Search for C-odd partner of X(3872) at Belle

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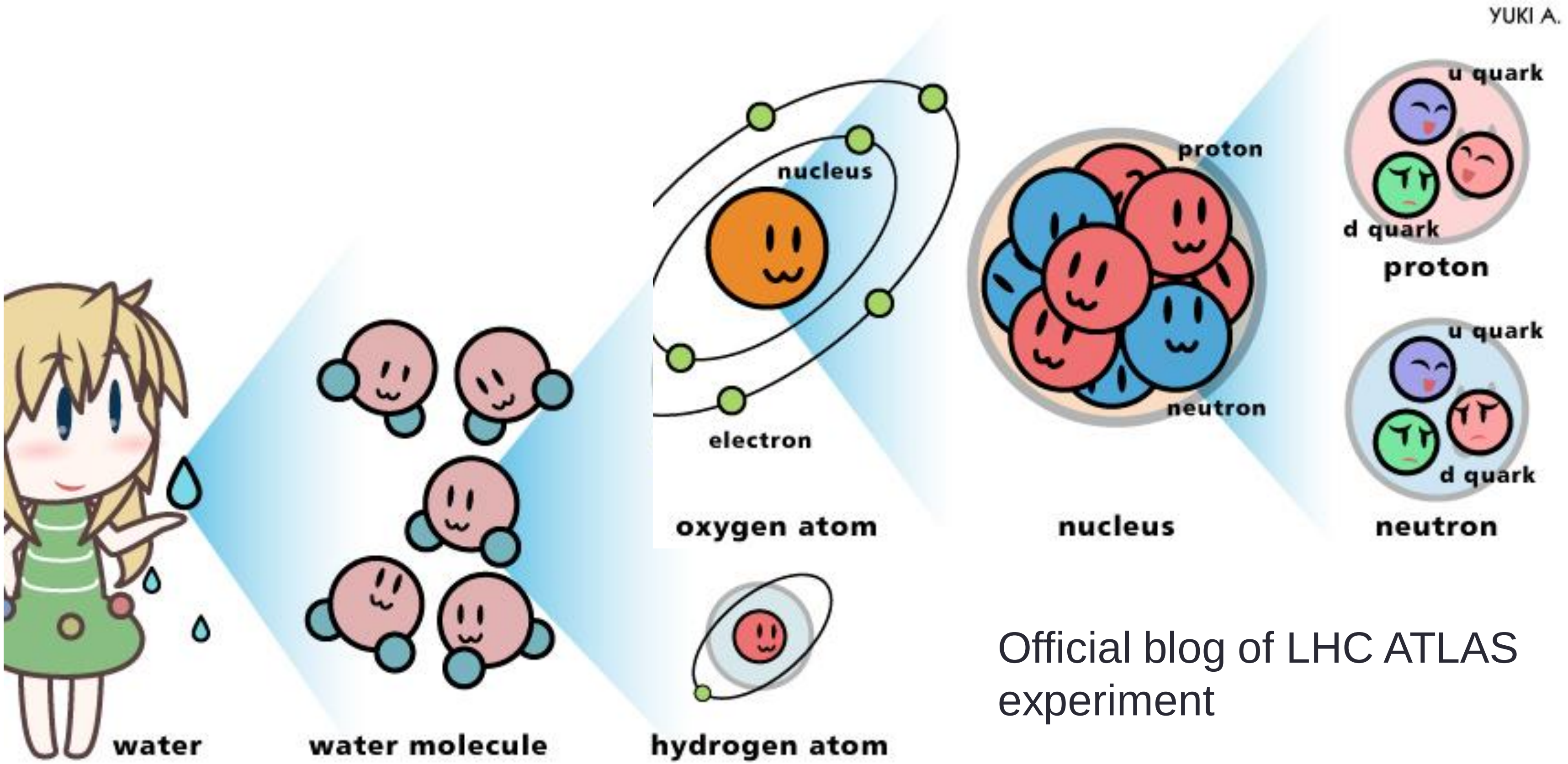
Outline

- Introduction
  - About X(3872)
  - Motivation
- Experiment
  - KEKB accelerator
  - Belle detector
- Analysis
  - How to search
- BelleII project
- Summary

INTRODUCTION

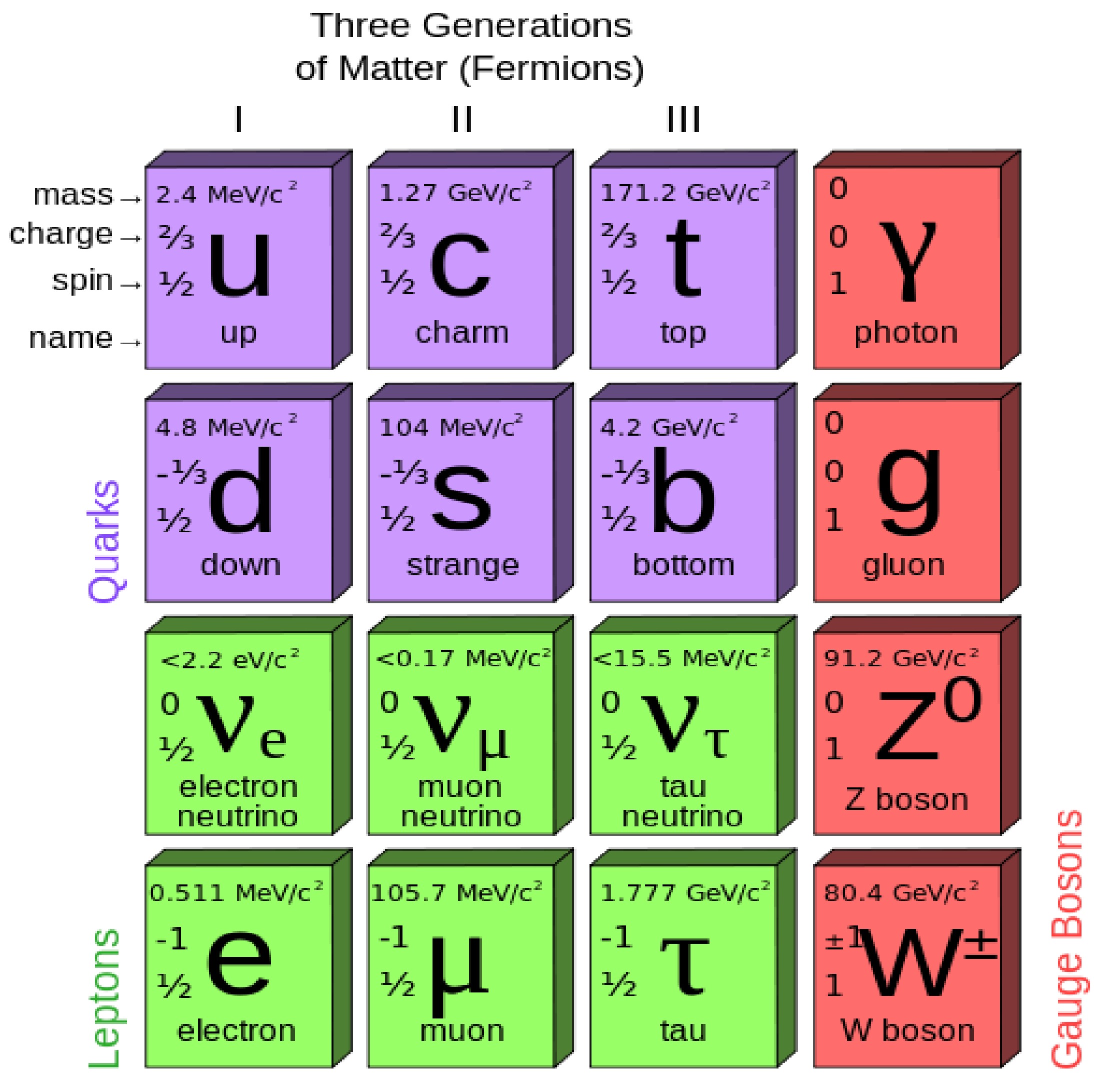
Elementary particles

What is the most basic and smallest particle?



Official blog of LHC ATLAS experiment

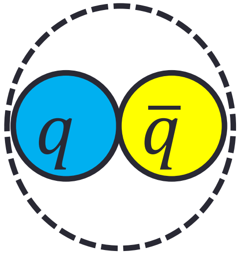
Elementary particle in the Standard Model



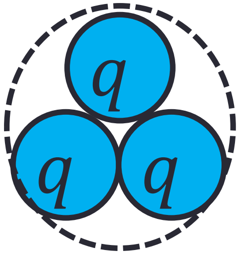
What is Hadrons?

Quarks do not appear as a single particle.
Usually two kinds of hadrons have been observed.

Mesons : Bound state of quark anti-quark



Baryons : Bound state of 3 quarks



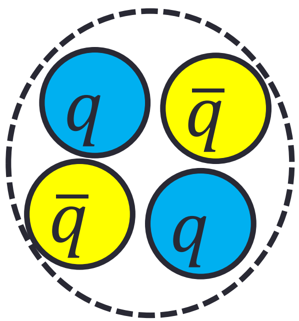
Strong interaction is described by QCD.

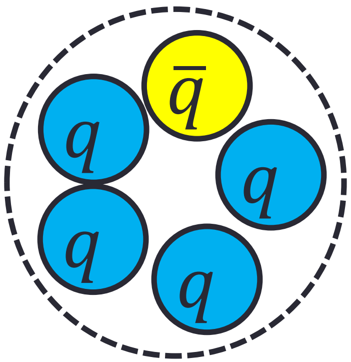
But QCD allows other configurations...

About exotic hadrons

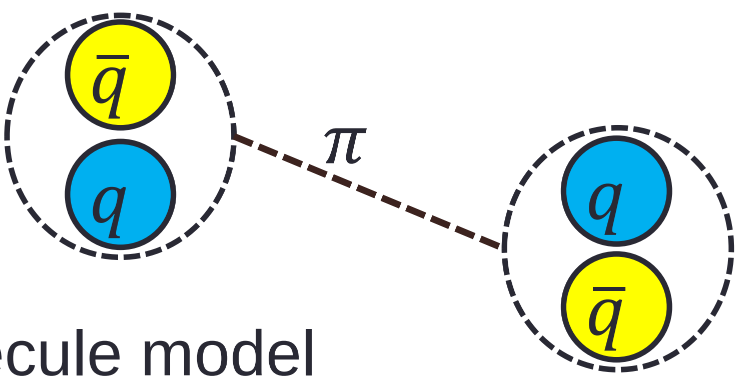
Exotic state has been searched for a long time.
For example …

Tetra quark
($qq\bar{q}\bar{q}$)





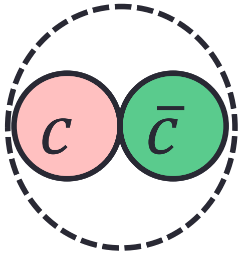
Penta quark ($qqqq\bar{q}$)



Molecule model
($q\bar{q}$~$q\bar{q}$)

About charmonium

Charmonium is $c\bar{c}$ states mesons.



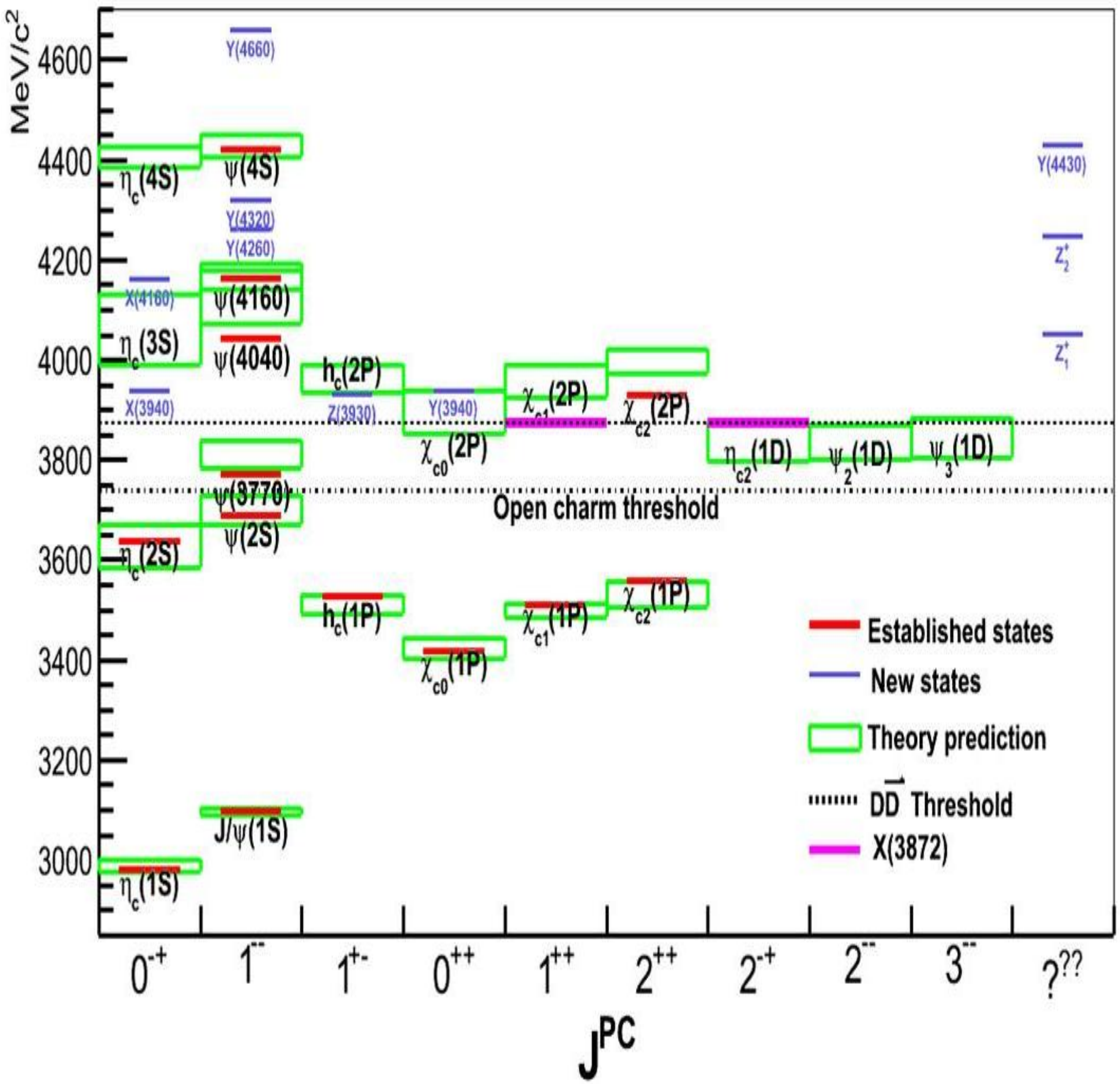
J/ψ, χ_{c1}, χ_{c2} etc.

The $c\bar{c}$ states are characterized by

P : Parity
C : Charge conjugation
L : Orbital angular momentum
S : The quark pair's total spin
$J = L + S$: Total spin

Charmonium	J^{PC}
J/ψ	1^{--}
χ_{c1}	1^{++}
χ_{c2}	2^{++}

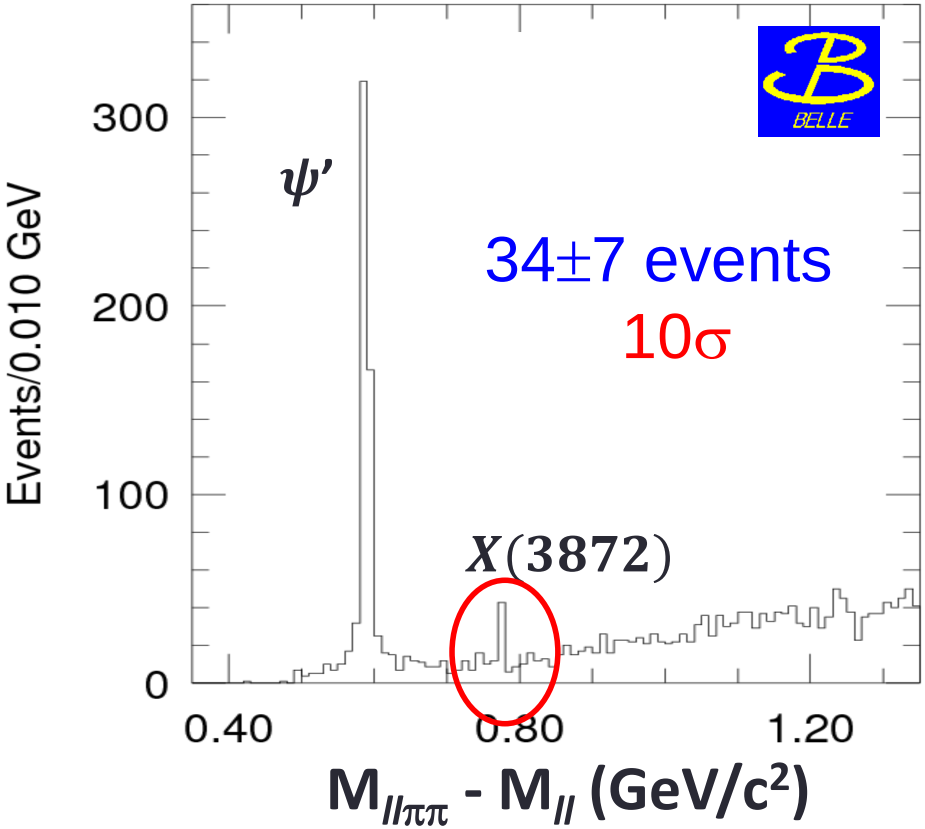
Charmonium spectrum



What is X(3872)?

$X(3872)$ is discovered by Belle in $J/\psi\pi^+\pi^-$ decay mode in 2003.

PRL 91,262001(2003)



Very narrow

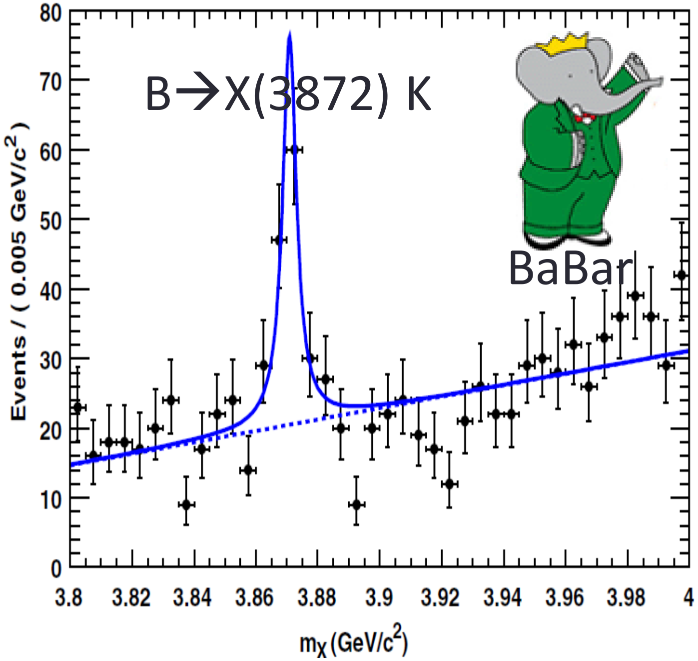
Mass = 3872 MeV

X(3872)→ $J/\psi\pi^+\pi^-$

X(3872) as of today

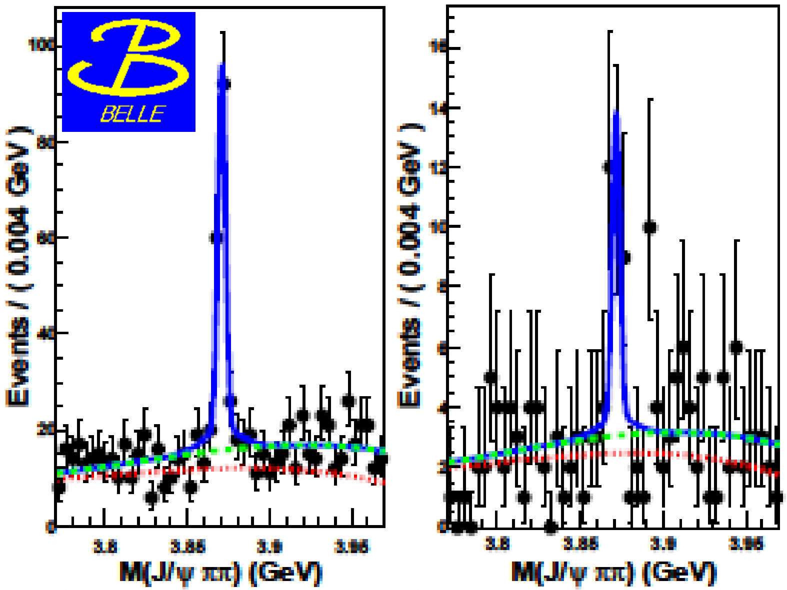
$X(3872)$ is confirmed by CDF, DO, BaBar, CMS and LHCb.

BaBar



PRD 71,071103(2005)

Belle's recently search

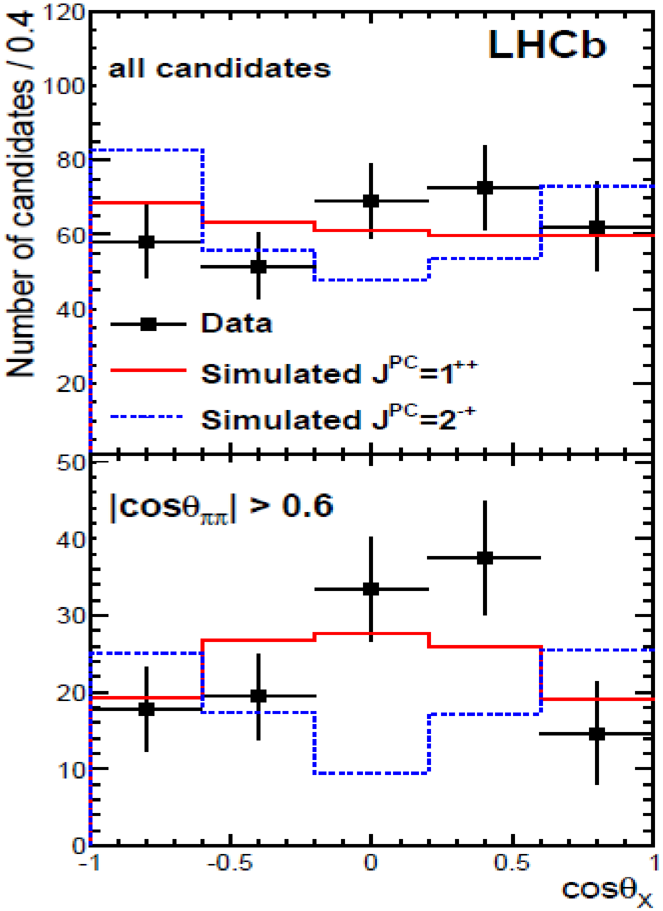


$B^+ \rightarrow X(3872)\, K^+$ $B^0 \rightarrow X(3872)\, K_S$

PRD 84,052004(2011)

X(3872) as of today

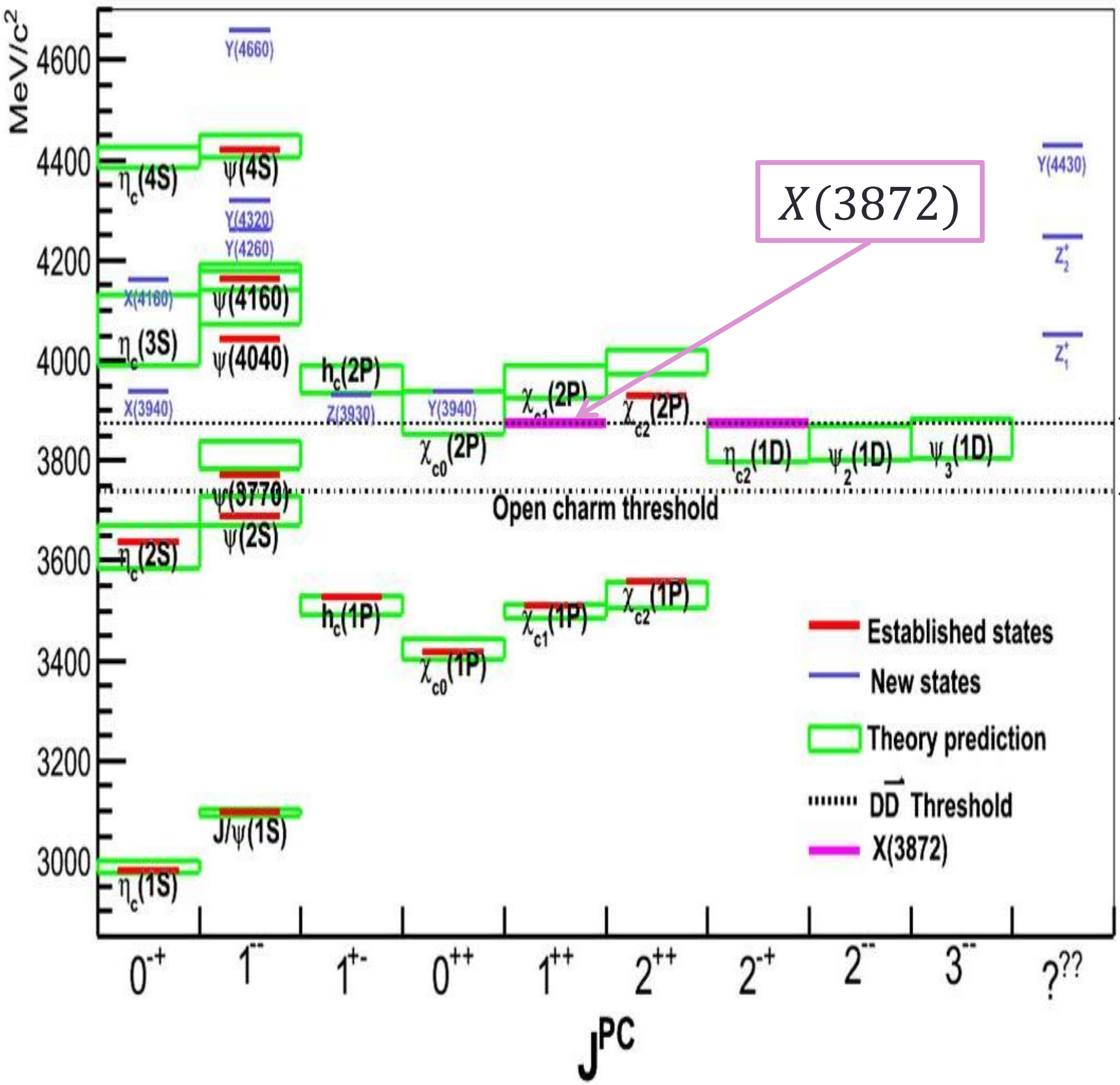
LHCb's recent result



Mass : $M = 3871.6 \pm 0.2$ MeV
Width: $\Gamma < 1.2$ MeV
$J^{PC} = 1^{++}$ (2^{-+} is rule out by LHCb)

arXiv:1302.6269

Is X(3872) exotic?



