B_s physics at the $\Upsilon(5S)$

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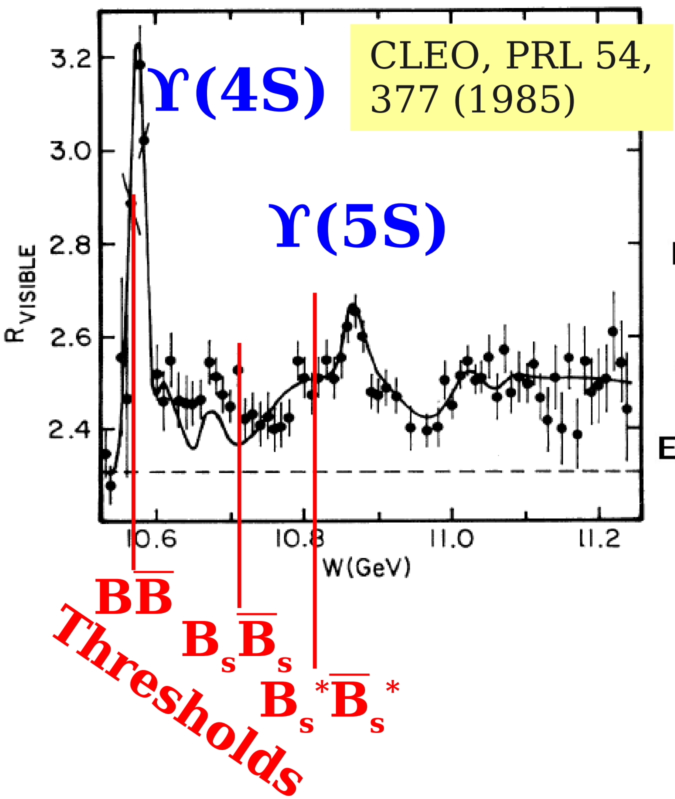
Physics at the LHC 2010
Hamburg, 7-12 June 2010

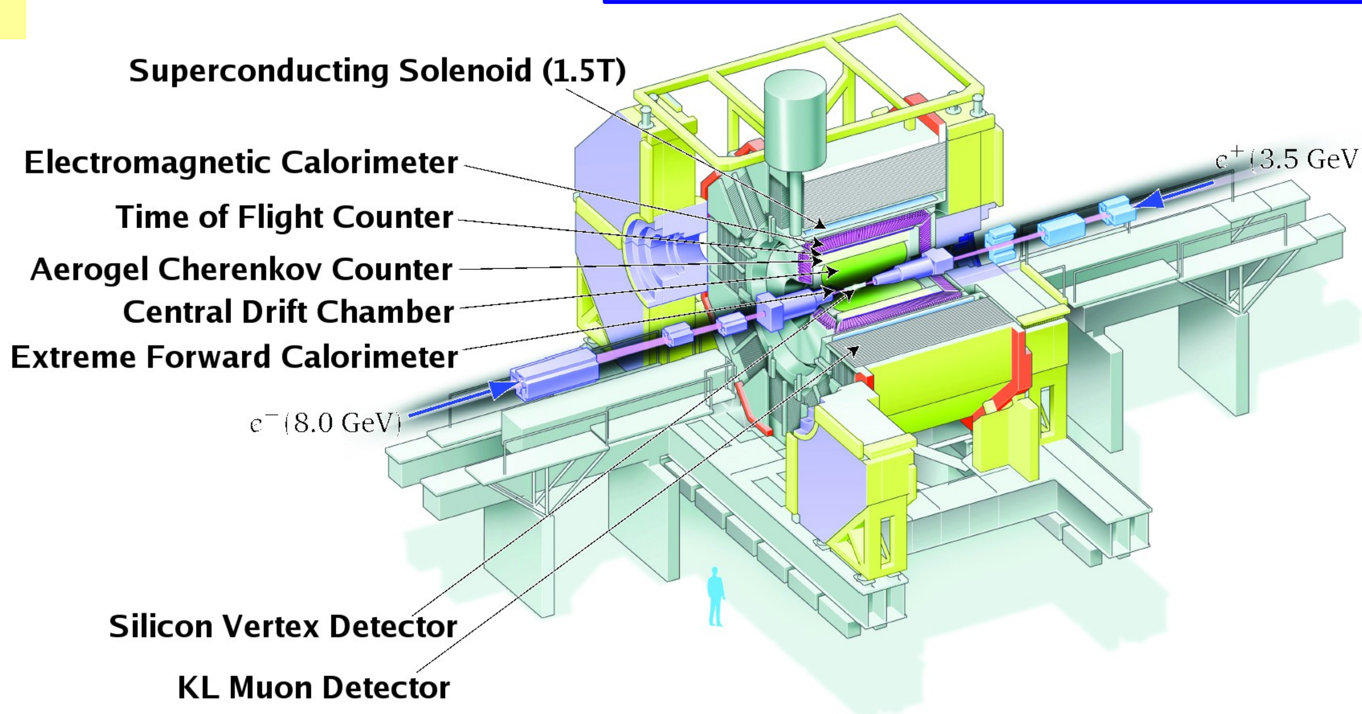
KEKB and Belle detector

KEKB : asymmetric e^+e^- collider (3.6 on 8.2 GeV for $\Upsilon(5S)$): Tsukuba, Japan

B meson factory: $e^+e^- \rightarrow \Upsilon(4S), \Upsilon(5S) \rightarrow B\overline{B}$

Solid angle coverage	~92%
Particle identification	π,K,e,μ,p





Luminosity

Peak $2.11\ 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (World record with crab cavities (06/2009))

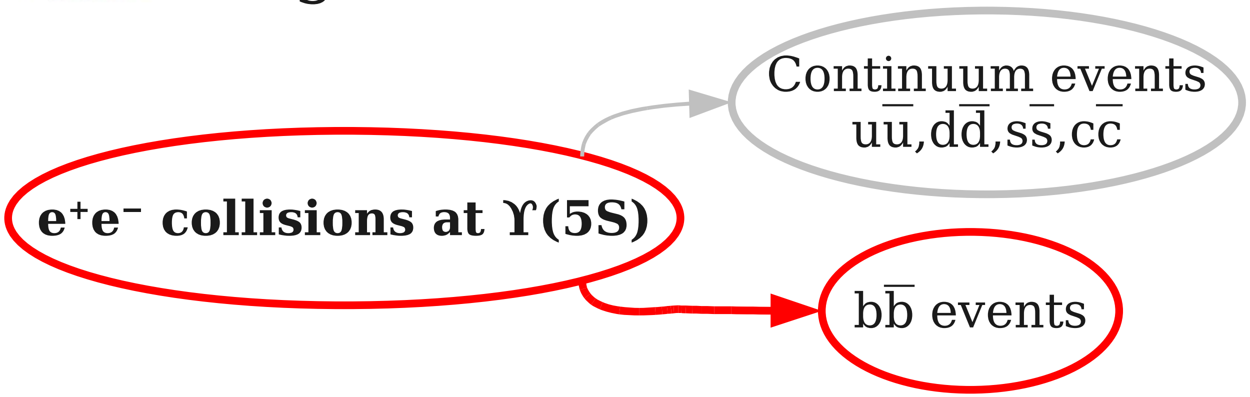
Integrated Total: $> 1.0\ \mathrm{ab}^{-1}$

$\Upsilon(4S)$: 710 fb^{-1} (~772M $B\overline{B}$ pairs, $B=B^+$ or B^0)

$\Upsilon(5S)$: ~120 fb^{-1}

Today's results: 23.6 fb^{-1}

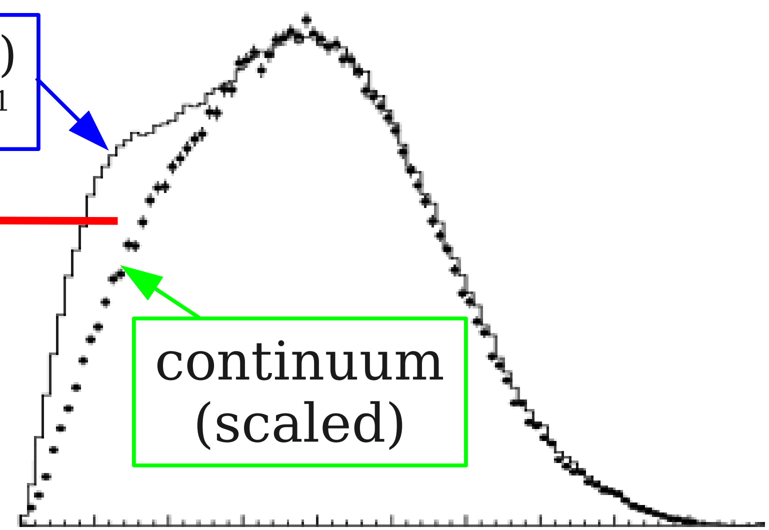
B_s production at the Υ(5S)



$b\bar{b}$ cross-section measured with
Υ(4S) off-resonance data (continuum) subtraction

$$\sigma_{b\bar{b}}^{\Upsilon(5S)} = \frac{N_{b\bar{b}}^{\Upsilon(5S)}}{\mathcal{L}_{\Upsilon(5S)}} = \frac{1}{\mathcal{L}_{\Upsilon(5S)}} \frac{1}{\epsilon_{\Upsilon(5S)}^{b\bar{b}}} \left(N_{\text{hadr}}^{\Upsilon(5S)} - N_{\text{hadr}}^{\text{cont}} \frac{\mathcal{L}_{\Upsilon(5S)}}{\mathcal{L}_{\text{cont}}} \frac{E_{\Upsilon(5S)}^2}{E_{\text{cont}}^2} \frac{\epsilon_{\Upsilon(5S)}^{\text{rec}}}{\epsilon_{\text{cont}}^{\text{rec}}} \right)$$

