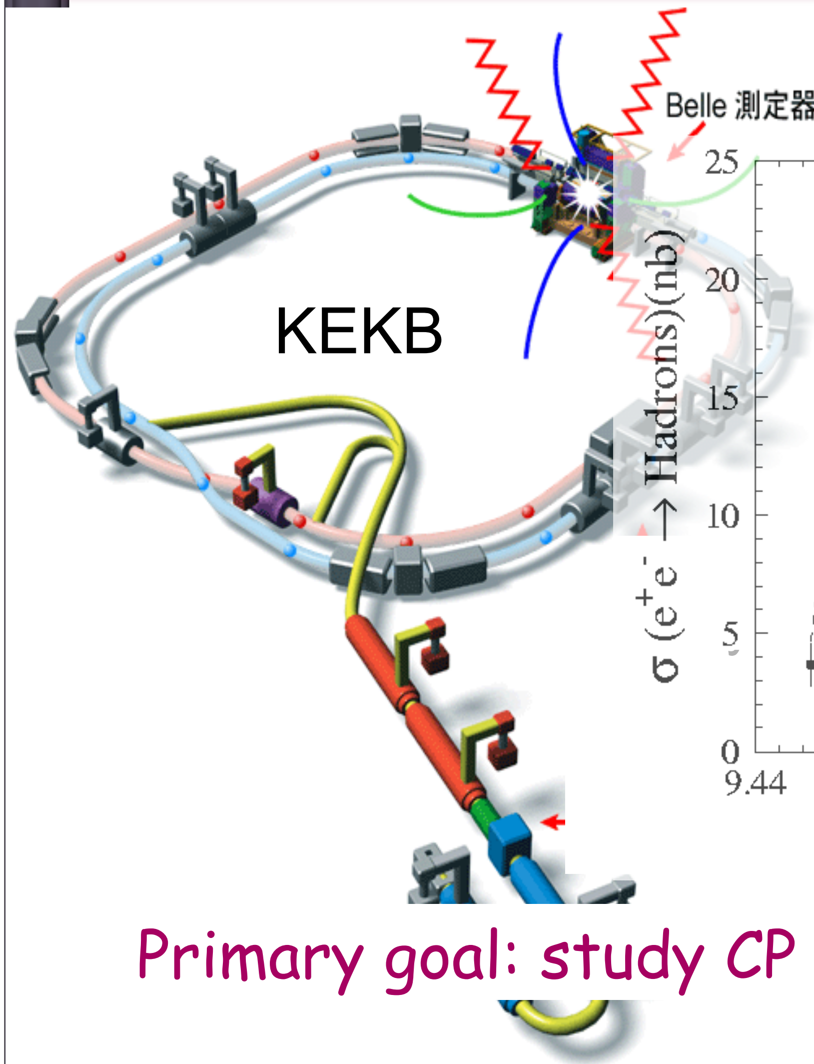
Rencontres de Moriond/Electroweak, March, 2010

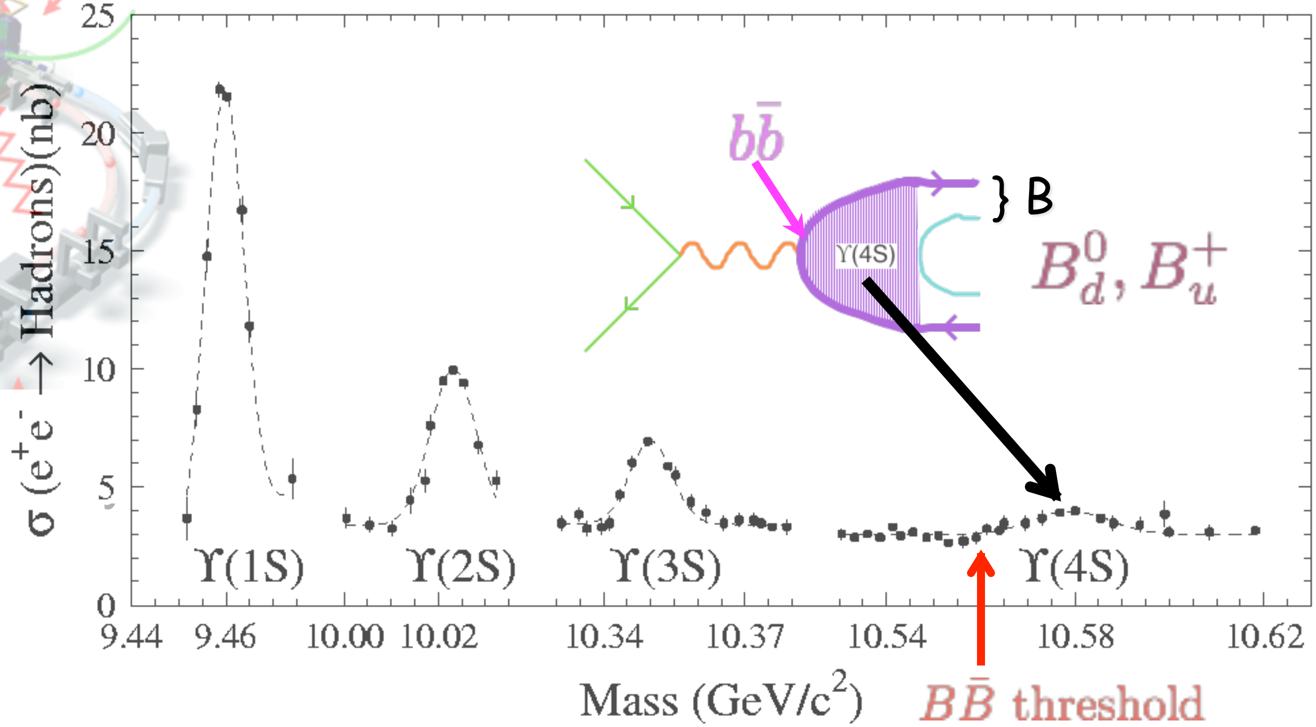
Strange Beauty and other Beasts from $\Upsilon(5S)$ at Belle

- $\Upsilon(5S)$ Resonance
  - motivation
  - data
  - recent results
  - outlook

K. Kinoshita
University of Cincinnati
Belle Collaboration

B factory: $e^+e^- \to \Upsilon(4S) \to B\bar{B}$



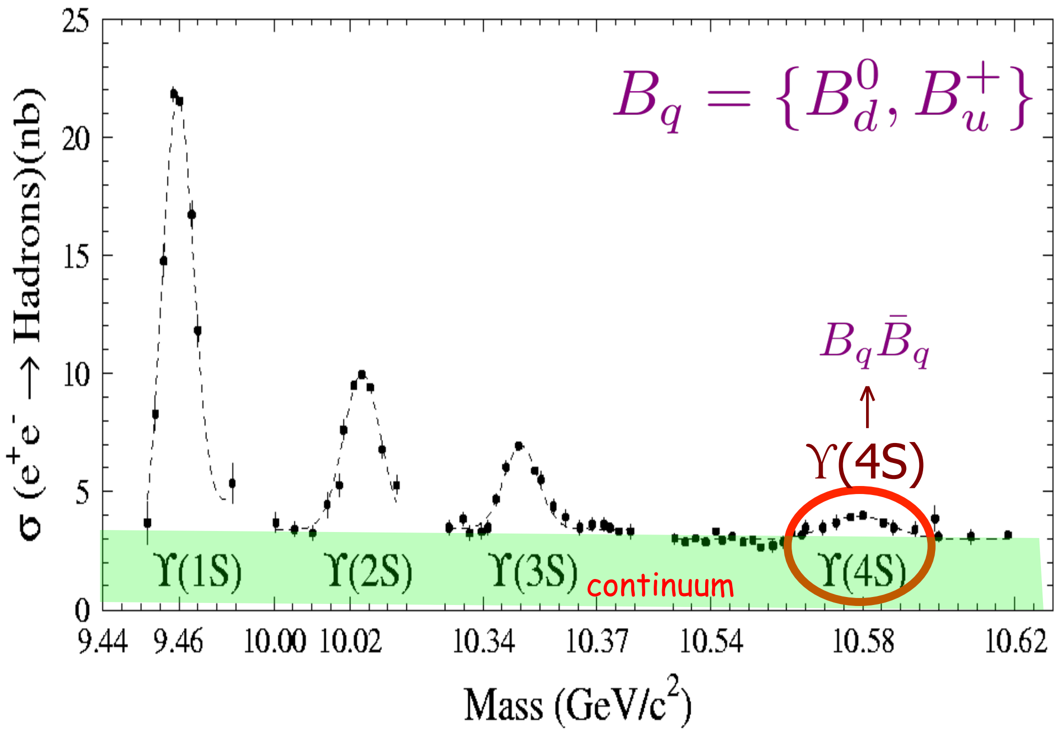


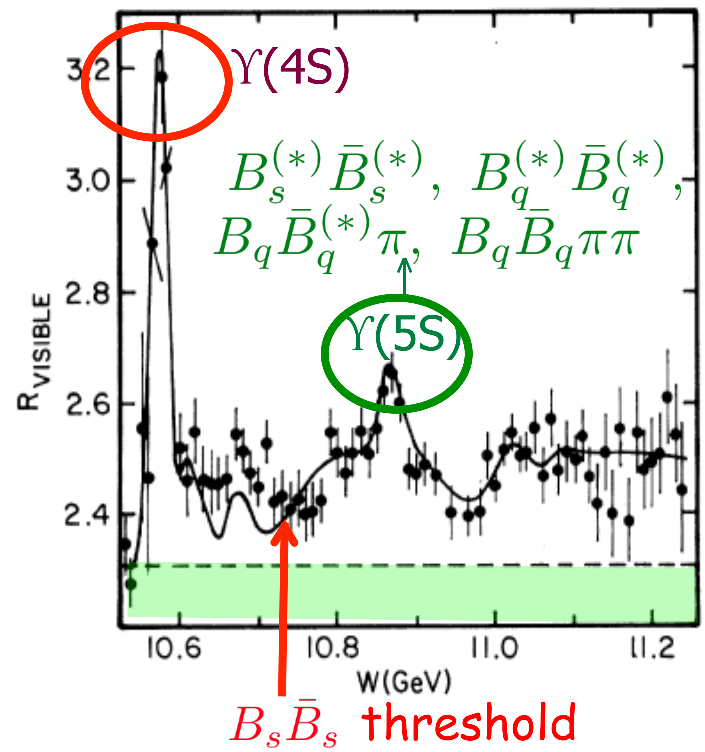
Primary goal: study CP violation in weak decays of B meson

DONE!

