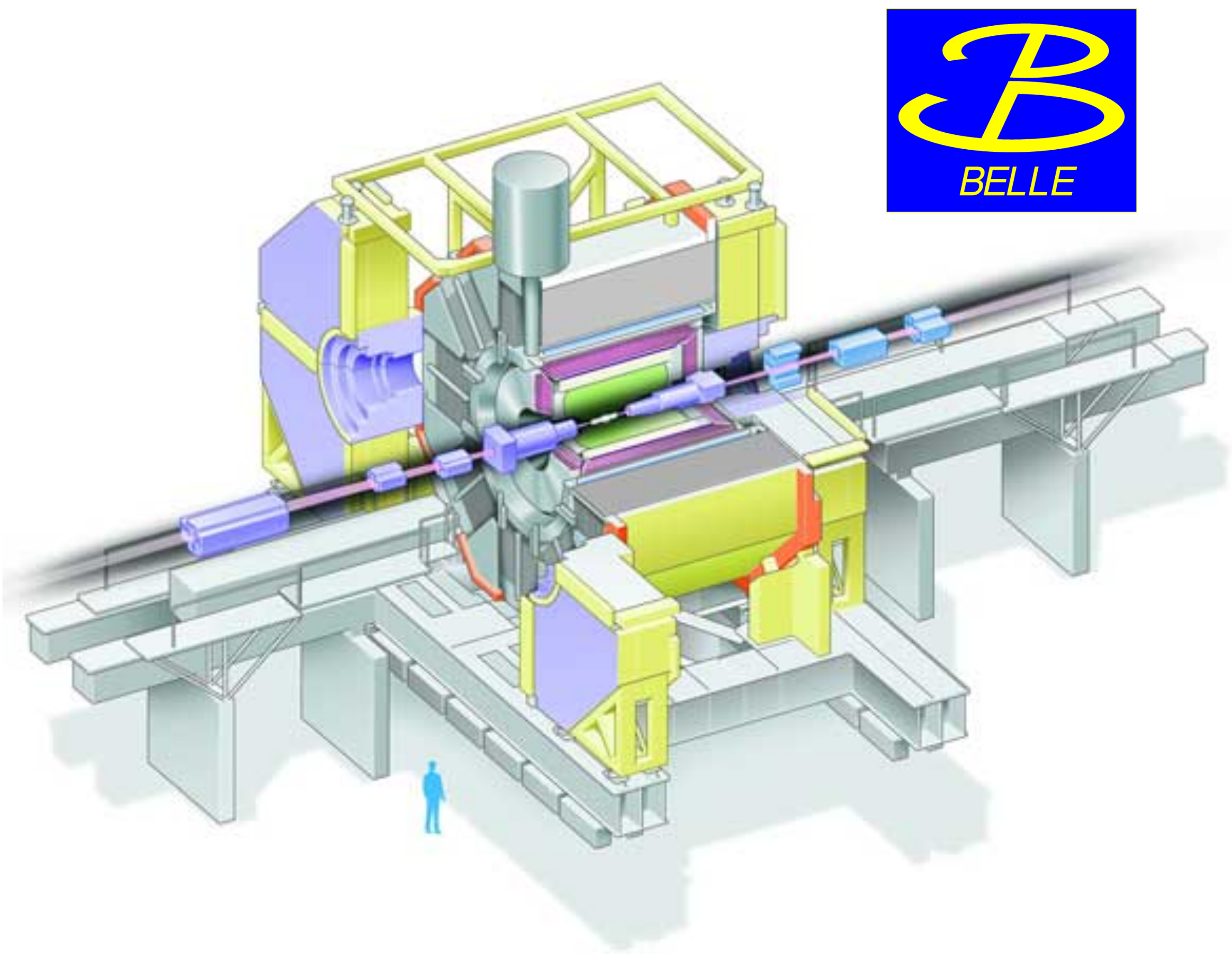
Recent results in hadron spectroscopy at Belle and prospects for Belle II

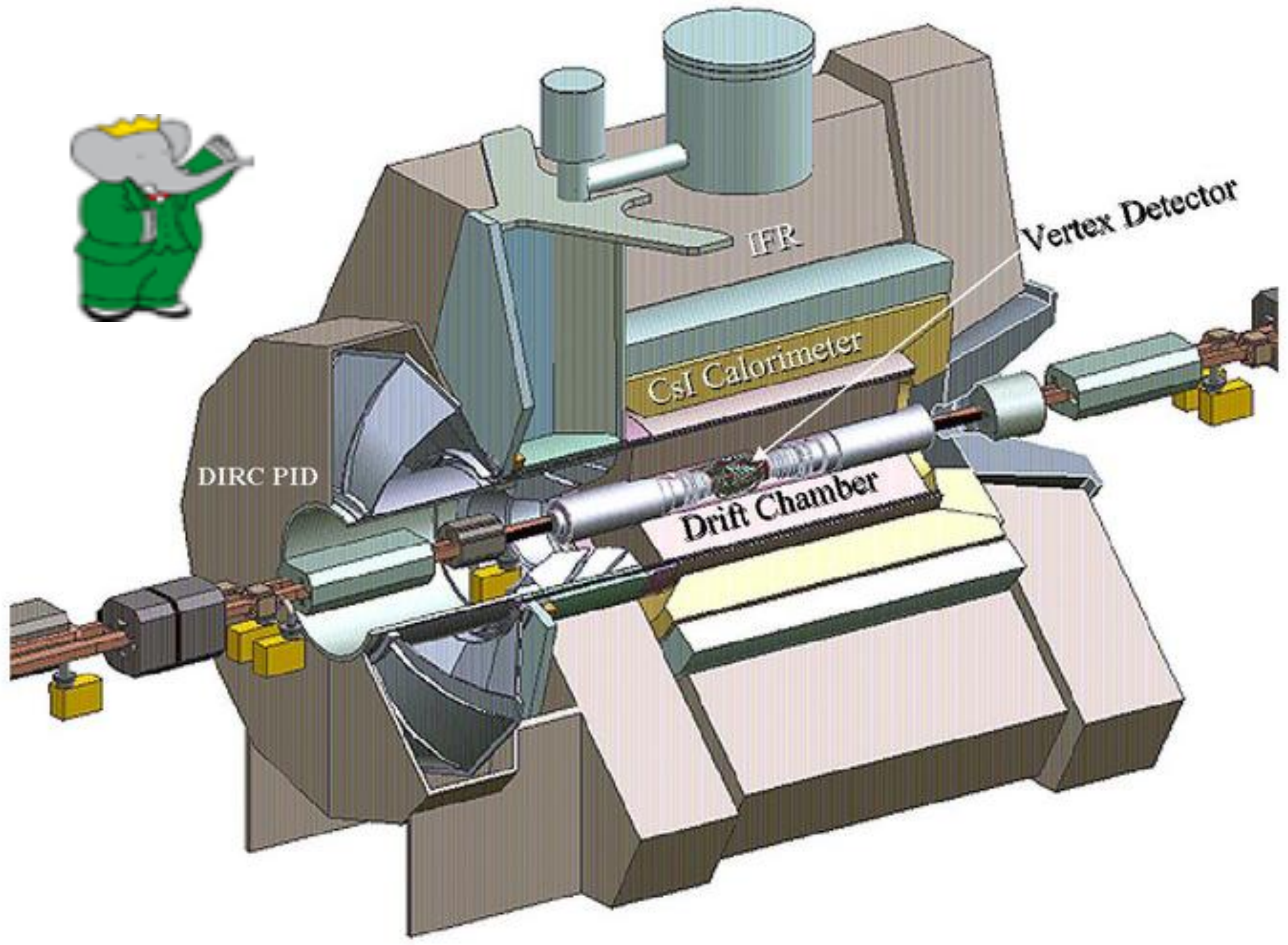
Jake Bennett
The University of Mississippi
GHP 2019, April 10-12, 2019

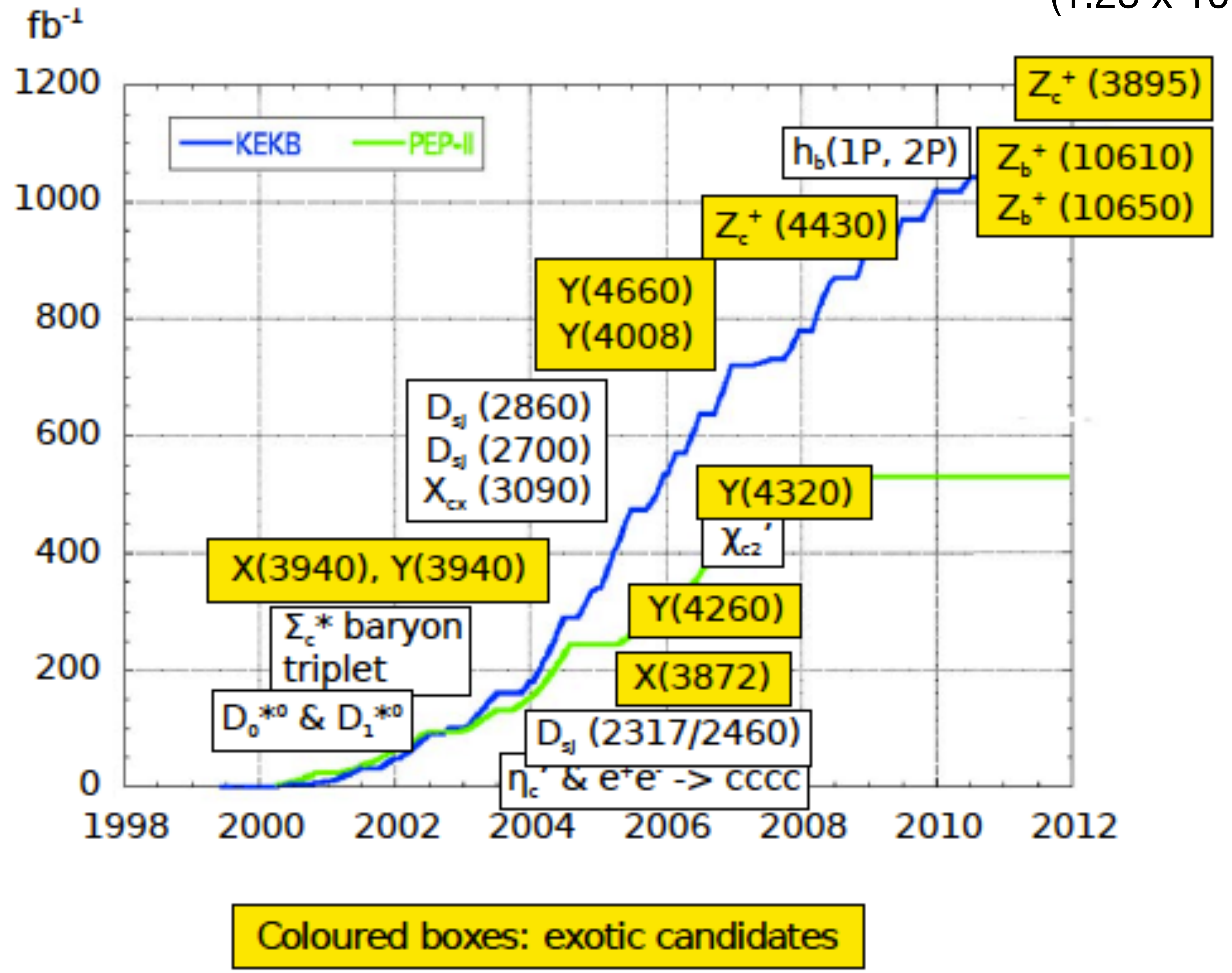
B factories

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

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



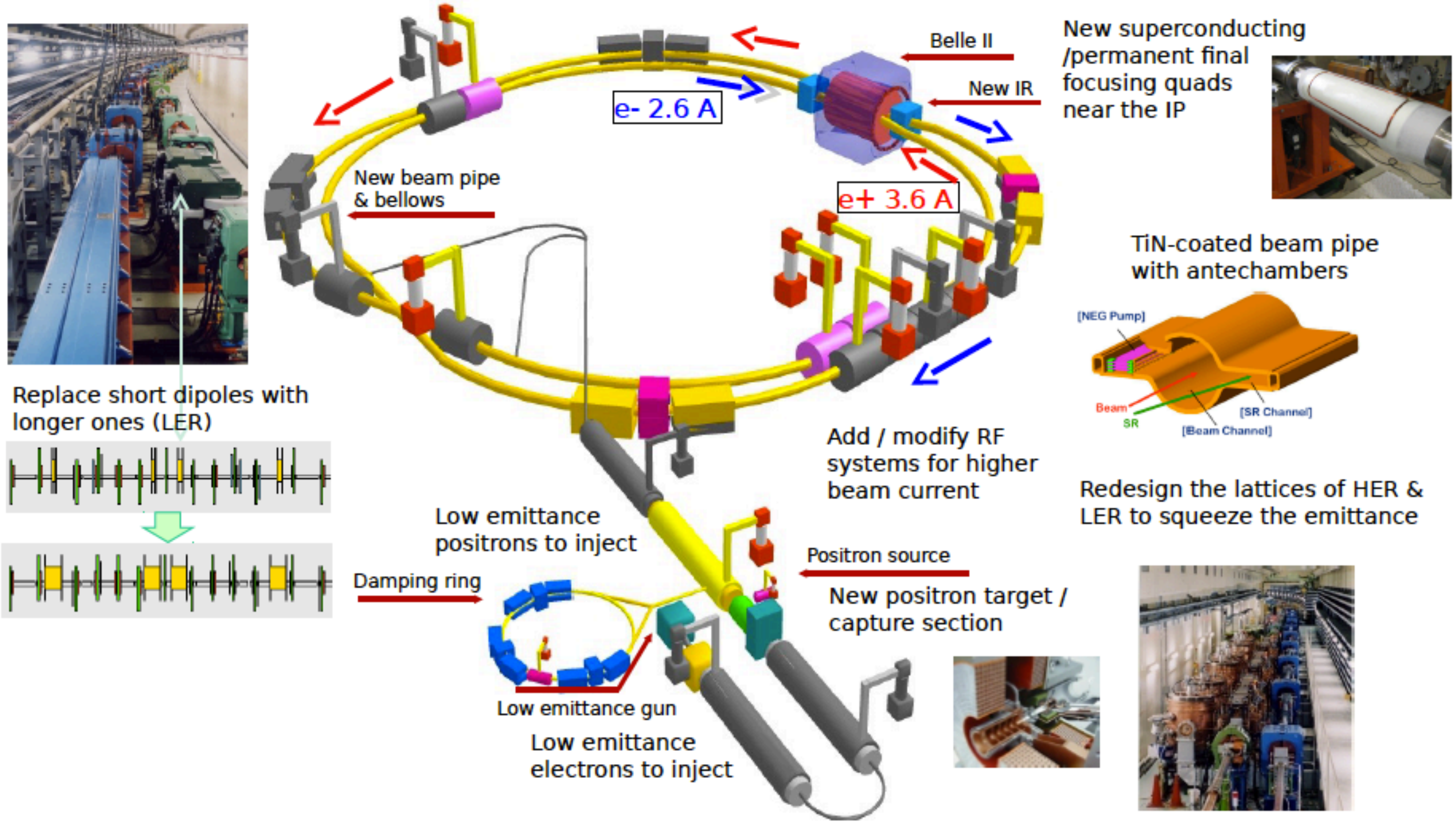




Even ~10 years after data taking, Belle is producing new results in hadron spectroscopy

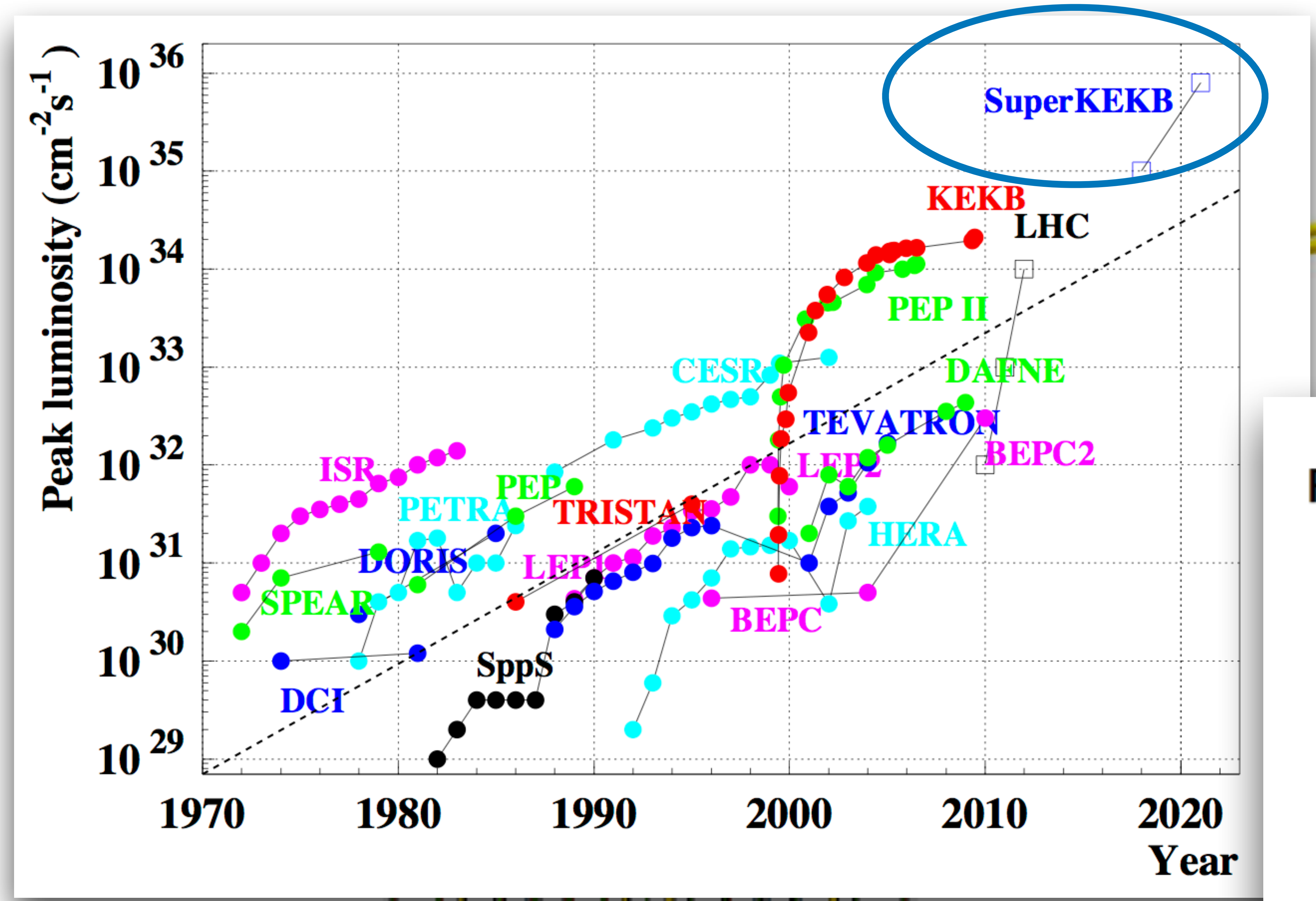
~350 papers published since shutdown!

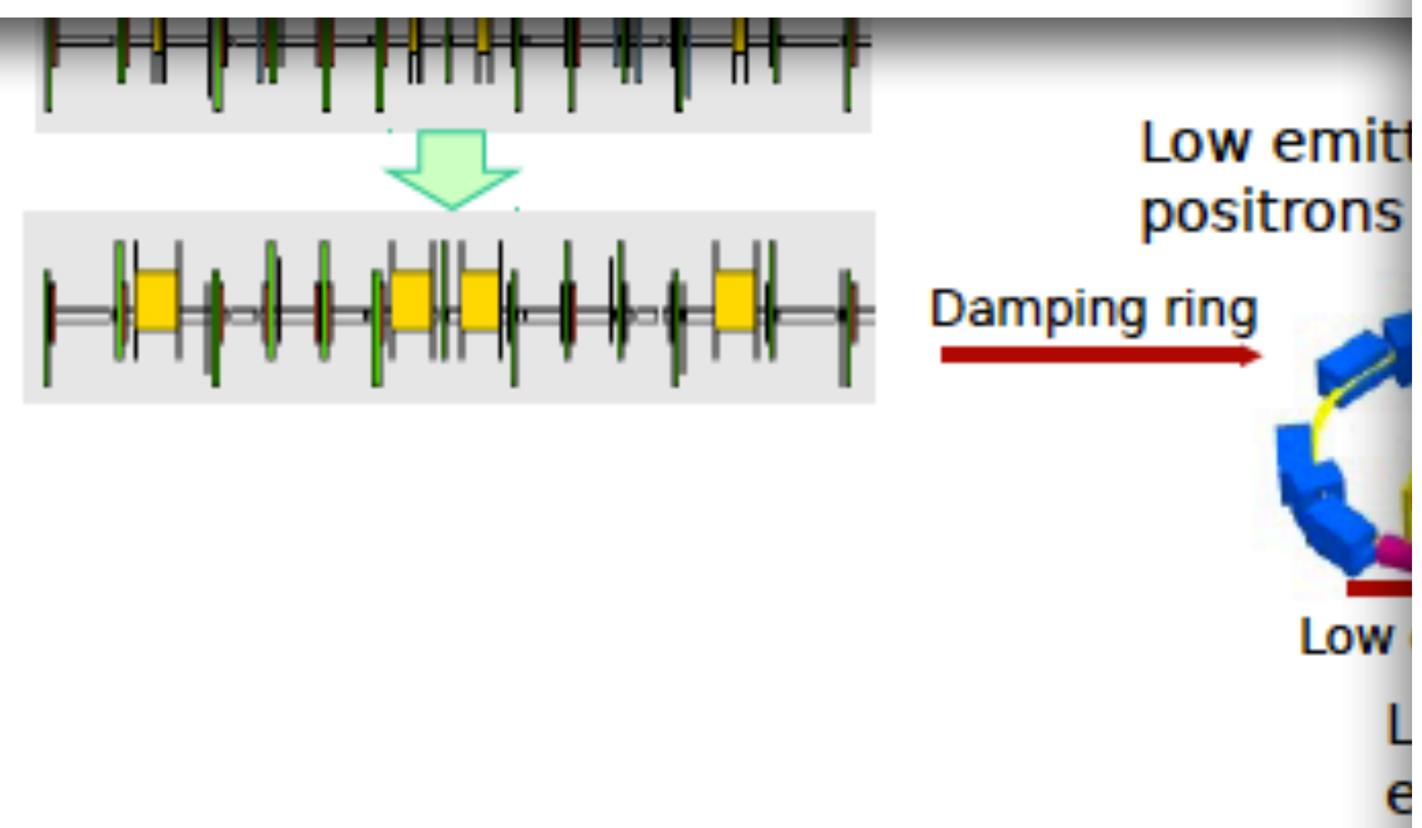
SuperKEKB: The next generation B-factory

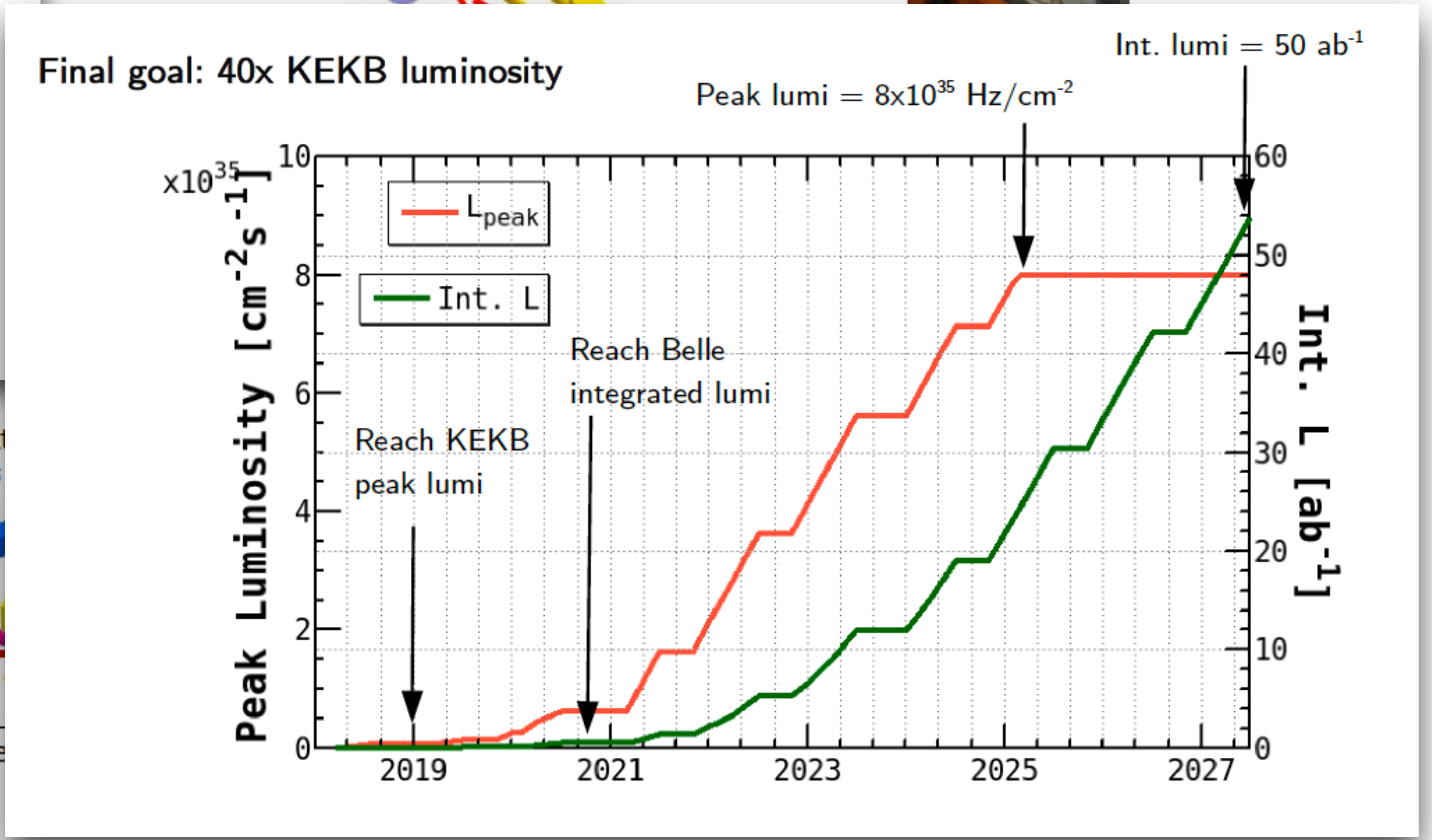


*gray - recycled, color - new

SuperKEKB: The next generation B-factory



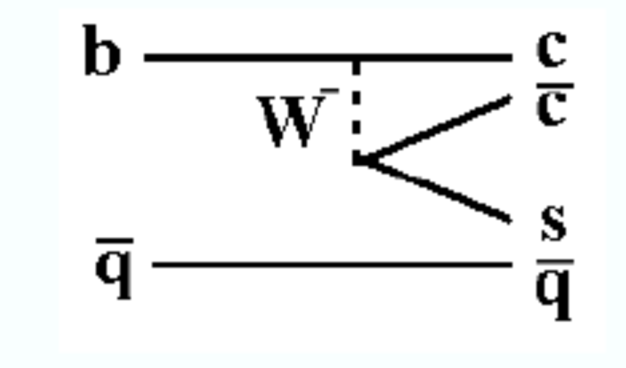


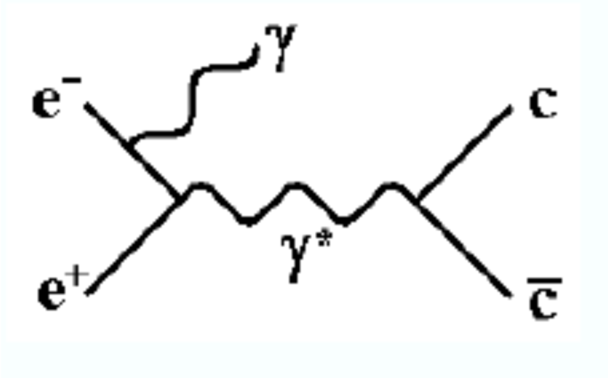


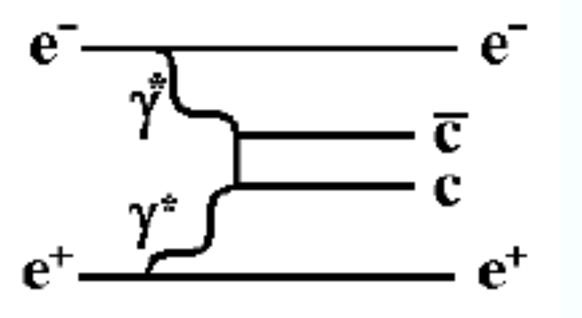
*gray - recycled, color - new

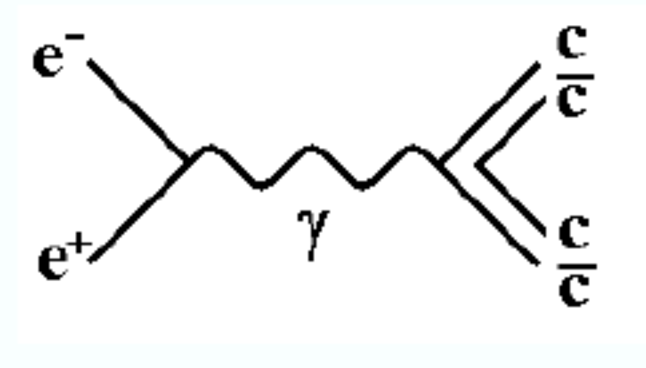
Benefits of hadron spectroscopy at B-factories

