B physics at Tevatron

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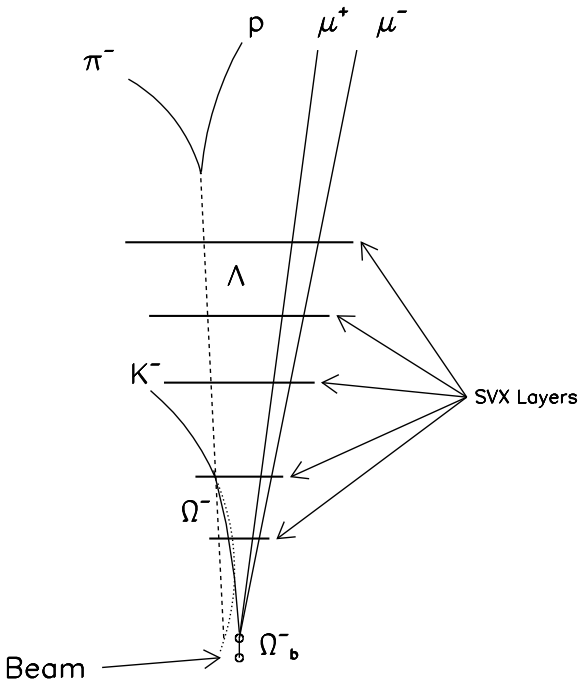
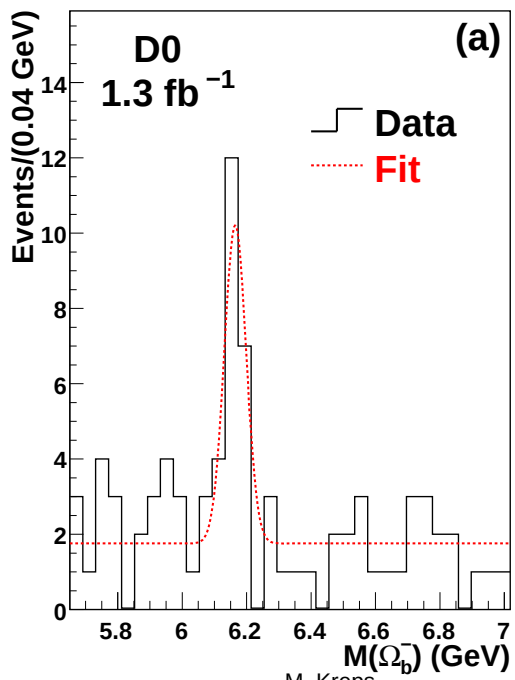
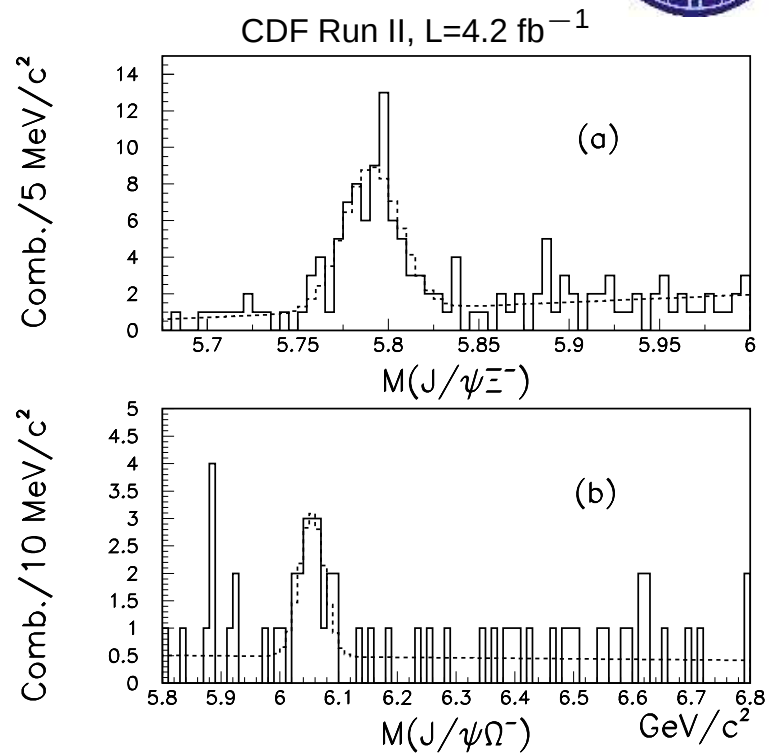
für Bildung
und Forschung

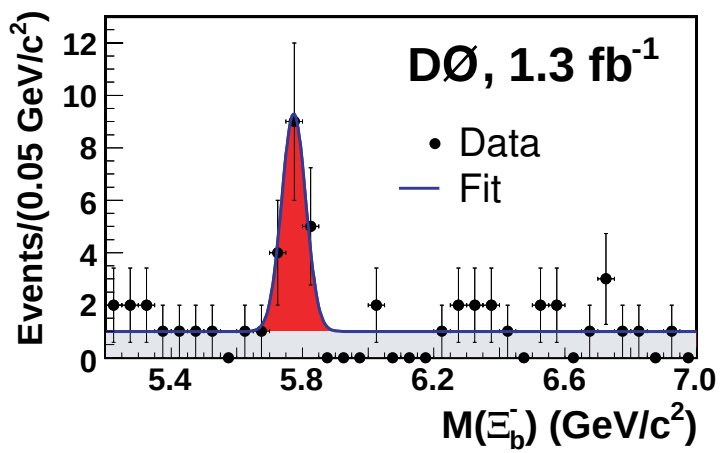
Ω_b observation

- Three years ago only observed *b*-baryon was Λ_b
- Lot of progress in last years
- Latest addition $\Omega_b \to J/\psi\Omega$
- Used data: 1.3 fb^{-1} (DØ)
  4.2 fb^{-1} (CDF)



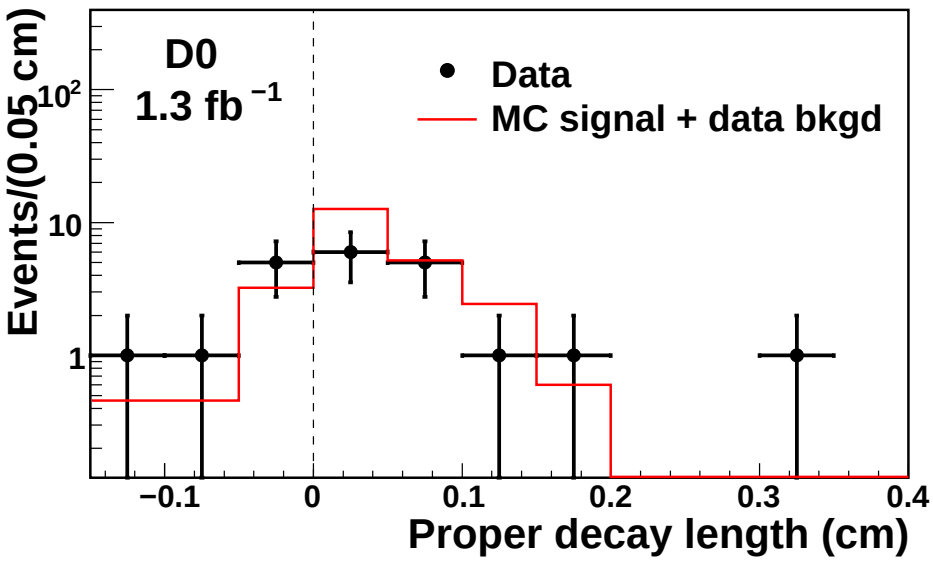


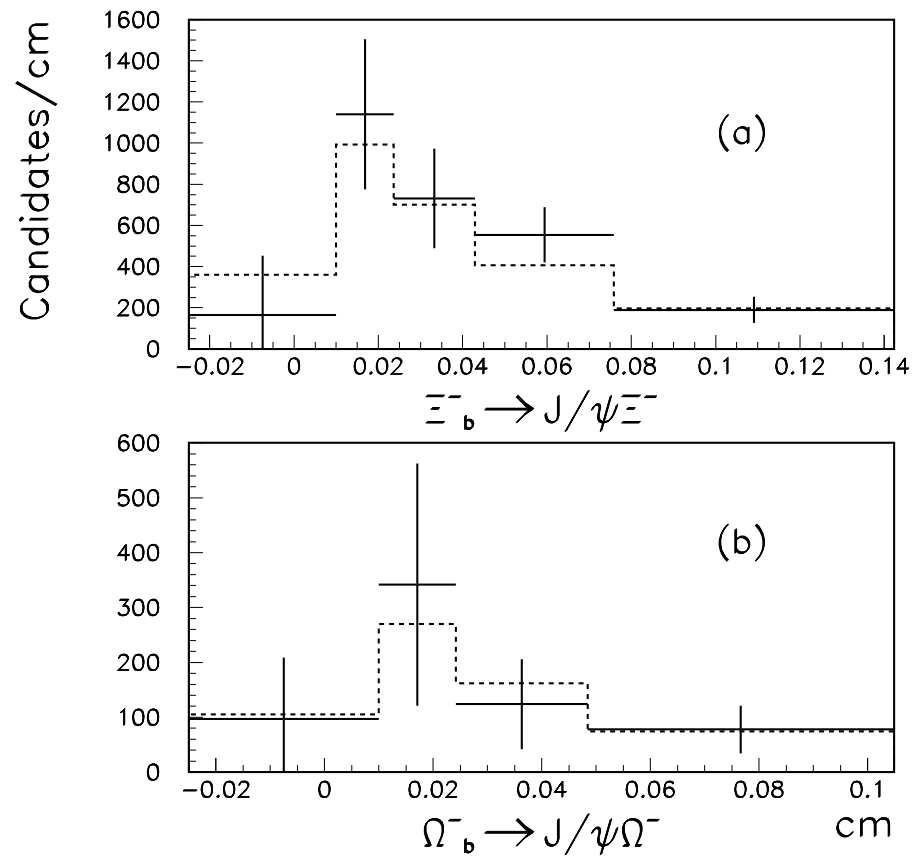




Ω_b observation

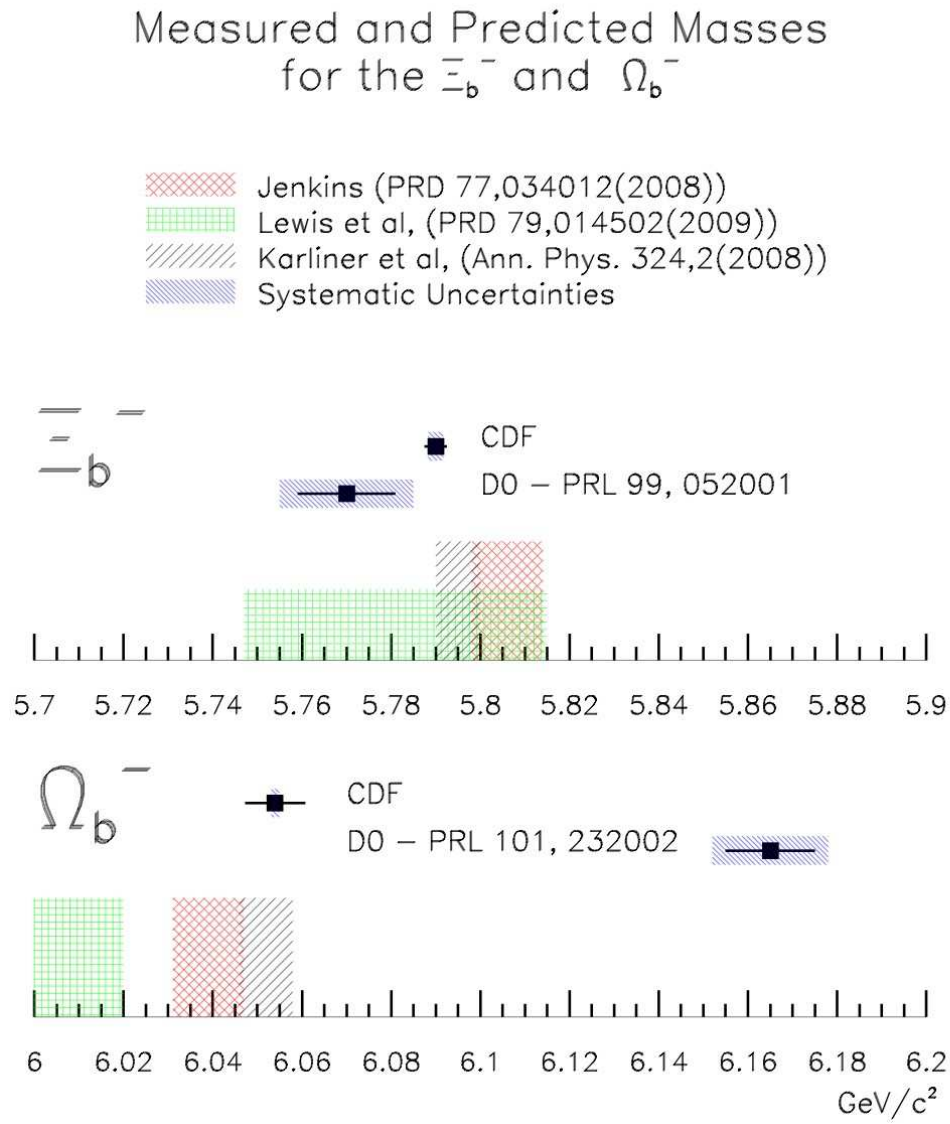
- Observed events: $17.8 \pm 4.9 \pm 0.8$ (DØ) and 16^{+6}_{-4} (CDF)
- Significance: 5.4σ (DØ) and 5.5σ (CDF)
- Rate of Ω_b^- / Ξ_b^-: $0.8 \pm 0.32^{+0.14}_{-0.22}$ (DØ)
  $0.27 \pm 0.12 \pm 0.01$ (CDF)
- CDF measures also lifetime:
  $\tau(\Xi_b) = 1.56^{+0.27}_{-0.25} \pm 0.02$ ps
  $\tau(\Omega_b) = 1.13^{+0.53}_{-0.40} \pm 0.02$ ps





Ω_b observation

- Measured masses:
  DØ: $6165 \pm 10 \pm 13$ MeV
  CDF: $6054.4 \pm 6.8 \pm 0.9$ MeV
- Clear discrepancy of about 6σ
- Rates consistent within large uncertainties
- No reason found
- More work needed to resolve it



B_s system

- B_s system is unique due to fast oscillation and non-zero $\Delta\Gamma$
- Time evolution of states described by

