News from Tevatron

Michal Kreps

On behalf of the CDF and DØ Collaborations

Karlsruhe Institute of Technology

Bundesministerium für Bildung und Forschung

Lifetimes

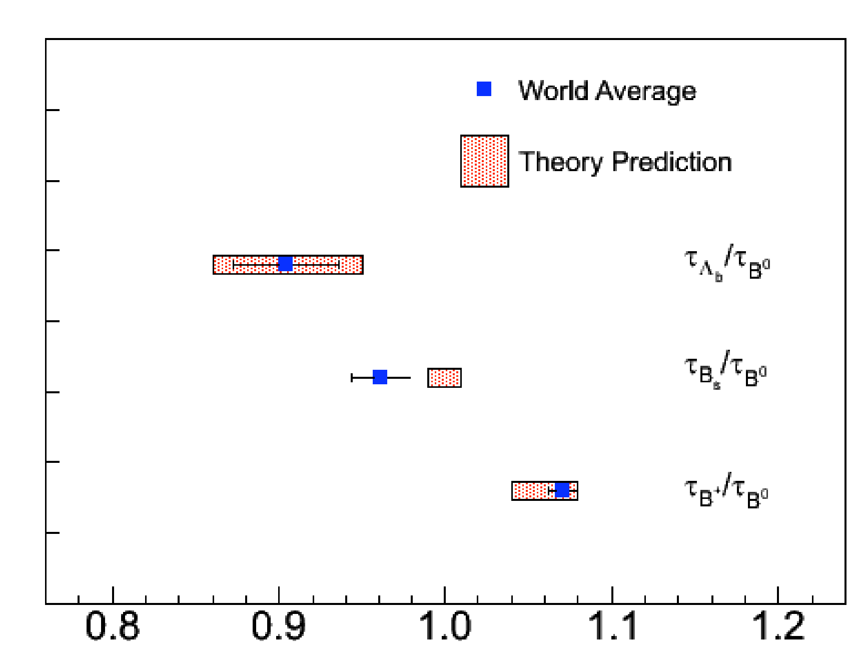
- In spectator model: *b* quark decays as free particle

$\Rightarrow$ All *b*-hadrons have same lifetime

- Effect of spectator quark introduces differences
- Hierarchy of lifetimes predicted in 1994 by Bigi et al.

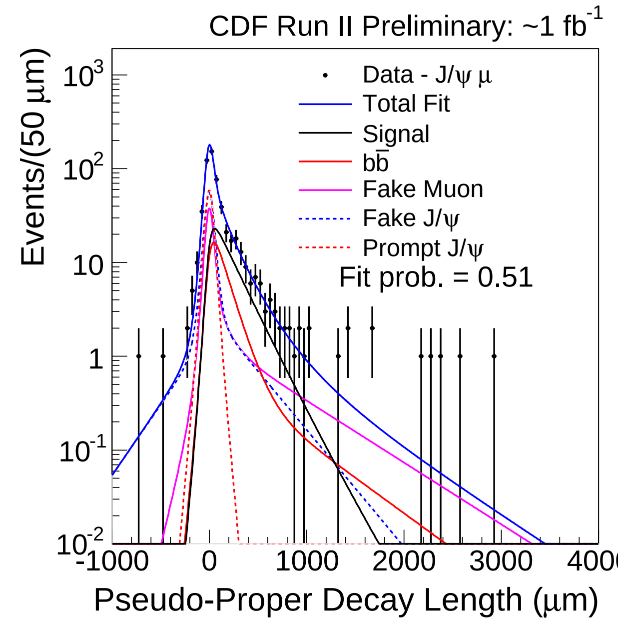
$$\tau(B^+) > \tau(B^0) \approx \tau(B_s) > \tau(\Lambda_b)$$

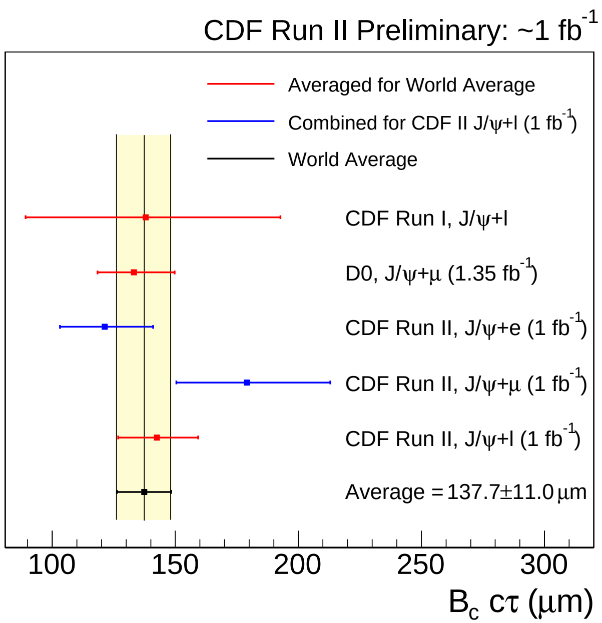
- Special case B_c
  - Interplay of two weakly decaying quarks
  - Expect lifetime shorter than any other *b*-hadron
  - Theory in range 0.47 - 0.59 ps
- Concentrate on B_s, B_c and Λ_b

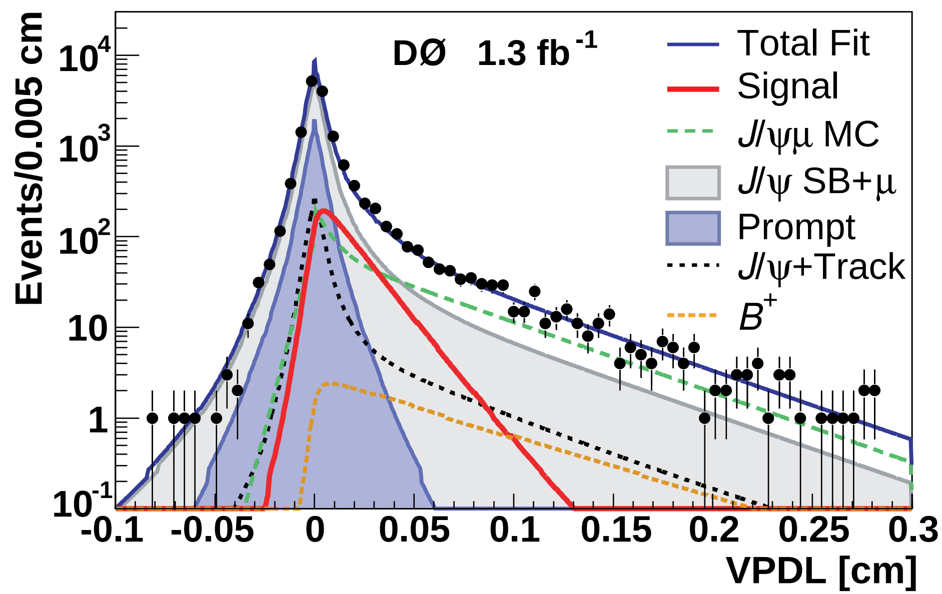


B_c Lifetime

- Both experiments $B_c \to J/\psi l \nu X$
- Main issue is to control and understand backgrounds
- CDF: combined e and μ
  $\tau(B_c) = (0.475^{+0.053}_{-0.049} \pm 0.018)ps$
- DØ: only μ
  $\tau(B_c) = (0.448^{+0.038}_{-0.036} \pm 0.032)ps$







Λ_b Lifetime

- Long standing puzzles:

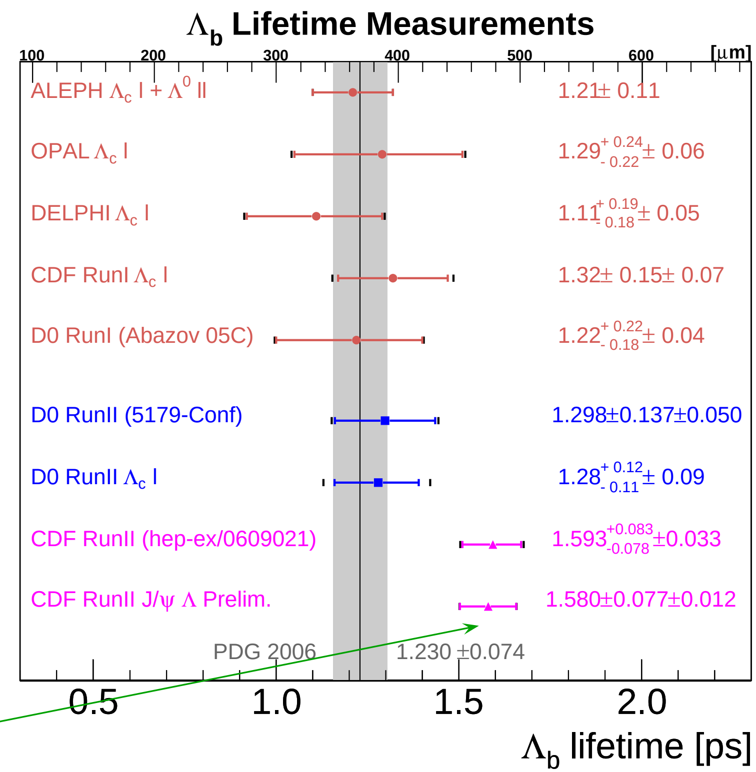
$\rightarrow$ Theory and experiment don't agree well

$$\frac{\tau(\Lambda_b)}{\tau(B^0)}(th) = 0.88 \pm 0.05$$

$$\frac{\tau(\Lambda_b)}{\tau(B^0)}(exp) = 0.804 \pm 0.049$$

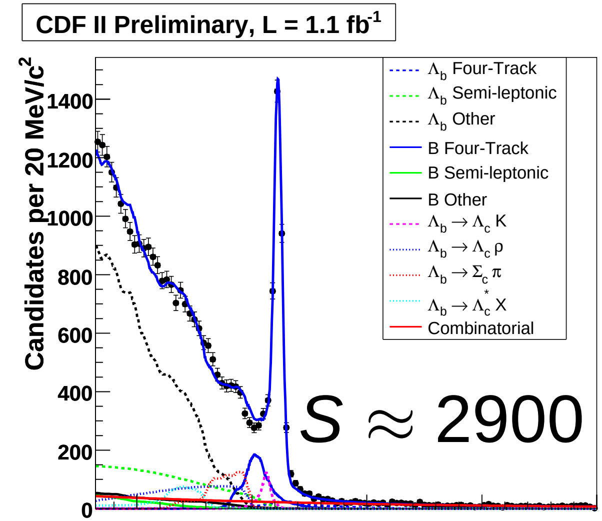
$\rightarrow$ CDF measurement in $\Lambda_b \rightarrow J/\psi\Lambda$ significantly above WA

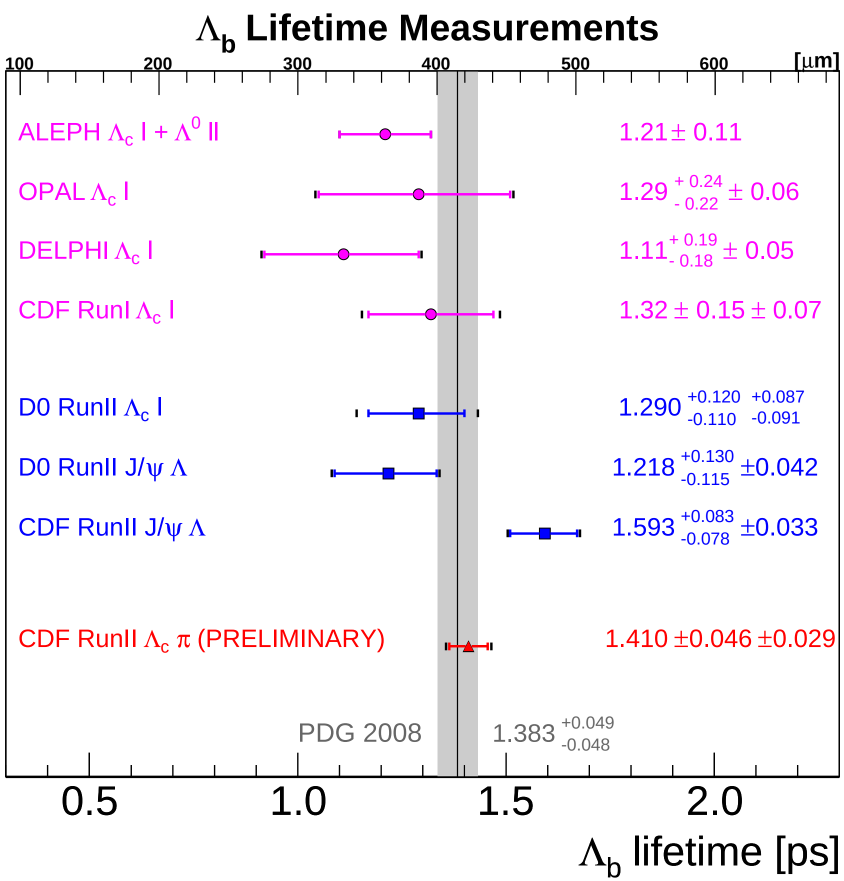
$\Rightarrow$ Use large $\Lambda_b \rightarrow \Lambda_c\pi$ sample

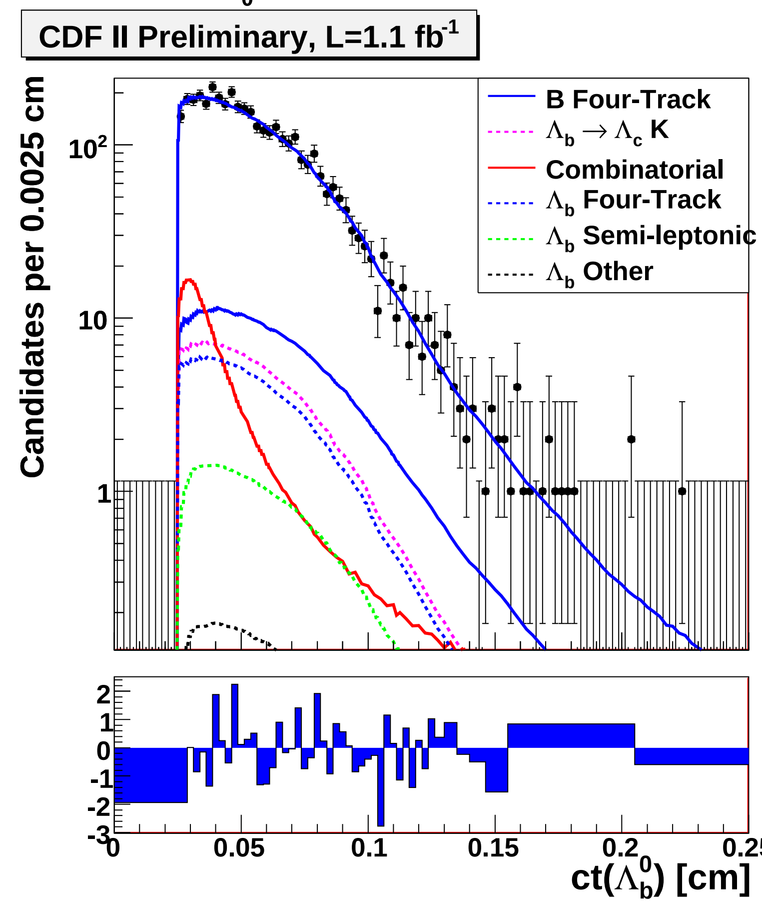


Λ_b Lifetime

- τ = 1.410 $\pm$ 0.046 $\pm$ 0.029 ps
- $\tau(\Lambda_b)/\tau(B^0)$ = 0.922 $\pm$ 0.039
- Most precise Λ_b lifetime measurement







$\mathrm{B_s}$ 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 $\phi_s = \arg(-M_{12}/\Gamma_{12})$
- B_{sH}/B_{sL} mixture in final state important for τ measurement

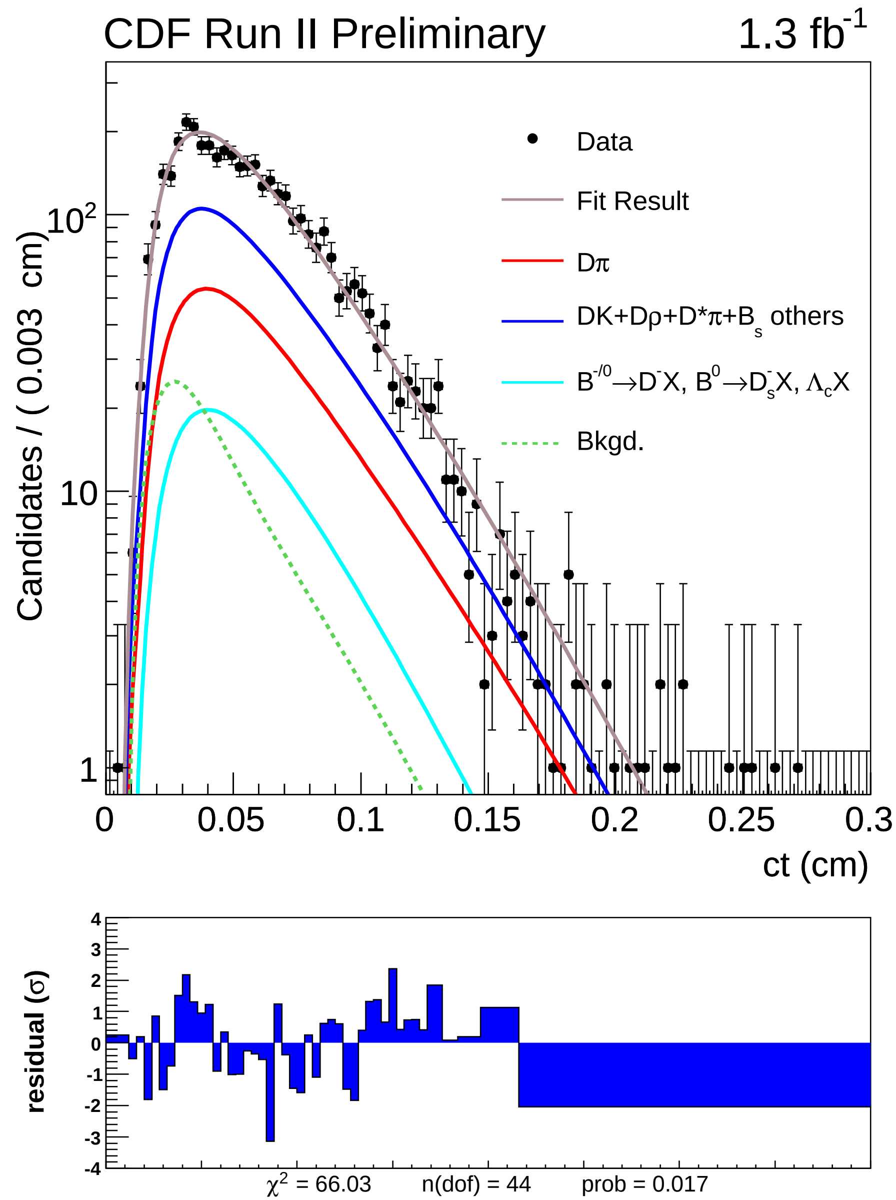
$B_s \to D_s\pi X$

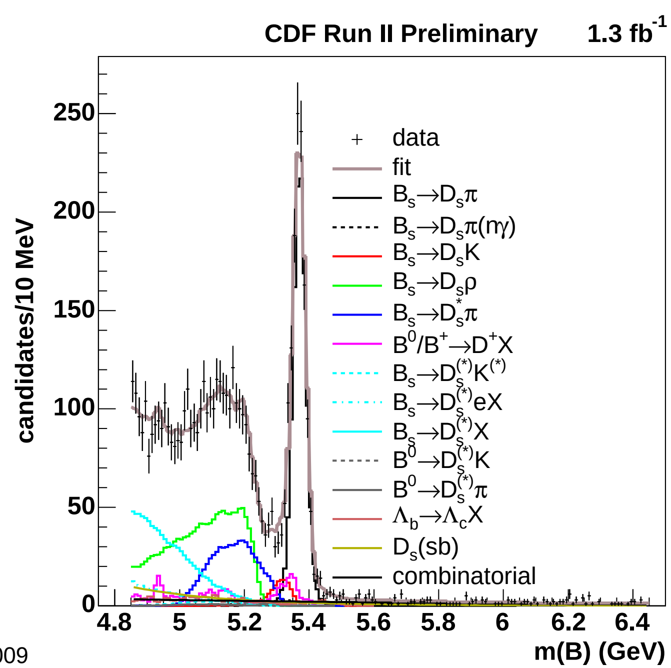
- $\approx$ 1100 fully rec. B_s
- $\approx$ 2000 partially rec. B_s
- 1 : 1 mixture of B_{sH}/B_{sL}

