Search for New Physics in the B_s Sector at the Tevatron

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for the CDF and D0 collaborations

DIS 2009

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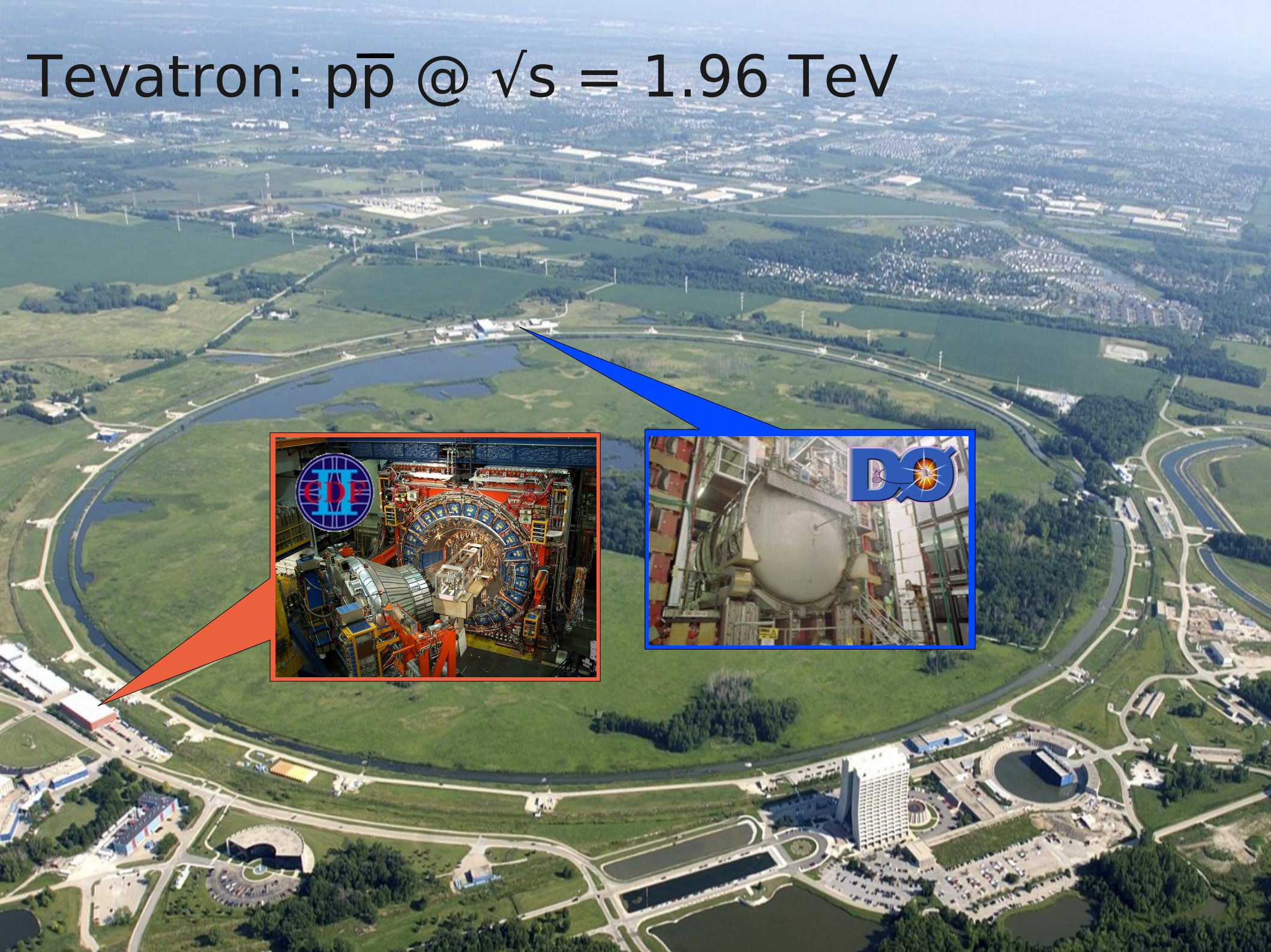
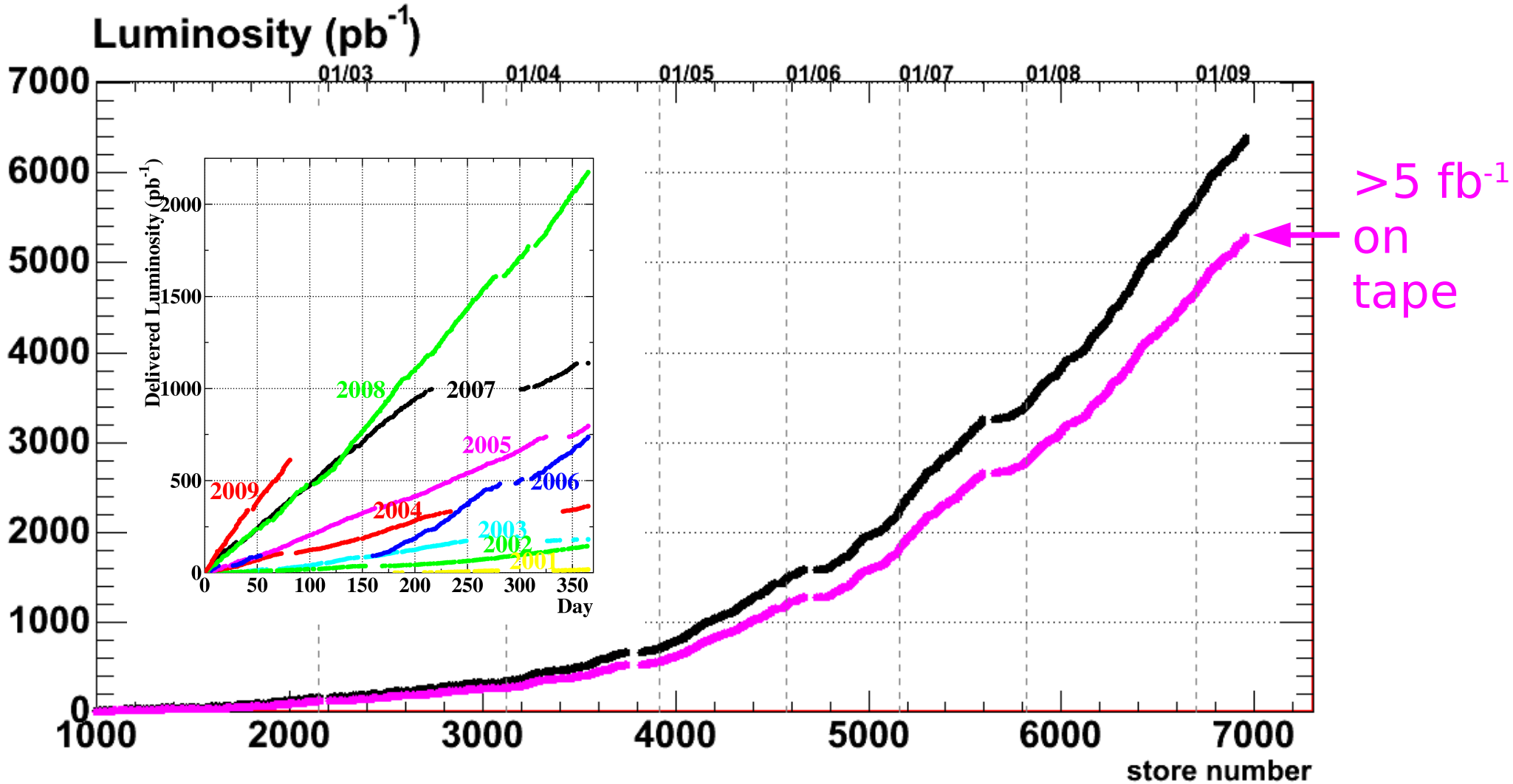
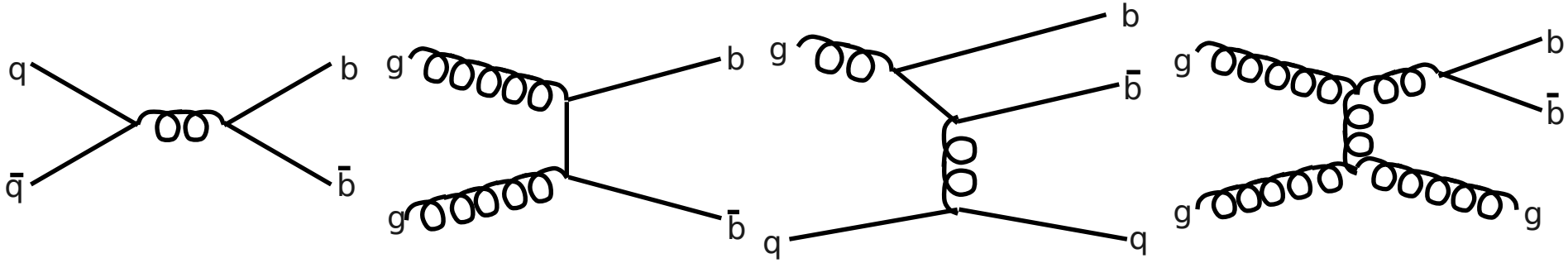
Tevatron: $p\bar{p}$ @ $\sqrt{s}$ = 1.96 TeV



Tevatron Performance



B_s Production at the Tevatron

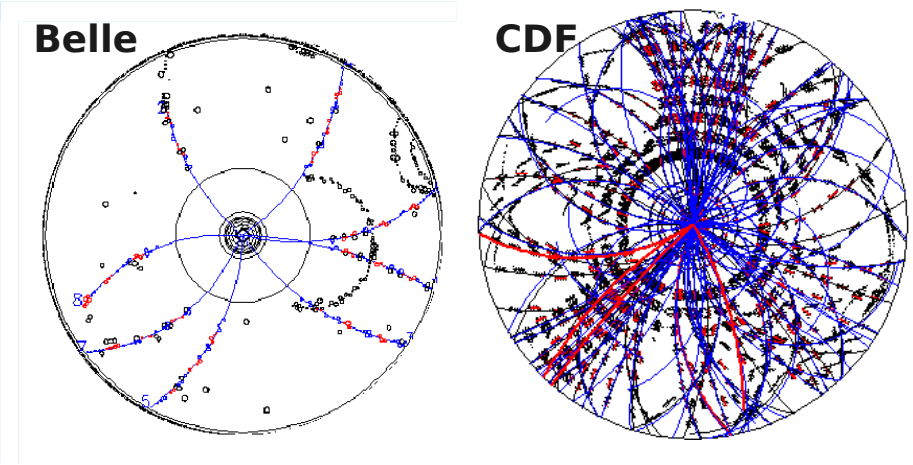


- ➔ Huge $b\bar{b}$ cross section
- ➔ Production of all heavy hadron species in fragmentation

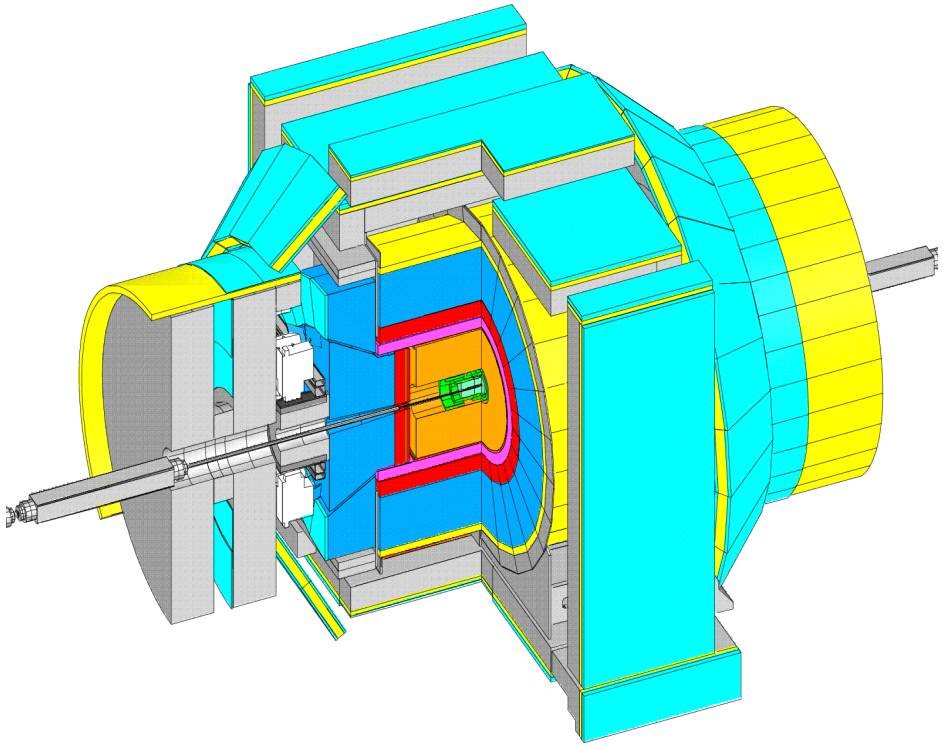
but

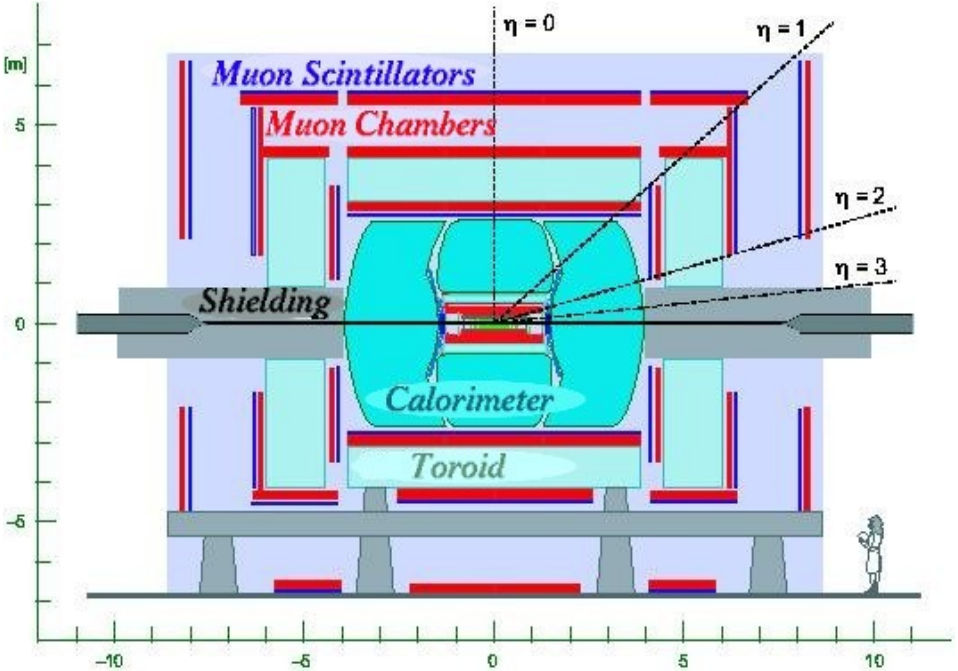
- ✗ inelastic cross section $\sim 10^3$ times larger than $\sigma(b\bar{b})$
  → Trigger

