Branching Fraction Measurement of $B^{\pm} \rightarrow \chi_{c1} \pi^{+}\pi^{-} K^{\pm}$ and Search for a Narrow Resonance with the Belle Experiment

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- The Belle Experiment
- Event Selection and Reconstruction of $B^{\pm} \rightarrow \chi_{c1} \pi^{+}\pi^{-} K^{\pm}$
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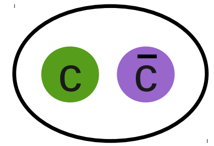
  - Invariant Mass Spectrum of $\chi_{c1} \pi^{+}\pi^{-}$
- Conclusion

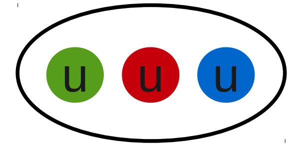
Why Exotic Hadrons ?

- we see two types of conventional structures in hadrons: meson & baryon

Meson

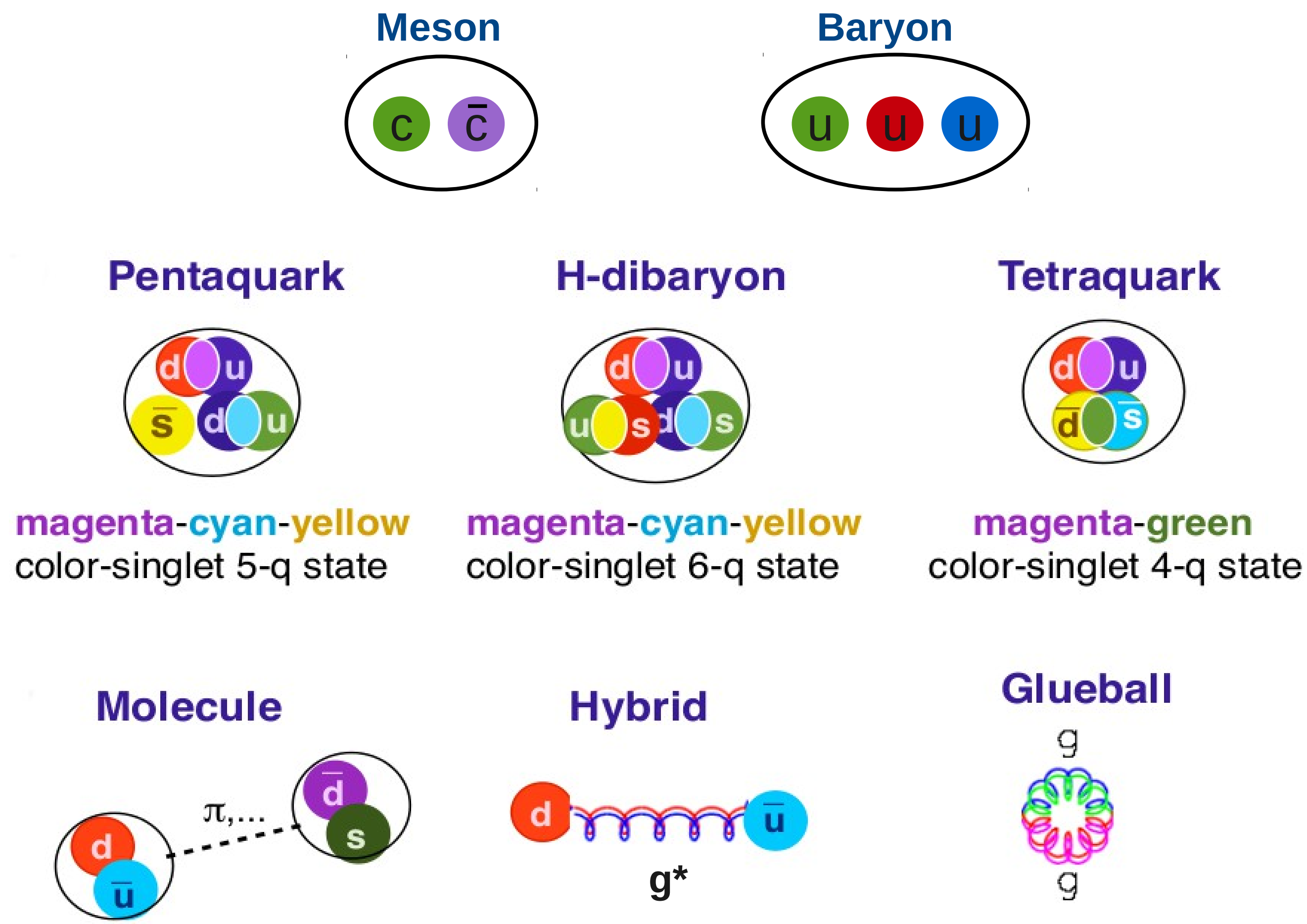


Baryon



Why Exotic Hadrons ?

- we see two types of conventional structures in hadrons: meson & baryon
- other combinations are not explicitely forbidden by QCD !
  - new forms of matter such as mesonic molecules, tetraquarks, quark-gluon hybrids and others
- QCD motivated models for hadrons predict these exotic states in their calculations



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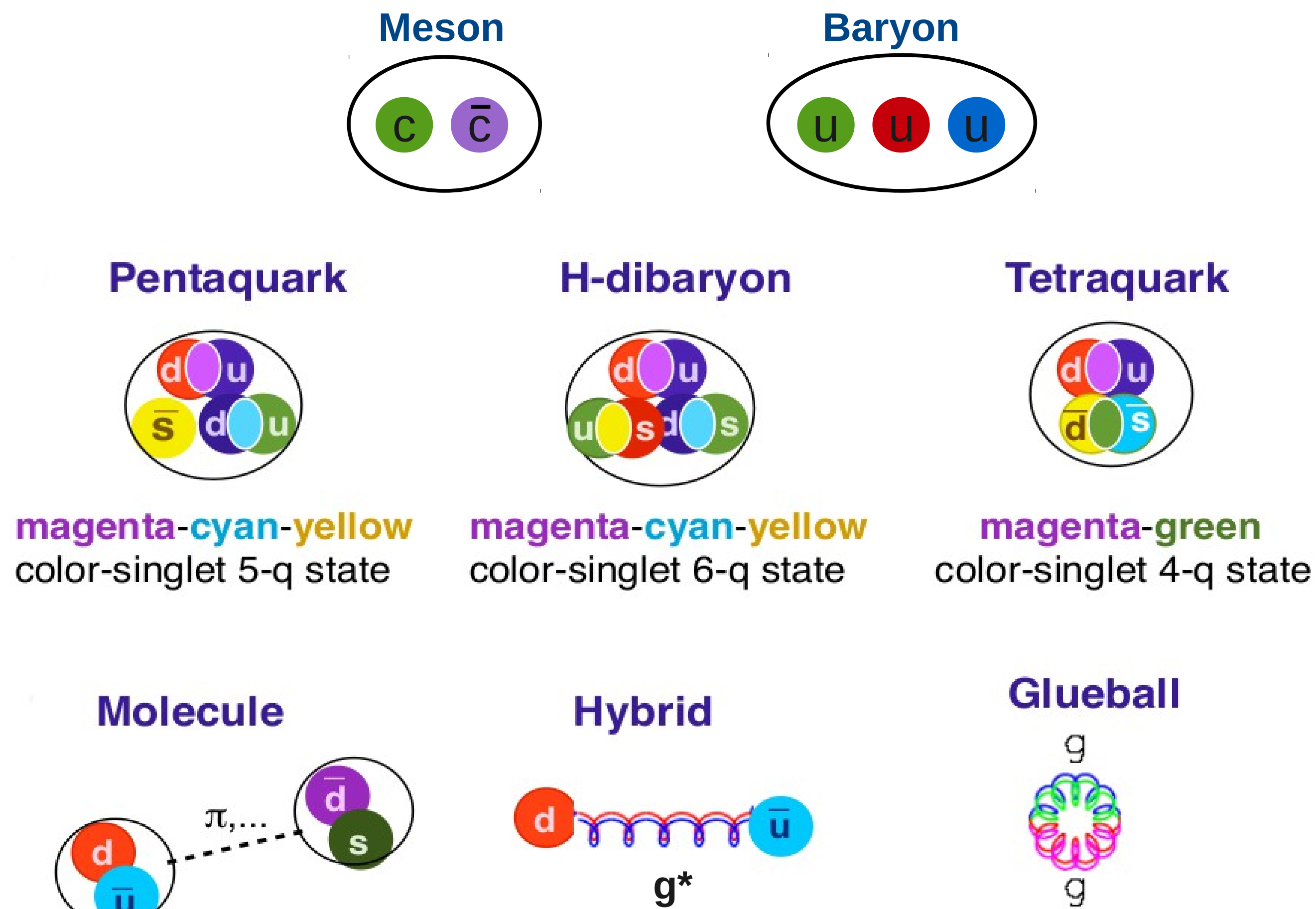
- other combinations are not explicitely forbidden by QCD !
  - new forms of matter such as mesonic molecules, tetraquarks, quark-gluon hybrids and others
- QCD motivated models for hadrons predict these exotic states in their calculations
- lack of experimental evidence for a long time, but many discoveries recently

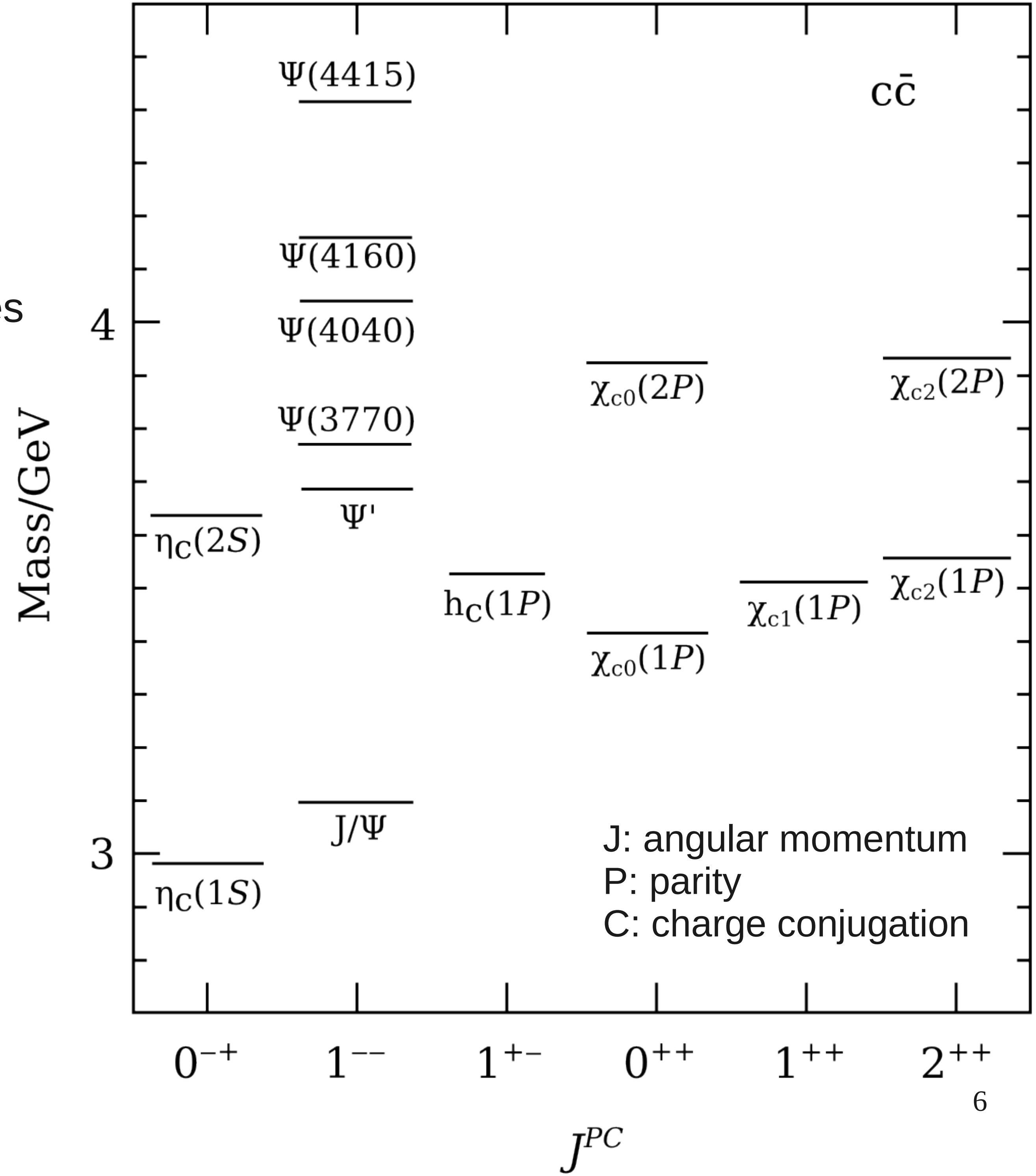
➔ unusual hadron structures might be a key to reveal a new aspect of QCD



Charmonium(-like) States

- light flavours (*u, d, s*) may mix,
  still interesting i.e. for glueball searches
- relation between observed states
  and constituent quarks is desired
  to be rather straightforward

➔ advantage of heavy flavours (*c, b*):
higher masses serve as cut-off and
allow usage of non-relativistic QCD
to precisely calculate spectrum



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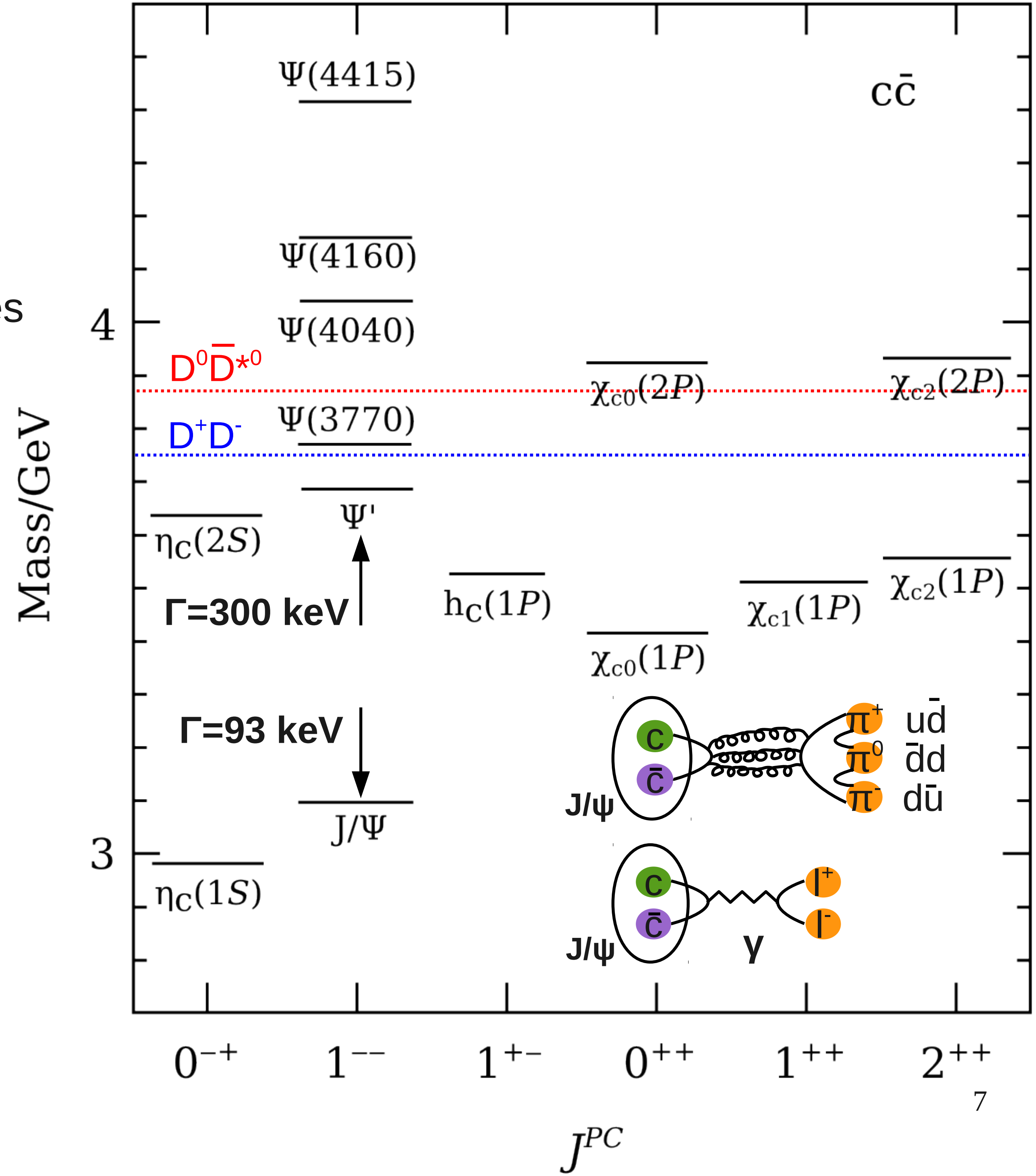
- trends in the spectrum:
  - narrow states below open charm ($D\bar{D}$) threshold, electromagnetic decays compete with hadronic decays (suppressed by OZI rule!)



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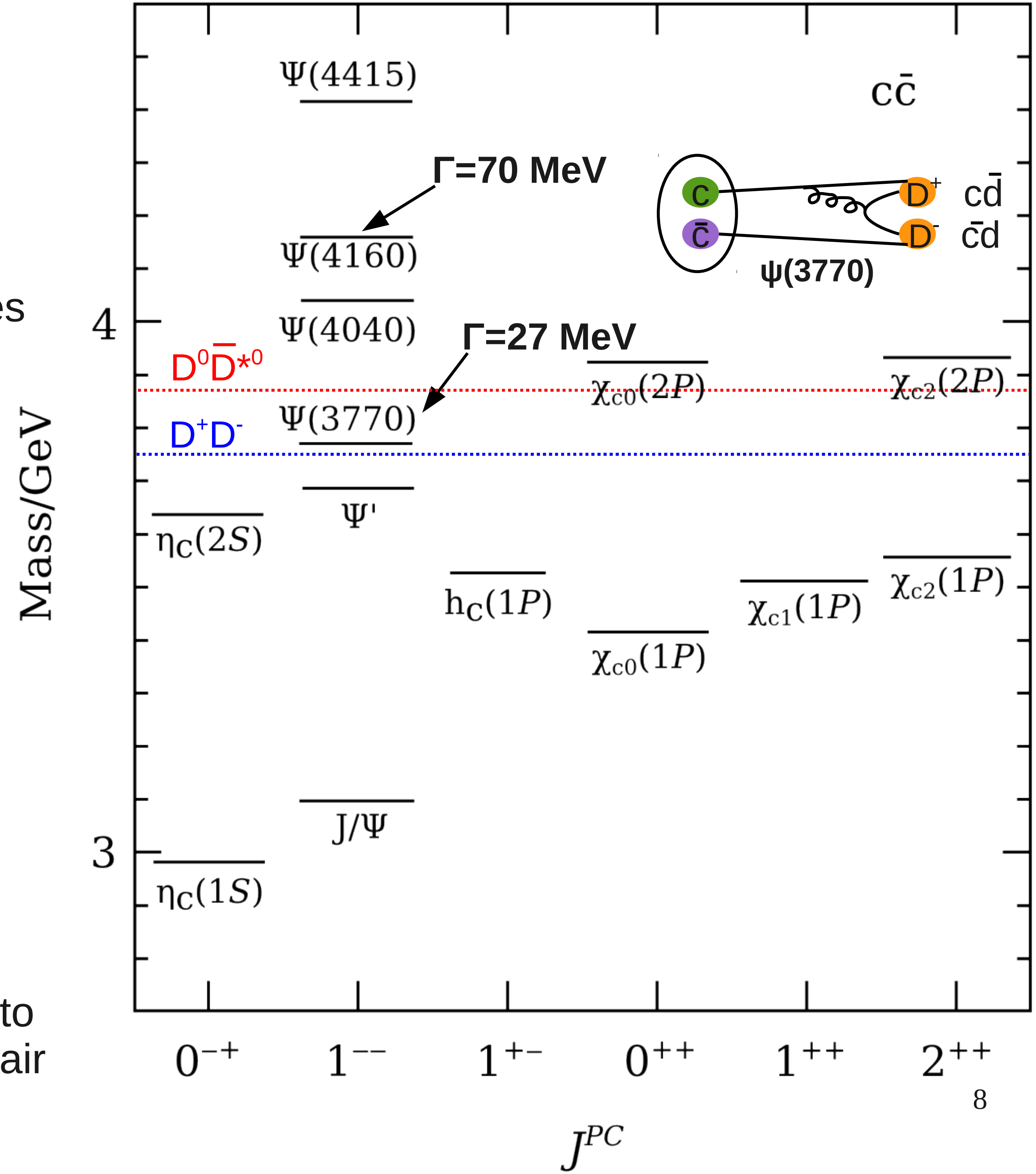
trends in the spectrum:

- narrow states below open charm ($D\bar{D}$) threshold
- broad states above threshold due to strong decay to charmed meson pair



Charmonium(-like) Production in B Factories

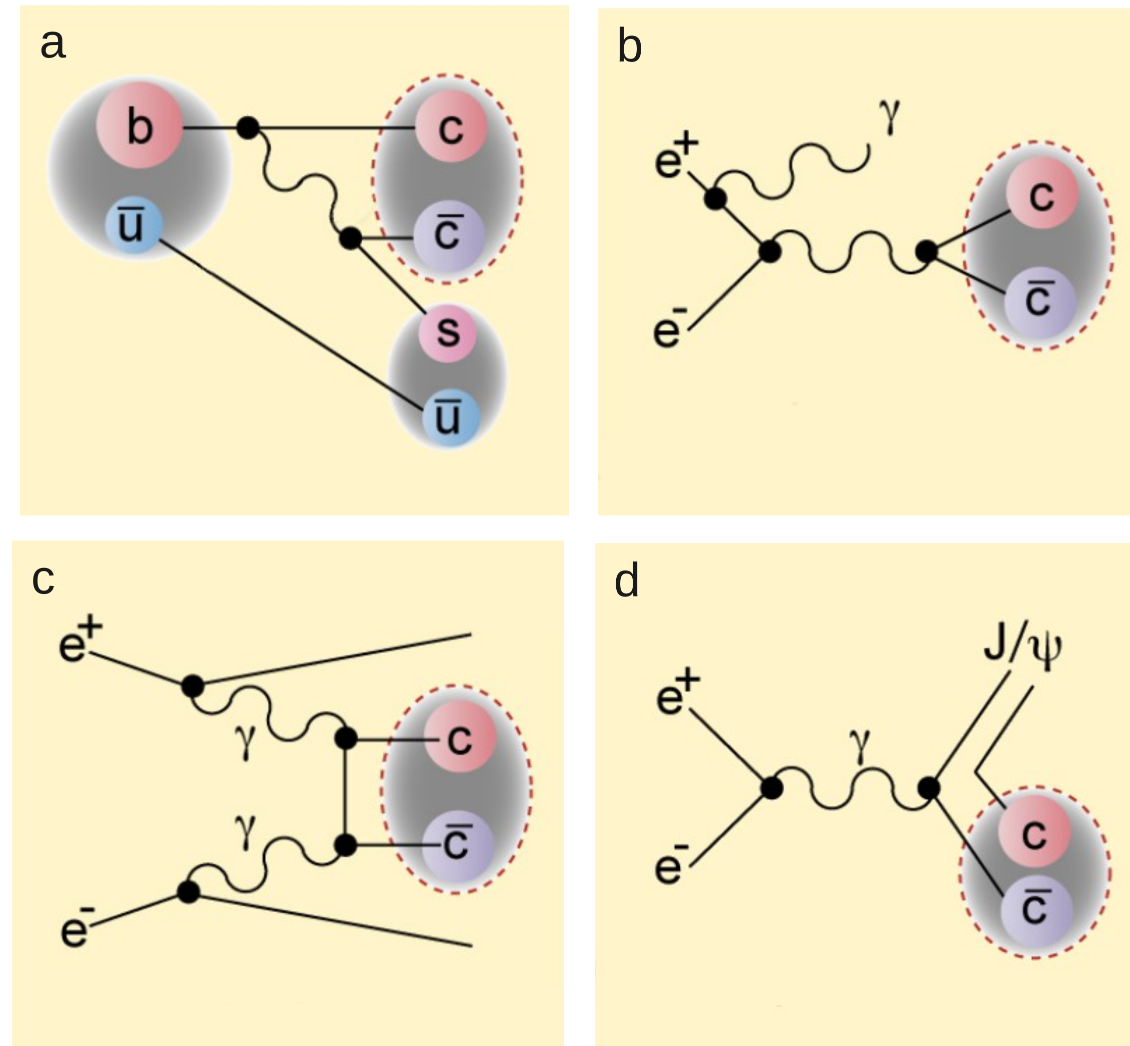
- various processes to produce charmonium(-like) particles
- allowed/ favoured quantum numbers depend on production process

(a) B meson decays

(b) initial state radiation

(c) two-photon collisions

(d) double charmonium production



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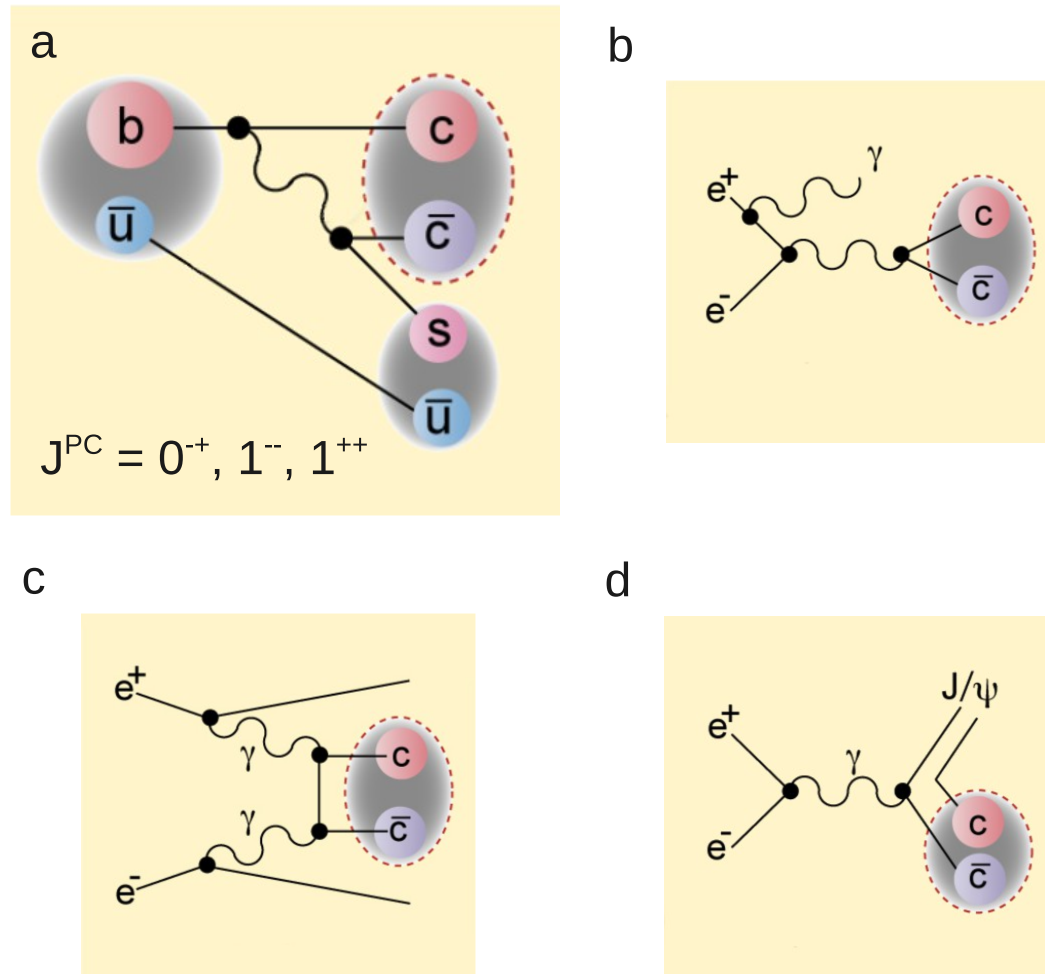

