Exotics at Belle & Perspectives at Belle II

12.03.2018 I Elisabetta Prencipe

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(Kopaonik, Serbia)

DFG Deutsche Forschungsgemeinschaft

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Outline

- Introduction
- Recent achievements in spectroscopy at Belle:
  - ☑ overview of Y states via ISR production mechanism
  - ☑ Z charged states: can they come from Y states?
  - ☑ the $X^*(3860)$ – new results in 2017!
  - ☑ search for glueballs and pentaquarks – new results in 2017!
  - ☑ bottomonium: main achievements and future perspectives
- Open questions and possible interpretation
- The Belle II experiment – phase II successfully started
- Perspectives in search for exotics at Belle II
- Summary

Introduction

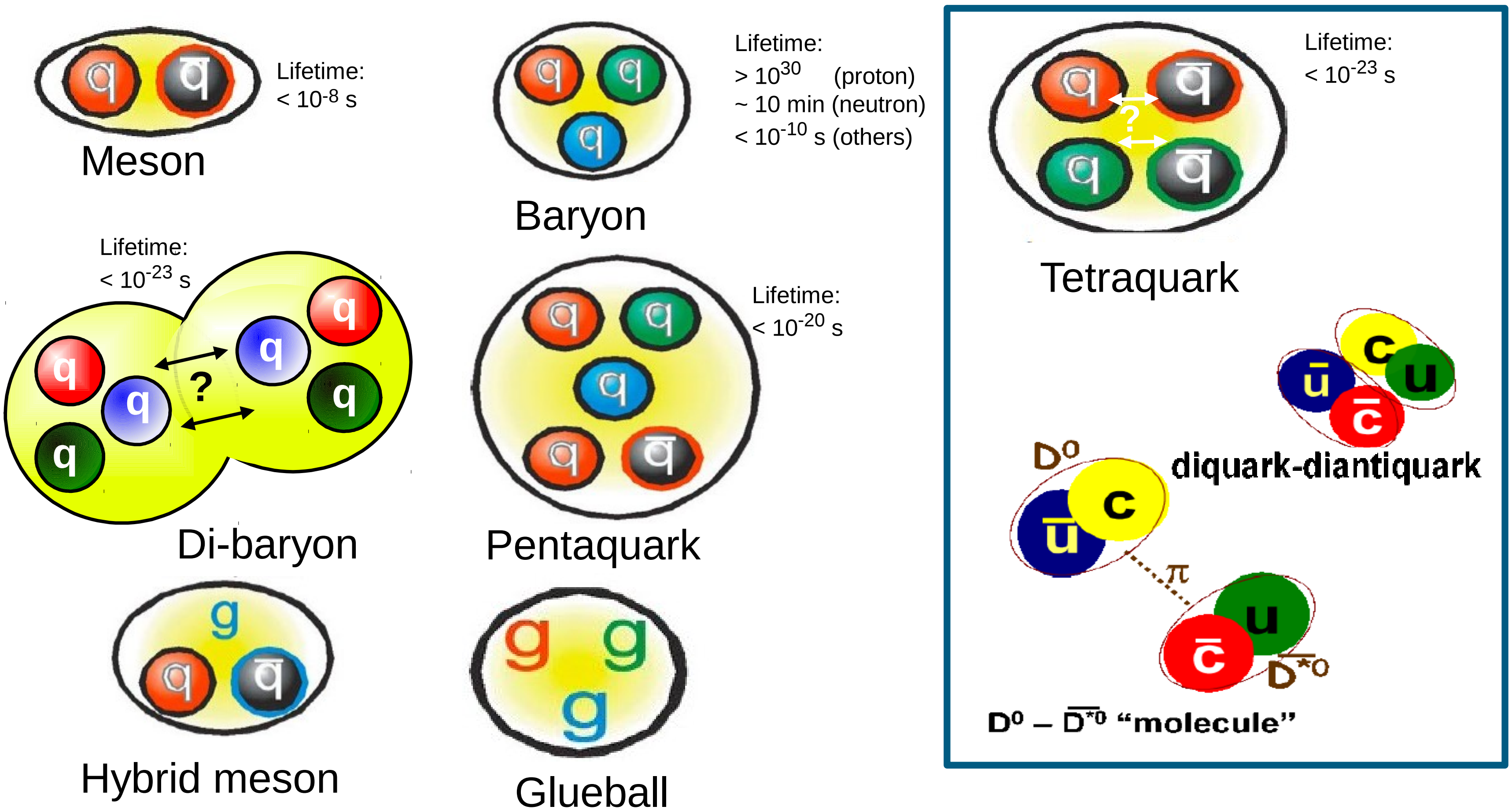
- Gell-Mann Zweig idea: Constituent Quark Model (CQM).

  Still valid since 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). These are 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*!

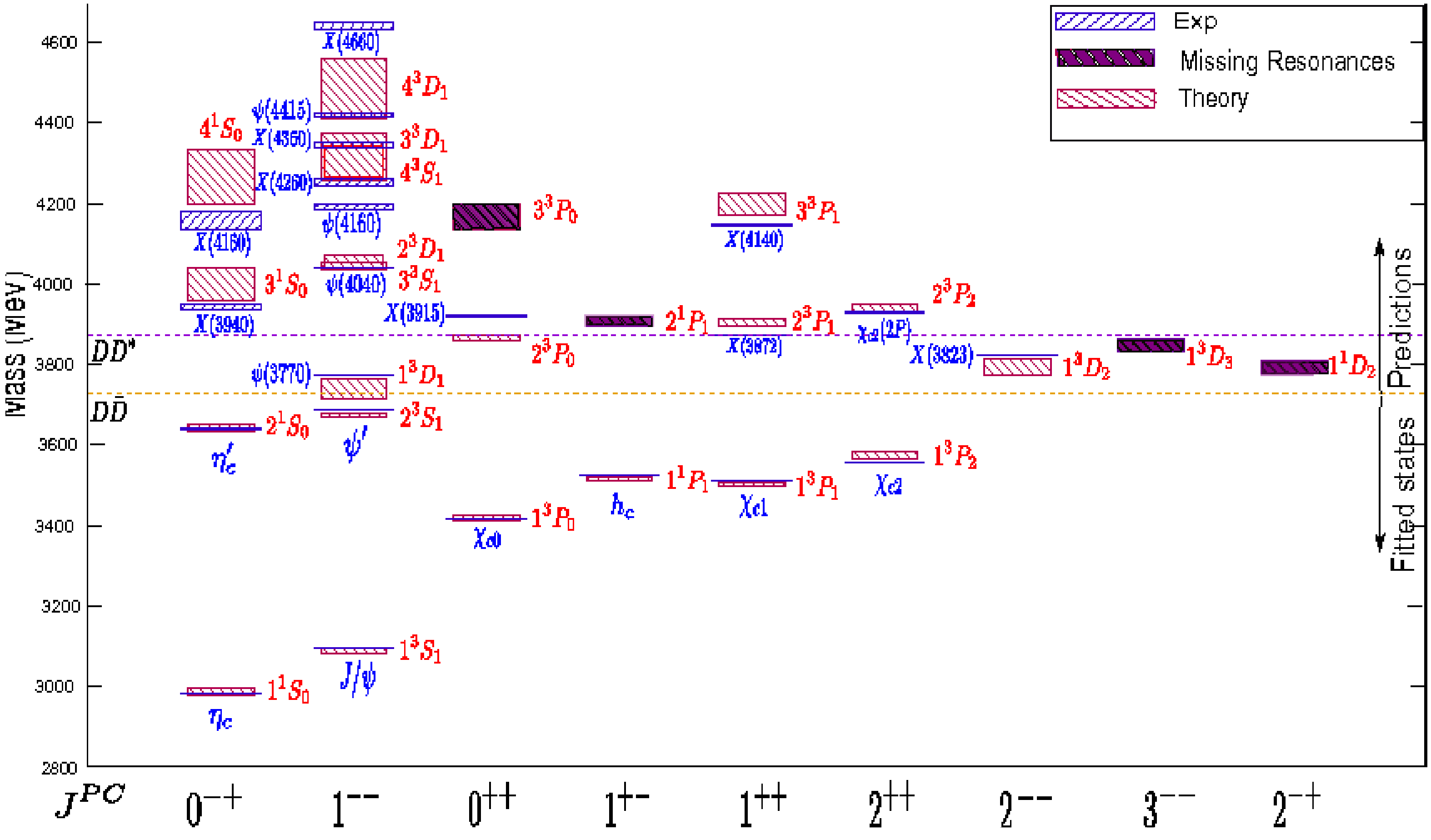
  Substantial contribution from Belle to into the field

Quark Bound States



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

Charmonium Spectrum



- Overall agreement experiments-theory so far: precision ~2-3 MeV; but....

For >30 years theory and experiments agreed.
Then something happened.

How has the story begun?

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Then something happened.

How has the story begun?

Phys. Rev. Lett. 91 (2003) 262001 Belle, accepted 23 December 2003

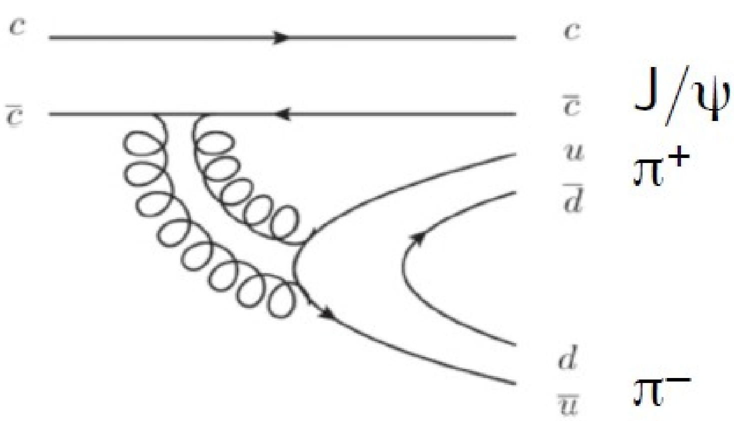
Observation of a Narrow Charmoniumlike State in Exclusive $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ Decays

CITED 1630 times!

Remark

$$\underbrace{B^{\pm} \to K^{\pm} \; J/\psi\pi^{+}\pi^{-}}$$

resonant state?



$\mathcal{B}$(B decay)$\times\mathcal{B}$(X(3872) decay)$\simeq$ 10^{-5}

Small! B factory needed to search for it

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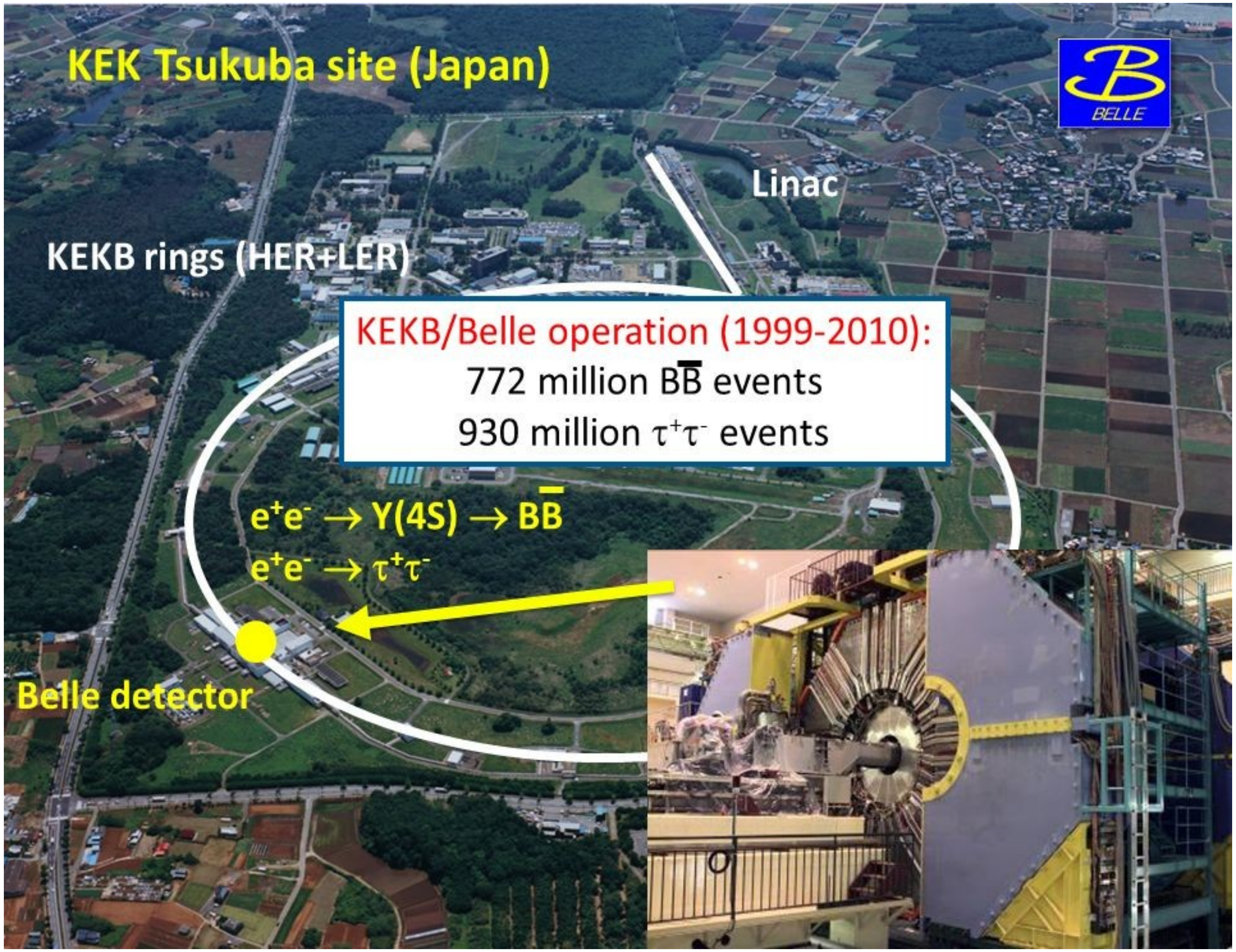
The KEK Facility in Tsukuba (Japan)



Recorded luminosity = 1.02 ab^{-1}

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

$\sim$ 100 fb^{-1}

Peak luminosity achieved: $2.1 \times 10^{34} cm^2/s^{-1}$

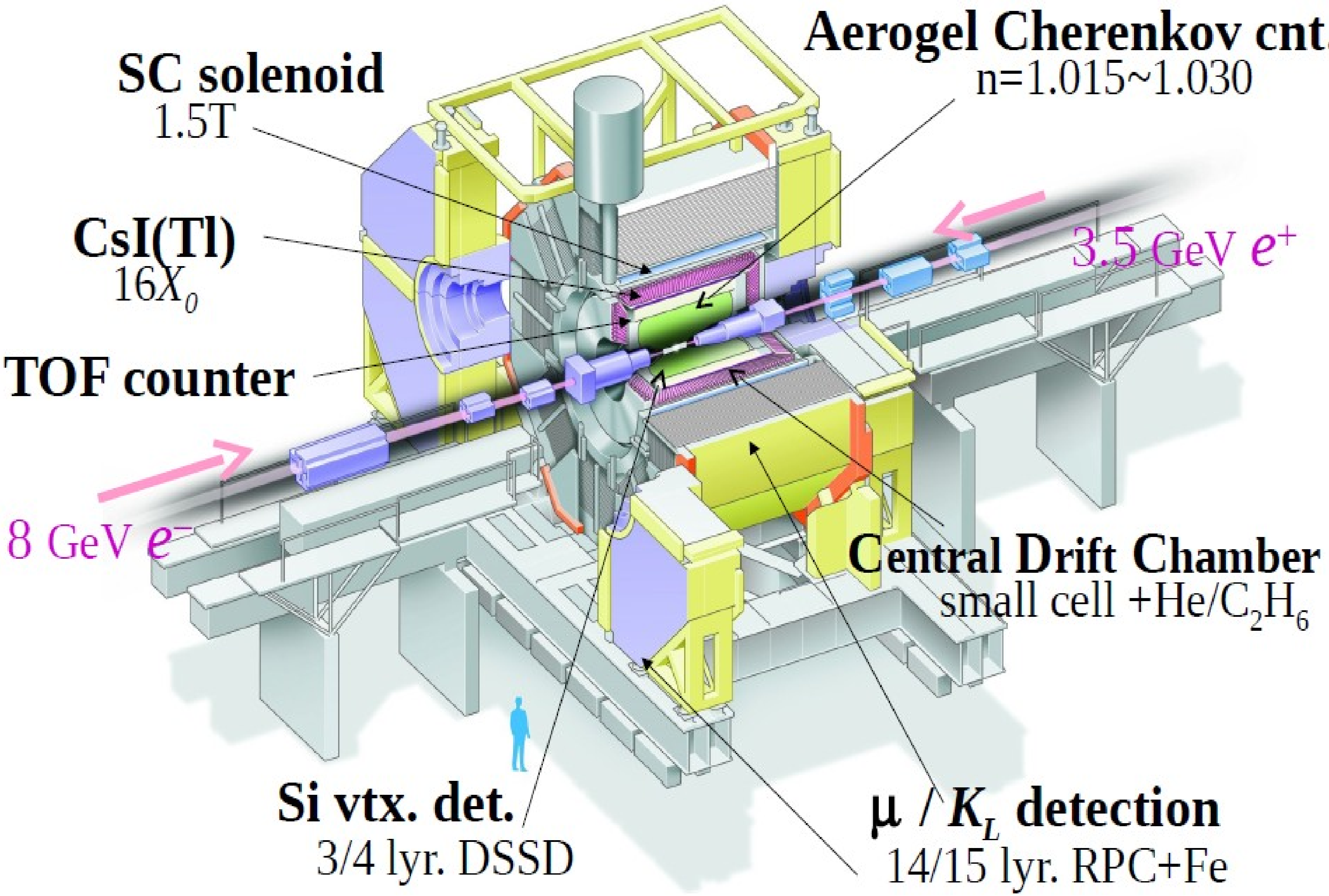
$\beta\gamma = 0.42$

$p(e^-) = 8.0$ GeV/c

$p(e^+) = 3.5$ GeV/c

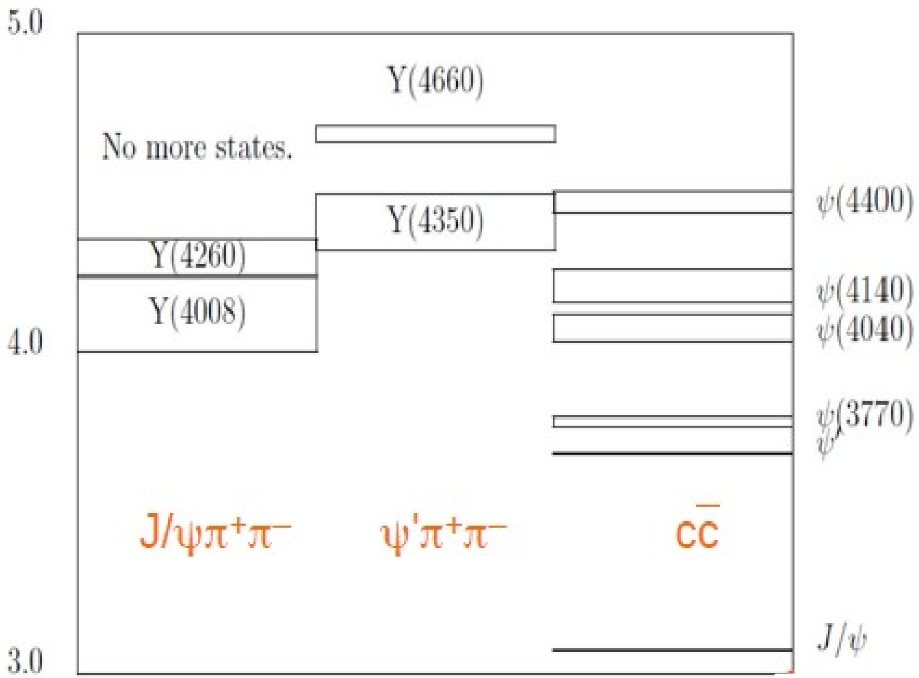
Crossing angle = 22 mrad

The Belle Detector



Y Family - Summary

Contribution from Belle



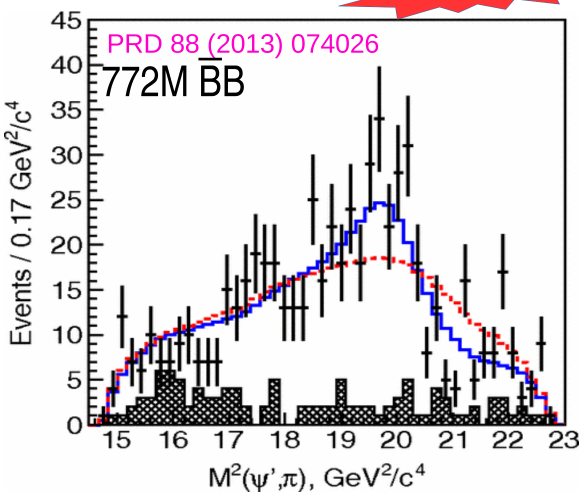
	Mass (MeV/c^2)	Width (MeV)
Y(4008)	$4008\pm40\,^{+114}_{-28}$	226±44±87
Y(4260)	4258.6±8.3±12.1	134.1±16.4±5.5
Y(4360)	4361±9±9	74±15±10
Y(4660)	4664±11±5	48±15±3

- ISR studies: unique at B factories
- Clear signature: $J^{PC} = 1^{--}$
- No mixing ⇨ surprising!

