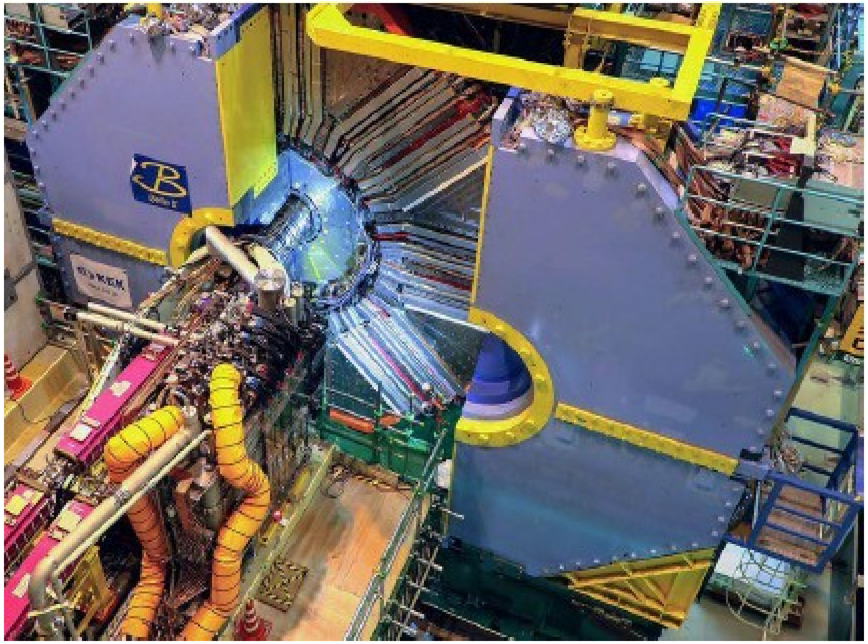

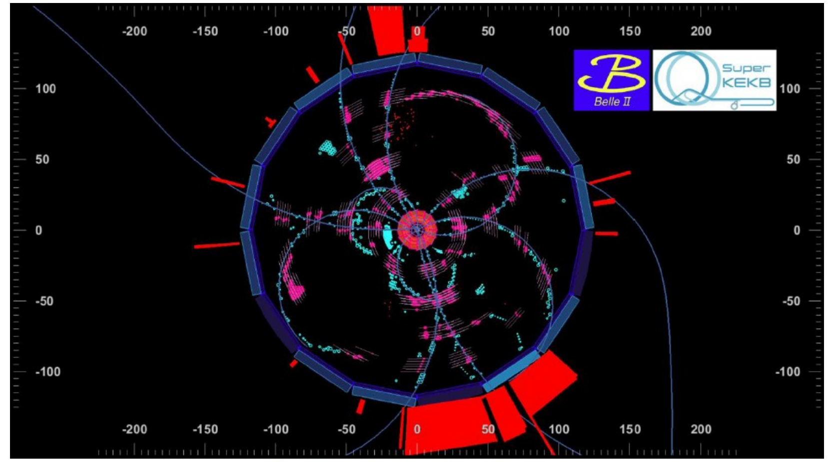

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Charmonium and Bottomonium Spectroscopy at Belle II

02.09.2019 I Elisabetta Prencipe on behalf of the Belle II Collaboration

International Workshop on Partial Wave Analyses and Advanced Tools for Hadron Spectroscopy PWA11/ATHOS6, Rio de Janeiro

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Outline

- Introduction
- Motivation
  - how can we improve the B-factories achievements?
  - 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 Phase 3 data
- Summary

Introduction

- Gell-Mann Zweig idea: Constituent Quark Model

  Still valid for half century → it classifies all known hadrons

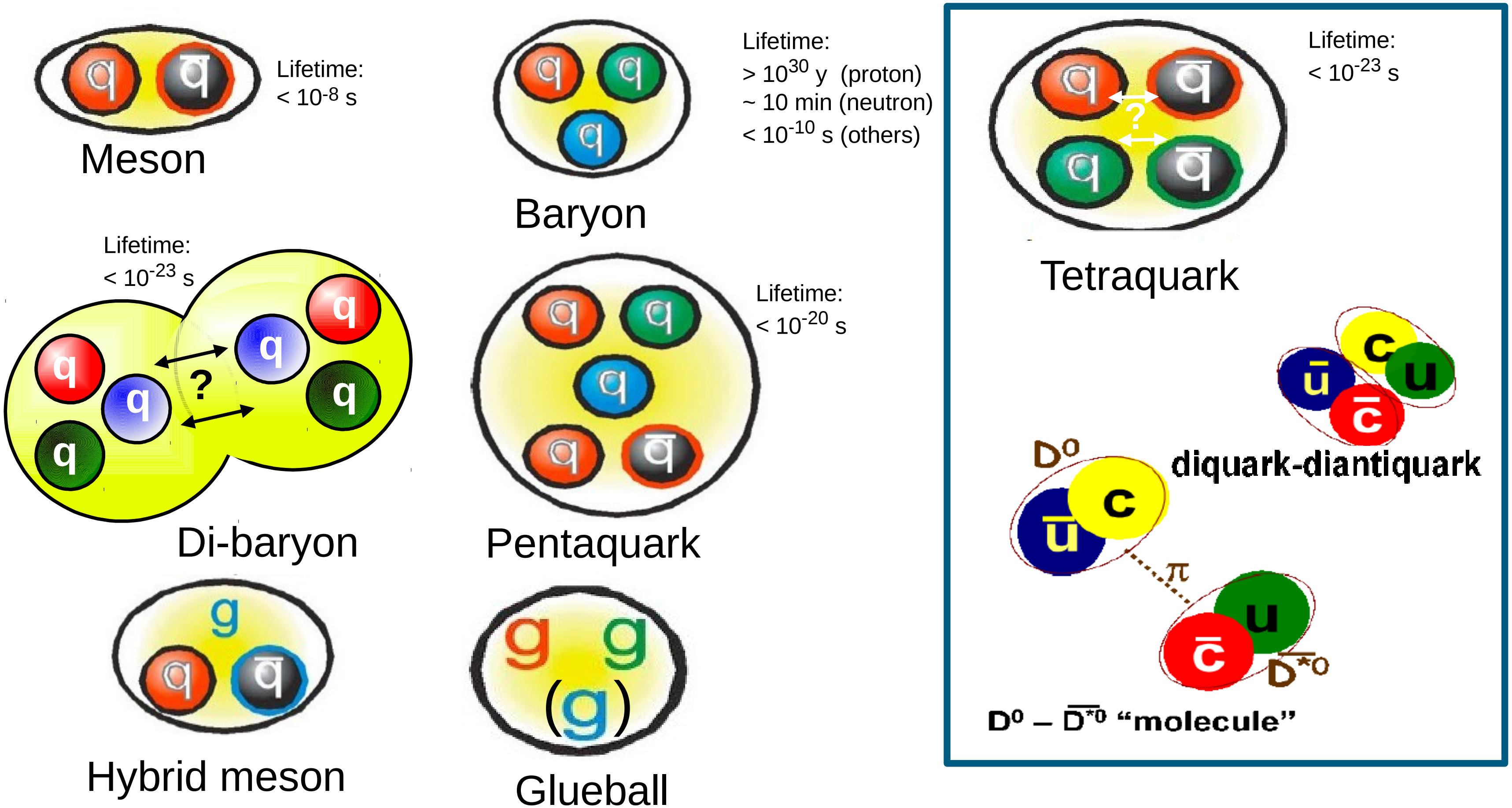
- QCD-motivated models predict the existence of hadrons with more complex structures than simple *qq* (mesons) or *qqq* (baryons) → the so-called XYZ *“charmonium”-like* states
- <u>**Lot of experimental effort to prove the existence of XYZ!**</u>
- No unambiguous evidence for hadrons with *non-CQM-like* structures has been found
- New possibilities, started with the observation of the X(3872):

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

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

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

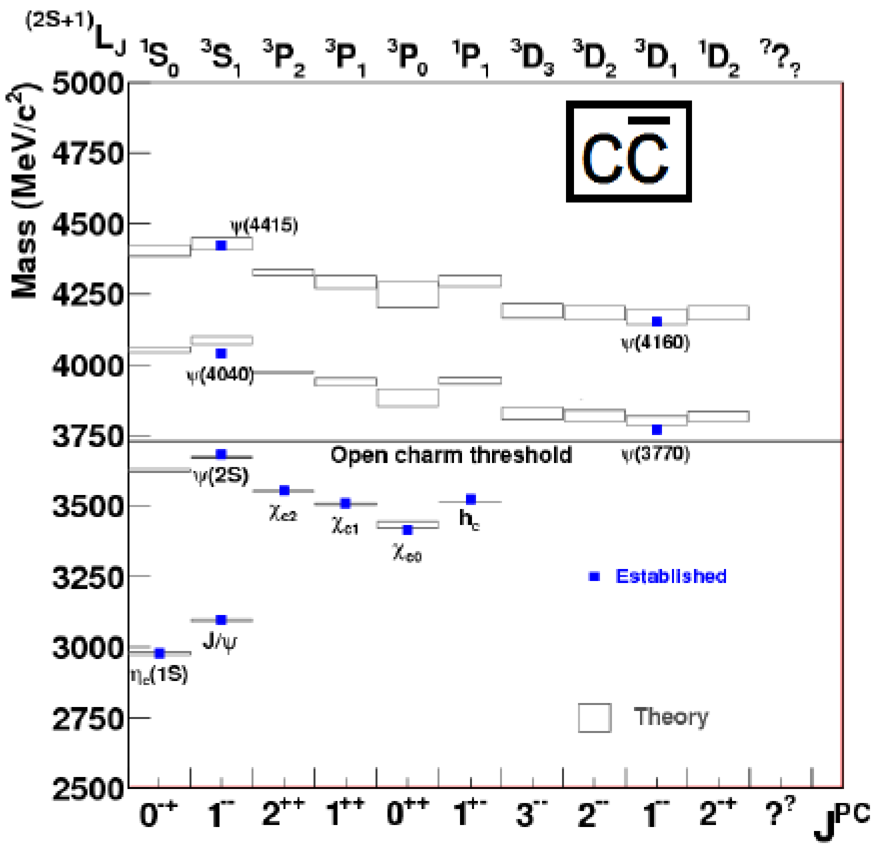
Quark Bound States

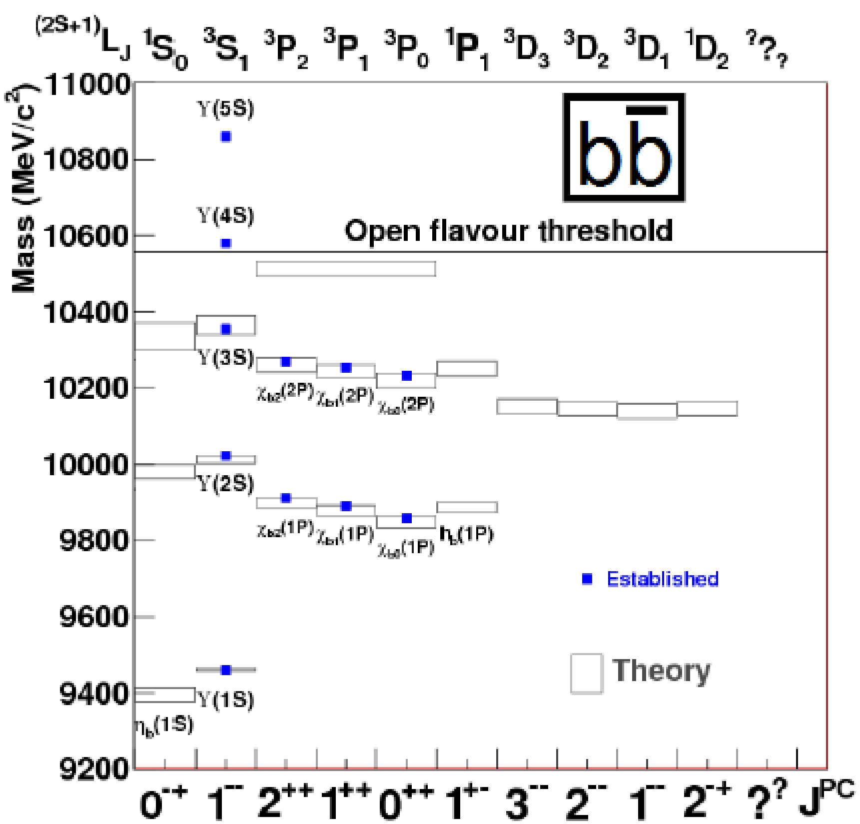


...and superposition of different states: $c_1|\bar{q}q\rangle + c_2|\bar{q}q\bar{q}q\rangle + ...$

-Onia (conventional and exotics)

- States described by potential models, NRQCD,…, before B-factories era





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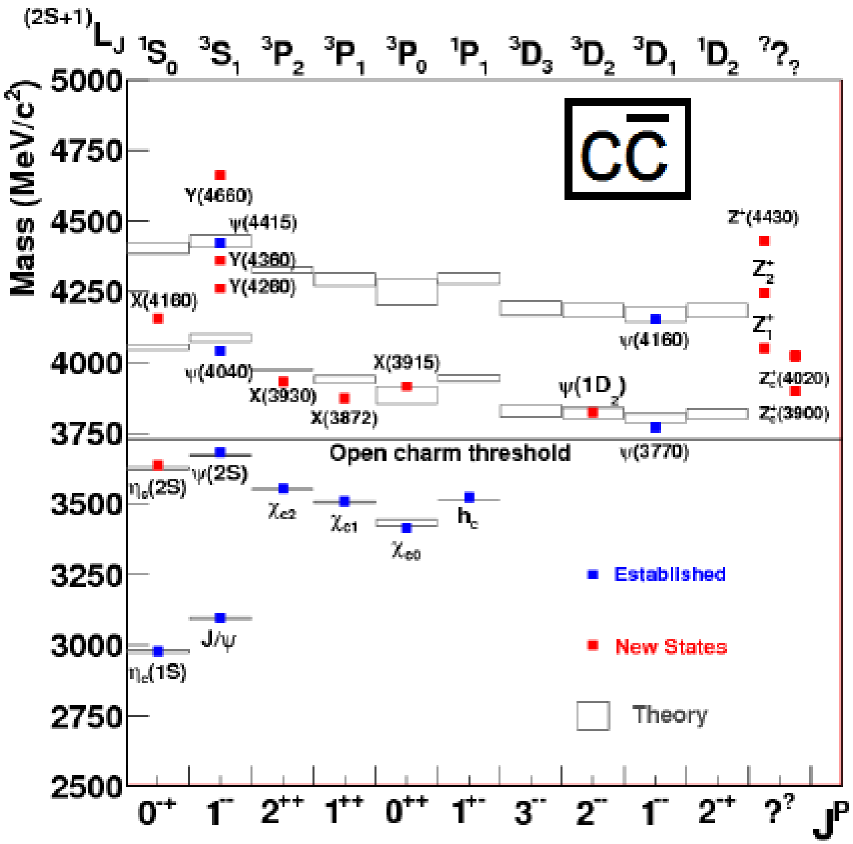

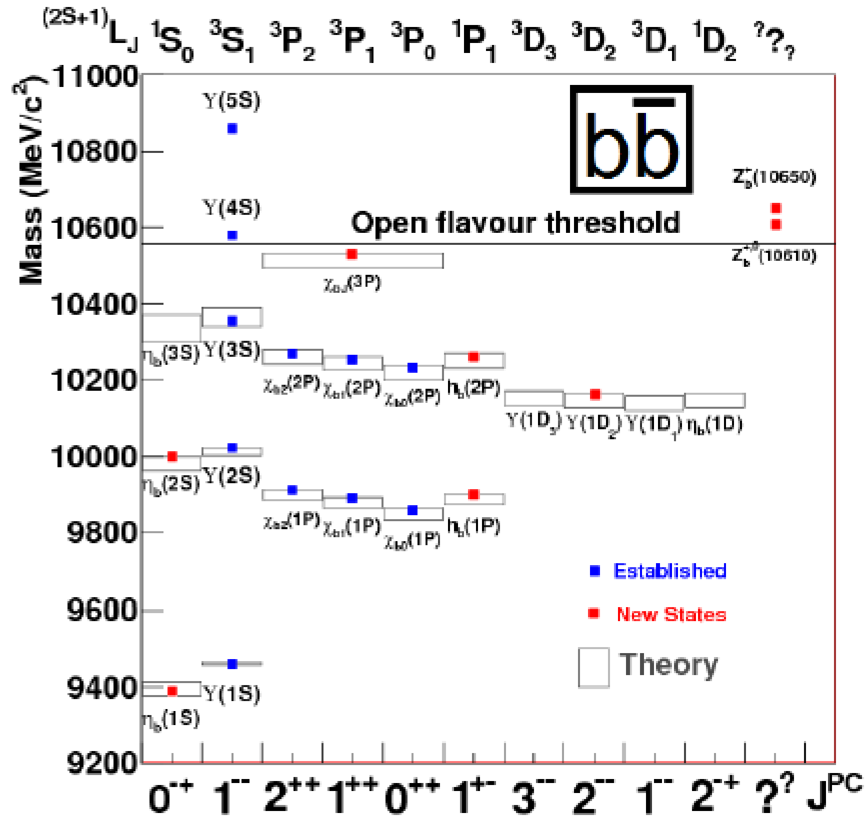

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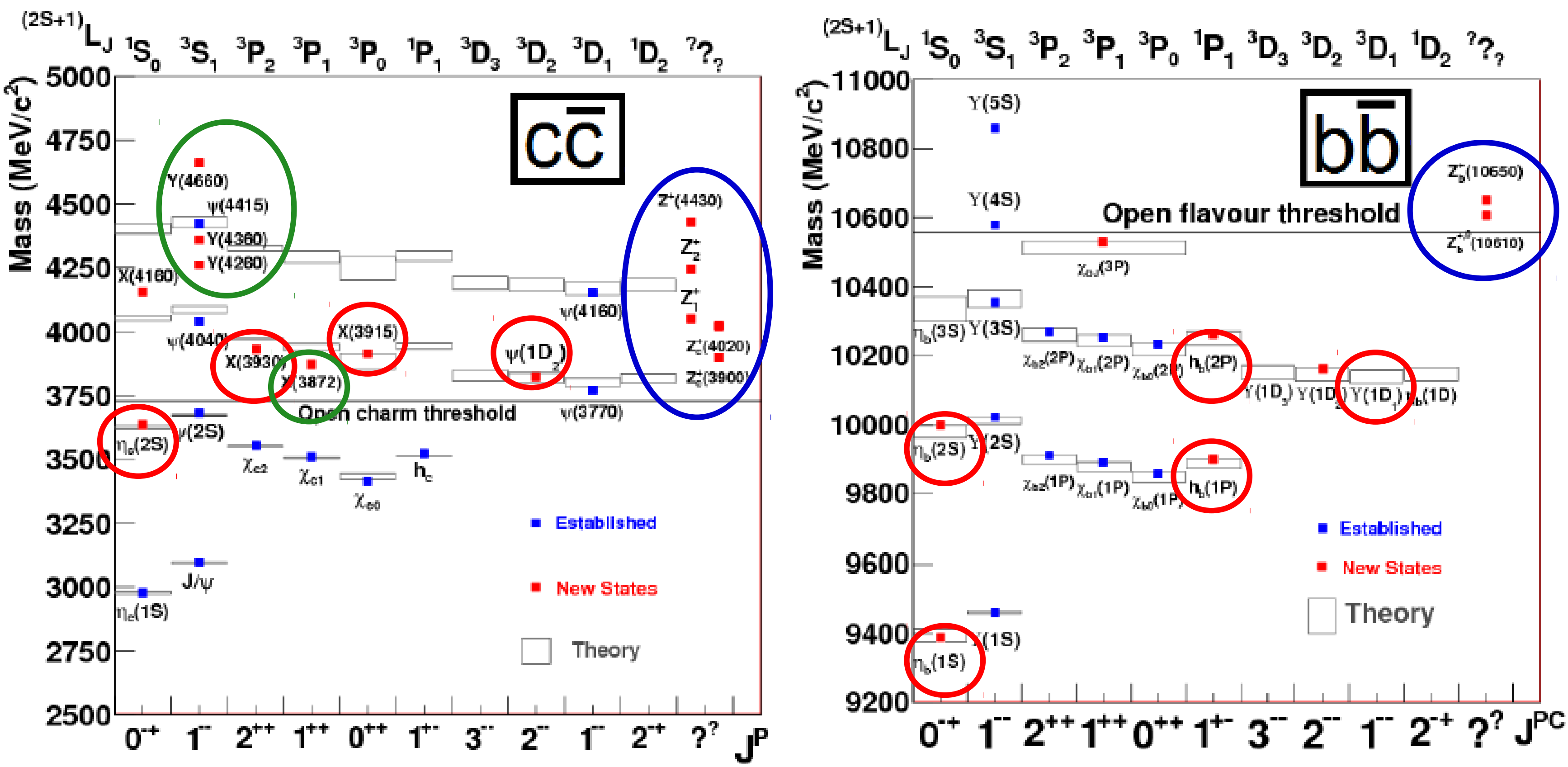