$\rightarrow$ $\tau = 1.518 \pm 0.041 \pm 0.027 ps$

$\rightarrow$ $\tau(B_s)/\tau(B^0) = 0.99 \pm 0.03$

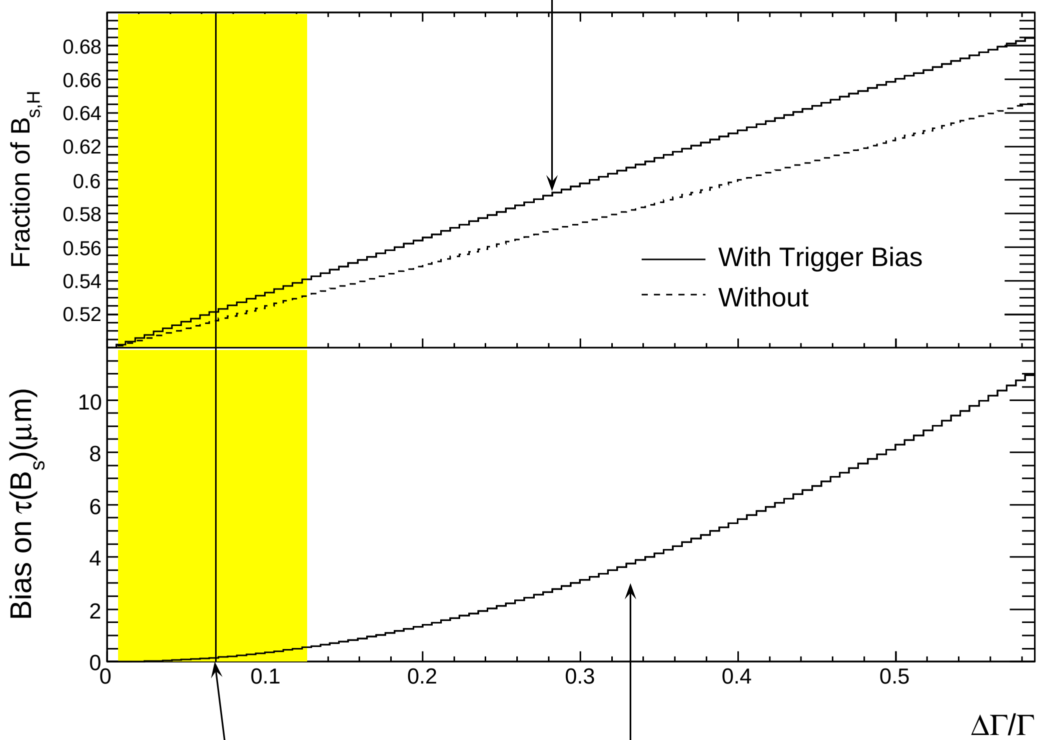
- World best measurement





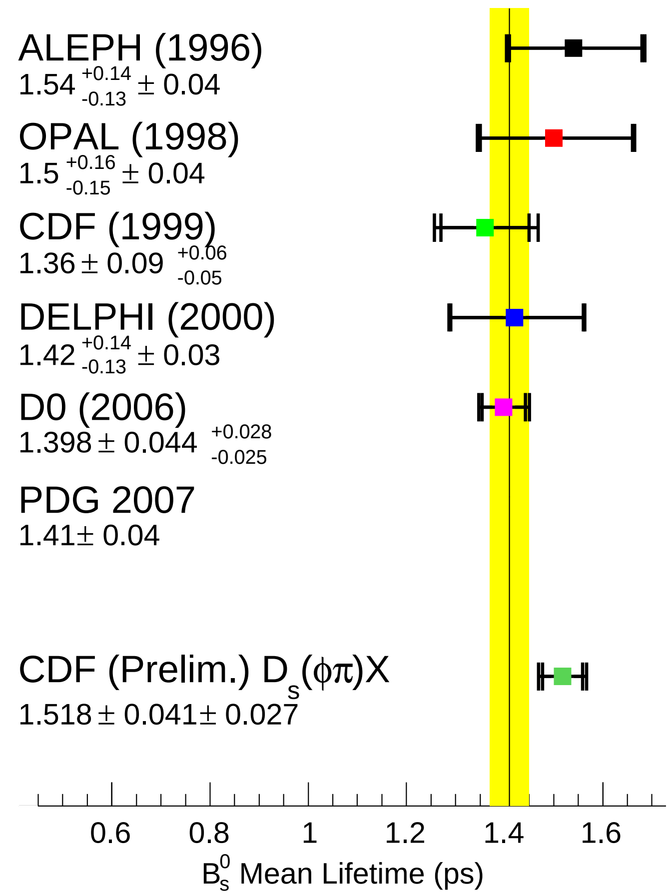
$B_s \to D_s \pi X$

Effect of $\Delta\Gamma$ on B_{sH}/B_{sL} ratio



Effect of $\Delta\Gamma$ on measured τ

Predicted $\Delta\Gamma$



Effect likely below 0.002 ps

$\mathrm{B_s} \to \mathrm{J}/\psi\phi$ Lifetime

- Three possible angular momenta in decay

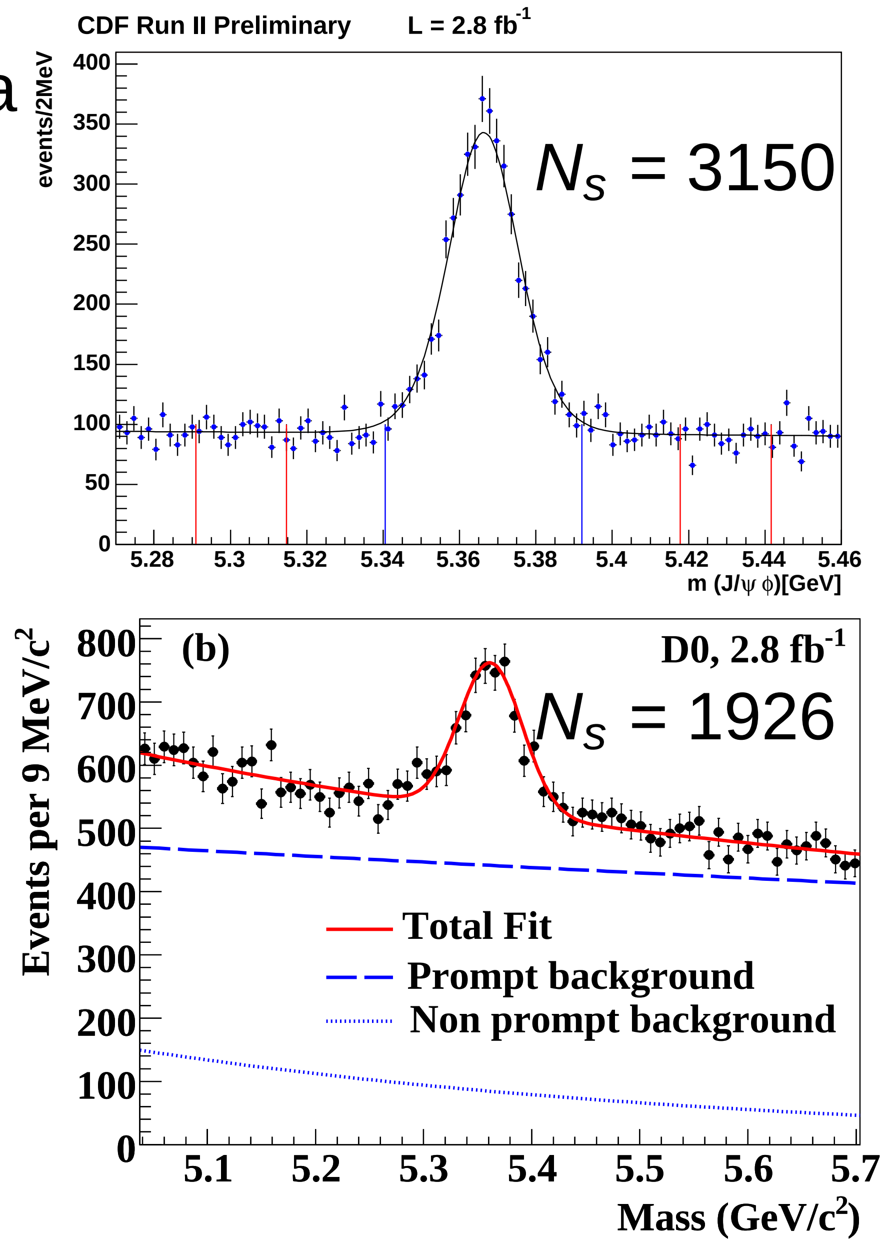
→ $L = 0$ and $L = 2 \Leftrightarrow$ CP-even

→ $L = 1 \Leftrightarrow$ CP-odd

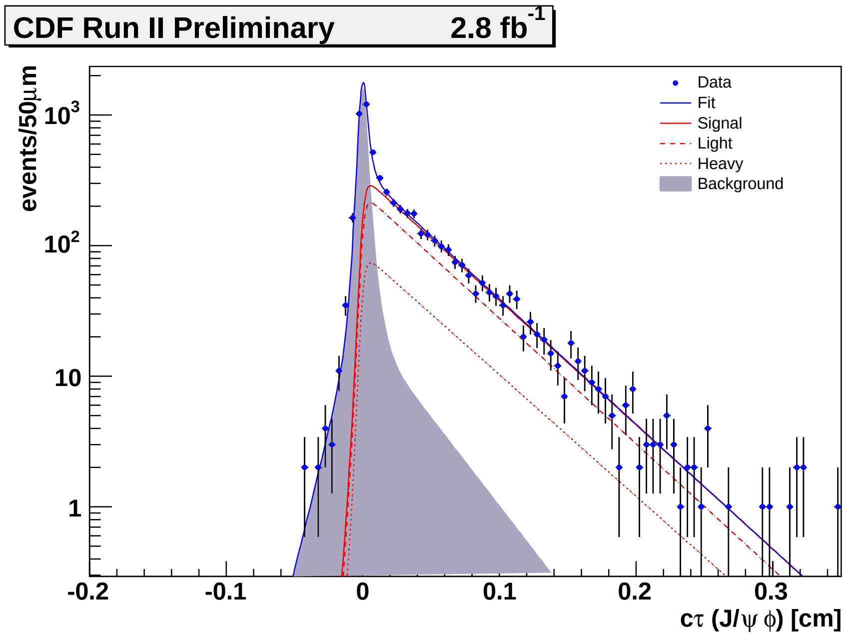
- A priori unknown B_{sH}/B_{sL} ratio
- Assume SM $\Leftrightarrow$ no CP violation

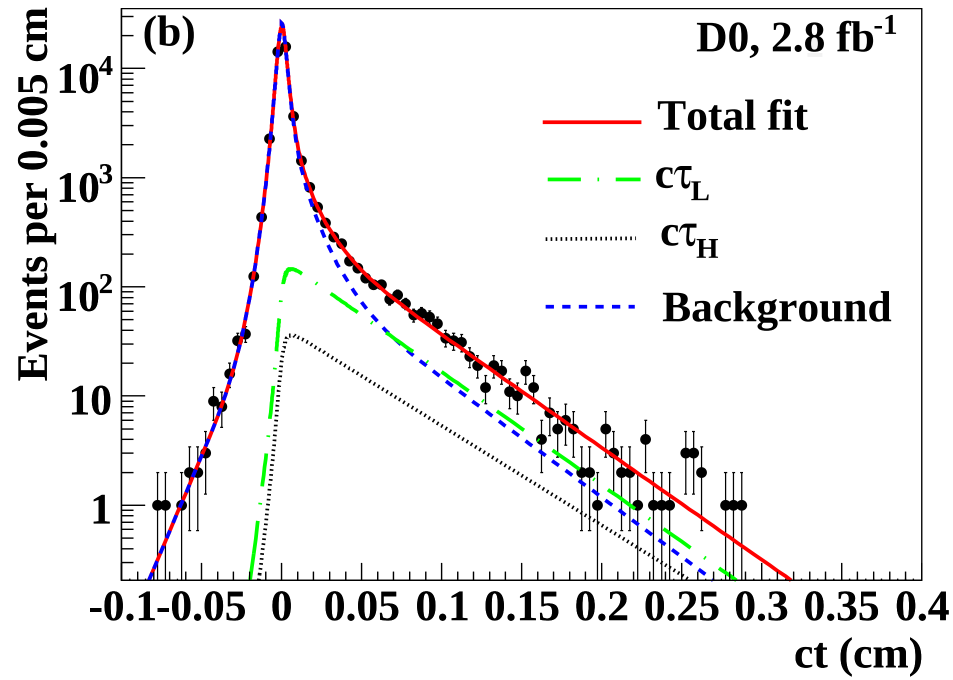
⇒ CP and mass eigenstates coincide

- Angular analysis to separate CP eigenstates (transversity basis)
- Measure τ and $\Delta\Gamma$



$\mathrm{B_s} \rightarrow J/\psi\phi$ Lifetime





$$\tau = 1.53 \pm 0.04 \pm 0.01\text{ps}$$
$$\Delta\Gamma = 0.02 \pm 0.05 \pm 0.01\text{ps}^{-1}$$

$$\tau = 1.49 \pm 0.06 \pm 0.03\text{ps}$$
$$\Delta\Gamma = 0.085^{+0.072}_{-0.078} \pm 0.001\text{ps}^{-1}$$

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

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

Finding NP in ϕ_s

- Measurement of semileptonic CP asymmetry $\leftrightarrow A_{SL} = -|\Gamma_{12}/M_{12}| \sin \phi_s$

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

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

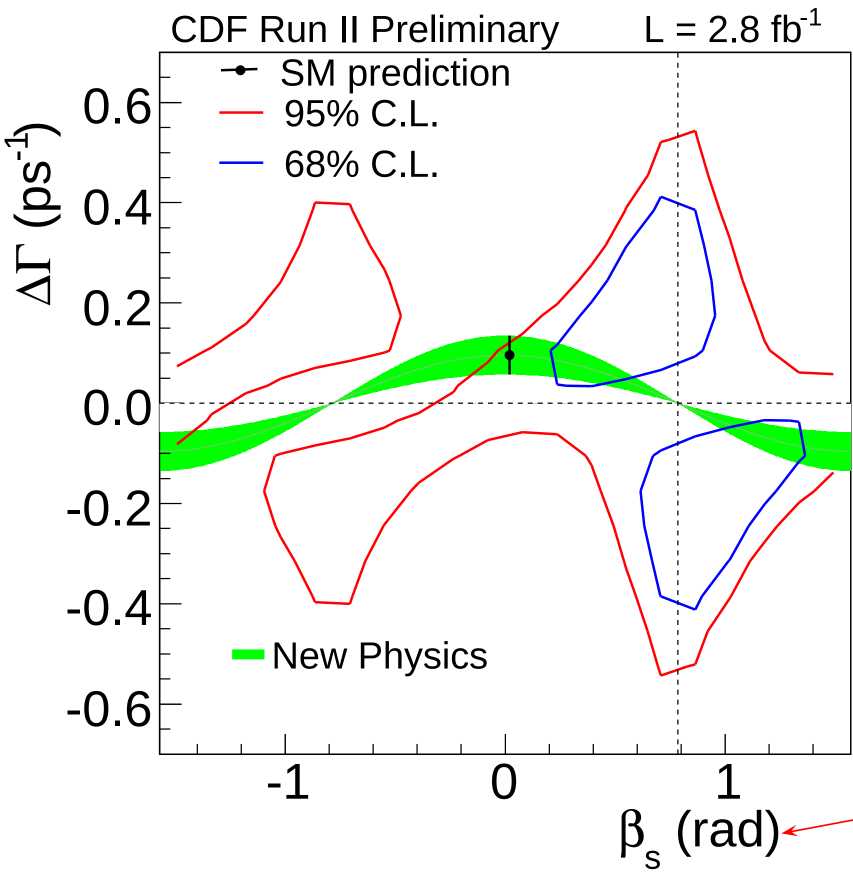
$\longrightarrow$ Need input for $|\Gamma_{12}| \leftrightarrow$ can come from $\mathcal{B}(B_s \rightarrow D_s^{(*)} D_s^{(*)})$

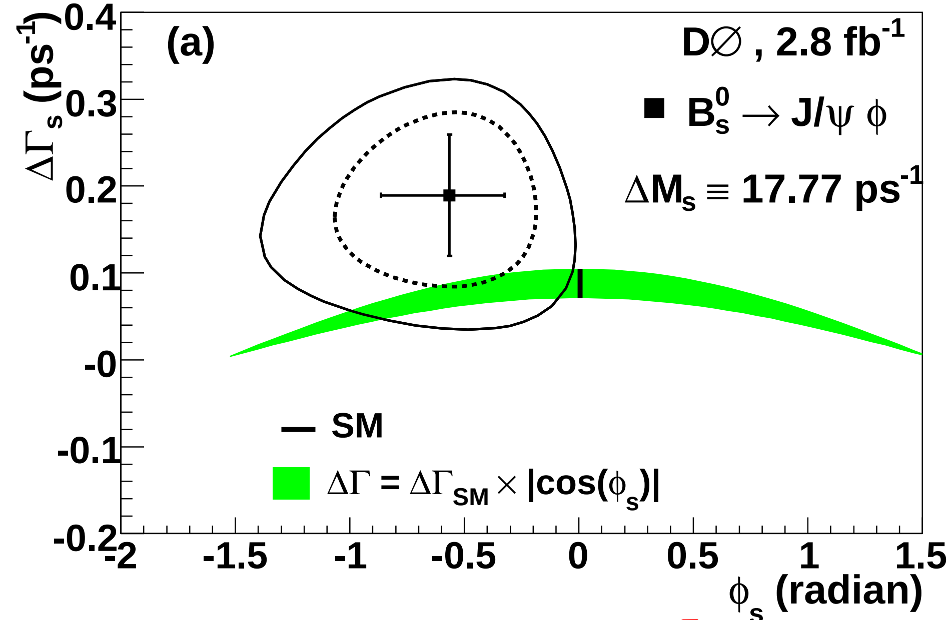
- Measurement of CP violation in CP modes

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

$\longrightarrow$ ϕ_s not only phase entering here, but SM value small $\rightarrow$ search for sizable NP can neglect SM value

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



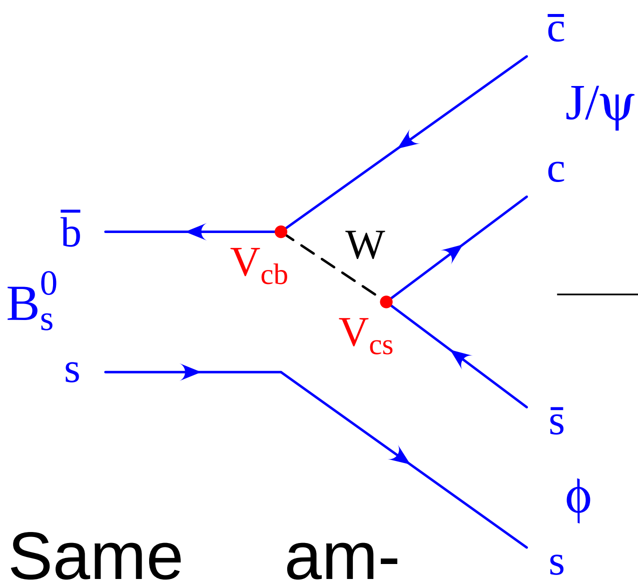


$\phi_s = -2\beta_s$

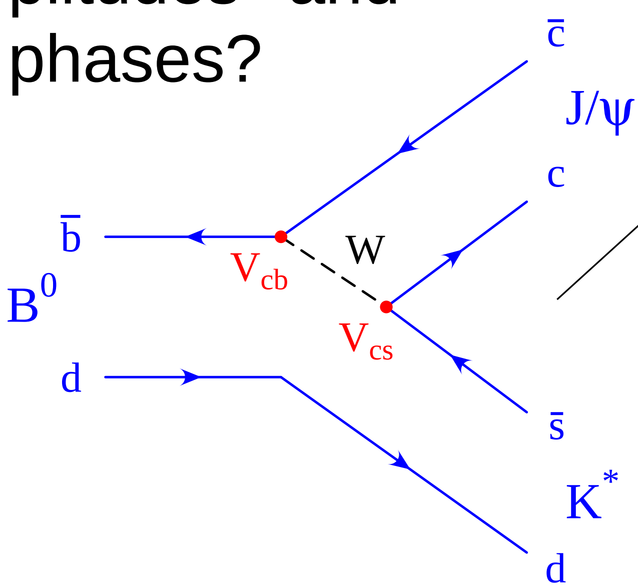
SM p-value 0.07 $\Leftrightarrow \approx 1.8\sigma$

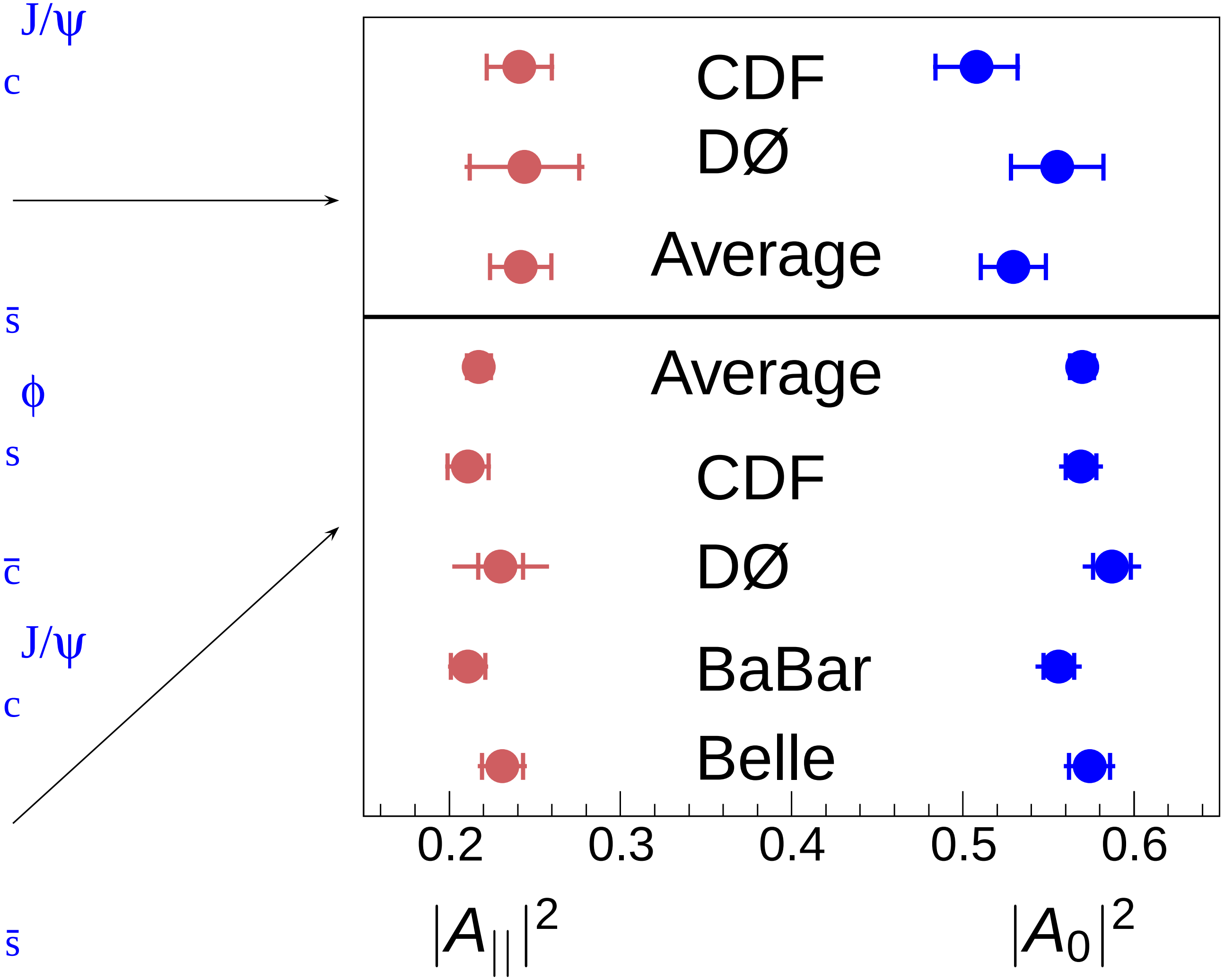
SM p-value 0.066 $\Leftrightarrow \approx 1.8\sigma$
Strong phases constrained to $B^0 \to J/\psi K^*$

Constraining strong phases



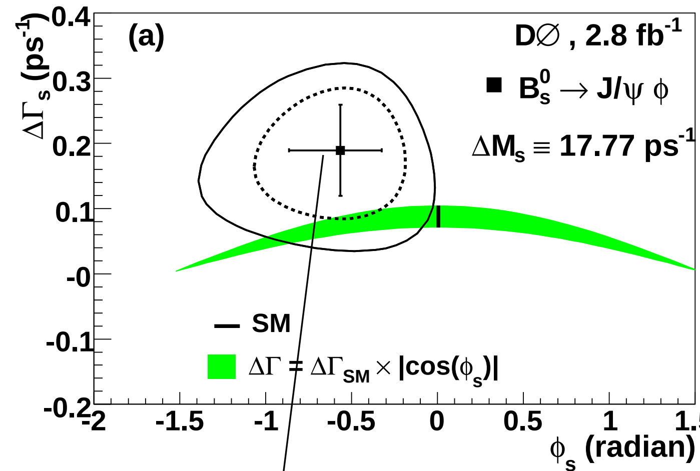
Same amplitudes and phases?

