Recent *B* Physics Results at DØ

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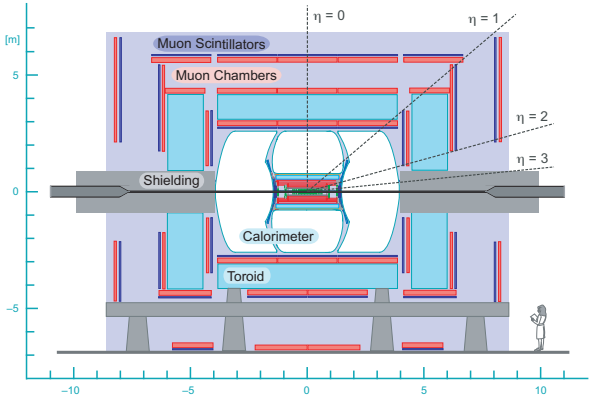
Representing the DØ Collaboration

Lake Louise Winter Conference

February 18 – 23, 2008

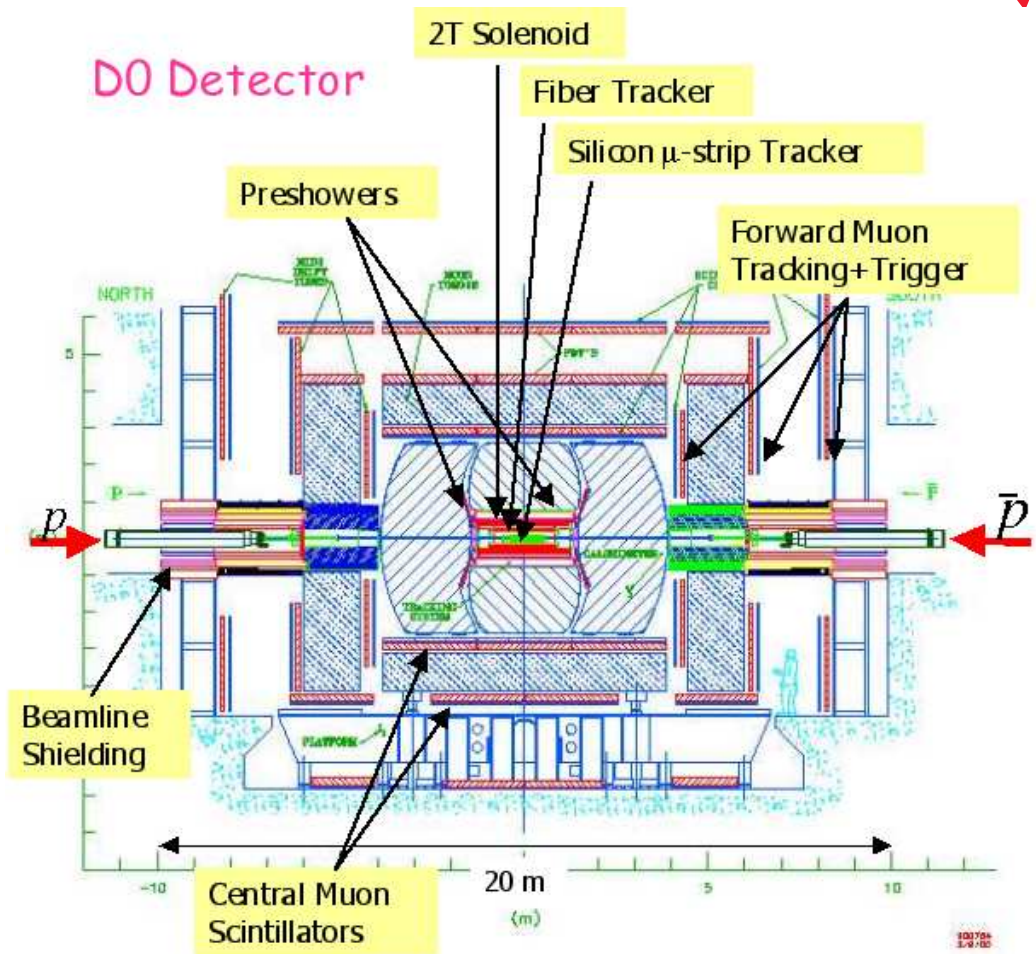
Lake Louise, Alberta, Canada



- Study of production and properties of heavy-flavor hadrons
- Indirect searches for new physics (NP)