- ✗ Background tracks from fragmentation
  → High combinatorial background



CDF and D0 Detectors





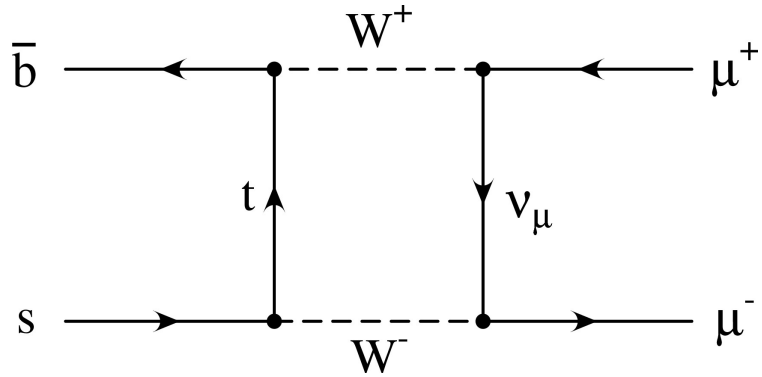
CDF

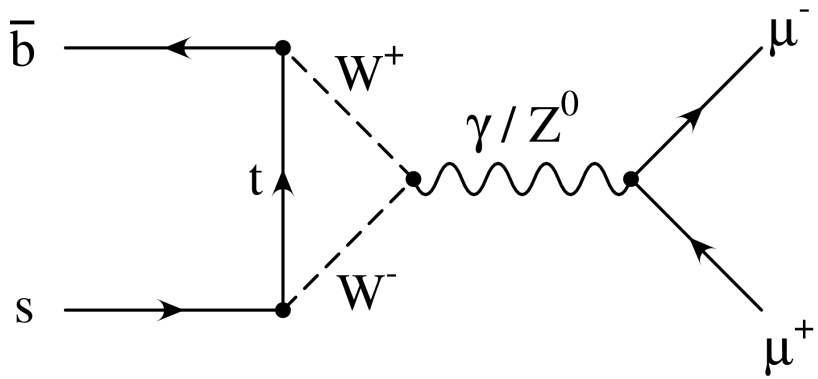
- Excellent mass resolution
- Displaced track and di-muon triggers

D0

- Large tracking and muon coverage
- Single + di-muon triggers

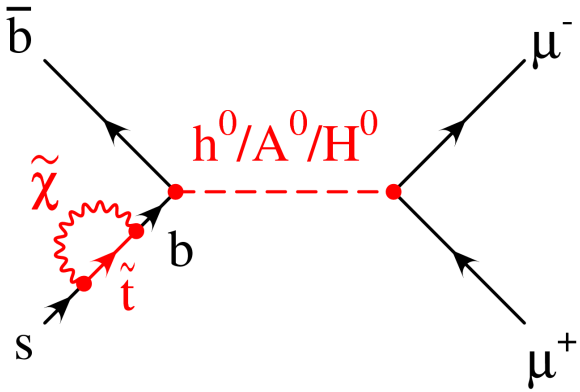
$B^0_{(s)} \to \mu^+ \mu^-$

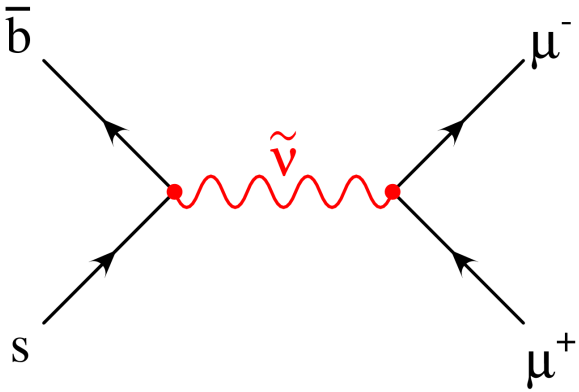




SM: $BR(B_s \to \mu^+ \mu^-) = (3.42 \pm 0.54) \times 10^{-9}$ Buras, Phys. Lett. B566, 115 (2003)

$BR(B^0 \to \mu^+ \mu^-) = (1.00 \pm 0.14) \times 10^{-10}$ suppressed by $(V_{td}/V_{ts})^2$





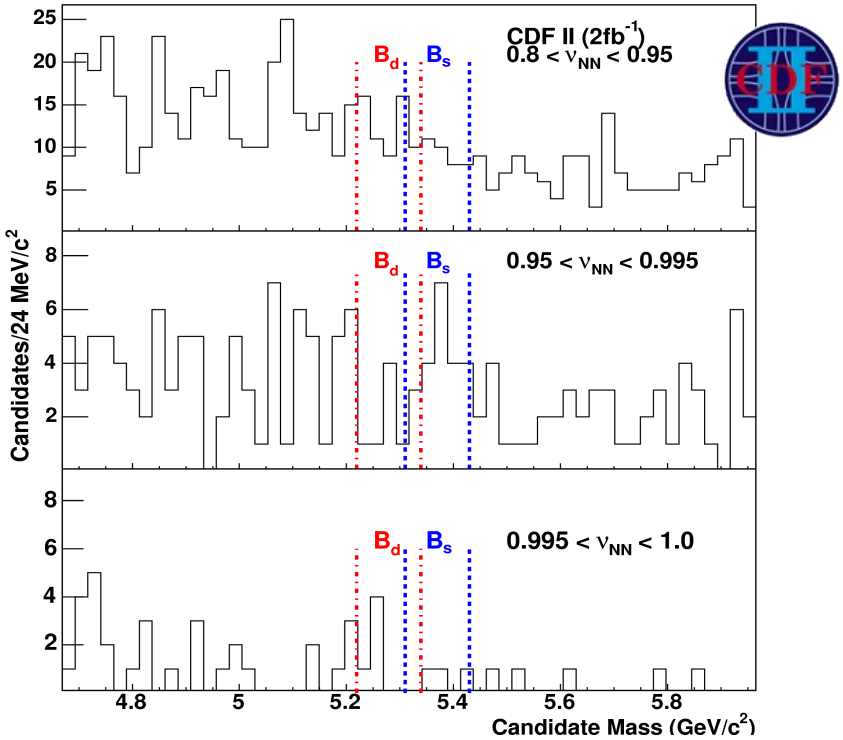
At current sensitivity any signal would indicate new physics

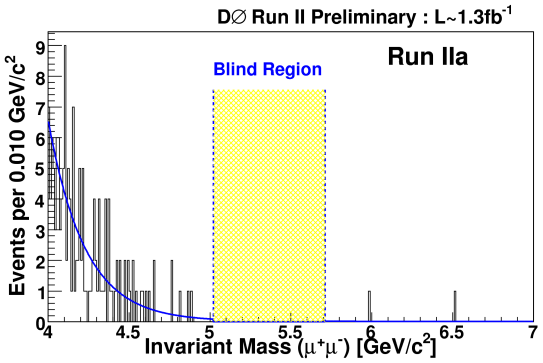
NP: MSSM: $BR \sim \tan^6(\beta)$

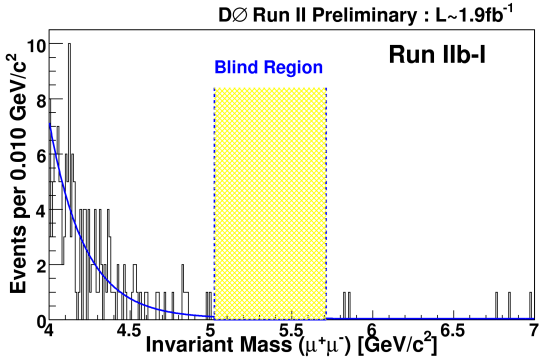
R-parity violating SUSY: enhancement also at low $\tan(\beta)$

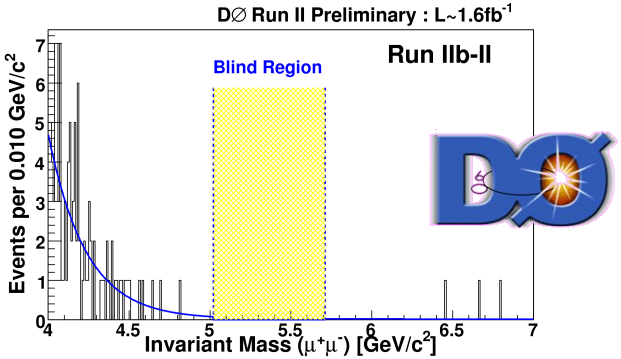
$B^0_s \to \mu^+ \mu^-$ Analysis

- Selection based on
  - Neural network (CDF)
  - Boosted decision tree (D0)
- Combinatorial background
  - fit to mass sidebands
- $B \to h^+h'^-$ background
  about ten times smaller

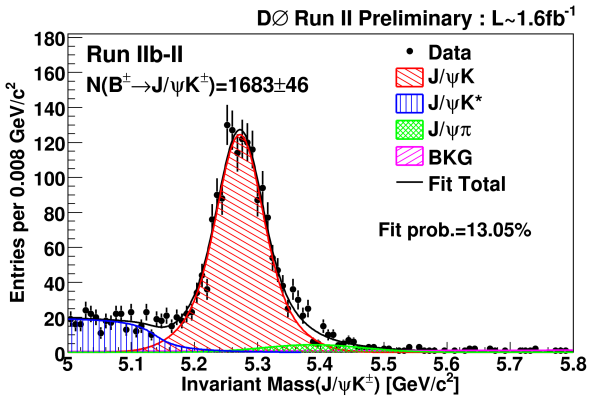








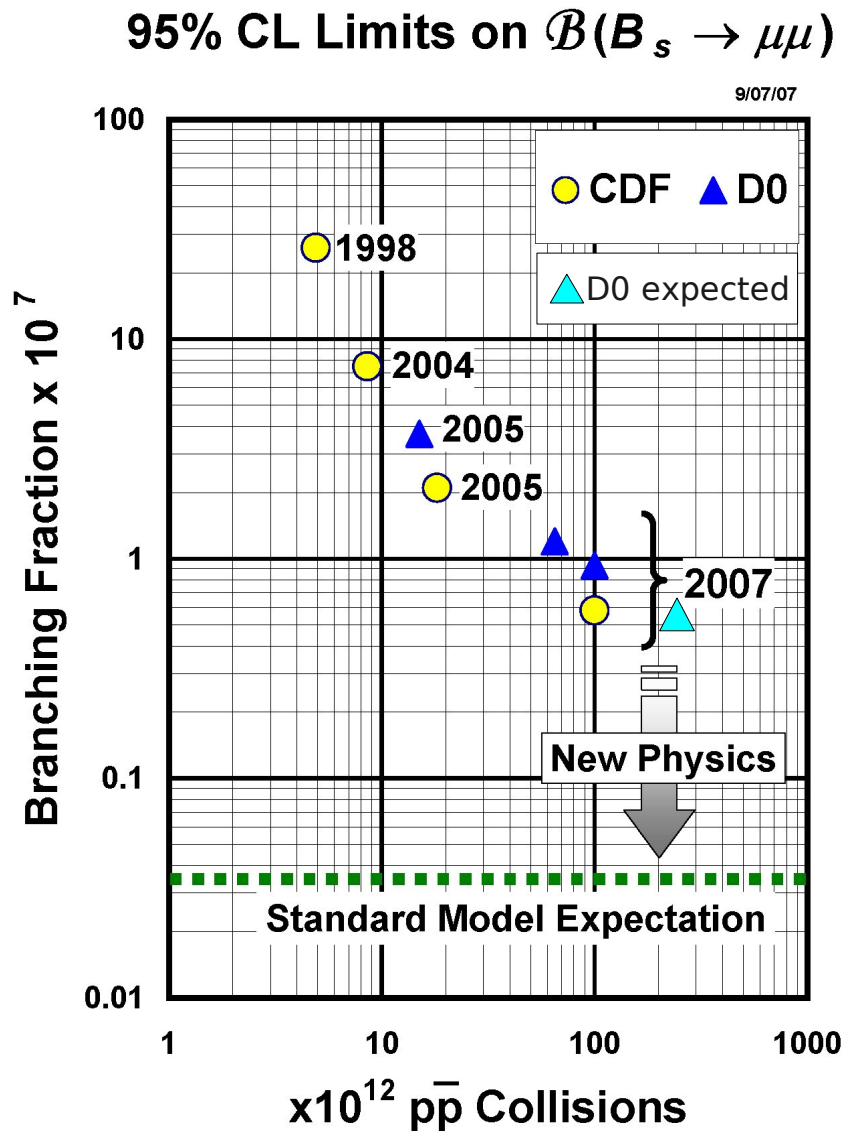
$B^0_s \to \mu^+ \mu^-$ Limit



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

Limits on $BR(B_s \to \mu^+ \mu^-)$ at 90% CL

- CDF (2 fb^{-1}): 4.7×10^{-8}
  PRL 100, 101802
- D0 (5 fb^{-1}): 4.3×10^{-8} (expected)
  D0 note 5906
- SM: 3.4×10^{-9}



