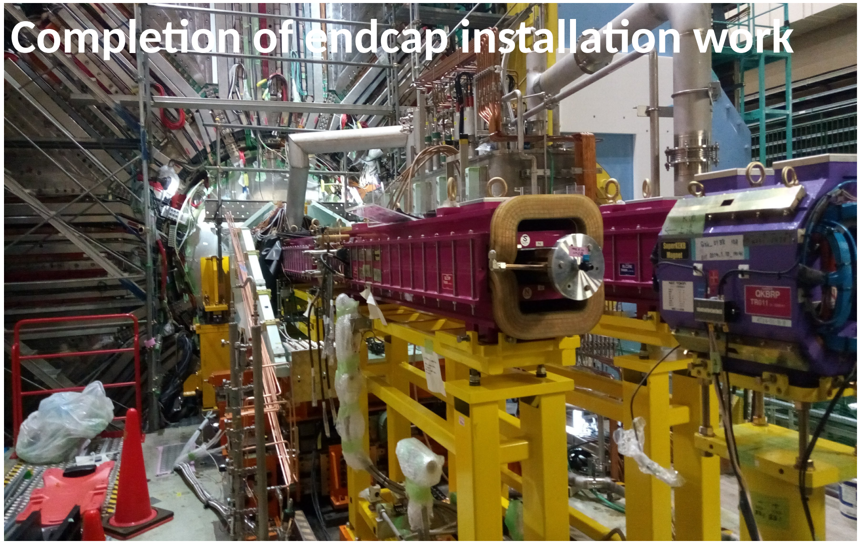
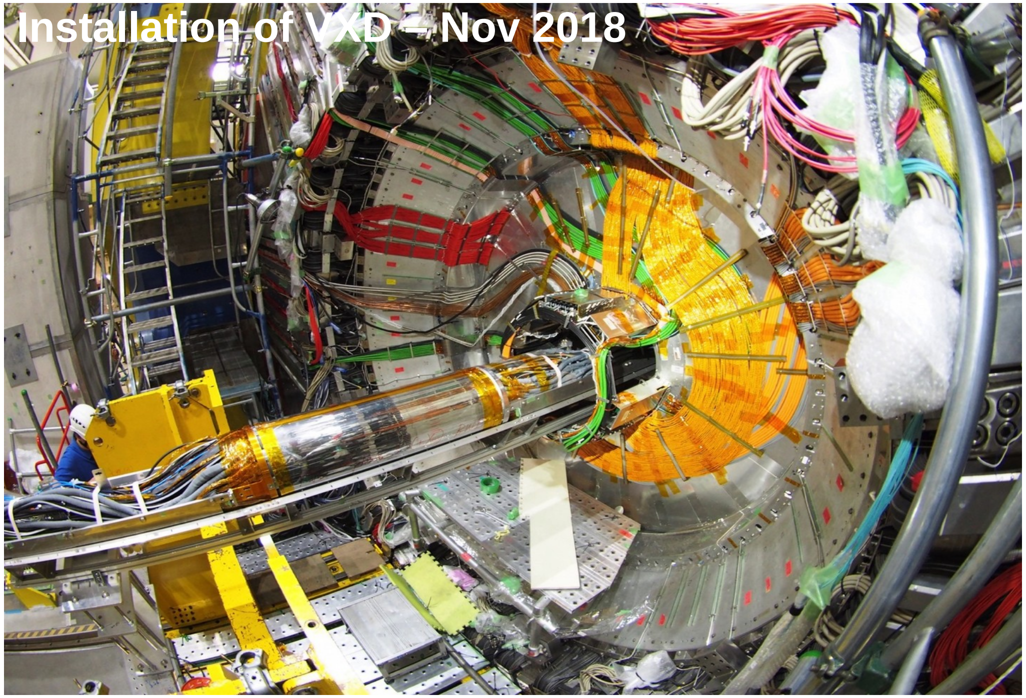




X, Y, Z Search at Belle II

26.02.2019 I Elisabetta Prencipe on behalf of the Belle II Collaboration

International Workshop on e^+e^- collisions
from Phi to Psi 2019 (Novosibirsk, Russia)

DFG Deutsche Forschungsgemeinschaft

Belle II

JÜLICH Forschungszentrum

Outline

- Introduction
- Motivation
  - how can we improve the Belle achievements?
  - open questions
  - new and unique opportunities at Belle II
- The Belle II experiment – waiting for Phase 3 starting
- Perspectives in search for exotics at Belle II
  - Charmonium
  - Bottomonium
- Summary

Introduction

- Gell-Mann Zweig idea: Constituent Quark Model

  Still valid for half century → it classifies all known hadrons

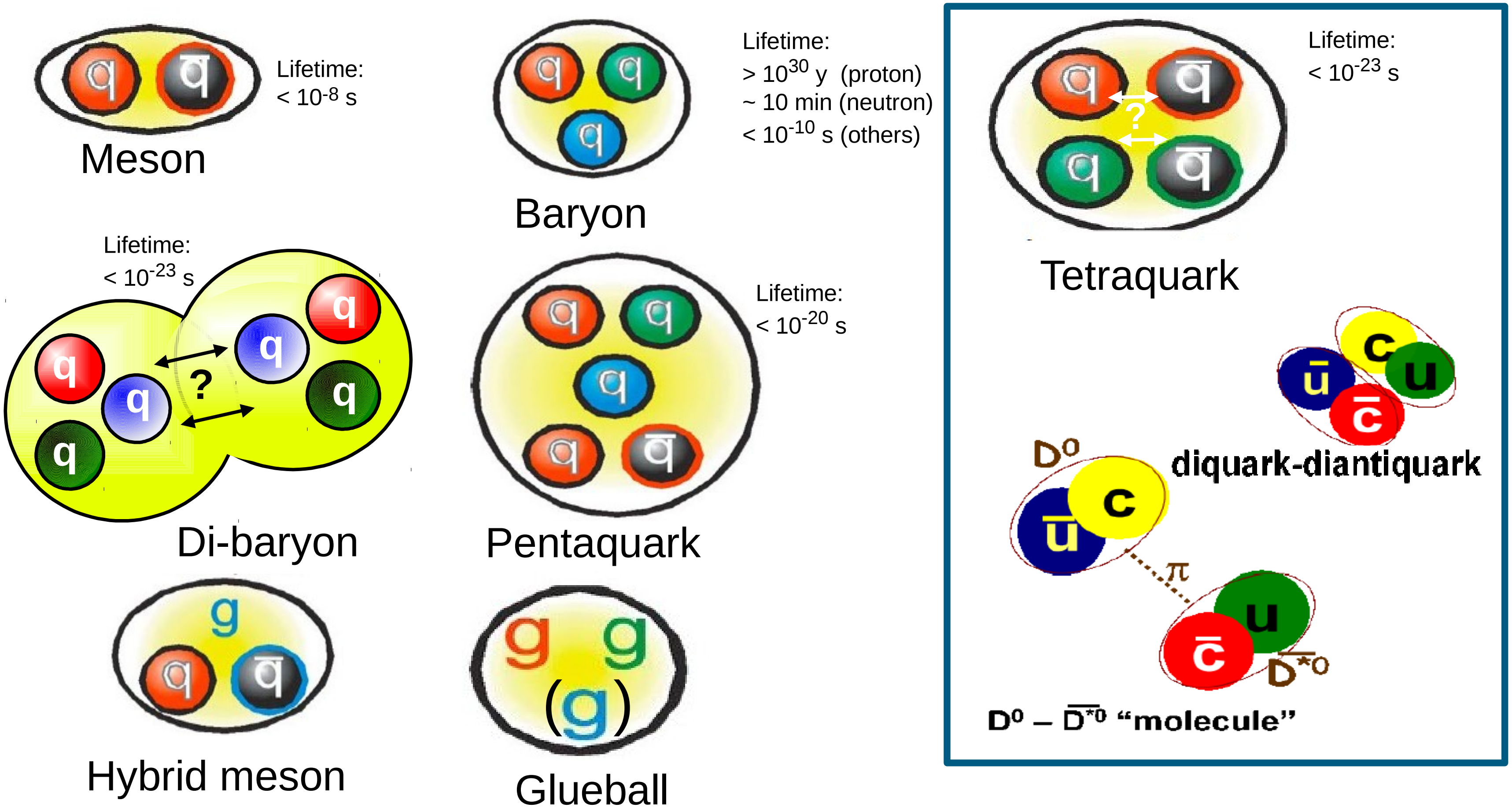
- QCD-motivated models predict the existence of hadrons with more complex structures than simple *qq* (mesons) or *qqq* (baryons) → the so-called XYZ *"charmonium"-like* states
- **Lot of experimental effort to prove the existence of XYZ!**
- No unambiguous evidence for hadrons with *non-CQM-like* structures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

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

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

  Substantial contribution from Belle (1999-2010) into the field

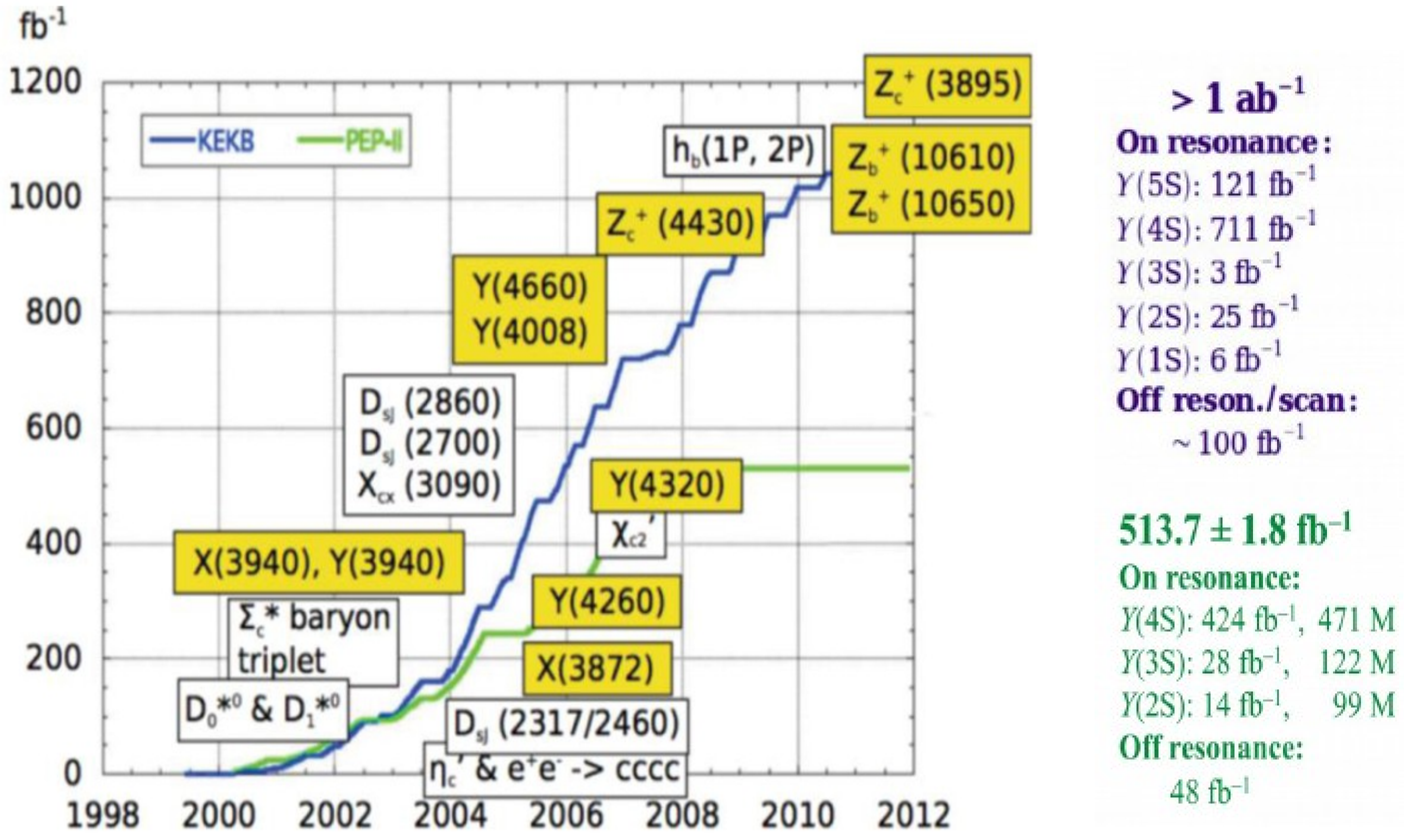
Quark Bound States



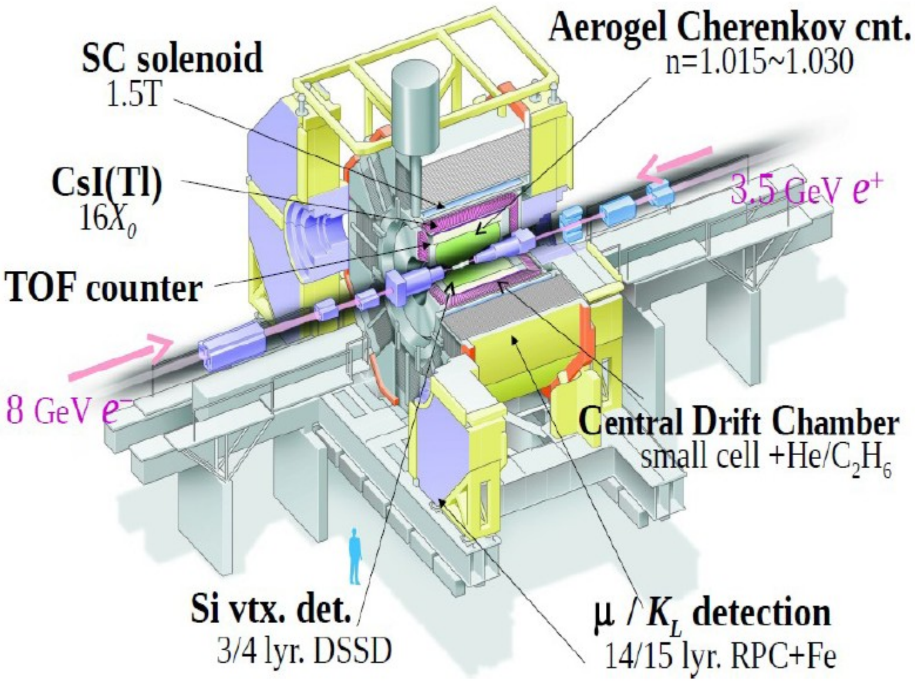
...and superposition of different states: $c_1|\bar{q}q\rangle + c_2|\bar{q}q\bar{q}q\rangle + \dots$

- BaBar + Belle:

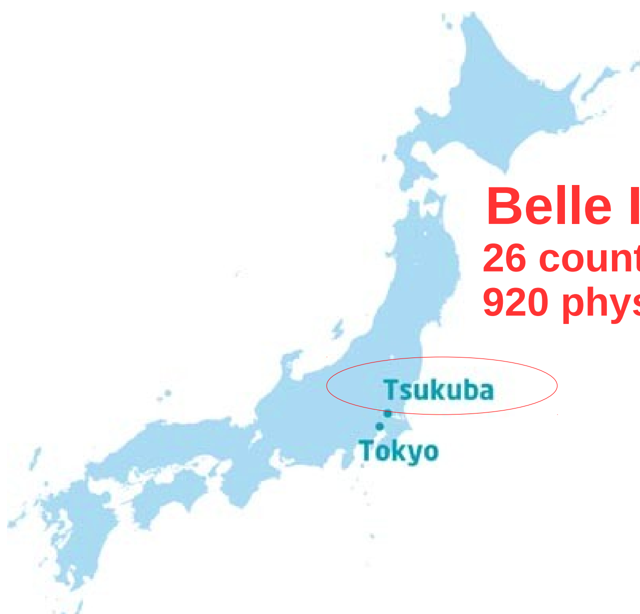
>1.5 ab^{-1} integrated luminosity - triumph in the history of B-factories!