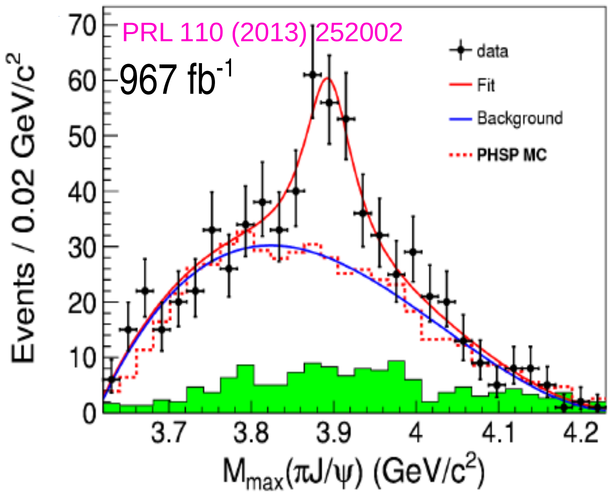
Z Charged States

Main achievements at Belle

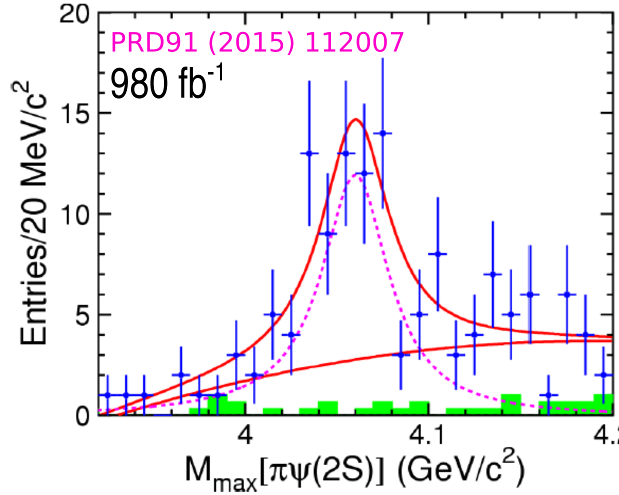
$B^0 \to K^- \pi^+ \psi'$ Update



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



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



$M = 4485 \pm 22^{+28}_{-11}$ MeV/c²
$\Gamma = 200^{+21}_{-46}\,{}^{+26}_{-35}$ MeV
6.4σ, $J^P = 1^+$

$M = 3894.5 \pm 6.6 \pm 4.5$ MeV/c²
$\Gamma = 63 \pm 24 \pm 26$ MeV
>5.2σ

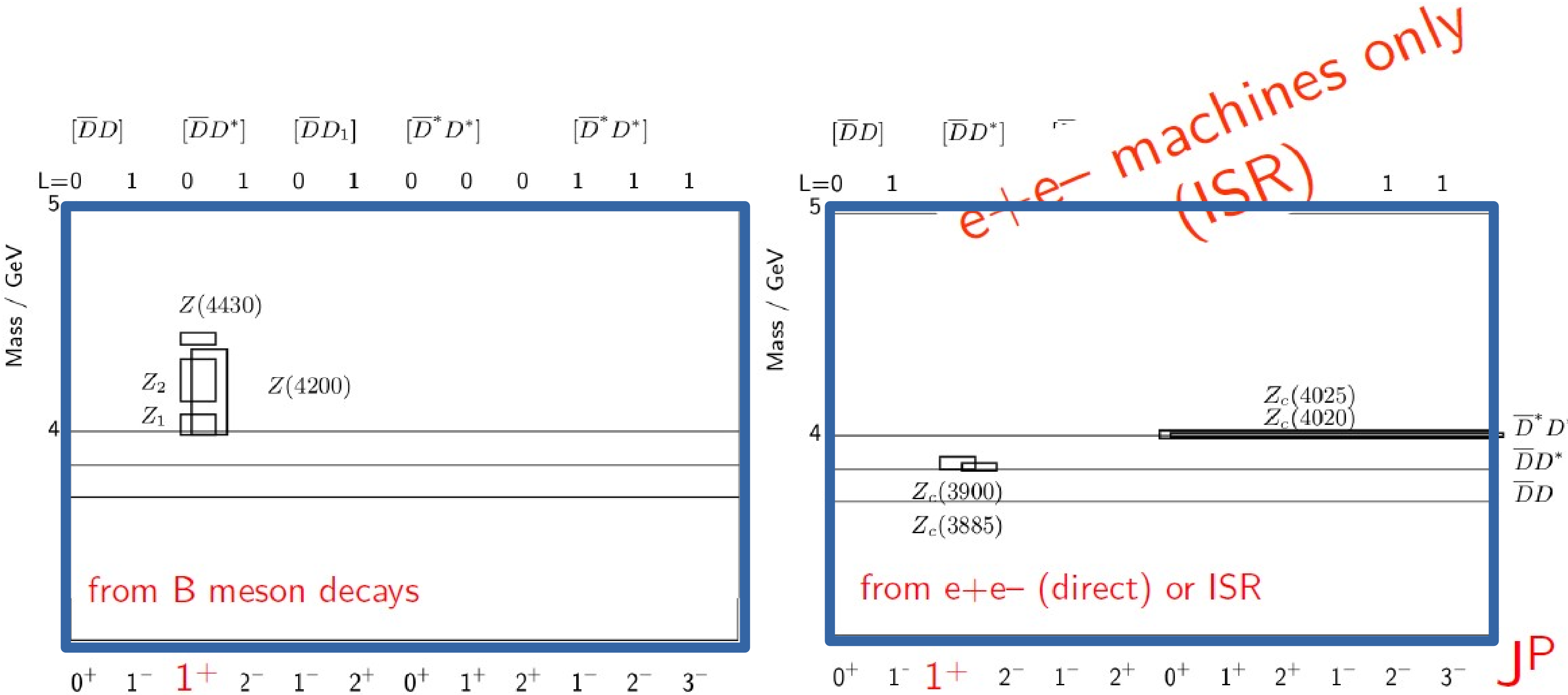
$M = 4054 \pm 3 \pm 1$ MeV/c²
$\Gamma = 45 \pm 11 \pm 6$ MeV
>3.5σ

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

BESIII confirmation:
PRL 110 (2013) 252001

Two different classes of Z states?

Understanding the pattern



– large widths
– not connected to thresholds?

– narrow widths
– near thresholds

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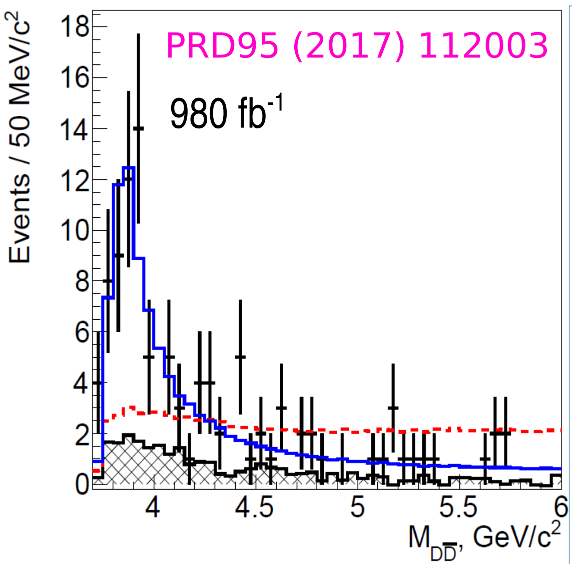
$X^*(3860)$: New State in $e^+e^-\to J/\psi D\bar{D}$

PRD 95 (2017) 112003



$M = 3862^{+26}_{-32}\,{}^{+40}_{-13}$ MeV/c^2

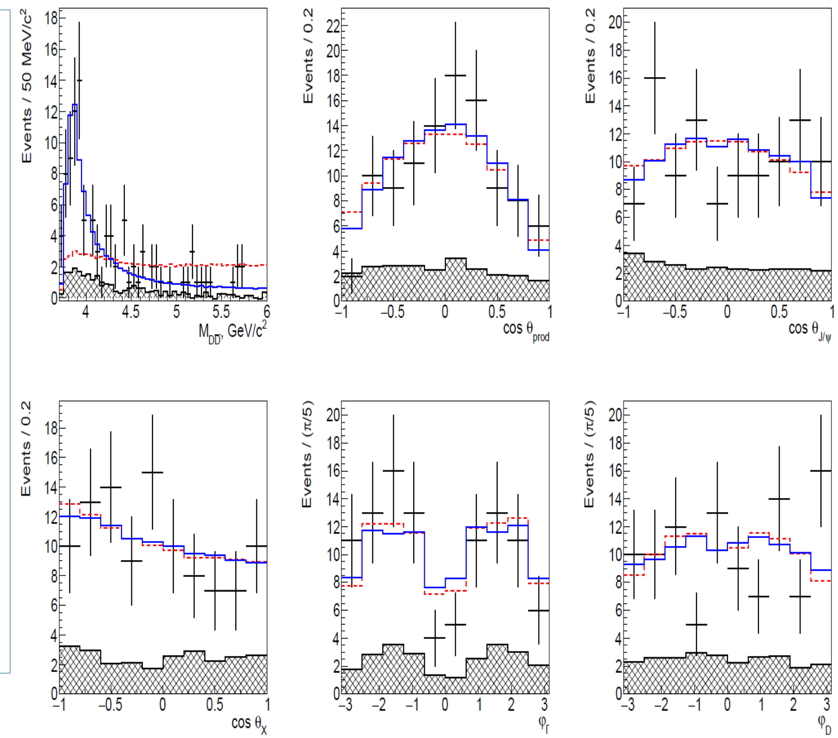
$\Gamma = 201^{+156}_{-67}\,{}^{+83}_{-82}$ MeV

$J^{PC} = 0^{++}$ (2^{++} not escl.)

Candidate for $\chi_{c0}(2P)$,

With $\chi_{c2}(2P) = Z(3900)$

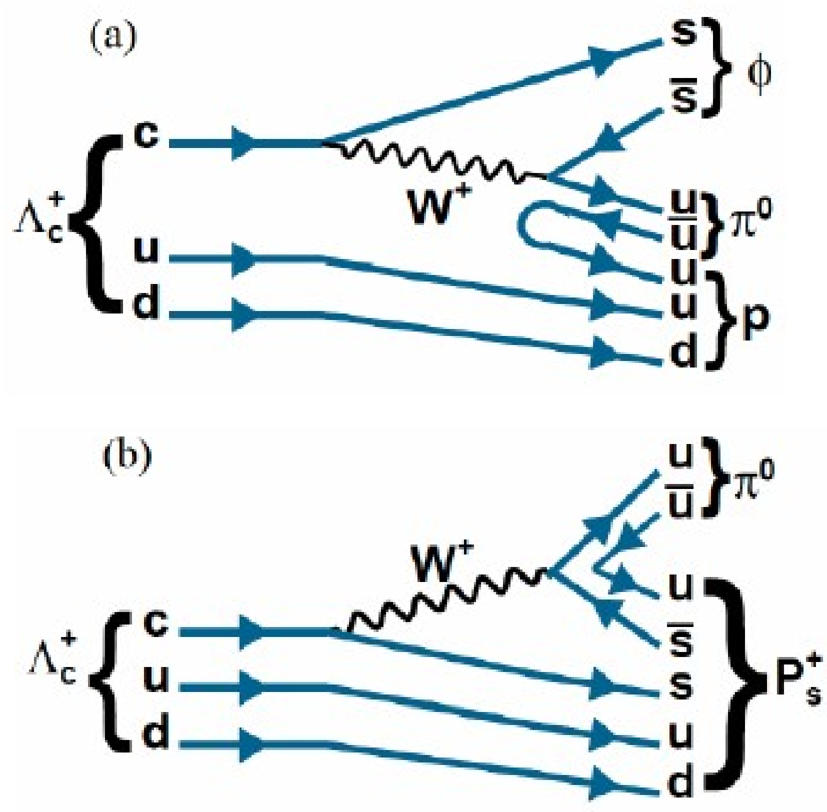
and $\chi_{c1}(2P) = X(3872)$?



- Strategy:
  - $J/\psi \to e^+e^-$, $\mu^+\mu^-$;
  - D^+ reconstructed to 5 decay modes, D^0 to 4.
  - $J/\psi D$ recoil in D mass region
  - Mass constraint to improve the mass resolution
  - PWA

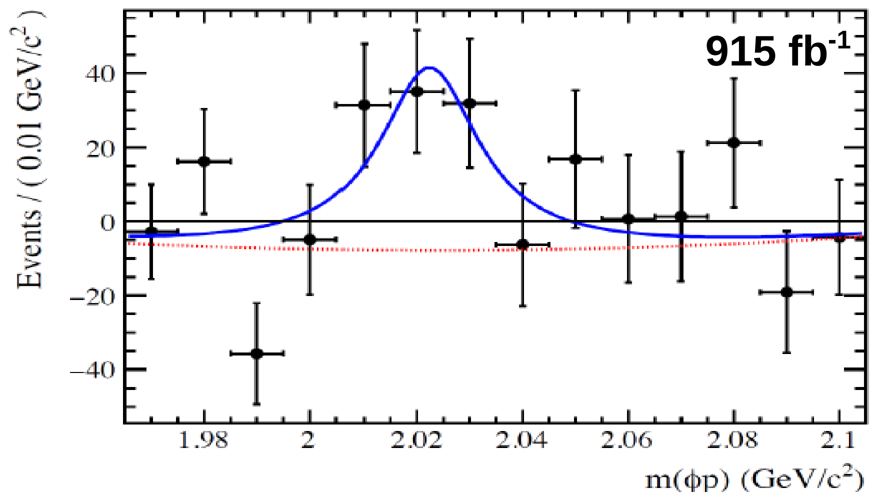
Search for Pentaquarks P_s at Belle

PRD 96 (2017) 051102



Feynman diagram for the decay:
(a) $\Lambda_c^+ \to \phi p \pi^0$ and (b) $\Lambda_c \to P_s^+ \pi^0$

Not the same as in LHCb!



- Best candidate found:
  $M = (2025 \pm 5)$ MeV/c^2
  $\Gamma = (22 \pm 12)$ MeV
  77.6±28.1 fitted events $\Lambda_c \to P_s^+ \pi^0$
  $\hookrightarrow \phi p$

only UL found!

- $B(\Lambda_c \to P_s^+ \pi^0) \times B(P_s^+ \to \phi p) < 8.3 \times 10^{-5}$
  @90%c.l.

What can we do more?

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 (~0.5M $ per 1 Quartz bar)
- 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

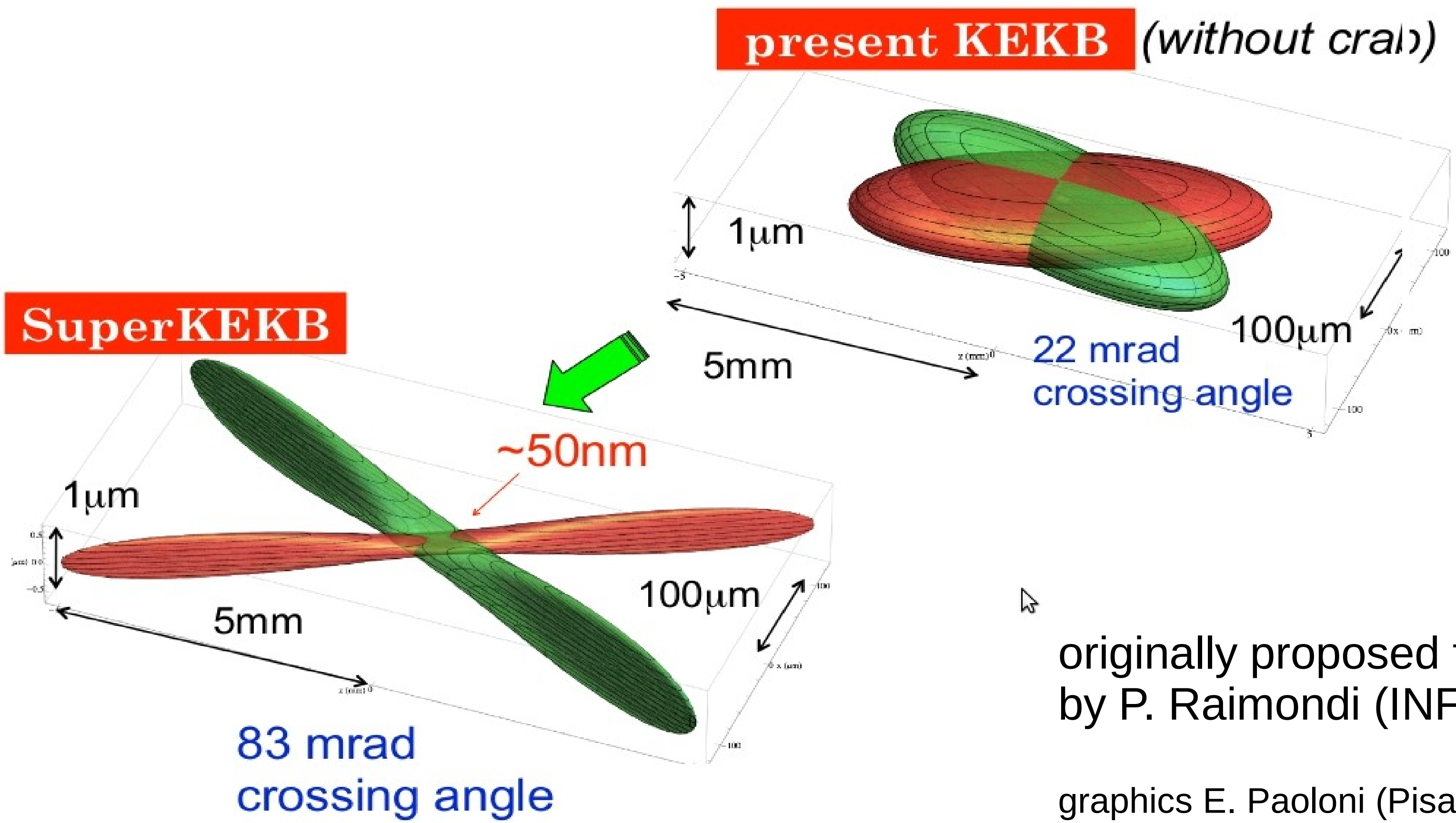
  – factor 20 by "nano-beam" principle (collision point in vertical direction will be only 59 nm)

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

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

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

Nano-Beam Scheme

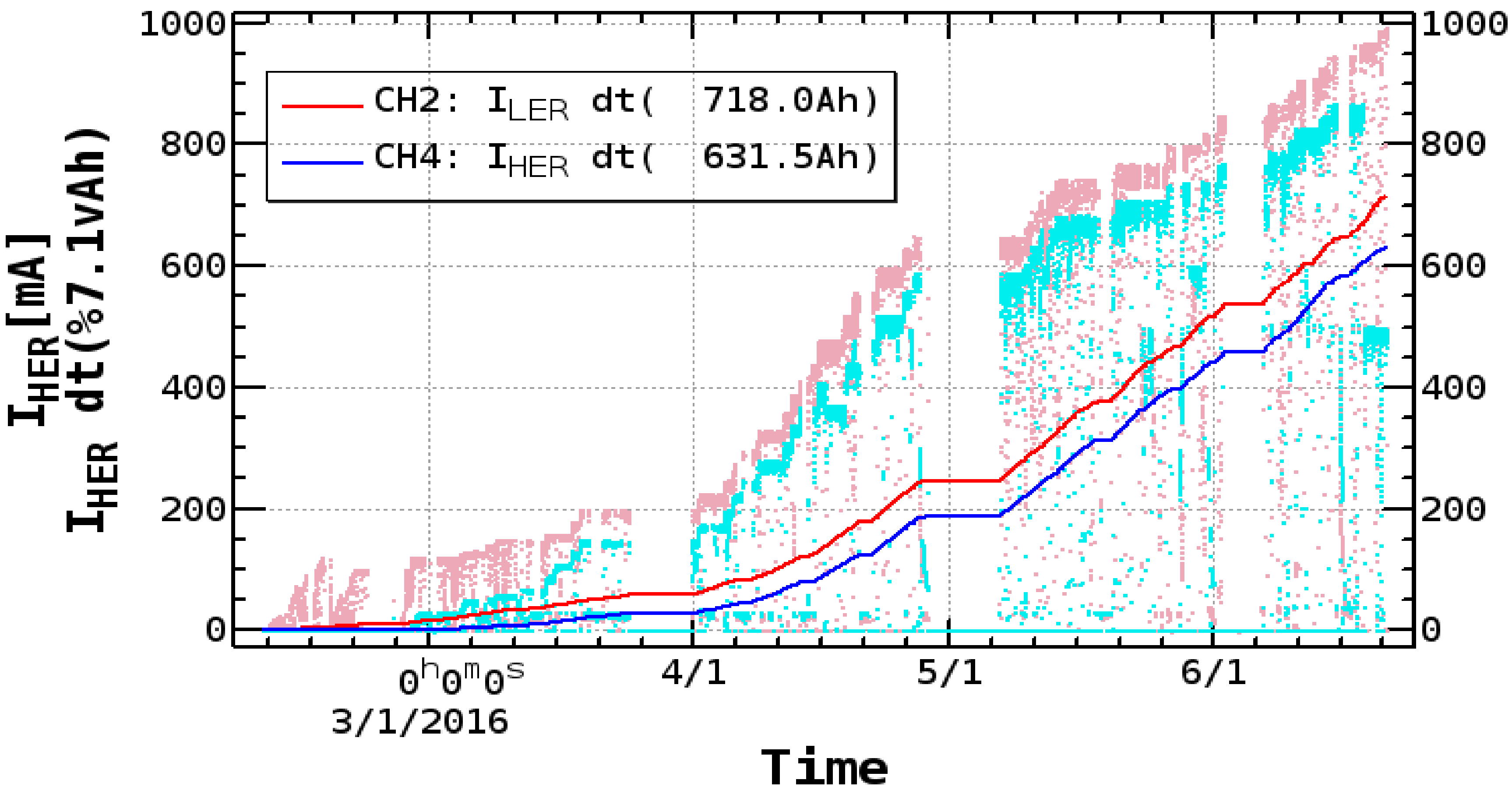


originally proposed for SuperB
by P. Raimondi (INFN)

graphics E. Paoloni (Pisa)