$B^0_s \to \mu^+ \mu^- \phi$

- FCNC: $b \to s\, \gamma^{(*)}$
- Normalization: $B^0_s \to J/\psi\, \phi$

➢ Limits on $BR(B_s \to \mu^+\mu^-\phi)$ / $BR(B_s \to J/\psi\, \phi)$ at 95% CL:

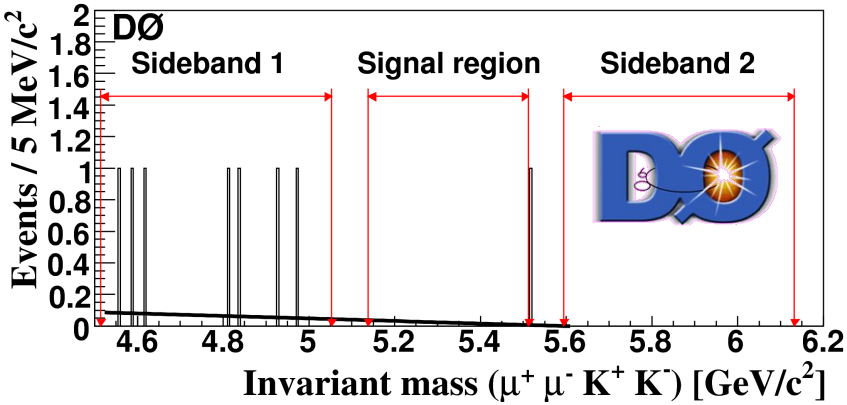
➔ D0 (0.45 fb^{-1}): 4.4×10^{-3}
PRD 74, 031107

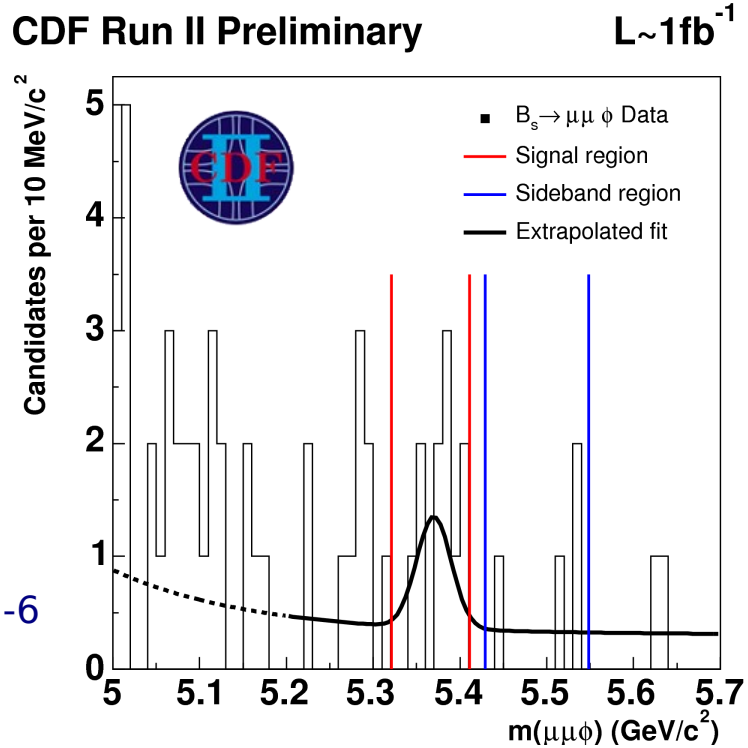
➔ CDF (0.92 fb^{-1}): 2.61×10^{-3}
CDF note 8543

➢ CDF: 2.4 σ signal

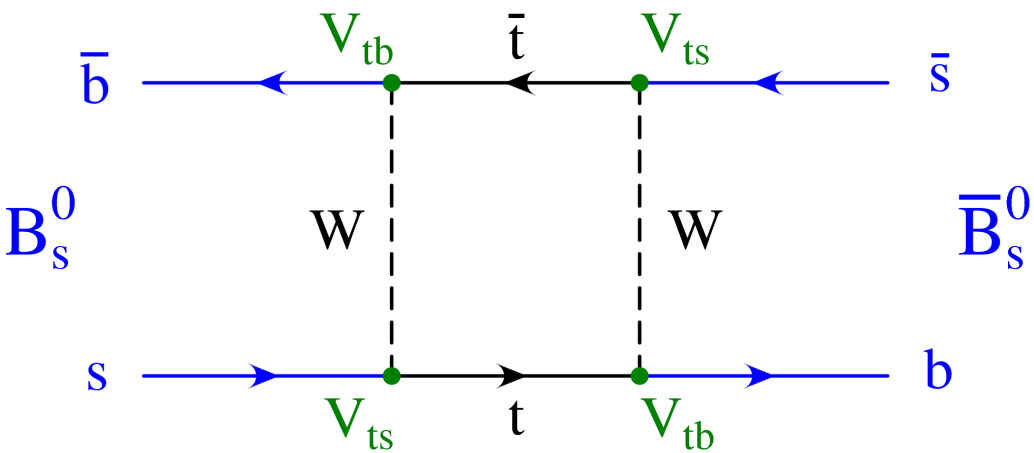
➔ BR = $(1.16 \pm 0.56 \pm 0.42) \times 10^{-6}$

➔ SM: 1.6×10^{-6}





B^0_s Oscillations



- Eigenstates with defined mass and lifetime:

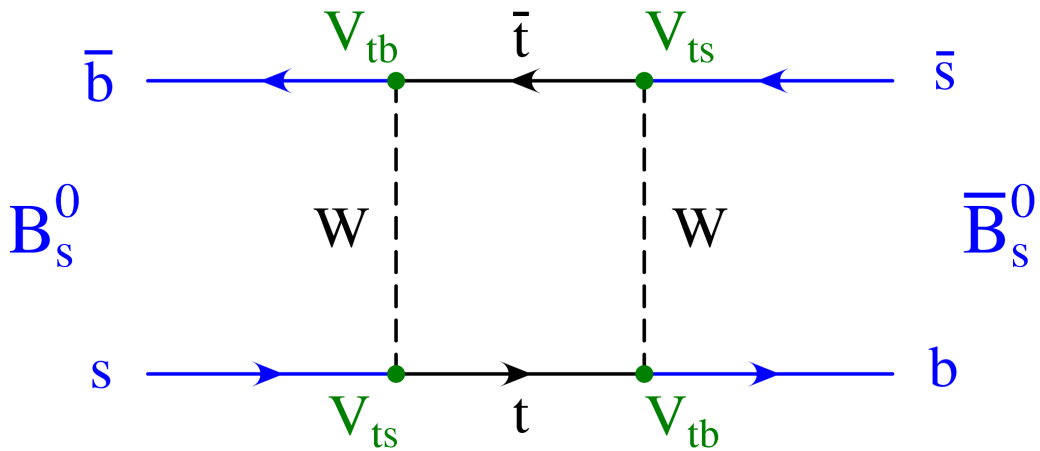
$$\begin{aligned} |B_{sL}\rangle &= p\,|B_s\rangle + q\,|\bar{B}_s\rangle \\ |B_{sH}\rangle &= p\,|B_s\rangle - q\,|\bar{B}_s\rangle \end{aligned}$$

- Schrödinger-Equation:

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

- Lifetime difference: $\Delta\Gamma = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos(\phi)$
- Mass difference: $\Delta m = m_H - m_L \approx 2|M_{12}|$ → oscillation
- Phase: $\phi \approx \arg(-M_{12}/\Gamma_{12})$ → CP violation

B^0_s Mixing Frequency

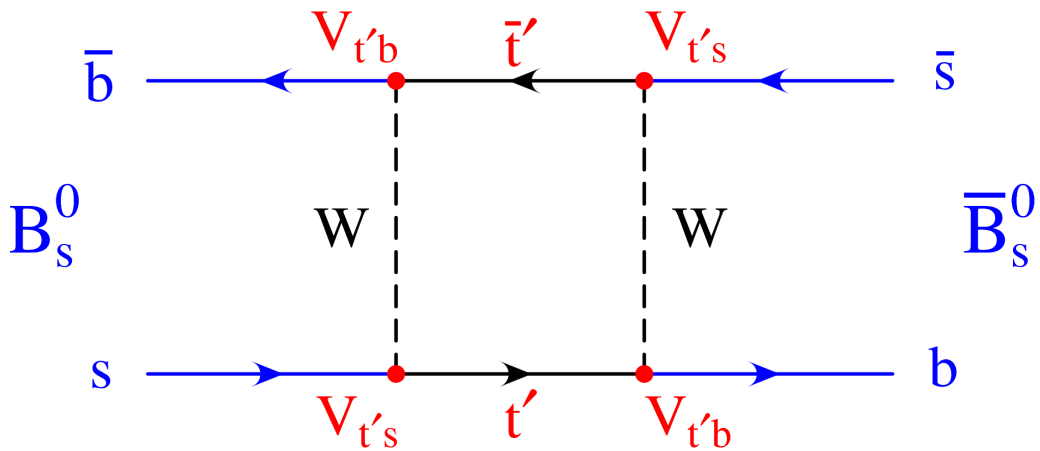


- Oscillation frequency in the SM:

$$\Delta m_s = m_H - m_L \sim m_{B_s} f^2_{B_s} B_{B_s} \left|V_{tb} V^*_{ts}\right|^2$$

- Measured Δm_s consistent with (less precise) SM prediction

B^0_s Mixing Frequency



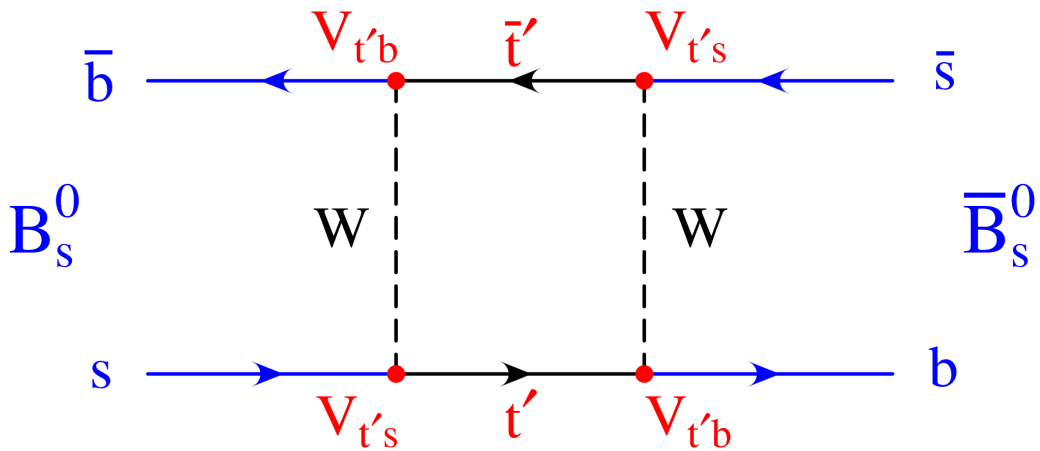
- Oscillation frequency in the SM:

$$\Delta m_s = m_H - m_L \sim m_{B_s} f_{B_s}^2 B_{B_s} \left|V_{tb}V_{ts}^*\right|^2$$

- Measured Δm_s consistent with (less precise) SM prediction

➢ No new physics?

B^0_s Mixing Frequency



- Oscillation frequency in the SM:

$$\Delta m_s = m_H - m_L \sim m_{B_s} f_{B_s}^2 B_{B_s} \left|V_{tb}V_{ts}^*\right|^2$$

- Measured Δm_s consistent with (less precise) SM prediction

➢ Phase can still contain significant contribution from NP!

➔ SM: $\phi = 0.004$

If $|\phi| \gg 0 \Rightarrow$ New Physics

CP Violation in Semileptonic Decays

- Flavor specific decay mode:

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

- Semileptonic asymmetry:
  $a_{SL} = \Delta\Gamma / \Delta m \tan(\phi)$
  - SM: $a^{s}_{SL} = 2 \times 10^{-5}$

- *Untagged, time-integrated analysis:*

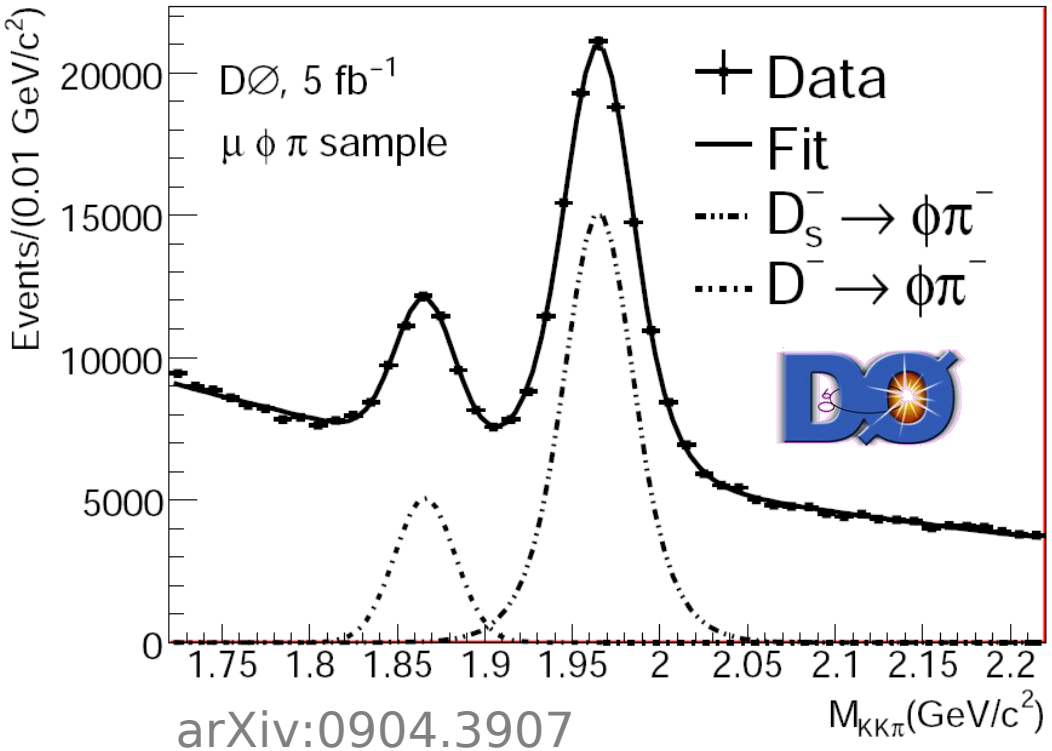
$$\Gamma(B/\bar{B} \to f) - \Gamma(B/\bar{B} \to \bar{f}) = 2\,N\,|A_f|^2\,\exp(-\Gamma t)\,a\cosh\left(\frac{\Delta\Gamma t}{2}\right)$$

