Charm at super Belle

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Super KEKB Meeting

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Outline

- Introduction
- Leptonic and semileptonic $D_{(s)}$ decays
- Rare decays
- Charmonium production in e^+e^-
- Spectroscopy: $c\bar{c}$ and exotics
- Summary

D^0-$\bar{D}^0$ mixing and CPV covered on Thursday

Charm at SuperB Factory

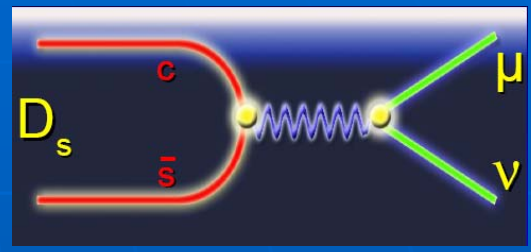
- B Factory at Y(4S) is a factory of charm:

  $\sigma(e^+e^- \to B\bar{B}) \sim 1.1$nb $\sigma(e^+e^- \to c\bar{c}) \sim 1.3$nb
- Physics of charmed hadrons
  - ⇘ test theoretical calculations (QCD and lattice QCD)
  - ⇘ improve precision of CKM related measurements
  - ⇘ search for new phenomena within SM and beyond
- Can we compete with Charm Factory?

Facility	num. of $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$	int. luminosity [fb^{-1}]	Comment
existing B factories	2.5×10^6	1000	final data set
Super-KEKB	14×10^6	5000	purity $\sim 99\%$
Charm factory	0.4×10^6	20	single D^0 reconstructed; coherent state
Tevatron	0.5×10^6	0.35	
LHCb	15×10^6	2	

* Charm Factory: Cleo (0.6/fb) + BESIII (2-3 years of running)

Leptonic $D_{(s)}^+$ decays



- Partial width for P→lν decay P=D^+,D_s^+

$$\Gamma(P^+ \to \ell^+ \nu) = \frac{1}{8\pi} G_F^2 f_P^2 m_\ell^2 M_P \left(1 - \frac{m_\ell^2}{M_P^2}\right)^2 |V_{Qq}|^2$$

- Leptonic part: V_{cd} (V_{cs})
- Hadronic part: decay constants: f_D (f_{Ds})
  (nQCD involved: requires LQCD)

- Measurement of f_D and f_{Ds} (f_{Ds}/f_D): test of LQCD
- Impact on B decays e.g. constraint of 'mixing side' of UT:

$|V_{td}/V_{ts}| \sim \sqrt{(\Delta m_d/\Delta m_s)(m_{Bd}/m_{Bs})}\, f_{Bs}/f_{Bd}$

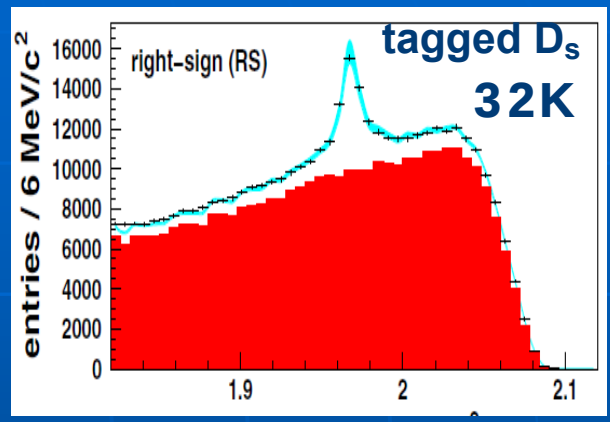
$= 0.2060 \pm 0.0007(\text{exp})\ ^{+0.0081}_{-0.0060}\ (\text{LQCD})$

More precise knowledge of f_{Bs}/f_{Bd} needed!

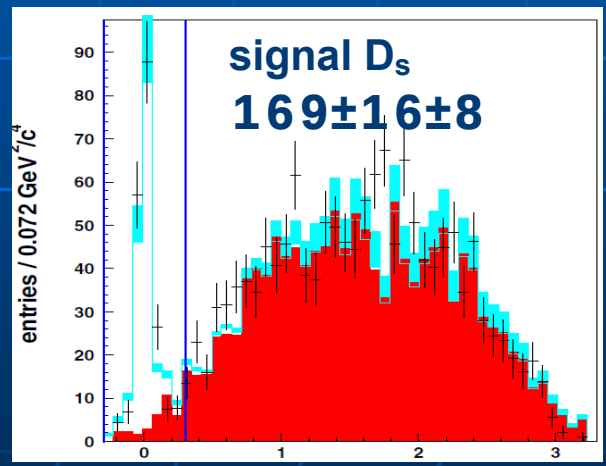
PRL 100, 241801 (2008)

$D_s^+ \to \mu\nu$ at Belle

- $D_s^+ \to \mu\nu$ most accesible:
  $\Gamma(\tau\nu):\Gamma(\mu\nu):\Gamma(e\nu)=10:1:10^{-5}$ $BR(\tau \to h\nu)\sim 11\%$
- $e^+e^- \to DKX\ D_s^*$ $D_s^* \to D_s\gamma$ $X=n\pi(\gamma)$
- Number of tagged D_s from $M_{recoil}(DKX\gamma)$
  $\to$ normalization for absolute BF
- Number of signal $D_s^+ \to \mu\nu$ from $M^2_{recoil}(DKX\gamma\mu)$



$M_{recoil}(DKX\gamma)$



$M^2_{recoil}(DKX\gamma\mu)$

$$\mathcal{B}(D_s \to \mu\nu_\mu) \times 10^3 = 6.44 \pm 0.76(\text{stat}) \pm 0.57(\text{syst}).$$

$$f_{D_s} = [275 \pm 16(\text{stat}) \pm 12(\text{syst})]\ \text{MeV}.$$

- For 548/fb : uncertainty of ~10% and needs improvement!

Leptonic decays: status

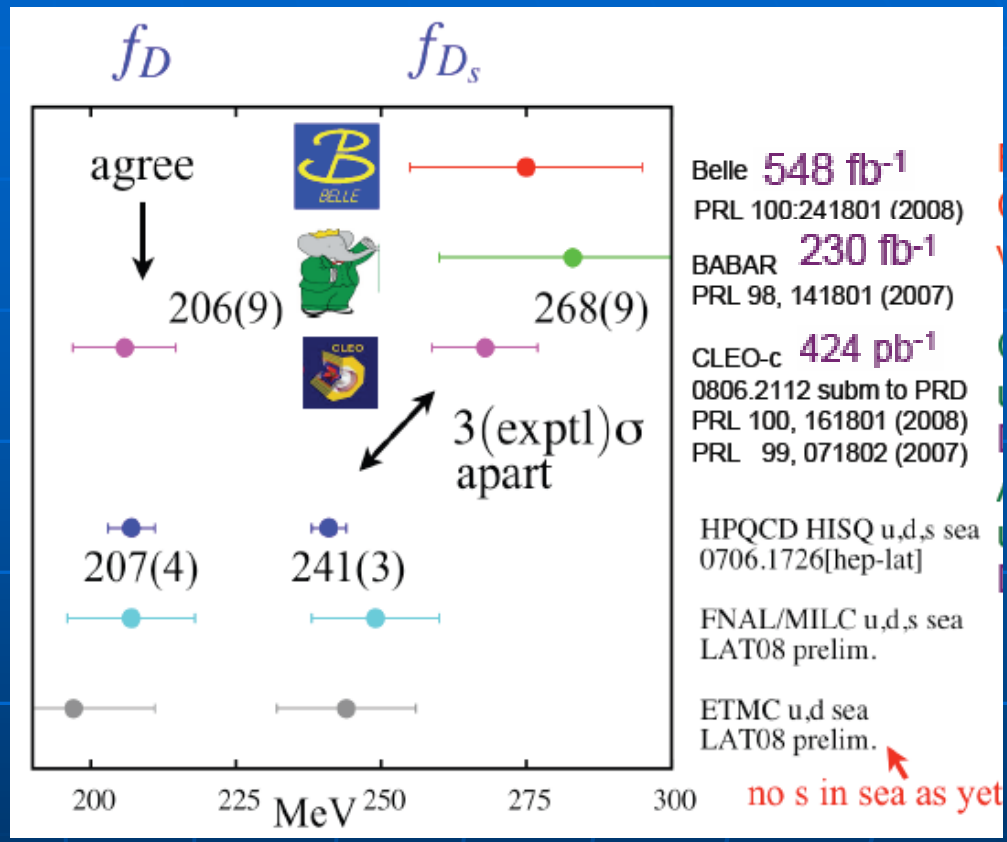
- Experiment vs lattice:

