Belle and Belle II status and plans for radiative decays of the X(3872)

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IISER Mohali

(on behalf of Belle II)

LHCb meets Theory: Probing the nature of the state using radiative decays

27 June 2024

Outline

- Tales of two B
- Charmonium at *B*-factory
- Radiative decays of *X(3872)*
- Prospects in Belle II
- Summary

Tales of two B

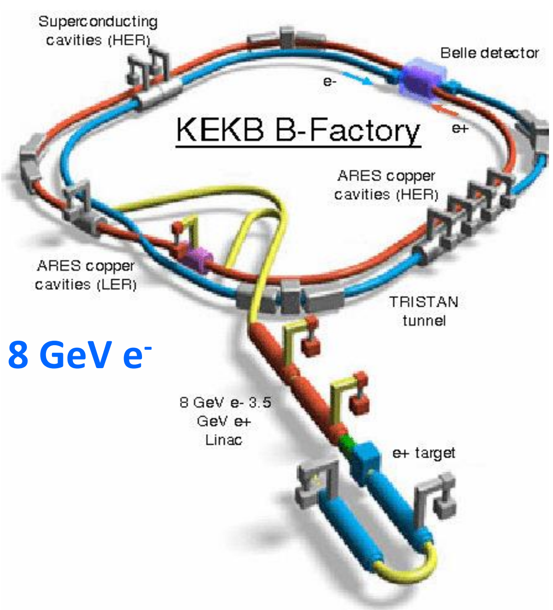
$e^+ e^-$ asymmetric colliders, excellent machine build

- ➢ To test Standard Model mechanism for CP violation in B decays.
- ➢ For precision test and search for New Physics beyond the Standard Model

> 1ab^{-1}

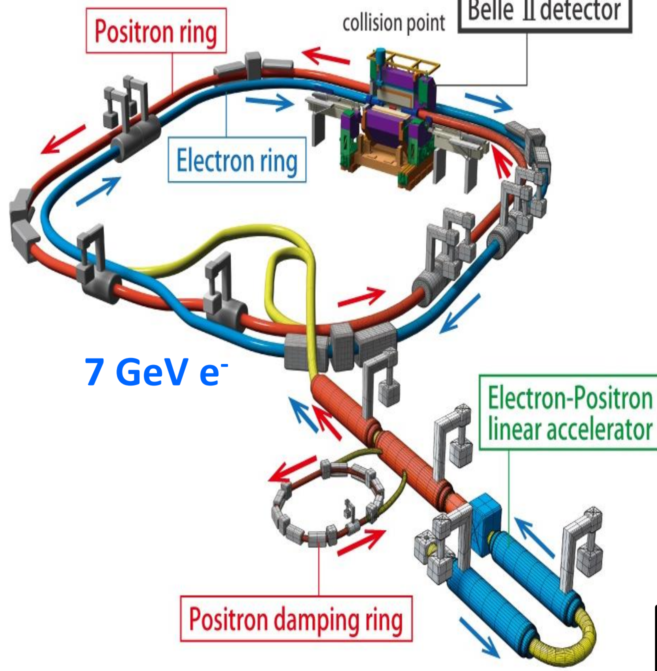
3.5 GeV e^+

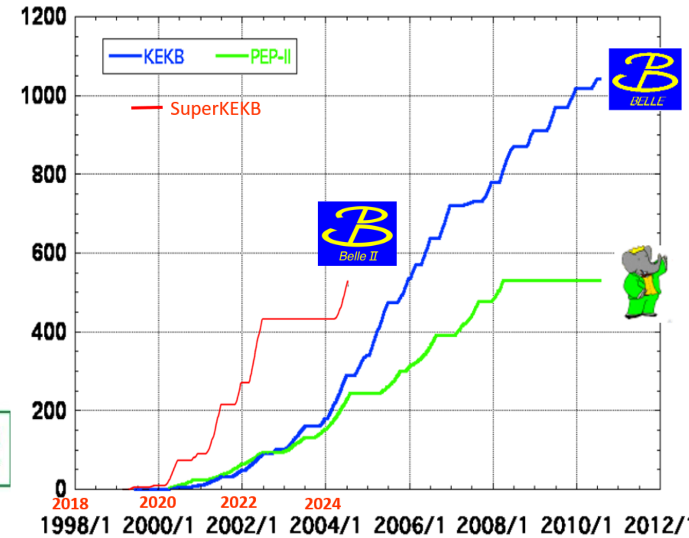
8 GeV e^-



4.0GeV e^+

7 GeV e^-





KEKB

$\beta\gamma = 0.42$

SuperKEKB

$\beta\gamma \sim 0.28$

- Large amount of data recorded by Belle .
- Belle II doing great job in accumulating data.

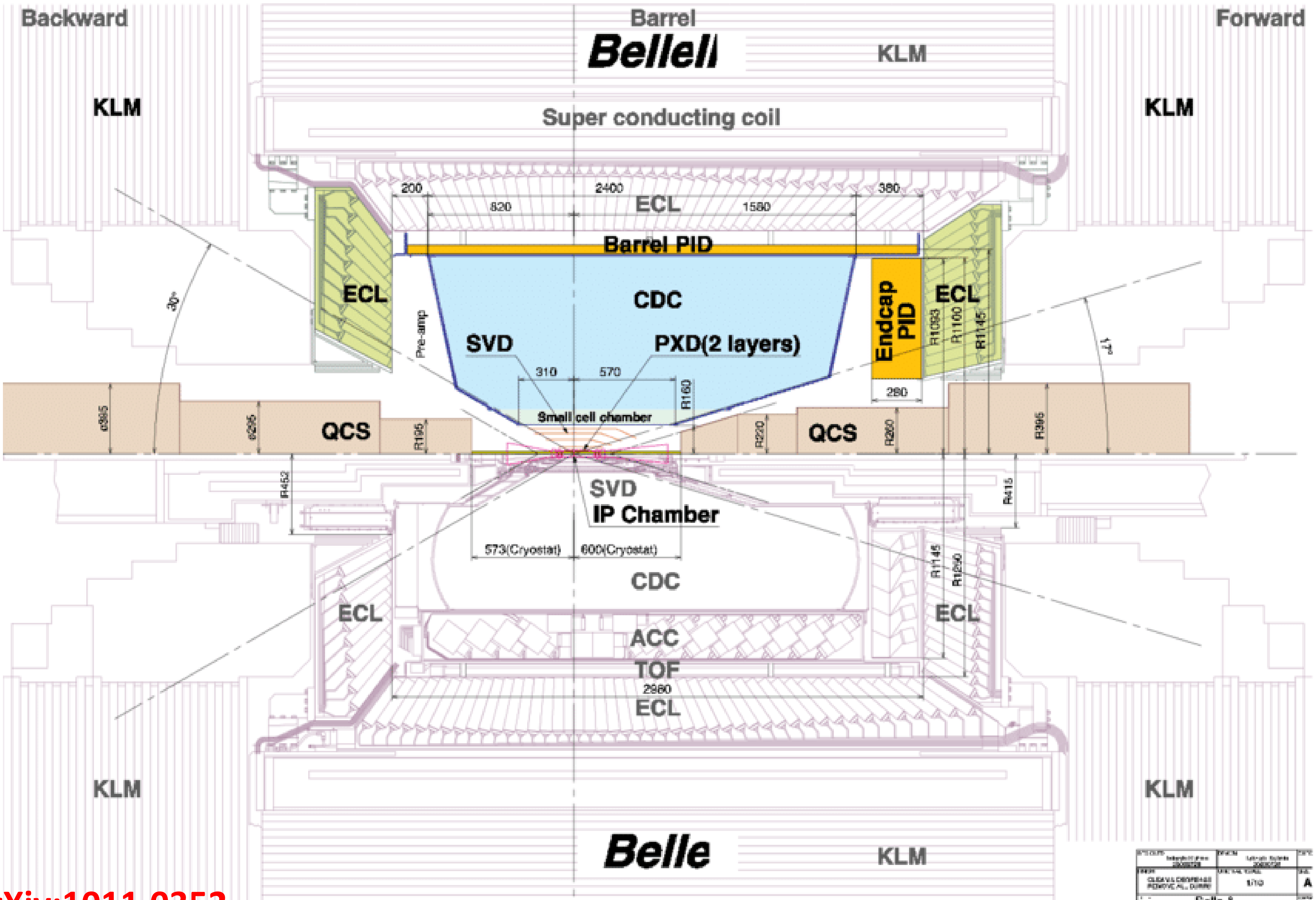
On-resonance:
4S : 711 fb^{-1}
5S : 121 fb^{-1}
3S : 3 fb^{-1}
2S : 25 fb^{-1}
1S : 6 fb^{-1}
Off-resonance/scan ~100 fb^{-1}

Total Integrated luminosity usable : 424 fb^{-1}

4S = 363 fb^{-1}

Clean and ideal place to carry charmonium spectroscopy related business.

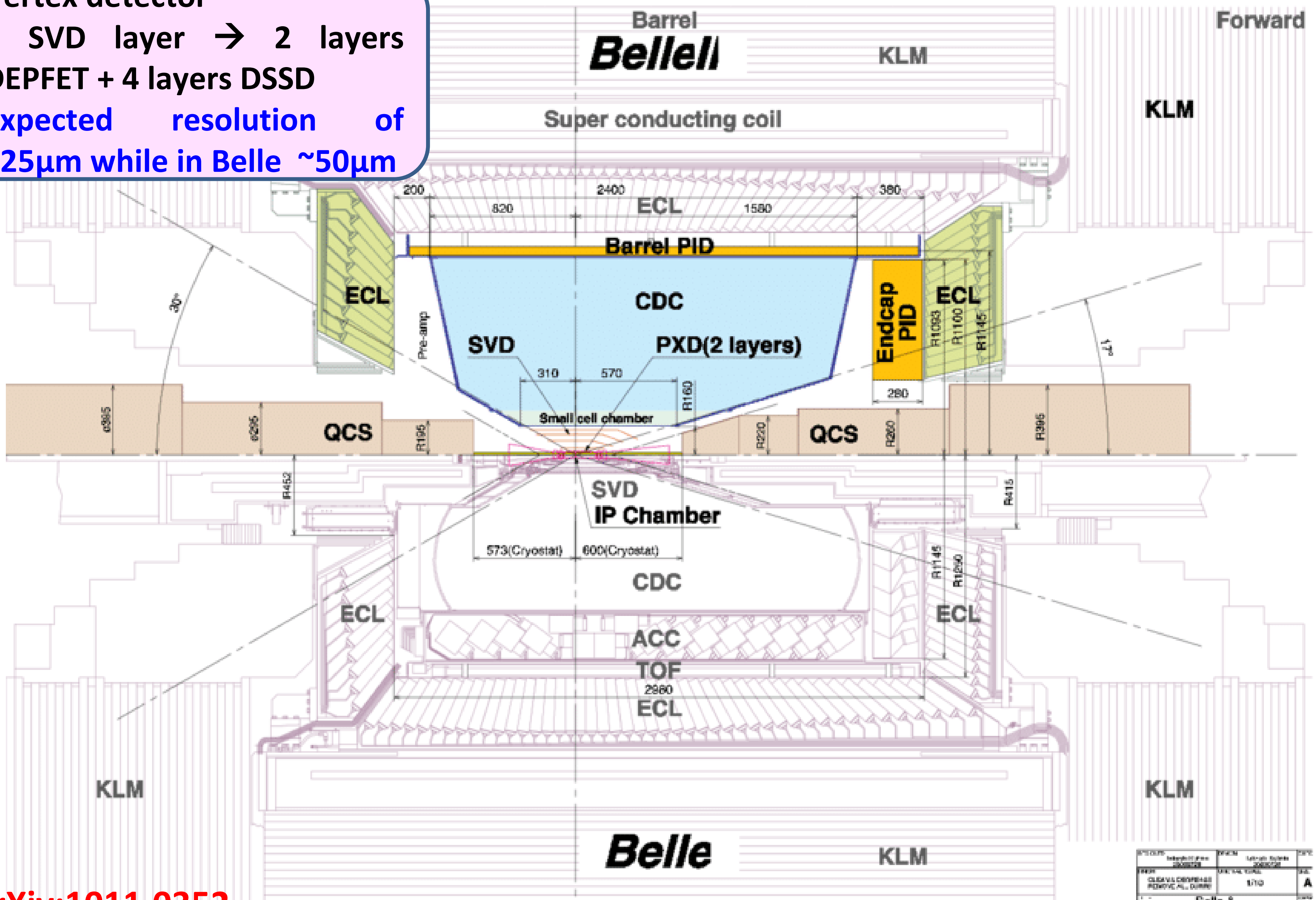
Belle to Belle II



arXiv:1011.0352

Belle to Belle II

Vertex detector
4 SVD layer → 2 layers DEPFET + 4 layers DSSD
Expected resolution of ~25μm while in Belle ~50μm



