



# Exotic and Conventional Quarkonium Physics Prospects at Belle II

**Bryan Fulsom**

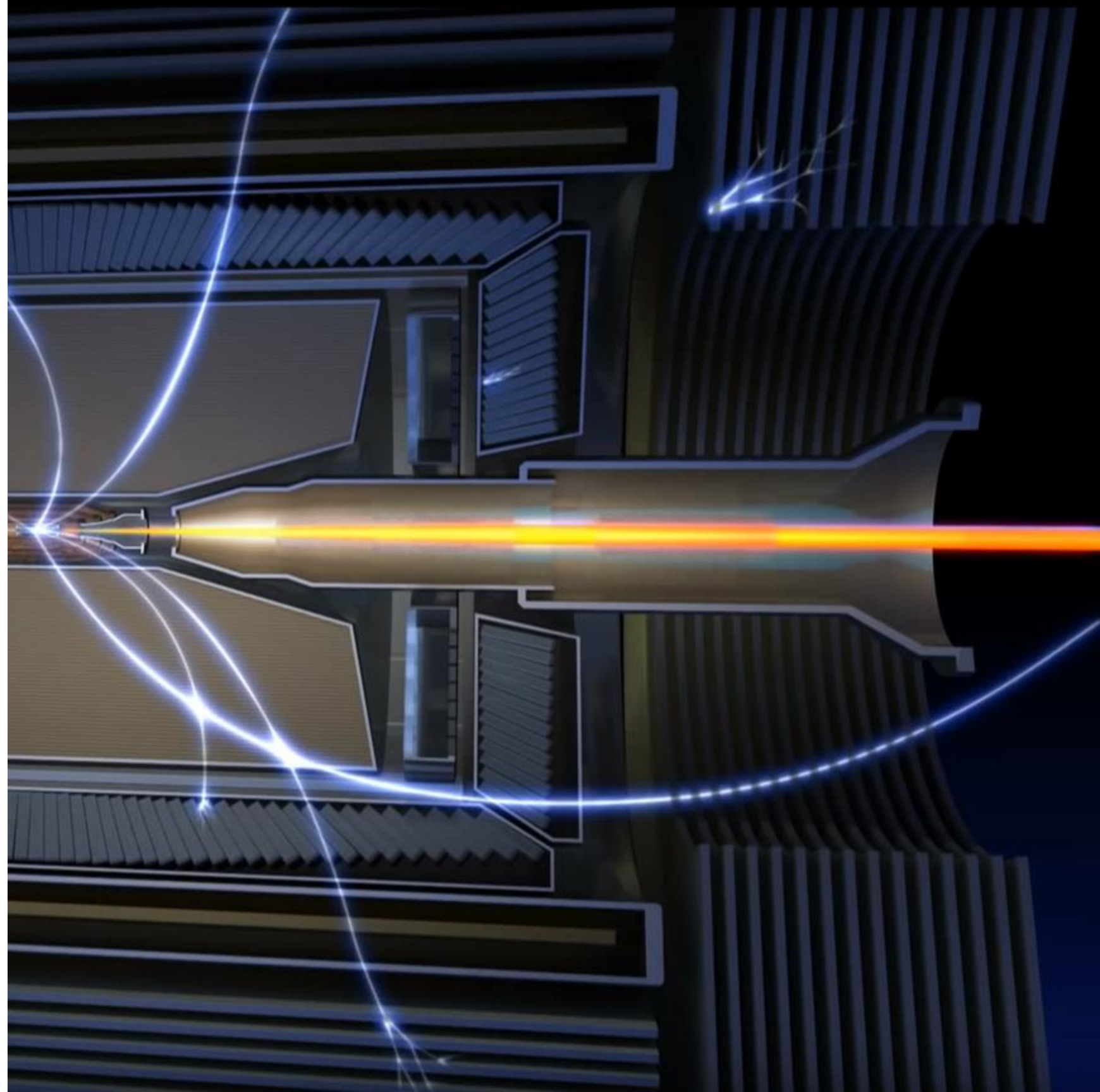
**Pacific Northwest National Laboratory**

29<sup>th</sup> International Symposium on Lepton Photon

Interactions at High Energies

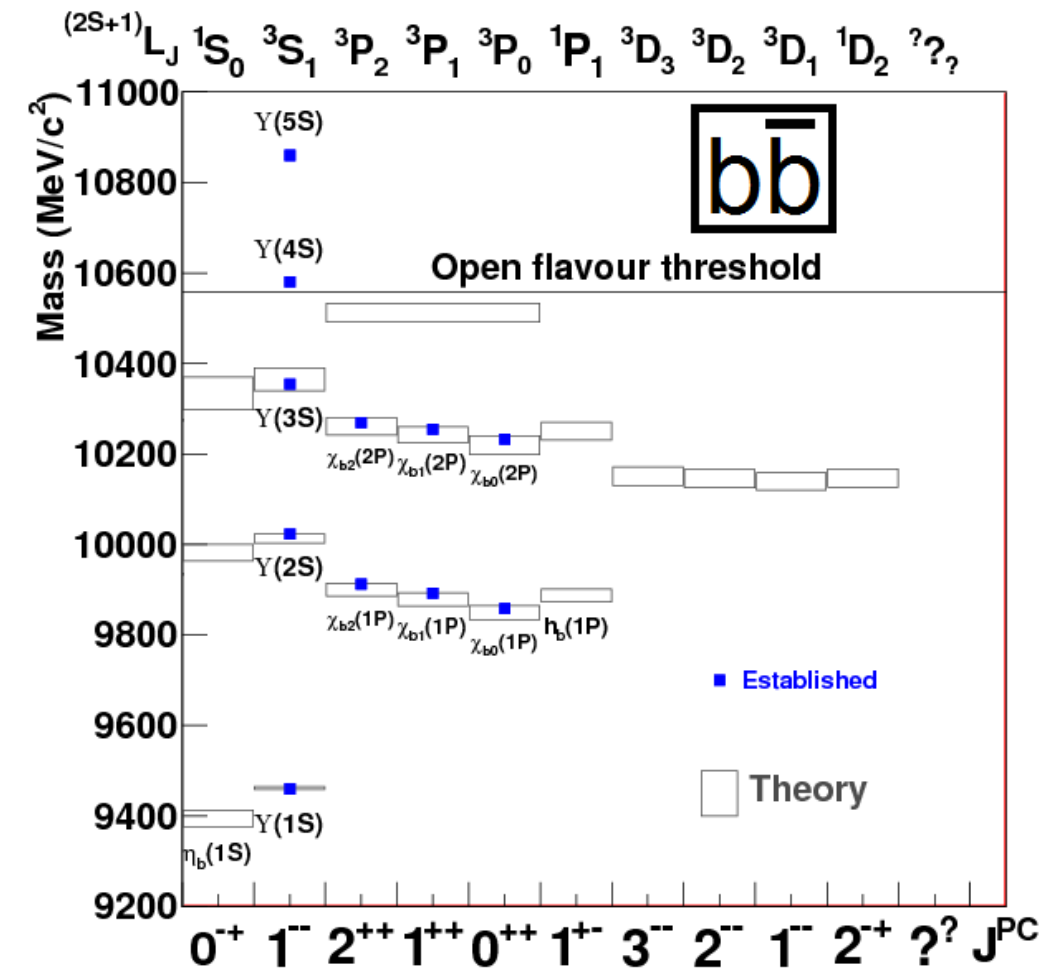
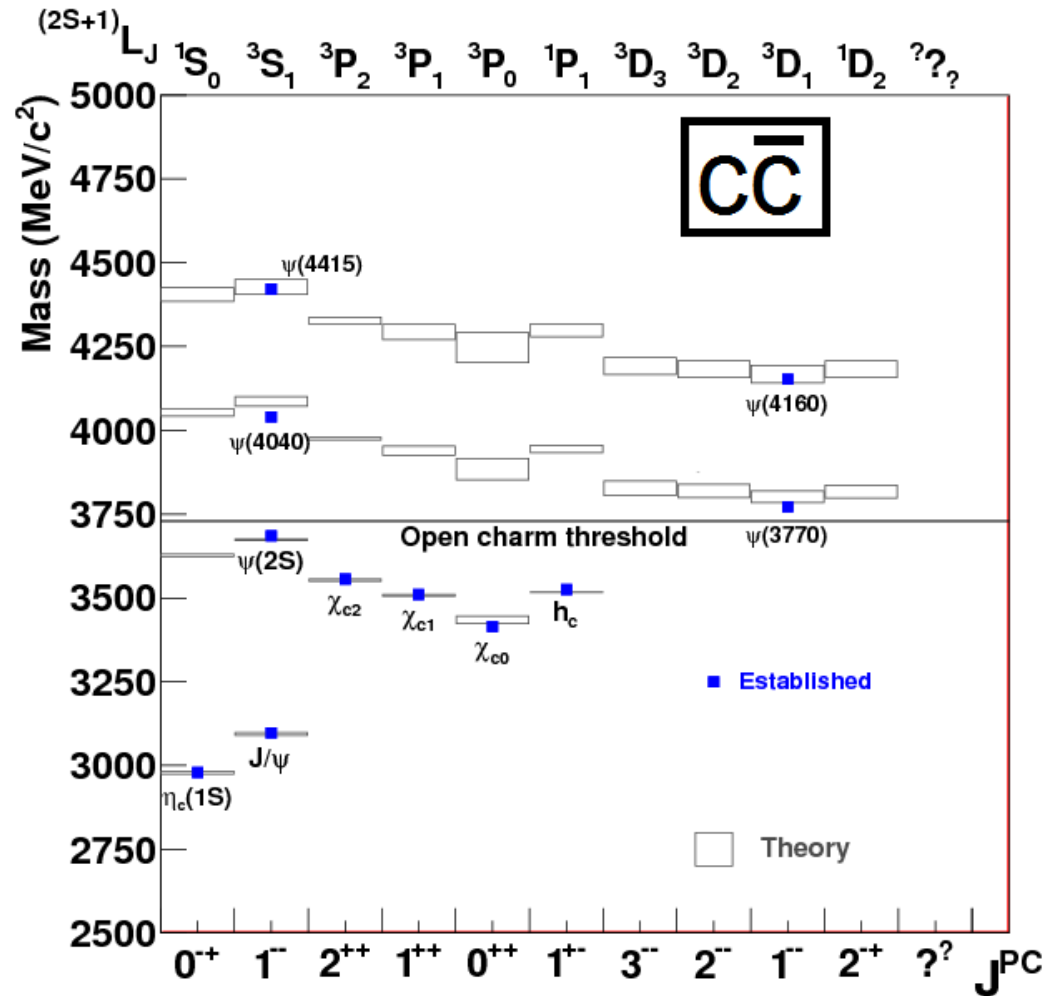


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# Quarkonium and exotic states

