Search for double charm production and T_{cc} at Belle

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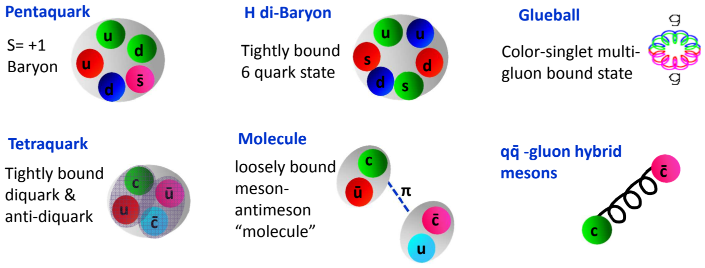
Workshop on High-Energy-Physics

Introduction

Exotic hadrons

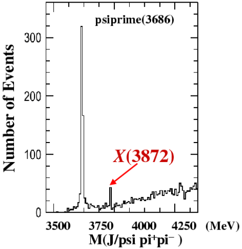
- Are hadrons all mesons and baryons? - No!



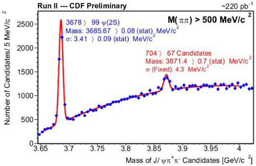
- Remained puzzle..
  - How can we put the puzzle together? - gather more pieces!

Adapted from S. Olsen’s talk

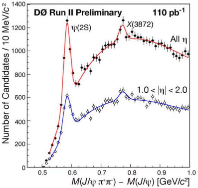
$X(3872)$



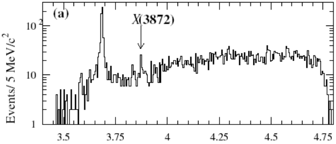
- $c\bar{c}$ or $c\bar{c}u\bar{u}$?
- discovered in 2003 at Belle by $B \to K(J/\psi\pi^+\pi^-)$ mode (S.-K. Choi, S.Olsen et al. Belle PRL 91, 262001)
- confirmed by many other experiments



CDF



D0



BaBar

$X(3872)$ - Con't

Is the X(3872) the conventional ψ_{c2}?

$X(3872)$ - Con't

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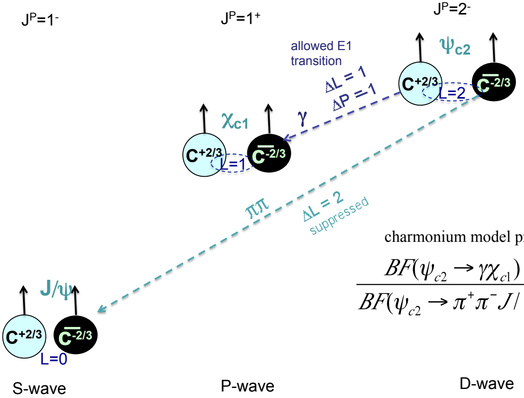


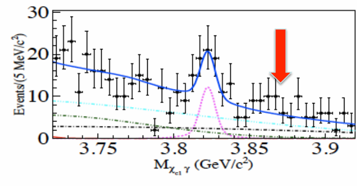
charmonium model prediction

$$\frac{BF(\psi_{c2} \to \gamma \chi_{c1})}{BF(\psi_{c2} \to \pi^+ \pi^- J/\psi)} > 5$$

Adapted from T. Browder's talk

X(3872) - Con't

Does the X(3872)→$\gamma\chi_{c1}$?



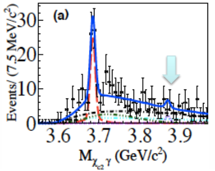
B→KX_{3872}

→$\gamma\chi_{c1}$?

(The extra peak at 3823 is the conventional triplet D-wave charmonium state)

B→Kψ'

→$\gamma\chi_{c2}$



No X(3872) signal is seen

$$\frac{BF(\psi_{c2} \to \gamma\chi_{c1})}{BF(\psi_{c2} \to \pi^+\pi^- J/\psi)} < 0.25$$

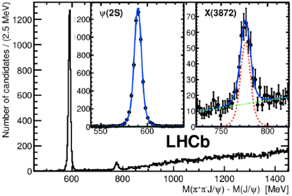
V. Bhardwaj et al. (Belle)
PRL 111, 032001 (2013)

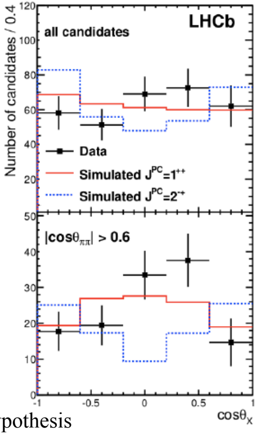
Adapted from T. Browder's talk

$X(3872)$ - Con't

LHCb multi-dimensional angular analysis conclusively rules out the spin 2 assignment and *closes the door for conventional charmonium*.

