Rare B Decays at Belle & BaBar

Hiroaki Aihara
University of Tokyo

Presented at 31st SLAC Summer Institute Topical Conference, August 6-8

Outline

- Excited Heavy Quark - Light Quark Mesons

  D^{**0} $(c\bar{u})$ and D_{sJ}^{+} $(c\bar{s})$

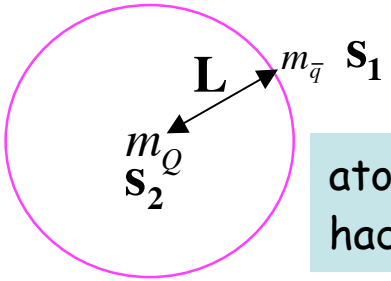
- Electroweak Penguin Decays

- □ to □□ Decays

Spectroscopy of orbitally excited heavy (Q) and light (q) quark system

$Q\bar{q}$ meson is analogous to the hydrogen atom in the limit of $m_Q \to \infty$.

(Heavy Quark Symmetry)



atom: photon exchange
hadron: gluon exchange

$\mathbf{L}$ = the orbital angular momentum

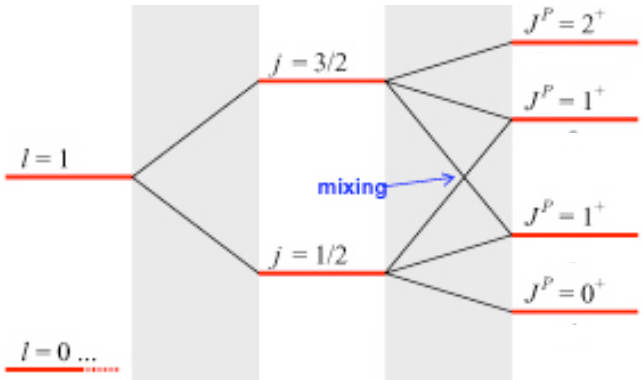
$\mathbf{j} = \mathbf{L} + \mathbf{s}_1$ = the total angular momentum of q

$\mathbf{J} = \mathbf{j} + \mathbf{s}_2$ = Total angular momentum

In $m_Q \to \infty$, $\mathbf{j}$ is a good quantum number.

For p-wave (L = 1) states, $1 \otimes \frac{1}{2} = \frac{1}{2} \oplus \frac{3}{2}$, i.e. $j = \frac{1}{2}, \frac{3}{2}$.

The levels split by $\mathbf{L} \cdot \mathbf{s}_1$ force to make the fine structure.



Each j state further split due to $\mathbf{L} \cdot \mathbf{s}_2$, $\mathbf{s}_1 \cdot \mathbf{s}_2$, and the tensor force to make the hyperfine structure $1/m_Q m_q$.

$$\mathbf{J} = \frac{1}{2} \otimes \frac{1}{2} = 0 \oplus 1, \quad \frac{3}{2} \otimes \frac{1}{2} = 1 \oplus 2 \quad \Rightarrow \quad J_j^P = \left(0^+_{1/2}, 1^+_{1/2}\right), \quad \left(1^+_{3/2}, 2^+_{3/2}\right)$$

Two axial vector states, $1^+_{1/2}$ and $1^+_{3/2}$, can mix.

Why care ?

- Their mass spectra and decay widths provides tests of QCD, in particular, the confinement potential.
  - QCD motivated quark potential models.

$$\text{Coulomb}\left(\frac{1}{r}\right) + \text{linear}\left(r\right)$$

  - Heavy Quark Effective Theory
  - Chiral symmetry of QCD

Heavy quark spectroscopy started here at SLAC in 1974.

Expected decays of $L=1$ $(c\bar{u})$ and $(c\bar{s})$ mesons

Conservation of angular momentum (J and j) and parity

$0^+_{1/2} \to 0^-0^-$ via an S wave (large phase space): broad $\Gamma \geq 200$ MeV

$1^+_{1/2} \to 1^-0^-$ via a S wave : broad $\Gamma \geq 200$ MeV

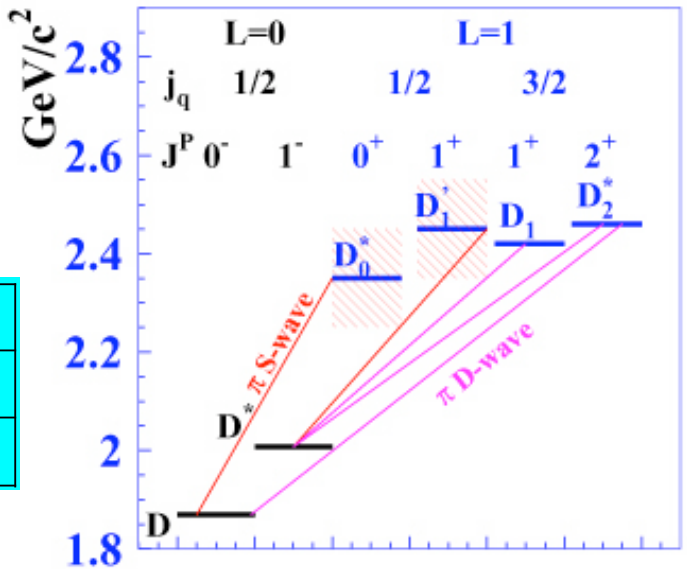
$1^+_{3/2} \to 1^-0^-$ via a D wave (small phase space) : narrow $\Gamma \leq 20$ MeV

$2^+_{3/2} \to 0^-0^-$ or 1^-0^- via a D wave : narrow $\Gamma \leq 20$ MeV

$\left(1^+_{3/2}, 2^+_{3/2}\right)$ doublets have been observed for both $c\bar{u}$ and $c\bar{s}$.

PDG2002

$c\bar{u}$	mass(MeV/c^2)	width(MeV)	modes
$D_1(2420)^0$	2422.2 ± 1.8	$18.9^{+4.6}_{-3.5}$	$D^*(2010)^+\pi^-$
$D_2^*(2460)^0$	2458.9 ± 2.0	23 ± 5	$D^+\pi^-, D^*(2010)^+\pi^-$



Similarly the j=3/2 pair of $c\bar{s}$ has been observed.

$c\bar{s}$	mass(MeV/c^2)	width(MeV)	modes
$D_{S1}(2536)^+$	$2535.35 \pm 0.34 \pm 0.5$	< 2.3	$D^*(2010)^+K^0, D^*(2007)^0K^+$
$D_{SJ}(2573)^+$	$2572.4 \pm 1.5^{+5}_{-4}$	15	D^0K^+

What about j=1/2 pairs ?

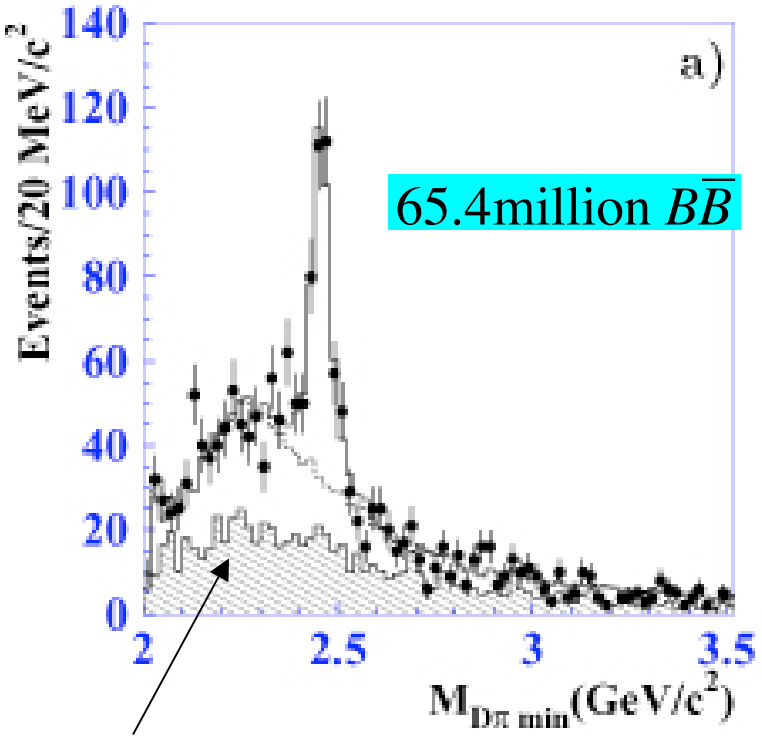
Quark models predict 2.4 ~2.5 GeV/c^2 for $c\bar{u}$ and 2.4~2.6 GeV/c^2 for $c\bar{s}$.

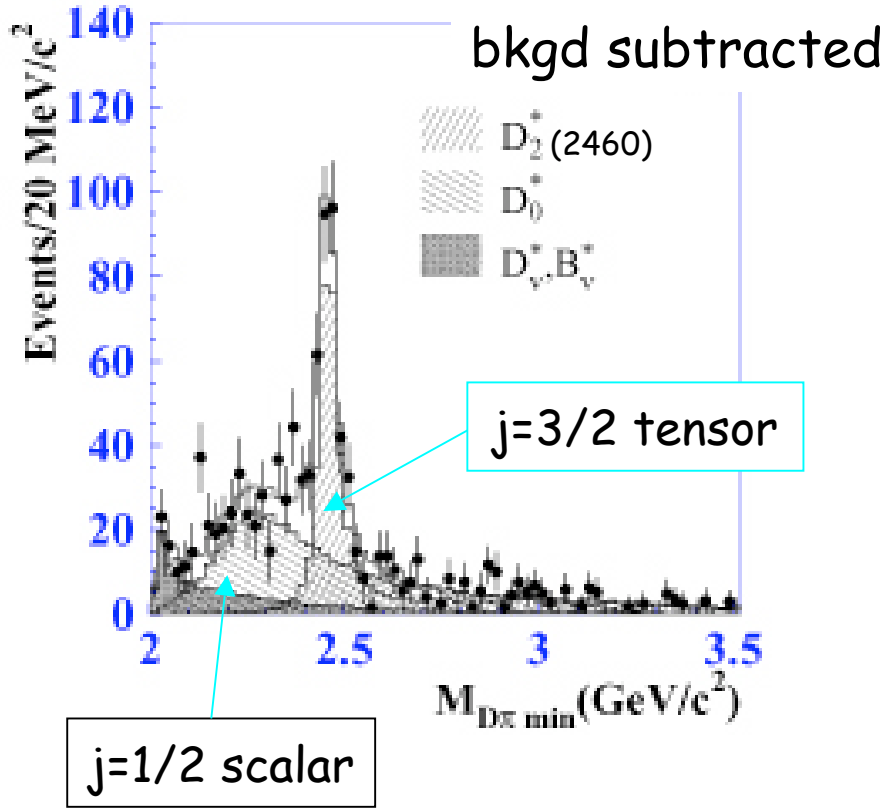
Expected decay modes : broad resonances

$$c\bar{u} \to D^+\pi^0, \quad D^{*+}\pi^0$$

$$c\bar{s} \to D^0K^+, \quad D^{*0}K^+$$

Belle : $B^{\square} \square D^{+}\square^{\square}\square^{\square}$ analysis





An unbinned fit to B to D$\square\square$ Dalitz plot is performed including signal plus virtual states and background. Helicity analysis is also done.