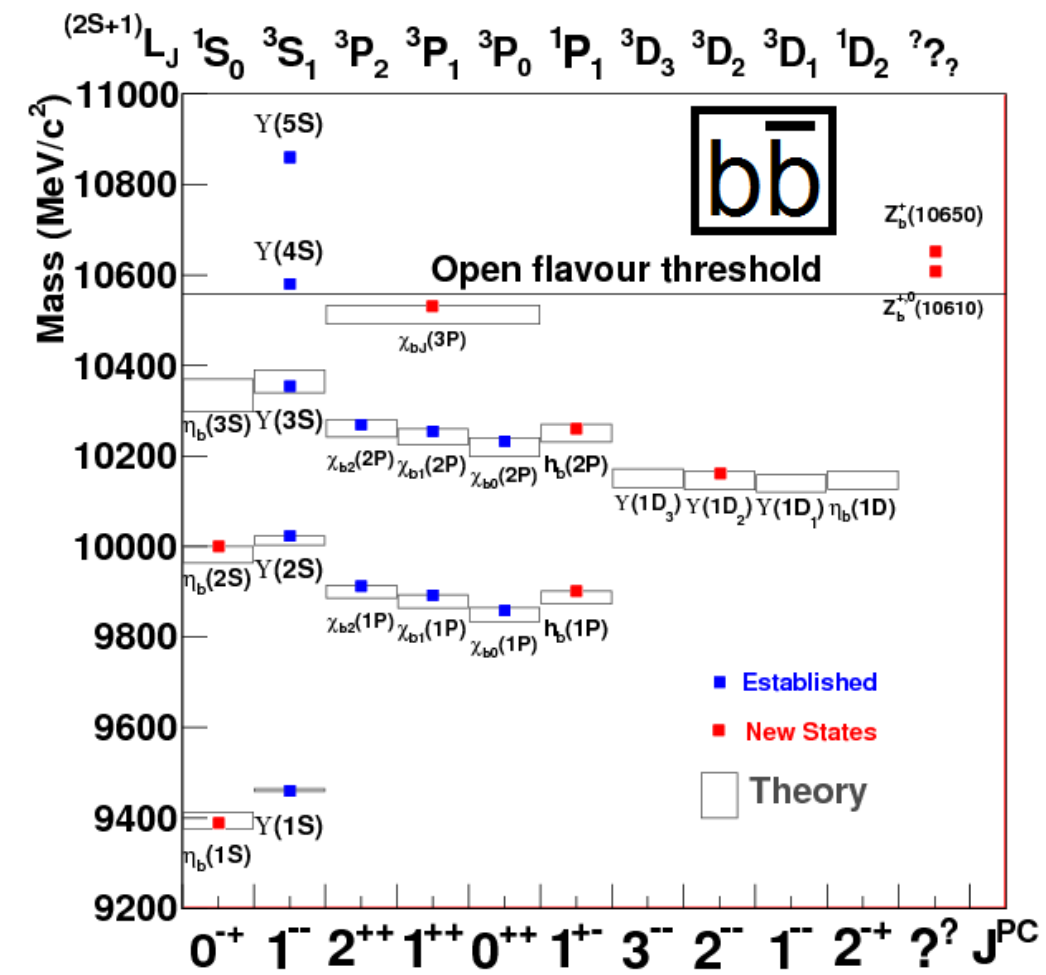
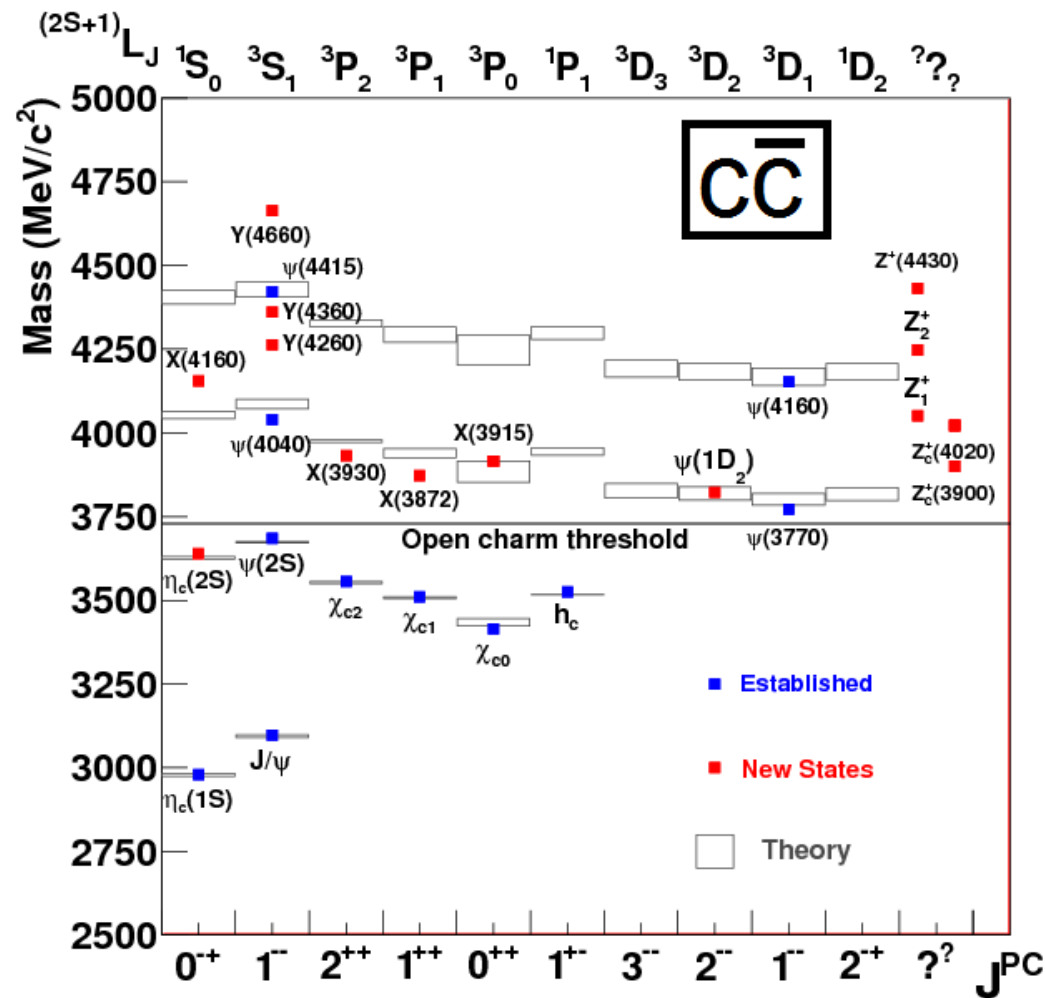
- Well-known  $q\bar{q}$  system described by potential models, NRQCD, lattice, ...



- Before the era of the B-Factories...

# Quarkonium and exotic states

- Well-known  $q\bar{q}$  system described by potential models, NRQCD, lattice, ...



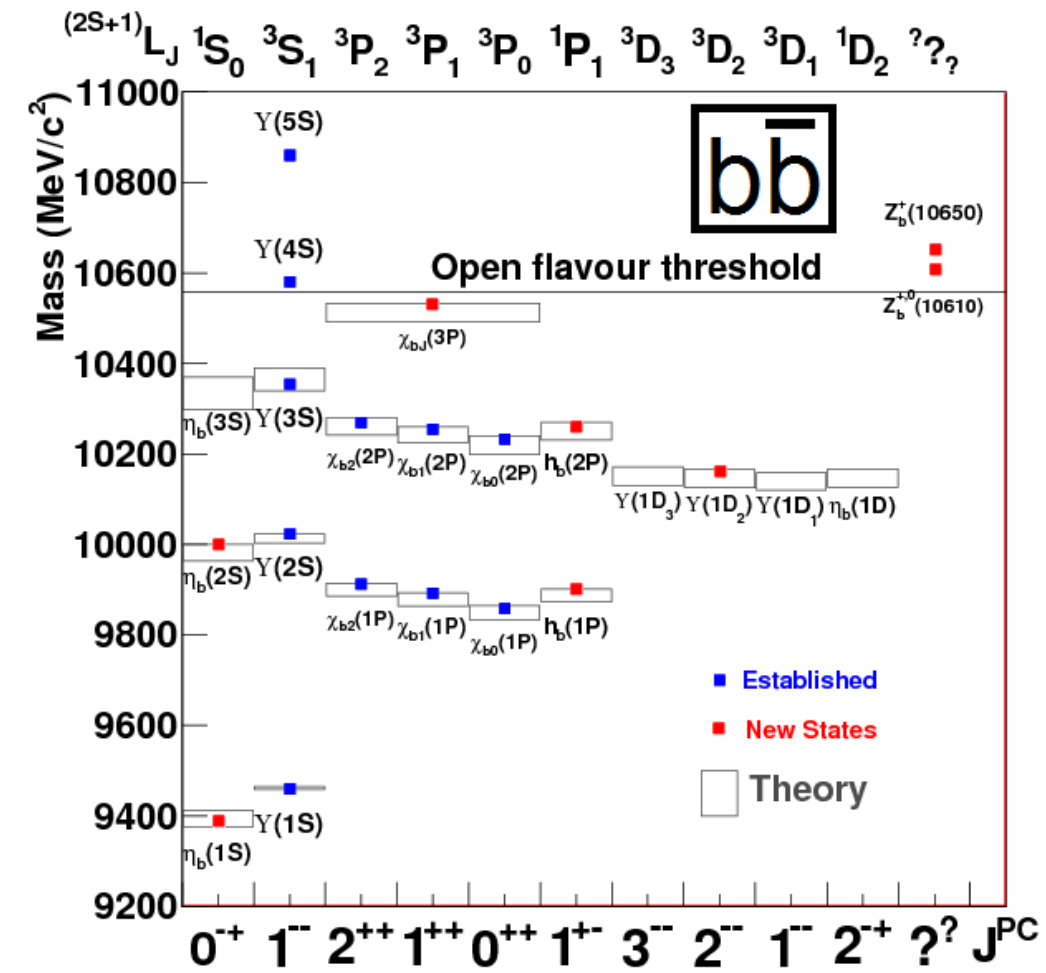
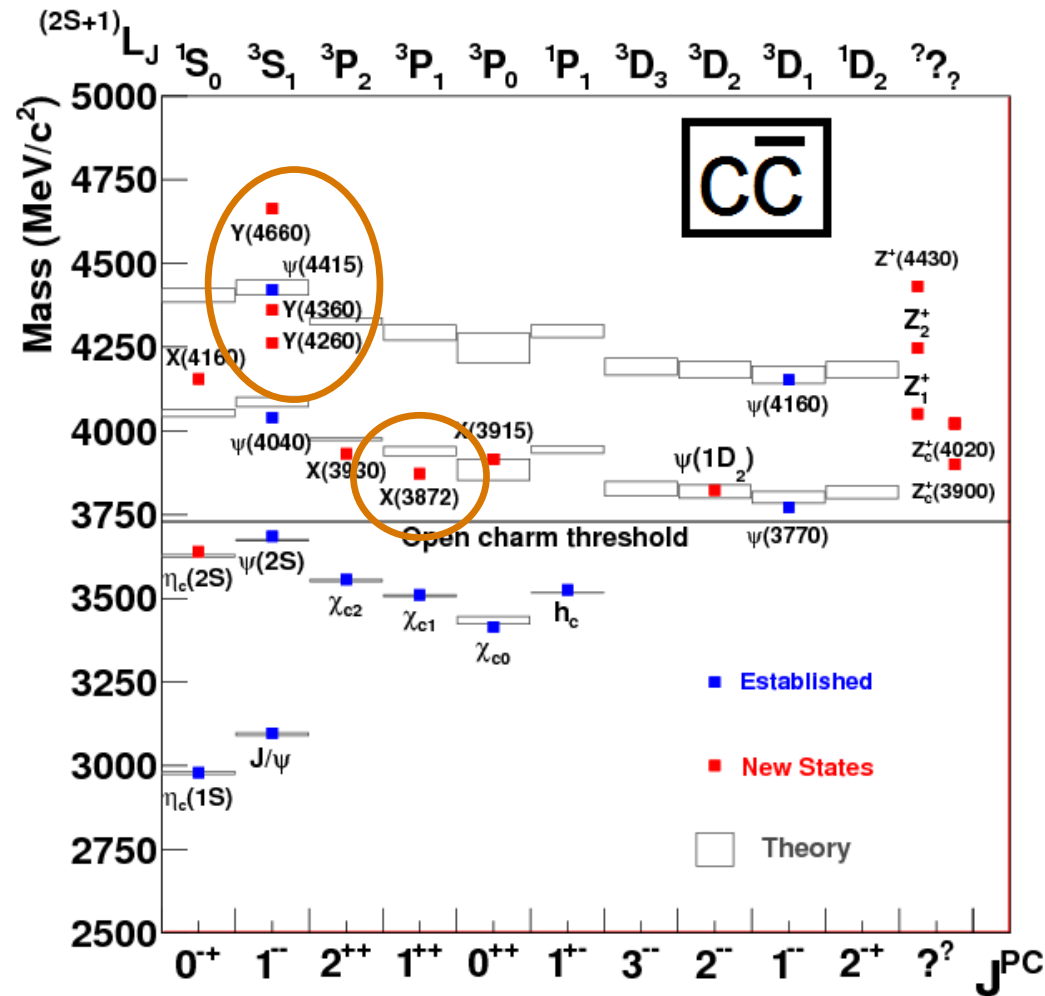
...and after





