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

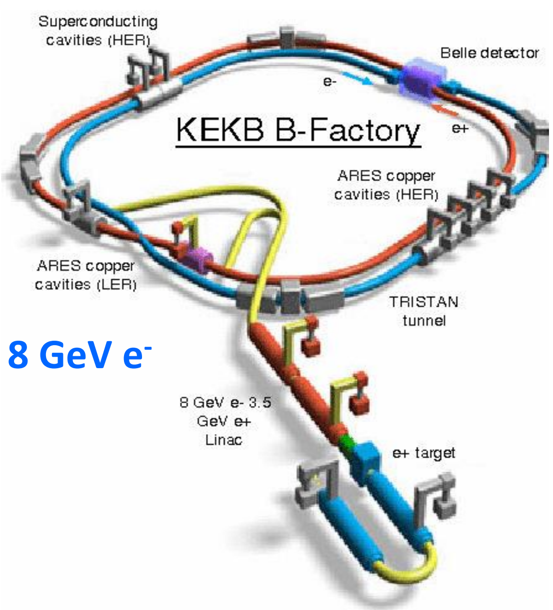
Tales of two B

$e^+ e^-$ 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**

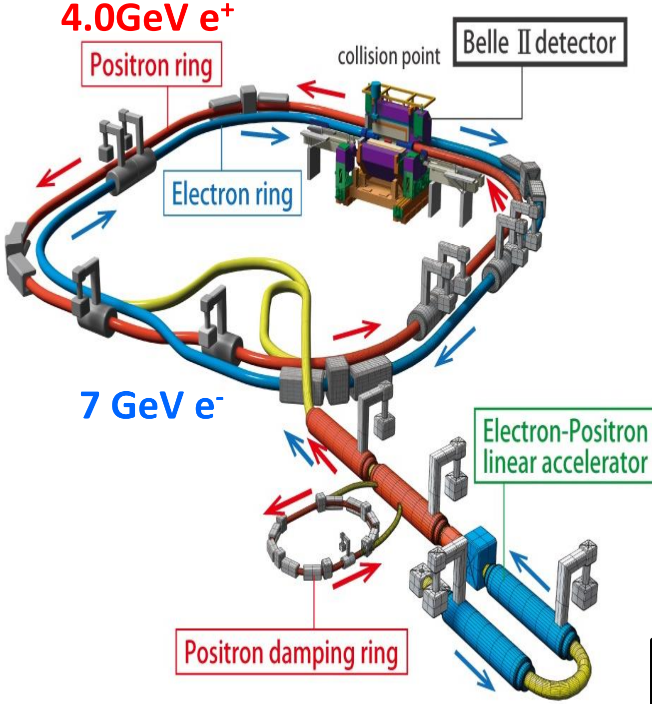
$> 1ab^{-1}$

3.5 GeV e^+

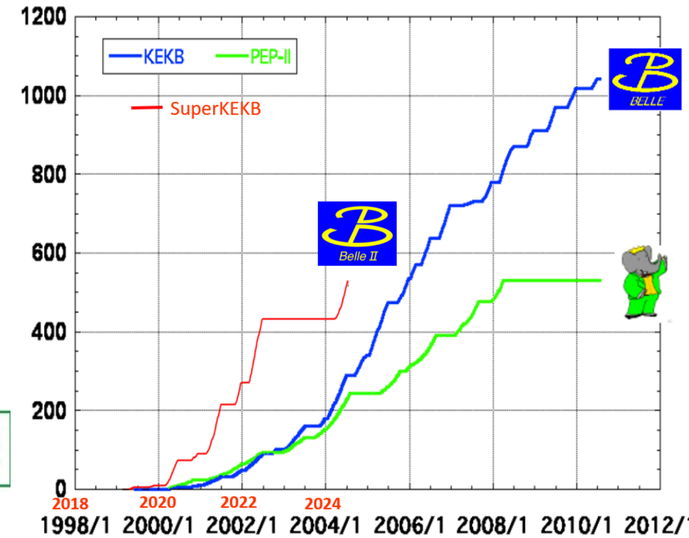


8 GeV e^-

4.0GeV e^+



7 GeV e^-



KEKB

$\beta\gamma \sim 0.42$

SuperKEKB

$\beta\gamma \sim 0.28$

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

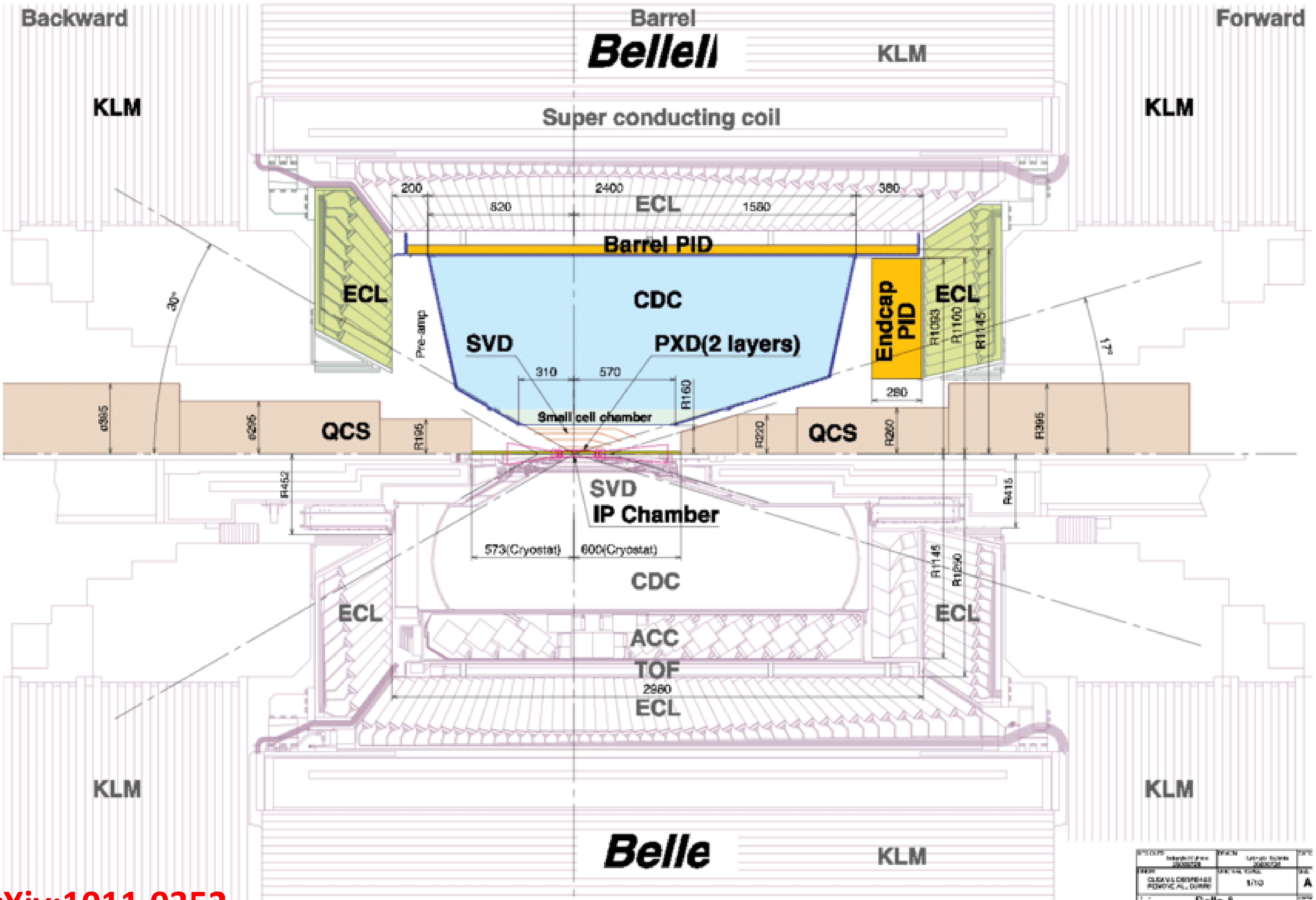
On-resonance:
4S : 711 fb^{-1}
5S : 121 fb^{-1}
3S : 3 fb^{-1}
2S : 25 fb^{-1}
1S : 6 fb^{-1}
Off-resonance/scan
~100 fb^{-1}

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

4S = 363 fb^{-1}

Clean and ideal place to carry charmonium spectroscopy related business.

