CP Violation Studies in the B_s^0 System at D0

Fermilab Joint Experimental-Theoretical Seminar,
Thursday 20 October 2011

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Today's Topics

1) CP violation study of the decay $B_s^0 \to J/\psi\phi$

Submitted to PRD
Sep 14th 2011
arXiv: 1109.3166

Measurement of the CP-violating phase $\phi_s^{J/\psi\phi}$ using the flavor-tagged decay $B_s^0 \to J/\psi\phi$ in 8 fb^{-1} of $p\overline{p}$ collisions

We report an updated measurement of the CP-violating phase, $\phi_s^{J/\psi\phi}$, and the decay-width difference for the two mass eigenstates, $\Delta\Gamma_s$, from the flavor-tagged decay $B_s^0 \to J/\psi\phi$. The data sample corresponds to an integrated luminosity of 8.0 fb^{-1} accumulated with the D0 detector using $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV produced at the Fermilab Tevatron collider. The 68% confidence level intervals, including systematic uncertainties, are $\Delta\Gamma_s = 0.163^{+0.065}_{-0.064}$ ps^{-1} and $\phi_s^{J/\psi\phi} = -0.55^{+0.38}_{-0.36}$. The p-value for the Standard Model point is 29.8%.

2) Branching ratio measurement of the decay $B_s^0 \to J/\psi f_0$

Submitted to PRD
(today!)

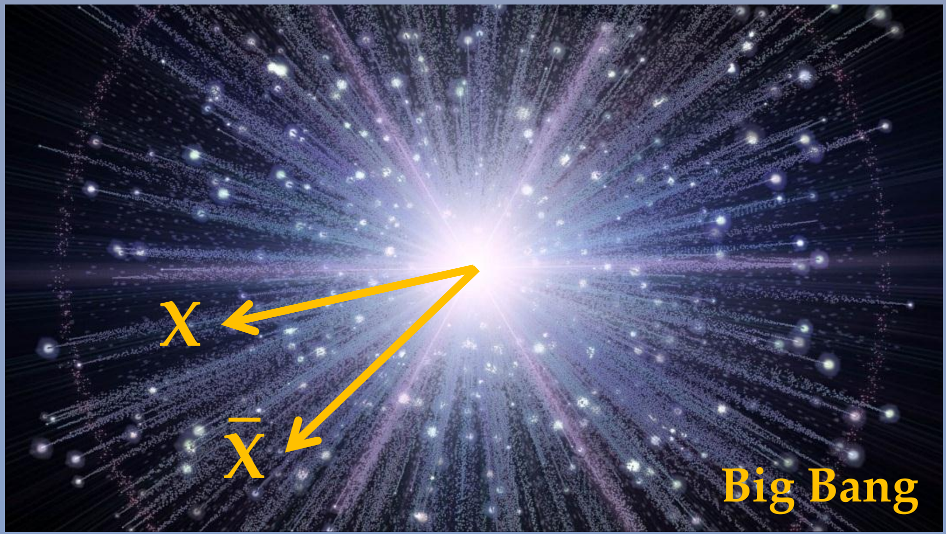
Measurement of the relative branching ratio of $B_s^0 \to J/\psi f_0(980)$ to $B_s^0 \to J/\psi\phi$

We present a measurement of the relative branching fraction, $R_{f_0/\phi}$, of $B_s^0 \to J/\psi f_0(980)$, with $f_0(980) \to \pi^+\pi^-$, to the process $B_s^0 \to J/\psi\phi$, with $\phi \to K^+K^-$. The $J/\psi f_0(980)$ final state corresponds to a CP-odd eigenstate of B_s^0 that could be of interest in future studies of CP violation. Using approximately 8 fb^{-1} of data recorded with the D0 detector at the Fermilab Tevatron Collider, we find $R_{f_0/\phi} = 0.275 \pm 0.041$ (stat) ± 0.061 (syst).

CP Violation: What, Why, How?

During the big-bang, matter and antimatter were produced in equal quantities;

We now observe a matter-dominated universe – what happened to the antimatter?



~10^{10} years later…

Theories of baryogenesis can address this asymmetry, but they require several ingredients, one of which is **CP violation (CPV)**.

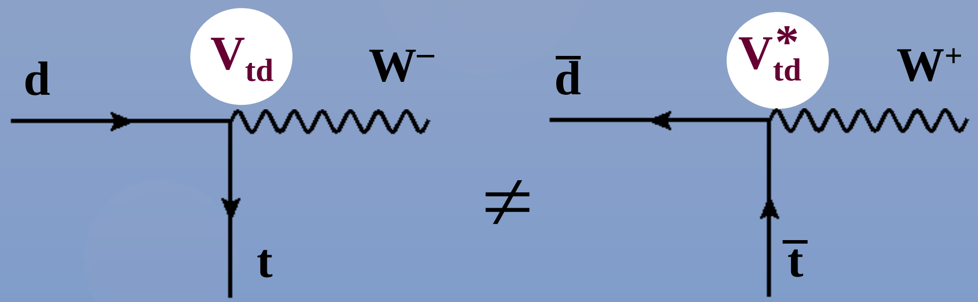
CP: Fundamental symmetry in which antiparticles behave exactly like particles in a mirror.

CP Violation in the Standard Model

Weak interactions governed by mixing matrices (neutrino, quark) – which have complex phases: $\mathbf{V_{ij} \neq V_{ij}^{*}}$

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

CKM phase means quark and antiquark couplings can be different: CP Violation.



Degree of CPV in the Standard Model is **far too small** to account for observed matter-antimatter asymmetry.

New physics models can significantly enhance size of CP violating phases.

Searches for anomalous CPV are a sensitive probe of possible physics beyond the SM

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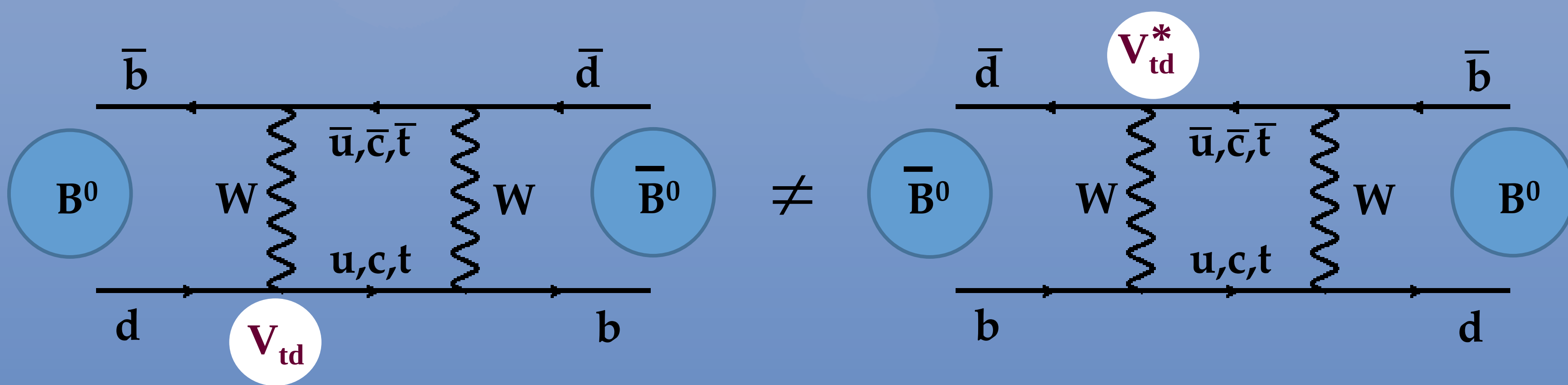
One consequence: rates for B meson mixing different for charge conjugate process: $\mathbf{\Gamma(B\to\bar{B}) \neq \Gamma(\bar{B}\to B)}$.



Interesting phenomena to study – can help us understand CPV in SM and beyond.

Neutral B Meson Mixing

Flavor eigenstates of B mesons (B_s^0, $\bar{B}_s^0$) differ from the **mass** eigenstates (B_{sH}, B_{sL}).

⇒ Neutral B mesons oscillate between flavor eigenstates as they evolve:

$$i\frac{d}{dt}\begin{pmatrix} |B_s^0\rangle \\ |\bar{B}_s^0\rangle \end{pmatrix} = \begin{pmatrix} M - \frac{i\Gamma}{2} & M_{12} - \frac{i\Gamma_{12}}{2} \\ M_{12}^* - \frac{i\Gamma_{12}^*}{2} & M - \frac{i\Gamma}{2} \end{pmatrix} \begin{pmatrix} |B_s^0\rangle \\ |\bar{B}_s^0\rangle \end{pmatrix}$$

Schrödinger equation

Mixing arises from non-zero off-diagonal elements – i.e **driven by Γ_{12} and M_{12}**.

Access these elements via experimental observables:

$\Delta M_s = M_{sH} - M_{sL} \approx 2|M_{12}|$

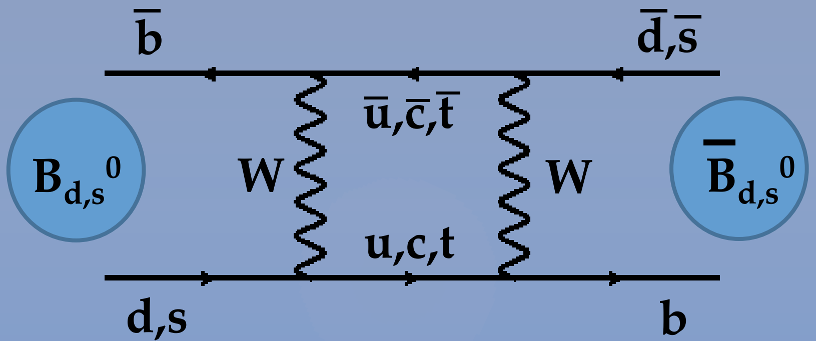
Sets oscillation frequency:
17.77 ± 0.12 ps^{-1} (CDF)
17.63 ± 0.11 ps^{-1} (LHCb)

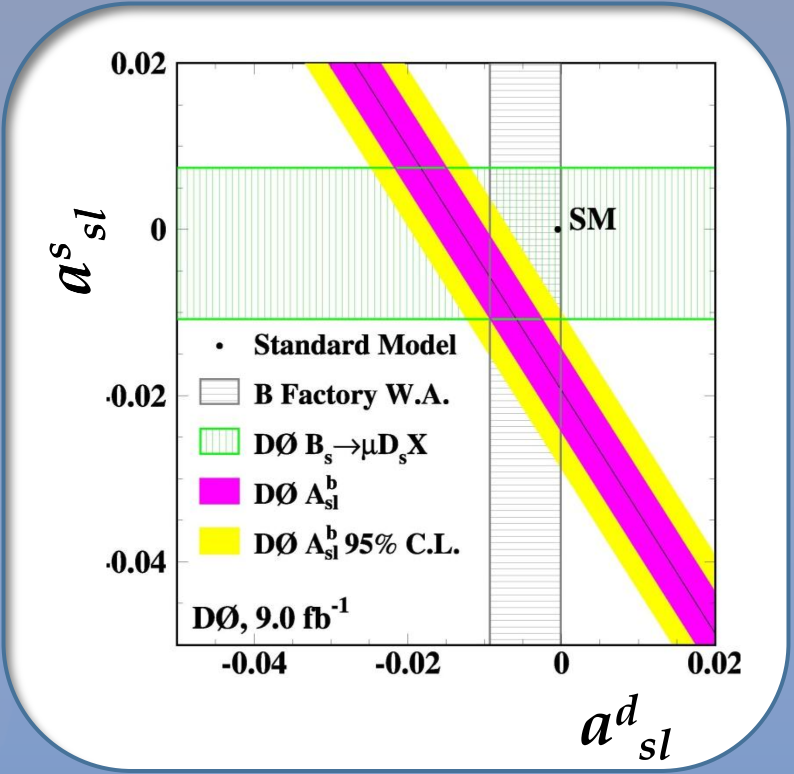
$\Delta\Gamma_s = \Gamma_{sL} - \Gamma_{sH} \approx 2|\Gamma_{12}| \cdot \cos\{\arg[-M_{12}/\Gamma_{12}]\}$

Sets lifetime difference
0.09 ± 0.02 ps^{-1} (SM prediction)
0.12 ± 0.06 ps^{-1} (World Average)

CPV in Mixing

Mixing via box diagrams – pick up phase from the CKM matrix:





$\varphi_s = \arg(-M_{12}/\Gamma_{12}) \approx 0.004$ (SM)

Recent dimuon asymmetry evidence from D0 can be interpreted as CPV in mixing:

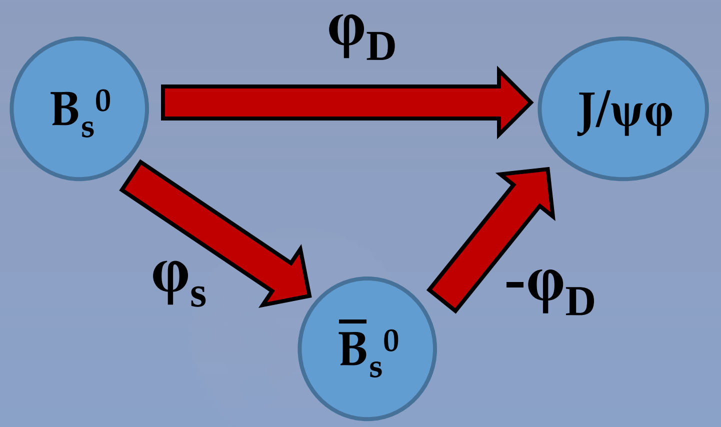
New particles in box diagrams can enhance this phase significantly (H$^+$, t`, W`…).

$$a^s_{sl} = \frac{\Delta\Gamma_s}{\Delta M_s} \tan(\varphi_s)$$

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

Same final states available to B_s^0 and $\bar{B}_s^0$:

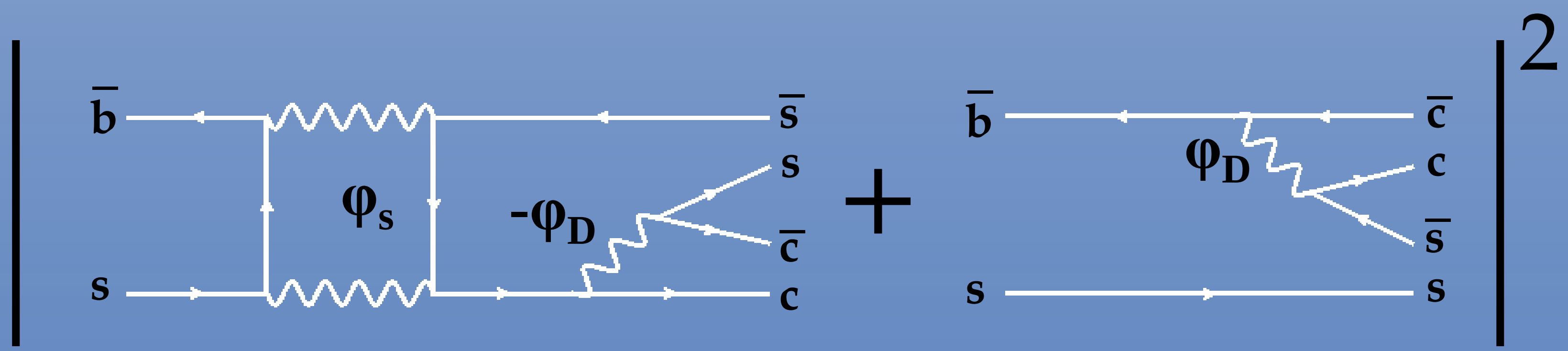
- Amplitudes interfere,
- Final CPV phase is combination of mixing (φ_s) and decay (φ_D) phases:



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

Enhancements to **mixing phase** will give same enhancement to $\varphi_s^{J/\psi\varphi}$.

Decay rate ~



Measuring CPV in Interference (1)

For a decay into a well-defined CP-eigenstate i, time-dependence of decay amplitude A_i

$$A_i^{B_s^0}(t) = N(\tau_s, \Delta\Gamma_s, \varphi_s^{J/\psi\varphi})\, e^{-\Gamma_s t/2}\left[e^{\left(\frac{-\Delta\Gamma_s}{4} + i\frac{\Delta M_s}{2}\right)t} + e^{-\left(\frac{-\Delta\Gamma_s}{4} + i\frac{\Delta M_s}{2}\right)t} \pm e^{-i\varphi_s^{J/\psi\varphi}}\left(e^{\left(\frac{-\Delta\Gamma_s}{4} + i\frac{\Delta M_s}{2}\right)t} - e^{-\left(\frac{-\Delta\Gamma_s}{4} + i\frac{\Delta M_s}{2}\right)t}\right)\right]$$

CP-even → $+$
CP-odd → $-$

Plus similar relation $\bar{A}(t)$ for $\bar{B}_s^0$

Decay rates:

$$\Gamma(B_s^0 \rightarrow J/\psi\varphi)(t) = |A_i(t)|^2$$

$$\Gamma(\bar{B}_s^0 \rightarrow J/\psi\varphi)(t) = |\bar{A}_i(t)|^2$$

4 parameters (τ_s, ΔM_s, $\Delta\Gamma_s$, $\varphi_s^{J/\psi\varphi}$)

Measuring CPV in Interference (2)

Final state can be in one of three angular momentum states, and:

$$CP|X\rangle = (-1)^L|X\rangle$$

Hence admixture of CP even and odd.