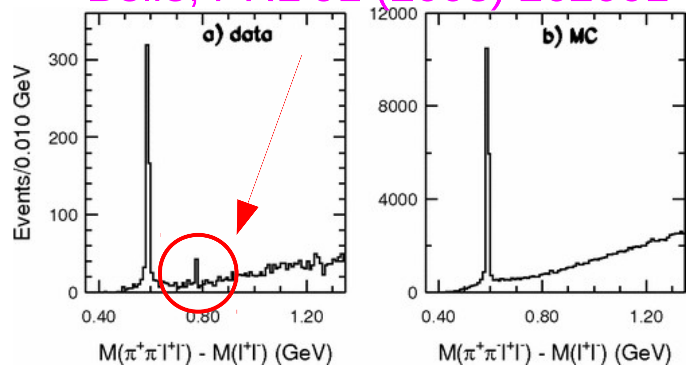
Nomenclature

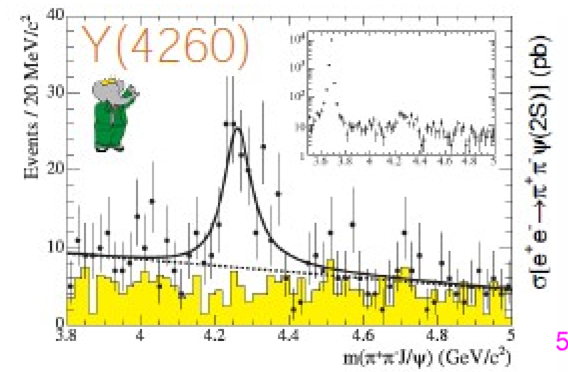
X, such as the X(3872)
- consistent with $D^0\overline{D}^{*0}$ molecular state
- found in B decays, large production also in pp
- no partners found

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

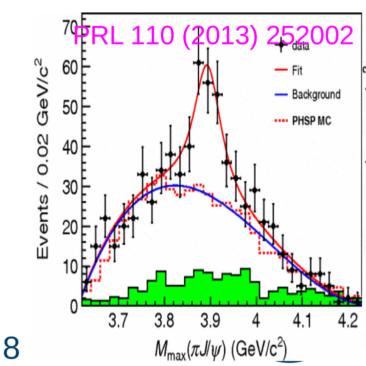
Z, such as the $Z_c(3900)$ and the $Z_b(10610)$
- seen in decays of $q\overline{q}$ and B decays
- charged states: cannot be charmonia
- b- and c- *onia*: similarities

Belle, PRL 91 (2003) 262001

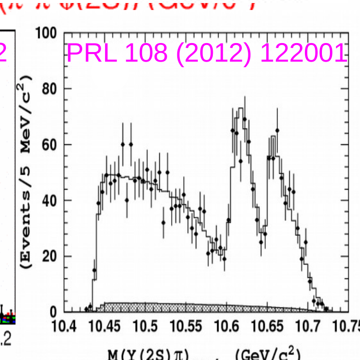




PRL 110 (2013) 252002



PRL 108 (2012) 122001



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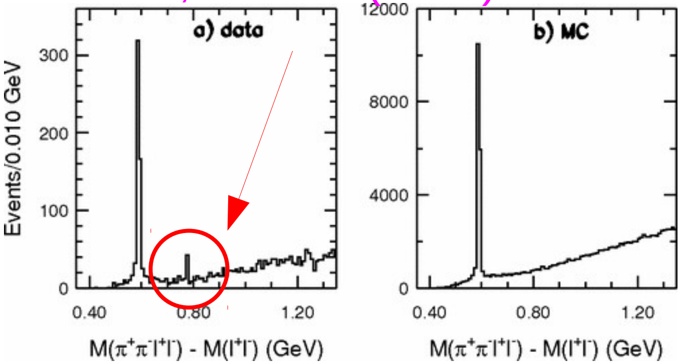

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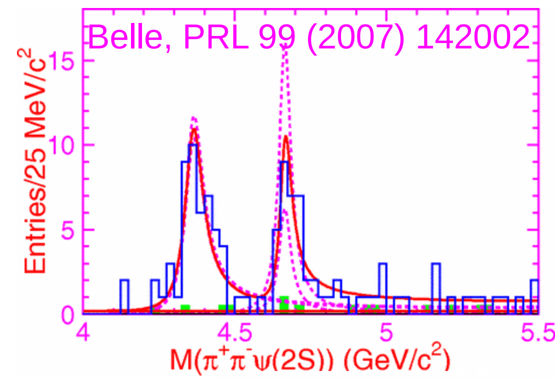

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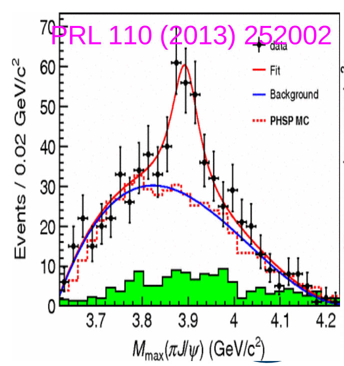
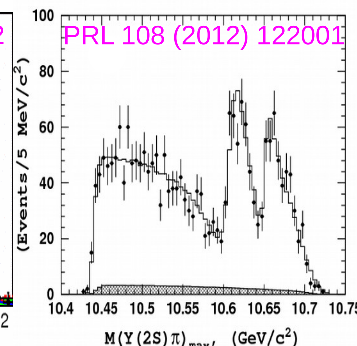
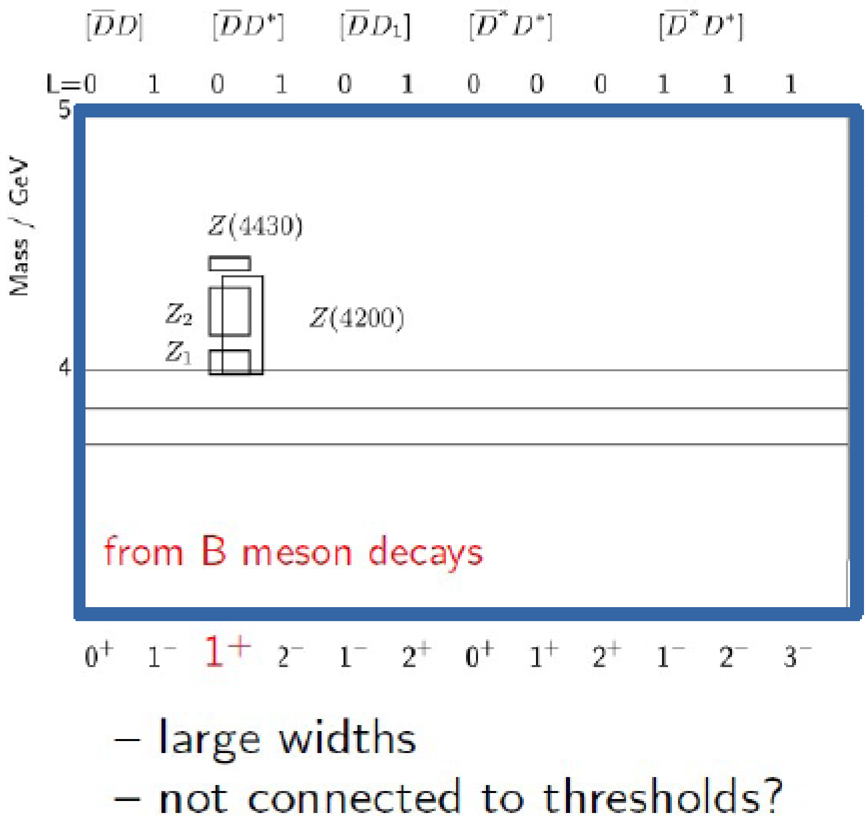
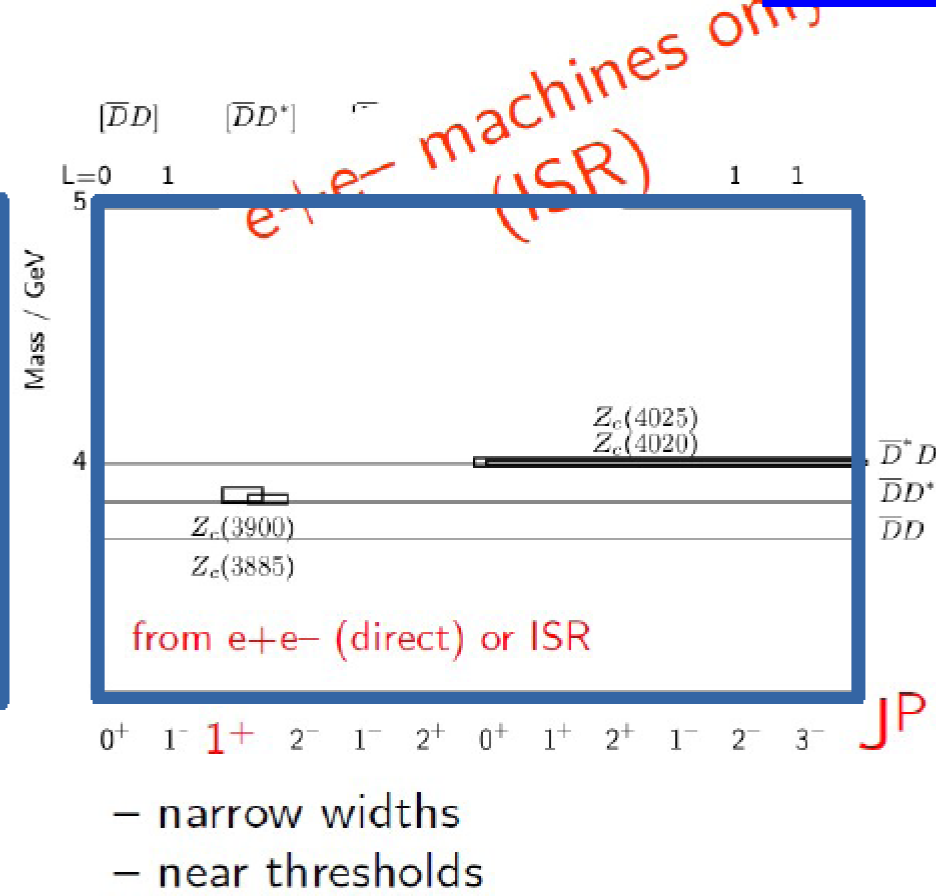




Two different classes of Z states?

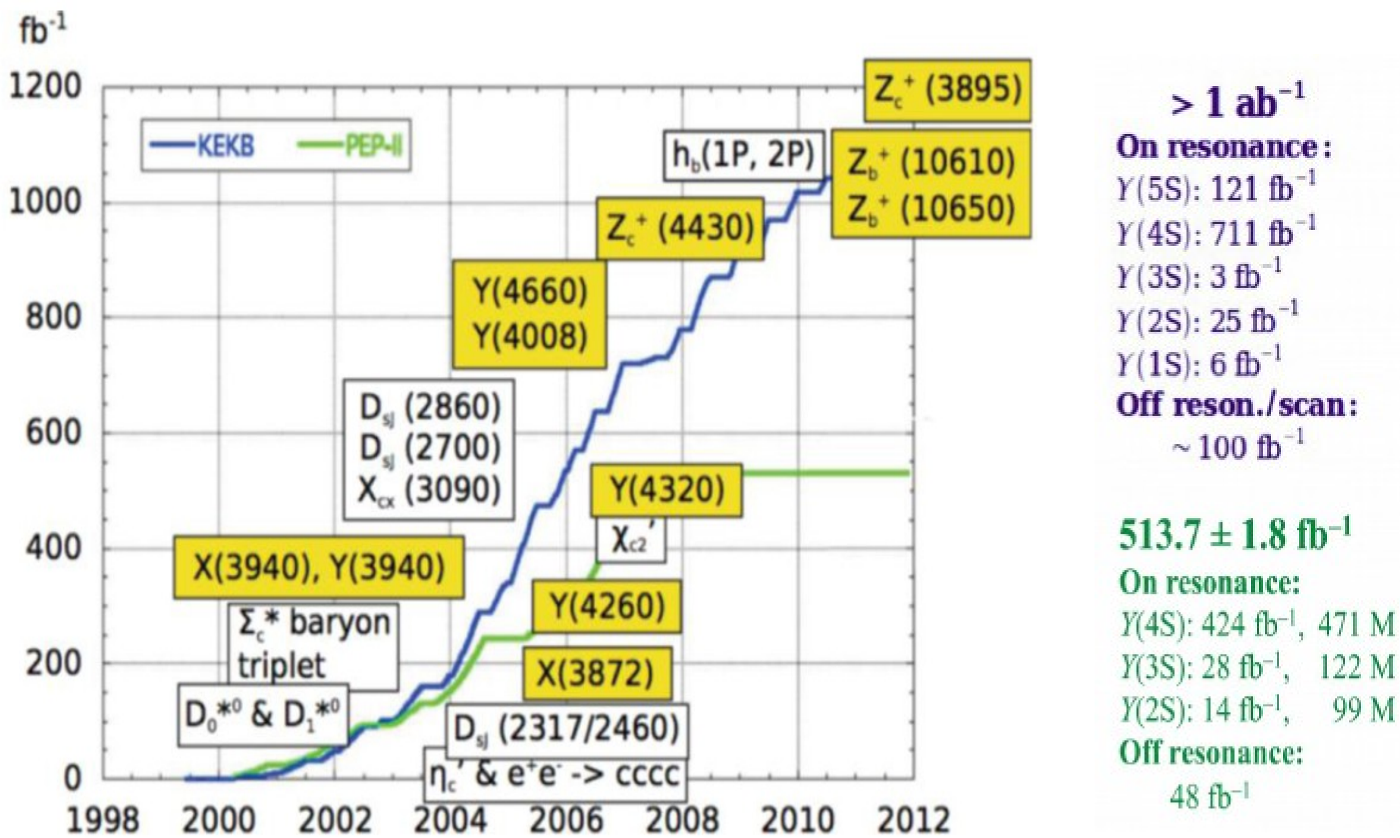




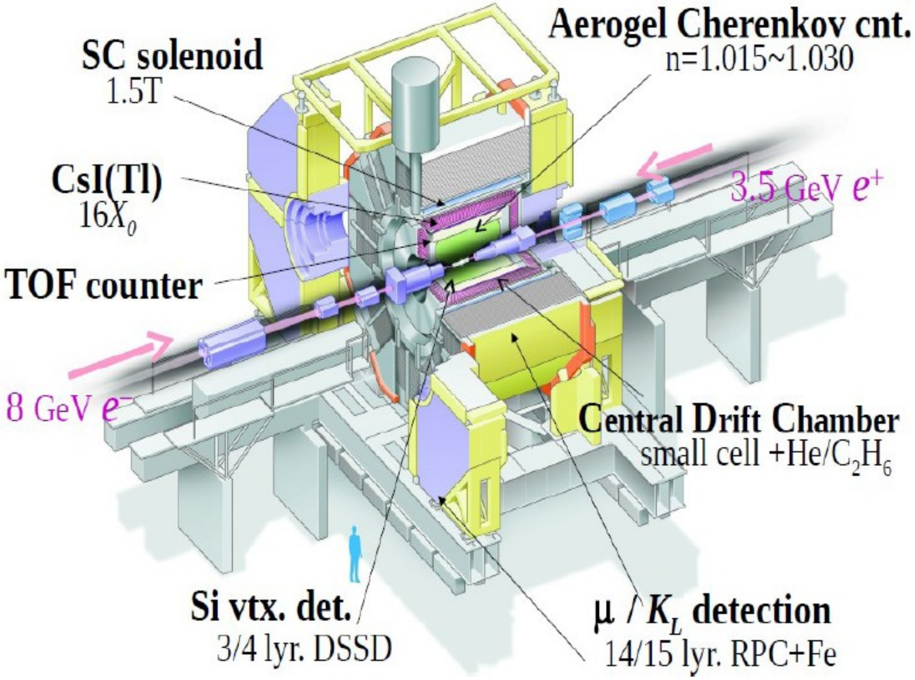
- Belle II is in a unique position to look for both Z types:
  - through B decays (LHCb, no BES III)
  - threshold state (BES III, no LHCb)

- BaBar + Belle:

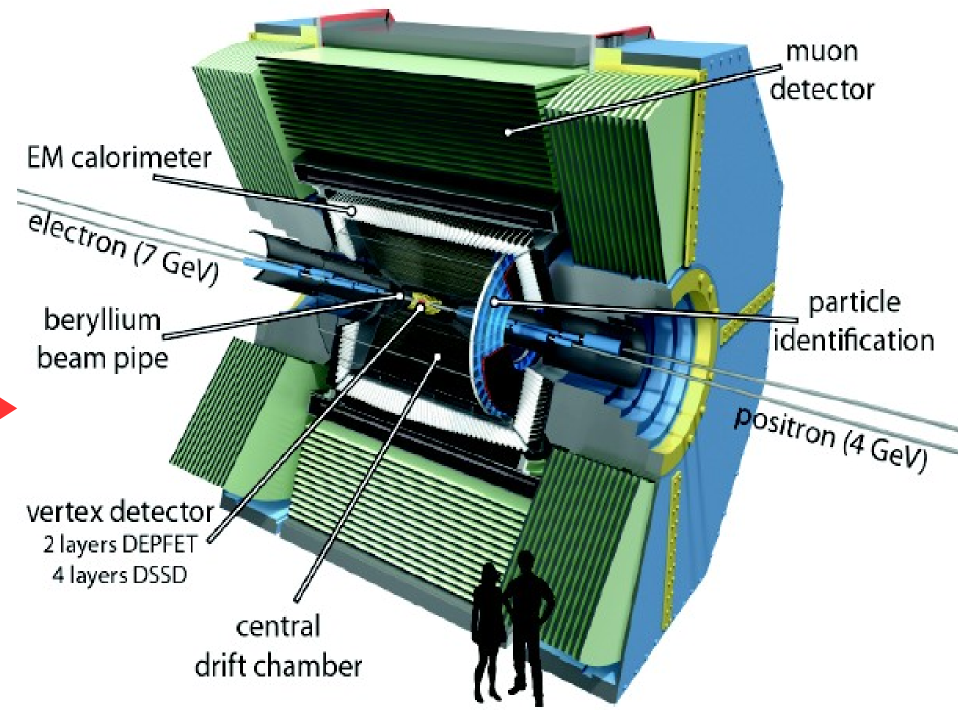
>1.5 ab^{-1} integrated luminosity - triumph in the history of B-factories!