# Quarkonium and exotic states

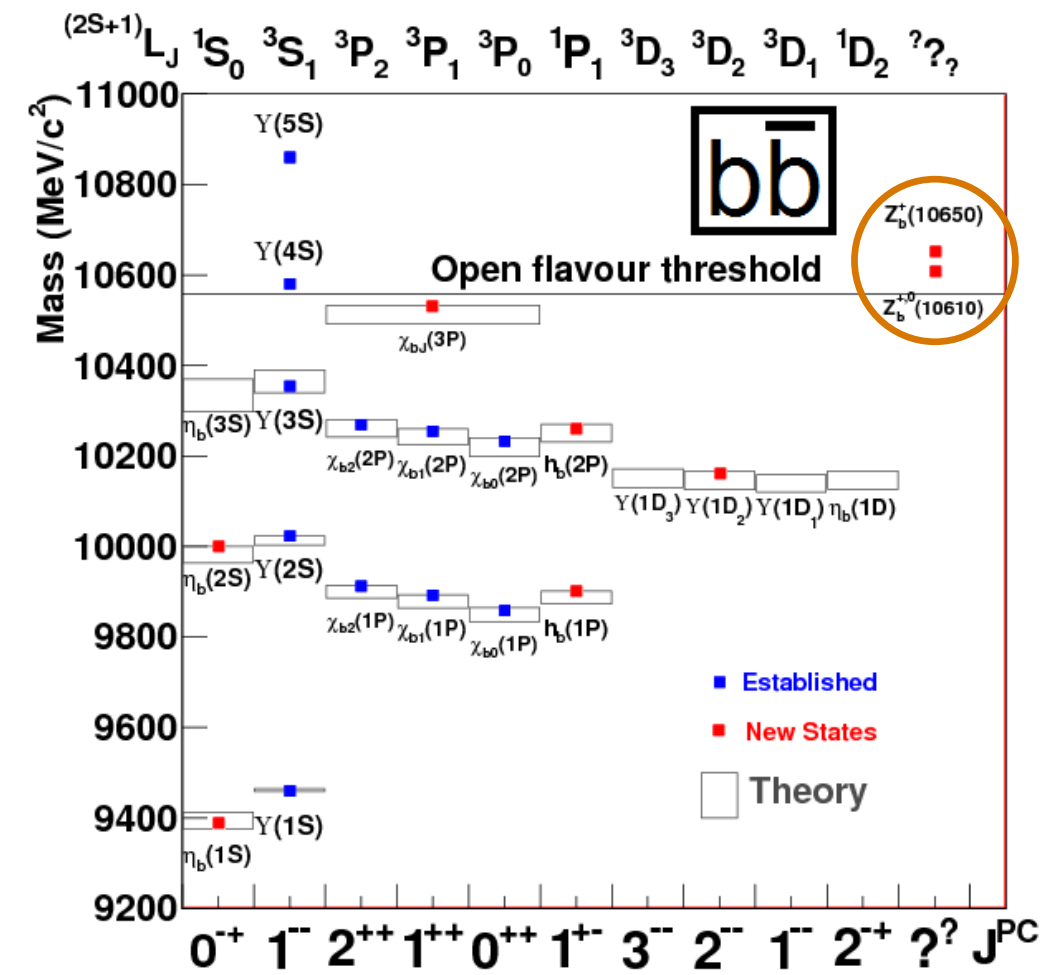
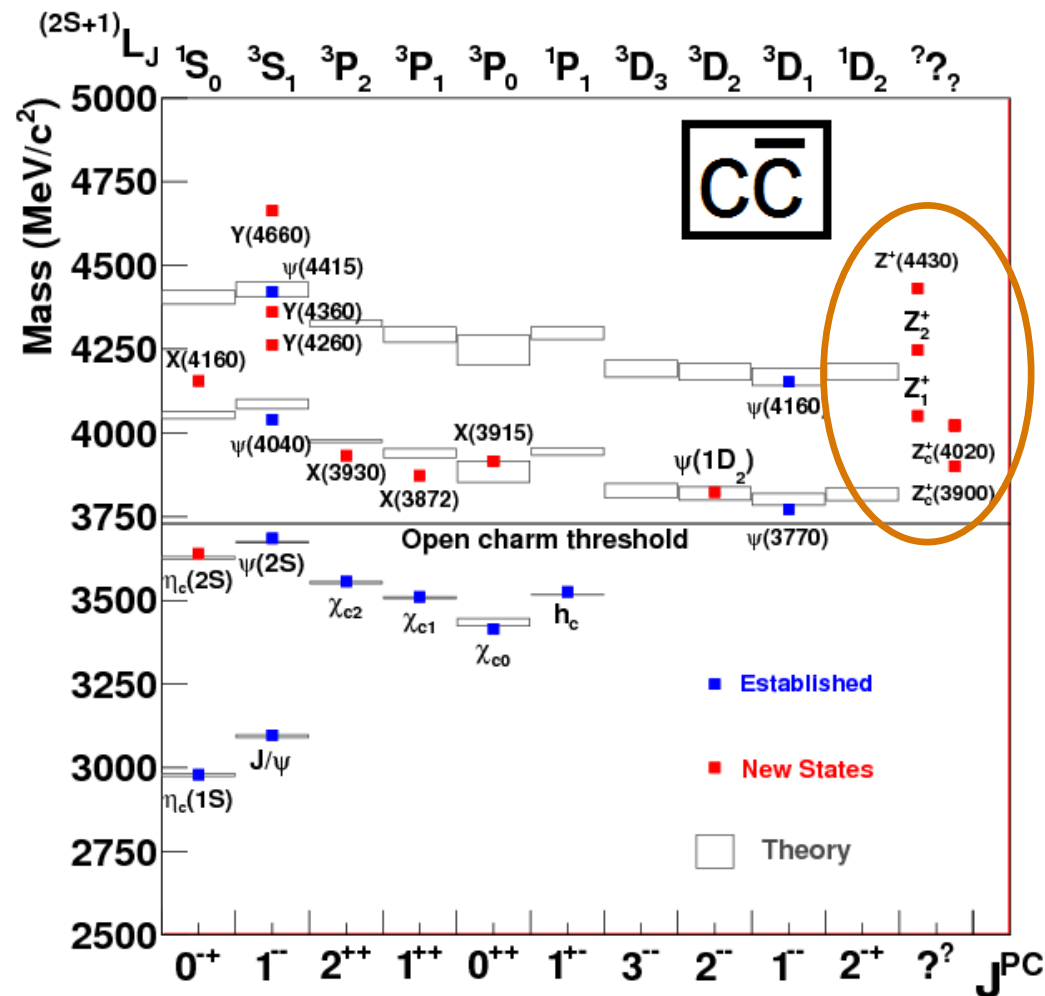
- Well-known  $q\bar{q}$  system described by potential models, NRQCD, lattice, ...



- Many discoveries are difficult to explain by quarkonium model

# Quarkonium and exotic states

- Well-known  $q\bar{q}$  system described by potential models, NRQCD, lattice, ...



- Several states have non-zero charge, cannot be a  $c\bar{c}/b\bar{b}$  pair

# The New Alphabet: X, Y, Z...

- X(3872)

PRL 91, 262001 (2003)

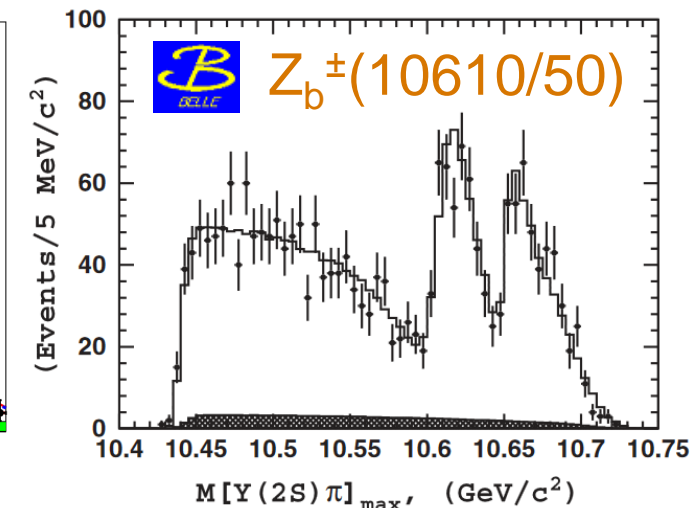
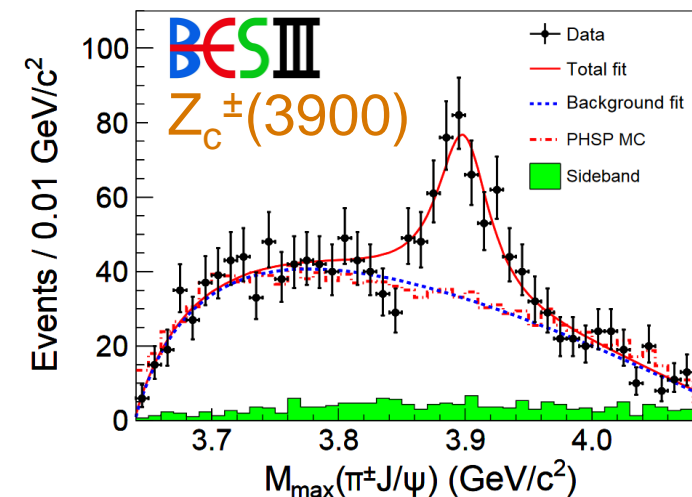
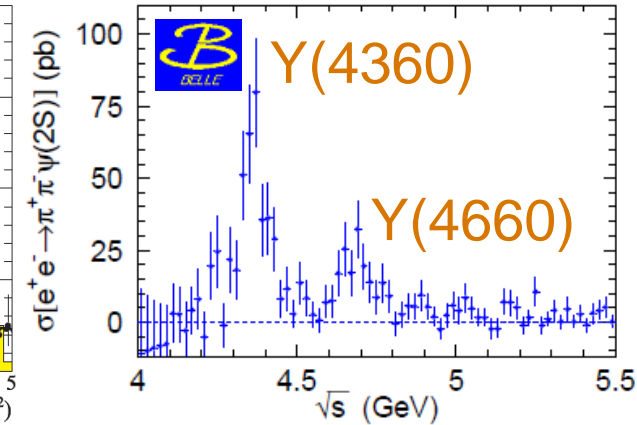
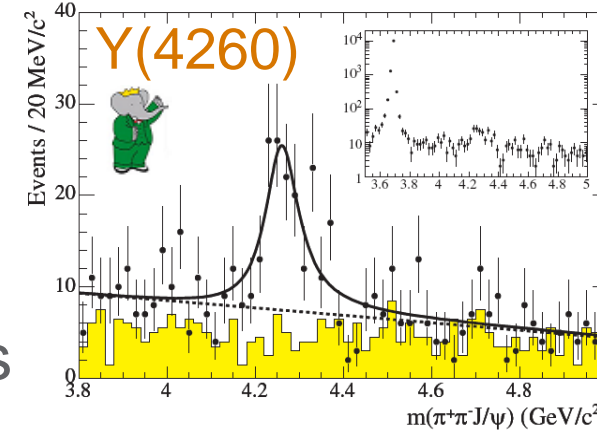
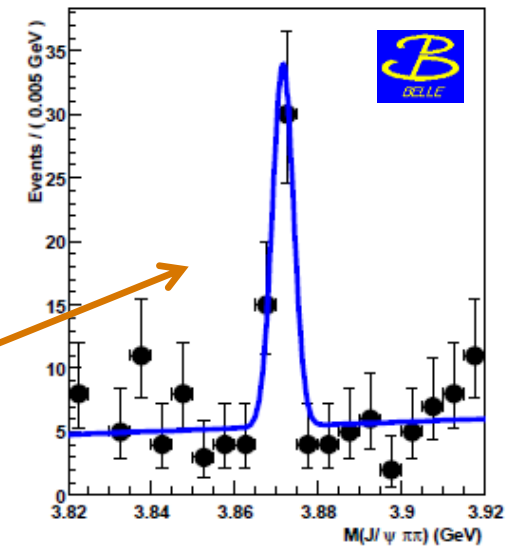
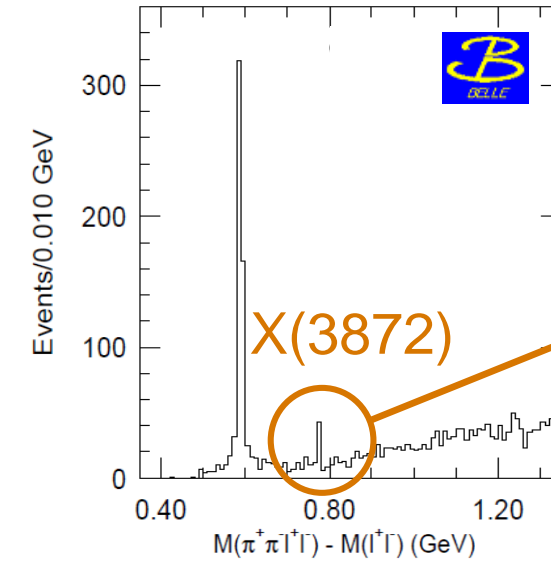
- Mass consistent with  $D^0\bar{D}^{0*}$  molecular state
- Found in B decay, large production also in pp
- No partners found

- Y(4260, 4320, 4660...)

