$B_s^0 \rightarrow$ CP eigenstate decays

5th International Workshop at High-1

(2011/02/09)

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- Results and outlook in the Belle experiment.
- Not comprehensive.

B_s^0 production at ϒ(5S): $\sigma(b\bar{b})$

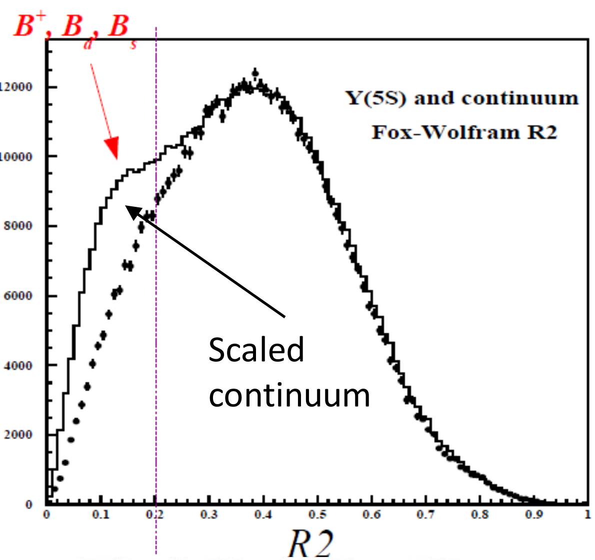
u,d,s,c events

Hadronic ϒ(5S) events

$b\bar{b}$ events

CLEO (PRD 75,012002)
BELLE (PRL 98,052001)

$\sigma(b\bar{b}) = (0.302 \pm 0.014)$ fb



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

Scale factor

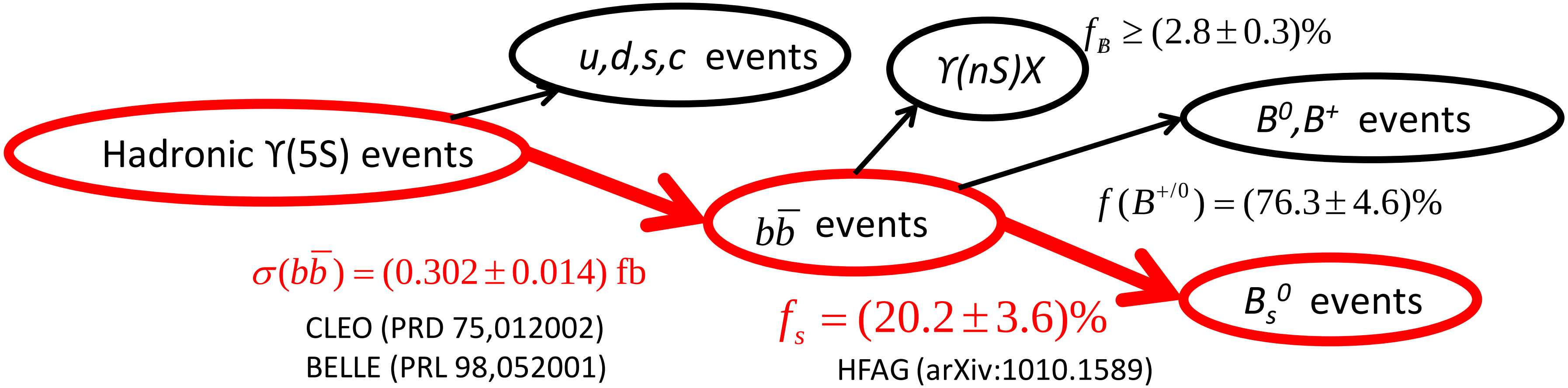
$$N_{5S}^{b\bar{b}} = \frac{1}{\epsilon_{5S}^{b\bar{b}}}\left(N_{5S}^{\mathrm{had}} - N_{\mathrm{cont}}^{\mathrm{had}} \frac{\mathcal{L}_{5S}}{\mathcal{L}_{\mathrm{cont}}} \frac{E_{\mathrm{cont}}^2}{E_{5S}^2} \frac{\epsilon_{5S}^{\mathrm{con}}}{\epsilon_{\mathrm{cont}}^{\mathrm{con}}}\right).$$

On resonance data

Continuum below open-beauty threshold

2nd Fox-Wolfram moments: different for continuum and $B\bar{B}$ events

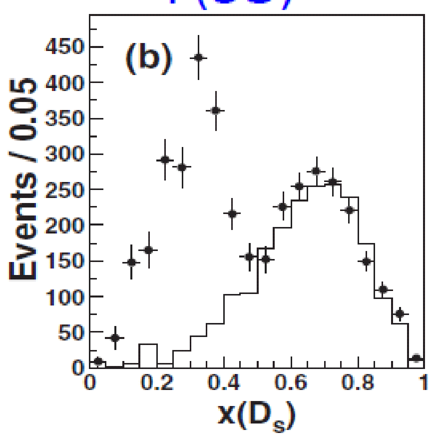
B_s^0 production at Υ(5S): f_s



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

theory → Close to 100%

Υ(4S), Babar → Small number: ~8. 7%



Normalized D_s momentum

f_s: 15% uncertainty, dominant systematic error for branching fraction measurements.

Alternative method for f_s measurement

Model independent way: calculate the fraction of same sign leptons.