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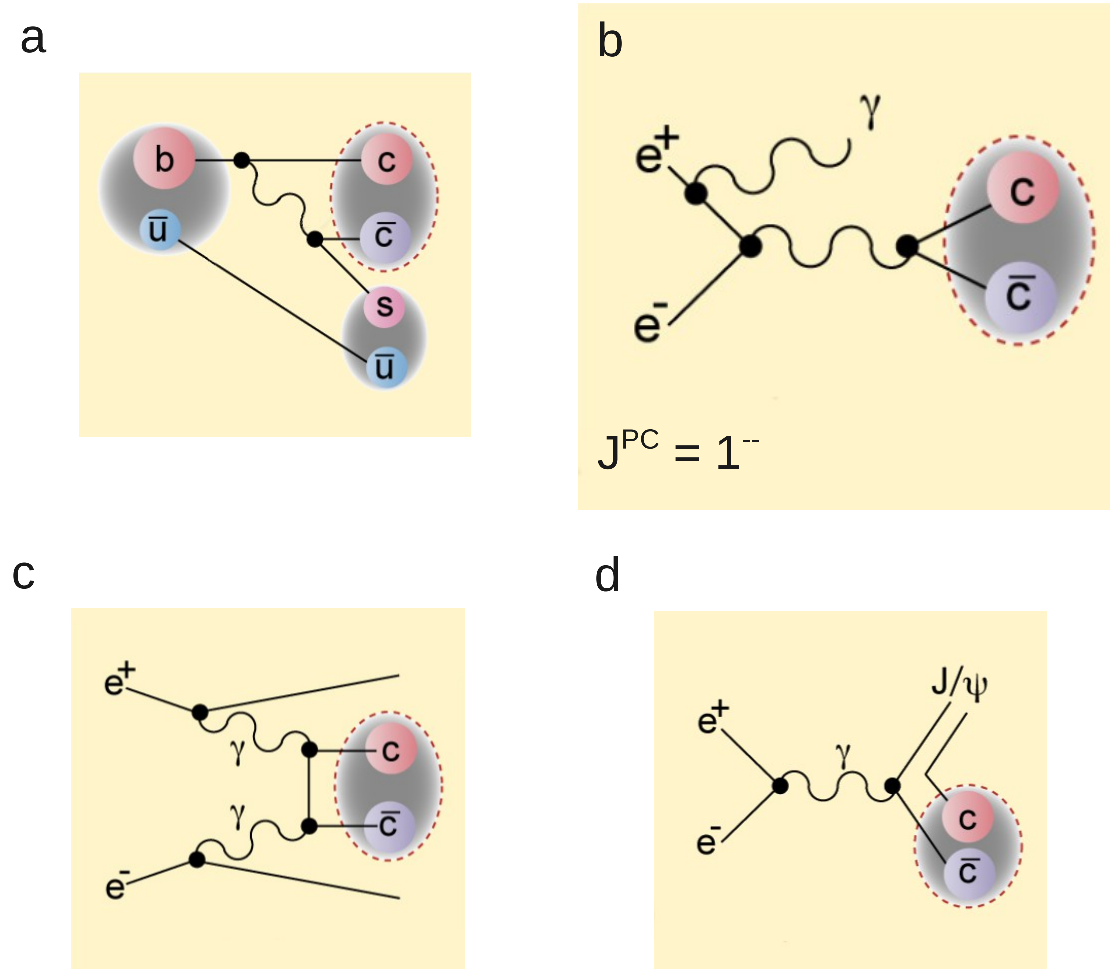

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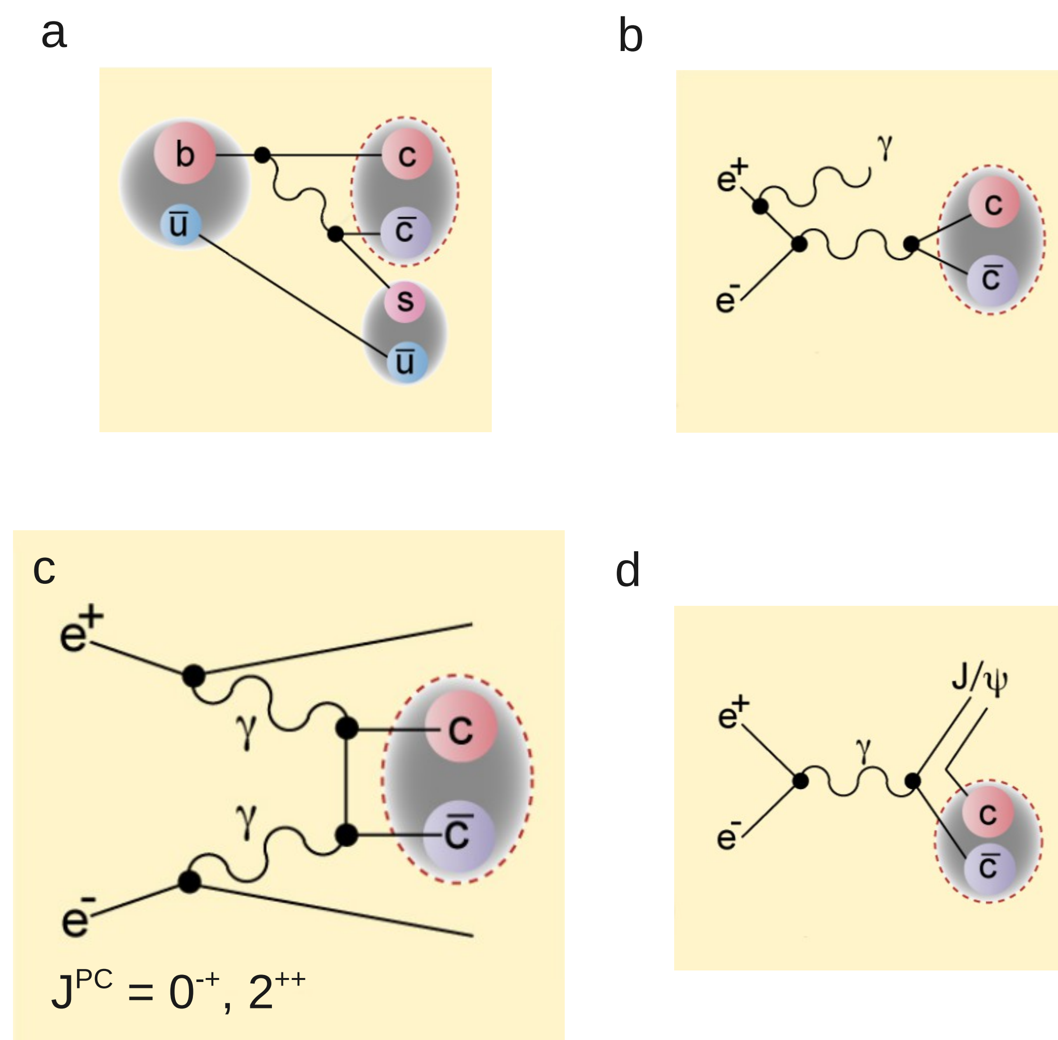

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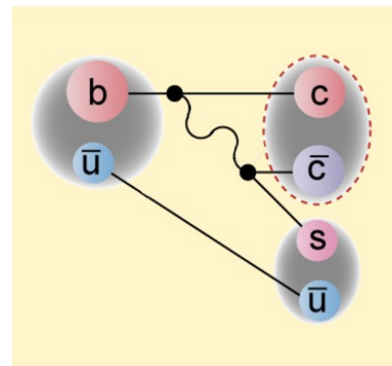
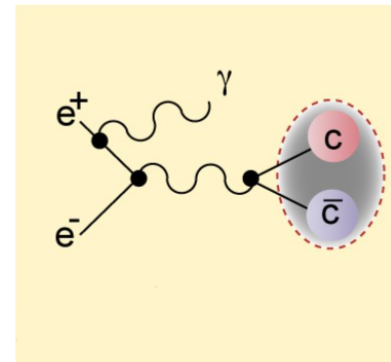
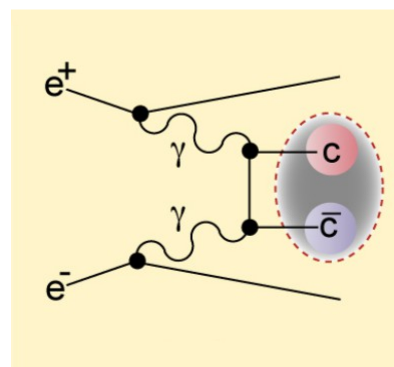
a



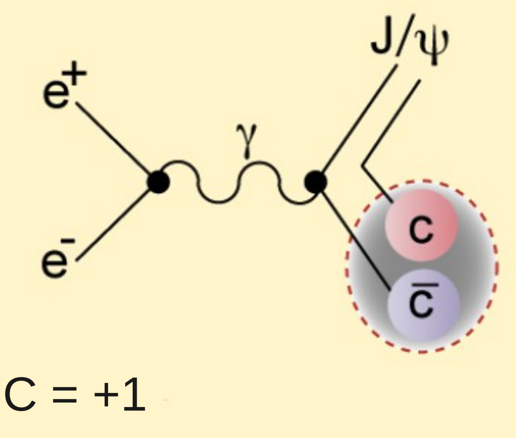
b



c



d



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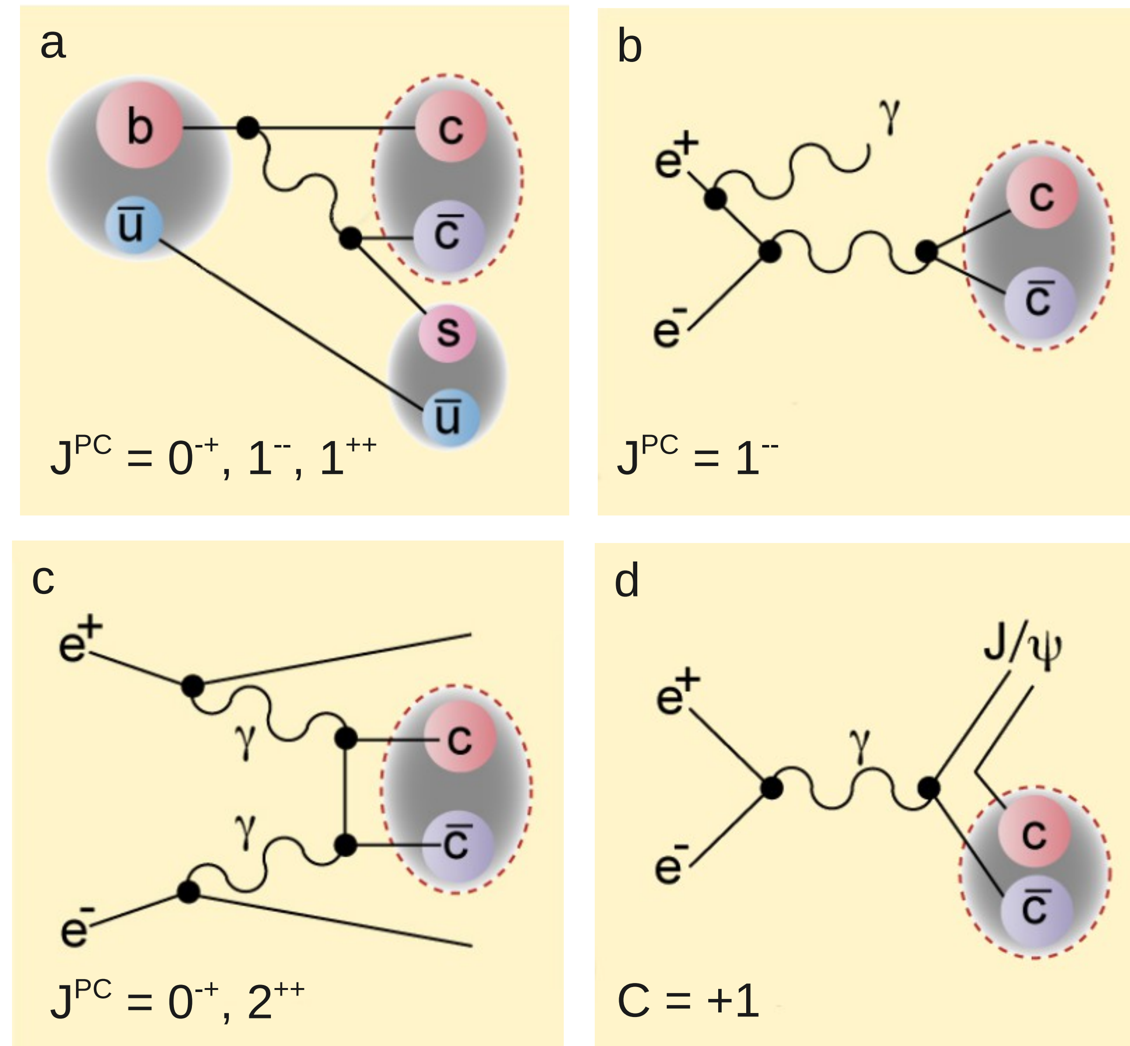
➔ ideal clean environment for charmonium spectroscopy

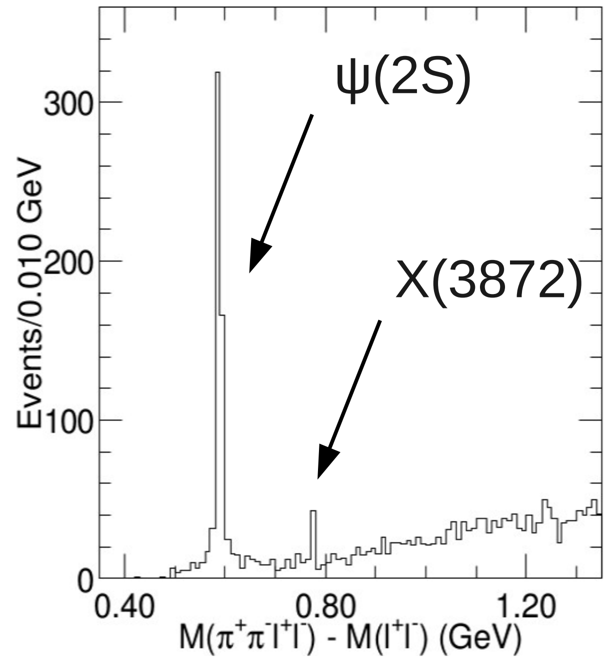


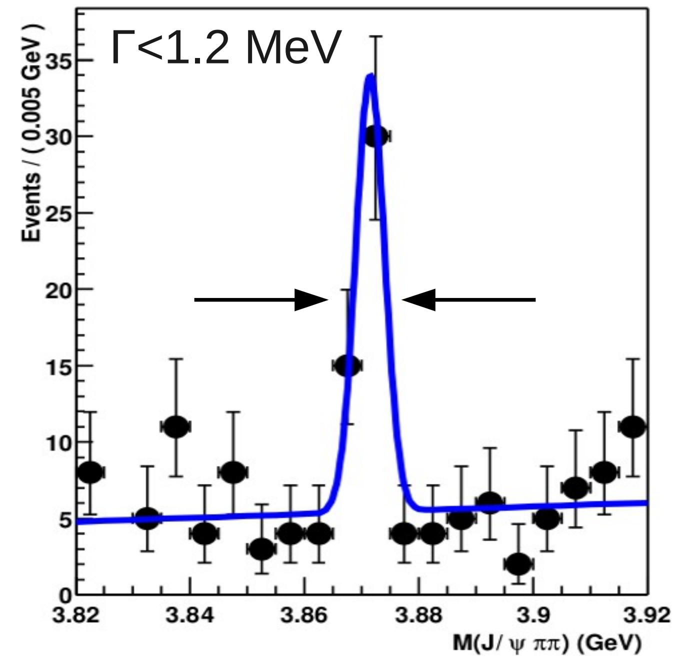
The Discovery of X(3872)

- Belle, 2003:
  very narrow peak found above the $D\bar{D}$ threshold in $B^+ \to (J/\psi\pi^+\pi^-)K^+$!
- does not match properties of known conventional charmonium states

➔ are there other decay modes ?

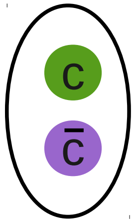
➔ how is X(3872) related to $D^0\bar{D}^{*0}$ as it is very close to this threshold ?



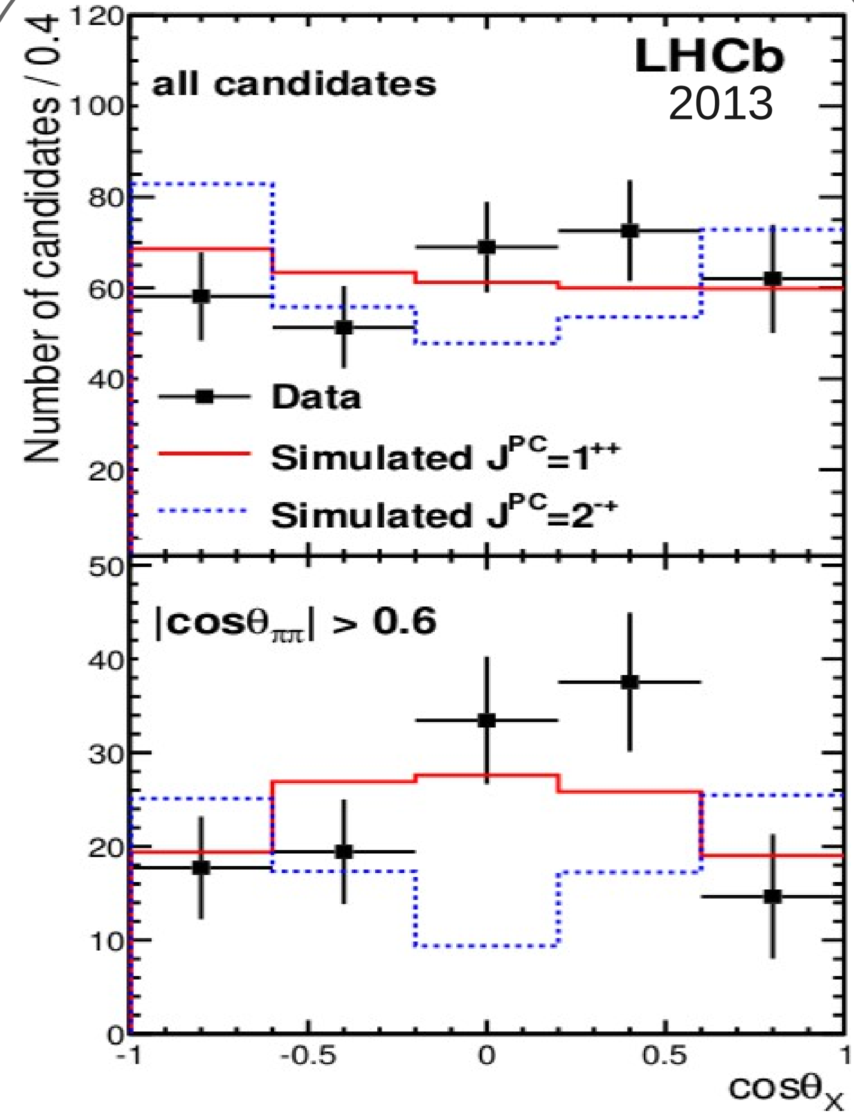


X(3872) Properties

- **quantum numbers $J^{PC} = 1^{++}$** determined from angular distribution of $J/\psi\pi^+\pi^-$



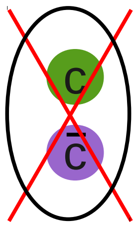
  - might be a *conventional $c\bar{c}$ state,* maybe the as yet unseen $\chi_{c1}(2P)$



(θ_x being X(3872)'s helicity angle)

X(3872) Properties

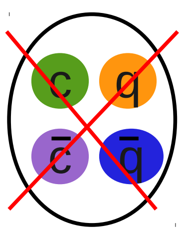
- quantum numbers $J^{PC} = 1^{++}$ determined from angular distributions of $J/\psi\pi^+\pi^-$ and $J/\psi(\pi^+\pi^-\pi^0)$



- **isospin violation** found in equally often decays to two pions via ρ (I=1) and three pions via ω (I=0)
  - ➔ mass difference of 50 MeV to χ_{c1}(2P) and isospin violation disfavour assignment as *conventional* $c\bar{c}$!

$$\frac{\mathcal{B}(X(3872) \to J/\psi\omega)}{\mathcal{B}(X(3872) \to J/\psi\rho)} = 1.0 \pm 0.4 \pm 0.3$$

- no partner found: charged or differing mass, suggests strong **isospin 0** compontent, C-odd



  - ➔ isospin violation and lack of partner states disfavour *tetraquark* hypothesis according to model predictions !

- charged partner search in $J/\psi\pi^+\pi^0$
- C-odd partner search in $J/\psi\eta$ and $\chi_{c1}\gamma$
- different mass search in charged vs. neutral B decays

$$\frac{\mathcal{B}(B^+ \to X(3872)K^+)}{\mathcal{B}(B^0 \to X(3872)K^0)} \sim 0.5$$

X(3872) Properties

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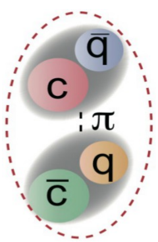
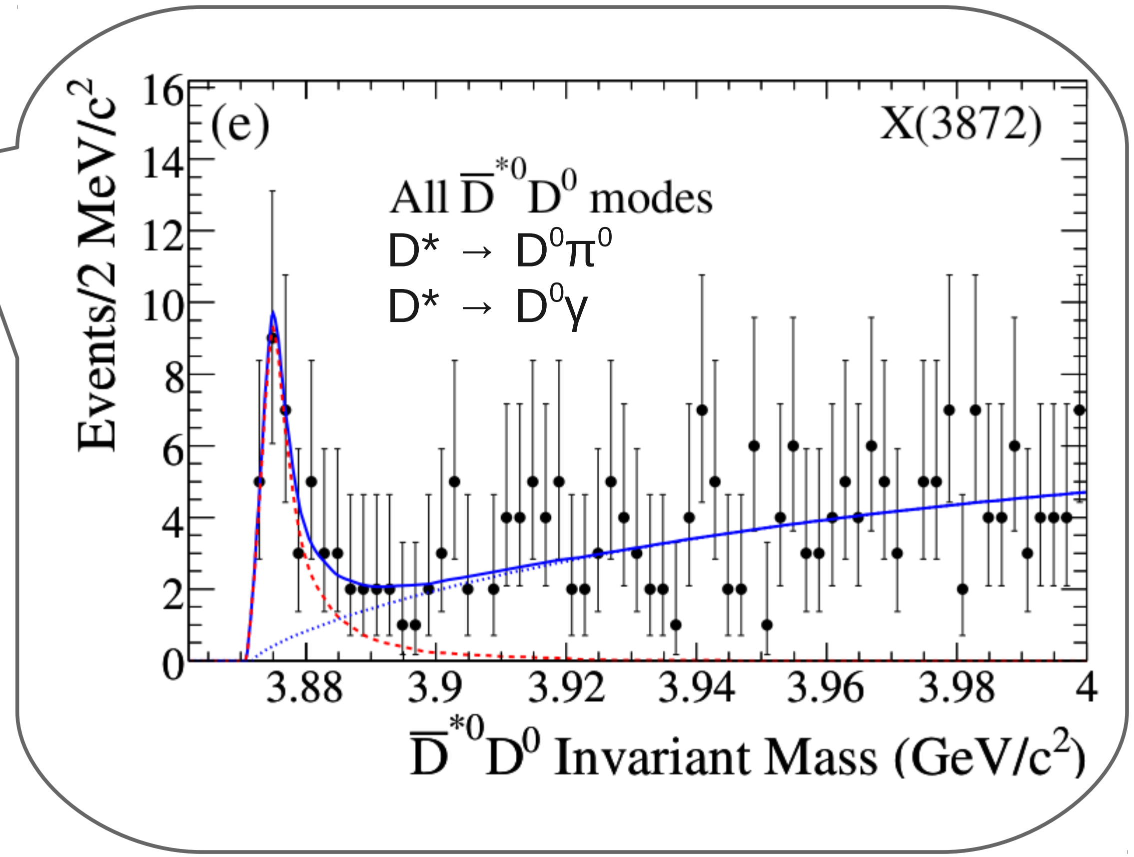
- isospin violation found in equally often decays to two pions via ρ (I=1) and three pions via ω (I=0)
- no partner found: C-odd, charged or differing mass suggests strong isospin 0 component
- **mass** (3871.69 ± 0.17) MeV is very close to the $D^0\bar{D}^{*0}$ threshold at (3871.80 ± 0.09) MeV !
- **decays** to $D^0\bar{D}^{*0}$ have been observed with $Br(X(3872) \rightarrow D^0\bar{D}^{*0}) \approx 10x\ Br(X(3872) \rightarrow J/\psi\pi^+\pi^-)$



→ might be a $D^0\bar{D}^{*0}$ *(di-mesonic) molecule*



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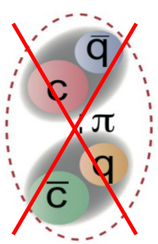
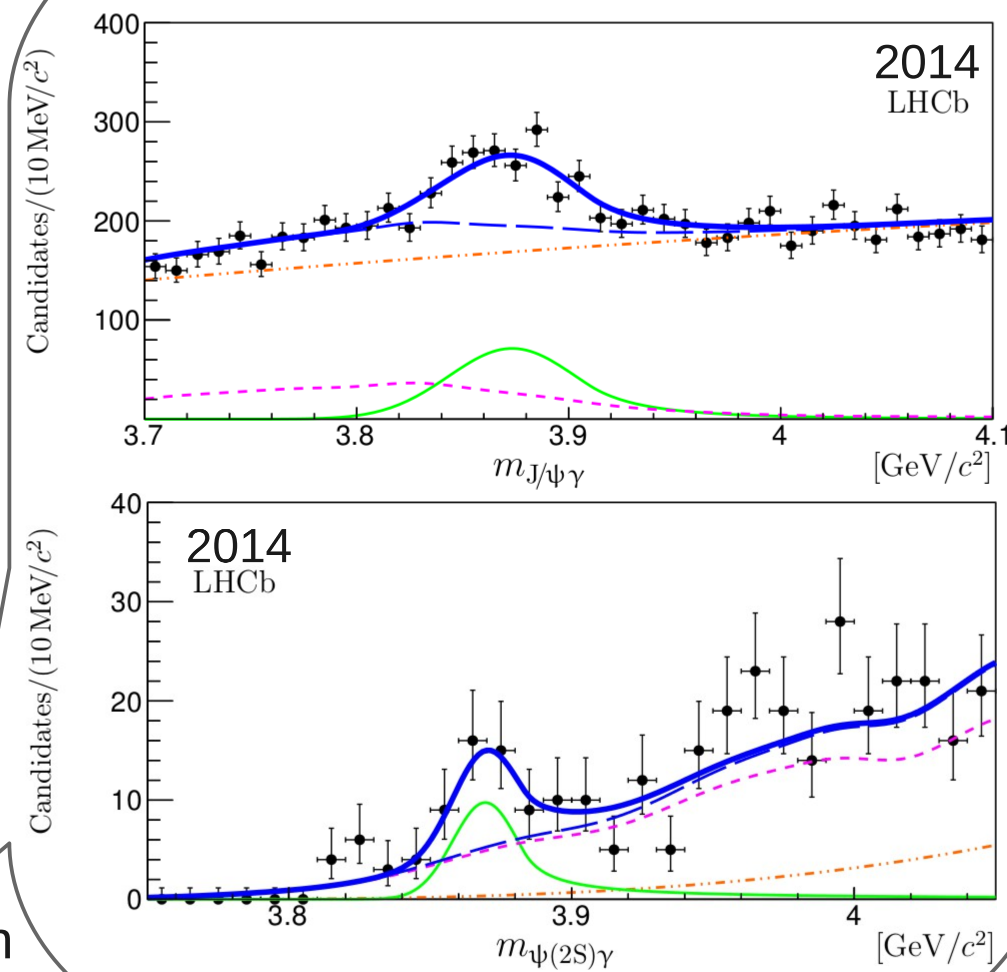
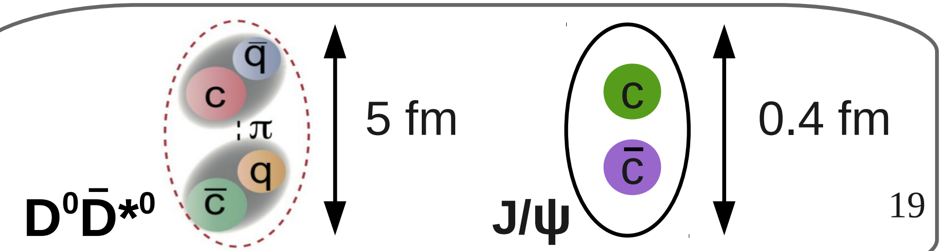
- isospin violation found in equally often decays to two pions via ρ (I=1) and three pions via ω (I=0)
- no partner found: C-odd, charged or differing mass suggests most likely isospin 0
- mass (3871.69 ± 0.17) MeV is very close to the $D^0\bar{D}^{*0}$ threshold at (3871.80 ± 0.09) MeV !
- decays to $D^0\bar{D}^{*0}$ have been seen with $Br(X(3872) \rightarrow D^0\bar{D}^{*0}) \approx 10x\ Br(X(3872) \rightarrow J/\psi\pi^+\pi^-)$
- **radiative decays**: measured opposite of prediction $Br(X(3872) \rightarrow \psi(2S)\gamma) \approx 2.5x\ Br(X(3872) \rightarrow J/\psi\gamma)$
- also: pure molecule would be too **fragile** to be produced at Tevatron (CDF) or LHC (LHCb)



→ disfavours *pure molecule* hypothesis !





