B_s Physics

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for the CDF, D0, and
Belle collaborations

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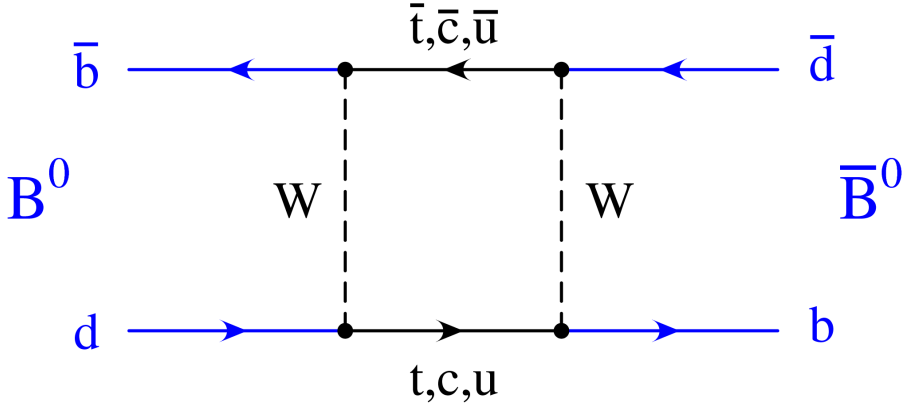
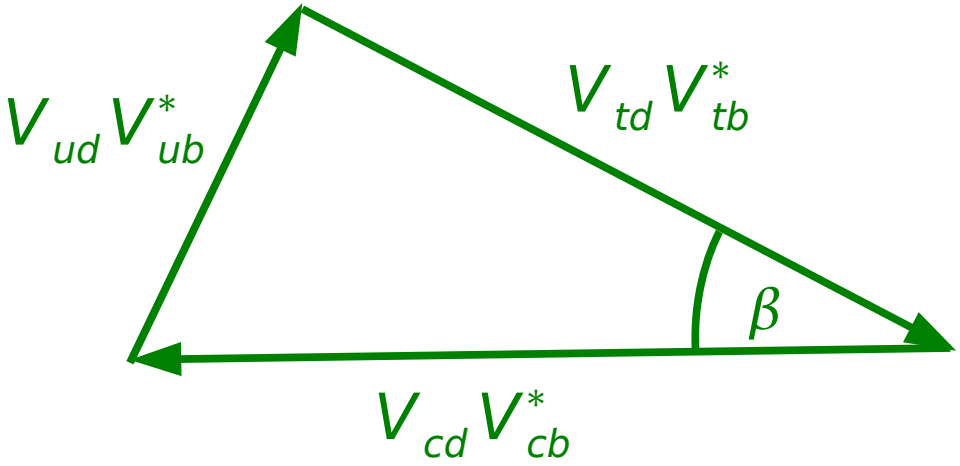
B^0 System

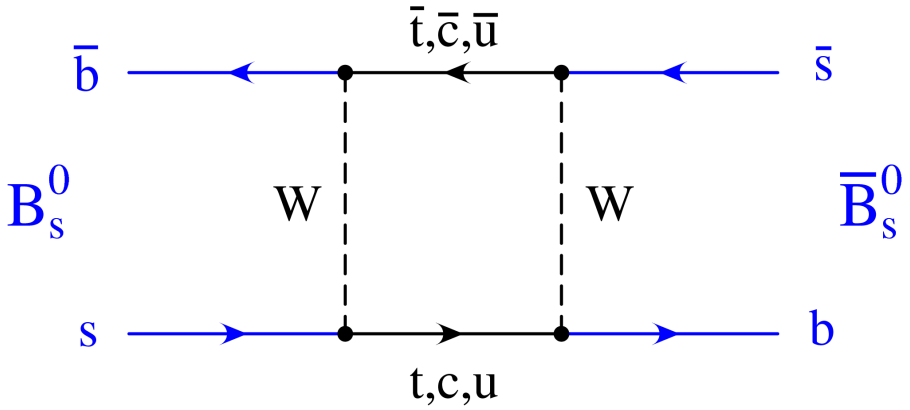


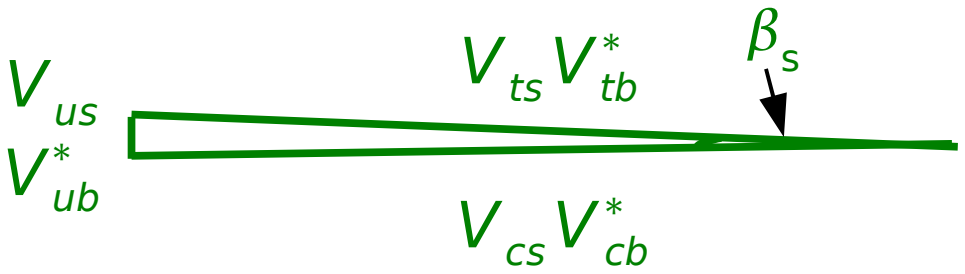


$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Large CP violation in SM
- Precisely measured by B factories
- ➔ Tight constraints on new physics models

B_s System





$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Tiny CP violation in SM
- Experimentally not well constrained
- ➔ Large contribution from new physics still possible

B_s System

- Schrödinger equation:

$$i\frac{d}{dt}\begin{pmatrix}|B_s^0(t)\rangle\\|\bar{B}_s^0(t)\rangle\end{pmatrix} = \left(\mathbf{M}-\frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix}|B_s^0(t)\rangle\\|\bar{B}_s^0(t)\rangle\end{pmatrix}$$

- Eigenstates with defined mass and lifetime:

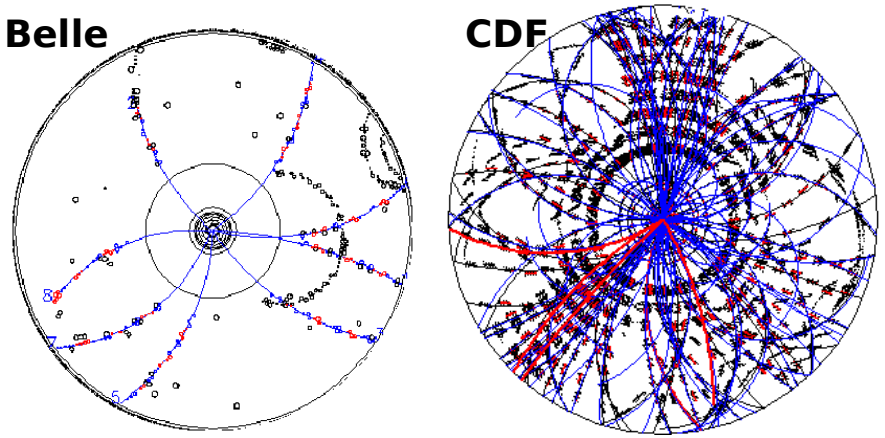
$$\begin{aligned}|B_{sL}\rangle &= p|B_s\rangle + q|\bar{B}_s\rangle\\ |B_{sH}\rangle &= p|B_s\rangle - q|\bar{B}_s\rangle\end{aligned}$$

- Mass difference: $\Delta m = m_H - m_L \approx 2|M_{12}| \rightarrow$ oscillation
- Lifetime difference: $\Delta\Gamma = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos(\phi)$
- Phase: $\phi \approx \arg(-M_{12}/\Gamma_{12}) \rightarrow$ CP violation

“B_s Factory” Tevatron

- ➔ Huge $b\bar{b}$ cross section (strong interaction)
- ➔ B_s produced in fragmentation

- ✗ High combinatorial background



- ✗ Inelastic cross section ~10^3 times larger than $\sigma(b\bar{b})$

- ➔ Triggers are essential
  - Dimuons (CDF, D0)
  - Single muons (D0)
  - Displaced tracks (CDF)

CP Violation in Semileptonic Decays

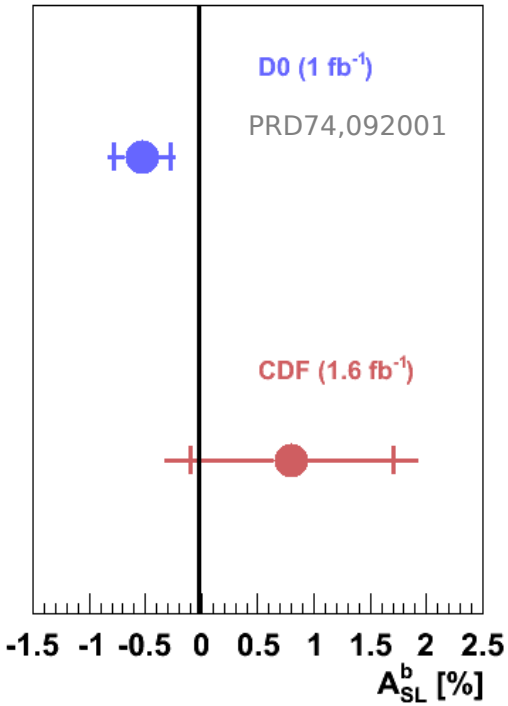
- CP violation in mixing (no direct CPV):
- Semileptonic charge asymmetry:

$$a^b_{SL} = \frac{\Gamma(\bar{B} \to B \to \mu^+ X) - \Gamma(B \to \bar{B} \to \mu^- X)}{\Gamma(\bar{B} \to B \to \mu^+ X) + \Gamma(B \to \bar{B} \to \mu^- X)}$$

- Like-sign dimuon charge asymmetry:

$$A^b_{SL} = \frac{\Gamma(B\bar{B} \to \mu^+\mu^+ X) - \Gamma(B\bar{B} \to \mu^-\mu^- X)}{\Gamma(B\bar{B} \to \mu^+\mu^+ X) + \Gamma(B\bar{B} \to \mu^-\mu^- X)}$$

- CPT conservation: $a_{SL}^b = A_{SL}^b$



- $a_{SL}^b = (0.506 \pm 0.043)\, a_{SL}^d + (0.494 \pm 0.043)\, a_{SL}^s$
- $a_{SL} = |\Gamma_{12}|/|M_{12}| \sin(\phi) = \Delta\Gamma/\Delta m \tan(\phi)$
- SM expectation [JHEP0706,072]: $a_{SL}^b = (-2.3\ ^{+0.5}_{-0.6}) \times 10^{-4}$

Analysis Strategy

- S muons: b/c hadrons, J/ψ, η, ω, τ, etc.
  L muons: decay in flight π/K, fake π/K/p

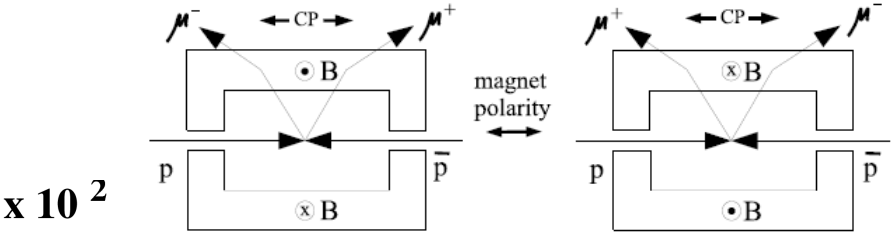
- Single muon sample (1.5 x 10^9 events):
  - Measure $a = (n^+ - n^-) / (n^+ + n^-)$
  - Correct for L muons and detection asymmetry → a_s
  - Correct for non B→μX decays: $a_{SL}^{b} = a_s / (0.070 \pm 0.006)$