$B_s^0 \rightarrow J/\psi\ \varphi$

Pseudoscalar (spin 0)

Vector (spin 1)

Vector (spin 1)

$\uparrow\uparrow$: L=2, CP even, amplitude $A_{||}(t)$

$\uparrow\downarrow$: L=0, CP even, $A_0(t)$

$\uparrow\rightarrow$: L=1, CP odd, $A_\perp(t)$

Decay rates include contributions from all three polarizations:

$$\mathbf{\Gamma(B_s^0 \rightarrow J/\psi\varphi)(t) = |A_{||}(t) + A_0(t) + A_\perp(t)|^2}$$

8 parameters:

$\boldsymbol{\tau_s, \Delta M_s, \Delta\Gamma_s, \varphi_s^{J/\psi\varphi}}$,

2 relative phases: $\boldsymbol{\delta_\perp, \delta_{||}}$,

2 magnitudes at t=0: $\boldsymbol{A_0, A_{||}}$

Measuring CPV in Interference (3)

Also allow contribution from 'S-wave' decay to non-resonant K^+K^-.

Quantify by fractional contribution F_S, and relative phase δ_S.

$B_s^0 \rightarrow J/\psi\ K^+K^-$

Pseudoscalar (spin 0)

Vector (spin 1)

S-wave (spin 0)

L=1, CP odd

Decay rates now have four squared amplitudes, plus interference terms:

$$\boldsymbol{\Gamma(B_s^0 \rightarrow J/\psi\varphi)(t) = |A_{\parallel}(t) + A_0(t) + A_{\perp}(t) + A_S(t)|^2}$$

10 parameters:
$\boldsymbol{\tau_s, \Delta M_s, \Delta\Gamma_s, \varphi_s^{J/\psi\varphi}}$,
2 relative phases: $\boldsymbol{\delta_{\perp}, \delta_{\parallel}}$,
2 magnitudes at t=0: $\boldsymbol{A_0, A_{\parallel}}$
$\boldsymbol{F_S, \delta_S}$

Measuring CPV in Interference (4)

Initial states B_s^0 and $\overline{B}_s^0$ have different decay amplitudes.

Sensitivity to physical parameters improved by disentangling two initial flavor states.

$B_s^0 \rightarrow J/\psi\ K^+K^-$

$\overline{B}_s^0 \rightarrow J/\psi\ K^+K^-$

Without knowledge of initial flavor, measure average of B_s^0 and B_s^0 contributions:

$$\boldsymbol{\Gamma_{notag} = [\ \tfrac{1}{2}\,\Gamma\,(B_s^0) + \tfrac{1}{2}\,\Gamma(\overline{B}_s^0)\ ]}$$

For events with initial flavor tagged with probability $P(B_s^0)$:

$$\boldsymbol{\Gamma_{tag} = [\ P(B_s^0)\,\Gamma(B_s^0) + [1 - P(B_s^0)]\,\Gamma(\overline{B}_s^0)\ ]}$$

10 parameters:
$\boldsymbol{\tau_s, \Delta M_s, \Delta\Gamma_s, \varphi_s^{J/\psi\varphi}}$,
2 relative phases: $\boldsymbol{\delta_\perp, \delta_\parallel}$,
2 magnitudes at t=0: $\boldsymbol{A_0, A_\parallel}$
$\boldsymbol{F_S, \delta_S}$

Angular Analysis

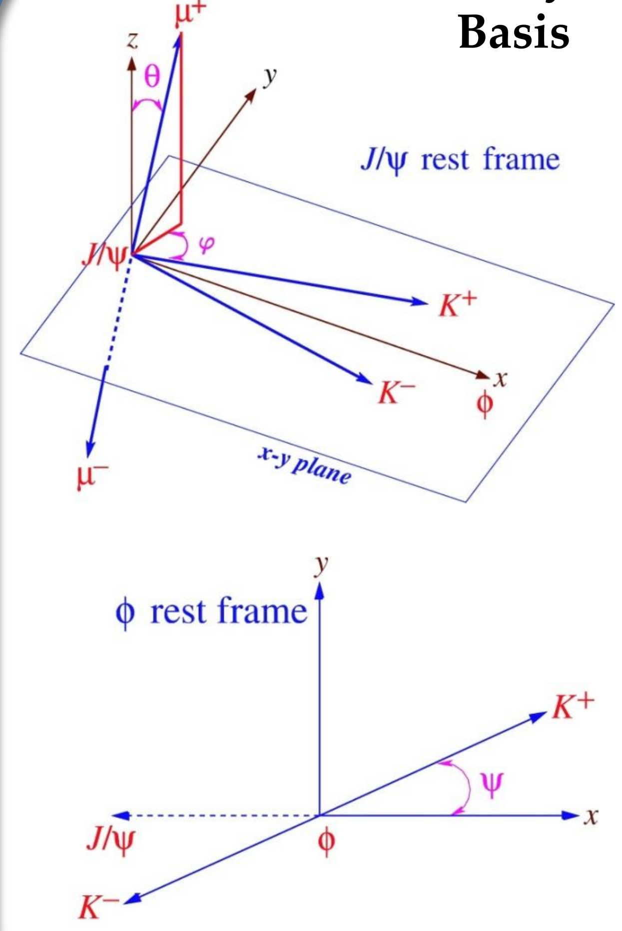
Different polarization states can only be disentangled by angular analysis;

⇒ Use angles to obtain probability of given B_s^0 candidate being in each polarization state.

Choose 'transversity basis', and fit to three angles (plus time):

$$\Gamma(\overset{(-)}{B_s^0}\rightarrow J/\psi\varphi) = \overset{(-)}{F}(t, \theta, \varphi, \psi)$$

Transversity Basis



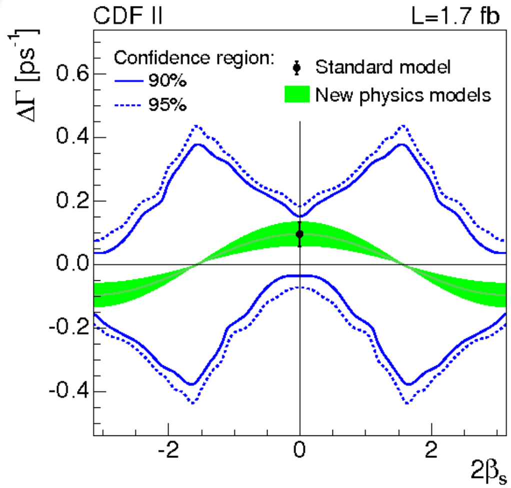
Some History

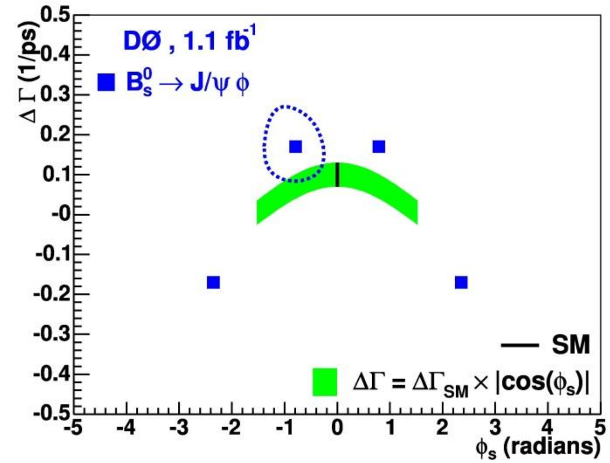
2007

First constraints on $\varphi_s^{J/\psi\varphi}$

- No Flavor tagging;
- S-wave neglected;

D0: $\varphi_s^{J/\psi\varphi} = -0.79 \pm 0.56\ ^{+0.14}_{-0.01}$





$2\beta_s \xleftrightarrow{\times -1} \varphi_s^{J/\psi\varphi}$

Note four-fold ambiguity in fit solution:

1) $\varphi_s^{J/\psi\varphi} \to \pi - \varphi_s^{J/\psi\varphi}$ $\quad \Delta\Gamma_s \to -\Delta\Gamma_s$ $\quad \delta_\perp \to \pi - \delta_\perp$ $\quad \delta_\parallel \to 2\pi - \delta_\parallel$

2) $\varphi_s^{J/\psi\varphi} \to \pi + \varphi_s^{J/\psi\varphi}$ $\quad \Delta\Gamma_s \to -\Delta\Gamma_s$

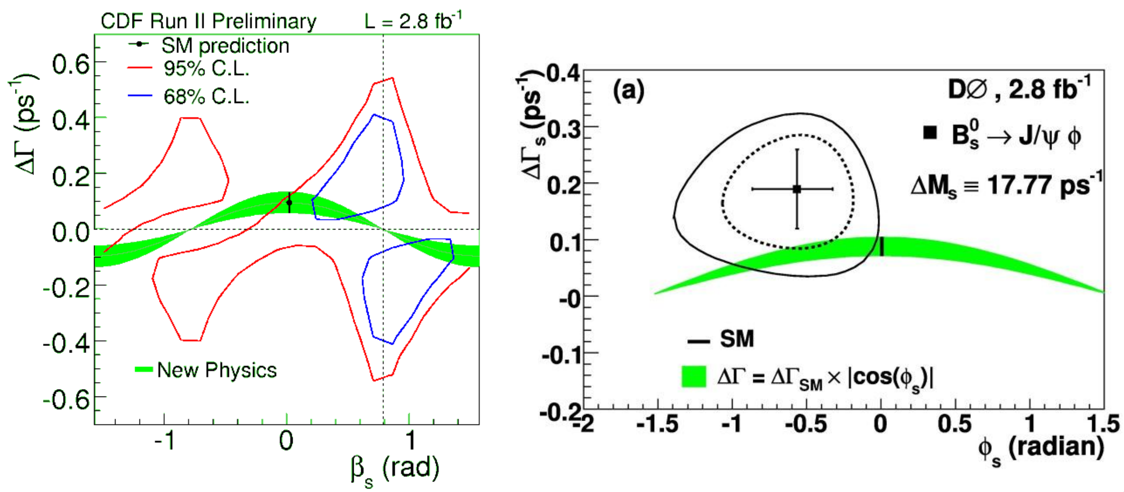
(exact for no flavor tagging; removed for perfect flavor tagging)

Some History

2008

- First use of flavor tagging;
- ~2σ from SM point

D0: $\varphi_s^{J/\psi\varphi} = -0.57^{+0.24}_{-0.30}\,{}^{+0.07}_{-0.02}$



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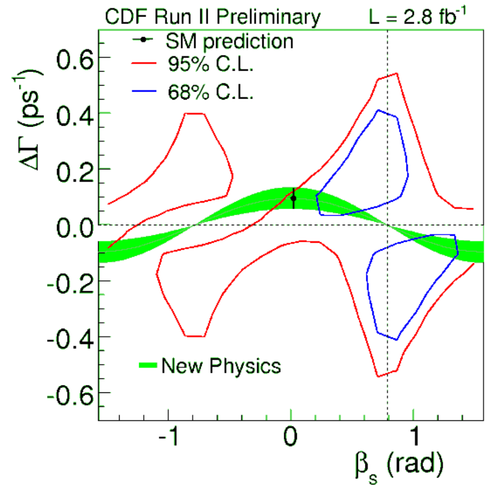
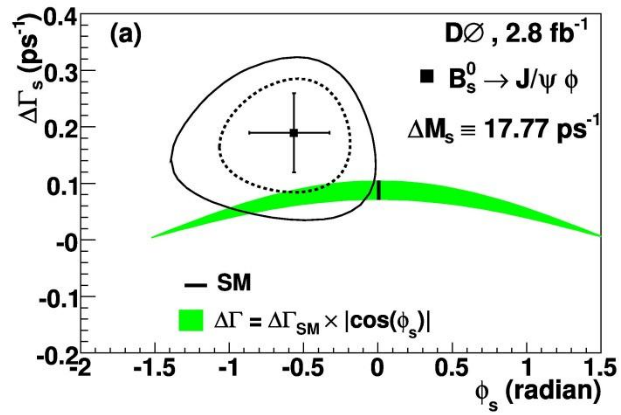




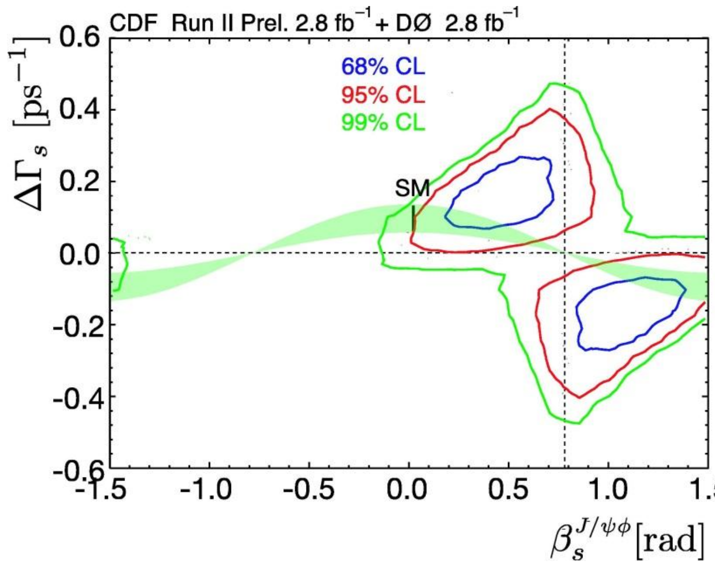
2009

First Tevatron combination

Hints of intriguing discrepancy with SM.

Standard Model
p-value = 2.0%

2.3σ disagreement



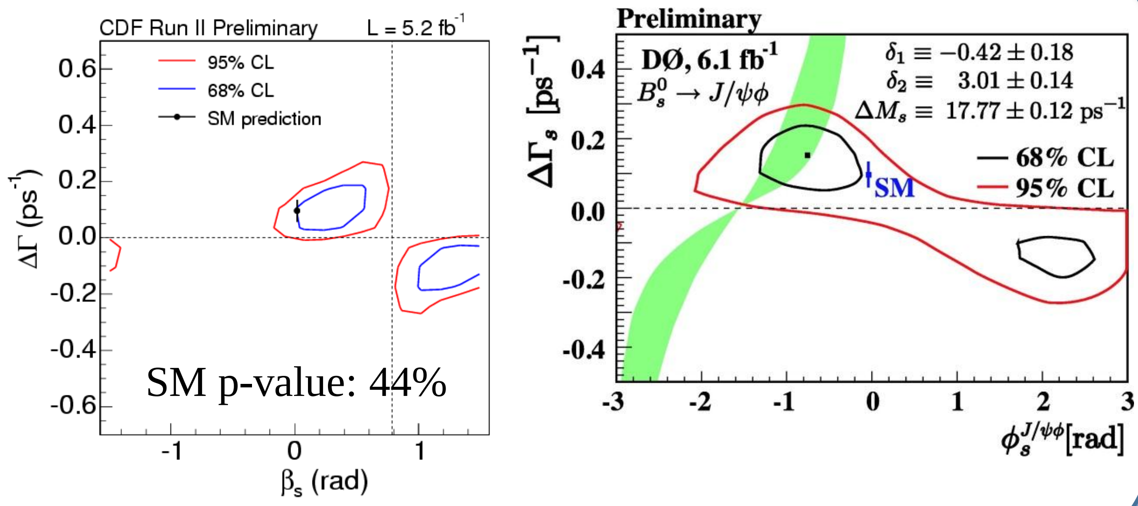
Some History

2010

Updates from both experiments.

