Searches for CP Violation in the B^0_s System Using $B^0_s \to J/\psi+(\varphi/f_0/f_2)$ Decays

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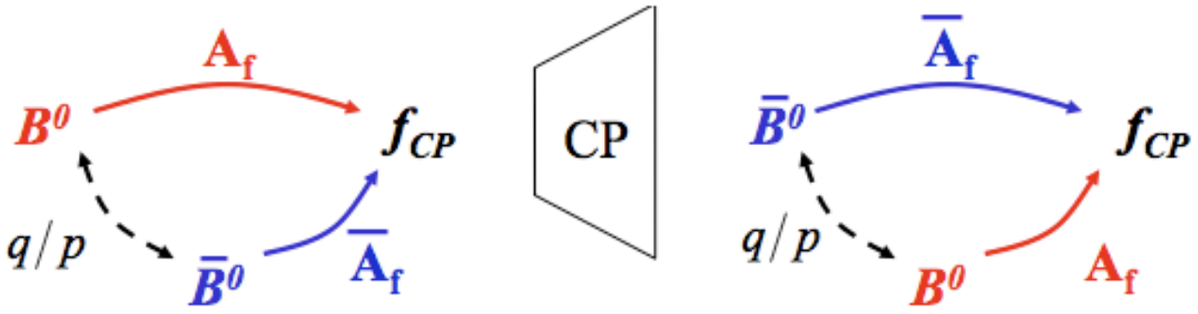
CP Violation in B^0_s

- B^0_s is one of the least explored systems
- Study of CP violation in B^0_s mixing may help explain the observed CP violation in Universe and lead to possible new physics
- Predicted CP rated is very small in SM - search for large deviations
- Mixing induced CP violation
  - Assume no CP in decays
  - 2 observables phases
  - φ_s - accessible through semileptonic decays
  - $ß_s$- accessible through $B^0_s \rightarrow J/\psi+X$ decays

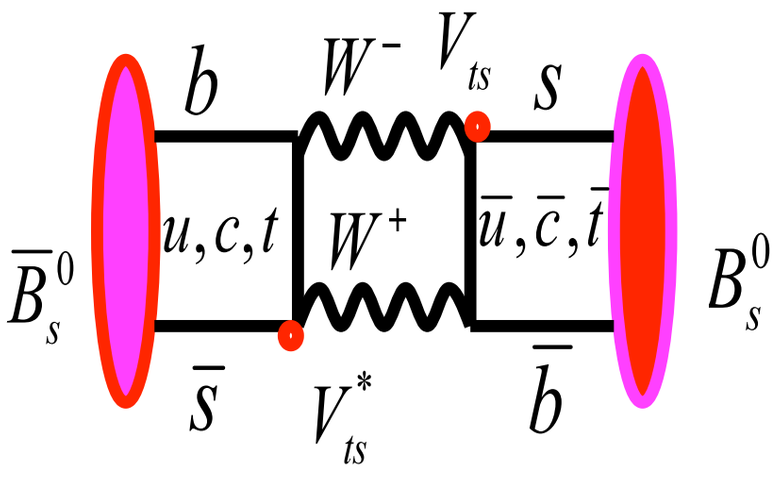


Interference between mixing and decay to a CP eigenstate

$$\Rightarrow \quad \Gamma\left(B^0_{phys}(t) \rightarrow f_{CP}\right) \neq \Gamma\left(\bar{B}^0_{phys}(t) \rightarrow f_{CP}\right)$$

$$\beta_s^{SM} = \arg\left[-V_{ts}V_{tb}^* / V_{cs}V_{cb}^*\right] = \lambda\eta^2 \approx 1^\circ \quad (\beta = 22^\circ)$$

$$\varphi_s = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right) = (4.2 \pm 1.3) \times 10^{-3}$$



- Contribution of new particles in the box diagrams may enhance both

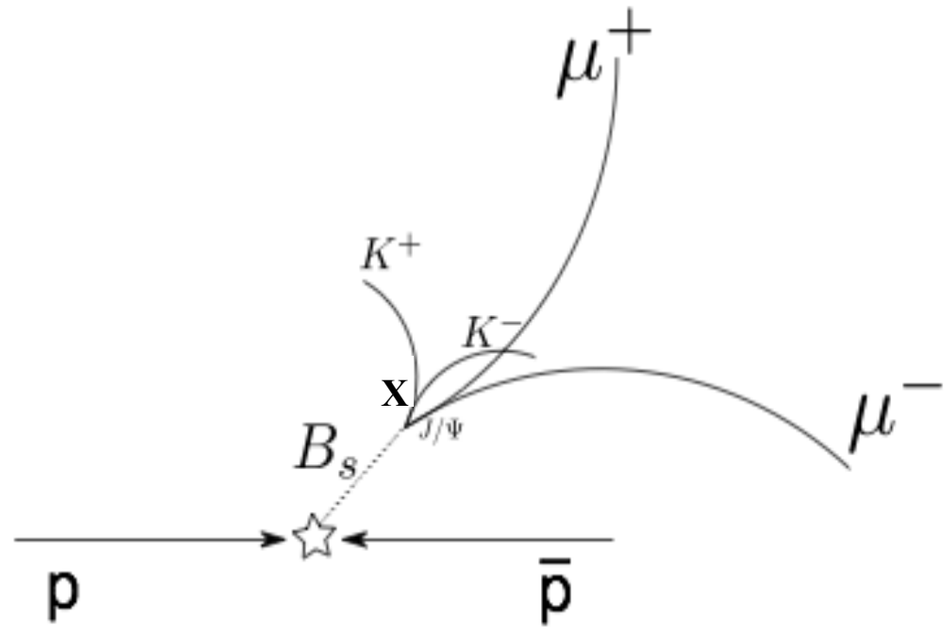
$2\beta_s = 2\beta^{SM}{}_s - \phi_s^{NP}$

$\phi_s = \phi^{SM}{}_s - \phi_s^{NP}$ with $\phi_s^{NP} >> \phi^{SM}{}_s, 2\beta^{SM}{}_s$

$-2\beta_s \sim \phi_s \sim \phi_s^{NP}$

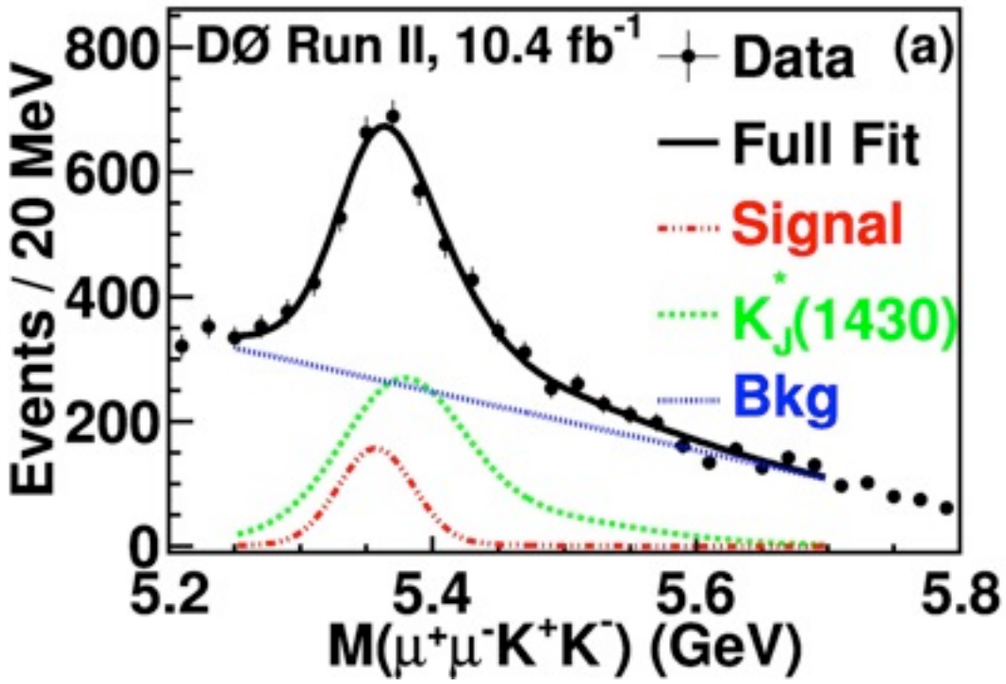
CP Violation in $B^0_s \rightarrow J/\psi + X$