- Produced in initial state radiation and  $E_{CM}$  scans
- $J^{PC}=1^{--}$  overpopulated for charmonium

- $Z_c$  and  $Z_b$

- Seen in decays of  $q\bar{q}$  and other XY states
- Non-zero charge: cannot be  $q\bar{q}$
- Similarities between c and b systems





# A new form of matter?

- Meson Molecules

- Weakly bound state of two mesons

e.g.: Tornqvist, PLB 590, 209 (2004)

- “Tetraquarks”

- Color-singlet diquarks bound directly by strong force

Polosa et al., PRD 89, 114010 (2014)

- Other exotica

- Hybrids: quarkonium with bound excited gluon

Barnes et al., PRD 52, 5242 (1995)

- Hadoquarkonium: qq-light hadron interaction

Dubinskiy et al., PLB 671, 82 (2009)

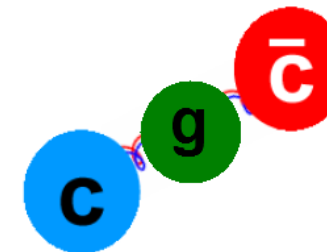
- Nothing special

- Kinematic effects / standard quarkonium

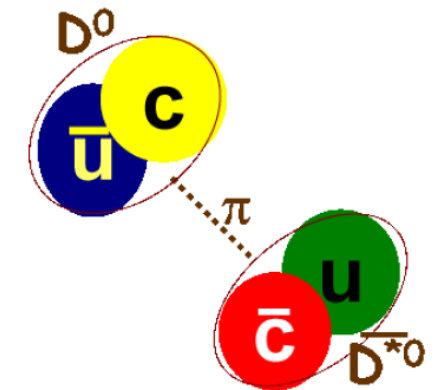
e.g.: Swanson, PRD 91, 034009 (2015)



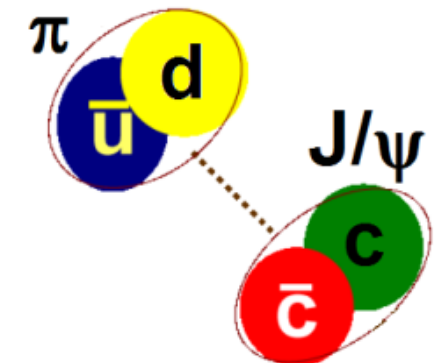
diquark-diantiquark



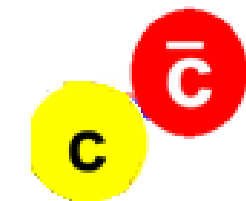
q $\bar{q}$ -gluon “hybrid”



$D^0 - \bar{D}^{*0}$  “molecule”



hadroquarkonium



conventional quarkonium



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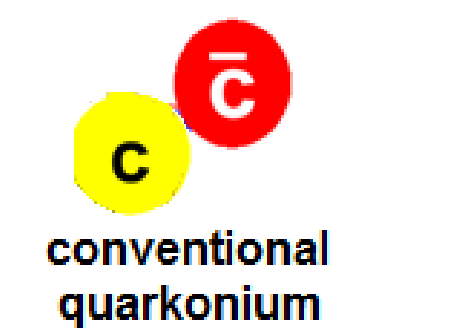
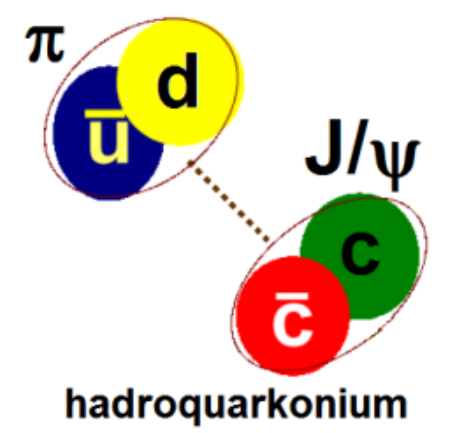
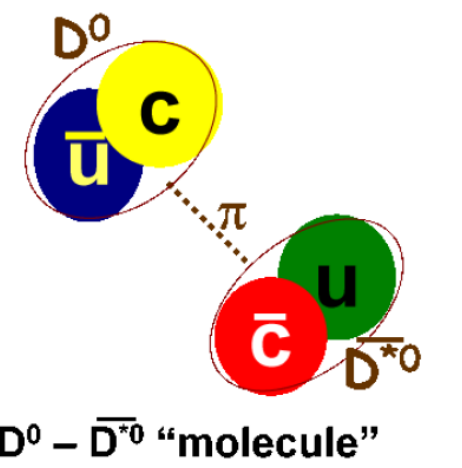
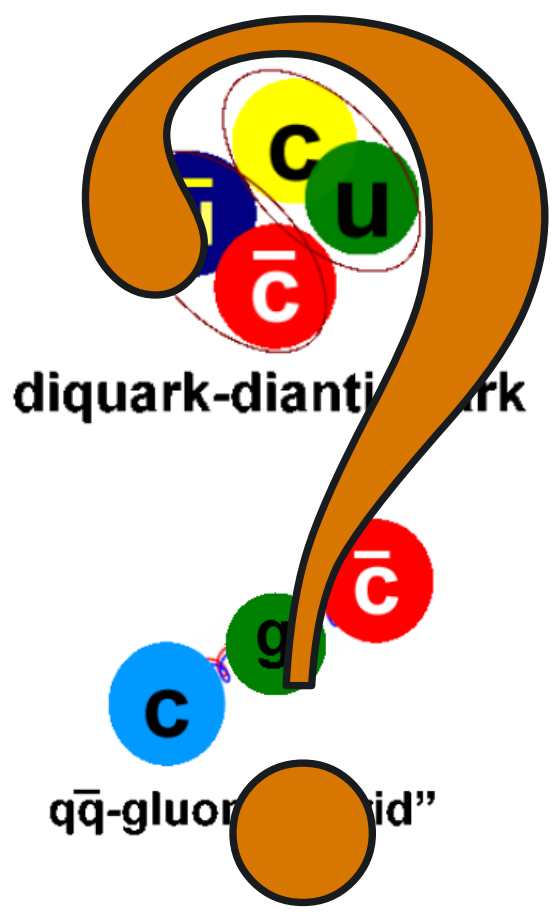
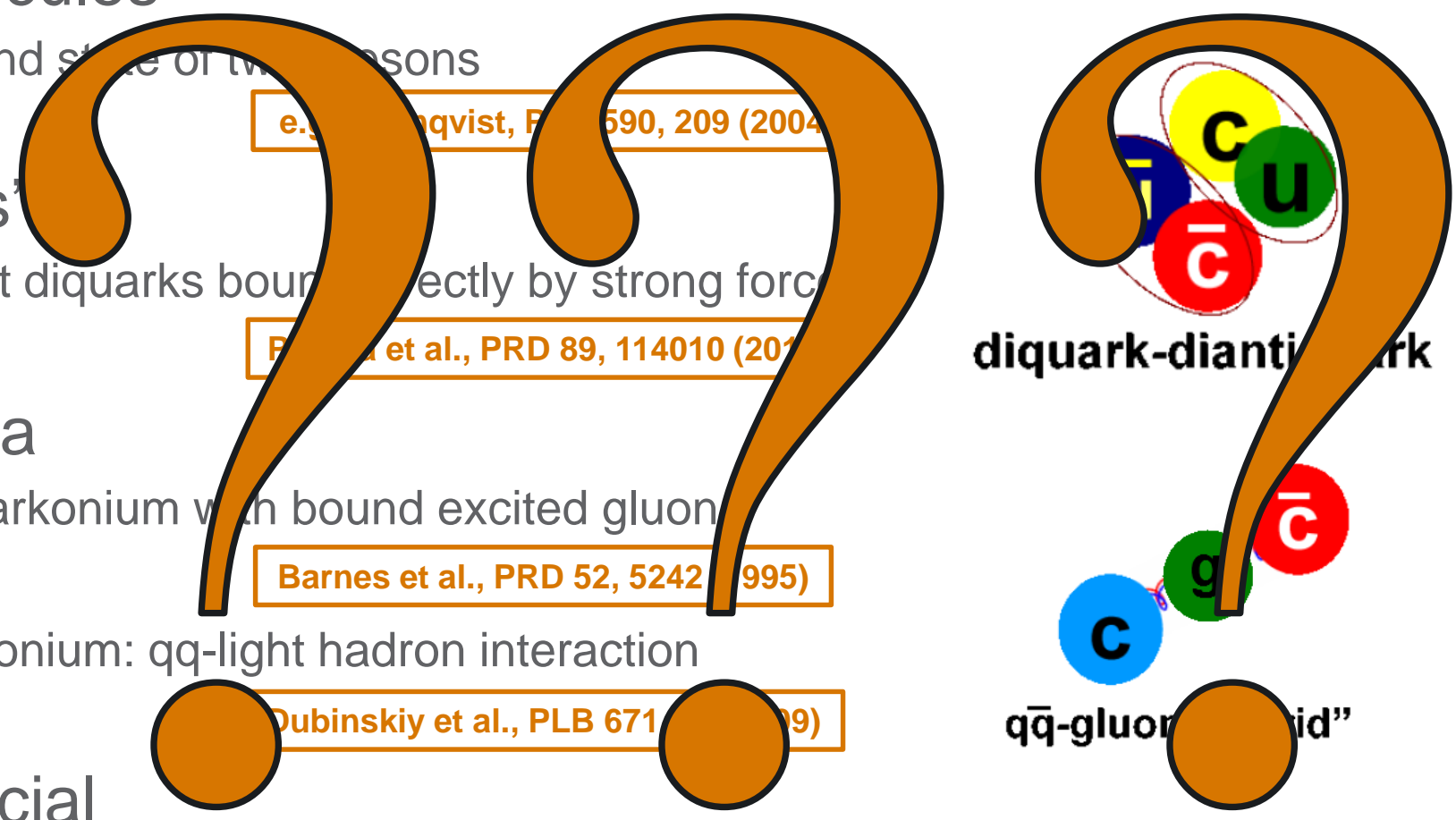
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[Dubinskiy et al., PLB 671 \(2007\)](#)