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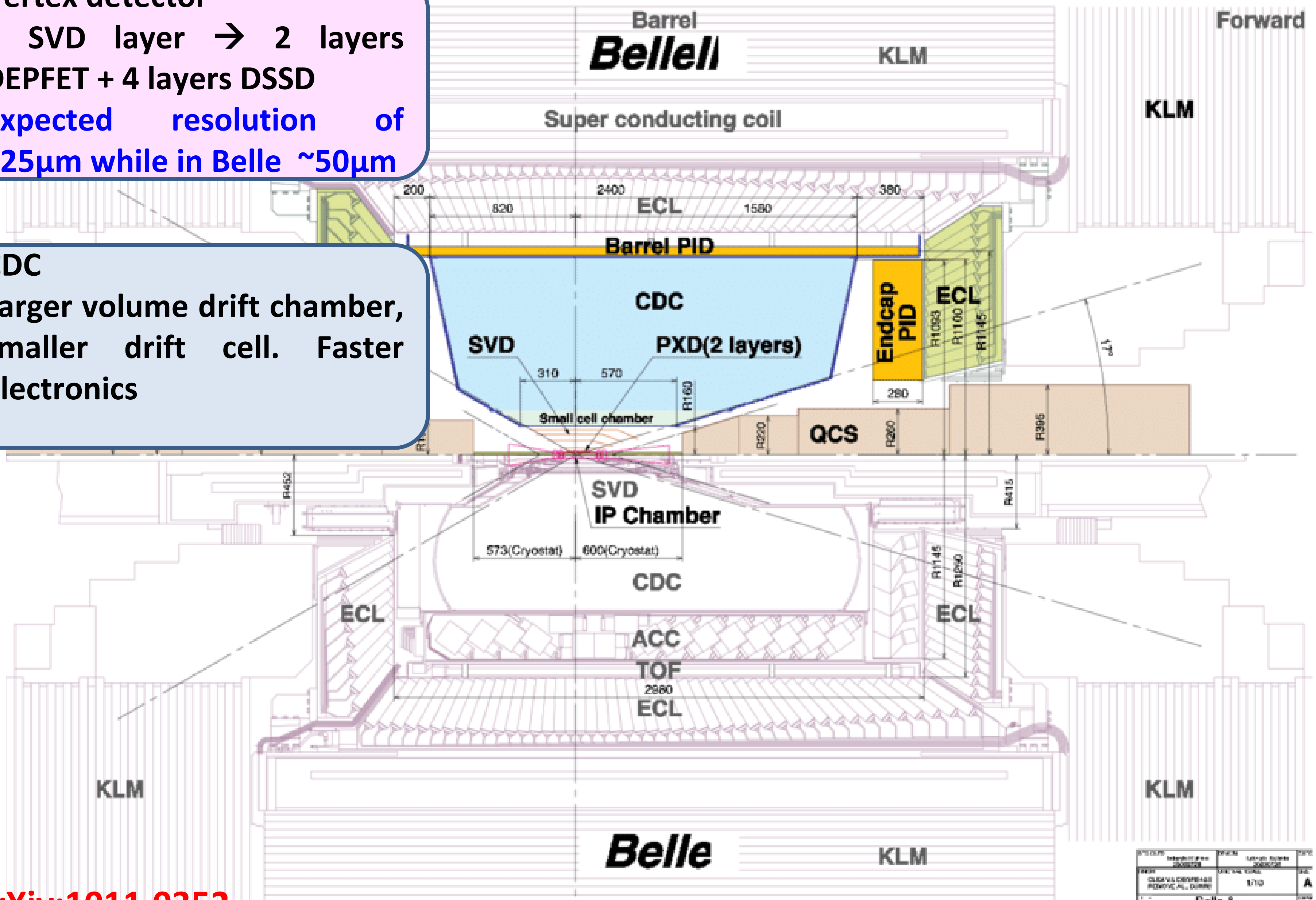

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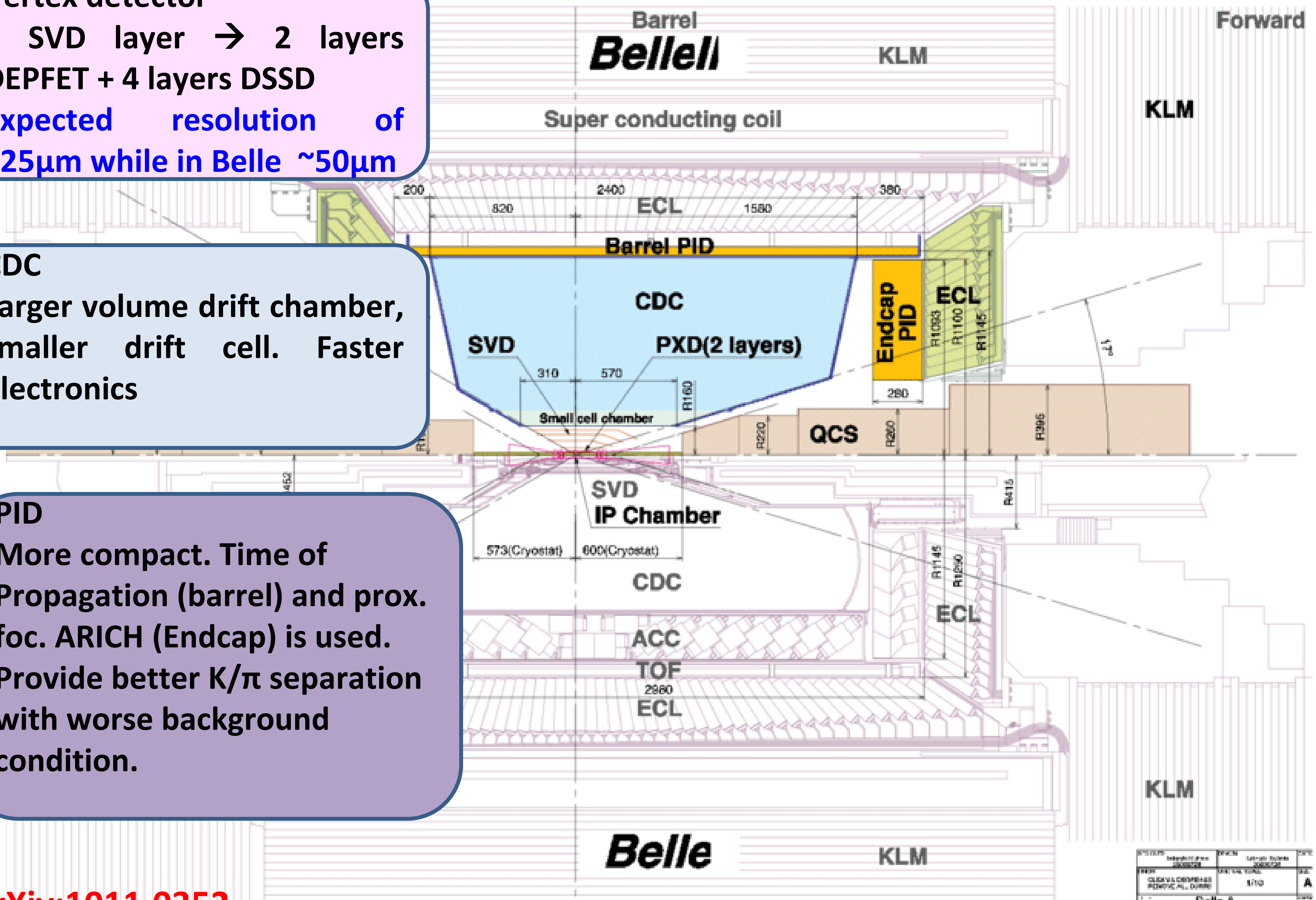
More compact. Time of Propagation (barrel) and prox. foc. ARICH (Endcap) is used. Provide better K/π separation with worse background condition.



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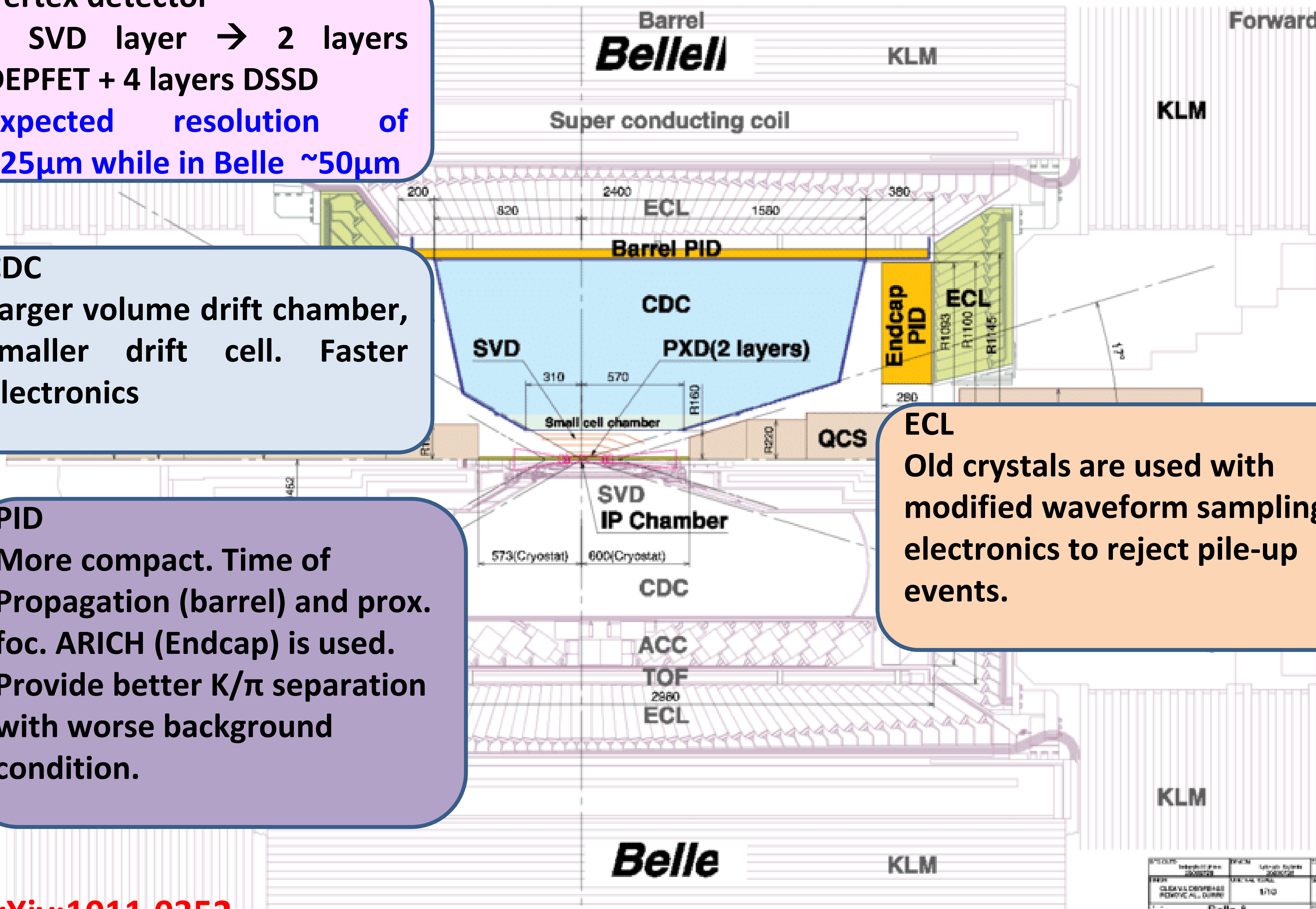

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ECL
Old crystals are used with modified waveform sampling electronics to reject pile-up events.

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KLM
Resistive place counter (Barrel)
Scintillation + WLSF + MCCP (endcap)

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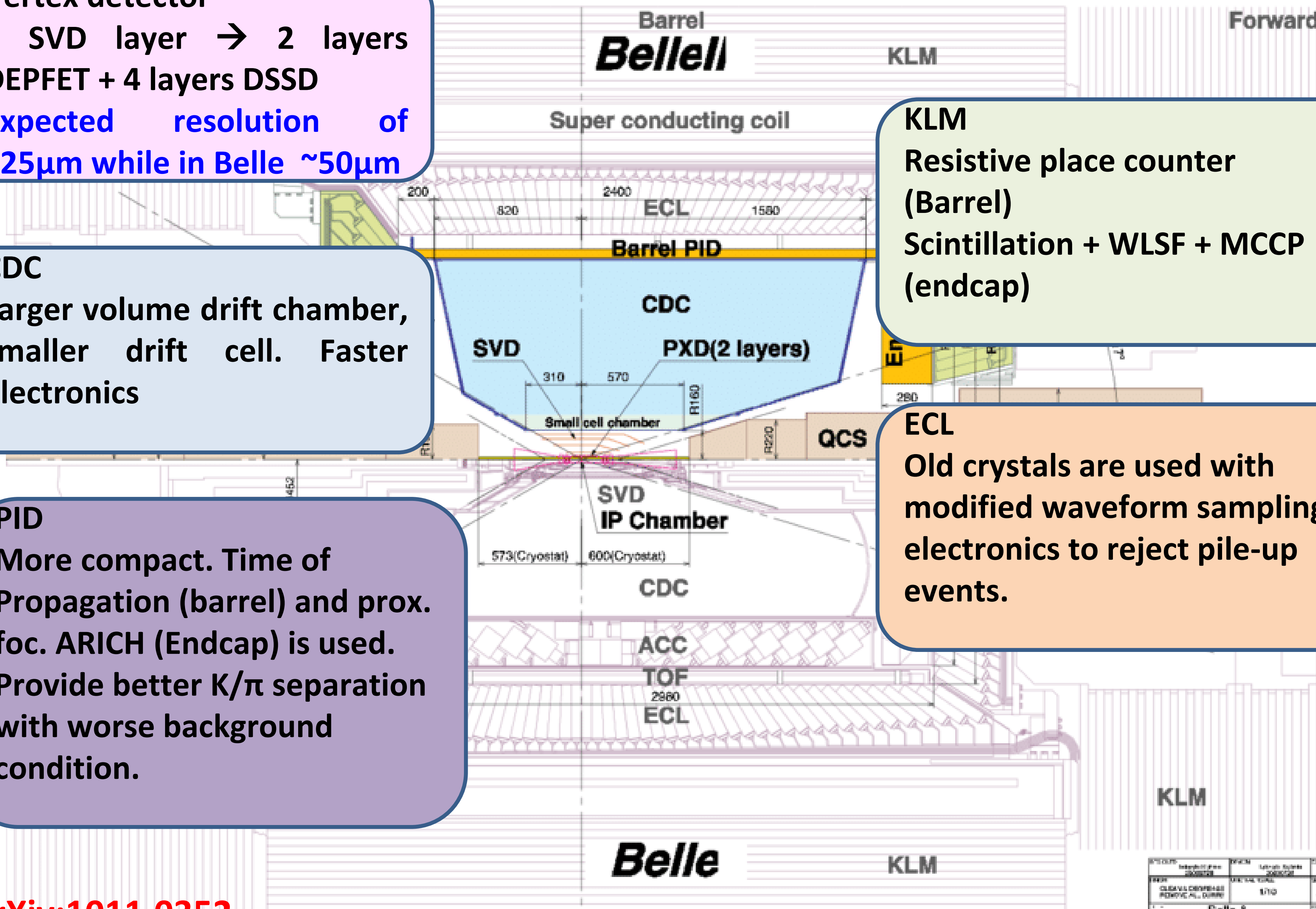