Sia & Stone, PRD 74, 031501 (2006)

Probability for two B decays to same or opposite flavor:

$$P_{\pm\pm} = P(BB) + P(\bar{B}\bar{B}) \qquad P_{\pm\mp} = P(B\bar{B}) + P(\bar{B}B)$$

For B^0, mixing parameter $x=\Delta m/\Gamma=0.774 \pm 0.008$

C=−1 state:

$$P^{C_-}_{\pm\pm} = \chi = \frac{x^2}{2(1+x^2)} = 18.7\%$$

$$P^{C_-}_{\pm\mp} = 1-\chi = \frac{2+x^2}{2(1+x^2)} = 81.3\%$$

C=+1 state:

$$P^{C_+}_{\pm\pm} = \frac{x^2(3+x^2)}{2(1+x^2)^2} = 42.2\%$$

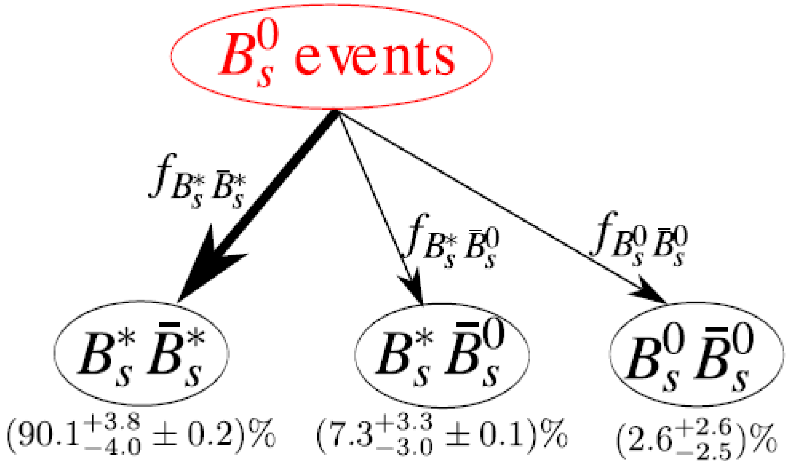
$$P^{C_+}_{\pm\mp} = \frac{2+x^2+x^4}{2(1+x^2)^2} = 57.8\%$$

Same story for B_s^0, except that $x = 21.6 \pm 0.5$, so in all cases:

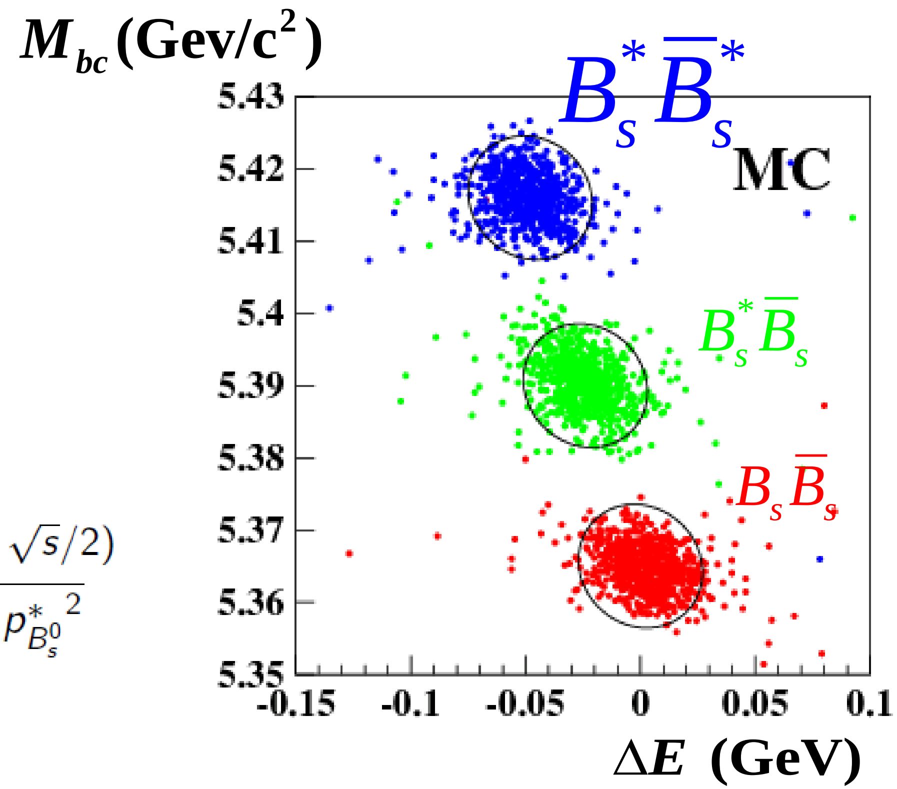
$$P_{\pm(\pm,\mp)} \simeq 1/2$$

$\Upsilon(5S)$ decay mode with a $B^0\bar{B}^0$ pair	C-parity of the $B\bar{B}$ pair
$B^{0*}B^{0*}$	-1
$B^{0*}\bar{B}^0$	$+1$
$B^0\bar{B}^0$	-1
$B^{0*}\bar{B}^{0*}\pi^0$	-1
$B^{0*}\bar{B}^0\pi^0$	$+1$
$B^0\bar{B}^0\pi^0$	-1
$B^0\bar{B}^0\pi^0\pi^0$	-1
$B^0\bar{B}^0\pi^+\pi^-$	$(-1)^{l_{\pi\pi}+1} \approx -1$
$B^0\bar{B}^0\gamma_{\rm ISR}$	-1

B_s^0 reconstruction



Belle (PRL 102,021801)



- Full reconstruction of the B_s^0. Observables: $(E_b^* = \sqrt{s}/2)$
  - Beam-constrained mass: $M_{bc} = \sqrt{{E_b^*}^2 - {p_{B_s^0}^*}^2}$
  - Energy difference: $\Delta E = E_{B_s^0}^* - E_b^*$
- 3 production modes:
  $\Upsilon(5S) \to B_s^* \bar{B}_s^*$, $\Upsilon(5S) \to B_s^* \bar{B}_s^0$ and $\Upsilon(5S) \to B_s^0 \bar{B}_s^0$.
- $\boldsymbol{B_s^*} \to B_s^0 \gamma$ **cannot be reconstructed** (γ too soft)
- In the $(M_{bc}, \Delta E)$ plane, $\boldsymbol{B_s^0}$ candidates are in **3 signal regions**

CP eigenstate in B_s^0 decay

In general overview, Bs decays to CP eigenstate can be used for searching for New Physics and test the CKM source of CP violation.

- Dunietz, Fleischer & Nierste, Phys. Rev. D 63, 114015 (2001)

In particular for $B_s^0 \rightarrow$ CP eigenstates:

- $B_s^0 \rightarrow K^+ K^-$:
  - Branching Fraction, CP asymmetry sensitive to New Physics.

    - London, & Matias, PRD70, 031502 (2004)
  - Can measure $\phi_3(\gamma)$ via U-spin and $B^0 \rightarrow \pi^+\pi^-$.