- 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!

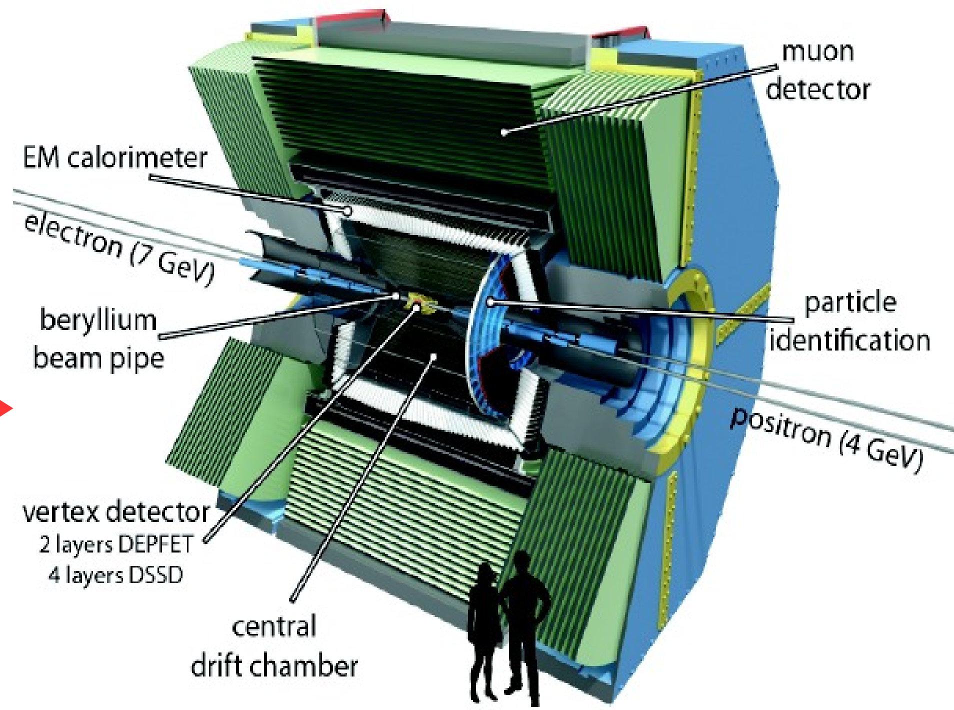


← Belle detector



Belle II detector →

26 countries,
920 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?

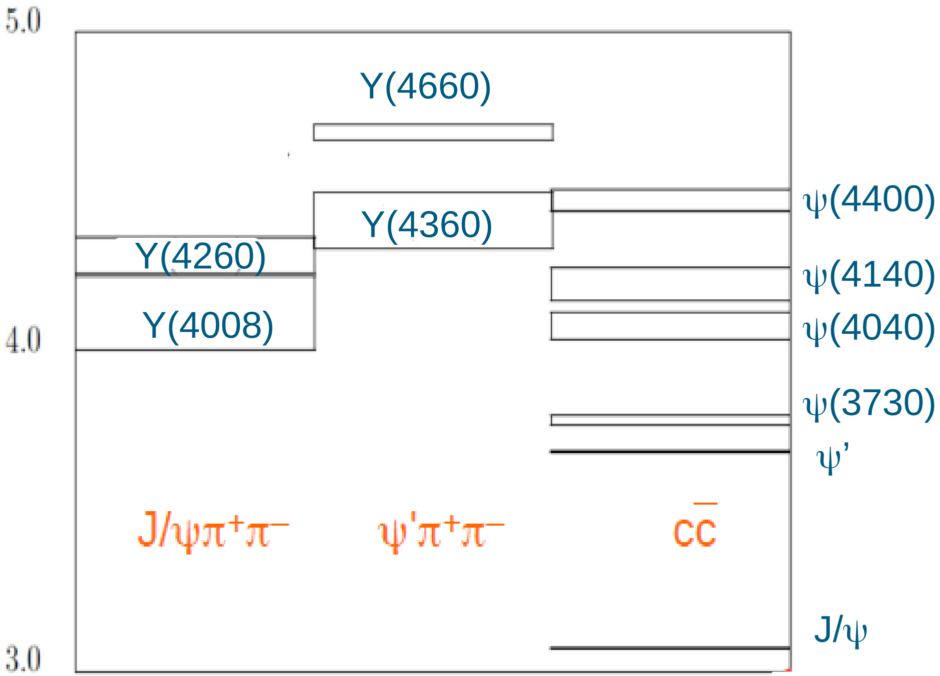
  \- factor 2 by beam current: 1.64/1.19 A (Belle) → 3.6/2.6 A for e^+(e^-) beam in Belle II

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

DETAILS IN BACKUP SLIDES

Y Family - Summary

Contribution from Belle



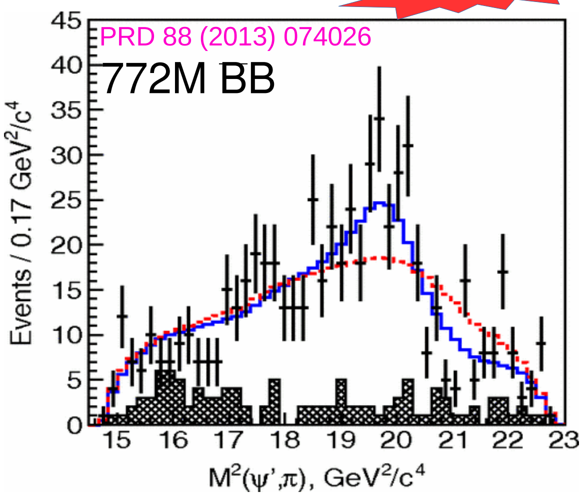
	Mass (MeV/c^2)	Width (MeV)
Y(4008)	$4008 \pm 40^{+114}_{-28}$	226±44±87
Y(4260)	4258.6±8.3±12.1	134.1±16.4±5.5
Y(4360)	4361±9±9	74±15±10
Y(4660)	4664±11±5	48±15±3

- ISR studies: unique at B factories
- Clear signature: $J^{PC} = 1^{--}$
- No mixing ⇨ surprising!
- Limited statistics at B-factories for such rare events: need more data!

Z Charged States

Main achievements at Belle

$B^0 \to K^- \pi^+ \psi'$ **Update**



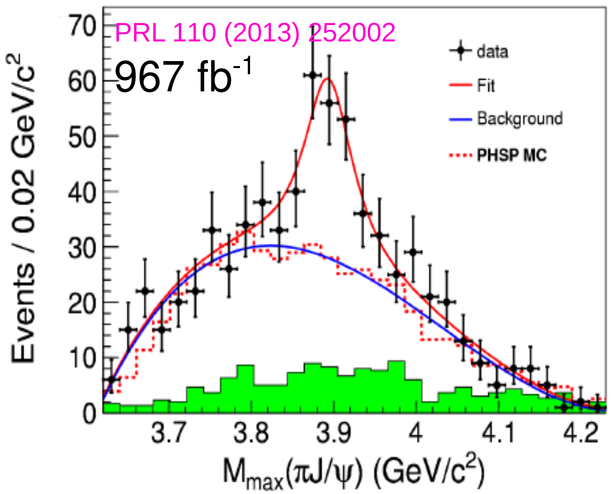
$M = 4485 \pm 22 ^{+28}_{-11}$ MeV/c^2

$\Gamma = 200^{+21}_{-46}{}^{+26}_{-35}$ MeV

5.2σ, $J^P = 1^+$

First observation: Belle, PRL 100 (2008) 142001; Confirmed by LHCb: PRD 92(2015) 112009

$e^+e^- \to \pi^+\pi^- J/\psi$, $Z_c(3900) \to \pi J/\psi$



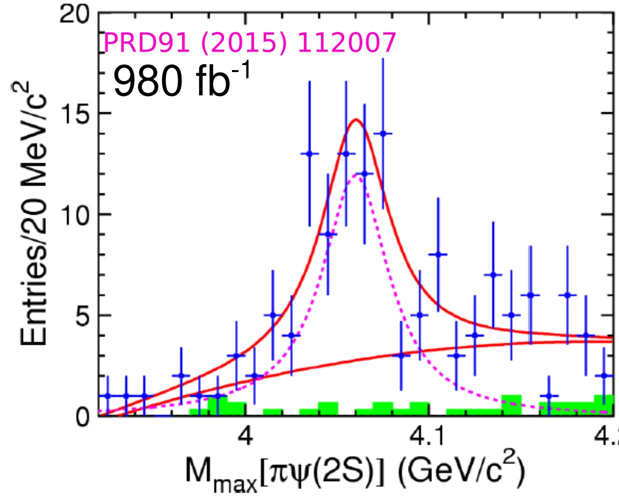
$M = 3894.5 \pm 6.6 \pm 4.5$ MeV/c^2

$\Gamma = 63 \pm 24 \pm 26$ MeV

$>5.2\sigma$

BESIII confirmation/following PRL 110 (2013) 252001

$e^+e^- \to \pi^+\pi^- \psi'$, $Z_c(4050) \to \pi\psi'$

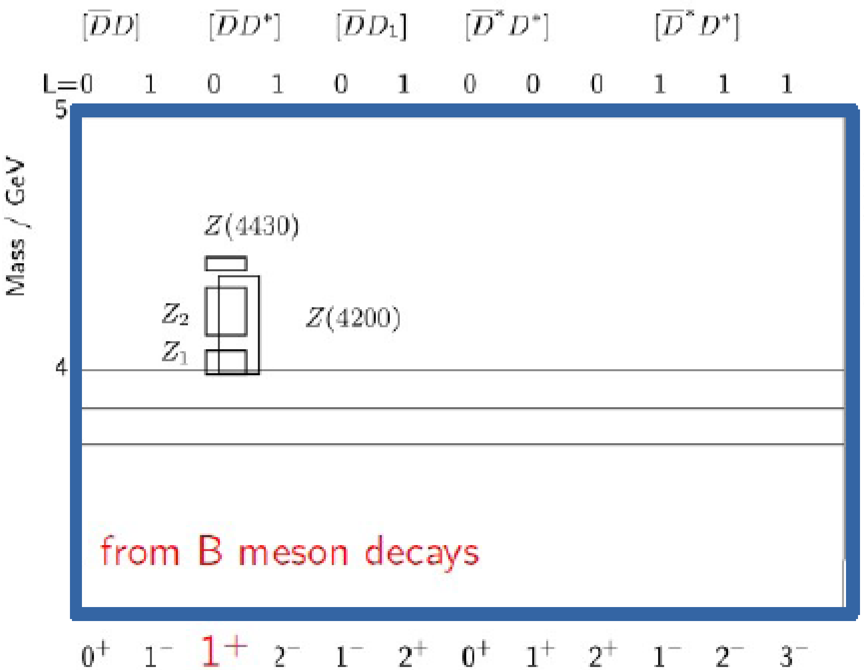


$M = 4054 \pm 3 \pm 1$ MeV/c^2

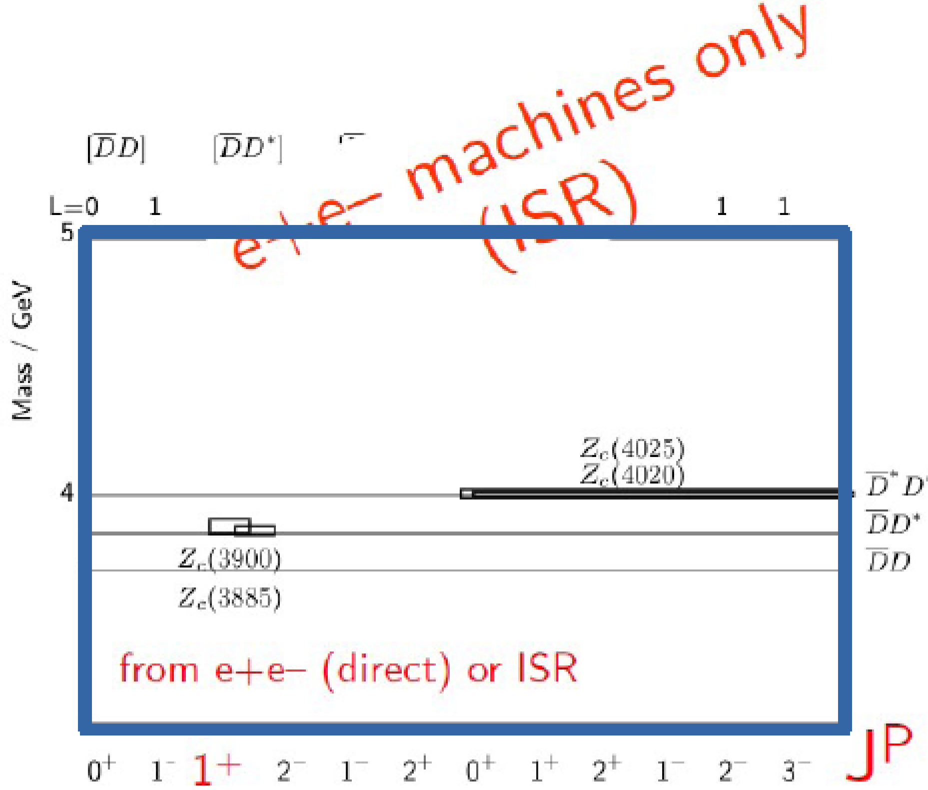
$\Gamma = 45 \pm 11 \pm 6$ MeV

$>3.5\sigma$

Two different classes of Z states?



– large widths
– not connected to thresholds?