$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}|B_s^0(t)\rangle\\ |\bar{B}_s^0(t)\rangle\end{pmatrix} = \left(\mathbf{M}-\frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix}|B_s^0(t)\rangle\\ |\bar{B}_s^0(t)\rangle\end{pmatrix}$$

- $\mathbf{M}$ and $\mathbf{\Gamma}$ are complex 2×2 matrices
- Observable parameters:
  - Mean mass m_s
  - Mass difference $\Delta m_s = m_H - m_L = 2|M_{12}|$
  - Mean lifetime $\tau = 2/(\Gamma_H + \Gamma_L)$
  - Width difference $\Delta\Gamma = \Gamma_L - \Gamma_H = 2|\Gamma_{12}|\cos(\phi_s)$
  - CPV phase $\phi_s = \arg(-M_{12}/\Gamma_{12})$

New physics in ϕ_s

- If there is new physics, than $\phi_s = \phi_s^{SM}(= 0.004) + \phi_s^{NP}$
- Measurement of semileptonic CP asymmetry $\leftrightarrow A_{SL} = -|\Gamma_{12}/M_{12}| \sin\phi_s$

$\rightarrow$ Difficult due to smallness of the A_{SL}

- Measurement of $\Delta\Gamma \leftrightarrow \Delta\Gamma = \Gamma_L - \Gamma_H = 2|\Gamma_{12}| \cos(\phi_s)$

$\rightarrow$ Need input for $|\Gamma_{12}| \leftrightarrow$ can come from $\mathcal{B}(B_s \rightarrow D_s^{(*)} D_s^{(*)})$

- Measurement of CP violation in CP modes

$\rightarrow$ Golden mode pursued currently is $B_s \rightarrow J/\psi\phi$

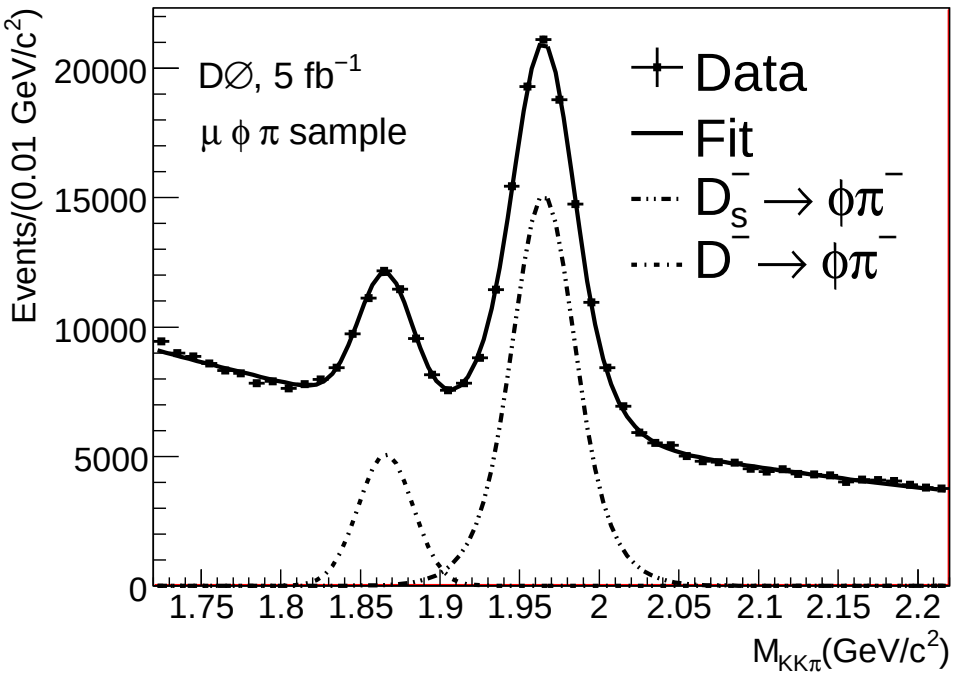
$\rightarrow$ Does not measure ϕ_s, but phase between mixing and $b \rightarrow c\bar{c}s$ transition β_s

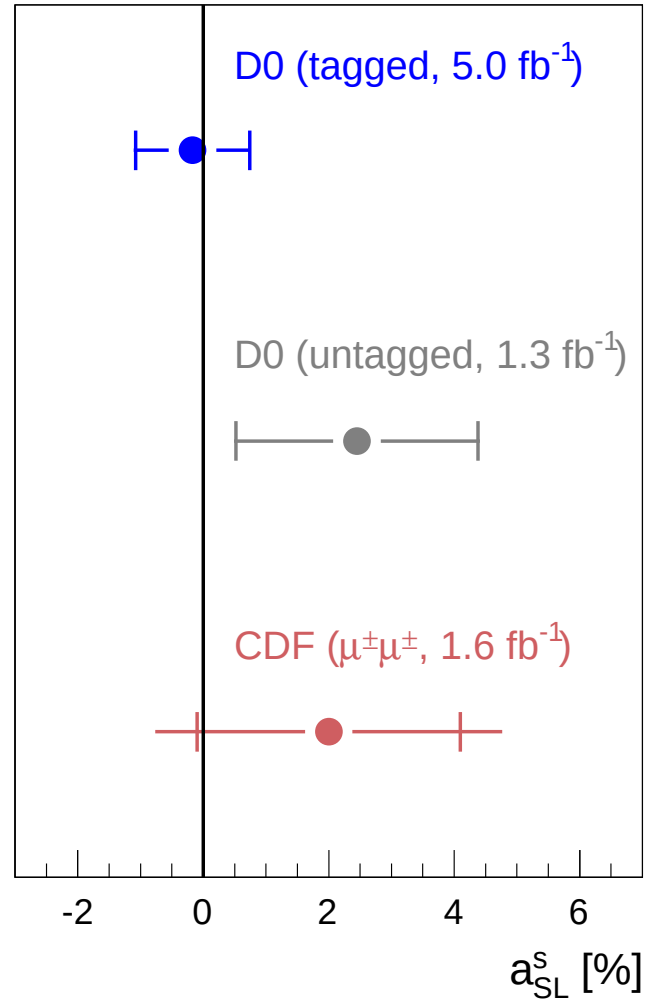
- In presence of new physics $-2\beta_s = -2\beta_s^{SM}(= 0.04) + \phi_s^{NP}$
- With current experimental precision SM values negligable and we are testing NP contribution

A_{sl} in B_s

- Uses $B_s \to D_s^- \mu^+ X$ with $D_s^- \to \phi\pi$ and $D_s^- \to K^* K$
- Measures difference in mixing rate for B_s and $\bar{B}_s$
- Tagged time dependent analysis
- SM expectation $a_{SL} = 2 \times 10^{-5}$

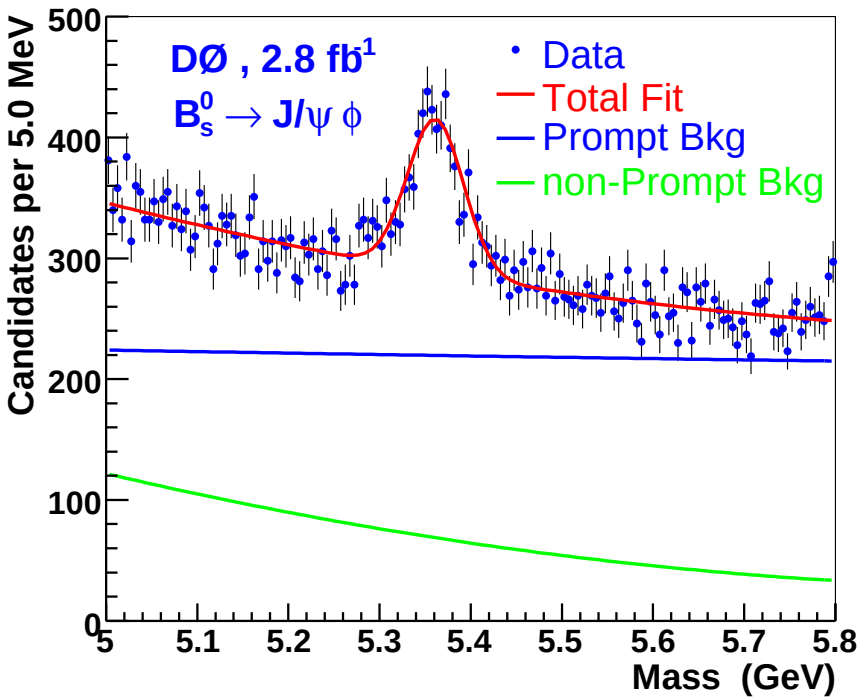
$$a_{SL} = -0.17 \pm 0.91^{+0.12}_{-0.23}\%$$

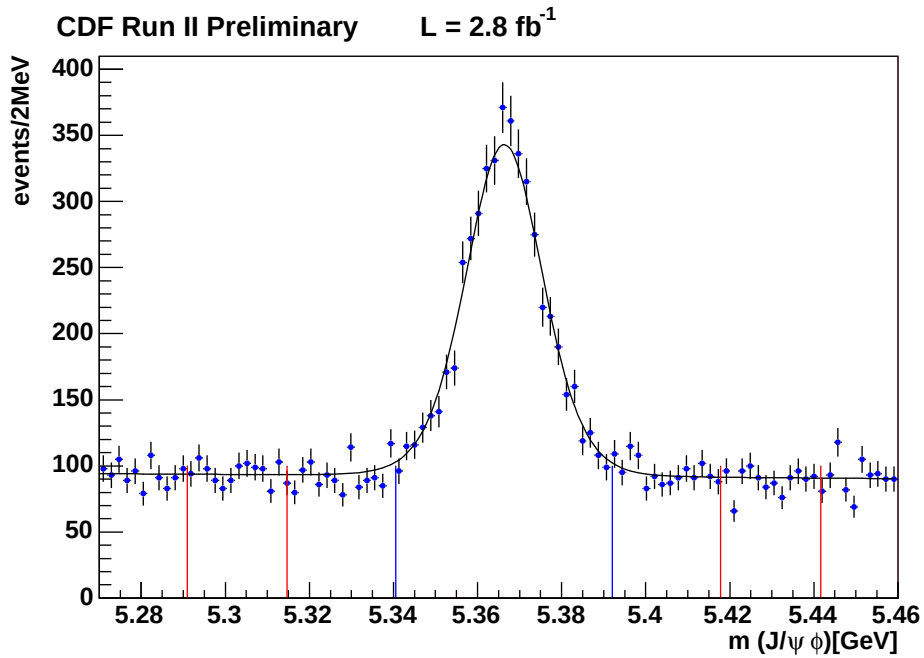




CPV in $B_s \to J/\psi\phi$

- Both experiments using 2.8 fb^{-1} of data
- Dimuon trigger
- Cut based selection at DØ, Neural network at CDF
- Signal events: 1967 ± 65 (DØ) and ≈ 3150 (CDF)



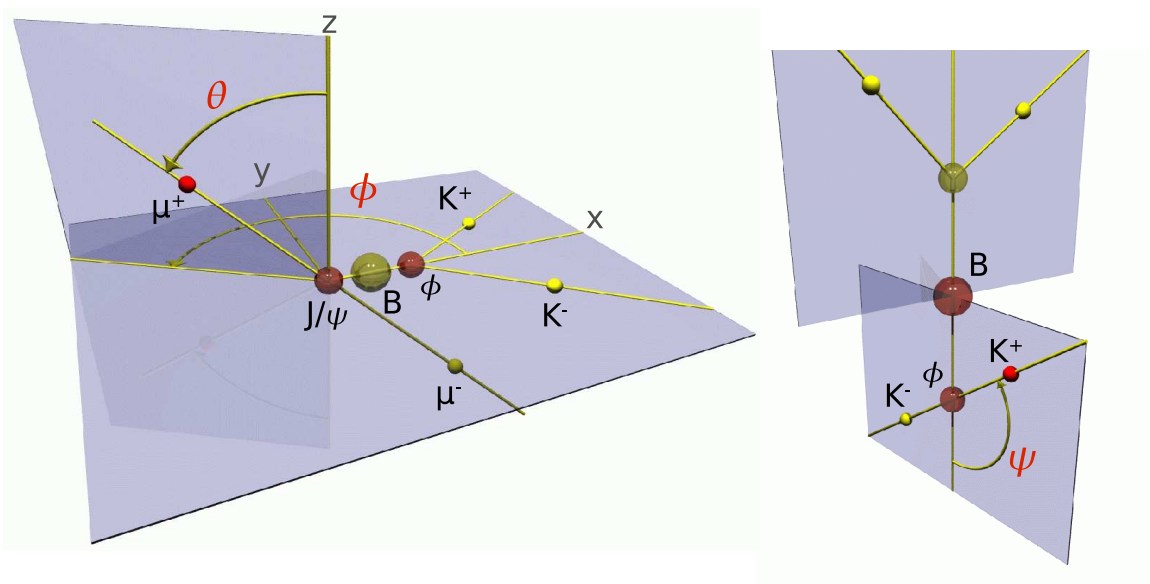


CP-even vs. CP-odd

- Full decay $B_s \to J/\psi\phi$ with $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$
- B_s is pseudoscalar, J/ψ and ϕ vectors $\Rightarrow L = 0, 1, 2$
- $L = 0, 2$ are CP-even, $L = 1$ CP-odd

$\Rightarrow$ Angular distributions can statistically separate CP-even from CP-odd component

- Use transversity basis as used in previous analyses



Signal PDF

- Signal PDF for single tag

$$P_s(t, \vec{\rho}, \xi | \mathcal{D}, \sigma_t) = \frac{1+\xi\mathcal{D}}{2} P(t, \vec{\rho}|\sigma_t)\epsilon(\vec{\rho}) + \frac{1-\xi\mathcal{D}}{2} \overline{P}(t, \vec{\rho}|\sigma_t)\epsilon(\vec{\rho})$$

- $\xi = -1, 0, 1$ is tagging decision
- $\mathcal{D}$ is event-specific dilution
- $\epsilon(\vec{\rho})$ - acceptance function in angular space
- $P(t, \vec{\rho}|\sigma_t)$ ($\overline{P}(t, \vec{\rho}|\sigma_t)$) is PDF for B_s ($\overline{B}_s$)