    - Fleischer, Phys. Lett. B 459, 306 (1999)
- CP violation in $b \rightarrow c\bar{c}s$ transition is very small in SM, while NP may contribute.
  - Modes: $B_s^0 \rightarrow D_s^{(*)+} D_s^{(*)-}$, $B_s^0 \rightarrow J/\psi(\phi, f\_0, \eta('))$, … .
  - BF($B_s^0 \rightarrow D_s^{(*)+} D_s^{(*)-}$) also related to $\Delta\Gamma_{CP}$ in Bs mixing

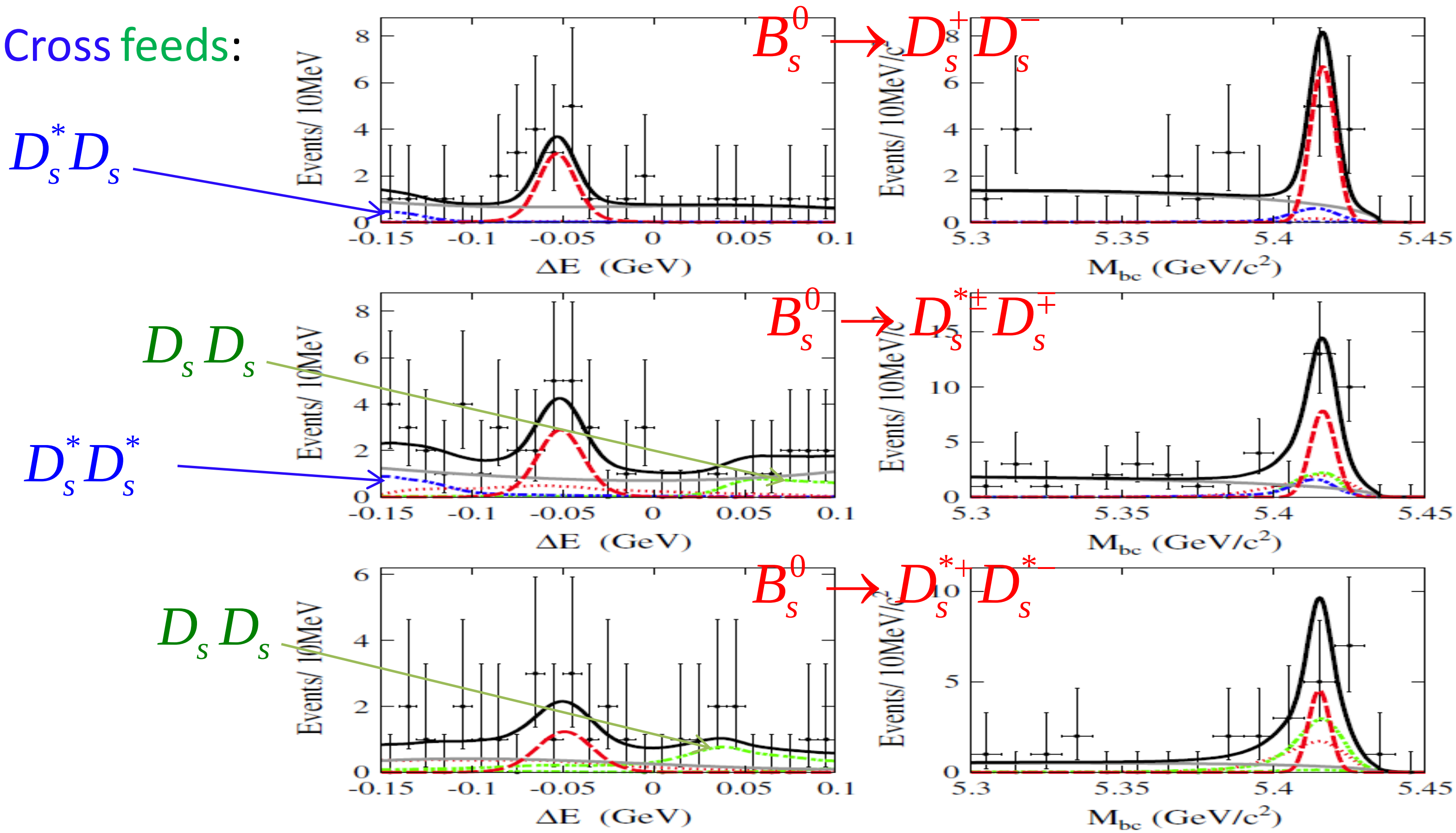
    - Aleksan et al., Phys. Lett. B 316, 567 (1993)

$$2BF(B_s^0 \rightarrow D_s^{(*)+} D_s^{(*)-}) \simeq \Delta\Gamma_{CP} / \Gamma$$

Establishing those modes is the first step.

$B_s^0 \to D_s^{(*)+} D_s^{(*)-}$ analysis

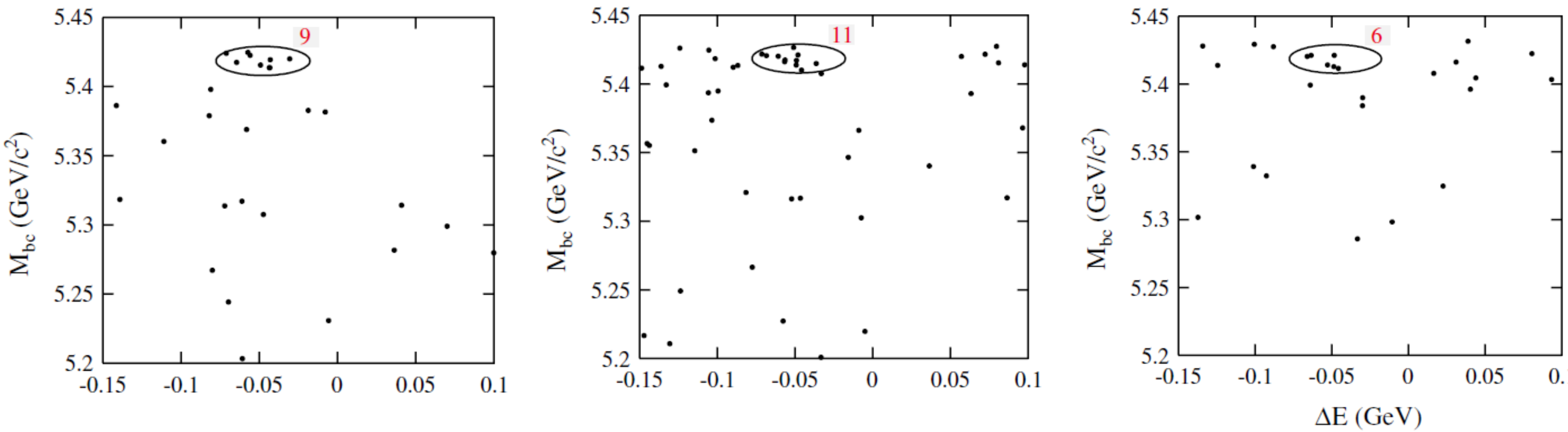
S. Esen et al. (Belle) PRL 105, 201802 (2010)