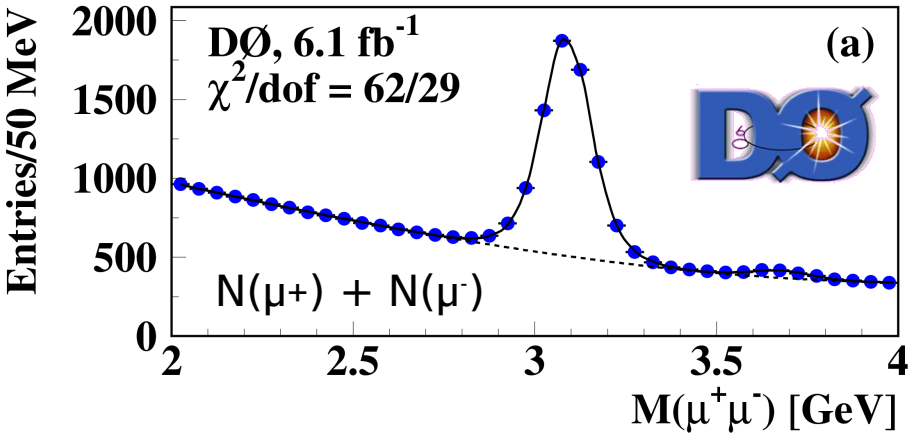
- Dimuon sample (3.6 x 10^6 events):
  - Measure $A = (N^{++} - N^{--}) / (N^{++} + N^{--})$
  - Correct for L muons and detection asymmetry → A_s
  - Correct for non B→μX decays: $A_{SL}^{b} = A_s / (0.486 \pm 0.032)$

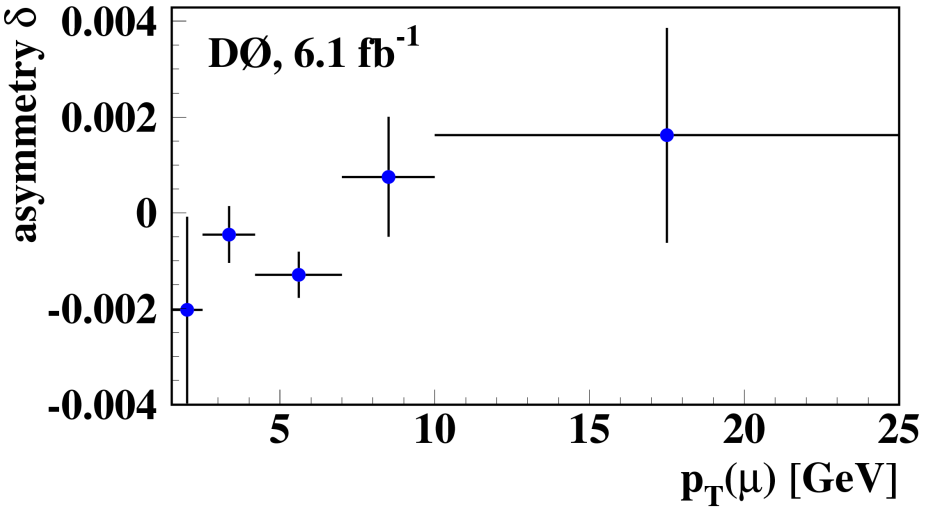
→ Improved result by combination of a and A

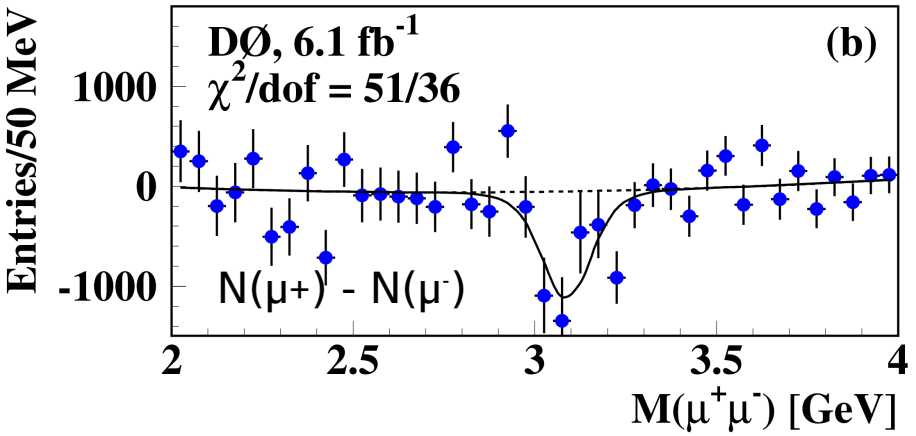
Muon Identification Asymmetry

- Asymmetry and systematic uncertainty reduced by regular reversal of magnet polarity
- Residual muon detection asymmetry measured with $J/\psi \rightarrow \mu^+\mu^-$ data



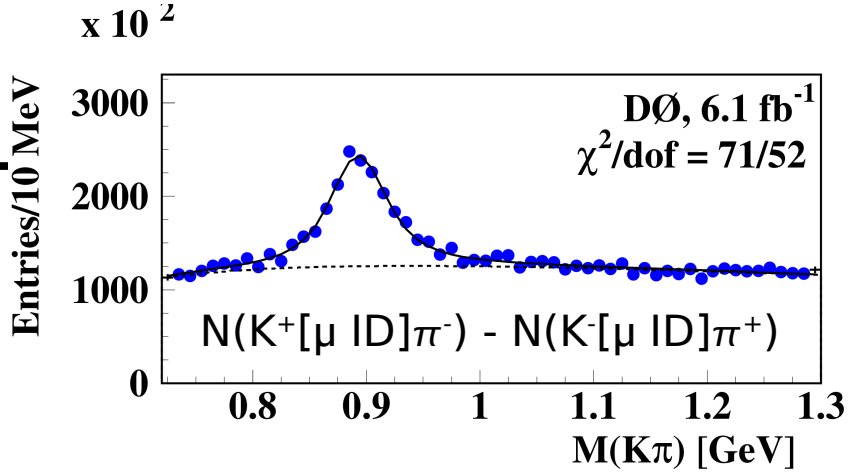


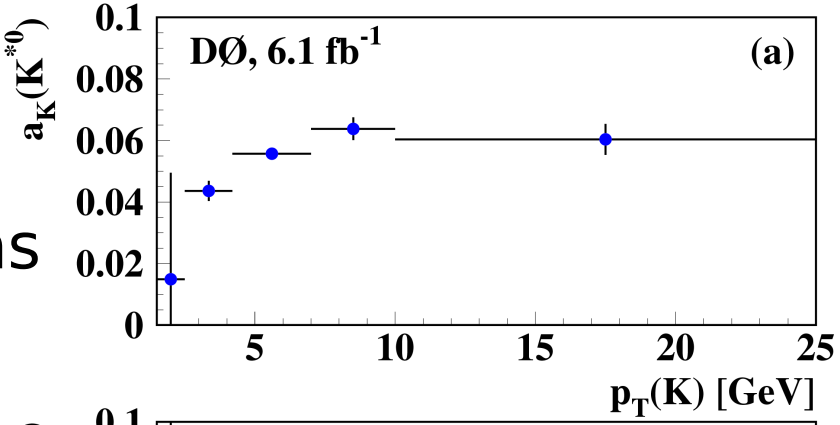


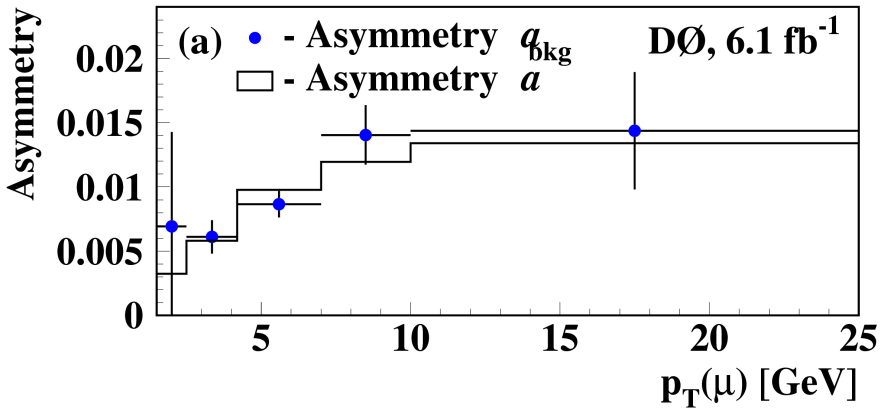


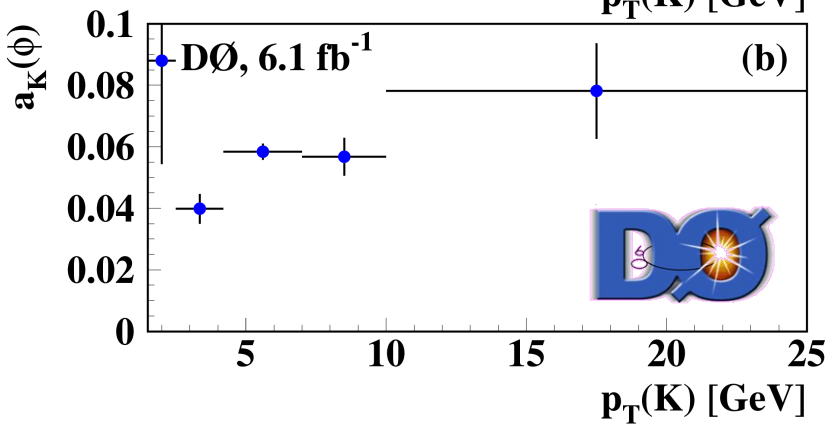
L Muon Backgrounds

- Fractions and asymmetries determined (mainly) from data:
  $K^{*+} \to K_s\pi^+$, $K^{*0} \to K^+\pi^-$, $\phi \to K^+K^-$, $K_s \to \pi^+\pi^-$, $\Lambda \to p\pi$-
- ➔ Closure test:
  measured a = asymmetry predicted by background fractions and asymmetries (a_s negligible)





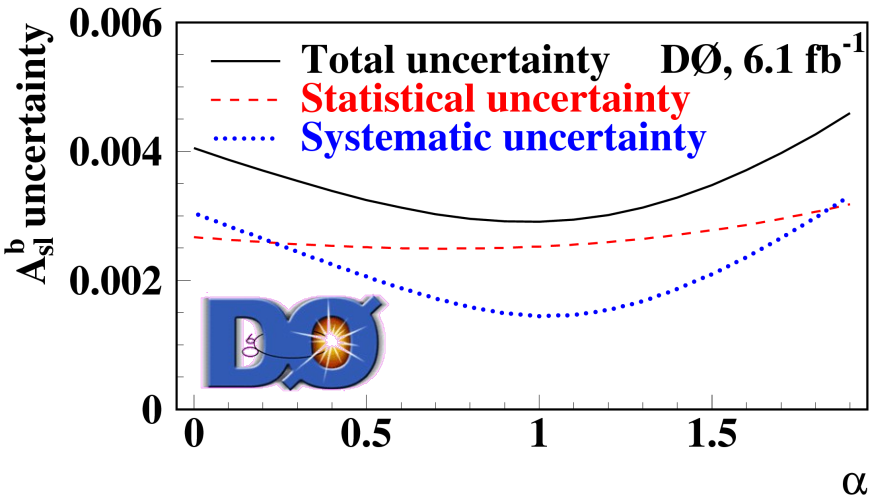




Non B→μX Correction and Combination

- Non B→μX correction factor (assuming $a_{non\text{-}B}$=0) from MC:
  - a_s: 0.070 ± 0.006
  - A_s: 0.486 ± 0.032
- Background uncertainties (partially) cancel in A - αa