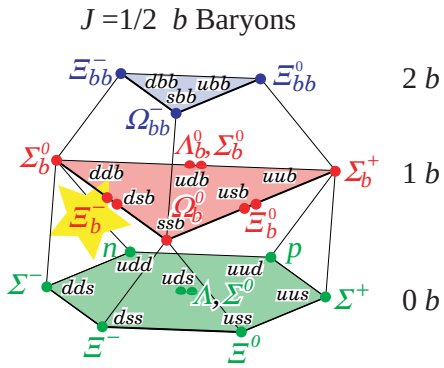
DØ Detector

- Multi-purpose detector
- Silicon and fiber trackers immersed in 2 T solenoid, coverage $|\eta| < 3$
- Muon system (central + forward), coverage $|\eta| < 2$
  - Includes its own magnet – toroid
- Two magnets – solenoid and toroid – flip polarity every two weeks
  - Unique feature of DØ

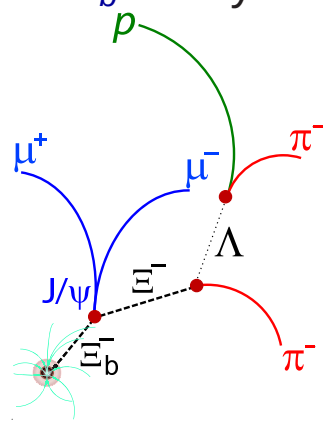


“Three-Scoop” Baryon $\Xi_b^-(dsb)$

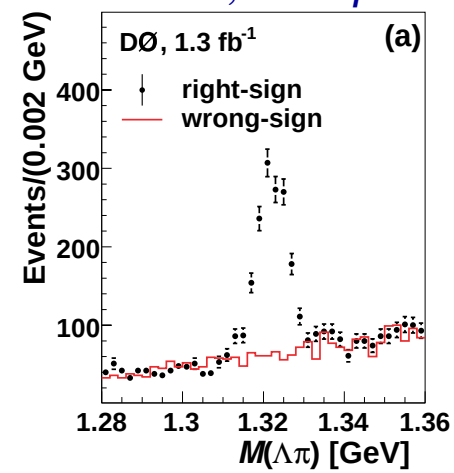
b-Baryon 20-plet:



Ξ_b decay:



$\Xi^- \to \Lambda\pi^-, \Lambda \to p\pi^-$:

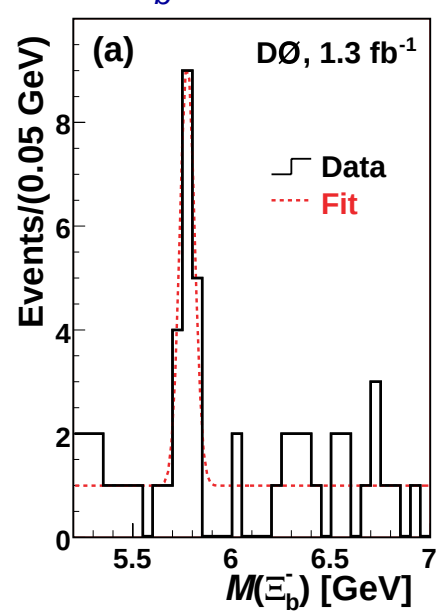


- $N(\Xi_b^-) = 15.2 \pm 4.4$ (stat.) $\pm^{+1.9}_{-0.4}$ (syst.)
- Stat. significance 5.5σ
- $m(\Xi_b^-) = 5.774 \pm 0.011$ (stat.) ± 0.015 (syst.) GeV/c^2
- Relative production rate:

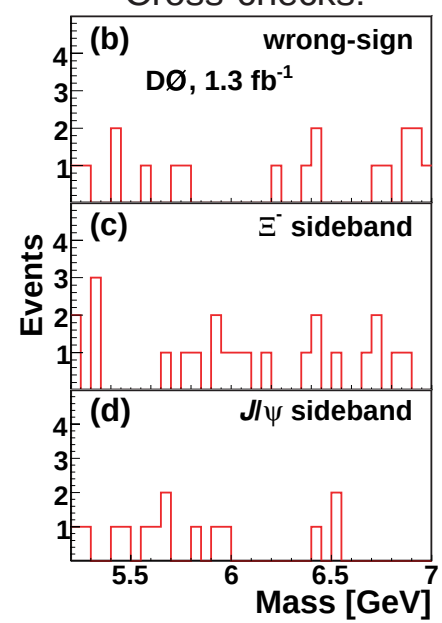
$$\frac{f(b\to\Xi_b^-)\cdot Br(\Xi_b^-\to J/\psi\Xi^-)}{f(b\to\Lambda_b)\cdot Br(\Lambda_b\to J/\psi\Lambda)} = 0.28 \pm 0.09^{+0.09}_{-0.08}$$

- DØ : [PRL**99**, 1052001 (2007)]
  CDF: [PRL**99**, 052002 (2007)]

$\Xi_b^- \to \Xi^- J/\psi$:



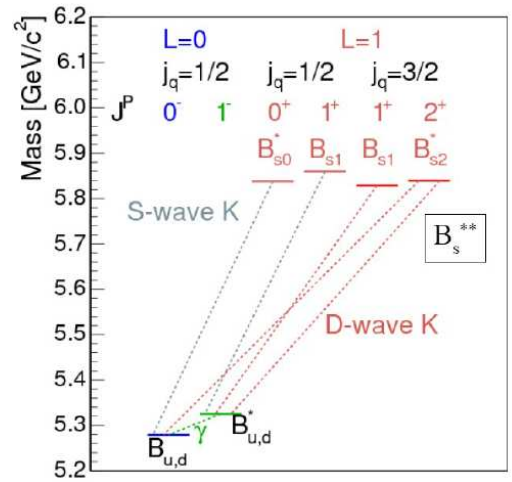
Cross-checks:



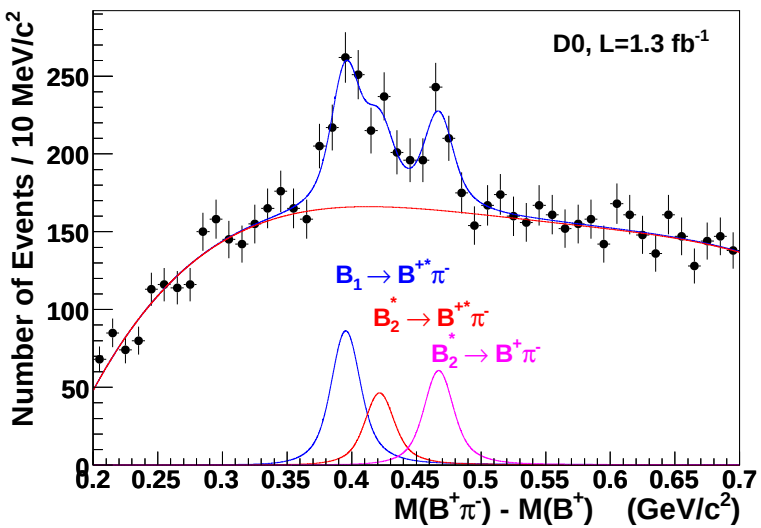
Orbitally Excited *b* Mesons

- In HQET Qq meson is similar to hydrogen atom
- Predicted: Two broad $j_q = \frac{1}{2}$ and two narrow $j_q = \frac{3}{2}$ excited states
- Search for narrow states: $B^{**} \to B^{(*)}\pi$ (left) and $B_s^{**} \to B^{(*)}K$ (right)
- $B_s^{**} \to B_s^{(*)}\pi$ forbidden by isospin
- Expect 3 peaks: $B_{(s)1} \to B^*\pi(K)$, $B^*_{(s)2} \to B^*\pi(K)$, $B^*_{(s)2} \to B\pi(K)$
- $B_{(s)1} \to B\pi(K)$ is forbidden

Diagram for B_s (similar one for B_d)

