Measurement of $\phi_s^{J/\Psi\Phi}$ at DØ

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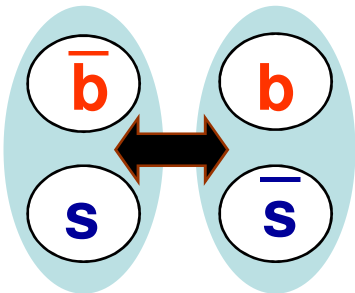
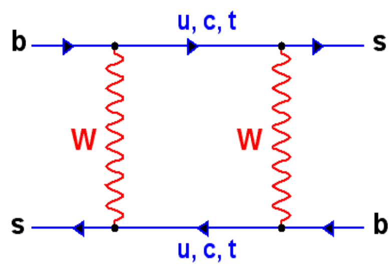
for the DØ collaboration

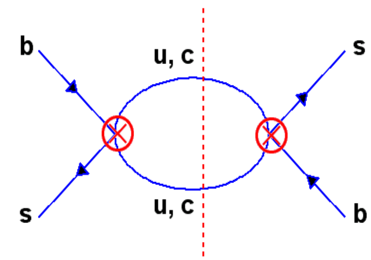
DPF 2011
Brown University, USA

B_s Mixing



Schrödinger Equation: $$i\frac{\partial}{\partial t}\begin{pmatrix}|B_s^0(t)\rangle\\ |\overline{B}_s^0(t)\rangle\end{pmatrix}=\begin{pmatrix}M_{11}-\frac{i}{2}\Gamma_{11} & M_{12}-\frac{i}{2}\Gamma_{12}\\ M_{21}-\frac{i}{2}\Gamma_{21} & M_{22}-\frac{i}{2}\Gamma_{22}\end{pmatrix}\begin{pmatrix}|B_s^0(t)\rangle\\ |\overline{B}_s^0(t)\rangle\end{pmatrix}$$





Three physical quantities; M_{12} , $|\Gamma_{12}|$ and $arg(-M_{12}/\Gamma_{12})$

Diagonalization gives two physically observed "Light" and "Heavy" mass eigenstates

$$|B_s^H\rangle = N\,[\,p\,|B_s^0\rangle - q\,|\overline{B}_s^0\rangle\,]$$

$$|B_s^L\rangle = N\,[\,p\,|B_s^0\rangle + q\,|\overline{B}_s^0\rangle\,]$$

$$\Gamma_s = \frac{\Gamma_L + \Gamma_H}{2}$$

$$\overline{\tau}_s = \frac{1}{\Gamma_s}$$

B_s Mixing

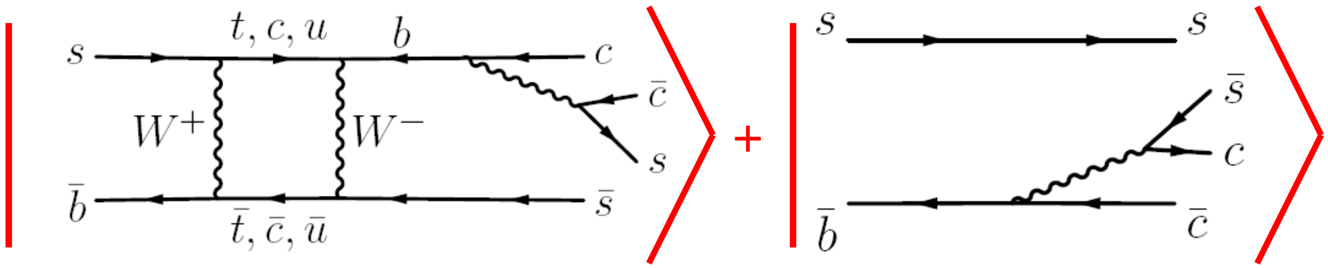
Observable		SM expectation (arXiv:1102.4274)
CP violation weak phase	$\phi_s = arg(-M_{12}/\Gamma_{12})$	$(3.8 \pm 1.1)\ 10^{-3}$ rad
Decay width difference	$\Delta\Gamma_s = \Gamma_L - \Gamma_H = 2\|\Gamma_{12}\|\cos\phi_s$	$(0.087 \pm 0.021)\ ps^{-1}$
frequency of B_s- $\bar{B}_s$ oscillations	$\Delta M_s = M_H - M_L = 2\|M_{12}\|$	$(17.77 \pm 0.12)\ ps^{-1}$ (measured value)

$$|B_s^{Odd}\rangle = 1/\sqrt{2}\,(|B_s^0\rangle - |\bar{B}_s^0\rangle)$$

$$|B_s^{Even}\rangle = 1/\sqrt{2}(|B_s^0\rangle + |\bar{B}_s^0\rangle)$$

CP Eigenstates

CP-phase in $B_s \rightarrow J/\psi\phi$



- ✓ CP violating mixing phase in $B_s \rightarrow J/\psi\phi$ ($\phi_s^{J/\psi\phi}$ or $-2\beta_s$) is not equal to the CP violating mixing phase of B_s system i.e. $\phi_s^{J/\psi\phi} \neq \phi_s$
- ✓ Still small in SM ! $\phi_s^{J/\psi\phi} = -2\arg[-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*] = (-0.04 \pm 0.01)$ rad
- ✓ New physics contributions alter $\phi_s^{J/\psi\phi}$ in the same way as for ϕ_s

$$\phi_s^{J/\psi\phi} \rightarrow \phi_s^{J/\psi\phi,SM} + \phi_s^{NP}$$

$$\phi_s \rightarrow \phi_s^{SM} + \phi_s^{NP}$$

Large measured value of $\phi_s^{J/\psi\phi}$ is unambiguous sign of new physics!

