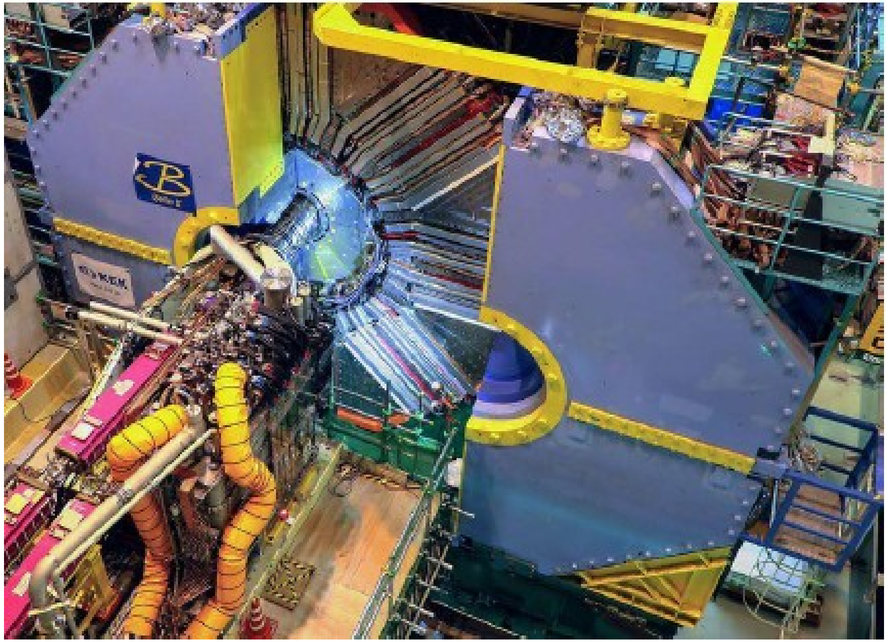
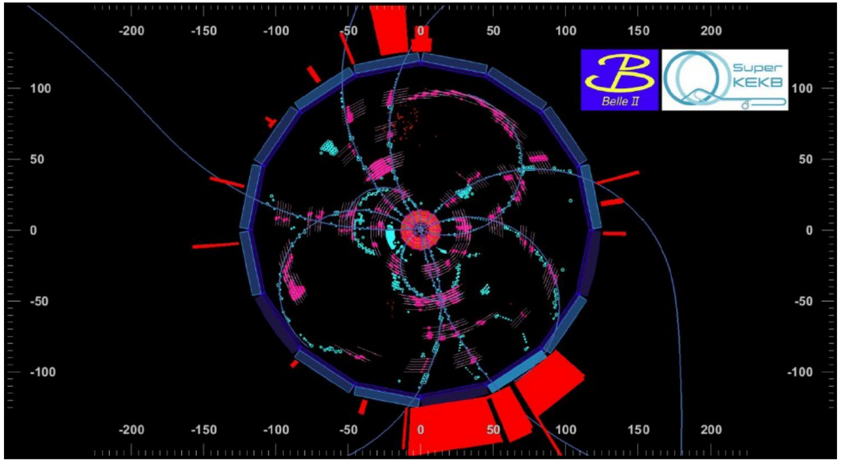




Bundesministerium für Bildung und Forschung

DFG Deutsche Forschungsgemeinschaft

JENNIFER2 EU grant n.822070

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Belle II

ErUM-FSP T09 Belle II

Recent Results and Perspectives in Spectroscopy Studies at Belle II

ECT* WORKSHOP, Trento (IT) - MASS IN THE STANDARD MODEL AND CONSEQUENCES OF ITS EMERGENCY - 19-23.April.2021

Elisabetta Prencipe, JLU – University of Giessen (DE)

Outline

- Introduction
- Motivation

  - recent results from B-factories

  - open questions

  - new and unique opportunities at Belle II
- The Belle II experiment
- Perspectives in search for exotics at Belle II

  - Charmonium

  - Bottomonium

  - "re-discovery" channels with Early Phase 3 data
- Summary

Introduction

- Gell-Mann Zweig idea: Constituent Quark Model (CQM)

  Still valid for half century → it classifies all known hadrons

- QCD-motivated models predict the existence of hadrons with more complex structures than simple *qq* (mesons) or *qqq* (baryons) → the so-called XYZ *"charmonium"-like* states

- **Lot of experimental effort to prove the existence of XYZ!**

- No unambiguous evidence for hadrons with *non-CQM-like* structures has been found

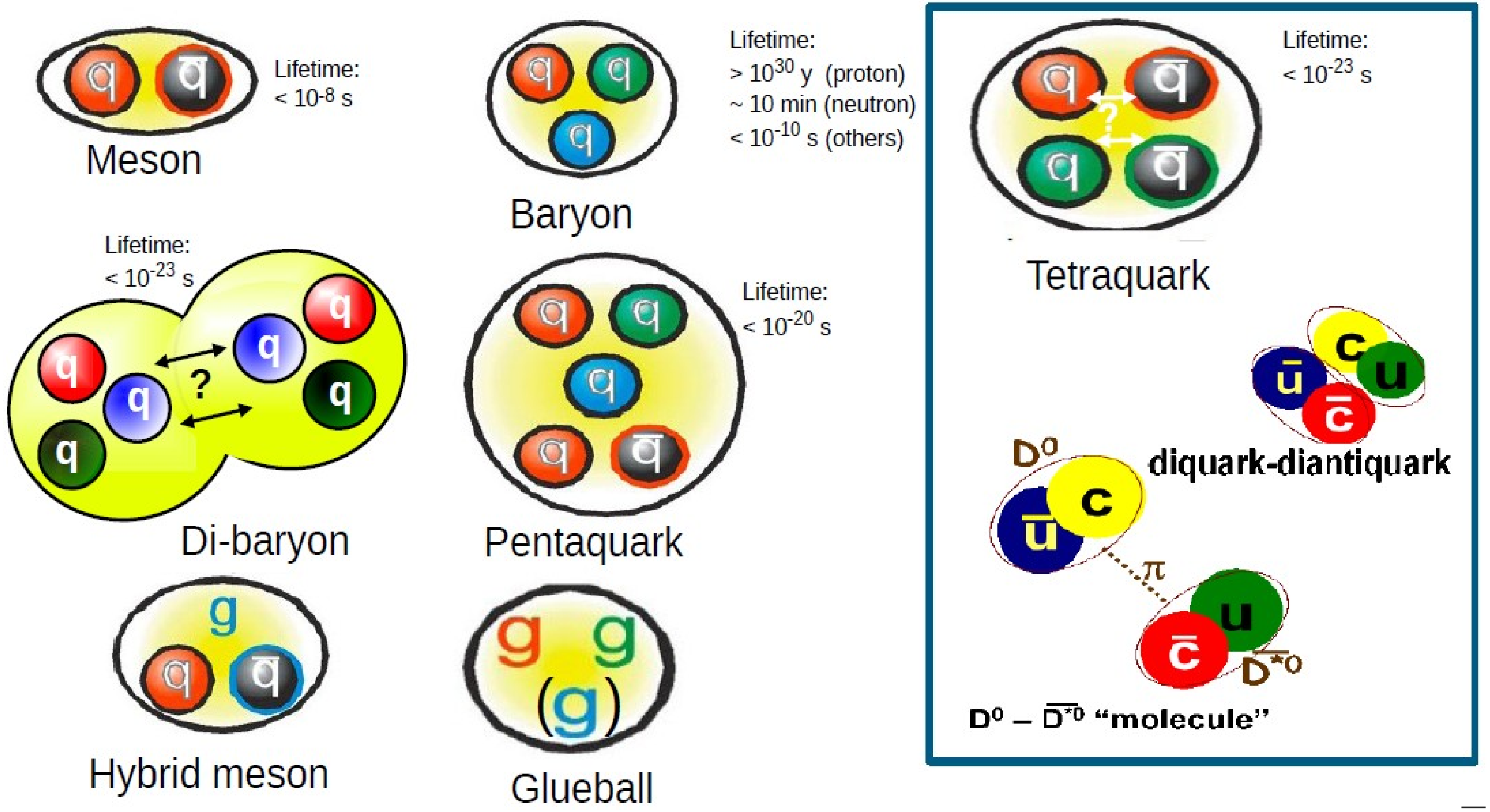
- New possibilities, started with the observation of the X(3872):

  - tetraquarks
  - hybrids
  - molecular states
  - hadrocharmonium
  - pentaquarks
  - hexaquarks
  - glueballs
  - cusps…

- Evidence that there is more than *mesons* and *baryons*!