$D\bar{D}^{*0}$ threshold

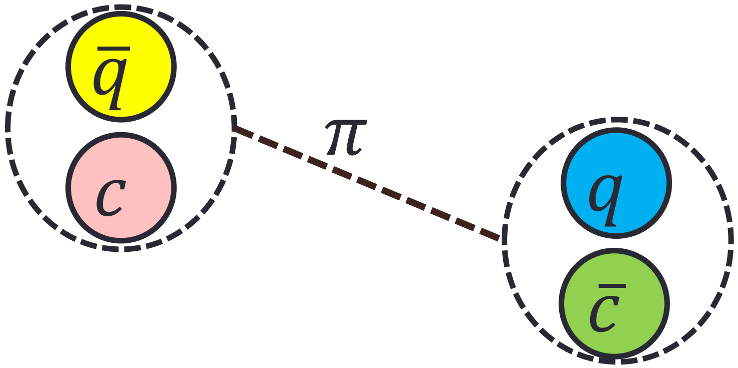
$2M_D$

1) No $c\bar{c}$ candidate
2) Narrow width, though $M_{X(3872)} > 2M_D$
3) Decay into $J/\psi\pi\pi$ even $M_{X(3872)} > 2M_D$
4) Near $D\bar{D}^{*0}$ threshold $M_{X(3872)} \simeq M_D + M_{D^*}$

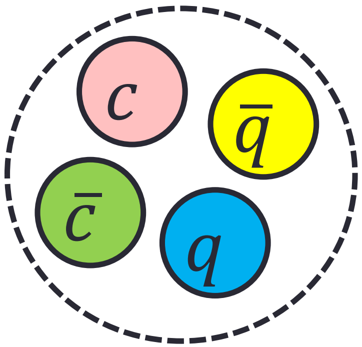
X(3872) possibility

It has some theoretical models

- Molecule model
- Tetra-quark model
- Hybrid meson
- Mixing model



Molecule model



Tetra-quark model

Why do we search C-odd partner of X(3872)?

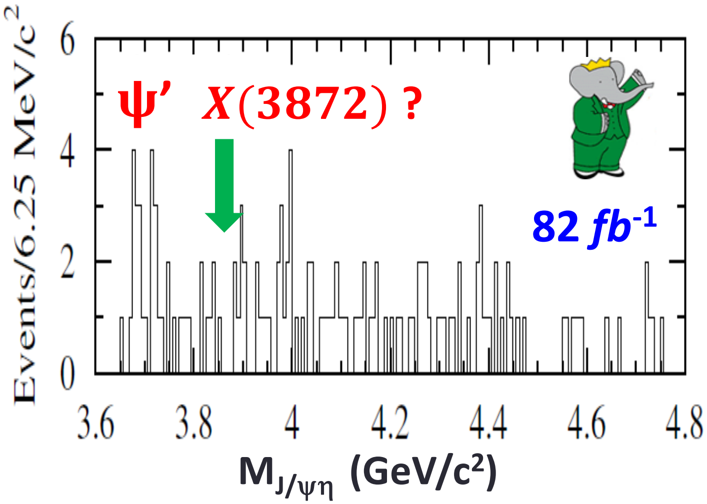
In either tetraquark or molecule pictures, X(3872) can have C-odd partner which may decay into

- ✓ $X(3872)^{C-} \rightarrow J/\Psi\eta$ **K. Terasaki, PTEP 127, 577 (2012).**
- ✓ $X(3872)^{C-} \rightarrow \chi_{c1}\gamma$

Note that previously unseen $\psi_2(1D)$ can decay into $\chi_{c1}\,\gamma$.

S. Godfrey & N. Isgur, PRD 32, 189 (1985)
E. Eichten et al., PRL 89,162002 (2002),PRD 69, 094019 (2004)

Available information of $B \rightarrow J/\psi\eta\, K$



BaBar measurement

Both modes are combined

$B^{+} \rightarrow J/\psi\eta K^{+}$ and $B^0 \rightarrow J/\psi\eta K^0$

$\mathrm{Br}(B^{+} \rightarrow X(3872)K^{+}) \cdot Br(X(3872) \rightarrow J/\psi\eta) < 7.7 \times 10^{-6}$

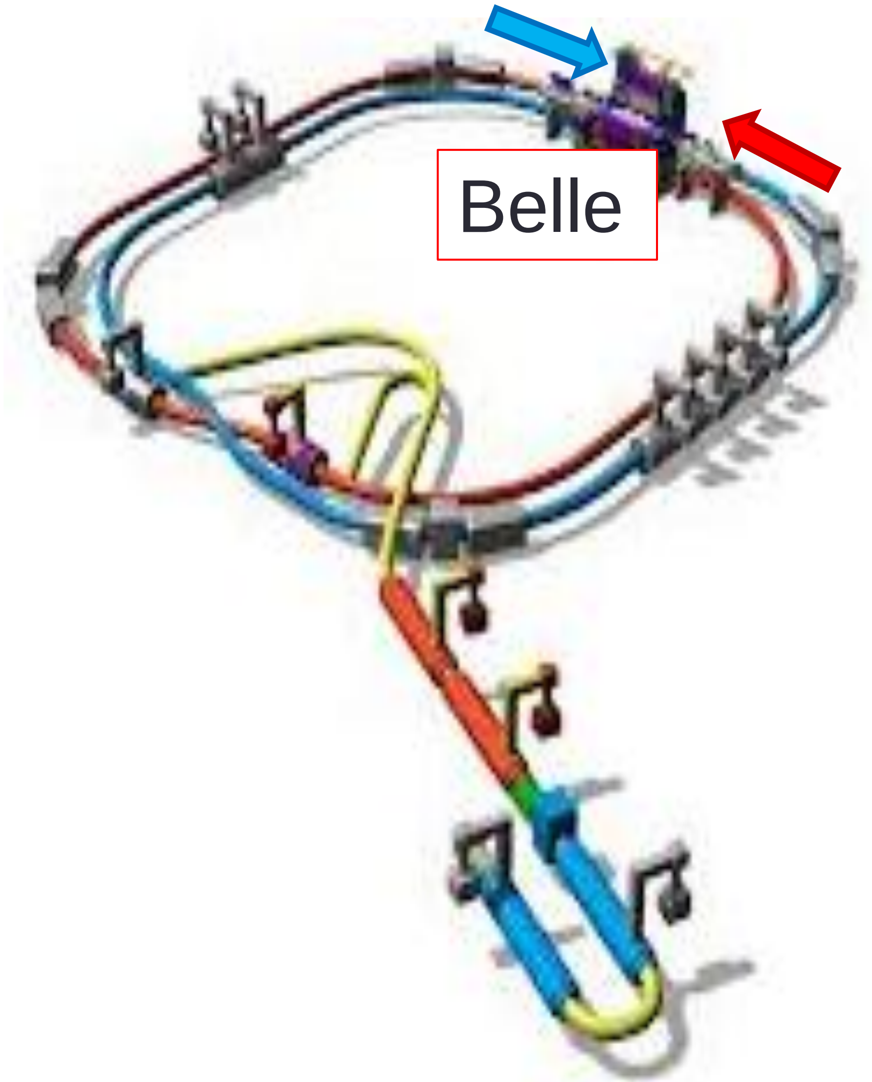
(90% CL)

BaBar,PRL 93, 041801 (2004)

With more data (9 times), Belle may find or rule out the X(3872) C-odd partner.

EXPERIMENT

KEKB accelerator



- Circumference 3 km
- Asymmetric energy e^+e^- collider
  - Electron : 8GeV
  - Positron : 3.5GeV
- The center-of-mass energy 10.58GeV
  - To produce $\Upsilon(4S)$


Υ(4S)

$\bar{B}^0$ or B^+

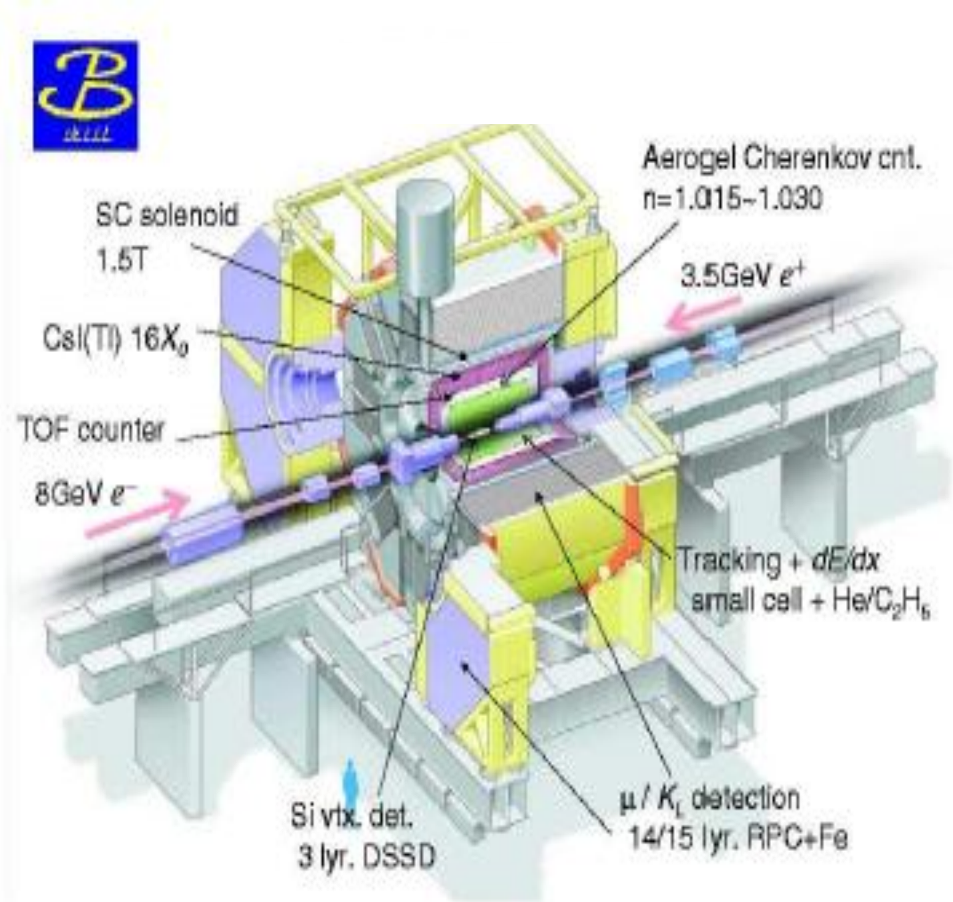
B^0 or B^-

Final state particles produced

- Electron → e^+, e^-
- Muon → μ^+,μ^-
- Pion→π^+,π^-
- Kaon→ K^+, K^-, K_S^0
- Proton→ p, $\bar{p}$
- Gamma→γ

Neutron, Neutrinos

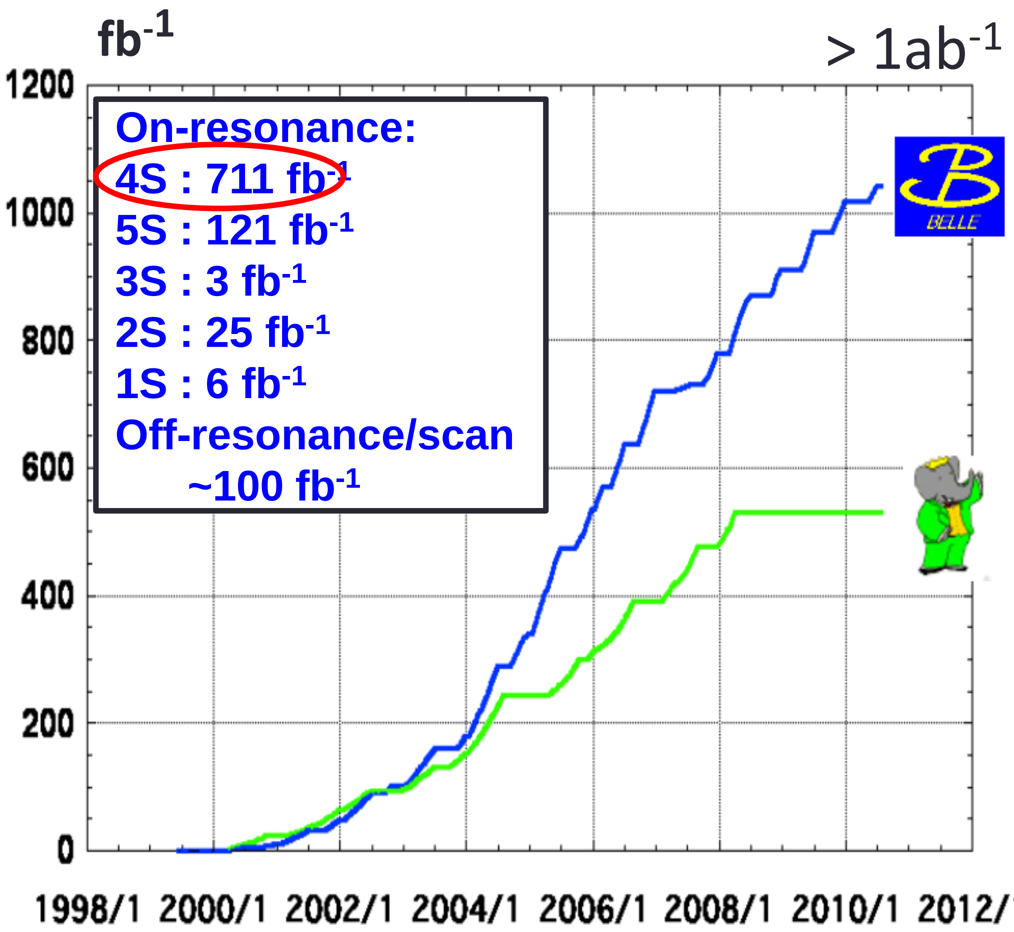
Belle detector



Silicon Vertex Detector (SVD)
To measure interaction point
Central Drift Chamber (CDC)
Tracking of charged particles and particle identification
Aerogel Cherenkov Counter (ACC)
Particle identification of K and π
Time Of Flight counter (TOF)
To give particle identification
Electromagnetic Calorimeter (ECL)
To measure energy of γ and electron
K_L^0 and Muon detector (KLM)
Identification of K_L^0 and muon

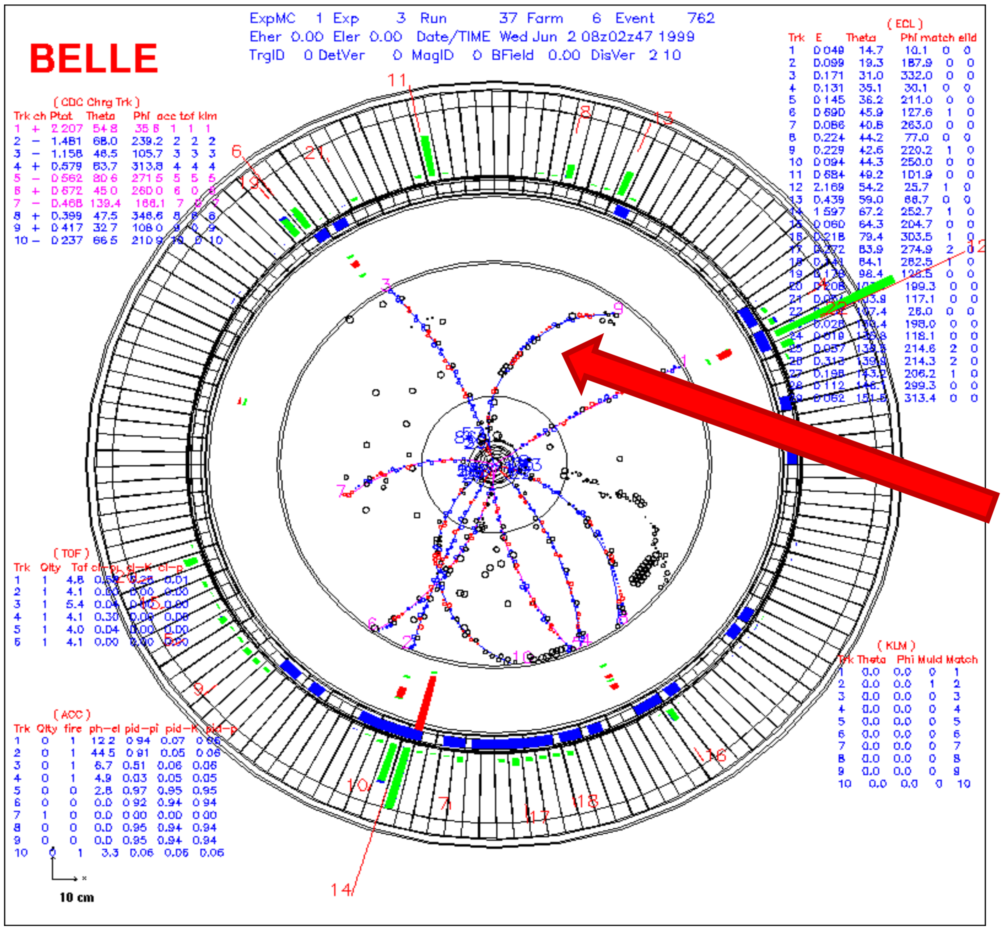
High resolution (Both charged particle and γ)
4π acceptance
Good particle identification

Data sample



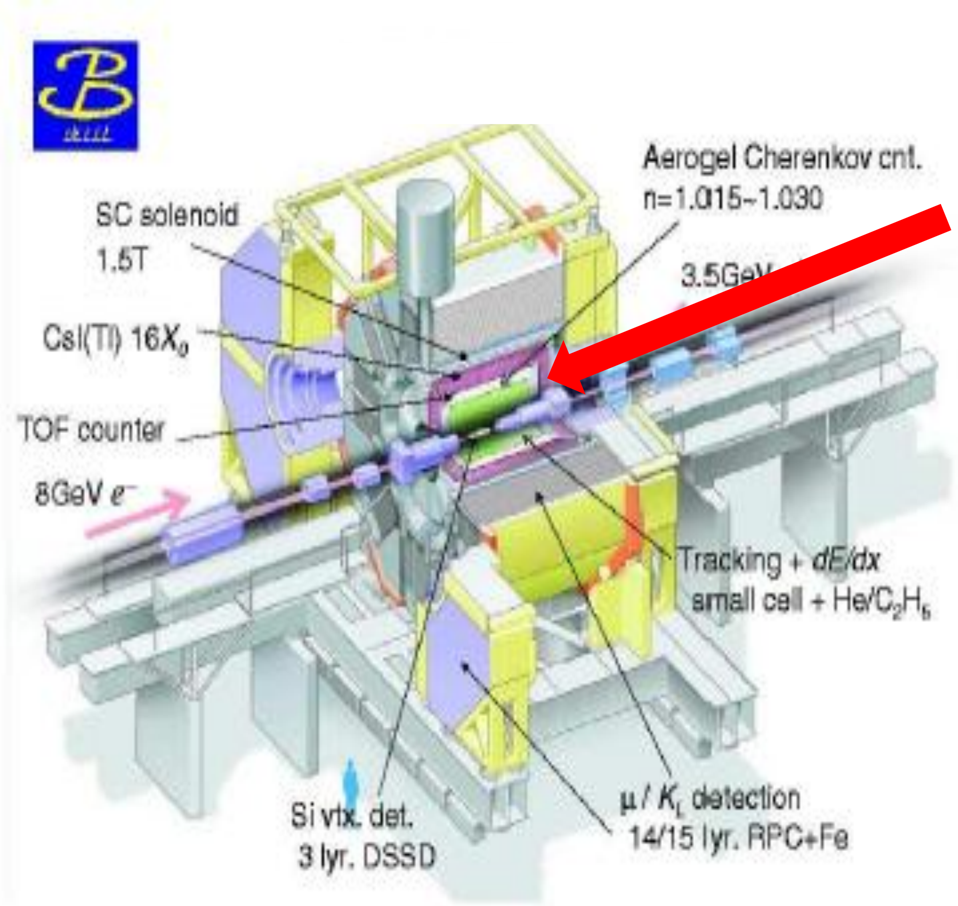
Belle collected 711fb^{-1} $\Upsilon(4S)$ data until 2010. (772×10^6 $B\bar{B}$ pairs)

How do we detect charged particle?



Charged tracks are found by **CDC**.
At last, combined **SVD**'s information.

SVD and CDC



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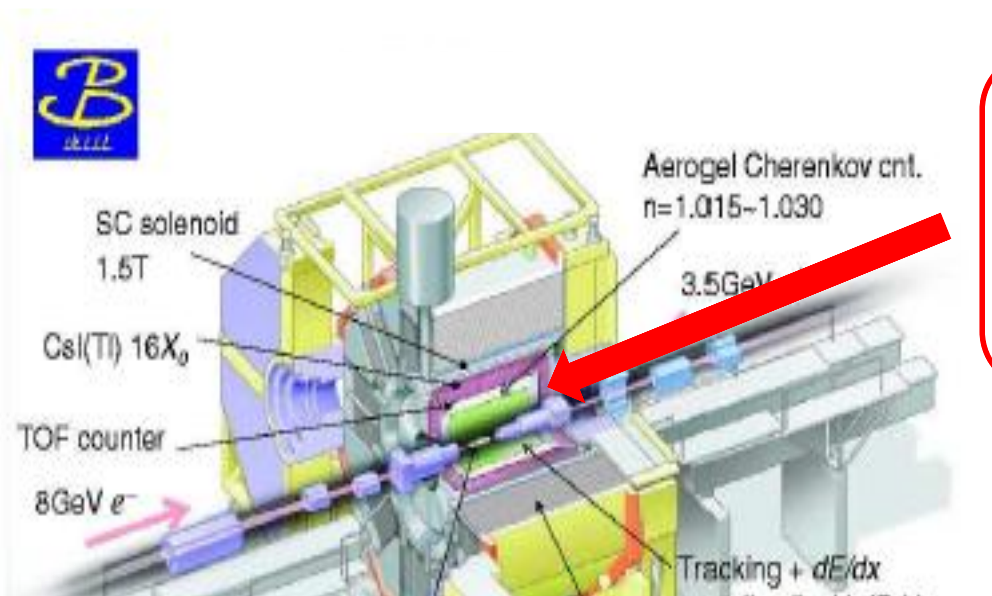

