Measurements of CP violation in the B_s system at D0

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on behalf of DØ collaboration

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Outline

- Introduction
- CP violation in $B_s \rightarrow J/\psi\ \phi$
- Branching ratio $B_s \rightarrow J/\psi\ f_0$

CP Violation @ D0

I. CP violation in decay:

a) Study of Direct CP Violation in $B^{\pm}\to J/\psi K^{\pm}(\pi^{\pm})$ Decays

Phys. Rev. Lett. **100**, 211802 (2008), 2.8 fb^{-1}

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

$$A_{CP}(B^{\pm}\to J/\psi \pi^{\pm}) = -0.09 \pm 0.08(stat.) \pm 0.03(syst.)$$

II. CP violation in mixing:

$$a_{sl} = \frac{\frac{d\Gamma}{dt}\left(\bar{B}(t)\to f\right) - \frac{d\Gamma}{dt}\left(B(t)\to \bar{f}\right)}{\frac{d\Gamma}{dt}\left(\bar{B}(t)\to f\right) + \frac{d\Gamma}{dt}\left(B(t)\to \bar{f}\right)}$$

a) Search for CP Violation in $B_s^0\to\mu^+D_s^-X$ Decays in pp Collisions at $\sqrt{s}$ = 1.96 TeV

Phys. Rev. D **82**, 012003 (2010), 5.0 fb^{-1}

a) Evidence for an Anomalous Like-Sign Dimuon Charge Asymmetry

Phys. Rev. D **82**, 032001, (2010), 6.1 fb^{-1}

(update will be presented today by G. Borissov)

CP Violation @ D0

III. CP violation in interference between a decay with mixing and a decay without mixing:

a) Evidence for the Decay $B_s^0 \to D_s^{(*)} D_s^{(*)}$ and a Measurement of $\Delta\Gamma_s^{CP}/\Gamma_s$
Phys. Rev. Lett. **102**, 091801 (2009), 2.8 fb^{-1}

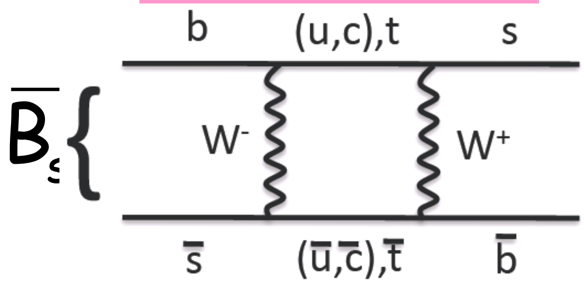
b) Measurement of the B_s^0 Mixing Parameters from the Flavor-Tagged Decay $B_s^0 \to J/\psi\varphi$
Phys. Rev. Lett. **101** , 241801 (2008), 2.8 fb^{-1} (update in this presentation)

b) Measurement of the relative branching fraction of B0s-->J/psi f0(980), f0(980)-->pi+pi- to B0s-->J/psi phi, phi-->K+K- , 8 fb-1 (in this presentation)

$$A_{f_{CP}} = \frac{\frac{d\Gamma}{dt}\left(\overline{B}(t) \to f_{CP}\right) - \frac{d\Gamma}{dt}\left(B(t) \to f_{CP}\right)}{\frac{d\Gamma}{dt}\left(\overline{B}(t) \to f_{CP}\right) + \frac{d\Gamma}{dt}\left(B(t) \to f_{CP}\right)}$$

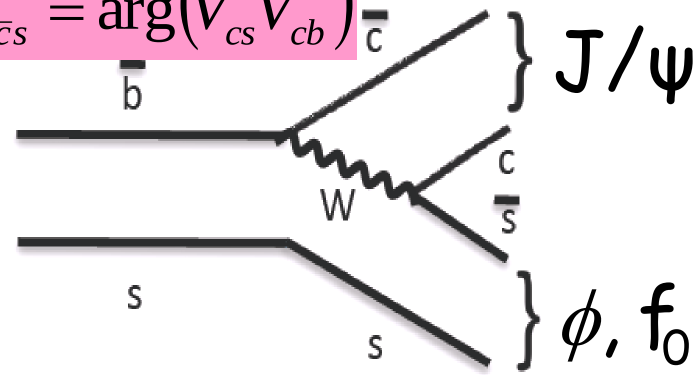
CP Violation in $B_s \to J/\psi + \phi, f_0$

$$\phi_M = \arg\left(V_{tb}V_{ts}^*\right)^2$$



+

$$\phi_{c\bar{c}s} = \arg\left(V_{cs}V_{cb}^*\right)$$

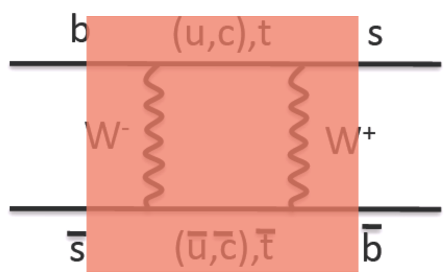


small

$$-2\beta_s^{SM} = \phi_M - 2\phi_{c\bar{c}s} \approx -0.04$$

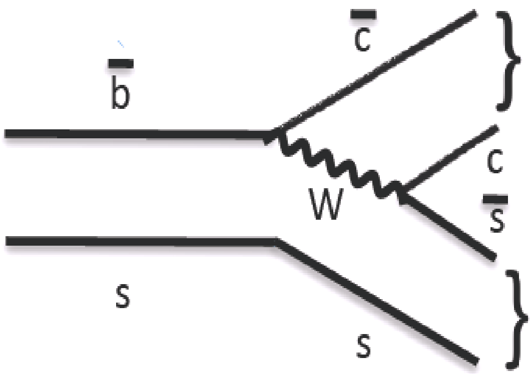
+

New Physics

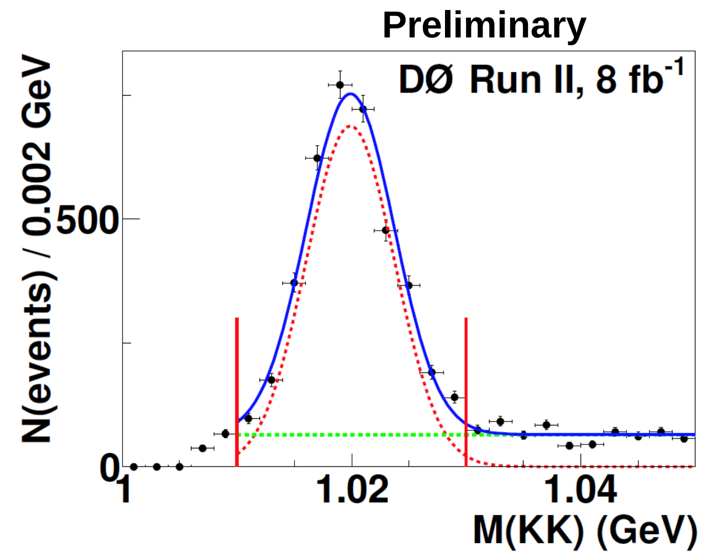


$$\phi_s \equiv \phi_s^{J/\psi\phi} \equiv -2\beta_s = -2\beta_s^{SM} + \phi_{NP} \approx \phi_{NP}$$

Final CP-states



	J/ψ, $s=1$	
	ϕ, $s=1$	f_0, $s=0$
$L=0$ (CP-even)	X	-
$L=1$ (CP-odd)	X	X
$L=2$ (CP-even)	X	-



S-wave K^+K^- could contribute ~10% under the ϕ-peak in $B_s \to J/\psi + \phi$ (S.Stone and L.Zhang, Phys. Rev. D 79, 074024 (2009)). It has to be taken into account with unknown phase and fraction.

$$\sqrt{1-F_s}\,g(\mu)\mathbf{A}(\mathbf{t}) + e^{-i\delta_s}\sqrt{F_s}\,h(\mu)\mathbf{B}(\mathbf{t})$$

Extraction of ϕ_s, $\Delta\Gamma_s$, Δm_s, ...