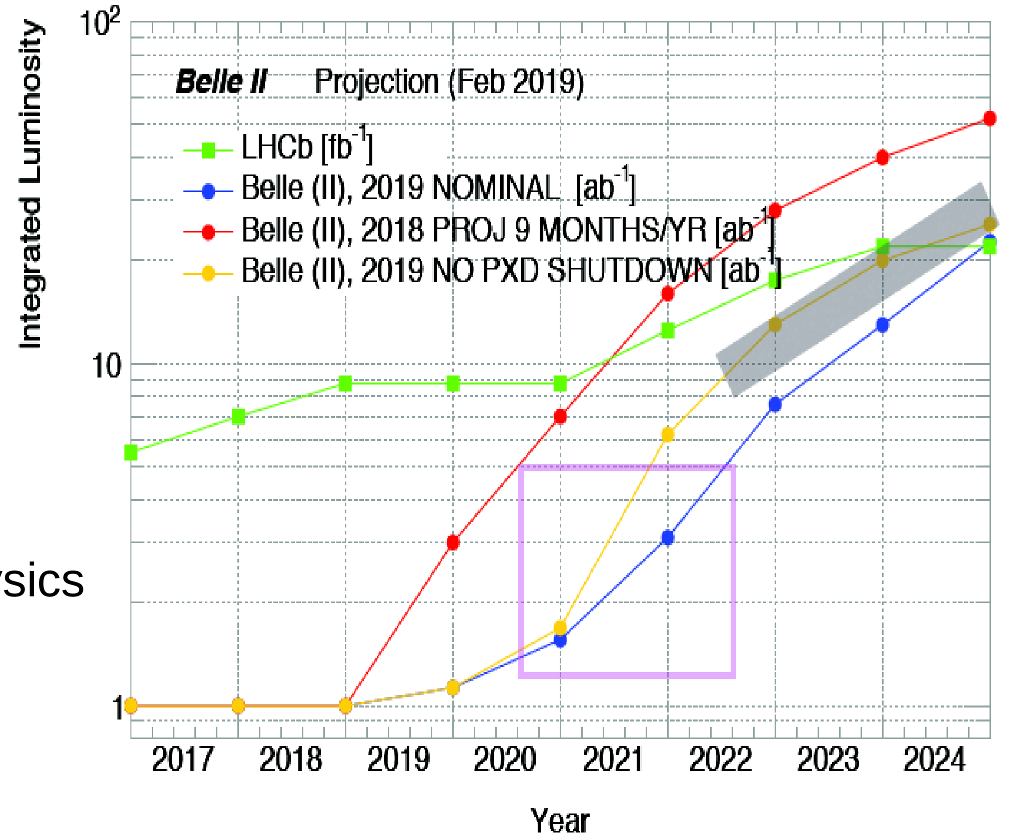
– narrow widths
– near thresholds

- 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)

Luminosity: long term perspectives

- Scenarios:

  - Feb 2018:
    nominal projection 9 months/year
  - Feb 2019:
    nominal projection 8 months/year
  - Special case without shutdown for
    the PXD (&TOP) in 2020 →
    introduced to assess impact on physics
    in 2021-2022



- **Phase 2**, until 17th July 2018: L = $504.9\ pb^{-1}$
- **Phase 3**, will start on 11th March 2019

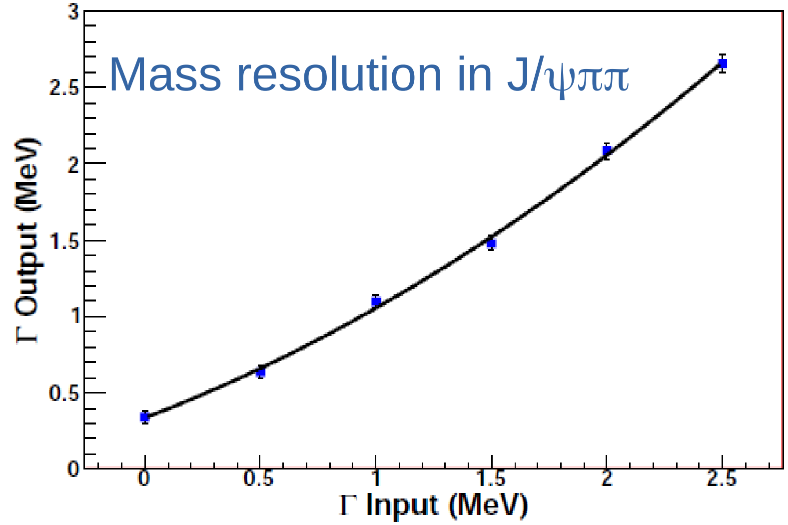
X(3872) total width

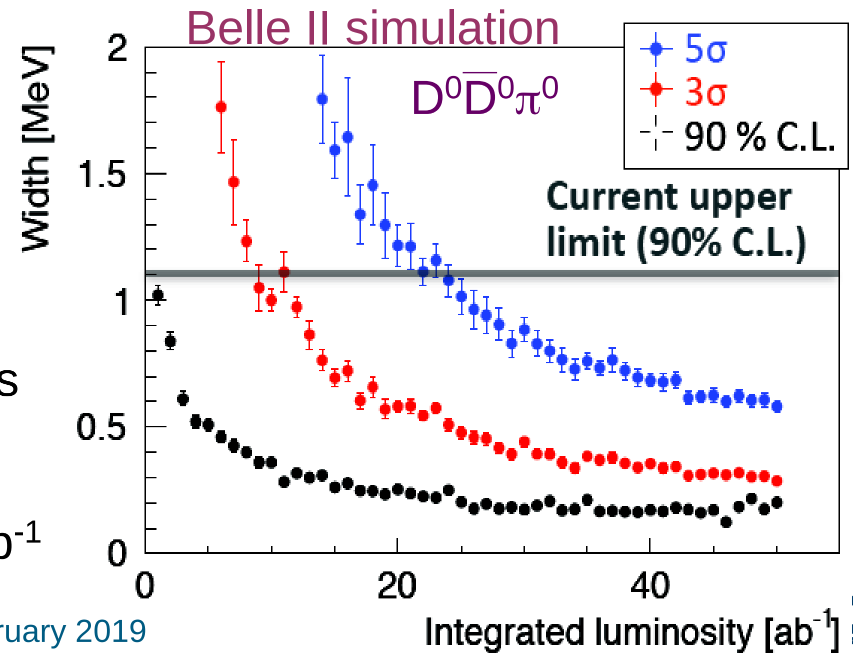
- Known upper limit: Γ < 1.2 MeV (estimated from $X(3872) \rightarrow J/\psi\pi^+\pi^-$), on full Belle data sample
- Very promising: $X(3872) \rightarrow D^0\overline{D}^{0*}$

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)→$J/\psi\pi^+\pi^-$ in 2020 will be about Belle yield of ψ' → $J/\psi\pi^+\pi^-$
- Radiative decay X(3872)→$J/\psi\gamma$: expected yield N≃350 in 2020
- 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 **$D^*\overline{D}^*$** 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)	$B\to KX(3872)$, $X(3872)\to J/\psi\pi^+\pi^-$	≃14400
Y(4260)	ISR, $Y(4260)\to J/\psi\pi^+\pi^-$	≃29600
Z(4430)	$B\to K^\mp Z(4430)$, $Z(4430)\to J/\psi\pi^\pm$	≃10200

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

Charmonium in ISR: Perspectives at Belle II

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

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

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

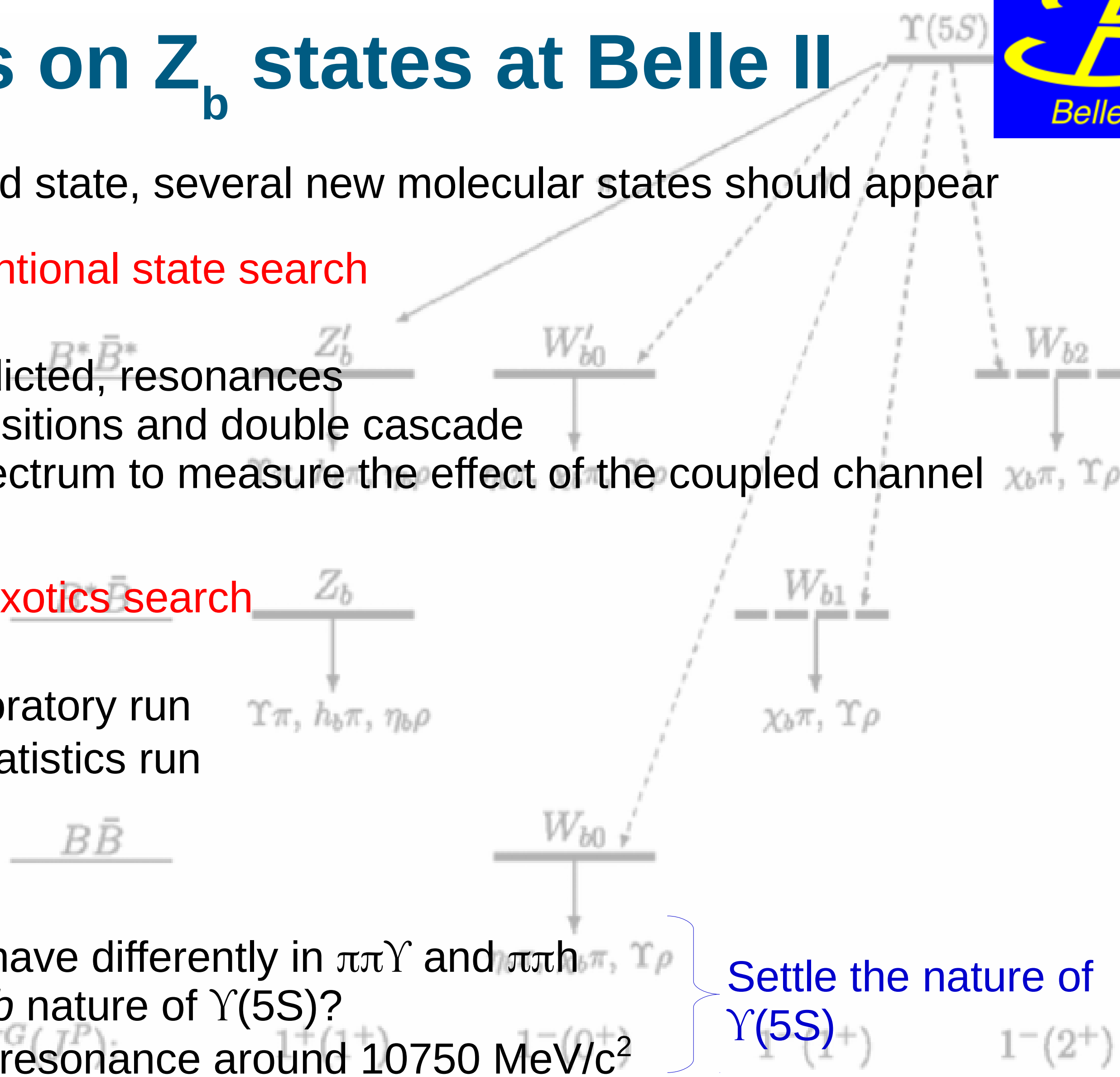
Υ(6S) and Υ(5S): new exotics search

- 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 $\pi\pi h$
    → hint of a non-*bb* nature of Υ(5S)?
  - investigate an extra resonance around 10750 MeV/c^2

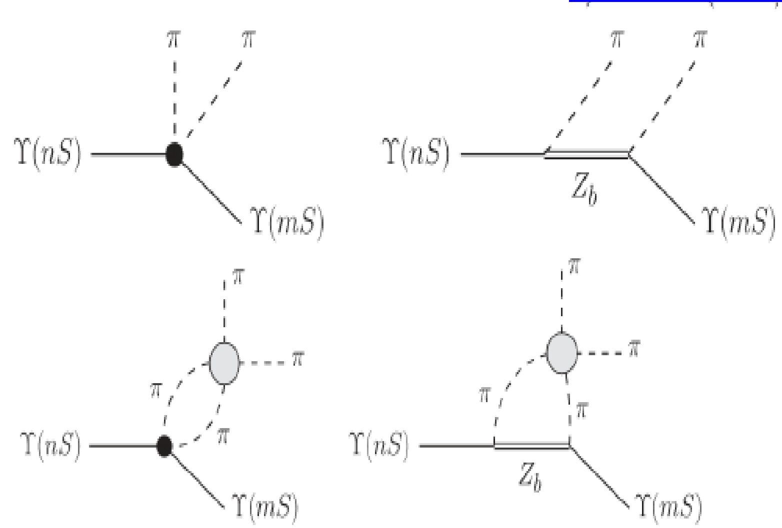
Settle the nature of Υ(5S)



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

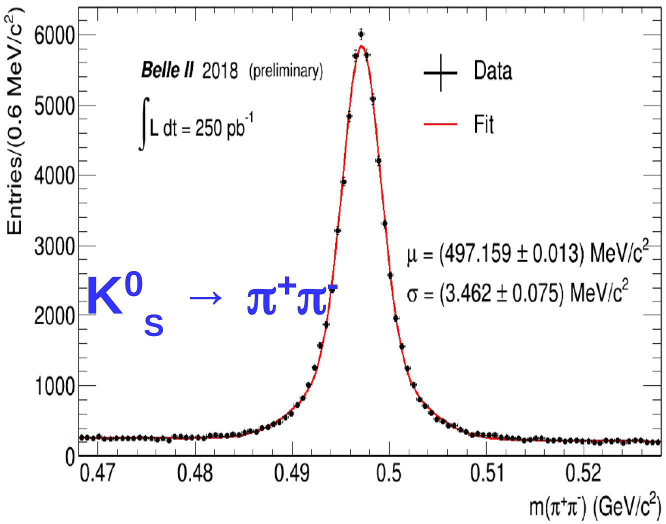
Υ(3S): charmonia in production

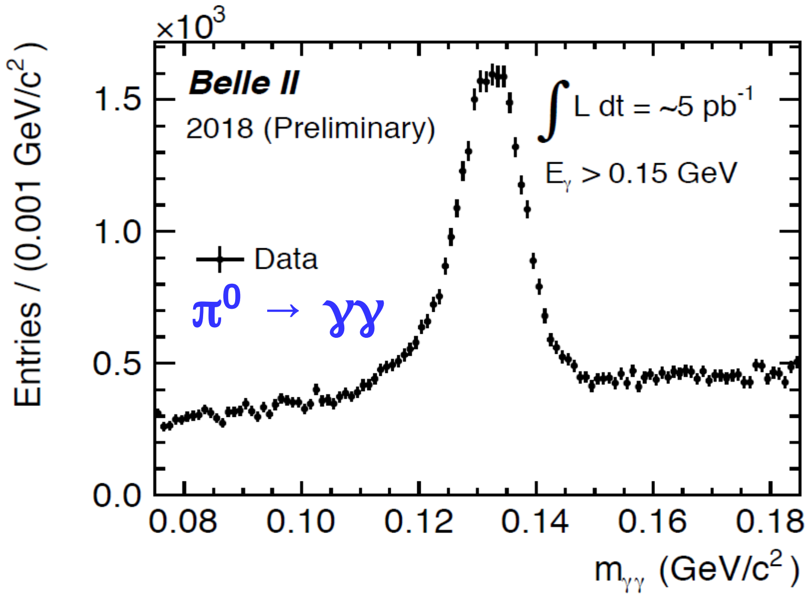
- Belle II goals with 300 fb^{-1}:
  - up to 5x sensitivity in inclusive production from Υ(3S)
  - up to 15x in double charmonium
  - inclusive rate of X(3872)
  - $D\bar{D}^*$ correlation in $\Upsilon(3S) \rightarrow D\bar{D}^*$ + hadron to test the nature of the X(3872)

