Exotic quarkonium physics prospects at Belle II

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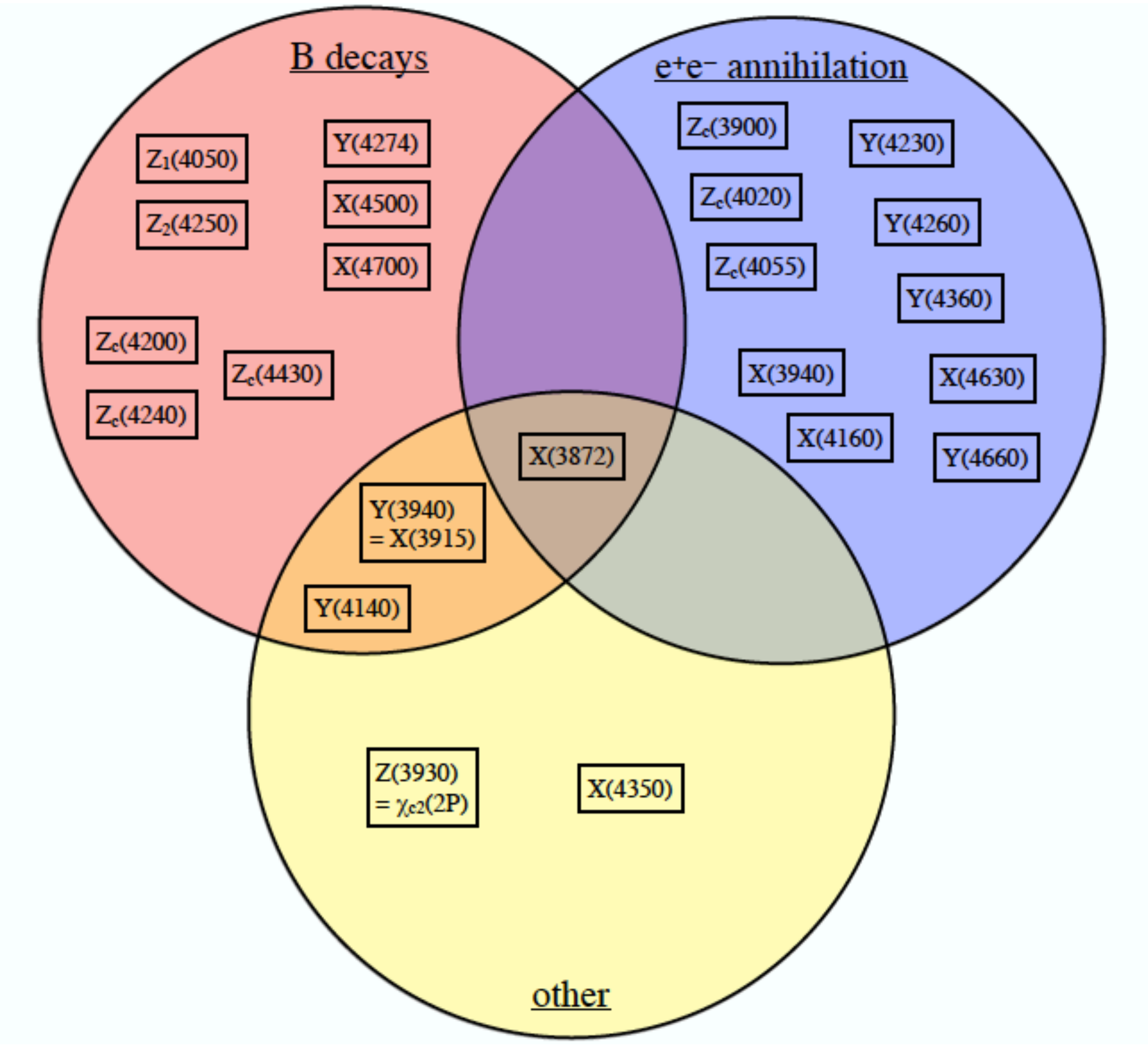
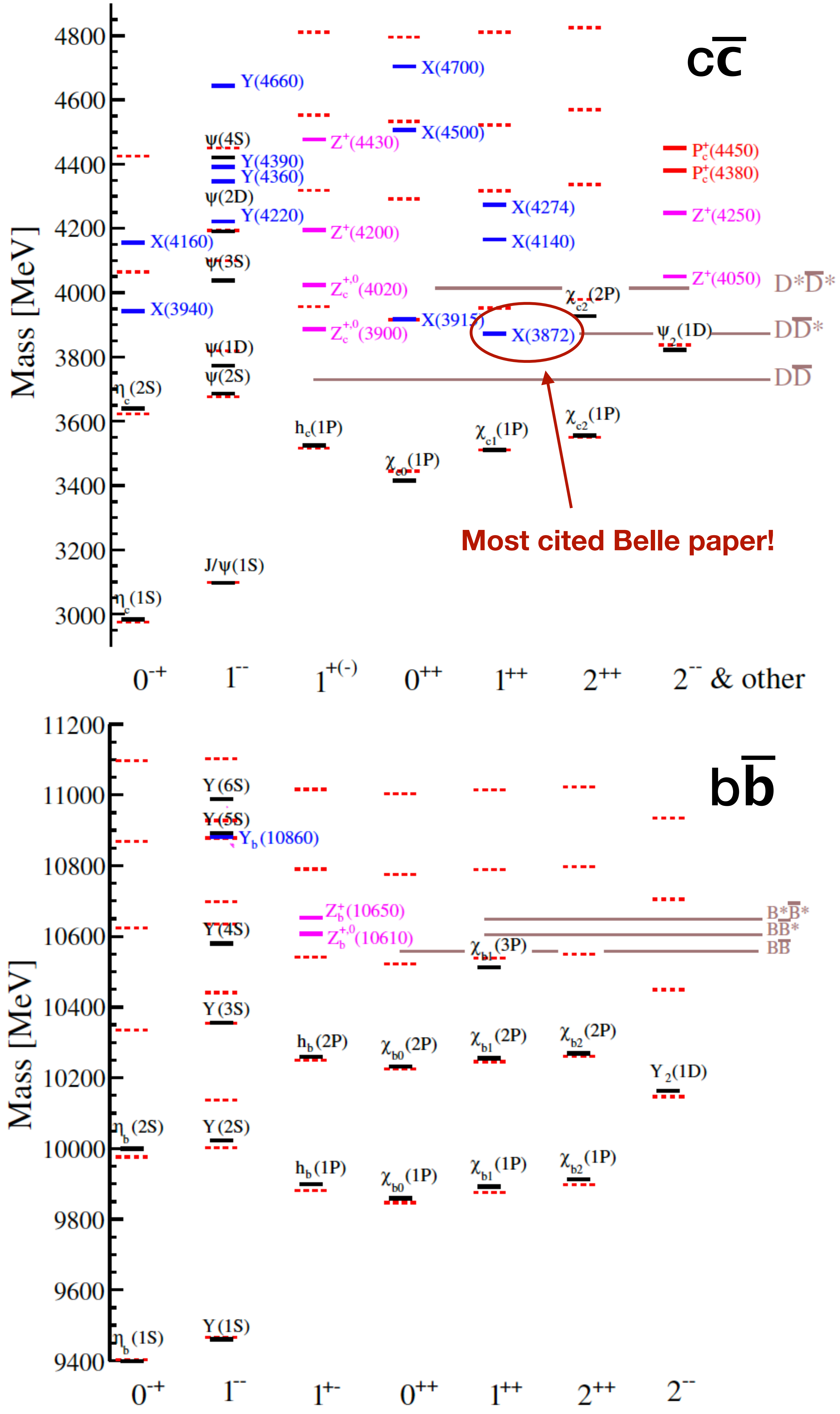
Quarkonium-like states, the XYZ zoo

- Potentially exotic X, Y, Z states
  - Very likely more degrees of freedom than just heavy quark and antiquark
  - Charged states explicitly “exotic” (non-$q\bar{q}$)
  - Many states close to and above open flavor strong decay threshold
- First possibility to explore nonstandard configurations long conjectured
  - Hybrids, multiquark states
- Important to characterize these states
  - Determine quantum numbers
  - Which are exotic?
  - What configuration is the dominant contribution?
  - Are there more states (yes!)
  - Compare and contrast XYZ in charm and beauty sectors
  - Compare information from different experiments, production and decay mechanisms



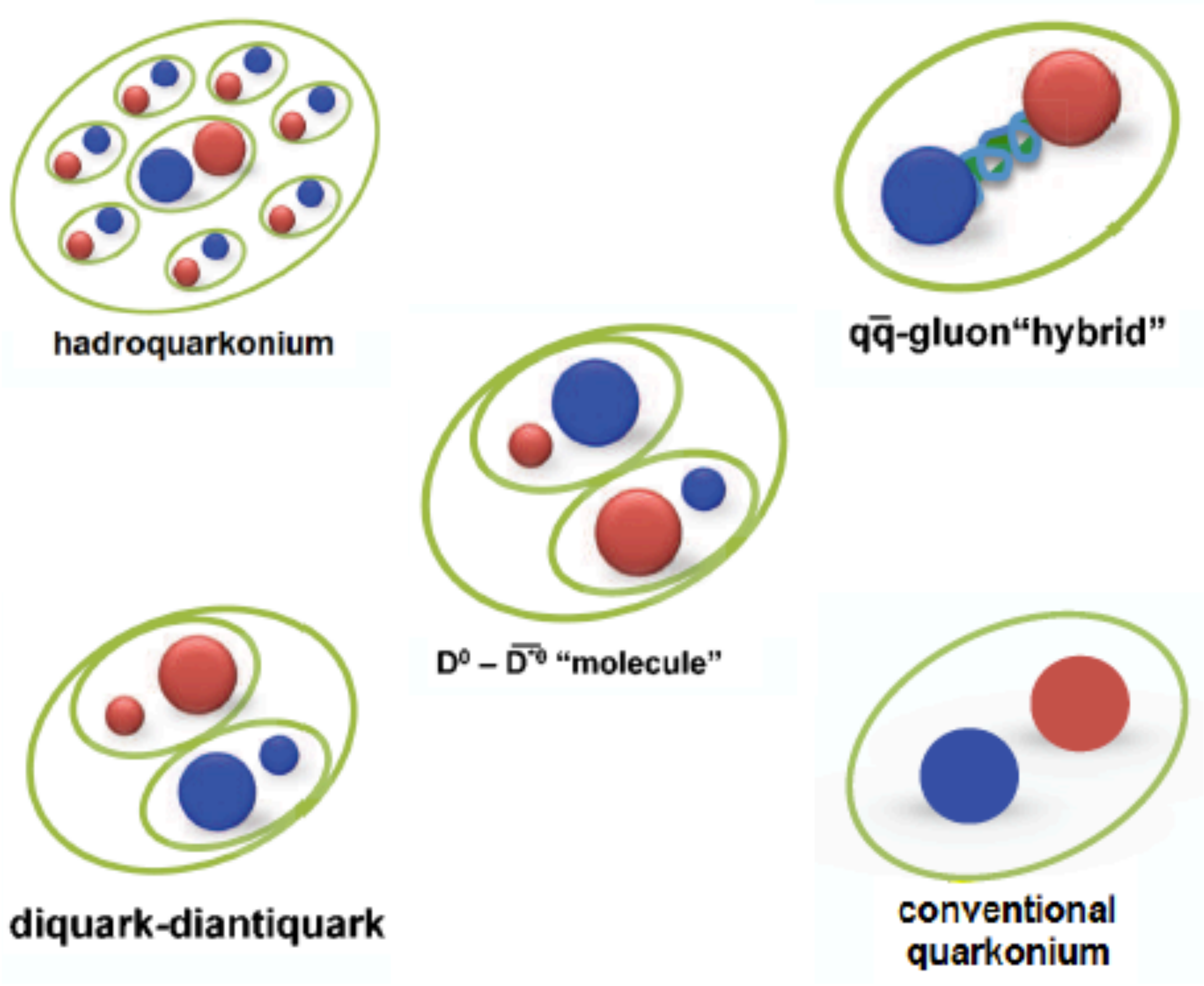
Lebed, Mitchell, Swanson, Heavy-Quark QCD Exotica, PPNP 93, 143 (2017)



S. Olsen et al., Rev. Mod. Phys. 90, 015003(2018)

Quarkonium-like models

- Most models can be classified according to quark clustering and degrees of freedom
    - **Hadroquarkonium**: compact quarkonium-like core surrounded by light quarks
    - **Tetraquarks**: compact diquark and anti-diquark substructures
    - **Hadronic molecules**: heavy and light quarks and anti-quarks combine to form a hadron pair
    - **Hybrids**: both quarks and gluons act as active degrees of freedom (contribute to quantum numbers)
    - **Kinematical effects**
    - All of the above…



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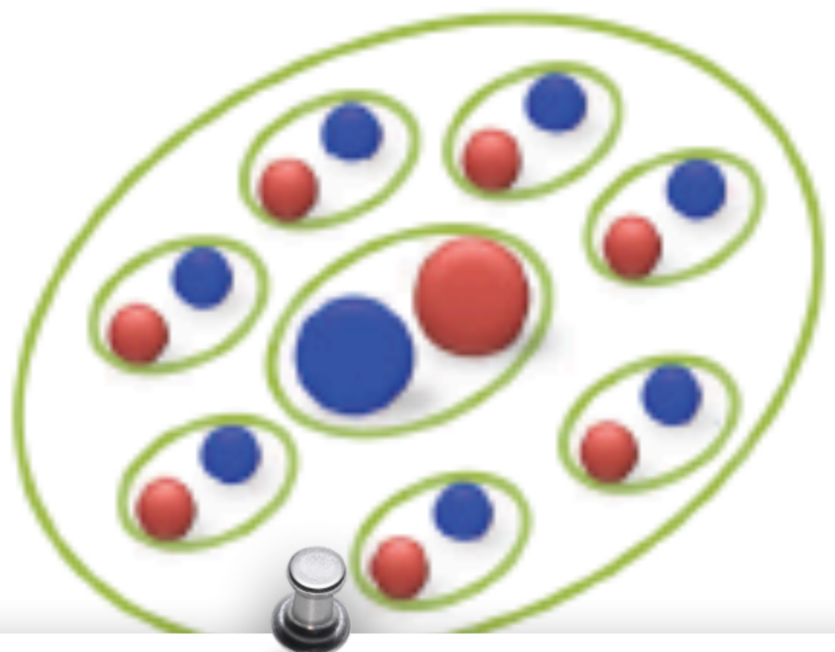
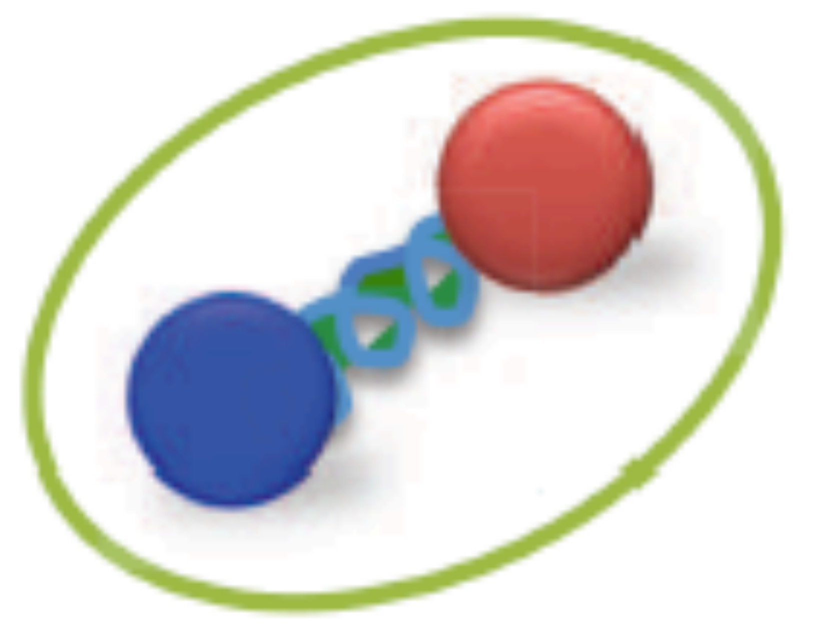
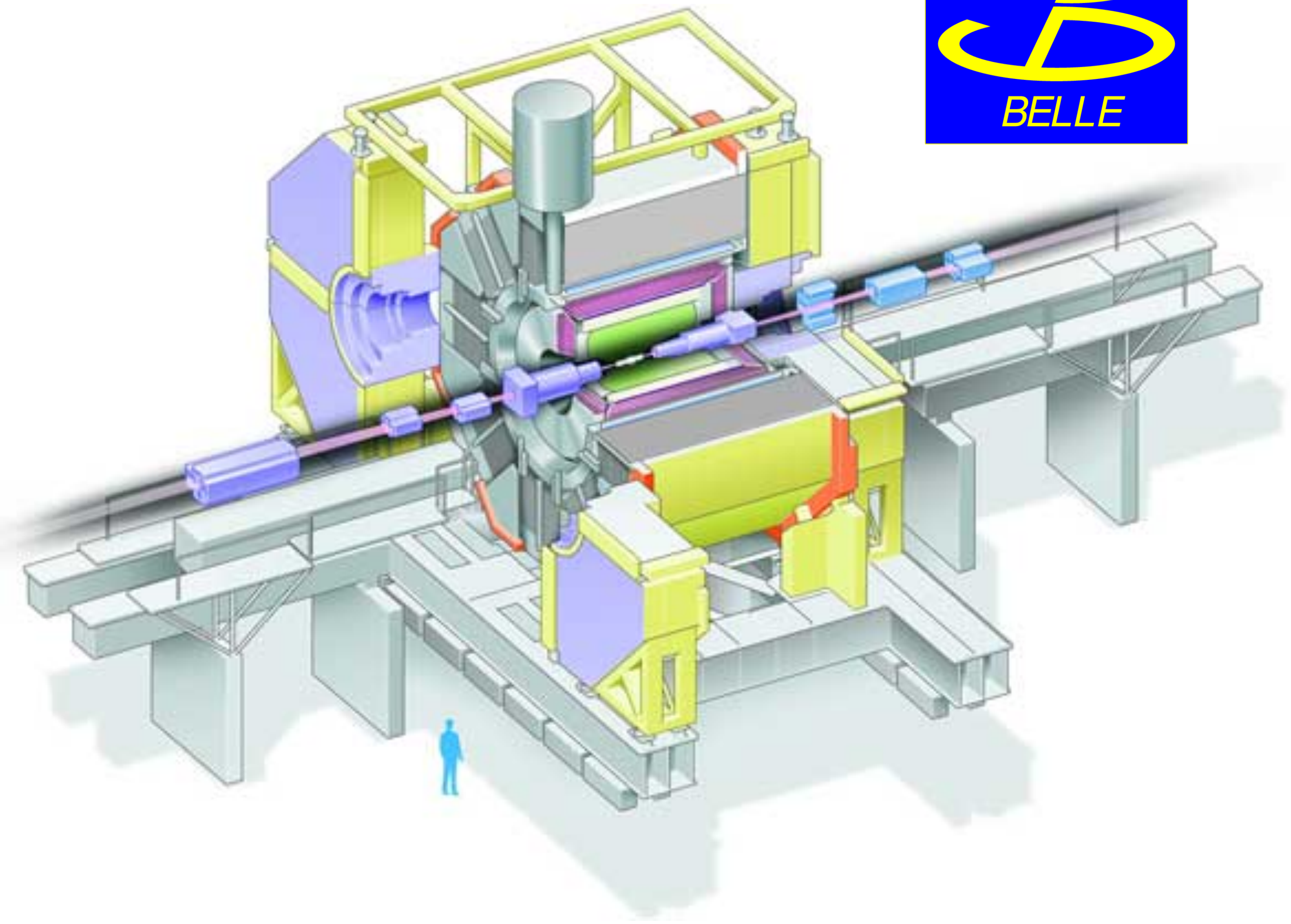


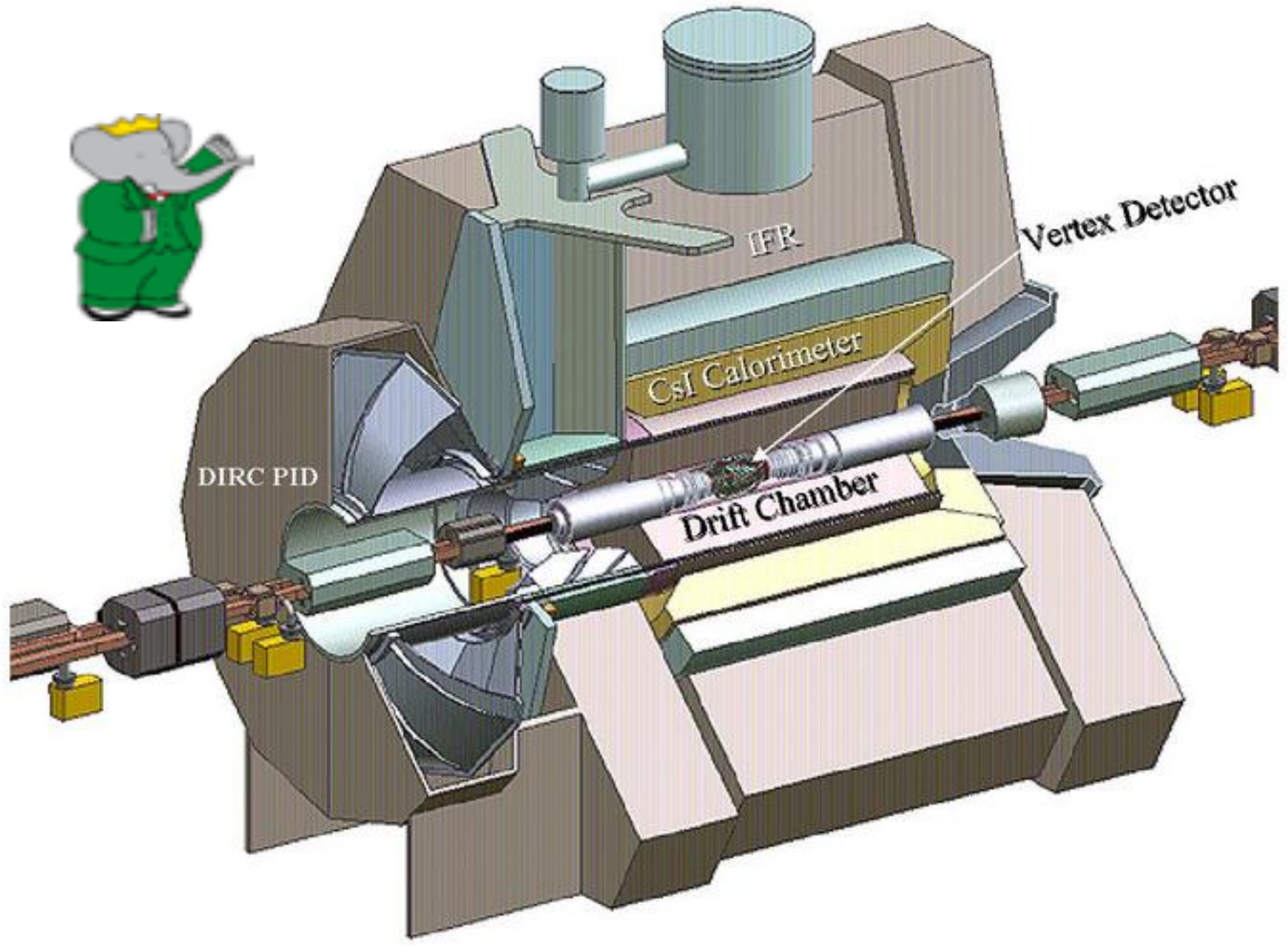


High Priority:

- Identify most prominent component in wave function
- Seek unique picture describing all XYZ states, not state-by-state