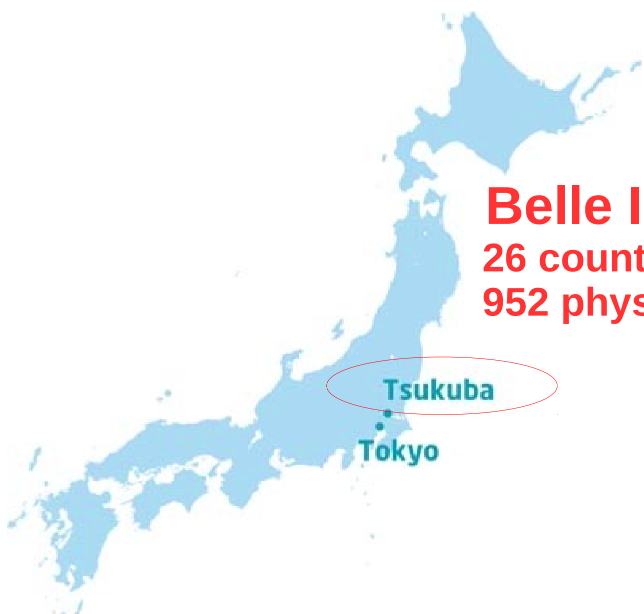


- Not only B-factory, but $c\bar{c}$-factory with so high luminosity
- Still statistics limitation in spectroscopy for rare processes ($BR<10^{-5}$)
- Upgrade needed!



Belle detector





Belle II detector

26 countries,
952 physicists

From Belle to Belle II

What has been changed?

- PXD, vertex resolution in z direction (beam direction) will be factor 2 better than before:
  50 μm (Belle) → 25 μm (Belle II)
- TOP: no TOF (time-of-flight) detector anymore, but TOP (time-of-propagation) will do the timing of the Cerenkov light. Time resolution ~50 ps. TOP detector surface is polished to nanometer precision for total reflection of Cerenkov light
- KLM: inner 2 layers of barrel + all layers in the endcap replaced by scintillators, because of large background
- ECL readout electronics exchanged, fast FADC sampling for identify pile-up of pulses
- Huge gain in luminosity in Belle II compared to Belle: factor x40. How?

  - factor 2 by beam current: 1.64/1.19 A (Belle) → 3.6/2.6 A for $e^+(e^-)$ beam in Belle II

  - factor 20 by "nano-beam" principle (collision point in vertical direction will be only 59 nm)

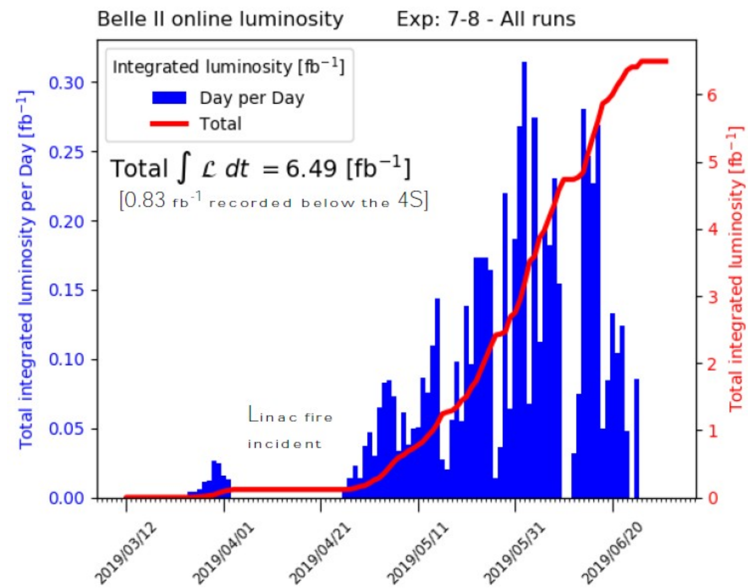
$$\beta_y(z) = \beta_y^*\left(1 + \frac{(z - Z_0)^2}{\beta_y^{*2}}\right)$$

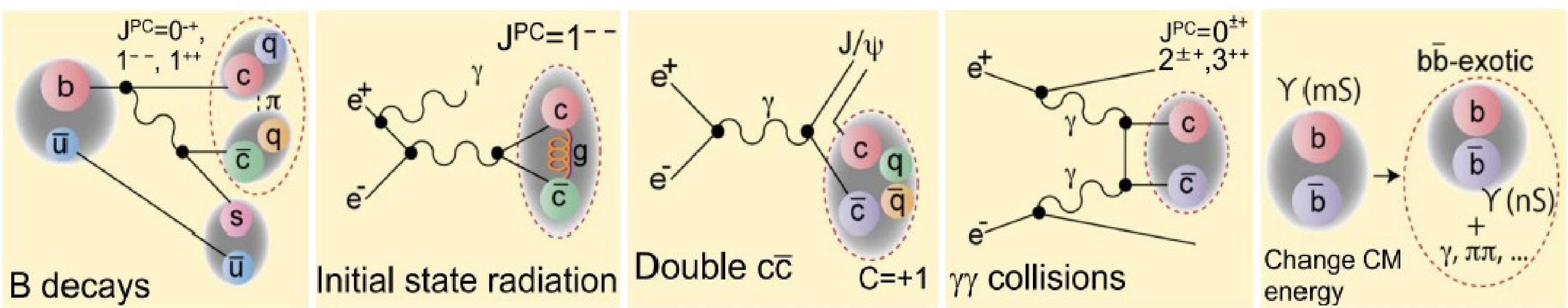
β^*_y function: 5.9 mm (Belle), 0.27 mm (Belle II)

$$\sigma_y(z) \propto \sqrt{\beta_y(z)}$$

Luminosity and long term perspectives

- **Phase 2**, concluded on 17.07.2018: L = **504.9 pb^{-1}**
- **Phase 3**, concluded on 01.07.2019: L = **6.5 fb^{-1}**
- **Summer 2020**, expected up to 200 fb^{-1}
- **By 2026**, expected up to 50 ab^{-1}





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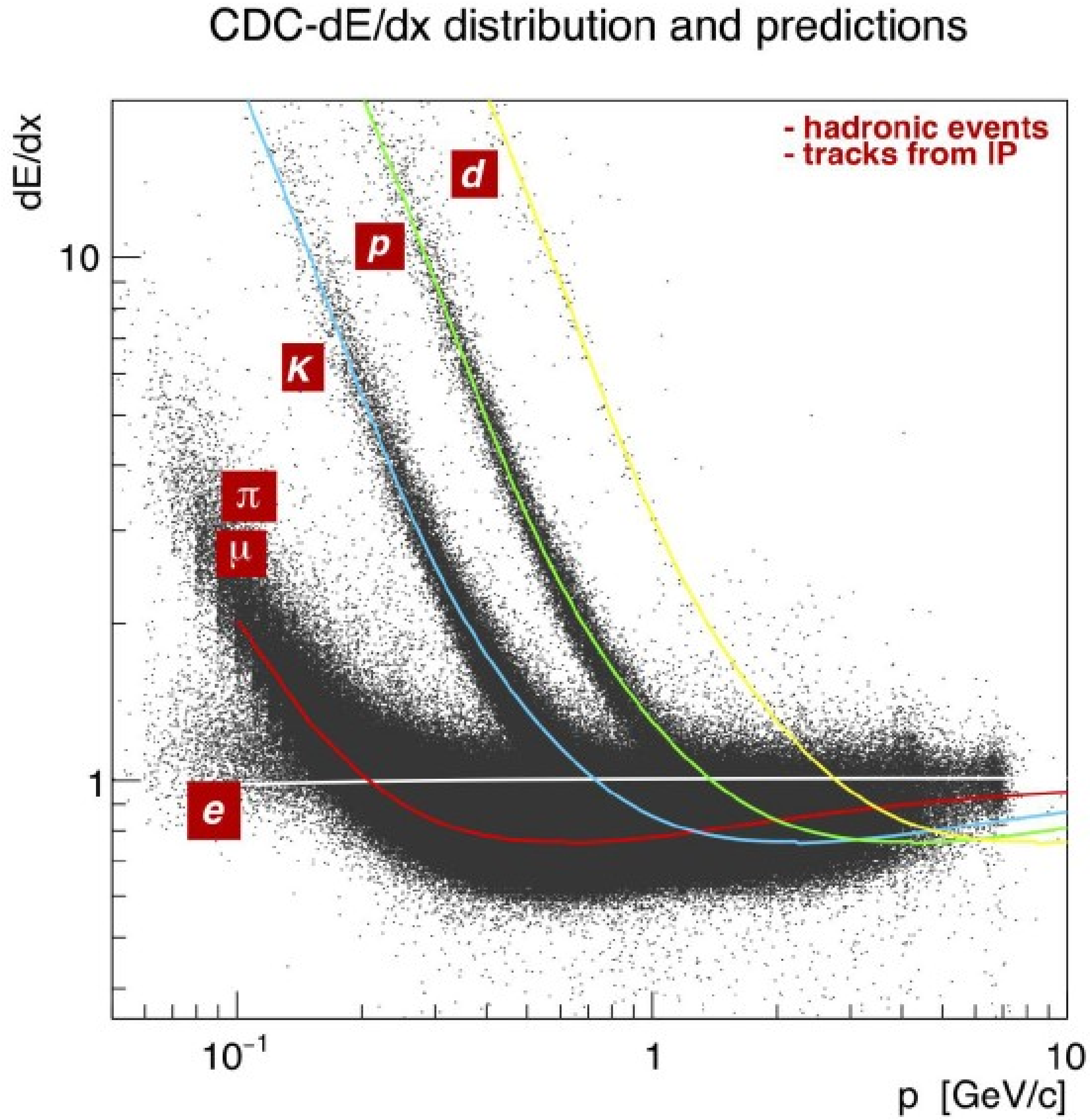
Belle II is performing well!



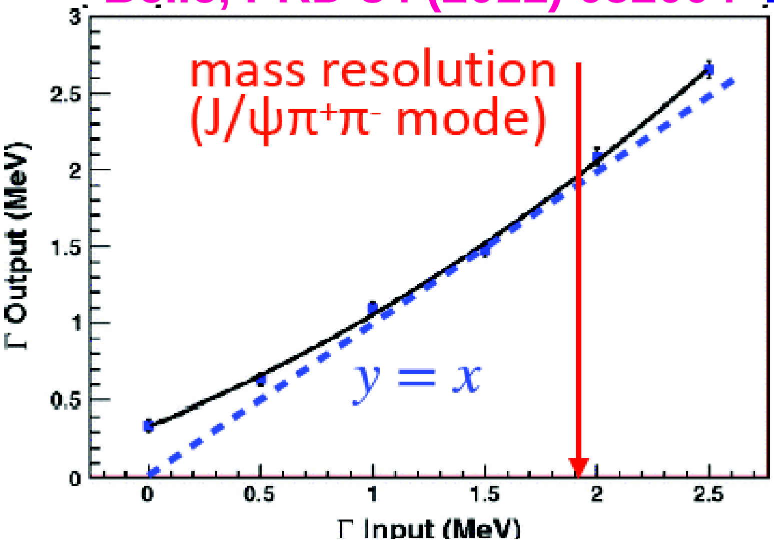
X(3872) total width

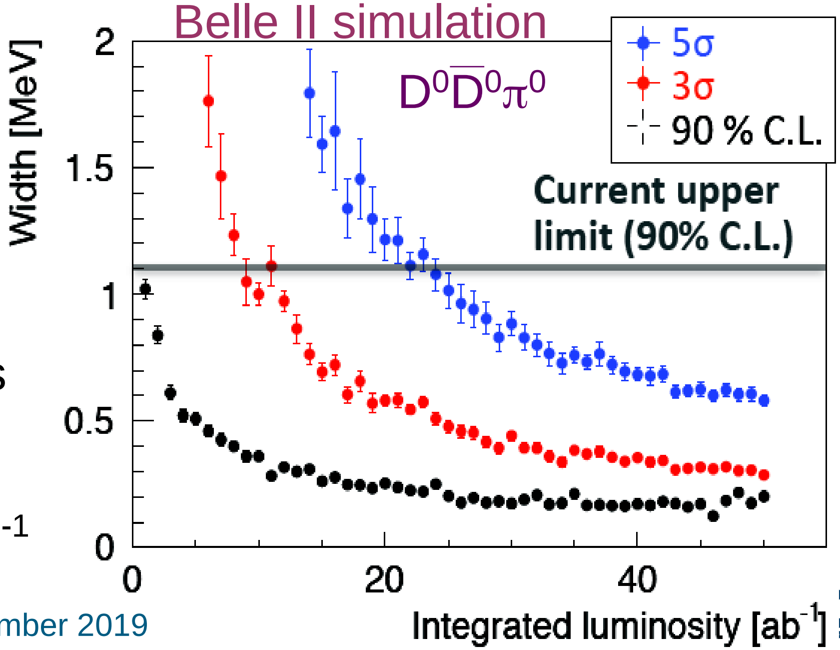
- Known upper limit: Γ < 1.2 MeV (estimated from X(3872)$\rightarrow J/\psi\pi^+\pi^-$), on full Belle data sample
- Very promising: X(3872) $\rightarrow D^0\overline{D}^{0*}$

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

- Due to very low Q value, the mass resolution is extremely good → expected great improvement in the width measurement with 50 ab^{-1}

Belle, PRD 84 (2011) 052004





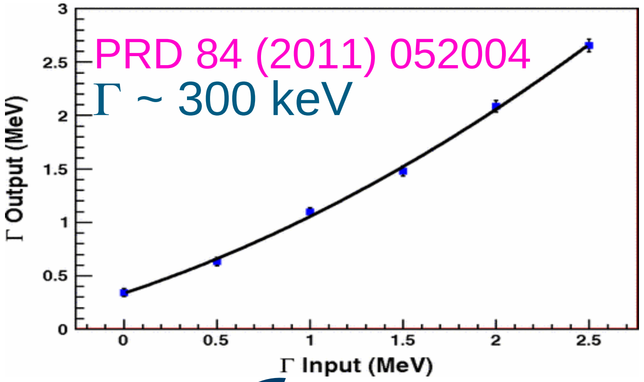
H. Hirata, Master thesis 2019

XYZ Expectations at Belle II

- Yield of X(3872)→J/ψπ⁺π⁻ in 2021 will be about Belle yield of ψ' → J/ψπ⁺π⁻
- Radiative decay X(3872)→J/ψγ: expected yield N≃350 in 2021
- The width of the X(3872) could be measured with a systematic error of
  ±0.11 MeV in radiaive X decay
  → monoenergetic photon provides 4-constraint fit (ΔE/E~2%)
  → systematic error on width may be ~110 keV
- Search for exotics at D^*D^* threshold (better slow pion detection at Belle II)
  slow pions reconstruction efficiency >60%(L. Koch, Master Thesis 2016)

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)	$B \to K^{\mp} Z(4430)$, $Z(4430) \to J/\psi\pi^{\pm}$	$\simeq 10200$

Expectation with 50ab^{-1} data at Belle II



Charmonium in ISR: Perspectives

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

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, <u>big advantage at Belle II</u>

Expectations on Z_b states at Belle II

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

Υ(6S) and Υ(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

Υ(6S) and Υ(5S): new exotics search

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

Υ(6S) and Υ(5S): scan

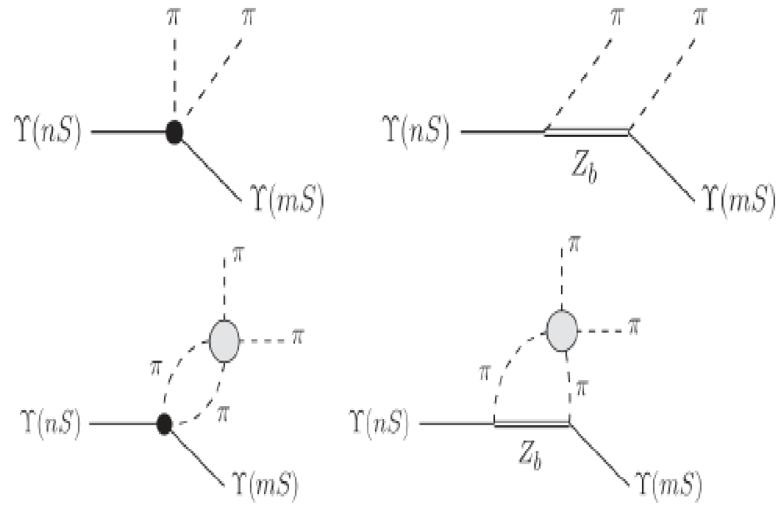
- Belle II goals:
  - Υ(6S) and Υ(5S) behave differently in $\pi\pi\Upsilon$ and $\pi\pi\eta$
    → hint of a non-*bb* nature of Υ(5S)?
  - investigate an extra resonance around 10.750 MeV/c^2

