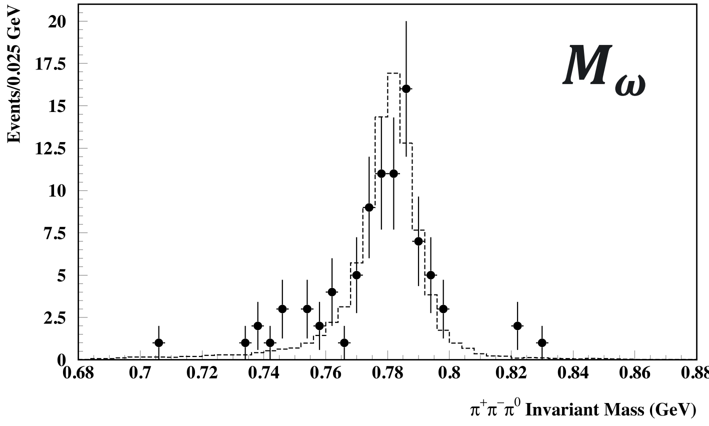
- $\chi_{b1,2}(2P)$ and $\chi_{b(0),1,2}(3P)$ states are kinematically accessible
- $\chi_{bJ}(2P) \rightarrow \omega\Upsilon(1S)$ Discovered by CLEO

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

  - Analyzed $(5.81 \pm 0.12)\times10^6\ \Upsilon(3S)$ 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:

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

  - High backgrounds for low energy photons make reconstruction of $\Upsilon(3S) \rightarrow \gamma\chi_{bJ}(nP)$ suboptimal

Data Samples

Dataset	$\sqrt{s}$ (MeV)	Exp.	Runs	$\mathcal{L}$ (fb^{-1})
$\Upsilon(4S)$ on-resonance	~ 10572	31-65	-	~~496.0~~ 513 fb^{-1}
$\Upsilon(4S)$ off-resonance	~ 10520	31-65	-	56.0
$\Upsilon(3S)$ on-resonance	10354.7	49	1001–1185	2.999
$\Upsilon(3S)$ off-resonance	10324.7	49	1193–1227	0.246
$\Upsilon(2S)$ on-resonance	10023.3	67	1016–1123	6.5
	10023.3	71	313–497, 537–696	18.2
$\Upsilon(2S)$ off-resonance	9993.3	71	498–536	1.7

- **Utilize:**
  - $\Upsilon(3S)$ **data available as all_mdsts**
  - **Stiff Pair skim of** $\Upsilon(4S)$ **data**
  - **Stiff Pair skim of** $\Upsilon(2S)$ **data** — for studies of track and π^0 finding efficiency
- **Analysis is now unblinded on the** $\chi_{bJ}(nP)$ **signal regions**
- **Together with Nishida-san & Nakazawa-san, we've recovered an additional 17** fb^{-1}

Count $\Upsilon(3S)$ via Decays to $\pi^+\pi^-\Upsilon(1S)$

Calculate $\Upsilon(3S)$ Population as:

$$N_{3S} = \frac{N_{\pi\pi\Upsilon}}{\epsilon\mathcal{B}\big(\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)\big)\mathcal{B}\big(\Upsilon(1S)\to\ell^+\ell^-\big)}$$

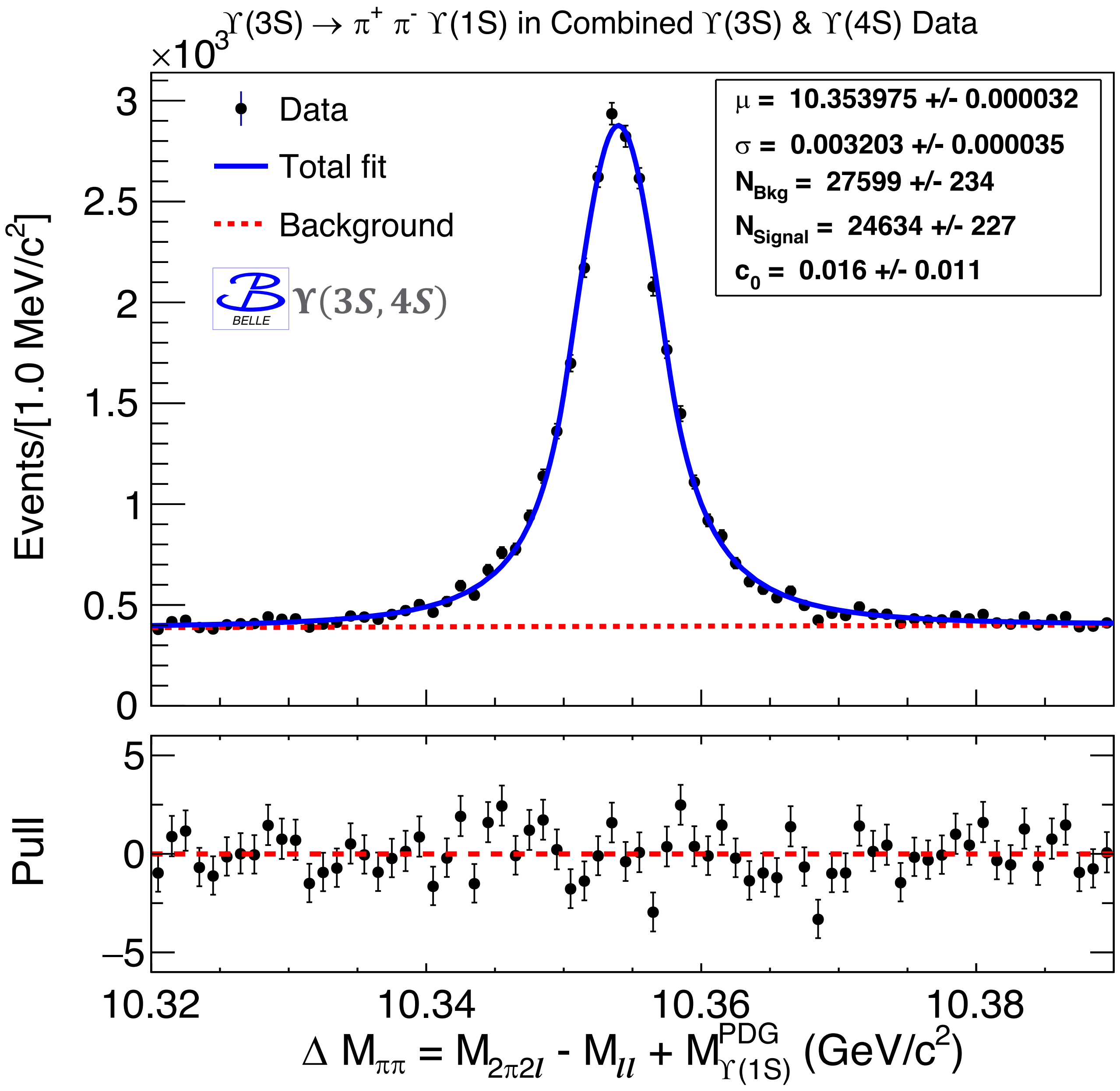
where $\ell = e, \mu$.

– $\Upsilon(3S)$ Population –

$$\left(27.94 \pm 0.26^{+0.48}_{-0.49} \pm 0.09\right)\cdot 10^6$$

$\mathcal{B}\big(\chi_{bJ}(2P)\to\omega\Upsilon\big)$ are calculated by normalizing to $\pi\pi$

- Affords cancelation of several systematics including track-finding, lepton PID, and $\mathcal{B}(\Upsilon(1S)\to\ell^+\ell^-)$.



Event Selection & Background Suppression

FSP Selections

- **At least 4 tracks** with $|dr| < 0.5$ cm, $|dz| < 2.0$ cm, and track fit CL > 0
- **At least 2 ECL clusters with**:
  - No matched track
  - $\frac{E_9}{E_{25}} > 0.9$
  - Shower Width > 6 cm

Hard Tracks (Leptons)

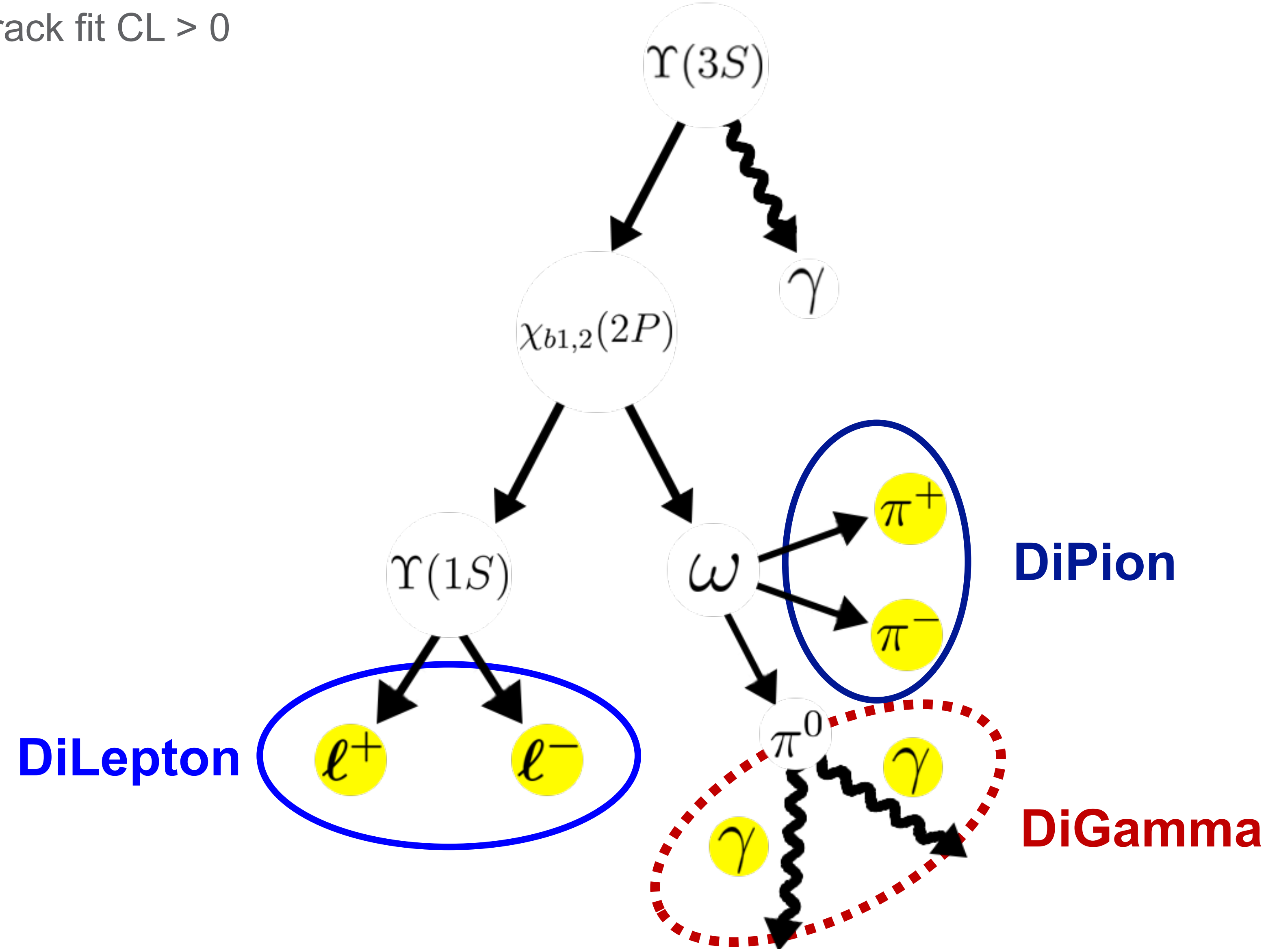
- $p_\ell^{CM} > 4.0$ GeV
- $M_{\ell\ell} \in (9.0, 9.8) \frac{\mathrm{GeV}}{\mathrm{c}^2}$
- Require exactly 1 di-lepton

Soft Tracks (Pions)

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

π^0 Candidates

- $p_{\pi^0}^{CM} \in [80,430] \frac{\mathrm{MeV}}{\mathrm{c}}$
- $M_{\pi^0} \in [0.11, 0.15] \frac{\mathrm{GeV}}{\mathrm{c}^2}$
- **Retain π^0 with smallest mass fit χ^2**