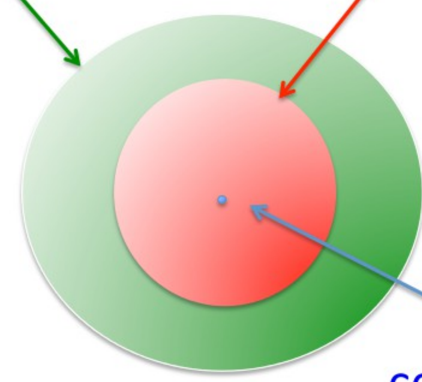
Interpretation for X(3872)

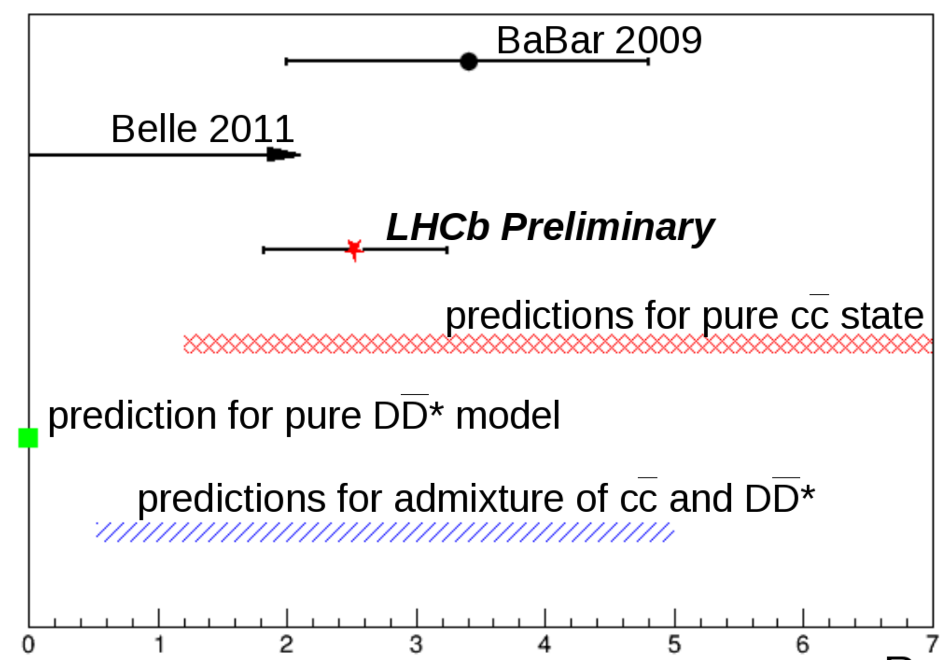
- most plausible interpretation of X(3872): admixture !

➔ $D\bar{D}$ molecule is mixing with an ordinary charmonium state with same J^{PC},

i.e. the as yet unseen $\chi_{c1}(2P)$

- ✓ quantum numbers
- ✓ molecular part can explain isospin violation
- ✓ conventional $c\bar{c}$ core can explain the production in high energy machines like Tevatron or LHC





Rψγ: ratio of branching fractions of X(3872) decay into ψ(2S)γ and J/ψγ

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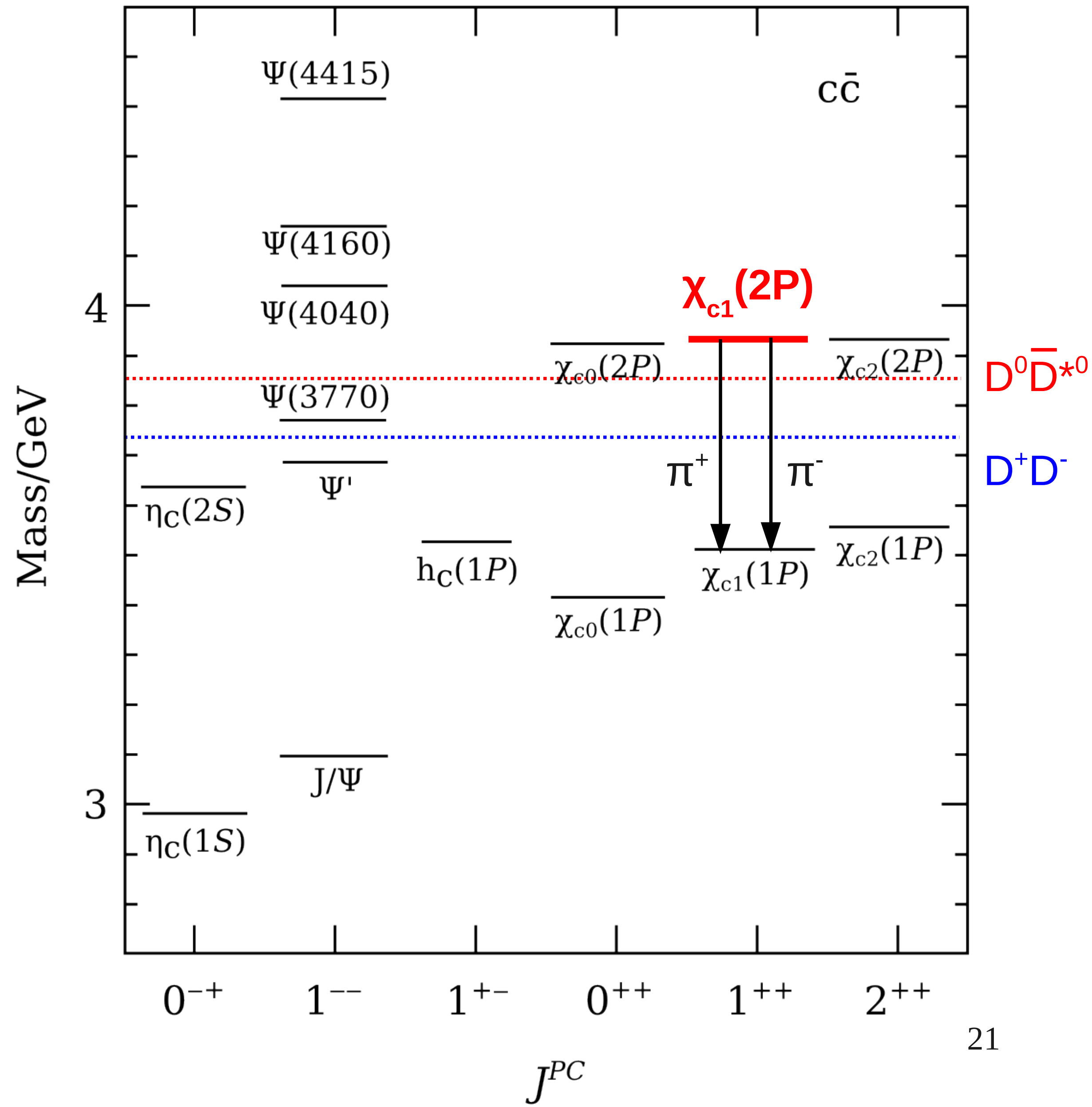
- if $\chi_{c1}(2P)$ is not mixing to form X(3872), it is still expected to decay to $\chi_{c1}(1P)\pi^+\pi^-$
  - $\chi_{c1}(2P)$ mass prediction at 3920 MeV
  - $\chi_{c1}(2P) \rightarrow \chi_{c1}\pi^+\pi^-$ dipion transition expected due to no quantum number conflict, as seen in $\psi(2S) \rightarrow J/\psi\ \pi^+\pi^-$



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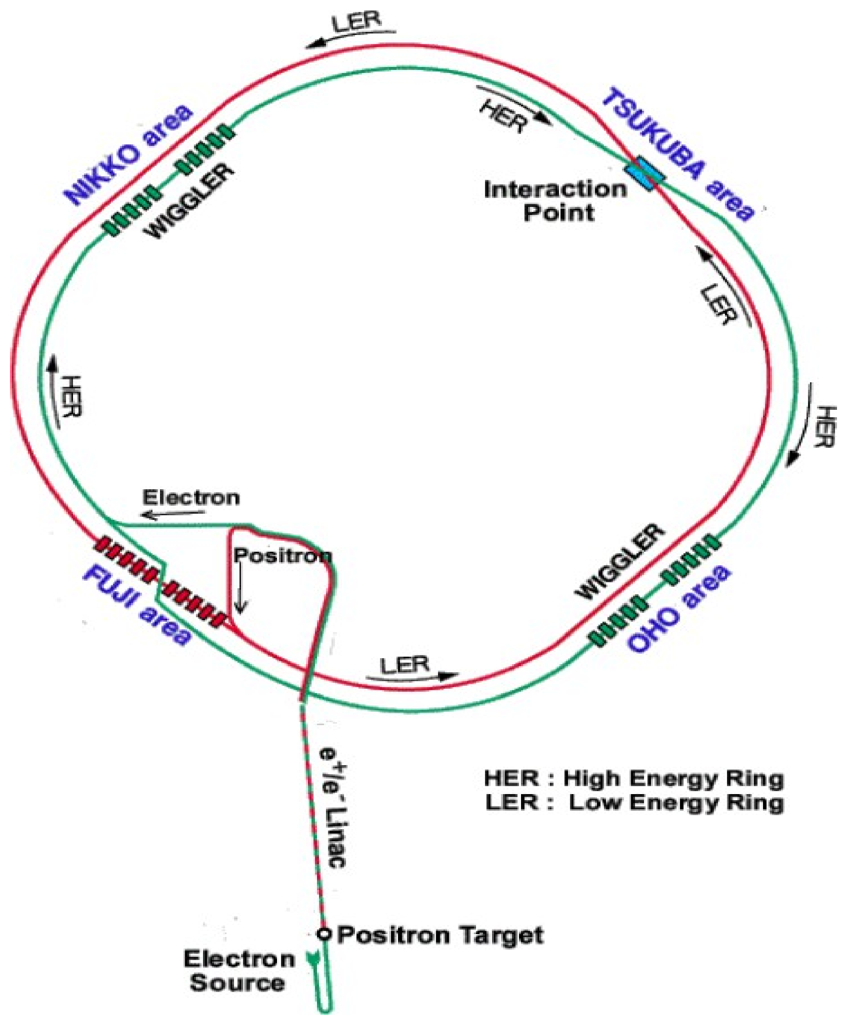
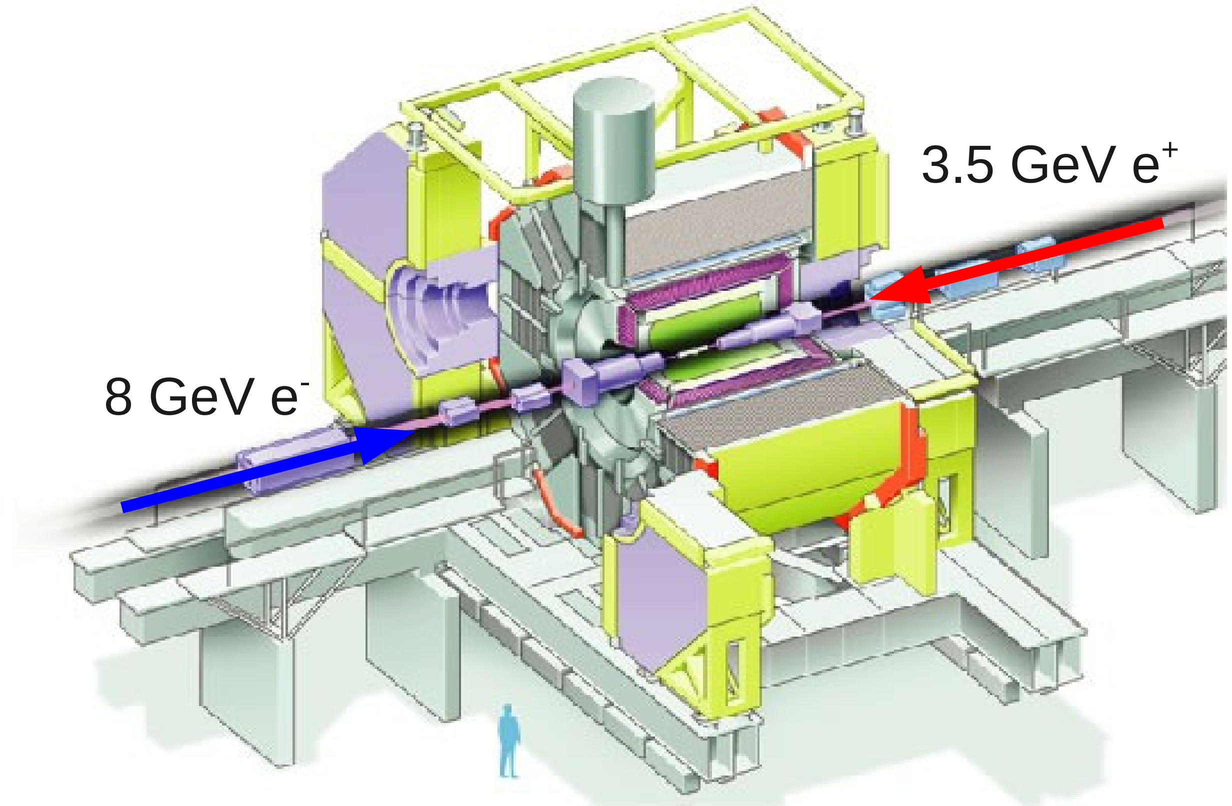
in both cases: **$\chi_{c1}\pi^+\pi^-$** is a suitable and interesting source to look for either X(3872) or $\chi_{c1}(2P)$!

The Belle Experiment





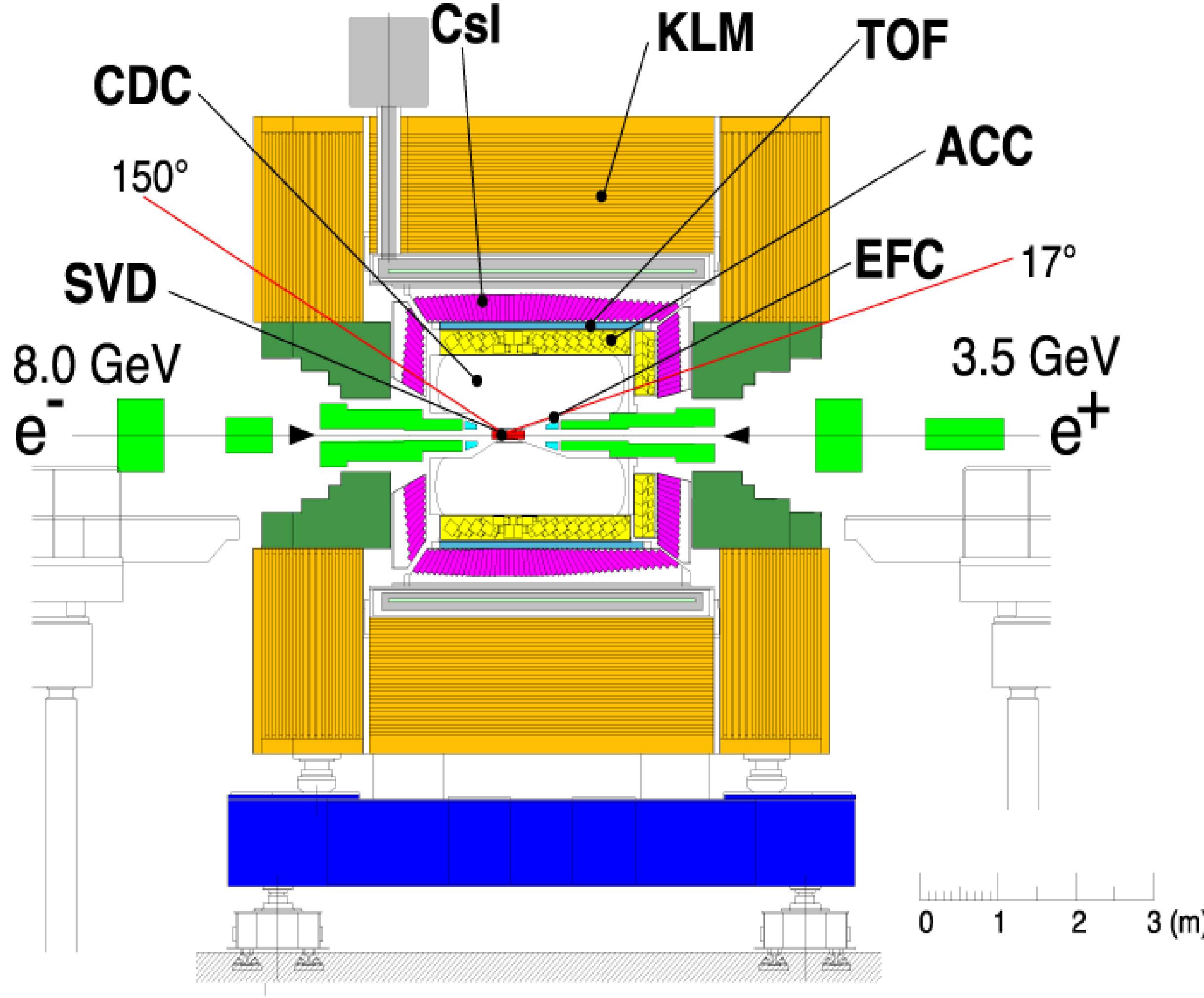
KEKB: 8 GeV e^- beam × 3.5 GeV e^+ beam mainly @ Υ(4S) resonance ($\sqrt{s}$ = 10.58 GeV)

Belle Detector: high resolution 4π spectrometer with particle identification capability

Belle Detector Performance

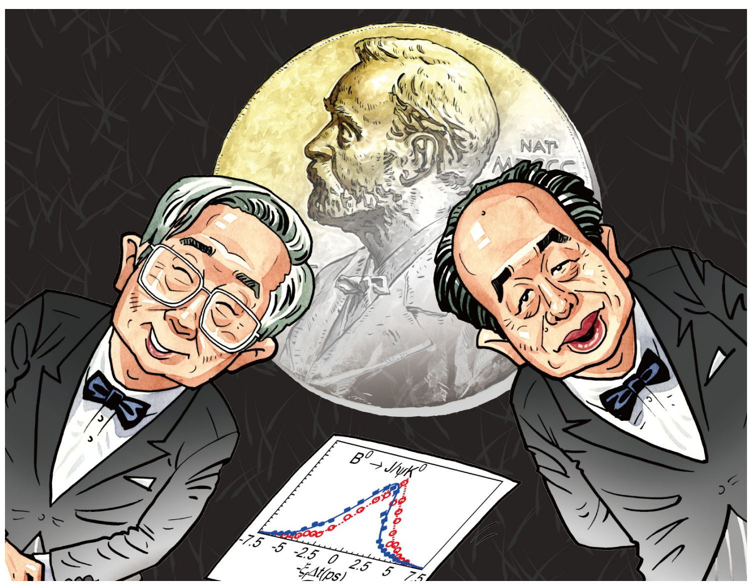
4π general purpose spectrometer with

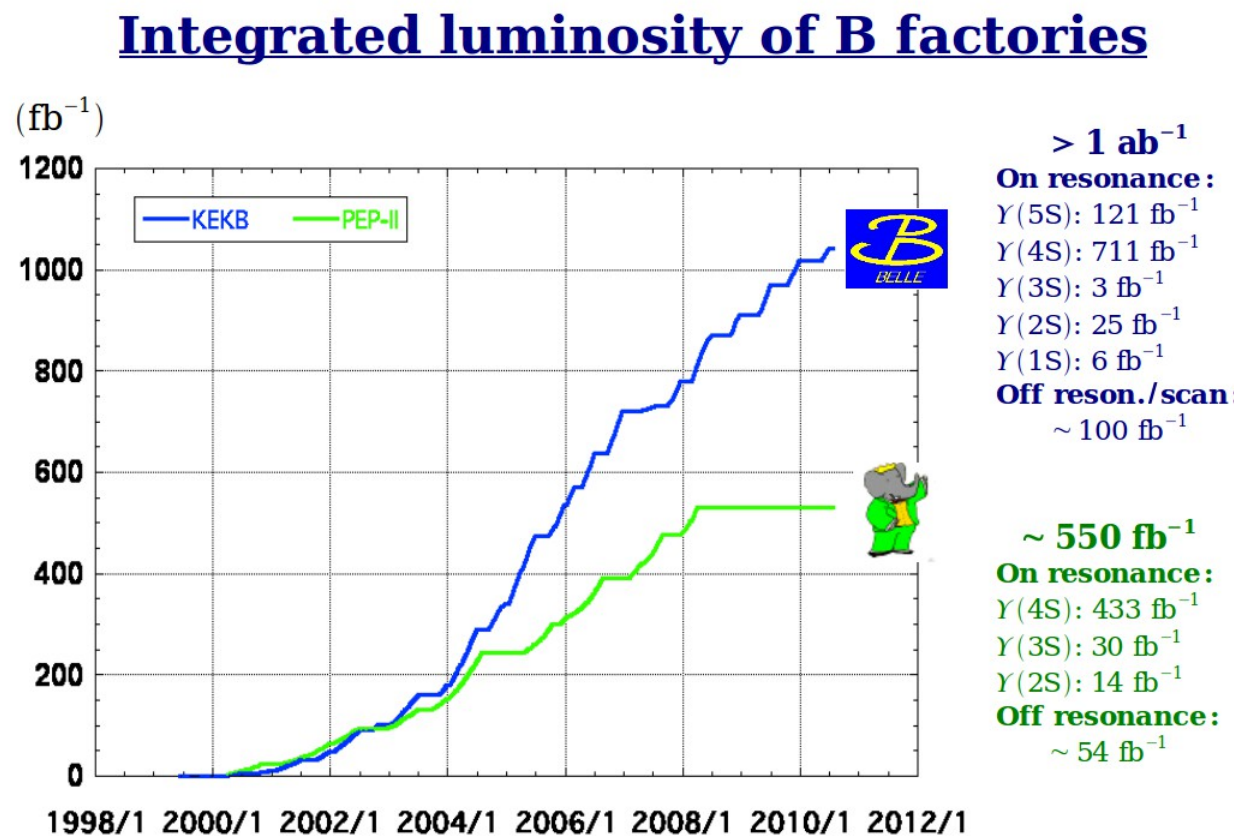
- high momentum resolution
  $\sigma_p/p = 0.3\%@1GeV/c$
- ability to detect photons down to 30 MeV
- good photon energy resolution
  $\sigma_M = 5$ MeV for $\pi^0 \rightarrow \gamma\gamma$
- lepton identification capability
  $\varepsilon > 0.9$, fake < 0.01
- K/ π/ p separation capability
  $\varepsilon \sim 0.9$, fake < 0.1
- excellent B decay vertex reconstruction
  $\sigma(\Delta z) = 80\mu m$!



Belle Experiment Achievements

- originally designed and operated to test SM mechansim for CP violation and measure time-dependent CP violation in the B system
- run 1999 – 2010:
  772M B meson pairs recorded
- all its features led to many discoveries, also beyond CP violation

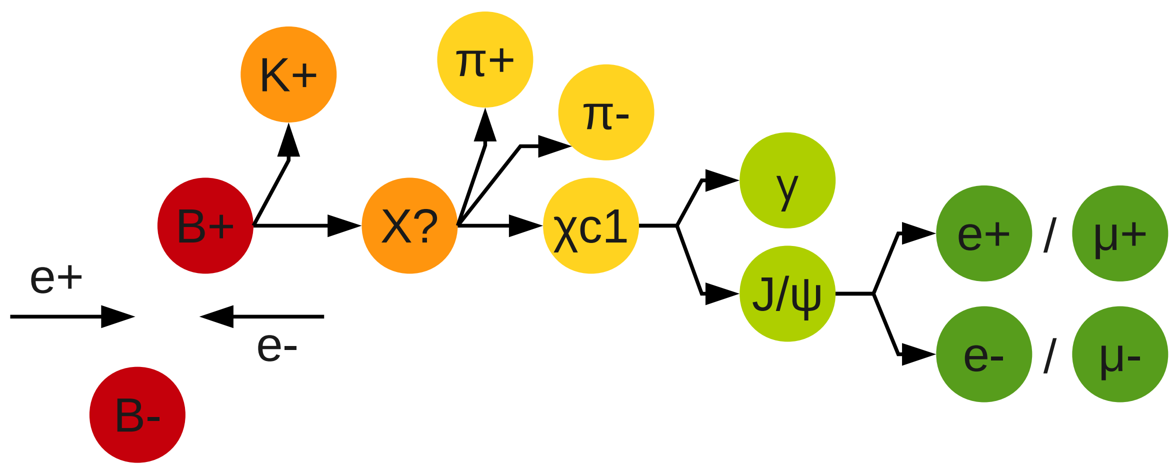




world's highest luminosity in e^+e^- at Y(4S) region !