	Process	Weight
T_1	$b \to \mu^- X$	$w_1 \equiv 1.$
T_{1a}	$b \to \mu^- X$ (nos)	$w_{1a} = (1-\chi_0)w_1$
T_{1b}	$\bar{b} \to b \to \mu^- X$ (osc)	$w_{1b} = \chi_0 w_1$
T_2	$b \to c \to \mu^+ X$	$w_2 = 0.113 \pm 0.010$
T_{2a}	$b \to c \to \mu^+ X$ (nos)	$w_{2a} = (1-\chi_0)w_2$
T_{2b}	$\bar{b} \to b \to c \to \mu^+ X$ (osc)	$w_{2b} = \chi_0 w_2$
T_3	$b \to c\bar{c}q$ with $c \to \mu^+ X$ or $\bar{c} \to \mu^- X$	$w_3 = 0.062 \pm 0.006$
T_4	$\eta, \omega, \rho^0, \phi(1020), J/\psi, \psi' \to \mu^+\mu^-$	$w_4 = 0.021 \pm 0.001$
T_5	$b\bar{b}c\bar{c}$ with $c \to \mu^+ X$ or $\bar{c} \to \mu^- X$	$w_5 = 0.013 \pm 0.002$
T_6	$c\bar{c}$ with $c \to \mu^+ X$ or $\bar{c} \to \mu^- X$	$w_6 = 0.660 \pm 0.077$



Source	From a	From A	From $A - \alpha a$
A or a (stat)	0.00066	0.00159	0.00179
f_K or F_K (stat)	0.00222	0.00123	0.00140
$P(\pi \to \mu)/P(K \to \mu)$	0.00234	0.00038	0.00010
$P(p \to \mu)/P(K \to \mu)$	0.00301	0.00044	0.00011
A_K	0.00410	0.00076	0.00061
A_π	0.00699	0.00086	0.00035
A_p	0.00478	0.00054	0.00001
δ or Δ	0.00405	0.00105	0.00077
f_K or F_K (syst)	0.02137	0.00300	0.00128
π, K, p multiplicity	0.00098	0.00025	0.00018
c_b or C_b	0.00080	0.00046	0.00068
Total statistical	0.01118	0.00266	0.00251
Total systematic	0.02140	0.00305	0.00146
Total	**0.02415**	**0.00405**	**0.00290**

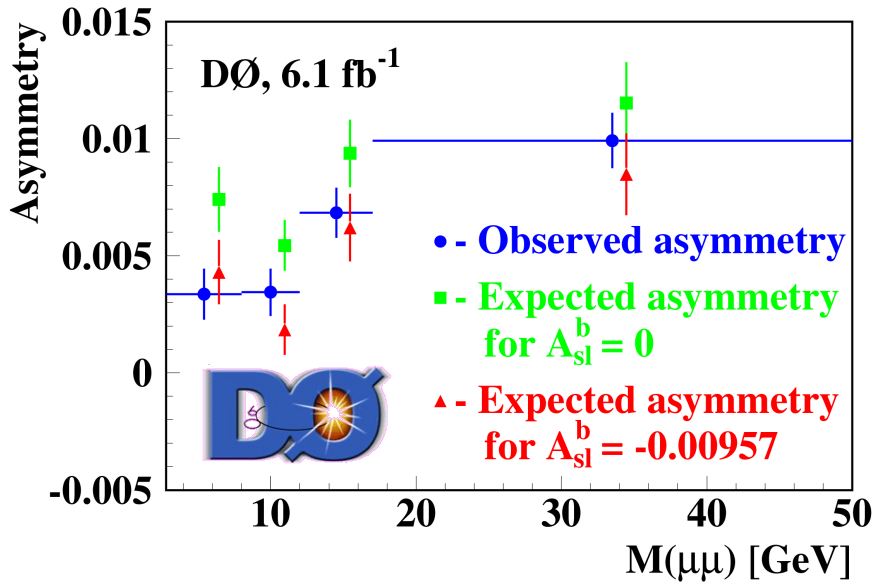
Result

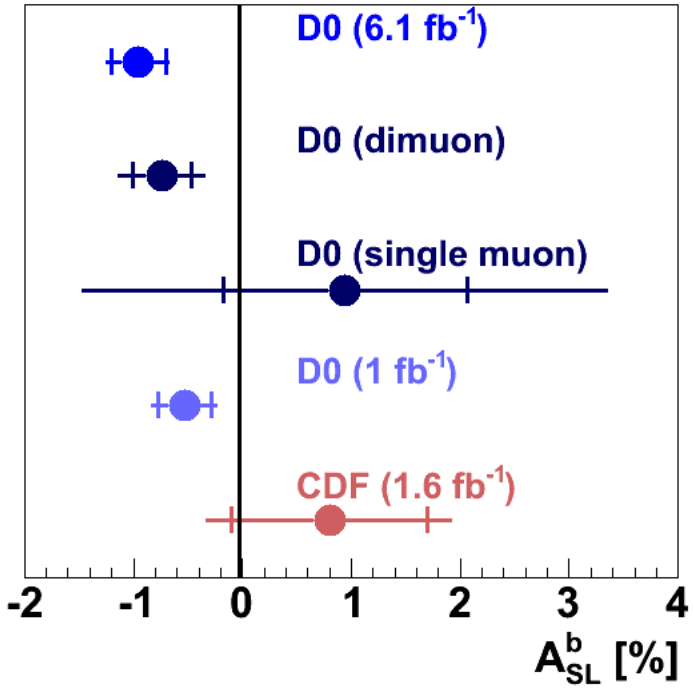
- Single muon: $A_{SL}^{b} = (+0.94 \pm 1.12 \pm 2.14)$ %
- Dimuon: $A_{SL}^{b} = (-0.736 \pm 0.266 \pm 0.305)$ %
- ➔ Combination: $A_{SL}^{b} = (-0.957 \pm 0.251 \pm 0.146)$ %
  (stable against selection variations)

PRL 105, 081801

PRD 82, 032001

- ➢ 3.2σ from SM → Evidence for anomalous like-sign dimuon charge asymmetry



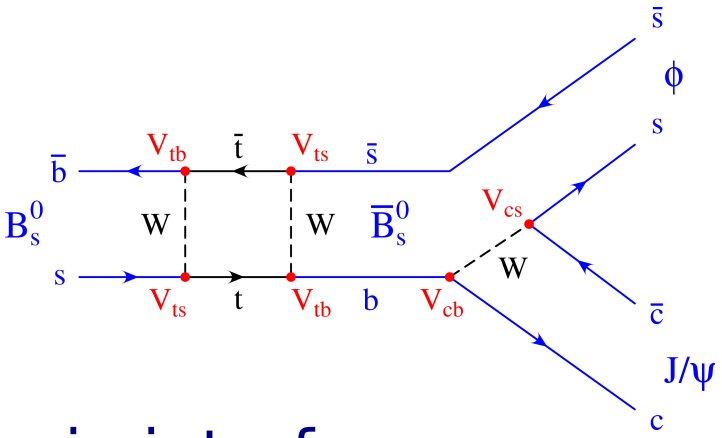


CP Violation in $B_s \to J/\psi\,\phi$

- Time dependent asymmetry of decay to CP eigenstate:

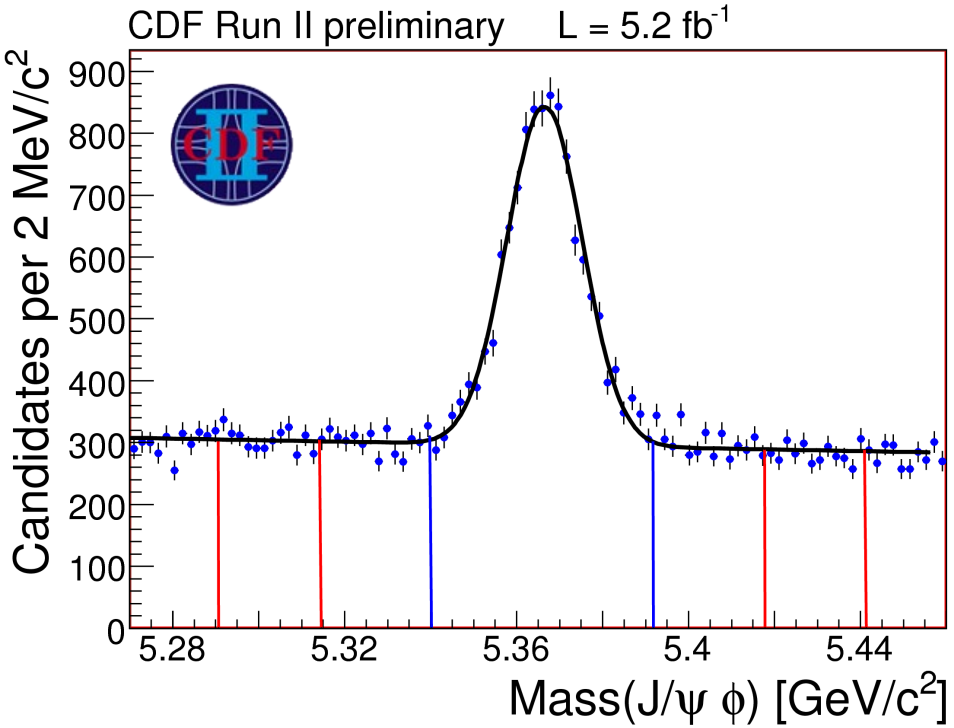
$$A_{CP}(t) = \frac{\Gamma(\bar{B}_s^0 \to f_{CP}) - \Gamma(B_s^0 \to f_{CP})}{\Gamma(\bar{B}_s^0 \to f_{CP}) + \Gamma(B_s^0 \to f_{CP})} \approx \pm \sin(\phi_s)\sin(\Delta m_s t)$$