[Phys. Rev. Lett. 110, 222001 (2013)]



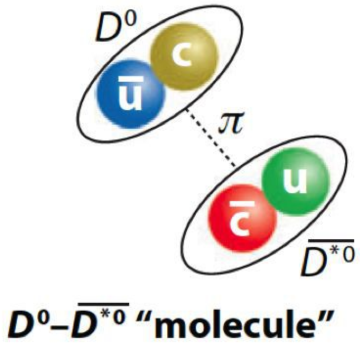


LHCb data favor the 1^{++} over the 2^{-+} hypothesis for the X(3872) at 8.4σ

Adapted from T. Browder's talk

$X(3872)$ - Con't

Is the X(3872) the conventstional ψ_{c2}?



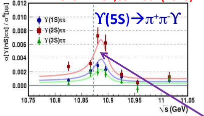
$Z_b(10610)^\pm$ & $Z_b(10650)^\pm$

"Υ(5S)" more interesting than other Υ states

Anomalous large production of Υ(nS) $\pi^+\pi^-$ was observed at the Υ(5S) by Belle with 21 fb^{-1}.

Belle,PRL100,112001(2008)

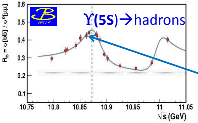
Belle PRD82,091106R(2010)



	Γ(MeV)
$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$	$0.59 \pm 0.04 \pm 0.09$
$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$	$0.85 \pm 0.07 \pm 0.16$
$\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$	$0.52^{+0.20}_{-0.17} \pm 0.10$
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	0.0060
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	0.0009
$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$	0.0019

x 10^{-2}

M = (10889.6±1.8±1.5) MeV
Γ = $54.7^{+8.5}_{-7.2}$±2.5 MeV



~2σ discrepancies in the peak mass and width

M = (10865±8) MeV
Γ = (110±13) MeV

Nature of Υ(5S) is puzzling

Exotic resonance Y_b near Υ(5S) analogue of Y(4260) resonance !

Belle found twin charged states $Z_b(10610)^+$ and $Z_b(10650)^+$ having masses just above $B^*\bar{B}$ and $B^*\bar{B}^*$ thresholds. Belle, PRL108, 122001 (2012)

5

Adapted from V. Bhardwaj's talk

$Z_b(10610)^{\pm}$ & $Z_b(10650)^{\pm}$

Nature of Z_b^+

$Z_b(10610)$

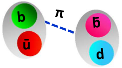
M=10607.2±2.0 MeV
Γ=18.4±2.4 MeV

PDG: $M_{\bar{B}} + M_{B^*} = 10604.8 \pm 0.4$ MeV

$Z_b(10650)$

M=10652.2±1.5 MeV
Γ=11.5±2.2 MeV

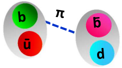
PDG: $M_{\bar{B}^*} + M_{B^*} = 10650.4 \pm 0.8$MeV



B^- B^{*0}

Bondar *et al.* arXiv:1105.4473
Sun *et al.* PRD 84, 054002 (2011)
Zhang *et al.* PLB 704,312 (2011)
Ohkoda *et al.* PRD 86, 014004 (2012), ...

Molecular picture

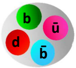


B^{*-} B^{*0}

$M_{Z_b(106010)} - (M_B + M_{B^*}) = +2.4 \pm 2.0$MeV

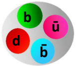
$M_{Z_b(106050)} - 2M_{B^*} = +1.8 \pm 1.7$ MeV

Slightly unbound threshold resonances?



Karliner arXiv:0802.0649
Ali *et al.* PRD 85, 054011 (2012), ...

Tetraquark picture



Coupled channel resonance : Dankiklin *et al.* PRD 85,034012 (2012)
Cusp: Bugg, Europhys. Lett.96,11002 (2011)

+ others ...
I.S.P.E
PRD84,094003(2011)