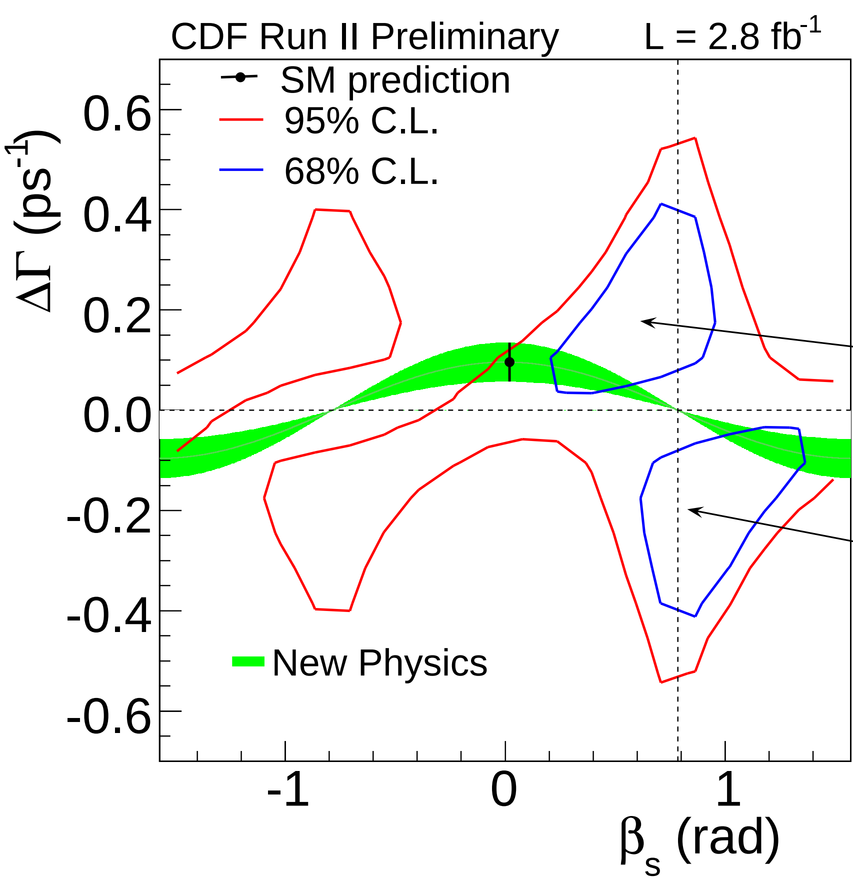


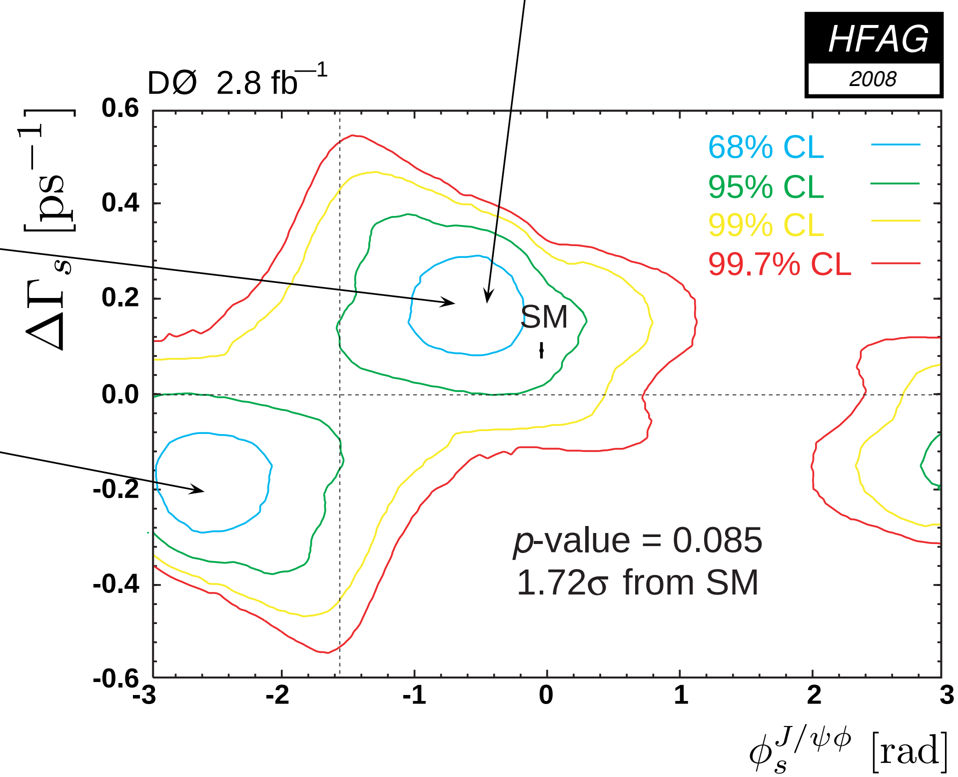


Effect of strong phases constraint

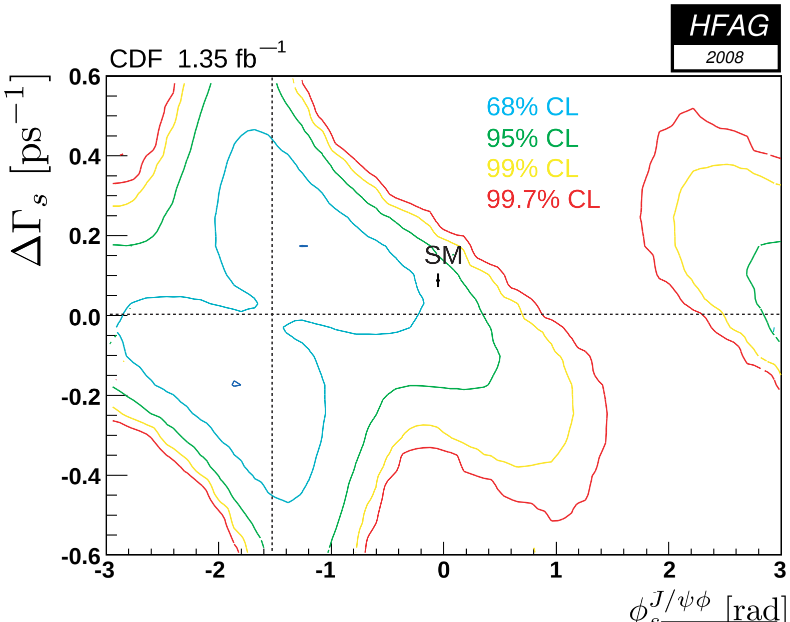
- When removing strong phase constraint second minima appear
- Two experiments quite comparable

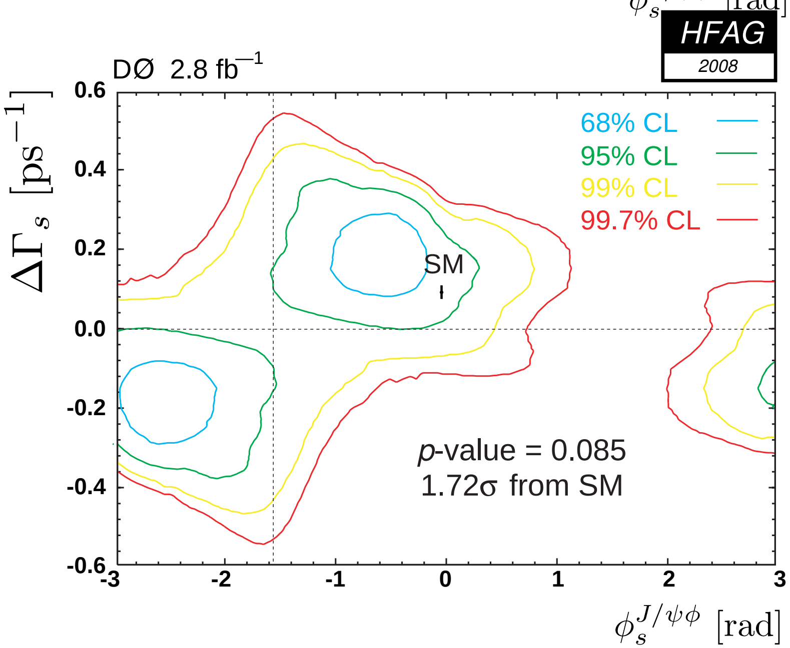


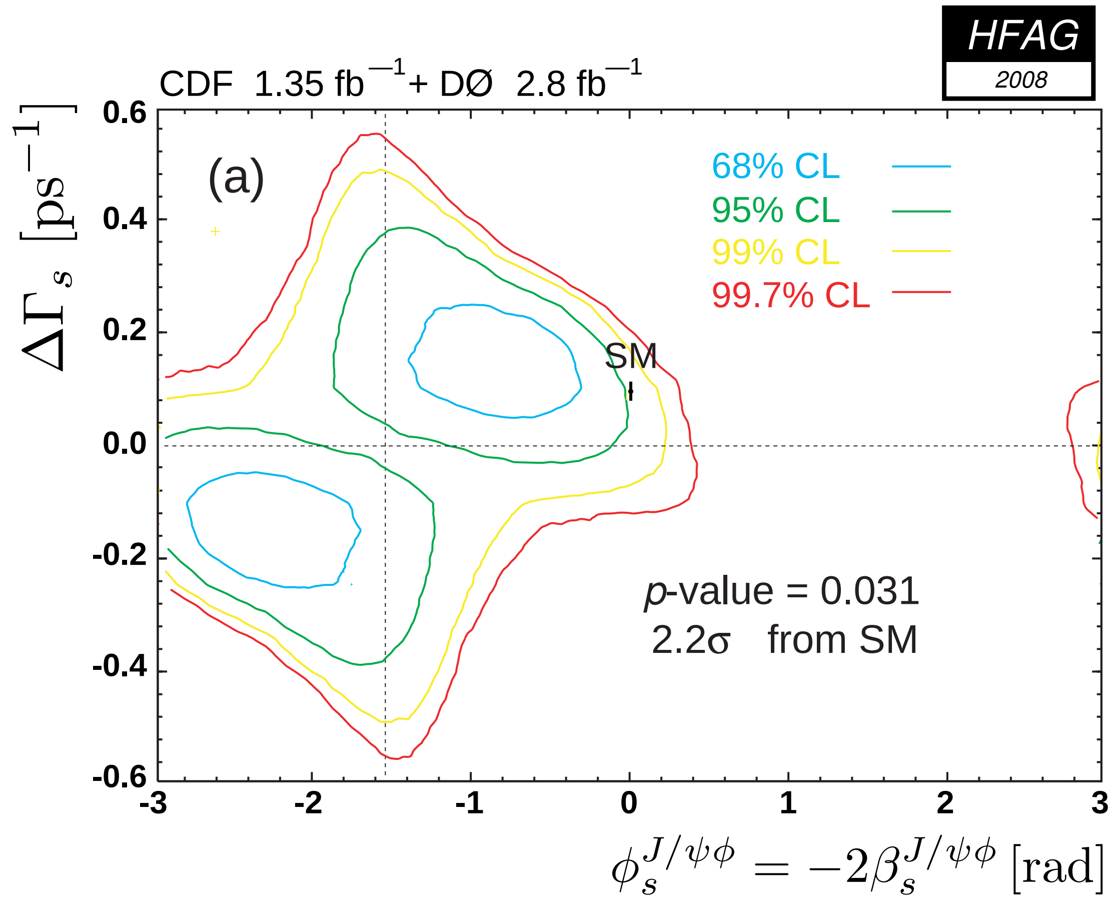




ϕ_s Combination







→ Combination with 2.8 fb^{-1} CDF result ongoing

→ Working on unified treatment of systematic uncertainties

$\mathrm{B_s} \to \mathrm{D_s^{(*)} D_s^{(*)}}$

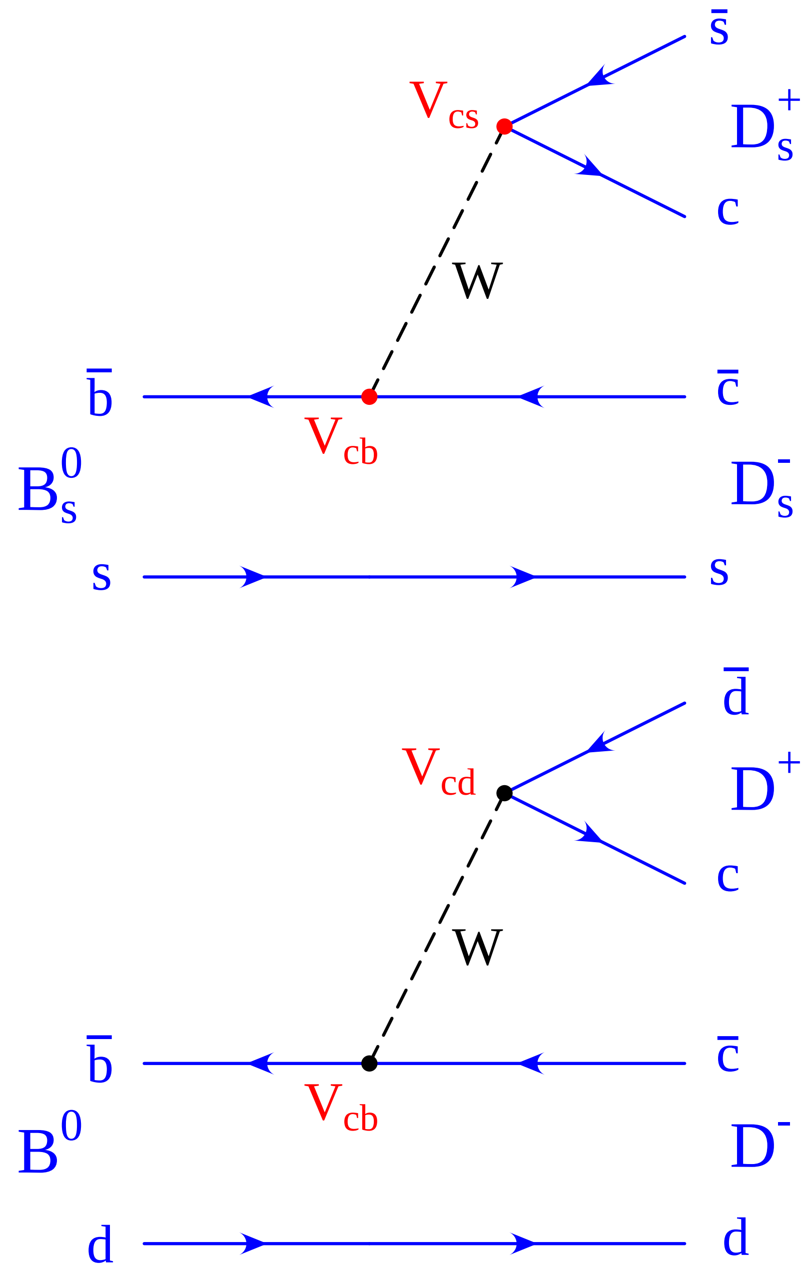
- $\Delta\Gamma$ and ϕ_s are related:
  $\Delta\Gamma = 2|\Gamma_{12}|\cos(\phi_s)$
- With $2|\Gamma_{12}| = \Delta\Gamma_{CP} = \Gamma^{even} = \Gamma^{odd}$

$\rightarrow$ $\Delta\Gamma$ measurement can be converted to ϕ_s

- Theory: $\Delta\Gamma_{CP}/\Gamma = 14.7 \pm 6\%$
- Dominant contribution from $B_s \to D_s^{(*)} D_s^{(*)}$
- In Shifman-Voloshin limit:
  $m_c \to \infty$, $m_b = 2m_c$, $N_{color} \to \infty$

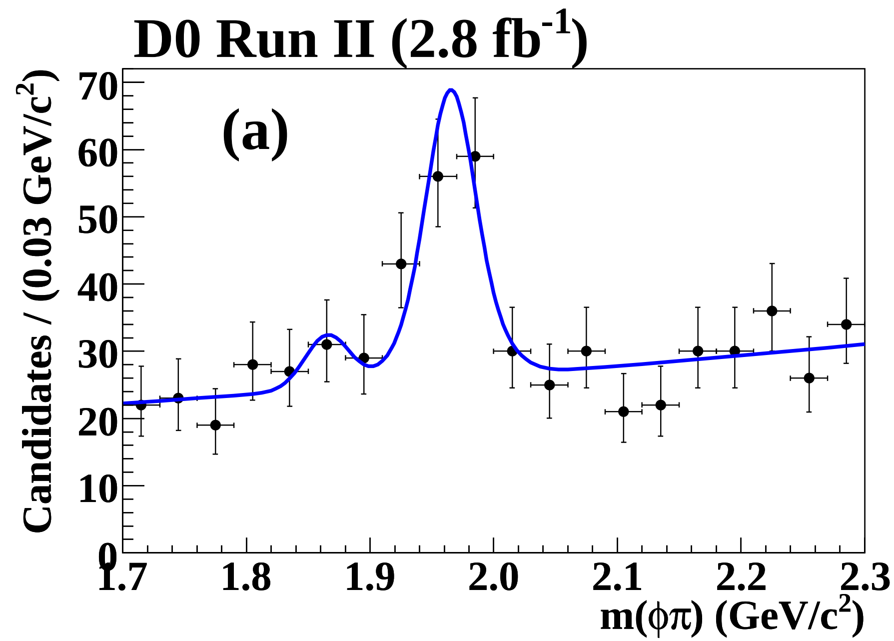
$\rightarrow$ $\Delta\Gamma_{CP} = 2\Gamma(B_s \to D_s^{(*)} D_s^{(*)})$

- Could one take CP-odd fraction in $B_s \to D_s^* D_s^*$ from $B^0 \to D^{*+} D^{*-}$?

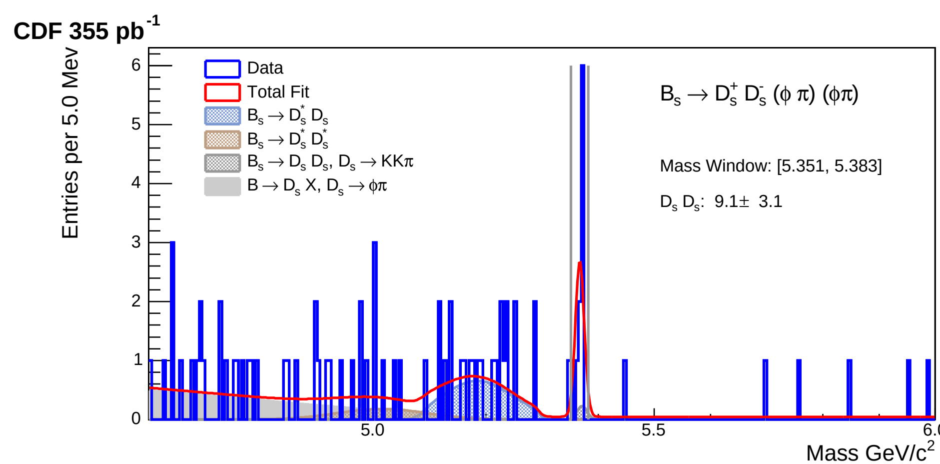


$B_s \to D_s^{(*)} D_s^{(*)}$

- $D_s \to \phi\mu\nu$
- $D_s \to \phi\pi$
- Normalize to $B_s \to D_s^{(*)}\mu\nu$
- $\mathcal{B}(B_s \to D_s^{(*)} D_s^{(*)}) =$ $3.5 \pm 1.0 \pm 1.1\%$
- $\Delta\Gamma_{CP}/\Gamma = 7.2 \pm 2.1 \pm 2.2\%$



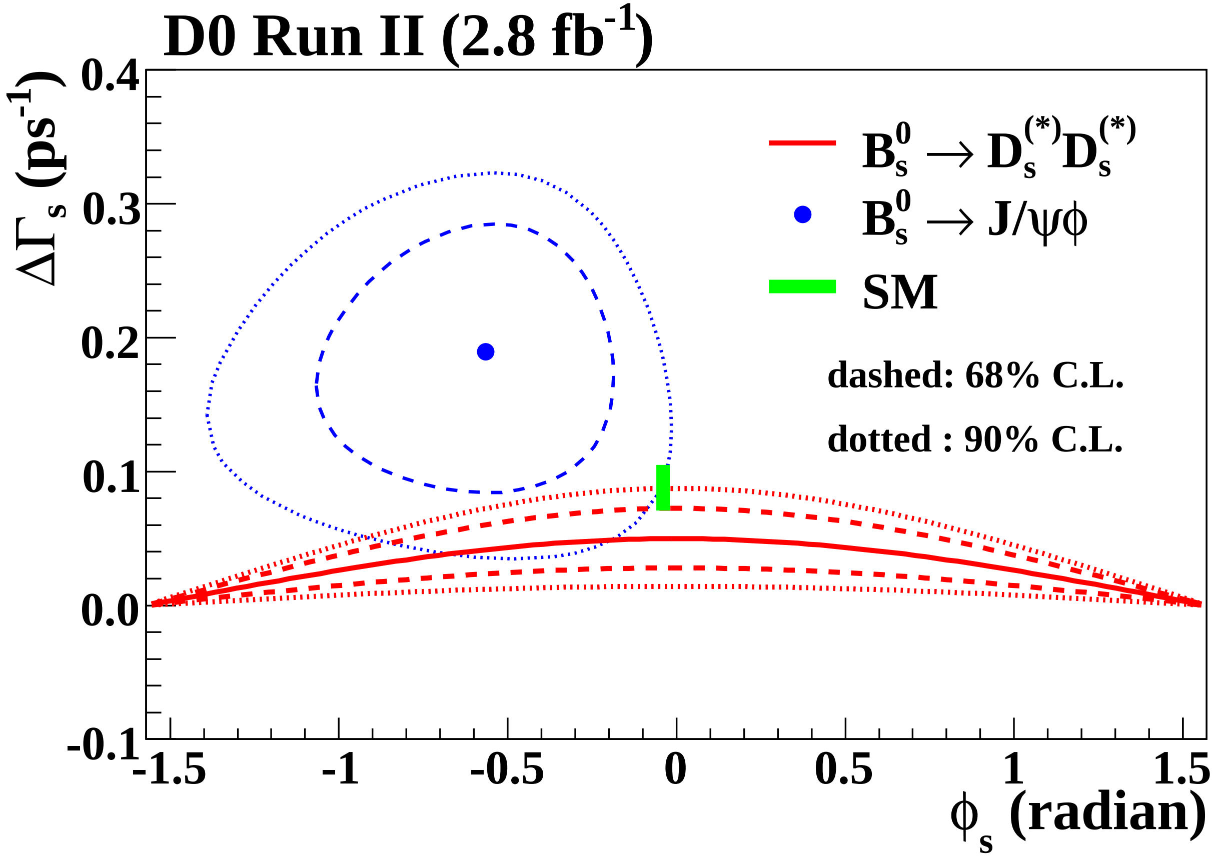
- $D_s \to \phi\pi$
- $D_s \to \phi\pi$, K^*K and $\pi\pi\pi$
- Normalize to $B^0 \to D_s D$
- $\mathcal{B}(B_s \to D_s D_s) = 0.94^{+0.44}_{-0.42}\%$
- $\Delta\Gamma_{CP}/\Gamma > 1.2\%@95\%$ C.L.