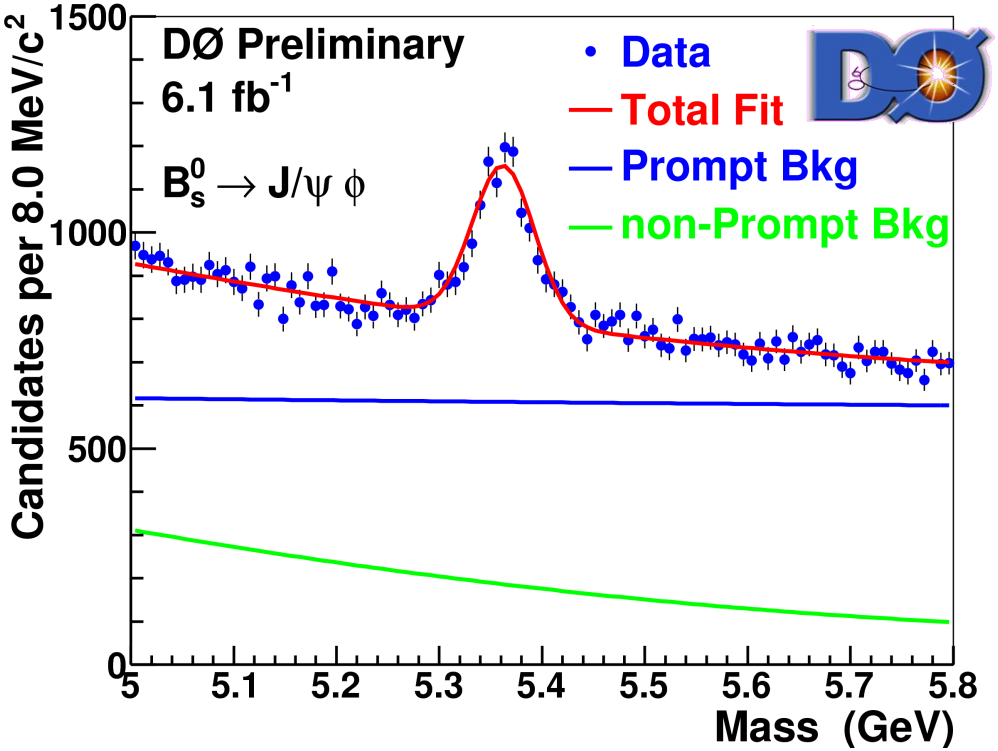
- ✗ Requires resolution of oscillations and flavor tagging
- ➔ Golden mode: $B_s \to J/\psi\,\phi$
  - ➢ *Mixture of CP eigenstates*
- ✗ Requires angular analysis



- ➢ Additional sensitivity to CP violation via interference of CP-even/odd components (mass ES ≠ CP ES)
- Mass ES can be identified if $\Delta\Gamma \neq 0 \to$ untagged analysis

Data Samples

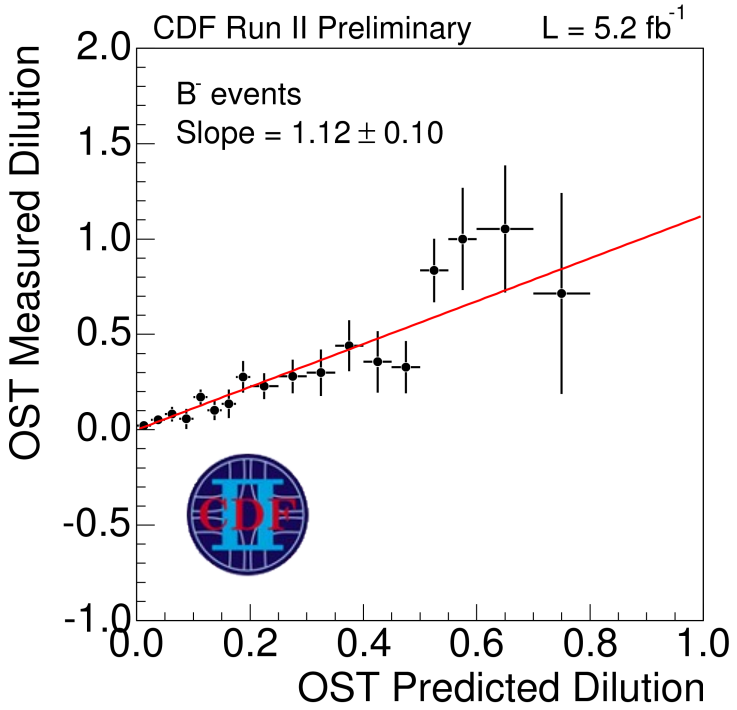


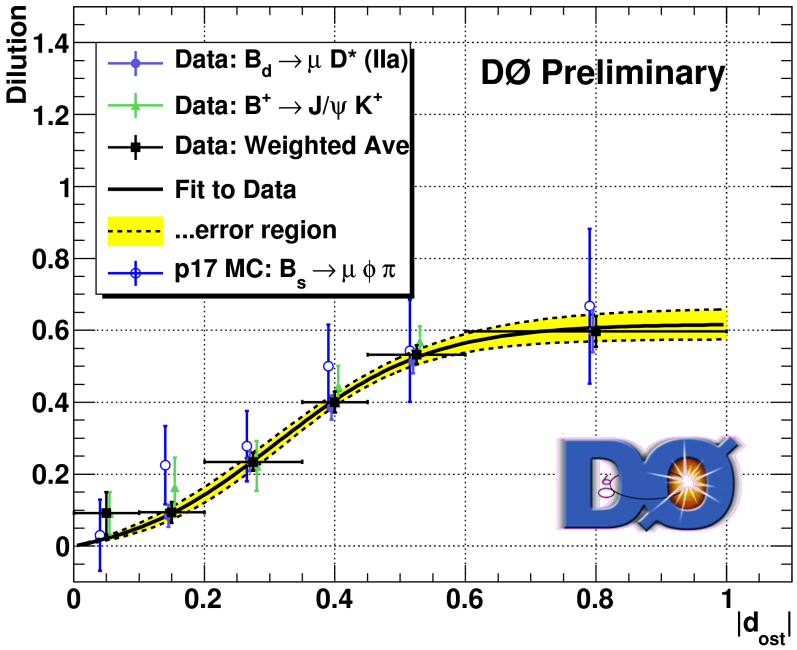


- Dimuon trigger
- 5.2 fb^{-1}
- Signal yield: ~6500

- Dimuon trigger
- 6.1 fb^{-1}
- Signal yield: ~3400

Flavor Tagging (Opposite Side)





- Electron, muon, and jet charge
- ➔ Combined with NN
- ✔ Calibrated on B^+ data

- Electron, muon, vertex, and event charge
- ➔ Combined with LHR
- ✔ Calibrated on B^+ and B^0 data

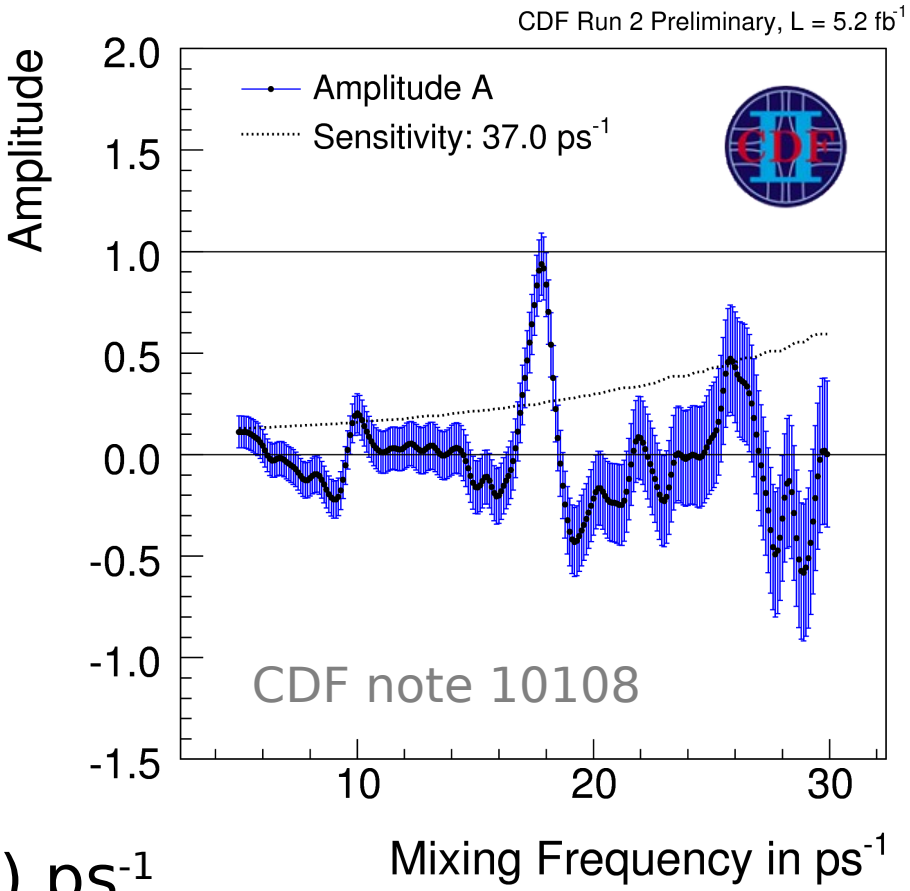
Flavor Tagging (Same Side)

- Same Side Kaon Tagger (as used for B_s mixing observation)

➢ First calibration on data via mixing fit using ~13k $B_s \rightarrow D_s(3)\pi$ decays:

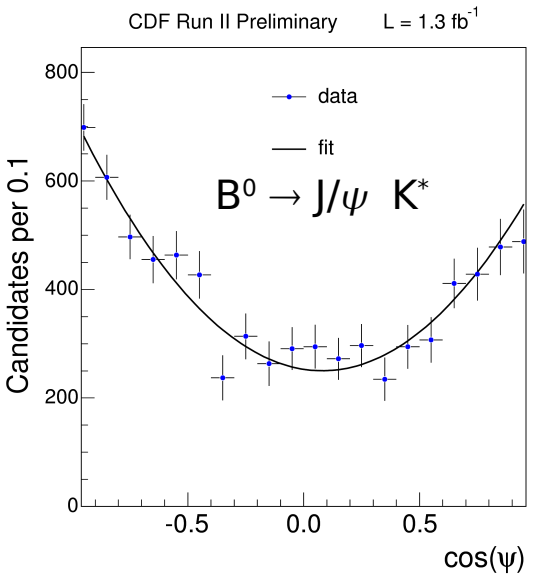
➔ $A = 0.94 \pm 0.15 \pm 0.13$

✔ $\Delta m_s = (17.79 \pm 0.07)\ ps^{-1}$ (stat. error only) agrees well with published result of $\Delta m_s = (17.77 \pm 0.10 \pm 0.07)\ ps^{-1}$