D0: $\varphi_s^{J/\psi\varphi} = -0.76^{+0.38}_{-0.36} \pm 0.02$

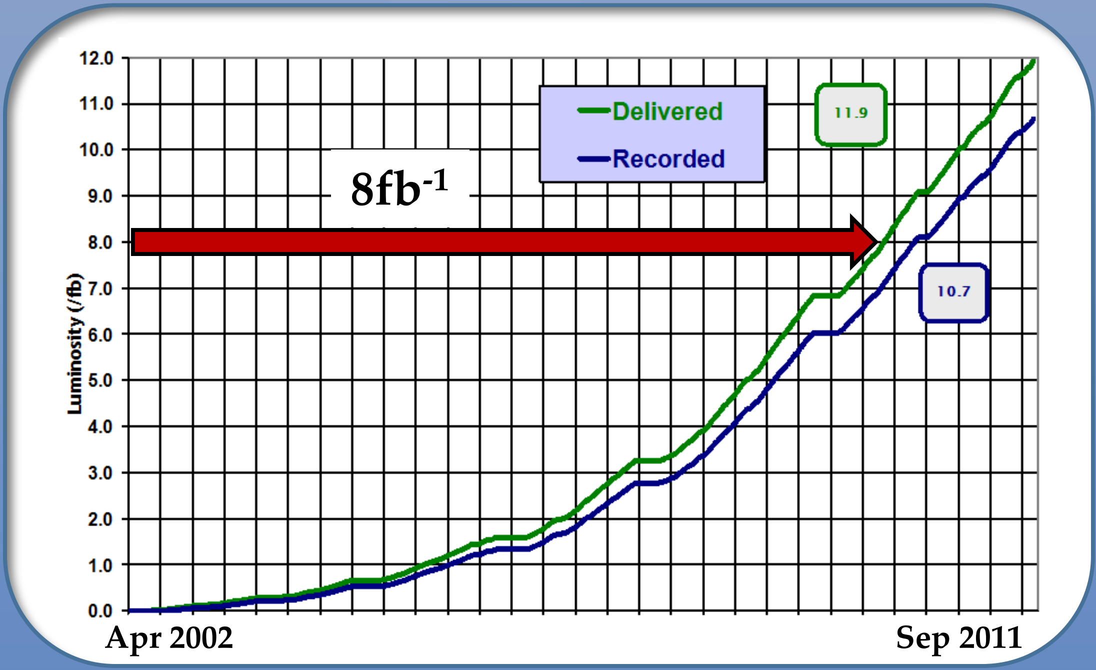
First inclusion of S-wave (CDF): $F_S < 6.7\%$ @95% CL



2011 D0 Update

Latest result includes the following improvements:

- BDT event selection;
- Inclusion of S-wave in fit;
- Strong phases δ are free parameters;
- Additional studies to validate measurement from fit.



Dataset increased from **6.1fb^{-1}→8fb^{-1}** compared to previous analysis.

Many thanks to all involved in delivering beam to D0.

The D0 Detector

Central tracking:

Silicon microstrips + scintillating fibers;

Invariant mass reconstruction: need good **track momentum** measurement;

Proper time resolution: need both **vertex location** and momentum measurements;

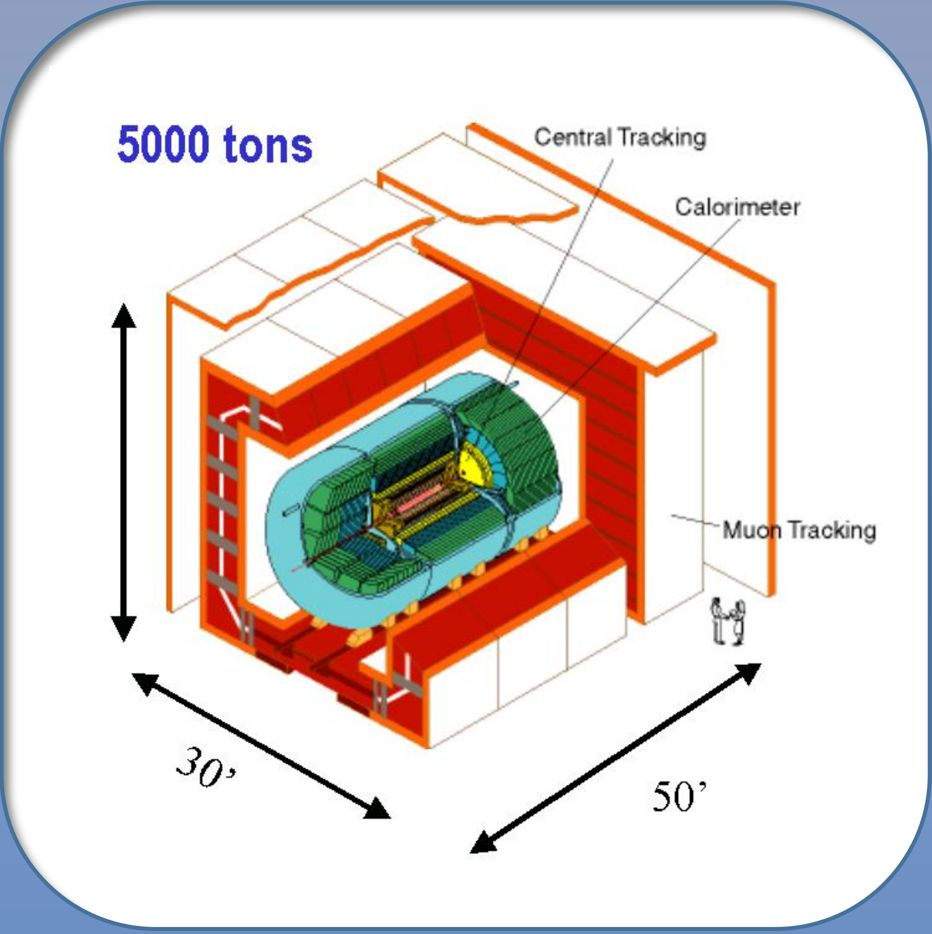
Muon System:

3 successive layers of muon tracking and scintillation planes;

Identify muons from J/ψ decays;

Wide acceptance up to |η|<2 increases yield;

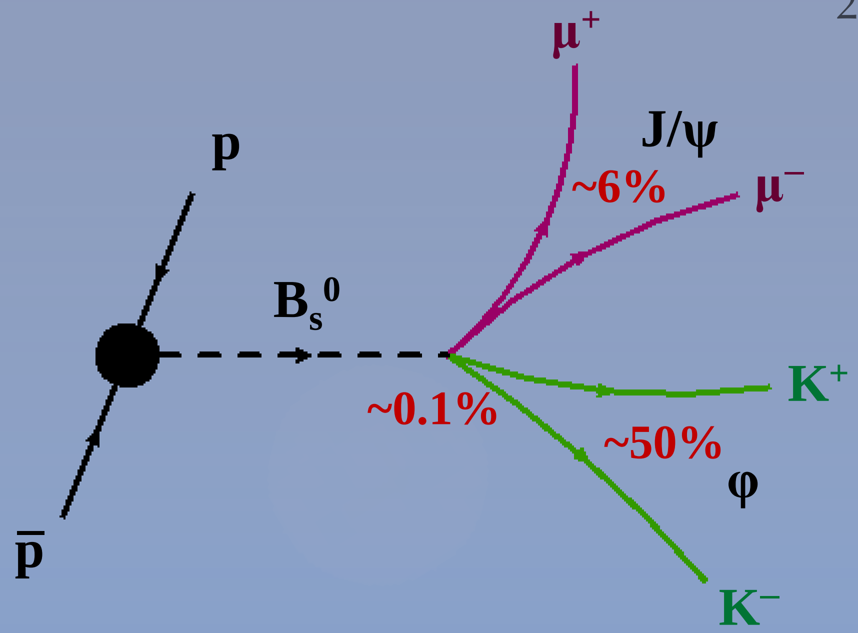
Thick shielding suppresses hadronic **punch-through**;

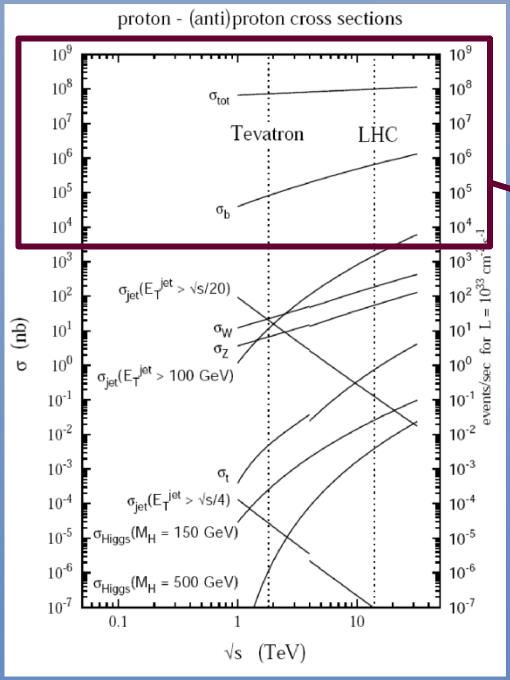


Collecting Events

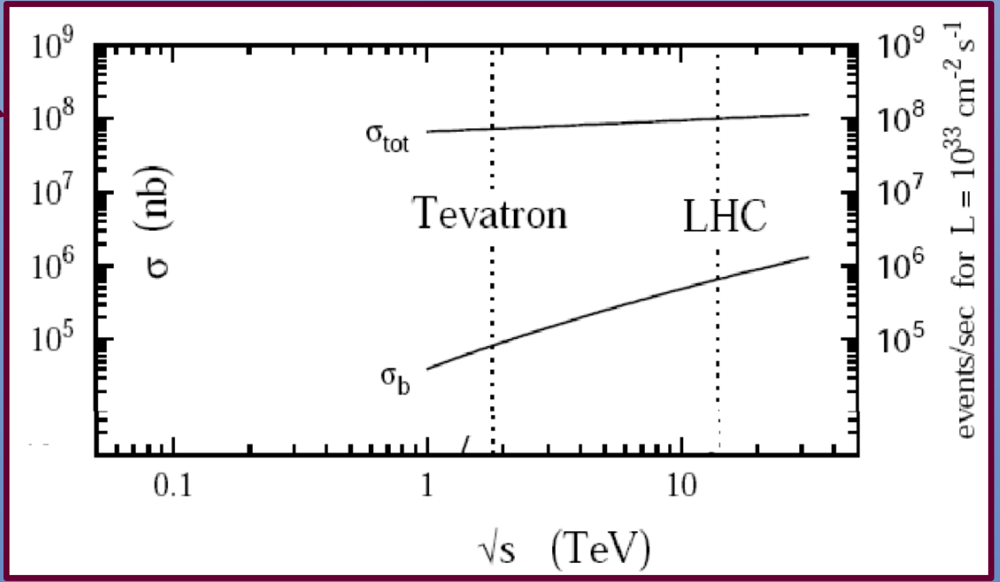
Muons: Well-defined experimental signature: provide trigger, and clean J/ψ sample;

Kaons: detected as charged tracks. No way to distinguish from pions;





~10⁴ $b\bar{b}$ events / second @ Tevatron luminosity



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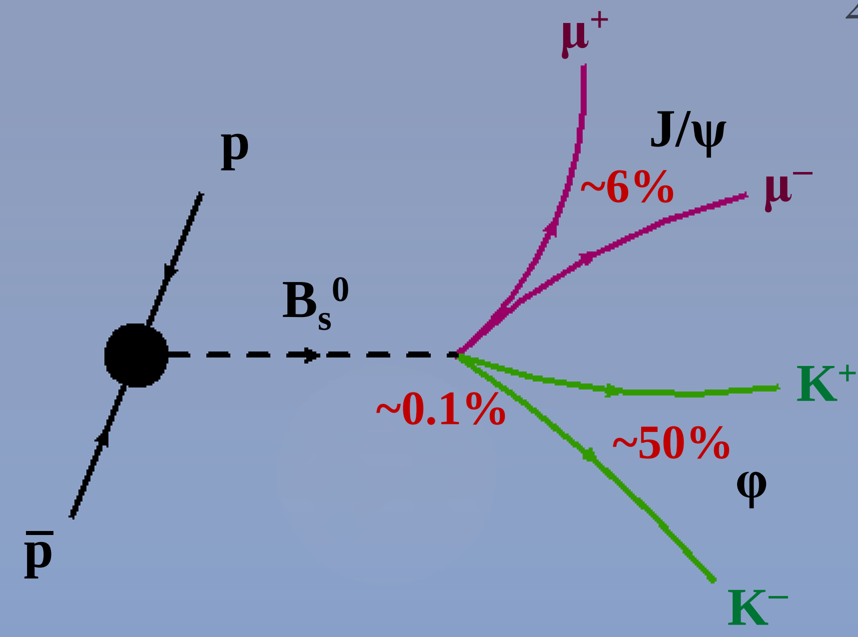

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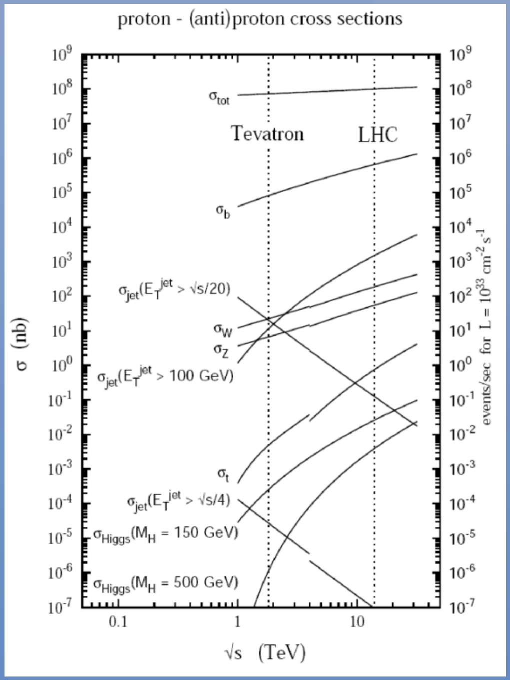
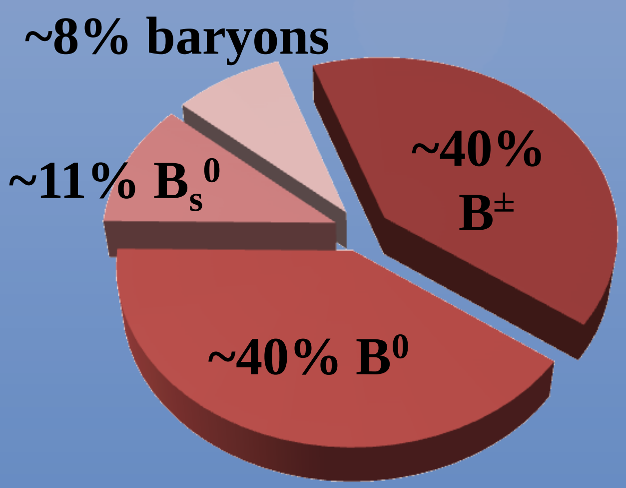




Suite of single and di-muon triggers used to collect events.

Events excluded if they only fire triggers with lifetime/IP requirements.

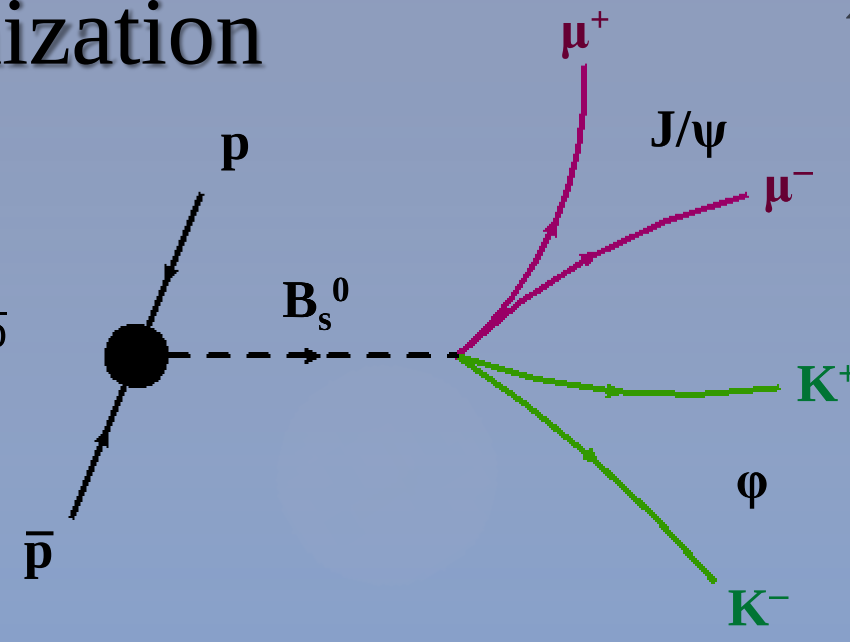
Event Selection: Optimization

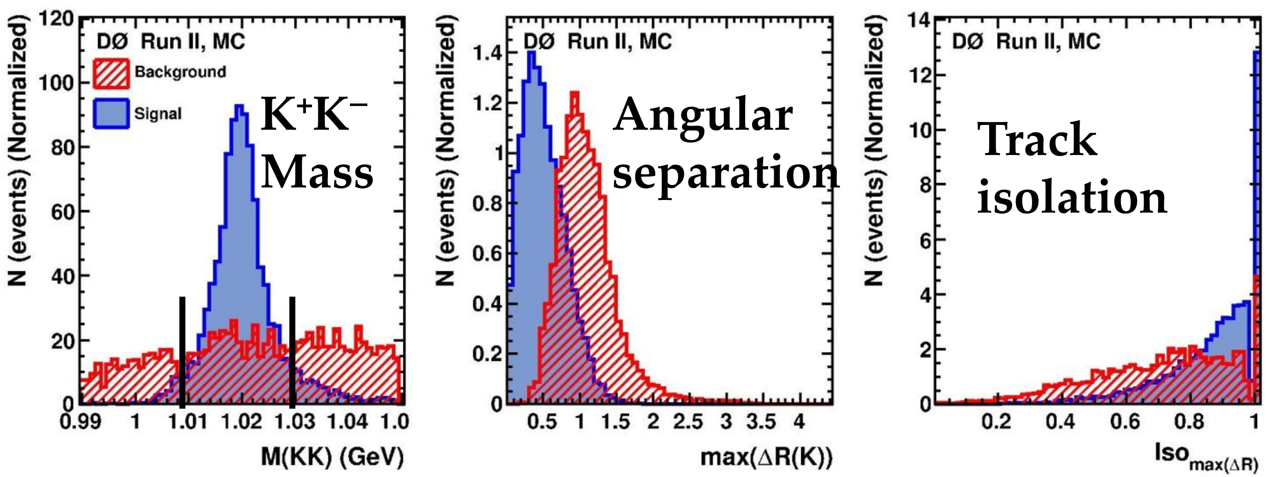
Two main backgrounds, in which real J/ψ mesons are combined with 'wrong' tracks:

1) '**Prompt**' J/ψ mesons produced in initial $p\bar{p}$ interaction;

2) '**Long-lived**' J/ψ mesons from B decay;

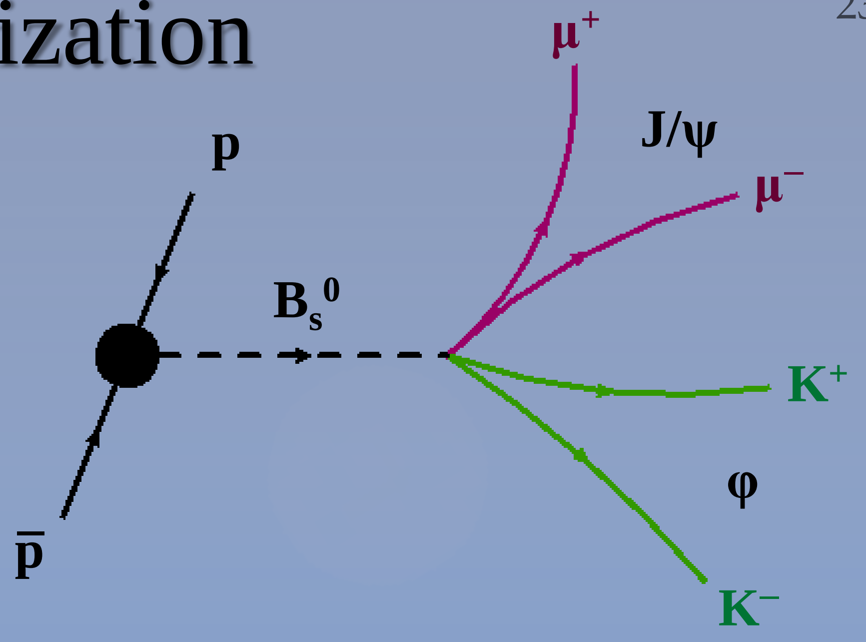
Take advantage of characteristics of signal events, to construct multivariate discriminant (**B**oosted **D**ecision **T**ree).





Separate BDTs trained for prompt and long-lived backgrounds, combining ~35 variables.

Event Selection: Optimization



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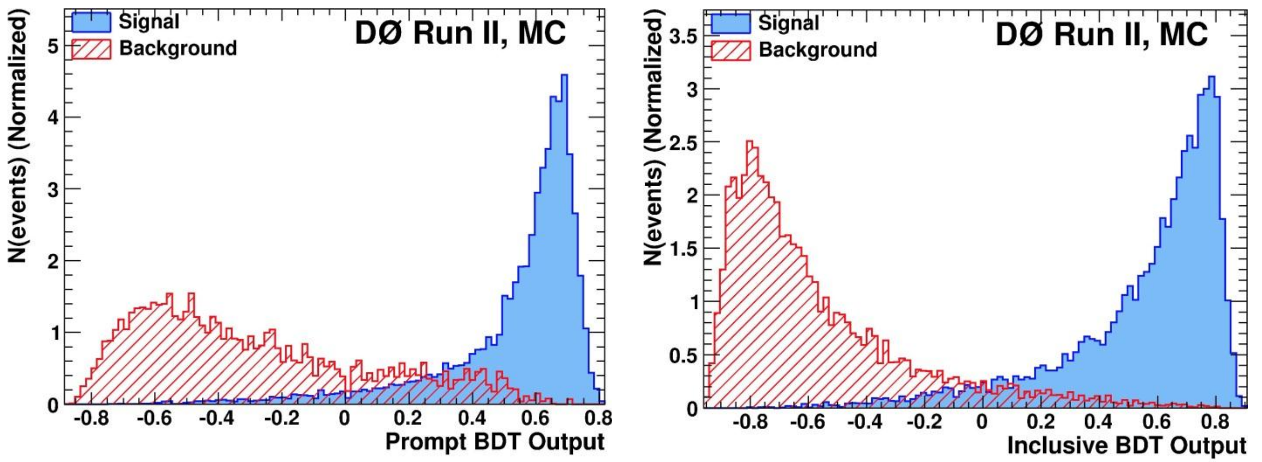


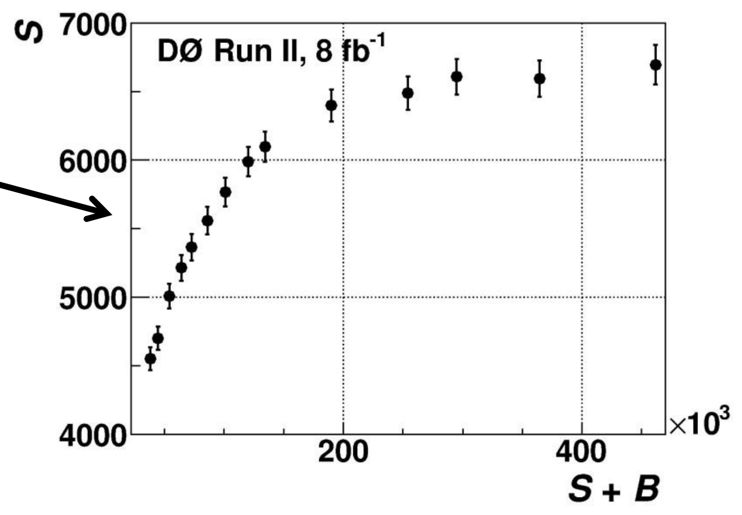
⇒ Two dials to turn to control signal purity;

Next find optimal cuts on these variables.

Event Selection: Optimization

Define 14 regions in N(signal);

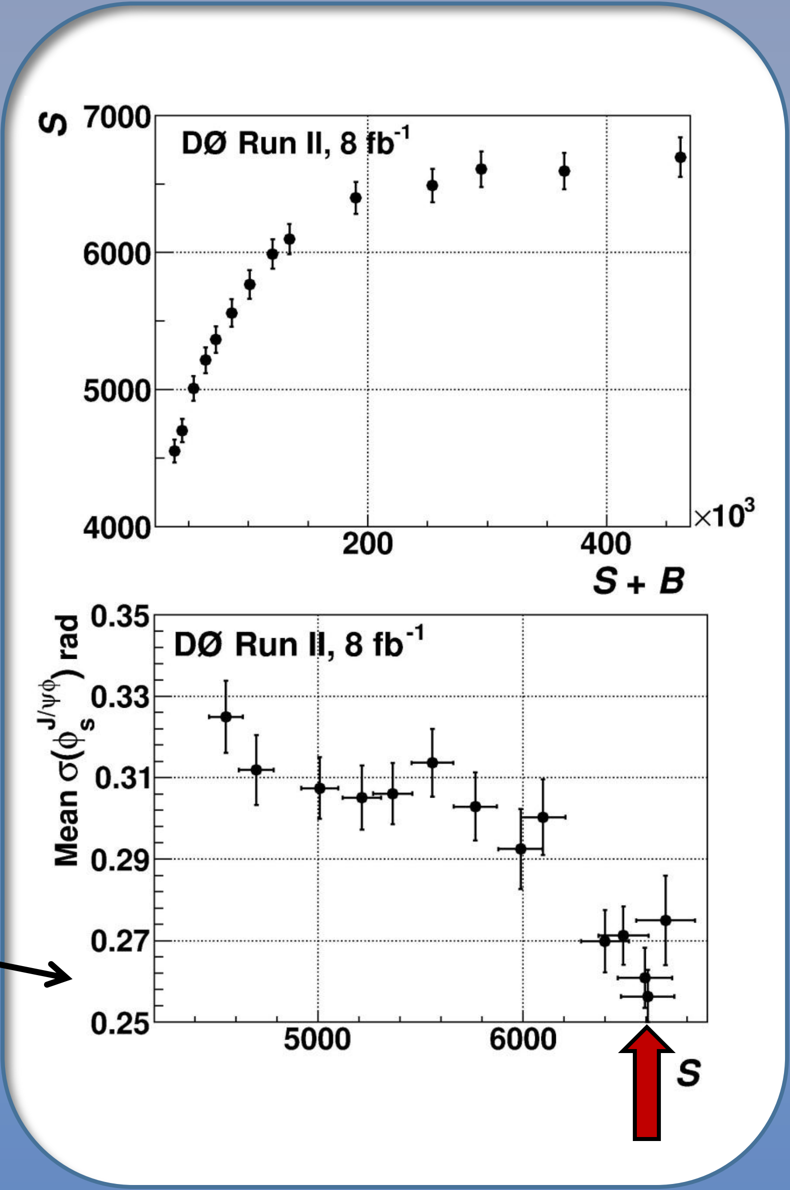
In each one, choose pair of BDT cuts that gives **best signal significance** S/√(S+B);



Event Selection: Optimization

Resulting set of 14 possible samples then tested using **pseudo-experiments**:

- Generate S signal, B background events;
- Set physics parameters from preliminary fit;
- Simulate backgrounds and experimental resolution using simplified model;
- Perform fit, to extract parameters and uncertainties in each pseudo-experiment;
- Choose sample with minimum mean $\boldsymbol{\sigma(\varphi_s^{J/\psi\varphi})}$ and $\boldsymbol{\sigma(\Delta\Gamma_s)}$;

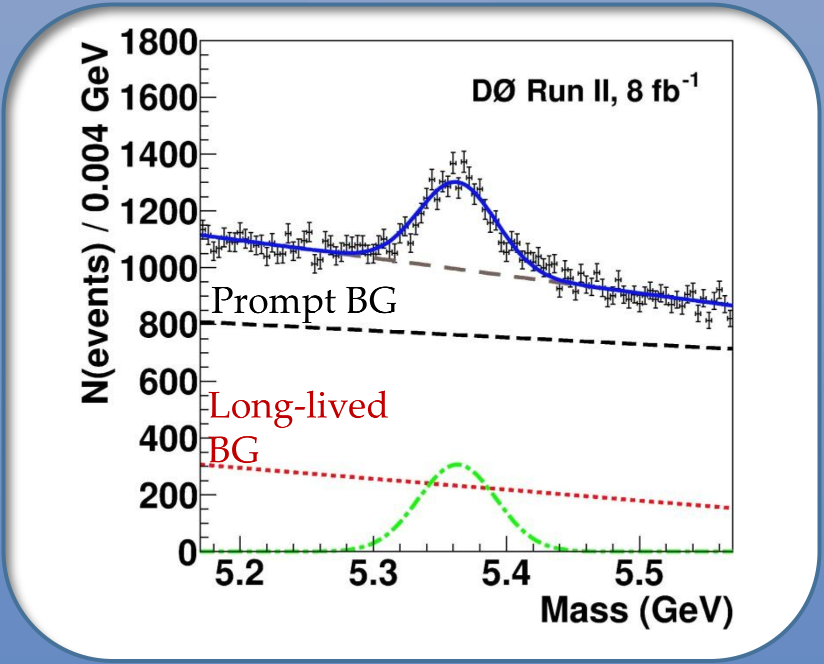


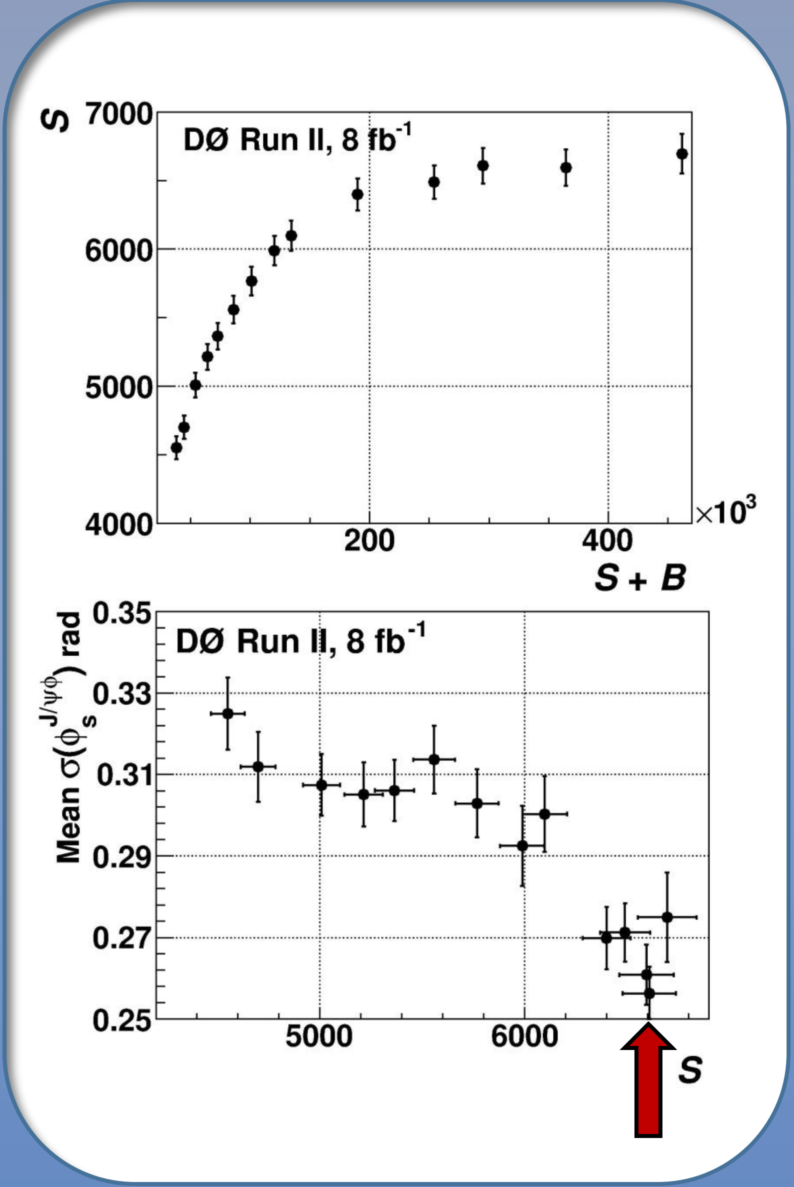
Event Selection: Optimization

Also apply hard mass cut:

1.01 < M(KK) < 1.03 GeV

Final selection gives signal yield of **~5600** signal candidates.





Flavor Tagging

Knowledge of initial flavor (B or $\bar{B}$), partially resolves one ambiguity in measurement:

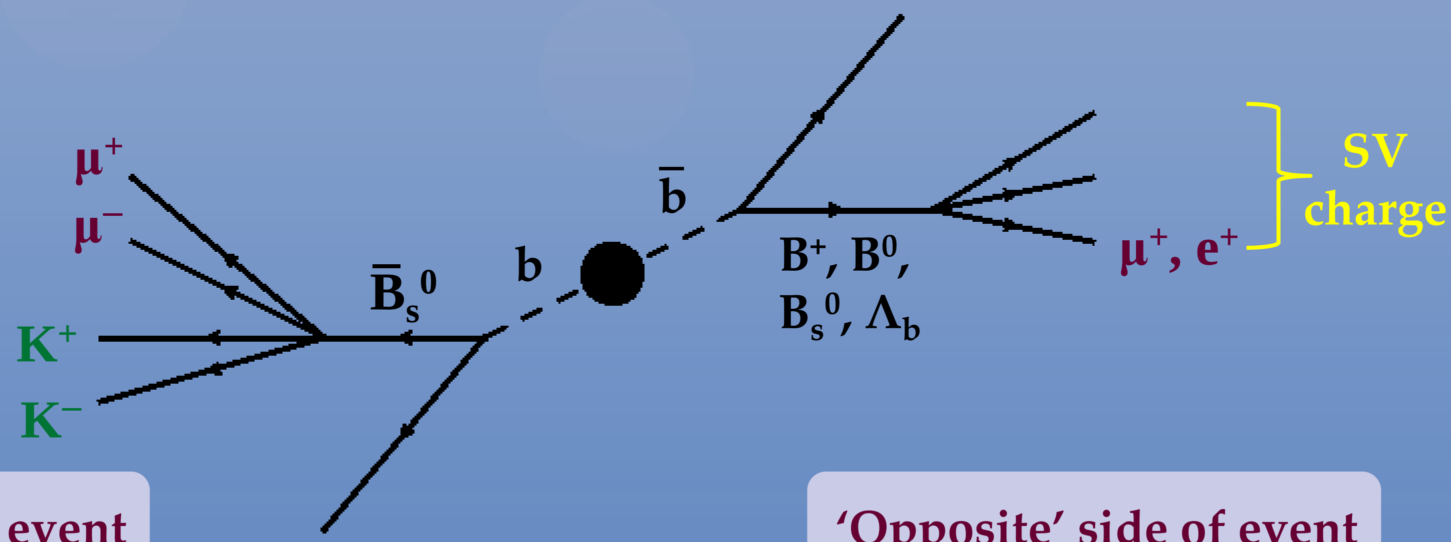
$$\varphi_s^{J/\psi\varphi} \rightarrow \pi + \varphi_s^{J/\psi\varphi} \qquad \Delta\Gamma_s \rightarrow -\Delta\Gamma_s$$

At Tevatron, b quarks produced ~100% of time in $b\bar{b}$ pairs: 'opposite' side gives information on initial flavor.