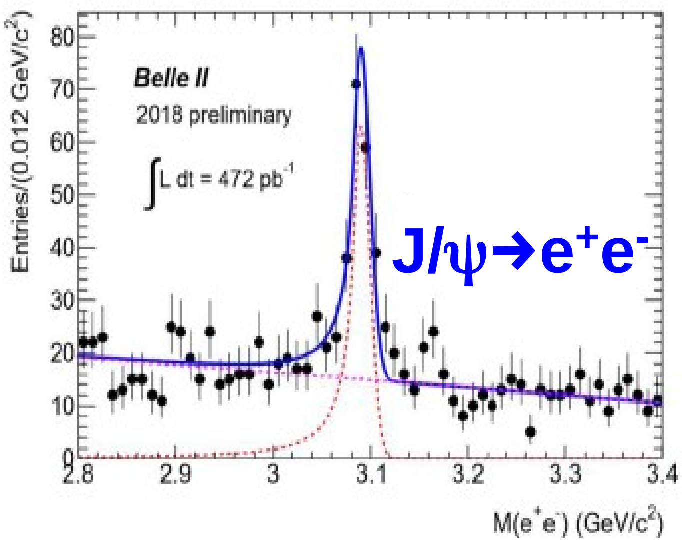
Υ(3S): rare χ_b decays

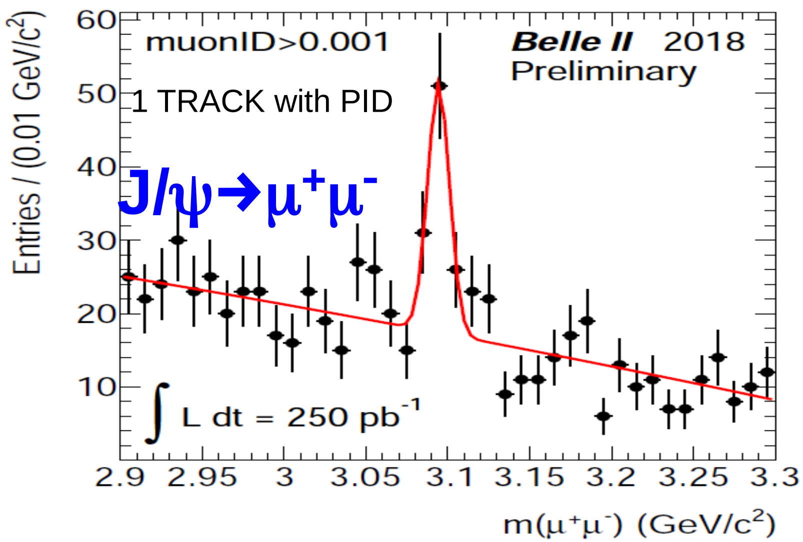
Υ(3S): deuteron production mechanism

Preliminary Study with Phase II Data

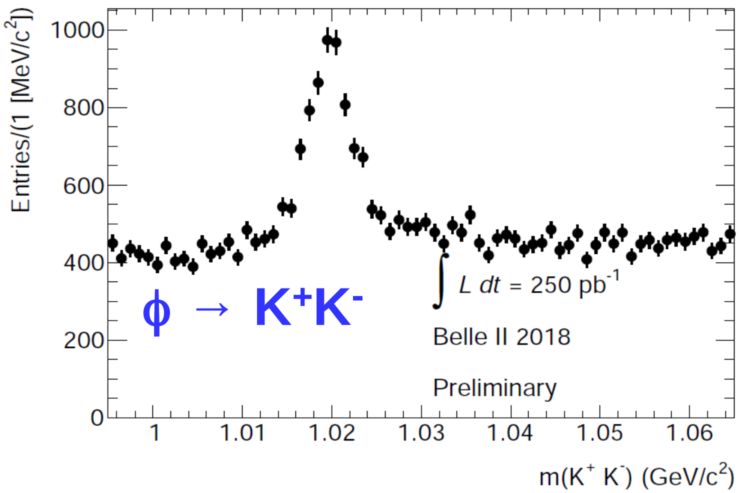


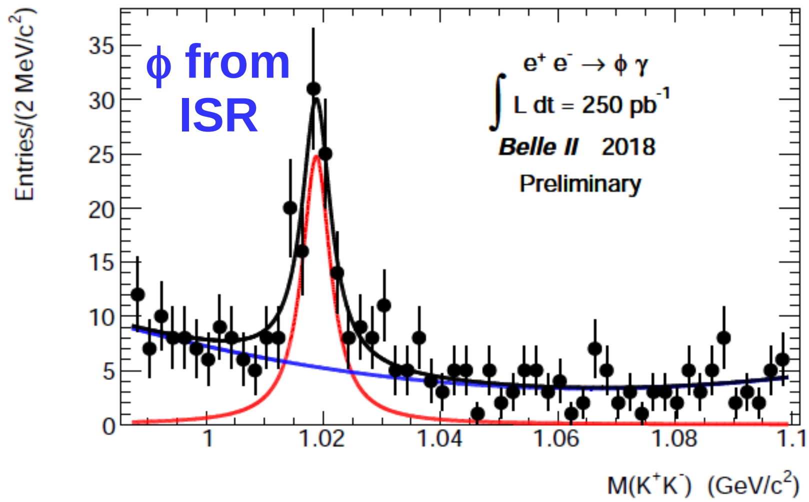


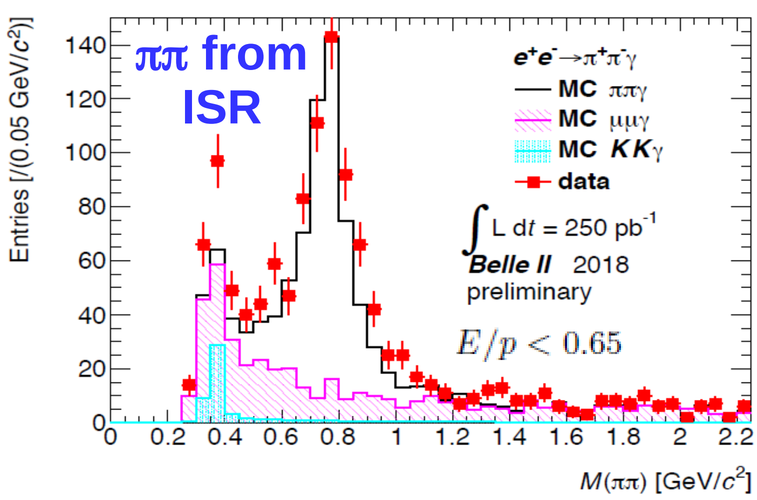


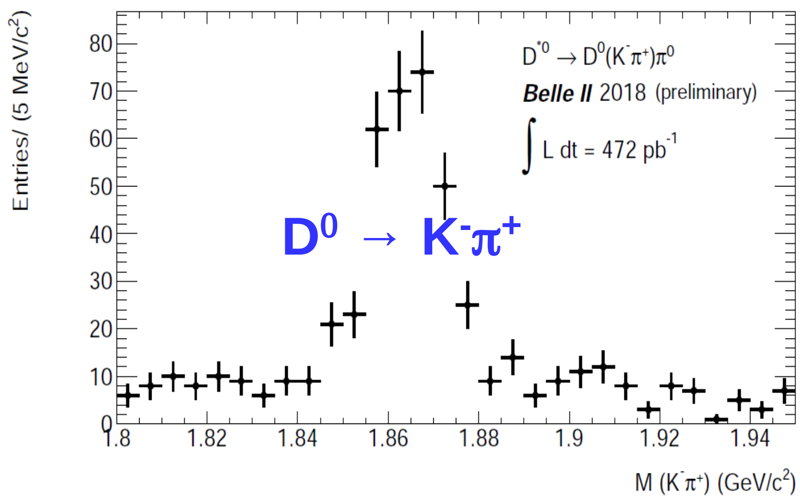


Preliminary Study with Phase II Data

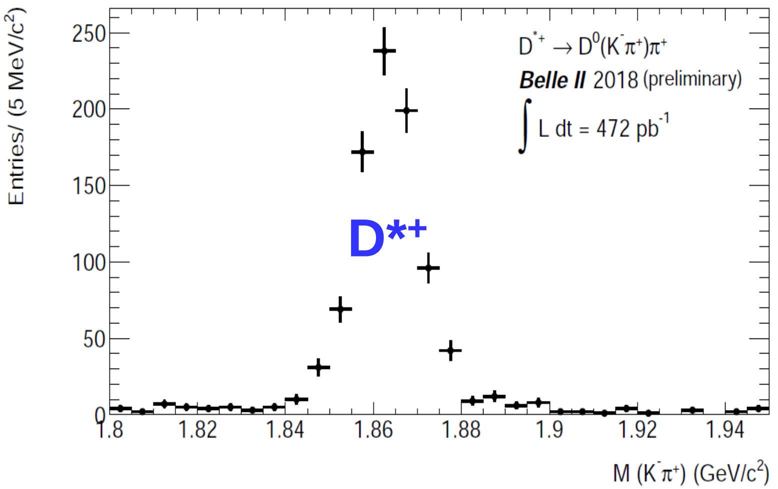


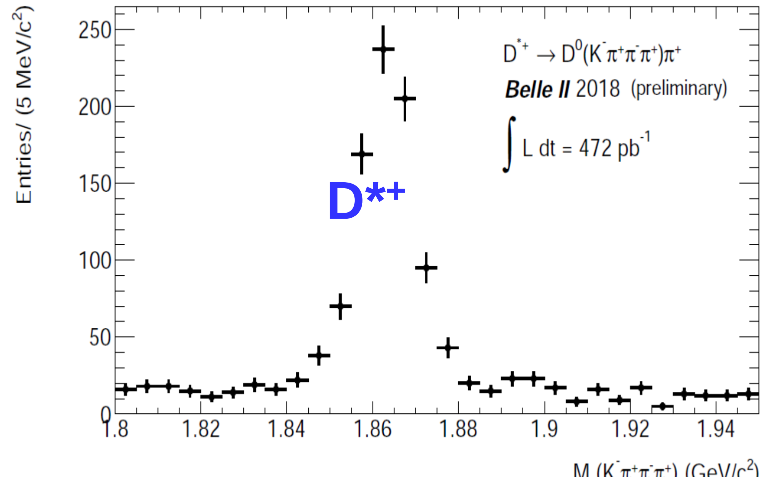


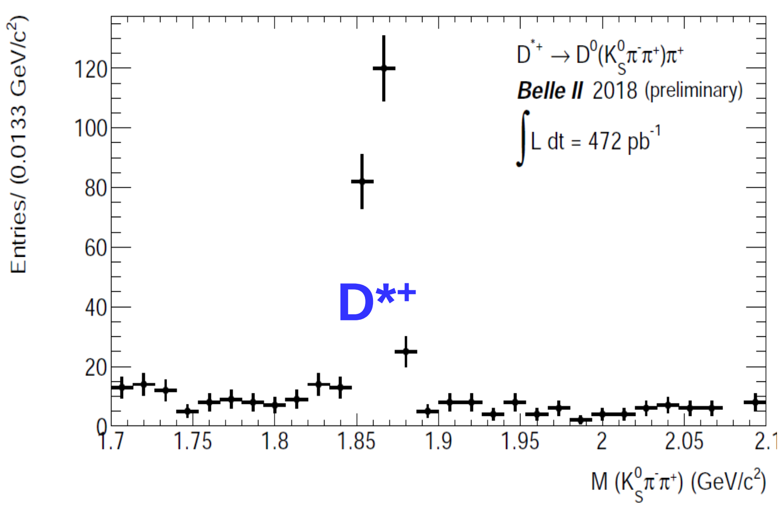


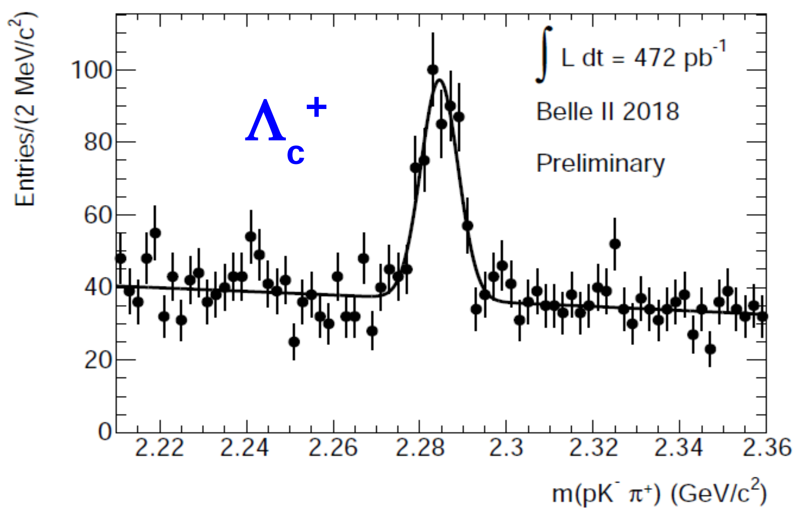


Preliminary Study with Phase II Data









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 in Belle II completed on 17th July 2018: ~500 pb^{-1} @ $\Upsilon(4S)$**
  → peak luminosity during Phase 2: 5×10^{33} cm^{-2} s^{-1}
  → first cosmics to test detector setup for Phase 3 started in January **2019**
  → ready for **Phase 3** in a few weeks: challenge to collect 60 fb^{-1}
  >10fb^{-1} @ Y(4S), with >1 fb^{-1} off-peak
- Expected 50 ab^{-1} integrated luminosity at Belle II in 2026
- With x50 more data than Belle, expected in Belle II great achievements in hadron spectroscopy:
  - ISR analysis as a unique case
  - improved search capability from $\Upsilon(6S)$ decays possible
  - good slow pion reconstruction to search for $D^*\bar{D}^{(*)}$ threshold exotic states

Thank you for your kind attention!

e.prencipe@fz-juelich.de

"The greatest danger for most of us lies not in setting our aim too high and falling short; but in setting our aim too low, and achieve our mark." (Michelangelo, 1475 - 1564)

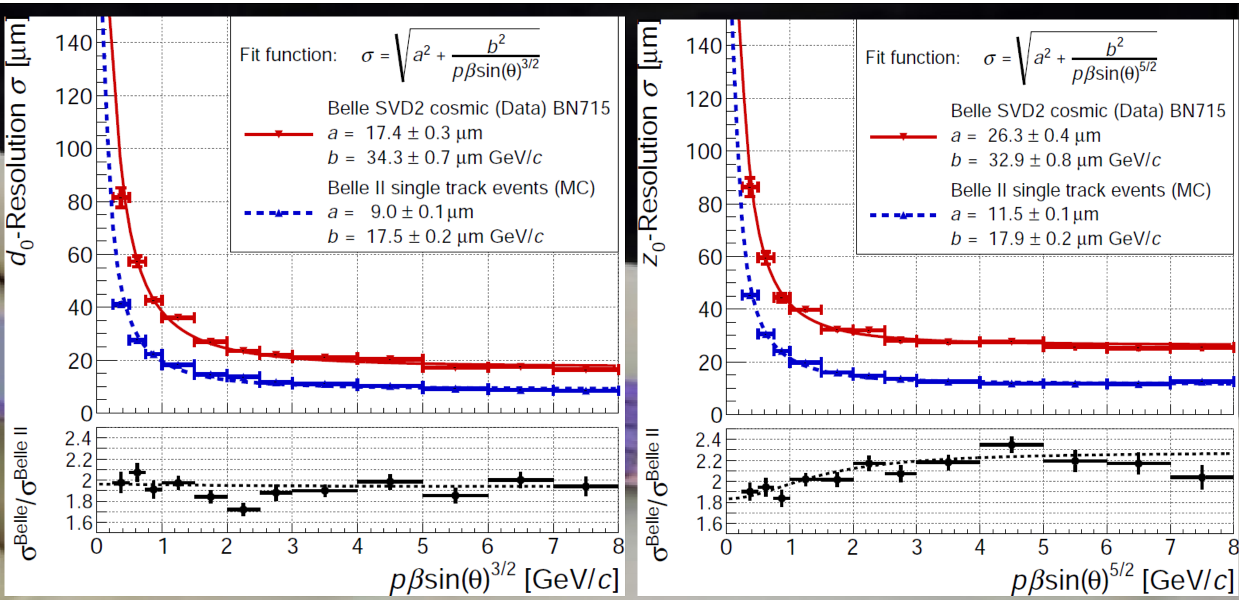
Backup slides

How can Belle II perform these challenging measurements?