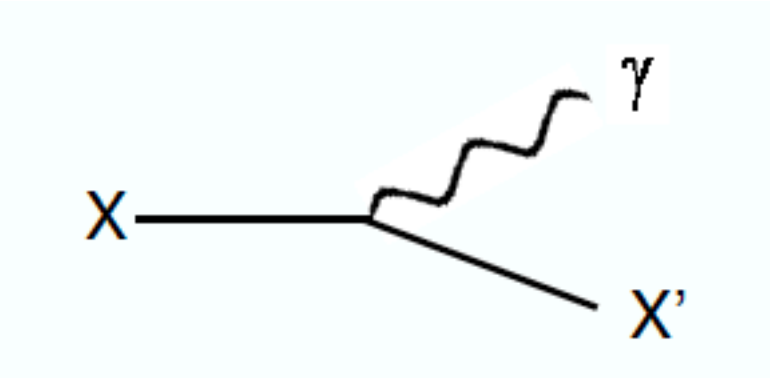
- Efficient reconstruction of neutrals (π^0, η, …)
- Reconstruct single resonance to explore recoiling system (e.g. $e^+e^- \to J/\psi\ X$)
- High resolution, hermetic detector with good PID capability
- Using tagged events (i.e. with a fully reconstructed partner B) to measure absolute branching fractions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

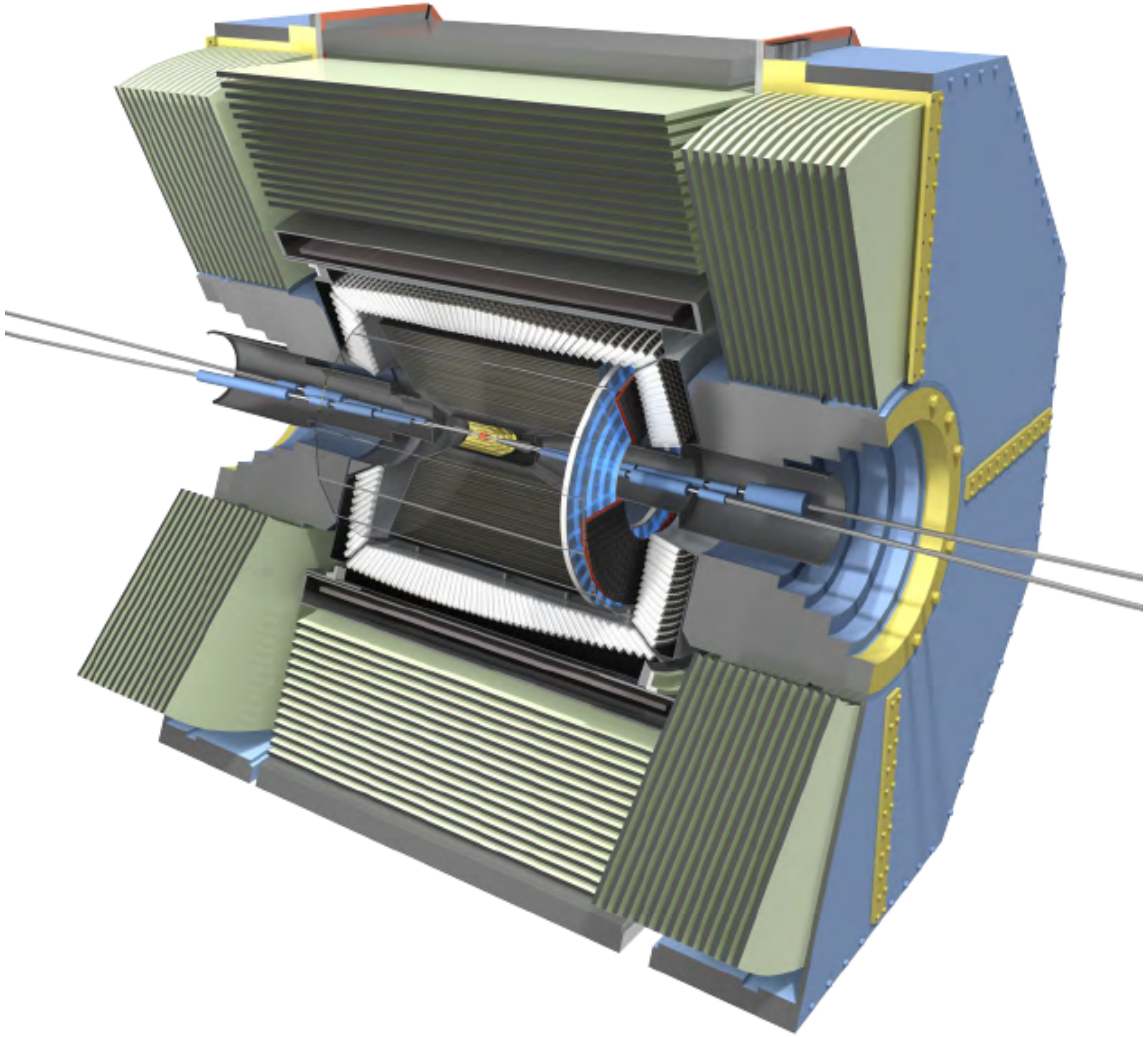










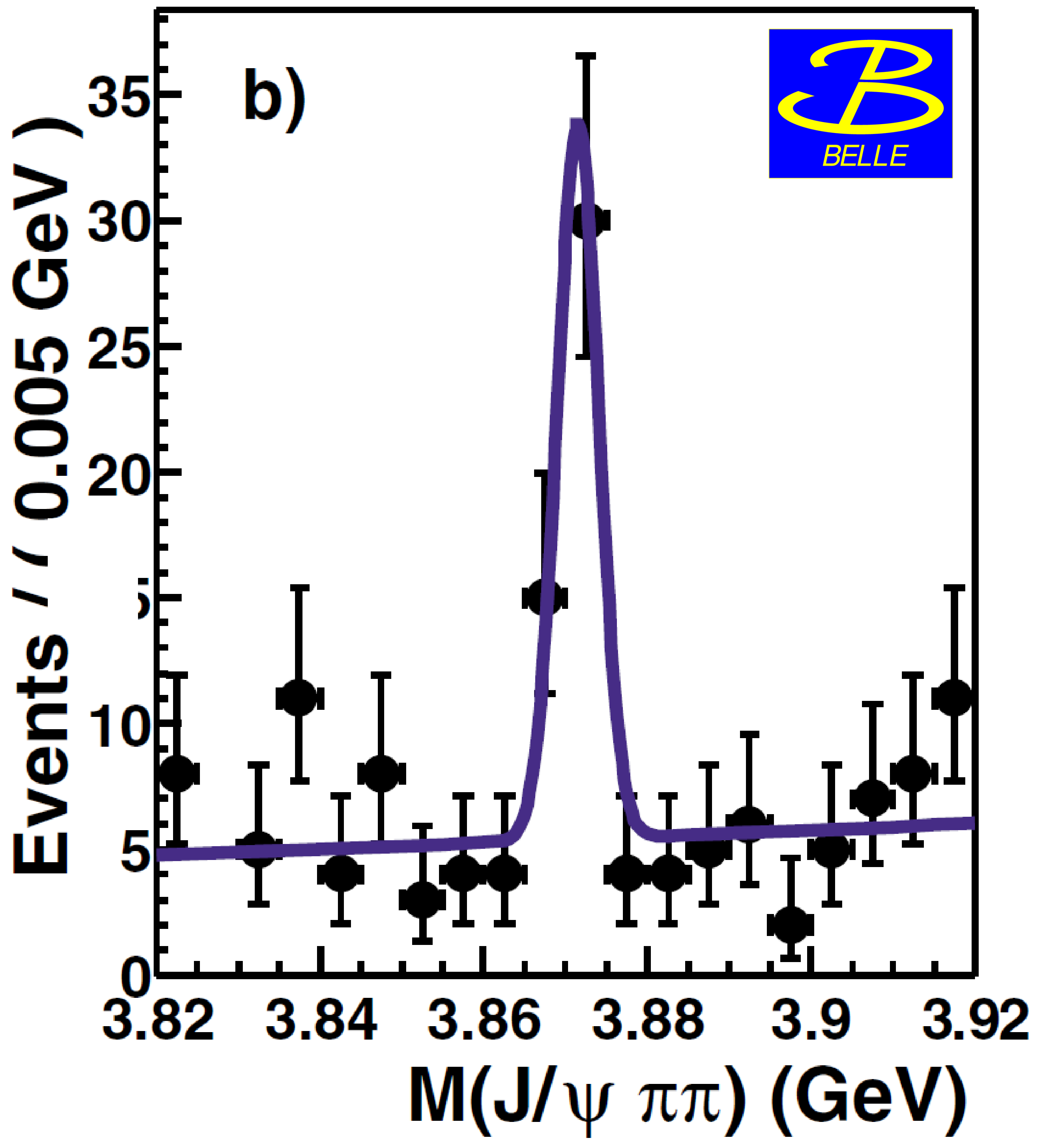


Hadron Spectroscopy at Belle

- 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!

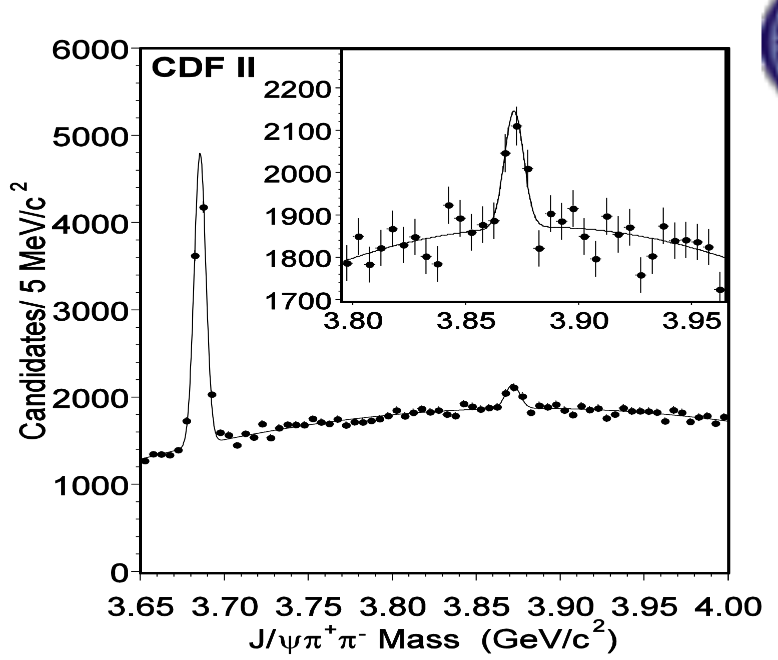
Belle PRL.91.262001 (2003)



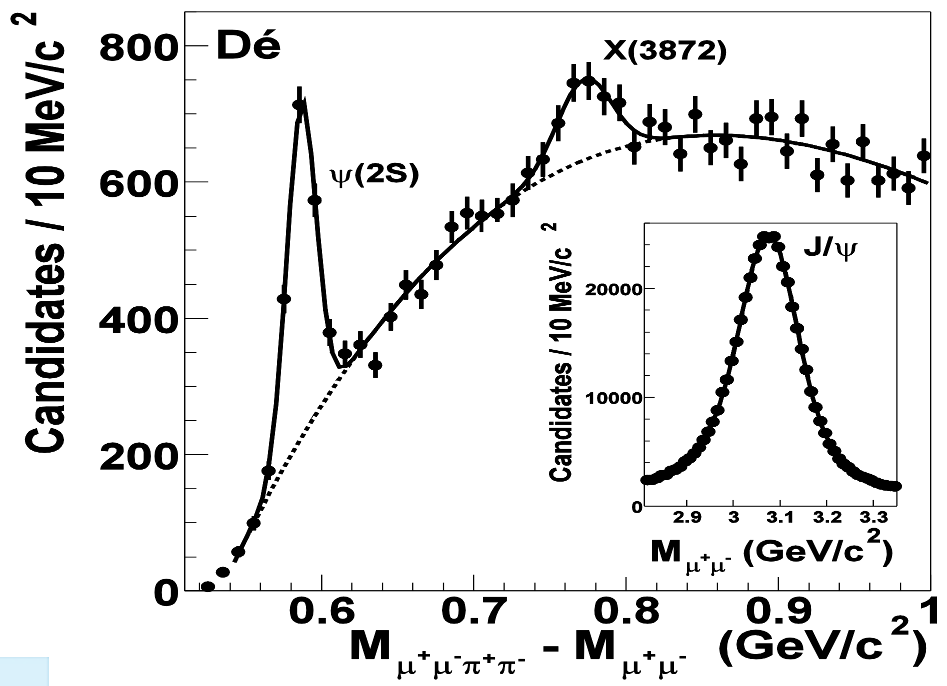
Most cited among > 500 papers in Belle
Still 100 citation/year!

X(3872): confirmed in many experiments!

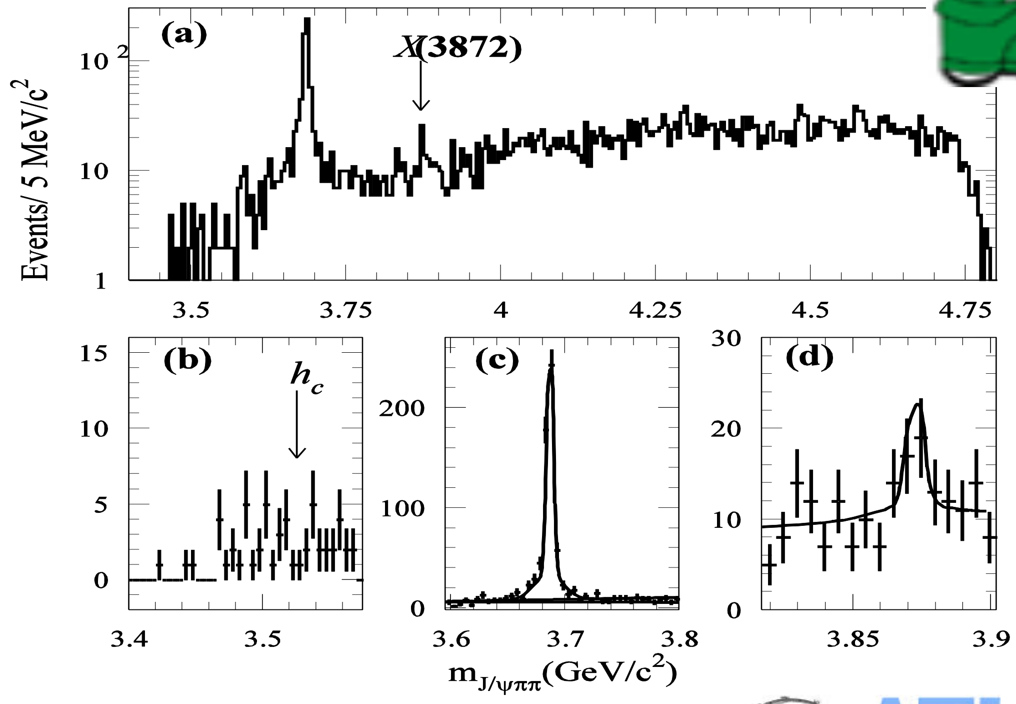
PRL.93.072001 (2004)

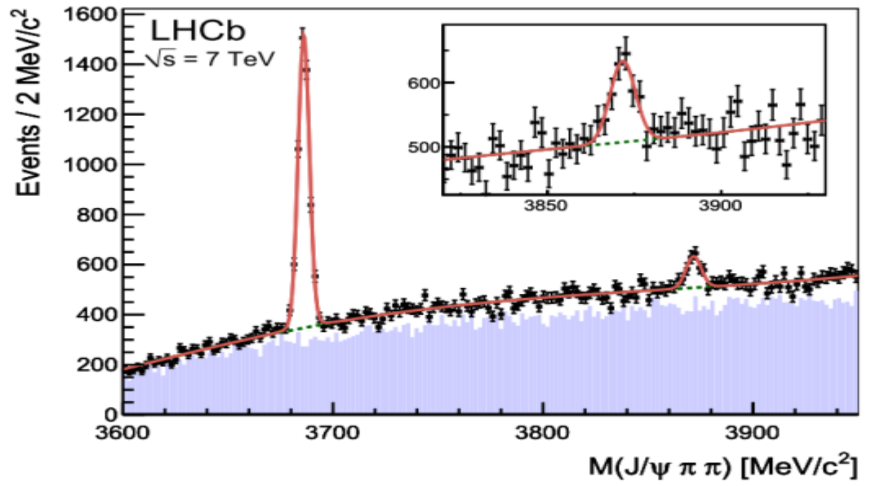


PRL.93.162002 (2004)

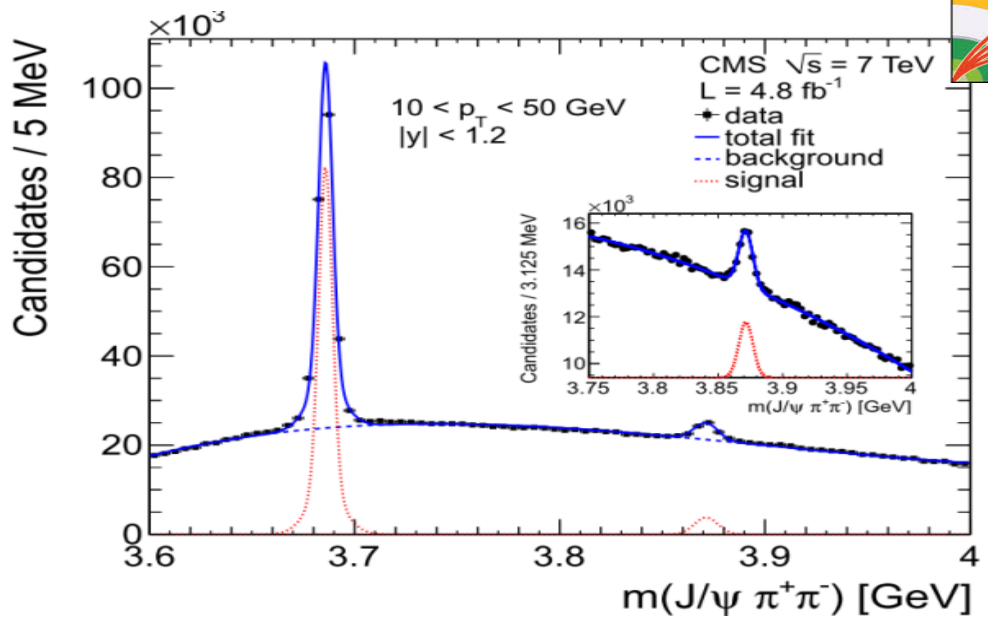


PRD.71.071103 (2005)

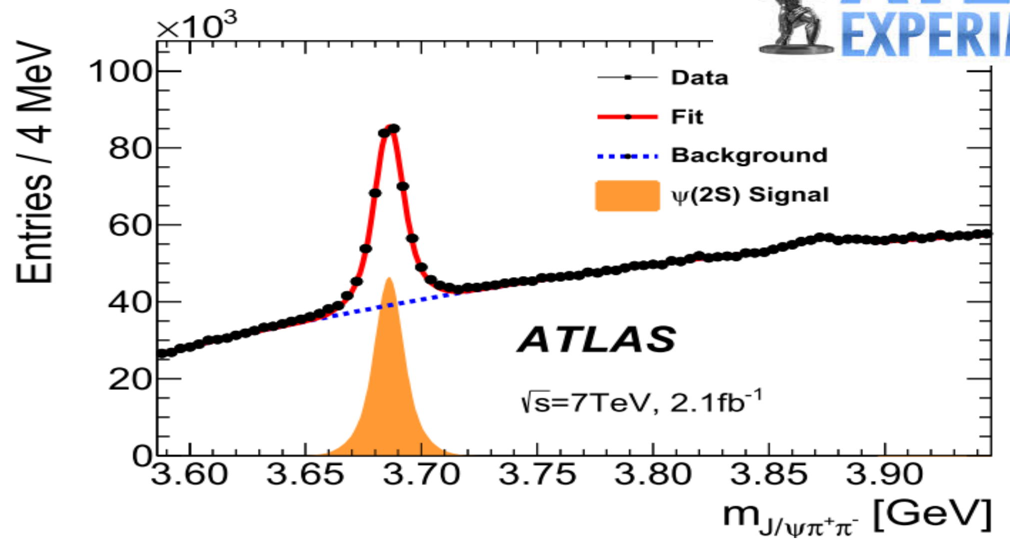




EPJC.72.1972 (2012)



JHEP.04.154 (2013)

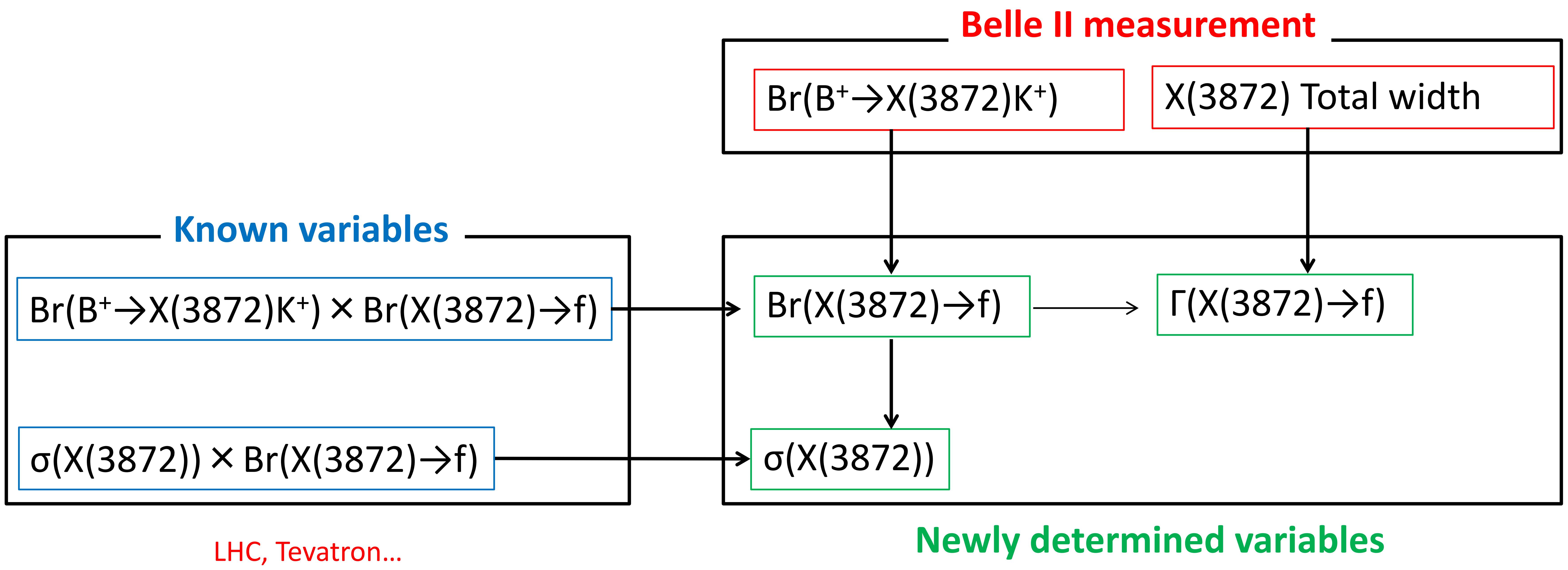


JHEP.79.2014 (2014)

- No quark model prediction in this mass region
- Mass is consistent with DD* with O(0.1) MeV precision suggesting DD* molecular state
- Differential cross section for "prompt production" (not from a B meson decay) is measured by LHC, though this should be suppressed for molecular state!
- Suggests X(3872) is superposition of molecular and $c\bar{c}$ state
- Precise measurements of production and decay processes are essential to understand the exotic nature

Absolute branching fraction measurement for X(3872)

- Many decay modes have been observed: J/ψ ρ, J/ψ ω, J/ψ γ, ψ(2S) γ, DD*, DDπ^0. etc.
- Branching fractions and decay widths not known
  - Essential dynamic information!
- Belle II can contribute to a deeper understanding of this state!