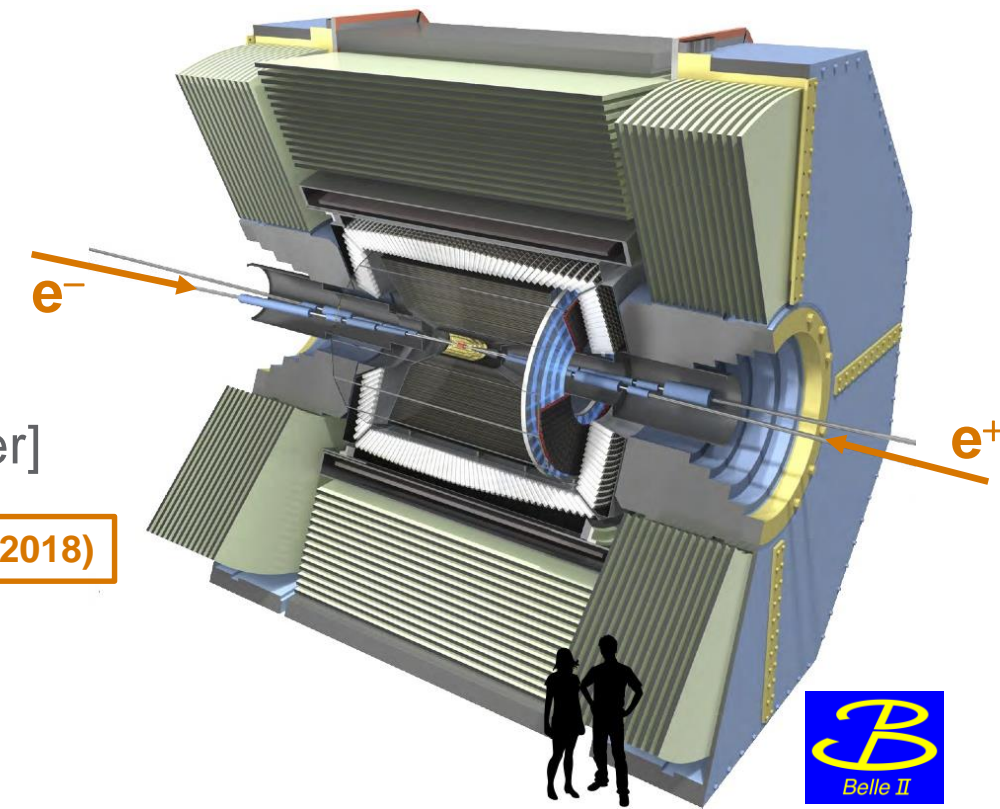
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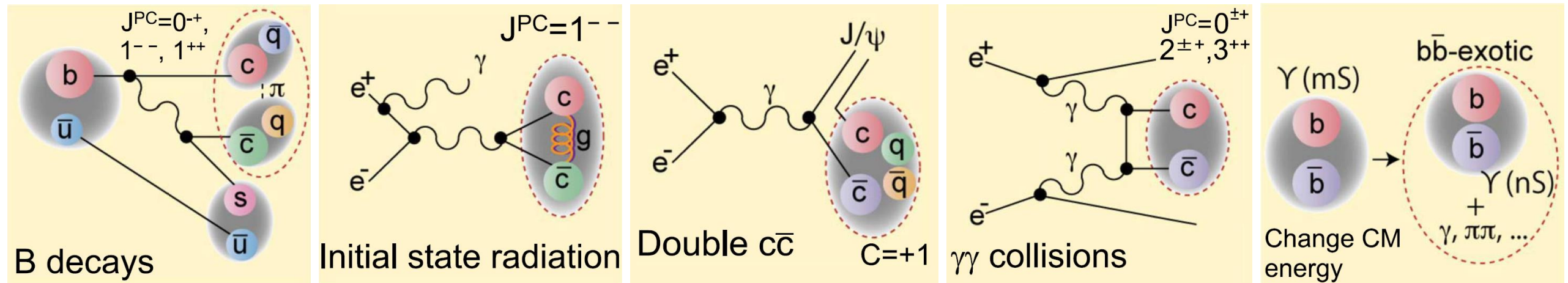


# Belle II Capabilities



- Upgraded detector and accelerator [see talk by T. Browder]
- Extensive quarkonium physics program [arXiv:1808.10567 \(2018\)](https://arxiv.org/abs/1808.10567)
- Advantages
  - 40x data of the B-Factories
  - Full event reconstruction and decays involving neutral final states
  - Multiple production mechanisms

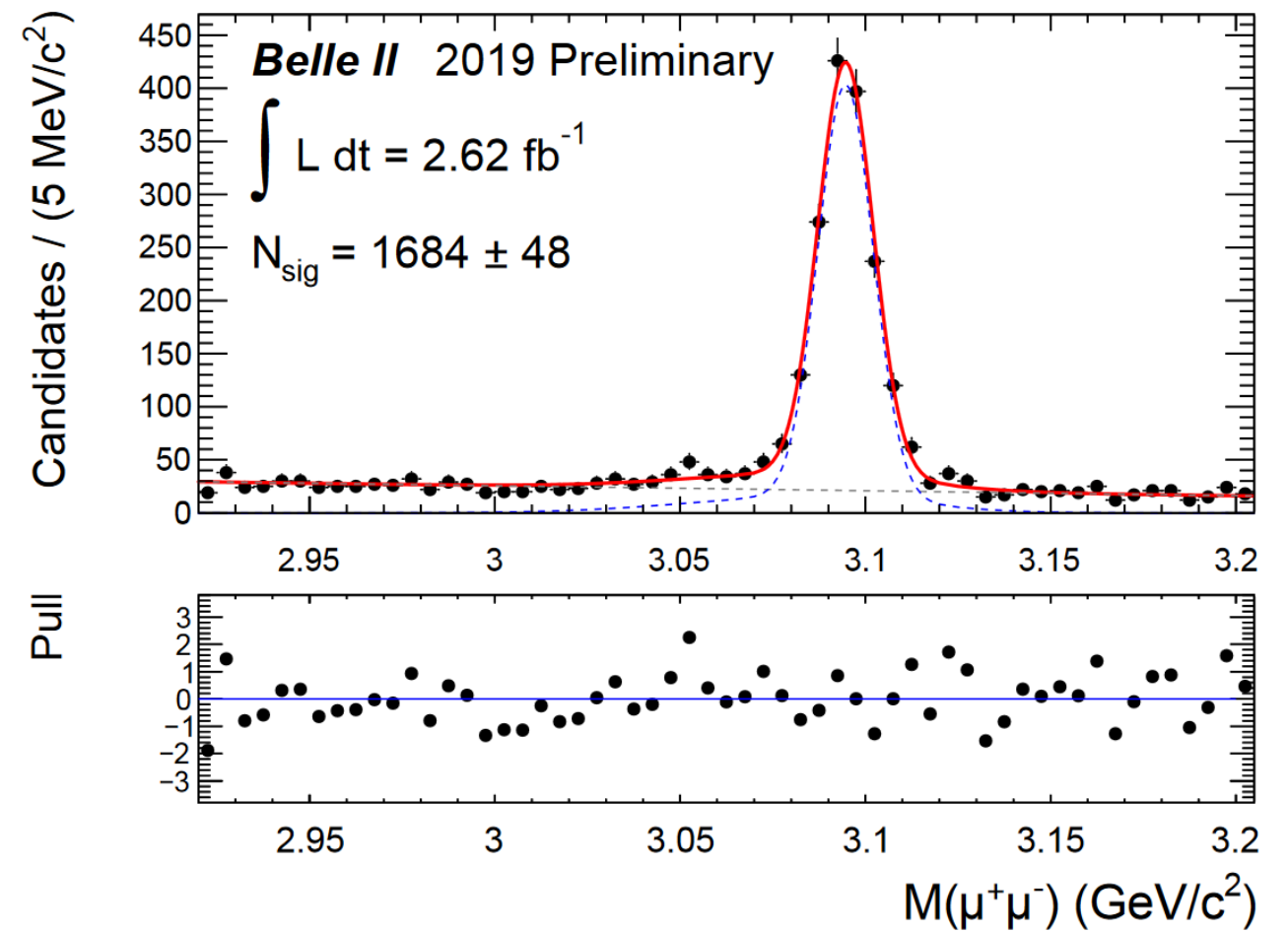
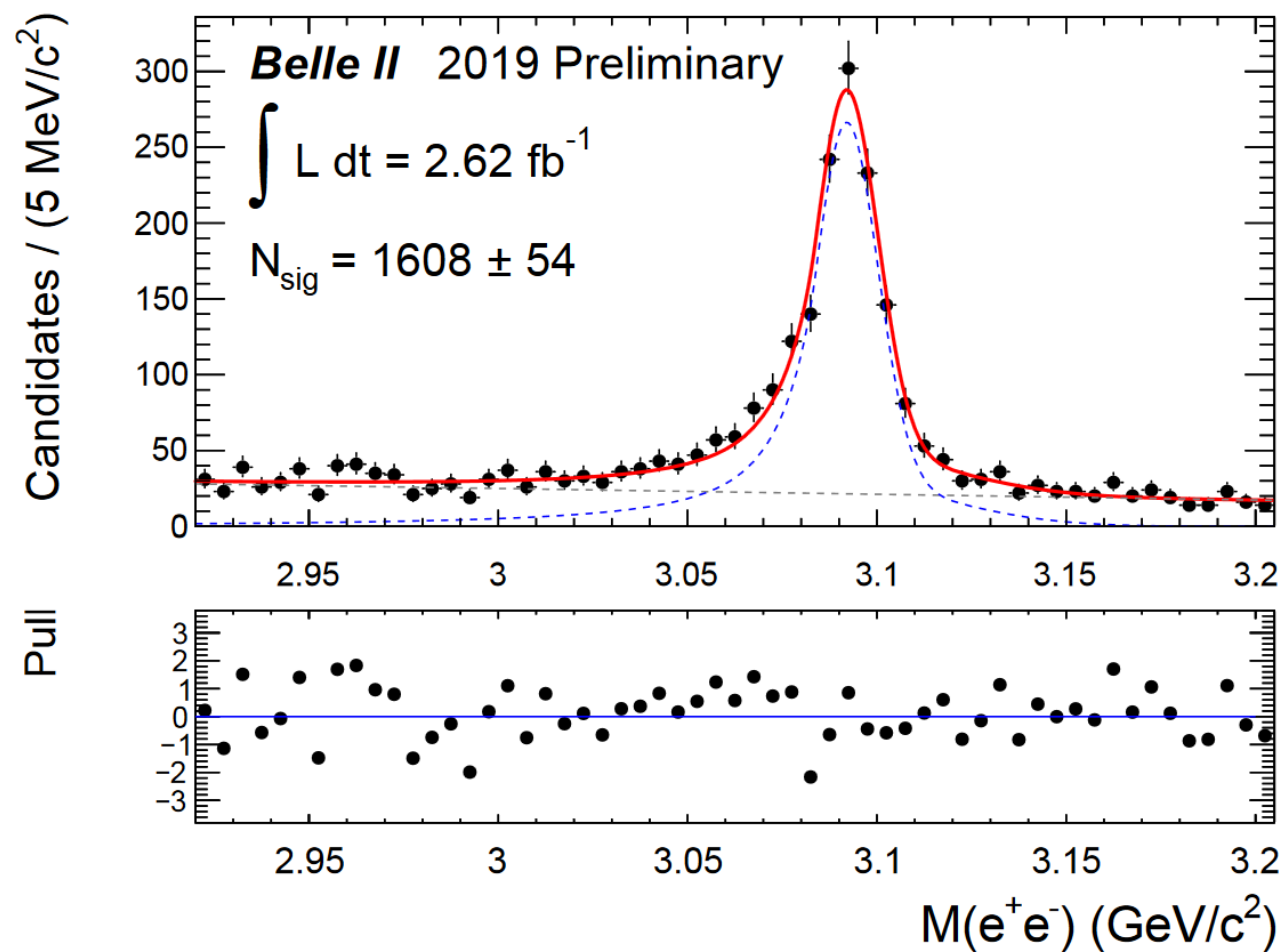
[arXiv:1011.0352 \(2011\)](https://arxiv.org/abs/1011.0352)



- Nominal  $\sqrt{s} = 10.58 \text{ GeV} = \Upsilon(4S)$ , potential to reach 11.24 GeV

# Charmonium Rediscovery [J/ψ(1S)] in early Belle II Data

- Inclusive J/ψ(1S) signals seen in e<sup>+</sup>e<sup>-</sup> and μ<sup>+</sup>μ<sup>-</sup> final states