Event Selection and Decay Reconstruction: $B^{\pm} \rightarrow \chi_{c1}\, \pi^{+}\pi^{-}\, K^{\pm}$

- analysis procedure: reconstruct $B^{\pm}$



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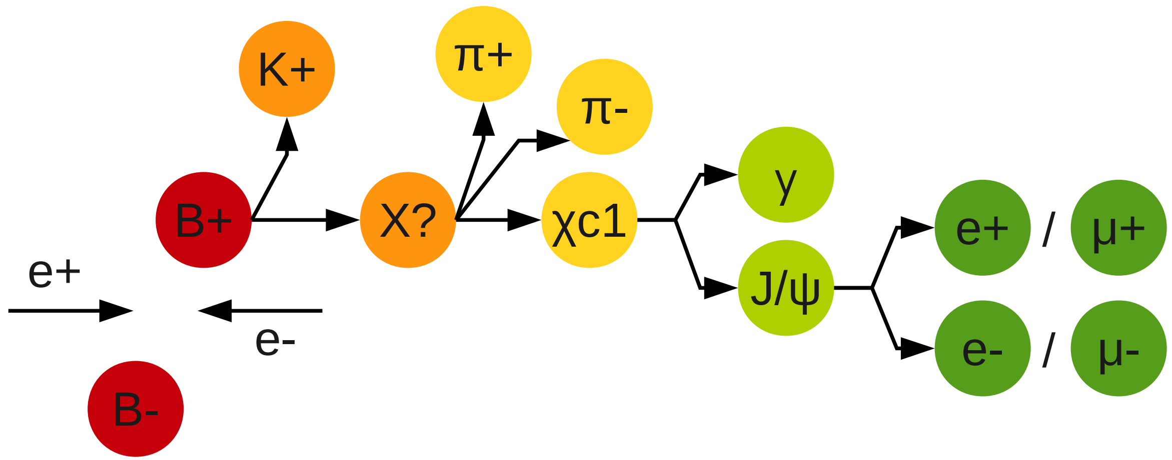

- dE/dx in *CDC*,
  E/p ratio (E in *ECL* and p in *CDC, SVD*)
  shower shape in *ECL*
  number of Cherenkov photons in *ACC*

- track penetration depth and
  hit scatter pattern in *KLM*
  reconstructed hits in KLM compared to
  extrapolation of *CDC* tracks

- selection cuts for intermediate particles:
  - impact parameters: distance to interaction point for charged tracks $|dr| < 1.5$ cm, $|dz| < 5.0$ cm
  - electron likelihood > 0.01
  - muon likelihood > 0.1

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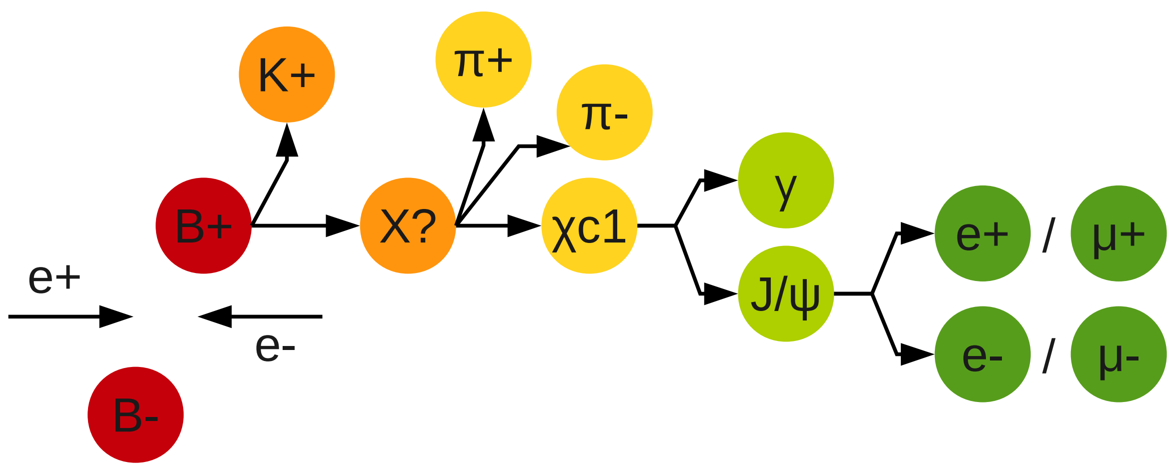

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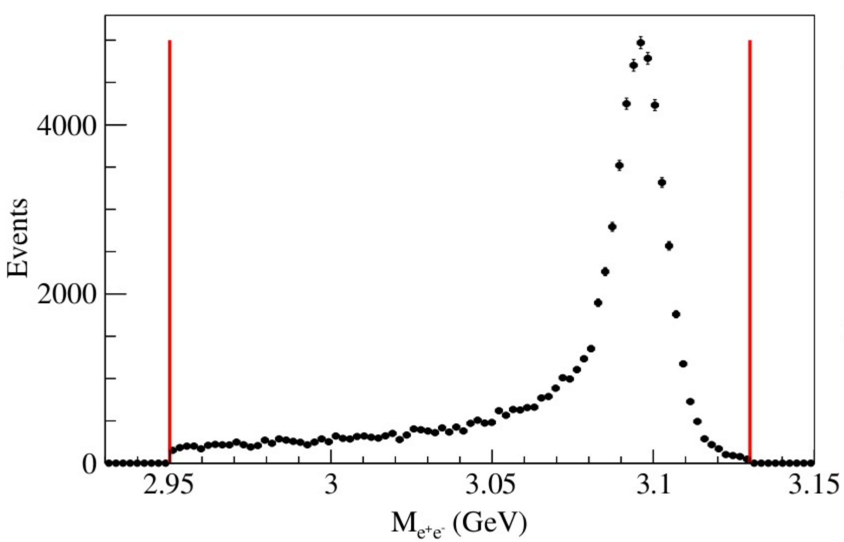
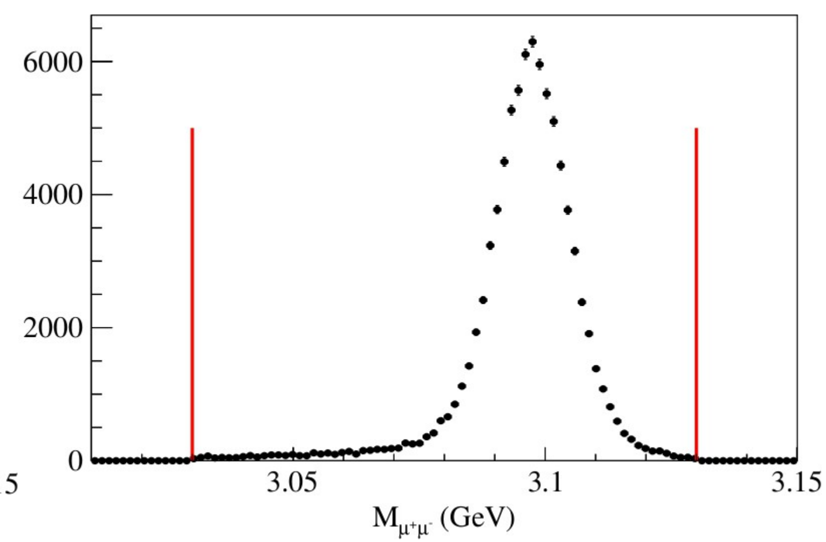
  - J/ψ window (nom. mass 3097 MeV): 2950/ 3030 MeV ≤ M(ee/μμ) ≤ 3130 MeV





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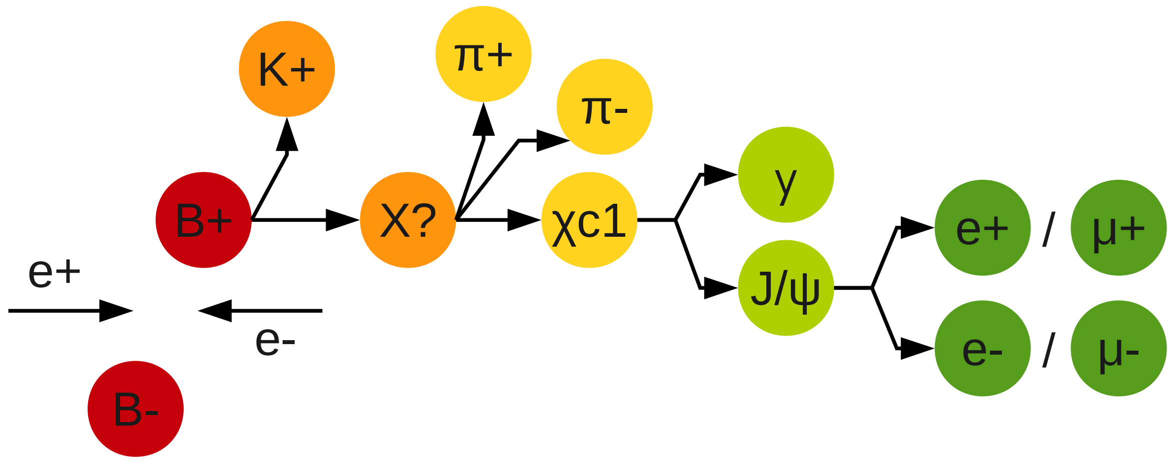

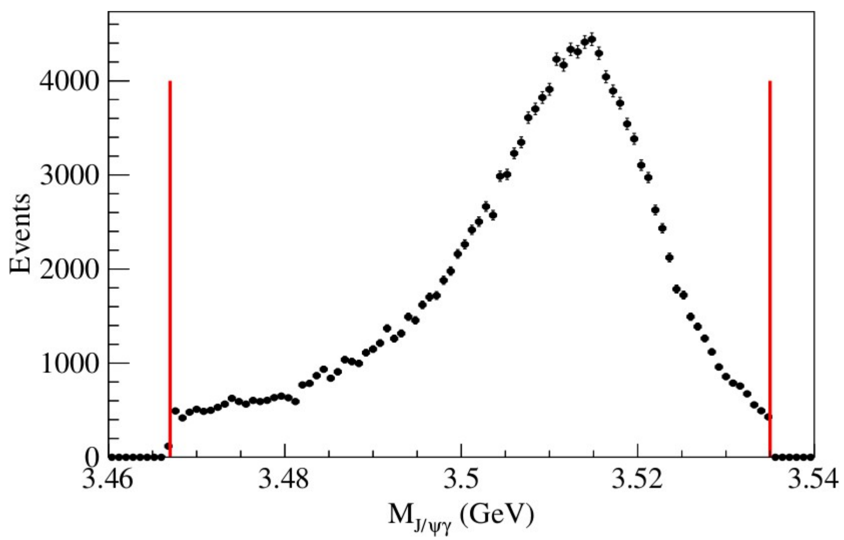

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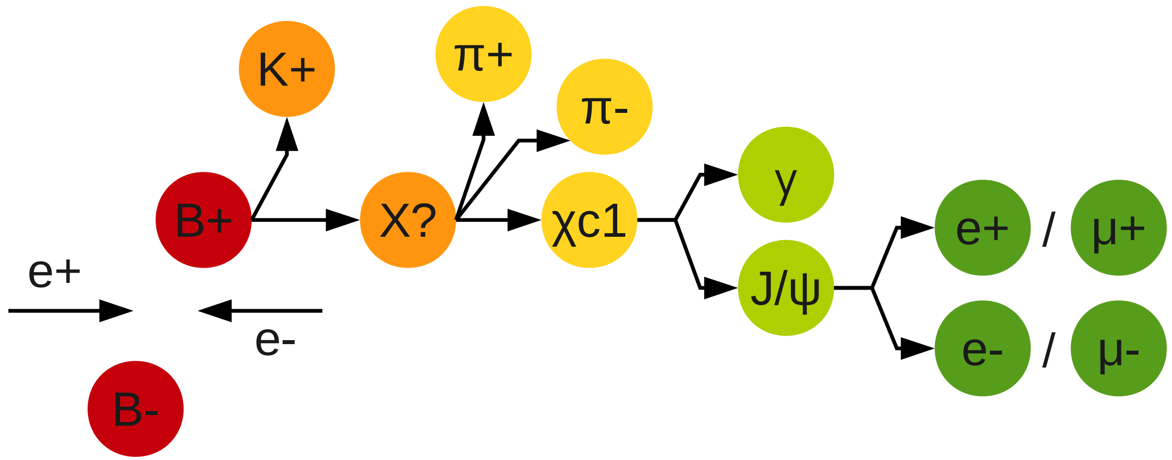
  - muon likelihood > 0.1
  - J/ψ window (nom. mass 3097 MeV):
    2950/ 3030 MeV ≤ M(ee/μμ) ≤ 3130 MeV
  - χ_{c1} window (nom. mass 3511 MeV):
    3467 MeV < M(J/ψ γ) < 3535 MeV
  - perform mass-constrained fits for J/ψ and χ_{c1} candidates

Event Selection and Decay Reconstruction: $B^{\pm} \rightarrow \chi_{c1} \pi^{+}\pi^{-} K^{\pm}$

- analysis procedure: reconstruct $B^{\pm}$



- kinematic variables in Y(4s) rest frame: beam-constrained mass M_{bc} and difference to beam energy ΔE

$$M_{\rm bc} = \sqrt{E_{\rm beam}^2 - (p_{\chi c1 \pi\pi} + p_K)^2}$$

$$\Delta E = (E_{\chi c1 \pi\pi} + E_K) - E_{\rm beam}$$

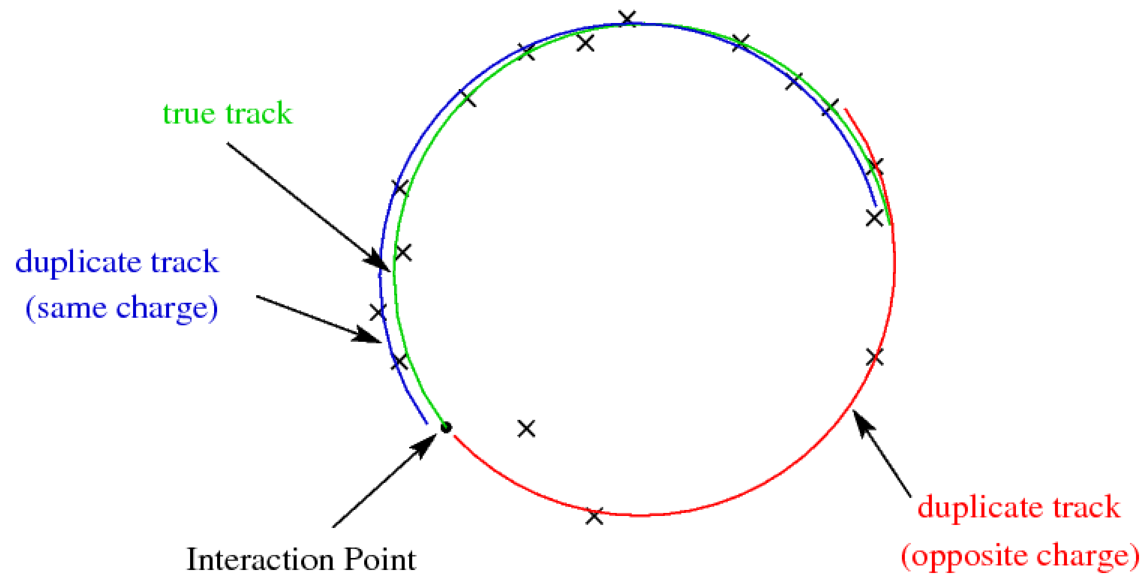
- selection cuts for intermediate particles:
  - impact parameters: distance to interaction point for charged tracks
    |dr| < 1.5 cm, |dz| < 5.0 cm
  - electron likelihood > 0.01
  - muon likelihood > 0.1
  - J/ψ window (nom. mass 3097 MeV):
    2950/ 3030 MeV ≤ M(ee/μμ) ≤ 3130 MeV
  - χ_{c1} window (nom. mass 3511 MeV):
    3467 MeV < M(J/ψ γ) < 3535 MeV
  - perform mass-constrained fits for J/ψ and χ_{c1} candidates

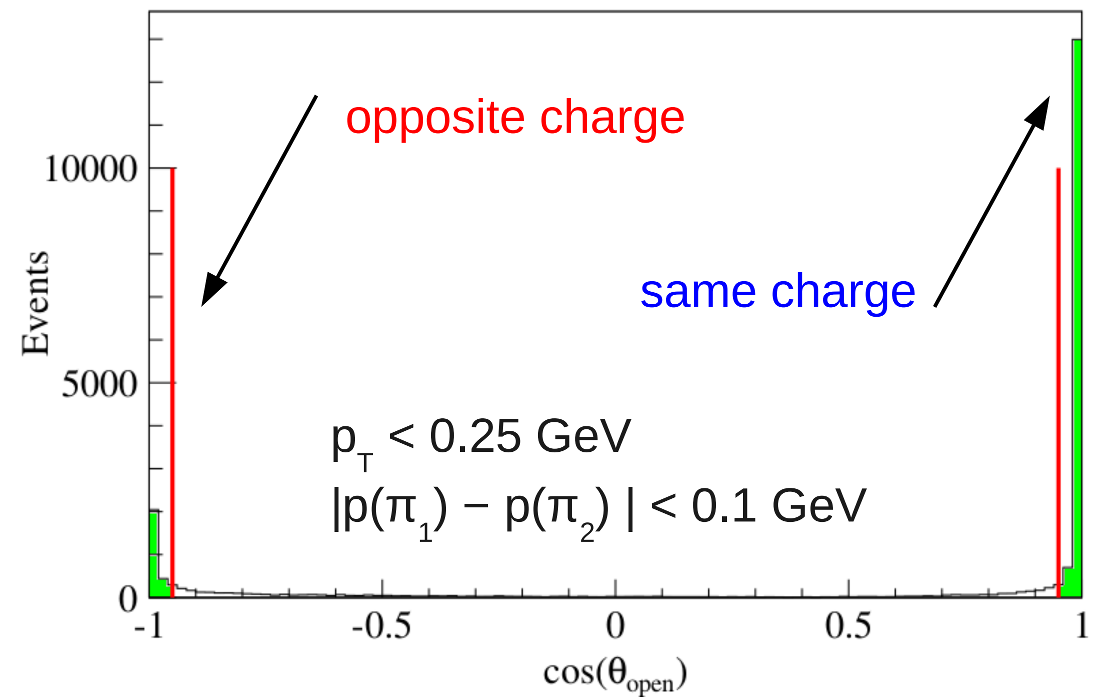
Pion Selection

- small Q-value in X(3872) → $\chi_{c1}\pi^+\pi^-$:
  3872 – (3511+140+140) ≈ 80 MeV
- pions have very low transverse momenta p_T
- results in curl up in CDC and possible duplicated reconstruction
- opening angle θ_{open} between pion tracks:
  - ~0° for same charge
  - ~180° for opposite charge

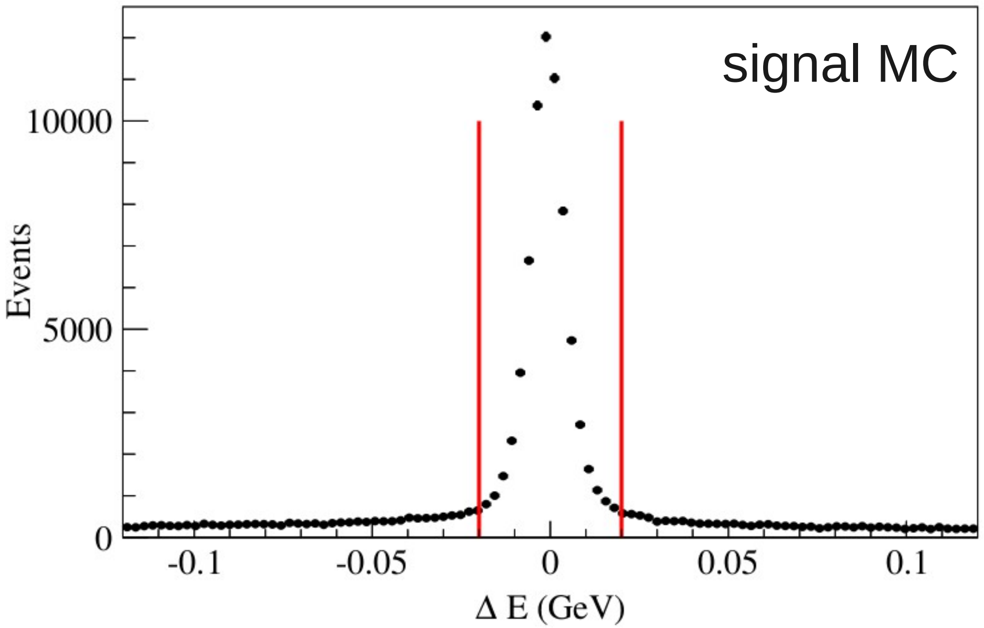
→ compare pions in pairs, select the one with smallest distance to interaction point

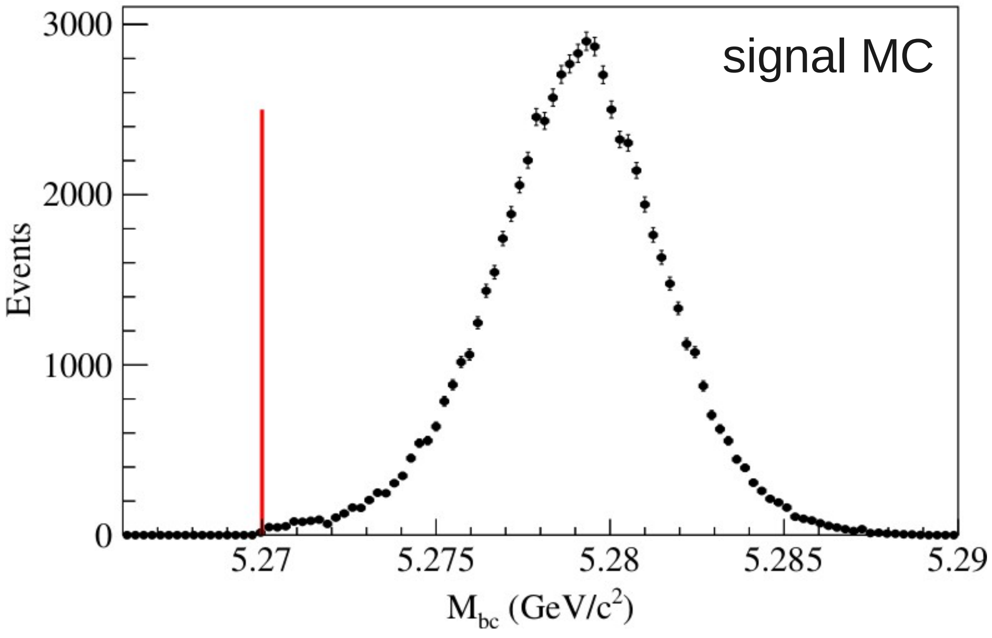
$$\left|\frac{dr}{15\text{mm}}\right|^2 + \left|\frac{dz}{50\text{mm}}\right|^2$$



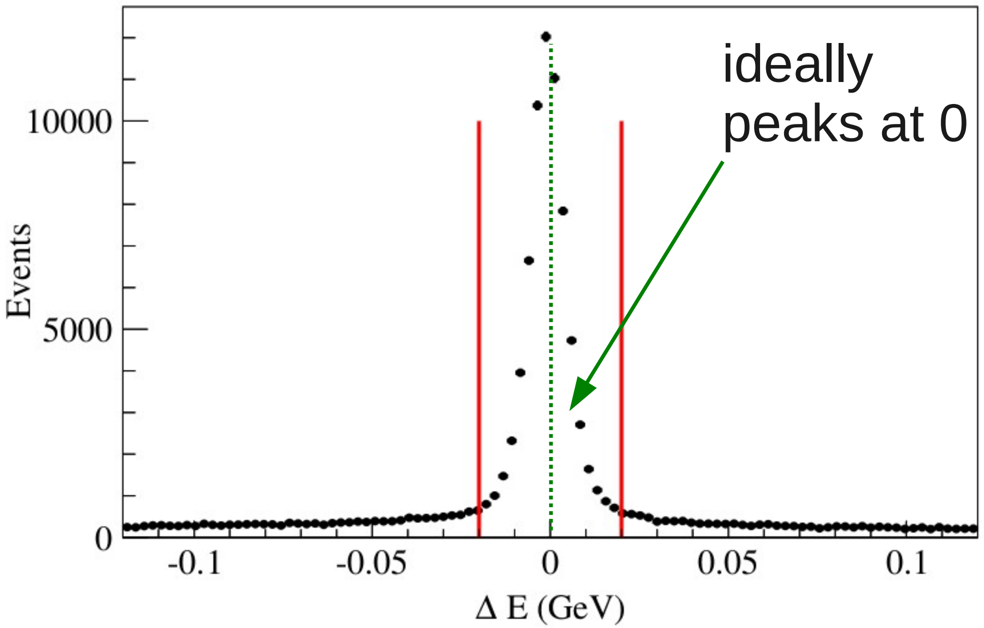


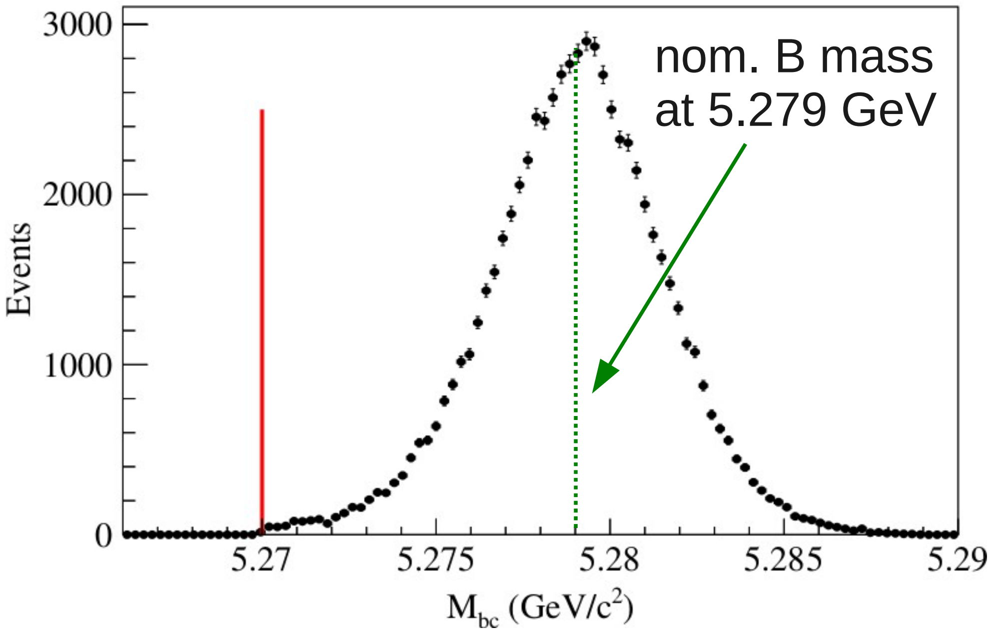
B Candidate Reconstruction





B Candidate Reconstruction

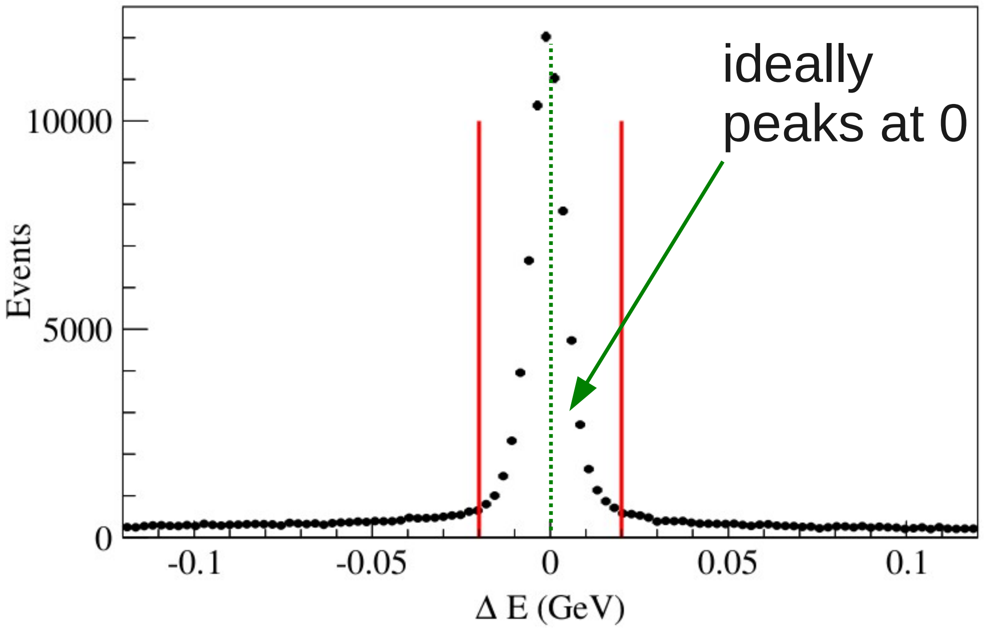


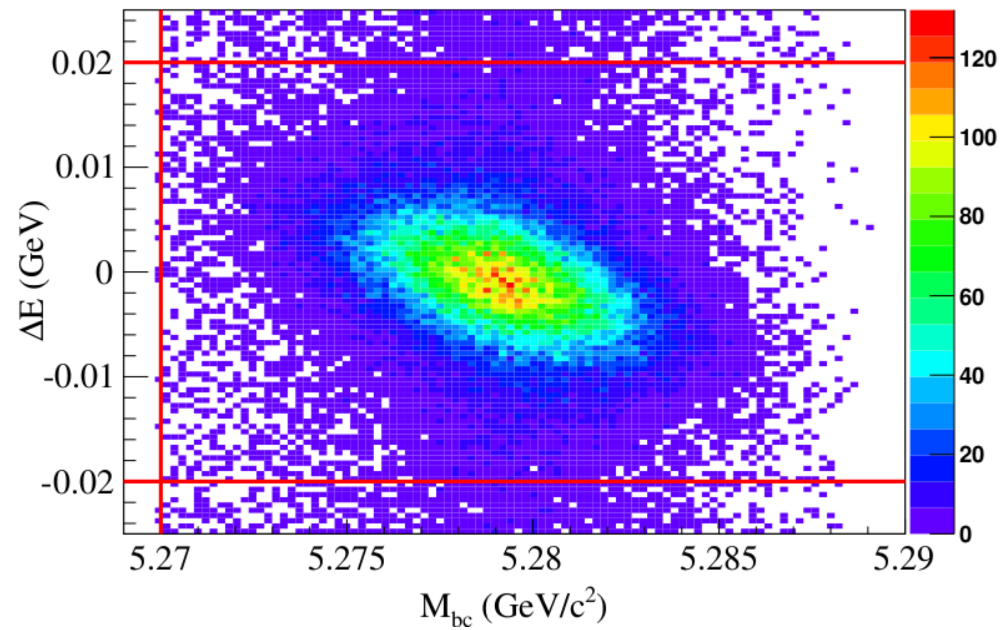


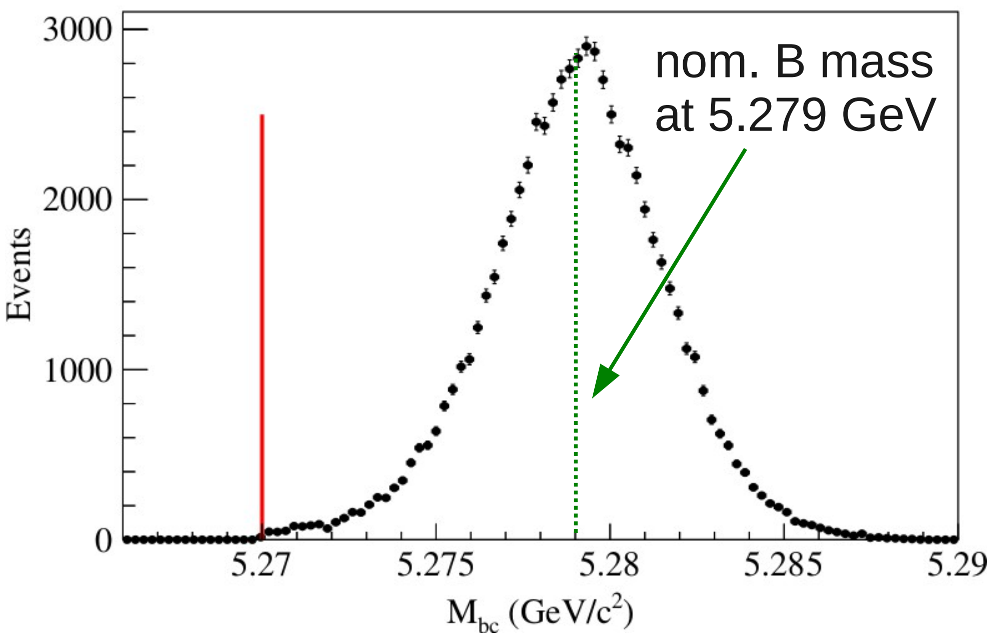
$$M_{\rm bc} = \sqrt{E_{\rm beam}^2 - (p_{\chi_{c1}\pi\pi} + p_K)^2}$$