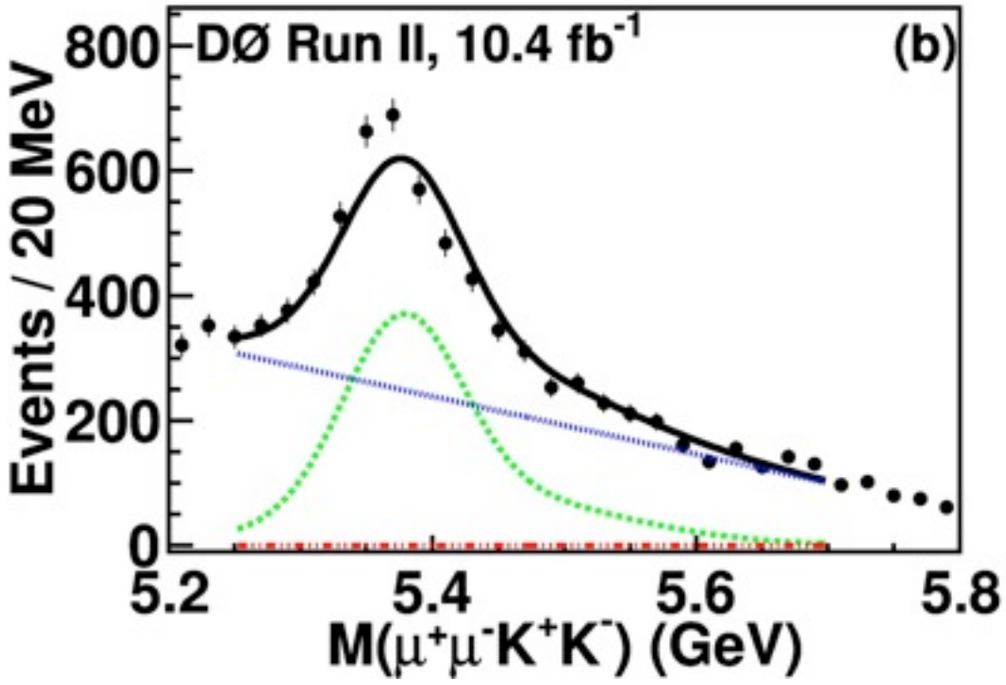
- Study $B^0_s \rightarrow J/\psi + X$ decays
- X may be a (non)resonant final state and affect the CP measurements
  - For example S-wave contributions
- $X=\varphi(K^+K^-)$ golden mode, used to measure CP-violating phase
- Study additional channels
- $X=f_0(980)(\pi^+\pi^-)$ also used to measure CP-violating phase
  - S. Stone and L. Zhang, Phys. Rev. D 79, 074024 (2009)
  - LHCb Phys. Lett. B698,115 (2011)
- Analysis of decay $B^0_s \rightarrow J/\psi K^+K^-$ for $1.35<M(K^+K^-)<2.0$
  - Measurement of branching ratio and study of spin have been performed for the resonant decay
  - LHCb: Phys. Rev. Lett. 108, 151801 (2012)



$B^0_s \rightarrow J/\psi + K^+K^-$ Selection

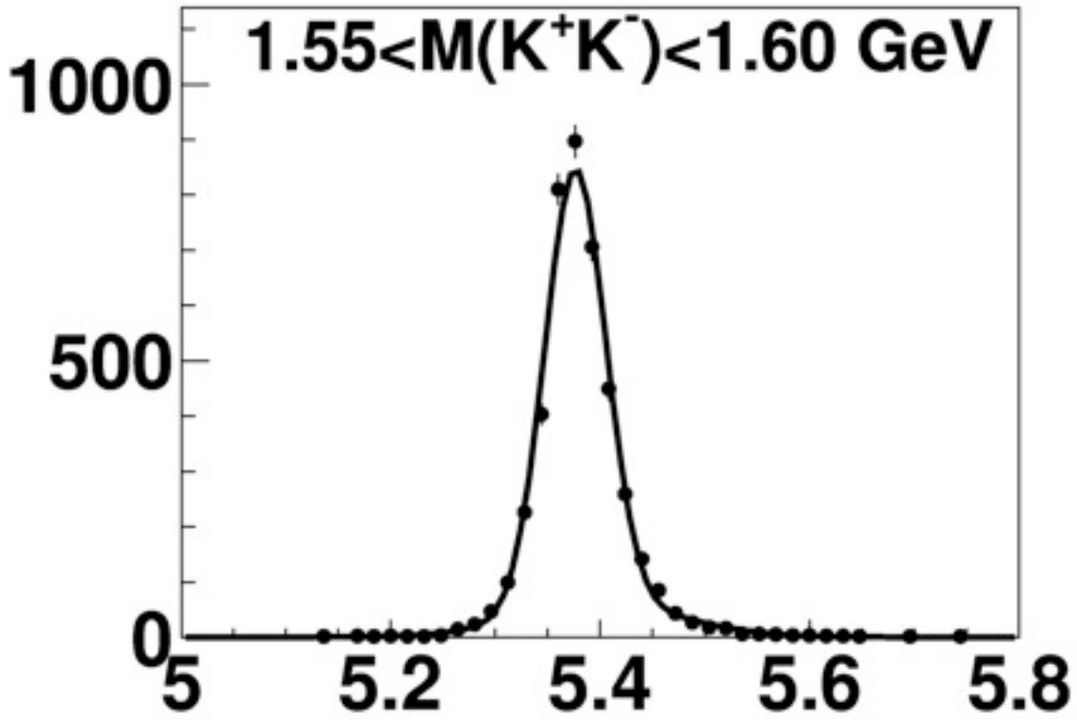
- Study $B^0_s \rightarrow J/\psi + K^+K^-$ decays
  - For each J/ψ candidate find K^+K^- pair with common vertex
    - assign kaon mass
    - require $m(K^+K^-) > 1.35$ GeV
    - Reconstruct B^0_s candidate by forming a vertex for J/ψ and K^+K^- pair
- Enhance signal by requiring $1.45 < m(K+K-) < 1.60$ GeV and $|\cos\psi| < 0.8$ (see later)
- Signal + Background model fit yields 578 ± 100 events with fit probability 0.338
- Background only fit probability 4.5×10^{-5}