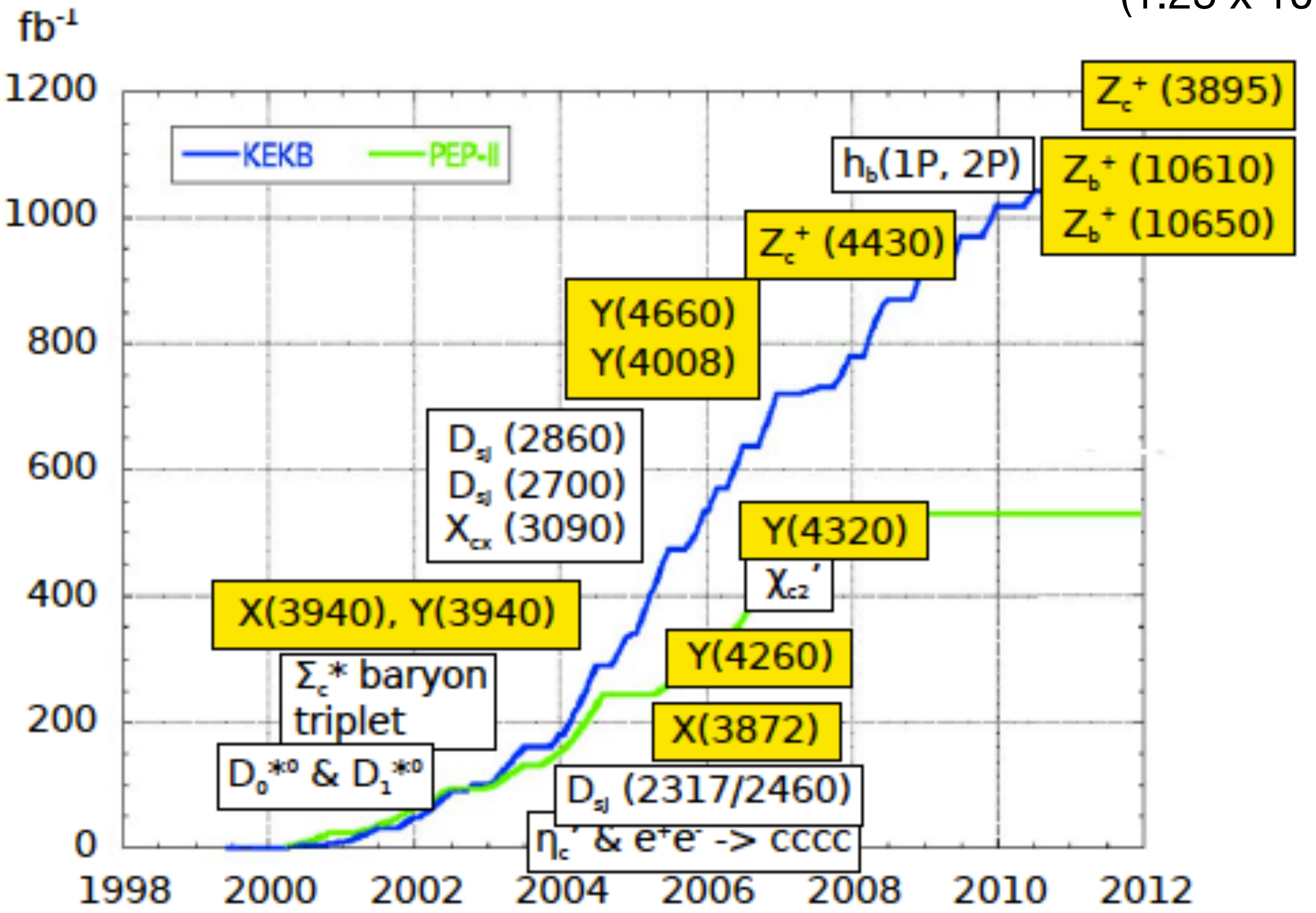
B factories





Belle/KEKB (KEK) and BaBar/PEP-II (SLAC)

Very successful physics programs with a total recorded sample over 1.5 ab^{-1}
(1.25×10^9 $B\bar{B}$)

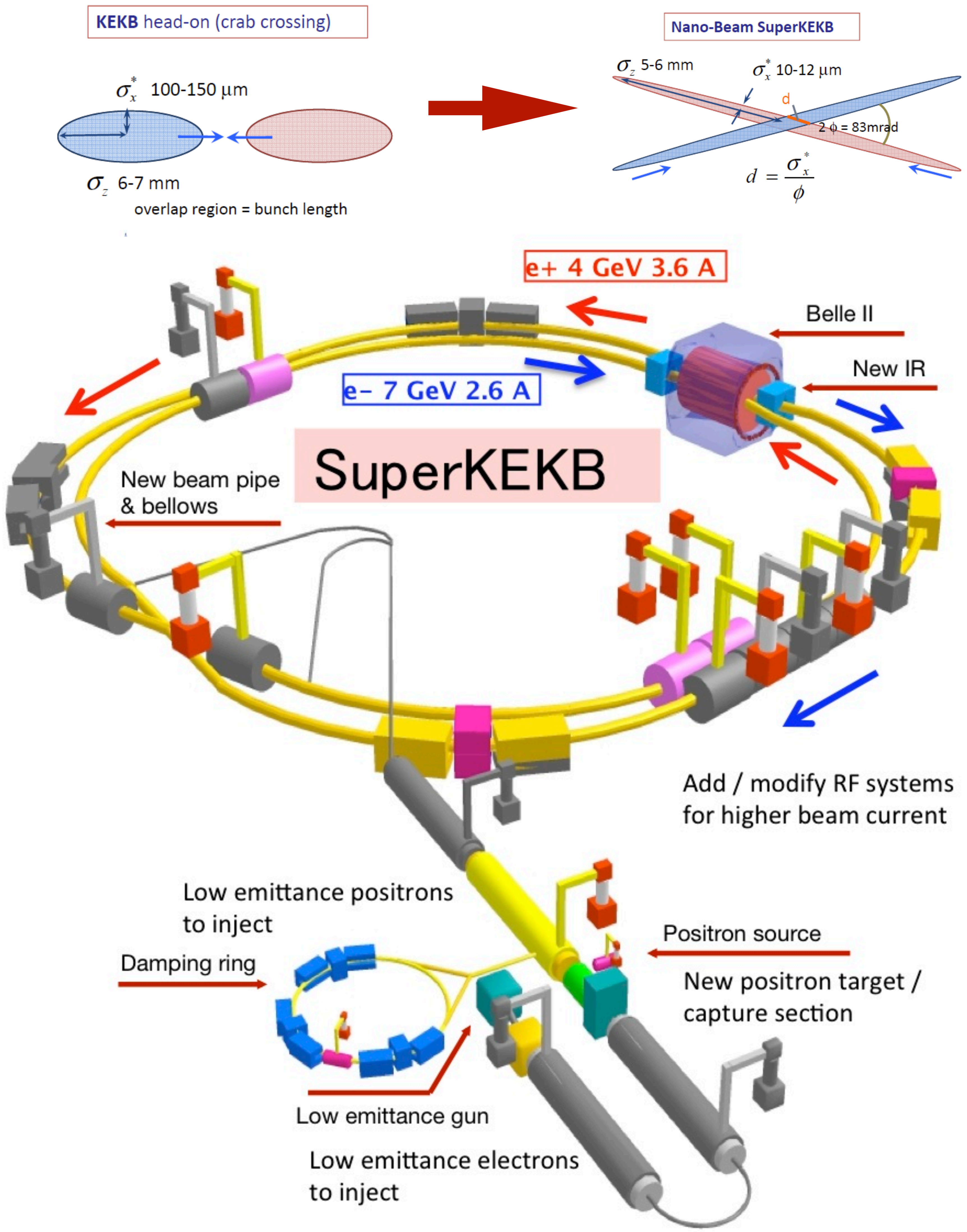


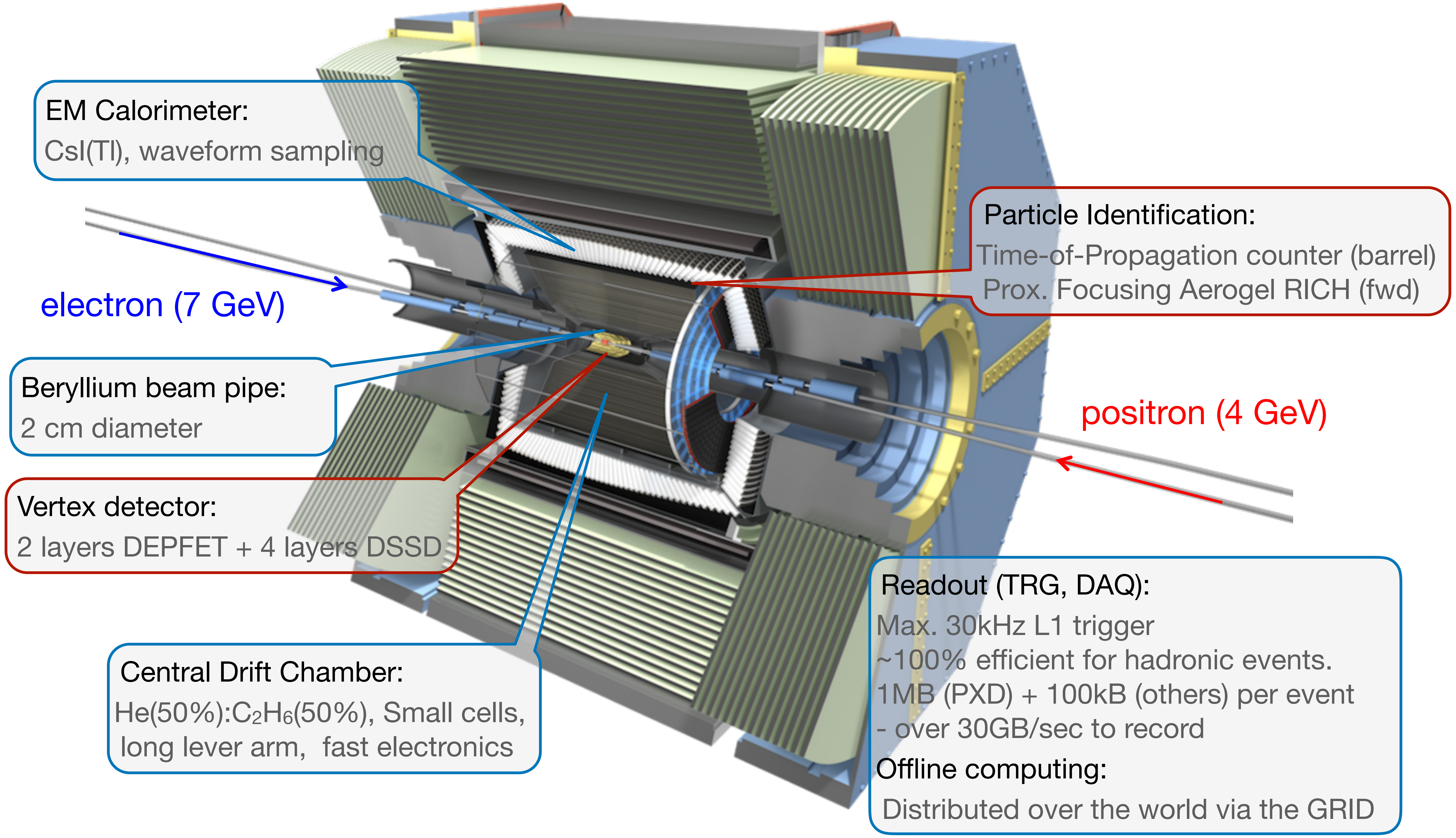
Coloured boxes: exotic candidates

Even ~10 years after data taking, Belle is producing new results in hadron spectroscopy

~350 papers published since shutdown!

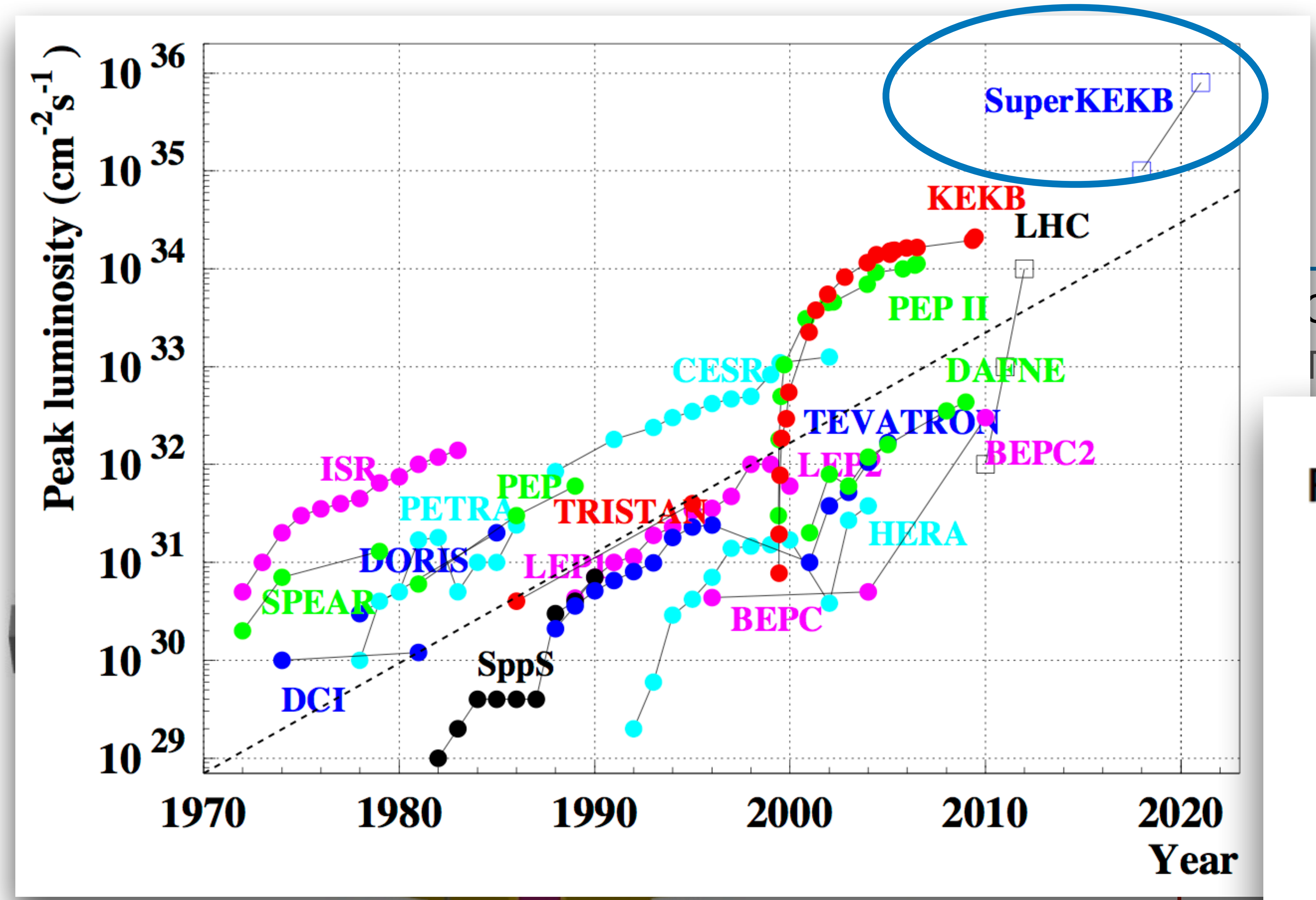
SuperKEKB: The next generation B-factory





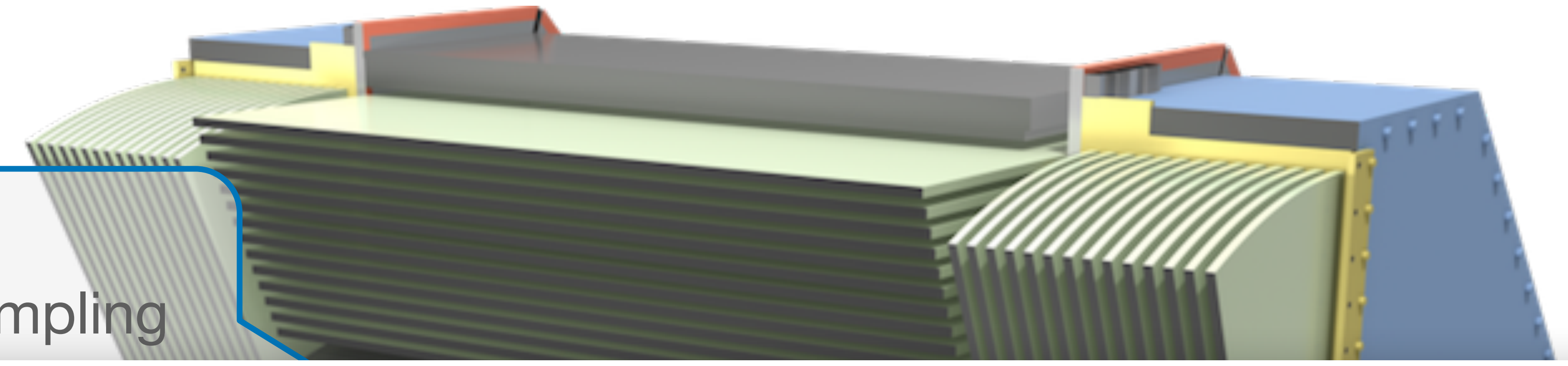
arXiv:1011.0352 [physics.ins-det]

SuperKEKB: The next generation B-factory



Calorimeter:

Tl), waveform sampling



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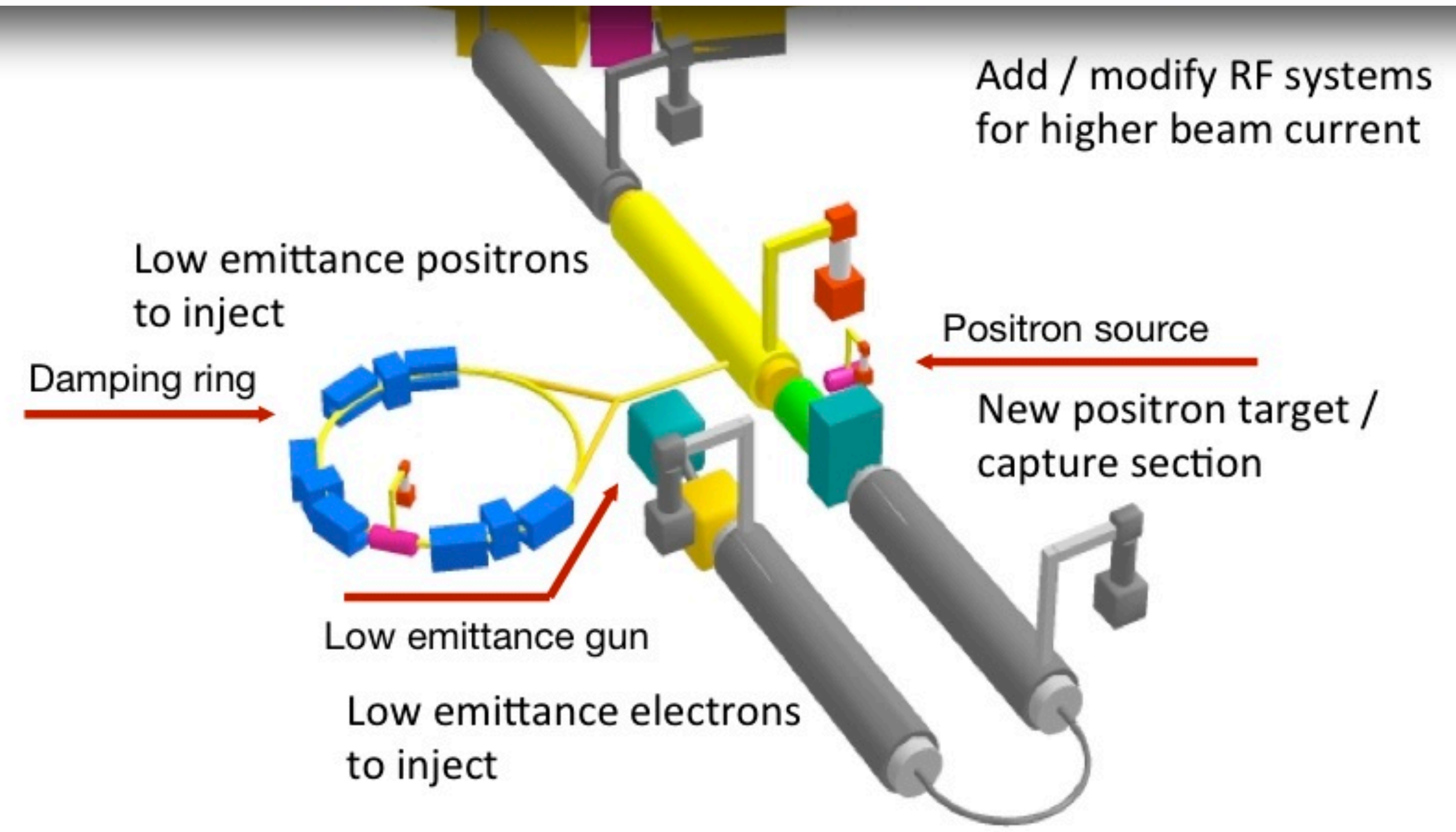
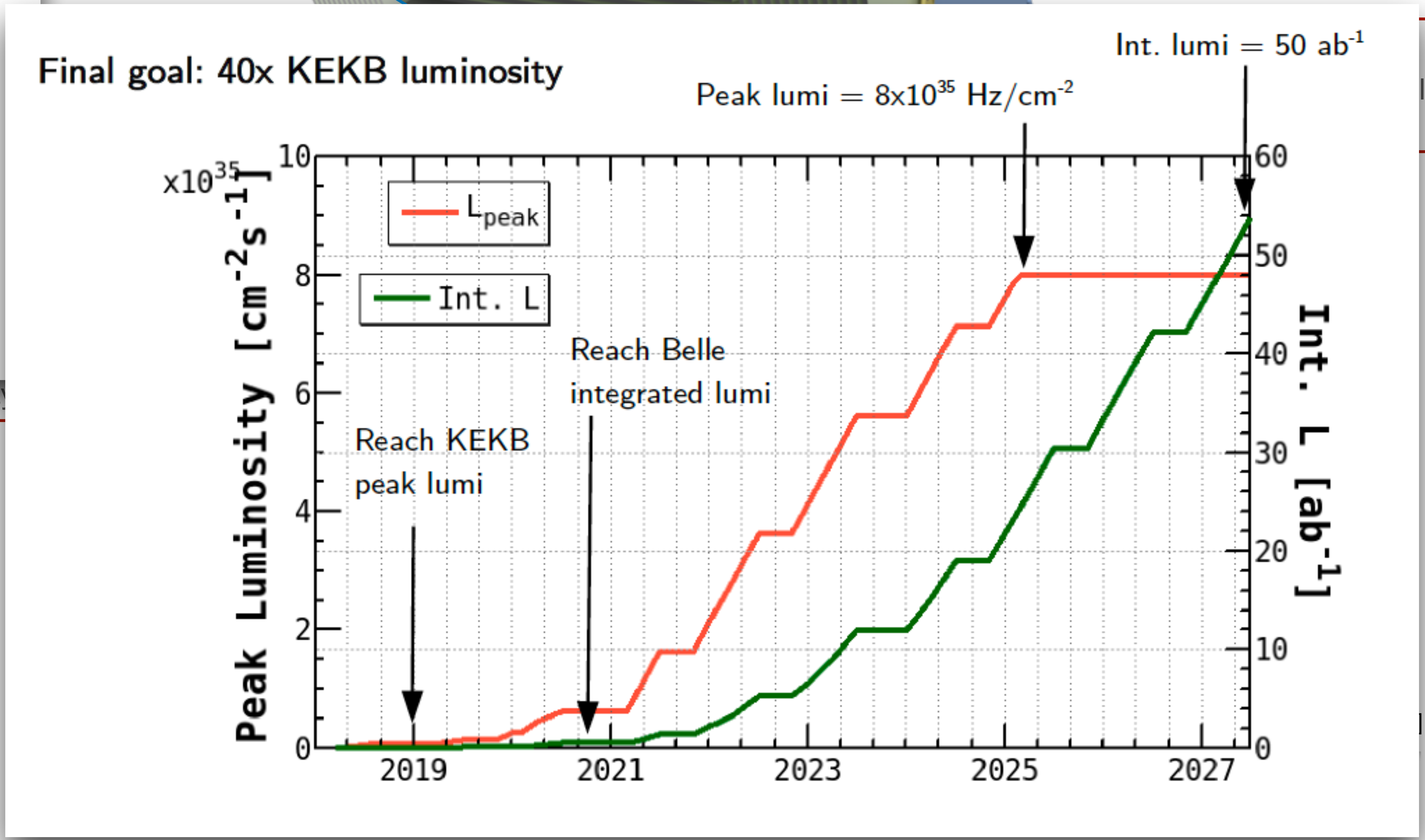
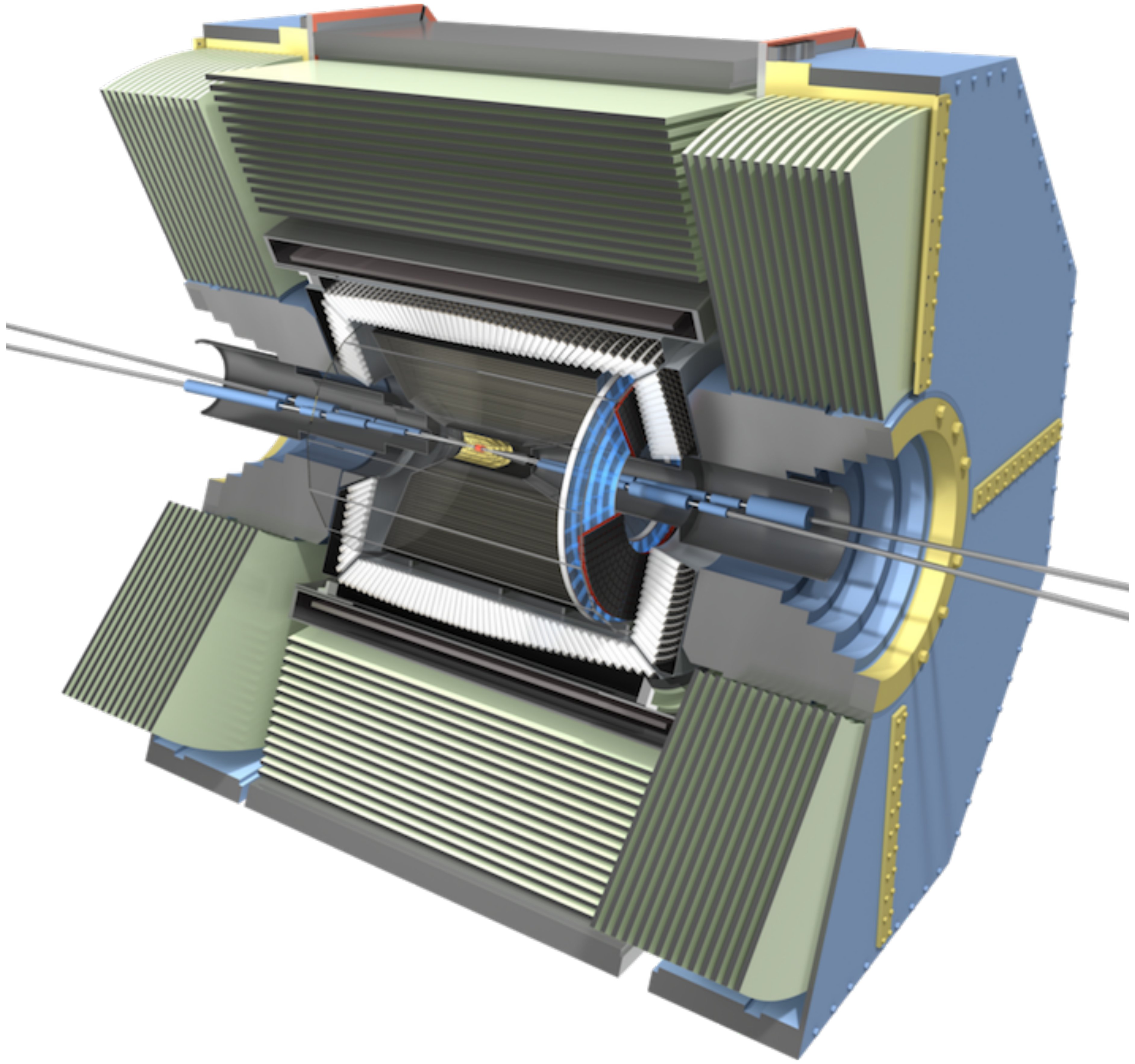