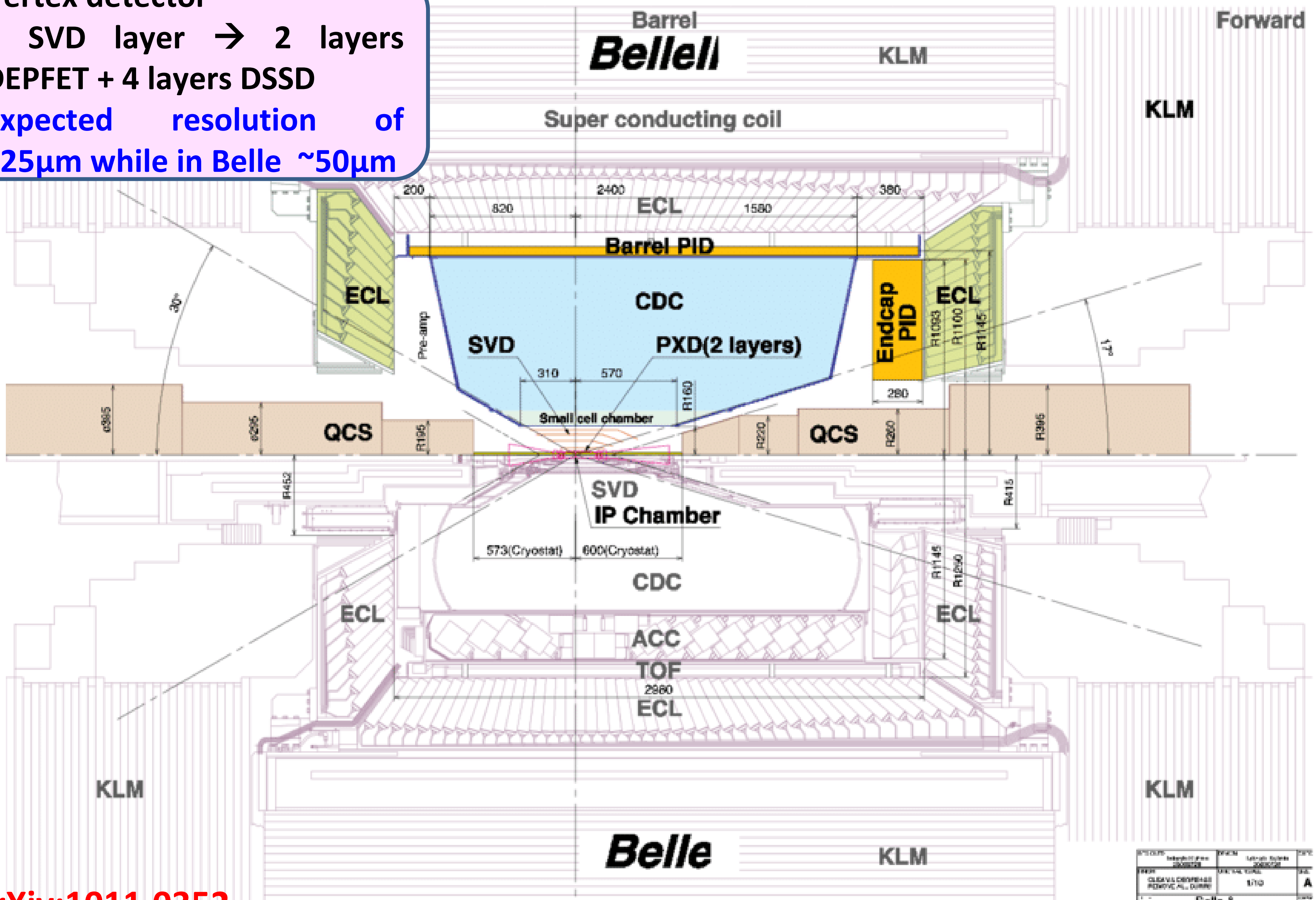
Belle to Belle II



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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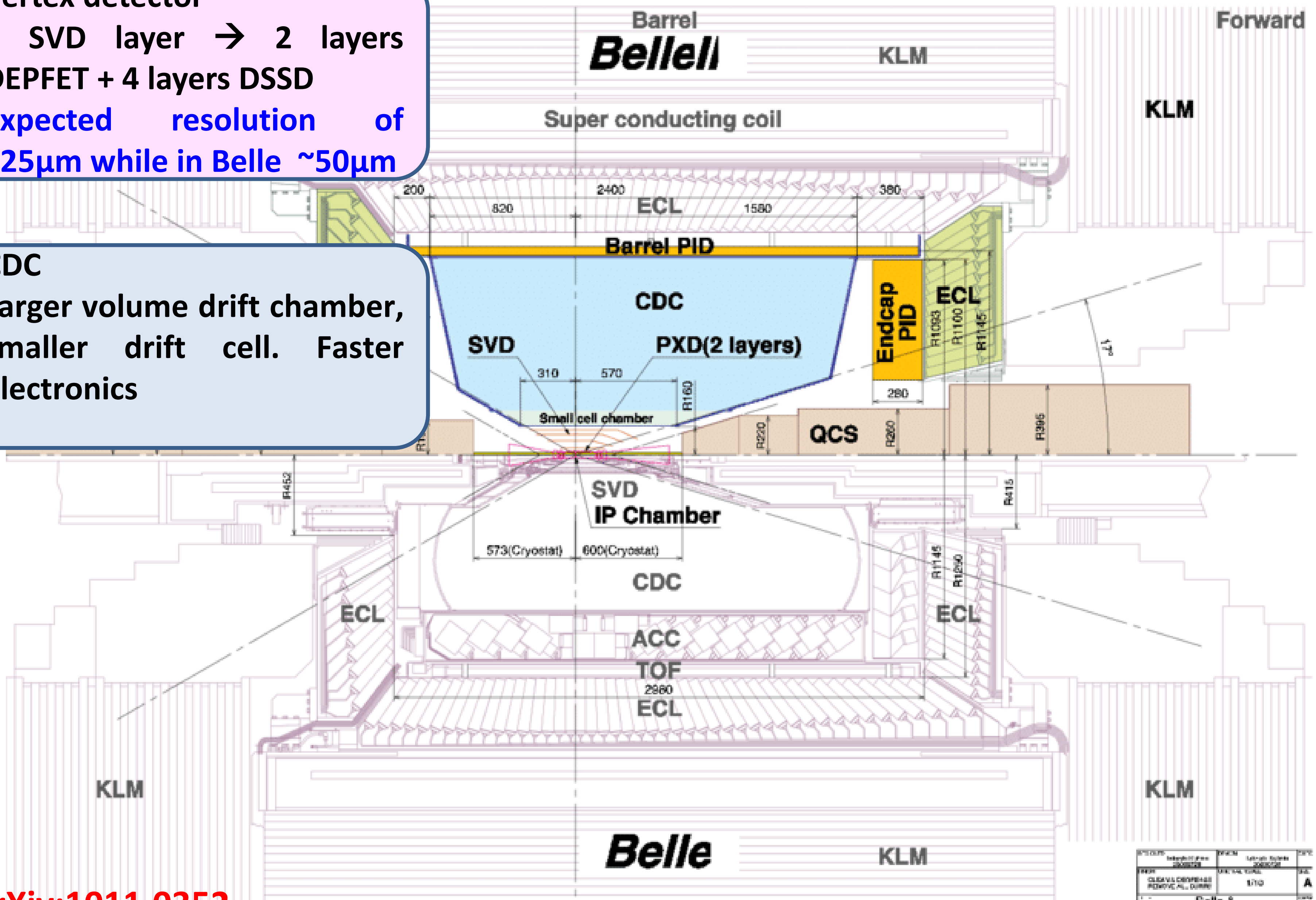

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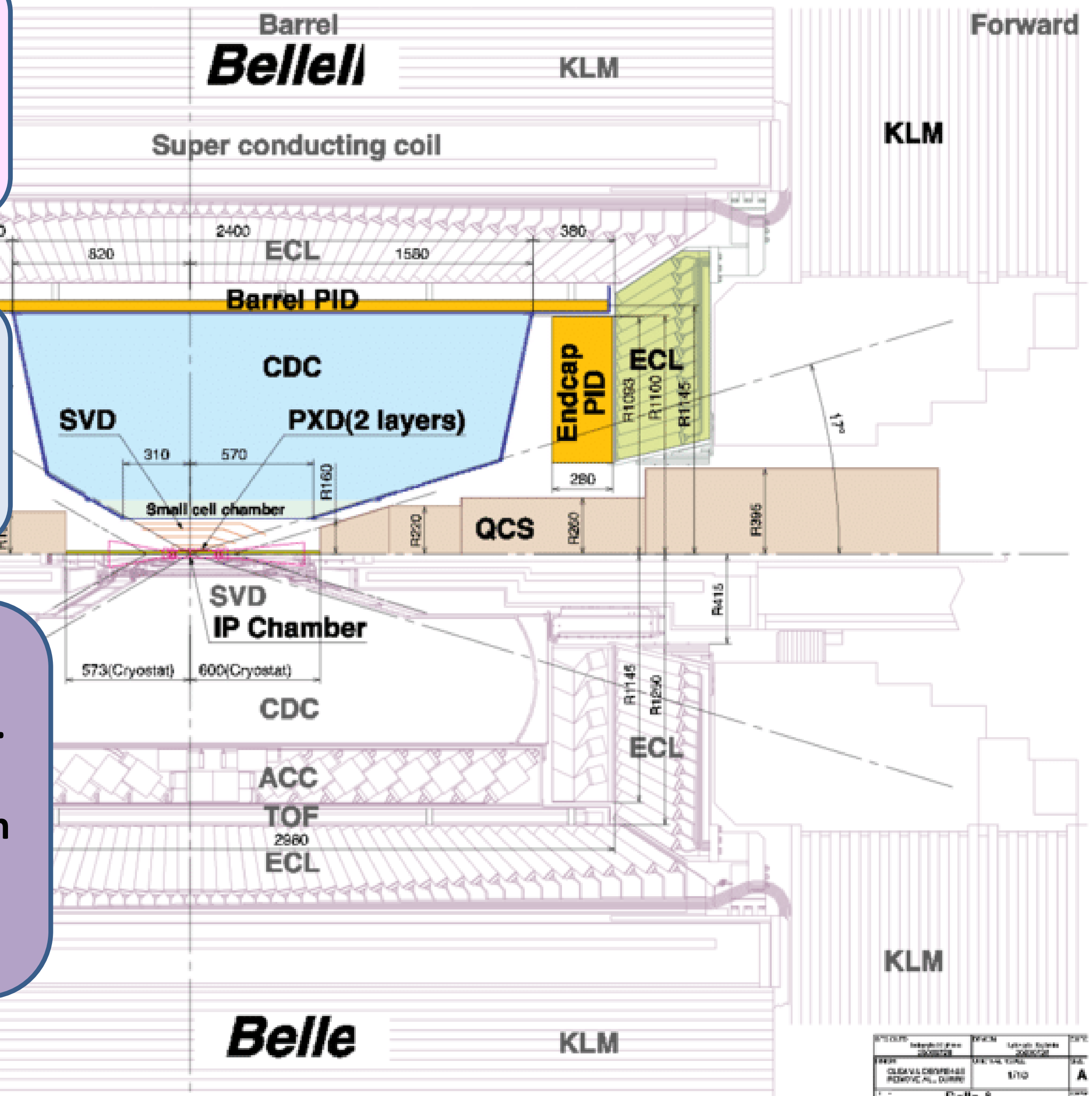

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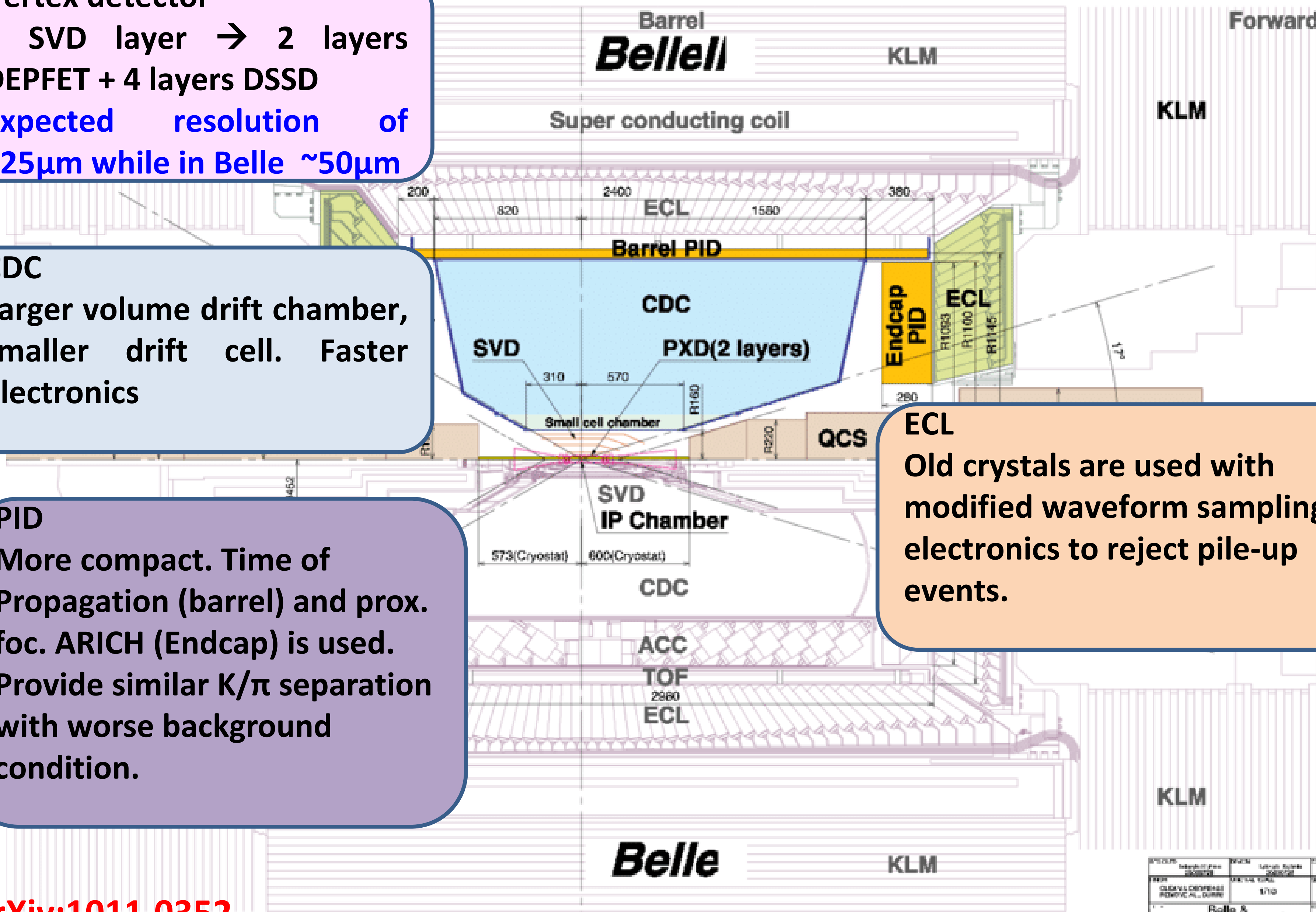

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ECL
Old crystals are used with modified waveform sampling electronics to reject pile-up events.

