Belle II Energy Scan Overview

Dec 03, 2021

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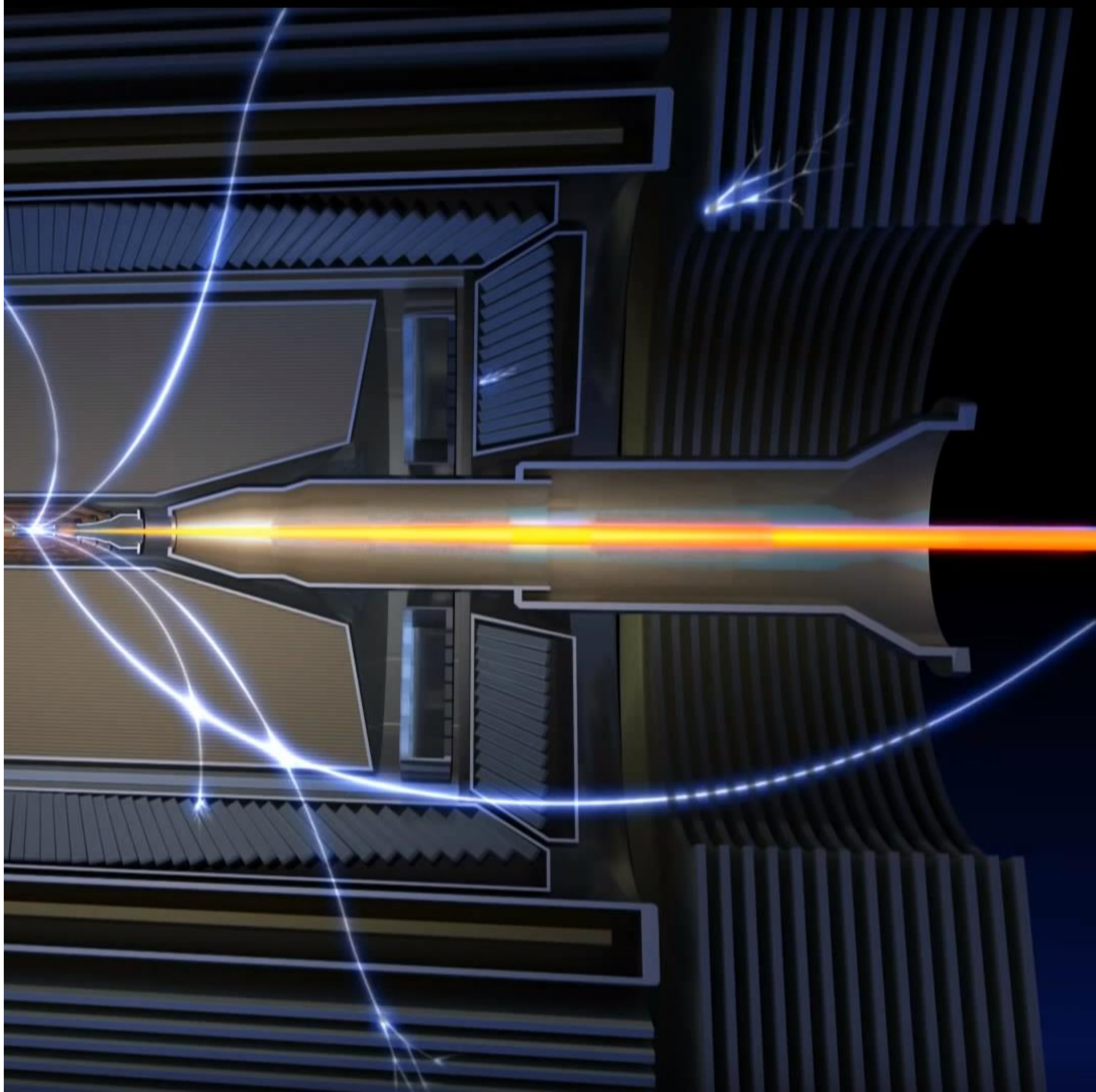
2021 Belle II Physics Week

PNNL is operated by Battelle for the U.S. Department of Energy



Presentation Overview

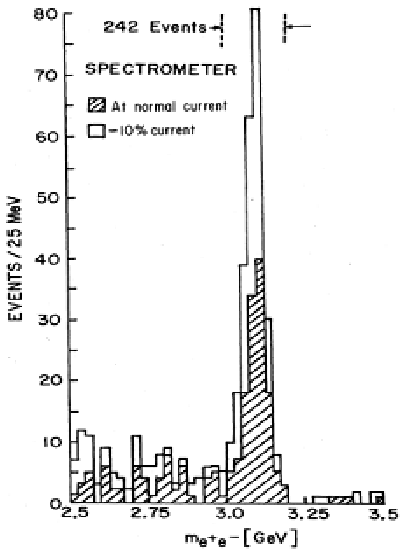
- What was the energy scan?
  - For 19 days in November, SuperKEKB and Belle II collected data at four center-of-mass energy points above the usual $\Upsilon(4S)$ resonance
- Why did we do it?
  - Review of quarkonium physics
  - Importance of these new energy points
- What happened during the energy scan?
- How do we analyze the data? / What do we do next?

What is quarkonium?

- Bound state of heavy quark-antiquark pair
- 1974: Discovery of J/ψ ($c\bar{c}$), evidence of charm/quark model
- 1977: Discovery of Υ ($b\bar{b}$)

BNL

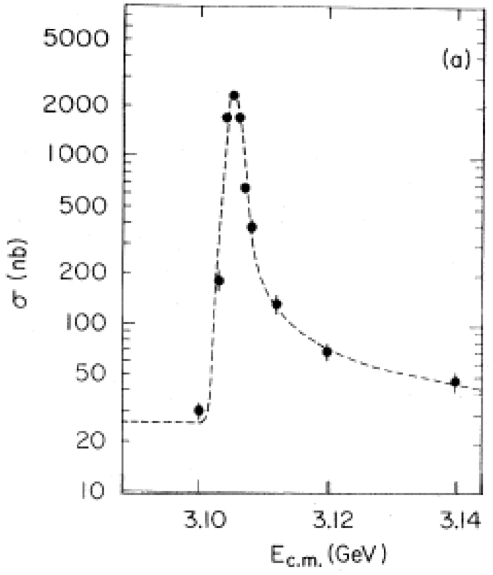
$p + Be \rightarrow X + J/\psi(e^+e^-)$



PRL 33, 1404 (1974)

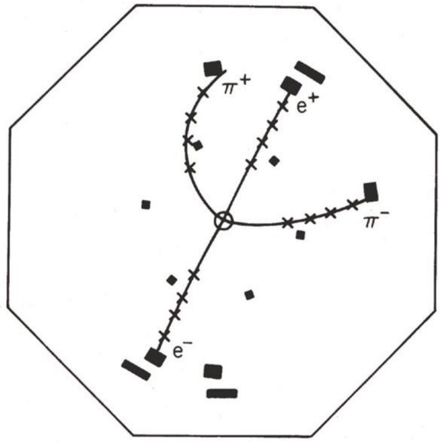
SLAC

$e^+e^- \rightarrow J/\psi \rightarrow$ hadrons, e^+e^-, $\mu^+\mu^-$



PRL 33, 1406 (1974)

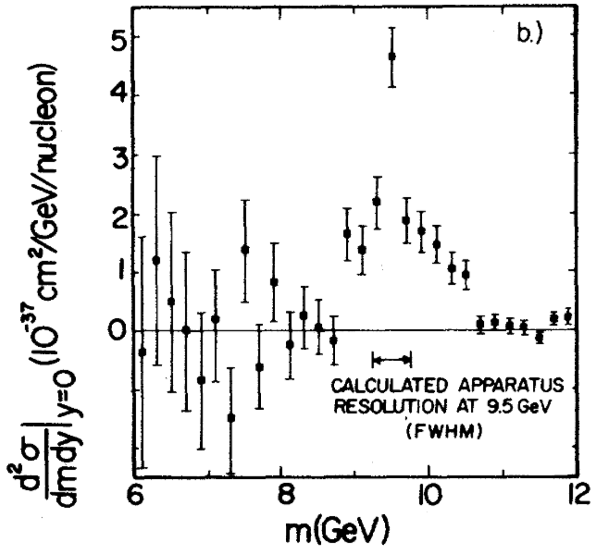
$e^+e^- \rightarrow \psi(2S) \rightarrow \pi^+\pi^-\ J/\psi(e^+e^-)$



SLAC Archives Slide747

FNAL

$p + N \rightarrow X + \Upsilon(\mu^+\mu^-)$



PRL 39, 252 (1977)

Theoretical Considerations

- Heavy quark mass → non-relativistic bound state
- Analogous to positronium (e^+e^-)
- NRQCD potential based on one gluon exchange:

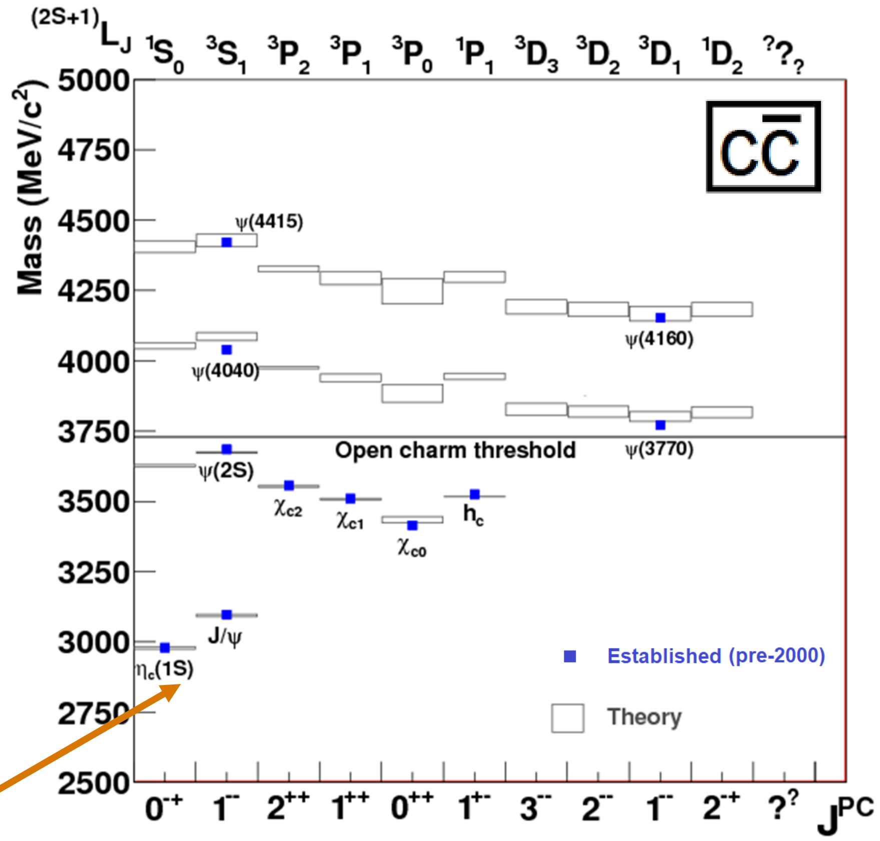
$$V(r) \sim \frac{-4}{3}\frac{\alpha_s}{r}$$

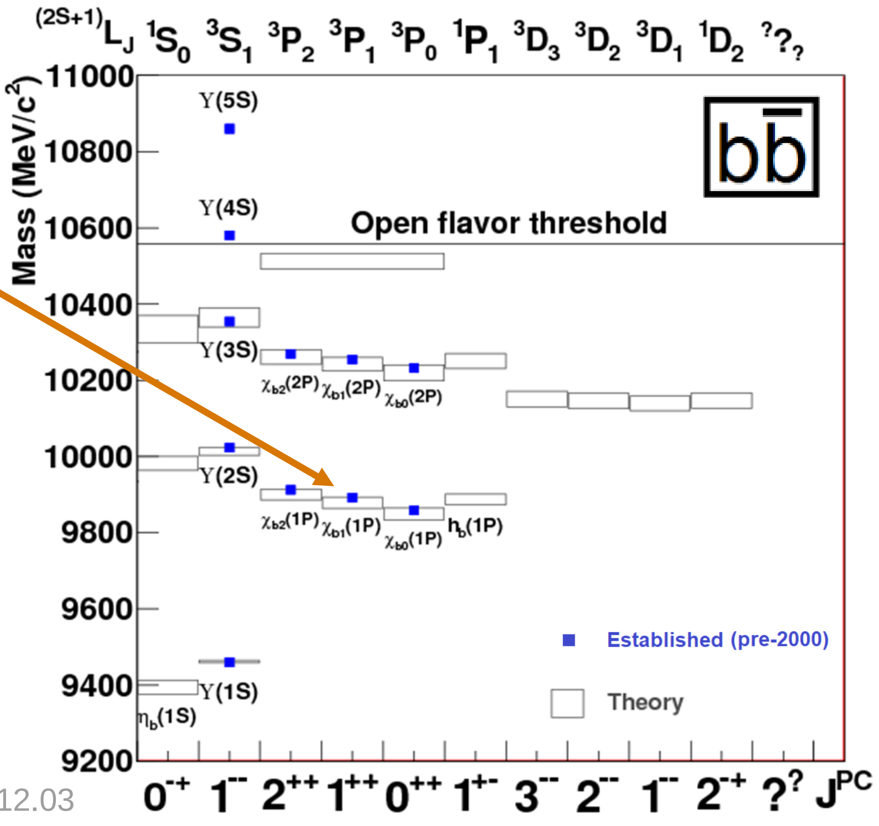
$$\begin{aligned} V_{spin}(r) \;=\; & \left(\frac{1}{2m_1^2}\vec{L}\cdot\vec{S}_1 + \frac{1}{2m_2^2}\vec{L}\cdot\vec{S}_2\right)\frac{1}{r}\frac{d}{dr}\left(V(r)+2V_1(r)\right) \\ & + \frac{1}{m_1 m_2}\vec{L}\cdot(\vec{S}_1+\vec{S}_2)\frac{1}{r}\frac{dV_2(r)}{dr} \\ & + \frac{1}{m_1 m_2}(\hat{r}\cdot\vec{S}_1\,\hat{r}\cdot\vec{S}_2 - \frac{1}{3}\vec{S}_1\cdot\vec{S}_2)V_3(r) + \frac{1}{3m_1 m_2}\vec{S}_1\cdot\vec{S}_2\,V_4(r) \end{aligned}$$

- Modern descriptions: EFT and lattice QCD
- Predictions: mass, width, J^{PC}, production, decay