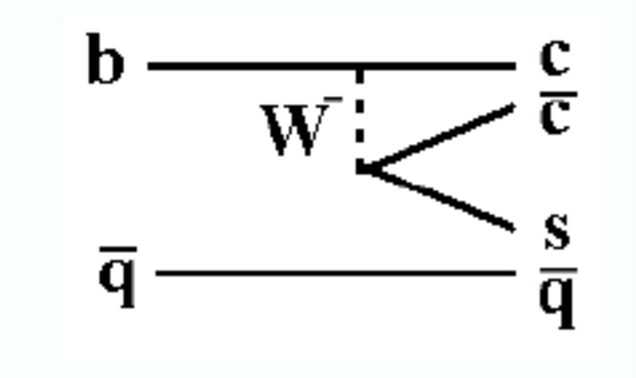
l)

Benefits of hadron spectroscopy at B-factories

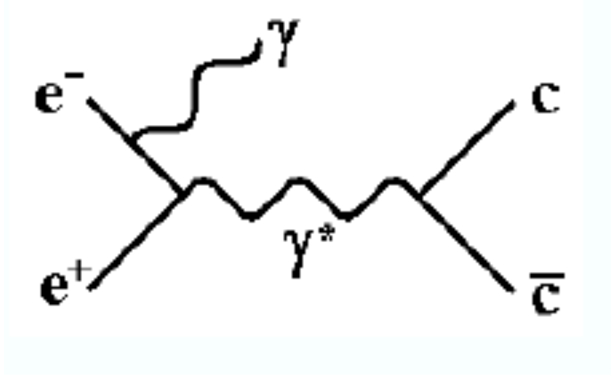
- High resolution, hermetic detector with good particle identification capability
- Efficient reconstruction of neutrals (π^0, η, …)
- Reconstruct single resonance to explore recoiling system (e.g. $e^+e^- \to J/\psi\ X$)
- Using tagged events (i.e. with a fully reconstructed partner B) to measure absolute branching fractions
  - Essential for XYZ studies!
- Variety of production mechanisms accessible



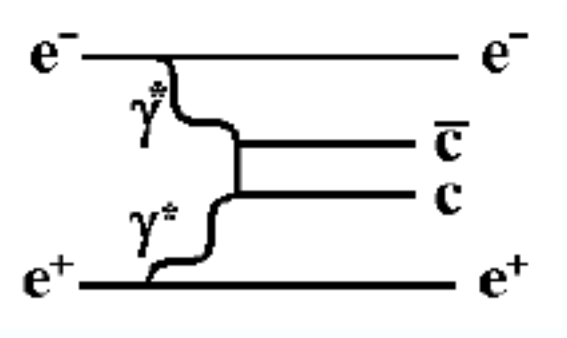
B decays



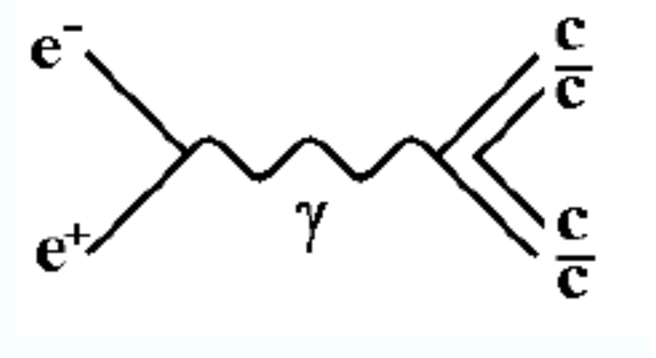
Initial state radiation



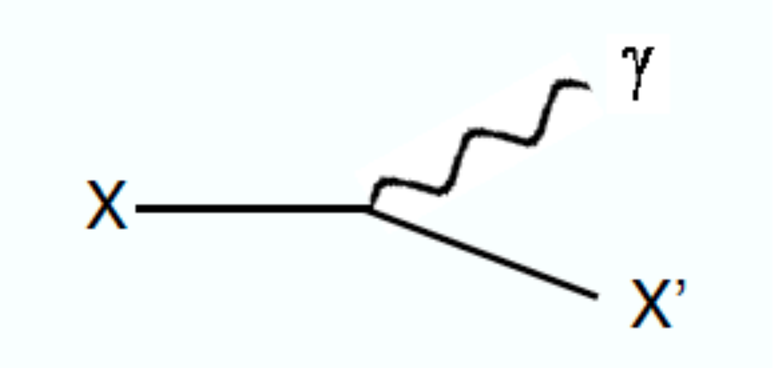
Two-photon



Double charmonium

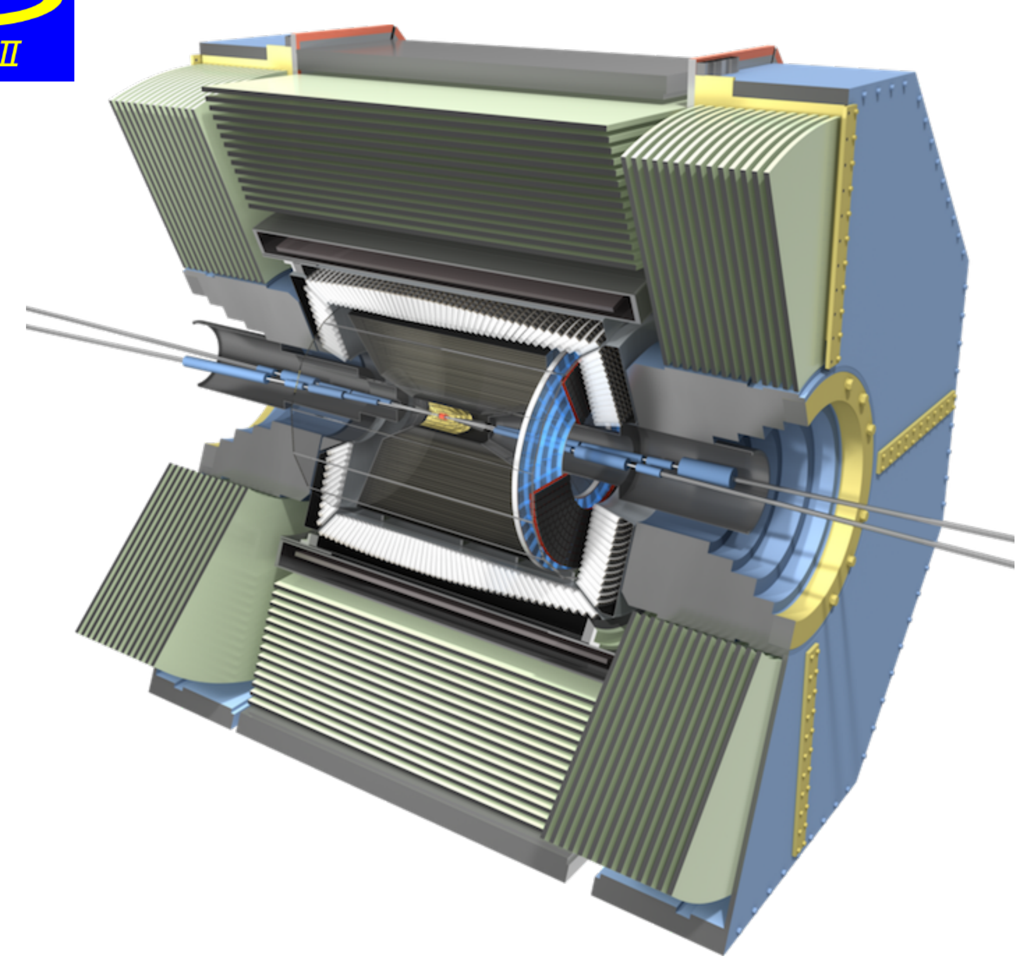


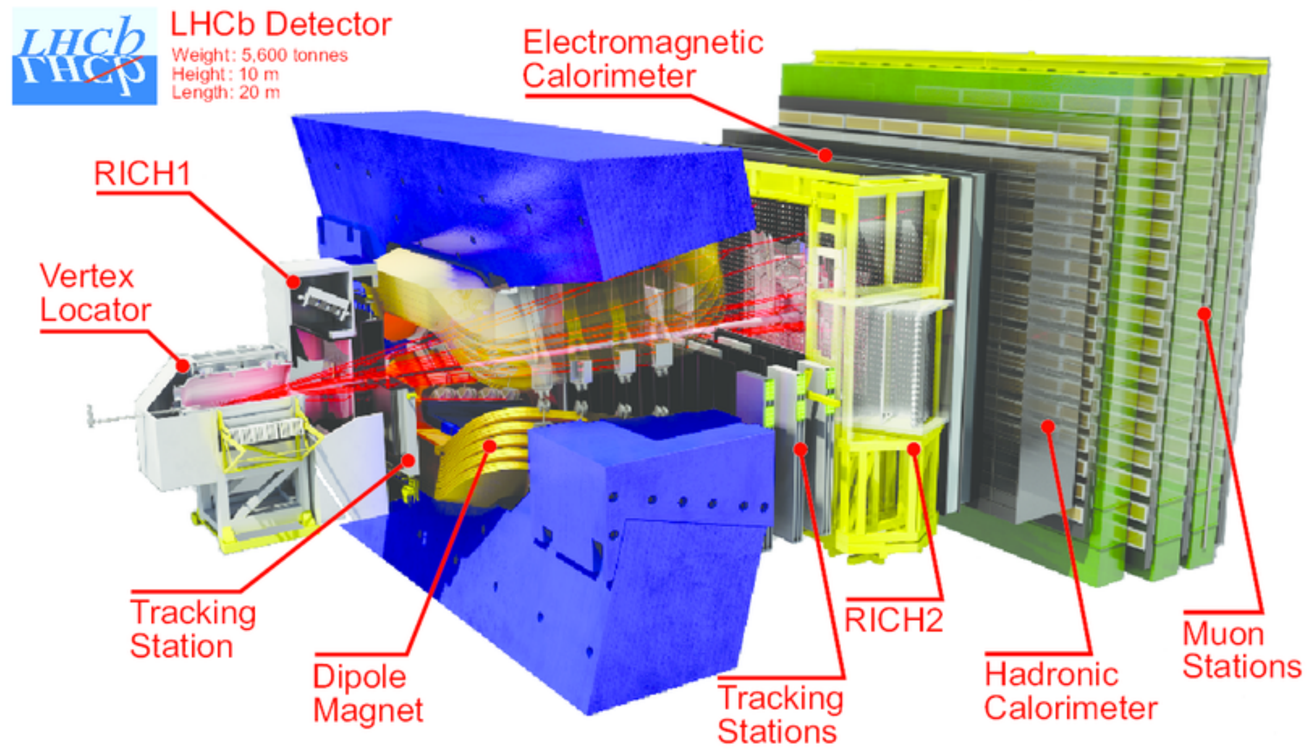
Quarkonium transitions



Belle II and LHCb: competition and complementarity

Property	LHCb	Belle II
$\sigma_{b\bar{b}}$ (nb)	~150,000	~1
Integrated luminosity (fb^{-1})	~25	~50,000
Background level	Very high	Low
Typical efficiency	Low	High
Neutral reconstruction	Inefficient	Efficient
Initial state	Not well known	Well known
Decay-time resolution	Excellent	Very good
Collision spot size	Large	Tiny
Heavy bottom hadrons	B_S, B_c, b-baryons	Partial B_S
τ physics capability	Limited	Excellent
B-flavor tagging efficiency	3.5-6%	~36%

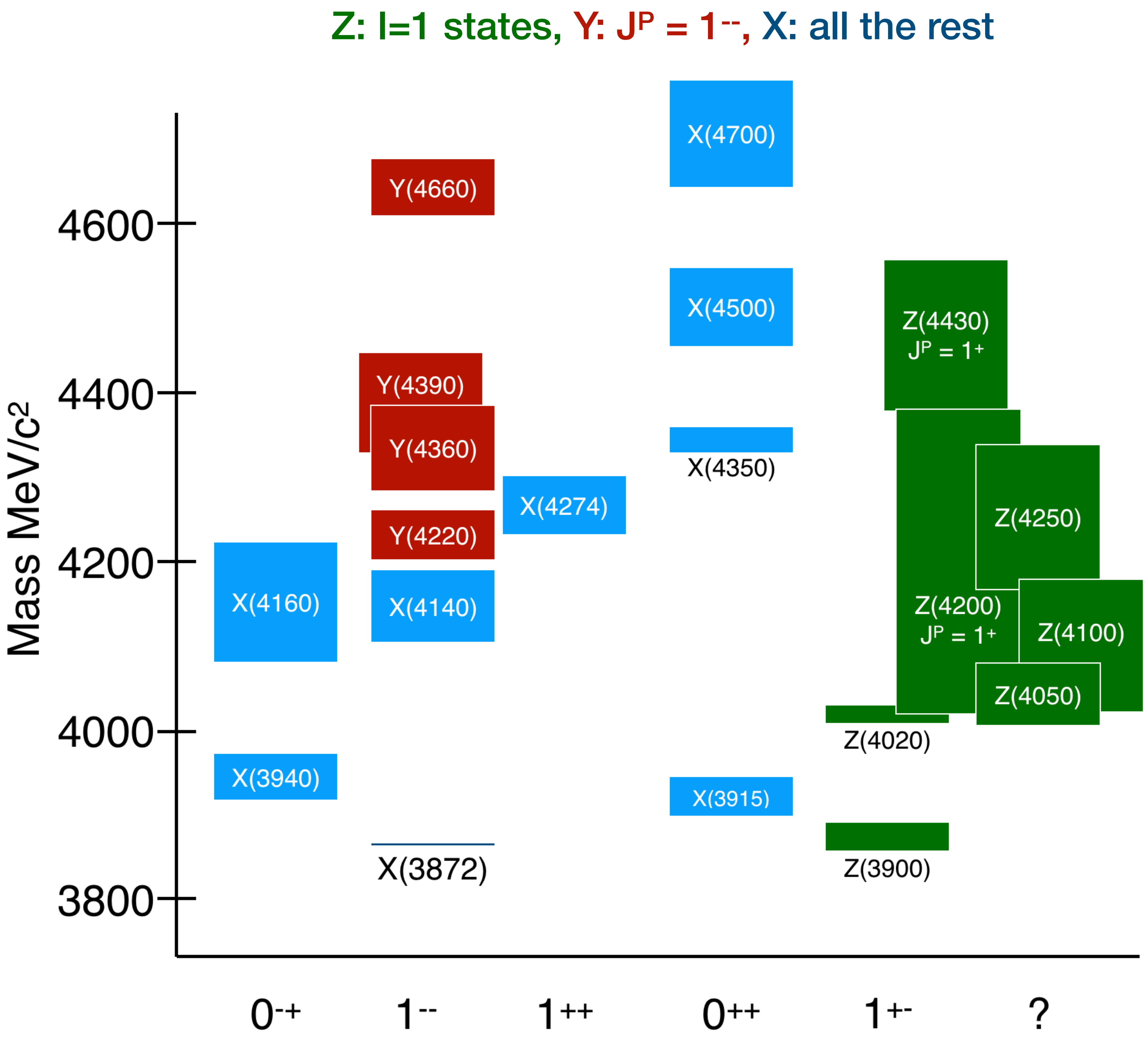




Prospects for XYZ at Belle II

- With full Belle II statistics, expect copious production of interesting known states
  - Enables search for new states near thresholds
  - Perform amplitude analyses to determine J^{PC}
  - Precise determination of resonance parameters (see Hirata-san's talk next!)

State	Production and Decay	N
X(3872)	$B \to K X(3872)$, $X(3872) \to J/\psi \pi^+\pi^-$	$\simeq 14400$
Y(4260)	ISR, $Y(4260) \to J/\psi \pi^+\pi^-$	$\simeq 29600$
Z(4430)	$B \to K^{\mp} Z(4430)$, $Z(4430) \to J/\psi \pi^{\pm}$	$\simeq 10200$



Prospects for XYZ at Belle II

- Belle II is uniquely positioned to:
  - study XYZ in both B decays and at threshold
    - Z states in B decays are wider and not obviously coupled to thresholds
    - Z states in direct production are narrower and near thresholds

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X(3872)	$B \to K X(3872)$, $X(3872) \to J/\psi \pi^+ \pi^-$	$\simeq 14400$
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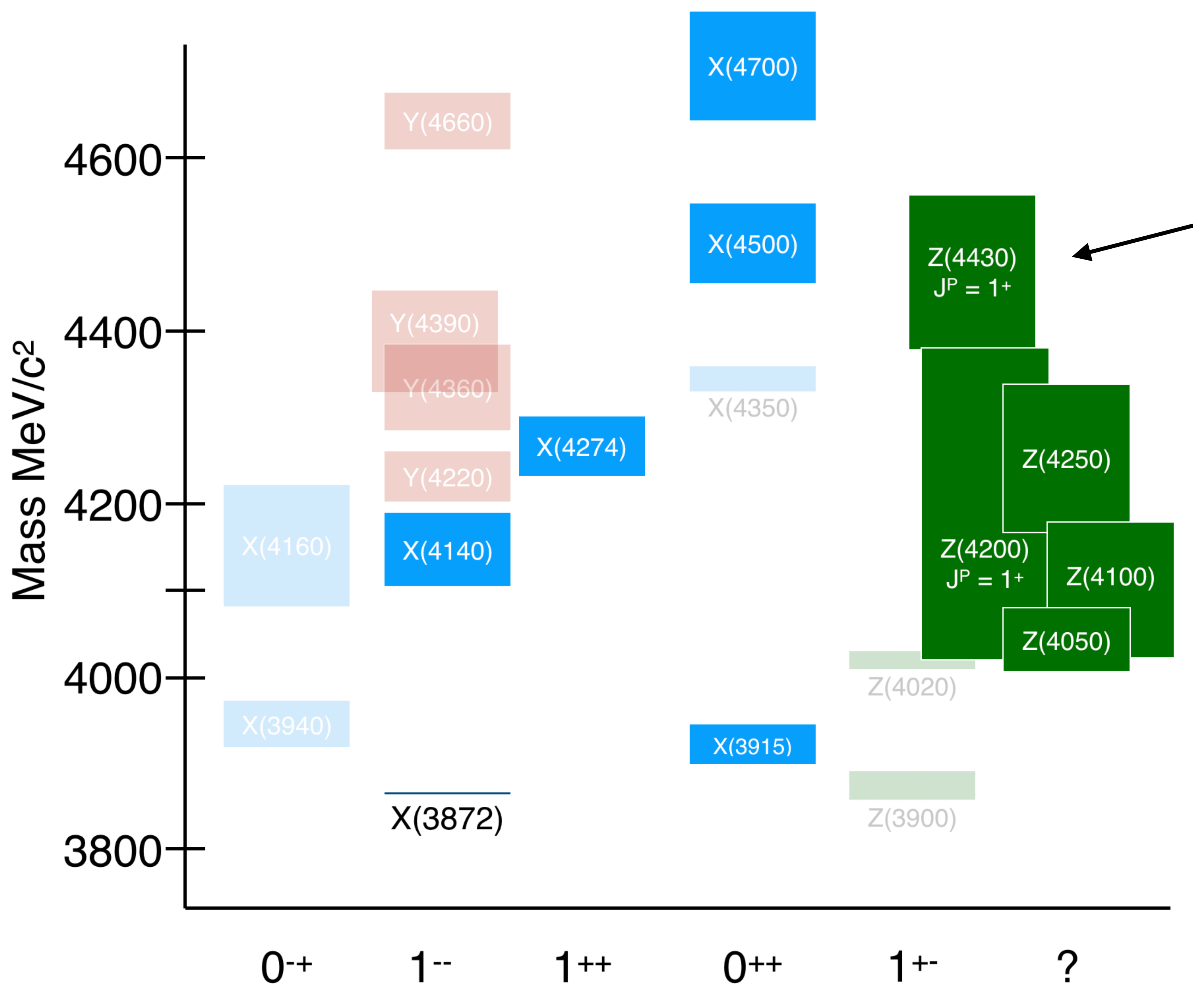
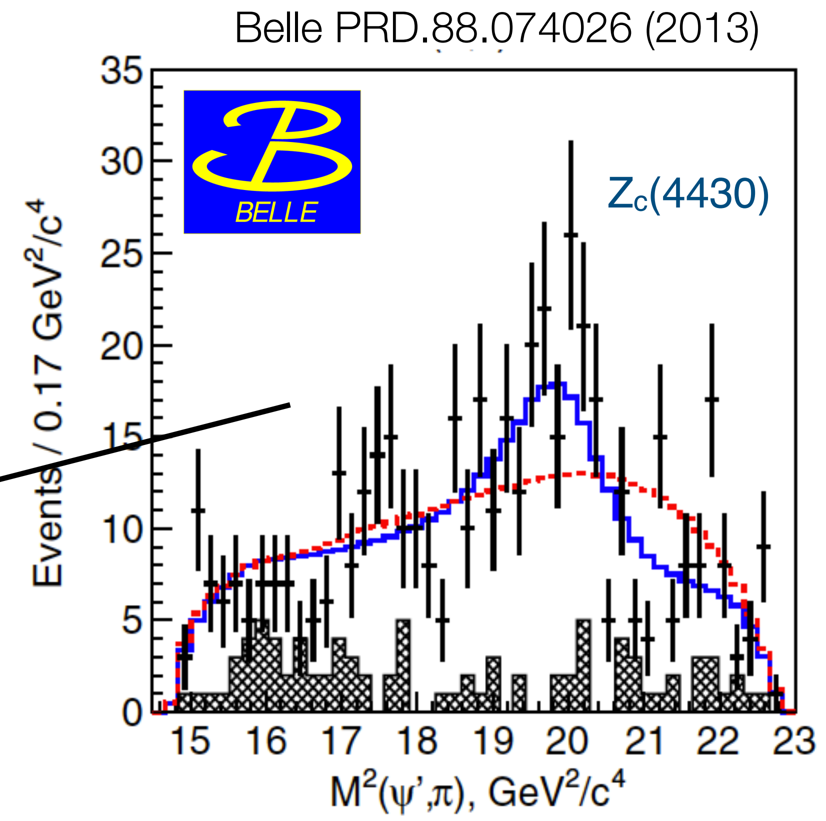
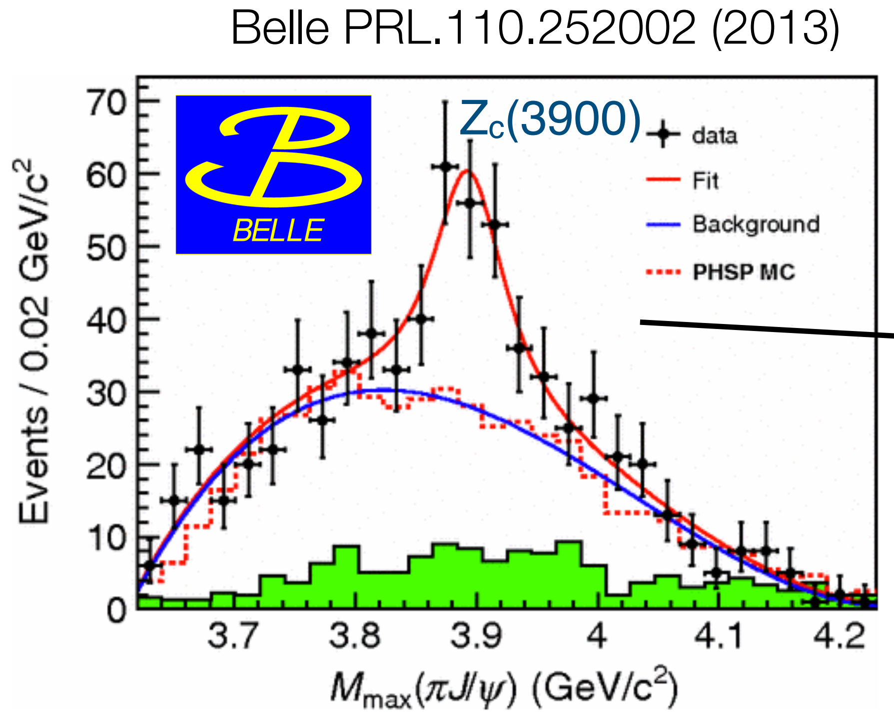
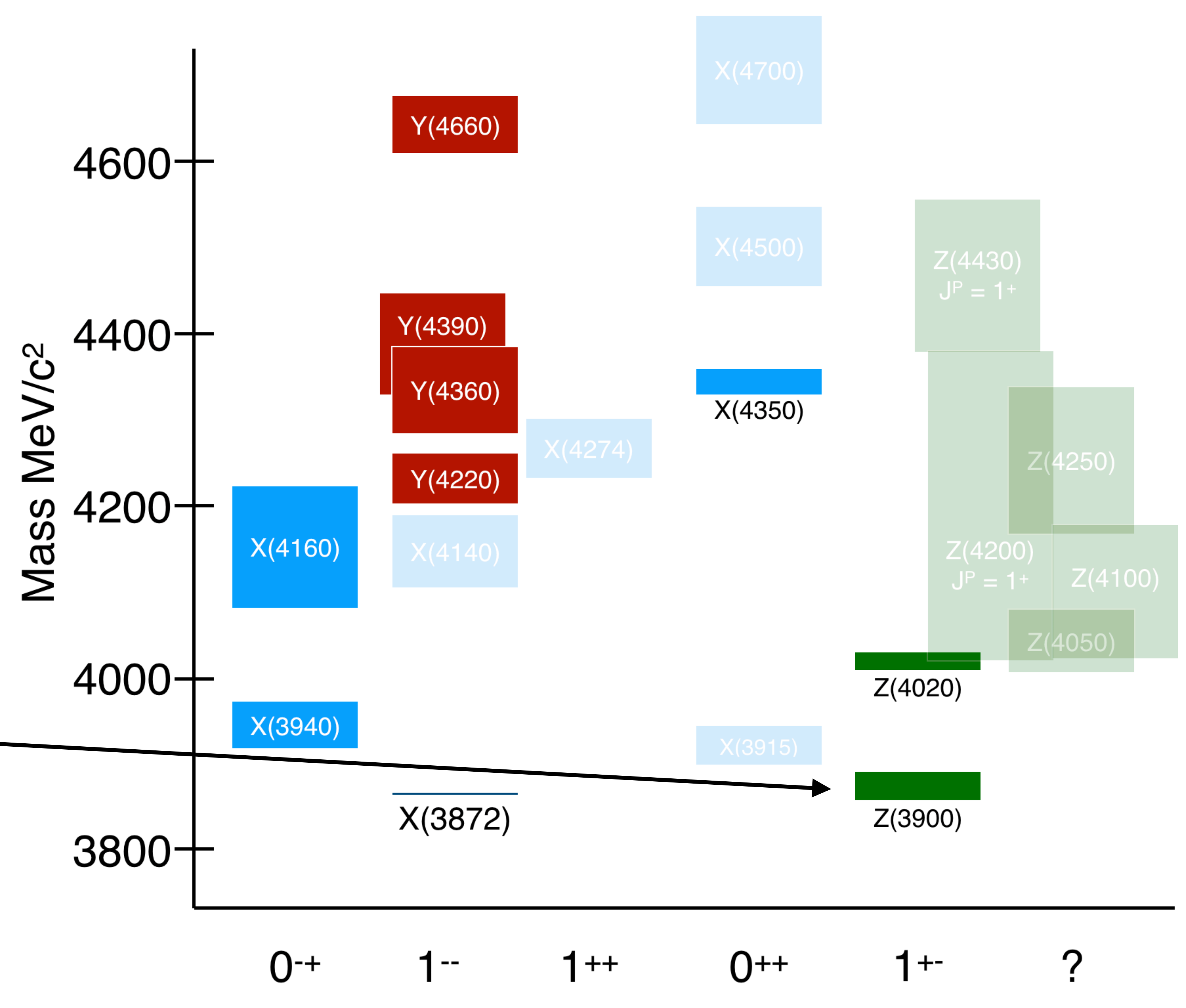
XYZ in B decays







