Review on Hadron Physics

08.10.2019 I Elisabetta Prencipe

Universal Physics in Many-Body Quantum Systems – From Atoms to Quarks
ECT* Trento (IT)

Outline

- Introduction
- Experiments covered in this talk: BELLE Belle II BABAR LHCb

- Hadron spectroscopy: too wide topic!
  In this talk: XYZ and charmed baryons
- General picture:
  - identify effective degree of freedom
  - generalized parton distribution
- What have we understood from recent observations?
- Outlook
- Summary

Introduction: QCD

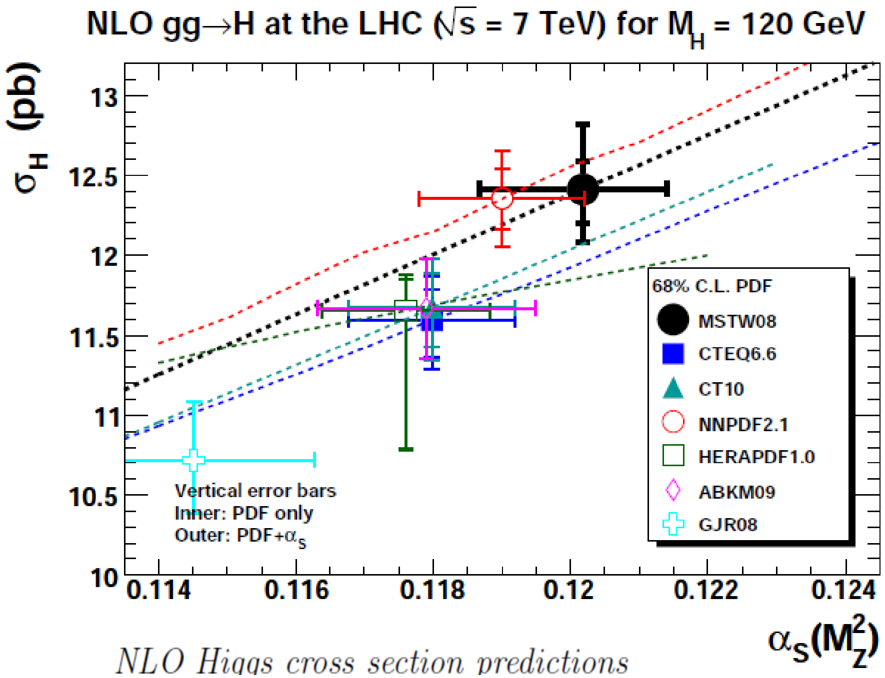
- Quantum-Chromodynamics (QCD):
  gauge field theory describing the strong interaction of quarks and gluons

$$L = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + \sum_k \overline{\psi}_k \left(i \not{D} - m_k \right) \psi_k$$

- Experimental results are consistent with QCD prediction within uncertainties
- L depends on 6 quark masses and the strong-fine structure constant α_S (classic)
- Quantum theory contains an additional parameter ϑ which violate CP
- Different quantities can be evaluated as function of α_S, which allows to evaluate it:

- α_S from Z decays and e^+e^- total rates
- α_S from deep inelastic scattering
  → structure functions
- α_S from fragmentation functions
- α_S from event shape and jet counting
- α_S from τ decays
- α_S from lattice gauge theory computations
- α_S from heavy-quark systems
- α_S from hadron-hadron scattering

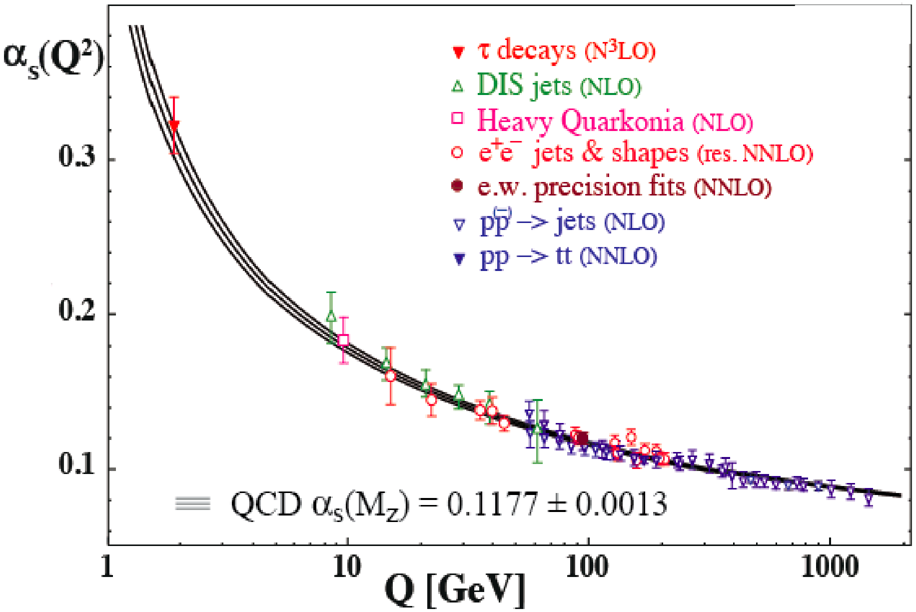
Introduction: α_s



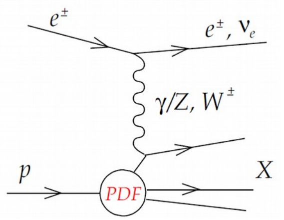
NLO Higgs cross section predictions ($M_H = 120$ GeV) using different PDFs at the LHC with $\sqrt{s} = 7$ TeV.

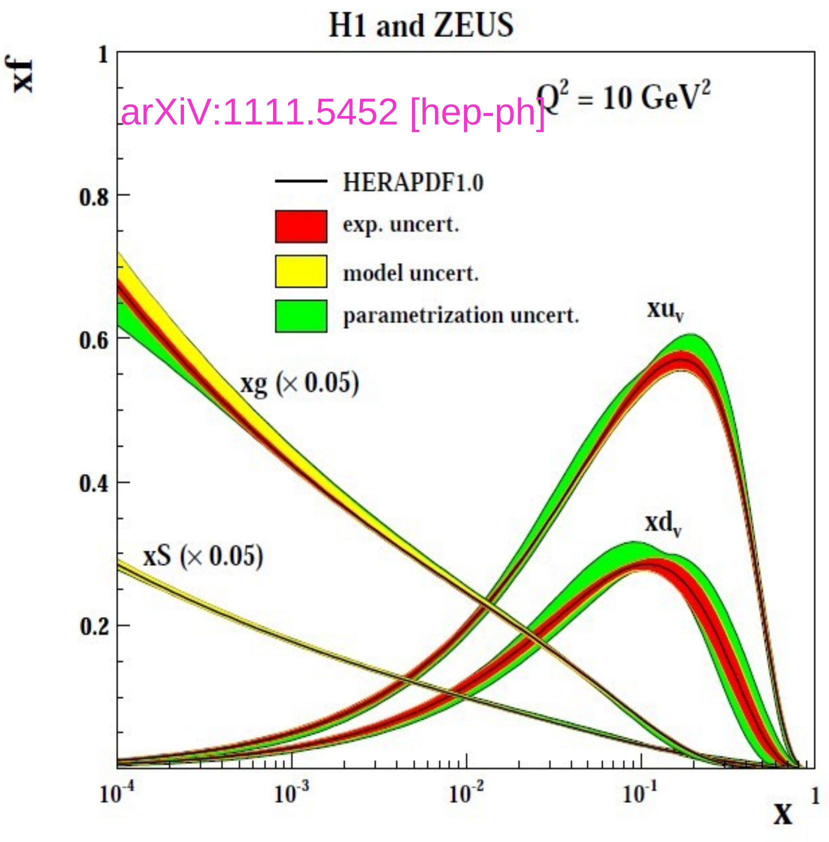
- Hadron physics is a wide wide field….
- The measurement of α_S still needs input at low energy regime

PRD 98 (2018) 030001



Introduction: GPD





arXiV:1111.5452 [hep-ph]

The parton distribution functions from HERAPDF1.0 at $Q^2 = 10$ GeV^2. The gluon and sea distributions are scaled down by a factor of 20. The experimental, model and parametrisation uncertainties are shown separately.

- Generalized Parton Distributions (GPD)= suitable theoretical tool to study the structure of the nucleon
- Internal dynamics of nucleons are determined by the strong interactions between quarks exchanging gluons
- A detailed description of the nucleon structure is still missing because QCD can only be solved in the perturbative regime of short distance phenomena probed in hard collisions, whereas the soft part of the interaction corresponding to the long-distance behaviour requires a non-perturbative and/or numerical treatment (e.g., in lattice simulations)

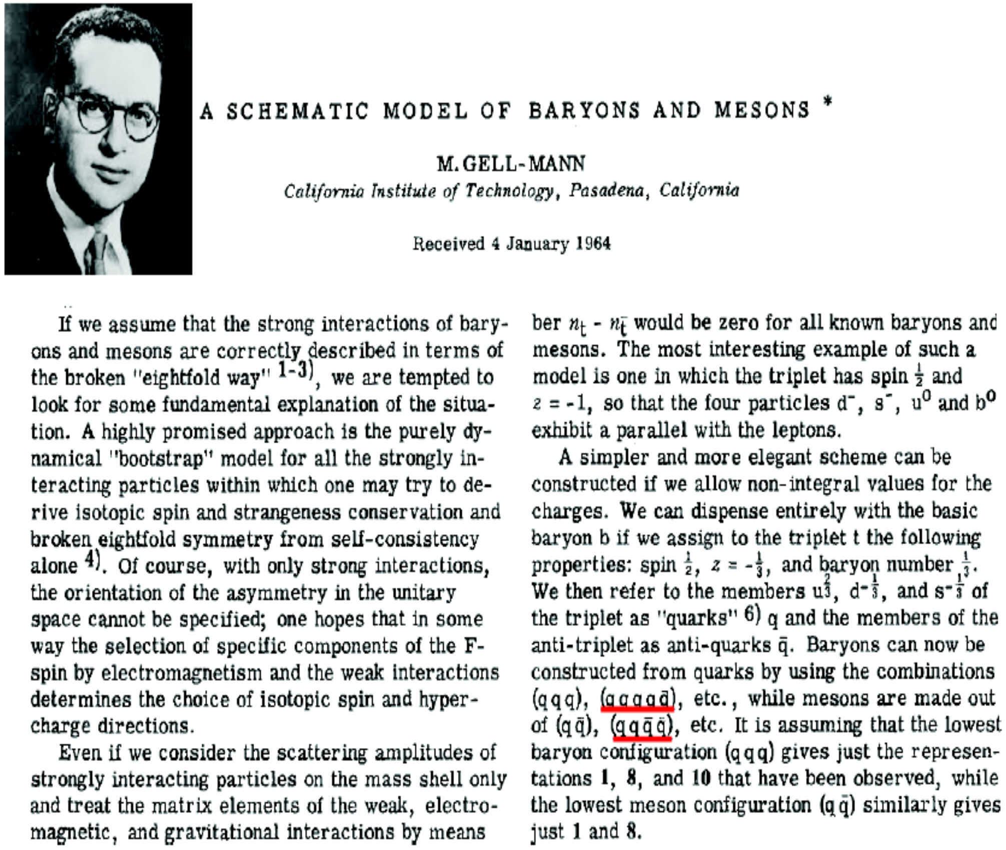
Two main issues can be here identified:

- Generalized Parton Distribution (GPD)
  → hadron tomography
- identify effective degree of freedom
  → hadron spectroscopy

Introduction: hadrons

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

  Still valid for half century → it classifies all known hadrons



A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

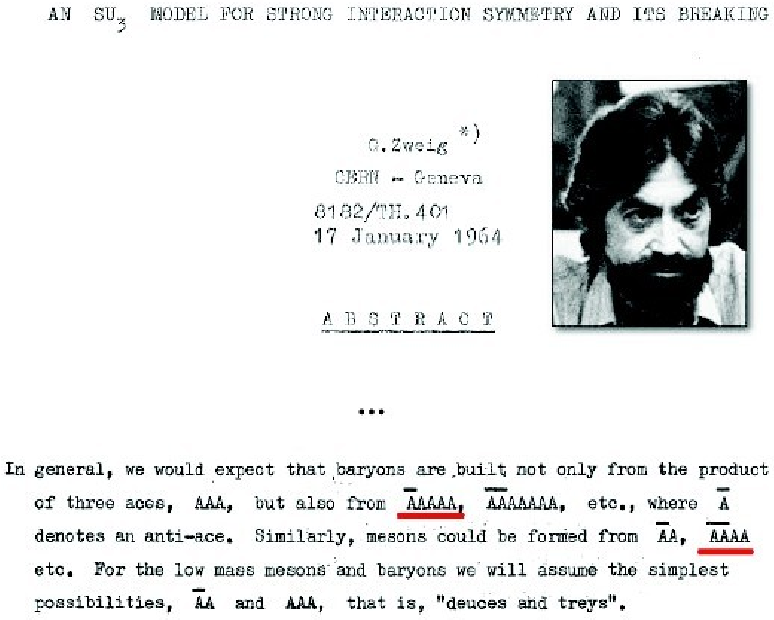
If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" 1-3), we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone 4). Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

…

ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\bar{q})$ similarly gives just **1** and **8**.



AN SU$_3$ MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

G.Zweig *)
CERN - Geneva
8182/TH.401
17 January 1964

A B S T R A C T

…

In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ and AAA, that is, "deuces and treys".

Introduction: hadrons

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

  Still valid for half century → it classifies all known hadrons

- QCD-motivated models predict the existence of hadrons with more complex structures than simple *qq* (mesons) or *qqq* (baryons) → the so-called XYZ *“charmonium”-like* states
- **<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
- hybrids
- molecular states
- hadrocharmonium
- pentaquarks
- hexaquarks
- glueballs
- cusps…

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

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

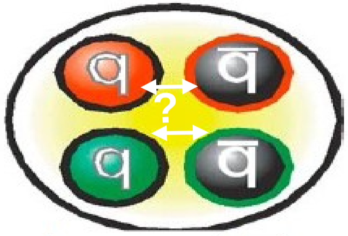
Quark Bound States

Lifetime:
< 10^{-8} s

Meson

Lifetime:
> 10^{30} y (proton)
~ 10 min (neutron)
< 10^{-10} s (others)

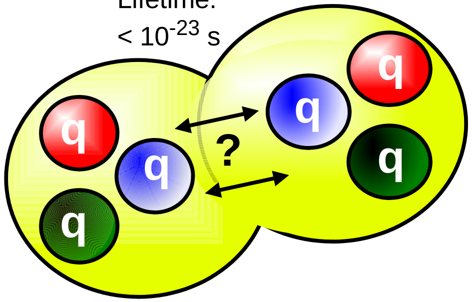
Baryon



Lifetime:
< 10^{-23} s

Tetraquark

Lifetime:
< 10^{-23} s

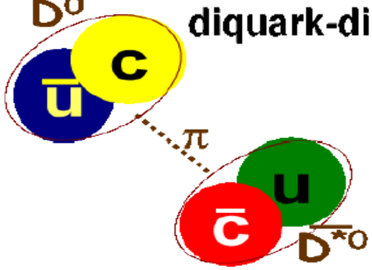


Di-baryon

Lifetime:
< 10^{-20} s

Pentaquark

diquark-diantiquark



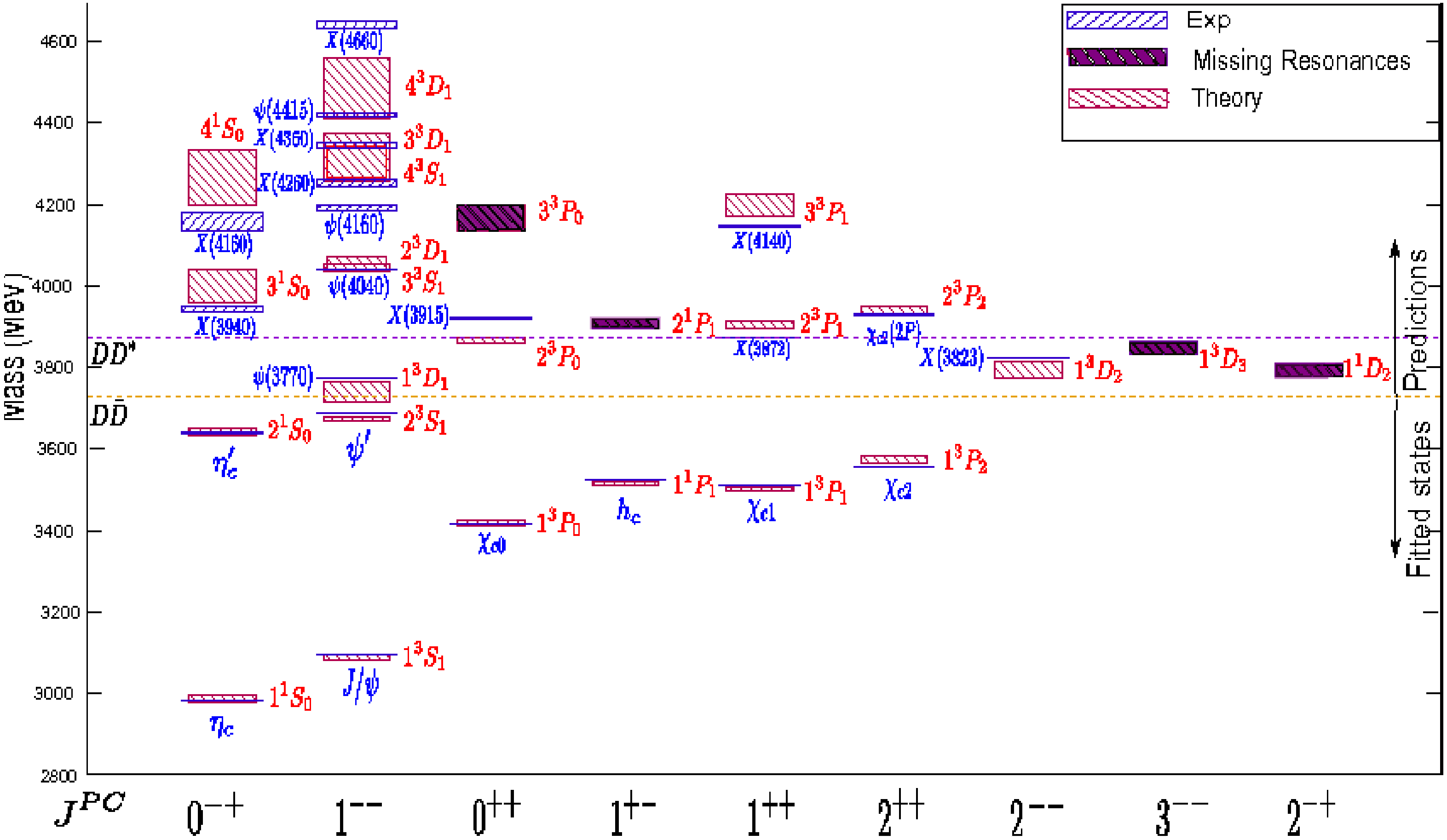
$D^0 - \bar{D}^{*0}$ "molecule"

Hybrid meson

Glueball

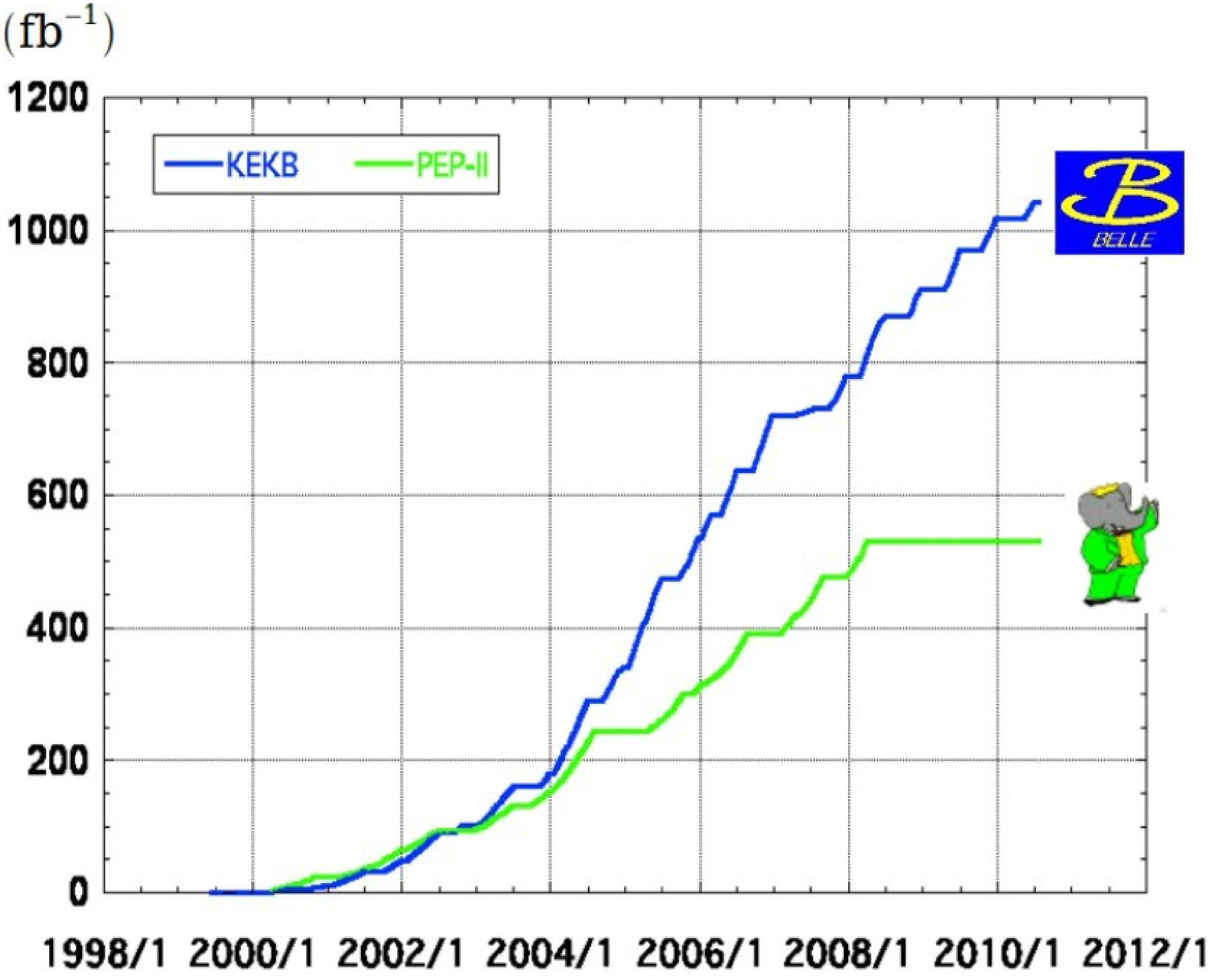
...and superposition of different states: $c_1|\bar{q}q\rangle + c_2|\bar{q}q\bar{q}q\rangle + \ldots$

Charmonium(*-like*) Spectrum



- Overall agreement experiments-theory so far: precision ~2-3 MeV; but since 2003 several new entries!

B factories



$> 1\ \mathrm{ab}^{-1}$

On resonance:

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

$\Upsilon(4S)$: 711 fb^{-1} 772M $B\overline{B}$

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

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

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

Off reson./scan:

~ 100 fb^{-1}

~ 550 fb^{-1}

On resonance:

$\Upsilon(4S)$: 433 fb^{-1} 470M $B\overline{B}$

$\Upsilon(3S)$: 30 fb^{-1}

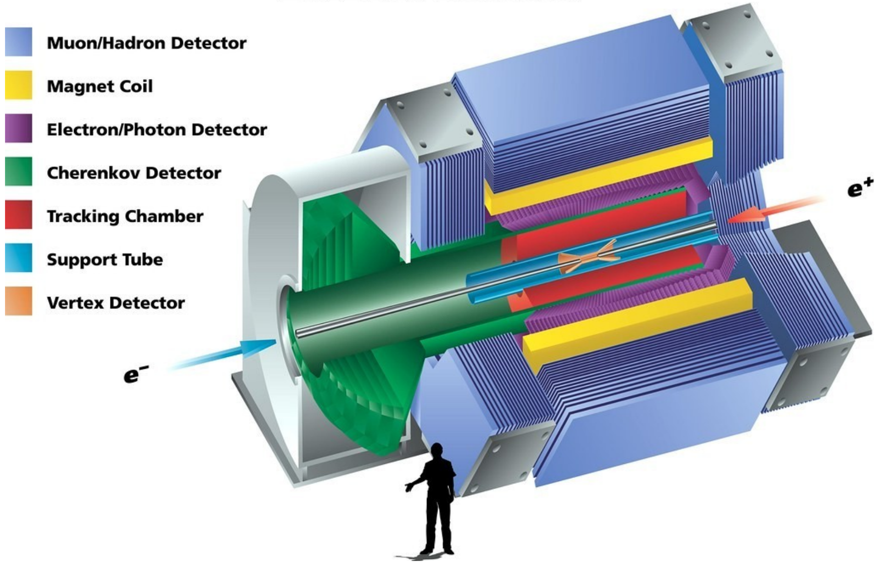
$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

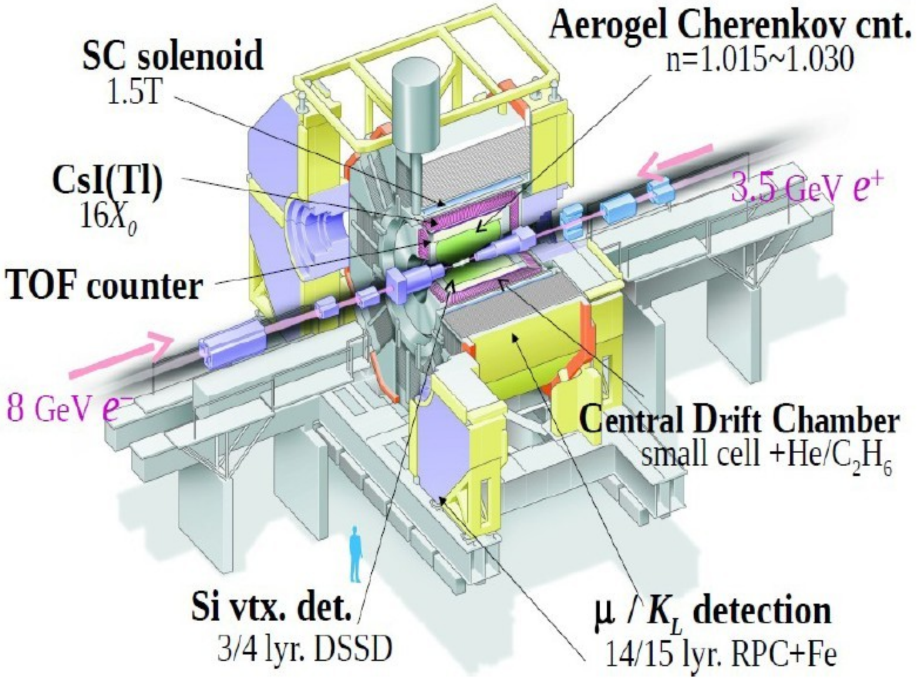
~ 54 fb^{-1}

...and there is more….