$$\Delta E = (E_{\chi_{c1}\pi\pi} + E_K) - E_{\rm beam}$$

B Candidate Reconstruction







- signal window cut:
  - $|\Delta E| < 0.02$ GeV
  - $M_{bc} > 5.27$ GeV

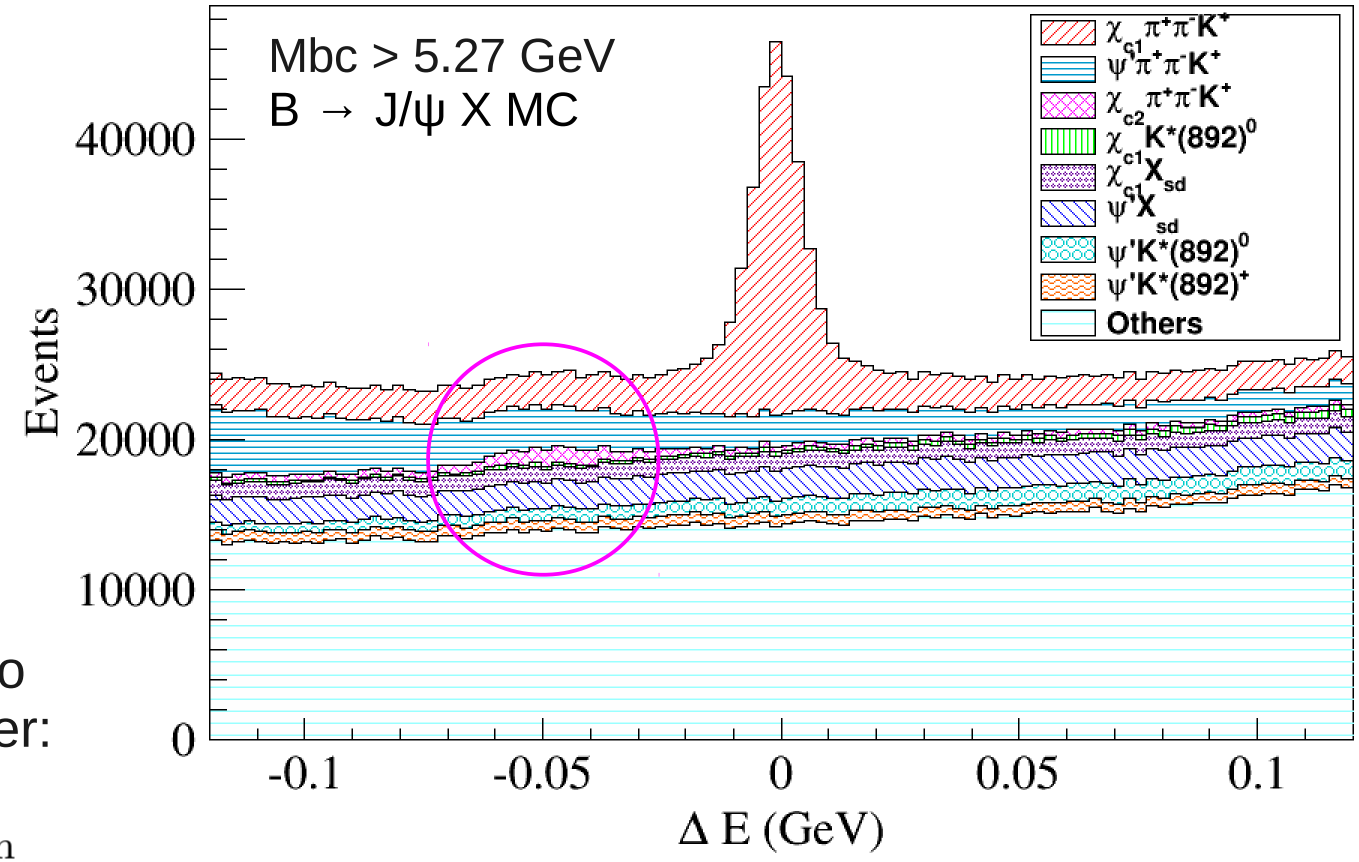
ΔE Distribution – Background Estimation

- B → J/ψ X MC sample for bkg study
  - 100x amount of data

- signal is included in the MC sample
- only peaking background coming from $B^{\pm} \rightarrow \chi_{c2}\, \pi^{+}\pi^{-}K^{\pm}$
  - shifted to negative ΔE region due to χ_{c2}'s slightly higher mass, remember:

$$\Delta E = \quad (E_{\chi_{c1}\pi\pi} + E_K) - E_{\mathrm{beam}}$$

- all other backgrounds are smooth



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$$\Delta E = (E_{\chi_{c1}\pi\pi} + E_K) - E_{\rm beam}$$

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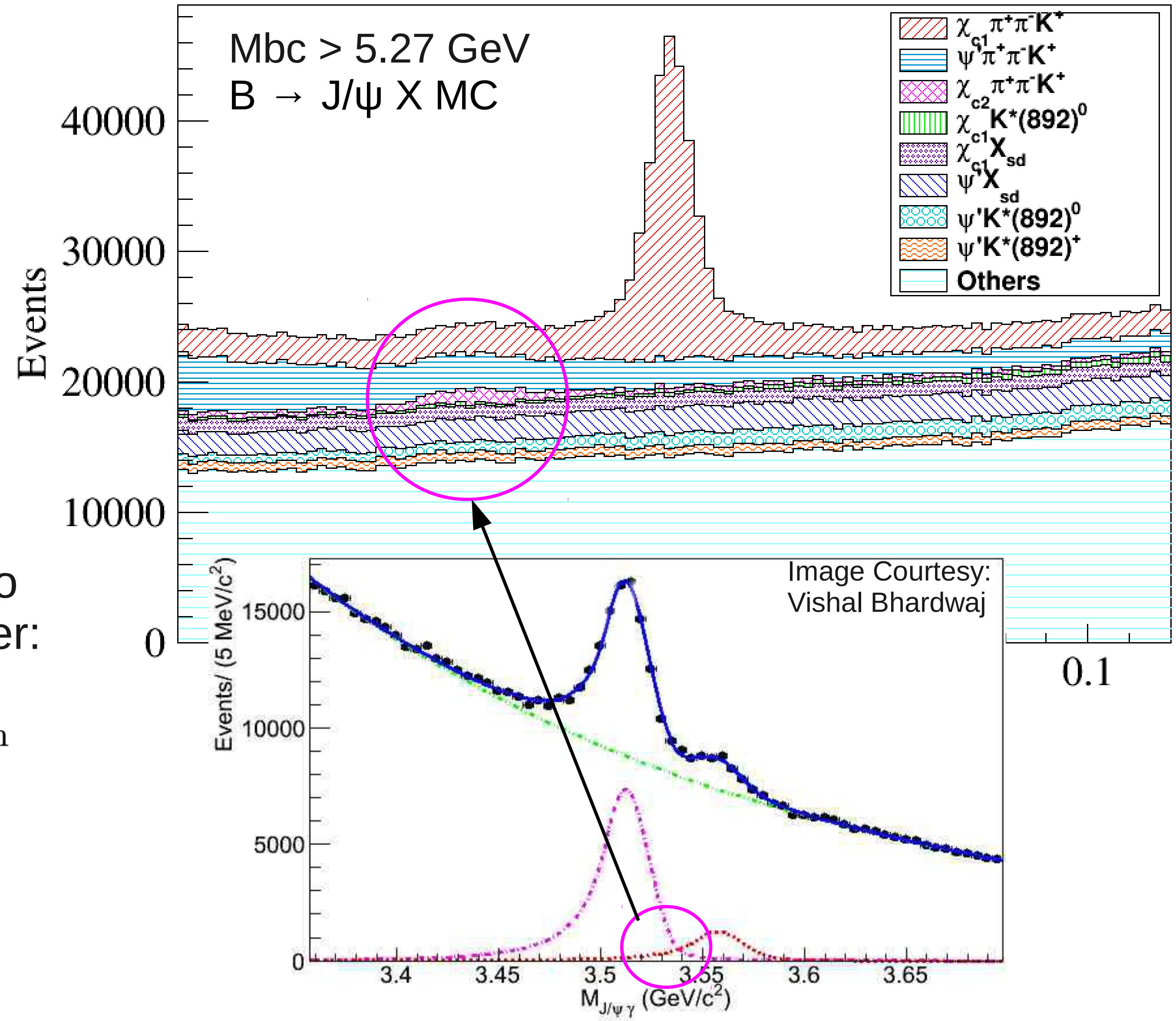
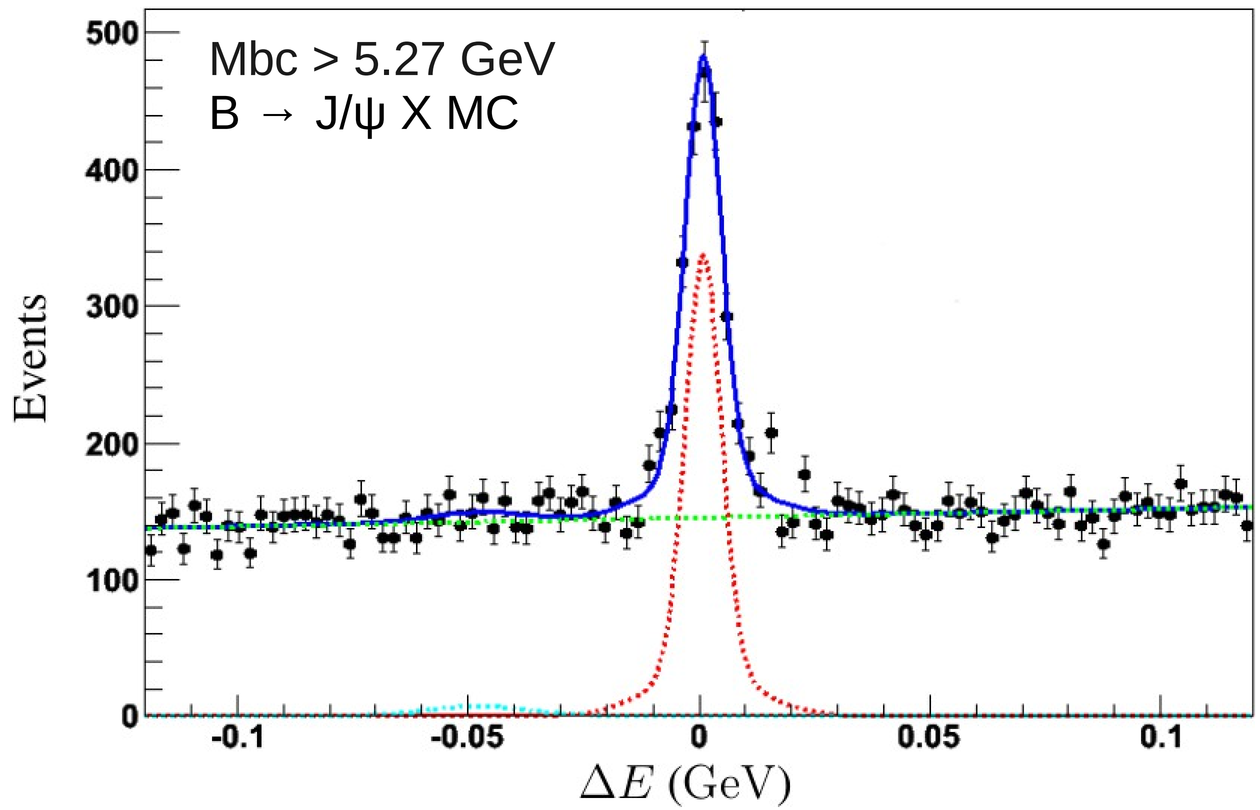


ΔE Distribution – PDF and MC Expectation

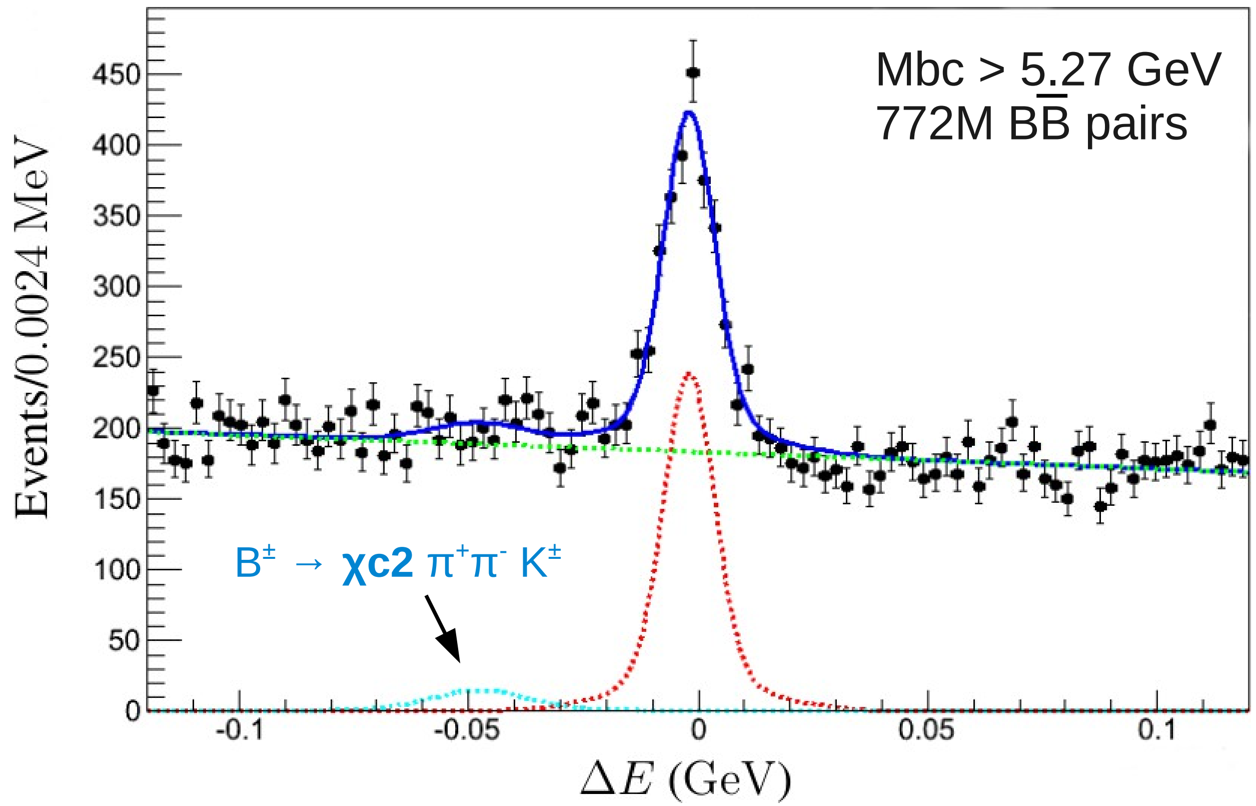
- unbinned maximum likelihood (UML) fit to B → J/ψ X MC sample to find probability density function (PDF)
  - signal: sum of two Gaussians
  - $B^{\pm} \rightarrow \chi_{c2} \pi^{+}\pi^{-}K^{\pm}$: sum of two Gaussians
  - flat bkg: 1st order Chebyshev polynomial



- expected peak yield for the as yet unseen decay $B^{\pm} \rightarrow \chi_{c1} \pi^{+}\pi^{-} K^{\pm}$: 1700 events
  - assuming $\mathcal{B}(B \to \chi_{c1}\pi^+\pi^-K) = \mathcal{B}(B \to J/\psi\pi^+\pi^-K) \cdot$ decay dynamics

ΔE Distribution – Looking at Data

first observation of the decay of $B^{\pm} \rightarrow \chi_{c1}\pi^{+}\pi^{-}K^{\pm}$ with a signal peak yield of 1597 ± 76 events



- comparing resolutions:
  σ(data) / σ(MC) = (1.18 ± 0.07)%
  - consistent within 10%

Reconstruction Efficiency Considerations

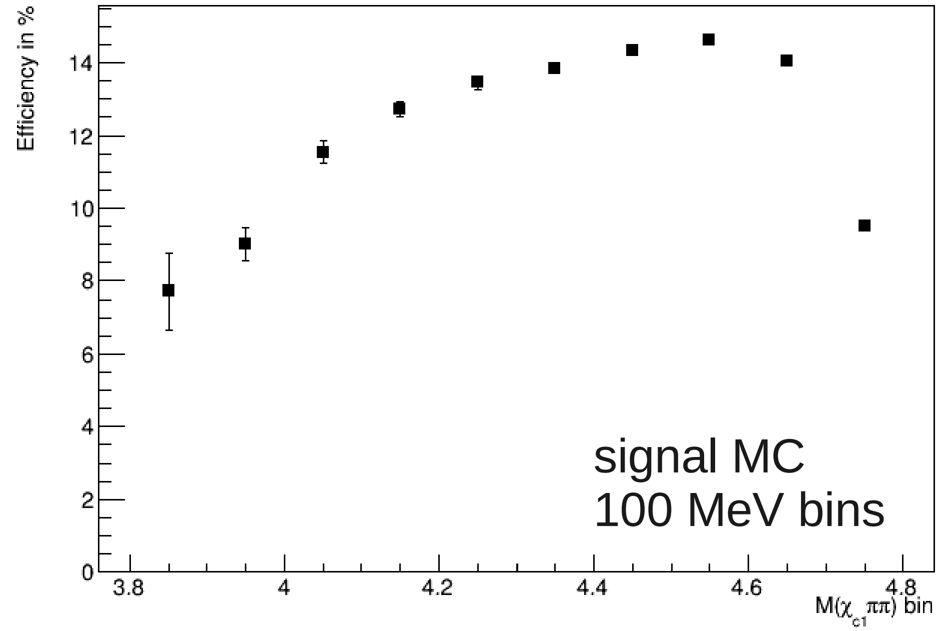
- efficiency is changing as a function of the invariant mass of $\chi_{c1}\ \pi^+\pi^-$

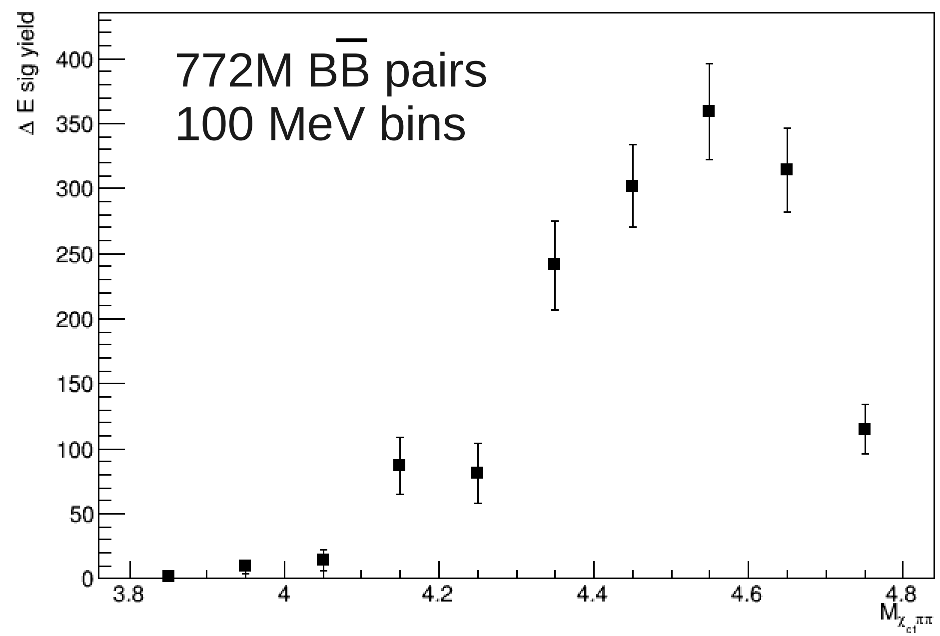
➔ using a reconstruction efficiency **weighted** with the obtained signal yield per $\chi_{c1}\pi^+\pi^-$ mass bin

$$\varepsilon = \frac{\sum_{i=1}^{10} \varepsilon(i) \cdot N_{\rm obs}(i)}{\sum_{i=1}^{10} N_{\rm obs}(i)}$$

- efficiency correction estimated from lepton and particle identification: 0.9622

➔ resultant reconstruction efficiency 12.90%





Branching Ratio of $B^{\pm} \to \chi_{c1}\pi^{+}\pi^{-}K^{\pm}$

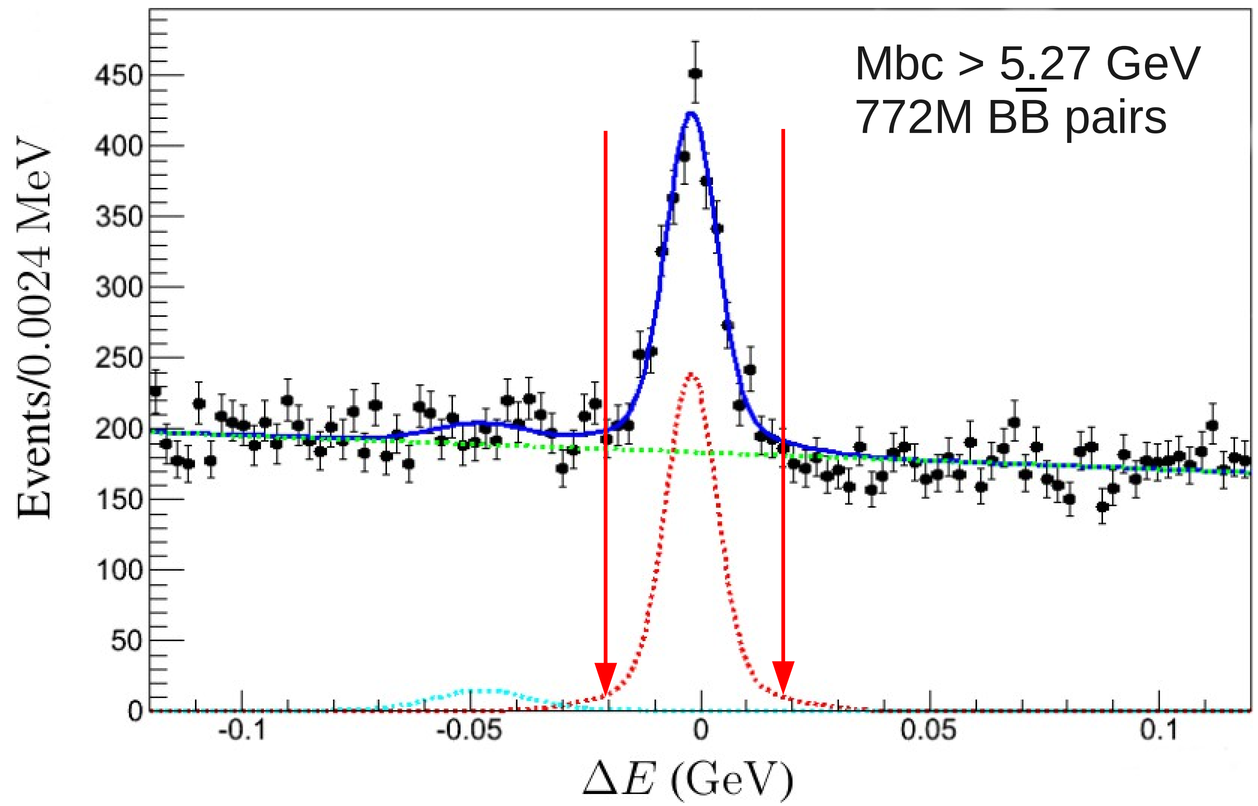
$$\mathcal{B}(B^+ \to \chi_{c1}\pi^+\pi^-K^+) = \frac{N_{\rm sig}}{\varepsilon_{det} \times \mathcal{B}(\chi_{c1} \to J/\psi\gamma) \times \mathcal{B}(J/\psi \to \ell^+\ell^-) \times N_{B\bar{B}}}$$

- N_{sig} – 1597 ± 76
- N_{BB} – 772 x10^{6}
- ε_{det} – 12.90%
- Br(χ_{c1} → J/ψγ) – (34.8 ± 1.5)%
- Br(J/ψ → e^+e^-) – (5.94 ± 0.06)%
- Br(J/ψ → $\mu^+\mu^-$) – (5.93 ± 0.06)%
- systematic uncertainty – 5.10%

$$\mathcal{B}(B^+ \to \chi_{c1}\pi^+\pi^-K^+) = (\ 3.89 \pm 0.19\ (\mathrm{stat}) \pm 0.20\ (\mathrm{syst})\ ) \times 10^{-4}$$

The χ_{c1} $\pi^+\pi^-$ Invariant Mass Distribution

- select B signal region to look into M(χ_{c1} $\pi^+\pi^-$)
  - |ΔE| < 0.02 GeV
  - M_{bc} > 5.27 GeV
- search for
  - a narrow resonance X(3872) at 3872 MeV or
  - an as yet unseen charmonium χ_{c1}(2P) at 3920 MeV