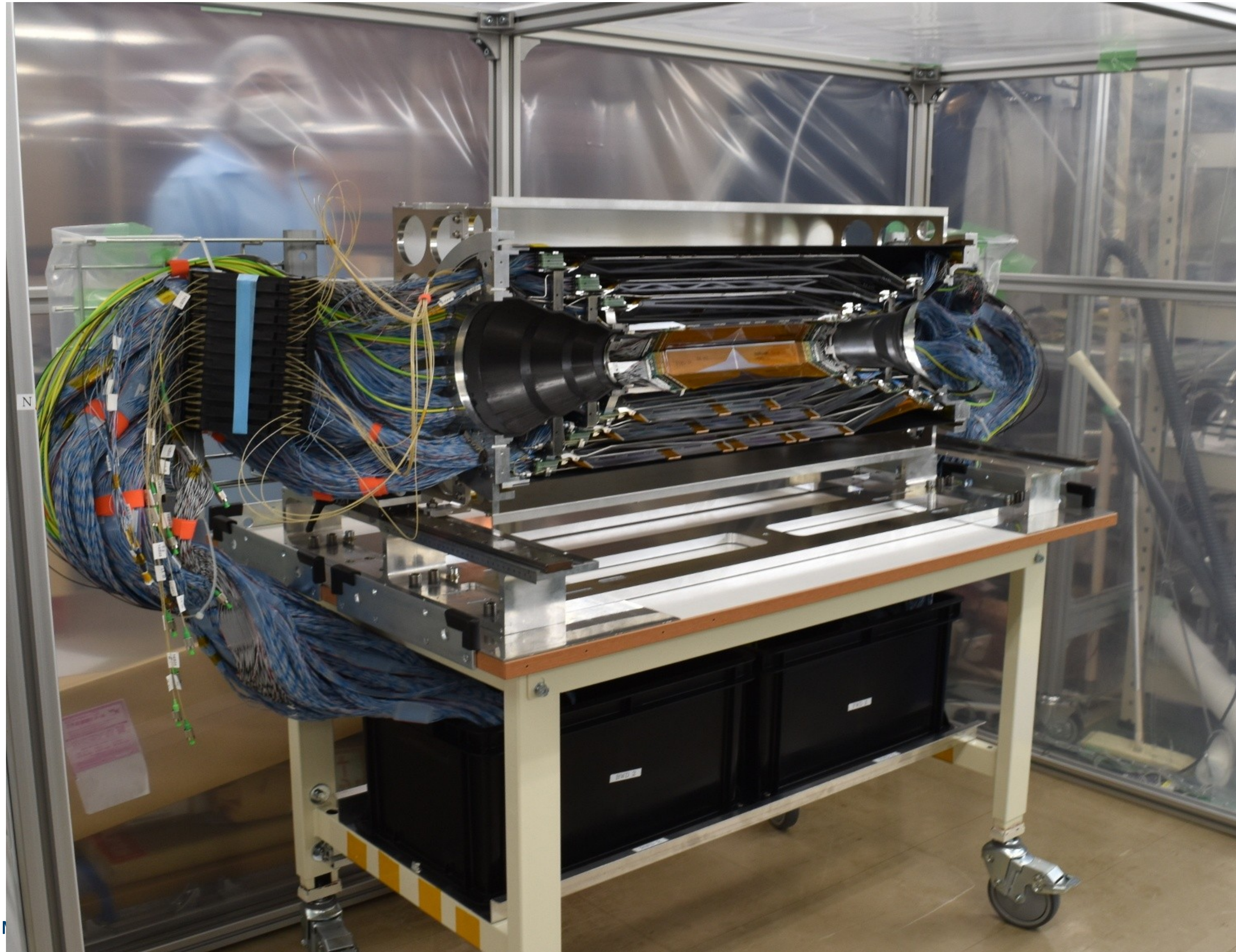
- most powerful e+e- collider in the world
- x40 more luminosity than Belle
- high vertex resolution
- excellent tracking perfomance
- improved slow pion detection

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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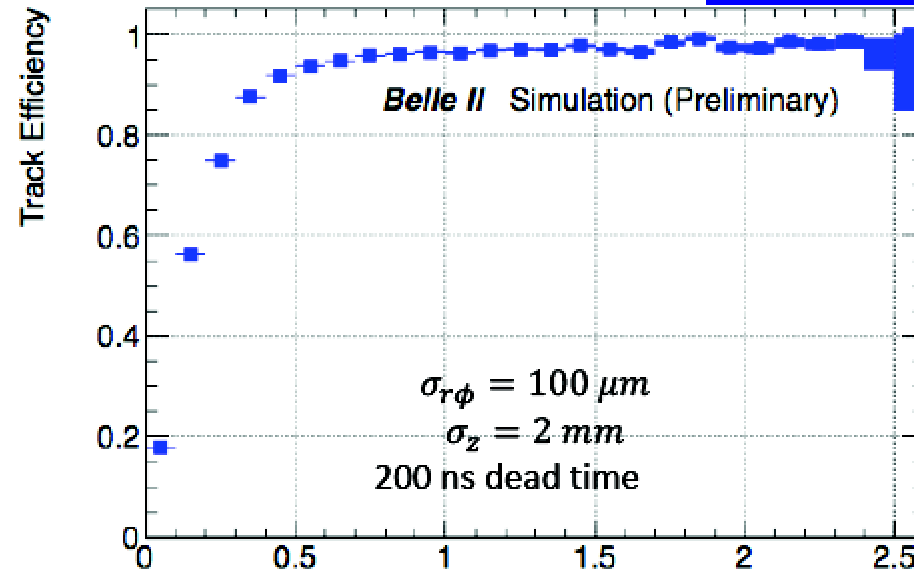
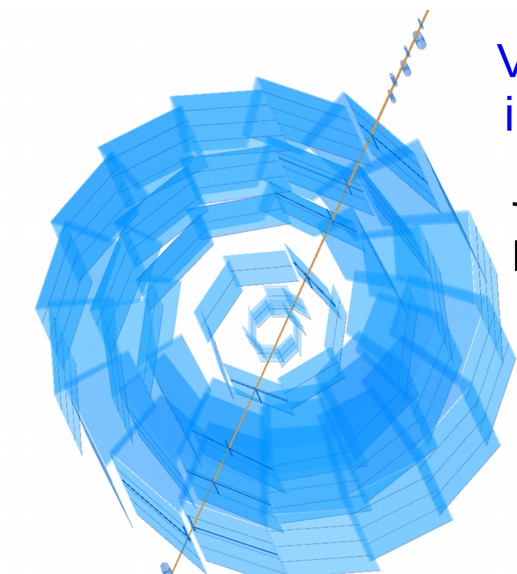
Central Drift Chamber (CDC)



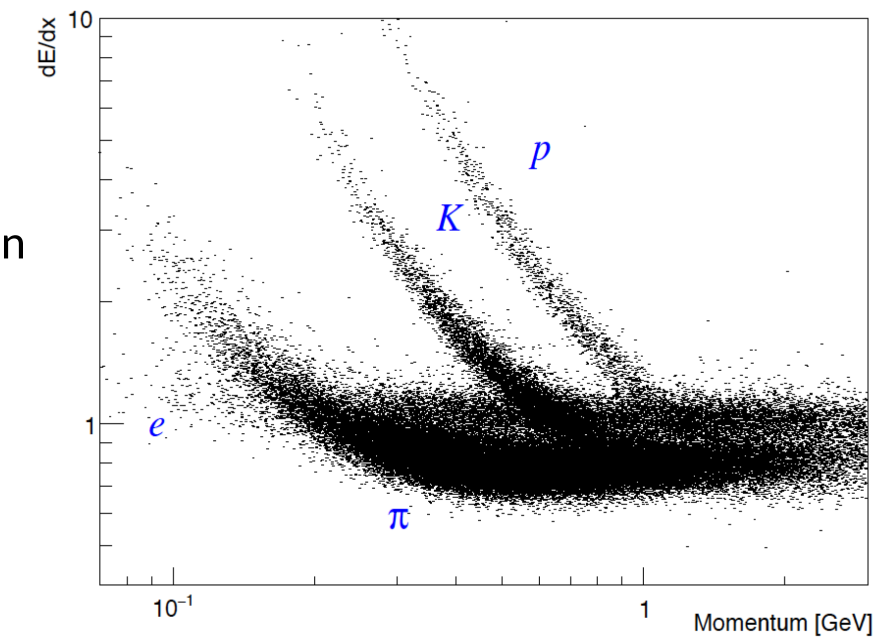


VXD + CDC hits
in EventDisplay

Jan 16, 2019:

First global SVD cosmic run

Exp. 5, Run 690, Evt. 14110
(Jan 27, 2019)



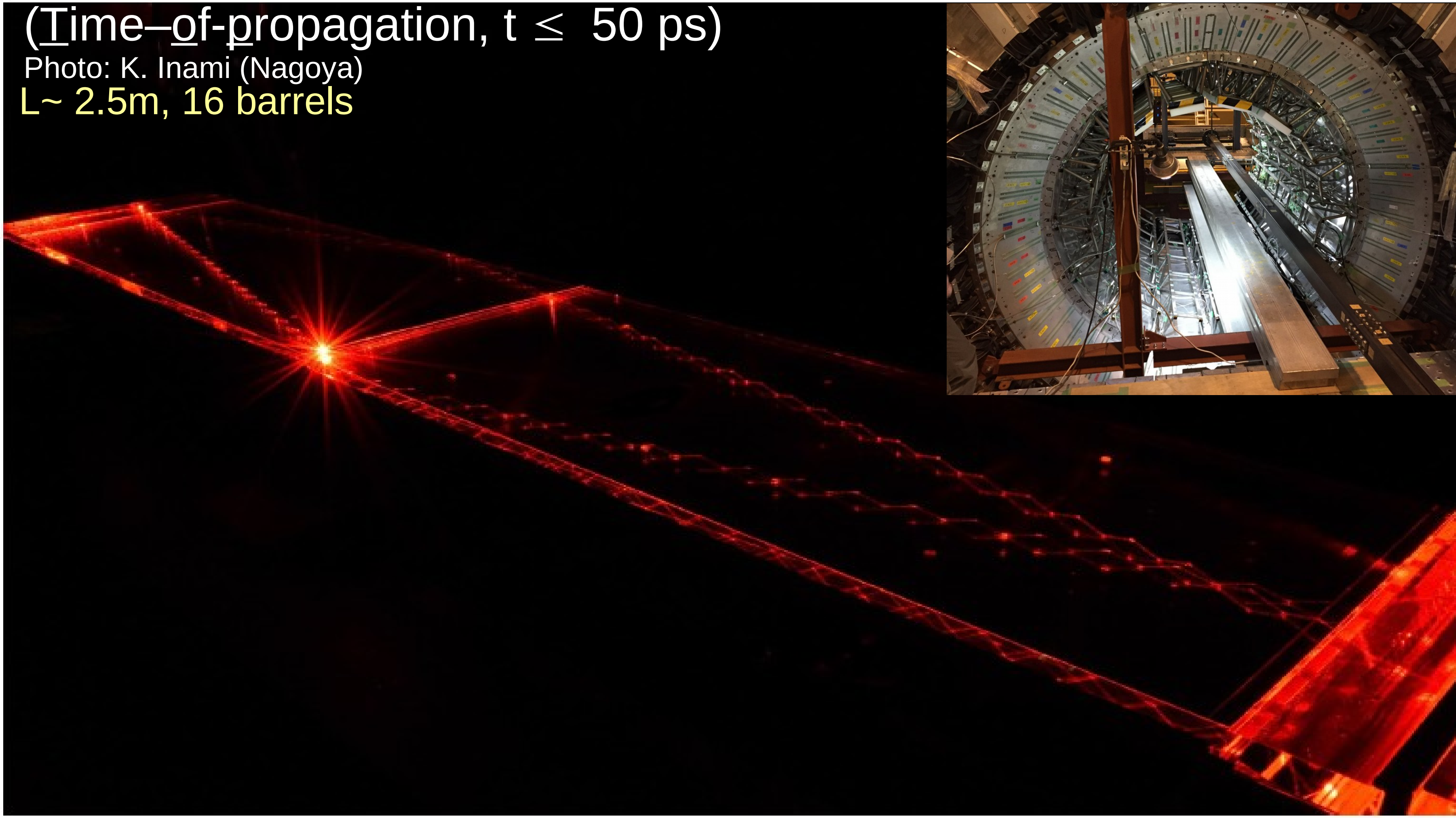
Cerenkov detector, laser in TOP module

Particle Identification

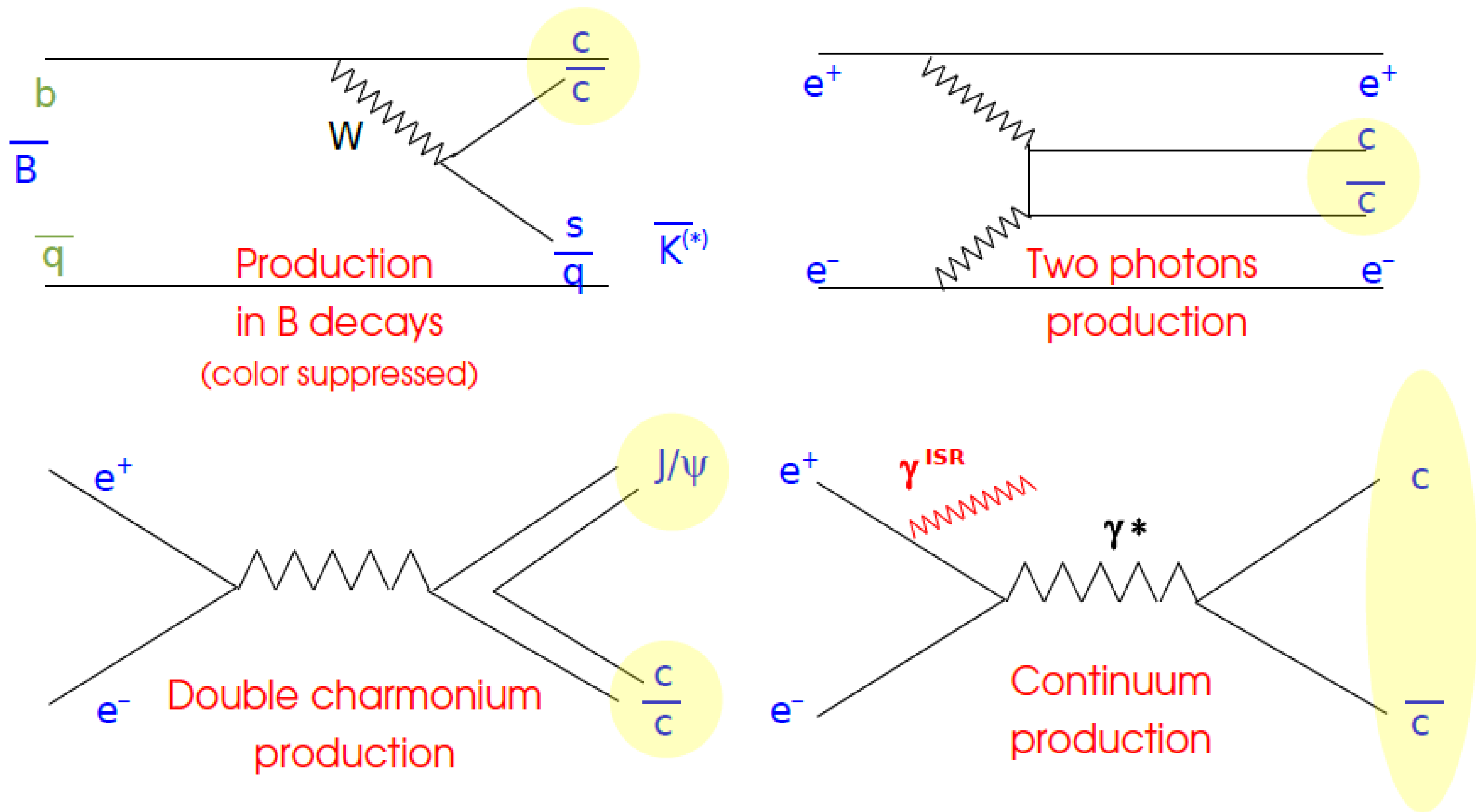
(Time–of-propagation, t ≤ 50 ps)

