$B_s^0 \to D_s^{(*)-} D_s^{(*)+}$ branching fractions and determination the $B_s^0 - \bar{B}_s^0$ width difference at Belle

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Flavor Physics

Standard Model:

- describes fundamental particles
  - ≻ the six type("flavors") of quarks

    u, d, s, c, b, t
  - ≻ the six type of leptons

    $e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau$
- explains their interactions via gauge bosons

  γ, W, Z, gluon

Heavy Flavor Physics:

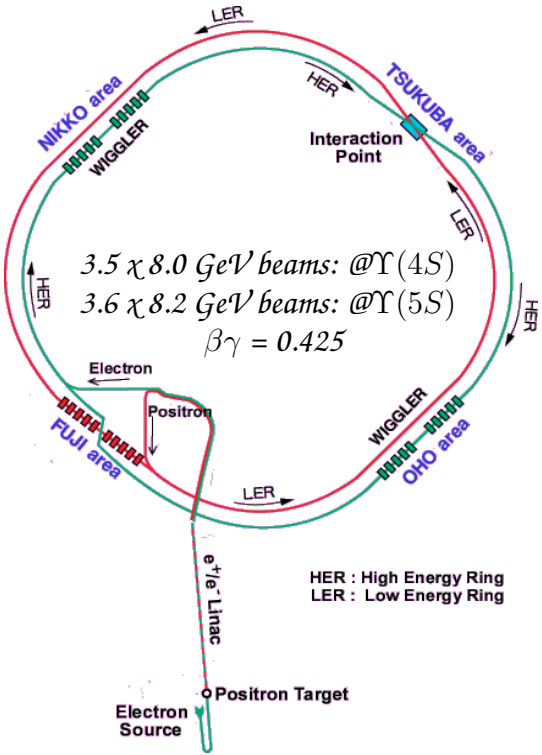
- investigates interactions that differ among flavors
- looks for properties of heavy flavor hadrons: b, c, τ
- significant amount of data from:

  Belle, BaBar, CDF, D0, CMS, ATLAS, and LHCb

  ↘ ↙

  B-factories $\longrightarrow$ dedicated to B mesons

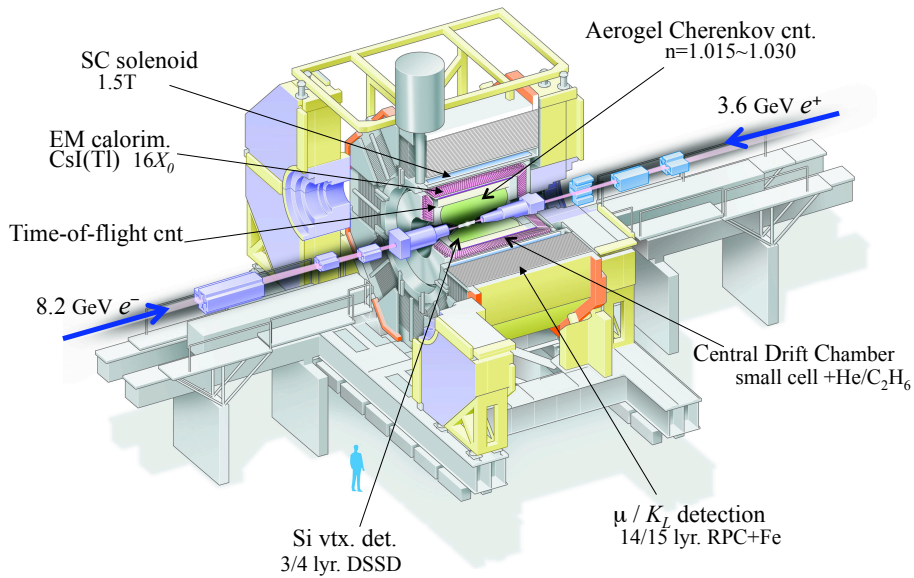
Belle/KEKB: $e^+e^- \to \Upsilon(nS)$



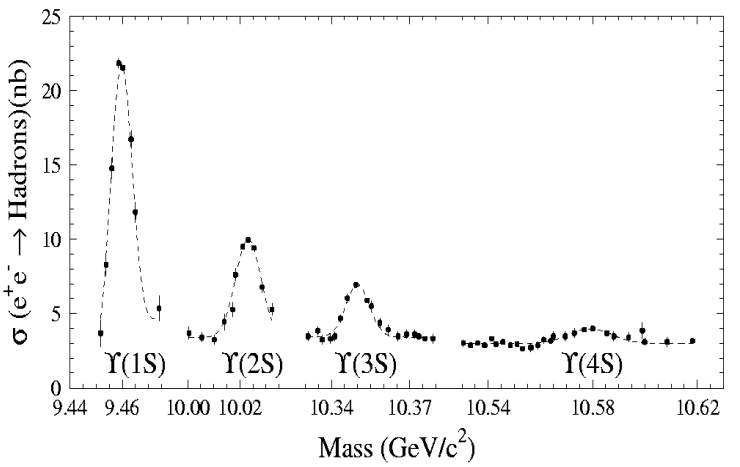
Primary goal :

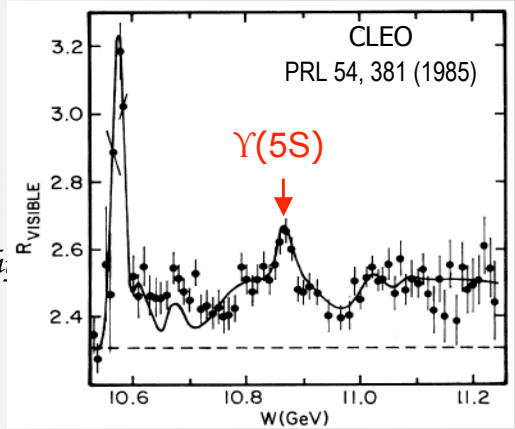
study CP violation in B sector

711 fb^{-1} = 770M B events recorded at $\Upsilon(4S)$



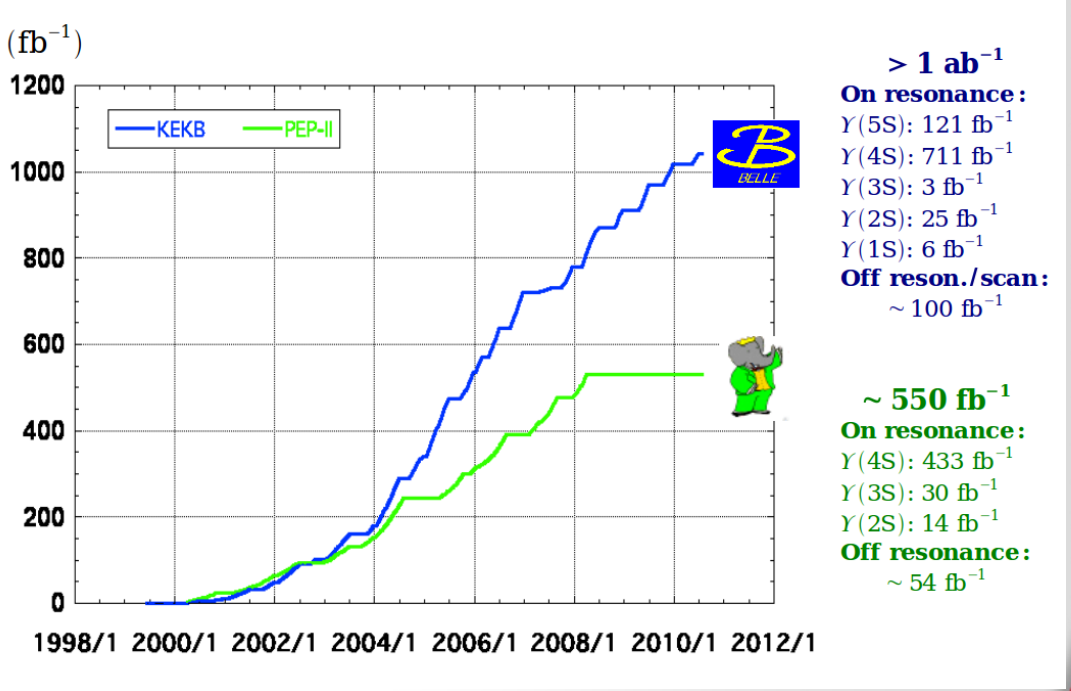
Υ Resonances ($b\bar{b}$ bound states)





- The Υ resonances are bound states of $b\bar{b}$ quarks.
- The lightest Υ resonance producing $B\bar{B}$ pair is $\Upsilon(4S)$
- The $\Upsilon(5S)$ resonance is heavy enough to produce $B_s^{(*)}\bar{B}_s^{(*)}$ pairs
- A large background due to light-quark pair production (u, d, s or c quark pairs)