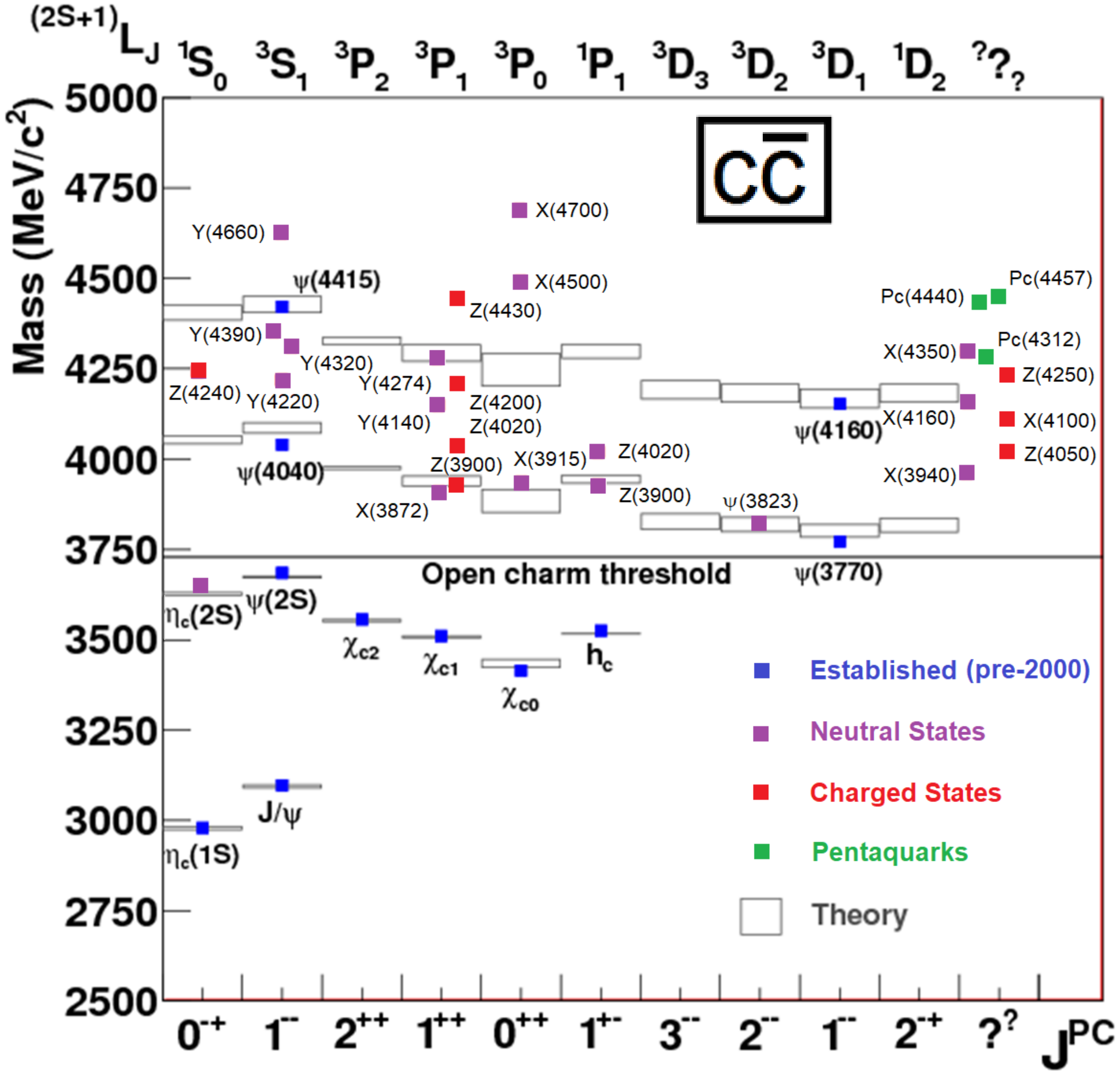
Hyperfine splitting

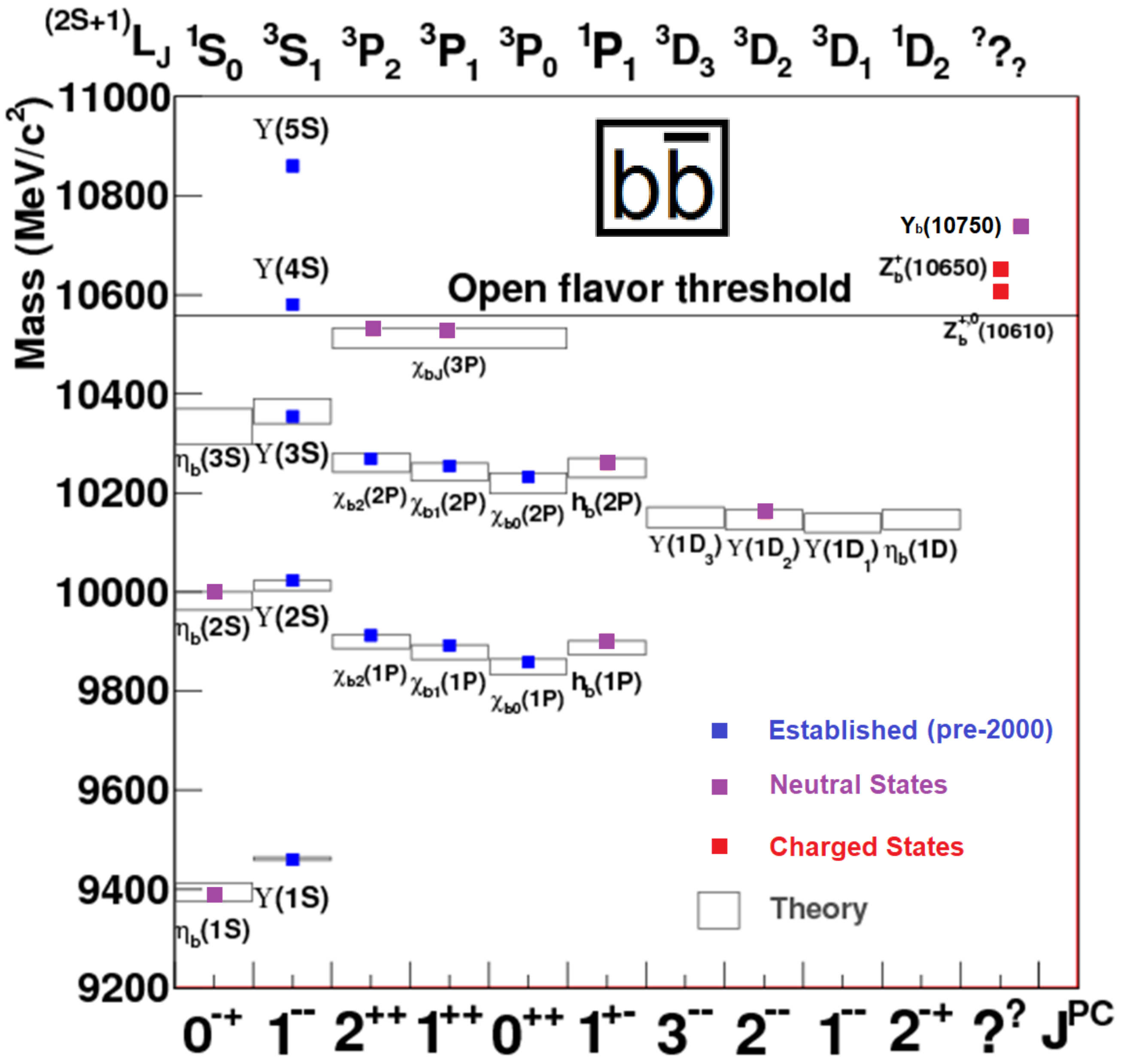
Fine splitting





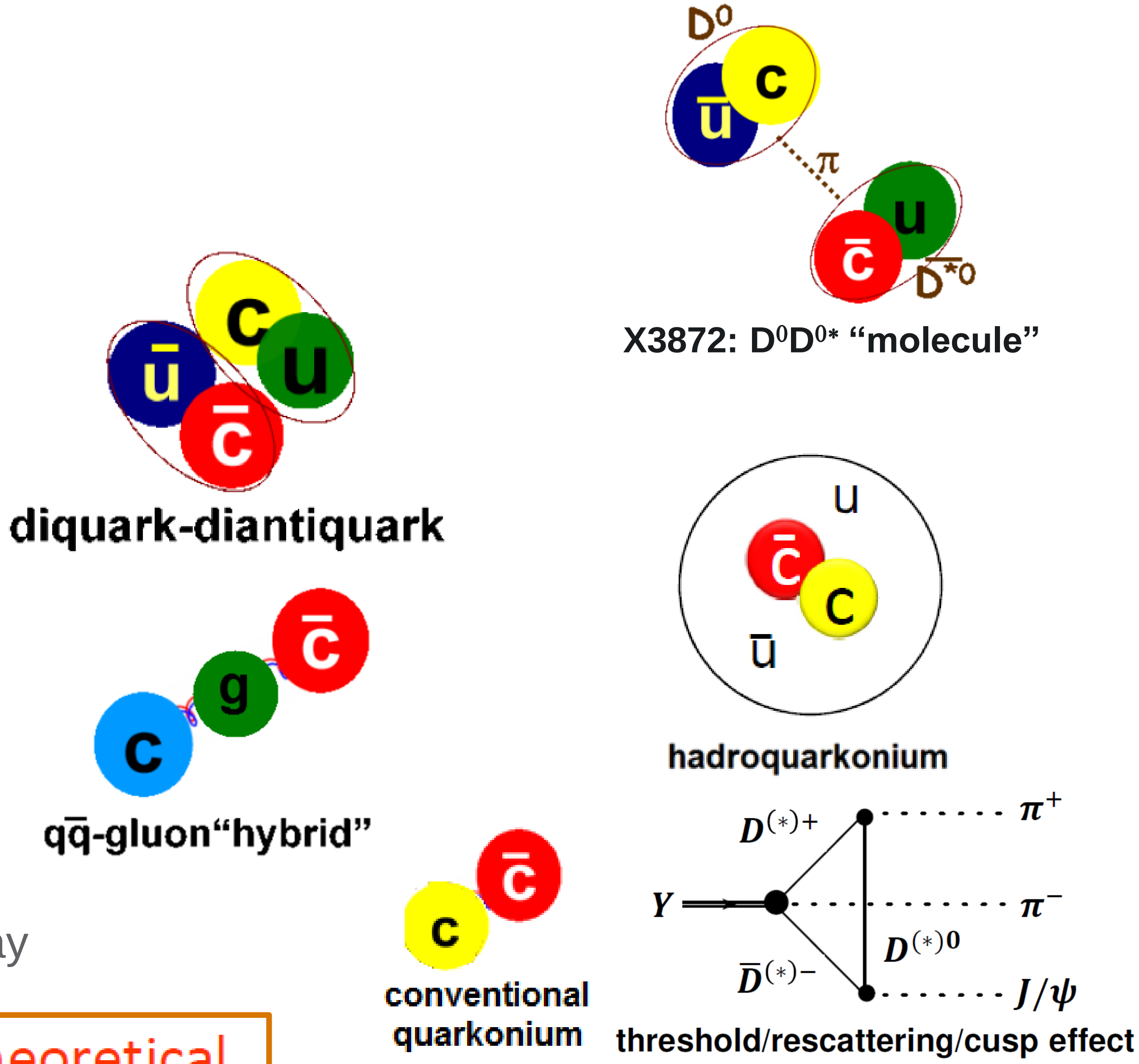
Reality Check





Interpreting new forms of matter

- Hadronic Molecules
  - Weakly bound state of mesons/baryons
- Tetraquarks/Pentaquarks
  - Di-quarks bound directly by strong force
- Other exotica
  - Hybrids: quarkonium with bound excited gluon
  - Hadroquarkonium: $q\bar{q}$-light hadron interaction
- “Nothing special”
  - Kinematic effects / standard quarkonium
- Lattice QCD
  - Challenging calculation, but some progress underway

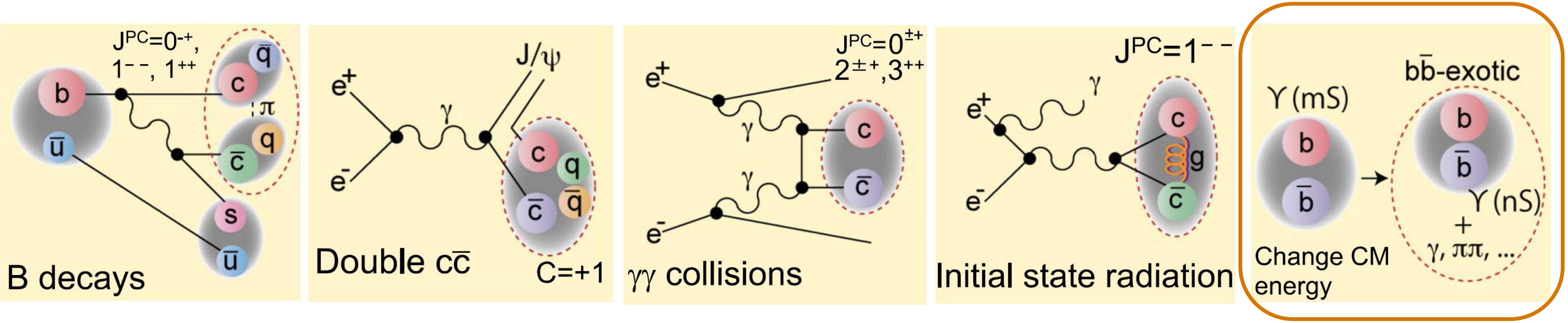


Adapted from Godfrey & Olsen, Ann. Rev. Part. Sci. 58 (2008) 51

It is becoming increasingly clear that no single theoretical paradigm explains all > 40 heavy-quark exotics

How do we study quarkonium experimentally? Production Mechanisms

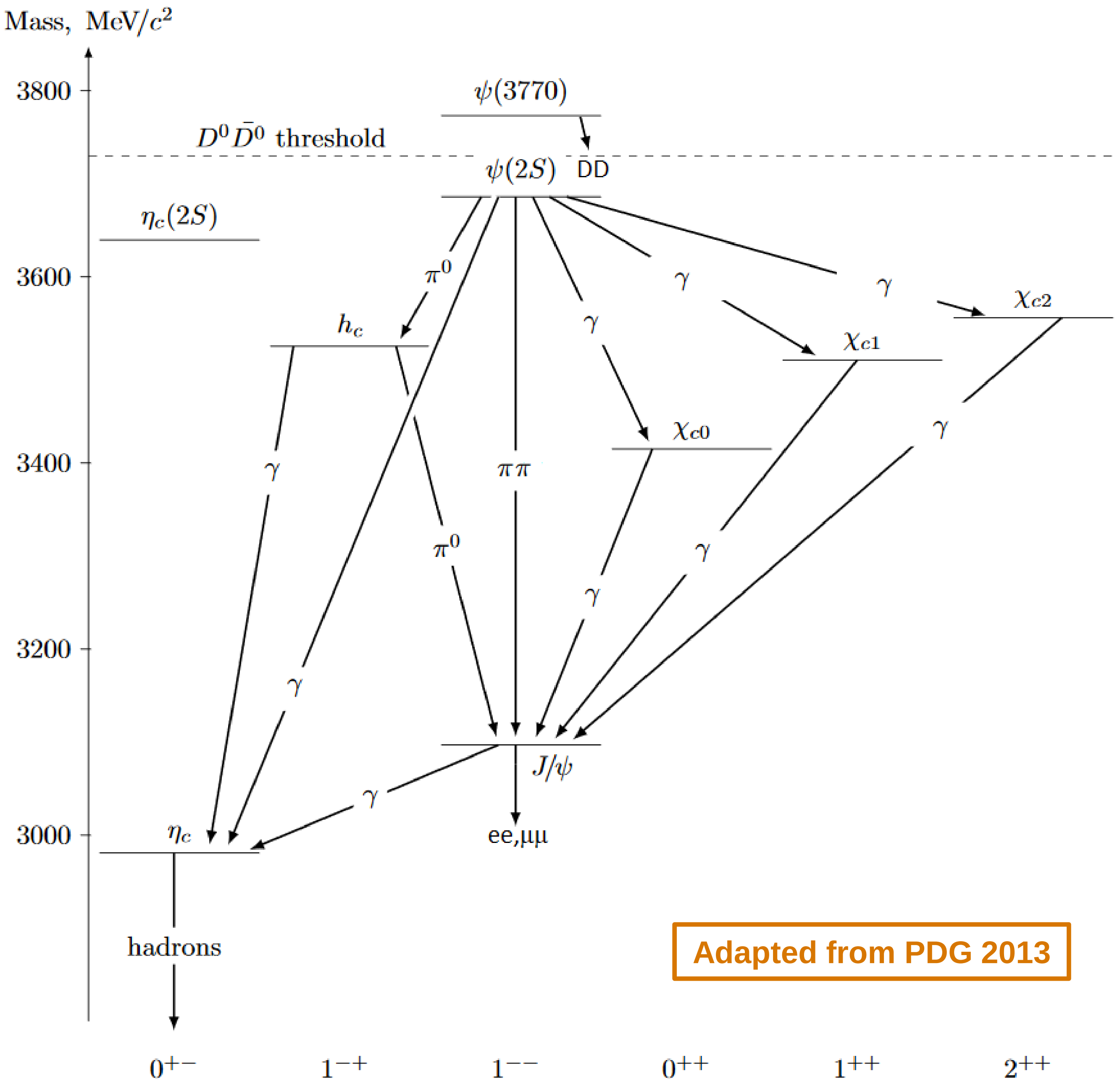
- Multiple methods to produce quarkonium/exotics at Belle II



- Production mode provides important information (e.g. J^{PC}, type)
- Several of these are unique to e^+e^- colliders

How do we study quarkonium experimentally? Decay Modes

- Search for transitions between states
  - Radiative (γ) and hadronic (ππ, π^0, η, …)
  - ~Governed by selection rules
- Below-threshold
  - ee/μμ : low rate but clean, ψ/ϒ states
  - hadronic: low rate/efficiency for N particles
- Above-threshold
  - Strong decays to $D\bar{D}$/$B\bar{B}$ dominate

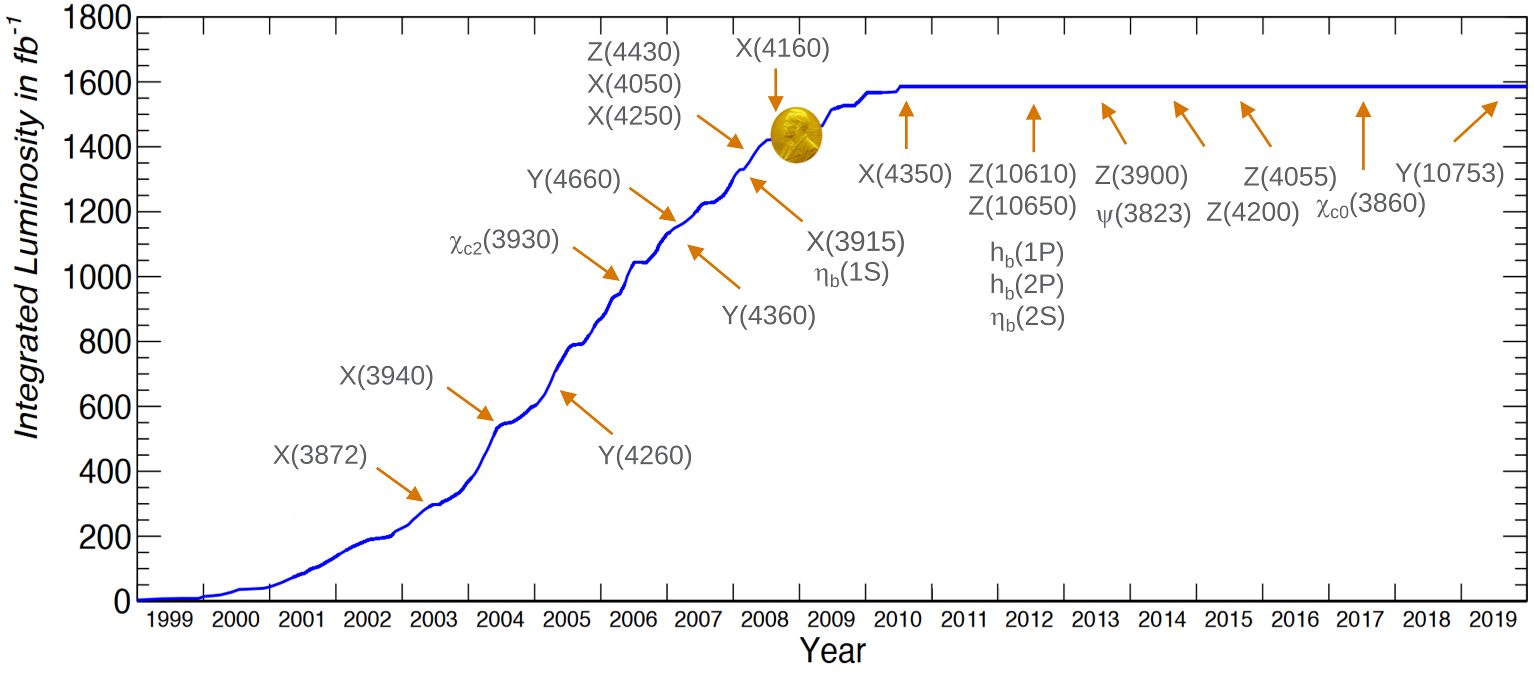


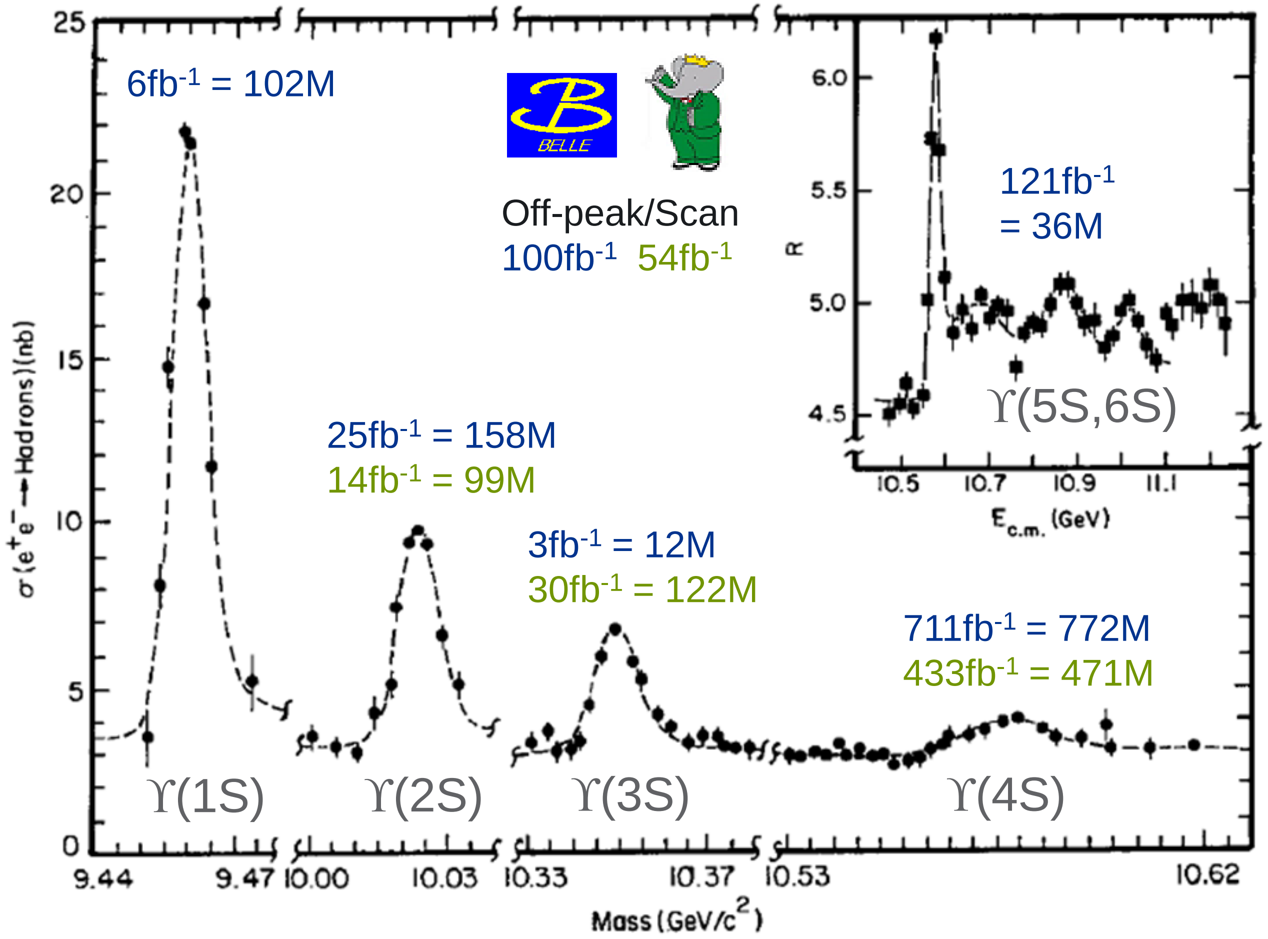
Adapted from PDG 2013

B-Factories Legacy

e.g.: “The Physics of the B Factories”, EPJC 74, 3026 (2014)