  f_D : consistent

  f_{Ds} : ~3σ discrepancy

- Statistical fluctuation?
- LQCD to be reexamined?
- H^+ or leptoquarks contribute?

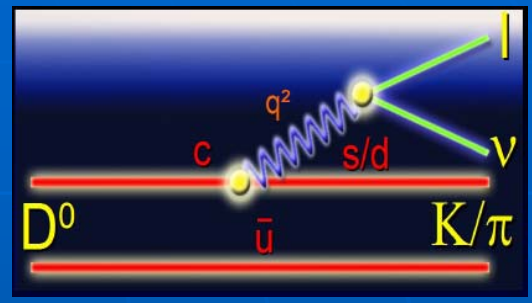
  PRL 100, 241802 (2008)



- Belle method established for $D_s^+ \to \mu\nu$:

  to be used for $D^+ \to \mu\nu$ ($BF \sim 4*10^{-4}$) with sBelle sample

Semileptonic $D_{(s)}$ decays



- Partial width of D→P'lν P'=K,π

$$\frac{d\Gamma}{dq^2} = \frac{G_f^2 |V_{q_1 q_2}|^2 p_{P'}^3}{24\pi^3} |f_+(q^2)|^2$$

$q^2 = (p_\nu + p_l)^2$

- Form Factor $f_+(q^2)$ describes hadronic part
- Simple pole model:

$$f_+^h(q^2) = \frac{f_+^h(0)}{1 - q^2/(m_{\rm pole}^h)^2}$$

Modified pole model:

$$f_+^h(q^2) = \frac{f_+^h(0)}{(1 - q^2/(m_{\rm pole}^h)^2)(1 - \alpha^h q^2/(m_{\rm pole}^h)^2)}$$

pole: D* for $D^0 \to \pi l\nu$, D^*_s for $D^0 \to Kl\nu$

- $D_s \to \phi l\nu$ $\Gamma = \Gamma(q^2, \chi, \theta_l, \theta_V)$ Form Factors: $V(q^2)$, $A_1(q^2)$, $A_2(q^2)$

measured: $r_V = V(0)/A_1(0)$ $r_2 = A_2(0)/A_1(0)$

- FF (normalization & q^2 dependence) to test LQCD
- To tune/check calculations in B sector e.g.: $|V_{ub}|$ from $B \to \pi l\nu$

accuracy ±3% from BF ±10-14% from Form Factor

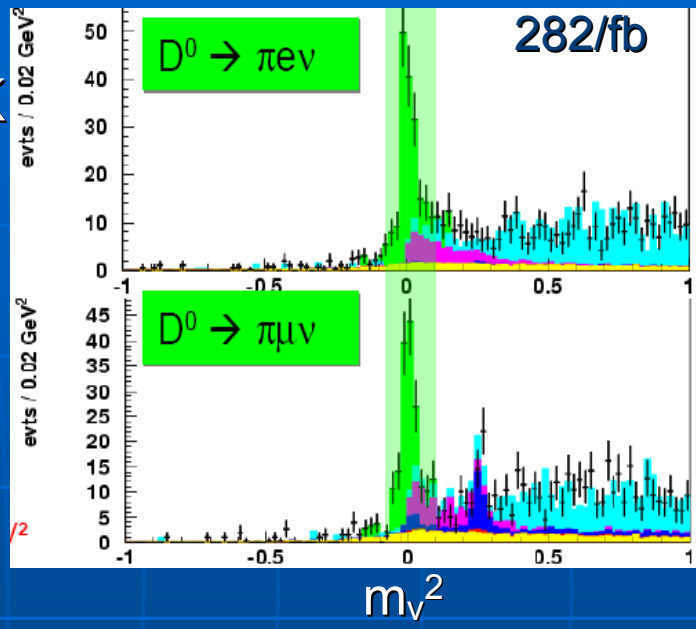
Goal: test LQCD to ≤ 5%

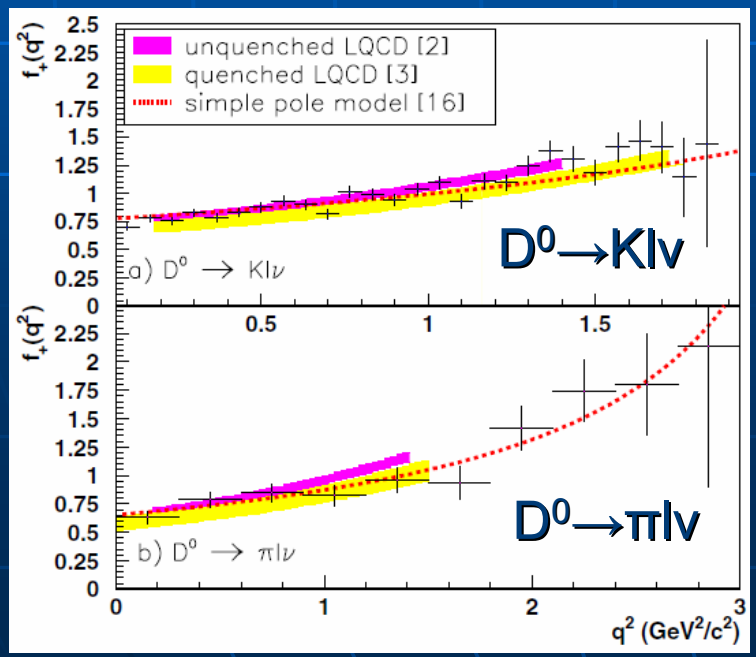
PRL 97, 061804 (2006)

$D^0 \to K/\pi\, l\nu$ at Belle

- $e^+e^- \to \underline{D}_{tag}^{(*)}\, X\, D_{sig}^*$ $\quad D_{sig}^* \to D^0\pi_s$ $\quad X = n\pi K$

- Number of tagged D^0 from $M_{recoil}(\underline{D}_{tag}^{(*)} X\pi_s)$ ($\to$inclusive D^0 sample, normalization)
- Number of signal $D^0 \to K/\pi l\nu$ from $M_{recoil}(\underline{D}_{tag}^{(*)} X\pi_s\ K/\pi l) = m_\nu^2$





$$\frac{f_+^\pi(0)^2|V_{cd}|^2}{f_+^K(0)^2|V_{cs}|^2} = 0.042 \pm 0.003_{stat} \pm 0.003_{syst}$$