If Z_b^+ is $B^*\bar{B}^{(*)}$ molecule, it should decay into $B^*\bar{B}^{(*)}$

8

Personal : Sorry, if I didn't cite your paper

Adapted from V. Bhardwaj's talk

$Z_b(10610)^{\pm}$ & $Z_b(10650)^{\pm}$

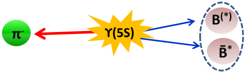
121 fb^{-1}

$\Upsilon(5S) \rightarrow B^* \bar{B}^{(*)} \pi$

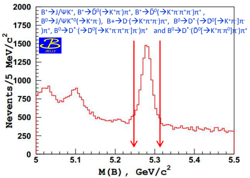
preliminary

Belle, arXiv:1209.6450

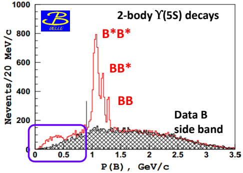
Masses of $Z_b(10610)^+$ and $Z_b(10650)^+$ close to $B\bar{B}^*$ and $B^*\bar{B}^*$ threshold



One B is fully reconstructed



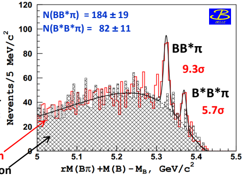
Select events by using cut in M(B) and p(B)



3 body $\Upsilon(5S) \rightarrow B^{(*)}B^{(*)}\pi$ decays and rad. return to $\Upsilon(4S)$: $P(B) < 0.9$ GeV/c

B is combined with π and recoil mass to (Bπ) combination is calculated

$$rM(B\pi) = \sqrt{E^2_{cms} - P^2_{B\pi}}$$



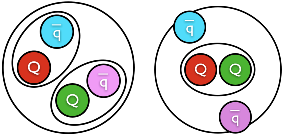
9

Look at recoil mass of (π) to see if there is Z_b peak.

Adapted from V. Bhardwaj's talk

$T_{cc}^{+}(cc\bar{u}\bar{d})$

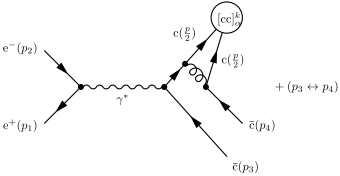
- $T_{cc}(1^{+})$
- Clearly not a meson, must contains 4 quarks!

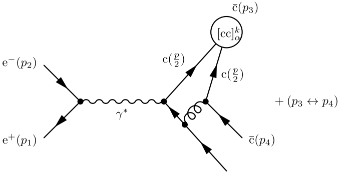


Which configuration?

- expected to be a bound state: B.E. $\approx$ 71MeV [1]

$$H_{\rm int} = C_{\rm H} \sum_{i<j} s_i \cdot s_j \frac{1}{m_i m_j}, \qquad C_{\rm H} = v_0 \vec{\lambda}_i \cdot \vec{\lambda}_j \langle \delta(r_{ij}) \rangle$$

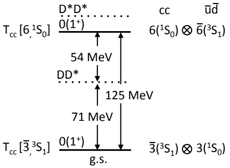




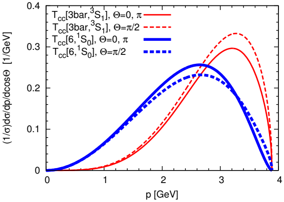
[1] http://arxiv.org/abs/1209.6207v1

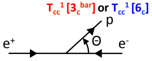
$T_{cc}(cc\bar{u}\bar{d})$ production in e^+e^- collider

- Two configurations,



- $\sigma(T_{cc}) = \mathcal{O}(0) \sim \mathcal{O}(2)$fb at Belle depends on $P_{T_{cc}}$ and θ [1]
- U.L $(\sigma) \leqslant 129$ fb for $T^1_{cc}[\bar{3}_c]$ and 43 for $T^1_{cc}[6_c]$

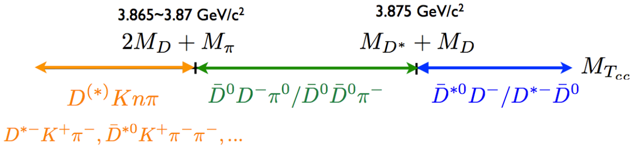




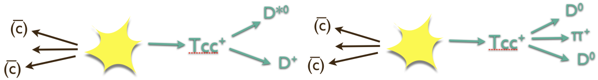
[1] http://arxiv.org/abs/1209.6207v1

how to search T_{cc} at Belle

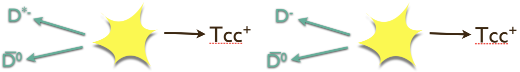
- Decay channels depends on T_{cc} mass [1]



- Decays of T_{cc}



- Recoil side

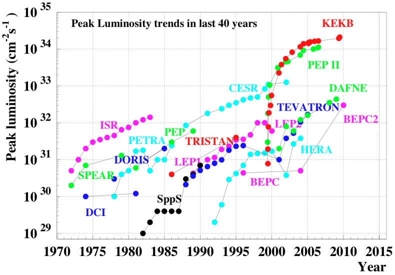


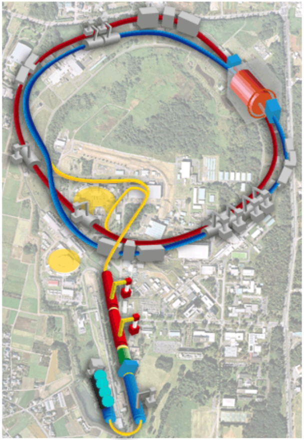
[1] Lee, Su Houng, Shigehiro Yasui, Wei Liu, and Che Ming Ko. Eur. Phys. J. C, 54 (2008): 259–265.