Settle the nature of Υ(5S)

Υ(3S): Opportunities at Belle II

- Exotic states contribute to the hadronic and radiative transitions from narrow quarkonia

  → complementary approach to the direct search from Υ(5S) and Υ(6S)



Υ(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

Υ(3S): charmonia in production

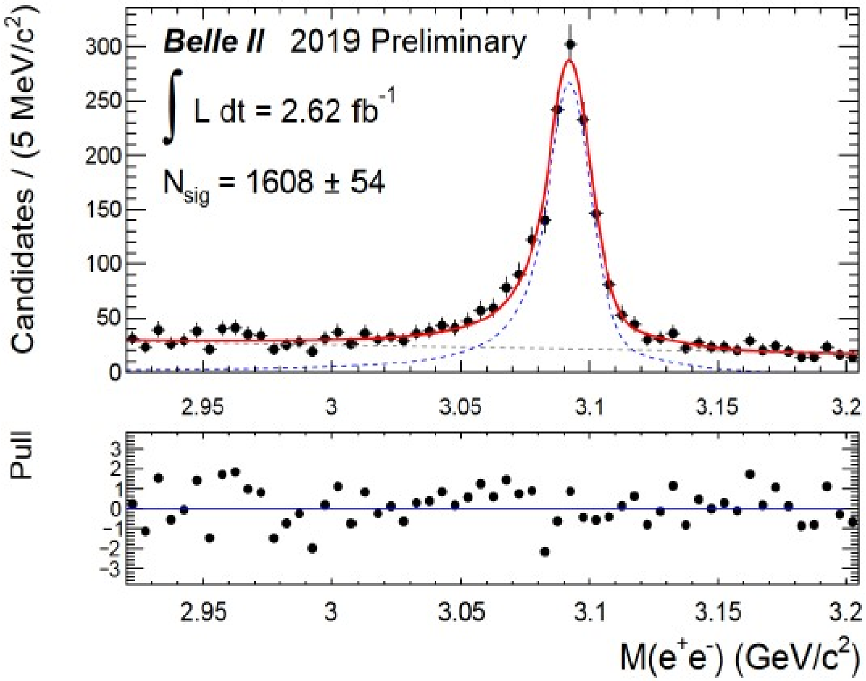
- Belle II goals with 300 fb^{-1}:
  - up to 5x sensitivity in inclusive production from Υ(3S)
  - up to 15x in double charmonium
  - inclusive rate of X(3872)
  - $D\bar{D}^*$ correlation in $\Upsilon(3S) \rightarrow D\bar{D}^*$ + hadron to test the nature of the X(3872)

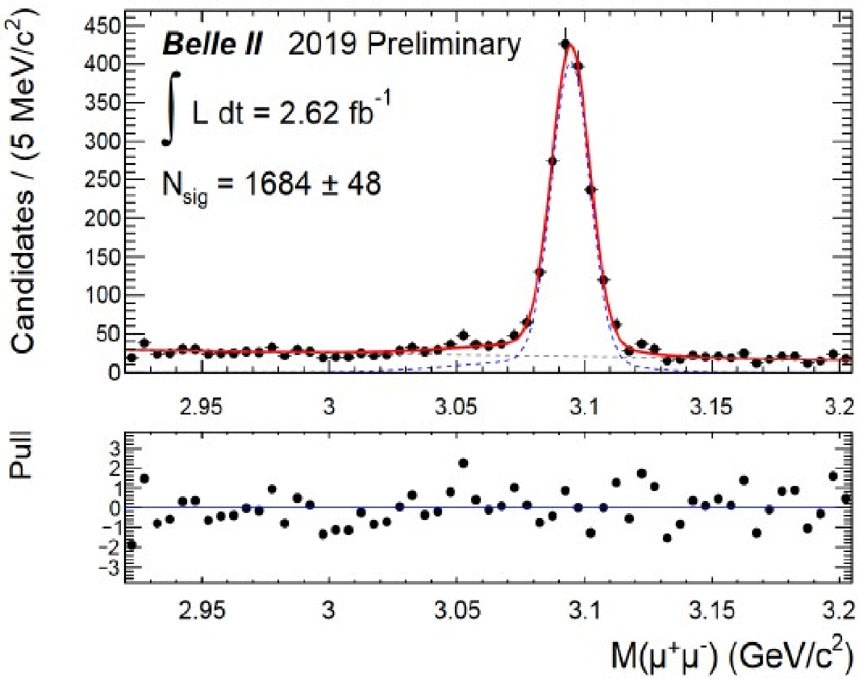
Υ(3S): rare χ_b decays

Υ(3S): deuteron production mechanism

“Re-discovery” with Phase 3 Data

J/ψ

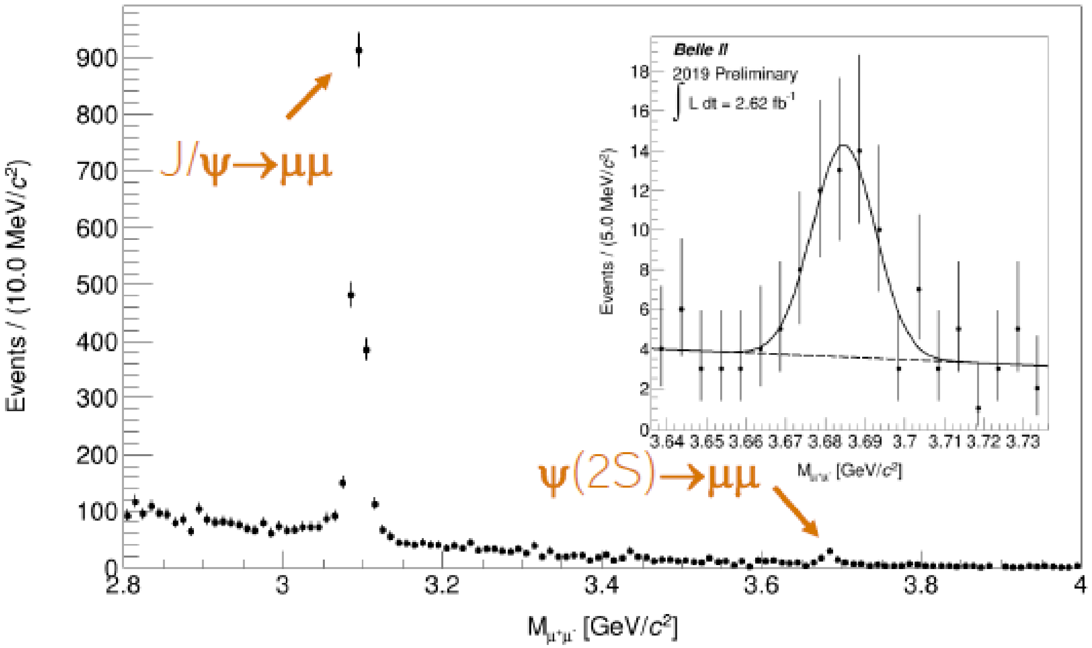


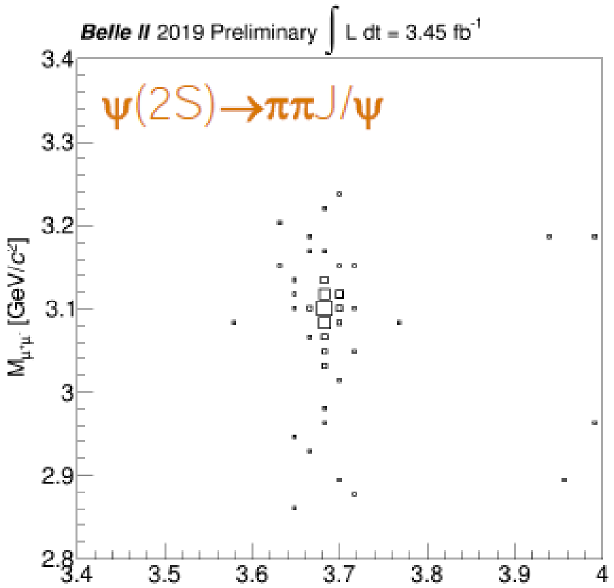


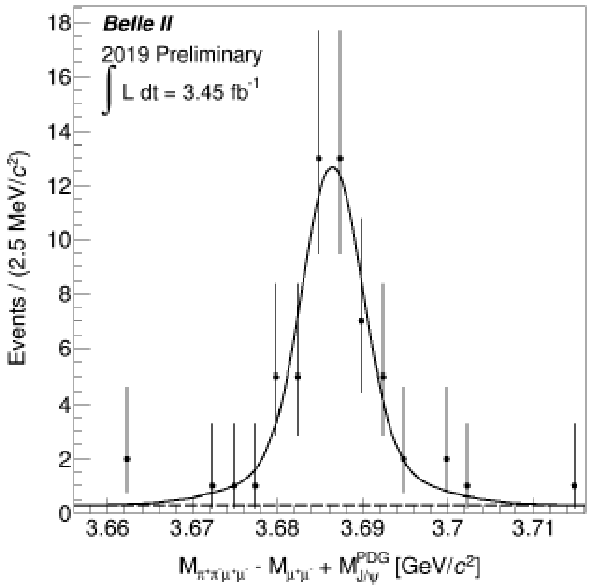
“Re-discovery” with Phase 3 Data

$\psi(2S)$

- Inclusive $\mu^+\mu^-$ search
- Isolate $\psi(2S) \to J/\psi\pi^+\pi^-$ from ISR production

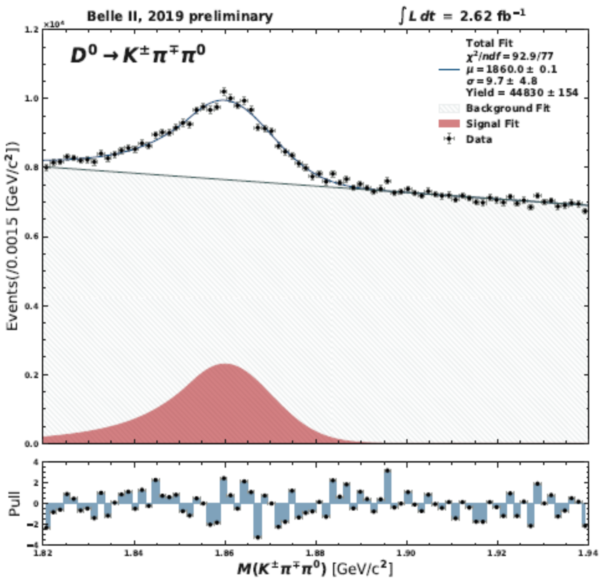


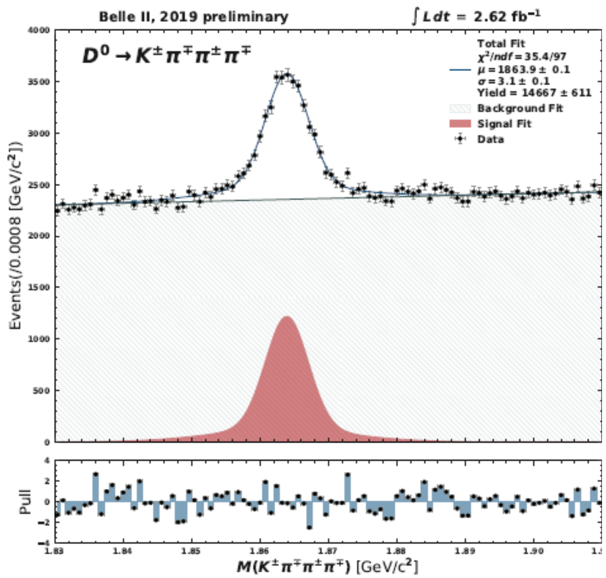


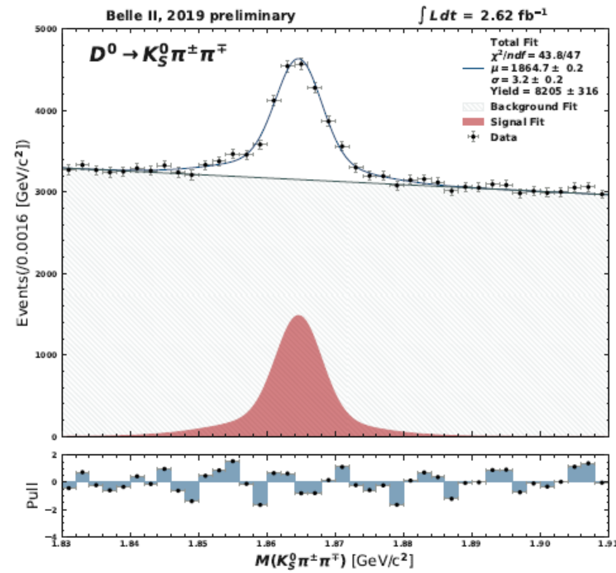


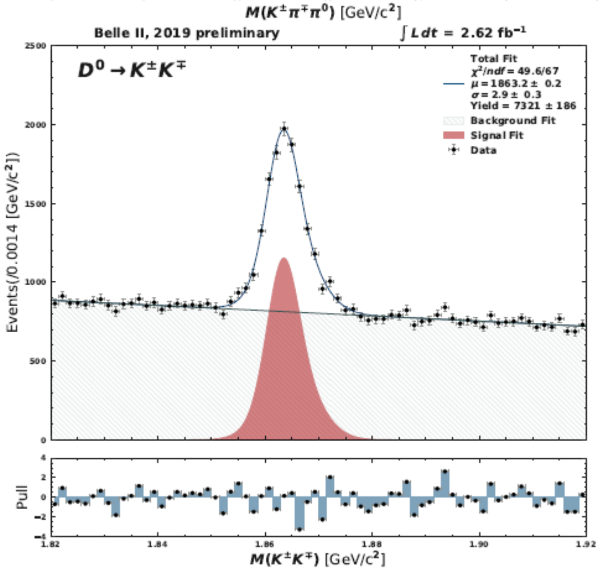
“Re-discovery” with Phase 3 Data

D^0 meson



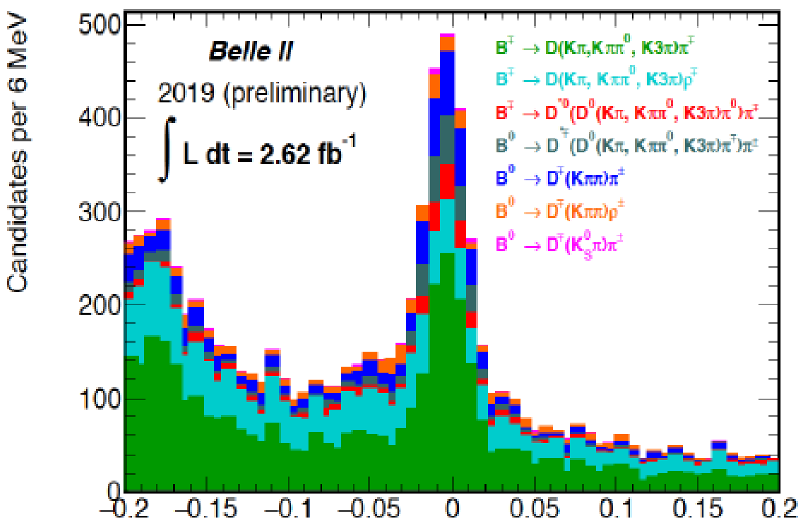


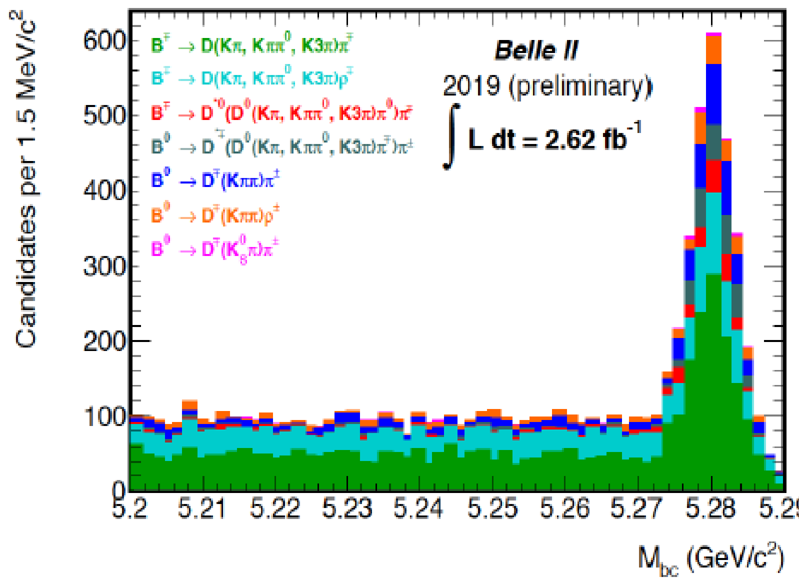




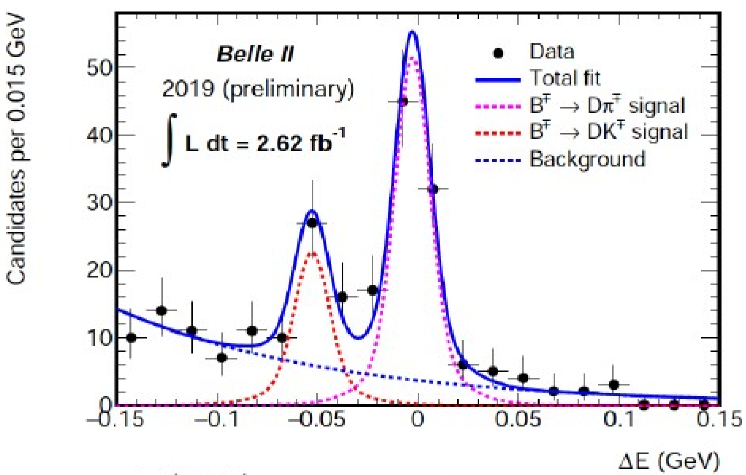
“Re-discovery” with Phase 3 Data

Fully hadronic B event reconstruction





$B^- \to DK^-$



N(D K) = 38±8, fit gives 6σ

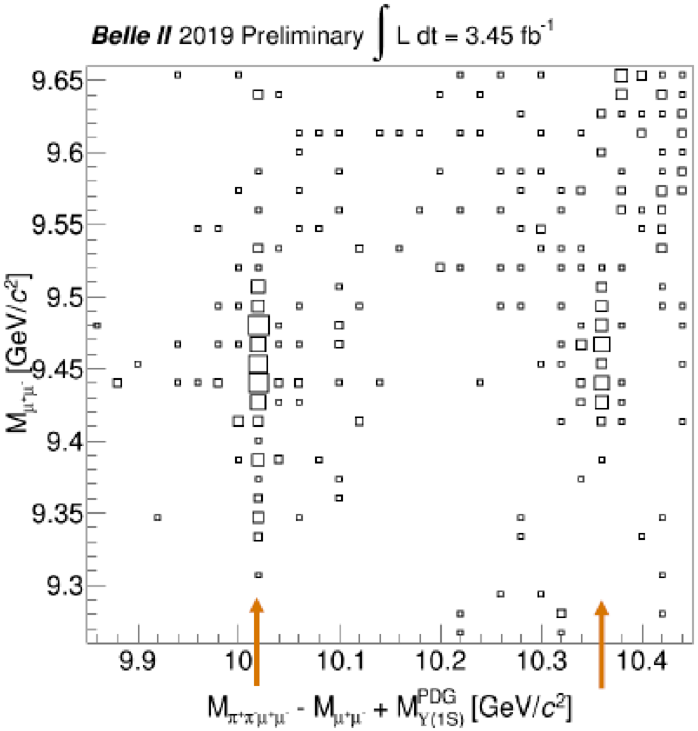
$$M_{bc} = \sqrt{(E_{cm}/2)^2 - p^2_{recon}}$$