Photo: K. Inami (Nagoya)

L~ 2.5m, 16 barrels

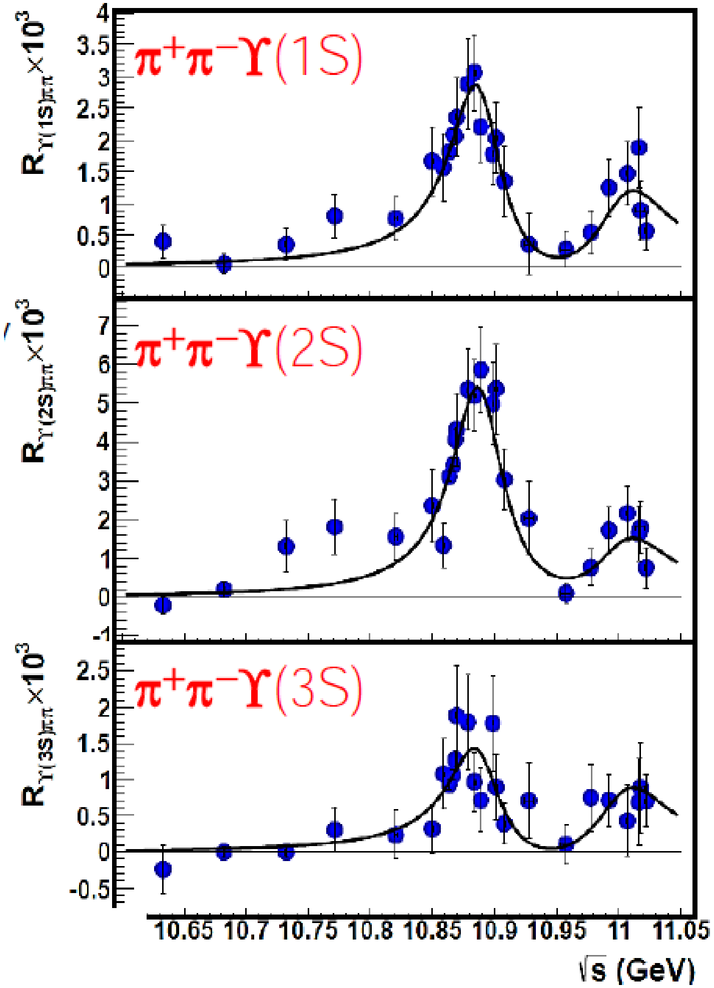


Charmonium Production at B Factories

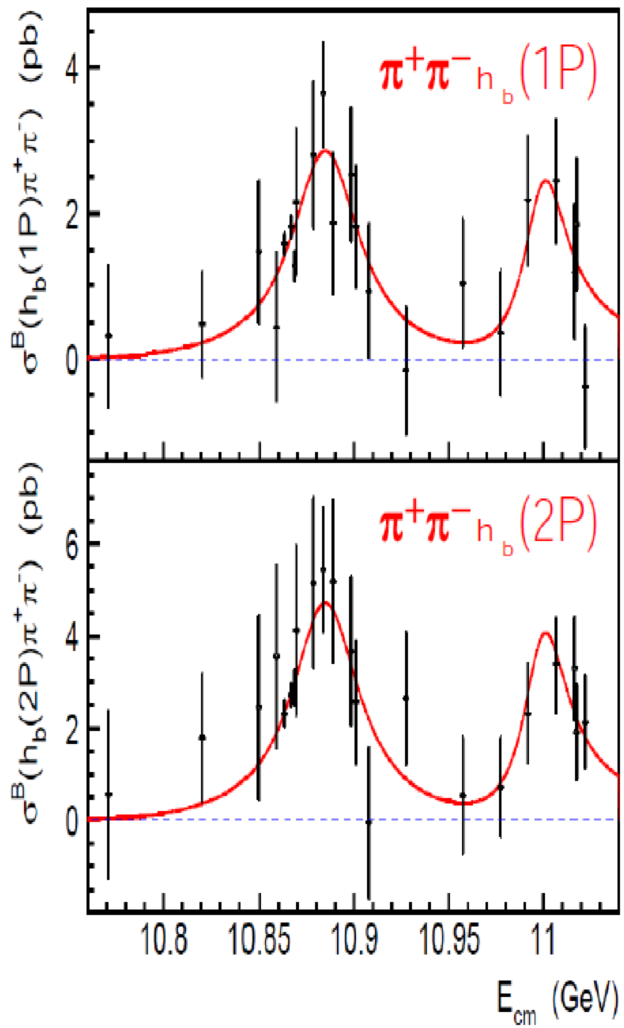


Main Achievements in Bottomonium at Belle

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



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



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

PRD 93, 011101(R) (2016)

PRL117, 142001 (2016)

JÜLICH Forschungszentrum

Main Achievements in Bottomonium at Belle

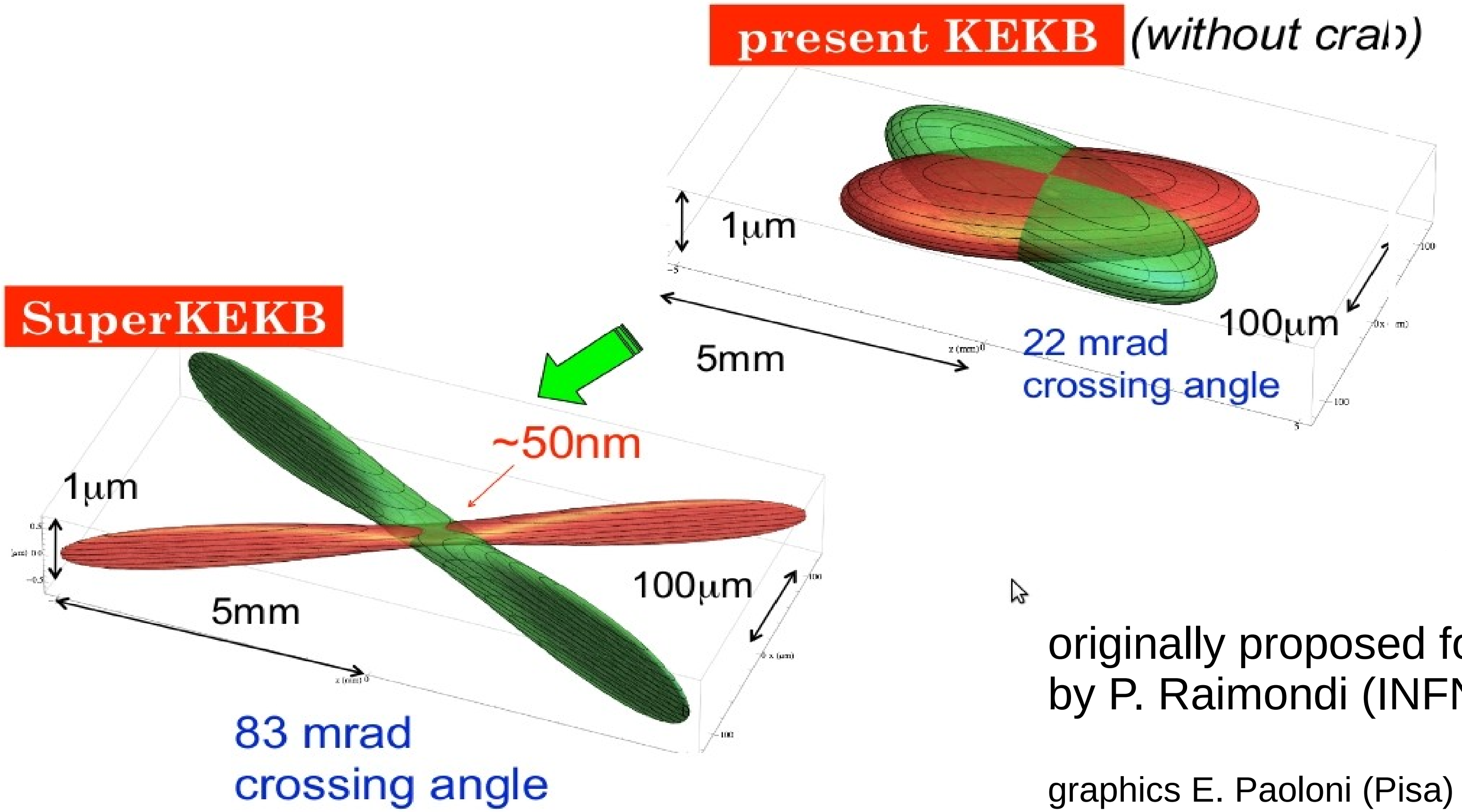
Z_b in Y(5S)→$\pi^+\pi^-\Upsilon$(nS)

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



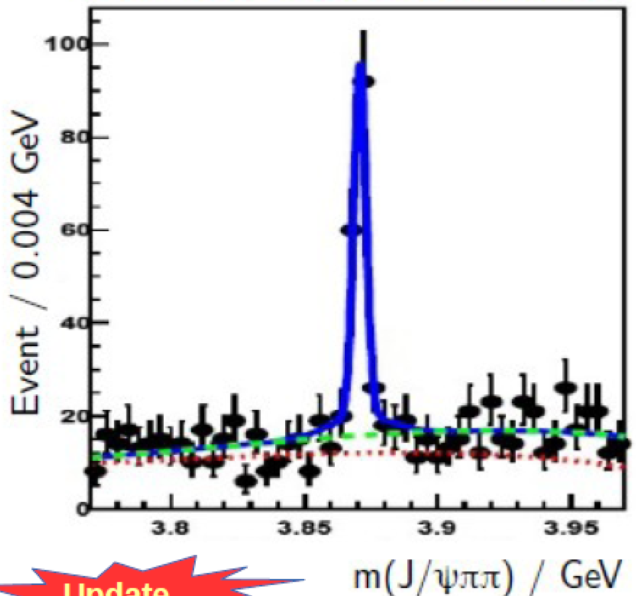
originally proposed for SuperB
by P. Raimondi (INFN)

graphics E. Paoloni (Pisa)

X(3872): ACHIEVEMENTS AND INTERPRETATION AT BELLE

~150 events in 10 years

Belle, Phys Rev D84(2011)052004



Update

$M_{X(3872)}$=(3871.85±0.27(stat)±0.19(syst)) MeV

$B(B^+ \to K^+ X(3872)) \times B(X(3872) \to \pi^+\pi^- J/\psi)$=

$(8.63 \pm 0.82(stat) \pm 0.52(syst)) \times 10^{-6}$

$B(B0 \to K^0 X(3872))/B(B+ \to K^+ X(3872))$=

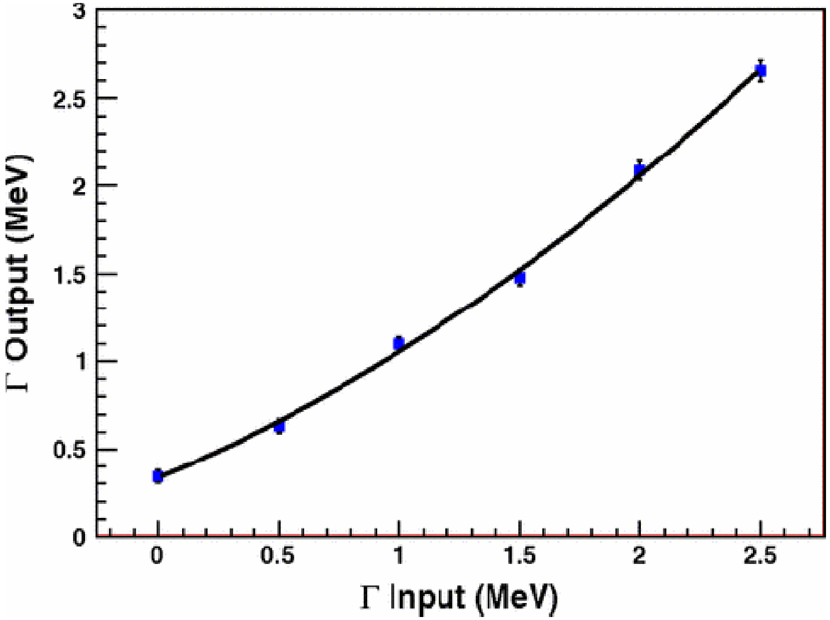
0.50±0.14(stat)±0.04(syst)

$\Delta M_{X[B0-B+]}$=(−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

X(3872): ACHIEVEMENTS AND INTERPRETATION AT BELLE

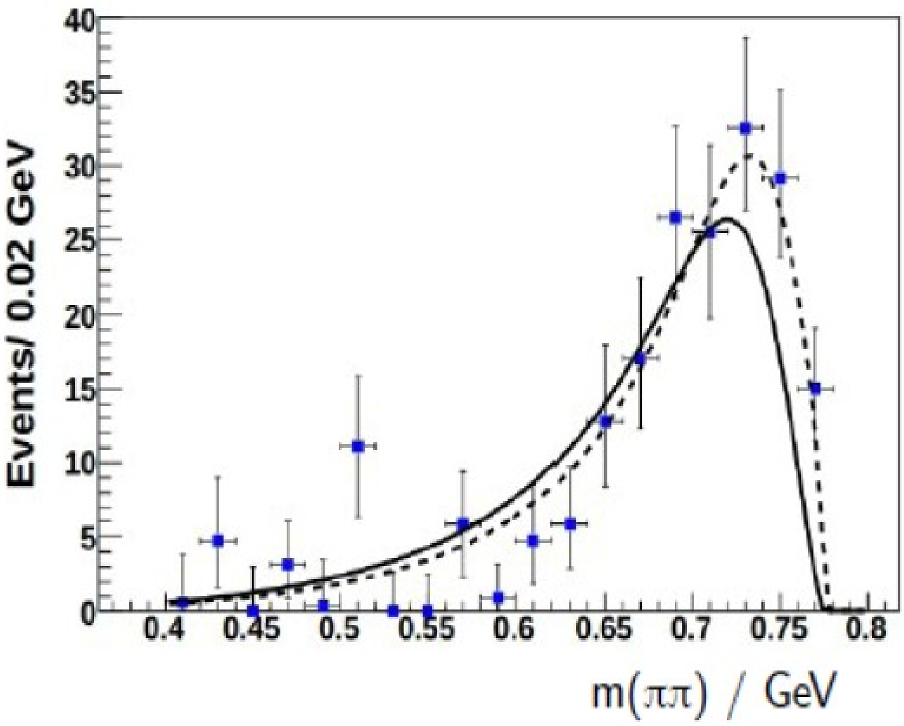
PRD 84 (2011) 052004



- 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)
  → bias 0.23±0.11 MeV
- procedure for upper limit:
  width in 3-dim fit fixed
  n_{signal} and n_{BG} floating
  → calculate likelihood
- $\Gamma_{X(3872)}$ < 0.95 MeV + bias

