Studies of CP violation in the $B_s^0 \to J/\psi\phi$ decay

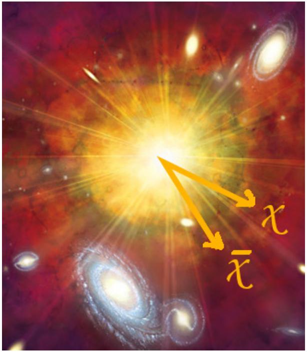
R. Magaña [1] on behalf of the **DØ Collaboration.**

[1]Cinvestav, México

26th Rencontres de Physique de la Vallée d'Aoste
Results and Perspectives in Particle Physics

CP Violation: What, Why, How?

- During the big-bang, matter and antimatter were produced in equal quantities
- Now we observe a matter dominated universe - What happened to the antimater?
- Theories of baryogenesis can address this asymmetry, but require several ingredients, one of which is **CP Violation (CPV)**



CP

Fundamental symmetry in which antiparticles behave exactly like particles in a mirror

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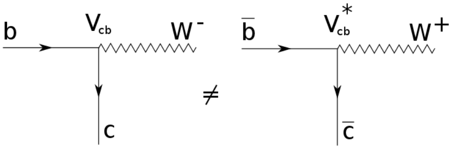
CP Violation in the standard model

- Weak interactions are governed by mixing matrices (neutrino,quark) - which have **complex phases.**
- CKM phases means quark and antiquark coupling can be different: CP Violation
- Degree of CPV in the Standard Model is **far too small** to account for observed matter-antimatter asymetry.
- New physics models can significantly enhance size of CP violating phases.

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



Search for anomalous CPV is a sensitive probe of posible physics beyond the SM

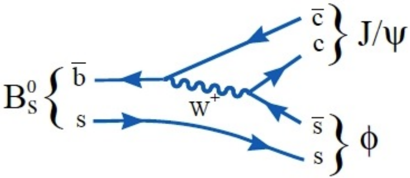
Motivation

- The two flavor eigenstates, mix via the weak interaction.

$$\left|B_s^H\right\rangle = p\left|B_s^0\right\rangle - q\left|\bar{B}_s^0\right\rangle$$

$$\left|B_s^L\right\rangle = p\left|B_s^0\right\rangle + q\left|\bar{B}_s^0\right\rangle$$

- The mass eigenstates of the B_s^0 system have **sizeable mass and decay width difference** ΔM_s **and** $\Delta\Gamma_s$



- The two vector mesons can have their spins transversely polarized with respect to their momentum and be either parallel $\left|\mathcal{P}_{||}\right\rangle$ or perpendicular to each other $|\mathcal{P}_{\perp}\rangle$. Alternatively, they can both be longitudinally polarized $|\mathcal{P}_0\rangle$.

CPV in Interference: $B_s^0 \to J/\psi\phi$

Same final state available to B_s^0 and $\overline{B}_s^0$

- Amplitudes interfere
- Final CPV phase is combination of mixing ϕ_s and decay ϕ_D phases:

$$\phi_s^{J/\psi\phi} = -2\arg\left(\frac{-V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -2\beta_s \approx -0.04(SM)$$

Enhancements to the mixing phase will give same enhancement to $\phi_s^{J/\psi\phi}$

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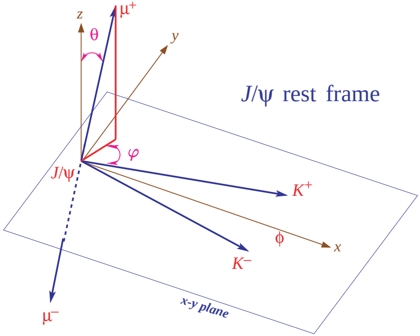
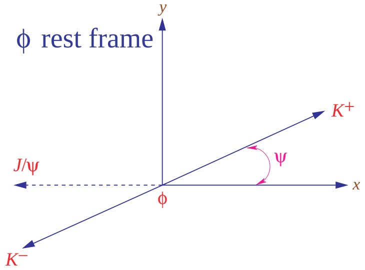
Event distribution





- $B_s \to J/\Psi\Phi$ admixture of CP-even/odd states
- Linear polarization eigenstates of the J/ψ and ϕ, provide a convenient basis for the analysis of the decay.
- Transversity basis $\vec{\omega} = (\psi, \theta, \varphi)$:
  - CP-odd (l=1): $A_\perp$
  - CP-even (l=0,2): A_0, $A_\parallel$