Transversity Basis

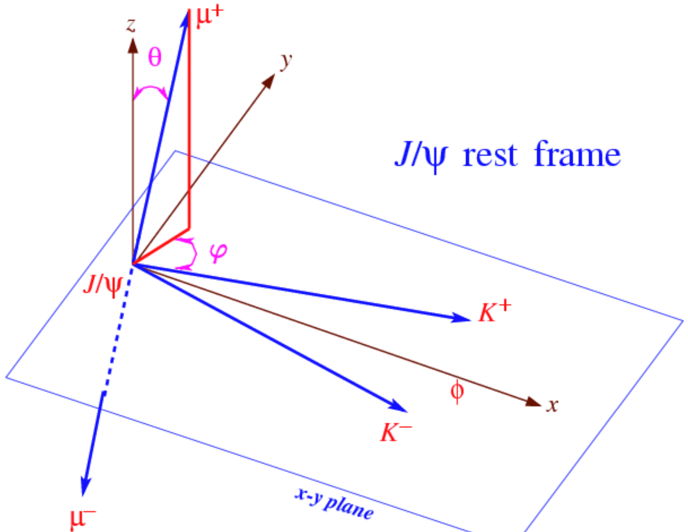
- $B_s \rightarrow V1 + V2$ ($J/\psi + \phi$) i.e. Spin $0 \rightarrow 1+1$ L= 0,1,2
- L = 0 and 2 corresponds to CP even; L=1 CP odd

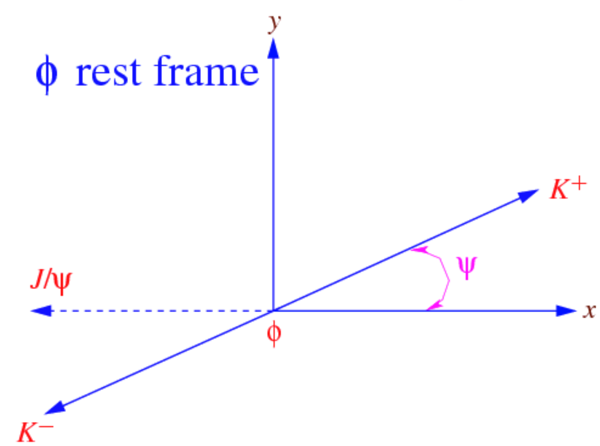
➢ The Angular distribution is written in terms of three time-dependent linear polarization amplitudes

➢ With respect to decay axis: Parallel, perpendicular orientations of the transverse polarization ($A_\perp$ & $A_\parallel$) and longitudinal polarization (A_0)

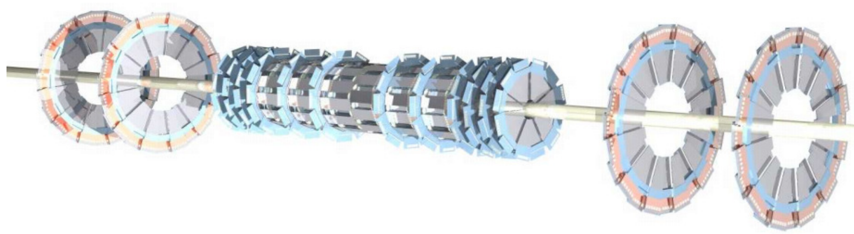
➢ The Initial magnitude of polarization amplitudes satisfy the normalization condition
$|A_\perp(0)|^2 + |A_\parallel(0)|^2 + |A_0(0)|^2 = 1$ where
$|A_\perp(0)|^2$ is CP-odd content (~20%)

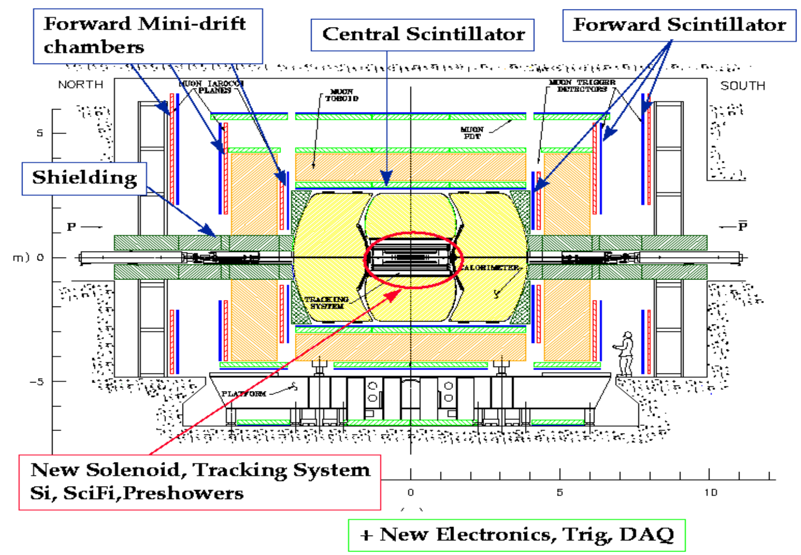
➢ Polarization amplitude phases relative to each other are known as "strong phases" which depend only on final state interactions
$\delta_\parallel = \arg(A_\parallel(0)\, A_0^*(0))$,
$\delta_\perp = \arg(A_\perp(0)\, A_0^*(0))$