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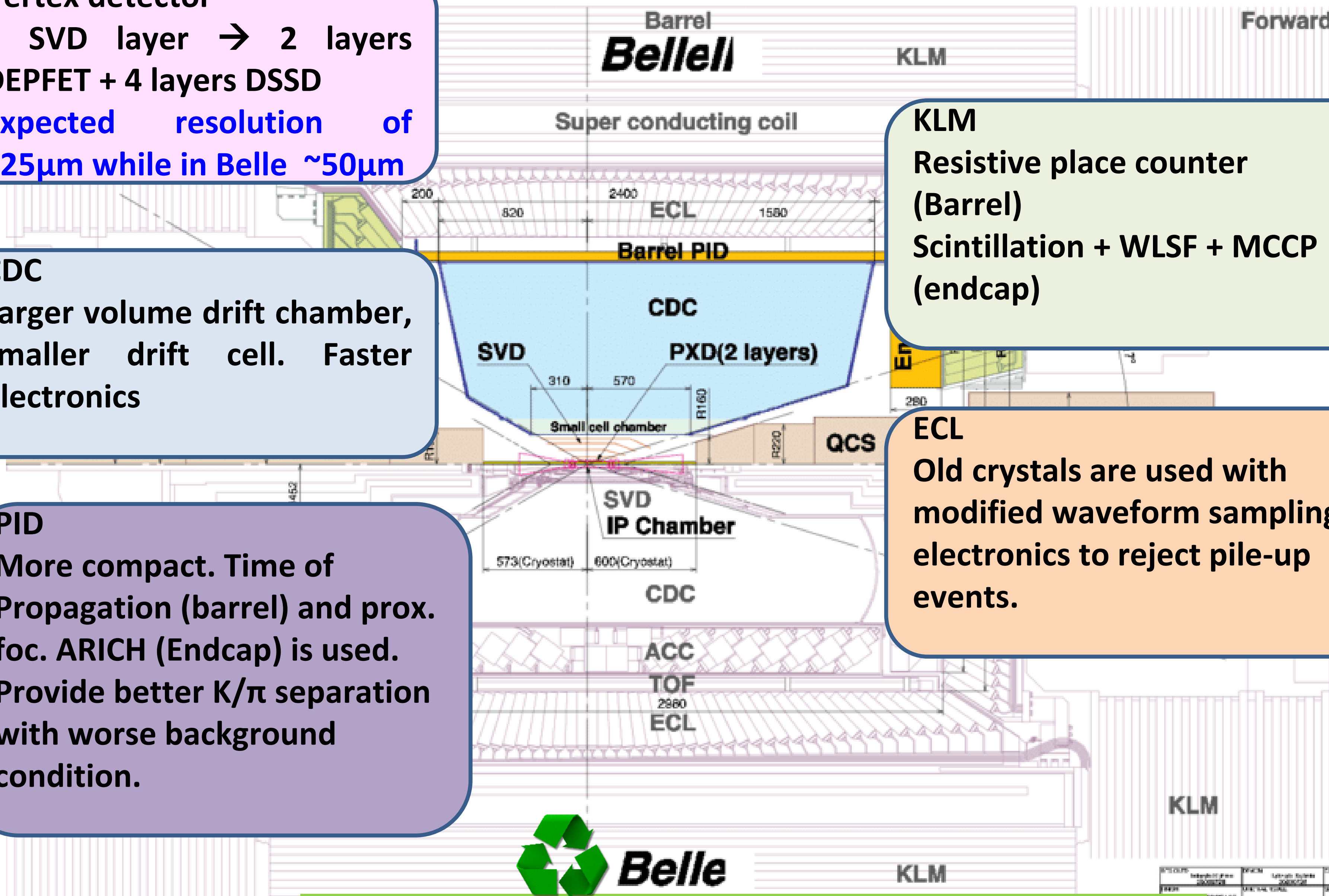
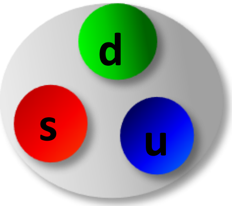


ECL crystals and part of KLM sub-detector are re-used.

arXiv:1011.0352

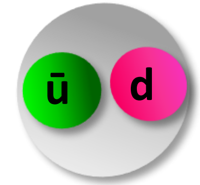
Real particles are color singlet



Baryons are red-blue-green triplets

Λ=usd

Mesons are color-anticolor pairs

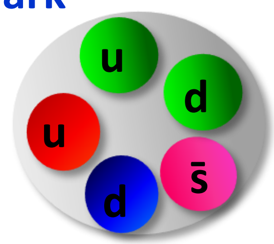


π=ūd

Other possible combinations of quarks and gluons :

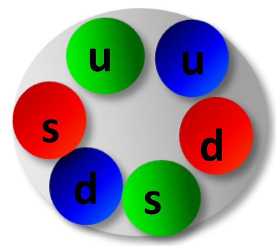
Pentaquark

S= +1 Baryon



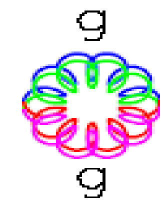
H di-Baryon

Tightly bound 6 quark state



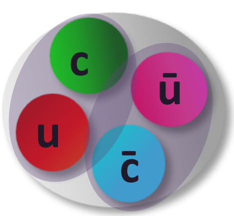
Glueball

Color-singlet multi-gluon bound state



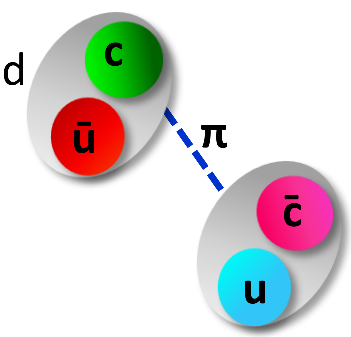
Tetraquark

Tightly bound diquark & anti-diquark

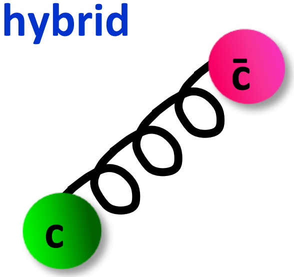


Molecule

loosely bound meson-antimeson "molecule"

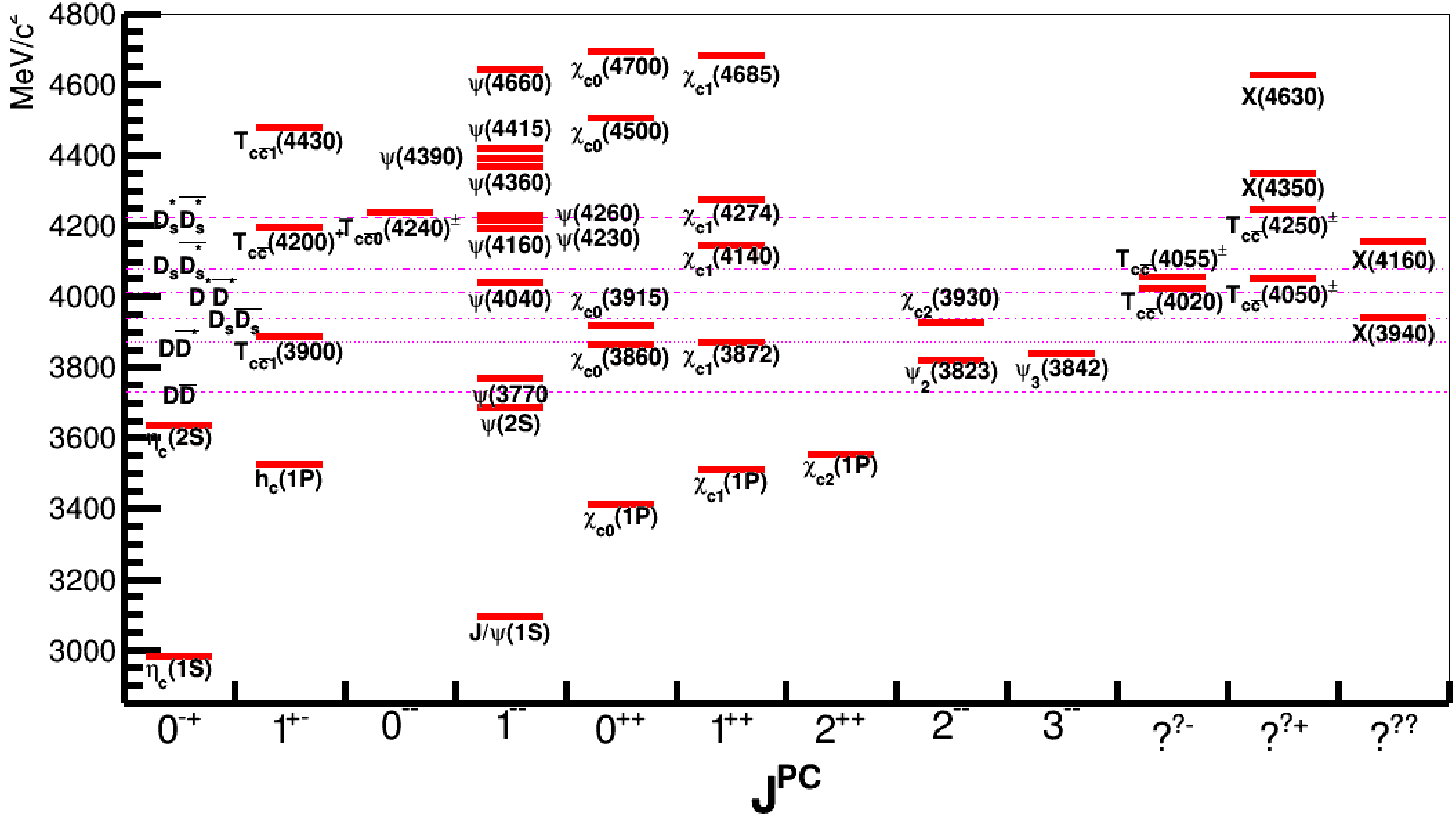


qq̄ -gluon hybrid mesons



artistic illustration

$c\bar{c}$ (-like) states till now

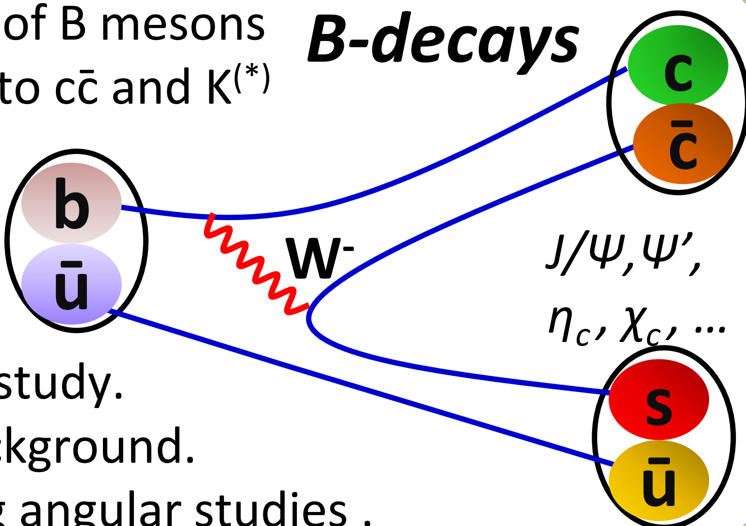


- 2 decades has passed after the discovery of first $c\bar{c}$-like [*X(3872)*] by the Belle collaboration.
- Plenty of states have been found.
- Several states are seen in one process (not easy to understand).
- States have a non-zero charge, suggesting them to be tetraquark/molecule-like states.
- Instead of conventional spectroscopy, it is now *exotic spectroscopy*.