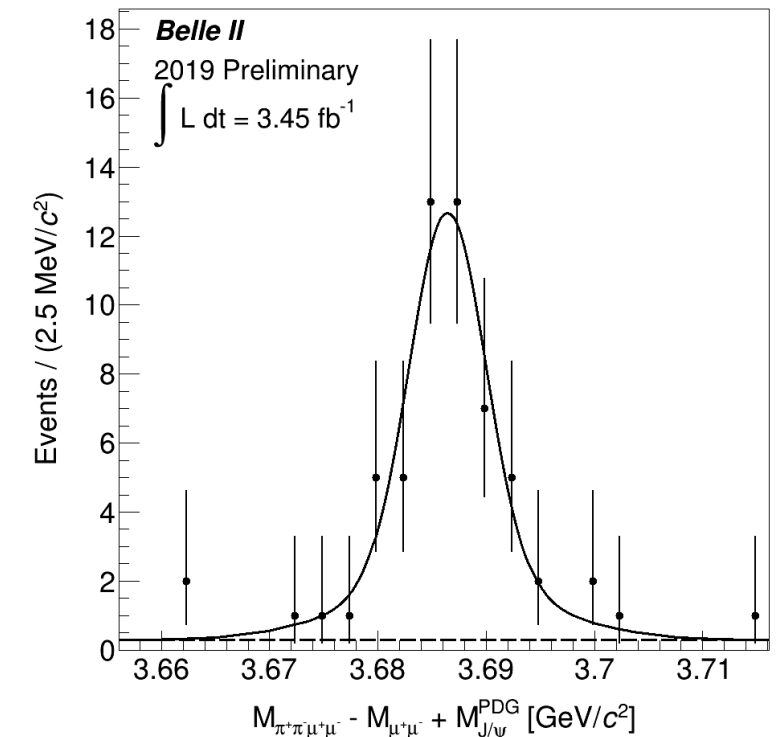
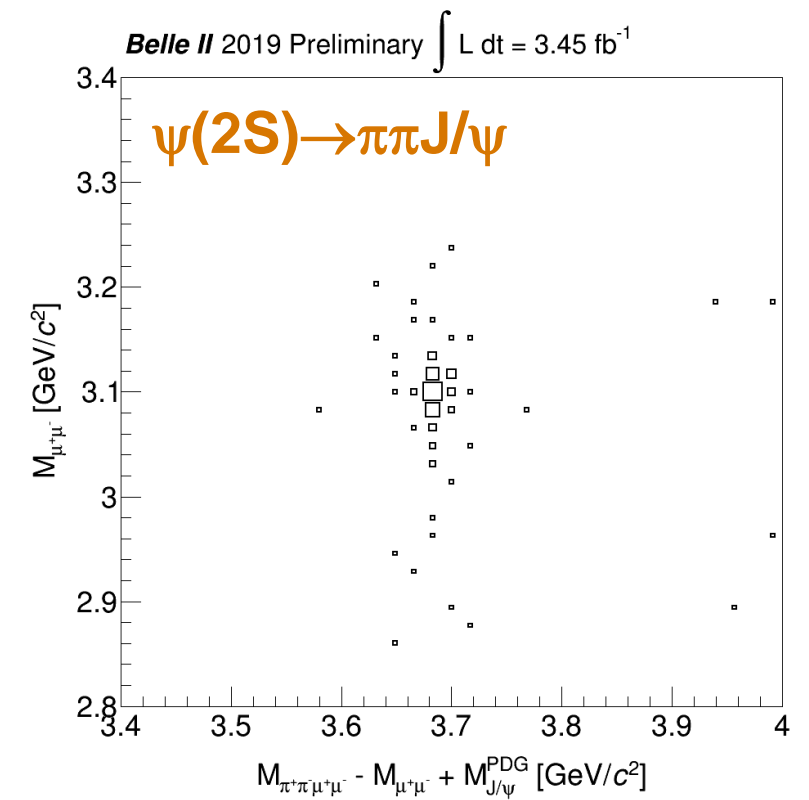
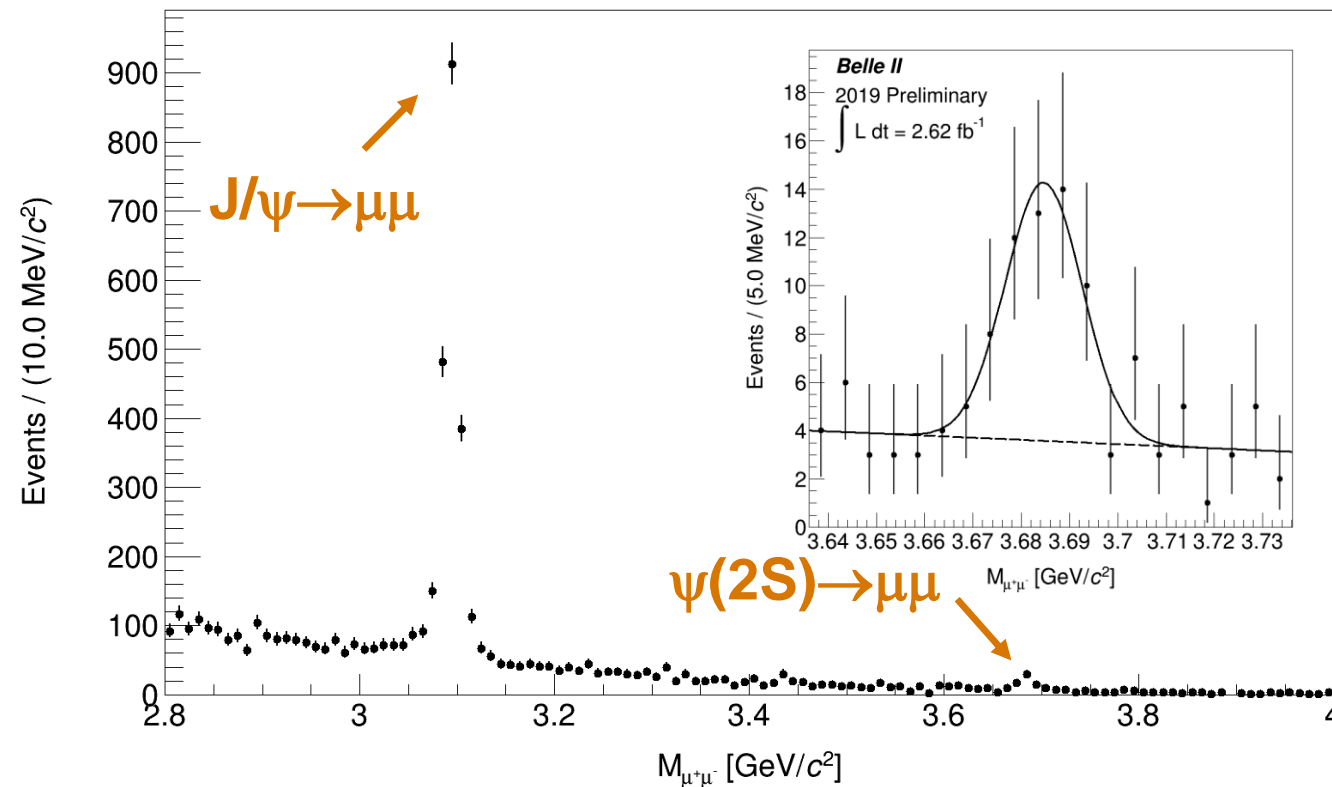


- Verification of tracking, electron ID, and muon identification system



# Charmonium Rediscovery [ $\psi(2S)$ ] in early Belle II Data

- Complimentary search strategies
  - Extend inclusive  $\mu^+\mu^-$  search window
  - Isolate  $\psi(2S) \rightarrow \pi^+\pi^- J/\psi(1S)(\mu^+\mu^-)$  from ISR production

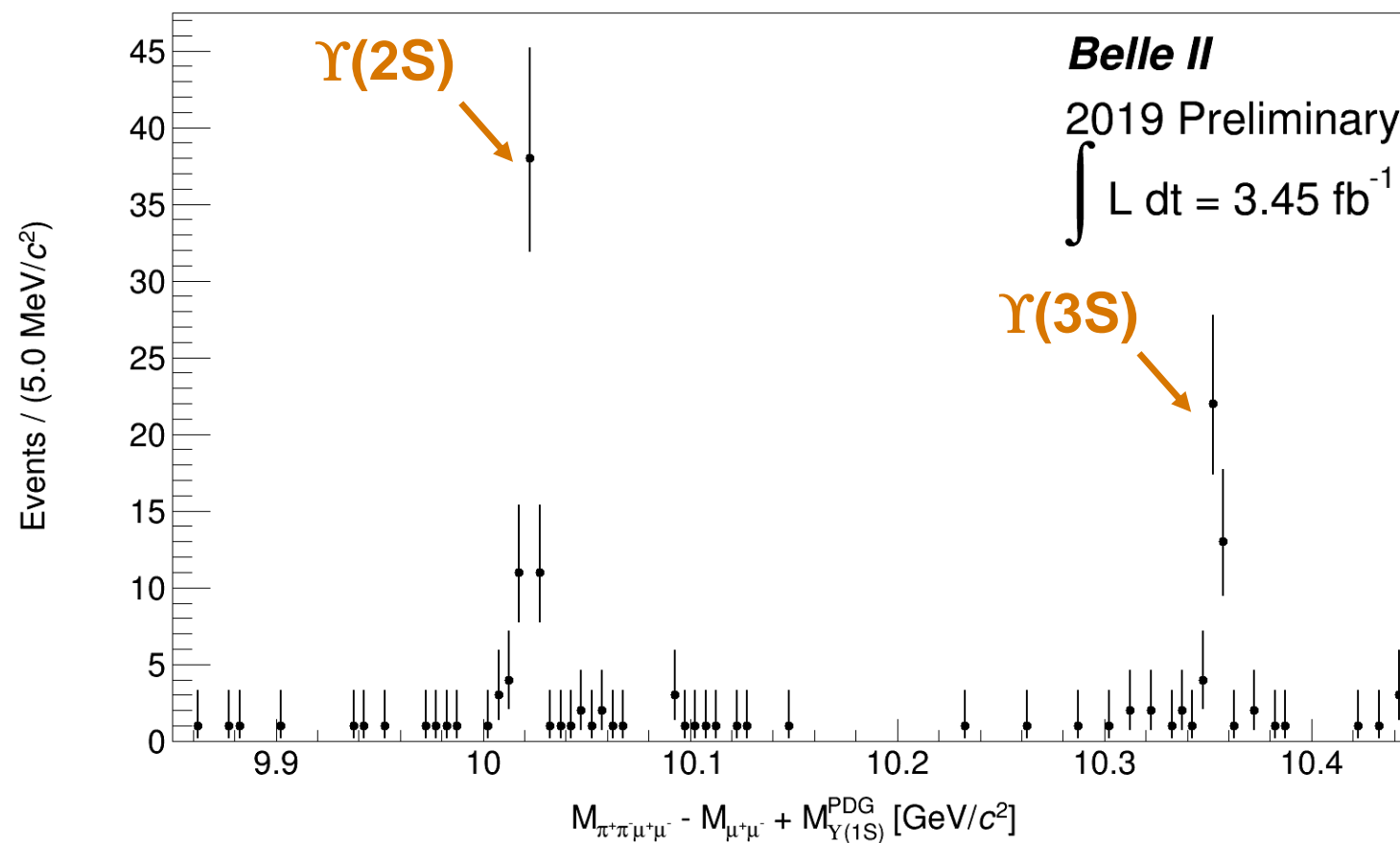
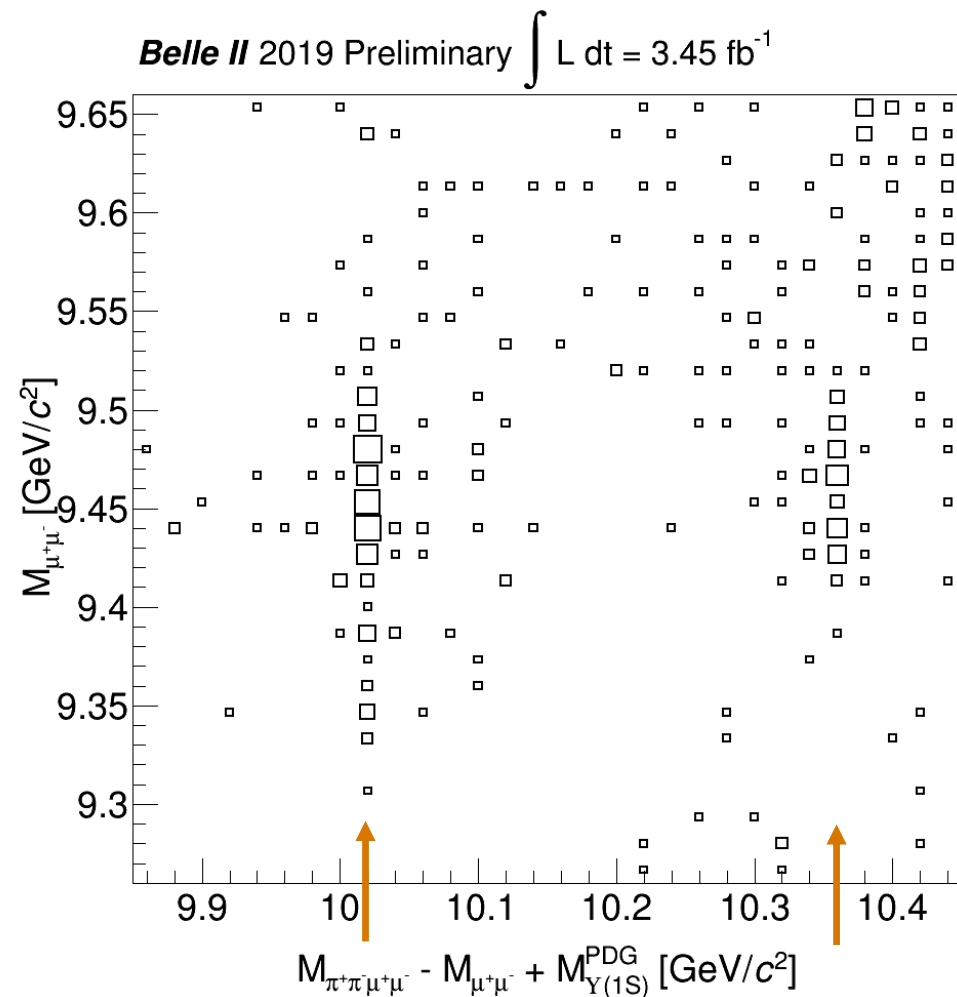