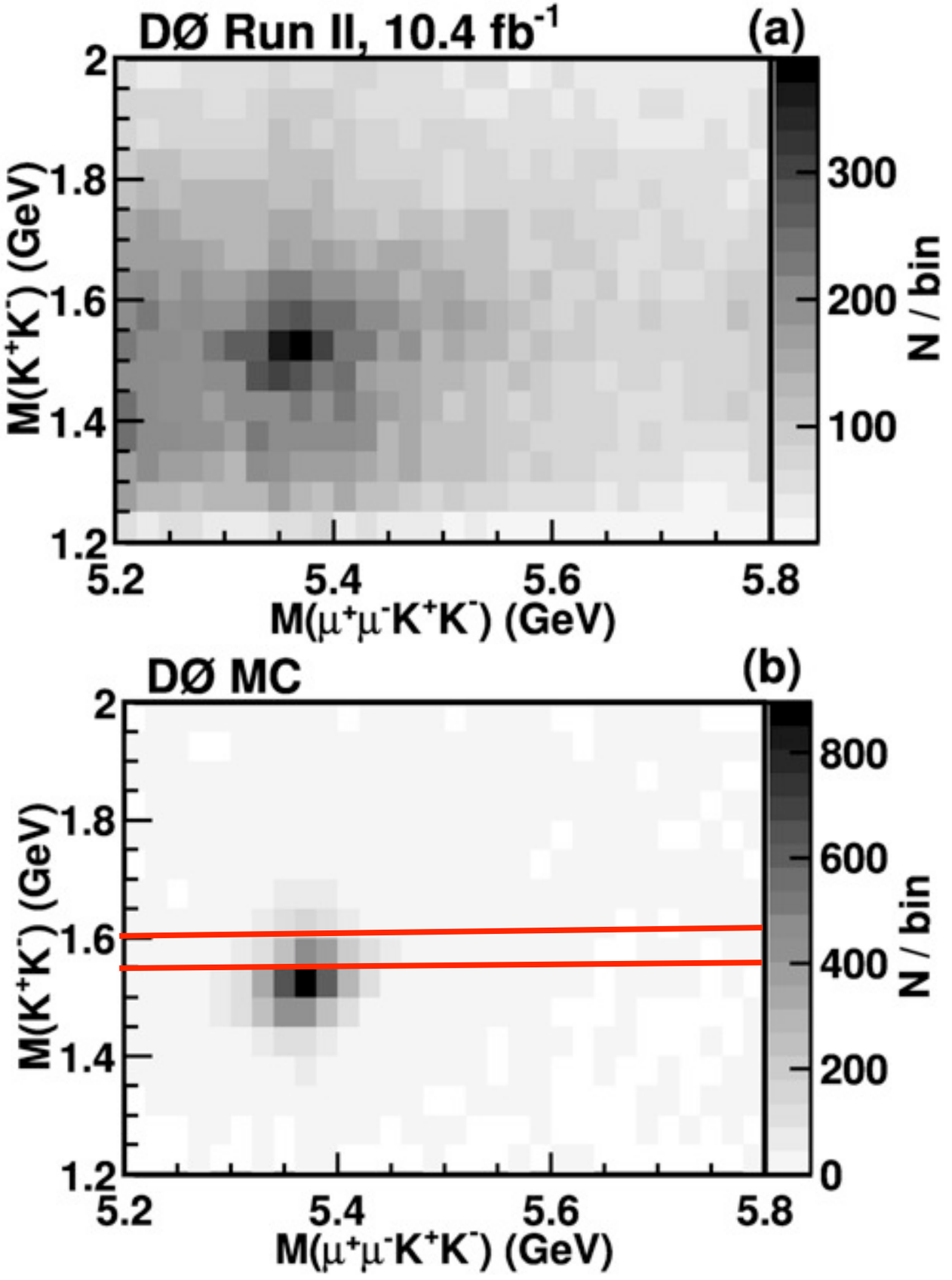




$J/\psi K^+K^-$ Sample Composition

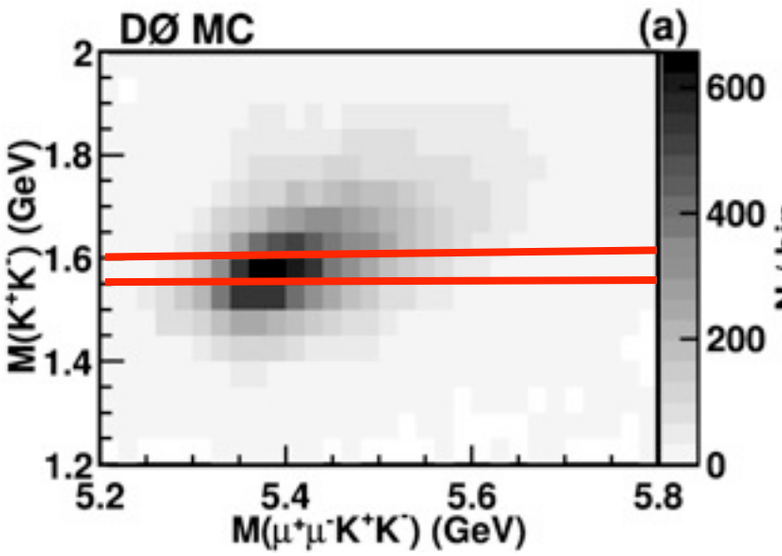
- Decays attributed to $f'_2(1525)$
  - PDG mass 1525±5 MeV, width 73^{+6}_{-5} MeV
  - BR to KK: 89%, ππ: 1%
- Other possible contributions due $f_2(1270)$
  - BR to 2π/4π: 87.6%, KK: 4.6%
- $f_0(1500)$
  - BR to 2π/4π: 85%, KK: 8%
- No peak observed under $J/\psi\pi^+\pi^-$ hypothesis
- Additional contribution possible due to $B^0 \rightarrow J/\psi K^*_J(1430)(\rightarrow K\pi)$