- *Tagged, time-dependent analysis:*

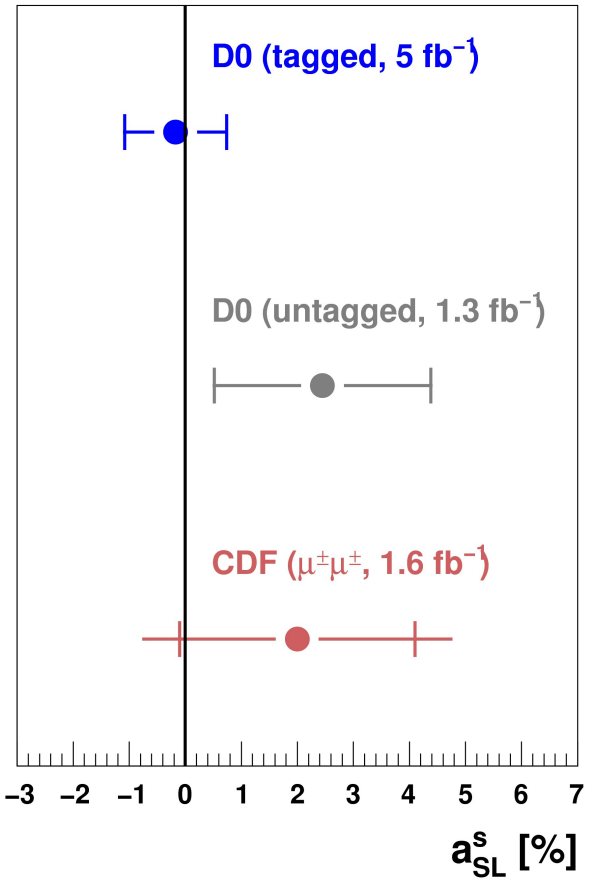
$$\Gamma(\bar{B} \to f/\bar{f}) - \Gamma(B \to f/\bar{f}) \propto \left[a\cosh\left(\frac{\Delta\Gamma t}{2}\right) + (2 \pm a)\cos(\Delta m t)\right]$$

Measurement of a_{SL}

- $B_s \to D_s^- \mu^+ X$, $D_s^- \to \phi\pi^-, K^{*0}K^-$
- Correction for missing momentum by simulation



arXiv:0904.3907

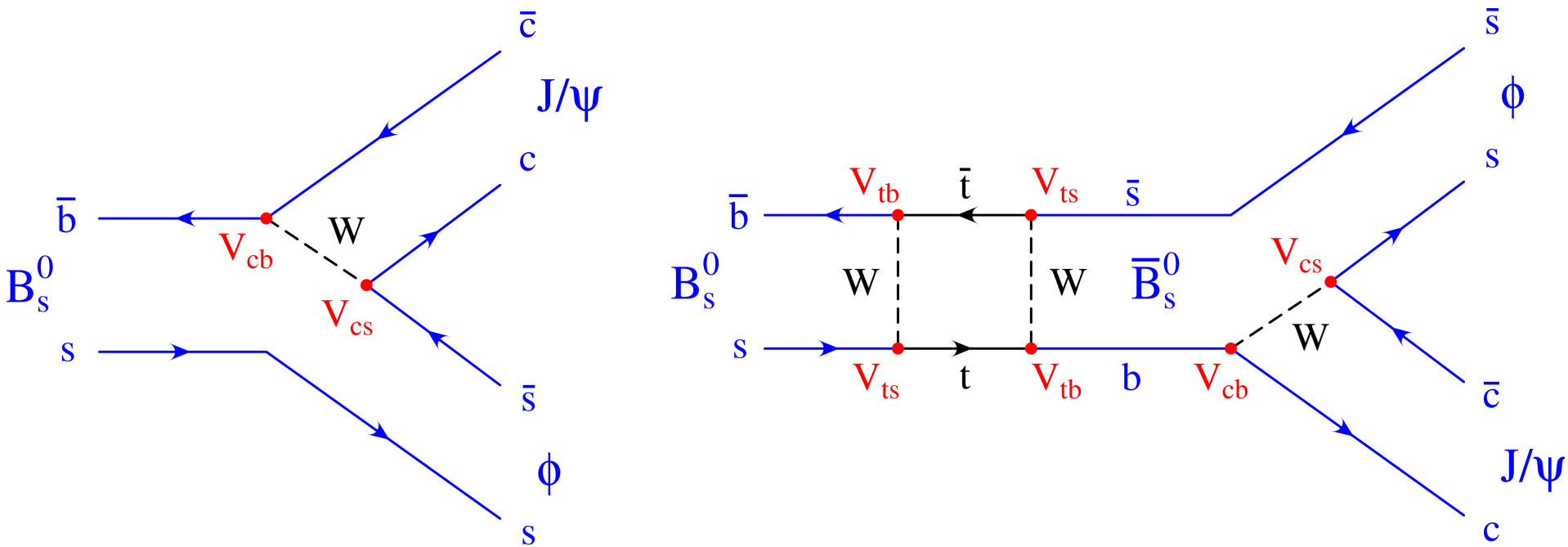


➔ No hint for new physics

CP Violation in $B^0_s \to J/\psi\,\phi$

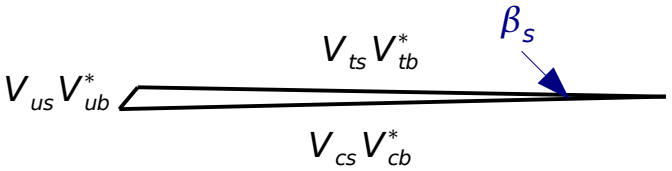
- Common decay mode:

  $B^0_s/\overline{B}^0_s \to J/\psi\,\phi,\ \ J/\psi \to \mu^+\mu^-,\ \ \phi \to K^+K^-$



- CP violating phase in interference:

$$\beta_s = \arg\left(-V_{tb}V^*_{ts}/V_{cb}V^*_{cs}\right) \approx 0.02$$



Measurement of CP Violation (1)

- If CP conserved:

  mass eigenstates = CP eigenstates:

$$|B_{sL}\rangle = |B_{s\,CP+}\rangle \qquad |B_{sH}\rangle = |B_{s\,CP-}\rangle$$

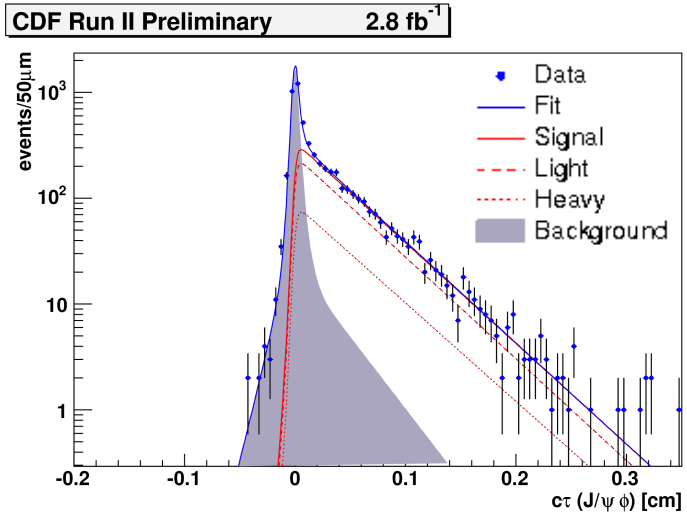
- Identification of mass eigenstates via lifetime, if $\Delta\Gamma \neq 0$

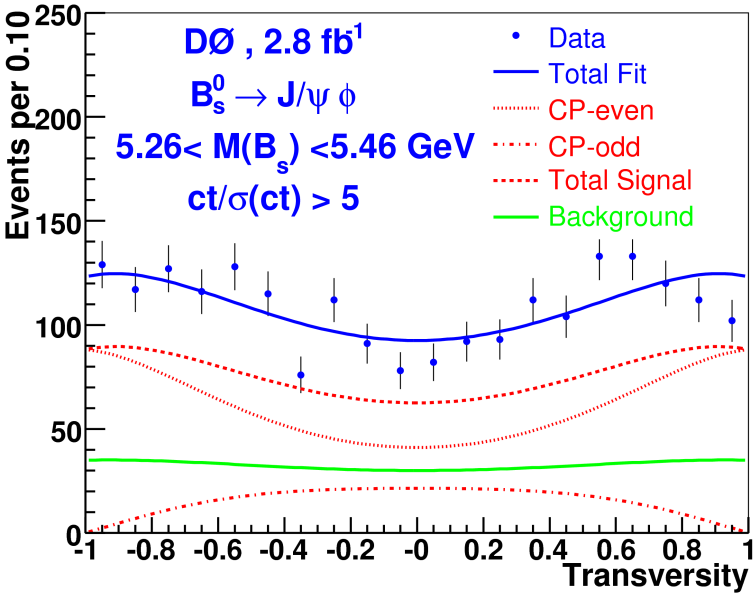
- Identification of CP eigenstates via decay products:

  $J^{PC}(J/\psi,\phi) = 1^{--} \Rightarrow CP(J/\psi\,\phi) = (-1)^L$

  $J(B^0_s) = 0 \Rightarrow L=0,1,2$

  - Angular analysis



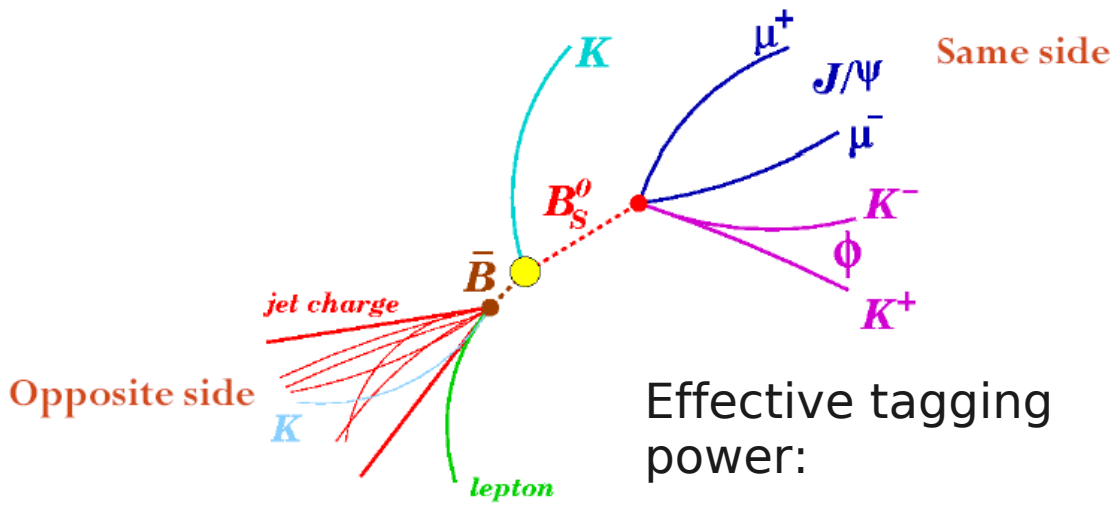


Measurement of CP Violation (2)

- B^0_s decay in CP eigenstate f_{CP}:

$$A_{CP}(t) = \frac{\Gamma(\bar{B}^0_s \to f_{CP}) - \Gamma(B^0_s \to f_{CP})}{\Gamma(\bar{B}^0_s \to f_{CP}) + \Gamma(B^0_s \to f_{CP})} \approx \pm \sin(2\beta_s)\sin(\Delta m_s t)$$