- 1999 ~ 2010 : BaBar (SLAC) & Belle (KEK)
- CKM / CPV in B decays
- Hints for NP in rare processes
- Discovery of “XYZ” states

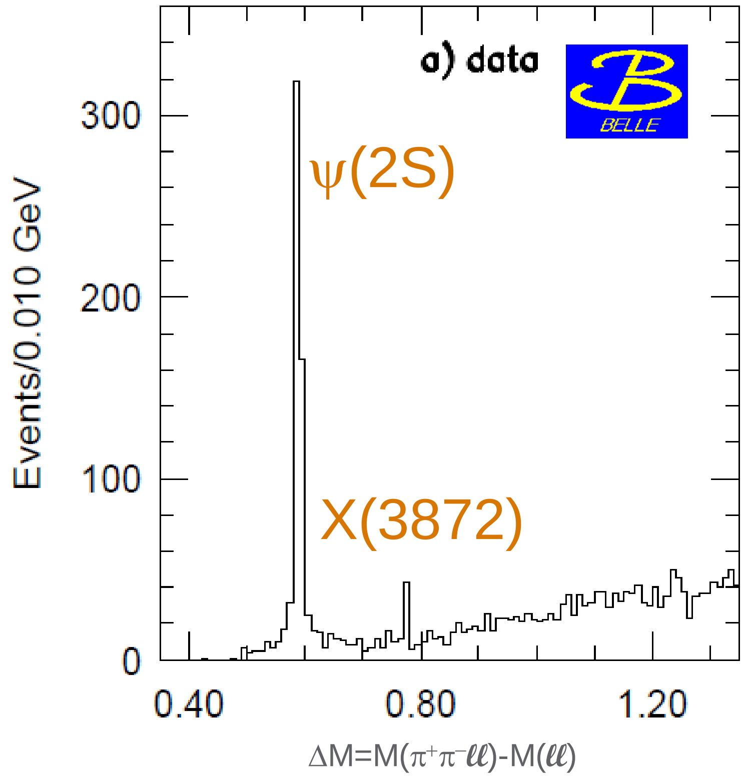




“XYZ” States

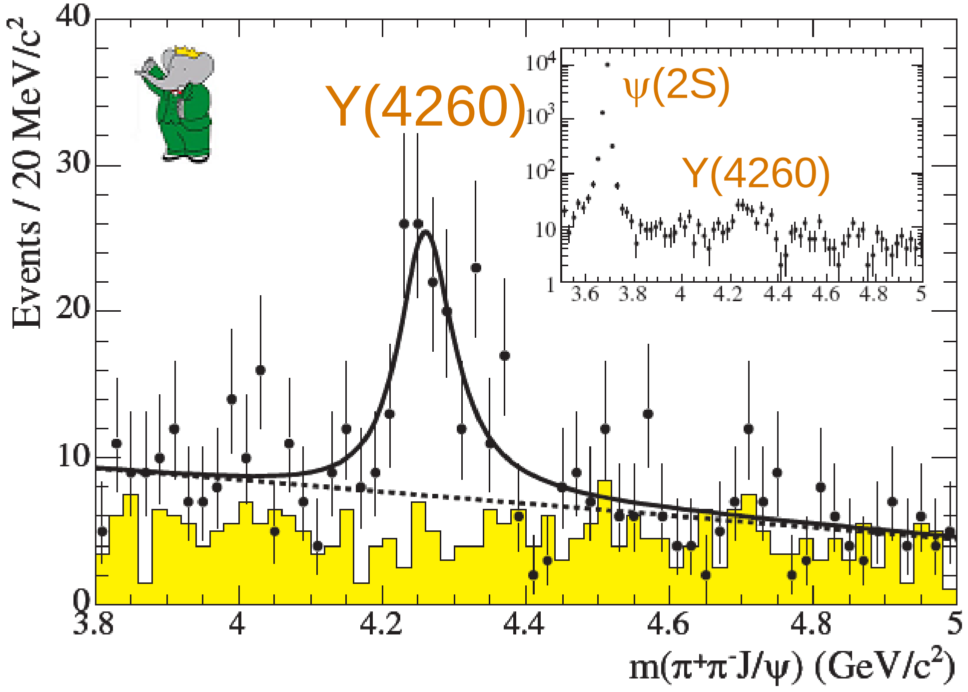
- Several charmonium-like states found at Belle and Babar (also BESIII, LHCb)
- Opened the door to a new era of discoveries

$B^{\pm} \rightarrow K^{\pm}X(3872) \rightarrow \pi^{-}\pi^{+} J/\psi$



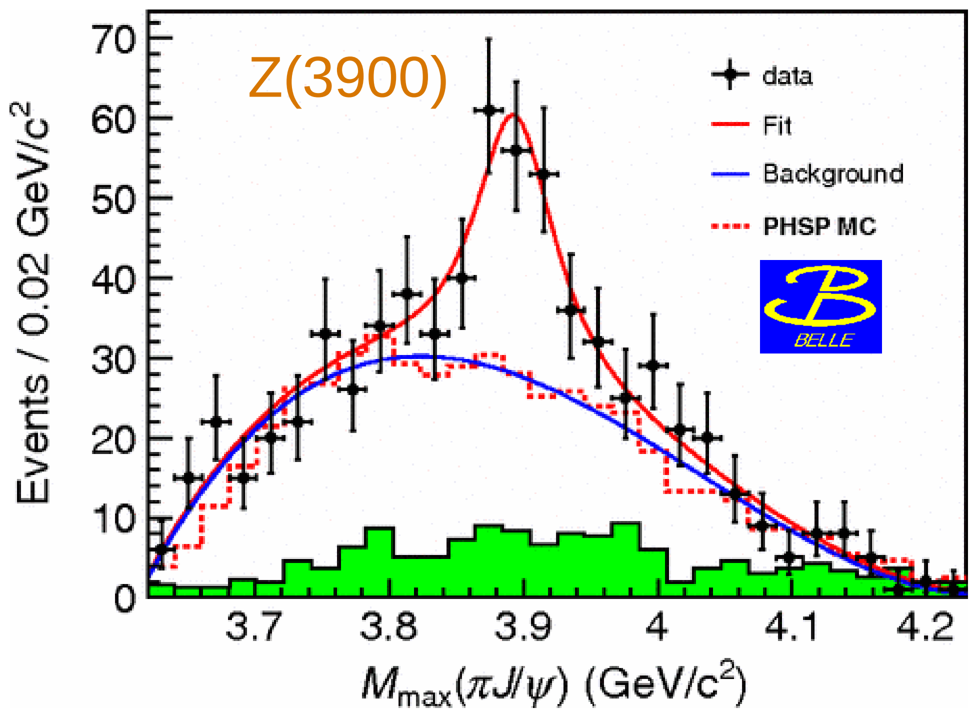
PRL 91, 261001 (2003)

$e^{+}e^{-}(\gamma) \rightarrow Y(4260) \rightarrow \pi^{-}\pi^{+} J/\psi$



PRL 95, 142001 (2005)

$Y(4260) \rightarrow \pi^{\mp} [Z_c^{\pm}(3900) \rightarrow \pi^{\pm} J/\psi]$

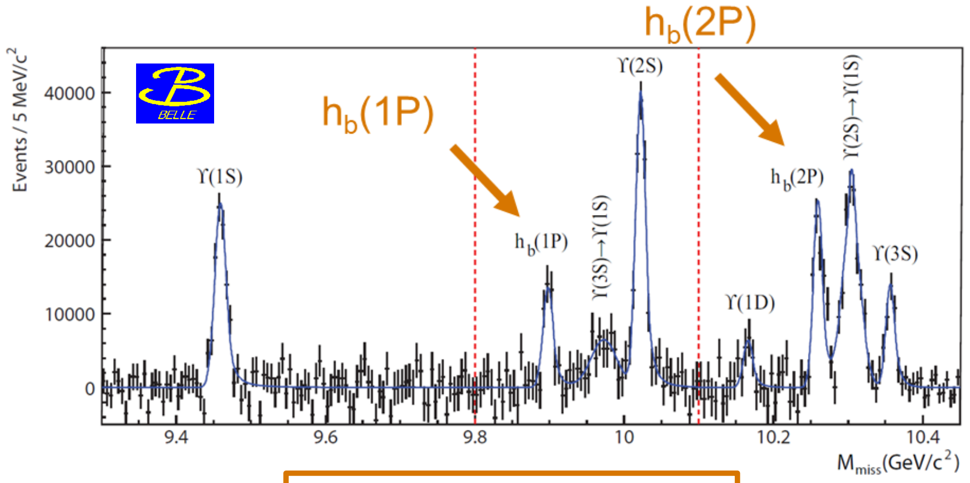


PRL 110, 252002 (2013)

Discoveries in the Bottomonium System

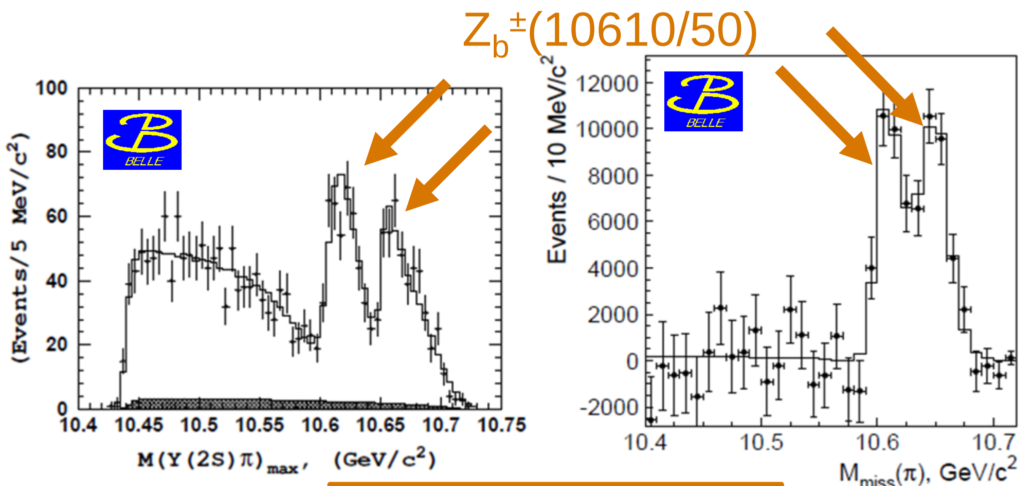
- The B-Factories extended their physics programs with non-$\Upsilon(4S)$ data
  - e.g.: BaBar $\Upsilon(3S)$ for discovery of $\eta_b(1S)$ and evidence for $h_b(1P)$
  - e.g.: Belle $\Upsilon(5S)$ for B_s physics and discovery of $h_b(1P,2P)$, $\eta_b(2S)$
  - Observation of “XYZ” states in bottom sector: $Y_b(10753)$, $Z_b^{\pm}(10610, 10650)$

$\Upsilon(5S)\rightarrow\pi^+\pi^-\, b\bar{b}$



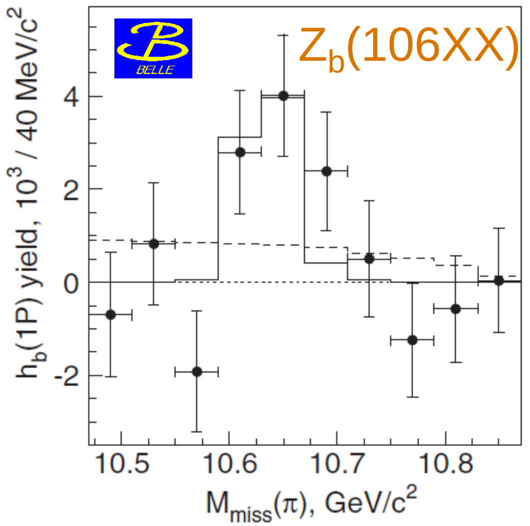
PRL 108, 032001 (2012)

$\Upsilon(5S)\rightarrow\pi^{\mp}[Z_b^{\pm}\rightarrow\pi^{\pm}\,\Upsilon(123S)/h_b(12P)]$



PRL 108, 122001 (2012)

$\Upsilon(6S)\rightarrow\pi^{\mp}[Z_b^{\pm}\rightarrow\pi^{\pm}h_b]$

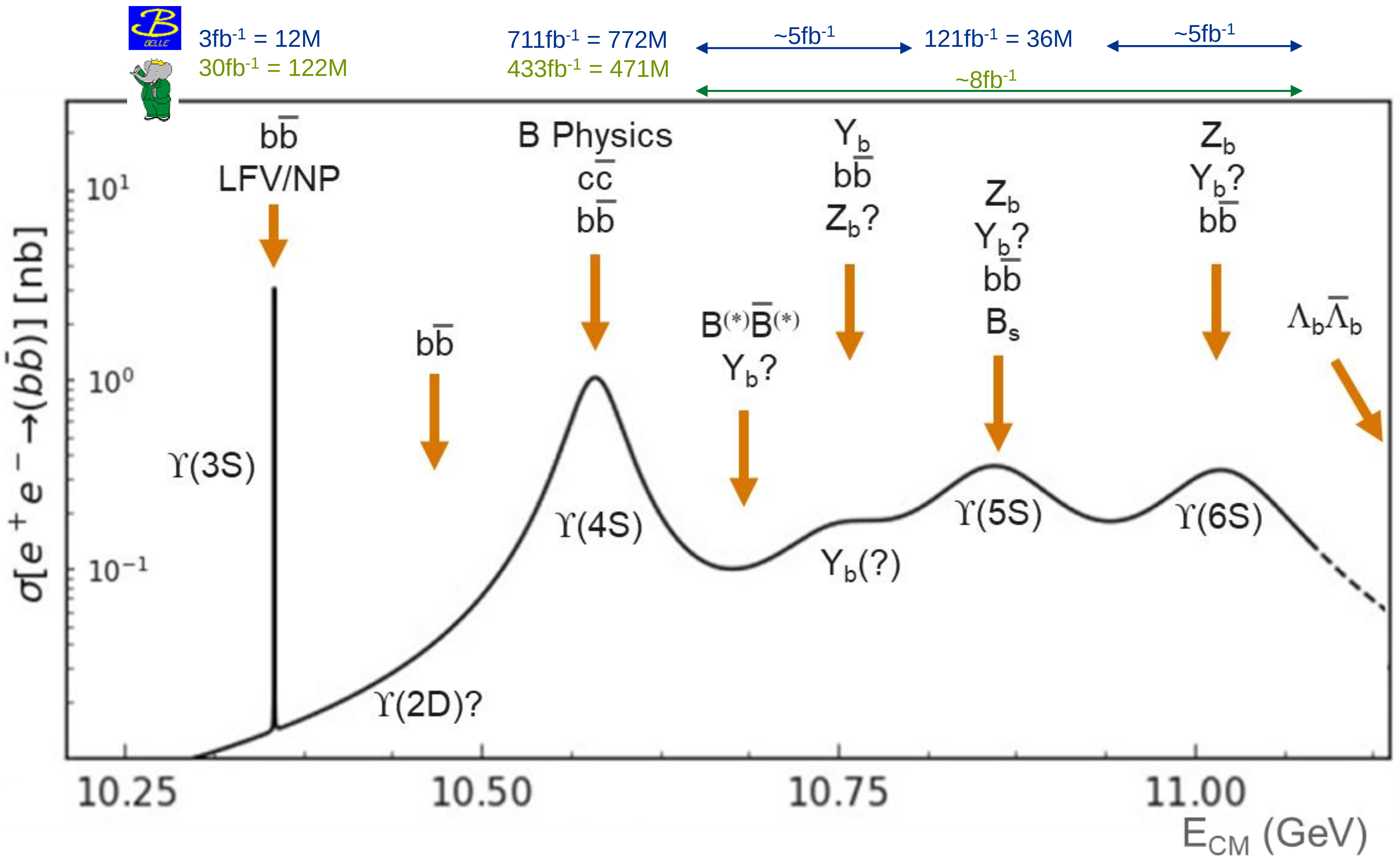


PRL 117, 142001 (2016)

- KEKB/Belle collected energy scan data (~1fb^{-1}) at several points up to ~11 GeV

A Question of Beam Energy

- Which energies? What can we do? What can we learn?