$b\bar{b}$: B_s, B^+, B^0



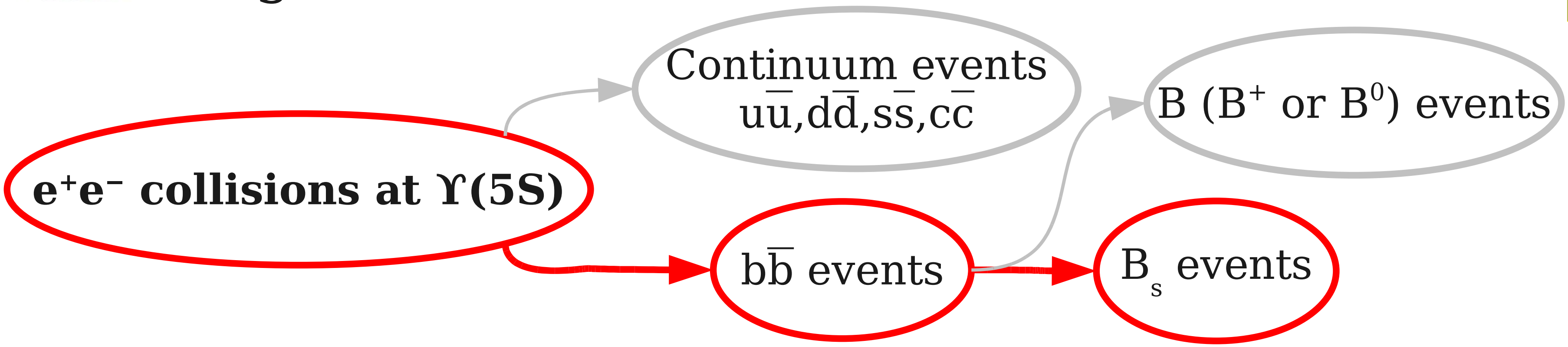
2nd Fox-Wolfram moment: ~ event is jet-like

$$\sigma_{b\bar{b}}^{\Upsilon(5S)} = (0.302 \pm 0.015)\ \text{nb}$$

$$\sigma_{b\bar{b}}^{\Upsilon(4S)} \sim 1.1\ \text{nb}$$

Drutskoy et al. (Belle), PRL 98, 052001 (2007)

B_s production at the $\Upsilon(5S)$

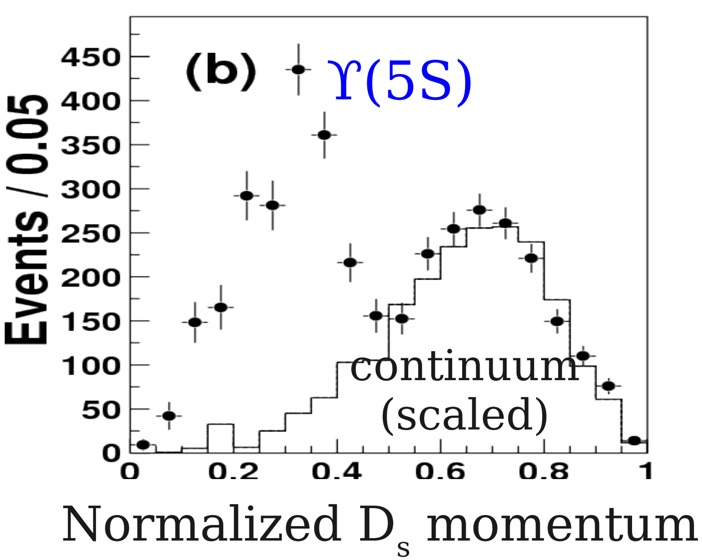


B_s meson production fraction (f_s) measured with inclusive D_s and D

$$\underbrace{\mathcal{B}(\Upsilon(5S) \to D_s X)/2}_{\Upsilon(5S)} = f_s \times \underbrace{\mathcal{B}(B_s \to D_s X)}_{\text{theory}} + (1 - f_s) \times \underbrace{\mathcal{B}(B \to D_s X)}_{\Upsilon(4S),\ \text{Babar}}$$

$$\mathcal{B}(B_s \to D_s X) = (92 \pm 11)\%$$

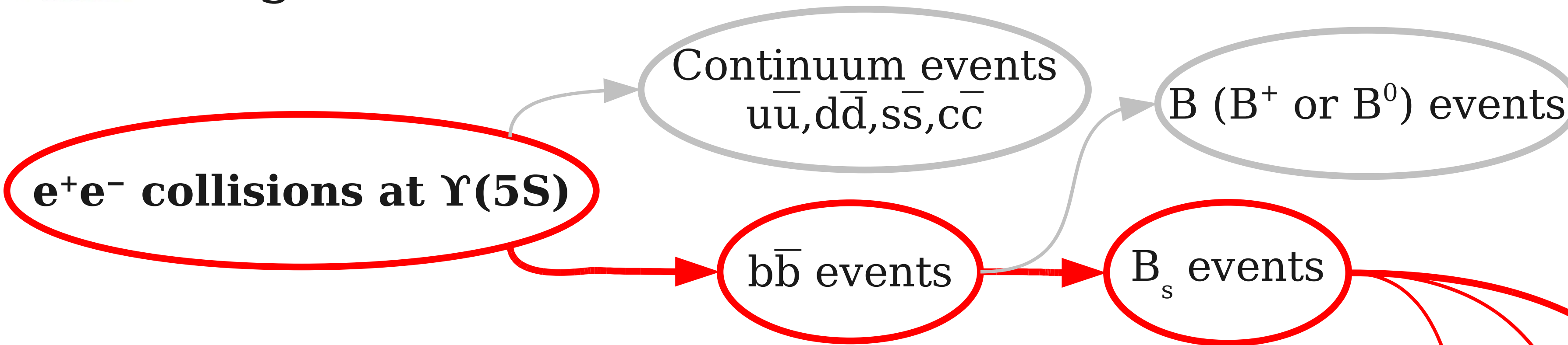
$$f_s = (18.0 \pm 1.3 \pm 3.2)\%$$



In 23.6 fb^{-1}, 2.8 million B_s mesons
~15% uncertainty, mainly due to f_s

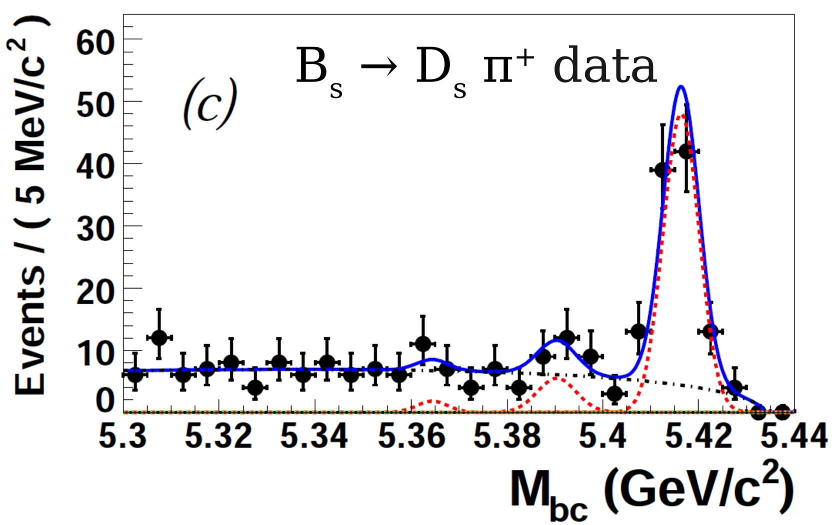
$$N_{B_s^0} = 2 \times \mathcal{L}_{\text{int}} \times \sigma_{b\bar{b}}^{\Upsilon(5S)} \times f_s$$