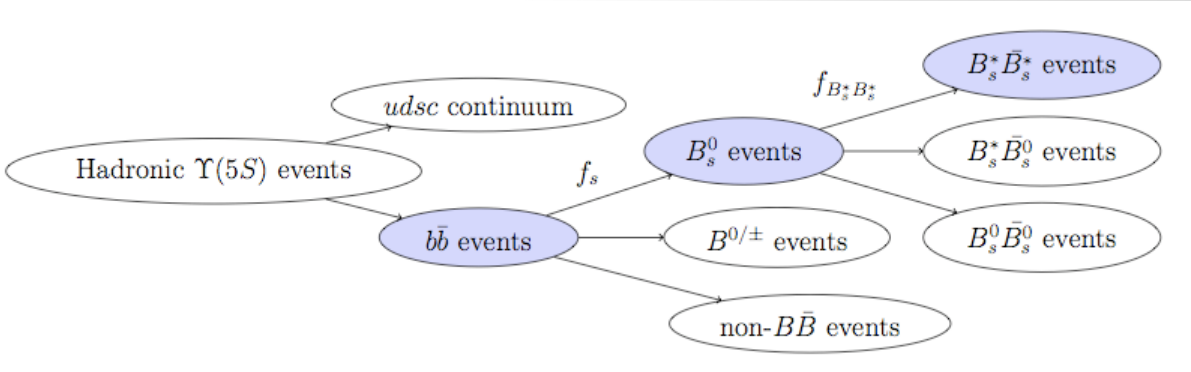
Integrated Luminosity of B Factories



- *World luminosity record* $L = 2.11 \times 10^{34} cm^{-1} s^{-1}$
- *Data taken at* $\Upsilon(4S)$, *below* $\Upsilon(4S)$ *(continuum), at* $\Upsilon(5S)$, *and above* $\Upsilon(5S)$ *(scan)*
- *121.4* fb^{-1} *data, corresponding to 7.11 million* $B_s^{(*)} B_s^{(*)}$ *pairs, used for this analysis*

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

Event Classification at $\Upsilon(5S)$



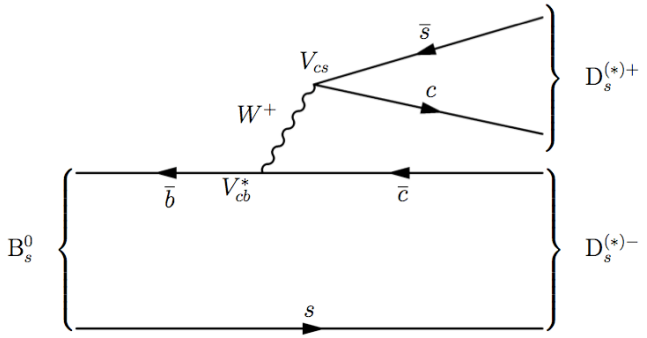
The total number of $B_s\bar{B}_s$ pairs: $N_{B_s\bar{B}_s} = \mathcal{L} \times \sigma_{b\bar{b}}^{\Upsilon(5S)} \times f_s$

- Luminosity: $\mathcal{L}$= 121.4fb^{-1}
- $e^+e^- \to b\bar{b}$ cross section at $\Upsilon(5S)$ energy: $\sigma_{b\bar{b}}^{\Upsilon(5S)} = 0.340 \pm 0.016$ nb
- Fraction of the $\Upsilon(5S)$ decays producing B_s^0 mesons: $f_s = (17.1 \pm 3.0)\%$

$$\mathcal{B}(\Upsilon(5S) \to D_sX)/2 = f_s \times \mathcal{B}(B_s^0 \to D_sX) + (1 - f_s) \times \mathcal{B}(B \to D_sX)$$

- $\succ$ $N_{B_s^{(*)}B_s^{(*)}}$ =$(7.11 \pm 1.30) \times 10^6$

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



- CKM- favored and flavor-neutral
- Dominant CP-even final states
- Two heavy D_s in the final state

– $D_s^+ D_s^-$ pure CP-even

– $D_s^{*\pm} D_s^{\mp}$ should be CP-even
for negligible CP violation in heavy quark limit Phys. Lett. B 316, 567 (1993)

– $D_s^{*+} D_s^{*-}$ predominantly CP-even:
expected CP-odd fraction is small Phys. Rev. D 42, 3732 (1990)

– possible access to $\Delta\Gamma_s$?

Event Selection

- Exclusively reconstruct B_s^0 decays to $D_s^+ D_s^-$, $D_s^{*\pm} D_s^{\mp}$ and $D_s^{*+} D_s^{*-}$
  - $D_s^+ \to \phi\pi^+, K_S K^+, K^{*0} K^+, \phi\rho^+, K^{*+} K_S, K^{*+} K^{*0}$
    - Charged tracks required to originate from near e^+e^- interaction point
    - Mass cut on intermediate resonances and $D_s^{\pm}$
  - $D_s^{*\pm} \to D_s^{\pm}\gamma$ with $|\Delta M_{D_s^* - D_s} - \Delta M^{PDG}| < 12 MeV$
- Background level is low
- Observables: the energy difference and the beam energy constrained mass
  - $\Delta E = E_{B_s^0} - E^*$ within $[-0.15, 0.1] GeV$
  - $M_{bc} = \sqrt{E^{*2} - p_{B_s^0}^2}$ within $[5.25, 5.45] GeV/c^2$

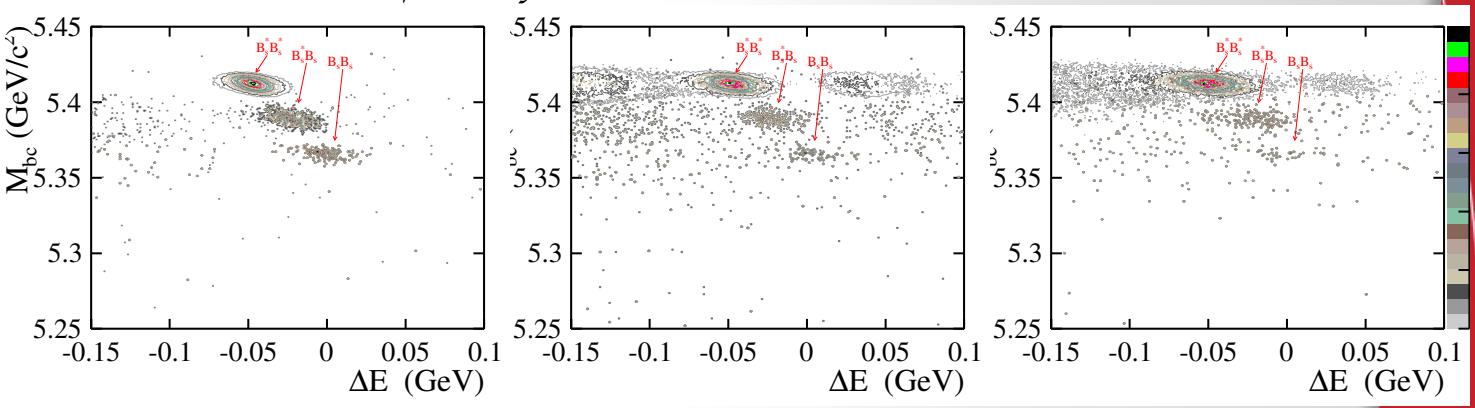
where

E^*_{beam}: the center of mass (CM) beam energy

$E_{B_s^0}$ and $p_{B_s^0}$: the energy and momentum of B_s^0 in the Υ (5S) CM rest frame.