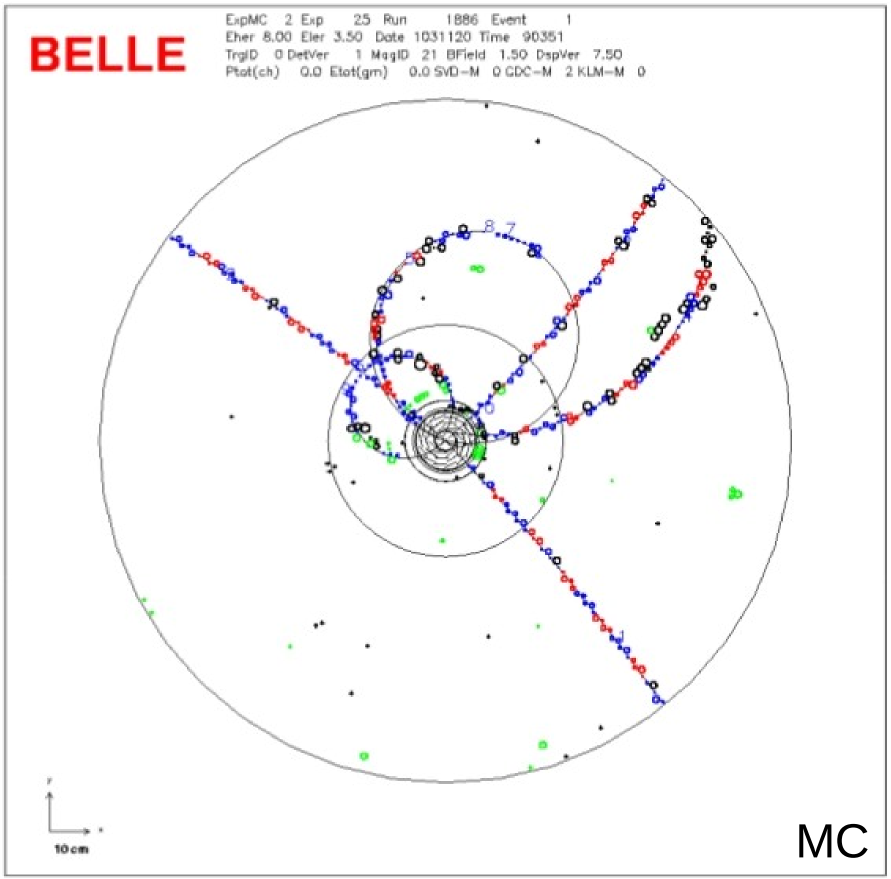
21.06.2016: LER beam current exceeded 1A

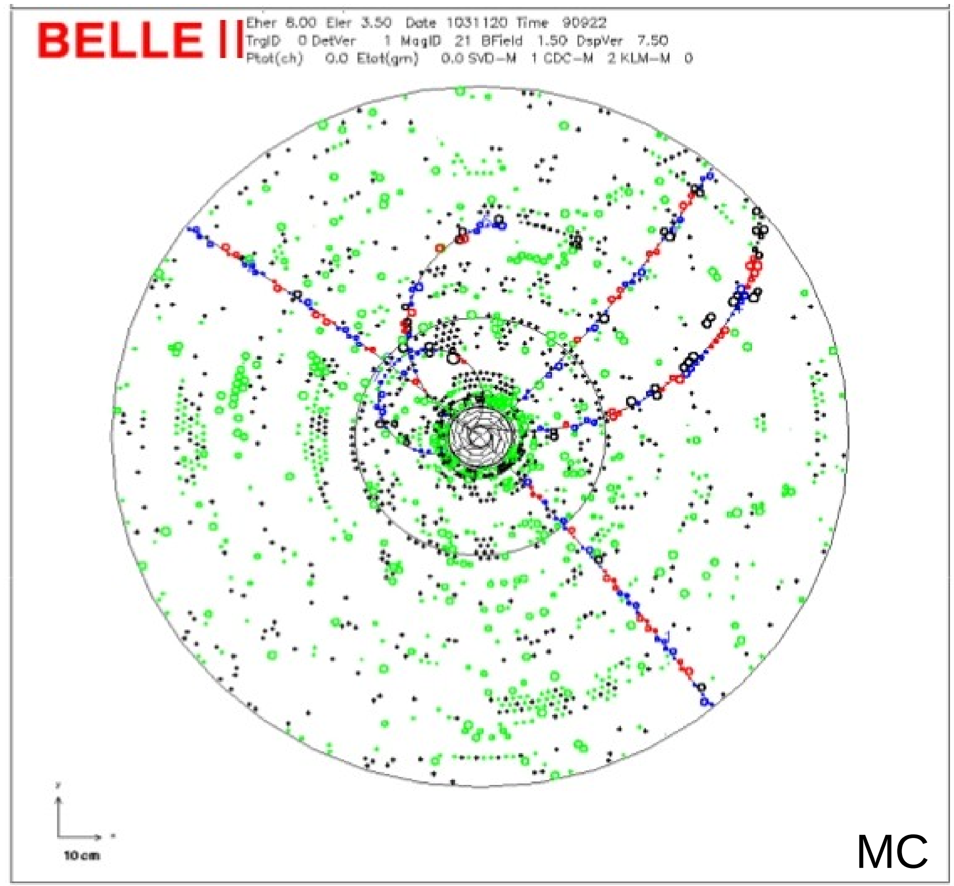
Phase-I operation at Belle II: detector commissioning



x40 more luminosity ⇨ higher background

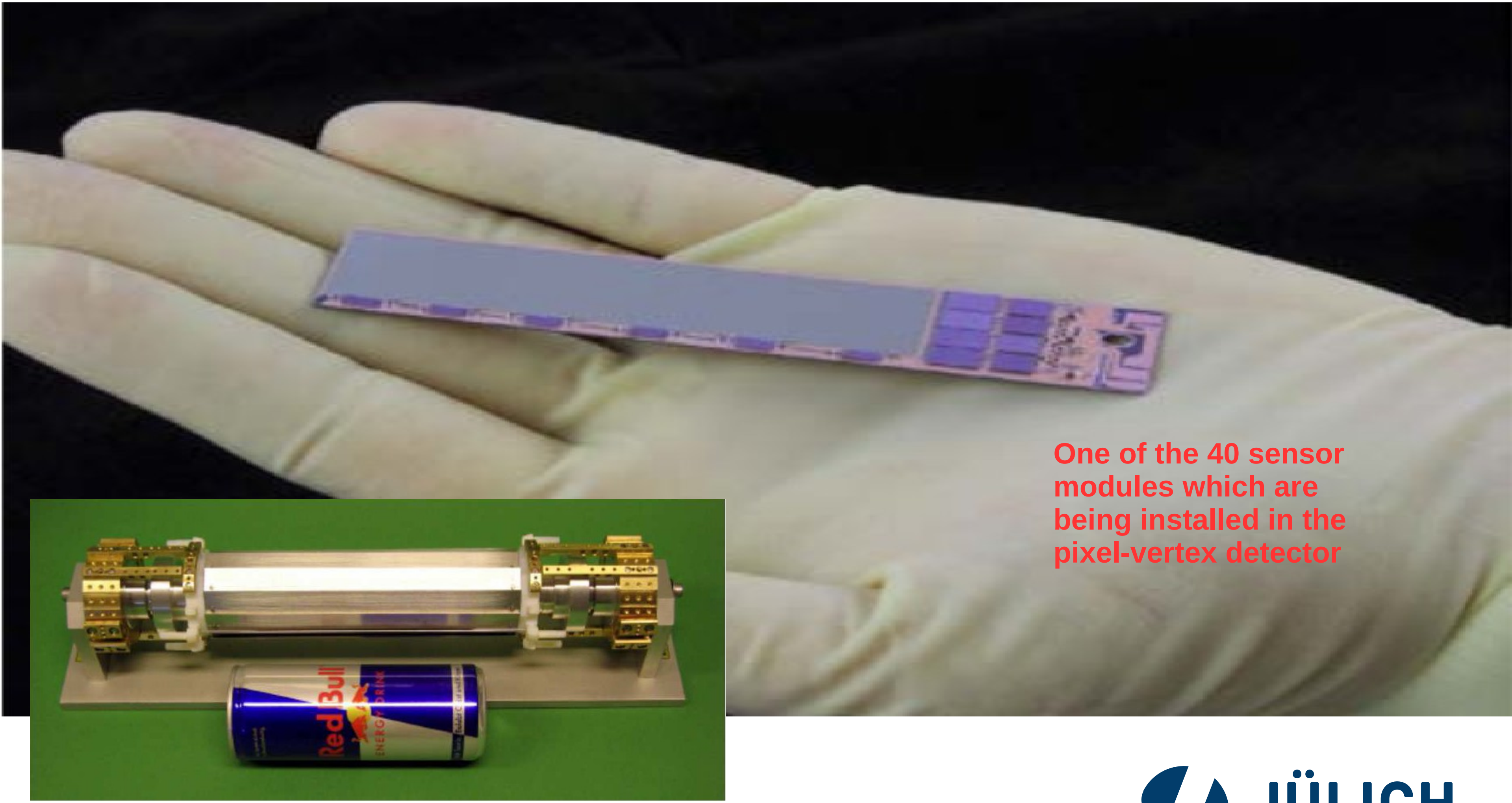
Phase-II data for background study, detector alignment and response (2018)





Vertex Pixel Detector (PXD)

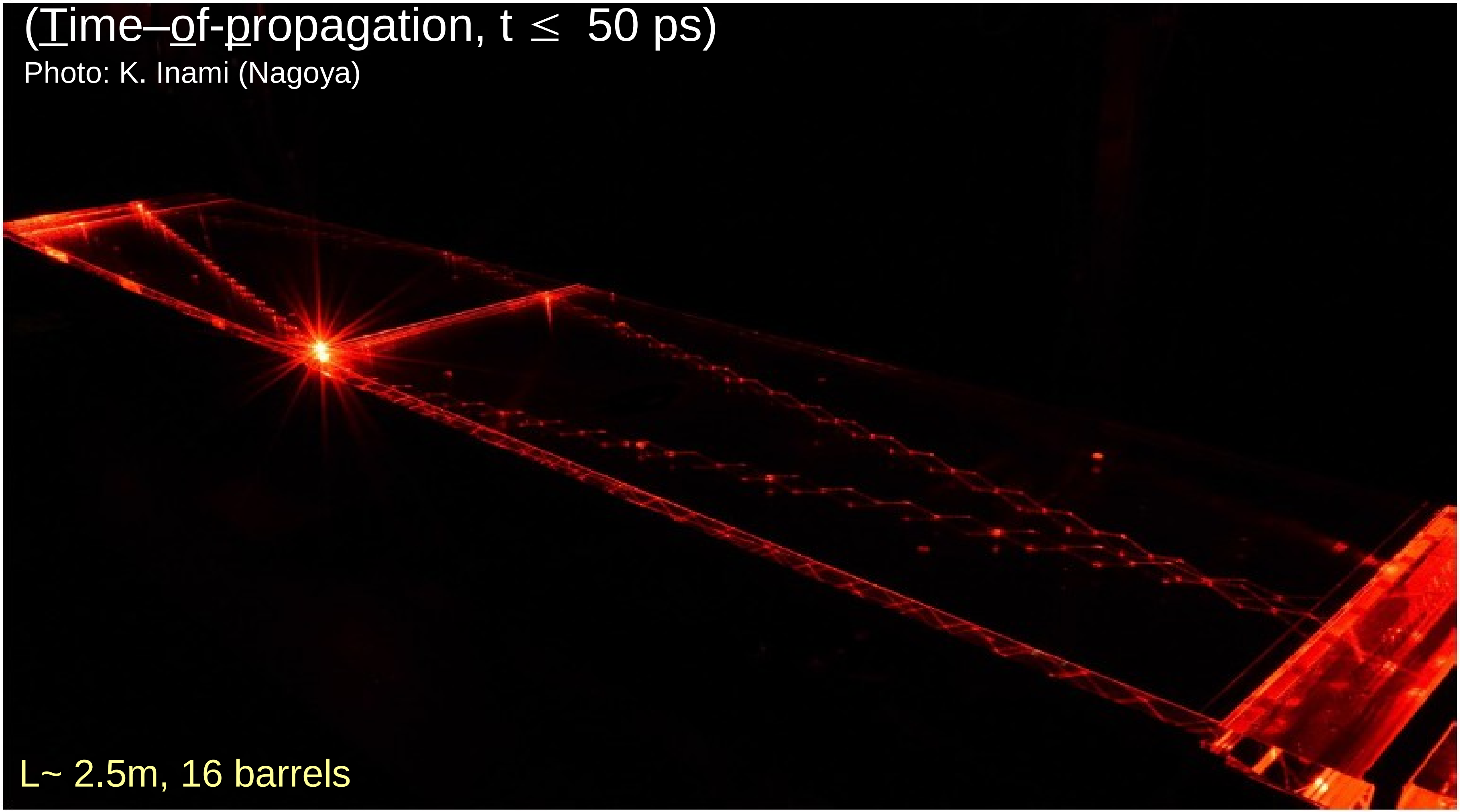
VXD consists of 2 layers of DEPFET (Pixel Detector) and 4 layers of double-sided silicon microstrip sensors (Silicon Vertex Detector), assembled over carbon fiber ribs.



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

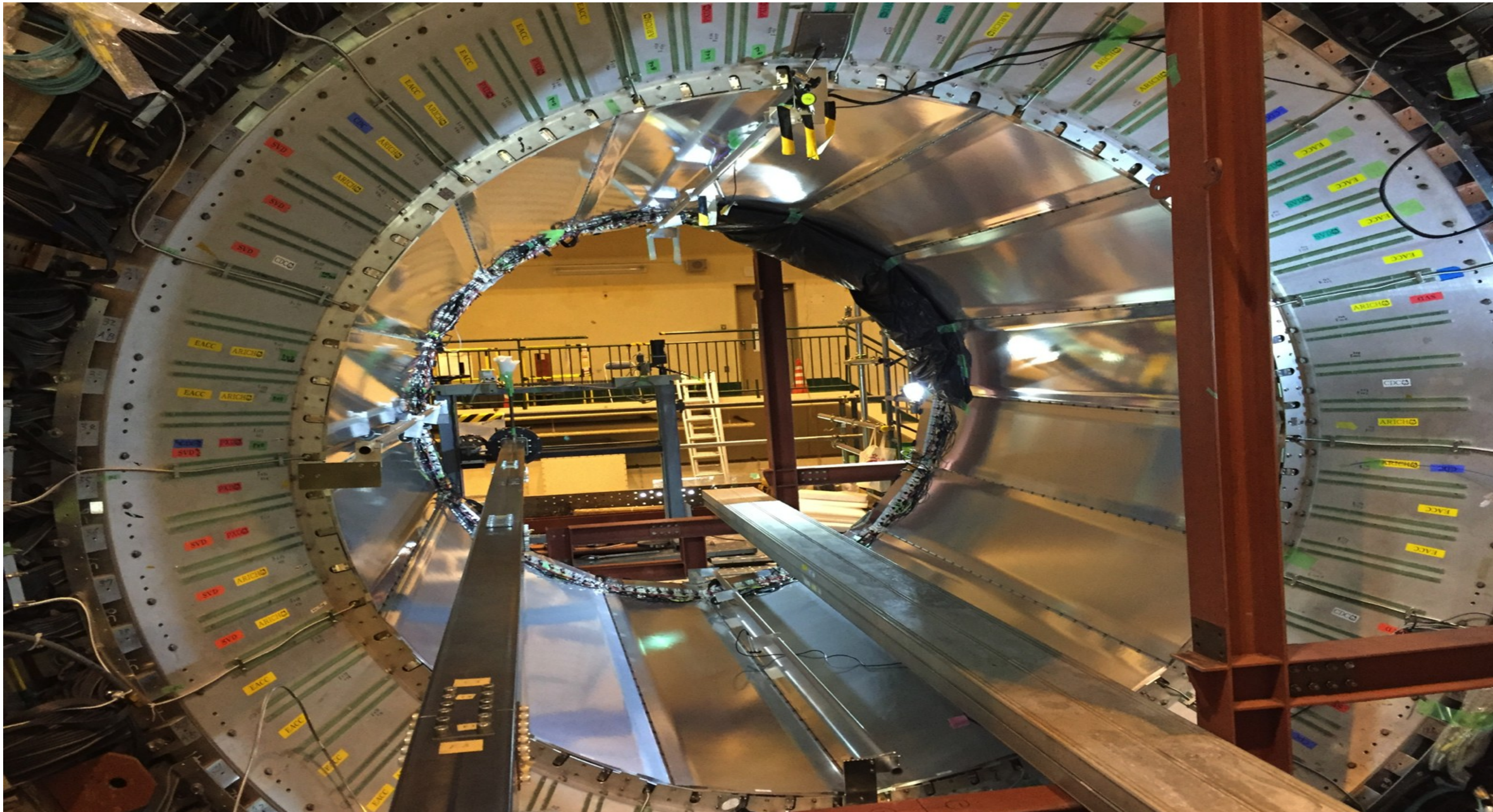
Cerenkov detector, laser in TOP module

Particle Identification



TOP installation, finished on 06.2016

Modules form a self-supporting arc



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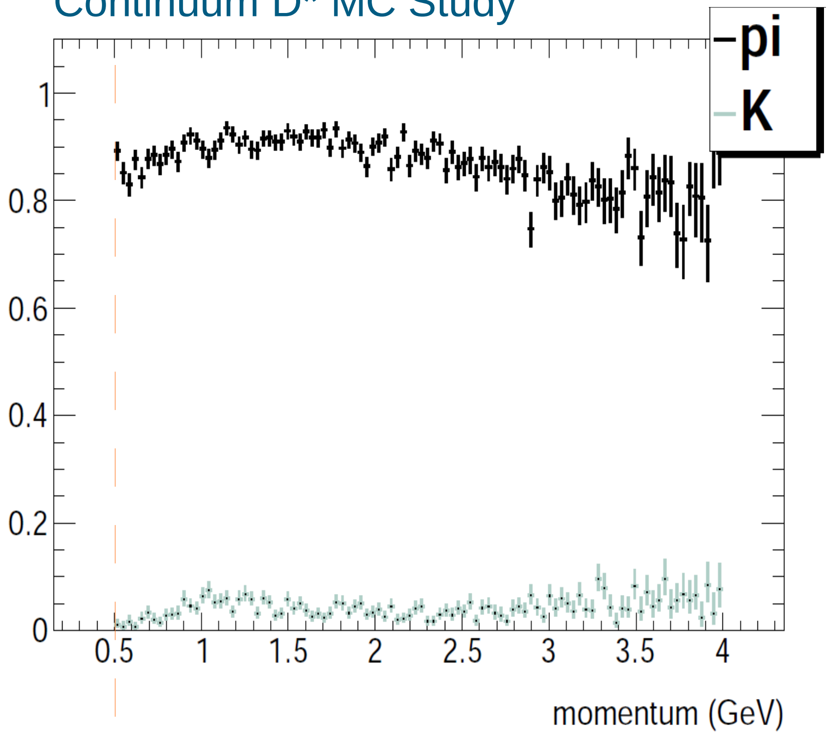
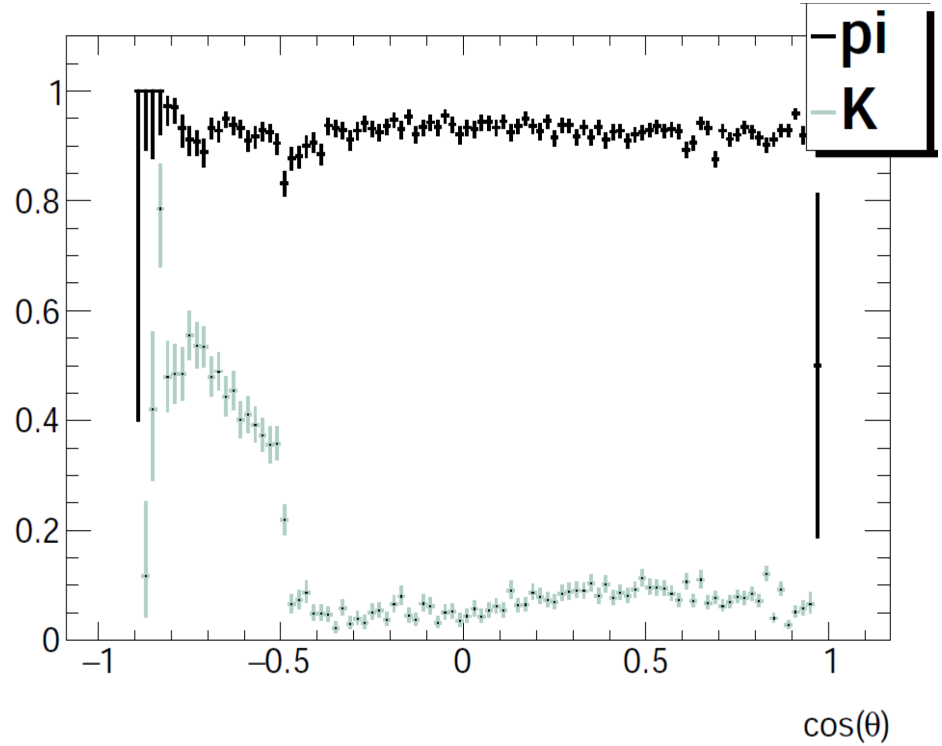
Particle Identification: MC Study