Signal PDF

$$\frac{d^4P(t,\vec{\rho})}{dt\,d\vec{\rho}} \propto |A_0|^2\mathcal{T}_+ f_1(\vec{\rho}) + |A_\parallel|^2\mathcal{T}_+ f_2(\vec{\rho}) + |A_\perp|^2\mathcal{T}_- f_3(\vec{\rho})$$
$$+ |A_\parallel||A_\perp|\mathcal{U}_\pm f_4(\vec{\rho}) + |A_0||A_\parallel|\cos(\delta_\parallel)\mathcal{T}_+ f_5(\vec{\rho})$$
$$+ |A_0||A_\perp|\mathcal{V}_\pm f_6(\vec{\rho})$$

$$\mathcal{T}_\pm = e^{-\Gamma t} \times [\cosh(\Delta\Gamma t/2) \mp \cos(2\beta_s)\sinh(\Delta\Gamma t/2)$$
$$\mp \eta\sin(2\beta_s)\sin(\Delta m_s t)]\,,$$
$$\mathcal{U}_\pm = \pm e^{-\Gamma t} \times \big[\sin(\delta_\perp - \delta_\parallel)\cos(\Delta m_s t)$$
$$- \cos(\delta_\perp - \delta_\parallel)\cos(2\beta_s)\sin(\Delta m_s t)$$
$$\pm \cos(\delta_\perp - \delta_\parallel)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)\big]\,,$$
$$\mathcal{V}_\pm = \pm e^{-\Gamma t} \times [\sin(\delta_\perp)\cos(\Delta m_s t)$$
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Signal PDF

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$$\mathcal{T}_\pm = e^{-\Gamma t} \times [\cosh(\Delta\Gamma t/2) \mp \cos(2\beta_s)\sinh(\Delta\Gamma t/2)$$
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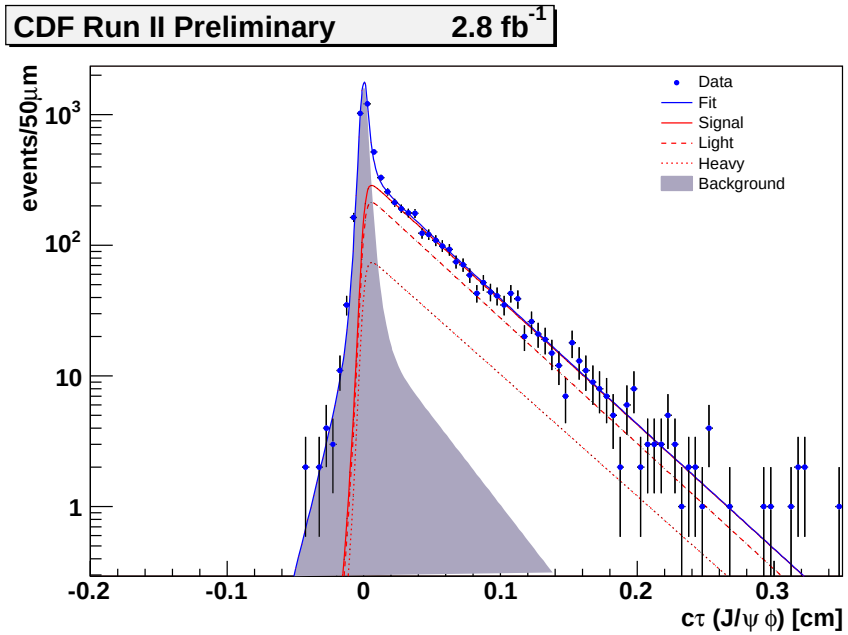
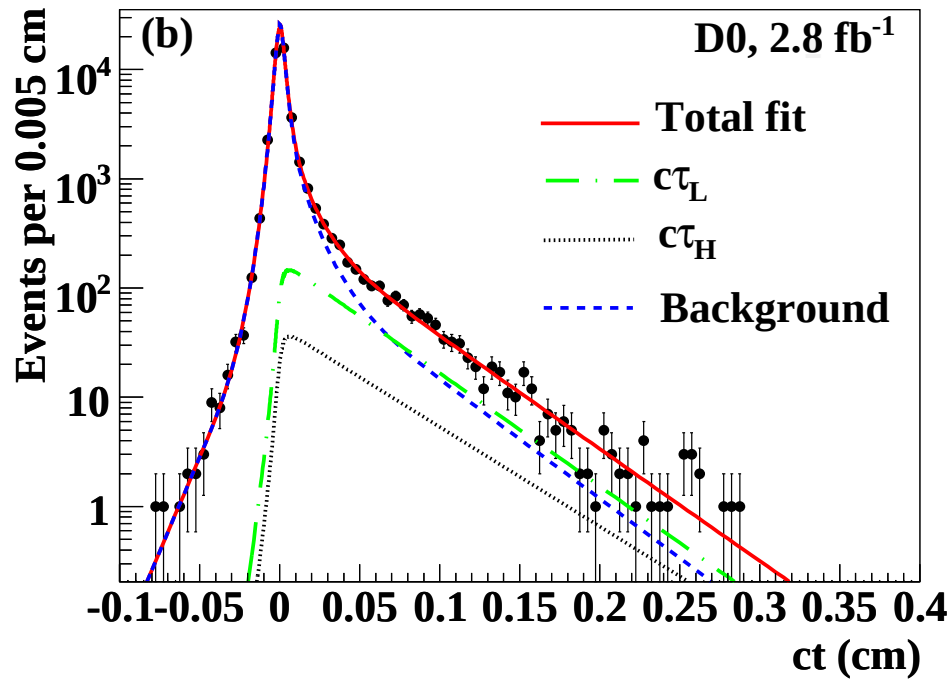
$B_s \to J/\psi\phi$ Lifetime





$\tau = 1.53 \pm 0.04 \pm 0.01\text{ps}$

$\Delta\Gamma = 0.02 \pm 0.05 \pm 0.01\text{ps}^{-1}$

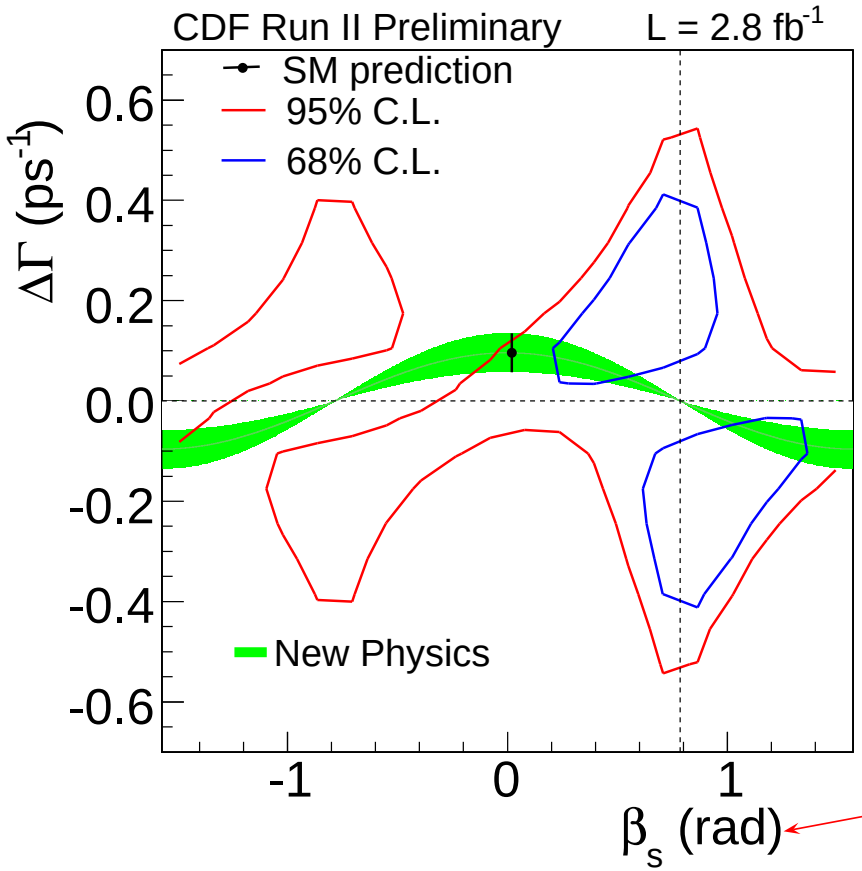
$\tau = 1.49 \pm 0.06 \pm 0.03\text{ps}$

$\Delta\Gamma = 0.085^{+0.072}_{-0.078} \pm 0.001\text{ps}^{-1}$

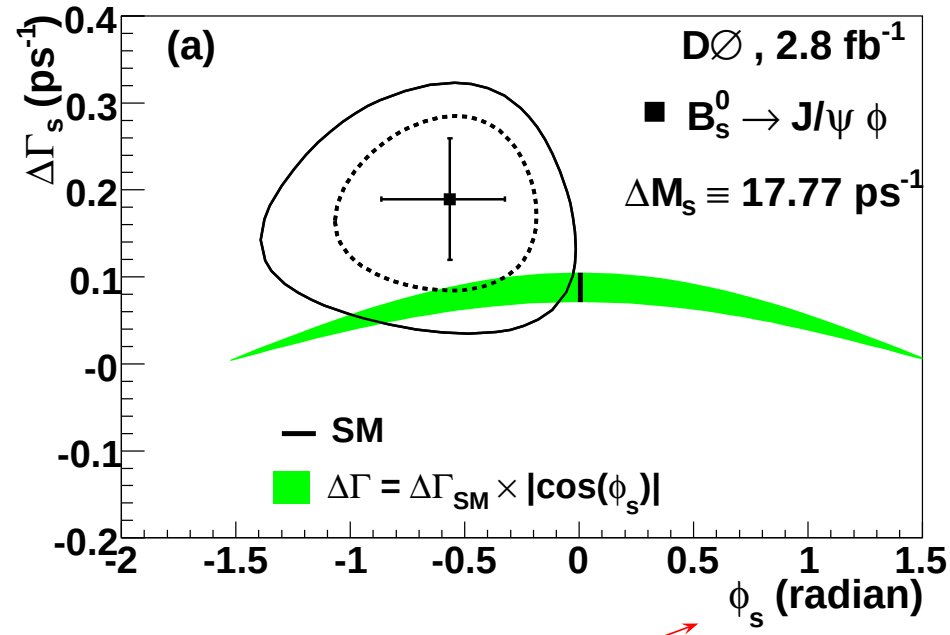
$B_s \to D_s \pi X$: $\tau = 1.518 \pm 0.041 \pm 0.027$ ps

PDG B^0: $\tau = 1.53 \pm 0.009$ ps

CPV in $B_s \to J/\psi\phi$



Published result



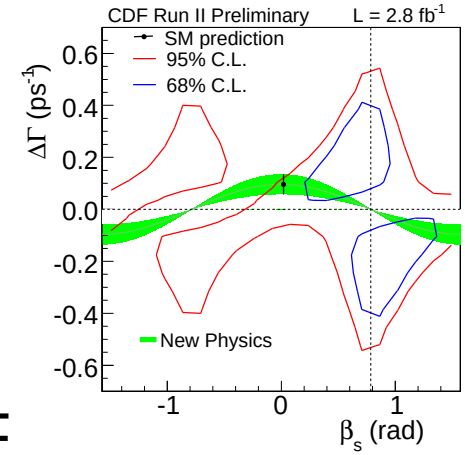
$\phi_s = -2\beta_s$

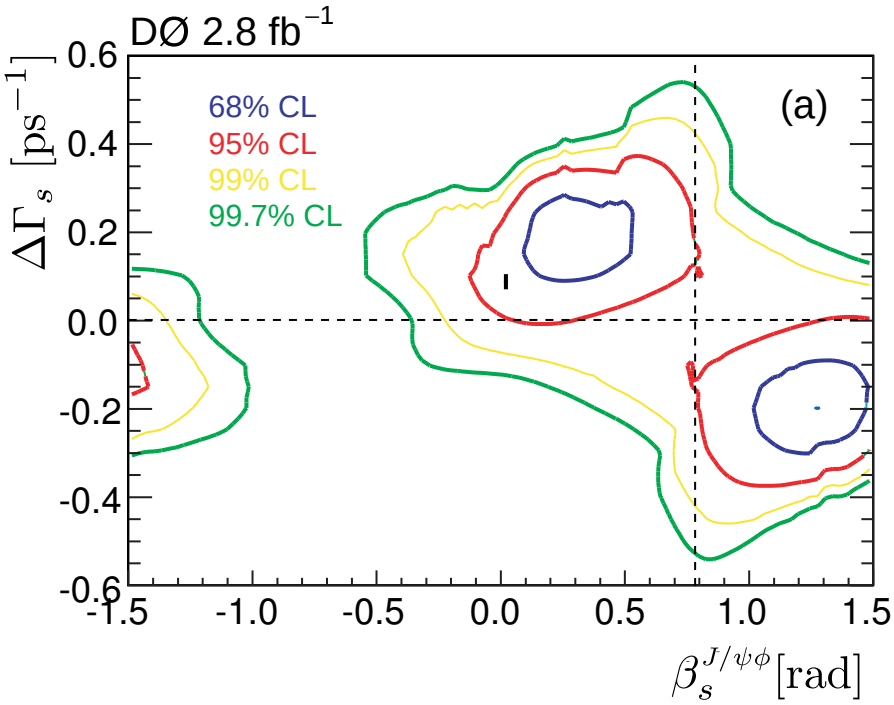
SM p-value 0.07 $\Leftrightarrow \approx 1.8\sigma$

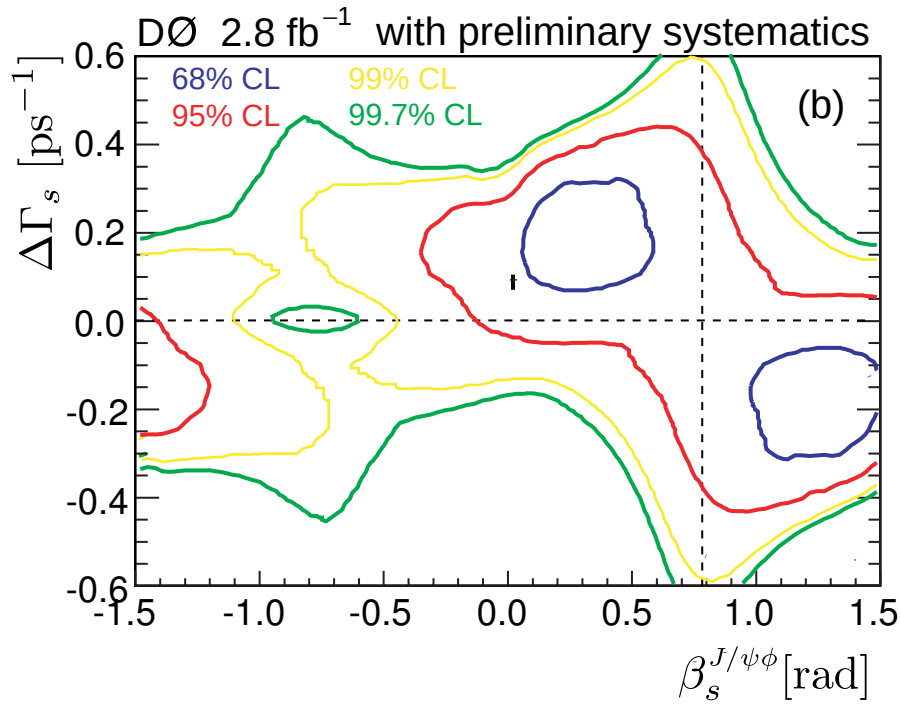
SM p-value 0.066 $\Leftrightarrow \approx 1.8\sigma$
Strong phases constrained to $B^0 \to J/\psi K^*$