B_s production at the $\Upsilon(5S)$



$B_s^{(*)}B_s^{(*)}$ production fractions measured with $B_s \to D_s \pi$ decays

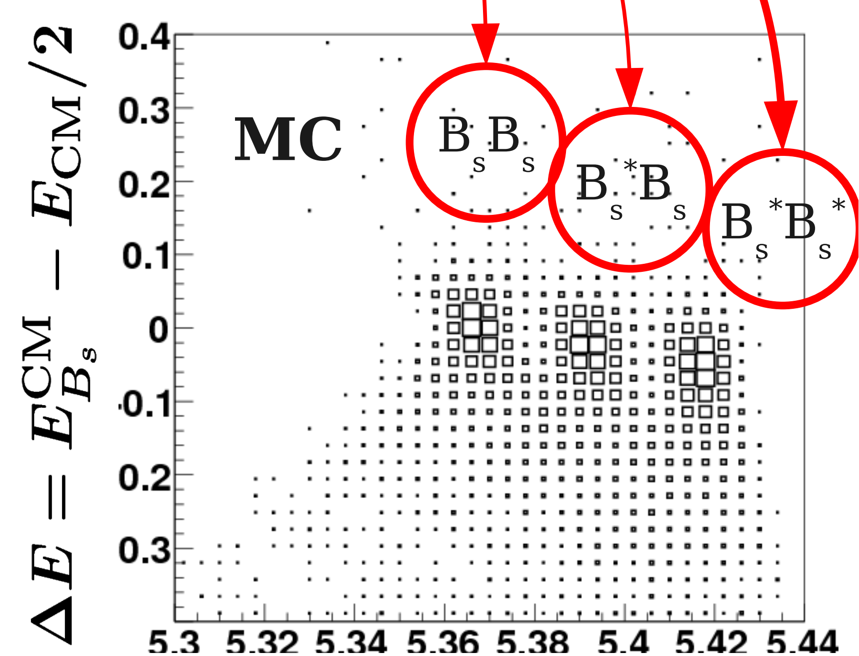
Photon from B_s^* to B_s decay is not reconstructed



$$f_{B_s^* B_s^*} = (90.1^{+3.8}_{-4.0} \pm 0.2)\%$$

$$f_{B_s^* B_s} = (7.3^{+3.3}_{-3.0} \pm 0.1)\%$$

Louvot et al. (Belle), PRL 100, 021801, 2009



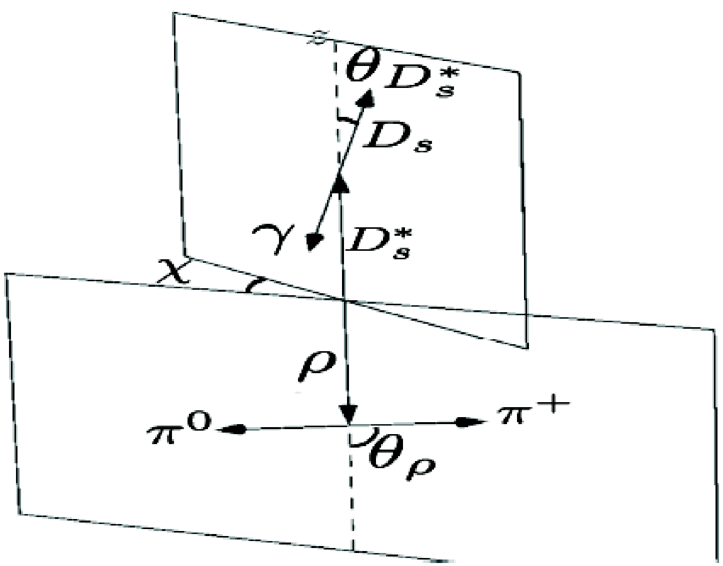
$$M_{\mathrm{bc}} = \sqrt{(E_{\mathrm{CM}}/2)^2 - (p_{B_s}^{\mathrm{CM}})^2}$$

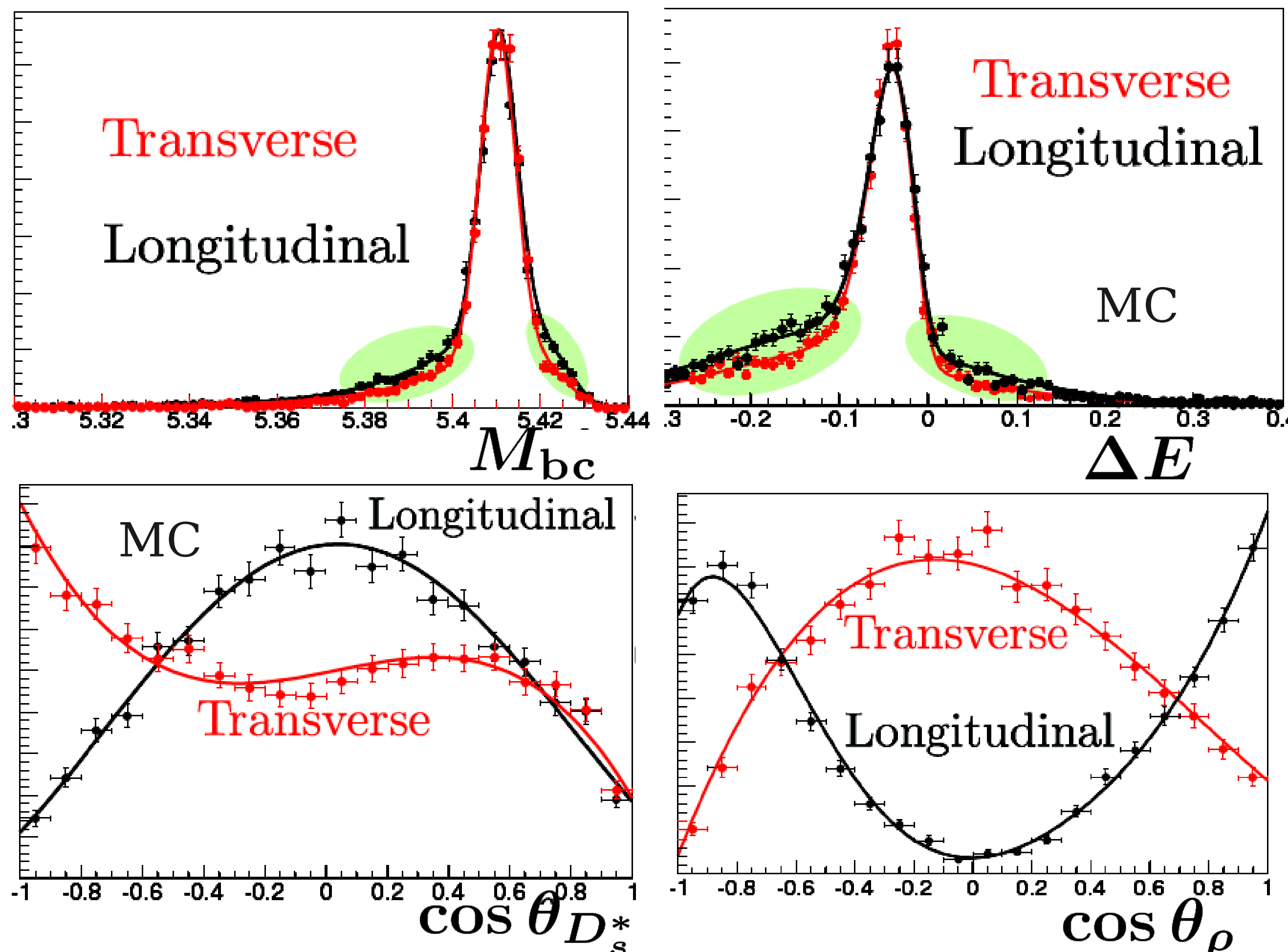
CKM-favored modes

- We have studied:
  - **$B_s \to D_s\, \pi$, $D_s^*\, \pi$, $D_s\, \rho$ and $D_s^*\, \rho$**
- With these high-statistics modes, we can measure
  - **$\Upsilon(5S) \to B_s^{(*)} B_s^{(*)}$ production fractions**, as already shown
  - **Absolute branching fractions** with reasonable accuracy (f_s is the limitation)
    - Proton colliders can't! We can give a reference for the LHC experiments to normalize their B_s branching fractions to.
  - **B_s and B_s^* properties**: masses, widths, angular distributions
    - Can be compared with B^0 and B^*: test of Heavy Quark Effective Theory (HQET), factorization, ...
- Let's have a look at $B_s \to D_s^*\, \rho$.

$B_s \to D_s^* \rho$

- **Decay of a pseudo-scalar to two vectors**
  - longitudinal and transverse polarizations possible
- BF measurement **depends** on the polarization: different M_{bc} and ΔE signal shapes, and different reconstruction efficiency.