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

X(3872): ACHIEVEMENTS AND INTERPRETATION AT BELLE



- Isospin-violating decay:

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

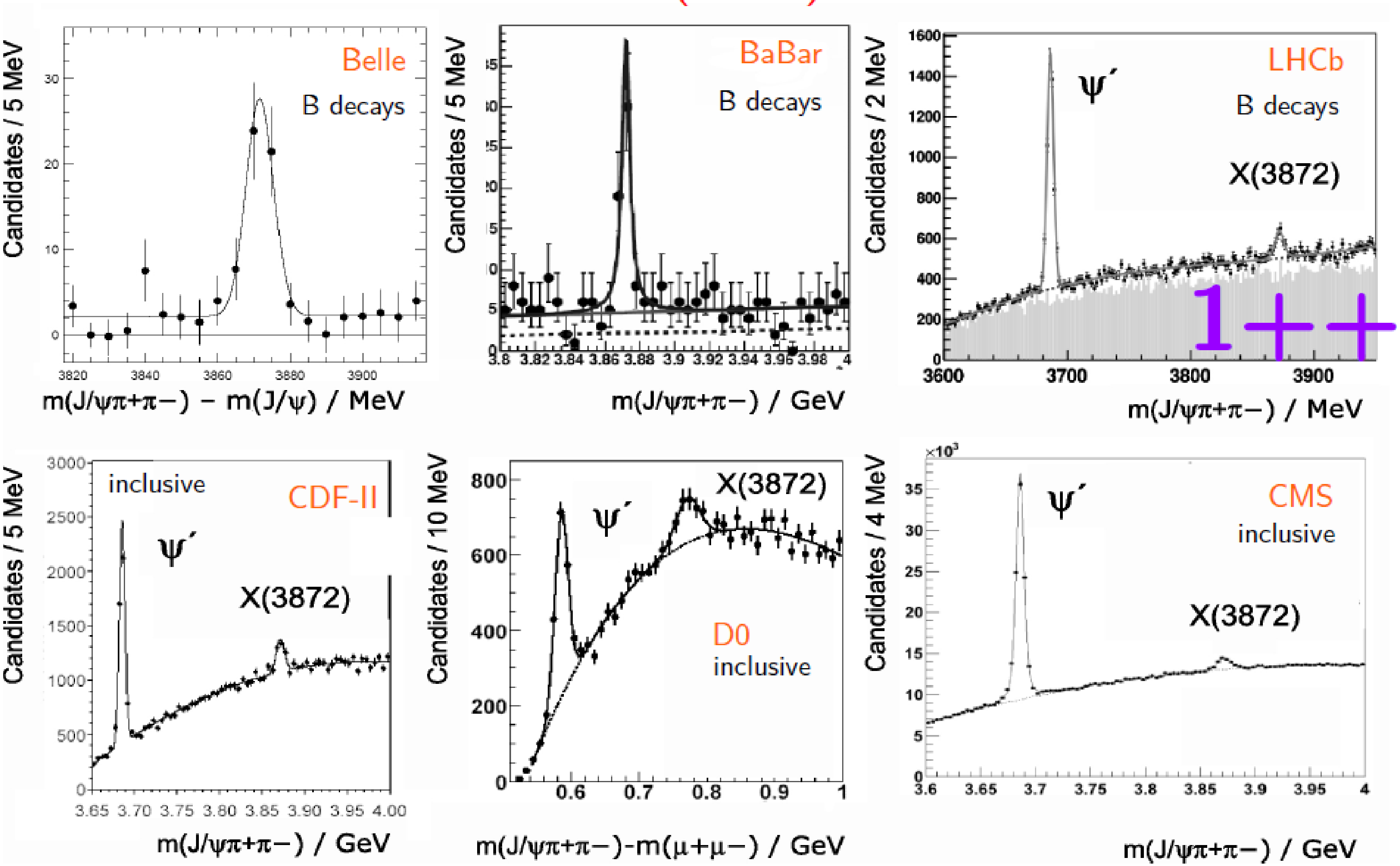
$J^{PC} = 1^{++}$, predicted nearby χ_{c1}'

Barnes et al, PRD72 (2005) 054026

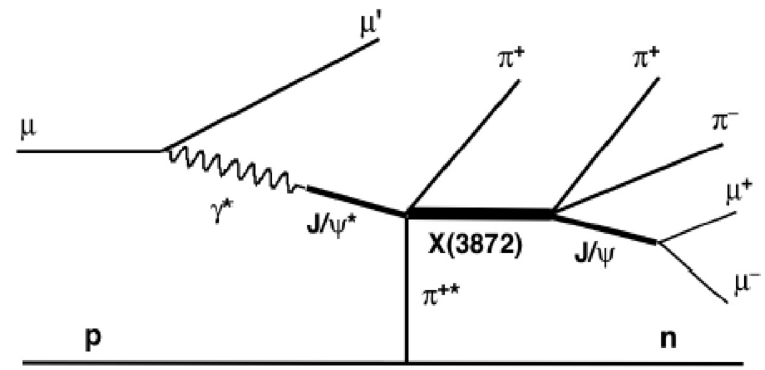
- Mass ⩾50 MeV higher
- Width ⩾100 larger

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
ψ´
CMS
inclusive
X(3872)
Candidates / 4 MeV
m(J/ψπ+π−) / GeV

Photoproduction of X(3872)

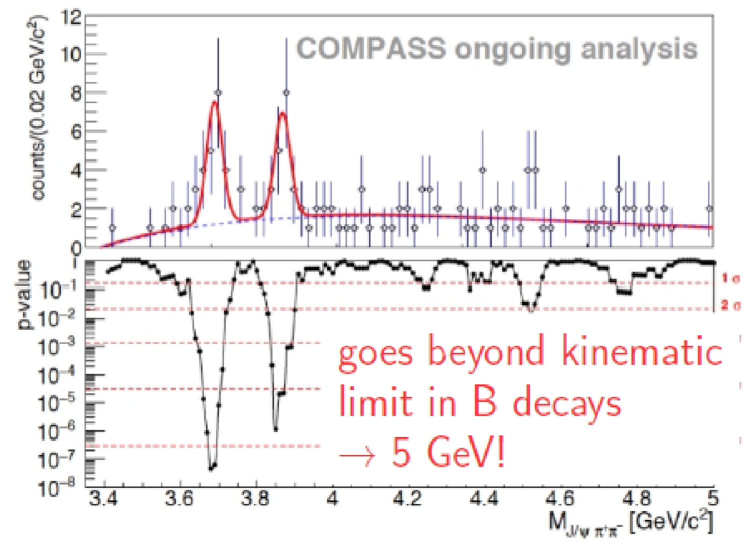


Muon data 2003-2010

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

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

$\sigma_M = 20.6 \pm 6.1$ MeV

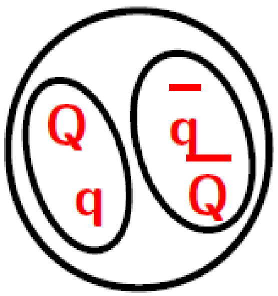


goes beyond kinematic limit in B decays → 5 GeV!

COMPASS, arXiv:1707.01796 [hep-ex]

Is the X(3872) exotic ?

TETRAQUARK

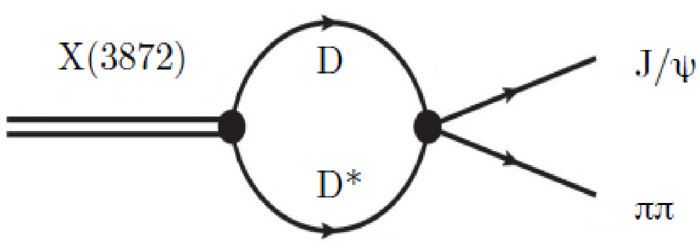


$[qQ]_8[\overline{qQ}]_8$

Diquarks
are colored

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

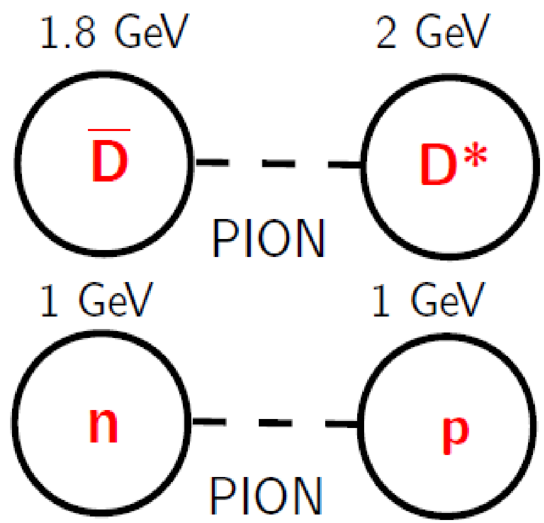
THRESHOLD CUSP



Bugg; Swanson

MOLECULE

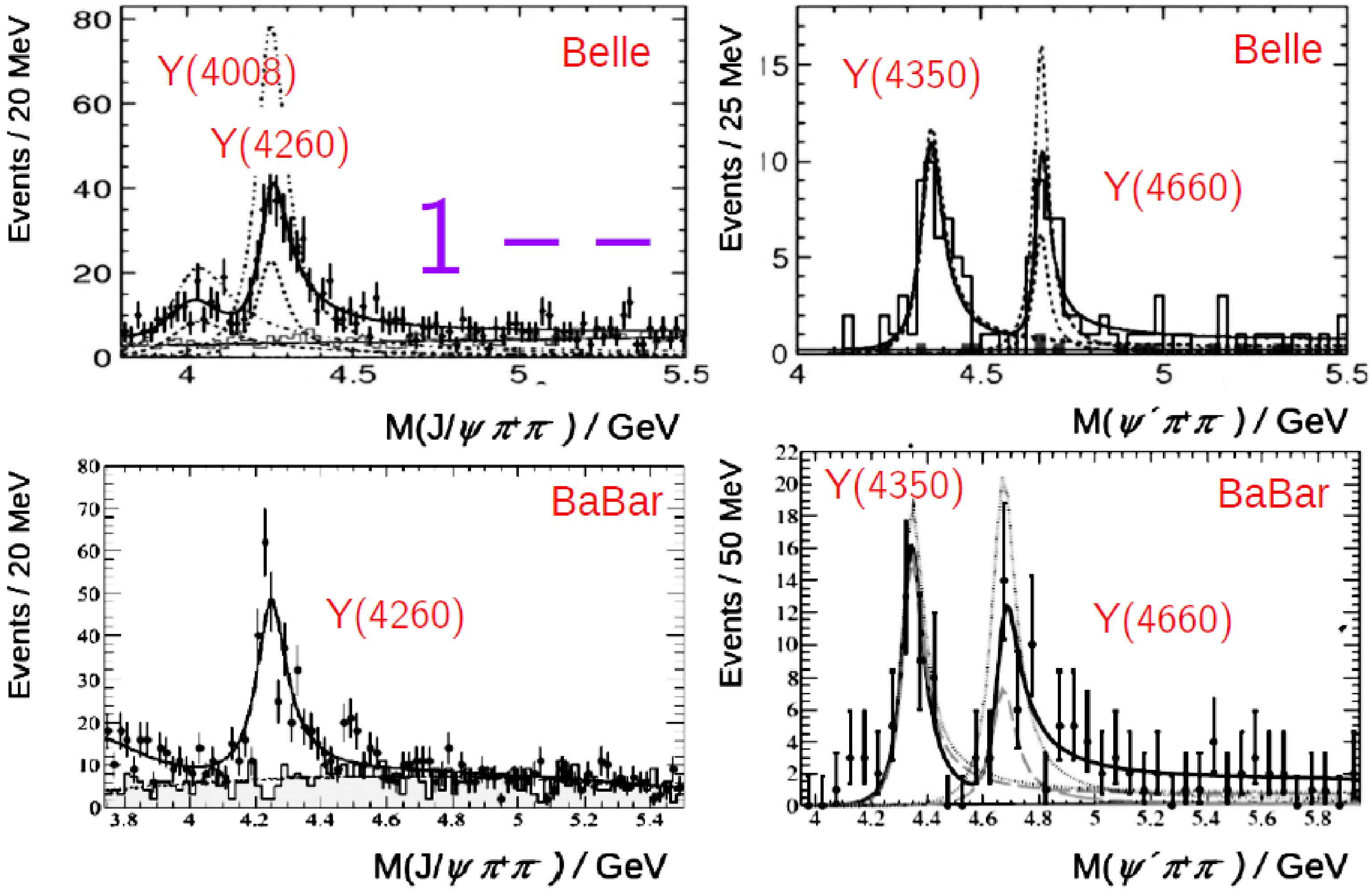
Intriguing Analogon



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

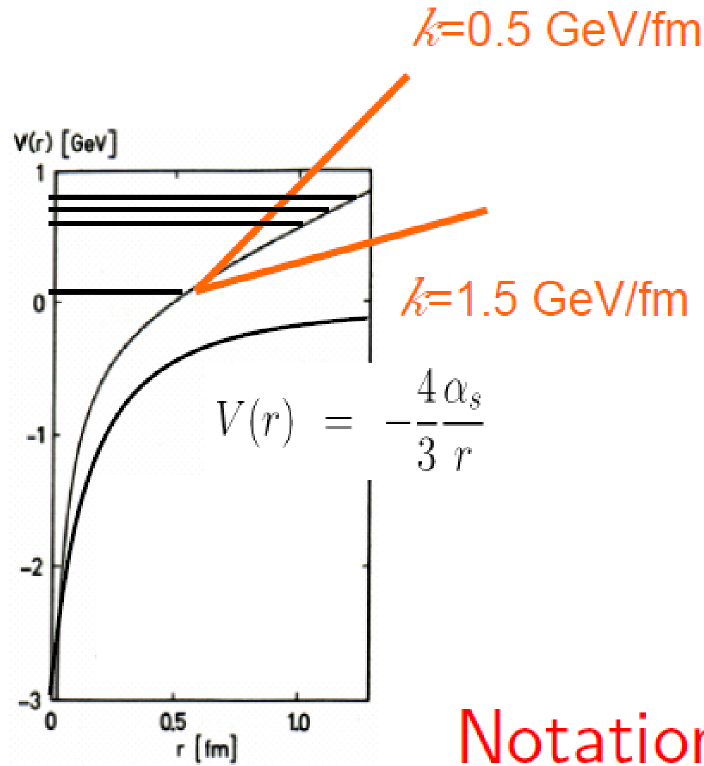
- Coulomb-Potential
  + Confinement-Term