1000 fb^{-1} = 1 ab^{-1} recorded by Belle as of 12/09

BUT wait, more than Υ(4S) …. Υ(10860), or Υ(5S)





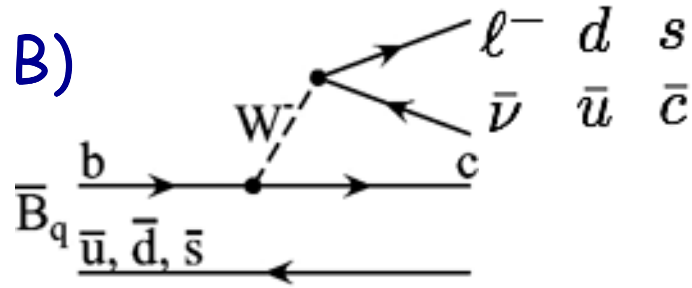
B_s are produced copiously in pp(bar) collisions (FNAL, LHC) –
can studying B_s at the Υ(5S) be competitive?

pro's

- CLEAN events, energy definition, γ's; ~100% trigger efficiency
- high luminosity, established detector, Υ(4S) data for comparison

B_s in Standard Model

- CP-asymmetry ~ 0 -> window to New Physics
- $\Delta\Gamma/\Gamma_{CP}/\Gamma=O(10\%)$
- Spectator decay (as w non-strange B)
  -> quark-hadron duality
- absolute BF's, modes w π^0, γ



spectroscopy

- $B_s^{(*)}$ mass
- $B_{(s)}^{(*)}(\pi)$ event fractions
- bottomonium, bottomonium-like states

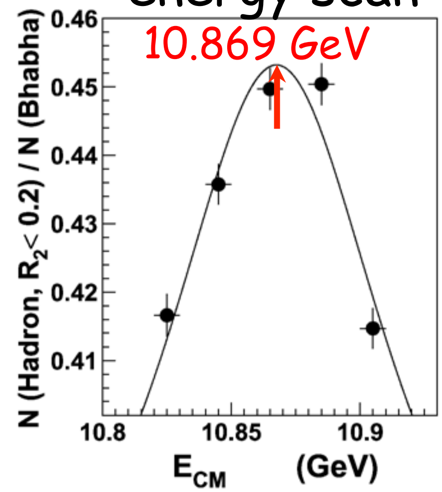
Data

June 2005: 3-day "engineering" run

- basic Υ(5S), $B_s^{(*)}$ properties,
- test KEKB at Υ(5S) - L_{max}~$1.39 \times 10^{34} cm^{-2} s^{-1}$
- 1.86 fb^{-1} at peak (10869 MeV)
  = 4 x largest previous sample (CLEO)

A. Drutskoy et al., PRL 98, 052001 (2007)
A. Drutskoy et al., PRD 76, 012002 (2007)

energy scan



June 2006: 20-day run

- + 21.7 fb^{-1} on resonance

K.F. Chen et al., PRL 100, 112001 (2008)
J. Wicht et al., PRL 100, 121801 (2008)
R. Louvot et al., PRL 102, 021801 (2009)
A. Drutskoy et al., arXiv:0909.5223
R. Louvot et al., arXiv:0909.2160
J. Li et al., arXiv:0912.1434
C.-C. Peng et al., BELLE-CONF-0904
S. Esen et al., NEW

this talk

December 2007: scan 6 pts

- + 7.9 fb^{-1} above resonance

K.F. Chen et al., arXiv:0808.2445

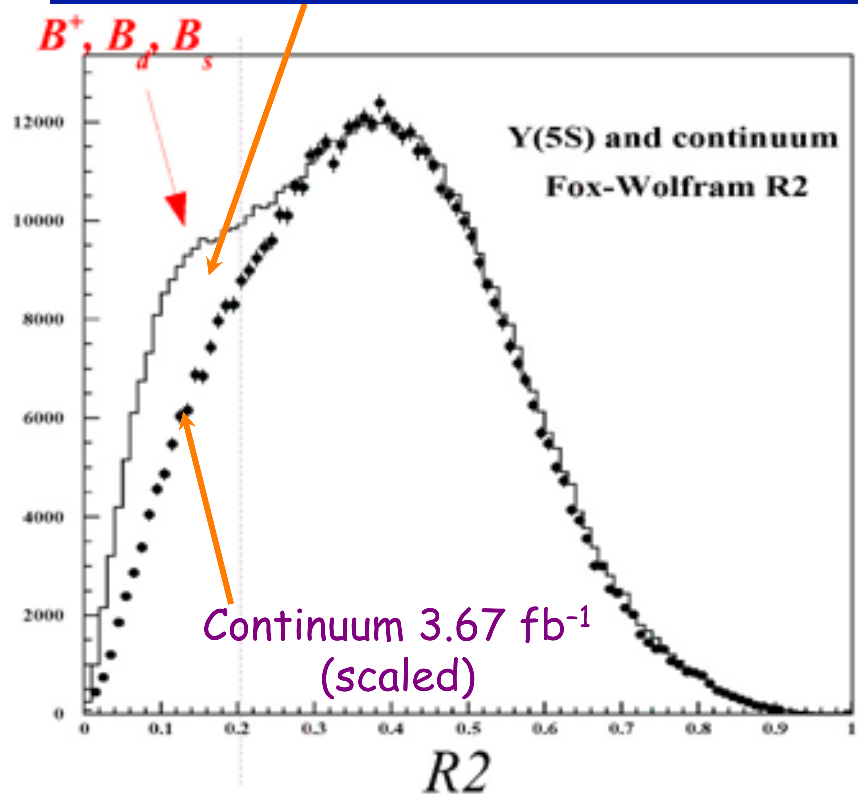
Oct 2008-Dec 2009:
extended run

- ~100 fb^{-1} on resonance

fundamentals 1.86 fb^{-1} PRL 98, 052001 (2007)

Event count

(3.01±0.02±0.16)x10^5 events/fb^{-1}

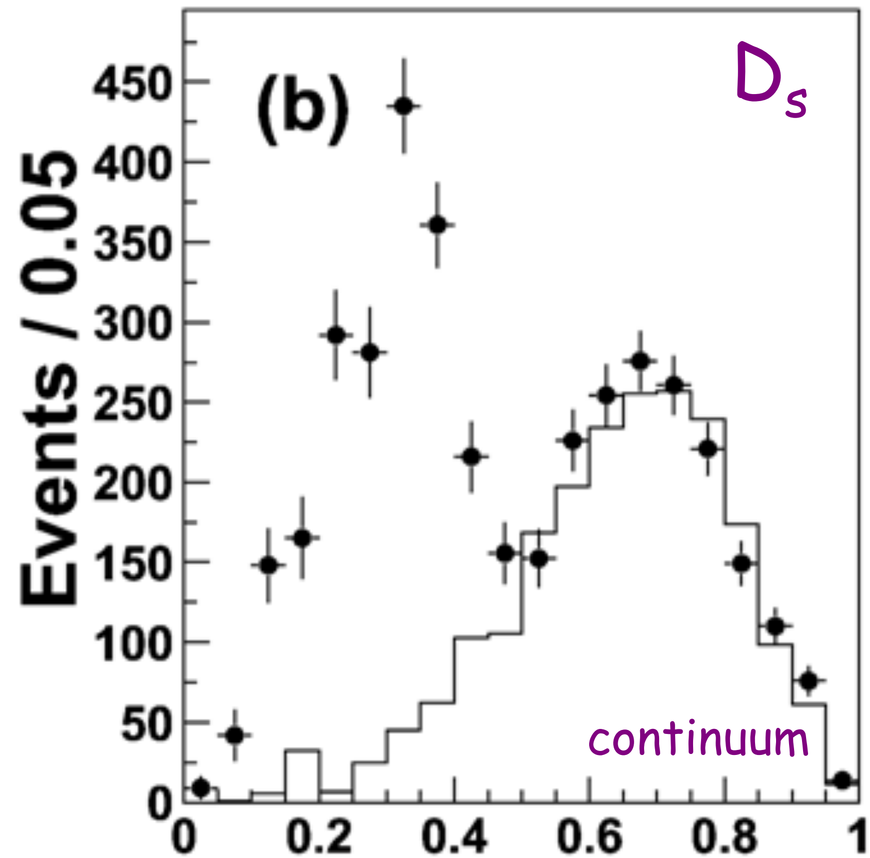


$$R_2 = \frac{\sum_{i,j} |p_i||p_j| P_2(\cos\theta)}{\sum_{i,j} |p_i||p_j| P_0(\cos\theta)}$$

Fox-Wolfram moments

B_s fraction in Υ(5S) events

inclusive D_s, D^0 production



$$x = p_{D_s} / \sqrt{E^2_{beam} - M^2_{D_s}}$$

$$f_s = (18.0 \pm 1.3 \pm 3.2)\%$$

B_s at Υ(5S): $B_s\bar{B}_s + B_s^*\bar{B}_s + \bar{B}_s^* B_s + B_s^*\bar{B}_s^*$

Full reconstruction of B_s candidates:

$B_s\bar{B}_s$

$$E_{B_s} = E_{beam}$$

$$p_{B_s} = \sqrt{E_{B_s}^2 - M_{B_s}^2}$$

$B_s^* \to B_s\gamma$

$$\Delta M \equiv M_{B_s^*} - M_{B_s} \approx 50\ \mathrm{MeV}/c^2$$

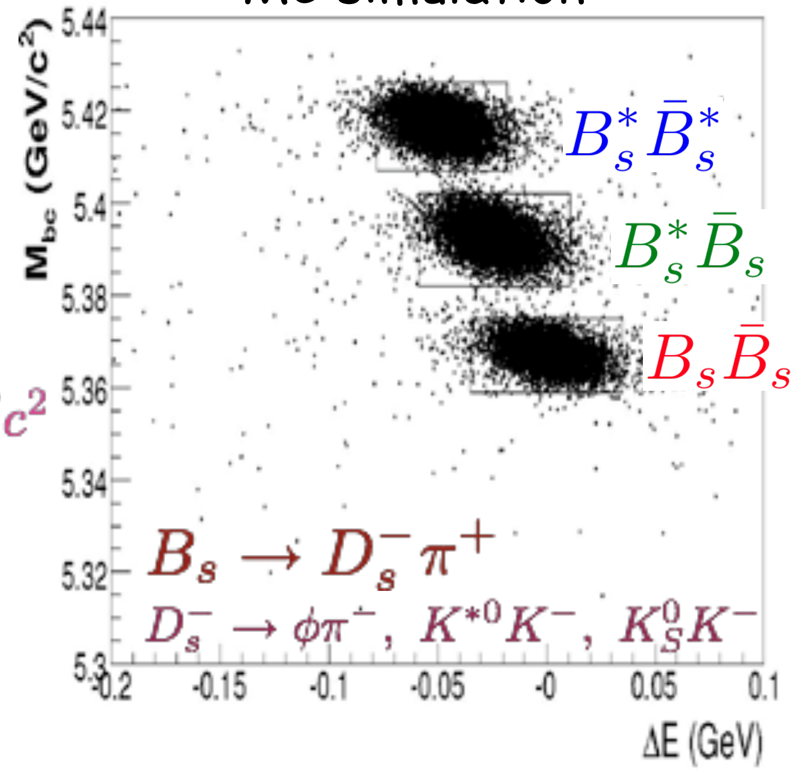
$B_s^*\bar{B}_s$

$$E_{B_s} \approx E_{beam} - \Delta M/2$$

$B_s^*\bar{B}_s^*$

$$E_{B_s} \approx E_{beam} - \Delta M$$

MC simulation



$$M_{bc} \equiv \sqrt{E_{beam}^2 - p_{cand}^2}$$

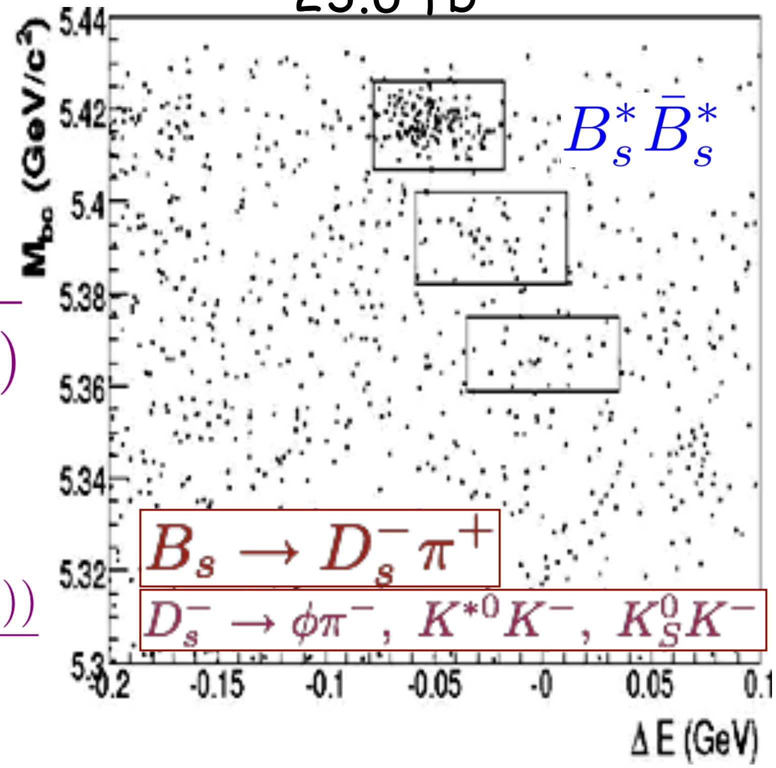
$$\Delta E \equiv E_{cand} - E_{beam}$$

B_s at Υ(5S): $B_s\bar{B}_s + B_s^*\bar{B}_s + \bar{B}_s^* B_s + B_s^*\bar{B}_s^*$

Full reconstruction of B_s candidates:

[PRL 102, 021801 (2009)]

23.6 fb^{-1}



$$M_{bc} \equiv \sqrt{E_{beam}^2 - p_{cand}^2}$$

$$\Delta E \equiv E_{cand} - E_{beam}$$

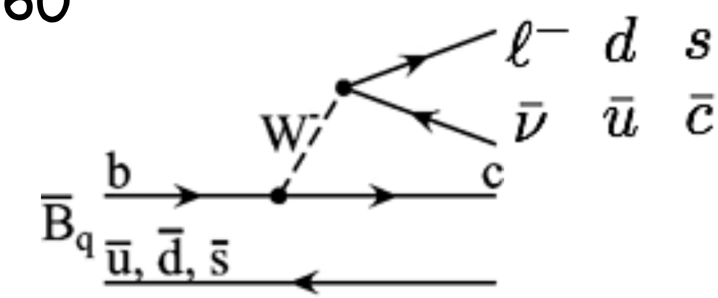
Comparing rates:

$$f_{B_s^* B_s^*} \equiv \frac{\sigma(e^+e^- \to B_s^*\bar{B}_s^*)}{\sigma(e^+e^- \to B_s^{(*)}\bar{B}_s^{(*)})} = (90.1^{+3.8}_{-4.0} \pm 0.2)\%$$

$$f_{B_s^* B_s} \equiv \frac{\sigma(e^+e^- \to B_s^*\bar{B}_s + B_s\bar{B}_s^*))}{\sigma(e^+e^- \to B_s^{(*)}\bar{B}_s^{(*)})} = (7.3 \pm 0.3 \pm 0.1)\%$$

$$B_s \to D_s^{*-}\pi^+,\ D_s^{(*)-}\rho^+$$

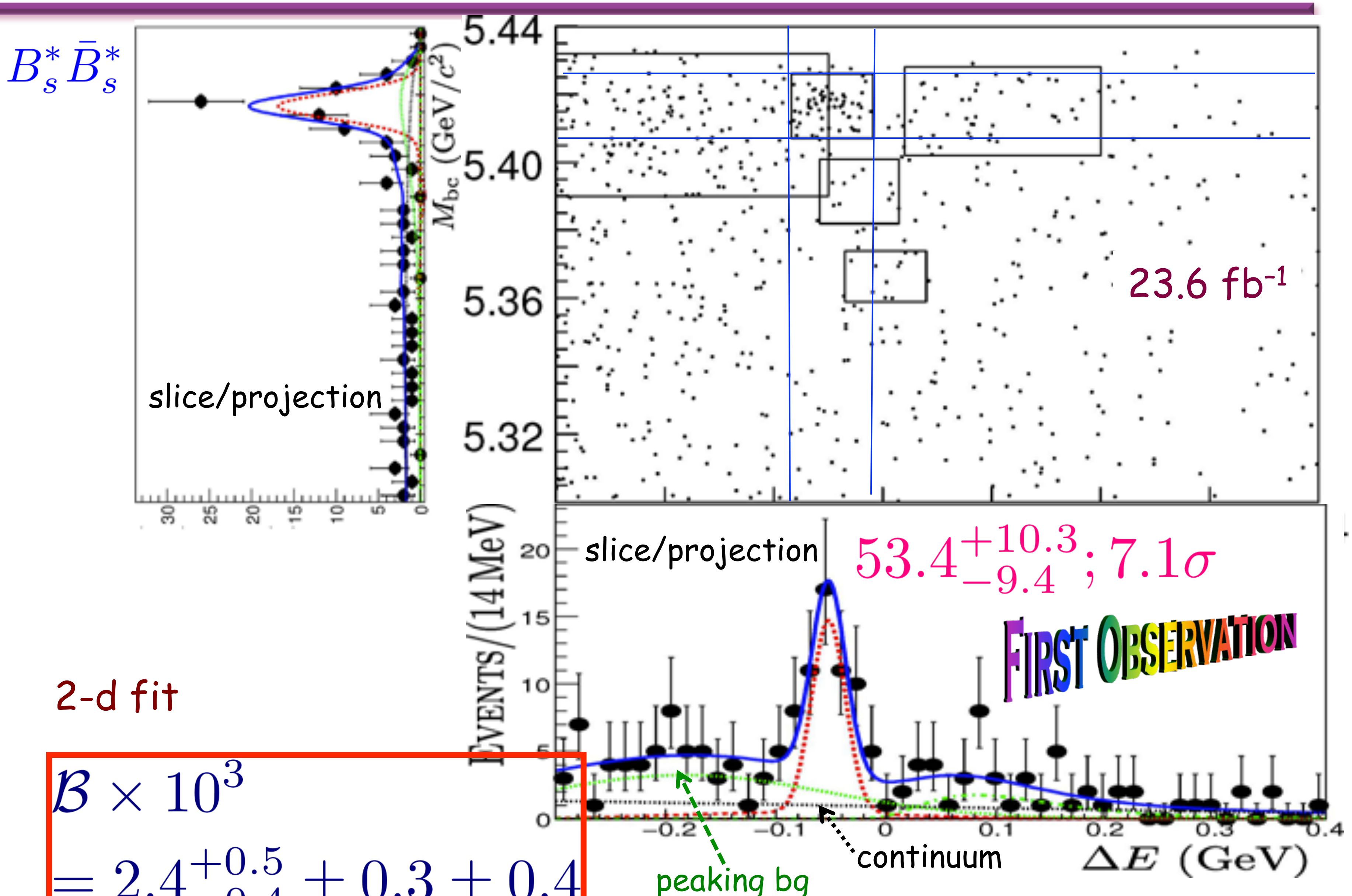
arXiv:0909.2160
R. Louvot



B_s decays: dominated by spectator process (as w $B_{u,d}$)

- Quark-hadron duality
  similar semileptonic widths
  B_q -> DX <=> B_s -> D_sX for many modes