Efficiency and fake rates

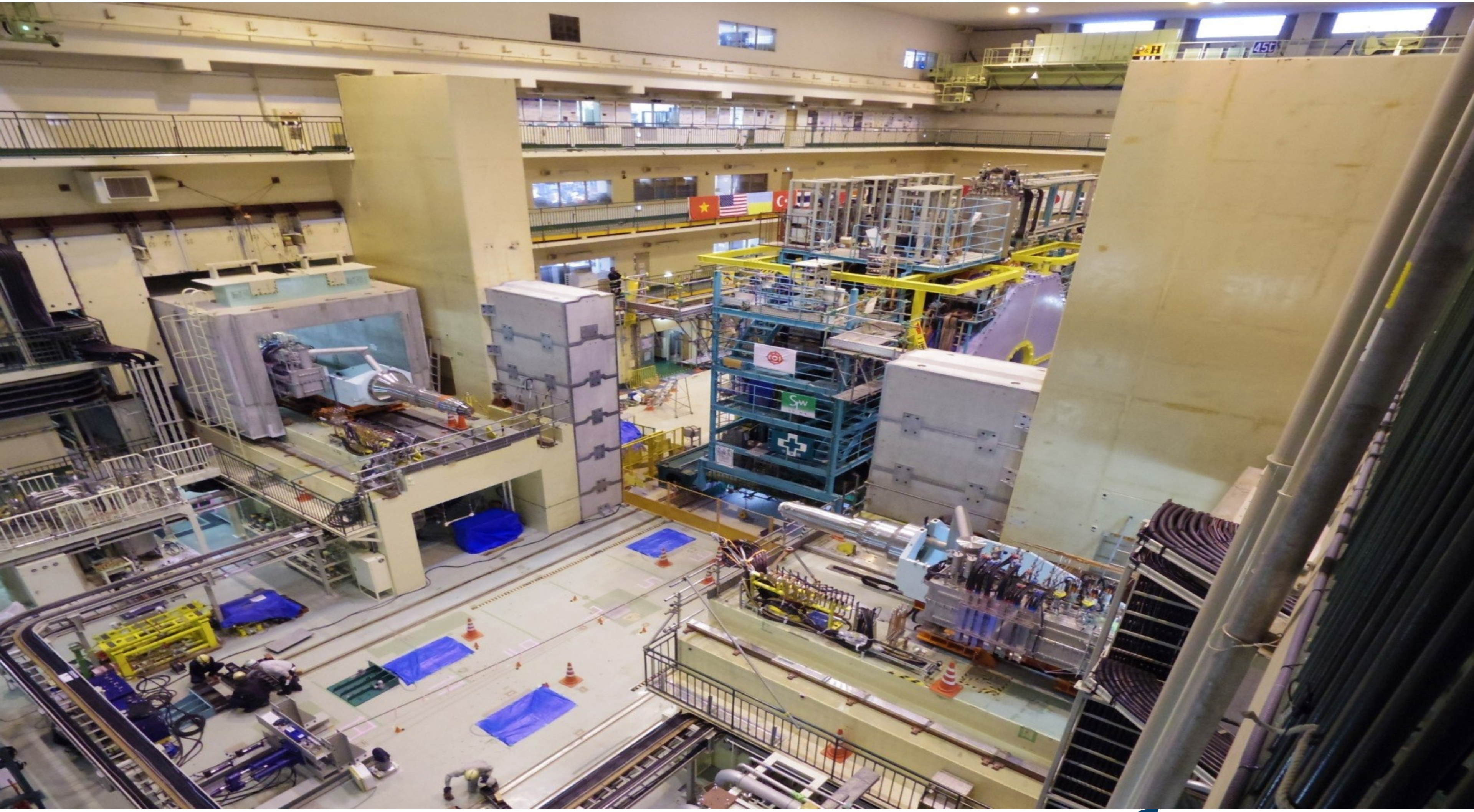
Continuum D* MC Study





excluded cosθ<-0.5 → low statistics

07.04.2017: Roll-in



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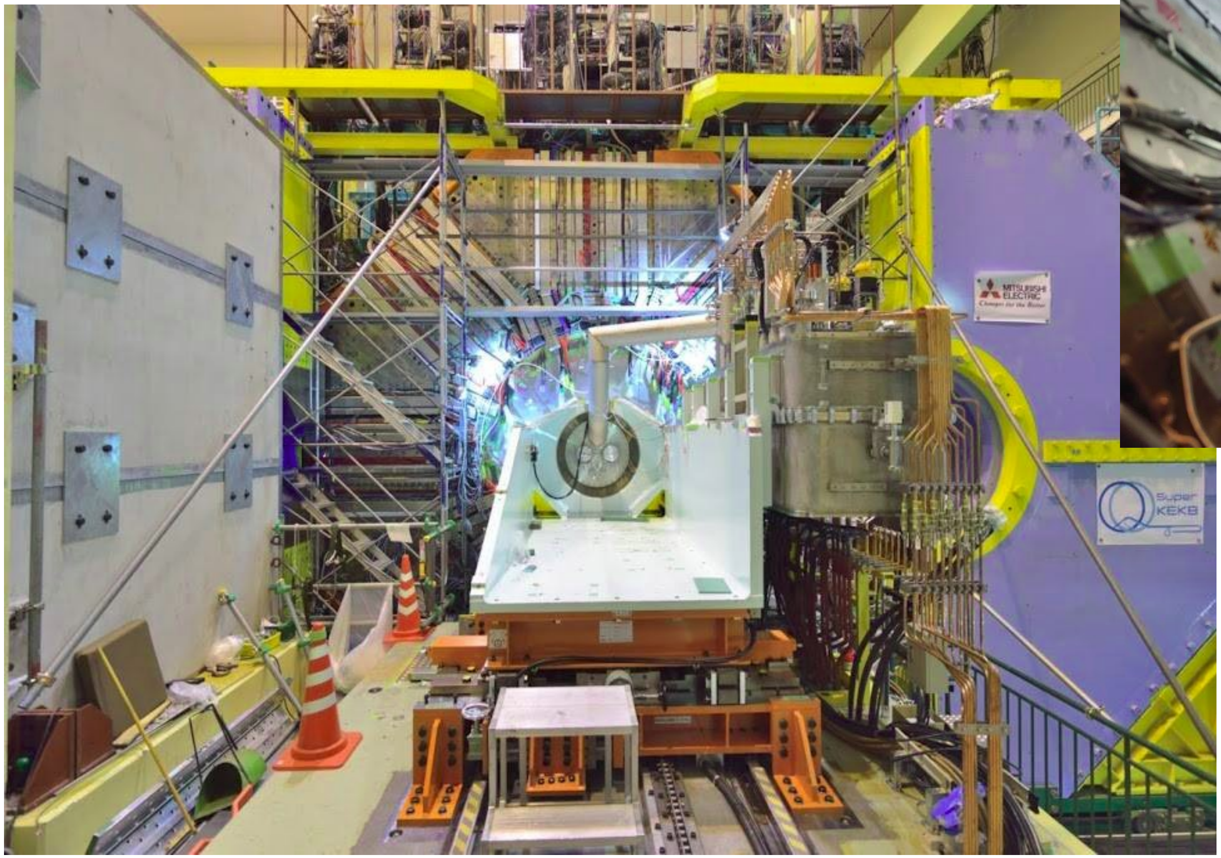
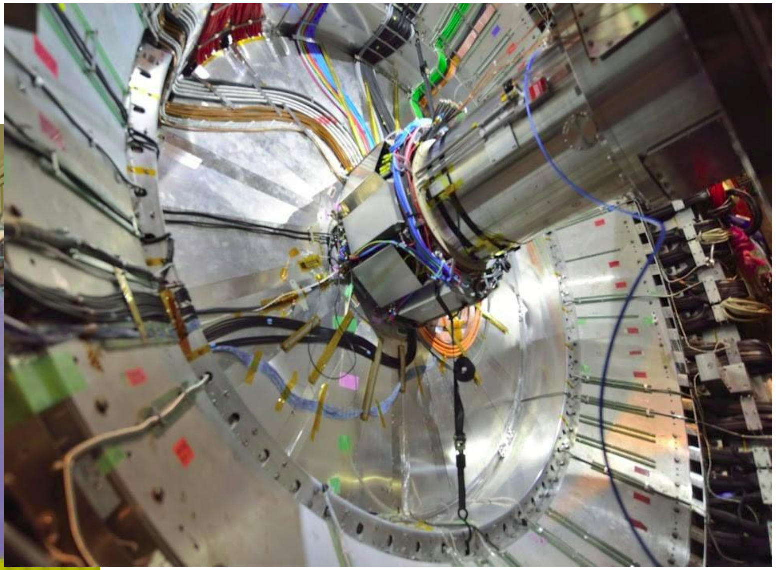
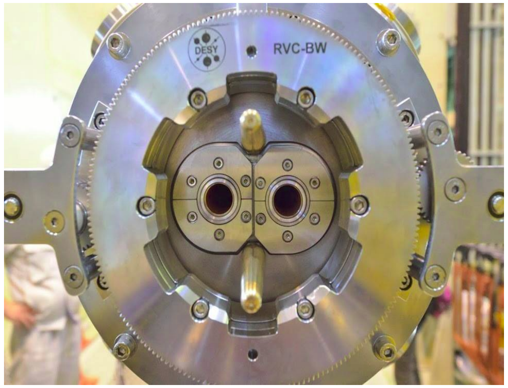
15.01.2018: MILESTONE!

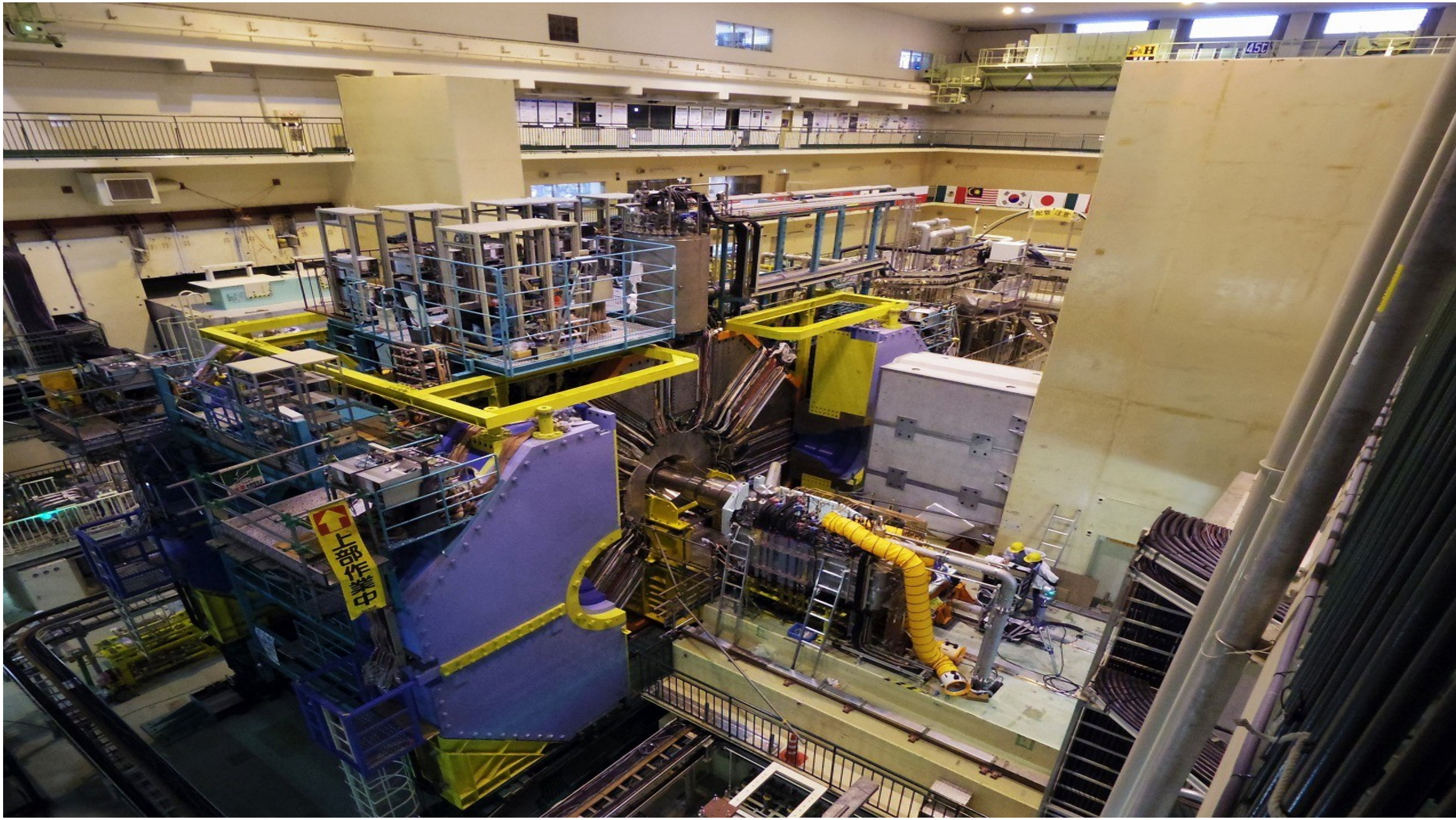
Superconductive magnet systems installed







February 2018: Belle II Ready To Start!



14.02.2018: Phase-II Has Started

14.02.2018: Phase-II Has Started

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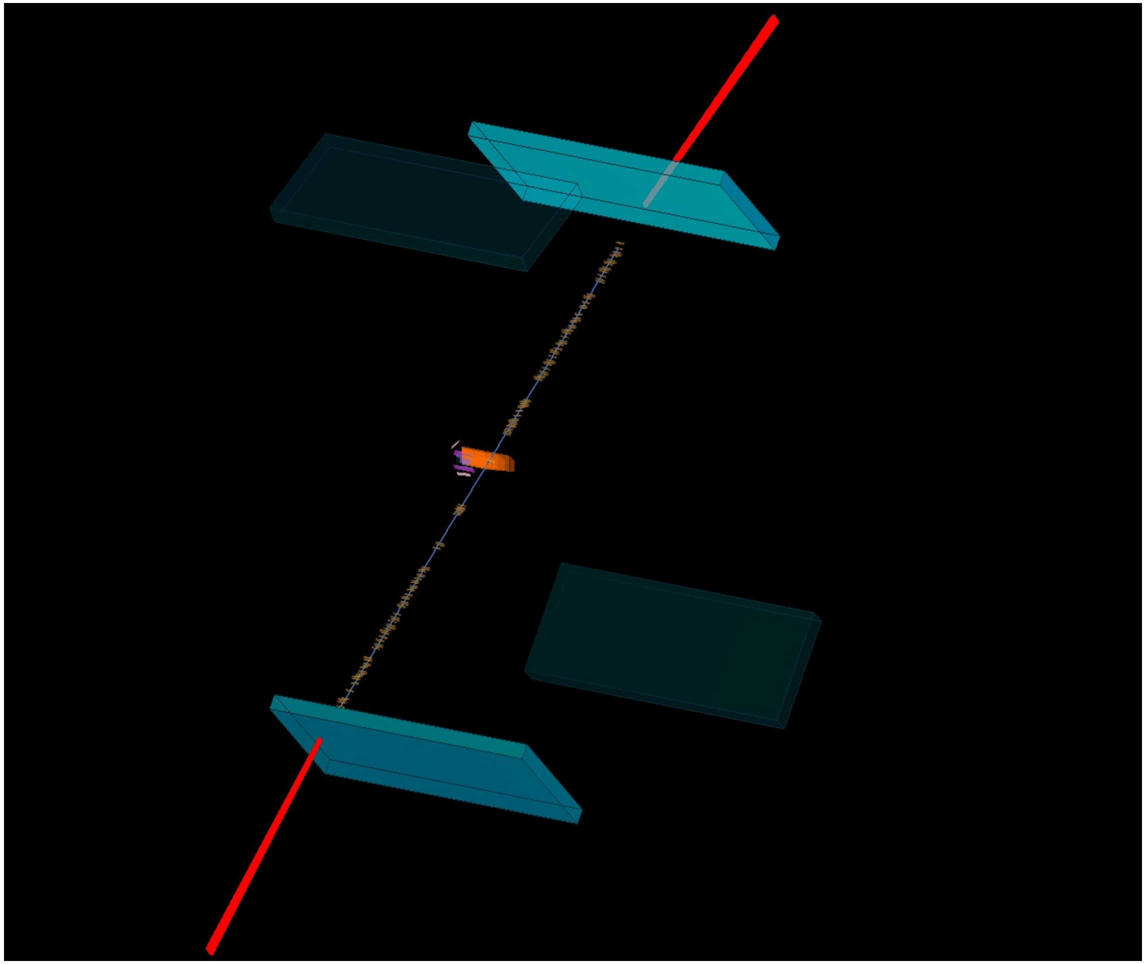
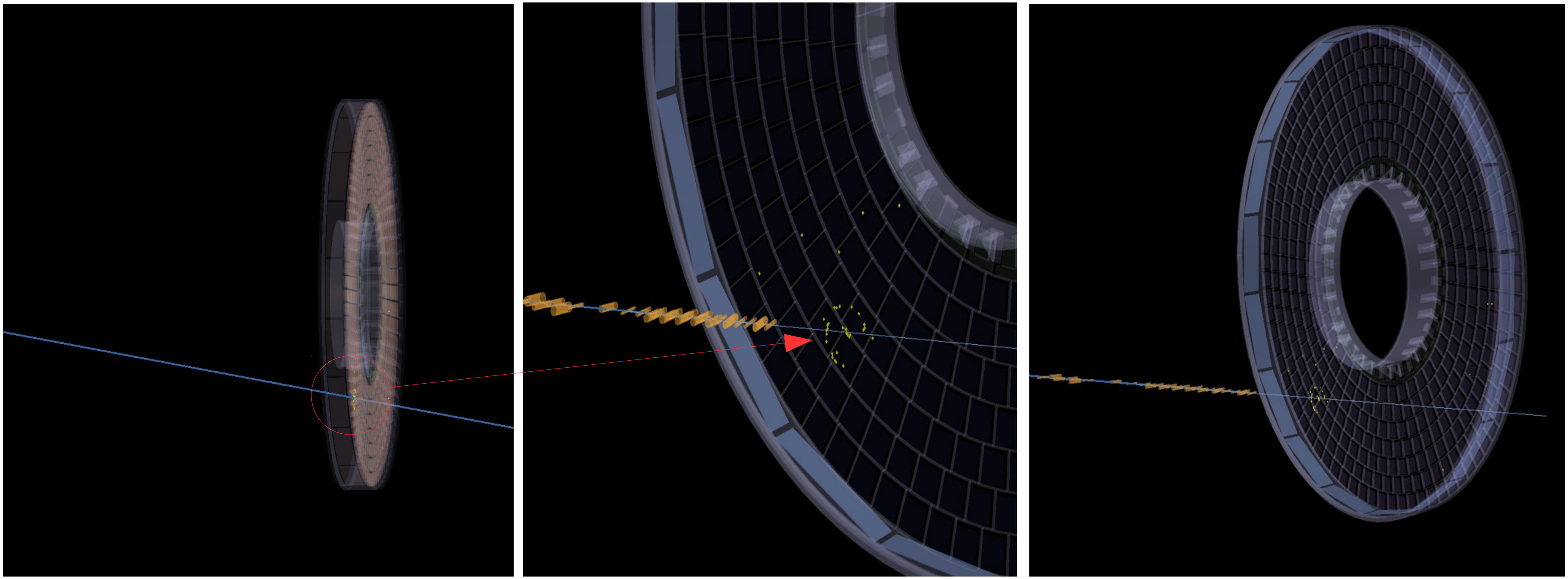
18.02.2018 - First Data
Cosmics in the PXD



- Two inner sub-detectors right now into the data acquisition system.
- The final Belle II vertex detector with its full *pixelated* silicon detector (PXD) and a double-sided microstrip silicon detector (SVD) is under construction and will be installed later this year.