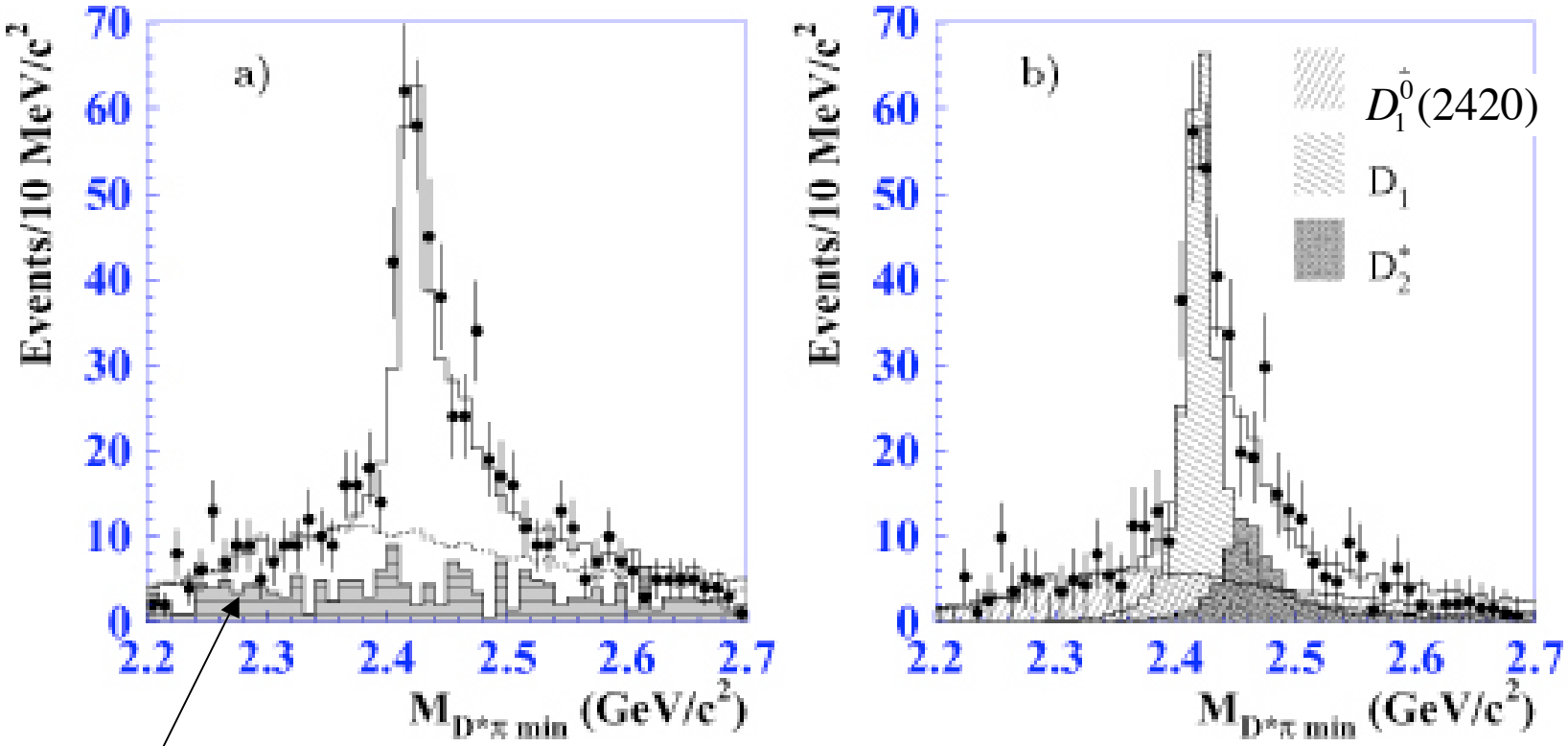
$0^+_{1/2}(c\bar{u})$

$$M(D_0^{*0}) = (2308 \pm 17 \pm 15 \pm 28)\ \mathrm{MeV}/c^2$$

$$\square(D_0^{*0}) = (276 \pm 21 \pm 18 \pm 60)\mathrm{MeV}$$

Belle : $B^{\square} \square D^{*+}\square^{\square}\square^{\square}$ analysis

hep-ex/0307021



background from sideband

$1^+(c\bar{u})$

$$M(D_1^{'0}) = (2427 \pm 26 \pm 20 \pm 15)\mathrm{MeV}/c^2$$

$$\square(D_1^{'0}) = (384^{+107}_{\square 75} \pm 24 \pm 70)\mathrm{MeV}$$

Two $c\bar{u}$ resonances, broad as expected, are found.

What about $c\bar{s}$ system ?

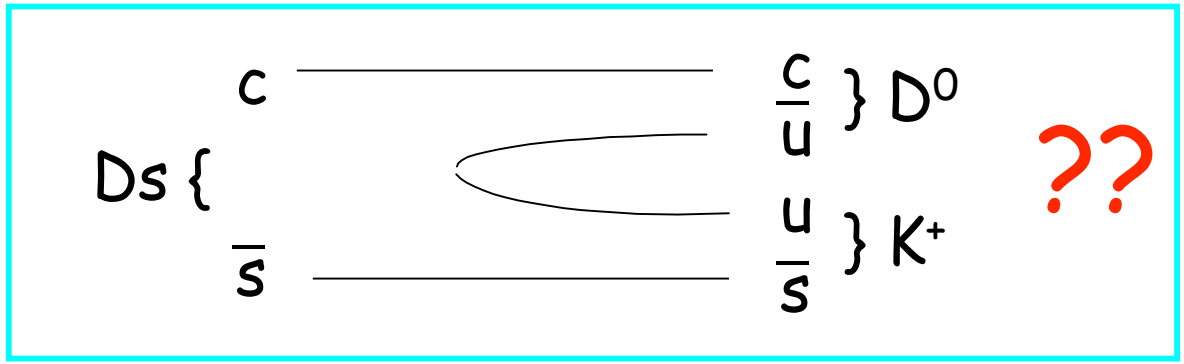
April 28, 2003

Comment: Marcello Giorgi
BaBar Spokesperson
(650) 926-2385
giorgi@slac.stanford.edu

SLAC experiment identifies new subatomic particle

Relevant Web URLs:
http://www.slac.stanford.edu/slac/media-info/20030428/photos.html
http://www-public.slac.stanford.edu/babar/

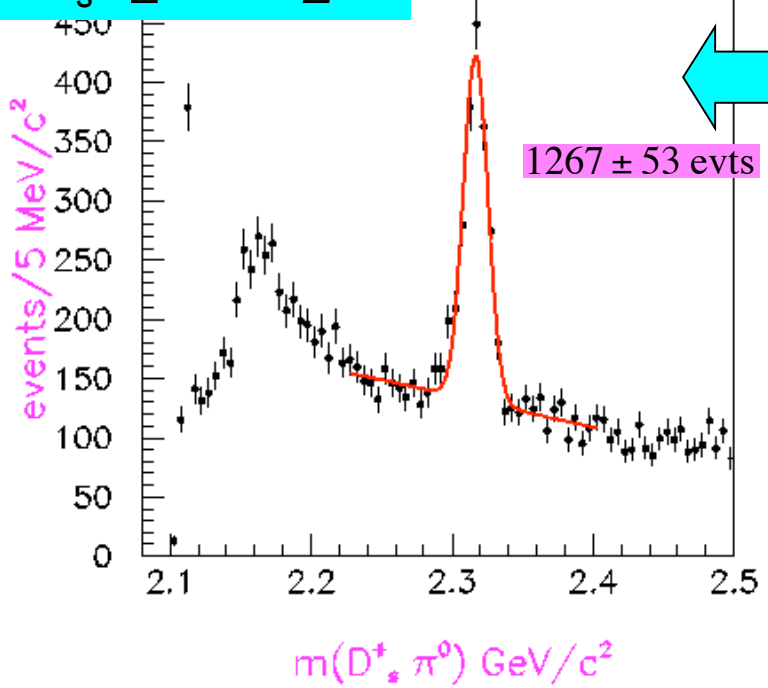
Physicist Antimo Palano representing the BABAR experiment presented the evidence for the identification of a new subatomic particle named Ds (2317) to a packed auditorium on Monday 28th April at the Department of Energy's Stanford Linear Accelerator Center (SLAC). Initial studies indicate that the particle is an unusual configuration of a 'charm' quark and a 'strange' anti-quark. A scientific paper was sent for publication in Physical Review Letters on April 11th 2003.



The New Narrow Sate at 2317 MeV/c^2 in M($D_s\pi^0$) !

BaBar 91 fb^{-1} PRL 90, 242001 (2003)

$D_s^+ \to K^+K^-\pi^+$



$p^*(D_s^+\pi^0)$ > 3.5 GeV/c : continuum

Fit to Gaussian:

Δm = (348.4 ± 0.4 ± 3.0) MeV/c^2

m = (2316.8 ± 0.4 ± 3.0) MeV/c^2,

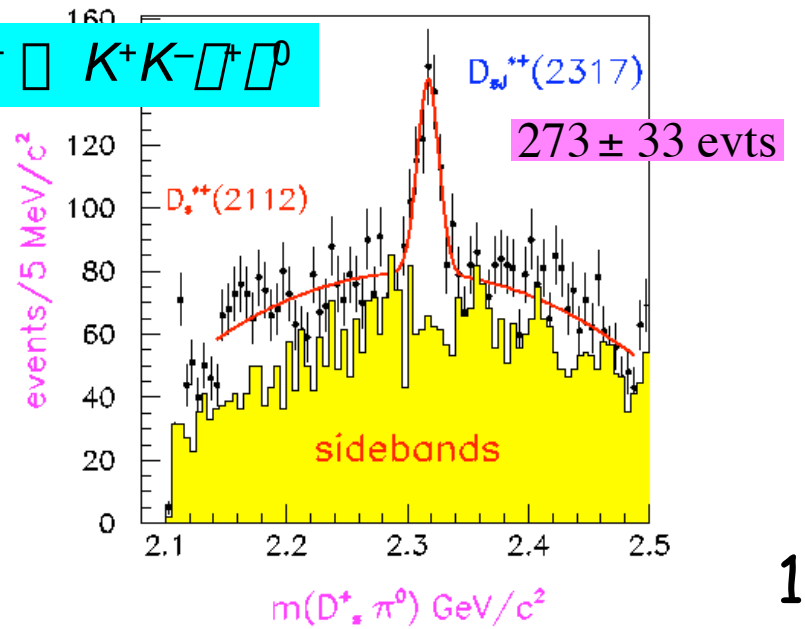
σ = (8.6 ± 0.4) MeV/c^2

- D_s^+ reconstructed in $K^+K^-\pi^+\pi^0$:

m = (2317.6 ± 1.3) MeV/c^2,

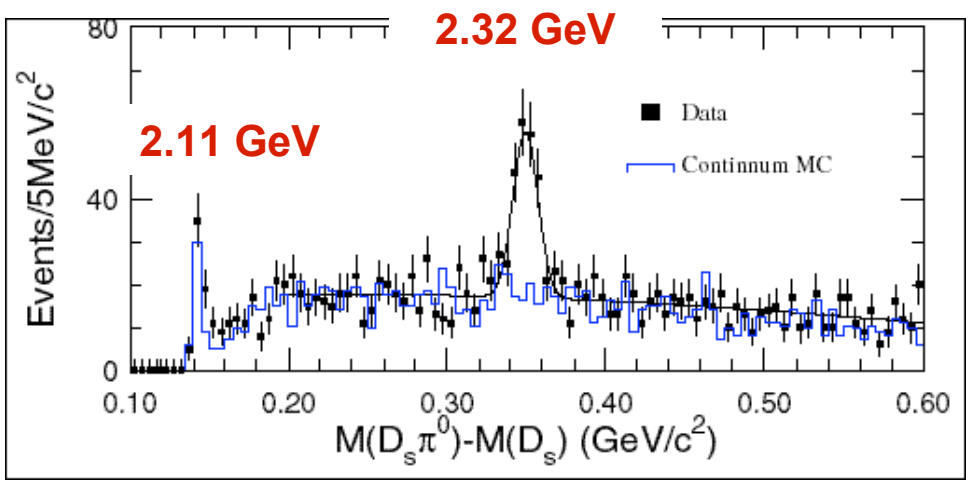
σ = (8.8 ± 1.1) MeV/c^2

$D_s^+ \to K^+K^-\pi^+\pi^0$



Confirmation of $D_{sJ}(2317)$ by CLEO and Belle

CLEO 13.5 fb^{-1} hep-ex/0305017



165 ± 20 evts

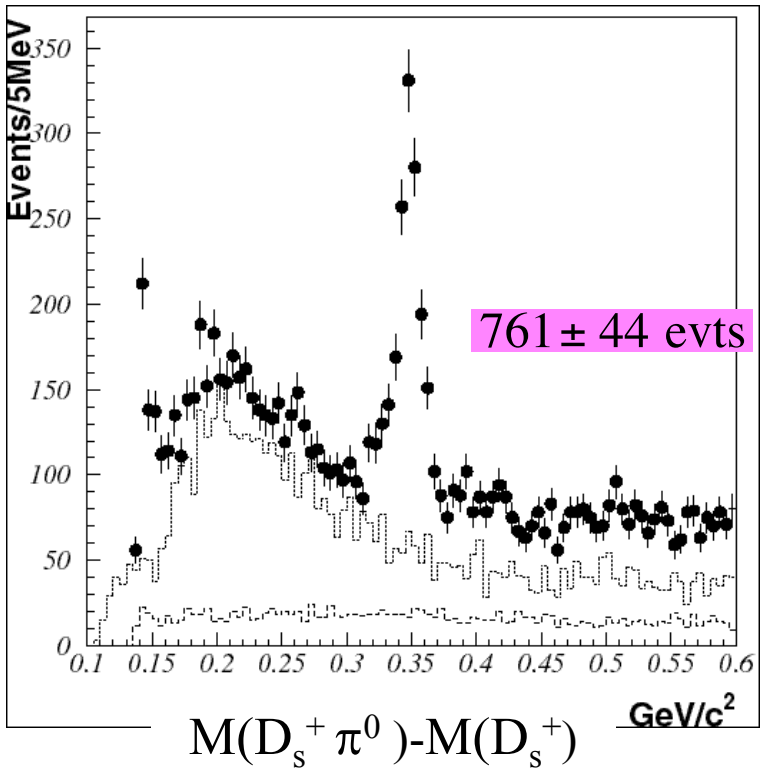
$$\Delta M = 350.4 \pm 1.2 \pm 1.0 \text{ MeV}/c^2$$