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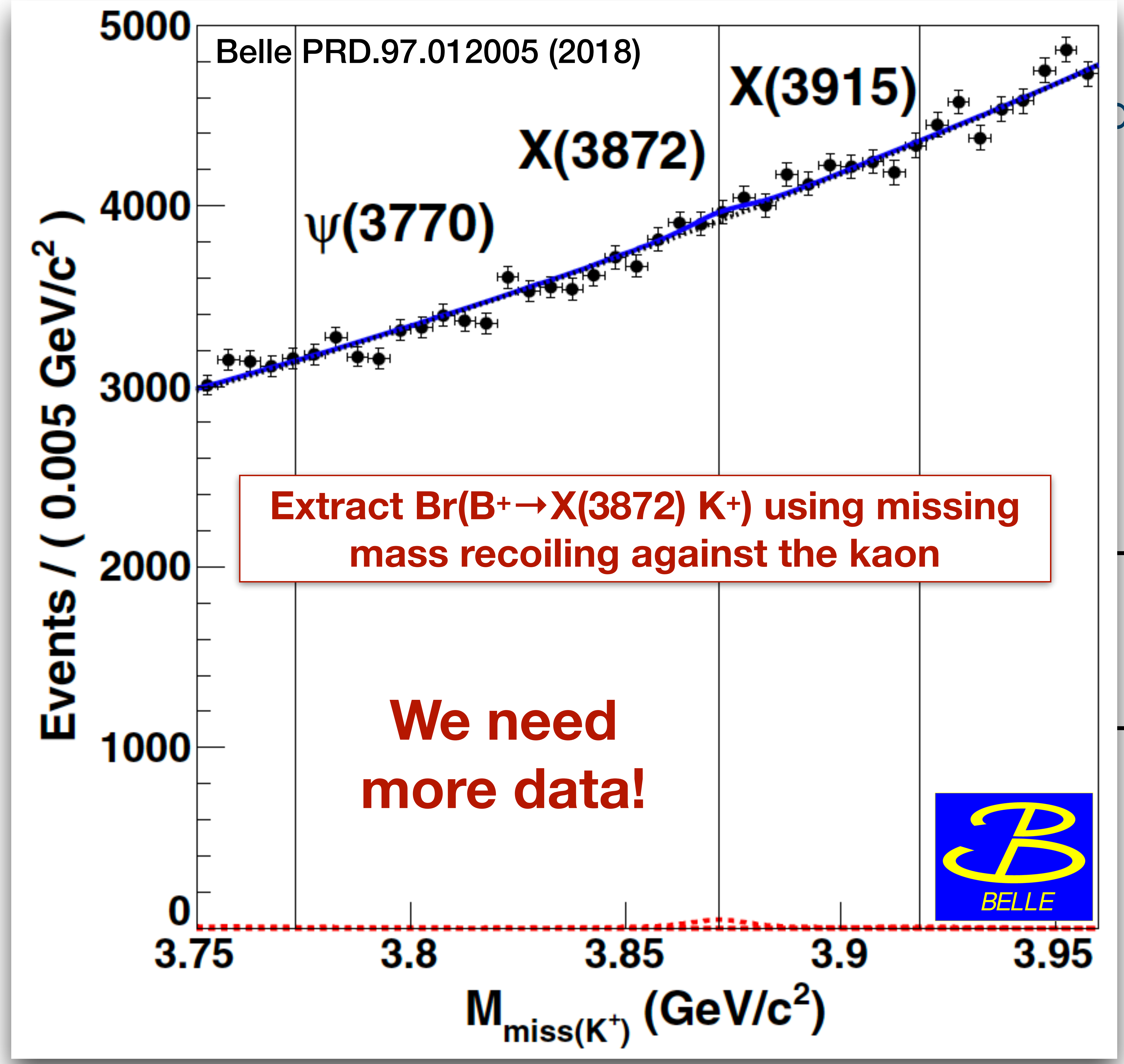
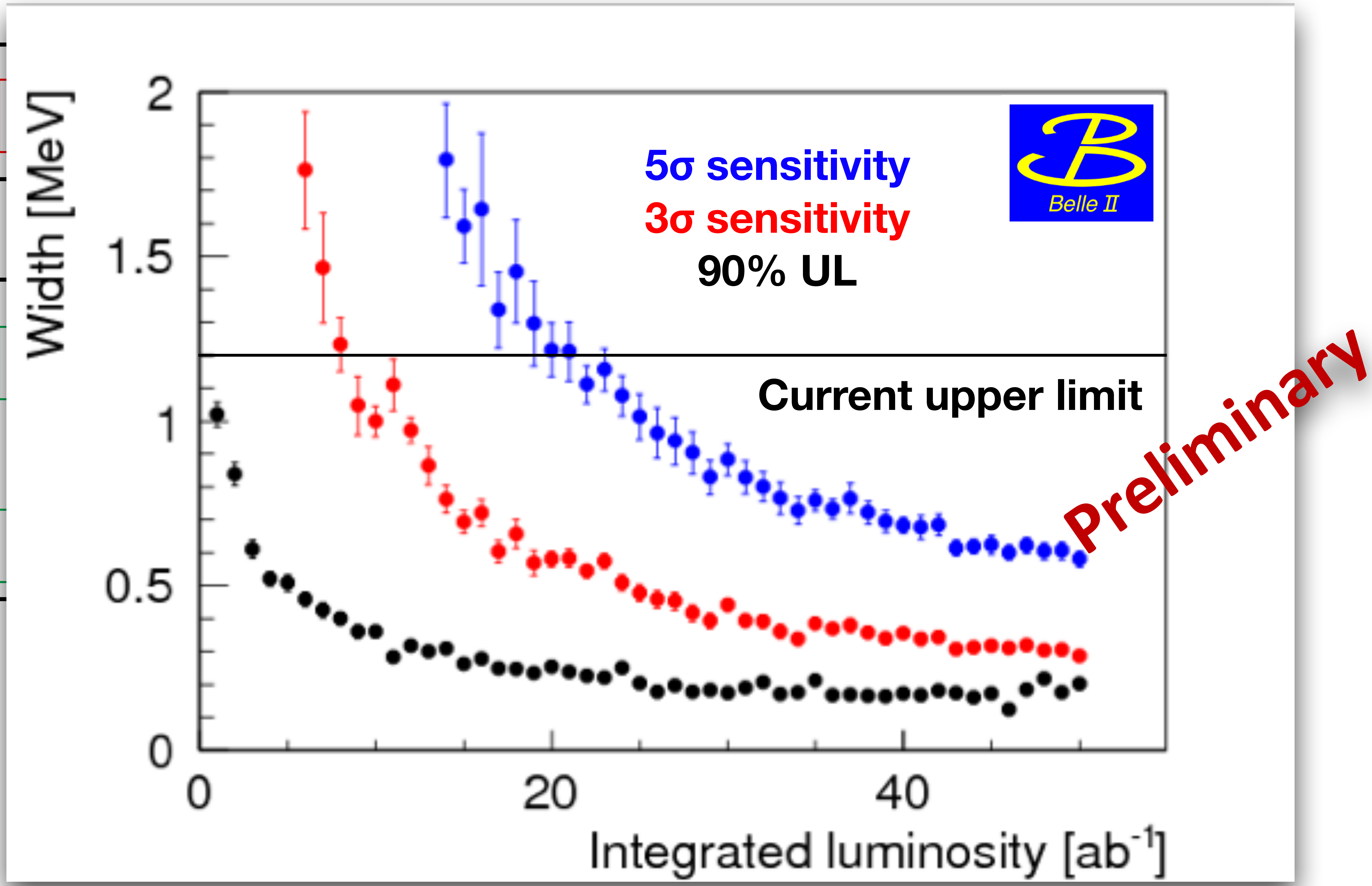
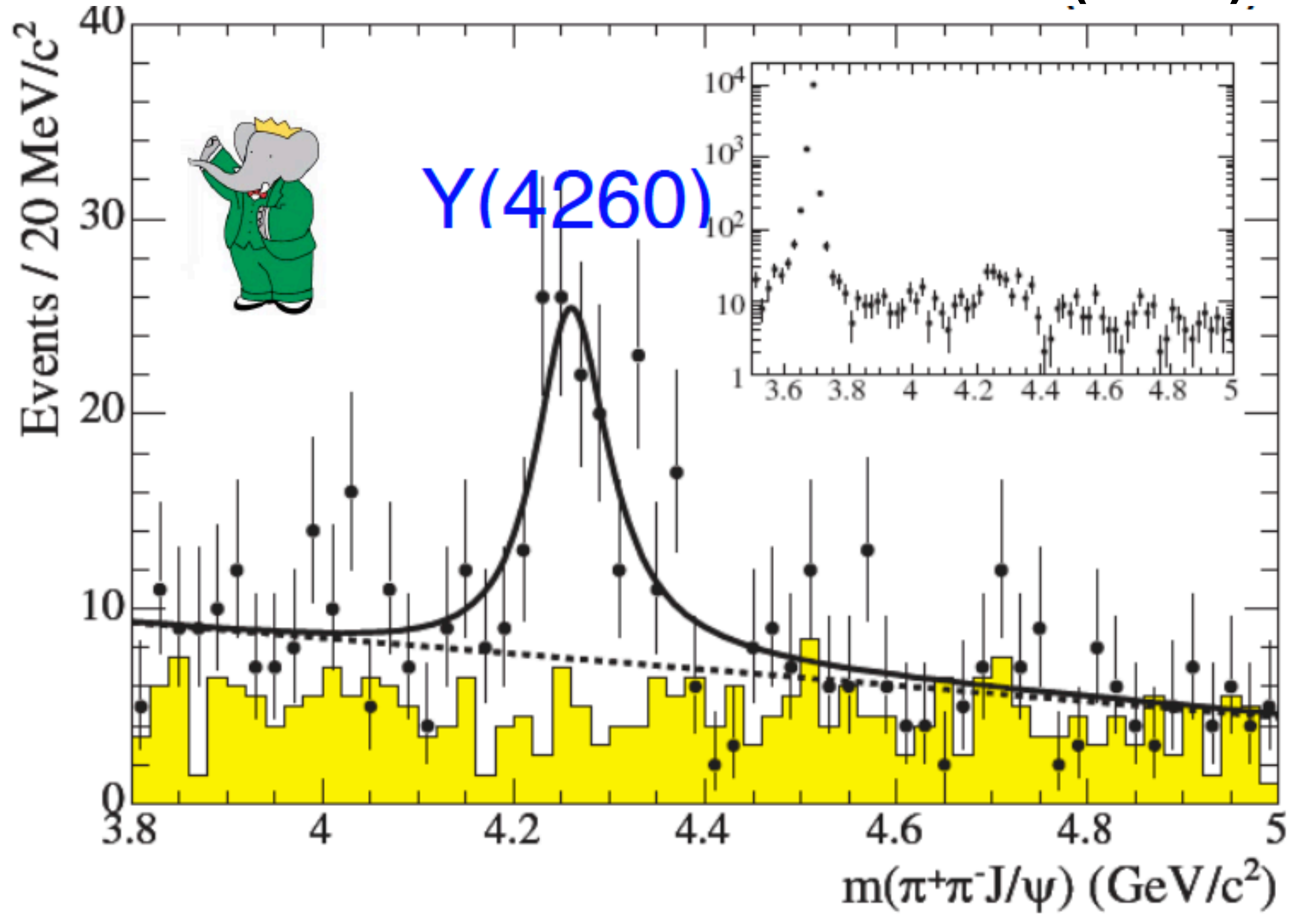


Mass resolution for $D\bar{D}\pi^0$ is ~680 keV: ~3 times better than $J/\psi\pi^+\pi^-$
Previously unmeasured due to low statistics

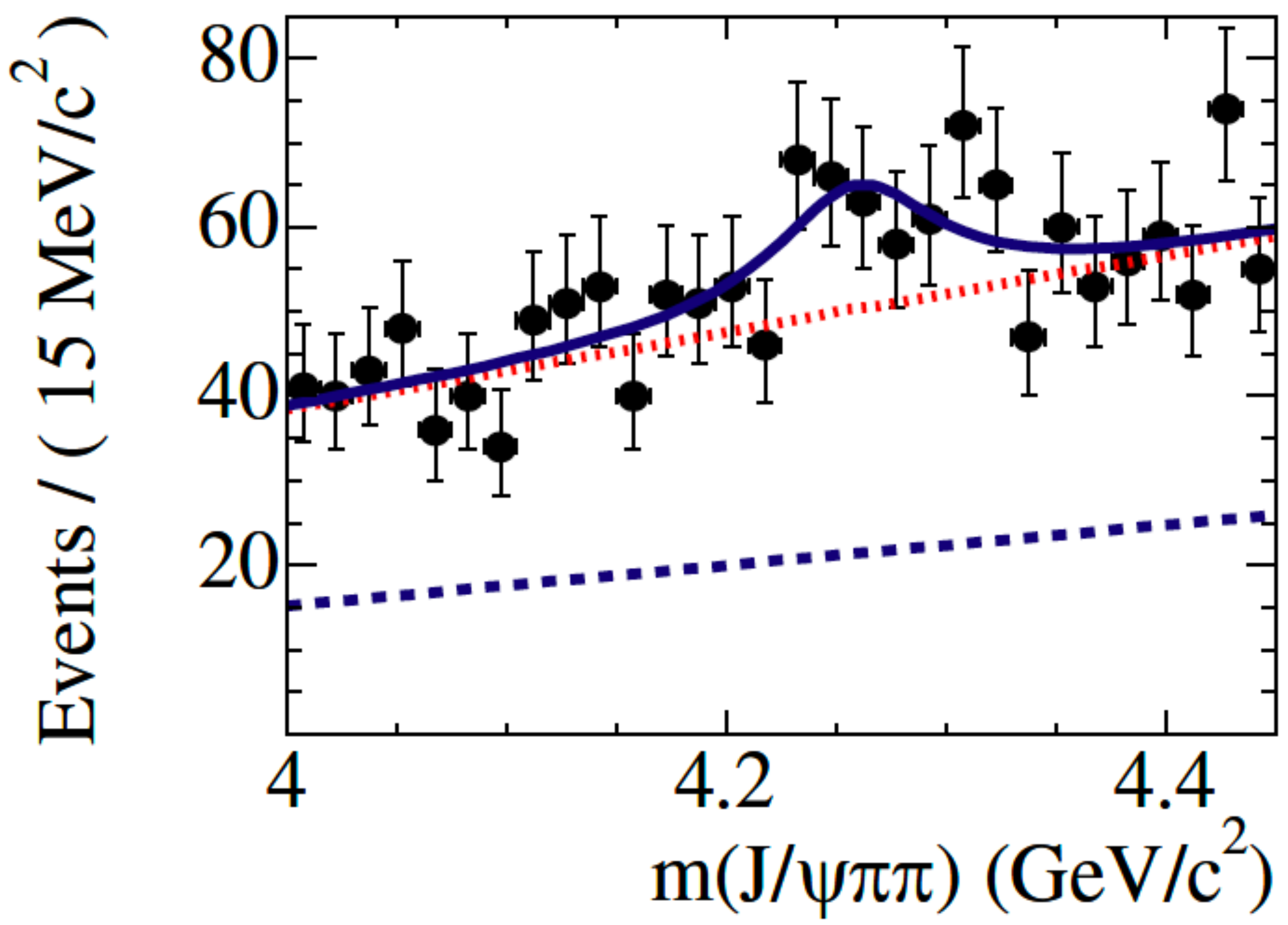


Y(4260) in B decays

BaBar PRL.95.142001 (2005)

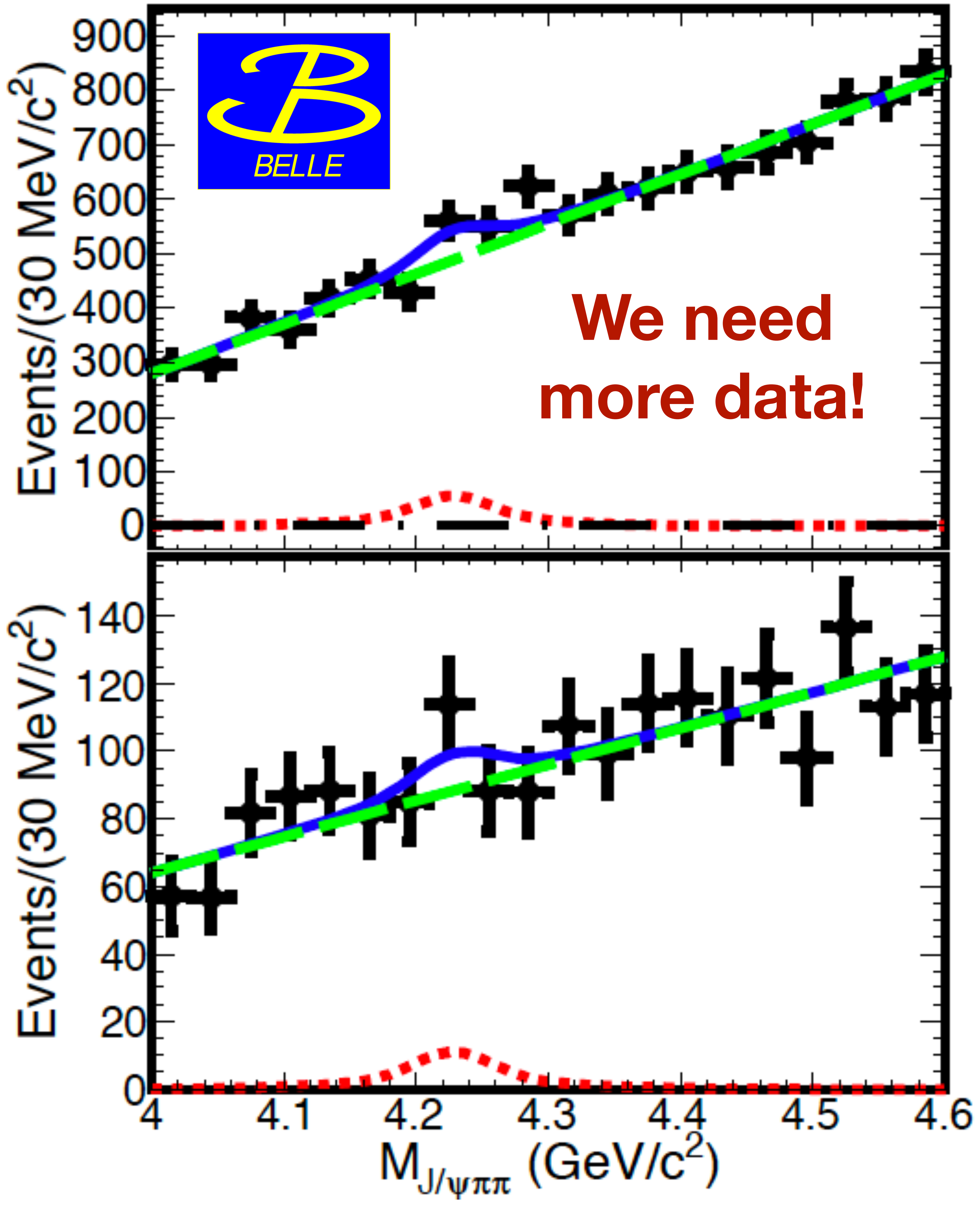


BaBar PRD.73.011101(R) (2006)



$$\mathcal{B}(B^- \to Y(4260)K^-, Y(4260) \to J/\psi\pi^+\pi^-) < 2.9 \times 10^{-5}$$

Belle arXiv:1901.06470



- Y(4260) discovered in $e^+e^+ \to \gamma_{ISR}\pi^+\pi^-J/\psi$
  - Overpopulation of charmonium states!
  - Molecular ($D_1\bar{D}$), hybrid, tetraquark all offer viable descriptions
- Some predictions (e.g. mixed-state model based upon QCD sum rules), suggest $B^+ \to Y(4260)K^+$ with $Y(4260) \to \pi^+\pi^-J/\psi$ may have a branching fraction in the range $3.0 \times 10^{-8} - 1.8 \times 10^{-6}$

Improved by factor of 2

$$\mathcal{B}(B^+ \to Y(4260)K^+) \times \mathcal{B}(Y(4260) \to J/\psi\pi^+\pi^-) < 1.4 \times 10^{-5}$$

$$\mathcal{B}(B^0 \to Y(4260)K^0) \times \mathcal{B}(Y(4260) \to J/\psi\pi^+\pi^-) < 1.7 \times 10^{-5}$$

New upper limit

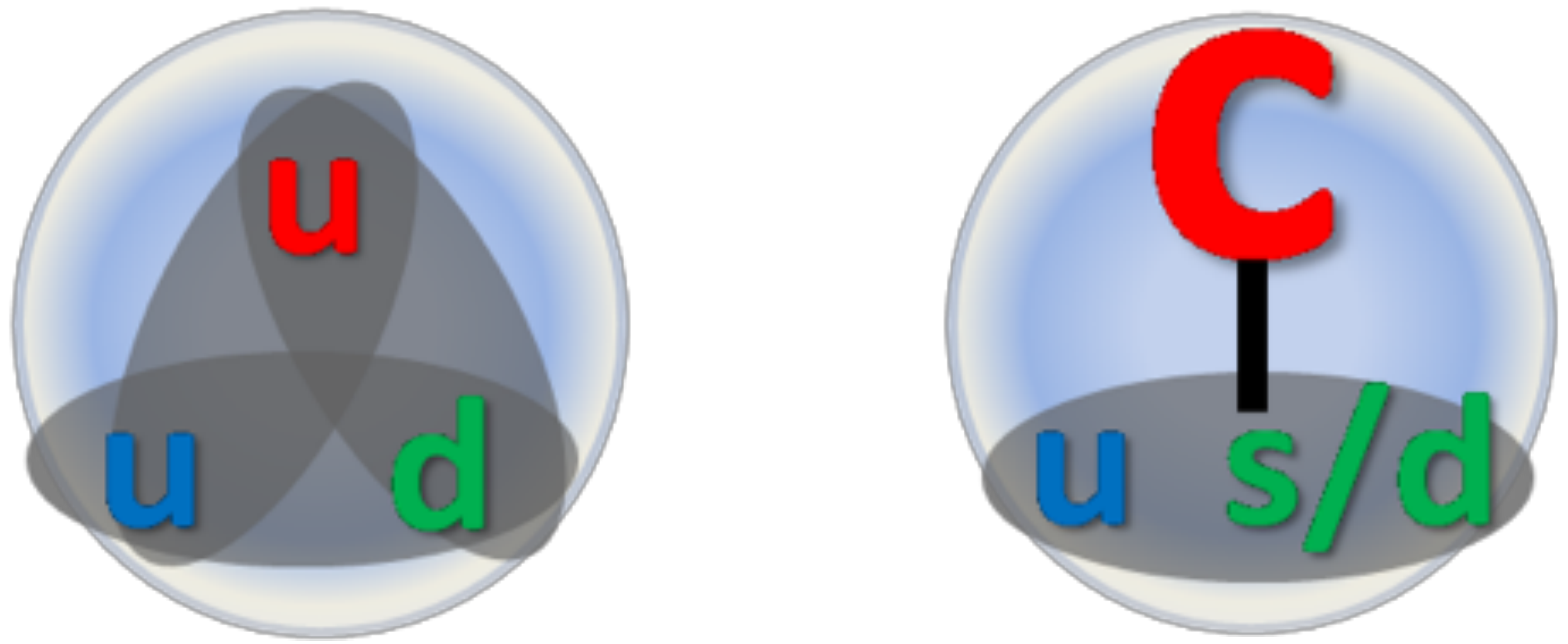
Charmed baryons

- Goal: discover charmed baryons, study their properties, and check the global consistency with the di-quark picture

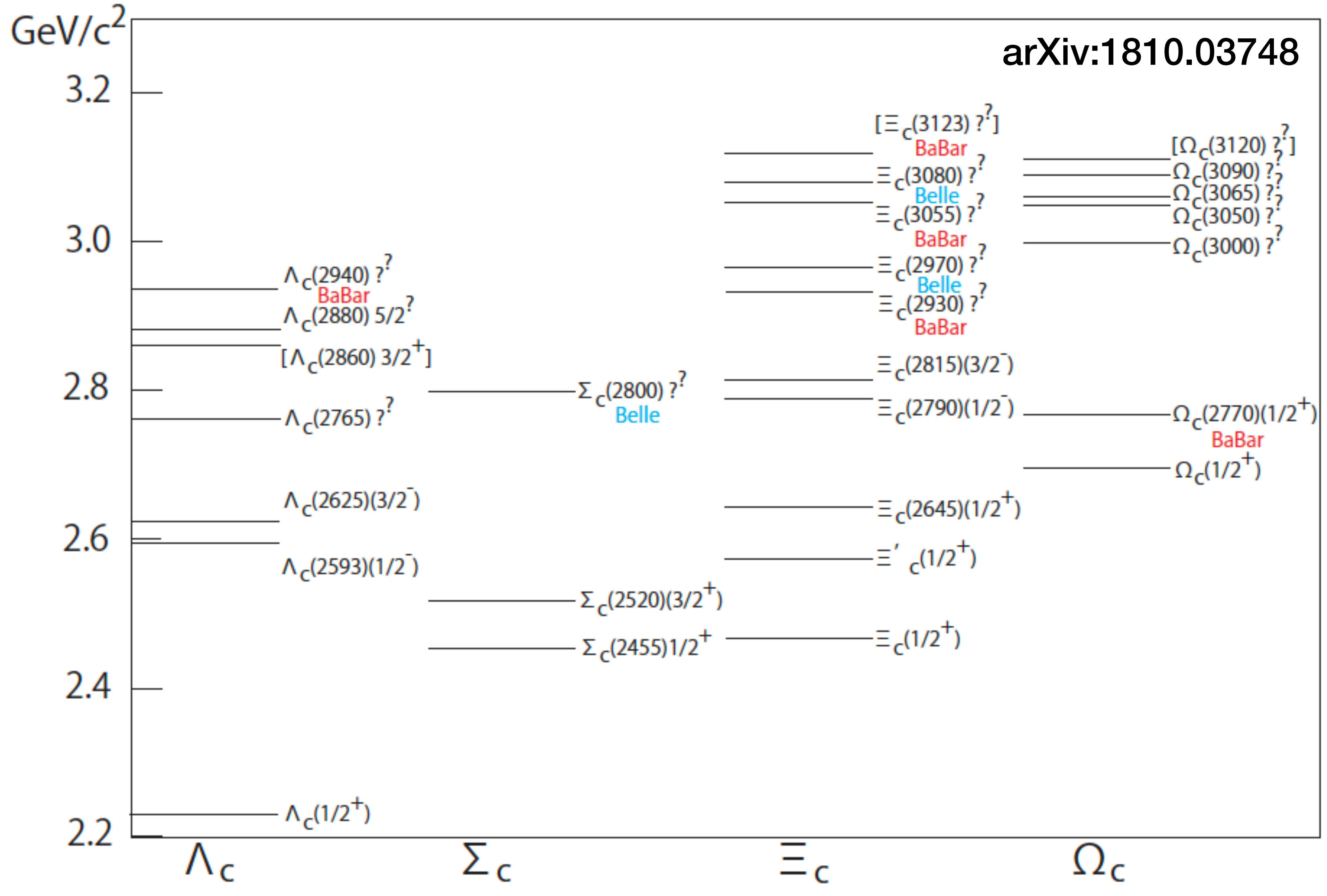
- Experimentally:
  - All ground states and many excited states observed
  - J^P for a few states determined
  - Many decay modes observed
  - Very precise mass determinations

- However…
  - Many missing J^P measurements!
  - Few analyses of substructure! (good opportunity to explore poorly understood baryon states!)