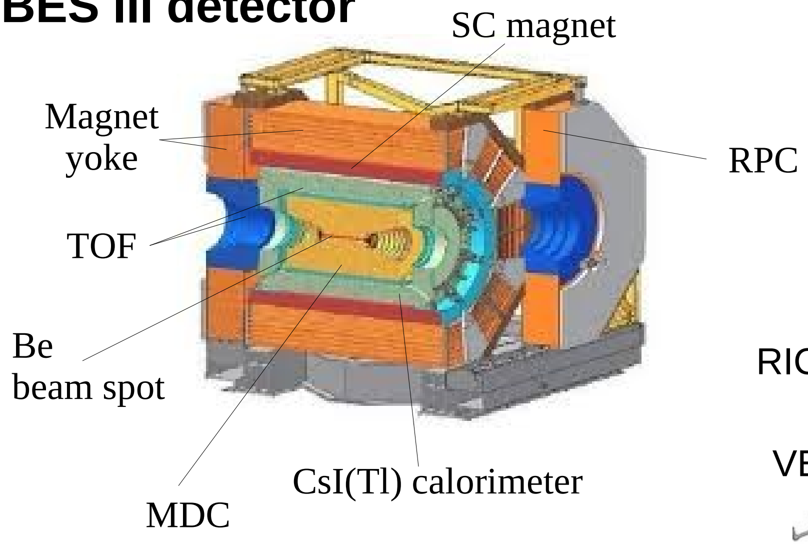
BABAR Detector



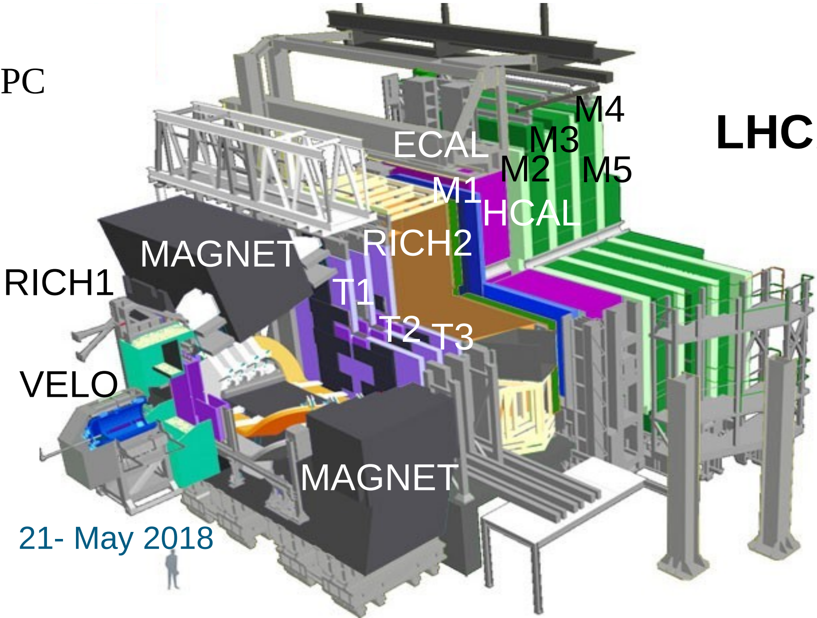
Belle detector



BES III detector

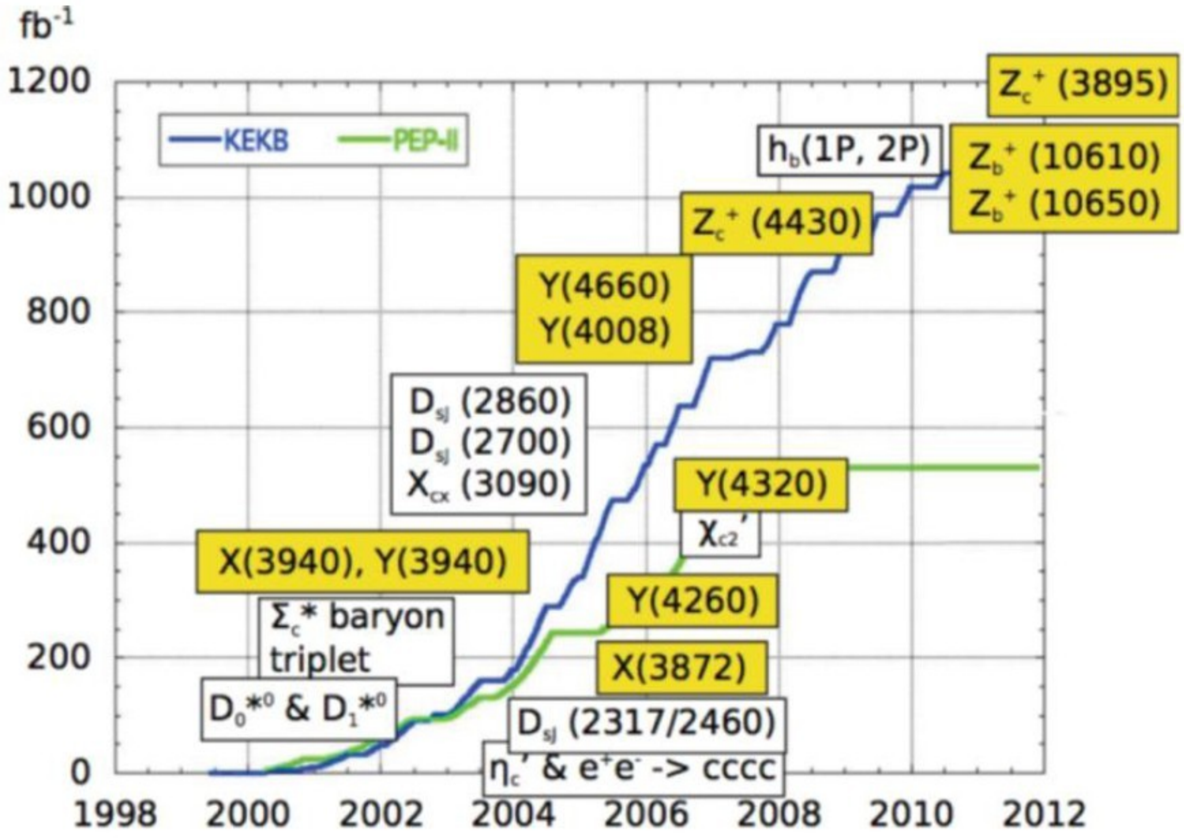


LHCb detector



- 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!

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). SVD rebuilt
- TOP: (time-of-propagation) + ARICH will do the timing of the Cerenkov light. TOP time resolution ~50 ps, with 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?

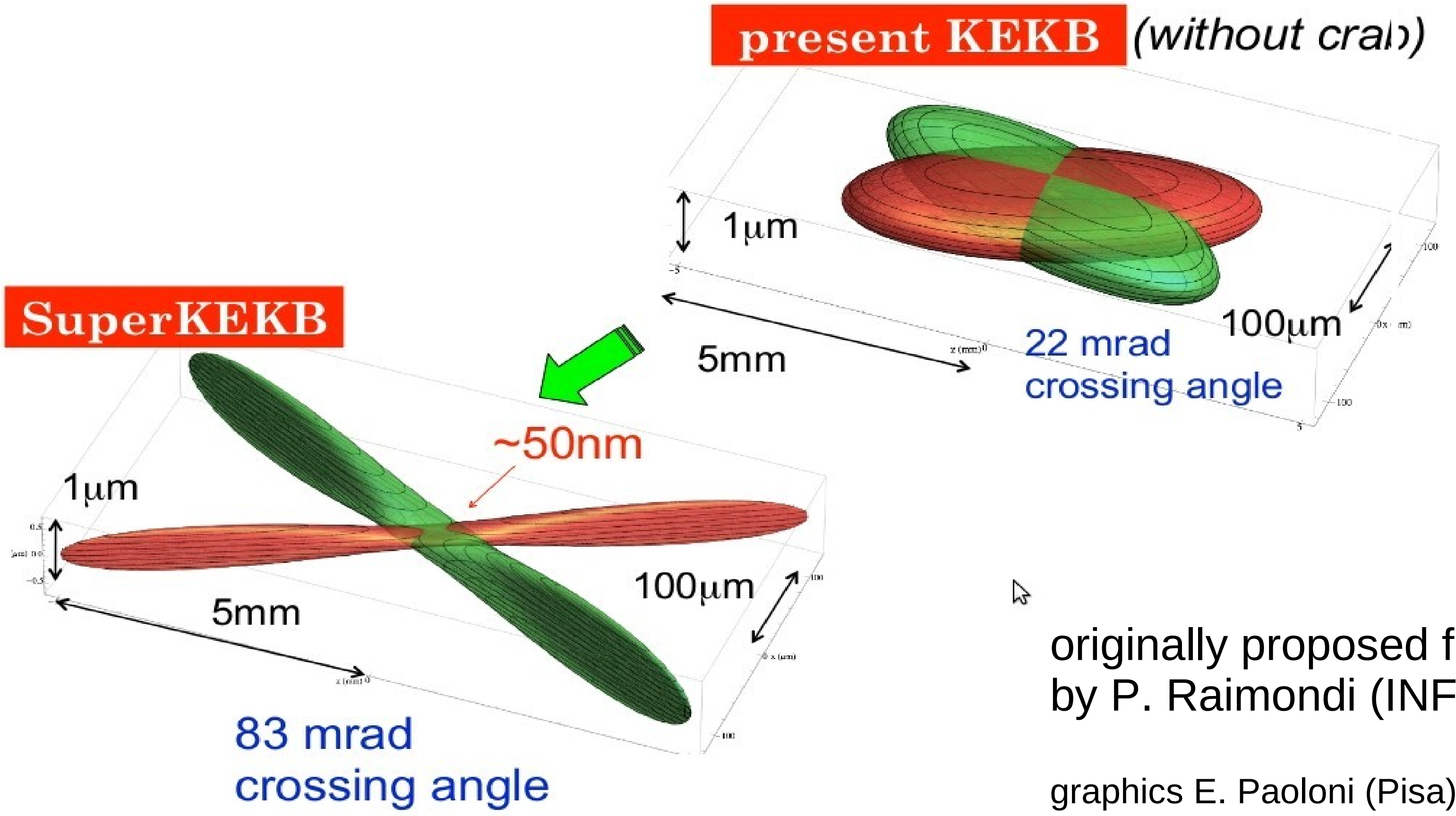
- factor 2 by beam current: 1.64/1.19 A (Belle) → 3.6/2.6 A for $e^+(e^-)$ beam in Belle II
- factor 20 by "nano-beam" principle (collision point in vertical direction will be only 59 nm)

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

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

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

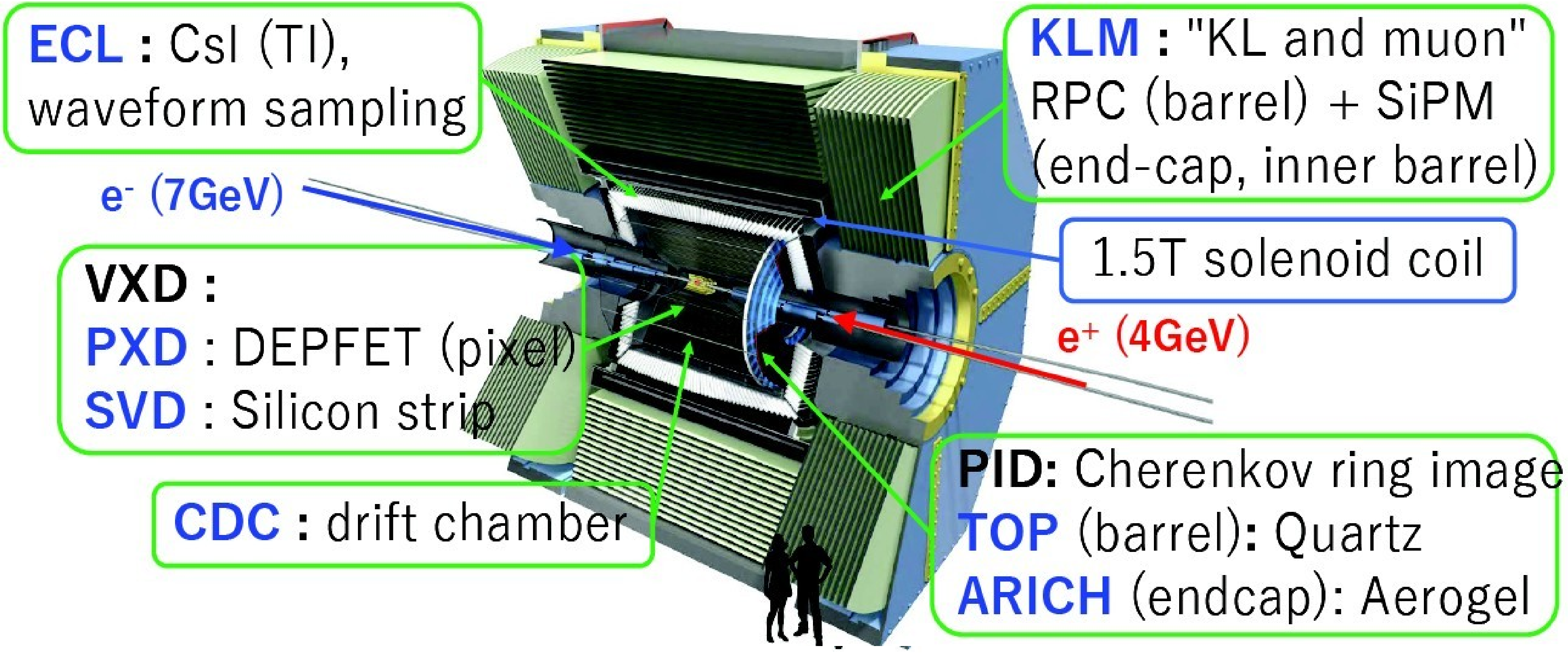
Nano-Beam Scheme



originally proposed for SuperB
by P. Raimondi (INFN)

graphics E. Paoloni (Pisa)

Belle II detector



ECL : CsI (Tl), waveform sampling

KLM : "KL and muon" RPC (barrel) + SiPM (end-cap, inner barrel)

e$^-$ (7GeV)

1.5T solenoid coil

VXD :

PXD : DEPFET (pixel)

SVD : Silicon strip

e$^+$ (4GeV)

CDC : drift chamber

PID: Cherenkov ring image

TOP (barrel): Quartz

ARICH (endcap): Aerogel

Issues to overcome

- Beam background
- High rate capability
- Boost ~ 2/3

Technical choice

- Finer segmentation, waveform sampling.
- Material change
- Larger angular coverage (CDC, SVD)
- Closer to the IP (PXD) 3 -> 2cm
- Particle ID improve (K/π)(TOP, ARICH)

Benefits of the B factories BaBar+Belle (II)

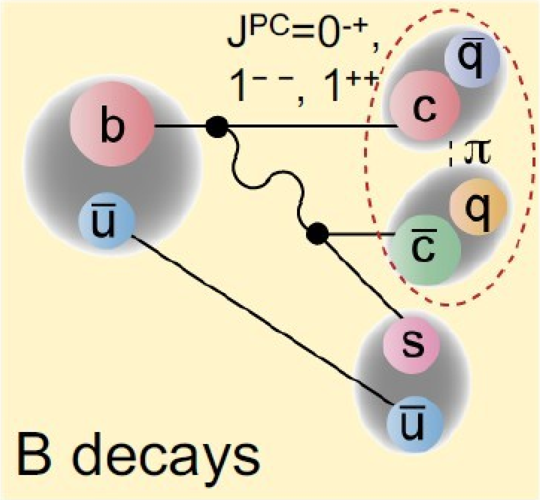
Example from BELLE II

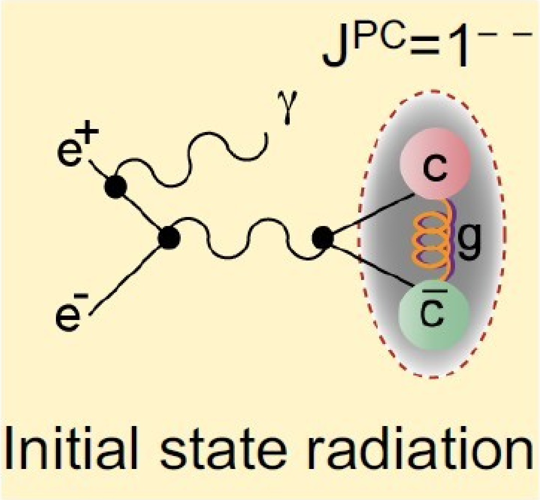
- 4π general purpose spectrometer with:
  - High momentum resolution, σ_p/p = 0.3%@1GeV/c
  - Ability to detect photons down 30 MeV
  - Good photon energy resolution, σ_M = 5 MeV for $\pi^0 \rightarrow \gamma\gamma$
  - Lepton identification capability, $\varepsilon > 0.9$
  - K/π/p separation capability, $\varepsilon \sim 0.9$
  - Excellent B decay vertex resolution, $\sigma_{\Delta z}$ = 25 μm
  - World highest luminosity

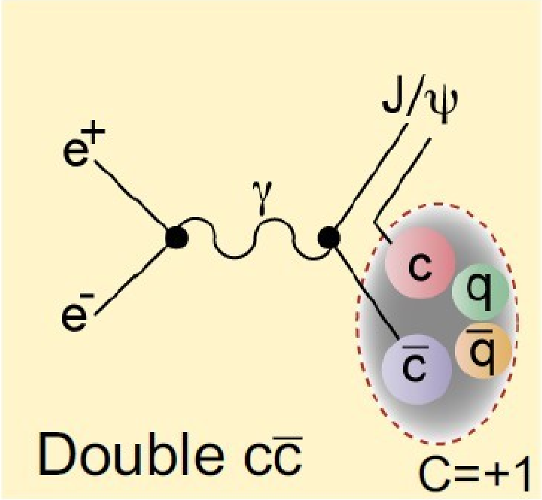
Advantages at BaBar+Belle (II)

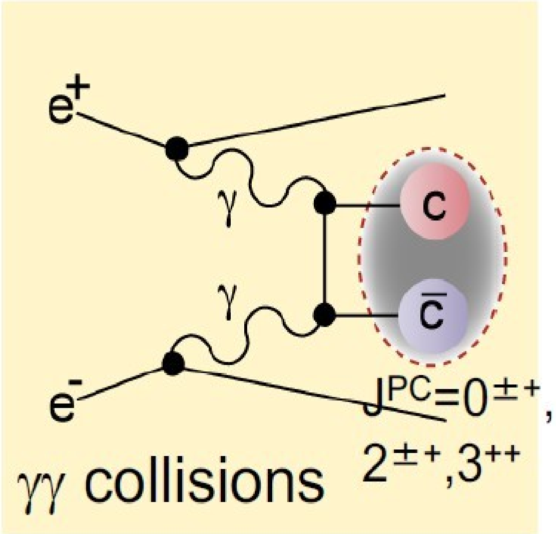
- Studying physics of strong interactions, among other topics, with:
  - Access to different production mechanisms
  - Access to a variety of final states
  - A variety of recorded reactions
  - Make predictions based on observations, using reactions which allow to access specific quantum numbers for exotic states
- Interplay among several approaches is effective

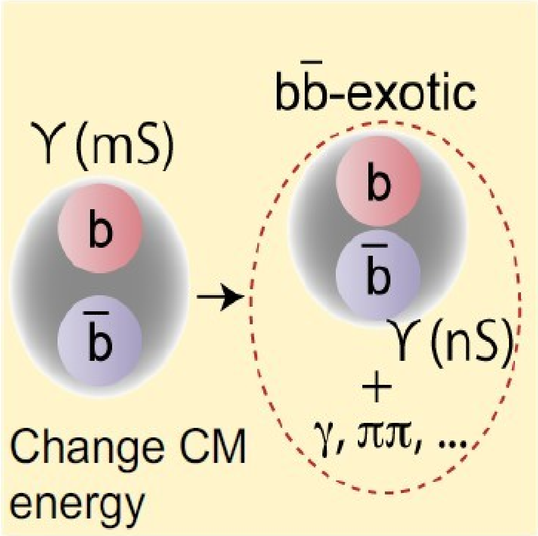
A variety of production mechanism for exotics @B-factories











Experimental techniques

e^+e^- colliders

- Direct formation
- Two photon production
- Initial state radiation (ISR)
- B meson decays

(BaBar, Belle(II), BES, Cleo(-c), CESR, LEP...)

Low hadronic background
High discovery potential

BUT

Direct formation limited to vector states
Limited mass and width resolution
for non vector states

$p\bar{p}$ annihilation

(LEAR, Fermilab E 760/835, $\overline{\text{P}}$ANDA)

Hadron production

(CDF, D0, LHC)

Electro/photon production

(HERA, JLAB)

High hadronic background

BUT

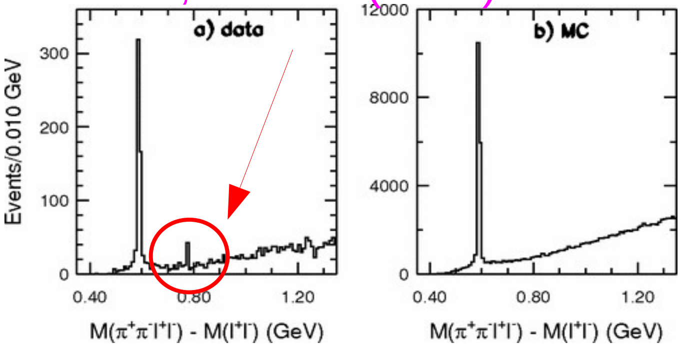
High discovery potential
Direct formation for all (non exotic) states
Excellent mass and width resolution
for all states

Nomenclature

X, such as the X(3872)

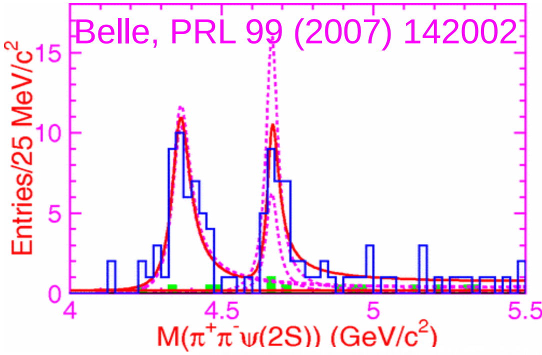
- consistent with $D^0\bar{D}^{*0}$ molecular state
- found in B decays, large production also in pp
- no partners found

Belle, PRL 91 (2003) 262001



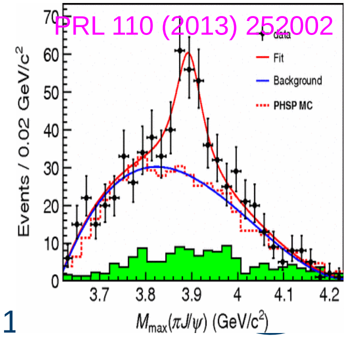
Y, such as the Y(4260), Y(4330), Y(4660)

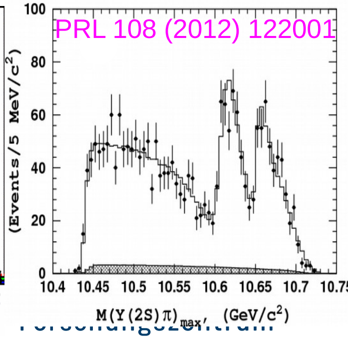
- produced in initial state radiation and $E_{c.m.}$ scan
- $J^{PC} = 1^{--}$
- overpopulated for charmonium


Belle, PRL 99 (2007) 142002

Z, such as the $Z_c(3900)$ and the $Z_b(10610)$

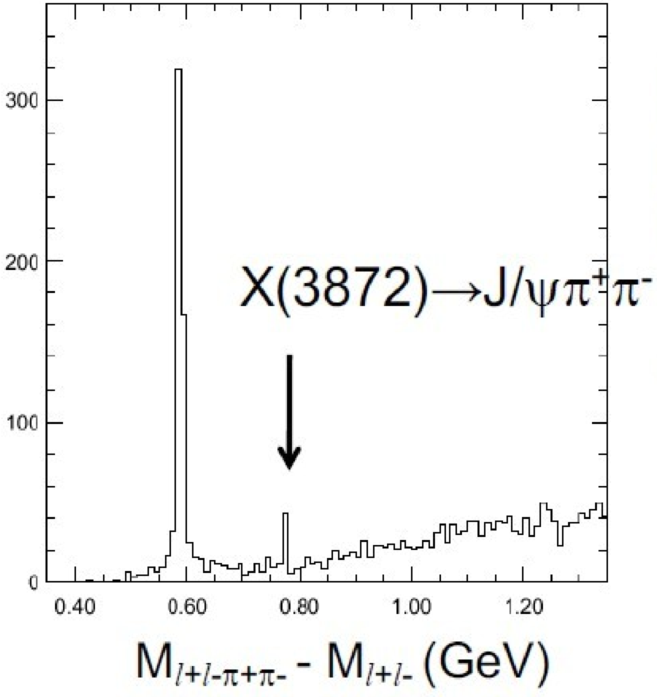
- seen in decays of $q\bar{q}$ and B decays
- charged states: cannot be charmonia
- b- and c- *onia*: similarities


PRL 110 (2013) 252002

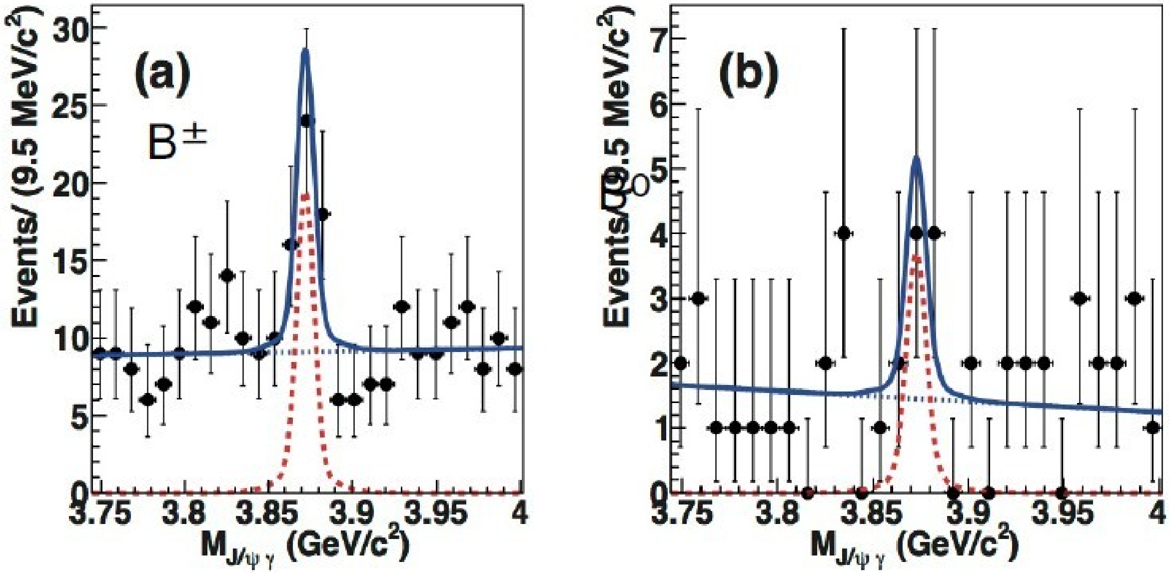

PRL 108 (2012) 122001

The exotic ‘saga’: how that started

PRL91 (2003) 261801



X(3872)→J/ψ γ; C=+1

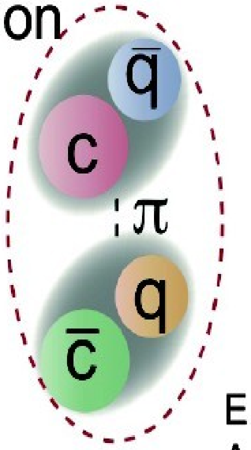


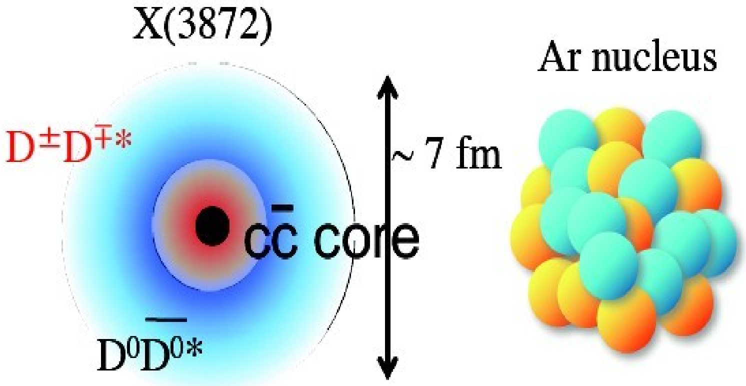
PRL07 (2011) 091803

- The highest Belle cited paper ever: >1630 citations up to now, since 2003 (inspires)
- Lots of progresses on this topic since 2003: $J^{PC} = 1^{++}$ (PRL110 (2013) 222001)

Interpretation for the X(3872)

Meson-meson molecule





E. J. Eichiten et al. Phys. Rev. D 73, 014014 (2006);
A. M. Badalin et al. Phys. Rev.D 85, 031103 (2012);
S. Takeuchi, K. Shimizu and M.Takizawa PTEP2014, 123D01(2014).