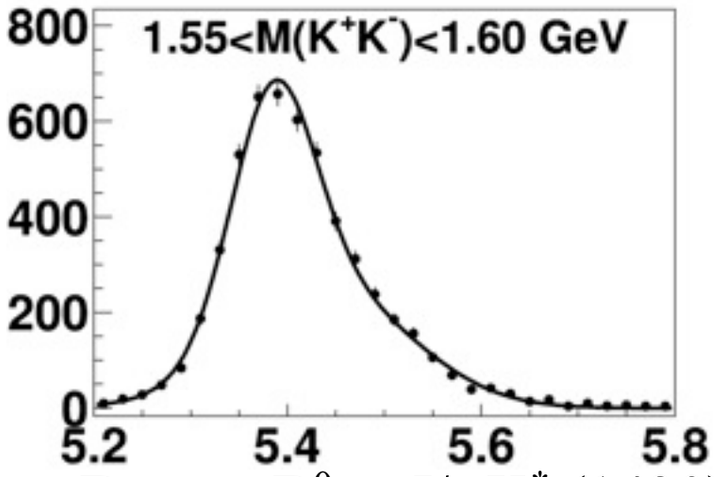




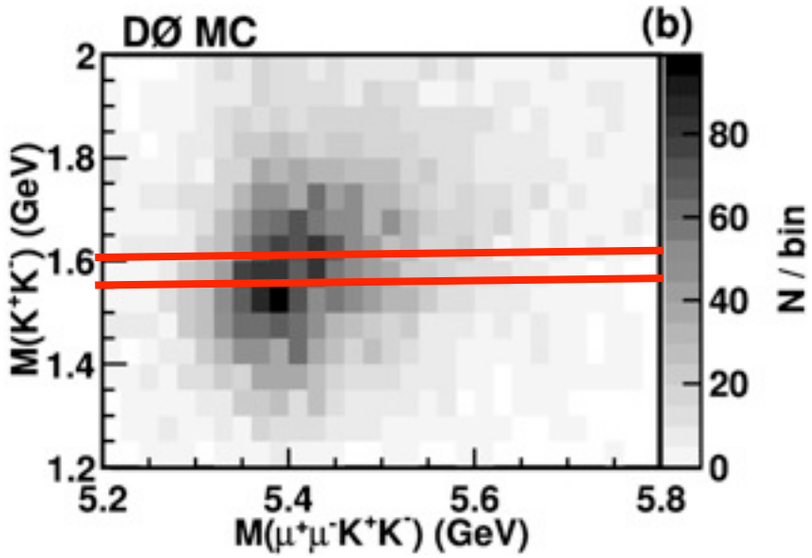
Peaking Backgrounds

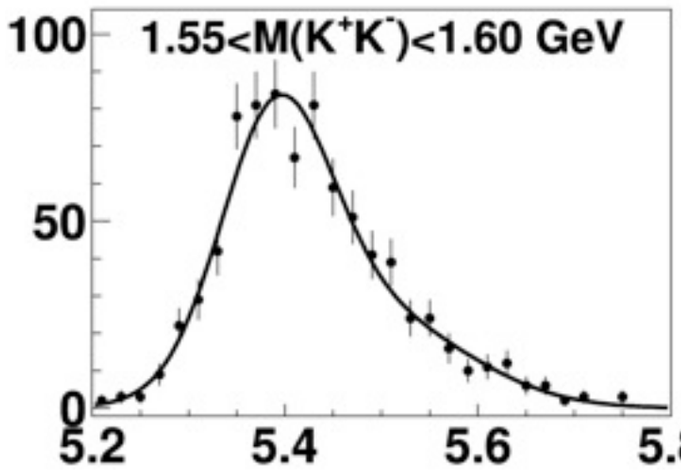
$B^0 \rightarrow J/\psi K^*_2(1430)$



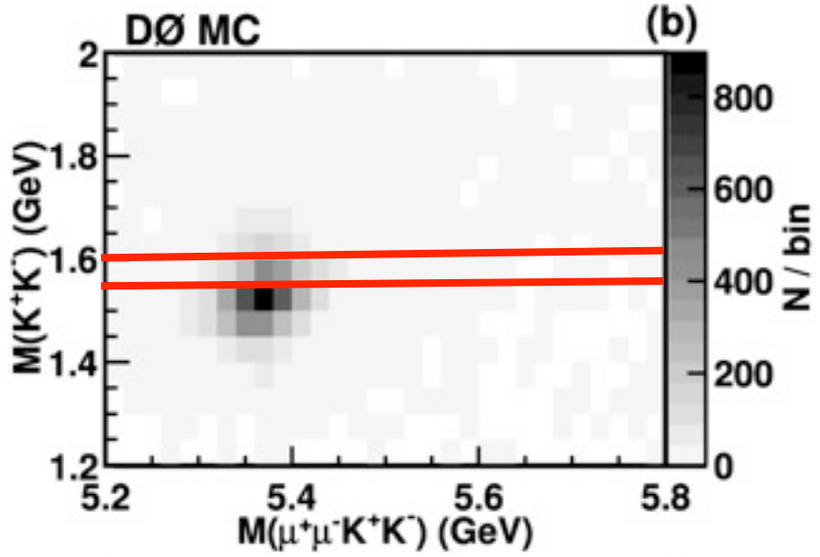


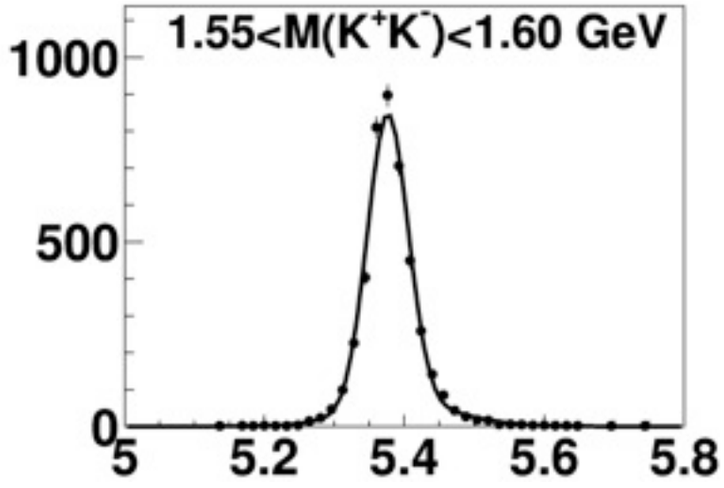
$B^0 \rightarrow J/\psi K^*_0(1430)$





Signal

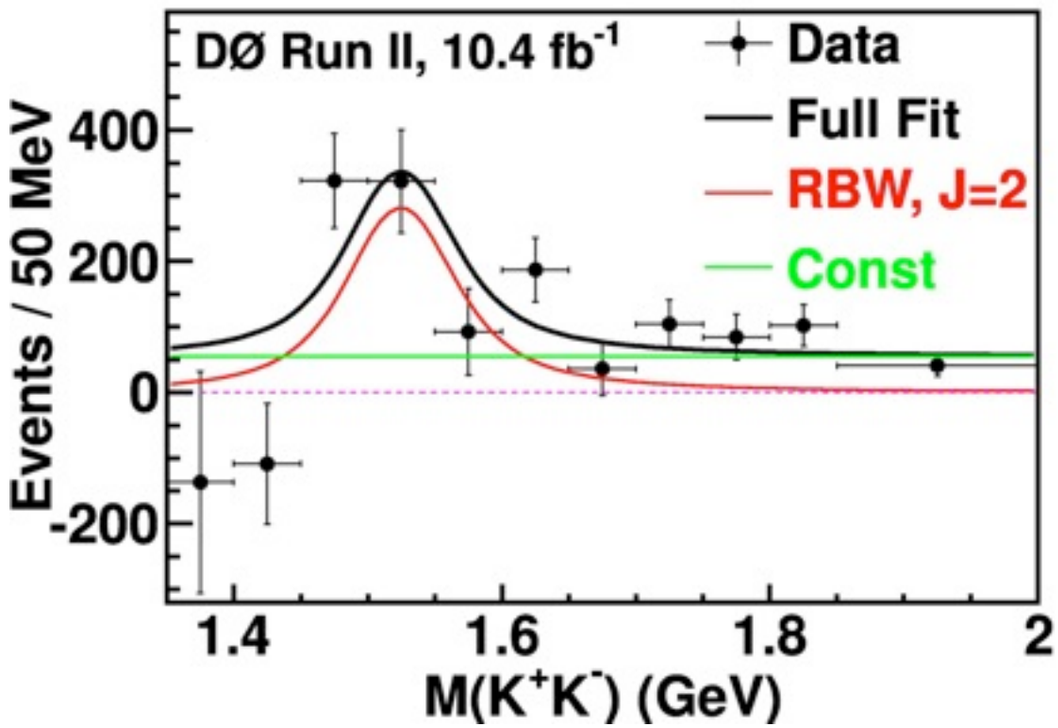


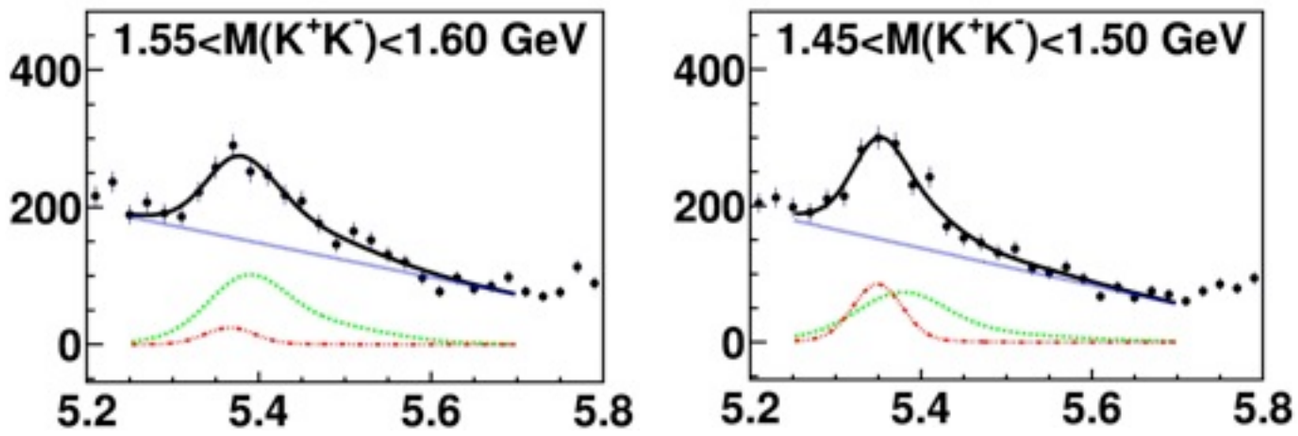


- Decays $B^0 \rightarrow J/\psi K^*_J(1430)(\rightarrow K\pi)$ contribute to the signal due to π misidentification as K
- Contribution estimated in the fit using templates of $B^0 \rightarrow J/\psi K^*_J$ in steps of $m(K^+K^-)$ of 50 MeV from MC
  - Signal and background templates are fitted with double Gaussian
  - Extract B^0_s yield as a function of $m(K^+K^-)$

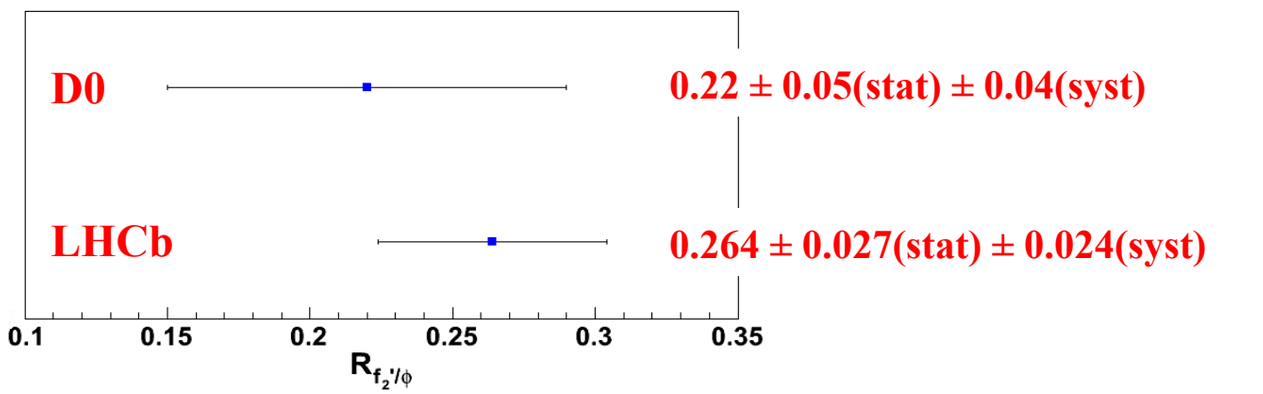
$J/\psi K^+K^-$ Signal Yield

- Extract signal in 50 MeV bin of $m(K^+K^-)$
- Relative normalization of two K*J(1430) states are allowed to vary
  - Normalization of Signal and all background are not constrained to be positive for unbiased rates close to zero
- Event yield versus $m(K^+K^-)$ distributions is fitted with signal (convoluted with Relativistic Breit-Wigner(J=2)) and a constant non-resonant term assumed to be S-wave
  - Signal: 669 ± 158
  - S-wave (in $m(K^+K^-)$ 1.4 to 1.7 GeV): 331 ± 73
  - Measure BR relative to $B^0 \rightarrow J/\psi\varphi$:





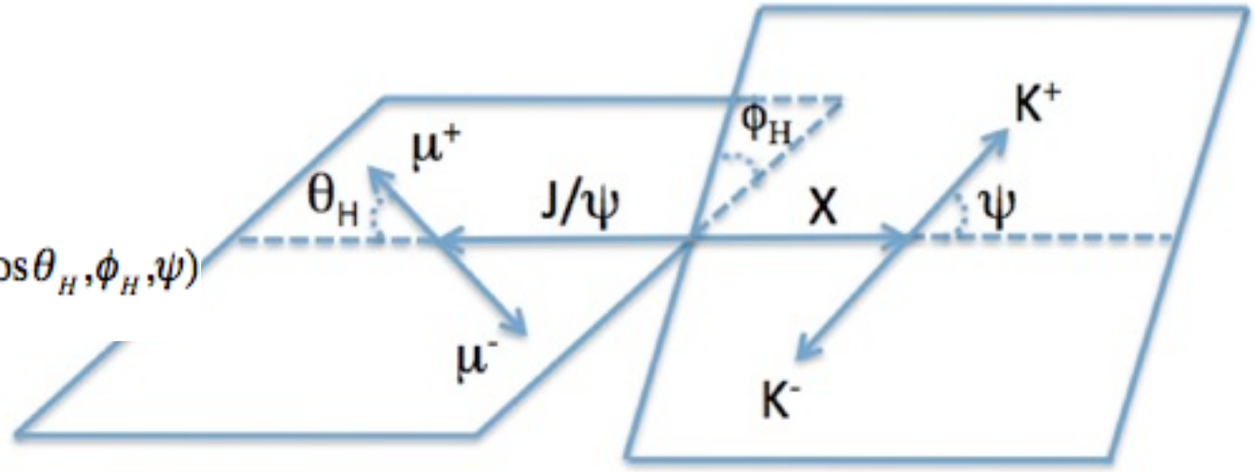
$$R_{f_2'/\phi} = \frac{\mathcal{B}(B_s^0 \to J/\psi f_2'(1525); f_2'(1525) \to K^+K^-)}{\mathcal{B}(B_s^0 \to J/\psi\phi; \phi \to K^+K^-)} = \frac{N_{B_s^0 \to J/\psi f_2'(1525)} \times \varepsilon_{\rm reco}^{B_s^0 \to J/\psi\phi}}{N_{B_s^0 \to J/\psi\phi} \times \varepsilon_{\rm reco}^{B_s^0 \to J/\psi f_2'(1525)}}$$