- Different CP-states correspond to different mass states in the limit of no direct CP-violation
  - CP-odd → B_s^H
  - CP-even → B_s^L

    → Δm_s
  - They also have different lifetimes → $\Delta\Gamma_s$
- Formulae adopted from F.Azfar et al., JHEP 1011:158,2010

$$\mathcal{A}_i(t) = F(t)\left[E_+(t) \pm e^{2i\beta_s} E_-(t)\right] a_i\,,$$
$$\bar{\mathcal{A}}_i(t) = F(t)\left[\pm E_+(t) + e^{-2i\beta_s} E_-(t)\right] a_i\,,$$

$$F(t) = \frac{e^{-\Gamma_s t/2}}{\sqrt{\tau_H + \tau_L \pm \cos 2\beta_s\,(\tau_L - \tau_H)}}\,,$$

$$E_\pm(t) \equiv \frac{1}{2}\left[e^{\left(\frac{-\Delta\Gamma_s}{4} + i\frac{\Delta M_s}{2}\right)t} \pm e^{-\left(\frac{-\Delta\Gamma_s}{4} + i\frac{\Delta M_s}{2}\right)t}\right]$$

$$P_B(\theta,\varphi,\psi,t) = \frac{9}{16\pi}|\mathbf{A}(t)\times\hat{n}|^2,$$
$$P_{\bar{B}}(\theta,\varphi,\psi,t) = \frac{9}{16\pi}|\bar{\mathbf{A}}(\mathbf{t})\times\hat{n}|^2$$

$$\hat{n} = (\sin\theta\cos\varphi, \sin\theta\sin\varphi, \cos\theta)$$

$$\mathbf{A}(t) = \left(\mathcal{A}_0(t)\cos\psi, -\frac{\mathcal{A}_\parallel(t)\sin\psi}{\sqrt{2}}, i\frac{\mathcal{A}_\perp(t)\sin\psi}{\sqrt{2}}\right)$$
$$\bar{\mathbf{A}}(t) = \left(\bar{\mathcal{A}}_0(t)\cos\psi, -\frac{\bar{\mathcal{A}}_\parallel(t)\sin\psi}{\sqrt{2}}, i\frac{\bar{\mathcal{A}}_\perp(t)\sin\psi}{\sqrt{2}}\right)$$

Extraction of ϕ_s, $\Delta\Gamma_s$, Δm_s, …

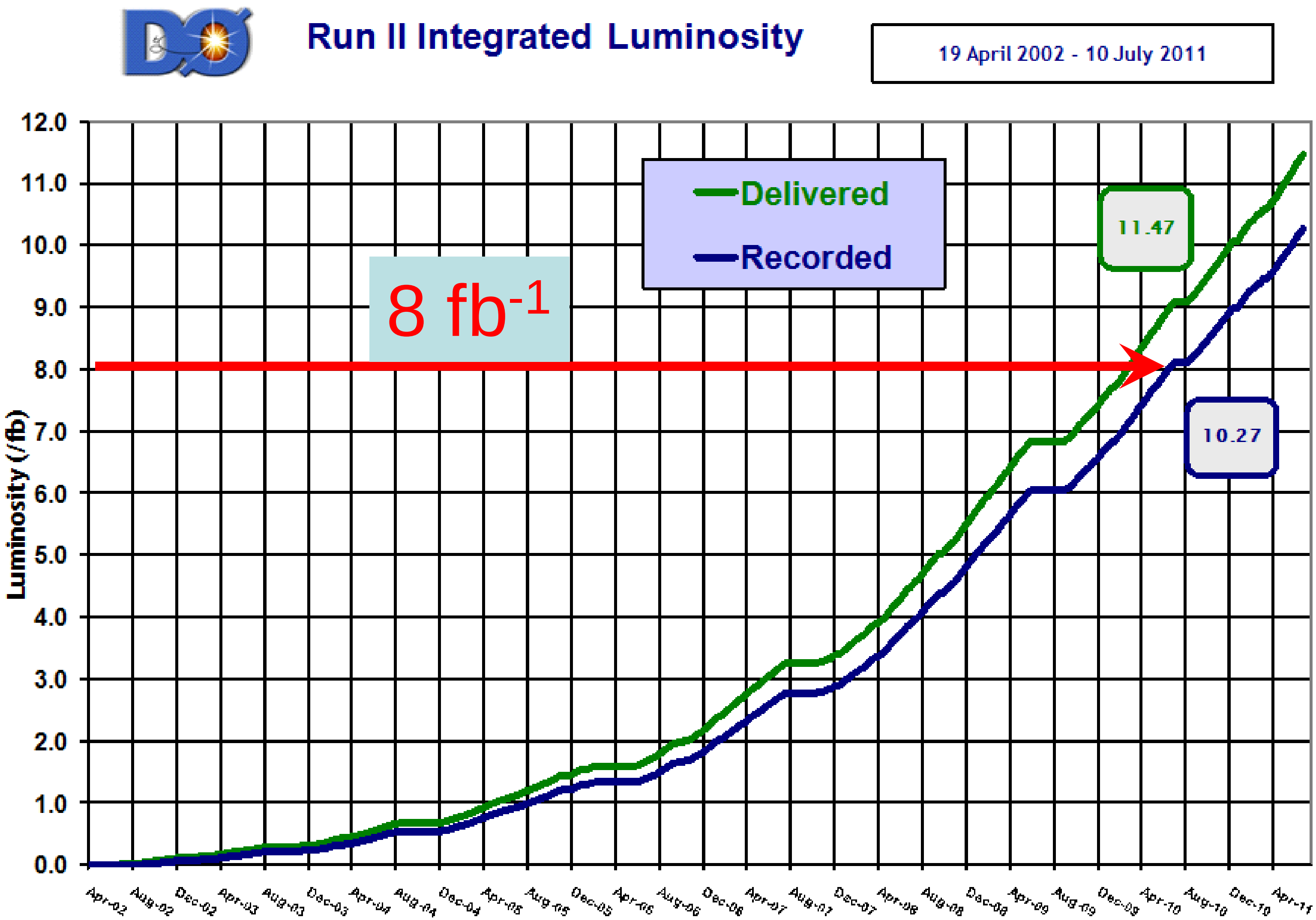
- Some combinations are sensitive to these parameters

$$\frac{P_\pm(t)-\overline{P}_\pm(t)}{P_\pm(t)+\overline{P}_\pm(t)}=\pm\left[\frac{2\sin(\Delta m_s t)\sin\phi_s}{(1\pm\cos\phi_s)e^{+\Delta\Gamma_s t/2}+(1\mp\cos\phi_s)e^{-\Delta\Gamma_s t/2}}\right],$$

where $P_+(t)\equiv|A_0(t)|^2+|A_\parallel(t)|^2$, $P_-(t)\equiv|A_\perp(t)|^2$.

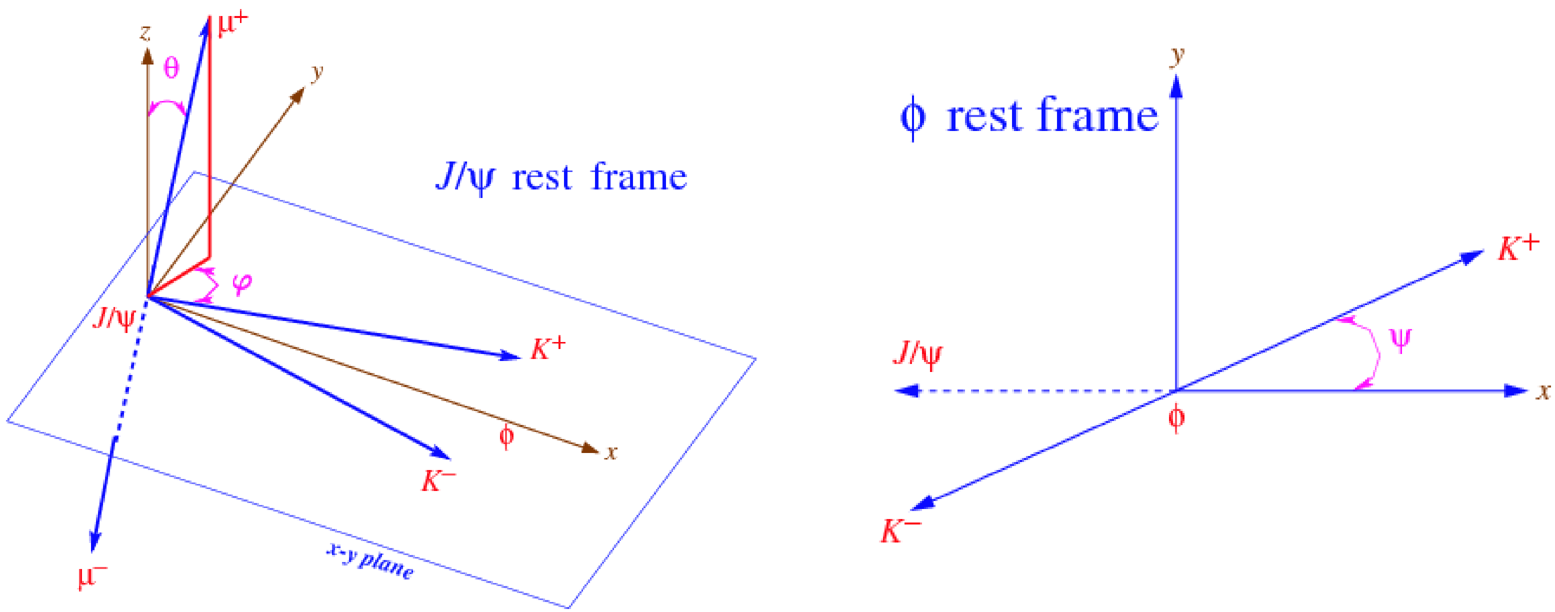
  - R. Fleischer, hep-ph/0703112

Data Samples



$B_s \to J/\psi + \phi$ analysis

- Admixture of CP-even (L=0,2; A_0, $A_{||}$) and CP-odd (L=1; $A_\perp$) states
- Angular analysis is used to separate the CP components and measure the lifetimes of each component and phase ϕ_s



Angles θ (transversity), φ and ψ. ψ is the angle between $\vec{p}'_{K+}$ and the x-axis in the rest frame of ϕ.