- Evidence for signal in both decay modes



# Bottomonium Rediscovery [ $\Upsilon(1S,2S,3S)$ ] in early Belle II Data

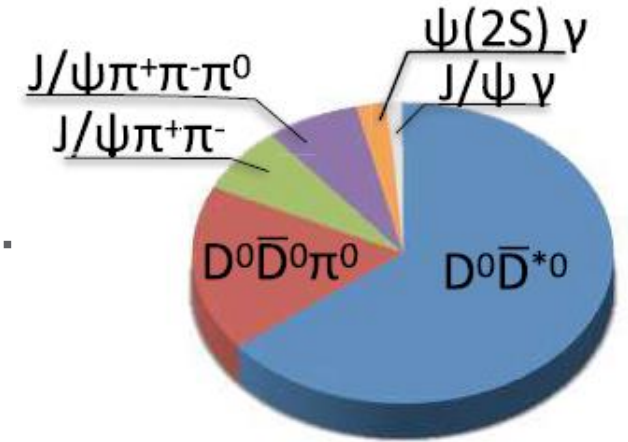
- $\Upsilon(2S,3S) \rightarrow \pi^+\pi^-\Upsilon(1S)(\mu^+\mu^-)$  produced by initial state radiation



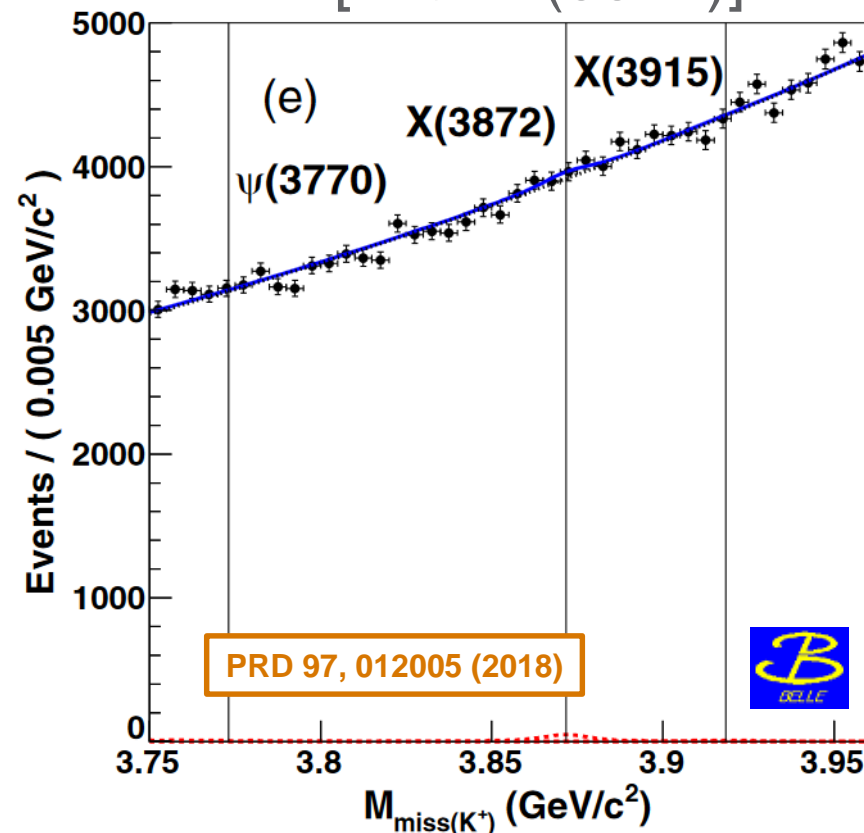
- Observation of transitions with cross sections consistent with expectations

# X(3872) Prospects

- Observed decays:  $\rho J/\psi$ ,  $\omega J/\psi$ ,  $\gamma J/\psi$ ,  $\gamma\psi(2S)$ ,  $D^0\bar{D}^{*0}$ ,  $D^0\bar{D}^0\pi^0$ , ...
- Branching fractions and decay widths not known



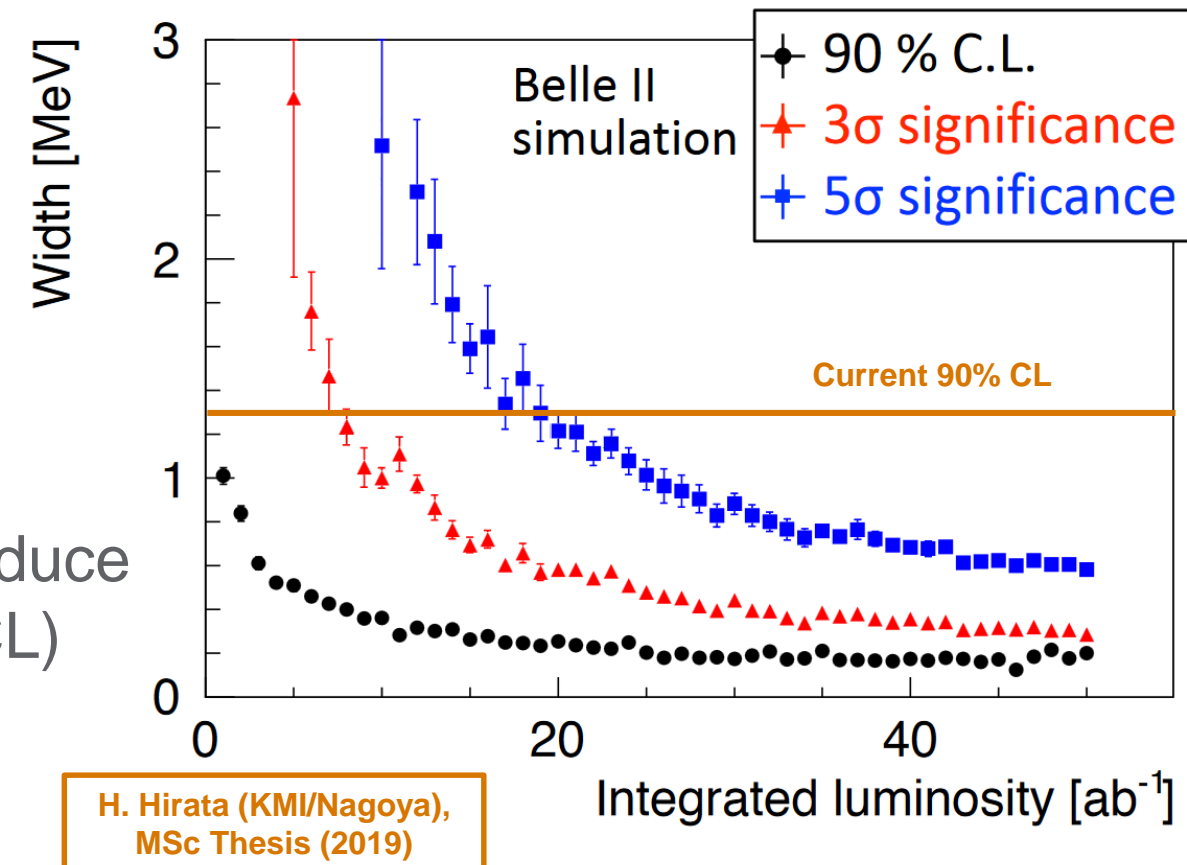
K recoil mass to determine  
 $\text{Br}[B \rightarrow KX(3872)]$



Best limit:

$$\Gamma_{X3872} < 1.3 \text{ MeV}$$

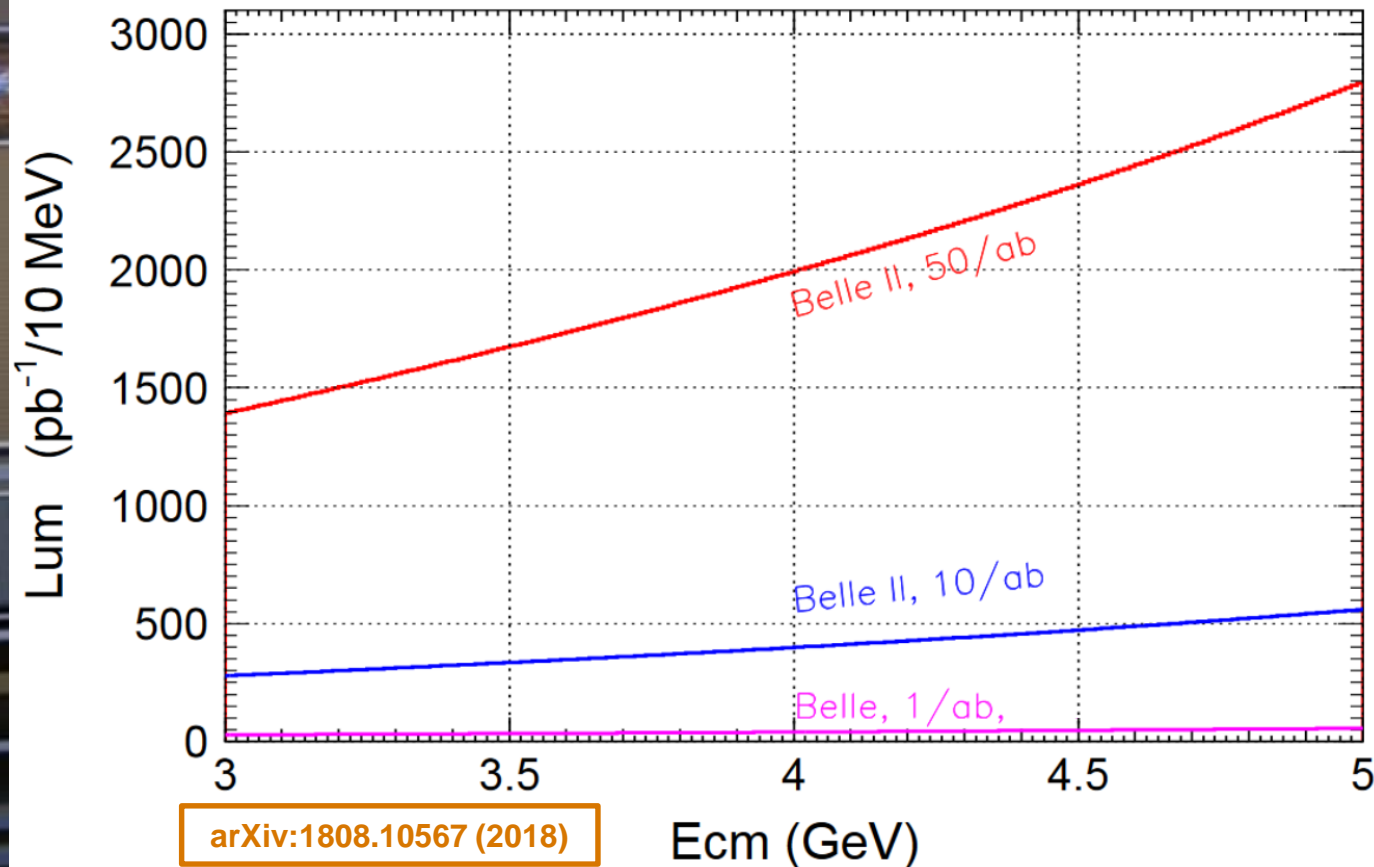
Full dataset can reduce  
to  $\sim 180 \text{ keV}$  (90%CL)  
or  $570 \text{ keV}$  ( $5\sigma$ )