arXiv:1011.0352

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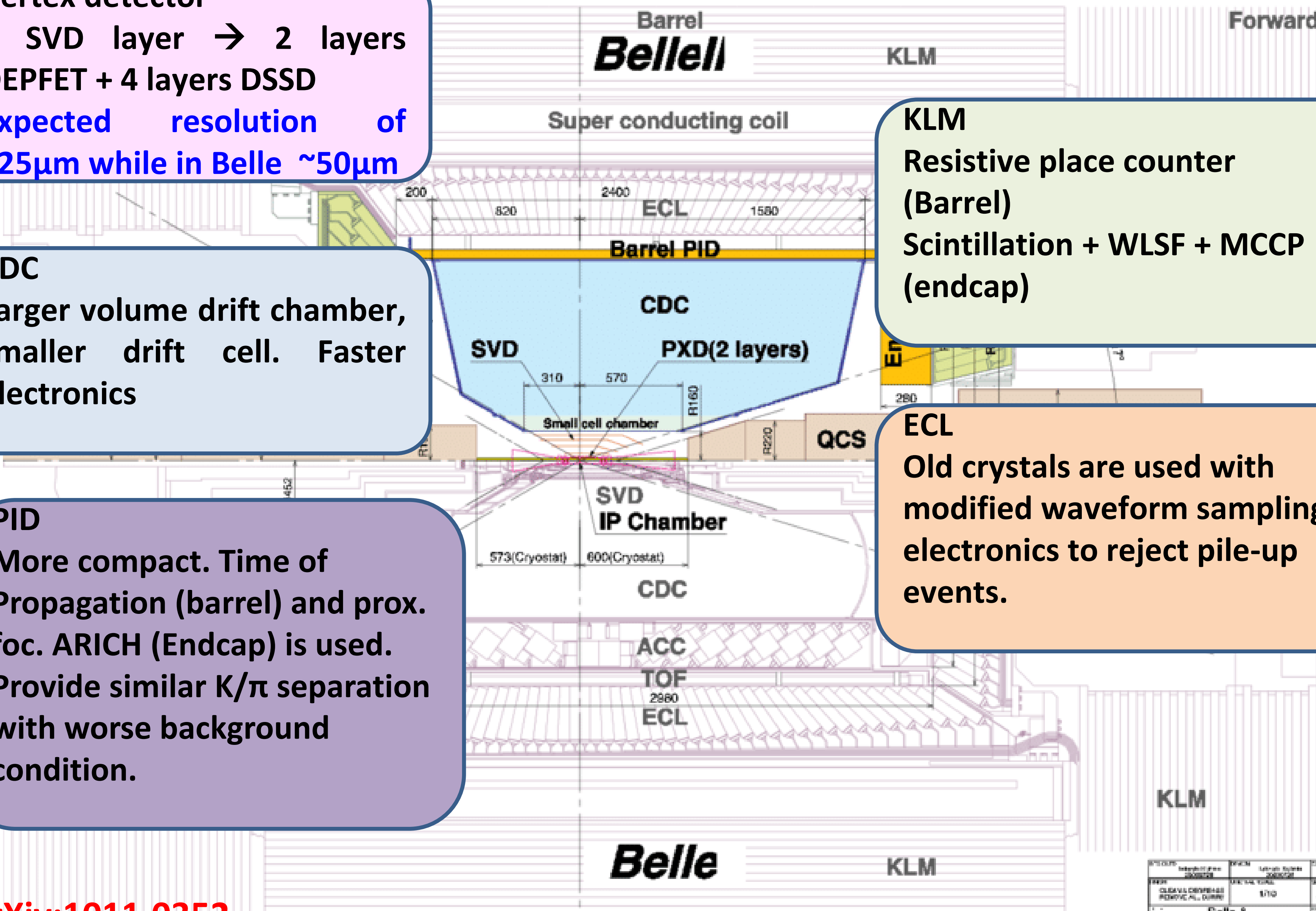

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KLM
Resistive place counter (Barrel)
Scintillation + WLSF + MCCP (endcap)

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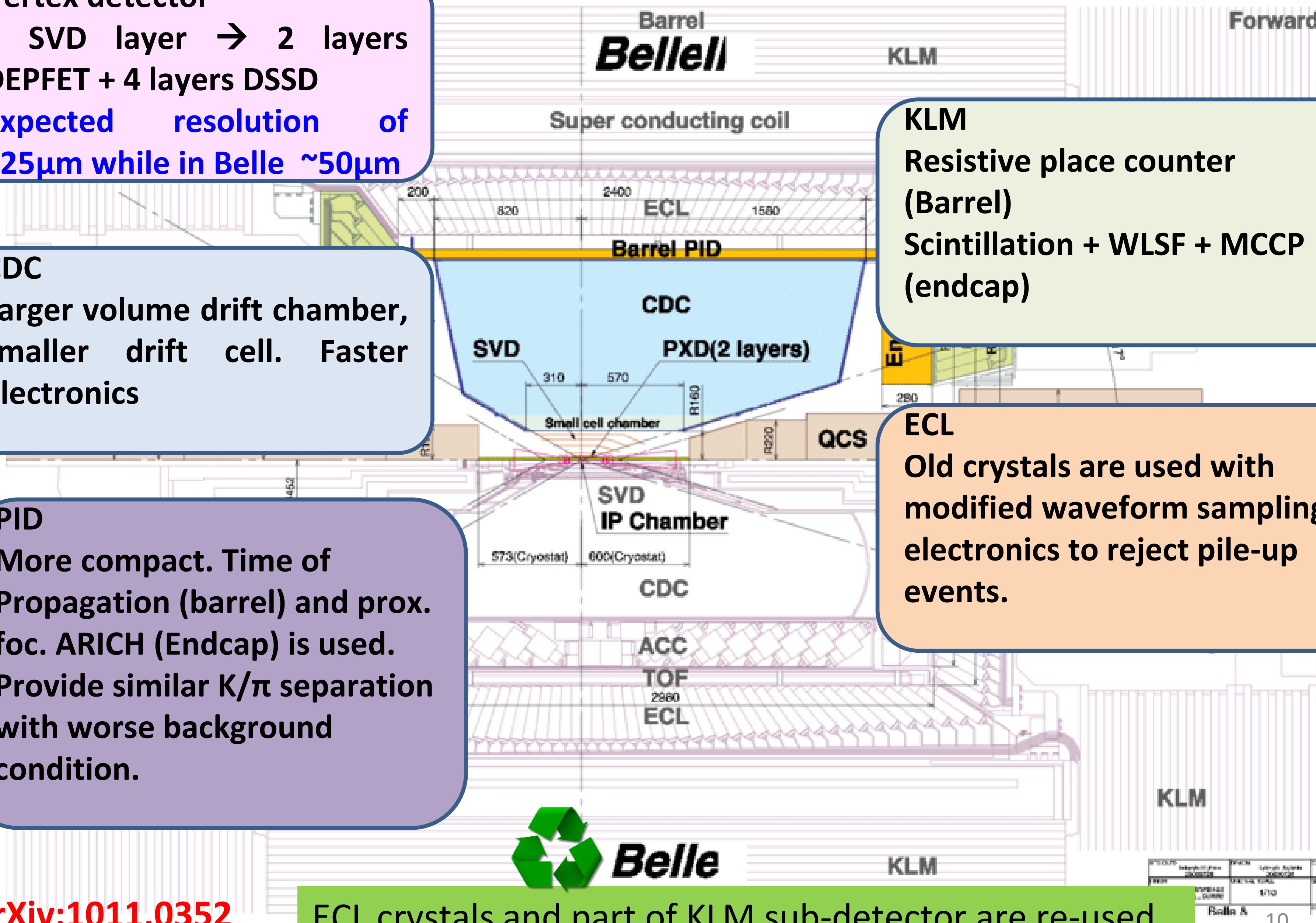
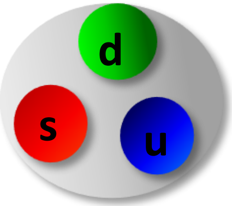


ECL crystals and part of KLM sub-detector are re-used.

arXiv:1011.0352

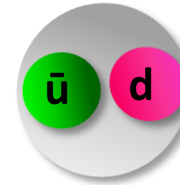
Real particles are color singlet



Baryons are red-blue-green triplets

Λ=usd

Mesons are color-anticolor pairs

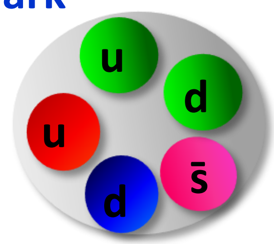


π=ūd

Other possible combinations of quarks and gluons :

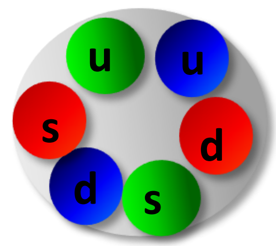
Pentaquark

S= +1
Baryon



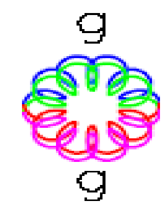
Hexaquark

Tightly bound
6 quark state



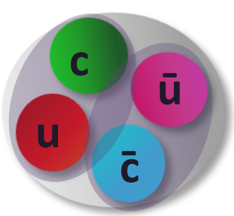
Glueball

Color-singlet multi-gluon bound state



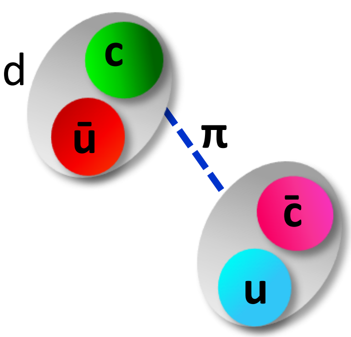
Tetraquark

Tightly bound
diquark &
anti-diquark

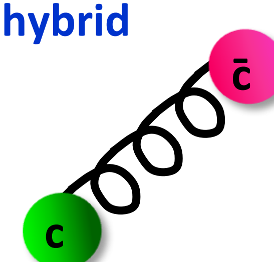


Molecule

loosely bound
meson-
antimeson
“molecule”