- BR(X(3872)$\rightarrow D^0\bar{D}^{*0}$) is x10 BR(X(3872)$\rightarrow J/\psi\pi^+\pi^-$)
- $D^0\bar{D}^{*0}$ component coupled with the same as J^{PC} $c\bar{c}$ χ_{c1}(2P) (unseen)
- D^+D^{*-} can explain why $J/\psi\pi^+\pi^-$ and $J/\psi\pi^+\pi^-\pi^0$ coexist
- $c\bar{c}$ component in prompt production at LHC seen (pure molecule interpretation is then too weak...)
- Most probable interpretation: admixture

X(3872): a look to the future

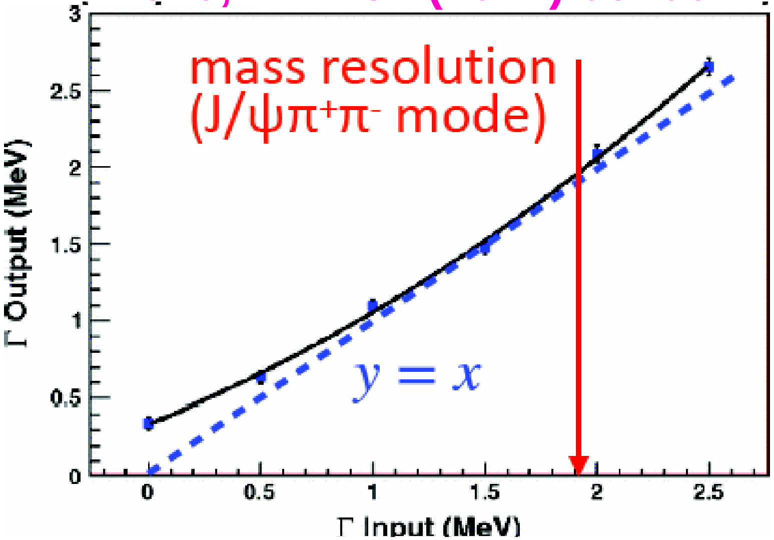
- Known upper limit: $\Gamma < 1.2$ MeV (estimated from $X(3872) \to J/\psi\pi^+\pi^-$), on full Belle data sample

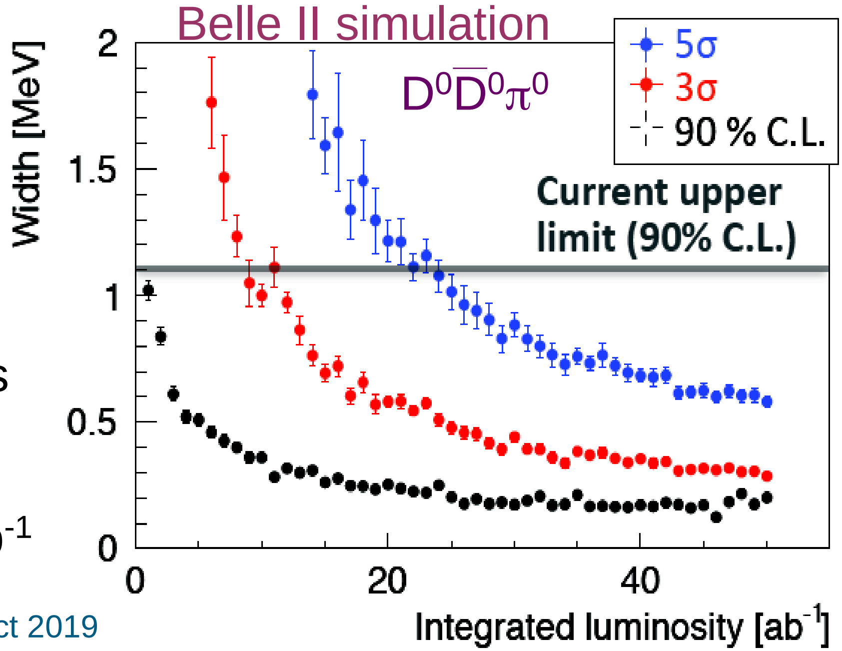
- Very promising: $X(3872) \to D^0\overline{D}^{0*}$

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}

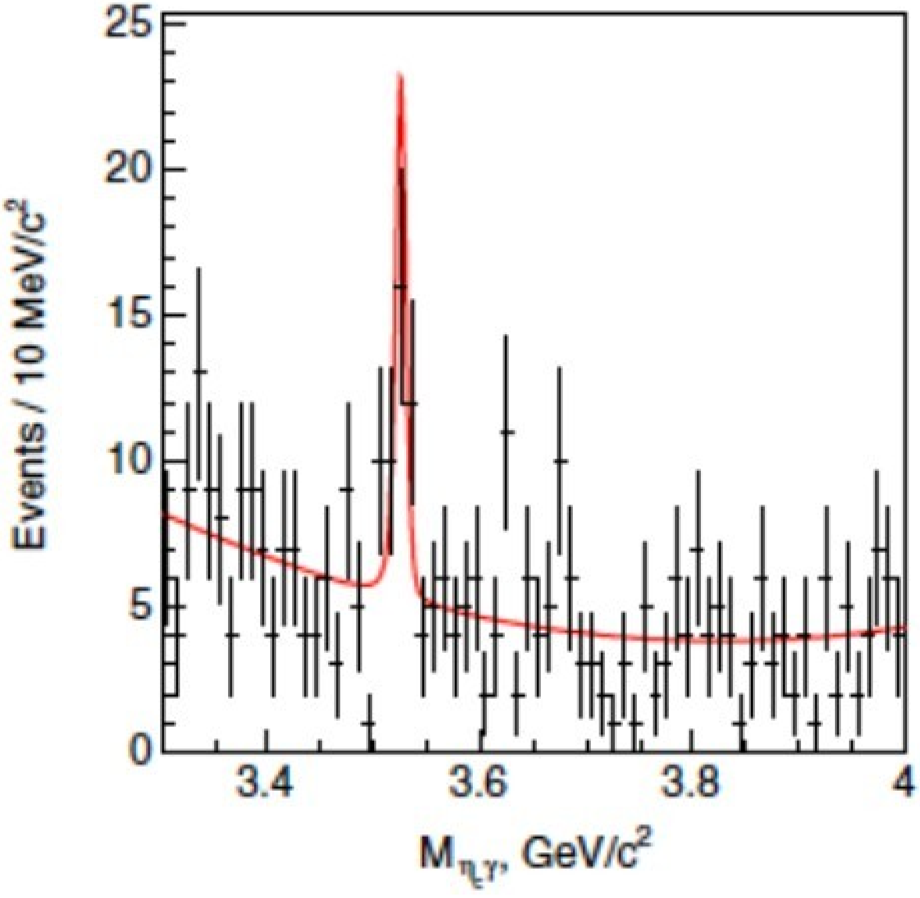
Belle, PRD 84 (2011) 052004





H. Hirata, Master thesis 2019

New observation for charmonium at Belle

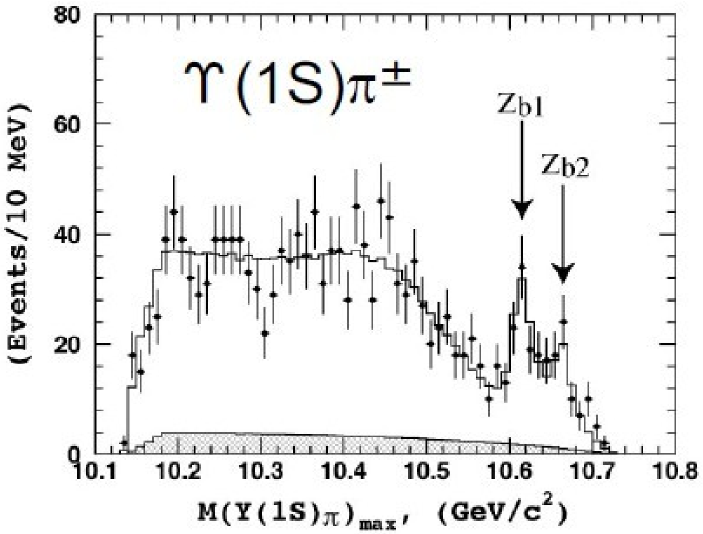


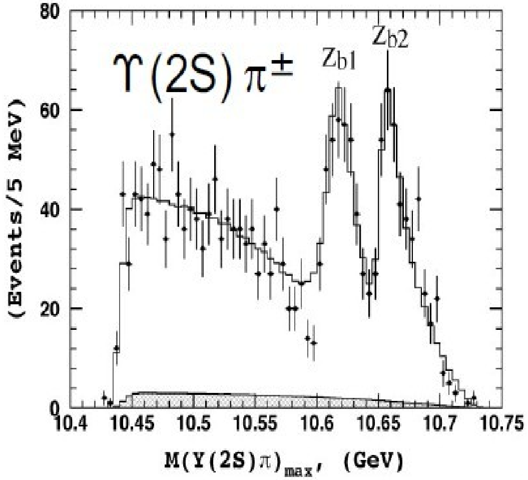
$B^+ \to h_c K^+$, $h_c \to \gamma\, \eta_c$

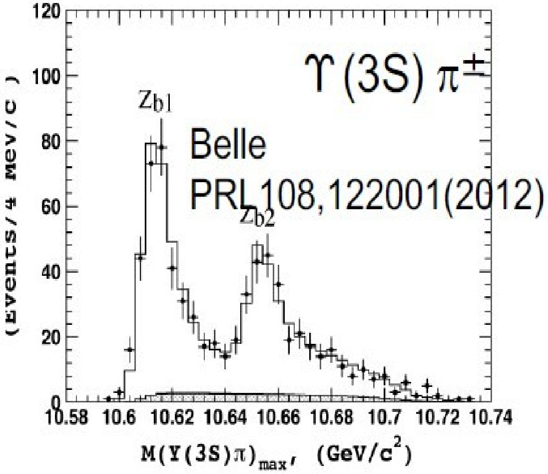
PRD100 (2019) 012001

- η_c reconstructed in 11 modes
- Multivariate analysis technique used to overcome factorization suppression
- First evidence of h_c in B decays
- Radiative decays into $\gamma\eta_c$ or $\gamma\eta_c(2S)$ are important to look for X(3872) C-odd partners.
  Great Belle contribution from this analysis!

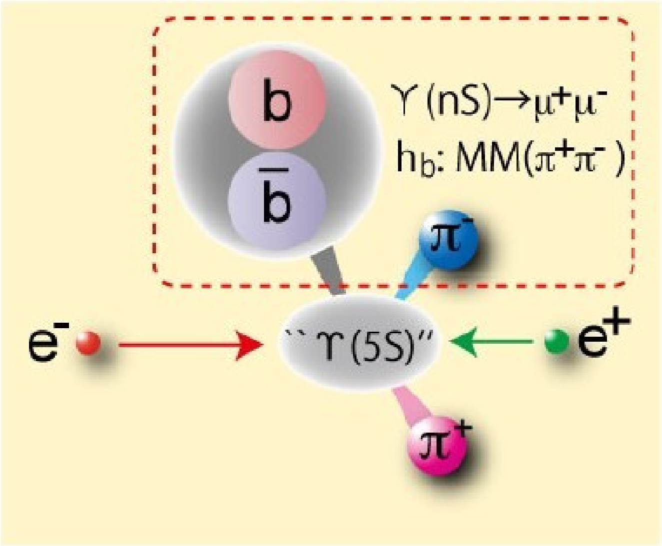
Υ(nS) transitions

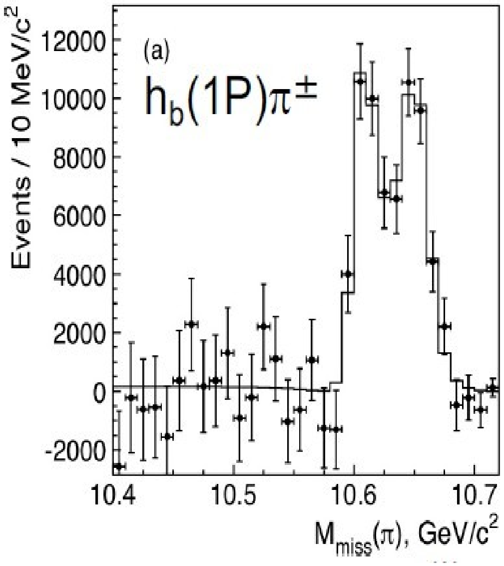


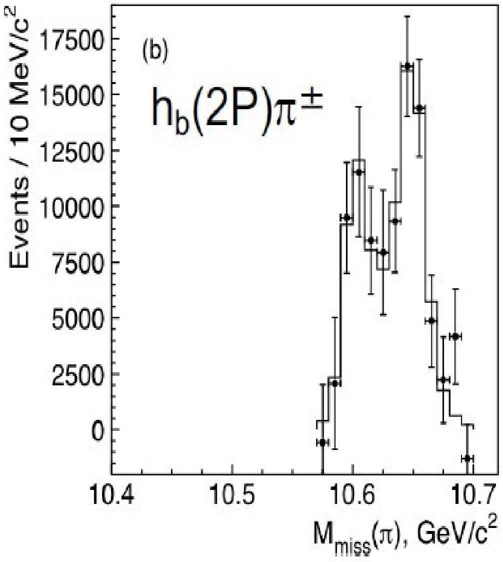




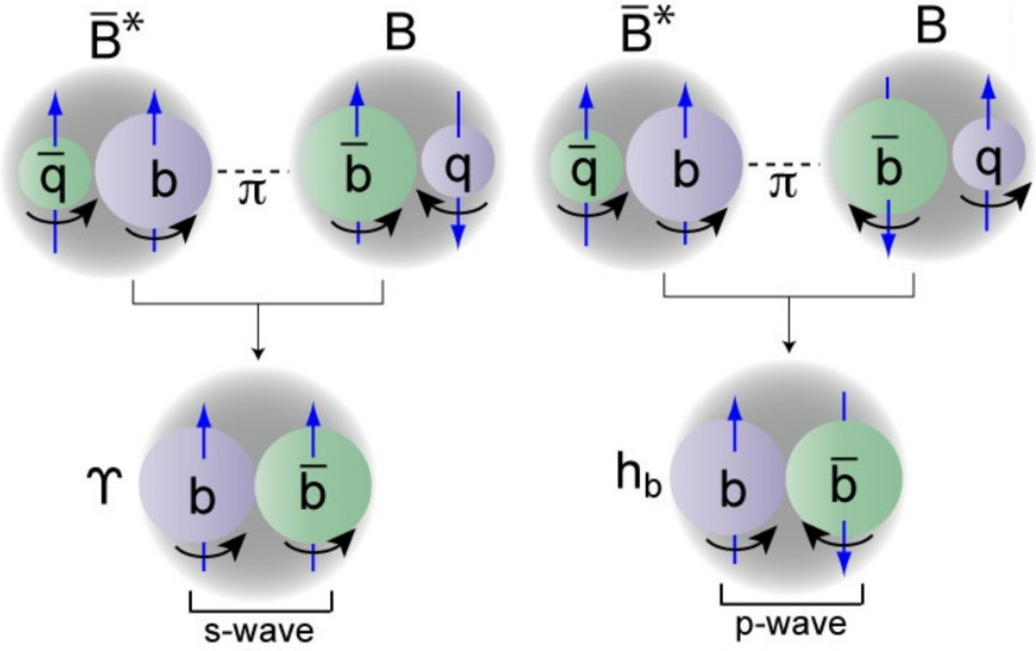
Belle
PRL108,122001(2012)







Molecular picture for ϒ(nS) transition

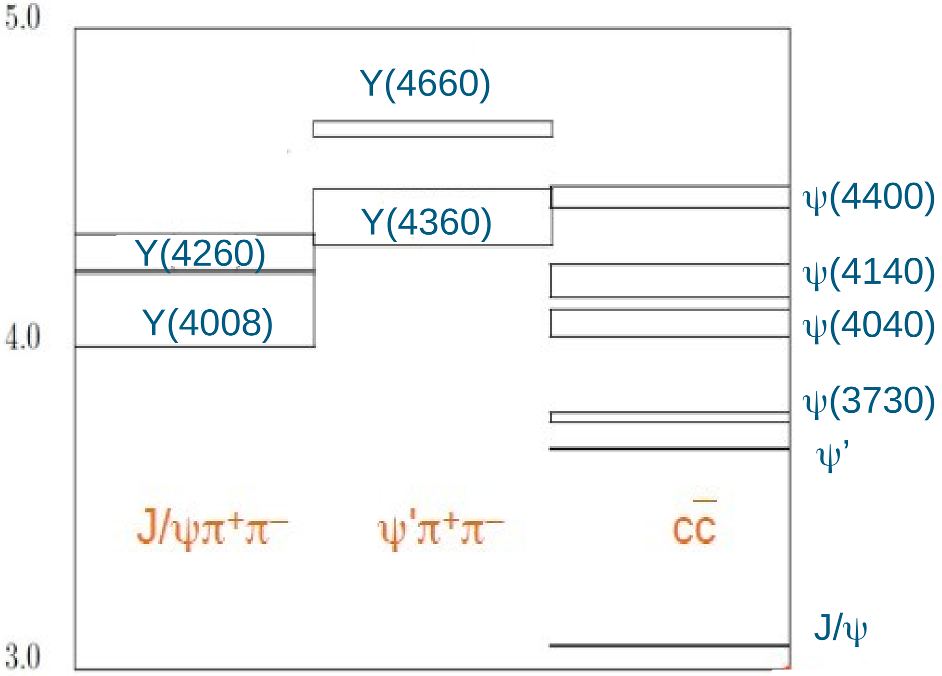


A. Bondar et al, PRD84 (2011) 054010

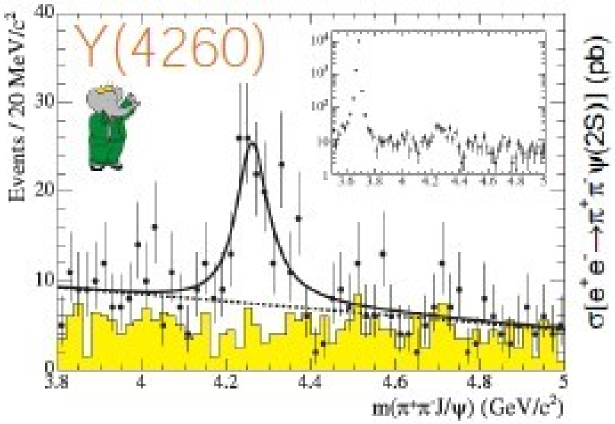
- Decays of ϒ(nS) and h_c can coexist
- Decay to $B^*B^{(*)}$ found to be dominant
- $J^P = 1^+$ supported by Dalitz analysis, PRD91 (2015) 072003
- Limited statistics!
- Belle II is suitable for this search

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



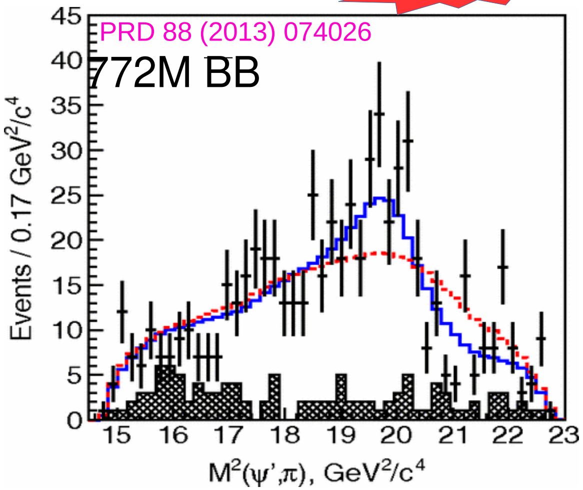
- ISR studies: unique at B factories
- Clear signature: $J^{PC} = 1^{--}$
- No mixing ⇨ surprising!
- Limited statistics at B-factories for such rare events: need more data!

Z Charged States

Main achievements at Belle

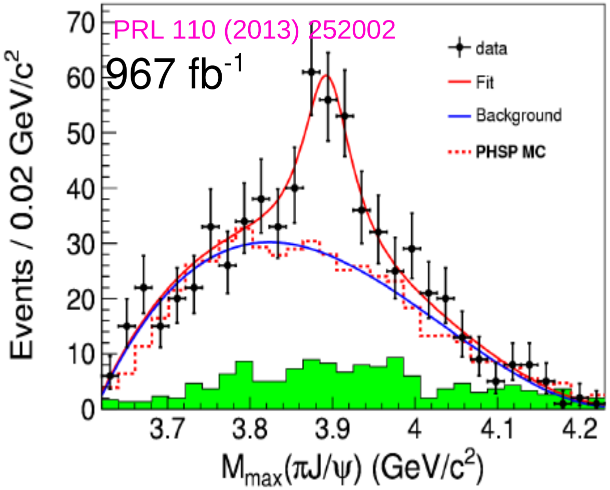
$B^0 \to K^- \pi^+ \psi'$

Update


PRD 88 (2013) 074026

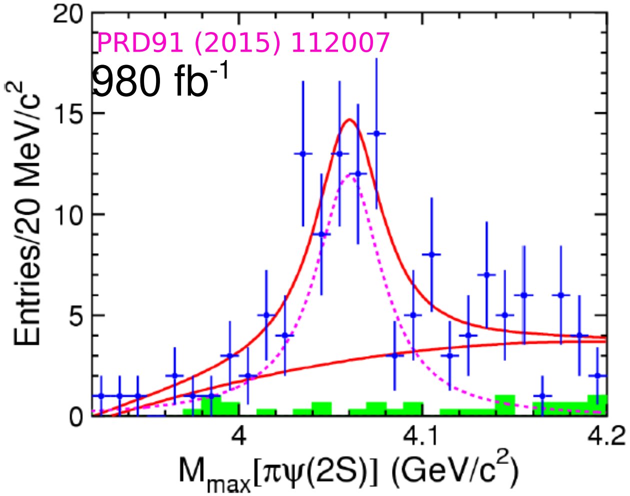
772M $B\bar{B}$

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


PRL 110 (2013) 252002

967 fb^{-1}

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


PRD91 (2015) 112007

980 fb^{-1}

$M = 4485 \pm 22\,^{+28}_{-11}$ MeV/c^2
$\Gamma = 200^{+21}_{-46}\,^{+26}_{-35}$ MeV
6.4σ, $J^P = 1^+$

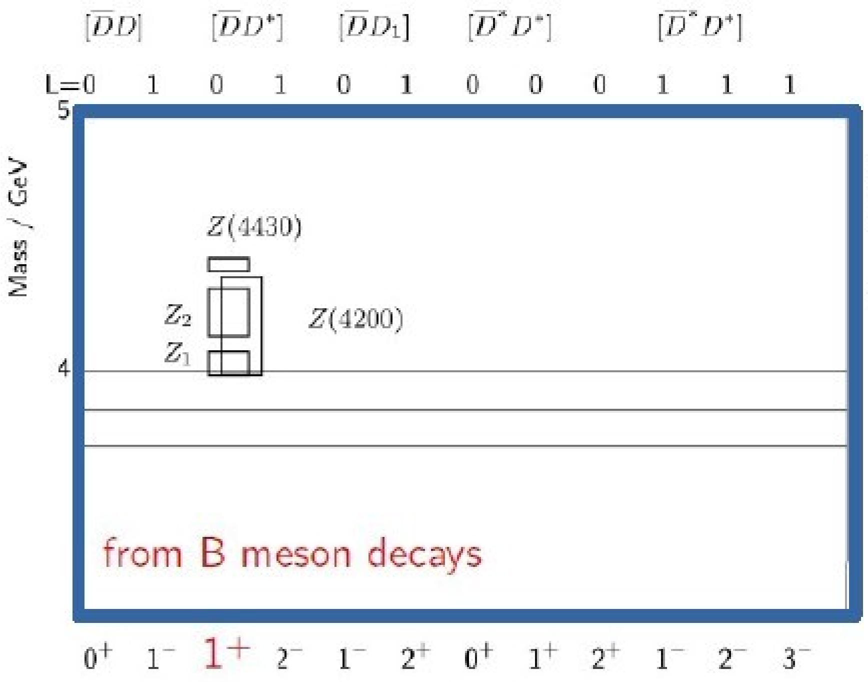
$M = 3894.5 \pm 6.6 \pm 4.5$ MeV/c^2
$\Gamma = 63 \pm 24 \pm 26$ MeV
$>5.2\sigma$

$M = 4054 \pm 3 \pm 1$ MeV/c^2
$\Gamma = 45 \pm 11 \pm 6$ MeV
$>3.5\sigma$

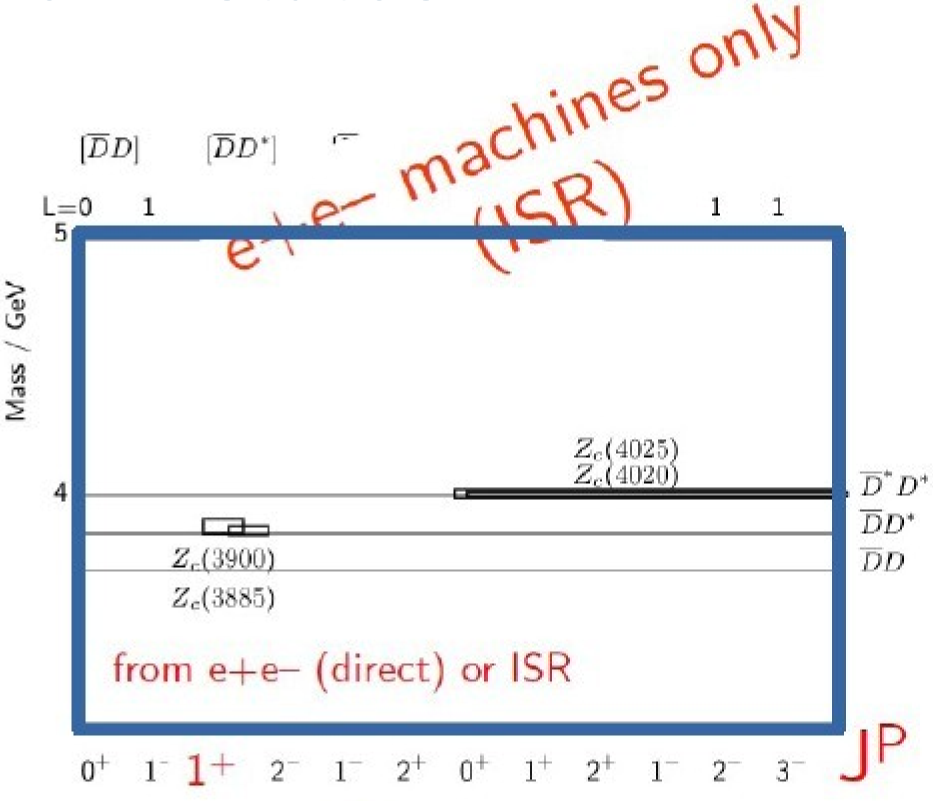
First observation: Belle, PRL 100 (2008) 142001;
Confirmed by LHCb: PRD 92(2015) 112009

BESIII confirmation/following PRL 110 (2013) 252001

Two different classes of Z states?



- large widths
- not connected to thresholds?

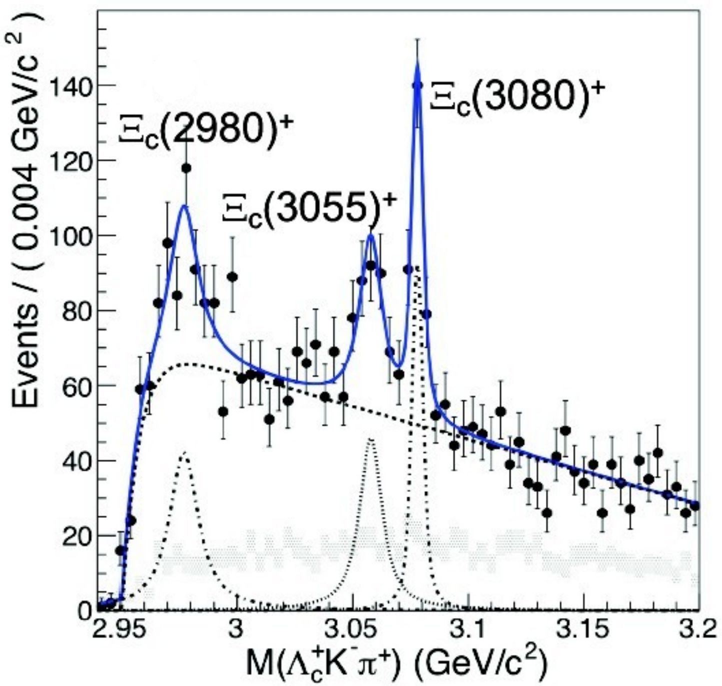


- narrow widths
- near thresholds

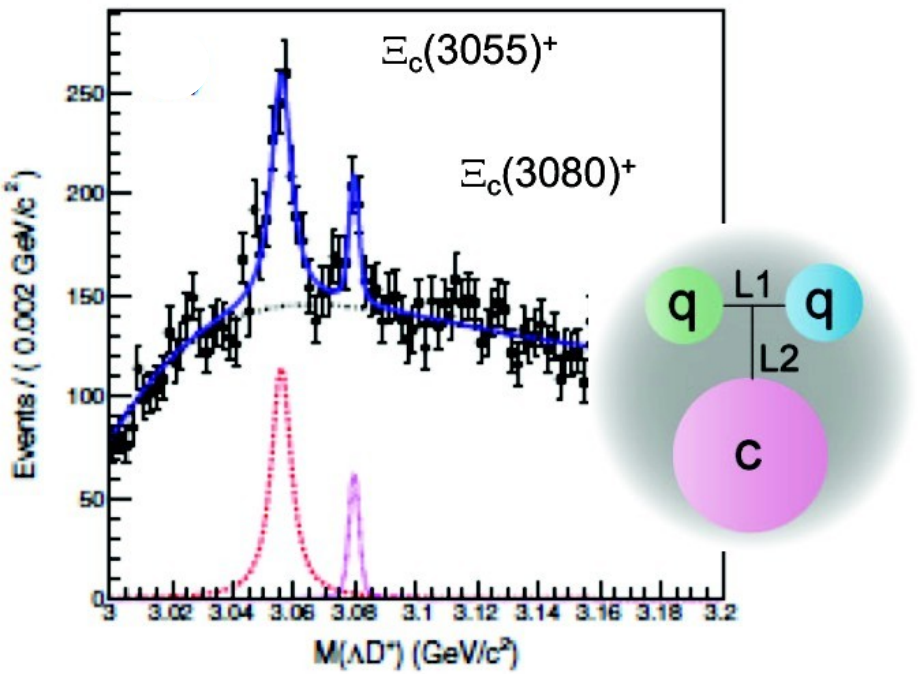
- Belle II is in a unique position to look for both Z types:
  - through B decays (LHCb, no BES III)
  - threshold state (BES III, no LHCb)

Charm baryons to check di-quark @ Belle

PRD89,052003(2014)



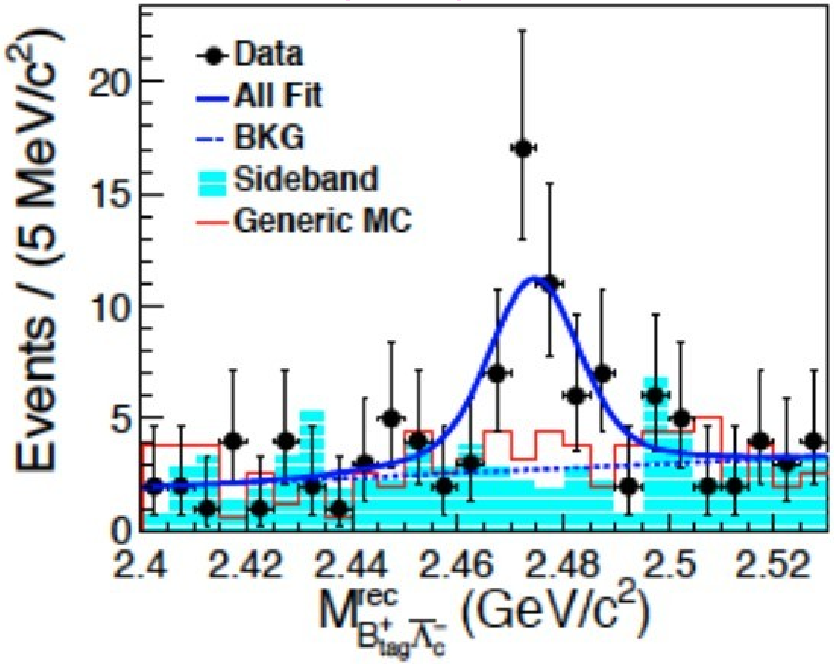
PRD94,032002(2016)

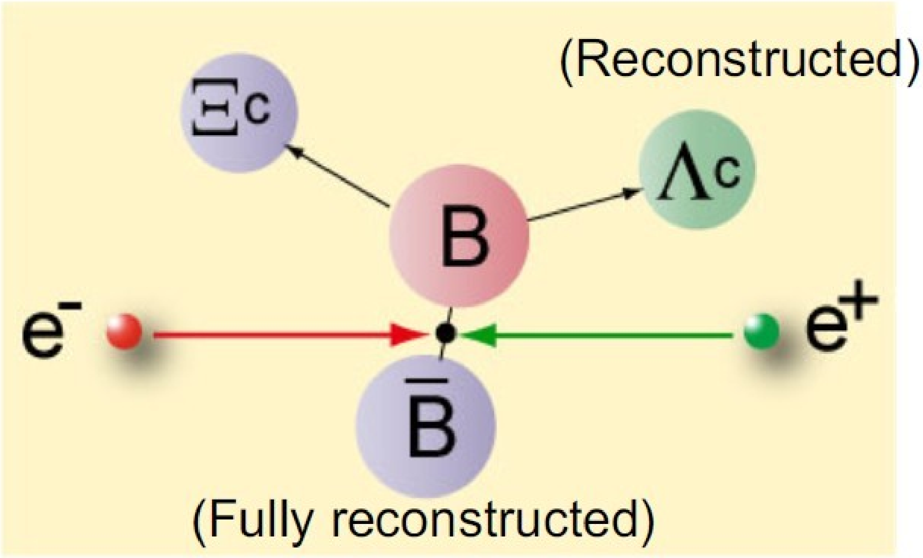


- Good place to check if di-quark structures behave as a good degree of freedom to form hadrons
- One of the constituent quark is heavy: correlation between the remaining light quarks would become clear
- “charm baryon + light hadron” or “charm meson + baryon”?