CPV in $B_s \to J/\psi\phi$

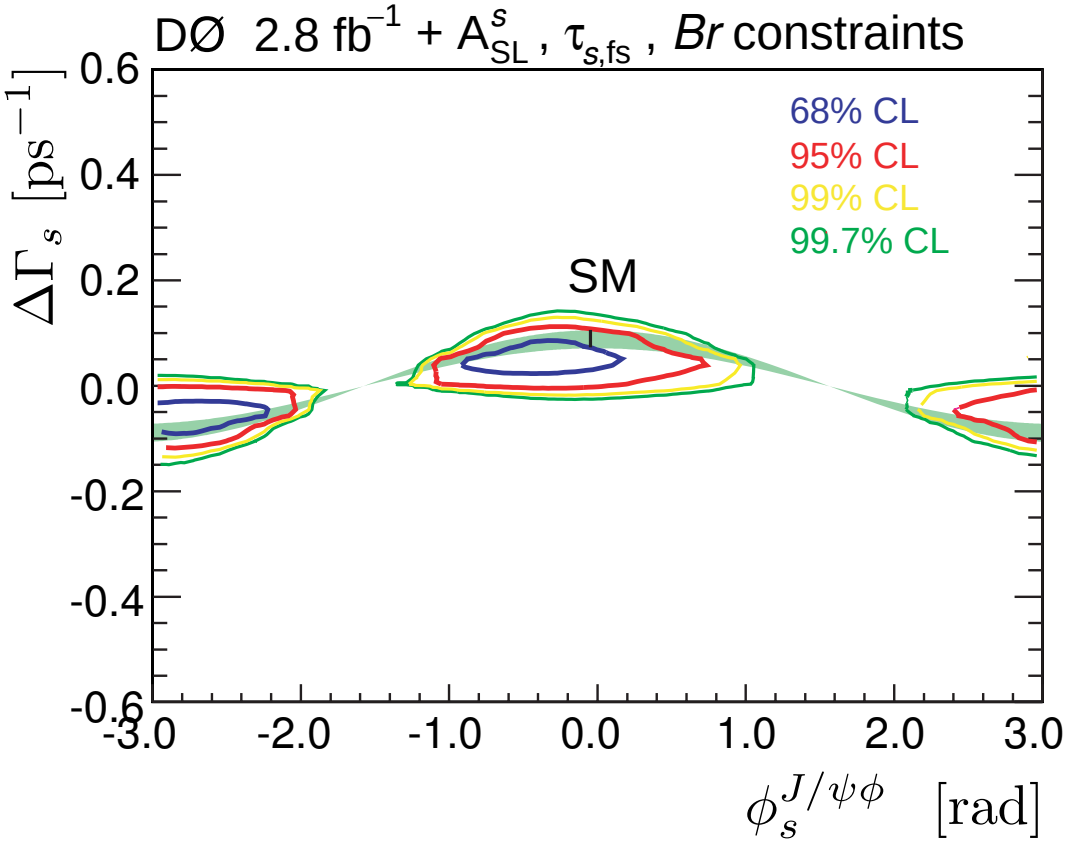
- DØ updates the published analysis
- Remove constraints on strong phases
- Ensure coverage
- Include systematic uncertainties
- Comparable in methods and sensitivity to CDF







Other constraints on ϕ_s

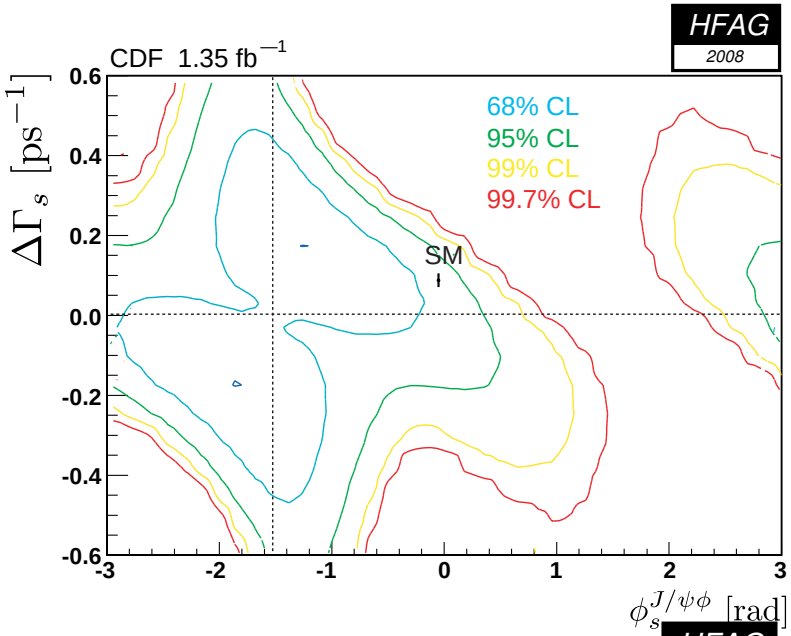


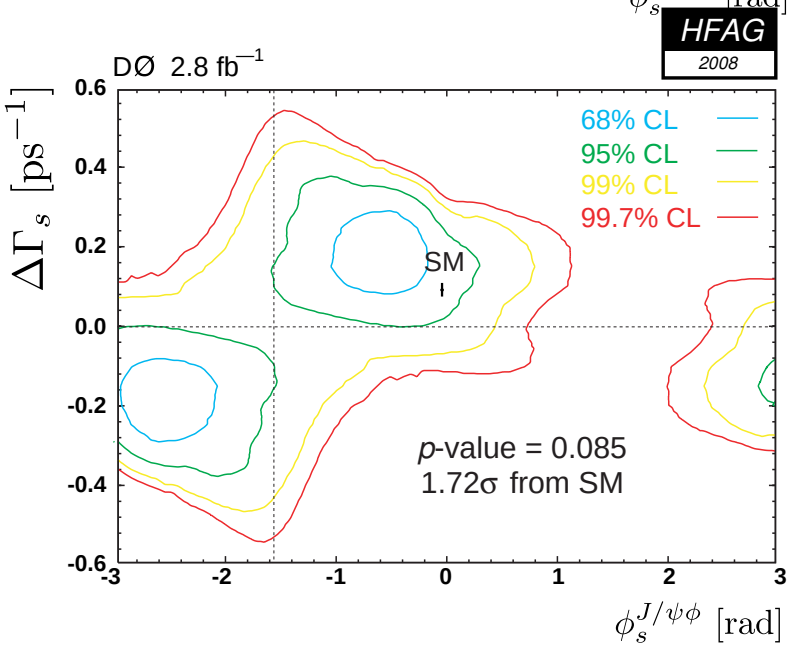
SM p-value 10%

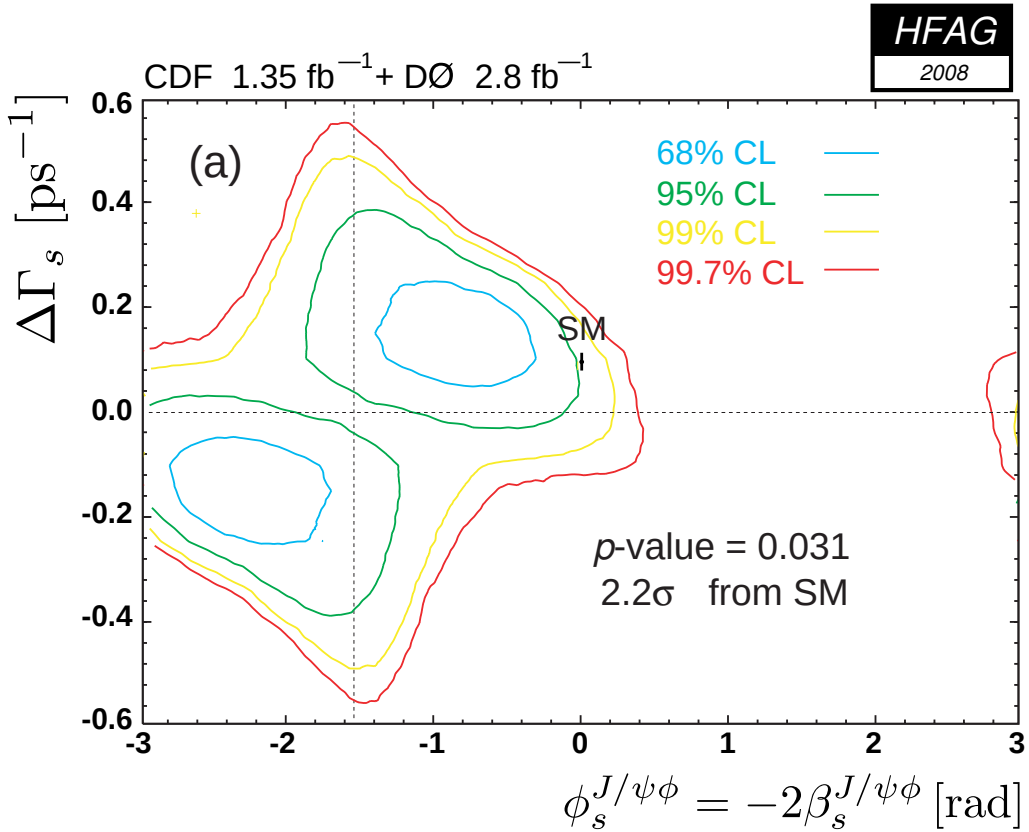
- Several quantities can constrain $\Delta\Gamma_s$ and ϕ_s:
  - A_{sl}
  - B_s lifetime in flavor specific decays
  - BF of $B_s \to D_s^{(*)} D_s^{(*)}$
- DØ contributes significantly to them

$\to$ Combine with CPV result in $B_s \to J/\psi\phi$

Tevatron ϕ_s combination







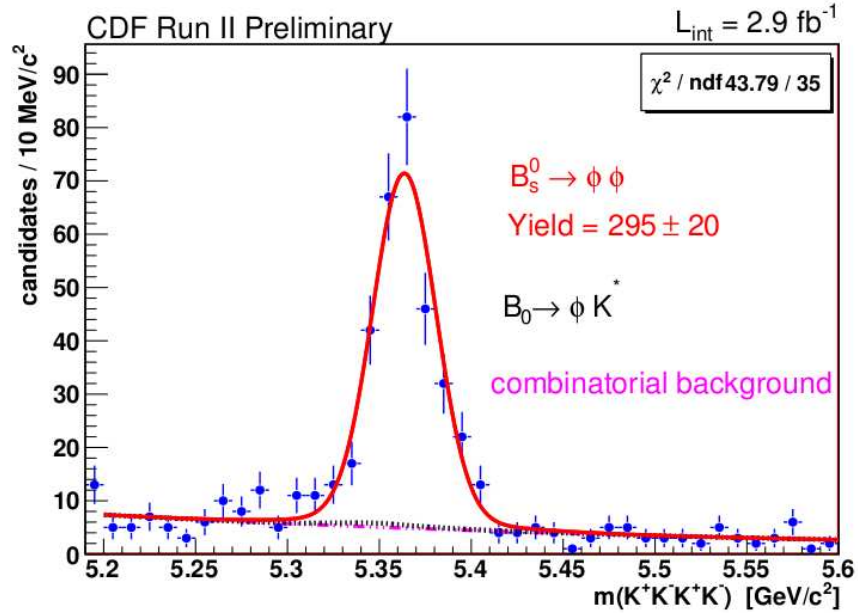
→ Lot of work to make CDF and DØ more uniform

→ Almost done with new combination

- Work on combine fit

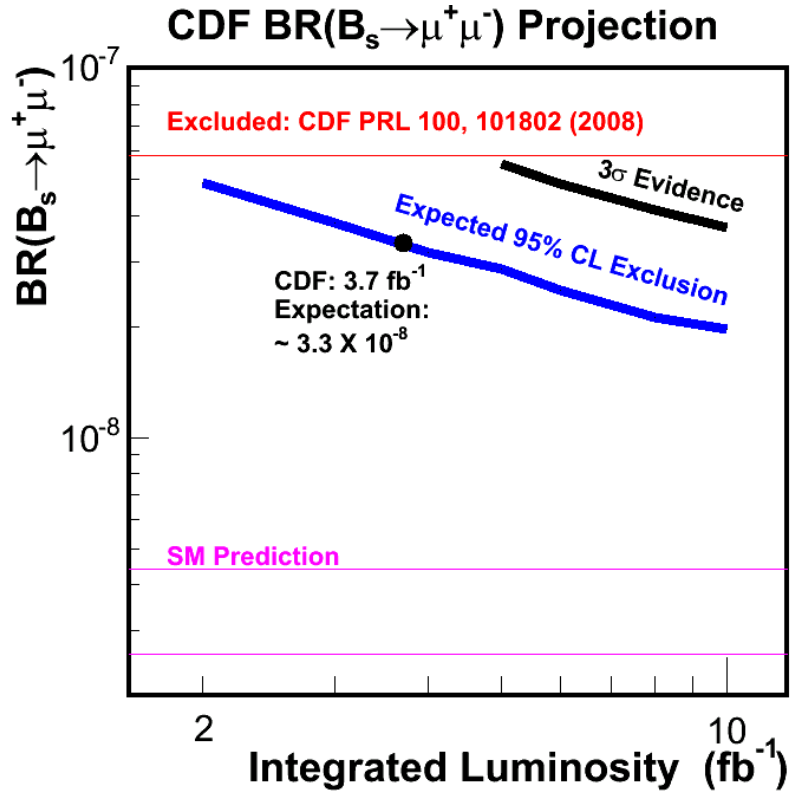
BF of $B_s \to \phi\phi$

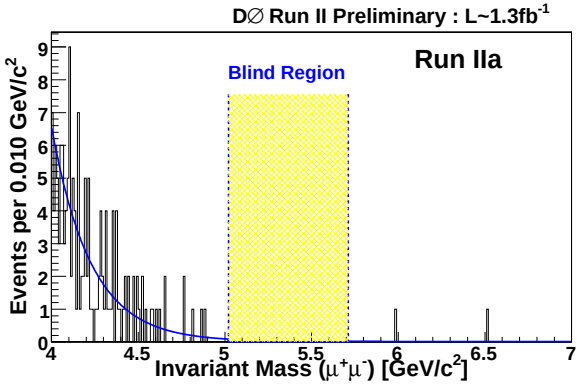
- $B_s \to \phi\phi$ decay proceed through $b \to s\bar{s}s$ transition $\Leftrightarrow$ interesting window to new physics
- Two types of NP contribution
  - $\to$ NP which would be seen in decays like $B^0 \to \phi K_s^0$
  - $\to$ NP contributing to $B_s \to J/\psi\phi$
- Only previous measurement from CDF using 8 events
- With 2.9 fb^{-1} observe 295 ± 20 events
- Measure branching fraction $[24.0 \pm 2.1 \pm 2.7 \pm 8.2] \cdot 10^{-6}$
- Consistent with SM
- Next step amplitude analysis

