CP Violation & B_s Physics at CDF & DØ

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(for the CDF & DØ collaborations)

XXII Rencontres de Physique de la Vallée d'Aoste
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Bs and CP related analysis

1) 20 or more B_s-specific results since last year La Thuile !
   - Will focus in a few analyses
   - and will show some more results

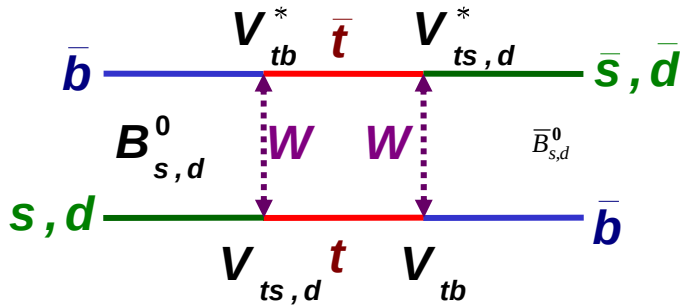
2) Concentrate on the Breadth of B_s Physics
   - Search for CP Violation in B_s
   - Bs Properties

3) Outline: Progress on B_s Physics since the start of Run II
   - Why the B_s ?
   - Experimental Ingredients
   - Results
   - Future Prospects

The Useful B_s

Electro-Weak Symmetry Breaking

- In SM: EW Sym. Breaking ⇔ Flavor Struct. (CKM matrix, CPV)
- 1 SM Higgs Doublet ⇓ Strong Flavor Constraints
  - FCNCs suppressed — Unitary V_{ckm}
  - *1 param for all CPV processes* — *No CPV in flavor diag.*



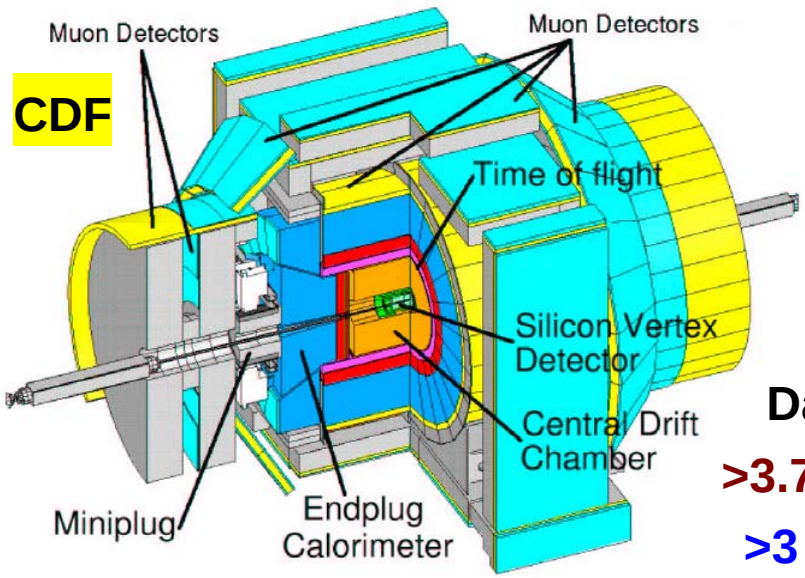
Direct Searches for Beyond the SM Effects

- Rare (Leptonic) Decays: many models predict large effects in B_s

QCD Modelling: compare & contrast with B_d

- SU(3) Flavor Symmetry, Heavy Quark Effective Theory
- Lattice ...

B_s at CDF and DØ

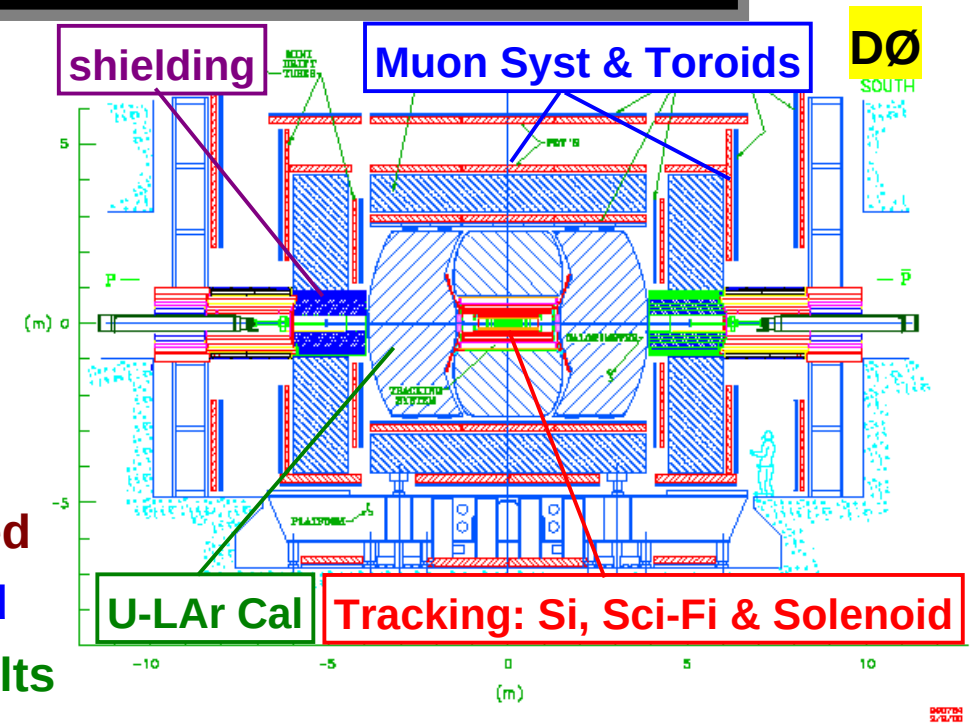


Data Samples

>3.7 fb^{-1} delivered

>3 fb^{-1} recorded

up to 2.8 fb^{-1} results



Production	LEP	B-Factories	Tevatron	LHCb
	E_{CM}=91 GeV	Υ(5S)	(in accept)	(in accept)
Approx B_s Rate	0.04 Hz	1 Hz	600 Hz	5000 Hz

Decay Mode	B.R.
$B_s \to D^-_s X$	94%
$B_s \to D^-_s l^+ \nu X$	7.9%
$B_s \to J/\psi(\mu^+\mu^-)\ \phi(K^+K^-)$	2.7×10^{-5}
$D^+_s \to \phi(K^+K^-)\ \pi^+$	2.2%
$D^+_s \to K^{*0}(K^-\pi^+)\ K^+$	2.5%
$D^+_s \to \pi^+\ \pi^-\ \pi^+$	1.2%

Important at the Tevatron

- **Triggering**
- **Muons**
- **Tracking/Vertexing**
- **(π / *K Separation*)**

$B^0_s \to J/\psi\ \phi$

B^0_s golden channel
No CP eigenstates
Transversity basis

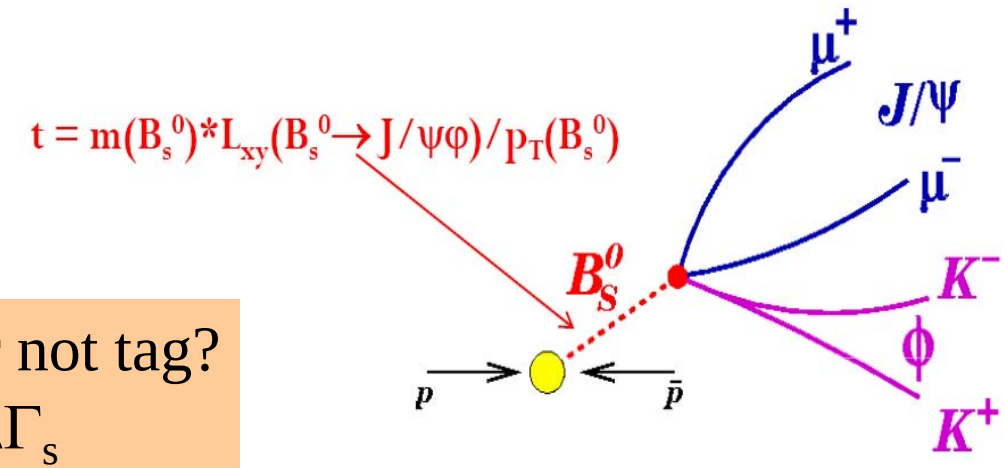
Why?