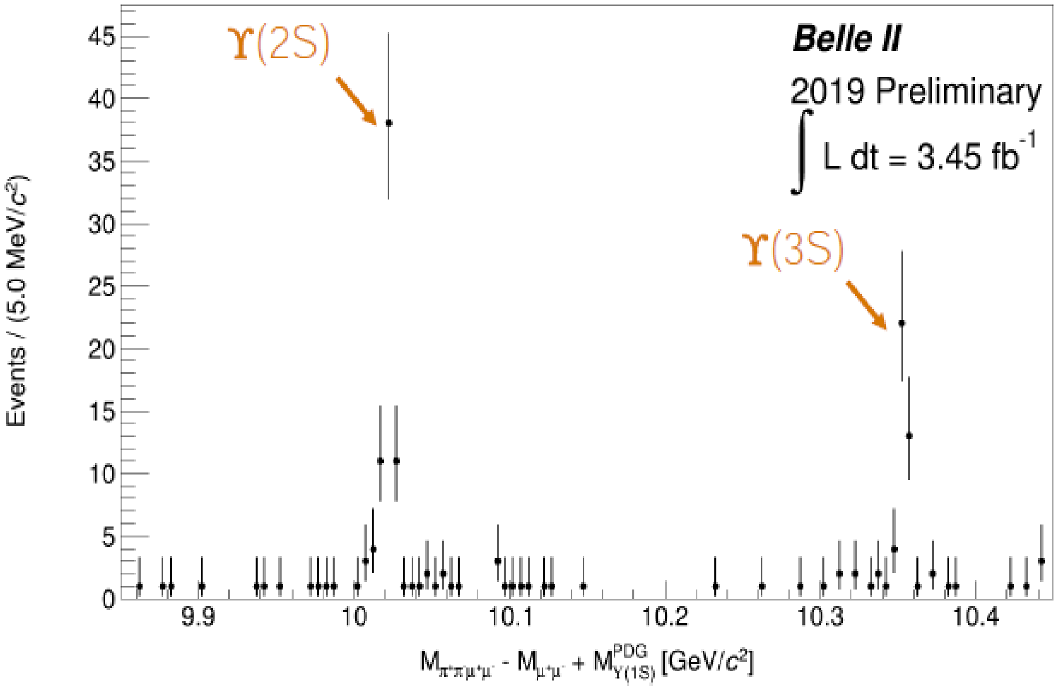
$$\Delta E = E_{cm}/2 - E_{recon}$$

"Re-discovery" with Phase 3 Data

ϒ(1S, 2S, 3S)

ISR process: $\Upsilon(2S,3S)\rightarrow\Upsilon(1S)\pi^+\pi^-$



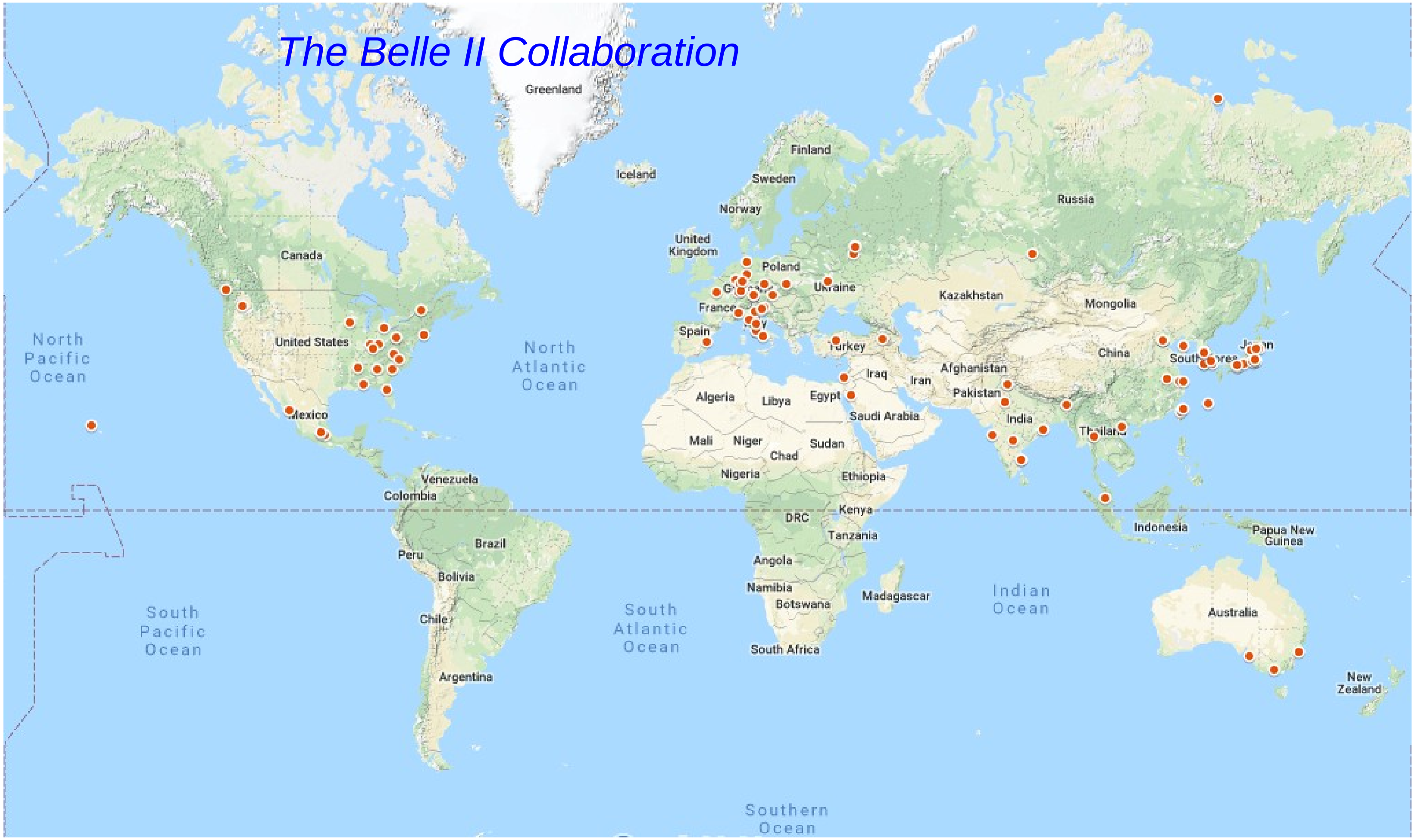


Summary

- 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: 8×10^{35} cm^{-2} s^{-1}.
- Improved tracking and PID in Belle II
- Phase 2 and 3 in Belle II completed!
- Expected by summer 2020: 200 fb^{-1}
- Expected 50 ab^{-1} integrated luminosity at Belle II in 7 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 $\Upsilon(6S)$ compared to Belle
  - good slow pion reconstruction to search for $D^*\overline{D}^{(*)}$ threshold exotic states

The Belle II Collaboration



Belle II

Thank you for your kind attention!

e.prencipe@fz-juelich.de

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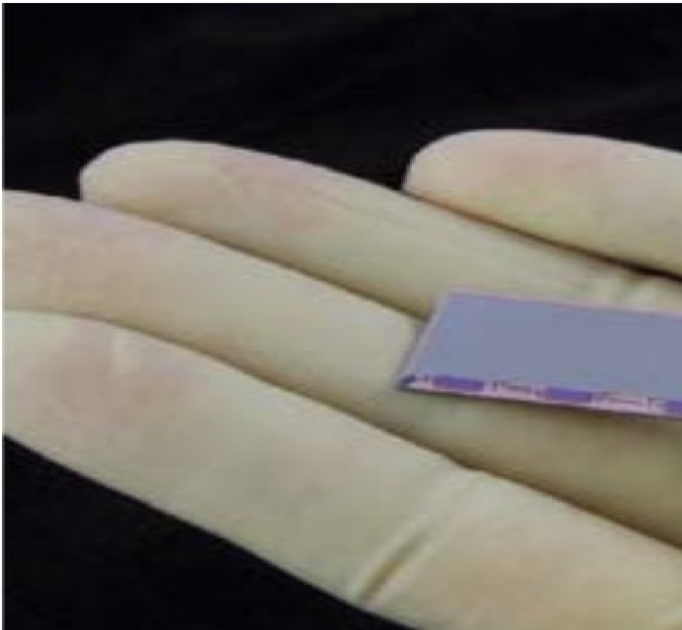
Backup slides

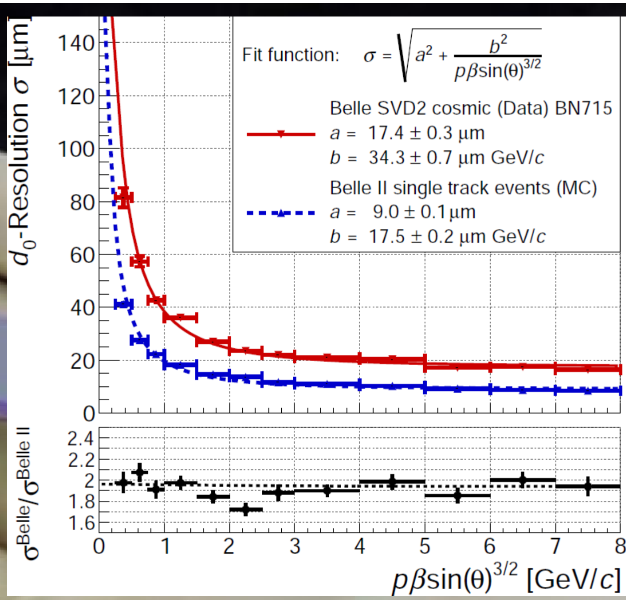
How can Belle II perform these challenging measurements?

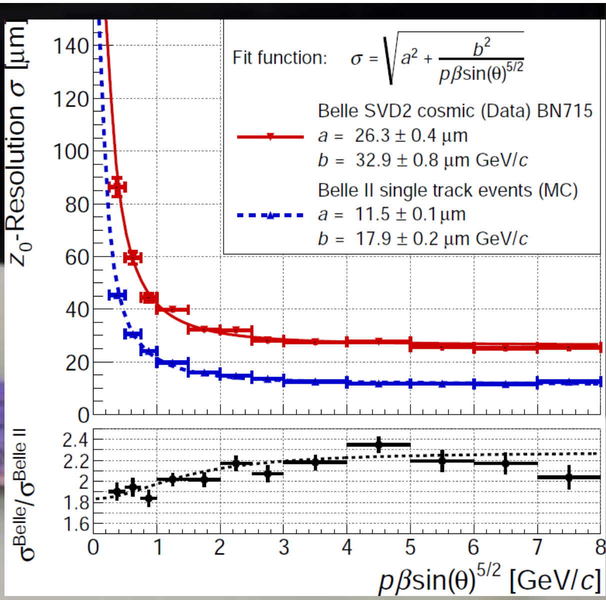
- most powerful e+e- collider in the world
- x40 more luminosity than Belle
- high vertex resolution
- excellent tracking perfomance
- improved slow pion detection

Vertex Pixel Detector (PXD)

VXD consists of 2 layers of DEPFET (Pixel Detector) and 4 layers of double-sided silicon microstrip sensors (Silicon Vertex Detector), assembled over carbon fiber ribs.







One of the 40 sensor modules which are being installed in the pixel-vertex detector

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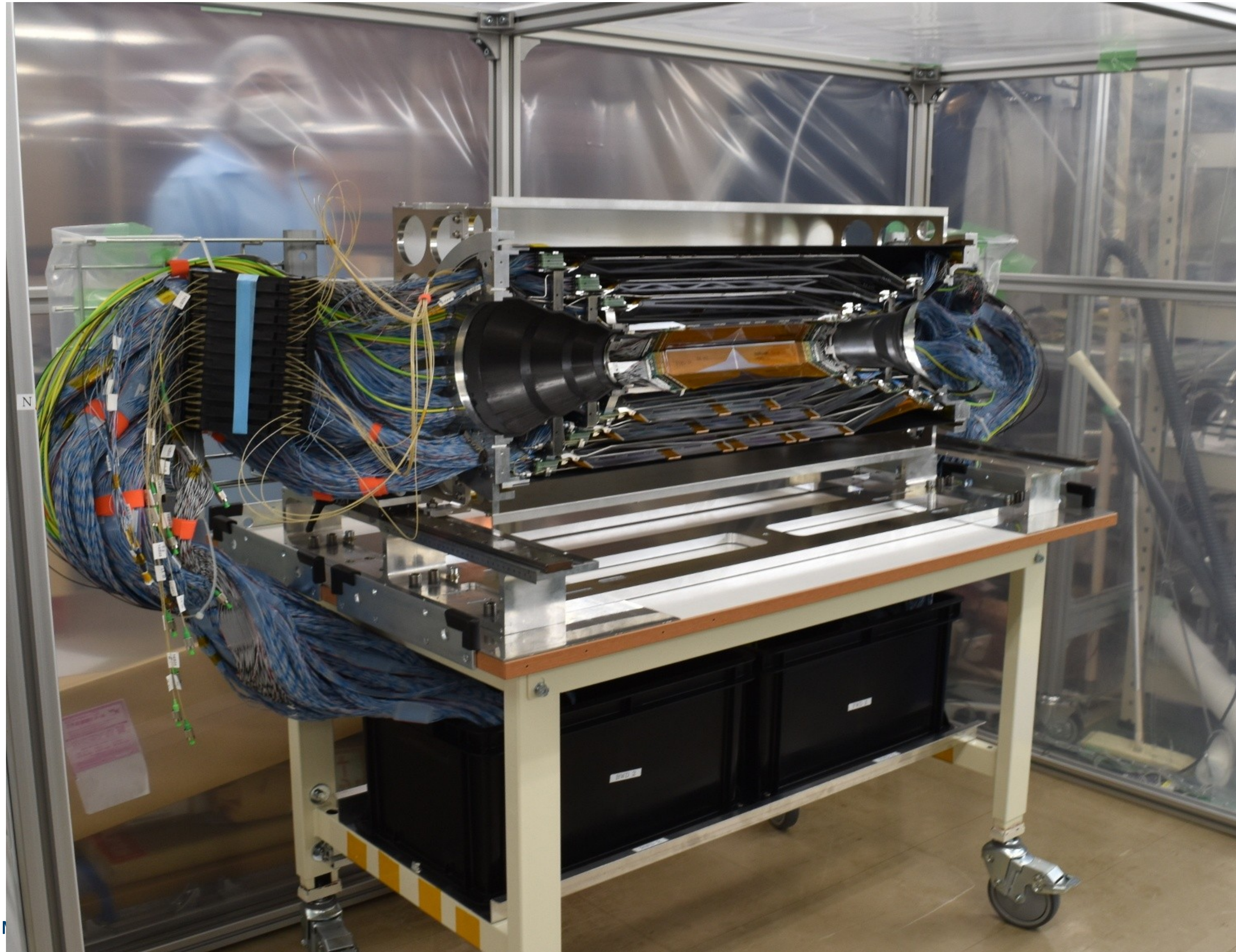
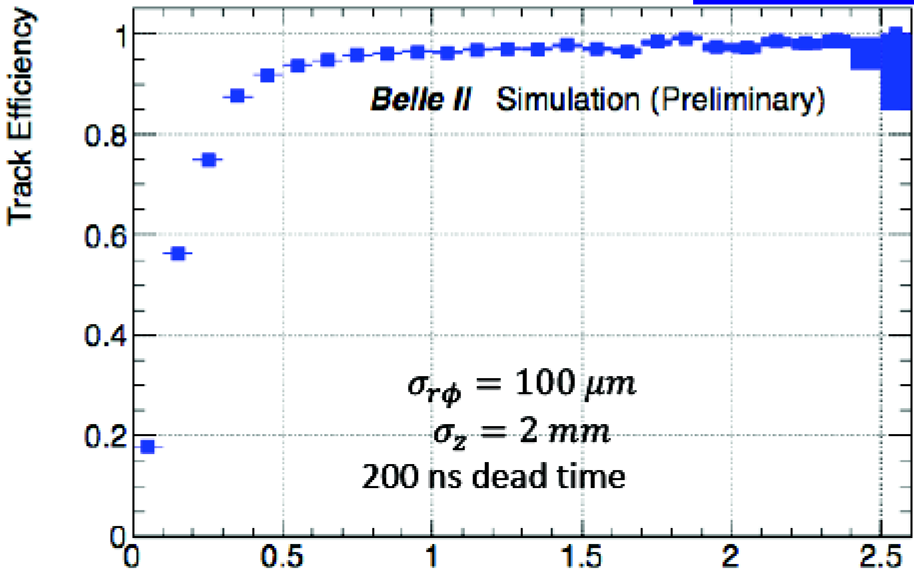
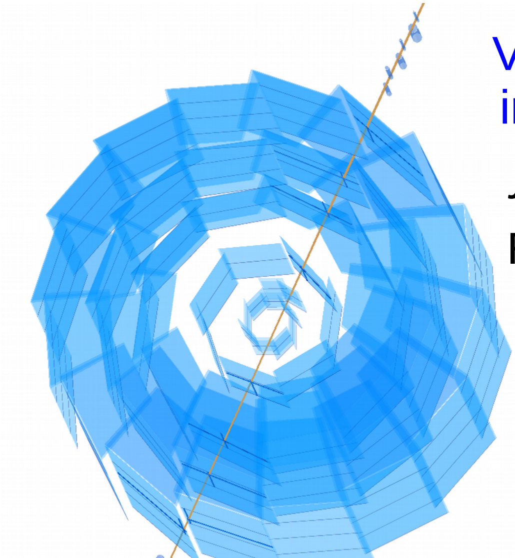