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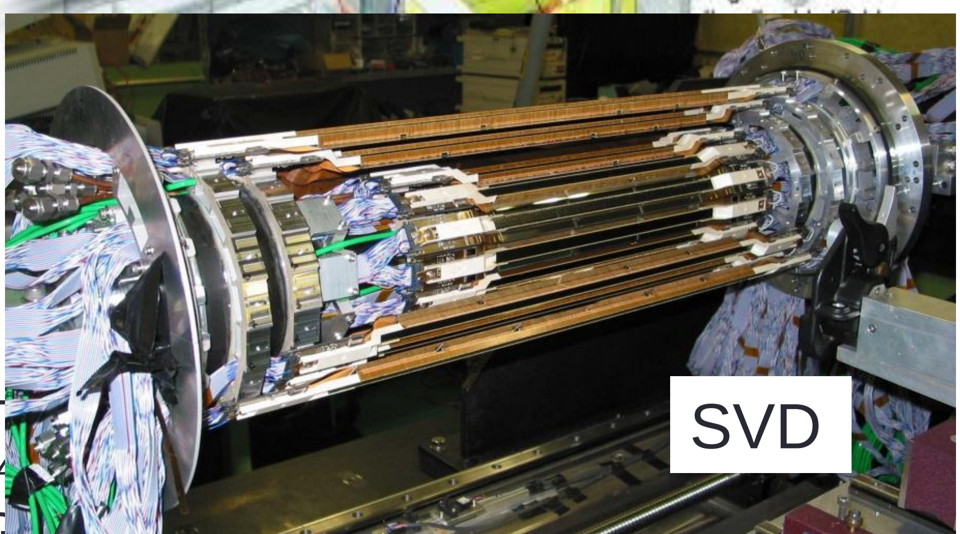
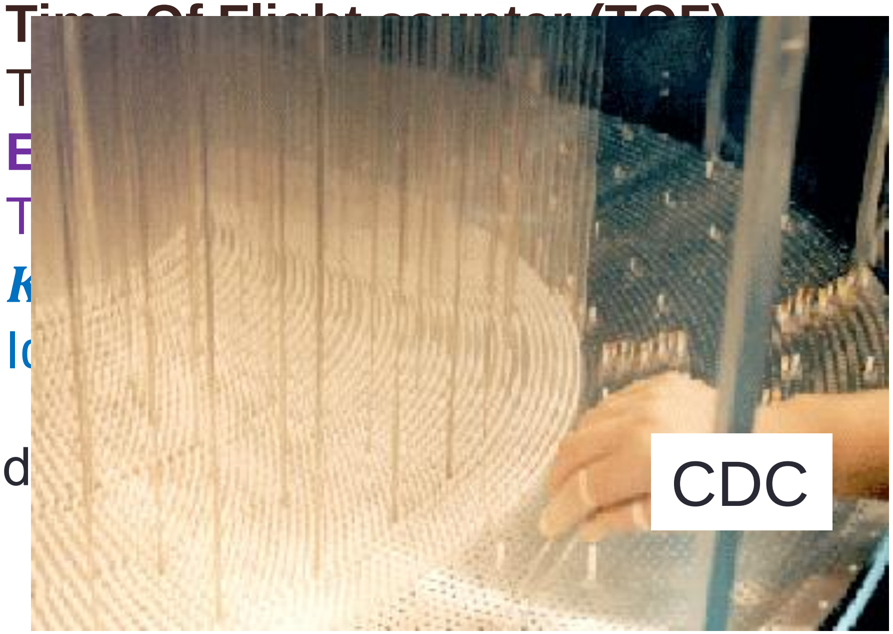
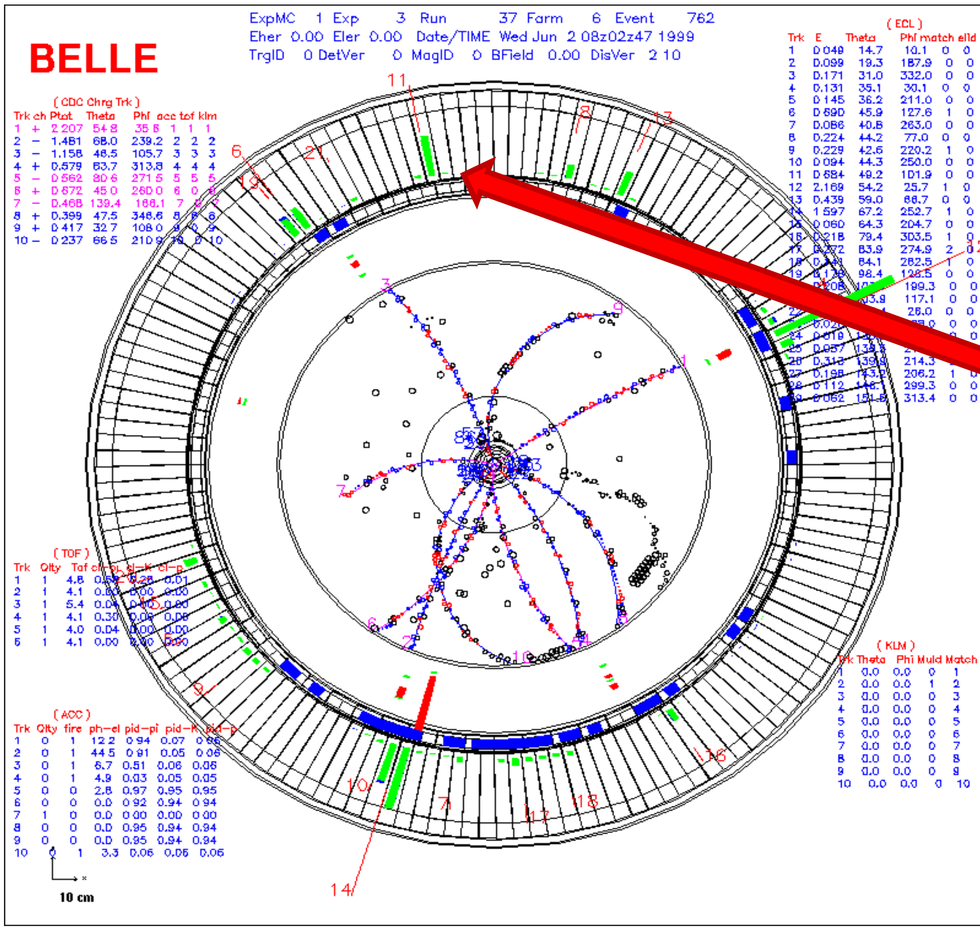


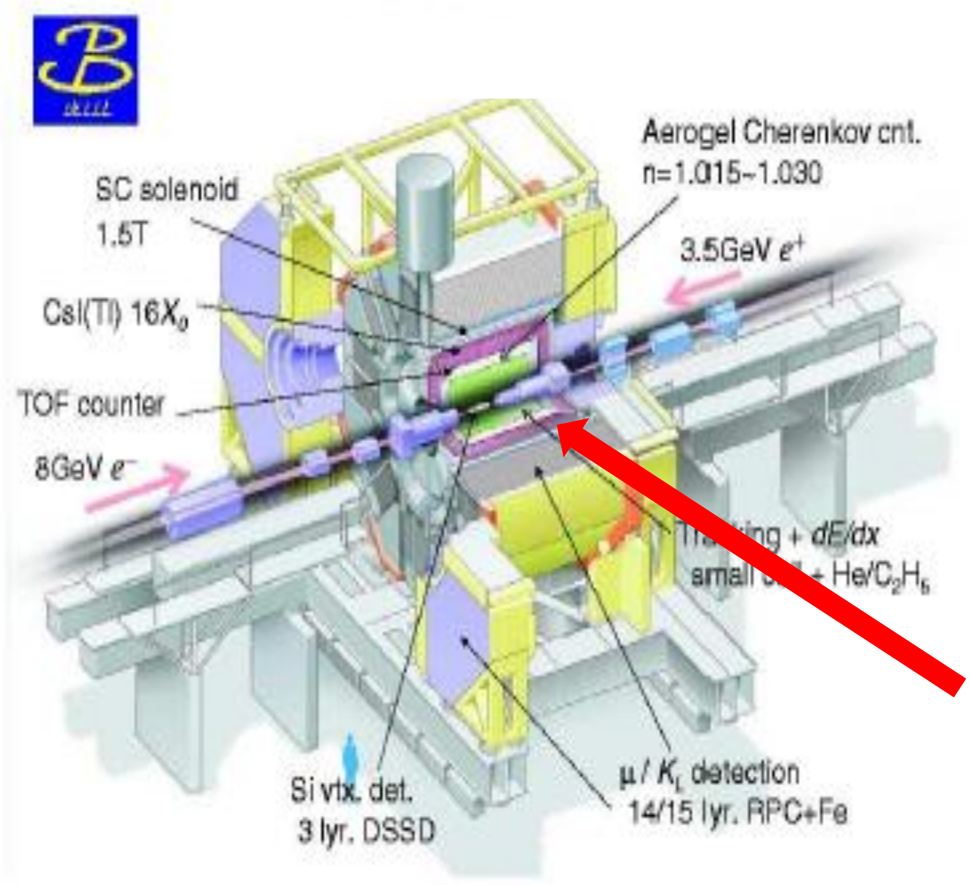


How do we detect photon?



Electron and gamma make shower in the **ECL**

ECL



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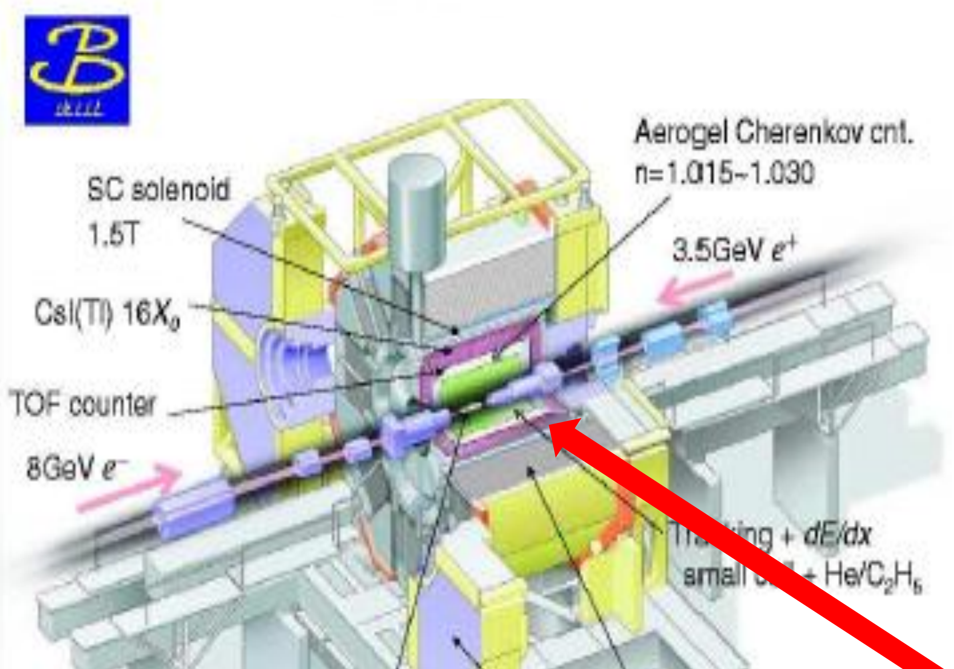

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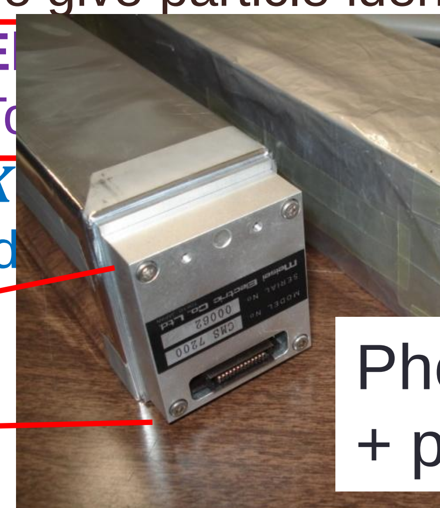
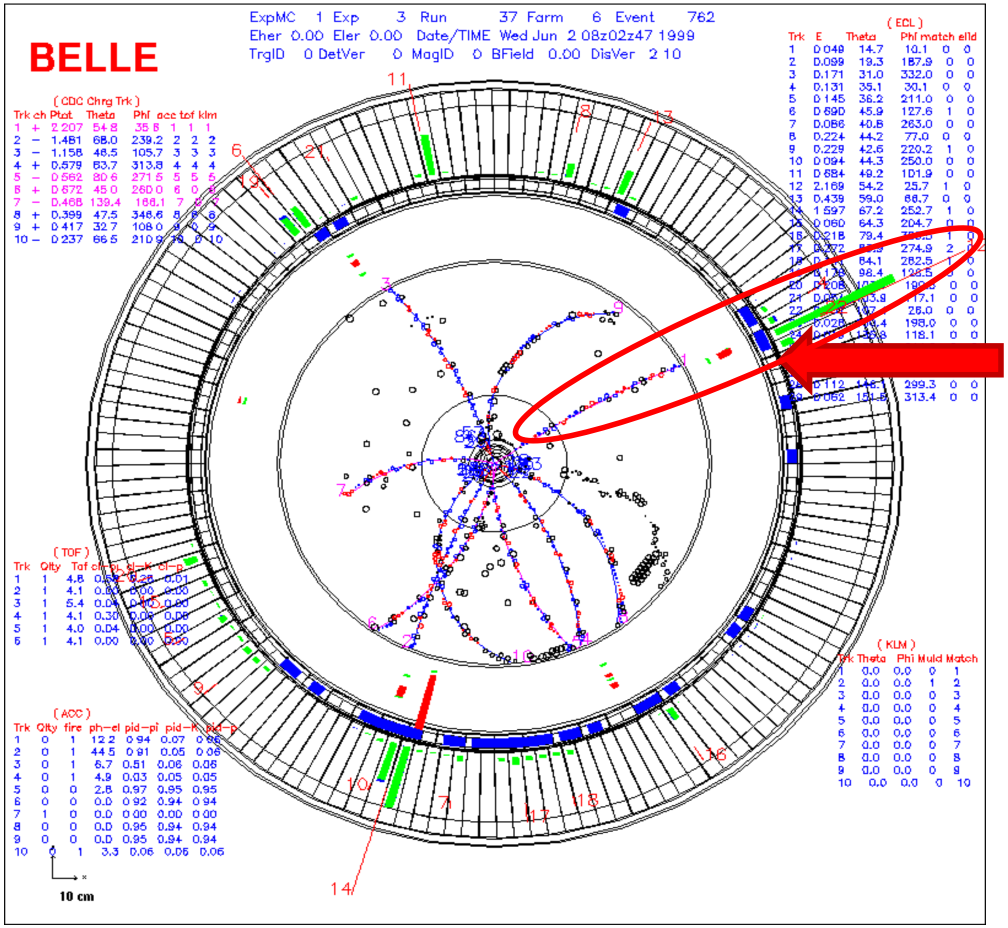
***K*… ctor (KLM)**
Id… nd muon



H… nd
4…
Good particle identification

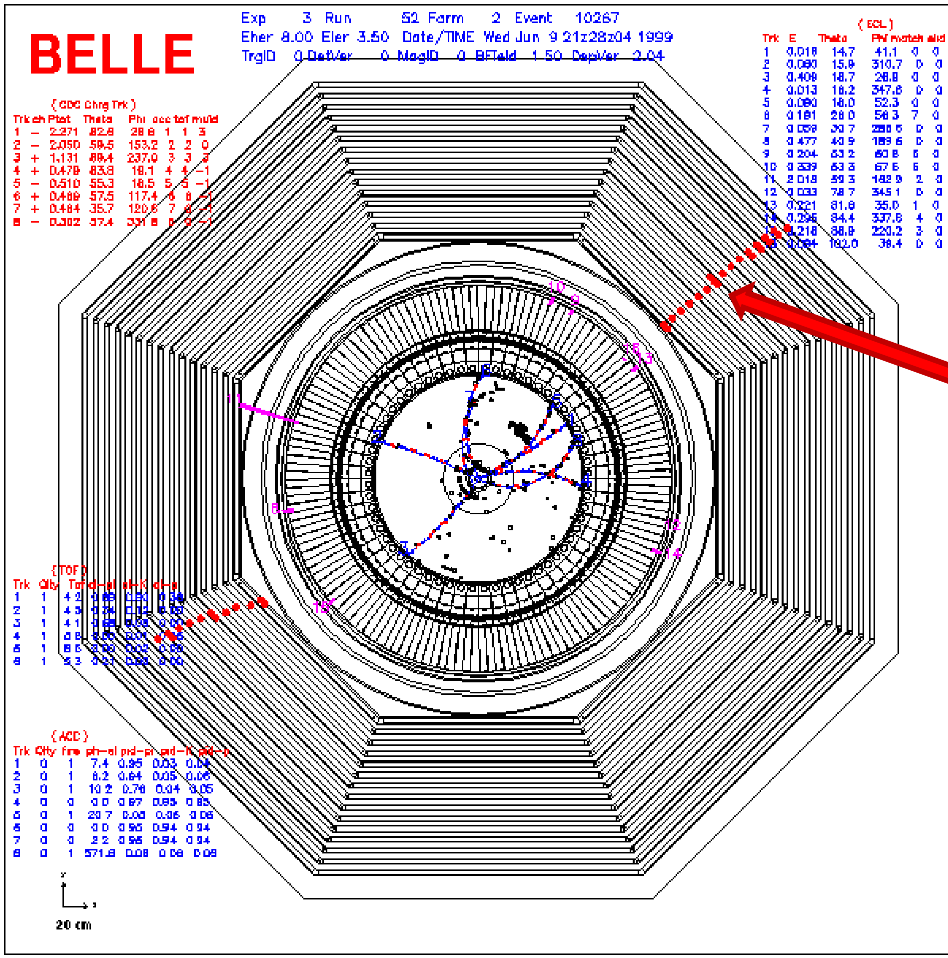
How do we identify electron?



Energy measured by ECL (E) and momentum measured by CDC (P)

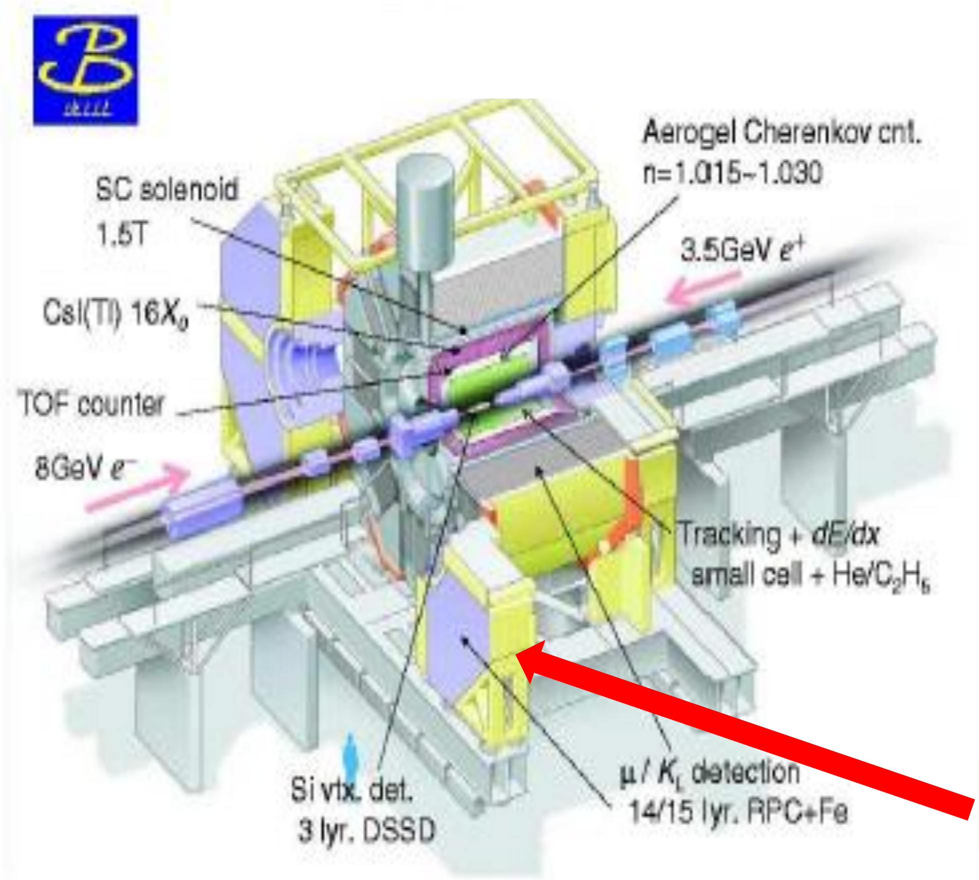
E/P~1

How do we identify muon?



Penetrating many layers of Iron absorber (KLM)

KLM



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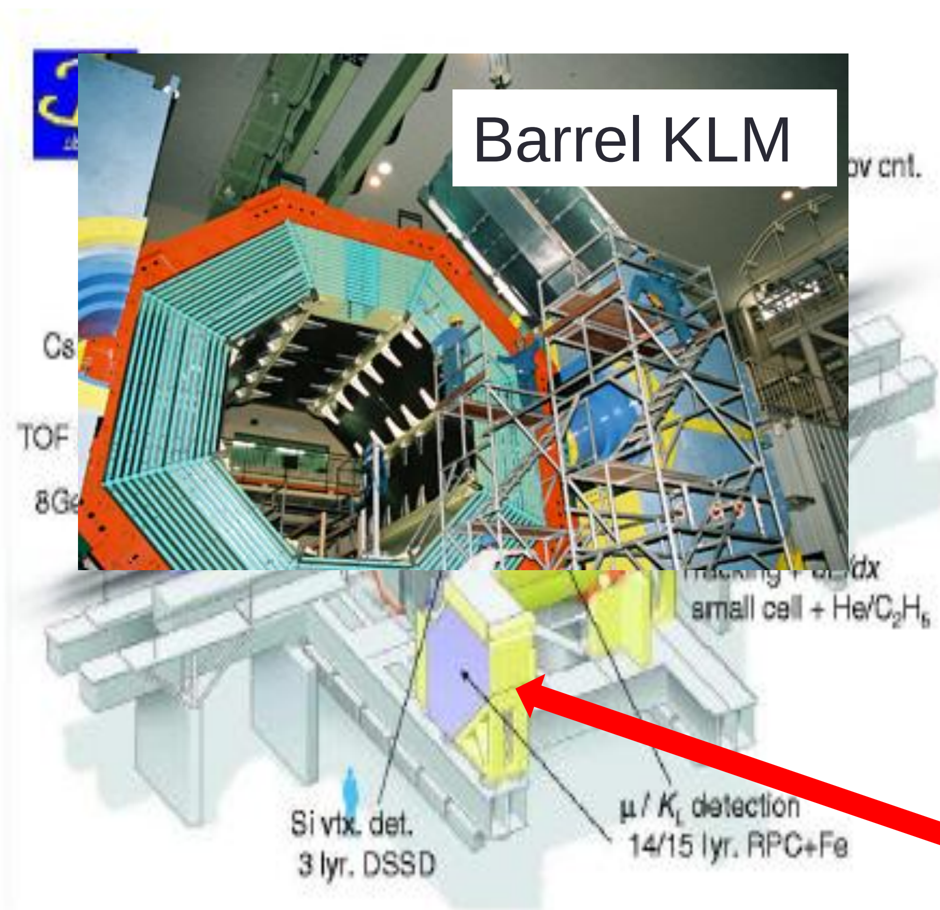

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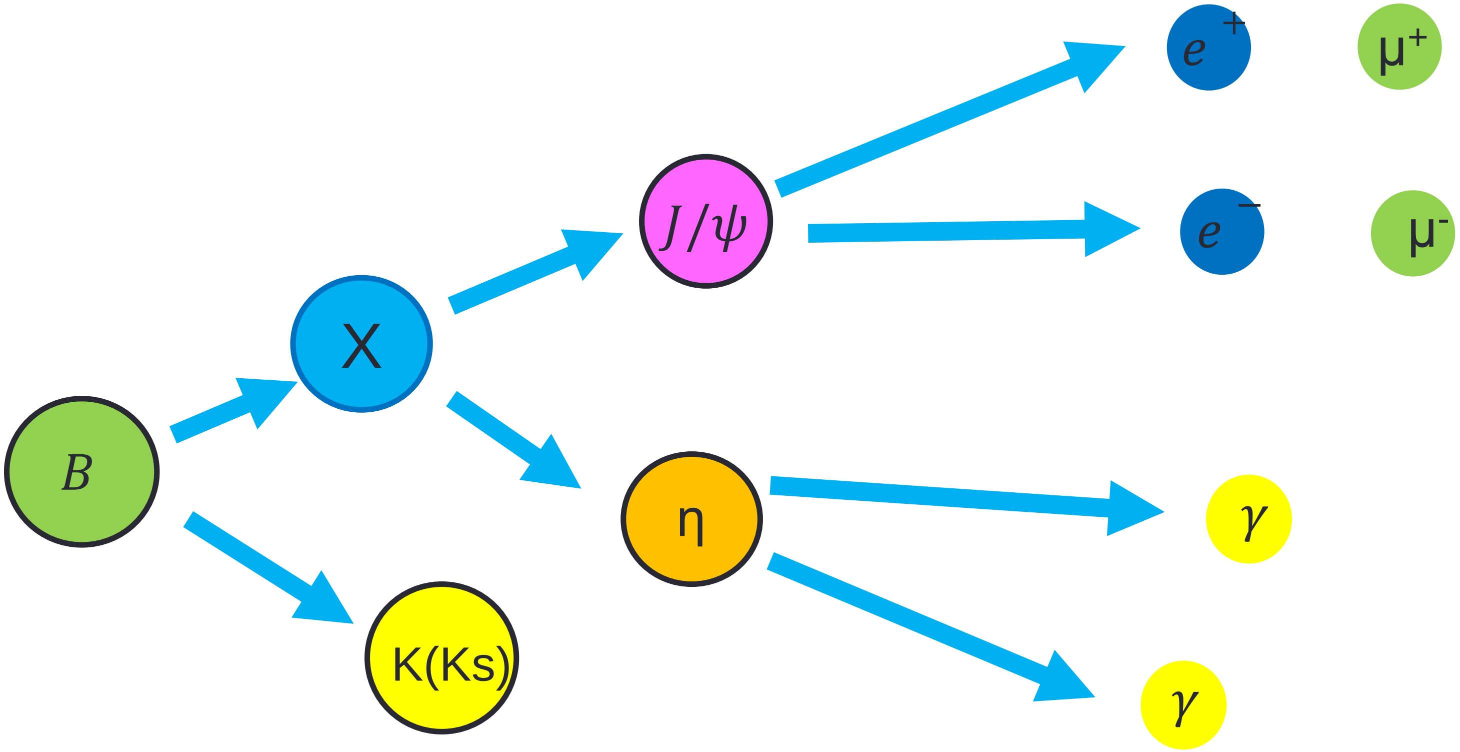
ANALYSIS