data $B_s \to D_s^{*-}\pi^+$

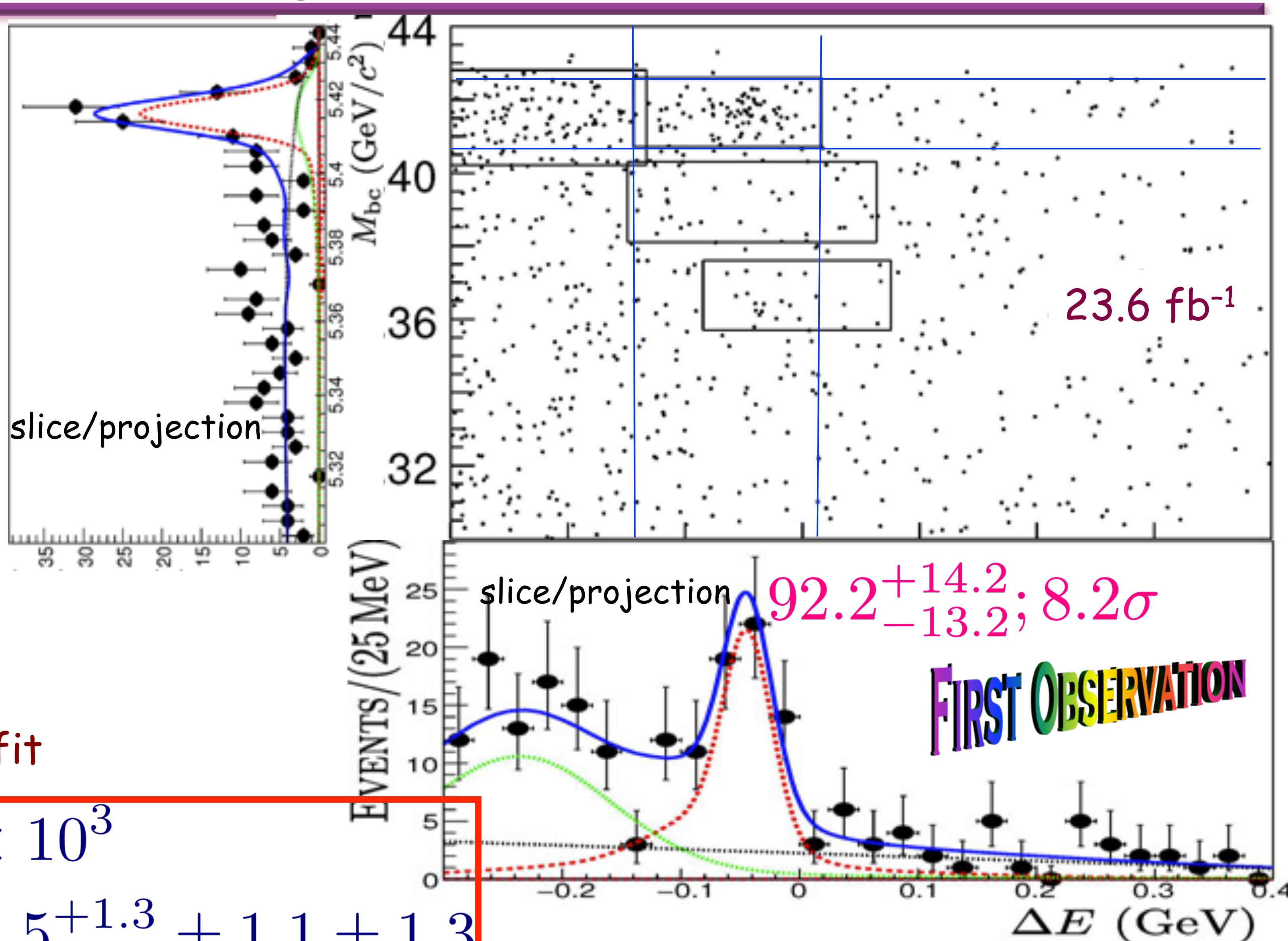


2-d fit

$$\mathcal{B} \times 10^3 = 2.4^{+0.5}_{-0.4} \pm 0.3 \pm 0.4$$

data $B_s \to D_s^- \rho^+$

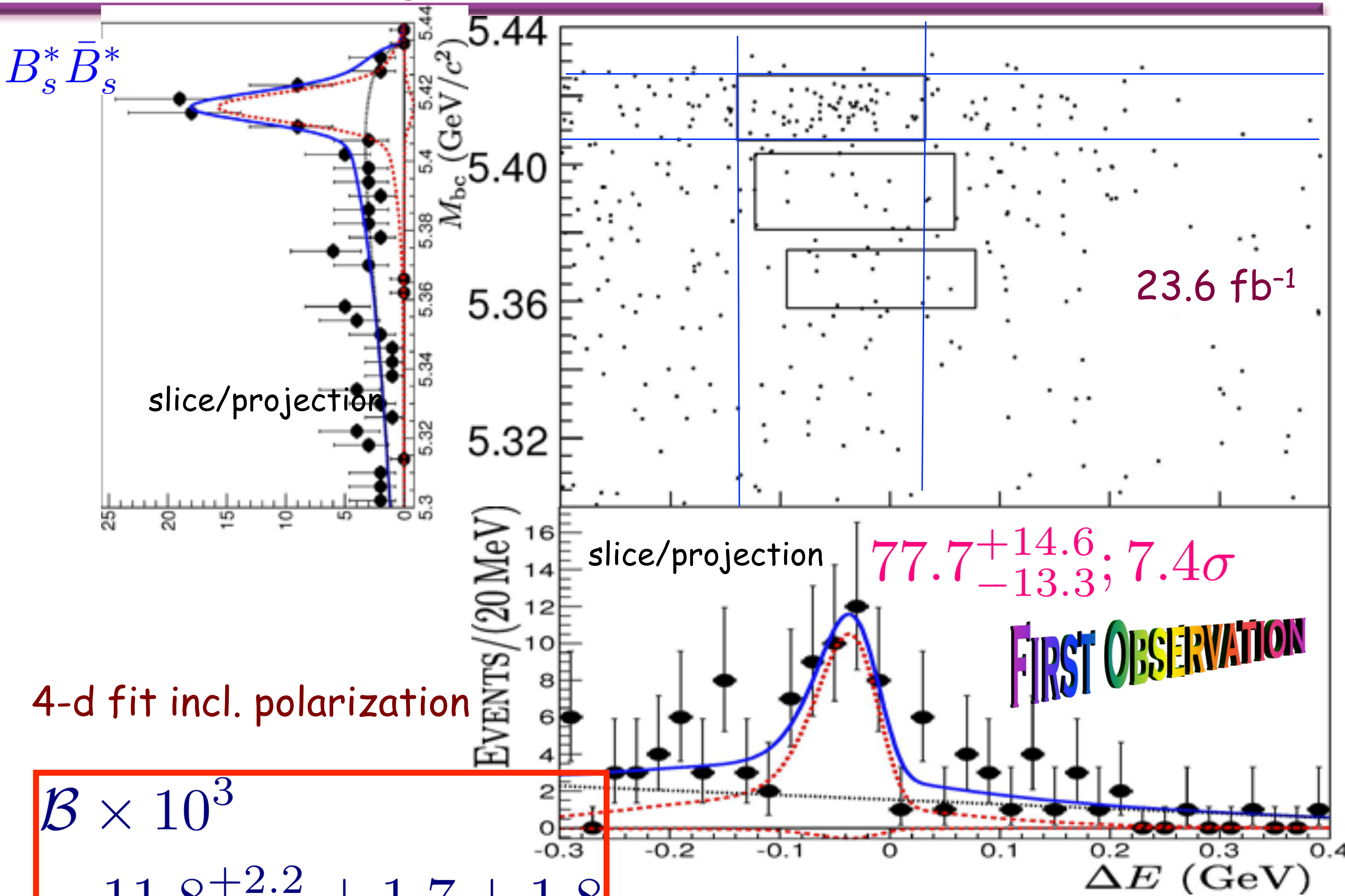
$B_s^* \bar{B}_s^*$



2-d fit

$$\mathcal{B} \times 10^3 = 8.5^{+1.3}_{-1.2} \pm 1.1 \pm 1.3$$

data $B_s \to D_s^{*-} \rho^+$



4-d fit incl. polarization

$$\mathcal{B} \times 10^3 = 11.8^{+2.2}_{-2.0} \pm 1.7 \pm 1.8$$

Data $B_s \to D_s^{*-}\rho^+$ polarization NEW

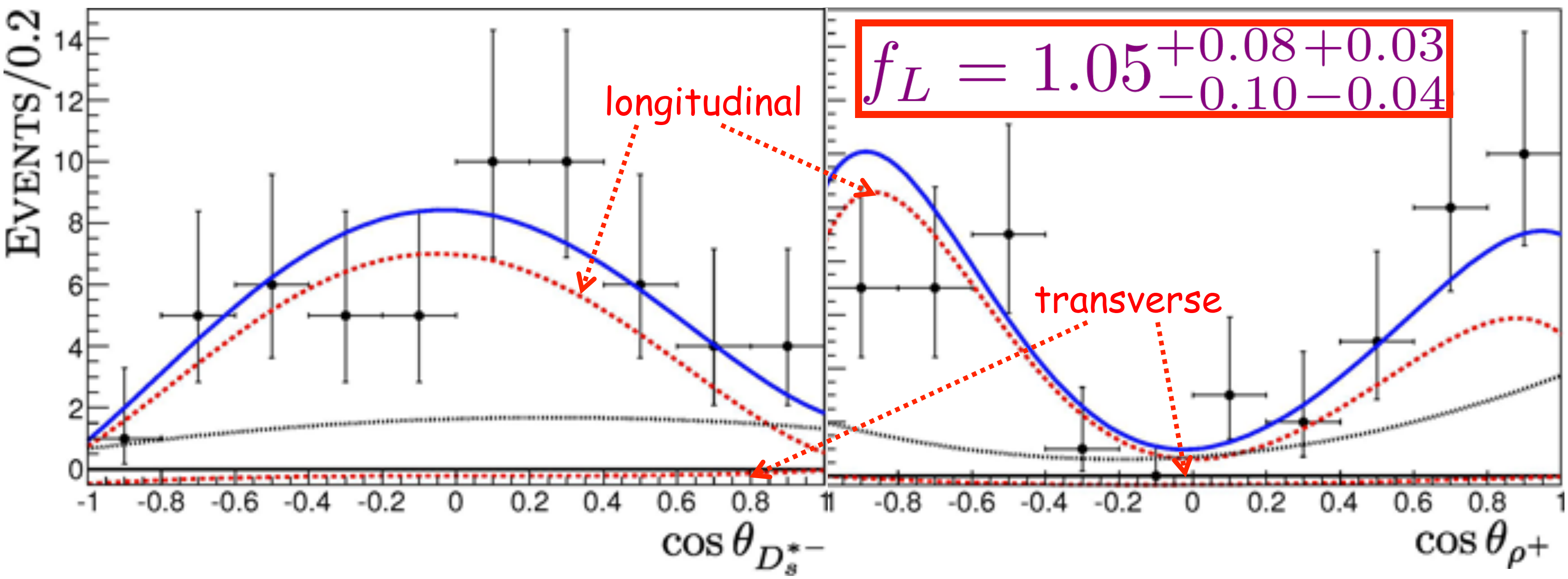
$B_s^* \bar{B}_s^*$

P-> VV decay: Polarization depends on hadronization detail
-> test of factorization hypothesis $f_L \approx 88\% (PRD\mathbf{42}, 3732(1990)$

$$\frac{d^2\Gamma(B_s^0 \to D_s^{*-}\rho^+)}{d\cos\theta_{D_s^{*-}}\, d\cos\theta_{\rho^+}}$$

helicity angles

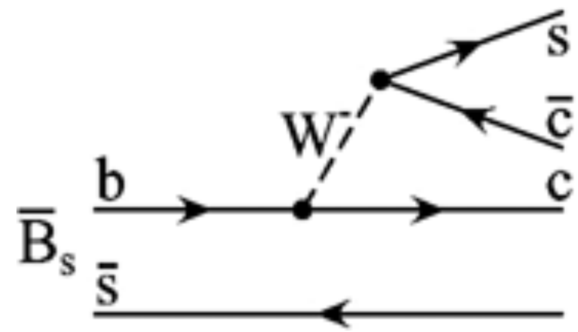
$$\propto 4 f_L \sin^2\theta_{D_s^{*-}} \cos^2\theta_{\rho^+} + (1-f_L)(1+\cos^2\theta_{D_s^{*-}})\sin^2\theta_{\rho^+}$$



$$B_s \to D_s^{(*)-} D_s^{(*)+}$$ PRELIMINARY

S. Esen

- CKM-favored AND flavor-neutral
  CP=+1 in heavy quark limit, m_c->∞
  ~ saturated by 2-body $D_s^{(*)+}D_s^{(*)-}$
  -> difference in widths of CP=±1



$$\frac{\Delta\Gamma_{CP}}{\Gamma} \approx \frac{2\mathcal{B}(B_s \to D_s^{(*)+} D_s^{(*)-})}{1 - \mathcal{B}(B_s \to D_s^{(*)+} D_s^{(*)-})}$$

Aleksan, Dunietz, Kayser Z. Phys., C54, 653 (1992)