XYZ in e^+e^- annihilation



Prospects for XYZ at Belle II

- Belle II is uniquely positioned to:
  - study XYZ in both B decays and at threshold
  - study line shapes with ISR production

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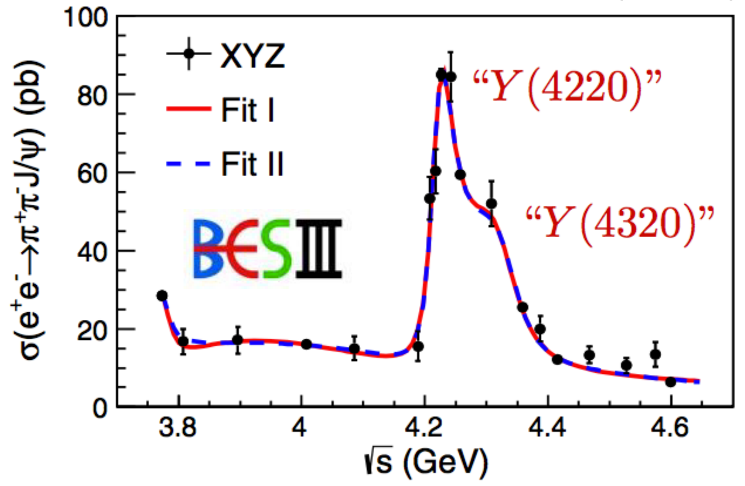
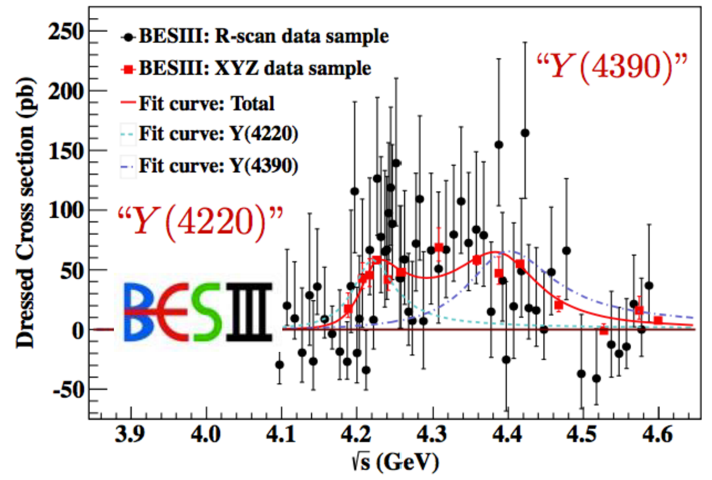
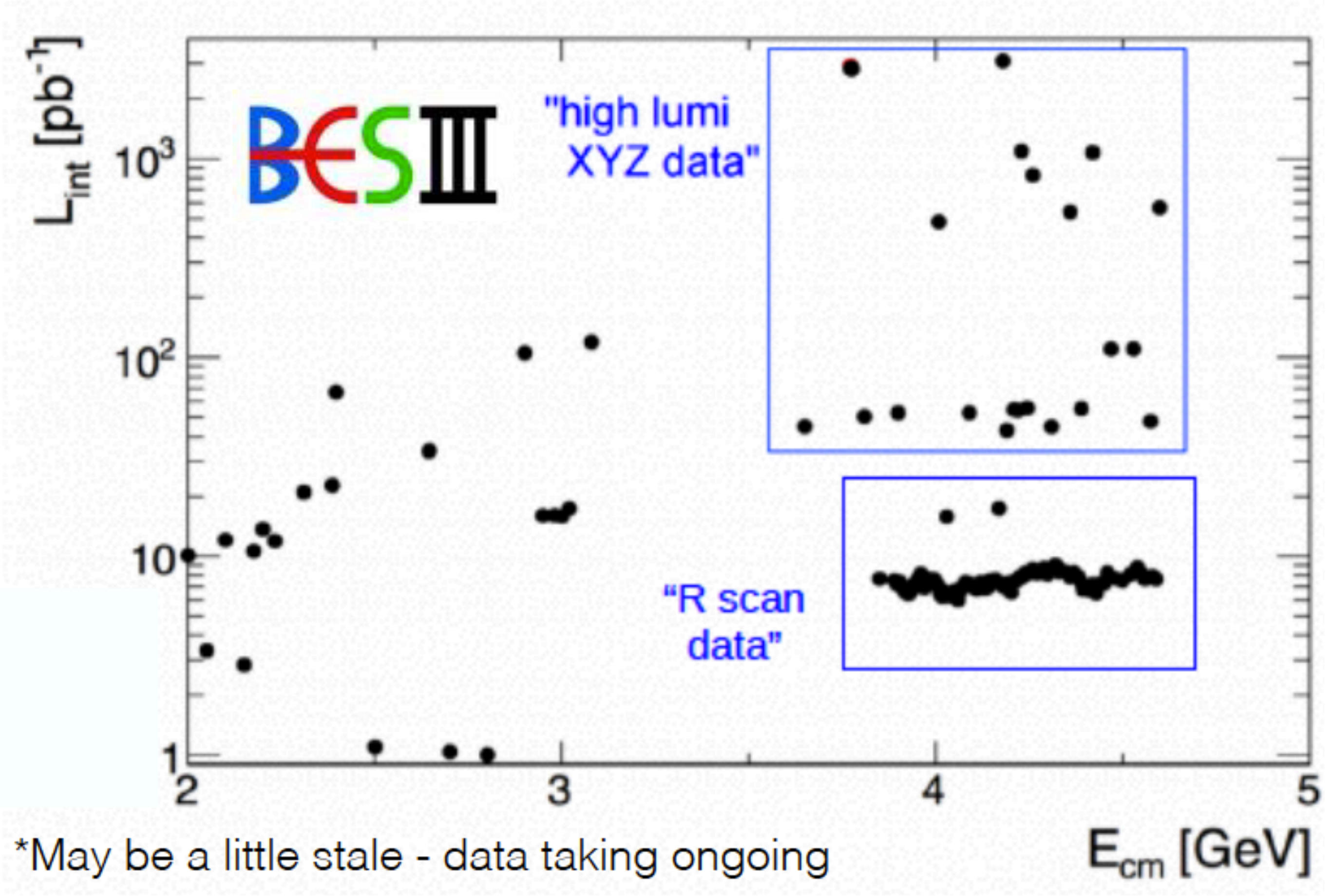
Golden channels	E_{cm} (GeV)	Statistics error (%)	XYZ
$\pi^+\pi^- J/\psi$	4.23	7.5 (3.0)	Y(4008), Y(4260), $Z_c(3900)$
$\pi^+\pi^- \psi(2S)$	4.36	12 (5.0)	Y(4260), Y(4360), Y(4660), $Z_c(4050)$
$K^+K^- J/\psi$	4.53	15 (6.5)	Z_{cs}
$\pi^+\pi^- h_c$	4.23	15 (6.5)	Y(4220), Y(4390), $Z_c(4020)$, $Z_c(4025)$
$\omega \chi_{c0}$	4.23	35 (15)	Y(4220)

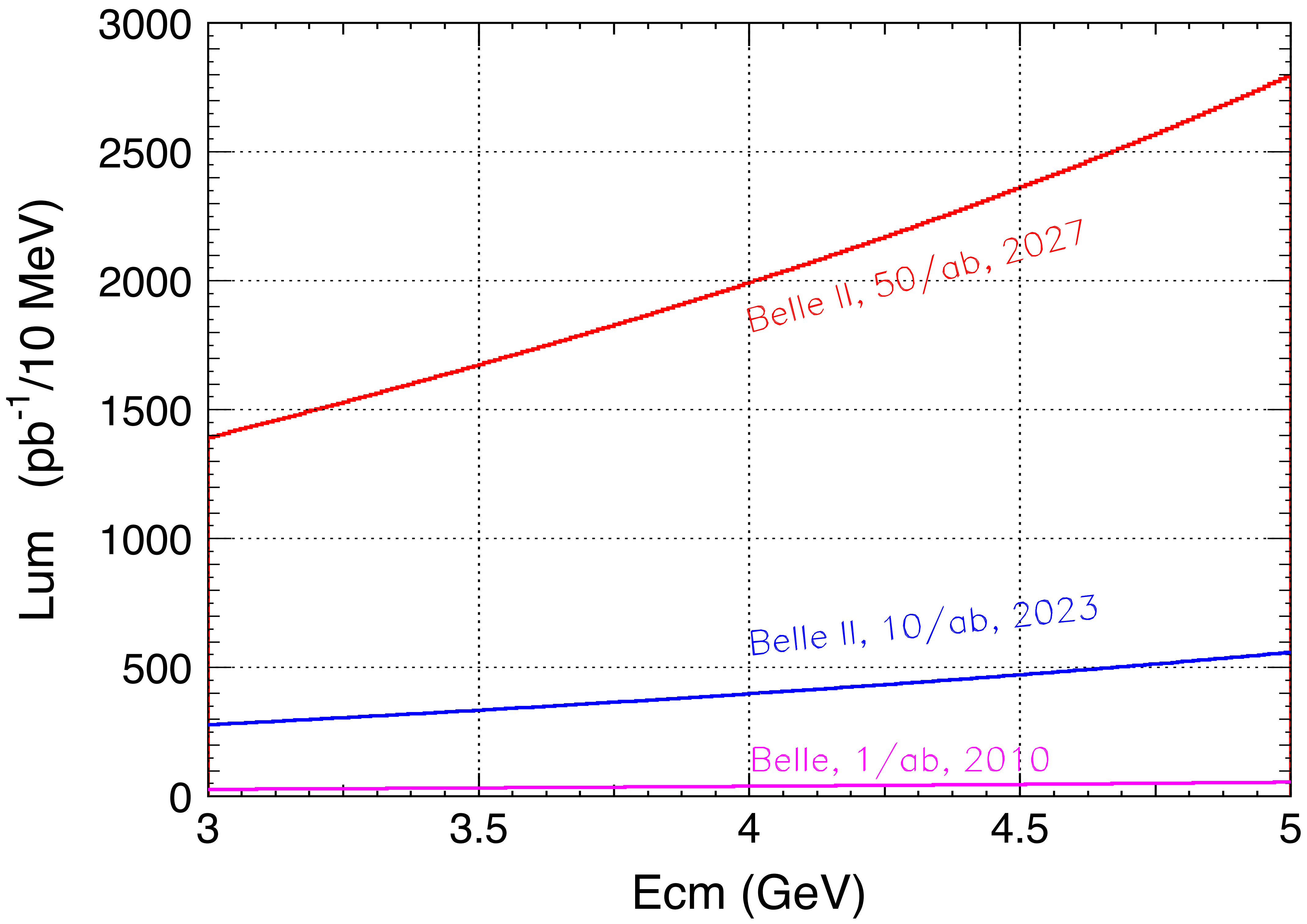
BESIII PRL.118.092001 (2017)



BESIII PRL.118.092002 (2017)



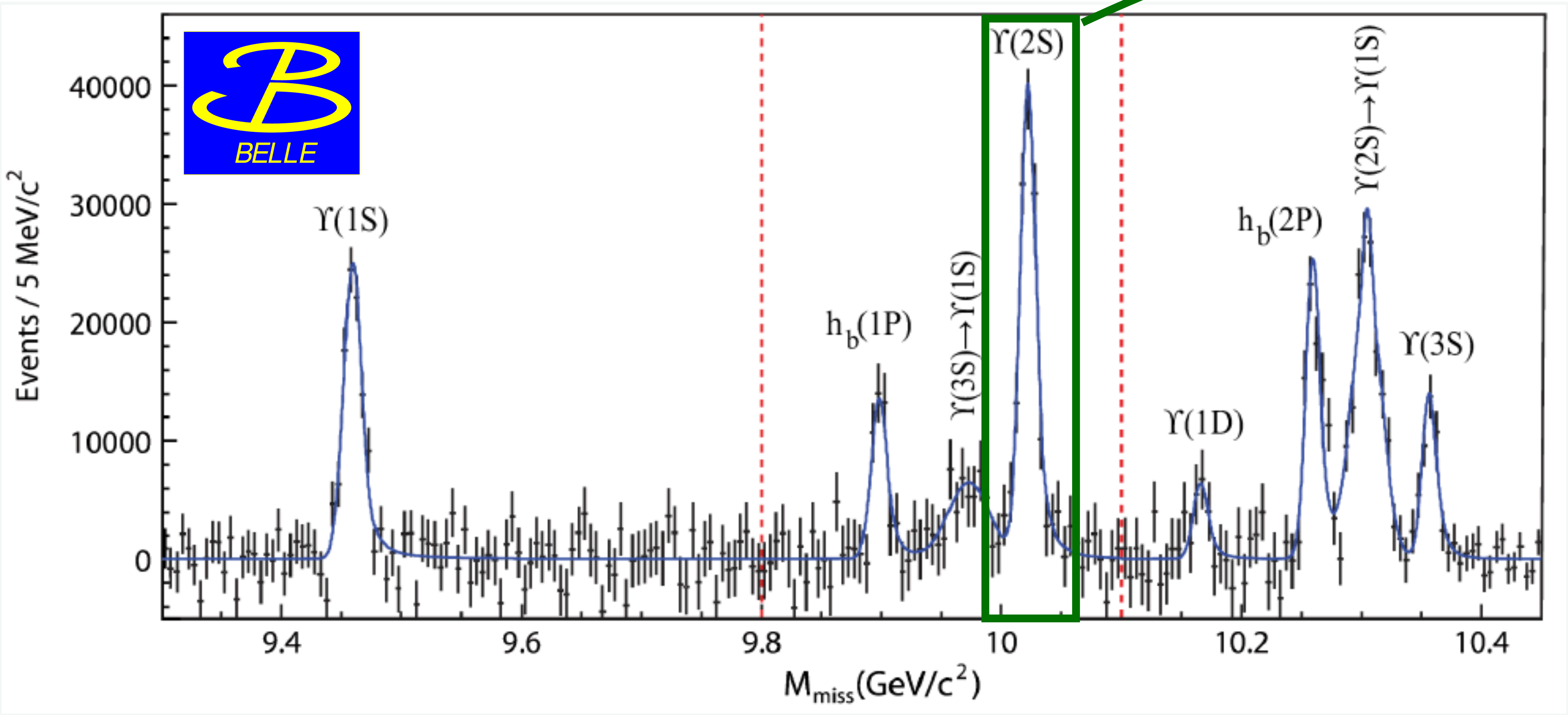




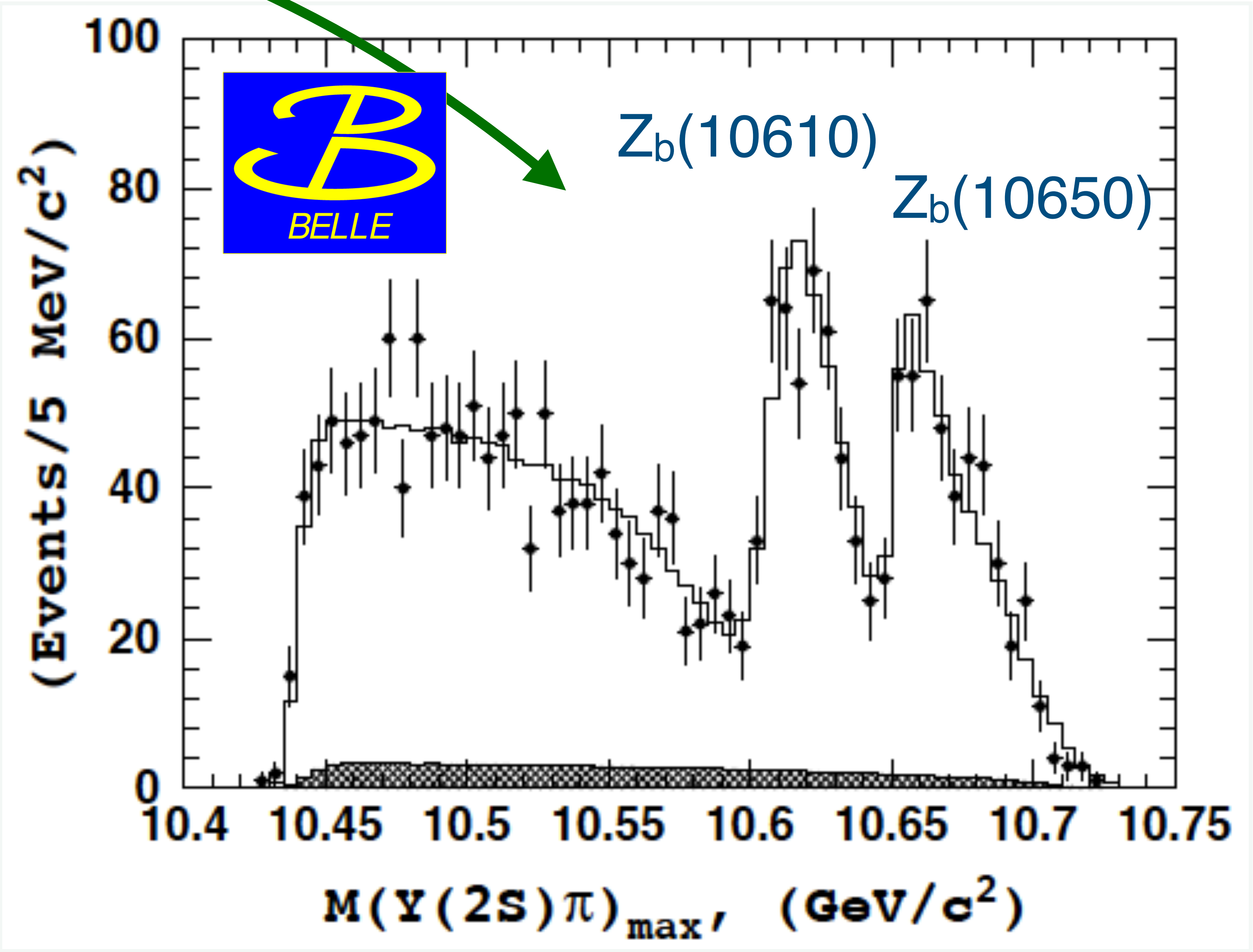
Prospects for XYZ at Belle II

- Belle II is uniquely positioned to:
  - study XYZ in both B decays and at threshold
  - study line shapes with ISR production
  - determine absolute branching fractions with recoil mass measurements
    - Important information to understand XYZ states

Belle PRL.108.032001 (2012)



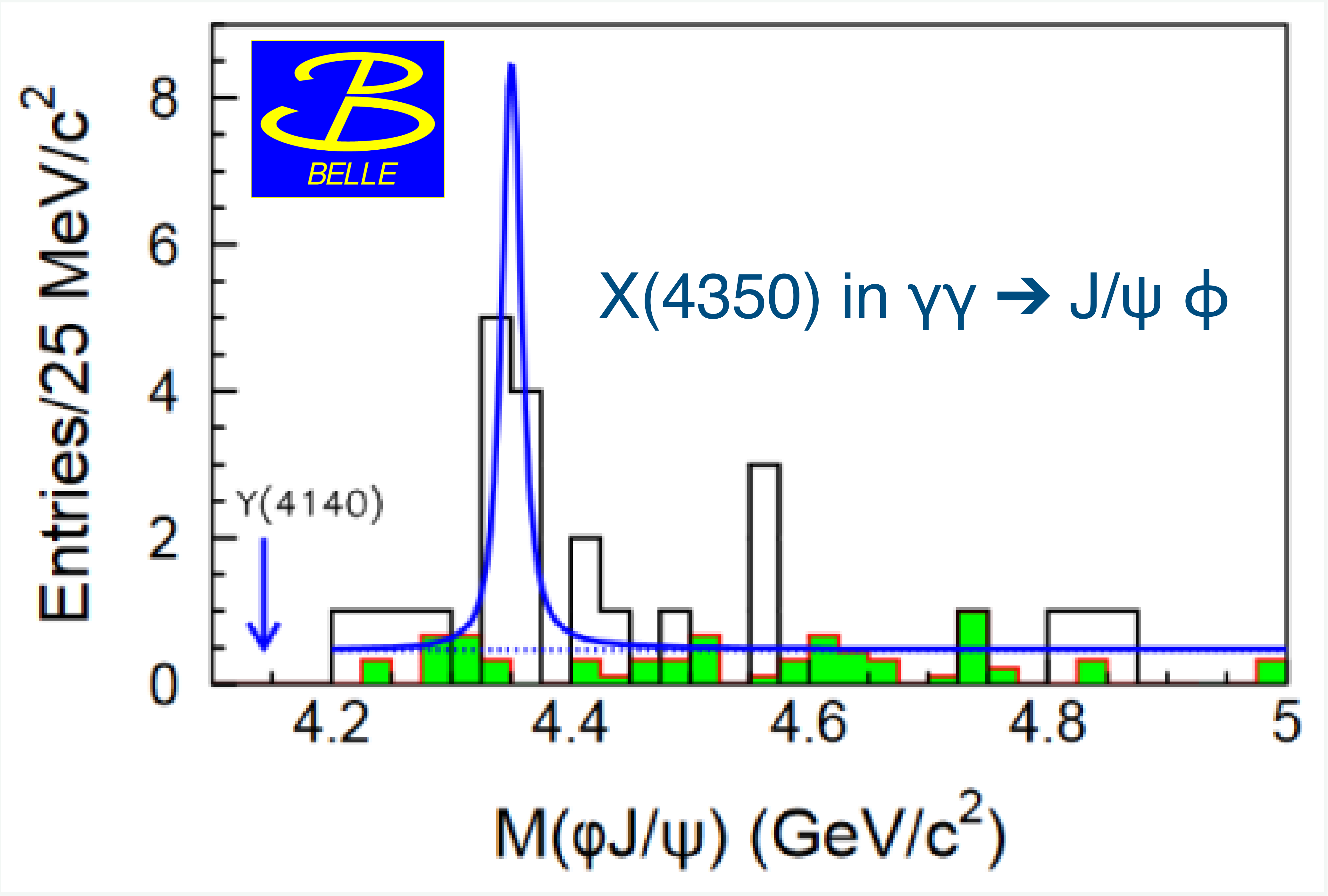
Belle PRL.108.122001 (2012)