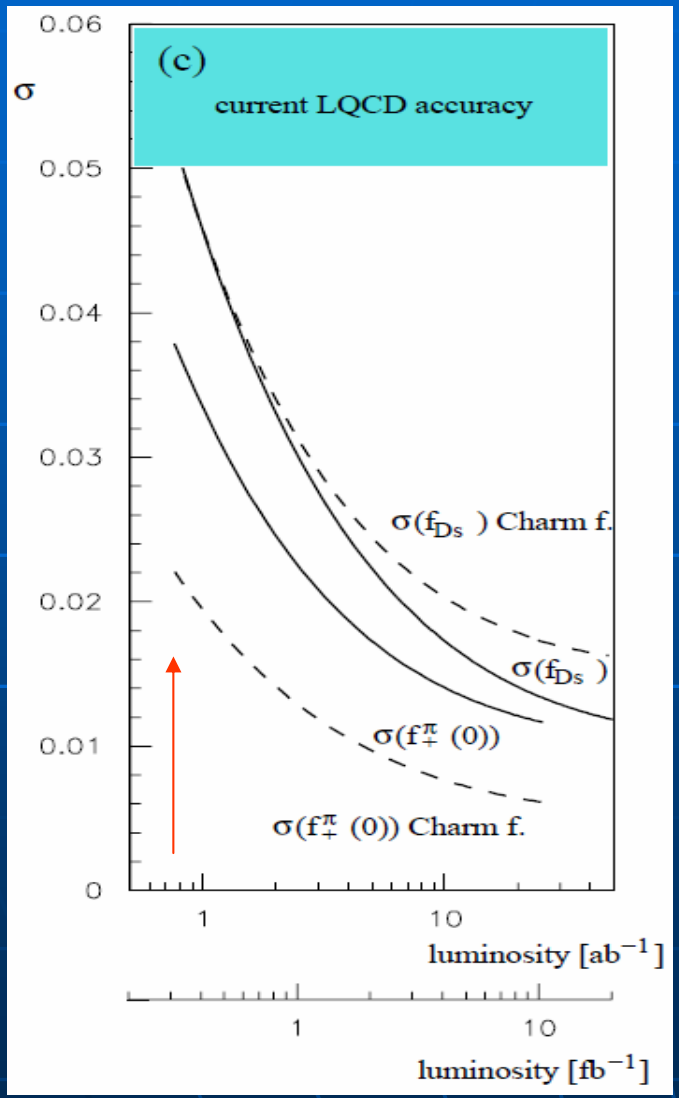
LQCD: 0.040±0.002(stat)±0.005(syst)

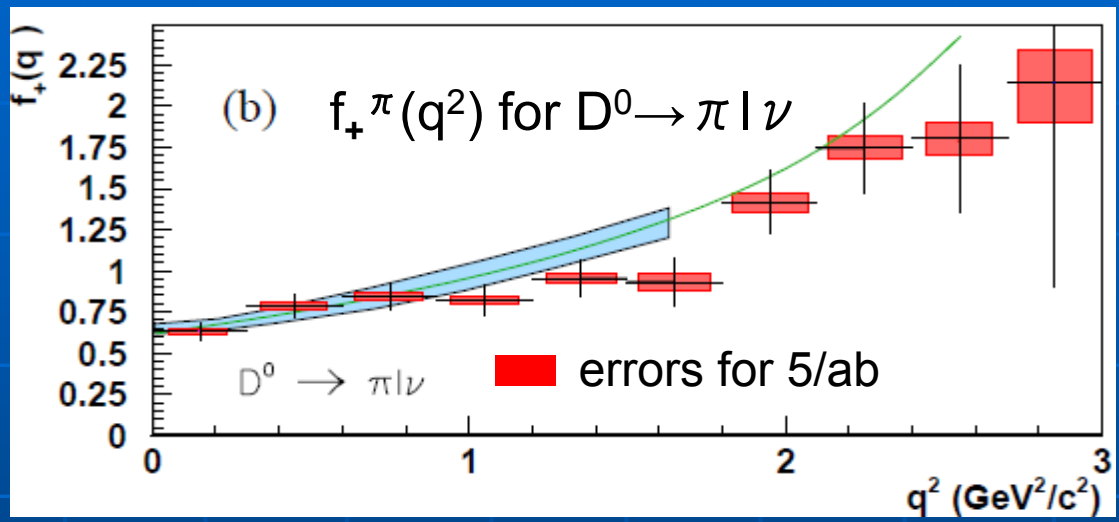
$f_+^K(0) = 0.695 \pm 0.007 \pm 0.022$

$f_+^\pi(0) = 0.624 \pm 0.020 \pm 0.030$

In agreement with CLEO

Prospects of (semi)leptonic $D_{(s)}$ decays





Decay mode	parameter	$L = 5$ ab^{-1}		$L = 50$ ab^{-1}	
		$\sigma_{\rm stat}$ [%]	$\sigma_{\rm syst}$ [%]	$\sigma_{\rm stat}$ [%]	$\sigma_{\rm syst}$ [%]
$D^0 \to \pi\ell\nu$	$f_+^\pi(0)$	1.5	1.0	0.5	1.0
$D_s \to \mu\nu$	f_{D_s}	2.0	1.0	0.6	1.0
$D_s \to \phi\ell\nu$	r_V	0.6	1.0	0.2	1.0
$D_s \to \phi\ell\nu$	r_2	1.0	2.4	0.3	2.4

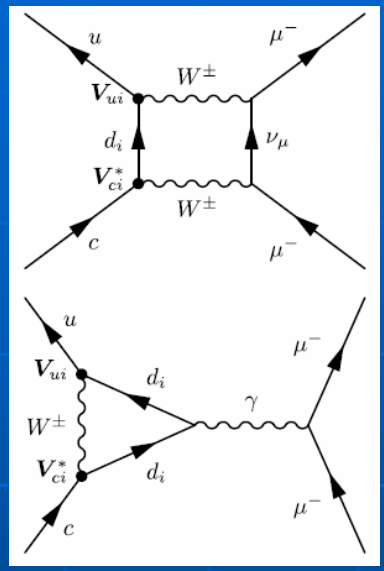
Rare decays

- Feasible exp. ground to look for New Physics: rare (loop) decays, mixing, CPV
- Leptonic rare/LFV decays: $D^0 \to \mu\mu$, ee, μe

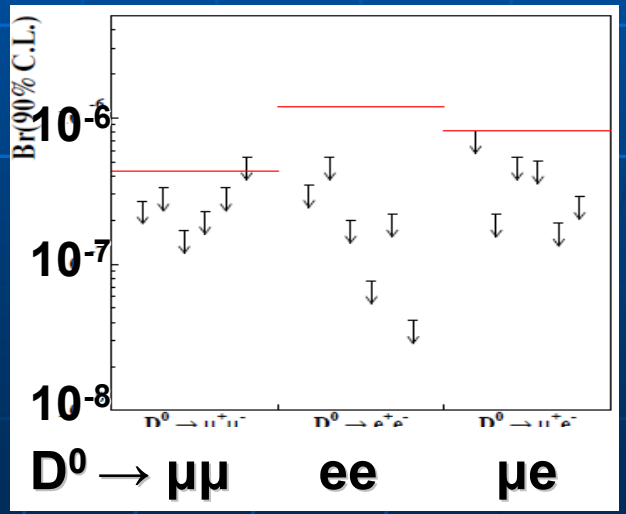
Channel	SM	SUSY $\not{R}_p$	mult. Higgs	PDG 2008 (90% C.L.)
$\mu^+\mu^-$	3×10^{-13}	4×10^{-6}	8×10^{-10}	$< 1.3 \times 10^{-6}$
e^+e^-	1×10^{-17}	1×10^{-10}	4×10^{-14}	$< 1.2 \times 10^{-6}$
$\mu^\pm e^\mp$	0	1×10^{-6}	7×10^{-10}	$< 8.1 \times 10^{-7}$

ICHEP 2008

- CDF preliminary $\mathcal{B}\mathrm{r}\left(D^0 \to \mu^+\mu^-\right) < 4.3 \times 10^{-7}$ (90% C.L.)