Event Distributions

- $\Upsilon(5S)$ decays through: $B_s^*\bar{B}_s^*$, $B_s^*\bar{B}_s$, $B_s\bar{B}_s$ with $f_{B_s^*\bar{B}_s^*}$ = 87%
  - B_s^* always decays to $B_s\gamma$
  - We don't reconstruct $\gamma \Rightarrow$ shifted ΔE and M_{bc}

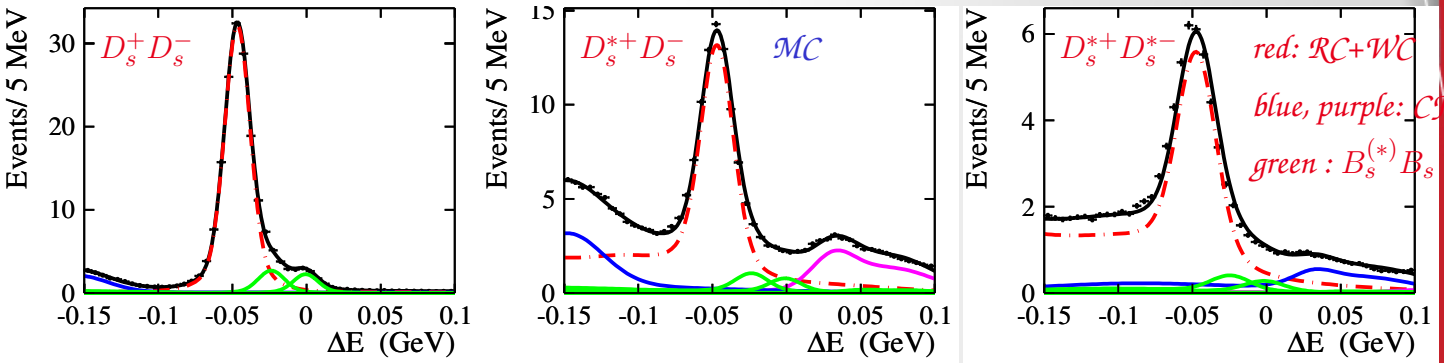


- cross contamination between modes
  - true D_s^{*+} decay, D_s^+ combined with a random photon $\longrightarrow$ WC
  - true D_s^+ decay, combined with a random photon $\longrightarrow$ CFup
  - true D_s^{*+} decay, lost its photon $\longrightarrow$ CFdown
  - true D_s^{*+} or D_s^+ decay $\longrightarrow$ RC

need to pick one, the best

Best Candidate Selection

- simultaneous fit of three modes to account for large cross-feeds between signal modes



- Relative fractions of signal components

B_s^0 Generated Modes	RC	WC	CF I	CF II
$D_s^+ D_s^-$	76.1	6.0 fixed	17.1 ($D_s^{*\pm} D_s^{\mp}$)	0.8 ($D_s^{*+} D_s^{*-}$)
$D_s^{*\pm} D_s^{\mp}$	44.4	38.5 fixed	8.2 ($D_s^+ D_s^-$) fixed	8.9 ($D_s^{*+} D_s^{*-}$)
$D_s^{*+} D_s^{*-}$	31.8	37.6 fixed	2.0 ($D_s^+ D_s^-$) fixed	28.6 ($D_s^{*\pm} D_s^{\mp}$) fixed

- one candidate per event selected with minimum χ^2 (MC: correct 75% of time)

$$\chi^2 = \frac{1}{2+N} \left\{ \begin{array}{l} \sum_{i=1}^{2} \left[(\widetilde{M}_{D_s^i} - M_{D_s})/\sigma_M \right]^2 + \\ \sum_{i=1}^{N} \left[(\widetilde{\Delta M}_{D_s^{*i} - D_s^i} - \Delta M_{D_s^* - D_s})/\sigma_{\Delta M} \right]^2 \end{array} \right\}$$

Background

- Continuum - $udsc$ events
  - small amount
  - 93% rejected based on event topology
- $\Upsilon(5S) \to B\bar{B}X \to D_s Y$
  - dominant source
  - can not be removed
  - not peaking in fit varibales
- Exited D_s states
  - consider $D_{sJ}(2317)D_s$, $D_{sJ}(2317)D_s^*$ and $D_{sJ}(2457)D_s$ modes
  - also $D_s D_s \pi^0$ mode
  - small branching fractions expected $\Rightarrow$ not a significant source

Yield Extraction

- 2D extended unbinned ML fit to ΔE and M_{bc} to obtain the signal yields in three signal modes.
- For each event (i), the contribution (j) from the signal and background is modeled independently.
- The likelihood function for each signal mode is defined as

$$\mathcal{L} = \frac{e^{-\Sigma Y_j}}{N!} \prod_{i=1}^{N} \sum_{j} Y_j \mathcal{P}_j^i, \tag{1}$$

- The combined likelihood to be maximized

$$\mathcal{L} = \mathcal{L}_{D_s^+ D_s^-} \cdot \mathcal{L}_{D_s^{*\pm} D_s^{\mp}} \cdot \mathcal{L}_{D_s^{*+} D_s^{*-}}. \tag{2}$$

- The yields of the RC components from $B_s^* B_s^*$ production are the common parameters.

Control Studies

– try the simultaneous fit with more statistics

– data/MC calibration factors for signal PDFs

– obtain the systematics errors for
continuum suppression, best candidate selection

Two samples:

$B_s \to D_s^{(*)-} h^+$ with $\Upsilon(5S)$ data

– Three decay modes: $D_s^- \pi^+$, $D_s^{*-} \pi^+$ and $D_s^- \rho^+$

– Same event selection

– Slightly modified best candidate selection

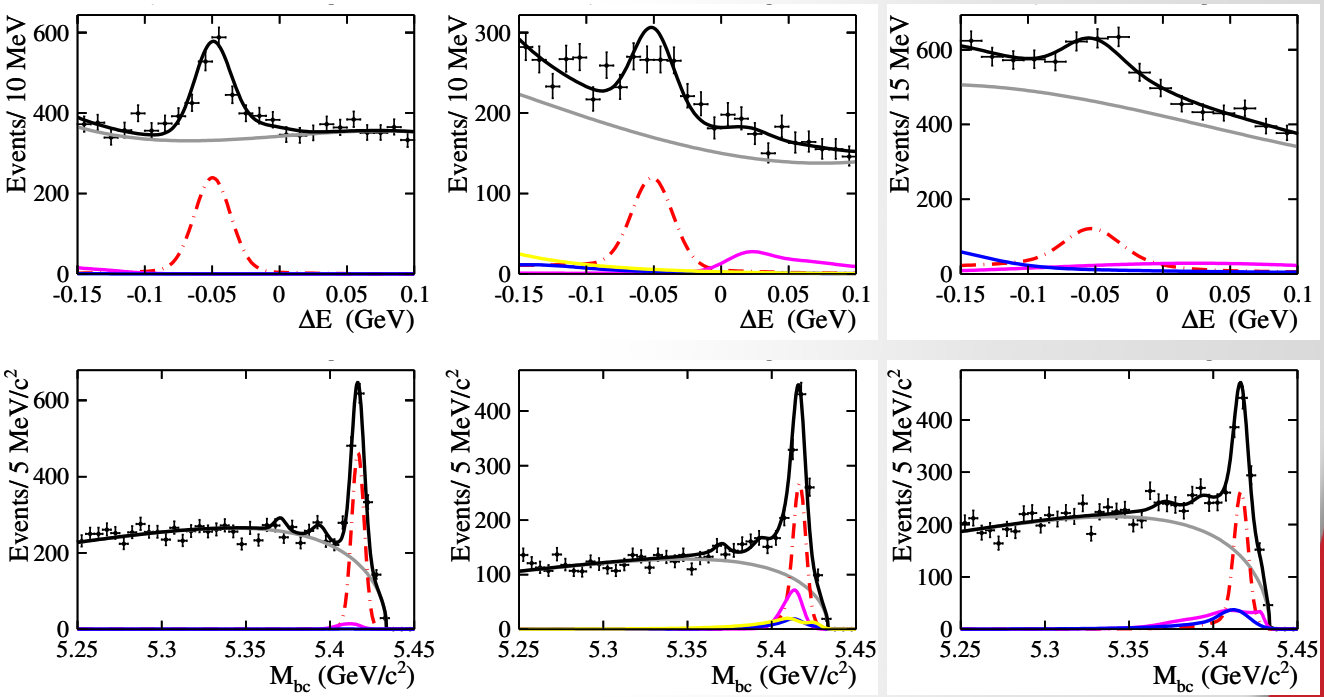
$B^0 \to D^{(*)+} D^-$ with $\Upsilon(4S)$ data

– Two decay modes: $D_s^+ D^-$ and $D_s^{*+} D^-$ where $D^- \to K^+ \pi^- \pi^-$