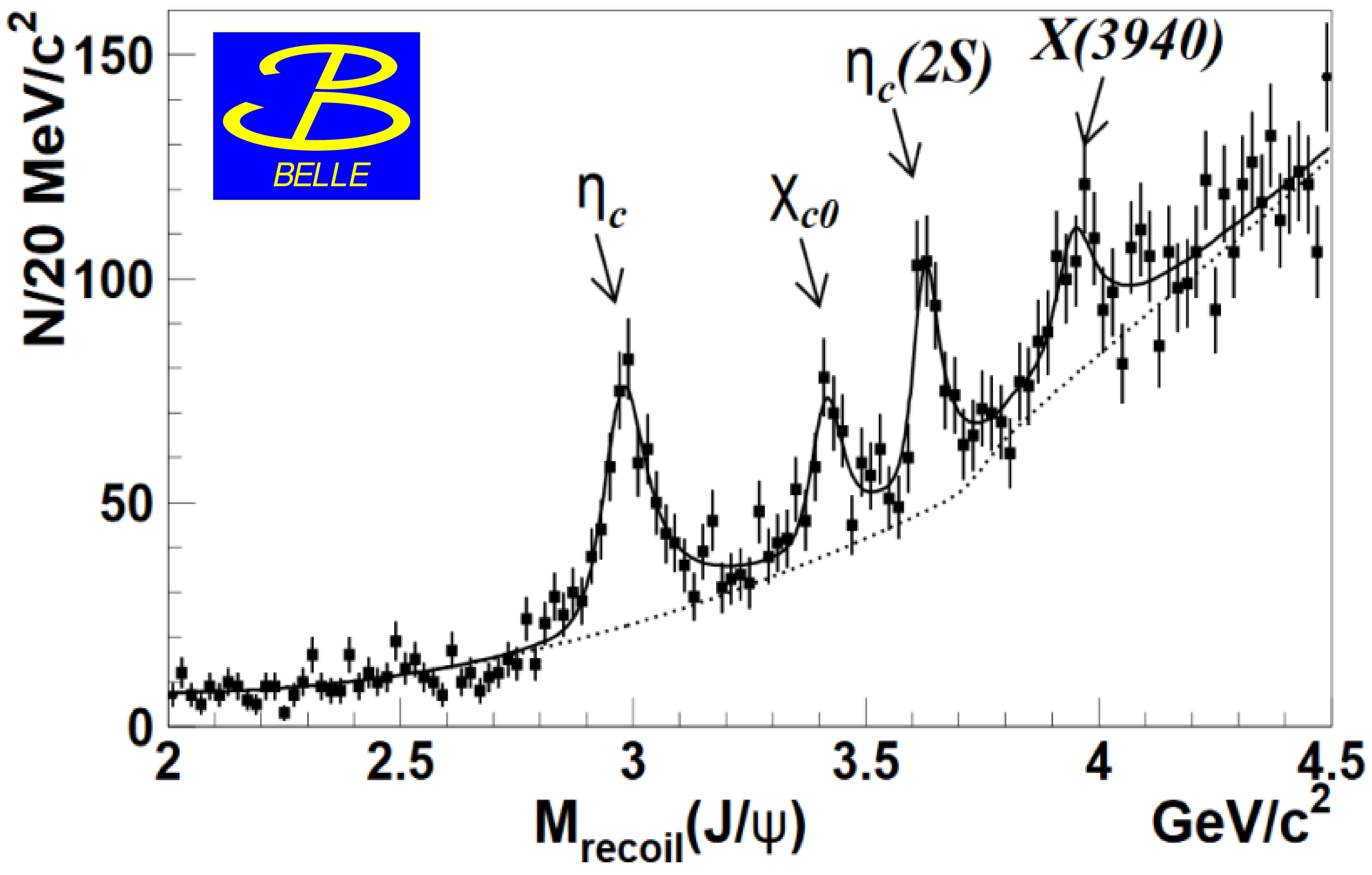
Prospects for XYZ at Belle II

- Belle II is uniquely positioned to:
  - study XYZ in both B decays and at threshold
  - study line shapes with ISR production
  - determine absolute branching fractions with recoil mass measurements
  - study XYZ two-photon and double charmonium production
    - Potential probe for new states using recoil against "onium" states

Belle PRL.104.112004 (2010)



Belle, PRL.98.082001 (2005)



Prospects for XYZ at Belle II

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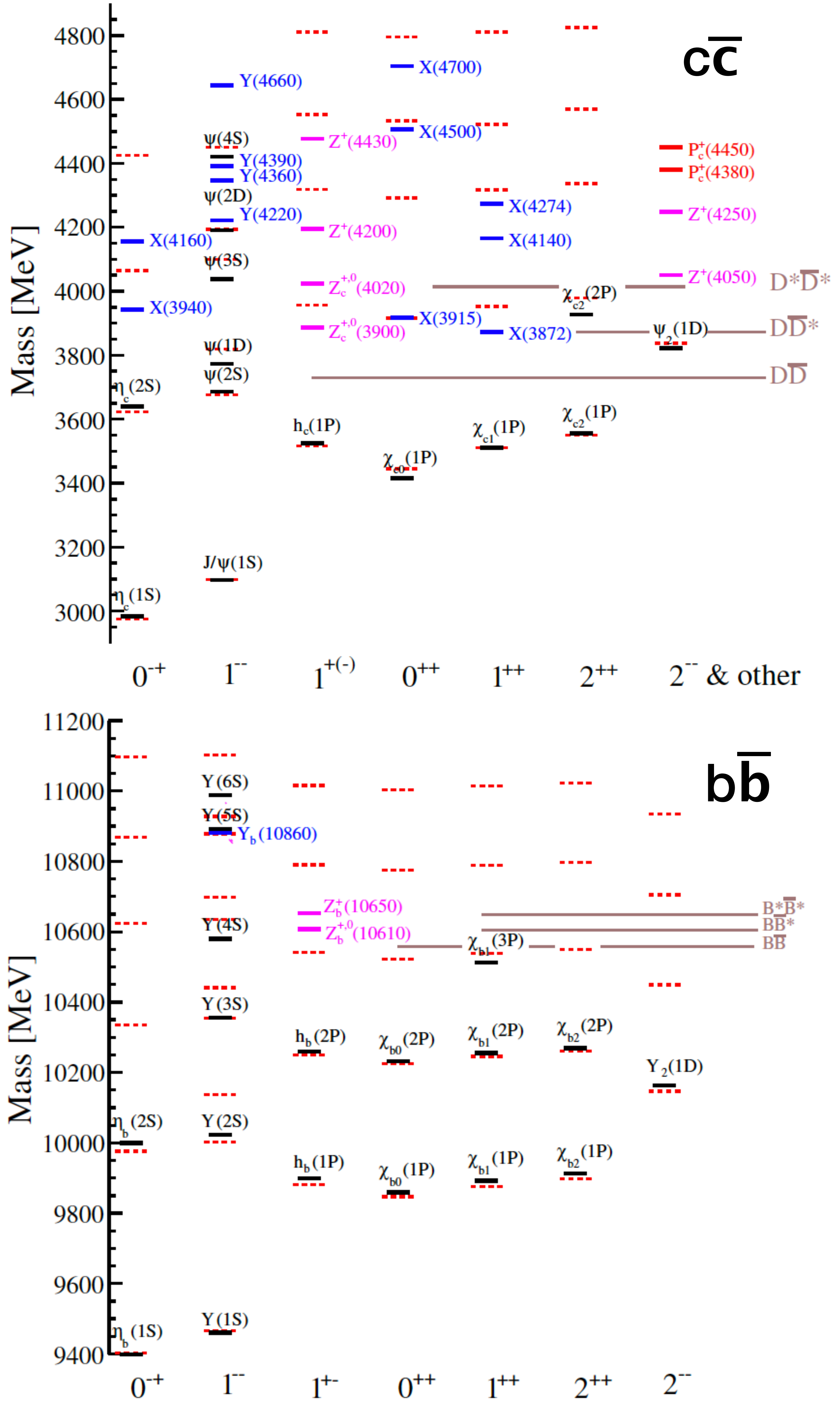
  - study XYZ in both B decays and at threshold
  - study line shapes with ISR production
  - determine absolute branching fractions with recoil mass measurements
  - study XYZ two-photon and double charmonium production
  - search for new XYZ states in the b sector

Experiment	Scans Off. Res.	$\Upsilon(6S)$ fb^{-1}	$\Upsilon(5S)$ fb^{-1}	$\Upsilon(5S)$ 10^6	$\Upsilon(4S)$ fb^{-1}	$\Upsilon(4S)$ 10^6
CLEO	17.1	-	0.1	0.4	16	17.1
BaBar	54	R_b scan			433	471
Belle	100	~ 5.5	36	121	711	772

Experiment	$\Upsilon(3S)$ fb^{-1}	$\Upsilon(3S)$ 10^6	$\Upsilon(2S)$ fb^{-1}	$\Upsilon(2S)$ 10^6	$\Upsilon(1S)$ fb^{-1}	$\Upsilon(1S)$ 10^6
CLEO	1.2	5	1.2	10	1.2	21
BaBar	30	122	14	99	—	
Belle	3	12	25	158	6	102

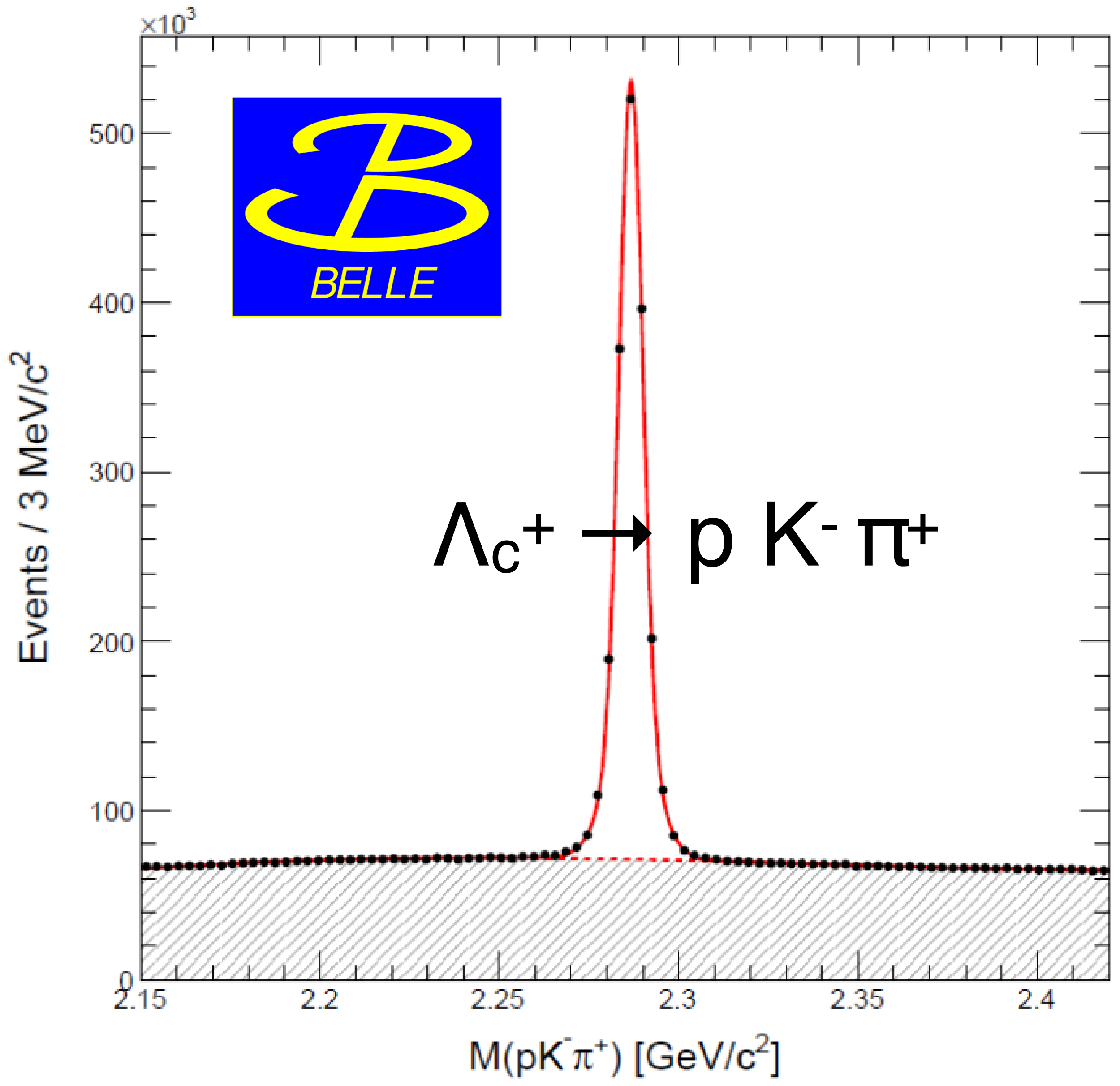


S. Olsen et al., Rev. Mod. Phys. 90, 015003(2018)

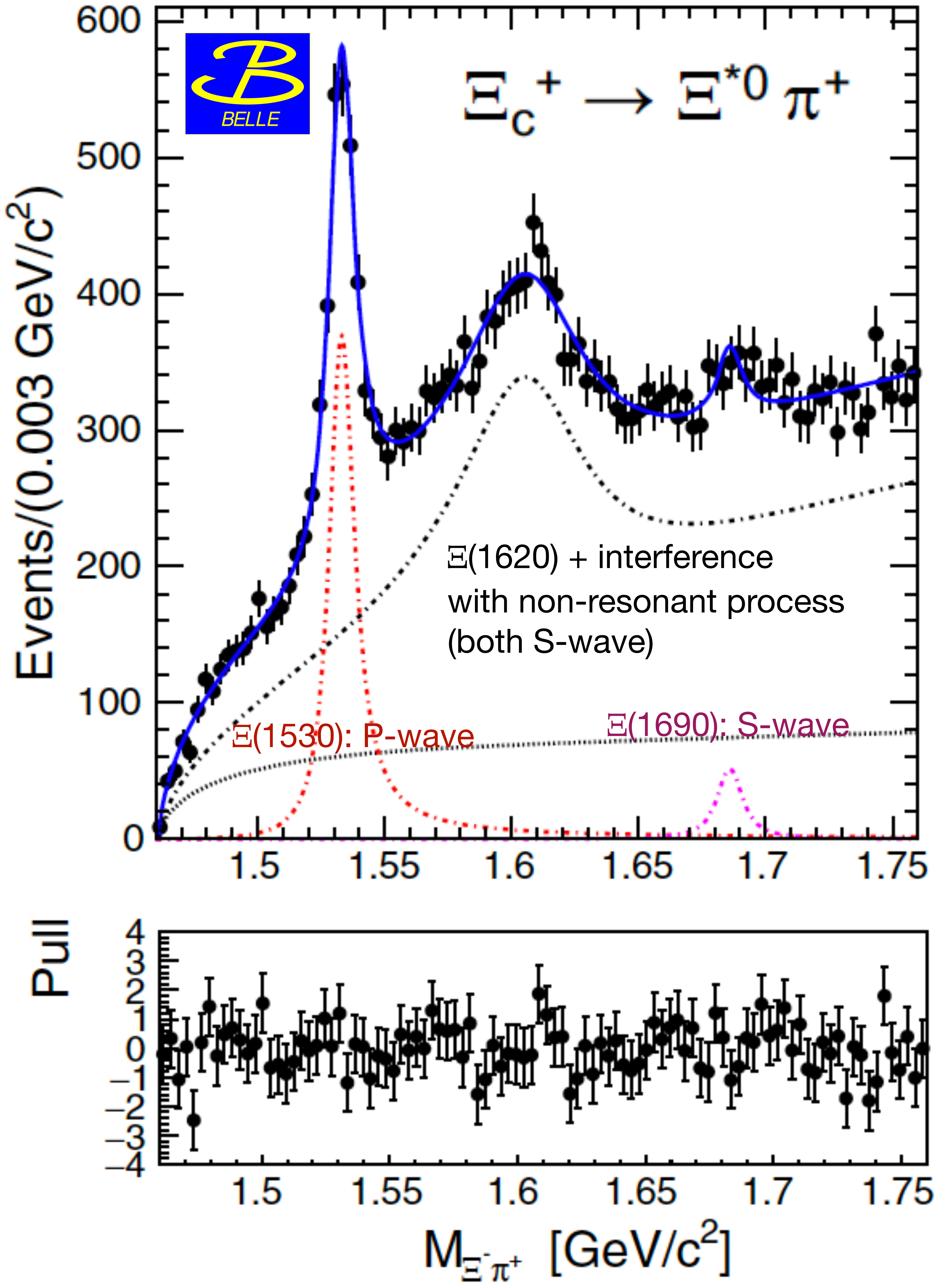
Prospects in baryon spectroscopy

- Mesons get all the attention…
- Baryon spectrum is much more complicated than quarkonia
  but exotic candidates exist even in the first excited states
  - Notable examples include the Λ(1405) and N(1440)
- Excited spectrum not well understood
  - Many missing states
  - Multiple candidates for known states
  - Few quantum number determinations for baryons containing c or b quarks
- Belle still actively publishing

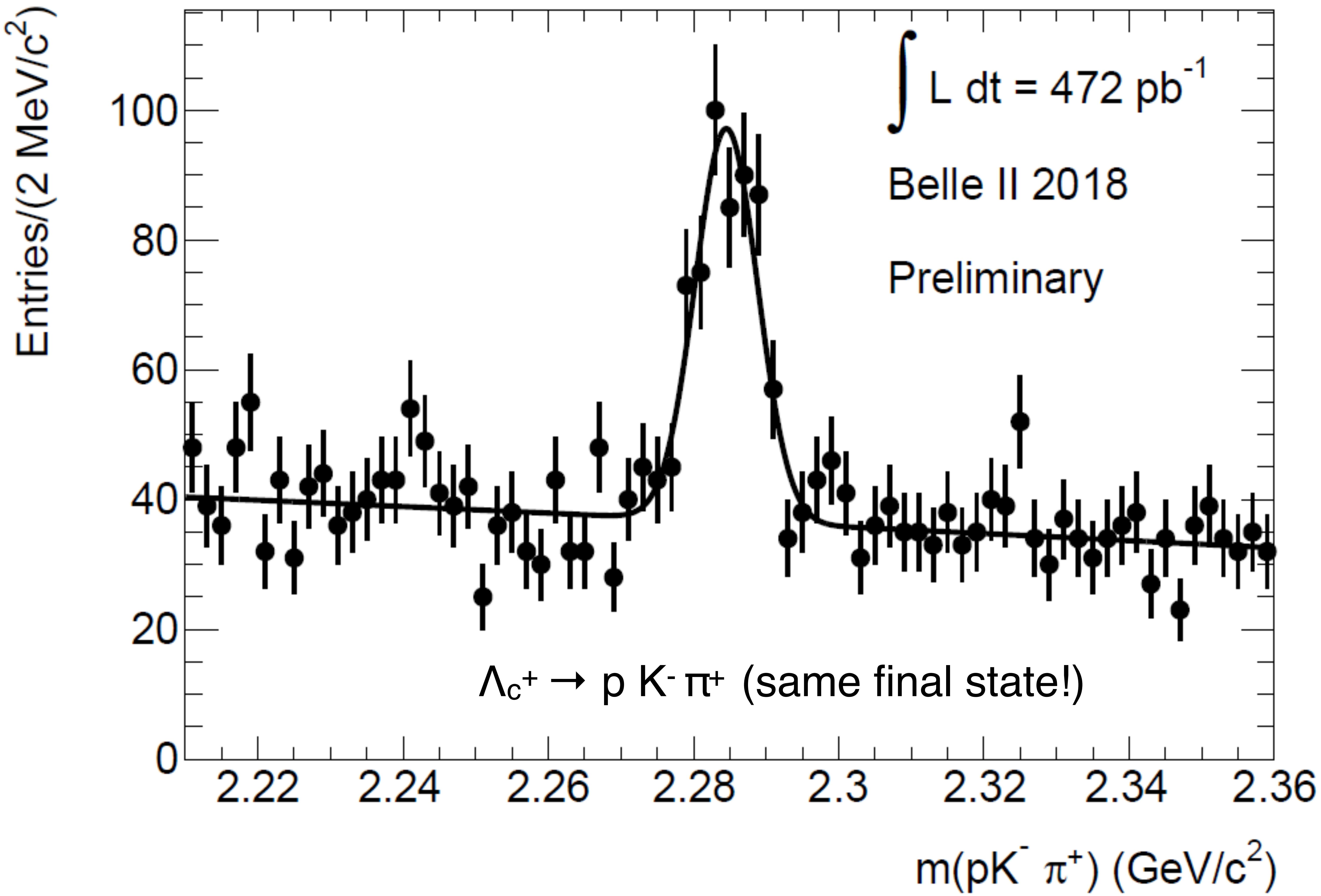
- Belle II can
  - measure quantum numbers for excited charmed baryons
  - search for excited baryons in charmed baryon decays
  - search for exotic candidate states



Belle PRL.122.072501 (2019)



Λ_c already observed with Phase 2 data!



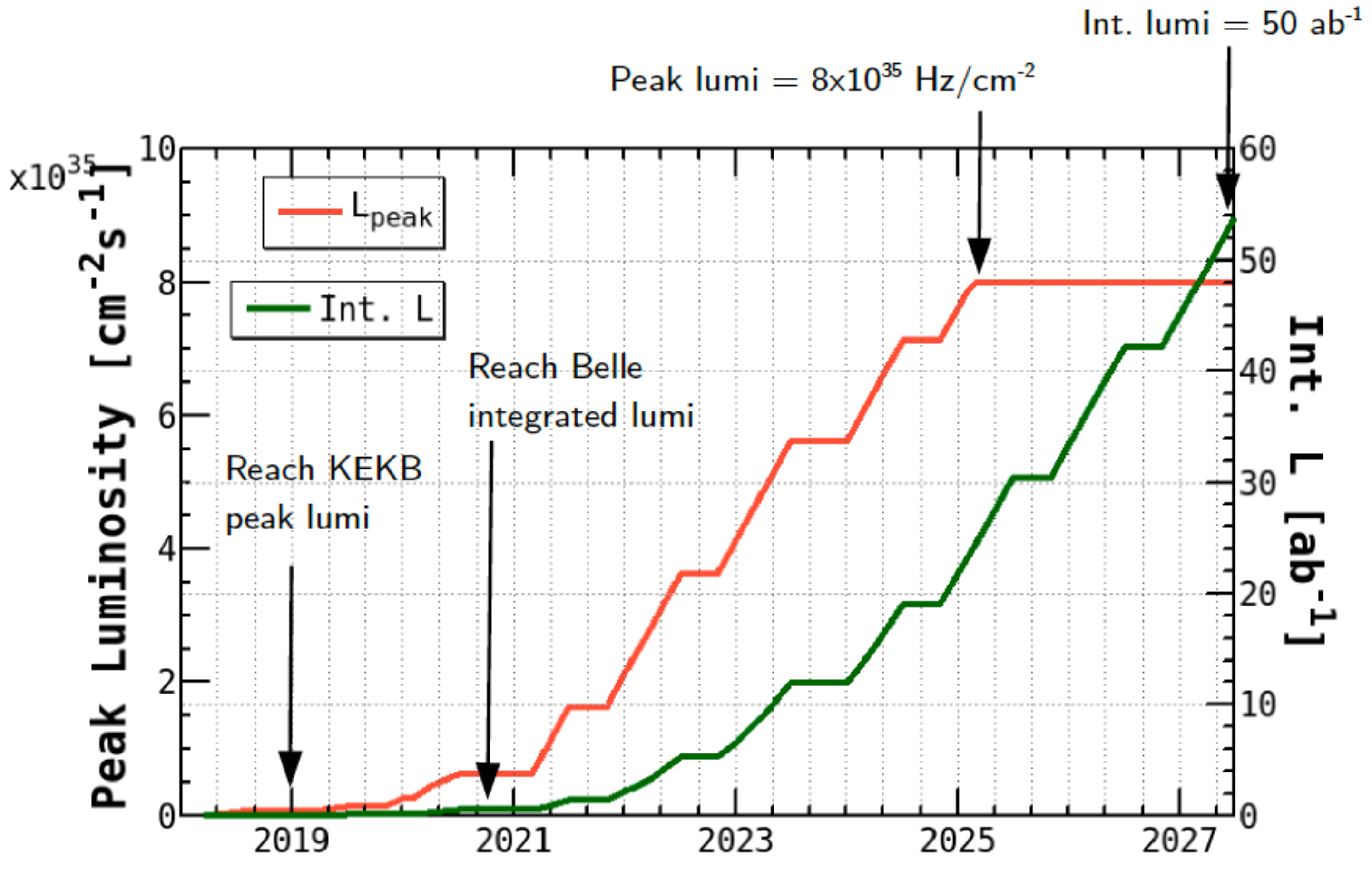
Summary

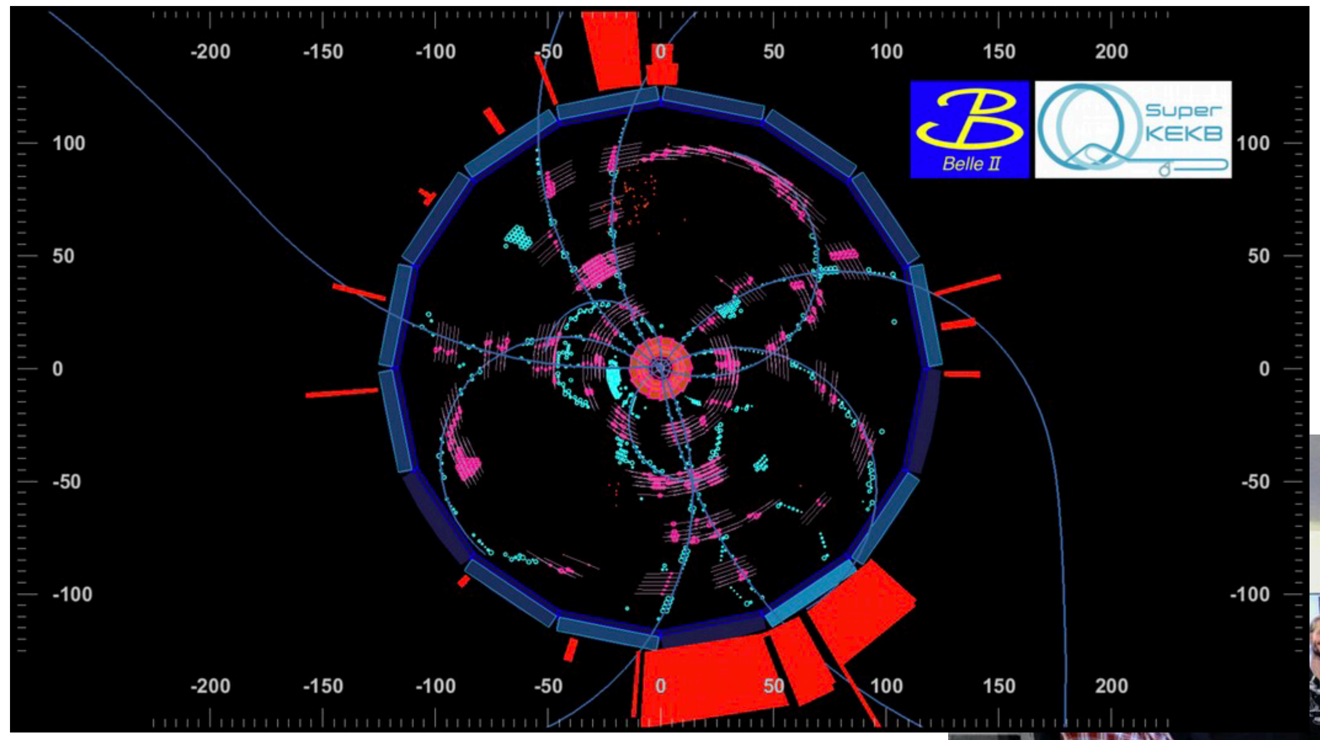
- Major upgrade at KEK for the next generation B-factory
  - Many detector components and electronics replaced, software and analysis tools also improved!
- Cosmic data taking with central DAQ in 2017, first physics without vertexing in early 2018, full detector operation in early 2019
- Belle-II experiment can make significant impacts in exotic quarkonium spectroscopy
  - Precisely measure line-shapes, map out resonances
  - Determine spin-parities, transitions, and quantum numbers
  - Search for new decay channels
  - Compare results for different production mechanisms
  - Study both meson and baryon states
  - And more!