  Substantial contribution from B-factories (1999-2010) into the field

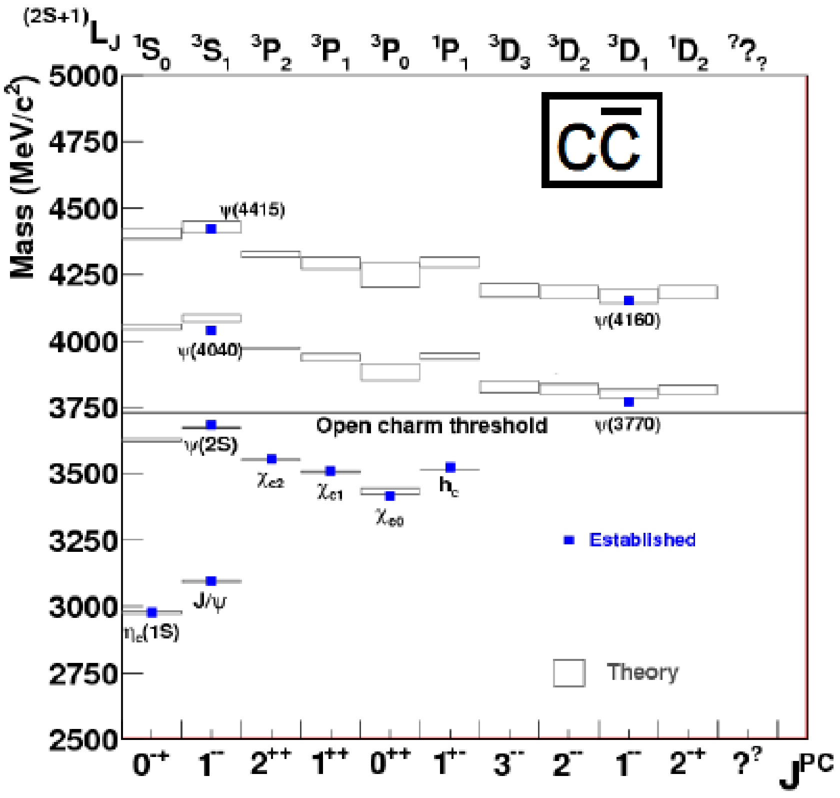
Quark Bound States

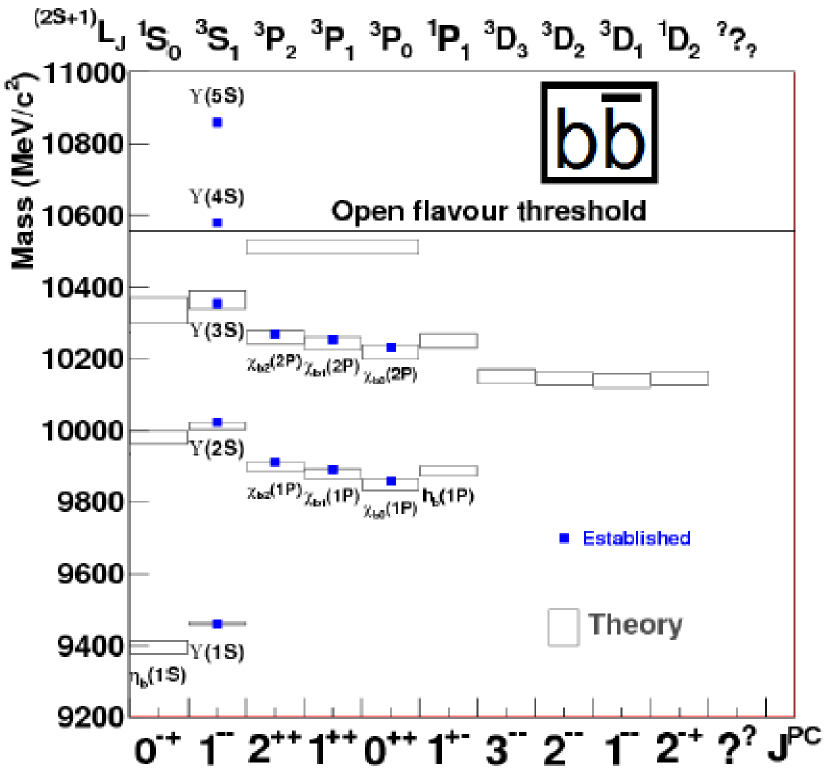


...and superposition of different states: $c_1|\bar{q}q\rangle + c_2|\bar{q}q\bar{q}q\rangle + \ldots$

-Onia (conventional and exotics)

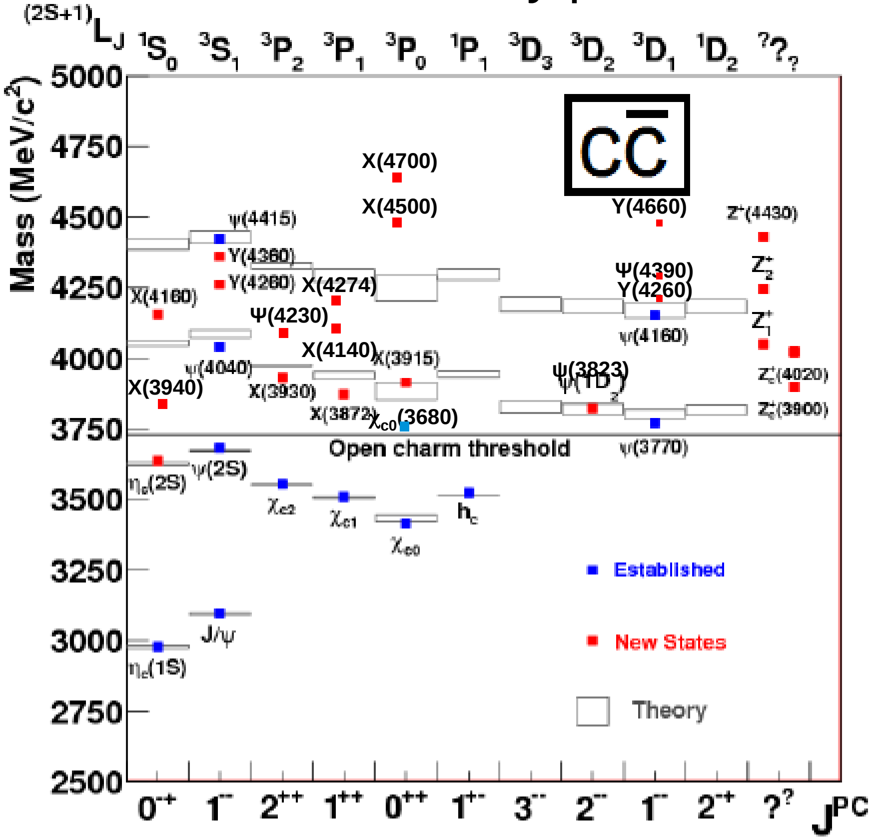
- States described by potential models, NRQCD,…, <u>before</u> 2003

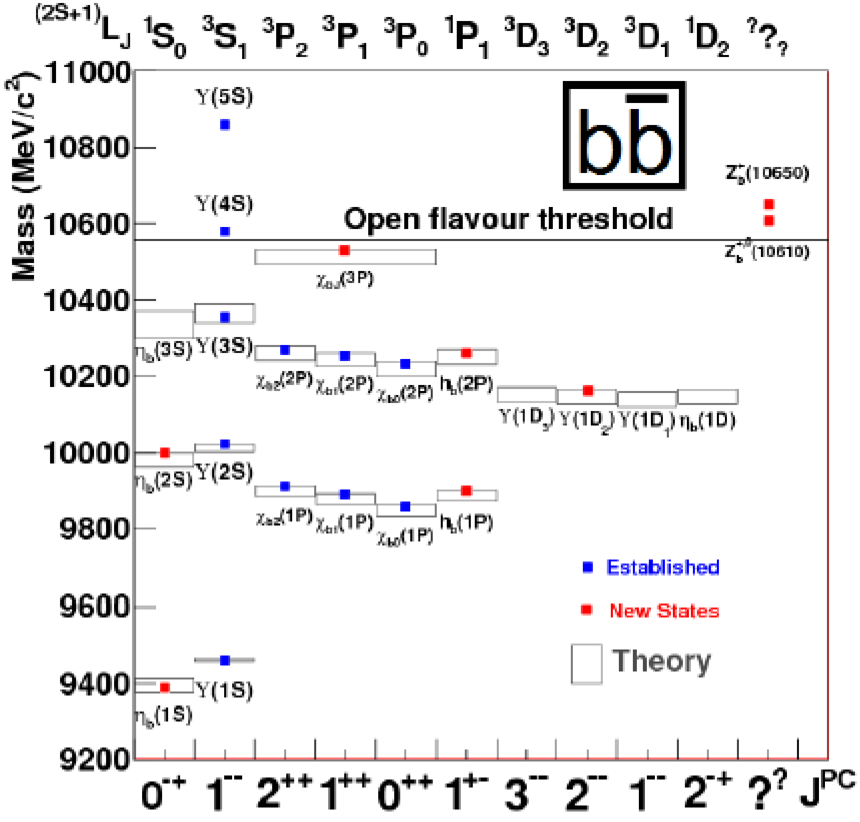




-Onia (conventional and exotics)

- States described by potential models, NRQCD,…, after 2003





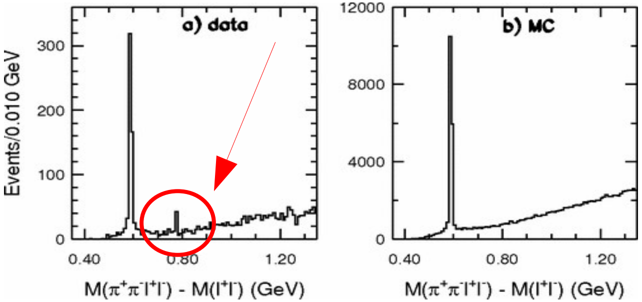
Nomenclature

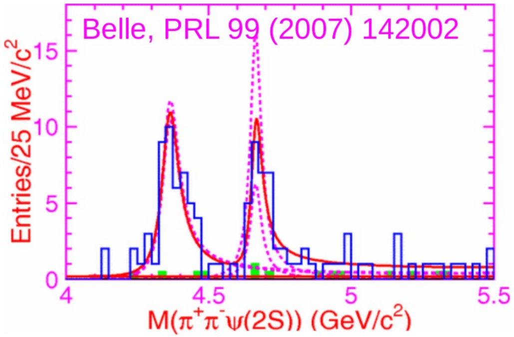
X, such as the X(3872)
- consistent with $D^0\overline{D}^{*0}$ molecular state
- found in B decays, large production also in pp
- no partners found

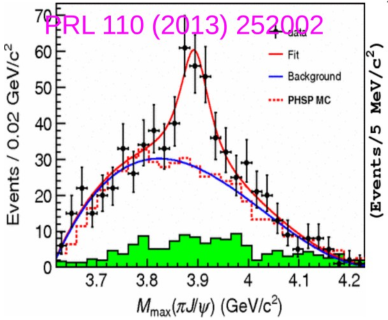
Y, such as the Y(4260), Y(4330), Y(4660)
- produced in initial state radiation and $E_{c.m.}$ scan
- $J^{PC} = 1^{--}$
- overpopulated for charmonium