Production of $c\bar{c}$ (-like)

B-decays

A few % of B mesons decay into $c\bar{c}$ and $K^{(*)}$

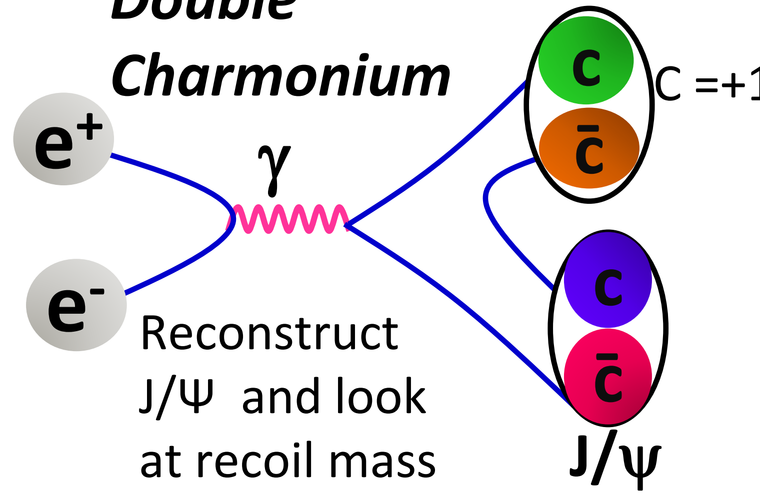


Easy to study.

Low background.

J^{PC} using angular studies .

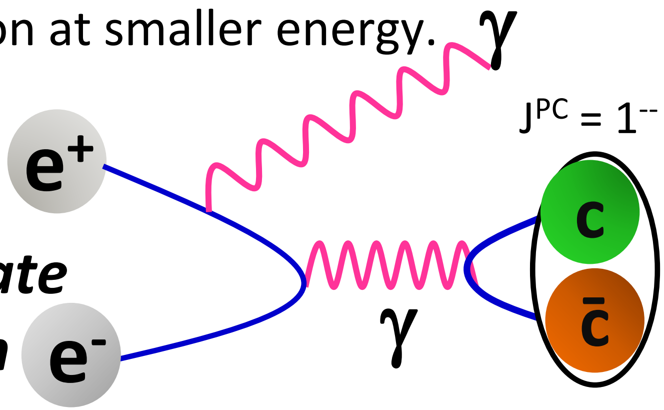
Double Charmonium



Reconstruct J/Ψ and look at recoil mass

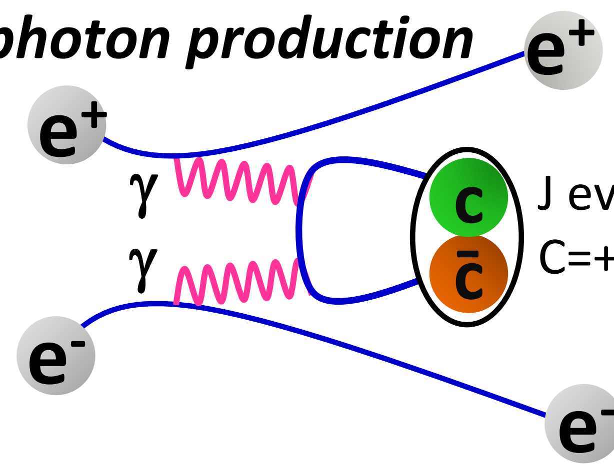
Initial state radiation

Annihilation at smaller energy.



Two photon production

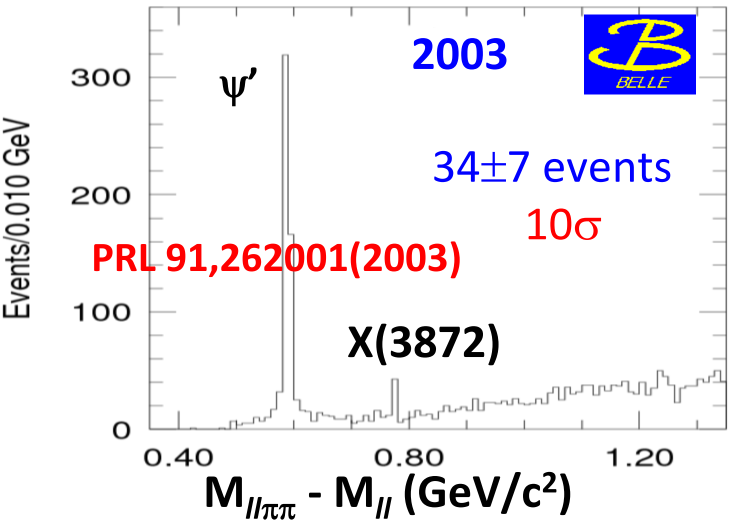
$c\bar{c}$ states produced without additional hadrons.



$X(3872)$ aka $\chi_{c1}(3872)$

The most famous $c\bar{c}$ (-like) state

X(3872) was discovered in 2003 by Belle.



World average mass → 3871.64±0.06 MeV/c^2 X(3872)→J/ψππ

LHCb	3871.64±0.06±0.01 JEHP, 08 (2020) 123
Belle	3871.85±0.27±0.19 **PRD 85,052004 (2011)**

Mass near D^0 and $\bar{D}^{*0}$ threshold → 3871.69± 0.07 MeV/c^2 **PDG**

How is it related to D^0 $\bar{D}^{*0}$? D^0 $\bar{D}^{*0}$ molecule or something else ?

X(3872) much narrower width (Γ = 1.19±0.21 MeV than other charmonium states above D $\bar{D}$ threshold.

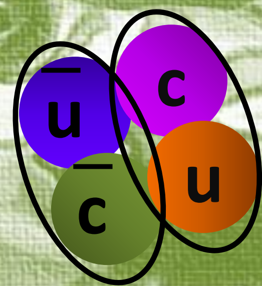
Observed in D^0 $\bar{D}^{*0}$ mode. **PRD 107, 112011 (2023), PRL 97,162002 (2006), PRD 77,011102 (2008) and PRD 81, 031103 (2010)**

eX(3872)otic

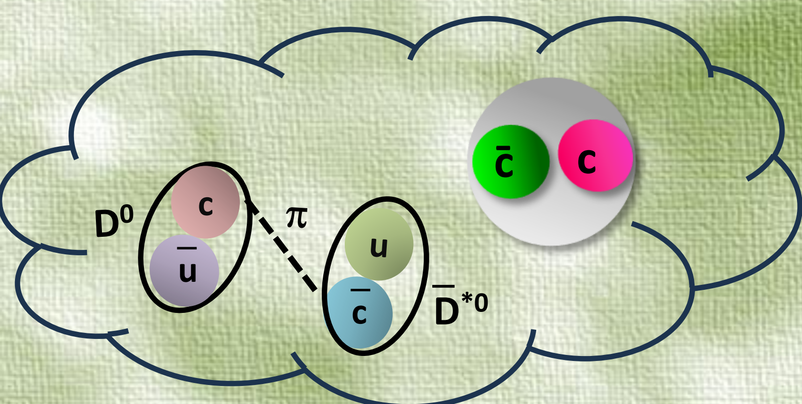
eX(3872)otic

X(3872) doesn't fit charmonium scheme with ease.
Many explanation for X(3872) are proposed :

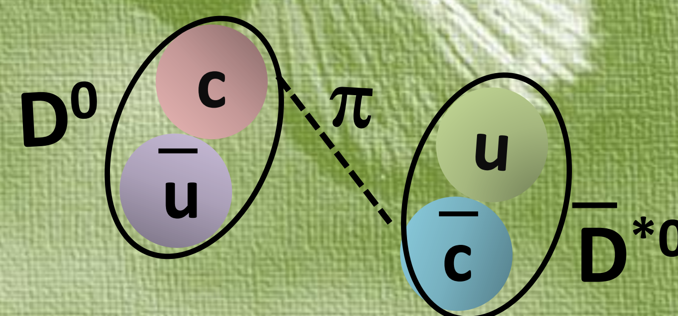
Tetraquark

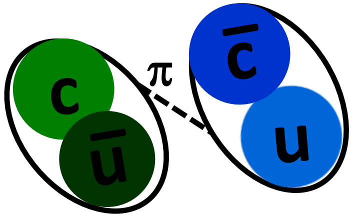


Admixture

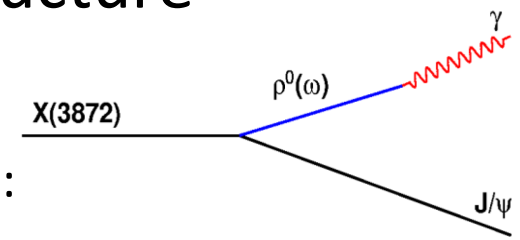


Molecular





Radiative decay and X(3872) structure

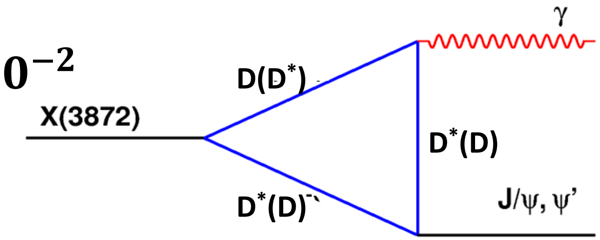


Radiative decays can proceed via two mechanisms:

- ✓ Vector meson dominance
- ✓ Light quark annihilation

If pure molecular :- Phys.Rept. 429,243(2006)

$\mathcal{BR}$(X(3872)→ ψ'γ) < $\mathcal{BR}$(X(3872)→ J/ψγ) $\sim 10^{-2}$



If tetraquark PRD 109,074009(2024)

$\mathcal{BR}$(X(3872)→ ψ'γ) ≳ $\mathcal{BR}$(X(3872)→ J/ψγ) $\sim 0.8 - 1.1$

If X(3872) is 1^{++} $c\bar{c}$:- PRD 73,014014(2006)

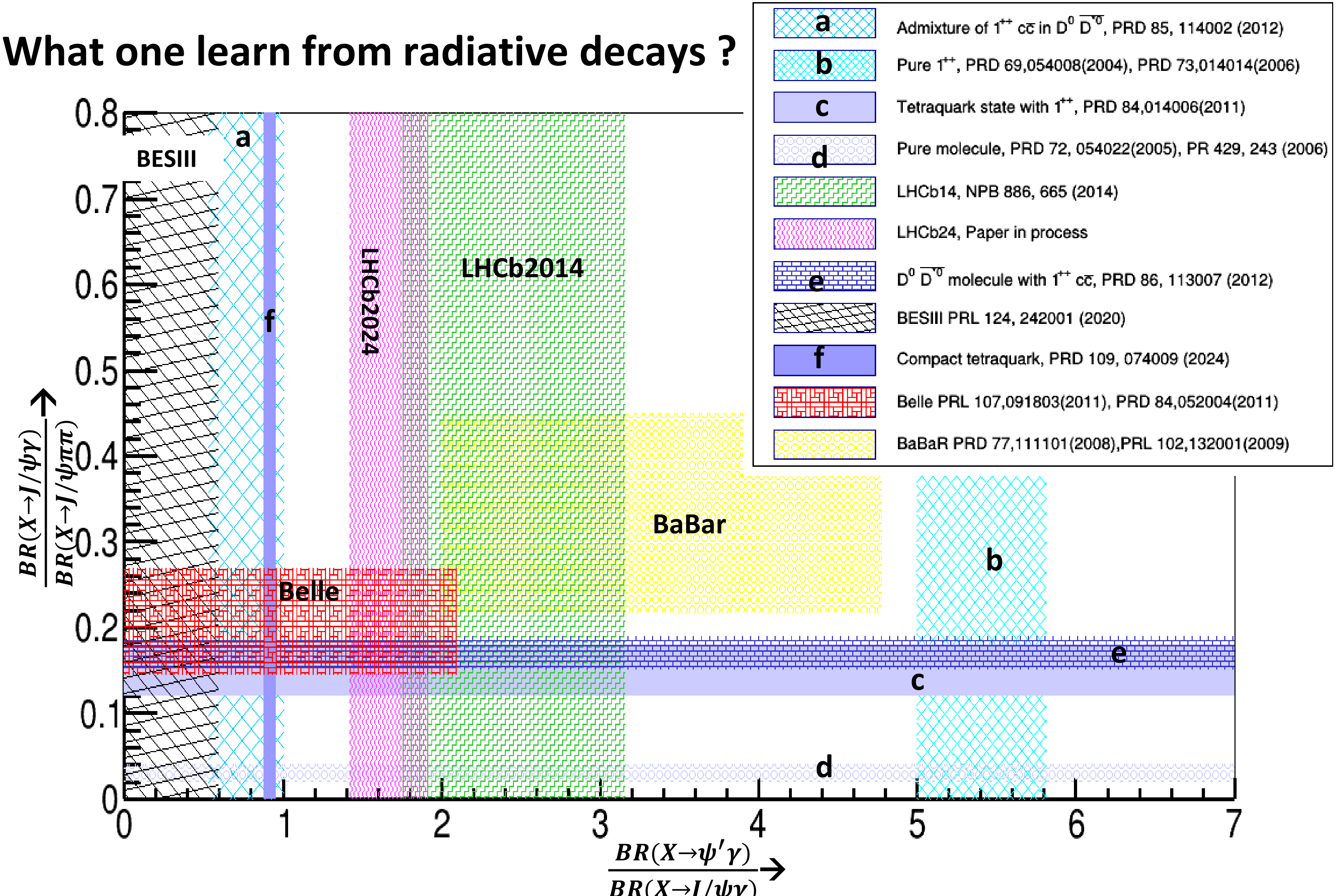
$\mathcal{BR}$(X(3872)→ ψ'γ) > $\mathcal{BR}$(X(3872)→ J/ψγ) $\sim 2.6 - 15$

If X(3872) is admixture of $D^0\,\bar{D}^{*0}$ bound state with a $c\,\bar{c}$ meson :

$\mathcal{BR}$(X(3872)→ ψ'γ) /$\mathcal{BR}$(X(3872)→ J/ψγ) will suggest the admixture ratio. $\sim 0.5 - 5$

Precise measurement of this ratio is important to understand X(3872) nature.

What one learn from radiative decays ?