Combine different discriminants to produce Opposite-Side Tagger (OST):

- Muon charge;
- Electron charge;
- Secondary Vertex charge;

Tagging efficiency ~19%



'Signal' side of event

'Opposite' side of event

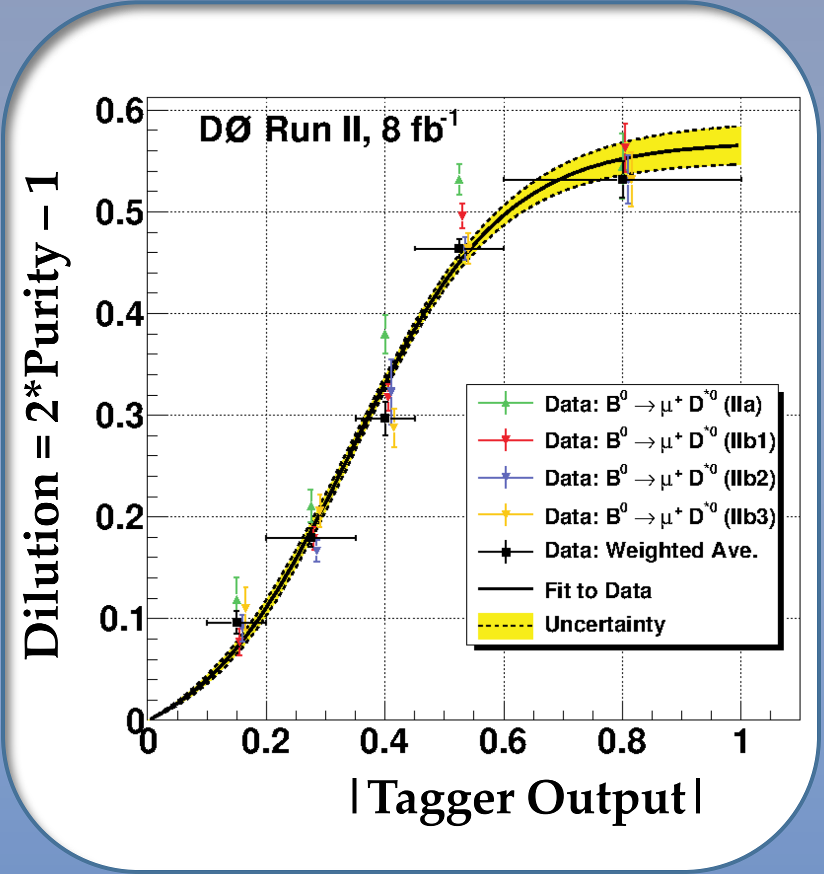
Flavor Tagging

Calibration of tagger is vital, to assign correct probability of $\Gamma(B_s^0)$ and $\Gamma(\bar{B}_s^0)$ to each event;

Convert tagger output into a meaningful flavor probability, expressed as 'dilution':

$$D = \frac{N_{cor} - N_{wr}}{N_{cor} + N_{wr}}$$

Number of events with **cor**rectly (**wr**ongly) identified initial flavor.



Use well-understood sample of $B^0 \rightarrow \mu D^{(*)} X$ to calibrate tagger.

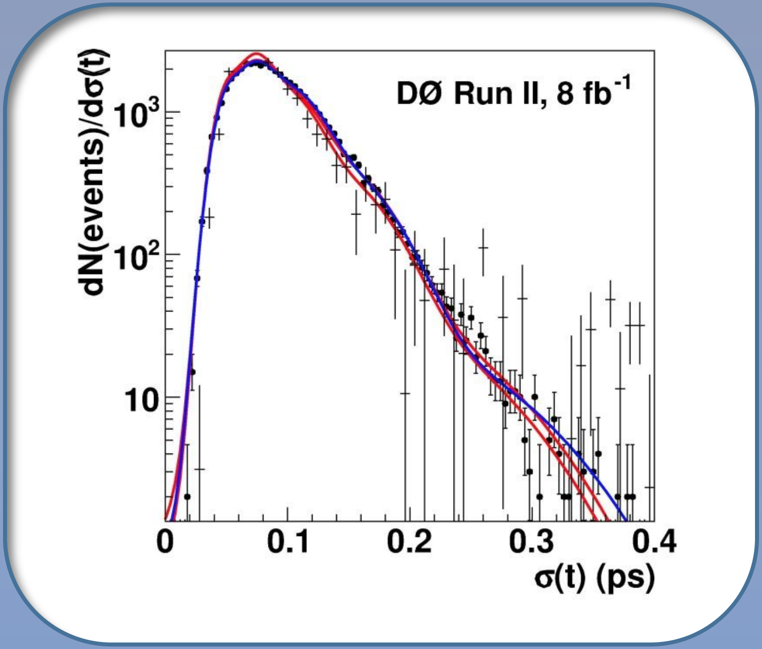
Detector Effects

A real experiment has:

1) Finite spatial vertex resolution ⇒ smearing of measured proper decay time.

Proper time in fit convoluted with Gaussian resolution of width σ(t) on event-by-event basis.

σ(t) distribution included in fit, with different models for signal, prompt and long-lived backgrounds.

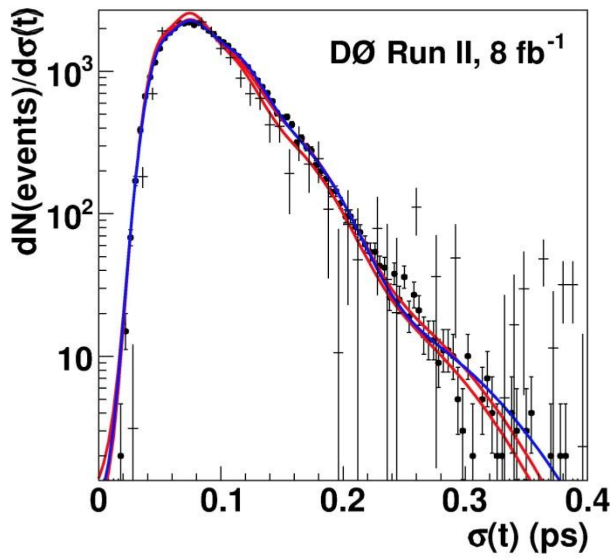


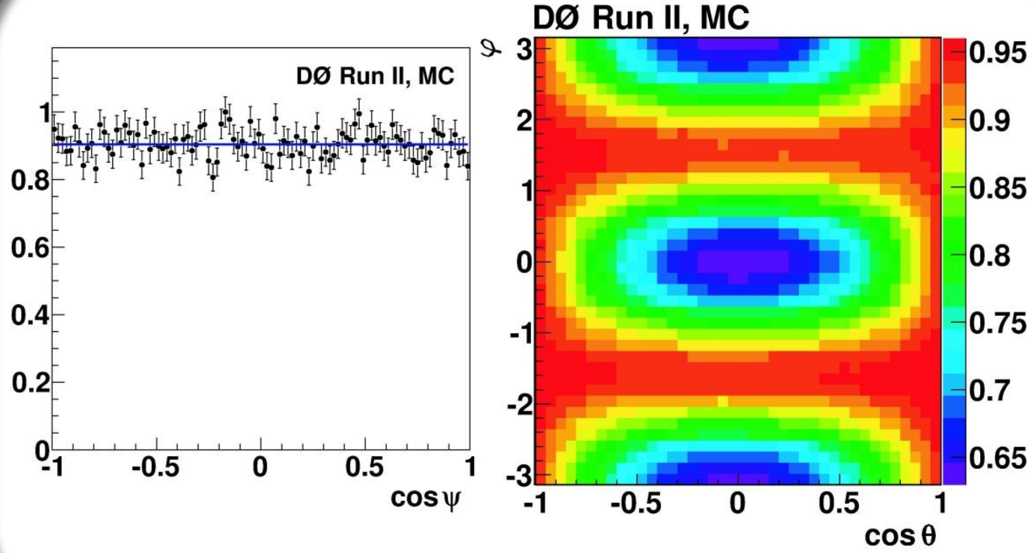
Detector Effects

A real experiment has:

1) Finite spatial vertex resolution ⇒ smearing of measured proper decay time.

2) Limited angular acceptance ⇒ distortion of angular variables.





Signal decay rate corrected by acceptance factor measured in simulation:

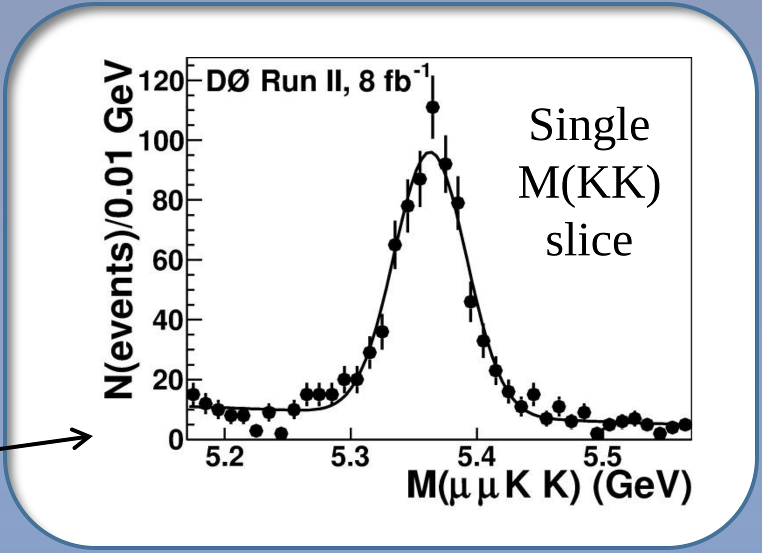
$$\varepsilon(\psi,\theta,\varphi) = P_k(\psi)\cdot Y_{lm}(\theta,\varphi)$$

S-wave Contribution

Fraction (**F_S**) and phase (**δ_S**) of non-resonant S-wave K^+K^- contribution are free parameters in the fit.

Alternative method based on mass fit gives cross-check of F_S measurement.

- Divide data into slices in $M(K^+K^-)$;
- Fit the $M(\mu^+\mu^-K^+K^-)$ distribution in each slice, to extract B_s^0 signal;



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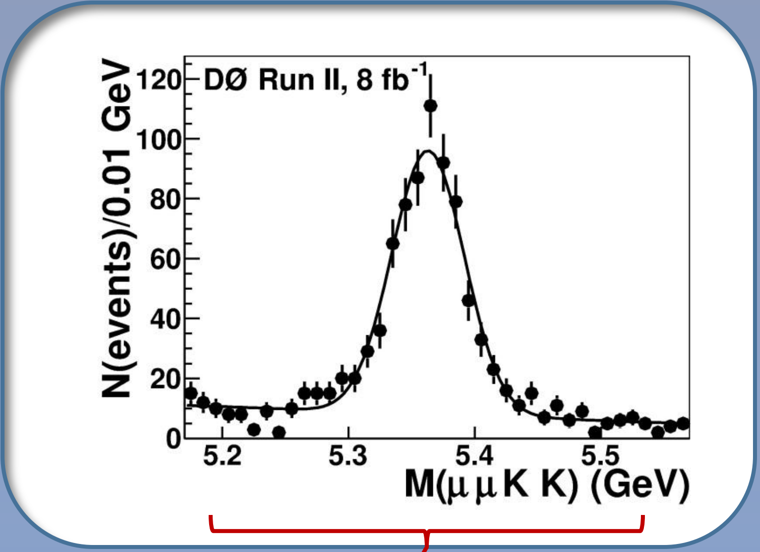
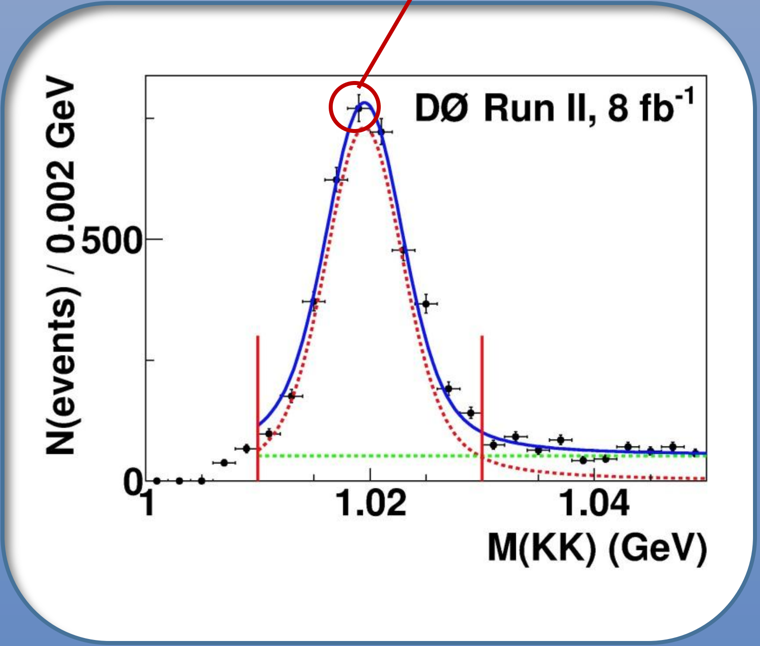


B_s^0 signal has two components:

1) Clear resonance at φ(1020) – 'P-wave'
2) Uniform non-resonant contribution – 'S-wave'.



Fitting to a number of different models yields:

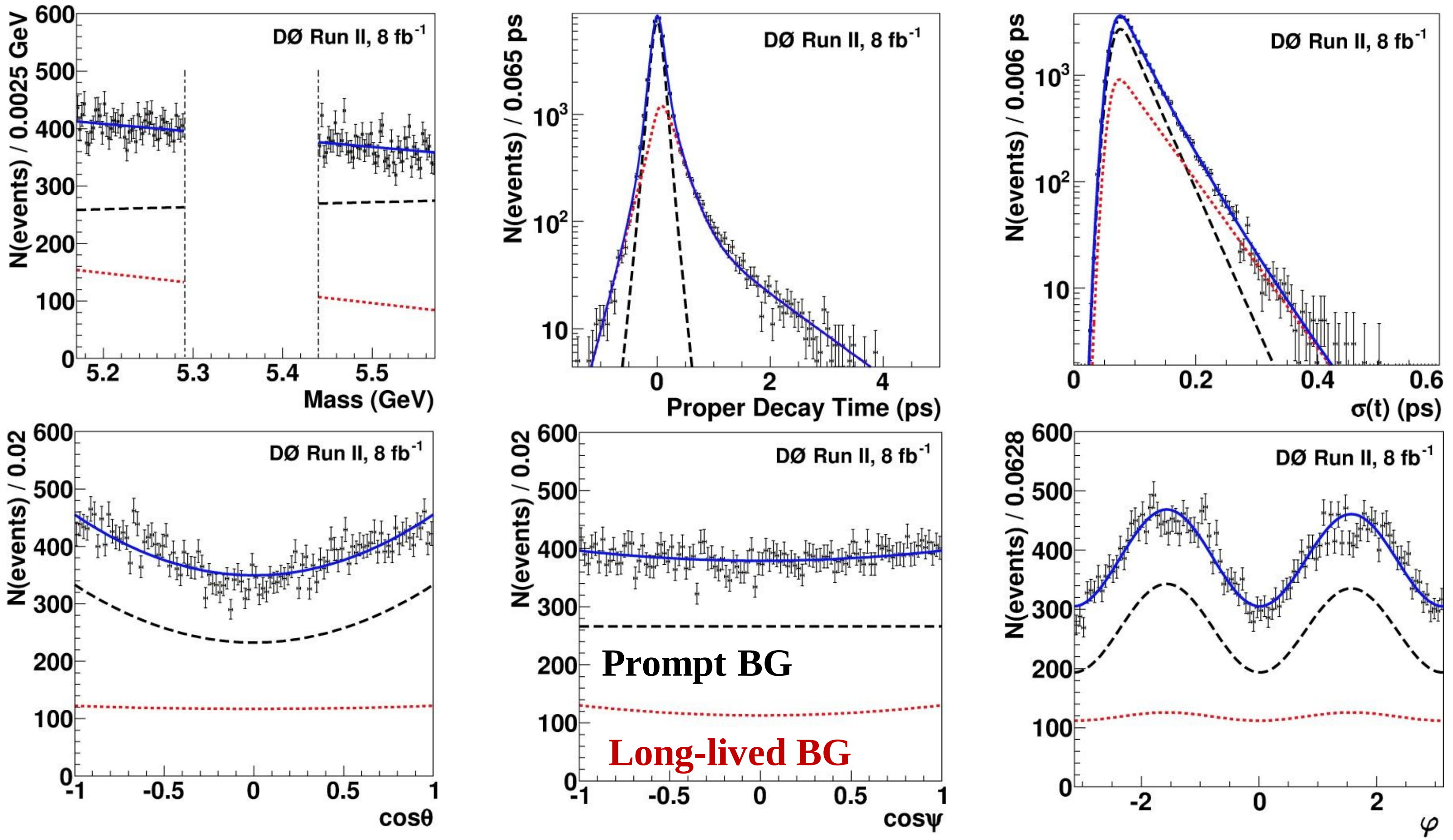
$$\mathbf{F_S = (12 \pm 3)\ \%}$$

Background Model

24 free parameters describe 6 background distributions

Full 6-dimensional fit is performed in signal-free region.