- Belle sensitivity for 690/fb (preliminary MC study)



- $D^0 \to \pi ll$ SM~10^{-6}

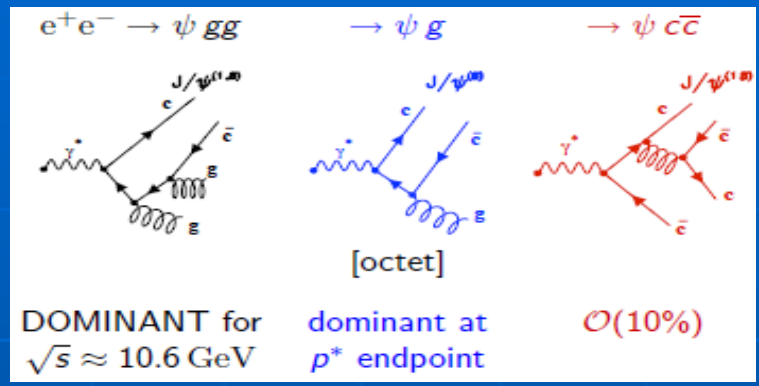
D0 $D \to \pi\mu\mu$ < 3.9×10^{-6}
CLEO-c $D \to \pi ee$ < 4.7×10^{-6}

- radiative decays SM~10^{-6} -10^{-4}

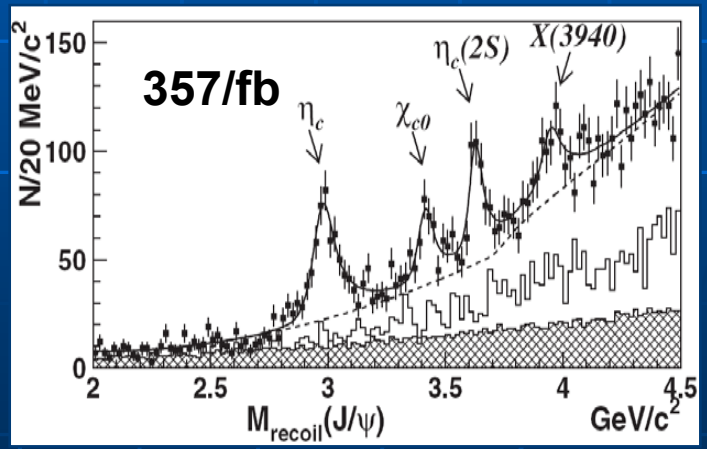
CLEO $D \to \gamma\gamma$ < 2.6×10^{-5} @90% C.L.
BABAR $D \to \phi\gamma$ $(2.73 \pm 0.30 \pm 0.36) \times 10^{-5}$
BABAR $D \to K^*\gamma$ $(3.22 \pm 0.20 \pm 0.27) \times 10^{-4}$

Charmonium production in e^+e^-

- NRQCD for prompt ψ production:
  ψgg ~ψg >>ψcc̲ (LO)
- Experiment:
- ➢ $e^+e^- \to J/\psi(c\underline{c})$ dominates:
  $\sigma(e^+e^- \to J/\psi\ (c\underline{c})) = 0.74 \pm 0.08^{+0.09}_{-0.08}$ pb
  $\sigma(e^+e^- \to J/\psi$ non-$(c\underline{c})) = 0.43 \pm 0.09 \pm 0.09$ pb (for 673/fb)
- ➢ it's a factory of charmonia with C=+ and J=0
  $\sigma * BF_{>2}$ [fb] (for 155/fb)



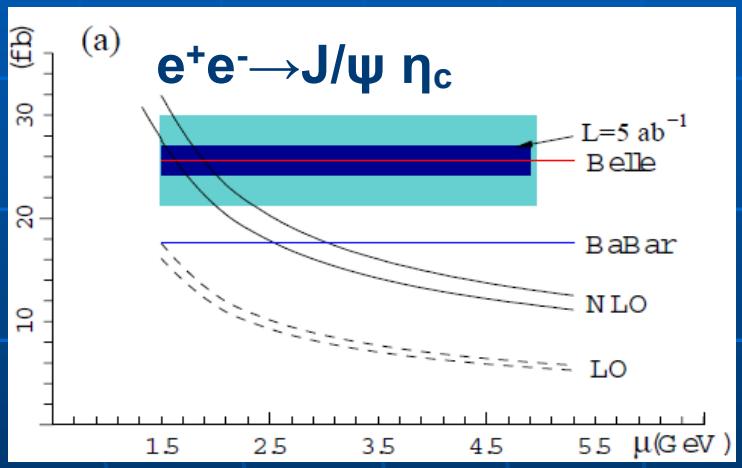
	η_c	χ_{c0}	$\eta_c(2S)$
J/ψ	25.6±2.8±3.4	6.4±1.7±1.0	16.5±1.7±0.4
ψ(2S)	16.3±4.6±3.9	12.5±3.8±3.1	16.3±5.1±3.8

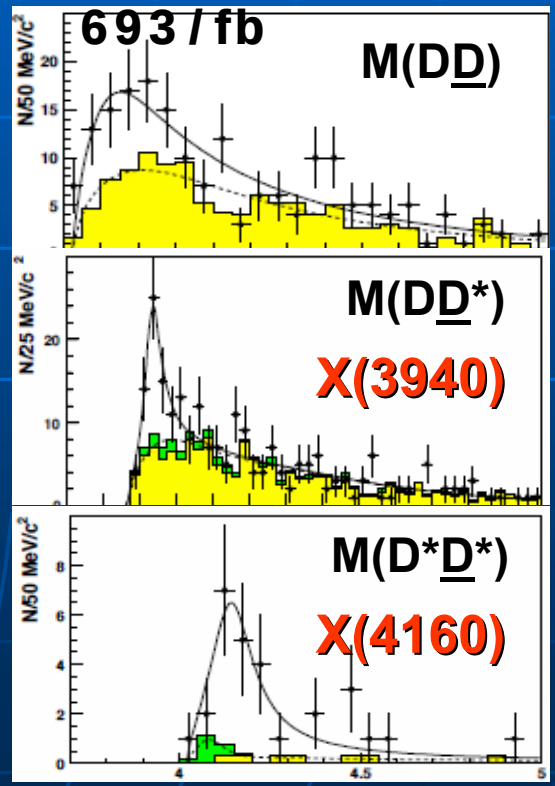


- LO + NLO +relativistic corrections can accomodate experimental results
- Open questions:NNLO and/or color octet needed?