DØ detector



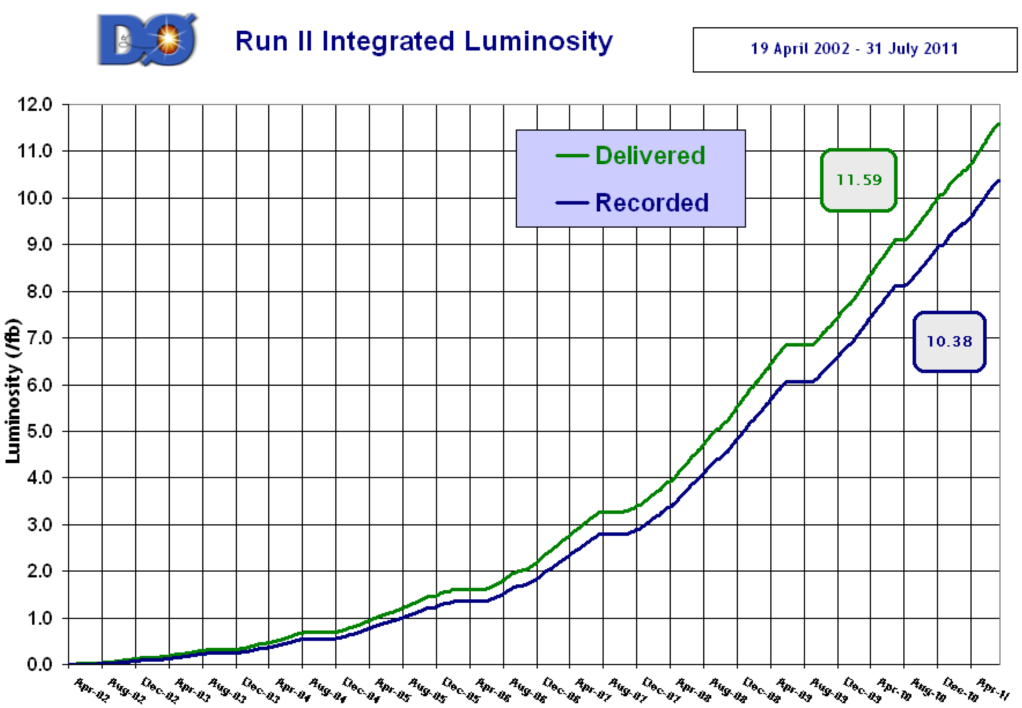


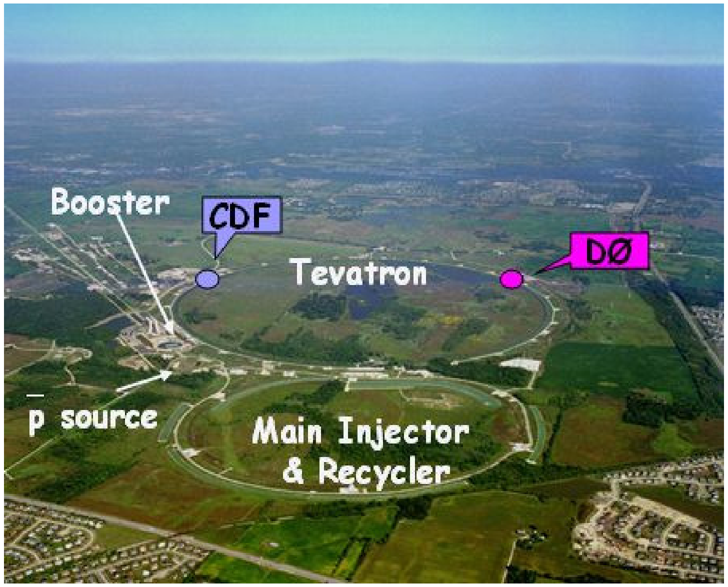
- Large acceptance $|\eta| < 2.2$
- Excellent triggering
- Cosmic ray rejection
- Low punch-through

- Low p_T Muon identification
  - $p_T > 1.5$ GeV, $|\eta| < 2$
- High tracking efficiency:
  - 95% $|\eta| < 3$ (Silicon disks)

Data sample

- p , $\bar{p}$ collisions at 1.96 TeV
- 8 fb^{-1} data will be used for this analysis



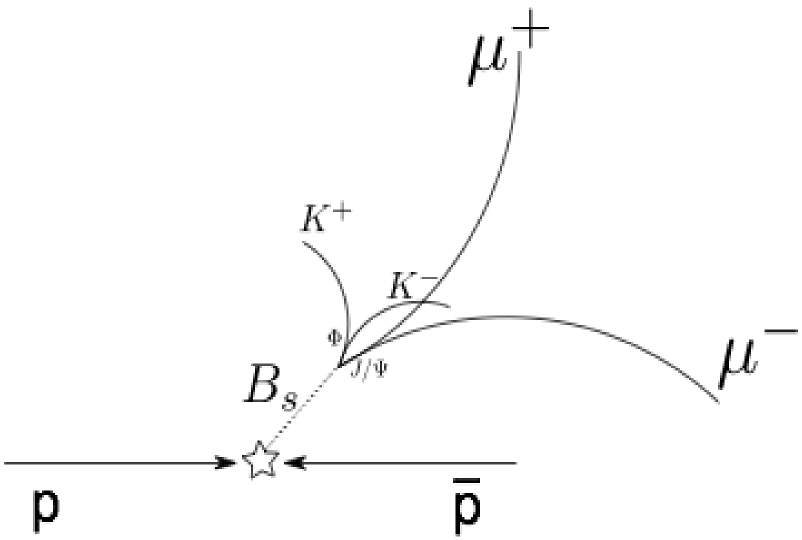


$B_s \rightarrow J/\psi\phi$ reconstruction

- We start with two reconstructed opposite charge muons to make J/ψ candidates

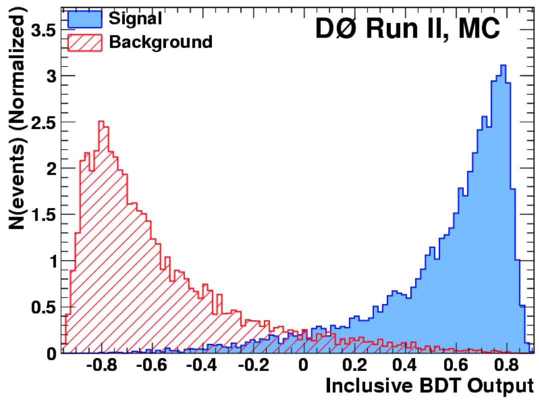
- For each J/ψ candidates, we search for ϕ candidates using opposite charge tracks assuming they are kaons

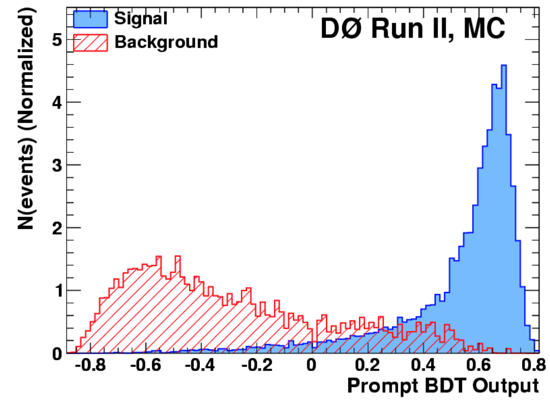
- For each J/ψ and ϕ candidates, we reconstruct a B_s candidate with following minimum cuts



p_T of $\mu^+\mu^-$	> 1.5 GeV
p_T of $K^+ K^-$	> 0.4 GeV
J/ψ candidate mass	2.84 → 3.35 GeV
ϕ candidate mass	0.98 → 1.04 GeV
B_s candidate mass	5.0 → 5.8 GeV