26.02.2018 – First Data
Cosmics in the ARICH



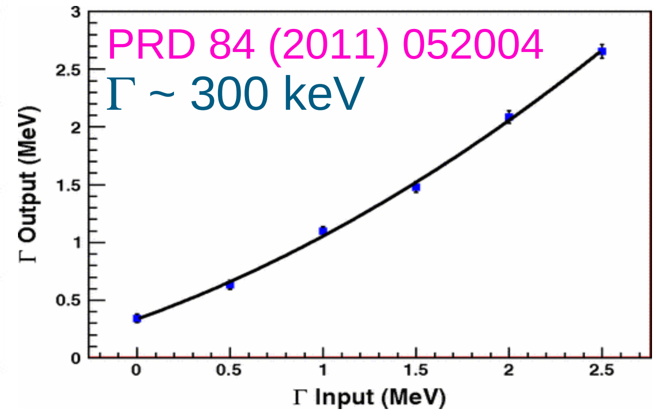
Which are the main improvements expected in spectroscopy with Belle II?

XYZ Expectations at Belle II

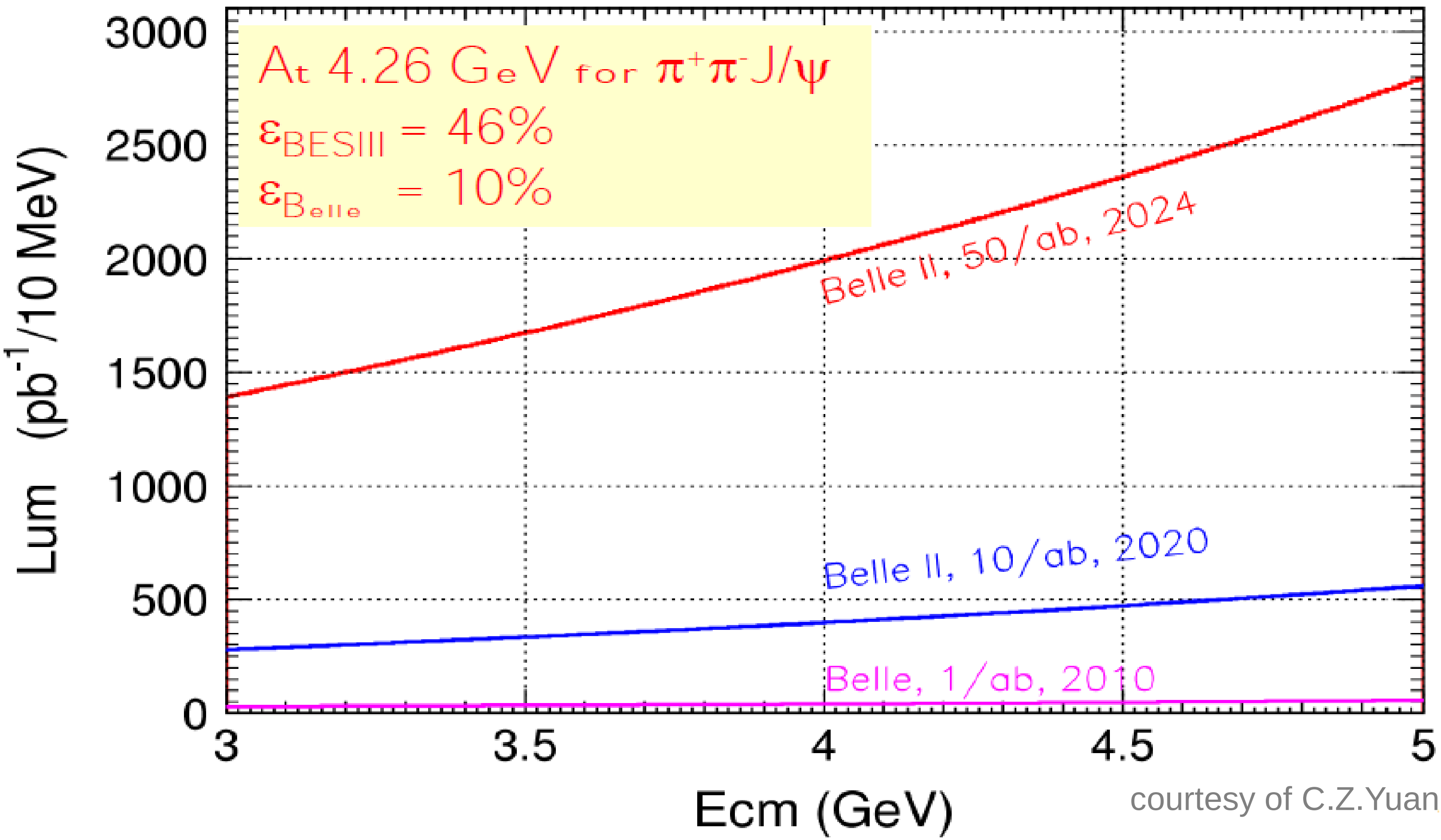
- Yield of $X(3872) \to J/\psi\pi^+\pi^-$ in 2020 will be about Belle yield of $\psi' \to J/\psi\pi^+\pi^-$
- The width of the X(3872) could be measured with a systematic error of ±0.11 MeV
- Width measurement possible in $X(3872) \to J/\psi\gamma$: expected yield $N \simeq 350$ in 2020 (scaled from Belle, Phys. Rev. Lett. 107(2011)091803), a factor x2 more than $X(3872) \to J/\psi\pi^+\pi^-$ at Belle, full dataset
  → monoenergetic photon provides 4-constraint fit ($\Delta E/E \sim 2\%$)
  → systematic error on width may be ~110 keV

State	Production and Decay	N
$X(3872)$	$B \to KX(3872)$, $X(3872) \to J/\psi\pi^+\pi^-$	$\simeq 14400$
$Y(4260)$	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 $50 ab^{-1}$ data at Belle II



Expected Luminosity at Belle II



courtesy of C.Z.Yuan

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 $\sqrt{s}$=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

Main Achievements in Bottomonium at Belle

Summary from PRL 116 (2016) 212001

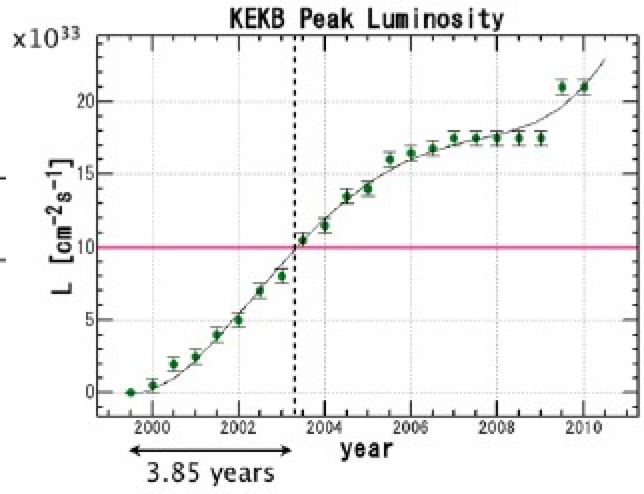
Branching Ratios

Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	$0.54^{+0.16+0.11}_{-0.13-0.08}$	$0.17^{+0.07+0.03}_{-0.06-0.02}$
$\Upsilon(2S)\pi^+$	$3.62^{+0.76+0.79}_{-0.59-0.53}$	$1.39^{+0.48+0.34}_{-0.38-0.23}$
$\Upsilon(3S)\pi^+$	$2.15^{+0.55+0.60}_{-0.42-0.43}$	$1.63^{+0.53+0.39}_{-0.42-0.28}$
$h_b(1P)\pi^+$	$3.45^{+0.87+0.86}_{-0.71-0.63}$	$8.41^{+2.43+1.49}_{-2.12-1.06}$
$h_b(2P)\pi^+$	$4.67^{+1.24+1.18}_{-1.00-0.89}$	$14.7^{+3.2+2.8}_{-2.8-2.3}$
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	$85.6^{+1.5+1.5}_{-2.0-2.1}$	...
$B^{*+}\bar{B}^{*0}$	...	$73.7^{+3.4+2.7}_{-4.4-3.5}$

Expectations on Z_b states at Belle II

Channel	Belle	BaBar	Belle II (per year)
$B\bar{B}$	7.7×10^8	4.8×10^8	1.1×10^{10}
$B_s^{(*)}\bar{B}_s^{(*)}$	7.0×10^6	–	6.0×10^8
$\Upsilon(1S)$	1.0×10^8		1.8×10^{11}
$\Upsilon(2S)$	1.7×10^8	0.9×10^7	7.0×10^{10}
$\Upsilon(3S)$	1.0×10^7	1.0×10^8	3.7×10^{10}
$\Upsilon(5S)$	3.6×10^7	–	3.0×10^9
$\tau\tau$	1.0×10^9	0.6×10^9	1.0×10^{10}

with full luminosity, assuming 100% running:
- 20 days/month
- 9 months/year



Summary

- Great achievements with Belle (~ 1 ab^{-1}) in spectroscopy: analyses still ongoing after so many years
- Z_b in $\Upsilon(5S) \rightarrow \pi^+\pi^-\Upsilon(nS)$, $\Upsilon(6S) \rightarrow \pi^+\pi^- h_b(nP)$ and $\Upsilon(6S) \rightarrow [B^{(*)}B^{(*)}]^+\pi^-$
- Search for Pentaquarks started with Belle data, but only UL so far
- No significant signal found for glueballs with Υ(1S, 2S) samples.
- Promising start of **phase-II in Belle II**: experiment in good shape! First cosmics seen already 3 weeks ago
- Expected 50 ab^{-1} integrated luminosity at Belle II in 10 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)

Thank you for your kind attention!

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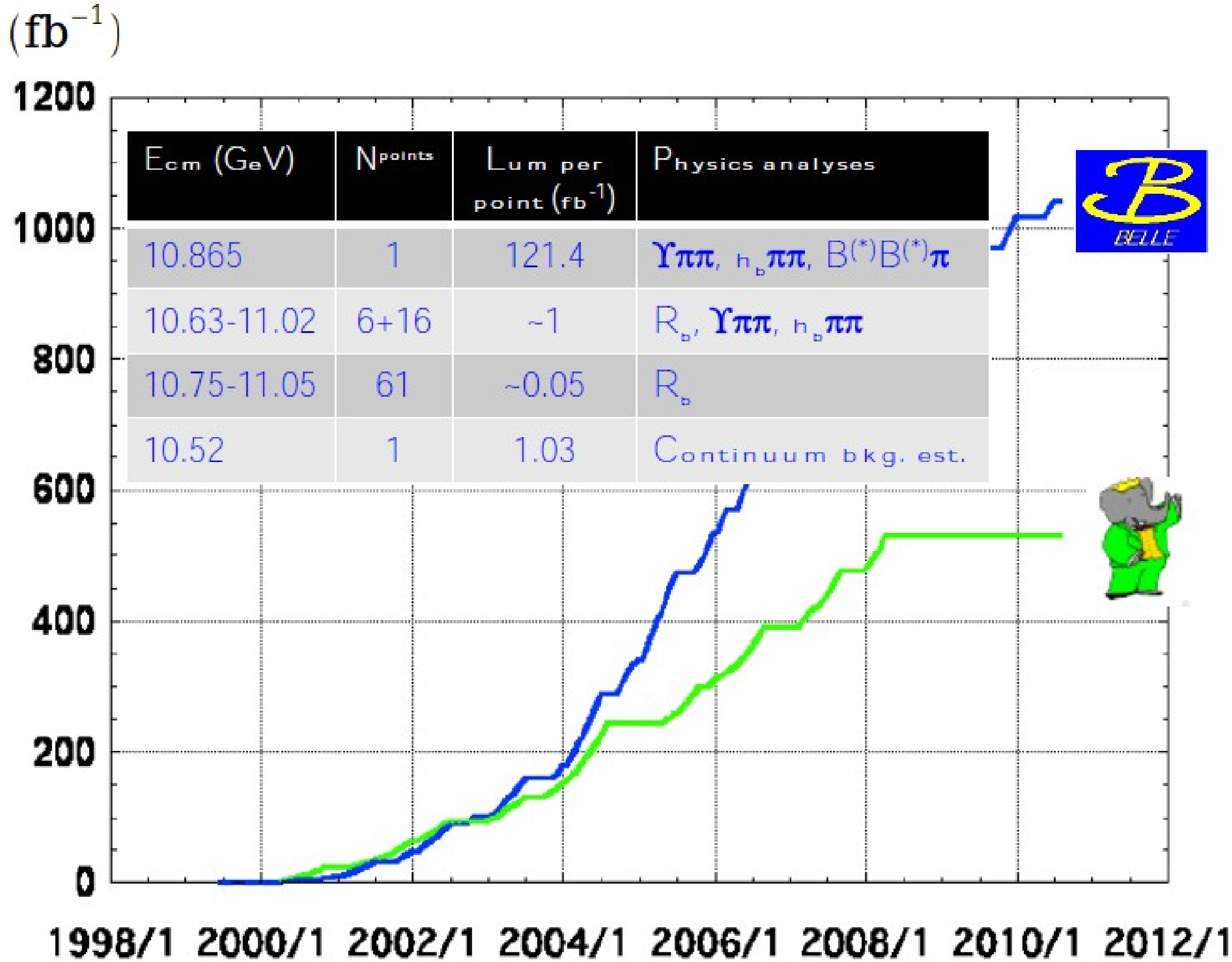
"The greatest danger for most of us lies not in setting our aim too high and falling short; but in setting our aim too low, and achieve our mark." (Michelangelo, 1475 - 1564)

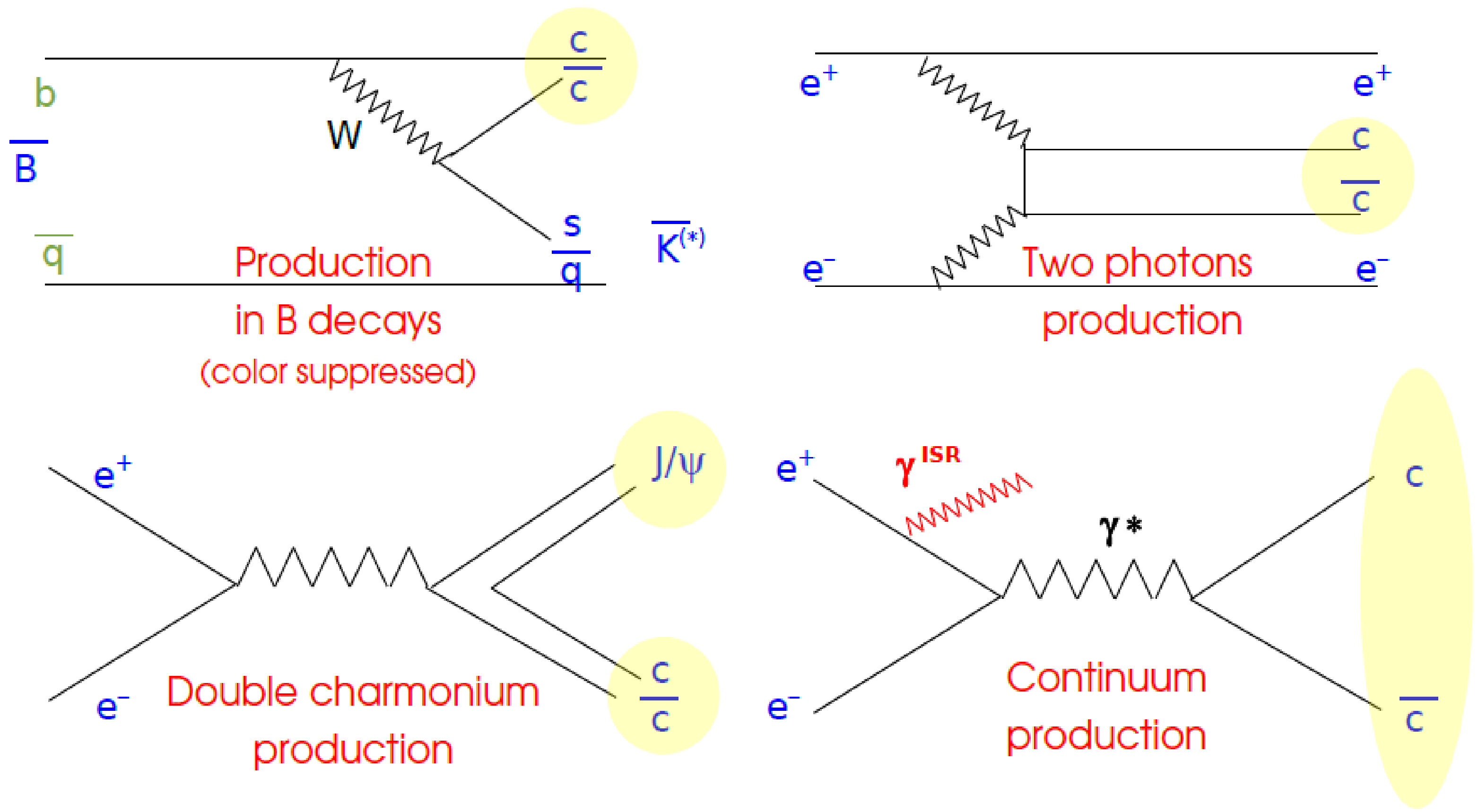
Backup slides

Luminosity at the B Factories



E_{cm} (GeV)	N_{points}	Lum per point (fb^{-1})	Physics analyses
10.865	1	121.4	$\Upsilon\pi\pi$, $h_b\pi\pi$, $B^{(*)}B^{(*)}\pi$
10.63-11.02	6+16	~1	R_b, $\Upsilon\pi\pi$, $h_b\pi\pi$
10.75-11.05	61	~0.05	R_b
10.52	1	1.03	Continuum bkg. est.

Charmonium Production at B Factories



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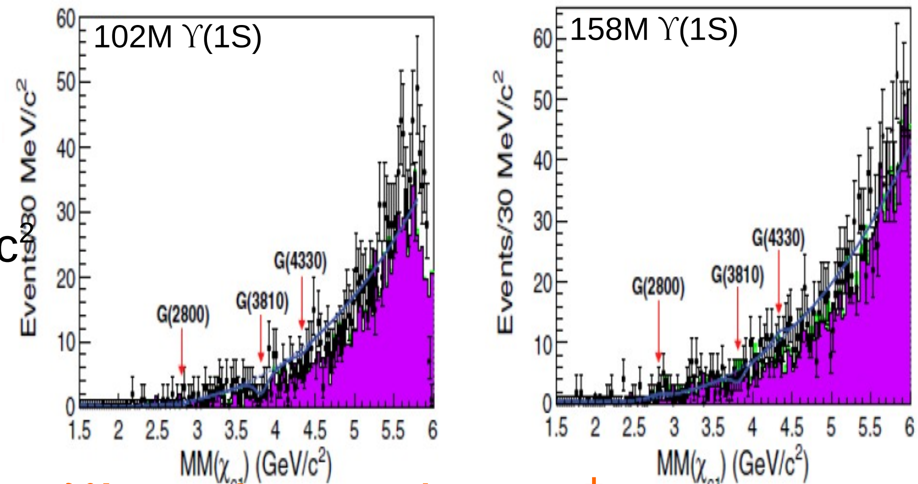
Search for 0^{--} glueballs

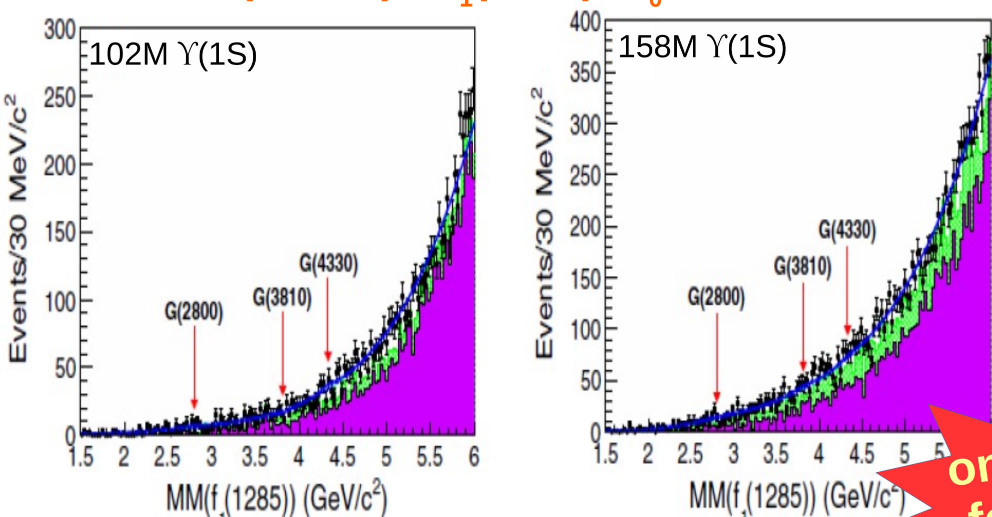
PRD 95 (2017) 012001

- Proposed production channels:
  $\Upsilon(1S, 2S) \to \chi_{c1} G_0^{--}$, $f_1(1285)^+ G_0^{--}$; $\chi_{b1} \to J/\psi G_0^{--}$, $\omega^+ G_0^{--}$
- Predicted G_0^{--} masses are 2.80, 3.81, and 4.33 GeV/c^2
  PRL 113 (2014) 221601, JHEP 1510 (2015) 137
- Mixing with quarkonia makes their search difficult