6 Ds modes is reconstructed: $\phi\pi^+$, $K_S^0 K^+$, $\bar{K}^{*0} K^+$, $\phi\rho^+$, $K_S^0 K^{*+}$ and $\bar{K}^{*0} K^{*+}$

Cross feed matrix used. (Cross feed due to missing or plus γ in Ds*→Ds γ).

Observation of $B_s^0 \to D_s^{(*)+} D_s^{(*)-}$



$\mathcal{B}(B_s^0 \to D_s^+ D_s^-) = (1.0^{+0.4+0.3}_{-0.3-0.2})\%$ $\mathcal{B}(B_s^0 \to D_s^{*\pm} D_s^{*\mp}) = (2.8^{+0.8}_{-0.7} \pm 0.7)\%$ $\mathcal{B}(B_s^0 \to D_s^{*+} D_s^{*-}) = (3.1^{+1.2}_{-1.0} \pm 0.8)\%$

First observation First evidence

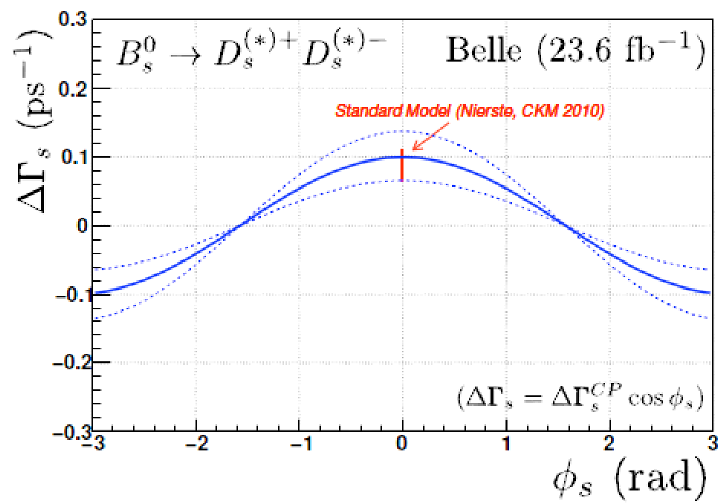
S. Esen et al. (Belle) PRL 105, 201802 (2010)

$$\mathcal{B}\left(B_s^0 \to D_s^{(*)+} D_s^{(*)-}\right) = \left(6.9^{+1.5}_{-1.3} \pm 1.9\right)\%$$

$$\frac{\Delta\Gamma_s^{CP}}{\Gamma_s} = \left(14.7^{+3.6}_{-3.0}{}^{+4.4}_{-4.2}\right)\%$$

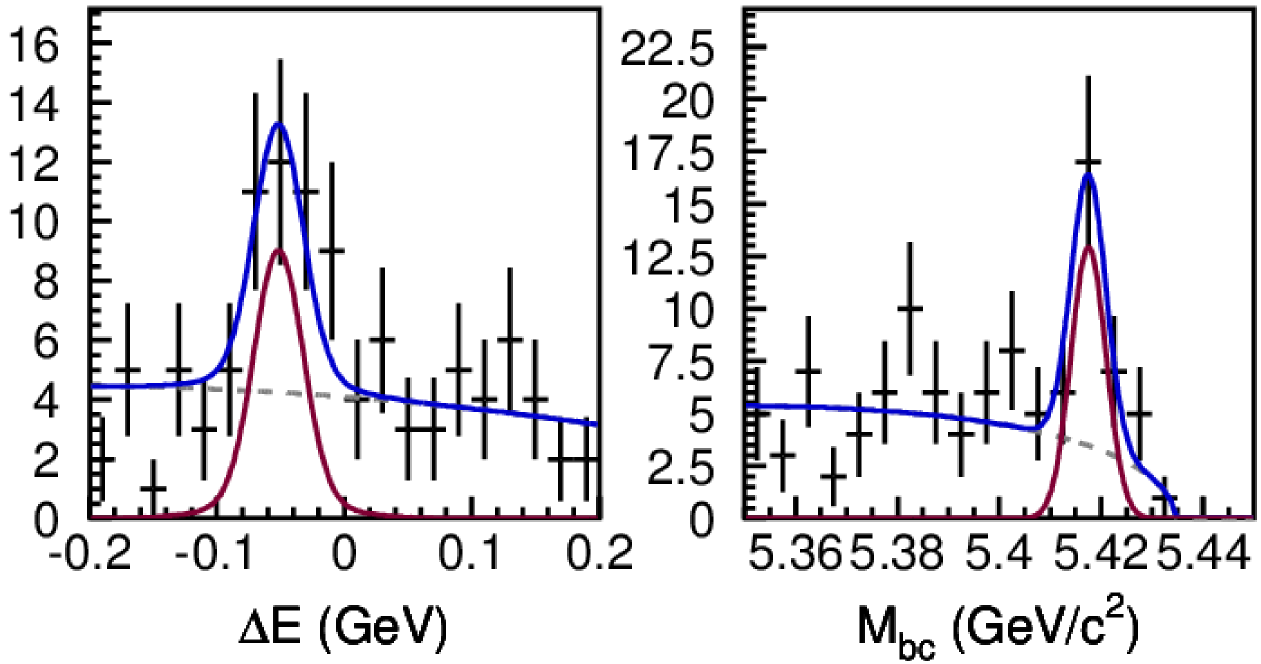
CDF: $(12 \pm 10)\%$ [PRL 100, 121803]
D0: $(7.2 \pm 3.0)\%$ [PRL 102, 091801]

Competitive precision with 23.6 fb^{-1}



$B_s^0 \to K^+K^-$

C.C. Peng et al. (Belle) PRD82, 072007 (2010)



23 ± 6 events observed (5.8σ)

$$\mathcal{B}(B_s^0 \to K^+K^-) = (3.8^{+1.0}_{-0.9} \pm 0.7)\times 10^{-5}$$

CDF: $(2.44\pm0.14\pm0.46)\times10^{-5}$
(Nucl.Phys.Proc.Suppl.170:39-45,2007.)