Belle experiment

KEKB

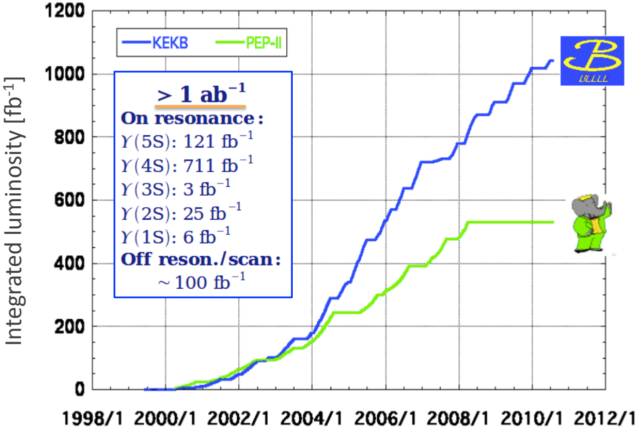
- e^+e^- collider of 10.58 GeV (CM) for $\Upsilon(4S)$ resonance
- Asymmetric energy: 8 GeV (e^-) and 3.5 GeV (e^+)
- World's highest luminosity of $\mathcal{L} = 2.11 \times 10^{34} \mathrm{cm}^2\mathrm{s}^1$ (2009).



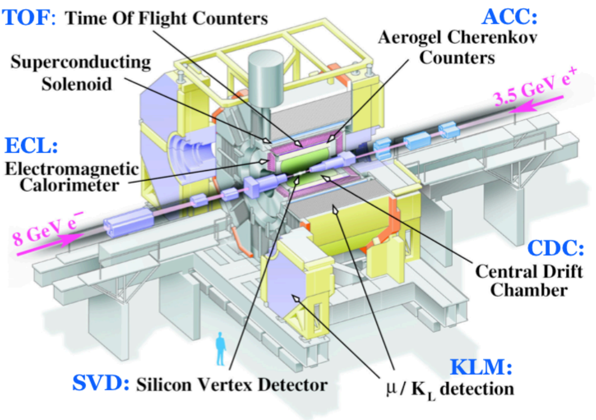


Integrated luminosity

- Data taking ended in 2010, and was reprocessed with better tracking by 2011.



Belle detector



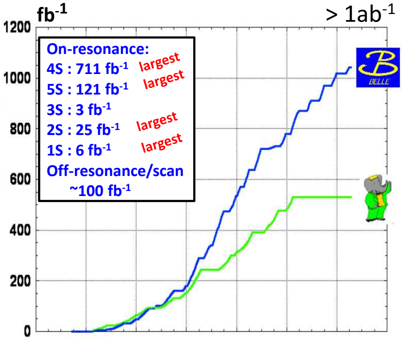
Belle collaboration

~400 members, 67 institutes, 16 countries

T_{cc} analysis

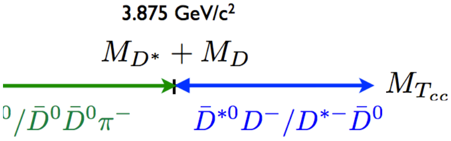
Belle data types

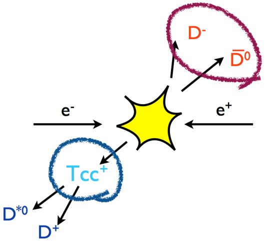
- $B\bar{B}$, $\Upsilon(4S)$ resonance : 711 fb^{-1}
- off-resonance (continuum) - no $B\bar{B}$ combination : $\sim$100 fb^{-1}
- other Υ(nS) resonances $\sim$ 150 fb^{-1}