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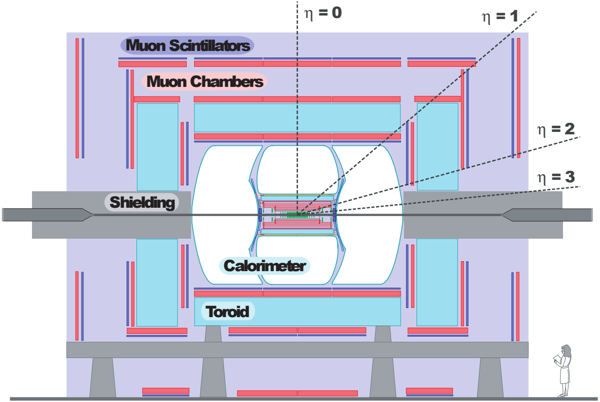
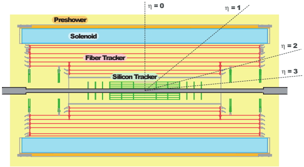
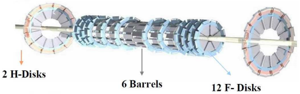
DØ Detector

- Excellent muon detection to $|\eta| < 2.2$, low punch-through
- Fiber and Silicon Tracker in $2T$ Solenoid







- Single and dimuon triggers

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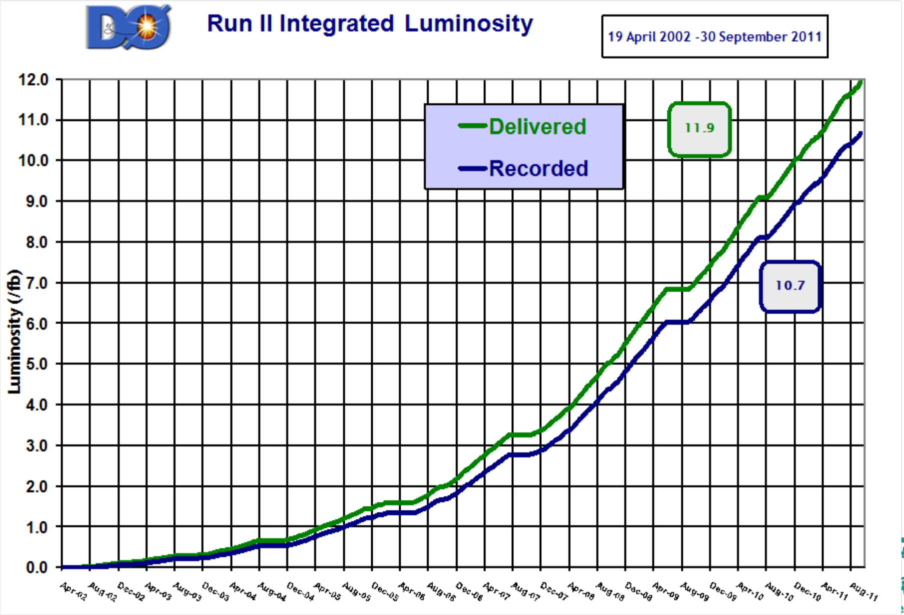
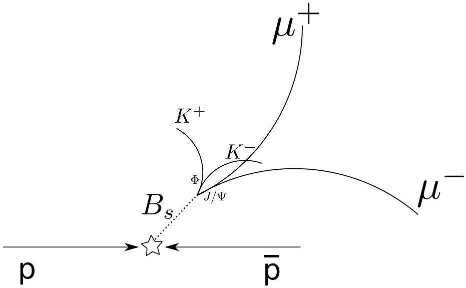
Data Samples



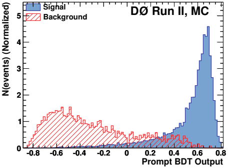
Event Selection

- We require two reconstructed muons of opposite charge.
- Form J/Ψ candidates
- Form Φ candiates from opposite charged tracks assuming the tracks are kaons.
- Form B_s candidates from J/Ψ and Φ candidates.
- Make cuts in the kinematic and the mass windows:
  - $P_t(K^{\pm}) > 0.4 GeV$
  - $2.84 < M(\mu^+\mu^-) < 3.35 GeV$
  - $0.98 < M(K^+K^-) < 1.04 GeV$
  - $5.0 < M(\mu^+\mu^-K^+K^-) < 5.8 GeV$
- With this loose selection we found approx. 5 million events.
- Remove IP biased triggers.