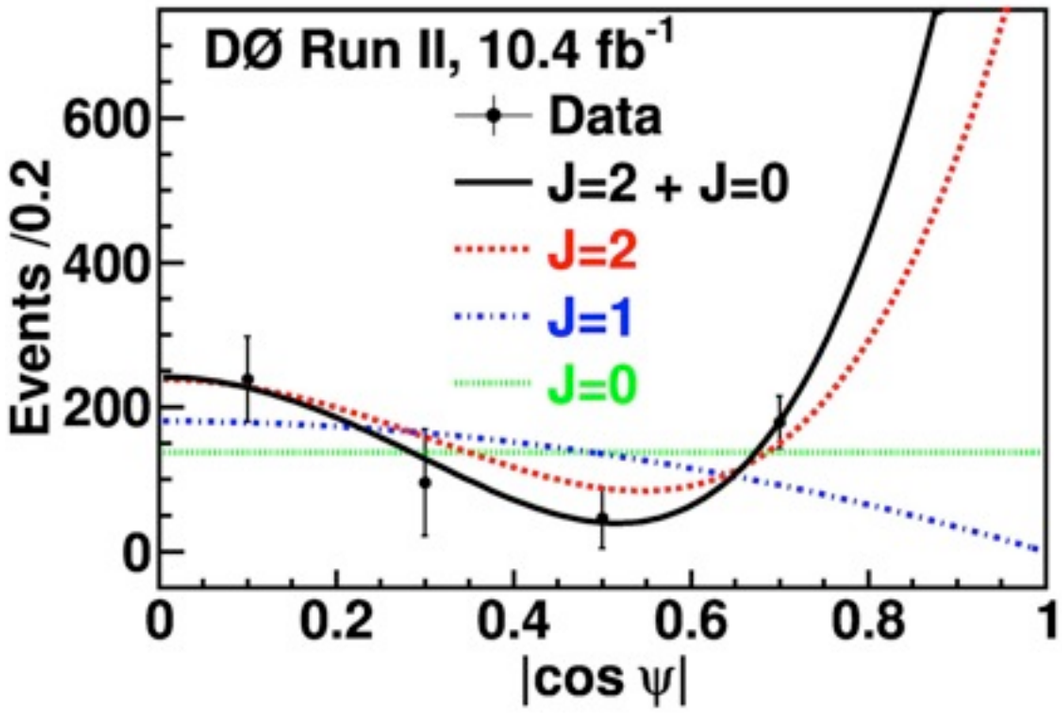
Spin Study

- Study spin configuration $J=0^+,1^-,2^+$
- Decay amplitude is given by:

$$\frac{d\Gamma}{d\cos\theta\, d\phi\, d\cos\psi} \propto \left|\sum_m A_m Y_1^m(\cos\theta_H,\phi_H) Y_J^{-m}(\cos\psi,0)\right|^2 D(\cos\theta_H,\phi_H,\psi)$$

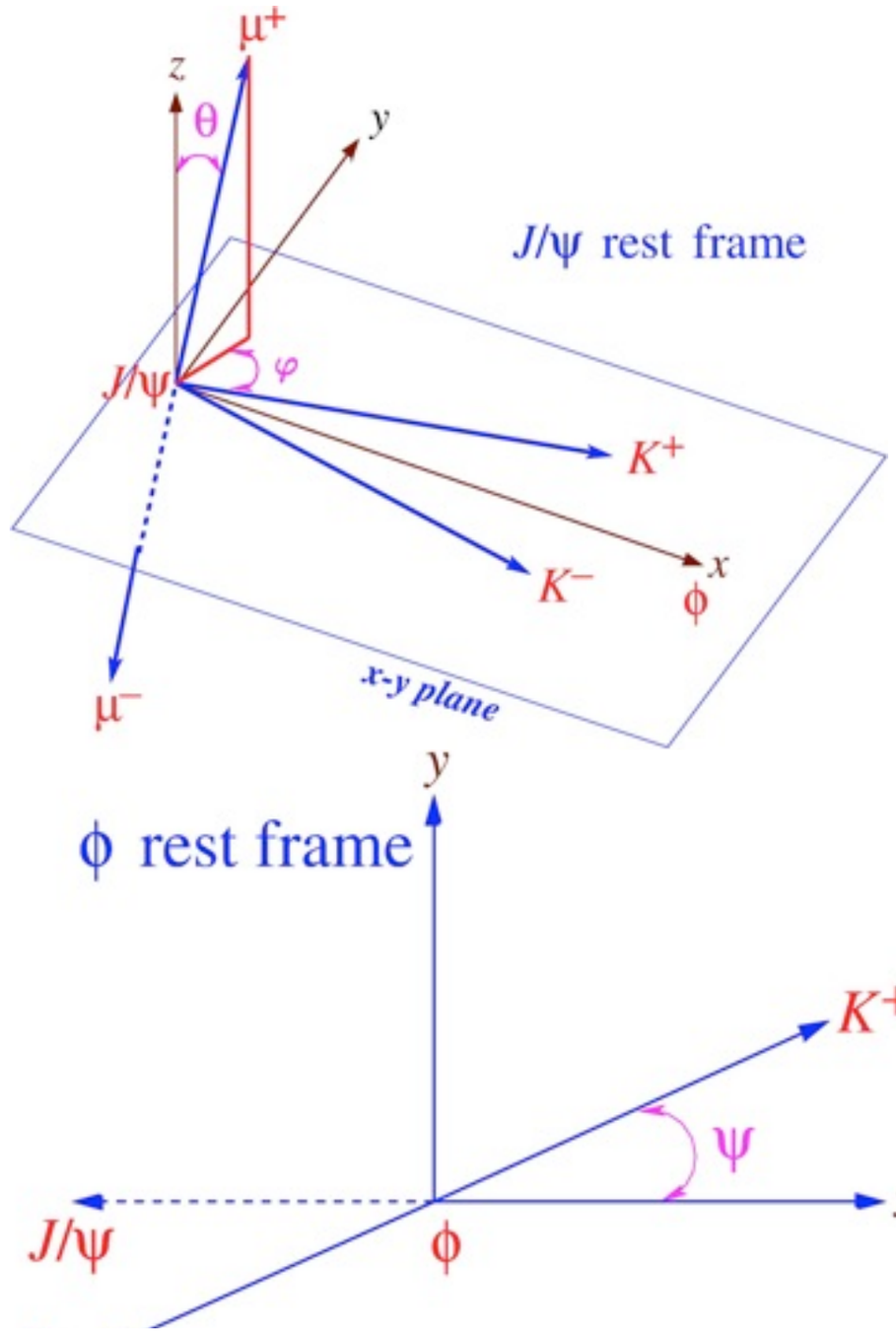


- θ, φ and ψ are angles in helicity basis and sum extends over equal helicities m of the J/ψ and the spin J of (K^+K^-) system
- D is acceptance for event reconstruction
- Decay amplitude is obtained in helicity angle ψ, integrate out other two angles
- D0 data favor spin=2
- D0 data also accommodate a fit of coherent superposition of J=0 and J=2,with S-wave fraction 0.17+-0.14
- Submitted to Phys. Rev. D



$\varphi^{J/\Psi\varphi}{}_s$ and $\Delta\Gamma_s$ in $B^0{}_s \rightarrow J/\Psi\varphi$

- Measure $\varphi^{J/\Psi\varphi}{}_s(\beta_s)$ and $\Delta\Gamma_s$ by studying time evolution of flavor tagged Bs→J/$\Psi(\mu^+\mu^-\varphi(K^+K^-))$decays
  - Pseudoscalar→Vector Vector
  - 3 possible angular momentum states
- The mass eigenstates are expected to be almost pure CP-eigenstates
  - **S,D** (CP even): linear combination of A0, A||
  - **P** (CP odd): A⊥



$$\Gamma(t) \approx \left|A_{even}(\theta,\psi,\varphi,t)\right|^2 + \left|A_{odd}(\theta,\psi,\varphi,t)\right|^2$$