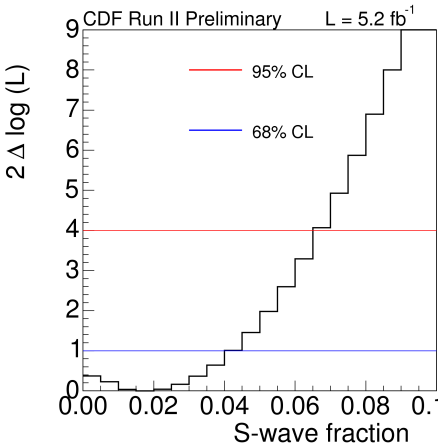
S-Wave Contamination

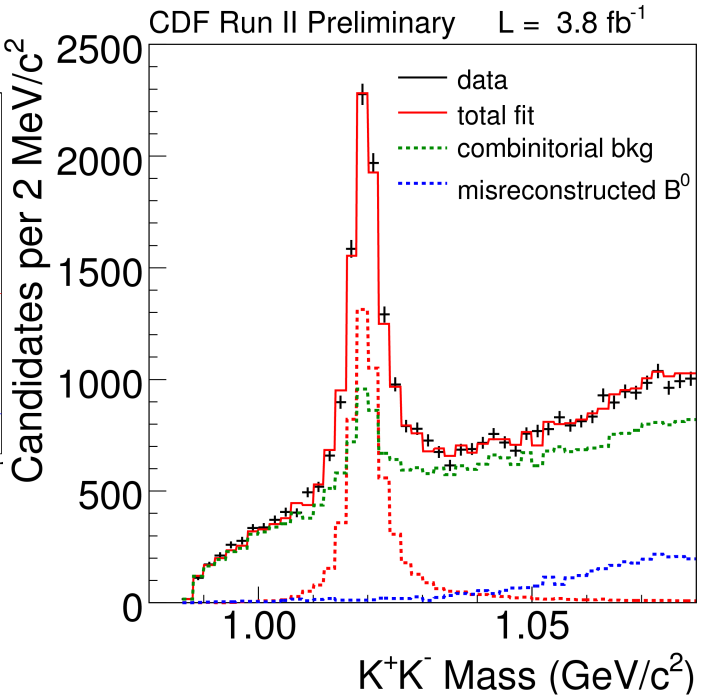
- $B_s \to J/\psi\ f_0$ ($f_0 \to K^+K^-$) or
  $B_s \to J/\psi\ K^+K^-$ (non-resonant)
  components could be present in data
- ➔ Would affect the angular distribution:
  Forward-backward asymmetry in cos(ψ)
  (observed for $B^0 \to J/\psi\ K^*$)
  - ✗ Bias of fit result
  - ✔ Interference would allow to resolve sign ambiguity

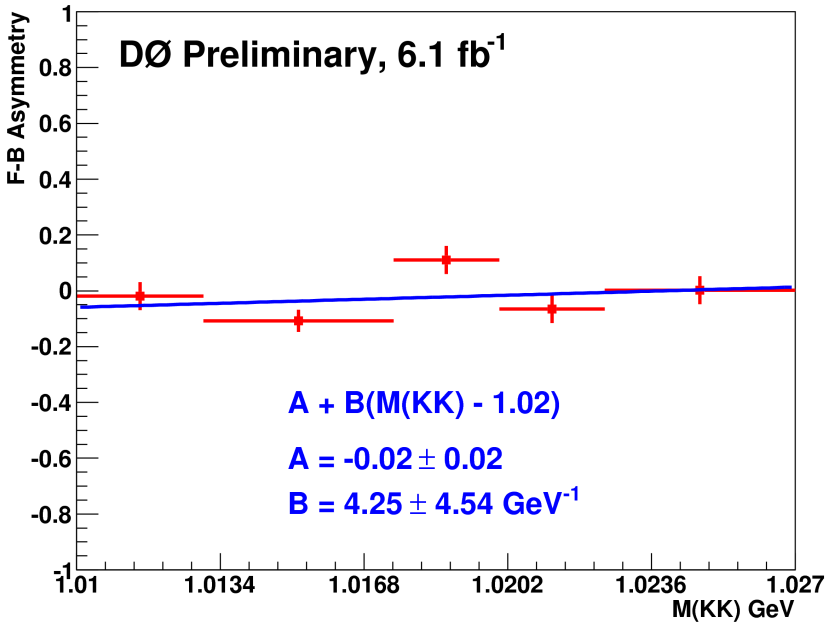


- CDF: Include S-wave component in fit
- D0: Measure FB asymmetry

S-Wave Results

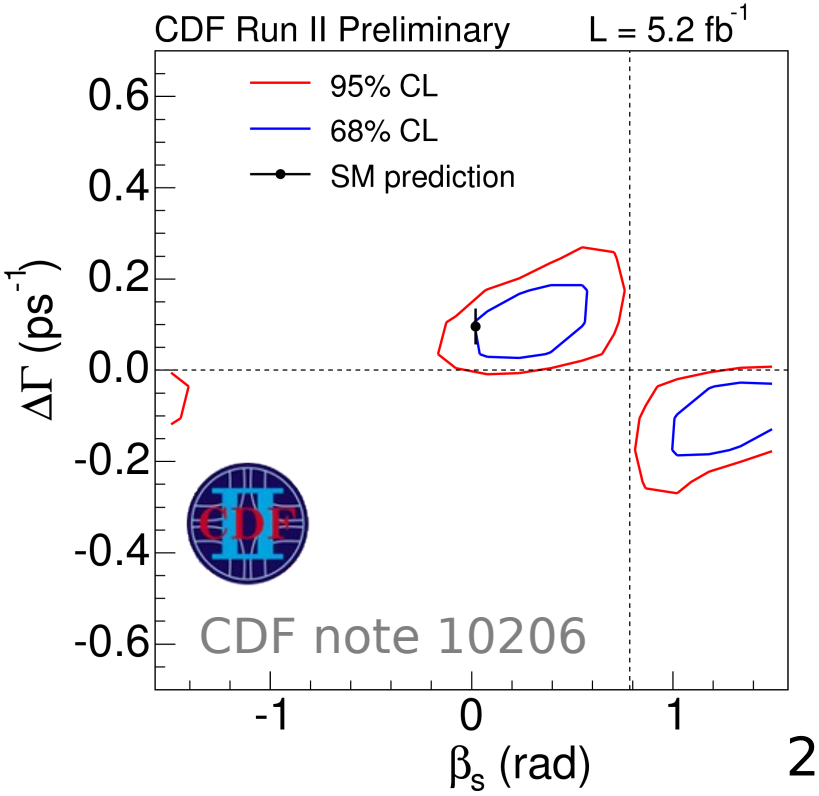




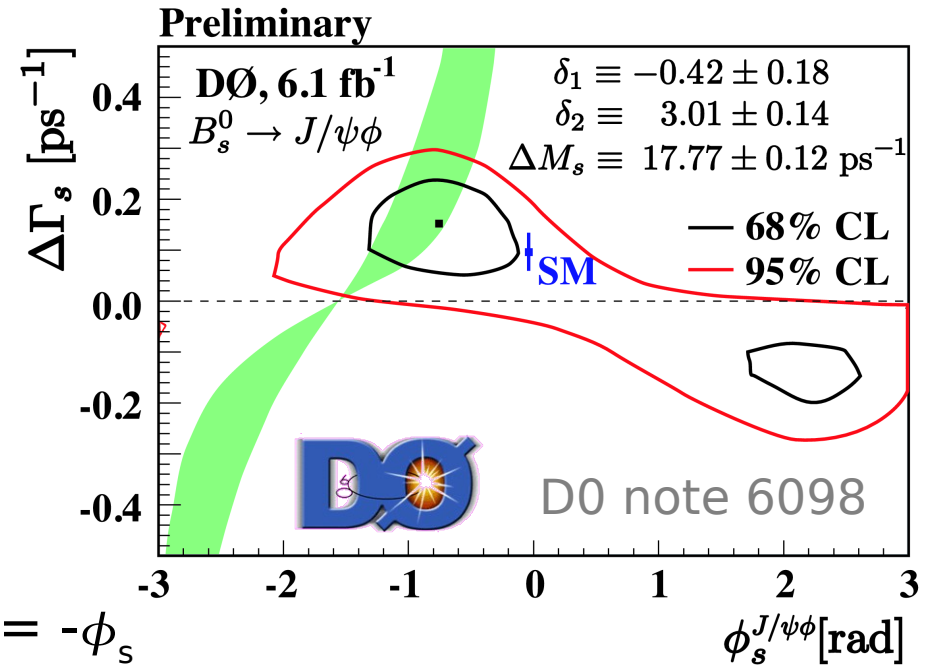


- Fitted S-wave contribution consistent with 0
- FB asymmetry consistent with 0

Results (2D)



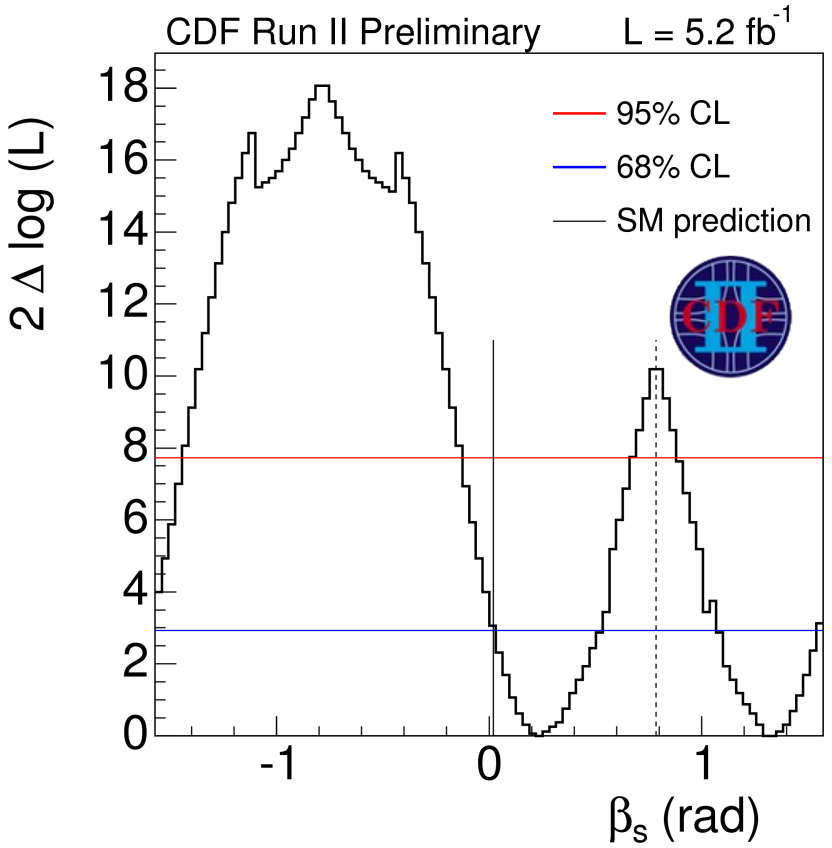
Coverage adjusted LH profiles

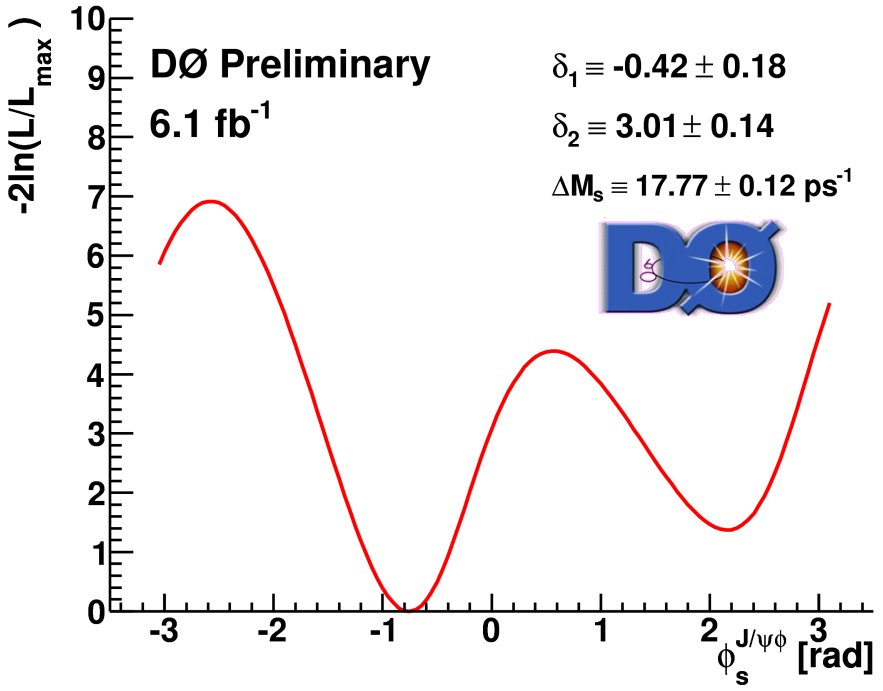


$2\beta_s = -\phi_s$

- D0: Constrain strong phases to the ones of $B^0 \to J/\psi\, K^*$ (motivated by agreement of amplitudes)
- ➔ Resolves ambiguity, removes fit bias → point estimate