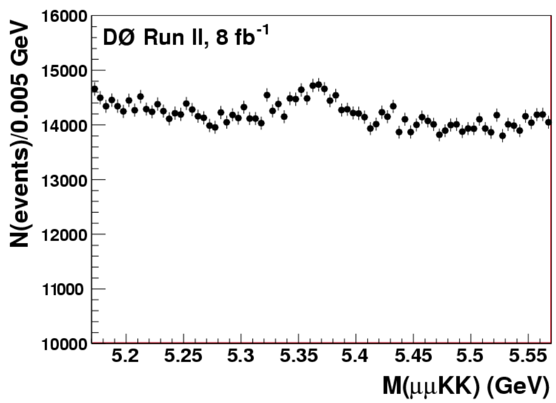
Final Event Selection

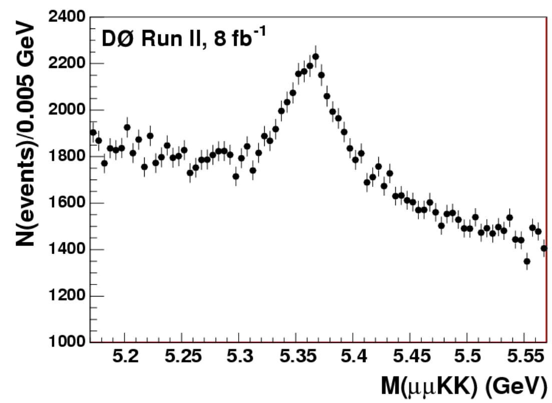




Boosted Decision Tree (BDT) method is used to suppress the background

- **Prompt $p\bar{p} \rightarrow J/\psi X$**
- **b-inclusive $p\bar{p} \rightarrow b\bar{b} \rightarrow J/\psi X$**



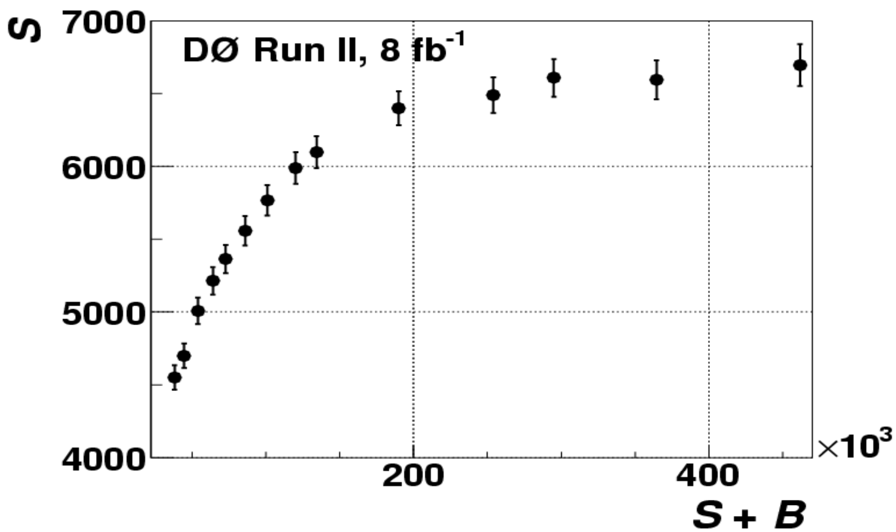


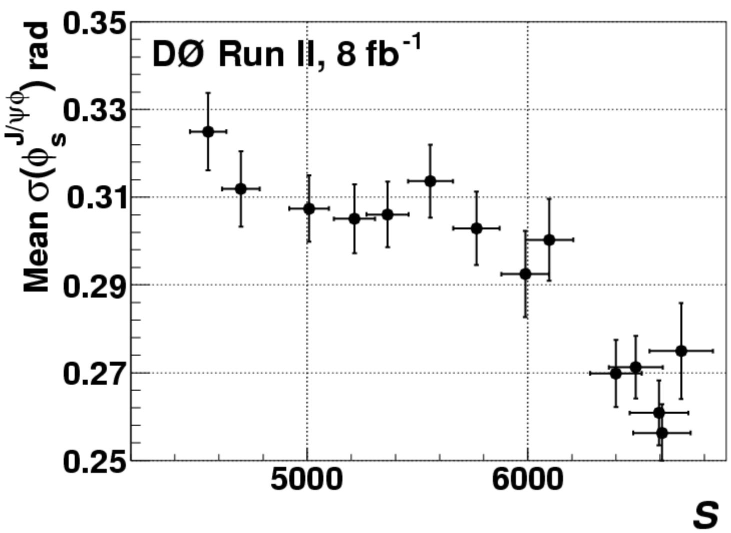
For cross-checks & systematic, we also have selection (simple cut sample) with tight kinematic, as were used for past publications (see, Phys. Rev. Lett. 101, 241801(2008))

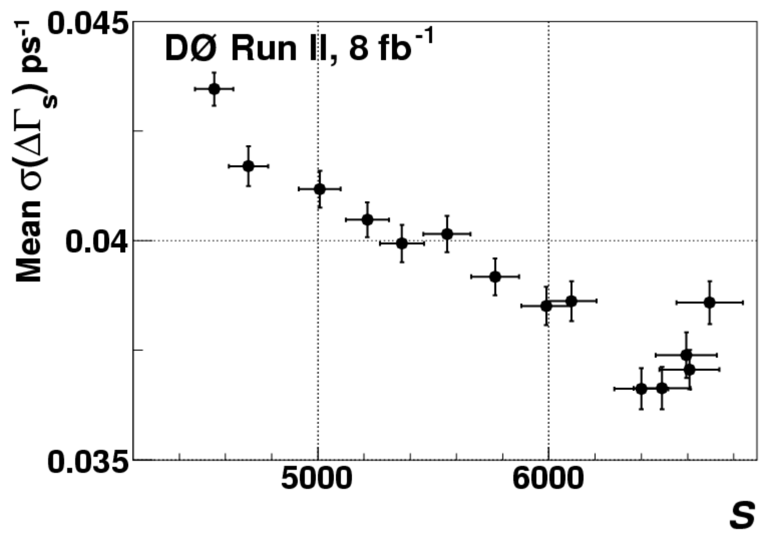
Event Selection Optimization

- With tight BDT discriminate variable, the signal purity is high but for loose BDT we have more signal candidates

- The final Cut is selected based on an ensemble study, providing least mean statistical error of $\sigma(\phi_s^{J/\psi\phi})$ & $\sigma(\Delta\Gamma_s)$