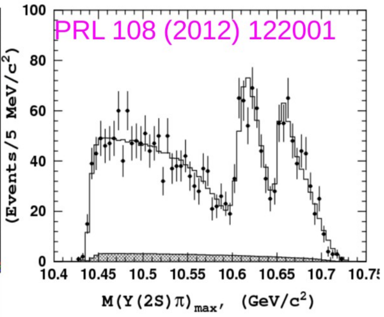
Z, such as the $Z_c(3900)$ and the $Z_b(10610)$
- seen in decays of $q\overline{q}$ and B decays
- charged states: cannot be charmonia
- b- and c- *onia*: similarities

Belle, PRL 91 (2003) 262001









Nomenclature

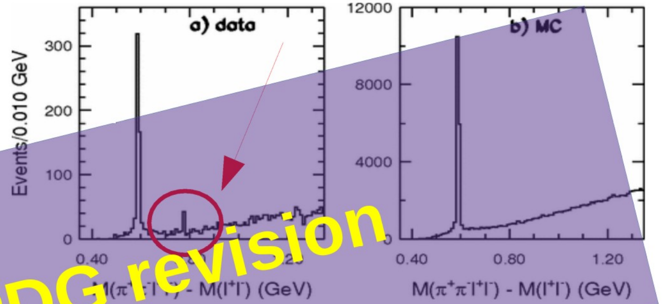
X, such as the X(3872)
- consistent with $D^0\overline{D}^{*0}$ molecular state
- found in B decays, large production also in pp
- no partners found

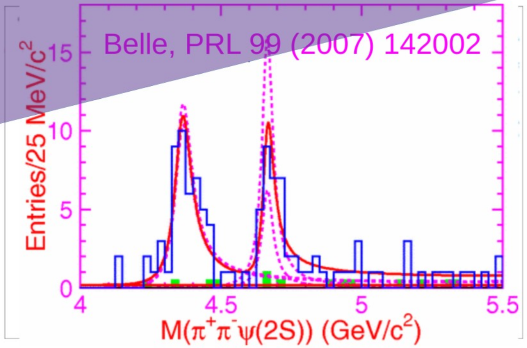
Y, such as the Y(4260), Y(4330), Y(4660)
- produced in initial state radiation and $E_{c.m.}$ scan
- $J^{PC} = 1^{--}$
- overpopulated for charmonium

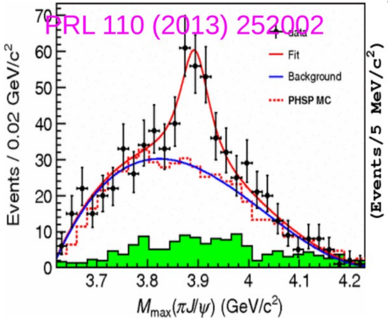
Z, such as the $Z_c(3900)$ and the $Z_b(10610)$
- seen in decays of $q\overline{q}$ and B decays
- charged states: cannot be charmonia
- b- and c- *onia*: similarities

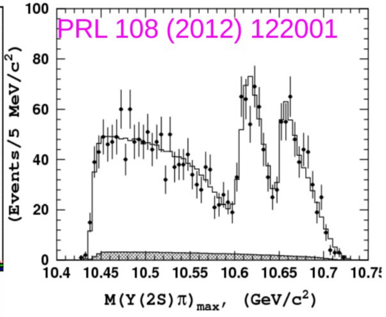
New naming in the recent PDG revision

Belle, PRL 91 (2003) 262001

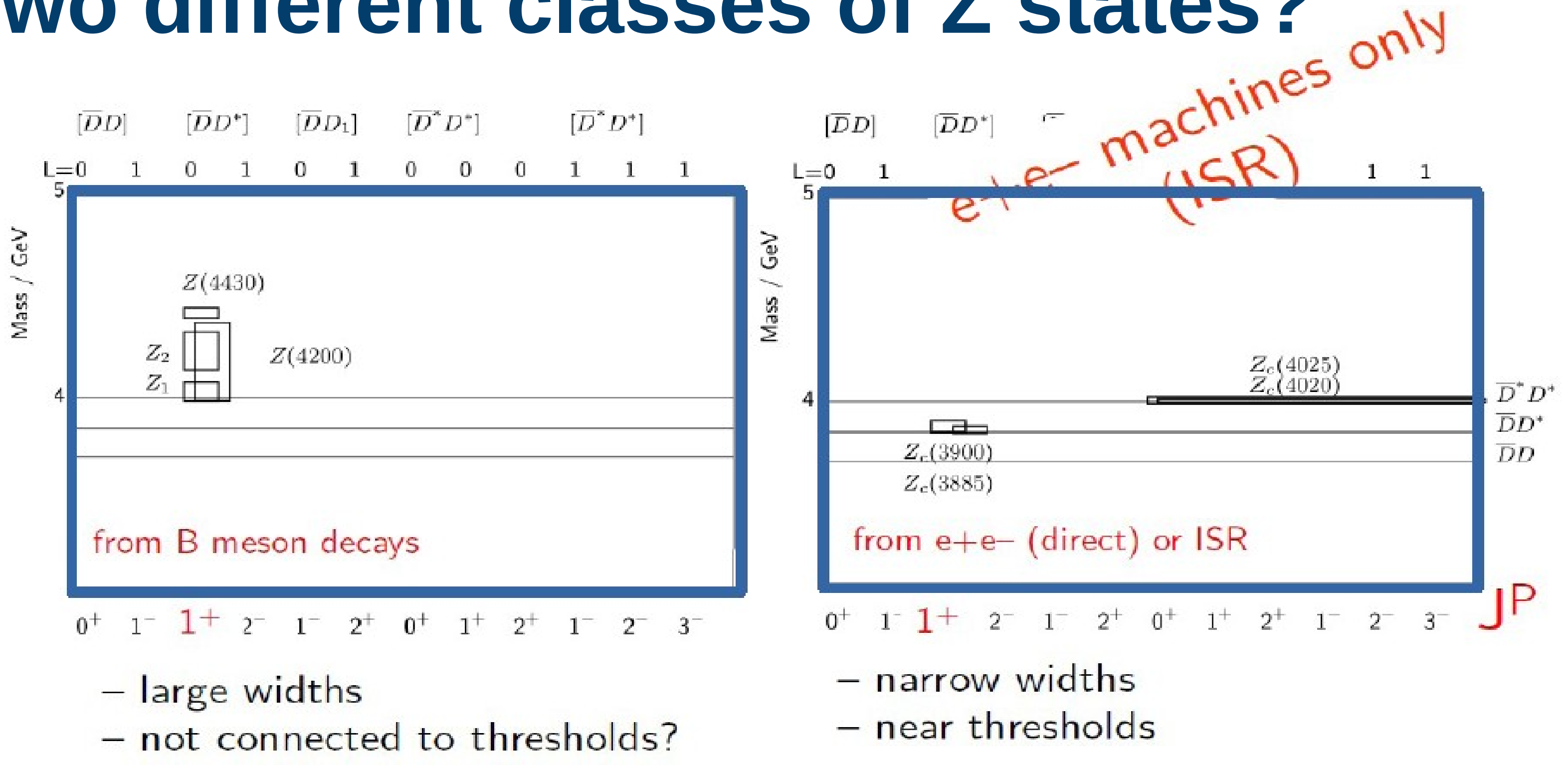








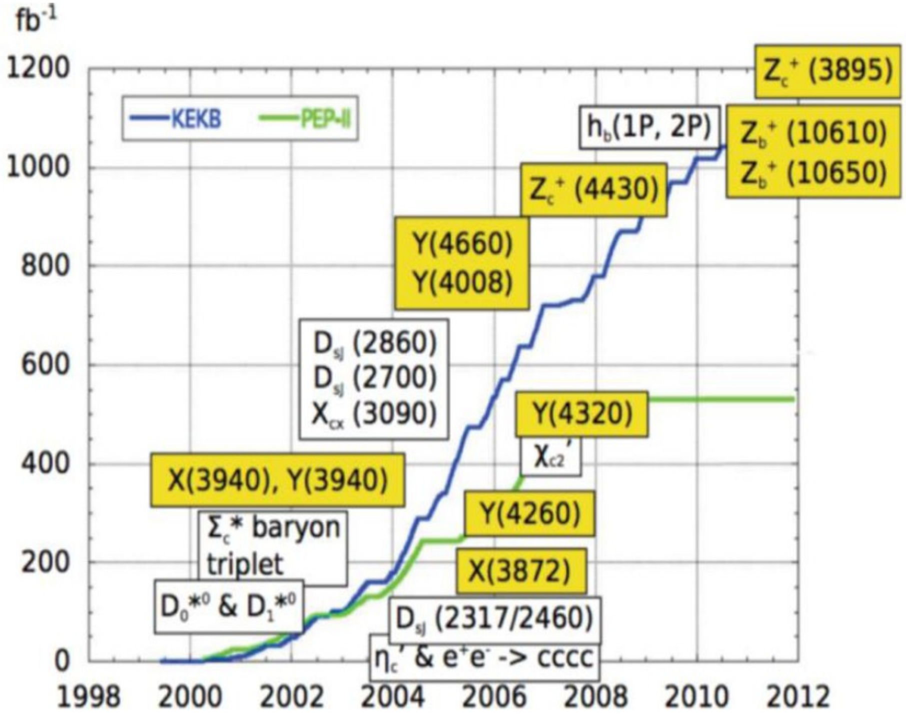
Two different classes of Z states?



- Belle II is in a unique position to look for both Z types:
  - through B decays (LHCb, not by BES III)
  - threshold state (BES III, not by LHCb)

- BaBar + Belle:

>1.5 ab^{-1} integrated luminosity - triumph in the history of B-factories!