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

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

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

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



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

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

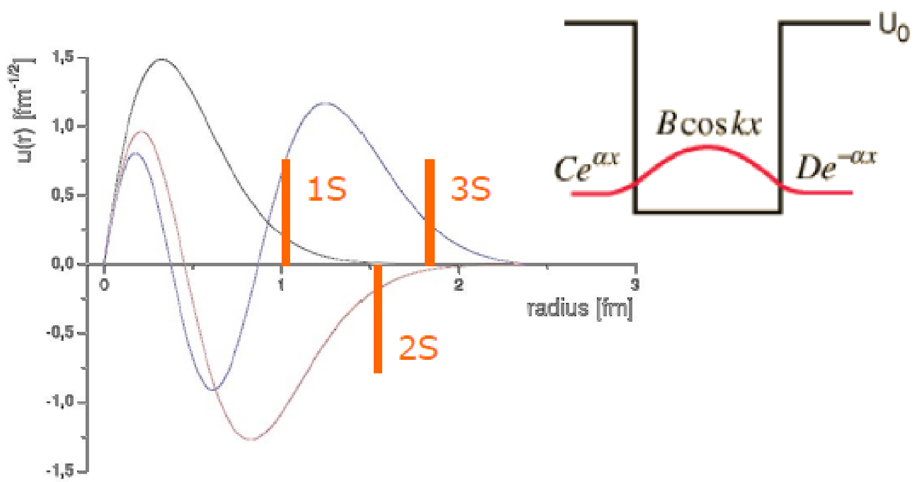
$$\left[-\frac{1}{m_q}\left(\frac{\partial^2}{\partial r^2} + \frac{2}{r}\frac{\partial}{\partial r} + \frac{l(l+1)}{m_q r^2} + V(r)\right)\right]R_{nl}(r) = E_{nl}R_{nl}(r)$$

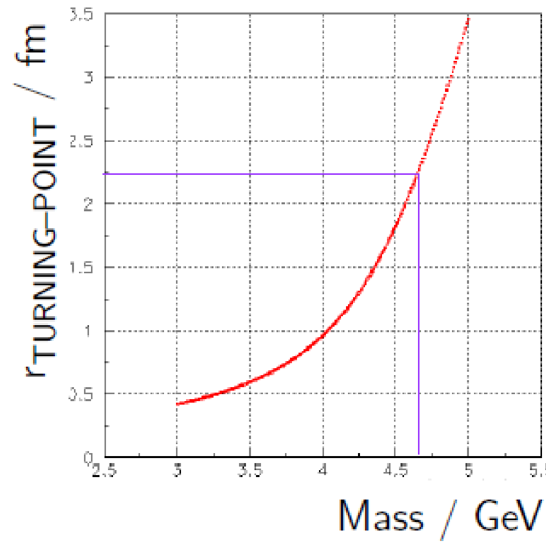
Notation
$n^{2S+1}L_J$
J^{PC}

JÜLICH Forschungszentrum

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

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

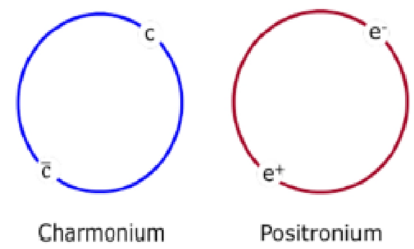




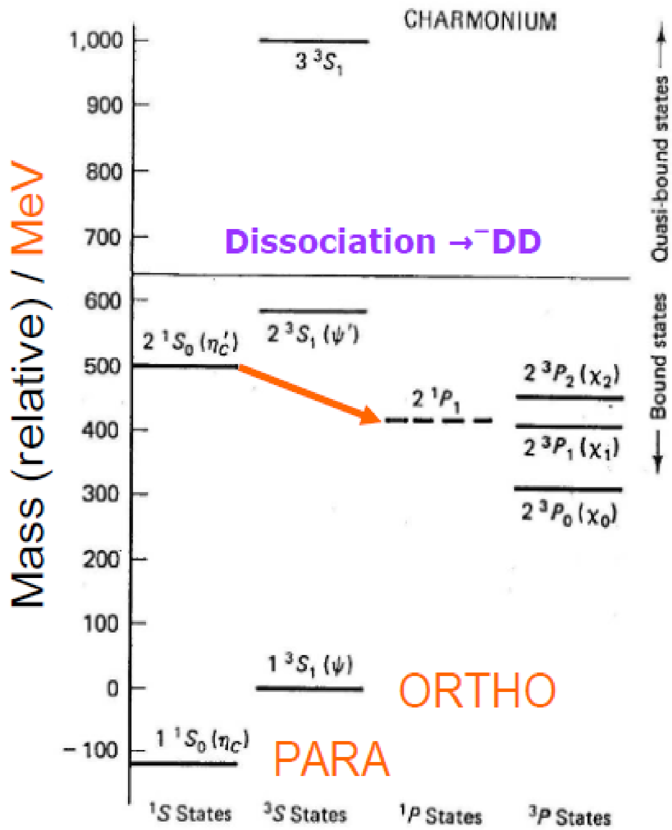
- m=4.660 GeV → turning point of wave function is 2.2 fm!
- large fraction of wave function in string breaking regime r>1.4 fm

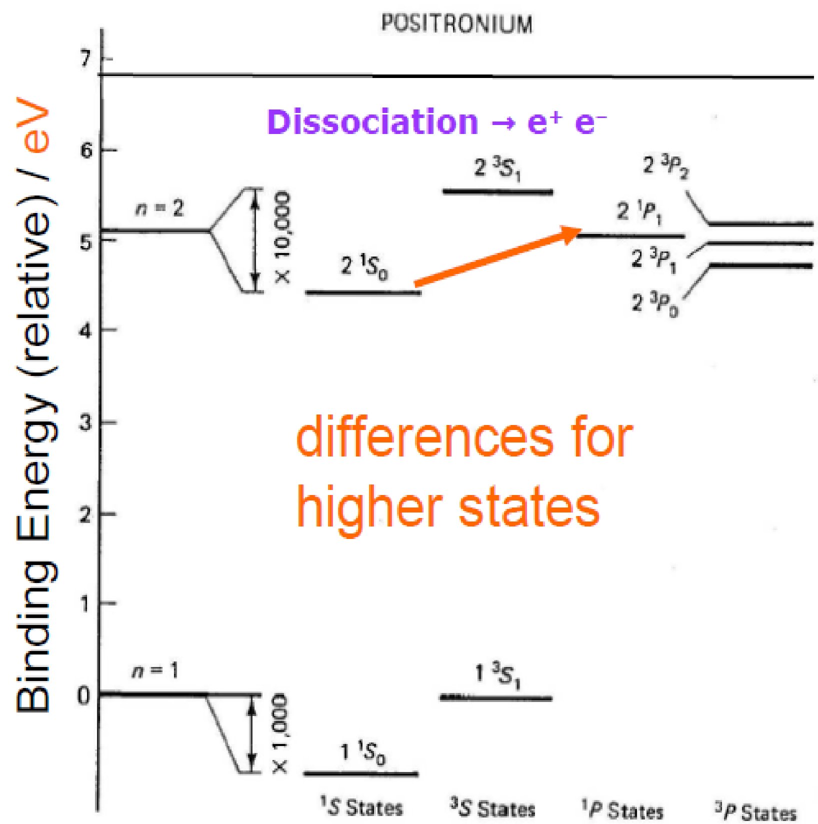
courtesy of J.S. Lange, HIRSCHEGG2018

Charmonium vs. Positronium

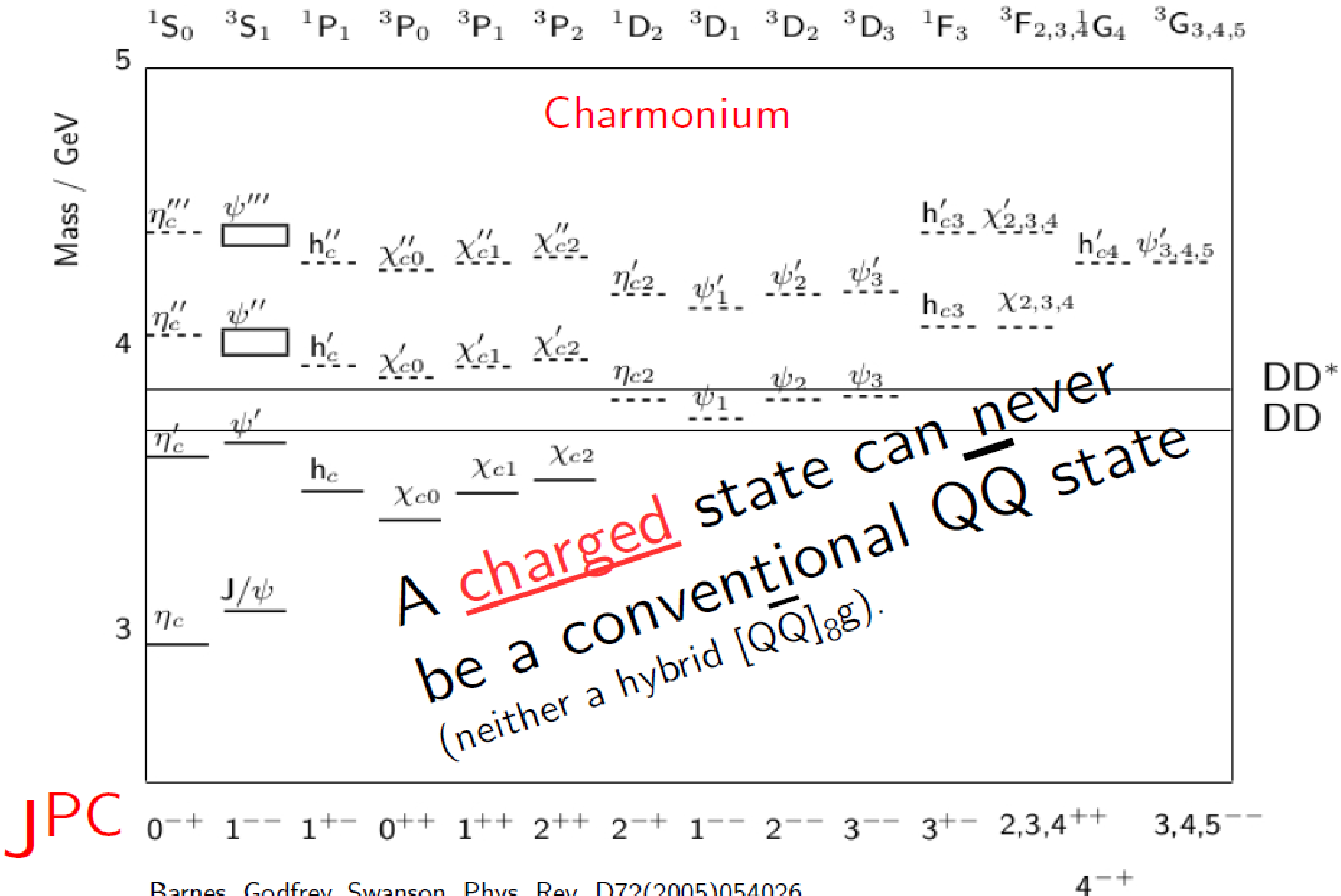


Decays to light quarks suppressed
→ narrow widths





courtesy of J.S. Lange, HIRSCHEGG2018



Barnes, Godfrey, Swanson, Phys. Rev. D72(2005)054026

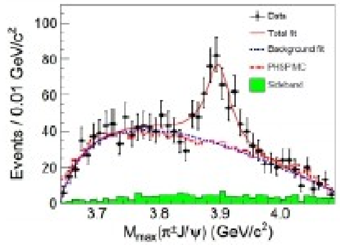
JÜLICH Forschungszentrum

Landiao LIU, QWG 2016

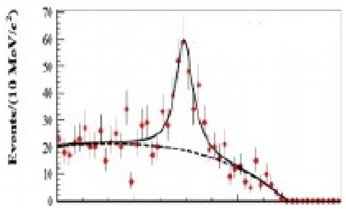
Z STATES AT BESIII

$D\bar{D}^*$ threshold

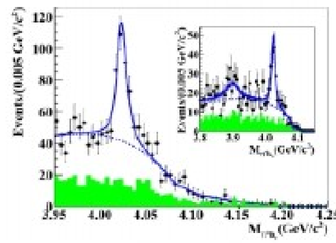
$D^*\bar{D}^*$ threshold



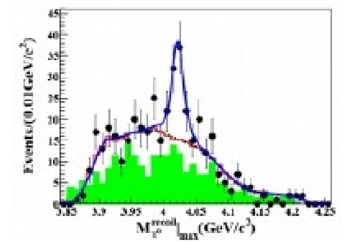
$e^+e^- \to \pi^+ \pi^- J/\Psi$



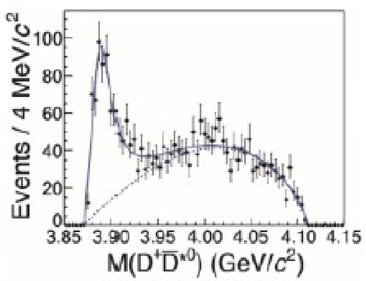
$e^+e^- \to \pi^0 \pi^0 J/\Psi$



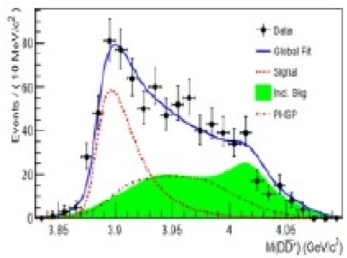
$e^+e^- \to \pi^+ \pi^- h_c$



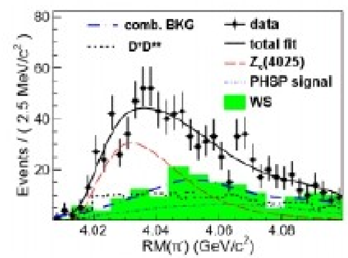
$e^+e^- \to \pi^0 \pi^0 h_c$



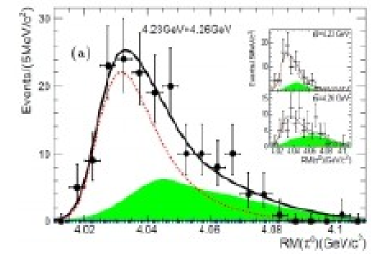
$e^+e^- \to \pi^+ (D\bar{D}^*)^-$



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



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



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

charged | neutral | charged | neutral

Recent hot topic: neutral partners → isospin triplets
All of them 1+, whereever tested.

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±3.6±4.9	$D^+\overline{D}^{0*}$	+22.4
$Z_c(3900)$	3899.0±3.6±4.9	$D^0\overline{D}^{+*}$	+23.9
$Z_c(3900)$	3894.5±6.6±4.5	$D^+\overline{D}^{0*}$	+17.9
$Z_c(3900)$	3894.5±6.6±4.5	$D^0\overline{D}^{+*}$	+19.4
$Z_c(3900)$	3885±5±1	$D^+\overline{D}^{0*}$	+8.4
$Z_c(3900)$	3885±5±1 MeV	$D^0\overline{D}^{+*}$	+9.9
$Z_c(3885)$	3883.9±1.5±4.2	$D^+\overline{D}^{0*}$	+7.4
$Z_c(3885)$	3883.9±1.5±4.2	$D^0\overline{D}^{+*}$	+8.8
$Z_c(4020)$	4022.9±0.8±2.7	$D^{0*}\overline{D}^{\pm*}$	+5.6
$Z_c(4025)$	4026.3±2.6±3.7	$D^{0*}\overline{D}^{\pm*}$	+9.0
$Z_c(4032)^+$	$\simeq$ 4032.1±2.4	$D^{0*}\overline{D}^{\pm*}$	+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)

A MC study of slow pion tracking efficiency, and pions from K^0_S in $B^0 \rightarrow \Phi K^0_S$ (fake rate of 50%). Master Thesis (Belle II) – L. Koch - 2016