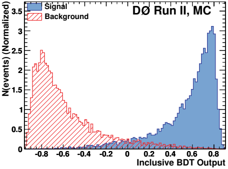


Background suppression

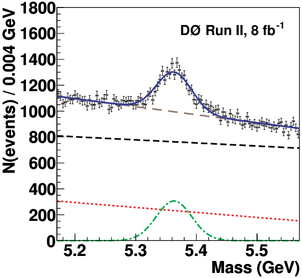
- BDT used to suppress background.
  - Prompt $p\bar{p} \to J/\Psi X$



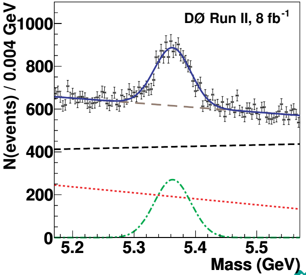
  - b-inclusive $p\bar{p} \to b\bar{b} \to J/\Psi X$



- Simple-Cut as in 2008 PRL, for cross-check and systematic uncertainties.



BDT Selection



Simple-Cut Selection

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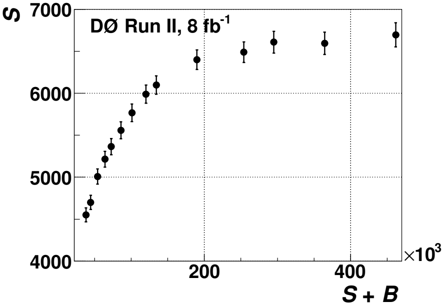
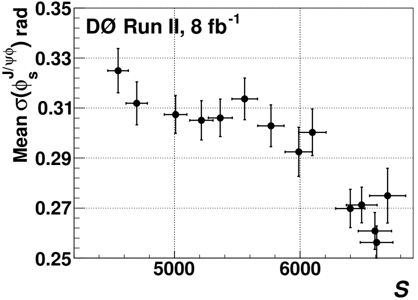
Optimizing selection





- Tight cuts implies better signal significance but fewer signal events
- Optimized selection cuts using toy Monte Carlo studies

Probability Distribution Function

$$\epsilon(\vec{\omega}) \times \left(\mathcal{B}_s(\lambda; t, \vec{\omega}) \frac{1-D}{2} + \overline{\mathcal{B}}_s(\lambda; t, \vec{\omega}) \frac{1+D}{2} \right) \otimes R(t)$$

where:

- $\vec{\omega} = (\psi, \theta, \varphi)-$ angles
- $D-$ initial flavor tagging dilution
- $\epsilon(\vec{\omega})-$ acceptance
- $R(t)-$resolution.

$$\mathcal{B}_s = \left| \left[\sqrt{1-F_s} g(\mu) \mathbf{A} + e^{-i\delta_s} \sqrt{F_s} h(\mu) \mathbf{B} \right] \times \hat{n} \right|^2$$

- $\mathbf{A}(\lambda; \mathbf{t}, \omega)-$ P-Wave
- $\mathbf{B}(\lambda; \mathbf{t}, \omega)-$ S-Wave.
- $\lambda = (\tau_s, \Delta\Gamma_s, \phi_s^{J/\Psi\phi}, |A_0|^2, |A_\perp|^2, F_s, \delta_s, \delta_\parallel, \delta_\perp, \Delta m_s)$

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Real Measurables

- Two constraints:
- $\Delta m_s \equiv 17.77 \pm 0.12$
- $\cos(\delta_\perp) < 0$

Parameter	Definition
$\lvert A_0 \rvert^2$	$\mathcal{P}$-wave amplitude squared
$\lvert A_\parallel \rvert^2$	$\mathcal{P}$-wave amplitude squared
$\overline{\tau}_s$ (ps)	B_s^0 mean lifetime
$\Delta\Gamma_s$ (ps^{-1})	Heavy-light decay width difference
F_S	K^+K^- $\mathcal{S}$-wave fraction
$\phi_s^{J/\psi\phi}$	*CP*-violating phase
$\delta_\parallel$	$\arg(A_\parallel/A_0)$
$\delta_\perp$	$\arg(A_\perp/A_0)$
δ_s	$\arg(A_s/A_0)$