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

- Extrapolation from $B_s \to J/\psi\Phi$

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

$\approx 0.2 - 0.3$

Stone et al., PRD79, 074024 (2009)

$= 0.42 \pm 0.11$

CLEO D_s+ -> $f_0 e^+ \nu$, PRD80,052009 (2009)

CDF: $B(B_s \to J/\psi\Phi\ ;\ \Phi \to K^+K^-) = (6.4 \pm 2.0) \times 10^{-4}$

$\Rightarrow B(B_s \to J/\psi f_0\ ;\ f_0 \to \pi^+\pi^-) =$ **$(1.3\text{-}2.7) \times 10^{-4}$**

- Theory (QCD @ LO)

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

QCD(LO), PRD81,074001 (2010)

BES, PRD80, 052009 (2009)

$=$ **$(1.6 \pm 0.3) \times 10^{-4}$**

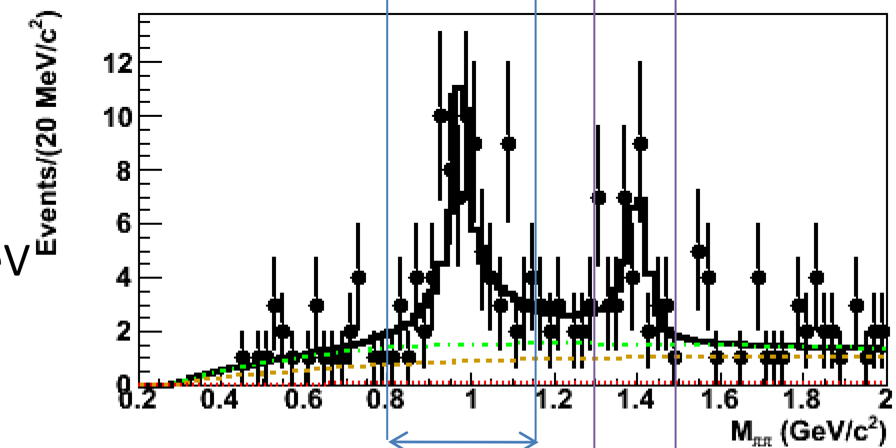
$B_s^0 \rightarrow J/\psi f_0(980)$

A surprise, two peaks observed!

121.4 fb^{-1} $\Upsilon(5S)$ data

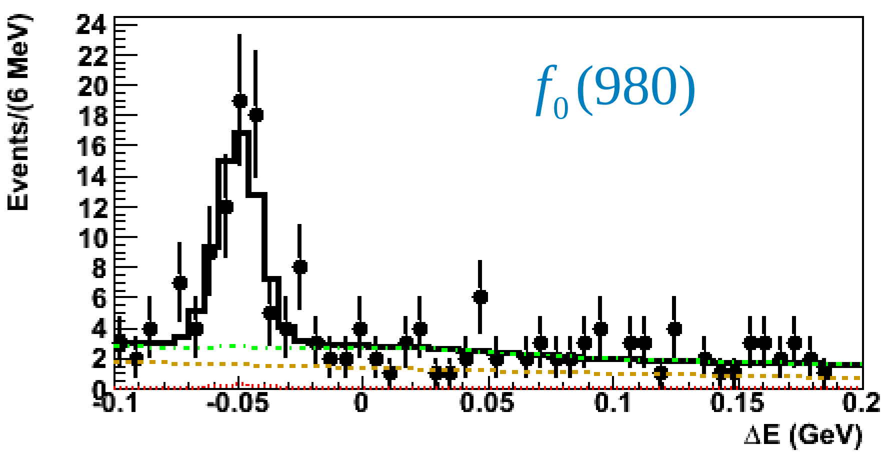
Paper to submit soon!