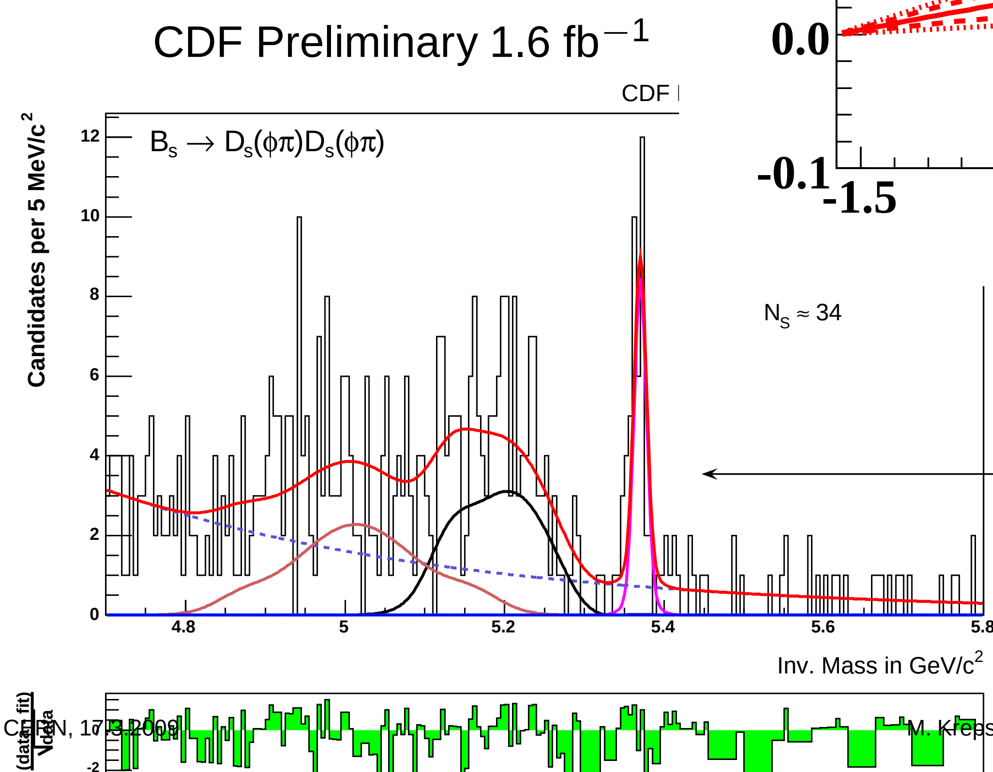


$B_s \to D_s^{(*)} D_s^{(*)}$

Could help

Theory uncertainties?



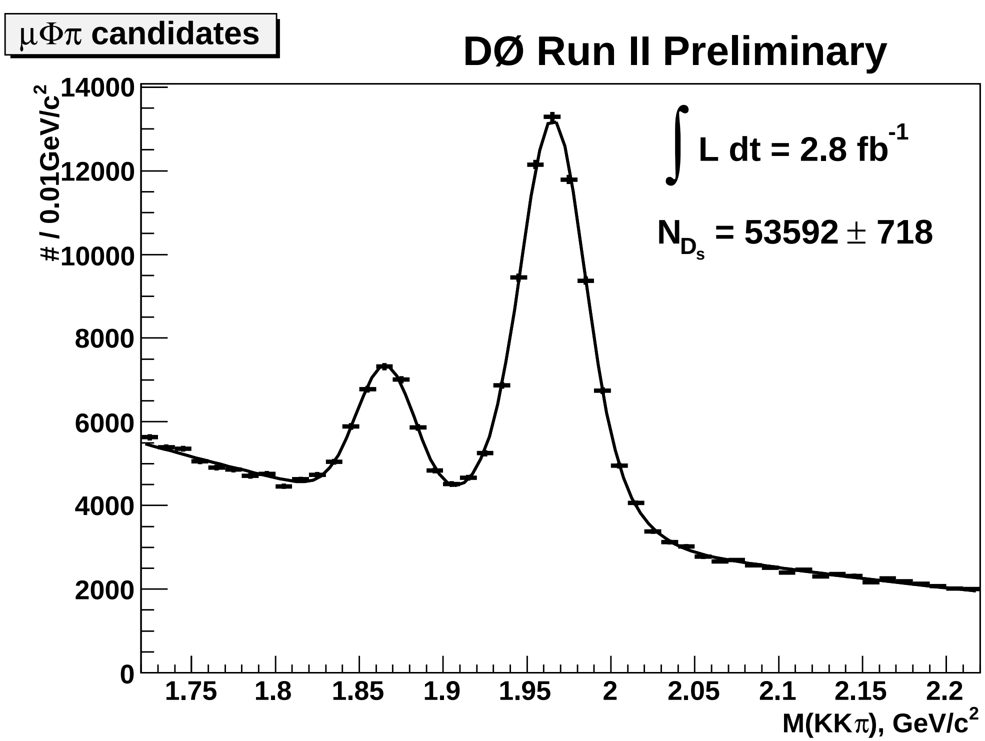


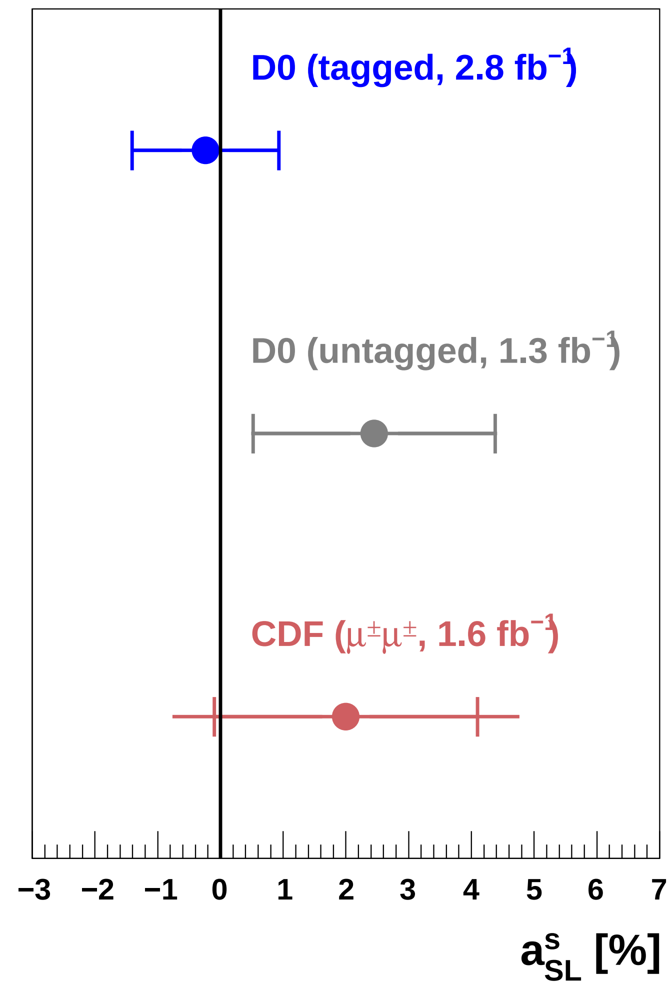
CDF should be able to measure also $B_s \to D_s^* D_s$ and $B_s \to D_s^* D_s^*$

Semileptonic CP asymmetry

- Uses $B_s \to D_s^- \mu^+ X$ with $D_s^- \to \phi\pi$
- Performs tagged time dependent analysis
- Assume no direct CP violation
- SM expectation $a_{SL} = 2 \times 10^{-5}$

$$a_{SL} = -0.24 \pm 1.17^{+0.15}_{-0.24}\,\%$$



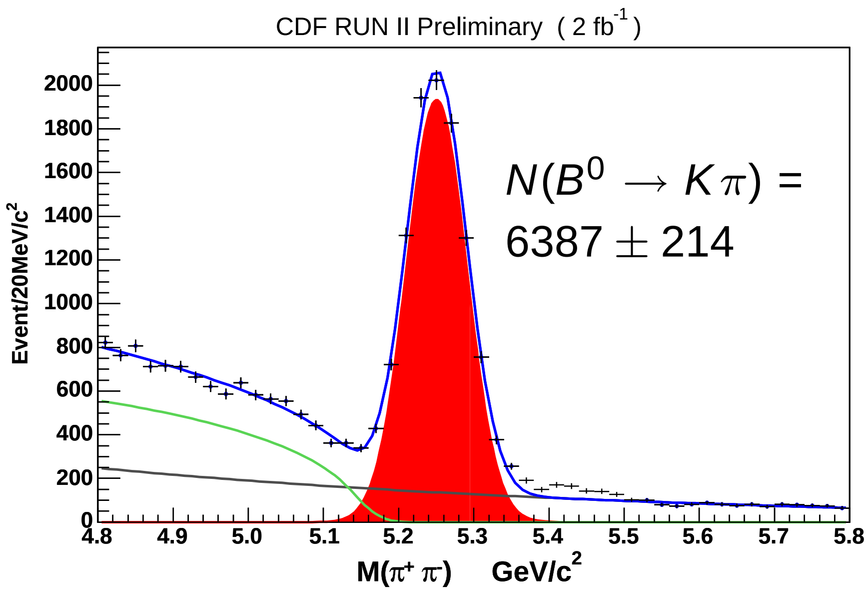


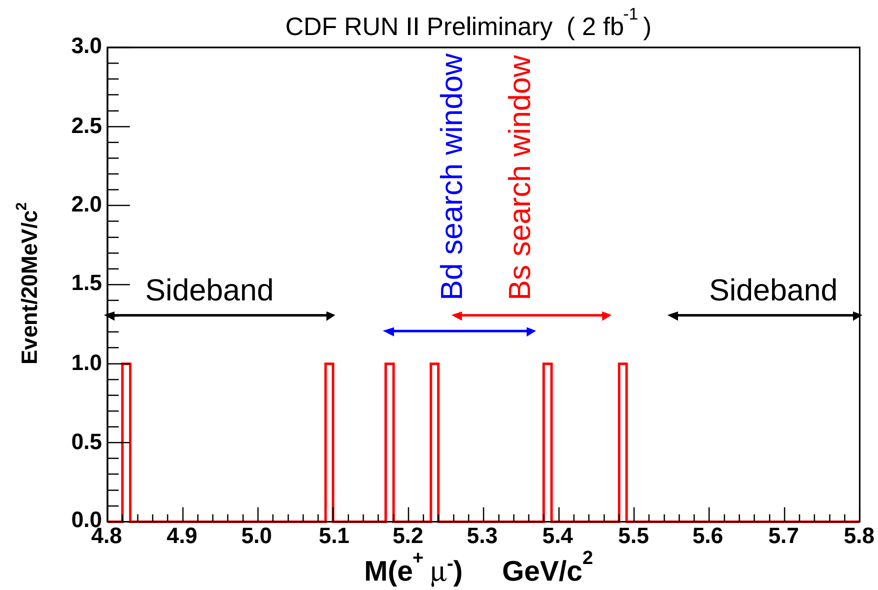
Rare decays to lepton pairs

- FCNC decays to l^+l^- from same generation
  - Strongly suppressed in SM
  - In SM only through box or loop diagrams
  - Many models of new physics can give significant enhancement
  - Observation at Tevatron would imply new physics
- Lepton flavor violating decays
  - Forbidden in SM
  - Observation of neutrino oscillation $\Rightarrow$ lepton flavor violating B decays should exist
  - Rate still extremely small
  - Can be enhanced in some new physics scenario like Pati-Salam leptoquarks
- $D^0 \rightarrow \mu\mu$ special case as it probes down type quarks in loop

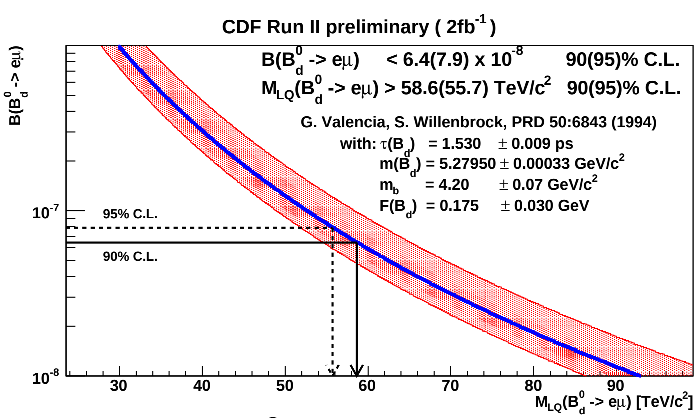
$\mathbf{B_{d,s} \to e\mu}$

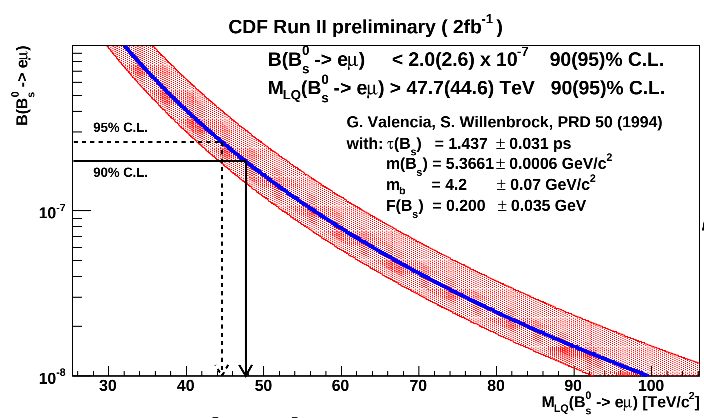
$$\mathcal{B}(B_s \to e\mu) < 2.0(2.6) \times 10^{-7} \text{ at } 90(95)\% \text{ C.L.}$$
$$\mathcal{B}(B^0 \to e\mu) < 6.4(7.9) \times 10^{-8} \text{ at } 90(95)\% \text{ C.L.}$$





B^0





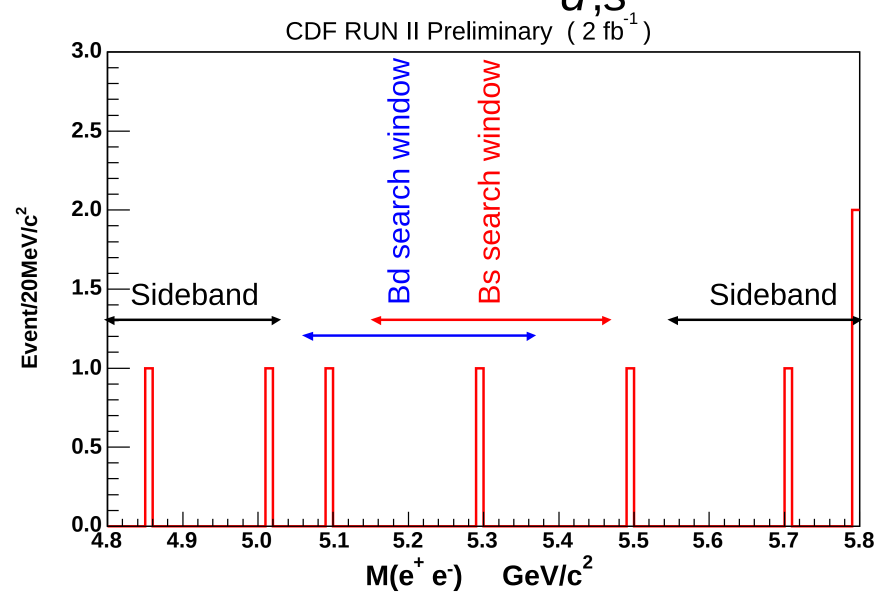
B_s

$$M_{LQ}(B^0) < 58.6 \text{ TeV} \qquad M_{LQ}(B_s) < 47.7 \text{ TeV}$$

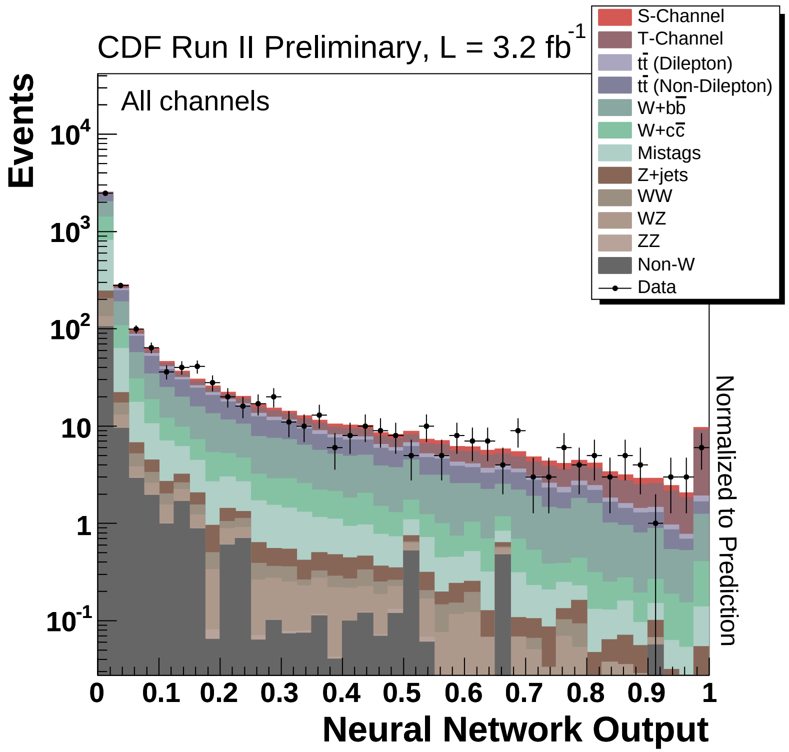
FCNC Rare decays

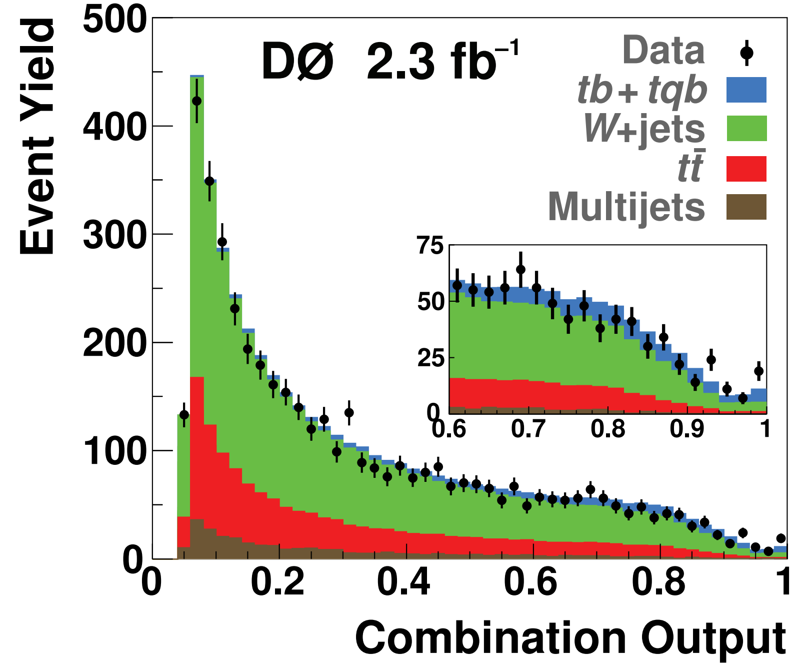
- All measurements best in world
- $\mathcal{B}(B_s \to e^+e^-) < 2.8(3.7) \times 10^{-7}$
- $\mathcal{B}(B^0 \to e^+e^-) < 8.3(10.6) \times 10^{-8}$
- CDF: $\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.5(1.8) \times 10^{-8}$
- CDF: $\mathcal{B}(D^0 \to \mu^+\mu^-) < 4.3(5.3) \times 10^{-7}$
- $\mathcal{B}(B_s \to \mu^+\mu^-)$ (1.3-2fb^{-1})
  DØ: $9.4(12) \times 10^{-8}$
  CDF: $4.7(5.8) \times 10^{-8}$
- DØ expected limit with 5 fb^{-1}
  $4.3(5.3) \times 10^{-8}$

$B_{d,s} \to e^+e^-$



Single Top





$\sigma = 2.3^{+0.6}_{-0.5}$ pb

Expected significance: $> 5.9\sigma$

Observed significance: 5.0σ

$V_{tb} = 0.91 \pm 0.11 \pm 0.07$

$V_{tb} > 0.71$ at 95% C.L.