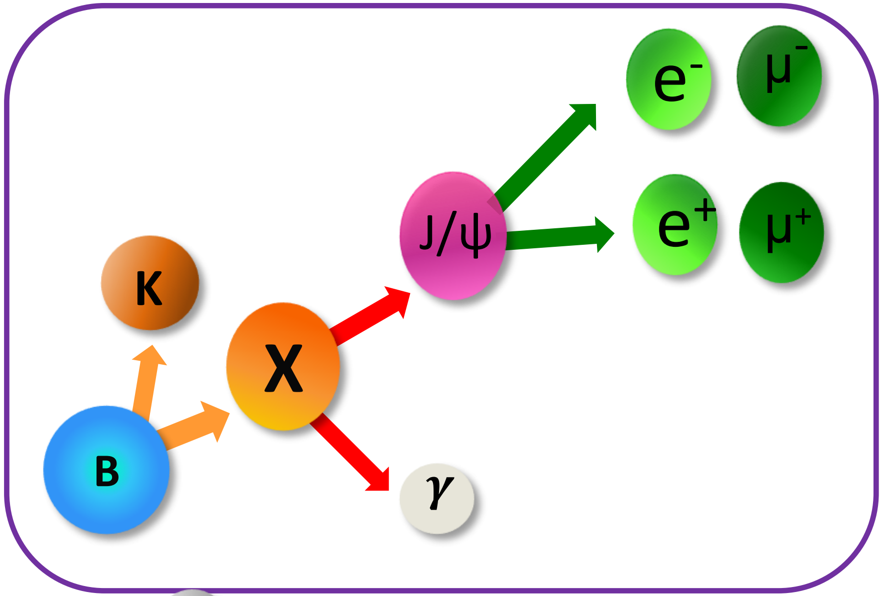


Will be easy for to test models, if theory can provide $\frac{BR(X\to J/\psi\gamma)}{BR(X\to J/\psi\pi\pi)}$, $\frac{BR(X\to J/\psi\omega)}{BR(X\to J/\psi\pi\pi)}$ and $\frac{BR(X\to\psi'\gamma)}{BR(X\to J/\psi\gamma)}$

Comparison can be more refined !

Analysis procedure

Reconstruct B (of interest)

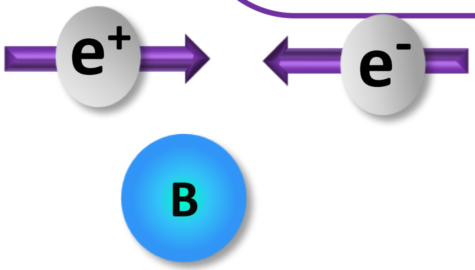


Common variable used in analyses

$$M_{bc} = \sqrt{E_{beam}^2 - p_B^2}$$

$$\Delta E = E_B - E_{beam}$$

$$M_{\psi\gamma}$$



Radiative decays in *B* meson

X(3872) , $\chi_{c1,c2}$ → $J/\psi\ \gamma$

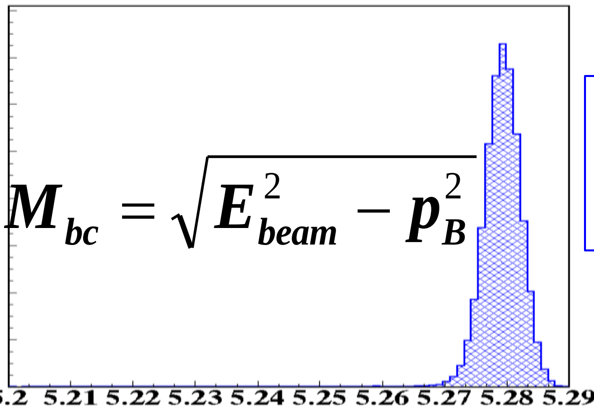
↳ $e^+ e^-$ or $\mu^+\mu^-$

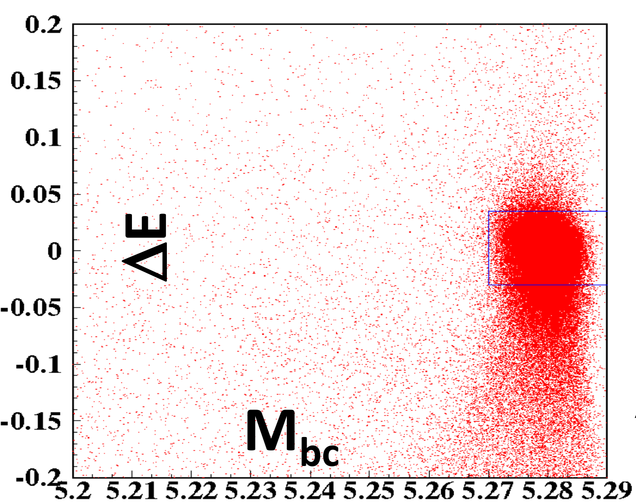
$\chi_{c1,c2}$ K (K_S^0) → B

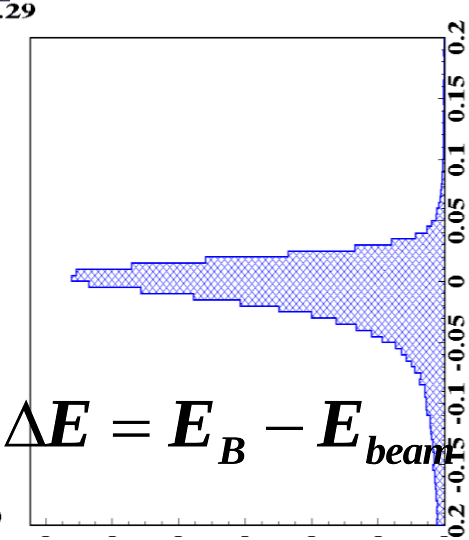
X(3872) K (K_S^0) → B

Reconstruction of B

$$M_{bc} = \sqrt{E_{beam}^2 - p_B^2}$$







$$\Delta E = E_B - E_{beam}$$

Signal window cut in ΔE & M_{bc}

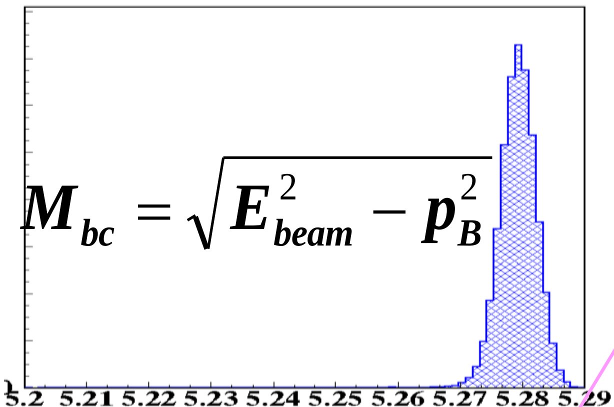
MC for illustration purpose

Radiative decays in *B* meson

MC for illustration purpose

X(3872) , $\chi_{c1,c2}$ → J/ψ γ

↳ $e^+ e^-$ or $\mu^+\mu^-$



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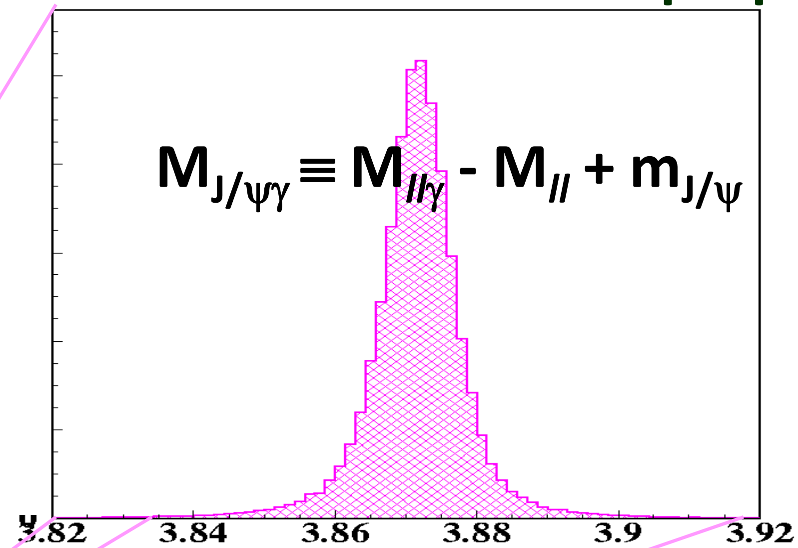
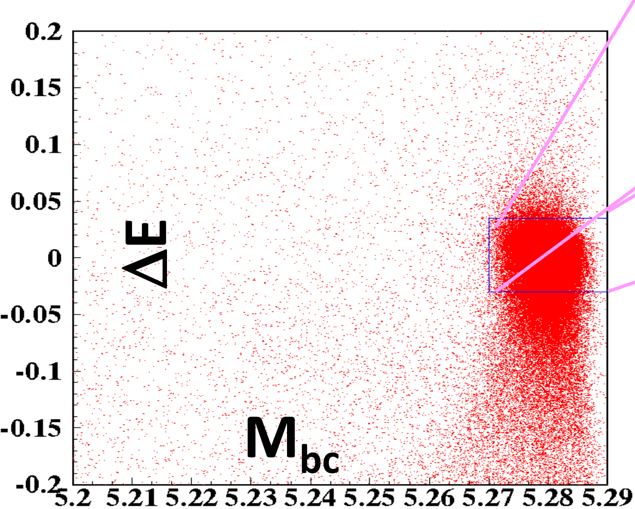
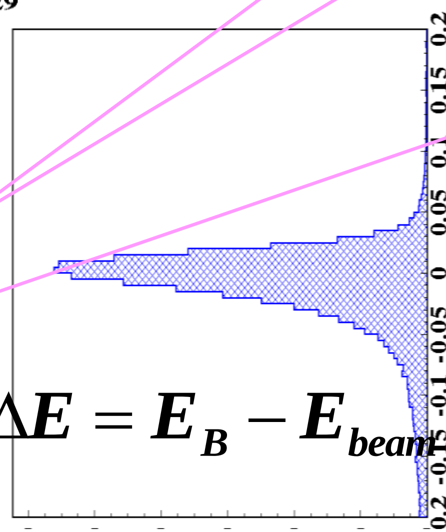


$$\mathbf{M_{J/\psi\gamma} \equiv M_{ll\gamma} - M_{ll} + m_{J/\psi}}$$





$$\Delta E = E_B - E_{beam}$$

Signal window cut in ΔE & M_{bc}

E_γ scaled (ΔE=0) to improve the resolution of $M_{J/\psi\gamma}$

Fit to $M_{J/\psi\gamma} \equiv M_{ll\gamma} - M_{ll} + m_{J/\psi}$; $m_{J/\psi}$ is PDG mass

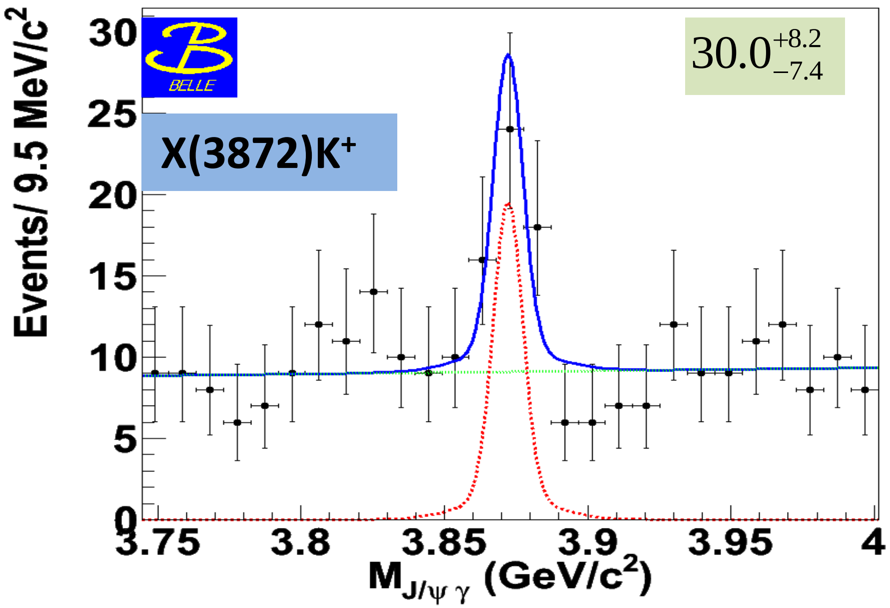
Used $B \to \chi_{c1} K$ as control mode

772 M $B\bar{B}$

PRL 107, 091803 (2011)