⇒ Excellent agreement between data and background model.

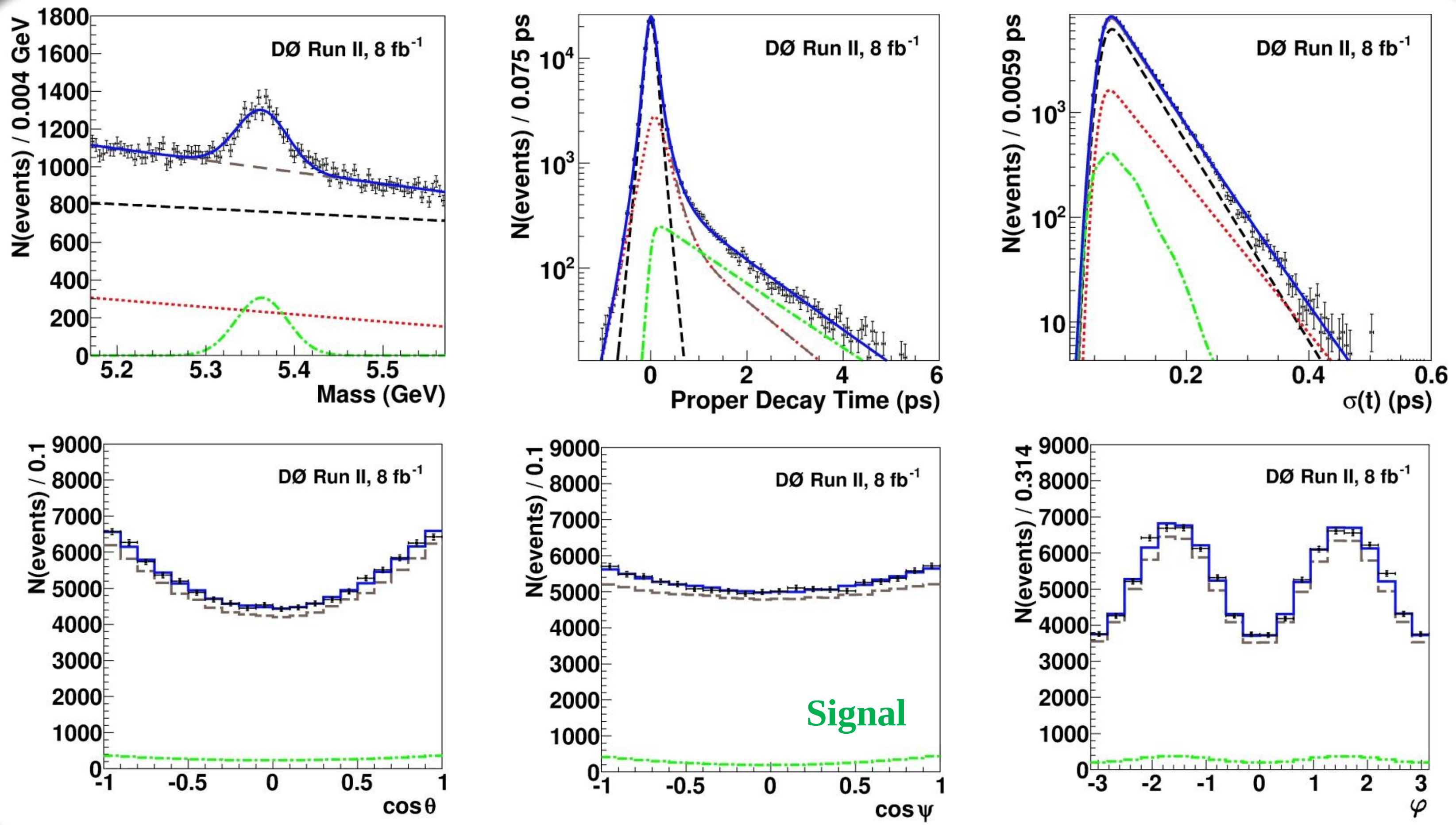


Fit Results: Projections

9 physics parameters from lifetime fit;
+ signal yield, mass and width

ΔM_s constrained to **(17.77 ± 0.12) ps^{-1}**.

cos($\delta_\perp$) < 0 removes one ambiguity (from $B^0 \to J/\psi K^*$)



Fit Results

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

Phase $\varphi_s^{J/\psi\varphi}$ consistent with previous results; now also agrees with SM prediction of −0.04 (***p*-value: 30%**);

S-wave fraction consistent with value from mass-fit method (12 ± 3 %);

Magnitudes and phases of polarization amplitudes consistent with $B^0 \rightarrow J/\psi K^*$ decay ($\delta_\perp$ = 2.91±0.06).

Alternative solution with $\boldsymbol{\delta_\perp} \approx 0$ discarded.

Correlations between $\boldsymbol{\delta_\perp}$ and $\boldsymbol{\delta_S}$ prevent extraction of separate point-estimates.

Fit Results

Likelihood fit gives best values of all free parameters;

However, it doesn't include systematic effects from external constants;

To include such effects, use Markov-Chain Monte Carlo (MCMC):

- Repeat fits with external conditions varied within expected uncertainties.
- MCMC uses a random walk to populate the 36 parameter space according to the likelihood function for each fit.
- Combine MCMC samples from all fits, and extract Bayesian credibility intervals.

$$\begin{aligned}
\overline{\tau}_s &= 1.443^{+0.038}_{-0.035}\ \text{ps},\\
\Delta\Gamma_s &= 0.163^{+0.065}_{-0.064}\ \text{ps}^{-1},\\
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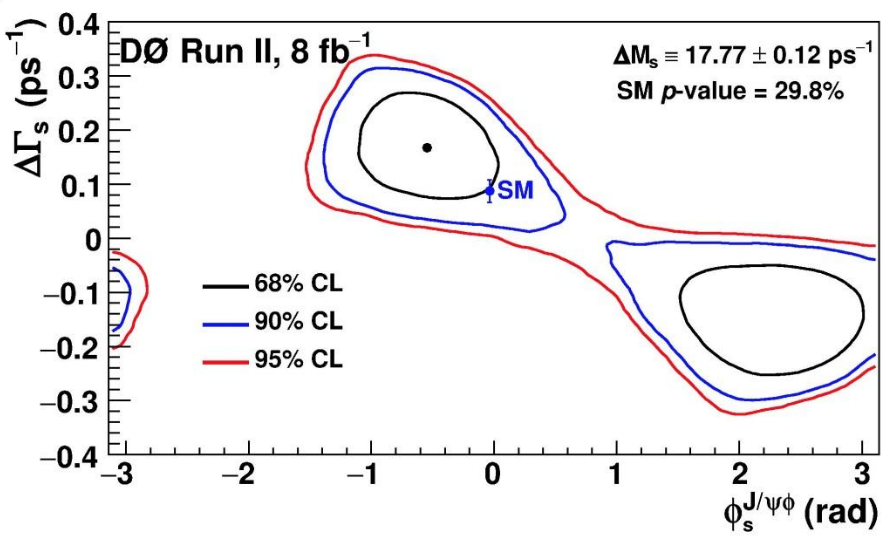
\end{aligned}$$



Systematics

Flavor Tagging:

Vary dilution calibration curve within uncertainties: negligible effect on final results.

Proper decay time resolution:

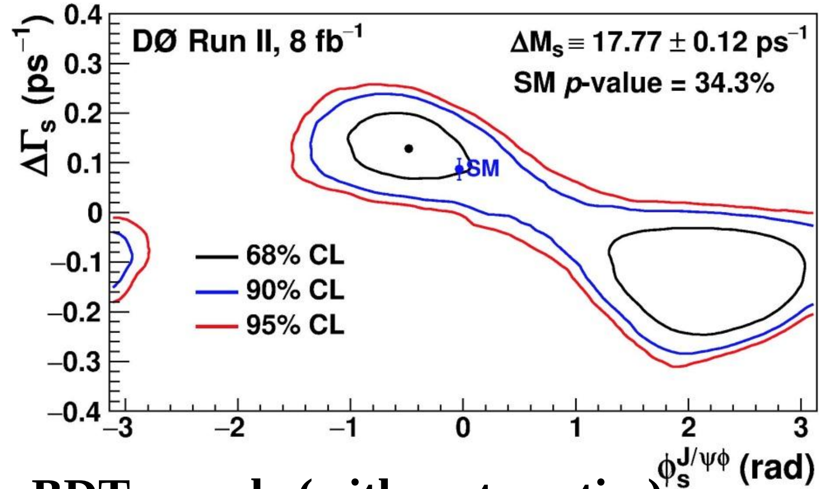
Vary σ(t) signal model within uncertainties;

M(KK) resolution:

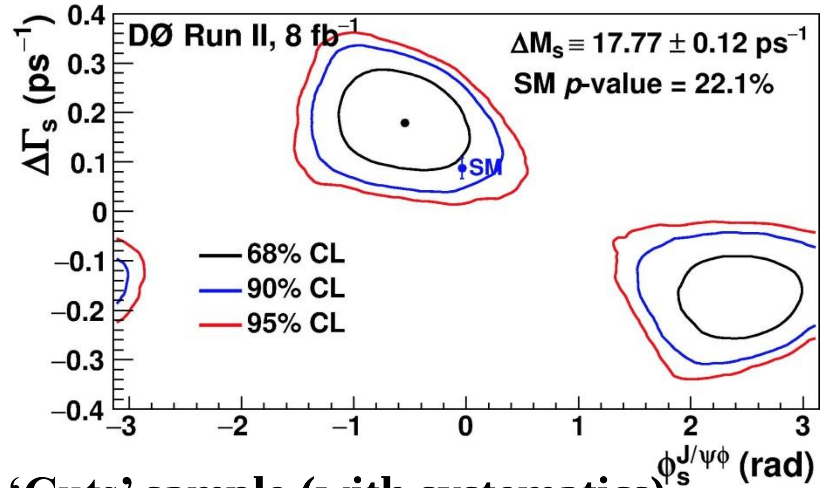
Use alternative model for P-wave;

Detector acceptance:

Repeat measurement with cut-based event selection (as in previous publication): different kinematic ranges ⇒ different angular acceptance functions.



BDT sample (with systematics)



'Cuts' sample (with systematics)

Parameter Correlations

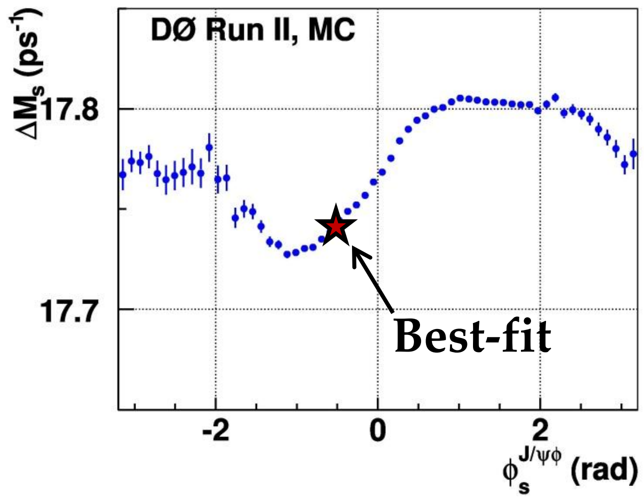
Use MCMC chains to scan over $\varphi_s^{J/\psi\varphi}$ range;

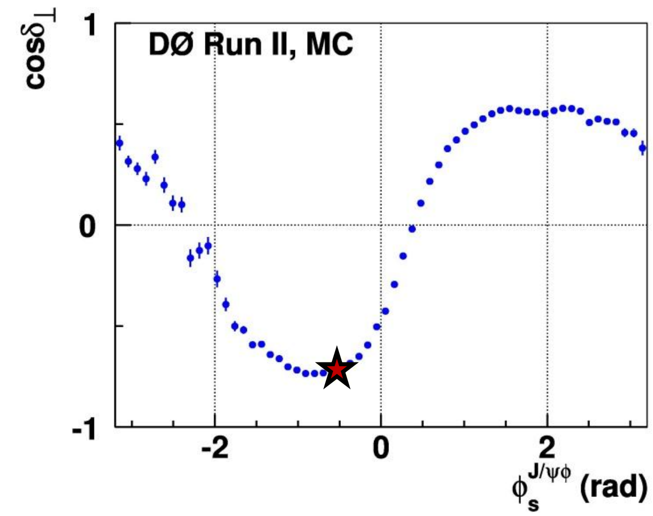
Observe how best-fit values of other parameters evolve.

For $\varphi_s^{J/\psi\varphi} \approx 0.0$:

1) Strong positive correlation between ($\varphi_s^{J/\psi\varphi}$, ΔM_s): phase changes sign at $\Delta M_s \approx 17.77$ ps^{-1};

2) Strong positive correlation between ($\varphi_s^{J/\psi\varphi}$, $\cos\delta_\perp$). From $B^0 \rightarrow J/\psi K^*$, $\cos\delta_\perp = -0.97$.





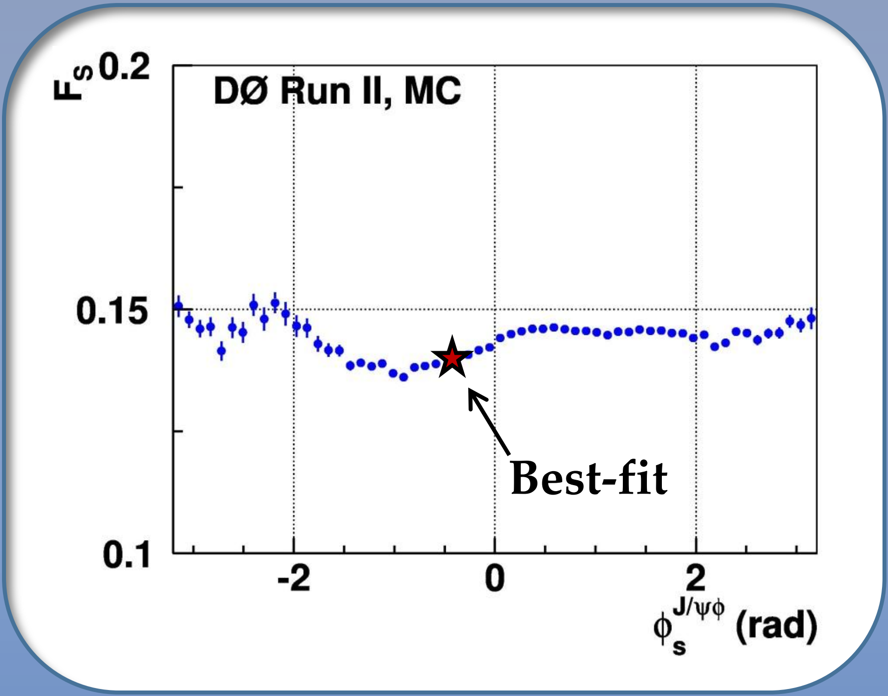
Parameter Correlations

Use MCMC chains to scan over $\varphi_s^{J/\psi\varphi}$ range;

Observe how best-fit values of other parameters evolve.

For $\varphi_s^{J/\psi\varphi} \approx 0.0$:

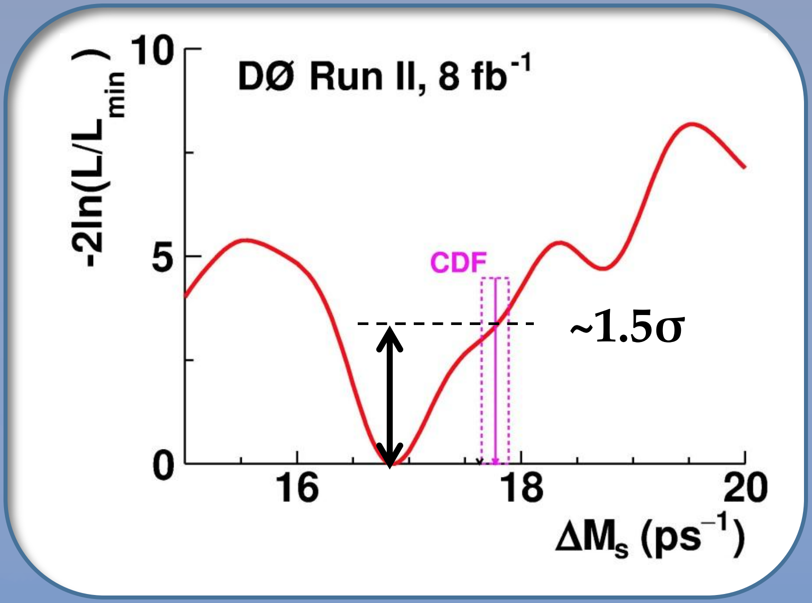
3) Very weak correlation between ($\varphi_s^{J/\psi\varphi}$, F_s).