$B \to J/\psi\eta K$ analysis



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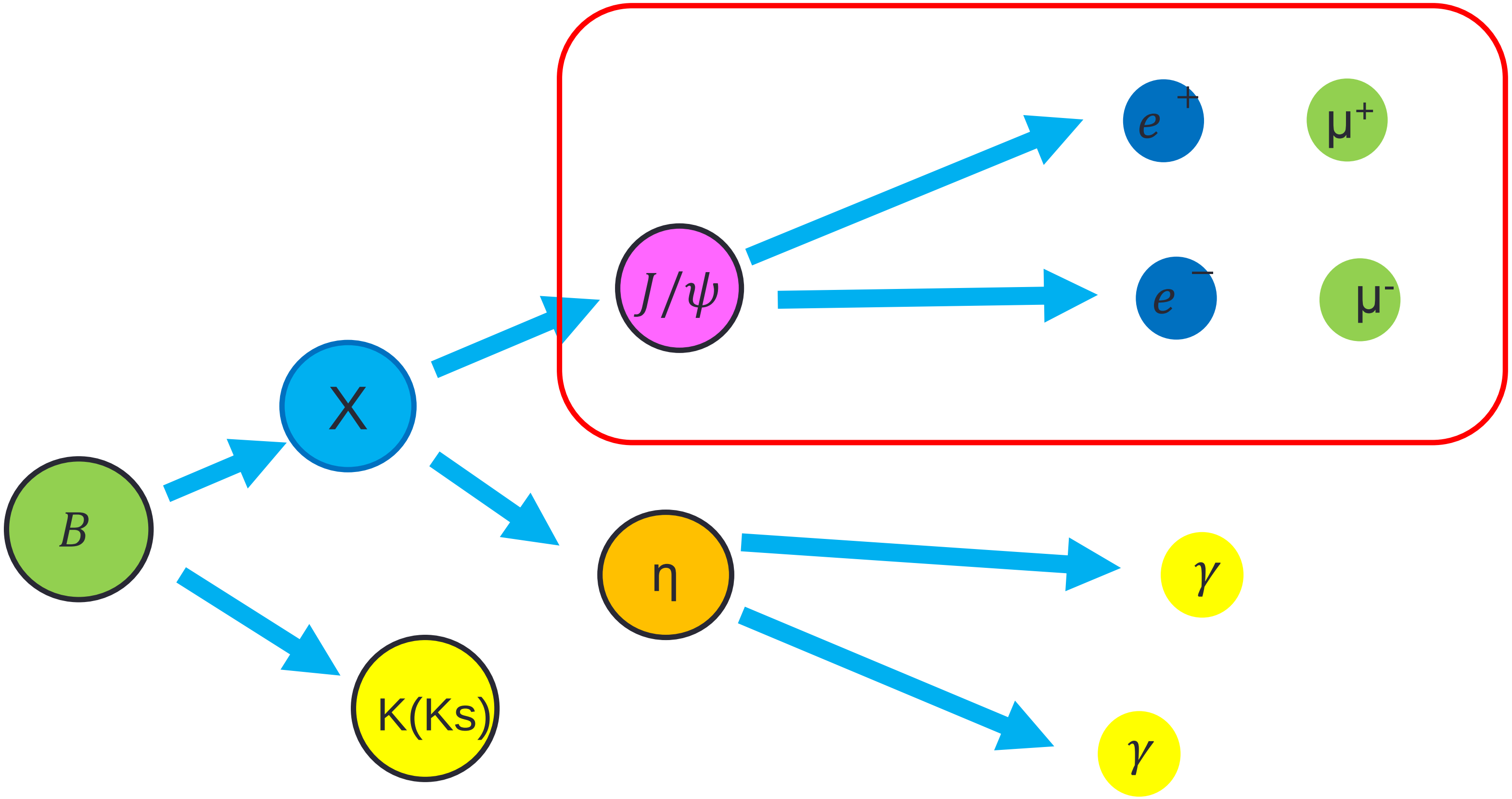
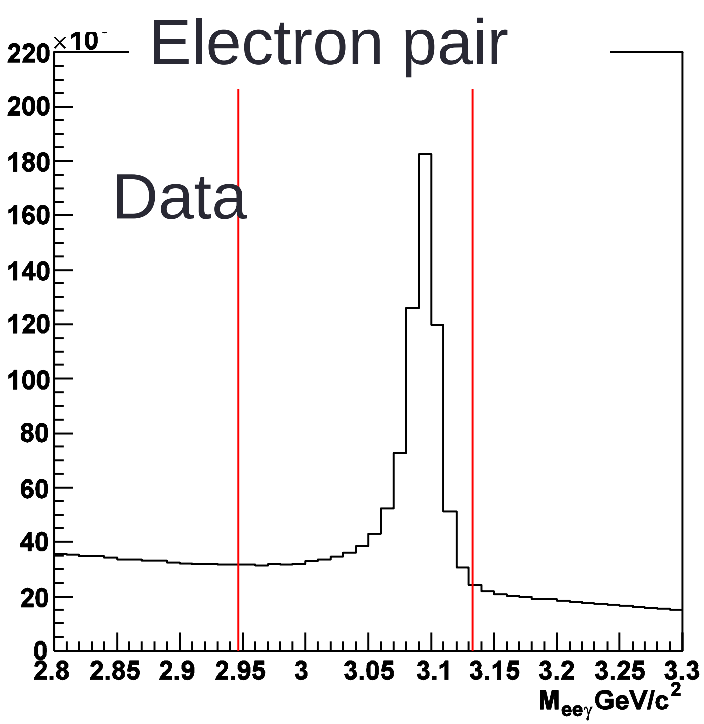
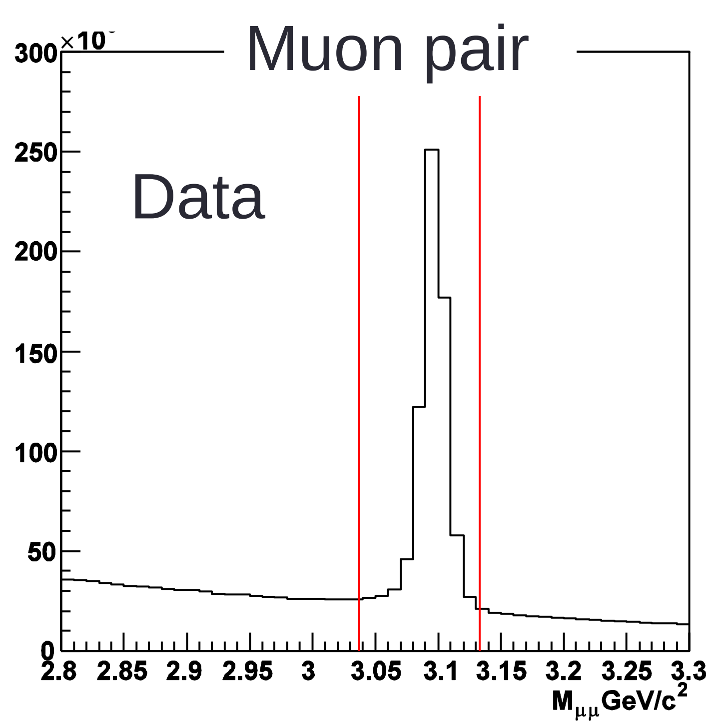


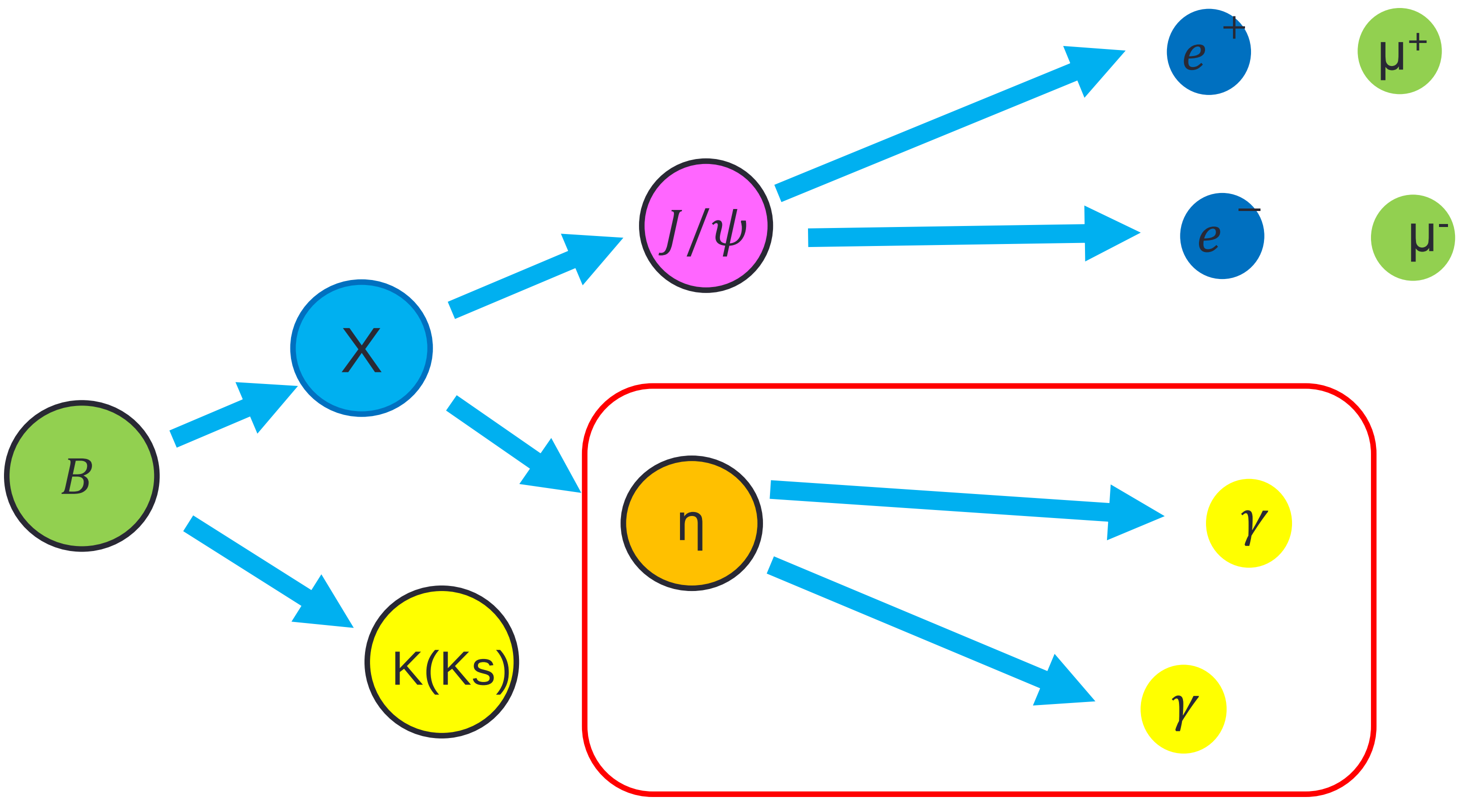
J/ψ reconstruction

- Using lepton pair ($e^{+}e^{-}(\gamma)$and $\mu^{+}\mu^{-}$)



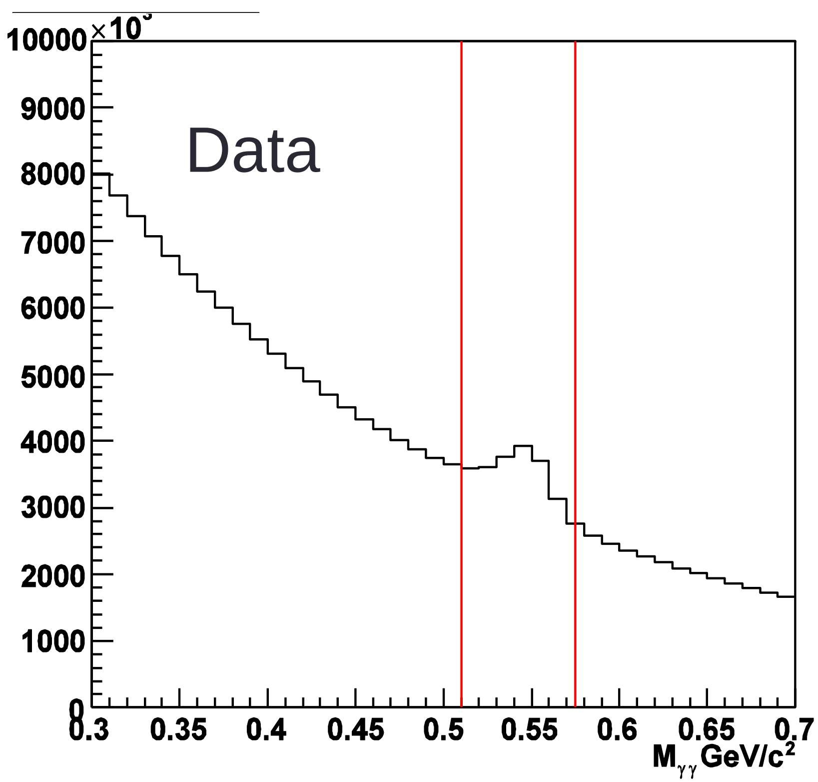


$B \to J/\psi \eta K$ analysis



η reconstruction

- Reconstructed by γ pair



γ make many background. So, we try to reduce it using under condition

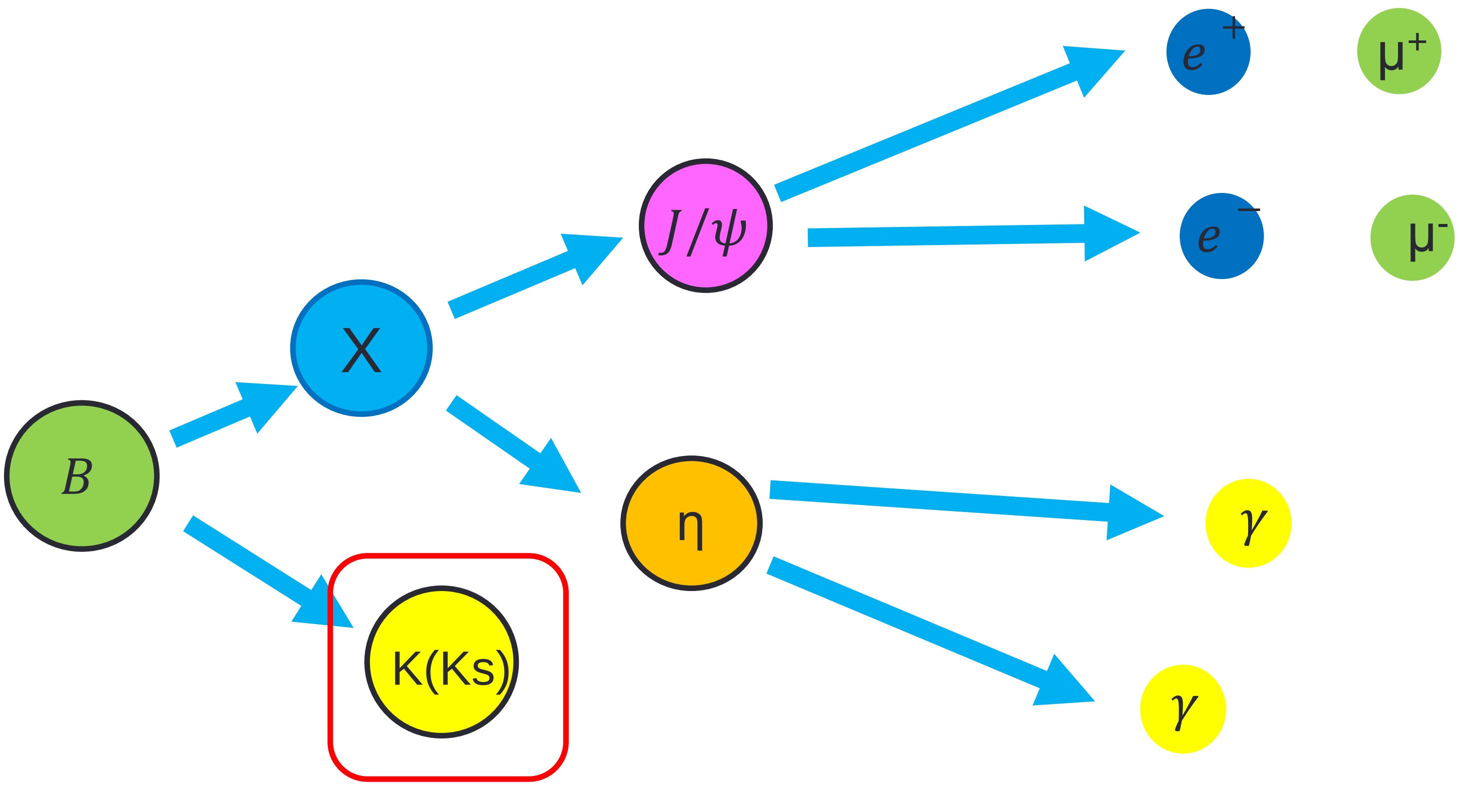
1) Energy threshold
   E_{th}>100MeV

2) Energy balance

$$A_E = \frac{|E_1 - E_2|}{E_1 + E_2} < 0.8$$

3) For π^0 veto
   $0.125 GeV/c^2 < M_{\gamma\gamma} < 0.140 GeV/c^2$

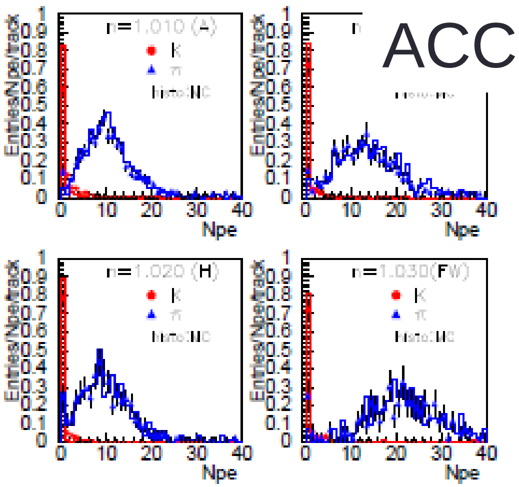
$B \to J/\psi\eta K$ analysis

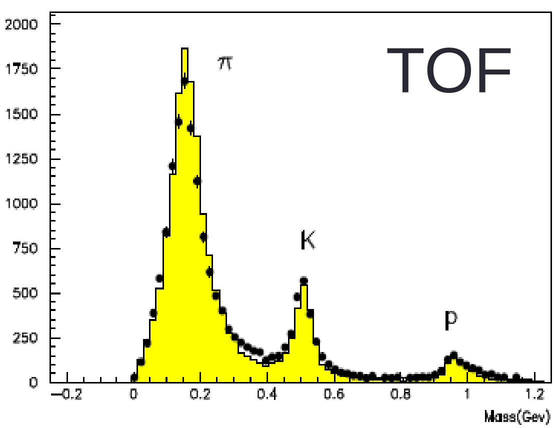


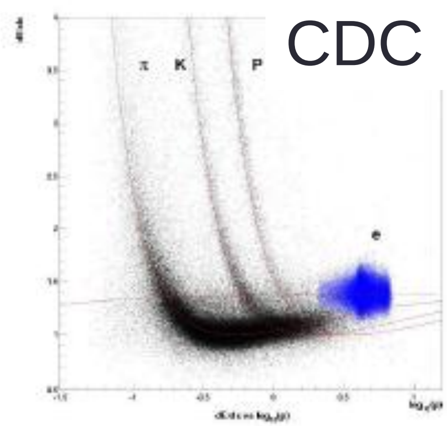
$K^{\pm}$ selection

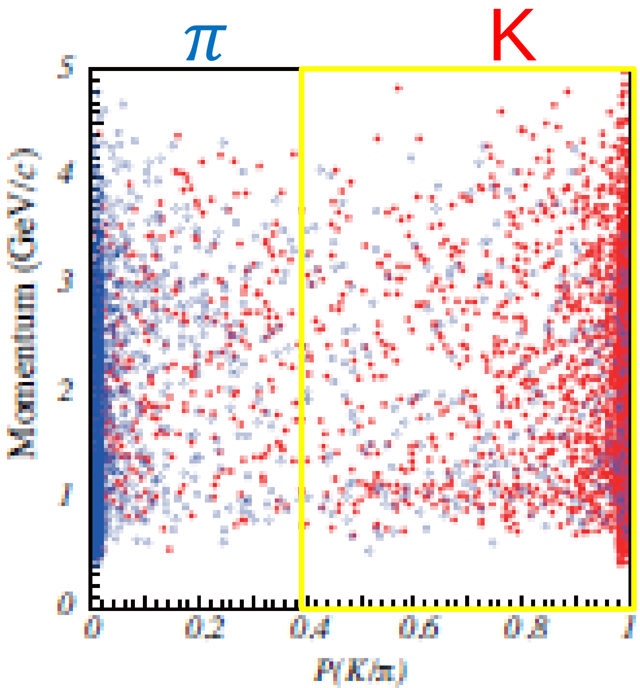
Number of photoelectron (ACC)
Time of flight (TOF)
Energy loss (CDC)

Distinguished from each information.



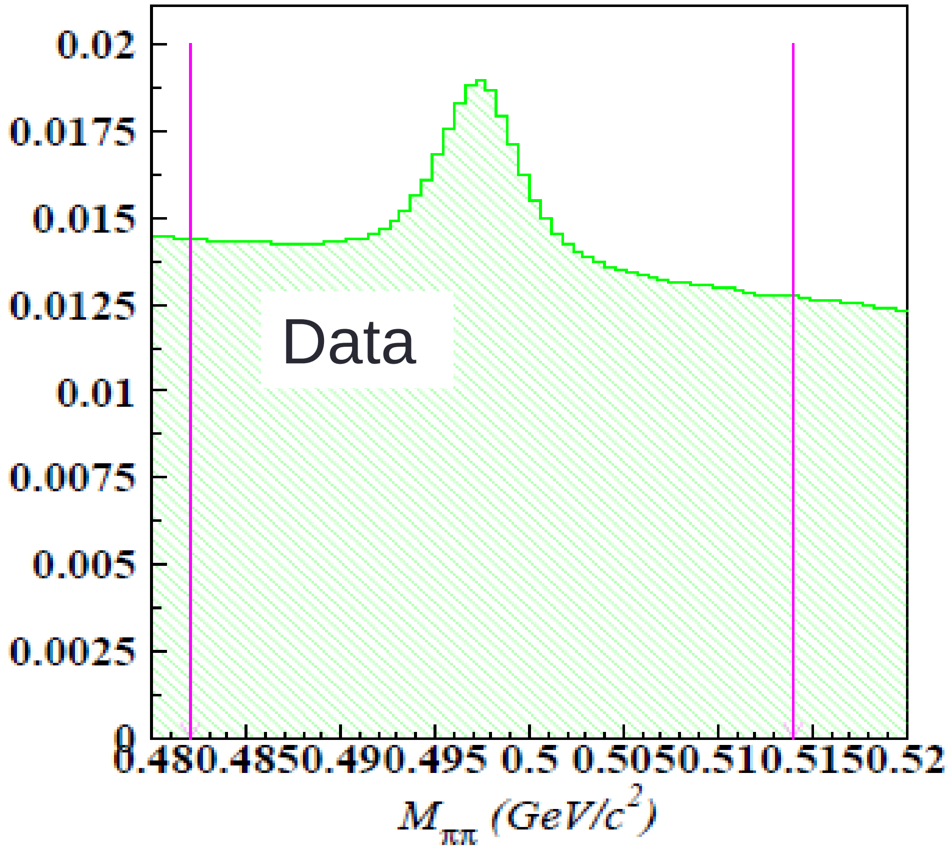




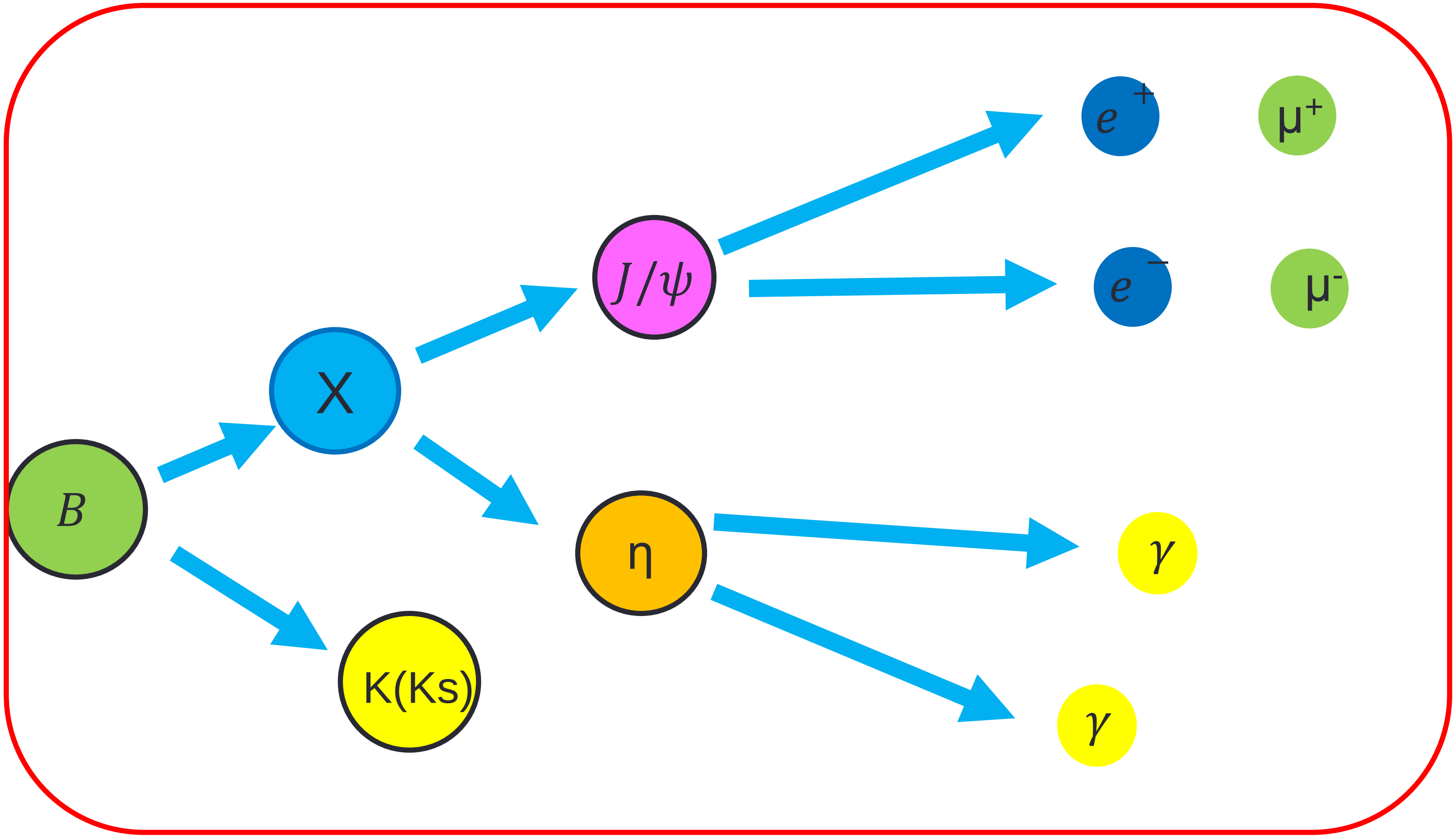


K_S^0 reconstruction

K_S^0 is reconstructed by $\pi^+\pi^-$



$B \to J/\psi\eta K$ analysis



B reconstruction

Common variable used in analyses

Beam constraint mass

$$M_{bc} = \sqrt{E_{beam}{}^2 - \left|\vec{p}_{J/\psi}{}^* + \vec{p}_\eta{}^* + \vec{p}_K{}^*\right|^2}$$