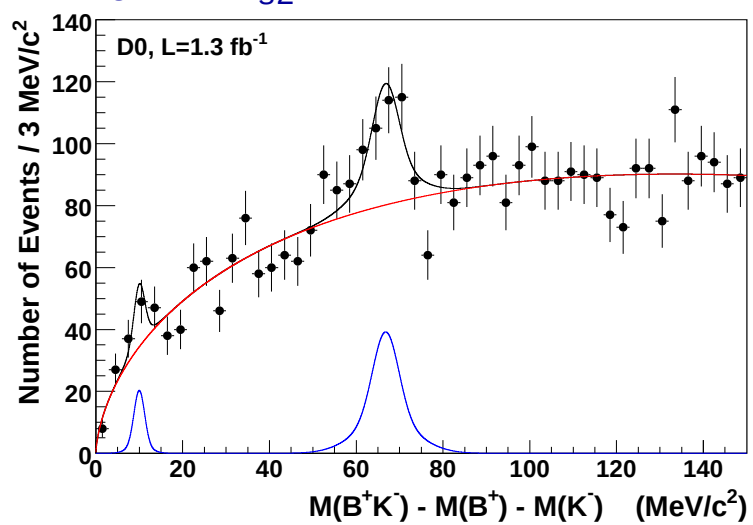


Fit for B_1 and B_2^* [PRL **99**, 172001 (2007)]



- Stat. significance $> 7\sigma$
- All masses and branchings are measured

Fit for B_{s1} and B_{s2}^* [hep-ex/0711.0319, Acc. by PRL]



- $N(B_{s2}^*) = 125 \pm 25$(stat.); Significance 4.8σ
- Mass and branching are measured
- $N(B_{s1}) = 25 \pm 10$(stat.); Significance $< 3\sigma$
- More data is required to claim observation of B_{s1}

$B_s \to \mu\nu D_{s1}(2536)X$

Motivation:

- Semileptonic decays of B_s into $L = 1$ states (D_s^{**}) comprise significant part of total B_s width
- Important in inclusive/exclusive decay rates, CKM elements, B_s-mixing
- Help us better understand D_{sJ}^{**} systems

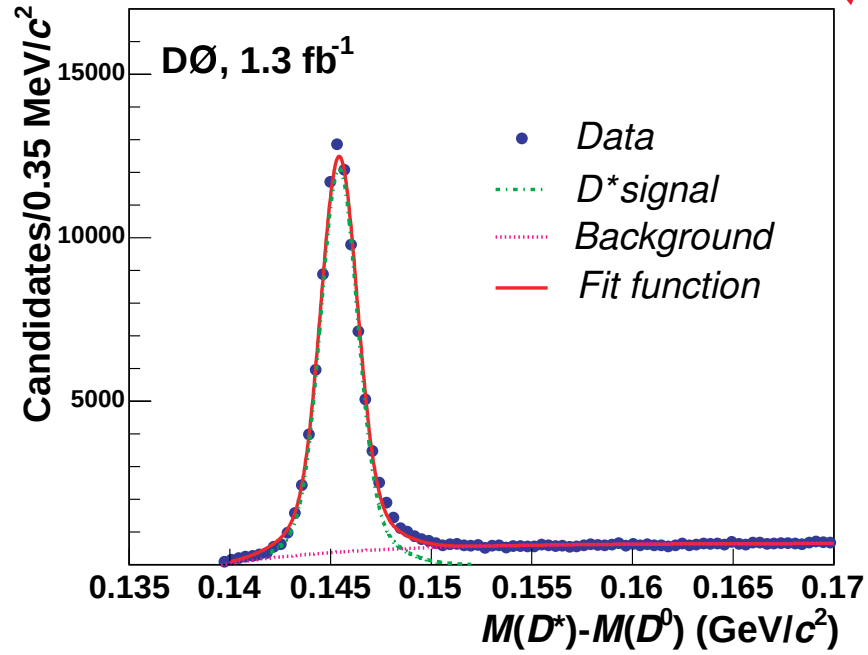
Analysis: [hep-ex/0712.3789]