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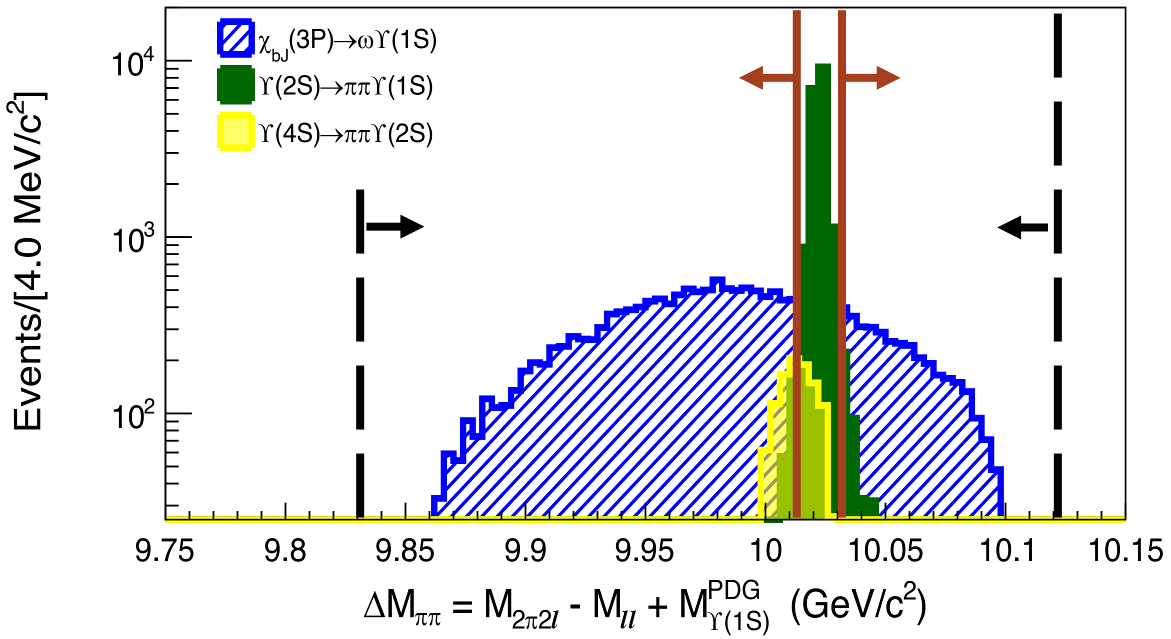
- **Retain π^0 with smallest mass fit χ^2**

Resonant $b\bar{b} \to \pi^+\pi^- b\bar{b}'$ Veto
- $\Delta M_{\pi\pi} \in [9.83, 10.12]$ GeV
- $\Delta M_{\pi\pi} \notin (10.017, 10.029)$ GeV

Rejects 92.4% of resonant background at cost of 7.3% of signal



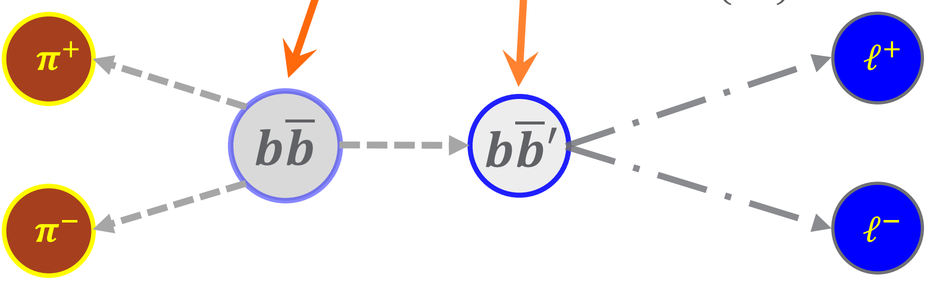
$\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ Veto: FOM Optimization

$\Delta M_{\pi\pi}$ < CUT \ $\Delta M_{\pi\pi}$ > CUT	10.027	10.028	10.029	10.03	10.031
10.018	172.42	172.58	172.58	172.35	172.03
10.017	172.84	173.02	173.03	172.81	172.50
10.016	172.77	172.96	172.98	172.76	172.45
10.015	172.48	172.67	172.70	172.48	172.17
10.014	172.13	172.32	172.35	172.14	171.83

$$\text{FOM} = \frac{N_S}{\sqrt{N_S + N_B}}$$

Define:

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



- Resonant bkgs are sharply peaked in $\Delta M_{\pi\pi}$
- $\Delta M_{\pi\pi}$ offers better separation than $M_{recoil}(\pi\pi)$

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Signal Extraction: ΔM_χ

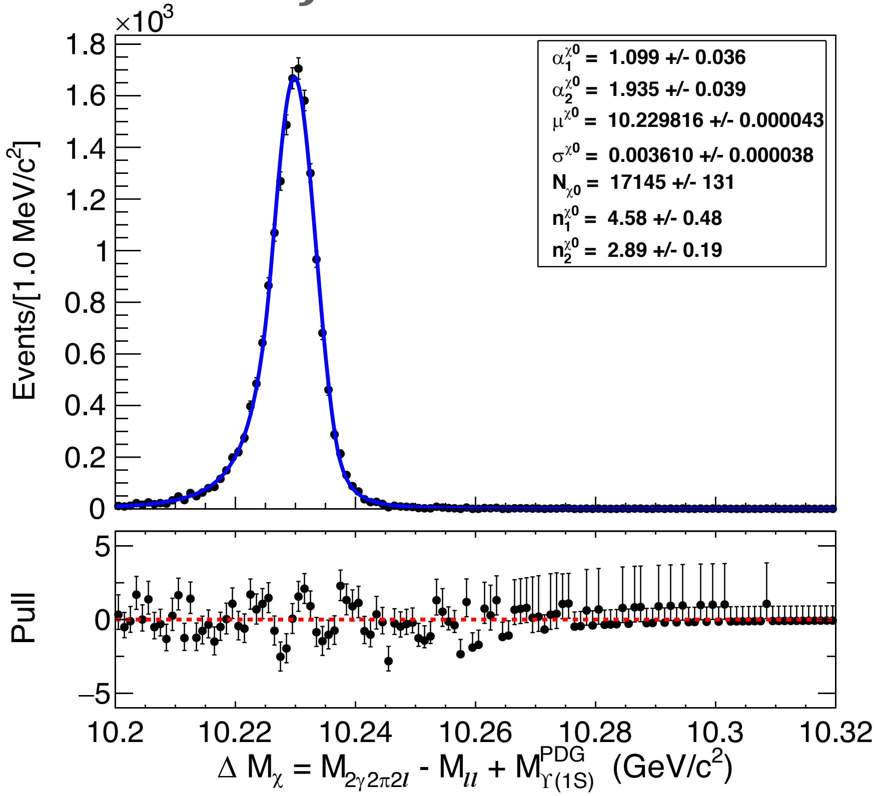
Definition of Fit Observable:

$$\Delta M_\chi = M_{2\gamma 2\pi 2\ell} - M_{\ell\ell} + M^{PDG}_{\Upsilon(1S)}$$

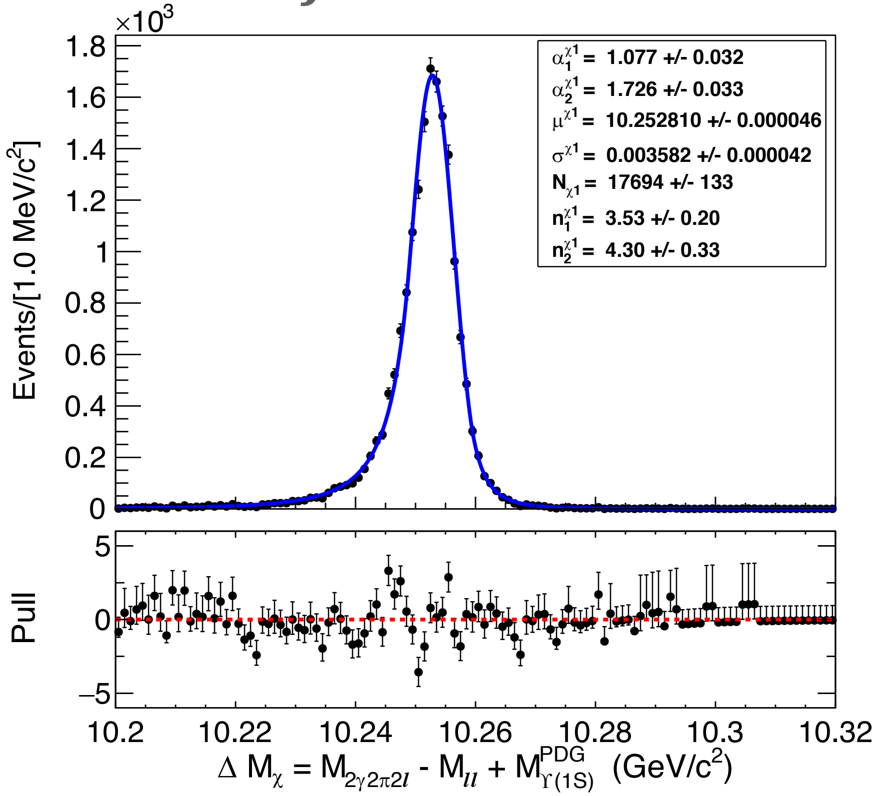
χ_{bJ} Mass

$\Upsilon(1S)$ Mass

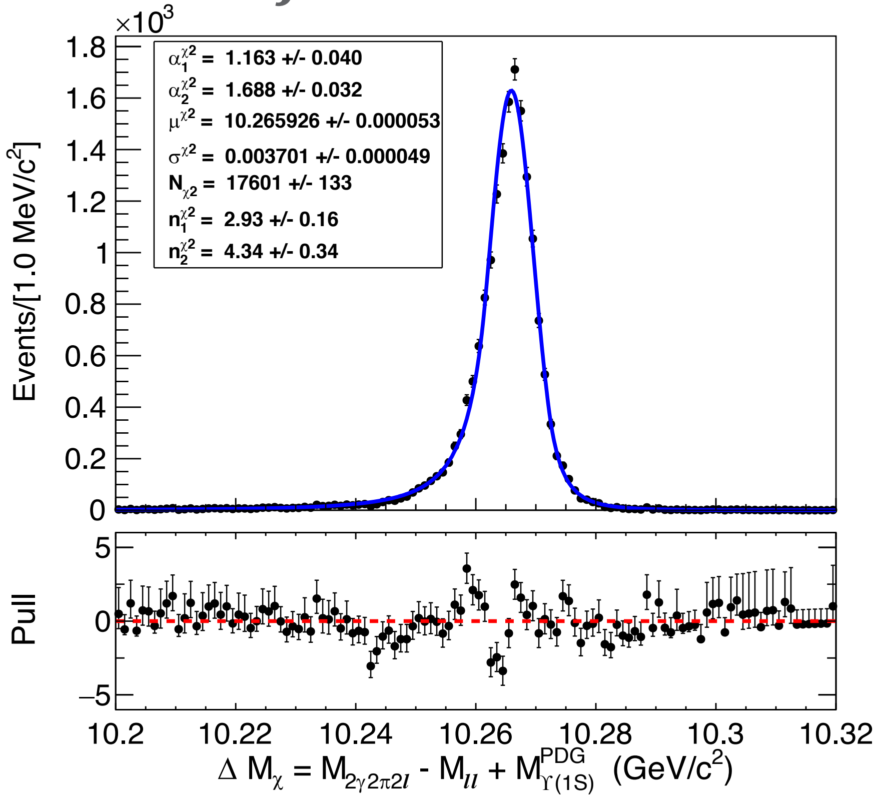
$J = 0$ SIGNAL



$J = 1$ SIGNAL



$J = 2$ SIGNAL



Shapes: Double-Sided Crystal Ball (DSCB) functions

- Reparameterize Signal Functions to account for Data-MC difference:

$$\mathcal{F}(\mu, \sigma, \alpha_1, \alpha_2, n_1, n_2) \mapsto \mathcal{F}(\mu, \rho \times \sigma, \alpha_1, \alpha_2, n_1, n_2),$$

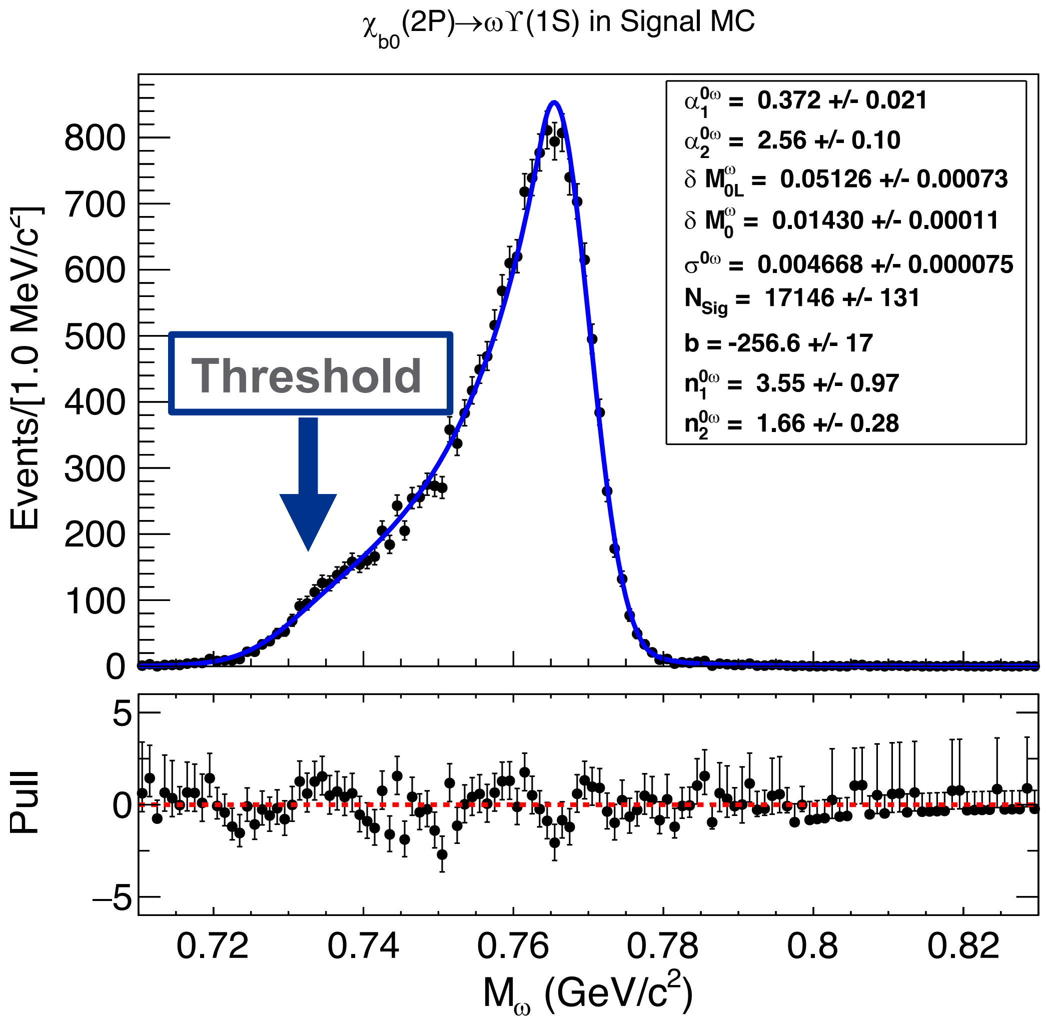
where **Red parameters are fixed**, **Blue are floated**, and ρ is a (common) "fudge factor"