What's special about 10.75 GeV?

- Recent analysis of $\pi^+\pi^-\Upsilon(\ell^+\ell^-)$ transitions

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Observation of a new structure near 10.75 GeV in the energy dependence of the $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ $(n = 1, 2, 3)$ cross sections

BELLE

The BELLE collaboration

R. Mizuk,[43,54] A. Bondar,[3,65] I. Adachi,[16,12] H. Aihara,[85] D.M. Asner,[2] ...

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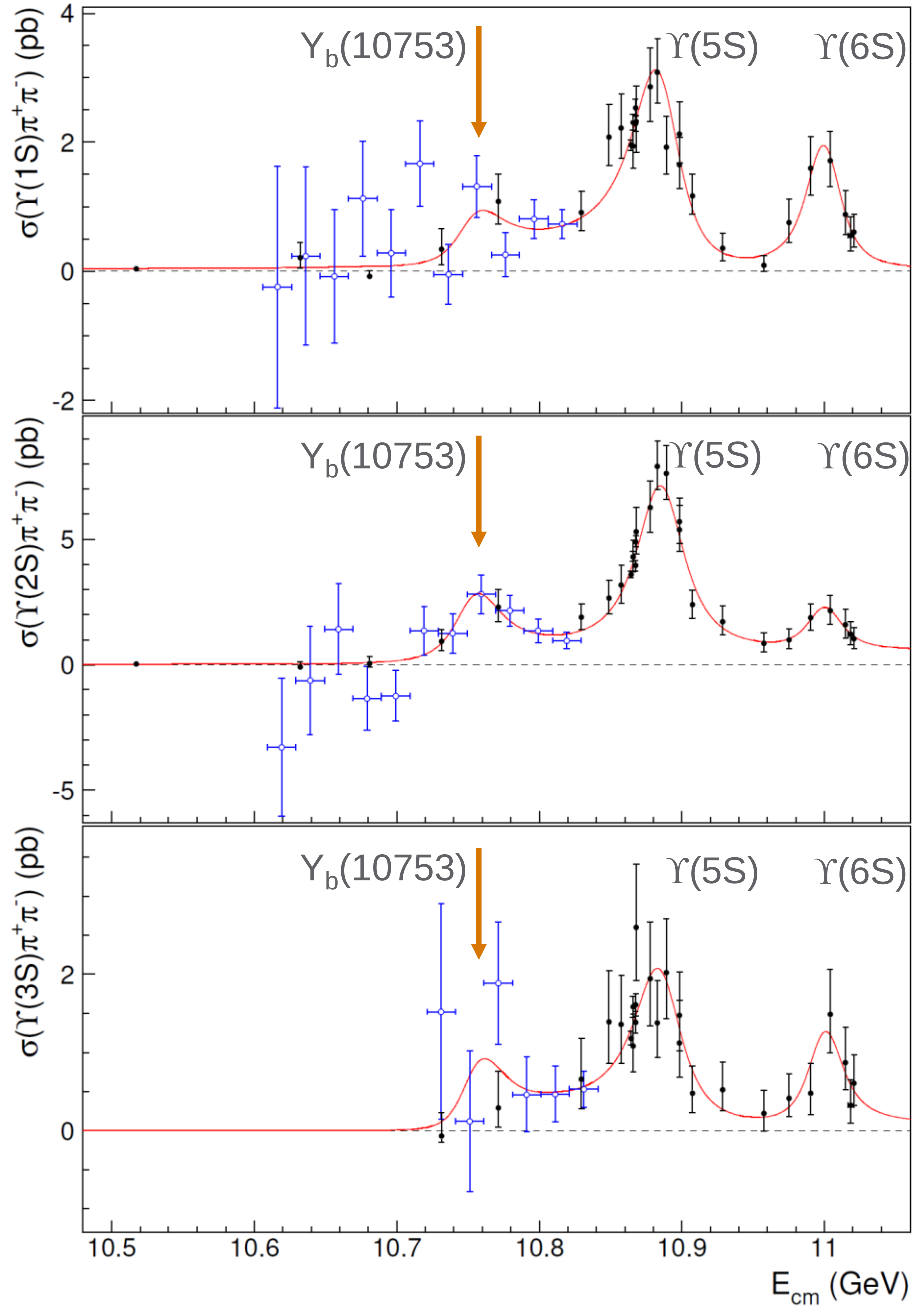

What's special about 10.75 GeV?

- Recent analysis of $\pi^+\pi^-\Upsilon(\ell^+\ell^-)$ transitions
- Results
  - Scan points: ~1 fb^{-1} each
  - 1 point "on-peak"
  - 2-3 points in the region of interest
  - Total significance: 5.2σ

	$\Upsilon(10860)$	$\Upsilon(11020)$	New structure
M (MeV/c^2)	$10885.3 \pm 1.5\,^{+2.2}_{-0.9}$	$11000.0^{+4.0}_{-4.5}\,^{+1.0}_{-1.3}$	$10752.7 \pm 5.9\,^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5}_{-3.9}\,^{+0.5}_{-1.1}$	$23.8^{+8.0}_{-6.8}\,^{+0.7}_{-1.8}$	$35.5^{+17.6}_{-11.3}\,^{+3.9}_{-3.3}$

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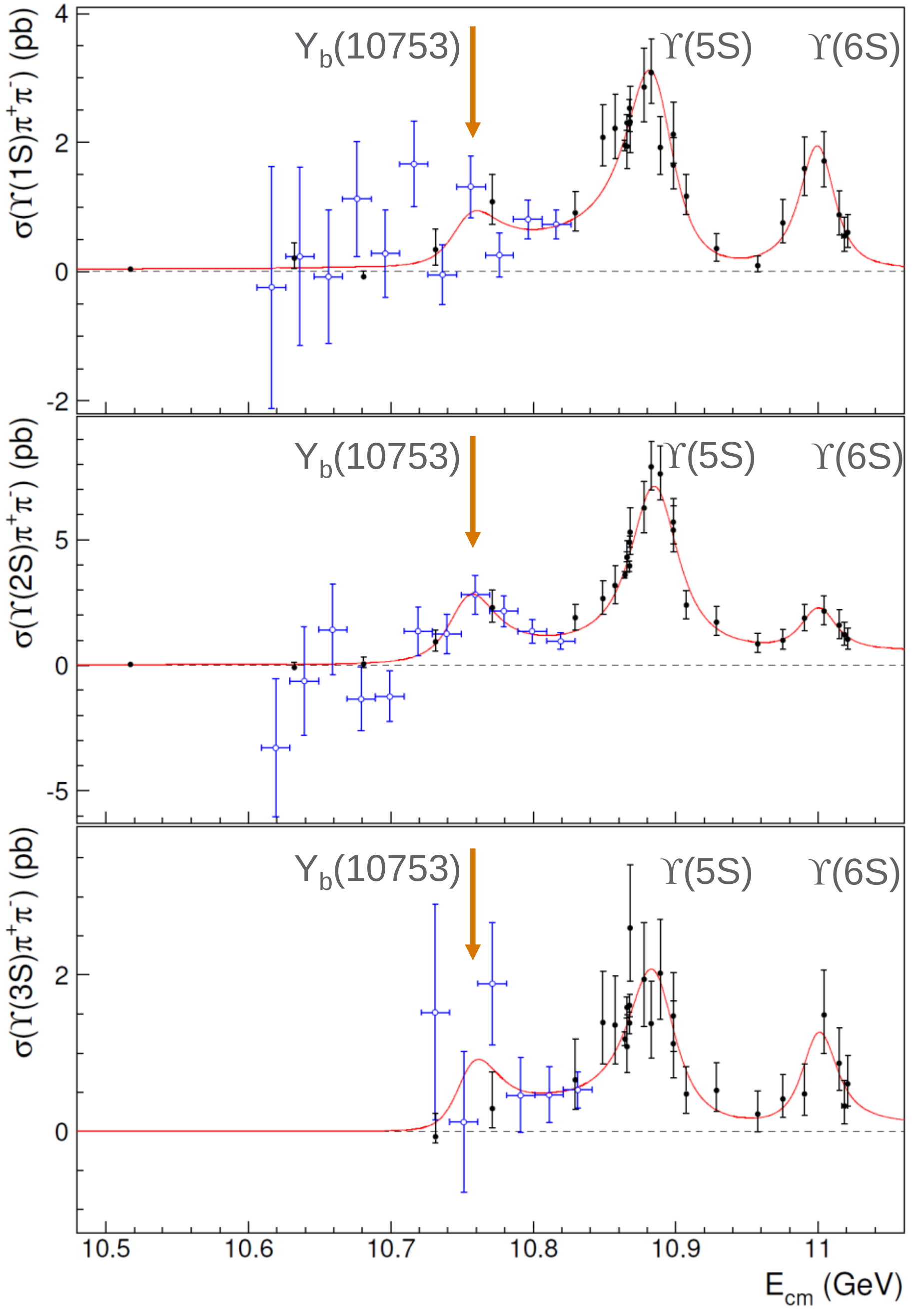
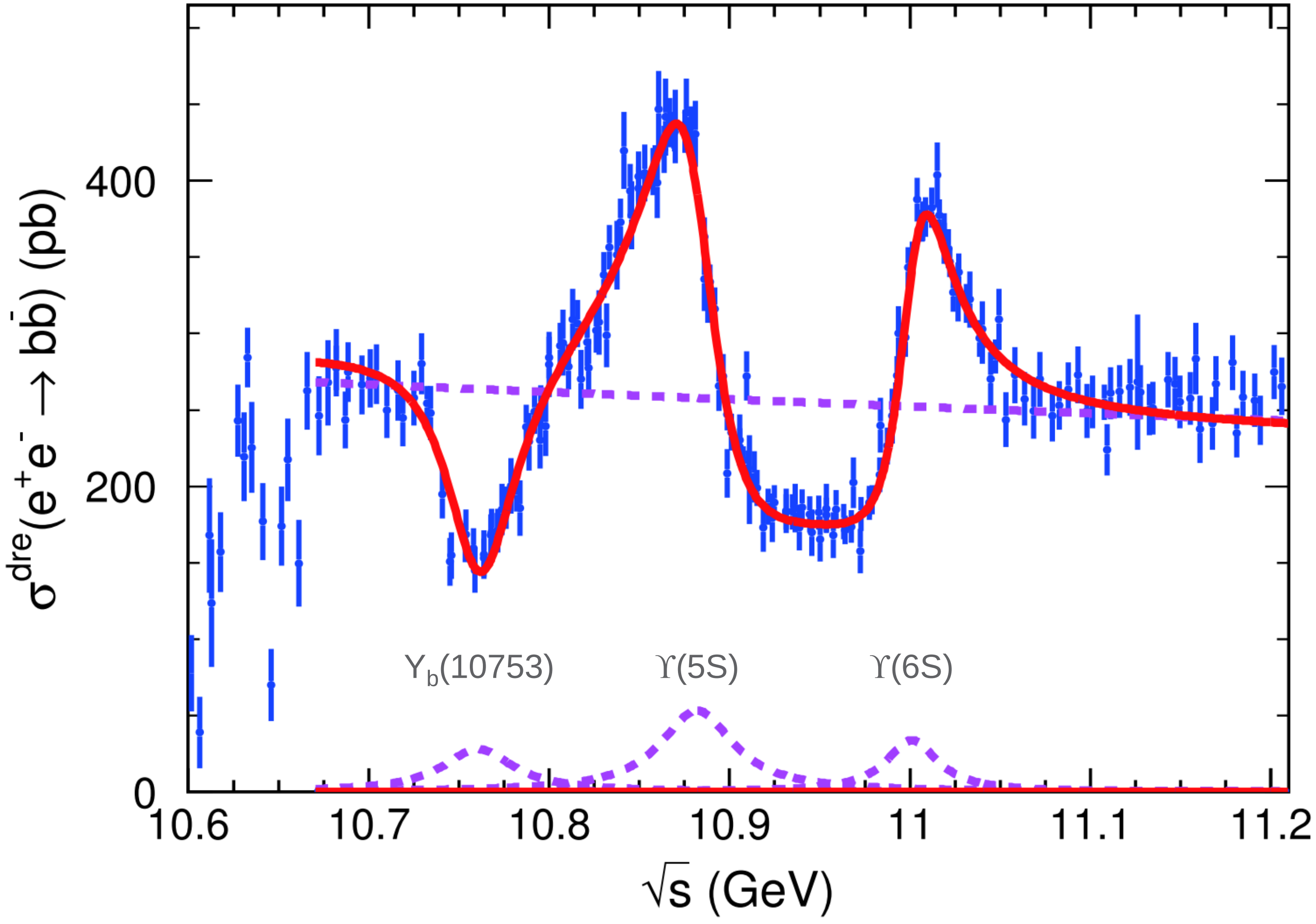


$Y_b(10753)$: Further Evidence?

CPC 44, 083001 (2020)

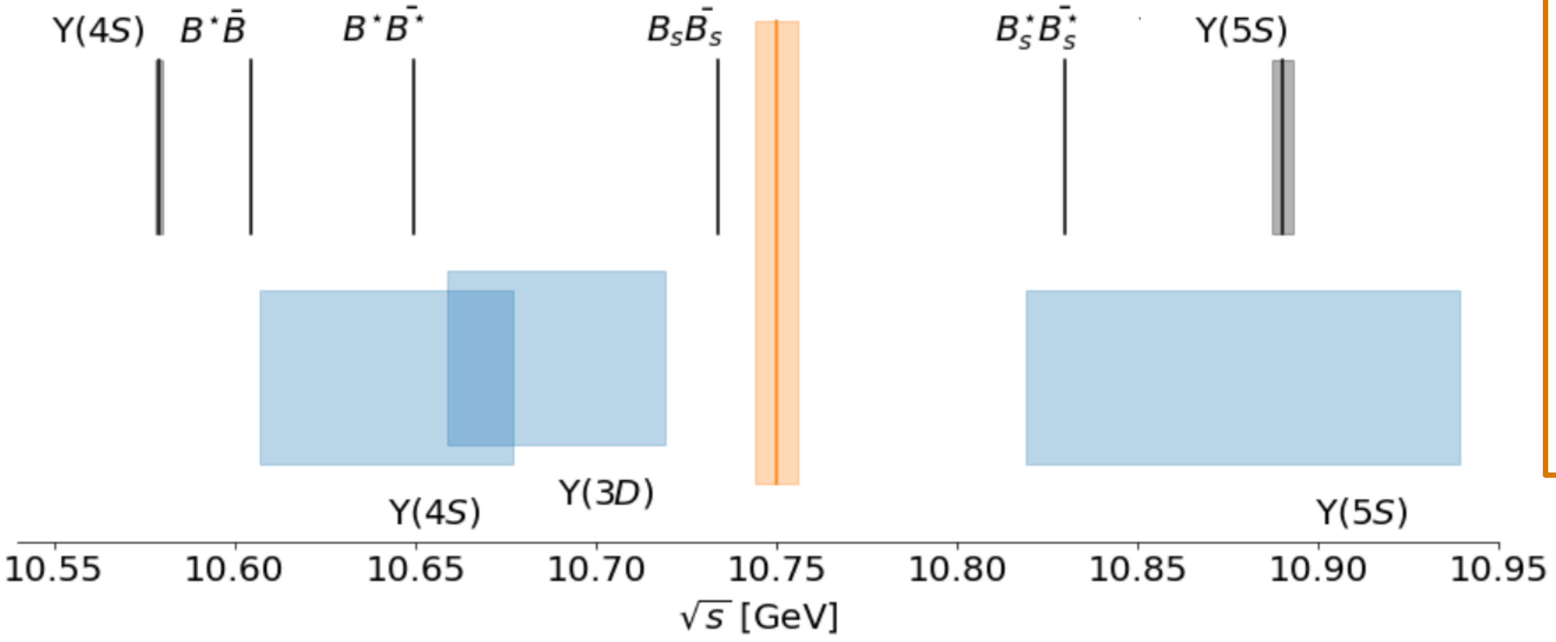
- Independent analysis
  - Refit of Belle + BaBar energy scans
  - Evidence for state in interference

Parameter	$Y(10750)$	$\Upsilon(5S)$	$\Upsilon(6S)$
Mass/(MeV/c^2)	10761 ± 2	10882 ± 1	11001 ± 1
Width/MeV	48.5 ± 3.0	49.5 ± 1.5	35.1 ± 1.2



Why is the $\Upsilon_b(10753)$ important?

- Uncertain nature
  - Molecular interpretation? Does not coincide with a threshold...
  - No clear conventional $b\bar{b}$ candidate
  - Potential tetraquark?



Conventional interpretations:
Chen, Zhang & He, PRD 101, 014020 (2020)
Li et al., EPJC 80, 59 (2020)
Liang, Ikeno & Oset, PLB 803, 135340 (2020)

"Exotic" interpretations:
Wang, CPC 43, 123102 (2019)
Ali, Maiani, Parkhomenko & Wang, PLB 802, 135217 (2020)
Bicudo, Cardoso & Wagner, arXiv:2008.05605 (2020)
Giron & Lebed, PRD 102, 014036 (2020)
...