$$M = 2318.5 \pm 1.2 \pm 1.0 \text{ MeV}/c^2$$

$$\Gamma = 8.4^{+1.4}_{-1.2} \text{ MeV}/c^2$$

$$\Gamma_{\text{det}} = 6.4 \pm 0.4 \text{ MeV}/c^2$$

Belle 86.9 fb^{-1} hep-ex/0307052



$$\Delta M = 348.7 \pm 0.5 \pm 0.7 \text{ MeV}/c^2$$

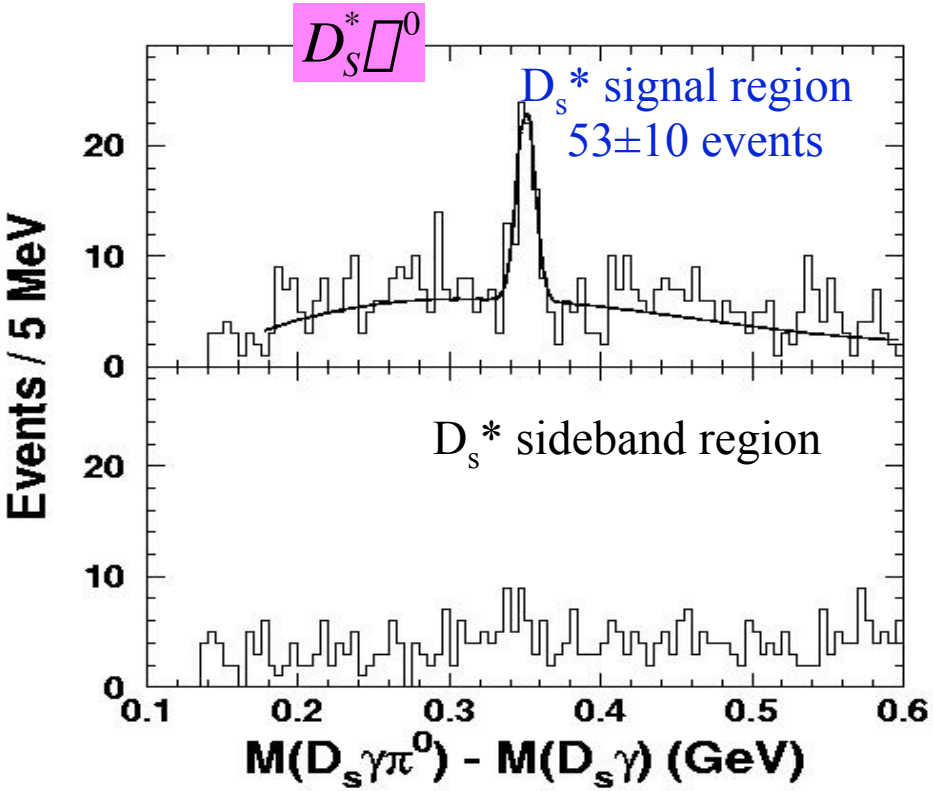
$$M = 2317.2 \pm 0.5 \pm 0.9 \text{ MeV}/c^2$$

$$\Gamma = 7.6 \pm 0.5 \text{ MeV}/c^2$$

Note $M < M_{D^0}(1864.5) + M_K(494) = 2358.5 \text{ MeV}/c^2$

The New Narrow Sate at 2460 MeV/c² in M($D_s\pi^0\gamma$)

CLEO 13.5 fb^{-1} hep-ex/0305017

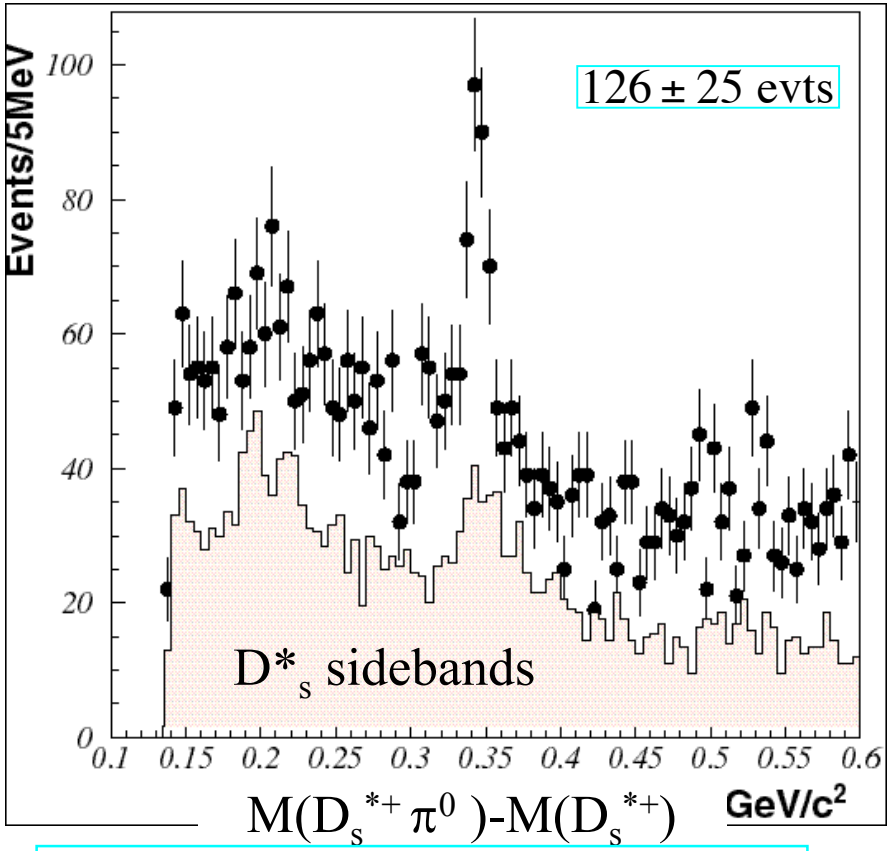


$$\Delta M = 351.2 \pm 1.7 \pm 1.0 \text{ MeV}/c^2$$

$$M = 2463.1 \pm 1.7 \pm 1.2 \text{ MeV}/c^2$$

$$\Gamma < 7 \text{ MeV}/c^2$$

Belle 86.9 fb^{-1} hep-ex/0307052

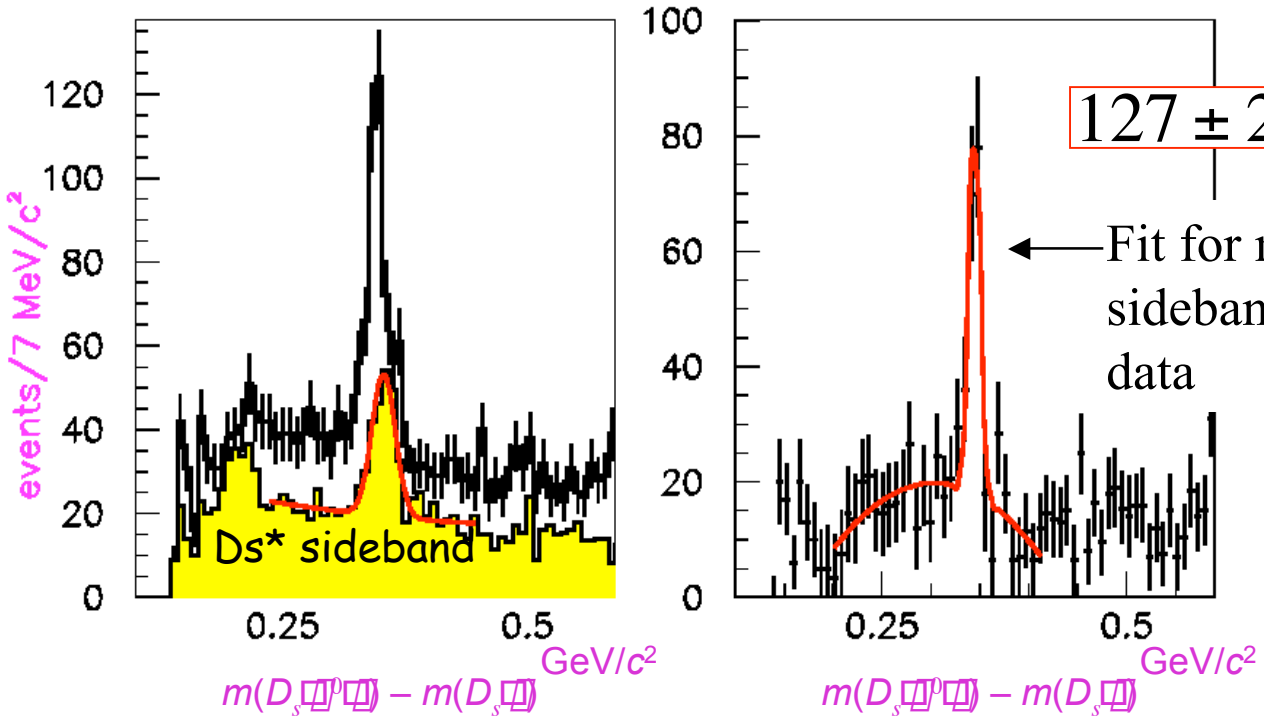


$$\Delta M = 344.1 \pm 1.3 \pm 0.9 \text{ MeV}/c^2$$

$$M = 2456.5 \pm 1.3 \pm 1.1 \text{ MeV}/c^2$$

$$\Gamma = 5.8 \pm 1.3 \text{ MeV}/c^2$$

BaBar presented $D_s^*\gamma^0$ peak near 2460 in their original publication, but did not claim a signal. Recently agreed that it was a signal.



127 ± 22 evts

Fit for mass to sideband subtracted data

$$\Delta M = 344.6 \pm 1.2 \pm 3 \text{ MeV}/c^2$$

$$M = 2457.0 \pm 1.4 \pm 3 \text{ MeV}/c^2$$

BaBar 91fb^{-1} preliminary

Note $M < M_{D^{*0}}(2006.7) + M_K(494) = 2500.7 \text{ MeV}/c^2$

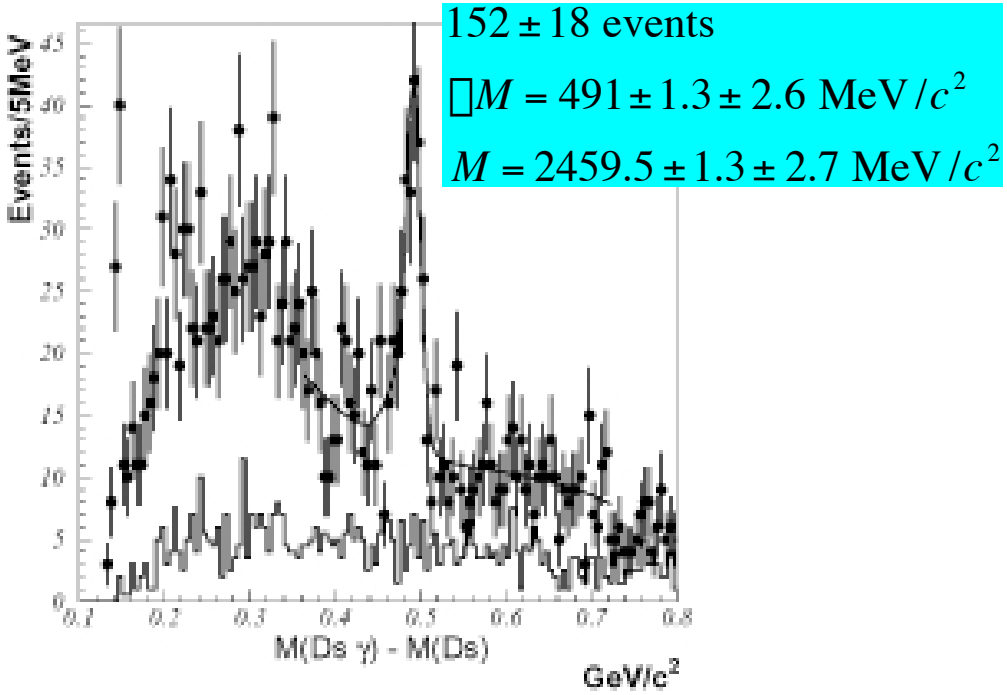
Spin - parity of New Narrow States at 2317 and 2460