$B^- \to \Lambda_c^- \Xi_c^0$: missing mass technique and absolute BR measurement

PRL122 (2019) 082001





$Br(B^- \to \Lambda_c^- \Xi_c^0) = (9.51 \pm 2.10 \pm 0.88) \times 10^{-4}$

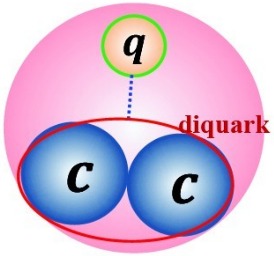
$Br(\Xi_c^0 \to \Xi^- \pi^+) = (1.80 \pm 0.50 \pm 0.14)\%$

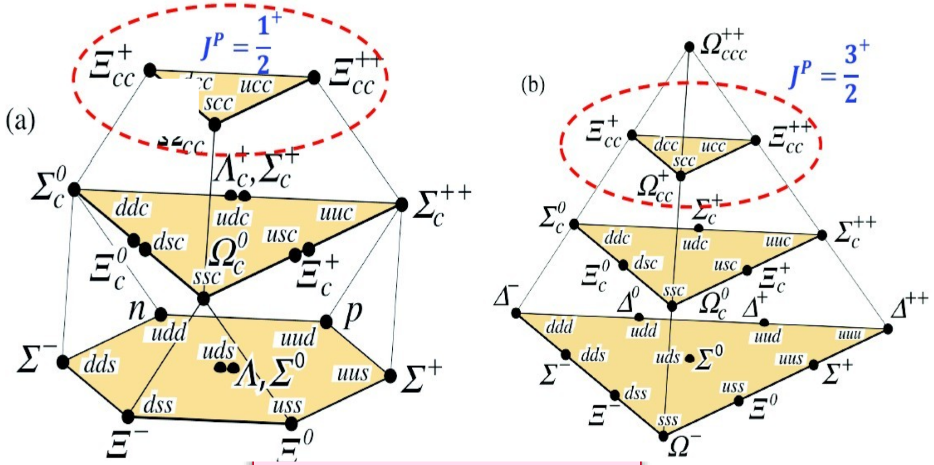
$Br(\Xi_c^0 \to \Lambda K^- \pi^+) = (1.17 \pm 0.37 \pm 0.09)\%$

$Br(\Xi_c^0 \to p K^+ K^- \pi^+) = (0.58 \pm 0.23 \pm 0.05)\%$

Double-Charm baryons @LHCb

- Not well established
- Test for QCD





PRL119 (2017) 112001

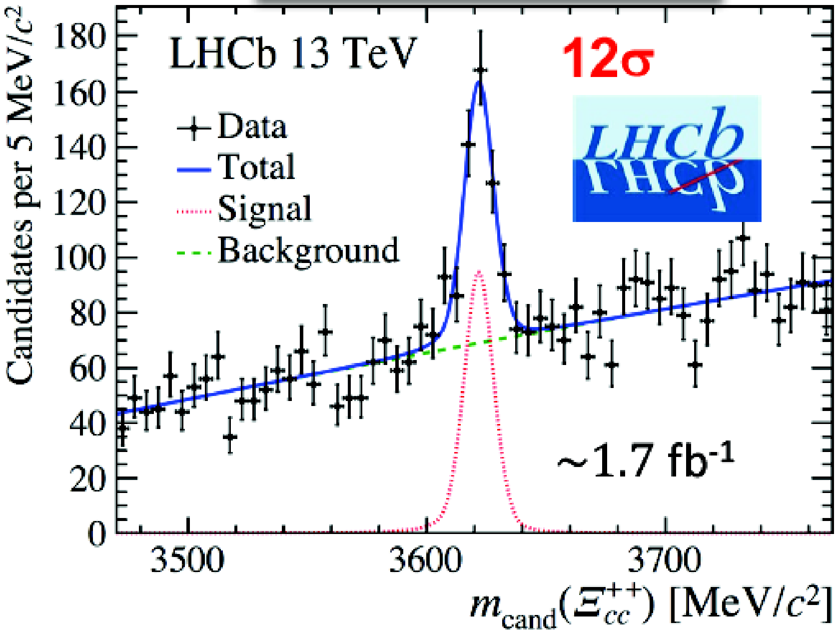
$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$

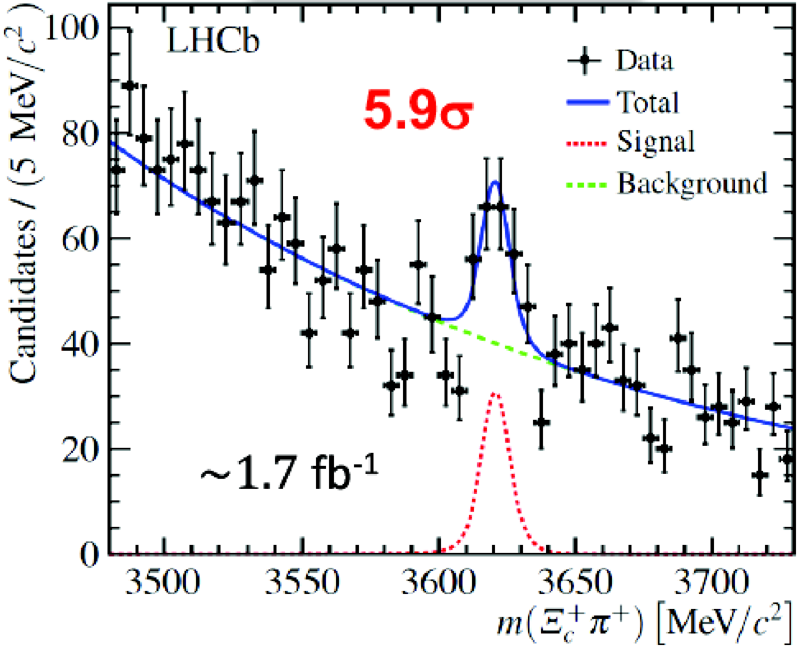
$N_{\text{sig}} = 313 \pm 33$

PRL121 (2018) 162002

$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$

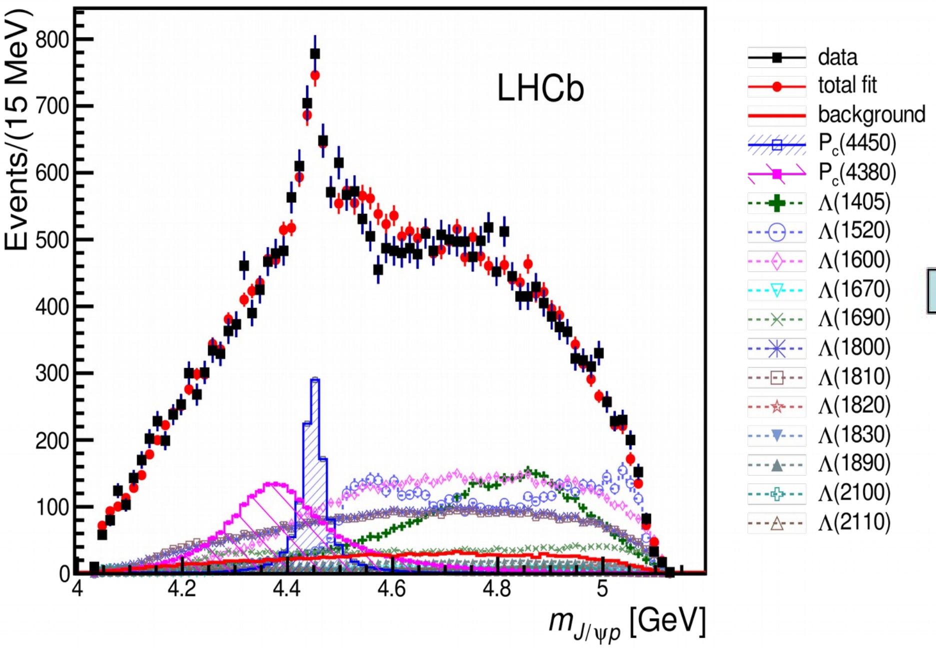
$N_{\text{sig}} = 91 \pm 20$

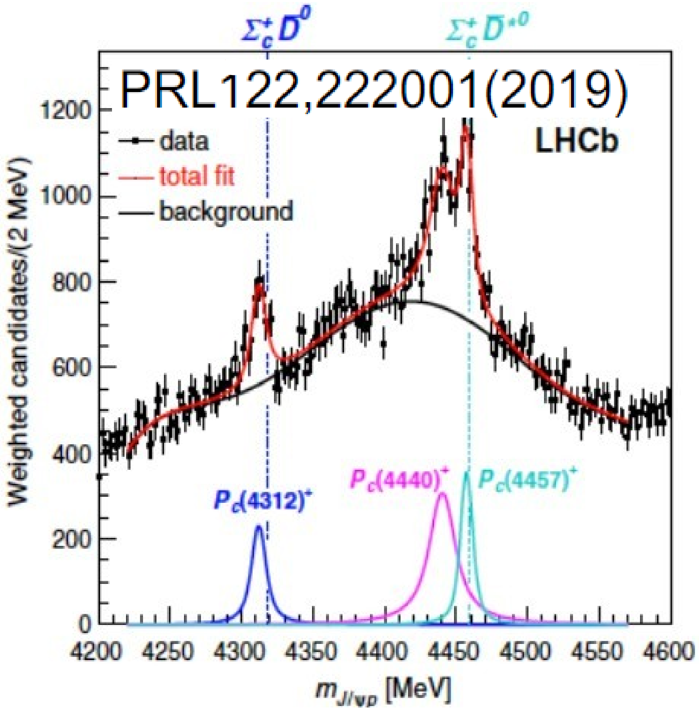




High statistics results: pentaquarks at LHCb

PRL115,072001(2015)





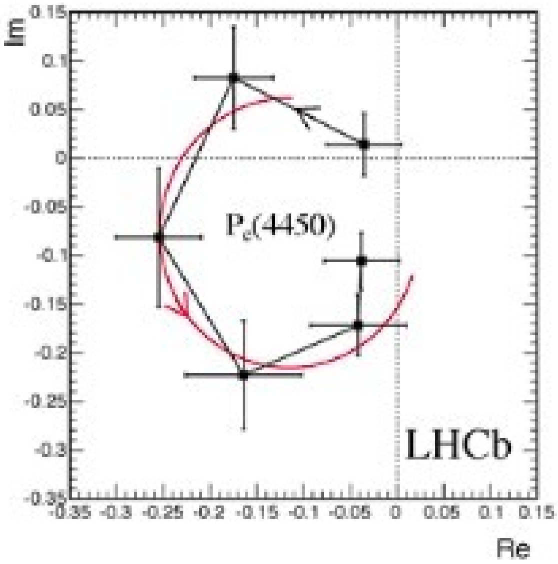
2015:

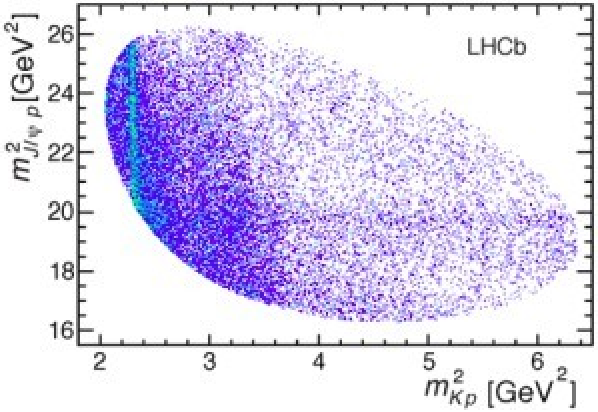
- 3 fb-1, @$\sqrt{s}$ = 7 and 8 TeV
- 26k $\Lambda_b \to J/\psi K^- p$ events
- Claim for 2 pentaquarks

2019:

- 3 + 6 fb-1, @$\sqrt{s}$ = 13 TeV
- 246k $\Lambda_b \to J/\psi K^- p$ events
- Claim for 3 pentaquarks

The Argand plot





- With the Argand plot study LHCb proved that P_c^+ possesses the properties of a resonant state
- Black (data) points follow the shape of a circle
- A clear horizontal line is seen in the Dalitz plot

What about hexaquark states?

DIBARYONS & MORE...

There are even more exotics possibilities in these decay channels

- Di-baryon search:

  - F. J. Dyson and N. H. Xuong prediction (1964)
    - d*(2380) observed at WASA-at-COSY (2014) in *np* scattering
    - mass value fits the theoretical prediction

    Phys. Rev. Lett 112 (2014) 202301

  - R. Jaffe (1977): predicted *udsuds* dibaryon

- Other possibilities?

  3 $D^{(*)}$ meson bound states (non-strange dibaryon predicted by Goldman in 1989)

  Canham & Hammer, Phys. Rev. D 80 (2009) 014009

$\underbrace{D\bar{D}^{*}}_{X(3872)}D^{(*)} \longleftarrow$ *ccc*-quark content

S-wave X(3872)D scattering cross section can be evaluated

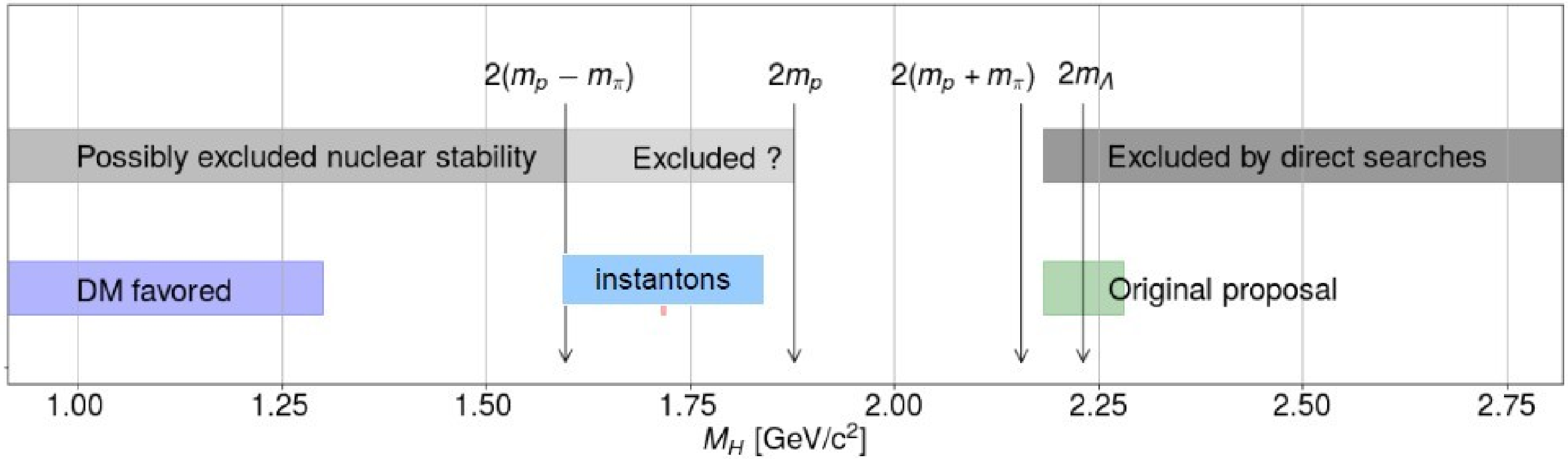
What about hexaquark states?

- Interest in the community. Predictions from:

- Kochelev, JETP Lett. 70 (1999) 491
- Farrar-Zaharijas, Int.J.Th.Phys. 42 (2003) 1211
- PRD70 92004) 014008
- Shuryak, J.Phys.Conf. Ser. 9 (2005) 213

- Recently discussed by:

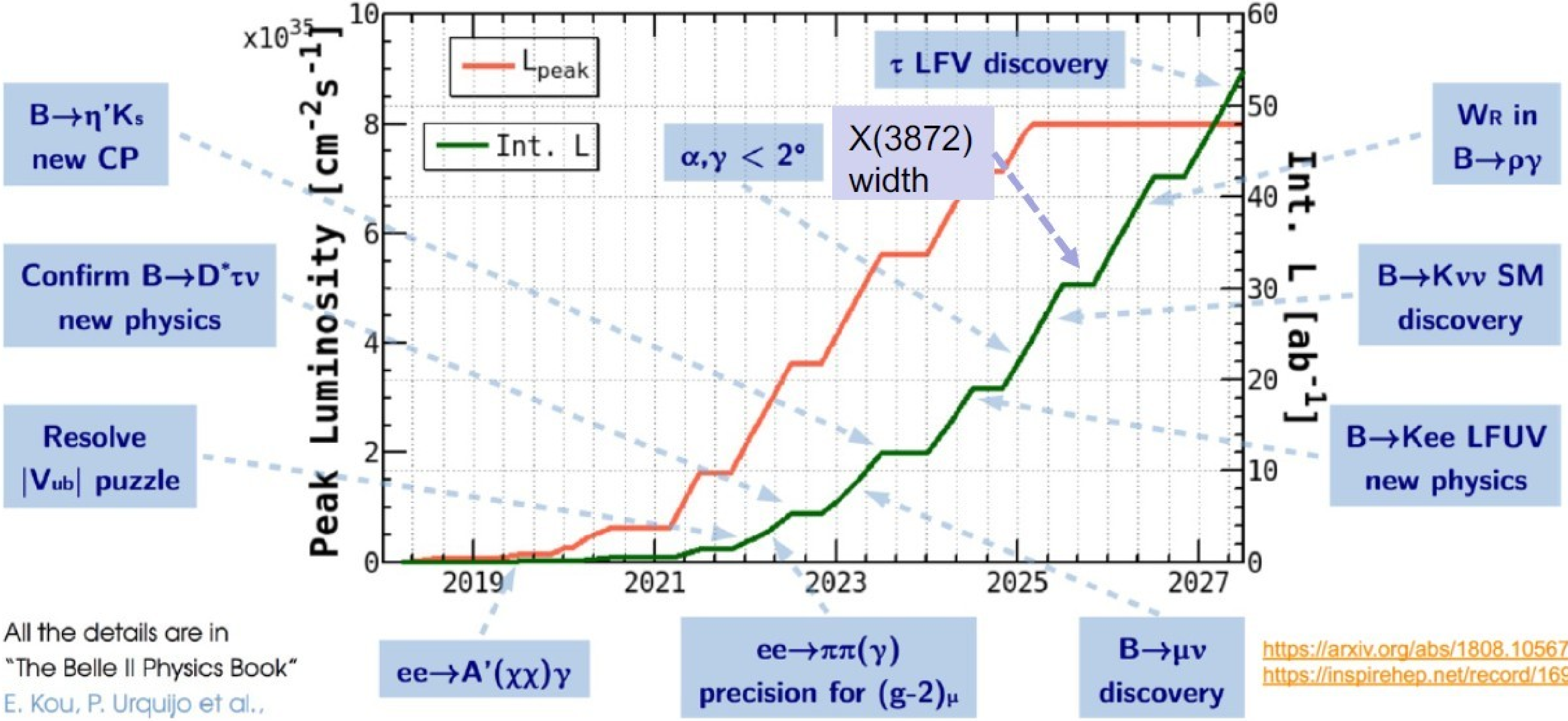
- Gross, Polosa et al, PRD98 (2018) 063005
- McDermott et al, PRD99 (2019) 035013
- Kolb, Turner, PRD99 (2019) 063519



A quick look to the future….

Run Perspectives at Belle II

Note : Physics cases are based on some assumptions ..



τ LFV discovery

$\alpha, \gamma < 2°$

X(3872) width

$B \to \eta' K_s$ new CP

Confirm $B \to D^* \tau \nu$ new physics

Resolve $|V_{ub}|$ puzzle

W_R in $B \to \rho \gamma$

$B \to K \nu\nu$ SM discovery

$B \to Kee$ LFUV new physics

$ee \to A'(\chi\chi)\gamma$

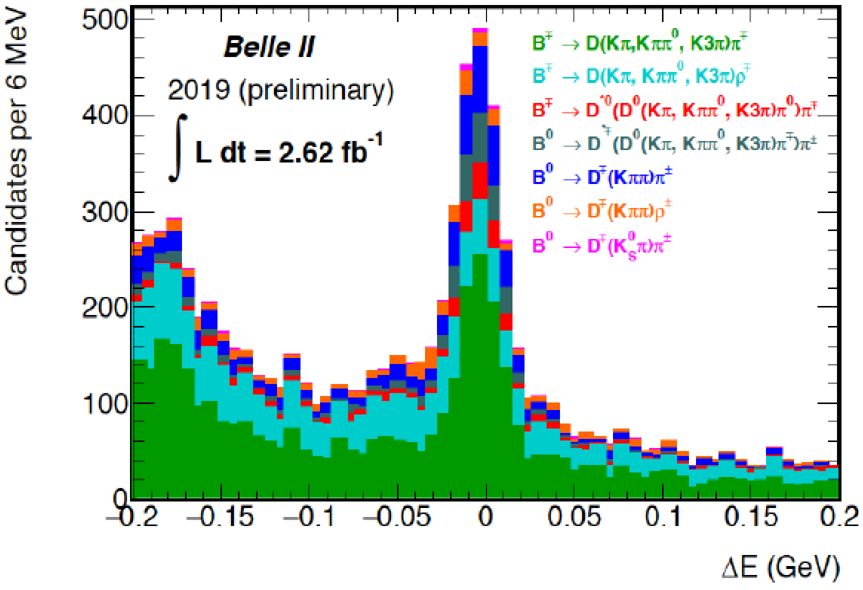
$ee \to \pi\pi(\gamma)$ precision for $(g\text{-}2)_\mu$

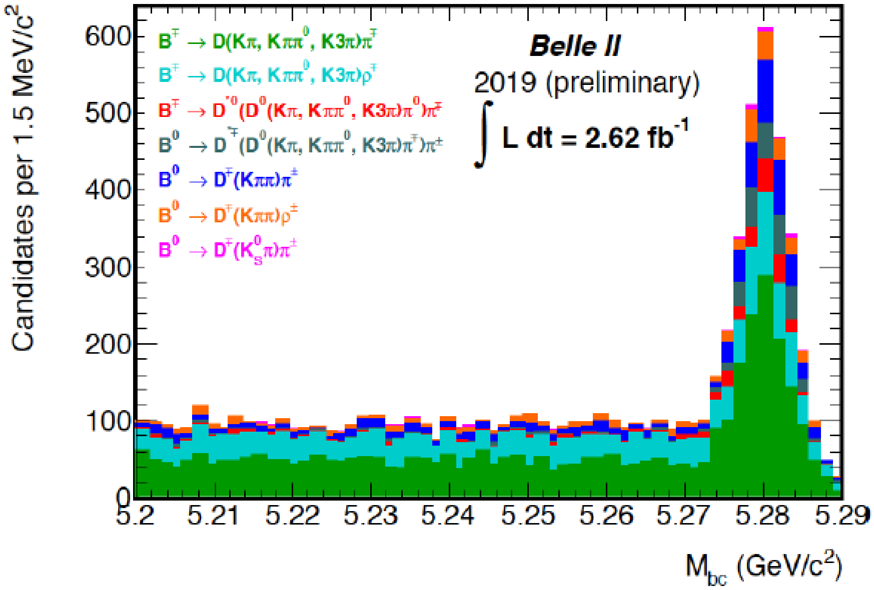
$B \to \mu\nu$ discovery

All the details are in
"The Belle II Physics Book"
E. Kou, P. Urquijo et al.,

https://arxiv.org/abs/1808.10567
https://inspirehep.net/record/1692393/

Fully reconstructed B mesons at Belle II





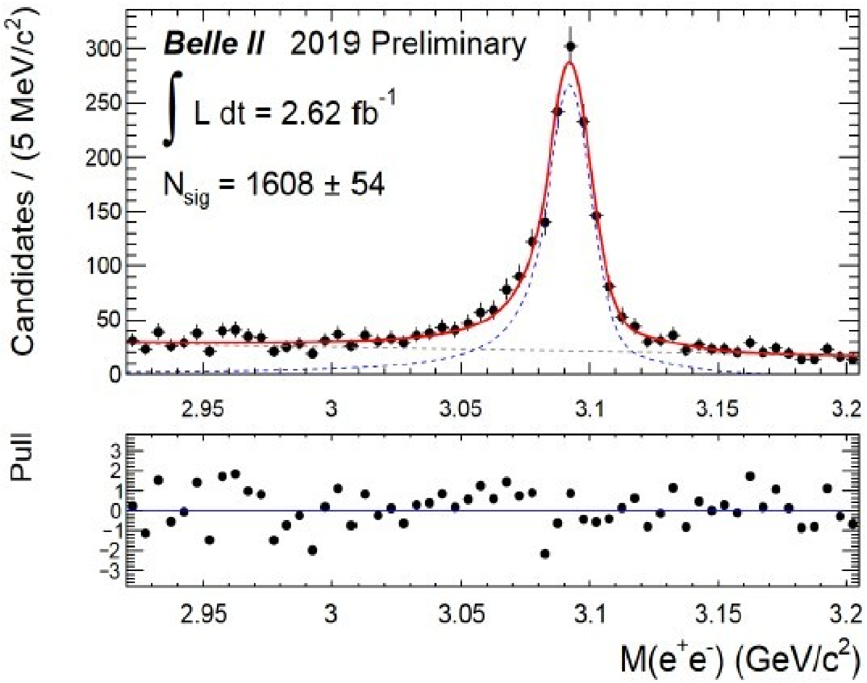
$$\Delta E = (E_{CM}/2) - E_{rec}$$

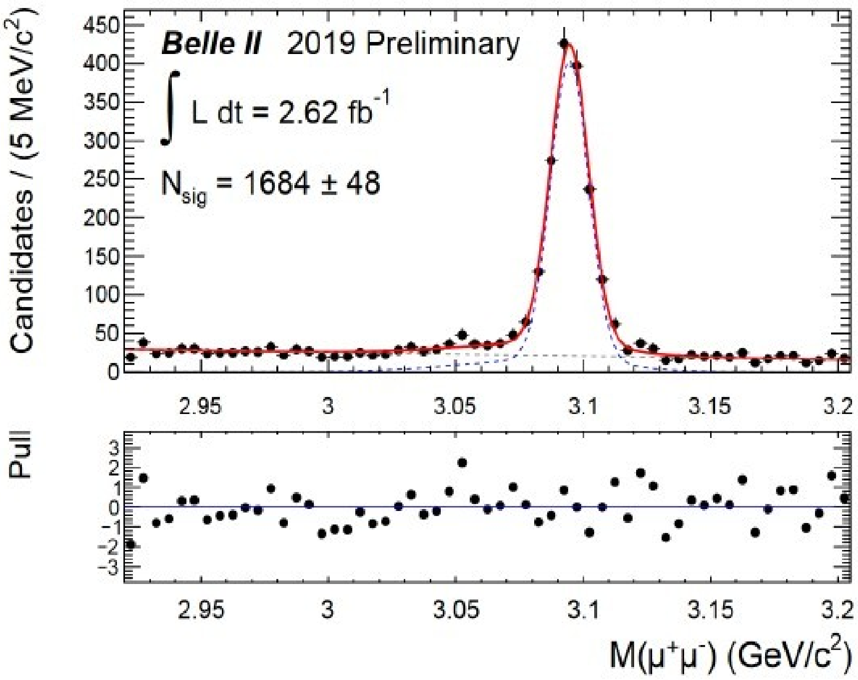
$$M_{bc} = \{ (E_{CM}/2)^2 - P_{rec}^{\;2} \}^{1/2}$$