If it is correct
M_{bc} = 5.279GeV/c^2

Energy difference

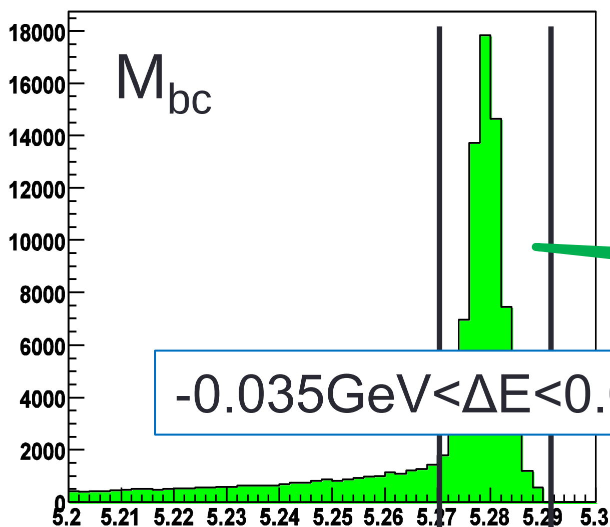
$$\Delta E = (E_{J/\psi}{}^* + E_\eta{}^* + E_K{}^*) - E_{beam}$$

If it is correct $\Delta E = 0$

E_{beam}	Beam energy
$\vec{p}_{J/\psi}{}^*, E_{J/\psi}{}^*$	J/ψ's momentum and energy
$\vec{p}_\eta{}^*, E_\eta{}^*$	η's momentum and energy
$\vec{p}_K{}^*, E_K{}^*$	K's momentum and energy

B reconstruction

…d in analyses

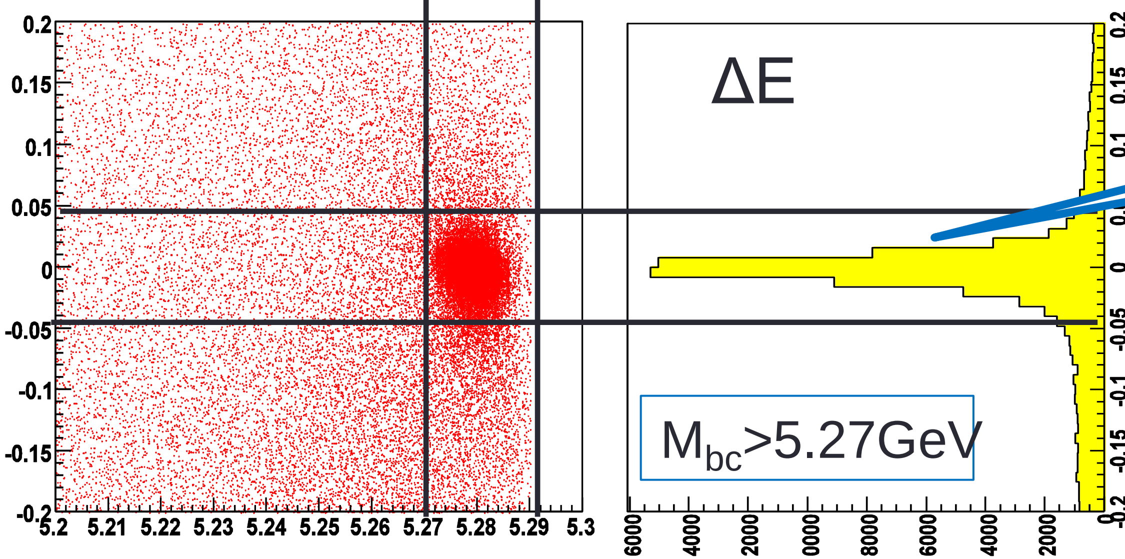


…raint mass

$\left| \vec{} \quad {}^* \quad \vec{p}_\eta{}^* + \vec{p}_K{}^* \right|^2$

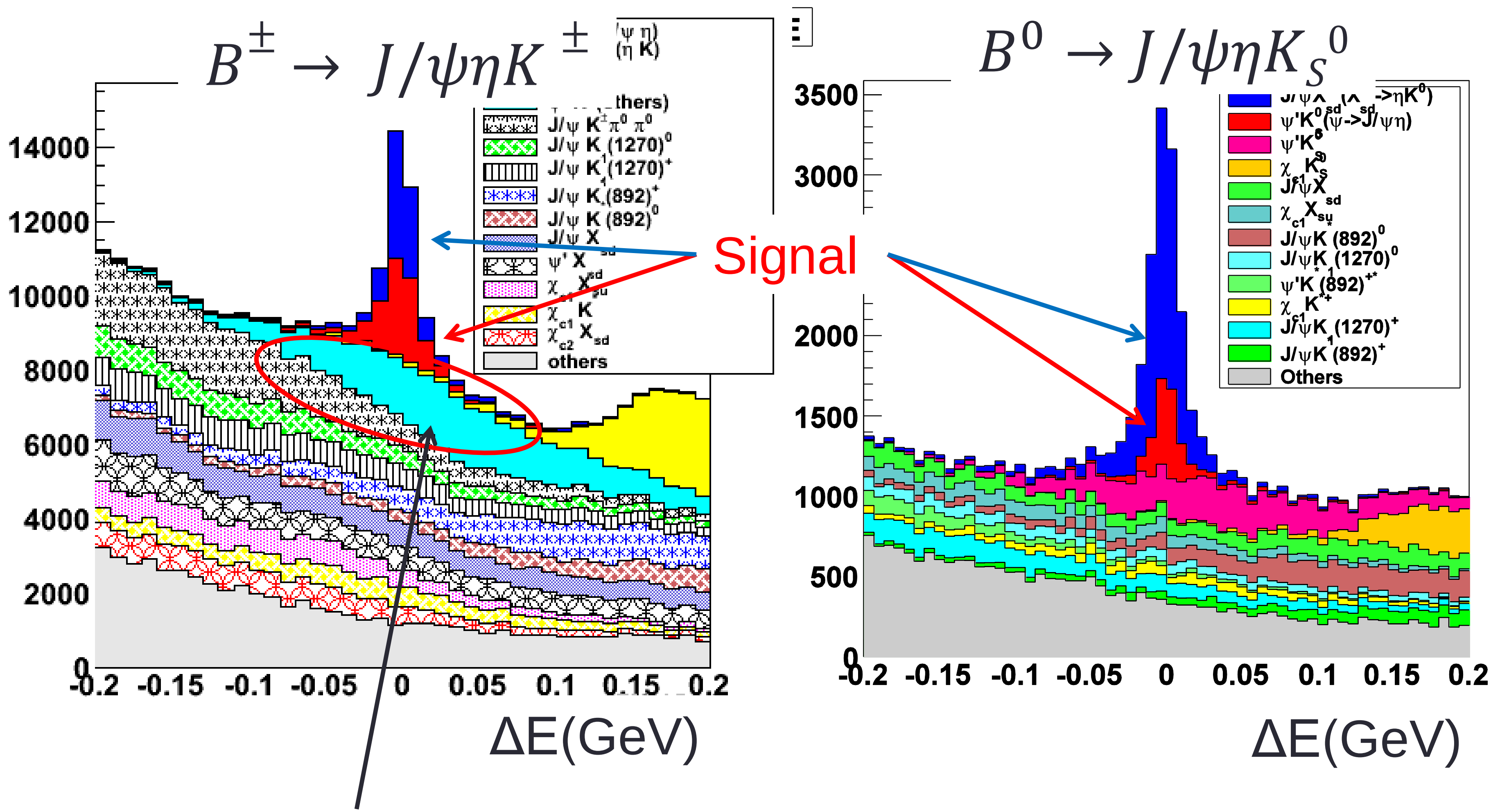
If it is correct
$M_{bc} = 5.279\text{GeV/c}^2$

…erence



If it is correct $\Delta E = 0$

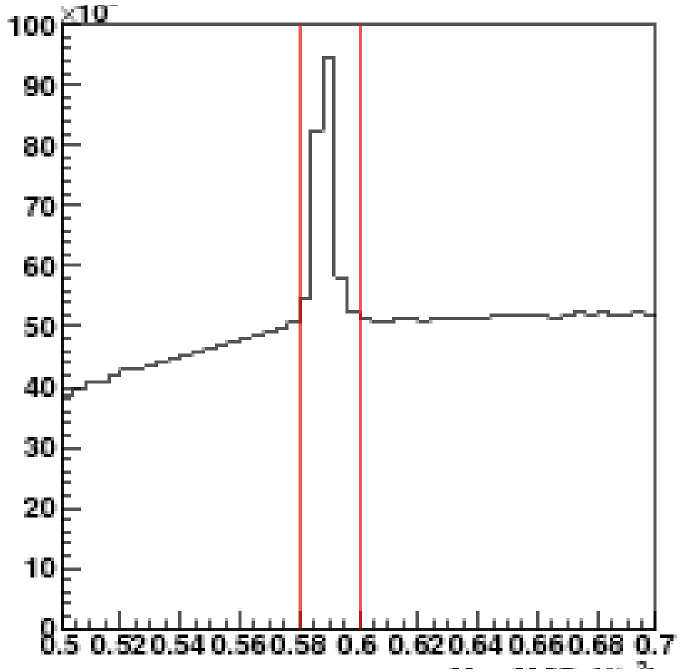
Background study of $B \to J/\psi\eta K$



B→ψ'K±(ψ'↛J/ψη) background

Background reduction of $\psi' \to J/\psi\pi^+\pi^-$ veto

The $\psi' \to J/\psi\pi\pi$ has peak.



$M_{J/\psi\pi\pi}$-$M_{J/\psi}$

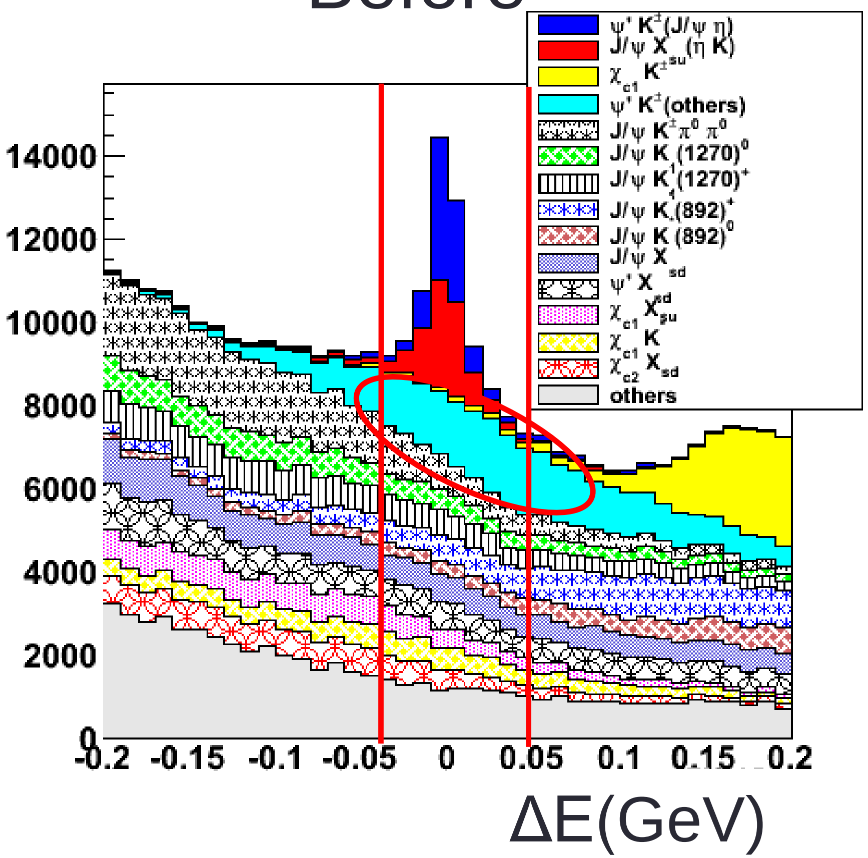
	N_S	N_B	S/N	F.O.M.
W/O veto	448.8	759.3	0.59	12.91
ψ' veto	422.0	649.1	0.65	12.89

Using F.O.M($=N_S/\sqrt{N_S+N_B}$), we estimated this veto effect.

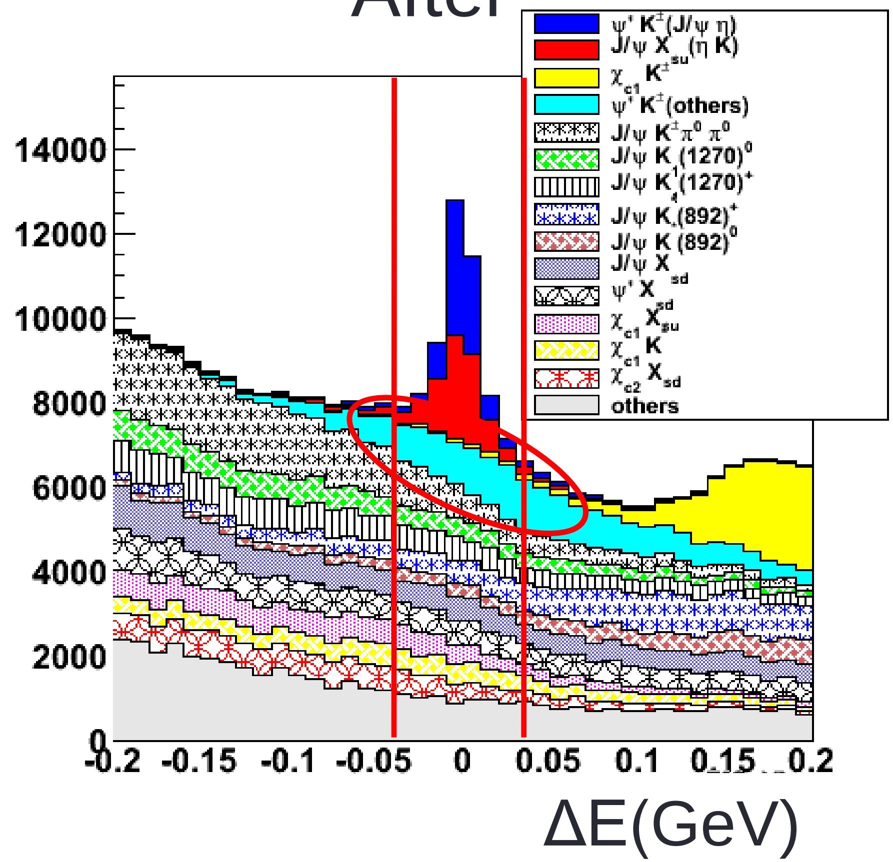
$0.58\mathrm{GeV}/c^2 < M_{J/\psi\pi\pi}-M_{J/\psi} < 0.60\mathrm{GeV}/c^2$ for ψ' veto.

After applied $\psi' \to J/\psi\pi\pi$ veto

Before



After



$B \to \psi' K^{\pm} (\psi' \nrightarrow J/\psi\eta)$ background decreases as expected around signal region. ($-0.035 < \Delta E < 0.03$)

Signal extraction

Using "Extended unbined maximum likelihood fit"

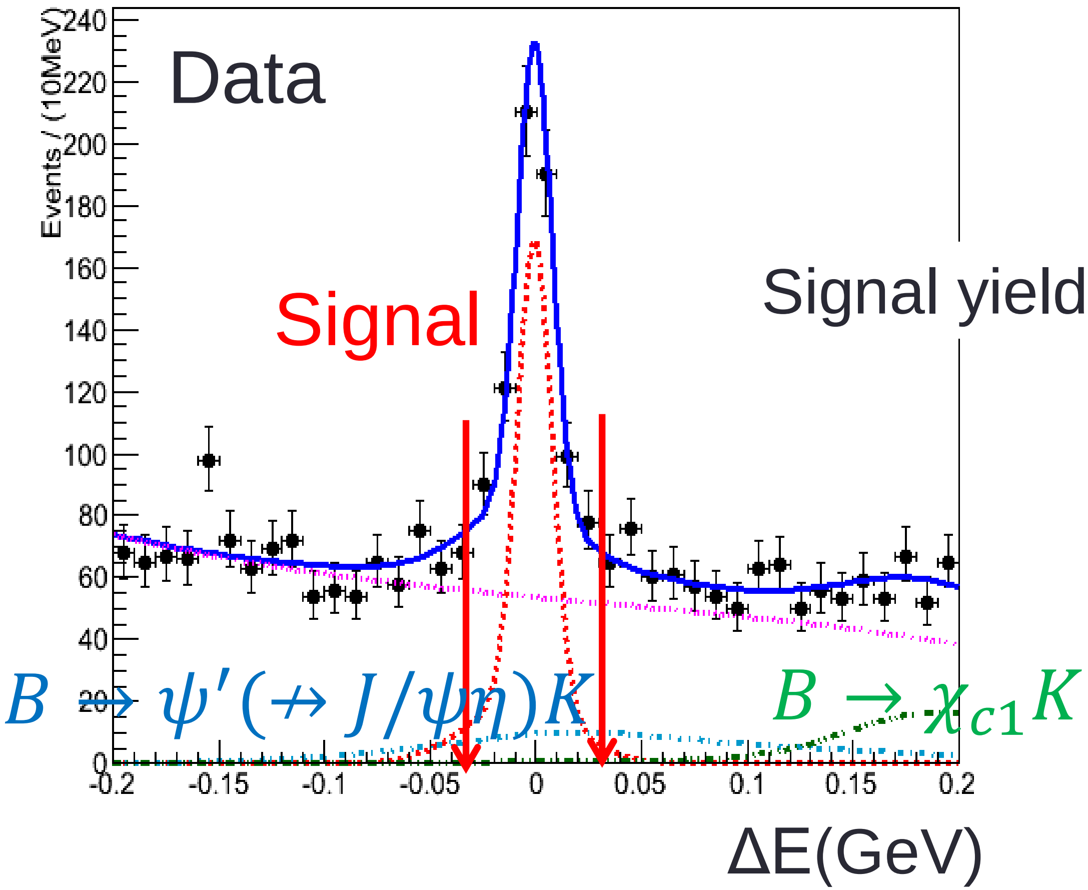
The likelihood function is defined as

$$L(n_{sig}, n_{bkg}) = \boxed{\frac{(n_{sig} + n_{bkg})^N}{N!} \exp[-(n_{sig} + n_{bkg})]} \times \prod_{i=1}^{N} \left[\frac{n_{sig}}{n_{sig} + n_{bkg}} P_{sig}(x_i) + \frac{n_{bkg}}{n_{sig} + n_{bkg}} P_{bkg}(x_i) \right]$$

where $P_{sig}(x)$ and $P_{bkg}(x)$ are a probability density function (PDF) of a measurement x for given parameters.

The set of parameters that maximize this likelihood function is most probable.

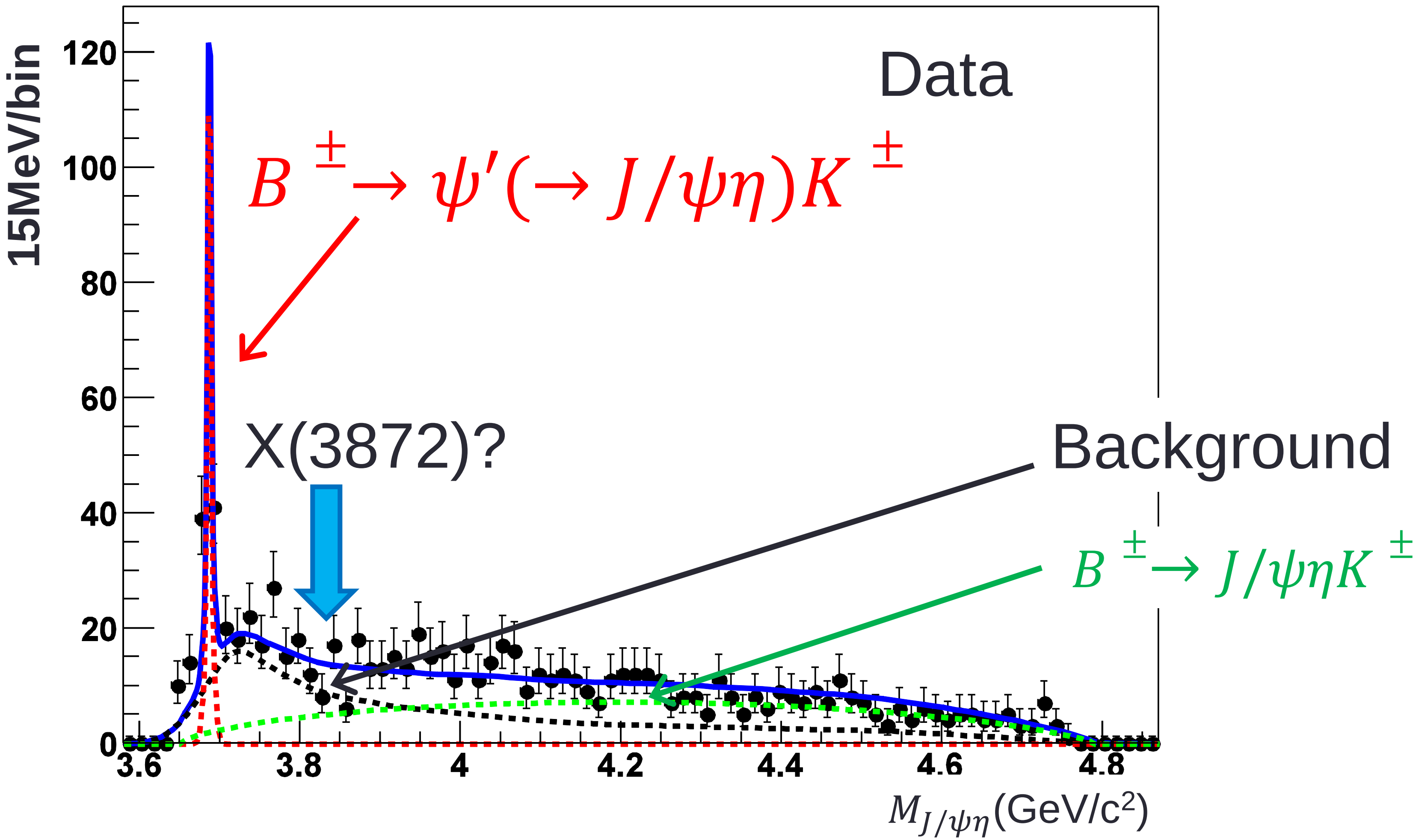
Result of $B^{\pm} \to J/\psi\eta K^{\pm}$



Signal yield is 403 ± 35 events.

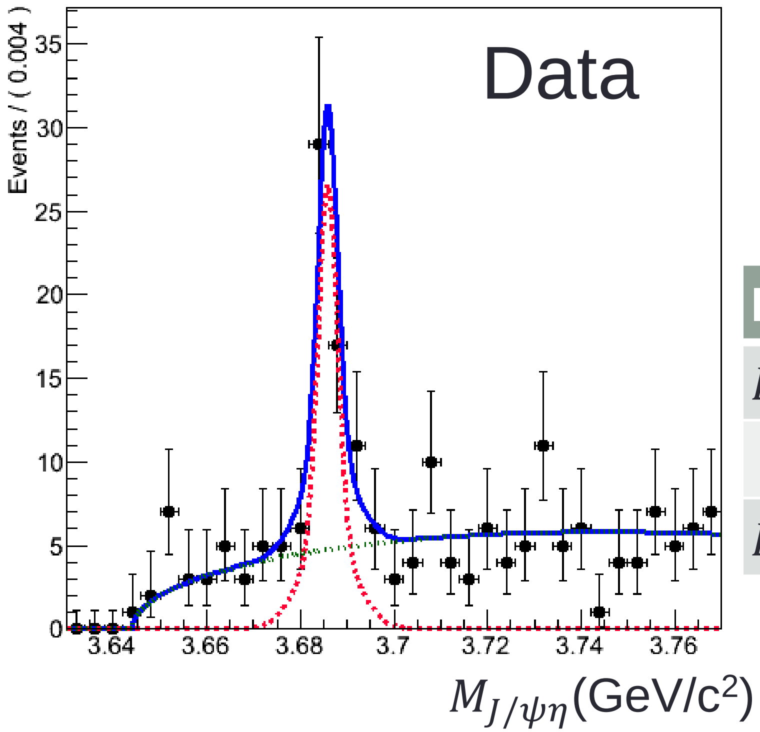
Next step
looking $M_{J/\psi\eta}$

$M_{J/\psi\eta}$ in $B^{\pm} \to J/\psi\eta K^{\pm}$



- $B^{\pm} \to J/\psi\eta K^{\pm}$ signal other than $B^{\pm} \to \psi'(\to J/\psi\eta)K^{\pm}$ has phase space like distribution.