$D_{SJ}(2317) \to D_S(0^{\square})\pi^0(0^{\square}) \to$ most likely 0^+

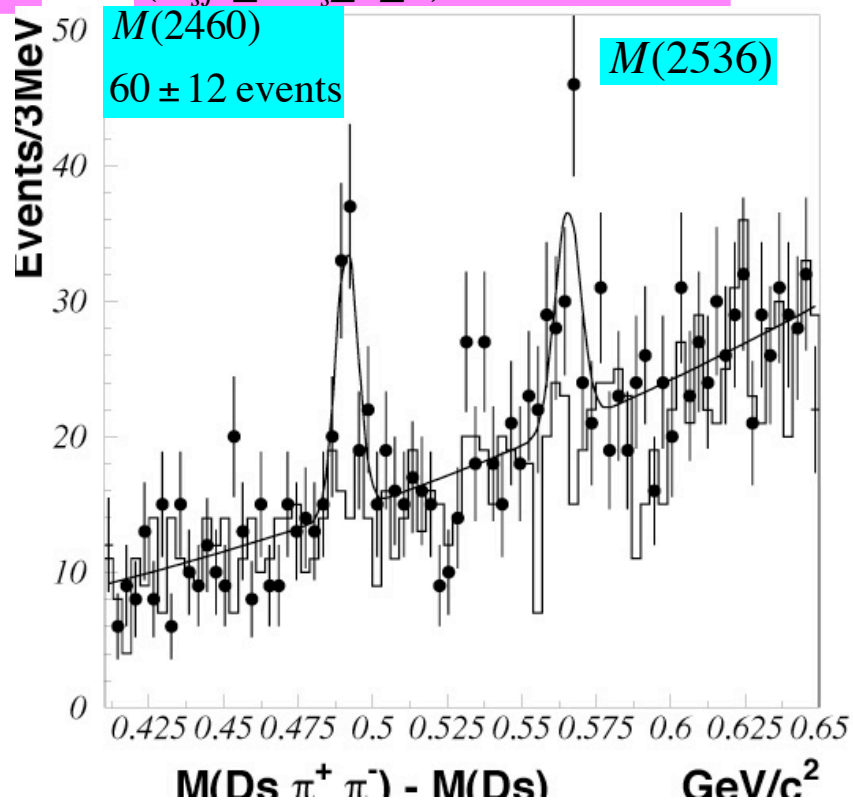
$D_{SJ}(2460) \to D_S^*(1^{\square})\pi^0(0^{\square}) \to$ most likely 1^+

Belle continuum analysis

Radiative decay ($D_{SJ} \to D_S\gamma$) is allowed for $0^{\square}$ and 1^+, but forbidden for 0^+ and $1^{\square}$.



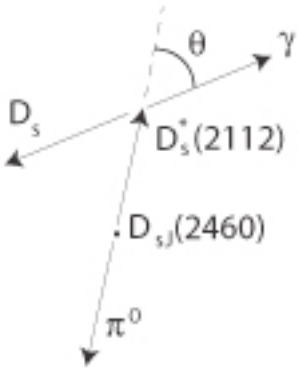
Same is true for dipion decays ($D_{SJ} \to D_s\pi^+\pi^-$).

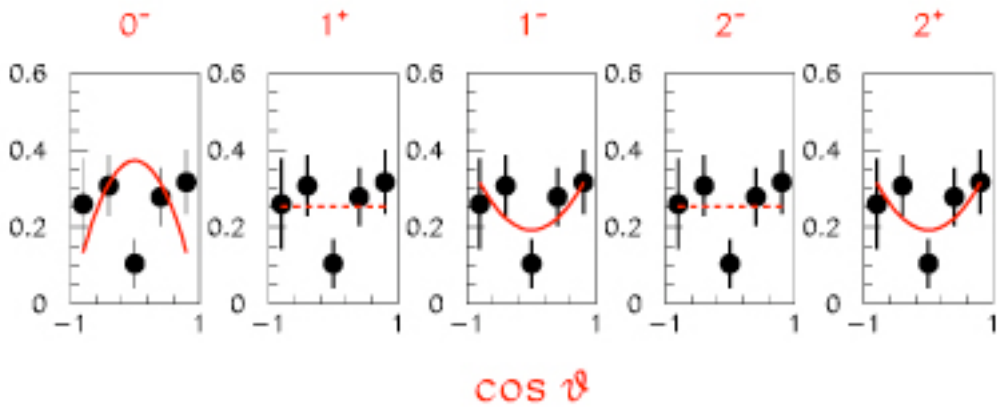


$D_{sJ}(2460) \to D_s\gamma$ observed. $\to 0^-, 1^+$

$D_{sJ}(2317) \to D_s\gamma$ not observed. $\to 0^+, 1^{\square}$

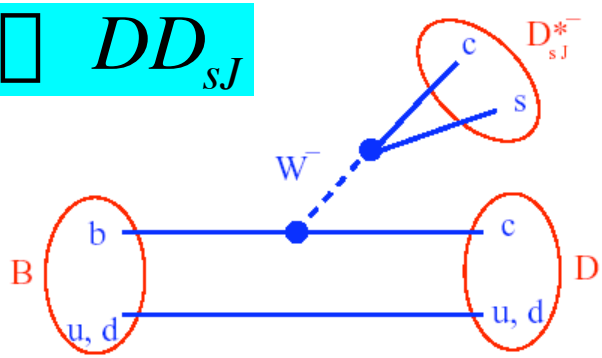
Helicity angle in $D_{sJ}(2460) \to D_s^*(2112)\pi^0$, $D_s^*(2112)\pi^0 \to D_s\gamma$ (BaBar preliminary)
Inconsistent with $J^P = 0^-$. [nb: no prediction for 1^+, 2^-.]





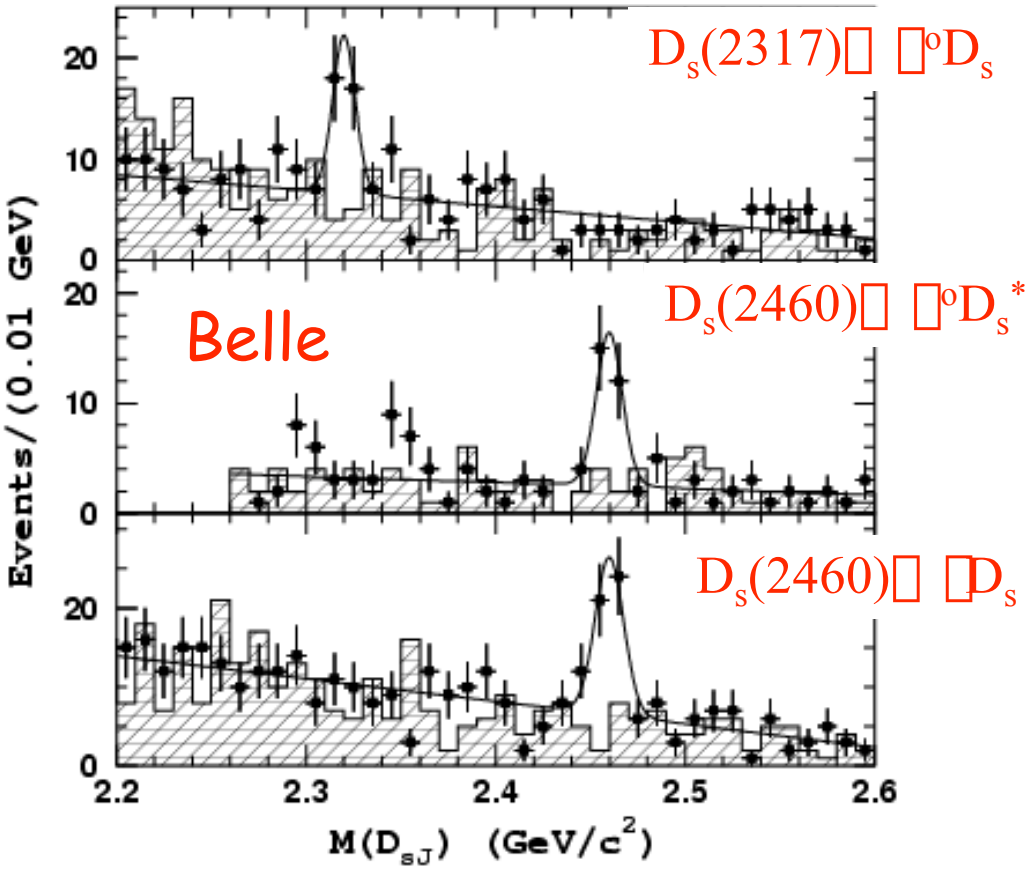
Belle observes the two states in B decays

$B \to D D_{sJ}$



based on 123.7 million BBbar events

efficiency ~ 10^{-4}



$$\to \quad Br = \left(8.5^{+2.1}_{-1.9} \pm 2.6\right) \times 10^{-4}$$

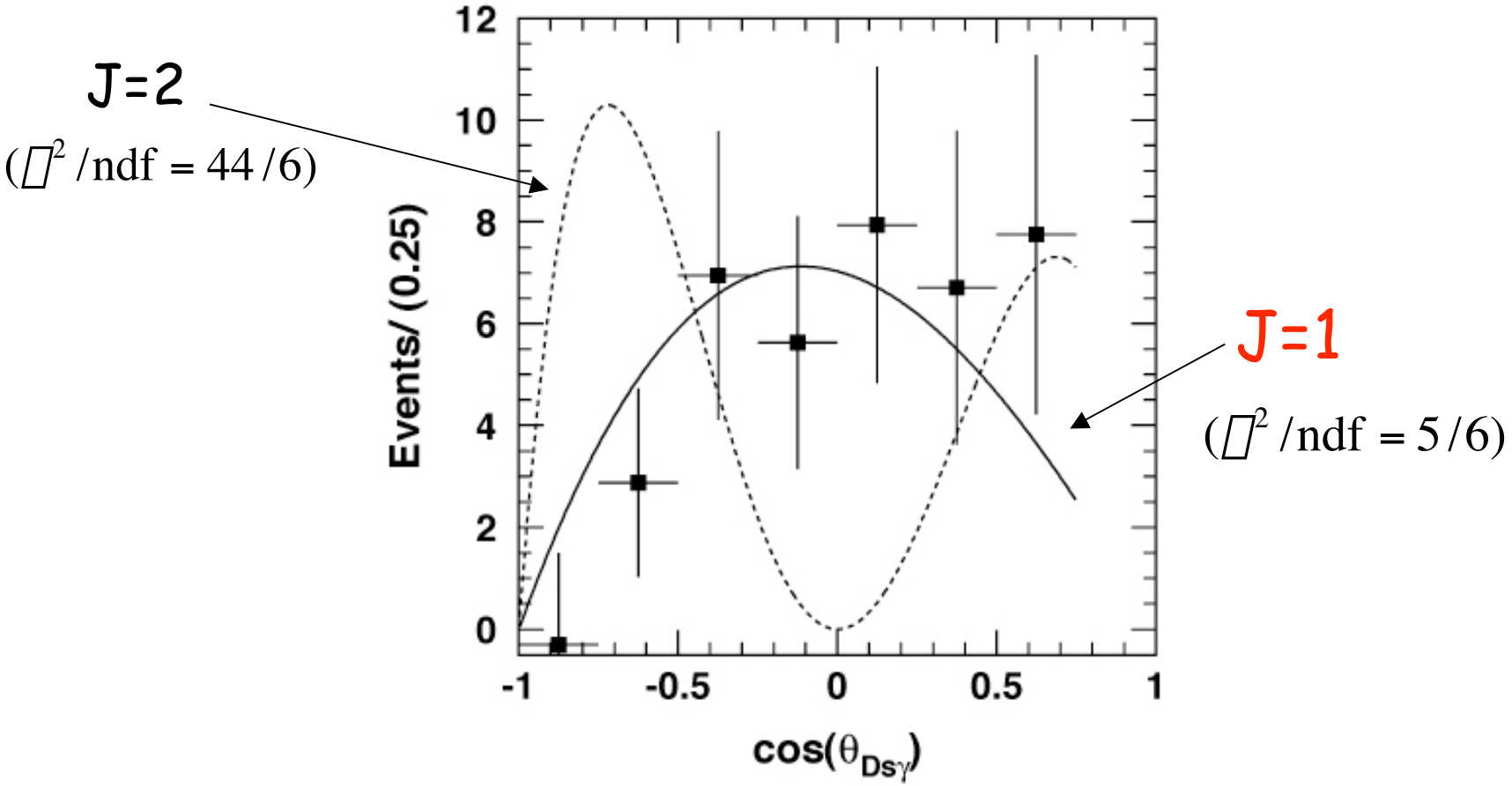
$$\to \quad Br = \left(17.8^{+4.5}_{-3.9} \pm 5.3\right) \times 10^{-4}$$

$$\to \quad Br = \left(6.7^{+1.3}_{-1.2} \pm 2.0\right) \times 10^{-4}$$

hep-ex/0307041

Belle Angular analysis in B to $DD_{sJ}(2460) \to DD_s\gamma$

Helicity angle consistent with 1^+ (angle of D_s in D_{sJ} restframe wrt to D_{sJ} direction in B rest frame)