Nucleon | **Charmed baryon**

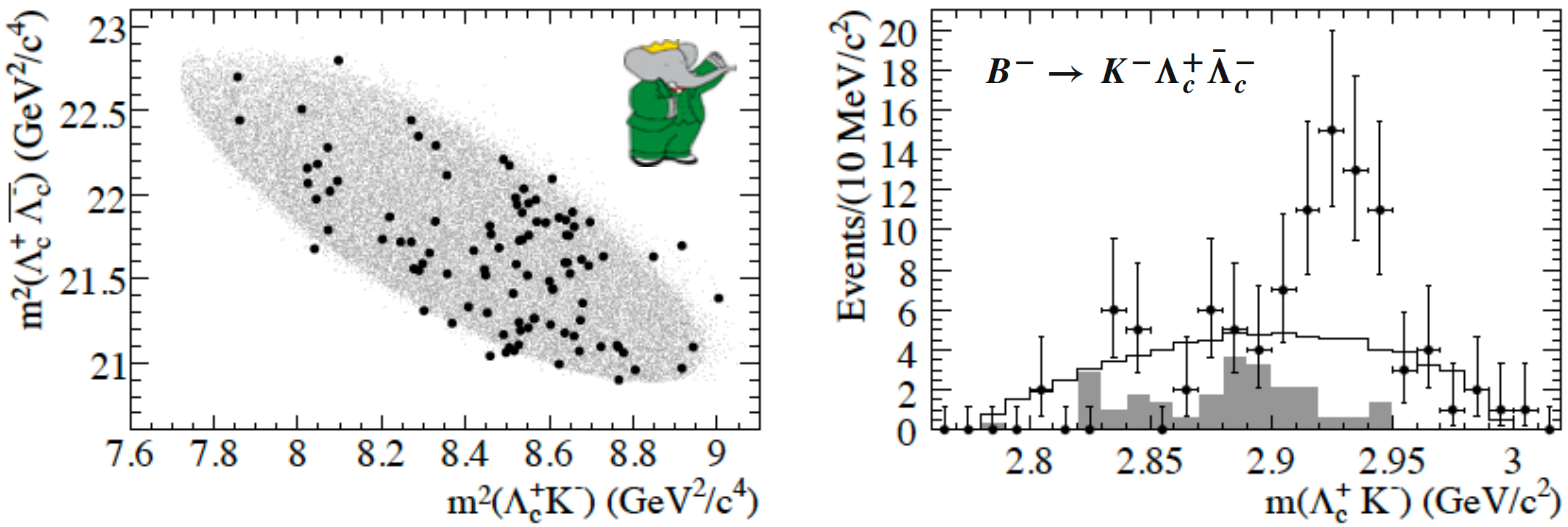


Cannot distinguish pairs | **Light di-quark and charm quark**

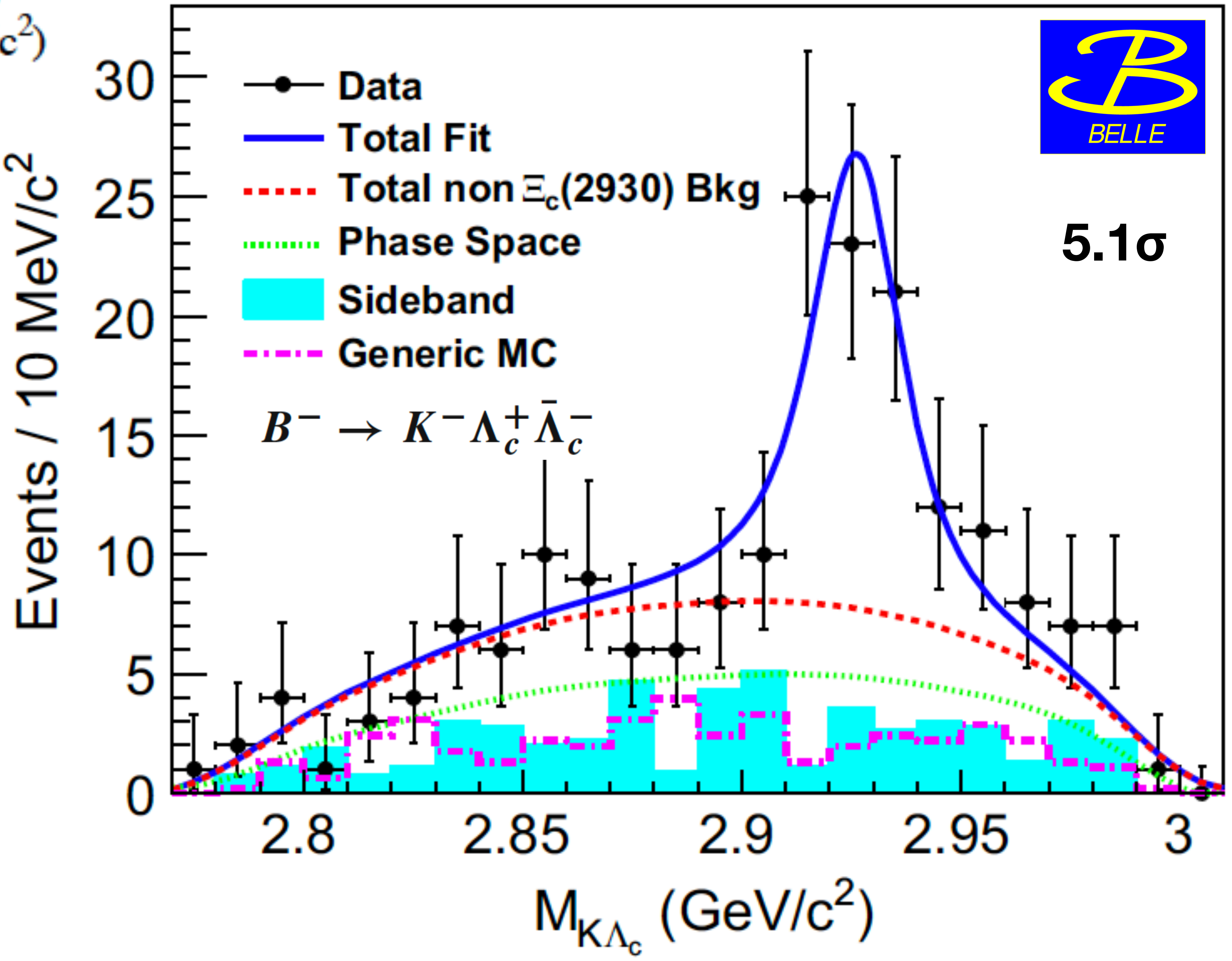


Excited charmed baryons in B decays

BaBar PRD.77.031101(R) (2008)



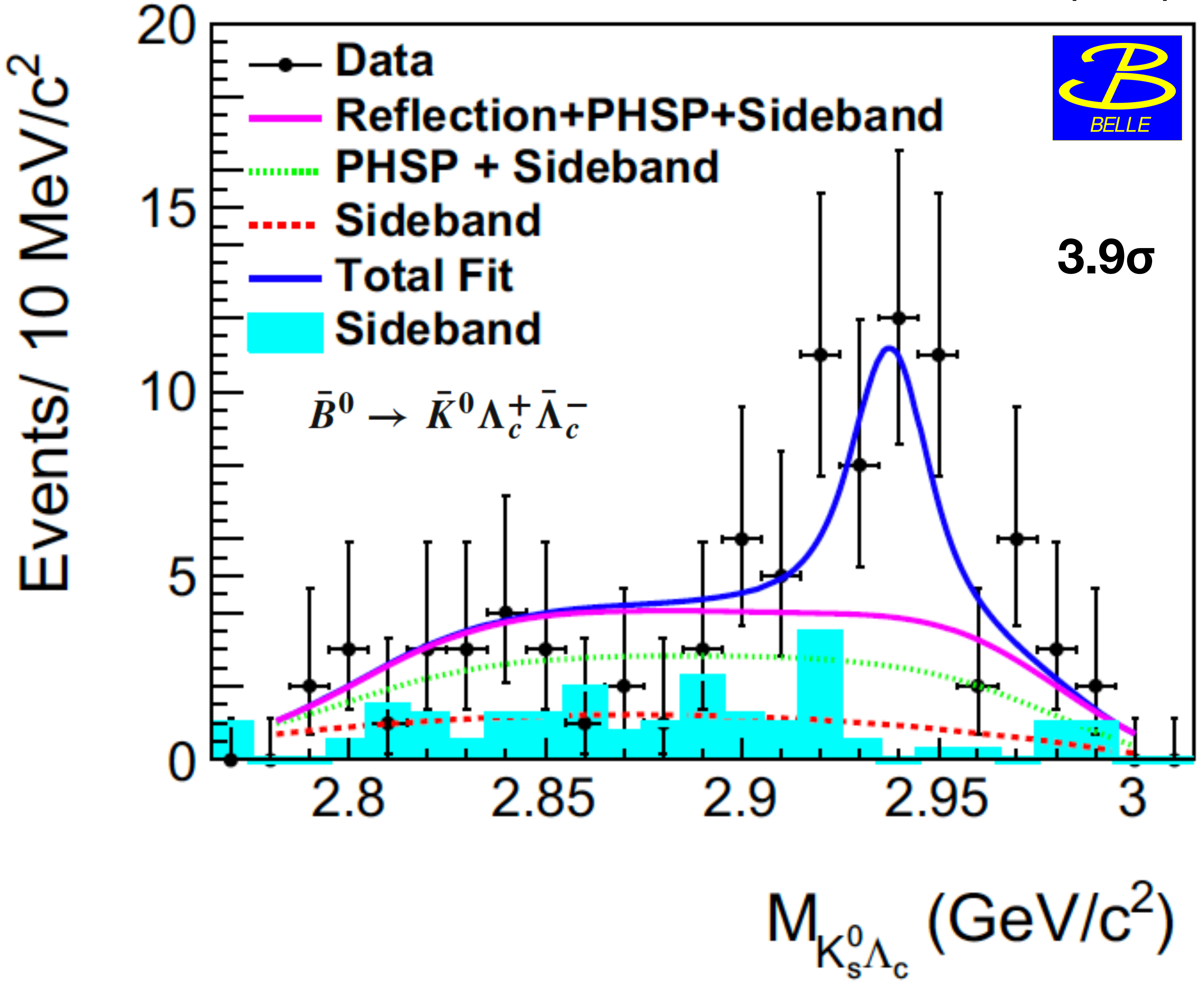
Belle EPJC.78.252 (2018)



- Ξ_c(2930) listed in PDG as 1-star state (Evidence of existence is poor)
  - Still accounted in theoretical models

Excited charmed baryons in B decays

Belle EPJC.78.928 (2018)



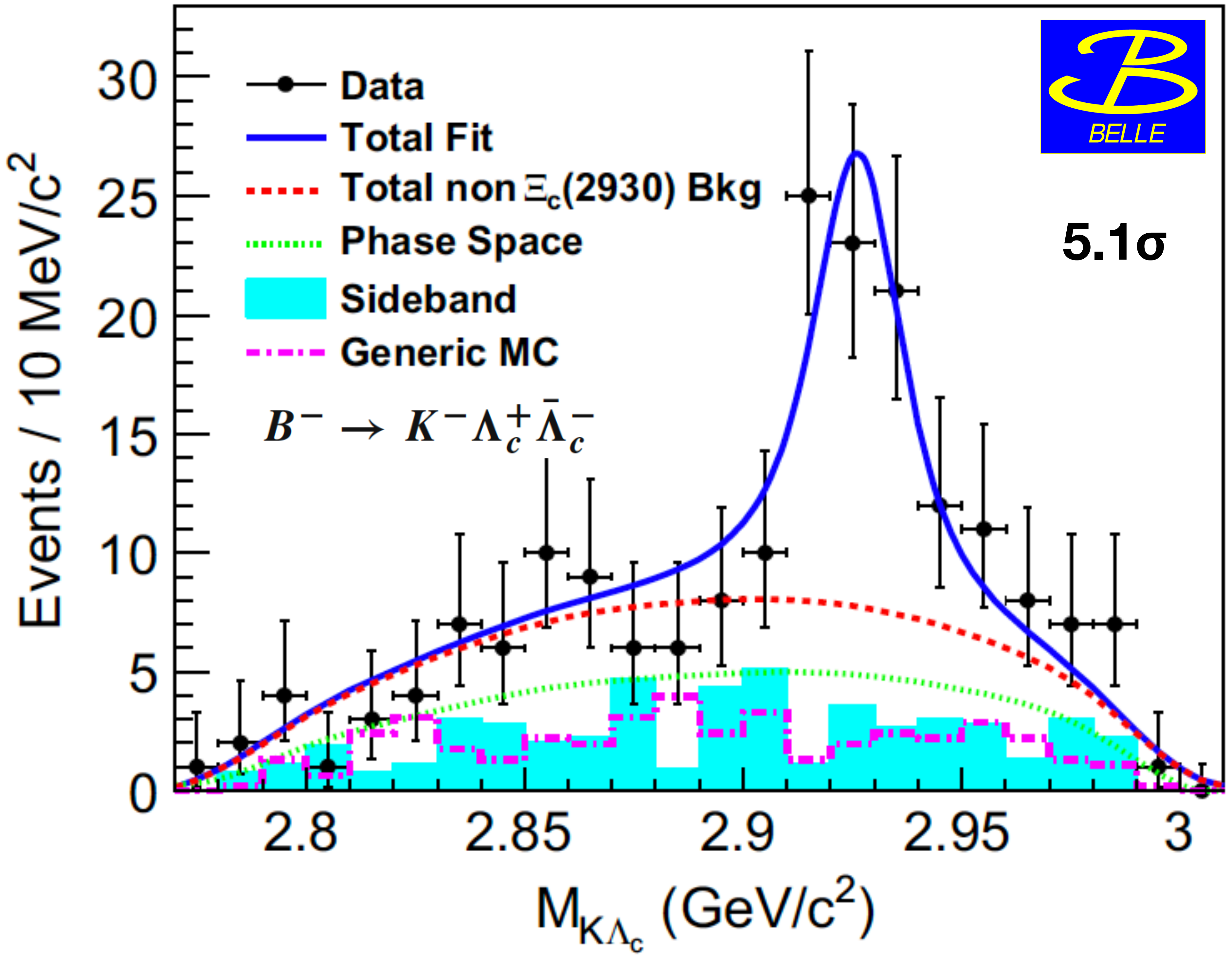
$$M_{\Xi_c(2930)^+} = [2942.3 \pm 4.4(\text{stat.}) \pm 1.5(\text{syst.})]\ \text{MeV}/c^2$$
$$\Gamma_{\Xi_c(2930)^+} = [14.8 \pm 8.8(\text{stat.}) \pm 2.5(\text{syst.})]\ \text{MeV}.$$

- Spin-parity analysis not performed due to low statistics

We need more data!

$$M_{\Xi_c(2930)} = (2928.9 \pm 3.0^{+0.9}_{-12.0})\ \text{MeV}/c^2$$
$$\Gamma_{\Xi_c(2930)} = (19.5 \pm 8.4^{+5.9}_{-7.9})\ \text{MeV}.$$

Belle EPJC.78.252 (2018)

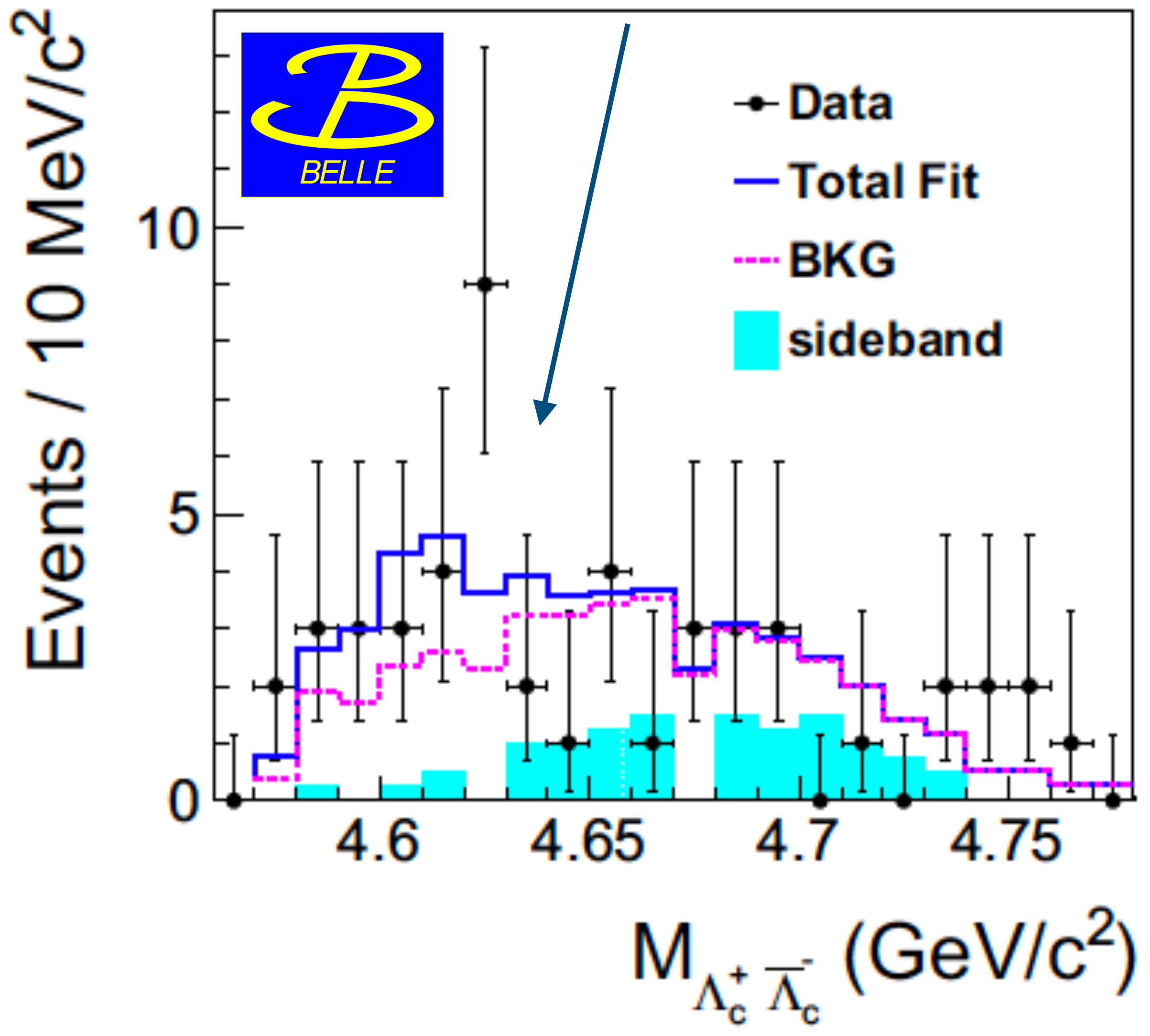


XYZ in B decays to baryons

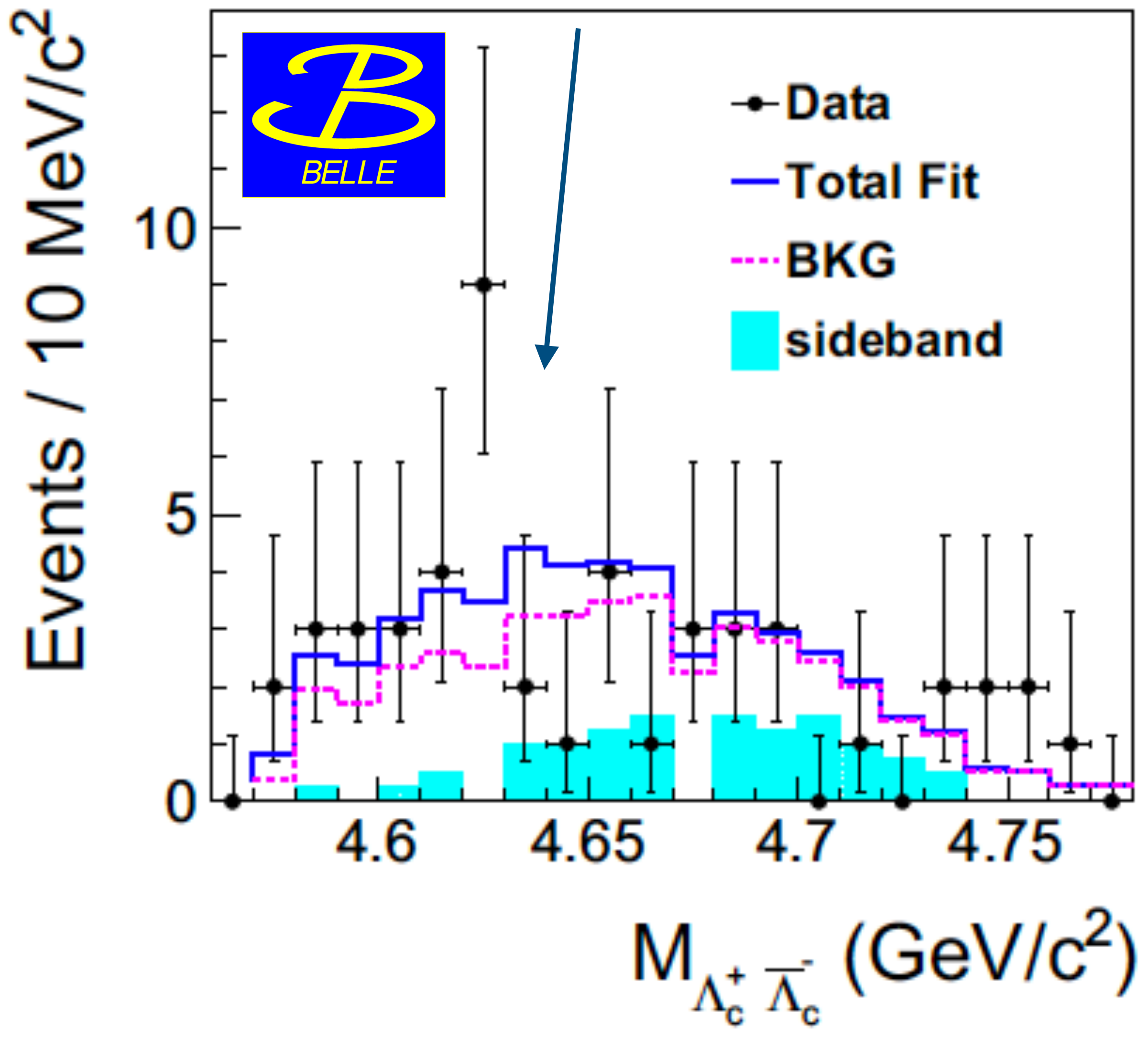
$\bar{B}^0 \to \bar{K}^0 \Lambda_c^+ \bar{\Lambda}_c^-$

Belle EPJC.78.252 (2018)

Add Y_η signal



Add Y(4660) signal

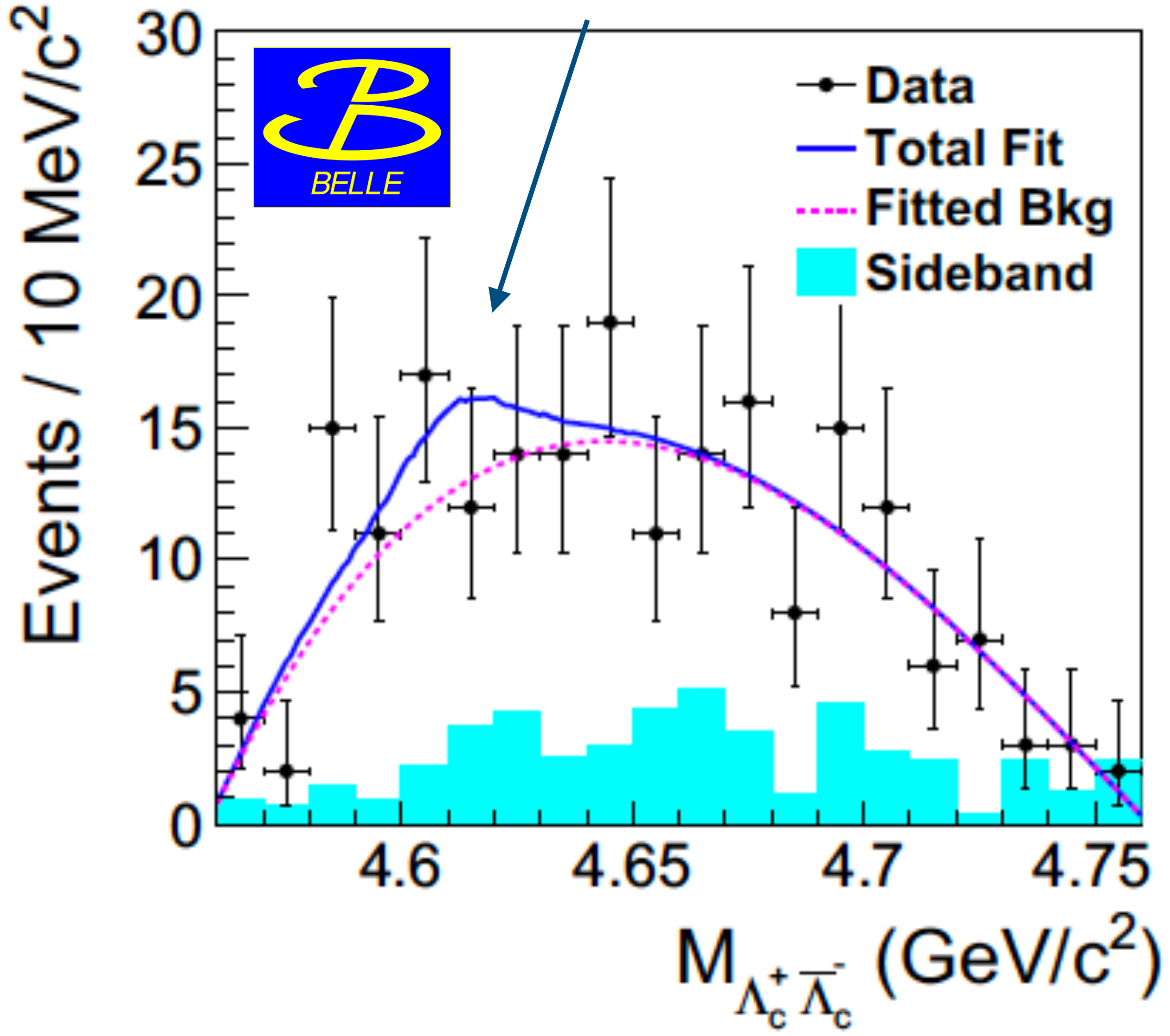


We need more data!