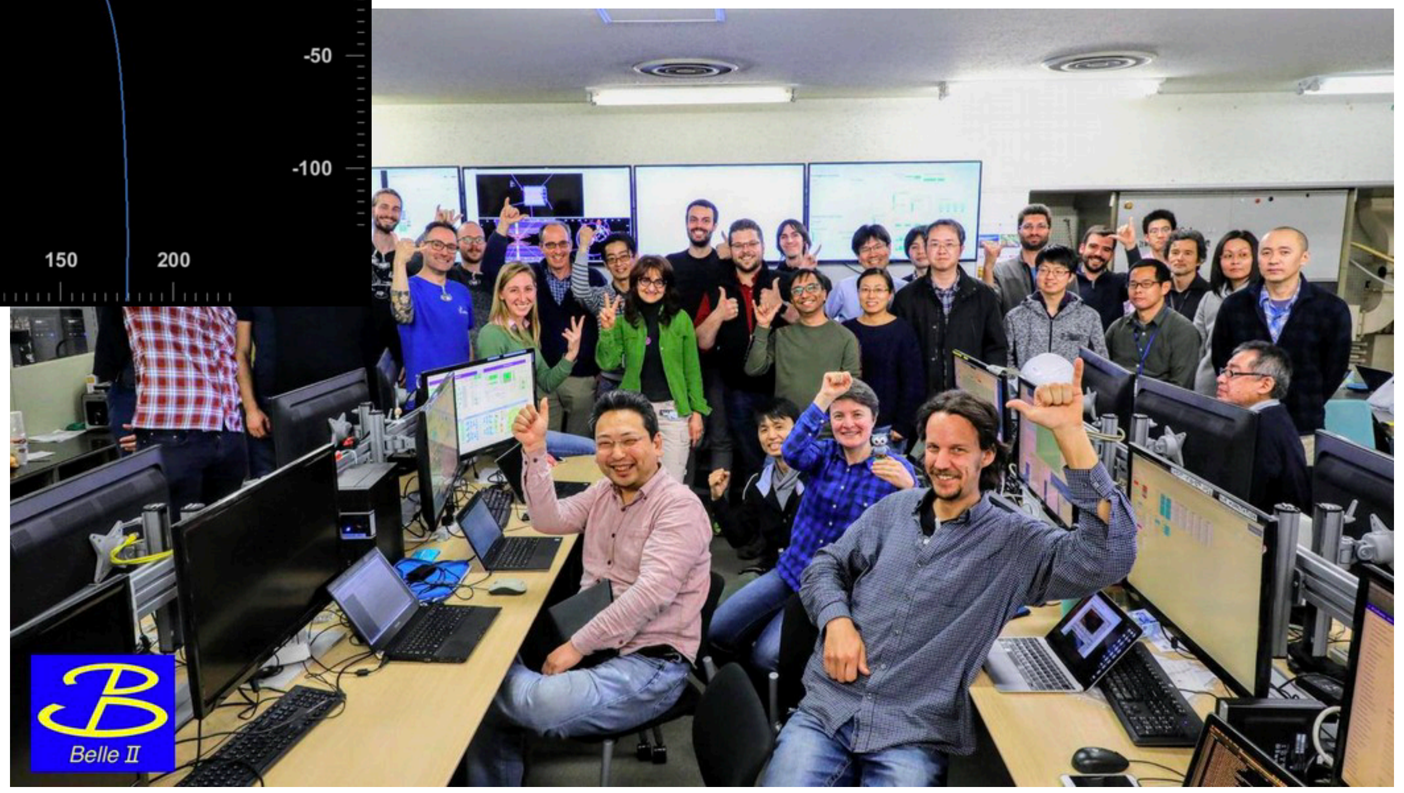
Extra

Transition from Belle to Belle II

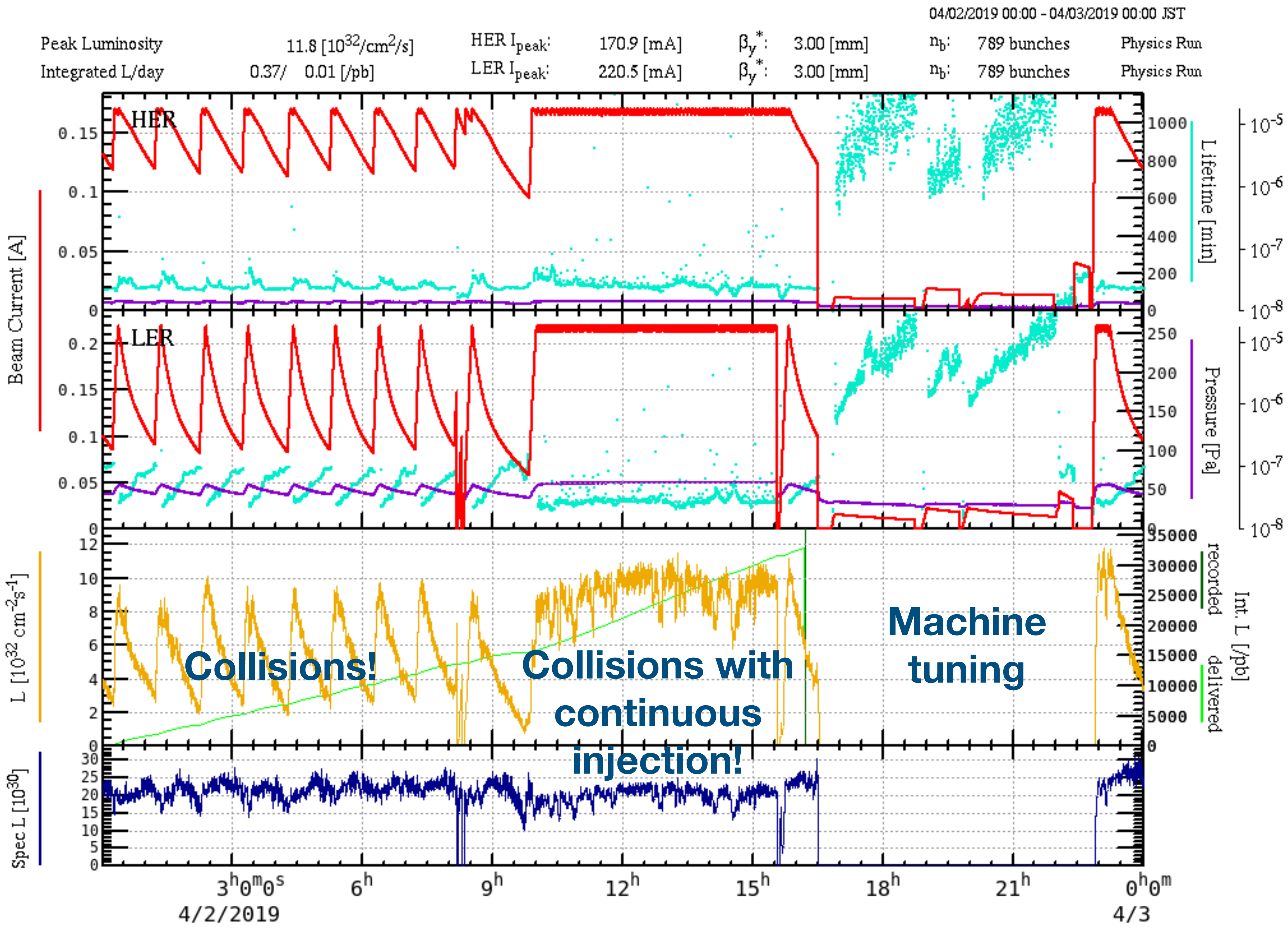
- Belle has made significant contributions to hadron spectroscopy
  - Discovery of many XYZ states
  - Better understanding of conventional hadronic states
  - Many hints of interesting physics!
  - … but we need more data!
- Belle-II will collect ~50 times as much data by leveraging upgrades to the KEK accelerator facility







Data taking has started!

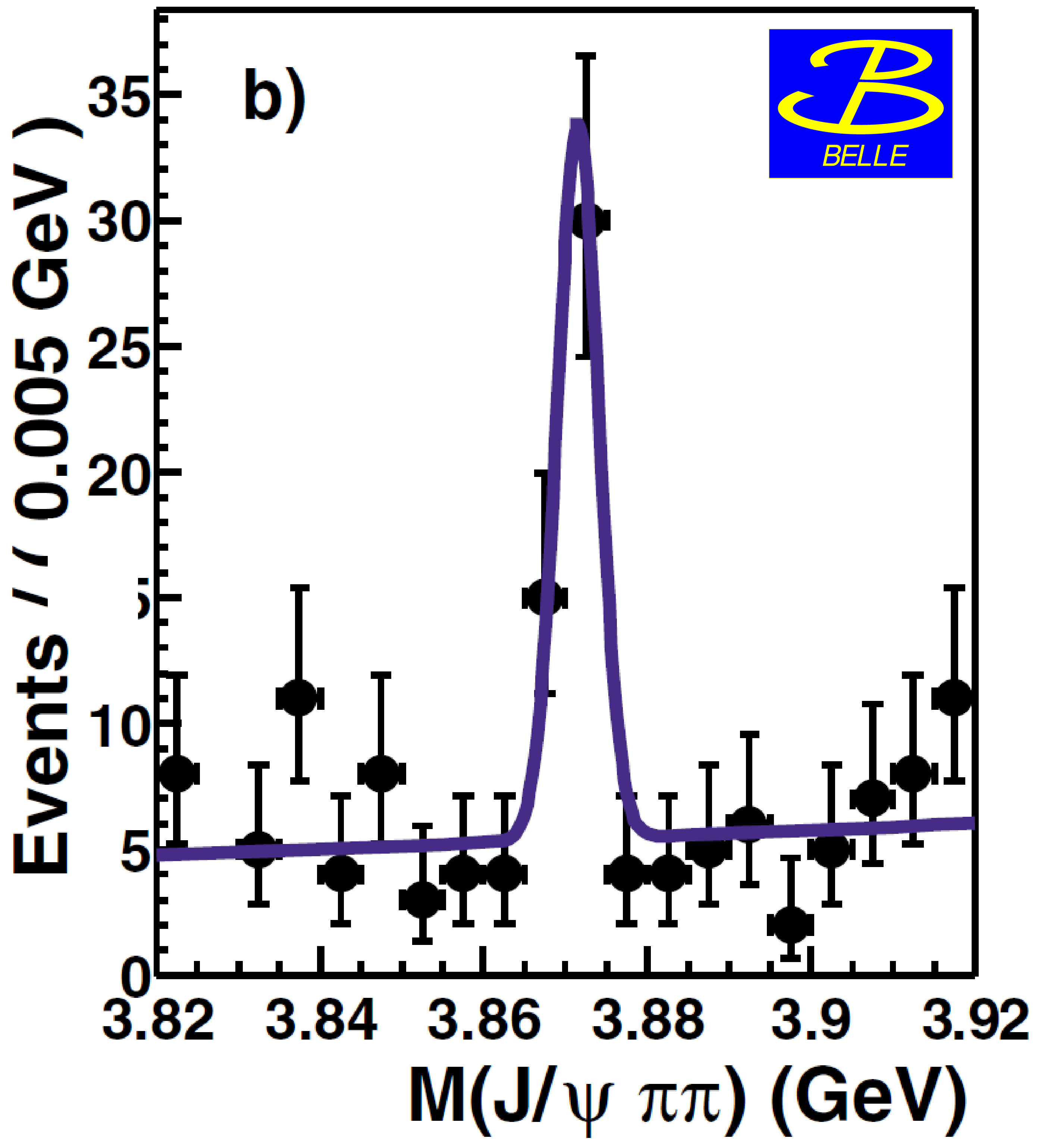


Hadron Spectroscopy at Belle

- Gell-Mann, Zweig's idea: Constituent Quark Model
  - Classifies all known hadrons
  - Still valid for half century
- QCD-motivated models have long predicted the existence of hadrons with more complex structures than simple $q\bar{q}$ (mesons) or qqq (baryons)
- Until the turn of the century, no unambiguous evidence for hadrons with non-CQM-like structure

- New possibilities, started with the observation of the X(3872):
  - tetraquarks, hybrids, molecular states, hadrocharmonium, pentaquarks, hexaquarks, glueballs, cusps…
- Evidence that there is more than mesons and baryons!
- Substantial contribution from Belle (1999-2010) to the field
- Experimental effort in hadron spectroscopy is as strong as ever!

Belle PRL.91.262001 (2003)



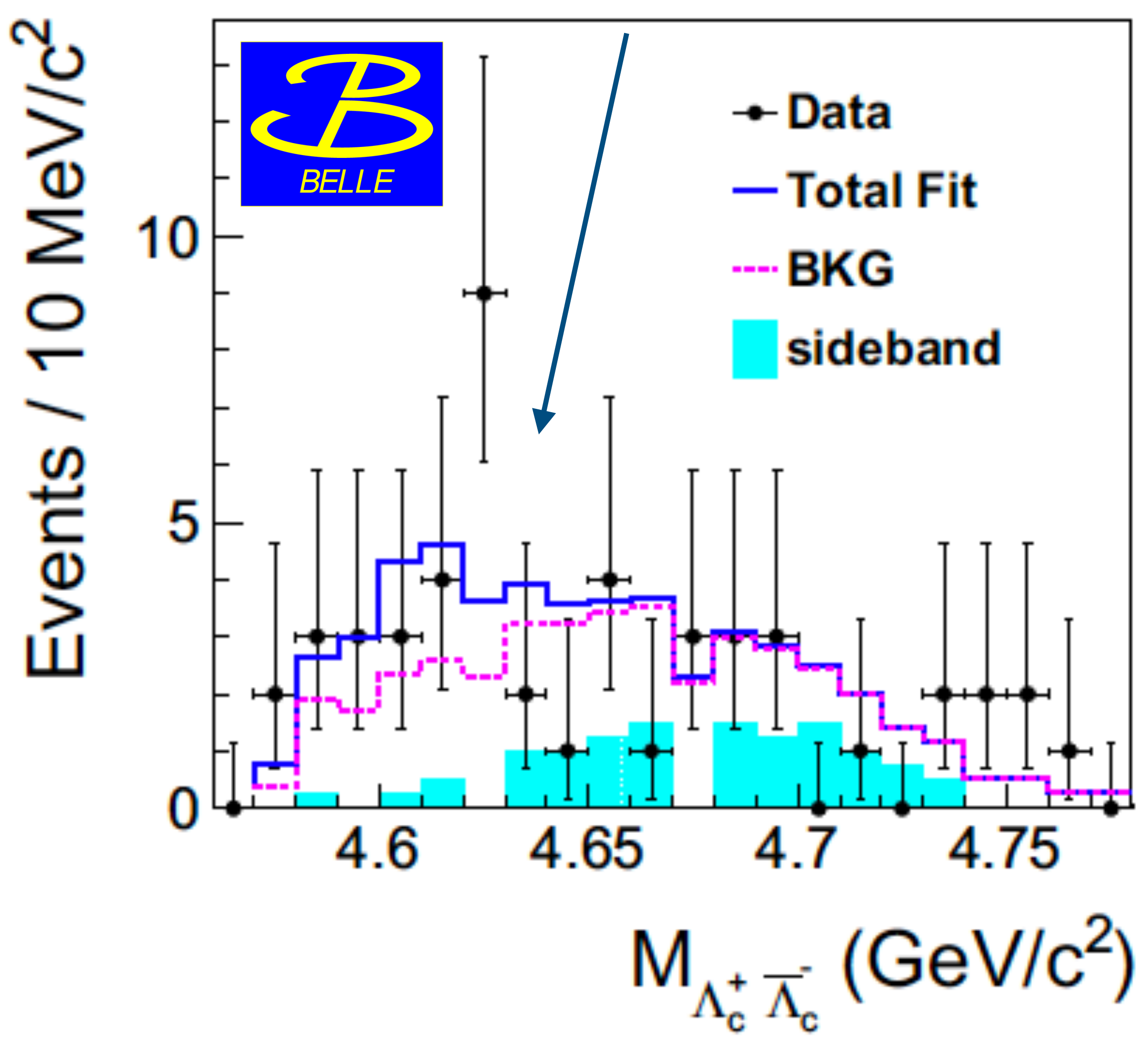
Most cited among > 500 papers in Belle
Still 100 citation/year!

XYZ in B decays to baryons

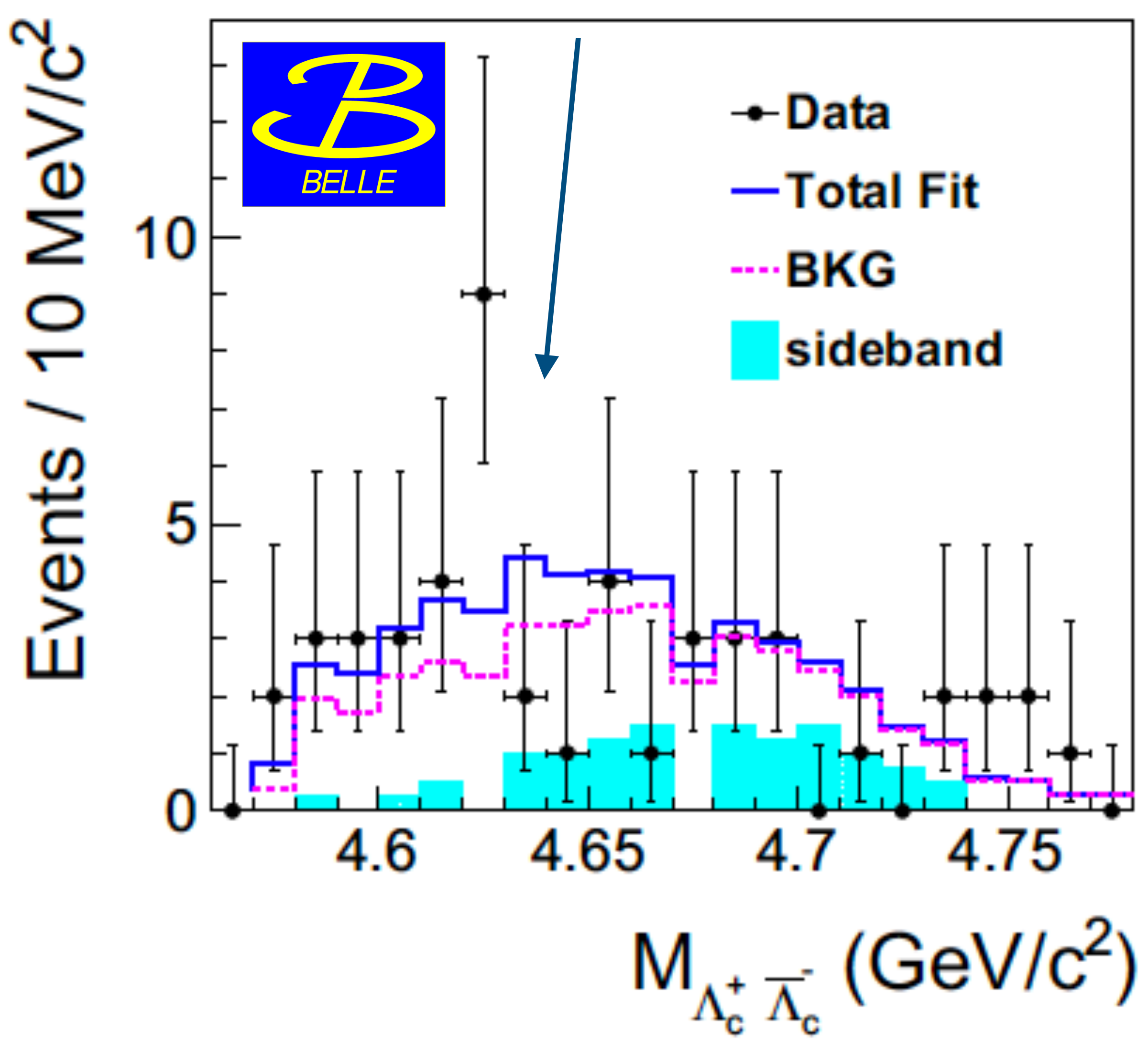
$\bar{B}^0 \to \bar{K}^0 \Lambda_c^+ \bar{\Lambda}_c^-$

Belle EPJC.78.252 (2018)

Add Y_η signal



Add Y(4660) signal



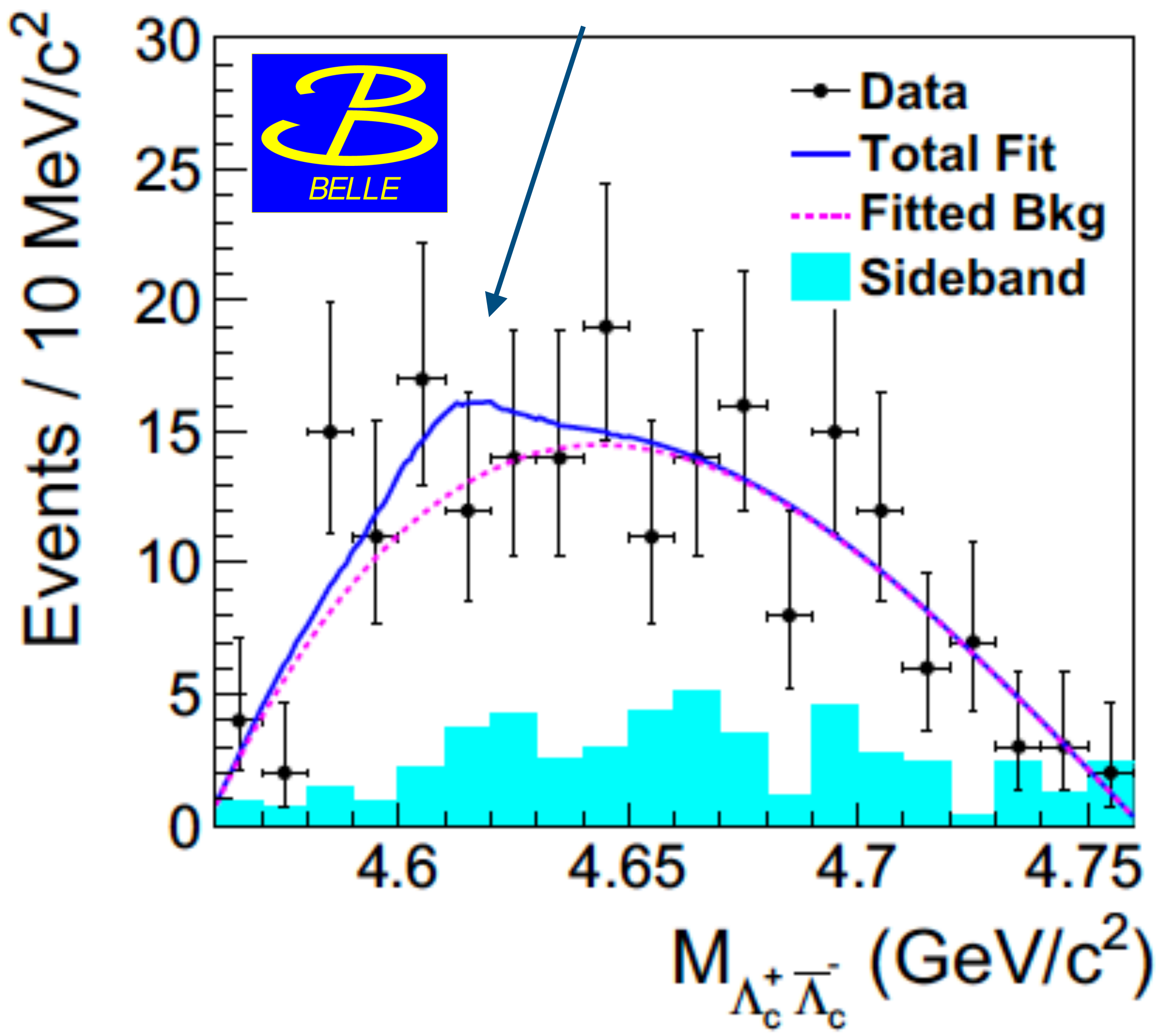
We need more data!