$$\Delta M_s = M_H - M_L$$
$$\Delta\Gamma_s = \Gamma_L - \Gamma_H$$

M_H & M_L CP Eigenstates

SM: $\phi_s = -2\,\beta_s = 0.04 \pm 0.01$
New Physics $\to \phi_s = -2\,\beta_s + \phi_s^{\Delta}$

To tag or not tag?
Δm_s ϕ_s $\Delta\Gamma_s$



$$|A_0(t)|^2 = |A_0(0)|^2 e^{-\Gamma t}\left[\cosh\frac{\Delta\Gamma t}{2} - |\cos\phi|\sinh\frac{|\Delta\Gamma|t}{2} + \sin\phi\,\sin(\Delta m t)\right]$$

$$|A_\parallel(t)|^2 = |A_\parallel(0)|^2 e^{-\Gamma t}\left[\cosh\frac{\Delta\Gamma t}{2} - |\cos\phi|\sinh\frac{|\Delta\Gamma|t}{2} + \sin\phi\,\sin(\Delta m t)\right]$$

$$|A_\perp(t)|^2 = |A_\perp(0)|^2 e^{-\Gamma t}\left[\cosh\frac{\Delta\Gamma t}{2} + |\cos\phi|\sinh\frac{|\Delta\Gamma|t}{2} - \sin\phi\,\sin(\Delta m t)\right]$$

$$\frac{d^3\Gamma[B_s(t)\to J/\psi(\to l^+l^-)\phi(\to K^+K^-)]}{d\cos\theta\, d\varphi\, d\cos\psi} \propto \frac{9}{32\pi}\Big[\, 2|A_0(t)|^2\cos^2\psi(1-\sin^2\theta\cos^2\varphi)$$
$$+\sin^2\psi\{|A_\parallel(t)|^2(1-\sin^2\theta\sin^2\varphi) + |A_\perp(t)|^2\sin^2\theta - \mathrm{Im}\,(A_\parallel^*(t)A_\perp(t))\sin 2\theta\sin\varphi\}$$
$$+\frac{1}{\sqrt{2}}\sin 2\psi\{\,\mathrm{Re}\,(A_0^*(t)A_\parallel(t))\sin^2\theta\sin 2\varphi + \mathrm{Im}\,(A_0^*(t)A_\perp(t))\sin 2\theta\cos\varphi\,\}\Big]\ . \quad (6$$

$$\frac{d^3\Gamma[\overline{B}_s(t)\to J/\psi(\to l^+l^-)\phi(\to K^+K^-)]}{d\cos\theta\, d\varphi\, d\cos\psi} \propto \frac{9}{32\pi}\Big[\, 2|\overline{A}_0(t)|^2\cos^2\psi(1-\sin^2\theta\cos^2\varphi)$$
$$+\sin^2\psi\{|\overline{A}_\parallel(t)|^2(1-\sin^2\theta\sin^2\varphi) + |\overline{A}_\perp(t)|^2\sin^2\theta - \mathrm{Im}\,(\overline{A}_\parallel^*(t)\overline{A}_\perp(t))\sin 2\theta\sin\varphi\}$$
$$+\frac{1}{\sqrt{2}}\sin 2\psi\{\,\mathrm{Re}\,(\overline{A}_0^*(t)\overline{A}_\parallel(t))\sin^2\theta\sin 2\varphi + \mathrm{Im}\,(\overline{A}_0^*(t)\overline{A}_\perp(t))\sin 2\theta\cos\varphi\,\}\Big]\ , \quad (7$$

Δm_s
$\Delta\Gamma_s$
ϕ_s

CP even $A_{0,\parallel}$
CP odd $A_\perp$

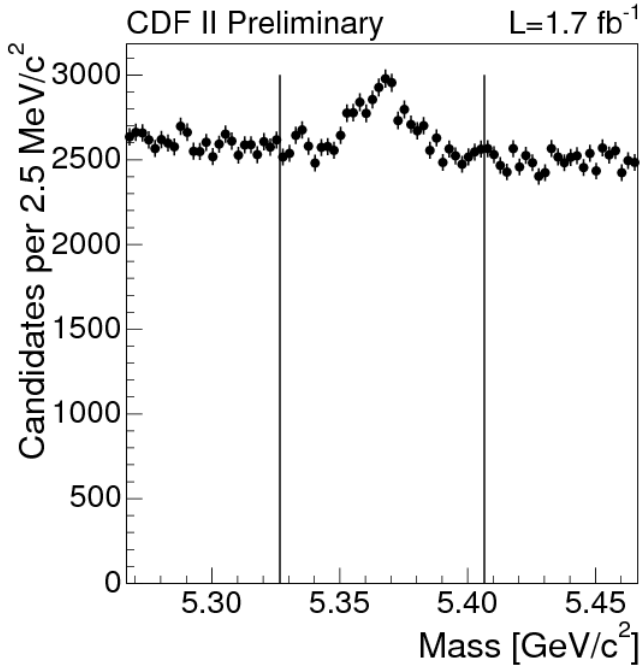
$B^0_s \rightarrow J/\psi\ \phi$ (CDF)

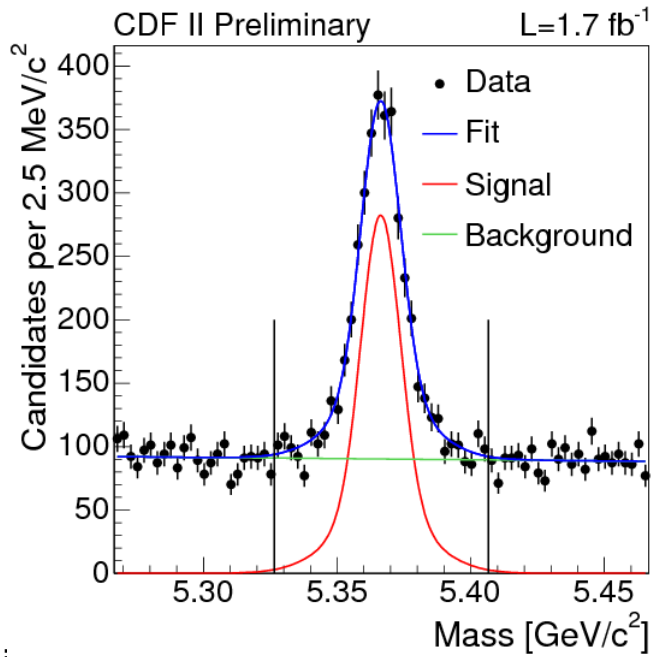
Untagged and $\phi_s=0$

B^0 as a cross check and competitive
Int Lum ~ 1.7 fb^{-1} (dimuon trigger)

Loose selection
(kinematic & quality cuts)
NN: MC(signal) & SB(Back)
kinematic & vertex qualities
2,500 evts
Toy MC : Systematic sources

- Back angular model
- Mass model
- Lifetime resolution
- B0d, B0s cross feed
- Acceptance model
- Alignment