$B_s \to D_s^{(*)-} D_s^{(*)+}$

Reconstruction

$$D_s^{*+} \to D_s^+ \gamma$$

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

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

$$D_s^+ \to \bar{K}^{*0} K^+ \qquad \bar{K}^{*0} \to K^- \pi^+$$

$$D_s^+ \to \phi \rho^+ \qquad \rho^+ \to \pi^+ \pi^0$$

$$D_s^+ \to K^{*+} K_S^0 \qquad K^{*+} \to K_S^0 \pi^+$$

$$D_s^+ \to K^{*+} \bar{K}^{*0}$$

$B_s \to D_s^{(*)-} D_s^{(*)+}$

Reconstruction

- Candidate selection

$$5.2 < M_{\rm bc}c^2/{\rm GeV} < 5.45$$
$$-0.15 < \Delta E/{\rm GeV} < 0.1$$

- One candidate (all channels) per event

  selection: lowest chisquare based on $M(D_s), M(D_s^*) - M(D_s)$

$D_s^+ D_s^-$ $$\chi^2 = \frac{1}{2}\Sigma\left[\frac{m_{D_s^\pm} - m_{D_s^\pm}^{PDG}}{\sigma_{m_{D_s^\pm}}}\right]^2$$

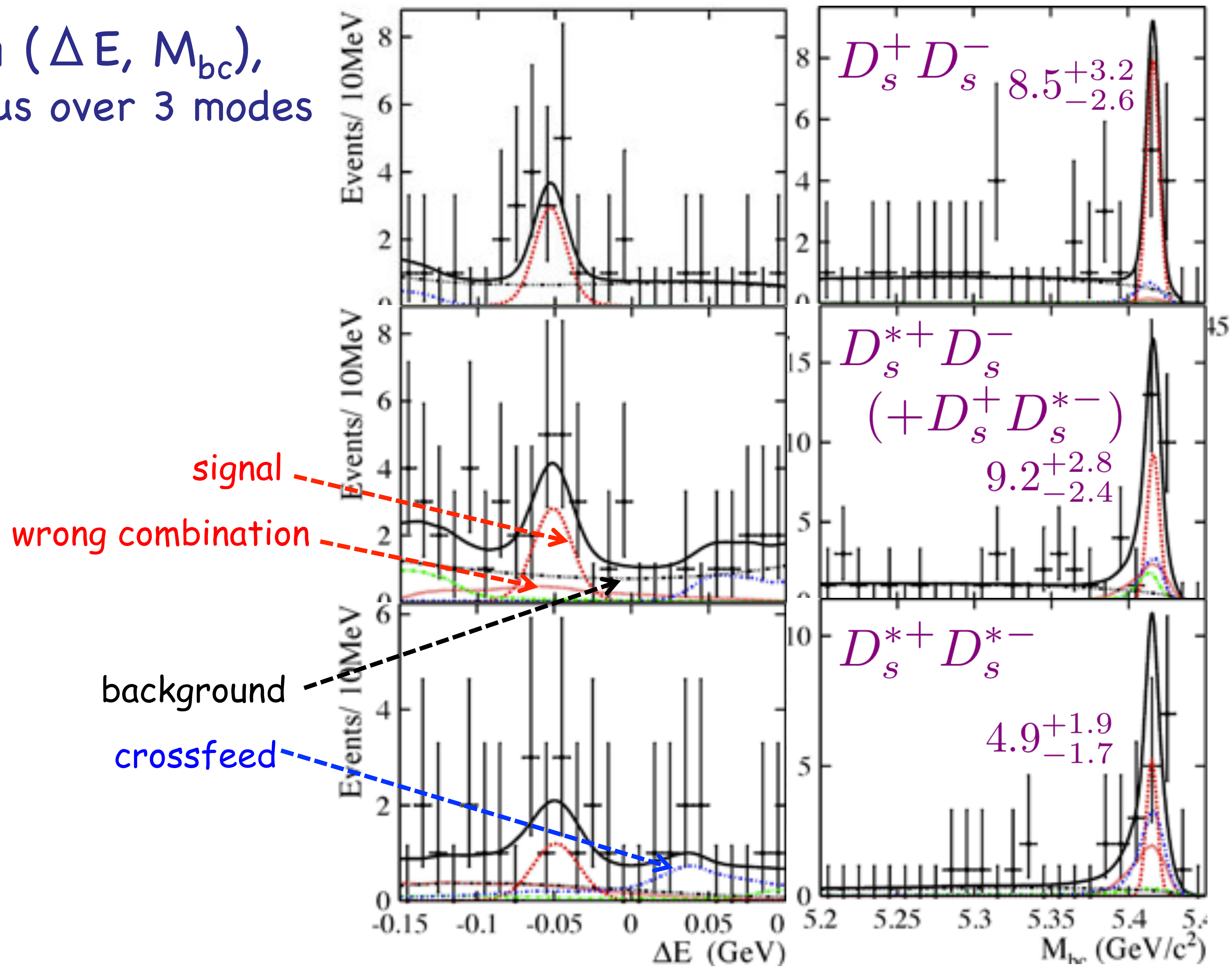
$D_s^{*+} D_s^-$ $$\chi^2 = \frac{1}{3}\left[\Sigma\left[\frac{m_{D_s^\pm} - m_{D_s^\pm}^{PDG}}{\sigma_{m_{D_s^\pm}}}\right]^2 + \left[\frac{\Delta M_{D_s^*} - \Delta M_{D_s^*}^{PDG}}{\sigma_{\Delta M_{D_s^*}}}\right]^2\right]$$

$D_s^{*+} D_s^{*-}$ $$\chi^2 = \frac{1}{4}\left[\Sigma\left[\frac{m_{D_s^\pm} - m_{D_s^\pm}^{PDG}}{\sigma_{m_{D_s^\pm}}}\right]^2 + \Sigma\left[\frac{\Delta M_{D_s^*} - \Delta M_{D_s^*}^{PDG}}{\sigma_{\Delta M_{D_s^*}}}\right]^2\right]$$

$B_s \to D_s^{(*)-} D_s^{(*)+}$

23.6 fb^{-1}

2-d fit in (ΔE, M_{bc}),
simultaneous over 3 modes



$B_s \to D_s^{(*)-} D_s^{(*)+}$

Branching fraction PRELIMINARY

Mode	Y (events)	$\mathcal{B}$ (%)	S (σ)
$D_s^+ D_s^-$	$8.5^{+3.2}_{-2.6}$	$1.0^{+0.4}_{-0.3}{}^{+0.3}_{-0.2}$	6.2
$D_s^* D_s$	$9.2^{+2.8}_{-2.4}$	$2.8^{+0.8}_{-0.7} \pm 0.7$	6.6 FIRST OBSERVATION
$D_s^* D_s^*$	$4.9^{+1.9}_{-1.7}$	$3.1^{+1.2}_{-1.0} \pm 0.8$	3.2 FIRST EVIDENCE
Sum	$22.6^{+4.7}_{-3.9}$	$6.9^{+1.5}_{-1.3} \pm 1.9$	

$$\frac{\Delta\Gamma_{CP}}{\Gamma} = \frac{2\mathcal{B}}{1-\mathcal{B}} = 0.147^{+0.036}_{-0.030}{}^{+0.044}_{-0.042} \pm 0.004$$

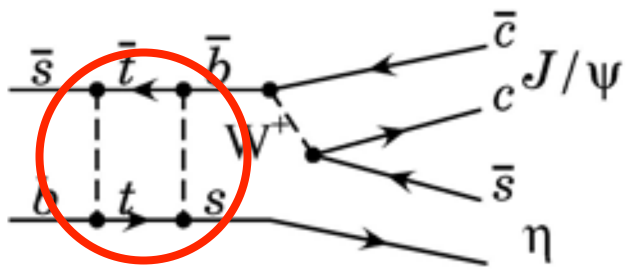
$$[PDG : 0.092^{+0.051}_{-0.054}]$$

[theory; Aleksan et al., PLB 316, 567 (1993)]

more theory input requested!

Other CP Eigenstates

B-factory measurement: mixing-mediated CP oscillations depends on complex argument of mixing box diagram



$\arg(V_{tb}^{*2} V_{ts}^{2}) = 0$ for B_s
=> window to non-SM CP-violation

CP violation in CKM is insufficient to explain baryon asymmetry
Mod. Phys. Lett A9, 75 (1994); PRD 51, 379 (1995); Nucl.Phys. B287, 757 (1987)

$B_s \to J/\psi\eta^{(\prime)}$

arXiv:0912.1434
J. Li

CP eigenstate; expectation

$\mathcal{B}(B_s \to J/\psi\eta) \approx 3.5 \times 10^{-4}$ $\mathcal{B}(B_s \to J/\psi\eta') \approx 4.9 \times 10^{-4}$

Based on flavor SU(3) symmetry + PDG: $\mathcal{B}(B_d^0 \to J/\psi K^0) = 8.71 \times 10^{-4}$

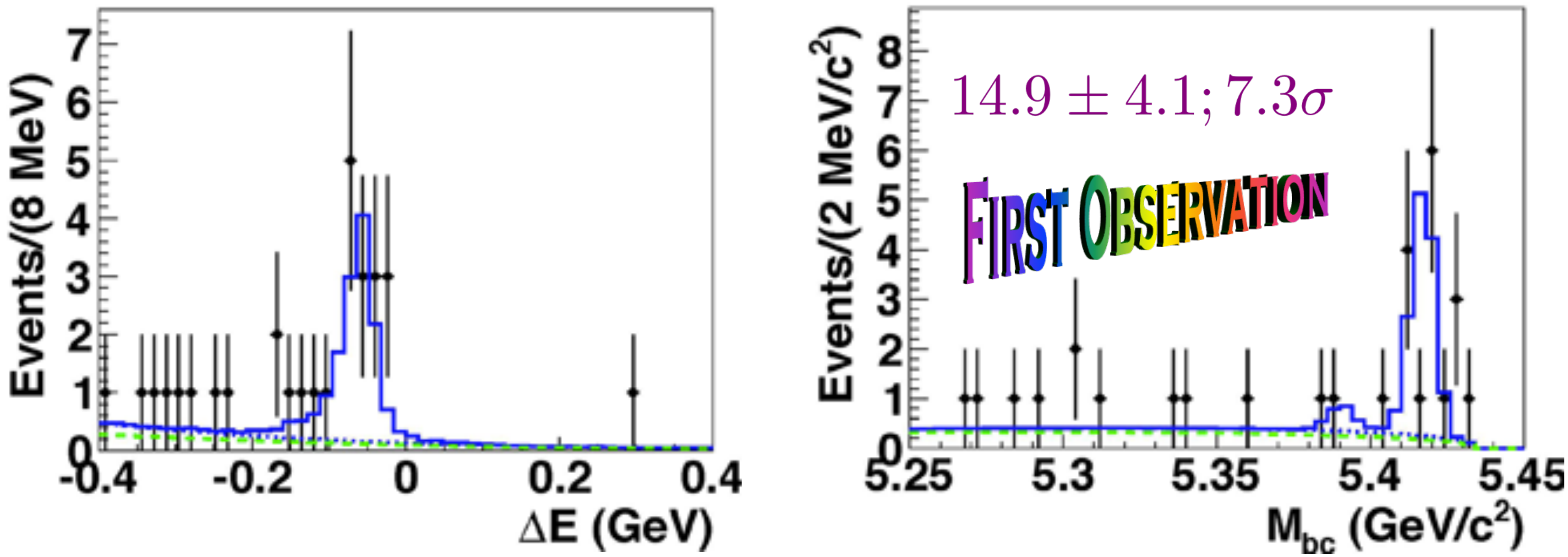
Reconstruction

$$J/\psi \to e^+e^-,\ \mu^+\mu^-$$
$$\eta \to \gamma\gamma,\ \pi^+\pi^-\pi^0$$
$$\eta' \to \eta\pi^+\pi^-,\ \rho^0\gamma$$