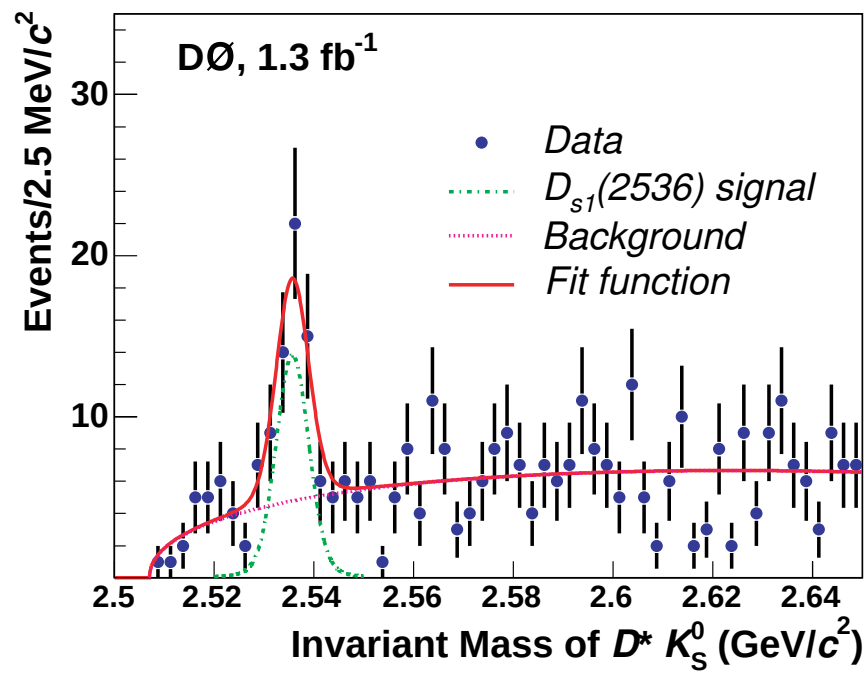
- Start reconstruction with $B \to \mu D^0 X, D^0 \to K\pi$
- Add a soft pion π_s to get $B \to \mu D^* X, D^* \to D^0 \pi_s$ (top plot)
- Then add $K_S^0 \to \pi^+\pi^-$ and get D_s^{**} (bottom plot)

Results:

- $N(D_{s1}) = 45.9 \pm 9.1$ (stat.)
- Statistical significance 6.1σ
- $m(D_{s1}) = 2535.7 \pm 0.6 \pm 0.5$ GeV/c^2 (agrees with PDG)
- $Br(B_s^0 \to D_{s1}\mu\nu X) =$
  $= 1.03 \pm 0.20(\text{stat.}) \pm 0.17(\text{syst.}) \pm 0.14(B)\%$
- Largest uncertainty - from K_S^0 acceptance
- First Br measurement
- Consistent with predictions: $0.2 - 1.1\%$

[PRD**52**, 2783 (1995)], [PRD**61**, 014016], [J.Phys. G **29**, 2059 (2003)]





Lifetimes (Λ_b, B_c)

- Heavy-Quark Expansion is successful for lifetimes of B-mesons, less successful with B-baryons
- Same techniques used as for CKM calculations
- Stringent verification needed $\Rightarrow \Lambda_b$ lifetime is important

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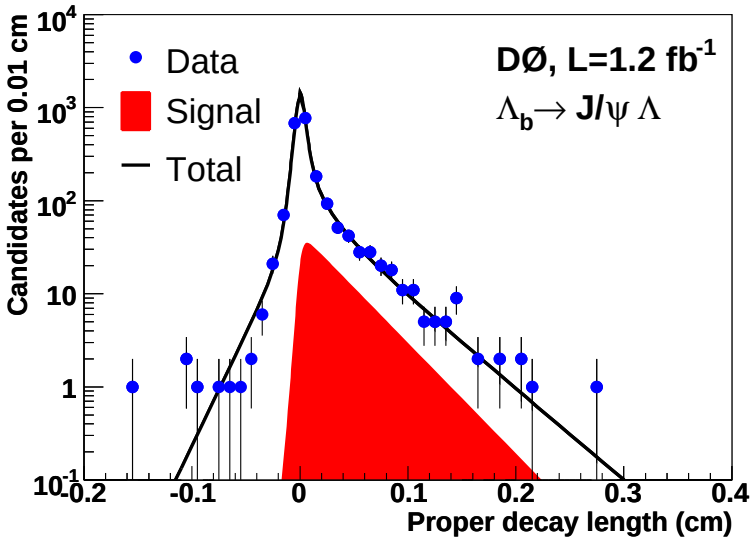
- $\Lambda_b \to \mu\nu\Lambda_c X, \Lambda_c \to K^0_S p$ [PRL**99**, 182001 (2007)]
  - $\tau(\Lambda_b) = 1.290^{+0.119+0.087}_{-0.110-0.091}$ ps
- $\Lambda_b \to J/\psi\Lambda$ (and $B_d \to J/\psi K^0_S$) [PRL**99**, 142001 (2007)]
  - $\tau(\Lambda_b) = 1.218^{+0.130}_{-0.115} \pm 0.042$ ps
  - $\tau(B_d) = 1.501^{+0.078}_{-0.074} \pm 0.050$ ps
  - Ratio consistent with prediction: 0.88 ± 0.05 ps [Eur.Phys.J.**C33** (2004)]