N

Central Drift Chamber (CDC)

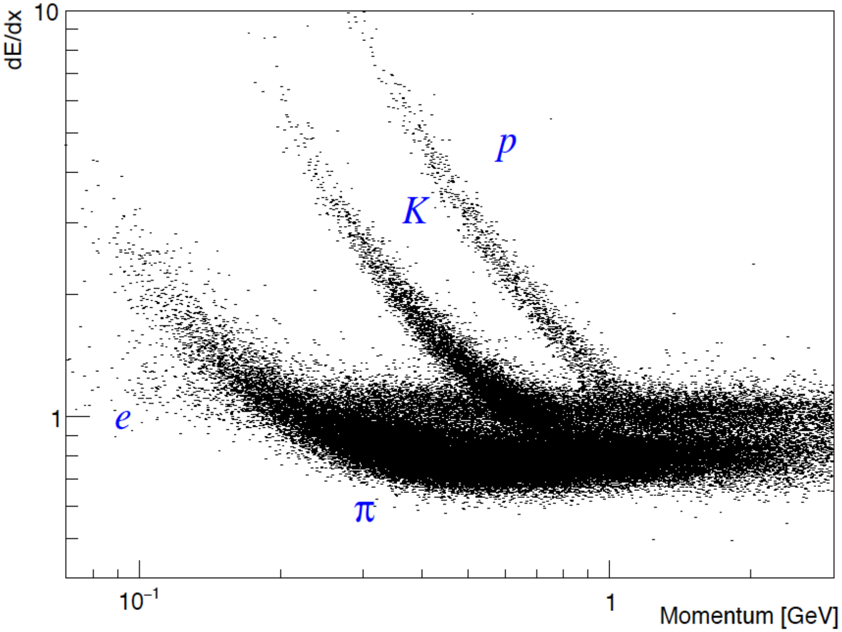




VXD + CDC hits
in EventDisplay

Jan 16, 2019:

First global SVD cosmic run



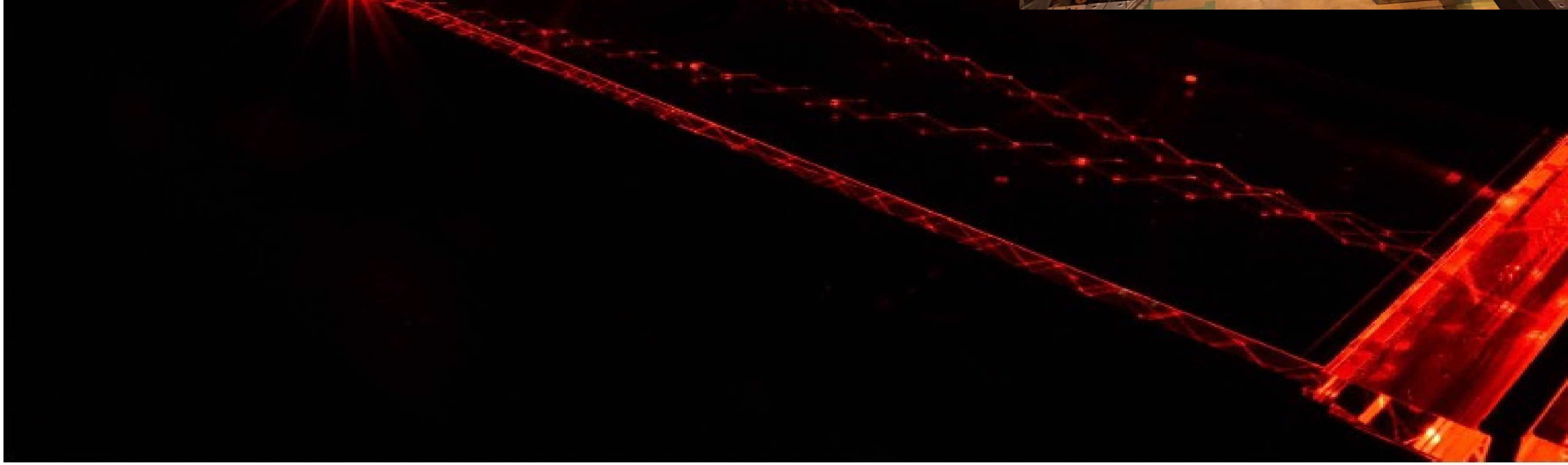
Cerenkov detector, laser in TOP module

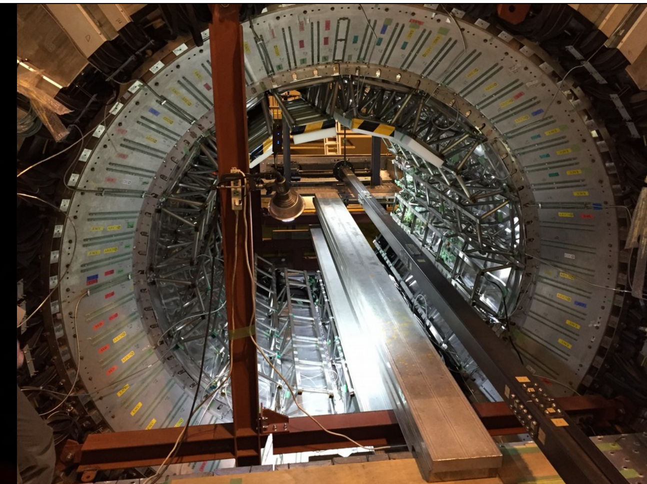
Particle Identification

(Time–of-propagation, t $\leq$ 50 ps)

Photo: K. Inami (Nagoya)

L~ 2.5m, 16 barrels

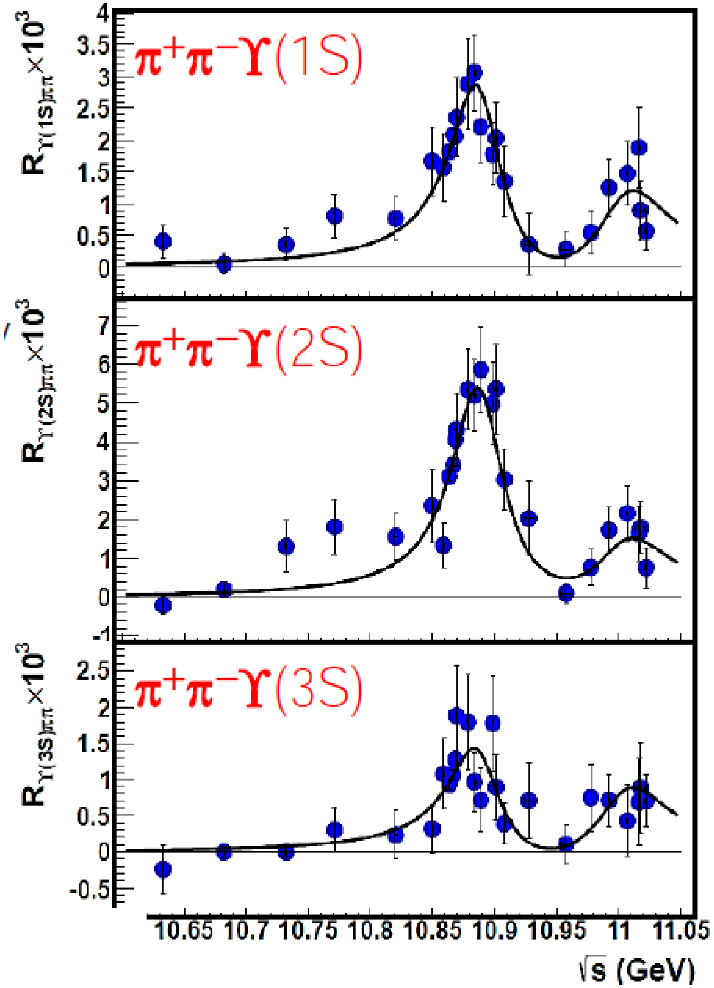


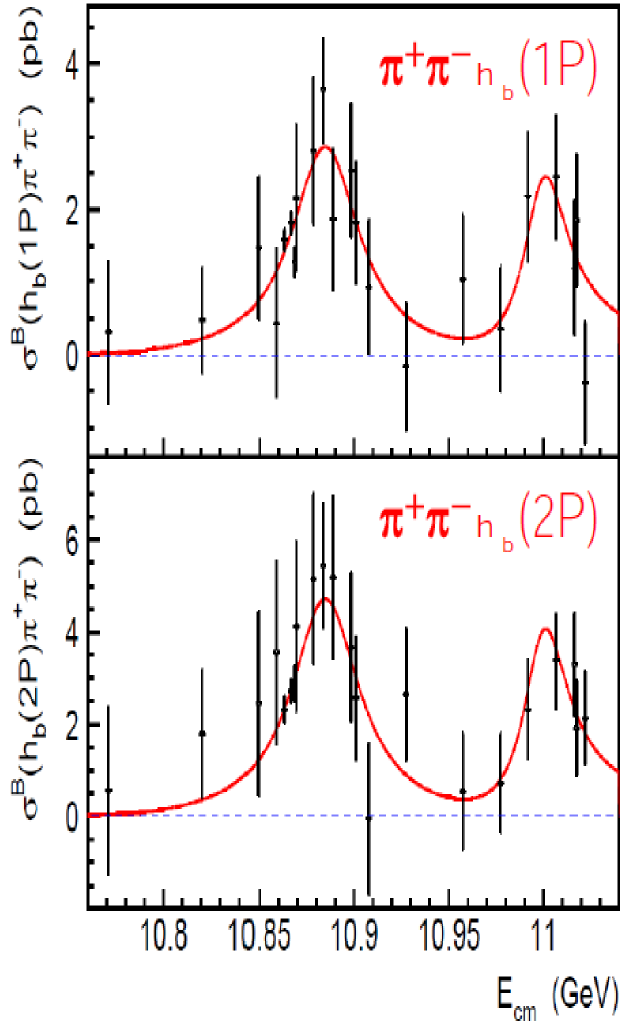


Main Achievements in Bottomonium at Belle

$e^+e^- \to \pi^+\pi^-\Upsilon(nS)$

$e^+e^- \to \pi^+\pi^- h_b(nP)$





fit to $|A_{5S}+e^{i\phi}A_{6S}|^2$

PRD 93, 011101(R) (2016)

PRL117, 142001 (2016)

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Main Achievements in Bottomonium at Belle

Z_b in Y(5S)→$\pi^+\pi^-\Upsilon$(nS)

Parameter	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$
$f_{Z_b^{\mp}(10610)\pi^{\pm}}$, %	$4.8 \pm 1.2^{+1.5}_{-0.3}$	$18.1 \pm 3.1^{+4.2}_{-0.3}$	$30.0 \pm 6.3^{+5.4}_{-7.1}$
$Z_b(10610)$ mass, MeV/c^2	$10608.5 \pm 3.4^{+3.7}_{-1.4}$	$10608.1 \pm 1.2^{+1.5}_{-0.2}$	$10607.4 \pm 1.5^{+0.8}_{-0.2}$
$Z_b(10610)$ width, MeV/c^2	$18.5 \pm 5.3^{+6.1}_{-2.3}$	$20.8 \pm 2.5^{+0.3}_{-2.1}$	$18.7 \pm 3.4^{+2.5}_{-1.3}$
$f_{Z_b^{\mp}(10650)\pi^{\pm}}$, %	$0.87 \pm 0.32^{+0.16}_{-0.12}$	$4.05 \pm 1.2^{+0.95}_{-0.15}$	$13.3 \pm 3.6^{+2.6}_{-1.4}$
$Z_b(10650)$ mass, MeV/c^2	$10656.7 \pm 5.0^{+1.1}_{-3.1}$	$10650.7 \pm 1.5^{+0.5}_{-0.2}$	$10651.2 \pm 1.0^{+0.4}_{-0.3}$
$Z_b(10650)$ width, MeV/c^2	$12.1^{+11.3+2.7}_{-4.8-0.6}$	$14.2 \pm 3.7^{+0.9}_{-0.4}$	$9.3 \pm 2.2^{+0.3}_{-0.5}$
ϕ_Z, degrees	$67 \pm 36^{+24}_{-52}$	$-10 \pm 13^{+34}_{-12}$	$-5 \pm 22^{+15}_{-33}$
$c_{Z_b(10650)}/c_{Z_b(10610)}$	$0.40 \pm 0.12^{+0.05}_{-0.11}$	$0.53 \pm 0.07^{+0.32}_{-0.11}$	$0.69 \pm 0.09^{+0.18}_{-0.07}$
$f_{\Upsilon(nS)f_2(1270)}$, %	$14.6 \pm 1.5^{+6.3}_{-0.7}$	$4.09 \pm 1.0^{+0.33}_{-1.0}$	–
$f_{\Upsilon(nS)(\pi^+\pi^-)_S}$, %	$86.5 \pm 3.2^{+3.3}_{-4.9}$	$101.0 \pm 4.2^{+6.5}_{-3.5}$	$44.0 \pm 6.2^{+1.8}_{-4.3}$
$f_{\Upsilon(nS)f_0(980)}$, %	$6.9 \pm 1.6^{+0.8}_{-2.8}$	–	–

$$\sigma_{Z_b^{\pm}(10610)\pi^{\mp}} \times \mathcal{B}_{\Upsilon(1S)\pi^{\mp}} = 109 \pm 27^{+35}_{-10} \text{ fb}$$

$$\sigma_{Z_b^{\pm}(10610)\pi^{\mp}} \times \mathcal{B}_{\Upsilon(2S)\pi^{\mp}} = 737 \pm 126^{+188}_{-85} \text{ fb}$$

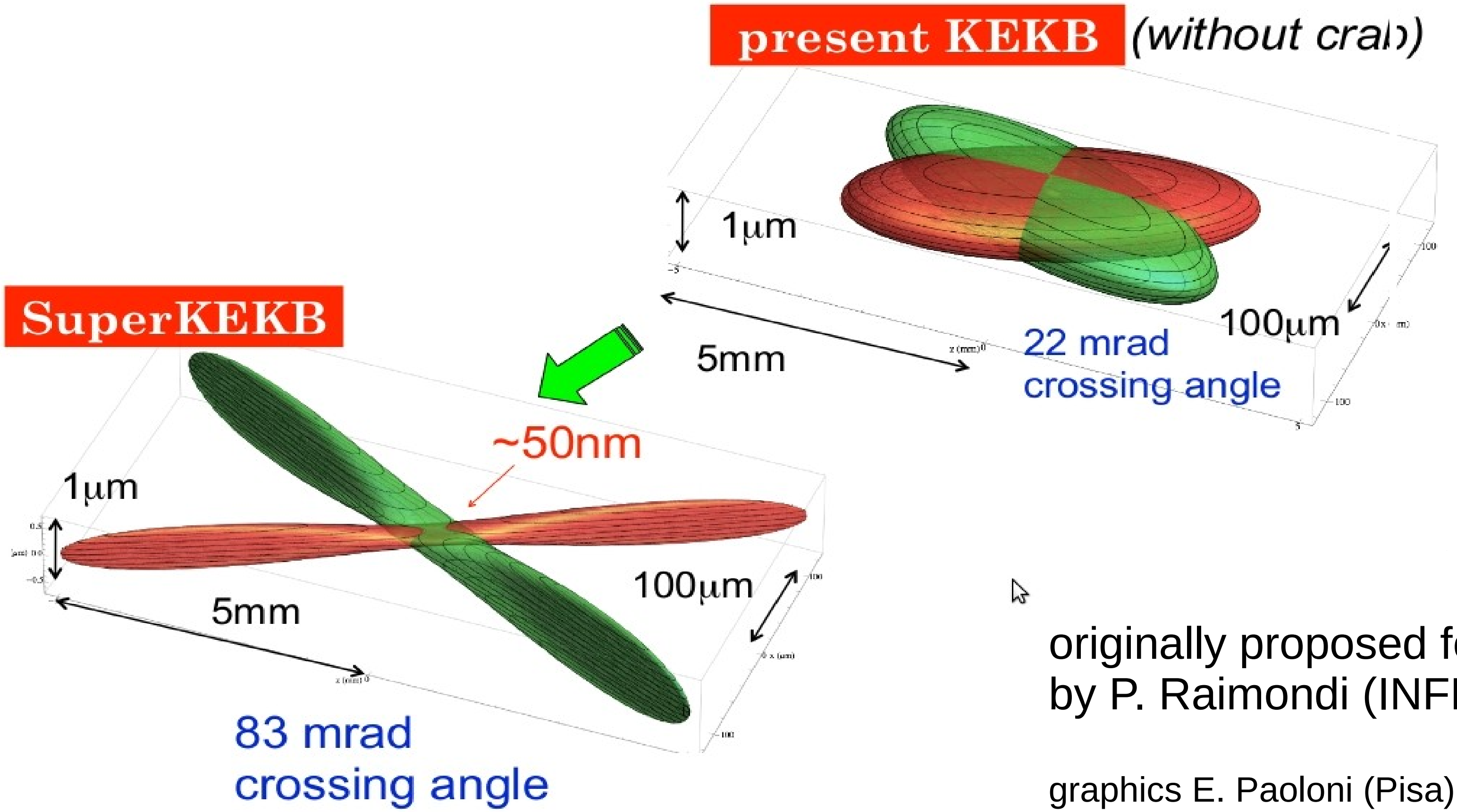
$$\sigma_{Z_b^{\pm}(10610)\pi^{\mp}} \times \mathcal{B}_{\Upsilon(3S)\pi^{\mp}} = 438 \pm 92^{+92}_{-114} \text{ fb}$$

$$\sigma_{Z_b^{\pm}(10650)\pi^{\mp}} \times \mathcal{B}_{\Upsilon(1S)\pi^{\mp}} = 20 \pm 7^{+4}_{-3} \text{ fb}$$

$$\sigma_{Z_b^{\pm}(10650)\pi^{\mp}} \times \mathcal{B}_{\Upsilon(2S)\pi^{\mp}} = 165 \pm 49^{+43}_{-20} \text{ fb}$$

$$\sigma_{Z_b^{\pm}(10650)\pi^{\mp}} \times \mathcal{B}_{\Upsilon(3S)\pi^{\mp}} = 194 \pm 53^{+43}_{-25} \text{ fb}$$

Nano-Beam Scheme



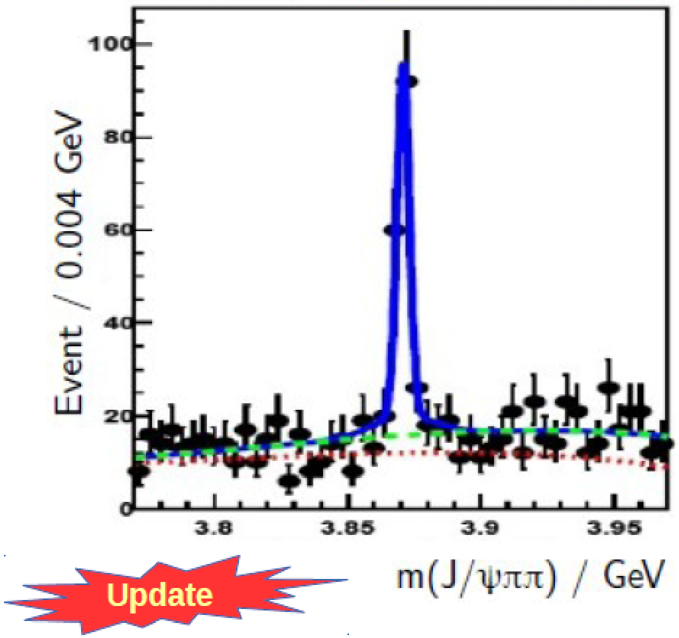
originally proposed for SuperB
by P. Raimondi (INFN)

graphics E. Paoloni (Pisa)

X(3872): ACHIEVEMENTS AND INTERPRETATION AT BELLE

~150 events in 10 years

Belle, Phys Rev D84(2011)052004



$M_{X(3872)}$=(3871.85±0.27(stat)±0.19(syst)) MeV
$B(B^+ \to K^+ X(3872)) \times B(X(3872) \to \pi^+\pi^- J/\psi)$=
(8.63±0.82(stat)±0.52(syst))×10^{-6}
$B(B0 \to K^0 X(3872))/B(B+ \to K^+ X(3872))$=
0.50±0.14(stat)±0.04(syst)
$\Delta M_{X[B0\text{-}B+]}$=(−0.71±0.96(stat)±0.19(syst)) MeV.