- 22k fully reconstructed B events on 2.6 fb^{-1}
- Charged and neutrals well reconstructed
- K_S efficiently reconstructed

“Re-discovery” with Phase 3 Data

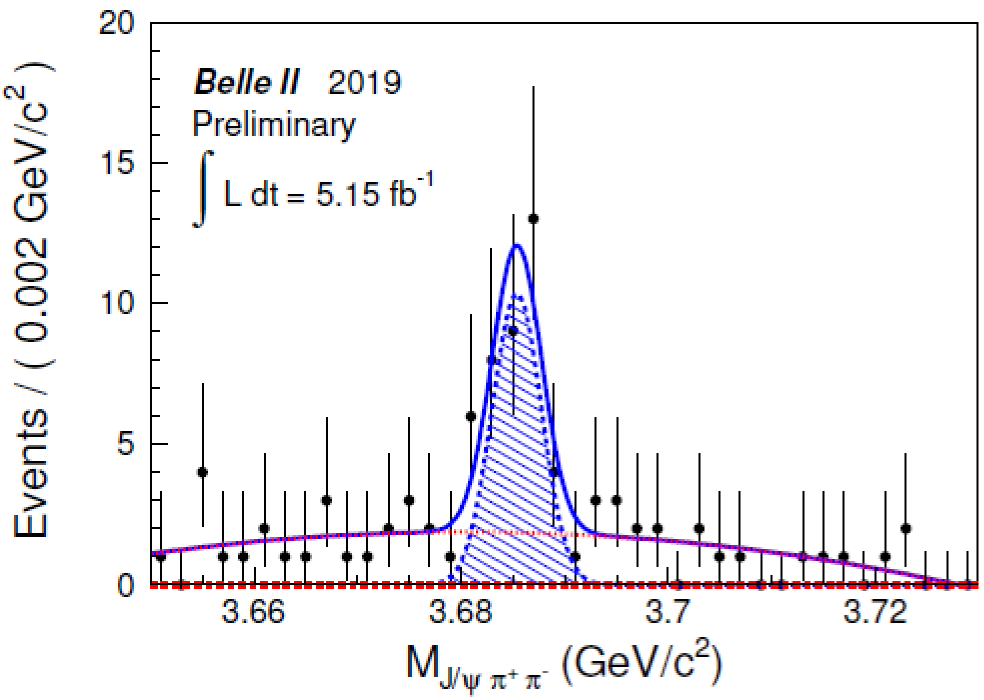
J/ψ





“Re-discovery” with Phase 3 Data

ψ(2S)



Analysis of B→ψ(2S)K, ψ(2S)→J/ψ$\pi^+\pi^-$

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

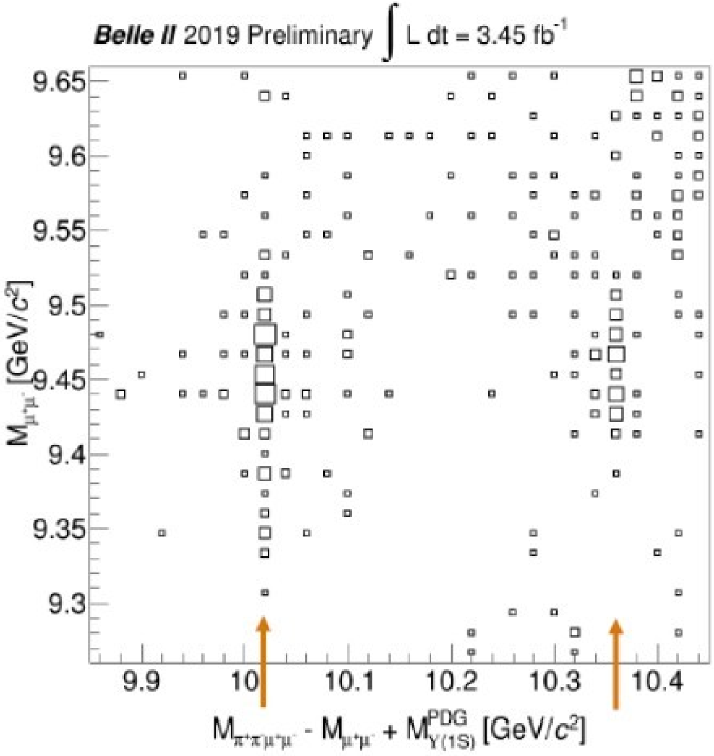
- SuperKEKB can reach $E_{c.m.} \cong 11$ GeV
  $\Rightarrow \Upsilon(6S)$ running possible – unique possibility!

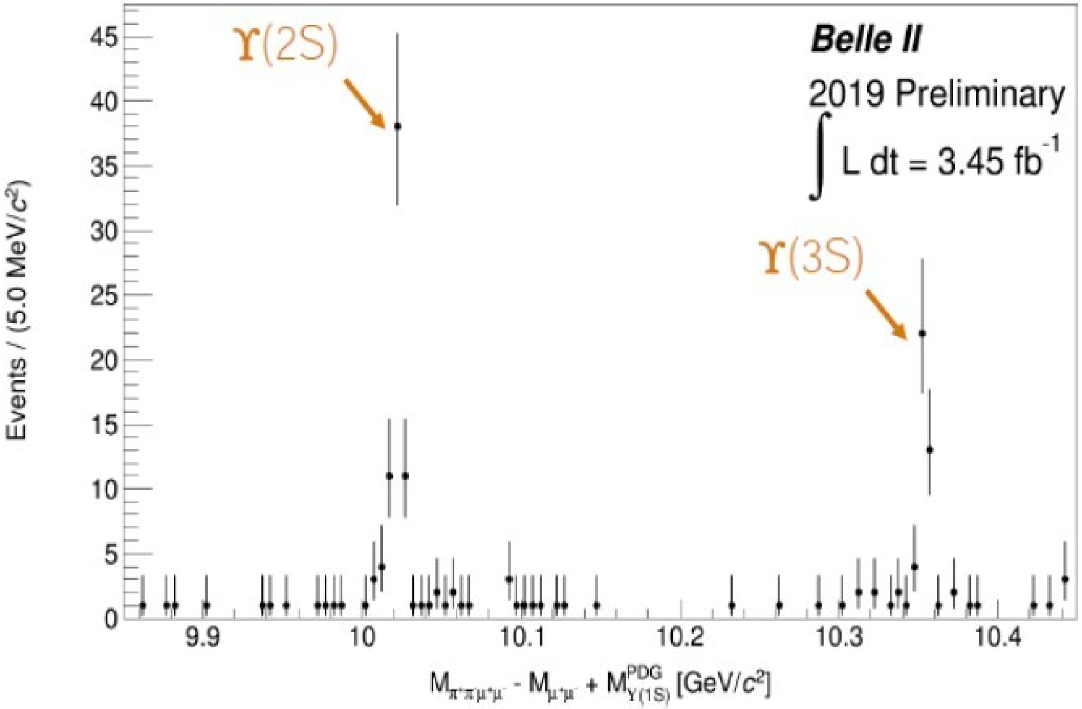
- With the high luminosity, for the 1st time study radiative transitions between bottomonia states possible (suppressed by 1/137). Marginal statistics so far at Belle, big advantage at Belle II

Rediscovery with Belle II Phase 3 data

Υ(1S, 2S, 3S)

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





Expectations on Z_b states at Belle II

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

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

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

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

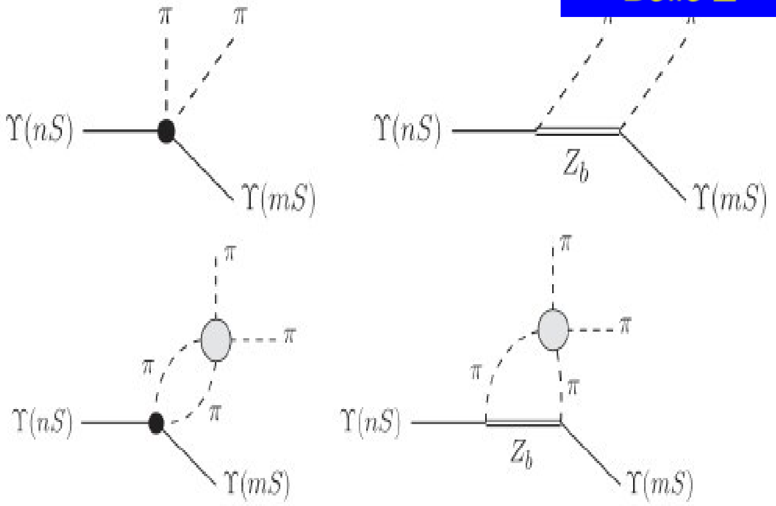
- Belle II goals:
  - $\Upsilon(6S)$: $100\ \mathrm{fb}^{-1}$ exploratory run
  - $\Upsilon(5S)$: $1\ \mathrm{ab}^{-1}$ high statistics run

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

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

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

ϒ(3S): Opportunities at Belle II



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

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

ϒ(3S): exotics in transitions

- Belle II goals:
  - Y(3S)→ ππϒ(1S, 2S) still limited by statistics
  - perform full amplitude analysis
  - search for missing ππ/η 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 Y(3S) → $D\bar{D}^*$ + hadron to test the nature of the X(3872)

ϒ(3S): rare χ_b decays

ϒ(3S): deuteron production mechanism

Summary

- Hadron physics is a wide field, involving from CKM element studies to quarkonia
- Quarkonia represent a unique system for testing QCD in the border between non-perturbative and perturbative regime
- Narrow heavy quarkonia provide useful tests for many processes, which may test models for physics beyond the SM
- QCD is the weakest sector of the SM at low energy
  →limit to find NP in the quark sector
- Υ(nS) study can help in understanding hexaquarks(S)
- Belle II will collect up to 50 ab^{-1} in 7 years: great opportunity in hadron physics!
  →unique opportunities in the sector of Bottomonium and radiative decays
- LHCb performed already great! Limitation in analysis involving low-energy photon
  →looking for the upgrade!
- Still lots of surprises are expected in this field, once huge data sets are collected

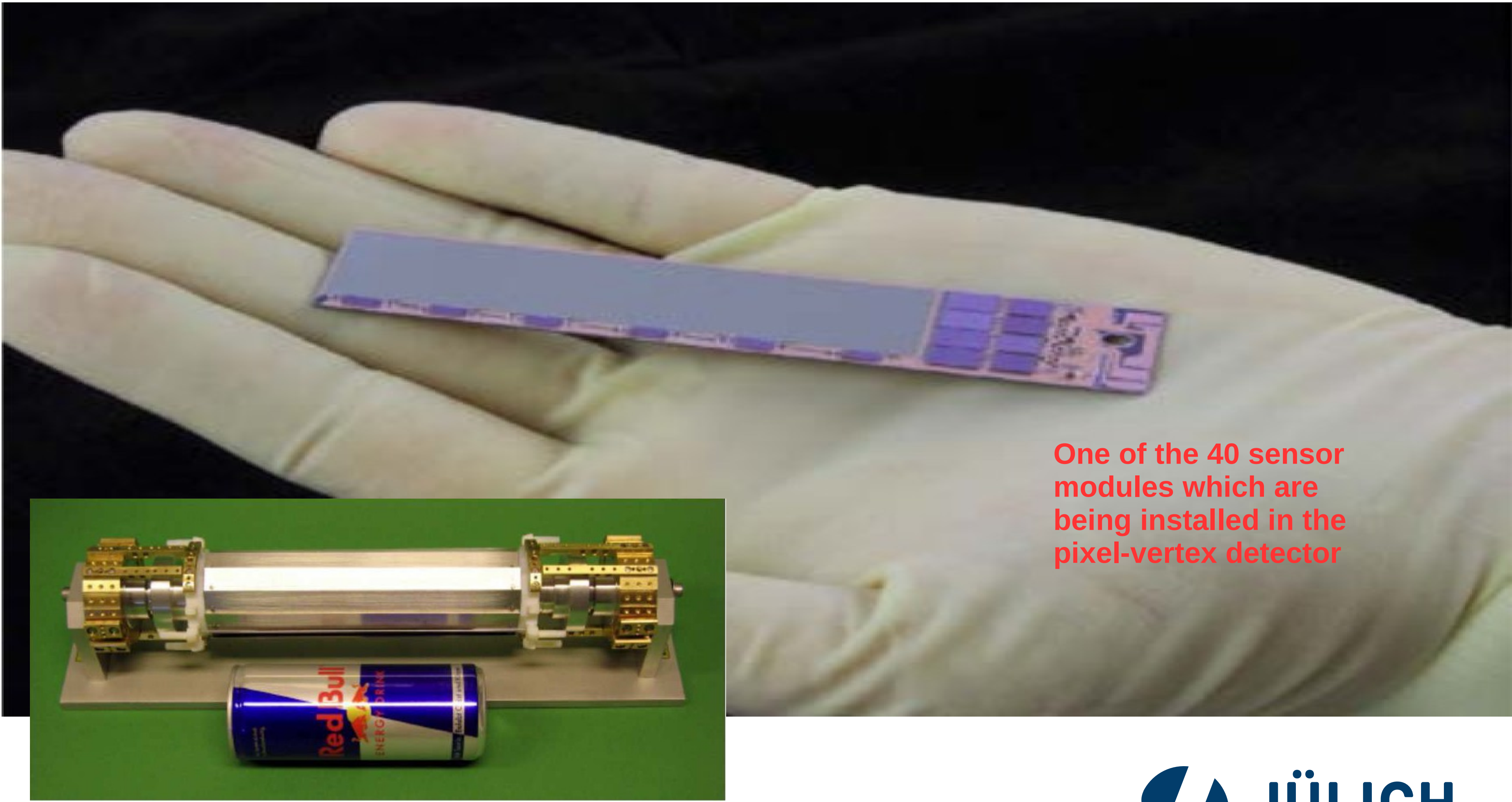
Thank you for your kind attention!

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)

Vertex Pixel Detector (PXD)

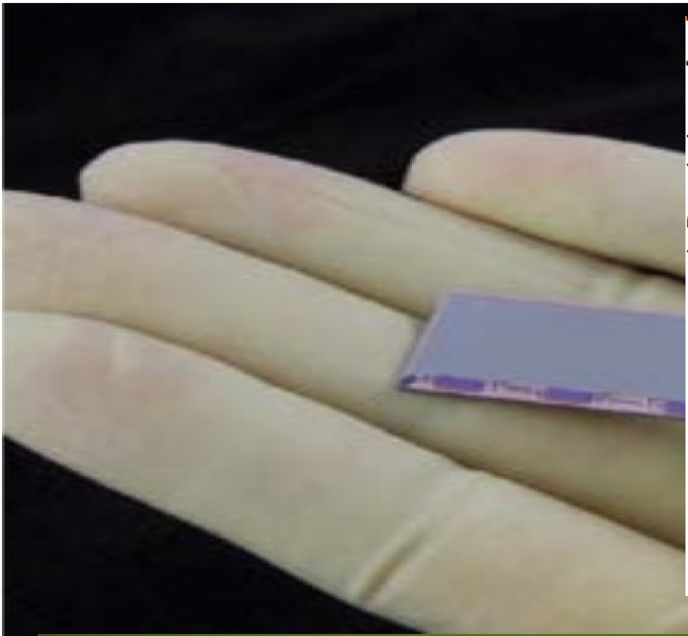
VXD consists of 2 layers of DEPFET (Pixel Detector) and 4 layers of double-sided silicon microstrip sensors (Silicon Vertex Detector), assembled over carbon fiber ribs.

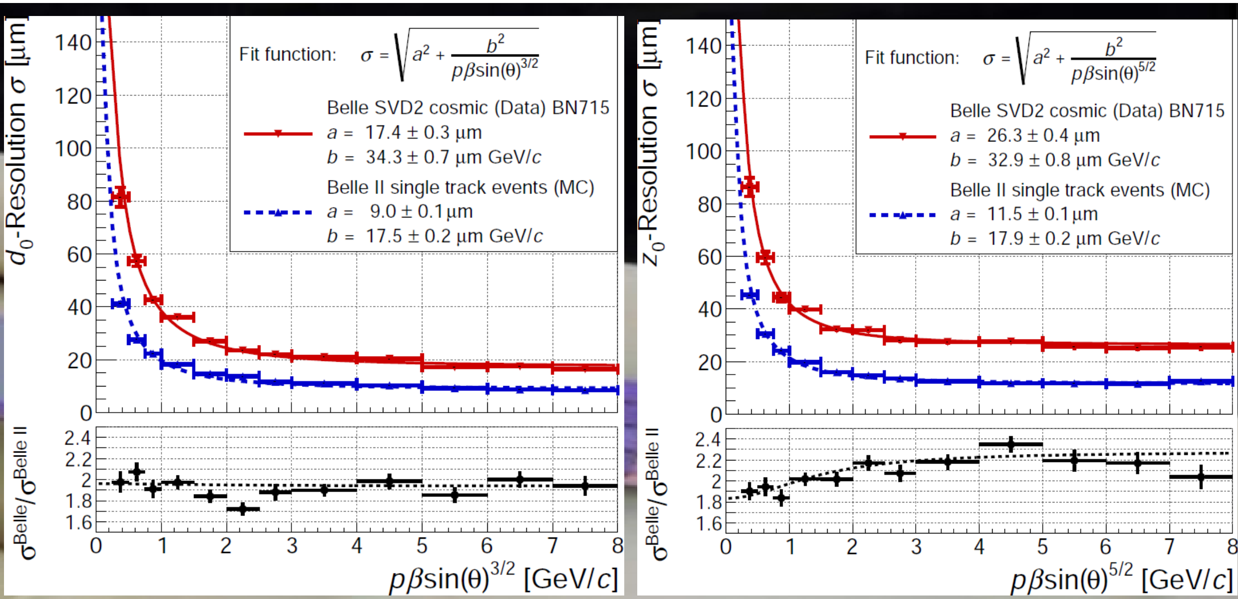


One of the 40 sensor modules which are being installed in the pixel-vertex detector

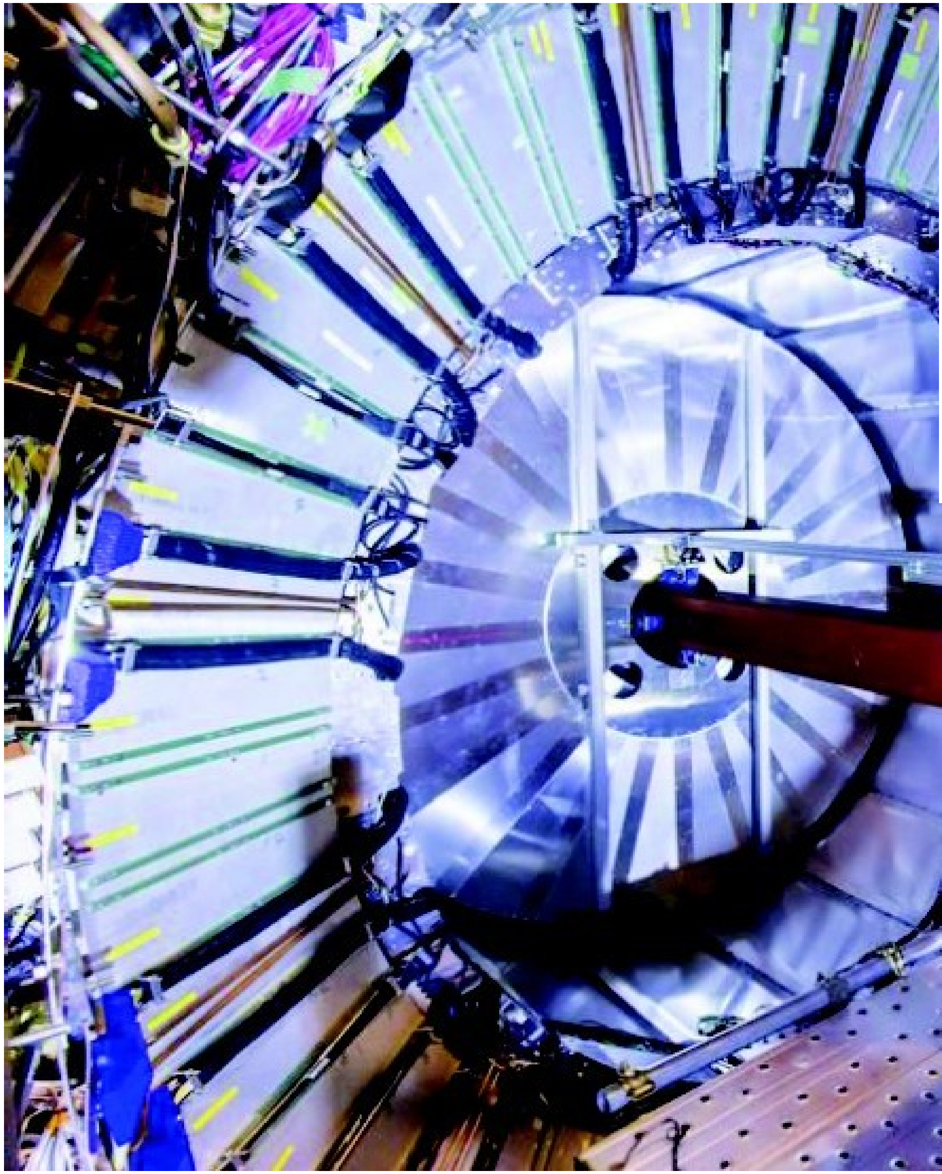
Vertex Pixel Detector (PXD)

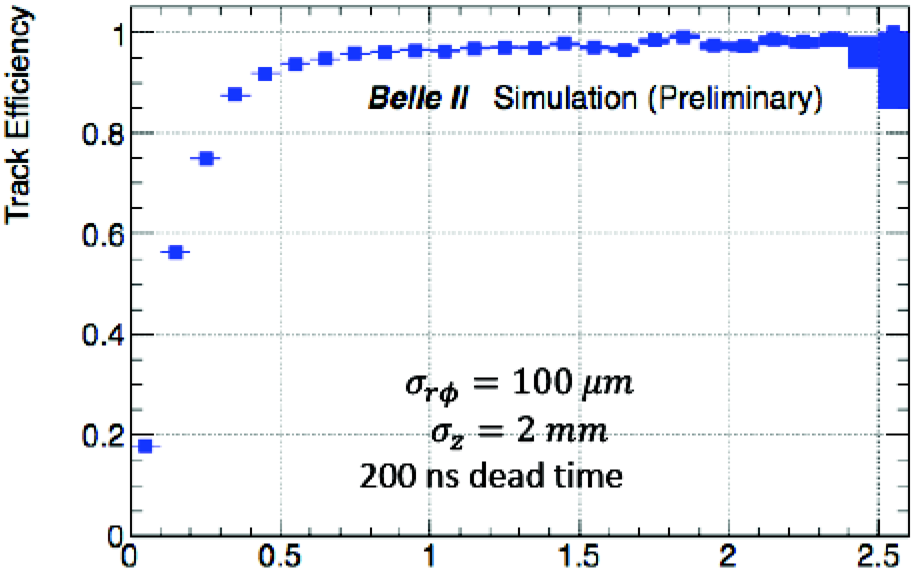
VXD consists of 2 layers of DEPFET (Pixel Detector) and 4 layers of double-sided silicon microstrip sensors (Silicon Vertex Detector), assembled over carbon fiber ribs.

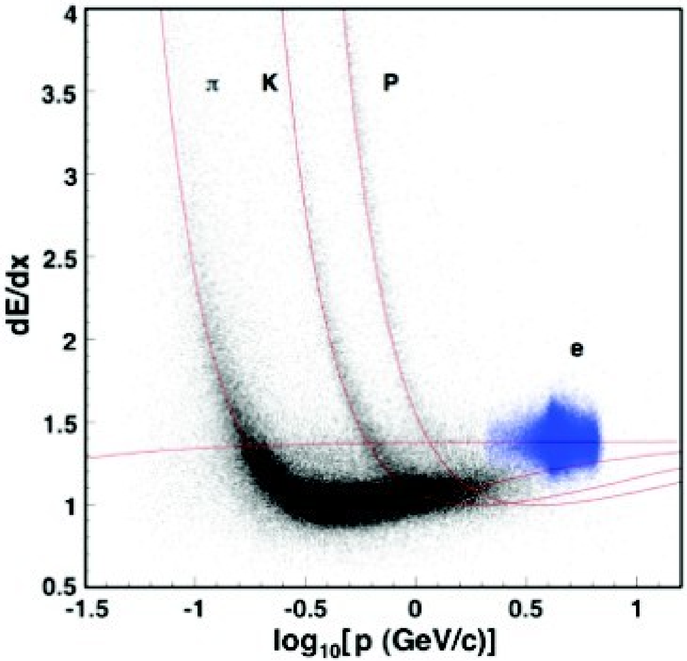




Central Drift Chamber (CDC)

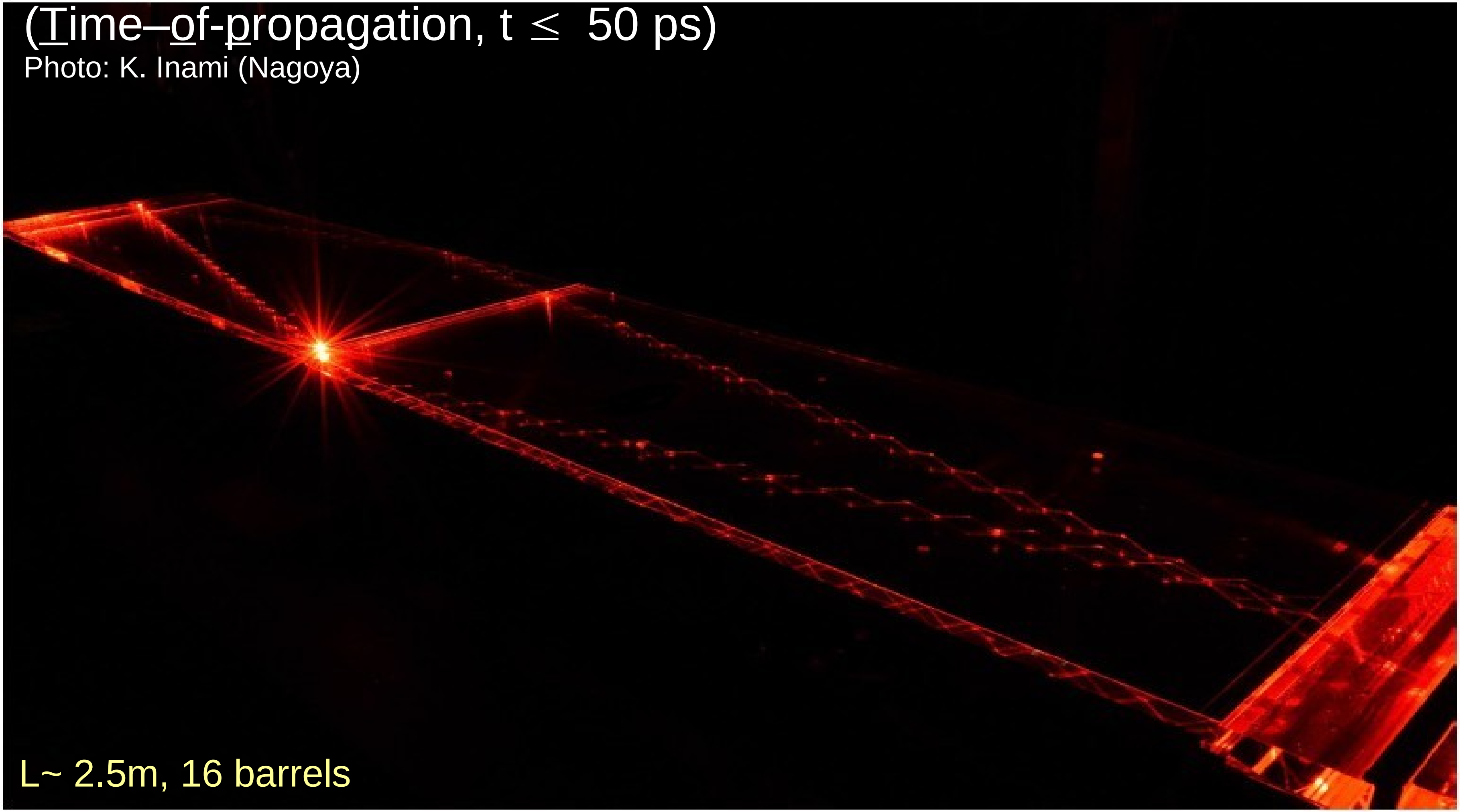






Cerenkov detector, laser in TOP module

Particle Identification



(Time–of-propagation, t ≤ 50 ps)