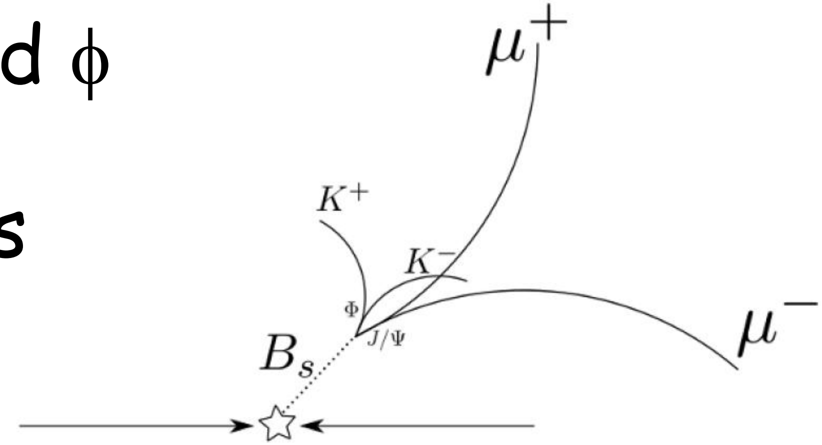
$B_s \to J/\psi + \phi$ analysis

- Definitions of nine real measurables

Parameter	Definition
$\vert A_0\vert^2$	$\mathcal{P}$-wave longitudinal amplitude squared, at $t = 0$
$A1$	$\vert A_{\vert\vert}\vert^2/(1-\vert A_0\vert^2)$
$\overline{\tau}_s$ (ps)	B_s^0 mean lifetime
$\Delta\Gamma_s$ (ps^{-1})	Heavy-light decay width difference
F_S	K^+K^- $\mathcal{S}$-wave fraction
β_s	CP-violating phase ($\equiv -\phi_s^{J/\psi\phi}/2$)
$\delta_{\vert\vert}$	$\arg(A_{\vert\vert}/A_0)$
$\delta_\perp$	$\arg(A_\perp/A_0)$
δ_s	$\arg(A_s/A_0)$

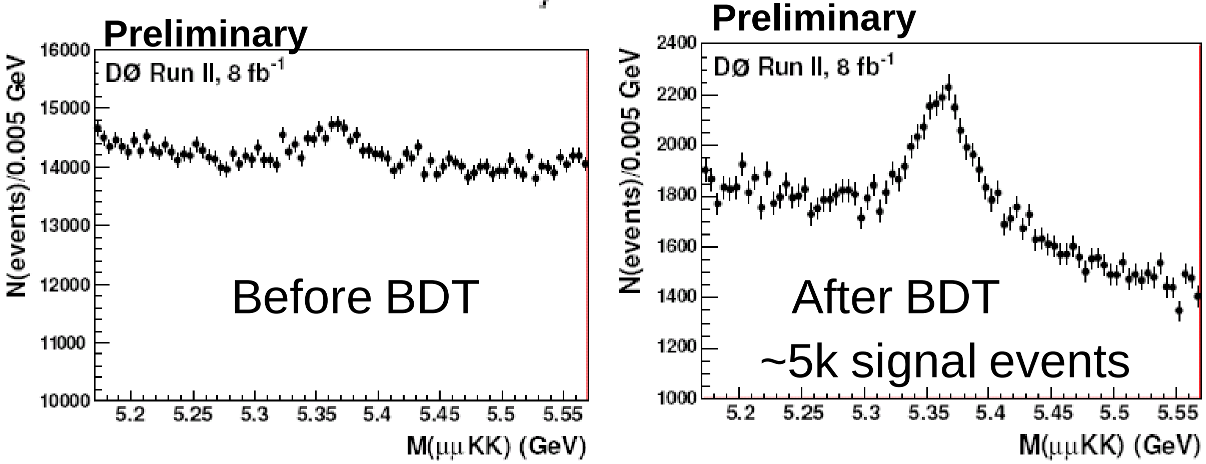
Event selection

- Two reconstructed muons of opposite charge ➔ J/ψ candidates
- ϕ candidates from opposite charged tracks assuming the tracks are kaons
- B_s candidates from J/ψ and ϕ candidates
- Cuts on kinematic and mass variables
  - $P_t(K^{\pm})>0.4$GeV
  - $2.84<M(\mu^+\mu^-)<3.35$GeV
  - $1.01<M(K^+K^-)<1.03$GeV
  - $5.0<M(\mu^+\mu^-K^+K^-)<5.8$GeV



Background Suppression

- The BDT is used to suppress background
  - Prompt $(p\bar{p} \rightarrow J/\Psi X)$
  - b-inclusive $b\bar{b} \rightarrow J/\Psi X$



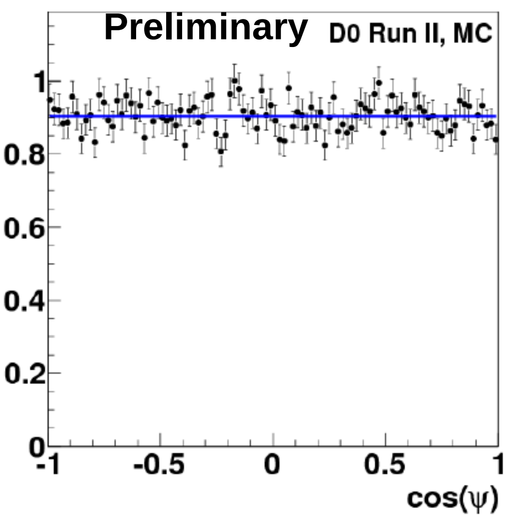
- Simple-cut selections (a la published in 2008) were used for cross-check and systematic uncertainties

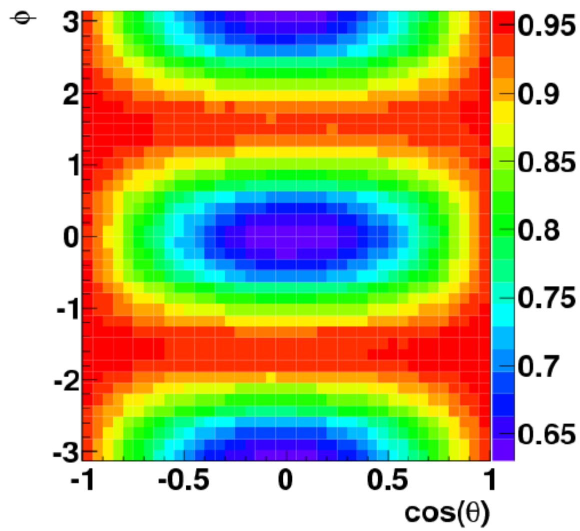
Probability Density Function

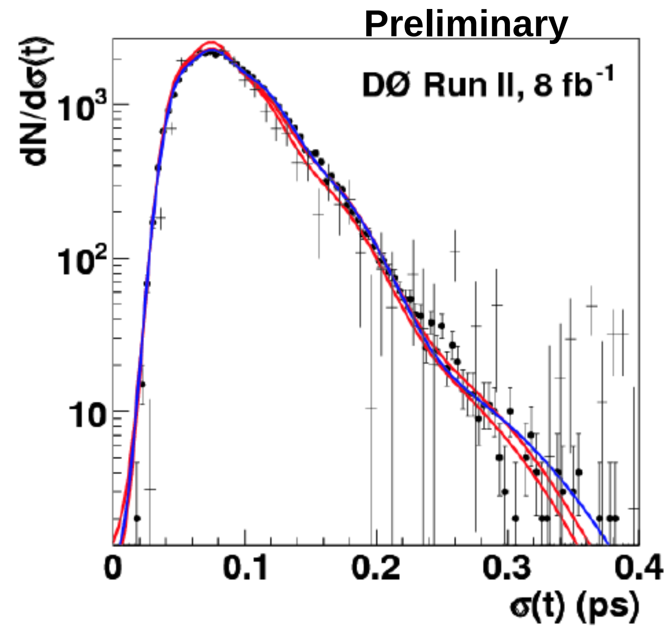
$$\epsilon(\vec{\omega}) \times \left(\mathcal{B}_s(\lambda; t, \vec{\omega}) \frac{1-D}{2} + \overline{\mathcal{B}}_s(\lambda; t, \vec{\omega}) \frac{1+D}{2} \right) \otimes R(t)$$

- where
  - $\vec{\omega} = (\psi, \theta, \varphi)$ - angles
  - D – initial state tagging dilution,
  - $\epsilon(\vec{\omega})$ - acceptance,
  - R(t) – resolution
  - $\lambda = (\tau_s, \Delta\Gamma_s, \phi_s^{J/\Psi\phi}, |A_0|^2, |A_\perp|^2, F_s, \delta_s, \delta_{\|}, \delta_\perp, \Delta m_s)$