M_ω signal shape of χ_{b0}

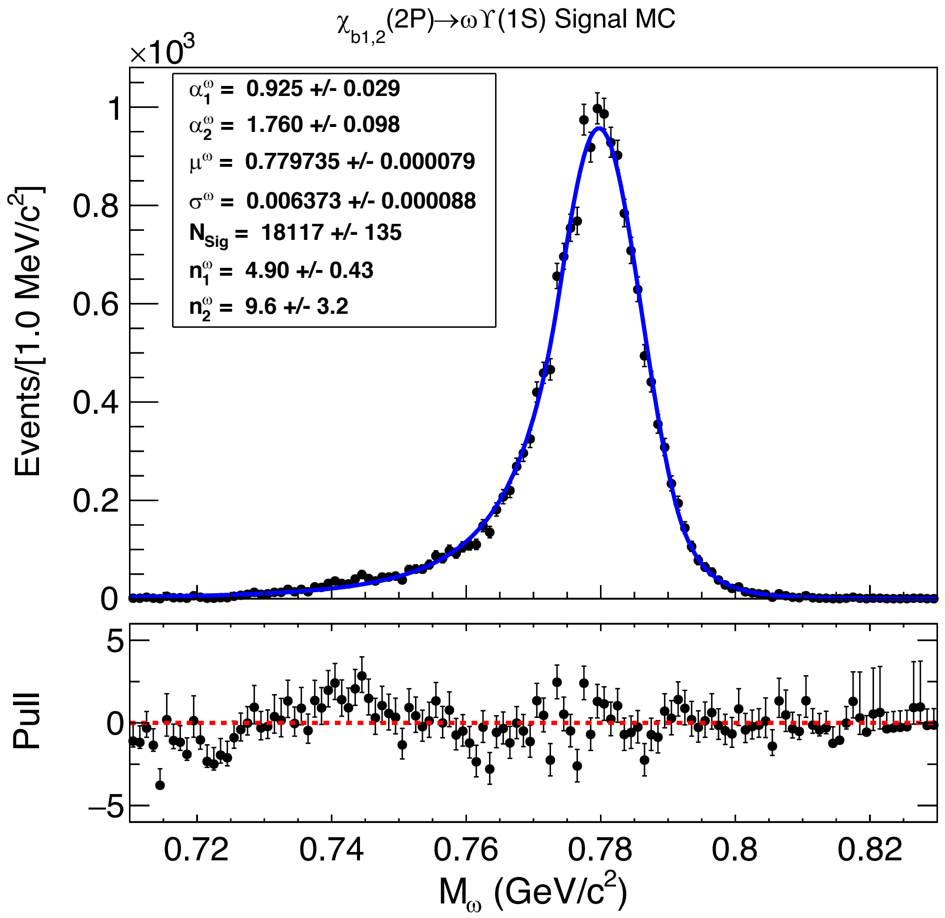
J=0 signal shape differs from that of J=1,2.

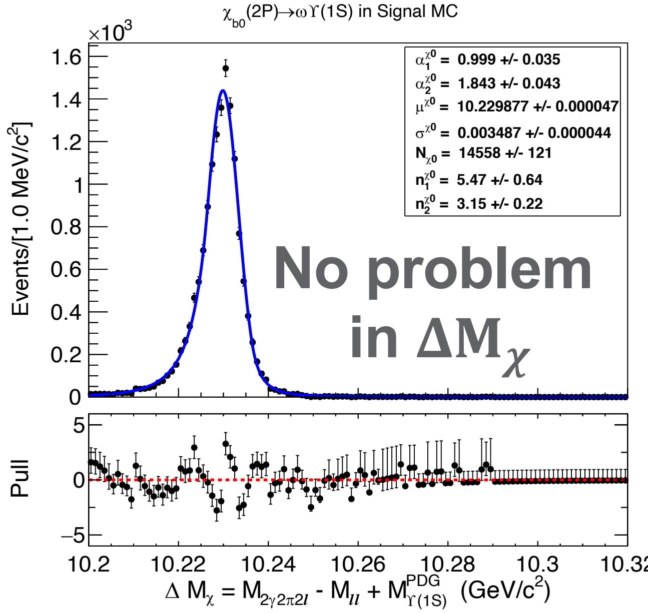
- Mean is shifted low
- Strange threshold in tail

→ Define signal shape as product of sigmoid $\left(f(b, \delta M_{0L}^{\omega})\right)$ and DSCB



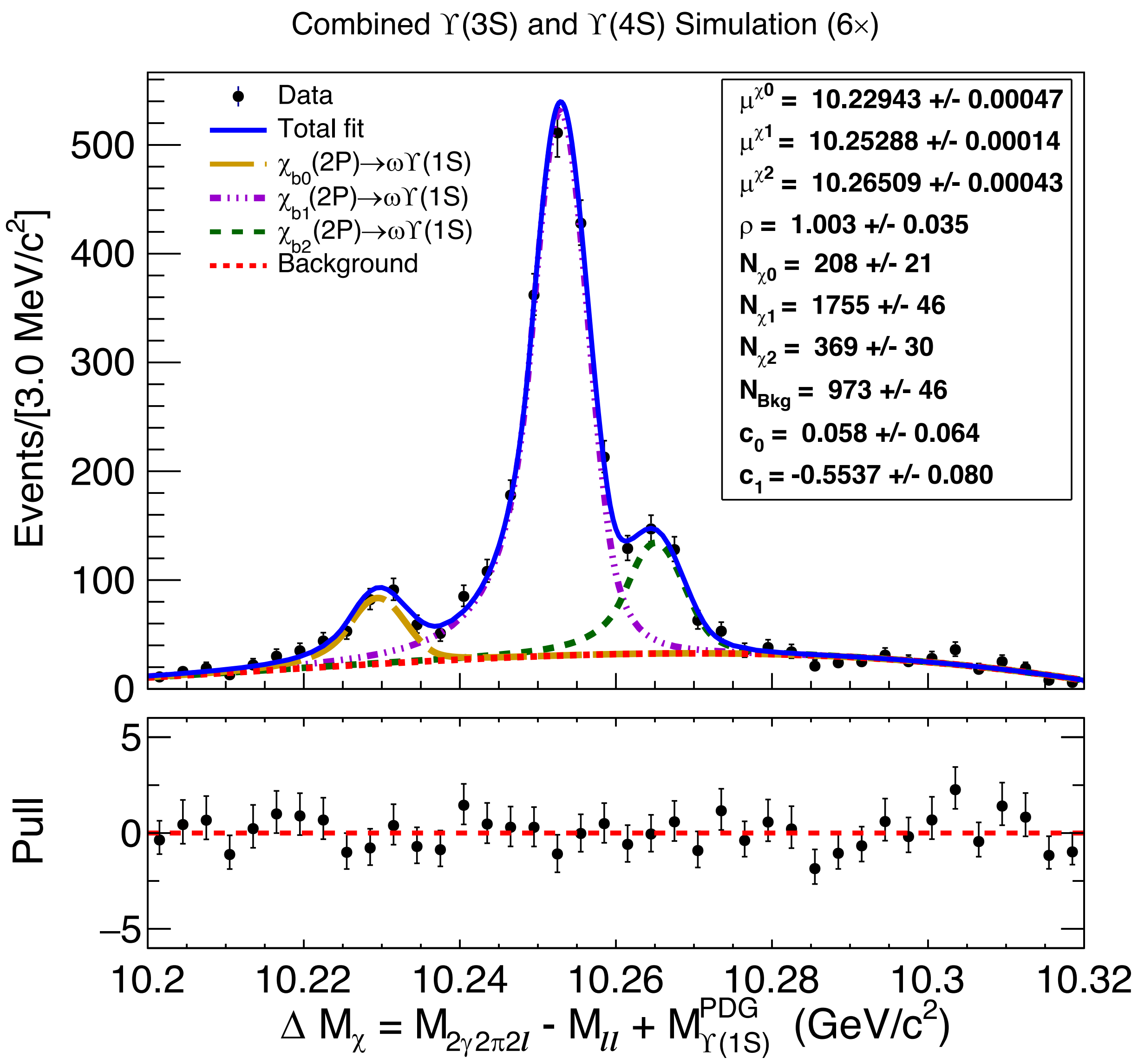
J=1,2 signal shape for comparison:

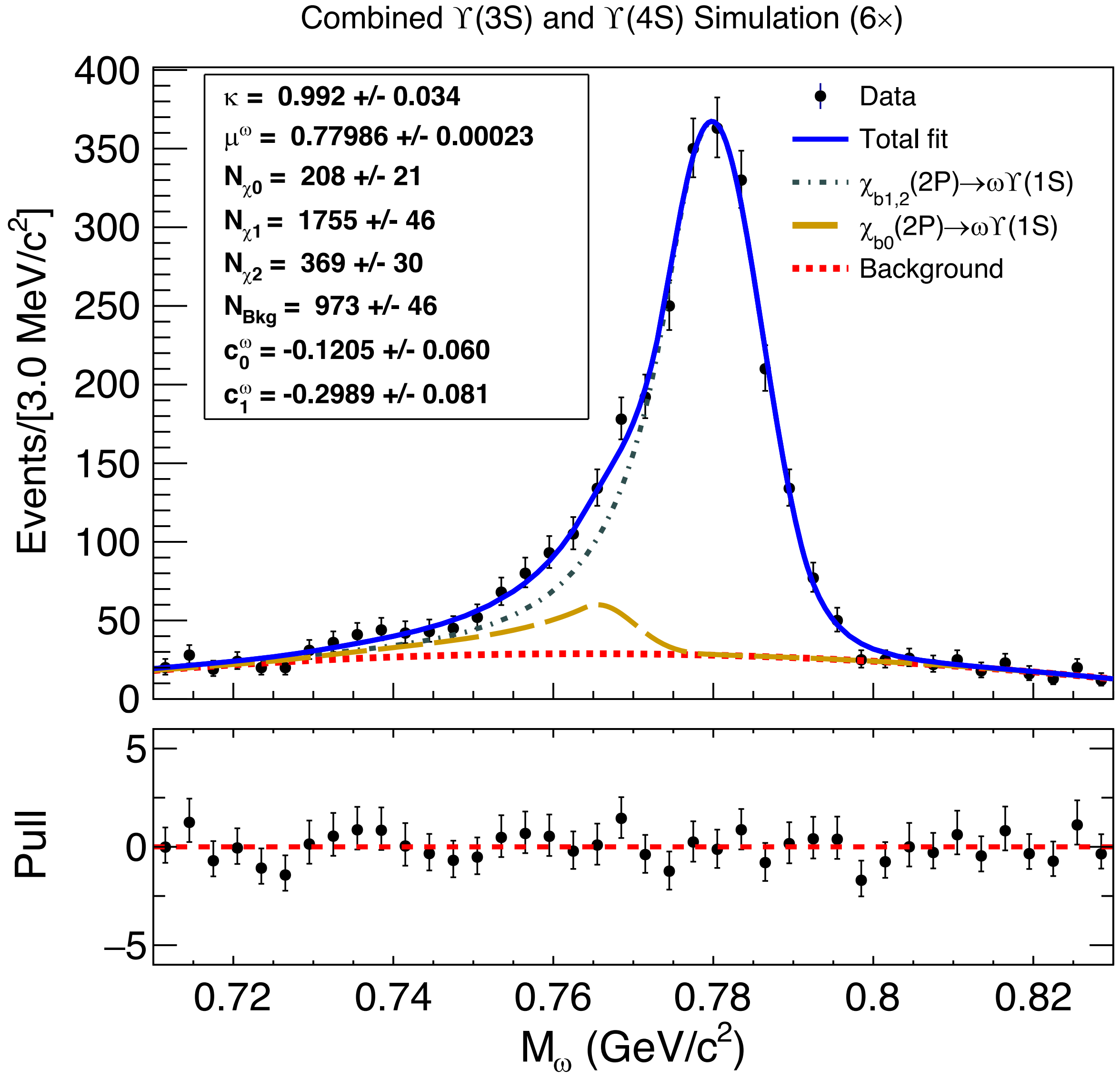




Fit Strategy: Simultaneous Fit to ΔM_χ & M_ω

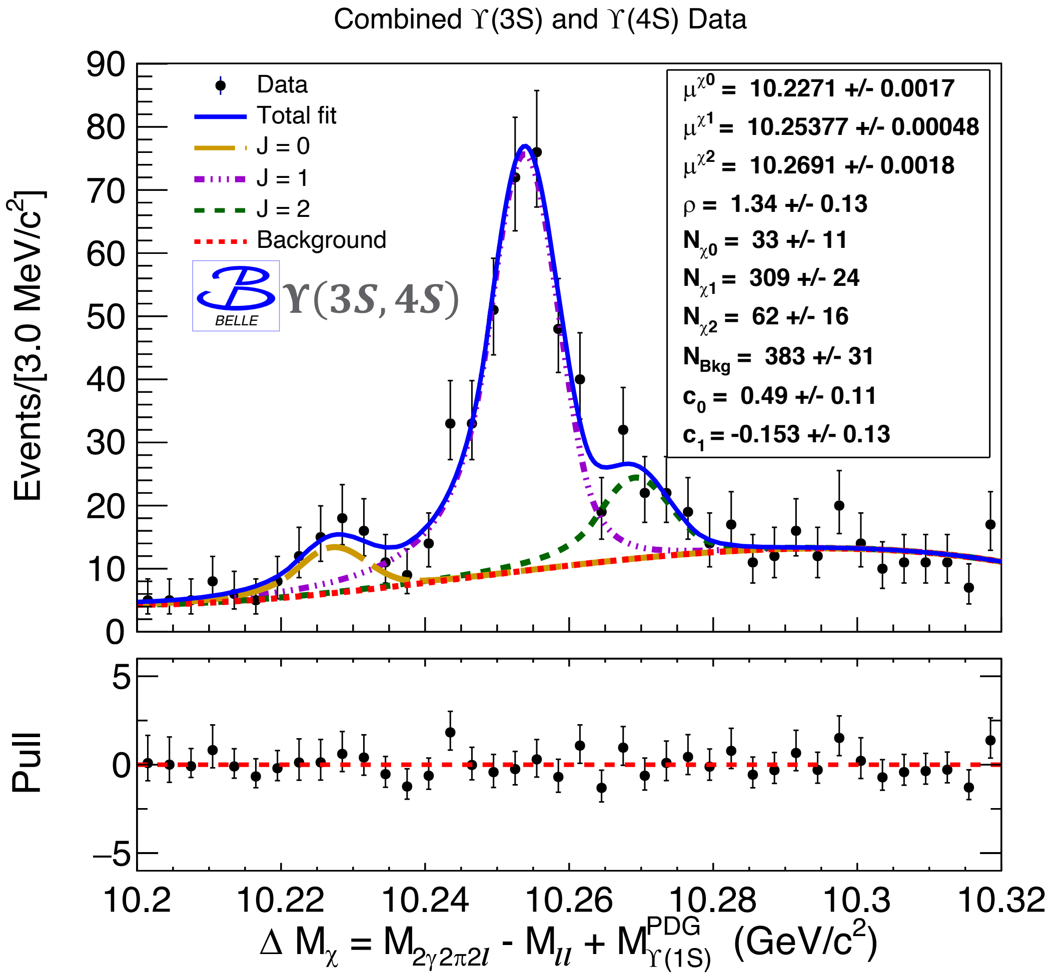
- All signal shapes are DSCB, except J=0 signal in M_ω
- ρ, κ are introduce to account for Data/MC difference in resolution.

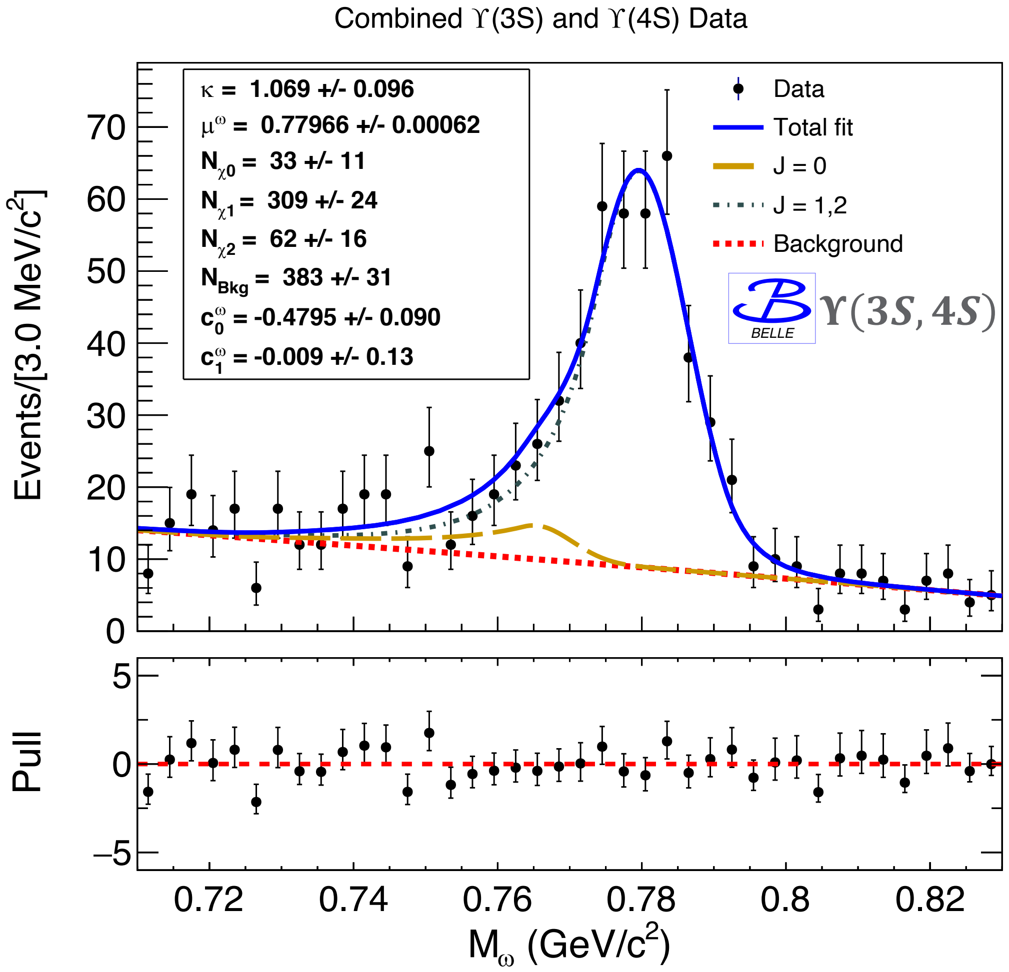




Search for $\chi_{bJ}(2P) \to \omega\Upsilon(1S)$

Simultaneously Fit M_ω and ΔM_χ in $\Upsilon(3S)$ & $\Upsilon(4S)$ Data





– $\Upsilon(3S)$ Population –

$(28.17 \pm 0.27 \pm 1.74) \cdot 10^6$

Results

Channel	$\mathcal{B}(\chi_{bJ}(2P) \to \omega\Upsilon(1S))$
$J = 0$	$(0.56^{+0.18}_{-0.19} \pm 0.05 \pm 0.06)$ %
$J = 1$	$(2.38 \pm 0.19^{+0.06}_{-0.09} \pm 0.22)$ %
$J = 2$	$(0.46 \pm 0.12^{+0.02}_{-0.04} \pm 0.06)$ %

J	Significance
0	3.2σ
1	14.5σ
2	3.9σ

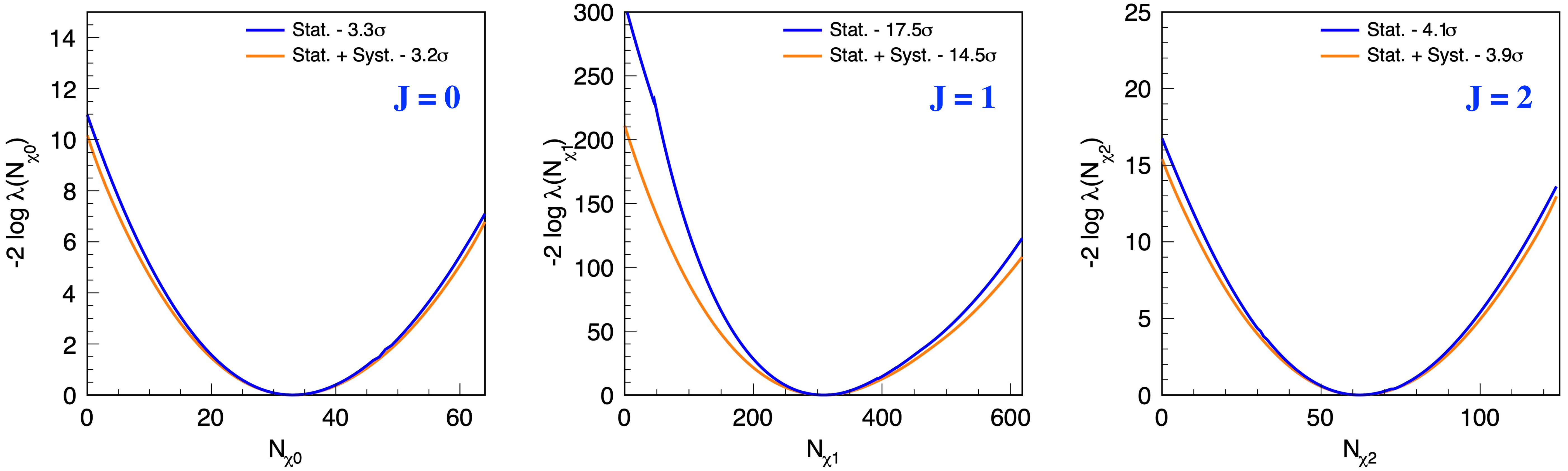
Normalize to $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)[\ell^+\ell^-]$ Channel:

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

Compare with PDG

Channel	Branching Fraction	Consistency
J=1	$(1.63^{+0.35+0.12}_{-0.31-0.11})$ %	1.8σ
J=2	$(1.10^{+0.32+0.08}_{-0.28-0.07})$ %	2.0σ

Signal Significance: Profile Likelihood Scan



Signal Significance is determined from a profile likelihood scan.

Profile Likelihood $\lambda(\nu) = \frac{\mathcal{L}(\nu|\hat{\hat{\boldsymbol{\theta}}})}{\mathcal{L}(\hat{\nu}|\hat{\boldsymbol{\theta}})}$

Likelihood for a fixed value

Likelihood value in data

Significance:

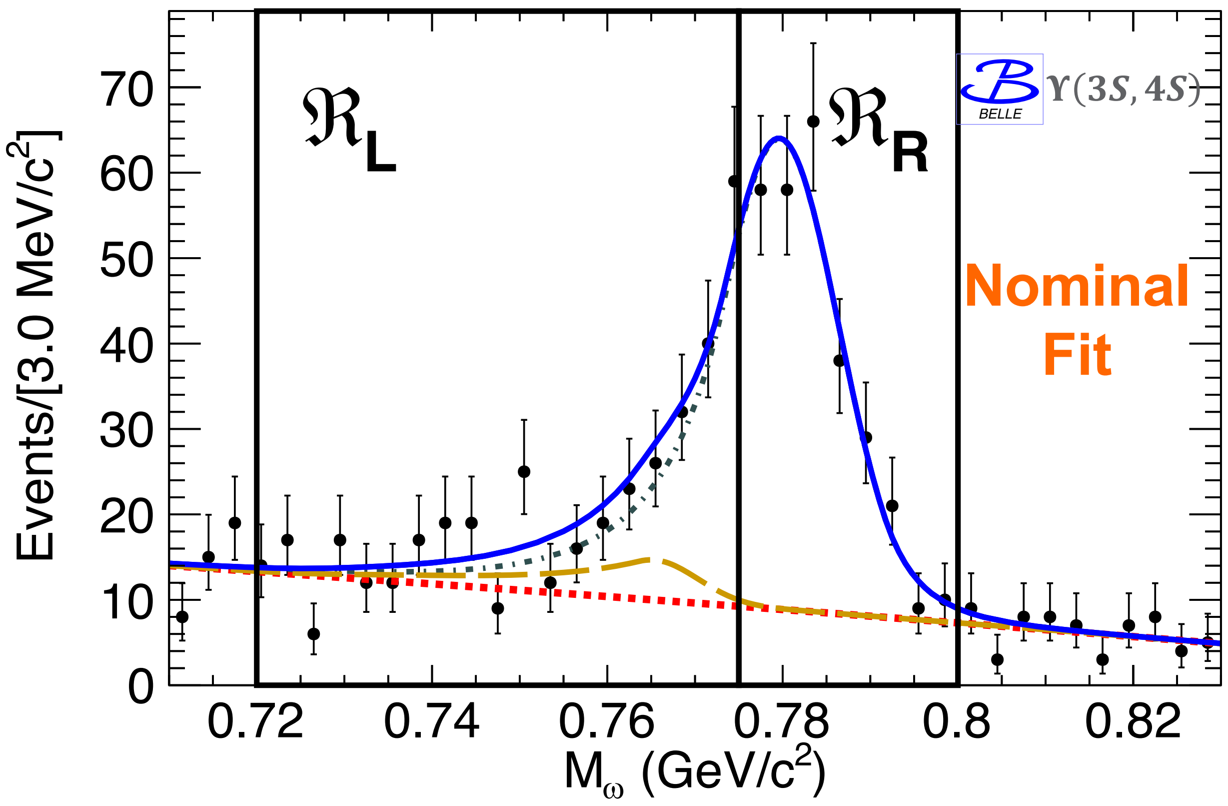
$$Z = \sqrt{-2log\lambda(\nu = 0)}.$$

Systematic uncertainties affecting the yield are convoluted with distribution of likelihood and Z is recalculated.