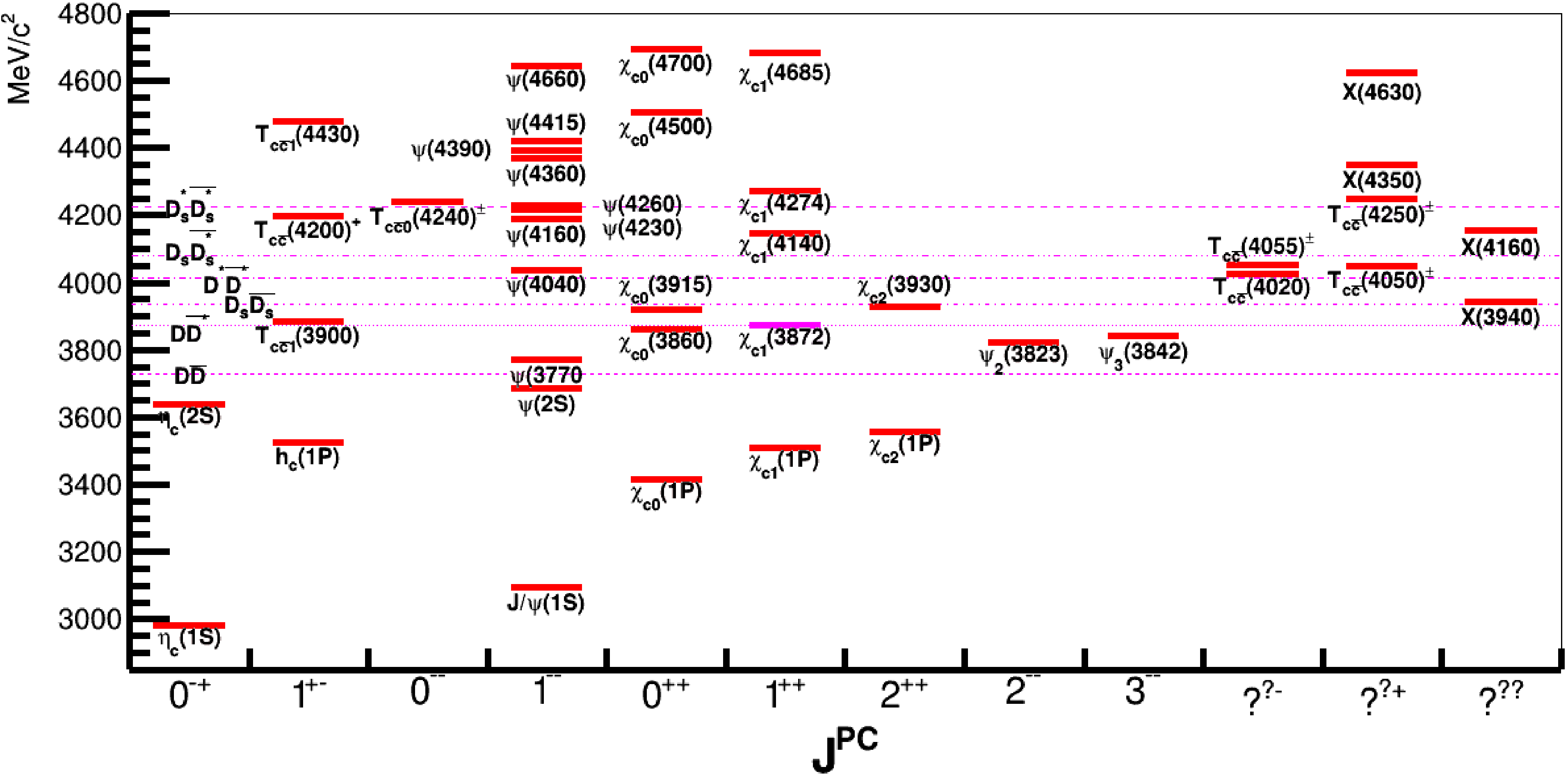


qq̄ -gluon hybrid mesons



artistic illustration

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

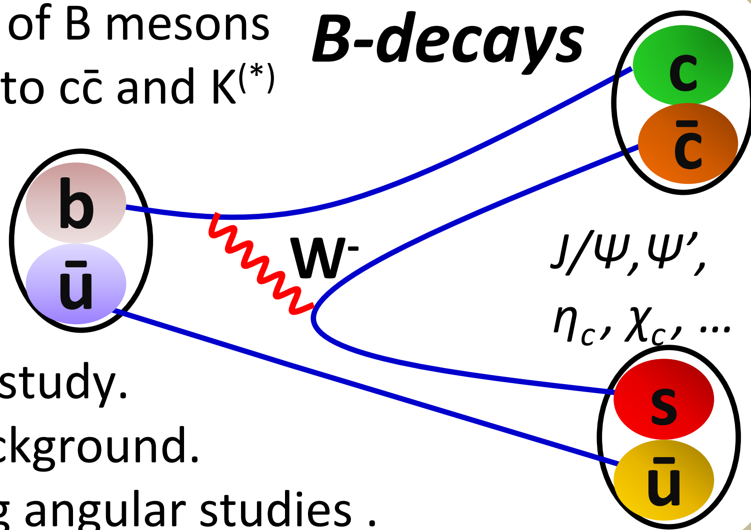


- 2 decades has passed after the discovery of first $c\bar{c}$-like [*X(3872)*] by the Belle collaboration.
- Plenty of states have been found.
- Several states are seen in one process (not easy to understand).
- States have a non-zero charge, suggesting them to be tetraquark/molecule-like states.
-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

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

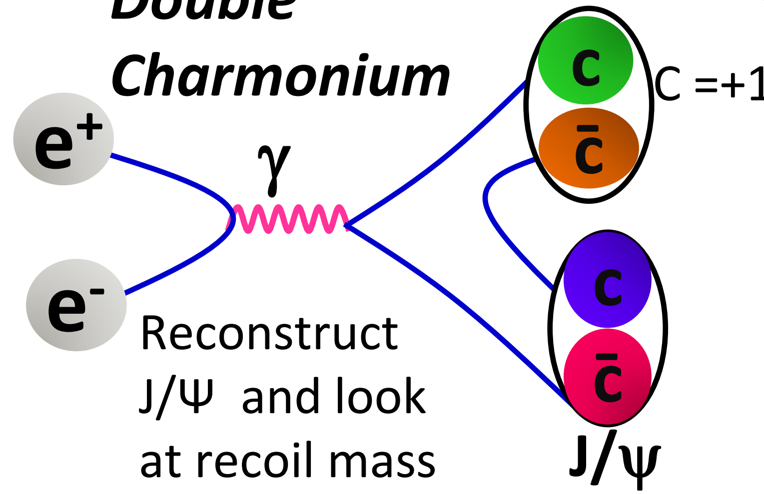
B-decays

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



Easy to study.
Low background.
J^{PC} using angular studies .

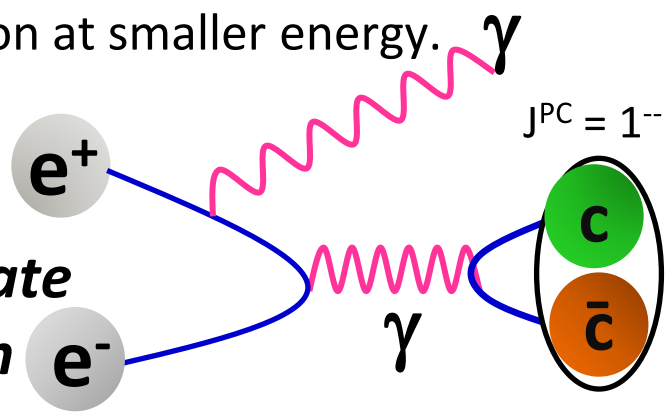
Double Charmonium



Reconstruct J/Ψ and look at recoil mass

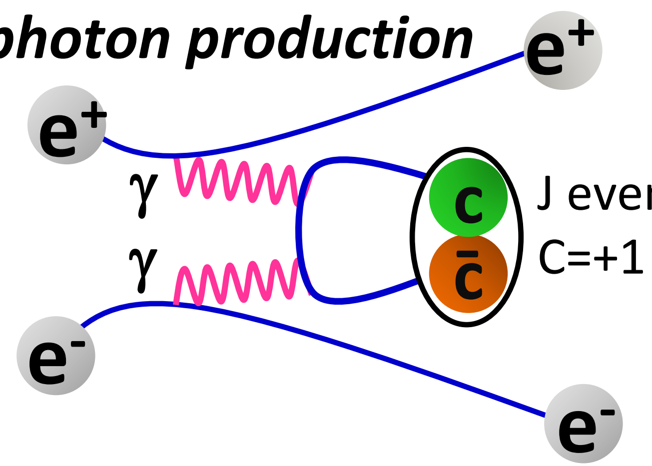
Initial state radiation

Annihilation at smaller energy.



Two photon production

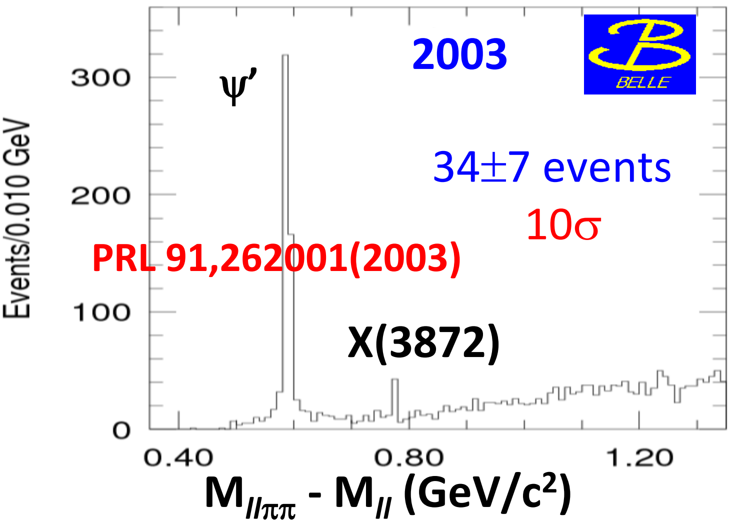
$c\bar{c}$ states produced without additional hadrons.



$X(3872)$ 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)**

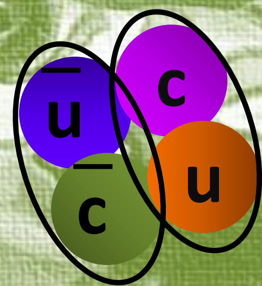
eX(3872)otic

eX(3872)otic

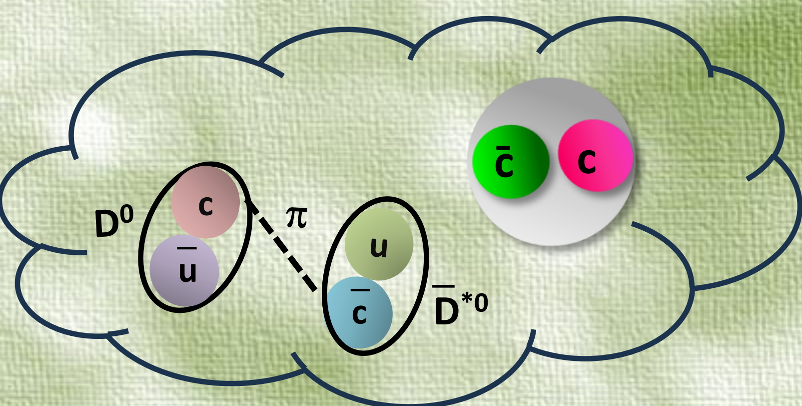
X(3872) doesn't fit charmonium scheme with ease.

Many explanation for X(3872) are proposed :

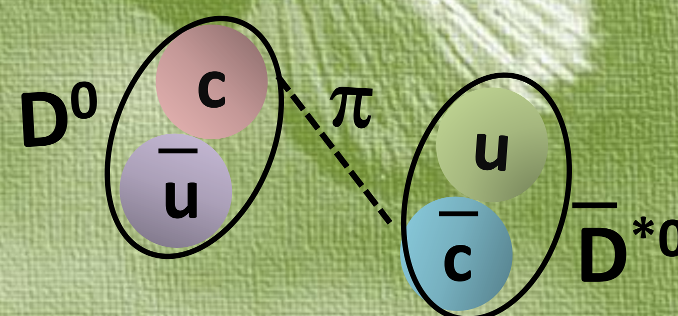
Tetraquark

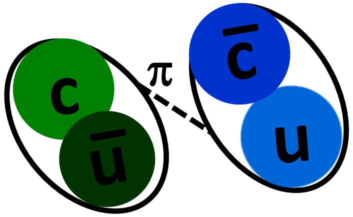


Admixture

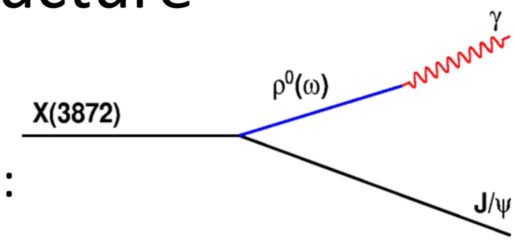


Molecular



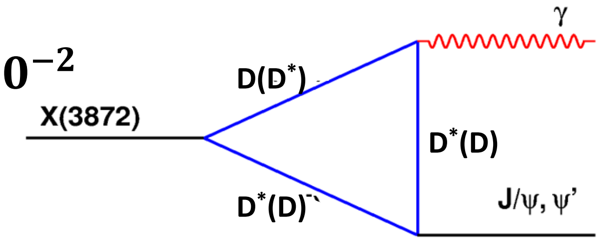


Radiative decay and X(3872) structure



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)**

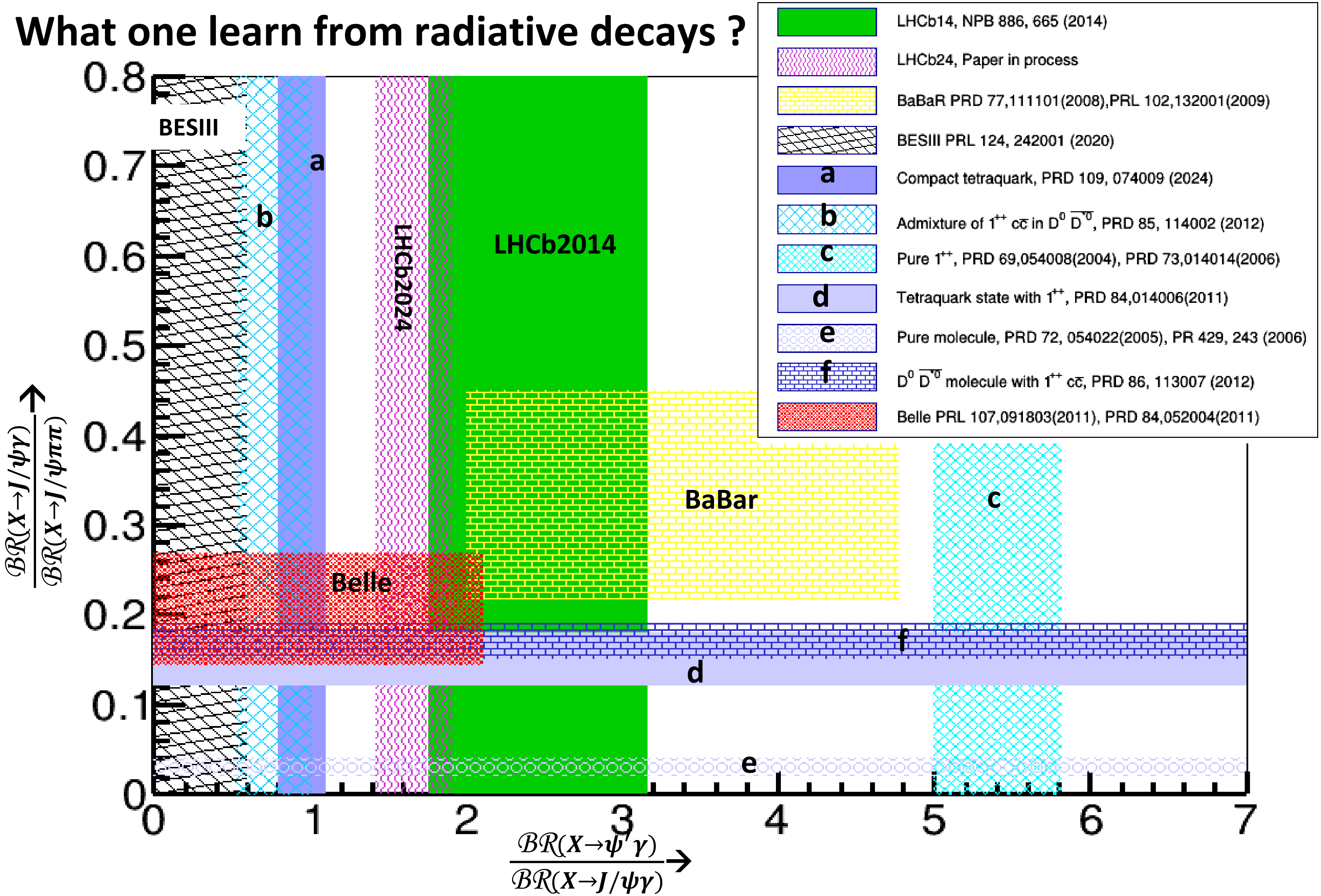
$\mathcal{BR}$(X(3872)→ ψ'γ) > $\mathcal{BR}$(X(3872)→ J/ψγ) $\sim 5 - 15$

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 ?