> 1 ab^{-1}

On resonance:

Υ(5S): 121 fb^{-1}

Υ(4S): 711 fb^{-1}

Υ(3S): 3 fb^{-1}

Υ(2S): 25 fb^{-1}

Υ(1S): 6 fb^{-1}

Off reson./scan:

~ 100 fb^{-1}

513.7 ± 1.8 fb^{-1}

On resonance:

Υ(4S): 424 fb^{-1}, 471 M

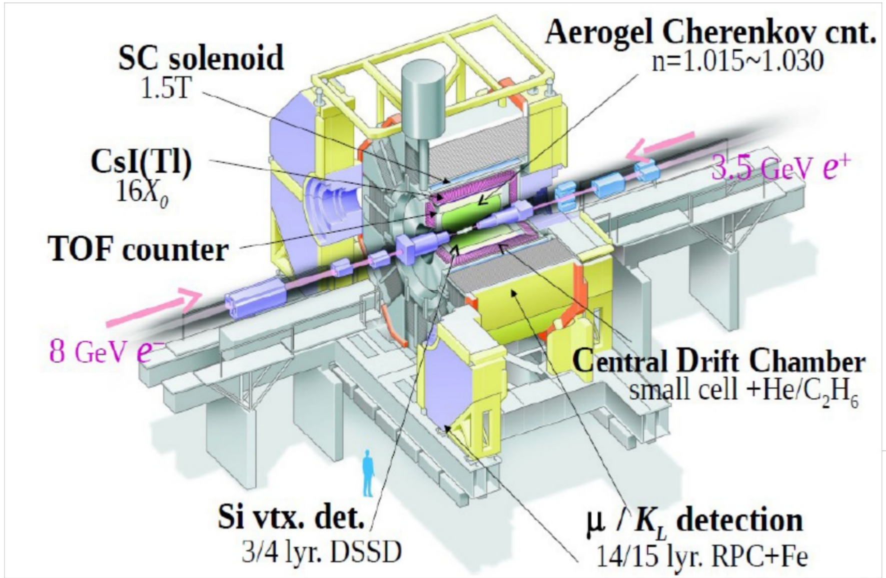
Υ(3S): 28 fb^{-1}, 122 M

Υ(2S): 14 fb^{-1}, 99 M

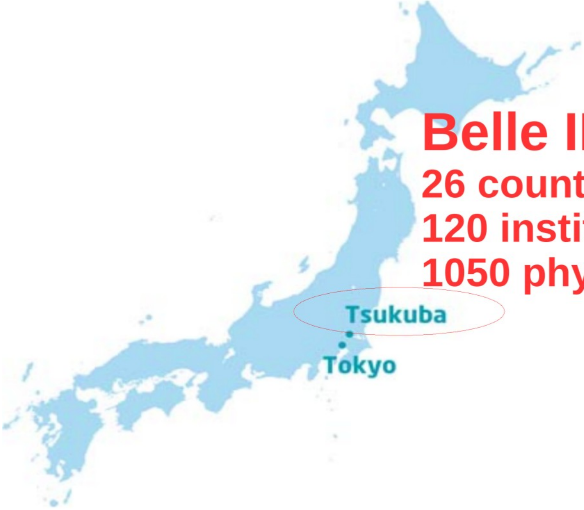
Off resonance:

48 fb^{-1}

- Not only B-factory, but $c\bar{c}$-factory with so high luminosity
- Statistics limited for rare processes (BR<10^{-5})
- Upgrade needed!

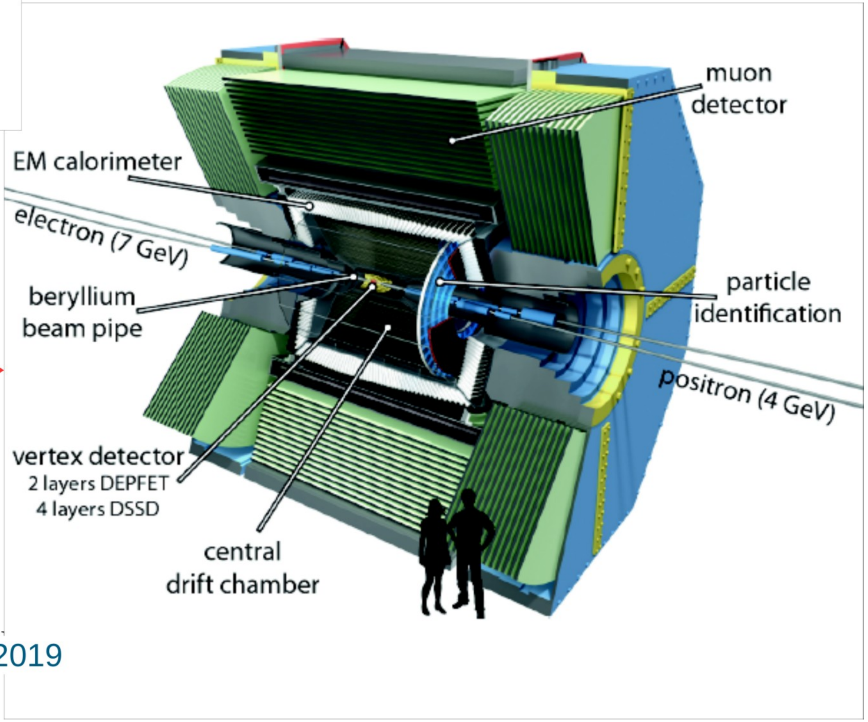


← **Belle detector**

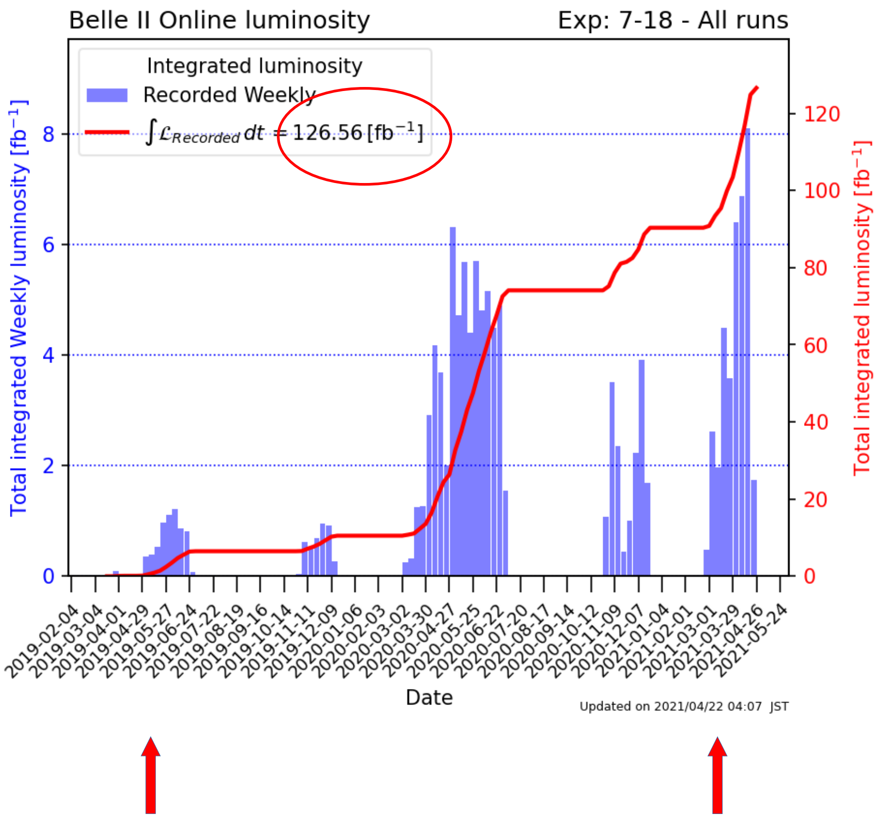


Belle II detector →

26 countries,
120 institutions,
1050 physicists



Current situation



Corona-pandemic affected activity at KEKB

BUT

we are very active and data taking is ongoing!