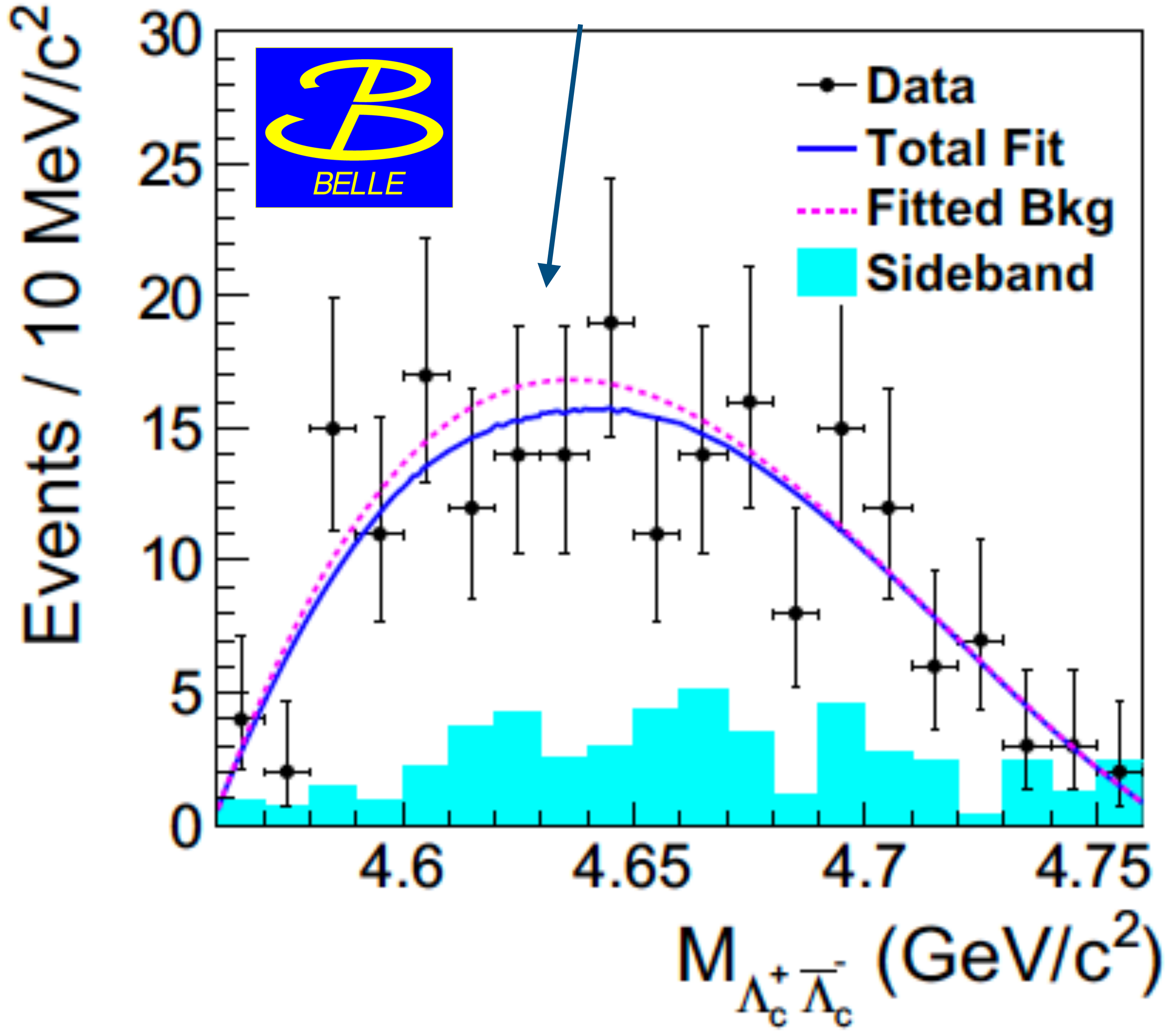
$B^- \to K^- \Lambda_c^+ \bar{\Lambda}_c^-$

Belle EPJC.78.928 (2018)

Add Y_η signal



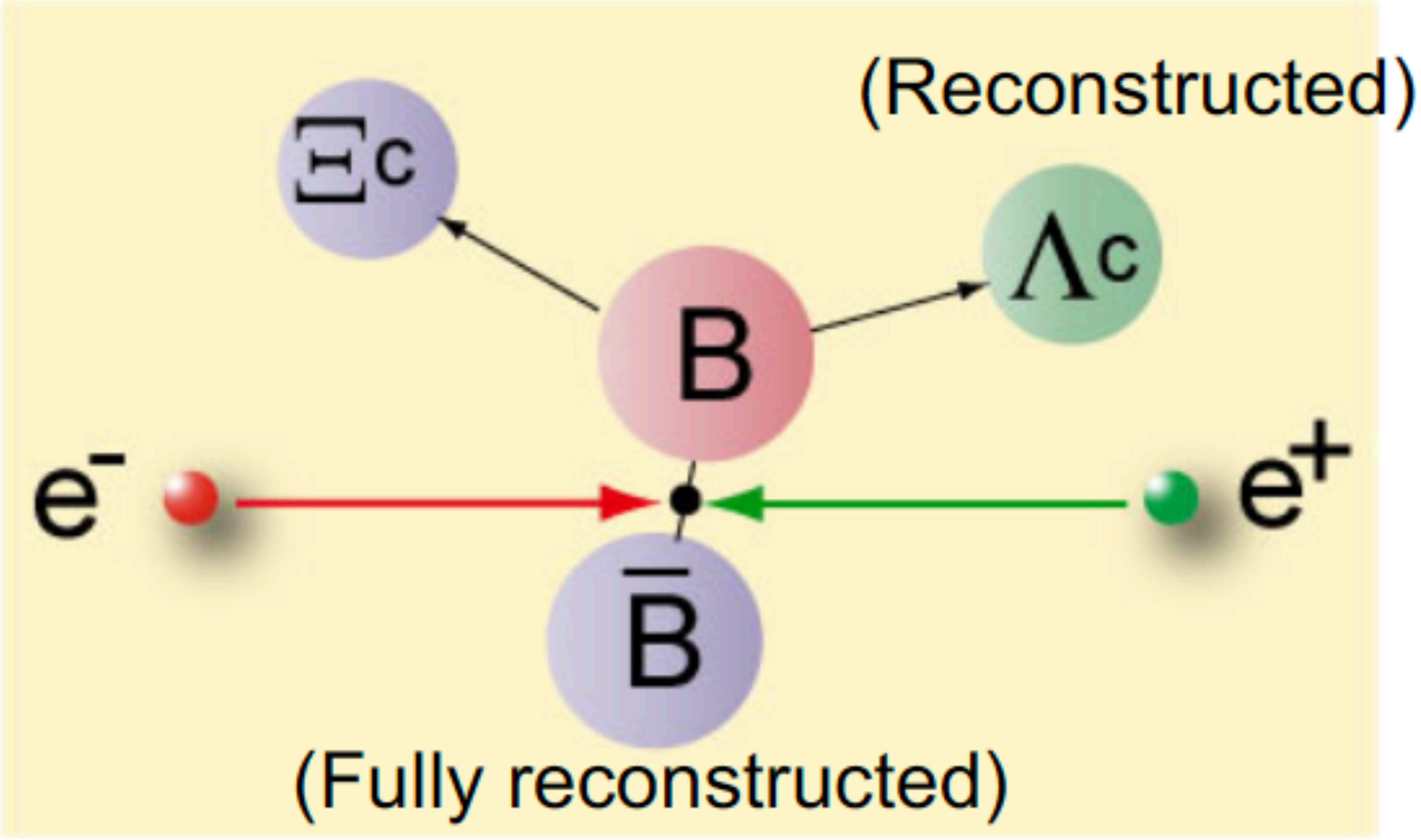
Add Y(4660) signal



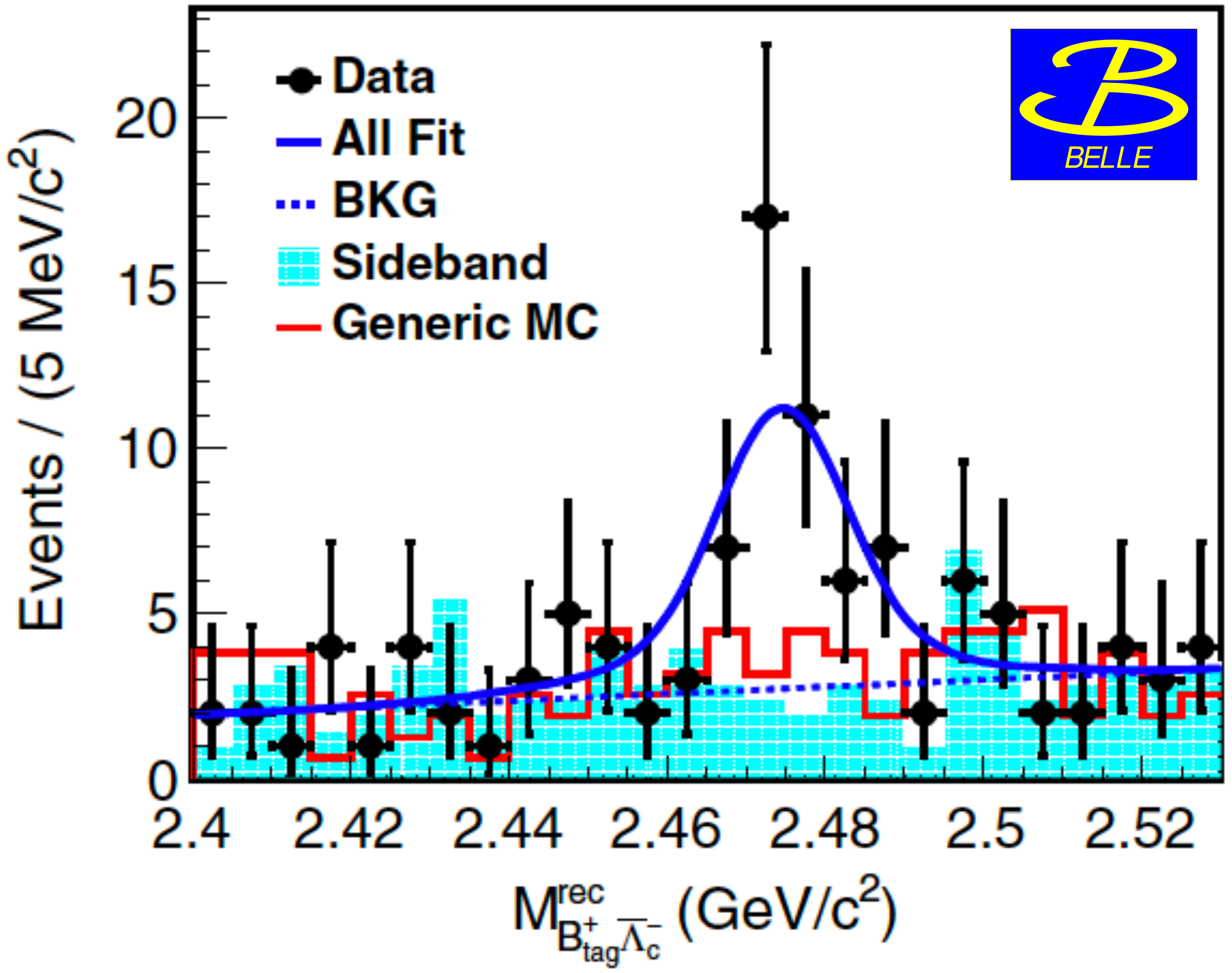
- Can also search for the charmonium-like state Y(4660) and its spin partner, Y_η in the $\Lambda_c\bar{\Lambda}_c$ invariant mass spectrum
- No clear signals are observed and 90% credibility level (C.L.) upper limits on their production rates are determined

Charmed baryons from B decays with missing mass

- Use missing mass technique to measure absolute branching fraction measurements
  - Needed to determine the absolute branching fractions of other decays (e.g. $\mathcal{B}(\Xi_c \to \Xi\pi)$ needed for other Ξ_c decays)



Belle PRL.122.082001 (2019)



$$\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+) = (1.80 \pm 0.50 \pm 0.14)\%,$$

$$\mathcal{B}(\Xi_c^0 \to \Lambda K^-\pi^+) = (1.17 \pm 0.37 \pm 0.09)\%,$$

$$\mathcal{B}(\Xi_c^0 \to pK^-K^-\pi^+) = (0.58 \pm 0.23 \pm 0.05)\%.$$

$$\mathcal{B}(B^- \to \bar{\Lambda}_c^-\Xi_c^0) = (9.51 \pm 2.10 \pm 0.88) \times 10^{-4}$$

First measurements!

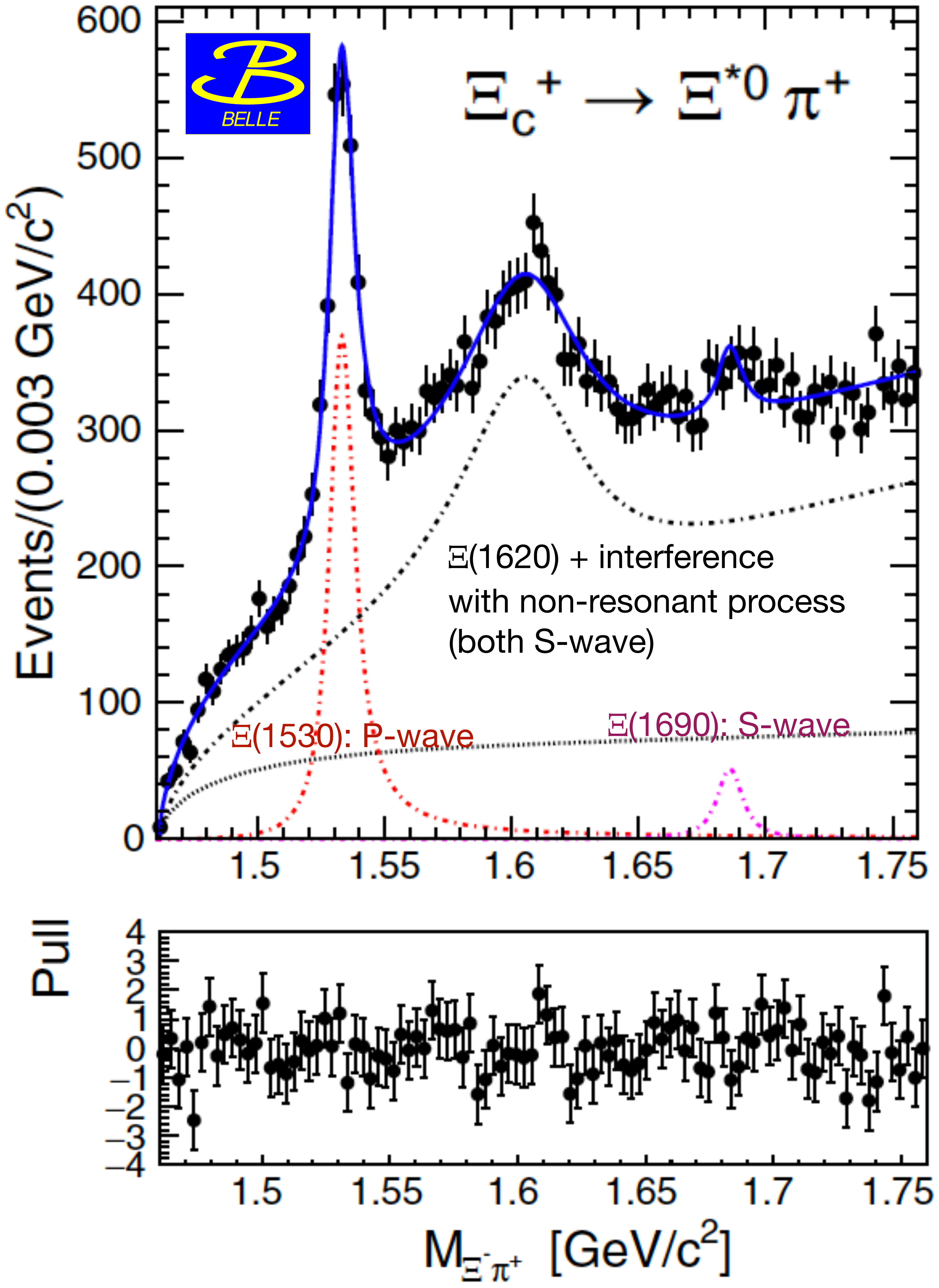
Excited hyperons in charm baryon decays

- Unusual excited states do not agree with quark model predictions
  - Use to probe limitations of quark models
  - Search for unrevealed aspects of QCD

- Ξ(1620) may not fit quark-model prediction
  - One-star rating in PDG
  - Doubly-strange analog to candidate meson-baryon molecular state Λ(1405)?

$$M = 1610.4 \pm 6.0(\mathrm{stat})^{+6.1}_{-4.2}\ (\mathrm{syst})\ \mathrm{MeV}/c^2$$
$$\Gamma = 59.9 \pm 4.8(\mathrm{stat})^{+2.8}_{-7.1}(\mathrm{syst})\ \mathrm{MeV}$$

Belle PRL.122.072501 (2019)

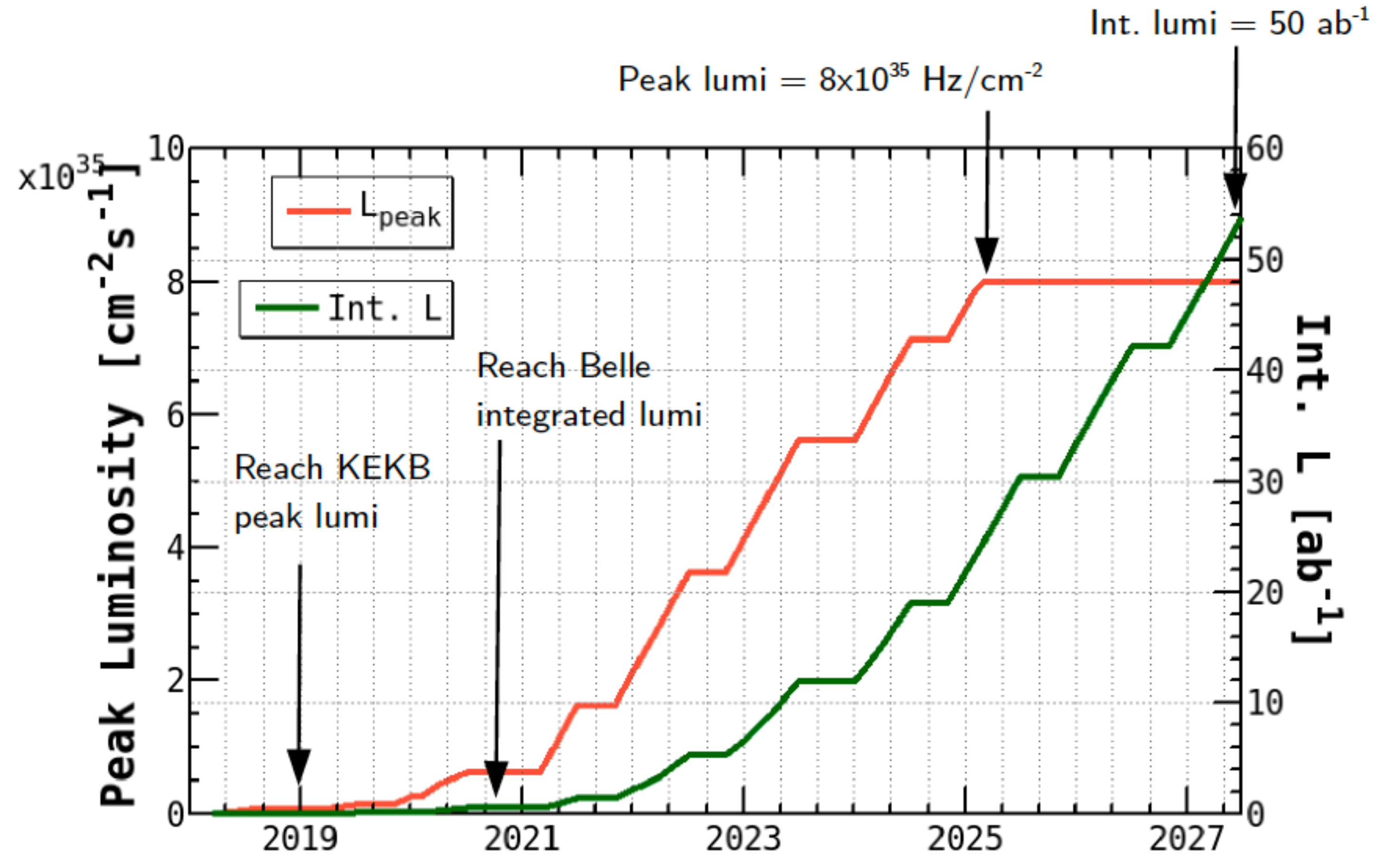


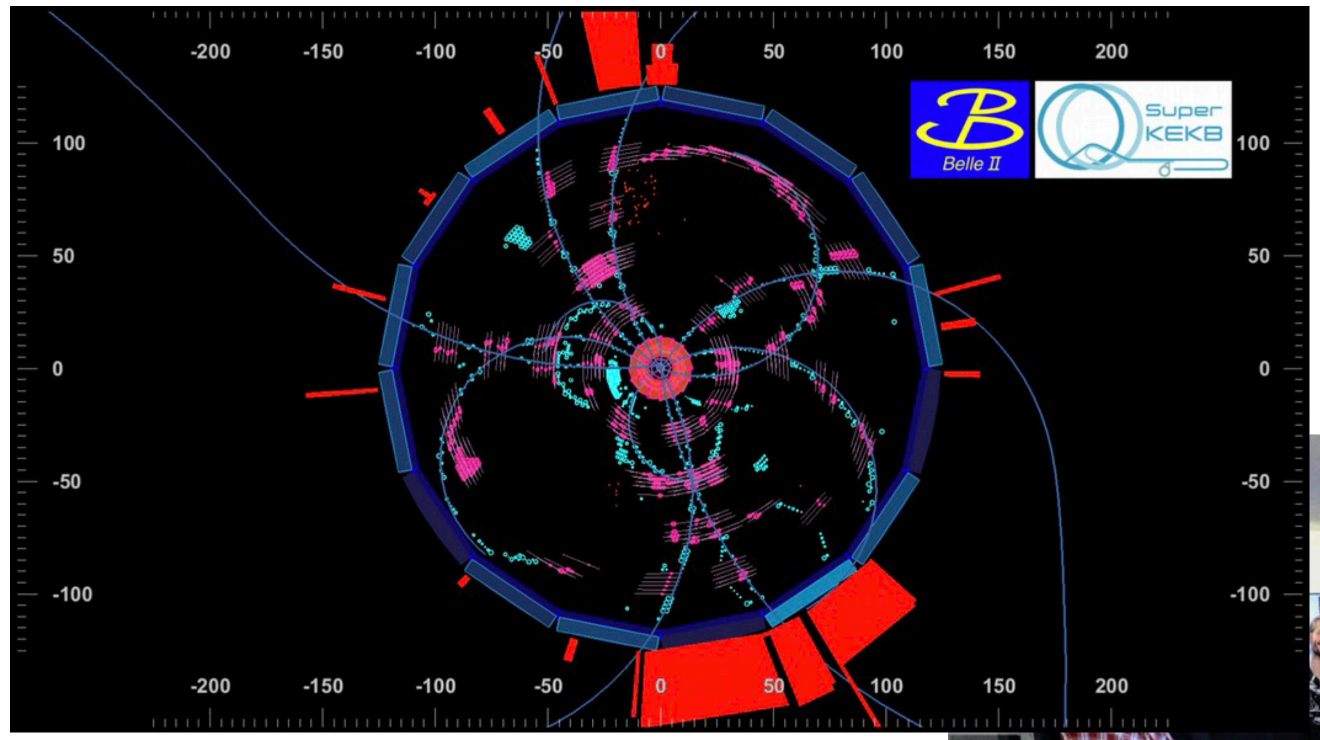
Transition from Belle to Belle II

- 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!