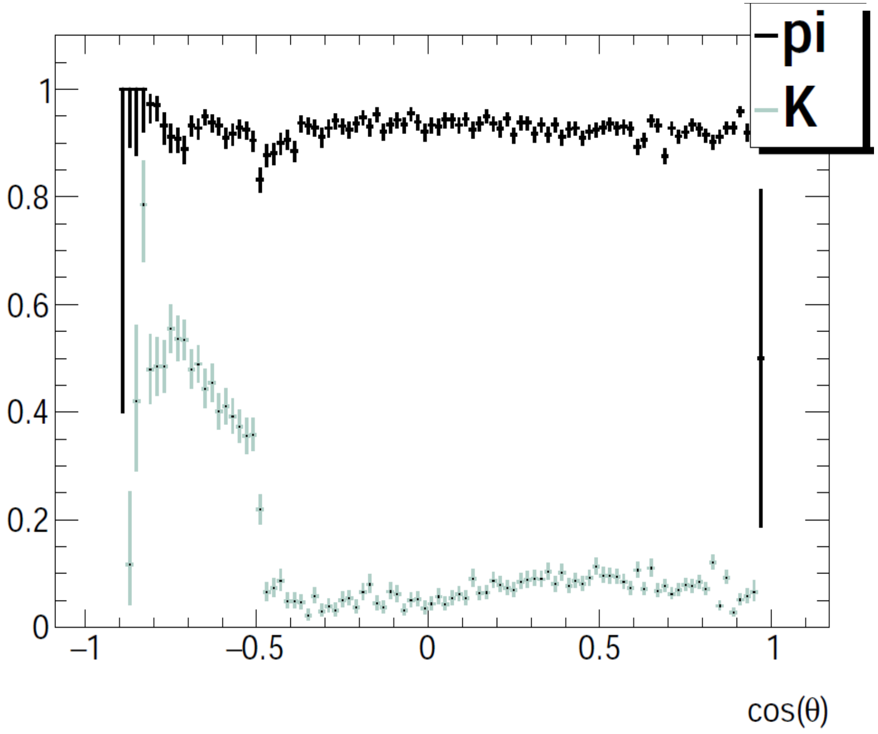
Photo: K. Inami (Nagoya)

L~ 2.5m, 16 barrels

MC Study

PID: Efficiency and fake rates

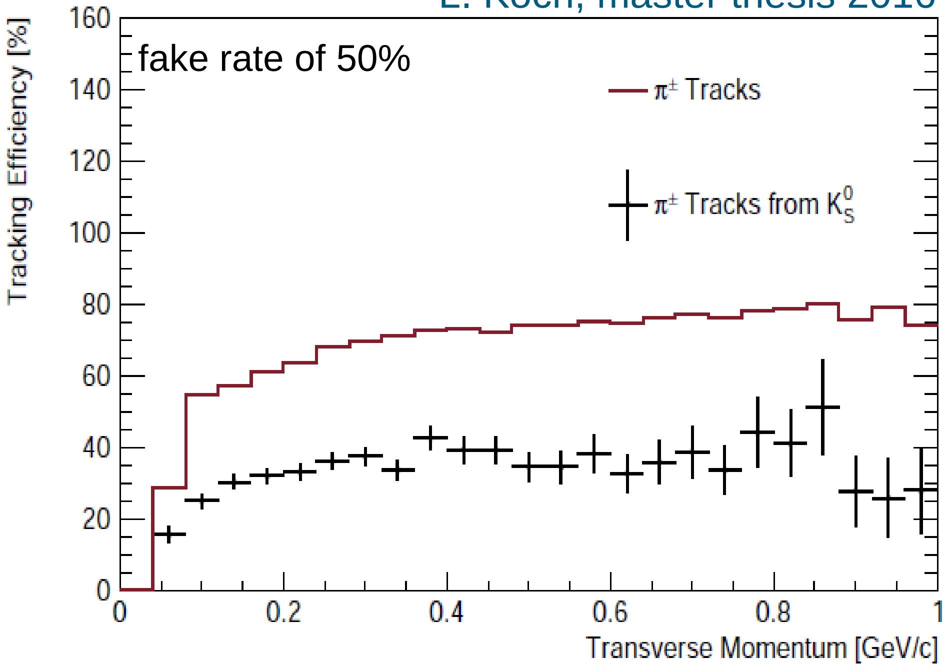
Continuum D* MC Study



Tracking Efficiency and fake rates

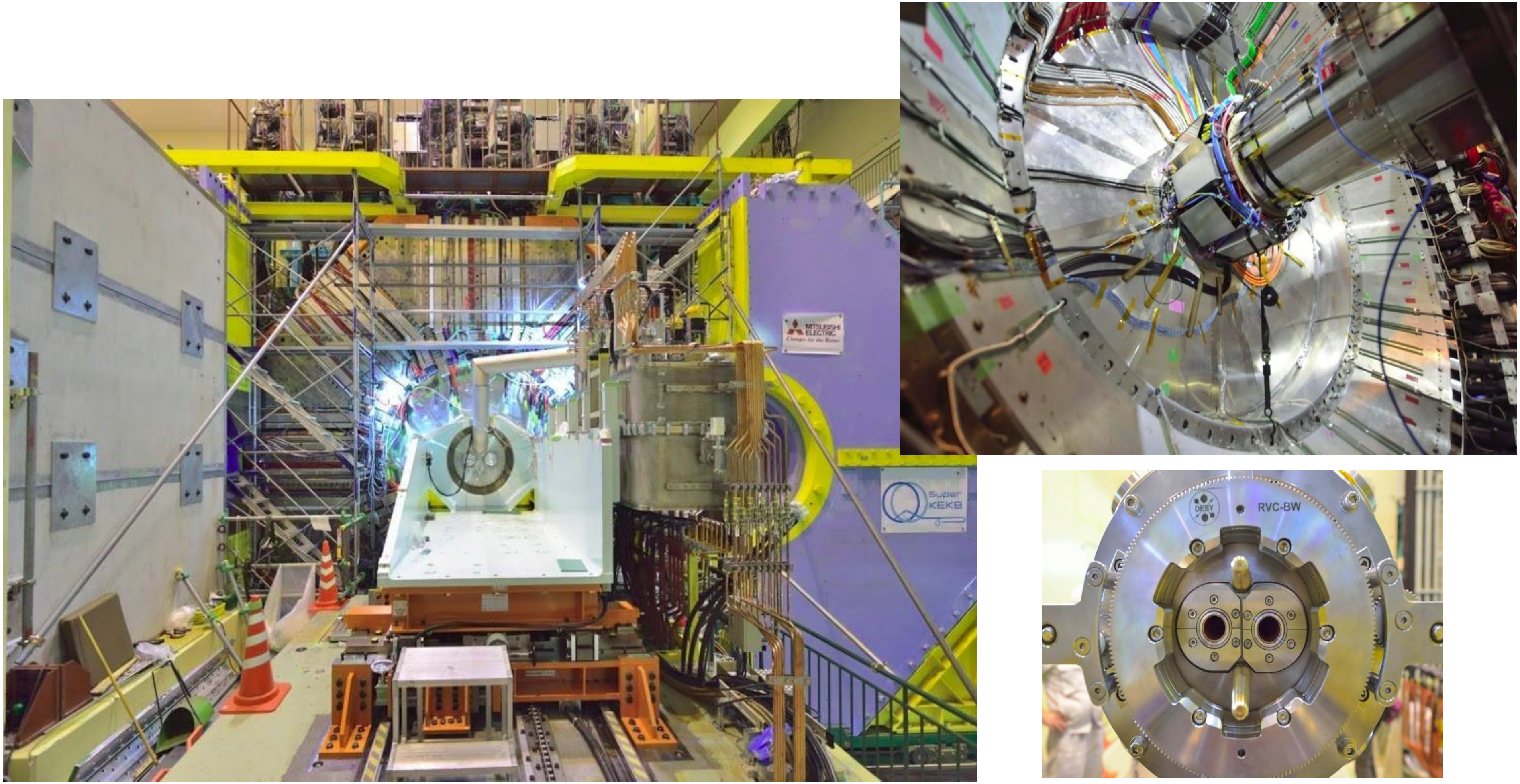
$B^0 \rightarrow \Phi K^0{}_S$

L. Koch, master thesis 2016

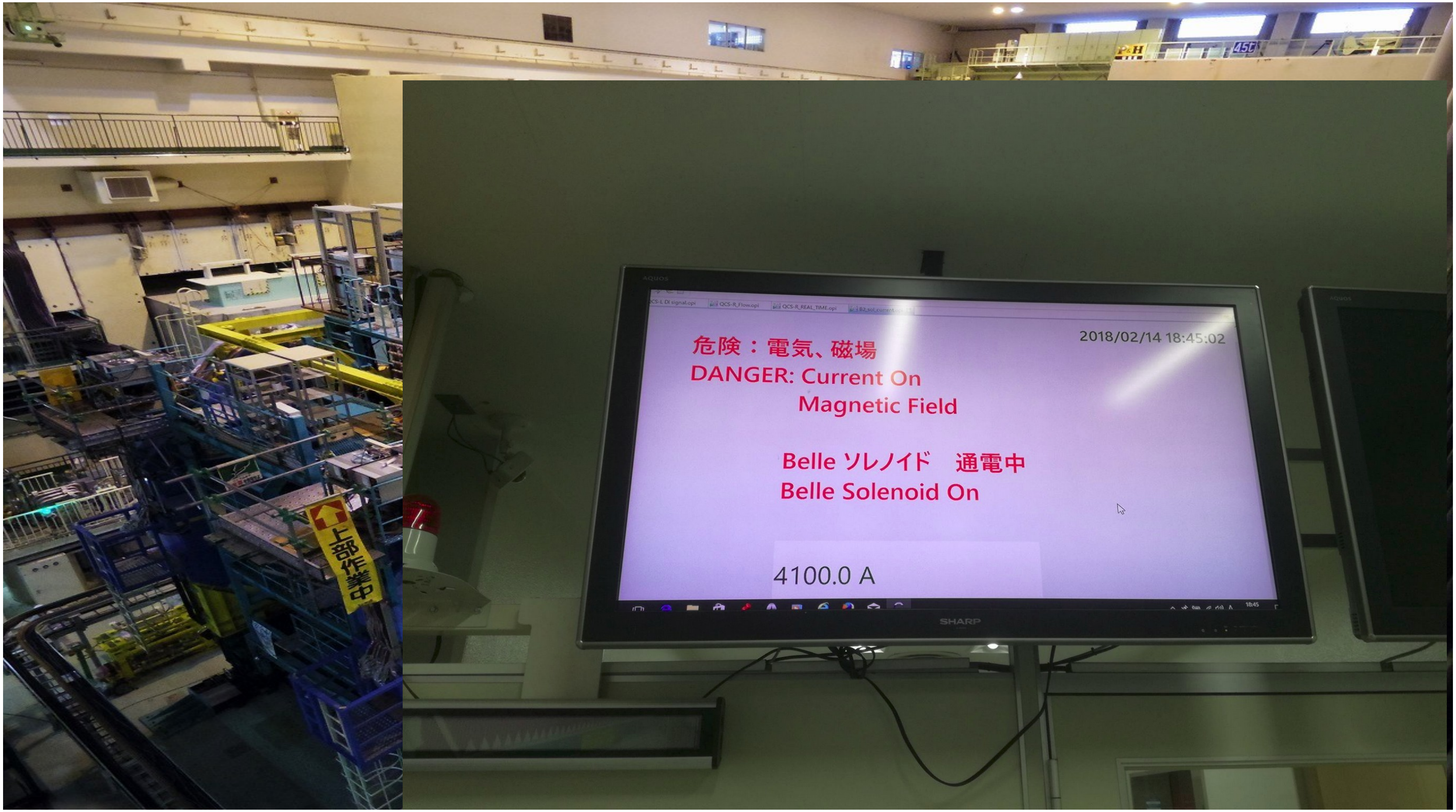


15.01.2018: MILESTONE!

Superconductive magnet systems installed



14.02.2018: Phase-II Has Started



2018/02/14 18:45:02

危険：電気、磁場
DANGER: Current On
Magnetic Field

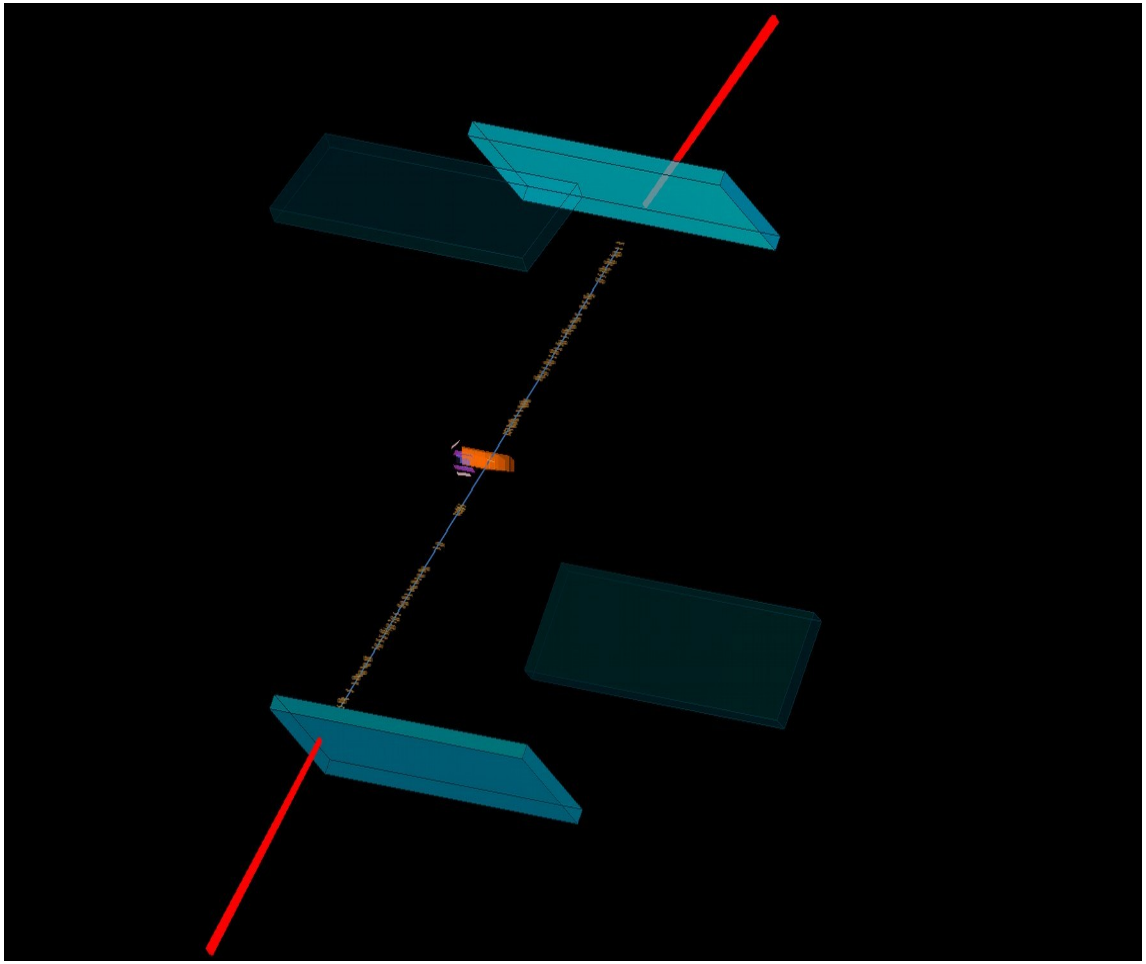
Belle ソレノイド　通電中
Belle Solenoid On

4100.0 A

14.02.2018: Phase-II Has Started

18.02.2018 - First Data

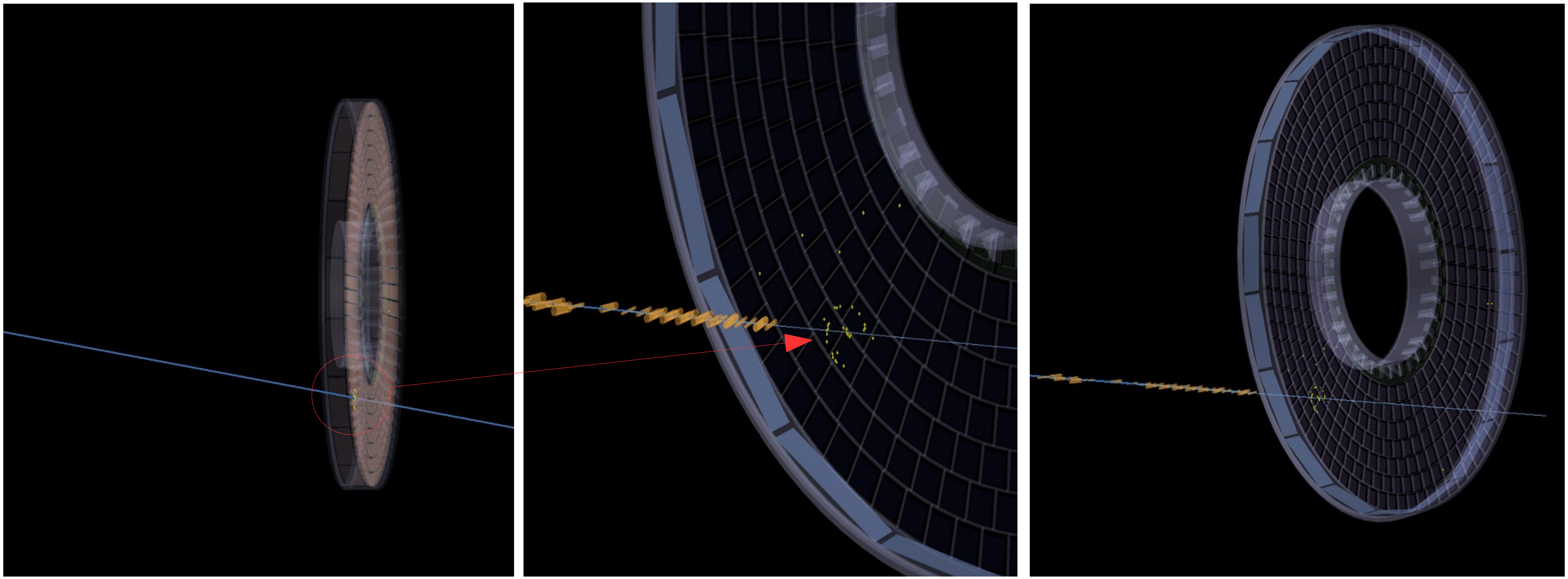
Cosmics in the PXD



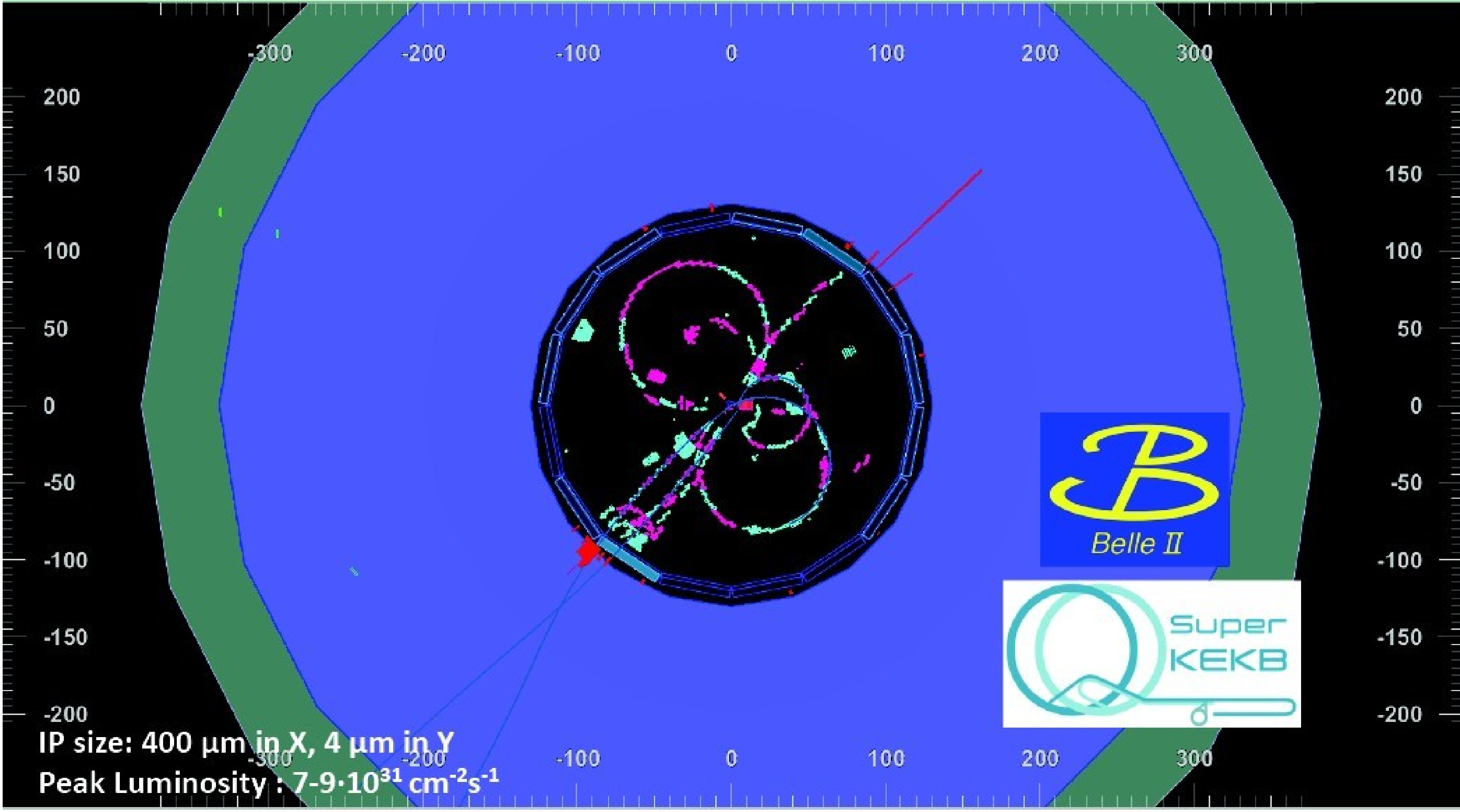
- Two inner sub-detectors right now into the data acquisition system.
- The final Belle II vertex detector with its full *pixelated* silicon detector (PXD) and a double-sided microstrip silicon detector (SVD) is under construction and will be installed later this year.

26.02.2018 – First Data

Cosmics in the ARICH

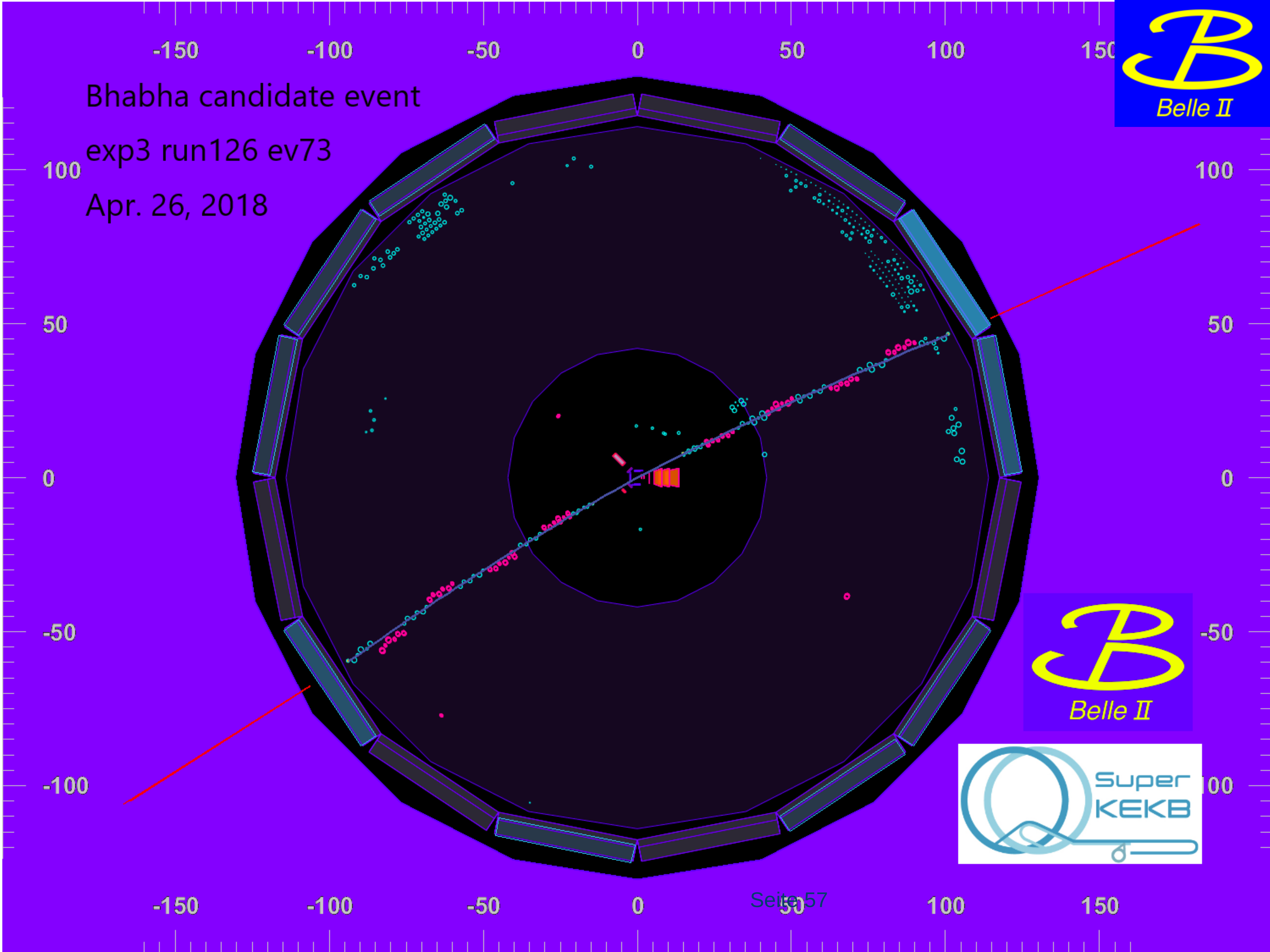


A hadronic event recorded at h. 00:38, **26.04.2018** – **first collision confirmation**