- ✗ Oscillation has to be resolved
- ✗ Production flavor has to be determined

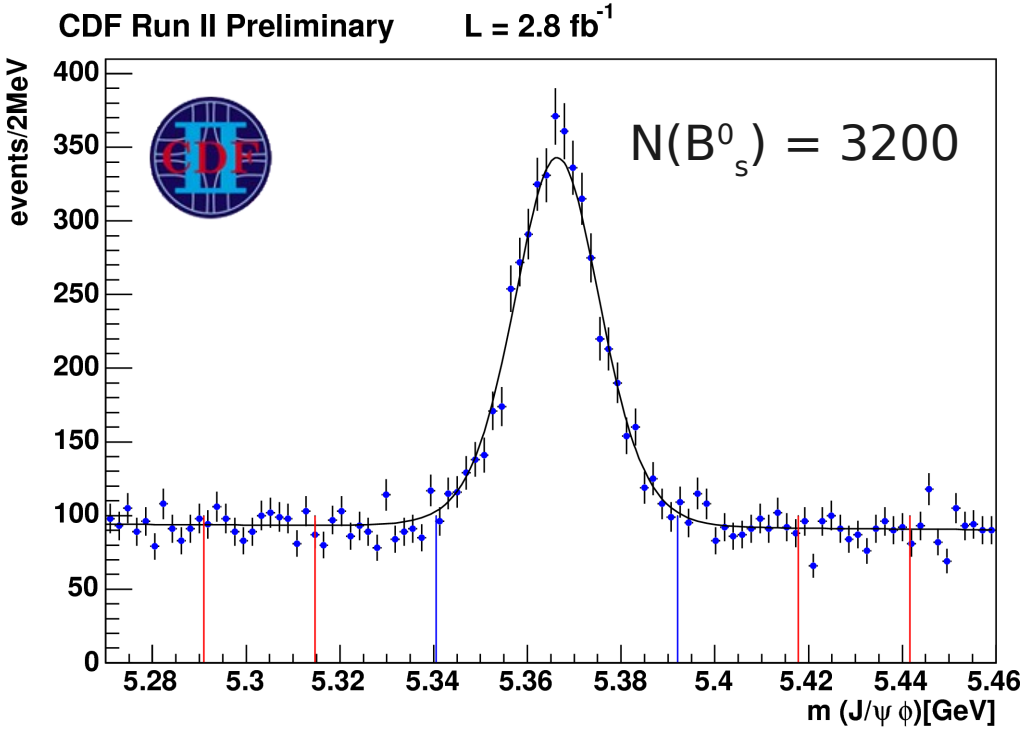


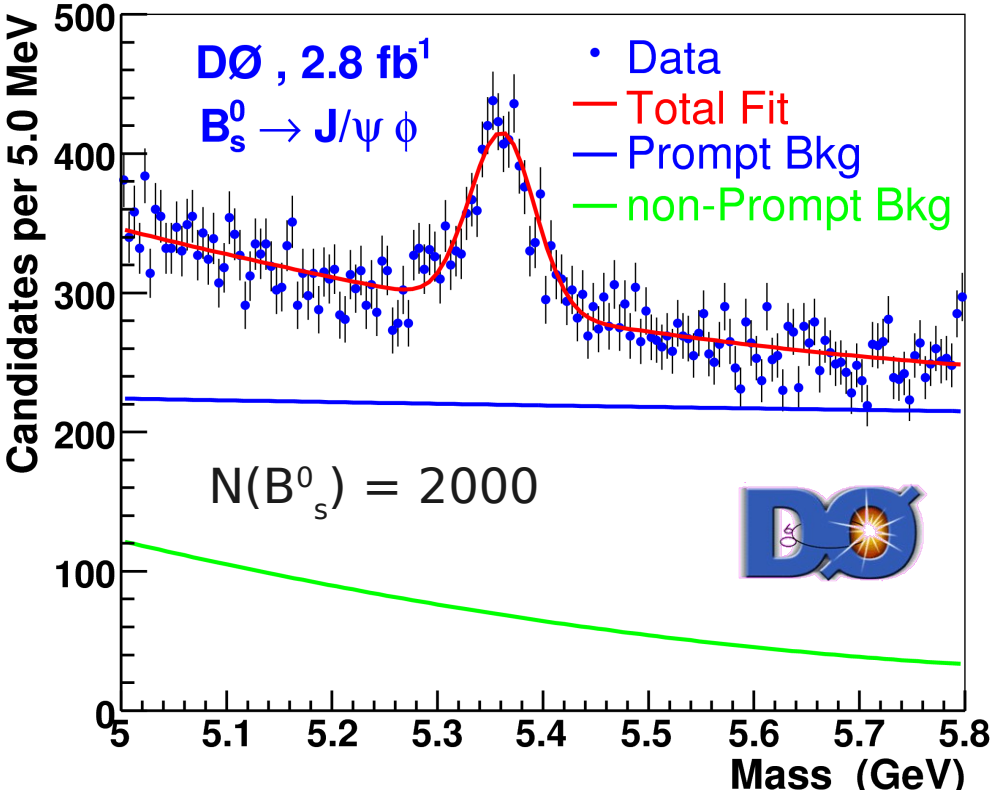
Effective tagging power:

εD^2 = 4-5 %

- ➢ Sensitive on CP violation even for $\Delta\Gamma$=0

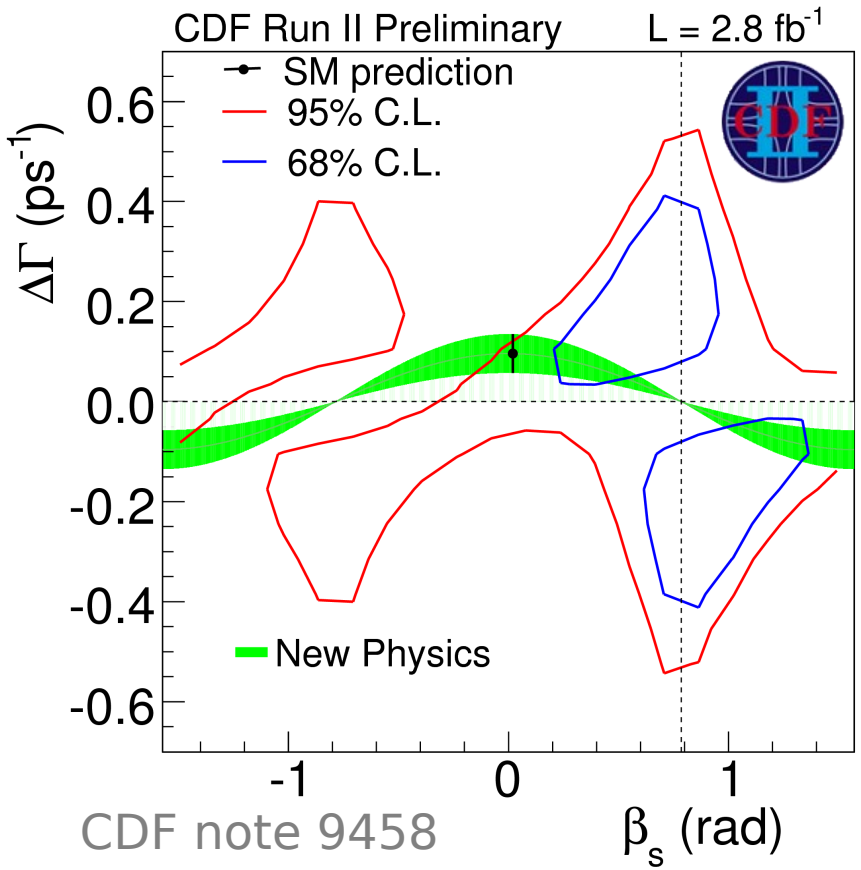
$B^0_s \to J/\psi\,\phi$ Data Samples



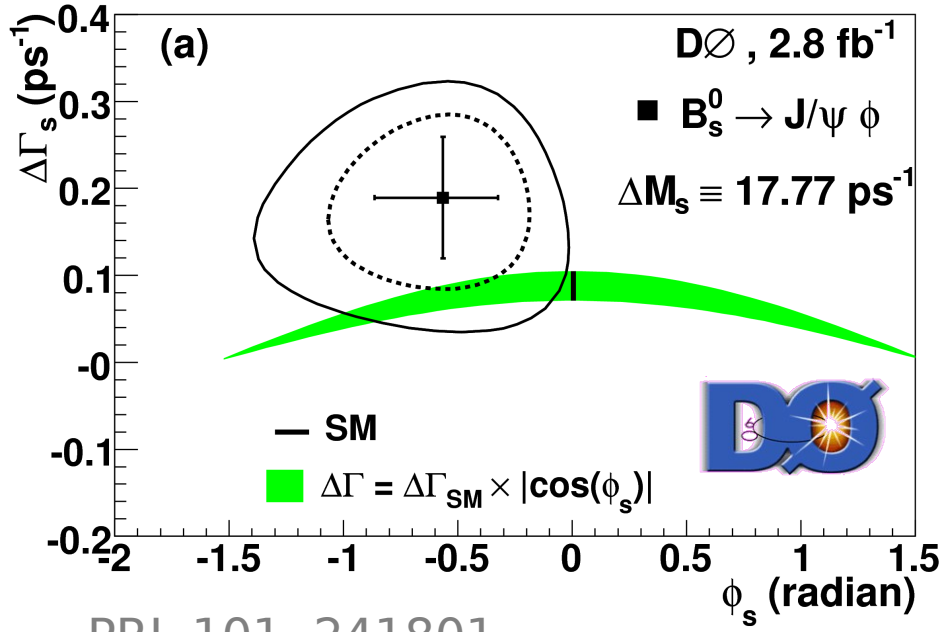


- 2.8 fb^{-1}
- Di-muon trigger
- Selection with neural network (CDF) or cut based (D0)

$B^0_s \to J/\psi\,\phi$ Result



CDF note 9458



PRL 101, 241801

Constraint on strong phases

$2\beta_s = -\phi_s$

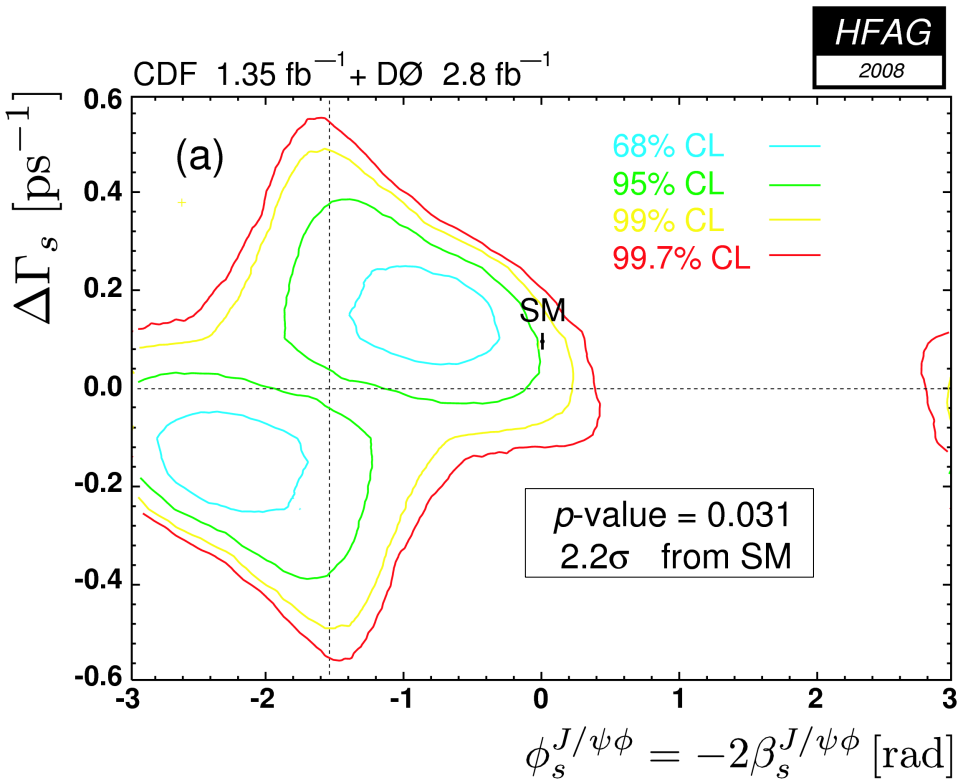
- SM p-value = 7% (1.8 σ)

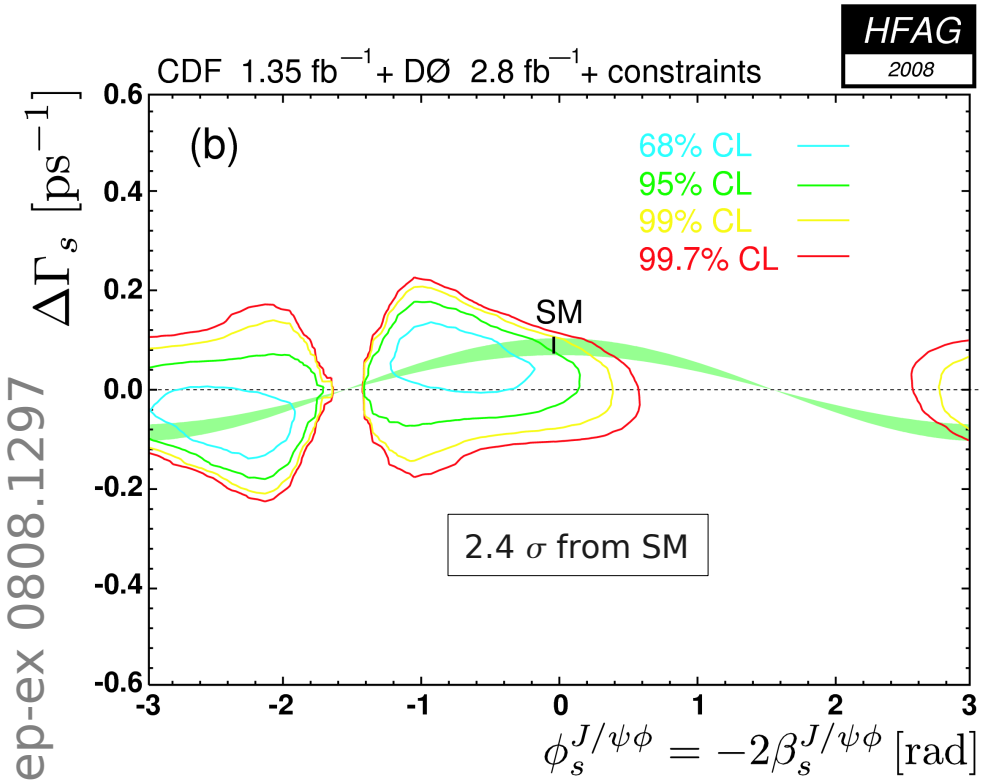
$\beta_s \in [0.28, 1.29]$ @ 68% CL

- SM p-value = 8.5% (1.7 σ)

$\phi_s = -0.57\ ^{+0.24}_{-0.30}$ (stat) $^{+0.07}_{-0.02}$ (syst)

Combination





hep-ex 0808.1297

- Old CDF result
- No constraint on strong phases

- Constraints on B_s lifetime and a^s_{SL}

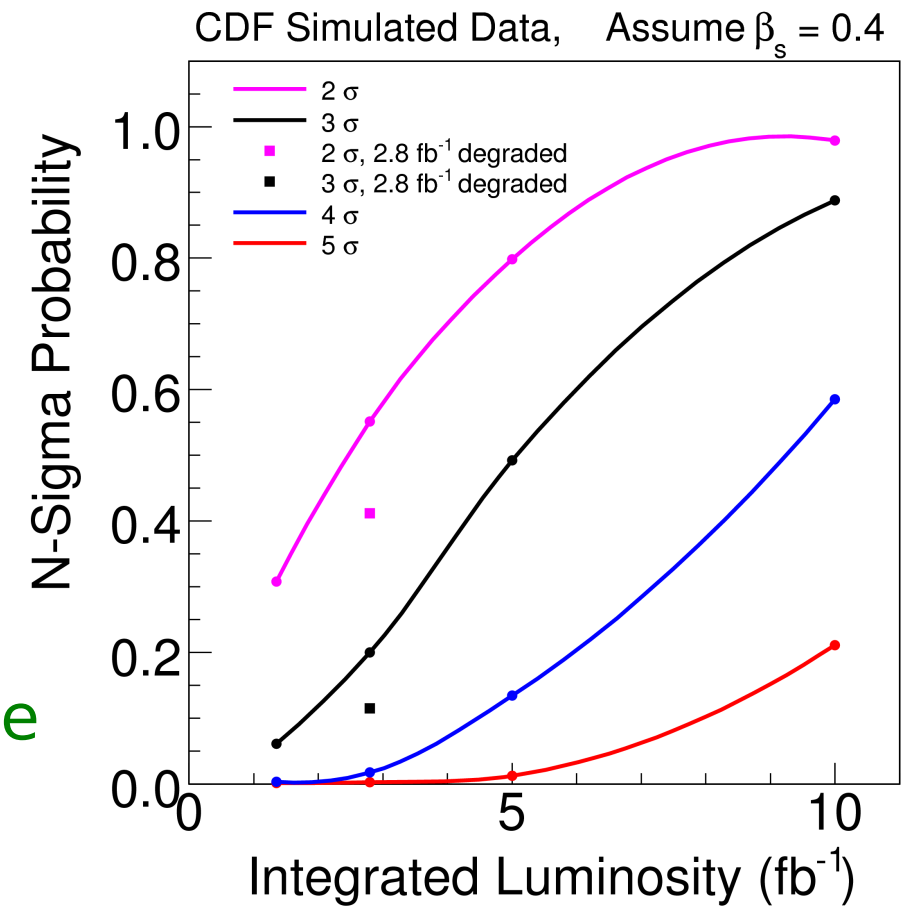
➔ Hint for new physics?