Fit Equation

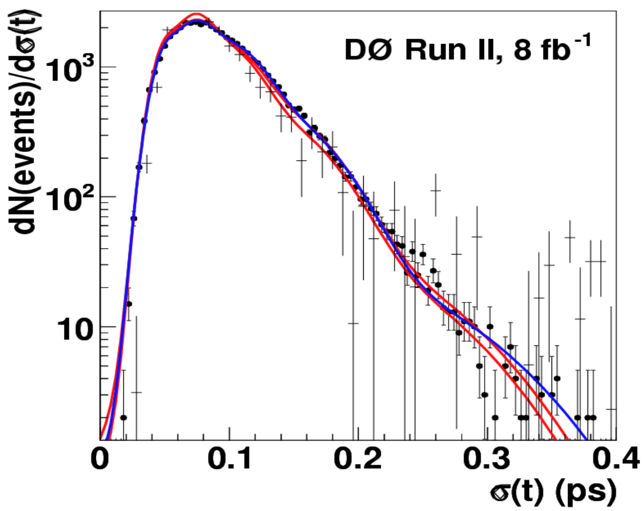
$$\epsilon(\vec{\omega}) \times \left[\mathcal{B}_S(\lambda;\ t,\ \vec{\omega})\ \frac{1-D}{2} + \overline{\mathcal{B}}_S(\lambda;\ t,\ \vec{\omega})\ \frac{1+D}{2} \right] \otimes R(t)$$

$\epsilon(\vec{\omega}) \rightarrow$ *angular acceptance function* ; $\vec{\omega} = (\psi, \theta, \phi)$, *transversity angles*

$\mathcal{B}_S(\lambda;\ t,\ \vec{\omega})\ /\ \overline{\mathcal{B}}_S(\lambda;\ t,\ \vec{\omega}) \rightarrow$ *time dependent angular PDF for* $B_s\ /\ \overline{B}_s$

$D \rightarrow$ *flavor tagging dilution at time* $t = 0$

$R(t) \rightarrow$ *proper decay time resolution*



Time resolution event by event

$$\lambda = (\tau_s,\ \Delta\Gamma_s,\ \phi_s^{J/\psi\phi},\ \Delta M_s,\ |A_0|^2,\ |A_\perp|^2,\ \delta_{||},\ \delta_\perp,\ F_s, \delta_s)$$

$$\mathcal{B}_S = \left| \left[\sqrt{1-F_s}\, g(M_{KK})\mathrm{A} + e^{i\delta_s}\sqrt{F_s}\, h(M_{KK})\mathrm{B} \right] \times \hat{n} \right|^2$$

$A/\ B \equiv A(\lambda;\ t,\ \vec{\omega})/\ B(\lambda;\ t,\ \vec{\omega})$ *corresponds to* $P-wave/\ S-wave$

$h(M_{KK}) = Uniform\ distribution\ in\ Range\ 1.01 \rightarrow 1.03\ GeV$

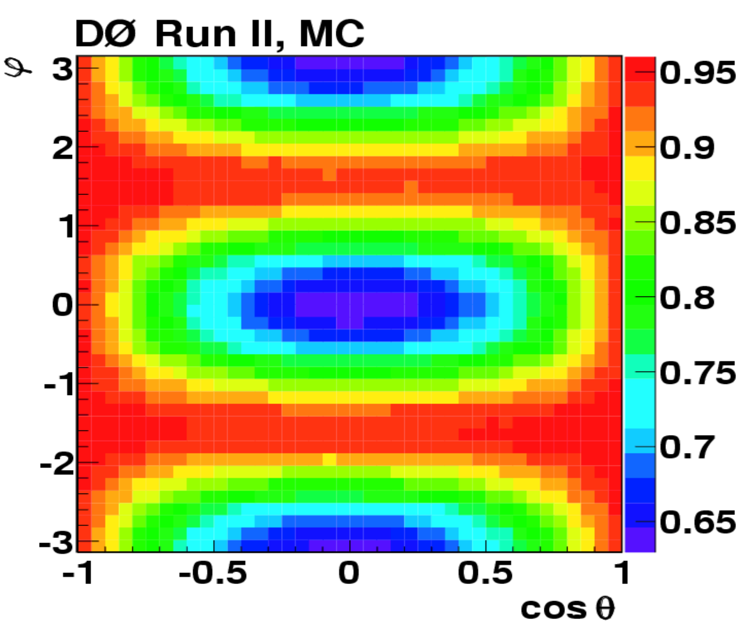
$$g(M_{KK}) = \sqrt{\frac{\Gamma_\phi/2}{\Delta\omega}} \cdot \frac{1}{M_{KK} - M_\phi + i\Gamma_\phi/2} \rightarrow non-relativistic\ Breit-Wigner$$

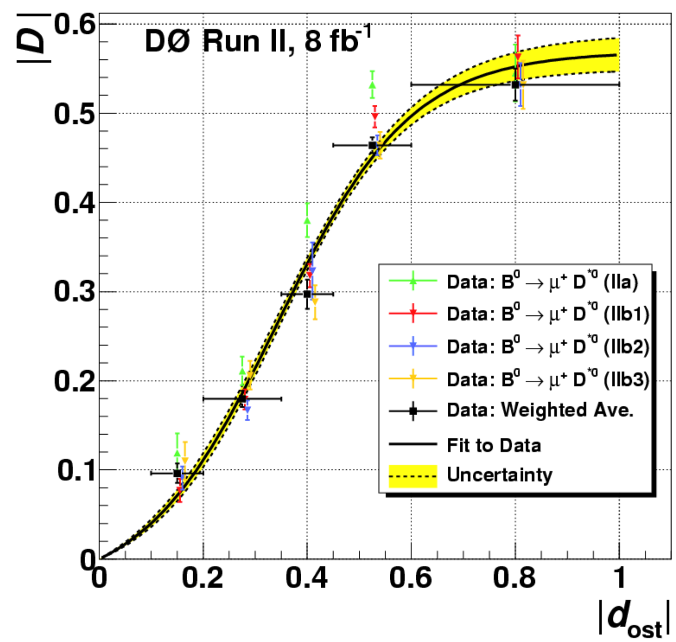
F.Azfar et al., JHEP 1011:158,2010

Acceptance & Flavor Tagging

- Acceptance functions are obtained using flat MC in angular distribution
- Same selection cuts as used for generating the sample, angle ψ acceptance is flat
- 2D acceptance is used which include any correlation effect

- We used only opposite side tagging
- The algorithm search for muon, electron or net charge of decay vertex, ~18% efficient
- Dilution calibration is obtained using $B \rightarrow \mu\nu D^*$ data sample