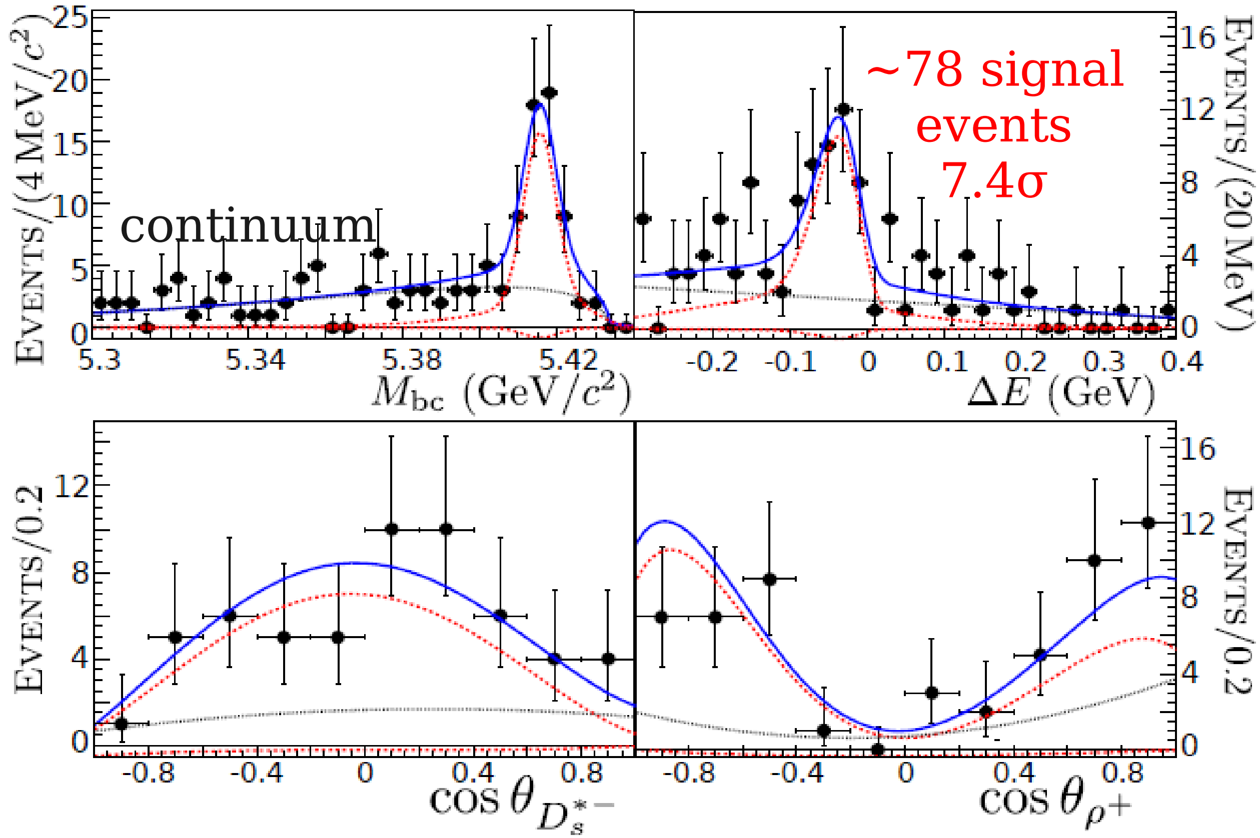




$B_s \to D_s^* \rho$ results

R. Louvot et al. (Belle), PRL 104, 231801 (2010); 23.6 fb^{-1}

4D fit
M_{bc}, ΔE and two angles



First observation!

$$\mathcal{B}(B_s^0 \to D_s^{*-}\rho^+) = (11.8^{+2.2}_{-2.0}(\text{stat.}) \pm 1.7(\text{syst.}) \pm 1.8(f_s))10^{-3}$$

Fraction of longitudinal polarization: $f_L = 1.05^{+0.10+0.03}_{-0.08-0.04}$

Large longitudinal polarization as expected from B^0 partner decay: $f_L(B^0 \to D^* \rho^+) = (88.5 \pm 2.0)\%$

CLEO, PRD 67, 112002 (2003)

theory: $f_L \sim 87\%$ Ali et al., Z.Phys.C 1, 269 (1979)

$B_s \to D_s^{(*)} h$ results

R. Louvot et al. (Belle), PRL 100, 021801 (2009); PRL 104, 231801 (2010); 23.6 fb^{-1}

Branching fractions (10^{-3})

$B_s^0 \to$	Belle		HQET	B^0 partner	CDF (355 pb^{-1})
$D_s^- \pi^+$	$3.67^{+0.35+0.43}_{-0.33-0.42} \pm 0.49$	f_s	2.8	2.68 ± 0.13	$3.8 \pm 0.3 \pm 1.3$
$D_s^{*-} \pi^+$	$2.4^{+0.5}_{-0.4} \pm 0.3 \pm 0.4$		2.8	2.76 ± 0.13	–
$D_s^- \rho^+$	$8.5^{+1.3}_{-1.2} \pm 1.1 \pm 1.3$		7.5	7.6 ± 1.3	–
$D_s^{*-} \rho^+$	$11.9^{+2.2}_{-2.0} \pm 1.7 \pm 1.8$		8.9	6.8 ± 0.9	–

Branching fractions in good agreement with HQET, B^0 partner and CDF

Neutrals (K_S, ρ, γ, π^0) are challenging at proton-colliders but "easy" for us.

CDF, PRL 98, 061802 (2007)

HQET: Deandrea et al., PLB 318, 549 (1993)

Mass (MeV/c^2)

	Belle	CDF (220 pb^{-1})
B_s^0	$5364.4 \pm 1.3 \pm 0.7$	$5366.01 \pm 0.73 \pm 0.33$
B_s^*	$5416.4 \pm 0.4 \pm 0.4$	–

PRL 96, 202001 (2006)

B_s mass: good agreement with CDF but less precise

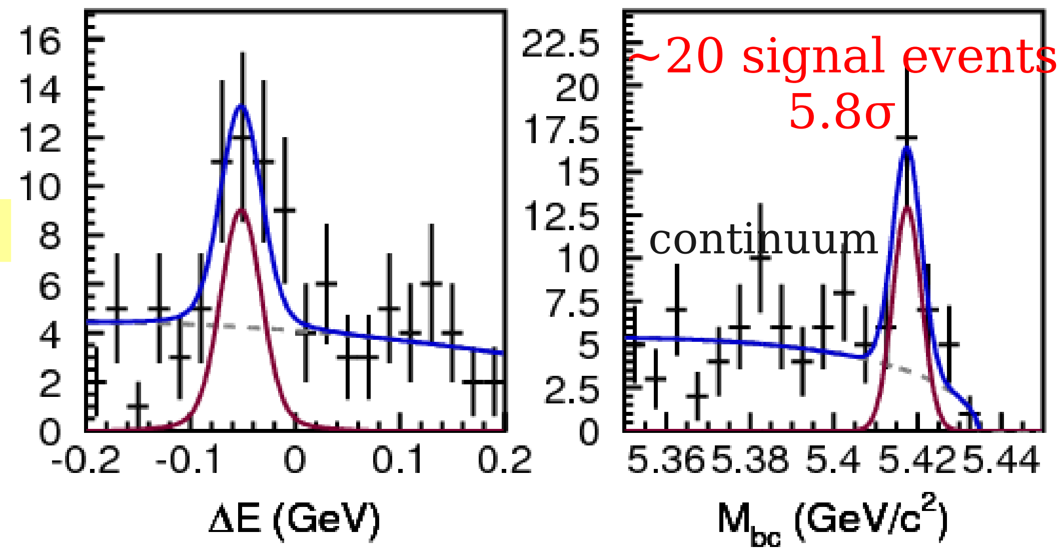
B_s^* mass: improve on CLEO (420 pb^{-1} at $\Upsilon(5S)$)

Charmless: $B_s \to h\ h$

Preliminary, EPS09; 23.6 fb^{-1}

- $B_s \to K^+K^-$ and $B^0 \to \pi^+\pi^-$ are related by SU(3)
  - can probe **New Physics** by comparing CP asymmetries
    London et al., PRD 70, 031502 (2004)
  - can measure the CKM angle **γ/ϕ_3** using the U-spin symmetry.
    Fleischer, PLB 459, 306 (1999)

$B_s \to K^+ K^-$



$B_s^0 \to$	$\mathcal{B}$ (10^{-6}) Belle	CDF (1 fb^{-1})
K^+K^-	$38^{+10}_{-9} \pm 7$	$24.4 \pm 1.4 \pm 4.6$
$K^0\bar{K}^0$	< 66	$-$
$K^-\pi^+$	< 26	$5.0 \pm 0.7 \pm 0.8$
$\pi^+\pi^-$	< 12	< 1.2

CDF, hep-ex/0612018 (2006)
CDF, PRL 103, 031801 (2009)

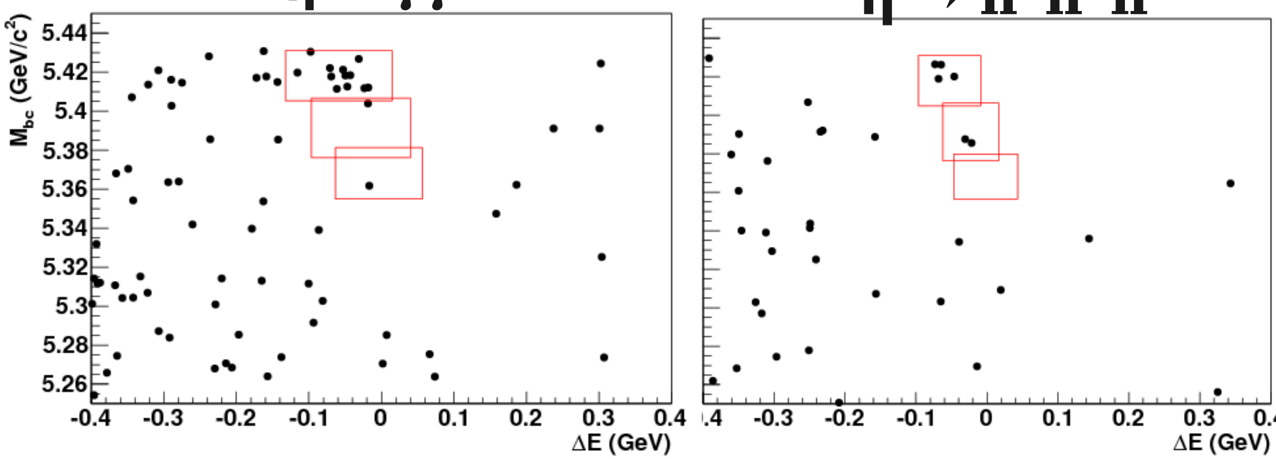
$B_s \to J/\psi\ \eta$

Adachi et al. (Belle), arXiv:0912.1434 (2009); 23.6 fb^{-1}

CP-eigenstate Dunietz et al., PRD 63, 114015 (2001)
measure CP violation parameters: β_s, $\Delta\Gamma_s/\Gamma_s$, ...