– Similar kinematics

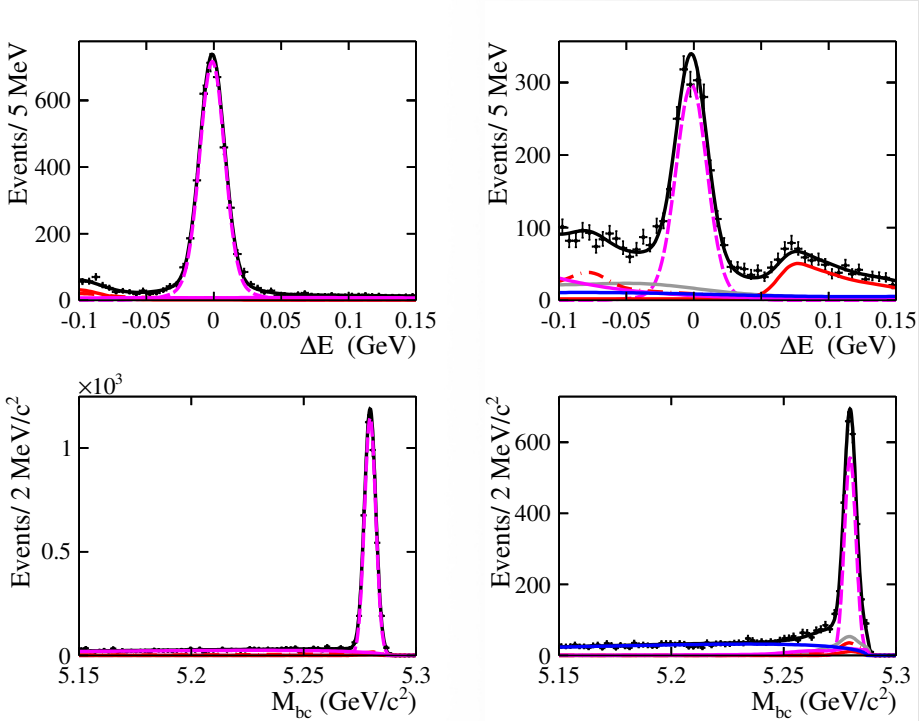
– Same event selection

Control Sample: $B_s \to D_s^{(*)} h$



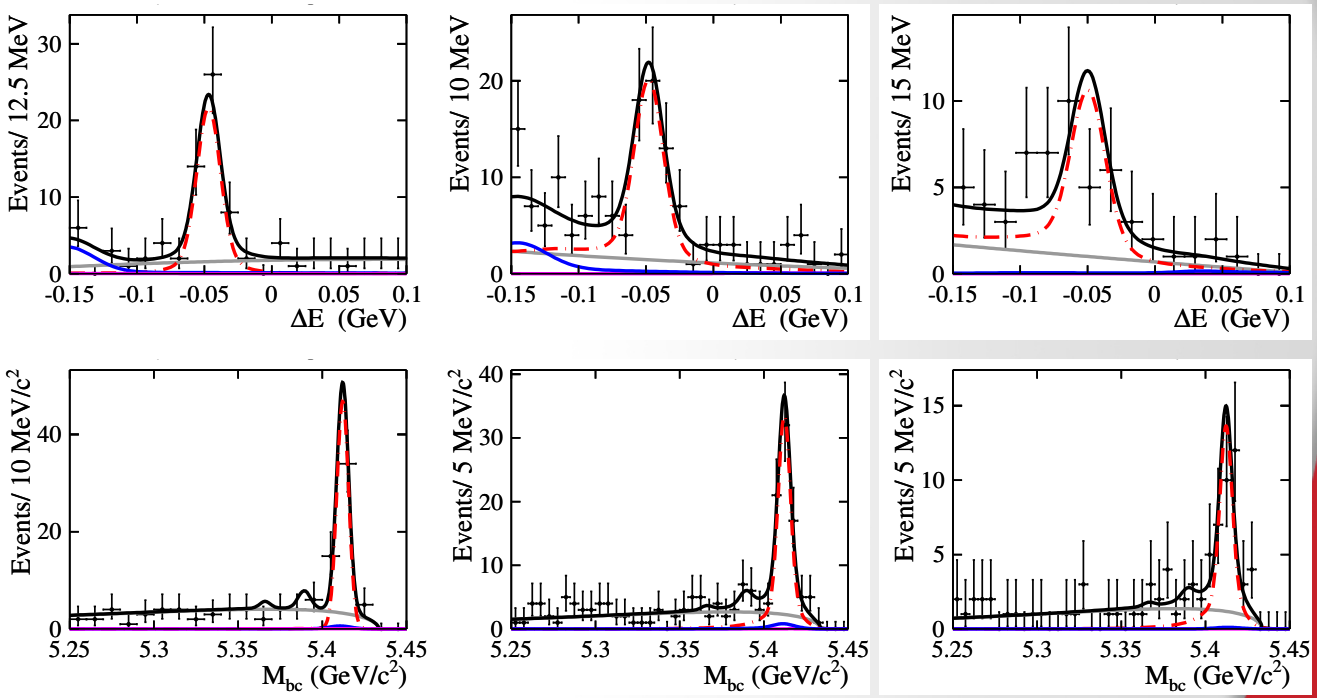
Mode	$B(B_s \to D_s^- \pi^+)$ (10^{-3})	$BF(B_s \to D_s^{*-} \pi^+)$ (10^{-3})	$BF(B_s \to D_s^- \rho^+)$ (10^{-3})
This study	3.42 ± 0.13	3.48 ± 0.02	8.53 ± 0.51
PDG	3.2 ± 0.5	2.1 ± 0.6	7.4 ± 1.8

Control sample: $B^0 \to D_s^{(*)} D$



	$B(B^0 \to D_s^- D^+)$ (10^{-3})	$BF(B^0 \to D_s^{*-} D^+)$ (10^{-3})
with BCS /event	6.76 ± 0.12	6.65 ± 0.17
without BCS /event	7.13 ± 0.11	6.75 ± 0.18
PDG	7.2 ± 0.8	7.4 ± 1.6