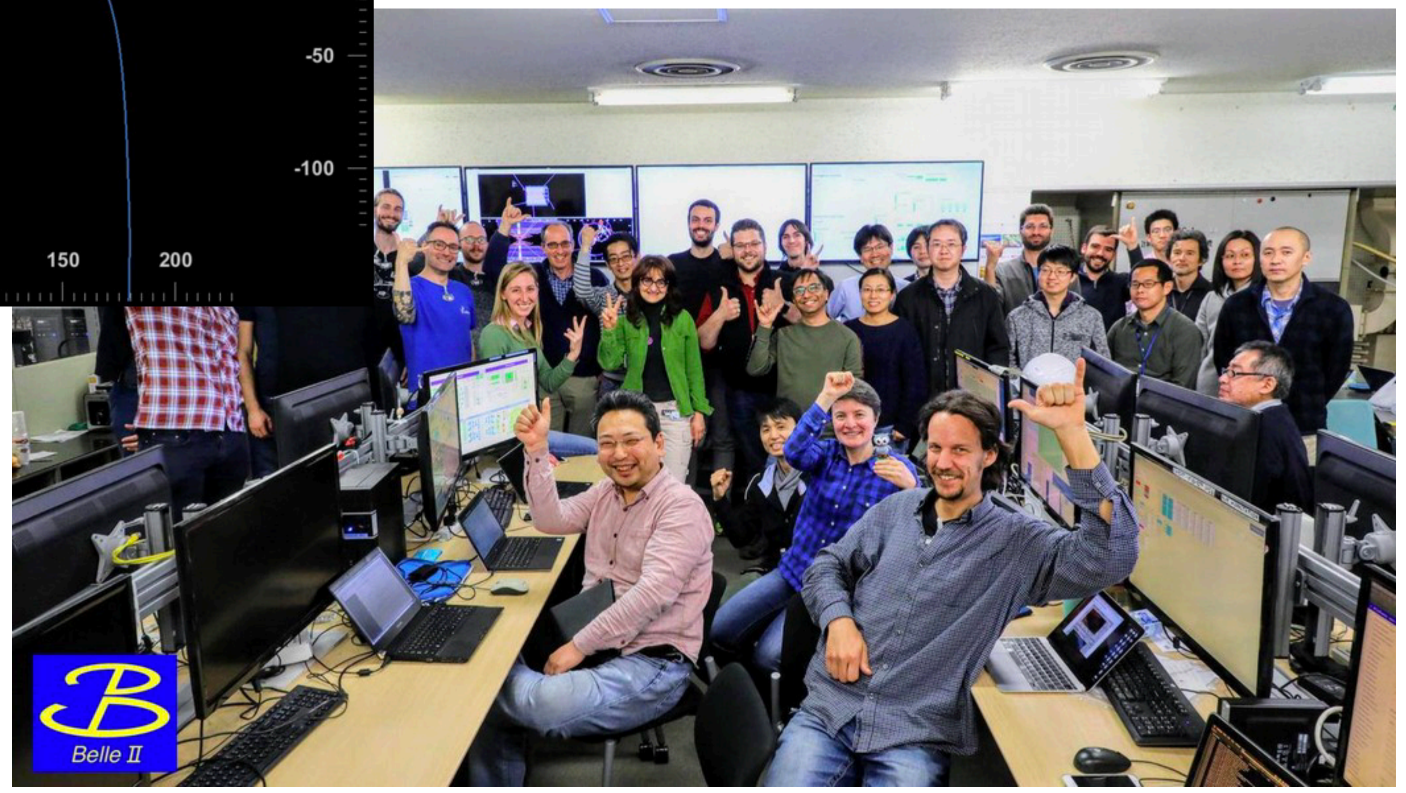
Transition from Belle to Belle II

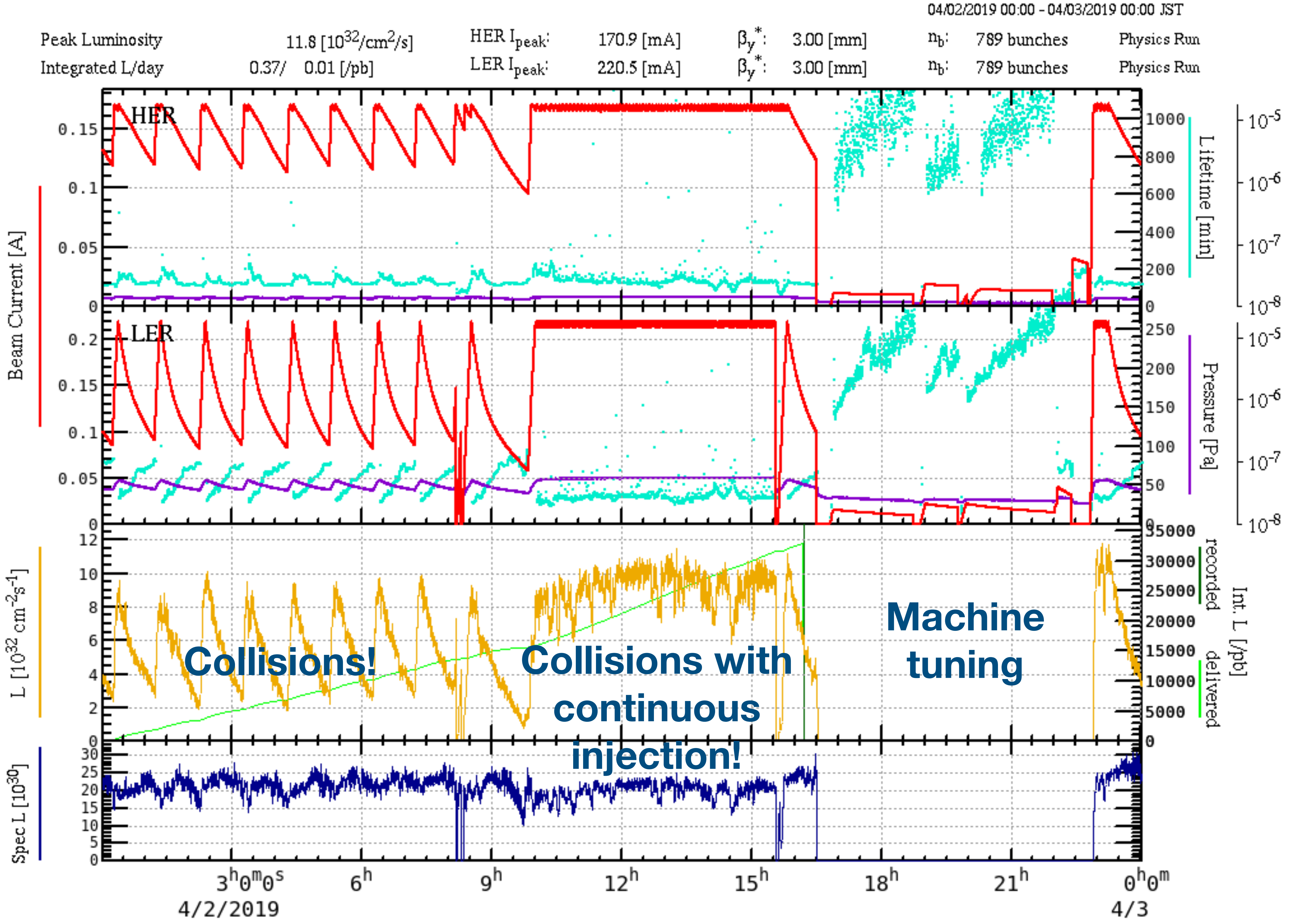
- Belle has made significant contributions to hadron spectroscopy
    - Discovery of many XYZ states
    - Better understanding of conventional hadronic states
    - Many hints of interesting physics!
    - … but we need more data!
- Belle-II will collect ~50 times as much data by leveraging upgrades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



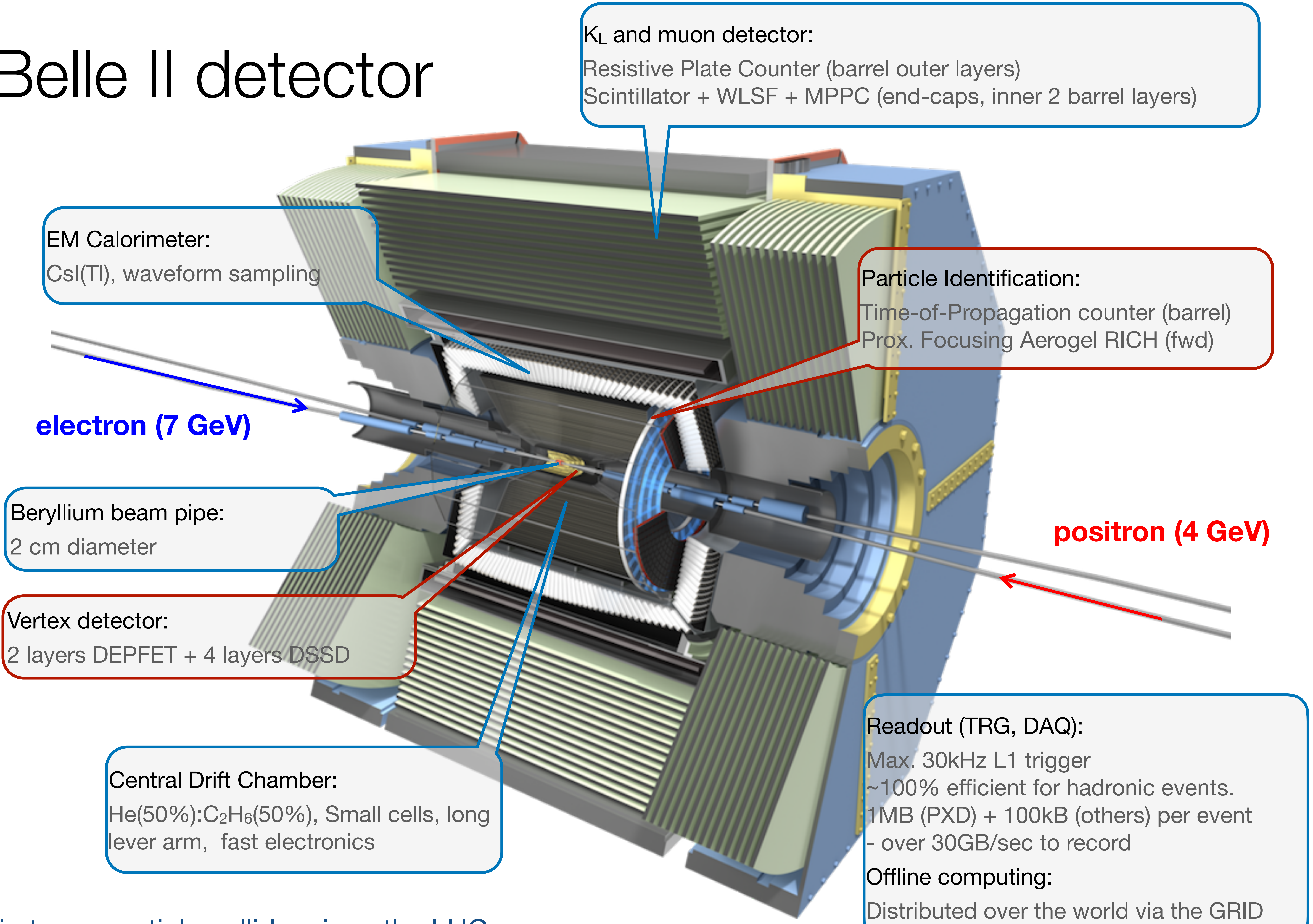


Data taking has started!





The Belle II detector

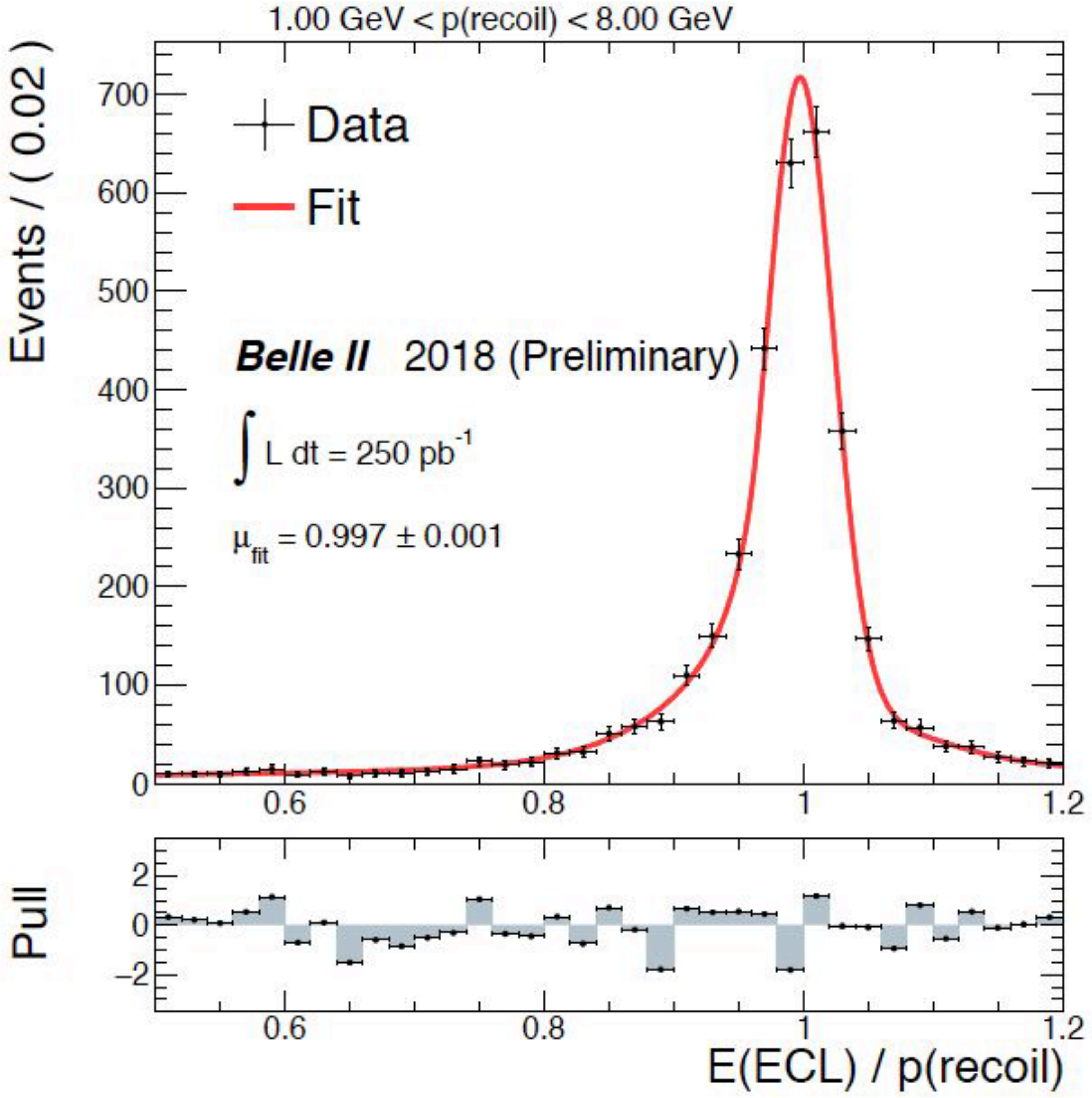


First new particle collider since the LHC
(intensity rather than energy frontier; e$^+$e$^-$ rather than pp)

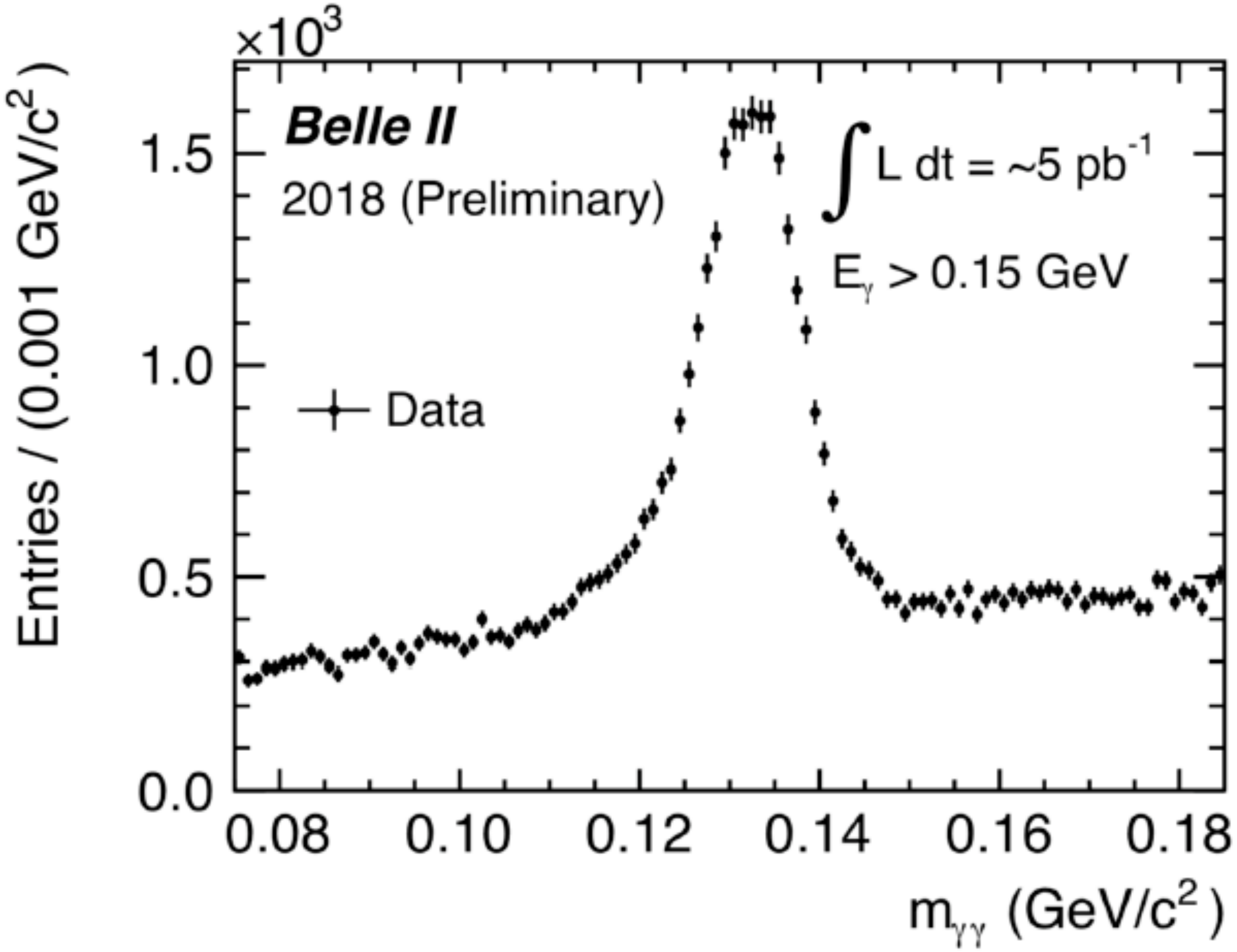
arXiv:1011.0352 [physics.ins-det]