Summary of p-wave charm mesons

- Broard, as expected, j=1/2 $c\bar{u}$ doublets observed :

$$D_0^{*0}(2308) \;\; \& \;\; D_1^{0'}(2427)$$

- Narrow, unexpected, $c\bar{s}$ states observed and their spin-parity determined :

$$D_{sJ}(2317) = D_{s0}^{*+}(2317)$$

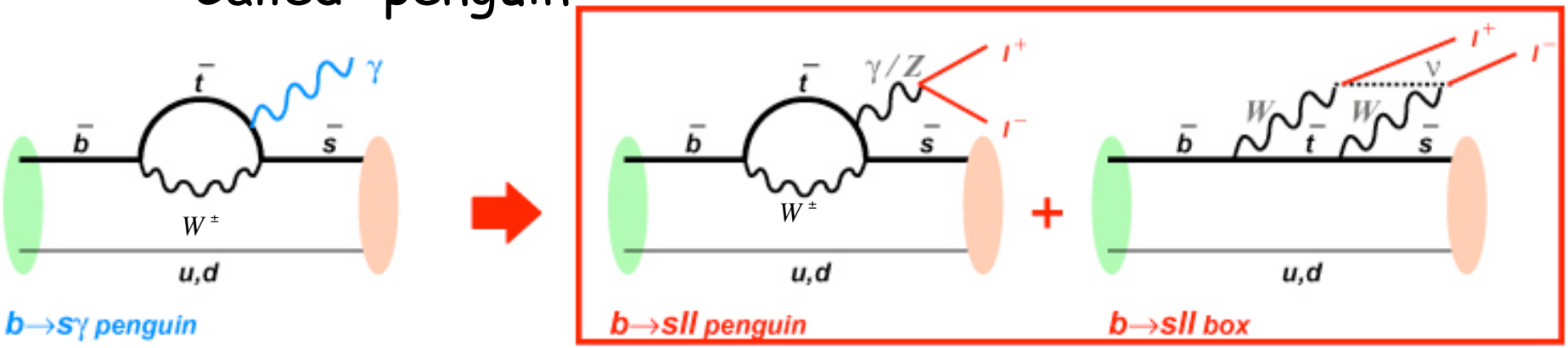
$$D_{sJ}(2460) = D_{s1}^{+}(2457)$$

QCD potential models need to reconcile with the above experimental findings.

Electroweak Penguin Decays

$b \to s\gamma$ and $b \to s\ell^+\ell^-$ decays proceed through flavor changing neutral current (FCNC) diagrams.

Called "penguin"



$Br(b \to s\gamma) \sim 3.4 \times 10^{-4}$

$Br(b \to s\ell^+\ell^-) \sim \alpha_{em} Br(b \to s\gamma) \sim 10^{-6}$

Very rare !!

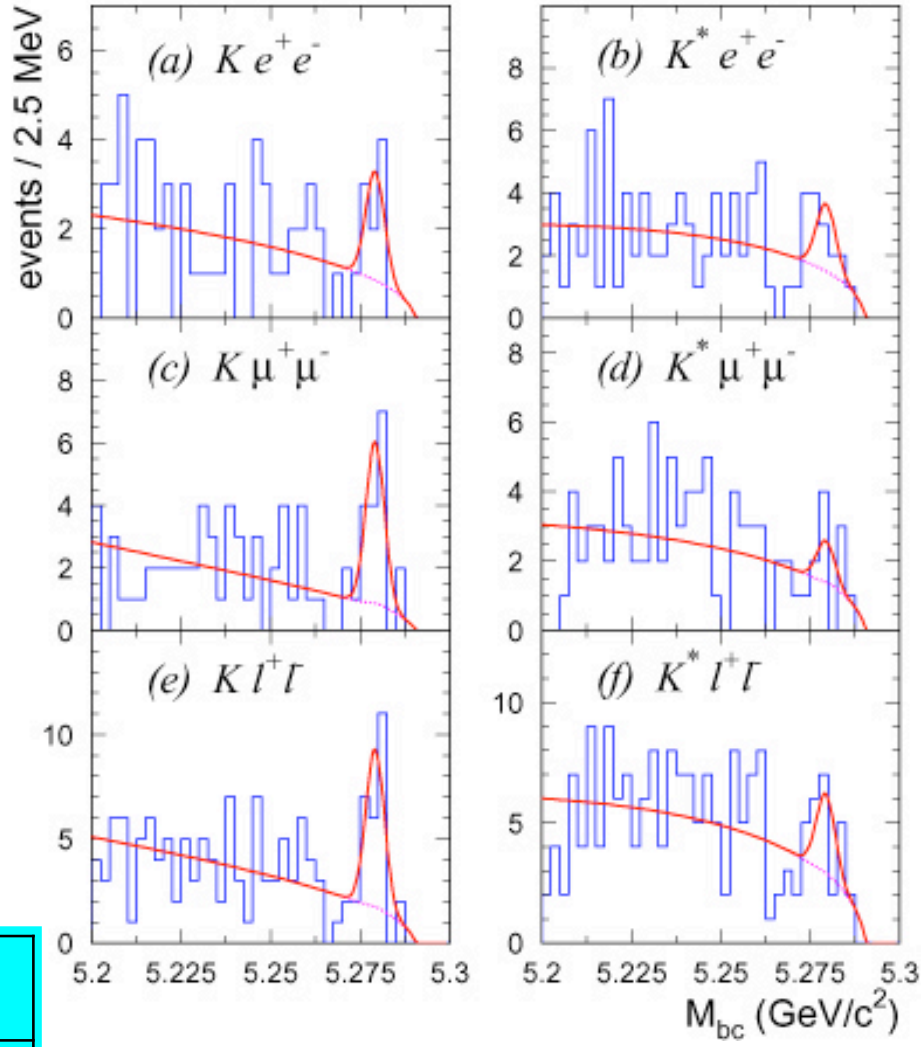
New particles can contribute to the decay rate via loops. "Search for new physics using quantum (penguin) loop effects."

B to Kll first seen by Belle in 2001. (PRL88, 021801 (2002))

Belle 60fb^{-1} (2002) update

- 142 fb^{-1} = 152million BBbar update next week -

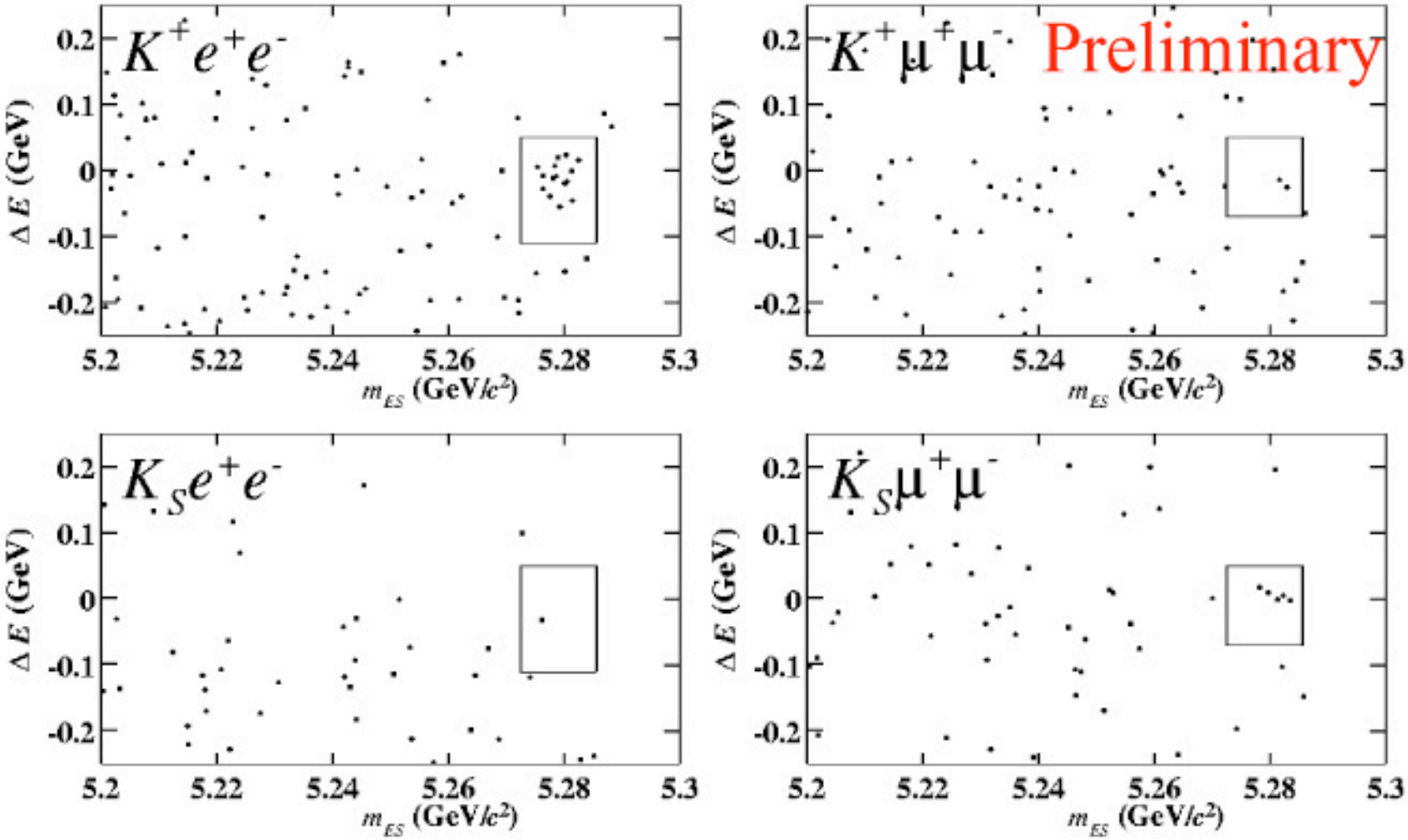
- K: $K^{\pm}$ or K_S^0
- K^*: $K^+\pi^-$, $K_S^0\pi^+$, $K^+\pi^0$ with $|m_{K\pi} - m_{K^*}| < 75\ \mathrm{MeV}/c^2$
- a pair of e or μ
  $p(e) > 0.5\ \mathrm{GeV}/c$
  $p(\mu) > 1.0\ \mathrm{GeV}/c$
  $m_{\ell\ell} > 0.2\ \mathrm{GeV}/c^2$
- Veto J/ψ, $\psi(2S)$