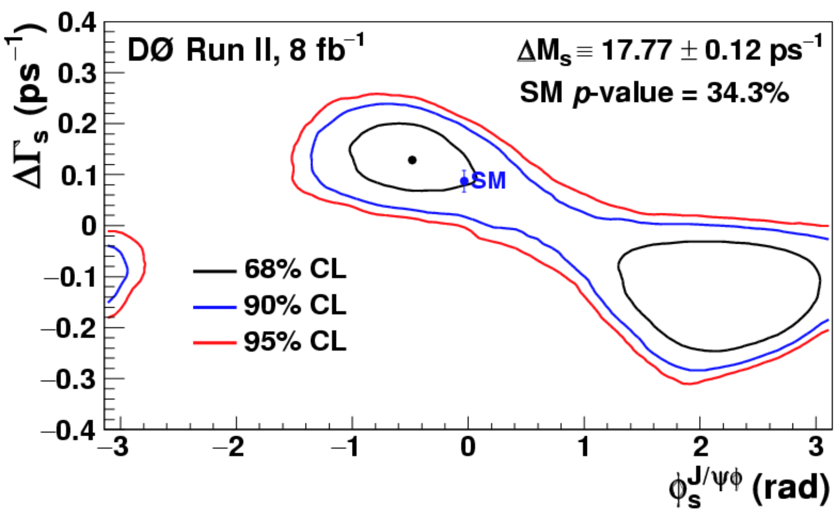
Physics Parameters

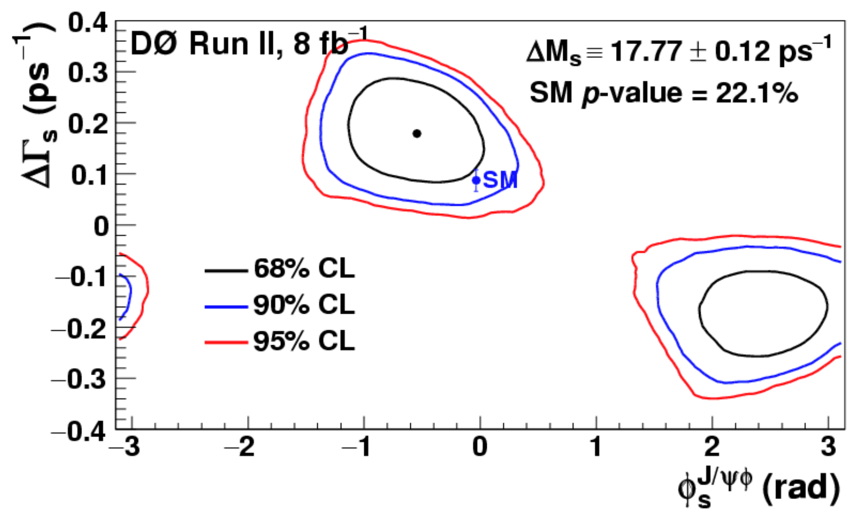
Parameter	Definition
$\lvert A_0\rvert^2$	$\mathcal{P}$-wave longitudinal amplitude squared, at $t = 0$
$A1$	$\lvert A_\parallel\rvert^2/(1 - \lvert A_0\rvert^2)$
$\overline{\tau}_s$ (ps)	B_s^0 mean lifetime
$\Delta\Gamma_s$ (ps^{-1})	Heavy-Light decay width difference
β_s	CP-violating weak phase ($\equiv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

Two constraints to the Fit ♦ $\Delta M_s = 17.77 \pm 0.12\ ps^{-1}$ ♦ $\cos(\delta_\perp) < 0$