$\sigma = 3.94 \pm 0.88$ pb

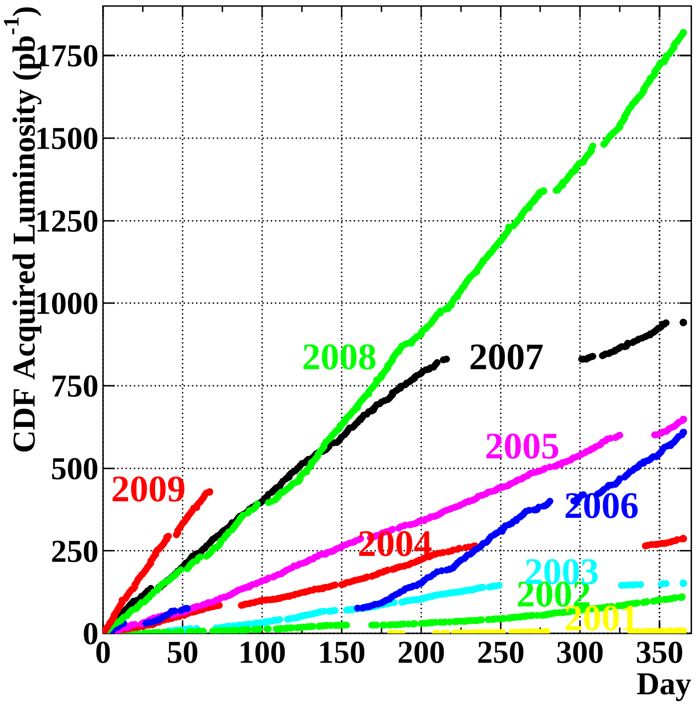
Expected significance: 4.5σ

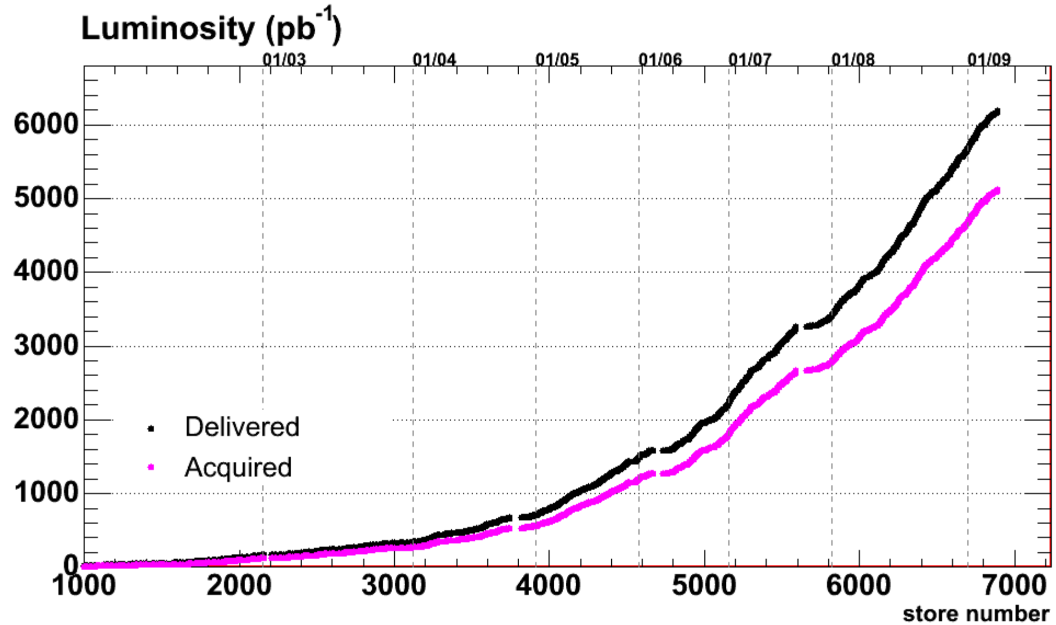
Observed significance: 5.0σ

$V_{tb} = 1.07 \pm 0.12$

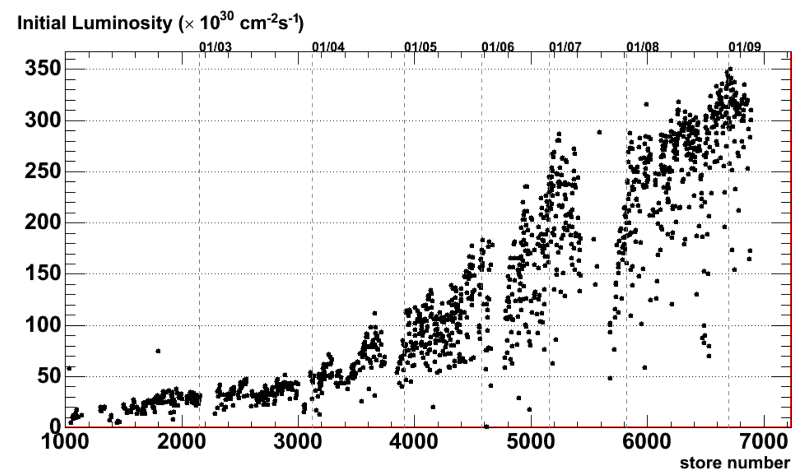
$V_{tb} > 0.78$ at 95% C.L.

Prospects



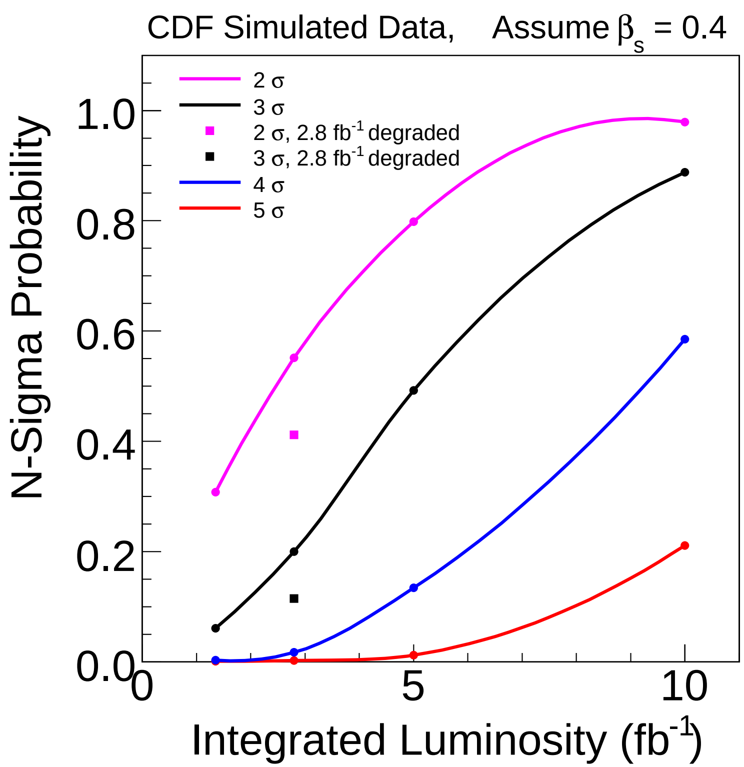


- Plots show collected at CDF
- DØ plots look similar
- Get about 1.5-2 fb^{-1} per year
- Projections:
  FY 2010: $\approx$ 9 fb^{-1}
  FY 2011: $\approx$ 12 fb^{-1}

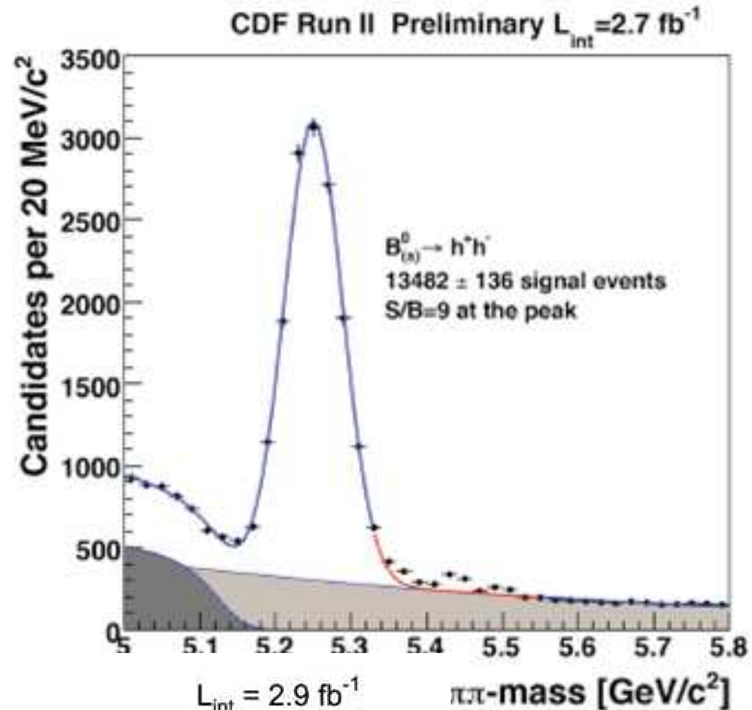


Main challenge is triggering

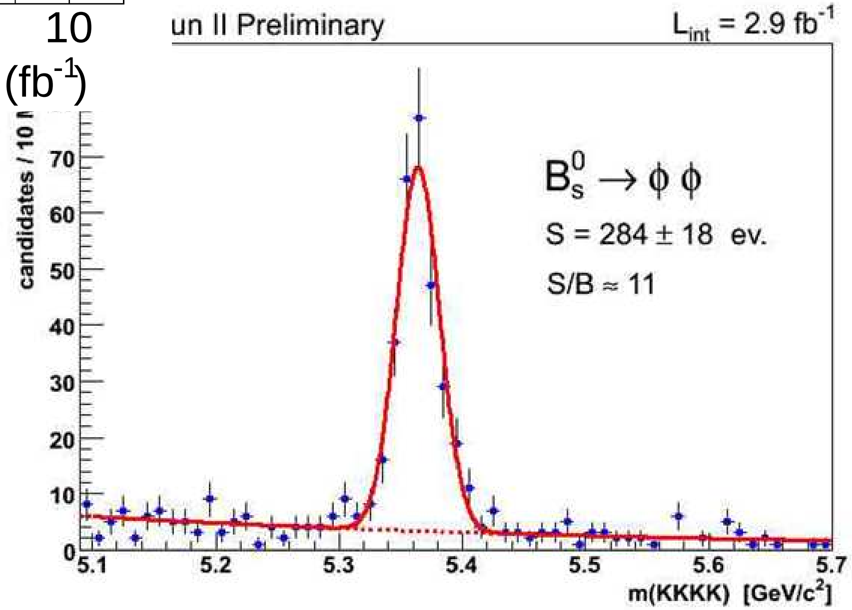
Prospects



CDF Simulated Data, Assume β_s = 0.4
2 σ
3 σ
2 σ, 2.8 fb^{-1} degraded
3 σ, 2.8 fb^{-1} degraded
4 σ
5 σ
N-Sigma Probability
Integrated Luminosity (fb^{-1})



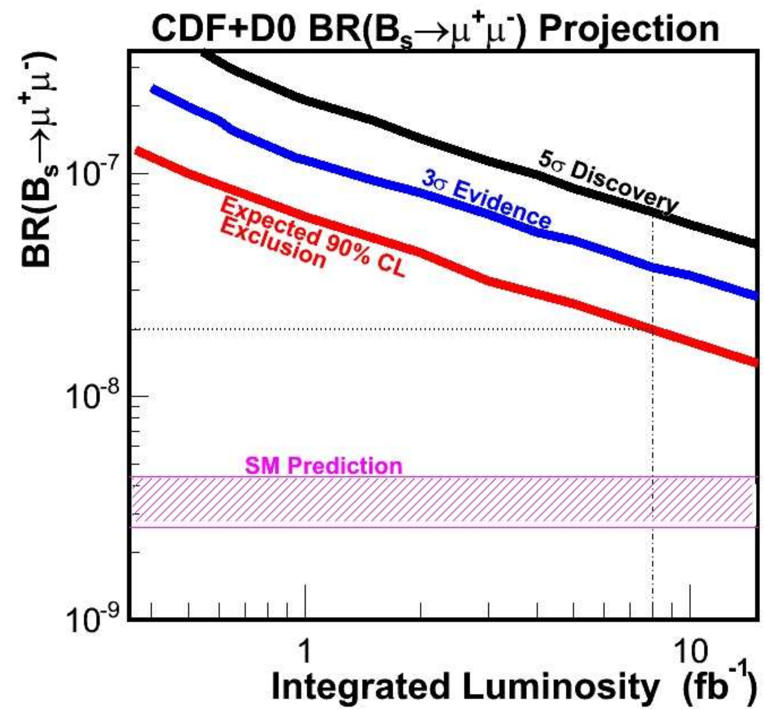
CDF Run II Preliminary L_{int}=2.7 fb^{-1}
Candidates per 20 MeV/c^2
$B^0_{(s)} \to h^+h^-$
13482 ± 136 signal events
S/B=9 at the peak
ππ-mass [GeV/c^2]

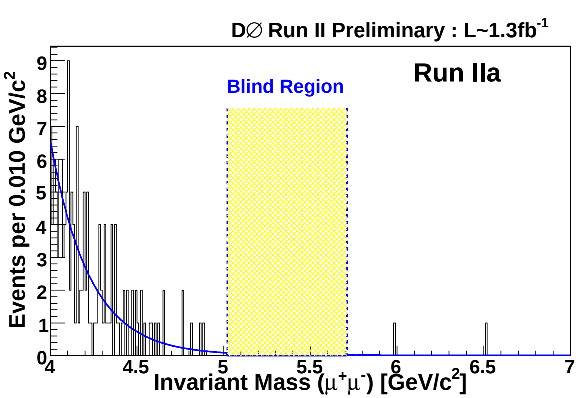


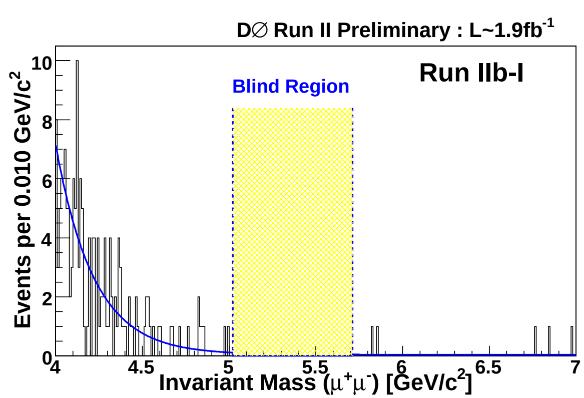
un II Preliminary
L_{int} = 2.9 fb^{-1}
candidates / 10 M
$B^0_s \to \phi\,\phi$
S = 284 ± 18 ev.
S/B ≈ 11
m(KKKK) [GeV/c^2]

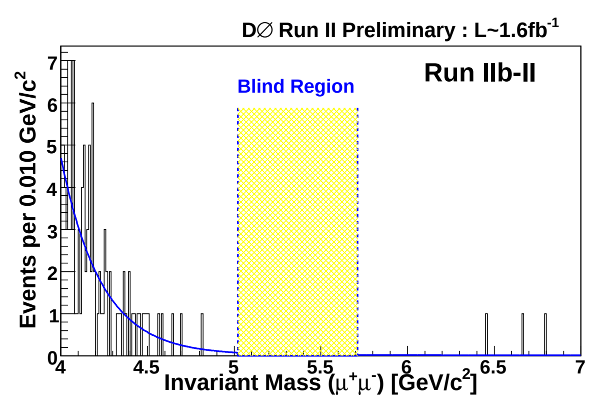
Prospects

- DØ presented yesterday partial update with 5 fb^{-1}
- Data still blinded
- Expects limit $4.3(5.3) \times 10^{-8}$
- CDF update also on way
- Based on extrapolation expect $\approx 3 \times 10^{-8}$ at 90% C.L.







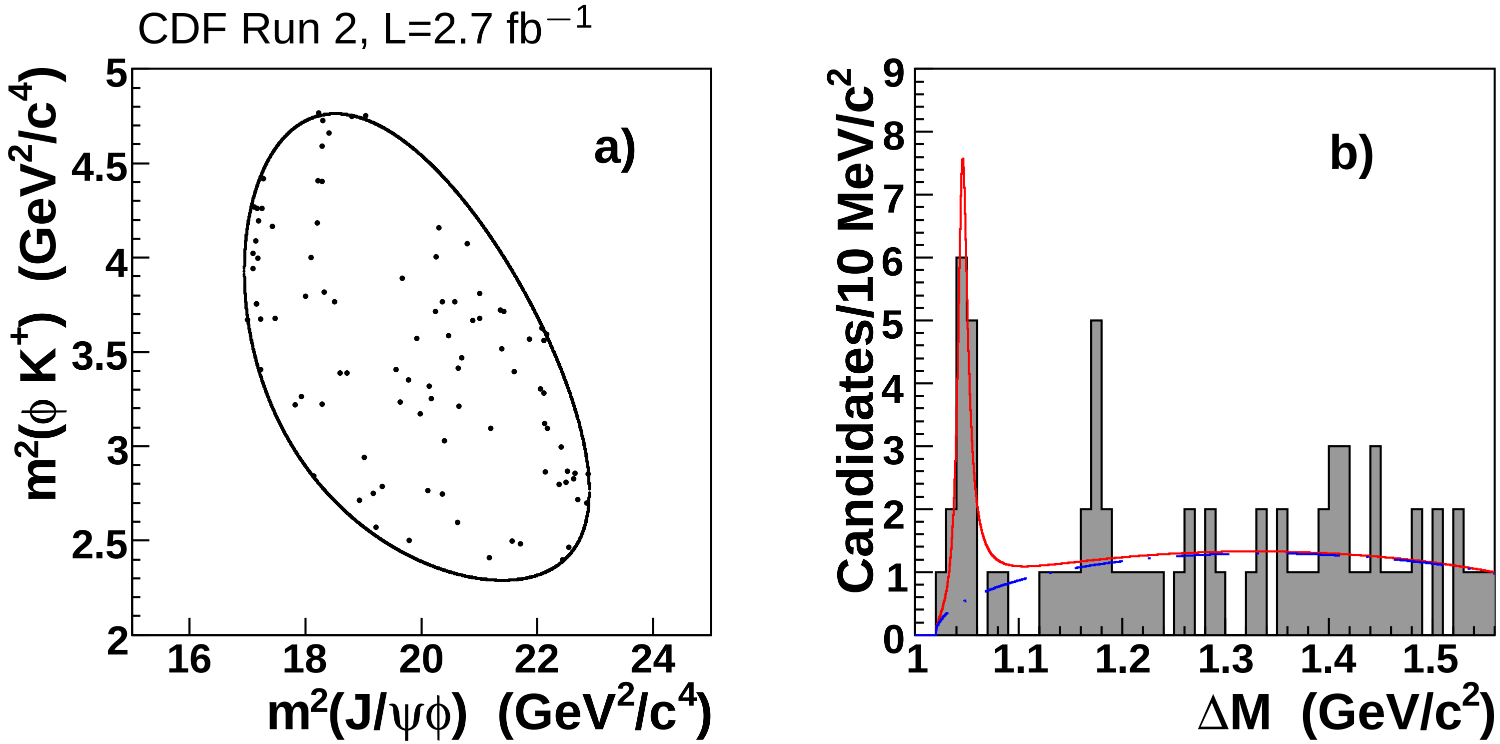


Conclusions

- Rich program in Flavor physics at Tevatron
- People still active to improve analyzes
- 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 $b \rightarrow s$ transition good prospects to get evidence for it
- Expect updates of several analyzes by this summer
- As we have limited man/woman power we cannot do everything

$\Rightarrow$ Guide us where to look

Resonance in $J/\psi\phi$



$M = 4143.0 \pm 2.9(\mathrm{stat}) \pm 1.2(\mathrm{syst})\ \mathrm{MeV}/c^2$

$\Gamma = 11.7^{+8.3}_{-5.0}(\mathrm{stat}) \pm 3.7(\mathrm{syst})\ \mathrm{MeV}/c^2$

$N = 14 \pm 5$

Significance 3.8σ with flat combinatorial background

B-meson mixing

- Mass and flavour eigenstates of the B_s differ

$\Rightarrow$ B_s– $\overline{B}_s$ oscillations

- In standard model (SM) governed by weak interaction

$\rightarrow$ phenomenology depends on CKM matrix

- Time development described by the Schrödinger equation

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

- $\mathbf{M}$ and $\mathbf{\Gamma}$ are complex 2×2 matrices
- Mass difference $\Delta m = m_H - m_L = 2|M_{12}|$ between B_{sH}^0 and B_{sL}^0 determines B_s mixing frequency

$\rightarrow$ From B_s mixing frequency measurement $\Rightarrow$ no large NP contribution possible to size of the $|M_{12}|$

B-meson mixing

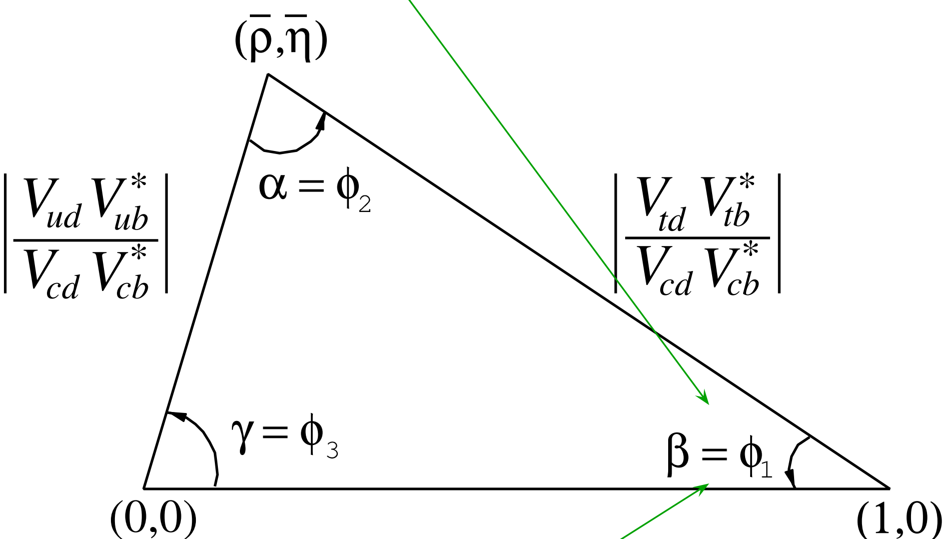
- Mean B_s lifetime $\tau = 2/(\Gamma_H + \Gamma_L)$ expected equal to B^0 lifetime
- Decay width difference $\Delta\Gamma = \Gamma_L - \Gamma_H$ can be sizable
  - Measured first by CDF with 260 pb^{-1}
  - Measurement by DØ with 1.1 fb^{-1}
  - In SM we expect $\Delta\Gamma = 0.096 \pm 0.039\ \text{ps}^{-1}$
- As M and Γ are complex we have phase $\phi_s = \arg(-M_{12}/\Gamma_{12})$
  - SM expectation $\phi_s^{SM} = 4 \times 10^{-3}$
  - Can receive large contribution from new physics (NP) in B_s mixing diagram, $\phi_s = \phi_s^{NP} + \phi_s^{SM}$