Charmonium production in e^+e^-

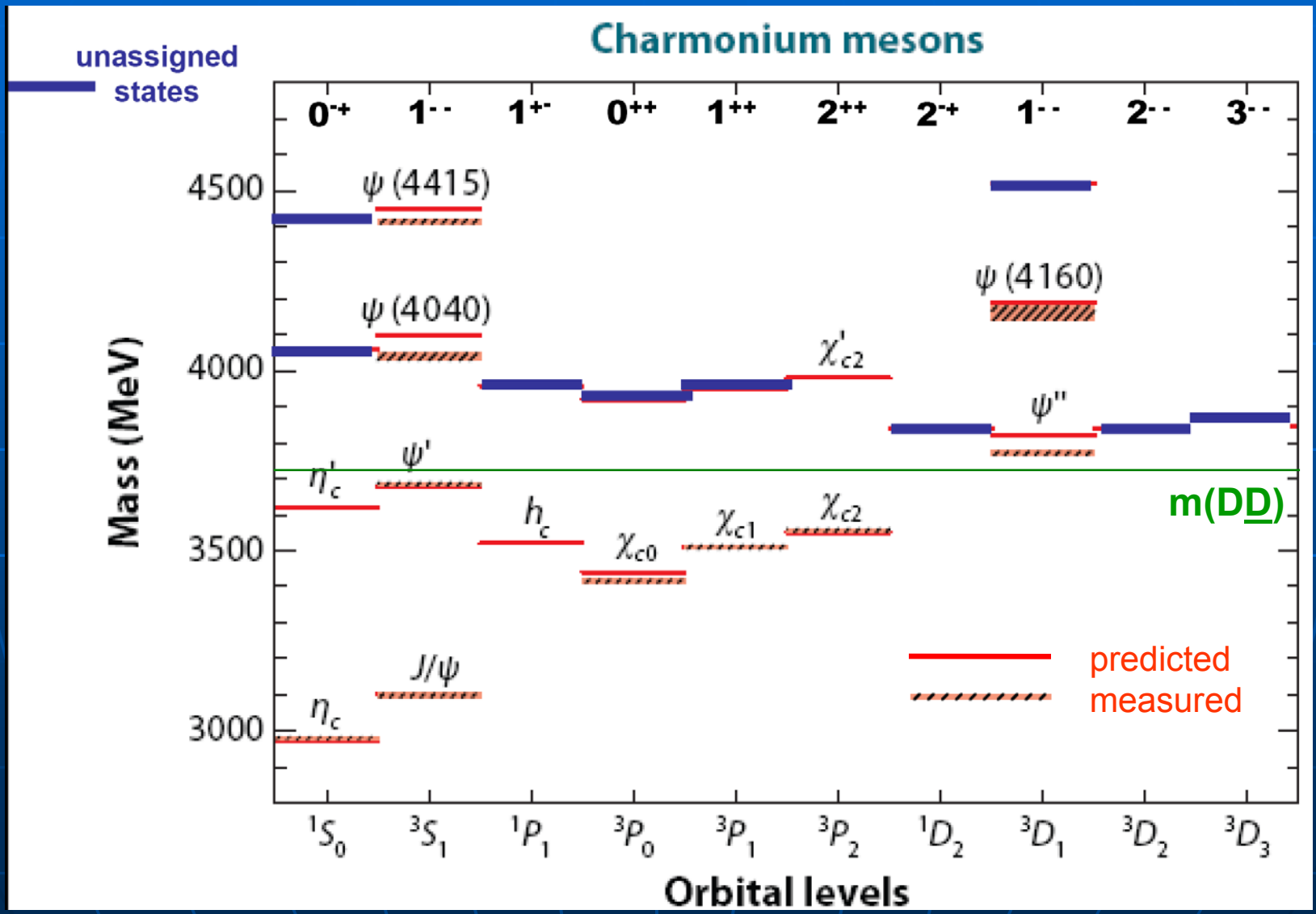
- Experimental role is still leading
  To do with sBelle:
- Precise measurements of $e^+e^- \to J/\psi(c\bar{c})$ and $\psi(2S)(c\bar{c})$ (x-sections, production/helicity angle)
- Study of $e^+e^- \to \eta_c(c\bar{c})$, $\chi_{cJ}(c\bar{c})$, $\eta_c(2S)(c\bar{c})$





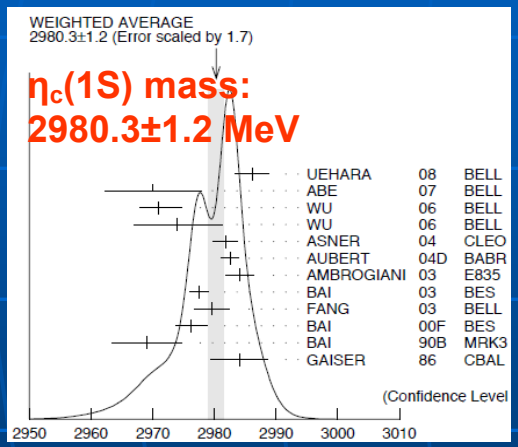
- $e^+e^- \to J/\psi D^{(*)}\bar{D}^{(*)}$: new states in $D^{(*)}\bar{D}^{(*)}$ system
- high statistic measurement of mass/width/shape
- angular analysis of X states needed

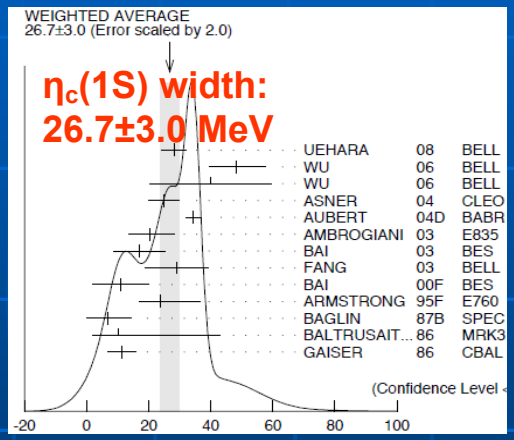
Charmonium spectrosocpy



Charmonia below DD

- **η_c η_c':** mass, width, line shape measurement
- Precise measurements of hyperfine splittings: $m(\eta_c) - m(\psi)$
  → test of models and LQCD (hyperfine splitting underestimated)



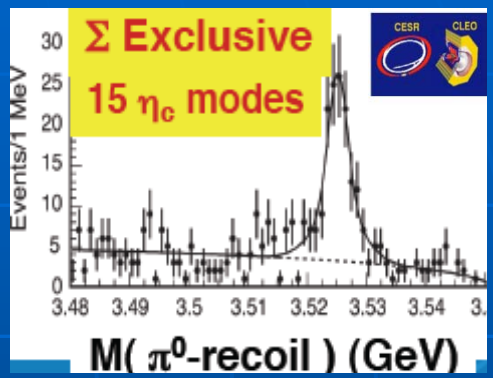


Effect of η_c line shape?
Only in M1 transition $\psi \to \gamma\eta_c$?