MC type

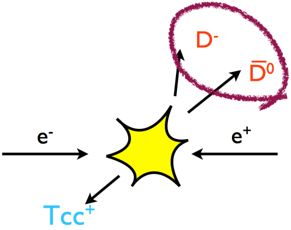
- Background MC according to sources of data
  - $B\bar{B}$, $\Upsilon(4S)$, resonance : only using 56 fb^{-1}
  - continuum
  - other Υ(nS) resonances
- and signal MC
  - $e^+e^- \to \gamma^* \to$?
    - Check from the highest mass range : higher than D^*D threshold
    - Simplify the model : recoil side decays to $\bar{D}^0 D^-$
    - $e^+e^- \to \gamma^* \to T_{cc}^+ (T_{cc}^+ \to D^{*0} D^+) \bar{D}^0 D^-$
      where $D^{*0} \to D^0 \pi^+$, $D^0 \to K^- \pi^+$, and $D^+ \to K^- \pi^+ \pi^+$

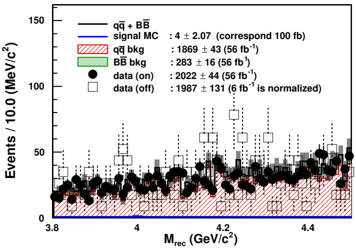




Recoil mass

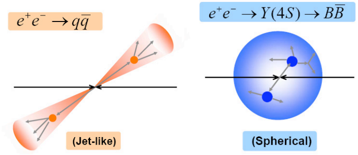
- Using two charmed mesons, we calculate $M_{\text{recoil}} = \sqrt{(P_{beam} - P_{D^0} - P_{D^-})^2}$
- Background sources :
  - mostly random combinations
  - possible peaking background from $e^+e^- \to B\bar{B}$: $B\bar{B}$ mixing could make peak
  - The problem is high background level $\to$ hard to see the signal
  - $N_{\text{sig}} = \epsilon \times \mathcal{L} \times \sigma(T_{cc}) \times \mathcal{B}(D^0) \times \mathcal{B}(D^+)$

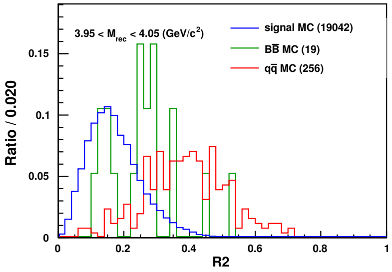




Background suppression

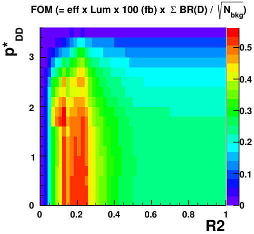
- Signal has 4D production ($M_{4D} \sim 8$ GeV): spherical event shape
- $e^+e^- \to q\bar{q}$: jet-like
- $R2$: event shape parameter in range of (0,1)
  $R2 = H_2/H_0$ where $H_l = \Sigma_{i,j} \frac{|p_i||p_j|}{E_{vis}^2} P_l(\cos\theta_{ij})$

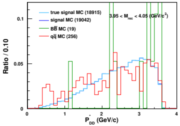


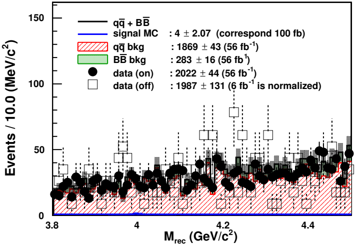


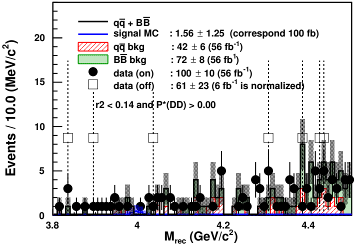
Background suppression - Con't

- Figure of merit = $N_{\rm sig}/\sqrt{N_{\rm bkg}}$ where
  $N_{\rm sig} = \epsilon \times \mathcal{L} \times \sigma(T_{cc}) \times \mathcal{B}(D^0) \times \mathcal{B}(D^+)$
- Maximum value at $R2 < 0.14$ & $P^*_{DD} > 1.6$
- Ignore cut on P^*_{DD}



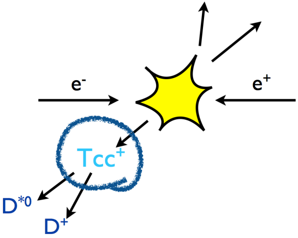


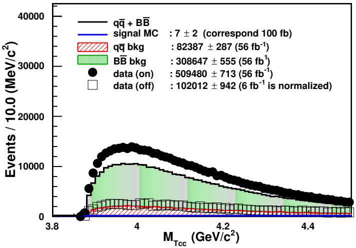




Invariant mass

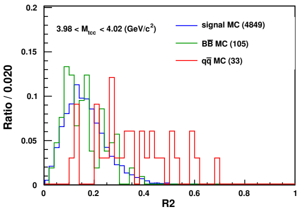
- T_{cc} is reconstructed by $D^{*0}(\rightarrow D^0\pi^0)D^+$
- $M_{T_{cc}} = \sqrt{(E_{D^{*0}} + E_{D^+})^2 - |\vec{P}_{D^{*0}} + \vec{P}_{D^+}|^2}$
- background sources :
    - mostly random combinations
    - possible peaking background from $e^+e^- \rightarrow B\bar{B}$: $B\bar{B}$ mixing could make peak
    - The problem is high background level $\rightarrow$ hard to see the signal