- Big picture: relationship to puzzles in XYZ/charmonium system

Pacific Northwest NATIONAL LABORATORY

Some Key Theoretical Predictions

- $B\overline{B}$:$B\overline{B}^*$:$B^*\overline{B}^*$ ratios predicted by almost all models

PLB 803, 135340 (2020)

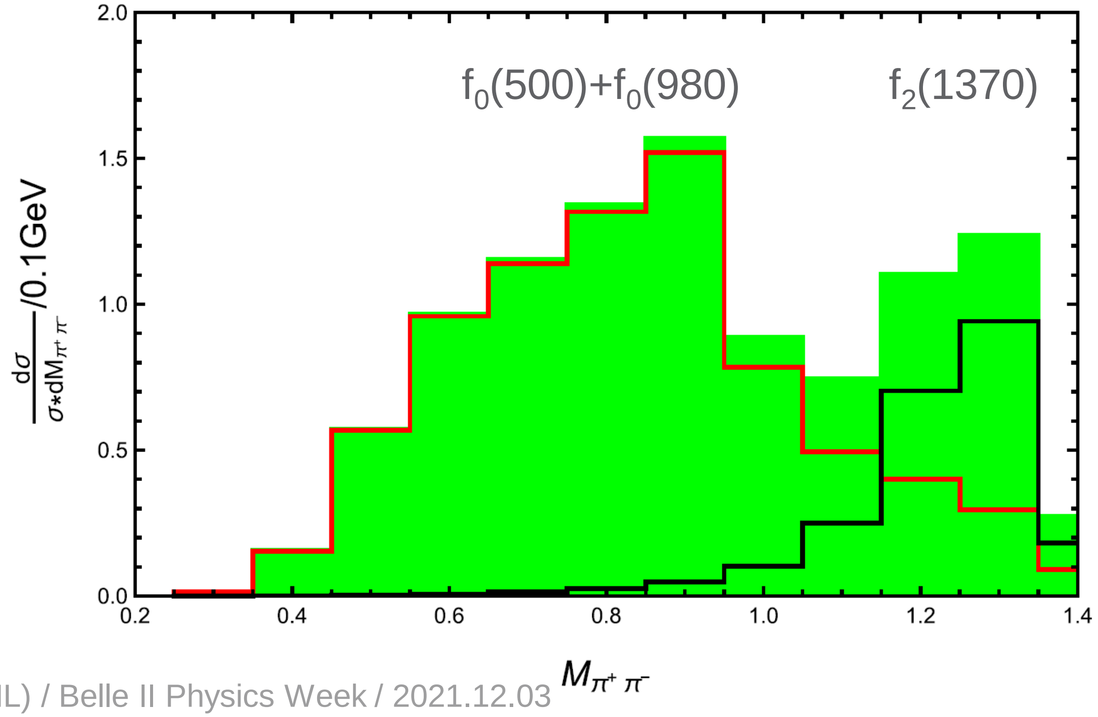
- BF(Y_b(10753)→$\omega\eta_b$(1S)) may be large for tetraquark hypothesis

CPC 43, 123102 (2019)

- Tetraquark M($\pi\pi$) shape prediction

PLB 802, 135217 (2020)

Mode	$\mathcal{B}(4q)$ (%)	$\mathcal{B}(b\bar{b})$ (%)
$B\overline{B}$	$39.3^{+38.7}_{-22.9}$	21.3
$B\overline{B}^*$	$\sim$0.2	14.3
$B^*\overline{B}^*$	$52.3^{+54.9}_{-31.7}$	64.1
$B_s\overline{B}_s$	-	0.3
$\omega\eta_b$	$7.9^{+14.0}_{-5.0}$	-
$\omega\chi_{bJ}$	-	$\sim$0.3
$f_0(1370)\Upsilon$	$0.2^{+0.6}_{-0.2}$	-
$\eta\Upsilon$	-	$\sim$0.2
$\eta'\Upsilon$	-	$\sim$0.06
ηh_b	-	$\sim$0.2



Input from Belle: $B\bar{B}$:$B\bar{B}^*$:$B^*\bar{B}^*$

- Fit to m_{BC} for B mesons reconstructed with FEI

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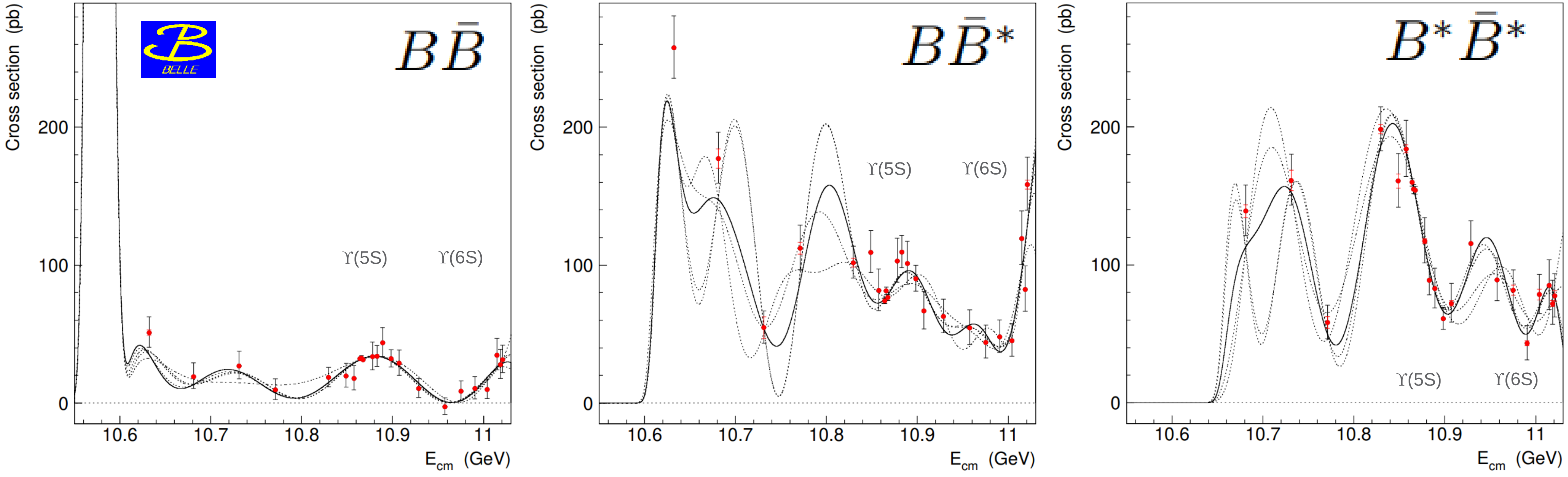
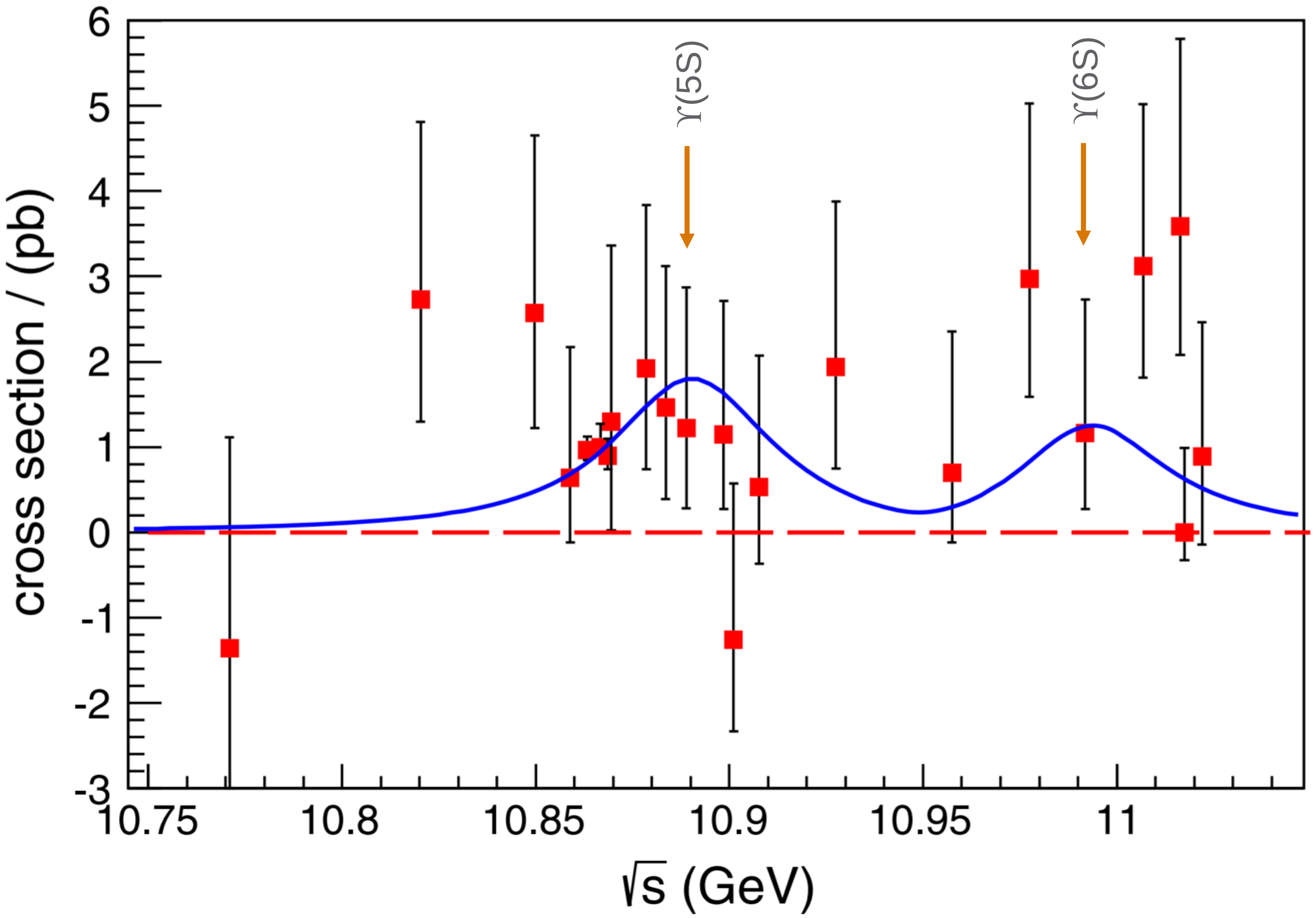


- Lineshape fit inconclusive
- Require 3-4 additional points

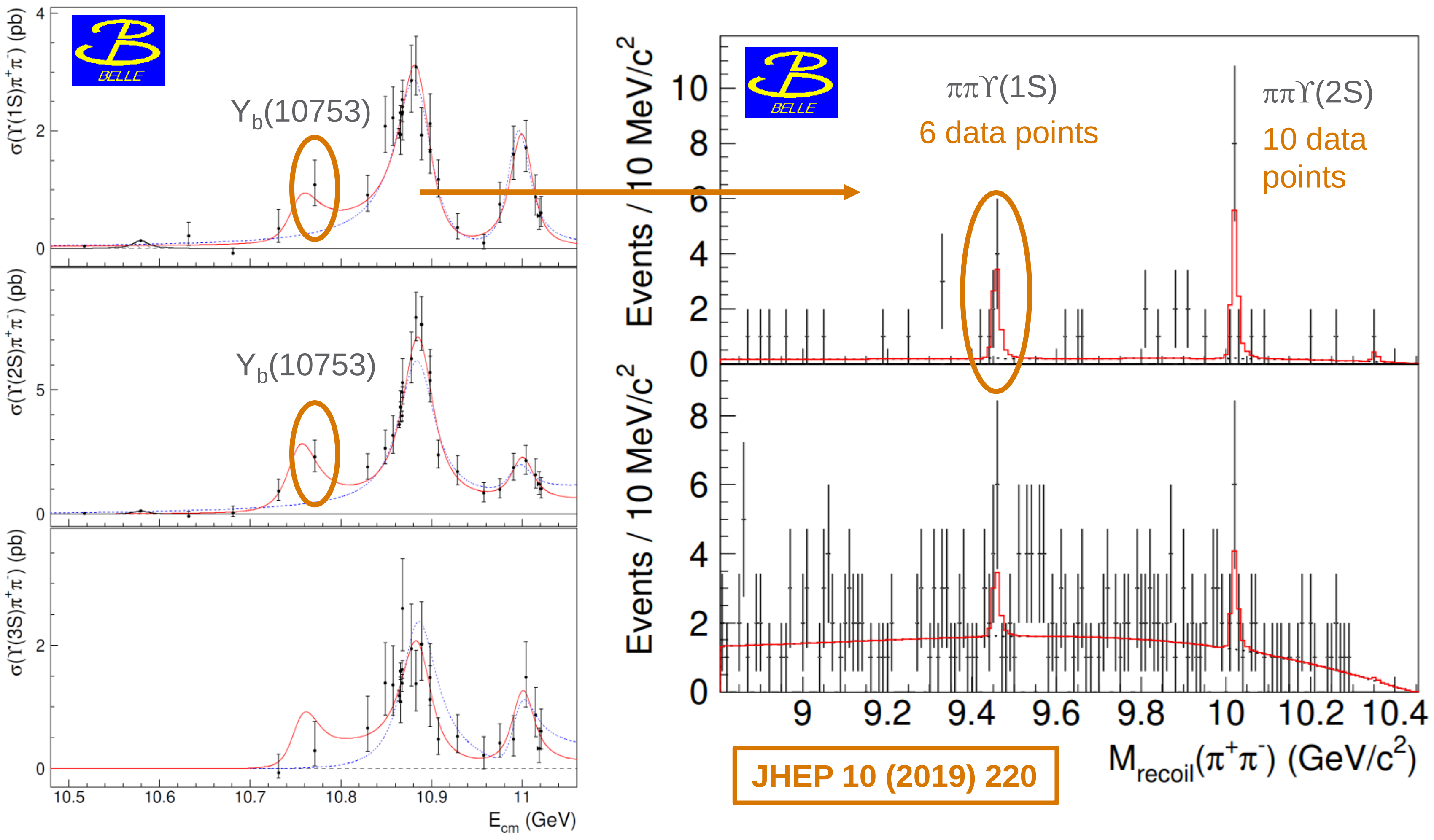
Input from Belle: $\pi^+\pi^-\pi^o\chi_{b1,2}(1P)$ Decays

- Observation of $\Upsilon(6S)\to\pi^+\pi^-\pi^o\,\chi_{b1,2}(1P)[\gamma\Upsilon(1S)]$ decays
  - ω and $\pi^+\pi^-\pi^o$ components combined
  - Cannot distinguish $\chi_{b1,2}(1P)$
- Low statistics at other points
- No clear interpretation
- Need more data and energies

PRD 98 091102 (2018)



Input from Belle: Dalitz analysis



- Insufficient data: need greater statistics to populate Dalitz plot

Energy Scan Decisions

- Considerations
  - Potential for early physics impact by Belle II
  - Limited luminosity requirement (O(15/fb))
  - Υ(6S) requires accelerator infrastructure upgrade
  - Collaboration with SuperKEKB accelerator group scheduling

- Proposed near-term non-Υ(4S) plans
  - **10.751 GeV (10 fb^{-1})**: to study cross section enhancements
  - **10.657, 10.706, 10.810 (1+2+3 fb^{-1})**: additional points for other decays
  - **11 GeV (30+ fb^{-1})**: to study Υ(6S) on-peak

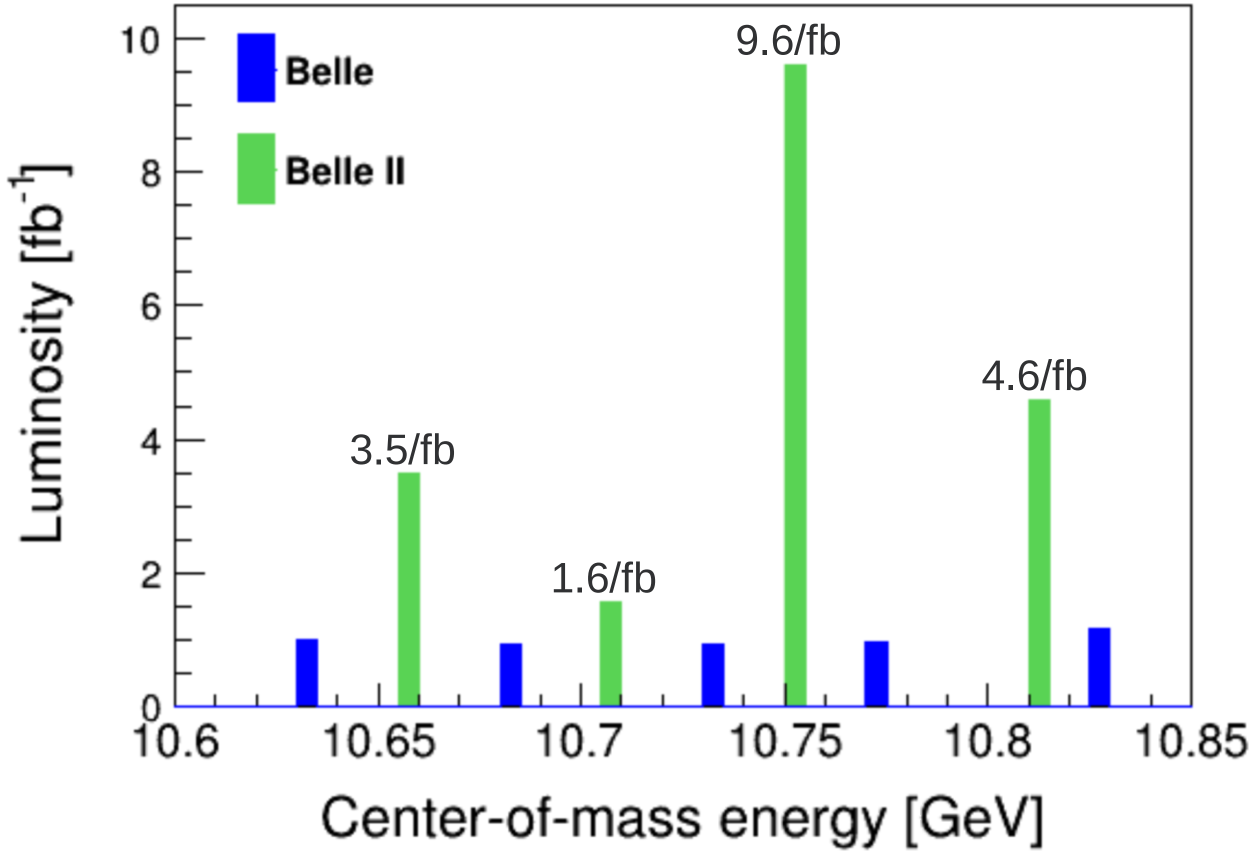
Nov 2021

Post-upgrade

Energy Scan Data Collection

- Energy scan took place Nov. 10 – 29, 2021 (JST)

	Nov 10 Wed	11 Thu	12 Fri	13 Sat	14 Sun	15 Mon	16 Tue
Owl		-	0.3/fb				0.1/fb
Day	Maintenance -	-	0.7/fb			3.5/fb **10.706 GeV**	0.4/fb
Swing	**10.657 GeV** -	-	1.0/fb	1.9/fb	3.1/fb	-	0.8/fb
	17 Wed	**18 Thu**	**19 Fri**	**20 Sat**	**21 Sun**	**22 Mon**	**23 Tue**
Owl	1.3/fb	0.1/fb					
Day	1.6/fb **10.751 GeV**	0.2/fb					
Swing	-	0.6/fb	2.2/fb	3.8/fb	5.7/fb	7.0/fb	8.6/fb
	24 Wed	**25 Thu**	**26 Fri**	**27 Sat**	**28 Sun**	**29 Mon**	**30 Tue**
Owl	9.2/fb	9.3/fb	0.2/fb			4.6/fb	
Day	Maintenance -	9.6/fb **10.810 GeV**	0.6/fb			**Υ(4S)**	
Swing	- Contingency	-					



Energy Scan Steps in Context

- Unique points between previous Belle energies
- Higher statistics (~2-10x) to confirm past measurements and improve fits