- η_c': $K_sK\pi$ is only known decay; PDG08: m=3637±4 MeV Γ=14±7 MeV
- $B \to K\eta_c$ and $\eta_c \to K_sK\pi$ at Belle with 500/fb
  m and Γ accuracy:
  η_c: σ(m)~2MeV σ(Γ)~3MeV η_c': σ(m)~6MeV σ(Γ)~9MeV
- sBelle: precision + other decay modes

Charmonia below DD

- **$h_c(1P)$** finally observed by Cleo: $\psi(2S)\to\pi^0 h_c$ $h_c\to\gamma\eta_c$
- $m(h_c) = 3525.20 \pm 0.18 \pm 0.12$ MeV
- hyperfine splittng $\chi_c(^3P_J) - h_c(^1P_1)\sim 0$
  challenge for theory

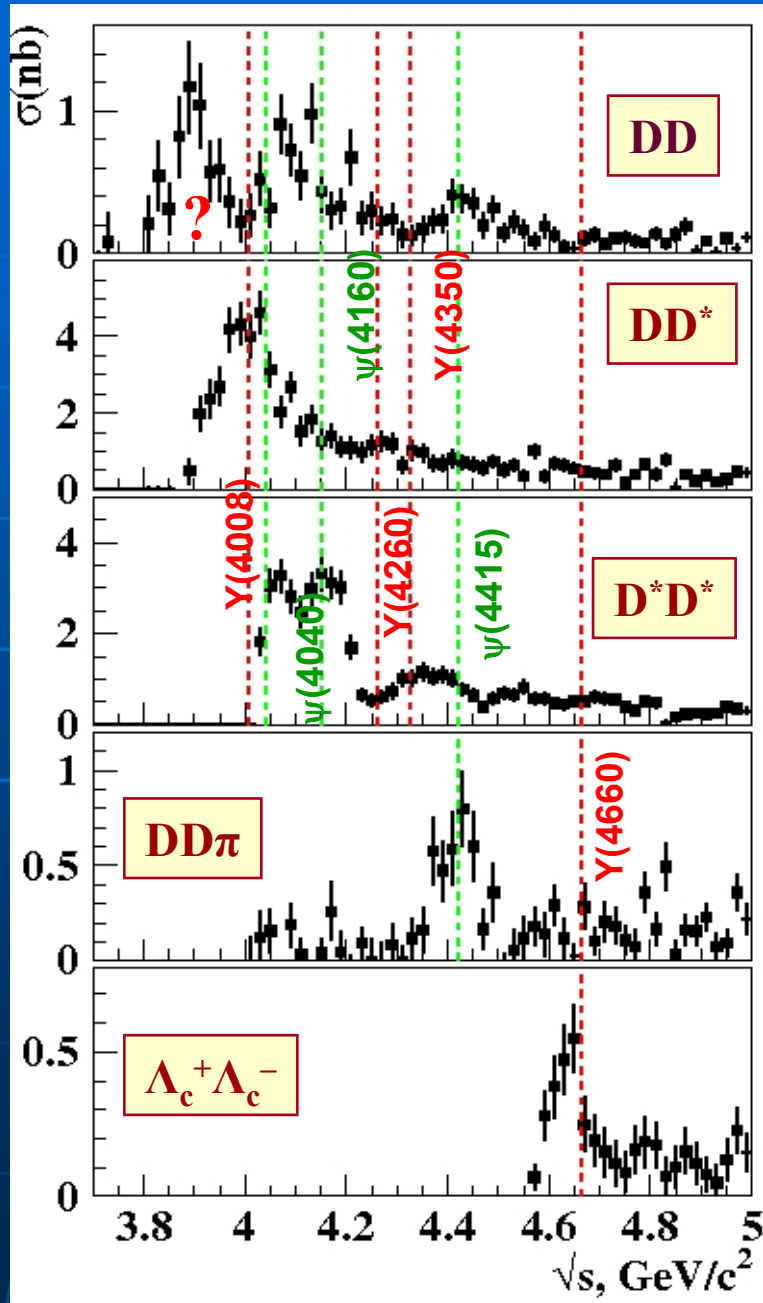


- Confirmation of h_c at sBelle?
- $B\to h_c K$ $h_c\to\eta_c\gamma$ factorization violating mode
  Belle with 253/fb: BF<$3.8*10^{-5}$ @90%C.L
  assuming $BF(h_c\to\eta_c\gamma)=0.5$
- $e^+e^-\to\eta_c h_c$, $\chi_{c0}h_c$: in recoil of C=+1 charmonia
  η_c , χ_{c0} reconstructed with BF~$O(10^{-3})$
  → 5/ab needed

Charmonia above D$\underline{D}$

- Parameters of vector states:
  ψ(3770), ψ(4040), ψ(4160), ψ(4415)
- From fit to inclusive hadronic x-section by BES
- Belle: access to 1^{--} states through ISR
- Fits to exclusive x-sections: strong model dependence.
  Fits to be attempted with more precise x-section measurements.

- Missing components requiring sBelle data:
  D$\underline{D}$*π, D*$\underline{D}$*π, $D_s\underline{D}_s$, $D_s\underline{D}_s$*, D_s*$\underline{D}_s$*
- Insight into Y family



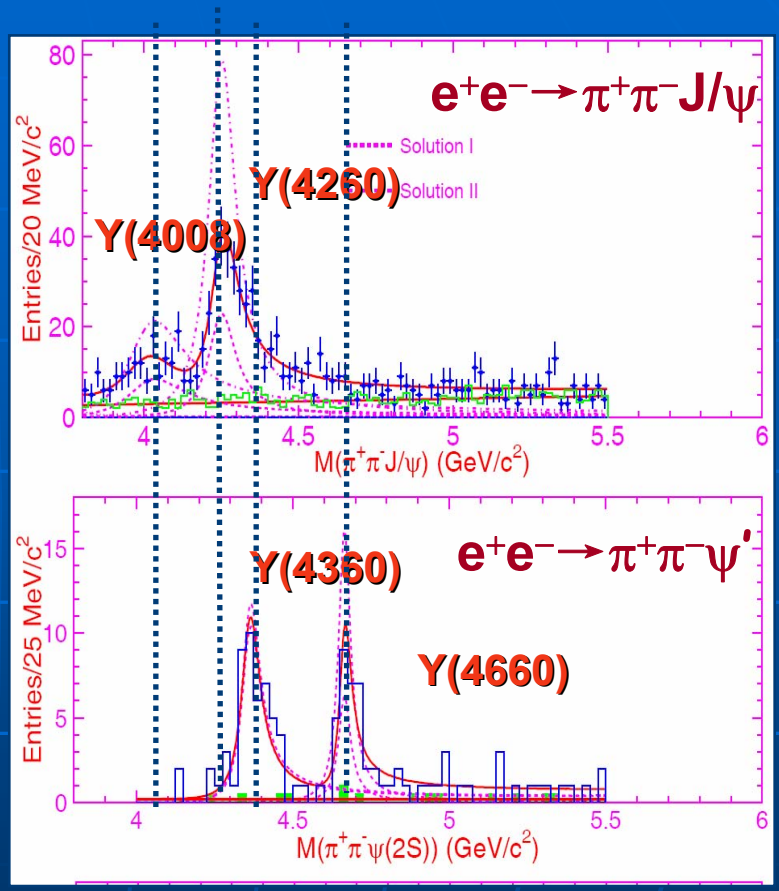
1^{--} Y family

Exotic family?