- X(3872) observed in different decay modes, and different production mechanisms
- At $D\bar{D}^*$ threshold E_B = 160±330 keV, but no threshold effect
- $\Gamma \leq 1.2$ MeV → too narrow! Bugg, JPHG35 (2008) 075005
- The $D\bar{D}^*$ decay of the X(3872) is dominant ~ x10 than other X(3872) decay modes → a molecule?
- Isospin-violating decay: $B(X(3872) \to J/\psi\rho)$, ~$10^2$ too large

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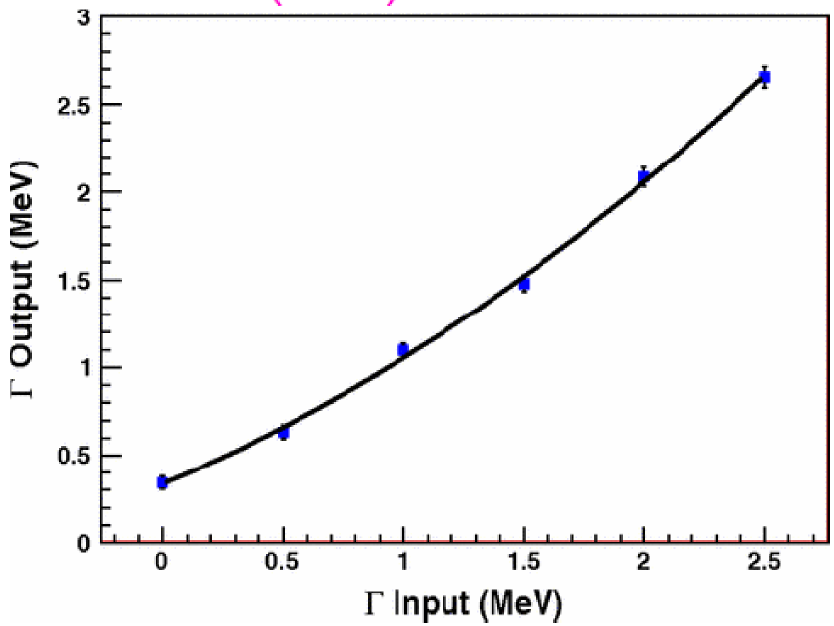
X(3872): ACHIEVEMENTS AND INTERPRETATION AT BELLE

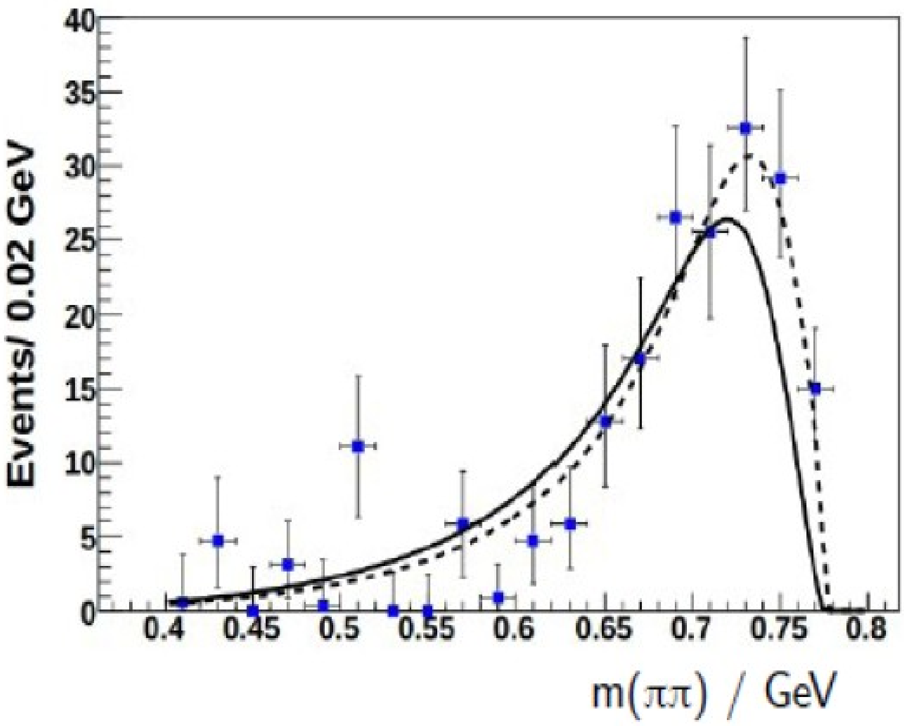
- Correlation function from MC
  Γ(output) = f(Γ(input))
- 3-dim fits validated with ψ' width
  $\Gamma_{\psi'}$=0.52±0.11 MeV
  (PDG: 0.304±0.009 MeV)
  $\rightarrow$ bias 0.23±0.11 MeV
- procedure for upper limit:
  width in 3-dim fit fixed
  n_{signal} and n_{BG} floating
  $\rightarrow$ calculate likelihood
- $\Gamma_{X(3872)}$ < 0.95 MeV + bias

PRD 84 (2011) 052004



Reference channel: B $\rightarrow \psi(2s)\pi^+\pi^-$

X(3872): ACHIEVEMENTS AND INTERPRETATION AT BELLE



- Isospin-violating decay:

B(X(3872)→ J/ψρ), factor 10^2 too large

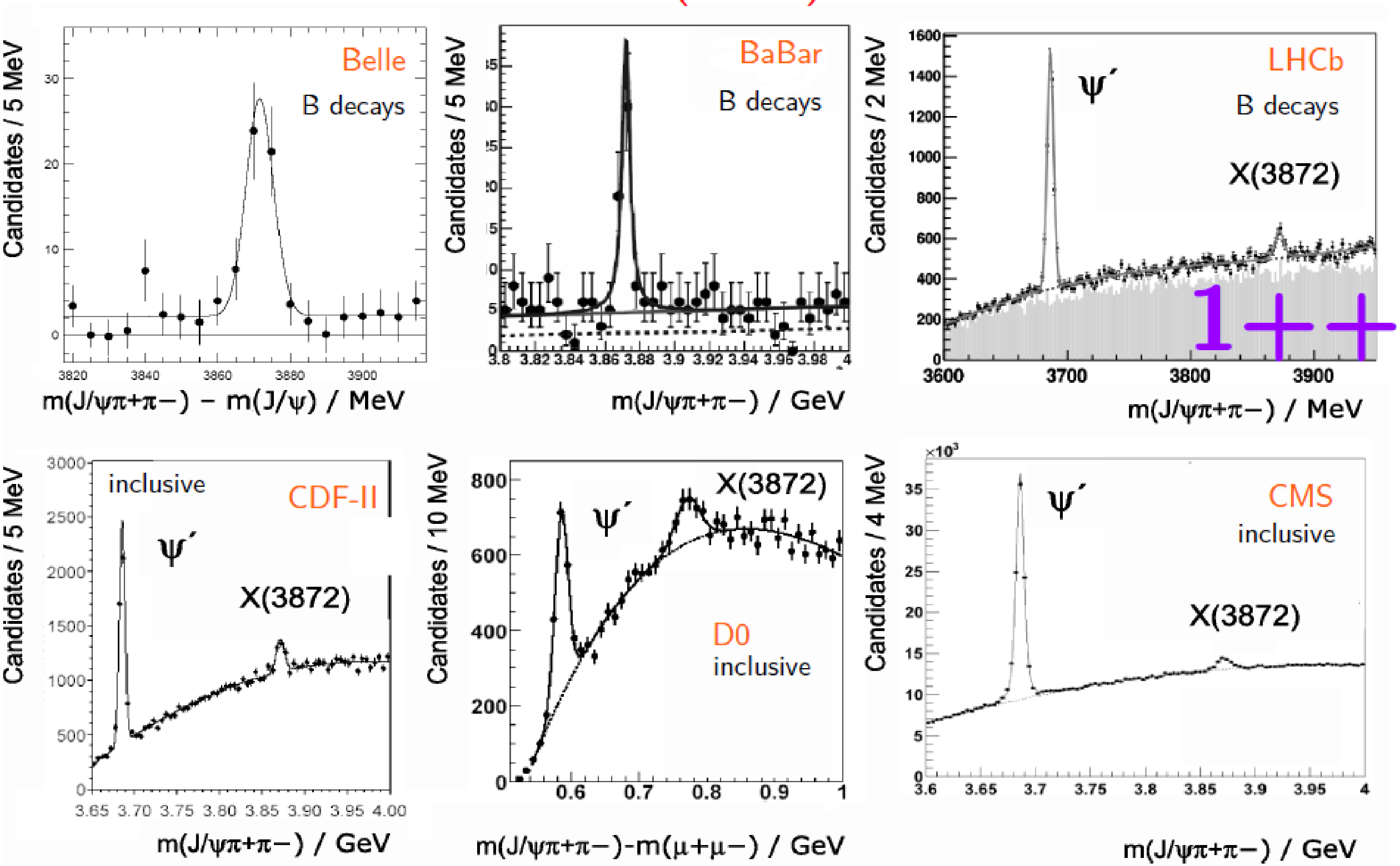
$J^{PC} = 1^{++}$, predicted nearby χ_{c1}'

Barnes et al, PRD72 (2005) 054026

- Mass ⩾50 MeV higher
- Width ⩾100 larger

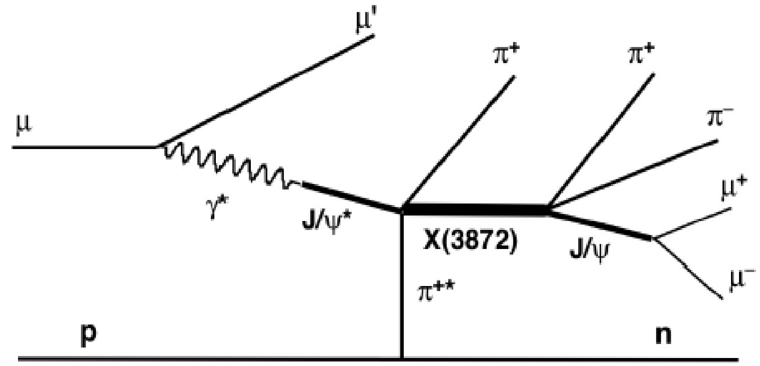
What can be done better to disclose the nature of the X(3872)?

X(3872)



Belle
B decays
Candidates / 5 MeV
m(J/ψπ+π−) – m(J/ψ) / MeV
BaBar
B decays
Candidates / 5 MeV
m(J/ψπ+π−) / GeV
LHCb
B decays
ψ´
X(3872)
1++
Candidates / 2 MeV
m(J/ψπ+π−) / MeV
inclusive
CDF-II
ψ´
X(3872)
Candidates / 5 MeV
m(J/ψπ+π−) / GeV
X(3872)
ψ´
D0
inclusive
Candidates / 10 MeV
m(J/ψπ+π−)-m(μ+μ−) / GeV
CMS
inclusive
ψ´
X(3872)
Candidates / 4 MeV
m(J/ψπ+π−) / GeV

Photoproduction of X(3872)

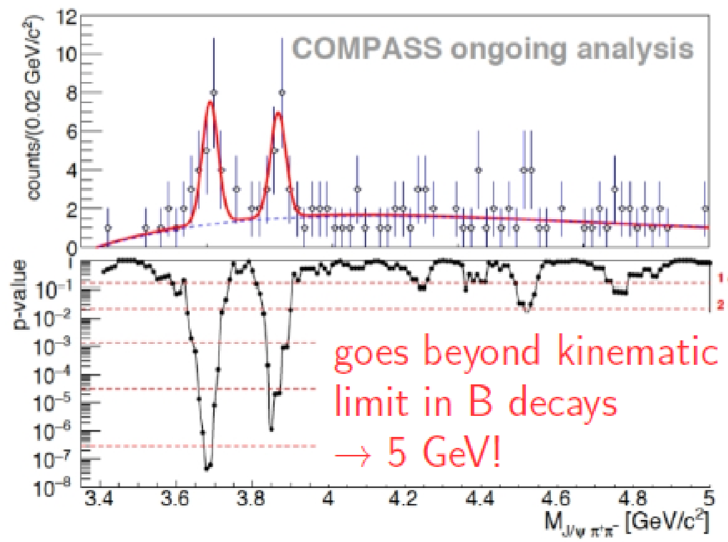


Muon data 2003-2010

$N_{\psi(2S)} = 16.1 \pm 5.2$

$N_{X(3872)} = 13.9 \pm 4.9$

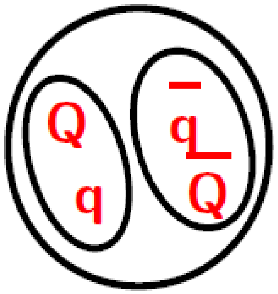
$\sigma_M = 20.6 \pm 6.1$ MeV



COMPASS, arXiv:1707.01796 [hep-ex]

Is the X(3872) exotic ?

TETRAQUARK

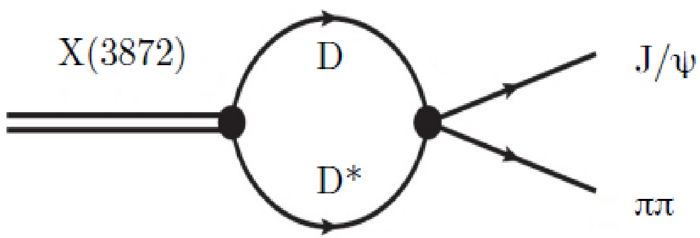


$[qQ]_8[\overline{qQ}]_8$

Diquarks
are colored

Maiani, Riquer, Piccinini, Polosa, Burns;
Ebert, Faustov, Galkin; Chiu, Hsieh;
Ali, Hambrock, Wang