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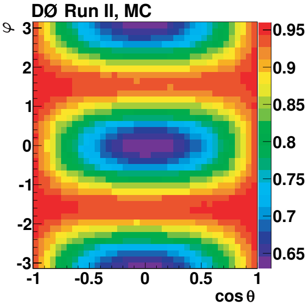
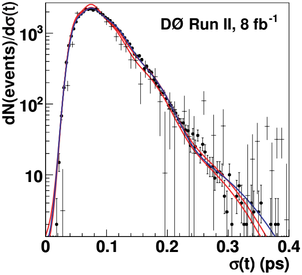
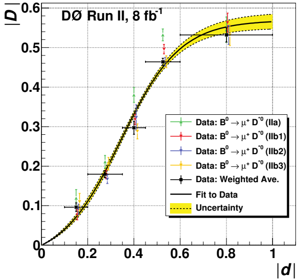
Acceptance, Resolution and Flavor Tagging



- Data selection criteria were applied to flat MC
- 2D $cos(\theta), \phi$ acceptance



- Event-by-Event resolution width
- Distribution of proper decay time resolution
  - MC - Dots
  - Data - Crosses



- Opposite Flavor tagging using:
  - Muon
  - Electron
  - Jet Charge

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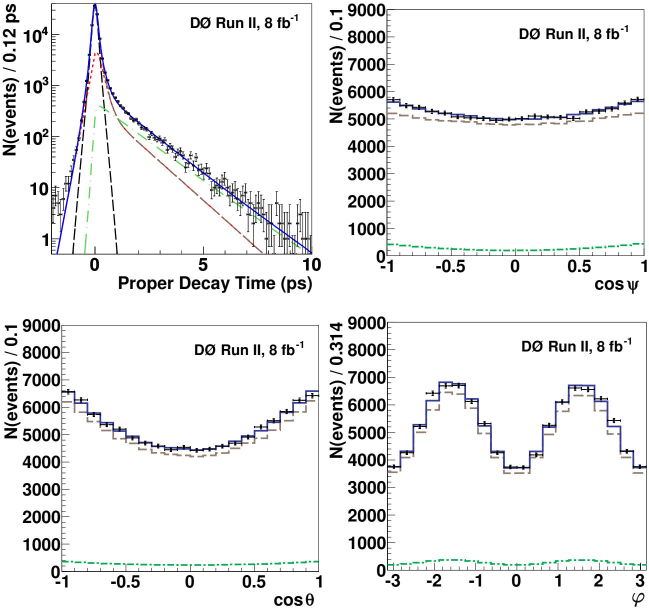
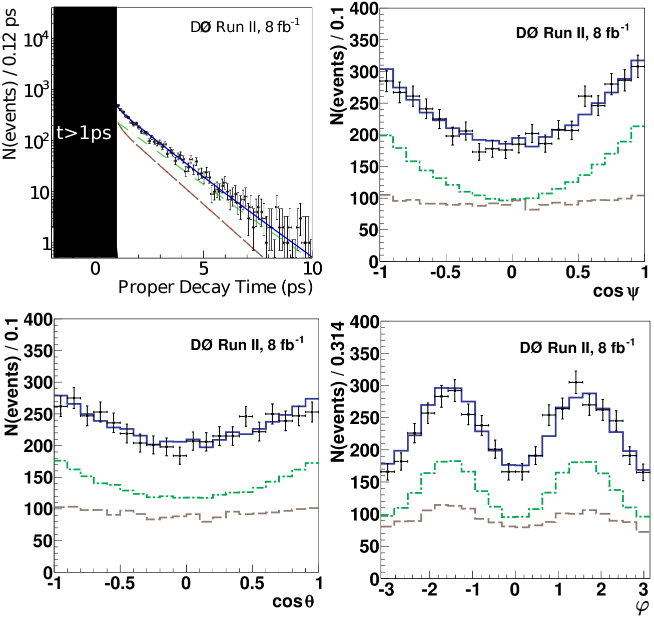
Maximum Likelihood Fit



Maximum Likelihood Fit (Signal Enriched)