Resolve ψ'K and others

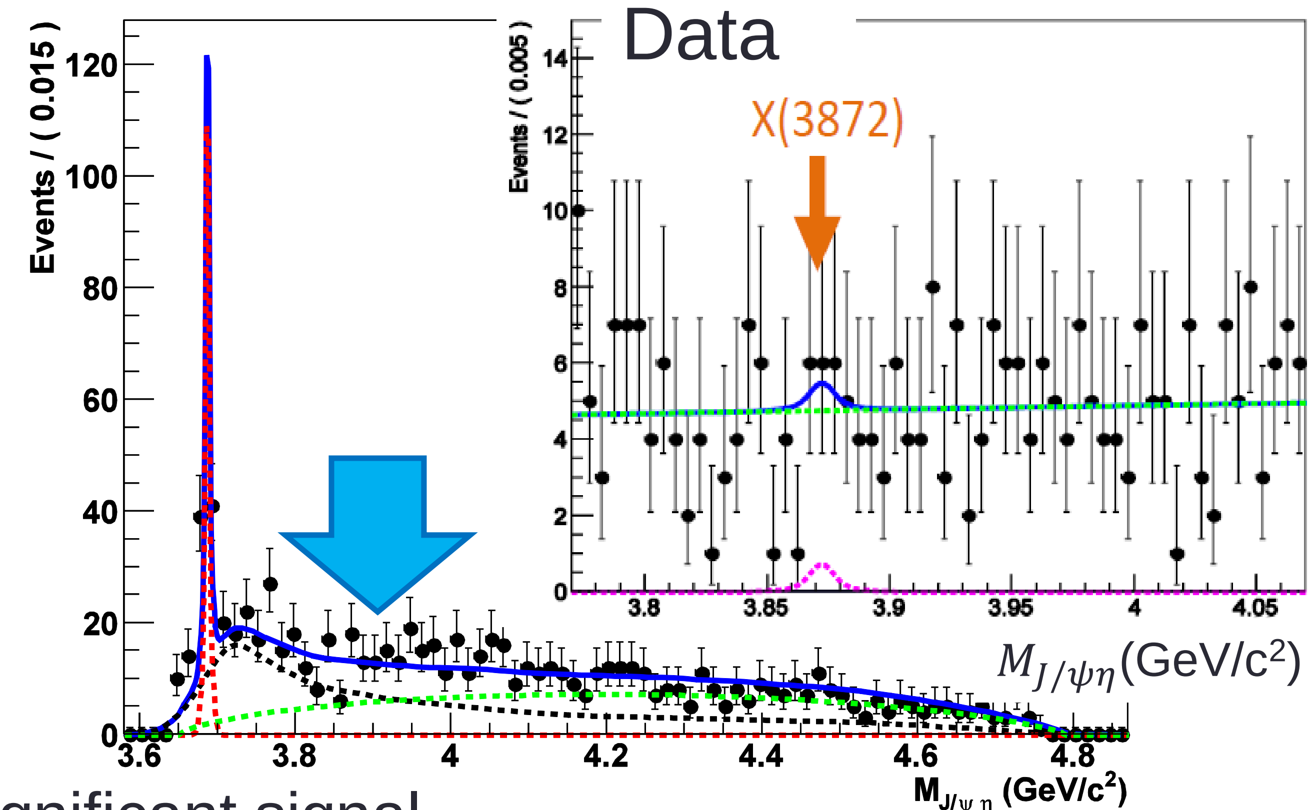


$B^{\pm} \to J/\psi\eta K^{\pm}$(Others) is obtained by subtracting ψ'K contribution.

Decay mode	yield	ε(%)	Br($\times 10^{-4}$)
$B^{\pm} \to J/\psi\eta K^{\pm}$(Total)	403 ± 35	9.1	1.3 ± 0.1
$B^{\pm} \to \psi'(\to J/\psi\eta)K^{\pm}$	46 ± 8	8.5	0.2 ± 0.03
$B^{\pm} \to J/\psi\eta K^{\pm}(\mathrm{Other})$	357 ± 38	9.1	1.1 ± 0.1

ψ'signal yield is 45.6 ± 8.2 events

X(3872) search



No significant signal

To get 90 % C.L. U.L. for

Br($B^{\pm} \rightarrow X(3872)(\rightarrow J/\psi\eta)K^{\pm}$) $< 3.8 \times 10^{-6}$

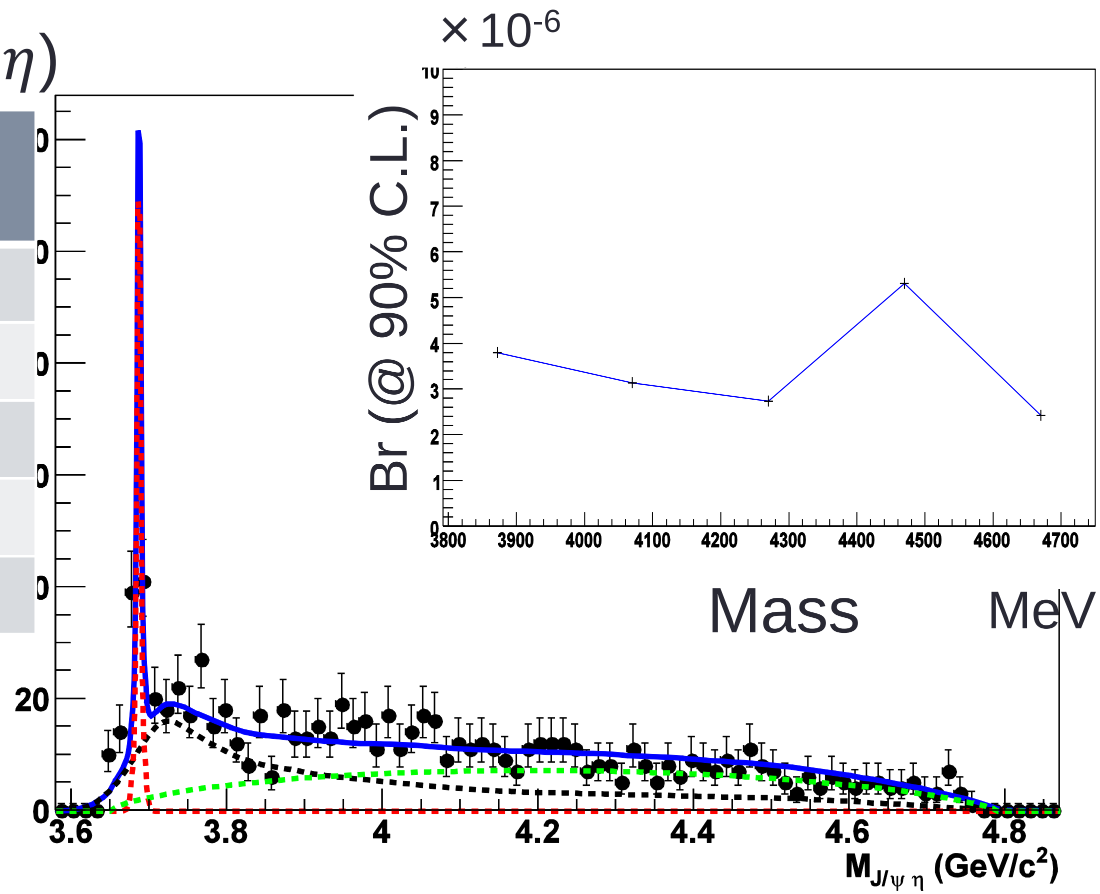
(PDG$< 7.7 \times 10^{-6}$)

Narrow resonances search

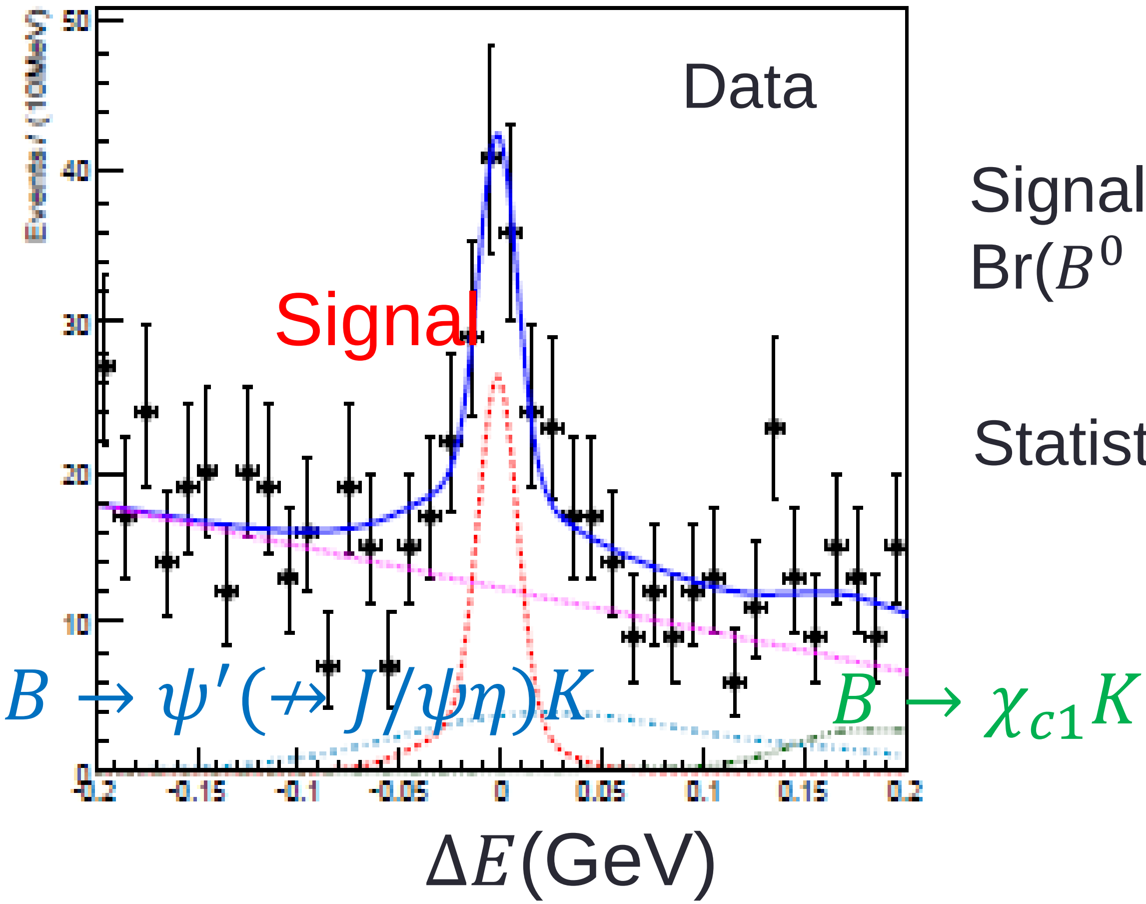
- U.L. (@ 90 % C.L.) is also provided at different masses using 0 width hypothesis

$\mathrm{Br}(B \to \boldsymbol{X}\mathrm{K}) \times \mathrm{Br}(\boldsymbol{X} \to J/\psi\eta)$

X	U.L. (×10^-6) Include systematics
X(3872)	3.8
4070	3.1
4270	2.7
4470	5.3
4670	2.4



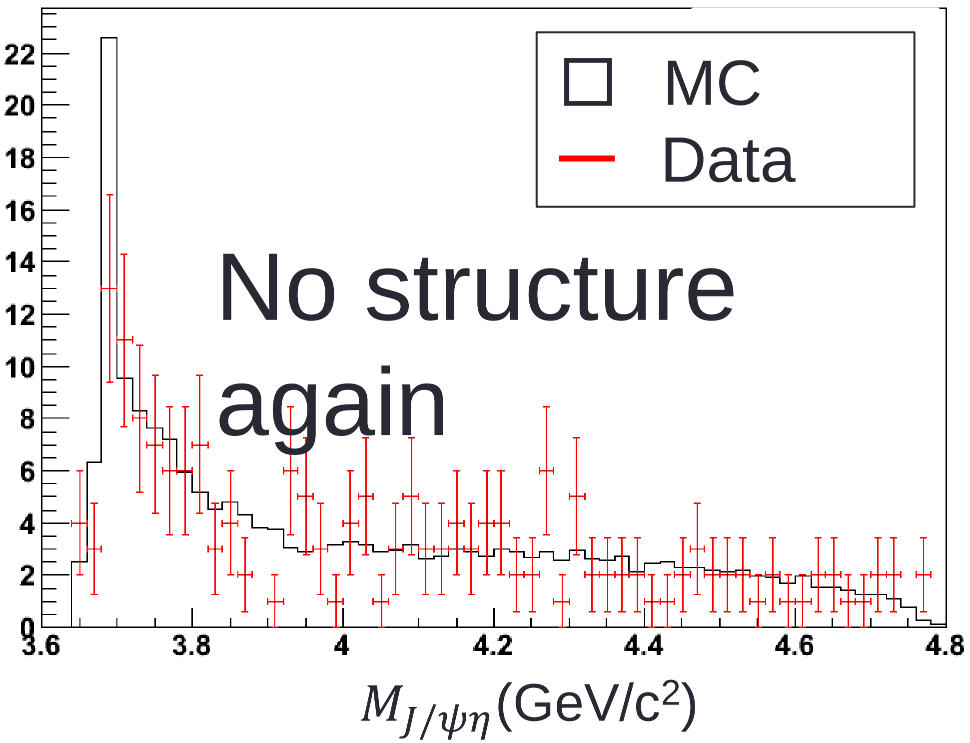
$B^0 \to J/\psi \eta K_S{}^0$



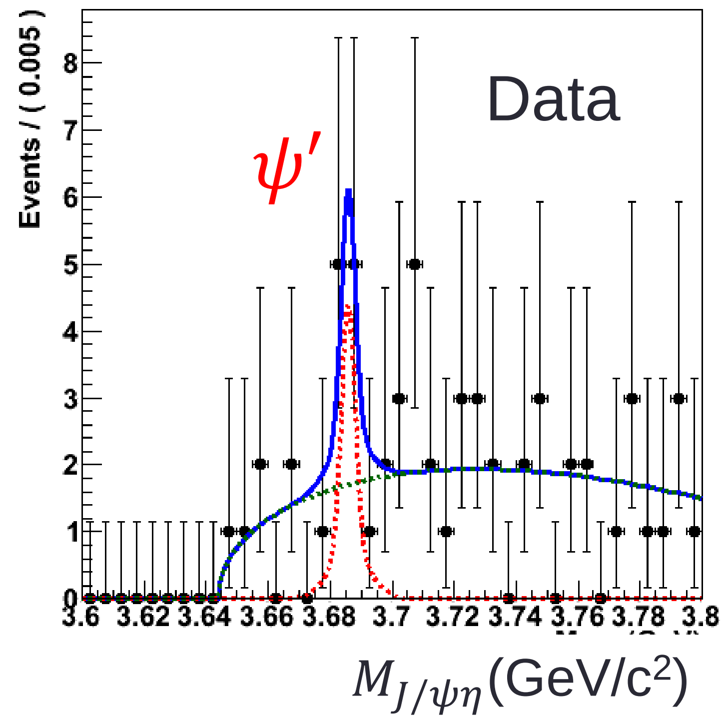
Signal yield is 94 ± 14 events.
Br($B^0 \to J/\psi \eta K_S{}^0$)
=$(5.2 \pm 0.8) \times 10^{-5}$

Statistical significance=8σ

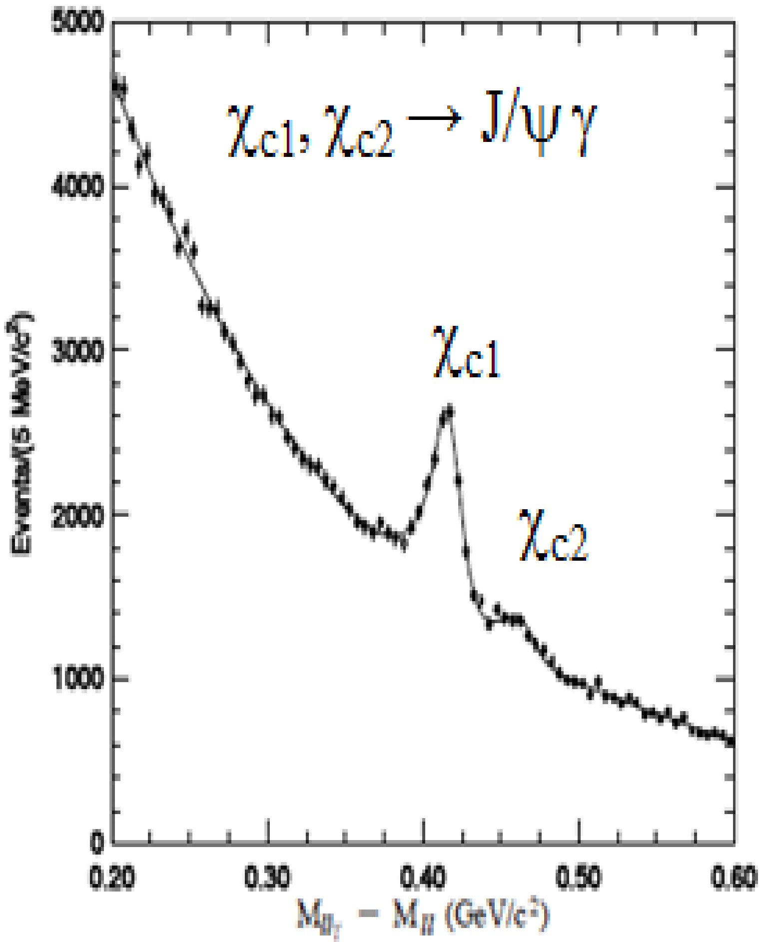
$M_{J/\psi\eta}$ in $B^0 \to J/\psi\eta K_S{}^0$

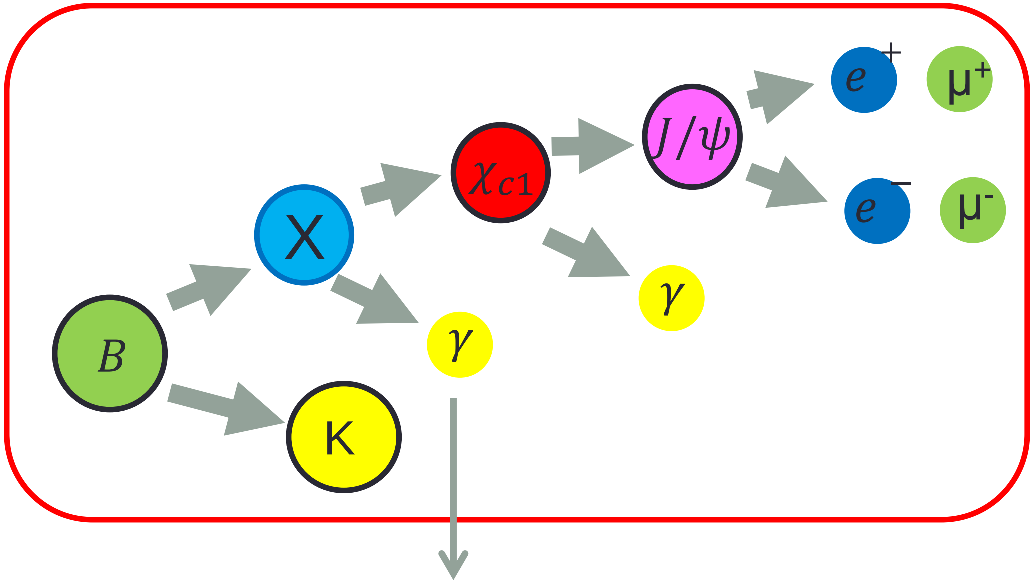


No structure again



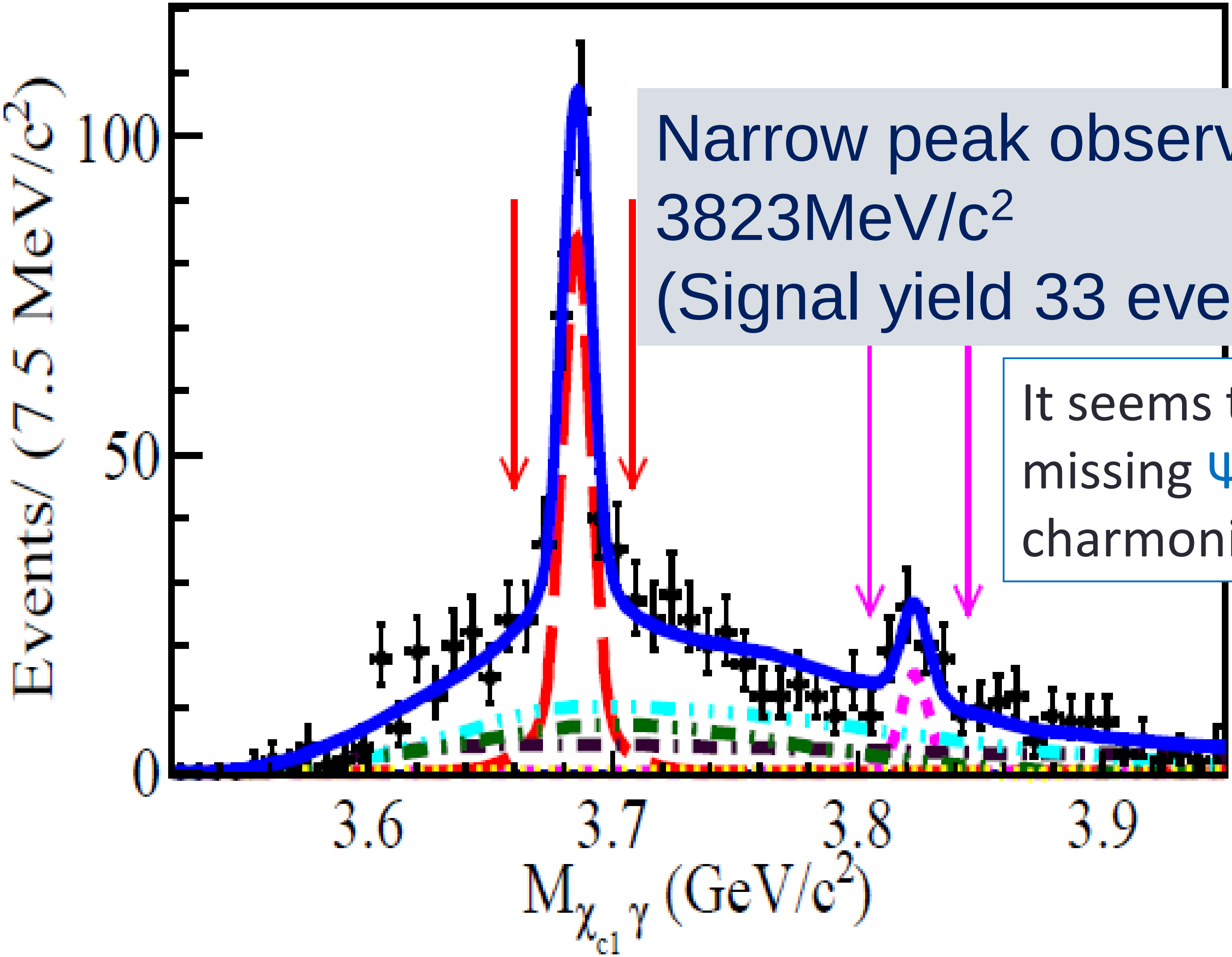
$B^{\pm} \rightarrow \chi_{c1_{(c2)}} \gamma K^{\pm}$ analysis





This γ's energy scale adjusted to make ΔE = 0 in order to improve mass resolution of $\chi_{c1(c2)}\gamma$.

$M_{\chi c1\gamma}$ distribution



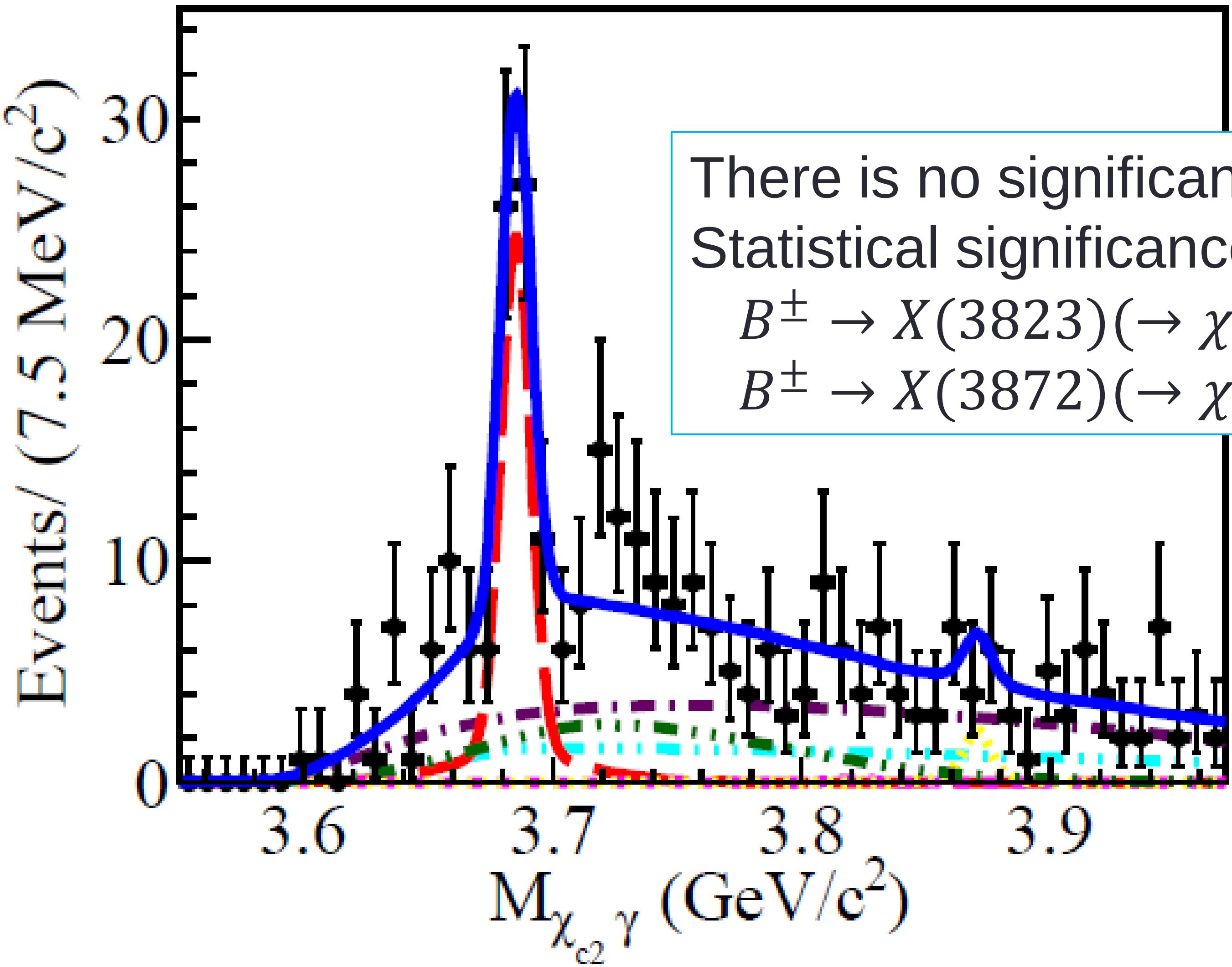
Narrow peak observed at 3823MeV/c^2
(Signal yield 33 events.)