The reported significance has been verified using 100k toy MC samples, cf. BN1505.

Cross Check: Refit with Tight M_ω Cut

Combined Υ(3S) and Υ(4S) Data



- Naïvely, ∃ **Insufficient phase space** for transition:

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

- **The $\chi_{b0}(2P)$ is a wide state, $\Gamma_{\chi_{b0}} \gg \Gamma_{\chi_{b1,2}}$**

→ $\boldsymbol{\Gamma_{\chi_{b0}} = 2.6}$ **MeV** [Godfrey & Moats 2015]

→ $\boldsymbol{\Gamma_\omega = 8.68}$ **MeV** [PDG]

Precedent in $c\bar{c}$ Sector

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

- $\chi_{c1}(3872)$ lies ~8 MeV below threshold
- $\Gamma(X(3872)) < 1.2$ MeV (Belle 1107.0163)
- BaBar & Belle have see with $< 5\sigma$

- BES III recently observed transition (5.7σ)
  - 2019 – 1903.04695
  - Employ PHSP to model $X \to \omega\, J/\psi$

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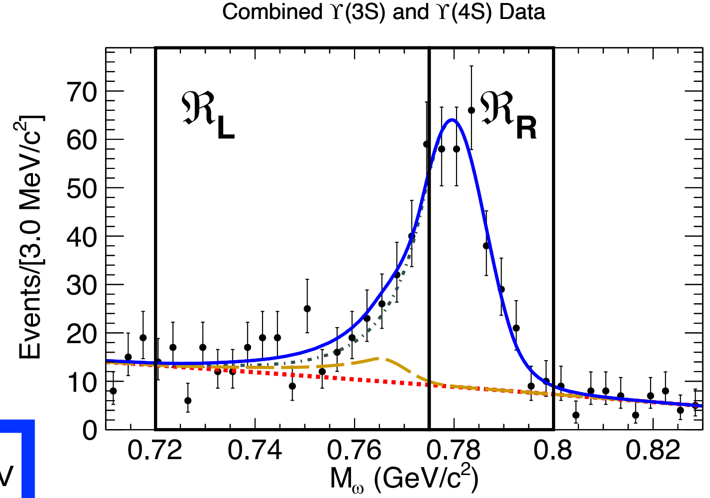
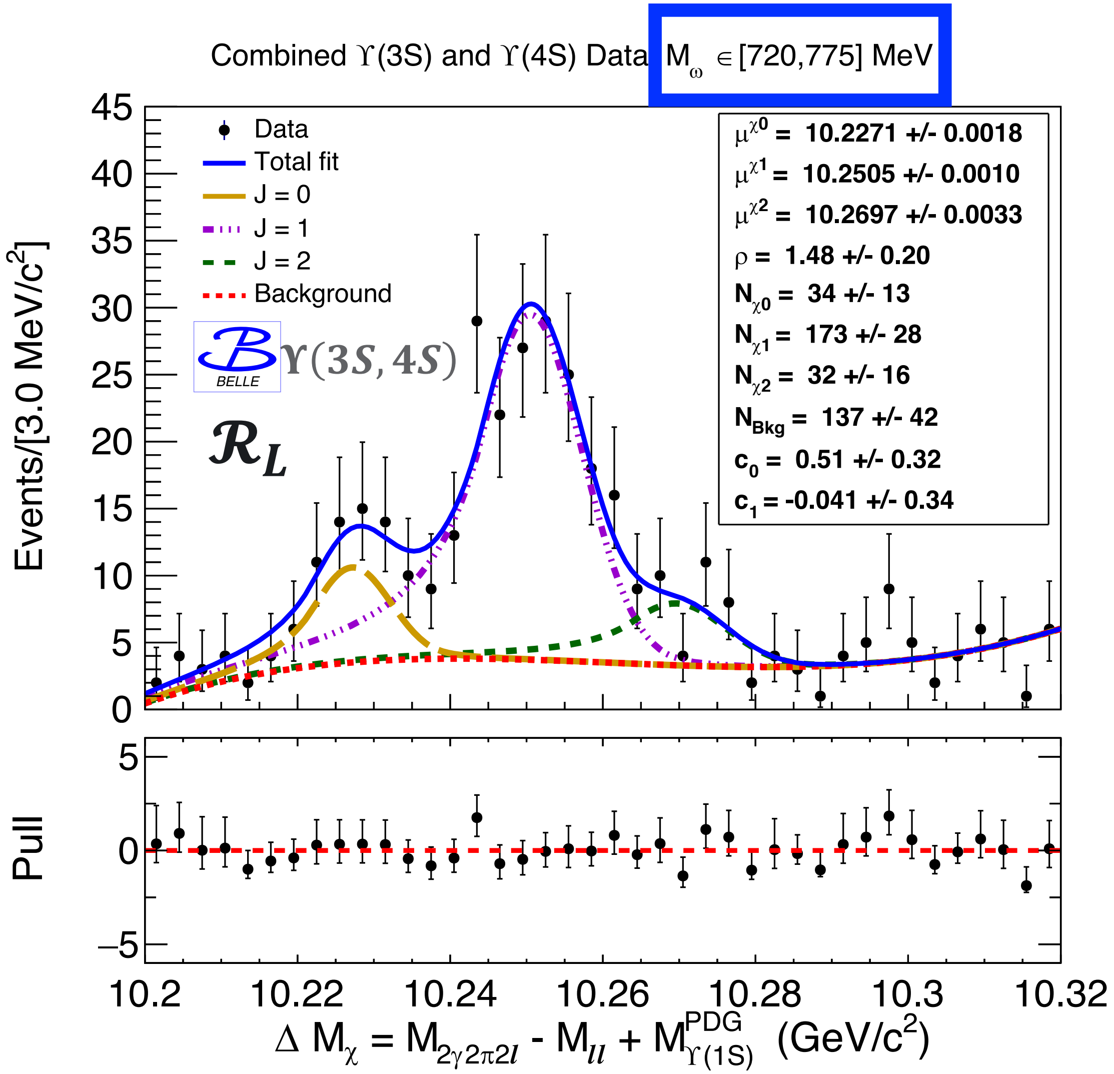
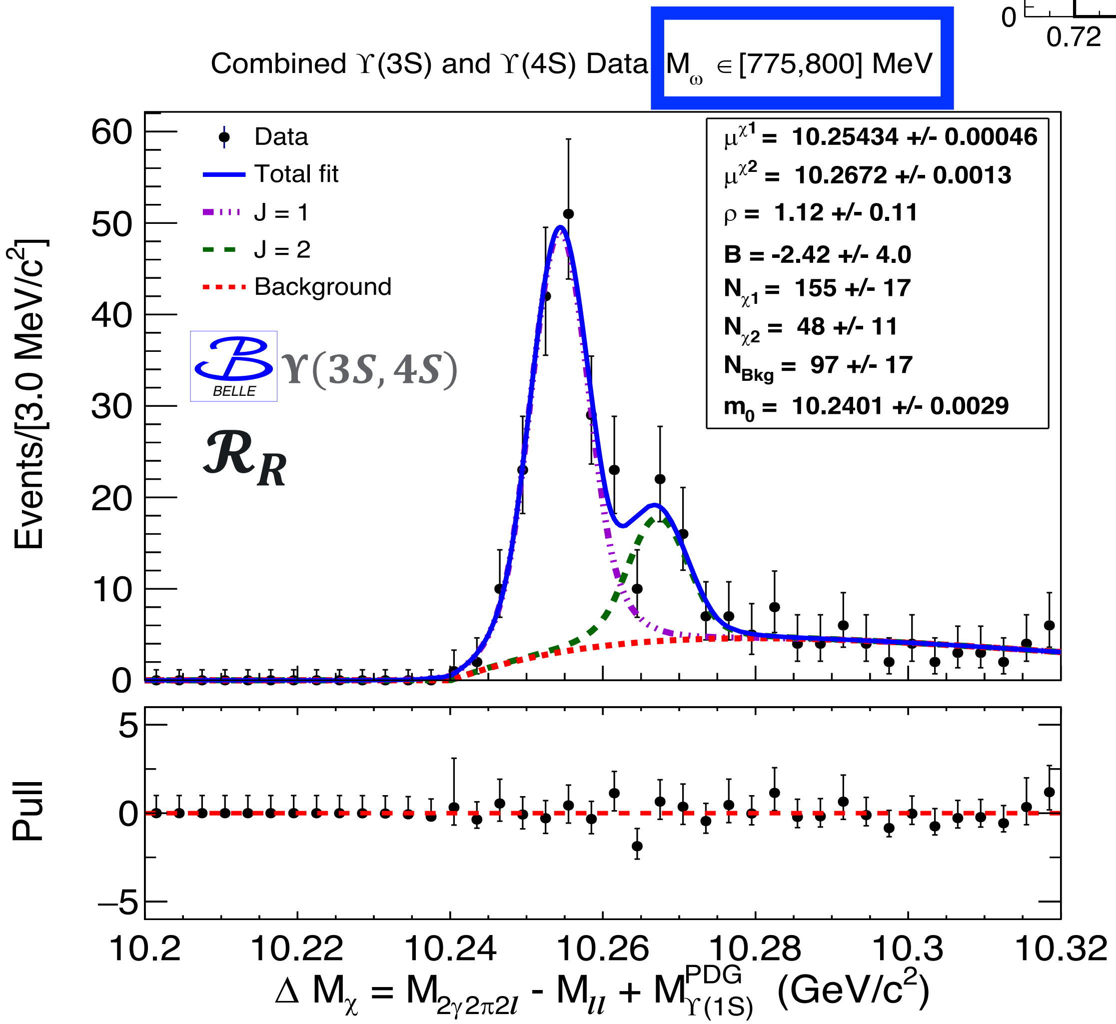
Cross Check: Refit with Tight M_ω Cut







Background: 3rd order polynomial
→ Studied in M_{π^0} Sidebands

Background: RooDstD0BG
→ Studied in M_{π^0} Sidebands

Systematic Uncertainty

Decay	$\chi_{b0}(2P) \to \omega\Upsilon(1S)$	$\chi_{b1}(2P) \to \omega\Upsilon(1S)$	$\chi_{b2}(2P) \to \omega\Upsilon(1S)$
Track-Finding	0.0%	0.0%	0.0%
π^0 Reconstruction	1.7%	1.7%	1.7%
Fit Procedure	$^{+8.9\%}_{-9.1\%}$	$^{+0.7\%}_{-3.0\%}$	$^{+3.8\%}_{-7.7\%}$
$\Upsilon(3S)$ Population	$^{+1.2\%}_{-1.1\%}$	$^{+1.2\%}_{-1.1\%}$	$^{+1.2\%}_{-1.1\%}$
Input Branching Fractions	10.4%	9.4%	12.4%
Reconstruction Efficiency	0.8%	0.8%	0.8%
Total	$^{+3.0\%}_{-3.1\%} \pm 10.4\%$	$^{+2.4\%}_{-3.7\%} \pm 9.4\%$	$^{+4.4\%}_{-8.0\%} \pm 12.4\%$

TABLE IX: Systematic uncertainties on the $\chi_{b1,2}(2P) \to \omega\Upsilon(1S)$ branching fractions, by decay channel. The individual systematic uncertainties are summed in quadrature to obtain the total systematic error. Note that the large uncertainty from the input branching fractions is reported separately.