IP size: 400 µm in X, 4 µm in Y

Peak Luminosity : 7-9·10^{31} $cm^{-2}s^{-1}$



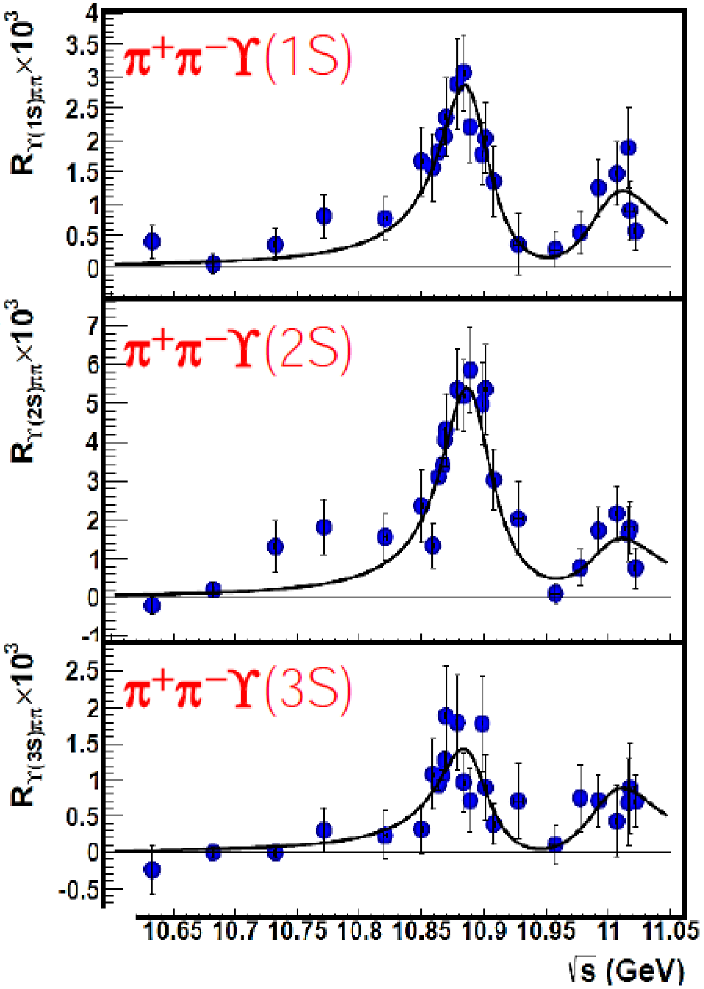
Bhabha candidate event

exp3 run126 ev73

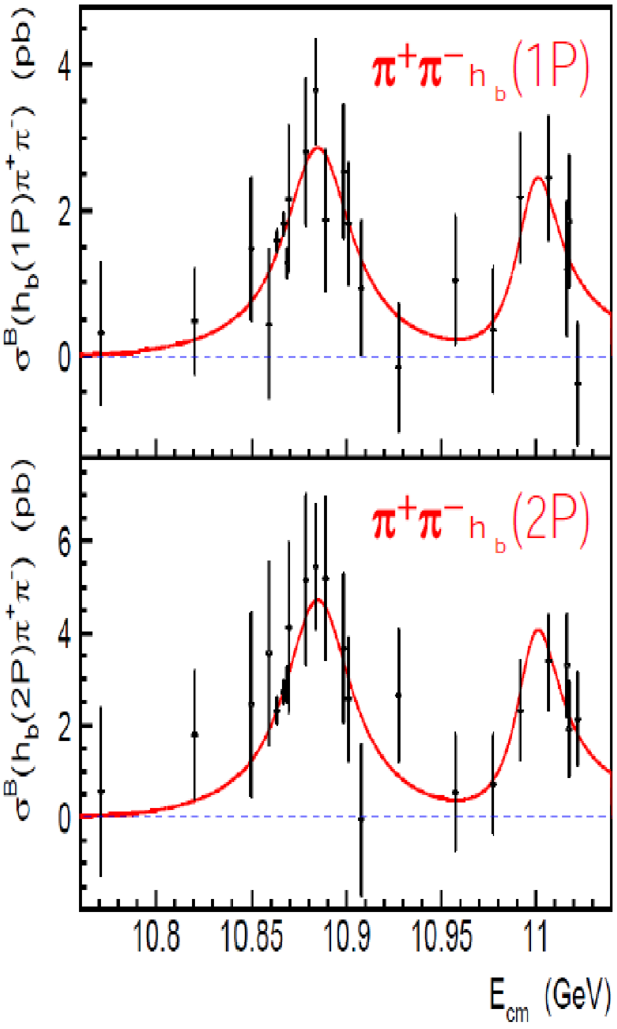
Apr. 26, 2018

Main Achievements in Bottomonium at Belle

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



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



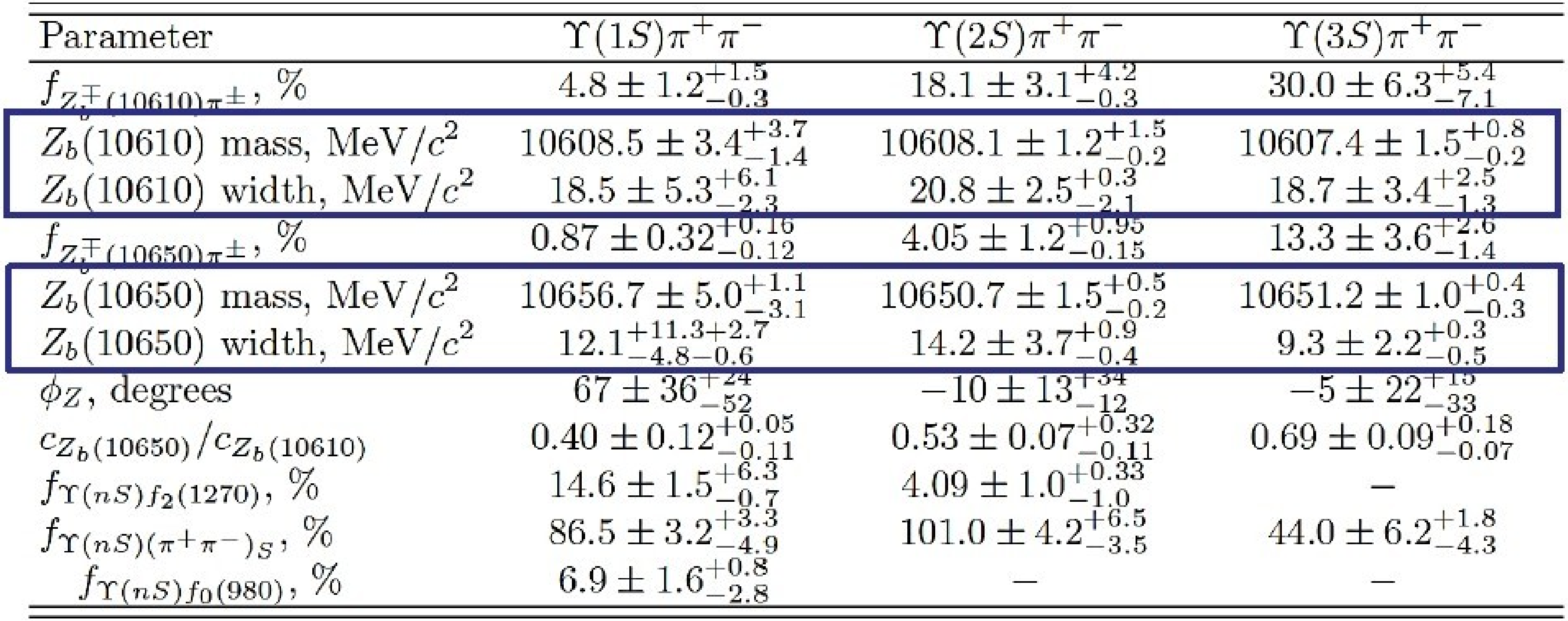
fit to $|A_{5S}+e^{i\phi}A_{6S}|^2$

PRD 93, 011101(R) (2016)

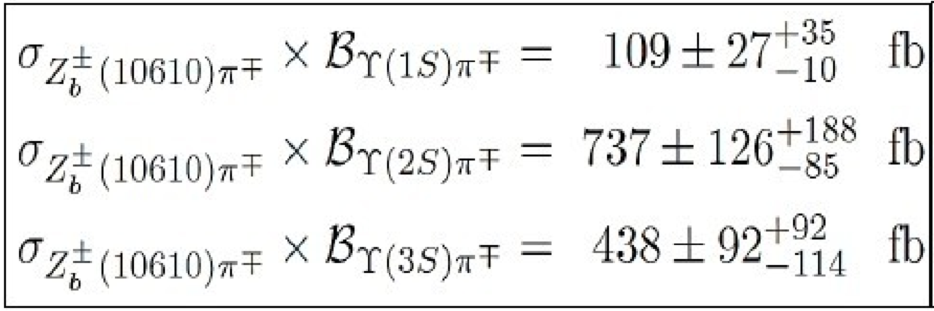
PRL117, 142001 (2016)

Main Achievements in Bottomonium at Belle

Z_b in Y(5S)→$\pi^+\pi^-\Upsilon$(nS)



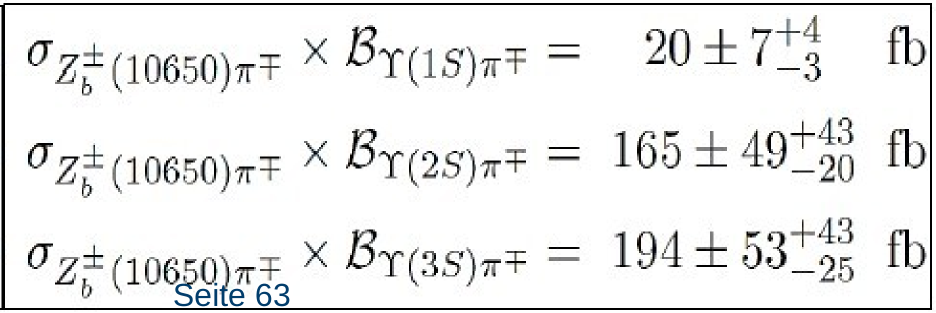
Parameter	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$
$f_{Z_b^{\mp}(10610)\pi^{\pm}}$, %	$4.8 \pm 1.2^{+1.5}_{-0.3}$	$18.1 \pm 3.1^{+4.2}_{-0.3}$	$30.0 \pm 6.3^{+5.4}_{-7.1}$
$Z_b(10610)$ mass, MeV/c^2	$10608.5 \pm 3.4^{+3.7}_{-1.4}$	$10608.1 \pm 1.2^{+1.5}_{-0.2}$	$10607.4 \pm 1.5^{+0.8}_{-0.2}$
$Z_b(10610)$ 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	$67 \pm 36^{+24}_{-52}$	$-10 \pm 13^{+34}_{-12}$	$-5 \pm 22^{+15}_{-33}$
$c_{Z_b(10650)}/c_{Z_b(10610)}$	$0.40 \pm 0.12^{+0.05}_{-0.11}$	$0.53 \pm 0.07^{+0.32}_{-0.11}$	$0.69 \pm 0.09^{+0.18}_{-0.07}$
$f_{\Upsilon(nS)f_2(1270)}$, %	$14.6 \pm 1.5^{+6.3}_{-0.7}$	$4.09 \pm 1.0^{+0.33}_{-1.0}$	–
$f_{\Upsilon(nS)(\pi^+\pi^-)_S}$, %	$86.5 \pm 3.2^{+3.3}_{-4.9}$	$101.0 \pm 4.2^{+6.5}_{-3.5}$	$44.0 \pm 6.2^{+1.8}_{-4.3}$
$f_{\Upsilon(nS)f_0(980)}$, %	$6.9 \pm 1.6^{+0.8}_{-2.8}$	–	–



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

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

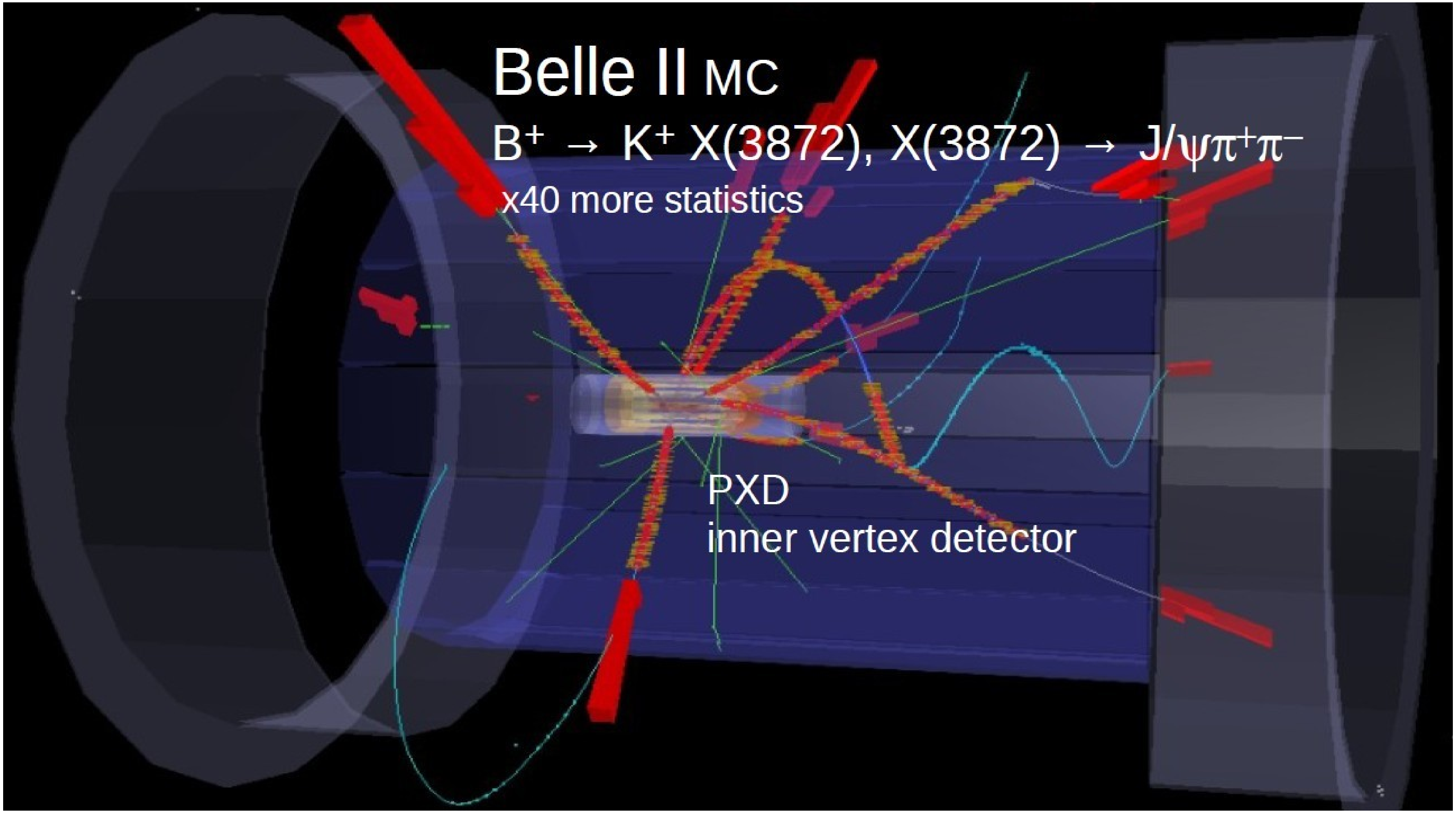
$$\sigma_{Z_b^{\pm}(10610)\pi^{\mp}} \times \mathcal{B}_{\Upsilon(3S)\pi^{\mp}} = 438 \pm 92^{+92}_{-114} \text{ fb}$$



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

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

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



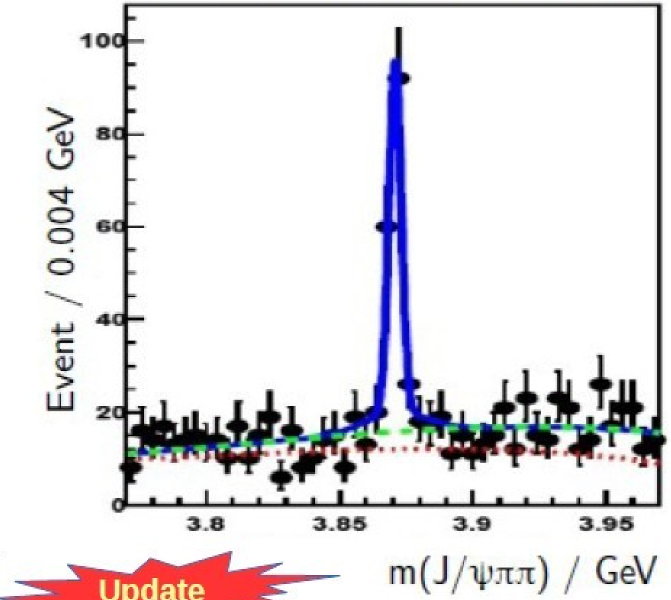
Belle II MC

$B^+ \rightarrow K^+ X(3872)$, $X(3872) \rightarrow J/\psi\pi^+\pi^-$

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}

$\mathcal{B}(B0 \to K^0X(3872))/\mathrm{B}(B+ \to K^+X(3872))$=

0.50±0.14(stat)±0.04(syst)

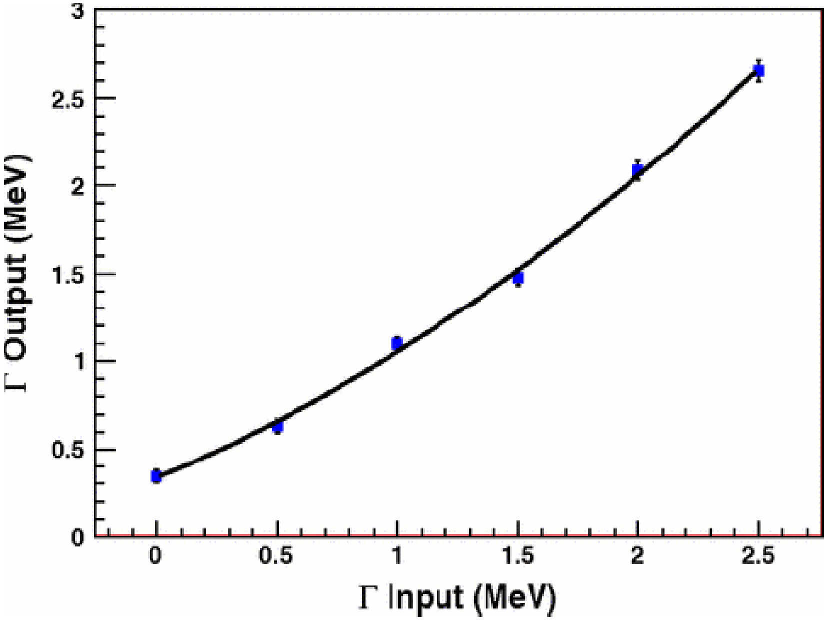
$\Delta M_{X[B0\text{-}B+]}$=(−0.71±0.96(stat)±0.19(syst)) MeV.

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

X(3872): ACHIEVEMENTS AND INTERPRETATION AT BELLE

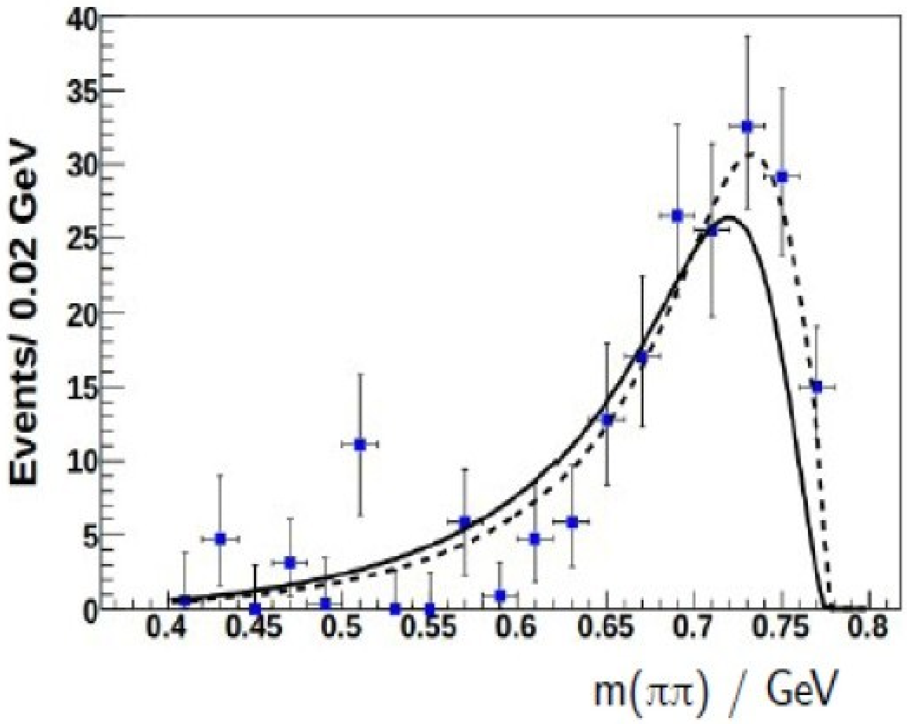
- Correlation function from MC
  Γ(output) = f(Γ(input))
- 3-dim fits validated with ψ´width
  $\Gamma_{\psi'}$=0.52±0.11 MeV
  (PDG: 0.304±0.009 MeV)
  → bias 0.23±0.11 MeV
- procedure for upper limit:
  width in 3-dim fit fixed
  n_{signal} and n_{BG} floating
  → calculate likelihood
- $\Gamma_{X(3872)}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

PRD 84 (2011) 052004



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

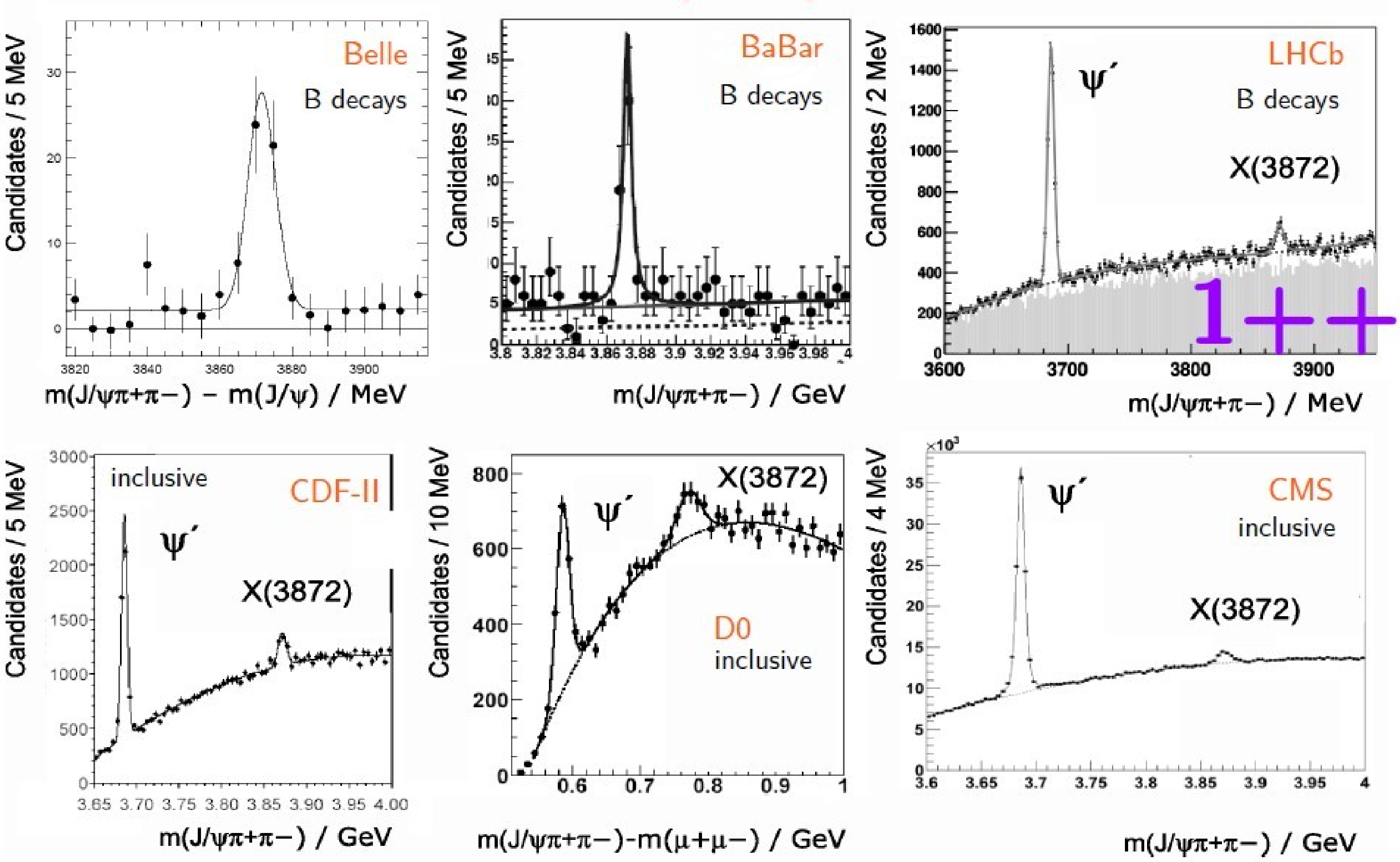
$J^{PC} = 1^{++}$, predicted nearby χ_{c1}'

Barnes et al, PRD72 (2005) 054026

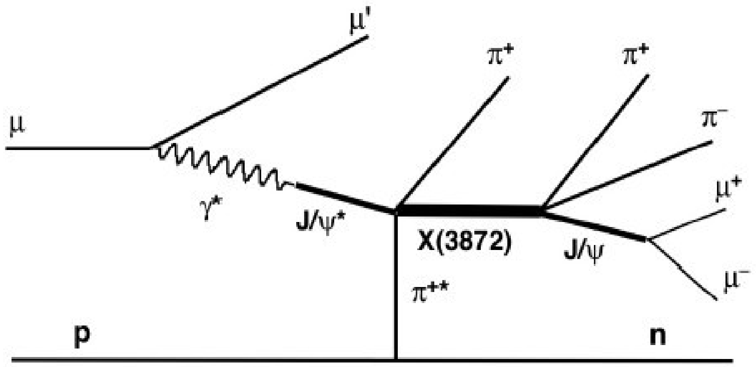
- Mass ⩾50 MeV higher
- Width ⩾100 larger

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

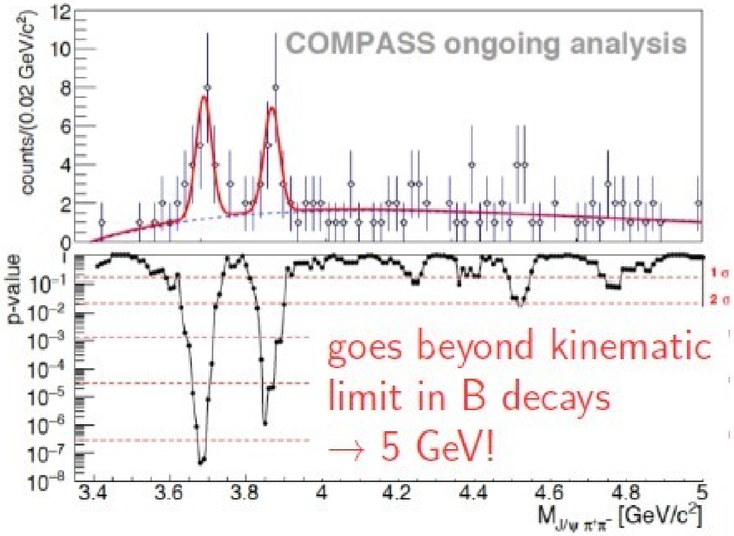
X(3872)


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
ψ´
B decays
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

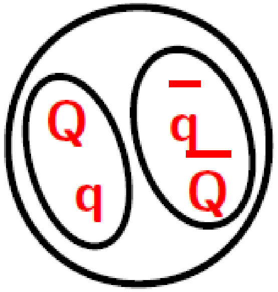


goes beyond kinematic limit in B decays → 5 GeV!

COMPASS, arXiv:1707.01796 [hep-ex]

Is the X(3872) exotic ?