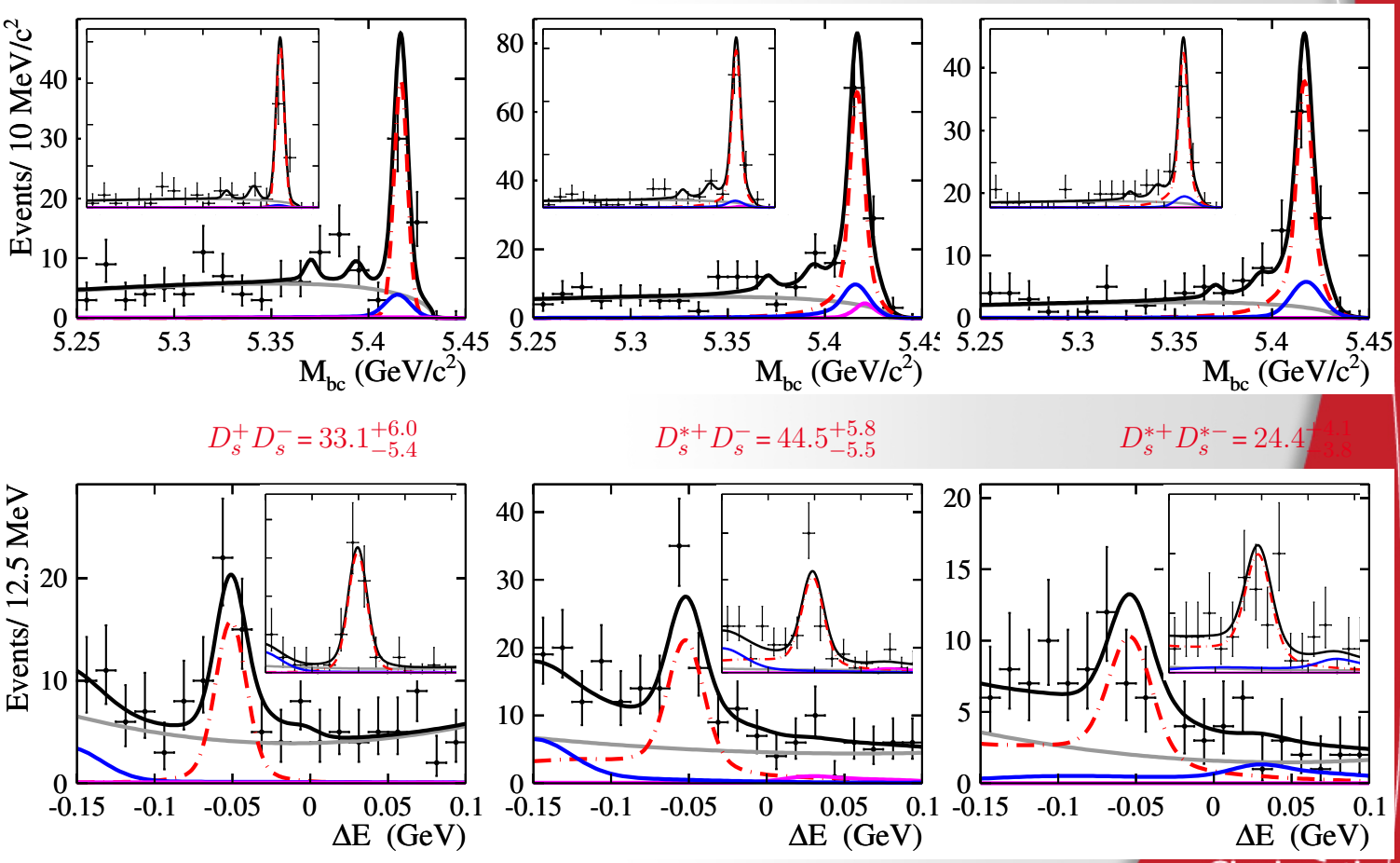
Generic MC Samples



	input	*0*	*1*	*2*	*3*	*4*	*5*
$D_s D_s$	*0.86*	$0.68^{+0.11}_{-0.10}$	$0.71^{+0.11}_{-0.10}$	$0.84^{+0.12}_{-0.11}$	$1.10^{+0.13}_{-0.12}$	$0.99^{+0.13}_{-0.12}$	$1.00^{+0.13}_{-0.12}$
$D_s^* D_s$	*1.89*	$1.84^{+0.23}_{-0.21}$	$1.70^{+0.22}_{-0.20}$	$2.05^{+0.24}_{-0.22}$	$1.77^{+0.22}_{-0.21}$	$1.70^{+0.22}_{-0.21}$	$2.14^{+0.25}_{-0.23}$
$D_s^* D_s^*$	*1.97*	$1.47^{+0.29}_{-0.27}$	$1.85^{+0.29}_{-0.26}$	$1.66^{+0.27}_{-0.25}$	$2.42^{+0.31}_{-0.29}$	$1.26^{+0.26}_{-0.24}$	$1.90^{+0.31}_{-0.29}$

Fit Results with 121.4 fb^{-1}

signal region: $\Delta E[-0.1, 0.0]$ *and* $M_{bc}[5.4, 5.43]$ *(small figures)*



Systematic Errors (%)

Source	$D_s^+ D_s^-$		$D_s^* D_s$		$D_s^{*+} D_s^{*-}$	
	$+\sigma$	$-\sigma$	$+\sigma$	$-\sigma$	$+\sigma$	$-\sigma$
Signal PDF Shape	2.7	2.2	2.2	2.4	5.1	3.8
Background PDF Shape	1.5	1.3	1.3	1.4	2.9	2.8
WC + CF fraction	0.5	0.5	4.7	4.5	11.0	9.7
$\mathcal{R}$ requirement ($q\bar{q}$) suppr.	3.1	0.0	0.0	2.7	0.0	2.1
Best candidate selection	5.5	0.0	1.5	0.0	1.5	0.0
$K^\pm$ Identification	7.0	7.0	7.0	7.0	7.0	7.0
K_s Reconstruction	1.1	1.1	1.1	1.1	1.1	1.1
π^0 Reconstruction	1.1	1.1	1.1	1.1	1.1	1.1
γ	-	-	3.8	3.8	7.6	7.6
Tracking	2.2	2.2	2.2	2.2	2.2	2.2
Polarization	0.0	0.0	0.8	2.4	0.4	0.2
MC statistics for ε	0.2	0.2	0.4	0.4	0.5	0.5
$D_s^{(*)}$ BF's	8.6	8.6	8.6	8.6	8.7	8.7
$N_{B_s^{(*)} B_s^{(*)}}$			18.3			
$f_{B_s^* \overline{B}_s^*}$			2.0			
Total	22.7	21.8	22.7	22.9	26.2	25.5

"External errors

Results

Mode	$\mathcal{Y}$ (events)	ε_{MC} ($\times 10^{-4}$)	$\mathcal{B}$ (%)	S
$D_s^+ D_s^-$	$33.1^{+6.0}_{-5.4}$	4.72	$0.58^{+0.11}_{-0.09} \pm 0.13$	11.6
$D_s^{*+} D_s^- + D_s^{*-} D_s^+$	$44.5^{+5.8}_{-5.5}$	2.08	$1.8 \pm 0.2 \pm 0.4$	13.3
$D_s^{*+} D_s^{*-}$	$24.4^{+4.1}_{-3.8}$	1.01	$2.0 \pm 0.3 \pm 0.5$	8.6
Sum	$102.0^{+9.3}_{-8.6}$		$4.3 \pm 0.4 \pm 1.0$	

Branching Fraction

$$\mathcal{B} = \frac{Y}{2 \times N_{B_s^* B_s^*} \times \varepsilon_{MC} \times \varepsilon_{PID}}$$

Significance

$$S = \sqrt{-2ln(\mathcal{L}_0/\mathcal{L}_{max})}$$

Experimental Results

- Belle measured: three decay modes exclusively
- CDF measured: B_s^0 production rate times $B_s^0 \to D_s^{(*)+} D_s^{(*)-}$ branching ratios relative to the normalization mode $B^0 \to D_s^+ D^-$
- The D0 measured: $B_s^0 \to D_s^{(*)+} D_s^{(*)-}$ via an inclusive analysis

Mode	Belle[1] (10^{-2})	CDF[2] (10^{-2})	D0[3] (10^{-2})
$D_s^+ D_s^-$	$0.58^{+0.11}_{-0.09} \pm 0.13$	$0.49 \pm 0.06 \pm 0.05 \pm 0.08$	
$D_s^{*\pm} D_s^{\mp}$	$1.8 \pm 0.2 \pm 0.4$	$1.13 \pm 0.12 \pm 0.09 \pm 0.19$	
$D_s^{*+} D_s^{*-}$	$2.0 \pm 0.3 \pm 0.5$	$1.75 \pm 0.19 \pm 0.17 \pm 0.28$	
$D_s^{(*)+} D_s^{(*)-}$	$4.3 \pm 0.4 \pm 1.0$	$3.38 \pm 0.25 \pm 0.30 \pm 0.56$	$3.5 \pm 1.0 \pm 1.1$

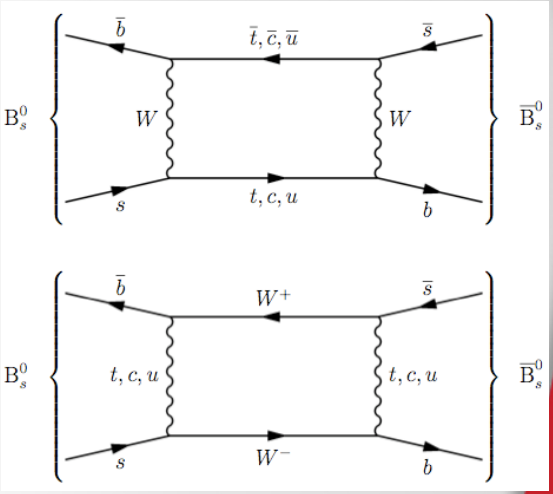
(1) S. Esen et al.(Belle Collaboration), arXiv:1208.0323 (to be published in PRD(RC))
(2) T.Aaltonen et al., (CDF Collaboration) PRD 85 (2012), 072002
(3) V.M.. Abazov et al.(D0 Collaboration), PRL 102 (2009), 091801

$B_s - \bar{B}_s$ Width Difference

Neutral B -meson Mixing

Time evolution of the $B_s^0 - \bar{B}_s^0$ *system:*

$$i\frac{d}{dt}\begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix} = \begin{pmatrix} M_s - i\Gamma_s/2 & M_{12} - i\Gamma_{12}/2 \\ M_{12}^* - i\Gamma_{12}^*/2 & M_s - i\Gamma_s/2 \end{pmatrix}\begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix}$$



The mass eigenstates:

$$|B_{sH}^0\rangle = p\,|B_s^0\rangle + q\,|\bar{B}_s^0\rangle$$
$$|B_{sL}^0\rangle = p\,|B_s^0\rangle - q\,|\bar{B}_s^0\rangle$$

with $|p|^2 + |q|^2 = 1.$

Define:

$\Delta m_s = M_H - M_L > 0$ *and* $\Delta\Gamma_s = \Gamma_L - \Gamma_H$ (> 0 *PRL 108, 241801 (2012)*)

World averages (HFAG)

$$\Delta m_s = 17.69 \pm 0.08\ ps^{-1} \text{ and } \ 1/\Gamma_s = 1.495 \pm 0.015\ ps$$

$B_s^0 - \bar{B}_s^0$ mixing parameters

Observation of $\Gamma_s \ll \Delta m_s$ *implies*

$$\Gamma_{12} \ll M_{12},$$

and thus, to a good approximation:

$$\Delta m_s \approx 2|M_{12}|,$$
$$\Delta\Gamma_s \approx 2|\Gamma_{12}| \cos\phi_s,$$

with the CP *violating phase*

$$\phi_s = arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$$

which is predicted to be small in the SM. Phys. Rev. D 84, 033005 (2011)