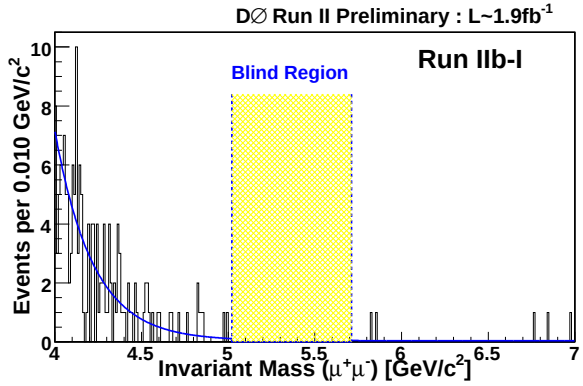


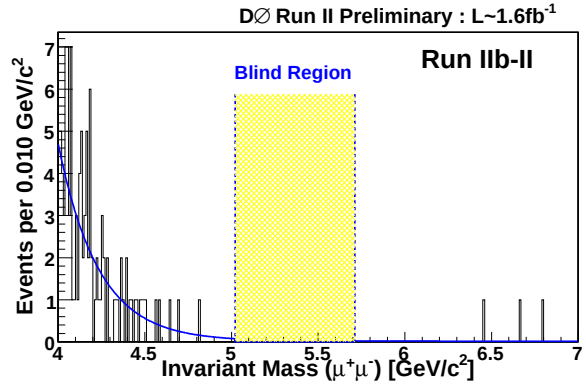
FCNC $B_s \to \mu\mu$ decays

- SM expectation: $3.42 \pm 0.54 \times 10^{-9}$
- Existing results (1.3-2fb^{-1})
  DØ: $9.4(12) \times 10^{-8}$
  CDF: $4.7(5.8) \times 10^{-8}$
- On way to update with more data
- Data still blind
- Expected limit
  DØ: 5.3×10^{-8}
  CDF: 3.3×10^{-8}

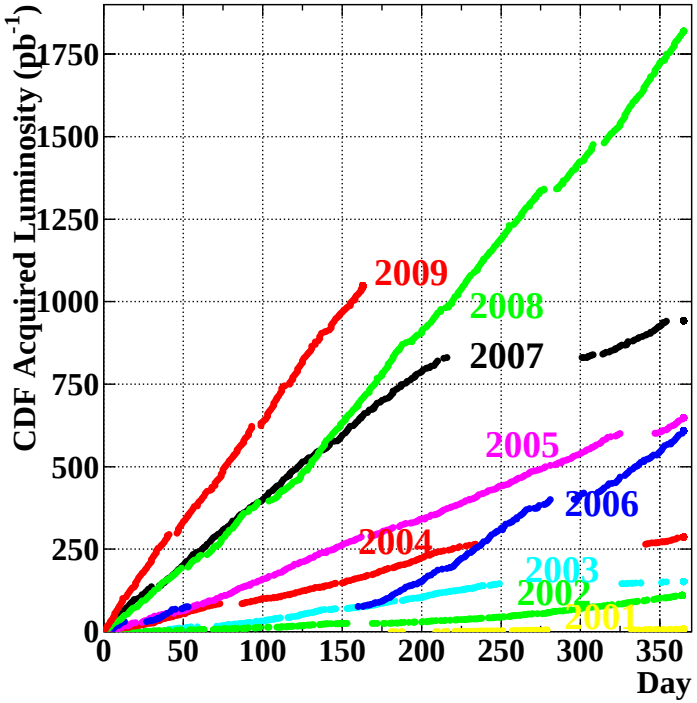


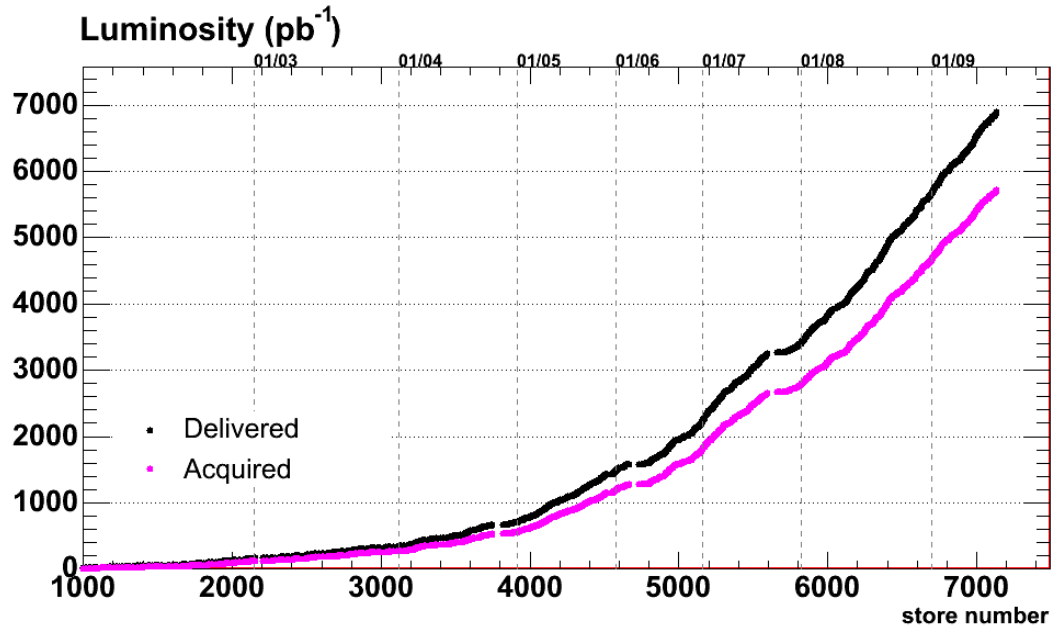


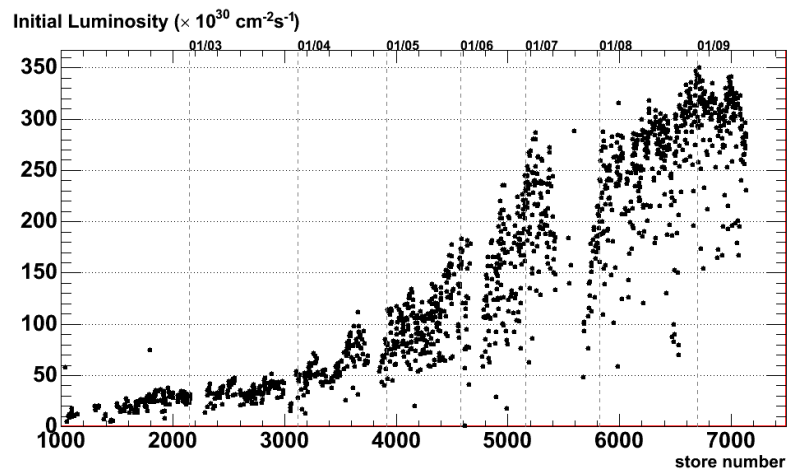




Prospects



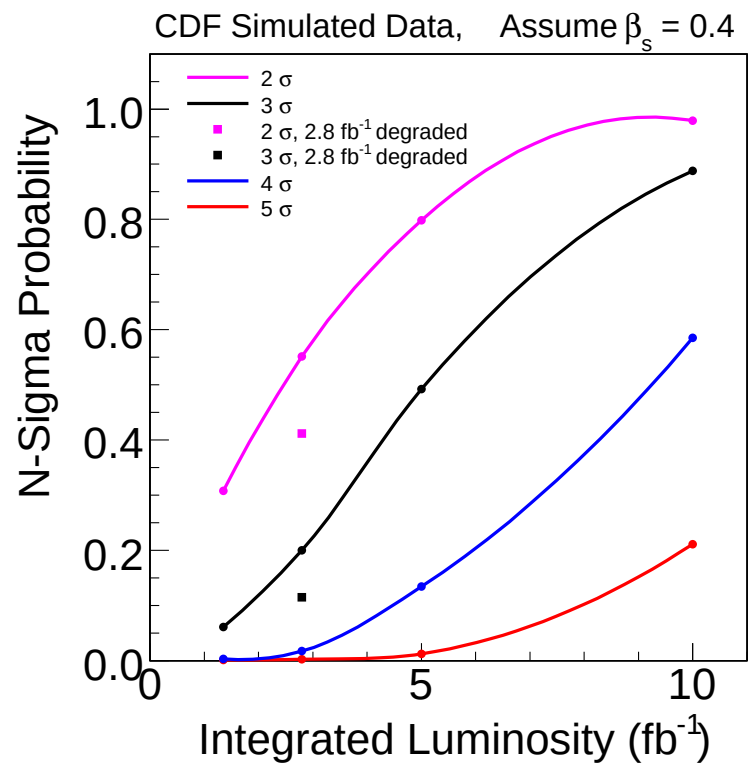




- Plots show collected at CDF
- DØ plots look similar
- Get about 1.5-2 fb^{-1} per year
- Projections:
  FY 2010: $\approx$ 9 fb^{-1}
  FY 2011: $\approx$ 12 fb^{-1}

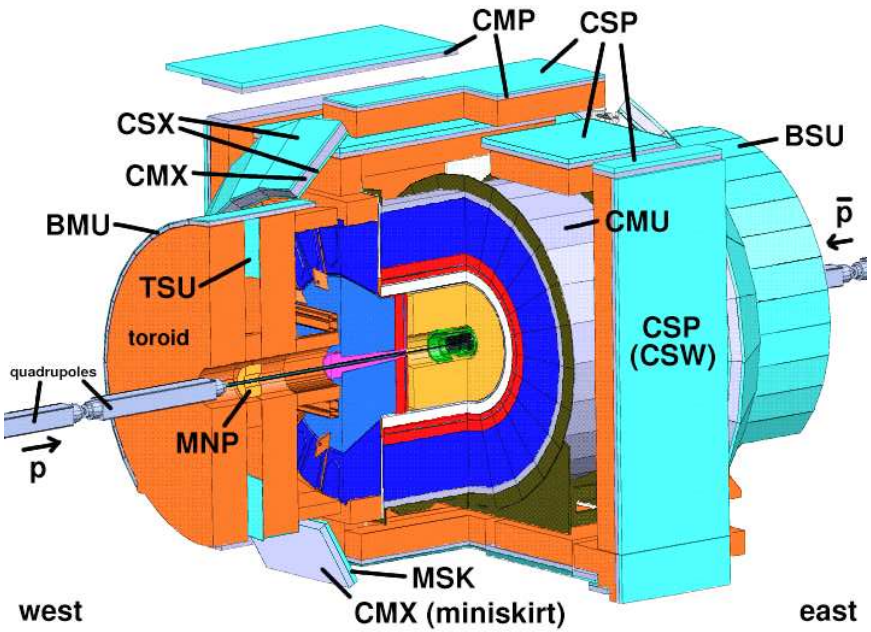
Conclusions

- Rich program in Flavor physics at Tevatron
- In many cases competitive to B factories
- In B_s and $b-$baryon sector still unique place in the world
- If there is sizable new physics in $b \to s$ transition good prospects to get evidence for it
- Expect update on CPV in $B_s \to J/\psi\phi$ still this year
- Lot can be still done $\Rightarrow$ stay tuned for new results from Tevatron

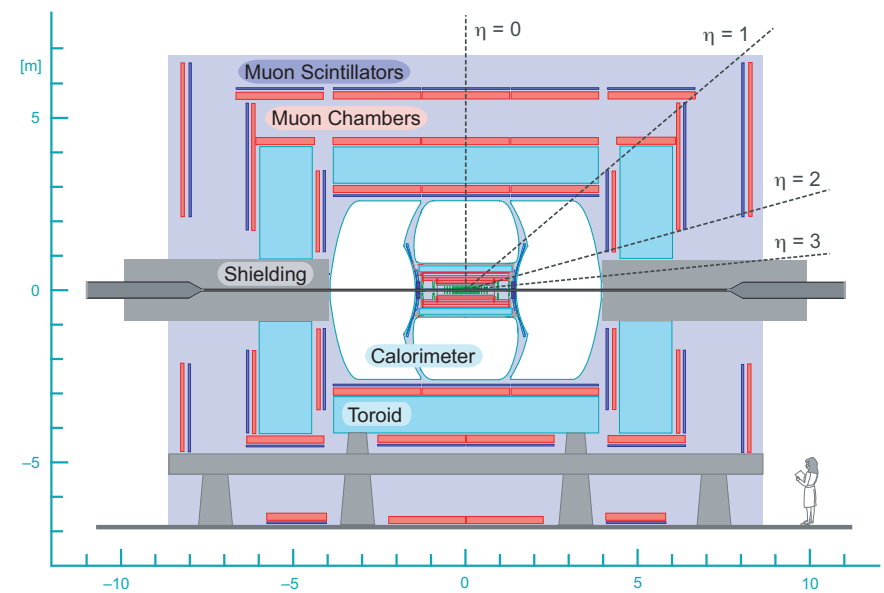


Backup

Experiments



- Excellent momentum and mass resolution
- Silicon tracking at trigger level
- Particle identification