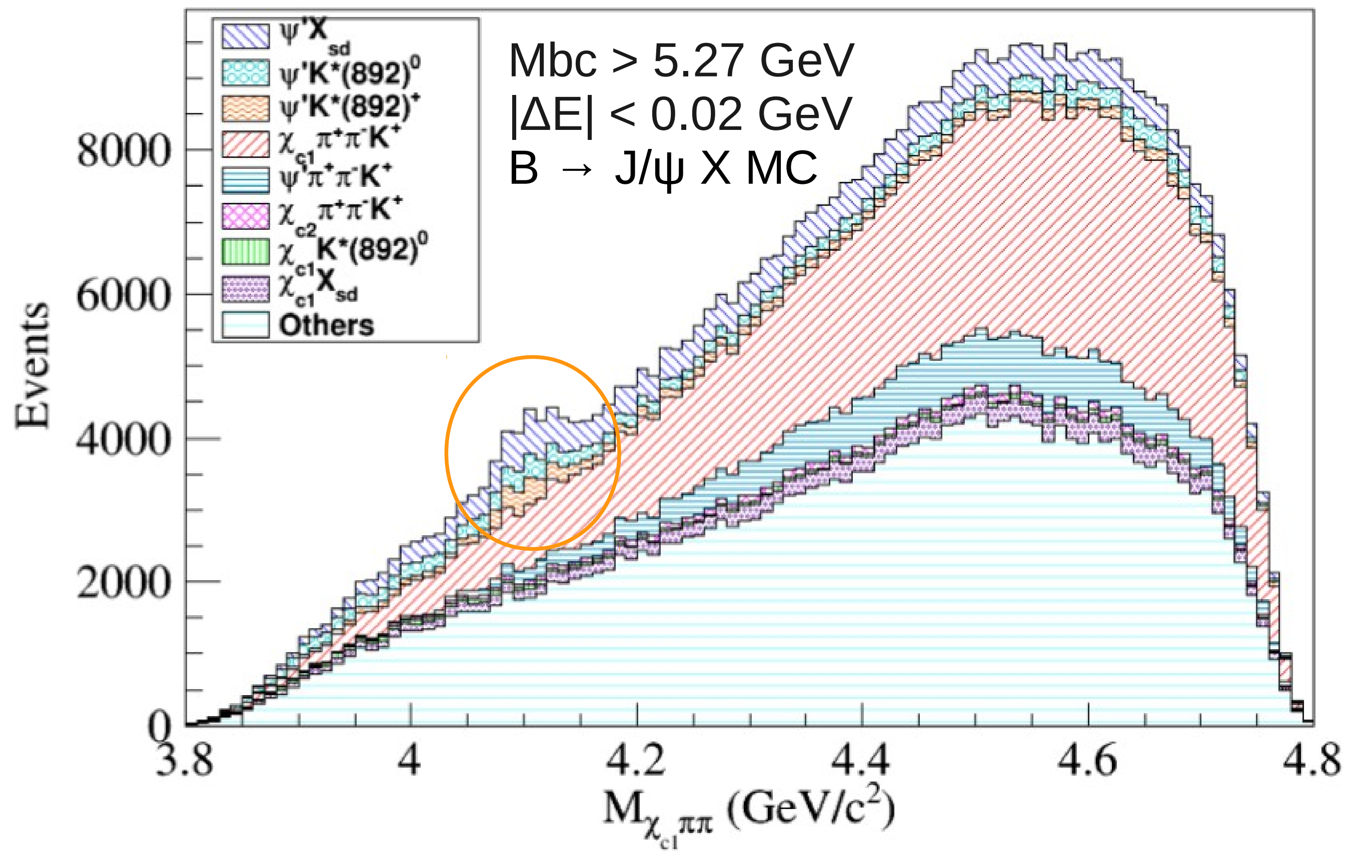
M(χ_{c1} $\pi^+\pi^-$) Distribution – Expected Background

- no peaking structure except for a ψ(2S) reflection at 4.1 GeV
- ψ(2S) → J/ψ $\pi^+\pi^-$

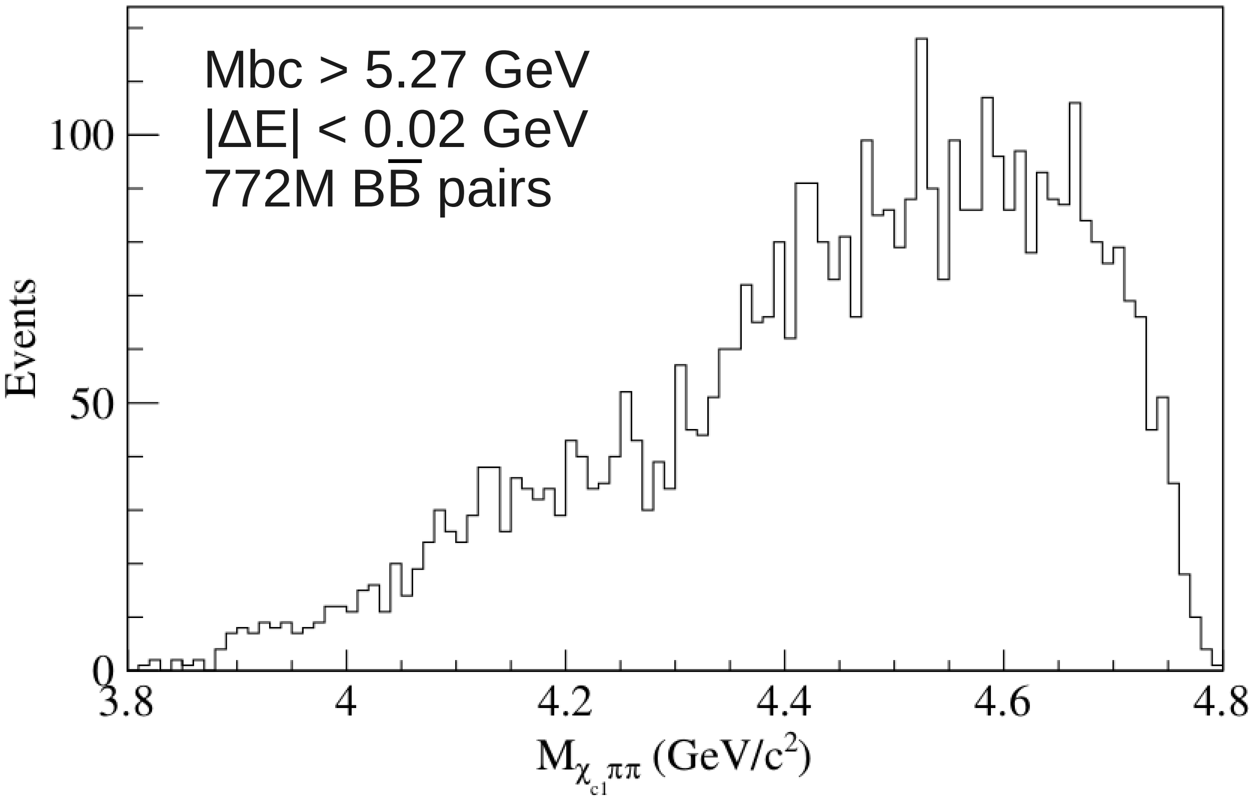
  \+ γ

➔ results in a fake χ_{c1} !

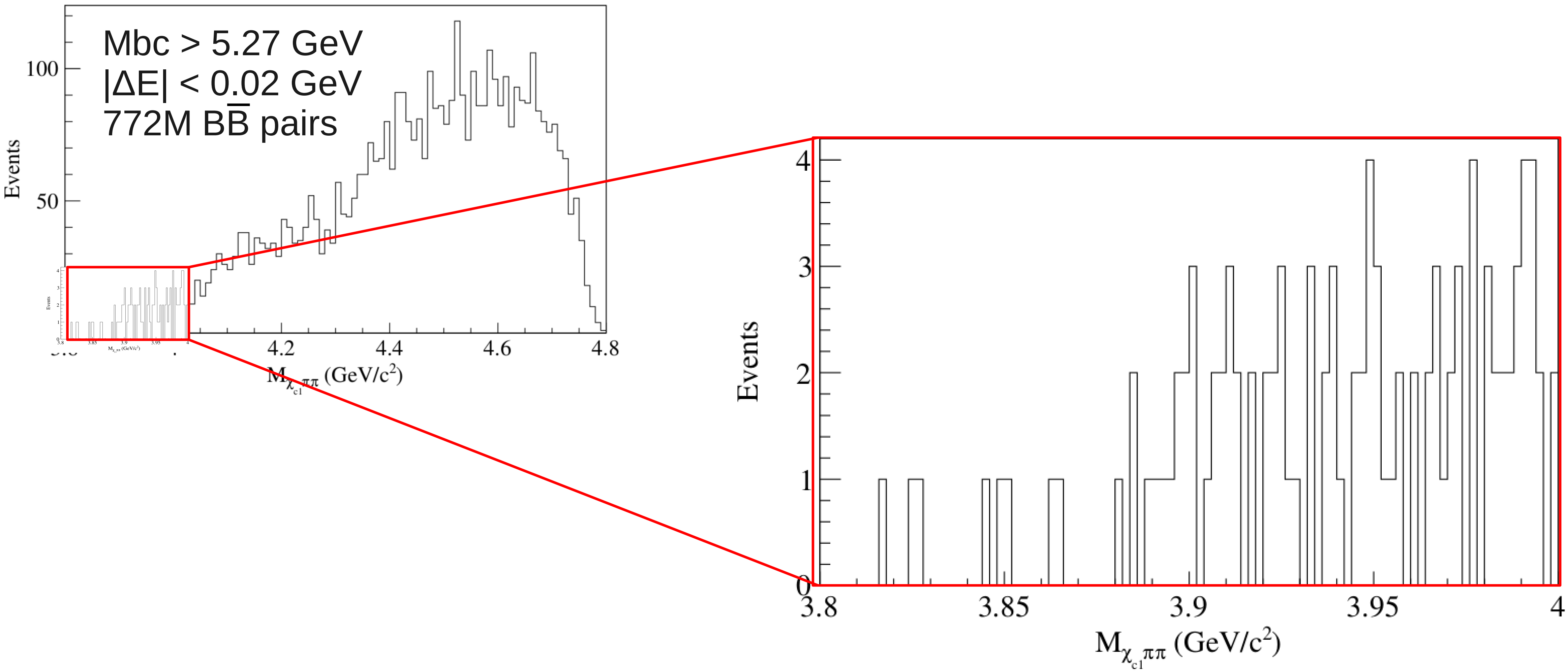
➔ but: region above 4.0 GeV is not of interest for this analysis



M(χ_{c1} $\pi^+\pi^-$) Distribution – Looking at Data



$M(\chi_{c1}\ \pi^+\pi^-)$ Distribution – Looking at Data



X(3872) → $\chi_{c1}\ \pi^+\pi^-$

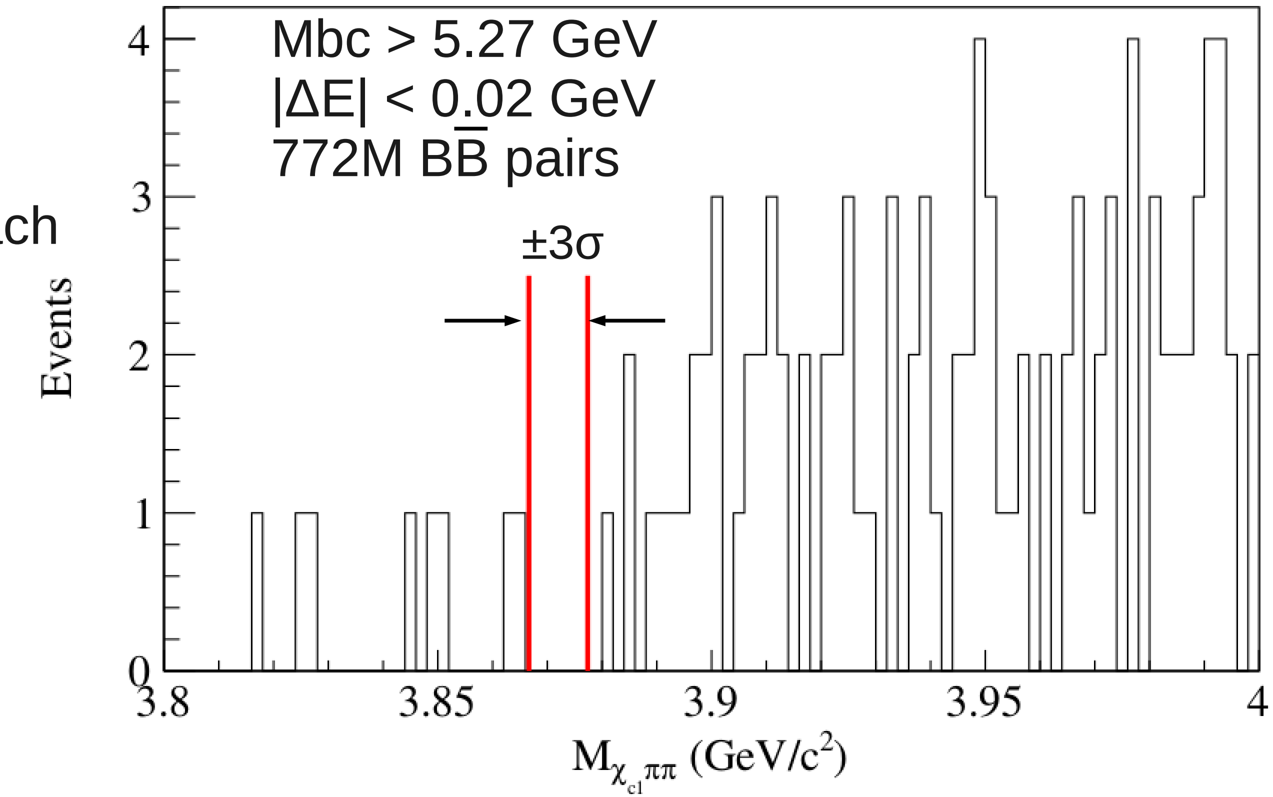
- assuming B(X(3872) → $\chi_{c1}\pi^+\pi^-$) to be similar to B(X(3872) → J/ψ$\pi^+\pi^-$)

➔ roughly 15 events expected and seeing X(3872) → $\chi_{c1}\pi^+\pi^-$ is within sensitivity reach

- not enough statistics for a conclusive fit

- use approach of Feldman-Cousins at 90% confidence level: estimated signal events N_{sig} < 2.44

- reconstruction efficiency ε_{det} = 5.59%



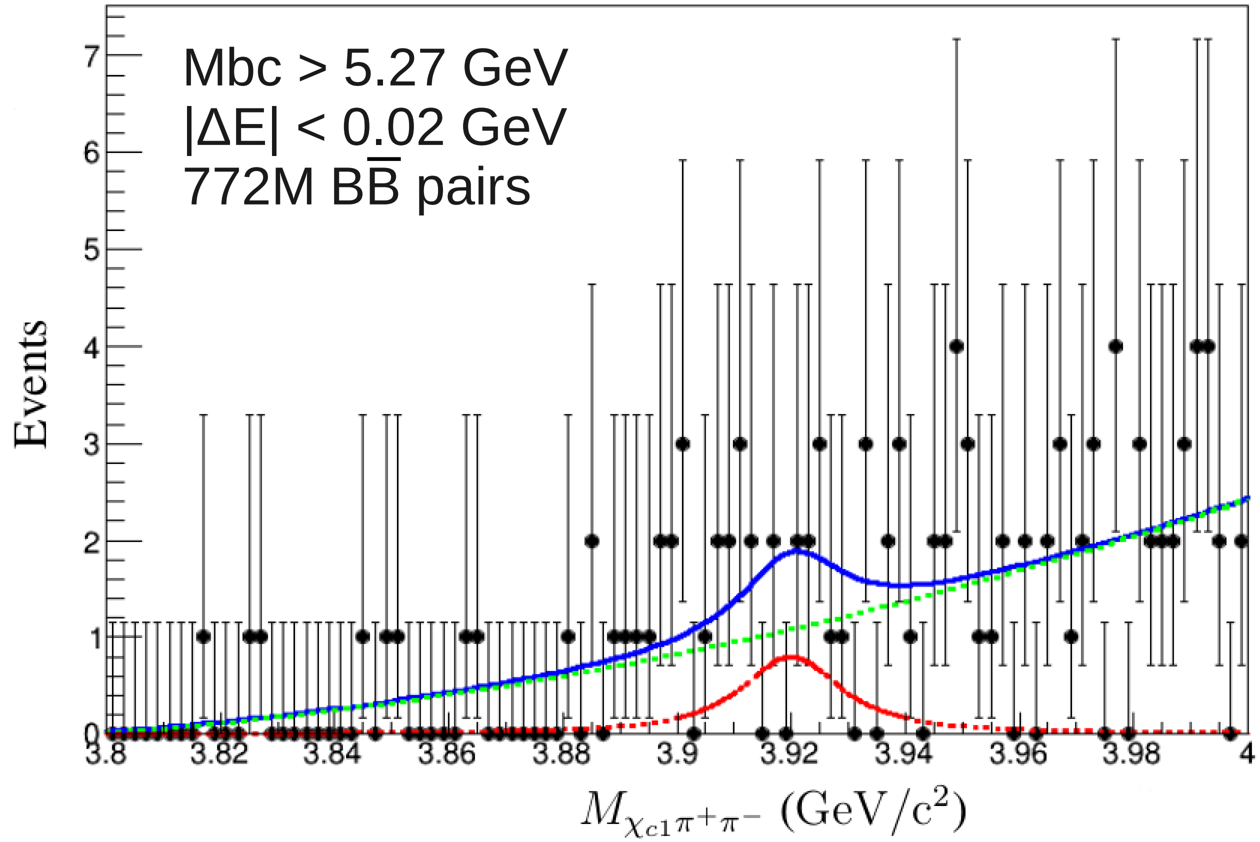
$$\mathcal{B}(B^{\pm} \to X(3872)\ K^{\pm}) \times \mathcal{B}(X(3872) \to \chi_{c1}(1P)\pi^{+}\pi^{-}) < \ 1.4 \times 10^{-6}\ @\ 90\%\ \text{C.L.}$$

$\chi_{c1}(2P) \rightarrow \chi_{c1}\,\pi^+\pi^-$

- natural width estimated from other $\chi_{cJ}(2P)$ states → 20 MeV
- resolution estimated from MC studies (Gauss standard deviation) → 2 MeV

➔ fit with convolution of Gauss and Breit-Wigner → (12.2 ± 9.1) yield

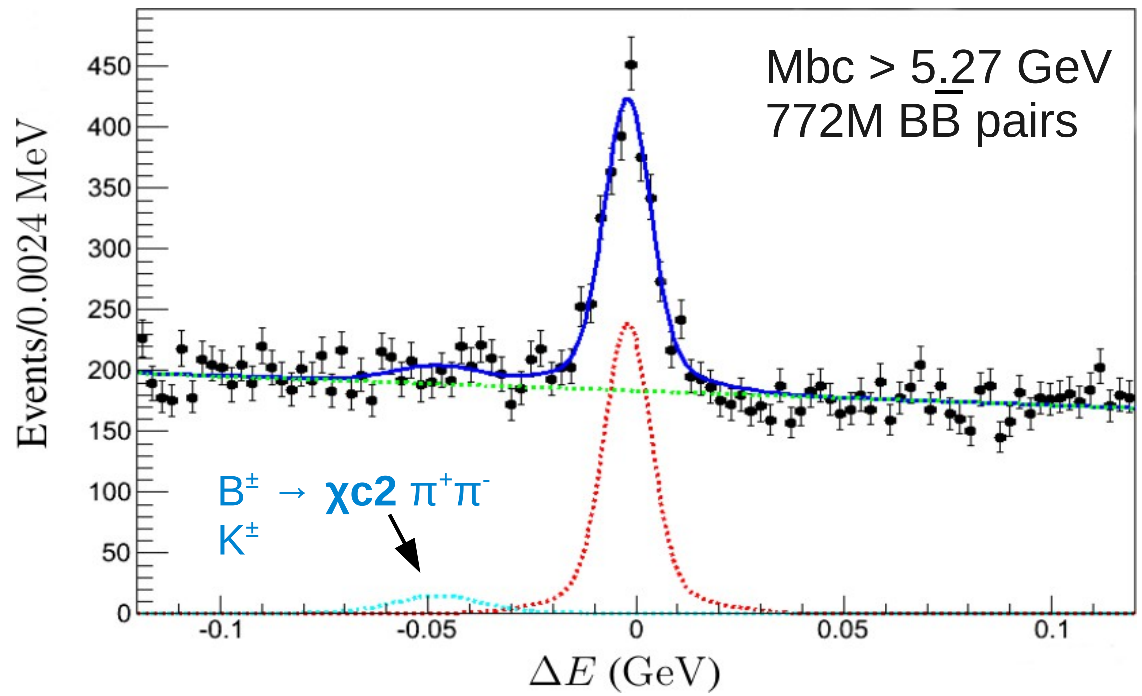
- considering 90% confidence level: estimated signal events N_{sig} < 30.34
- reconstruction efficiency ε_{det} = 8.91%

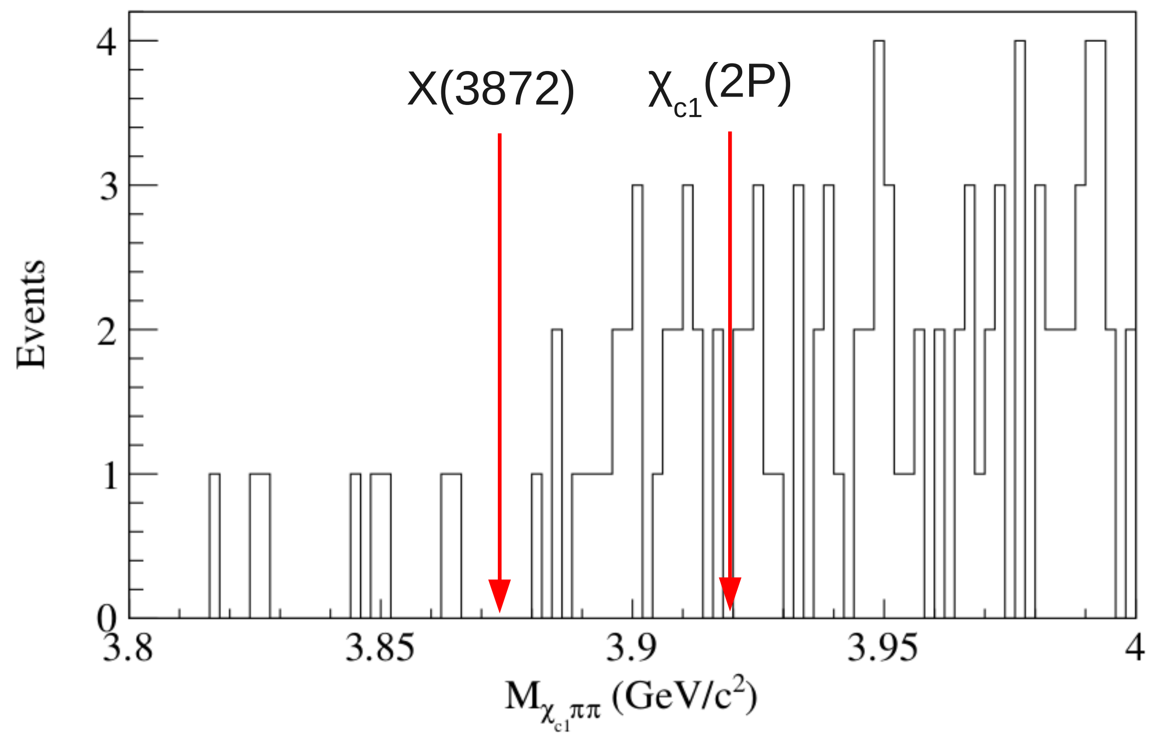


$$\mathcal{B}(B^{\pm} \rightarrow \chi_{c1}(2P)K^{\pm}) \times \mathcal{B}(\chi_{c1}(2P) \rightarrow \chi_{c1}(1P)\pi^+\pi^-) < \; 1.1 \times 10^{-5} \text{ @ } 90\% \text{ C.L.}$$

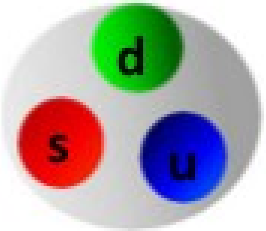
Conclusion

- $B^{\pm} \rightarrow \chi_{c1} \pi^+\pi^- K^{\pm}$ unseen before this analysis and important to pinpoint X(3872)'s structure
- very interesting to look for:
  X(3872) or χ_{c1}(2P) decaying to $\chi_{c1} \pi^+\pi^-$
- first observation of $B^{\pm} \rightarrow \chi_{c1} \pi^+\pi^- K^{\pm}$
  with (1597 ± 76) signal events from
  772M $B\overline{B}$ pairs dataset
  - branching fraction 3.89×10^{-4}
- $\chi_{c1} \pi^+\pi^-$ invariant mass spectrum:
  - no statistically significant evidence for
    - either X(3872): upper limit 1.4×10^{-6}
    - nor χ_{c1}(2P): upper limit 1.1×10^{-5}





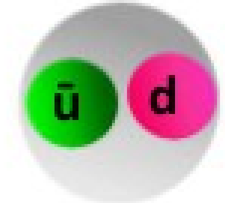
Backup



Baryons are red-blue-green triplets

Λ=usd

Mesons are color-anticolor pairs

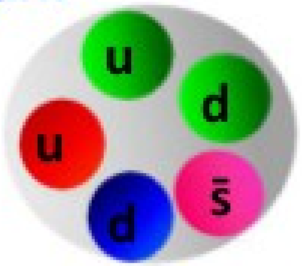


π=ūd

Other possible combinations of quarks and gluons :

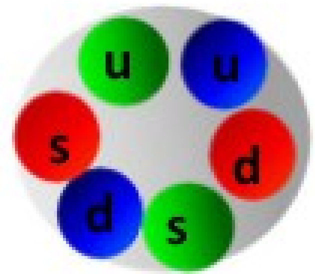
Pentaquark

S= +1 Baryon



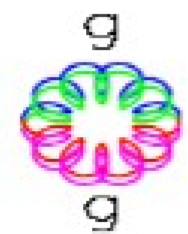
H di-Baryon

Tightly bound 6 quark state



Glueball

Color-singlet multi-gluon bound state

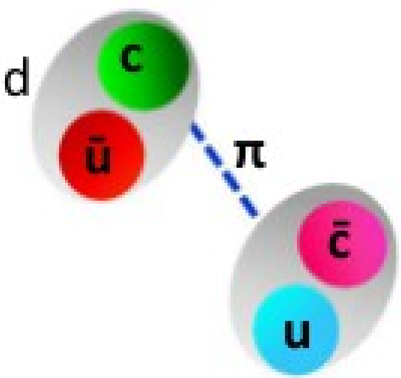


Tetraquark

Tightly bound diquark & anti-diquark

Molecule

loosely bound meson-antimeson "molecule"



$q\bar{q}$ -gluon hybrid mesons

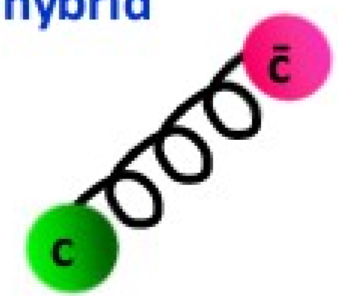
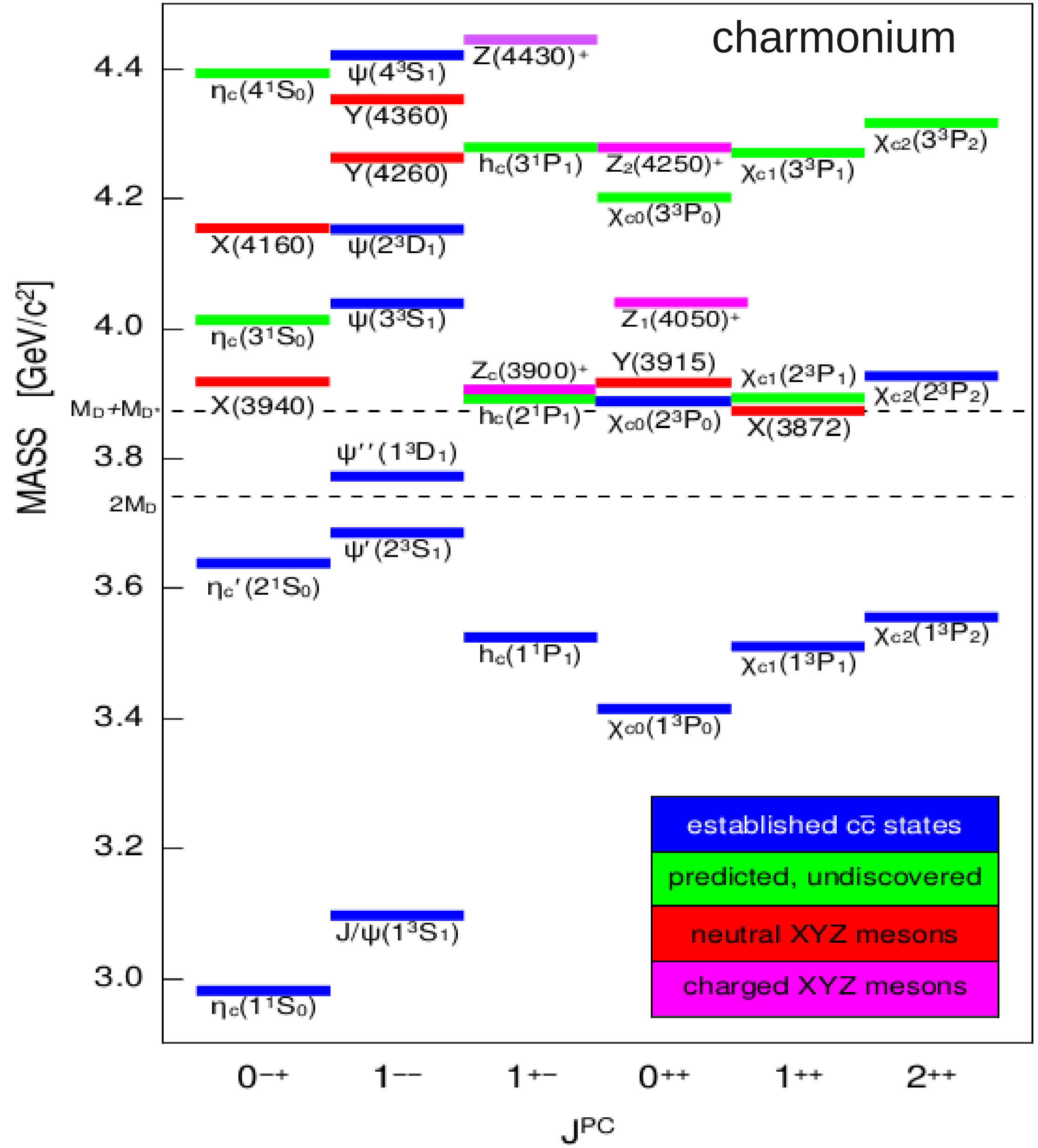