B→X(3872)K

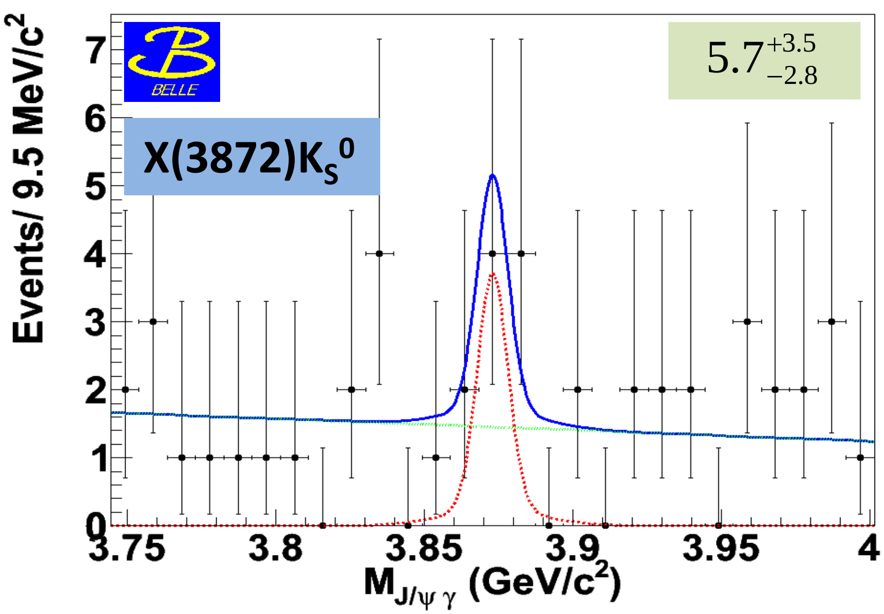
B→(J/ψγ) K



Mode	Events	Significance
$B^+ \to X(3872)\,K^+$	$30.0^{+8.2}_{-7.4}$	4.9 σ
$B^0 \to X(3872)\,K_S^0$	$5.7^{+3.5}_{-2.8}$	2.4 σ

Clear observation of X(3872) → J/ψγ in $B^+ \to X(3872)K^+$

- $\mathcal{BR}$ ($B^+ \to X(3872)\,K^+$) x $\mathcal{BR}$(X(3872) → J/ψγ) is (1.78±0.46±0.12) x 10^{-6}



$$\frac{\mathcal{BR}(X(3872) \to J/\psi\gamma)}{\mathcal{BR}(X(3872) \to J\psi\pi\pi)} = 0.22 \pm 0.05$$

Using Belle X(3872)→J/ψππ result from PRD84,052004 (2011)

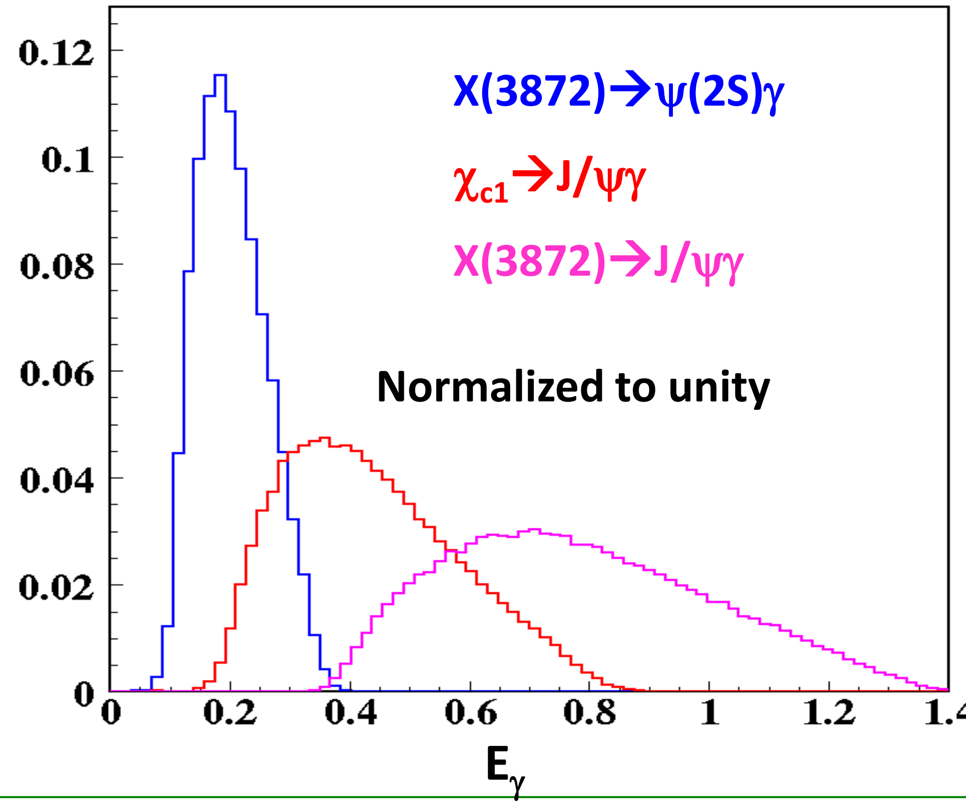
- $\mathcal{BR}$ ($B^0 \to X(3872)\,K^0$) x $\mathcal{BR}$(X(3872) → J/ψγ) is < 2.4 x 10^{-6} (@ 90% CL)

MC

Search for $X(3872) \rightarrow \psi(2S)\gamma$

$B \rightarrow (\psi(2S)\gamma)\ K$

$X(3872) \rightarrow \psi(2S)\ \gamma$
$\quad \rightarrow J/\psi\pi^+\pi^-$
or
$\quad \rightarrow e^+ e^-$ or $\mu^+\mu^-$



○ **Low energy γ**

○ **Cuts used to reduce background in $B \rightarrow (J/\psi\gamma)\ K$ study, reduce more signal than background in $B \rightarrow (\psi(2S)\gamma)\ K$**

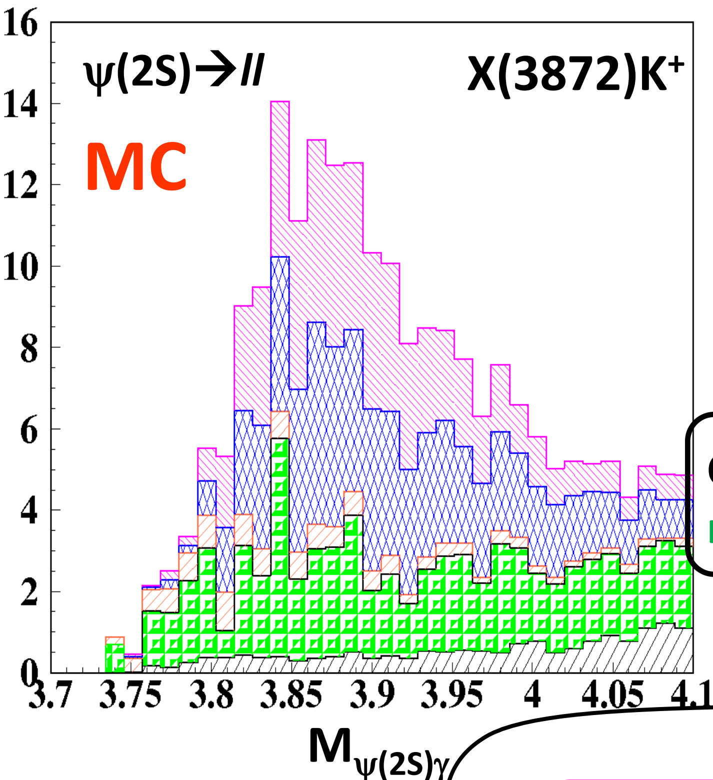
Photon selection

✓ $E_\gamma > 100$ MeV

○ **$\psi(2S)\ K^*$ veto used to reduce background coming from $B \rightarrow \psi(2S)K^*$**

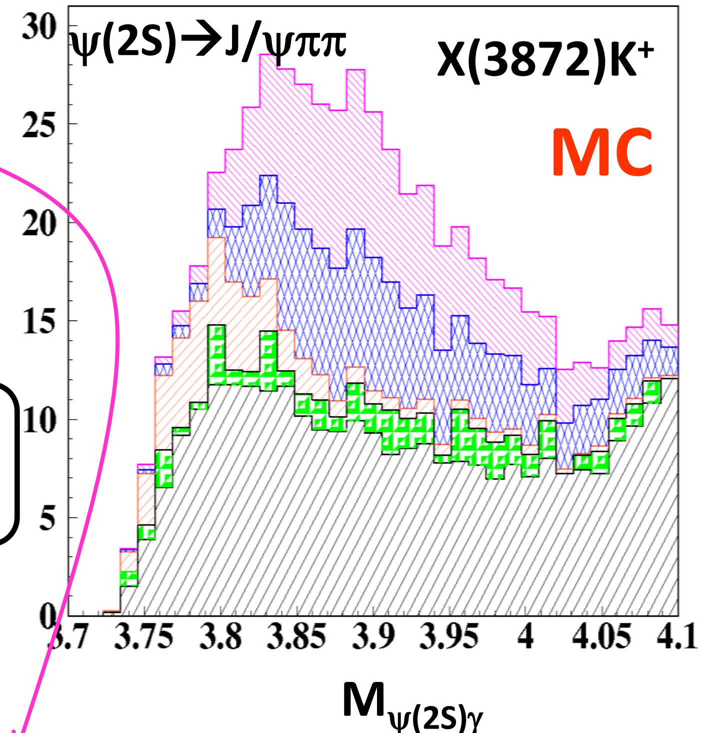
Background study

Belle MC



Consist of 5 parts :

- $B^0 \to \psi(2S) K^{*0}$
- $B^+ \to \psi(2S) K^{*+}$
- $B^+ \to \psi(2S) K^+$
- $B^0 \to \psi(2S) K_S^0$



Combinatorial including non ψ component

Parameterize and fix using generated ψ(2S)K* and ψ(2S)K large samples (few 100 x data size)

Parameterize and fix using large B→ ψ X MC and non-ψ data sideband

ψ refers to J/ψ or ψ(2S)

$B \to X(3872)K$

772 M $B\bar{B}$

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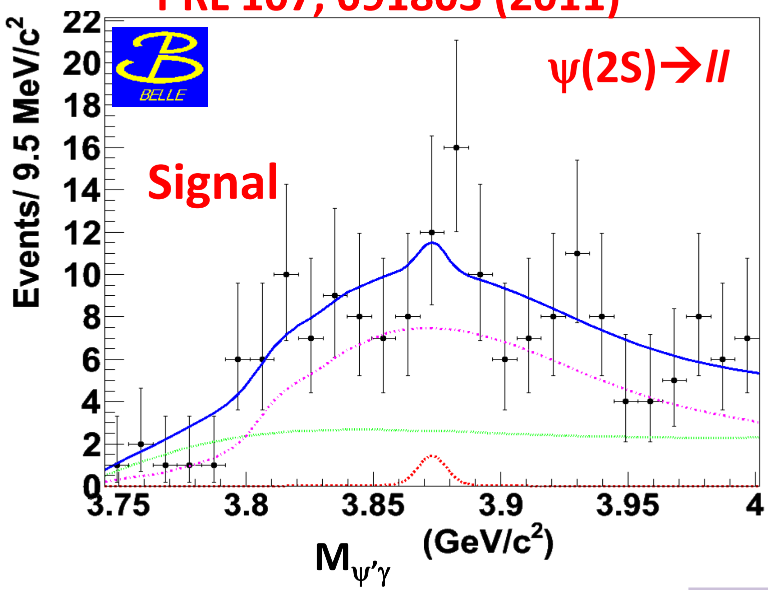
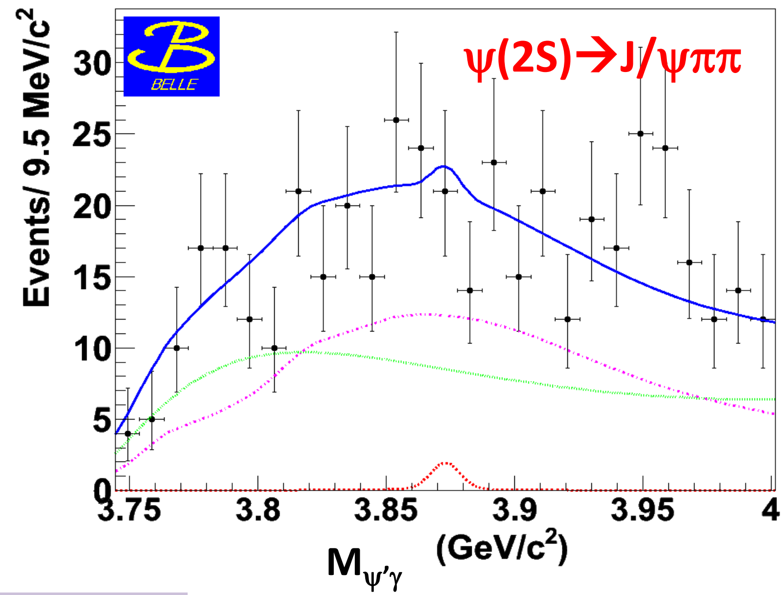
$B \to (\psi(2S)\gamma)\,K$