Summary and Outlook

- $B_s \to \mu\mu$ limit reaches interesting new physics region

- Measured B_s mixing phase consistent with SM at 1.7σ (D0) and 1.8σ (CDF)
- Combination at $\sim 2\sigma$
- ➔ Hint, but no evidence, for new physics

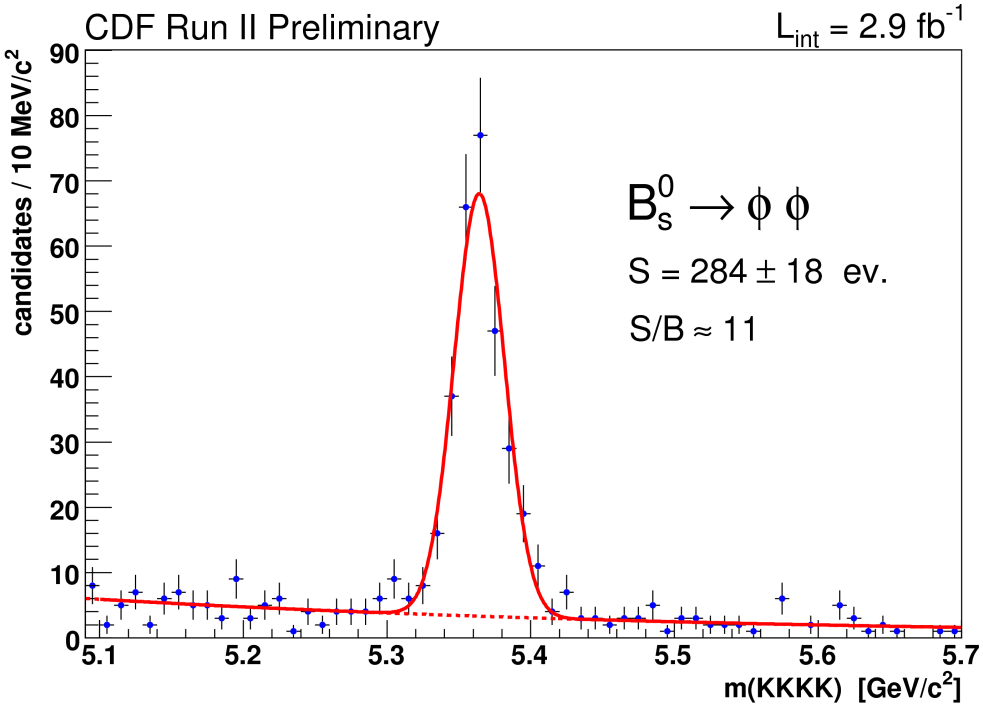
- If $\beta_s \gg \beta_s^{SM} \to$ Realistic chance for evidence or even observation of new physics at the Tevatron

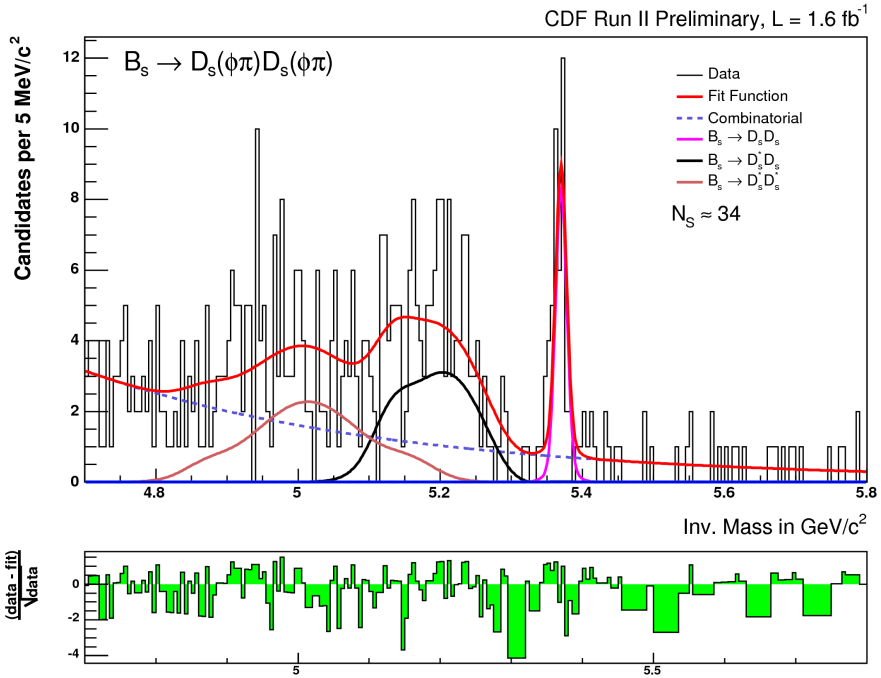


Backup

Teaser

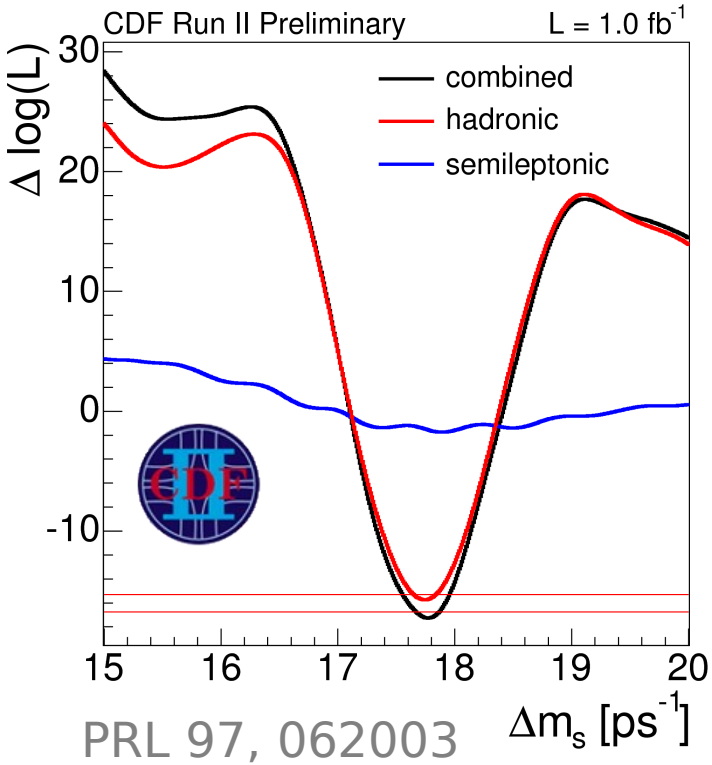
$B_s \to \phi\ \phi$



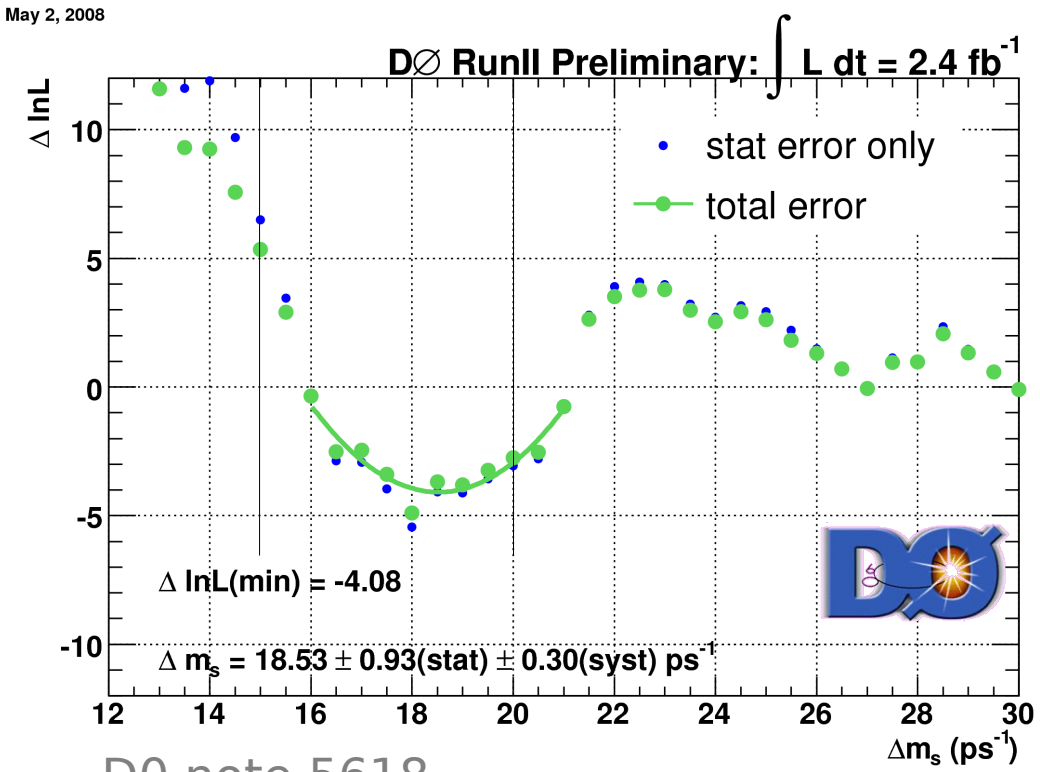


$B_s \to D_s^{(*)}\ D_s^{(*)}$

B^0_s Mixing Measurements



PRL 97, 062003

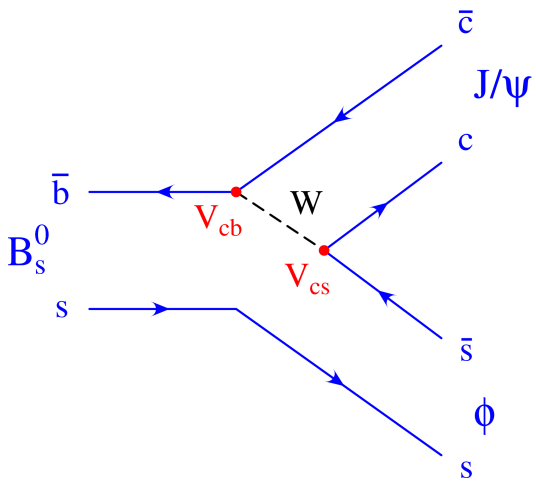


D0 note 5618

- CDF : $\Delta m = 17.77 \pm 0.10$ (stat) ± 0.07 (syst) ($>5\sigma$)
- D0 : $\Delta m = 18.53 \pm 0.93$ (stat) ± 0.30 (syst) (2.9σ)