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

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FSP Selections

- At least 4 tracks with $|dr| < 0.5$ cm, $|dz| < 2.0$ cm, and track fit CL > 0
- At least 2 ECL clusters with:
  - No matched track
  - $\frac{E_9}{E_{25}} > 0.9$
  - width > 6 cm,

Hard Tracks (Leptons)

- $p_\ell^{CM} > 4.0$ GeV
- $M_{\ell\ell} \in (9.0, 9.8)\,\frac{\mathrm{GeV}}{\mathrm{c}^2}$
- Require exactly 1 di-lepton

Soft Tracks (Pions)

- $p_\pi^{CM} < 0.75$ GeV/c
- $cos(\psi_{\pi\pi}) < 0.95$
- Require exactly 1 di-pion

π^0 Candidates

- $p_{\pi^0}^{CM} \in [80,750]\,\frac{\mathrm{MeV}}{\mathrm{c}}$
- $M_{\pi^0} \in [0.11, 0.15]\,\frac{\mathrm{GeV}}{\mathrm{c}^2}$
- **Retain π^0 with smallest mass fit χ^2**

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

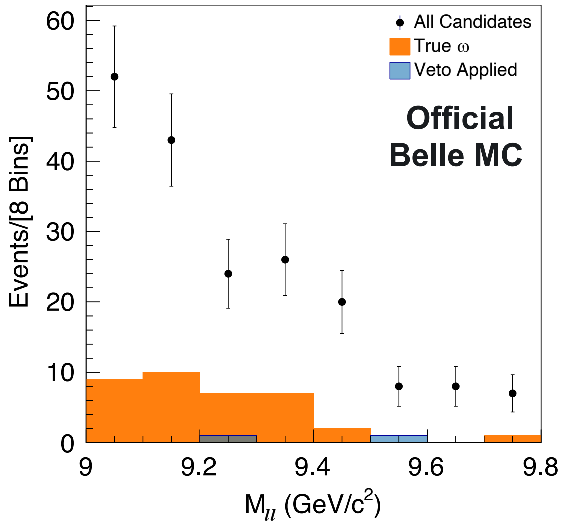
- $\Delta M_{\pi\pi} \notin (10.014, 10.030)$ GeV
- $\Delta M_{\pi\pi} < 10.32$ GeV

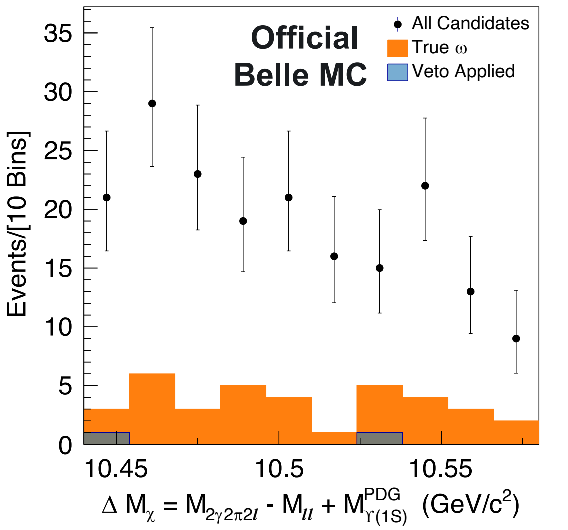
$\chi_{bJ}(3P)$ Continuum Veto

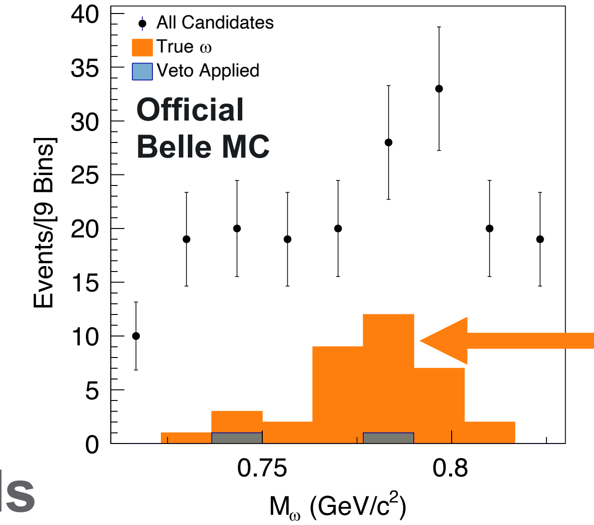
- MuID > 0.2 for leptons
- $M_{\ell\ell} \in [9.2, 9.6]$ GeV

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

Official Belle MC: $e^+e^- \to q\bar{q}\ \ (q = u, d, s, c)$



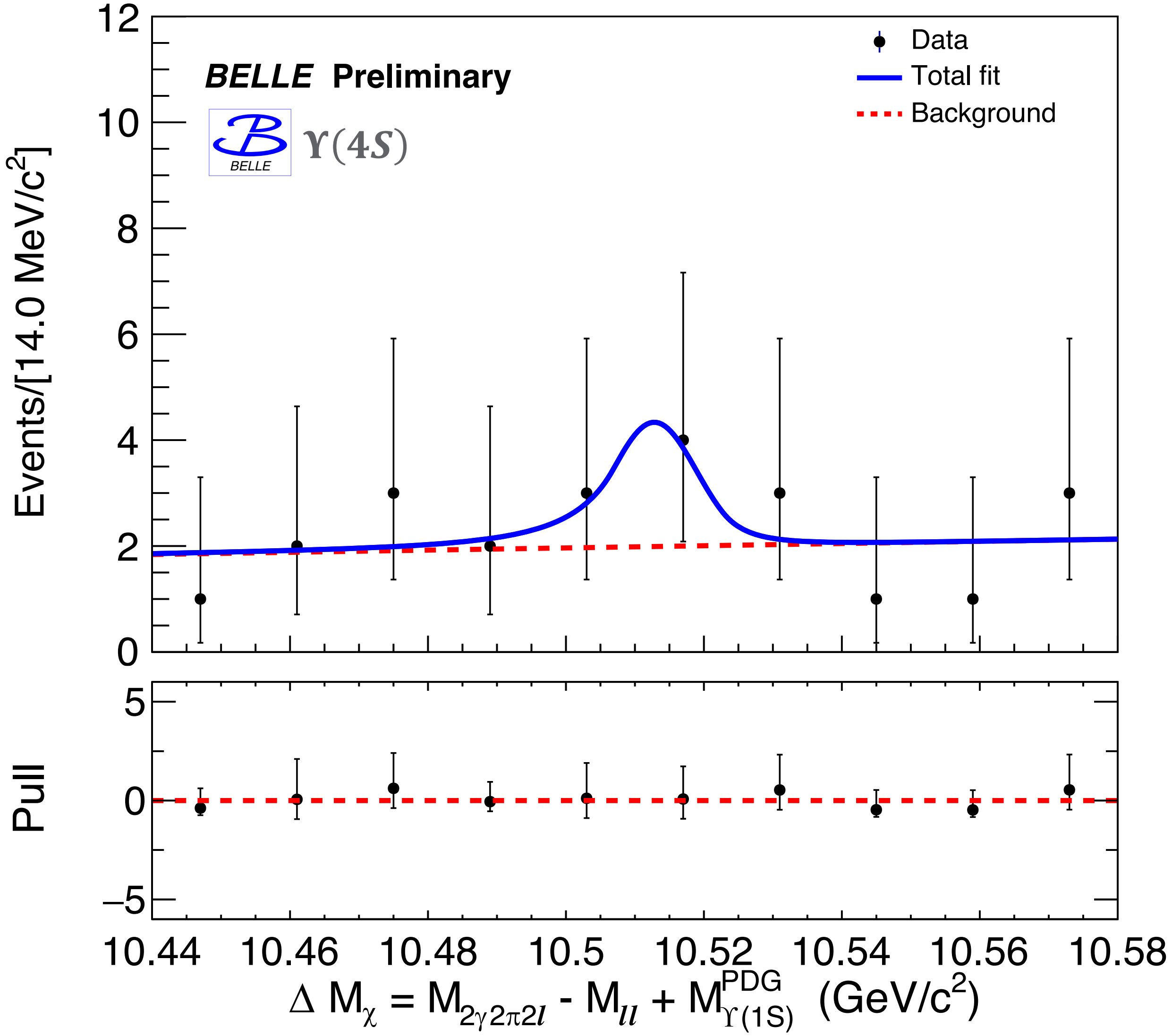




Peaking Background: $q\bar{q} \to \omega + h$

Removed by continuum veto

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



$513\ \mathrm{fb}^{-1}$ 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)	BR (%)	Width (keV)
$\Upsilon(4^3S_1)$ 10.579^a	$\ell^+\ell^-$		0.459	0.39	1.8×10^{-3}	0.32 ± 0.04^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	$2.2\times10^{-3}\%$	

Can estimate conservative upper limit on expected BF

- *Assume* $\mathcal{B}(\chi_{b1}(3P)\to\omega\Upsilon(1S)) \simeq \mathcal{B}(\chi_{b1}(2P)\to\omega\Upsilon(1S))$
- **Estimate: $\mathcal{B}\sim 8.4\times10^{-7}$**

From the fit, a 90% CL upper limit is determined:

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

Summary

- **We present Results:**
  - **First measurement of $\chi_{bJ}(2P) \rightarrow \omega\Upsilon(1S)$ *since discovery in 2004***

$$\mathcal{B}(\chi_{b0}(2P) \to \omega\Upsilon(1S)) = \left(0.56^{+0.18}_{-0.19} \pm 0.05 \pm 0.06\right)\% \quad 3.2\sigma$$

$$\mathcal{B}(\chi_{b1}(2P) \to \omega\Upsilon(1S)) = \left(2.38 \pm 0.19^{+0.06}_{-0.09} \pm 0.22\right)\% \quad 14.5\sigma$$

$$\mathcal{B}(\chi_{b2}(2P) \to \omega\Upsilon(1S)) = \left(0.46 \pm 0.12^{+0.02}_{-0.04} \pm 0.06\right)\% \quad 3.9\sigma$$

  - **New limit set:**

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

***Paper Draft in progress* – Pending Referee Approval we will proceed to CWR**

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Thank you

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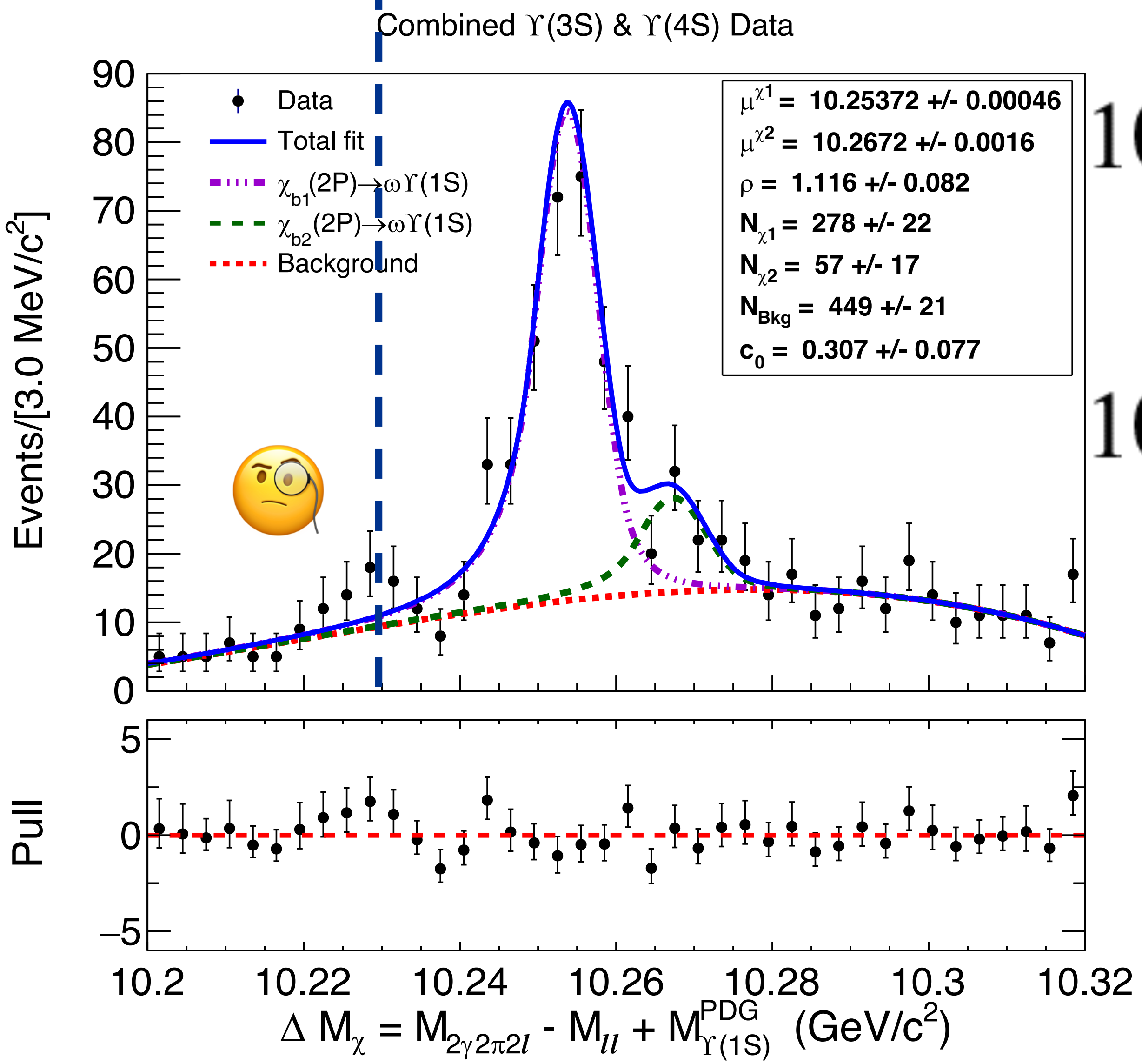
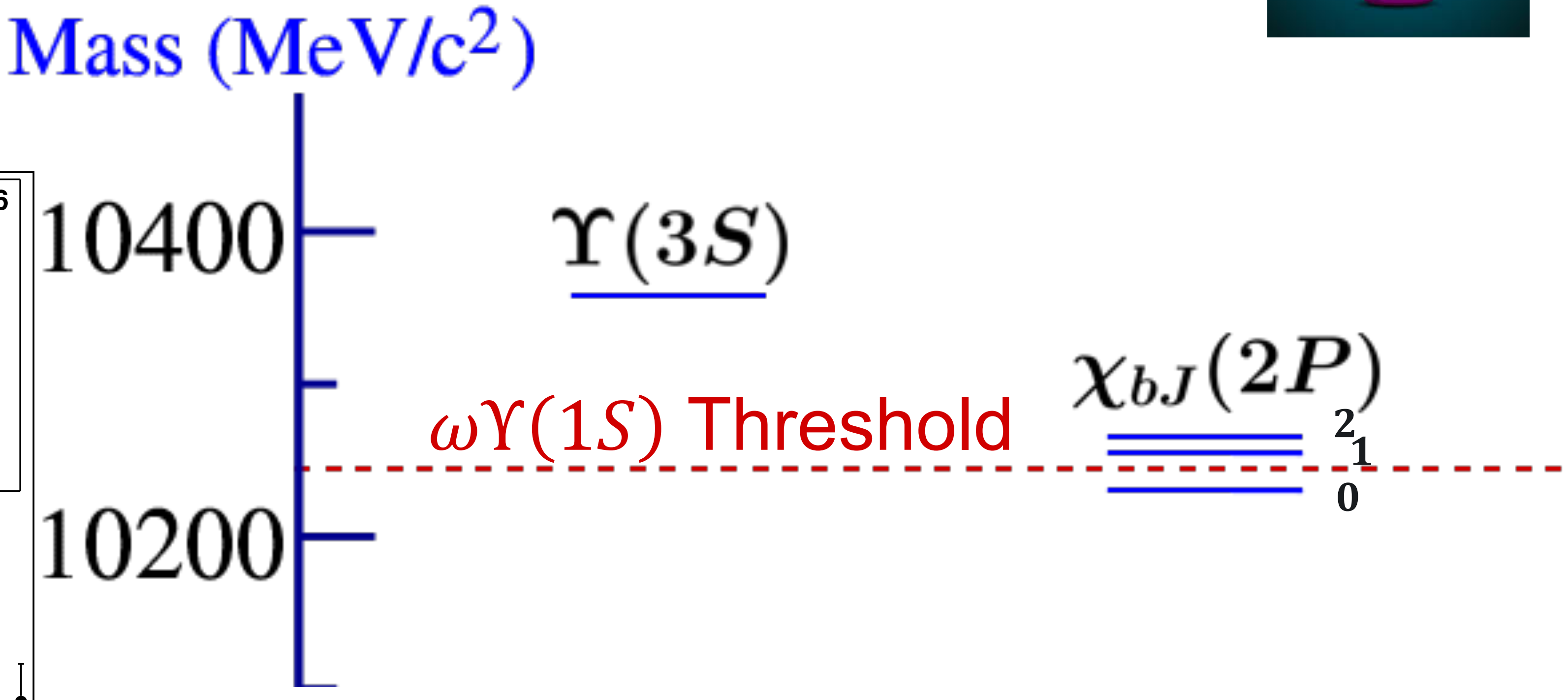
Fit without