- Δm_s :
sensitive to new physics
well measured
consistent w/ SM

ϕ_s:
very sensitive to NP

$\Delta\Gamma_s$:
moderately sensitive to NP
not well known

Measuring $\Delta\Gamma_s$

- Neglecting CP violation, the heavy and light mass eigenstates have definite CP parity. For $\phi_s = 0, \Delta\Gamma_s = \Delta\Gamma_s^{CP}$
- The decay channels common to B_s^0 and $\bar{B}_s^0$ mesons contribute to Γ_{12} and thus determine $\Delta\Gamma_s$.
- CKM favored $b \to c\bar{c}s$ transition dominates such modes
- CP specific or flavor specific modes can be used to extract $\Delta\Gamma_s$ Phys. Rev. D 52, 3048 (1995); Phys. Lett. B 316, 567 (1993)
- $\succ$ Best probed with $B_s \to J/\psi\phi$ angular analysis
- $\succ$ $B_s^0 \to D_s^{(*)+} D_s^{(*)-}$ constitute significant fraction of $b \to c\bar{c}s$
  - predominantly CP-even.
  - large branching fraction
  - non-negligible theoretical uncertainties Phys. Rev. D 84, 074037 (2011)

$\Delta\Gamma_s/\Gamma_s$ via $B_s^0 \to D_s^{(*)+} D_s^{(*)-}$ Decays

- In the heavy quark limit, while $(m_b - 2m_c) \to 0$ and $N_c \to \infty$
  - $b \to c\bar{c}s$ processes contribute constructively to $\Delta\Gamma_s$
  - $\Gamma[B_s^0(CP+) \to D_s^{(*)-} D_s^{(*)+}]$ saturates $\Delta\Gamma_s^{CP}$
  - assuming negligible CP violation, we can estimate $\Delta\Gamma_s/\Gamma_s$

$$\frac{\Delta\Gamma_s}{\Gamma_s} = \frac{2\mathcal{B}(B_s^0 \to D_s^{(*)-} D_s^{(*)+})}{1 - \mathcal{B}(B_s^0 \to D_s^{(*)-} D_s^{(*)+})}$$

Aleksan et. al., PLB 316, 567 (1993) , Dunietz et. al. , PRD 63, 114015 (2001)

some theoretical uncertainty

- 3-body $D_s^{(*)} D_{(s)}^{(*)} X$ and $D_{sJ} D_s$ final states are not included
- $D_s^{*+} D_s^{*-}$ mode is expected to have a small CP-odd component

$\Delta\Gamma_s$ Measurements

	$\mathcal{Y}$ (events)	$\mathcal{B}$ (%)
$B_s \to D_s^{(*)} D_s^{(*)}$	$102.0^{+9.3}_{-8.6}$	$4.3 \pm 0.4 \pm 1.0$
$\Delta\Gamma_s/\Gamma_s$	$(9.0 \pm 0.9 \pm 2.2)$ %	

$$\Delta\Gamma_s/\Gamma_s = 2\mathcal{B}/(1-\mathcal{B})$$

using $\Gamma_s = 1.463 \pm 0.030\ ps^{-1} \Rightarrow \Delta\Gamma_s = 0.062 \pm 0.016\ ps^{-1}$

- *Theoretical Estimations:*
  $\Delta\Gamma_s/\Gamma_s = (13.3 \pm 3.2)\%$ *arXiv:hep-ph/1102.4274*
  only with $D_s^{(*)+} D_s^{(*)-}$: $\Delta\Gamma_s/\Gamma_s = (10.2 \pm 3.0)\%$ *Phys. Rev. D 84, 074037*

- *Experimental Results*

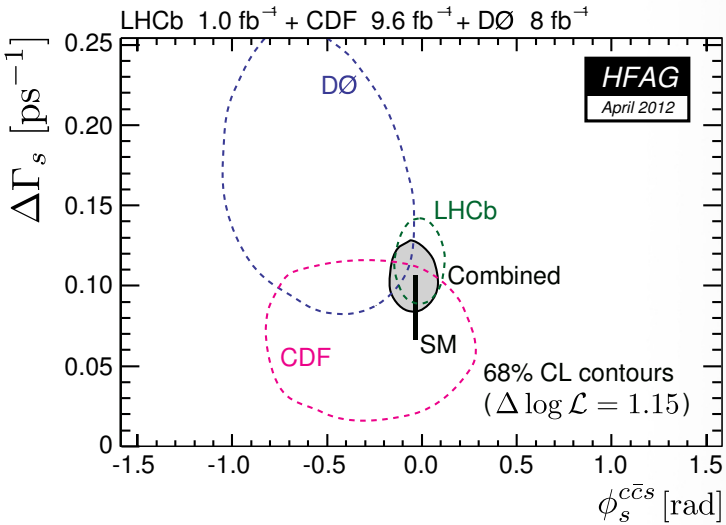
	mode	$\Delta\Gamma_s$ (ps^{-1})	*ref.*
LHCb	$B_s \to J/\psi\phi$	$0.123 \pm 0.029 \pm 0.011$	*PRL 108 (2012) 101803*
ATLAS	$B_s \to J/\psi\phi$	$0.053 \pm 0.021 \pm 0.008$	*arXiv:1208.0572*
CDF	$B_s \to J/\psi\phi$	$0.075 \pm 0.035 \pm 0.006$	*PRD 85 (2012) 072002*
D0	$B_s \to J/\psi\phi$	$0.163^{+0.065}_{-0.064}$	*PRD 85 (2012) 032006*
CDF	$B_s \to D_s^{(*)+} D_s^{(*)-}$	0.048 ± 0.010	*PRD 108 (2012) 201801*
Belle	$B_s \to D_s^{(*)+} D_s^{(*)-}$	0.062 ± 0.016	*arXiv:1208.0323*

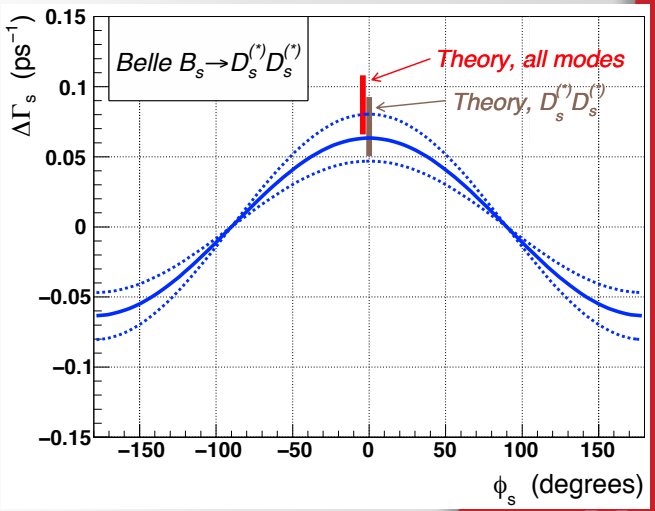
$\Delta\Gamma_s$ with CPV

putting back ϕ_s into equation:

$$\frac{\Delta\Gamma_s}{\Gamma_s} = \frac{1/\cos\phi_s - \sqrt{(1/\cos\phi_s)^2 - 4\mathcal{B}(1-\mathcal{B})}}{(1-\mathcal{B})}$$

Dunietz, Fleischer, Nierste, PRD 63, 114015 (2001)
Chua, Hou, Shen, Phys. Rev. D 84, 074037 (2011)