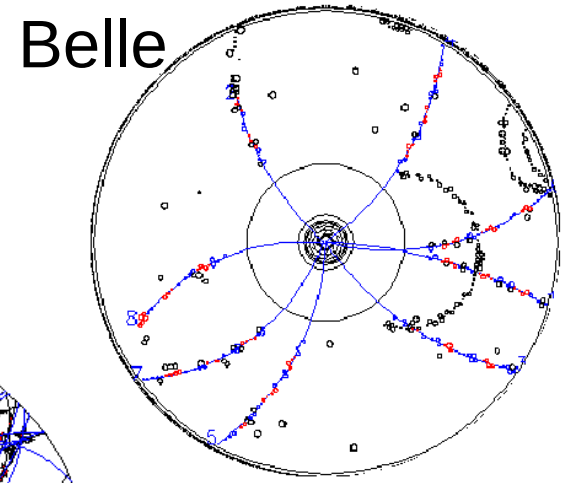
- Excellent muon coverage
- Very strong in semileptonic and J/ψ decays

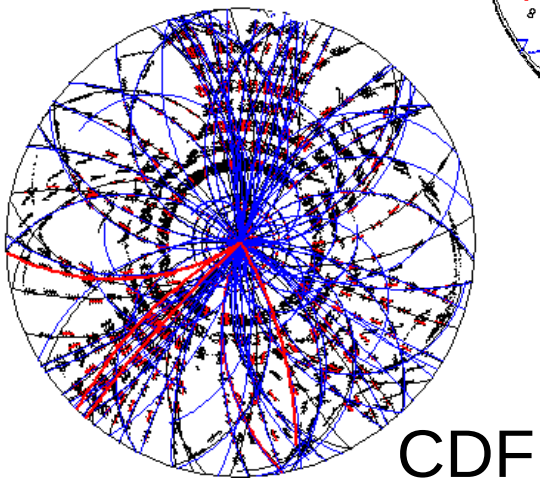
Trigger

- Huge $b\bar{b}$ and $c\bar{c}$ cross section compared to e^+e^-
- Enough energy to produce all heavy hadron species in fragmentation
- But inelastic cross section $\approx 10^3$ times larger than $\sigma(b\bar{b})$

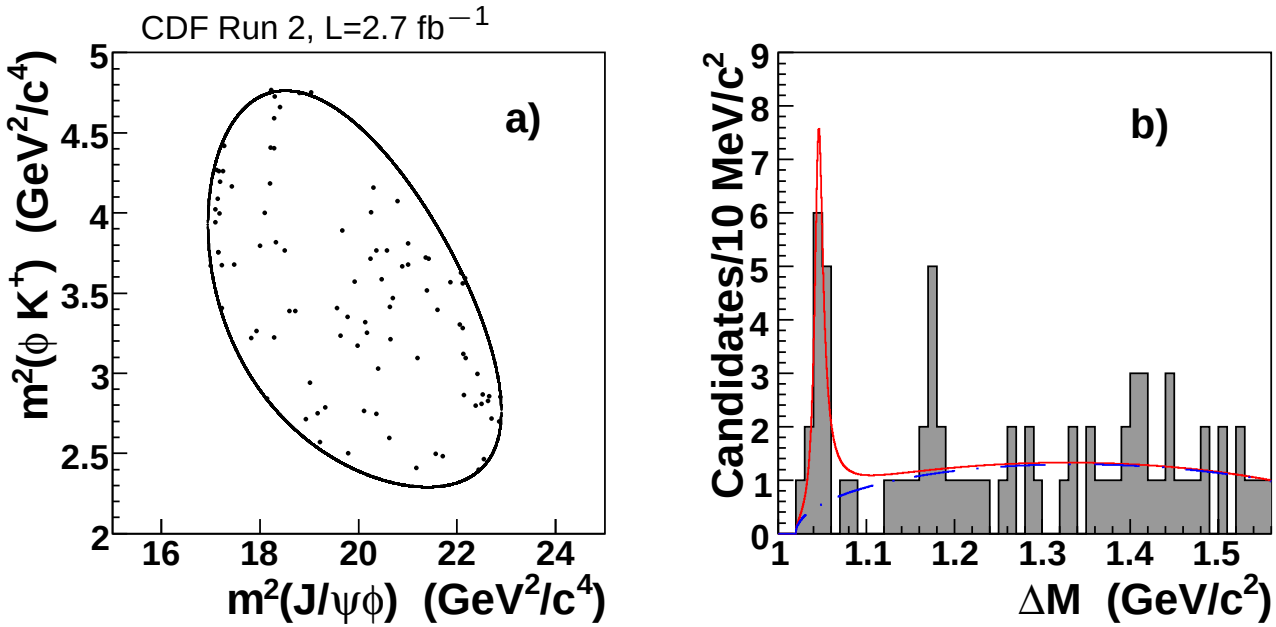
$\rightarrow$ Need highly selective trigger

- At CDF:
  - Muon pairs
  - Lepton+displaced track
  - Two displaced tracks
- At DØ:
  - Muon pairs
  - Single muon





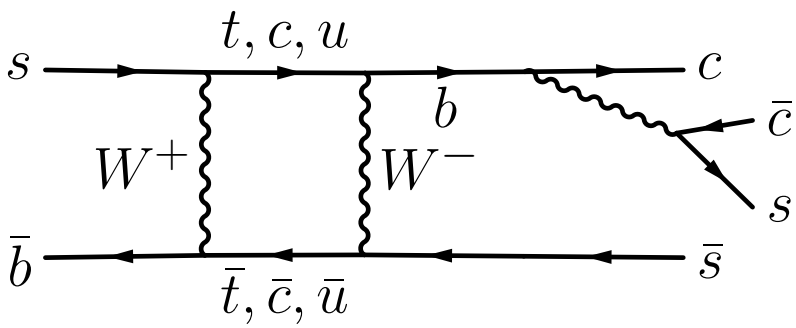
Narrow resonance in $J/\psi\phi$

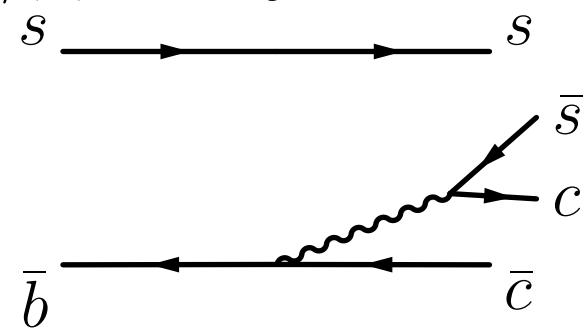


- Search for exotic charmonium like resonances
- Use exclusive $B^+ \to J/\psi\phi K^+$ decays
- $M = 4143.0 \pm 2.9(\text{stat}) \pm 1.2(\text{syst})$ MeV/c^2
  $\Gamma = 11.7^{+8.3}_{-5.0}(\text{stat}) \pm 3.7(\text{syst})$ MeV/c^2
  $N = 14 \pm 5$
- Significance 3.8σ with flat combinatorial background

$B_s \to J/\psi\phi$ Decay

- B_s mixing phase (or V_{ts} phase) last experimentally unconstrained part of CKM
- Best testing laboratory is $B_s \to J/\psi\phi$ decay





- We measure phase between B_s mixing and $b \to c\bar{c}s$
  - In SM $2\beta_s^{\rm SM} = 2\arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*) \approx 0.04$
  - In presence of NP $2\beta_s = 2\beta_s^{\rm SM} - \phi_s^{\rm NP}$
- With our precision, SM contributions can be neglected

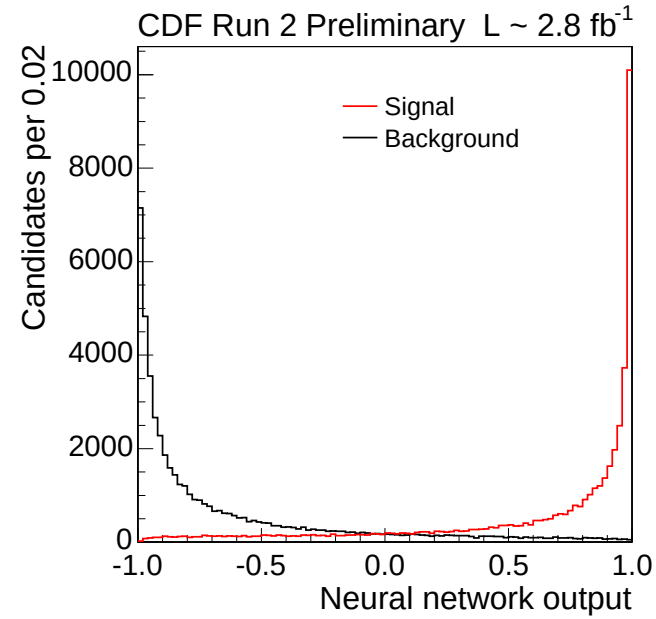
$\Rightarrow\ 2\beta_s = -\phi_s^{\rm NP} = -\phi_s$

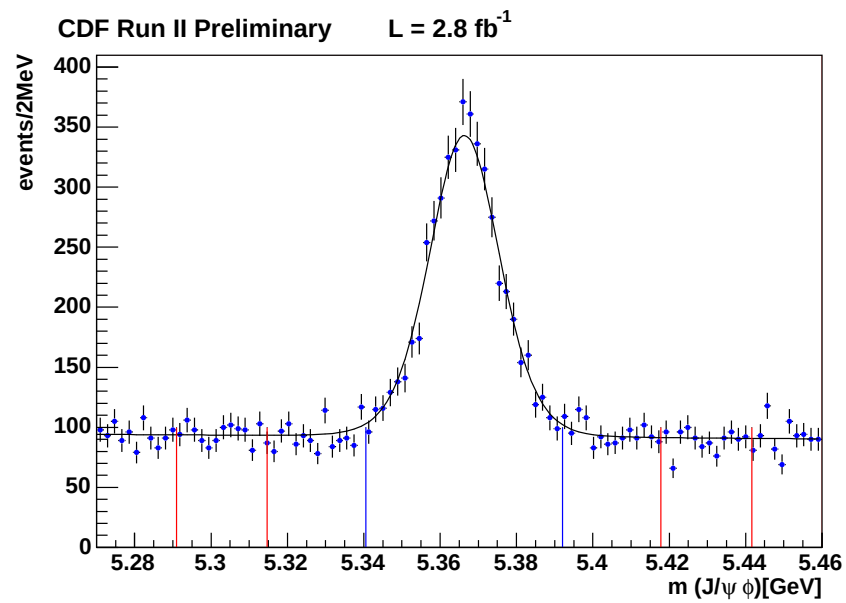
$\mathbf{B_s \to J/\psi\phi}$ Analysis outline

1. Reconstruct data and select events
2. Disentangle *CP*-even and *CP*-odd fraction $\Leftrightarrow$ Angular analysis
3. Determine flavour at production time $\Leftrightarrow$ Flavour tagged analysis
4. Perform unbinned maximum likelihood fit to extract interesting quantities

Data sample and Selection

- Collected by dimuon trigger
- Data sample
  - CDF: $\int \mathcal{L} = 2.8\ \mathrm{fb}^{-1}$
- Selection of events:
  - neural network
  - combining kinematics
  - topology
  - μ PID quantities
- About 3150 signal events



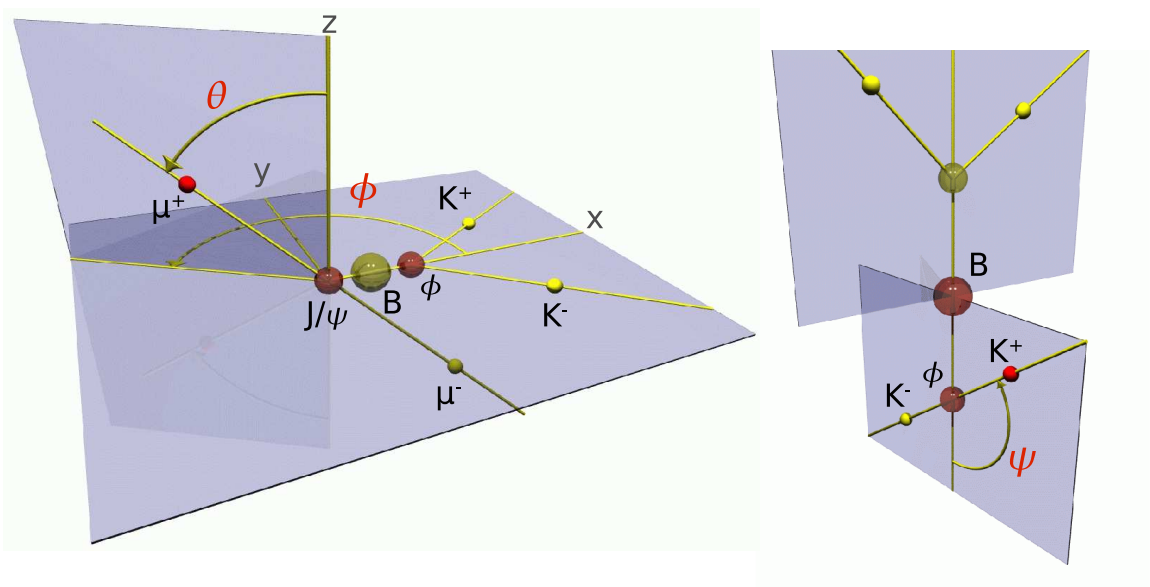


CP-even vs. CP-odd

- Full decay $B_s \to J/\psi\phi$ with $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$
- B_s is pseudoscalar, J/ψ and ϕ vectors $\Rightarrow L = 0, 1, 2$
- $L = 0, 2$ are CP-even, $L = 1$ CP-odd

$\Rightarrow$ Angular distributions can statistically separate CP-even from CP-odd component

- Use transversity basis as used in previous analyses



Likelihood - background

- Using empirical description
- All parameters floating in final fit
- Mass space:
  - Linear function for prompt background
  - Linear function for non-prompt background
- Decay time space (convolved with Gaussian resolution):
  - δ-function at $t = 0$ for prompt
  - positive and negative exponential for mismeasured events
  - exponential for long lived background
- Angular space:
  - Product of polynomials in $\cos^2(\theta_T)$, $\cos(2\phi_T)$ and $\cos(\psi_T)$
  - Correlations found to be negligible