Image Courtesy: Vishal Bhardwaj

Status on Exotic Hadrons

- unexpected and still-fascinating X(3872) has been joined by more than a dozen other "XYZ" states that appear to lie outside the quark model
- charmonium(-like) states:
  - X(3915), Y(3940), X(3940), X(4160)
  - Y(4260), Y(4360), Y(4660)
  - $Z^+(3900)$, $Z^+_1(4050)$, $Z^+_2(4250)$, $Z^+(4430)$

charged states alligned according to best guess
at quantum numbers of neutral charged partner



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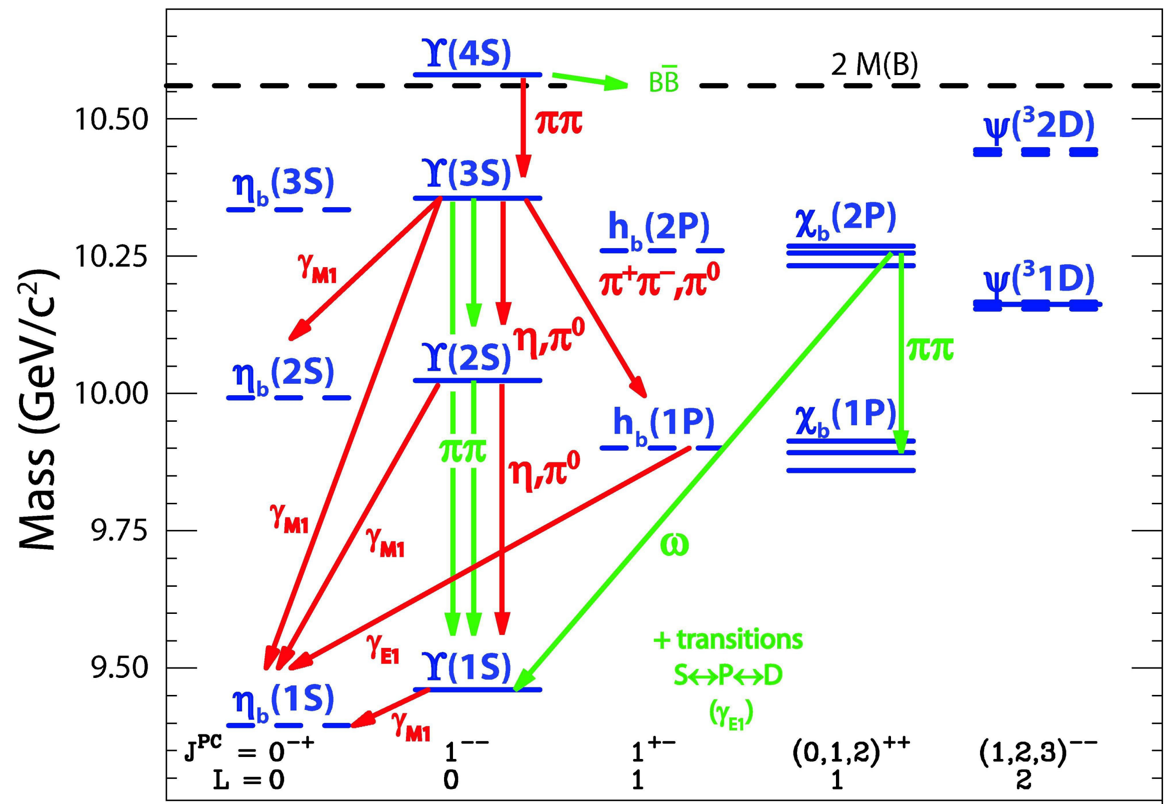
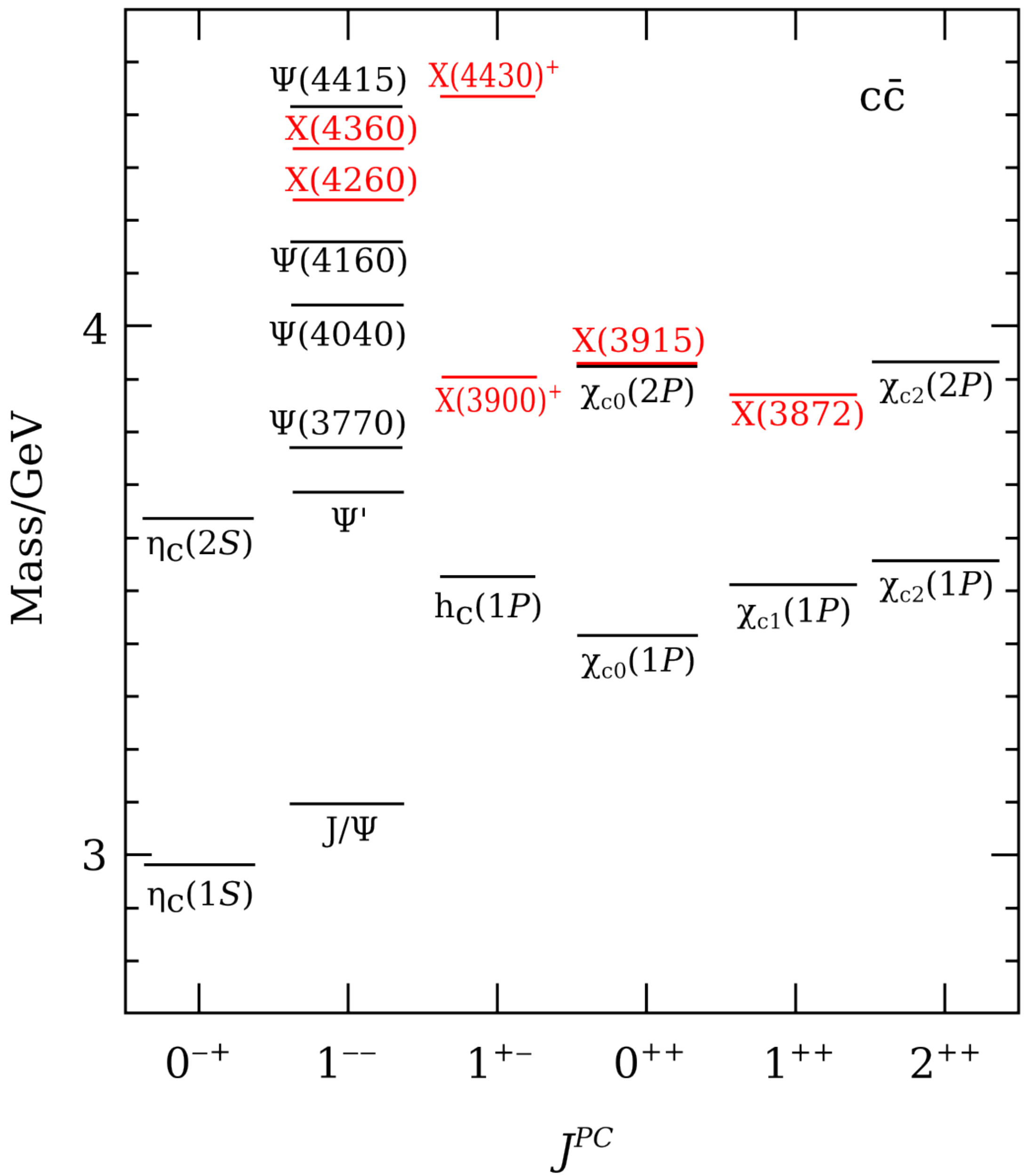
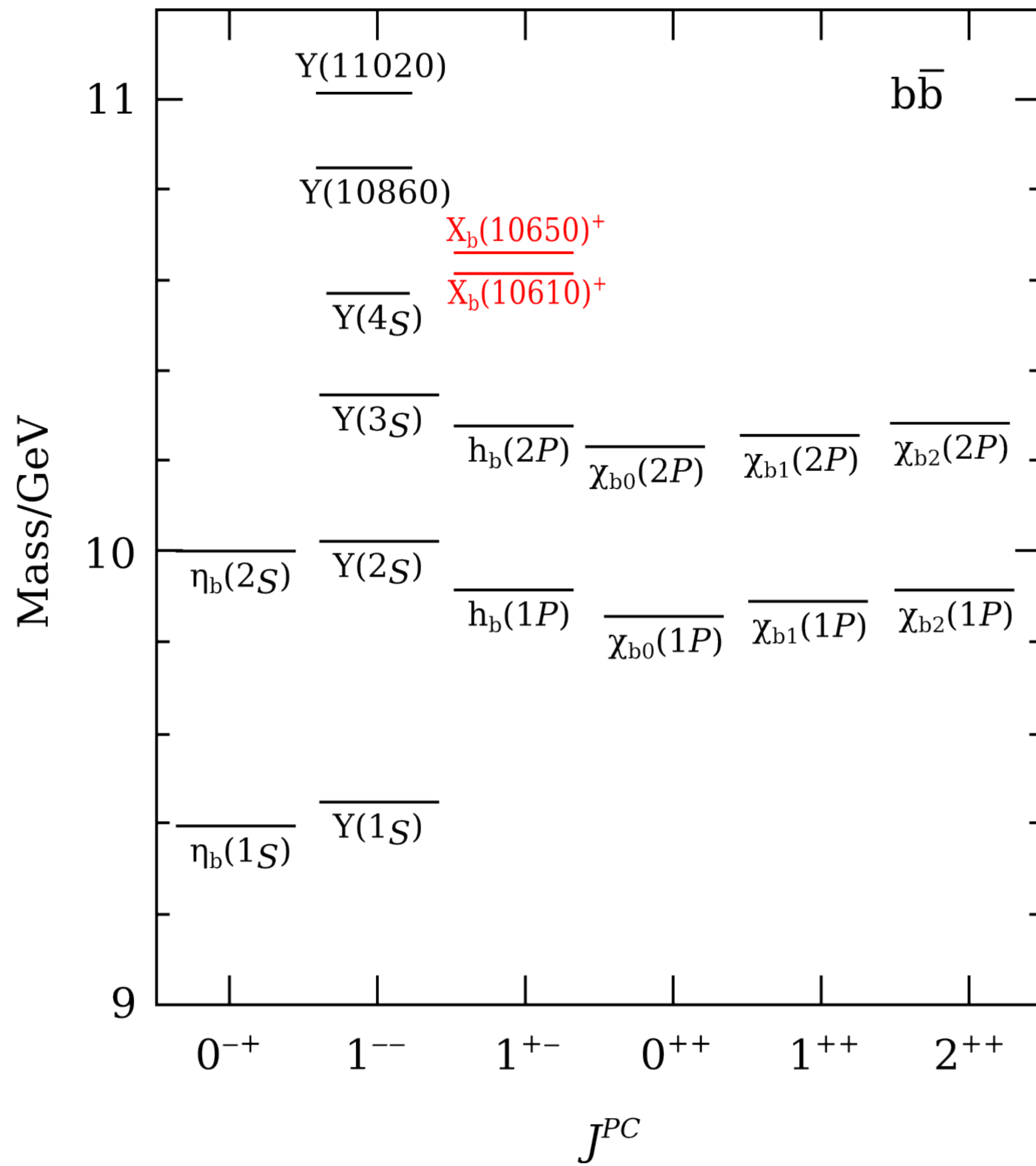
- charmonium(-like) states:
  - X(3915), Y(3940), X(3940), X(4160)
  - Y(4260), Y(4360), Y(4660)
  - $Z^+(3900)$, $Z^+_1(4050)$, $Z^+_2(4250)$, $Z^+(4430$
- also, bottomonium(-like) states:
  - $Z^+_b(10610)$ and $Z^+_b(10650)$ as $B(*)^+B^{*0}$ molecule candidates
  - equivalent to Y(4260) at 10.89 GeV?

bottomonium



Charmonium vs. Bottomonium – Status in PDG





On the origin of the narrow peak and the isospin symmetry breaking of the X(3872)

Sachiko Takeuchi[1,4], Kiyotaka Shimizu[2], and Makoto Takizawa[3,4]

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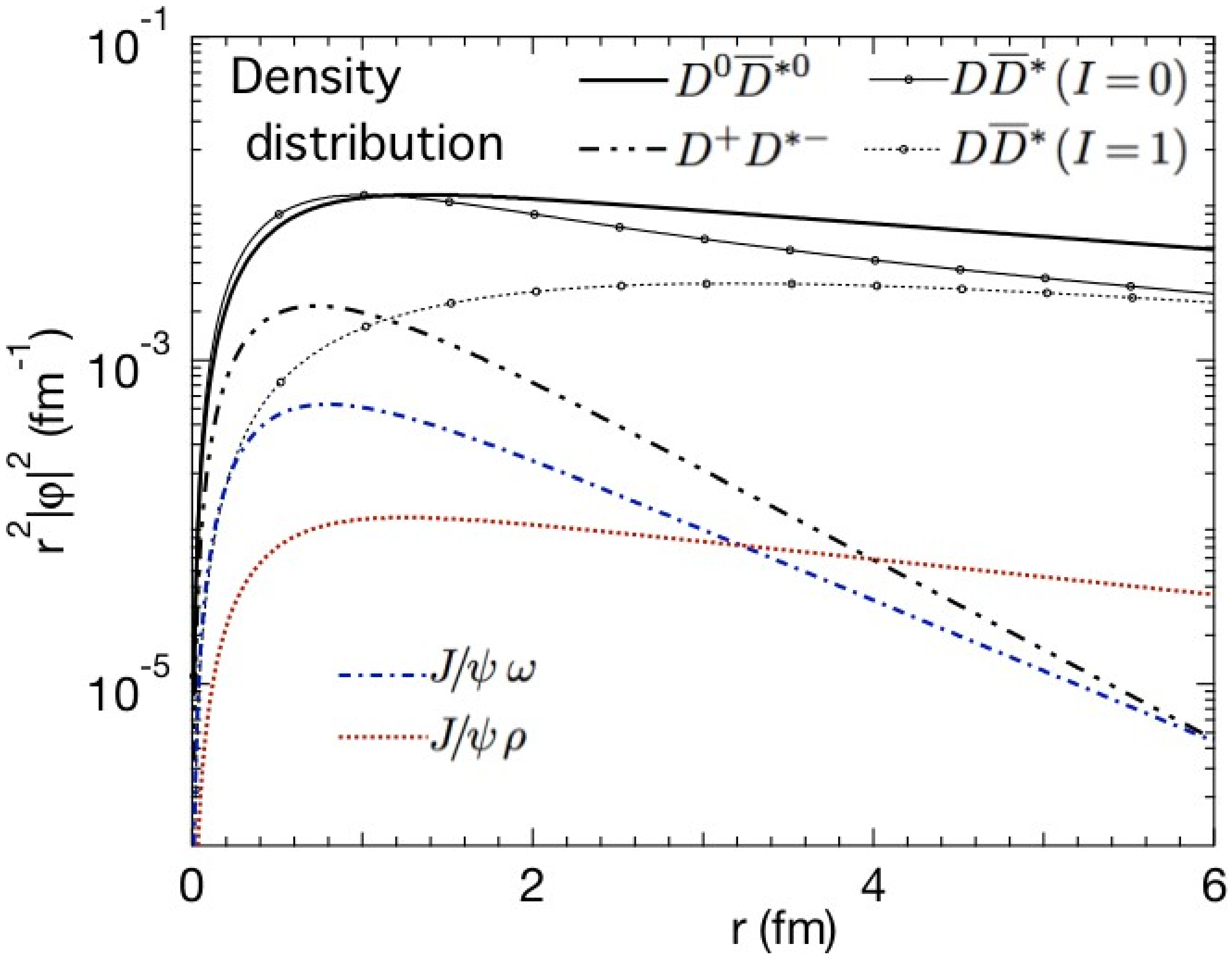
[*] *E-mail: s.takeuchi@jcsw.ac.jp*

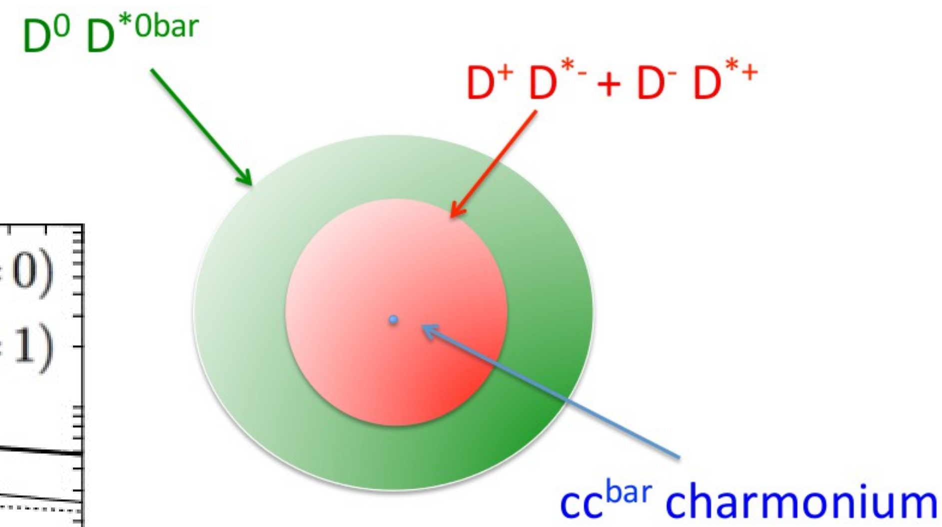
19/8/2014

The $X(3872)$ formation and decay processes in the B-decay are investigated by a $c\bar{c}$-two-meson hybrid model. The two-meson state consists of the $D^0\overline{D}^{*0}$, D^+D^{*-}, $J/\psi\rho$, and $J/\psi\omega$ channels. The energy-dependent decay widths of the ρ and ω mesons are introduced. The D-$\overline{D}^*$ interaction is taken to be consistent with a lack of the $B\overline{B}^*$ bound state. The coupling between the $D\overline{D}^*$ and $J/\psi\rho$ or the $D\overline{D}^*$ and $J/\psi\omega$ channels is obtained from a quark model. The $c\bar{c}$-$D\overline{D}^*$ coupling is taken as a parameter to fit the $X(3872)$ mass. The spectrum is calculated up to 4 GeV.

It is found that very narrow $J/\psi\rho$ and $J/\psi\omega$ peaks appear around the $D^0\overline{D}^{*0}$ threshold. The size of the $J/\psi\pi^3$ peak we calculated is 1.29-2.38 times as large as that of $J/\psi\pi^2$. The isospin symmetry breaking in the present model comes from the mass difference of the charged and neutral D and D^* mesons, which gives a sufficiently large isospin mixing to explain the experiments. It is also found that values of the ratios of the transfer strengths can give the information on the $X(3872)$ mass or the size of the $c\bar{c}$-$D\overline{D}^*$ coupling.

X(3872) as Admixture





density of each component differs as a function of the distance r from the object's center !

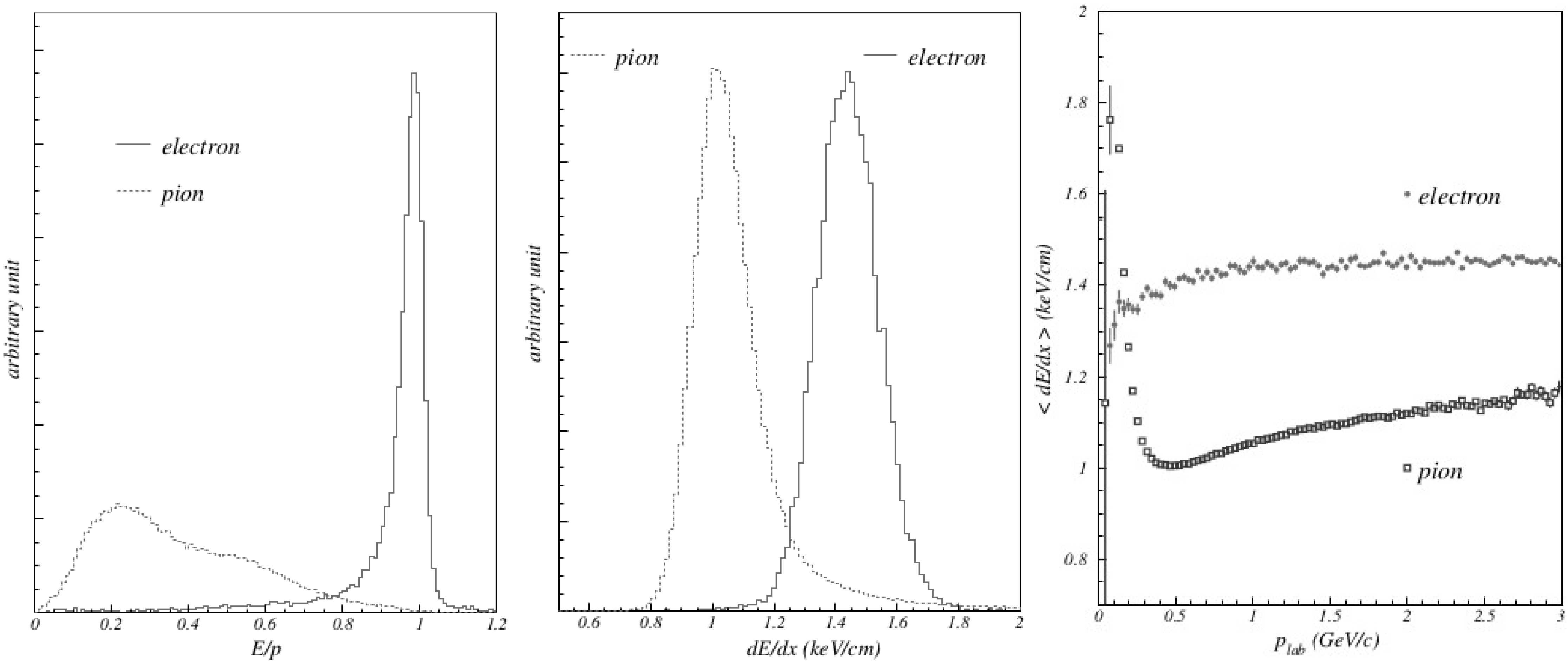
Belle Subdetectors

- The Belle detector consists listed in order of radial distance from the interaction point of
  - a six-layer silicon vertex detector (SVD2),
  - a ~50-layer central drift chamber (CDC),
  - an array of ~1200 aerogel Cherenkov counters (ACC),
  - ~130 time-of-flight scintillation counters (TOF),
  - an electromagnetic calorimeter containing 8736 CsI(Tl) crystals (ECL),
  - and the KLM detector.
- All but the KLM are contained in a superconducting solenoid with a central magnetic field of 1.5 T. The fourteen ~5-cm thick iron absorber plates of the KLM also serve as the solenoid’s return yoke.

Systematic Uncertainties

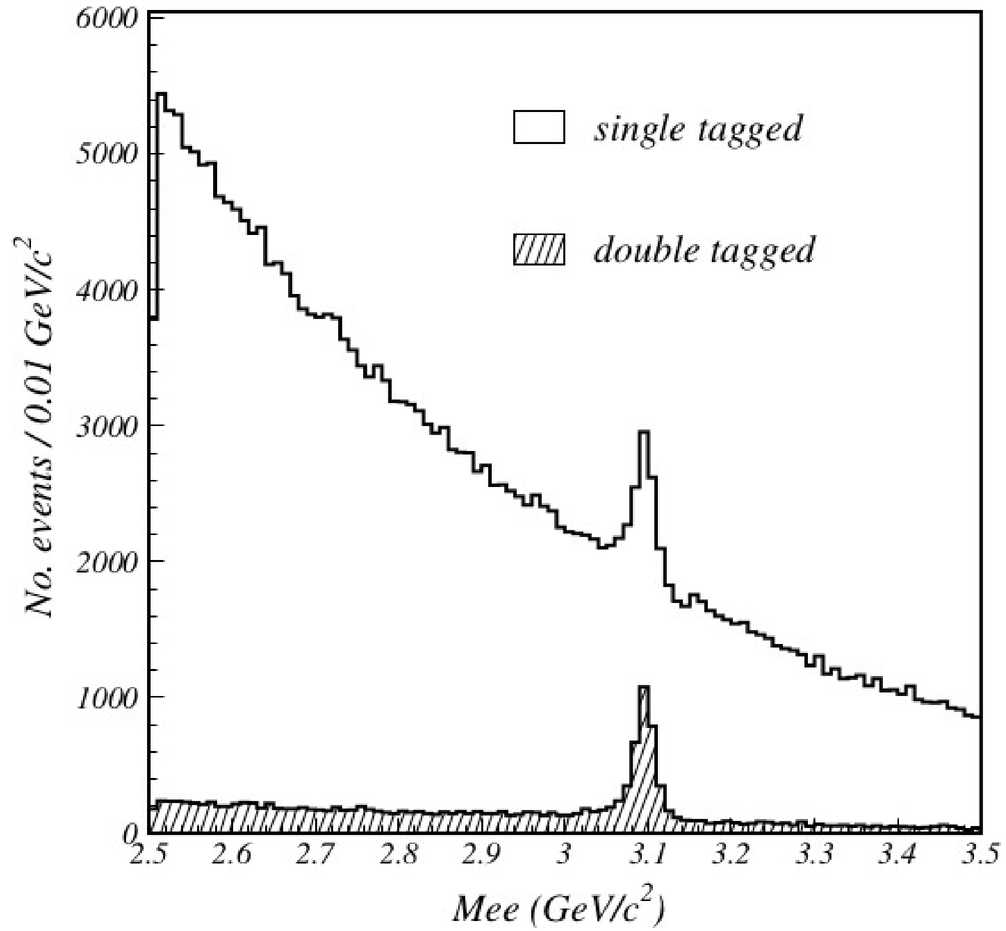
- PDF – 2.96%: modeling and set parameters used for fitting distributions
- pion ID – 1.96%: Estimations are made based on a $D^{*+} \rightarrow D^0(K^-\pi^+)\pi_{slow}$ process.
- lepton ID (e, μ) – 1.77%: $J/\psi \rightarrow e^+e^-$ (for EID) and $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ (for muID)
- tracking – 1.71%: Track finding efficiency has been measured by the number of partially and fully reconstructed D* decays in $D^* \rightarrow \pi D^0$, with $D^0 \rightarrow \pi\pi K_S$ and $K_S \rightarrow \pi^+\pi^-$. By calculating the ratio of tracking efficiency in data and MC, the systematic uncertainty associated with tracking has also been evaluated.
- 2ndary BF – 1.50%
- N_{BB} – 1.37%: official number of Bs from Y(4S) recorded by Belle $(771.581 \pm 10.566) \times 10^6$
- kaon ID – 1.23%: see pion ID
- π^0 veto – 1.22%: obtaining the ratio of ΔE signal yield when using the cut, and without using the cut, for data and Monte Carlo, and then dividing those in a double ratio, R(data/MC)
- signal MC – 0.52%: limited MC sample of 0.5M events used to calculate efficiency
  - → **total: 5.10%**

Electron Identification (EID)



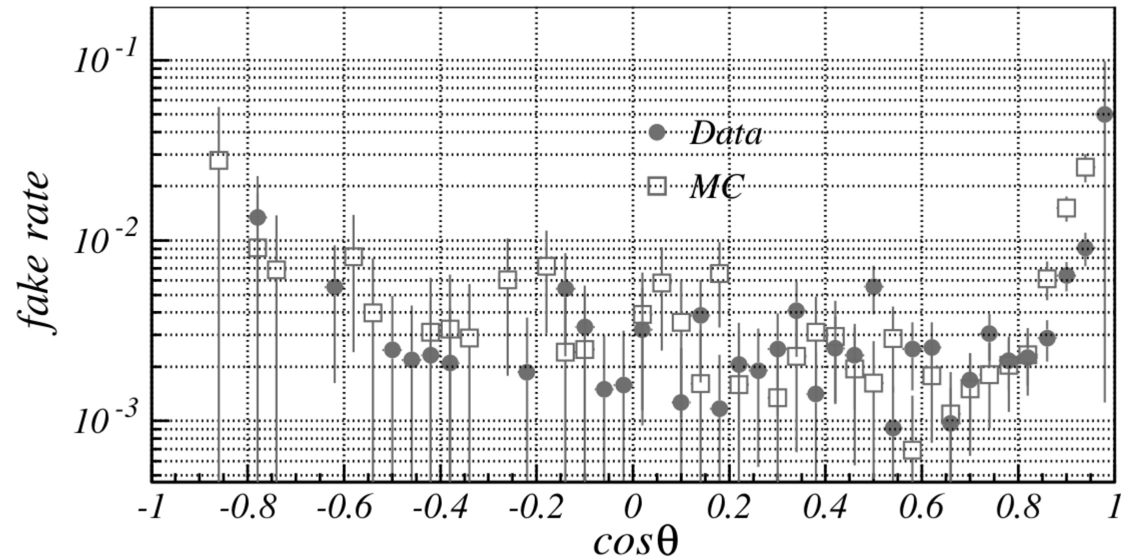
EID Efficiency

- One can also obtain the EID efficiency or inefficiency by comparing the $J/\psi \rightarrow e^+e^-$ yield for the cases one or two electrons are tagged, or the difference of the two cases.
- The signal yield for single tagging and the difference between single- and double-tagged events can be translated to an (in)efficiency which is consistent with the inefficiency that is predicted by the MC.
- The EID efficiency expected from the generic hadronic MC is consistent with that for single electrons in real hadronic data within 1%. The EID inefficiency is verified to be consistent between data and MC within a 1.4% uncertainty.