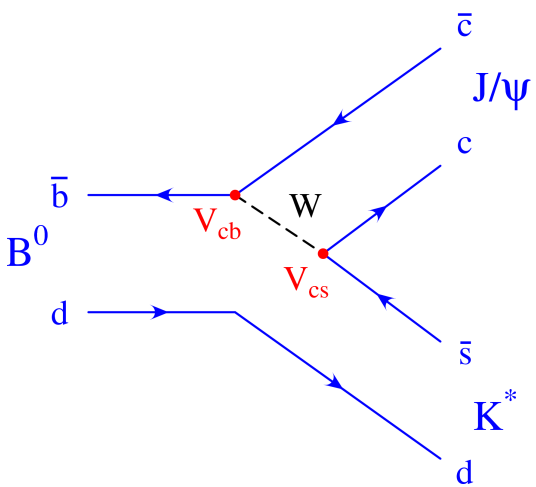
Strong Phases

- Same phases in



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

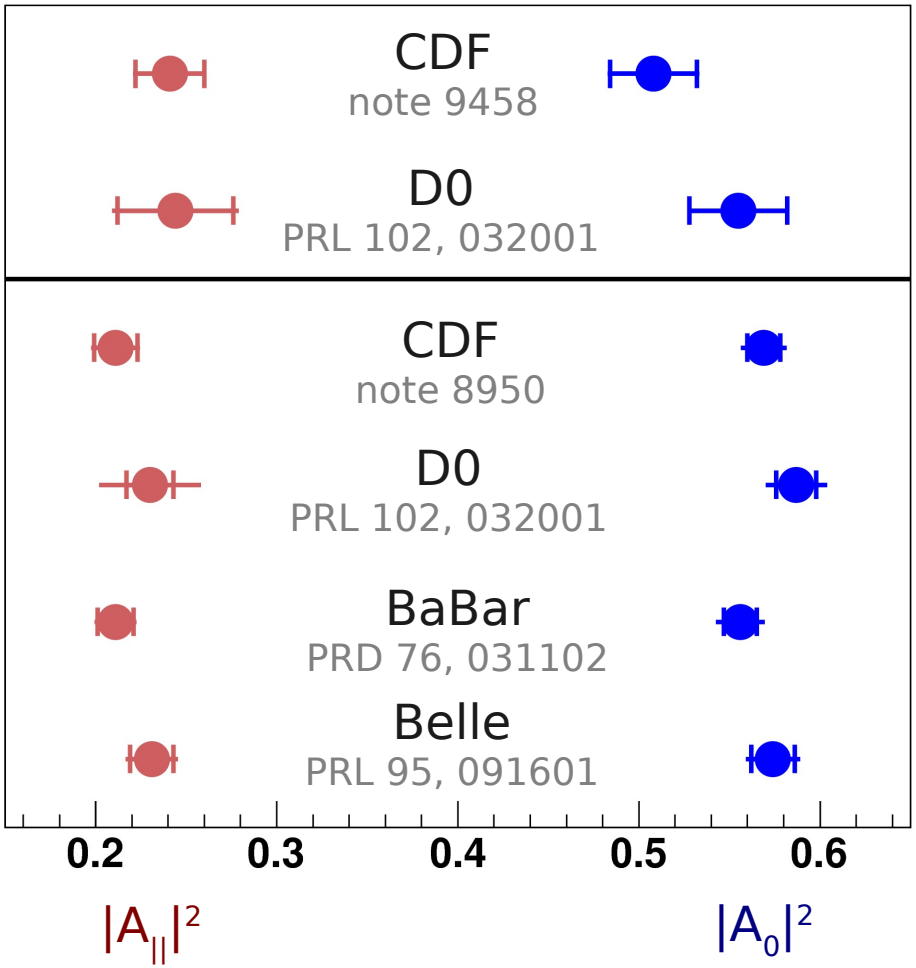
and



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

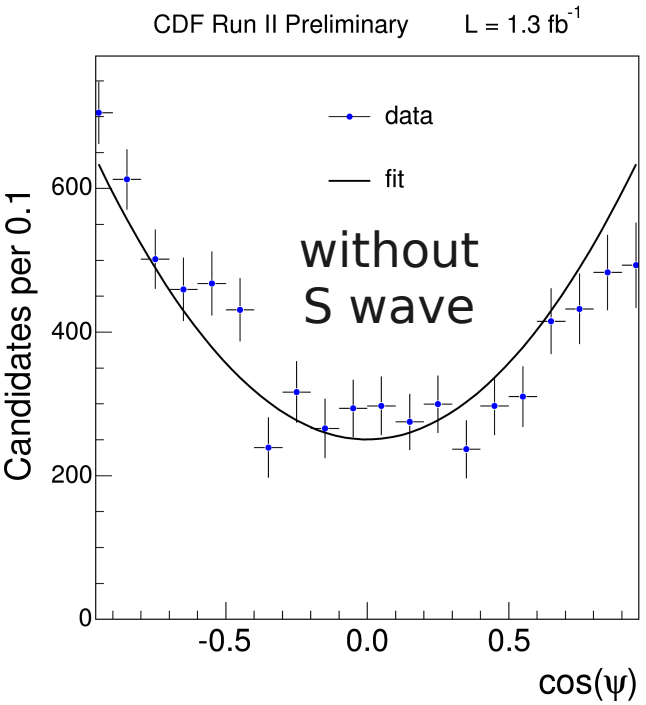
?

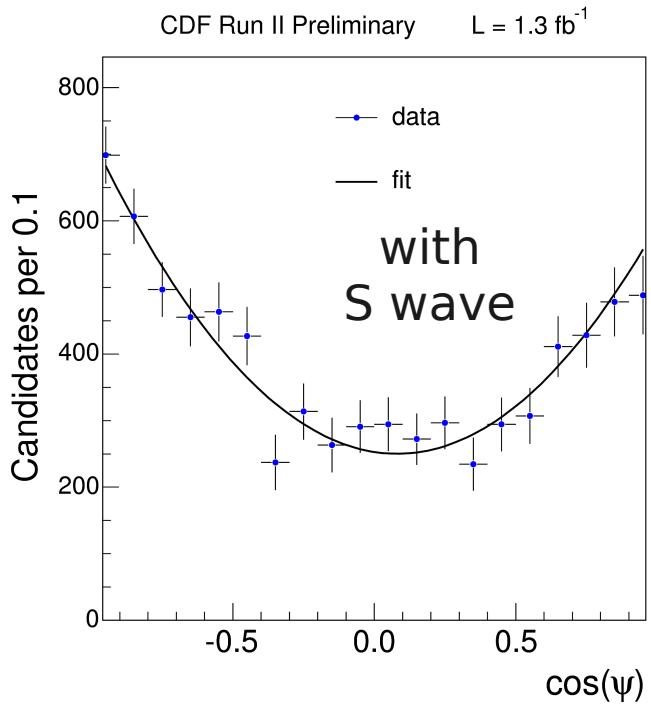
Polarization amplitudes: $A_0, A_\perp, A_{||} \Leftrightarrow L=0,1,2$

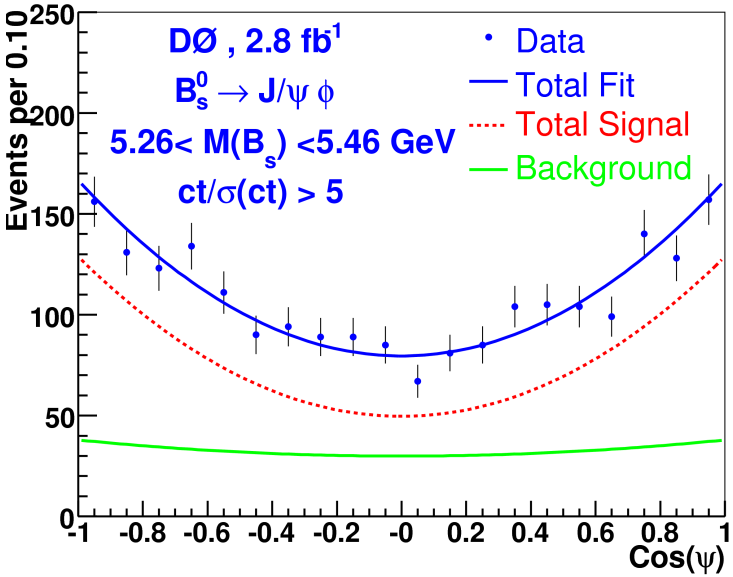


S Wave Interference

- cos(ψ) distribution sensitive on S wave interference







D0: (4.0 ± 1.0) %

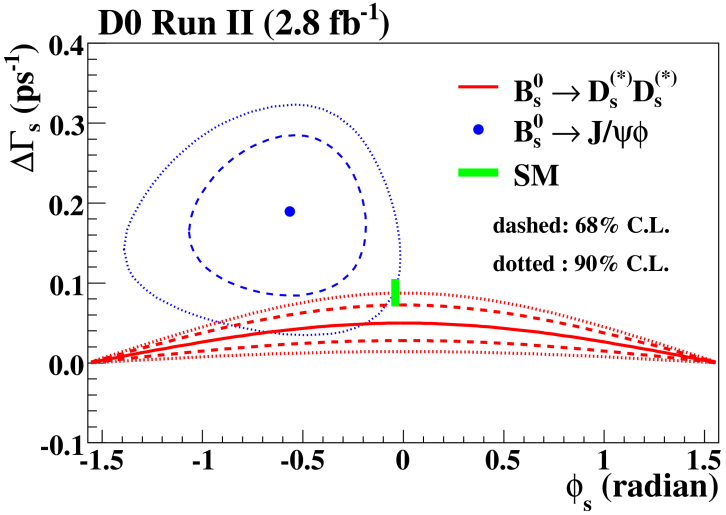
- Evidence for S wave interference in $B^0 \to J/\psi\ K^*$
- No S wave interference needed to describe $B_s \to J/\psi\ \phi$

$\Delta\Gamma$

- $\Delta\Gamma = 2|\Gamma_{12}|\cos(\phi)$

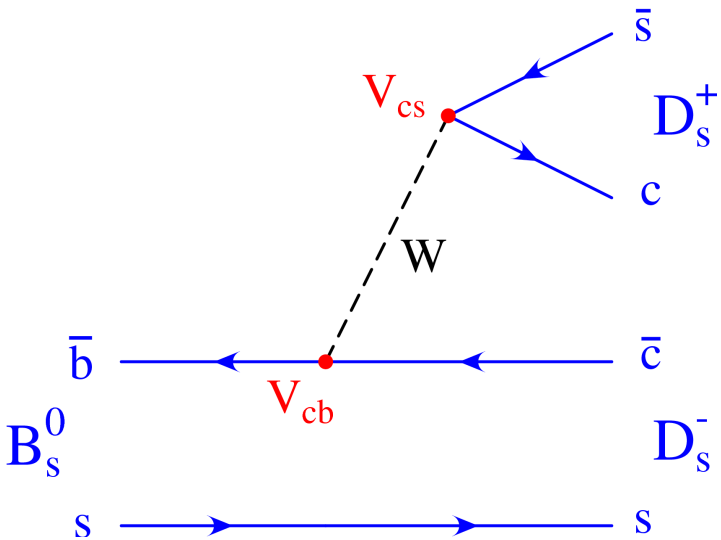
  $2|\Gamma_{12}| = \Delta\Gamma_{CP} = \Gamma^{even} - \Gamma^{odd}$

- Theory: JHEP 06, 072
  $\Delta\Gamma_{CP}/\Gamma = 14.7 \pm 6.0\ \%$



- Dominant contribution to Γ^{even}:
  - $B_s \to D_s^{(*)} D_s^{(*)}$

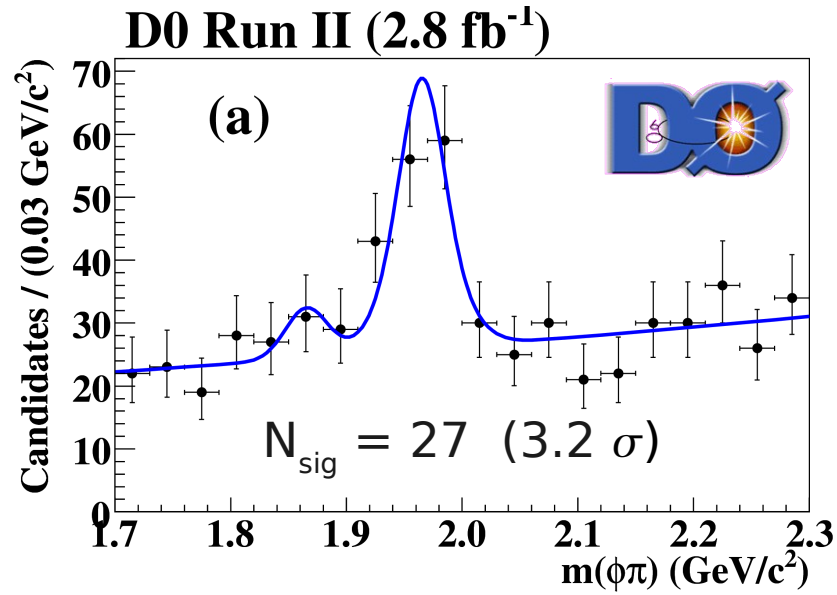
- Shifman-Voloshin Limit:
  $m_c \to \infty$, $m_b = 2m_c$, $N_{color} \to \infty$
  - $\Delta\Gamma_{CP} = 2\Gamma(B_s \to D_s^{(*)} D_s^{(*)})$



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

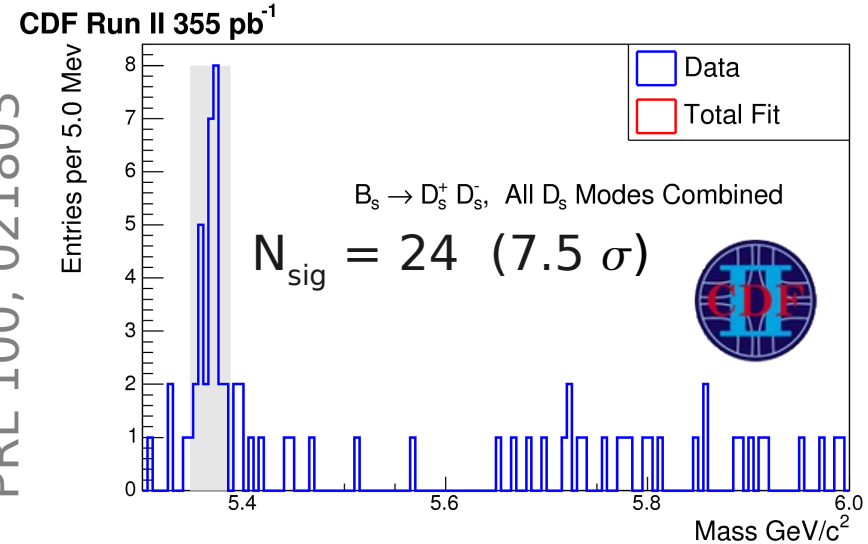
- $D_s^{(*)} \to \phi\mu\nu$ (μ trigger)
- $D_s^{(*)} \to \phi\pi$
- Normalized to $B_s \to D_s^{(*)}\mu\nu$
- $B(B_s \to D_s^{(*)} D_s^{(*)}) =$ $3.5 \pm 1.0(\text{stat}) \pm 1.1(\text{syst})$ %
- ➔ $\Delta\Gamma_{CP}/\Gamma = 7.2 \pm 2.1 \pm 2.2$ %

PRL 102, 091801



- $D_s \to \phi\pi$ (disp. track trigger)
- $D_s \to \phi\pi$, K*K, $\pi\pi\pi$
- Normalized to $B^0 \to DD_s$
- $B(B_s \to D_s D_s) = 0.94^{+0.44}_{-0.42}$ %
- ➔ $\Delta\Gamma_{CP}/\Gamma > 1.2$ % @ 95% CL