Signal PDF

- Signal PDF for single tag

$$P_s(t, \vec{\rho}, \xi | \mathcal{D}, \sigma_t) = \frac{1+\xi\mathcal{D}}{2} P(t, \vec{\rho}|\sigma_t)\epsilon(\vec{\rho}) + \frac{1-\xi\mathcal{D}}{2} \overline{P}(t, \vec{\rho}|\sigma_t)\epsilon(\vec{\rho})$$

- $\xi = -1, 0, 1$ is tagging decision
- $\mathcal{D}$ is event-specific dilution
- $\epsilon(\vec{\rho})$ - acceptance function in angular space
- $P(t, \vec{\rho}|\sigma_t)$ ($\overline{P}(t, \vec{\rho}|\sigma_t)$) is PDF for B_s ($\overline{B}_s$)

Signal PDF

$$\frac{d^4P(t,\vec{\rho})}{dt\,d\vec{\rho}} \propto |A_0|^2\mathcal{T}_+ f_1(\vec{\rho}) + |A_\parallel|^2\mathcal{T}_+ f_2(\vec{\rho}) + |A_\perp|^2\mathcal{T}_- f_3(\vec{\rho})$$
$$+ |A_\parallel||A_\perp|\mathcal{U}_\pm f_4(\vec{\rho}) + |A_0||A_\parallel|\cos(\delta_\parallel)\mathcal{T}_+ f_5(\vec{\rho})$$
$$+ |A_0||A_\perp|\mathcal{V}_\pm f_6(\vec{\rho})$$

$$\mathcal{T}_\pm = e^{-\Gamma t} \times [\cosh(\Delta\Gamma t/2) \mp \cos(2\beta_s)\sinh(\Delta\Gamma t/2)$$
$$\mp \eta\sin(2\beta_s)\sin(\Delta m_s t)]\,,$$
$$\mathcal{U}_\pm = \pm e^{-\Gamma t} \times \big[\sin(\delta_\perp - \delta_\parallel)\cos(\Delta m_s t)$$
$$- \cos(\delta_\perp - \delta_\parallel)\cos(2\beta_s)\sin(\Delta m_s t)$$
$$\pm \cos(\delta_\perp - \delta_\parallel)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)\big]\,,$$
$$\mathcal{V}_\pm = \pm e^{-\Gamma t} \times [\sin(\delta_\perp)\cos(\Delta m_s t)$$
$$- \cos(\delta_\perp)\cos(2\beta_s)\sin(\Delta m_s t)$$
$$\pm \cos(\delta_\perp)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)]\,.$$

Signal PDF

$$\frac{d^4P(t,\vec{\rho})}{dt\,d\vec{\rho}} \propto |A_0|^2\mathcal{T}_+ f_1(\vec{\rho}) + |A_\parallel|^2\mathcal{T}_+ f_2(\vec{\rho}) + |A_\perp|^2\mathcal{T}_- f_3(\vec{\rho})$$
$$+ |A_\parallel||A_\perp|\mathcal{U}_\pm f_4(\vec{\rho}) + |A_0||A_\parallel|\cos(\delta_\parallel)\mathcal{T}_+ f_5(\vec{\rho})$$
$$+ |A_0||A_\perp|\mathcal{V}_\pm f_6(\vec{\rho})$$

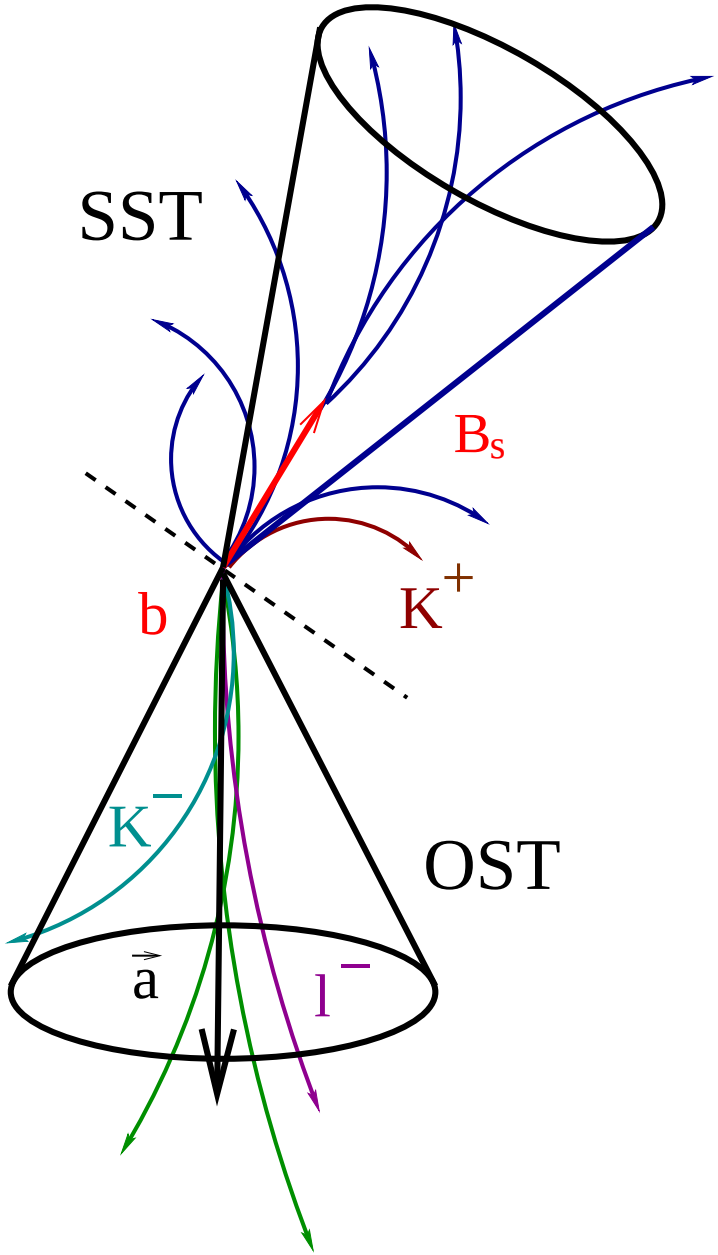
$$\mathcal{T}_\pm = e^{-\Gamma t} \times [\cosh(\Delta\Gamma t/2) \mp \cos(2\beta_s)\sinh(\Delta\Gamma t/2)$$
$$\mp \eta \sin(2\beta_s)\sin(\Delta m_s t)],$$
$$\mathcal{U}_\pm = \pm e^{-\Gamma t} \times \big[\sin(\delta_\perp - \delta_\parallel)\cos(\Delta m_s t)$$
$$- \cos(\delta_\perp - \delta_\parallel)\cos(2\beta_s)\sin(\Delta m_s t)$$
$$\pm \cos(\delta_\perp - \delta_\parallel)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)\big],$$
$$\mathcal{V}_\pm = \pm e^{-\Gamma t} \times [\sin(\delta_\perp)\cos(\Delta m_s t)$$
$$- \cos(\delta_\perp)\cos(2\beta_s)\sin(\Delta m_s t)$$
$$\pm \cos(\delta_\perp)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)].$$

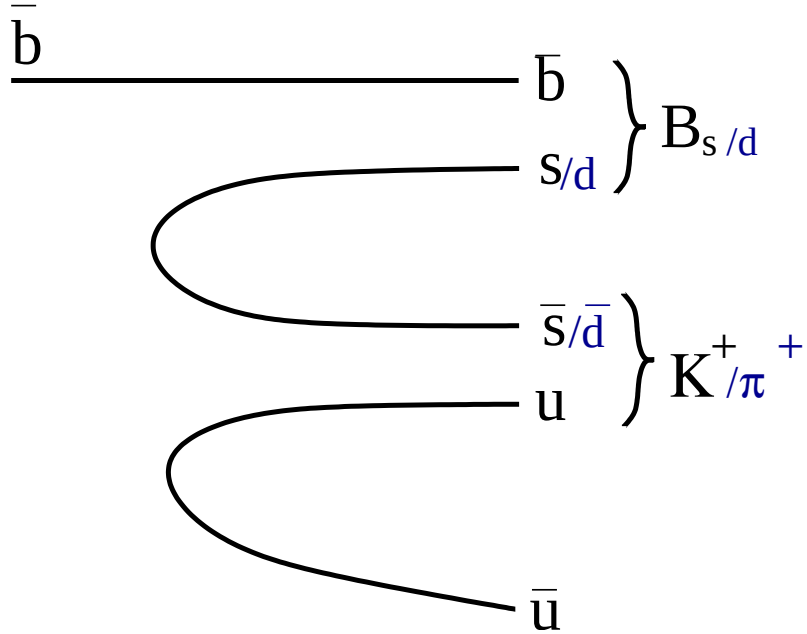
Signal PDF

$$\frac{d^4P(t,\vec{\rho})}{dt\,d\vec{\rho}} \propto |A_0|^2\mathcal{T}_+ f_1(\vec{\rho}) + |A_\parallel|^2\mathcal{T}_+ f_2(\vec{\rho}) + |A_\perp|^2\mathcal{T}_- f_3(\vec{\rho})$$
$$+ |A_\parallel||A_\perp|\mathcal{U}_\pm f_4(\vec{\rho}) + |A_0||A_\parallel|\cos(\delta_\parallel)\mathcal{T}_+ f_5(\vec{\rho})$$
$$+ |A_0||A_\perp|\mathcal{V}_\pm f_6(\vec{\rho})$$

$$\mathcal{T}_\pm = e^{-\Gamma t} \times [\cosh(\Delta\Gamma t/2) \mp \cos(2\beta_s)\sinh(\Delta\Gamma t/2)$$
$$\mp \eta \sin(2\beta_s)\sin(\Delta m_s t)]\,,$$
$$\mathcal{U}_\pm = \pm e^{-\Gamma t} \times \big[\sin(\delta_\perp - \delta_\parallel)\cos(\Delta m_s t)$$
$$- \cos(\delta_\perp - \delta_\parallel)\cos(2\beta_s)\sin(\Delta m_s t)$$
$$\pm \cos(\delta_\perp - \delta_\parallel)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)\big]\,,$$
$$\mathcal{V}_\pm = \pm e^{-\Gamma t} \times [\sin(\delta_\perp)\cos(\Delta m_s t)$$
$$- \cos(\delta_\perp)\cos(2\beta_s)\sin(\Delta m_s t)$$
$$\pm \cos(\delta_\perp)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)]\,.$$

Flavour tagging





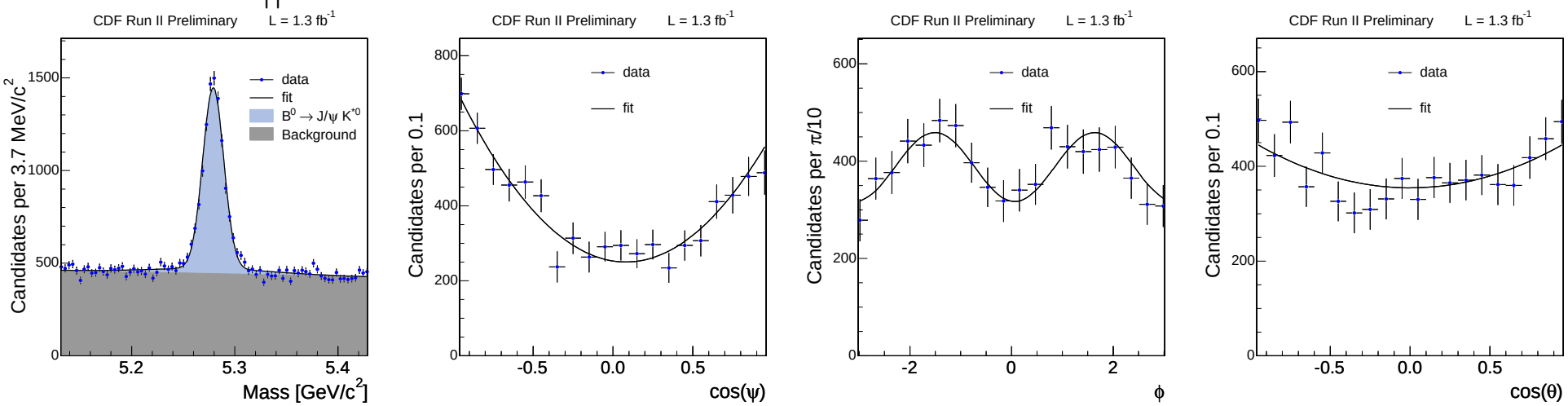
Performance:

- OST: ϵD^2 = 1.2%
  efficiency=96%
  dilution=11%
- SST: ϵD^2 = 3.6%
  efficiency=50%
  dilution=27%

$B^0 \to J/\psi K^{*0}$

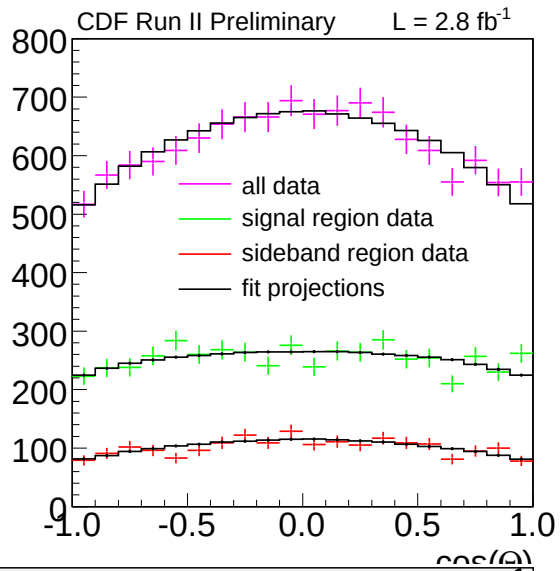
- Test angular analysis on similar $B^0 \to J/\psi K^{*0}$ decay
- Compare amplitudes to B-factories results
- Belle and *BABAR* comparable