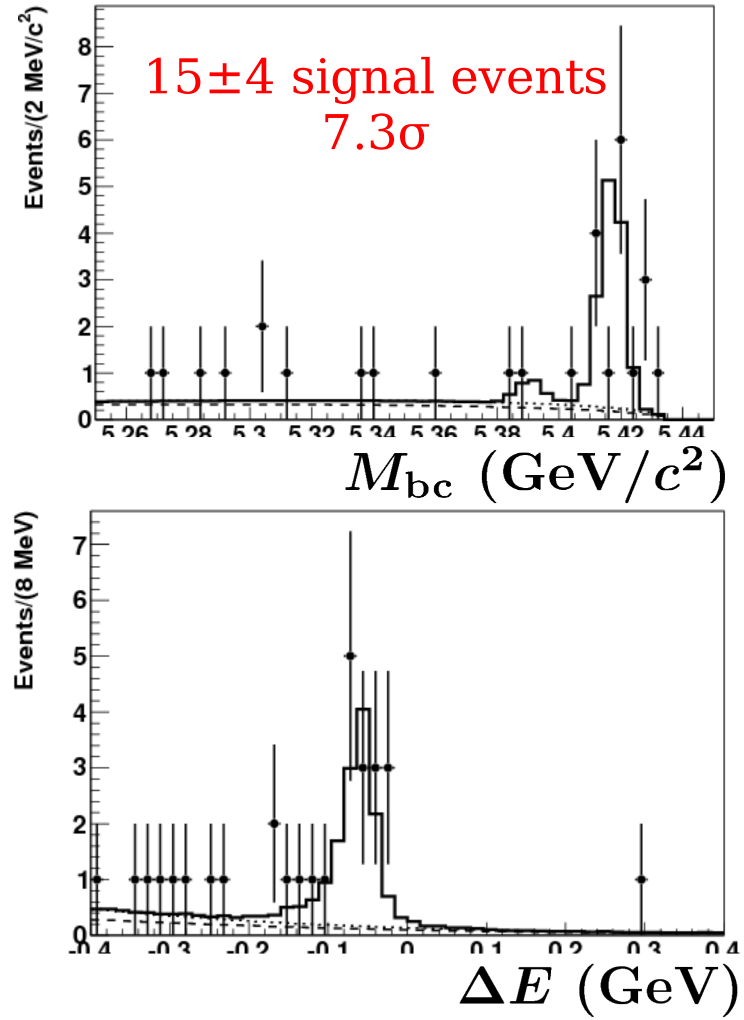
$J/\psi \to e^+e^-, \mu^+\mu^-$

$\eta \to \gamma\gamma$ **$\eta \to \pi^+\pi^-\pi^0$**



Simultaneous fit of the two η decays
Very little background from continuum and $B \to J/\psi$

η modes combined

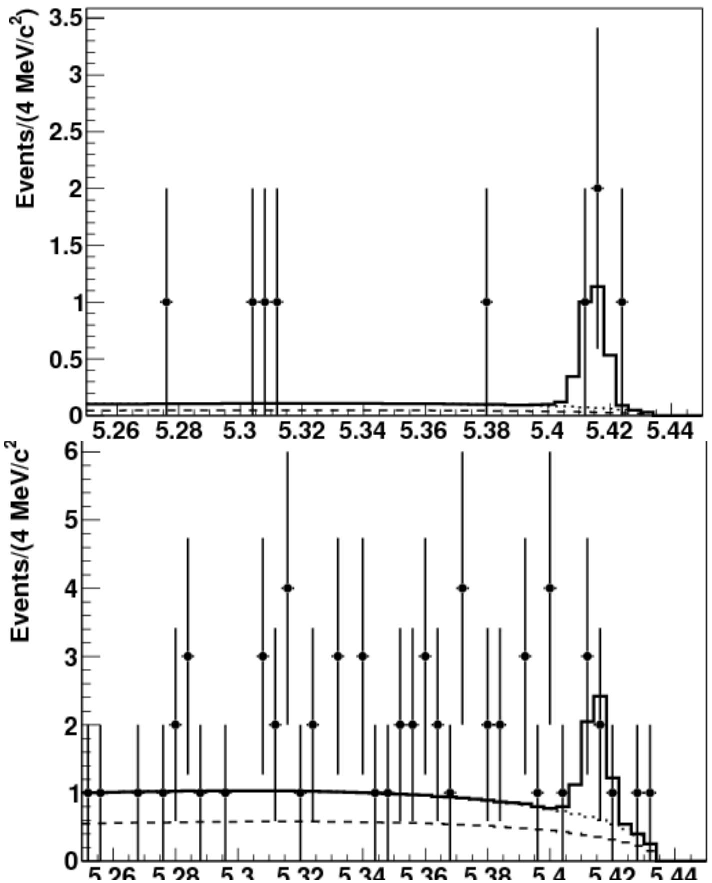


First observation!

$$\mathcal{B}(B_s^0 \to J/\psi\eta) = (3.3 \pm 0.9(\text{stat.}) \pm 0.3(\text{syst.}) \pm 0.4(f_s)) \times 10^{-4}$$

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

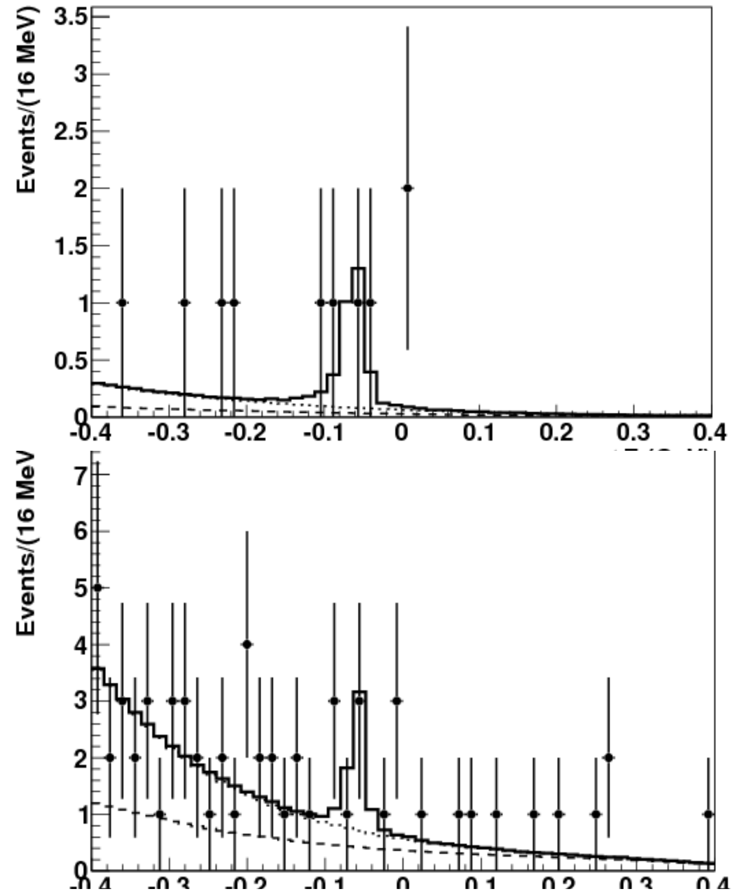
Adachi et al. (Belle), arXiv:0912.1434 (2009); 23.6 fb^{-1}



M_{bc} (GeV/c^2)

$\eta' \to \eta\pi\pi$
with
$\eta \to \gamma\gamma$
$\eta \to \pi\pi\pi^0$

$\eta' \to \rho^0\gamma$



ΔE (GeV)

11±5 signal events
3.8σ

CP-eigenstate

First evidence!

$$\mathcal{B}(B_s^0 \to J/\psi\eta') = (3.1 \pm 1.2(\text{stat.})^{+0.5}_{-0.6}(\text{syst.}) \pm 0.4(f_s)) \times 10^{-4}$$

$B_s \to J/\psi\ f_0(980)$

- **Silver mode for LHCb** to measure β_s, the CP-violating phase in the B_s mixing Stone et al., arXiv:0909.5442 (2009)
  - BF smaller than $B_s \to J/\psi\ \phi$ BUT $J/\psi\ f_0$ is a pure CP-eigenstate
    - **No angular analysis required**
- Branching fraction expectations:

$$\frac{\mathcal{B}(B_s^0 \to J/\psi f_0)\mathcal{B}(f_0 \to \pi^+\pi^-)}{\mathcal{B}(B_s^0 \to J/\psi \phi)\mathcal{B}(\phi \to K^+K^-)} \approx 0.2$$

Stone et al., PRD 79, 074024 (2009)

$$= 0.42 \pm 0.11$$

CLEO ($D_s \to f_0 e\nu$), PRD 80, 052009 (2009)

Using CDF's $B_s \to J/\psi\ \phi$ measurement, we have:

$$\mathcal{B}(B_s^0 \to J/\psi f_0)\mathcal{B}(f_0 \to \pi^+\pi^-) = (1.3 - 2.7)10^{-4}$$

Also

$$\mathcal{B}(B_s^0 \to J/\psi f_0)\mathcal{B}(f_0 \to \pi^+\pi^-) = (3.4 \pm 2.4)10^{-4} \times (50^{+7}_{-9})\%$$

QCD (LO) PRD 81, 074001 (2010) — BES, PRD 80, 052009 (2009)