Sensitivity to ΔM_s

Repeat fits with range of input ΔM_s values:

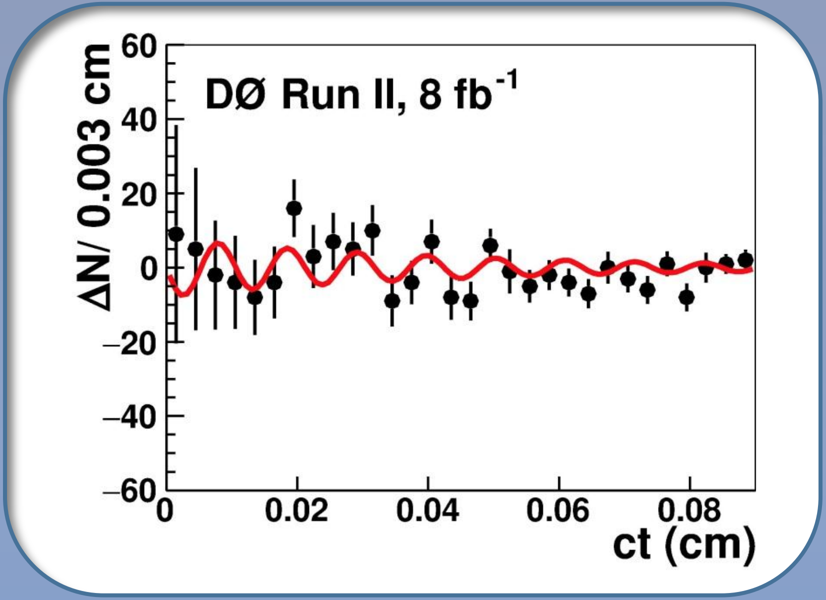
Best fit: $\Delta M_s \approx 17\ ps^{-1}$, $\varphi_s^{J/\psi\varphi} \approx -0.8$.



Mixing Analysis

Look for B_s^0 oscillations as function of time:

$$\Delta N \equiv [N(B_s^0) - N(\overline{B}_s^0)] \sim \sin(\Delta M_s t) \cdot e^{-t/\tau}$$



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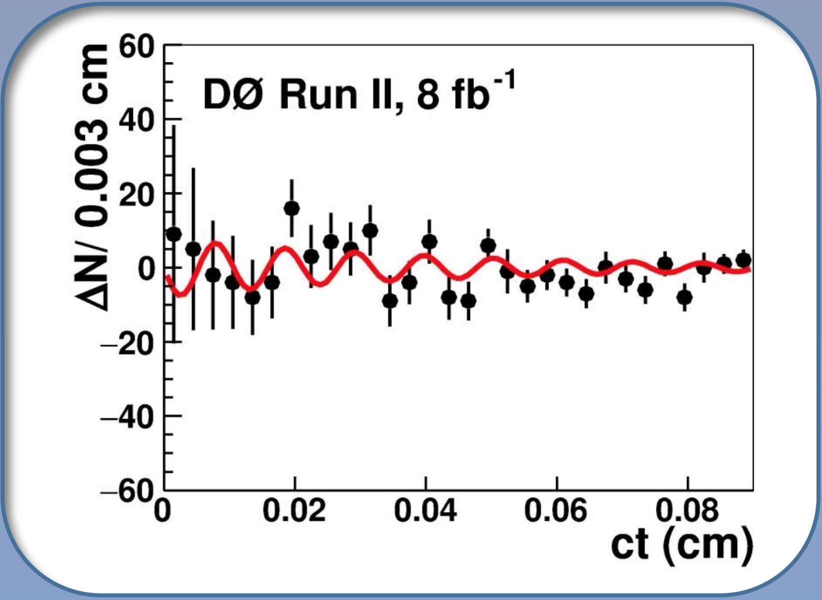

Oscillatory behavior indicates CPV in mixing;

Magnitude of oscillations:

$$N_0 = N_S \cdot C \cdot \sin(\varphi_s^{J/\psi\varphi})$$

N_S : Number of signal events (~5600);

C : dilution factor due to imperfect tagging, limited time resolution, CP admixture (~0.0025).

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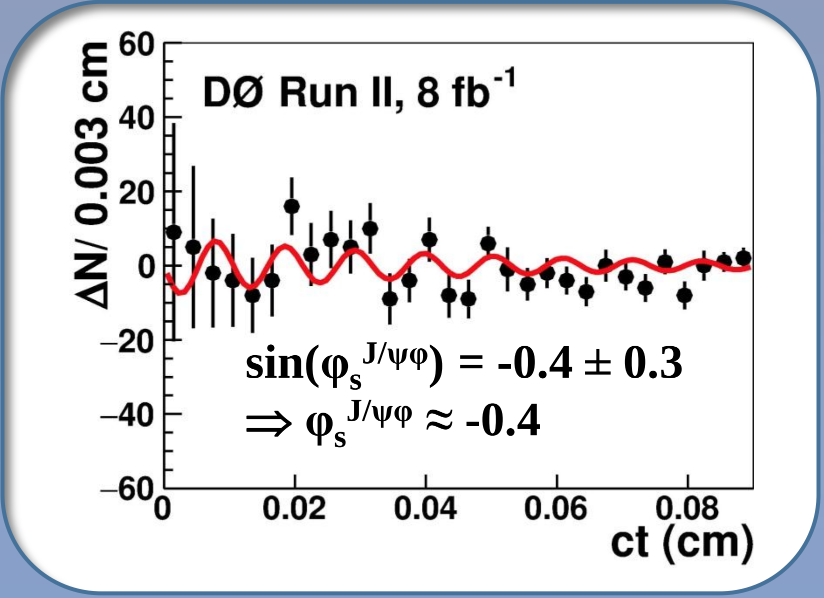

$\Rightarrow$ Extract $\varphi_s^{J/\psi\varphi}$ by fitting the oscillation magnitude.

Frequency $\mathbf{\Delta M_s}$ fixed at 17.77 ps^{-1}.

Mixing Analysis

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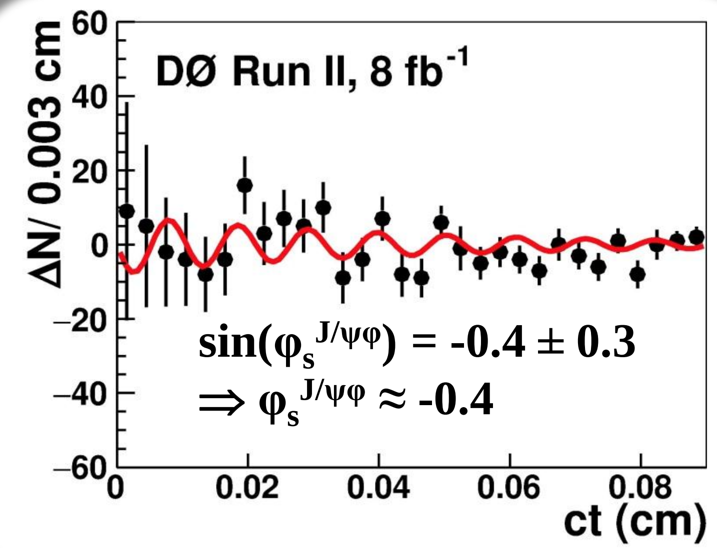
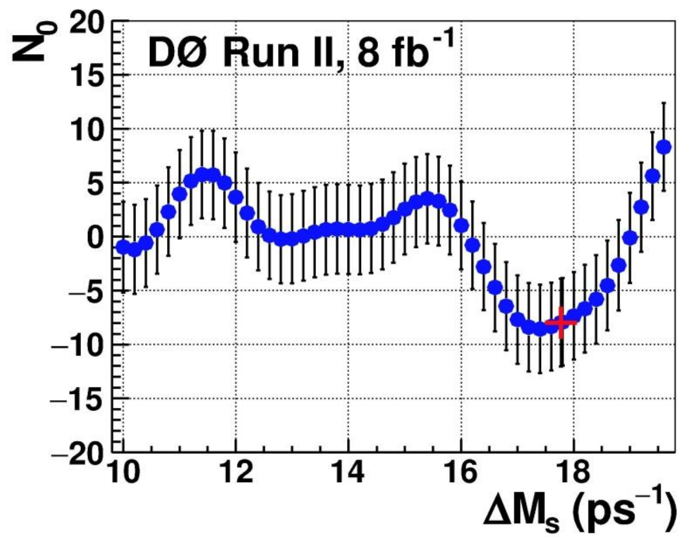


Repeating with different input frequencies: →



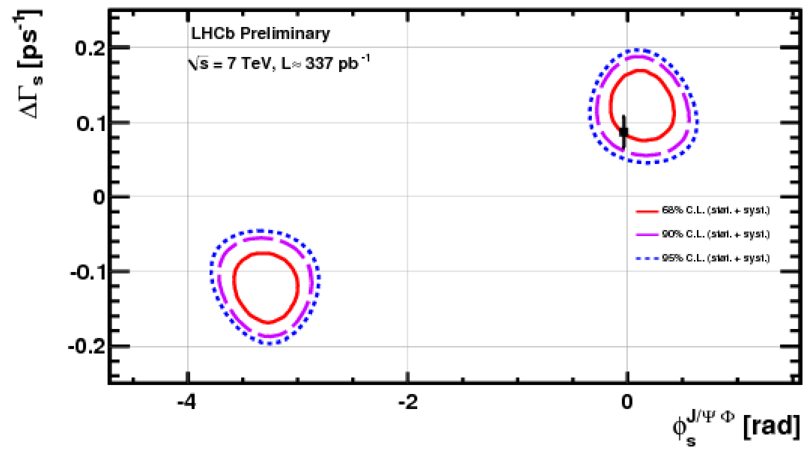
For 16 ps^{-1} < ΔM_s < 19 ps^{-1}, **fit favors negative phase $\varphi_s^{J/\psi\varphi}$**.

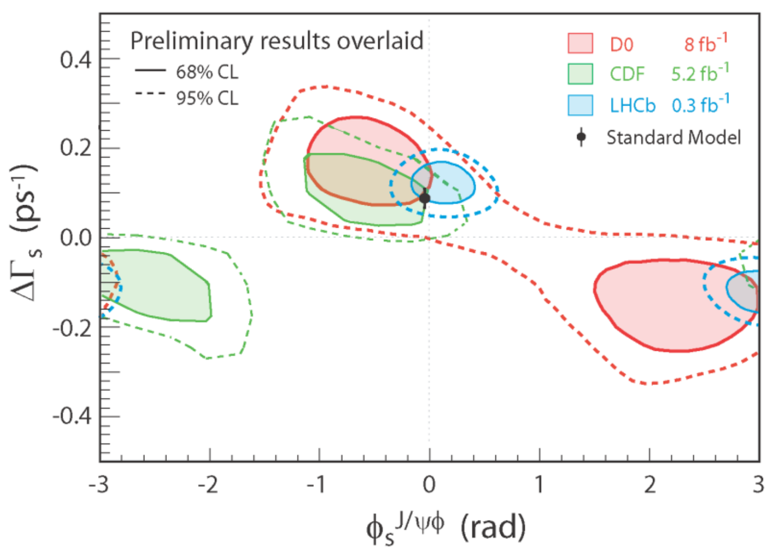
Future Prospects

Recent result from LHCb: consistent with Tevatron results, and with SM:

$\varphi_s^{J/\psi\varphi}$ **= +0.13 ± 0.18 ± 0.07**

Coming year(s) will see allowed space in $(\varphi_s^{J/\psi\varphi}, \Delta\Gamma_s)$ plane significantly reduced.





Additional Channels

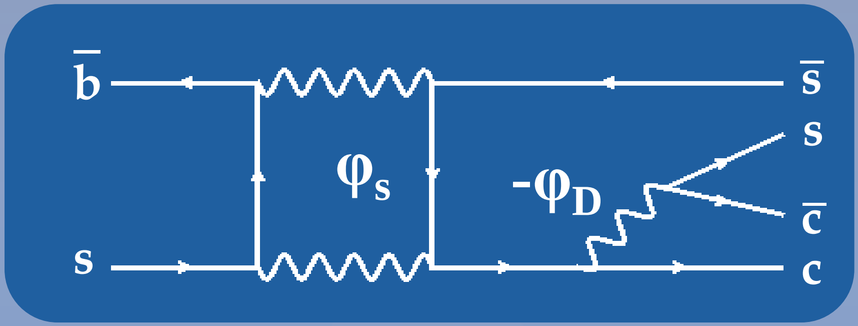
J/ψφ final state is challenging!

CP superposition: strong phases, angular analysis, S-wave.

Other channels offer complimentary access to $\varphi_s^{J/\psi\varphi}$ **…**

$B_s^0 \rightarrow J/\psi\ f_0(980)$

Same quarks, same couplings as $J/\psi\varphi$ **BUT** **Final state has well-defined angular momentum**



f_0 (spin 0)

J/ψ (spin 1)

L=1, CP-odd

Recall:

$$\Gamma(B_s^0 \rightarrow J/\psi\varphi)(t) = |A_i(t)|^2$$

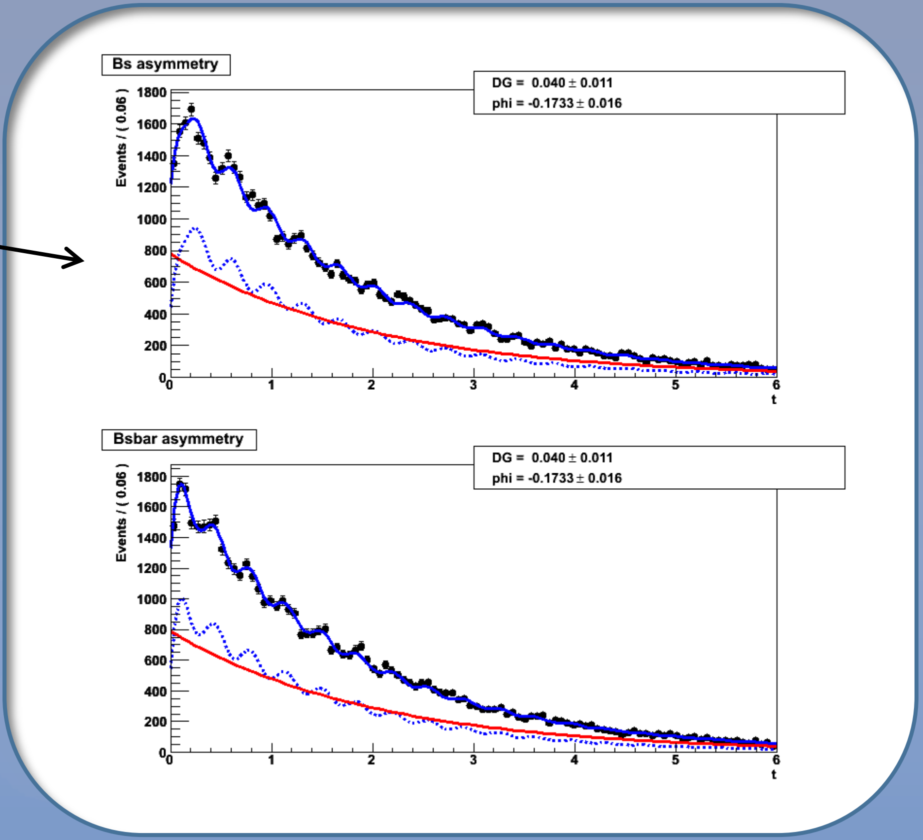
$$\Gamma(\bar{B}_s^0 \rightarrow J/\psi\varphi)(t) = |\bar{A}_i(t)|^2$$

4 parameters
(τ_s, ΔM_s, $\Delta\Gamma_s$, $\varphi_s^{J/\psi\varphi}$)

Can make independent measurement of $\varphi_s^{J/\psi\varphi}$, *if signal yield is large enough*.

$B_s^0 \rightarrow J/\psi\ f_0(980)$

Toy Monte Carlo studies demonstrate potential sensitivity to mixing (and hence CPV) in this channel.



But first:

1) Reconstruct decay $B_s^0 \rightarrow J/\psi\ f_0$;

2) Measure decay branching ratio relative to $J/\psi\varphi$ final state.