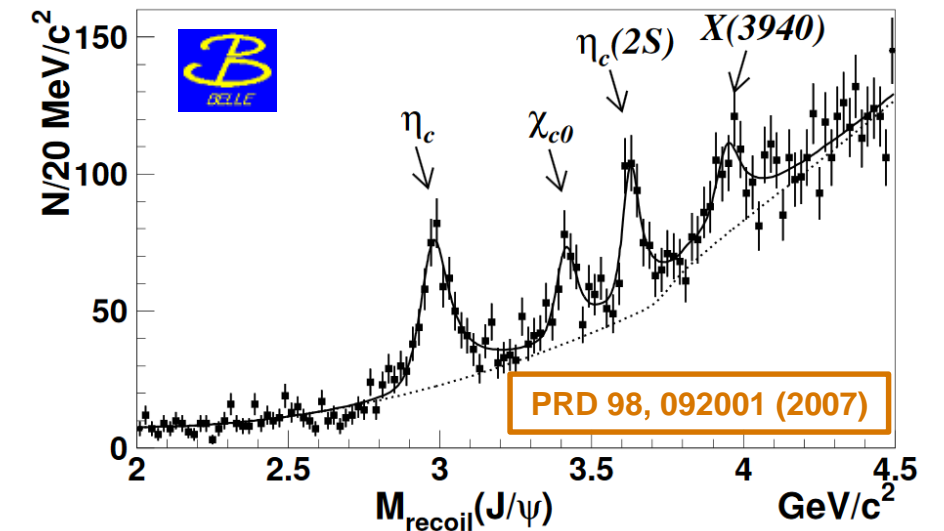
# Other Charmonium and Exotics

- Belle II focus: more data, neutrals, unique production mechanisms

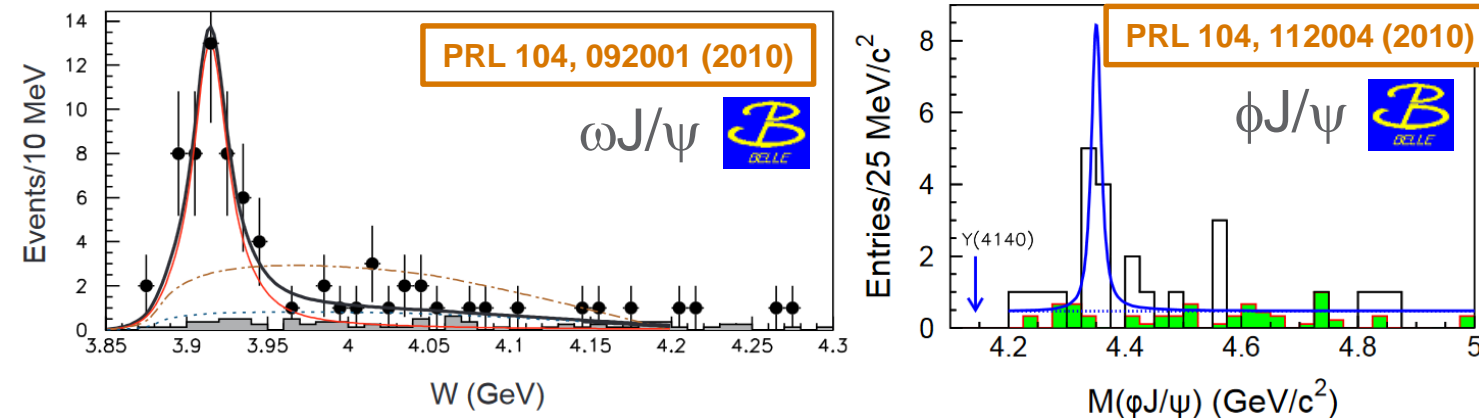
ISR equivalent luminosity, competitive with BESIII scan for  $J^{PC}=1^{--}$  “Y” exotic states



Double- $c\bar{c}$  recoils: pathway to new states

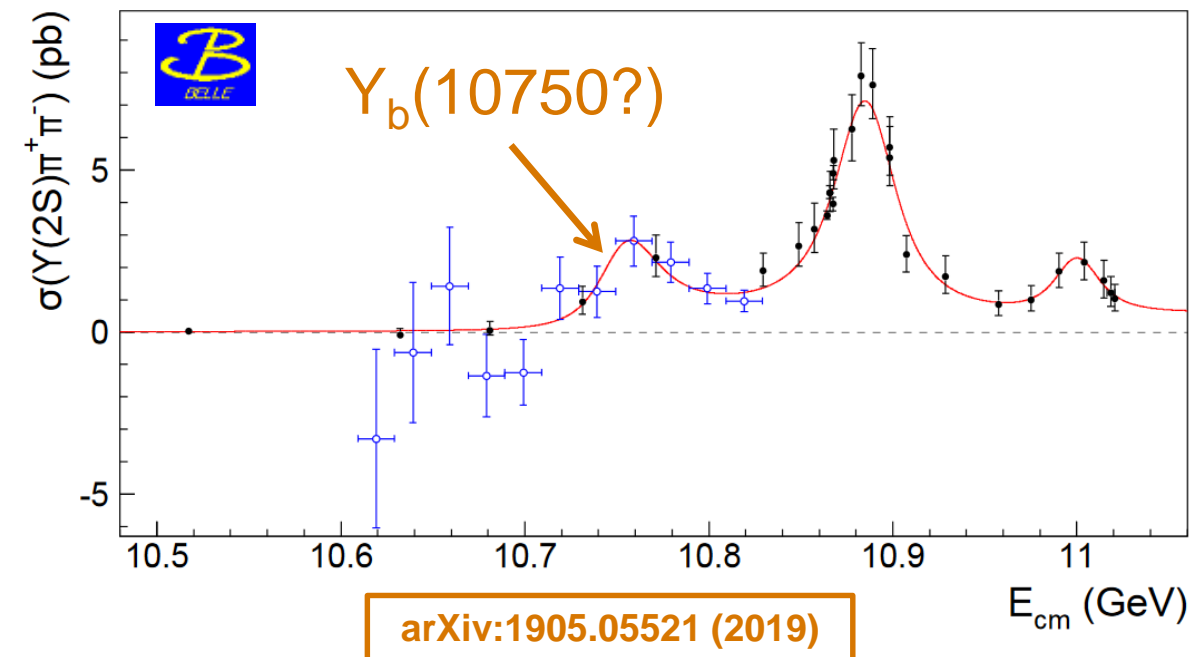
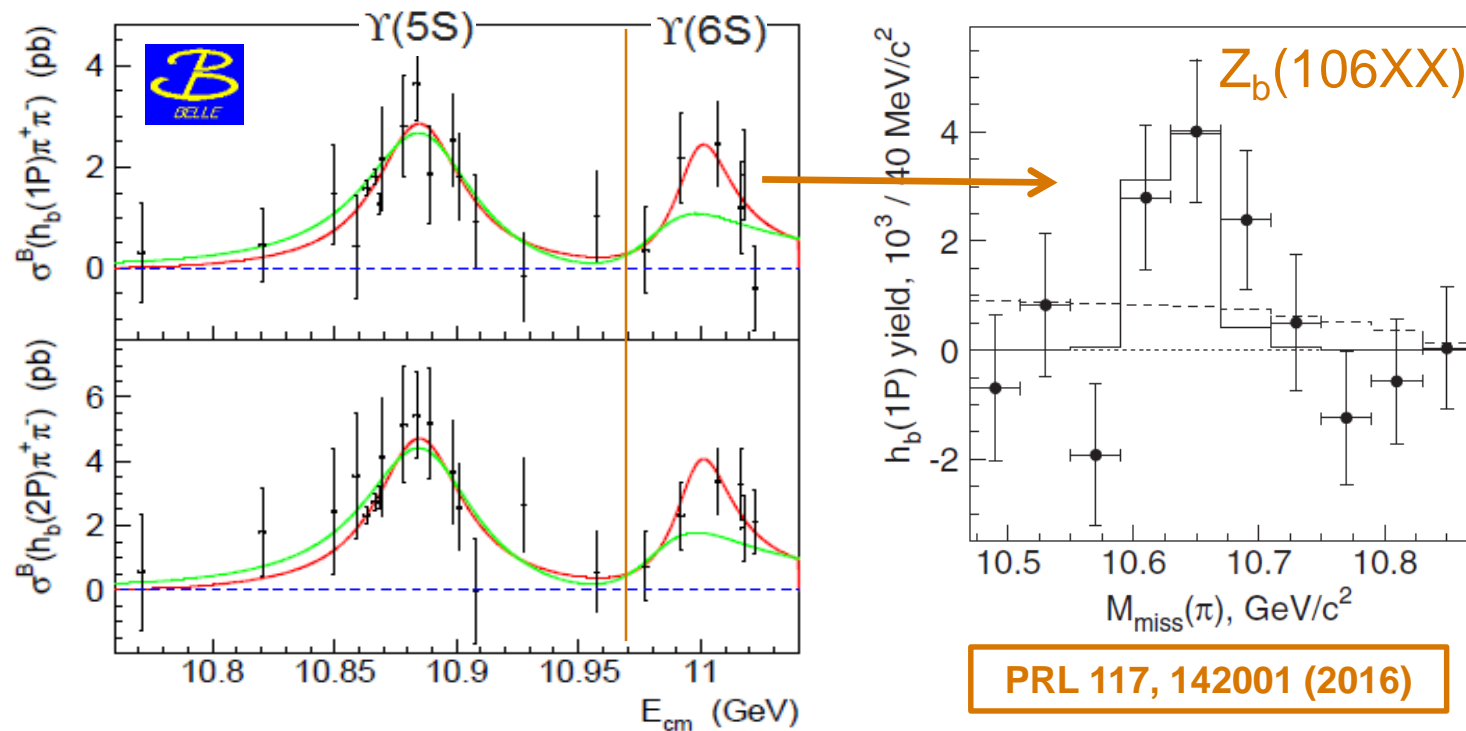
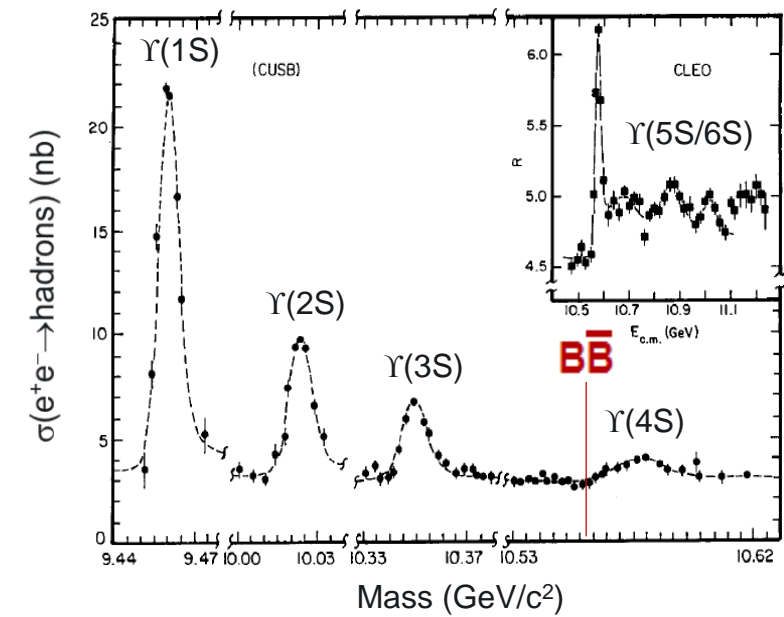


$\gamma\gamma$  production of  $c\bar{c}$  and exotics



# Bottomonium physics opportunities

- Limited non- $\Upsilon(4S)$  data provides significant returns
  - Bottomonium study:  $\eta_b(1S,2S)$ ,  $h_b(1P,2P)$ ,  $\Upsilon(1D)$
  - New Physics:  $\Upsilon \rightarrow$  invisible,  $\Upsilon/\chi_b \rightarrow \ell\ell$  LFV
  - Exotic partners ( $XYZ_b$ ): hints in  $<6\text{fb}^{-1}$   $\Upsilon(6S)$ , new states in  $E_{\text{CM}}$  scan



- Unique opportunity for SuperKEKB/Belle II



# Conclusion

- Quarkonium system
  - Reborn after discoveries of the B-Factory era
  - Searching for explanation of families of exotic multiquark particles
- Belle II
  - Start of the next generation B-Factory
  - First indications of quarkonium in early data
  - Unique opportunities in production and decay
  - Poised to continue the successes of Belle
- Stay tuned for results!

**Thank you**