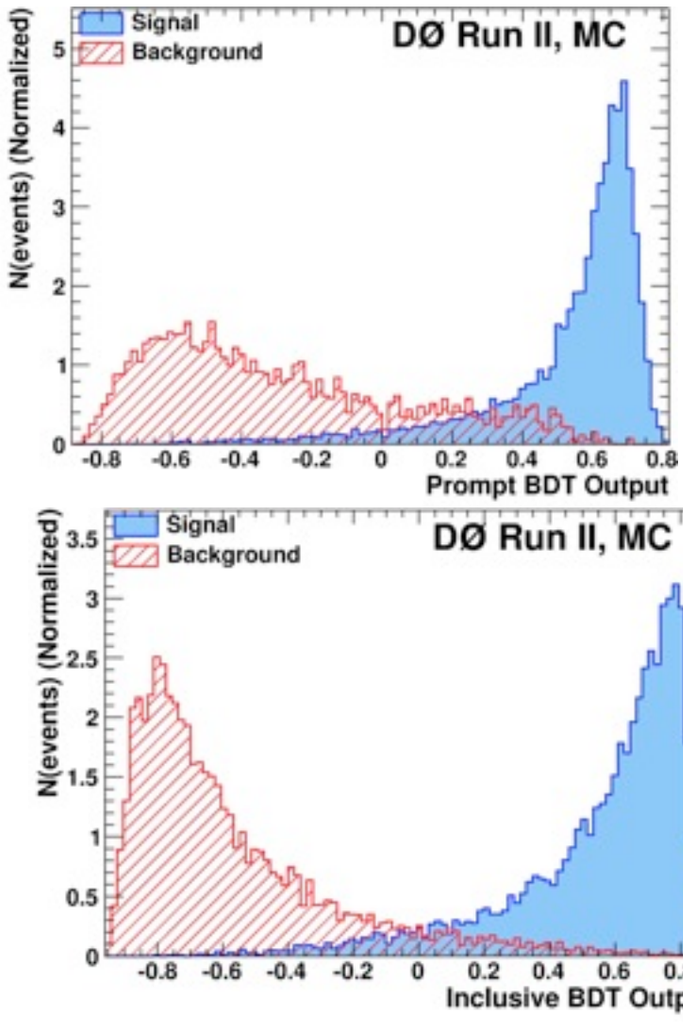
$$+A^* A(CPC)$$ CP-conserving interference

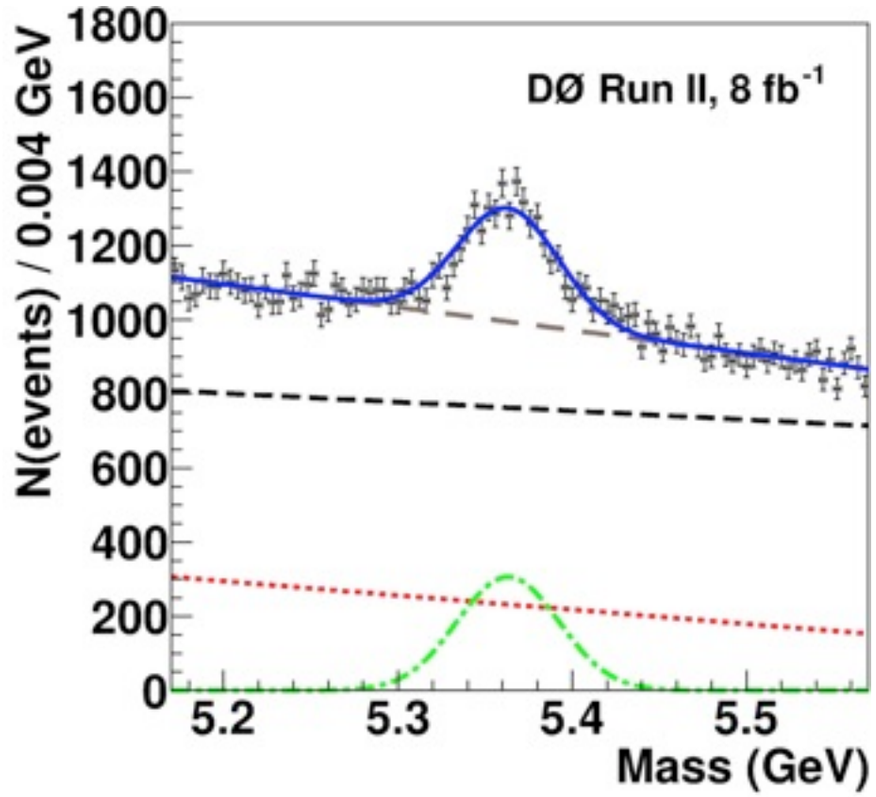
$$+A^* A(CPV)(e^{-\Gamma_L t} - e^{-\Gamma_H t})\sin\phi_s^{J/\psi\varphi}$$ CP-violating interference

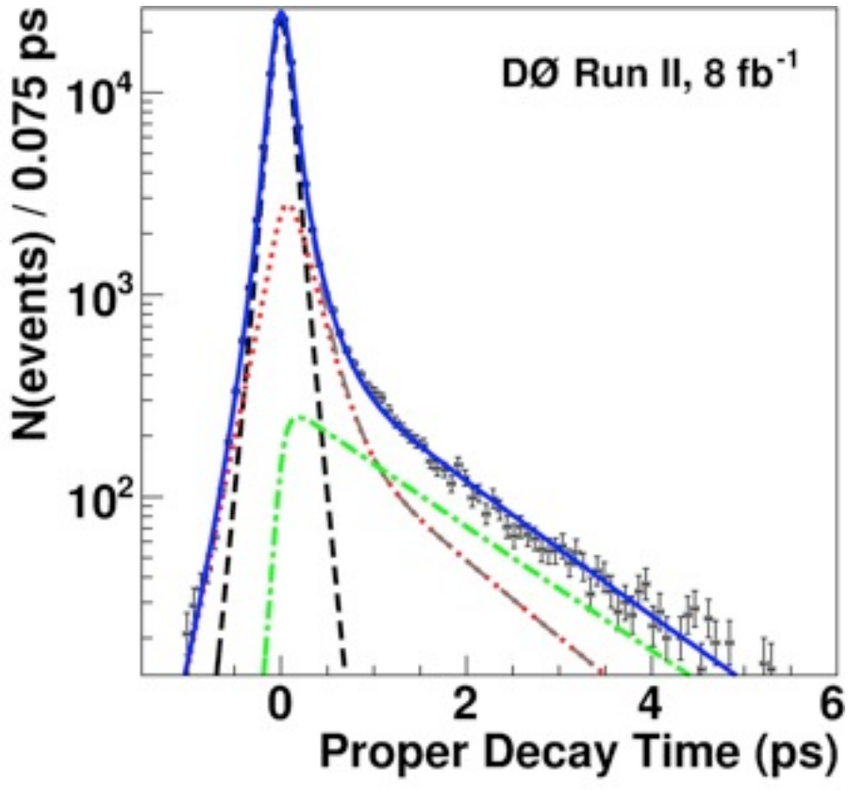
$B^0_s \rightarrow J/\psi\varphi$ Event Selection

- $B^0_s \rightarrow J/\psi\varphi$ selection criteria are designed to minimize measurement uncertainties on $\varphi^{J/\psi\varphi}_s$ and $\Delta\Gamma_s$

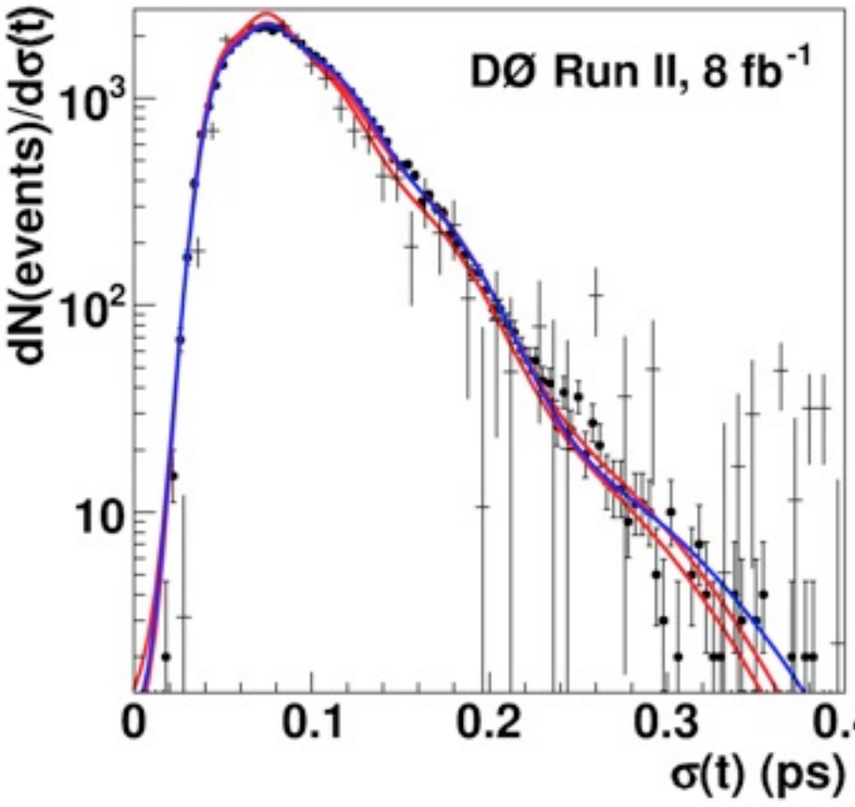
- Based on Boosted Decision Tree multivariate technique
- Square cuts as a cross check and systematics