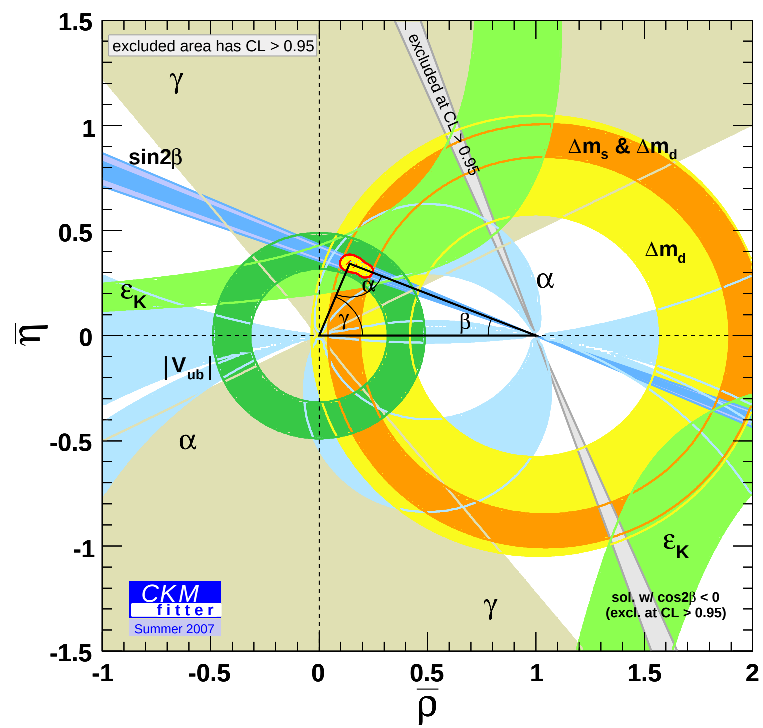
$\rightarrow$ In theory we have relation $\Delta\Gamma = 2|\Gamma_{12}|\cos(\phi_s)$

$\Rightarrow$ Large deviation of $\Delta\Gamma$ and ϕ_s from SM is clear evidence of NP

Origin of mixing phase in SM

$$\begin{pmatrix} 1-\frac{\lambda^2}{2}-\frac{\lambda^4}{8} & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{A^2\lambda^5}{2}[1-2(\rho+i\eta)] & 1-\frac{\lambda^2}{2}-\frac{\lambda^4}{8}(1+4A^2) & A\lambda^2 \\ A\lambda^3[1-(1-\frac{\lambda^2}{2})(\rho-i\eta)] & -A\lambda^2+\frac{A\lambda^4}{2}[1-2(\rho+i\eta)] & 1-\frac{A^2\lambda^4}{2} \\ \text{Large CPV} & \text{Small CPV} & \end{pmatrix}$$





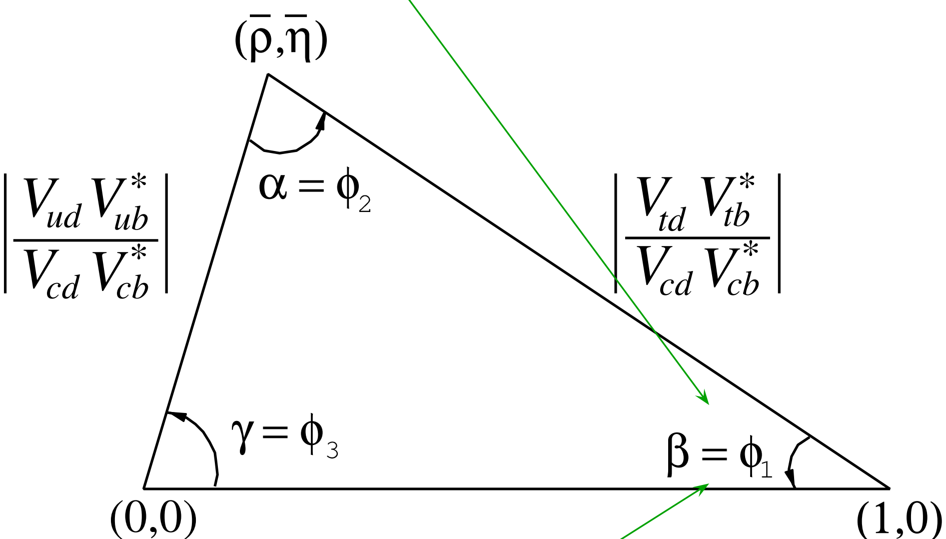
Determines CPV in $B^0 \to J/\psi K_S$

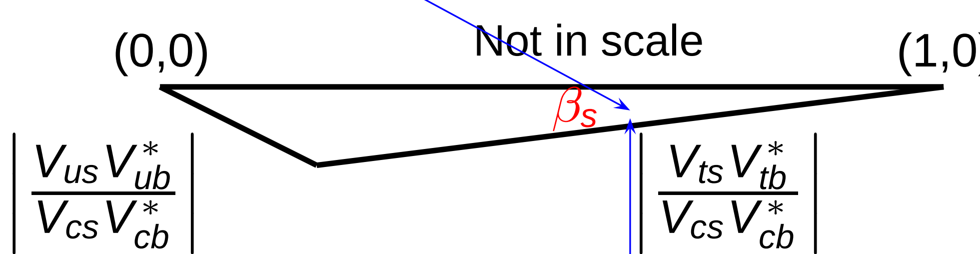
Origin of mixing phase in SM

$$\left(\begin{array}{ccc} 1-\frac{\lambda^2}{2}-\frac{\lambda^4}{8} & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{A^2\lambda^5}{2}[1-2(\rho+i\eta)] & 1-\frac{\lambda^2}{2}-\frac{\lambda^4}{8}(1+4A^2) & A\lambda^2 \\ A\lambda^3[1-(1-\frac{\lambda^2}{2})(\rho-i\eta)] & -A\lambda^2+\frac{A\lambda^4}{2}[1-2(\rho+i\eta)] & 1-\frac{A^2\lambda^4}{2} \end{array}\right)$$

Large CPV

Small CPV



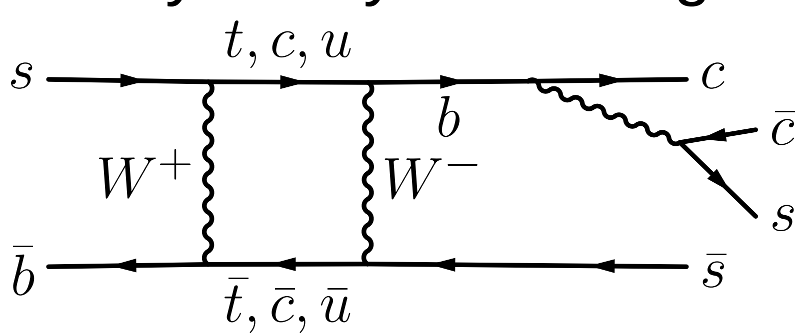


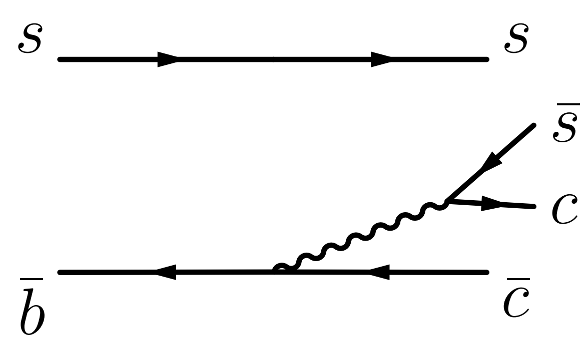
Determines CPV in $B_s \to J/\psi\phi$

Determines CPV in $B^0 \to J/\psi K_s$

Testing B_s mixing phase

- 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
- Decay in Feynman diagrams

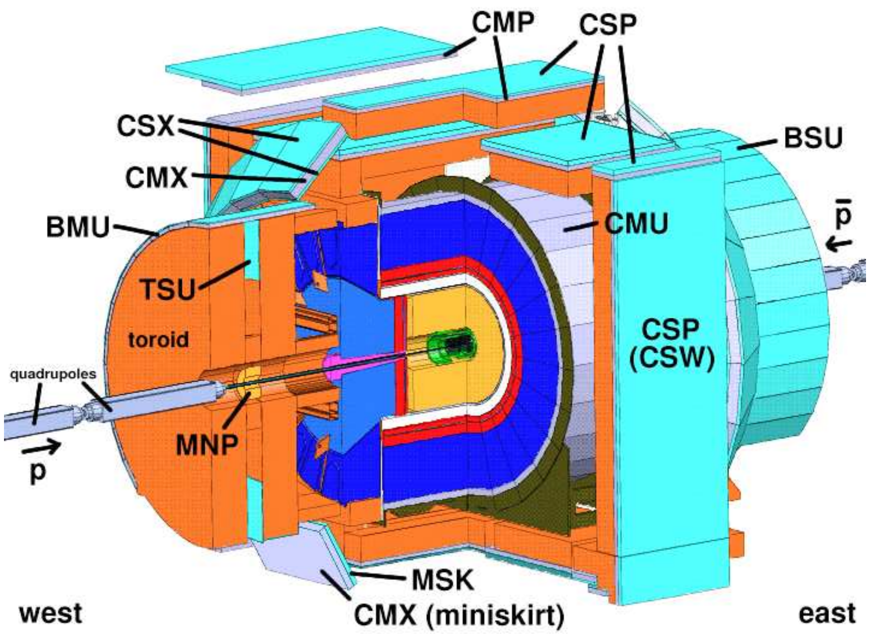




- We measure phase between B_s mixing and $b \to c\bar{c}s$
  - In SM $2\beta_s^{SM} = 2\arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*) \approx 0.04$
  - In presence of NP $2\beta_s = 2\beta_s^{SM} - \phi_s^{NP}$
- With our precision, SM contributions can be neglected

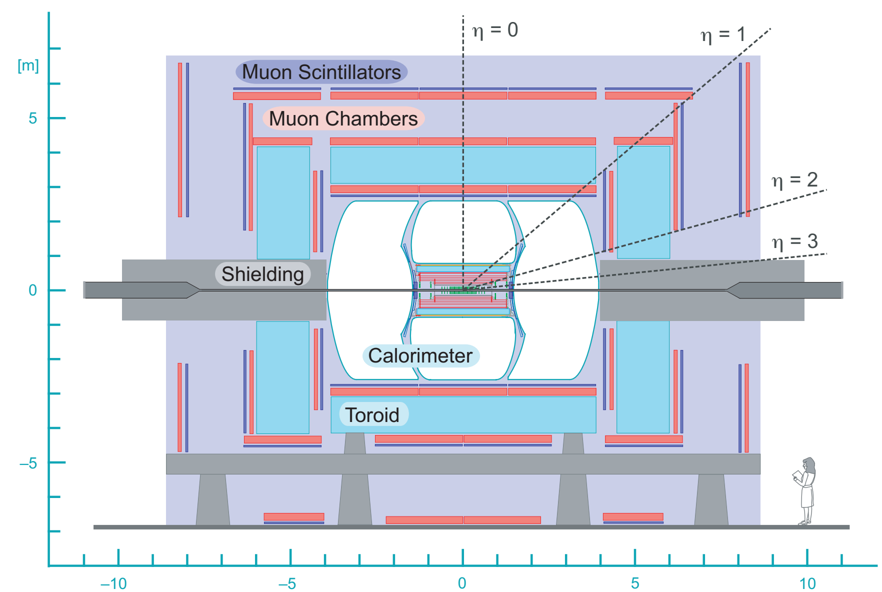
$\Rightarrow$ $2\beta_s = -\phi_s^{NP} = -\phi_s$

Experiments



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

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



Adding flavour tagging

- 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 ($\overline{B}_s$)

Adding flavour tagging

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

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

Same structure as untagged likelihood, green terms modified

Adding flavour tagging

What is new comparing to untagged case:

$$\mathcal{T}_\pm = e^{-\Gamma t} \quad \times \quad [\cosh(\Delta\Gamma t/2) \mp \cos(2\beta_s)\sinh(\Delta\Gamma t/2)$$
$$\mp\, \eta \sin(2\beta_s)\sin(\Delta m_s t)]\,,$$

$$\begin{aligned}
\mathcal{U}_\pm = \pm e^{-\Gamma t} \quad & \times \quad \left[\sin(\delta_\perp - \delta_\parallel)\cos(\Delta m_s t)\right. \\
& - \quad \cos(\delta_\perp - \delta_\parallel)\cos(2\beta_s)\sin(\Delta m_s t) \\
& \pm \quad \left.\cos(\delta_\perp - \delta_\parallel)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)\right]\,, \\
\mathcal{V}_\pm = \pm e^{-\Gamma t} \quad & \times \quad [\sin(\delta_\perp)\cos(\Delta m_s t) \\
& - \quad \cos(\delta_\perp)\cos(2\beta_s)\sin(\Delta m_s t) \\
& \pm \quad \cos(\delta_\perp)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)]\,.
\end{aligned}$$

Adding flavour tagging

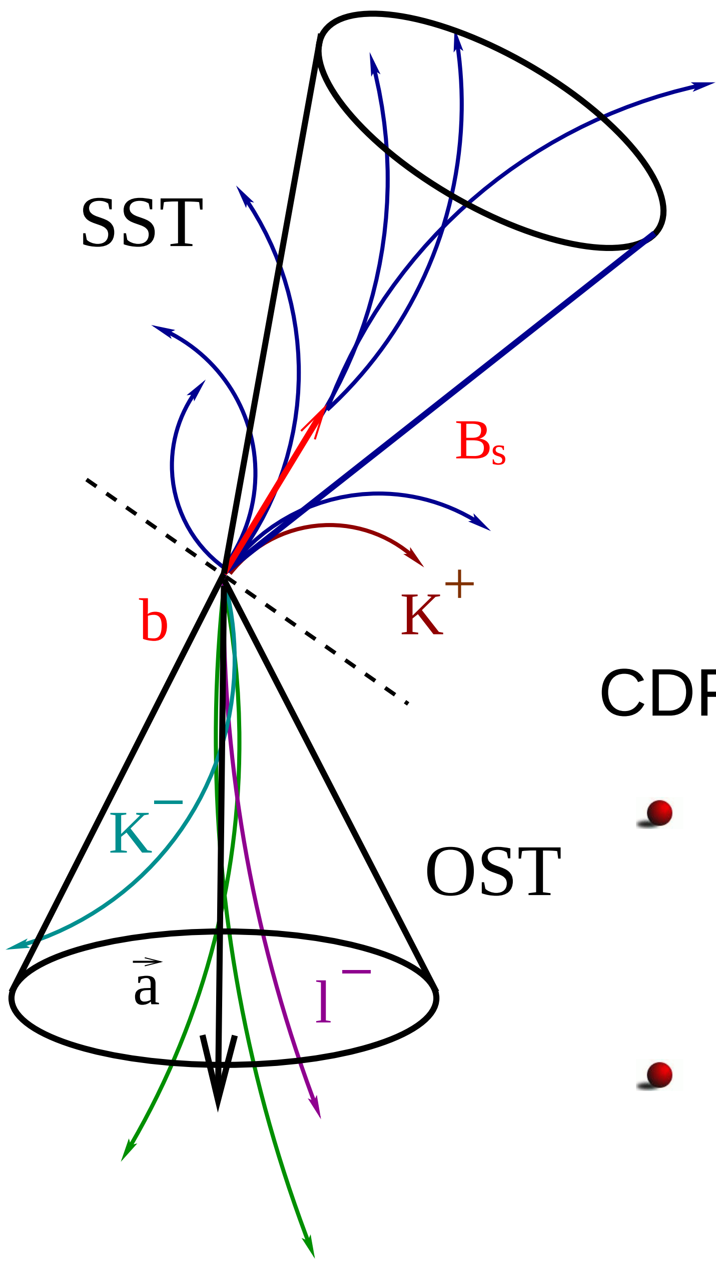
Another point worth to mention:

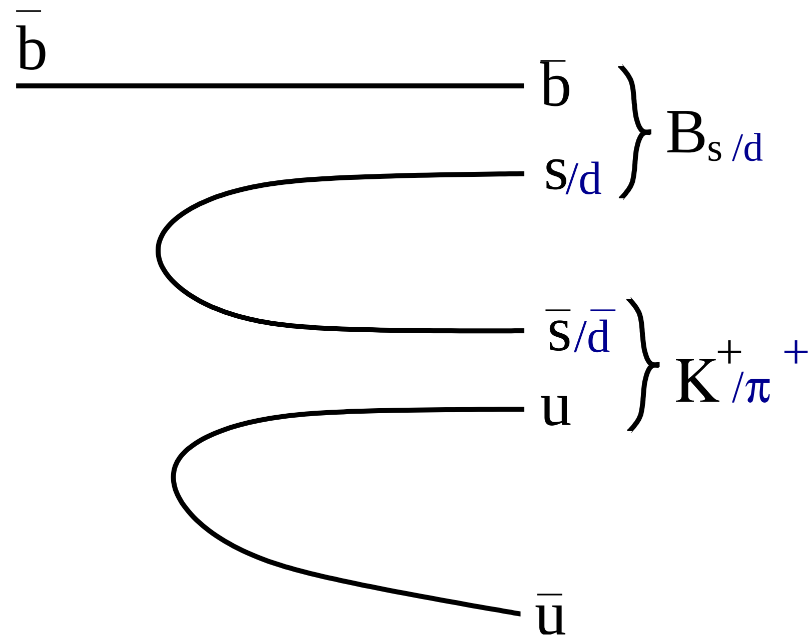
$$
\begin{aligned}
\mathcal{T}_{\pm} = e^{-\Gamma t} \quad \times \quad & [\cosh(\Delta\Gamma t/2) \mp \cos(2\beta_s)\sinh(\Delta\Gamma t/2) \\
& \mp \eta \sin(2\beta_s)\sin(\Delta m_s t)]\,,
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{U}_{\pm} = \pm e^{-\Gamma t} \quad & \times \quad \big[\sin(\delta_\perp - \delta_\parallel)\cos(\Delta m_s t) \\
& - \quad \cos(\delta_\perp - \delta_\parallel)\cos(2\beta_s)\sin(\Delta m_s t) \\
& \pm \quad \cos(\delta_\perp - \delta_\parallel)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)\big]\,, \\
\mathcal{V}_{\pm} = \pm e^{-\Gamma t} \quad & \times \quad [\sin(\delta_\perp)\cos(\Delta m_s t) \\
& - \quad \cos(\delta_\perp)\cos(2\beta_s)\sin(\Delta m_s t) \\
& \pm \quad \cos(\delta_\perp)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)]\,.
\end{aligned}
$$

Can be used to measure B_s mixing frequency independent of CPV

Flavour tagging





CDF performance:

- OST: $\epsilon D^2 = 1.2\%$
  efficiency=96%
  dilution=11%
- SST: $\epsilon D^2 = 3.6\%$
  efficiency=50%
  dilution=27%

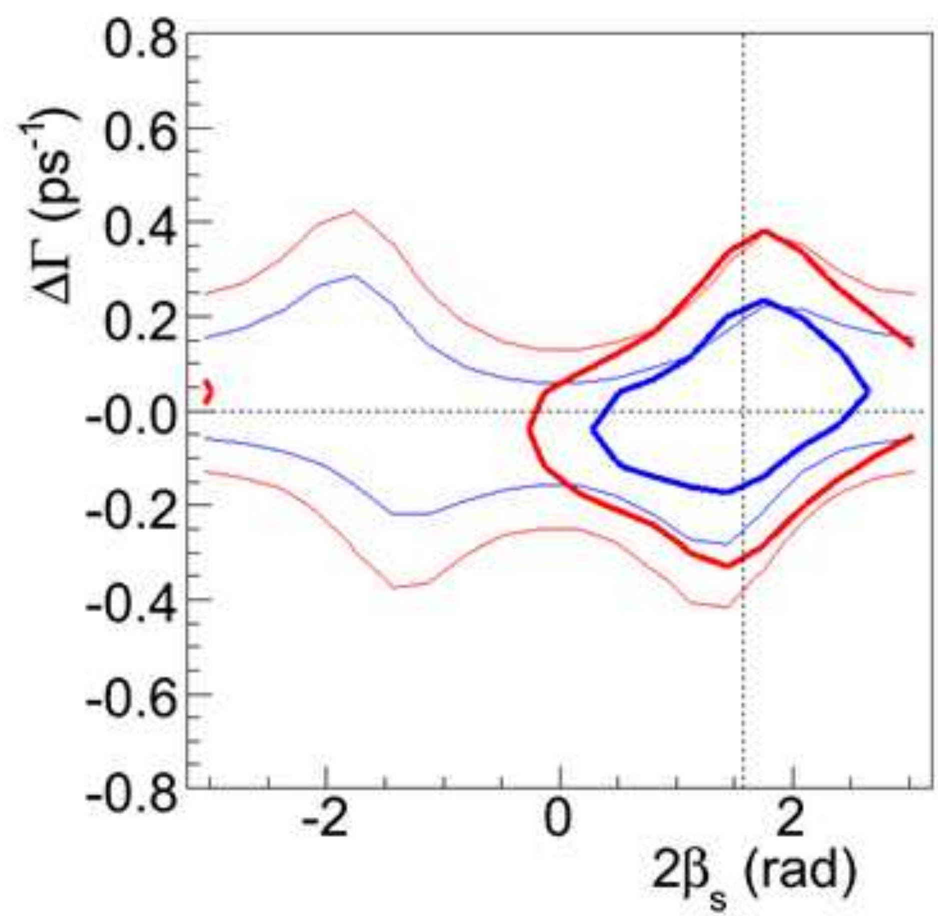
DØ performance:

- OST: $\epsilon D^2 = 2.5\%$
  efficiency=99.7%
  dilution=15.8%
- full: $\epsilon D^2 = 4.7\%$
  efficiency=100%
  dilution=22%

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

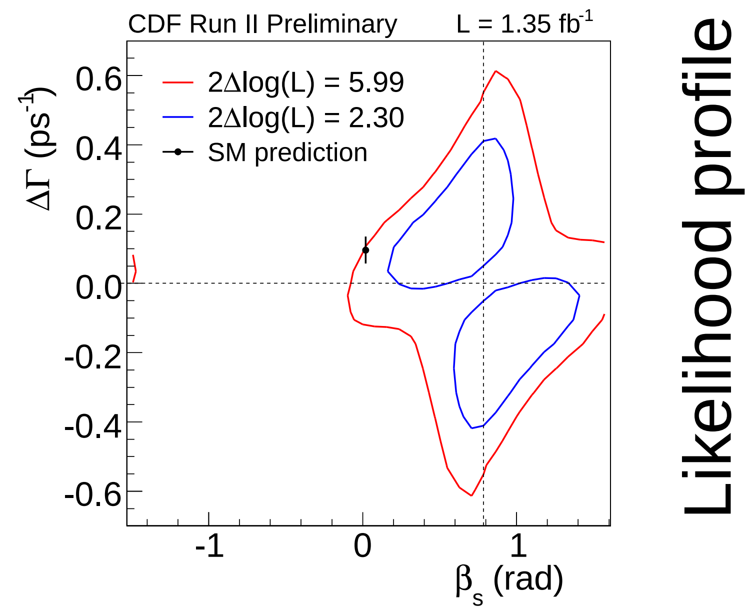


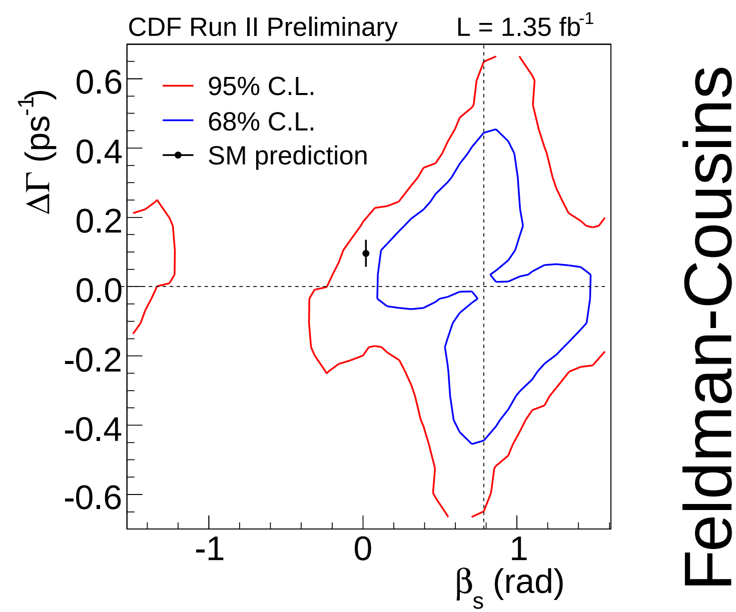
Statistical issues

- Bias from untagged case effectively removed
- Likelihood still irregular with two overlapping minima
- Uncertainties are clearly underestimated

$\Rightarrow$ To assure coverage, CDF quotes confidence region using $\mathcal{L}/\mathcal{L}_0$ ordering

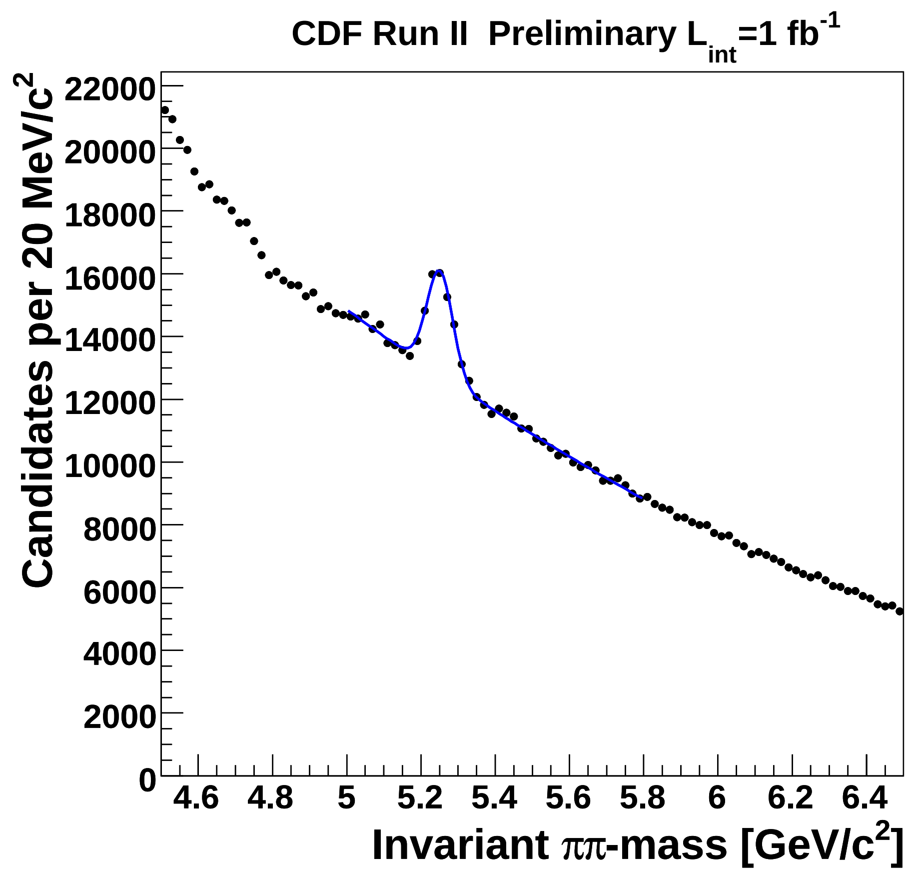
- DØ gives point estimate, but uncertainties clearly underestimated





$B \to hh'$ Trigger

- Hard to trigger, only two "stable" hadrons in final state
- Exploit long lifetime of the *B*-hadrons
- Trigger selection:
  - Two tracks with opposite charge
  - Track's $d_0 > 100\mu$m
  - Track's $p_T > 2.0$GeV$/c$
  - B vertex $L_{xy} > 200\mu$m
  - B's $d_0 < 140\mu$m
  - Opening angle 20° - 135°
  - $p_T(1) + p_T(2) > 5.5$GeV$/c$



Confirm trigger cuts offline
Peak already visible

Selection

- Tighten trigger cuts
- Add two more variables
  - χ^2 of the 3D vertex fit
  - Isolation $I = p_T(B)/[p_t(B) + \sum_i p_T(i)]$
- Minimize statistical uncertainty of quantity to be measured
- Derived two set of criteria
  - Looser for measurement of $A_{\mathrm{CP}}(B^0 \to K^+\pi^-)$

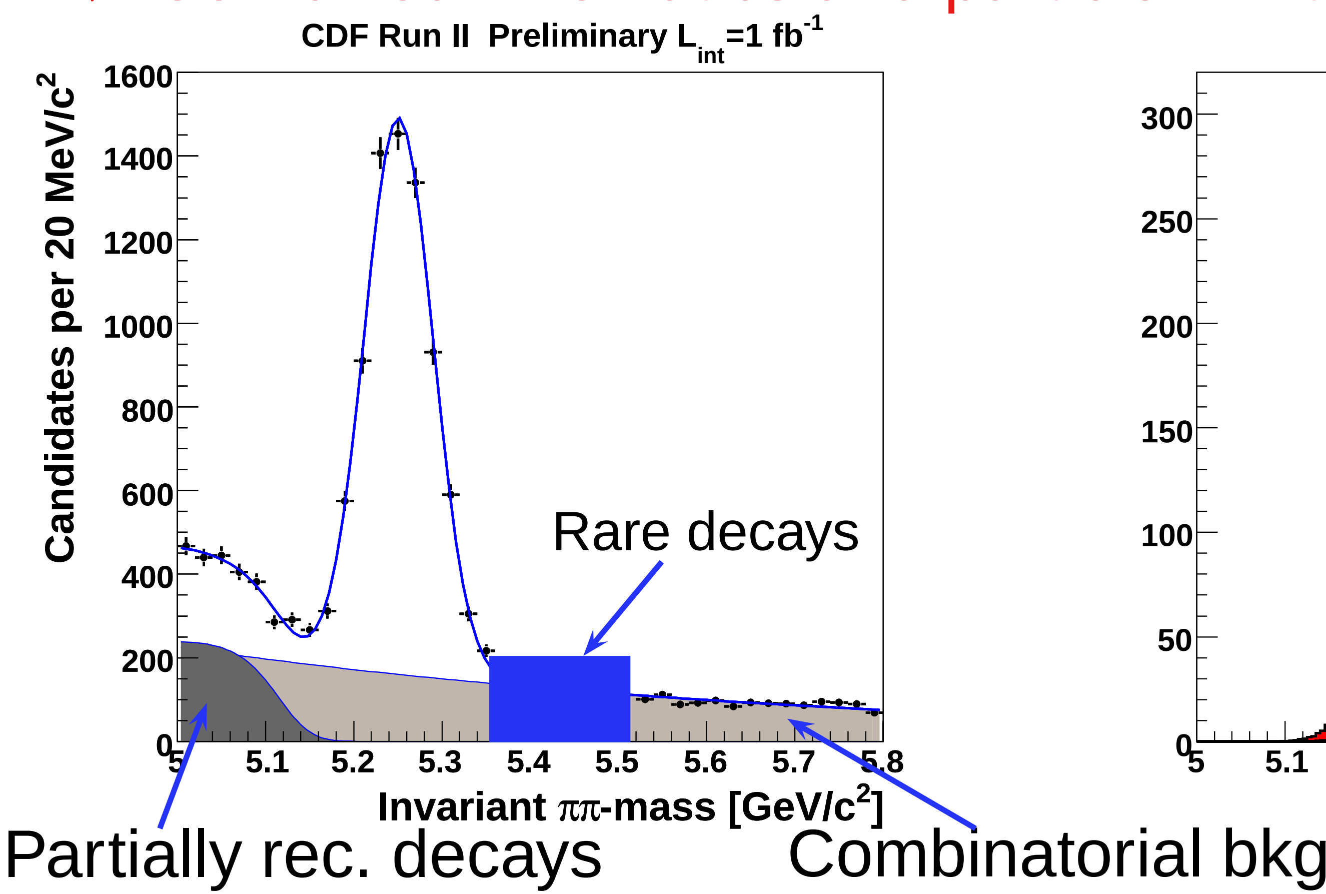
  $\longrightarrow$ Useful for all large-yield modes
  - Tighter for measurement of $\mathcal{B}(B_s \to K^-\pi^+)$

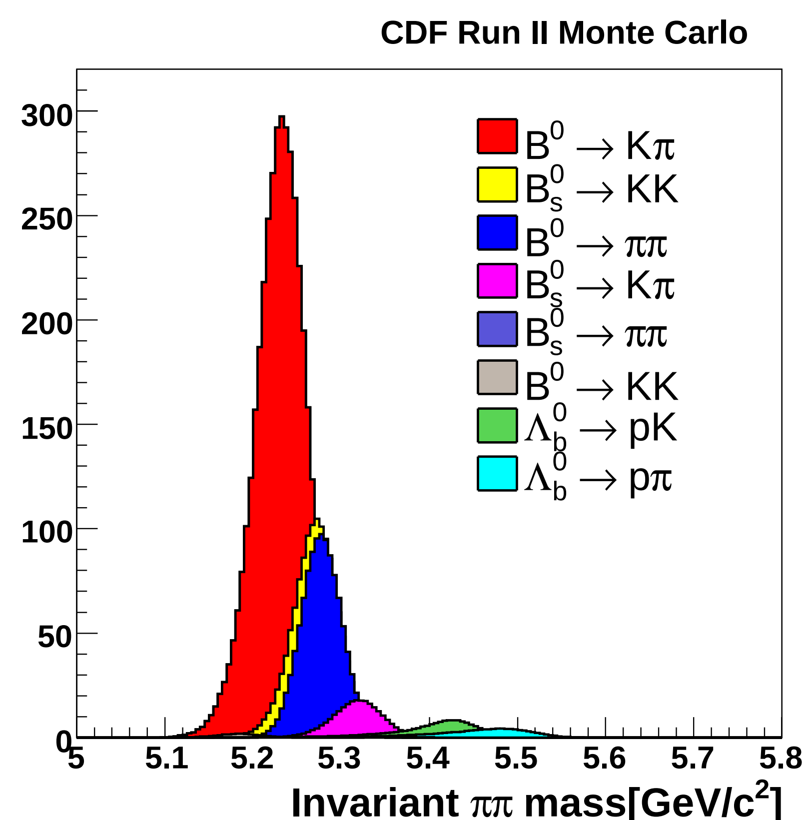
  $\longrightarrow$ Good for all rare modes

Disentangling modes

- Despite excellent mass resolution ($\approx 22\mathrm{MeV}/c^2$) different decays overlaps
- Event-by-event particle ID not sufficient to separate modes

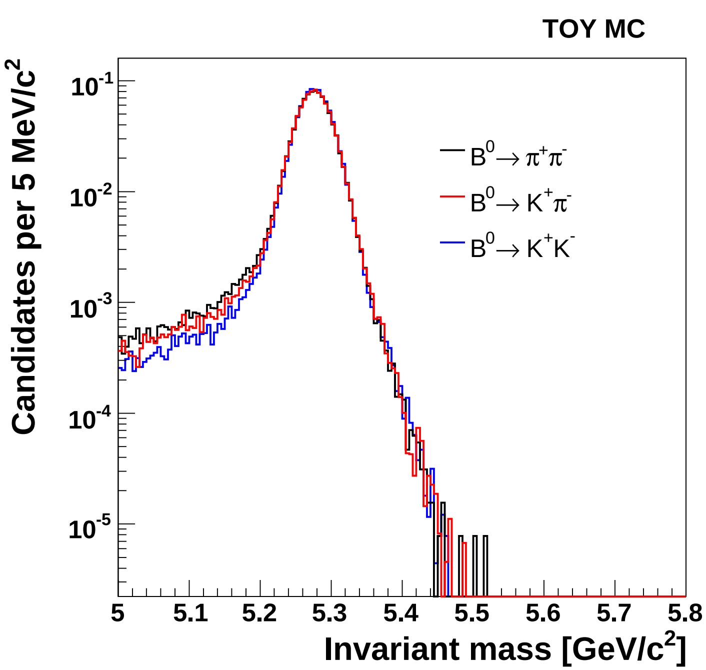
$\Rightarrow$ Combined kinematics and particle ID fit

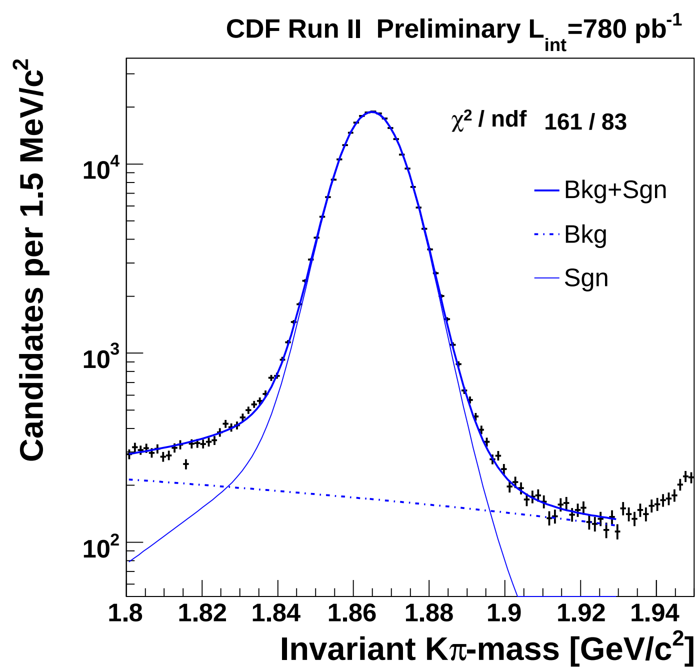




Mass description

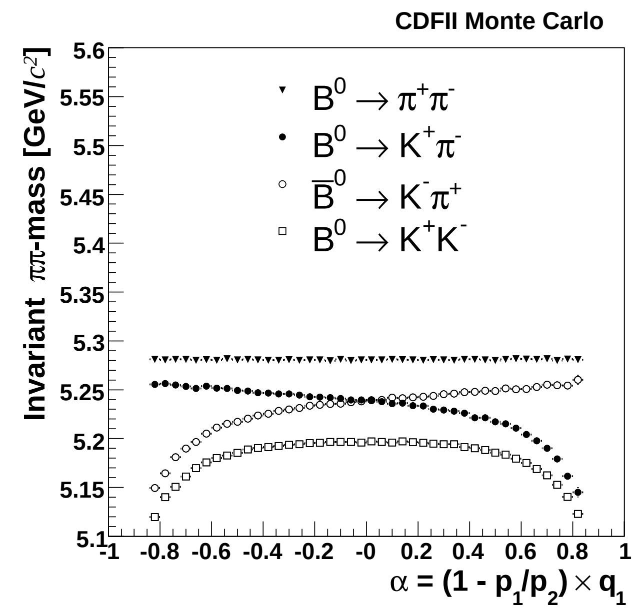
- Need very precise description
  - tails of final state radiation
  - non-Gaussian resolutions tails
- $D^0 \to K\pi$ from D^* provides clean, high statistics control sample
- Very good description of control D^0 sample

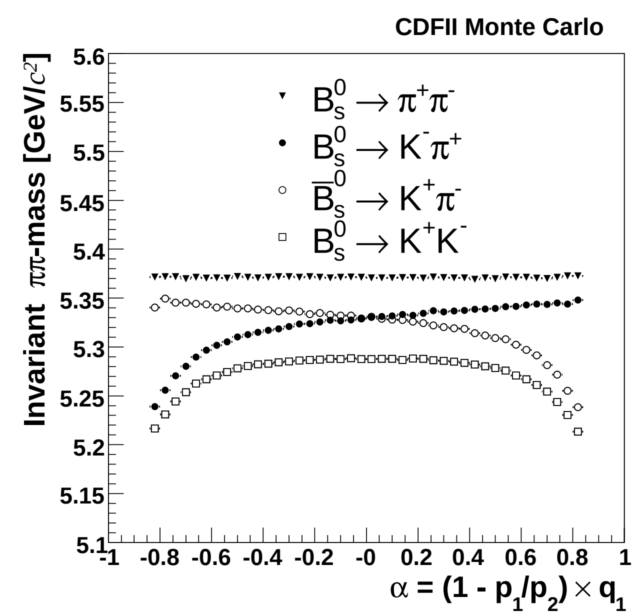




Momentum

- Pion mass used to calculate two track invariant mass $M_{\pi\pi}$
- Unique transformation from $M_{\pi\pi}$ to any $M_{hh'}$ if momentum of tracks known
- Use variables:
  - $M_{\pi\pi}$ - invariant $\pi\pi$-mass
  - $\alpha = (1 - p_1^{\text{min}}/p_2^{\text{max}})q_1^{\text{min}}$ - signed momentum imbalance
  - $p_{\text{tot}} = p_1^{\text{min}} + p_2^{\text{max}}$ - scalar sum of momenta



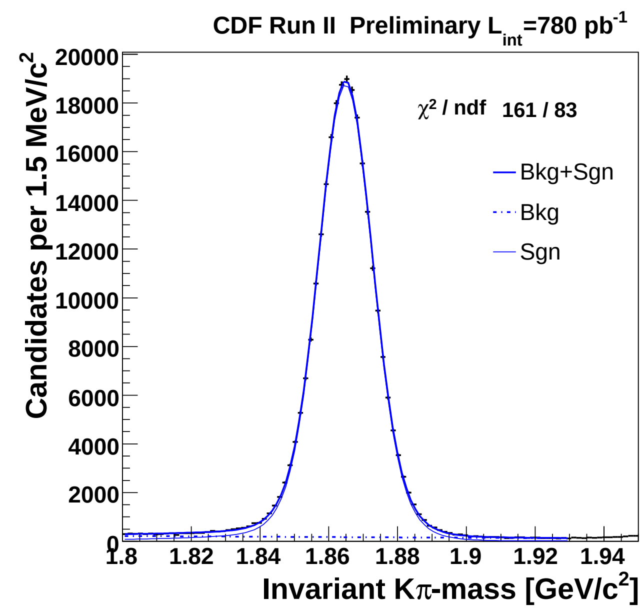


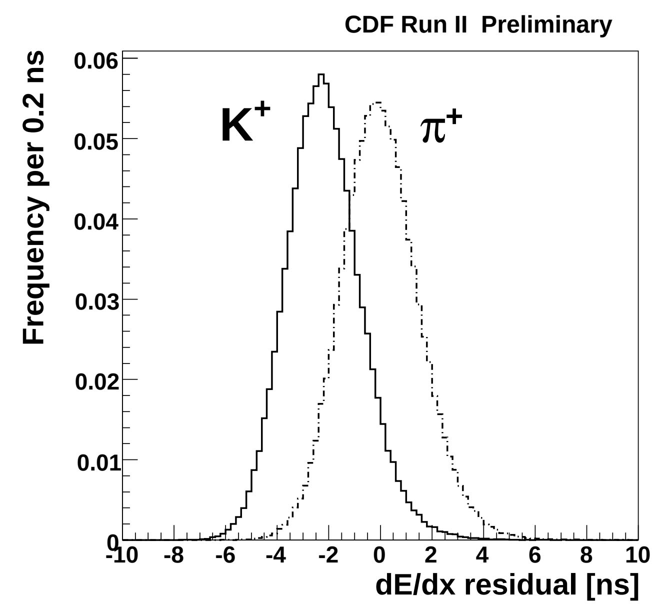
Particle ID

- Use dE/dx measurement in COT
- High statistics, high purity sample of D^0 from D^* available for calibration
- In likelihood use

$$\text{ID} = \frac{dE/dx(\text{meas}) - dE/dx(\pi)}{dE/dx(K) - dE/dx(\pi)}$$

- around 1.4σ separation between K and π for $p > 2\text{GeV}$
- Complements kinematics