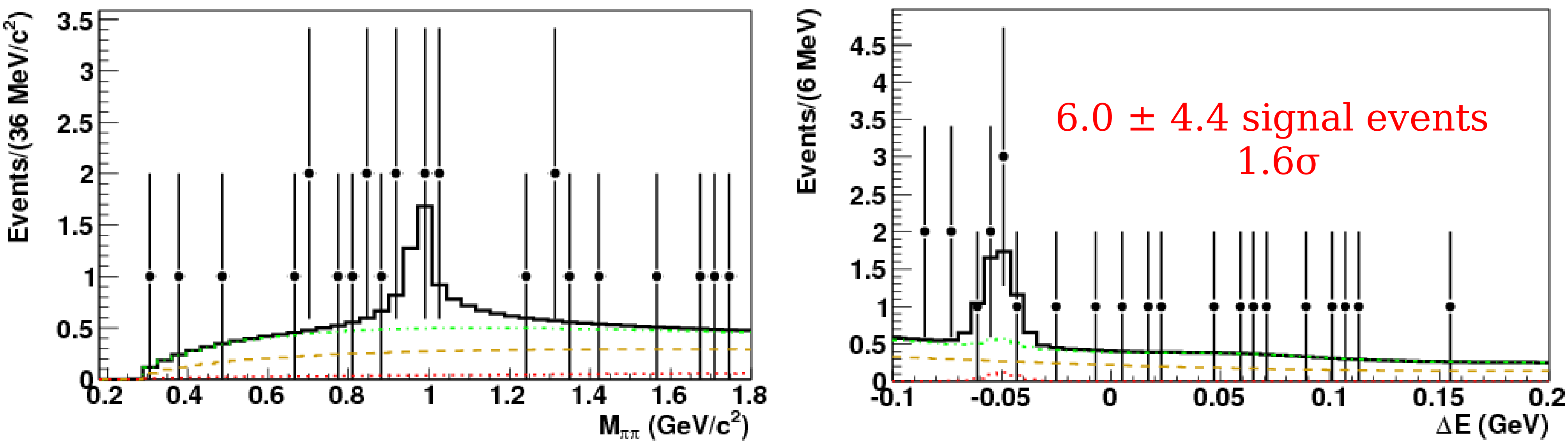
$$= (1.6 \pm 1.3)10^{-4}$$

$B_s \to J/\psi\, f_0(980)$ results

First shown at FPCP 2010; 23.6 fb^{-1}

$J/\psi \to e^+e^-, \mu^+\mu^-$ and $f_0 \to \pi^+\pi^-$

Cut on M_{bc}, and do a fit on $M_{\pi\pi}$ and ΔE



Background from continuum (~50%), $B \to J/\psi X$ (~50%) and non-resonant $B_s \to J/\psi\pi\pi$ (small peak in ΔE).

$$\mathcal{B}(B_s^0 \to J/\psi f_0)\mathcal{B}(f_0 \to \pi^+\pi^-) < 1.63 \times 10^{-4}\ (\text{CL } 90\%)$$

Expectations:
$$\mathcal{B}(B_s^0 \to J/\psi f_0)\mathcal{B}(f_0 \to \pi^+\pi^-) = (1.3 - 2.7)10^{-4}$$
$$= (1.6 \pm 1.3)10^{-4}$$

We need to analyze our 120 fb^{-1} of data as soon as possible!

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

- In the heavy quark limit, assuming $|m_b - 2\,m_c| \to 0$, $N_{colors} \to \infty$
  - Predominantly CP-even eigenstates
  - CKM-favored: $\Gamma(B_s \to D_s^{(*)} D_s^{(*)})$ is expected to saturate $\Delta\Gamma_s^{CP}$

$$\Gamma(B_s^0 \to D_s^{(*)} D_s^{(*)}) \approx \Delta\Gamma_s^{CP} = \Gamma(CP\text{−even}) - \Gamma(CP\text{−odd}) = \frac{\Delta\Gamma_s}{\cos\phi}$$

where ϕ is a CP-violating phase.
Assuming negligible CP-violation ($\phi \sim 0$), we can derive

$$\frac{\Delta\Gamma_s}{\Gamma_s} = \frac{\Gamma_{s,L} - \Gamma_{s,H}}{\Gamma_s} = \frac{2\mathcal{B}(B_s^0 \to D_s^{(*)} D_s^{(*)})}{1 - \mathcal{B}(B_s^0 \to D_s^{(*)} D_s^{(*)})}$$

Aleksan et al., PLB 316, 567 (1993)

- Our analysis:
  - Reconstruction of $B_s \to D_s^* D_s^*$, $B_s \to D_s^* D_s$ and $B_s \to D_s D_s$ **separately**
    - $D_s^* \to D_s \gamma$ with six D_s decays: $\phi\pi$, $K_S K$, $K^* K$, $\phi\rho$, $K_S K^*$, $K^* K^*$
  - Due to **very large cross-feeds** (reconstruct three times the same event in all modes): select a maximum of one candidate per event among the three modes:
    - minimum χ^2 computed with $M(D_s)$ and $M(D_s^*) - M(D_s)$

$B_s \to D_s^{(*)} D_s^{(*)}$ results

S. Esen et al. (Belle), arXiv:1005.5177 [hep-ex], submitted to PRL; 23.6 fb^{-1}

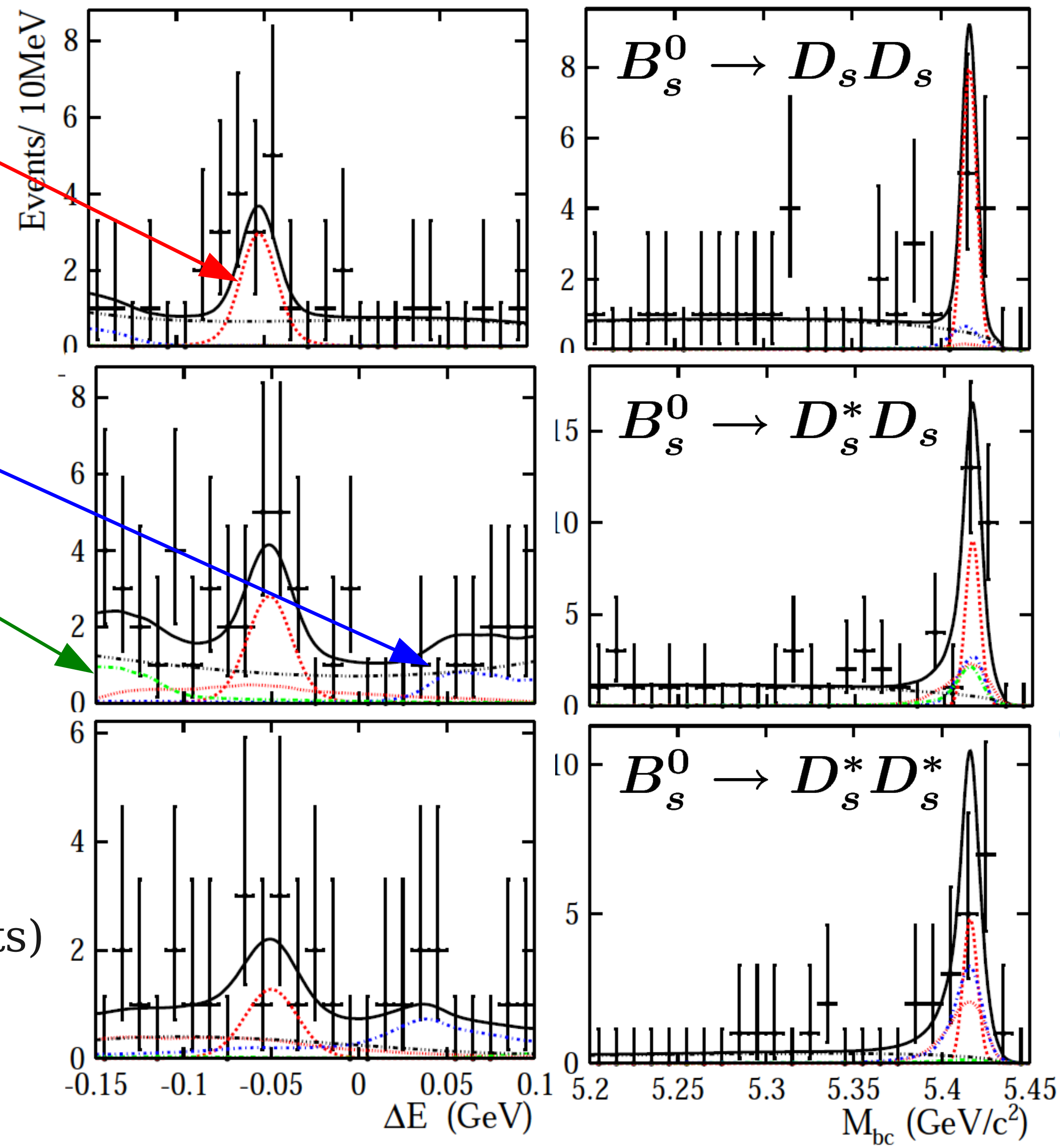
Signals:

Correctly reconstr. (sharp ΔE peak)

Wrong combinations (broad ΔE peak)

Cross-feeds:

- One photon gained
  - ie. $D_s D_s$ rec. as $D_s^* D_s$
- One photon missed
  - ie. $D_s^* D_s^*$ rec. as $D_s^* D_s$