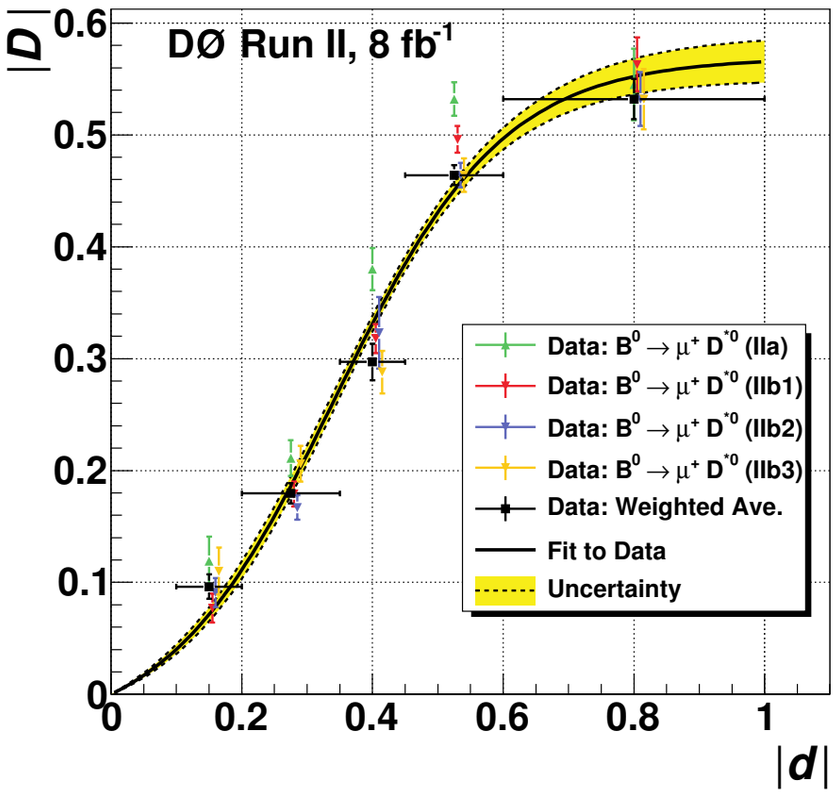


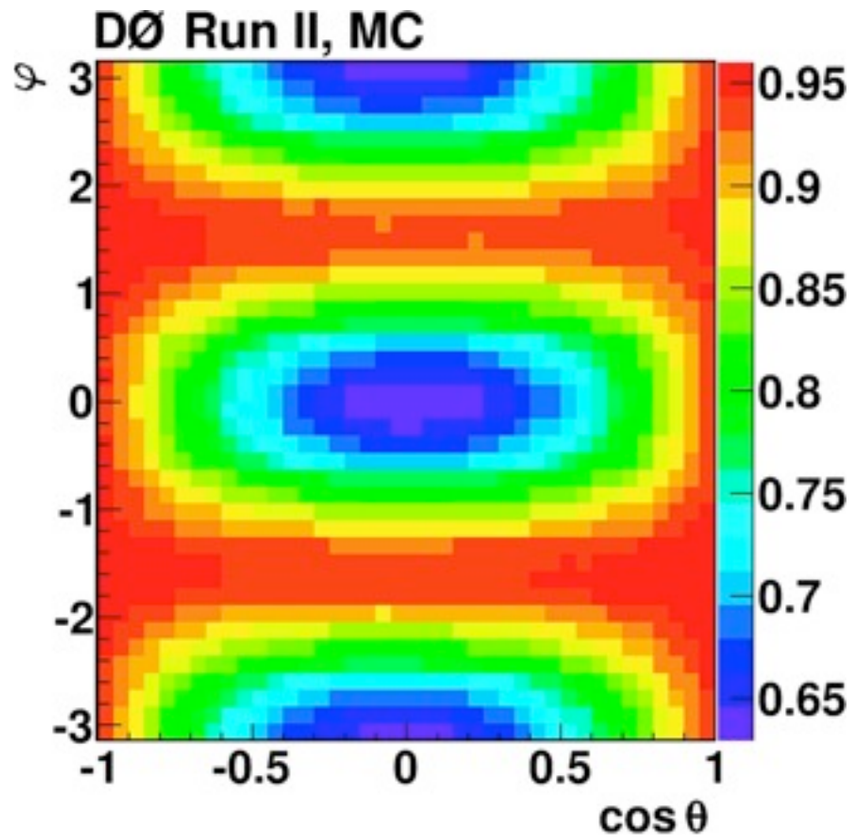




Resolution, Flavor Tagging, Acceptance







- Use event-by-event resolution
  - Approximated as sum of several Gaussians
  - Variation for systematics

- Use combined OST
  - Muon
  - Electron
  - Jet vertex charge
  - Dilution calibrated using B^0_d decays

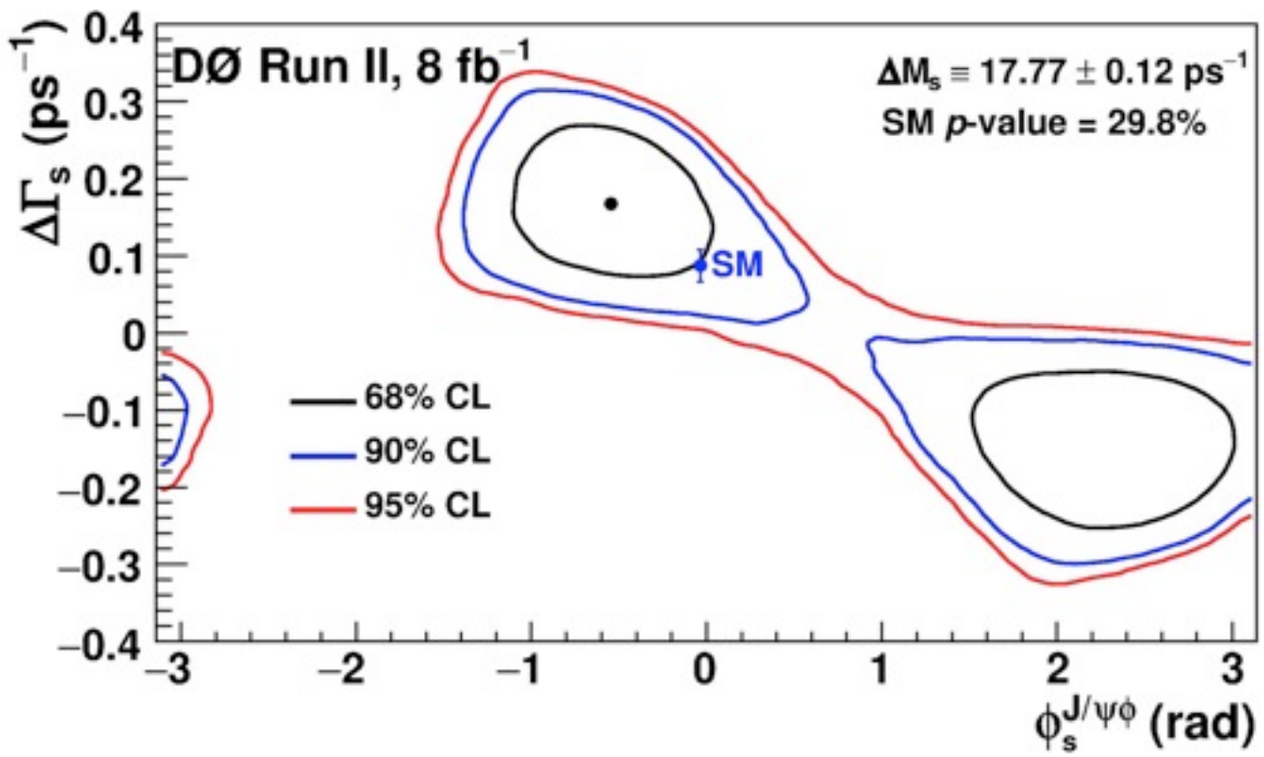
- Correct for acceptance 2D acceptance in cos(θ),φ
- Data selection criteria applied to MC generated uniform in all angles

$\varphi^{J/\Psi\varphi_s}$ and $\Delta\Gamma_s$ Fit Results

- Use Markov chain technique to draw contours in $\Delta\Gamma_s$ vs $\varphi^{J/\Psi\varphi_s}$ parameter space
- Sample randomly likelihood using Metropolis-Hasting algorithm
- Use sampled likelihood to obtain contours and combine systematic uncertainties
  - Combine BDT and cut based results

Phys. Rev. D **85**, 032006 (2012)

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
$(\delta_\perp\text{-}\delta_s)$	$-0.11^{+0.027}_{-0.025}$
$F_S(eff)$	0.173 ± 0.036