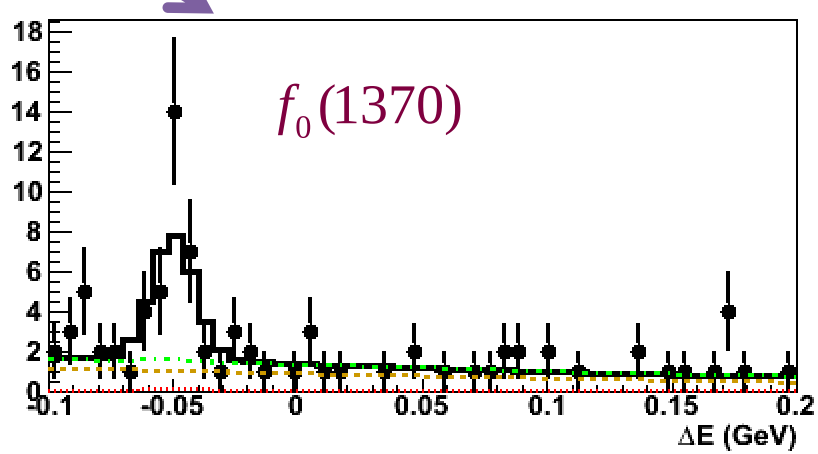
$-0.797 \leq \Delta E < -0.197$ GeV



$0.8 \leq m(\pi\pi) < 1.16$ GeV

$1.3 \leq m(\pi\pi) < 1.5$ GeV





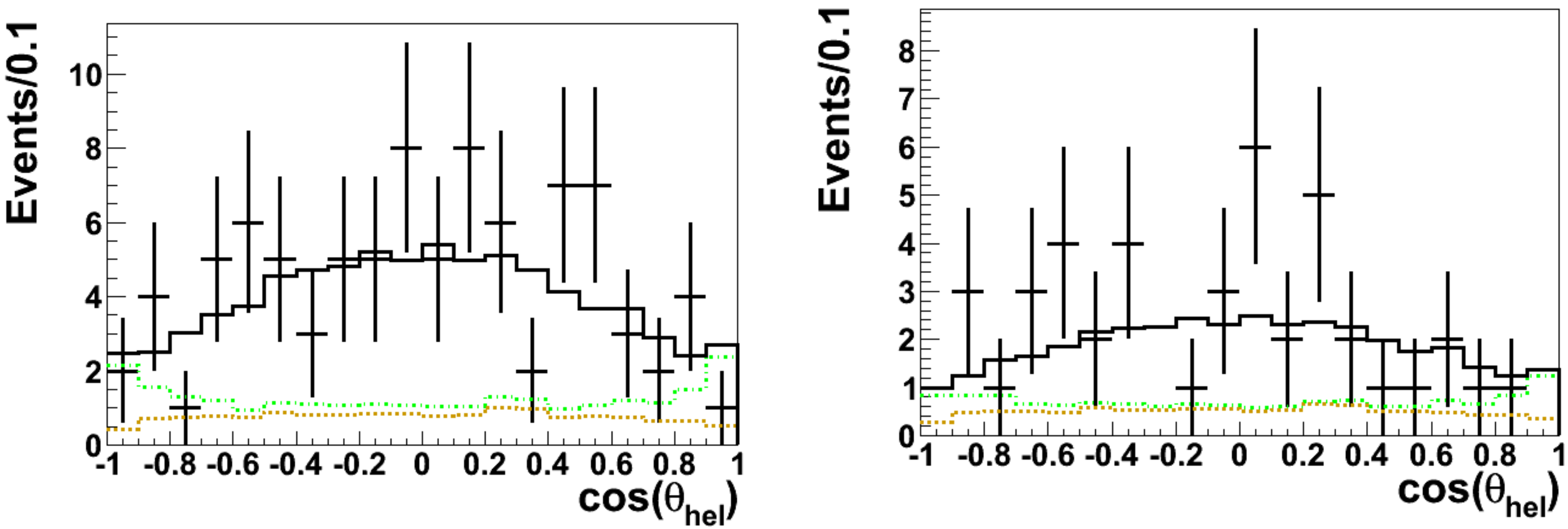
Summary and Other Bs0 CP decays

Belle has analyzed the following Bs0 CP eigenstate decays:
$B_s^0 \to K^+ K^-$, $D_s^{(*)+} D_s^{(*)-}$, $B_s^0 \to J/\psi(\phi, f\_0, \eta('))$, …

Other CP decays to be studied:
- $B_s \to D_{CP} K_S(K^{*0})$, $D_{CP}\eta$. $D_{CP}=D^0$ decay to CP eigenstates.
  Pure CP eigenstate.
  (C.F.: $BF(B^0 \to D^0\pi^0) = (2.61 \pm 0.24) \times 10^{-4}$)
- Rare decay: $B_s \to \eta(') \, \eta(')$, $\phi\phi$.

Also, we need tagging of all CP-eigenstate modes to do a time-dependent study to extract Bs0 mixing parameter $\Delta\Gamma$.

BACKUP


Events/0.1
cos(θ_hel)
Events/0.1
cos(θ_hel)

B_s Time distribution (1)

Master Equation for untagged quantum correlated B_s decay time difference Δt

$$\Gamma(B(t)\to f) = \frac{\Gamma(B\to f)}{2} e^{-|\Delta t|\Gamma}\left\{(1+|\lambda|^2)\cosh\frac{\Delta\Gamma\Delta t}{2} + 2\,\mathrm{Re}(\lambda)\sinh\frac{\Delta\Gamma\Delta t}{2}\right\}$$

$$\lambda = \frac{q\bar{A}_f}{pA_f} = \eta_f e^{-i\phi} \qquad \phi = -2\beta_s = -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

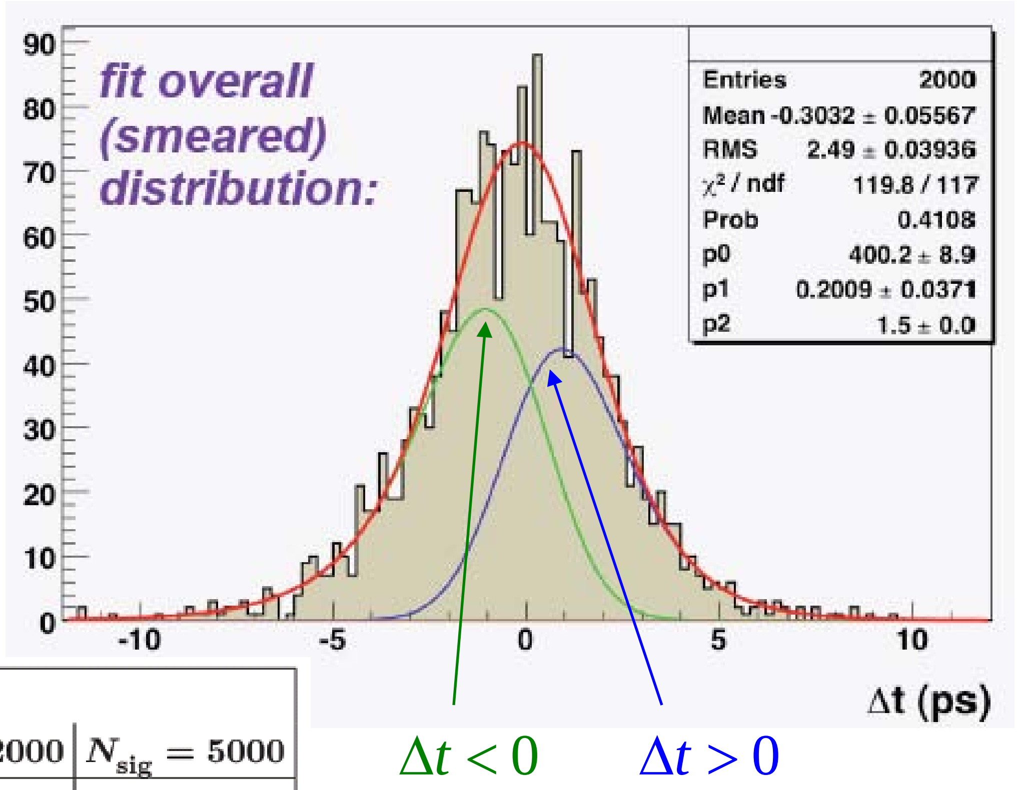
$$\left|\left\langle f_{CP+} \mid B_s^0 \right\rangle\right|^2 = \begin{cases} e^{-\left(\Gamma+\frac{\Delta\Gamma\cos\phi}{2}\right)\Delta t} \approx e^{-\Gamma_H \Delta t} & \Delta t < 0 \\ e^{-\left(\Gamma-\frac{\Delta\Gamma\cos\phi}{2}\right)\Delta t} \approx e^{-\Gamma_L \Delta t} & \Delta t > 0 \end{cases}$$