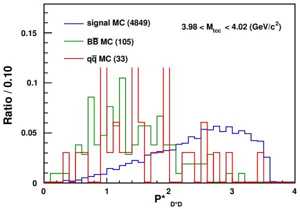




Background suppression

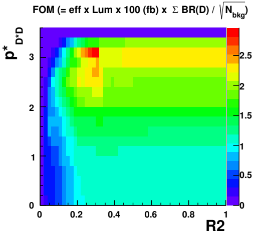
- Signal has $4D$ production ($M_{4D} \sim 8$ GeV): spherical event shape
- $e^+e^- \to q\bar{q}$: jet-like
- $R2$: event shape parameter in range of (0,1)
  $R2 = H_2/H_0$ where $H_l = \Sigma_{i,j} \frac{|p_i||p_j|}{\mathrm{E}_{\mathrm{vis}}^2} P_l(\cos\theta_{ij})$
- $P_{T_{cc}}$: momentum of D^*D system in e^+e^- CM frame

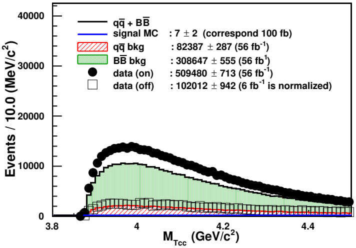


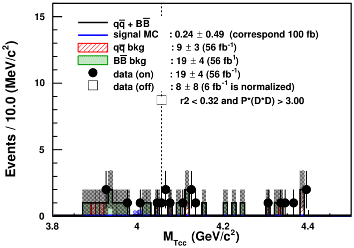


Background suppression - Con't

- Figure of merit = $N_{\rm sig}/N_{\rm bkg}$ where
  $N_{\rm sig} = \epsilon \times \mathcal{L} \times \sigma(T_{cc}) \times \mathcal{B}(D^0) \times \mathcal{B}(D^+)$
- Maximum value at $R2 < 0.32$ & $P^*_{DD} > 3.0$
- Too aggressive cut, but if we follow,

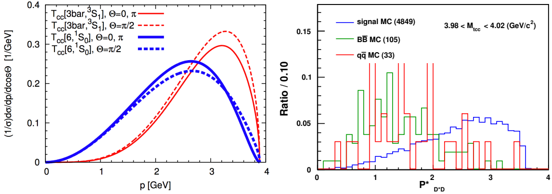






Momentum distribution of T_{cc}

- Cross-section of T_{cc} depends on it's momentum [1]
- If we can separate it's distribution, we could know it's configuration

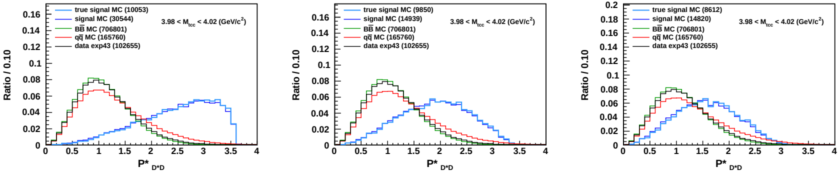


- Also momentum is used to suppress background event, previously,
- We our signal MC is made by phase space model - can we believe this?

[1] http://arxiv.org/abs/1209.6207v1

Pausing T_{cc} study

- What if we add additional π on our signal MC?



$T_{cc}^{+}D^{0}D^{-}$ | $T_{cc}^{+}D^{0}D^{0}\pi^{-}$ | $T_{cc}^{+}D^{0}D^{-}\pi^{+}\pi^{-}$

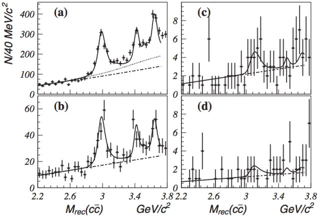
- Strongly depends on recoil side final states.
- T_{cc} from $cc\bar{c}\bar{c}$ production $\Rightarrow$ check general $cc\bar{c}\bar{c}$ momentum distribution
  - are many π generated?
- $\sigma(cc\bar{c}\bar{c})$ will give us a guideline for T_{cc} study, too.