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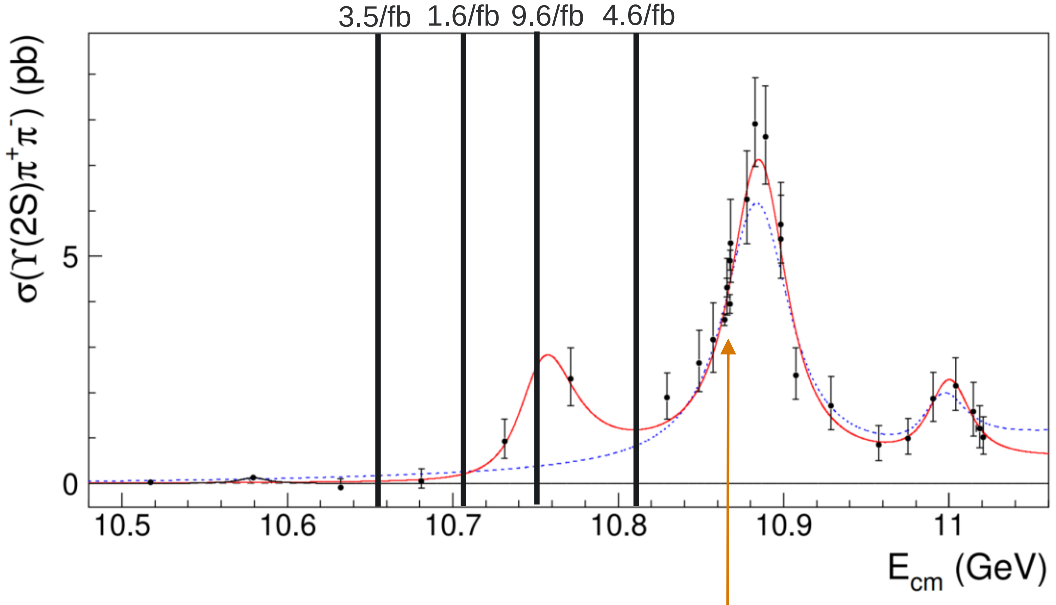

All points ~1/fb except these (~20+/fb)

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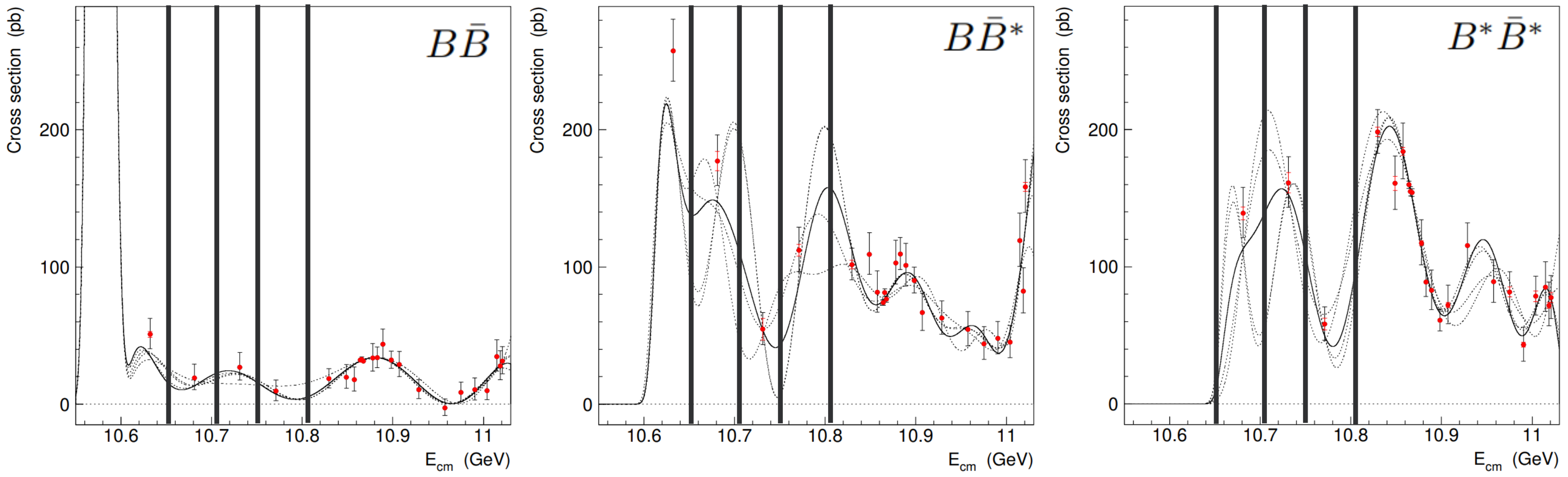
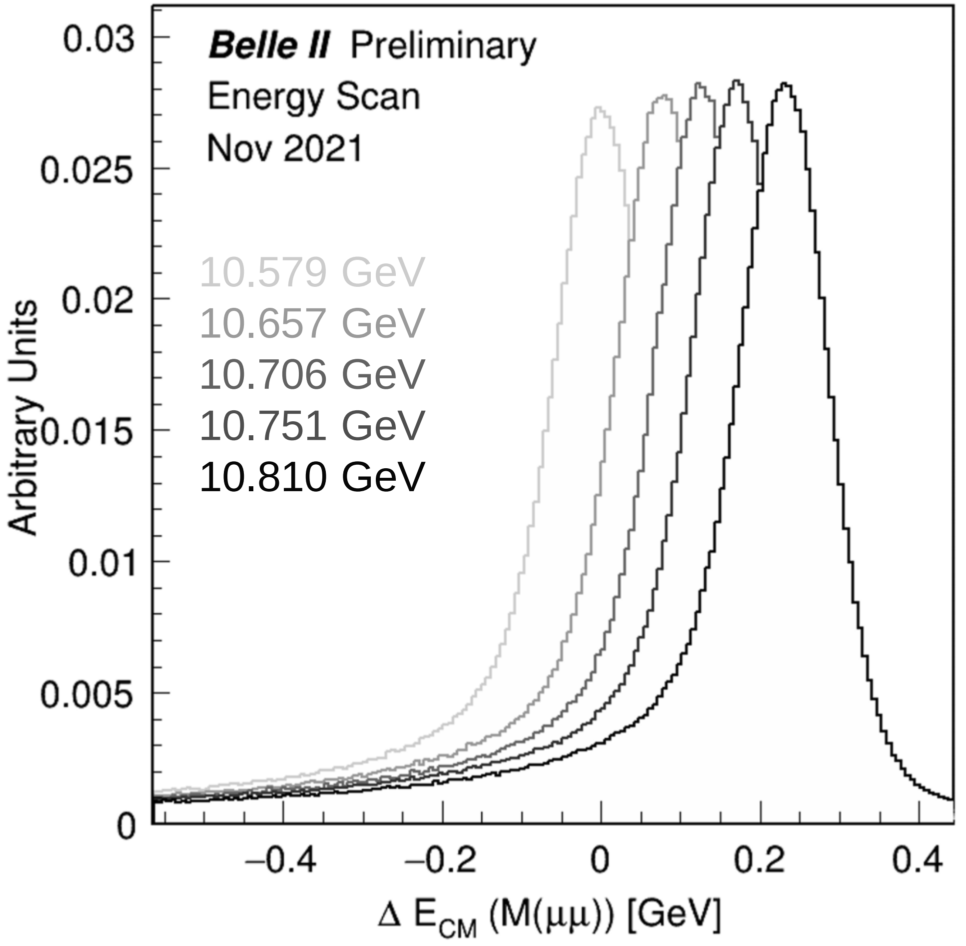


Energy Scan Step Summary

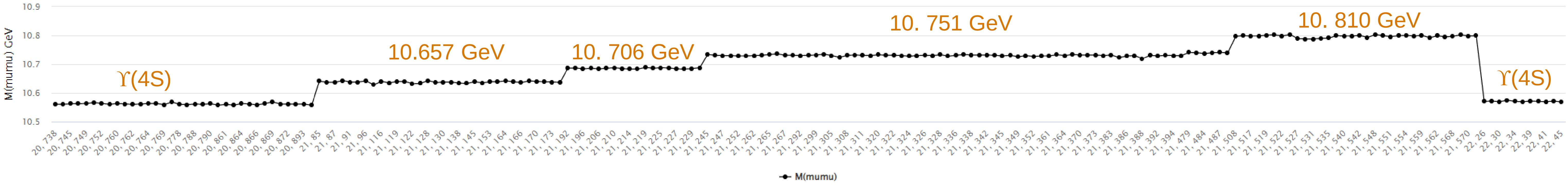
- Use M(μμ) to estimate beam energy

- Caveats:
  - Radiative effects (μμγ)
  - Online conditions DB
  - Calibration/PID/etc.

Energy (GeV)	Δ_{nom}(MeV)	$\Delta_{\mu\mu}$(MeV)
10.810	230.6	~231.7
10.751	171.6	~169.9
10.706	126.6	~125.4
10.657	77.6	~76.9
10.5794	-	-



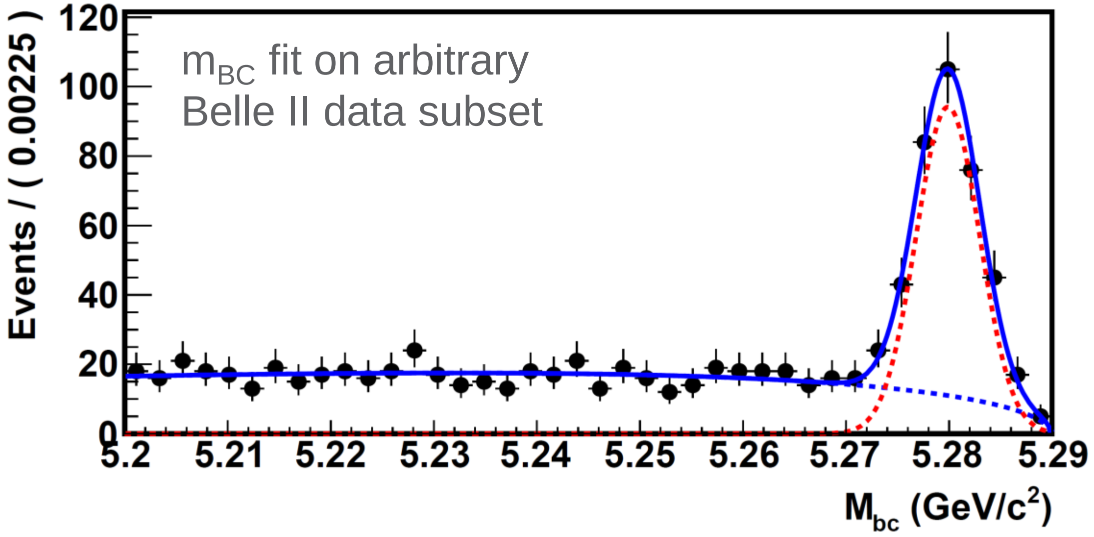
- Will re-measure offline

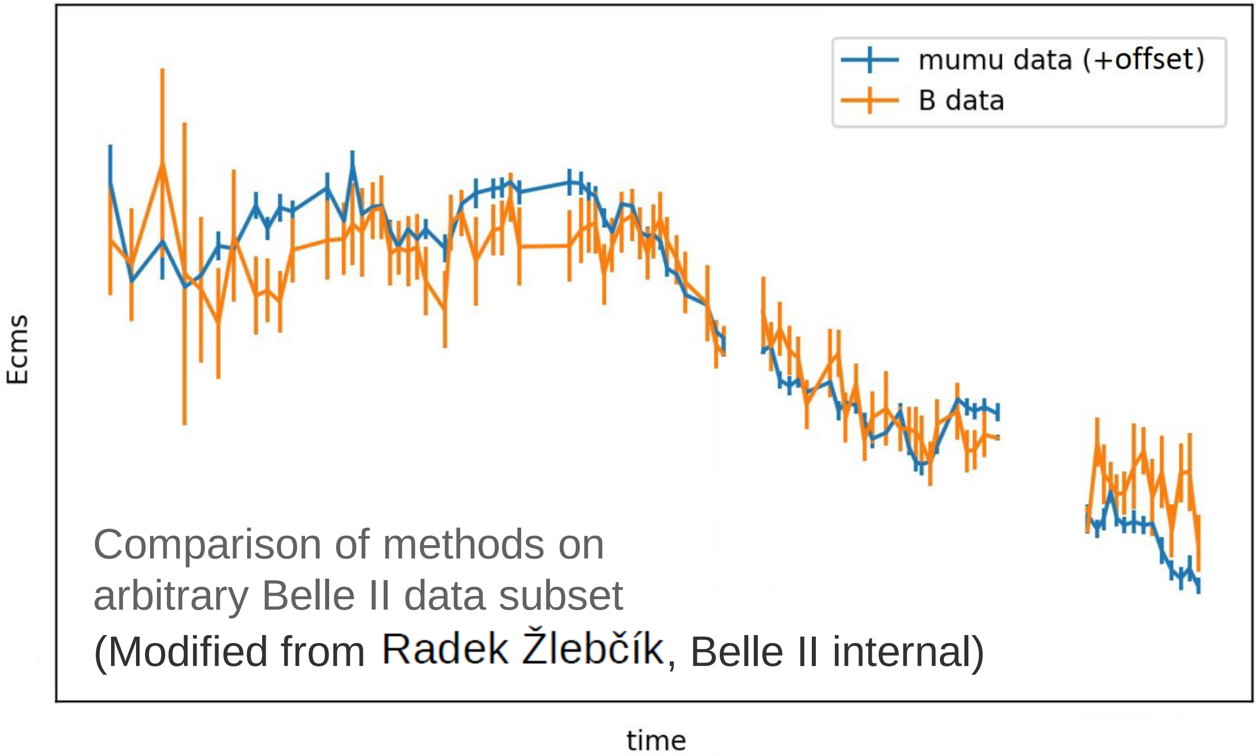


Beam energy determination (Work in progress)

B mesons
BELLE2-NOTE-PH-2020-002
-Reconstruct $B \rightarrow D\pi$ decays, measure shift in m_{BC}
-Narrow peak but only on-resonance

$M(\mu\mu)$
-High stats, poor resolution, available off-resonance





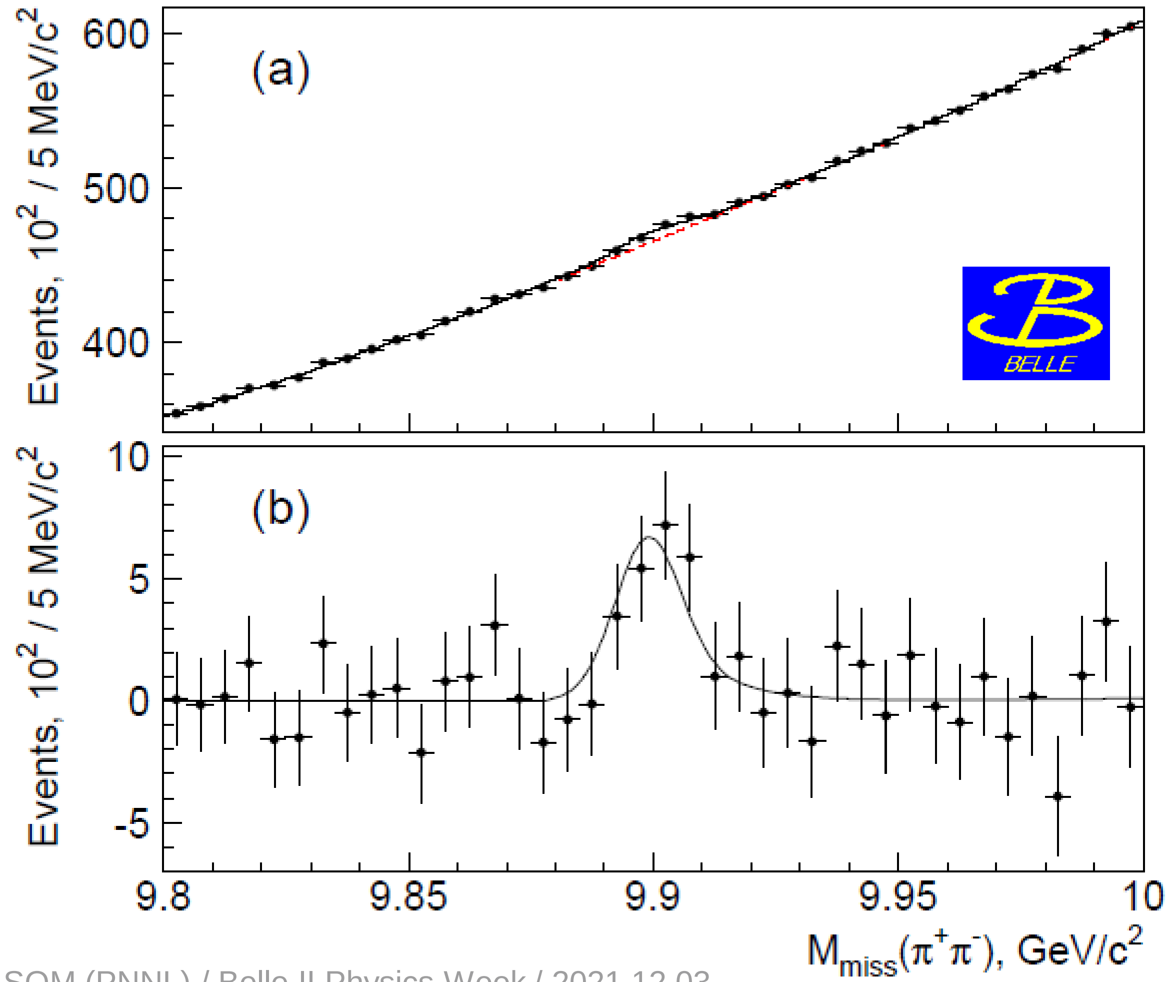
Comparison of methods on arbitrary Belle II data subset
(Modified from Radek Žlebčík, Belle II internal)

- BaBar energy scan: $M(\mu\mu)$ ~21 MeV bias corrected to $\Upsilon(3S)$ data — PRL 102 012001 (2019)
- Belle $\pi\pi\Upsilon(pS)$: ~9 MeV bias, $M(\mu\mu)$ and $m_{REC}(\pi\pi)$ from $\Upsilon(5S)$ data — JHEP 10 (2019) 220

Inclusive vs. Exclusive Analysis

- **Inclusive**: reconstruct only part of the event (“top down”)
  - E.g.: $e^+e^- \to \pi^+\pi^- X$
  - E.g.: $m_X = m_{miss/REC} = \mathrm{sqrt}[(p_{ee} - p_{\pi\pi})^2]$
- Potential advantages:
  - Large statistics
  - Better resolution
  - Do not need to reconstruct X
- Potential disadvantages:
  - High background
  - Combinatorics
  - Other peaking decays

$\Upsilon(5S) \to \pi^+\pi^- h_b(1P)$



$h_b(1P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\eta_b(1S)\gamma$	(52^{+6}_{-5}) %