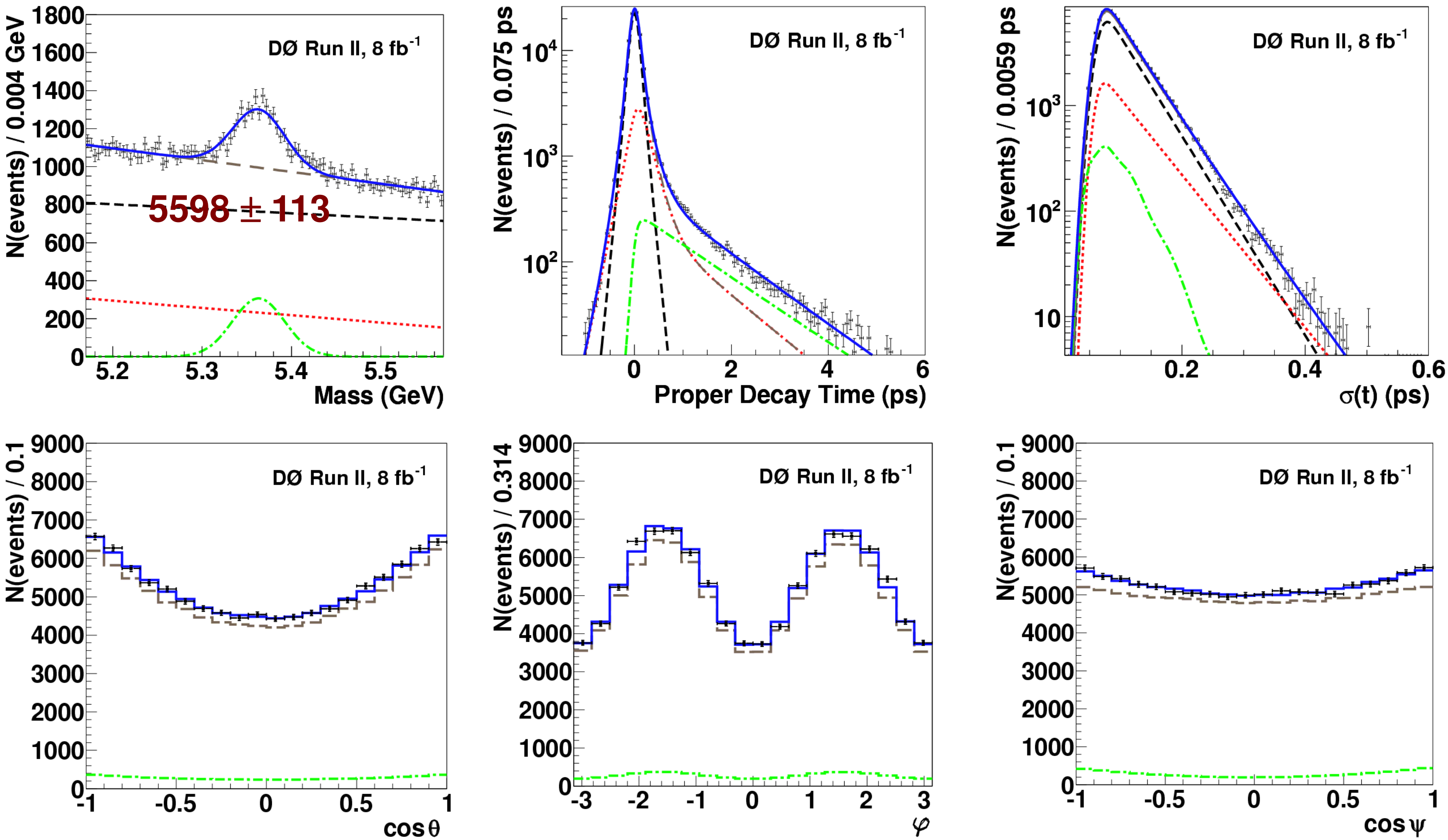
Fit Results

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}
$\phi_s^{J/\psi\phi}$	$-0.49^{+0.48}_{-0.40}$	$-0.56^{+0.36}_{-0.32}$
$\lvert A_0\rvert^2$	$0.552^{+0.016}_{-0.017}$	0.565 ± 0.017
$\lvert A_\parallel\rvert^2$	$0.219^{+0.020}_{-0.021}$	$0.249^{+0.021}_{-0.022}$
$\delta_\parallel$	-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





Fit Projections



Systematics

Flavor mistagging : **Variation in the calibration curve for different running period of time & averaging**

Proper time resolution : **Alternative parameterizations by randomly altering parameter values**

Detector Acceptance : **Swapping detector acceptance from the square cut sample**

M(KK) resolution : **Increasing BW function width by a factor of 2 & swapping smearing from MC**

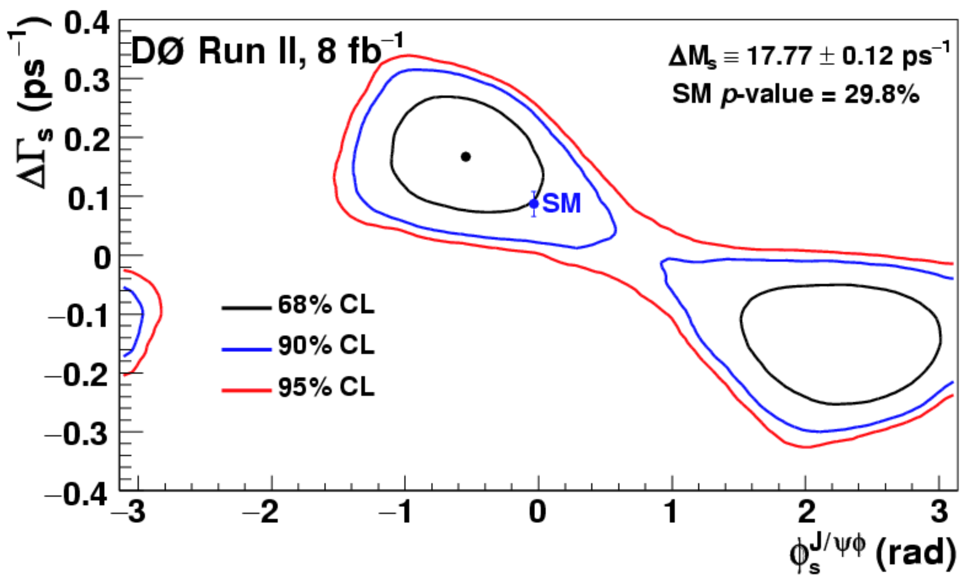
Maximum likelihood fit to each alternative fit provide systematic error, which are very small compare to statistical error

To combine all the systematical effect of alternative universe, we generate Markov chains of very large states using Markov Chain Monte Carlo (MCMC) method and add them together

Results including systematics

To obtain the final CL contours, MCMC chains for the different systematic effect were added for the BDT and simple cut

$\overline{\tau}_s$	$1.443^{+0.038}_{-0.035}$ 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
$(\delta_{\perp}\text{-}\delta_s)$	$-0.11^{+0.027}_{-0.025}$
$F_S(eff)$	0.173 ± 0.036



Summary & Outlook

- Measurement of CP violation weak phase have been performed from tagged angular analysis of $B_s \rightarrow J/\psi\phi$ at D0 with $8 fb^{-1}$ data

- The updated measurement include S-wave contribution from K^+K^-

- The results are consistent with SM predicted values and previous measurement

- We measure ~15% S-wave in the $B_s \rightarrow J/\psi\phi$ decay, which is cross-checked by an independent measurement

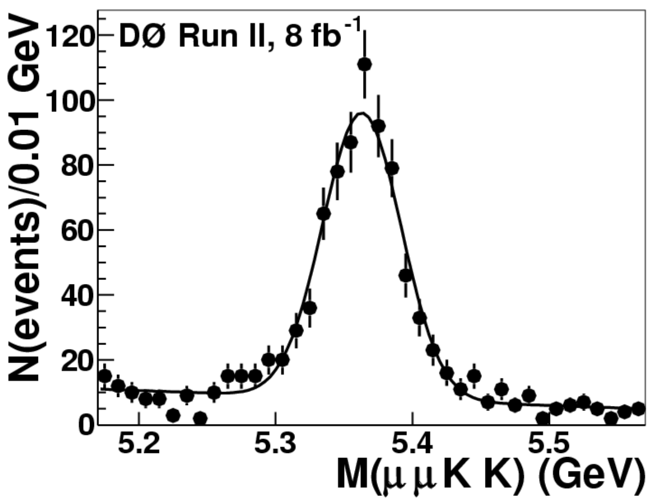
- We will do combination of all DØ results of CP violation