- Large $\Gamma(Y\to\psi\pi\pi)\sim O(MeV)$
- Small $\Gamma(D^{(*)}\underline{D}^{(*)})$: qualitative conclusion
- Not enough empty 1^{--} $c\underline{c}$ slots to fill

More ISR studies using sBelle data:

- Conclusion on Y(4008)?
- $Y\to\psi\pi^0\pi^0$
  check of isospin relation
- $Y\to D\underline{D}_1(2420)$, $\underline{D}^*D^*_0\to D\underline{D}^*\pi$
  test of molecular scenario
- $Y\to D\underline{D}_1(2420)$, $J/\psi\eta$, $J/\psi\eta'$, $\chi_{cJ}\omega$
  test of hybrid scenario

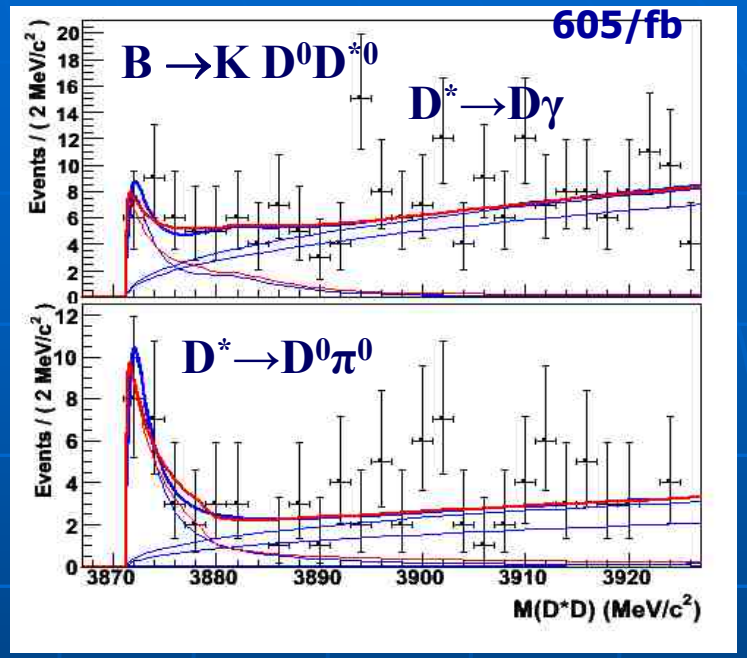


Action items for X(3872)

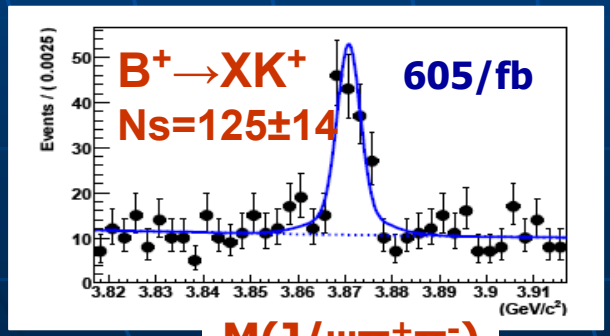
Studies of B→X(3872)K:

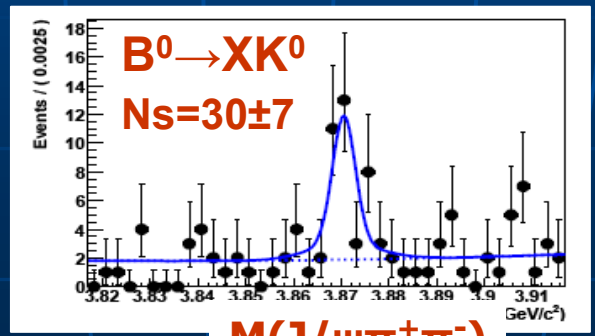
- X(3872)→$D^0\underline{D}^{*0}$: mass, width, line shape
- X(3872)→$D^0\underline{D}^0\pi^0$

- X→J/ψ$\pi^+\pi^-$ width
- X→J/ψ$\pi^0\pi^0$ check isospin relation
- X→J/ψ$\pi^+\pi^-\pi^0$ isospin violating mode
- X→J/ψ$\pi^+\pi^0$ critical for 4-quark scenario
- X→J/ψγ signal 14±4 (4σ) for 256/fb
  X→ψ'γ, $\chi_{c1}\gamma$
  problematic for molecular scenario



m(X)=$3872.6^{+0.5}_{-0.4}$ ±0.4MeV
Γ=$3.9^{+2.5}_{-1.3}{}^{+0.8}_{-0.3}$ MeV





$Z^{\pm}$ $c\bar{c}$-like states

Further studies with sBelle data:

- Precision mass/width
- Spin-parity determination
- Search for $Z^0 \to \psi\pi^0$, $\chi_{c1}\pi^0$

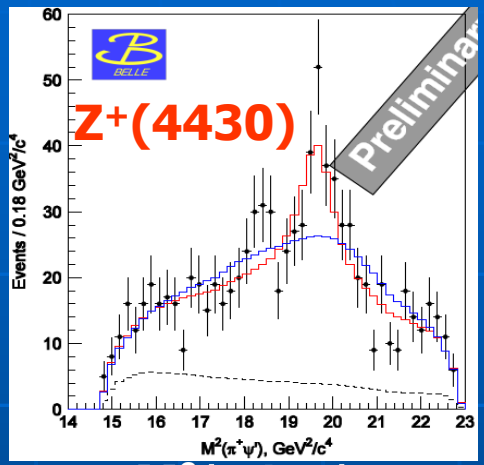
  test of [cu][$\bar{c}$d] tetraquark scenario
- $Z \to D^*\bar{D}_1(2420) \to D^*\bar{D}^*\pi$

  test of molecular scenario

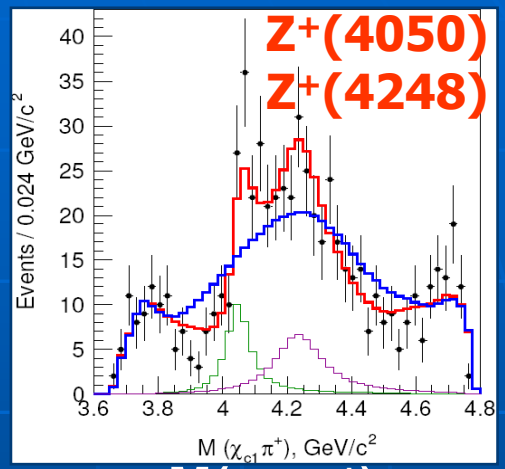
- Search for new $Z^{\pm}$'s:

  $Z \to D\bar{D}$, $D^*\bar{D}$, $D^*\bar{D}^*$

  $Z \to J/\psi\pi^+$, $\eta_c\pi^+$,...



$M^2(\psi'\pi^+)$



$M(\chi_{c1}\pi^+)$

$$M = (4443^{+15+17}_{-12-13})\ \mathrm{MeV}/c^2,$$
$$\Gamma = (109^{+86+57}_{-43-52})\ \mathrm{MeV},$$

$$M_1 = (4051 \pm 14^{+20}_{-41})\ \mathrm{MeV}/c^2,$$
$$\Gamma_1 = (82^{+21+47}_{-17-22})\ \mathrm{MeV},$$
$$M_2 = (4248^{+44+180}_{-29-35})\ \mathrm{MeV}/c^2,$$
$$\Gamma_2 = (177^{+54+316}_{-39-61})\ \mathrm{MeV},$$

Results of Dalitz plot fit for:

$B \to K\psi'\pi^+$ and $B \to K\chi_{c1}\pi^+$

for model without Z(s)

for model with Z(s)