Some results from phase 2: calorimetry

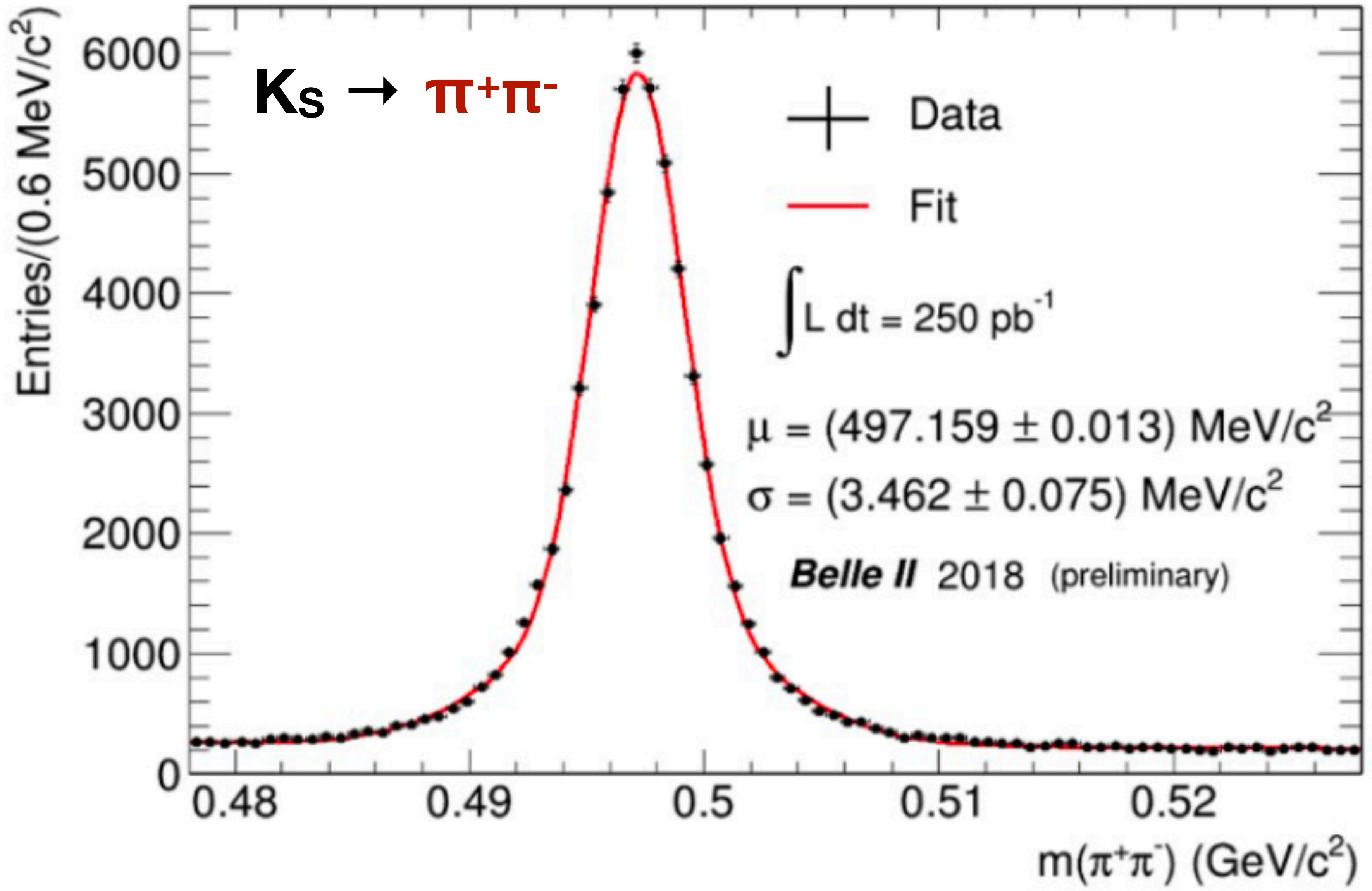
$e^+e^- \rightarrow \mu^+\mu^-\gamma$

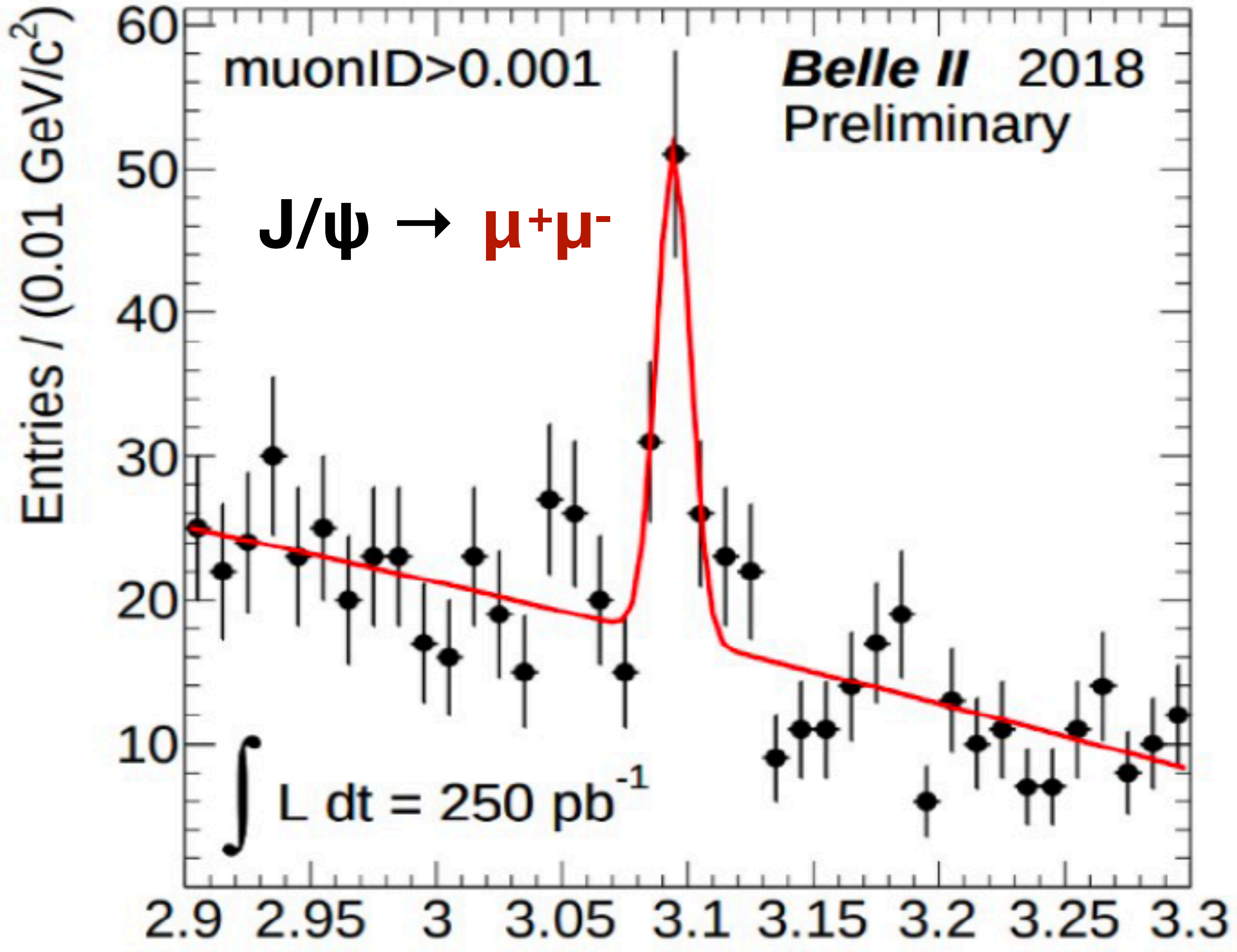


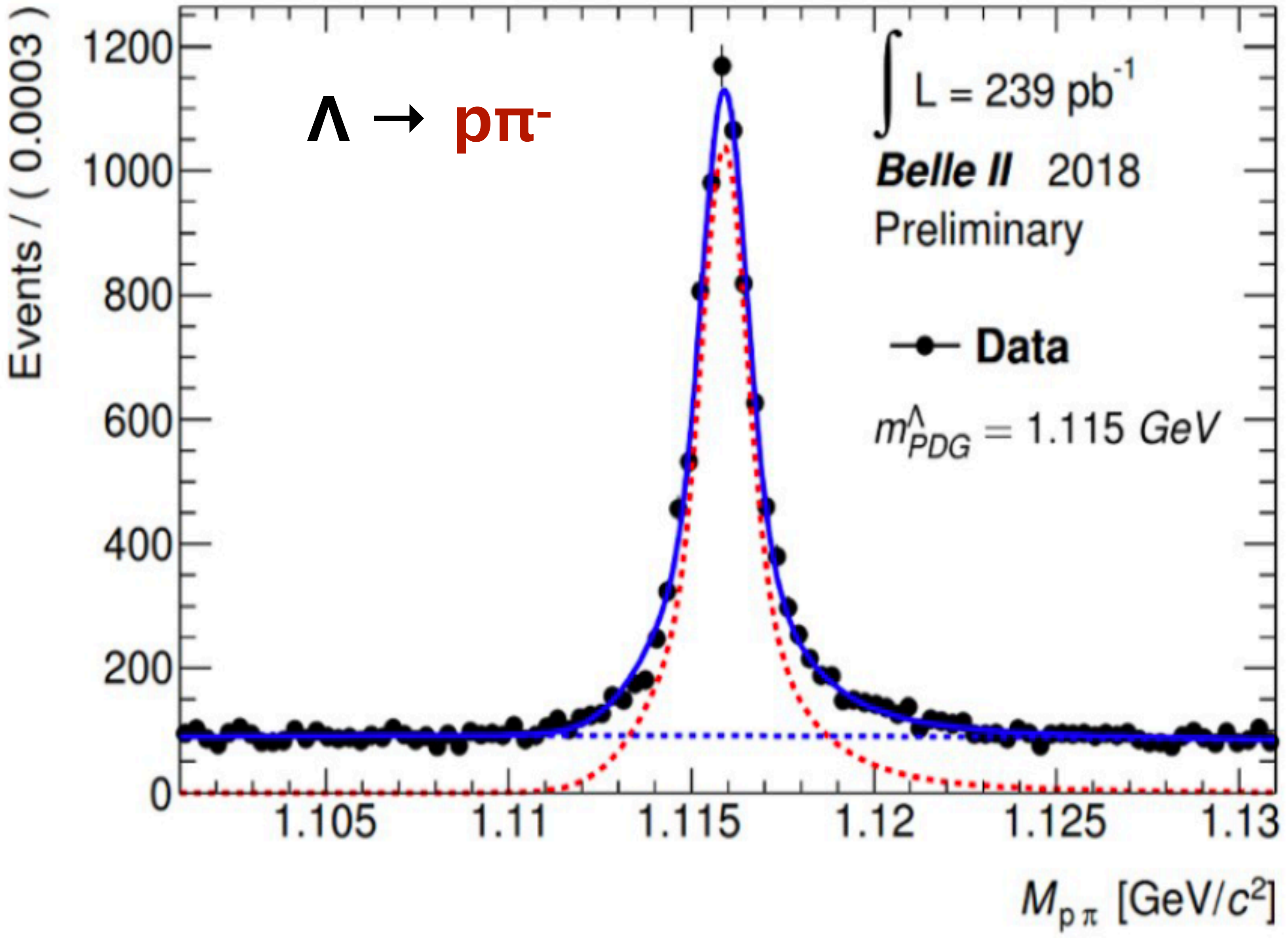
$\pi^0 \rightarrow \gamma\gamma$

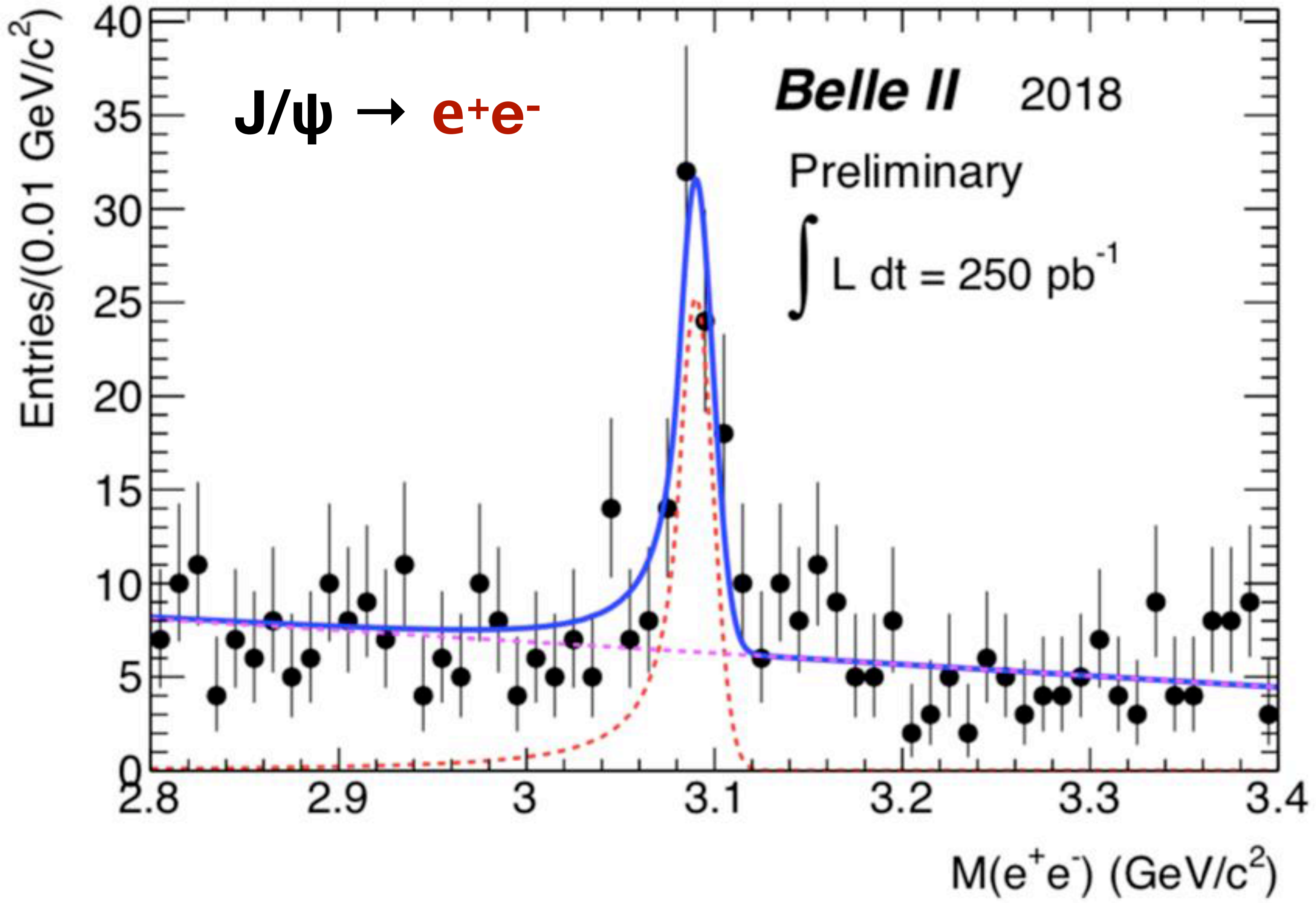


Some results from phase 2: tracking

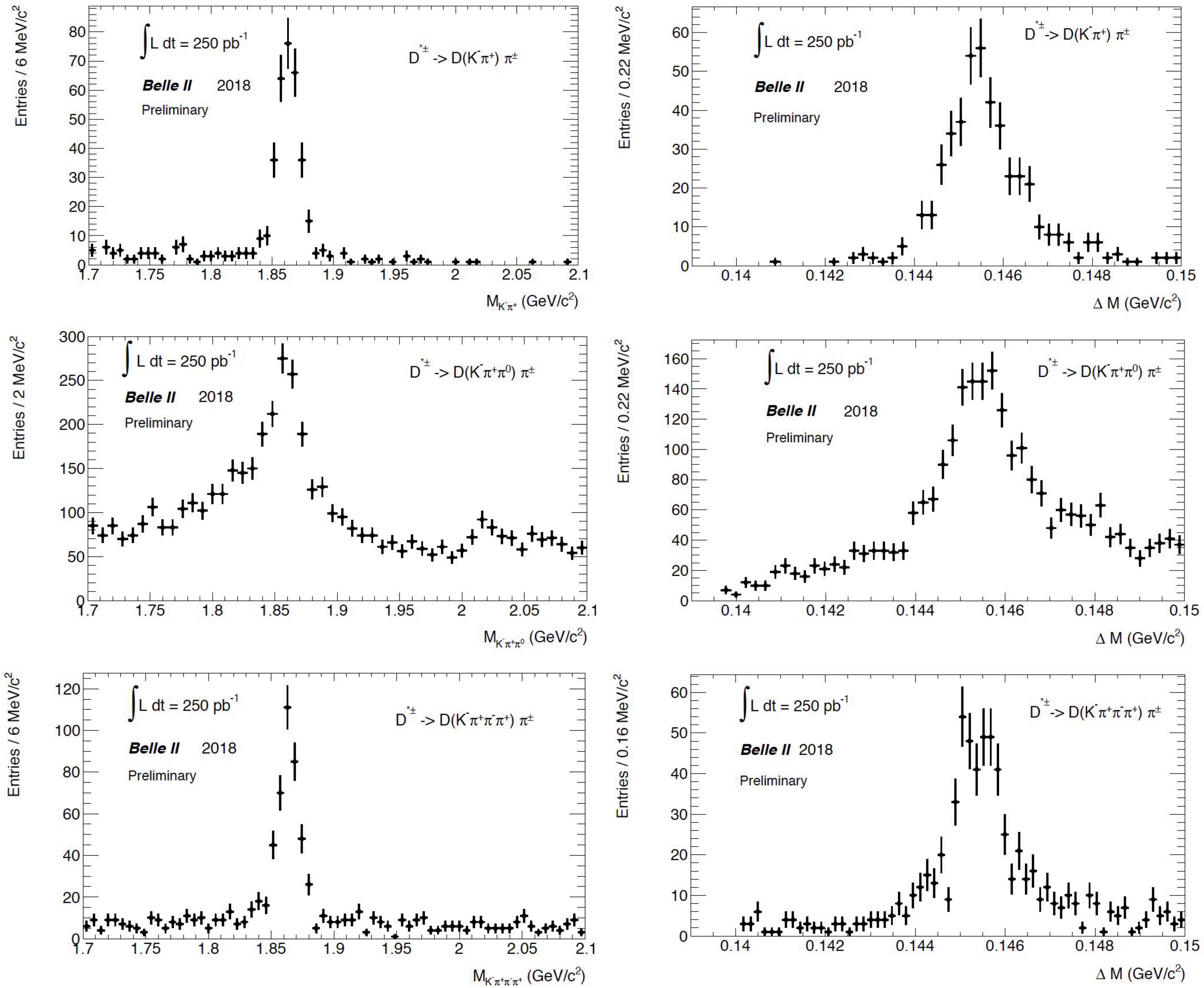








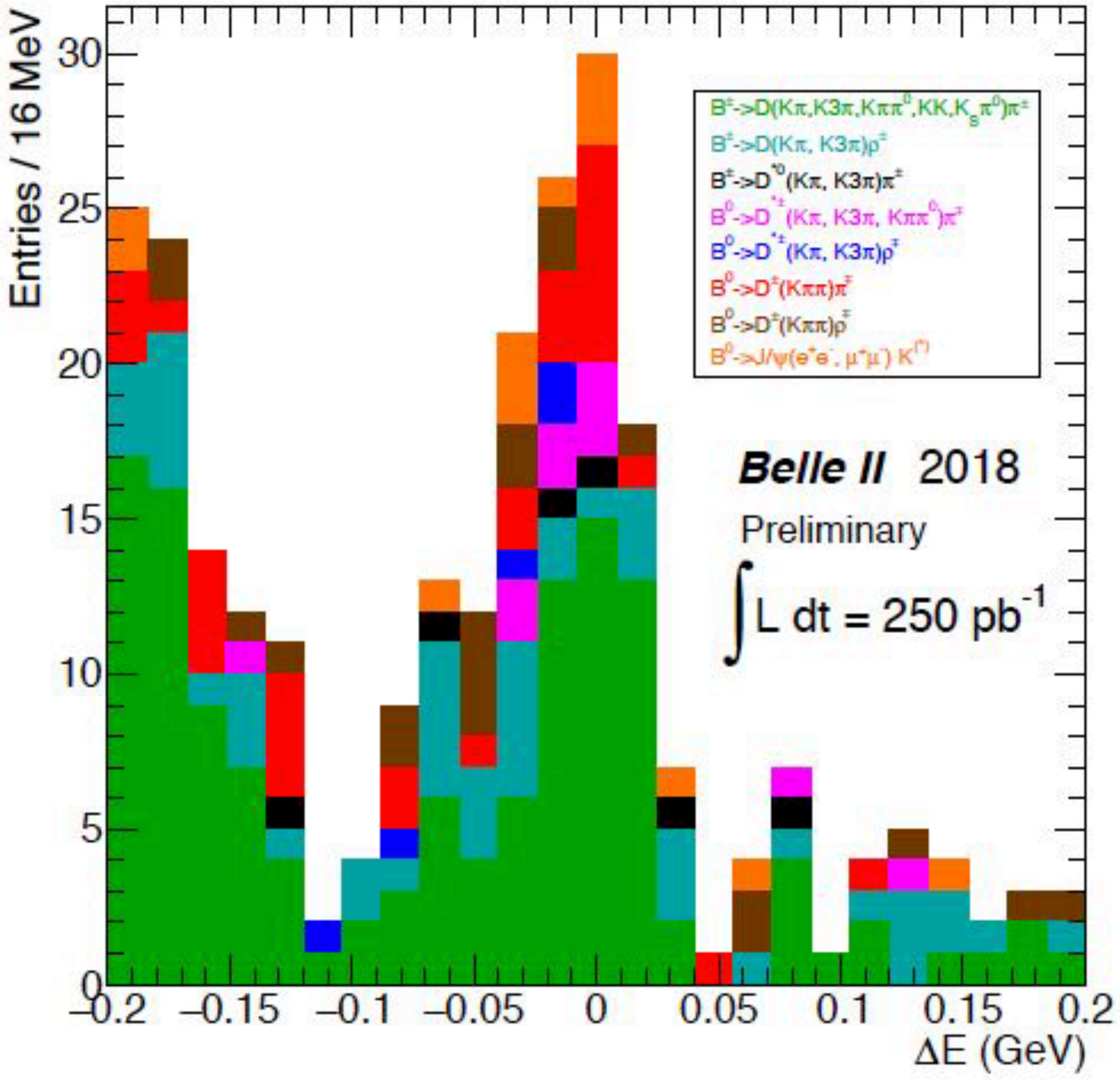
Some charming results from phase 2

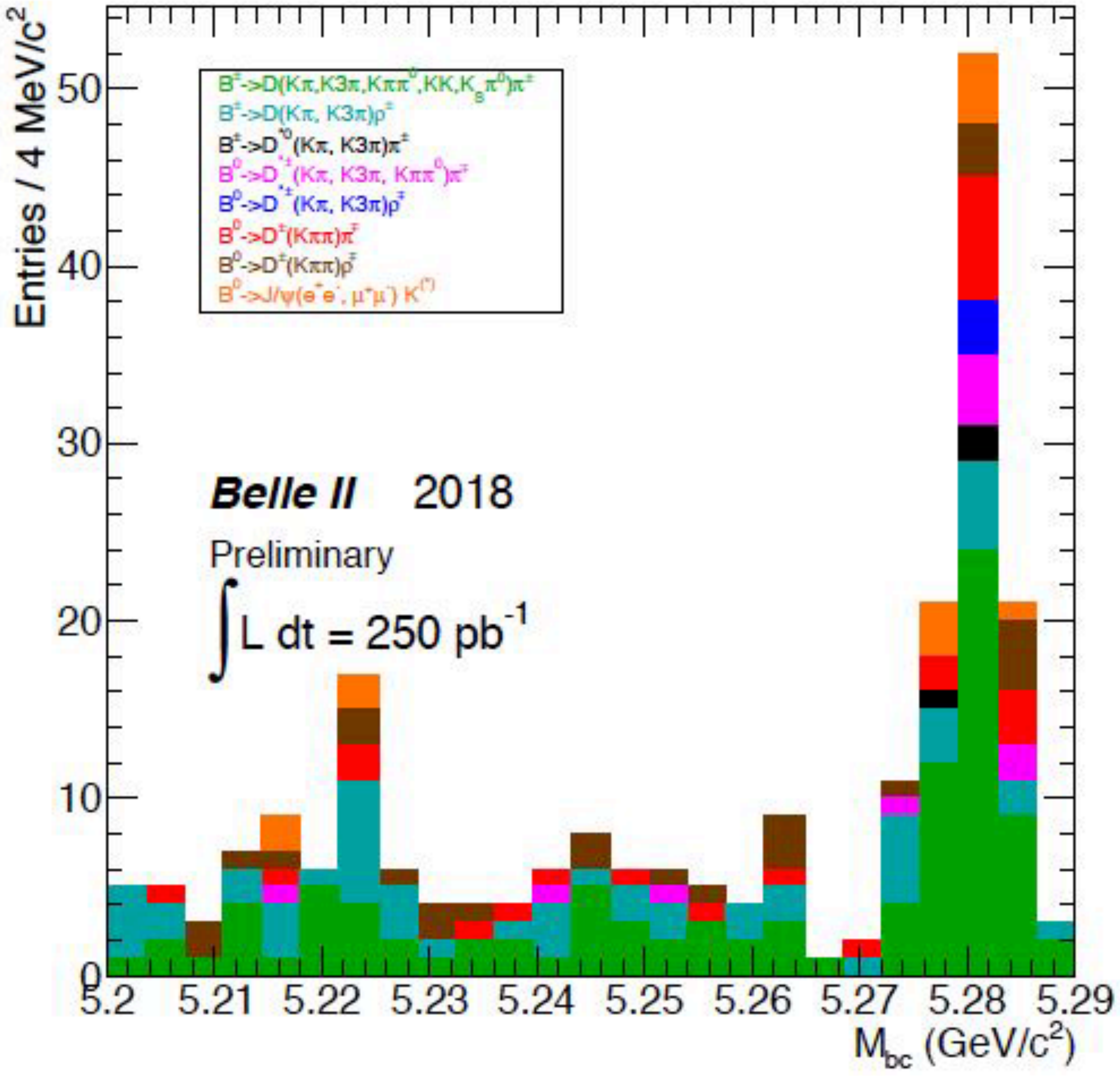


Includes Particle Identification cuts

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

Some beautiful results from phase 2

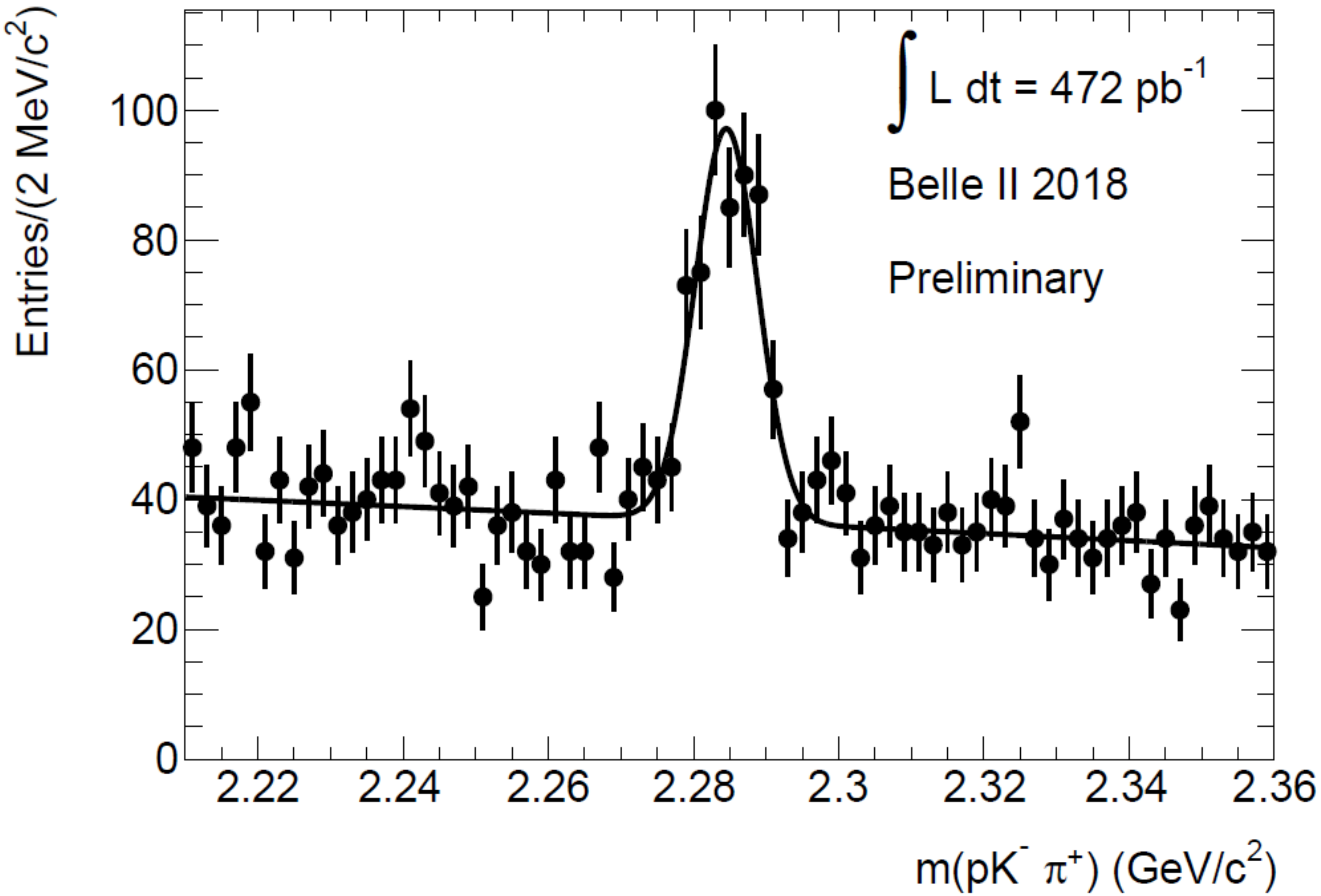




$$\Delta E = E_B - E_{beam}$$

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

Λ_c already observed with Phase 2 data!



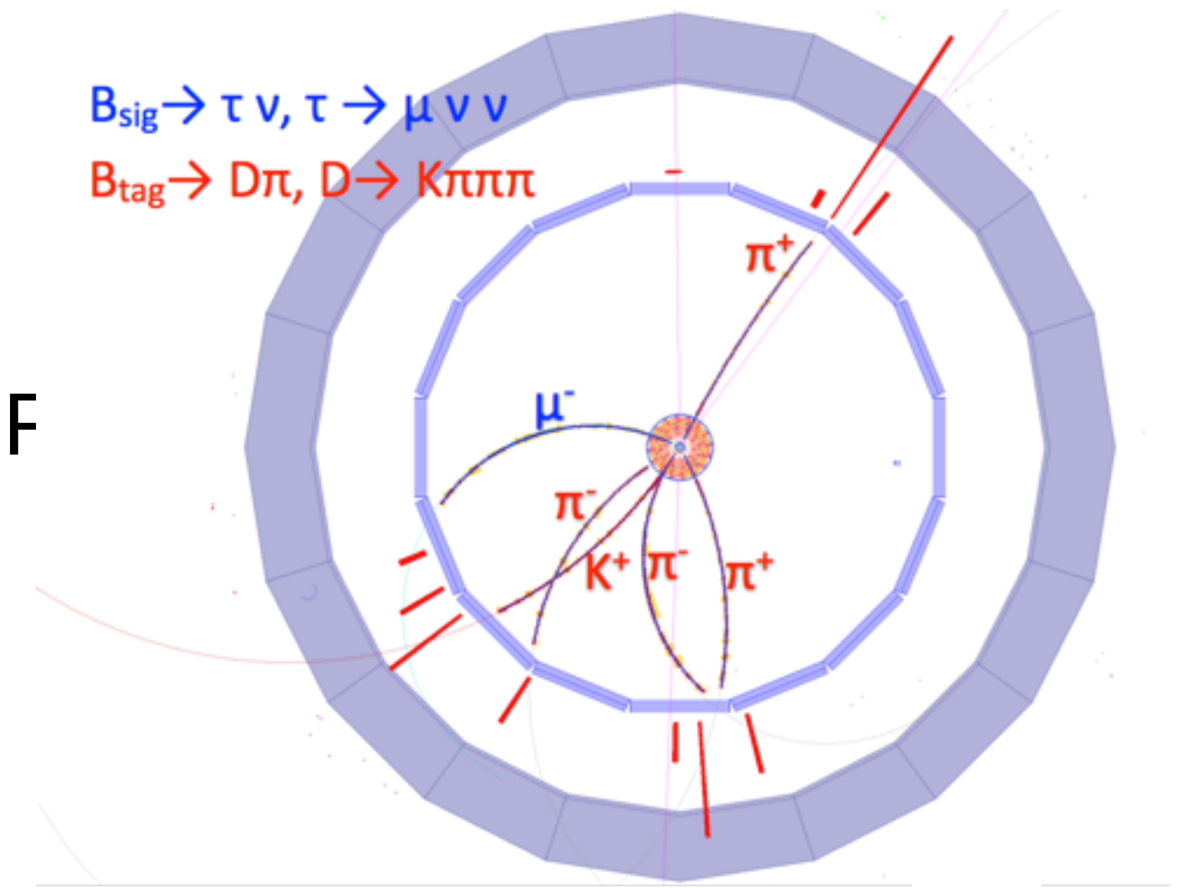
Summary

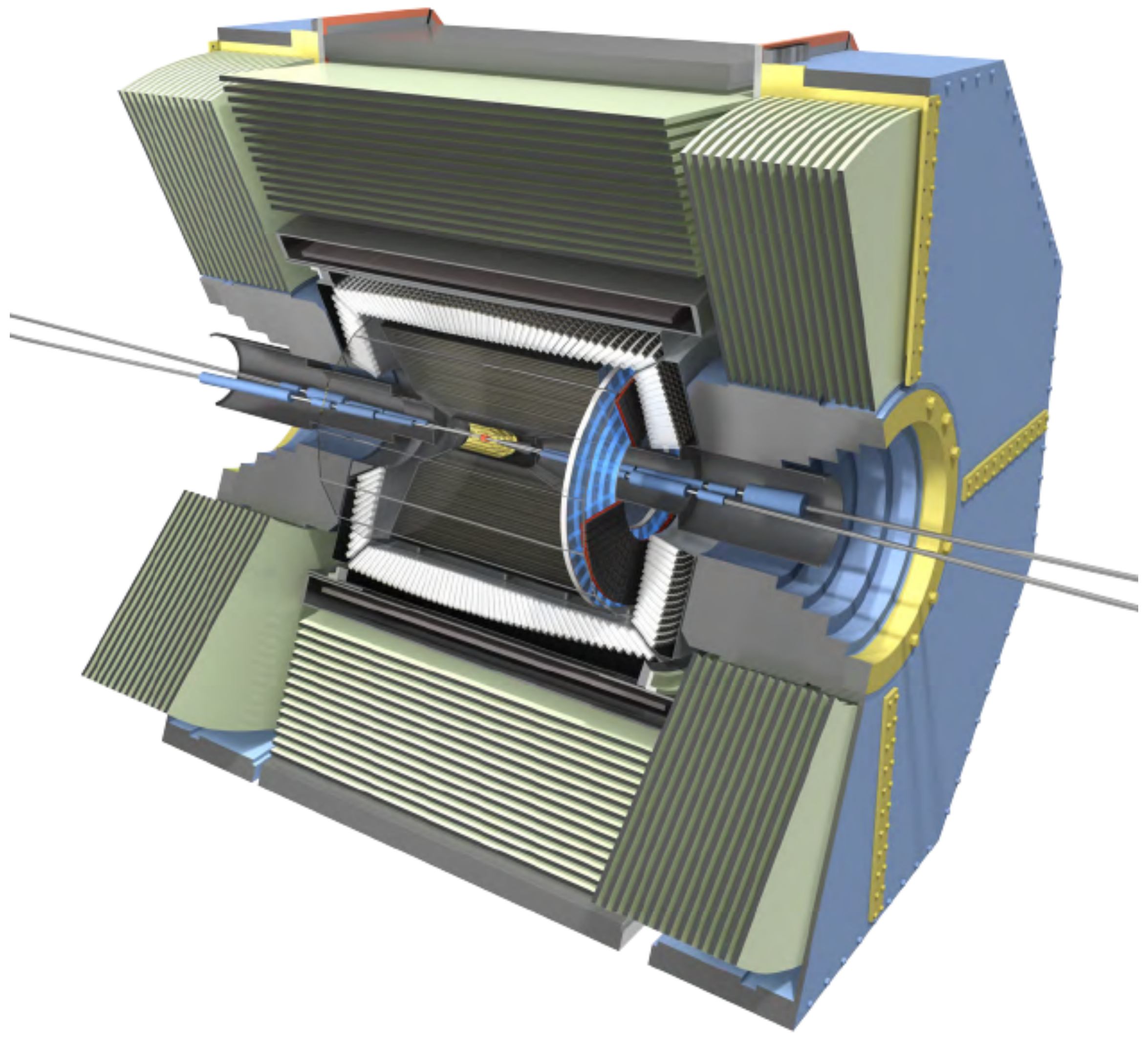
- Major upgrade at KEK for the next generation B-factory
  - Many detector components and electronics replaced, software and analysis tools also improved!
- Cosmic data taking with central DAQ in 2017, first physics without vertexing in early 2018, full detector operation in early 2019
- Belle-II experiment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