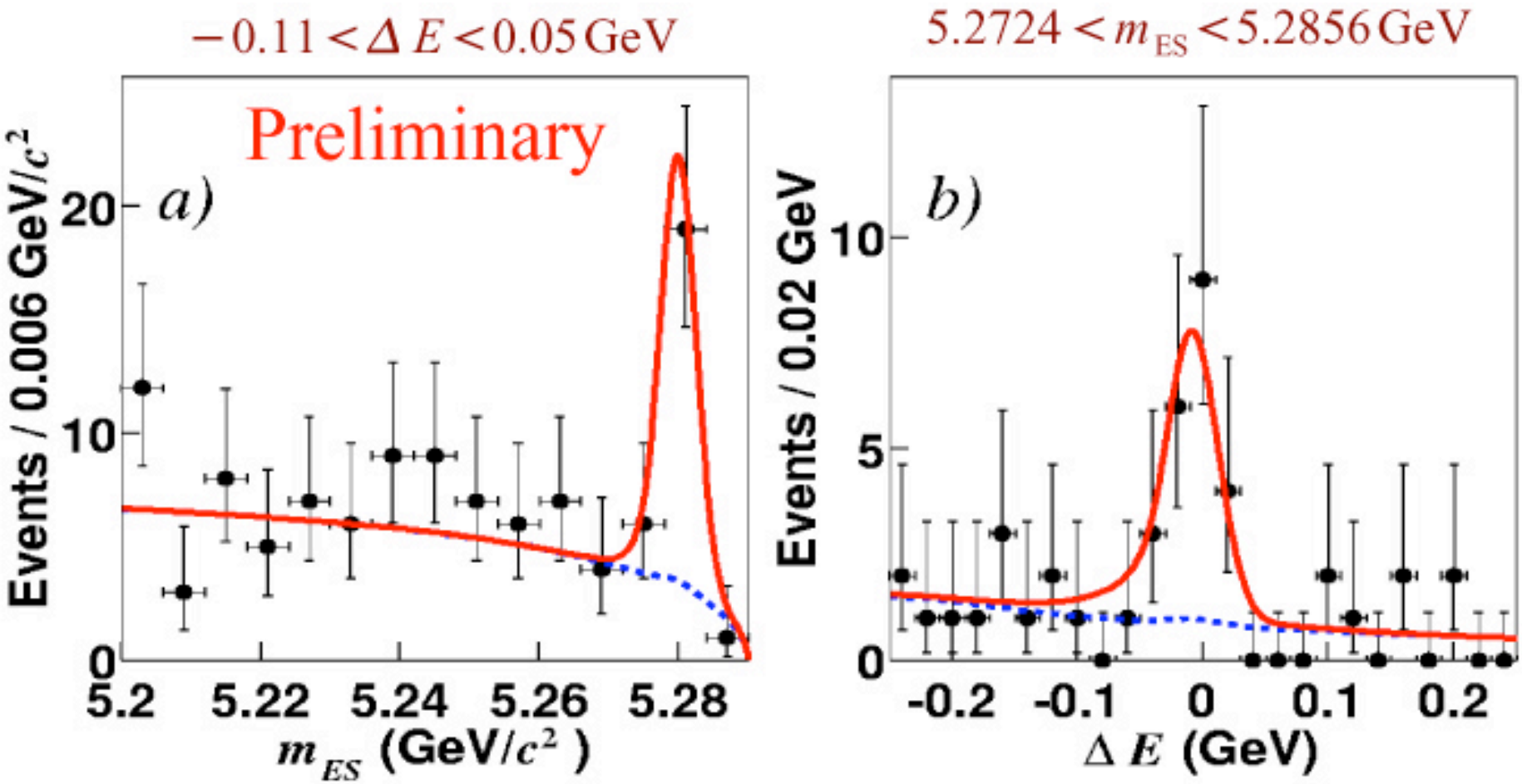
$B \to K\ell\ell$	$\left(0.58^{+0.17}_{-0.15} \pm 0.06\right) \times 10^{-6}$
$B \to K^*\ell\ell$	$< 1.4 \times 10^{-6}$

BaBar 88.5 million BBbar data

ΔE vs. m_{ES} in the $B \to K l^+ l^-$ modes

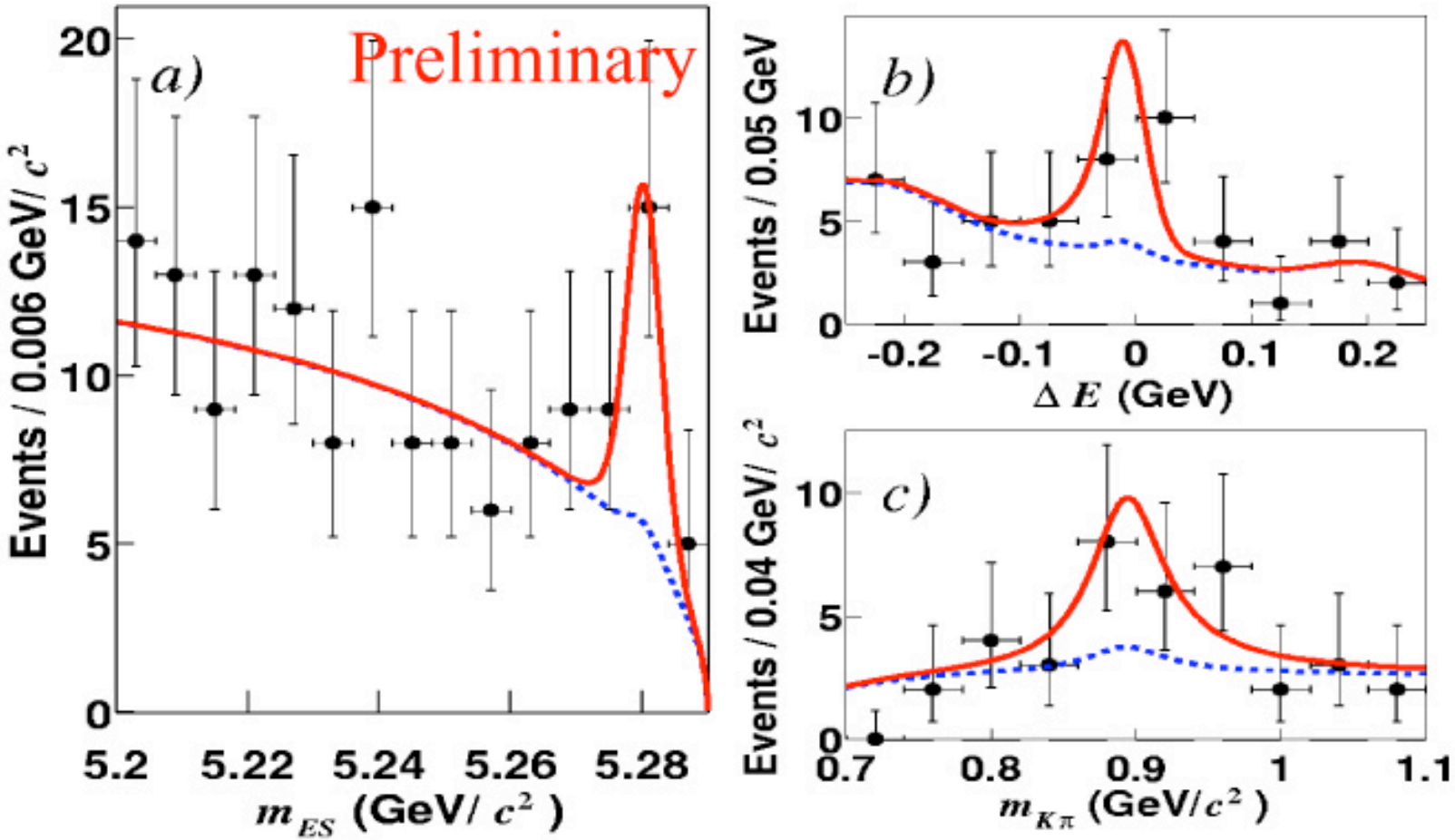


BaBar 81fb^{-1} (88.5 million BBbar) data



$$Br(B \to K l^+ l^-) = (0.68^{+0.17}_{-0.15} \pm 0.04) \times 10^{-6} \quad (7\sigma)$$

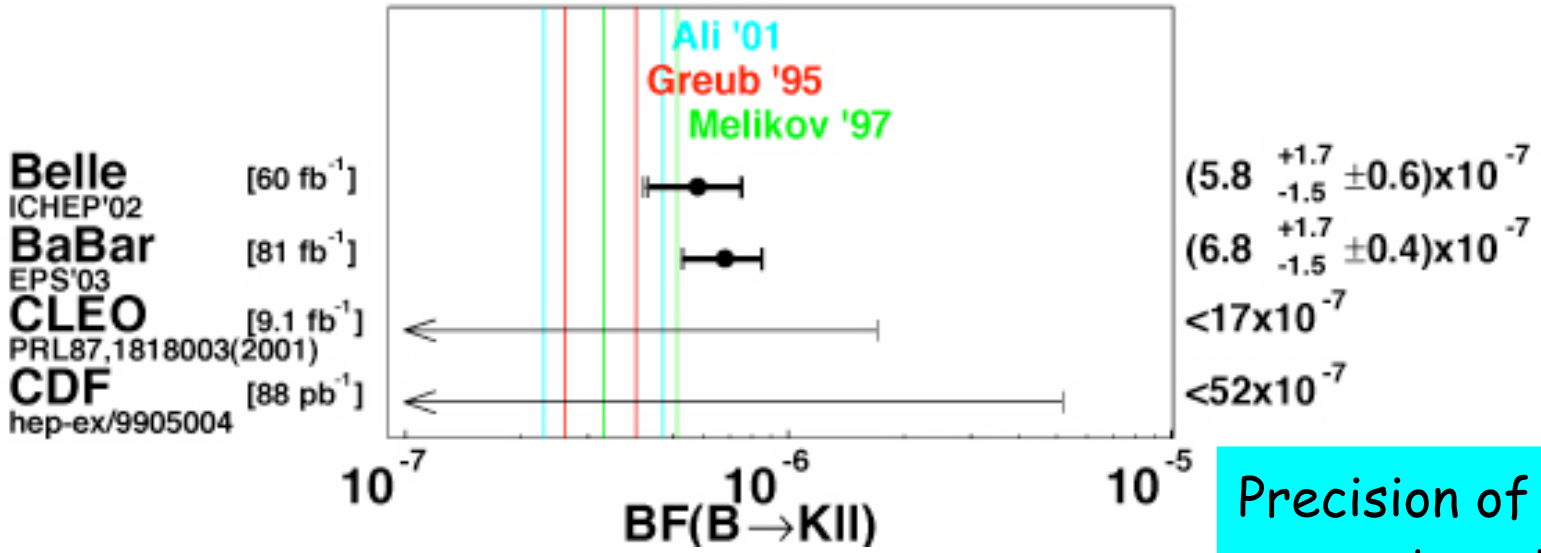
First evidence for B to K*ll seen by BaBar



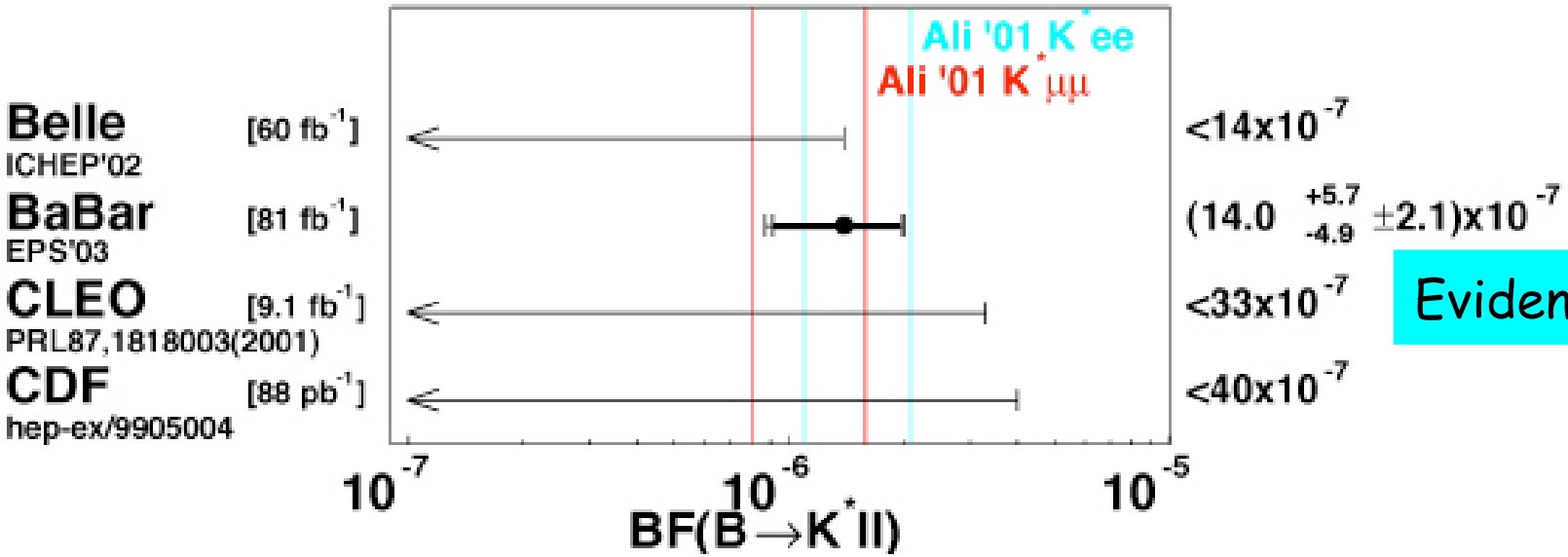
$$Br(B \to K^* l^+ l^-) = (1.40^{+0.57}_{-0.49} \pm 0.21) \times 10^{-6} \quad (3.0\sigma)$$

$$Br(B \to K^* l^+ l^-) \equiv Br(B \to K^* e^+ e^-) = 1.33 Br(B \to K^* \mu^+ \mu^-) \quad (\text{Ali 'et al 2001})$$

$B \to K, K^* \ell^+ \ell^-$ results



Precision of B to KII is as good as theory.