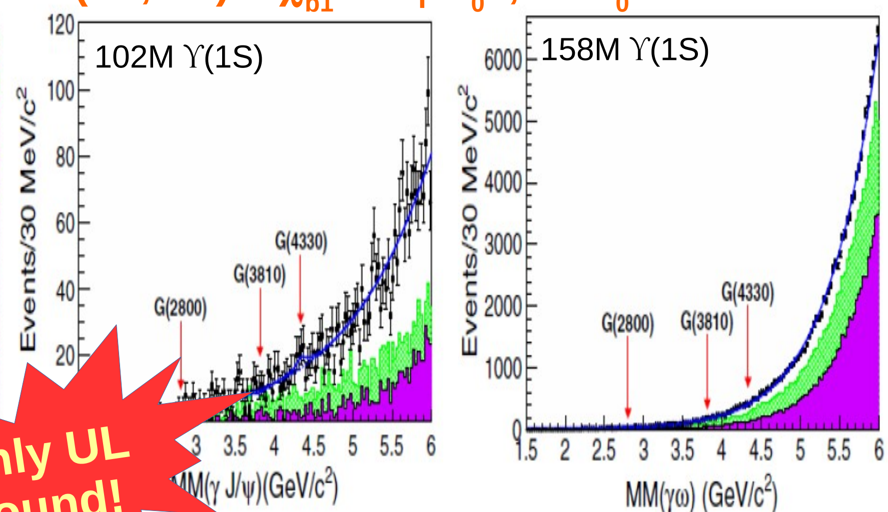
$\Upsilon(1S, 2S) \to \chi_{c1} G_0^{--}$



$\Upsilon(1S, 2S) \to f_1(1285)^+ G_0^{--}$



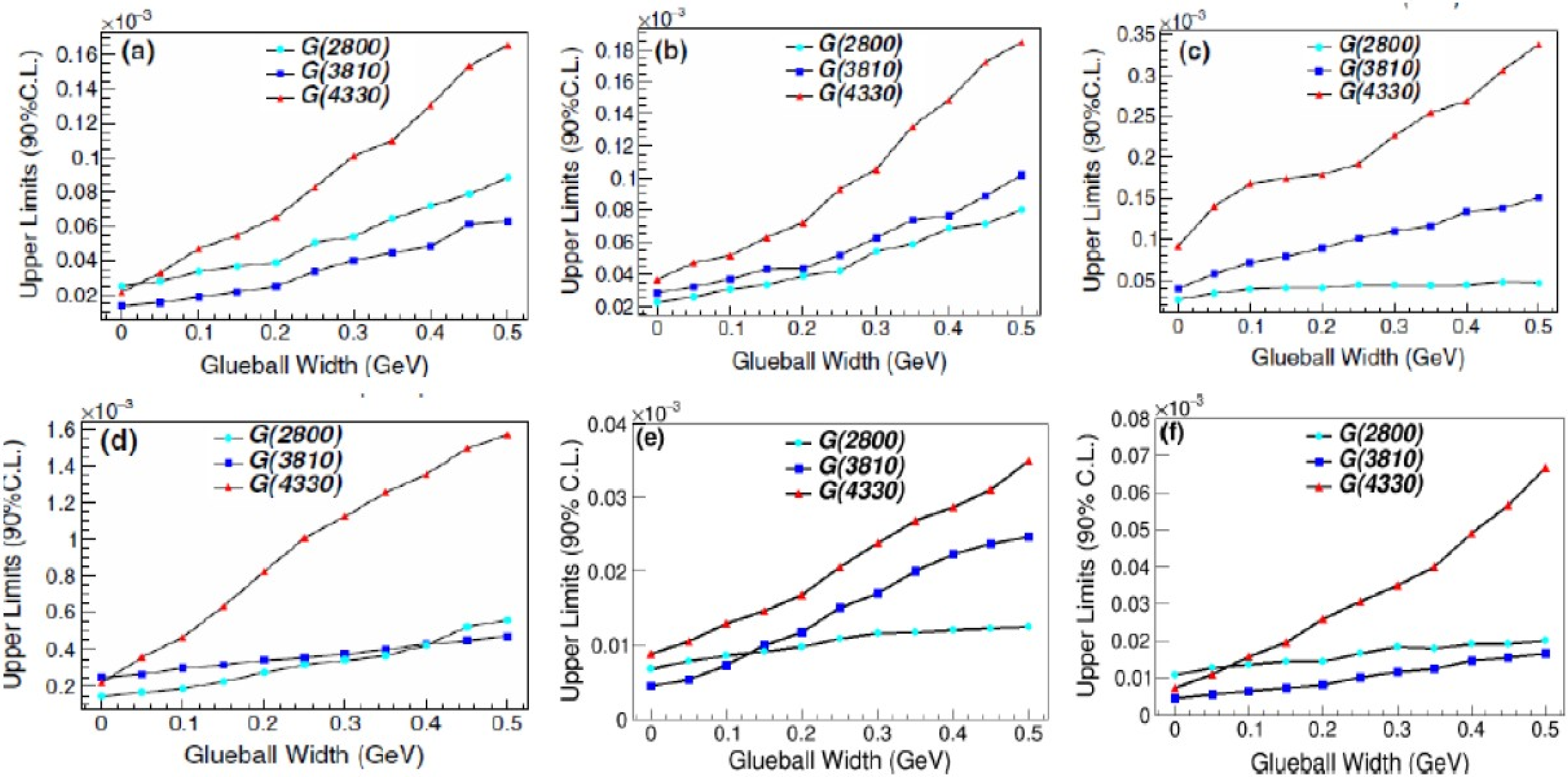
$\Upsilon(1S, 2S) \to \chi_{b1} \to J/\psi G_0^{--}$, $\omega^+ G_0^{--}$



only UL found!

Search for 0^{--} glueballs

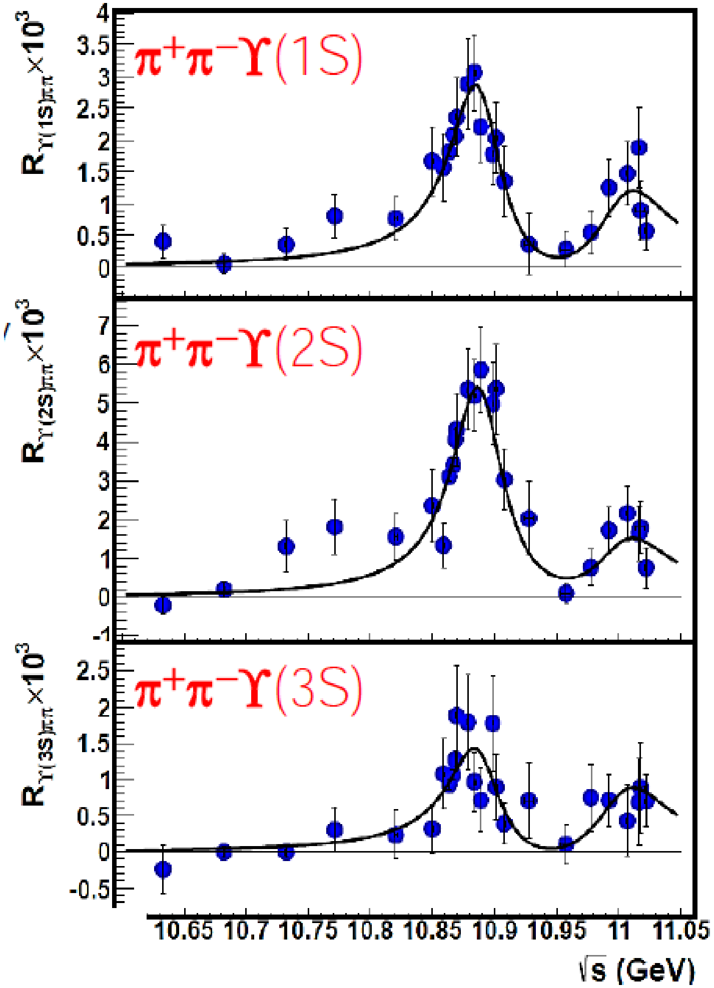
Upper limit on BR of the order of 10^{-5}-10^{-6} @ 90% c.l.



PRD 95 (2017) 012001

Main Achievements in Bottomonium at Belle

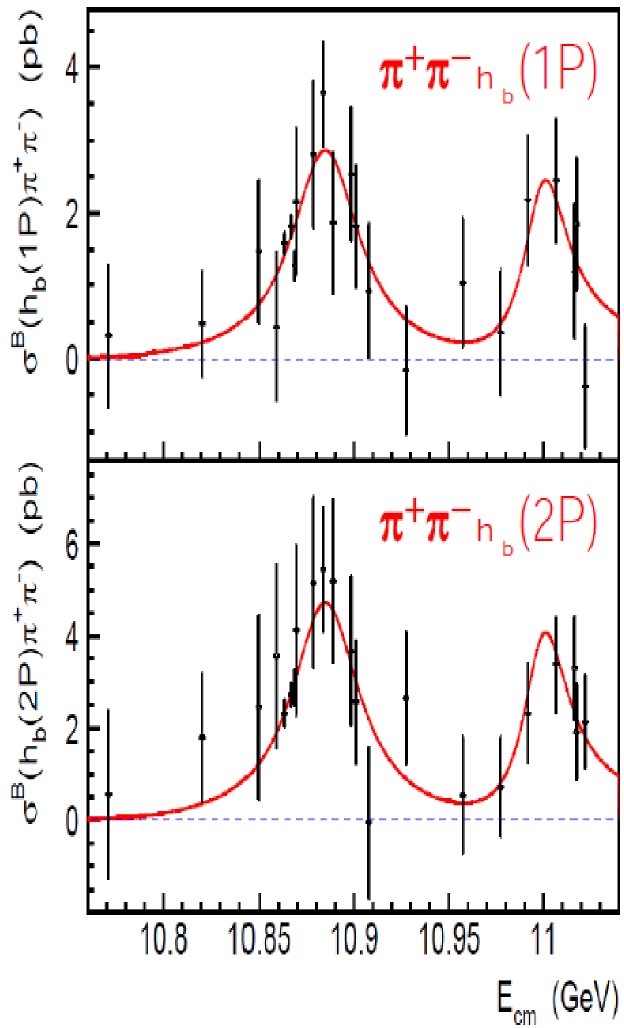
$e^+e^- \to \pi^+\pi^-\Upsilon(nS)$



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

PRD 93, 011101(R) (2016)

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



PRL117, 142001 (2016)

JÜLICH Forschungszentrum

Main Achievements in Bottomonium at Belle

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

Parameter	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$
$f_{Z_b^\mp(10610)\pi^\pm}$, %	$4.8\pm1.2^{+1.5}_{-0.3}$	$18.1\pm3.1^{+4.2}_{-0.3}$	$30.0\pm6.3^{+5.4}_{-7.1}$
$Z_b(10610)$ mass, MeV/c^2	$10608.5\pm3.4^{+3.7}_{-1.4}$	$10608.1\pm1.2^{+1.5}_{-0.2}$	$10607.4\pm1.5^{+0.8}_{-0.2}$
$Z_b(10610)$ width, MeV/c^2	$18.5\pm5.3^{+6.1}_{-2.3}$	$20.8\pm2.5^{+0.3}_{-2.1}$	$18.7\pm3.4^{+2.5}_{-1.3}$
$f_{Z_b^\mp(10650)\pi^\pm}$, %	$0.87\pm0.32^{+0.16}_{-0.12}$	$4.05\pm1.2^{+0.95}_{-0.15}$	$13.3\pm3.6^{+2.6}_{-1.4}$
$Z_b(10650)$ mass, MeV/c^2	$10656.7\pm5.0^{+1.1}_{-3.1}$	$10650.7\pm1.5^{+0.5}_{-0.2}$	$10651.2\pm1.0^{+0.4}_{-0.3}$
$Z_b(10650)$ width, MeV/c^2	$12.1^{+11.3+2.7}_{-4.8-0.6}$	$14.2\pm3.7^{+0.9}_{-0.4}$	$9.3\pm2.2^{+0.3}_{-0.5}$
ϕ_Z, degrees	$67\pm36^{+24}_{-52}$	$-10\pm13^{+34}_{-12}$	$-5\pm22^{+15}_{-33}$
$c_{Z_b(10650)}/c_{Z_b(10610)}$	$0.40\pm0.12^{+0.05}_{-0.11}$	$0.53\pm0.07^{+0.32}_{-0.11}$	$0.69\pm0.09^{+0.18}_{-0.07}$
$f_{\Upsilon(nS)f_2(1270)}$, %	$14.6\pm1.5^{+6.3}_{-0.7}$	$4.09\pm1.0^{+0.33}_{-1.0}$	–
$f_{\Upsilon(nS)(\pi^+\pi^-)_S}$, %	$86.5\pm3.2^{+3.3}_{-4.9}$	$101.0\pm4.2^{+6.5}_{-3.5}$	$44.0\pm6.2^{+1.8}_{-4.3}$
$f_{\Upsilon(nS)f_0(980)}$, %	$6.9\pm1.6^{+0.8}_{-2.8}$	–	–

$$\sigma_{Z_b^\pm(10610)\pi^\mp}\times\mathcal{B}_{\Upsilon(1S)\pi^\mp} = 109\pm27^{+35}_{-10}\ \text{fb}$$

$$\sigma_{Z_b^\pm(10610)\pi^\mp}\times\mathcal{B}_{\Upsilon(2S)\pi^\mp} = 737\pm126^{+188}_{-85}\ \text{fb}$$

$$\sigma_{Z_b^\pm(10610)\pi^\mp}\times\mathcal{B}_{\Upsilon(3S)\pi^\mp} = 438\pm92^{+92}_{-114}\ \text{fb}$$

$$\sigma_{Z_b^\pm(10650)\pi^\mp}\times\mathcal{B}_{\Upsilon(1S)\pi^\mp} = 20\pm7^{+4}_{-3}\ \text{fb}$$

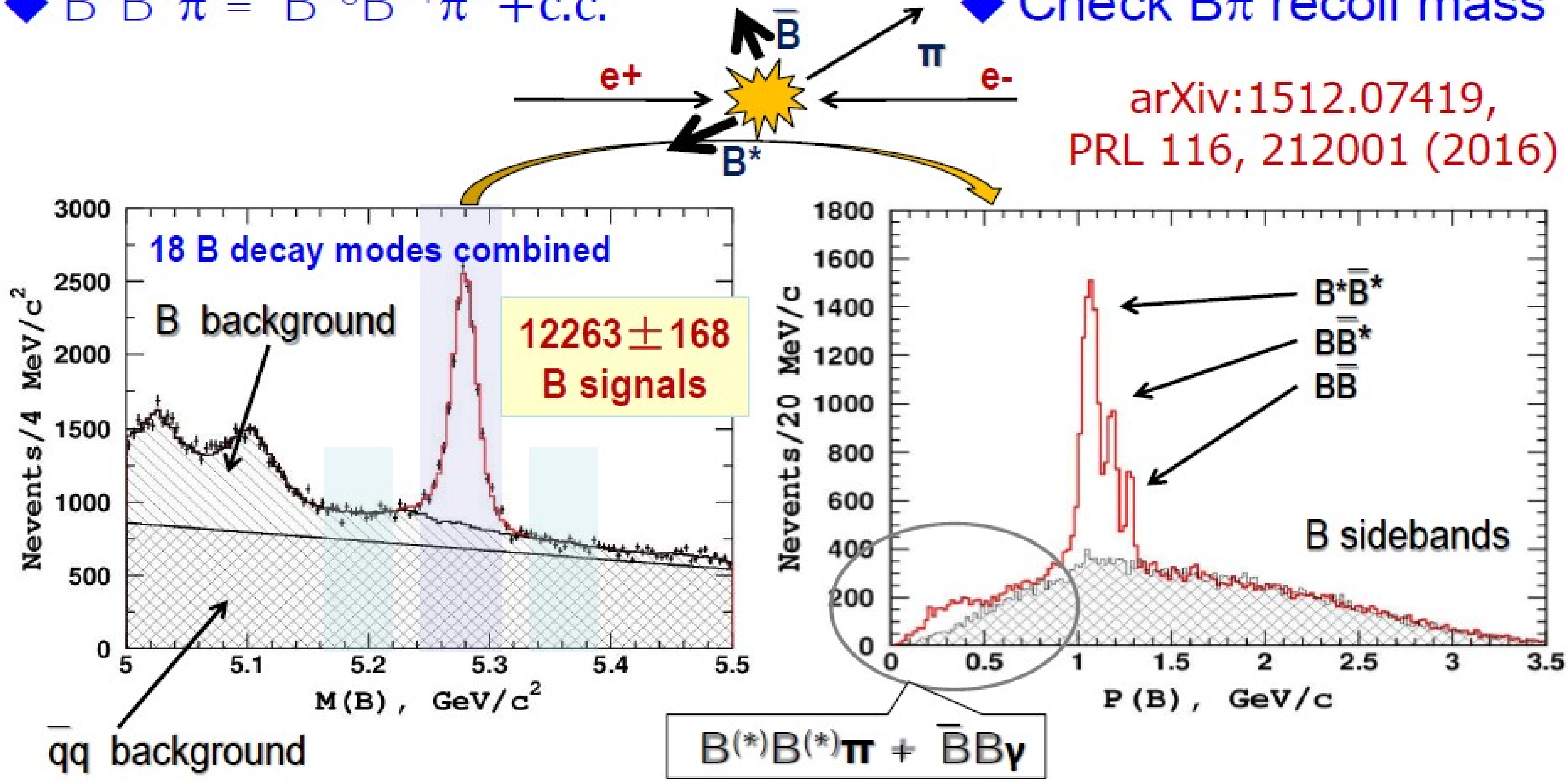
$$\sigma_{Z_b^\pm(10650)\pi^\mp}\times\mathcal{B}_{\Upsilon(2S)\pi^\mp} = 165\pm49^{+43}_{-20}\ \text{fb}$$

$$\sigma_{Z_b^\pm(10650)\pi^\mp}\times\mathcal{B}_{\Upsilon(3S)\pi^\mp} = 194\pm53^{+43}_{-25}\ \text{fb}$$

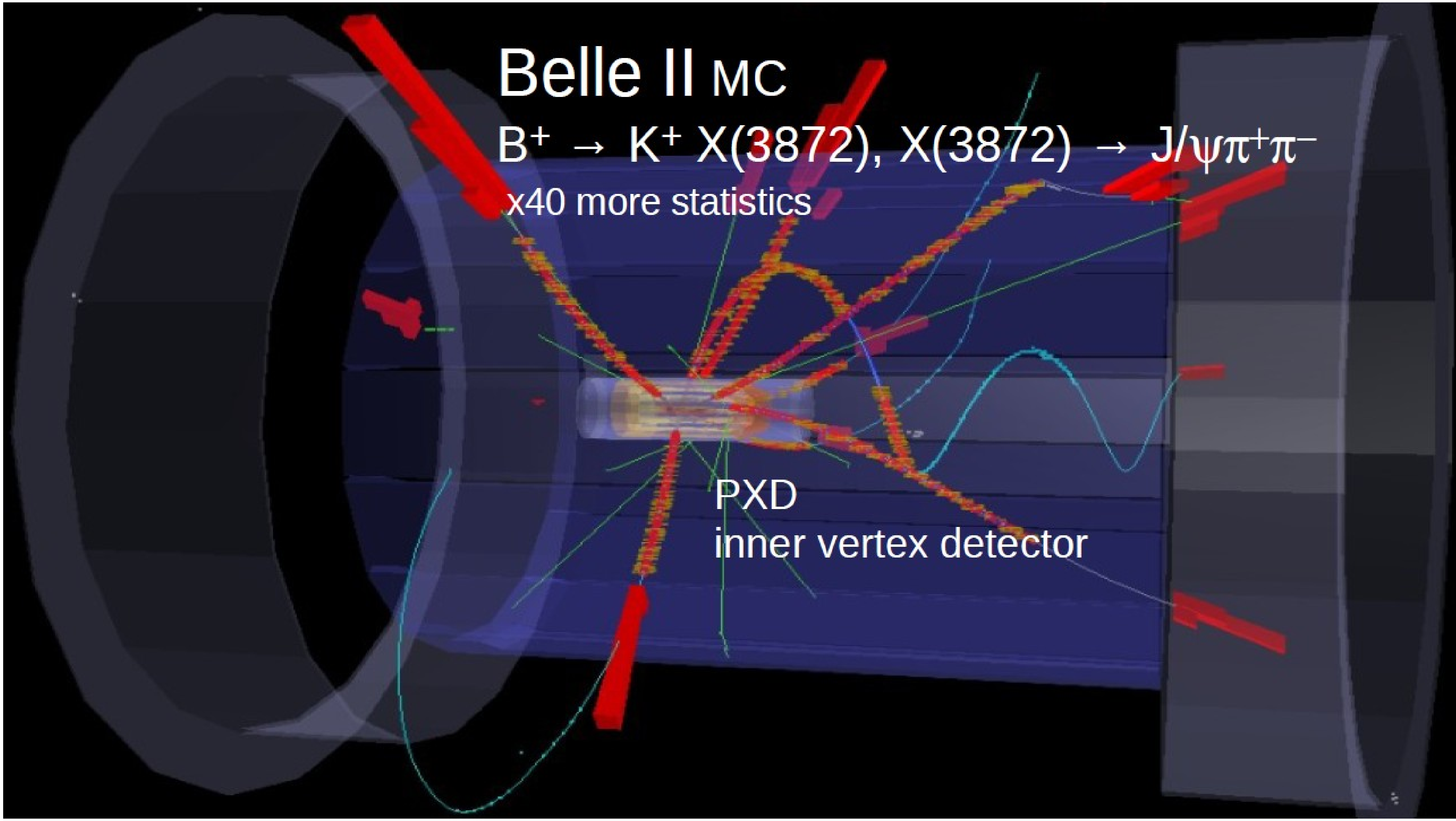
Z_b in $\Upsilon(5S) \to B^{(*)}B^{(*)}\pi^- + c.c.$