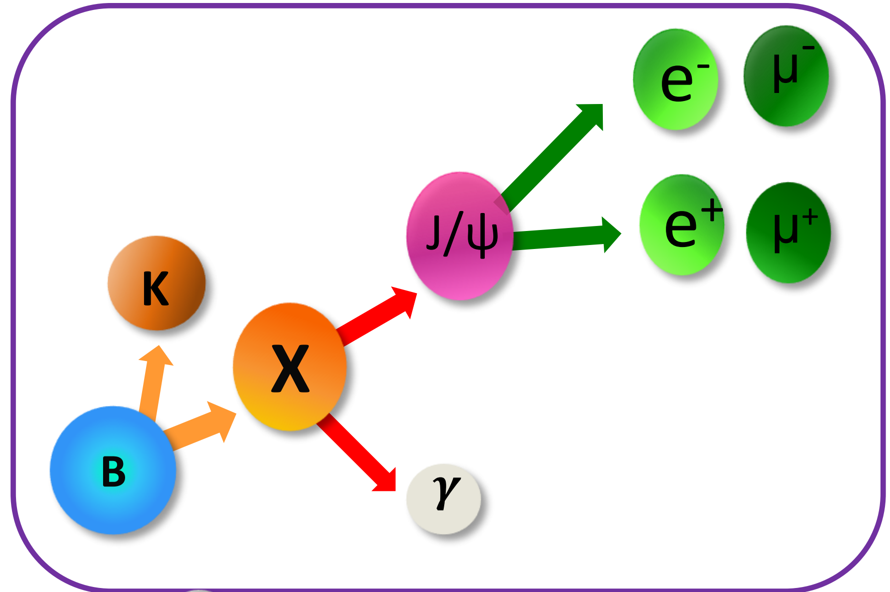


Will be easy for to test models, if theory can provide $\frac{\mathcal{BR}(X\to J/\psi\gamma)}{\mathcal{BR}(X\to J/\psi\pi\pi)}$, $\frac{\mathcal{BR}(X\to J/\psi\omega)}{\mathcal{BR}(X\to J/\psi\pi\pi)}$ **and** $\frac{\mathcal{BR}(X\to \psi'\gamma)}{\mathcal{BR}(X\to J/\psi\gamma)}$

Comparison can be more refined !

Analysis procedure

Reconstruct B (of interest)

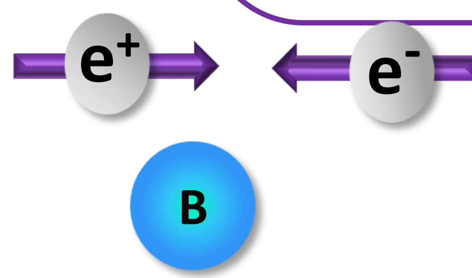


Common variable used in analyses

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

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

$$M_{\psi\gamma}$$

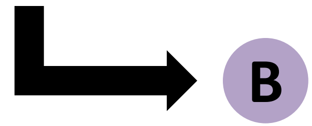


Radiative decays in *B* meson

X(3872) , $\chi_{c1,c2}$ → J/ψ γ

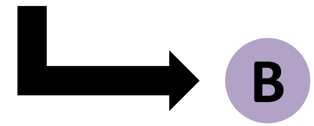
↳ $e^+ e^-$ or $\mu^+\mu^-$

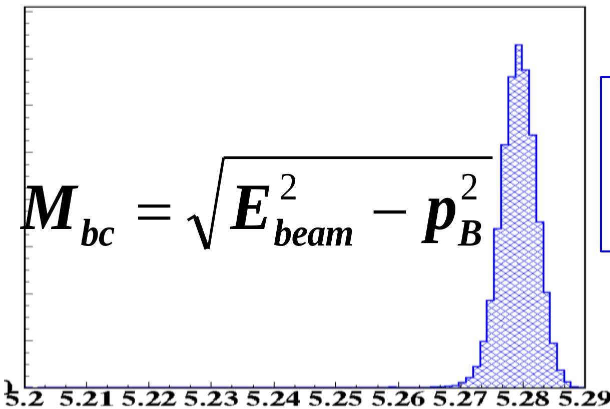
$\chi_{c1,c2}$ K (K_S^0)



Reconstruction of B

X(3872) K (K_S^0)





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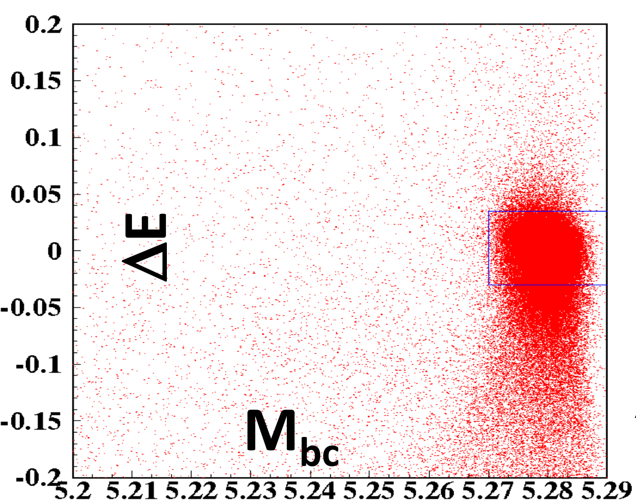
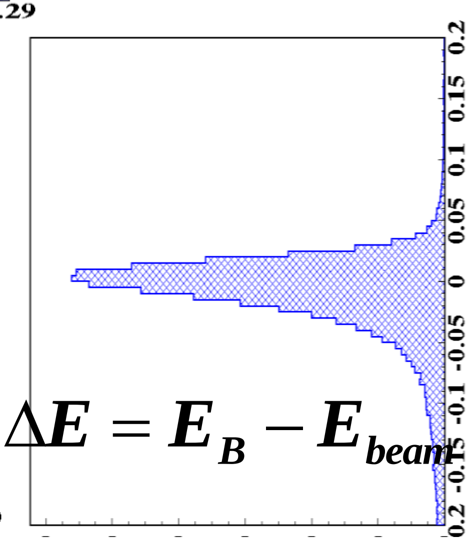




$$\Delta E = E_B - E_{beam}$$

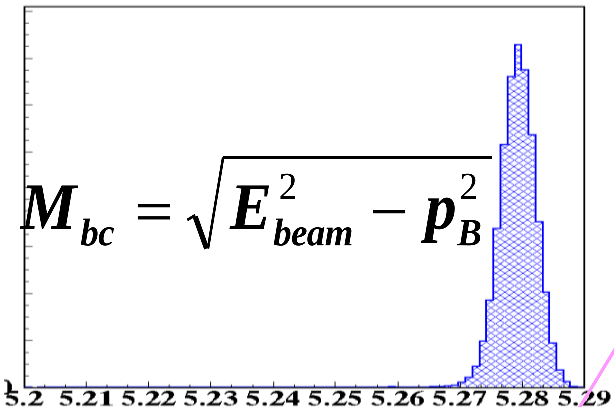
Signal window cut in ΔE & M_{bc}

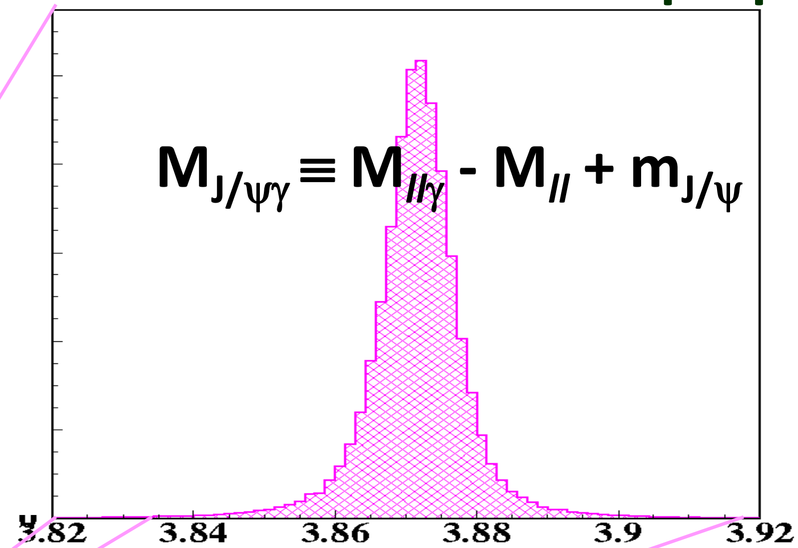
MC for illustration purpose

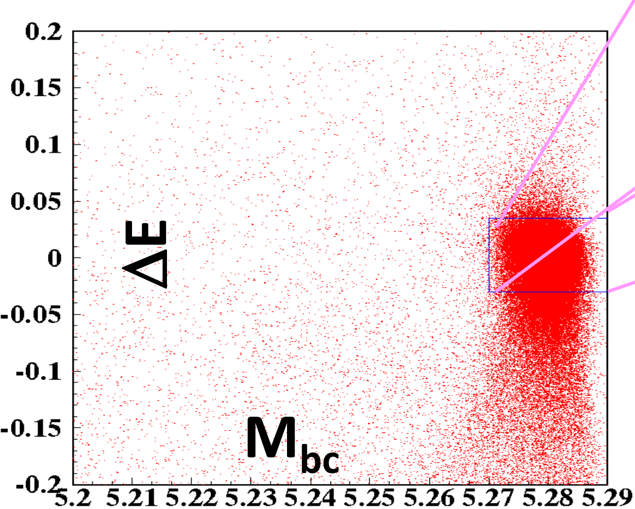
Radiative decays in B meson

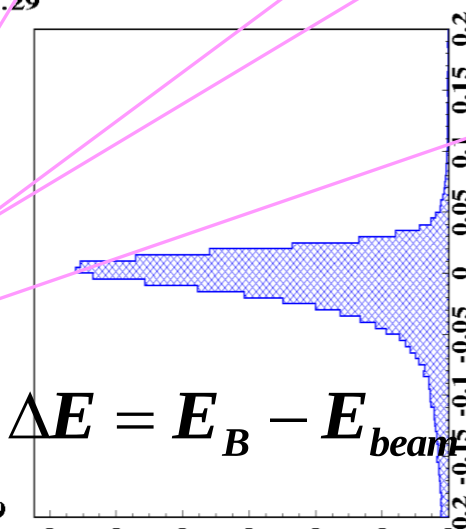
$X(3872)$, $\chi_{c1,c2} \rightarrow J/\psi\,\gamma$
↳ e^+e^- or $\mu^+\mu^-$