B_s Time distribution (2)

Toy MC study

$$\left|\left\langle f_{CP+} \mid B_s^0 \right\rangle\right|^2 = \begin{cases} e^{-\Gamma_H \Delta t} & \Delta t < 0 \\ e^{-\Gamma_L \Delta t} & \Delta t > 0 \end{cases}$$

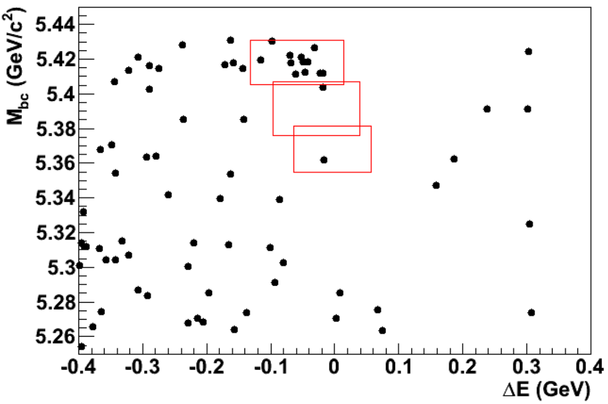
~ 300 fb^{-1} $\Upsilon(5S)$ data, using pure CP
$J/\psi(\eta,\eta',f_0)$,DsDs
(40 events in 23.6 fb^{-1})



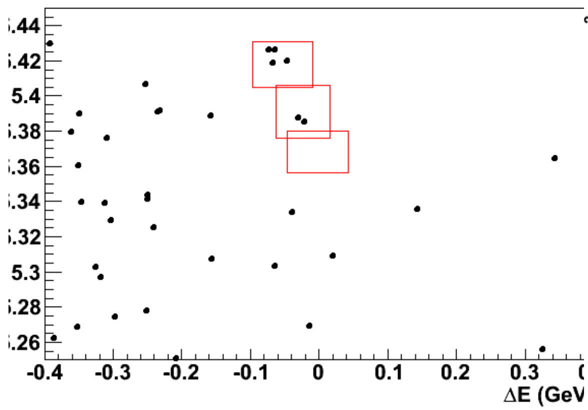
	$\delta(\Delta\Gamma/\Gamma) \times 100$			
	$N_{sig} = 500$	$N_{sig} = 1000$	$N_{sig} = 2000$	$N_{sig} = 5000$
$S/B = 0.40$	7.45 ± 0.17 (7.42 ± 0.17)	5.25 ± 0.12 (5.21 ± 0.12)	3.80 ± 0.09 (3.69 ± 0.08)	2.42 ± 0.05 (2.29 ± 0.05)
$S/B = 1.0$	6.88 ± 0.15 (6.89 ± 0.15)	4.91 ± 0.11 (4.66 ± 0.10)	3.38 ± 0.08 (3.53 ± 0.08)	2.18 ± 0.05 (2.17 ± 0.05)
$S/B = 2.0$	6.62 ± 0.15 (6.63 ± 0.15)	4.70 ± 0.11 (4.62 ± 0.10)	3.24 ± 0.07 (3.30 ± 0.07)	2.09 ± 0.05 (2.04 ± 0.05)

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

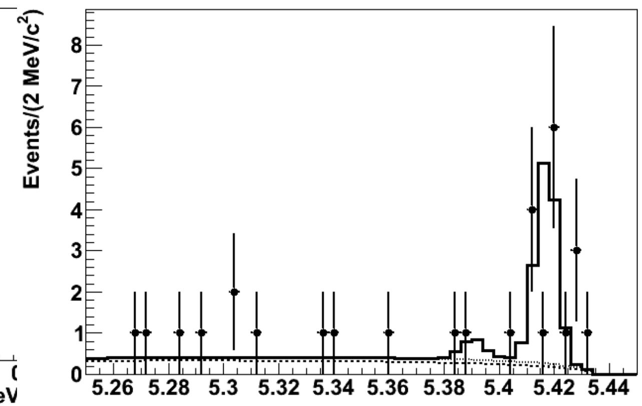
$\eta \to \gamma\gamma$

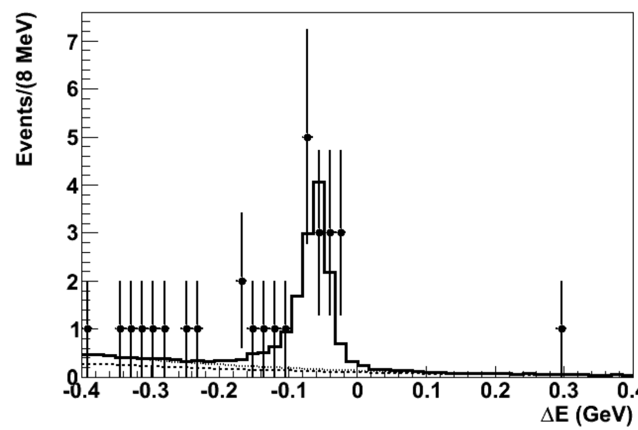


$\eta \to \pi^+\pi^-\pi^0$



combined





First observation

Simultaneous fit to two η decays.