Results (1D)





$2\beta_s = -\phi_s$

- 68% CL region for β_s:
  [0.02,0.52] U [1.08,1.55]
- Fit value:
  $\phi_s = -0.76\ ^{+0.38}_{-0.36} \pm 0.02$
  - Results of both experiments agree with the SM

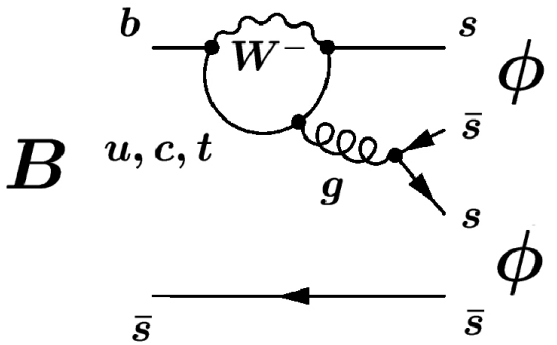
Further Point Estimates

- Fit assuming no CP violation (fixed $\beta_s=0$):
  - τ_s [ps] = $1.530 \pm 0.025 \pm 0.012$
  - $\Delta\Gamma_s$ [ps^{-1}] = $0.075 \pm 0.035 \pm 0.01$
  - $|A_{||}(0)|^2$ = $0.231 \pm 0.014 \pm 0.015$
  - $|A_0(0)|^2$ = $0.524 \pm 0.013 \pm 0.015$
  - $\varphi_\perp = 2.95 \pm 0.64 \pm 0.07$
- → Most precise measurements

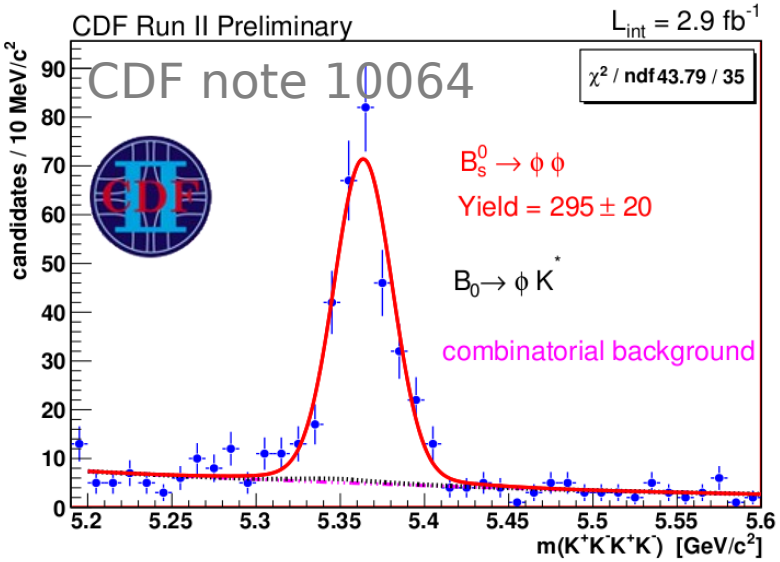
- Fit with constrained strong phases and ϕ_s floating:
  - τ_s [ps] = $1.47 \pm 0.04 \pm 0.01$
  - $\Delta\Gamma_s$ [ps^{-1}] = $0.15 \pm 0.06 \pm 0.01$
  - $A_\perp(0)$ = $0.44 \pm 0.03 \pm 0.01$
  - $|A_0(0)|^2 - |A_{||}(0)|^2$ = 0.35 ± 0.03

$B_s \to \phi\phi$

- b → s penguin dominated
- ➔ Null prediction for mixing induced CP violation in SM
- ➔ Comparison of $b \to c\bar{c}s$ and $b \to s\bar{s}s$ in B_s system (some discrepancy in B^0 system)



- ➢ BR = (2.40 ± 0.21 (stat) ± 0.27 (syst) ± 0.82(PDG)) x 10^{-5} measured by CDF last year with 2.9 fb^{-1} (displaced track trigger)
- ➢ Next step: polarization measurement on same data sample



$B_s \to \phi\phi$ Polarization

- Expectation from V-A nature of weak interaction and helicity conservation:
  - Dominantly longitudinal polarization: $|A_0| \gg |A_{||}| \approx |A_\perp|$
  - Confirmed in tree level B^0 decays, violated in $B^0 \to \phi K^*$

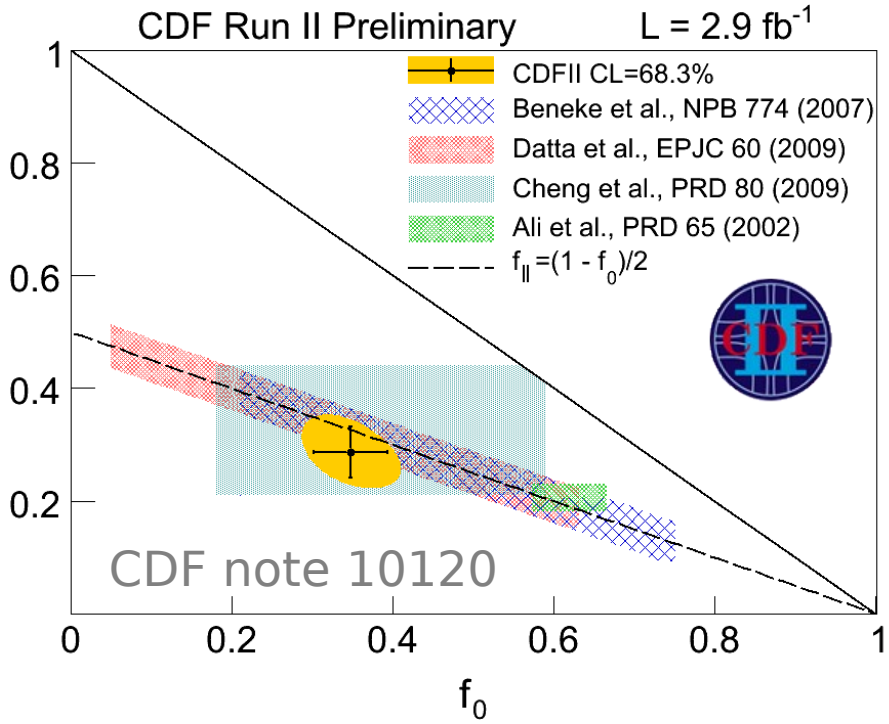
➔ ”Polarization puzzle”

➔ Predictions for $B_s \to \phi\phi$

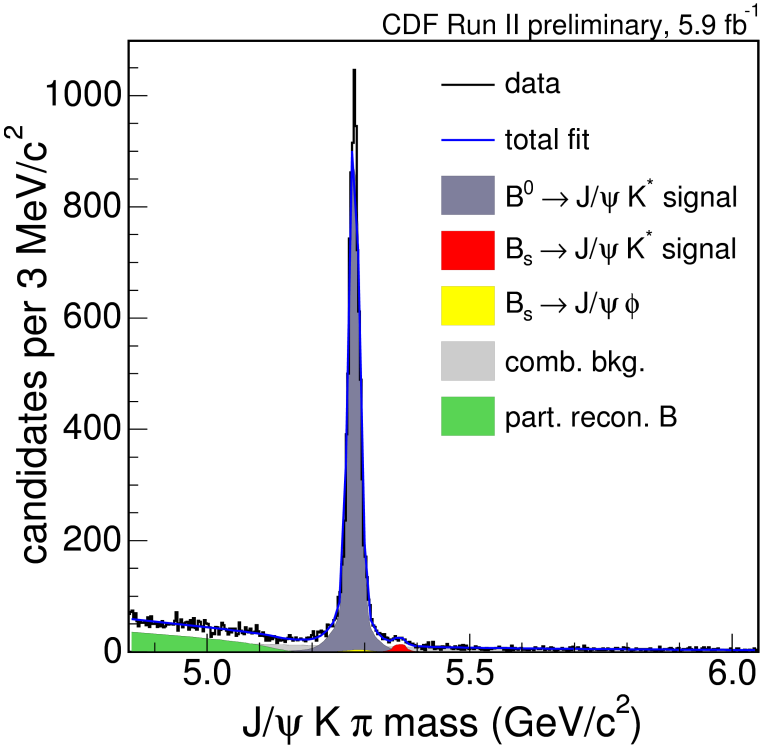
- Angular analysis:

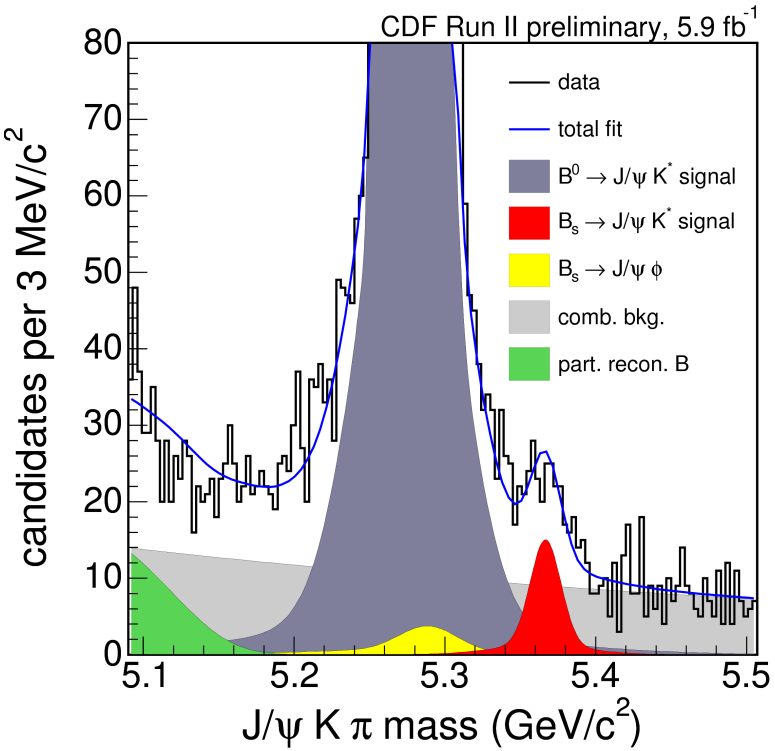
➔ $f_L = 0.348 \pm 0.041 \pm 0.021$

➢ Explanation by penguin annihilation (QCDF) favored over final state interaction (pQCD)