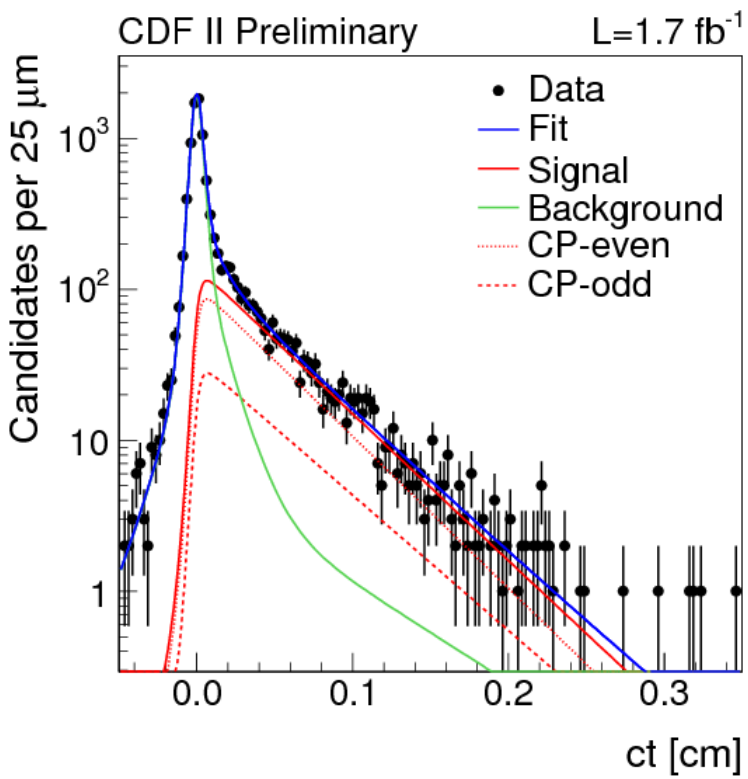


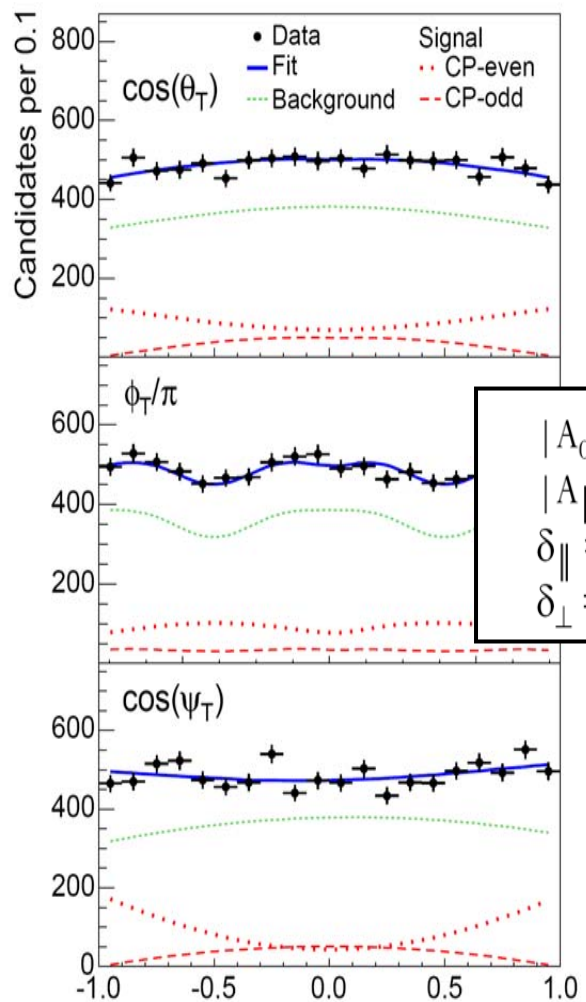


$B^0_s \to J/\psi\ \phi$ (CDF)

Fit Results: B^0_s

$$c\tau_s = 456 \pm 13 \pm 7\ \mu\text{m}$$
$$\Delta\Gamma = 0.076^{+0.059}_{-0.063} \pm 0.006\ \text{ps}^{-1}$$
$$|A_0|^2 = 0.530 \pm 0.021 \pm 0.007$$
$$|A_{||}|^2 = 0.230 \pm 0.027 \pm 0.009$$





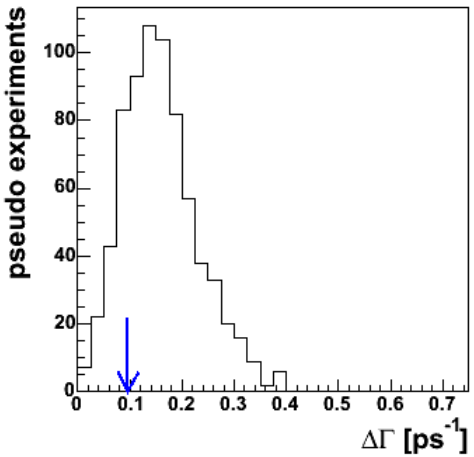
Fit Results: B^0

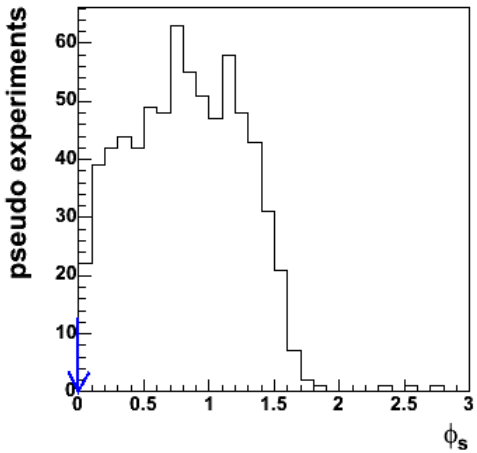
$$c\tau_d = 456 \pm 6 \pm 6\ \mu\text{m}$$
$$|A_0|^2 = 0.569 \pm 0.009 \pm 0.009$$
$$|A_{||}|^2 = 0.211 \pm 0.012 \pm 0.006$$
$$\delta_{||} = -2.96 \pm 0.08 \pm 0.03$$
$$\delta_{\perp} = 2.97 \pm 0.06 \pm 0.01$$

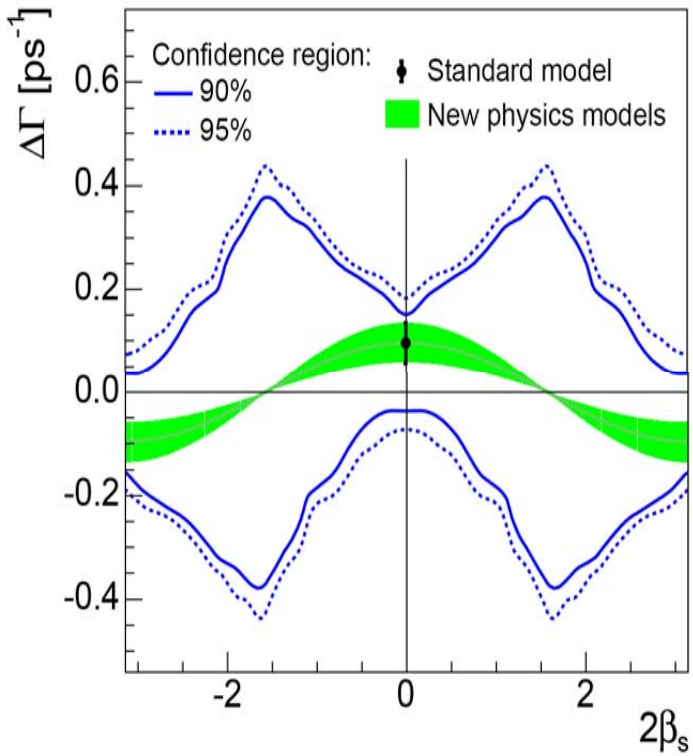
$|A_0(0)|^2 = 0.556 \pm 0.009$ (stat) ± 0.010 (syst)
$|A_{||}(0)|^2 = 0.211 \pm 0.010$ (stat) ± 0.006 (syst)
$\delta_{||} = -2.93 \pm 0.08$ (stat) ± 0.04 (syst)
$\delta_{\perp} = 2.91 \pm 0.05$ (stat) ± 0.03 (syst)

B Factories results

$B^0_s \rightarrow J/\psi\ \phi$ (CDF)







If ϕ_s is a parameter, Bias?

Fit result (ϕ_s) consistent with SM

$\Delta\Gamma_s = 0.1$ & $\phi_s = 0$ p-value 22%

$\Delta\Gamma$s & ϕs values excluded at 90% and 95% CL

$$2\beta_s \rightarrow -2\beta_s,\ \delta_\perp \rightarrow \delta_\perp + \pi$$

$$\Delta\Gamma \rightarrow -\Delta\Gamma,\ 2\beta_s \rightarrow 2\beta_s + \pi$$

4-fold ambiguity

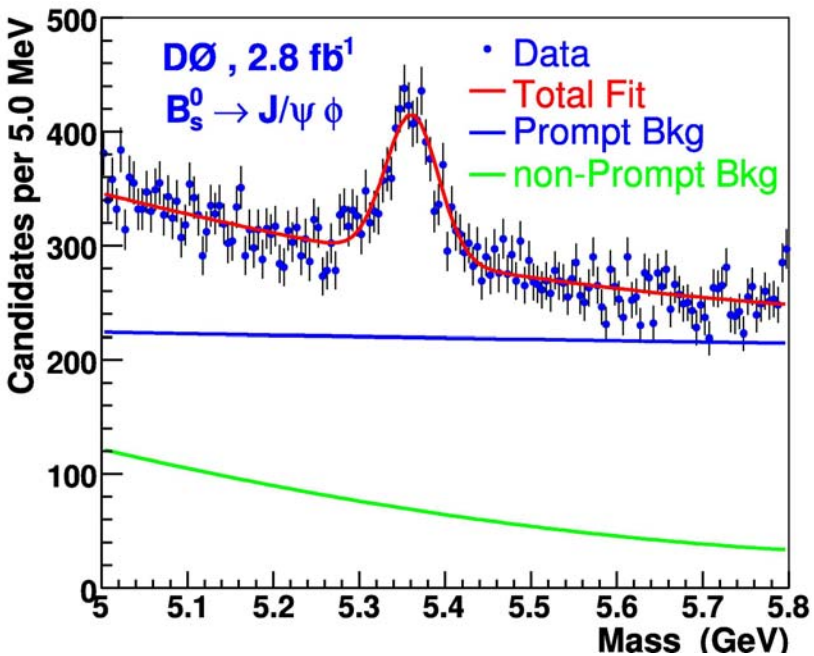
$B^0_s \to J/\psi\ \phi$ (DØ)