$B^{\pm} \to XK^{\pm}$

5^{+12}_{-11}

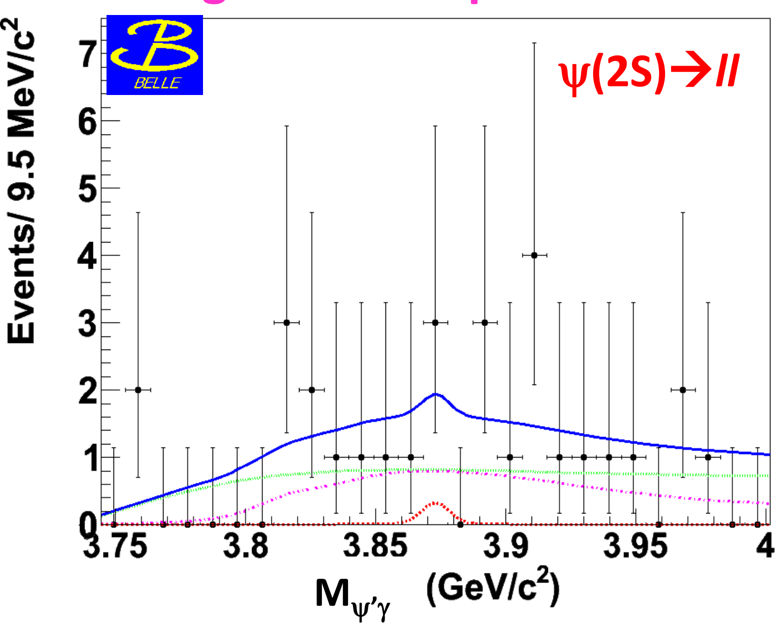
0.4 σ



$\psi(2S)K^*$, $\psi(2S)K$ background component

No signal observed

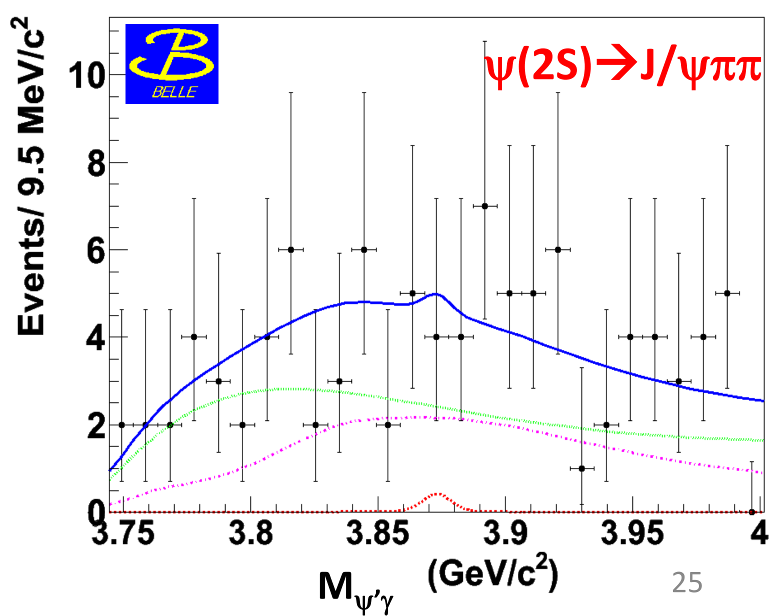
Combinatorial background



$B^0 \to XK_S^0$

$1.5^{+4.8}_{-3.9}$

0.3 σ



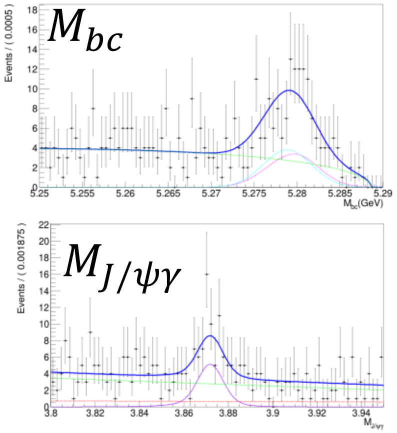
Belle + Belle II combine study

- One can reanalyse the Belle data while analysing the Belle II data.
- This way one can exploit the full potential of both experiments.
- Current available data set
  - Belle : 711 fb^{-1}
  - Belle II : 363 fb^{-1} *(processed good runs)*

Preliminary

Belle II MC toy

(for illustration pupose)



- Belle II reconstruction efficiency is 15-20 % more than Belle II.
  - Thanks to the better tracking and reconstruction algorithm.

- In Belle, we plan to re-analyse the data a bit differently
  - Extract signal using fit 2D UML fit to M_{bc} and $M_{\psi\gamma}$ distributions
  - This way one can be more confident about the robustness of the analysis.
  - Using BDT to suppress $B \to \psi(2S)K^*$ for better sensitivity.

- Will use $B^+ \to X(3872)K^+$ and $B^+ \to X(3872)K_S^0$ decay mode

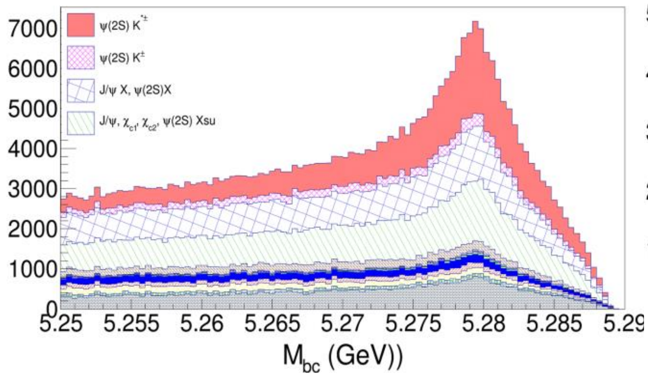
- Simultaneous fit to be performed to Belle and Belle II data set.

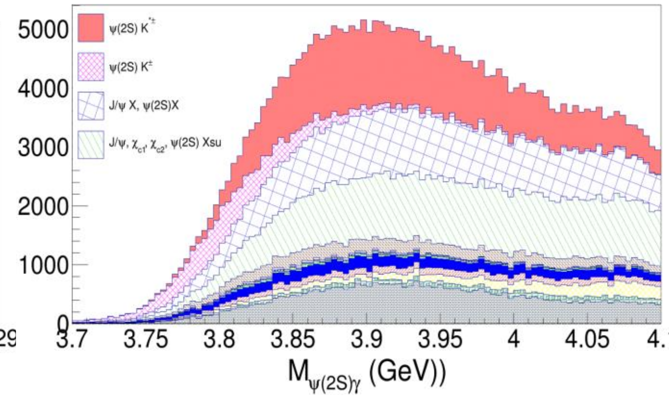
- Rough estimate suggest :
  - ~50 events for $B^+ \to X(3872)K^+$, $X(3872) \to J/\psi\gamma$
  - 24-34 events for $B^+ \to X(3872)K^+$, $X(3872) \to \psi(2S)\gamma$ (using recent LHCb result)

In Progress !

Background study

Preliminary MC
Arbitrary y-axis

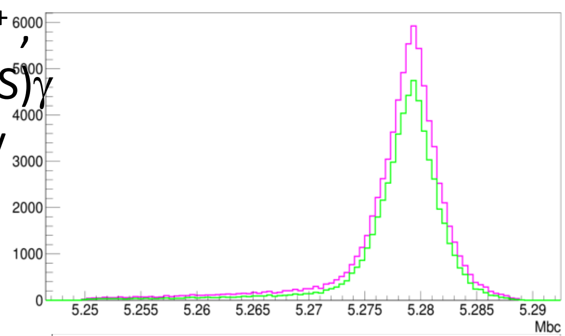


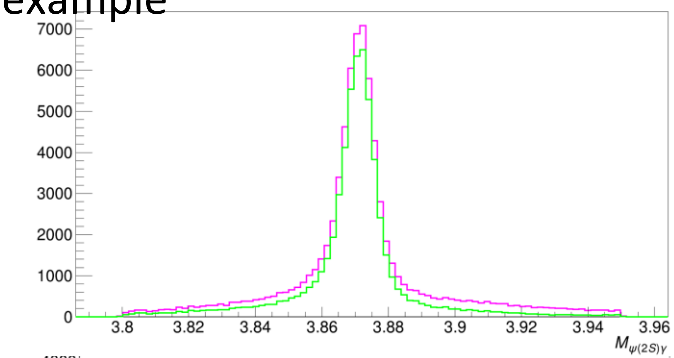


- Trying to reduce the K^* component using BDT.
- However, one has to be careful.
- Without understanding BDT, there is a danger of shaping background more like signal

One trained BDT example

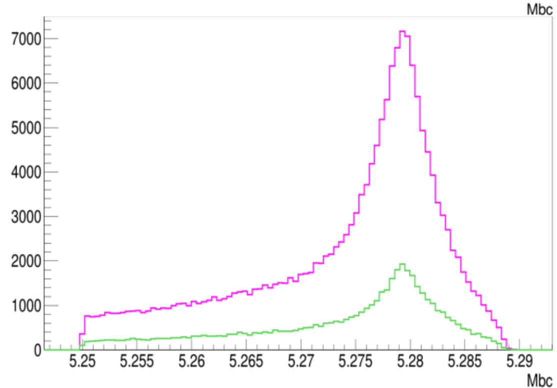
$B^+ \rightarrow X(3872) K^+$, $X(3872) \rightarrow \psi(2S)\gamma$
MC preliminary

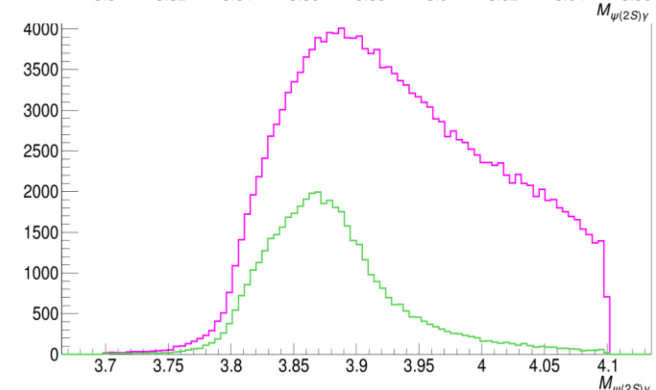




No BDT
After BDT cut

$B \rightarrow \psi(2S) K^*$
MC preliminary

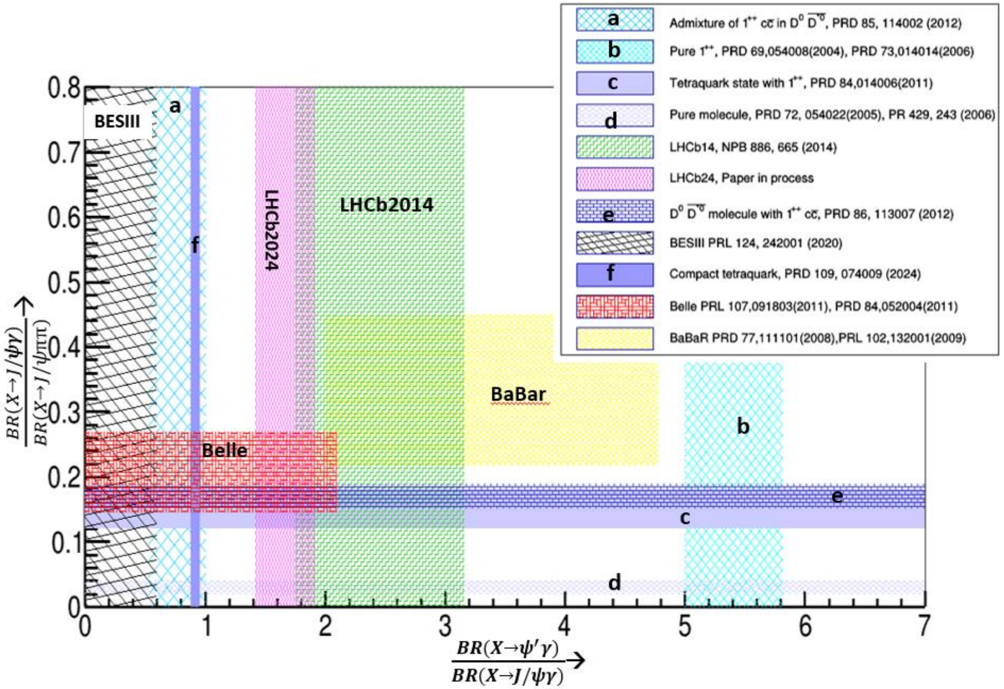




Conclusion

Radiative decays of X(3872) help in its understanding

- Belle previous result $\mathcal{BR}$(X(3872)→Ψ'γ)/ $\mathcal{BR}$(X(3872)→J/Ψγ) < 2.1 result is very well consistent with recent LHCb result and also BESIII result.