Detector Acceptance and Resolution



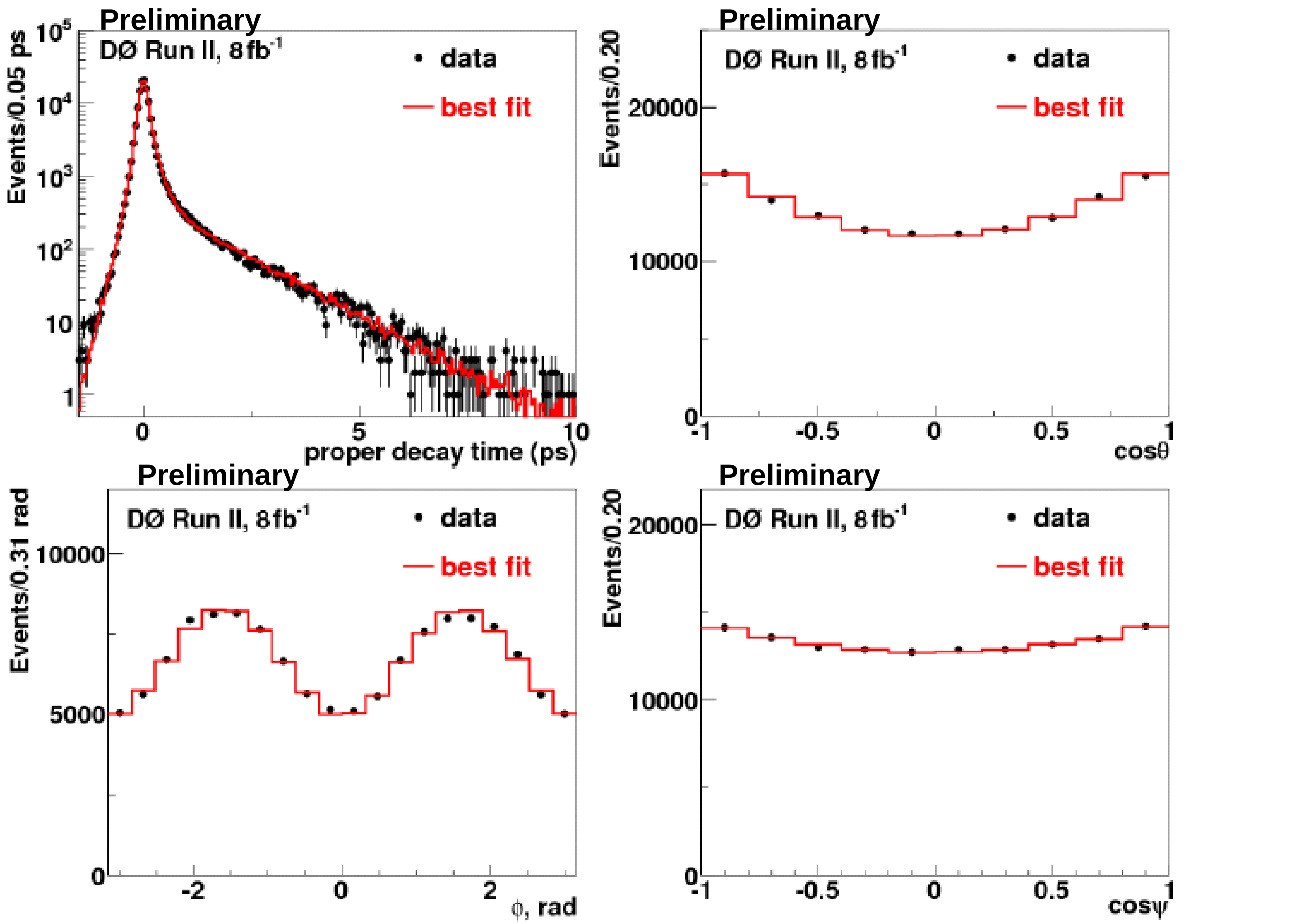




- Data selection criteria were applied to flat MC distributions weighted with data
  - difference in P_t distributions from trigger

- The distribution of the time resolution
  - MC – squares
  - Data - crosses

Maximum Likelihood Fit



Fit Results

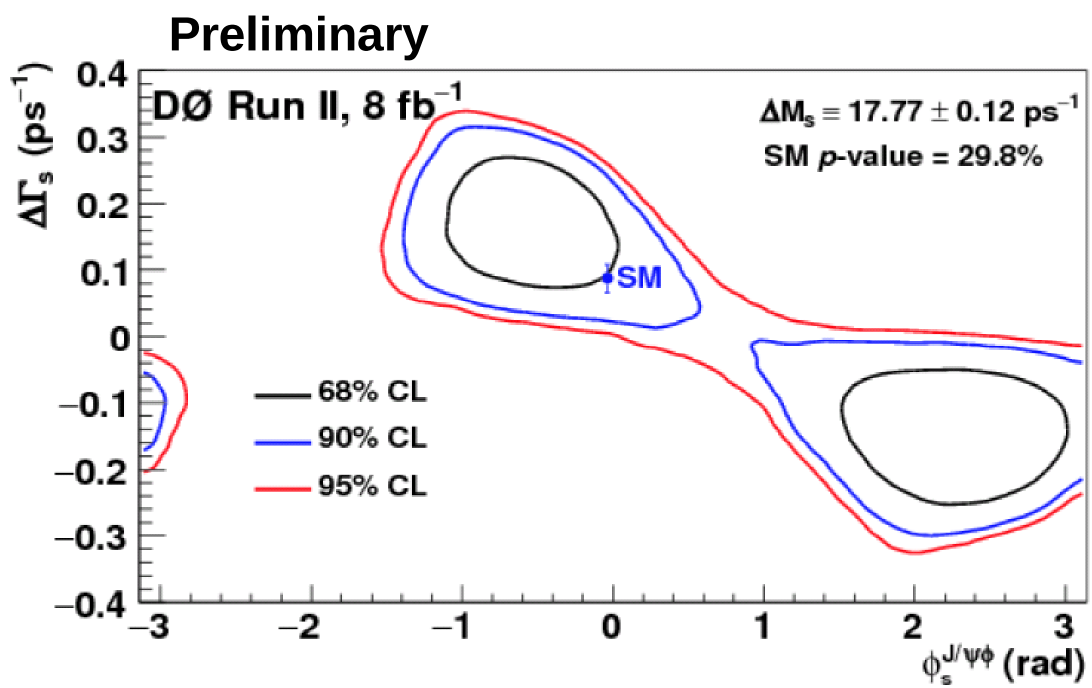
BDT sample	Simple-cut sample
$\overline{\tau}_s = 1.426^{+0.035}_{-0.032}$ ps,	$\overline{\tau}_s = 1.444^{+0.041}_{-0.033}$ ps,
$\Delta\Gamma_s = 0.129^{+0.076}_{-0.053}$ ps^{-1},	$\Delta\Gamma_s = 0.179^{+0.059}_{-0.060}$ ps^{-1},
$\phi_s^{J/\psi\phi} = -0.49^{+0.48}_{-0.40}$,	$\phi_s^{J/\psi\phi} = -0.56^{+0.36}_{-0.32}$,
$\lvert A_0\rvert^2 = 0.552^{+0.016}_{-0.017}$,	$\lvert A_0\rvert^2 = 0.565 \pm 0.017$,
$\lvert A_\parallel\rvert^2 = 0.219^{+0.020}_{-0.021}$,	$\lvert A_\parallel\rvert^2 = 0.249^{+0.021}_{-0.022}$,
$\delta_\parallel = 3.15 \pm 0.27$,	$\delta_\parallel = 3.15 \pm 0.19$,
$\cos(\delta_\perp - \delta_s) = -0.06 \pm 0.24$,	$\cos(\delta_\perp - \delta_s) = -0.20^{+0.26}_{-0.27}$,
$F_S(\text{eff}) = 0.146 \pm 0.035$.	$F_S = 0.173 \pm 0.036$.

Systematic Uncertainties

- Different widths of ϕ
- Variations of resolution parameters
- Variation of initial-state tagging parameters
- Acceptance
  - Difference between the BDT and Simple-cut samples
- Markov Chain Monte Carlo technique was used for systematics and combination

$B_s \rightarrow J/\psi + \phi$ Preliminary Result

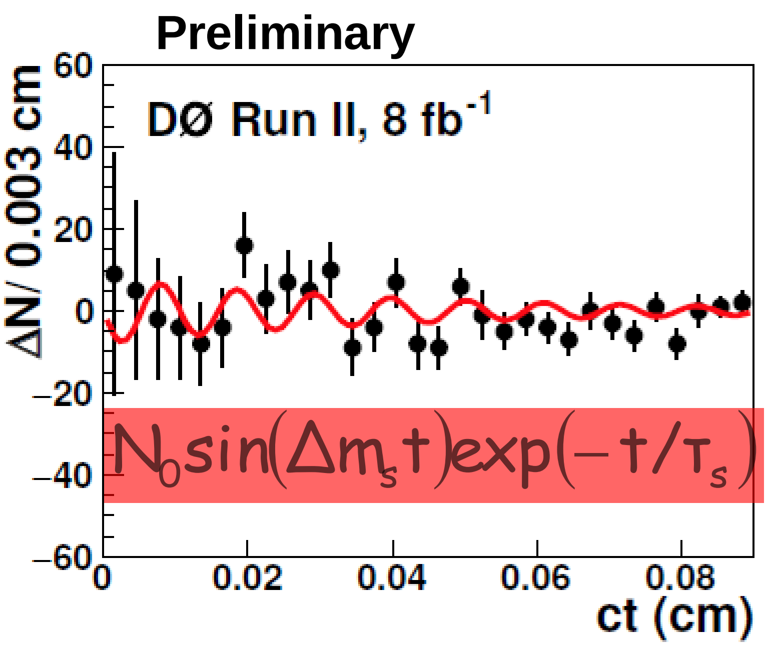
$$\overline{\tau}_s = 1.443^{+0.038}_{-0.035}\ \text{ps},$$
$$\Delta\Gamma_s = 0.163^{+0.065}_{-0.064}\ \text{ps}^{-1},$$
$$\phi_s^{J/\psi\phi} = -0.55^{+0.38}_{-0.36},$$
$$|A_0|^2 = 0.558^{+0.017}_{-0.019},$$
$$|A_{\parallel}|^2 = 0.231^{+0.024}_{-0.030},$$
$$F_S = 0.173 \pm 0.036,$$
$$\delta_{\parallel} = 3.15 \pm 0.22,$$
$$\cos(\delta_{\perp} - \delta_s) = -0.11^{+0.27}_{-0.25}.$$