MC for illustration purpose









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

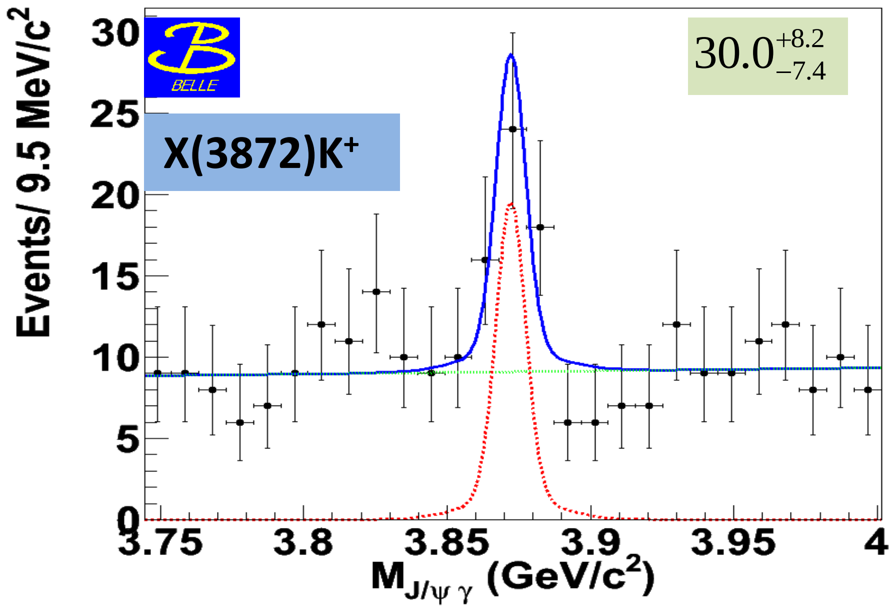
Used $B \rightarrow \chi_{c1} K$ as control mode

772 M $B\bar{B}$

PRL 107, 091803 (2011)

B→X(3872)K

B→(J/ψγ) K



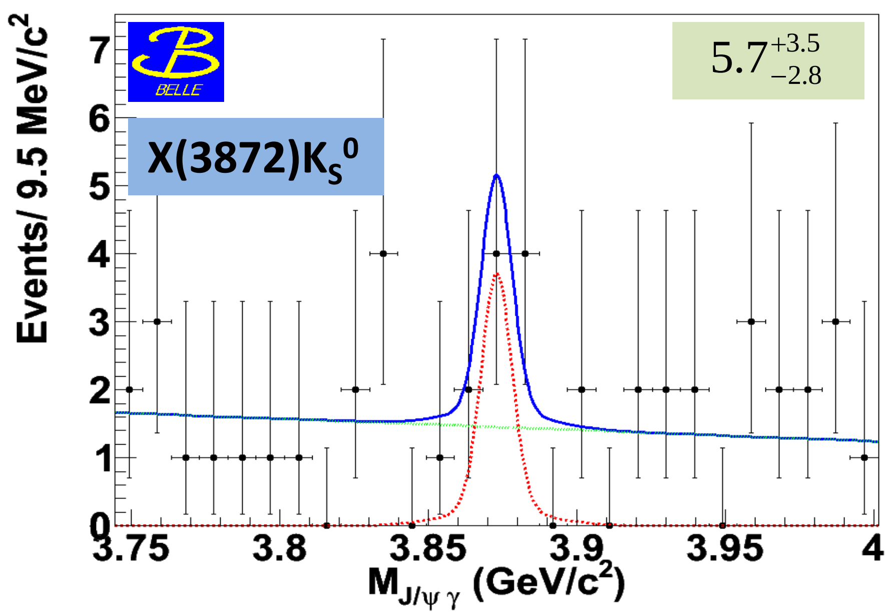
Mode	Events	Significance
$B^+ \to X(3872)\,K^+$	$30.0^{+8.2}_{-7.4}$	4.9 σ
$B^0 \to X(3872)\,K_S^0$	$5.7^{+3.5}_{-2.8}$	2.4 σ

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)

- Current measurements are statistically limited.
- With current statistics, one can expect. statistical uncertainty of ~ 0.38.

MC

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

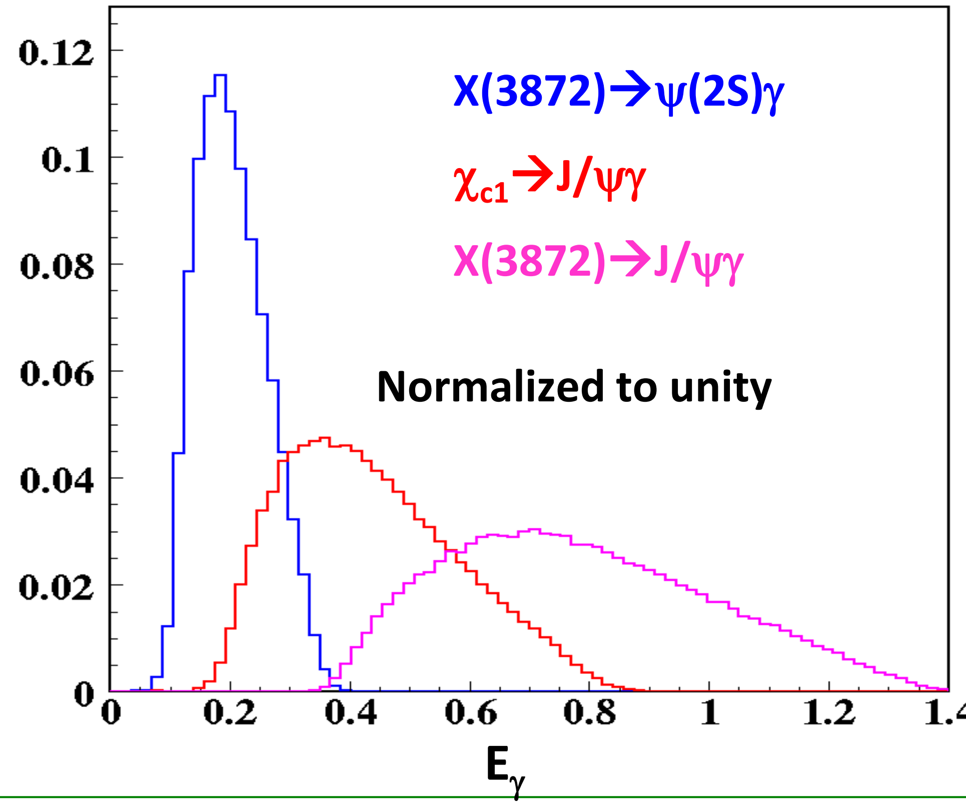
$B \rightarrow (\psi(2S)\gamma)\ K$

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

$\quad \rightarrow J/\psi\pi^+\pi^-$

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

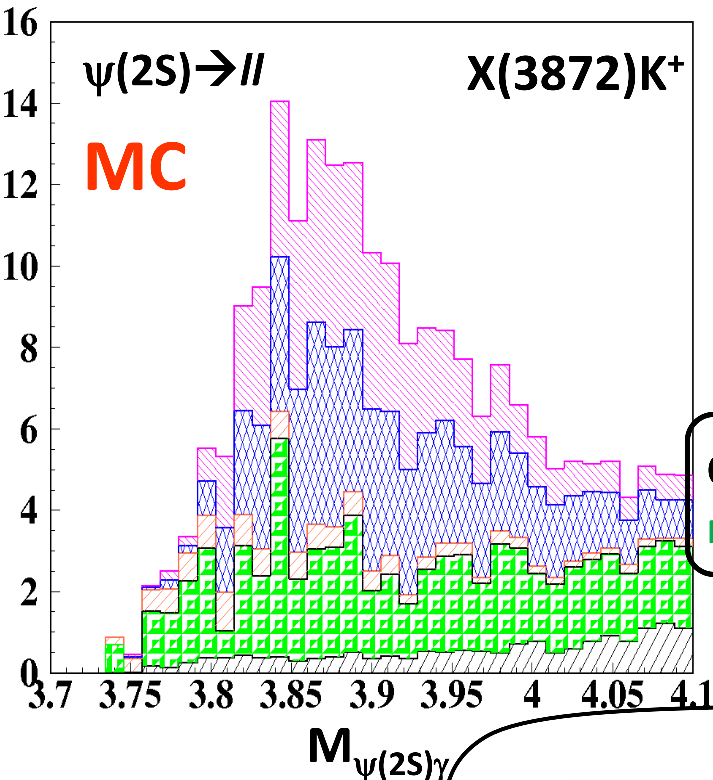
Photon selection

✓ $E_\gamma > 100$ MeV

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

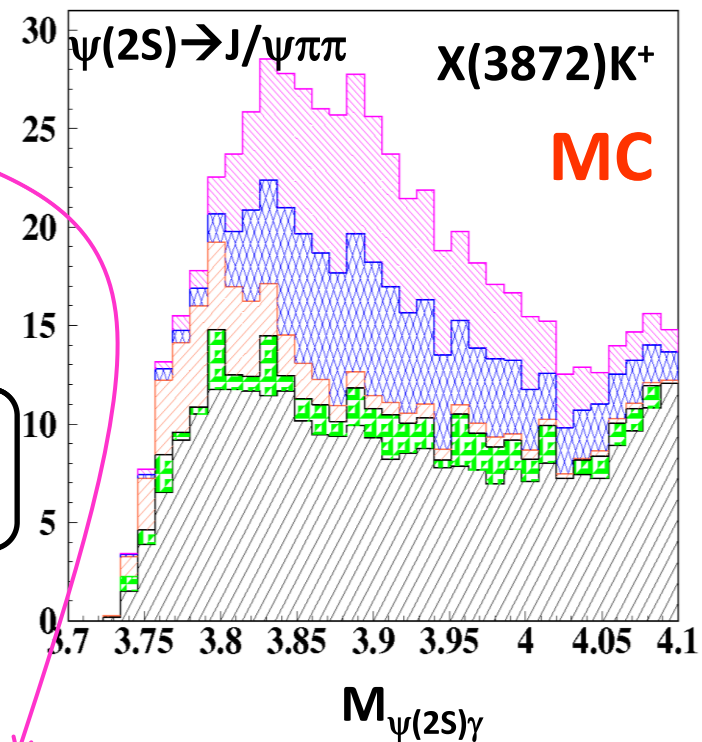
Background study

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→X(3872)K

772 M $B\bar{B}$

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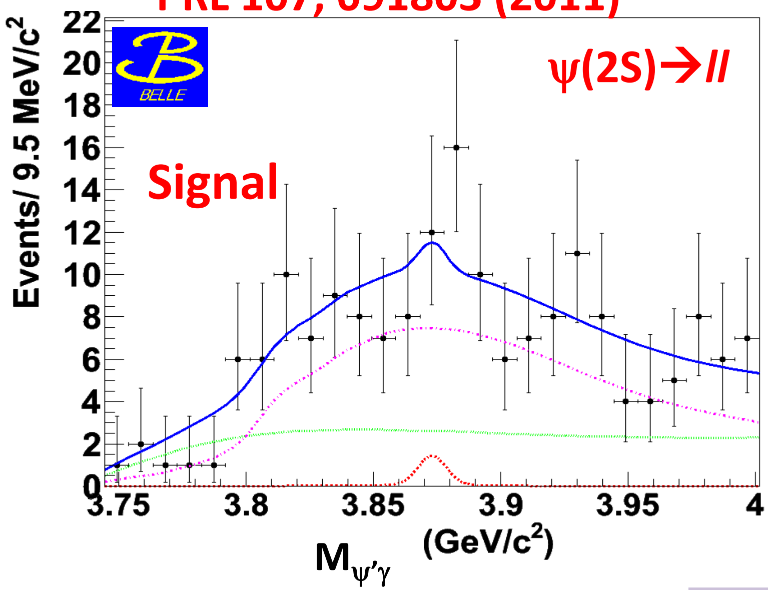
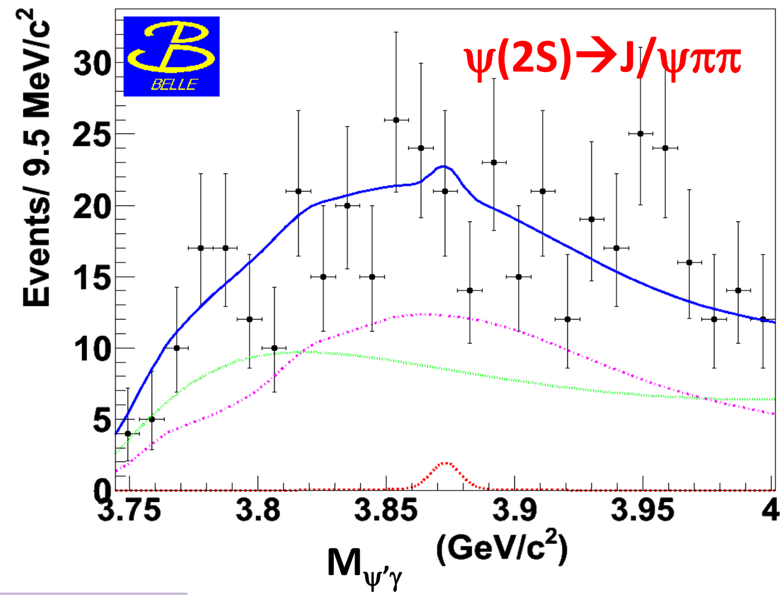
B→(ψ(2S)γ) K