- $BB\pi = \bar{B}^0 B^+ \pi^- + c.c.$
- $BB^*\pi = \bar{B}^{*0} B^+ \pi^- + c.c. / \bar{B}^0 B^{*+} \pi^- + c.c.$
- $B^*B^*\pi = \bar{B}^{*0} B^{*+} \pi^- + c.c.$

- One B is reconstructed
- Select a bachelor $\pi^\pm$
- Check $B\pi$ recoil mass



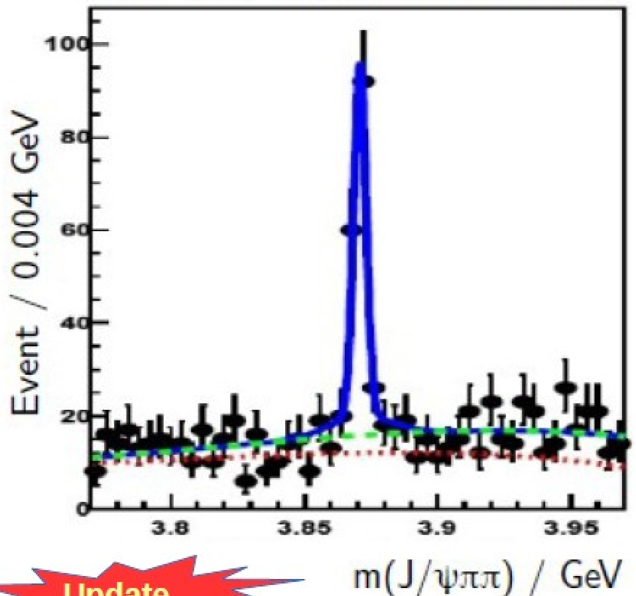
$N(BB\pi) = 13 \pm 25$ $N(BB^*\pi) = 357 \pm 30$ $N(B^*B^*\pi) = 161 \pm 21$


Belle II MC
B+ → K+ X(3872), X(3872) → J/ψπ+π−
x40 more statistics
PXD
inner vertex detector

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

$\mathcal{B}(B^+\to K^+X(3872))\times\mathcal{B}(X(3872)\to\pi^+\pi^-J/\psi)$=
(8.63±0.82(stat)±0.52(syst))×10^{-6}

$\mathcal{B}(B0\to K^0X(3872))/\mathcal{B}(B+\to K^+X(3872))$=
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: $\mathcal{B}(X(3872)\to J/\psi\rho)$, ~$10^2$ too large

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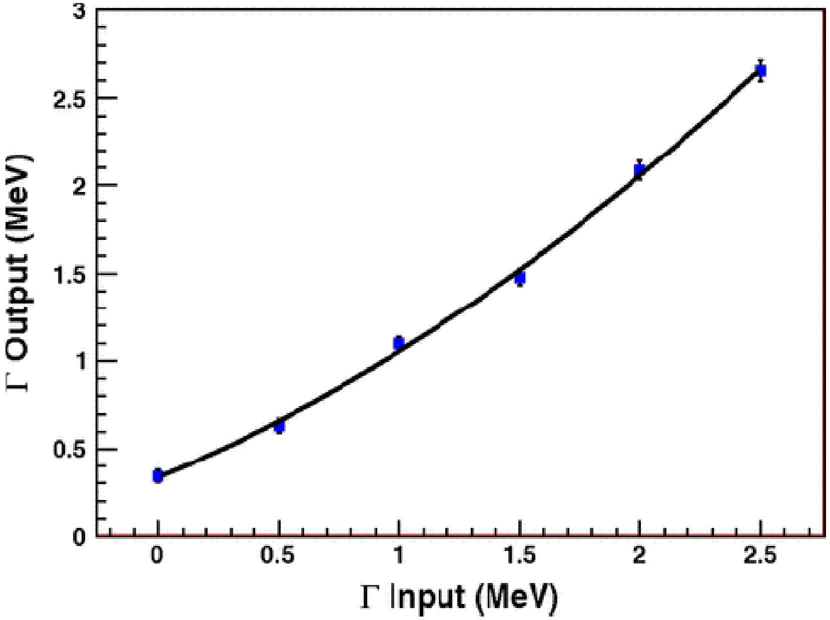
X(3872): ACHIEVEMENTS AND INTERPRETATION AT BELLE

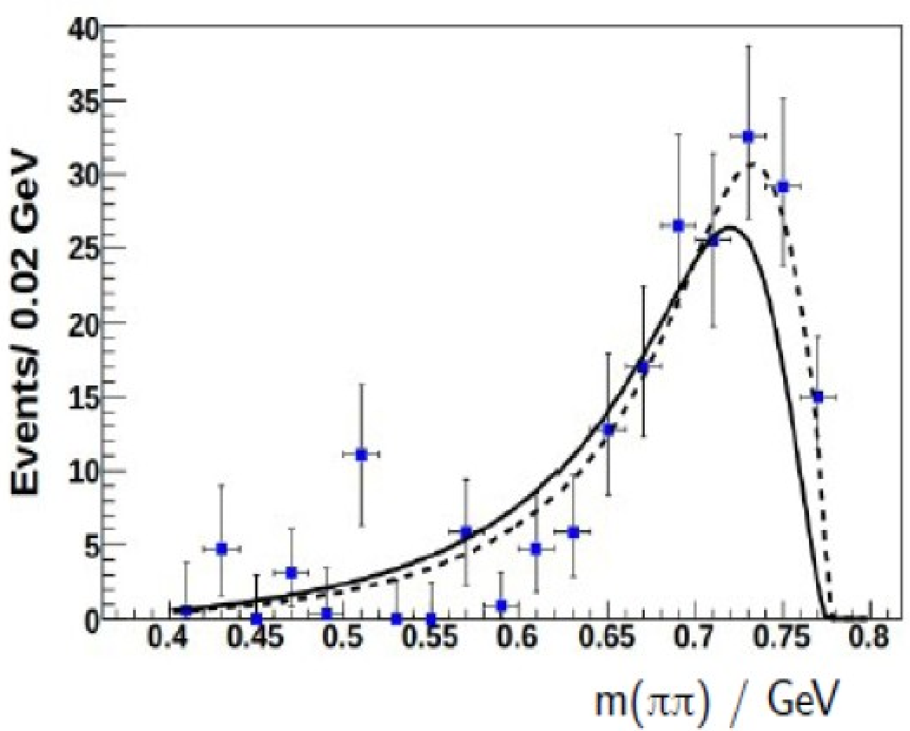
PRD 84 (2011) 052004

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

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)?

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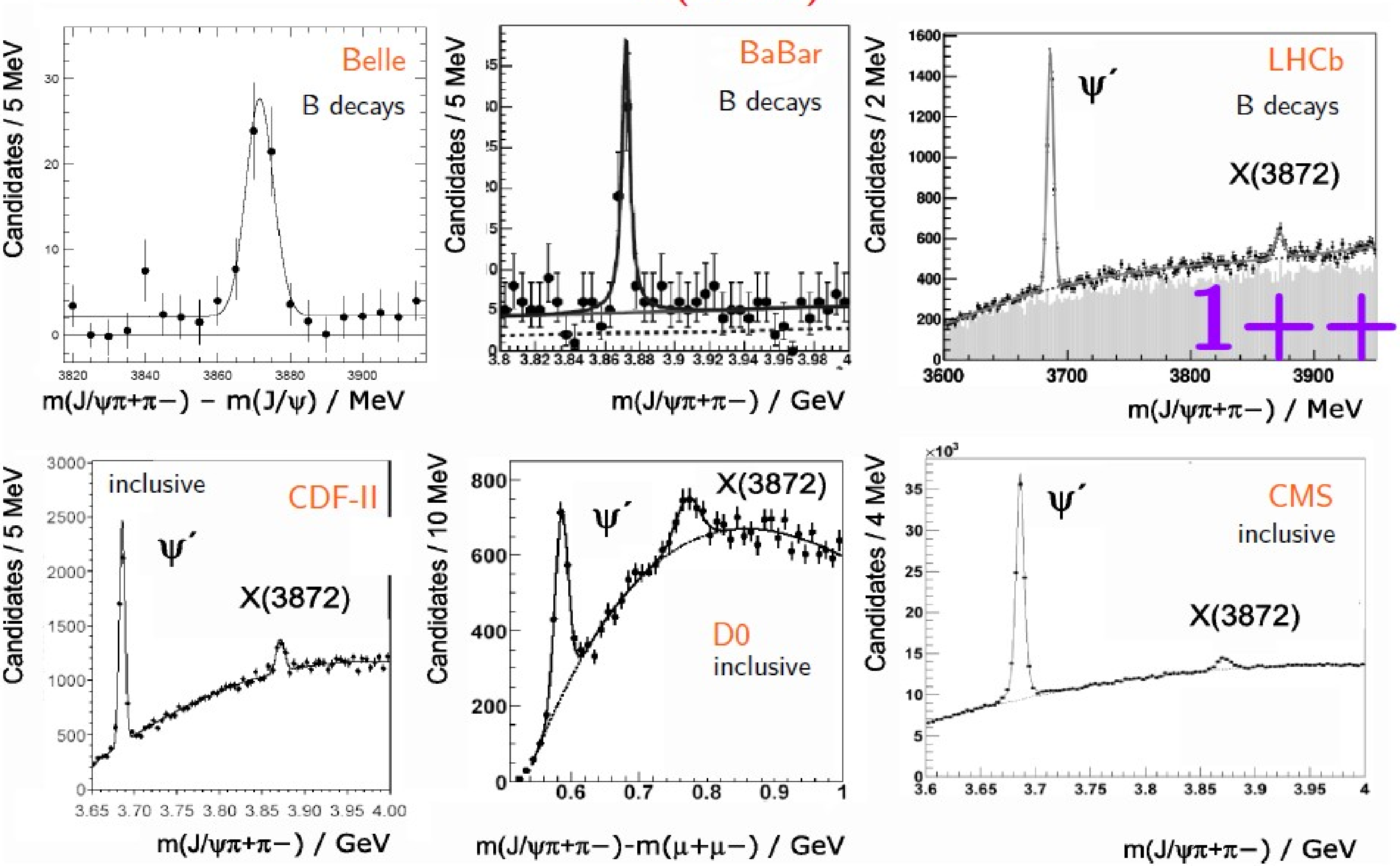
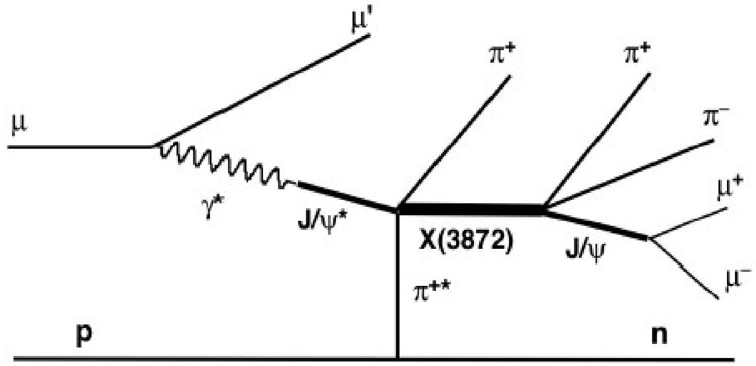
X(3872)


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
CDF-II
inclusive
ψ´
X(3872)
Candidates / 5 MeV
m(J/ψπ+π−) / GeV
D0
inclusive
ψ´
X(3872)
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)

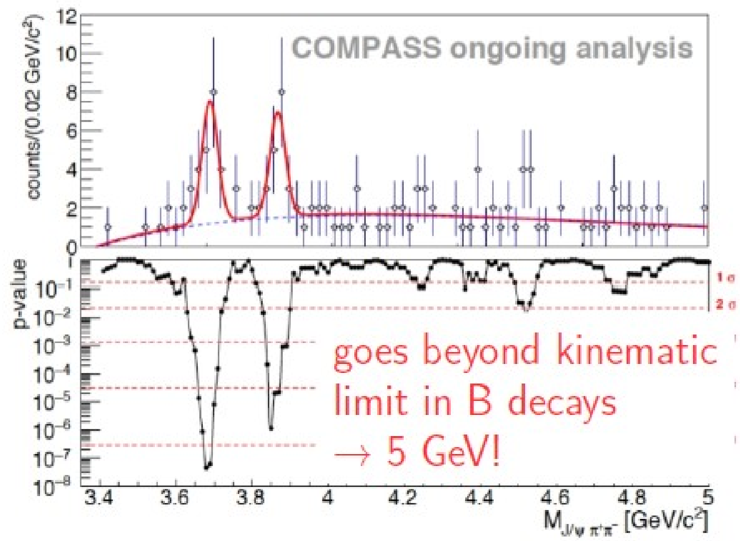


Muon data 2003-2010

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

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

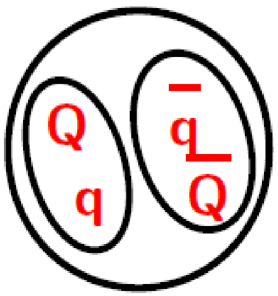
$\sigma_M = 20.6 \pm 6.1$ MeV



COMPASS, arXiv:1707.01796 [hep-ex]

Is the X(3872) exotic ?

TETRAQUARK



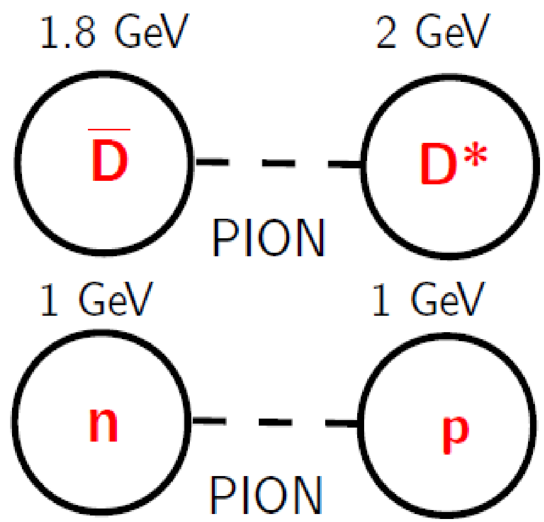
$[qQ]_8[\overline{qQ}]_8$

Diquarks
are colored

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

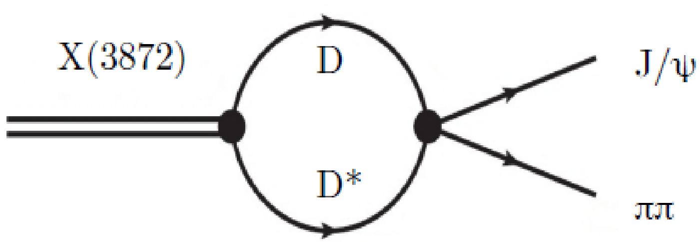
MOLECULE

Intriguing Analogon



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

THRESHOLD CUSP



Bugg; Swanson

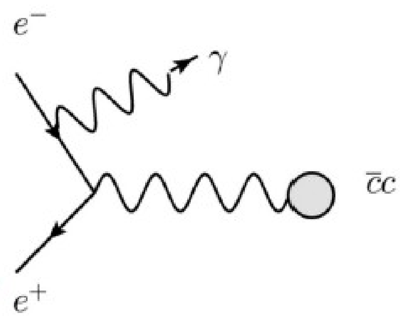
courtesy of J.S. Lange, HIRSCHEGG2018

Y(4260)

- Initial state radiation events

$$e^+e^- \rightarrow \gamma_{ISR} \underbrace{J/\psi\pi^+\pi^-}_{\text{resonant state?}}$$

- Quantum numbers
  $J^{PC}=1^{--}$

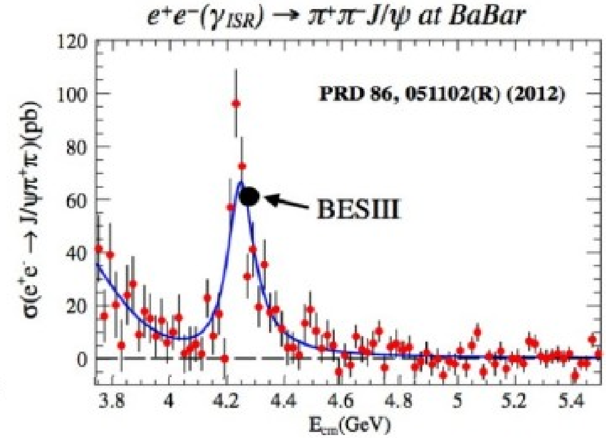


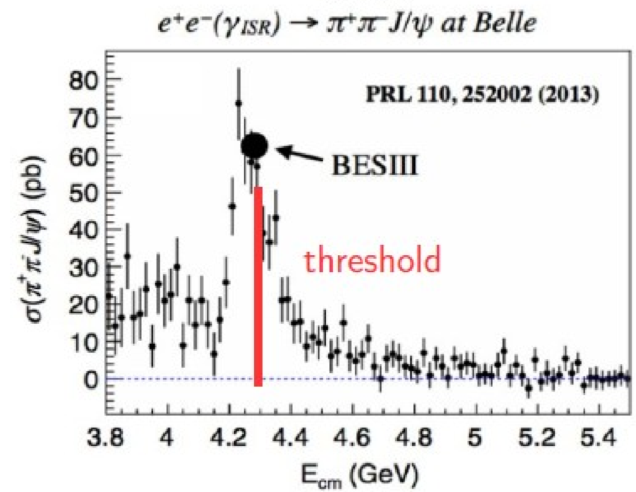
  (based upon production r

- decay to e^+e^- not seen (although 1– –)
- decay to $D^{(*)}D^{(*)}$ not seen (although phasespace huge)
- recent hot topic: lineshape distortion at $\overline{D}D_1(2460)$ threshold ?

BESIII, Phys. Rev. Lett. 118 (9) (2017) 092001

BESIII, PRL110(2013)252001





Y(4260) parameters

	BABAR	CLEO-c	Belle	Belle	*BABAR*	*BABAR*	BESIII
$\mathcal{L}$	211 fb^{-1}	13.3 fb^{-1}	553 fb^{-1}	548 fb^{-1}	454 fb^{-1}	454 fb^{-1}	9 fb^{-1}
N	125 ± 23	$14.1^{+5.2}_{-4.2}$	165 ± 24	324 ± 21	344 ± 39	–	3853 ± 68
$\mathcal{S}$	$\simeq 8\sigma$	$\simeq 4.9\sigma$	$\geq 7\sigma$	$\geq 15\sigma$	–	–	7.6σ
m	$4259\pm8^{+2}_{-6}$	$4283^{+17}_{-16}\pm4$	$4295\pm10^{+10}_{-3}$	$4247\pm12^{+17}_{-32}$	$4252\pm6^{+2}_{-3}$	$4244\pm5\pm4$	$4222.0\pm3.1\pm1.4$
Γ	$88\pm23^{+6}_{-4}$	70^{+40}_{-25}	$133\pm26^{+13}_{-6}$	$108\pm19\pm10$	$105\pm18^{+4}_{-6}$	$114^{+16}_{-15}\pm7$	$44.1\pm4.3\pm2.0$

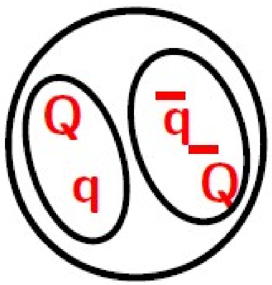
BaBar, Phys. Rev. Lett. 95(2005)142001
CLEO-c, Phys. Rev. D74(2006)091104
Belle, arXiv:hep-ex/0612006
Belle, Phys. Rev. Lett. 99(2007)182004
BaBar, arXiv:08081543[hep-ex]
BaBar, Phys. Rev. D86(2012)051102
BESIII, Phys. Rev. Lett. 118(2017)092001

Recent hot topic:
mass in direct e+e–
seems lower than in ISR

Is the Y(4260) exotic ?

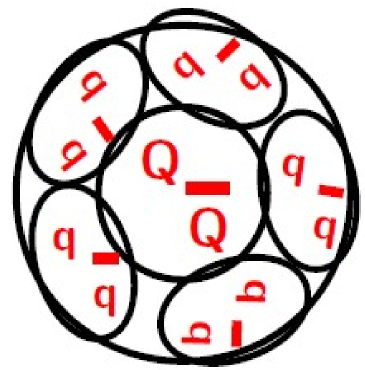
TETRAQUARK

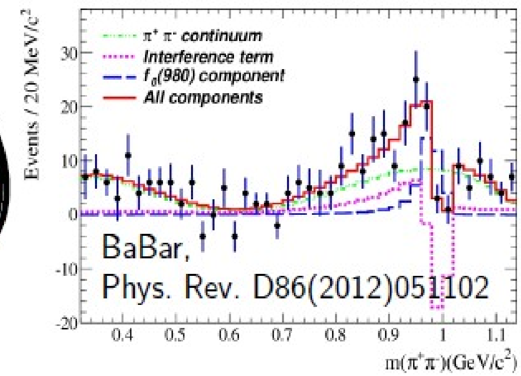
higher excitation ?