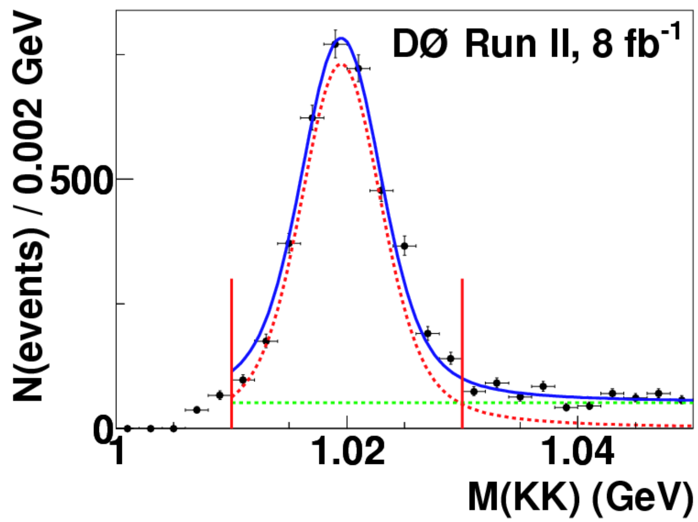
Additional Slides

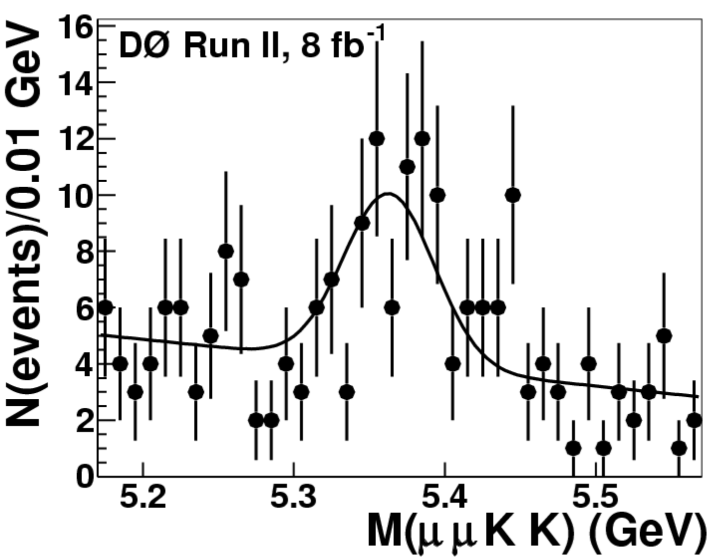
MCMC

- ✓ MCMC is a standard method to estimate CL region of correlated physics parameters
- ✓ We can start from a point X0 available to in the phase space of all physics parameters, in this case we start from the point we obtained from ML fit
- ✓ Generate a multivariate normal distribution exp(-(Xi-X0).Σ.(Xi-X0)/2) where Σ is covariance matrix
- ✓ If L(Xi)/L(X0) > Random number U(0, 1) , the Xi is accepted and new point Xi+1 is selected with Xi=X0
- ✓ We have generated 1M points for each MCMC chain

Independent measurement of F_s



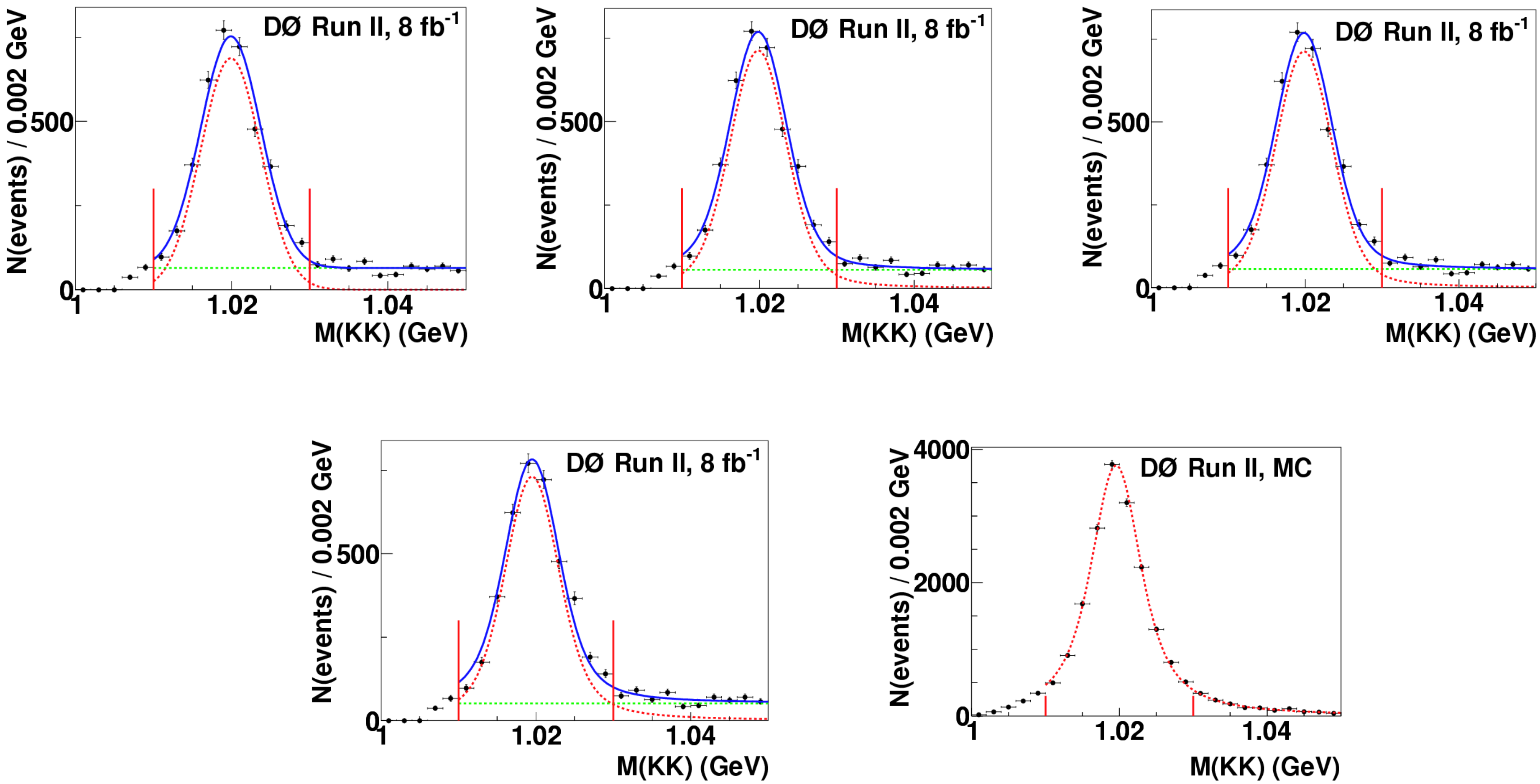




We independently measure the S-wave fraction by obtaining Bs candidates in the phi mass from 0.98→1.05 GeV in step of 2MeV

The number of fitted B_s signal Vs ϕ mass plot is fitted with BW with different assumptions assigned as total measurement error

We measure F_s=0.14+-0.01, consistent with likelihood fit results but with relatively large error


DØ Run II, 8 fb^{-1}
N(events) / 0.002 GeV
M(KK) (GeV)
0
500
1
1.02
1.04
DØ Run II, MC
4000
2000