It seems to be the missing Ψ_2 from the charmonium spectrum .

$Br(B^{\pm} \rightarrow X(3872)(\rightarrow \chi_{c1}\gamma)K^{\pm}) < 1.9 \times 10^{-4}$

Belle preliminary

$M_{\chi c2\gamma}$ distribution



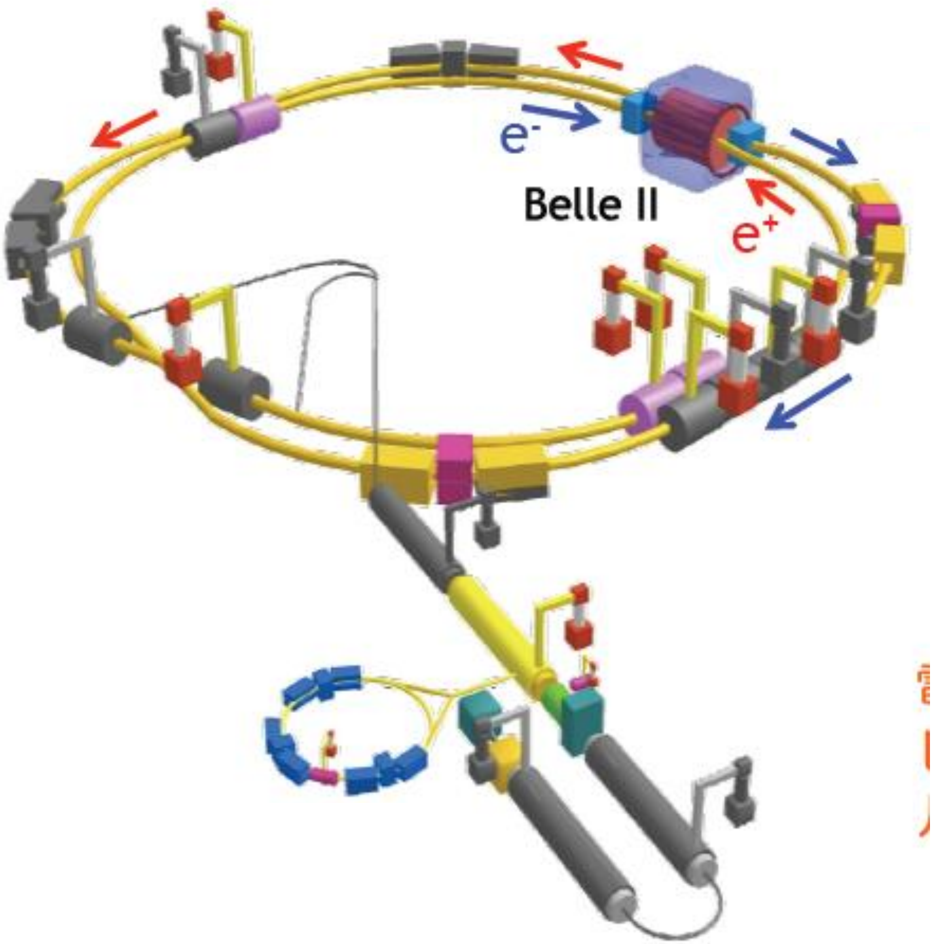
There is no significant peak.
Statistical significances are

$B^{\pm} \to X(3823)(\to \chi_{c1}\gamma)K^{\pm}$: 1.3σ

$B^{\pm} \to X(3872)(\to \chi_{c1}\gamma)K^{\pm}$: 0.8σ

BELLEII EXPERIMENT

Super KEKB accelerator



Beam energy

Electron : 8GeV

Positron : 3.5GeV

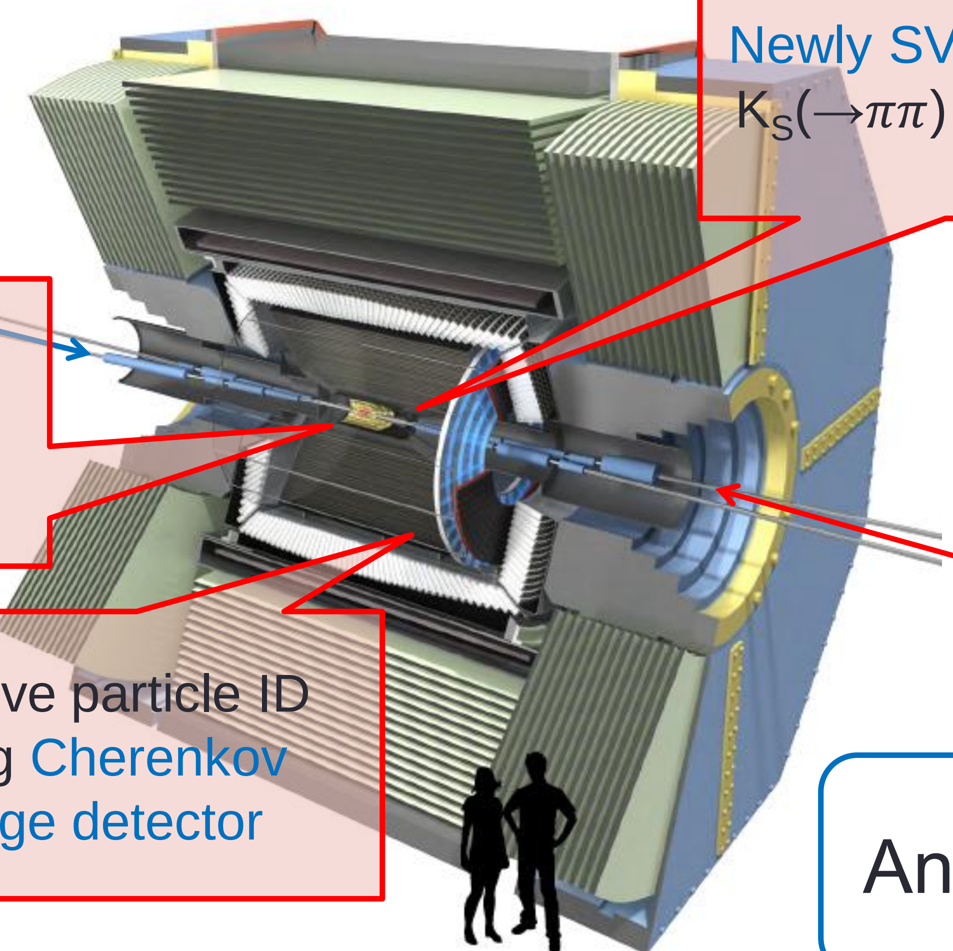
Electron : 7GeV

Positron : 4GeV

Luminosity 40 times

BelleII detector

High background countermeasure.



Newly SVD to improve $K_S(\rightarrow \pi\pi)$ acceptance

Electron (7 GeV)

Pixel detector for improve interaction point measurement

Positron (4 GeV)

Improve particle ID using Cherenkov image detector

And so on…

Interesting mode at BelleII experiment

- B➔$\tau\nu$
  - Related issues:φ1, B➔D$\tau\nu$ etc.
- B➔$K\pi$
  - Related issues:φ3
- B➔(ss)K_S
  - Related issues:φ1, B➔sγ etc.
- τ➔$\mu\gamma$
  - Related issues:τ➔$\mu\mu\mu$,τ➔$e\gamma$ etc.

We can explore the effects of New Physics in a variety of approaches.

Summary

- We search for X(3872)'s C-odd partner using J/$\psi\eta$ and $\chi_{c1}\gamma$
  - Peak at 3823 MeV in $\chi_{c1}\gamma$, likely to be ψ_2(1D).
  - Unfortunately we can not find C-odd partner of X(3872).

  We renew U.L.

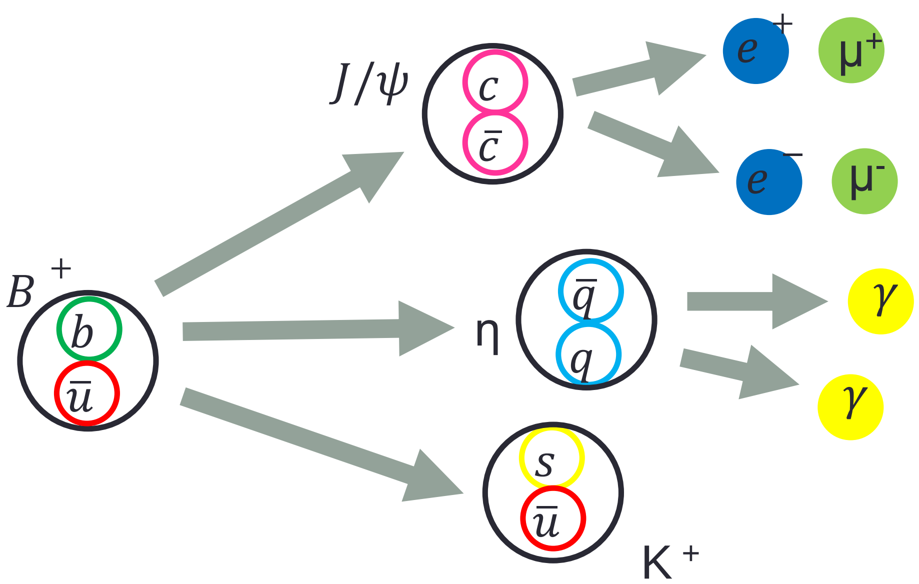
$$\mathrm{Br}(B^+ \rightarrow X(3872)K^+) \cdot Br(X(3872) \rightarrow J/\psi\eta)) < 3.8 \times 10^{-6}$$

We can search anything not only Belle but also BelleII experiment.

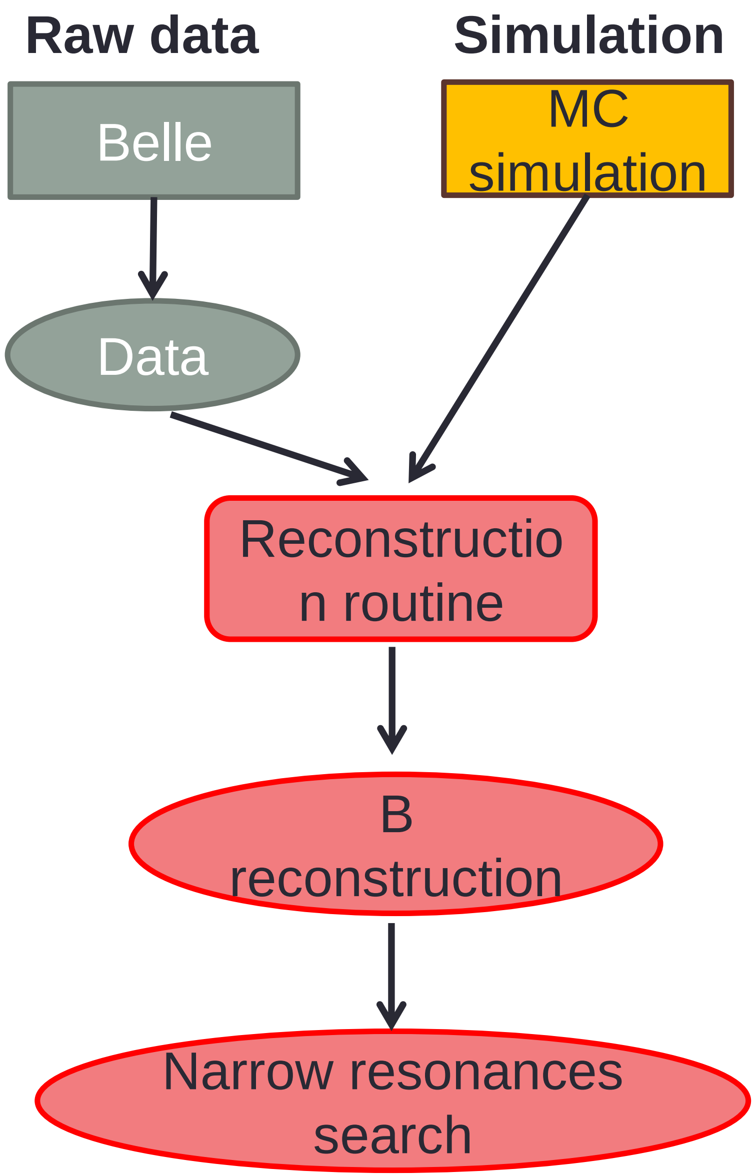
Thank you

BACK UP

Analysis method



$B \to J/\psi\eta K$ decay



MC sample

For study efficiency and background, we use MC simulation sample.
Two kind of MC samples are prepared.

Signal MC for efficiency study

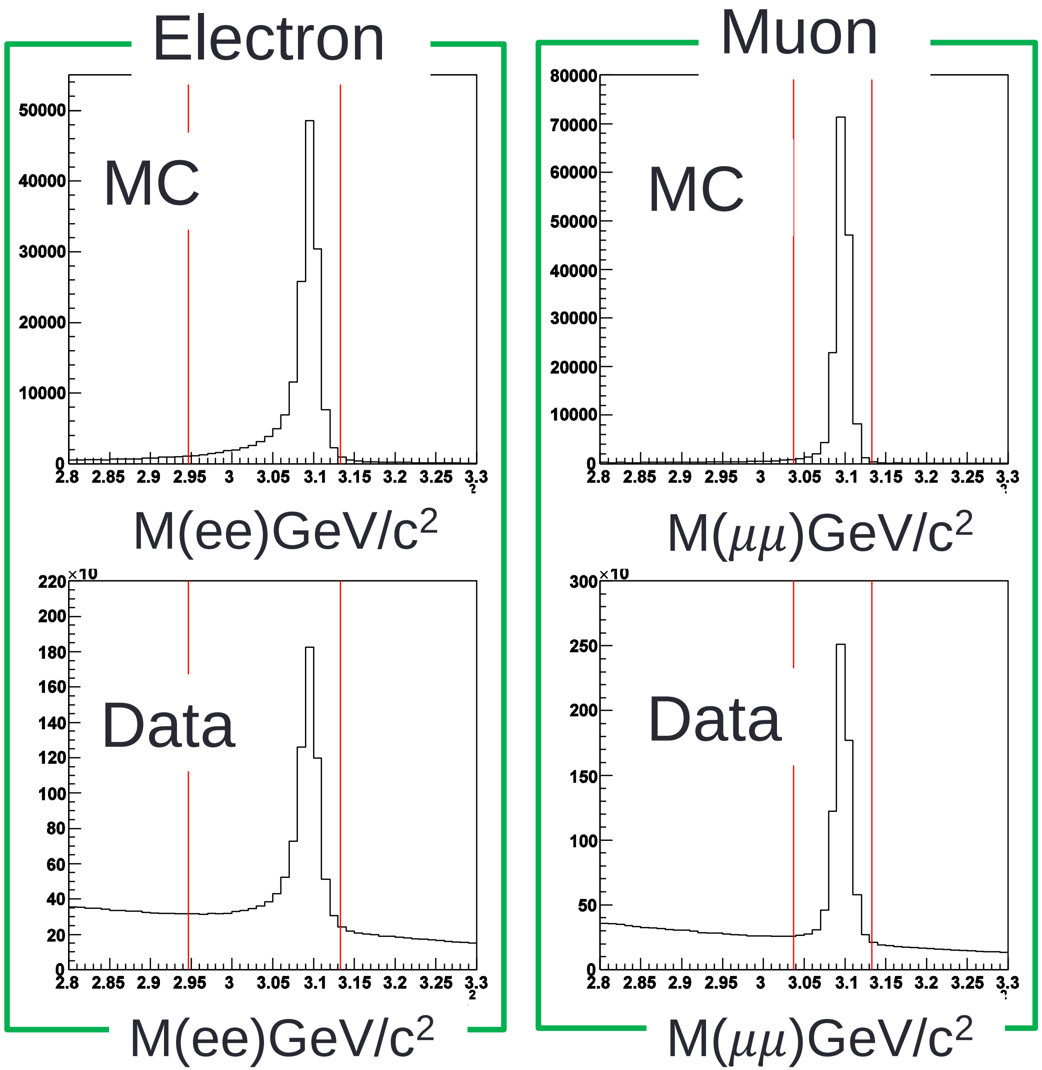
5×10^5 events generated with three body distribution obeying the available phase space of $B \rightarrow J/\psi\eta K$

For background study

The $B \rightarrow J/\psi X$ MC (100 times data, inclusive J/ψ MC) is prepared.
The most up-to-date B meson decay modes information are included.

J/ψ reconstruction

Using lepton pair (e^+e^- and $\mu^+\mu^-$)



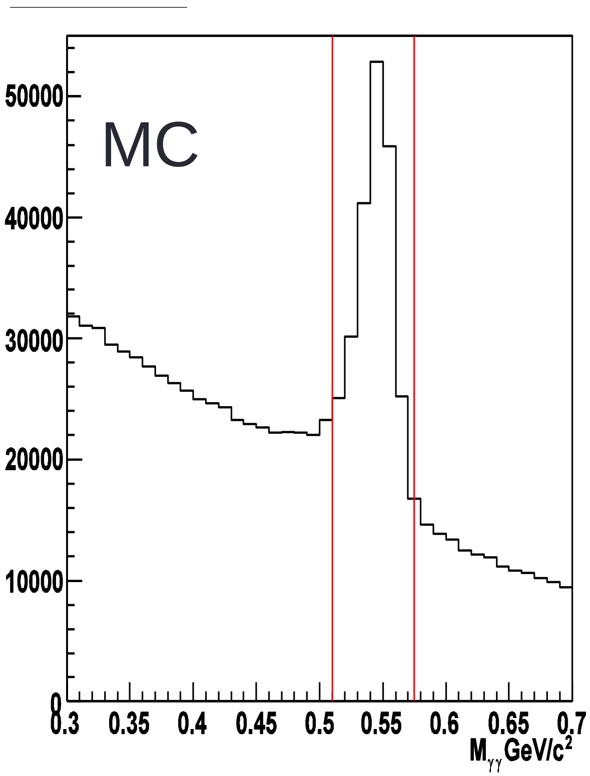
Electron case, momentum of e is lower than fact because of bremsstrahlung.
So, we added momentum of γ is less than 0.05rad

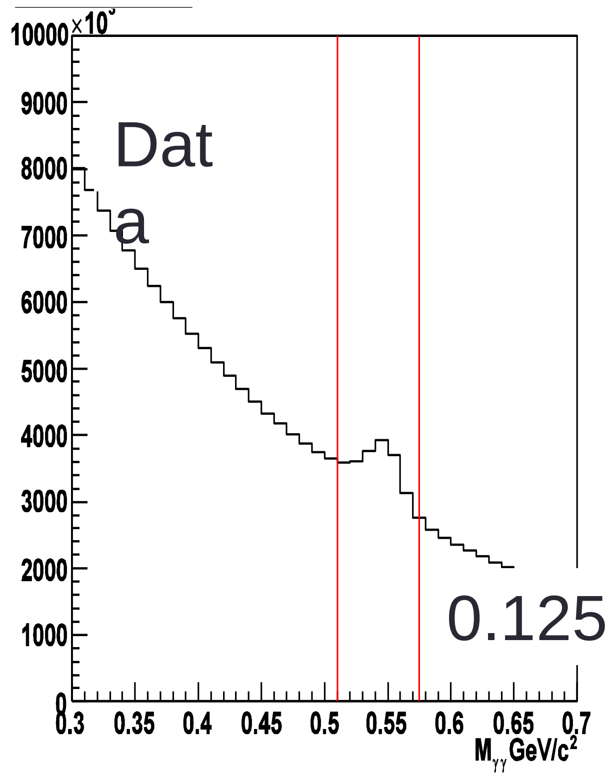
Mass window is
$-0.15\mathrm{GeV/c^2} < M_{J/\psi} - M_{ee\gamma} < 0.036\mathrm{GeV/c^2}$
$-0.06\mathrm{GeV/c^2} < M_{J/\psi} - M_{\mu\mu} < 0.036\mathrm{GeV/c}$

Where ($M_{J/\psi} = 3.09688\ \mathrm{GeV/c^2}$)

η reconstruction

Reconstructed by γ pair





1) Energy threshold
E_{th}>100MeV

2) Energy balance

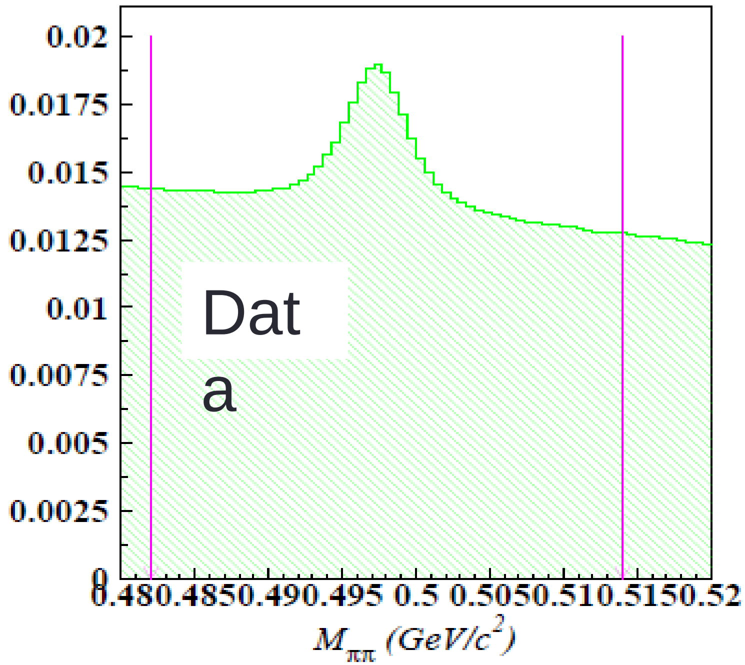
$$A_E = \frac{|E_1 - E_2|}{E_1 + E_2} < 0.8$$

3) For π^0 veto
$0.125\text{GeV/c}^2 < M_{\gamma\gamma} < 0.140\text{GeV}$
was removed.