Luminosity record: 2.4×10^{34} cm^{-2} s^{-1}

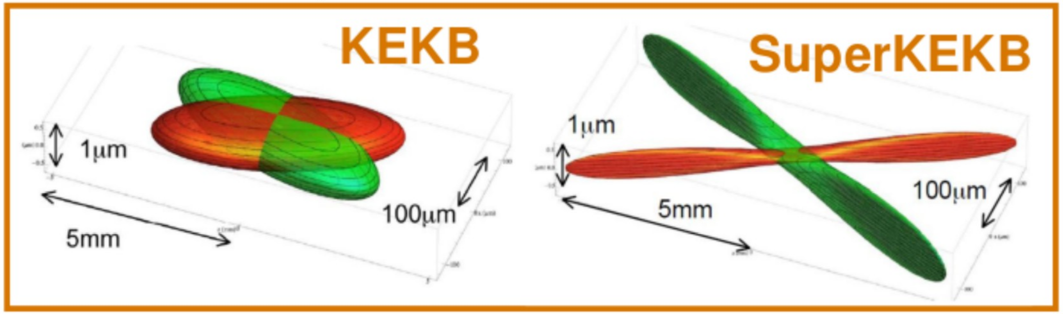
On 01.07.2019: L = **6.5 fb^{-1}**

On 20.04.2021: L = **126.56 fb^{-1}**

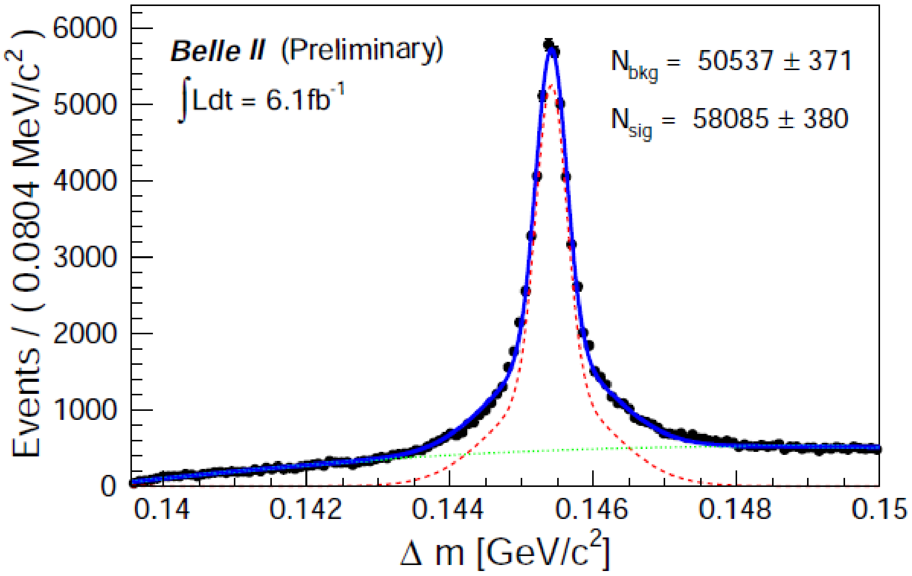
By 2026, expected up to **50 ab^{-1}**

Belle II detector – main changes

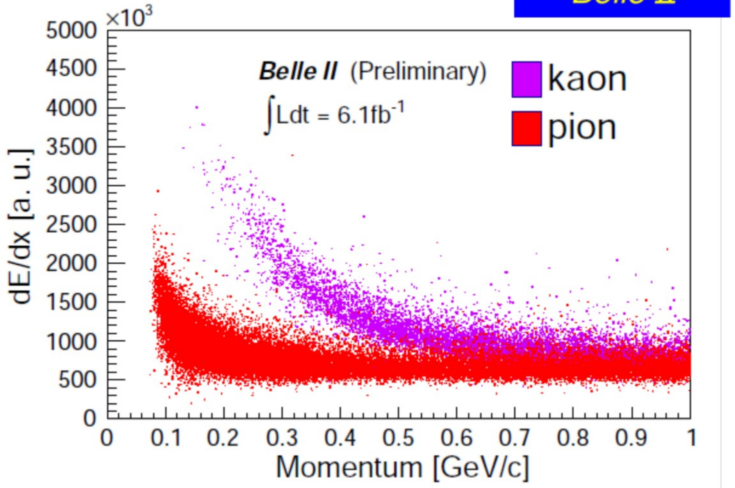
- Pixel Detector: improved vertex resolution in beam direction 50μm (Belle) → 25μm (Belle II).
- Time Of Propogation: TOP measures the timing of the Cherenkov light. Time resolution ~50ps. TOP detector surface is polished to nanometer precision for total reflection of Cherenkov light.
- K_L - Muon Detector: two inner layers of barrel + all layers in the end cap replaced by scintillators, because of large background.
- Electromagnetic Calorimeter: readout electronics replaced, fast FADC sampling for identify pile-up of pulses.
- Luminosity: ~30x instantaneous and integrated luminosity. Beam current, 1.64/1.19 A (Belle) → 3.60/2.60 A (Belle II) for e^+/e^- beam. Beta function at IP (β^*_y), 5.9/5.9 mm (Belle) → 0.27/0.31 mm (Belle II).
- Vertex detector: new design
- Drift Chamber: improved p_t resolution

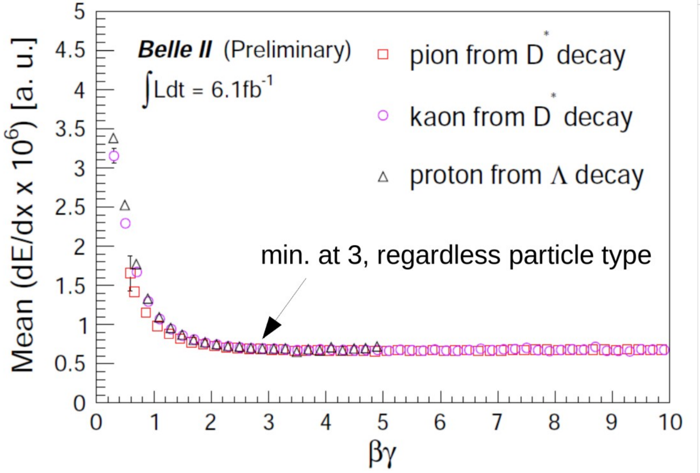


Belle II is performing well!

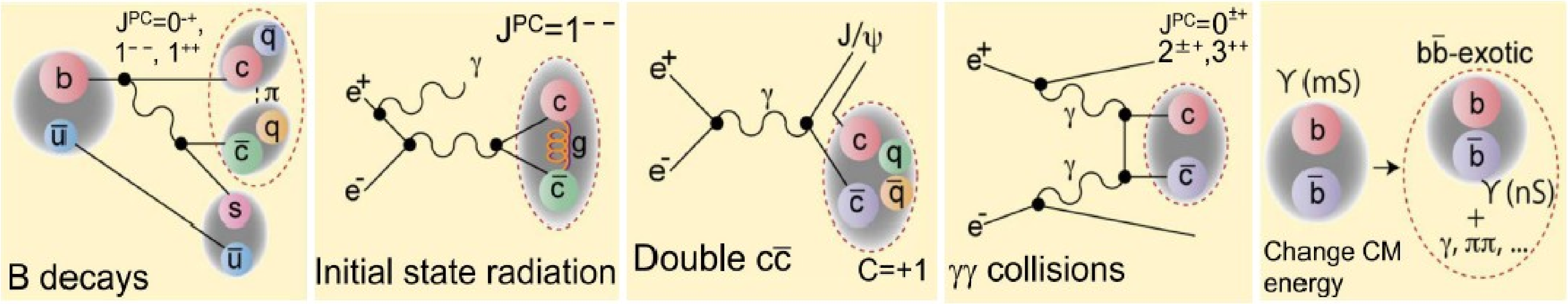


D^*–D^0 mass difference (Δm) from the D^* sample in data





Belle II: how to search for -onia



Unique @ e+e- machines!

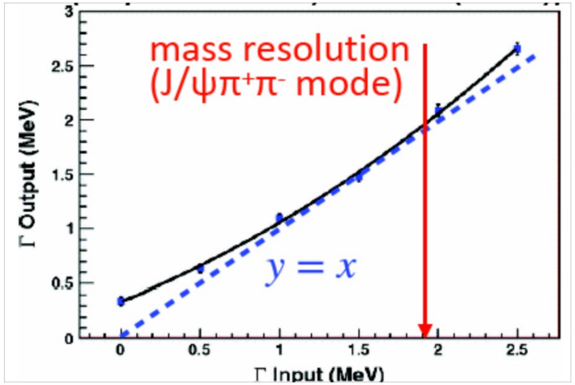
Search for the X(3872) at Belle II

- Width upper limit by Belle: $\Gamma < 1.2$ MeV (estimated from X(3872)→J/ψπ⁺π⁻),

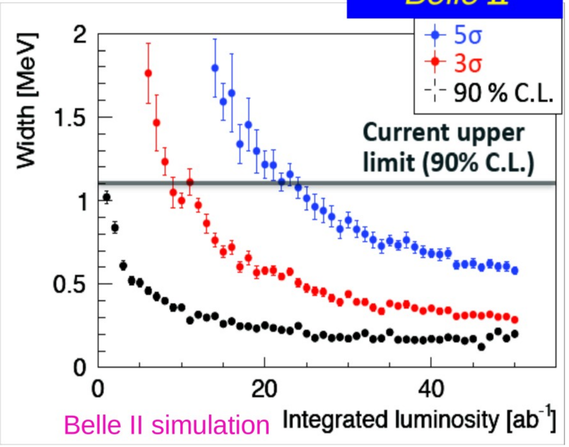
- Best BW width estimate by LHCb:

$$0.96^{+0.19}_{-0.18} \pm 0.21\, MeV$$ JHEP 08 (2020) 123

- Very promising: X(3872) → $D^0\bar{D}^{0*}$



Belle, PRD 84 (2011) 052004



Belle II simulation

mode	Q value [MeV]
$J/\psi\pi^+\pi^-$	495.65±0.17
$D^0\bar{D}^0\pi^0$	7.05±0.18
$D^0\bar{D}^{0*}$	0.01±0.18

- Due to very low Q value, the mass resolution is extremely good → expected great improvement on width with 50 ab^{-1}
- Search for exotics at DD* threshold (better slow pion detection at Belle II).
- Slow pion reconstruction efficiency >60%

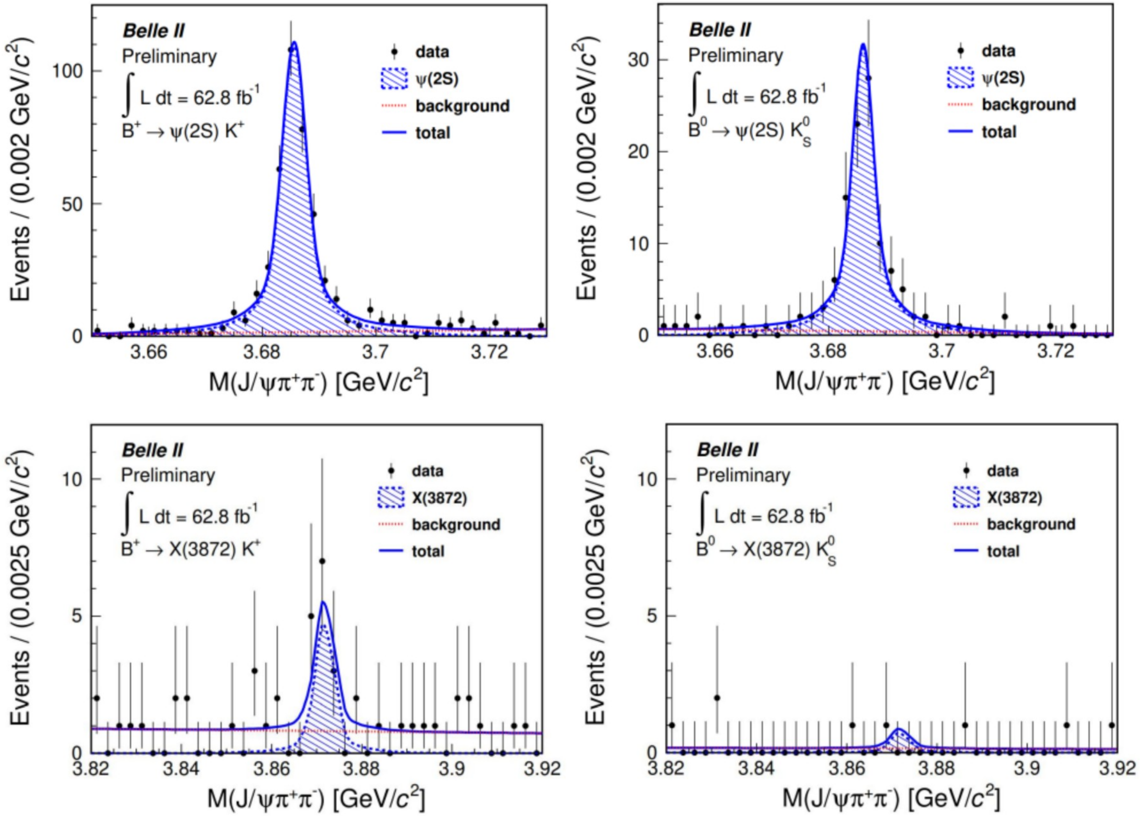
Projection on 50 ab^{-1} (extrapolated from Belle)