Backgrounds:

entirely from $B_{(s)}$ decays,

negligible continuum contribution

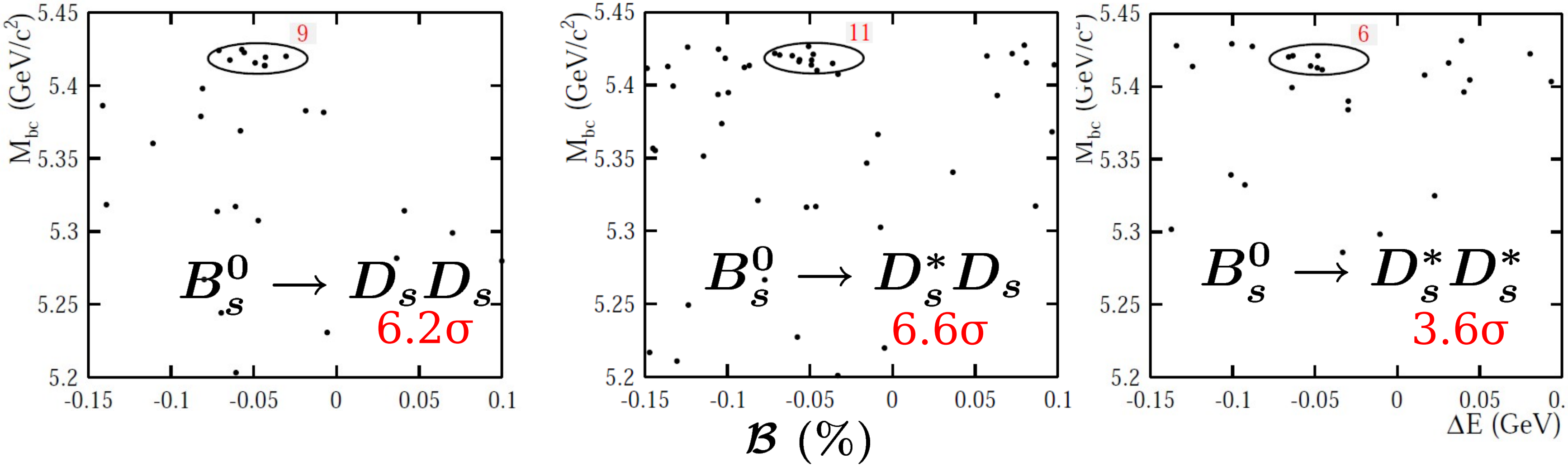
Simultaneous fit of the three modes

Fit validated with similar analyzes of

- $B^+ \to D_s^{(*)} D$ at $\Upsilon(4S)$ (1800 signal events)
- $B_s \to D_s^{(*)} \pi$ at $\Upsilon(5S)$ (170 signal events)

$B_s \to D_s^{(*)} D_s^{(*)}$ results

S. Esen et al. (Belle), arXiv:1005.5177 [hep-ex], submitted to PRL; 23.6 fb^{-1}



$B_s^0 \to$	Belle	Tevatron (PDG)
$D_s D_s$	$1.03^{+0.39+0.15}_{-0.32-0.13} \pm 0.21$	$1.07^{+0.36}_{-0.33} \pm 0.1$
$D_s^* D_s$	$2.75^{+0.83}_{-0.71} \pm 0.40 \pm 0.56$	–
$D_s^* D_s^*$	$3.08^{+1.22}_{-1.04} \pm 0.56 \pm 0.63$	–
$D_s^{(*)} D_s^{(*)}$	$6.85^{+1.53+1.26}_{-1.30-1.25} \pm 1.41$	$3.5 \pm 1.0 \pm 1.1$

CDF, 355 pb^{-1},
PRL 100, 021803 (2008)

D0, 2.8 fb^{-1}
PRL 102, 091801 (2009)

	$\Delta\Gamma_s/\Gamma_s$ (%)
Belle	$14.7^{+3.6+4.4}_{-3.0-4.2}$
D0	7.2 ± 3.0

First exclusive measurements of $B_s \to D_s^* D_s$ and $D_s^* D_s^*$
Competitive measurement of $\Delta\Gamma_s/\Gamma_s$ with ~20 events

$B_s \to J/\psi\phi$ (CDF, 5.2 fb^{-1}, FPCP 2010)

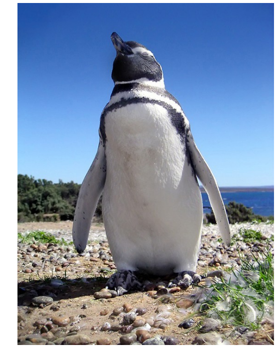
$$\Delta\Gamma_s/\Gamma_s = (11.5 \pm 5.4)\%$$

Summary

- Sample of 2.8 million B_s (23.6 fb^{-1}) studied
  - CKM-favored: $B_s \to D_s^* \pi^+$, $D_s^* \rho^+$ and $D_s \rho^+$
    - First observations, large signals seen
  - Charmless $B_s \to hh$: $B_s \to K^+ K^-$ observed
  - CP eigenstates:
    - $B_s \to J/\psi\, \eta$, $J/\psi\, \eta'$: first observation and evidence
    - No evidence of $B_s \to J/\psi\, f_0(980)$. Need full data sample update!
    - $B_s \to D_s^{(*)} D_s^{(*)}$ exclusively studied: $\Delta\Gamma_s/\Gamma_s$ measured.
  - Many of these final states can only be studied in the clean environment of an e^+e^- collider!
- Five times more data available! More results in the pipeline!
  - Belle has also reprocessed its data! Tracking is improved: you can even expect more than five times better.
  - We are also working on reducing the uncertainty on f_s toward 5%.

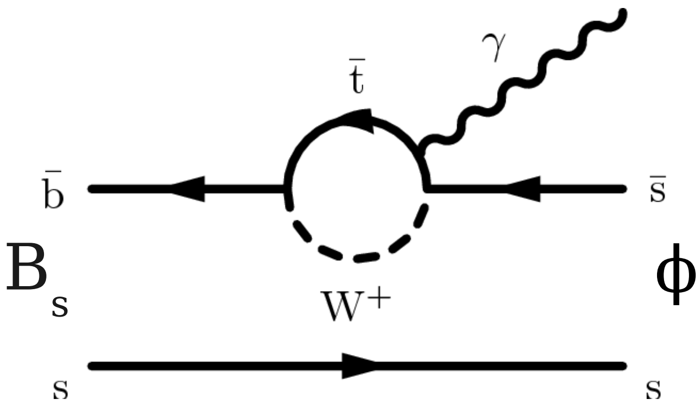
Penguin decays involve loop diagrams

Good probe for New Physics:
new particles can move observables away from their SM expectations



$B_s \to \phi\gamma$

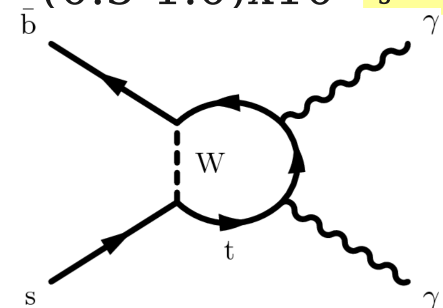
- Standard Model: electromagnetic penguin
  - BF = $(40\pm10)\times10^{-6}$ PRD 75, 054004 (2007) arXiv:0709.4422 (2007)



- We do not really expect to see NP in the rate; good agreements in:
  - Partner of $B^{+/0} \to K^*(892)^{+/0}\gamma$
  - Inclusive $b \to s\gamma$

$B_s \to \gamma\gamma$

- SM: annihilation penguin
  - BF=$(0.5\text{-}1.0)\times10^{-6}$ PRD 56, 5805 (1997) JHEP 0208 054 (2002)



- Very sensitive to NP!
  - SUSY with broken R-parity
    PRD 70, 035008 (2004)
  - 4^{th} quark generation
    arXiv:hep-ph/0302177 (2003)
  - Two Higgs doublet with FCNC
    PRD 58, 095014 (1998)

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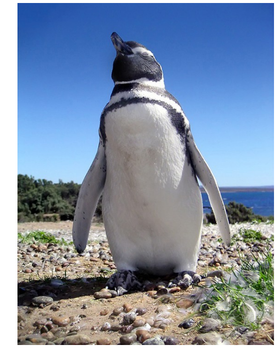

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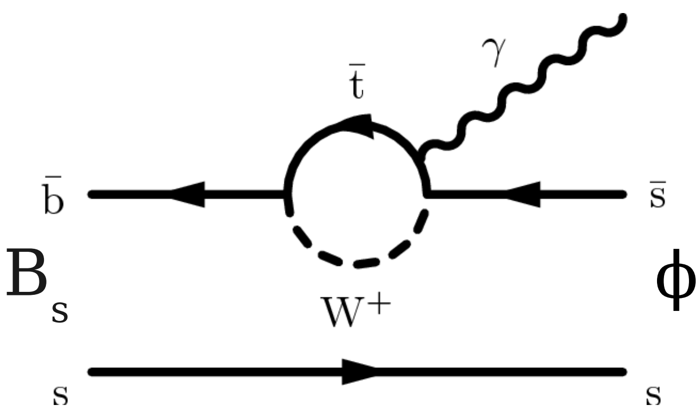

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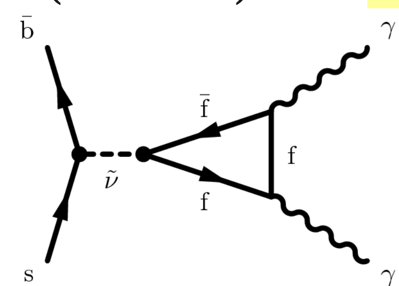
  - Partner of $B^{+/0} \to K^{*}(892)^{+/0}\, \gamma$
  - Inclusive $b \to s\, \gamma$