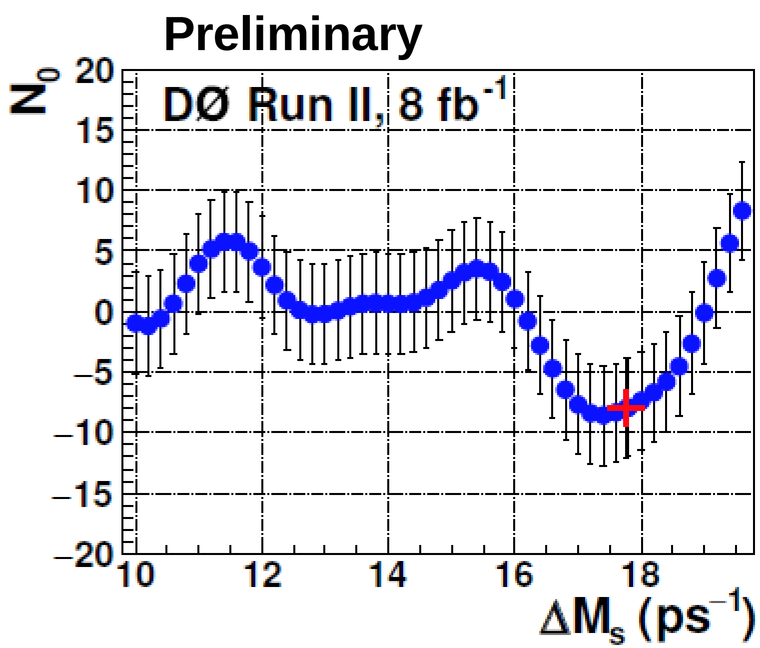


Sensitivity to Δm_s

- The mixing-induced *CP*-violation should manifest itself as a $B_s^0 - \overline{B}_s^0$ oscillation with the amplitude proportional to $\sin(\phi_s)$

$$\Delta N = N(B_s^0) - N(\overline{B}_s^0) = N_S \cdot C \cdot \sin(\phi_s)$$



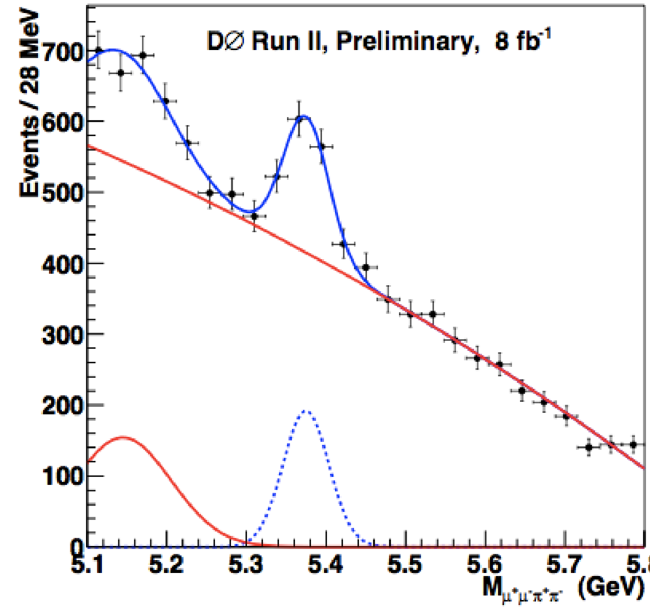


$B^0_s \to J/\psi\ f_0(980)$

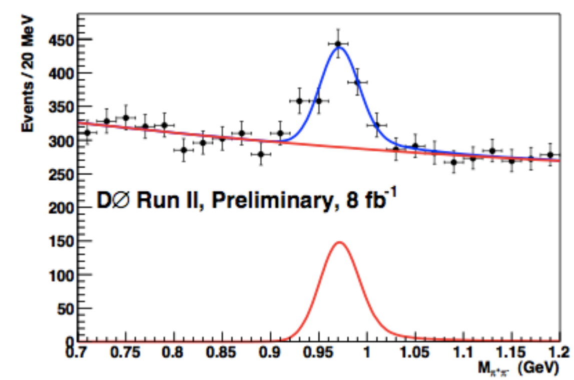
- CP-odd final state → complicated angular analysis is not needed
  - Independent measurement of β_s
- Measurement of lifetime gives independent information on $\Delta\Gamma_s$
- The first step is to measure the branching ratio
  - with respect to $B_s \to J/\psi + \phi$

$B^0_s \to J/\psi\ f_0(980)$

- Muon trigger
- Identical critera for $J/\psi\ f_0(980)$ and $J/\psi + \phi$
- BDT to suppress backgrounds



- 498±76 $J/\psi\ f_0(980)$ events



- Branching ratio

$$R = \frac{\mathcal{B}(B^0_s \to J/\psi f_0(980); f_0(980) \to \pi^+\pi^-)}{\mathcal{B}(B^0_s \to J/\psi\phi; \phi \to K^+K^-)} = 0.210 \pm 0.032\,(\mathrm{stat}) \pm 0.036\,(\mathrm{syst}).$$

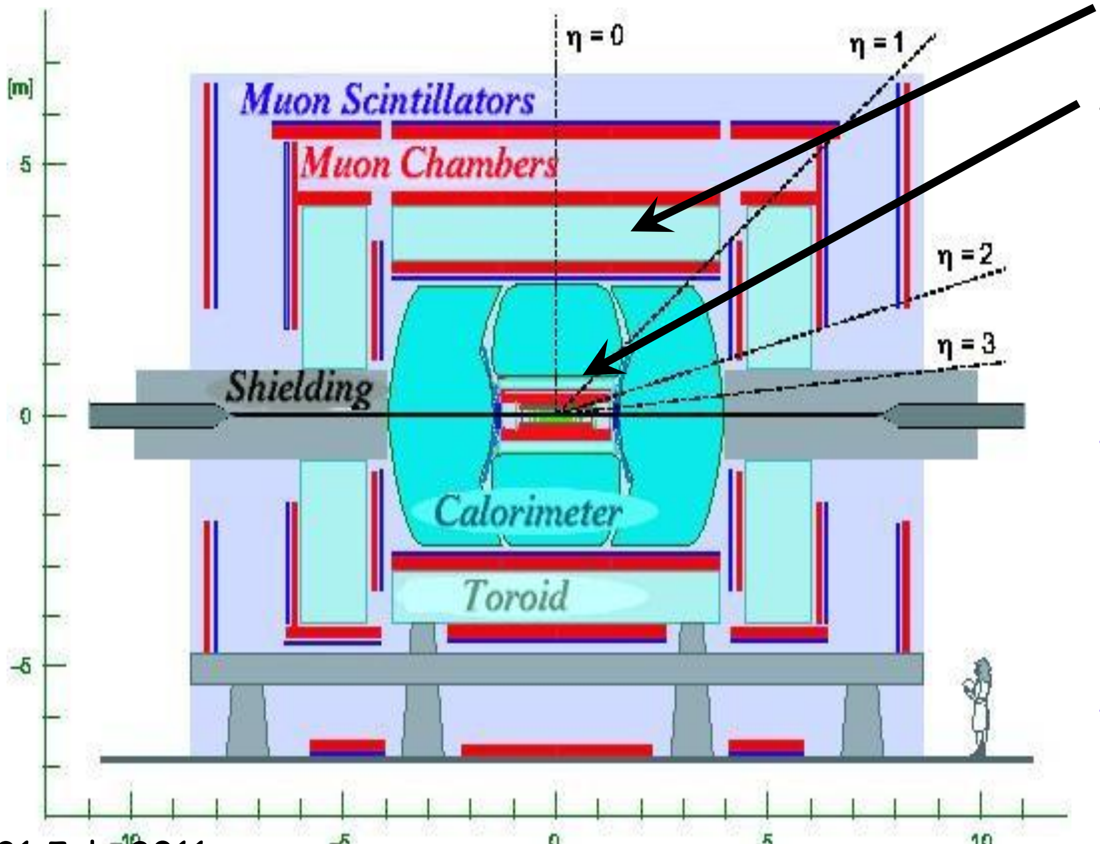
Summary

- B_s^0 mixing parameters, amplitudes and phases of the polarization amplitudes were measured in the $B_s \rightarrow J/\psi + \phi$ analysis using $8fb^{-1}$ data sample.
  - KK S-wave contamination increased the uncertainties.
- Measured branching ratio of $B^0_s \rightarrow J/\psi\ f_0(980)$ agrees with other experiments.
  - Next step is the CP-violation measurements.
- Combination with other D0 measurements of CP-violation parameters will be performed soon.
- Stay tuned!