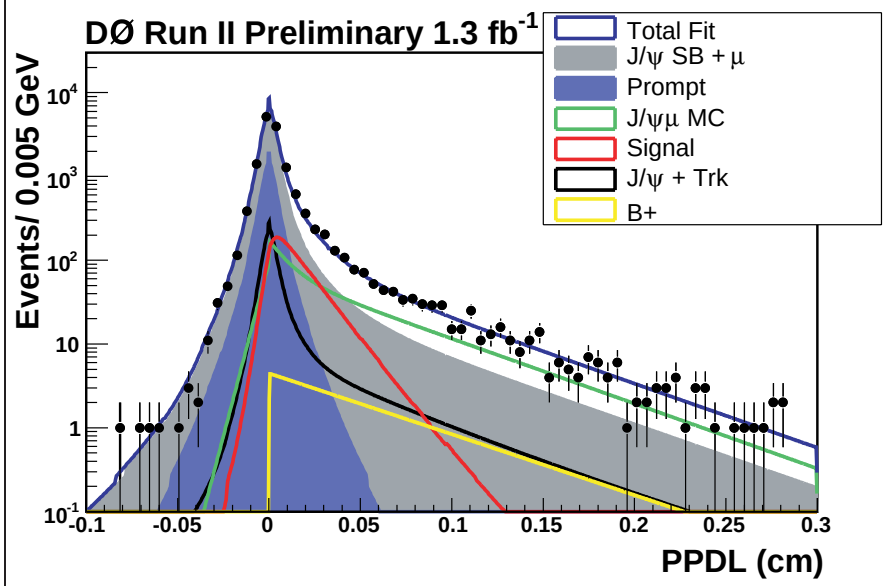


DØ Average $\tau(\Lambda_b) = 1.251^{+0.102}_{-0.096}$ ps [PRL **99**, 182001 (2007)]

$B_c \to \mu\nu_\mu J/\psi, J/\psi \to \mu^+\mu^-$

[DØ Conf. Note 5524]

- B_c - 2 heavy quarks, each can decay
- Shortest lifetime of all B-hadrons
- Three μ final state - take advantage of good DØ muon system
- Main physics bkg: $B_u \to J/\psi K, K \to \mu\nu\pi$



$\tau(B_c) = 0.444^{+0.039+0.039}_{-0.036-0.034}$ ps

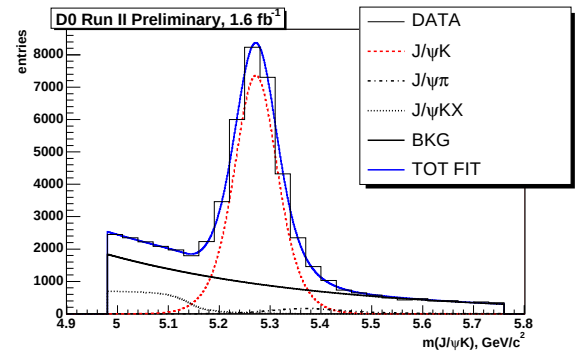
Direct CP-Violation

Charge asymmetry in $B \to J/\psi K$:

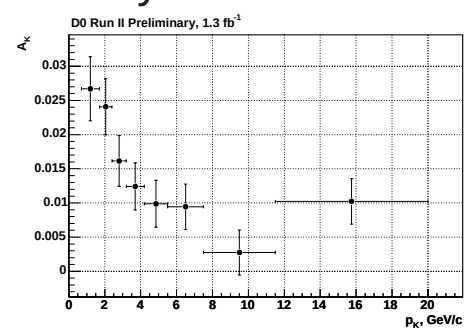
$$A_{CP} = \frac{N(B^+ \to J/\psi K^+) - N(B^- \to J/\psi K^-)}{N(B^+ \to J/\psi K^+) + N(B^- \to J/\psi K^-)}$$

SM: ~ 0.003, NP: ~ 0.01 [hep-ph/0605080]

- Detector asymmetries cancel because of flipping toroid polarity
- Physics asymmetry for K^+/K^- interaction with detector material: reaction $K^- +$ nucleon $\to \pi + \Sigma/\Lambda$ has no $K^+ +$ nucleon analog
- Finally:
  - ☞ $A_{CP}(B \to J/\psi K) = 0.0067 \pm 0.0074 \pm 0.0026$
  - ☞ PDG'06: $A_{CP}(B \to J/\psi K) = -0.024 \pm 0.014$



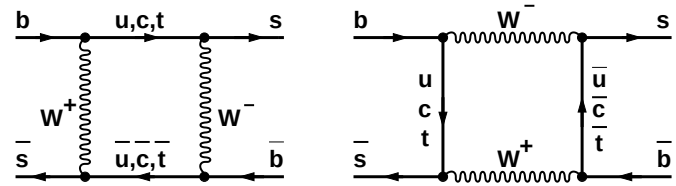
Asymmetry vs. kaon momentum



CP-Violation in Mixing

Schrödinger equation for B_s system:

$$i\frac{d}{dt}\begin{pmatrix}|\overline{B_s}(t)\rangle\\|B_s(t)\rangle\end{pmatrix} = (M - \tfrac{i}{2}\Gamma)\begin{pmatrix}|\overline{B_s}(t)\rangle\\|B_s(t)\rangle\end{pmatrix} \Longrightarrow \begin{matrix}|B_{s,H}\rangle = p|B_s(t)\rangle - q|\overline{B_s}(t)\rangle\\|B_{s,L}\rangle = p|B_s(t)\rangle + q|\overline{B_s}(t)\rangle\end{matrix}$$



Observables:

$\Delta M_s = M_H - M_L \approx 2|M_{12}^s|$ and $\Delta\Gamma_s = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}^s|\cos\phi_s$, where $\phi_s = \arg\left(-\frac{M_{12}^s}{\Gamma_{12}^s}\right)$ – CP-violating phase

$a_{SL}^s = \mathrm{Im}\,\frac{\Gamma_{12}^s}{M_{12}^s} = \frac{\Delta\Gamma_s}{\Delta M_s}\tan\phi_s$ – small and sensitive to NP

Two time-integrated DØ analyses:

Inclusive muons:

$$A_{SL}^{\mu\mu} = \frac{N(b\bar{b}\to\mu^+\mu^+X) - N(b\bar{b}\to\mu^-\mu^-X)}{N(b\bar{b}\to\mu^+\mu^+X) + N(b\bar{b}\to\mu^-\mu^-X)}$$

$A_{SL}^{\mu\mu} = -0.0064 \pm 0.0101$ [PRD**76**, 057101 (2007)]

Consistent with SM [hep-ph/0406300]

Semileptonic B_s decays

$$A_{SL}^s = \frac{N(B_s\to\mu^+D_s^-X) - N(B_s\to\mu^-D_s^+X)}{N(B_s\to\mu^+D_s^-X) + N(B_s\to\mu^-D_s^+X)}$$

$A_{SL}^s = 0.0123 \pm 0.0097 \pm 0.0017$ [PRL**98**, 151801 (2007)]

- SM: $2\cdot A_{SL}^s = (0.000021 \pm 0.000004)$ [hep-ph/0406300]
- NP may increase this value, up to 0.005