State	Production and Decay	N
X(3872)	B→KX(3872), X(3872)→J/Ψπ+π-	~14400
Y(4230)	ISR, Y(4230)→J/Ψπ+π-	~29600
Z(4430)	B→K±Z(4430),Z(4430)→J/Ψπ±	~10200

Search for the X(3872) at Belle II: ongoing

- Reconstruction of final states
  - $B^{\pm} \rightarrow \pi^{+}\pi^{-} J/\Psi(l^{+}l^{-}) K^{\pm}$
  - $B^{0} \rightarrow \pi^{+}\pi^{-} J/\Psi(l^{+}l^{-}) K_{S}$
- Selection criteria (standard)
  - Particle identification
  - Continuum: nTracks, R2
  - Kinematics: $M_{\pi+\pi-}$, M_{bc}, $|\Delta E|$
- First X(3872) at Belle II with 62.8 fb-
  - 14.4±4.6 events (4.6σ)
  - Belle: ~170 events in 772M $B\overline{B}$

Phys. Rev. D 84, 052004, 2011



Charmonium in ISR: Perspectives

- Line shape of the Y(4260)
- Strange partner of Z(3900) in KKJ/ψ
- Cross sections of exclusive $(\bar{c}c)$ + hadrons

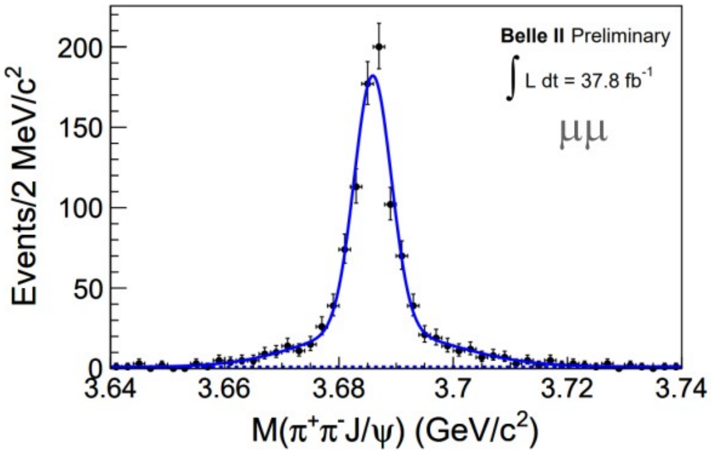
Golden Channels	$E_{c.m.}$ (GeV)	Statistical error (%)	Related XYZ states
$\pi^+\pi^- J/\psi$	4.23	7.5 (3.0)	$Y(4008)$, $Y(4260)$, $Z_c(3900)$
$\pi^+\pi^- \psi(2S)$	4.36	12 (5.0)	$Y(4260)$, $Y(4360)$, $Y(4660)$, $Z_c(4050)$
$K^+K^- J/\psi$	4.53	15 (6.5)	Z_{cs}
$\pi^+\pi^- h_c$	4.23	15 (6.5)	$Y(4220)$,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

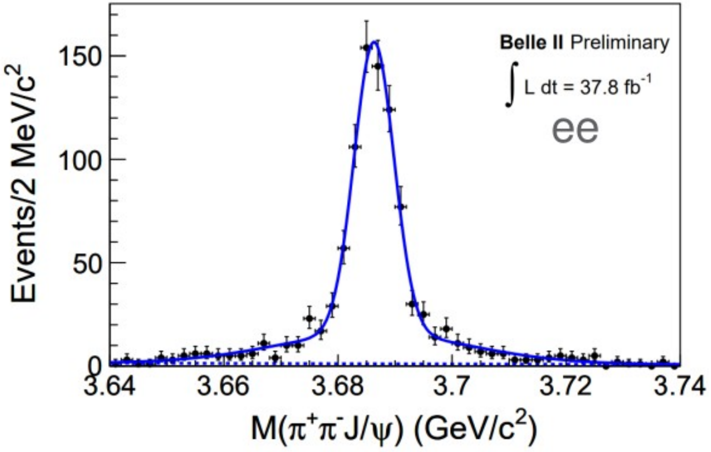
50 ab^{-1}

10 ab^{-1}

Charmonium in ISR: ongoing

- $e^+e^-\gamma_{ISR} \rightarrow \pi^+\pi^- J/\Psi(l^+l^-)$ reconstruction
  - Nominal PID requirements
  - $|M(J/\Psi) - M(PDG)| < 75$ MeV
  - ISR photon not required (high efficiency)
  - $|MM^2(\pi^+\pi^- J/\Psi)| < 2$ GeV/c²
- Clear observation of ISR Ψ(2S) signals
- Next step: Y(4230) rediscovery
  - Expect ~60 total events per 100 fb^{-1}





Why Bottomonium at Belle II?

- Bottomonium spectrum is significantly different from charmonium spectrum
  n=3 state (^3P) is below the threshold
  L=2 state (^1D) is below the threshold

- Z_b states were only found so far in $\Upsilon(5S)$ decays

- SuperKEKB can reach $E_{c.m.} \cong 11$ GeV
  $\Rightarrow \Upsilon(6S)$ running possible – unique possibility!

- With the high luminosity, for the 1st time study radiative transitions between bottomonia states possible (suppressed by 1/137). Marginal statistics so far at Belle, big advantage at Belle II

Bottomonium at Belle II: ongoing

- $e^+e^-\gamma_{ISR} \rightarrow \pi^+\pi^-$ Initial State Radiation (ISR) production:

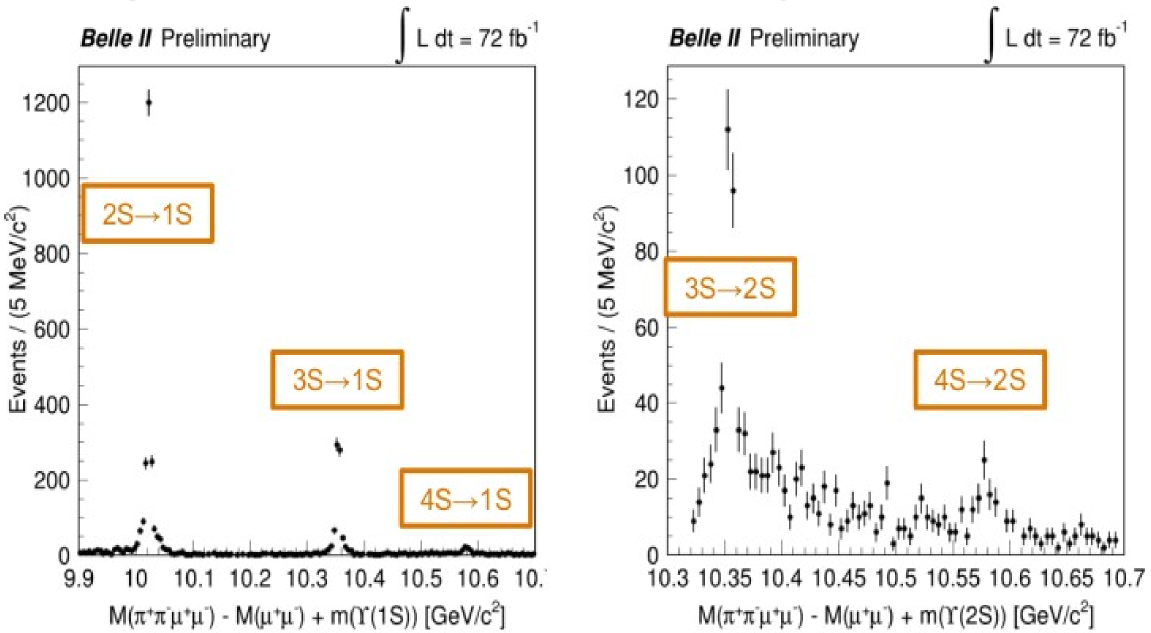
  $\gamma_{ISR}\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S)(l^+l^-)$

  $\gamma_{ISR}\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(1S,2S)(l^+l^-)$

- Direct transitions: $\Upsilon(4S) \rightarrow \pi^+\pi^-\Upsilon(1S,2S)$
- All signals observed in early Belle II data

- Future studies:

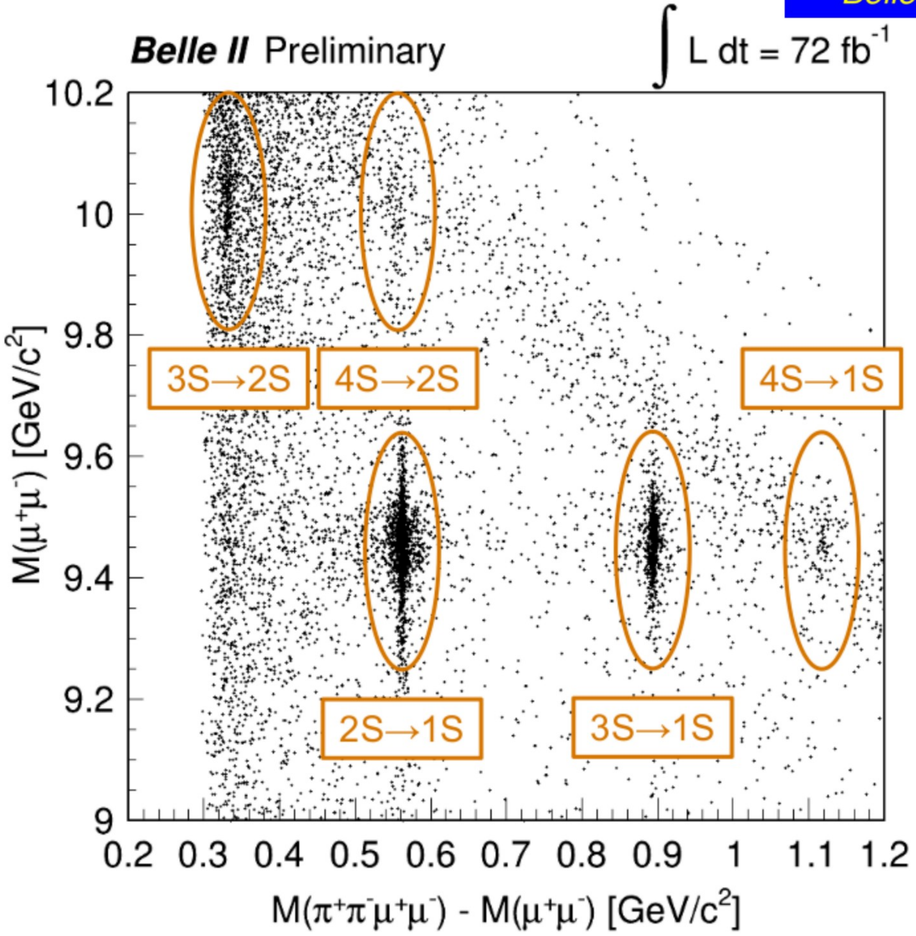
  $M(\pi^+\pi^-)$ in $\Upsilon(4S)$ transitions



Bottomonium at Belle II: ongoing

$\Upsilon \rightarrow \mu^+\mu^-$

- Υ-dipion transition in Early Phase 3 Data
- Clear evidence of signal with 72 fb^{-1}
- Clusters represent signal transitions



Expectations on Z_b states at Belle II

- If Z_b is a loosely-bound state, several new molecular states should appear

$\Upsilon(6S)$ and $\Upsilon(5S)$: conventional state search

- Belle II goals:
  - search for new, predicted, resonances
  - use both, single transitions and double cascade
  - fill the remaining spectrum to measure the effect of the coupled channel contribution

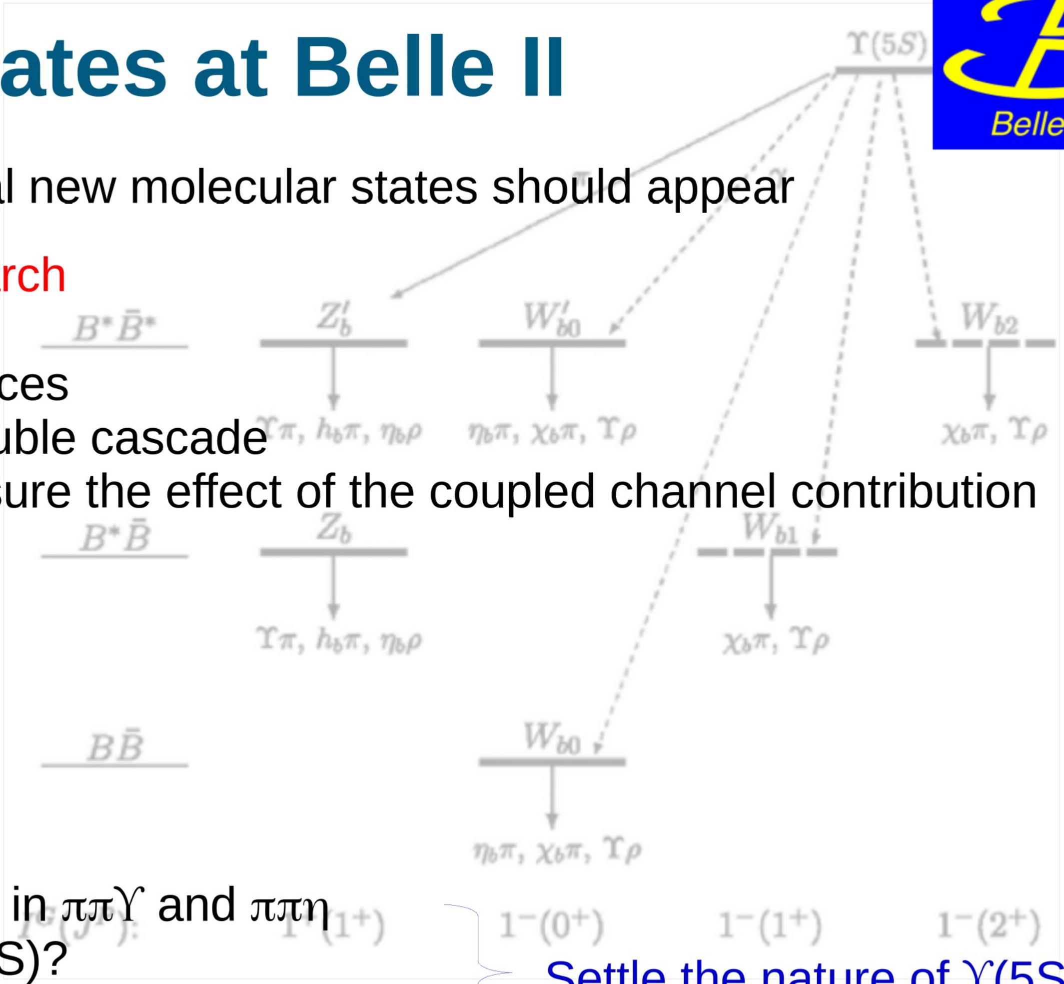
$\Upsilon(6S)$ and $\Upsilon(5S)$: new exotics search

- Belle II goals:
  - $\Upsilon(6S)$: 100 fb^{-1} exploratory run
  - $\Upsilon(5S)$: 1 ab^{-1} high statistics run

$\Upsilon(6S)$ and $\Upsilon(5S)$: scan

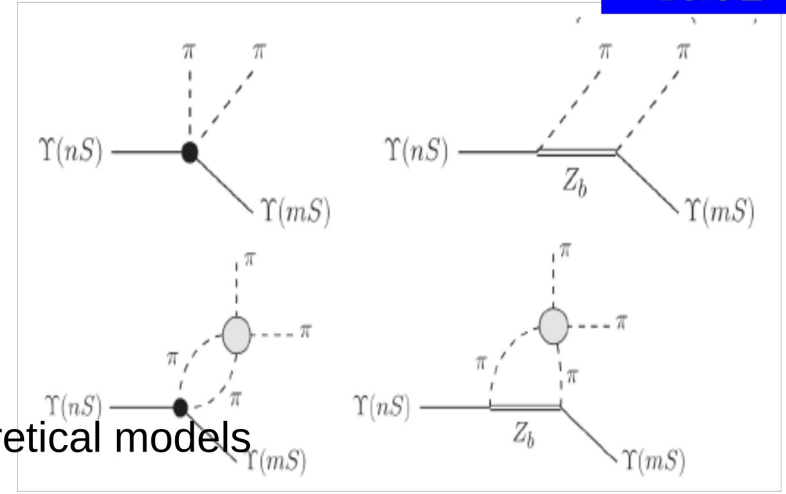
- Belle II goals:
  - $\Upsilon(6S)$ and $\Upsilon(5S)$ behave differently in $\pi\pi\Upsilon$ and $\pi\pi\eta$
    → hint of a non-*bb* nature of $\Upsilon(5S)$?
  - investigate an extra resonance around 10.750 MeV/c^2

Settle the nature of $\Upsilon(5S)$



$\Upsilon(3S)$: Opportunities at Belle II

- Exotic states contribute to the hadronic and radiative transitions from narrow quarkonia
  → complementary approach to the direct search from $\Upsilon(5S)$ and $\Upsilon(6S)$