$\eta_b(1S)$ DECAY MODES

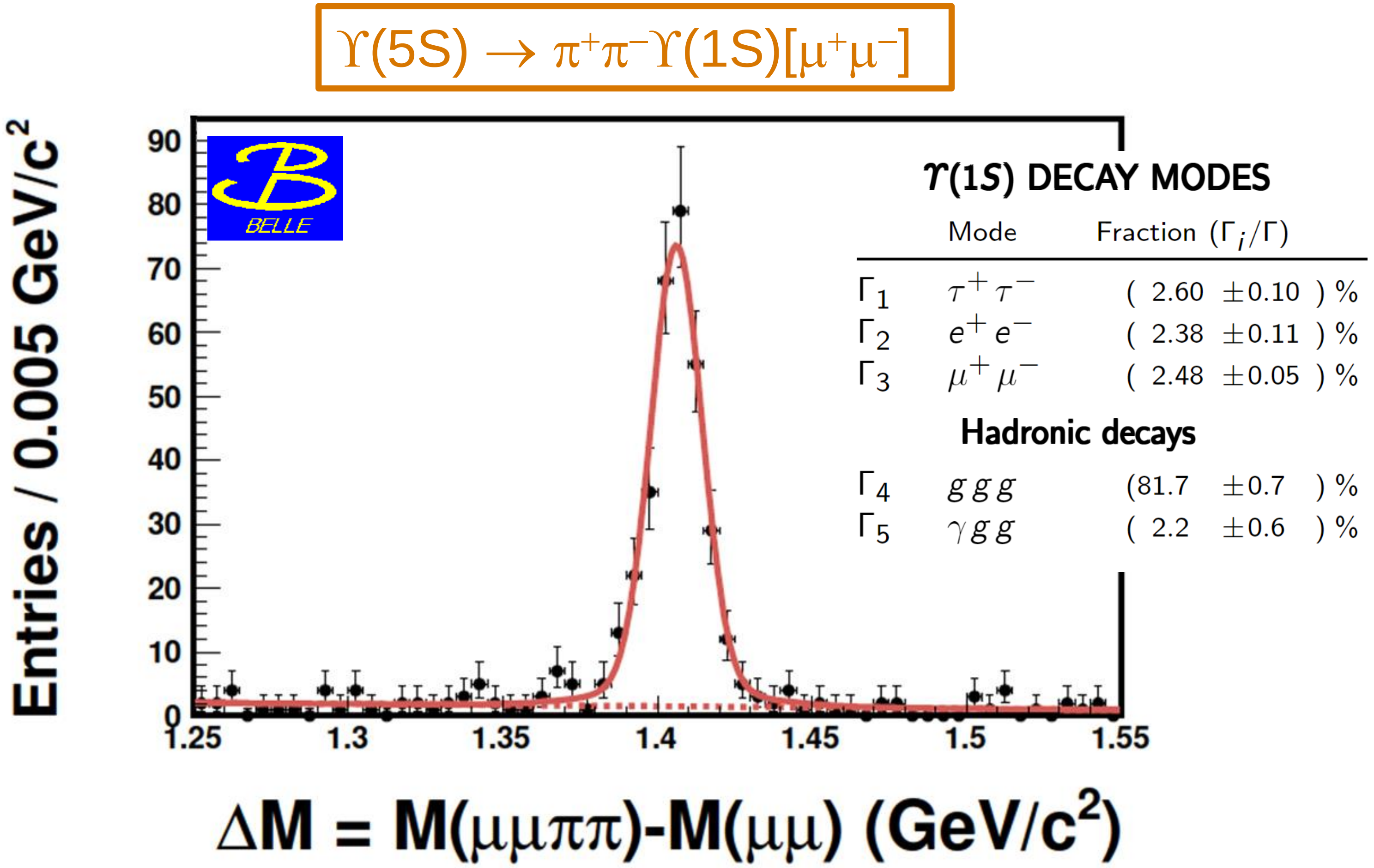
	Mode	Fraction (Γ_i/Γ)
Γ_1	hadrons	seen
Γ_2	$3h^+3h^-$	not seen
Γ_3	$2h^+2h^-$	not seen
Γ_4	$4h^+4h^-$	not seen
Γ_5	$\gamma\gamma$	not seen
Γ_6	$\mu^+\mu^-$	$<9 \times 10^{-3}$
Γ_7	$\tau^+\tau^-$	<8 %

Inclusive vs. Exclusive Analysis

- **Exclusive**: reconstruct a complete final state ("bottom-up")
  - E.g.: $e^+e^- \rightarrow \pi^+\pi^-\Upsilon(pS) \rightarrow e^+e^- / \mu^+\mu^-$
  - Use ΔM to account for $\sigma(\ell\ell)$

- Potential advantages
  - Low background
  - Few combinations, "clean" final state
  - Complete understanding of event

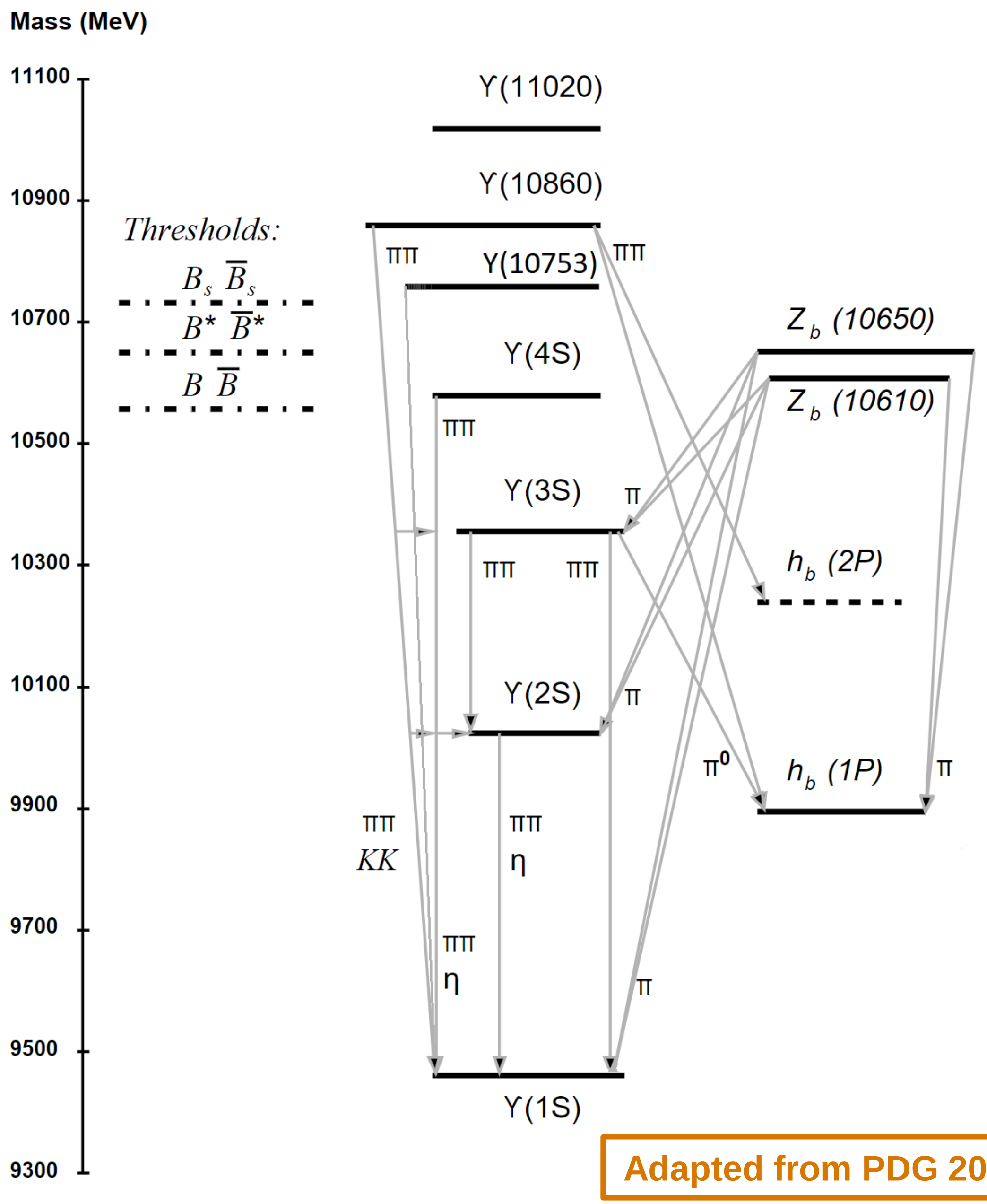
- Potential disadvantages
  - Efficiency loss
  - Branching fractions



Example analysis: Dipion transitions in Early Belle II $\Upsilon(4S)$data

BELLE2-NOTE-PH-2021-005, QWG/Moriond 2021

- Exclusive final state: $\pi^+\pi^-\ell^+\ell^-$ (e^+e^-, $\mu^+\mu^-$)
- Initial State Radiation production:
  - $\gamma_{ISR}\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S)$
  - $\gamma_{ISR}\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(1S,2S)$
- Direct transitions: $\Upsilon(4S) \rightarrow \pi^+\pi^-\Upsilon(1S,2S)$
- Analysis features
  - High p_T leptons, soft pions
  - Different quarkonium production mechanisms
  - Preview of $\Upsilon(10753) \rightarrow \pi^+\pi^-\Upsilon(1S,2S,3S)$

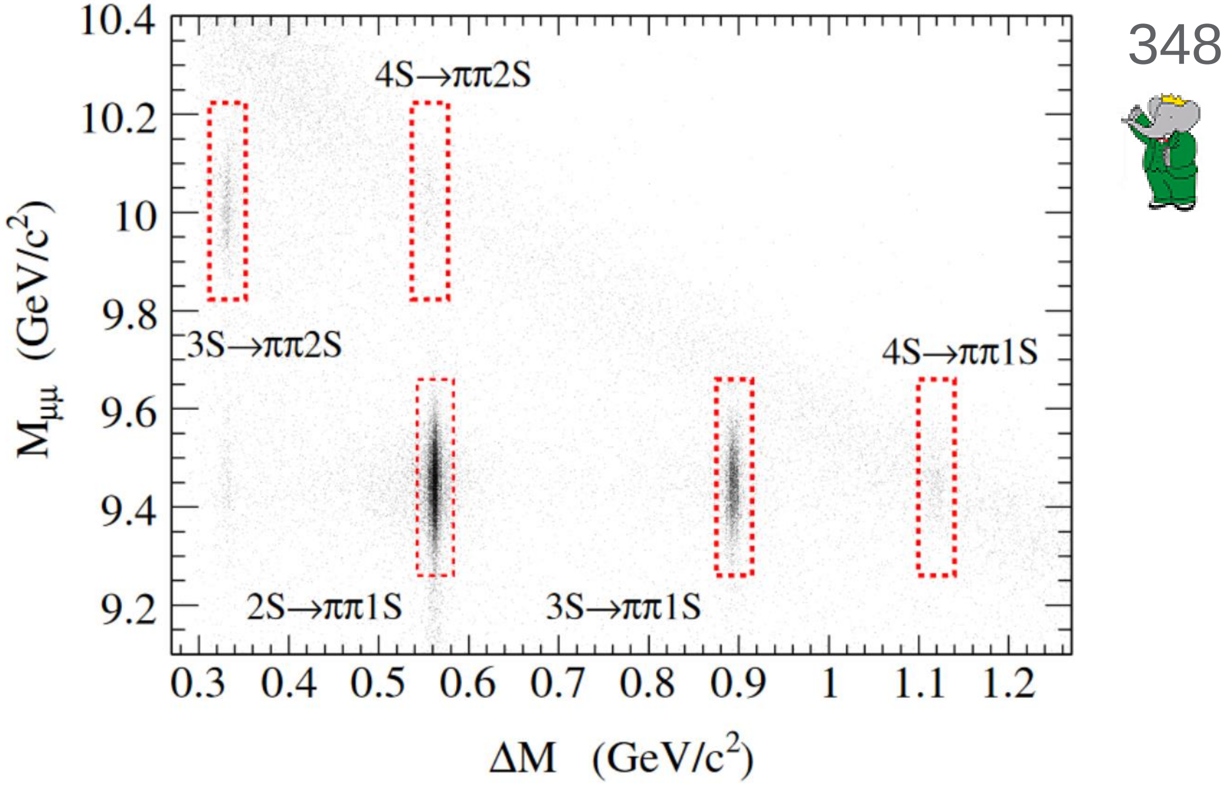


Adapted from PDG 2019

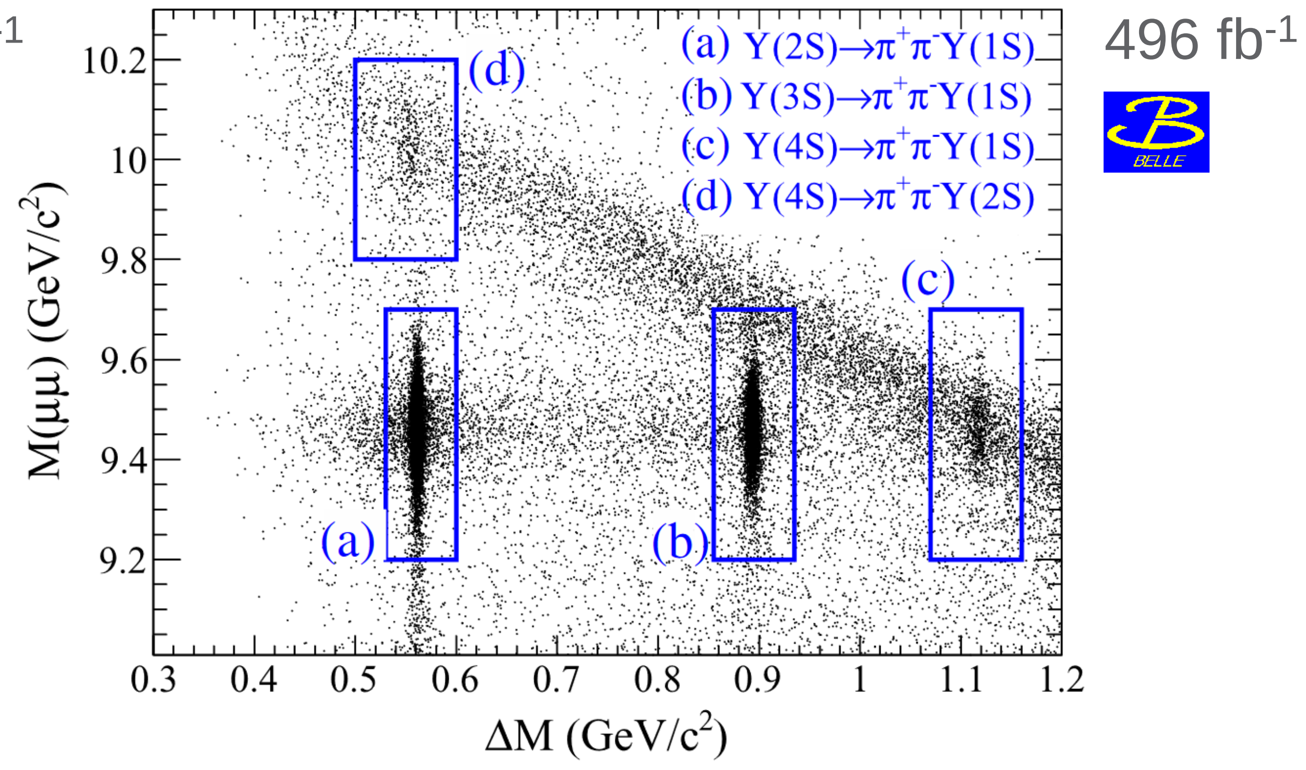
$\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S,2S)$ transitions

- Previously measured by BaBar and Belle

$\mathcal{BF}(\times 10^{-5})$	BaBar	Belle	Average
$\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S)$	8.2 ± 0.6	8.0 ± 0.7	8.1 ± 0.5
$\Upsilon(4S) \to \pi^+\pi^-\Upsilon(2S)$	7.9 ± 1.1	8.6 ± 1.3	8.2 ± 0.8



PRD 78, 112002 (2008)



PRD 96, 052005 (2017)

Basic Analysis Information

- Reconstruct $\pi^+\pi^-\ell^+\ell^-$ (e^+e^-, $\mu^+\mu^-$)

The lepton selection criteria are defined as:

- $|dr| < 1$ cm
- $|dz| < 3$ cm
- $-0.866 < \cos\theta < 0.9535$
- $p_T > 100$ MeV$/c$

Basic track quality

- at least 1 lepton $eID > 0.9$
- at least 1 lepton with $\mu ID > 0.9$

Only need 1 good lepton

- $4 < p^*(\ell\ell) < 5.5$ GeV$/c$
- $8.5 < M(\ell\ell) < 11$ GeV$/c^2$

Reduce "junk" and restrict to useful combinations

$$nTracks == 4 || nTracks == 5$$

Remove backgrounds (but not everything)

$$\cos\theta_{\pi\pi} < 0.95$$
$$m_{\pi\pi} > 50 \text{ MeV}/c^2$$

Remove photon conversions ($\gamma \to e^+e^-$)