It will be good to have theory result in three ratios :

$$\frac{BR(X\to J/\psi\gamma)}{BR(X\to J/\psi\pi\pi)}, \frac{BR(X\to J/\psi\omega)}{BR(X\to J/\psi\pi\pi)} \text{ and } \frac{BR(X\to \psi'\gamma)}{BR(X\to J/\psi\gamma)}$$

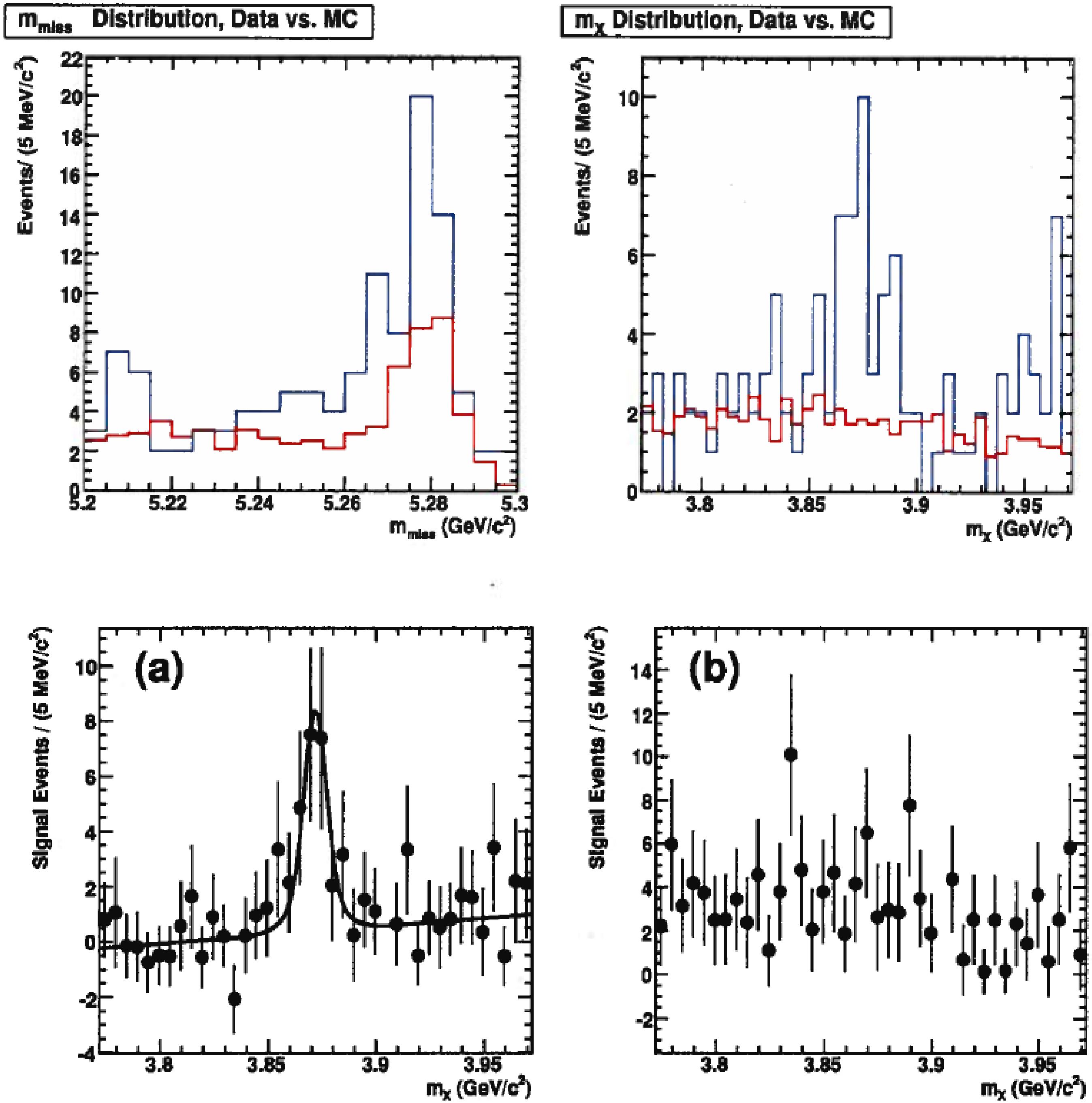
One should be able to constraint the model.

- Belle II is working to (re)analyse the radiative X(3872).
- We expect 24-34 signal events for $B^+ \to X(3872) K^+$, $X(3872) \to \psi(2S)\gamma$ (using LHCb recent result).

- Even after lot of work put by scientific community.
- X(3872) is still playing hide and seek.

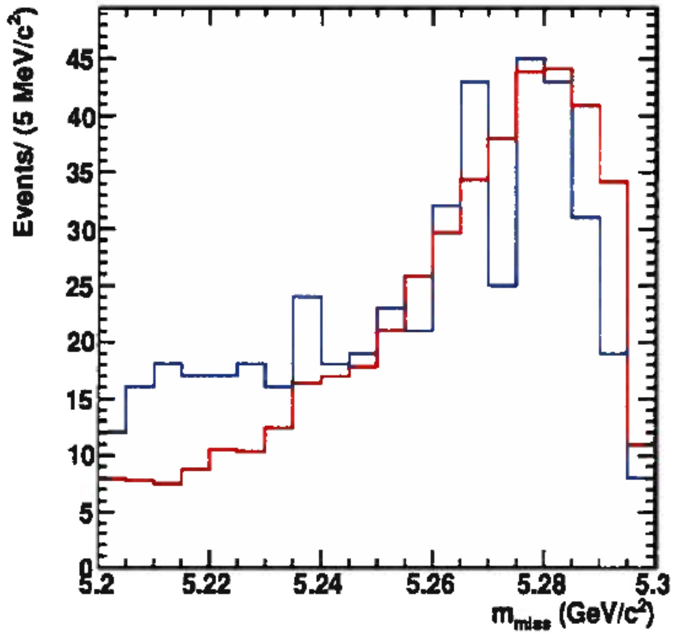
Three experiments: Belle II, BESIII and LHCb measurement will help in solving its mystery.

Thank you

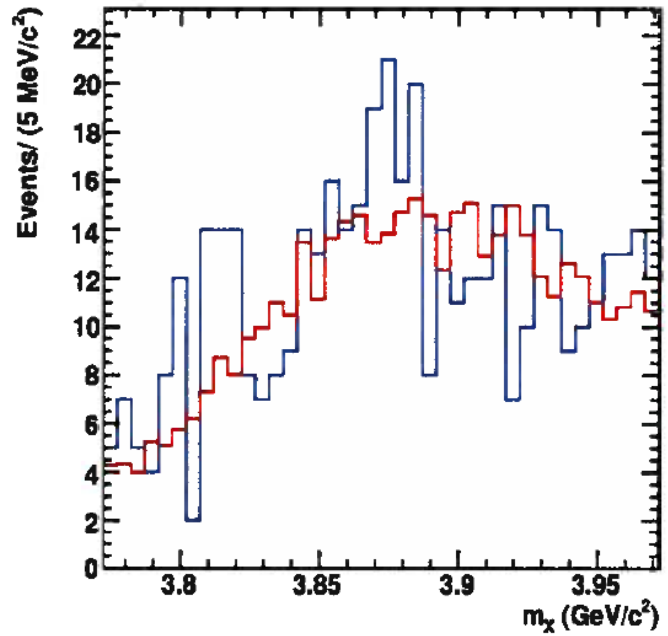

m_miss Distribution, Data vs. MC
Events/ (5 MeV/c²)
m_miss (GeV/c²)
m_X Distribution, Data vs. MC
m_X (GeV/c²)
(a)
(b)
Signal Events / (5 MeV/c²)

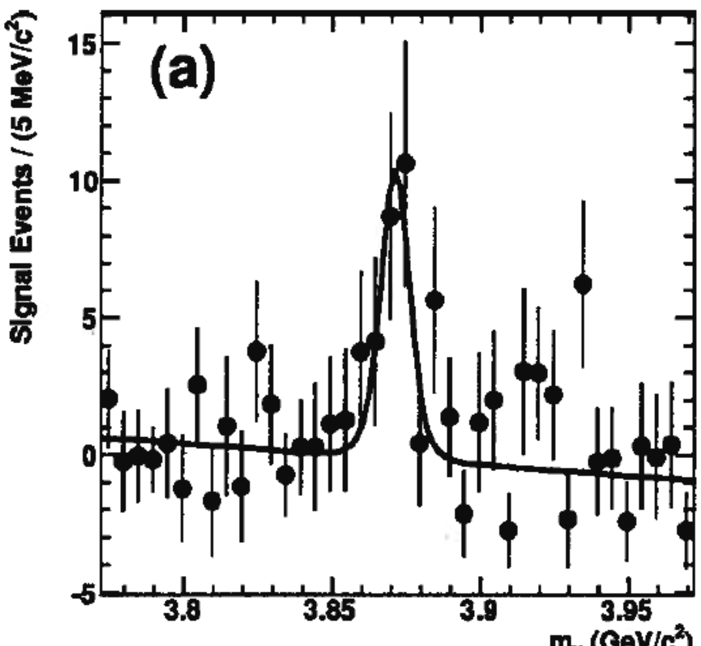
MC
data

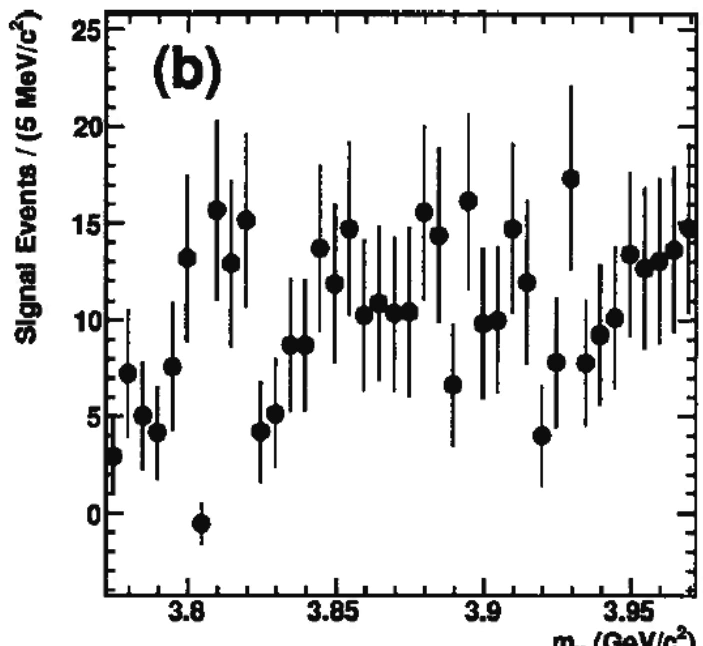
m_{miss} Distribution, Data vs. MC



m_X Distribution, Data vs. MC







772 M $B\bar{B}$

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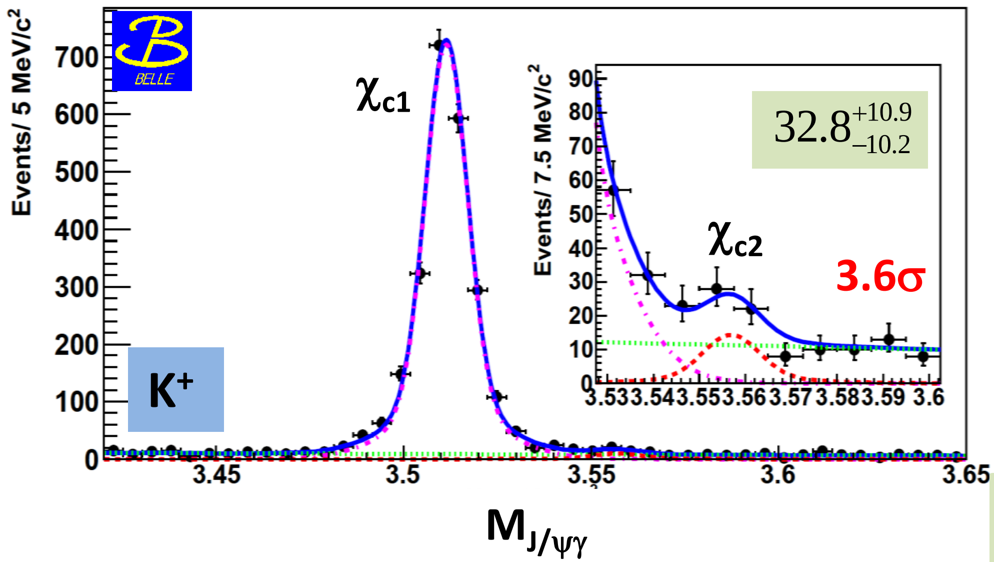
$B \to \chi_{c1,c2} K$

$B \to (J/\psi\gamma) K$

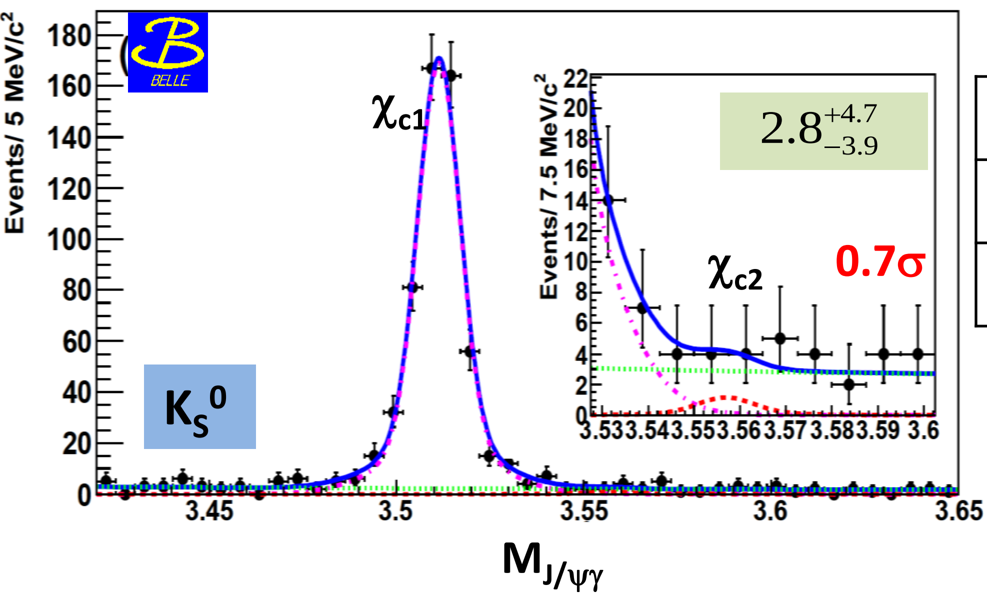


First Evidence for $B^+ \to \chi_{c2} K^+$

Mode	Events	Significance Σ (σ)
$B^+ \to \chi_{c1} K^+$	2308^{+53}_{-52}	
$B^+ \to \chi_{c2} K^+$	$32.8^{+10.9}_{-10.2}$	3.6

Significance include systematics

$\mathcal{BR}(B^+ \to \chi_{c2} K^+) = (1.11 \pm 0.35 \pm 0.09) \times 10^{-5}$



Mode	Events	Σ (σ)
$B^0 \to \chi_{c1} K_S^0$	542 ± 24	
$B^0 \to \chi_{c2} K_S^0$	$2.8^{+4.7}_{-3.9}$	0.7

$\mathcal{BR}(B^0 \to \chi_{c2} K^0) < 1.5 \times 10^{-5}$ (@ 90% CL)