Extra

Advantages of SuperKEKB and Belle II

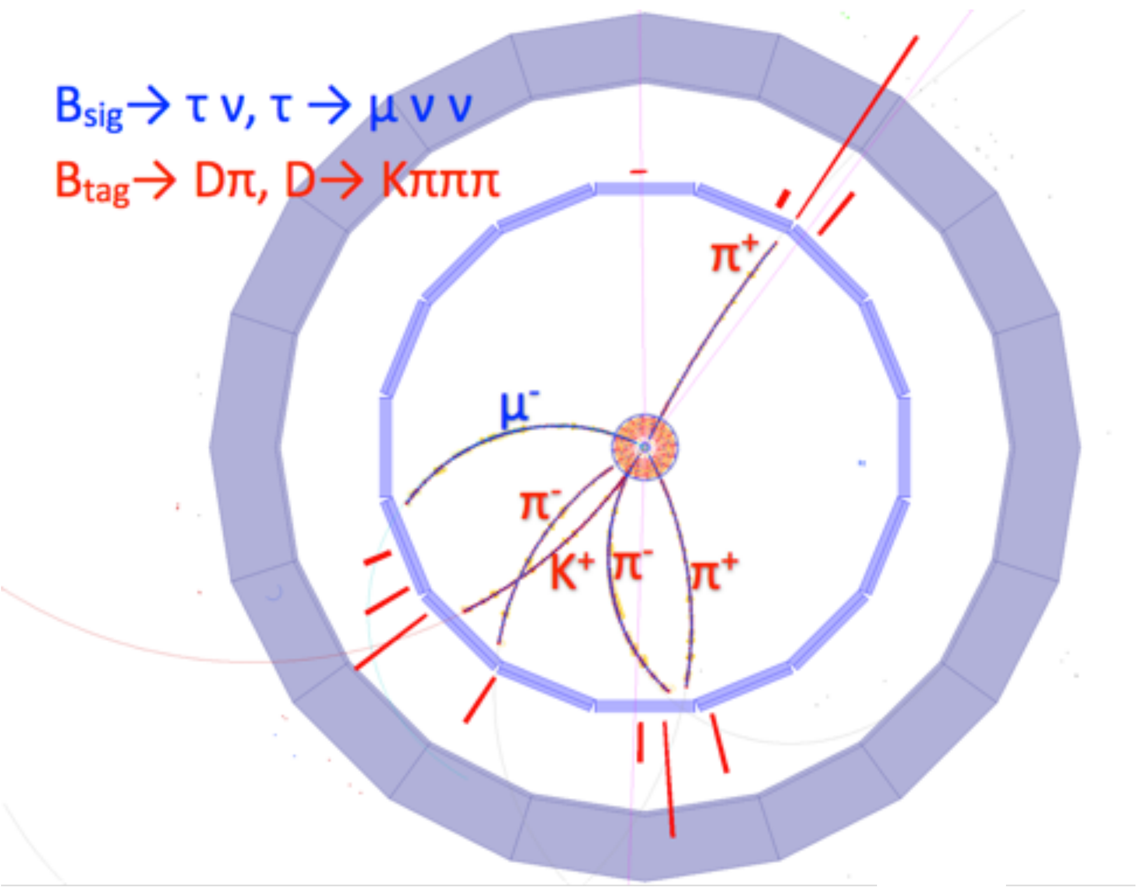
- Very clean sample of quantum correlated $B^0\bar{B}^0$ pairs
- High effective flavor-tagging efficiency
  - Belle II ~34% efficient vs. LHCb ~3%
  - Belle II can also measure K_S and K_L (impacts most time dependent CP
- Large sample of τ leptons for measurements of rare decays and searches for LFV
- Efficient reconstruction of neutrals (π^0, η, …)
- Dalitz plot analyses, missing mass analyses straightforward
- Systematics quite different than those of LHCb
  → NP seen by one experiment should be confirmed by the other

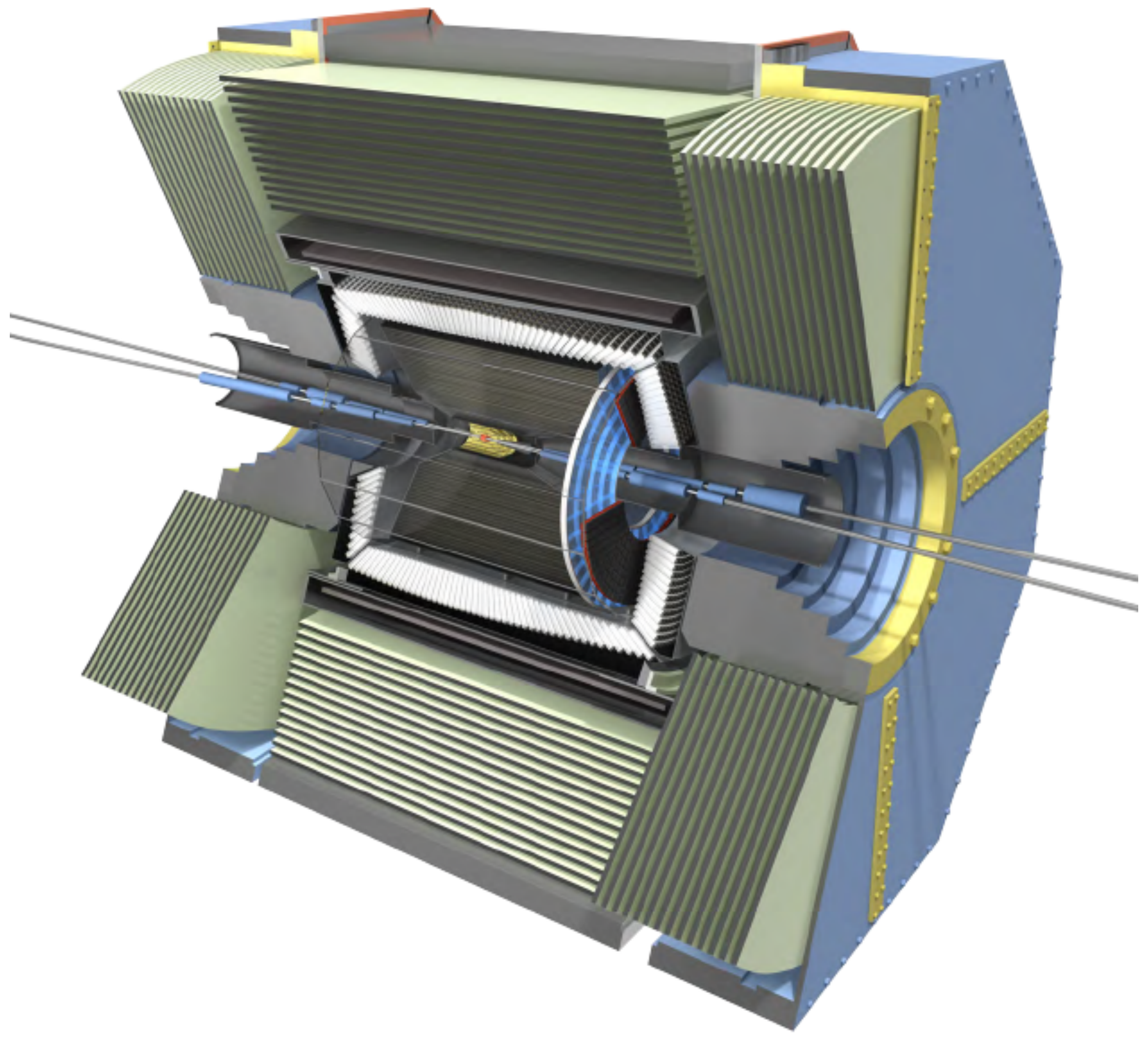




Benefits of hadron spectroscopy at B-factories

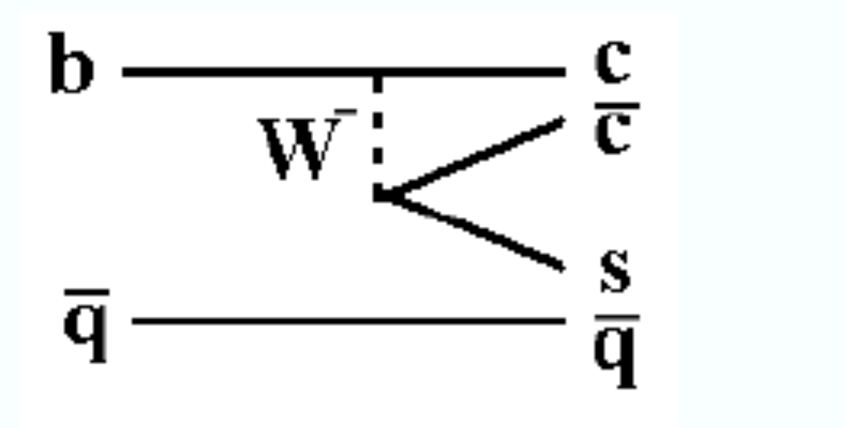
- Efficient reconstruction of neutrals (π^0, η, …)
- Reconstruct single resonance to explore recoiling system (e.g. $e^+e^- \to J/\psi\ X$)
- High resolution, hermetic detector with good PID capability
- Using tagged events (i.e. with a fully reconstructed partner B) to measure absolute branching fractions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

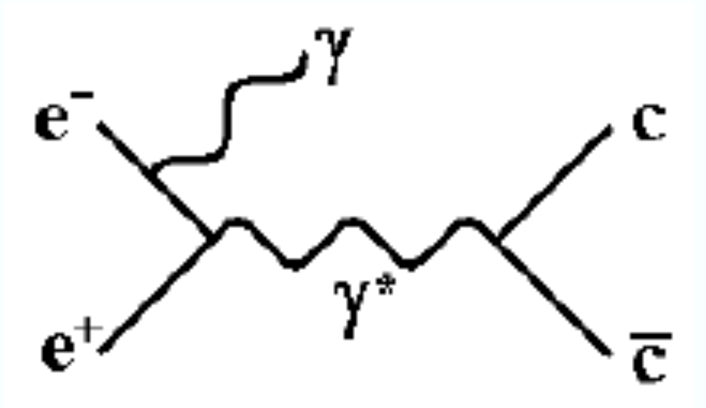


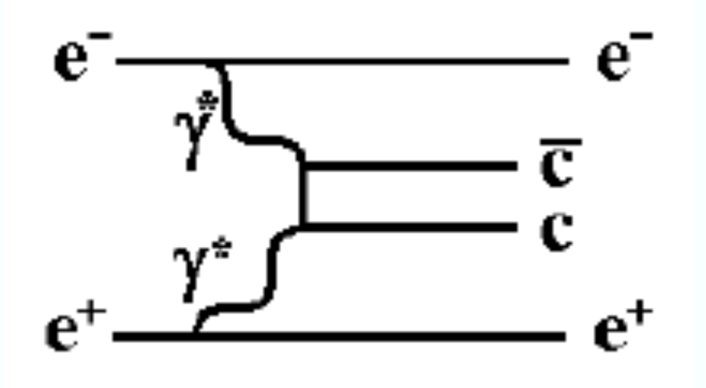


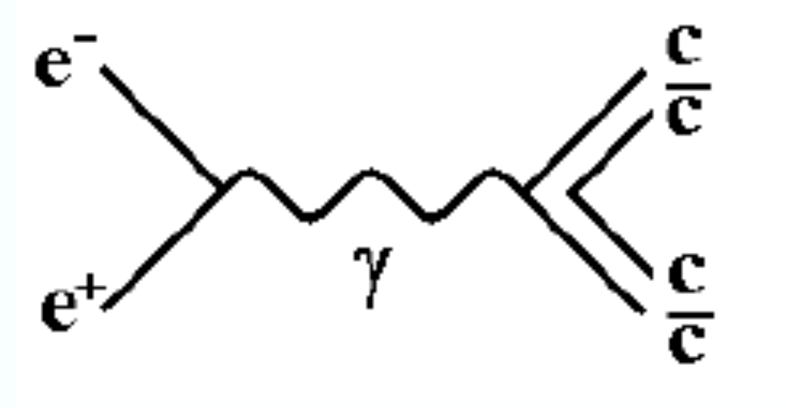
Quarkonium production at B-factories

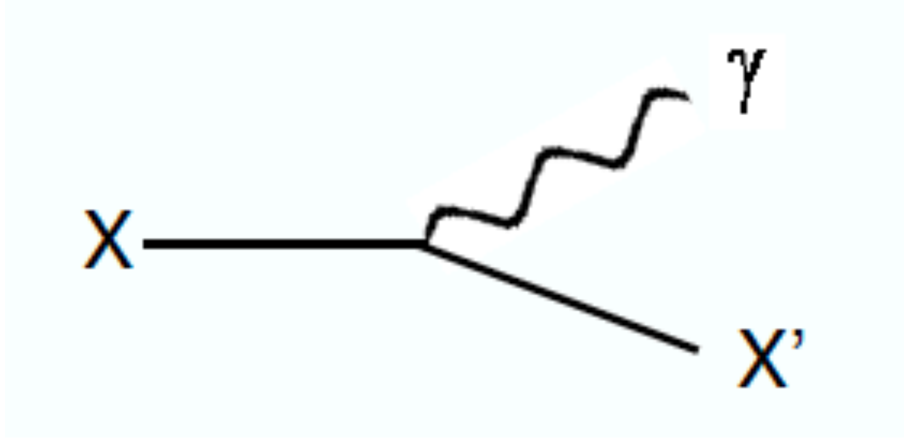
- B decays
  - Charmonium-like states only
  - All quantum numbers accessible
- Direct production / ISR
  - $J^{PC} = 1^{--}$
- Two-photon production
  - $J^{PC} = 0^{-+}, 0^{++}, 2^{++}$
- Double charmonium production
  - Seen for J = 0, $J^{PC} = 1^{--}$
- Quarkonium transitions
  - Hadronic or radiative decays between states





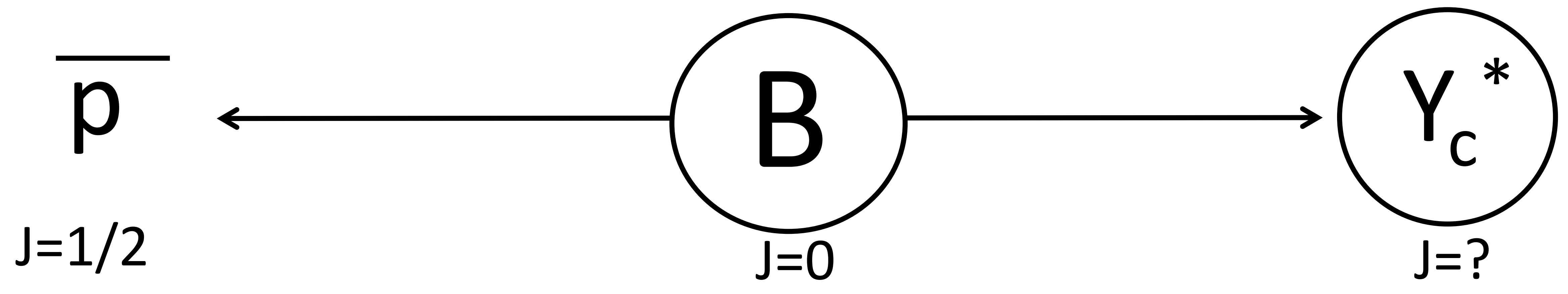






Charmed baryons

- Decay angular distribution depends on helicity fraction (ρ_{ii}).
  - difficult to predict in continuum production
- For unpolarized charm baryons, the angular distribution is flat
  - difficult to distinguish spin 1/2 and no polarization



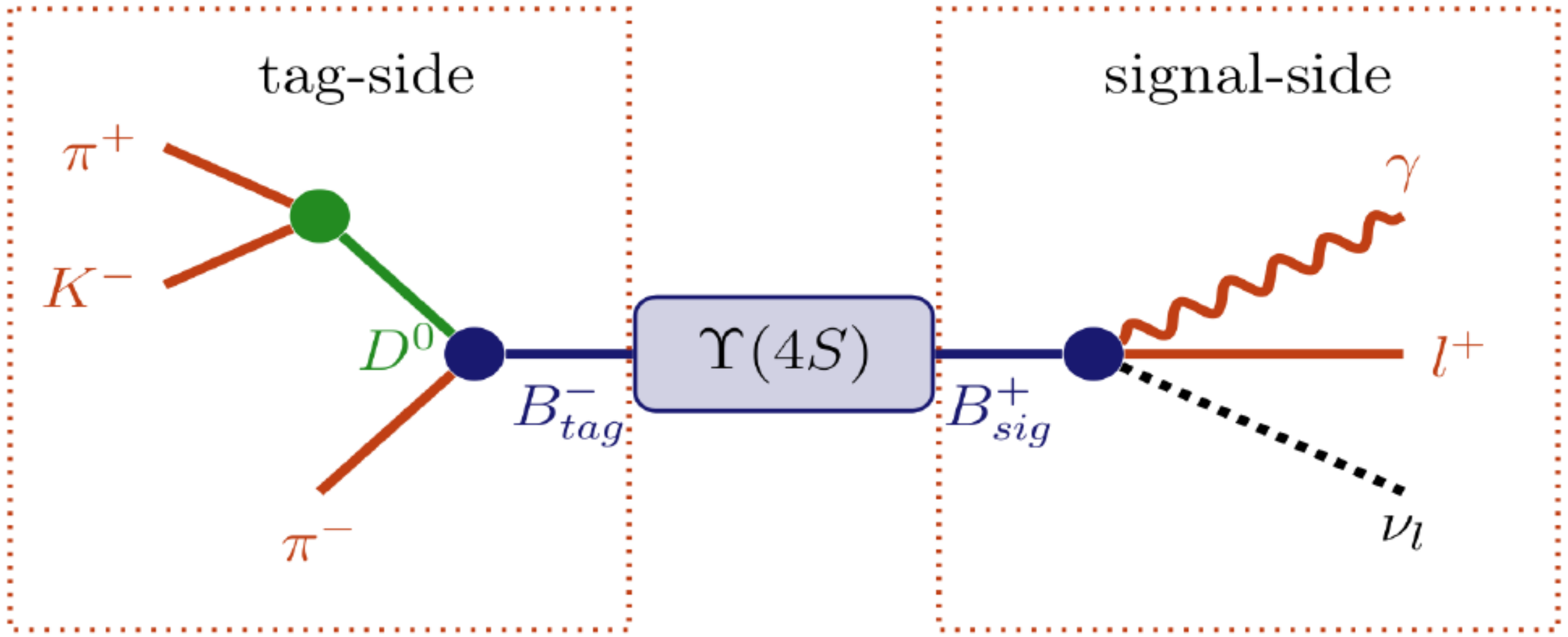
- B-meson two body decay constrains the helicity to be 1/2
  - B meson has spin zero and proton has spin 1/2
  - Large reduction in uncertainty
- Statistics at current B-factory is not good enough for higher excited states

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

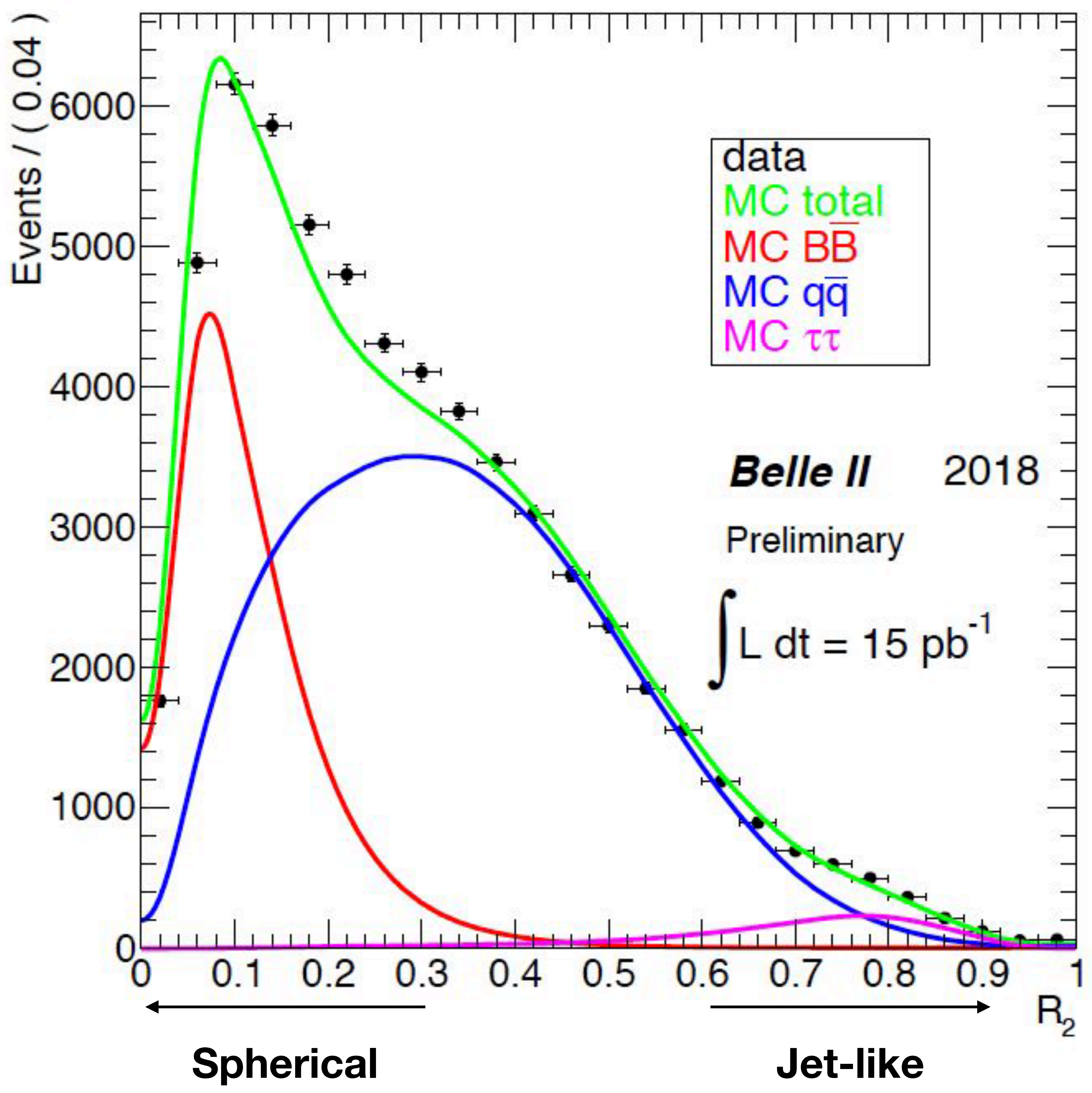
Full reconstruction:
($\varepsilon \approx 0.3$ - 1.5%)

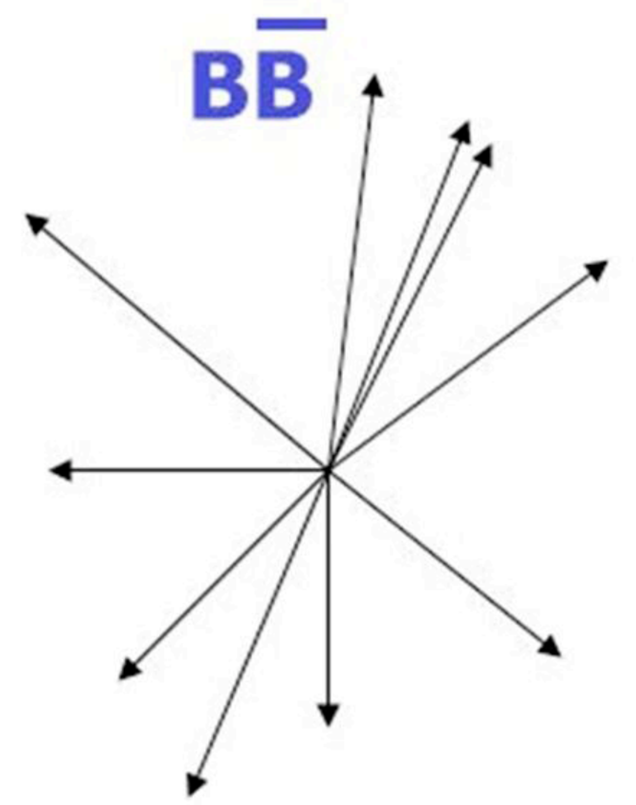
Signal side:
B → X$\ell\nu$ - Precise meas. of $|V_{ub}|$
B → $\tau\nu$ - Search for NP
B → $K\nu\bar{\nu}$ - Search for NP



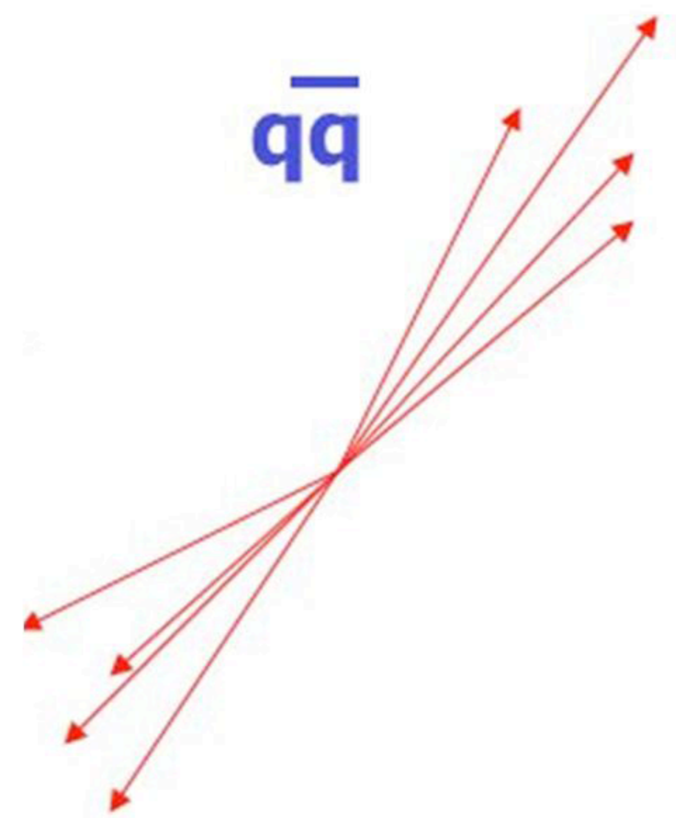
- Excellent tool for missing energy, missing mass analyses!
  - e.g. provide important high-mass sensitivity to the charged Higgs in the multi-TeV range

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!