$B^\pm \to XK^\pm$

5^{+12}_{-11}

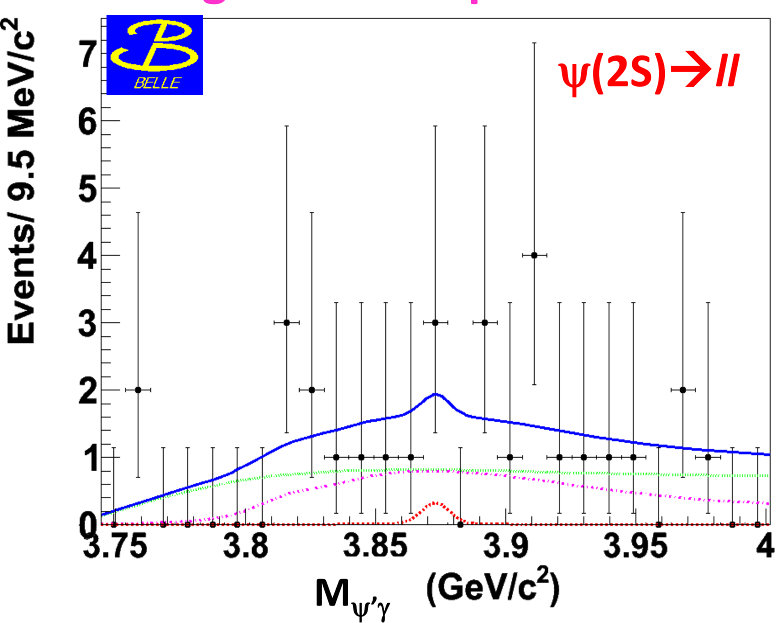
0.4 σ



ψ(2S)K*, ψ(2S)K background component

No signal observed

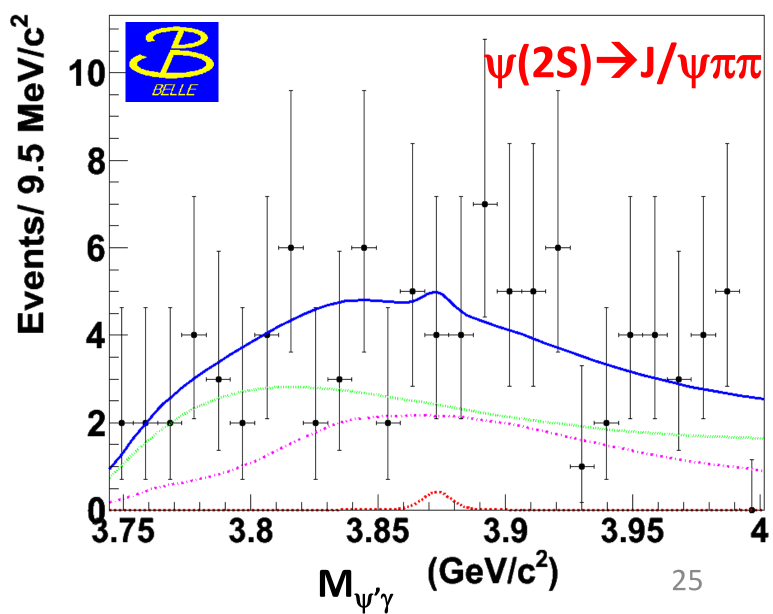
Combinatorial background



$B^0 \to XK_S^0$

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

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)*

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

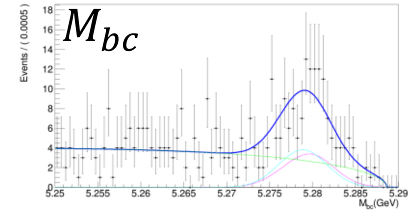
- In Belle, we plan to re-analyse the data differently
  - Extract signal using fit 2D UML fit to M_{bc} and $M_{\psi\gamma}$ distributions
  - This way one can be more confident about the robustness of the analysis.
  - Using BDT to suppress $B \to \psi(2S)K^*$ for better sensitivity.

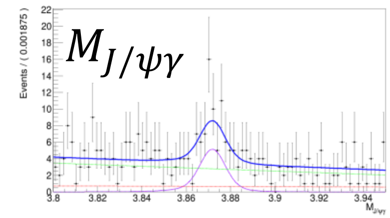
- Will use $B^+ \to X(3872)K^+$ and $B^+ \to X(3872)K_s^0$ decay mode

- 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)

Preliminary
Belle II MC toy
(for illustration purpose)

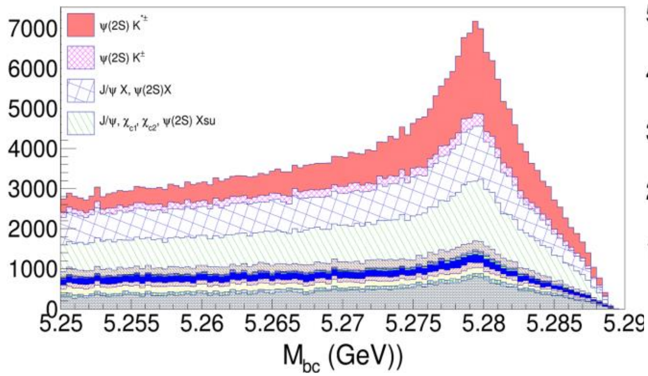


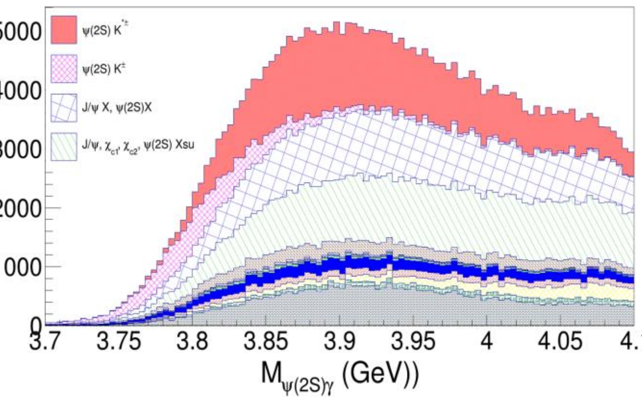


In Progress !

Background study

Preliminary MC
Arbitrary y-axis

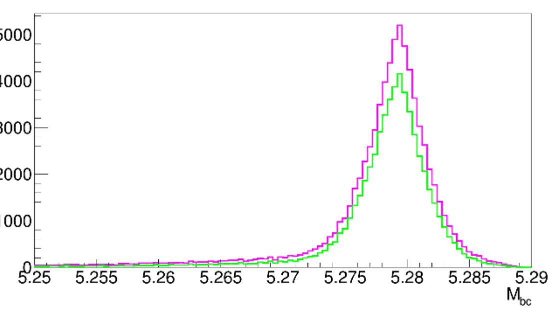




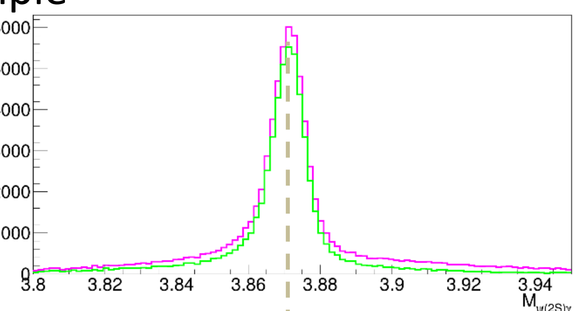
- Reduce the $K*$ component using BDT.
- However, one has to be careful.
- Without understanding BDT, there is a danger of shaping background more like signal

One trained BDT example

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

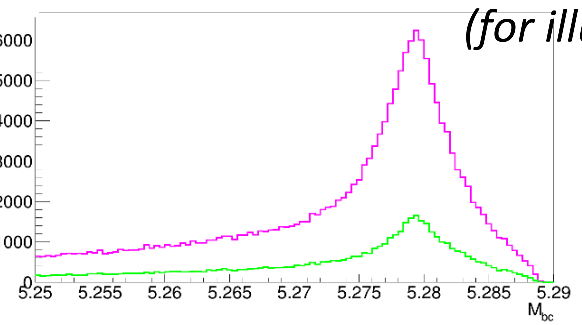


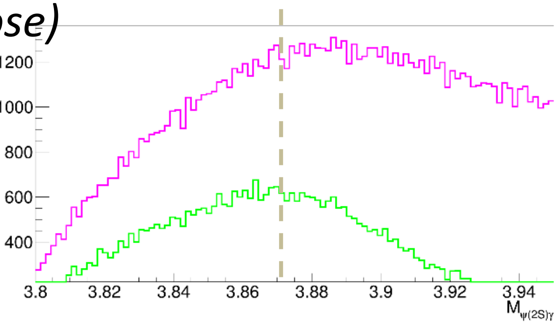
No BDT
After BDT cut



(for illustration purpose)

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

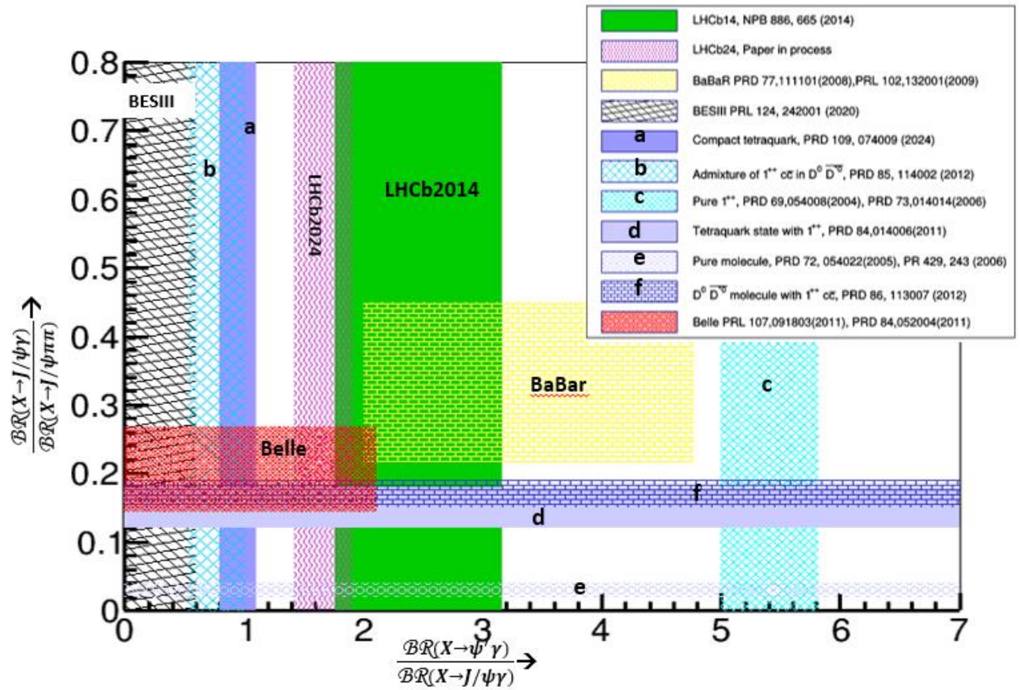




Conclusion

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 consistent with recent LHCb result and also BESIII result.