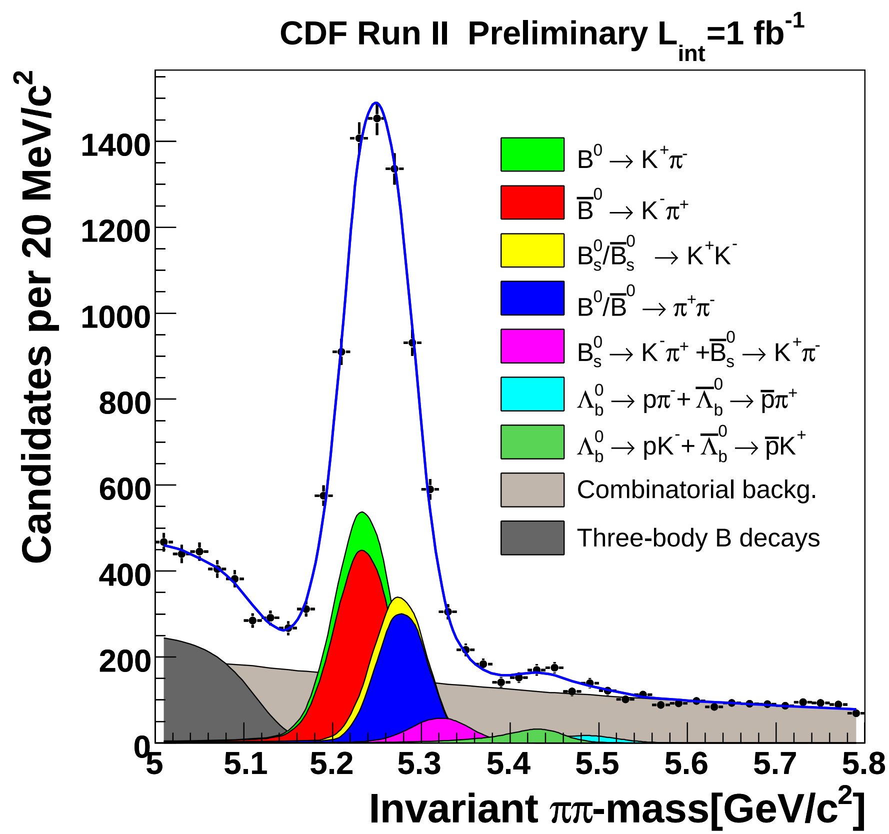


Large-yield branching fractions

$\frac{\mathcal{B}(B^0\to\pi^+\pi^-)}{\mathcal{B}(B^0\to K^+\pi^-)}$	$0.259 \pm 0.017 \pm 0.016$
$\mathcal{B}(B^0 \to \pi^+\pi^-)$	$(5.10 \pm 0.33 \pm 0.36) \cdot 10^{-6}$
$\frac{f_s}{f_d}\frac{\mathcal{B}(B_s\to K^+K^-)}{\mathcal{B}(B^0\to K^+\pi^-)}$	$0.324 \pm 0.019 \pm 0.041$
$\mathcal{B}(B_s \to K^+K^-)$	$(24.4 \pm 1.4 \pm 4.6) \cdot 10^{-6}$

Signal events:

$B^0 \to \pi^+\pi^-$	1121 ± 63
$B^0 \to K^+\pi^-$	4045 ± 84
$B_s \to K^+K^-$	1307 ± 64

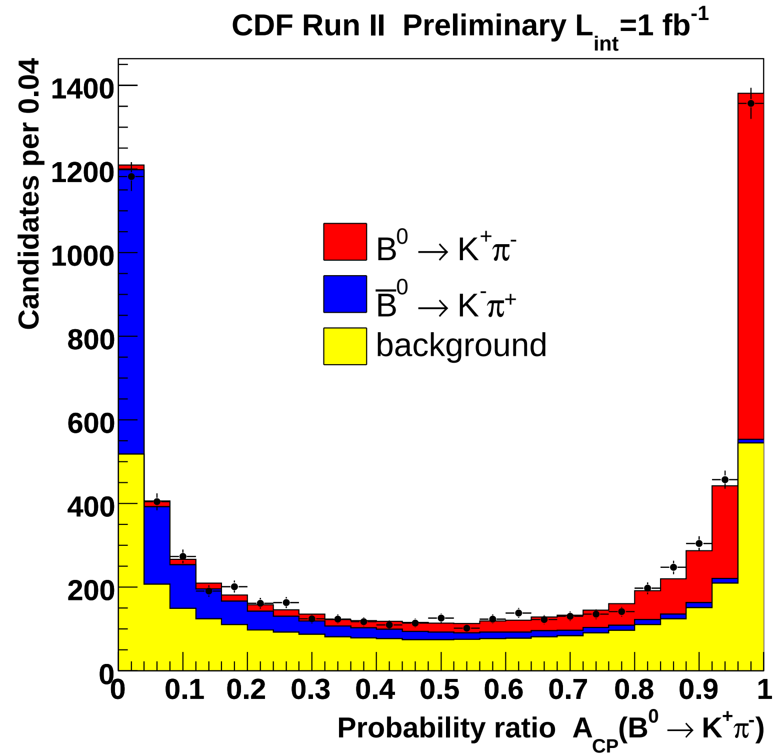


Large sample of $B_s \to K^+K^-$

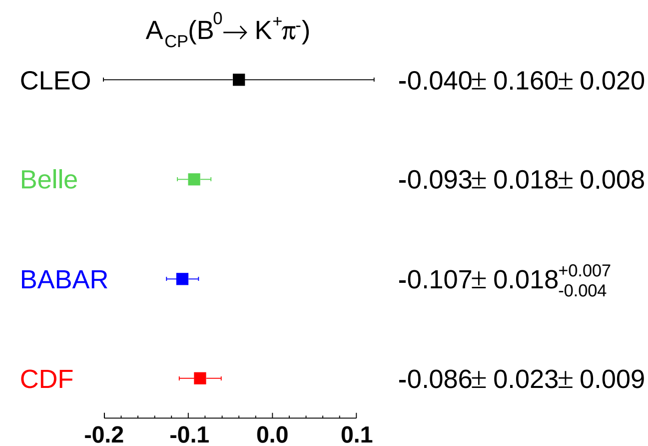
- $\to$ lifetime measurement
- $\to$ time-dependent tagged analysis

Direct CP asymmetry for $B^0 \to K^+\pi^-$

- Only significant difference in K^+/K^- interaction with material
- Calibrate with $D^0 \to h^+h^-$ with assumption $A_{CP}(D^0 \to K\pi) = 0$
- Dominant systematic uncertainty
  - Particle ID model
  - WA B meson masses



$$A_{CP} = \frac{N(\overline{B}^0 \to K^-\pi^+) - N(B^0 \to K^+\pi^-)}{N(\overline{B}^0 \to K^-\pi^+) + N(B^0 \to K^+\pi^-)}$$
$$= -0.086 \pm 0.023 \pm 0.009$$



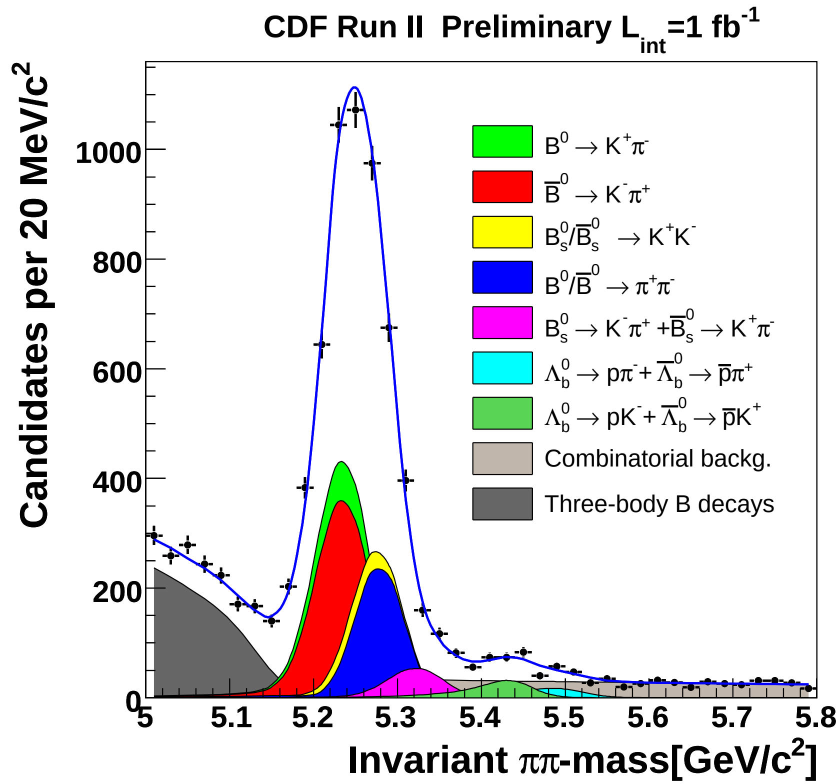
Rare modes results

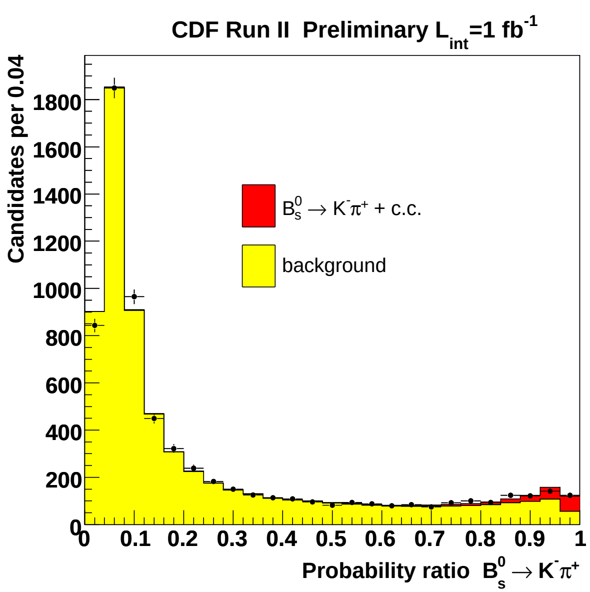
Three new modes observed:

$B_s \to K^-\pi^+ \quad 230 \pm 34 \pm 16 \quad 8\sigma$

$\Lambda_b \to p\pi^- \quad 110 \pm 18 \pm 16 \quad 6\sigma$

$\Lambda_b \to pK^- \quad 156 \pm 20 \pm 11 \quad 11\sigma$





$$\frac{f_s}{f_d}\,\frac{\mathcal{B}(B_s \to K^-\pi^+)}{\mathcal{B}(B^0 \to K^+\pi^-)} = 0.066 \pm 0.010 \pm 0.010$$

Using input from HFAG

$$\Rightarrow \mathcal{B}(B_s \to K^-\pi^+) = (5.0 \pm 0.75 \pm 1.0) \cdot 10^{-6}$$

$\mathbf{A_{CP}(B_s \to K^+\pi^-)}$ vs. $\mathbf{A_{CP}(B^0 \to K^+\pi^-)}$

SM (Lipkin, Phys. Lett. B621, 126; Gronau, Rosner, Phys. Rev. D71, 074019) predicts

$$\Gamma(\overline{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-) = \Gamma(B_s \to K^-\pi^+) - \Gamma(\overline{B}_s \to K^+\pi^-)$$

$\longrightarrow$ Provides model independent test for new physics

Can be used to predict $A_{\mathrm{CP}}(B_s \to K^-\pi^+)$ from other measurements

$$A_{\mathrm{CP}}(B_s \to K^-\pi^+) = -A_{\mathrm{CP}}(B^0 \to K^+\pi^-)\frac{\mathcal{B}(B^0 \to K^+\pi^-)}{\mathcal{B}(B_s \to K^-\pi^+)} \cdot \frac{\tau(B^0)}{\tau(B_s)}$$

Plugging in numbers

$$\Rightarrow A_{\mathrm{CP}}(B_s \to K^-\pi^+) \approx +37\%$$

Direct CP asymmetry for $B_s \to K^+\pi^-$

$$A_{CP} = \frac{N(\overline{B}_s \to K^+\pi^-) - N(B_s \to K^-\pi^+)}{N(\overline{B}_s \to K^+\pi^-) + N(B_s \to K^-\pi^+)}$$

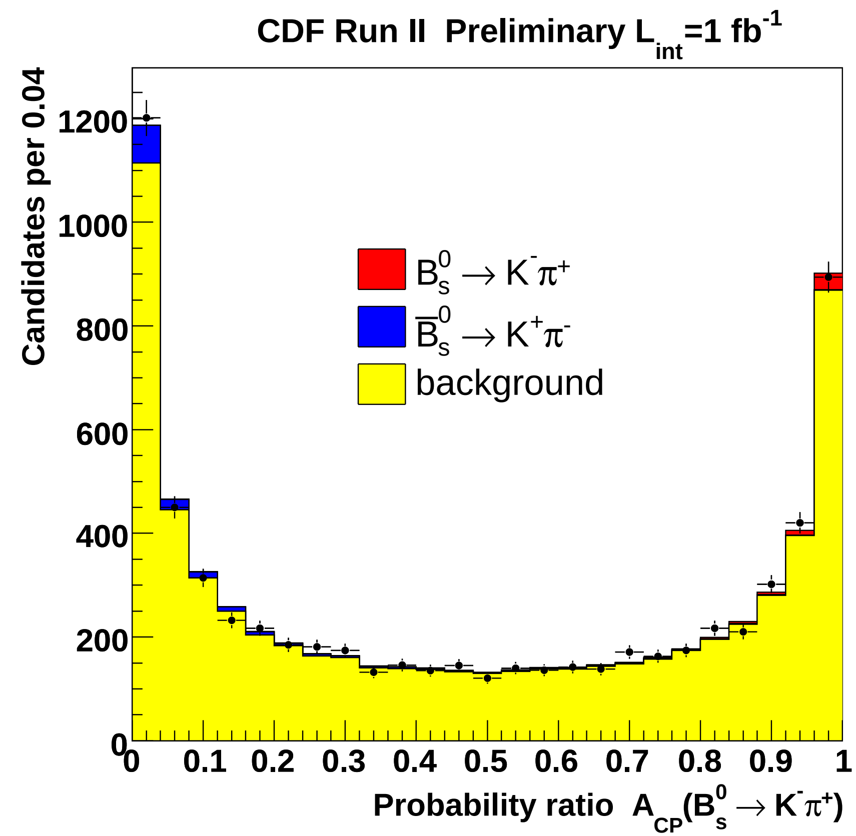
$$= +0.39 \pm 0.15 \pm 0.08$$

2.5σ Significance

- First indication of CP violation in B_s system
- Sign and size agree with SM expectation

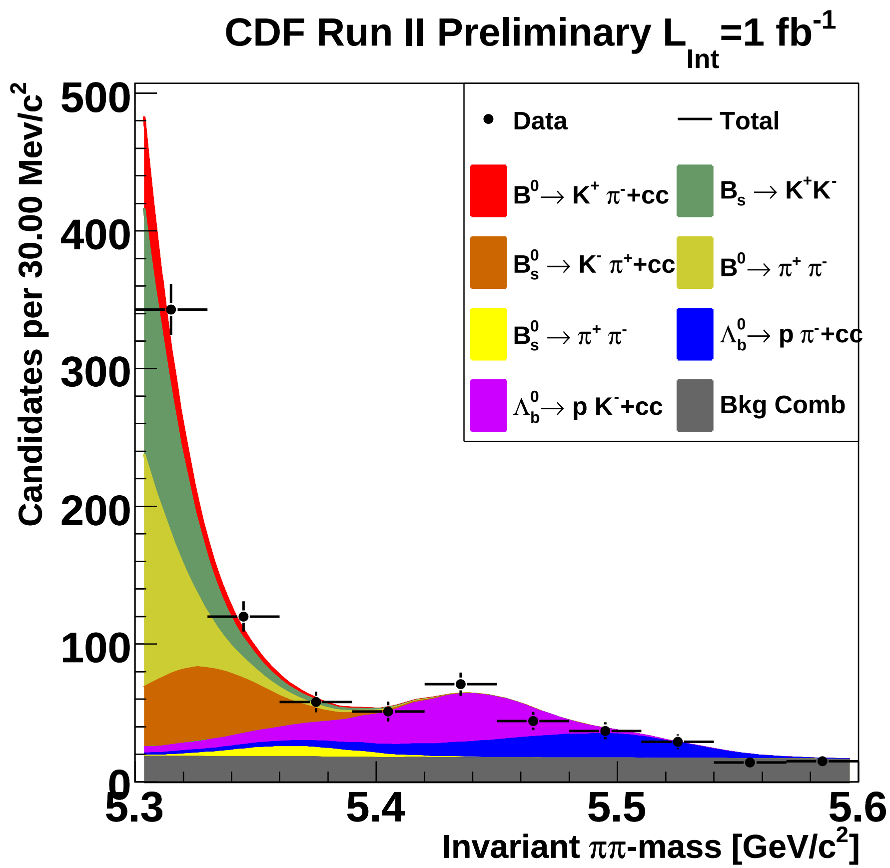
$\Rightarrow$ No evidence for 'exotic' sources of CP violation

- Will repeat with more data (already 2.5fb^{-1} on tape)



$\Lambda_b \to p\pi$ and $\Lambda_b \to pK$

- Same quark level transition as $B \to K\pi$
- SM expect large direct CPV for $\Lambda_b \to pK$ $[\mathcal{O}(10\%)]$
- Very little know from theory
- Another decay to test SM and search for new physics
- Branching fractions in talk of A. Warburton

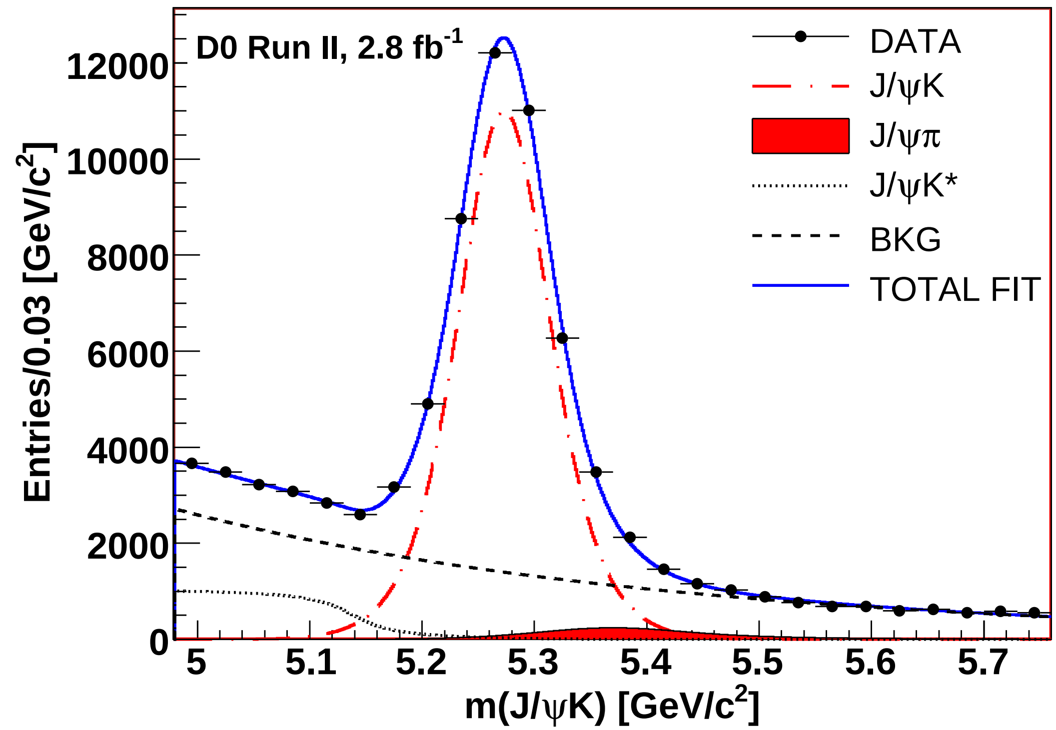


$$
\begin{aligned}
A_{CP}(\Lambda_b \to p\pi) &= 0.03 \pm 0.17 \pm 0.05 \\
A_{CP}(\Lambda_b \to pK) &= 0.37 \pm 0.17 \pm 0.03 \qquad (2.1\sigma)
\end{aligned}
$$

First measurement, consistent with SM expectation

$B^+ \to J/\psi K^+$

- Probes $b \to c\bar{c}s$ transition
- SM expects $A_{CP} \approx 0.003$
- NP can enhance it up to 0.01



- DØ has around 40 000 $B^+ \to J/\psi K^+$ signal events
- Main effort to understand detector asymmetry (uses $D^{*+} \to D^0\pi^+$ with $D^0 \to \mu^+\nu_\mu K^-$)
- $A_{CP}(B^+ \to J/\psi K^+) = 0.0075 \pm 0.0061 \pm 0.0027$
  $A_{CP}(B^+ \to J/\psi \pi^+) = -0.09 \pm 0.08 \pm 0.03$

Semileptonic CP asymmetry likelihood

$$
\begin{aligned}
\Gamma(B^0 \to f) &= N_f |A_f|^2 \frac{e^{-\Gamma t}}{2} \left\{ \cosh(\frac{\Delta\Gamma t}{2}) + \cos(\Delta m t) \right\} \\
\Gamma(\overline{B}^0 \to f) &= N_f |A_f|^2 (1+a) \frac{e^{-\Gamma t}}{2} \left\{ \cosh(\frac{\Delta\Gamma t}{2}) - \cos(\Delta m t) \right\} \\
\Gamma(B^0 \to \bar{f}) &= N_f |\overline{A}_{\bar{f}}|^2 (1-a) \frac{e^{-\Gamma t}}{2} \left\{ \cosh(\frac{\Delta\Gamma t}{2}) - \cos(\Delta m t) \right\} \\
\Gamma(\overline{B}^0 \to \bar{f}) &= N_f |\overline{A}_{\bar{f}}|^2 \frac{e^{-\Gamma t}}{2} \left\{ \cosh(\frac{\Delta\Gamma t}{2}) + \cos(\Delta m t) \right\}
\end{aligned}
$$