$B^- \to K^- \Lambda_c^+ \bar{\Lambda}_c^-$

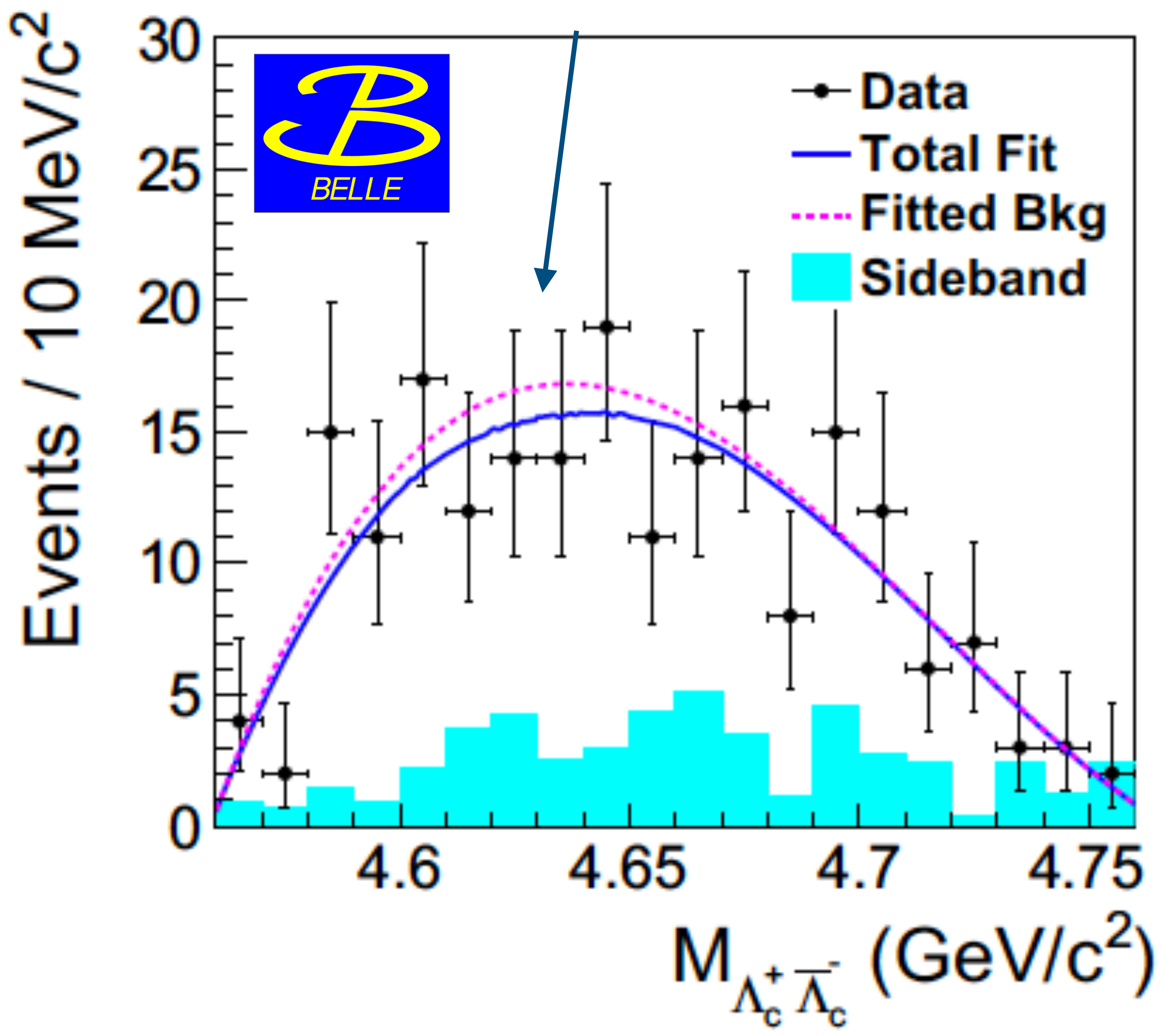
Belle EPJC.78.928 (2018)

- Can also search for the charmonium-like state Y(4660) and its spin partner, Y_η in the $\Lambda_c\bar{\Lambda}_c$ invariant mass spectrum
- No clear signals are observed and 90% credibility level (C.L.) upper limits on their production rates are determined