Evidence seen.

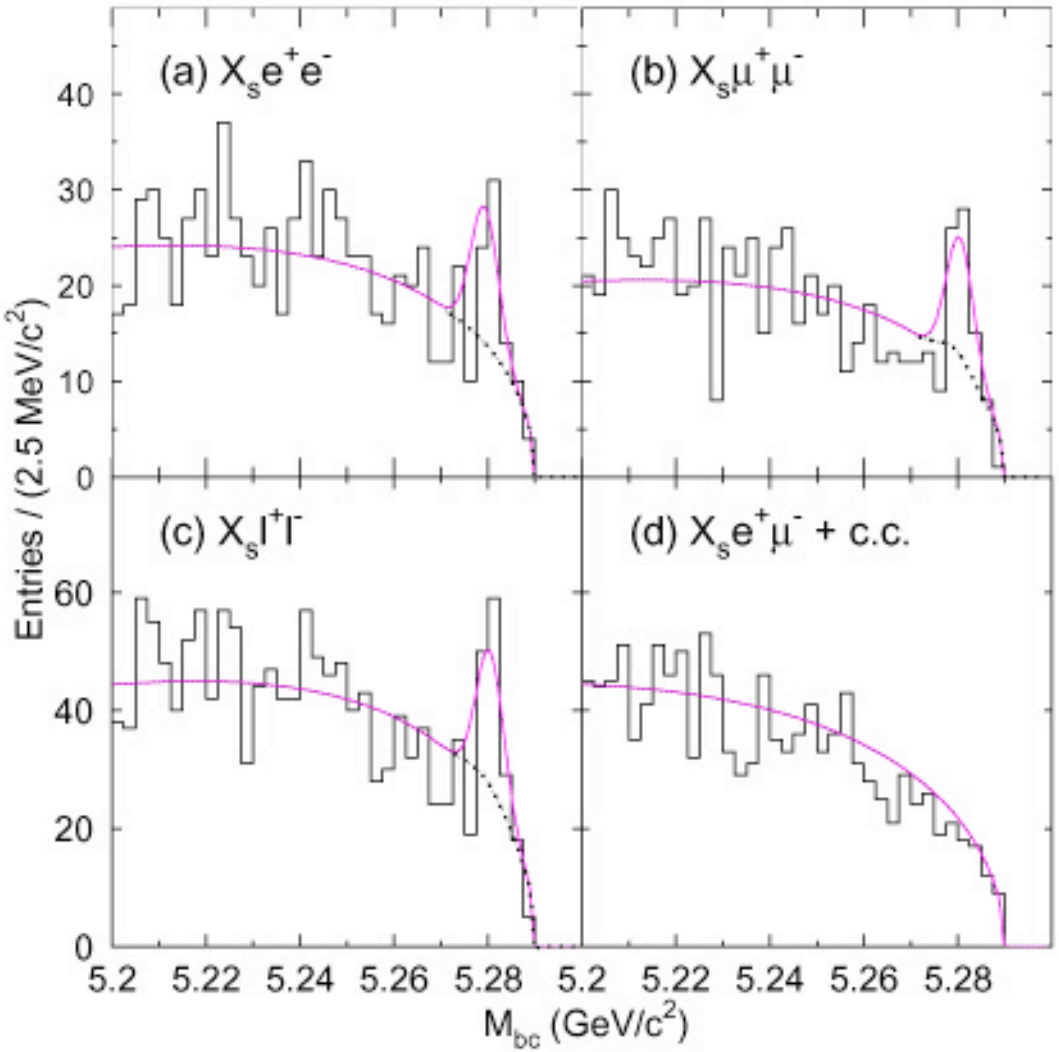
First measurement of semi-inclusive B to Xsll by Belle

- X_s:
  - 1 $K^{\pm}$ or K_S^0
  - 0–4 π ($\leq 1\ \pi^0$)
  - $m_{X_s} < 2.1\ \mathrm{GeV}/c^2$
- a pair of e or μ

  $p(e) > 0.5\ \mathrm{GeV}/c$

  $p(\mu) > 1.0\ \mathrm{GeV}/c$

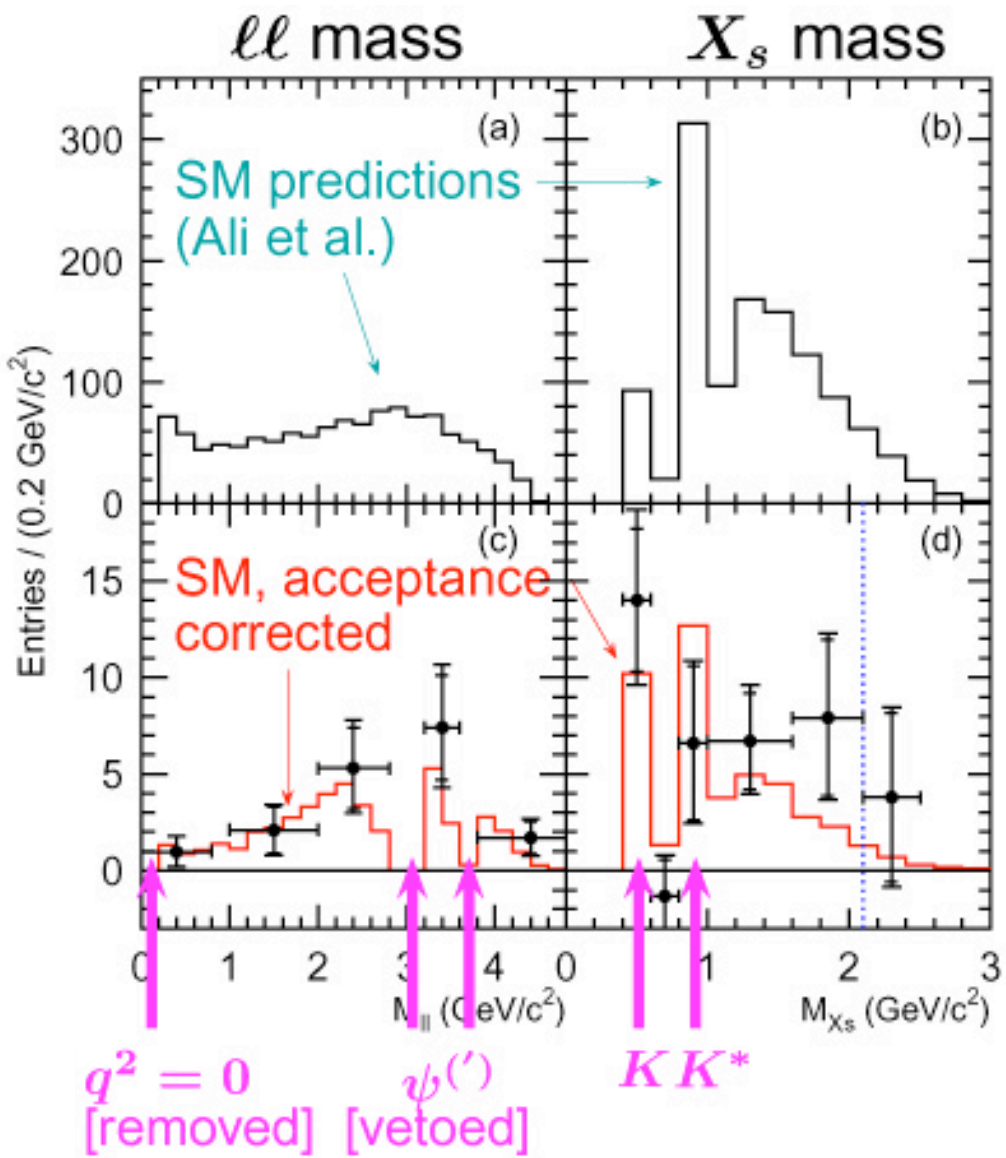
  $m_{\ell\ell} > 0.2\ \mathrm{GeV}/c^2$
- J/ψ, $\psi(2S)$ are vetoed



60 fb^{-1}

Clear signal (5.4□)

Semi-inclusive B to Xsll by Belle



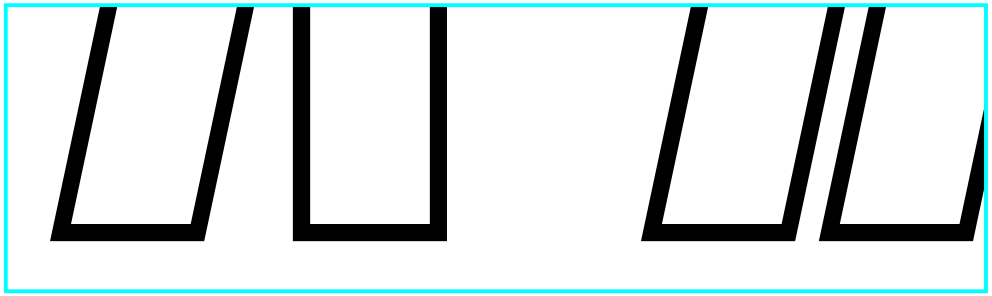
First measurement, using 60 fb^{-1}

	BR in 10^{-6}
$\mu\mu$	$7.9 \pm 2.1 \,^{+2.1}_{-1.5}$
ee	$5.0 \pm 2.3 \,^{+1.3}_{-1.1}$
$\ell\ell$	$6.1 \pm 1.4 \,^{+1.4}_{-1.1}$

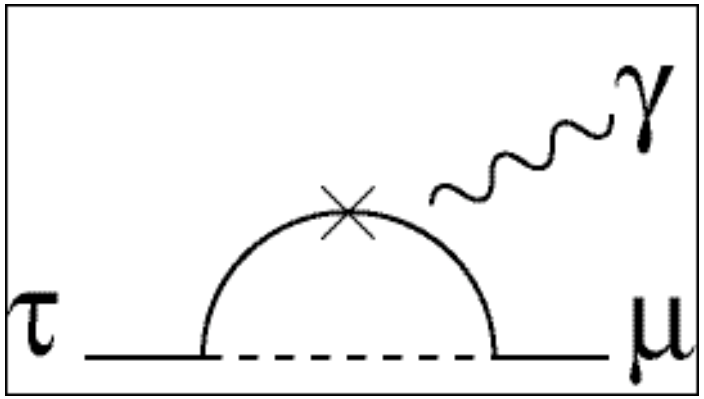
[Phys.Rev.Lett.90,021801(2003)]

K and K^* yields are compatible with exclusive analysis

Presence of electroweak penguin established. More data to look for a sign of new physics.



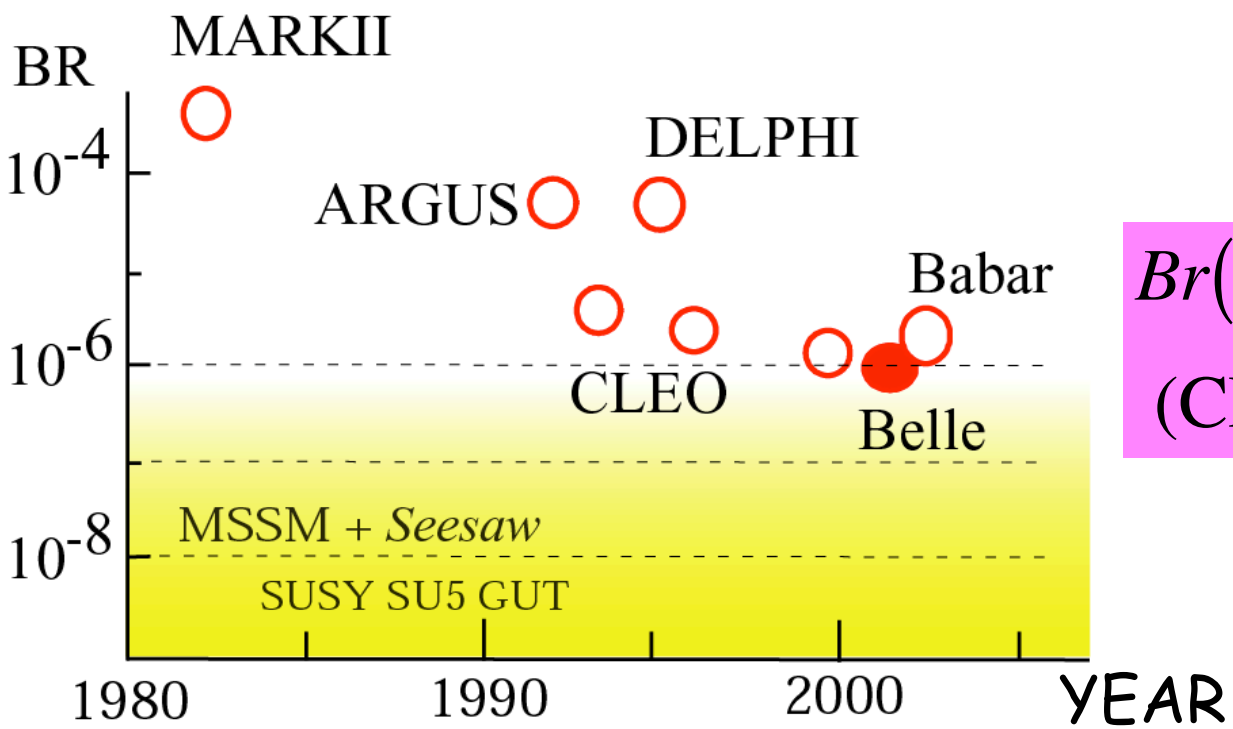
Lepton Flavor Violating Decay of τ Lepton



Similar to b to $s\gamma$, but highly suppressed.