The pion selection criteria are

- π: $|dr| < 1$ cm
- π: $|dz| < 3$ cm

Looser criteria to include soft pions

- π: $eID < 0.9$
- π: $\mu ID < 0.9$

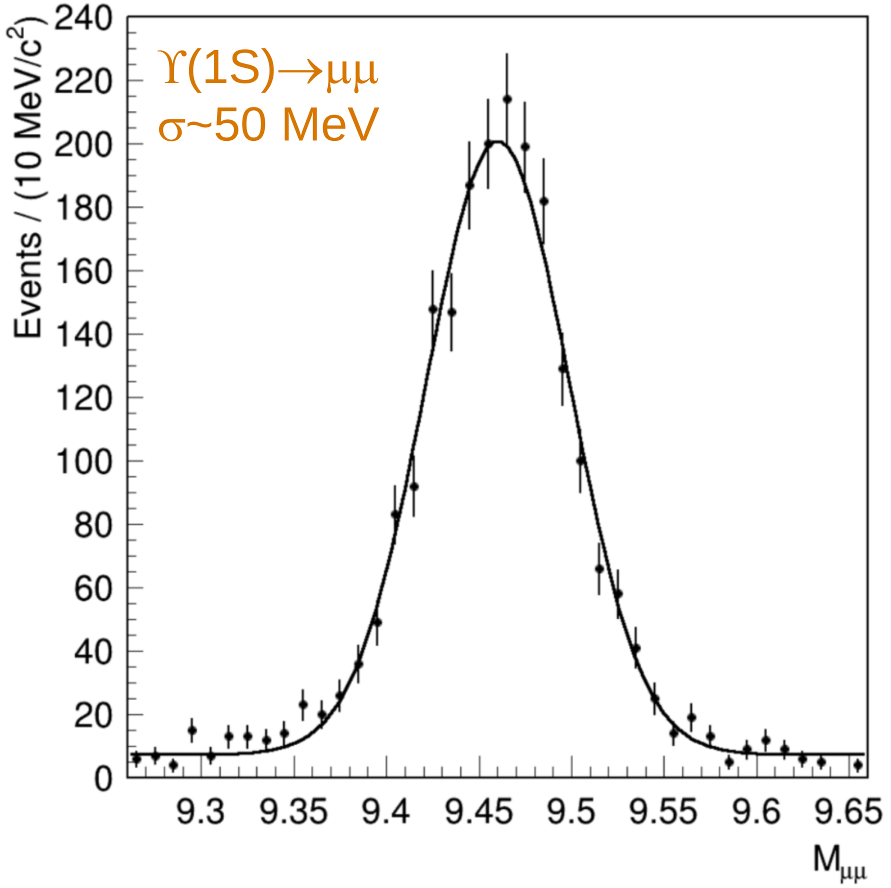
pions = not leptons

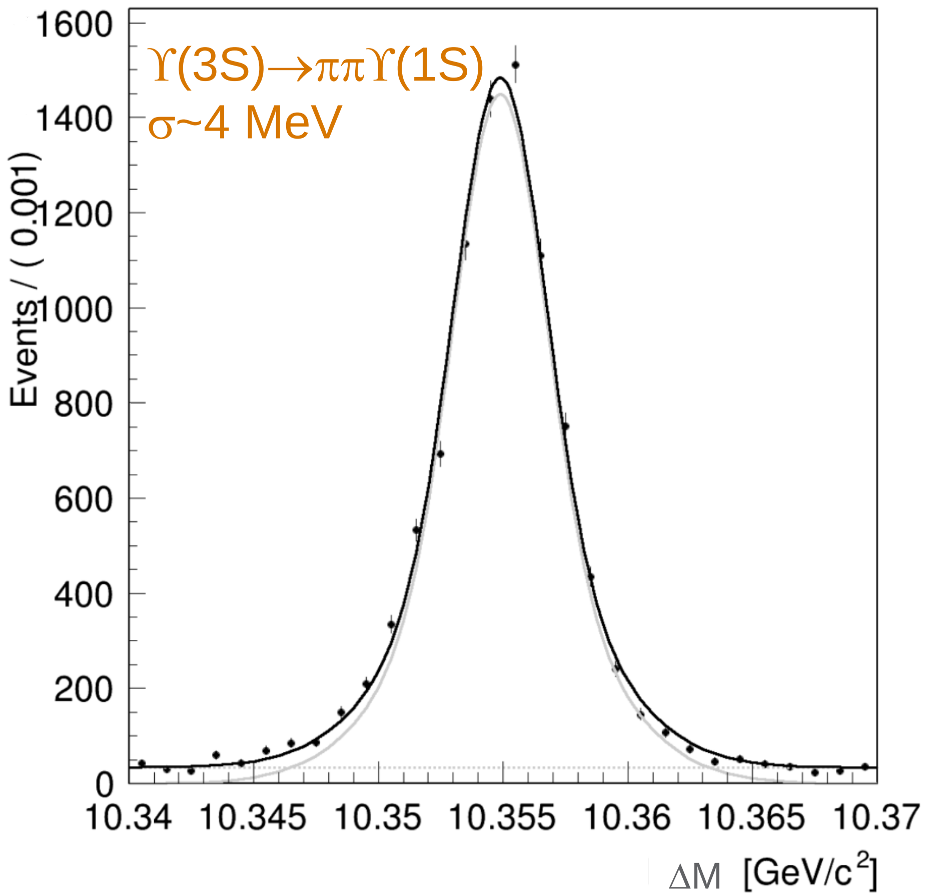
- $M(\pi\pi) < 2$ GeV$/c^2$

Restrict to useful combinations

M(ℓℓ) versus ΔM

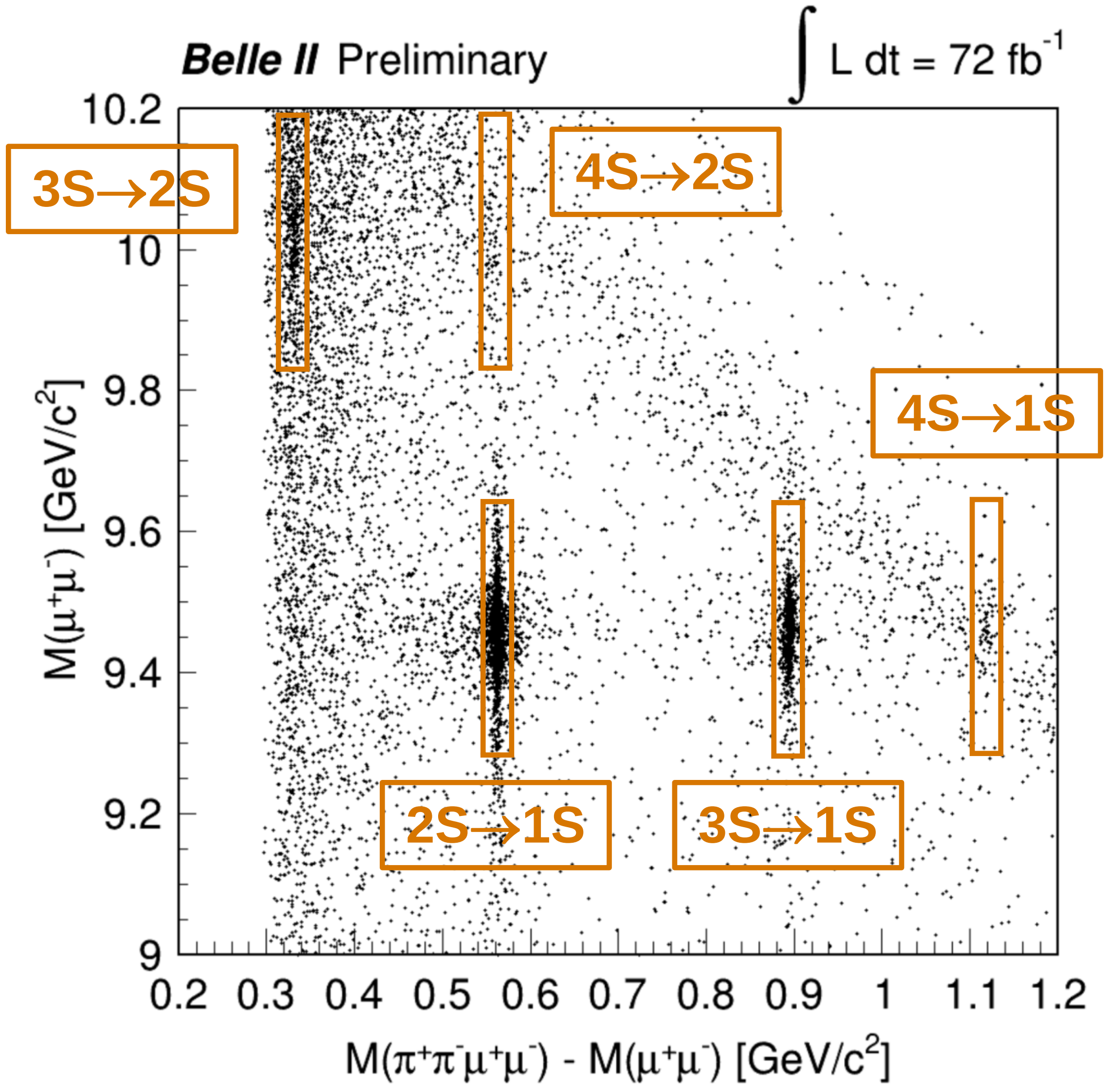
- Resolution improvement in $\Delta M = M(\pi\pi\ell\ell) - M(\ell\ell) + M_{PDG}(\Upsilon(1S))$ over $M(\ell\ell)$

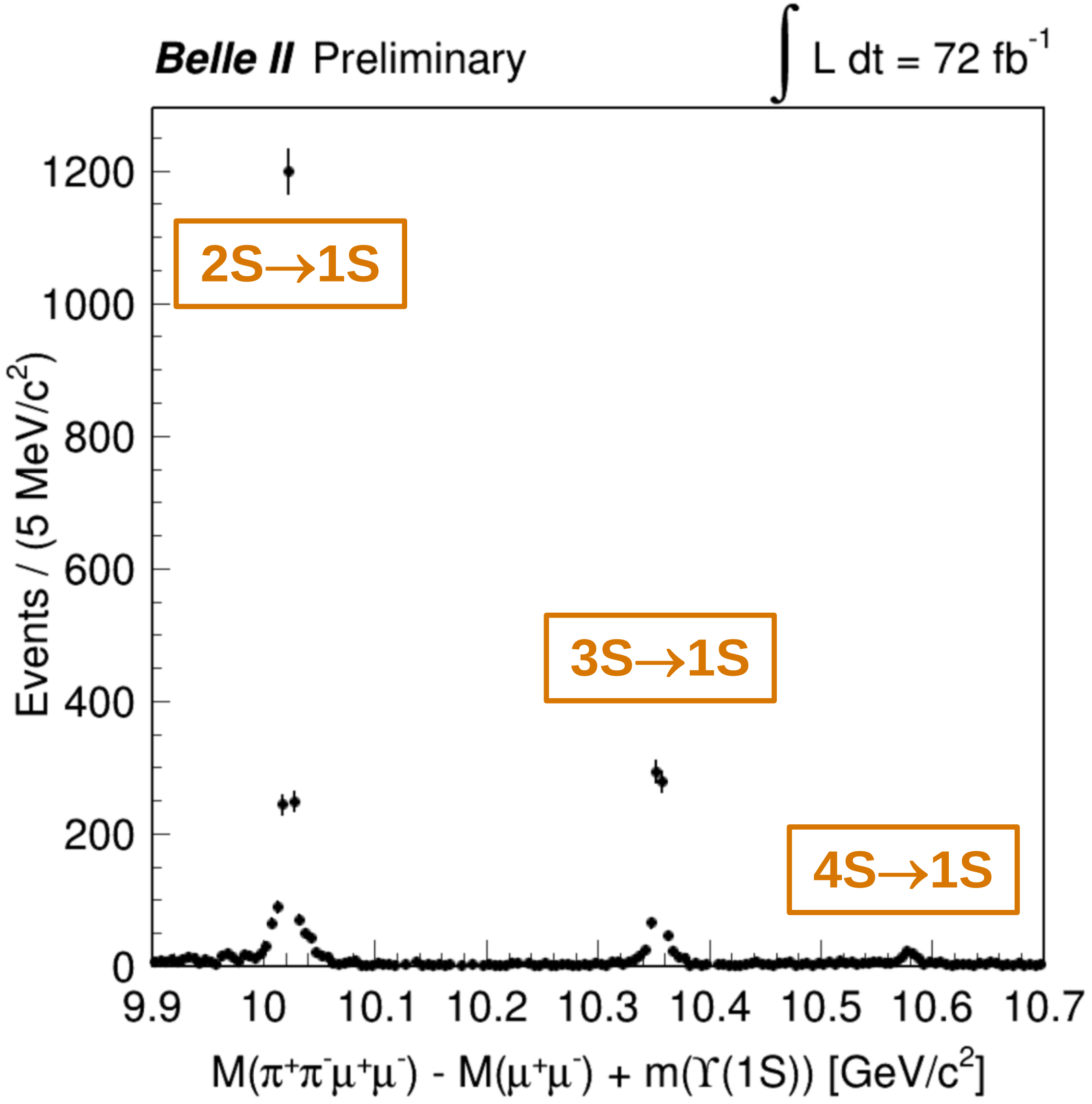




- Use $M(\mu\mu)$ to understand muon momentum calibration
- Fit ΔM with double-Gaussian to measure event yield / branching fractions

Example Results





Steps towards $\pi\pi\Upsilon$ Energy Scan Analysis

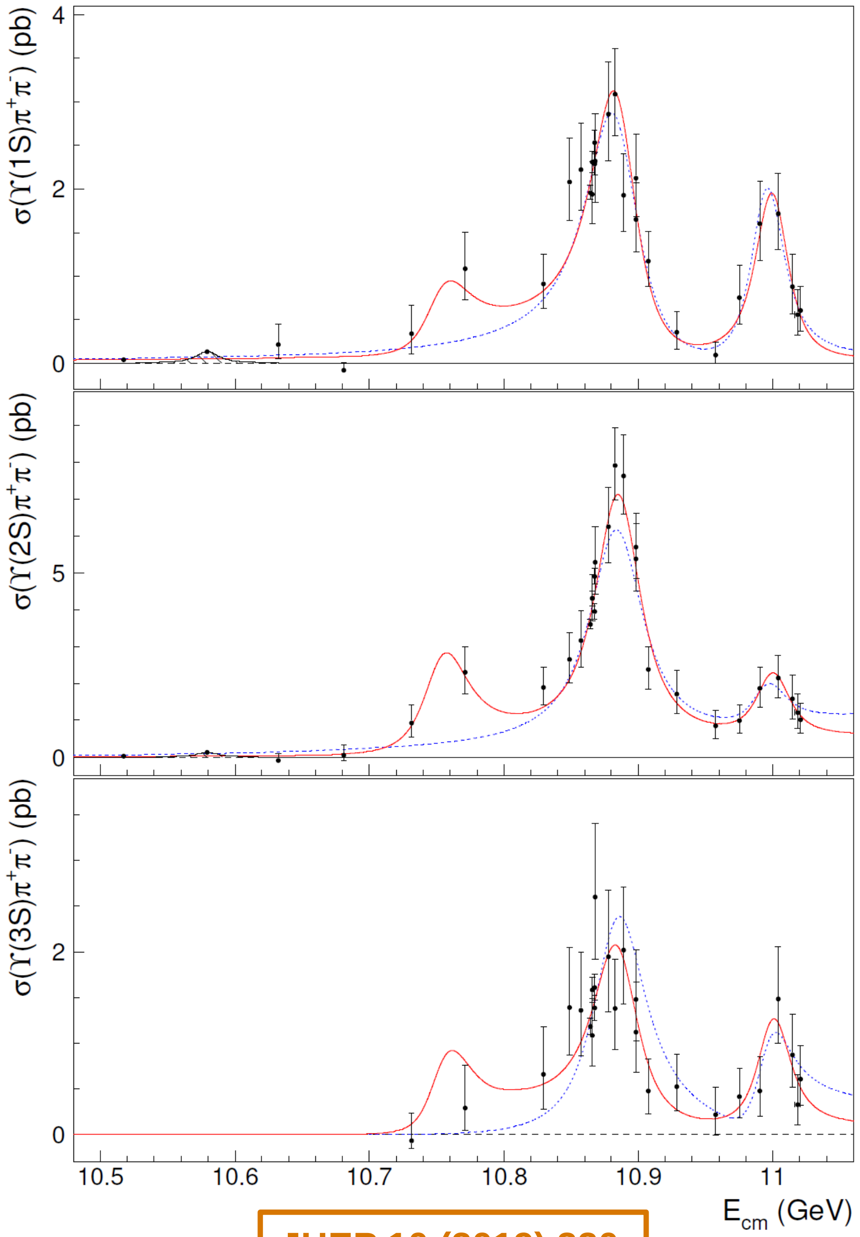
- At each E_{CM}: fit $\Delta M \rightarrow N_{evts} \rightarrow \sigma_{\pi\pi\Upsilon}$
- Include in fit with existing Belle data points
- Simultaneous fit with multiple B-W components

$$F_{\mathrm{BW}} = \frac{\sqrt{12\pi\,\Gamma\,\Gamma_{ee}^{0} \times \mathcal{B}_f}}{s - M^2 + iM\Gamma}\sqrt{\frac{\Gamma_f(s)}{\Gamma_f(M^2)}}$$

- With sufficient statistics, examine $M(\pi\pi)$

and $M(\pi\Upsilon)$ distributions for intermediate structure
  - Light mesons? Z_b? PHSP?

- To be continued…



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Expected Analyses and Publications

Mode	Belle Status	Belle II Outcome
Golden Modes		
$e^+e^- \to \pi^+\pi^-\Upsilon(pS)(\to \ell^+\ell^-)$	Published	B+BII combined
$B\overline{B}$ decomposition	Published	B+BII combined
$\pi^+\pi^-$ Dalitz	Needs data	First result
$Y_b \to \omega\eta_b(1S)$	Ongoing	B+BII or BII update
$Y_b \to \omega\chi_{bJ}(1P)$	In pub./needs data/points	B+BII combined
Silver Modes		
$Y_b \to \pi^+\pi^- X$ (inclusive)	Needs data	First result
$Y_b \to \eta X$ (inclusive)	Needs data	First result
$Y_b \to \eta\Upsilon(1S, 2S)(\to \ell^+\ell^-)$	Needs data	First search
$Y_b \to \eta'\Upsilon(1S)(\to \ell^+\ell^-)$	Needs data	First search
$Y_b \to \Upsilon(1S)$ (inclusive)	Needs data	First result
Bronze Modes		
$Y_b \to \gamma X_b$	Needs data	First search
$Y_b \to \pi^0\pi^0\Upsilon(pS)(\to \ell^+\ell^-)$	Needs data	First search
$Y_b \to KK(\phi)\Upsilon(pS)(\to \ell^+\ell^-)$	Needs data	First search
$Y_b \to \pi^0\pi^0 X$ (inclusive)	Needs data	First search
$Y_b \to \pi^0 X$ (incl. or excl.)	Needs data	First search
...		

Important and/or expected results

Interesting and/or established analyses

Difficult and/or unpredicted analyses

Next Steps

- Data processing/calibration
  - Some early 10.657 GeV data processed manually at KEKCC with online conditions
  - Central production and calibration expect completion December/January
- Associated performance studies
  - Beam energy measurements
  - High-p_T lepton calibration
  - Run 2021c at-large performance issues
- Conference targets
  - Spring (Lepton-Photon, Moriond): general advertisement of energy scan
  - Summer (ICHEP): preliminary results on main analyses
  - Fall (QWG): main target for several results
- Long-term motivation for $\Upsilon(6S)$ and other non-$\Upsilon(4S)$ runs

Summary

- QCD provides for a wide variety of conventional and exotic quark matter
- Experimental discoveries have propelled us into a new era of spectroscopy
- Belle II is poised to capitalize in this area to continue the successes of Belle
- Energy scan recently performed to understand features near 10.75 GeV
- Plenty of work to be done, please join the effort!

Thank you