$B_s \to \gamma\, \gamma$

- SM: annihilation penguin
  - BF=$(0.5\text{-}1.0)\times10^{-6}$ PRD 56, 5805 (1997) JHEP 0208 054 (2002)



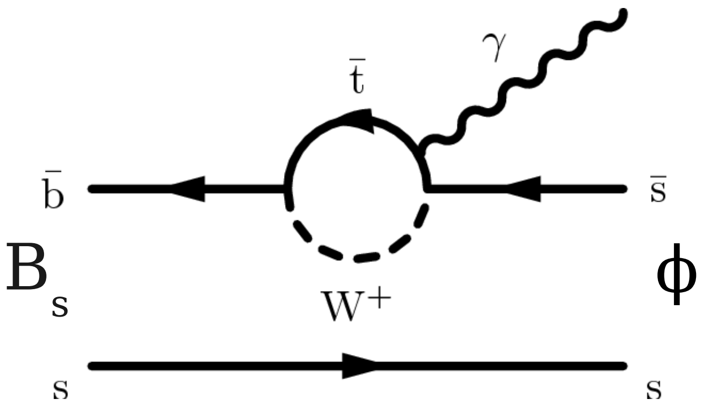
- Very sensitive to NP!
  - **SUSY with broken R-parity** PRD 70, 035008 (2004)
  - 4^{th} quark generation arXiv:hep-ph/0302177 (2003)
  - Two Higgs doublet with FCNC PRD 58, 095014 (1998)

Penguin decays involve loop diagrams

Good probe for New Physics:
new particles can move observables away from their SM expectations

$B_s \to \phi\gamma$

- Standard Model: electromagnetic penguin
  - $BF = (40\pm10)\mathrm{x}10^{-6}$ PRD 75, 054004 (2007) arXiv:0709.4422 (2007)



- We do not really expect to see NP in the rate; good agreements in:
  - Partner of $B^{+/0} \to K^*(892)^{+/0}\gamma$
  - Inclusive $b \to s\gamma$

$B_s \to \gamma\gamma$

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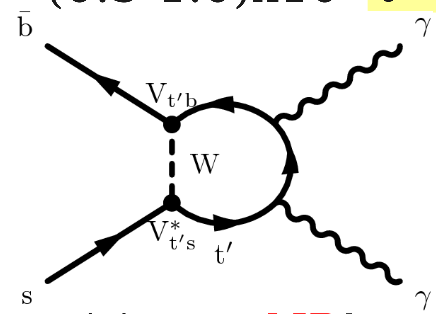

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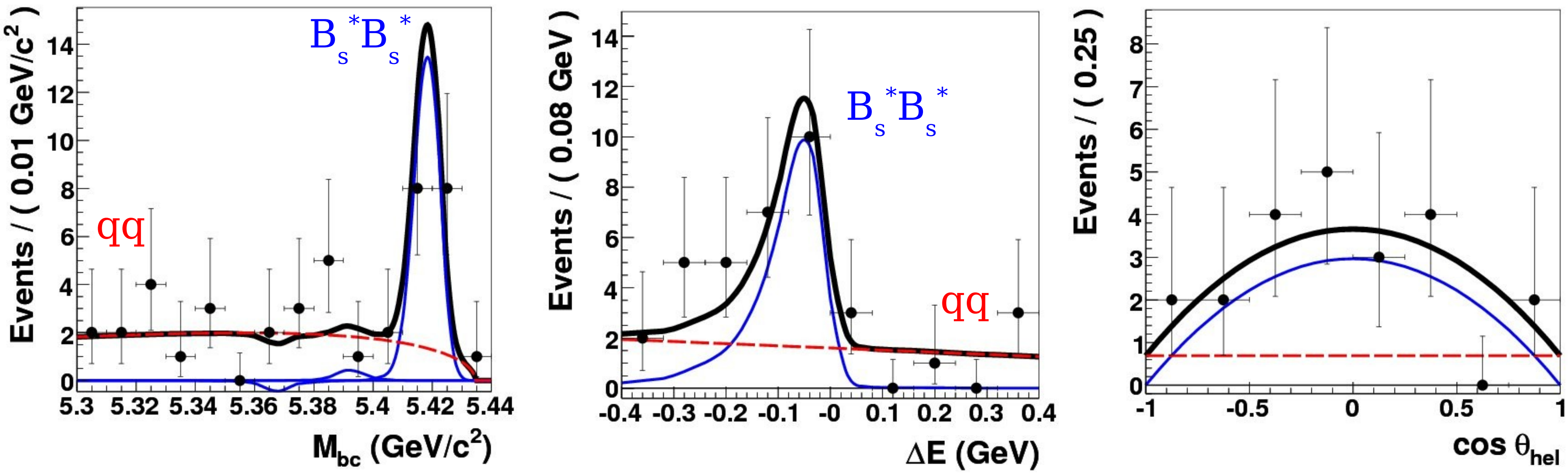
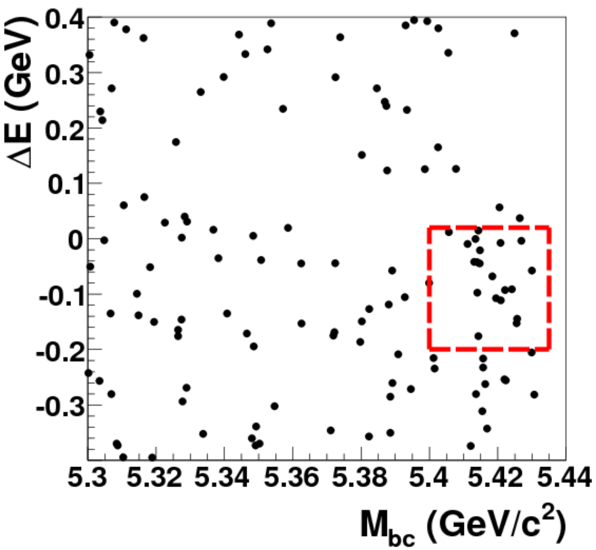
Result: $B_s \to \phi\,\gamma$



$\theta_{hel} = \measuredangle(B_s, K^+)$ in ϕ CM



First observation of a B_s radiative penguin decay!

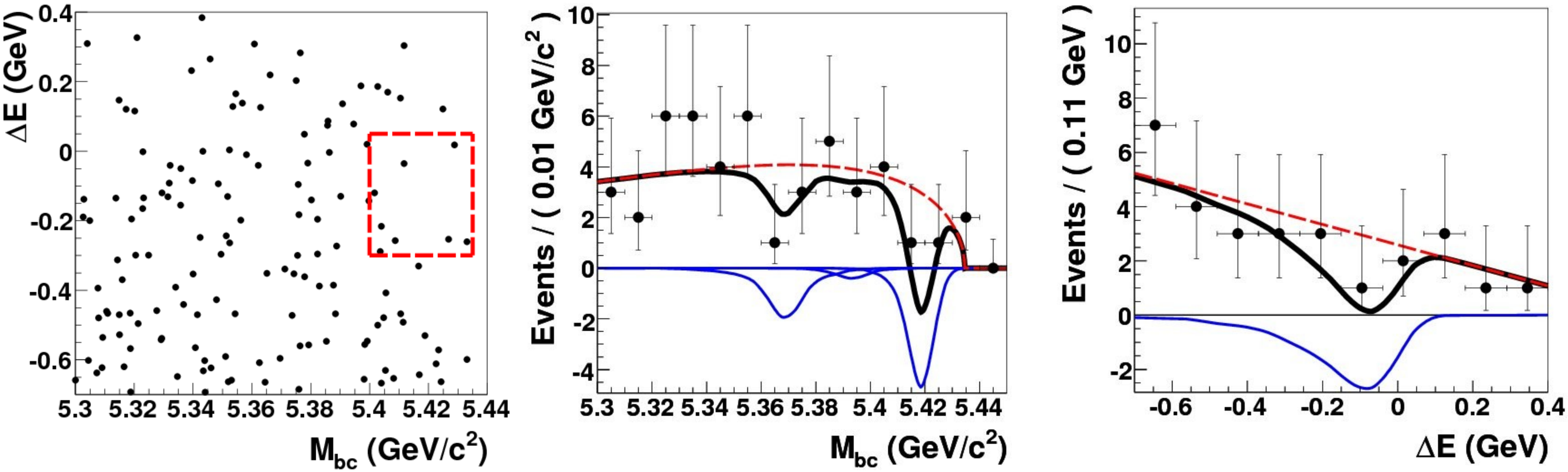
18±6 signal events

$$\mathcal{B}(B_s^0 \to \phi\gamma) = (57^{+18+12}_{-15-11}) \times 10^{-6}$$

compatible with SM

Wicht et al. (Belle),
PRL 100, 121801 (2008)

Result: $B_s \to \gamma\,\gamma$



No signal!

$$\mathcal{B}(B_s^0 \to \gamma\gamma) < 8.7 \times 10^{-6}\ (90\%\ \mathrm{CL})$$

~6x lower than previous limit (Belle, 2fb^{-1} at ϒ(5S))
~10x higher than SM!
Above the interesting NP region!

Need a Super B factory!

Wicht et al. (Belle),
PRL 100, 121801 (2008)