EID Fake Rate for Pions and Kaons

- Inclusive $K_S \rightarrow \pi^+\pi^-$ decays are used as a source of charged pions to measure the EID fake rate. No requirement is placed on the pion used to test the EID routines.
- The overall agreement between data and MC is good in the pion fake rate case.
- The fake rate for $K^\pm$ is examined using the decay chain $D^{*+} \rightarrow D^0(\rightarrow K^-\pi^+)\pi^+$. The strategy for evaluating the fake rate is to compare the signal yield of D^0 with and without applying EID for the kaons.
- Comparing events without EID and events after applying EID and taking the ratio, the fake rate for the kaons is measured to be comparable to the MC prediction.



$$\text{Fake rate} = \frac{\#\text{ of non-}e^\pm\text{ tracks found by tracking with the } L_{\text{eid}} > 0.5}{\#\text{ of non-}e^\pm\text{ tracks found by tracking}}.$$

Muon Identification (MuID)

- Muon identification begins with the reconstruction of a charged track in the CDC with matching SVD hits, and continues with its extrapolation through the outer detectors to its stopping point or its escape from the detector.

➔ A track is considered to be within the KLM acceptance if it crosses at least one RPC layer; this requires at least 0:6 GeV/c of momentum.

- A helical track, reconstructed in the CDC, isrefined by a Kalman filter to determine the helix parameters near the outermost layer of CDC. The helix parameterization is justified by the uniformity of the solenoidal magnetic field within the tracking volume and the small energy loss of the track within the CDC.

- Muon Likelihood: Two quantities are used to test the hypothesis that a track is a muon rather than a hadron
  - the difference between the measured and expected range of the track
  - the goodness of fit of the transverse deviations of all hits associated with the track (normalized by the number of hits)

MuID Efficiency

- High-purity muons are obtained with the two photon reaction, $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ by tagging one of the muons with a high muon likelihood and then examining the other minimum-ionizing track in the event.
- The contamination is predominantly from $e^+e^- \rightarrow \tau^+\tau^-$ where one τ decays leptonically to give a tag muon and the other decays to $\pi\nu$ to give a fake-muon candidate, or from $e^+e^- \rightarrow e^+e^-\pi\pi X$ where one of the pions is falsely tagged as a muon.
- The systematic uncertainty is estimated to be 2%, mainly from the residual hadron contamination in the muon sample.

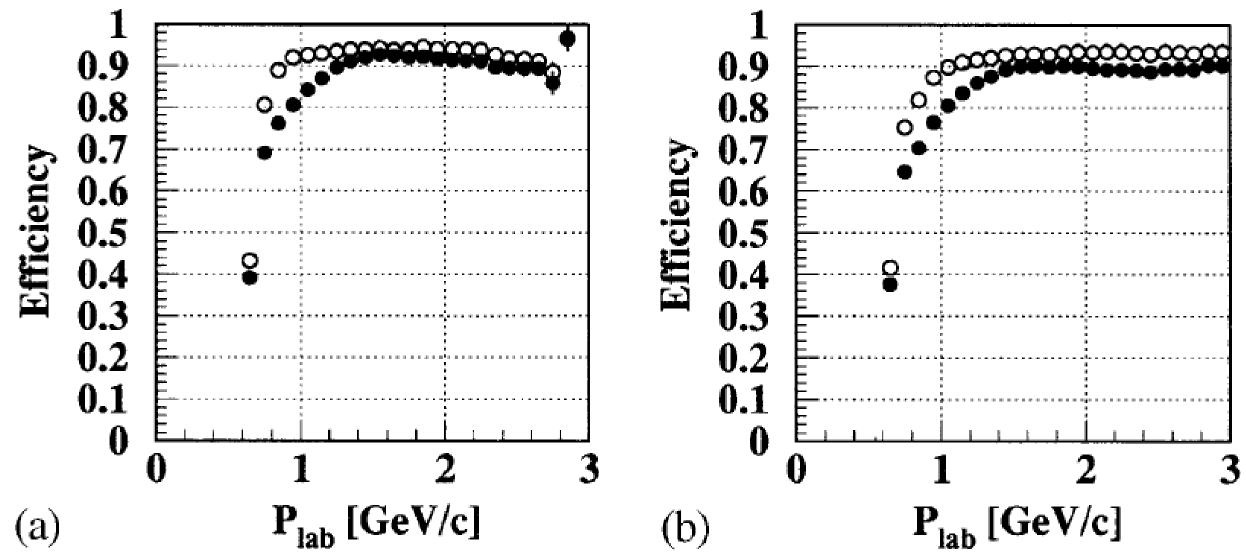


Fig. 9. Measured efficiency of muon identification as a function of momentum, measured by $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$: (a) barrel ($51^\circ < \theta < 117^\circ$), (b) whole polar angle region ($25^\circ < \theta < 145^\circ$), for $\mathscr{L}_\mu > 0.9$ (closed circles) and $\mathscr{L}_\mu > 0.1$ (open circles).

MuID Fake Rate for Pions and Kaons

- The majority of fake muons are punch-through or decay-in-flight pions and kaons.
- We measure the fake rate using the pions from $K_S \rightarrow \pi^+\pi^-$ and the kaons from $D \rightarrow K\pi$ where the D meson is identified by observing the slow pion in $D^* \rightarrow D\pi_{slow}$.
- A muon identification algorithm is used that uses the difference of muons from hadrons in the range and the scattering of the particles in the KLM.
- Fake rates of pions are approximately constant in the region p > 1.5 GeV/c. Fake rates of kaons are approximately constant in momentum above threshold.

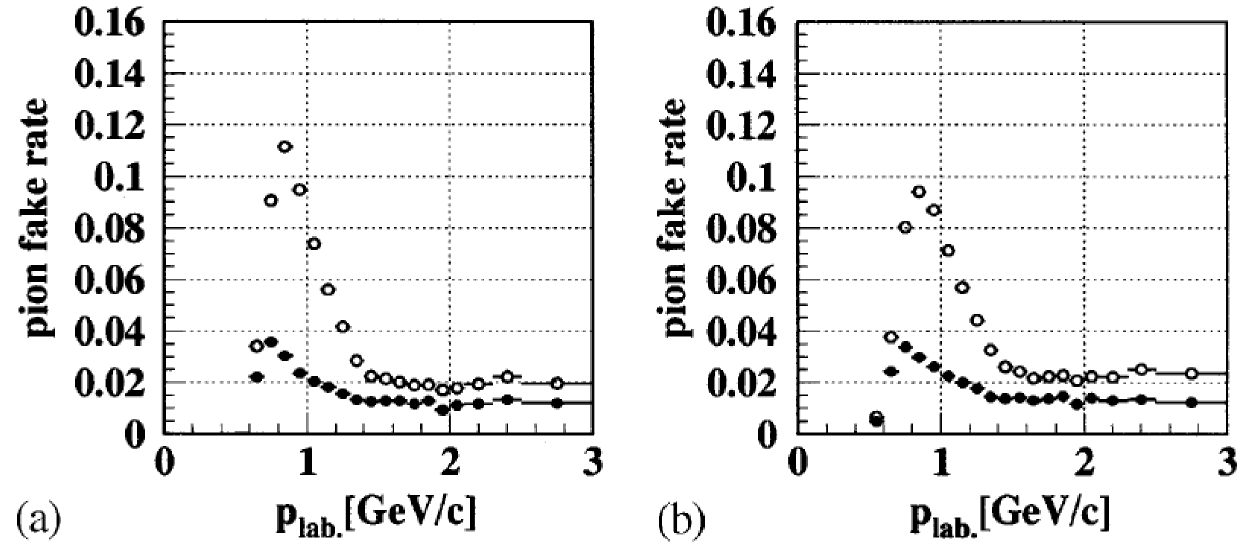
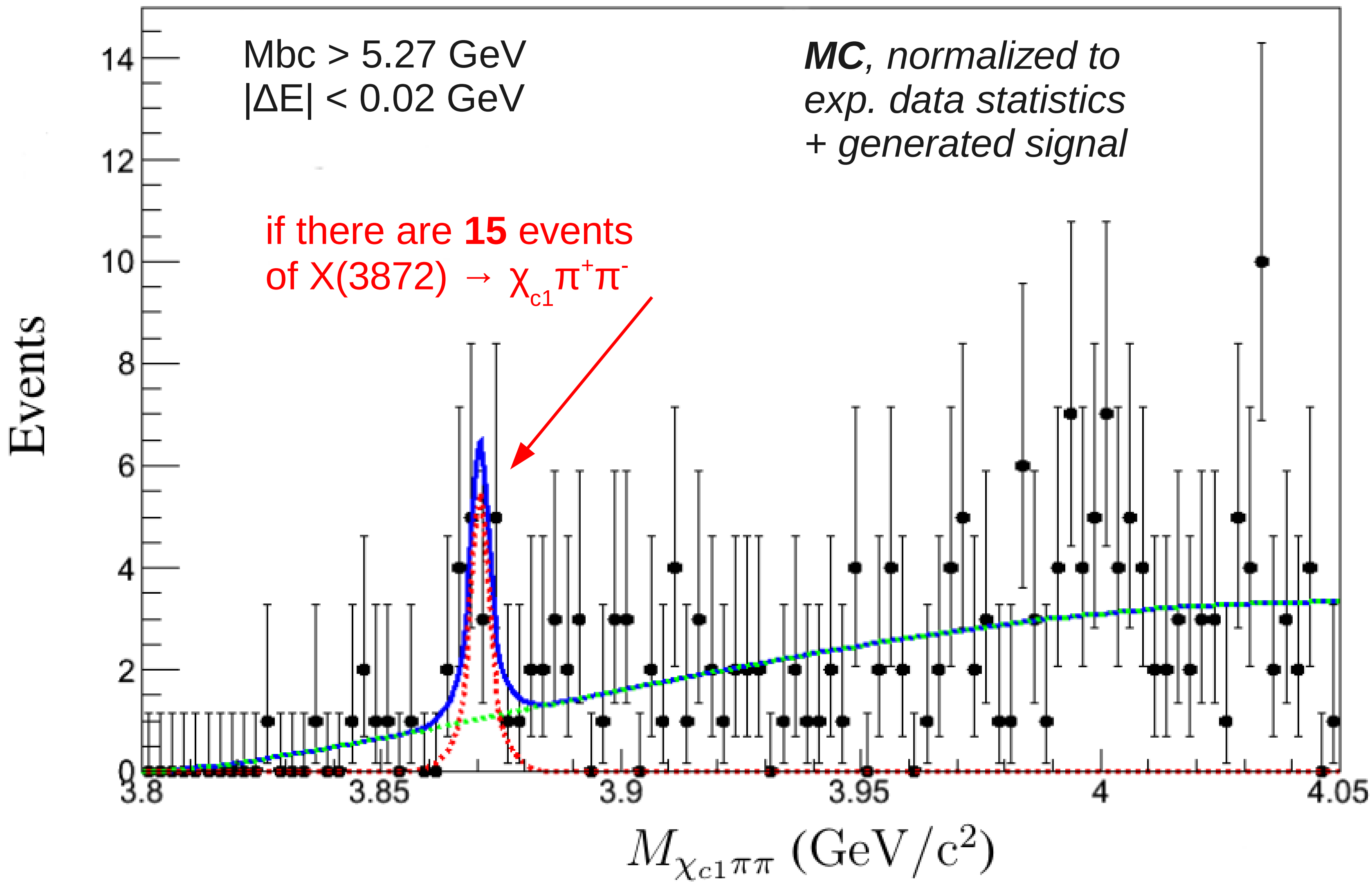
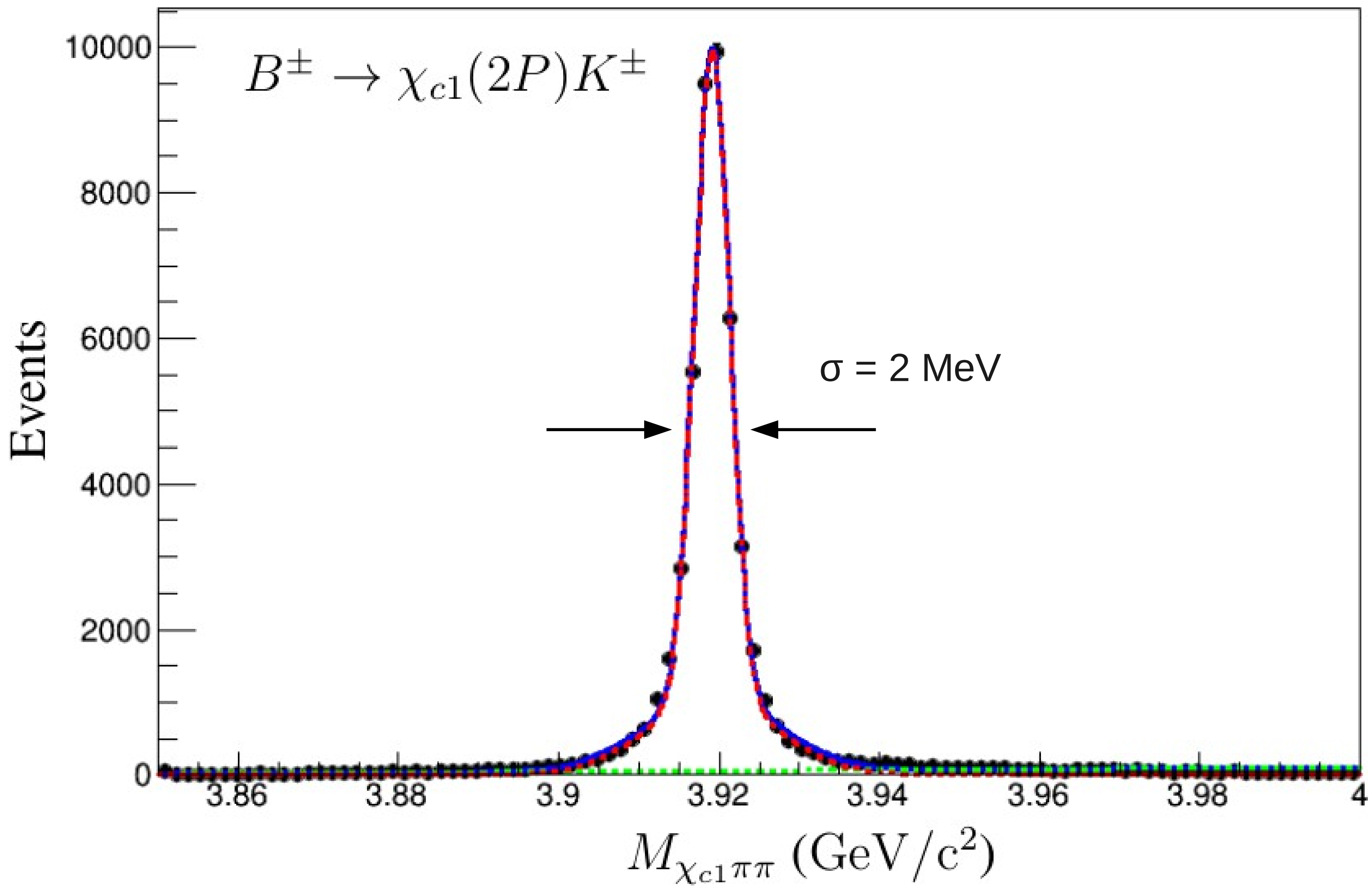


Fig. 14. Measured fake rate of pions vs. momentum by $Ks \rightarrow \pi^+\pi^-$: (a) barrel, (b) whole polar angle region, for $\mathscr{L}_\mu > 0.9$ (closed circles) and $\mathscr{L}_\mu > 0.1$ (open circles).

X(3872) → χ_{c1} $\pi^+\pi^-$ – PDF and MC Expectation

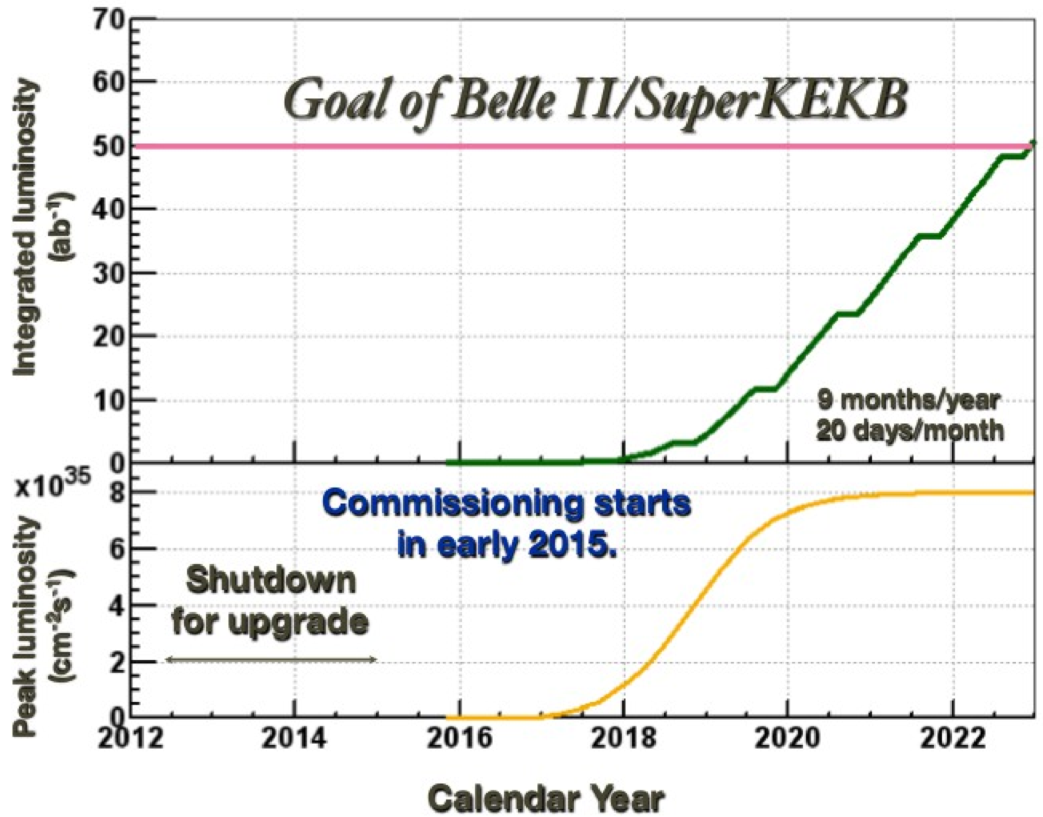


MC Study for χ_{c1}(2P)

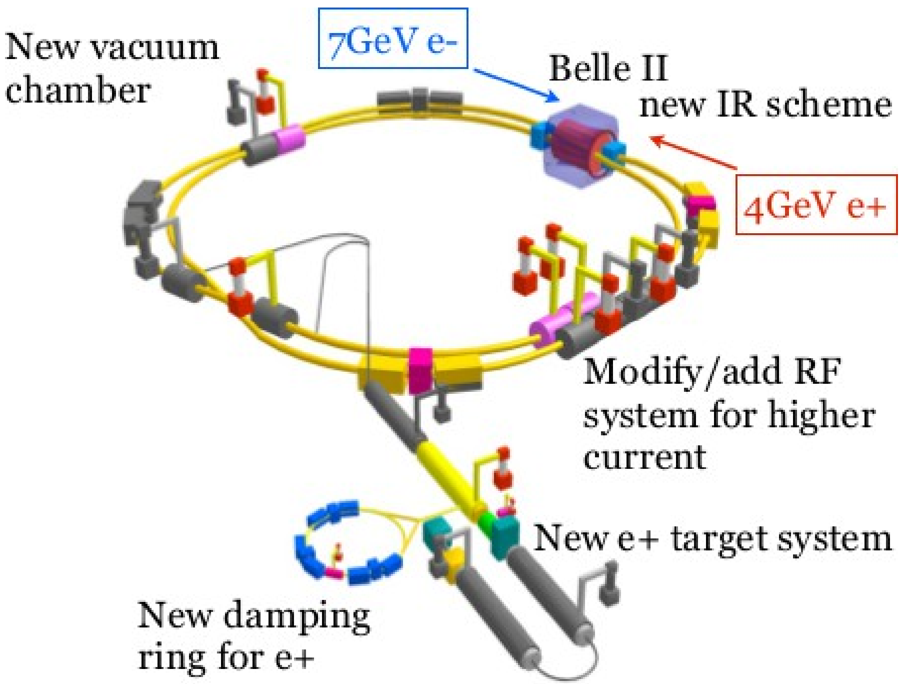


The Belle2 Experiment

- Experimental Challenges
  - 10-20 times higher beam-related backgrounds: Pile-up noise, Radiation damage,
  - 10 times higher event rate: Seamless data acquisition system, High level intelligent trigger
  - Improved performance: Vertex reconstruction, High particle ID capability, Hermetic coverage.



The Belle2 Experiment



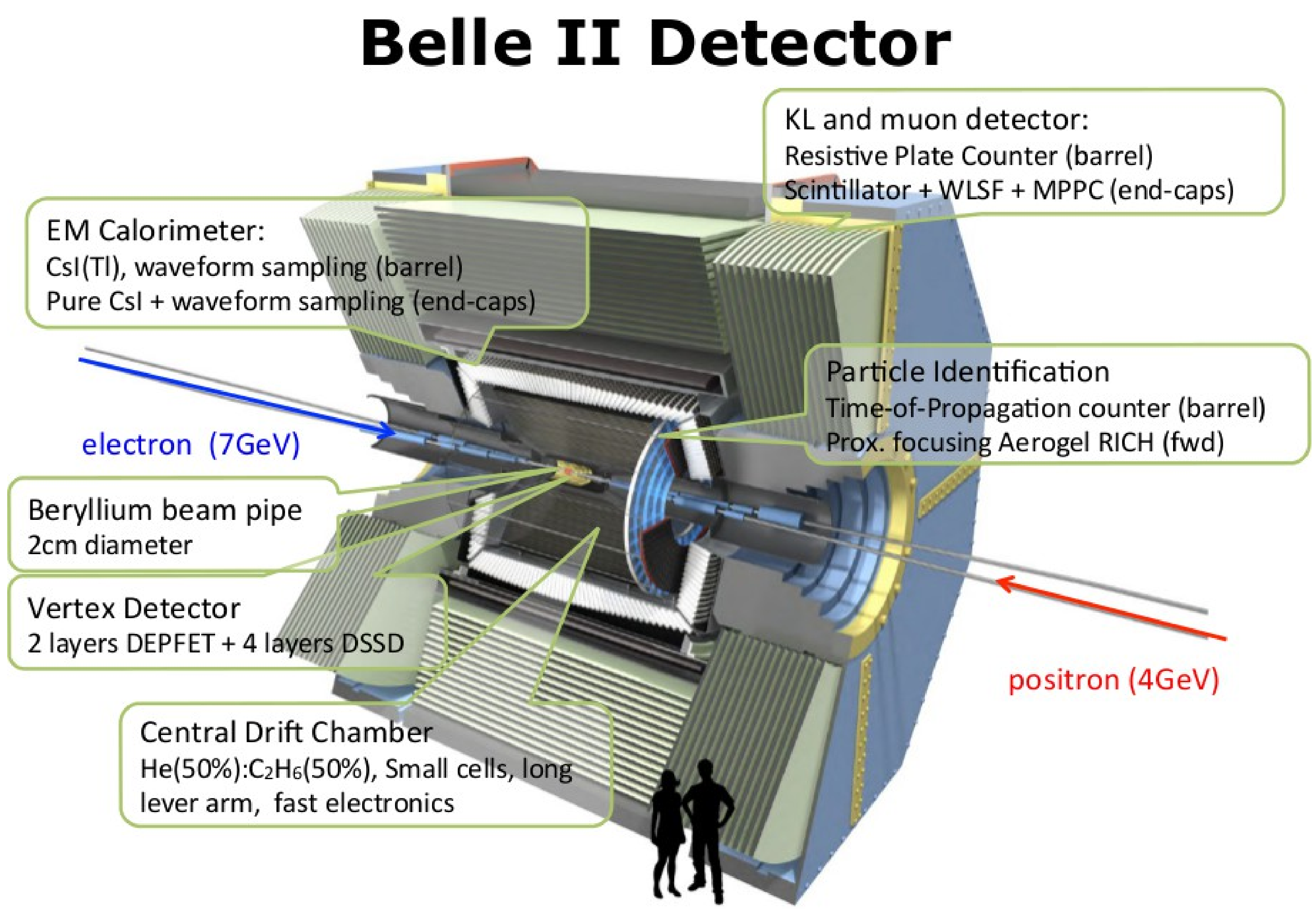


Image Courtesy: Ichiro Adachi (KEK)
Instr. for Colliding Beam Physics,
INSTR2014, Feb.24 - Mar.1, 2014

The Belle2 Experiment

- currents x2
- design luminosity of 8 x 10^{35} cm^{-2} s^{-1}
  → around 50 times as large as peak luminosity achieved by the KEKB collider
- large crossing angle → low-emittance “nano-beam” collisions (10μm x 60nm)
- vertex detector even closer to IP, 2 layers DEPFET pixel (14 & 22mm) sensors and 4 layers of DSSD
- CDC: larger radius and smaller cell size
- Time-Of-Propagation (TOP) counters: ring-image of Cherenkov light cones in quartz radiator bars, another ring-imaging Cherenkov counters with aerogel radiator in the forward end-cap
- ECL with wide dynamic range → 20 MeV to 7 GeV, 2MHz wave-form sampling readout → more robust against bkg, pure CsI crystals for end-cap → shorter time constant
- KLM modules will be replaced in the 2 innermost barrel layers and completely in the endcap
- Trigger rate 500Hz → 30kHz, Event size 40kB → 300kB(max)