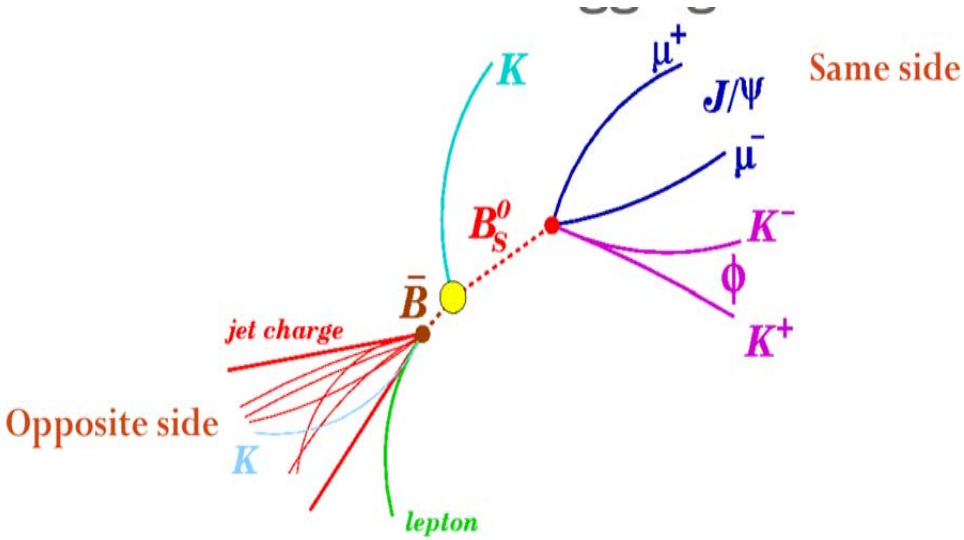
Previous → Current
Untagged → Tagged
1.1 fb^{-1} → 2.8 fb^{-1}

1967±65 B^0_s

Tagging Same Side
Opposite Side
B^0 & B^+
Tagging Power = (4.68±0.54)%

To tag or not tag?
Δm_s ϕ_s $\Delta\Gamma_s$





Unbinned Likelihood Fit:

Inputs: mass, PDL & angular vars

$$\mathcal{L} = \prod_{i=1}^{N} [f_{\rm sig}\mathcal{F}^i_{\rm sig} + (1 - f_{\rm sig})\mathcal{F}^i_{\rm bck}]$$

$B^0_s \to J/\psi\ \phi$

Weighted by P(Bs) and acceptance
Angular Acceptance (Polynomials)
Weighting: MC vs Data

Back
- PDL: Res(G) + 3 Exp(+,-,++)
- Angular: polys (cos θ, cosψ, ϕ)
- Mass: P1+P2

Δm_s ,ϕ_s vs strong phases (δ_1 and δ_2)
Fix Δm_s : 17.77±0.12 ps^{-1}
δ_1 and δ_2 : B factories

Fit results:

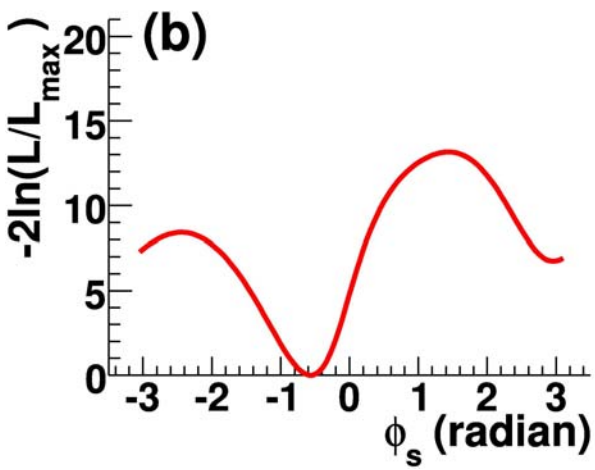
$$\overline{\tau}(B^0_s) = 1.52 \pm 0.05 \pm 0.01 \text{ ps}$$

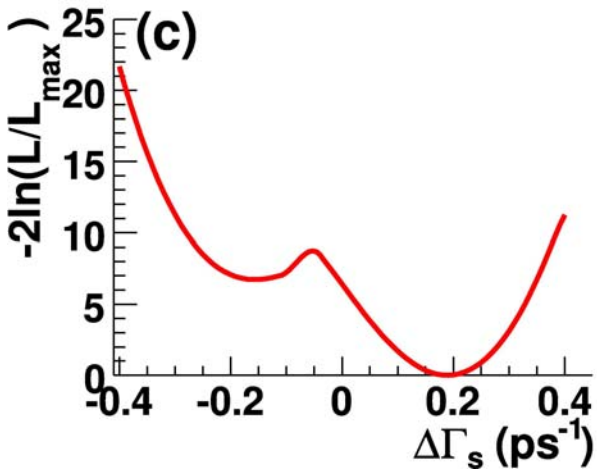
$$\Delta\Gamma_s = 0.19 \pm 0.07(\text{stat})^{+0.02}_{-0.01}(\text{syst}) \text{ ps}^{-1}$$