Double charm production study

Double charmonium production

- Belle and BABAR studied $J/\psi + c\bar{c}$ and $J/\psi + H_c$ channels.
- Measured σ is contrary to the non-relativistic QCD and perturbative QCD predictions.
- Predictions:
  - $\sigma(e^+e^- \to J/\psi c\bar{c}) \sim 0.1 pb$ [1]
  - $\sigma(e^+e^- \to J/\psi c\bar{c})/\sigma(e^+e^- \to J/\psi gg) \sim 10\%$ [2]
  - NLO corrections of $\sigma(e^+e^- \to J/\psi gg) \approx 0.5$ pb [3]
- Experiments:
  - BaBar (2005) : $\sigma(J/\psi c\bar{c}) \sim 0.44$ pb where $c\bar{c} = \eta_c(1S), \chi_{c0}$ and $\eta_c(2S)$
  - Belle (2009) :

    $\sigma(J/\psi c\bar{c}) = 0.74 \pm 0.08\ ^{+0.09}_{-0.08}$ pb

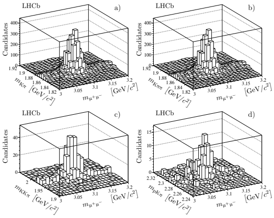


$M_{rec}(c\bar{c})$: (1) J/ψ, (b) ψ', (c) χ_{c1}, and (d) χ_{c2}

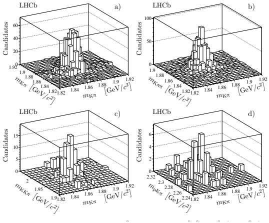
[1] V. V. Kiselev, A. K. Likhoded, and M. V. Shevlyagin, Phys. Lett. B 332, 411 (1994)
[2] Berezhnoy, A V, and A K Likhoded. Phys. Atom. Nucl. 70 (2007): 478–484.
[3] Y.-Q. Ma, Y.-J. Zhang, and K.-T. Chao, arXiv:0812.5106.

Double charm production

- No result from B factory
- LHCb, pp collider, reported in 2012
  - $J/\psi + H_c$ and double open charmed hadron (DD) production.
- $\sigma(J/\psi + H_c)$ and $\sigma(DD) \sim$ calculation based on Double Parton Scattering (DPS)
  - $\sigma(J/\psi D^0) = 161.0 \pm 3.7 \pm 12.2$ nb (146 nb)
  - $\sigma(D^0 D^+) = 690 \pm 40 \pm 70$ nb (2.0 μb)



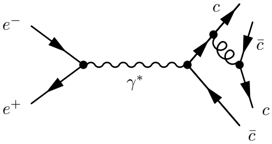
$J/\psi h_c$: a) $J/\psi D^0$, b) $J/\psi D^+$, c) $J/\psi D^+{}_s$ and $J/\psi \Lambda_c^+$

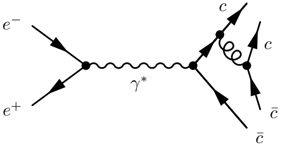


DD: a) $D^0 D^0$, b)$D^0 D^+$, c) $D^0 D^+{}_s$ and d) $D^0 \Lambda_c^+$

How to search the double charm production at Belle

- Open charm decay: 4 D mesons
- E $\sim$ 10.58 GeV (CM): enough energy to generate 4 D mesons
- $\sigma(e^+e^- \rightarrow c\bar{c}c\bar{c}) = 372$ fb at $\sqrt{s} = 10.6$ GeV
- $\sigma(J/\psi c\bar{c}) = 0.74 \pm 0.08\,^{+0.09}_{-0.08}$ pb, Belle(2009)
- Goal : To get the cross-section and the momentum distribution of 4 open charm decay at Belle





MC Type

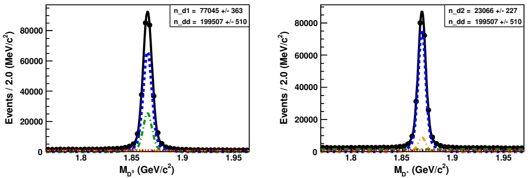
- Background MC according to sources of data
  - $B\bar{B}$, $\Upsilon(4S)$, resonance
  - continuum : only using 89 fb^{-1} (collected at $\sqrt{s} = 10.52$ GeV), to avoid $B\bar{B}$ mixing background come into.
  - other Υ(nS) resonances
- and signal MC
  - $e^+e^- \to \gamma^* \to$ final states including Ds
  - Simplest final state: $D^0D^+\bar{D}^0D^-$, $D^0 \to K\pi$, $D^+ \to K\pi\pi$ and $\bar{D}^0$&D^- decay generically