Useful to have theoretical predictions for a particular model in all three ratios :

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

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

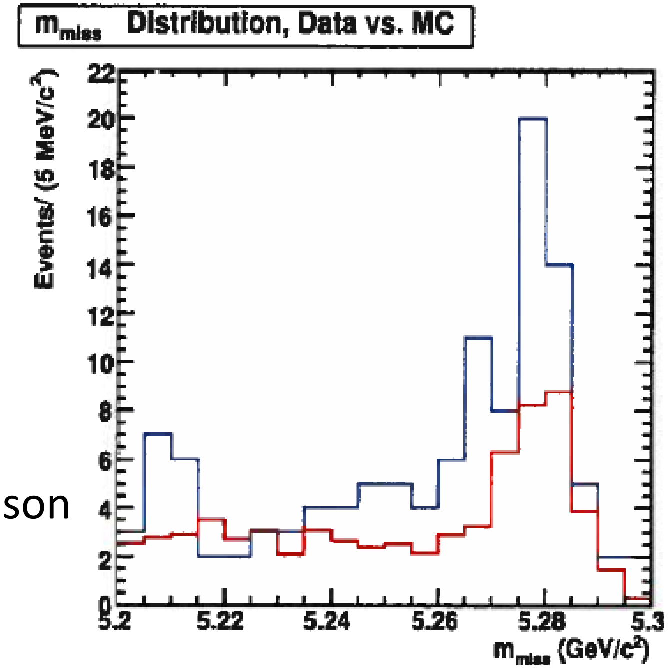
PRL 102, 132001 (2009)

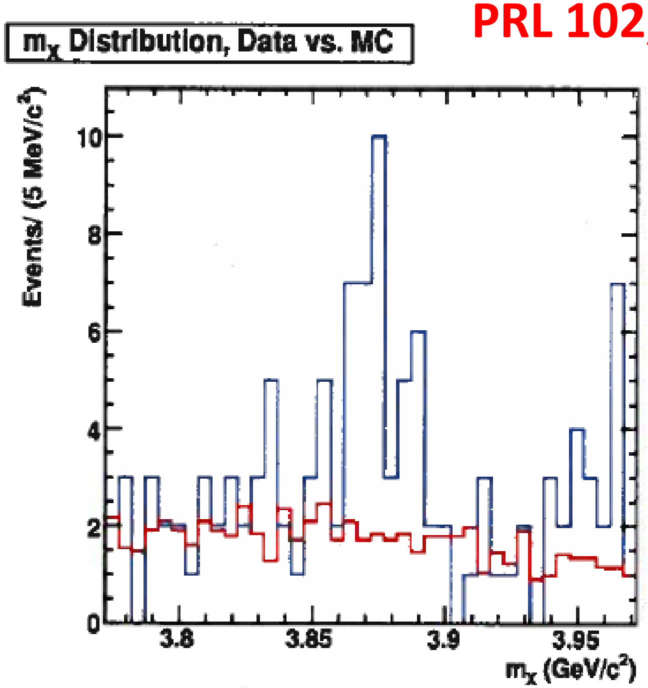
Babar

MC

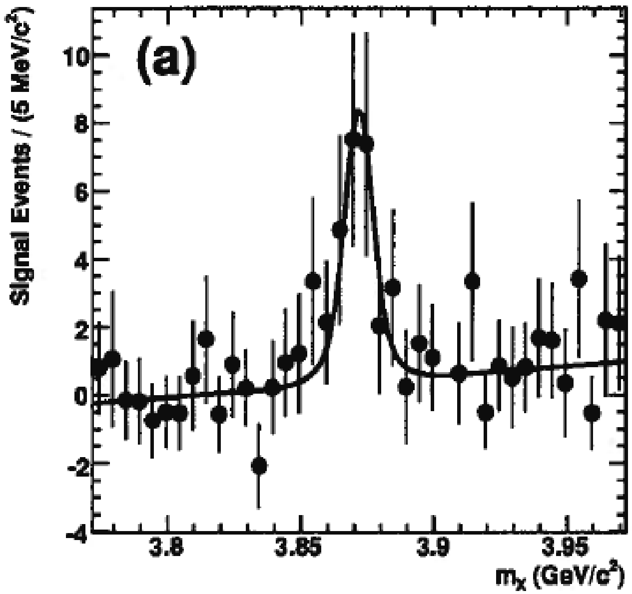
data

Raw comparison





sPlot fitting

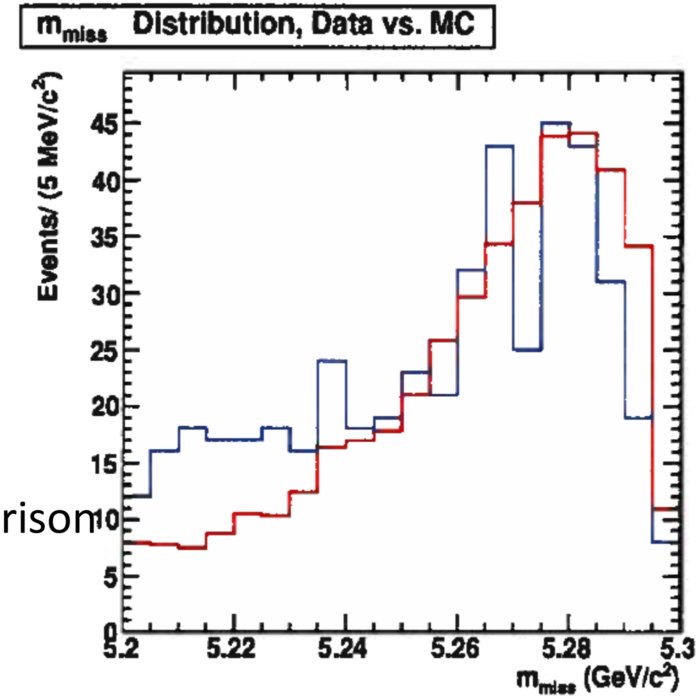


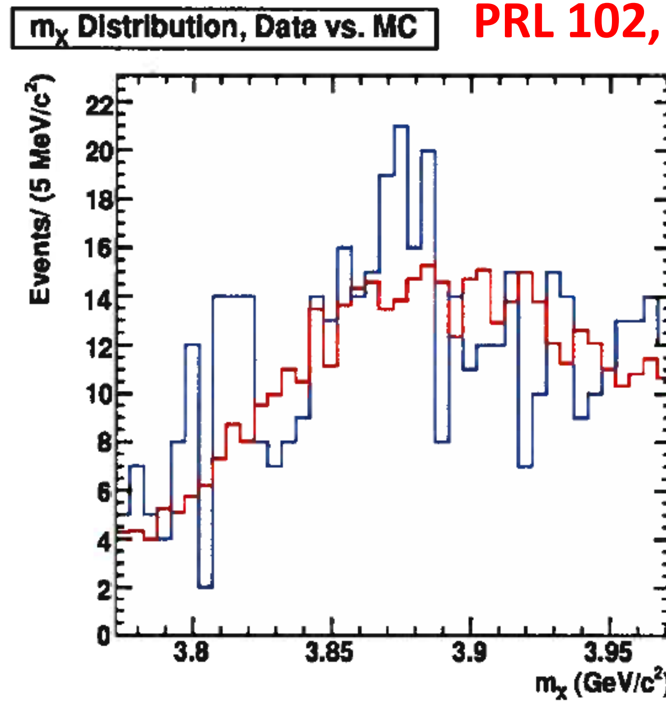
PRL 102, 132001 (2009)

Babar

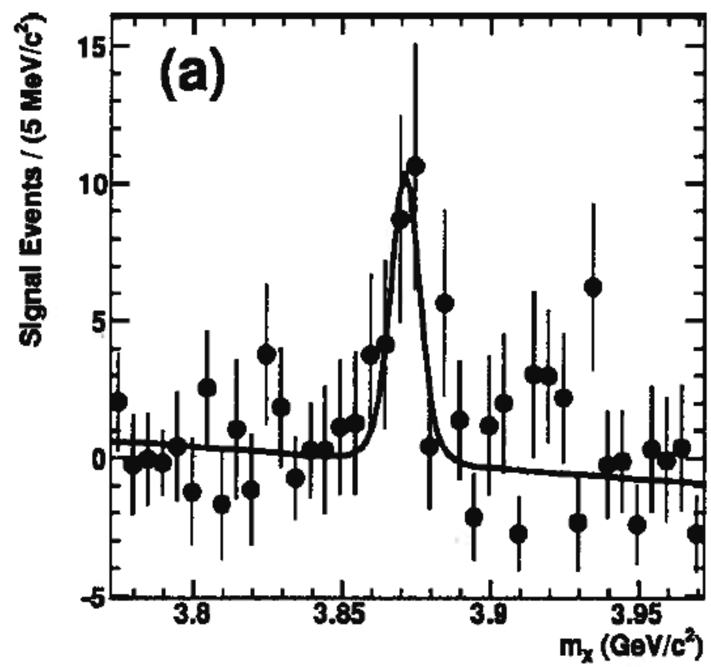
MC
data

Raw comparison





sPlot fitting



772 M $B\bar{B}$

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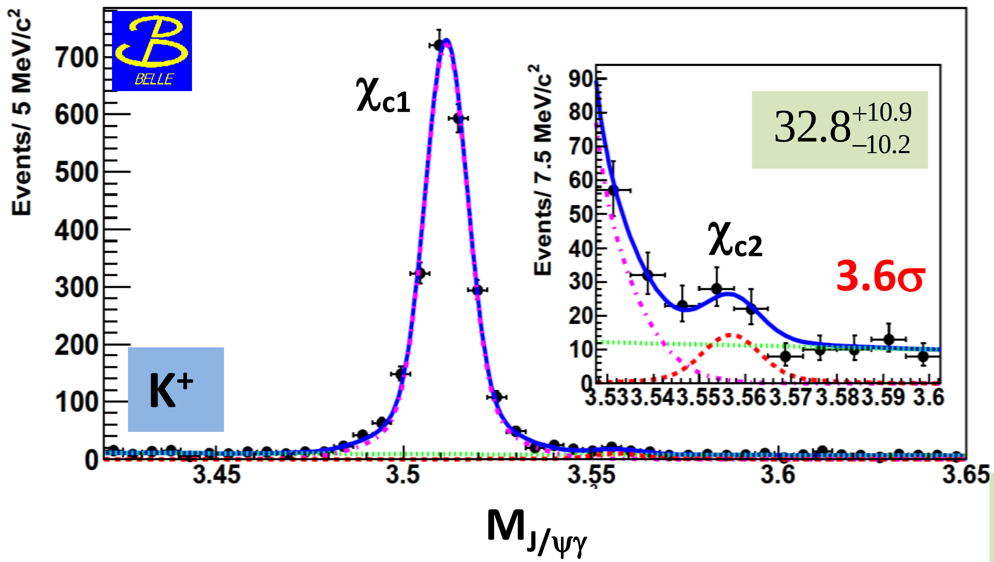
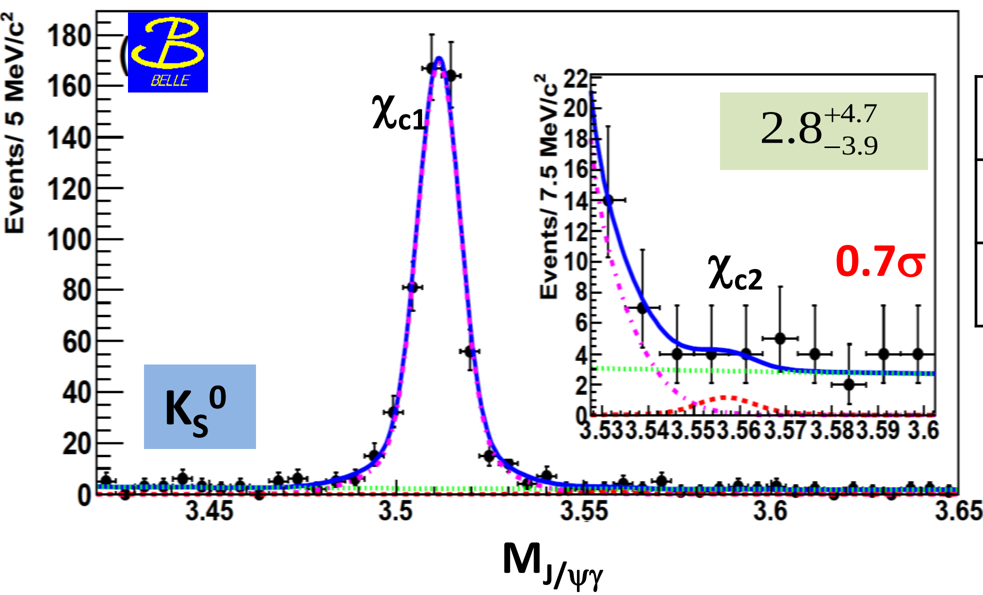
$B \to \chi_{c1,c2}$ K

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