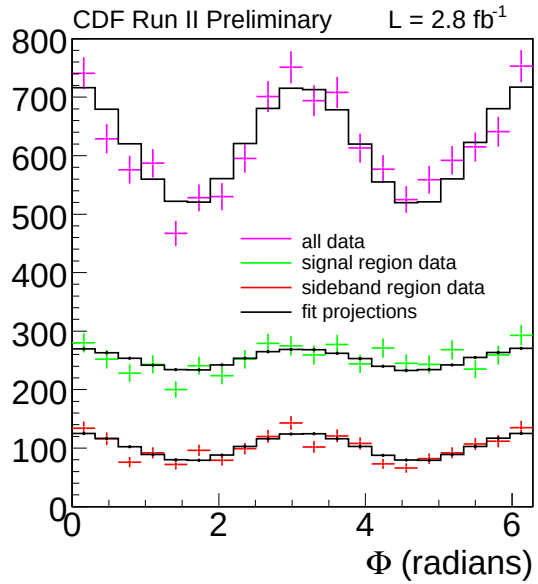
	CDF	*BABAR*
$\lvert A_0\rvert^2$	$= 0.569 \pm 0.009 \pm 0.009$	$0.556 \pm 0.009 \pm 0.010$
$\lvert A_{\parallel}\rvert^2$	$= 0.211 \pm 0.012 \pm 0.006$	$0.211 \pm 0.010 \pm 0.006$
$\delta_{\perp}$	$= -2.97 \pm 0.08 \pm 0.03$	$-2.93 \pm 0.08 \pm 0.04$
$\delta_{\parallel}$	$= 2.97 \pm 0.06 \pm 0.01$	$2.96 \pm 0.05 \pm 0.03$

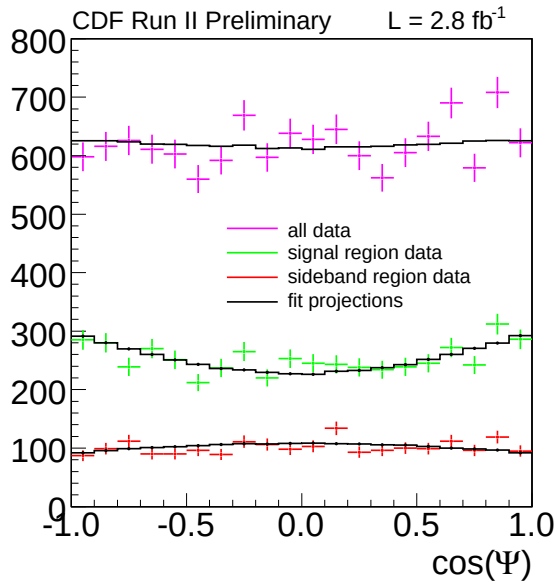


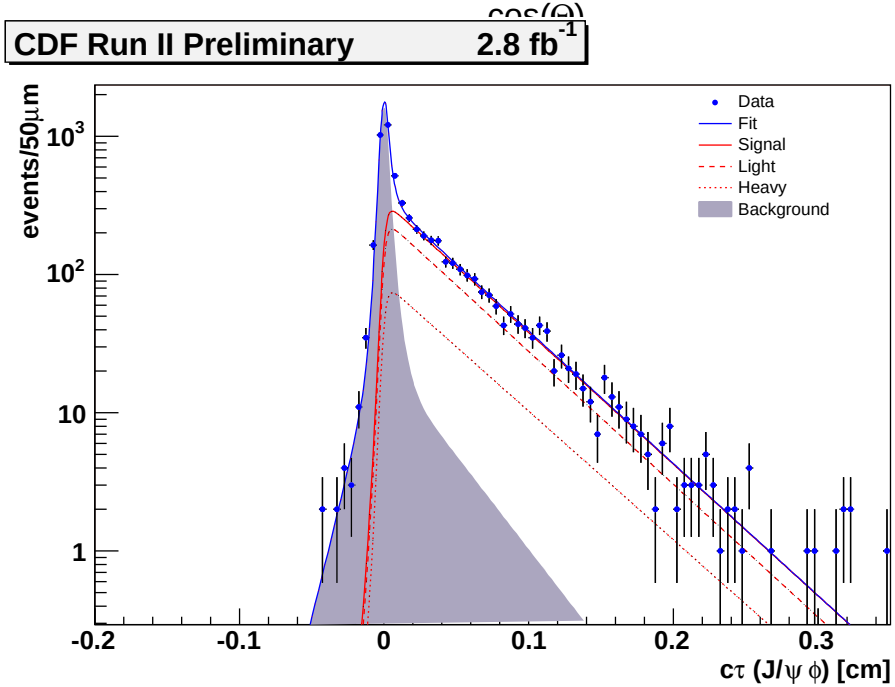
http://www-cdf.fnal.gov/physics/new/bottom/070830.blessed-BdPsiKS

Result with SM assumption









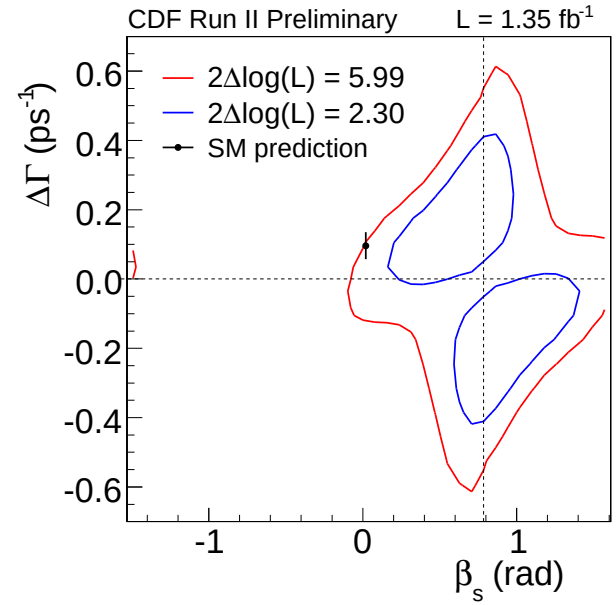
τ	$1.53 \pm 0.04 \pm 0.01$ ps
$\Delta\Gamma$	$0.02 \pm 0.05 \pm 0.01$ ps^{-1}
$\lvert A_0 \rvert^2$	$0.508 \pm 0.024 \pm 0.008$
$\lvert A_{\parallel} \rvert^2$	$0.241 \pm 0.019 \pm 0.007$

Statistical issues for β_s

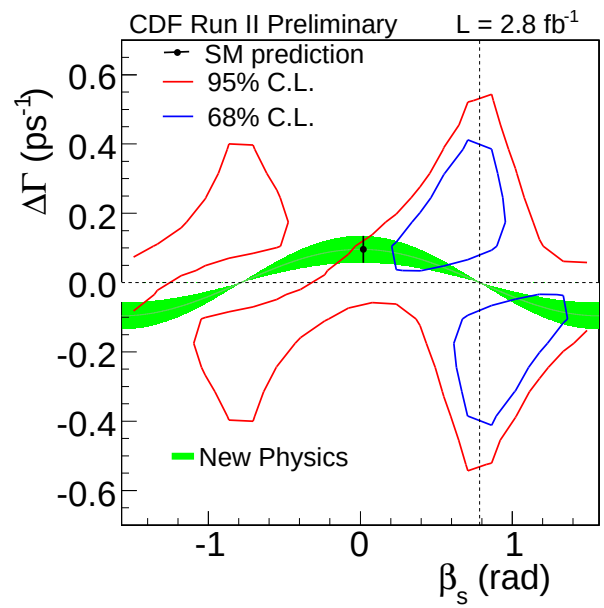
- Likelihood very irregular with two overlapping minima
- Uncertainties are underestimated
- Uncertainties depend strongly on true value

⇒ Quote confidence region

- Use $\mathcal{L}/\mathcal{L}_0$ ordering (Feldman-Cousins)
- Ensure coverage



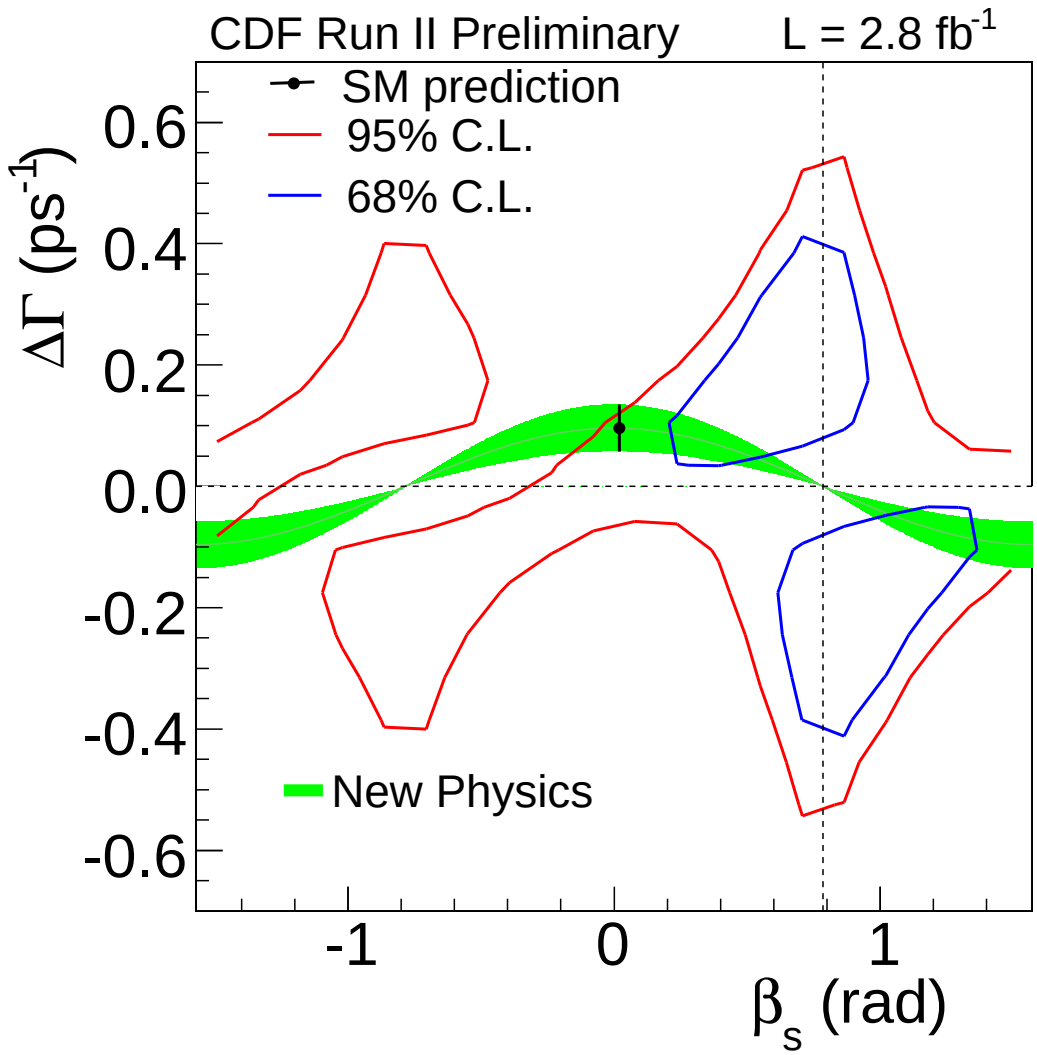
Likelihood profile



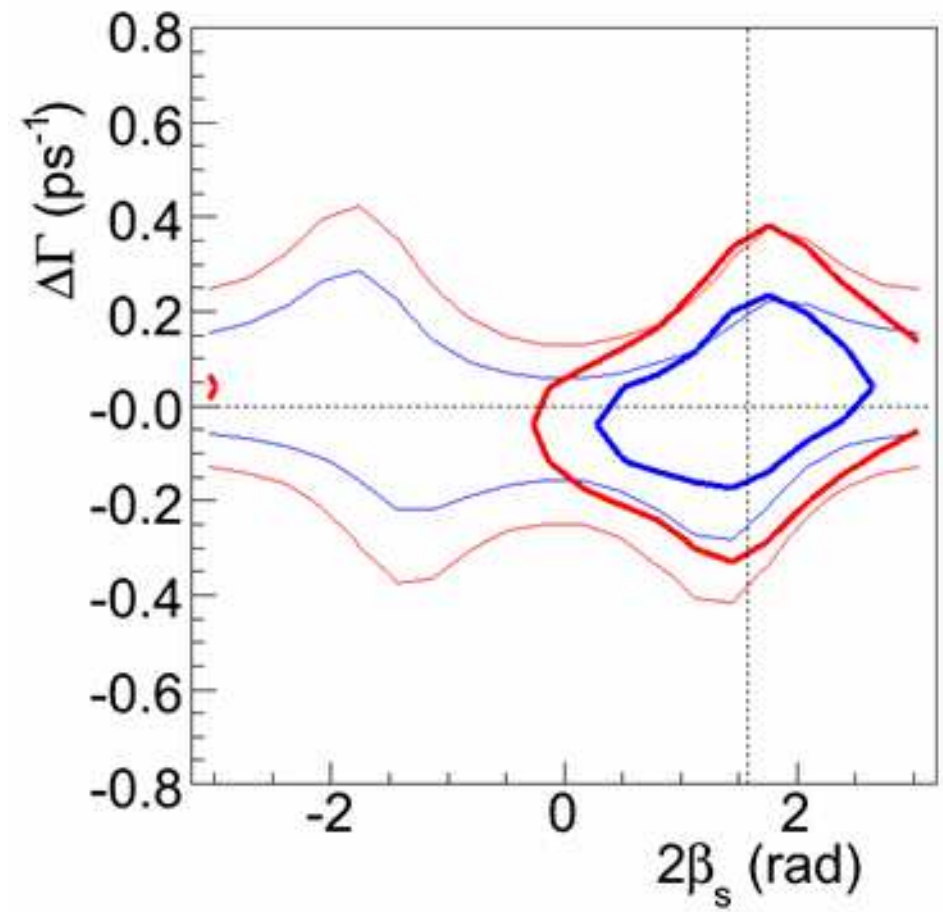
Feldman-Cousins

Result for β_s

- Negative β_s practically excluded
- Change at negative β_s most probably due to statistical fluctuation
- p-value for SM 7% (1.8σ)
- Most pressing open question whether possible S-wave *KK* interference with ϕ can bias result



Effect of flavour tagging

- With tagging of $\epsilon D^2 \approx 5\%$ we don't gain lot in precision
- Main effect in reducing ambiguities
- Untagged case symmetric under each
  - $2\beta_s \rightarrow -2\beta_s$
    $\delta_\perp \rightarrow \delta_\perp + \pi$
  - $\Delta\Gamma \rightarrow -\Delta\Gamma$
    $2\beta_s \rightarrow 2\beta_s - \pi$
- Tagged symmetry
  - $2\beta_s \rightarrow \pi - 2\beta_s$
    $\Delta\Gamma \rightarrow -\Delta\Gamma$
    $\delta_{||} \rightarrow 2\pi - \delta_{||}$
    $\delta_\perp \rightarrow \pi - \delta_\perp$

Single toy experiment