$$\phi_s = -0.57^{+0.24}_{-0.30}(\text{stat})^{+0.07}_{-0.02}(\text{syst})$$

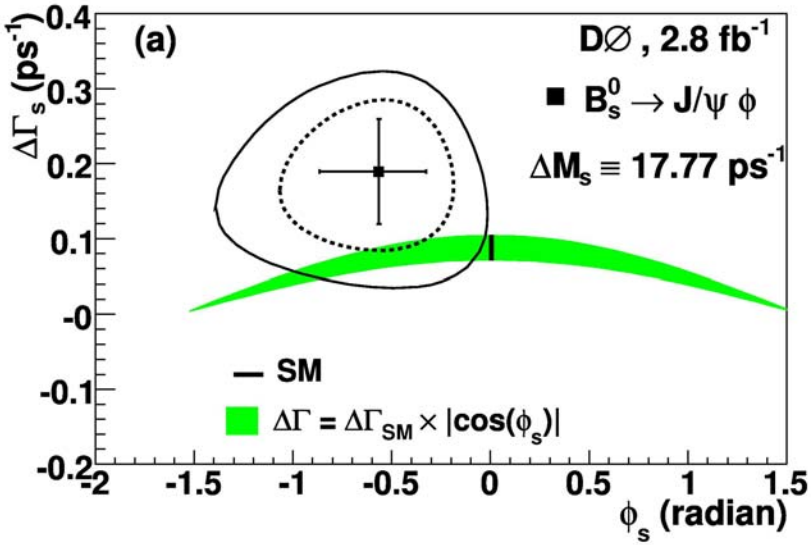
Systematic sources

- Acceptance
- Mass Model
- Flavor purity
- Back model
- Δm_s

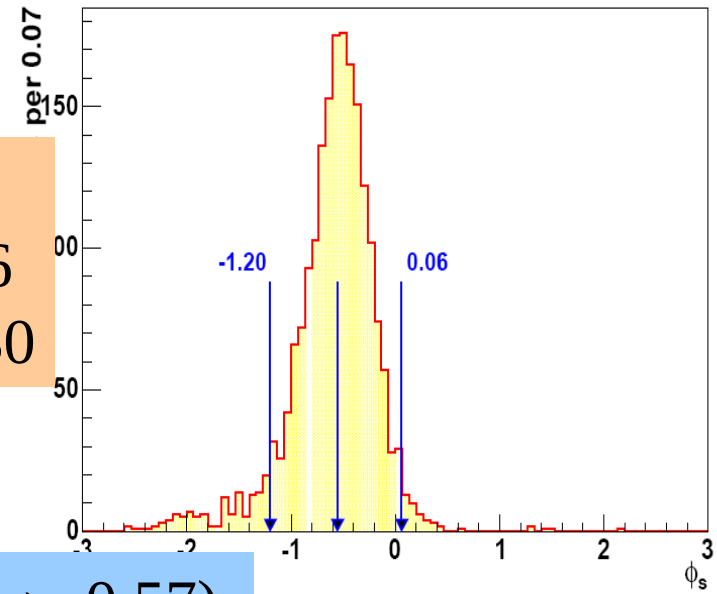




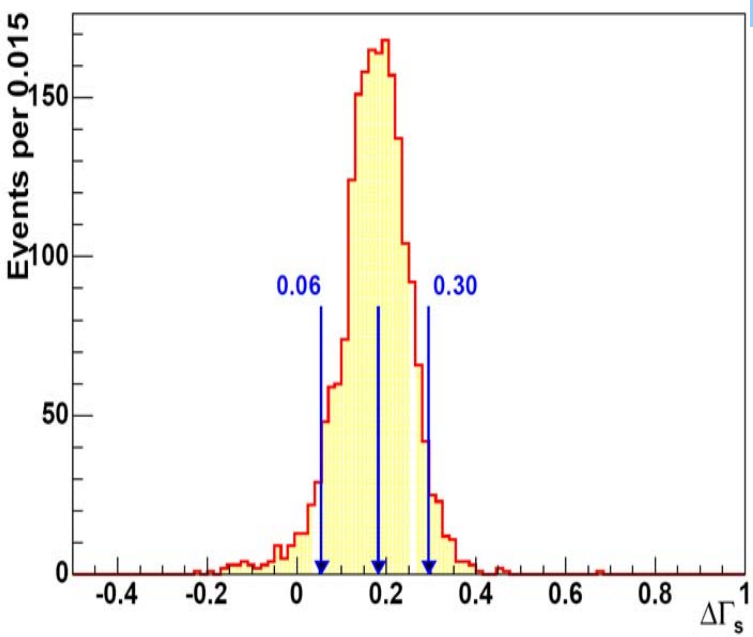
$B^0_s \rightarrow J/\psi\ \phi$



90% CL
$-1.20 < \phi_s < 0.06$
$0.06 < \Delta\Gamma_s < 0.30$



Prob. 6.6% (0.04 → -0.57)



$B^0_s \to J/\psi\ \phi$ (CDF) Bounds

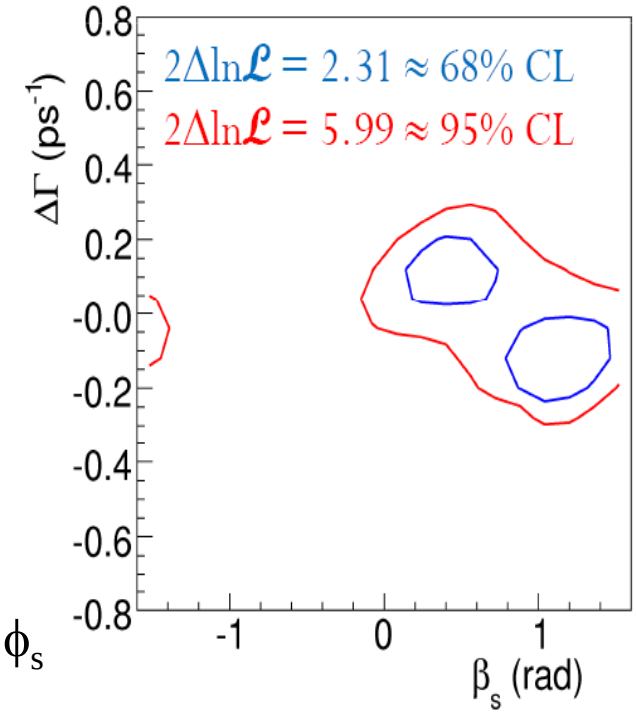
Tagged analysis:

Same technique (NN)

Same description of decay
Access to the three parameters

Tagging: OST
SST

Likelihood Fit: Δm_s constrained, $\Delta\Gamma_s$ ϕ_s
Variables: mass, pdl and angular,
pdl error and tagging info(Dilution,

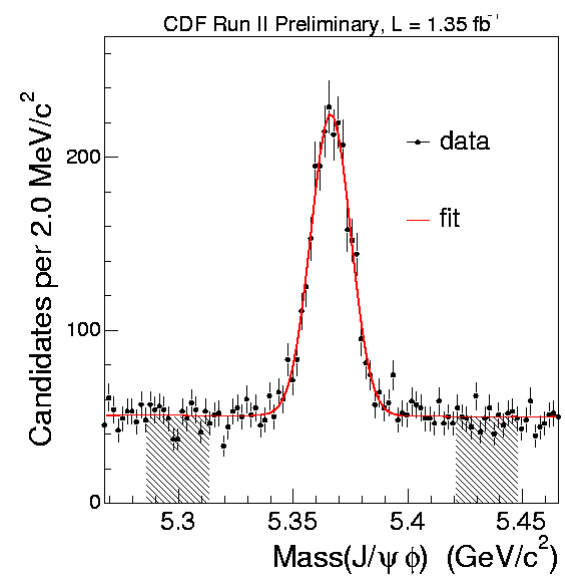


Likelihood profile is not parabolic; cannot reliably separate the two minima!

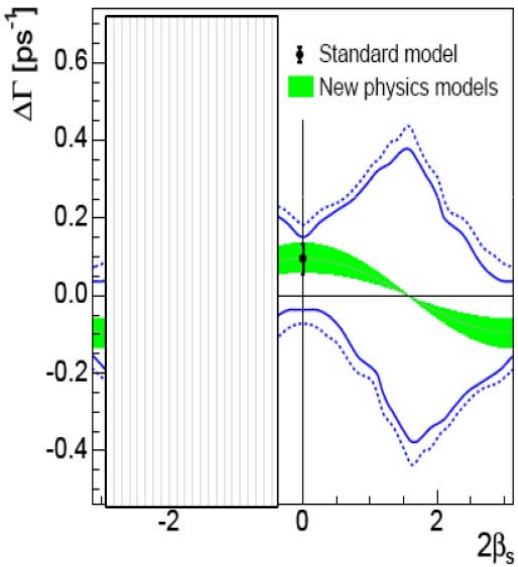
Generated with $\beta_s = 0.40$

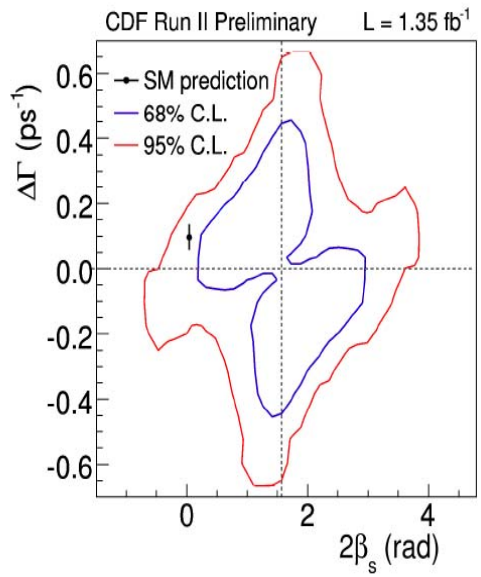
$$f_s P_s(m|\sigma_m) P_s(t, \vec{\rho}, \xi|\mathcal{D}, \sigma_t) P_s(\sigma_t) P_s(\mathcal{D})$$
$$+(1-f_s) P_b(m) P_b(t|\sigma_t) P_b(\vec{\rho}) P_b(\sigma_t) P_b(\mathcal{D}).$$

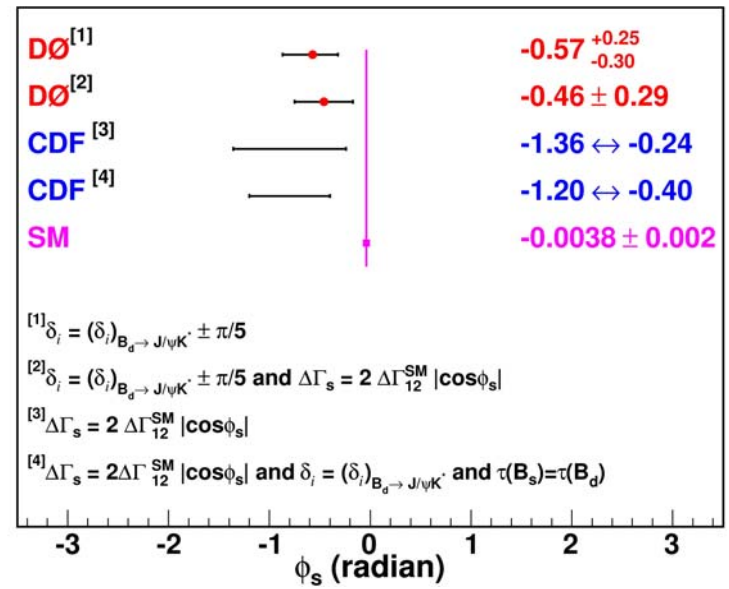
Single event likelihood:



$B^0_s \to J/\psi\ \phi$ (CDF) Bounds



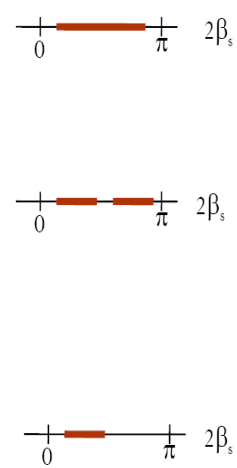




$$2\beta_s \to \pi - 2\beta_s$$

2-Fold ambiguity

Assuming SM prediction, ϕ_s=0.04
& $\Delta\Gamma_s$=0.096 ps-1
Prob of the observed values is 15%



- One-dimensional Feldman-Cousins confidence interval
  - $2\beta_s \in [0.32, 2.82]$ at 68% CL
- Constraining $\Delta\Gamma = 2|\Gamma_{12}|\cos(2\beta_s)$, where $|\Gamma_{12}| = 0.048 \pm 0.018$
  - $2\beta_s \in [0.24, 1.36] \cup [1.78, 2.90]$ at 68% CL
- Constraining $\Delta\Gamma = 2|\Gamma_{12}|\cos(2\beta_s)$, Γ to PDG B^0 lifetime, and $\delta_\parallel = -2.92 \pm 0.11$ and $\delta_\perp = 2.72 \pm 0.09$ (BABAR results, hep-ex/0411016)
  - $2\beta_s \in [0.40, 1.20]$ at 68% CL

CP Violation in $B^{\pm} \to J/\psi\, K^{\pm}$ (DØ)

SM predicts ~ 0.003
Measurement constraints NP
Int Lum ~ 2.8 fb^{-1}

$$A_{CP}(B^+ \to J/\psi K^+(\pi^+)) = \frac{N(B^- \to J/\psi K^-(\pi^-)) - N(B^+ \to J/\psi K^+(\pi^+))}{N(B^- \to J/\psi K^-(\pi^-)) + N(B^+ \to J/\psi K^+(\pi^+))}.$$

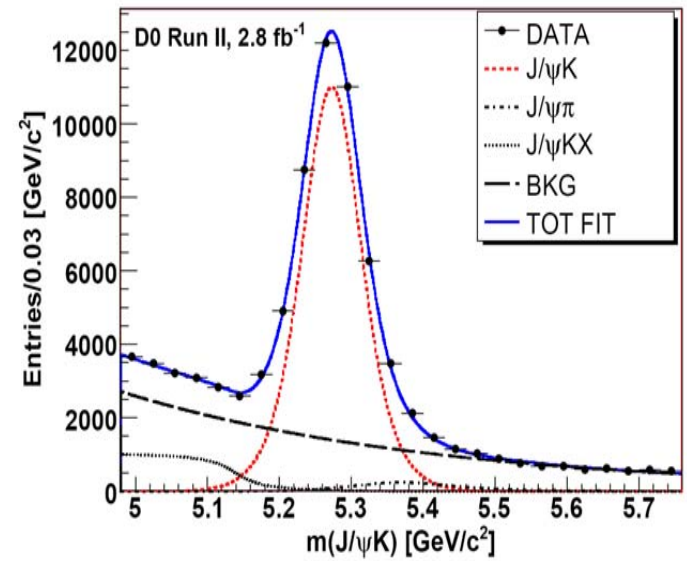
2μ + charged track

Unbinned fit:
B →J/ψ (K, π , K*), combinatorial

Asymmetry due to physics and detector Effects

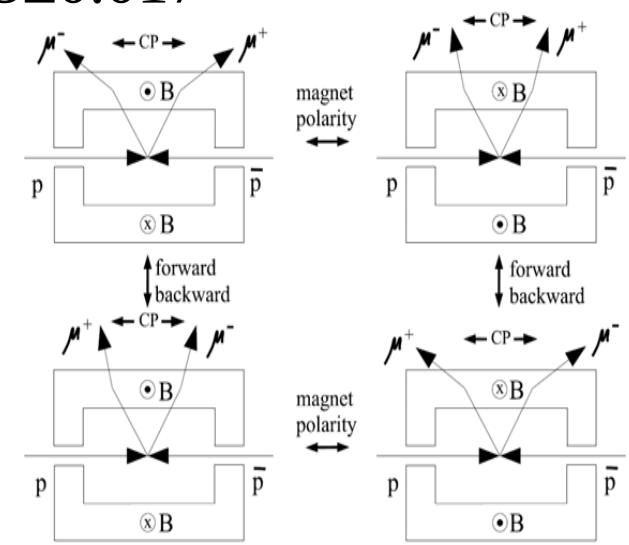
CP Violation, detector effects(polarity)
Samples: polarity, η and q(K)

Correction for K^+,K^- diff. efficiencies



$$A_{CP}(B^+ \to J/\psi K^+) = +0.0075 \pm 0.0061(\text{stat.}) \pm 0.0027(\text{syst.})$$

WA: 0.015±0.017



CP Asymmetry: SL B decays (CDF)

Asymmetry:
mixing & sequential decays (b →c →l)
SM predicts A_{CP} ~10^{-3}

$$A_{corr} = \frac{N^{++}_{true} - N^{--}_{true}}{N^{++}_{true} + N^{--}_{true}}$$

Strategy:
fit bidimensional $d_0/\sigma s(d_0)$ distribution.
B,Prompt,Charm (PP,BB,BP,CC)

Binned Fit: Templates different sources

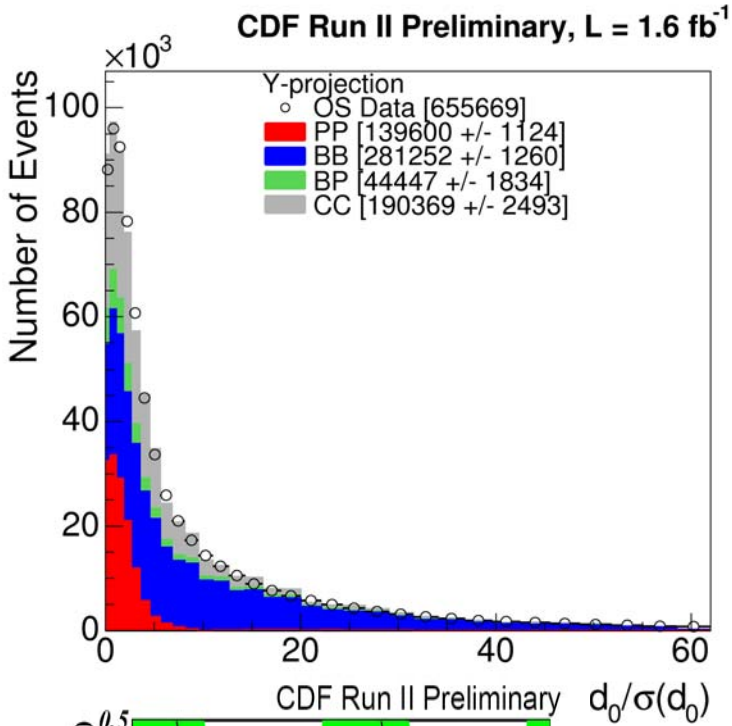
Corrections: K/π punchthrough or decay to μ
Detector and trigger induced asymmetry