SUSY predicts Br~10^{-7} to 10^{-9}

$$Br(\tau \to \mu\gamma) \sim 10^{5-6} \times Br(\tau \to e\gamma)$$



$$Br(\tau \to \mu\gamma) < 1.1 \times 10^{-6}$$

(CLEO@13.8fb^{-1})

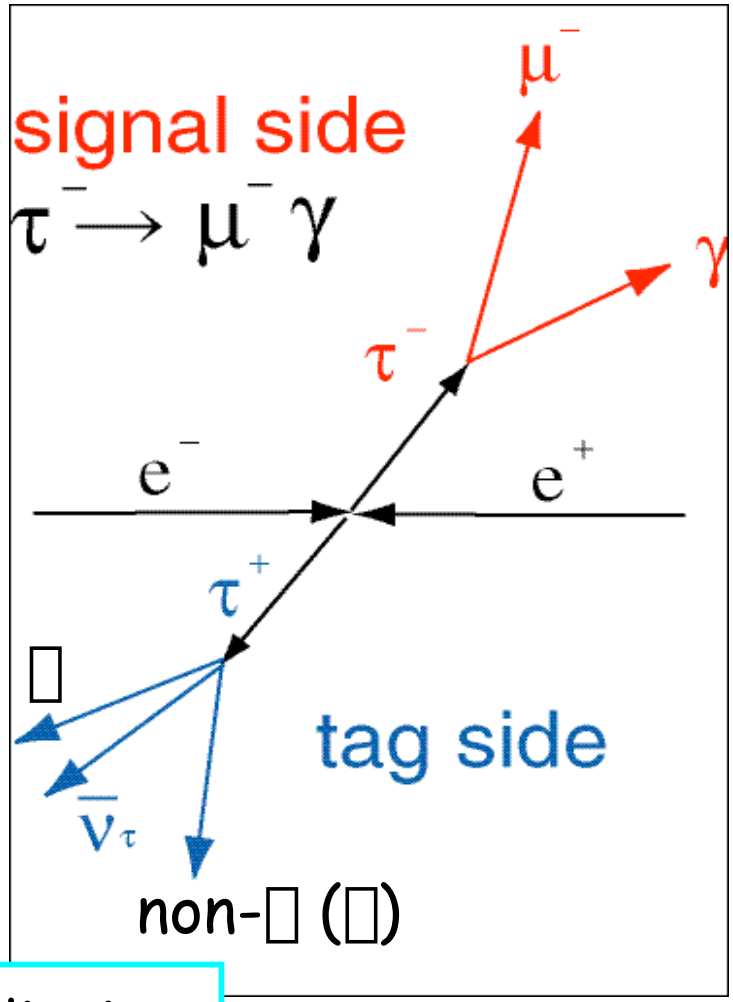
Belle □□ □□Search

Two oppositely charged particles plus 1 or more photons consistent with

□□ □□and

□□ non□+ □+ (0 or more) □s

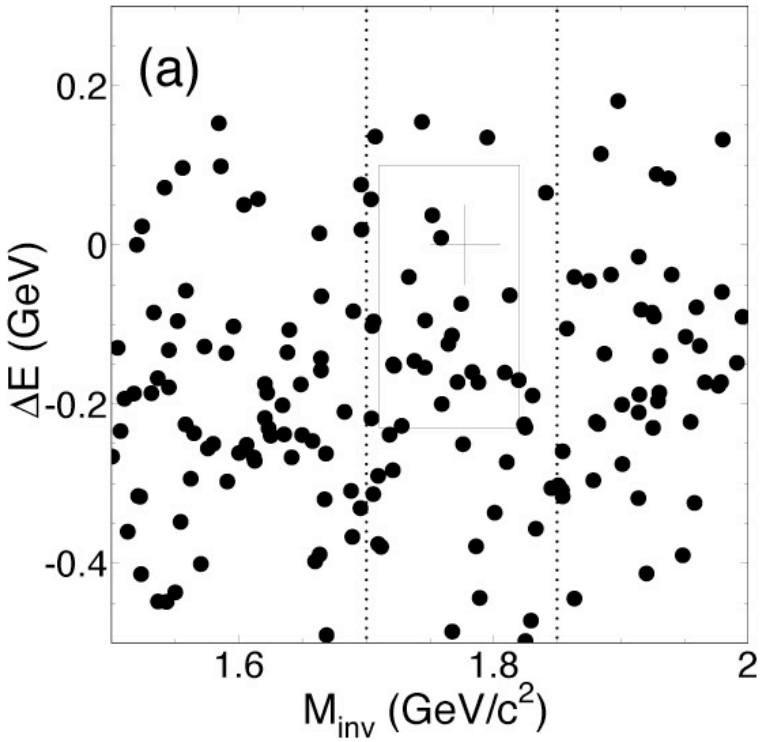
Difficulty of this analysis is due to a large amount of background mostly from $e^+e^- \to \tau^+\tau^-\gamma$ and $\tau^+\tau^-\gamma$



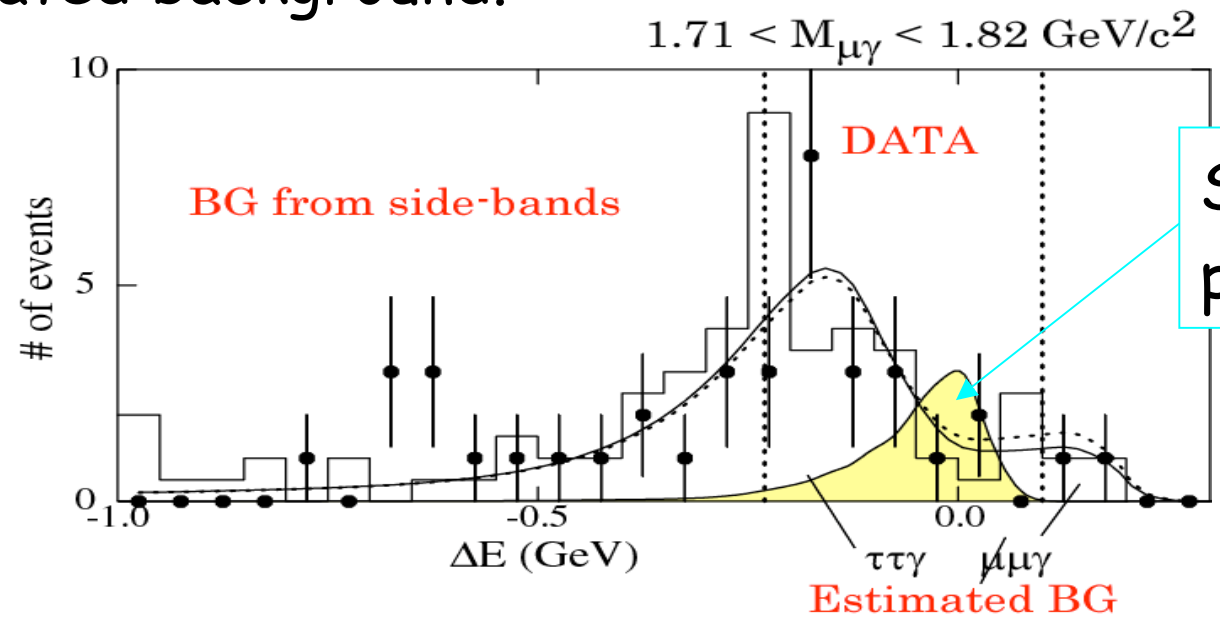
Photons are from the initial state radiation.

Impose presence of neutrino. $m_\tau^2 = E_{miss}^2 - \mathbf{p}_{miss}^2 = 0$

Belle 86.3 fb^{-1}(78.5million □-□bar pairs) analysis



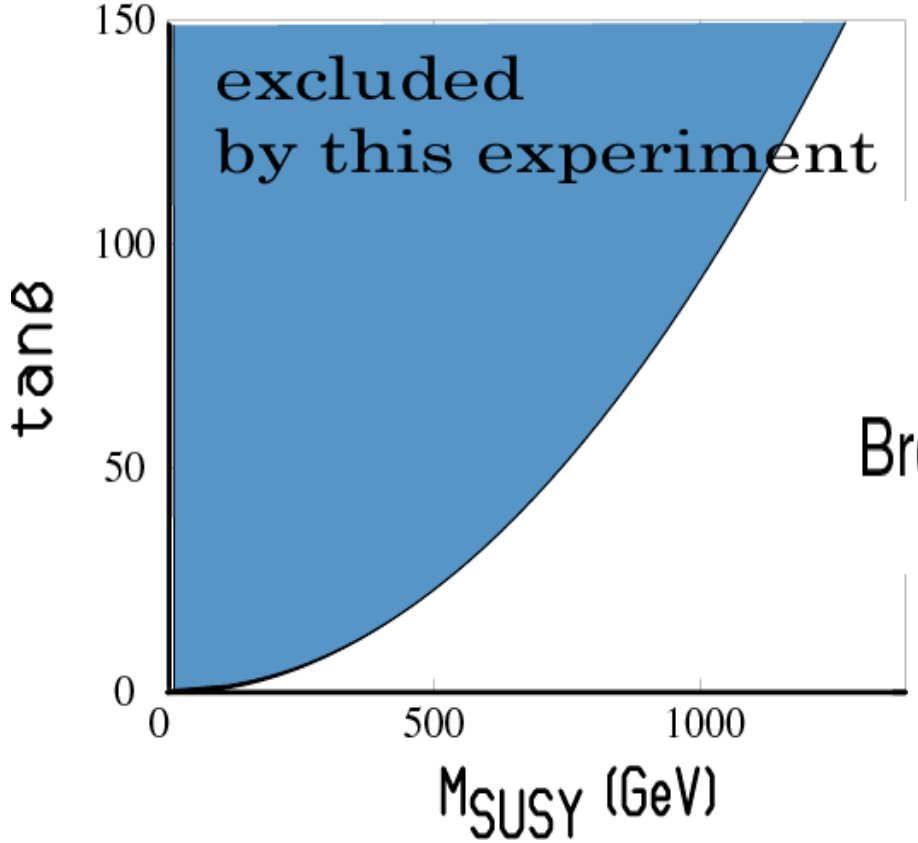
Remaining candidates in a signal region is consistent with the estimated background.



Signal would populate here.

Belle 86.3 fb^{-1} analysis

$$Br(\tau \to \mu\gamma) < 3.2 \times 10^{-7} \ (@90\%CL)$$



Dedes, J. Ellis, and M. Raidal, PL B549, 159 (2002)

$$Br(\tau \to \mu\gamma) = 1.3 \times 10^{-3} \left(\frac{\tan\beta}{60}\right)^2 \left(\frac{100\ \text{GeV}}{M_{SUSY}}\right)^4$$

Conclusion

- B factory is charm factory :

$$D_0^{*0}(2308) \quad \& \quad D_1^{0'}(2427)$$

$$D_{sJ}(2317) = D_{s0}^{*+}(2317)$$

$$D_{sJ}(2460) = D_{s1}^{+}(2457)$$

- B factory is penguin factory :

$b \to s\ell^+\ell^-$ established.

- B factory is tau factory.

New upper limit for $\tau \to \mu\gamma$