Backup Slides

DZero Detector

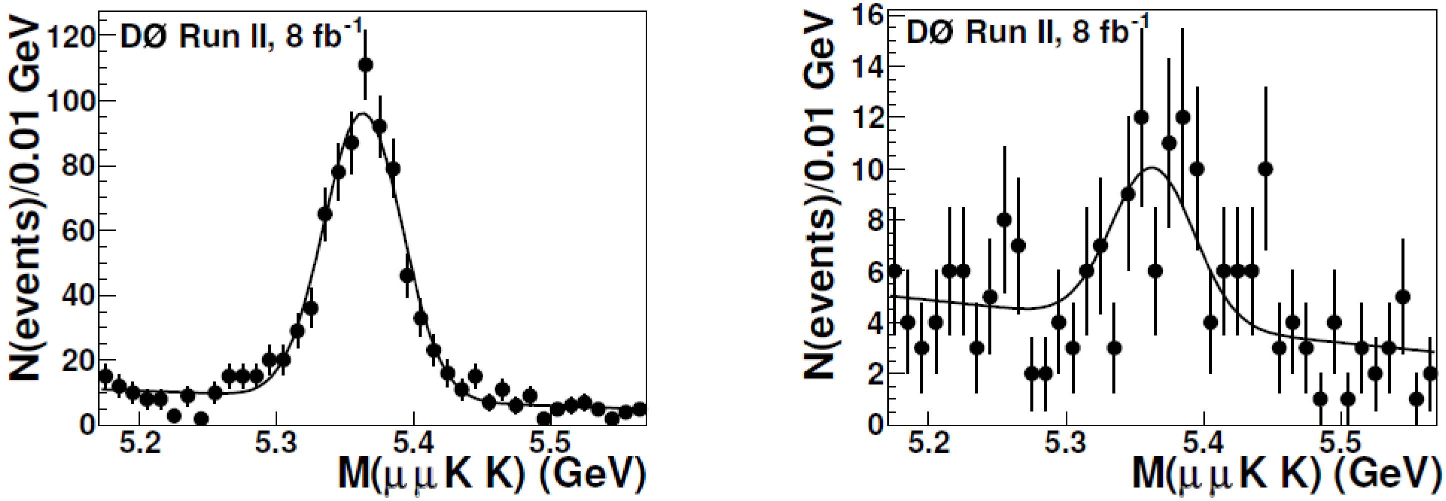
- Spectrometer : Fiber and Silicon Trackers in 2 T Solenoid
- Muons : 3 layer system & absorber in Toroidal field
- Hermetic : Excellent coverage of Tracking, Calorimeter and Muon Systems



Toroid & solenoid polarity flipped regularly

Low background single and dimuon triggers ➔ large B→μX semileptonic samples

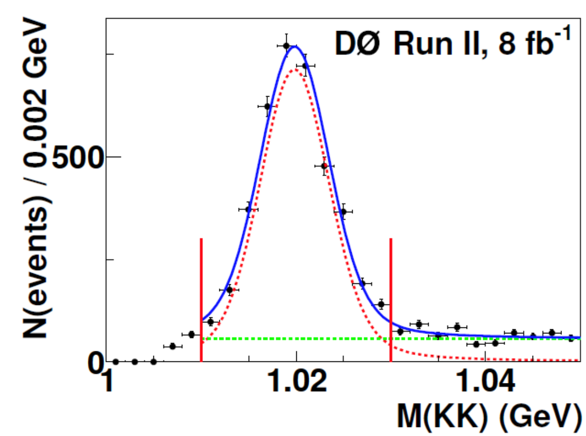
Independent Determination of F_s



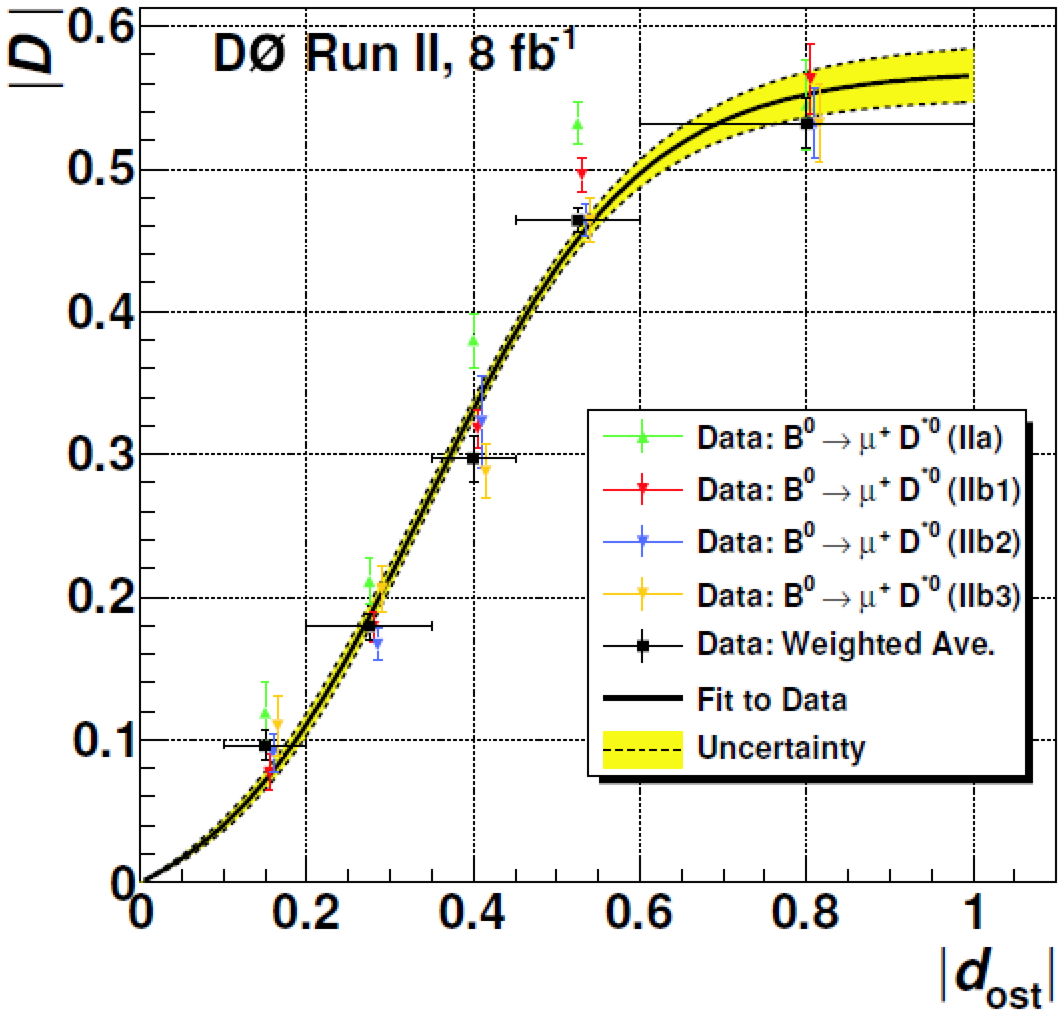
(a) $1.018 < M(K^+K^-) < 1.020$ GeV

(b) $1.048 < M(K^+K^-) < 1.050$ GeV

FIG. 16: The invariant mass distribution of B_s^0 candidates with $ct > 0.02$ cm in two slices of $M(K^+K^-)$. Fits to a sum of a Gaussian function and a polynomial are used to extract the B_s^0 yield in each slice.



Opposite Side Tagging



BDT variables (prompt)

Rank	Variable	Importance	Separation
1	KK invariant mass	0.3655	0.3540
2	Maximum ΔR between either K meson and the B_s^0 candidate	0.1346	0.4863
3	Isolation using the maximum ΔR between either K and the B_s^0	0.0390	0.1784
4	Uncorrected p_T of the B_s^0	0.0346	0.3626
5	Minimum ΔR between either K and the B_s^0	0.0335	0.4278
6	p_T of the trailing K meson	0.0331	0.4854
7	p_T of the ϕ meson	0.0314	0.4998
8	p_T of the leading K meson	0.0283	0.4884
9	Trailing muon momentum	0.0252	0.0809
10	p_T of the leading muon	0.0240	0.1601
11	Maximum ΔR between either muon and the B_s^0	0.0223	0.1109
12	Maximum χ^2 of of either K meson with the J/ψ vertex	0.0217	0.0162
13	Dimuon invariant mass	0.0215	0.0145
14	Maximum χ^2 of either of the K candidate track	0.0213	0.021
15	B_s^0 isolation using the larger K/B_s ΔR and tracks from the PV	0.0207	0.1739
16	p_T of the J/ψ meson	0.0205	0.1809
17	Minimum ΔR between either muon and the B_s^0 candidate	0.0188	0.1023
18	Trailing K momentum	0.0105	0.3159
19	χ^2 of the B_s^0 candidate vertex	0.0093	0.0119
20	B_s^0 isolation using $\Delta R < 0.75$	0.0241	
21	Minimum χ^2 of the J/ψ vertex with either K	0.0081	0.0069
22	p_T of the trailing muon	0.0079	0.0922
23	Minimum of the χ^2 of the J/ψ and ϕ vertices	0.0073	0.0057
24	Isolation using $\Delta R < 0.5$	0.0070	0.0405
25	Uncorrected B_s^0 total momentum	0.0068	0.2103
26	Minimum χ^2 of either K track fit	0.0065	0.0266
27	Isolation using $\Delta R < 0.5$ and particles from the PV	0.0057	0.0401
28	Leading K meson momentum	0.0051	0.3217
29	Leading muon momentum	0.0048	0.0908
30	ϕ meson momentum	0.0048	0.3233
31	Maximum χ^2 of the J/ψ or ϕ vertices	0.0044	0.0061
32	Isolation using $\Delta R < 0.75$ and particles from the PV	0.0037	0.0259
33	J/ψ meson momentum	0.0037	0.1004