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Fit Results

Parameter	BDT Sample	Simple Cut Sample
$\overline{\tau}_s$	$1.426^{+0.035}_{-0.032}$ ps	$1.444^{+0.041}_{-0.033}$ ps
$\Delta\Gamma_s$	$0.129^{+0.076}_{-0.053}$ ps^{-1}	$0.179^{+0.059}_{-0.060}$ ps^{-1}
$\phi_s^{J/\Psi\Phi}$	$-0.49^{+0.48}_{-0.40}$	$-0.56^{+0.36}_{-0.32}$
$\|A_0\|^2$	$0.552^{+0.016}_{-0.017}$	0.565 ± 0.017
$\|A_{\|\|}\|^2$	$0.219^{+0.020}_{-0.021}$	$0.249^{+0.021}_{-0.022}$
$\delta_{\|\|}$	-3.15 ± 0.27	-3.15 ± 0.19
$\cos(\delta_\perp - \delta_s)$	-0.06 ± 0.24	$-0.20^{+0.26}_{-0.027}$
$F_S(eff)$	0.146 ± 0.035	0.176 ± 0.036

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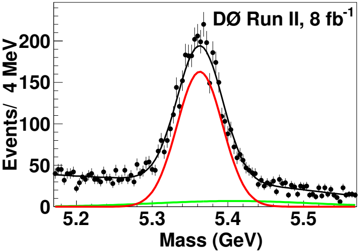
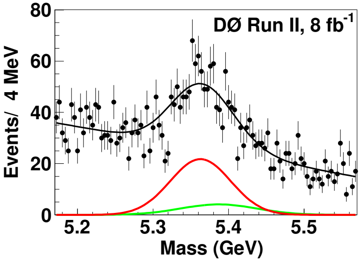
Independent determination of F_s

- The invariant mass distribution of B_s^0 candidates with $ct > 0.02$ cm in two slices of $M(K^+K^-)$
- Gaussian Signal
- First order polynomial + $B^0 \rightarrow J/\Psi K^*$ reflection template from MC background.
- $F_s = 0.12 \pm 0.03$



$1.01 < M(K^+K^-) < 1.03$



$1.03 < M(K^+K^-) < 1.05$

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Markov Chain technique

- Since ϕ_s is very correlated with $\Delta\Gamma_s$ we want to know how the likelihood depends on these variables.
- We can't simply make a grid in the parameters because we have many parameters.
- We use the Metropolis-Hasting algorithm to obtain a random sample of the likelihood.
- Finally we use this sample to obtain contours and combine systematics.

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Systematic Uncertainties

- Acceptance systematic from differences between BDT and Simple-cut samples
- Variation in resolution parameters
  - Random variations in the resolution parameters
- Different widths of Φ
  - Different resolution for the Φ mass, important since s-wave is around 15%
- Variation OST calibration curve
- Markov Chain technique for contours and systematics

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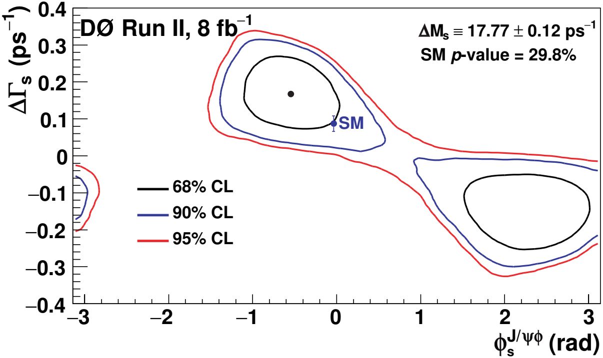
$B_s^0 \to J/\Psi\Phi$ Result

P	x
$\overline{\tau}_s$	$1.443^{+0.038}_{-0.035}$ ps
$\Delta\Gamma_s$	$0.163^{+0.065}_{-0.064}$ ps^{-1}
$\phi_s^{J/\Psi\Phi}$	$-0.55^{+0.38}_{-0.36}$
$\lvert A_0\rvert^2$	$0.558^{+0.017}_{-0.019}$
$\lvert A_{\parallel}\rvert^2$	$0.231^{+0.024}_{-0.030}$
$\delta_{\parallel}$	-3.15 ± 0.22
$(\delta_{\perp}$-$\delta_s)$	$-0.11^{+0.027}_{-0.025}$
$F_S(eff)$	0.173 ± 0.036



Summary

- Measurement of B_s^0 mixing parameters, polarization amplitudes and phases in the $B_s^0 \to J/\Psi\Phi$ analysis using $8fb^{-1}$ data sample.
- Inclusion of K^+K^- s-wave
- Multivariate selection and toy Monte Carlo optimization
- Bayesian confidence regions using Markov Chain
- Published 02/22/2012: **Phys. Rev. D85, 032006**.

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