$M^{PDG}_{\chi_{b0}(2P)} + (\mu^{\chi 1} - M^{PDG}_{\chi_{b1}(2P)})$





We Interpret this as the $\chi_{b0}(2P) \to \omega\Upsilon(1S)$

This is surprising:

- ∃ **Insufficient phase space** for transition:

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

- **The $\chi_{b0}(2P)$ is a wide state, $\Gamma_{\chi_{b0}} \gg \Gamma_{\chi_{b1,2}}$**
  - → $\Gamma_{\chi_{b0}} = 2.6$ MeV [Godfrey & Moats 2015]
  - → $\Gamma_{\omega} = 8.68$ MeV [PDG]

Similar Enhancement Seen in $c\bar{c}$ Region: $\chi_{c1}(3872) \to \omega J/\psi$

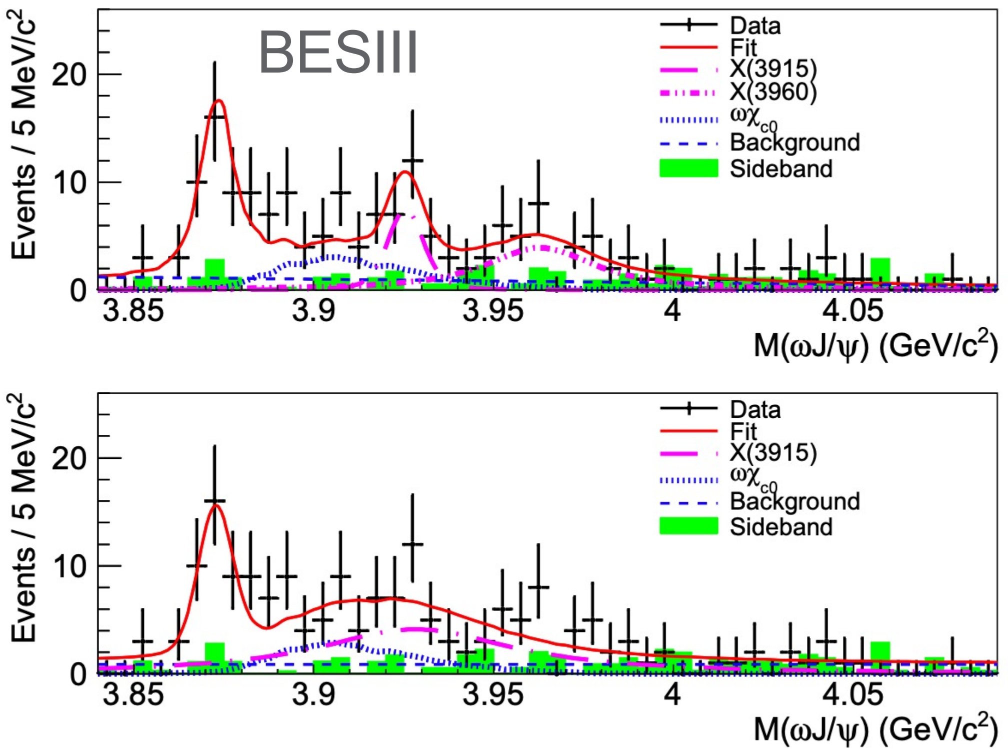


FIG. 2: The $M(\omega J/\psi)$ distribution with results of an unbinned maximum-likelihood fit to data including three BW resonances (upper) and including two BW resonances (bottom) as signal. Dots with error bars are data, the red solid curves show the total fit results, the blue dotted curves are the MC simulated $\omega\chi_{c0}$ background component, the blue dashed curves are the linear background component, the pink dotted-dashed curves are the $X(3915)$ resonance, the pink double-dotted dashed curve is the $X(3960)$ resonance, and the green shaded histograms are the normalized contribution from the J/ψ- and ω-mass sidebands.

- X lies ~ 8 MeV below threshold
- $\Gamma(X(3872)) < 1.2$ MeV (Belle 1107.0163)
- BaBar & Belle have see with $< 5\sigma$

- BES III recently observed transition (5.7σ)
  - 2019 – 1903.04695
  - Employ PHSP to model $X \to \omega J/\psi$

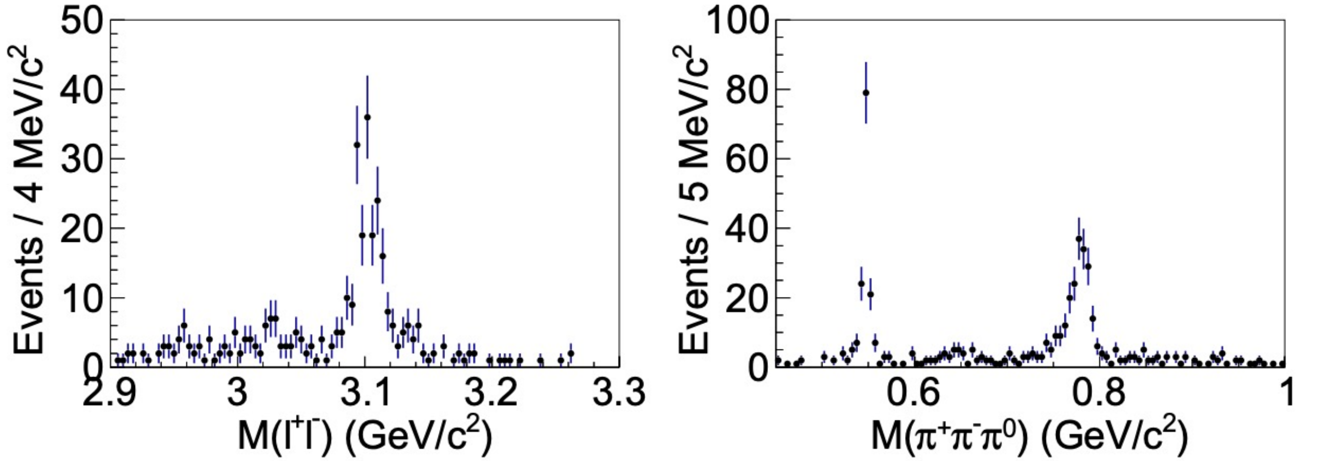


FIG. 1: The $M(\ell^+\ell^-)$ and $M(\pi^+\pi^-\pi^0)$ distributions from the full data sets.

Cross Check: Signal Shape Asymmetry

- **Question from Kirill Chilikin and Alex Bondar:** **Verify on control channel that π^0 in final state does not induce data/MC difference in asymmetry of signal shapes?**
- Control Channel: $\Upsilon(2S) \to \pi^0\pi^0[\Upsilon(1S)] \to 4\gamma[\ell^+\ell^-]$
  - **Reconstruct $\Upsilon(1S)$ and π^0's with ω-analysis cuts**
  - **Signal Shape:** DSCB w/ α_i, n_i fixed from MC
    → μ, σ are floated

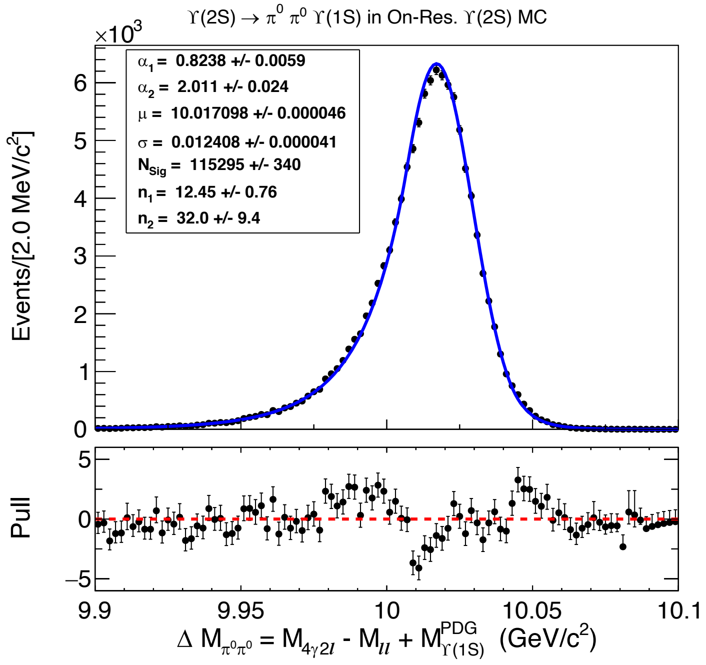
Result: $\mathcal{B}(2S \to \pi^0\pi^0 1S)$