TETRAQUARK

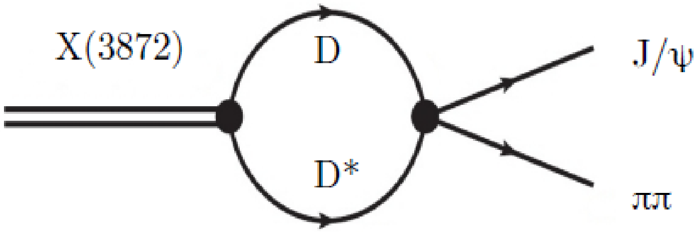


$[qQ]_8[\overline{qQ}]_8$

Diquarks
are colored

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

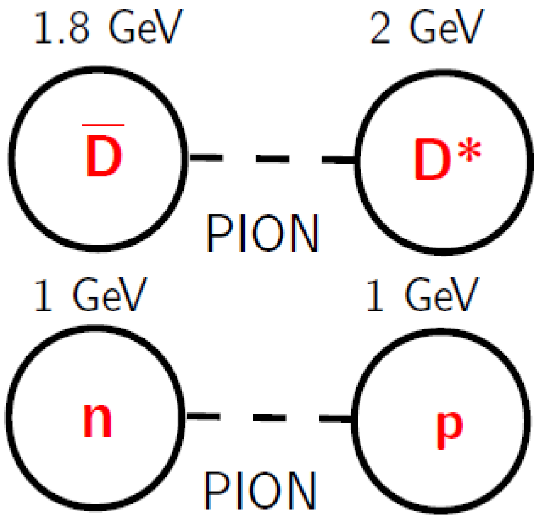
THRESHOLD CUSP



Bugg; Swanson

MOLECULE

Intriguing Analogon



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

courtesy of J.S. Lange, HIRSCHEGG2018

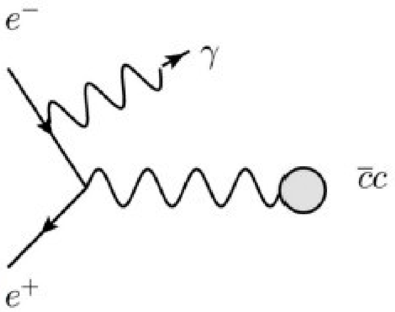
Y(4260)

- Initial state radiation events

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

- Quantum numbers

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



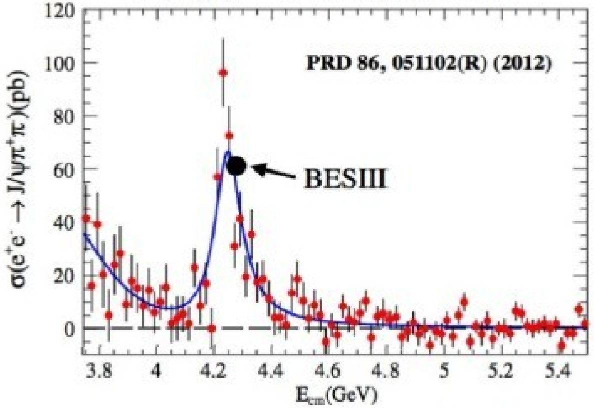
  (based upon production r

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

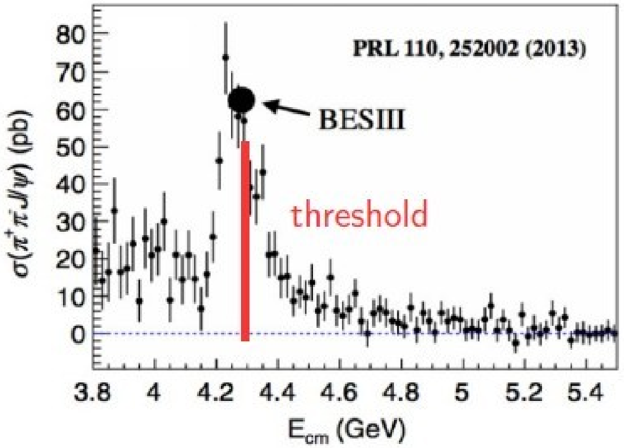
BESIII, Phys. Rev. Lett. 118 (9) (2017) 092001

BESIII, PRL110(2013)252001

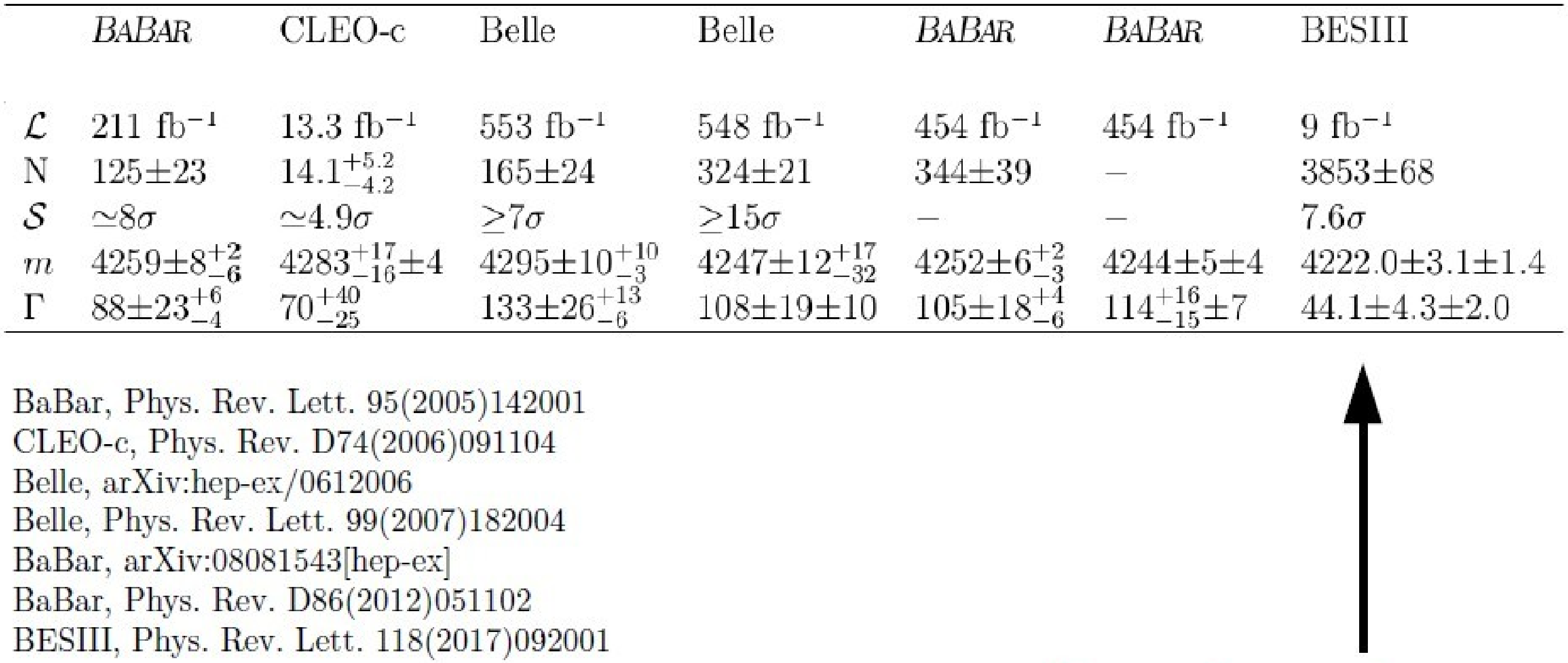
$e^+e^-(\gamma_{ISR}) \rightarrow \pi^+\pi^- J/\psi$ at BaBar



$e^+e^-(\gamma_{ISR}) \rightarrow \pi^+\pi^- J/\psi$ at Belle



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
$\mathcal{S}$	$\simeq8\sigma$	$\simeq4.9\sigma$	$\geq7\sigma$	$\geq15\sigma$	–	–	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}	$133\pm26^{+13}_{-6}$	$108\pm19\pm10$	$105\pm18^{+4}_{-6}$	$114^{+16}_{-15}\pm7$	$44.1\pm4.3\pm2.0$

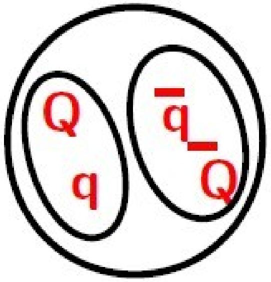
BaBar, Phys. Rev. Lett. 95(2005)142001
CLEO-c, Phys. Rev. D74(2006)091104
Belle, arXiv:hep-ex/0612006
Belle, Phys. Rev. Lett. 99(2007)182004
BaBar, arXiv:08081543[hep-ex]
BaBar, Phys. Rev. D86(2012)051102
BESIII, Phys. Rev. Lett. 118(2017)092001

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

Is the Y(4260) exotic ?

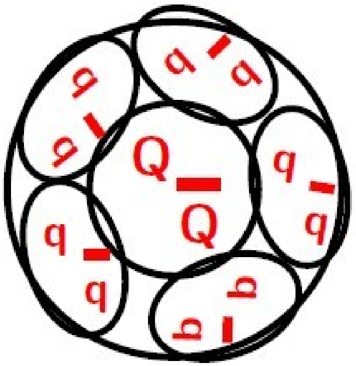
TETRAQUARK

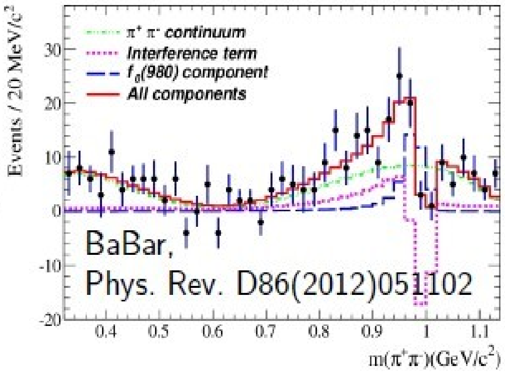
higher excitation ?



Maiani, Riquer, Piccinini, Polosa, Burns

HADRO-CHARMONIUM [$J/\psi\ f_0(980)$]



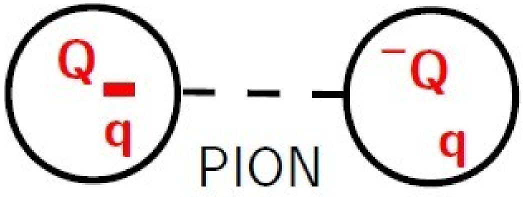


BaBar,
Phys. Rev. D86(2012)051102

Voloshin, Li
(Guo, Hanhart, Meissner)

MOLECULE

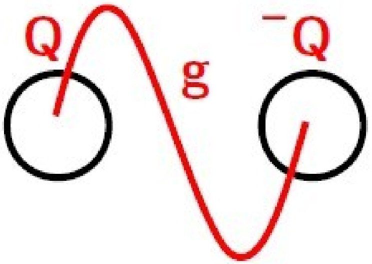
heavier mesons ($\bar{D}D_1(2460)$) ?



[Swanson, Rosner, Close
Guo, Hanhart, Meissner

HYBRID

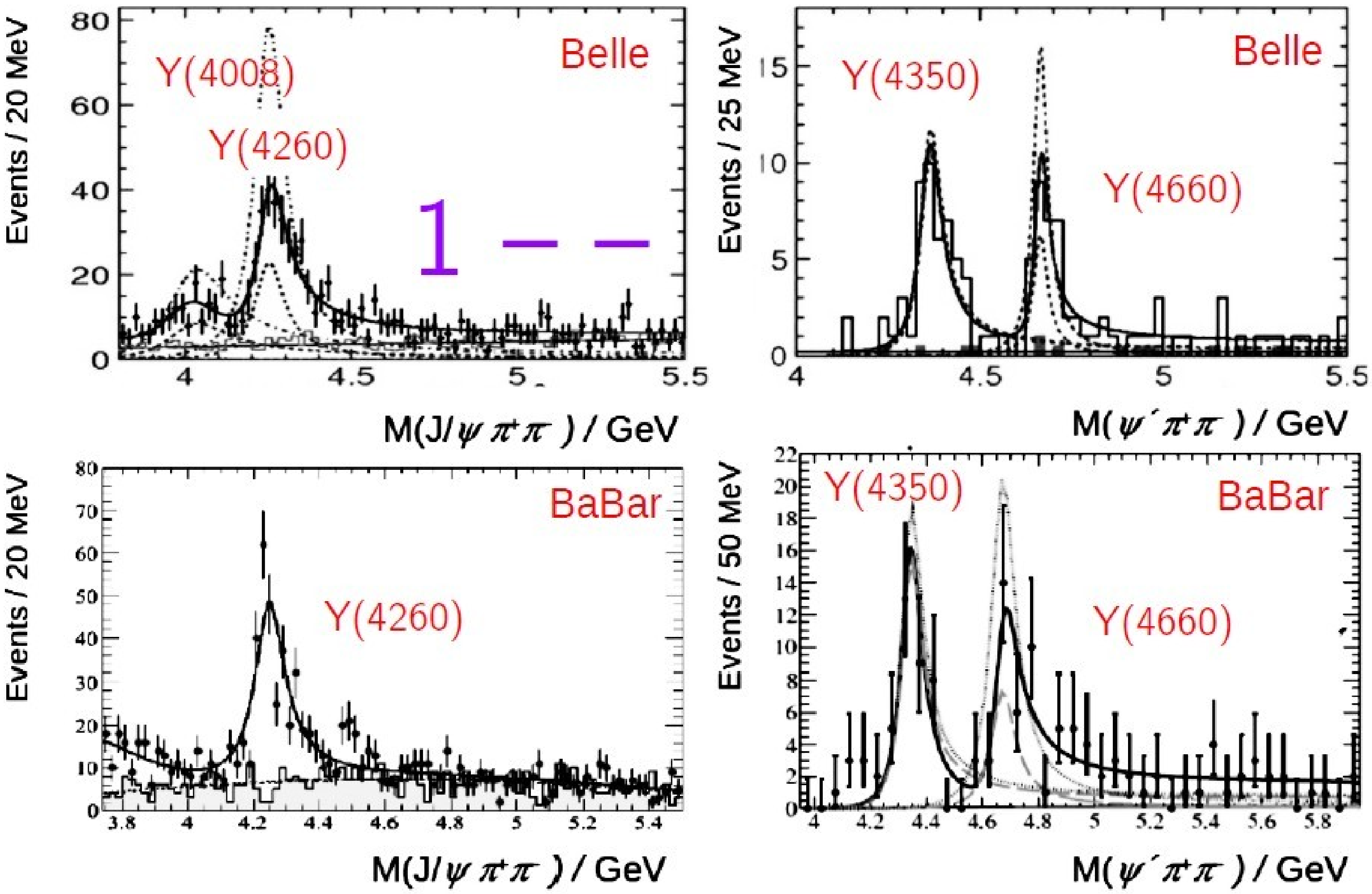
$[Q\bar{Q}]_8 g$



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

courtesy of J.S. Lange, HIRSCHEGG2018

Y STATES


Events / 20 MeV
80
60
40
20
0
Y(4008)
Y(4260)
Belle
4
4.5
5
5.5
M(J/ψ π⁺π⁻) / GeV
Events / 25 MeV
15
10
5
0
Y(4350)
Belle
Y(4660)
4
4.5
5
5.5
M(ψ´ π⁺π⁻) / GeV
Events / 20 MeV
80
70
60
50
40
30
20
10
0
BaBar
Y(4260)
3.8
4
4.2
4.4
4.6
4.8
5
5.2
5.4
M(J/ψ π⁺π⁻) / GeV
Events / 50 MeV
22
20
18
16
14
12
10
8
6
4
2
0
Y(4350)
BaBar
Y(4660)
4
4.2
4.4
4.6
4.8
5
5.2
5.4
5.6
5.8
M(ψ´ π⁺π⁻) / GeV

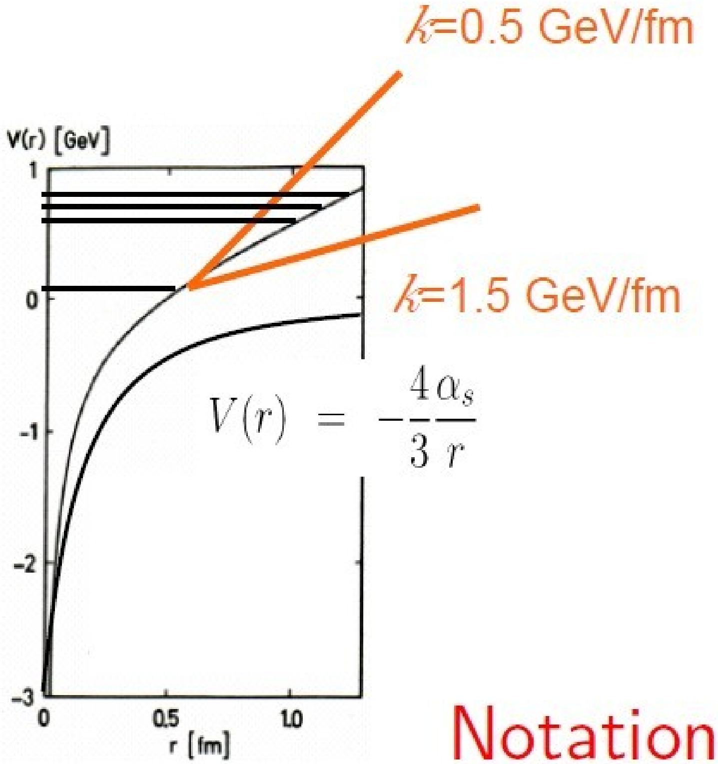
1 − −

Cornell–Potential

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

- Coulomb-Potential
  + Confinement-Term

$$
\begin{array}{lll}
 & V(r) = & -\frac{4}{3}\frac{\alpha_s}{r} + \boxed{kr} \\
\text{spin-spin} & & +\frac{32\pi\alpha_s}{9m_c^2}\delta_r\vec{S}_c\vec{S}_{\bar{c}} \\
\text{spin-orbit} & & +\frac{1}{m_c^2}\left(\frac{2\alpha_s}{r^3}-\frac{k}{2r}\right)\vec{L}\vec{S} \\
\text{tensor} & & +\frac{1}{m_c^2}\frac{4\alpha_s}{r^3}\left(\frac{3\vec{S}_c\vec{r}\cdot\vec{S}_{\bar{c}}\vec{r}}{r^2}-\vec{S}_c\vec{S}_{\bar{c}}\right)
\end{array}
$$



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

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

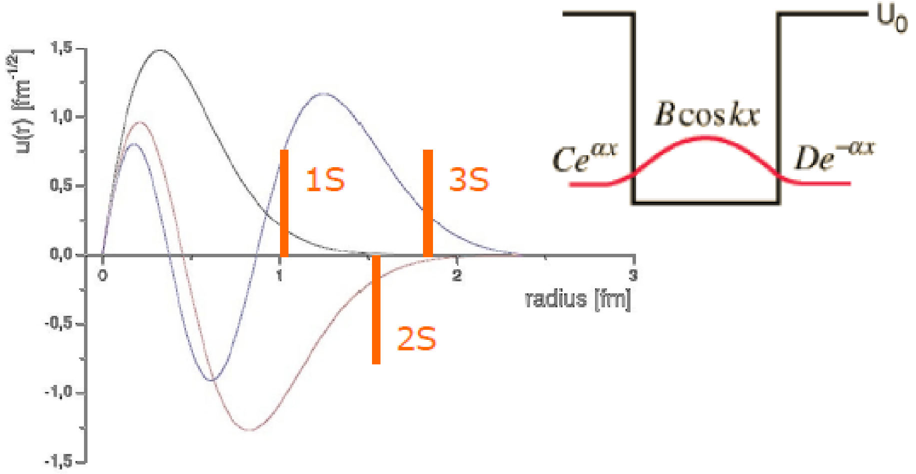
$$\Psi(r,\theta,\phi) = R_{nl}(r)Y_{lm}(\theta,\phi)$$

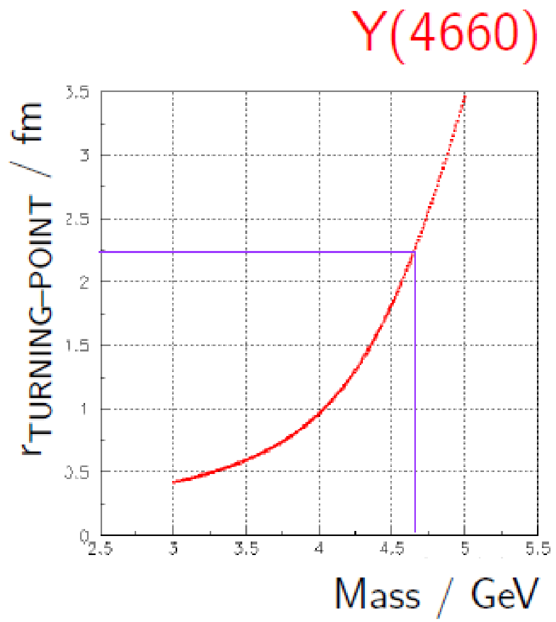
$$\left[-\frac{1}{m_q}\left(\frac{\partial^2}{\partial r^2}+\frac{2}{r}\frac{\partial}{\partial r}+\frac{l(l+1)}{m_q r^2}+V(r)\right)\right]R_{nl}(r) = E_{nl}R_{nl}(r)$$

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

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

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



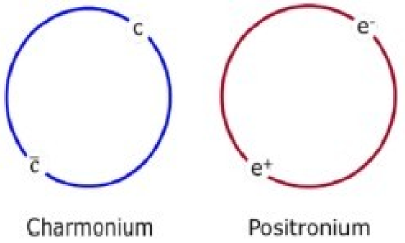


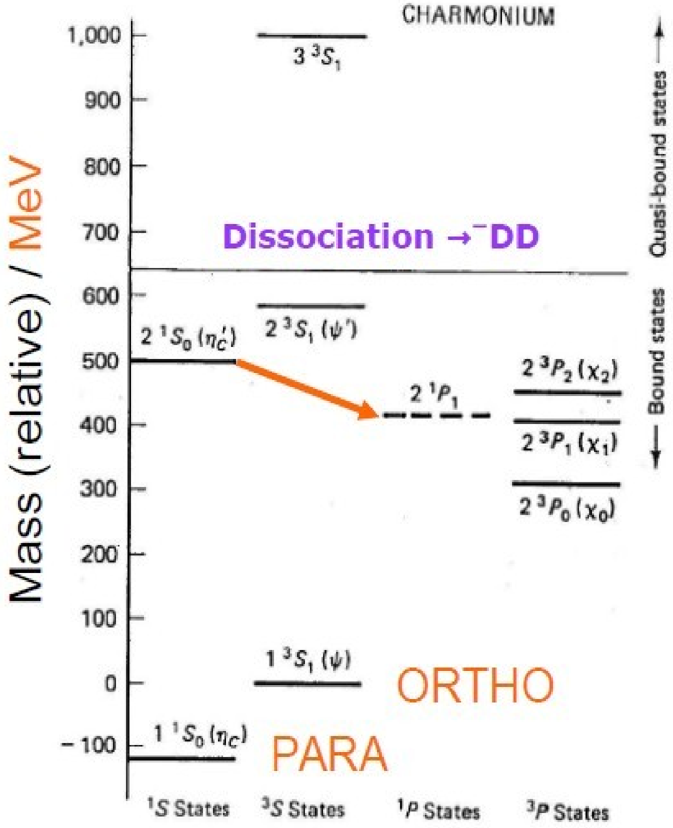
- m=4.660 GeV → turning point of wave function is 2.2 fm!
- large fraction of wave function in string breaking regime r>1.4 fm

courtesy of J.S. Lange, HIRSCHEGG2018

Charmonium vs. Positronium

Decays to light quarks suppressed
→ narrow widths

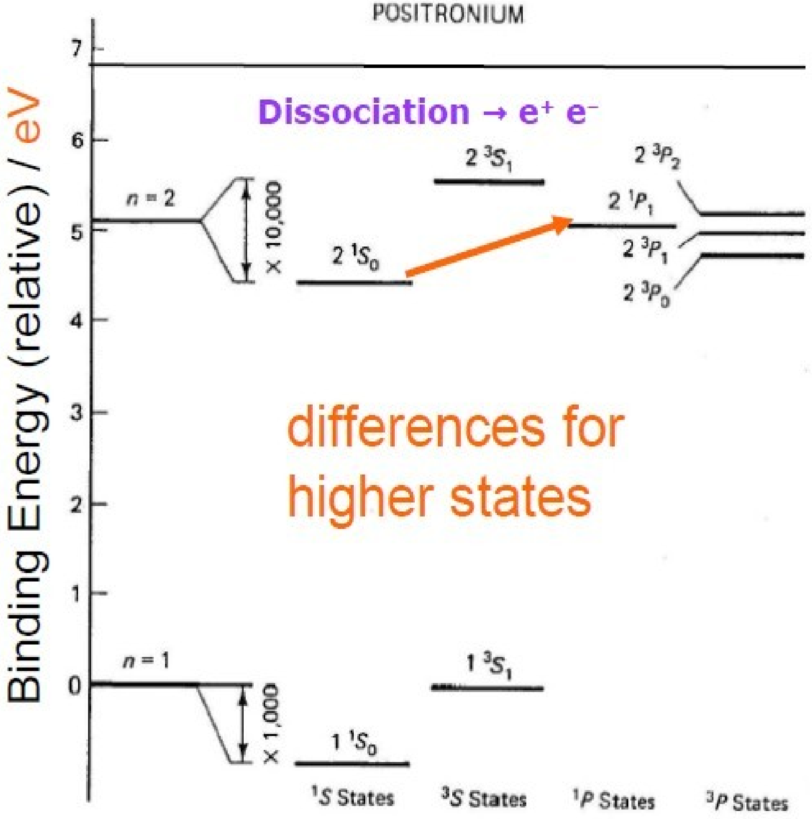




Dissociation → $\bar{D}D$

ORTHO

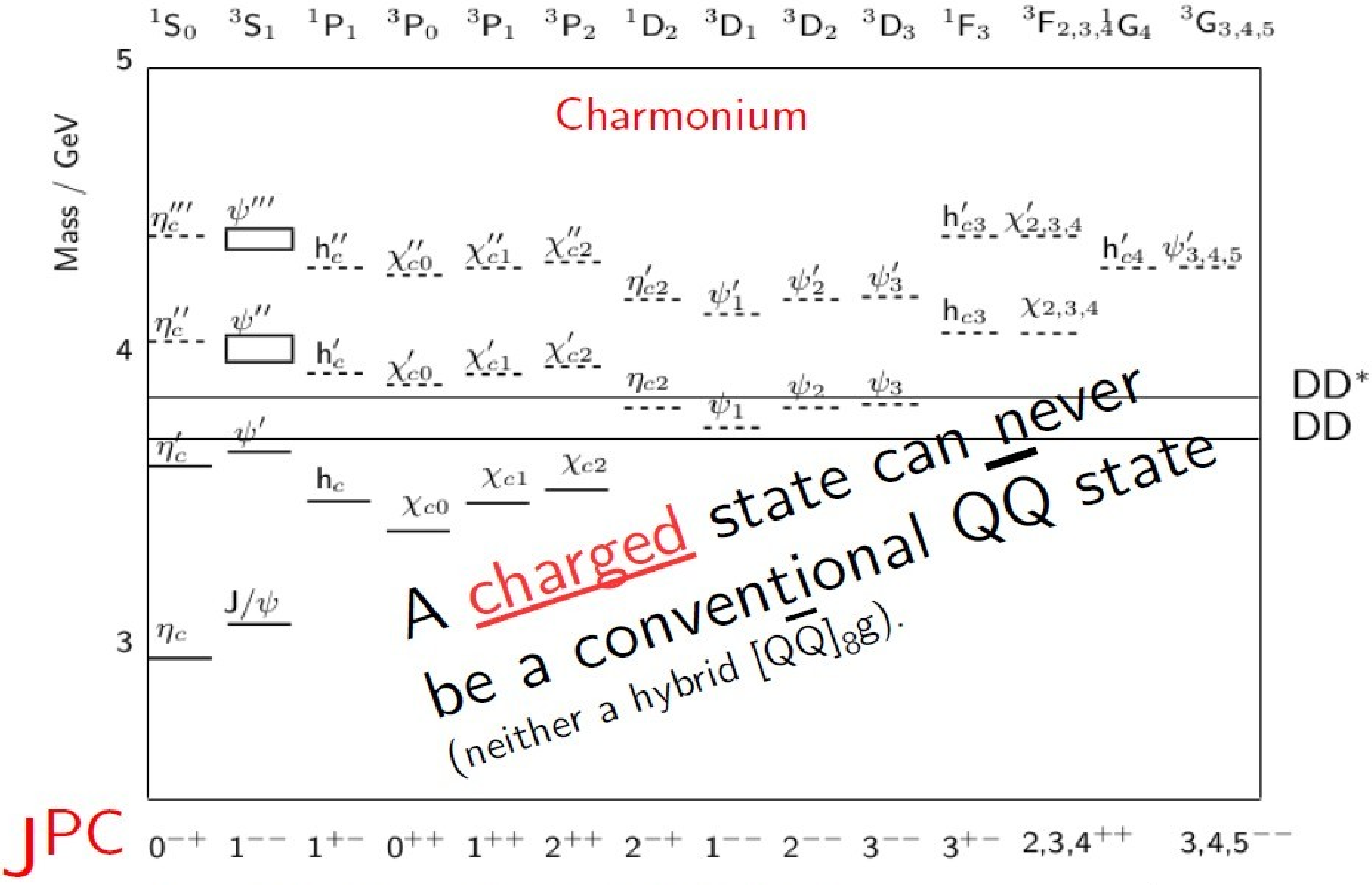
PARA



Dissociation → e⁺ e⁻

differences for higher states

courtesy of J.S. Lange, HIRSCHEGG2018



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

A charged state can never be a conventional $Q\bar{Q}$ state

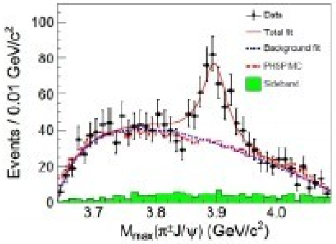
(neither a hybrid $[Q\bar{Q}]_8 g$).

Landiao LIU, QWG 2016

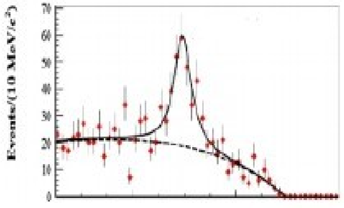
Z STATES AT BESIII

$D\bar{D}^*$ threshold

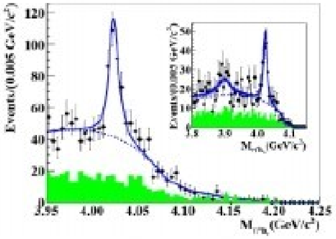
$D^*\bar{D}^*$ threshold



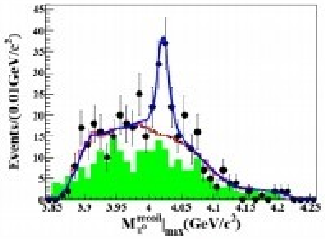
$e^+e^- \to \pi^+ \pi^- J/\Psi$



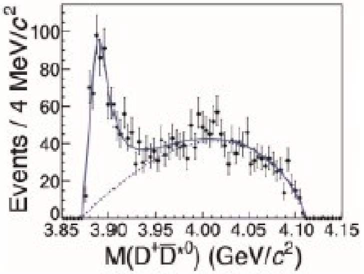
$e^+e^- \to \pi^0 \pi^0 J/\Psi$



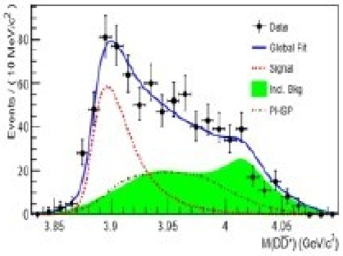
$e^+e^- \to \pi^+ \pi^- h_c$



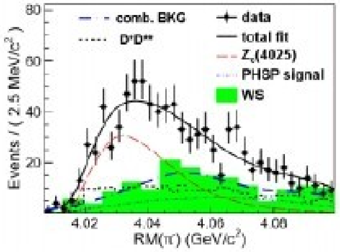
$e^+e^- \to \pi^0 \pi^0 h_c$



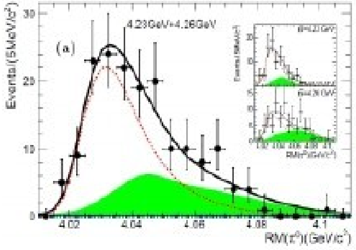
$e^+e^- \to \pi^+ (D\bar{D}^*)^-$



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



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



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

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)
$Z_c(3900)$	$3899.0\pm3.6\pm4.9$	$D^+\overline{D}^{0*}$	$+22.4$
$Z_c(3900)$	$3899.0\pm3.6\pm4.9$	$D^0\overline{D}^{+*}$	$+23.9$
$Z_c(3900)$	$3894.5\pm6.6\pm4.5$	$D^+\overline{D}^{0*}$	$+17.9$
$Z_c(3900)$	$3894.5\pm6.6\pm4.5$	$D^0\overline{D}^{+*}$	$+19.4$
$Z_c(3900)$	$3885\pm5\pm1$	$D^+\overline{D}^{0*}$	$+8.4$
$Z_c(3900)$	$3885\pm5\pm1$ 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)