$B_s \to J/\psi\eta$

2-d fit in (ΔE, M_{bc}), simultaneous over sub-modes

23.6 fb^{-1}

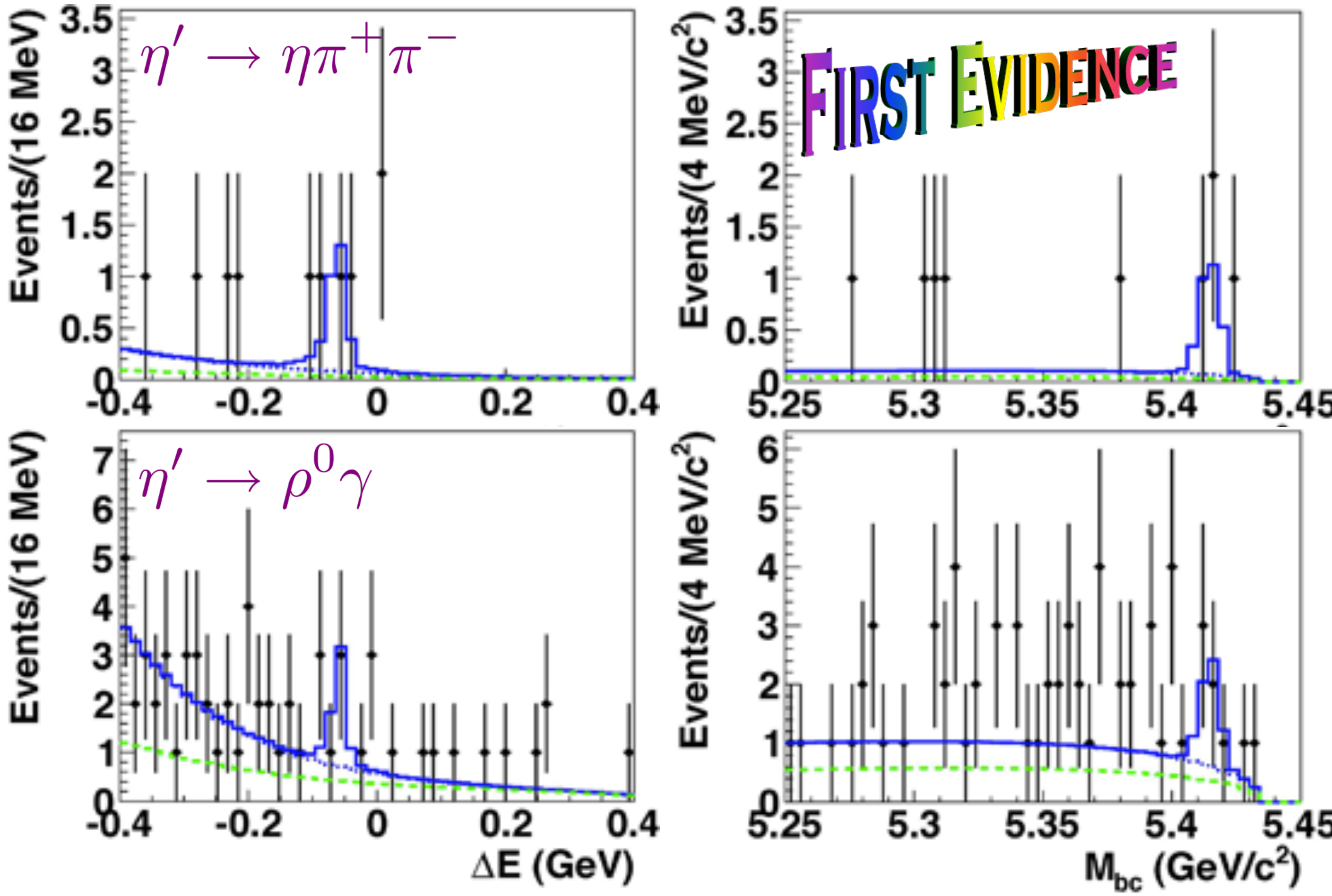


$$\mathcal{B}(B_s \to J/\psi\eta) = (3.32 \pm 0.87(stat)^{+0.32}_{-0.28}(sys) \pm 0.42(f_s)) \times 10^{-4}$$

$B_s \to J/\psi\eta'$

2-d fit in (ΔE, M_{bc}), simultaneous over sub-modes

$$\mathcal{B}(B_s \to J/\psi\eta') = (3.1 \pm 1.2(stat)^{+0.5}_{-0.6}(sys) \pm 0.38(f_s)) \times 10^{-4}$$



3.8σ

23.6 fb^{-1}

$$B_s \rightarrow hh$$

C. C. Peng

$B_s \to hh$

23.6 fb^{-1}

CP eigenstates

$\mathcal{B}(B_s \to K^+K^-) \times 10^5$

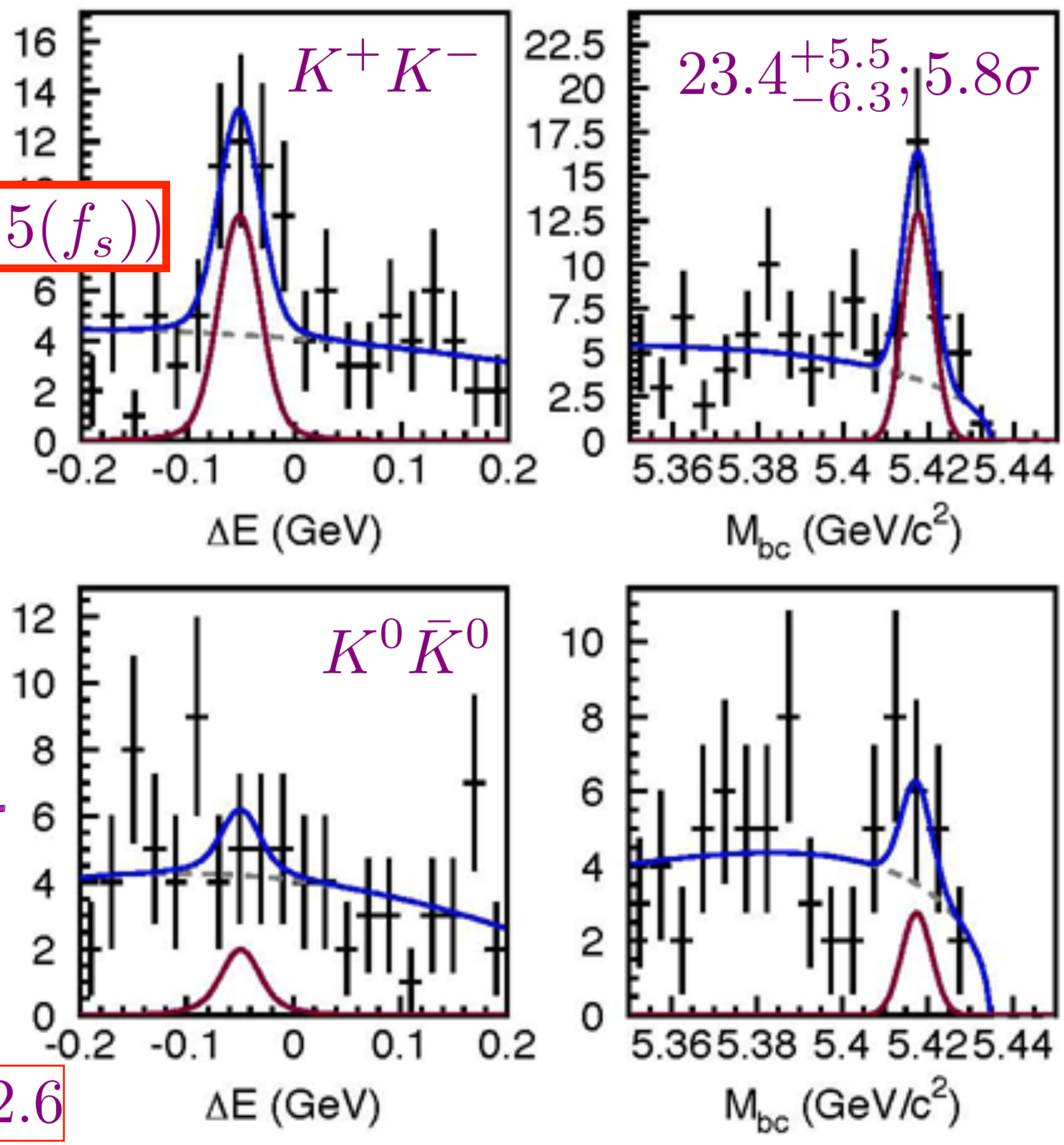
$= (3.8^{+1.0}_{-0.9}(stat) \pm 0.5 \pm 0.5(f_s))$

FIRST ABSOLUTE BF

$\mathcal{B}(B_s \to K^0\bar{K}^0) \times 10^5$

< 6.6

FIRST LIMIT



Also:

$\mathcal{B}(B_s \to K^-\pi^+) \times 10^5 < 2.6$

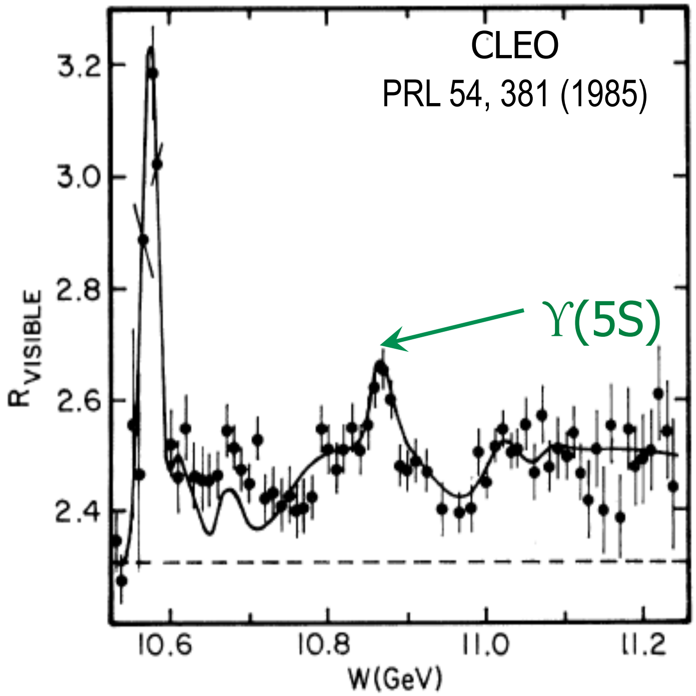
$\mathcal{B}(B_s \to \pi^-\pi^+) \times 10^5 < 1.2$

$$\Upsilon(5S) \to B\bar{B}X$$

arXiv:0909.5223
A. Drutskoy

$\Upsilon(5S) \rightarrow B\bar{B}X$

$B_q = \{B_d^0, B_u^+\}$



$B_s^{(*)}\bar{B}_s^{(*)}$

$B_q^{(*)}\bar{B}_q^{(*)}$

$B_q\bar{B}_q^{(*)}\pi$

$B_q\bar{B}_q\pi\pi$

Relative rates:
hadronization/spectroscopy

reconstruction

$B^+ \rightarrow J/\psi K^+$ $\qquad$ $J/\psi \rightarrow e^+e^-, \mu^+\mu^-$

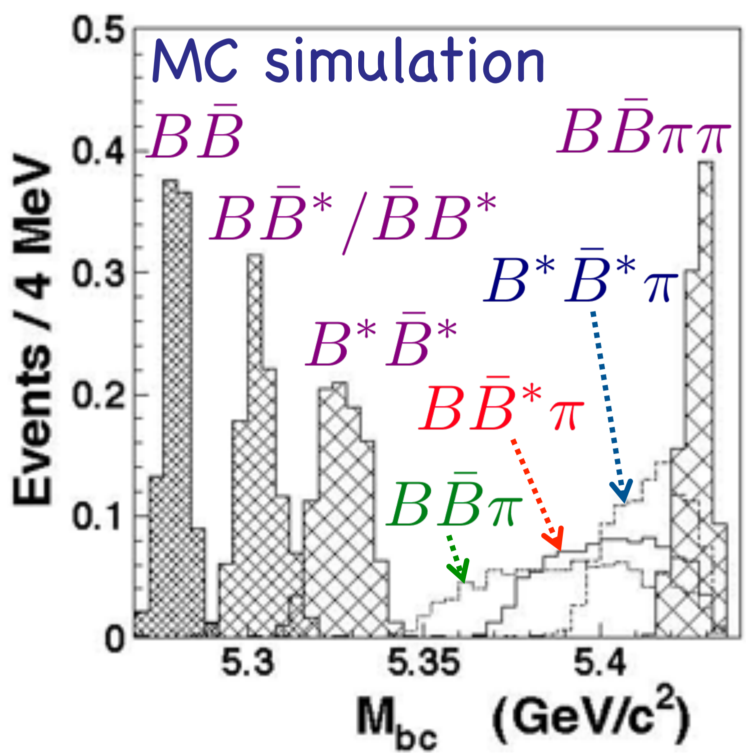
$B^0 \rightarrow J/\psi K^{*0}$ $\qquad$ $K^{*0} \rightarrow K^+\pi^-$

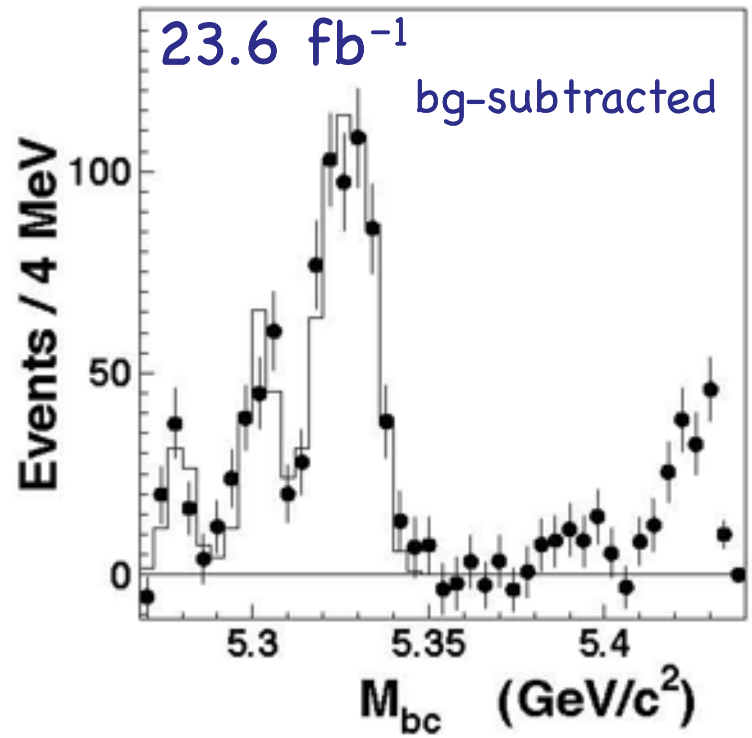
$B^+ \rightarrow \bar{D}^0\pi^+$ $\qquad$ $\bar{D}^0 \rightarrow K^+\pi^-, K^+\pi^+\pi^-\pi^-$

$B^0 \rightarrow D^-\pi^+$ $\qquad$ $D^- \rightarrow K^+\pi^-\pi^-$

$\Upsilon(5S) \to B\bar{B}X$

Distributions in M_{bc}





Channel	Fraction, %
$B\bar{B}$	$5.5\,^{+1.0}_{-0.9} \pm 0.4$
$B\bar{B}^* + B^*\bar{B}$	$13.7 \pm 1.3 \pm 1.1$
$B^*\bar{B}^*$	$37.5\,^{+2.1}_{-1.9} \pm 3.0$
Large M_{bc}	$17.5\,^{+1.8}_{-1.6} \pm 1.3$

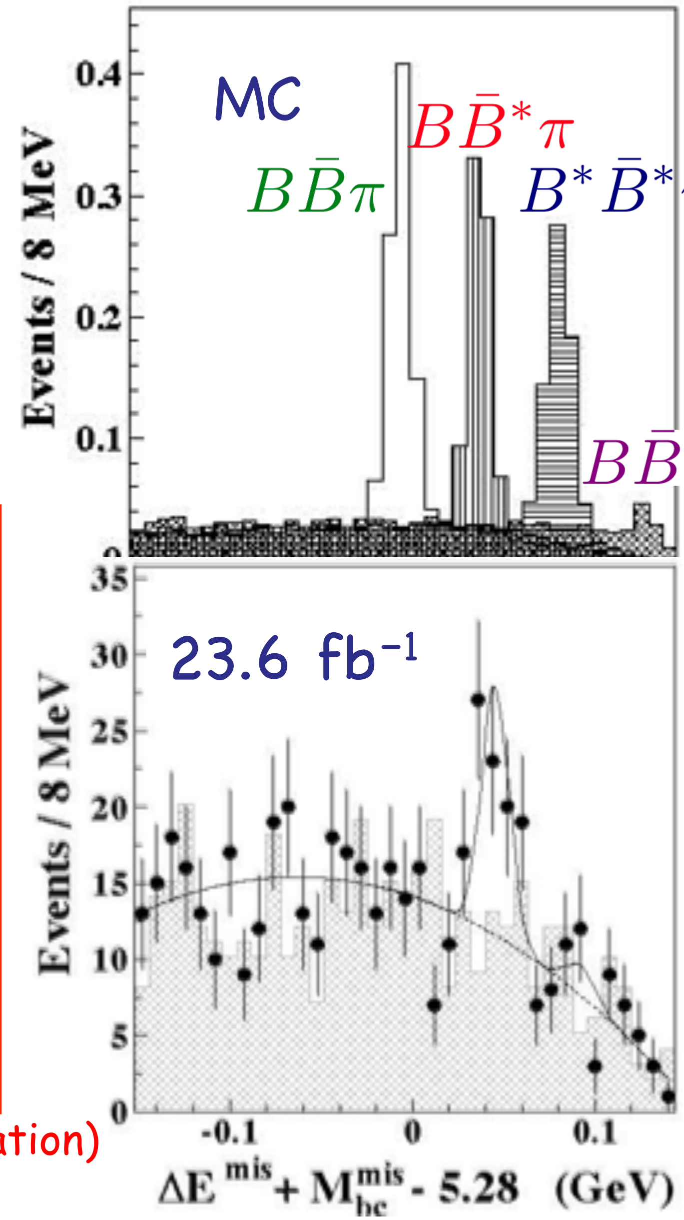
$\Upsilon(5S) \to B\bar{B}X$

$B\bar{B}\pi^+X$

Reconstruct Bπ, look for B$^{(*)}$ in missing ΔE, M_{bc}

Channel	Yield, events	Fraction, per $b\bar{b}$ event, %
$B\bar{B}\pi^+$	$0.2^{+7.2}_{-6.9}$	$0.0 \pm 1.2 \pm 0.3$
$B\bar{B}^*\pi^+ + B^*\bar{B}\pi^+$	$38.3^{+10.5}_{-9.8}$	$7.3^{+2.3}_{-2.1} \pm 0.8$
$B^*\bar{B}^*\pi^+$	$4.8^{+6.4}_{-5.9}$	$1.0^{+1.4}_{-1.3} \pm 0.4$
Residual		$9.2^{+3.0}_{-2.8} \pm 1.0$
Large M_{bc}	$228.7^{+22.9}_{-22.3}$	$17.5^{+1.8}_{-1.6} \pm 1.3$

initial state radiation (new interpretation)



Summary

KEKB and Belle at ϒ(10860)+

- 6/05, 6/06: 23 days, 23.6 fb^{-1}, 1.3M B_s events
- 12/07: energy scan, 6 pts, 8 fb^{-1}
- Strange beauty
  - measured $\Delta\Gamma/\Gamma$ via $B_s \to D_s^{(*+)} D_s^{(*)-}$
  - observed CP states $B_s \to J/\psi\eta^{(\prime)},\ K^+K^-$
  - & more $B_s \to D_s^{*-}\pi^+, D_s^{(*)-}\rho^+$
  - sought $B_s \to K^0\bar{K}^0$
- Beasts

$$\Upsilon(5\mathrm{S}) \to B_q^{(*)}\bar{B}_q^{(*)}(\pi)(\pi)$$

- more to come ...
  - 10/08-12/09: ~100 fb^{-1} at ϒ(5S) , ~6M B_s event, **ADDITIONAL**
  - possible scan near/above ϒ(5S) in Spring 2010
  - SuperKEKB/Belle II ~2014

Backup slides

$B_s \to D_s^{(*)-} D_s^{(*)+}$

Systematic errors

Source	$D_s^+ D_s^-$ $+\sigma$	$-\sigma$	$D_s^* D_s$ $+\sigma$	$-\sigma$	$D_s^{*+} D_s^{*-}$ $+\sigma$	$-\sigma$
DATA/MC calibration	0.3	0.3	0.0	0.1	0.2	0.1
CR PDF	0.7	0.7	0.2	0.3	0.5	0.4
Background PDF	1.1	1.3	1.9	2.0	3.0	3.0
WC+CF PDF	0.3	0.3	1.5	1.5	4.4	4.4
WC/CF fraction	0.2	0.2	5.0	5.0	8.7	8.7
Continuum suppression	1.8	1.8	1.8	1.8	1.8	1.8
Best candidate selection	6.9	0.0	2.2	0.0	2.2	0.0
$K^\pm$ identification	9.5	9.5	10.0	10.0	10.3	10.3
K_s	1.0	1.0	1.0	1.0	1.0	1.0
π^0	1.1	1.1	1.1	1.1	1.0	1.0
γ	-	-	3.8	3.8	7.6	7.6
Tracking	6.2	6.2	6.2	6.2	6.2	6.2
Polarization	0.2	0.0	0.8	0.5	0.7	0.3
Acceptance (ε)	1.1	1.1	0.9	0.8	1.0	1.0
$D_s^{(*)}$ BF's	12.4	12.4	12.4	12.4	12.5	12.5
Luminosity			± 1.3			
$\sigma_{\Upsilon(5S)}$			± 4.6			
$f_{B_s^{(*)}\overline{B}_s^{(*)}}$			± 15			
$N_{B_s^*\overline{B}_s^*}/N_{B_s^{(*)}\overline{B}_s^{(*)}}$			$^{+4.2}_{-4.4}$			
Total	24.6	23.7	24.8	24.8	27.2	27.2

$B_s \to J/\psi\eta'$

systematics

TABLE II: Relative systematic errors (in %) for $\mathcal{B}(J/\psi\eta^{(\prime)})$.