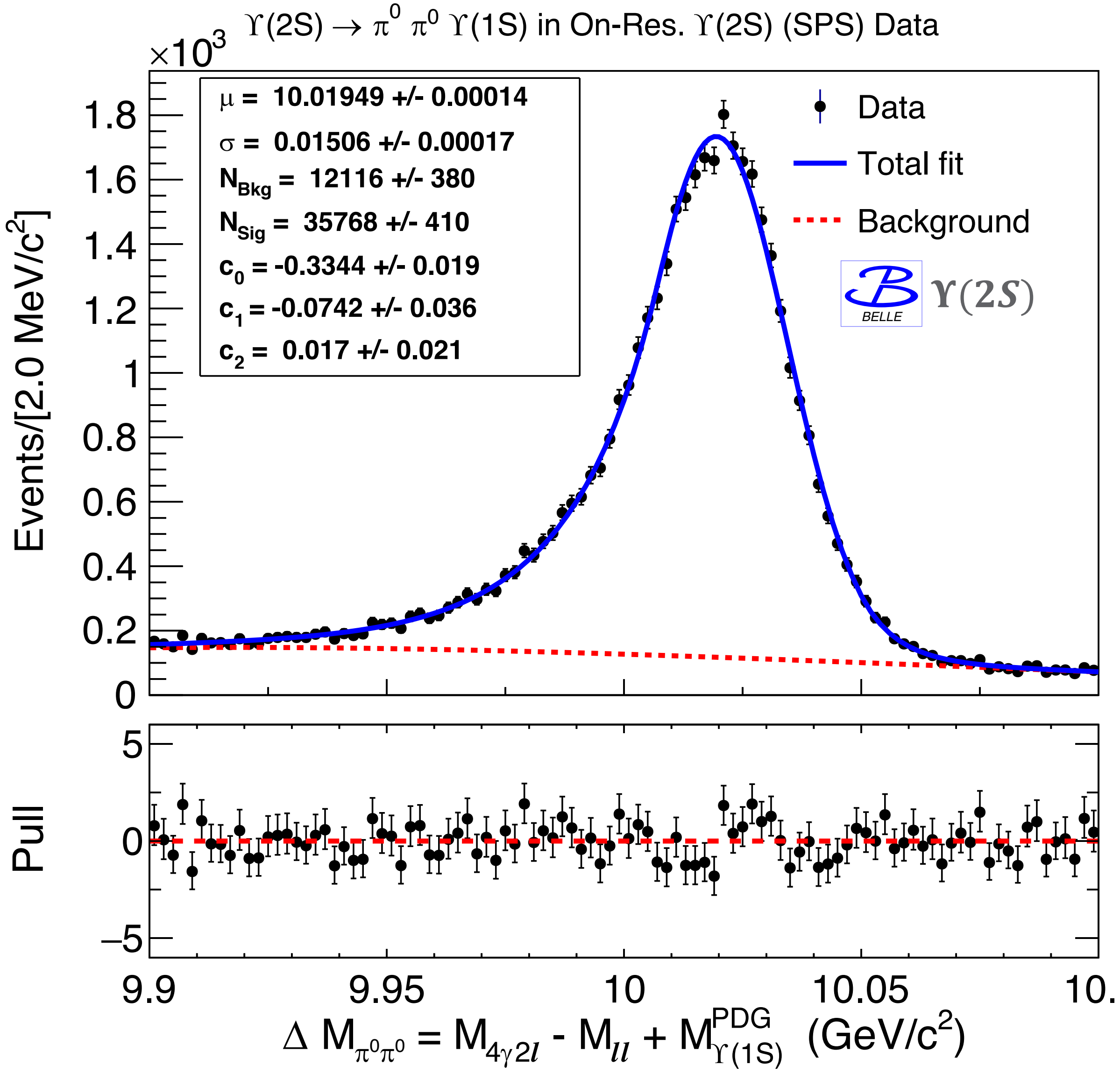
$$(8.75 \pm 0.10)\%$$

Compare with PDG:

$$(8.6 \pm 0.4)\%$$

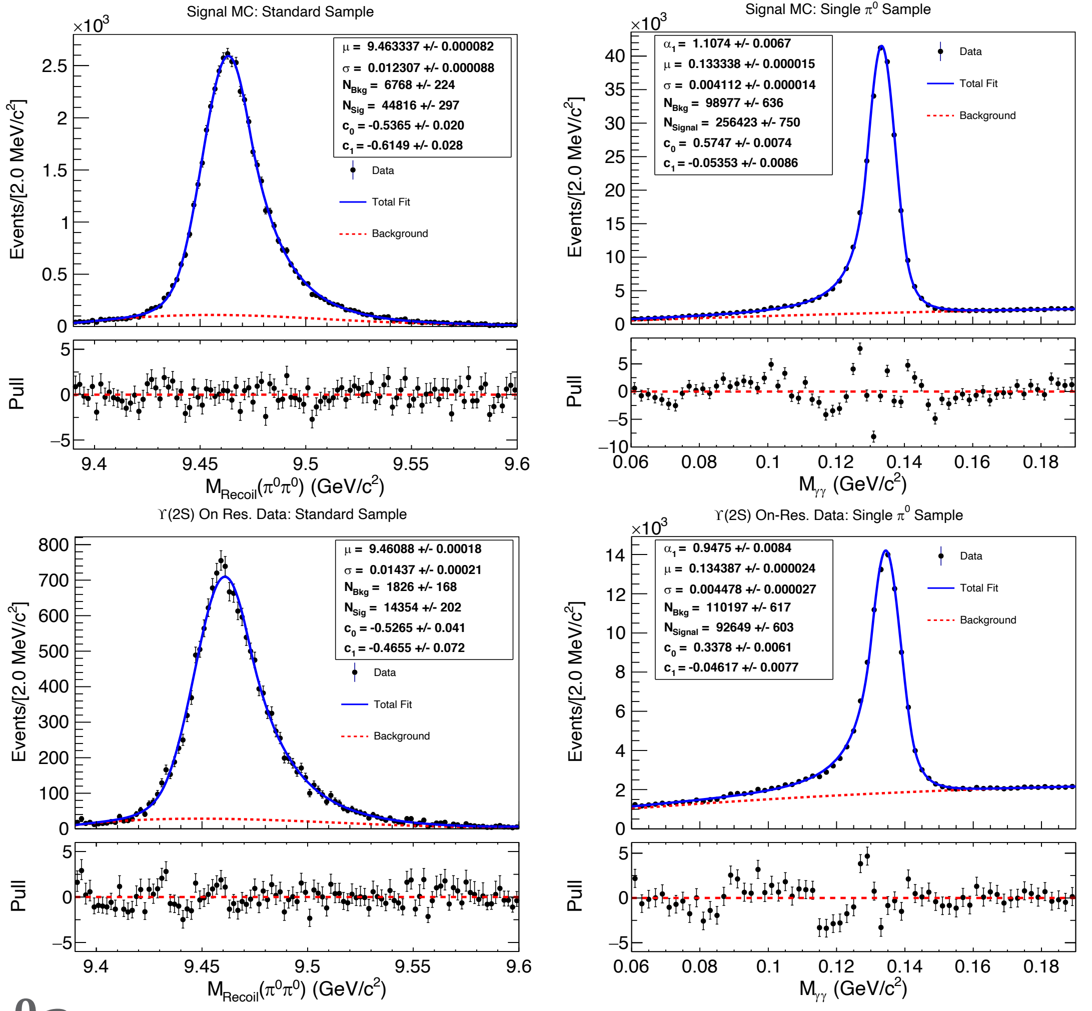
No significant data/MC difference in tail shapes.





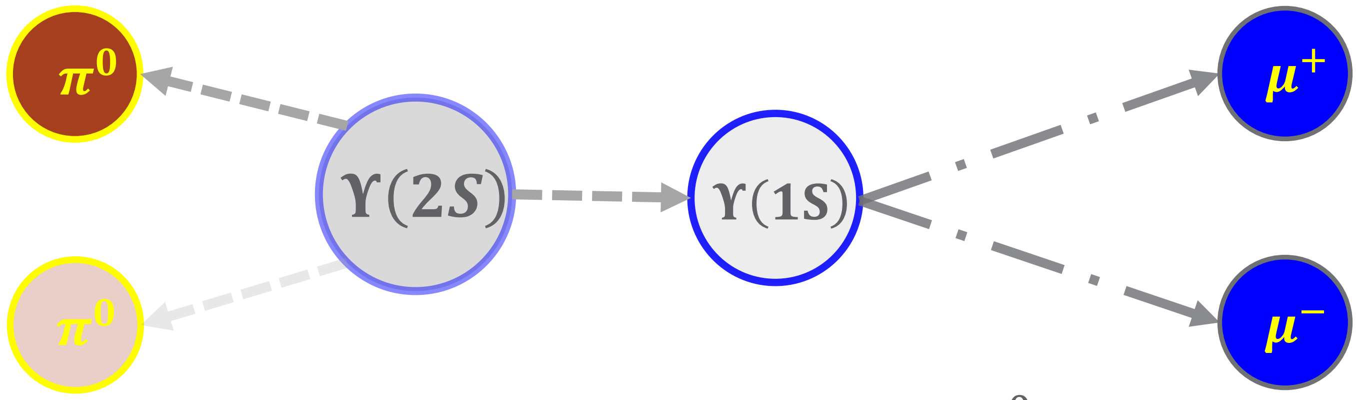
Small artifacts in MC pull are result of large statistics of fit

π^0 Reconstruction Syst. Uncert. $\Upsilon(2S) \to \pi^0\pi^0(\Upsilon(1S) \to \mu\mu)$



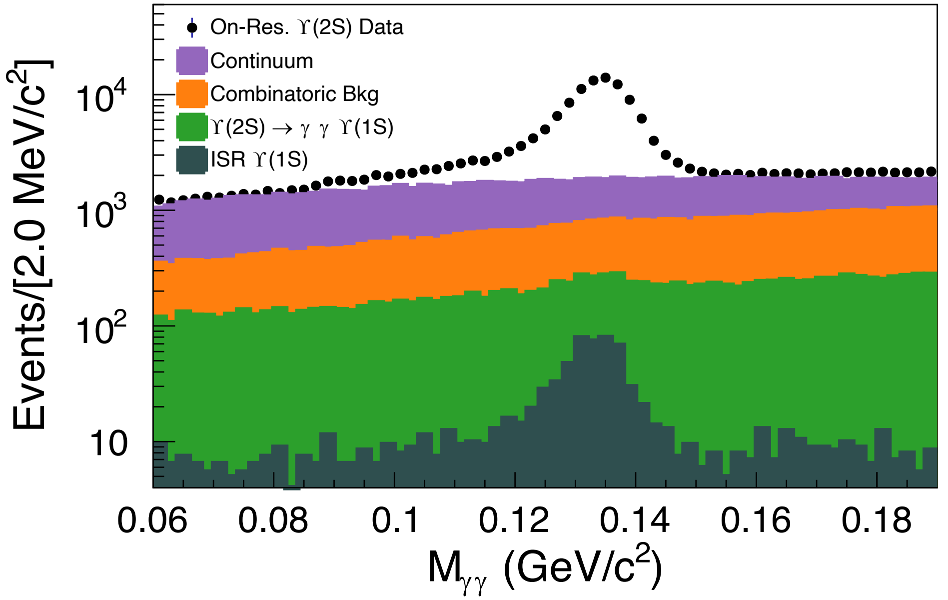
Assessing a systematic uncertainty for soft π^0's, with $p < 300\ MeV/c$

Denominator: Tag events with hardest π^0+$\Upsilon(1S)$ candidate

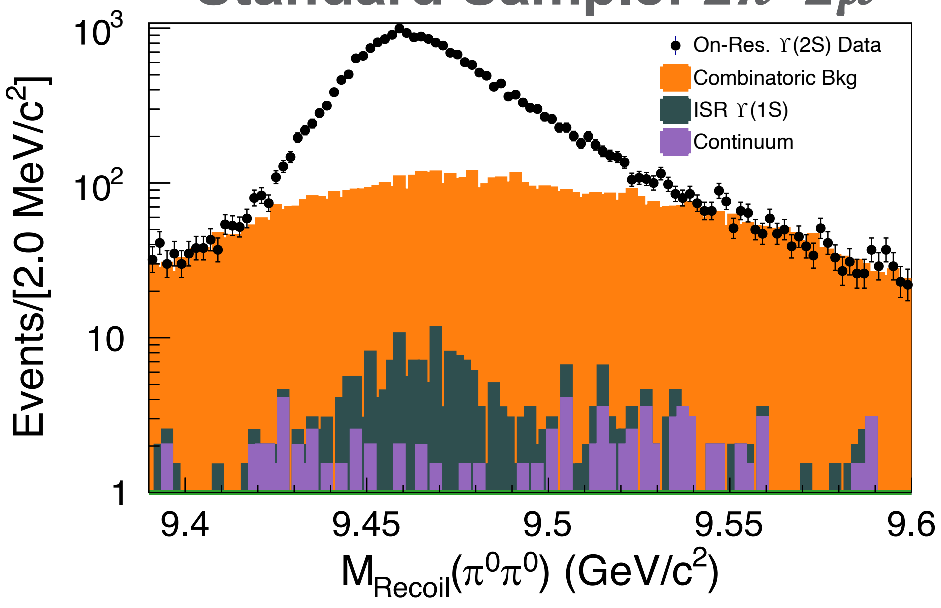


Numerator: Count how many times the π^0-pair is reconstructed

Single Pion Sample: $\pi^0 2\mu$



Standard Sample: $2\pi^0 2\mu$



Dataset	$N_i^{\pi^0 2\mu}$	$N_i^{2\pi^0 2\mu}$	$\epsilon_i = \frac{N_i^{2\pi^0 2\mu}}{N_i^{\pi^0 2\mu}}$
MC	256,418±750	44,816±297	(17.48±0.13)%
Data	84,225±548	14,353±202	(17.04±0.26)%

$\rho = \frac{\epsilon_{Data}}{\epsilon_{MC}}$, where $\epsilon_i = \frac{N_i^{2\pi 2\mu}}{N_i^{\pi 2\mu}}$

$$\rho = 0.975 \pm 0.017$$

Systematic Uncertainty from Measured BFs

Quantity	Value	Relative Uncertainty
$\mathcal{B}(\Upsilon(3S) \to \gamma\chi_{b2}(2P))$	$(13.1 \pm 1.6)\%$	12.2%
$\mathcal{B}(\Upsilon(3S) \to \gamma\chi_{b1}(2P))$	$(12.6 \pm 1.2)\%$	9.5%
$\mathcal{B}(\Upsilon(3S) \to \gamma\chi_{b0}(2P))$	$(5.9 \pm 0.6)\%$	10.2%
$\mathcal{B}(\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S))$	$(4.37 \pm 0.08)\%$	1.8%
$\mathcal{B}(\omega \to \pi^+\pi^-\pi^0)$	$(89.2 \pm 0.7)\%$	0.8%
$\mathcal{B}(\pi^0 \to \gamma\gamma)$	$(98.823 \pm 0.034)\%$	0.03%