Maiani, Riquer, Piccinini, Polosa, Burns

HADRO-CHARMONIUM [J/ψ $f_0(980)$]

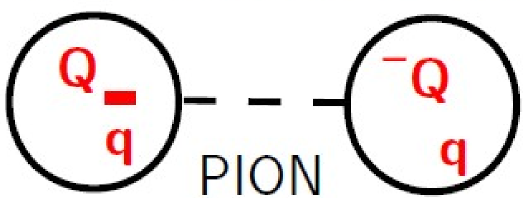




Voloshin, Li
(Guo, Hanhart, Meissner)

MOLECULE

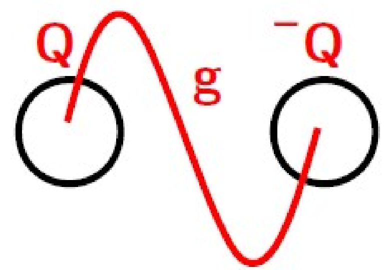
heavier mesons ($\bar{D}D_1(2460)$) ?



[Swanson, Rosner, Close
Guo, Hanhart, Meissner

HYBRID

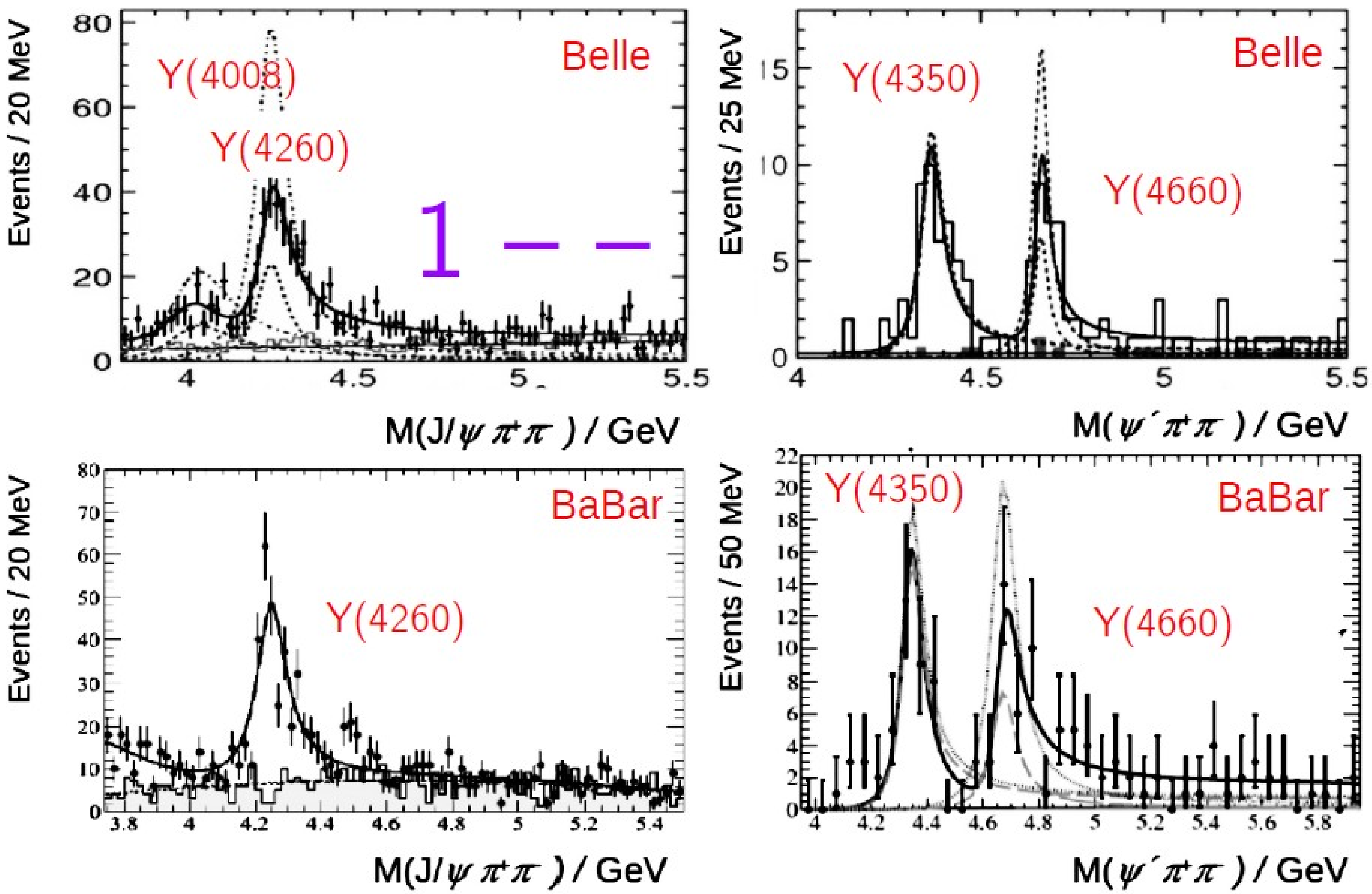
$[Q\bar{Q}]_8 g$



Zhu; Kou, Pene; Close, Page;
Lattice QCD, Bernard et al.; Mei, Luo

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
Y(4350)
BaBar
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

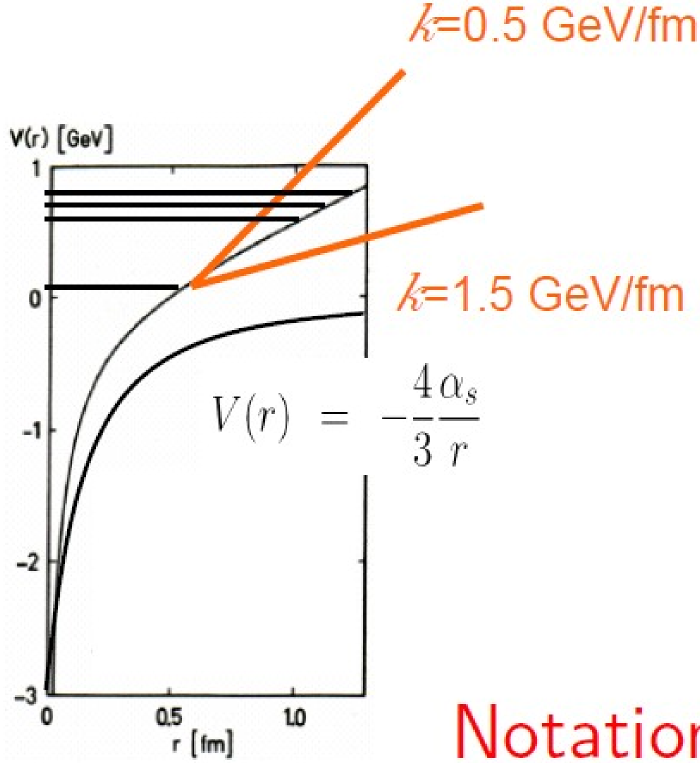
- Coulomb-Potential
  + Confinement-Term

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

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



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

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

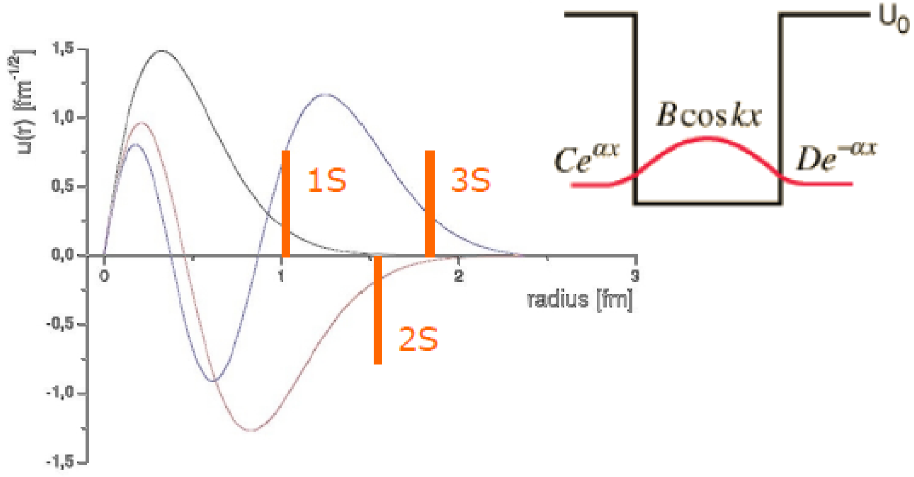
$$\Psi(r,\theta,\phi) = R_{nl}(r)Y_{lm}(\theta,\phi)$$

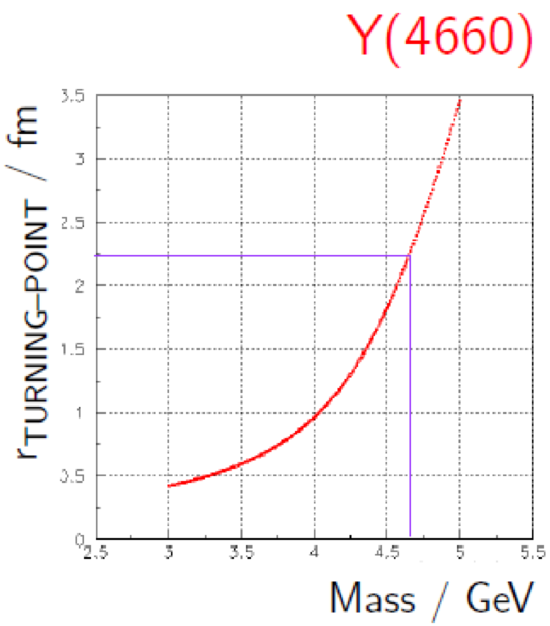
$$\left[-\frac{1}{m_q}\left(\frac{\partial^2}{\partial r^2} + \frac{2}{r}\frac{\partial}{\partial r} + \frac{l(l+1)}{m_q r^2} + V(r)\right)\right]R_{nl}(r) = E_{nl}R_{nl}(r)$$

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

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

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

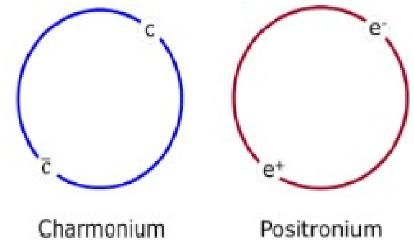




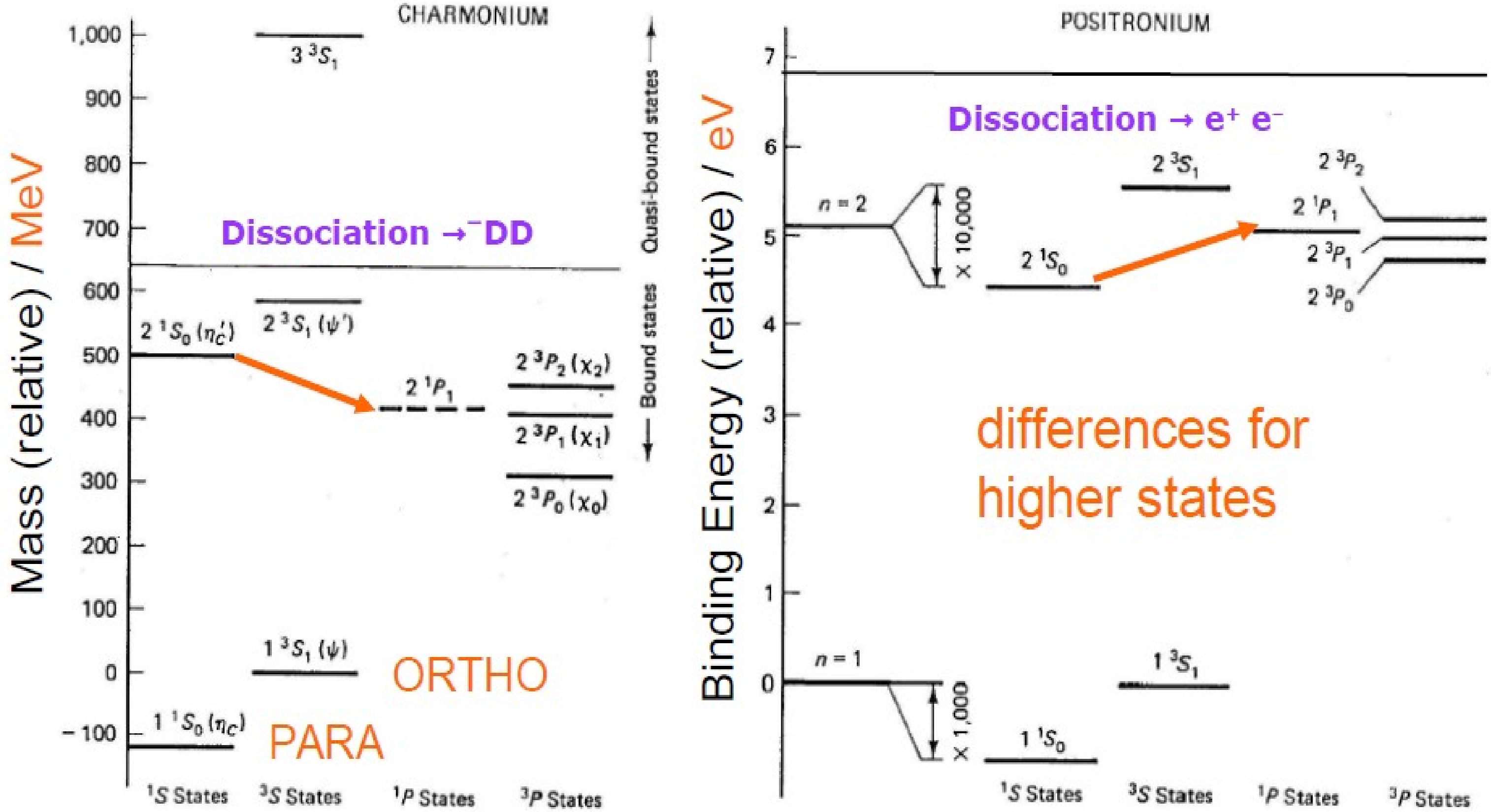
- m=4.660 GeV → turning point of wave function is 2.2 fm!
- large fraction of wave function in string breaking regime r>1.4 fm

courtesy of J.S. Lange, HIRSCHEGG2018

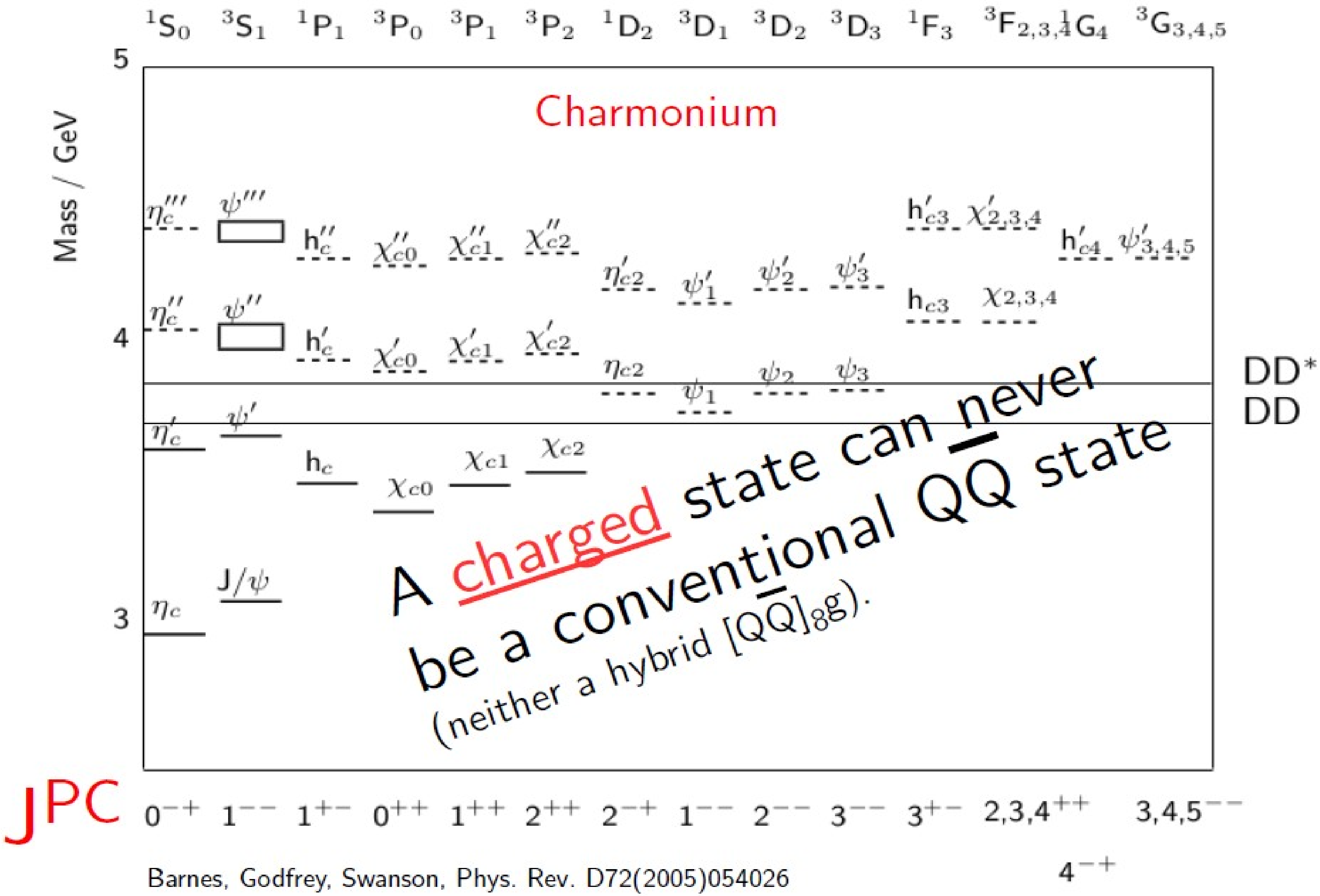
Charmonium vs. Positronium



Decays to light quarks suppressed
→ narrow widths



courtesy of J.S. Lange, HIRSCHEGG2018

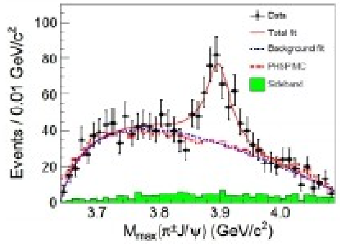


Barnes, Godfrey, Swanson, Phys. Rev. D72(2005)054026

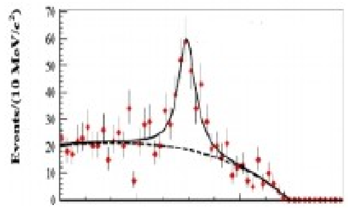
Z STATES AT BESIII

$D\bar{D}^*$ threshold

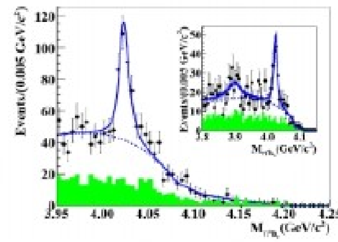
$D^*\bar{D}^*$ threshold



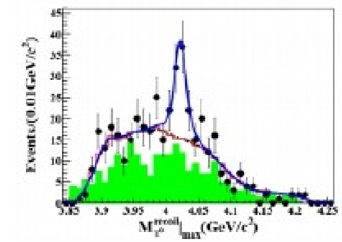
$e^+e^- \to \pi^+ \pi^- J/\Psi$



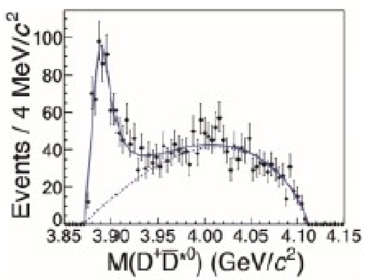
$e^+e^- \to \pi^0 \pi^0 J/\Psi$



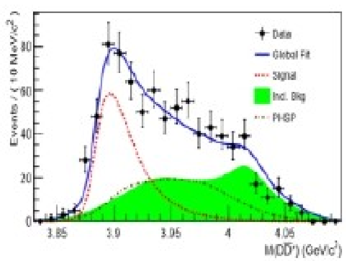
$e^+e^- \to \pi^+ \pi^- h_c$



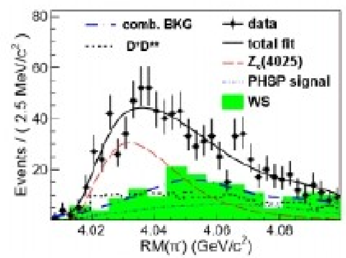
$e^+e^- \to \pi^0 \pi^0 h_c$



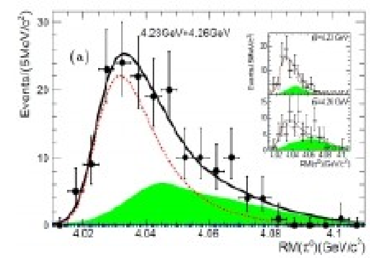
$e^+e^- \to \pi^+ (D\bar{D}^*)^-$



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



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



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

charged neutral charged neutral

Recent hot topic: neutral partners $\to$ 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)