Add Y_η signal

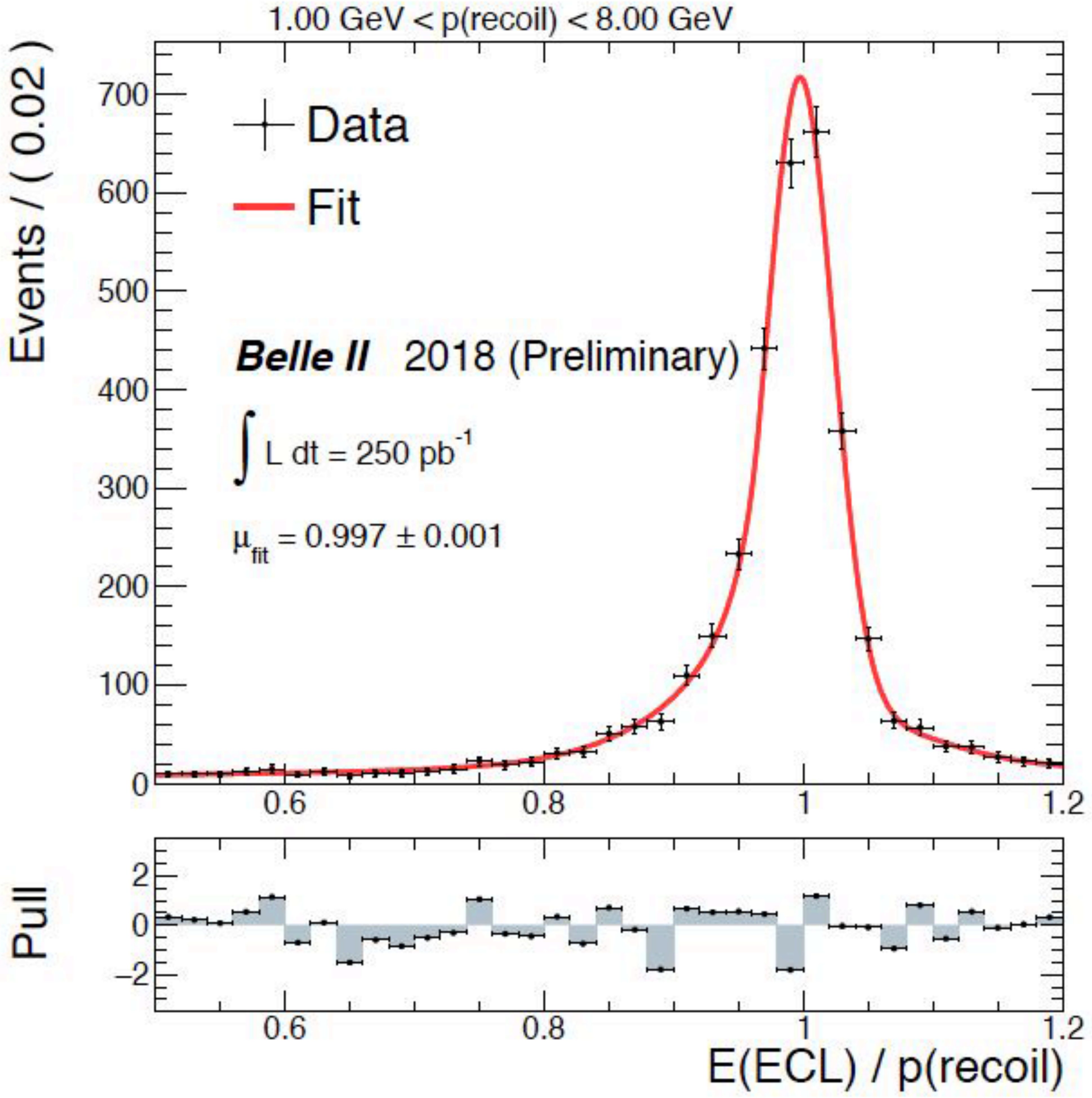


Add Y(4660) signal

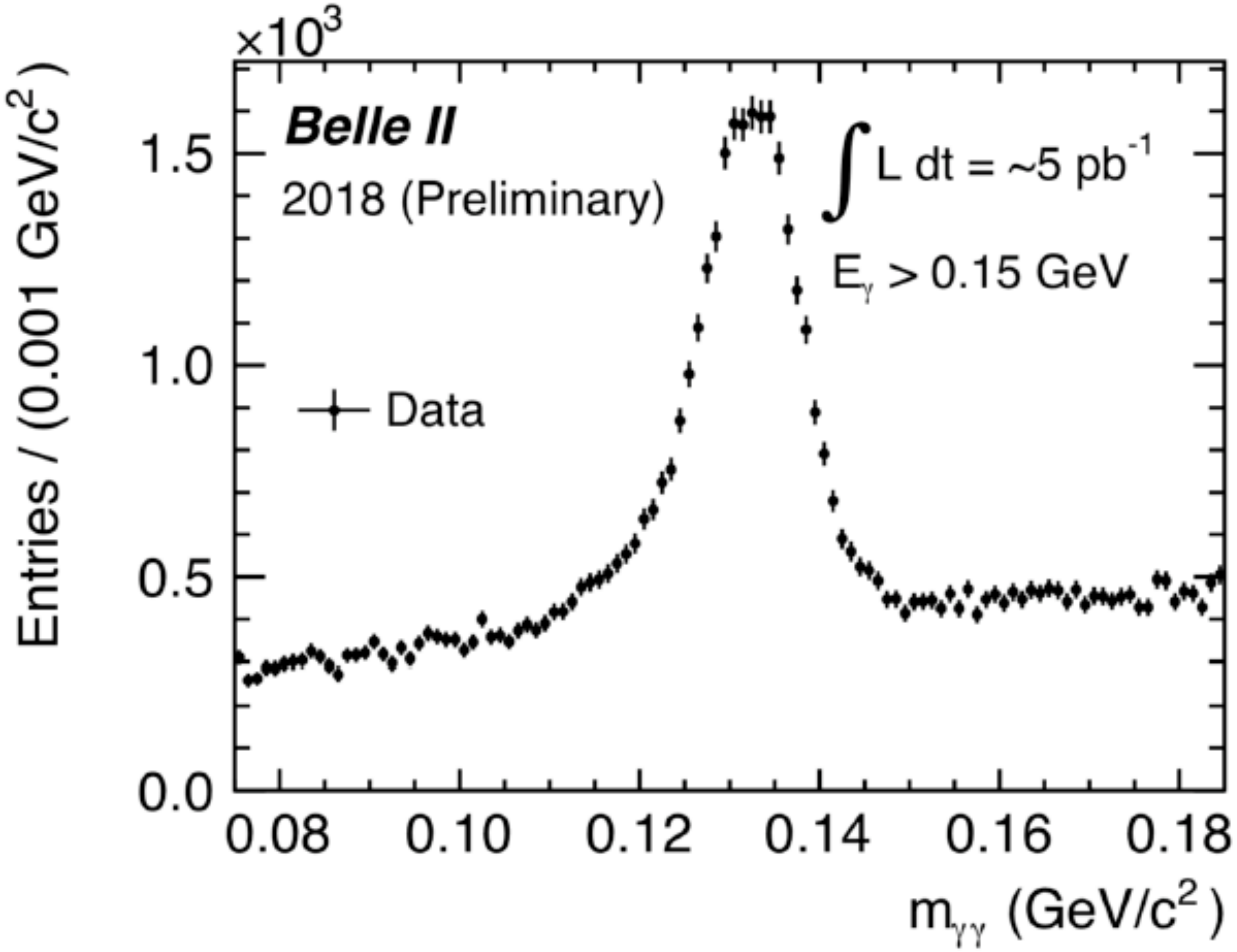


Some results from phase 2: calorimetry

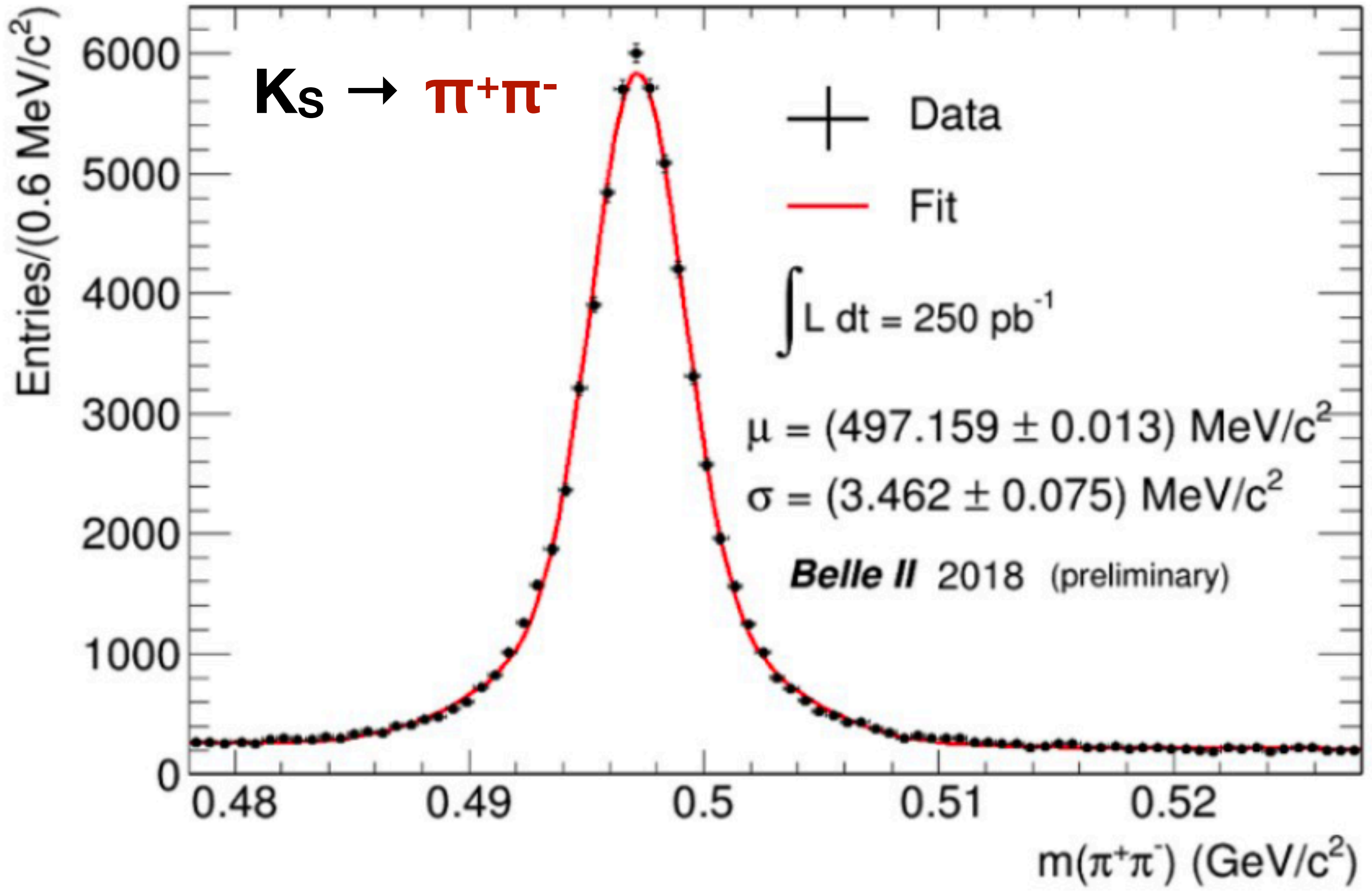
$e^+e^- \rightarrow \mu^+\mu^-\gamma$

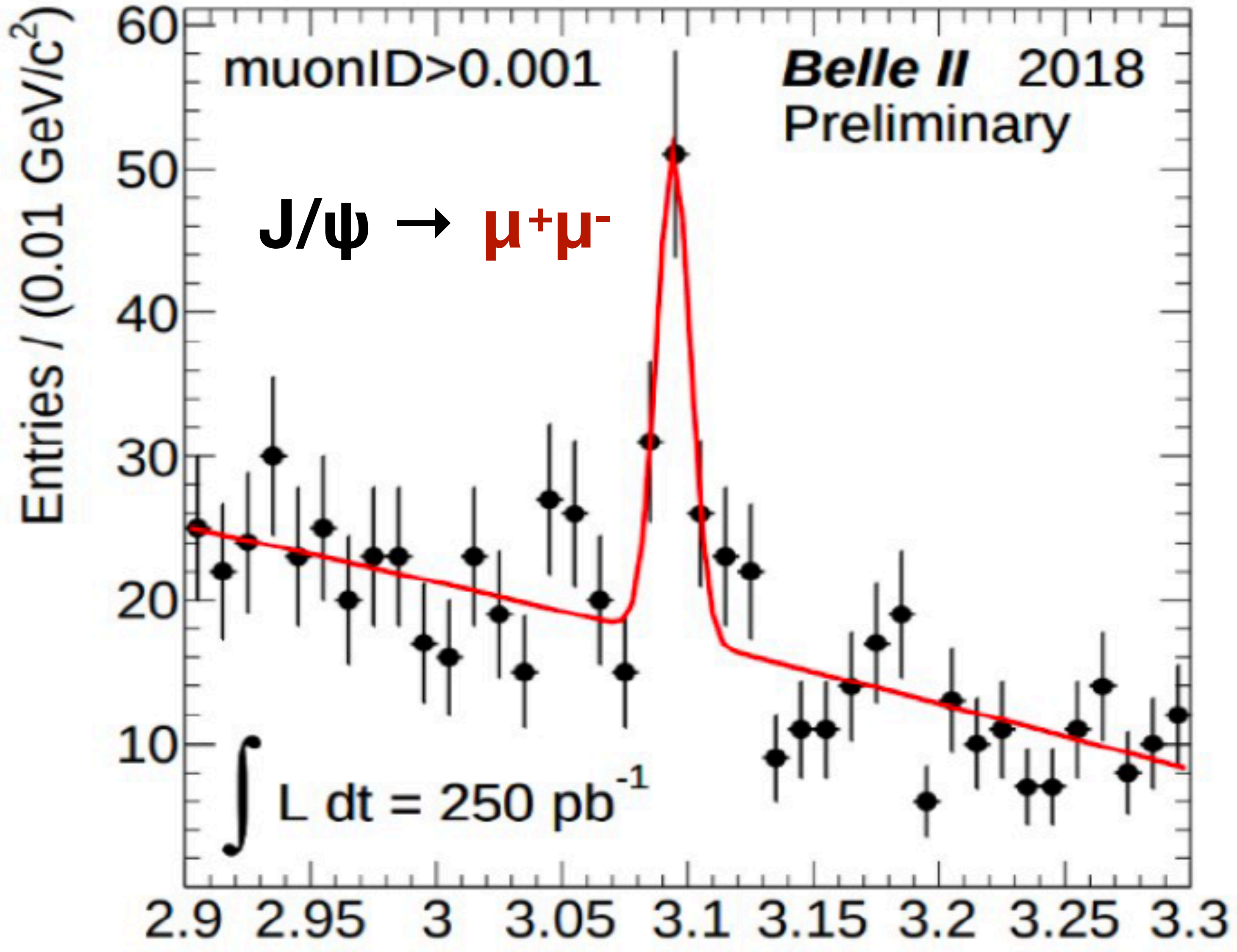


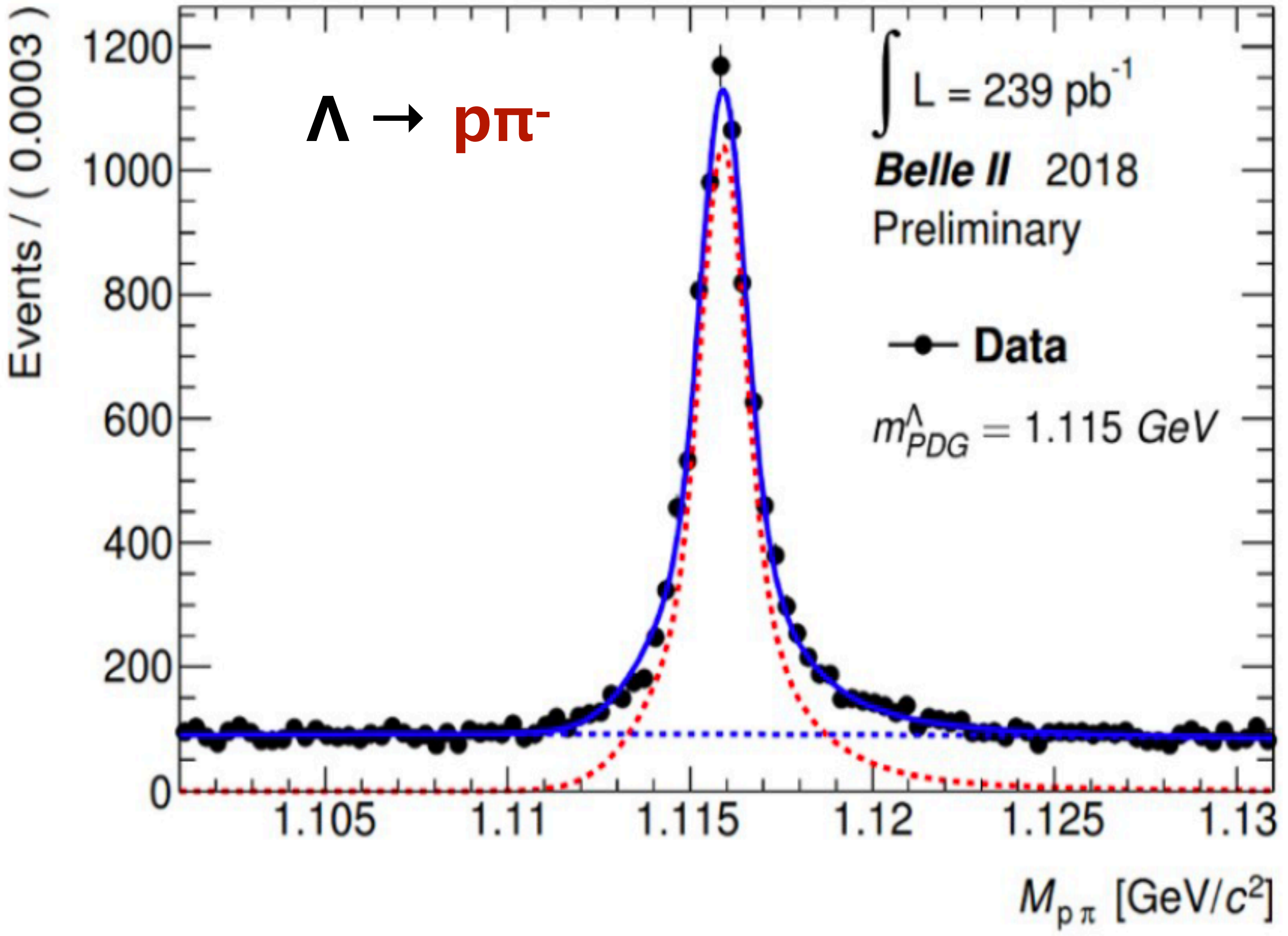
$\pi^0 \rightarrow \gamma\gamma$

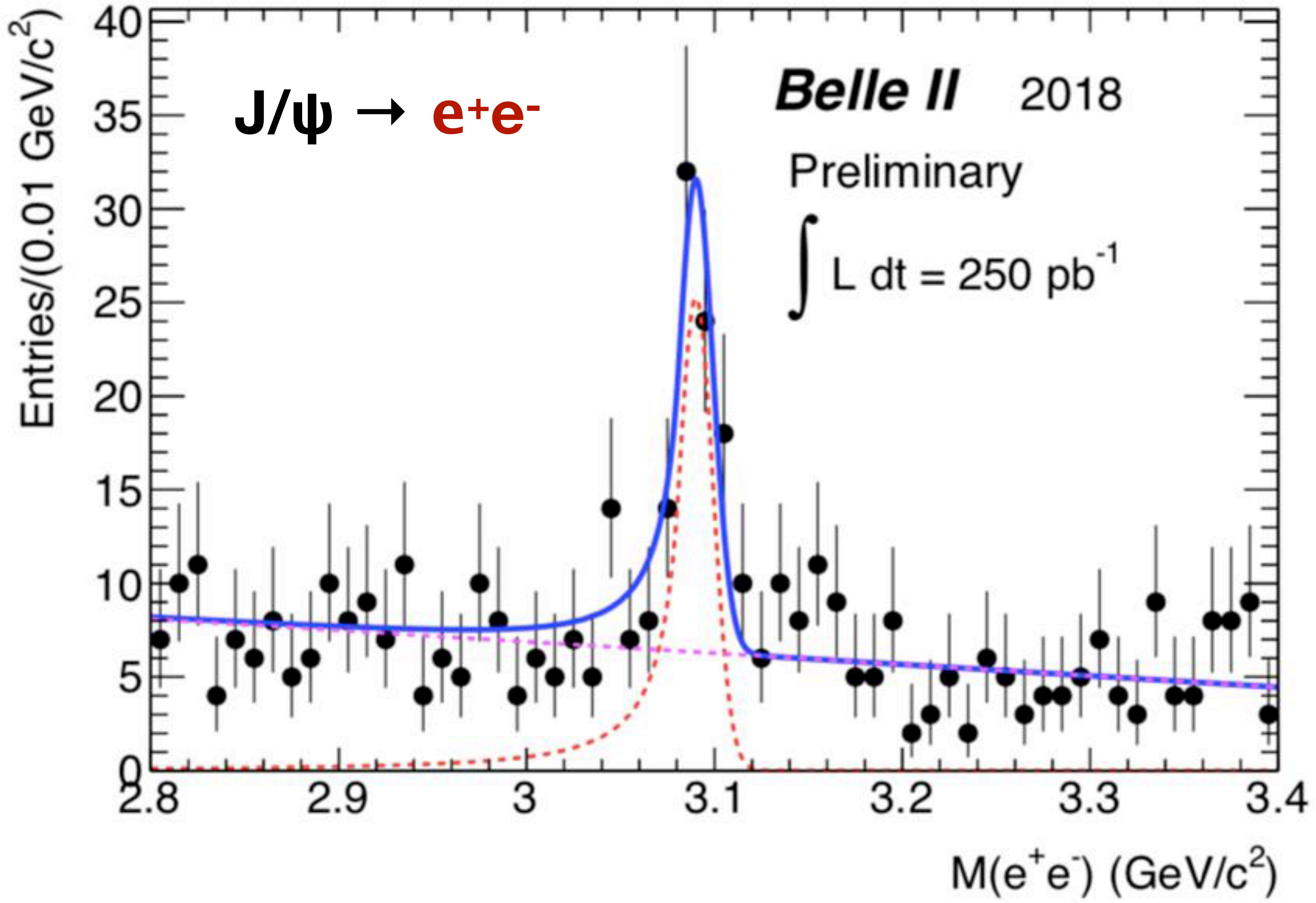


Some results from phase 2: tracking

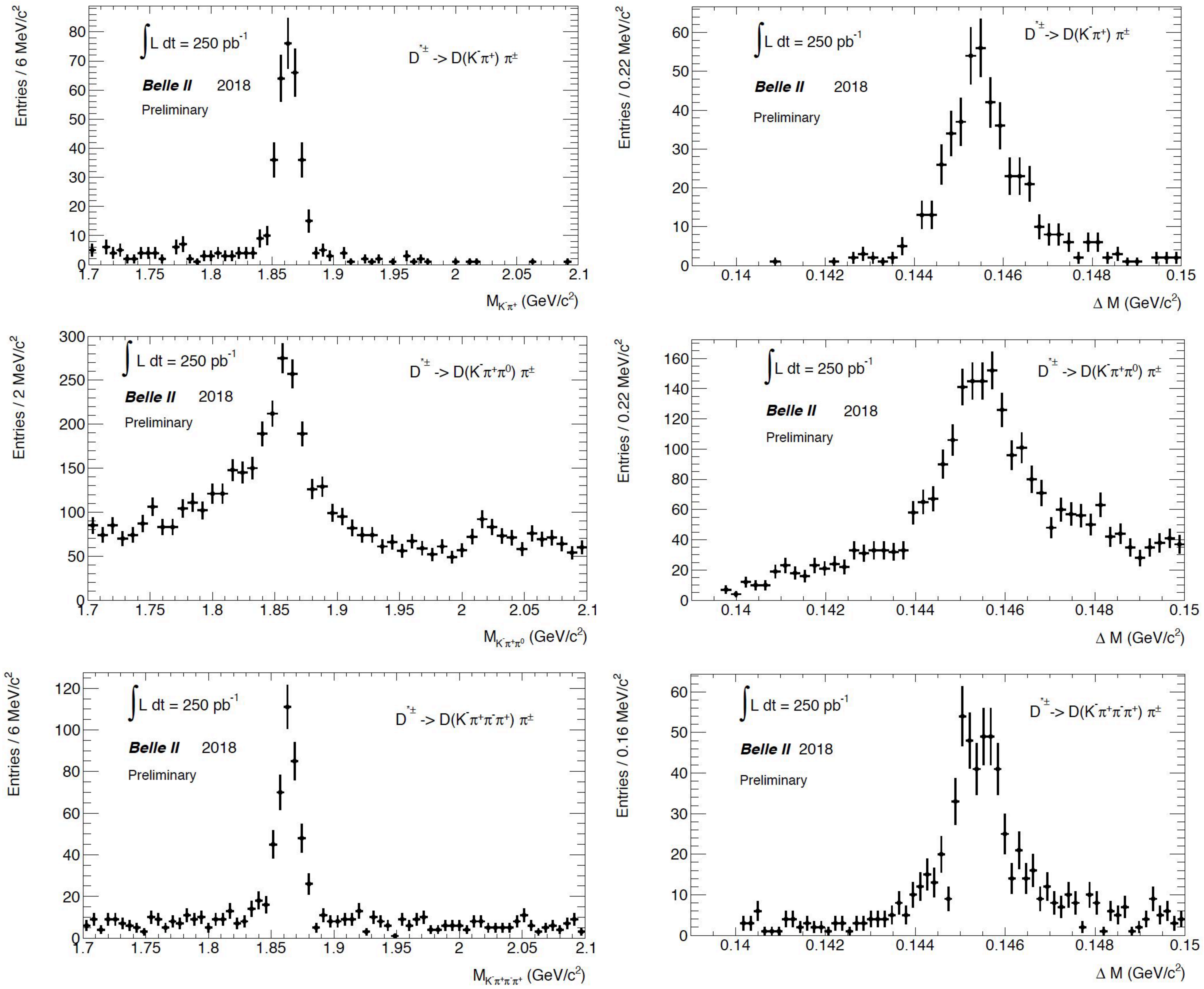








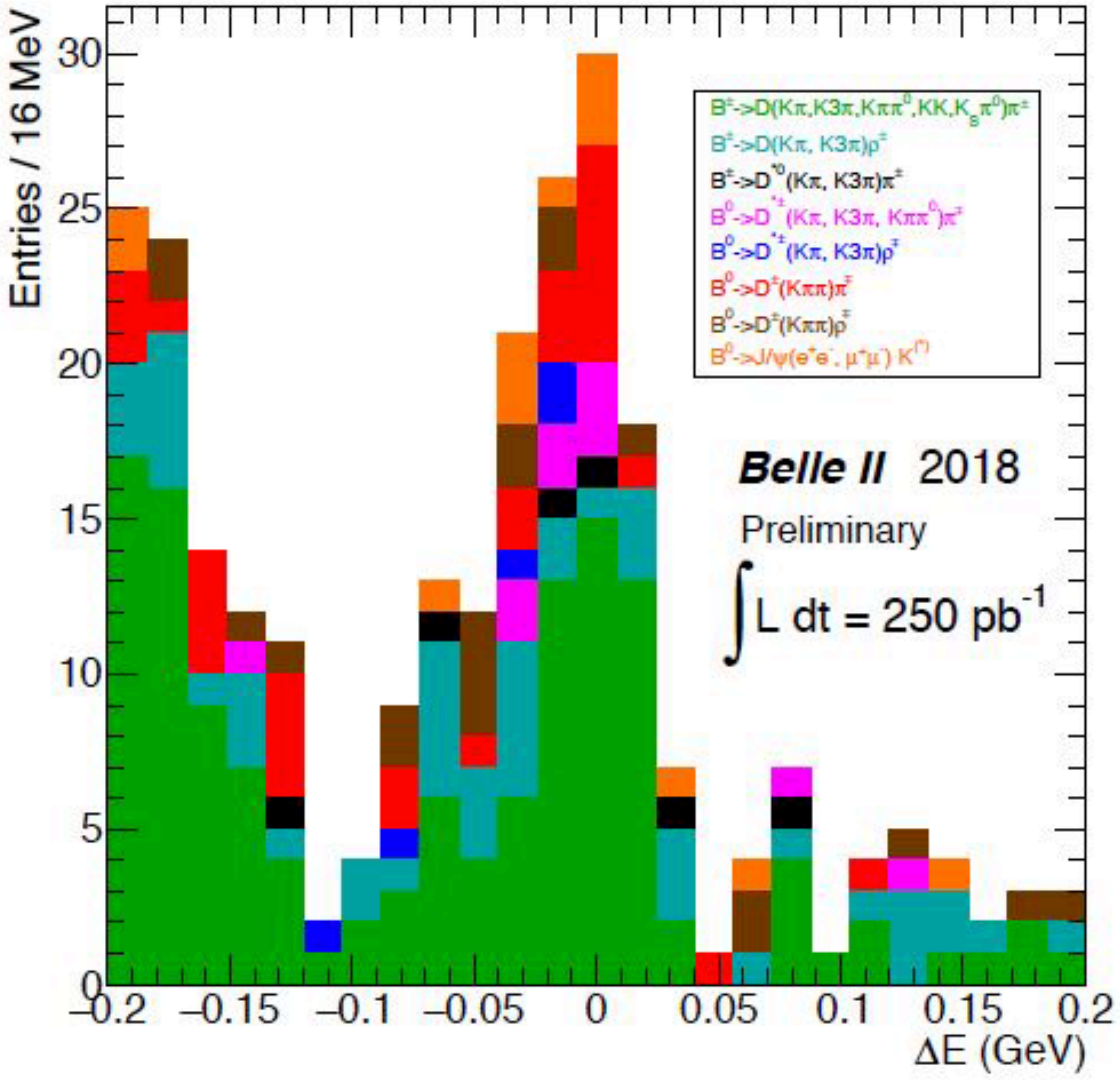
Some charming results from phase 2

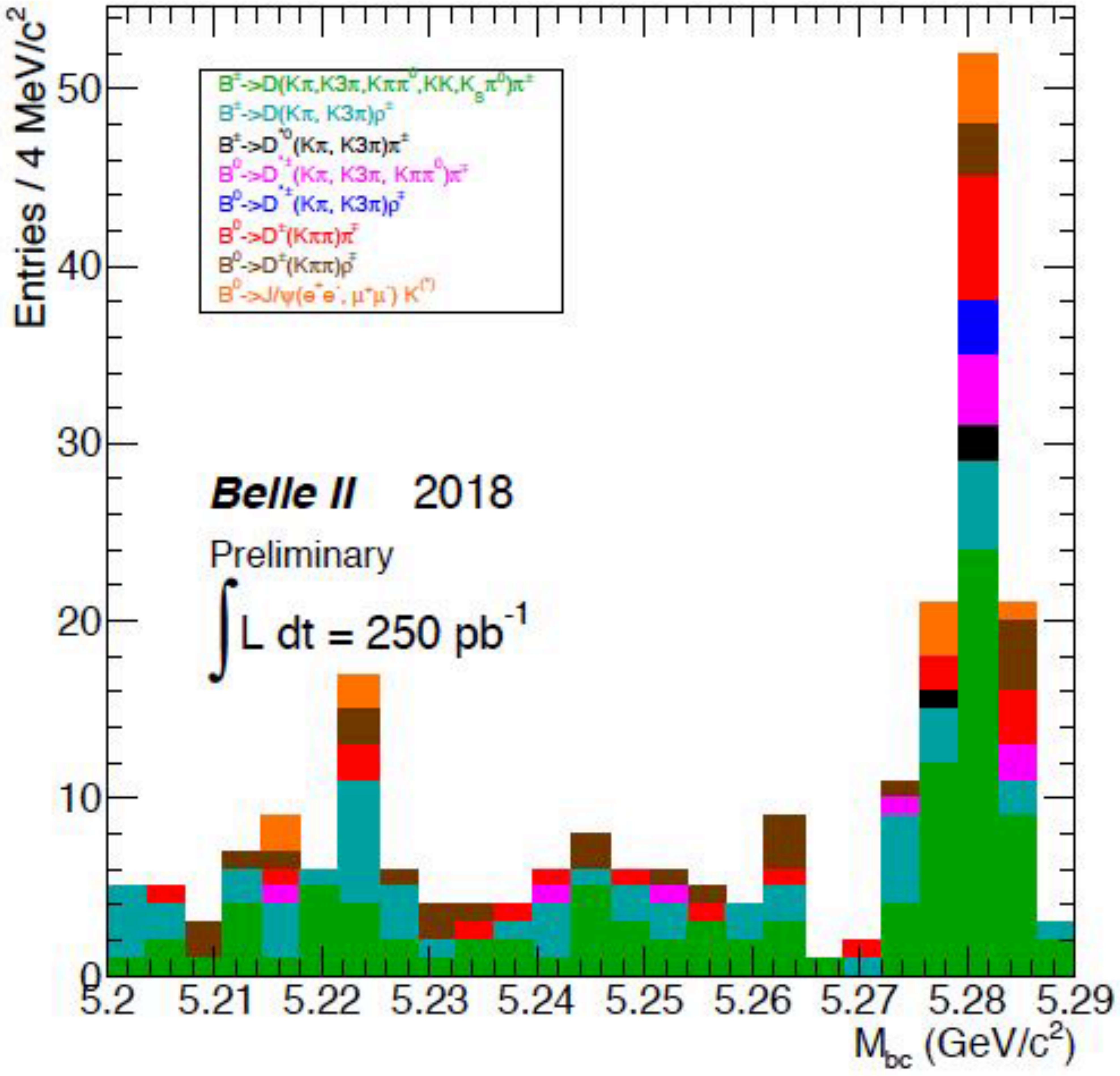


Includes Particle Identification cuts

Belle II is ready for charm physics, a building block for B physics!

Some beautiful results from phase 2

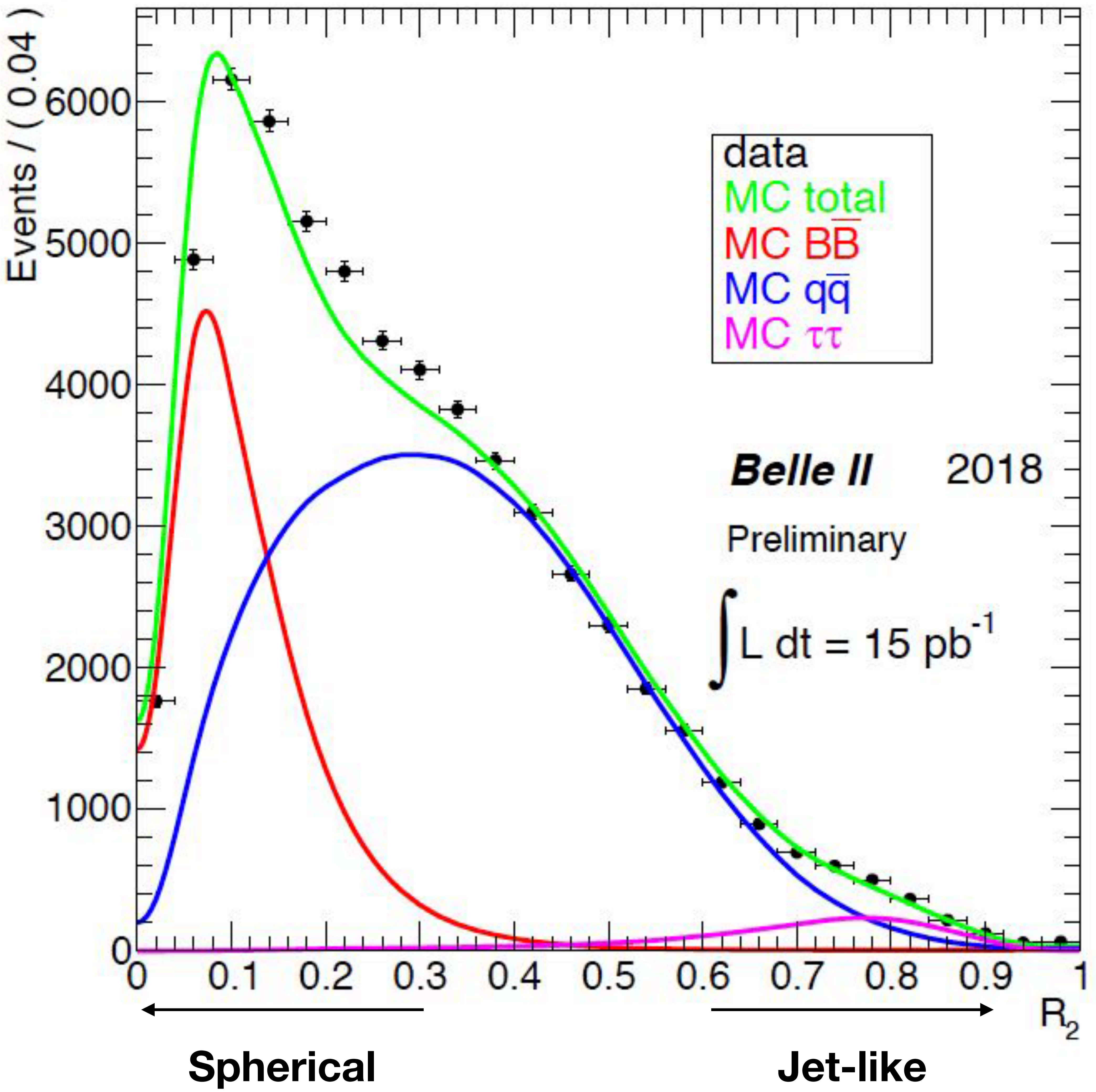


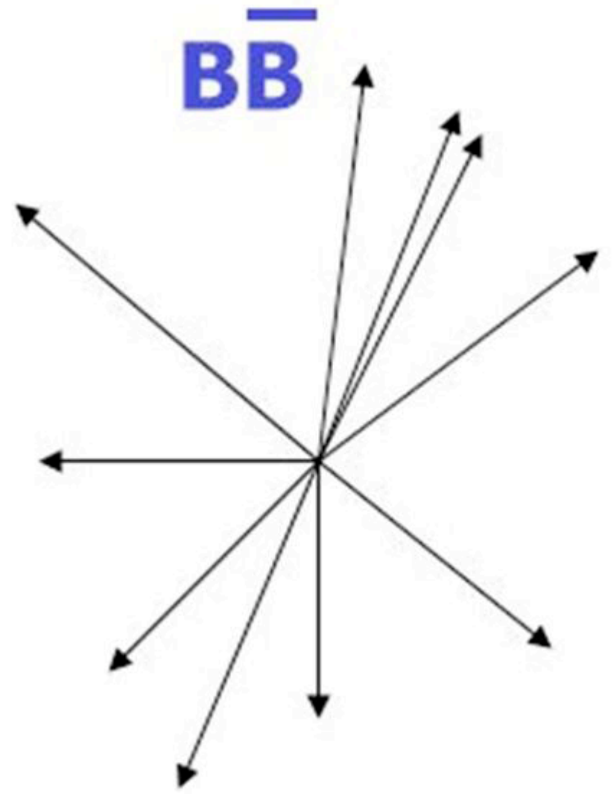


$$\Delta E = E_B - E_{beam}$$

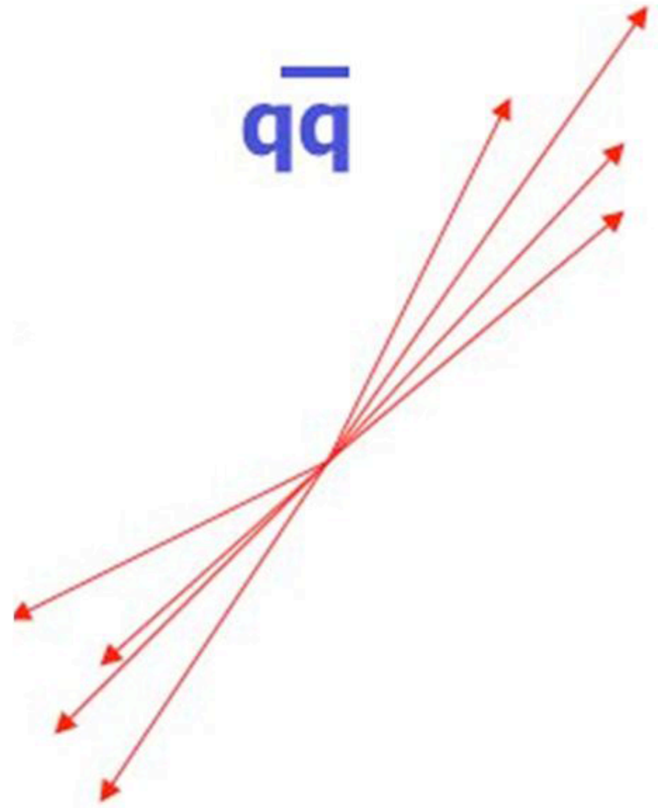
$$M_{BC} = \sqrt{(E_{beam})^2 + (p_B)^2}$$

Confirmation of B “rediscovery” from event topology





At the Y(4S), $B\bar{B}$ pairs are produced at rest in the CM with no extra particles



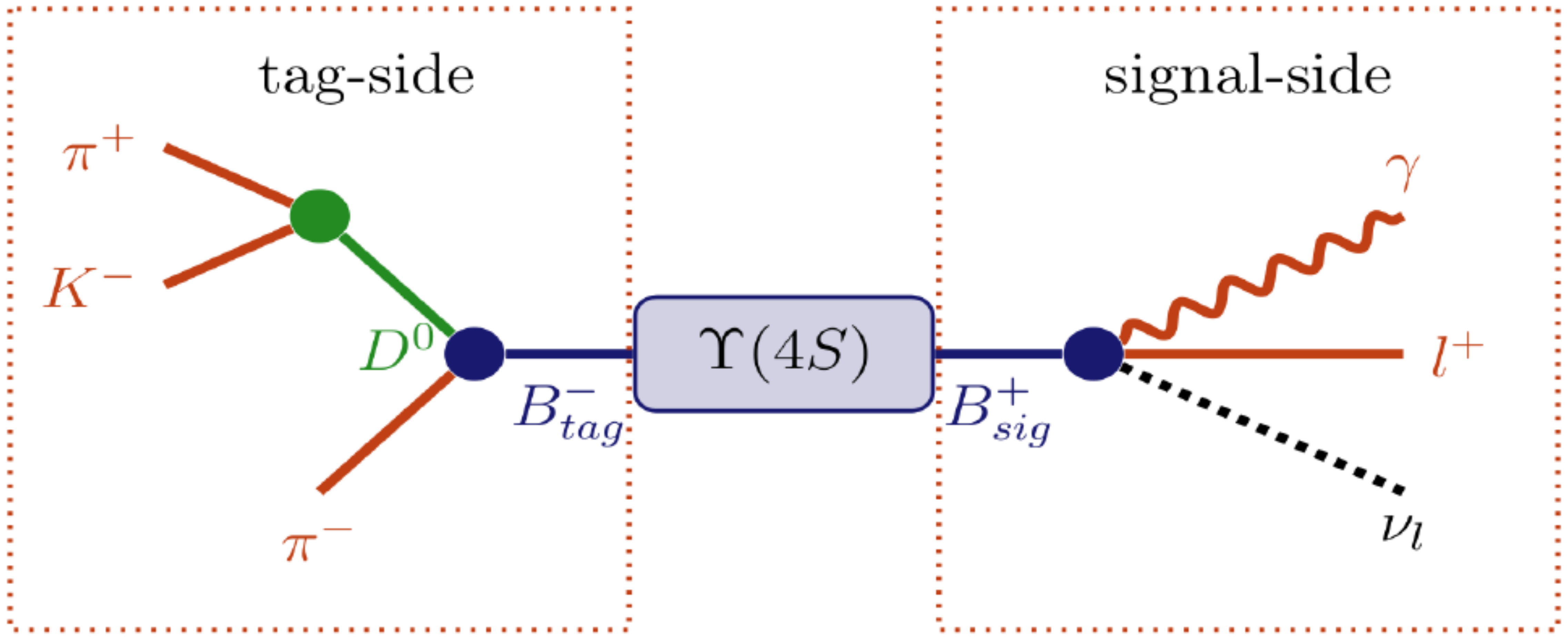
We are on the Y(4S) and recording $B\bar{B}$ pairs with ~99% efficiency!

Full reconstruction tagging

- A powerful benefit of physics at B factories: fully reconstruct one B (through > 1000 hadronic/semileptonic modes) to tag the flavor of the other B, determine its momentum, isolate tracks of signal side

Full reconstruction:
($\varepsilon \approx 0.3$ - 1.5%)

Signal side:
$B \to X\ell\nu$ - Precise meas. of $|V_{ub}|$
$B \to \tau\nu$ - Search for NP
$B \to K\nu\bar{\nu}$ - Search for NP



- Excellent tool for missing energy, missing mass analyses!
  - e.g. provide important high-mass sensitivity to the charged Higgs in the multi-TeV range