Source	$\mathcal{B}(J/\psi\eta)$	$\mathcal{B}(J/\psi\eta')$
Signal shape calibration	$+5.8, -2.9$	$+11.7, -16.8$
Beam energy	$+1.6, -0.0$	$+4.8, -4.3$
MC signal shape	$+1.0, -2.0$	$+2.6, -4.0$
$f_{B_s^{(*)}\bar{B}_s^{(*)}}$	$+0.7, -1.5$	$+4.6, -4.0$
Background parameters	$+0.9, -0.8$	$+6.0, -5.5$
Track reconstruction	2.5	4.2
Lepton identification	4.2	4.1
Pion identification	0.4	2.3
$\eta(\pi^0) \to \gamma\gamma$ selection	4.1	2.8
$\mathcal{B}(J/\psi \to ll)$	0.72	0.72
$\mathcal{B}(\eta^{(\prime)} \to \text{final states})$	0.49	2.3
Luminosity	1.3	1.3
$\sigma_{b\bar{b}}$	4.6	4.6
f_s	$+13.4, -13.3$	$+13.4, -13.3$
Total	$+16.8, -16.1$	$+21.9, -24.8$

$B_s \to h^+h^-$

systematics

TABLE II: Systematic error (%). The total systematic uncer tainty of each mode is the quadratic sum of each systemati uncertainty.

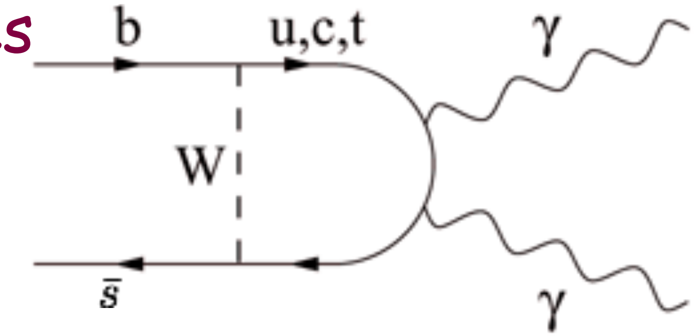
	K^+K^-	$K^-\pi^+$	$\pi^+\pi^-$	K^0K^0
Signal PDF	2.3	10.6	10.3	6.8
Continuum PDF	0.7	1.5	3.9	6.3
Cross-feed background	–	5.5	–	–
$\bar{B}^0 \to K^-\pi^+$ background	–	7.1	–	–
$\mathcal{R}$ requirement	12.0	12.8	16.5	4.8
$\mathcal{R}(K/\pi)$ requirement	1.4	1.4	1.3	–
K_S^0 reconstruction	–	–	–	9.8
Track reconstruction	2.0	2.0	2.0	0.0
$\sigma_{b\bar{b}}^{\Upsilon(5S)}$	4.8	4.8	4.8	4.8
$L_{\rm int}$	1.3	1.3	1.3	1.3
f_s	13.3	13.3	13.3	13.3
$f_{B_s^*\bar{B}_s^*}$	4.8	4.8	4.8	4.8
Signal MC statistics	0.4	0.5	0.5	0.6
Total	19.5	24.3	25.0	20.7

Searches for new modes of B_s PRL 100, 212801 (2008)

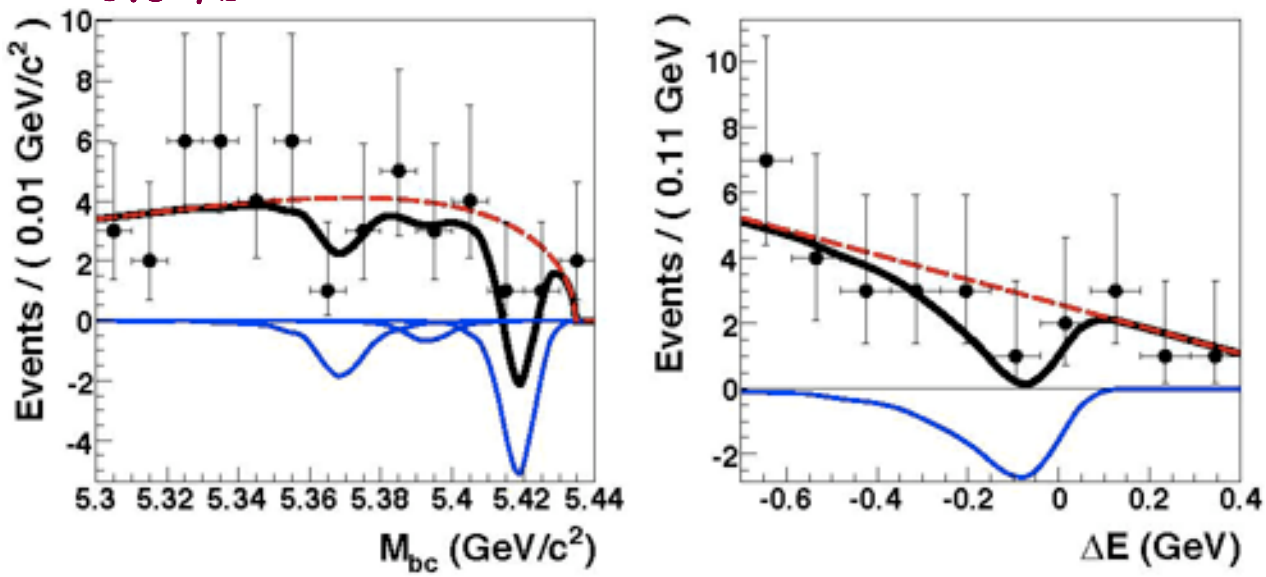
γγ: difficult for hadron machines

$$\mathcal{B}_{SM} \sim (0.4 - 1.0) \times 10^{-6}$$

beyond SM: up to 5×10^{-6}



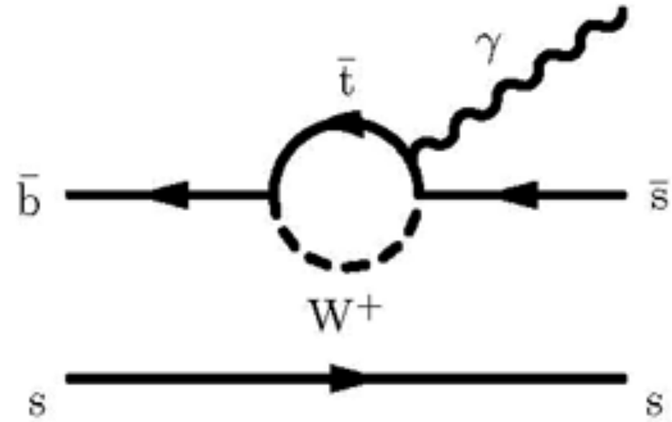
23.6 fb^{-1}



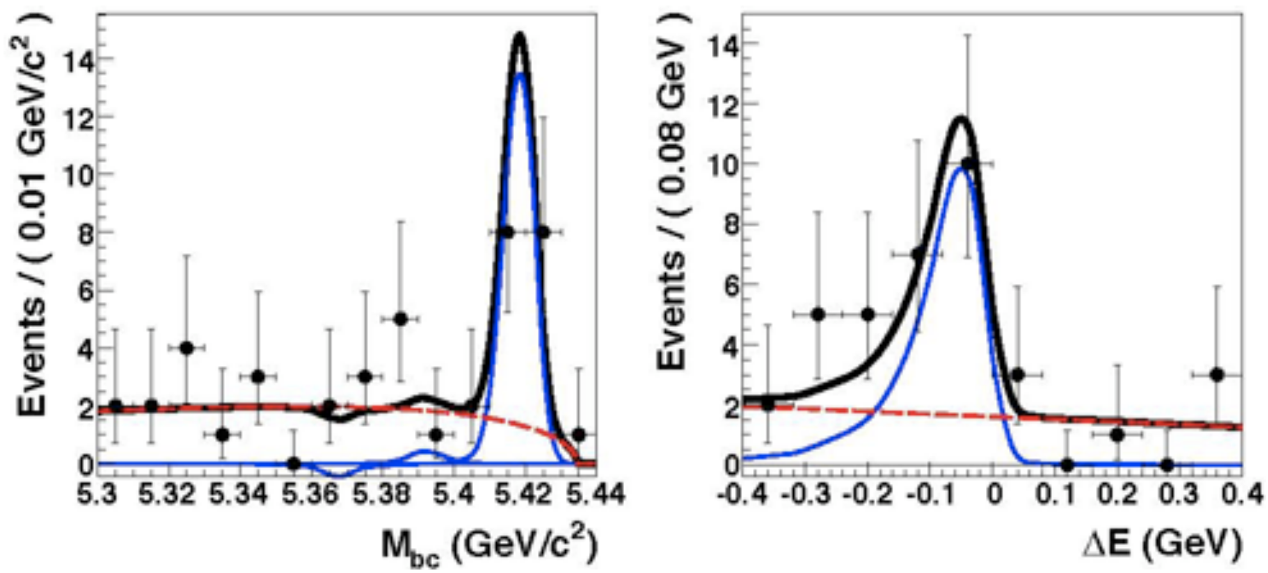
$$\mathcal{B} < 8.7 \times 10^{-6} \ (90\% \ CL)$$ (prev. Belle: $< 5.3 \times 10^{-5}$)

Searches for new modes of B_s

φγ



23.6 fb^{-1}



$$\mathcal{B} = (57^{+18}_{-15}(stat)^{+12}_{-11}(sys)) \times 10^{-6}$$

First observation