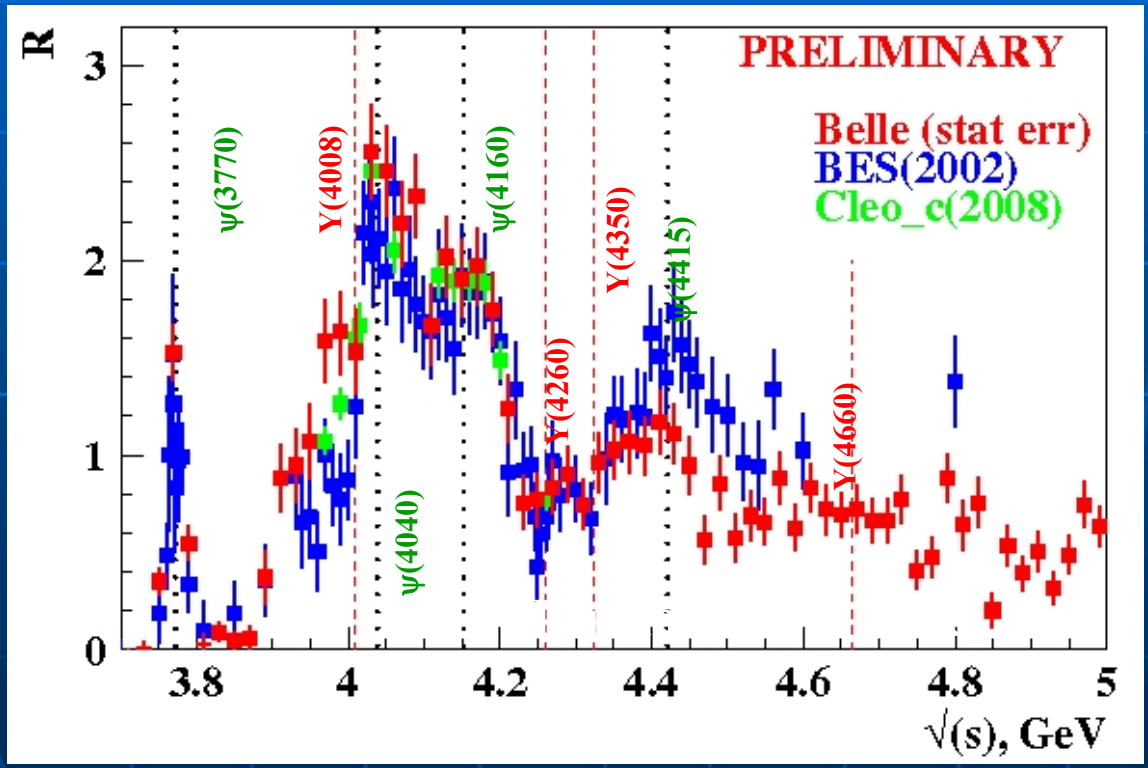
Summary

- A lot of charm studies with Belle data
- Good prospects for more with Super Belle:
  precision (semi)leptonic $D_{(s)}$ decays
  access to rare decays
  understand charmonium production
  identify XYZ states
  study of baryons/mesons

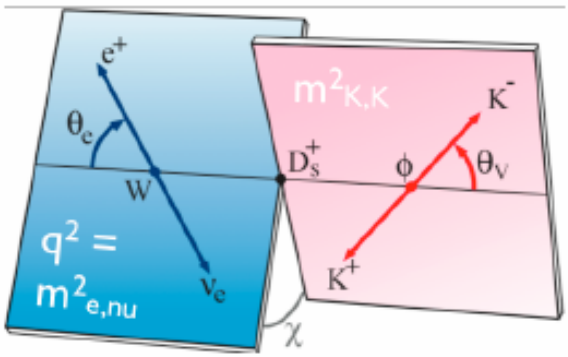
Backups

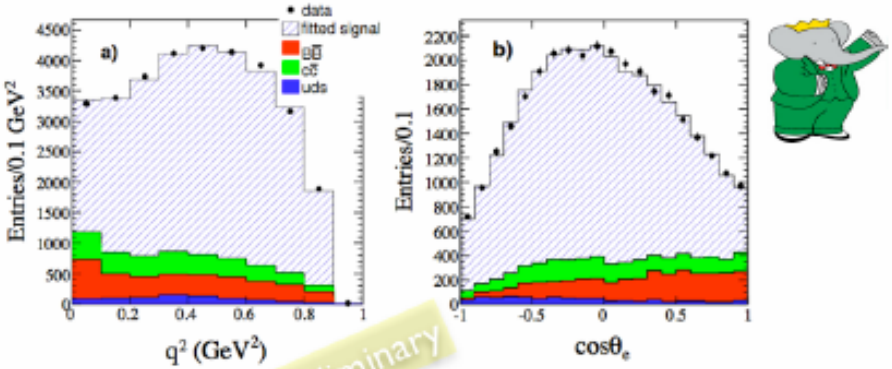
Hadronic x-sections

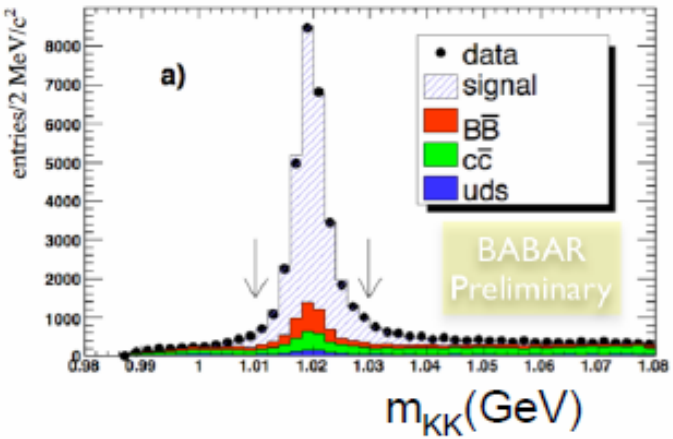
- From CLEO: scan at 3.97-4.26GeV in 12 points
- Total hadronic x-section above D$\underline{D}$ from BES
- Belle: sum of all measured exclusive contributions



$D_s \to K^+K^-e\nu$ Form Factors & LQCD







- $r_V = 1.868 \pm 0.061 \pm 0.079 \to r_V = 1.35 \pm 0.08$
- $r_2 = 0.763 \pm 0.072 \pm 0.062 \to r_2 = 0.98 \pm 0.09$
- $r_0 = 15.3 \pm 2.6 \pm 1.0$ - first evidence for $D_s \to f_0 e\nu$

Agrees well with hep-lat/0109035

Rare

- Radiative - $D \to (\gamma, \phi, K^*)\gamma$ SM 10^{-4} -10^{-6}
  - CLEO $D \to \gamma\gamma$ $< 2.6 \times 10^{-5}$ @90% C.L.
  - BABAR $D \to \phi\gamma$ $(2.73 \pm 0.30 \pm 0.36) \times 10^{-5}$ (new)
  - BABAR $D \to K^*\gamma$ $(3.22 \pm 0.20 \pm 0.27) \times 10^{-4}$ (new)
- Leptonic $D \to \mu\mu$ SM$<10^{-13}$ RPV SUSY$\sim 10^{-7}$
  - CDF $< 4.3 \times 10^{-7}$ @90% C.L. (new)
- GIM Suppressed $D \to \pi ll$ SM$\sim 10^{-6}$
  - Distinguish NP from SM with dilepton invariant mass, FB asymmetries
    - D0 $D \to \pi\mu\mu < 3.9 \times 10^{-6}$
    - CLEO-c $D \to \pi ee < 4.7 \times 10^{-6}$
- Lepton Flavor Violation - BABAR @90% C.L.
  - $D \to e^+\mu^- < 8.1 \times 10^{-7}$ $D^+ \to K^+e^-\mu^+ < 3.7 \times 10^{-6}$
  - $D_s^+ \to K^+e^-\mu^+ < 3.6 \times 10^{-6}$ $\Lambda_c^+ \to pe^-\mu^+ < 7.5 \times 10^{-6}$
- Lepton Number Violation $D^+ \to \pi^- e^+ e^+$
  - CLEO-c $< 3.6 \times 10^{-6}$ @90% C.L