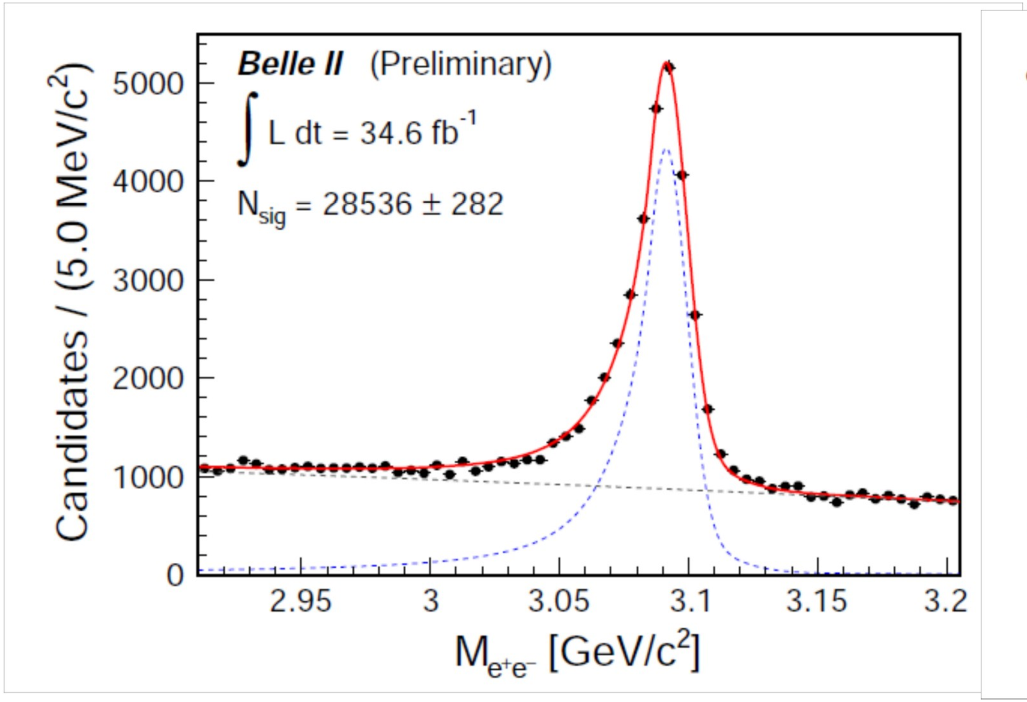
$\Upsilon(3S)$: exotics in transitions

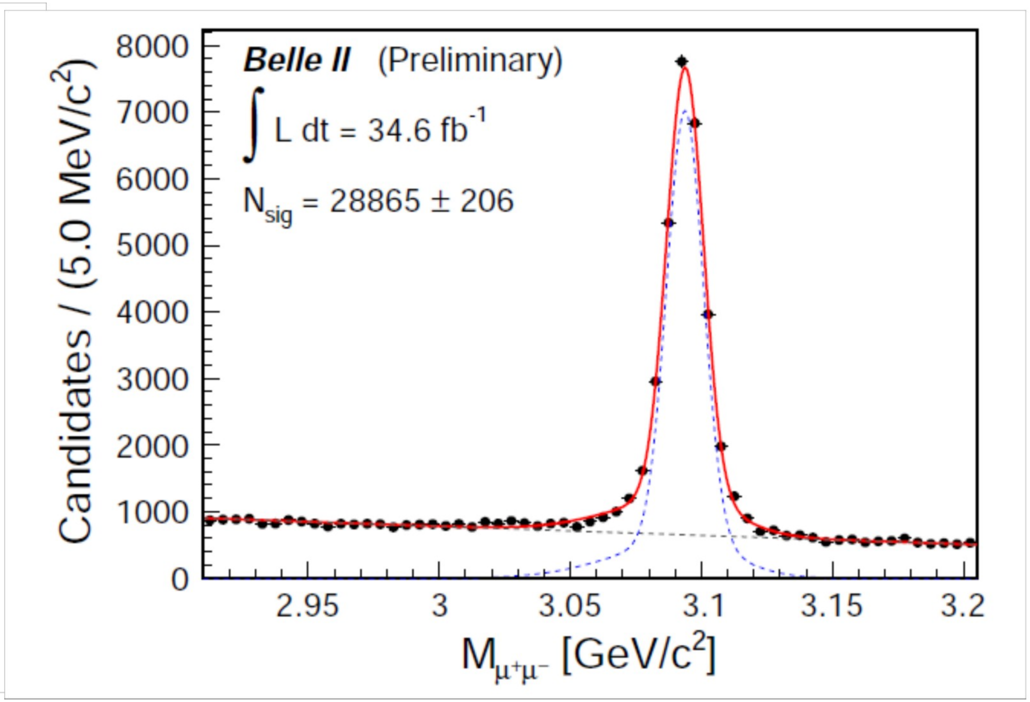
- Belle II goals:
  - $\Upsilon(3S) \rightarrow \pi\pi\Upsilon(1S, 2S)$ still limited by statistics
  - perform full amplitude analysis
  - search for missing $\pi\pi/\eta$ transitions to constraint further theoretical models
  - study hindered radiative transitions

$\Upsilon(3S)$: charmonia in production

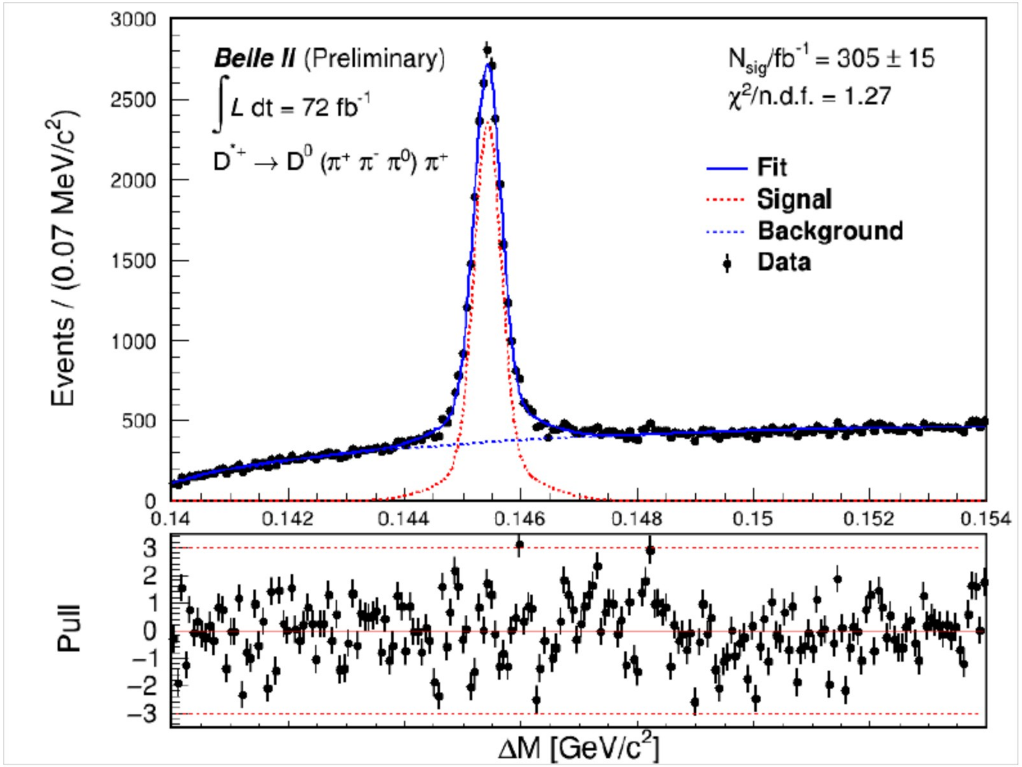
- Belle II goals with 300 fb^{-1}:
  - up to 5x sensitivity in inclusive production from $\Upsilon(3S)$
  - up to 15x in double charmonium
  - inclusive rate of X(3872)
  - $D\bar{D}^*$ correlation in $\Upsilon(3S) \rightarrow D\bar{D}^*$ + hadron to test the nature of the X(3872)
- $\Upsilon(3S)$: rare χ_b decays, deuteron production mechanism

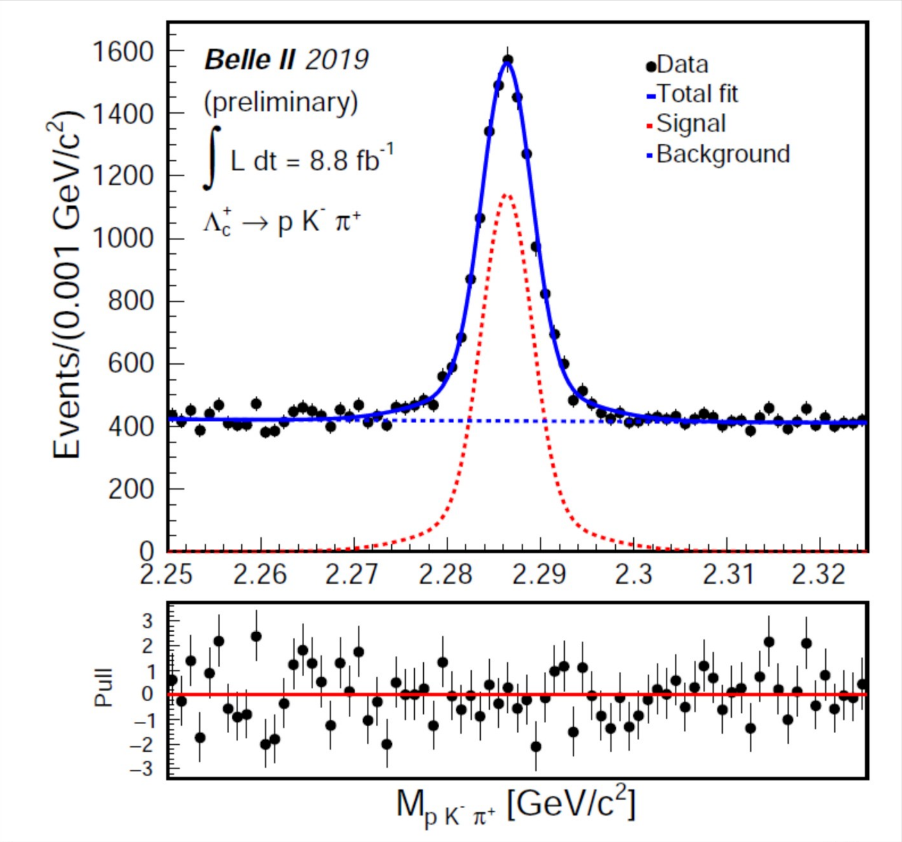
“Re-discovery” with Phase 3 Data: J/ψ





“Re-discovery” with Phase 3 Data: D^0, Λ_c





Summary

- Great achievements with Belle (~ 1 ab^{-1}) in spectroscopy,
  but still opportunities for unique physics with the new upgrade Belle II!
- In SuperKEKB e^+e^- collisions will reach unprecedented instantaneous luminosity: 6×10^{35} cm^{-2} s^{-1}.
- Improved tracking and PID in Belle II
- Challenge by summer 2020: 200 fb^{-1}
- Expected 50 ab^{-1} integrated luminosity at Belle II in 6 years
- With x50 more data than Belle, expected in Belle II great achievements in hadron spectroscopy:

  - ISR analysis as unique case
  - favorite Bottomonium search through Υ(6S) compared to Belle
  - good slow pion reconstruction to search for $D^*\overline{D}^{(*)}$ threshold exotic state
  - study of J/ψKK invariant mass in all possible mechanisms
  - search for new and conventional -onia with high precision
  - amplitude analysis

B2GM June 2019