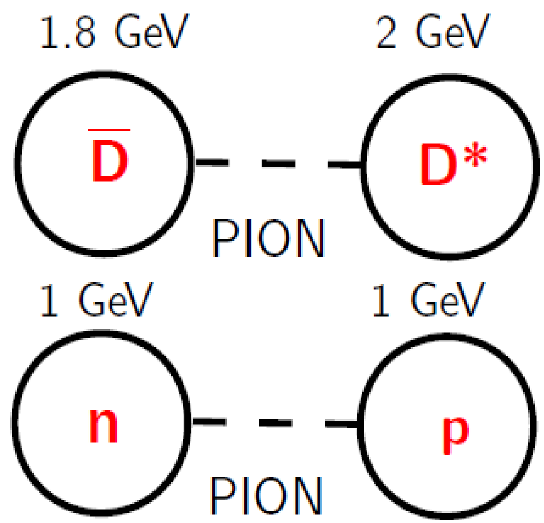
THRESHOLD CUSP



Bugg; Swanson

MOLECULE

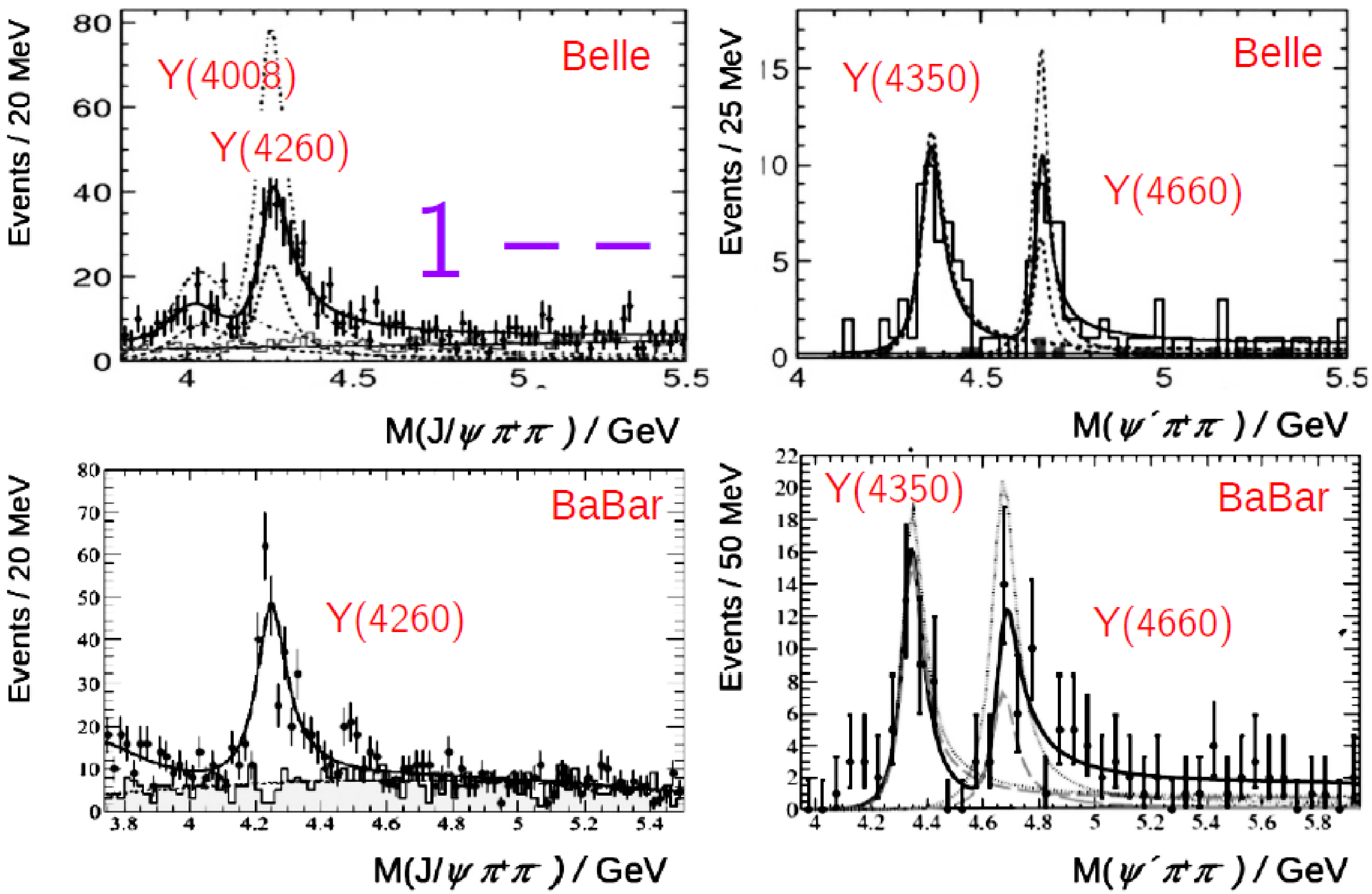
Intriguing Analogon



Tornqvist; Swanson; Braaten, Kusonoki,
Wong; Voloshin; Close, Page
Guo, Hanhart, Meissner

courtesy of J.S. Lange, HIRSCHEGG2018

Y STATES



Belle
Y(4008)
Y(4260)
1 – –
Events / 20 MeV
M(J/ψ π⁺π⁻) / GeV
Belle
Y(4350)
Y(4660)
Events / 25 MeV
M(ψ′ π⁺π⁻) / GeV
BaBar
Y(4260)
Events / 20 MeV
M(J/ψ π⁺π⁻) / GeV
BaBar
Y(4350)
Y(4660)
Events / 50 MeV
M(ψ′ π⁺π⁻) / GeV

Cornell–Potential

Eichten, Gottfried, et al. PRD 17(1978)3090
Barnes, Godfrey, Swanson, PRD 72(2005)054026

- Coulomb-Potential
  + Confinement-Term

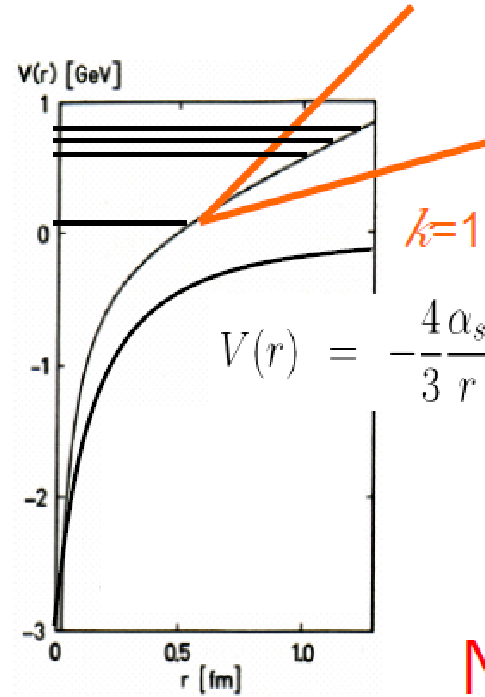
$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \boxed{kr}$$

spin-spin $$+\frac{32\pi\alpha_s}{9m_c^2}\delta_r \vec{S}_c\vec{S}_{\bar{c}}$$

spin-orbit $$+\frac{1}{m_c^2}\left(\frac{2\alpha_s}{r^3} - \frac{k}{2r}\right)\vec{L}\vec{S}$$

tensor $$+\frac{1}{m_c^2}\frac{4\alpha_s}{r^3}\left(\frac{3\vec{S}_c\vec{r}\cdot\vec{S}_{\bar{c}}\vec{r}}{r^2} - \vec{S}_c\vec{S}_{\bar{c}}\right)$$

k=0.5 GeV/fm



k=1.5 GeV/fm

- solve Schrödinger equation
  (quark mass heavy →\on-relativistic)
  →states

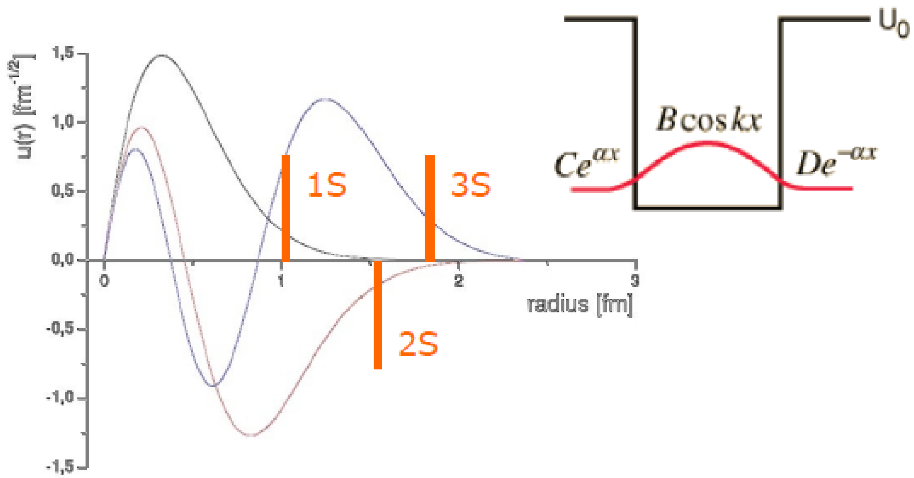
$$\Psi(r,\theta,\phi) = R_{nl}(r)Y_{lm}(\theta,\phi)$$

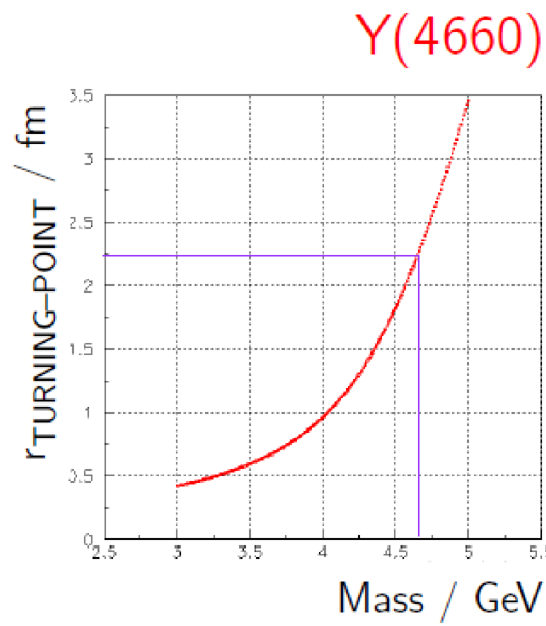
$$\left[-\frac{1}{m_q}\left(\frac{\partial^2}{\partial r^2} + \frac{2}{r}\frac{\partial}{\partial r} + \frac{l(l+1)}{m_q r^2} + V(r)\right)\right]R_{nl}(r) = E_{nl}R_{nl}(r)$$

Notation
$n^{2S+1}L_J$
J^{PC}

Cornell potential:
Wronski-Determinant must be zero at turning point

$$r_{\text{turning point}} = \frac{E-2m}{2\sigma} + \sqrt{\frac{4m^2-4mE+E^2}{4\sigma^2} + \frac{4\alpha_s}{3\sigma}}$$



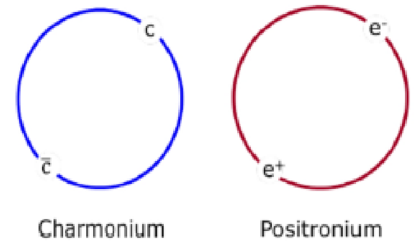


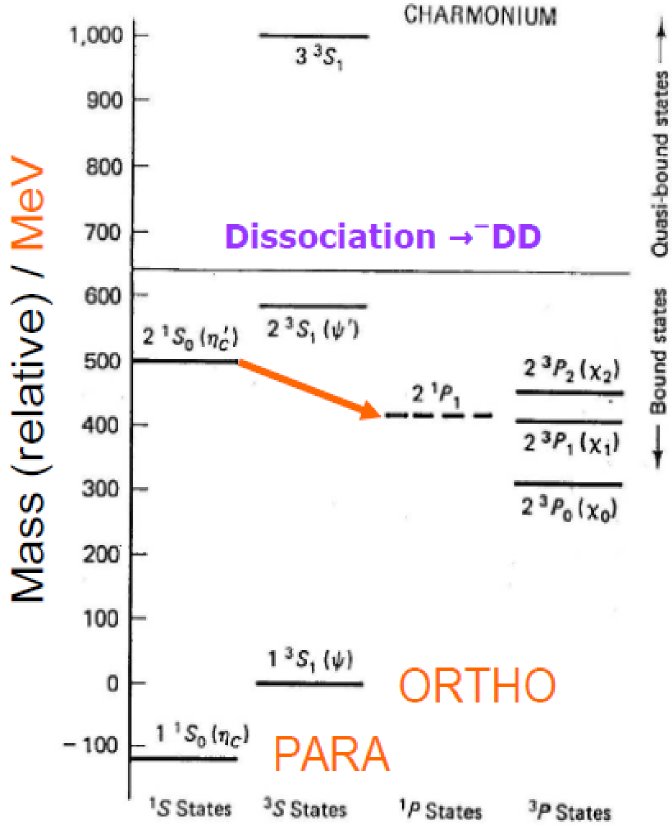
- m=4.660 GeV → turning point of wave function is 2.2 fm!
- large fraction of wave function in string breaking regime r>1.4 fm

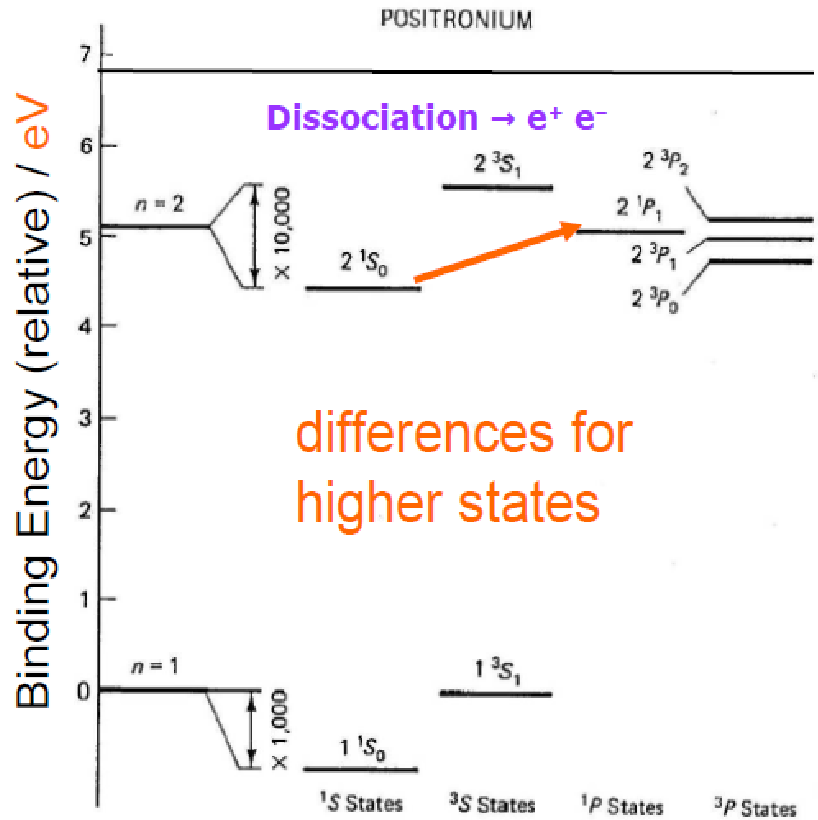
courtesy of J.S. Lange, HIRSCHEGG2018

Charmonium vs. Positronium

Decays to light quarks suppressed
→ narrow widths





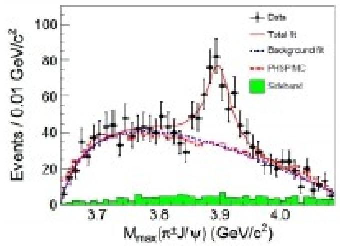


courtesy of J.S. Lange, HIRSCHEGG2018

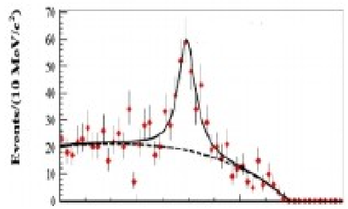
Landiao LIU, QWG 2016

Z STATES AT BESIII

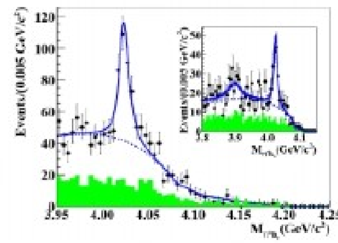
$D\bar{D}^*$ threshold | $D^*\bar{D}^*$ threshold



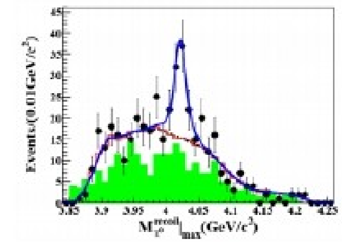
$e^+e^- \to \pi^+ \pi^- J/\Psi$



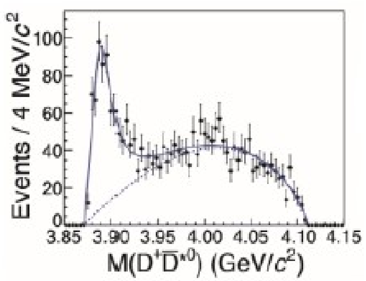
$e^+e^- \to \pi^0 \pi^0 J/\Psi$



$e^+e^- \to \pi^+ \pi^- h_c$

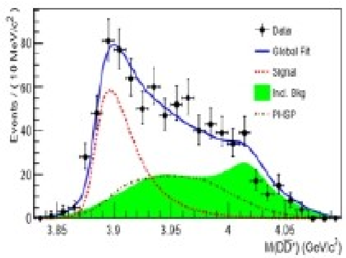


$e^+e^- \to \pi^0 \pi^0 h_c$



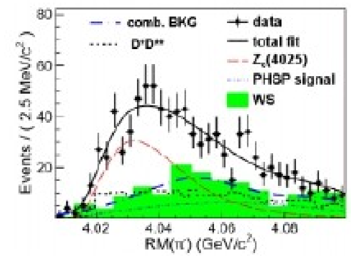
$e^+e^- \to \pi^+ (D\bar{D}^*)^-$

charged



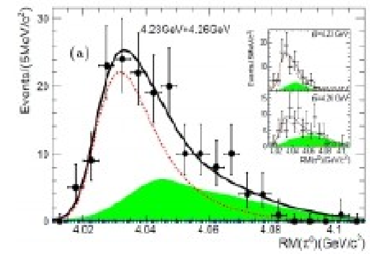
$e^+e^- \to \pi^0 (D\bar{D}^*)^0$

neutral



$e^+e^- \to \pi^+ (D^*\bar{D}^*)^-$

charged



$e^+e^- \to \pi^0 (D^*\bar{D}^*)^0$

neutral

Recent hot topic: neutral partners $\to$ isospin triplets

All of them 1+, whereever tested.

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Z states and „confinement“ ?

All measured Z_c^+ masses are above $D^{(*)}\overline{D}^{(*)}$ thresholds

State	m (MeV)	Threshold	Δm (MeV)
$Z_c(3900)$	$3899.0\pm3.6\pm4.9$	$D^+\overline{D}^{0*}$	$+22.4$
$Z_c(3900)$	$3899.0\pm3.6\pm4.9$	$D^0\overline{D}^{+*}$	$+23.9$
$Z_c(3900)$	$3894.5\pm6.6\pm4.5$	$D^+\overline{D}^{0*}$	$+17.9$
$Z_c(3900)$	$3894.5\pm6.6\pm4.5$	$D^0\overline{D}^{+*}$	$+19.4$
$Z_c(3900)$	$3885\pm5\pm1$	$D^+\overline{D}^{0*}$	$+8.4$
$Z_c(3900)$	$3885\pm5\pm1$ MeV	$D^0\overline{D}^{+*}$	$+9.9$
$Z_c(3885)$	$3883.9\pm1.5\pm4.2$	$D^+\overline{D}^{0*}$	$+7.4$
$Z_c(3885)$	$3883.9\pm1.5\pm4.2$	$D^0\overline{D}^{+*}$	$+8.8$
$Z_c(4020)$	$4022.9\pm0.8\pm2.7$	$D^{0*}\overline{D}^{\pm*}$	$+5.6$
$Z_c(4025)$	$4026.3\pm2.6\pm3.7$	$D^{0*}\overline{D}^{\pm*}$	$+9.0$
$Z_c(4032)^+$	$\simeq 4032.1\pm2.4$	$D^{0*}\overline{D}^{\pm*}$	$+15.0$

	possible?
threshold CUSP	no (must be @ threshold)
tetraquark	yes (spin–spin forces)
molecules	no, if bound state (pole below threshold, E_B>0)