Little background from continuum and B → J/ψ X

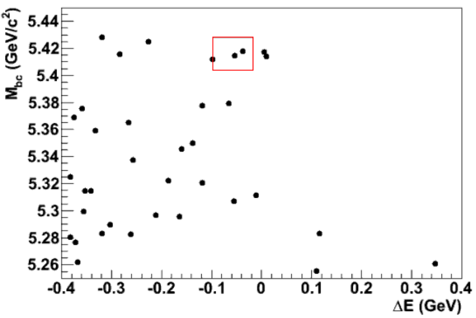
15±4 events in the $B_s^*B_s^*$ region, 7.3σ

$$\mathcal{B}(B_s^0 \to J/\psi\eta) = (3.32 \pm 0.87(\text{syst.})^{+0.32}_{-0.28} \pm 0.42(f_s)) \times 10^{-4}$$

arXiv:0912.1434 (2009); 23.6 fb^{-1}

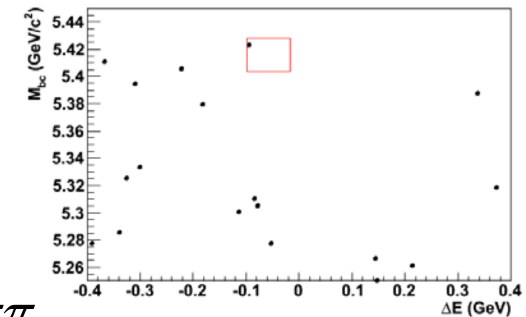
Evidence for $B_s \to J/\psi\eta'$

$\eta' \to \eta(\gamma\gamma)\pi\pi$

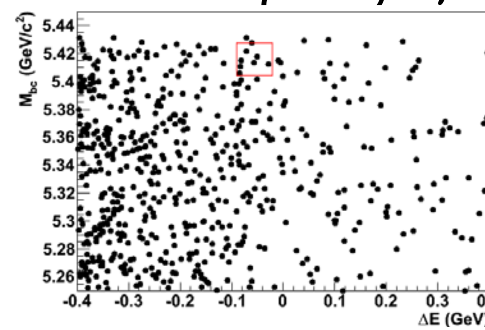


+

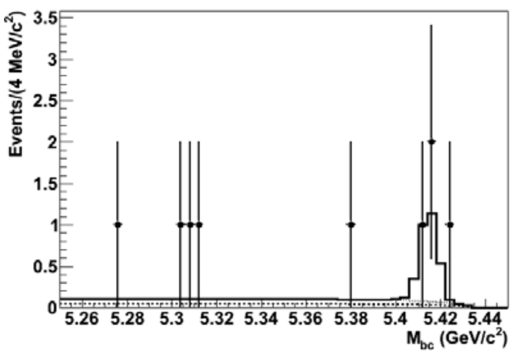
$\eta' \to \eta(\pi\pi\pi^0)\pi\pi$

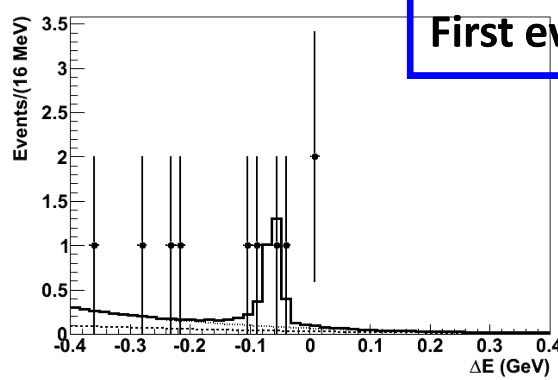


$\eta' \to \rho^0\gamma$



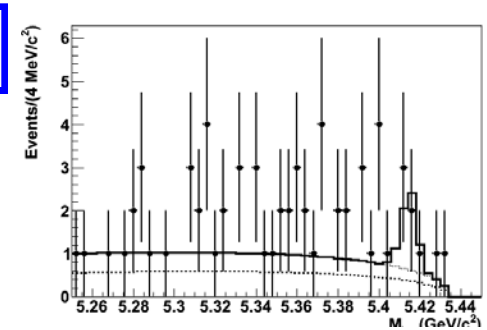
$\eta' \to \eta\pi\pi$

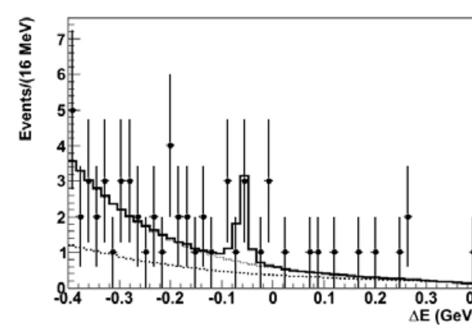




First evidence

+





Simultaneous fit to 3 η' sub modes.

11±5 events in the $B_s^*B_s^*$ region, 3.8 σ

$$\mathcal{B}(B_s^0 \to J/\psi\eta') = (3.1 \pm 1.2(\text{syst.})^{+0.5}_{-0.6} \pm 0.38(f_s)) \times 10^{-4}$$

arXiv:0912.1434 (2009); 23.6 fb^{-1}

Strategy to fit

In Mbc signal region:

- We choose a reduced ΔE region (avoid B^0,B^+ band) :

-0.1 GeV< ΔE<0.20 GeV.

  - To get rid of correlations, and reduce yields in $B_s \to J/\psi\phi$, $J/\psi\eta$.
  - To reduce correlations in $B_s \to J/\psi\eta'$.
  - To remove $J/\psi\ K_S$, $J/\psi\rho^0$,$J/\psi\pi^+\pi^-$ BG.

Fit region

-0.1 GeV< ΔE<0.20 GeV, $m(\pi^+\pi^-)$<1.8 GeV,

- The **final background categories** in fitting:
- $Bs \to J/\psi\eta'$.
- Non-resonant $Bs \to J/\psi\pi^+\pi^-$.
- $J/\psi K^+$, $J/\psi\pi^+$.
- Other J/ψ X BG (does not peak in ΔE and $m(\pi^+\pi^-)$, no correlation)
- Continuum BG.