Mass window is
$0.51 < M_{\gamma\gamma} < 0.575$ GeV/c^2

K_S^0 reconstruction

- K_S^0 is reconstructed by $\pi^+\pi^-$
  - Pion's momenta are calculated at the found vertex that is typically displaced from the interaction point
- Mass window
  482MeV/c^2 < $M\pi^+\pi^-$ < 514 MeV/c^2



Improve momentum resolution

Vertex constraint fit

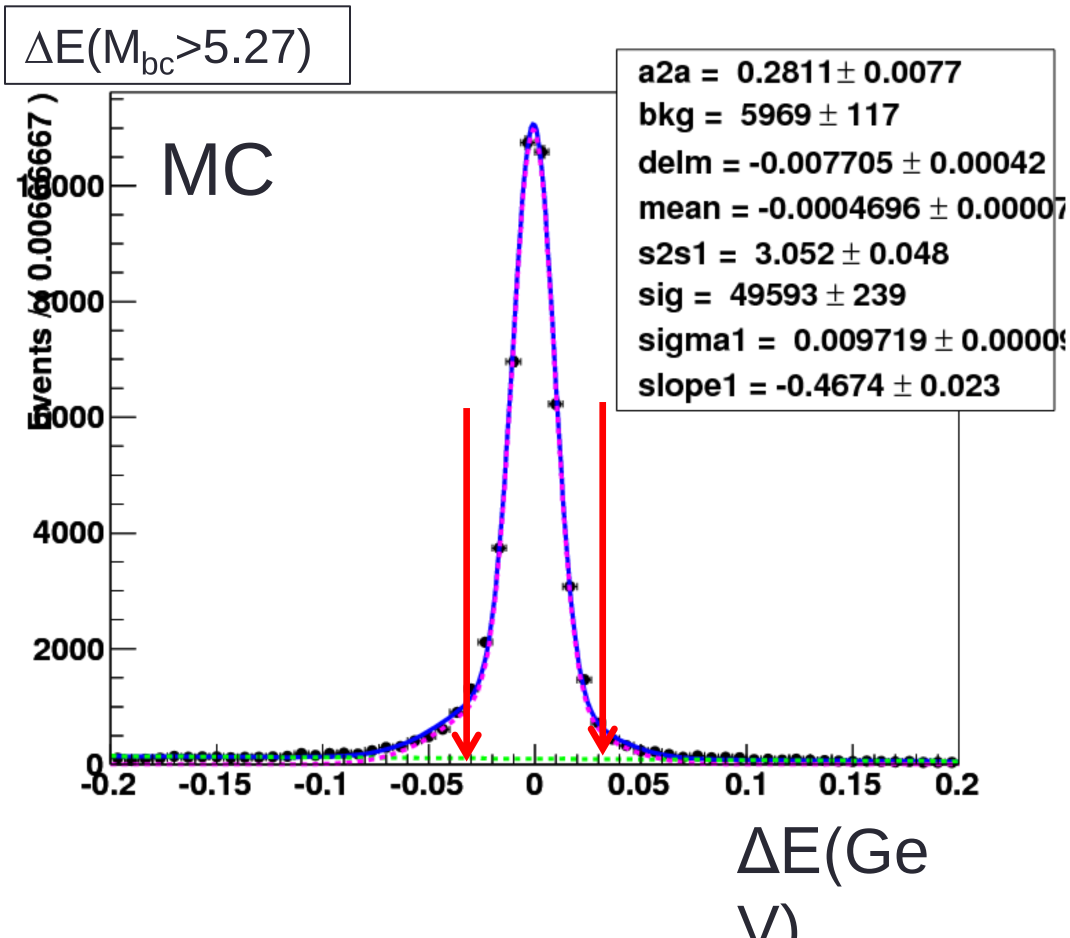
Daughter particles tracks must come from a common vertex(J/ψ, K_S)

Mass constraint fit

Invariant mass must be same as known M(J/ψ), M(η) and M(K_S)

Signal ΔE distribution PDF

We use double Gaussian for this fit.
Core part : 72% σ=9.7MeV
Tail part : 28% σ=29.6MeV

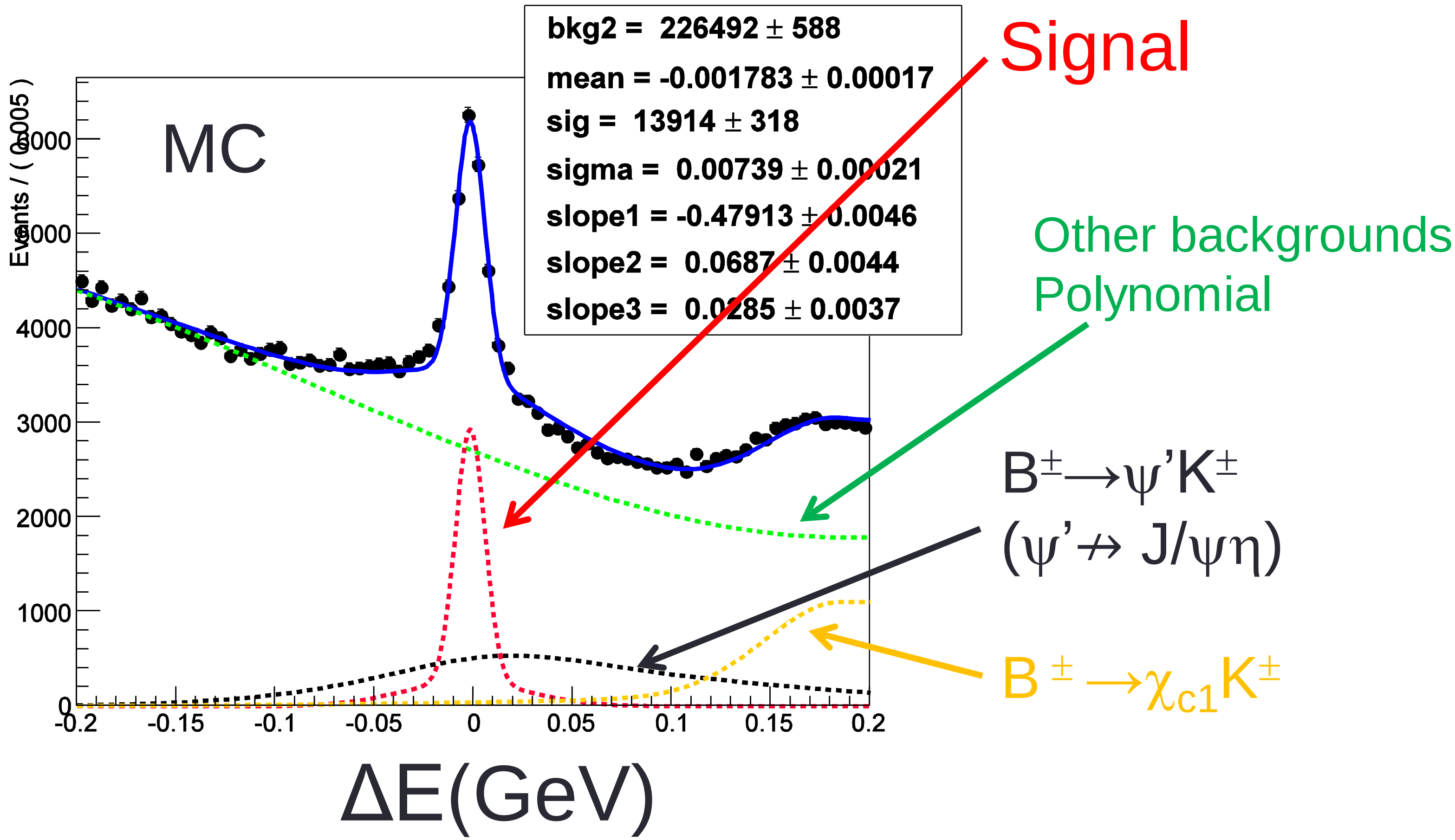


Efficiency is 9.9%.
(9.1% in signal region)

Determine PDFs by MC sample

Using background shape from inclusive J/psi MC, we make background PDFs.

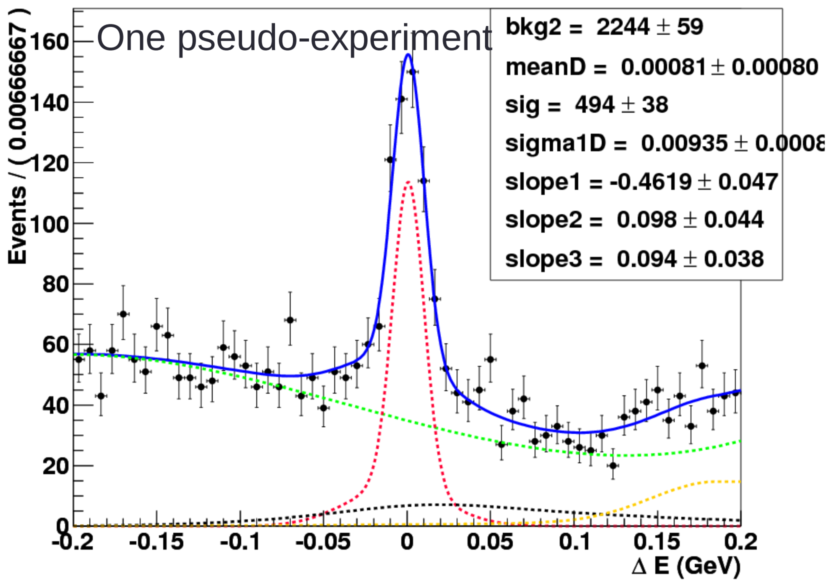
Especially, $B^{\pm}\text{->}\psi' K^{\pm}$ and $B^{\pm}\text{->}\chi_{c1}K^{\pm}$ have peaking structure, so we used bifurcated Gaussian

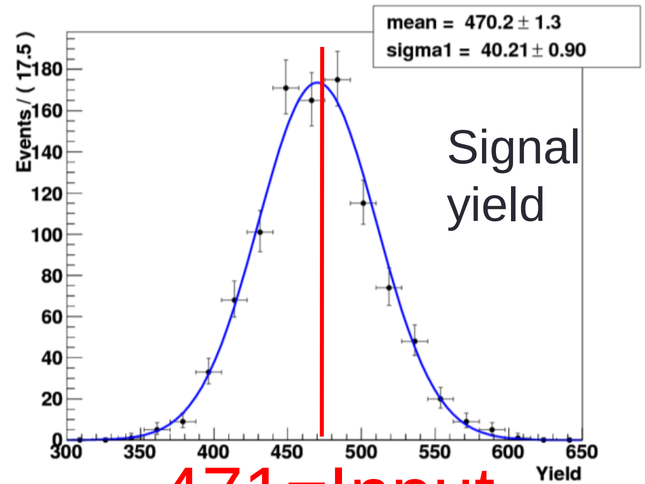


Ensemble test at ΔE distribution

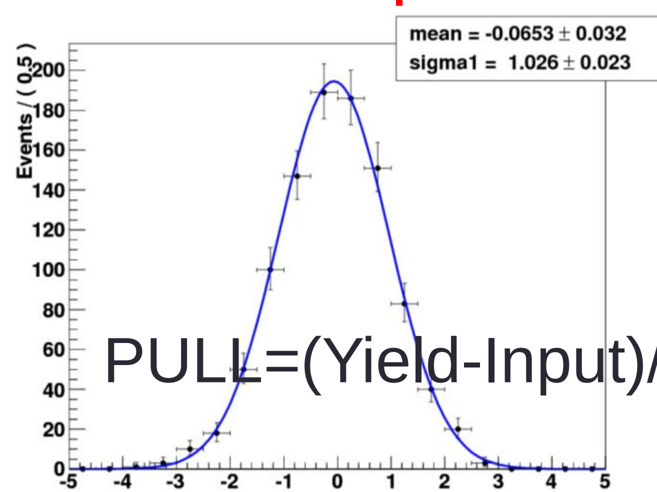
Using many MC data sets, (each has the same statistics as the exp-data), signal extraction procedure was repeated many times to see if returned values are consistent with input.

One MC data set = One pseudo experiment





471=Input



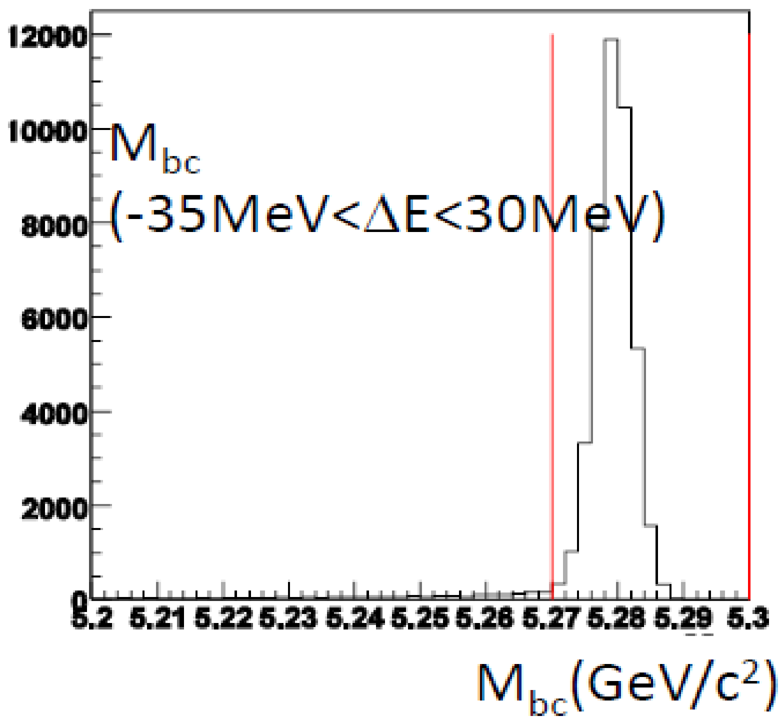
PULL=(Yield-Input)/σ_{Yield}

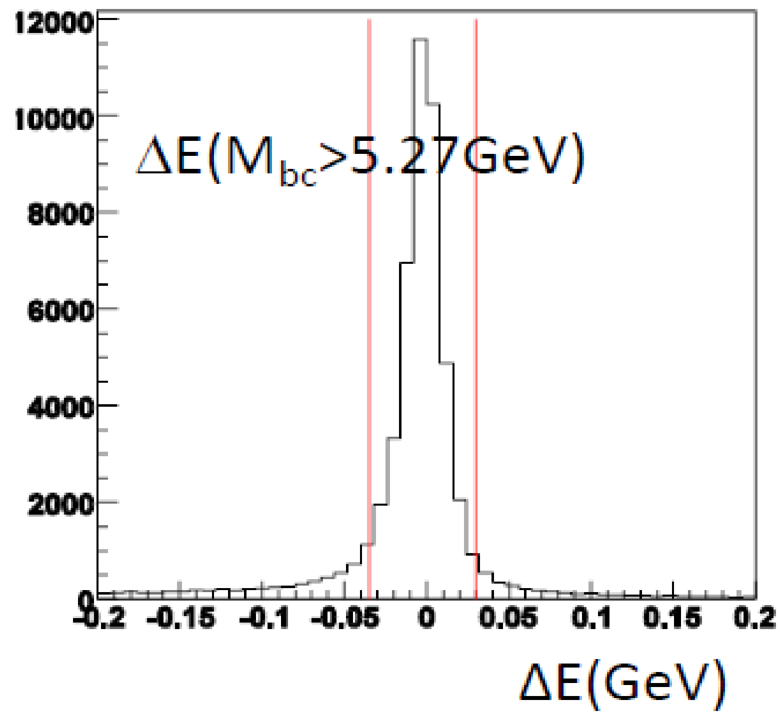
Returned value distributions are consistent with MC input.

$B^0 \to J/\psi \eta K_S{}^0$

For complete $B \to J/\psi \eta K$ analysis, we studied $B^0 \to J/\psi \eta K_S{}^0$
J/ψ and η reconstruction is same as charged B mode.
Now, we used reconstructed $K_S{}^0$

Signal MC

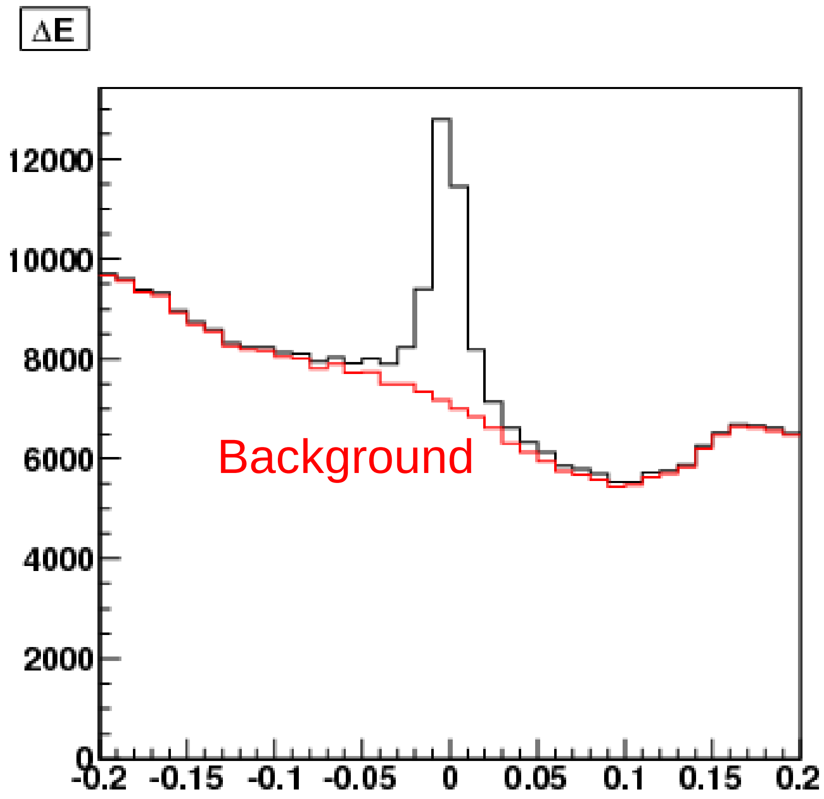


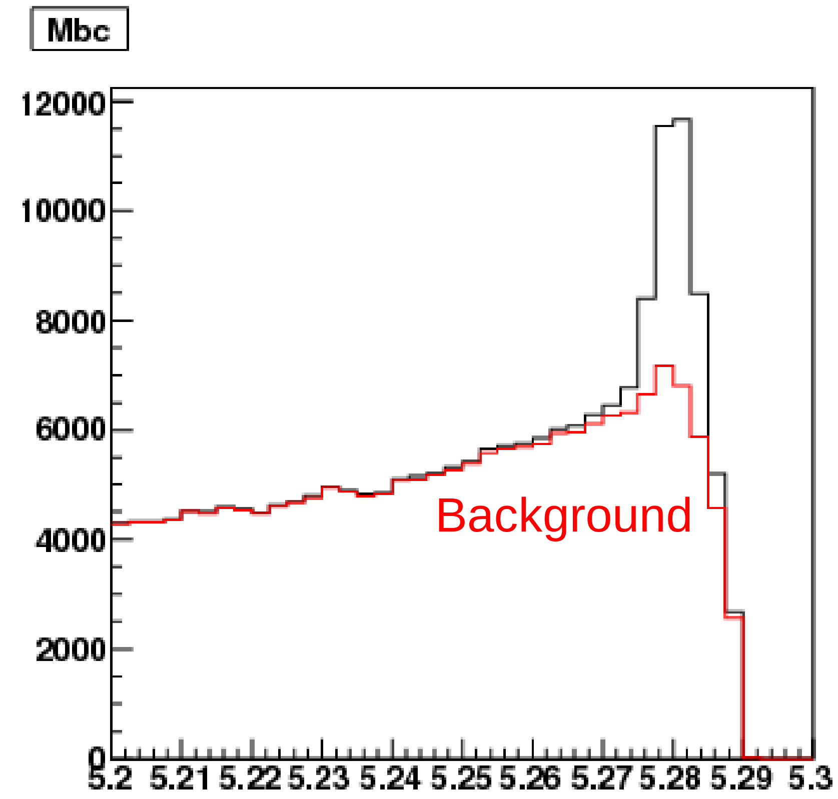


Systematic uncertainties

	$B^{\pm} \to J/\psi\eta K^{\pm}$	$B^{\pm} \to \psi'(\to J/\psi\eta)K^{\pm}$	$B^{0} \to J/\psi\eta K^{0}_{S}$
Tracking	0.9	0.9	1.3
K ID	1.4	1.4	N/A
Lepton ID	2.4	2.4	2.4
$\eta \to \gamma\gamma$ detection	4.0	4.0	4.0
$K^{0}_{S} \to \pi^{+}\pi^{-}$	N/A	N/A	0.7
Signal MC state	0.5	0.5	0.5
Secondary Br.	0.7	0.7	0.7
PDF uncertainty	7.3	3.9	8.4
	8.9%	6.4%	9.8%

M_{bc} and ΔE at inclusive J/ψ MC

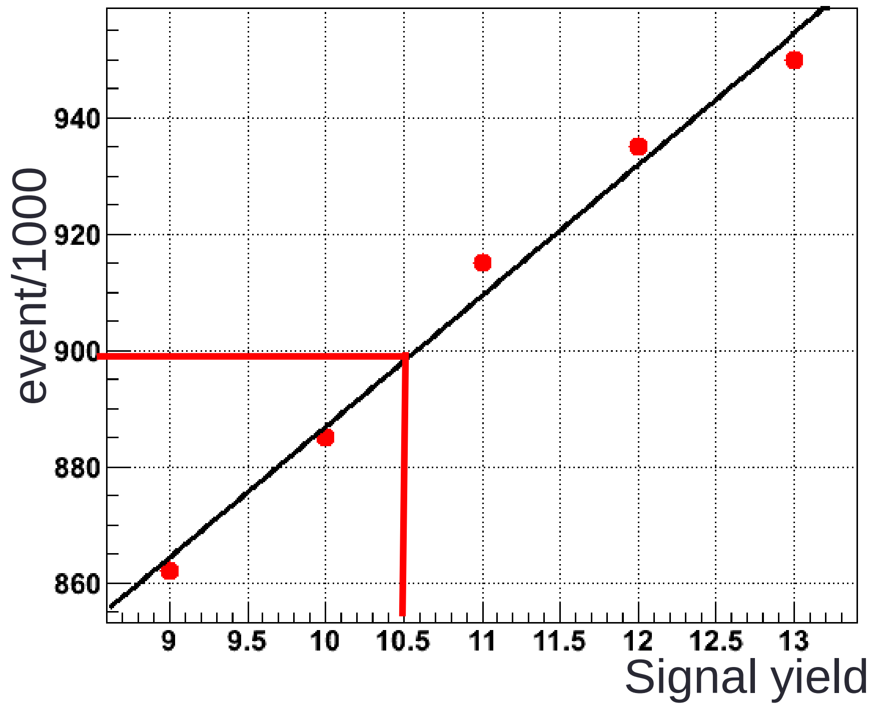




Upper limit of X(3872)

(Frequentist method)

- We generated 1000 toy MCs using signal shape (estimated from GSIM study) and background shape and yield from data.
- Toy study repeated with different signal yield.
- Red points show "how many events are over than 2.3"



Systematics not included yet.

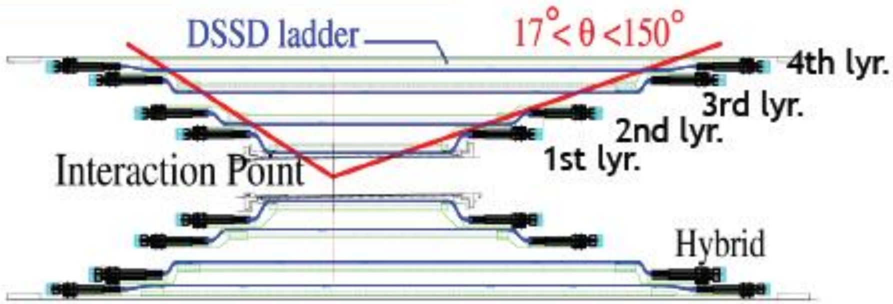
90% C.L. signal yield of X(3872) is 10.5.

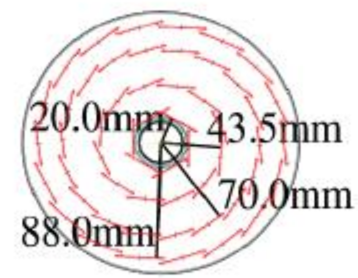
We can say Br(B →X(3872)K)･Br(X(3872)→J/ψη) is less than 3.63×10^{-6}

3-2

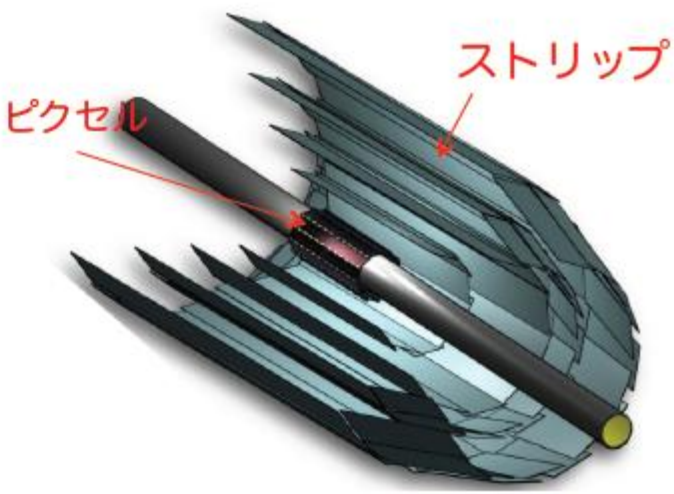
崩壊点検出器

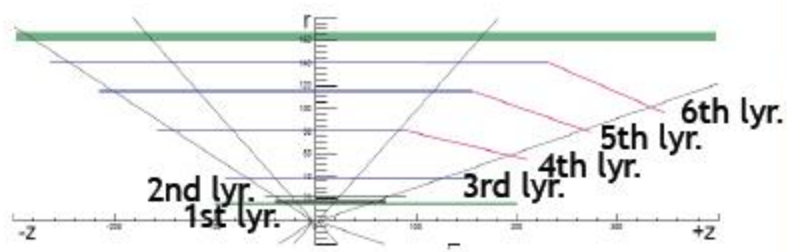
Belle: 4層のストリップ検出器





Belle II: 2層のピクセル + 4層のストリップ





ピクセル:
r=14,22mm
ストリップ:
r=38,80,115,140mm

崩壊点測定精度と
K_Sの構成効率の向上

Horii-san's slide at B2Js

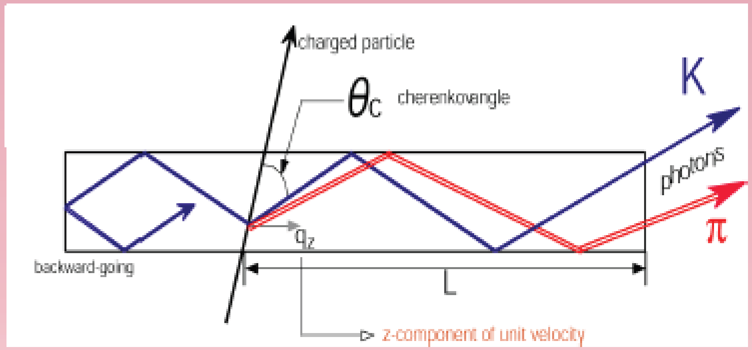
3-2

荷電粒子識別（K±とπ±の識別）

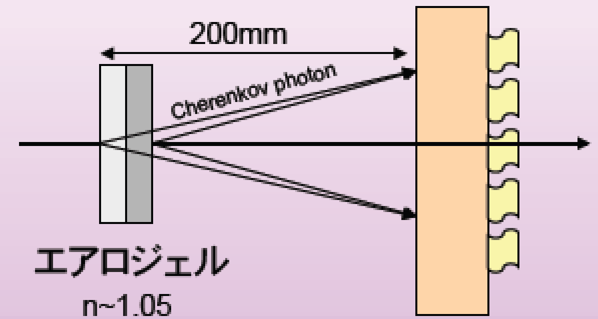
バレル: Time of Propagation Counter (TOP)

石英ガラスの板

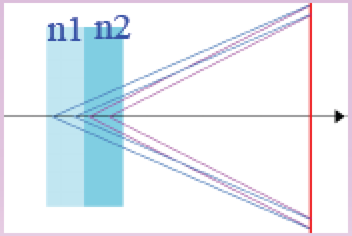
浜フォトのMCP-PMTでチェレンコフ光を検出。

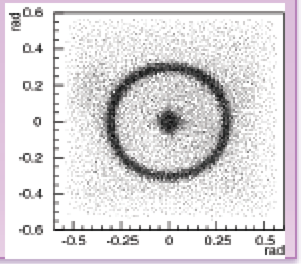


エンドキャップ: Aerogel RICH (ARICH)



浜フォトのHAPDで
チェレンコフ光を検出。





低物質量で、より良いK/π識別。

K± (π±)を95%の効率で選ぶ時、
π± (K±)はO(1)%の確率でしか残らない。

Horii-san's slide at B2Js