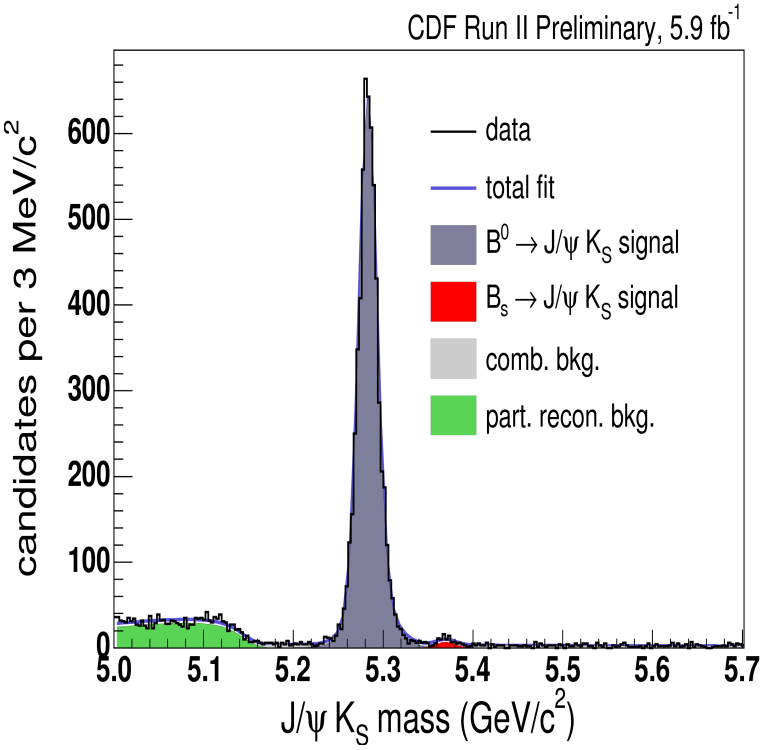
$B_s \to J/\psi\ K^*$

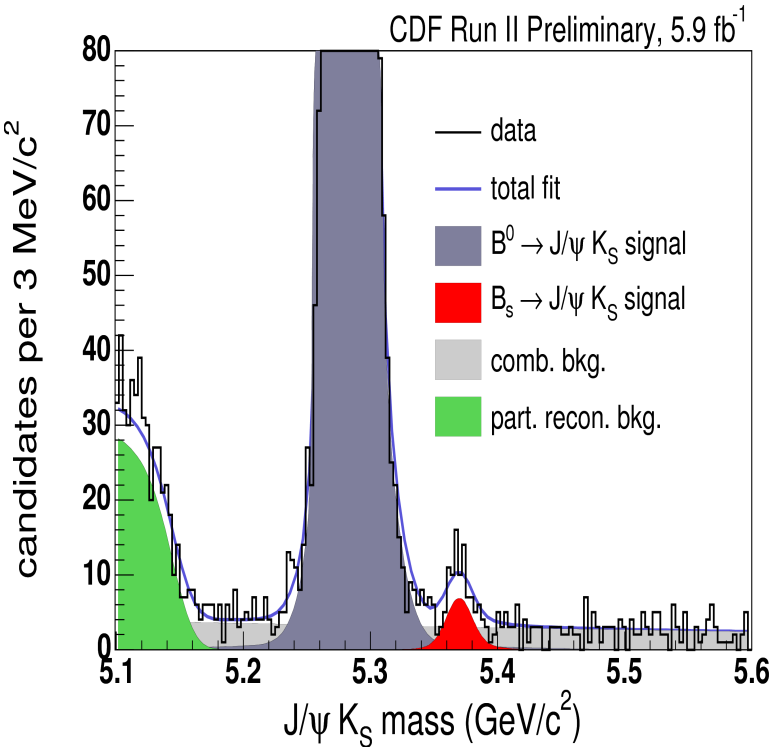




- Yield: 151 ± 25, significance: 8σ → First observation
- → BR($B_s \to J/\psi\ K^*$) [normalized to $B^0 \to J/\psi\ K^*$] =
  (8.3 ± 1.2 (stat) ± 3.3 (sys) ± 1.0 (frag) ± 0.4 (PDG)) x 10^{-5}
- ➢ Sensitive to hadronic terms entering $B_s \to J/\psi\ \phi$ observables

$B_s \to J/\psi\ K_S$



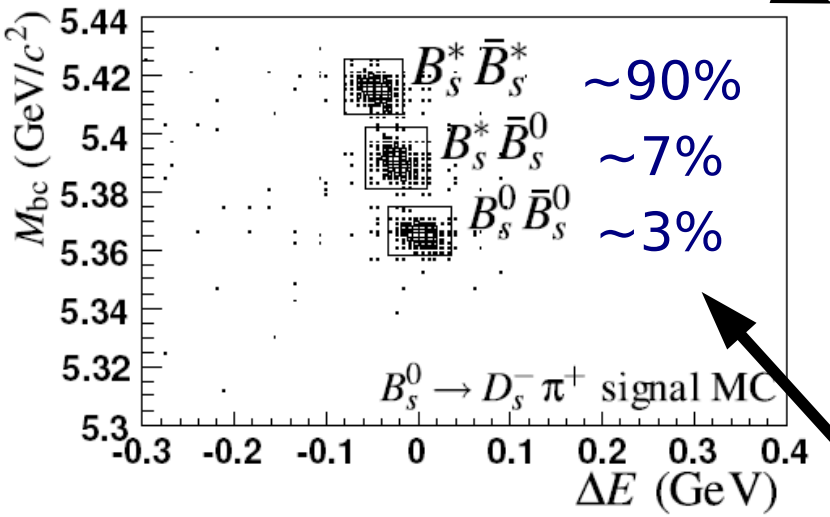


- Yield: 64 ± 14, significance: 7.2σ → First observation
- → BR($B_s \to J/\psi\ K^0$) [normalized to $B^0 \to J/\psi\ K_S$] =
  (3.5 ± 0.6 (stat) ± 0.4 (sys) ± 0.4 (frag) ± 0.1 (PDG)) x 10^{-5}
- ➢ CP eigenstate → direct measurement of Γ_H (in SM)

B_s Physics at Belle

e^+e^- @ 10867 MeV → Continuum ($q\bar{q}$)

→ Y(5S) ($b\bar{b}$)



~90%

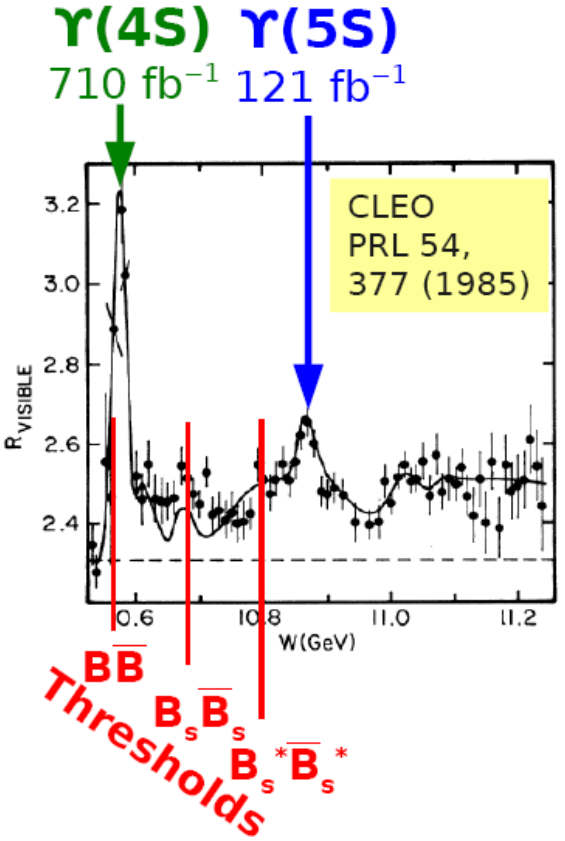
~7%

~3%

→ $B^{(*)}\bar{B}^{(*)}(\pi)(\pi)$

→ $B_s^{(*)}\bar{B}_s^{(*)}$

$f_s = (18.0 \pm 3.5)\%$

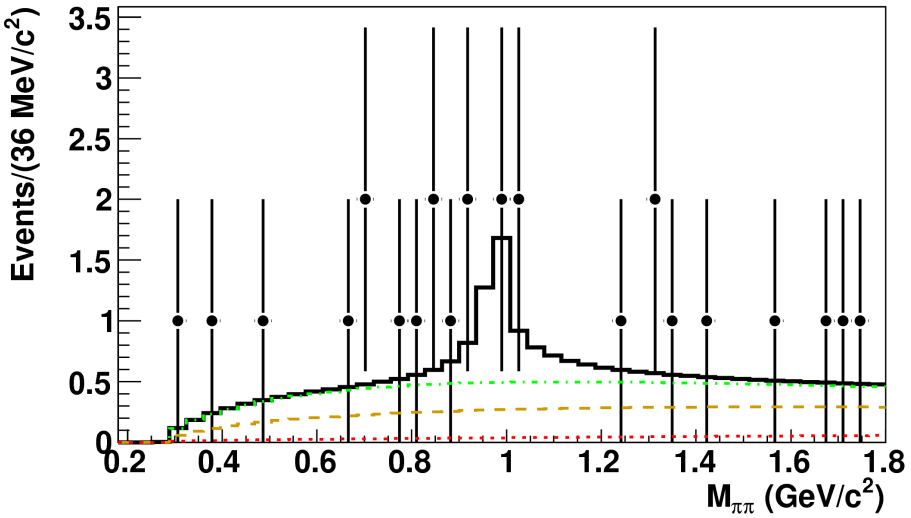


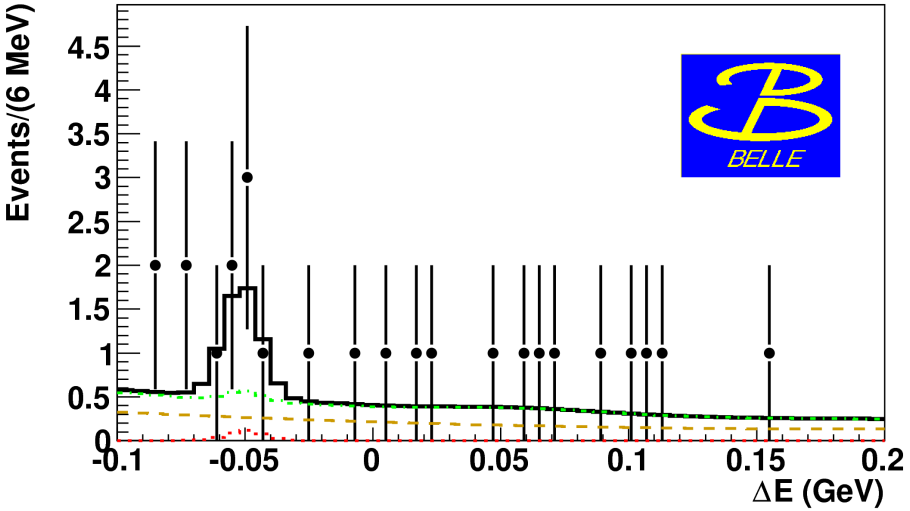
Compared to CDF/D0:

- ✔ Absolute BR measurements possible
- ✔ Reconstruction of neutrals (γ, π^0), better PID
- ✗ Vertex resolution / boost insufficient to resolve oscillations

$B_s \to J/\psi\ f_0$

- CP eigenstate → sensitive to CPV w/o angular analysis

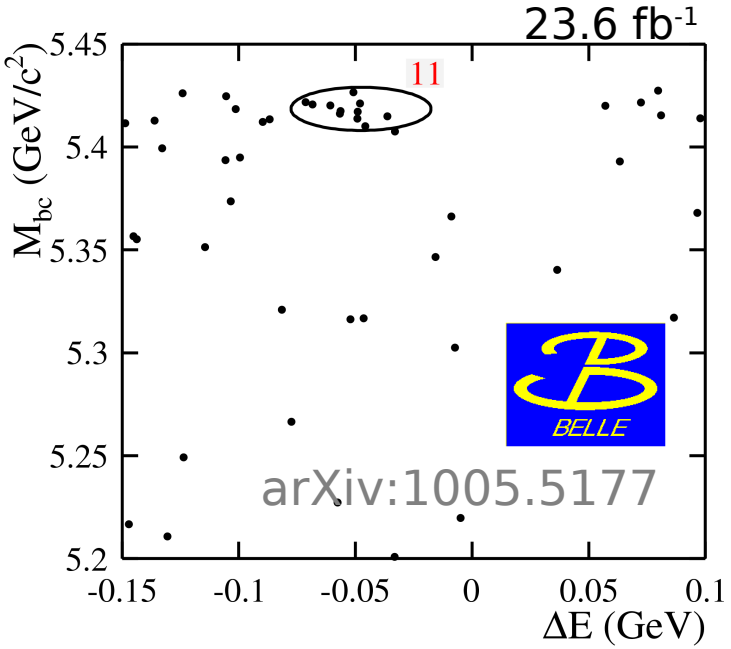




- Yield in 23.6 fb^{-1}: 6.0 ± 4.0 (1.6σ)
- BR($B_s \to J/\psi\ f_0$)BR($f_0 \to \pi^+\pi^-$) < 1.63 x 10^{-4} @ 90% CL
- Predictions:
  Extrapolation from $B_s \to J/\psi\ \phi$ (PRD 79, 074024): (1.3 - 2.7) x 10^{-4}
  QCD@LO (PRD 81, 074001): (1.6 ± 1.3) x 10^{-4}

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

- Cabibbo favored decay, predominantly CP even
- → $\Delta\Gamma_{CP} = \Gamma^{even} - \Gamma^{odd} \approx \Gamma(D_s^{(*)} D_s^{(*)})$ ($\Delta\Gamma = \Delta\Gamma_{CP} \cos\phi$)

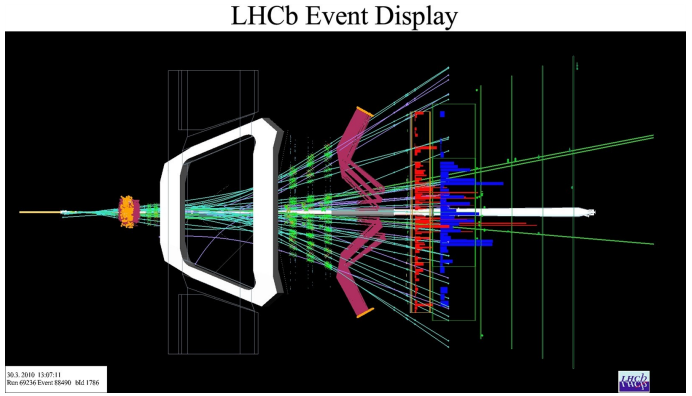


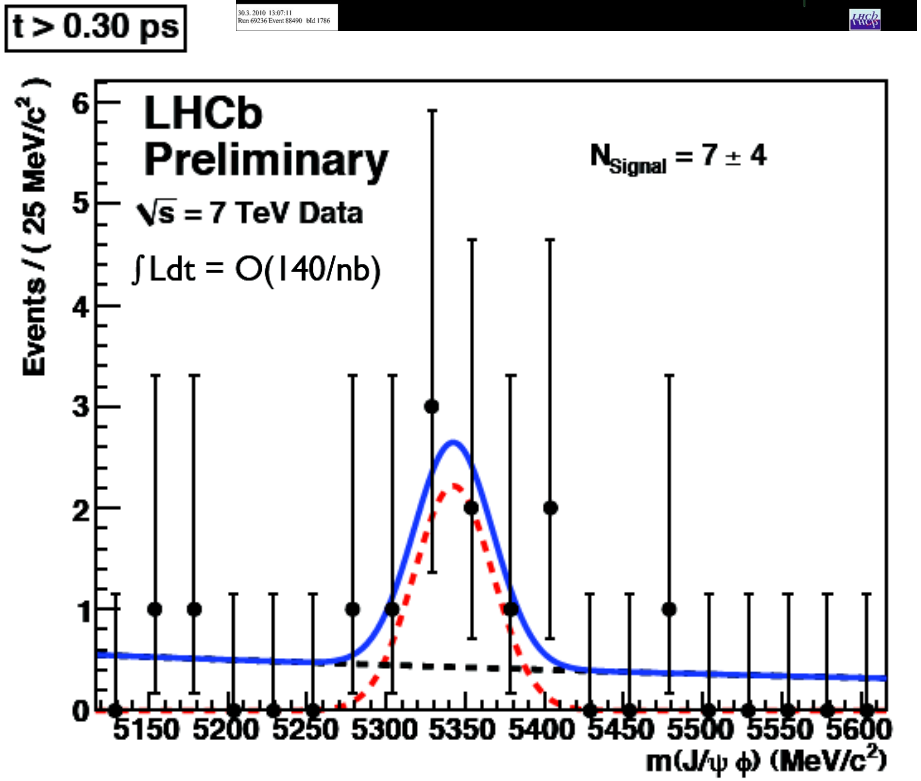
- $8.5\ ^{+3.2}_{-2.6}\ (6.2\sigma)$ $B_s \to D_s D_s$
  BR = $(1.0\ ^{+0.4}_{-0.3}\ ^{+0.3}_{-0.2})$ %
- $9.2\ ^{+2.8}_{-2.4}\ (6.6\sigma)$ $B_s \to D_s^* D_s$
  → first observation
  BR = $(2.8\ ^{+0.8}_{-0.7} \pm 0.7)$ %
- $4.9\ ^{+1.9}_{-1.7}\ (3.2\sigma)$ $B_s \to D_s^* D_s^*$
  → first evidence
  BR = $(3.1\ ^{+1.2}_{-1.0} \pm 0.8)$ %

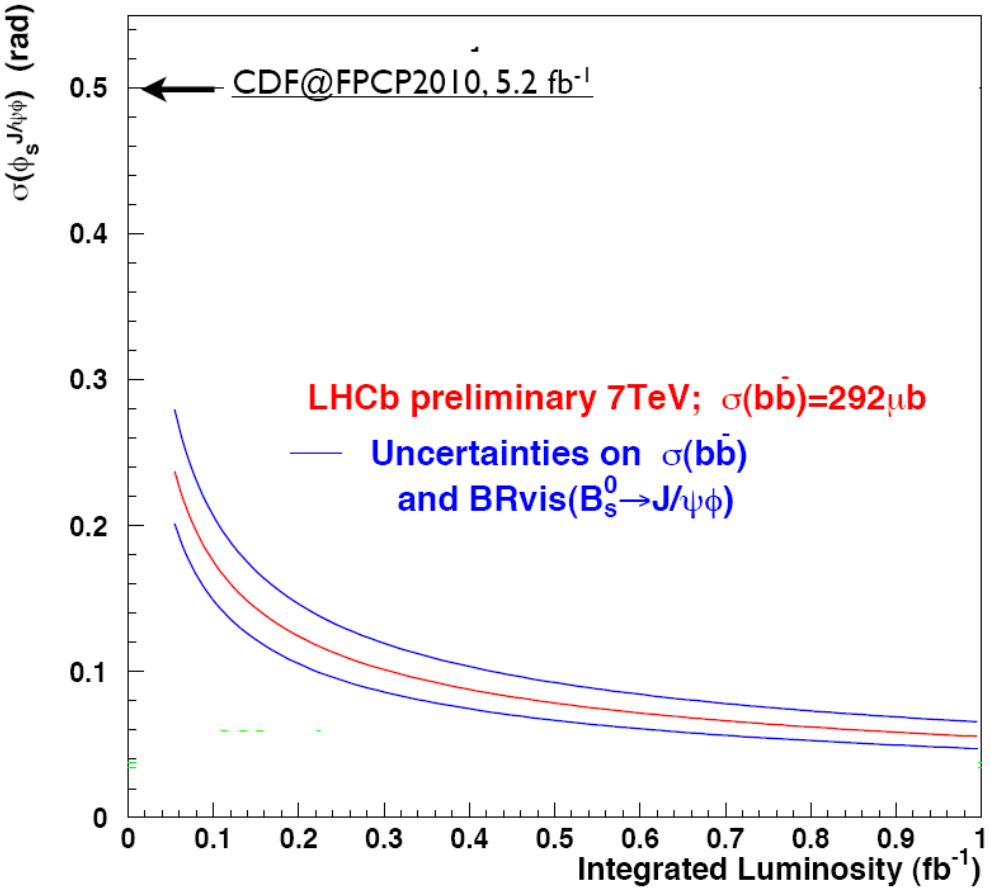
→ $\Delta\Gamma_{CP}/\Gamma = (14.7\ ^{+3.6}_{-3.0}\ ^{+4.4}_{-4.2})$ %

- D0 [PRL 102,091801]: (7.2 ± 2.1 ± 2.2) %,
- SM prediction [JHEP 0706:072]: (12.7 ± 2.4) %

LHCb


LHCb Event Display


t > 0.30 ps
LHCb
Preliminary
√s = 7 TeV Data
∫Ldt = O(140/nb)
N_Signal = 7 ± 4
Events / (25 MeV/c²)
m(J/ψ φ) (MeV/c²)


CDF@FPCP2010, 5.2 fb⁻¹
LHCb preliminary 7TeV; σ(bb̄)=292μb
Uncertainties on σ(bb̄)
and BRvis(B⁰s→J/ψφ)
σ(φs J/ψφ) (rad)
Integrated Luminosity (fb⁻¹)

Summary

- Large NP effects may still be present in the B_s system
  - Like-sign dimuon charge asymmetry measured by D0 is ~3σ away from the SM
  - Updated measurements of CP violation in $B_s \to J/\psi\,\phi$ agree with the SM
    - Tevatron rules B_s physics
    - Belle provides valuable complementary results
    - LHCb has started to catch up