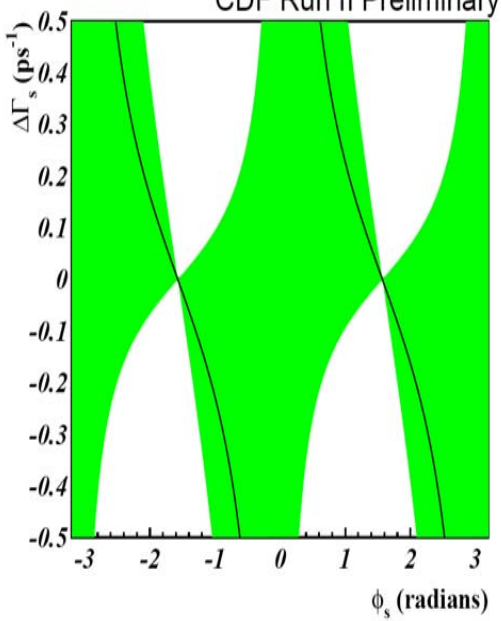
Systematics: Fake muon, trigger efficiency, detector acceptance, fit
Results:

$$A^{\mu\mu}_{SL} = 0.0080 \pm 0.0090(stat) \pm 0.0068(syst)$$

$$A^{s}_{SL} = 0.020 \pm 0.021(stat) \pm 0.016(syst) \pm 0.009(inputs)$$

$$A^{s}_{SL} = \frac{\Delta\Gamma_s}{\Delta M_s} \tan\phi_s$$



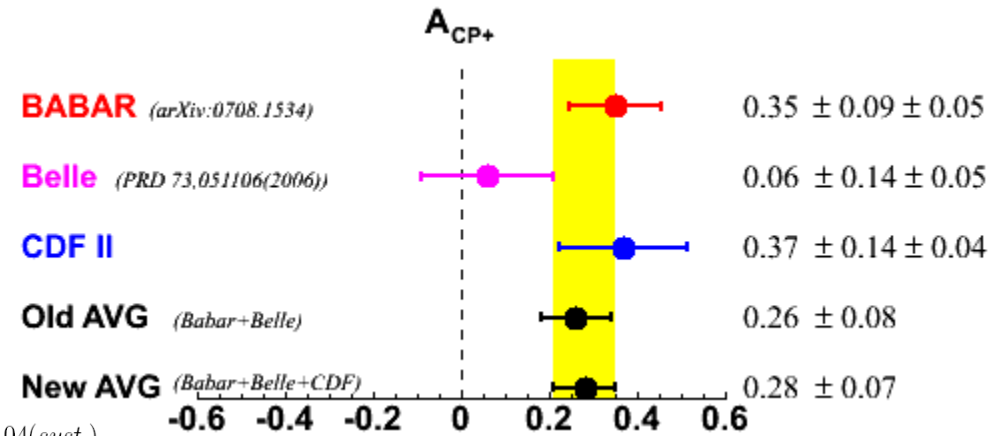


CP Asymmetries: $B^+ \to D^0_{CP} K^+$

B^+ asymm $\to$ CKM γ
Int Lum = $1 fb^{-1}$
Displaced tracks trigger
D0 reco $D^0_{CP} \to K^+K^-$ and $D^0_{CP} \to \pi^+\pi^-$
$D^0 \to K^-\pi^+$

Exp de la asymmetry

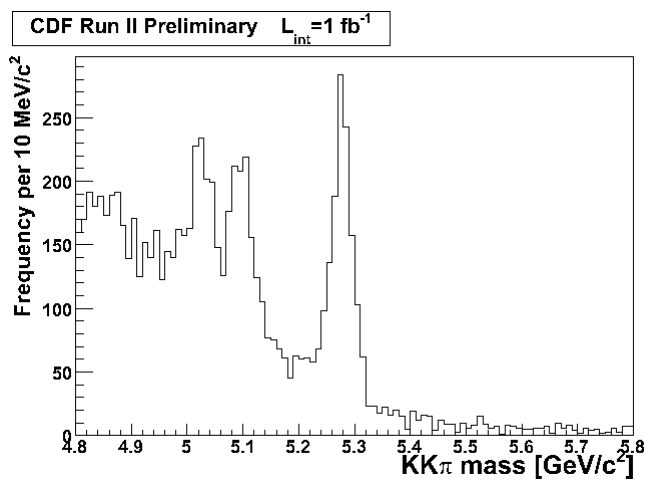
$$A_{CP+} = \frac{BR(B^- \to D^0_{CP+}K^-) - BR(B^+ \to D^0_{CP+}K^+)}{BR(B^- \to D^0_{CP+}K^-) + BR(B^+ \to D^0_{CP+}K^+)} = 0.37 \pm 0.14(stat.) \pm 0.04(syst.)$$

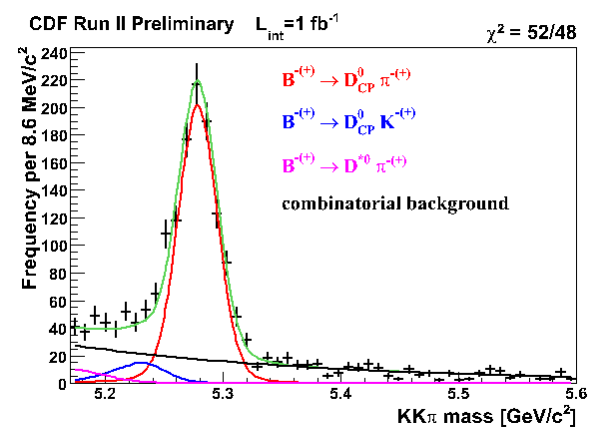


Relation between A_{CP+} & γ

$$R_{CP+} = 1 + r^2 + 2r\cos\delta\cos\gamma$$
$$A_{CP+} = 2r\sin\delta\sin\gamma / R_{CP+}$$

Cuts optimized for best resolution of A_{CP+}
Simultaneous Likelihood fit to the three channels





Detector effects and efficiencies
Systematics: Mass scale, dE/dx, Combinatorial

B_s Lifetime (Hadronic Decays) CDF

IntLum ~ 1.3 fb^{-1}

Displaced vertex triggers
- Rich B samples but …
- Lifetime dist. Affected (??)

Fully Reco: $B_s \to D_s^-(\phi\pi^-)\pi^+$ (~1,100)

Part Reco: $B_s \to D_s^-\rho^+(\pi^+\pi^0)$ (~1,100)

"Trigger turn-on" ⟸ MC simulation

MC samples: corrected for data

Procedure tested (B0, B+)

PDFs and Fractions

Fits: Mass then Lifetime

Mass PDFs
- Signal D+ track <= MC
- Back: D + rand. track Wrong Sign
- Back: D(non-res)+rand. Track

$$\mathcal{L} = \prod_{i=1}^{N_{\text{events}}} \left[f_{\text{FR}} P_{\text{FR}}(ct_i) + \sum_{j=1}^{m} f_{\text{PR},j} P_{\text{PR},j}(ct_i) + \sum_{k=1}^{n} f_{\text{Bkgd},k} P_{\text{Bkgd},k}(ct_i) \right]$$

Mass regions: FR (5.35,5.45)
PR (5.00,5.35)

LT PDFs:
- FR (MC)
- PR (MC and K factor)

Back: B0 or B+ or Combinatorial

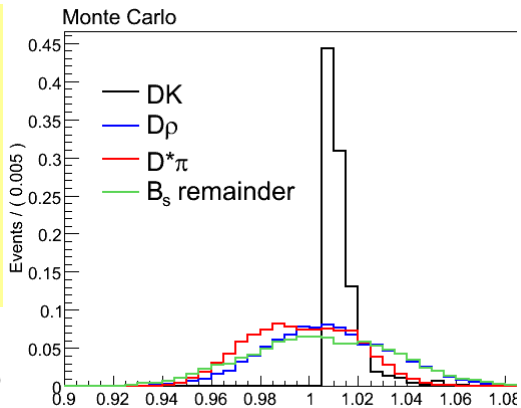
B_s Lifetime (Continued)

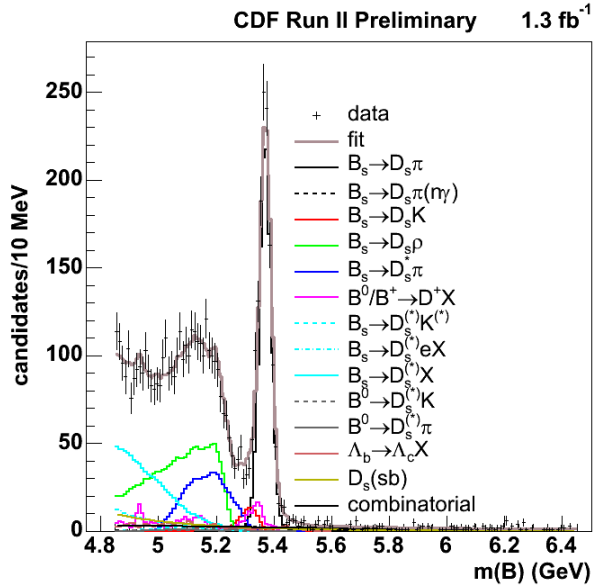
Proper Decay Length:

Fully Reco: $$ct \equiv \frac{L_{xy} \cdot m_B^{rec}}{p_{T_B}}$$

$$B_s \rightarrow D_s^- \rho^+ (\pi^+ \pi^0)$$

Part. Reco K $$= \frac{1}{\cos\theta_{\rm PR}} \cdot \frac{p_T({\rm PR})}{p_T({\rm MC})} \cdot \frac{m_B({\rm PDG})}{m_{rec}({\rm PR})}$$

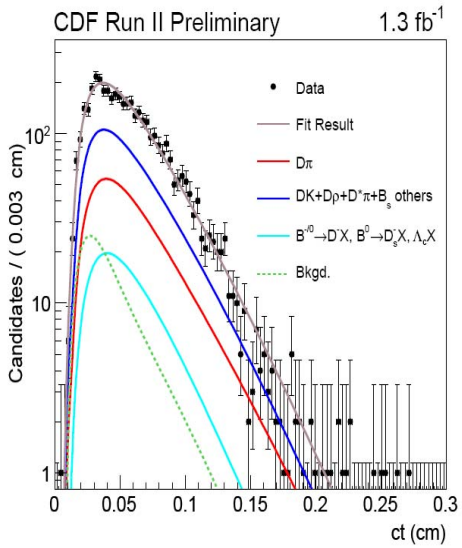


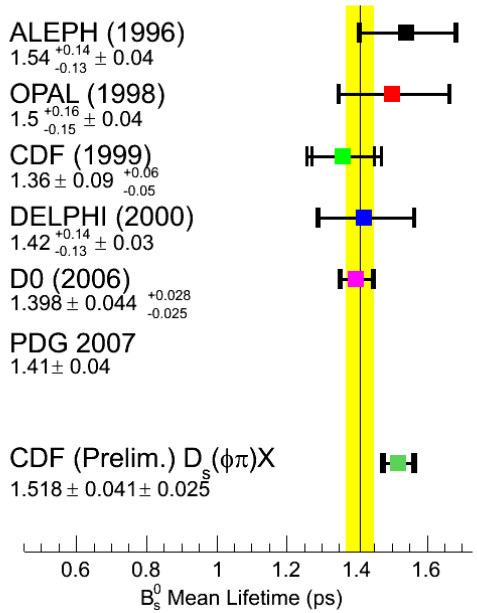


Systematic Sources:

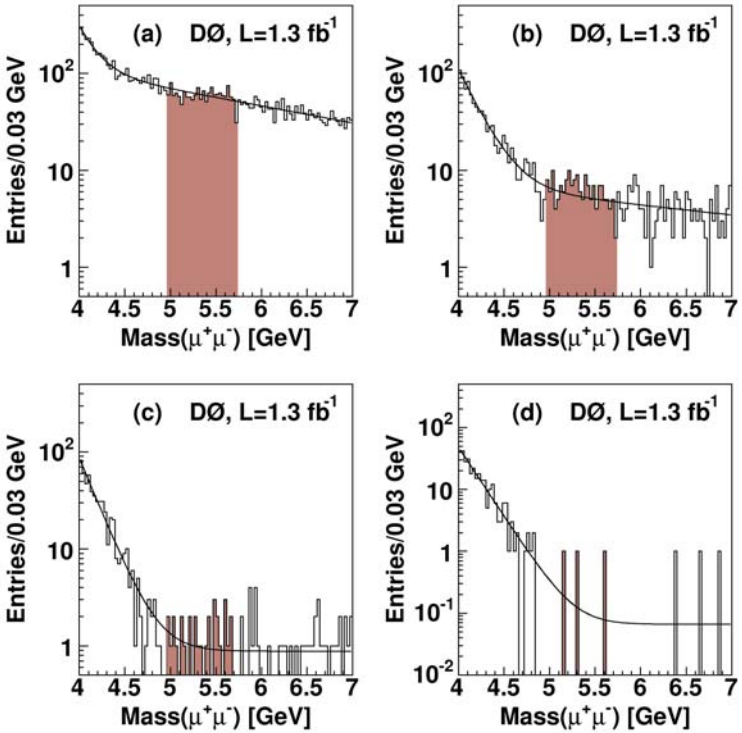
- Back Model and Fractions
- Fixed Single-B Background
- Reweight for pT and trigger
- Effic Parametrization
- Impact Parameter
- Alignment et al.

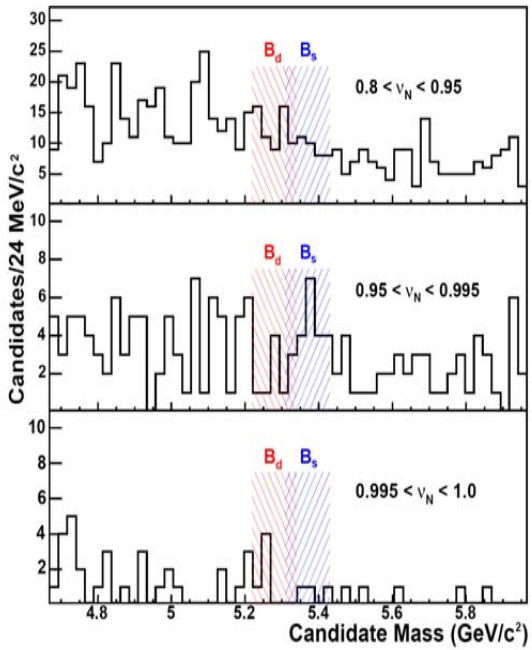
Toy MC

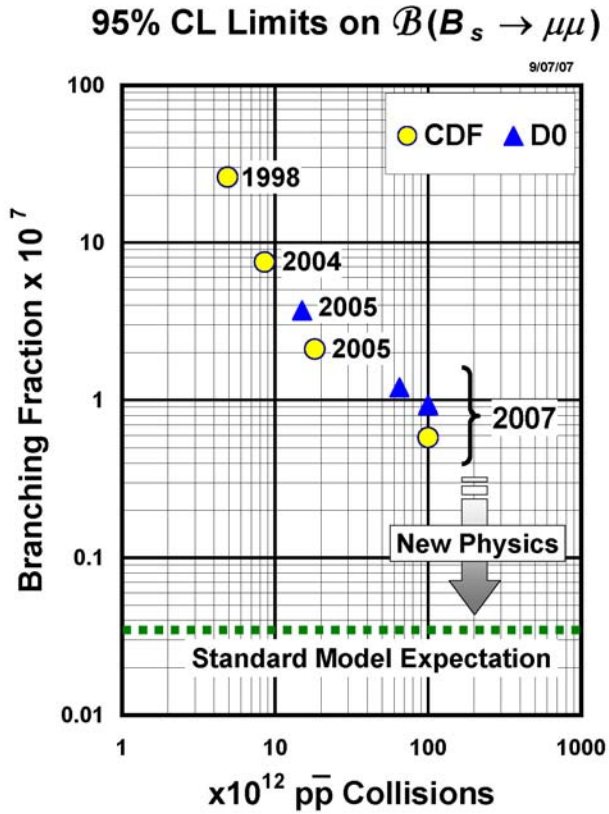




$B^0_s \rightarrow \mu^+\mu^-$







$\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-) < 1.2 \times 10^{-7}$ at the 95% C.L

$\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-) < 5.8 \times 10^{-8}$ (4.7×10^{-8})

DØ (1.3 fb^{-1})

CDF (2 fb^{-1})

SM Prediction: $\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-) = (3.42 \pm 0.54) \times 10^{-9}$

The Future

Detectors and Data Collection

- up to 8 fb^{-1} (per exp) with Run IIb
- DØ Layer-0 Silicon: 25% improvement in proper time res.

CP Violation

- fits to tagged $B_s \rightarrow J/\psi\ \phi$ sensitivity to ϕ_s, Δm_s New Physics??

B_s Properties: Lifetime, BRs, Spectroscopy...

- increasing sensitivity to rare modes

FCNC Decays

- should observe $\mu^+\mu^-\ \phi$ if close to SM prediction
- get within a factor of ~10 of $\mu^+\mu^-$ prediction