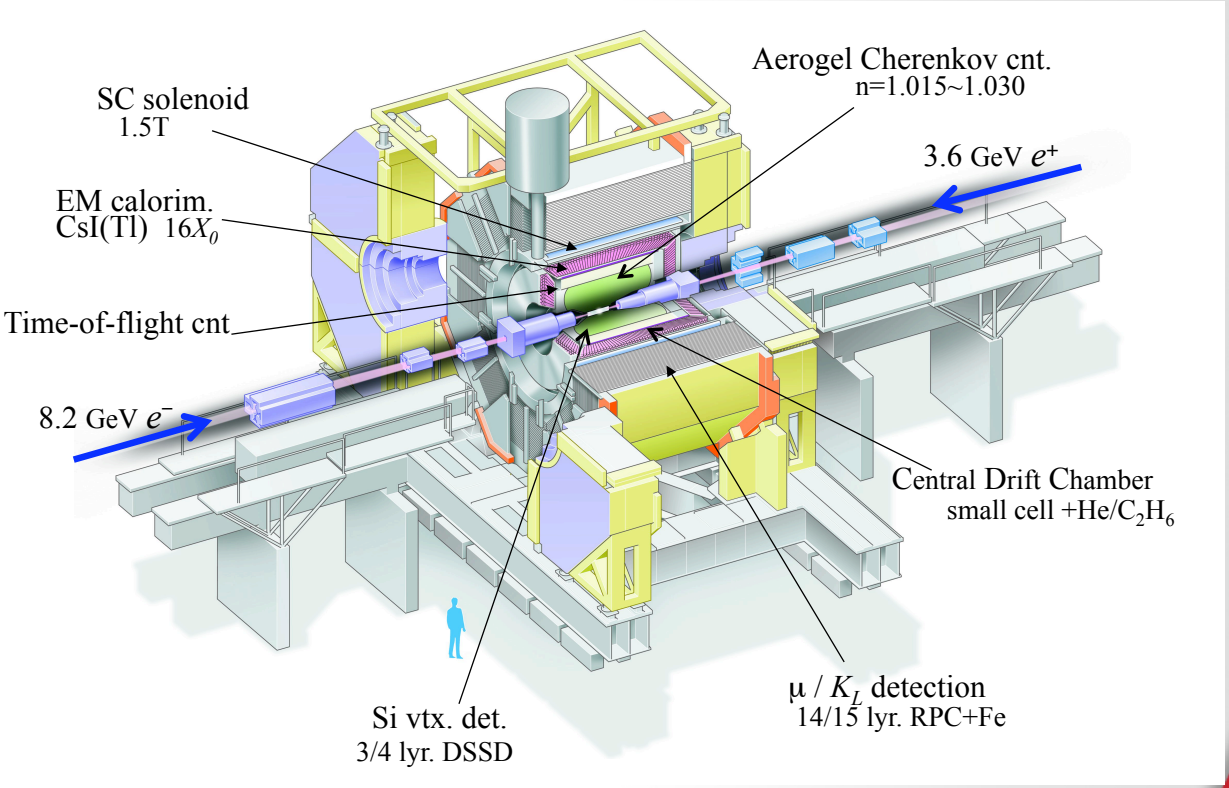


Conclusion

- Exclusive measurements with 121.4 fb^{-1} data
  - $\mathcal{B}(B_s \to D_s^+ D_s^-) = (0.58^{+0.11}_{-0.09} \pm 0.13)\%$
  - $\mathcal{B}(B_s \to D_s^{*\pm} D_s^{*\mp}) = (1.8 \pm 0.2 \pm 0.4)\%$
  - $\mathcal{B}(B_s \to D_s^{*+} D_s^{*-}) = (2.0 \pm 0.3 \pm 0.5)\%$
  - where sum is $\mathcal{B}(B_s \to D_s^{(*)+} D_s^{(*)-}) = (4.3 \pm 0.4 \pm 1.0)\%$
  - Good agreement with SM expectation and other measurements.
- Estimation of $\Delta\Gamma_s/\Gamma_s$, assuming negligible CPV
  - $\Delta\Gamma_s/\Gamma_s = (9.0 \pm 0.9 \pm 2.2)\%$
  - Theoretical uncertainties:
    size of 3-body partial widths is unknown, $\Rightarrow$ could be large
    CP-odd component of Ds*Ds* is unknown. $\Rightarrow$ expected to be $\sim 6\%$
- Results are submitted to PRD, arXiv:1208.0323

Backup

Belle Detector



PDF modeling

Fully factorized 2D PDF defined for each component (j):

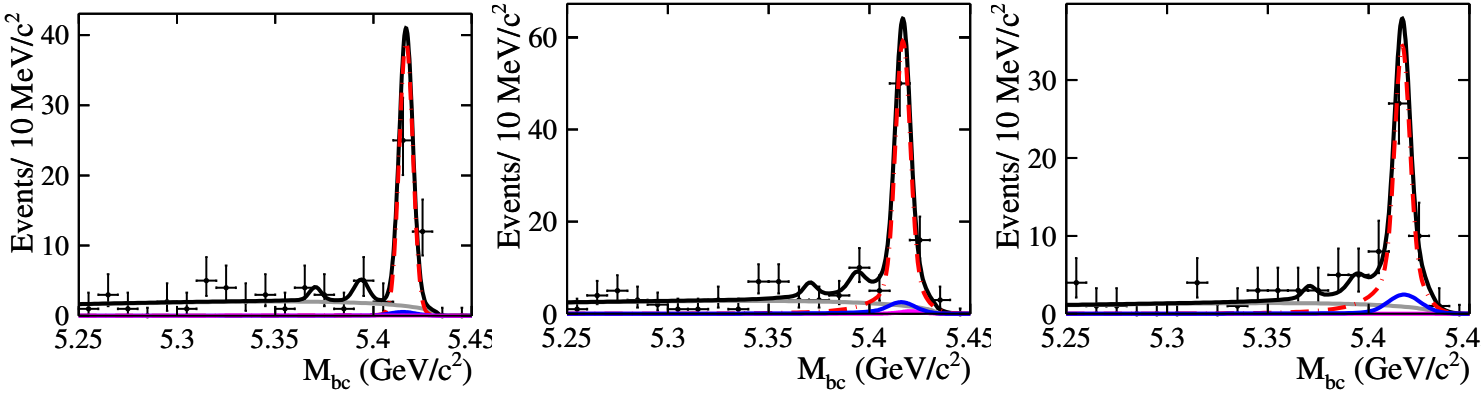
$$\mathcal{P}_j^i = \mathcal{P}_j(\Delta E^i)\mathcal{P}_j(M_{bc}^i)$$

		$D_s^+ D_s^-$	$D_s^{*\pm} D_s^{\mp}$	$D_s^{*+} D_s^{*-}$
ΔE	RC	2G (common mean)		
	WC	Cheby+2G	Cheby+2G	Cheby+G
M_{bc}	RC	G		
	WC	CBS+G		

		$D_s^+ D_s^-$	$D_s^{*\pm} D_s^{\mp}$	$D_s^{*+} D_s^{*-}$
ΔE	$CF \to D_s^+ D_s^-$	-	Cheby+G	Cheby
	$CF \to D_s^{*\pm} D_s^{\mp}$	Cheby+2G	-	Cheby+G
	$CF \to D_s^{*+} D_s^{*-}$	Cheby+G	3G	-
M_{bc}	$CF \to D_s^+ D_s^-$	-	CBS+G	Novo
	$CF \to D_s^{*\pm} D_s^{\mp}$	CBS+G	-	CBS+G
	$CF \to D_s^{*+} D_s^{*-}$	Novo+G	CBS+G	-

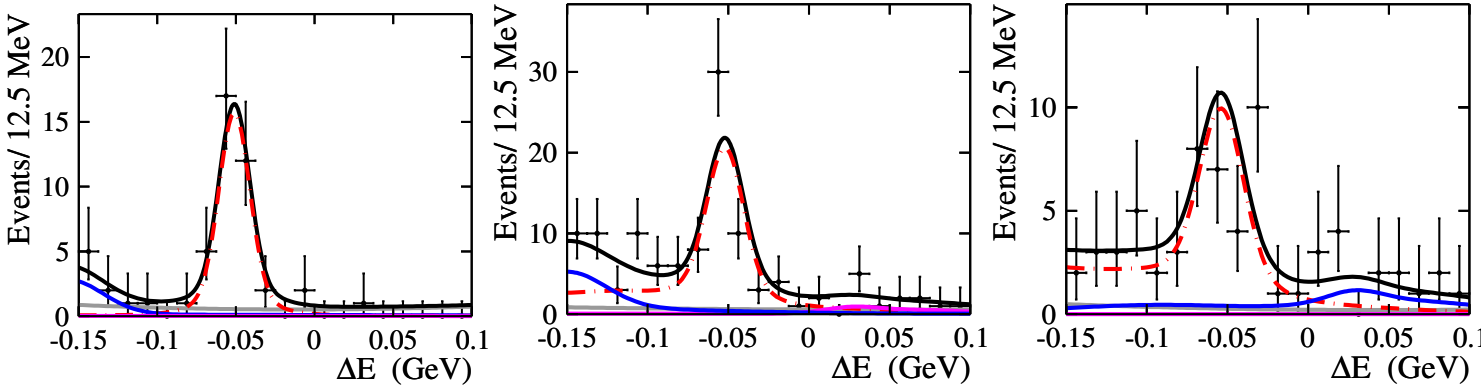
Signal Region Projections

select events in $\Delta E[-0.1, 0.0]$ *and* $M_{bc}[5.4, 5.43]$



$D_s^+ D_s^- = 33.1^{+6.0}_{-5.4}$ $D_s^{*+} D_s^- = 44.5^{+5.8}_{-5.5}$ $D_s^{*+} D_s^{*-} = 24.4^{+4.1}_{-3.8}$