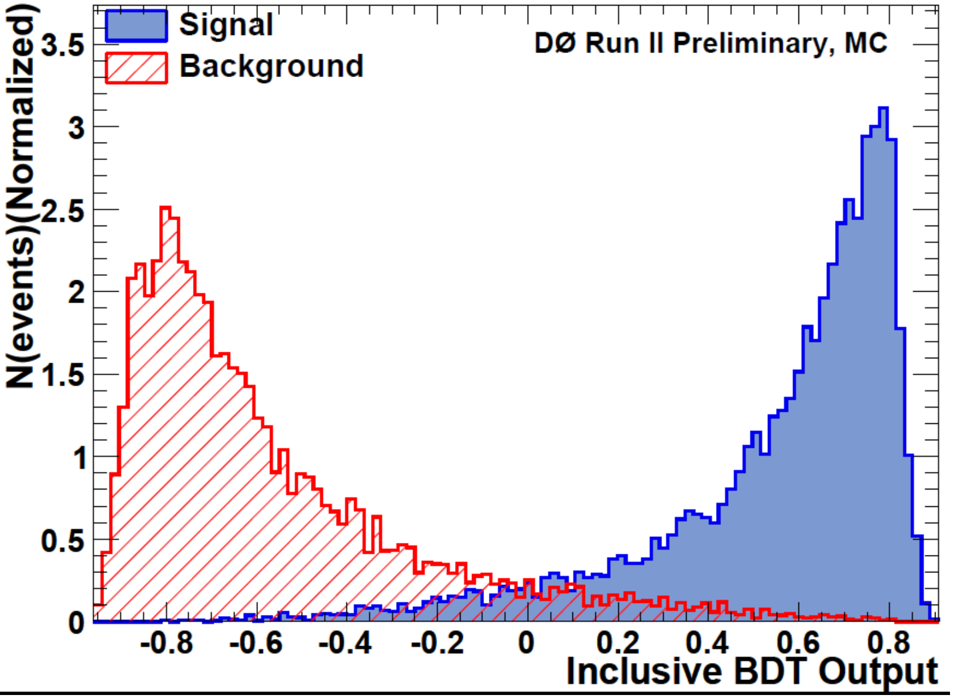
TABLE V: Variables used to train the prompt BDT, ranked by their importance in the training.

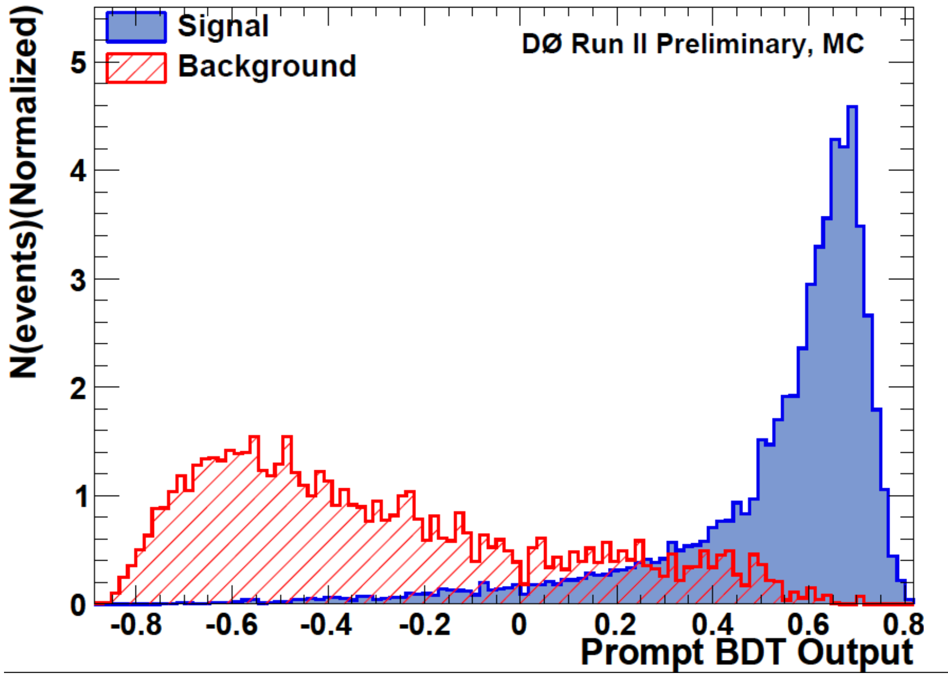
BDT variables (non-prompt)

Rank	Variable	Importance	Separation
1	KK invariant mass	0.2863	0.3603
2	B_s^0 isolation using the larger K/B_s ΔR and tracks from the PV	0.1742	0.4511
3	Minimum dE/dx of either K	0.0778	0.1076
4	χ^2 of B_s^0	0.0757	0.2123
5	p_T of the ϕ meson	0.0559	0.4856
6	p_T of the leading K meson	0.0504	0.4745
7	Isolation using the maximum ΔR between either K and the B_s^0	0.0429	0.4468
8	p_T of the trailing K meson	0.0350	0.4774
9	Maximum χ^2 of either K meson with the J/ψ vertex	0.0260	0.2051
10	Isolation using $\Delta R < 0.5$ and particles from the PV	0.0229	0.1703
11	Isolation using $\Delta R < 0.75$ and tracks from the PV	0.0154	0.2238
12	Minimum χ^2 of of either K with the J/ψ vertex	0.0151	0.1308
13	Minimum ΔR between either K meson and the B_s^0 candidate	0.0115	0.3104
14	Dimuon invariant mass	0.0099	0.0190
15	Total momentum of the ϕ meson	0.0091	0.3307
16	p_T of the J/ψ meson	0.0089	0.1198
17	Trailing muon momentum	0.0082	0.0594
18	Isolation using $\Delta R < 0.5$	0.0073	0.1695
19	Maximum ΔR between either K meson and the $B_s^0 candidate$	0.0070	0.3794
20	Maximum dE/dx of either K meson	0.0069	0.0528
21	Trailing K meson momentum	0.0068	0.3253
22	J/ψ vertex χ^2	0.0063	0.0057
23	Leading K meson momentum	0.0058	0.3277
24	Maximum χ^2 of either K candidate track	0.0054	0.0267
25	Isolation using $\Delta R < 0.75$	0.0046	0.2203
26	Minimum ΔR between either muon and the B_s^0 candidate	0.0041	0.0729
27	Minimum χ^2 of either K candidate track	0.0039	0.0284
28	uncorrected p_T of B_s^0 candidate	0.0036	0.2485
29	p_T of the trailing muon	0.0029	0.0702
30	J/ψ momentum	0.0027	0.0645
31	Maximum ΔR between either muon and the B_s^0 candidate	0.0026	0.0872
32	Vertex χ^2 of the ϕ meson	0.0017	0.0098
33	Uncorrected B_s^0 momentum	0.0014	0.1675
34	p_T of the leading muon	0.0011	0.1008
35	Leading muon momentum	0.0009	0.0547