Additional Channels for ß$_s$ Measurements

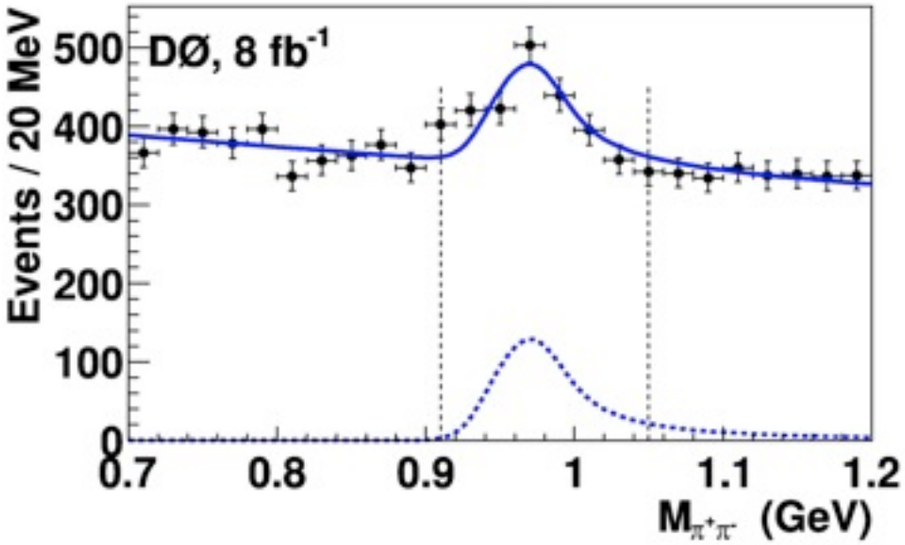
- *J*/ψf_0(980) final state corresponds to a *CP*-odd eigenstate of B^0_s
  - Could be used in studies of *CP* violation

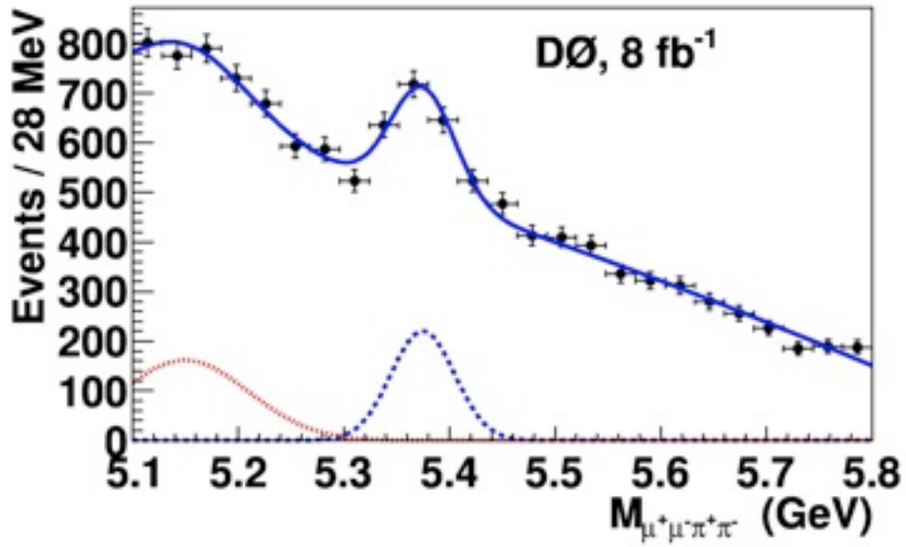
$$R_{f_0/\phi} = \frac{N_{B_s^0 \to J/\psi f_0(980)}}{N_{B_s^0 \to J/\psi \phi}} \cdot \frac{\varepsilon_{\rm reco}^{B_s^0 \to J/\psi \phi}}{\varepsilon_{\rm reco}^{B_s^0 \to J/\psi f_0(980)}}$$

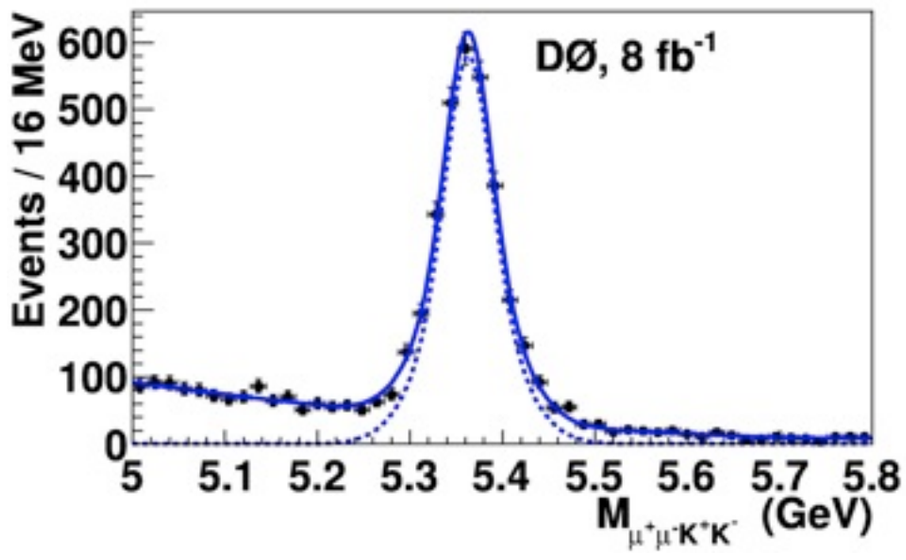
- Use BDT selection
- Normalize to $B^0_s \to J/\psi\varphi$

Phys. Rev. D **85**, 011103 (2012)

$$R_{f_0/\phi} = 0.275 \pm 0.041\,(\text{stat}) \pm 0.061\,(\text{syst})$$



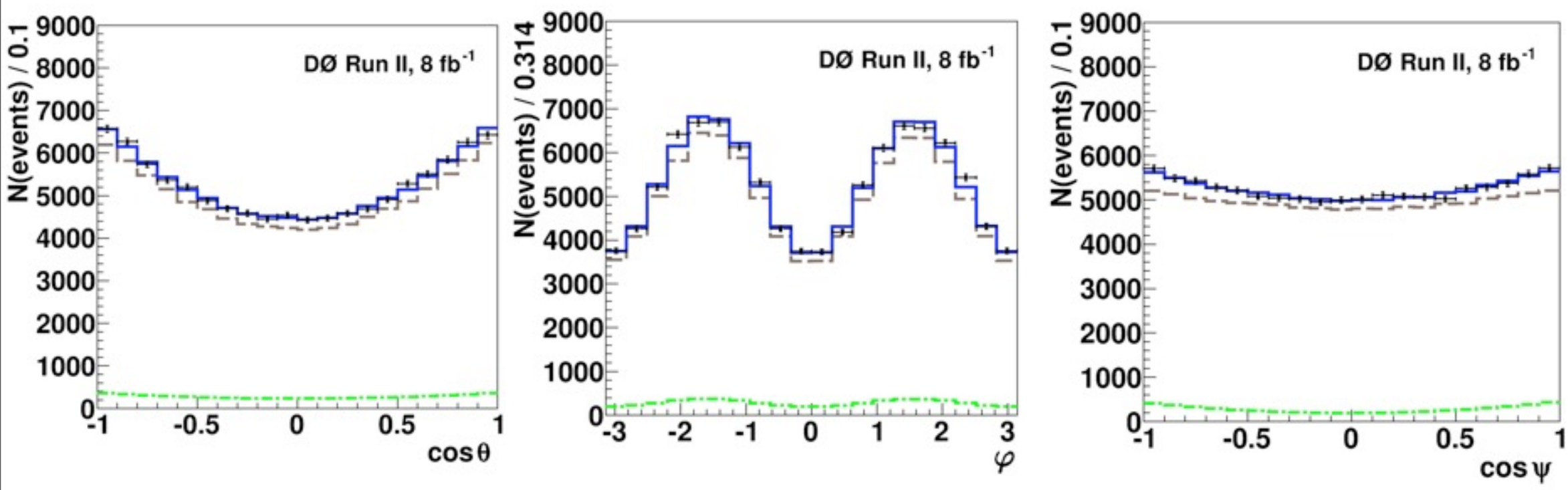




Summary

- Mature experiment still producing exciting results
  - Sizeable B^0_s sample has been accumulated
  - Almost full 10 fb-1 data sample analyzed
  - Adding new channels
  - Measured relative branching fraction of $B^0_s \rightarrow J/\psi f'_2(1525)$ to $B^0_s \rightarrow J/\psi\varphi$ and spin of the K^+K^- system
    - Consistent with J=2 or superposition of J=0,2 states
- Measured of B^0_s mixing parameters, polarization amplitudes and phases in the $B^0_s \rightarrow J/\psi\varphi$ decay channel using 8 fb^{-1} data sample
- Measured relative branching fraction of $B^0_s \rightarrow J/\psi f_0(1525)$ to $B^0_s \rightarrow J/\psi\varphi$
- Plan to use for phase measurement with full dataset

BACKUP


DØ Run II, 8 fb-1
N(events) / 0.1
cos θ
DØ Run II, 8 fb-1
N(events) / 0.314
φ
DØ Run II, 8 fb-1
N(events) / 0.1
cos ψ