PRL 100, 021803



CP Violation in Semileptonic Decays

- Flavor specific decay mode:

$$\Gamma(B \to f) = N\,|A_f|^2\,\frac{\exp(-\Gamma t)}{2}\left\{\cosh\left(\frac{\Delta\Gamma t}{2}\right) + \cos(\Delta m t)\right\}$$

$$\Gamma(\bar{B} \to f) = N\,|A_f|^2\,(1+a)\frac{\exp(-\Gamma t)}{2}\left\{\cosh\left(\frac{\Delta\Gamma t}{2}\right) - \cos(\Delta m t)\right\}$$

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- ➔ Semileptonic asymmetry: $a_{SL} = \Delta\Gamma / \Delta m \tan(\phi)$
  - ➔ SM: $a^s_{SL} = 2 \times 10^{-5}$
- Assume no direct CP violation: $|A_f| = |\bar{A}_{\bar{f}}|$

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➔ *Mixing analysis:*

$$\Gamma(unmixed) - \Gamma(mixed) = 2\,N\,|A_f|^2\,\exp(-\Gamma t)\cos(\Delta m t)$$

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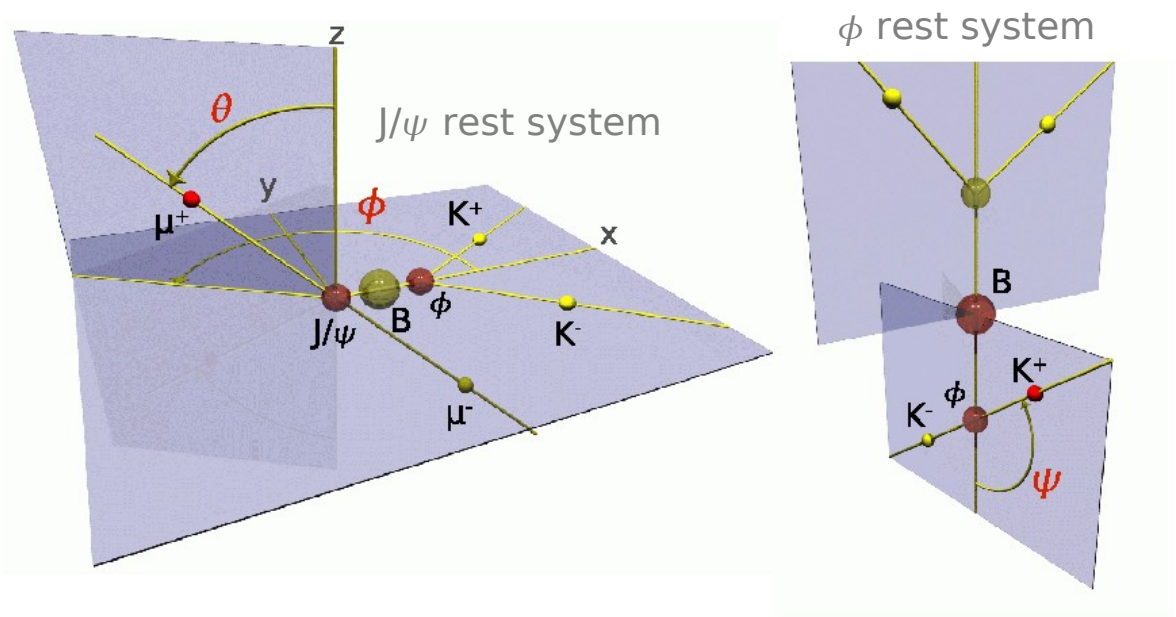
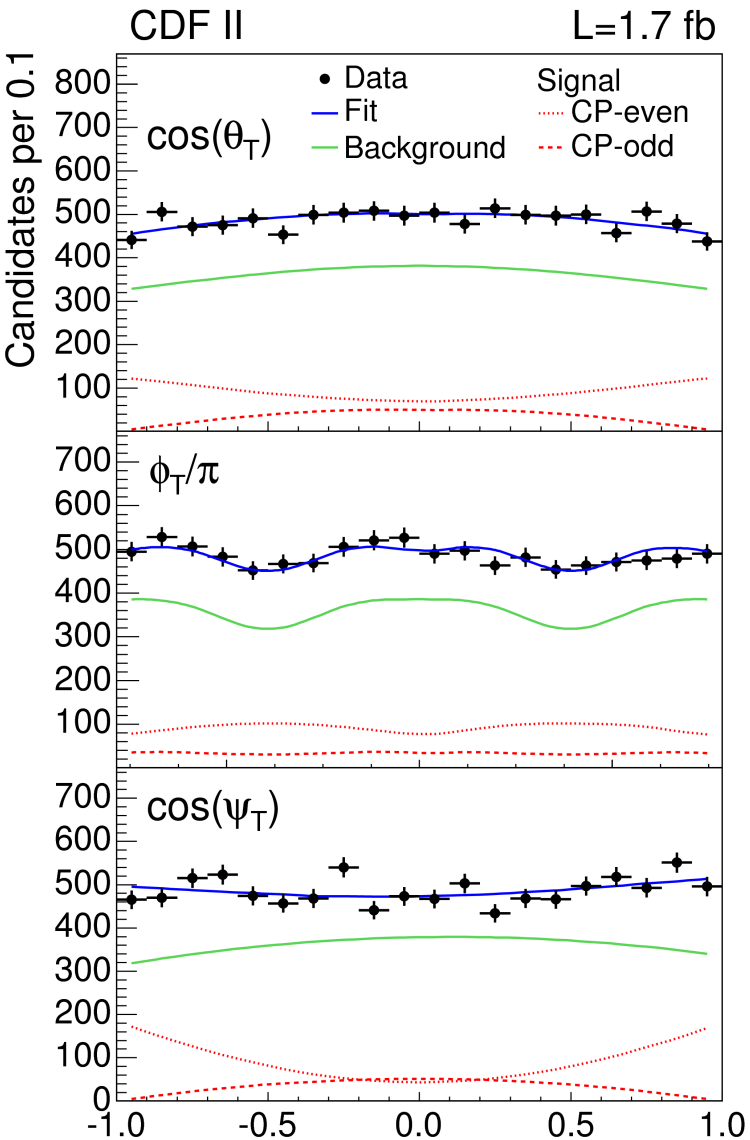
Angular Analysis



$$\vec{\rho} = (\cos(\theta_T), \phi_T, \cos(\psi_T))$$



Polarization amplitudes:

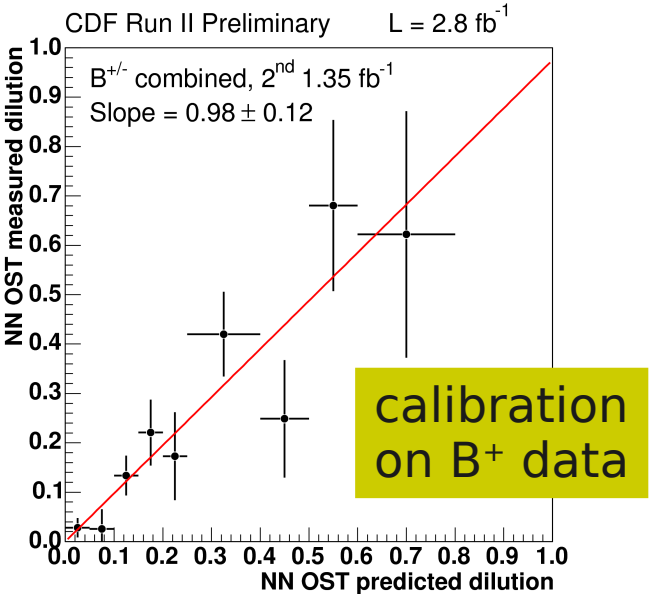
A_0, $A_{||}$ ⇒ CP even

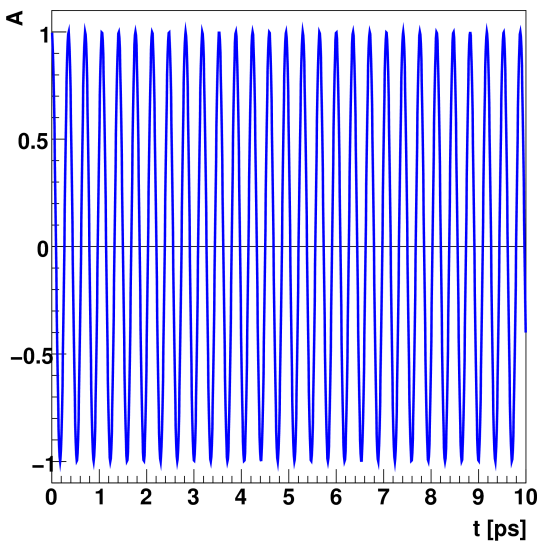
$A_\perp$ ⇒ CP odd

Tagging Performance

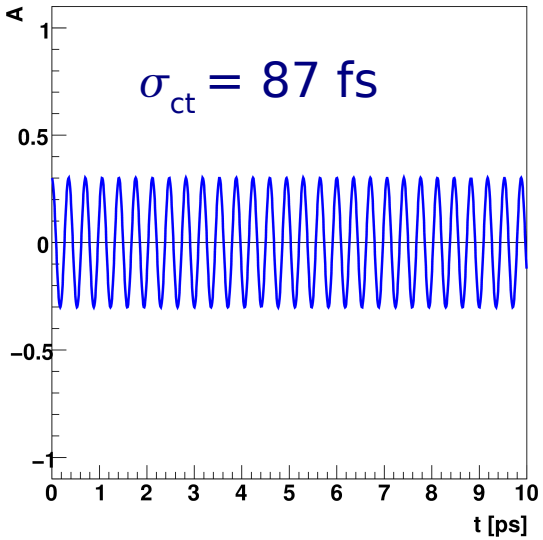
- Efficiency: $\epsilon = \frac{N_{tag}}{N_{tag} + N_{kein-tag}}$

- Dilution: $D = \frac{N_{richtig} - N_{falsch}}{N_{richtig} + N_{falsch}}$

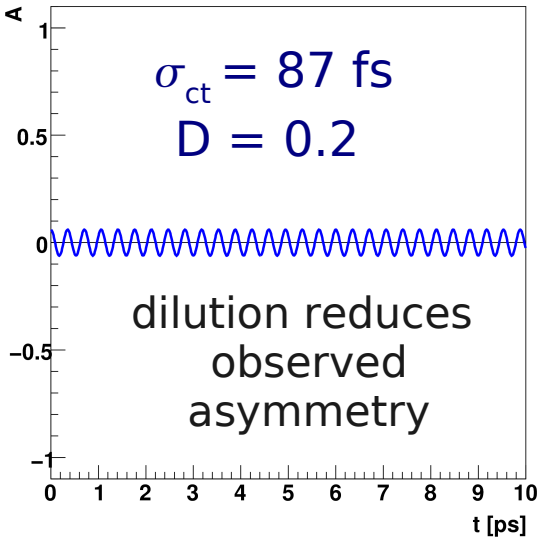




⇒



⇒



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Decay Rate PDF

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

$$
\begin{aligned}
\mathcal{T}_\pm(t) &= e^{-\Gamma t}\left[\cosh(\Delta\Gamma t/2) \mp \cos(2\beta_s)\sinh(\Delta\Gamma t/2)\right] \\
\mathcal{U}(t) &= e^{-\Gamma t}\left[\cos(\delta_\perp - \delta_{||})\sin(2\beta_s)\sinh(\Delta\Gamma t/2)\right] \\
\mathcal{V}(t) &= e^{-\Gamma t}\left[\cos(\delta_\perp)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)\right]
\end{aligned}
$$

- f_i : Angular distributions
- T,U,V : Lifetime distributions

Decay Rate PDF

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CP even

$$+ |A_\perp|^2 f_3(\vec{\rho})\mathcal{T}_-(t) + |A_0||A_{||}| f_5(\vec{\rho})\cos(\delta_{||})\mathcal{T}_+(t)$$

CP odd

$$+ |A_{||}||A_\perp| f_4(\vec{\rho})\mathcal{U}(t) + |A_0||A_\perp| f_6(\vec{\rho})\mathcal{V}(t)$$

interference

$$\mathcal{T}_\pm(t) = e^{-\Gamma t}\left[\cosh(\Delta\Gamma t/2) \mp \cos(2\beta_s)\sinh(\Delta\Gamma t/2)\right]$$

$$\mathcal{U}(t) = e^{-\Gamma t}\left[\cos(\delta_\perp - \delta_{||})\sin(2\beta_s)\sinh(\Delta\Gamma t/2)\right]$$

$$\mathcal{V}(t) = e^{-\Gamma t}\left[\cos(\delta_\perp)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)\right]$$

- Invariance under transformations:

$$2\beta_s \to -2\beta_s \;,\; \delta_\perp \to \delta_\perp + \pi$$

$$\Delta\Gamma \to -\Delta\Gamma \;,\; 2\beta_s \to 2\beta_s + \pi$$

→ 4-fold ambiguity

Decay Rate PDF with Tagging

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

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

B^0_s: $\eta = +1$

$\overline{B}^0_s$: $\eta = -1$

$$\mathcal{U}(t) = e^{-\Gamma t}\left[\cos(\delta_\perp - \delta_{||})\sin(2\beta_s)\sinh(\Delta\Gamma t/2) + \eta\cos(\Delta m_s t)\sin(\delta_\perp - \delta_{||}) - \eta\sin(\Delta m_s t)\cos(\delta_\perp - \delta_{||})\cos(2\beta_s)\right]$$

$$\mathcal{V}(t) = e^{-\Gamma t}\left[\cos(\delta_\perp)\sin(2\beta_s)\sinh(\Delta\Gamma t/2) + \eta\cos(\Delta m_s t)\sin(\delta_\perp) - \eta\sin(\Delta m_s t)\cos(\delta_\perp)\cos(2\beta_s)\right]$$

➔ ambiguity reduced from 4- to 2-fold