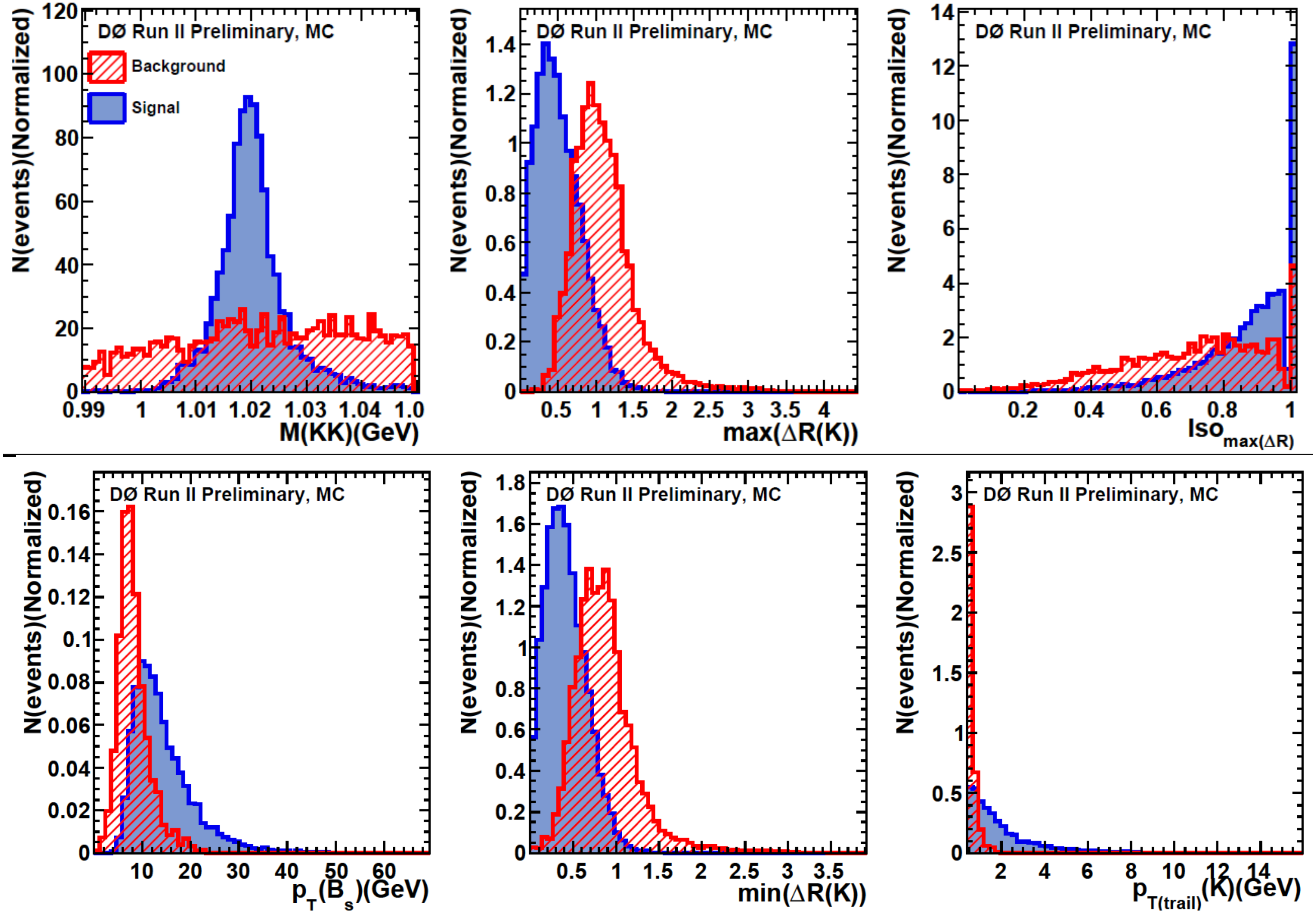
TABLE VI: Variables used to train the non-prompt BDT, ranked by their importance in the training.

BDT Output

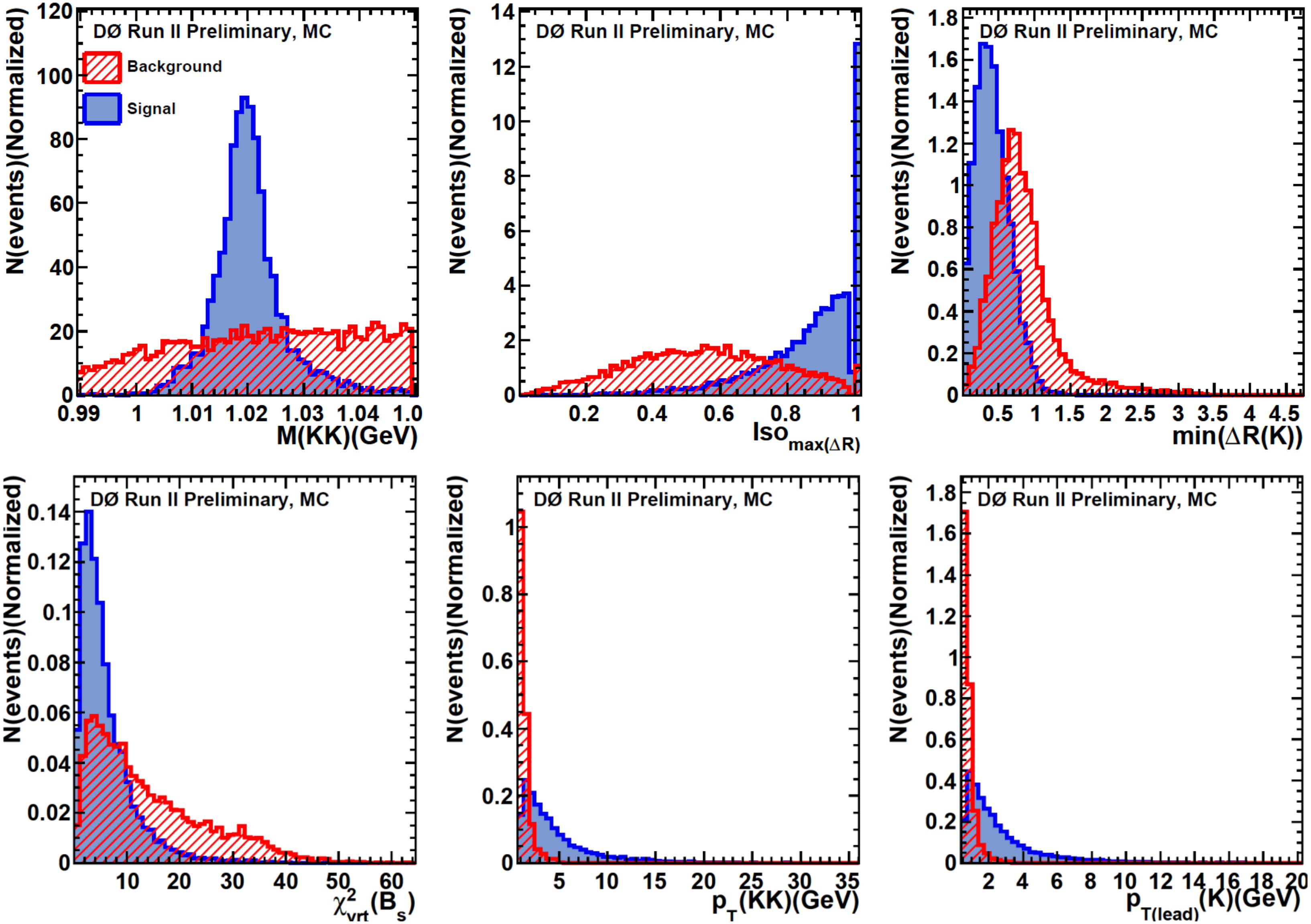

Signal
Background
DØ Run II Preliminary, MC
N(events)(Normalized)
Inclusive BDT Output


Signal
Background
DØ Run II Preliminary, MC
N(events)(Normalized)
Prompt BDT Output

BDT Variables (prompt)



BDT Variables (inclusive b)



Markov Chain Monte Carlo

- Since ϕ_s is correlated with $\Delta\Gamma_s$ we want to know how the likelihood depends on these variables.
- Start from the minimum obtained from the fit.
- Generate a multivariate gaussian $e^{-\frac{1}{2}(x-\mu)\cdot\Sigma\cdot(x-\mu)}$ point x
- Where Σ is the covariance matrix.
- Calculate $\alpha=L(x)/L(\mu)$
- Generate random number $r = U(0; 1)$
- If $r < \alpha$ accept the new point $\mu=x$
- Continue until reach the amount of points desired.
- We generate 1M events for each Markov Chain

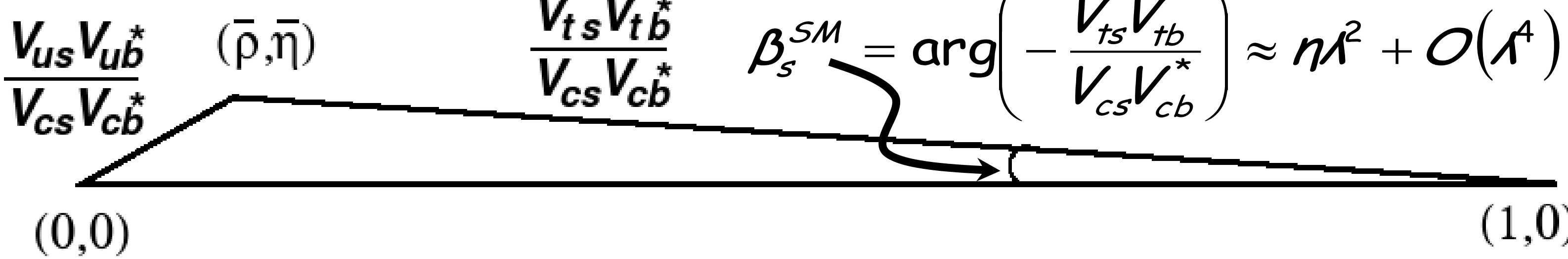
CP Violation in $B_s \to J/\psi + \phi, f_0$

- Standard Model Lagrangian

$$L = \frac{g}{\sqrt{2}} \left(\overline{u}, \overline{c}, \overline{t}\right)_L \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \gamma_\mu \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L W^\mu + h.c.$$

Unitarity ➔ $V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$ for B_s system

$$\beta_s^{SM} = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) \approx \eta\lambda^2 + O\left(\lambda^4\right) \approx 0.02$$



$$2\beta_s = 2\beta_s^{SM} - \phi_{NP} \approx -\phi_{NP}$$