Theoretical predictions:

$$R = \frac{\mathbf{ß}(B^0_s \rightarrow J/\psi f_0(980); f_0(980) \rightarrow \pi^+\pi^-)}{\mathbf{ß}(B^0_s \rightarrow J/\psi\varphi;\ \varphi \rightarrow K^+K^-)}$$

$$\approx 20 - 40\%$$

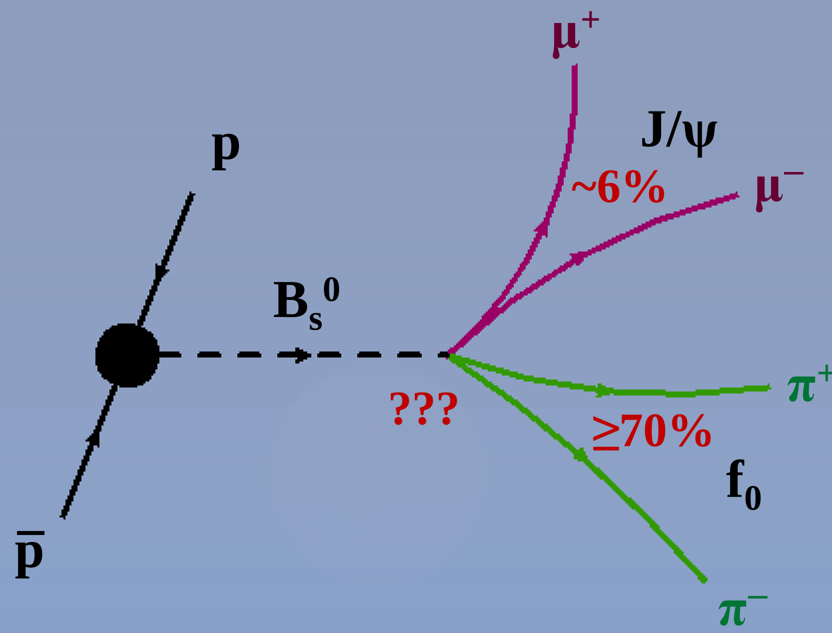
By measuring ratio of BRs, many systematic uncertainties cancel (trigger efficiency, muon ID/reconstruction efficiencies…)

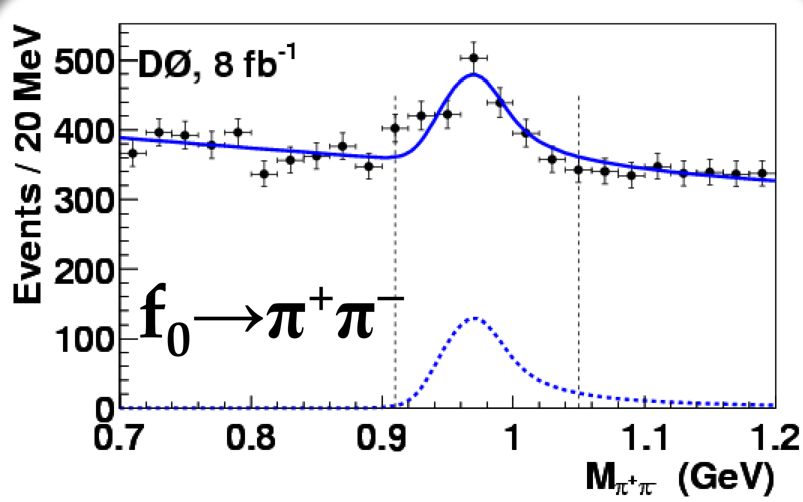
$B_s^0 \to J/\psi\ f_0(980)$

Reconstruct both final states:

- **$J/\psi\varphi$ ($\mu^+\mu^-K^+K^-$)**
- **$J/\psi f_0$ ($\mu^+\mu^-\pi^+\pi^-$)**

No way to separate kaons from pions – apply cuts on M(ππ), M(KK) to avoid ambiguity.





Event selection based on BDT developed for J/ψφ analysis:

- Separate trees for prompt and long-lived backgrounds;
- M(KK) removed from BDT;
- Final cut points chosen to optimise $S/\sqrt{(S+B)}$.

Cut on decay time: $\mathbf{t/\sigma(t) > 5}$

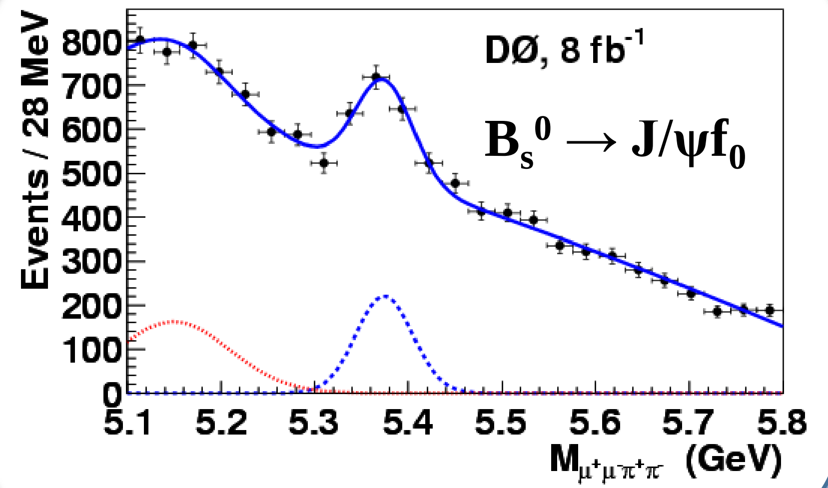
$B_s^0 \to J/\psi\, f_0(980)$

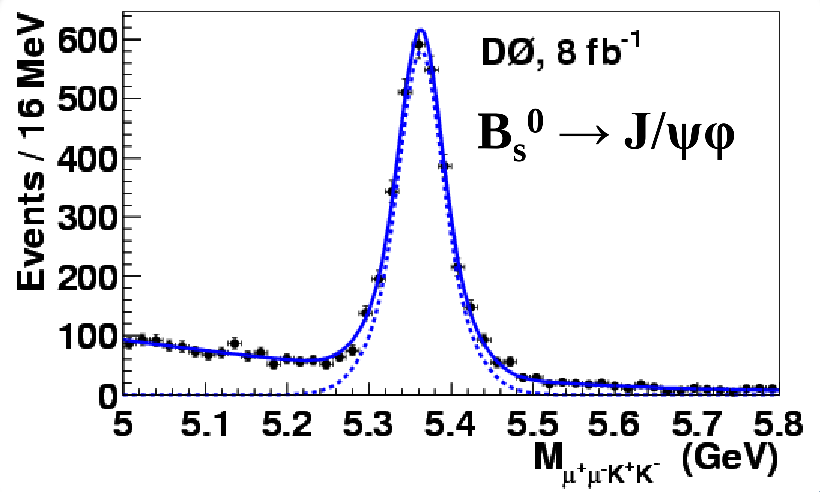
Analysis Method

1) Fit mass distributions to extract B_s^0 signal yield in each channel;

$N(B_s^0 \to J/\psi f_0) = 590 \pm 84$

$N(B_s^0 \to J/\psi \varphi) = 2929 \pm 62$





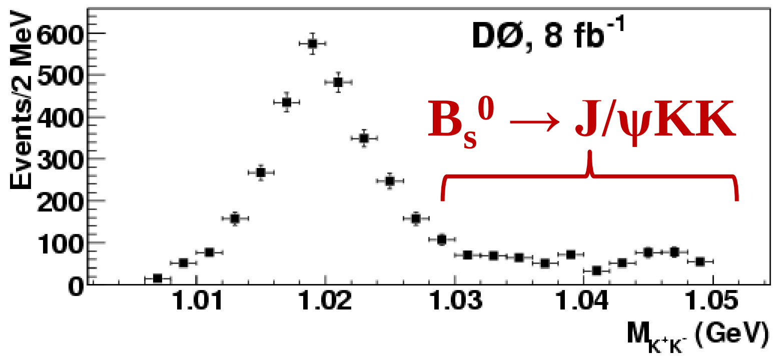
2) Extract relative reconstruction / selection efficiencies from simulation

$$\frac{\varepsilon_{reco}^{B_s^0 \to J/\psi\varphi}}{\varepsilon_{reco}^{B_s^0 \to J/\psi f_0}} = 1.20 \pm 0.04$$

$B_s^0 \rightarrow J/\psi\ f_0(980)$

3) Account for peaking backgrounds:

- Non-resonant $B_s^0 \rightarrow J/\psi K^+K^-$ (S-wave) in $J/\psi\varphi$: $(12 \pm 3)\%$ of signal. →



- Possible non-resonant $B_s^0 \rightarrow J/\psi\pi^+\pi^-$ found to be negligible.

  No B_s^0 peak observed outside f0 peak region in range:

  $0.8 < M(\pi^+\pi^-) < 0.9$ GeV.

$B_s^0 \to J/\psi\, f_0(980)$

Final Measurement:

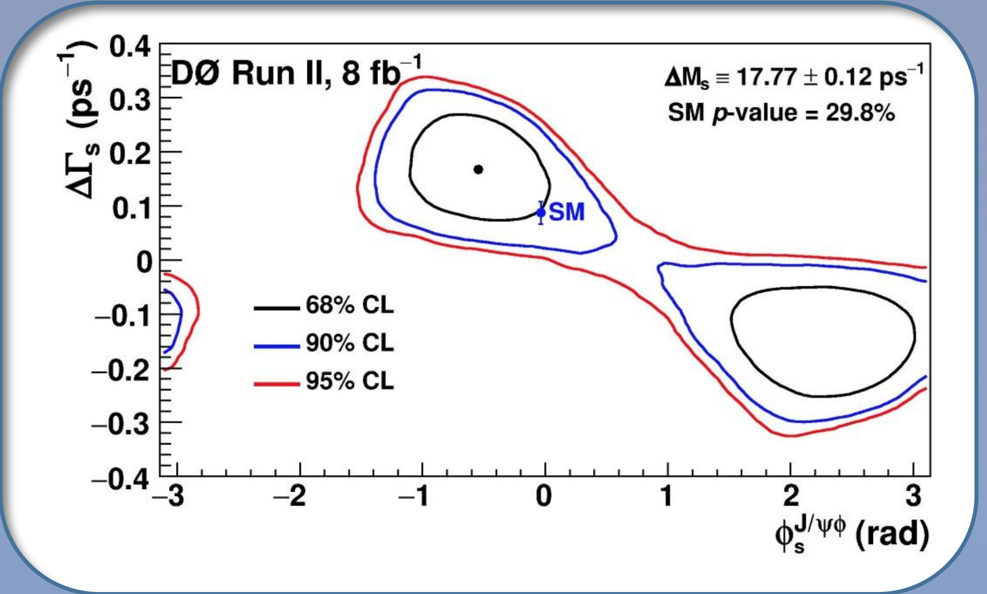
$$R = \frac{\mathcal{B}(B^0_s \to J/\psi f_0(980); f_0(980) \to \pi^+\pi^-)}{\mathcal{B}(B^0_s \to J/\psi \varphi;\ \varphi \to K^+K^-)}$$

$$= 0.275 \pm 0.041 \pm 0.061$$

Systematic uncertainties

Fit with different background models (yield)	**~17%**
Reweighting MC to match data distributions (efficiency)	**~9%**
Opening M(KK) window (yield)	**~4%**
Uncertainty on F_S (yield)	**~4%**

Summary

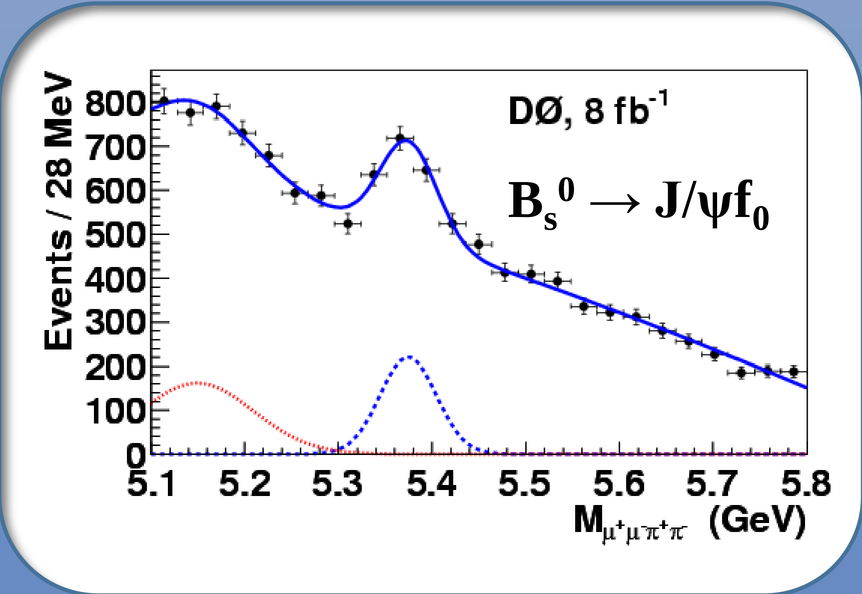


Updated CPV analysis in $\mathbf{B_s^0 \rightarrow J/\psi\varphi}$ submitted to Phys. Rev. D. (arXiv:1109.3166);

Results consistent with SM;

Significant S-wave fraction (~12-17%)

Combination with CDF in progress;



D0 measurement of $\mathbf{B_s^0 \rightarrow J/\psi f_0}$ decay BR submitted to Phys. Rev. D. (RC). (arXiv:1110.4272)

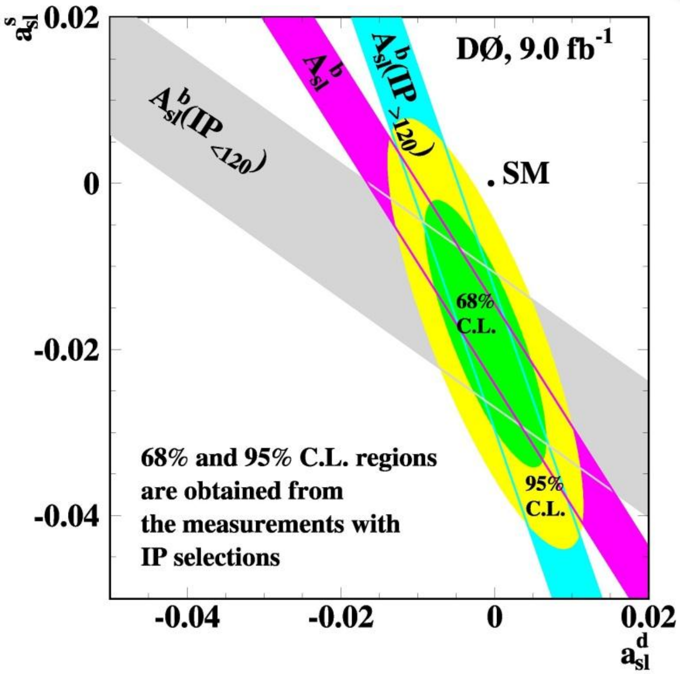
Relative branching ratio of ~27% consistent with results from Belle, CDF, LHCb

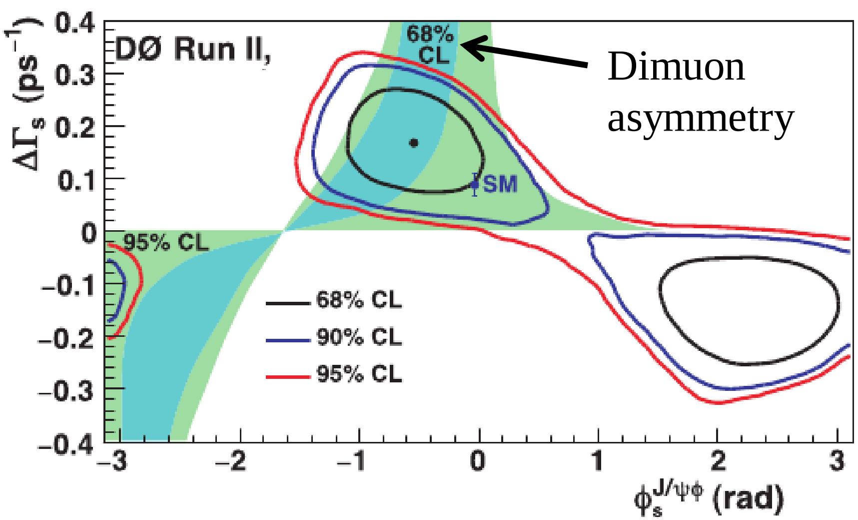
Next step: Lifetime and CPV analysis (currently ongoing)

CP Violation ?

Current results in $B_s^0 \to J/\psi\varphi$ suggest any CP violation in *interference* is small.

CPV in *mixing* can be probed by the dimuon asymmetry measurement: 2011 update suggests ~4σ deviation from SM.





Currently, no disagreement between experimental results (or LHCb result).

Promises to be an exciting few months/years!

The End

(Thank you)

S-wave and Symmetry

P-wave amplitude is symmetric in cosψ:
$\Gamma_P \sim \cos^2\psi$

S-wave independent of cosψ, $\Gamma_S \sim c$

P-S interference term gives characteristic asymmetry, **proportional to** $\cos\delta_S$;

Sign of asymmetry flips at the φ mass.

Fitting cosψ distribution to second-degree polynomial, small asymmetry is seen, and linear coefficient C_1 flips sign.

Marginally favors $\cos\delta_S < 0$;

Small asymmetry consistent with small value of $\cos\delta_S$.