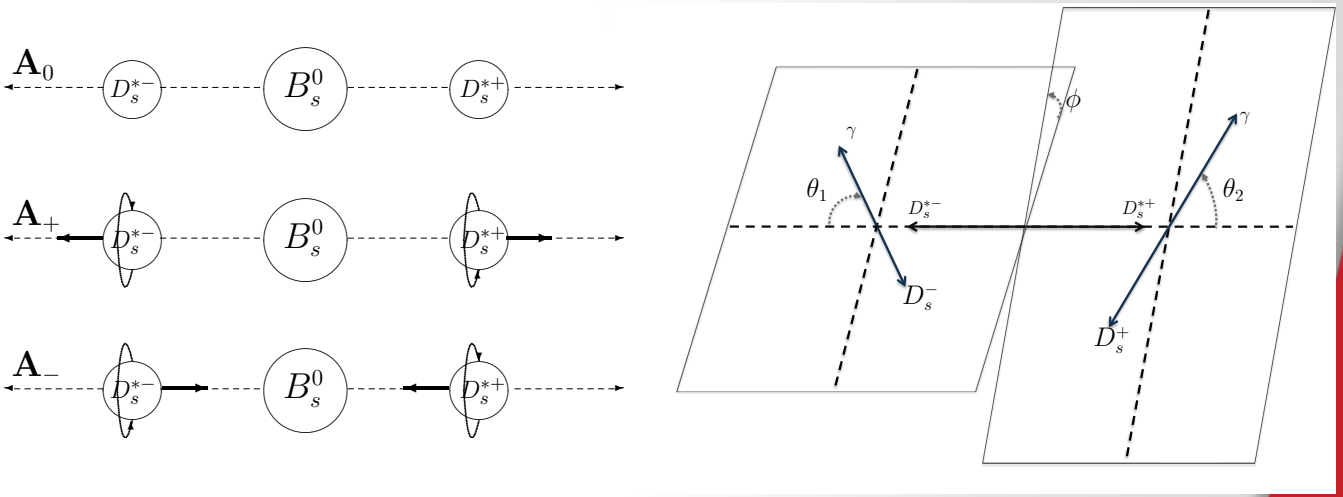
select events in $M_{bc}[5.4, 5.43]$



$B_s \to D_s^{*+} D_s^{*-}$ Polarization

Definitions in Helicity Basis

- The spin projections along the decay axis must be zero or in opposite directions
- Two helicity and one azimuthal angles
- Integrating over ϕ eliminates the interference terms

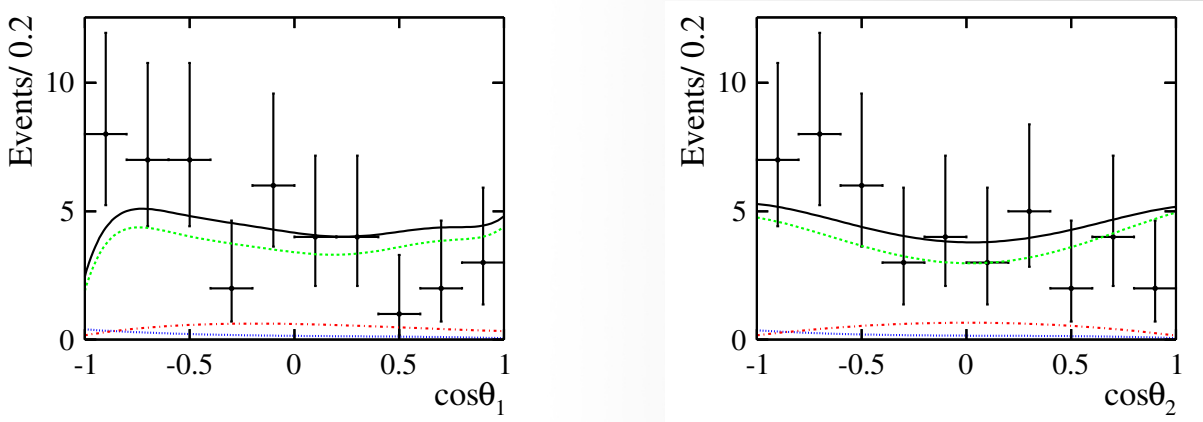


$$\frac{d^2\Gamma(\theta_1,\theta_2)}{d\cos\theta_1 d\cos\theta_2} \propto (|A_+|^2+|A_-|^2)\left[(\cos^2\theta_1+1)(\cos^2\theta_2+1)\right] + |A_0|^2\left[4\sin^2\theta_1\sin^2\theta_2\right]$$

Polarization Measurement

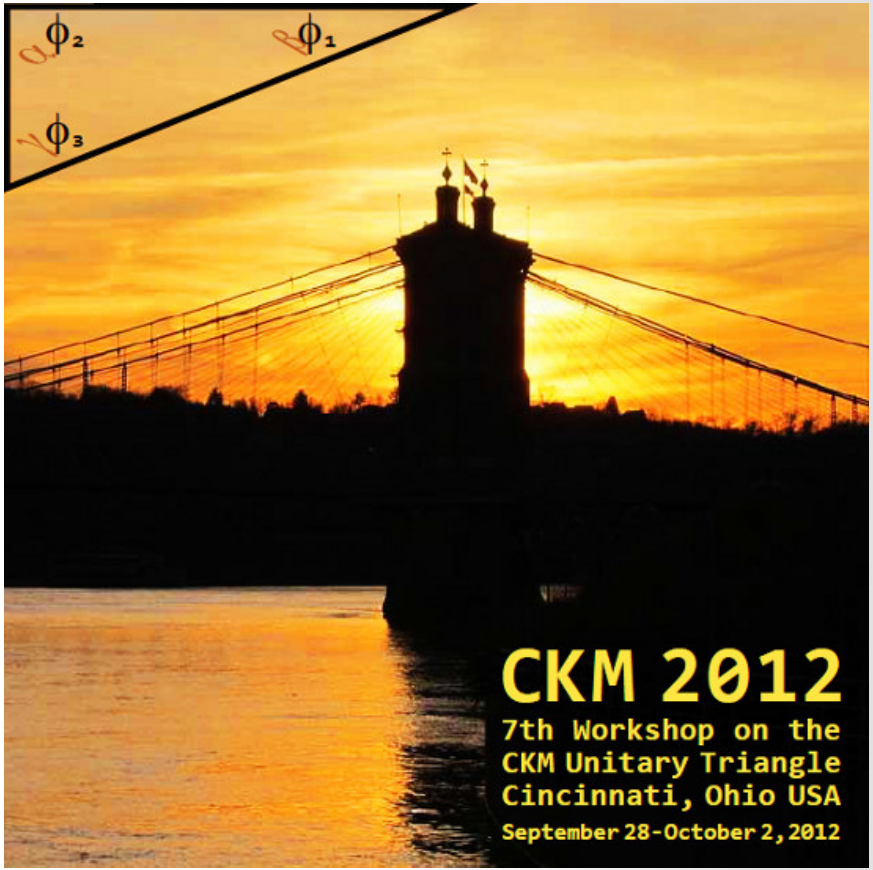
- CP-odd fraction is expected to be $\sim 6\%$ (J. Rosner, PRD 42, 3732 (1990))
- Longitudinal polarization fraction is expected to be $\sim 50\%$
- use same cuts as branching fraction measurement
- select events in 2.5σ signal M_{bc}-ΔE region ($B_s^* B_s^*$)
  - almost pure signal: expected background is less than 2 events.
  - expected signal: 45 ± 7 in total
- two polarization state:
  - $A_\pm$ transverse : CP-odd + CP-even
  - A_0 longitudinal : CP-even
- perform 2D fit in the helicity basis using angles θ_1 and θ_2
- measure longitudinal fraction $f_L \Rightarrow$ lower bound for CP-odd?

Longitudinal Polarization Fraction



$$f_L = 0.12^{+0.30+0.04}_{-0.28-0.05}$$

Source	$+\sigma$	$-\sigma$	Method
PDF Shape of RC	0.0126	0.0111	vary by $\pm\sigma$
PDF Shape of WC	0.0092	0.0076	vary by $\pm\sigma$
PDF Shape of background	0.0182	0.0181	vary by $\pm\sigma$
Fraction of WC	0.0092	0.0107	vary by 50%
Fraction of background	0.0280	0.0276	vary by 100%
Continuum Supp.	0	0.0272	fit with no cut
MC efficiency	0.0009	0.0004	vary by $\pm\sigma$
Sum	0.0380	0.0461	



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