Sources of peaking background

- Doubly Cabibbo suppressed (DCS) events
  Cabibbo favored modes
  $\mathcal{B}(D^0 \to K^-\pi^+) = 3.88 \times 10^{-2}$ and $\mathcal{B}(D^+ \to K^-\pi^+\pi^+) = 9.13 \times 10^{-2}$
  Cabibbo suppressed modes
  $\mathcal{B}(D^0 \to K^+\pi^-) = 1.47 \times 10^{-4}$ and $\mathcal{B}(D^+ \to K^+\pi^-\pi^-) = 5.27 \times 10^{-4}$
- $B\bar{B}$ mixing with various $B \to D$ and $B \to \bar{D}$ decays

2D fitting

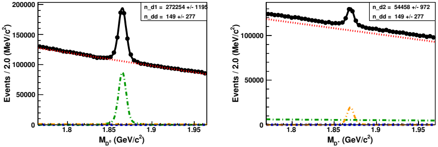
- Extract yield, $N_{D^0D^+}$, by two-dimensional binned maximum-likelihood fits on M_{D^0} and M_{D^+} plane.
- 2 Gaussian function for signal shape ($\mathcal{S}_{D^0}$ and $\mathcal{S}_{D^+}$)
- 1$^{\rm st}$ order polynomial function for background shape ($\mathcal{B}_{D^0}$ and $\mathcal{B}_{D^0}$).
- four components, D^0D^+ event ($\mathcal{S}_{D^0} \times \mathcal{S}_{D^+}$), D^0 with fake D^+ ($\mathcal{S}_{D^0} \times \mathcal{B}_{D^+}$), D^+ with fake D^0 ($\mathcal{B}_{D^0} \times \mathcal{S}_{D^+}$), and random background events ($\mathcal{B}_{D^0} \times \mathcal{B}_{D^+}$).



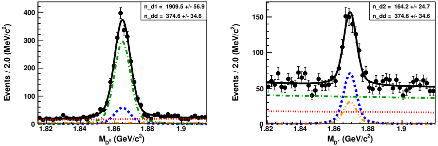
signal MC

2D fitting - Con't

- Peaking background event is enough large compare to signal
- We are plaining to extract N_{peaking} from the data
- Aware that MC need to be scaled through control sample study



background MC



peaking sources only

Cross-section of double charm production and interpretation

type of bkg MC	$N_{D^0D^+}$
including peaking bkg	24.8 $\pm$ 113.1
peaking bkg only	62.4 $\pm$ 14.1
double charm event in MC	–37.6 $\pm$ 114.0

$$
\begin{aligned}
N_{D^0D^+} &= \mathcal{L} \times \sigma(e^+e^- \to cc + X) \times \sigma(e^+e^- \to DD + X)/\sigma(e^+e^- \to cc + X) \\
&\quad \times \epsilon_{\mathrm{sig}} \times \mathcal{B}(D^0 \to K^-\pi^+) \times \mathcal{B}(D^+ \to K^-\pi^+\pi^+) \\
&= 89.1\mathrm{fb}^{-1} \times \sigma(e^+e^- \to cc + X) \times 6/16[1] \\
&\quad \times 0.199507 \times 0.0388 \times 0.0913.
\end{aligned}
$$

If we have ~340 of $N_{D^0D^+}$ ($\sim 3\times$ of $N_{D^0D^+}$ error using background MC in Table), we can estimate $\sigma(e^+e^- \to cc + X)$ 13 pb which are equivalent to 3σ of significancy.

[1] Daekyoung Kang et al., Phys. Rev. D 71, 071501 (2005)

Summay

- T_{cc} study ($e^+e^- \to T_{cc}\bar{D}\bar{D}$)
  - both M_{Rec} and $M_{T_{cc}}$ distribution checked
  - Too low signal = Too high background level
  - Need to improve background suppression or signal extraction method
  - Is P^* can be used to suppress background? $\to$ 4 open charm decay
- 4 open charm decay ($e^+e^- \to DD\bar{D}\bar{D}$)
  - To get momentum distribution of double charm decay through 4 open charm final state
  - and cross-section of itself
  - Using 89 fb^{-1} MC of off-resonance, 99% upper limit is higher than theoretical expectation
- Presently,
  - both study have difficulties to suppress background events
    $\to$ we are searching for a way to control background
  - and signal efficiency is also not good
    $\to$ for this we will add more channels and do simultaneous fitting
  - Using more data also can improve result: $\sim$1 ab^{-1} data stored in Belle.