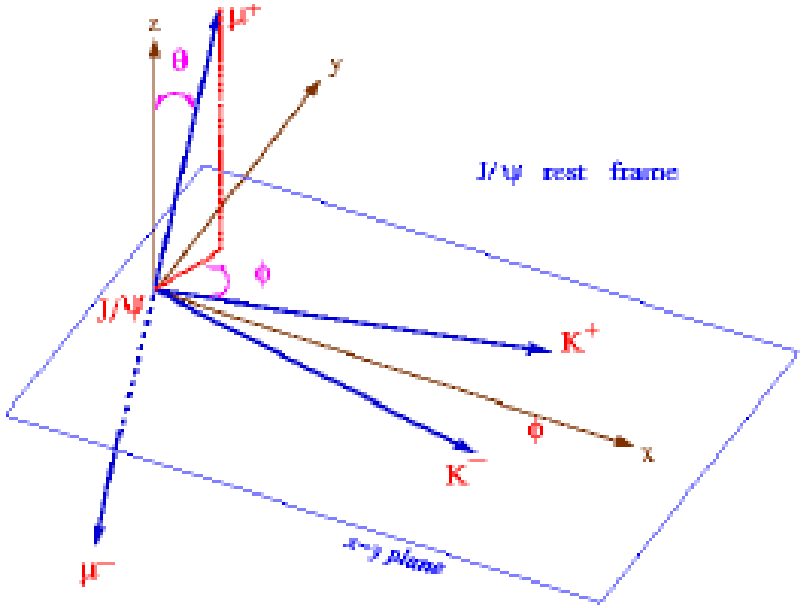
In both analyses detector systematics again cancels by flipping toroid polarity

Combined: $a_{SL}^s = 0.0001 \pm 0.0090$ [PRD **76**, 057101 (2007)]

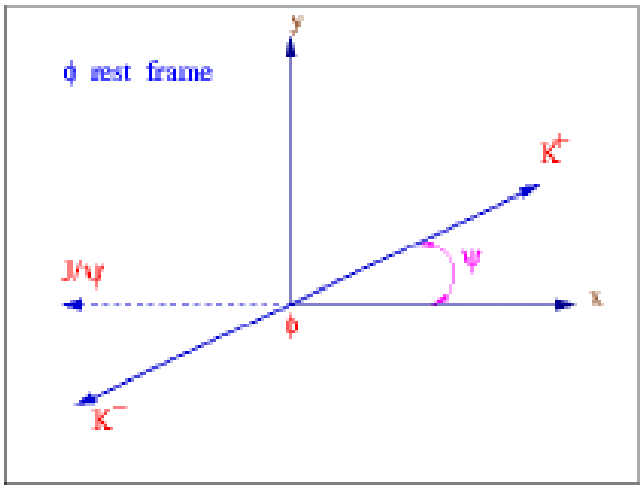
Thus, $\boxed{\Delta\Gamma_s\cdot\tan\phi_s = a_{SL}^s\cdot\Delta M_s = 0.02 \pm 0.16\ \mathrm{ps}^{-1}}$

$\Delta\Gamma_s$ and ϕ_s from $B_s \to J/\psi\phi$

- Mostly CP-even final state
- Angular analysis is needed to disentangle small CP-odd component
- Angular momenta: $|J=0\rangle \to |J=1\rangle + |J=1\rangle$
- Amplitudes:
  - $A_0(t)$ - both V's longitudinal, CP = +
  - $A_{\|}(t)$ - both V's transverse with polarizations parallel to each other, CP = +
  - $A_{\perp}(t)$ - both V's transverse with polarizations $\perp$ to each other, CP = –



- Rate $\frac{d^3\Gamma(B_S \to J/\psi\phi)}{d\cos\theta d\phi d\cos\psi}$ depends on angles ϕ, θ and ψ (see plots) and on the amplitudes $A_0(t)$, $A_{\|}(t)$ and $A_{\perp}(t)$
- The amplitudes depend on Γ_H, Γ_L, ΔM_s, ϕ_s *etc*
- This dependence is different for B_s and $\overline{B_s}$
- For given event the rate is multiplied by probability of B_s or $\overline{B_s}$ flavor (obtained from flavor tagging)



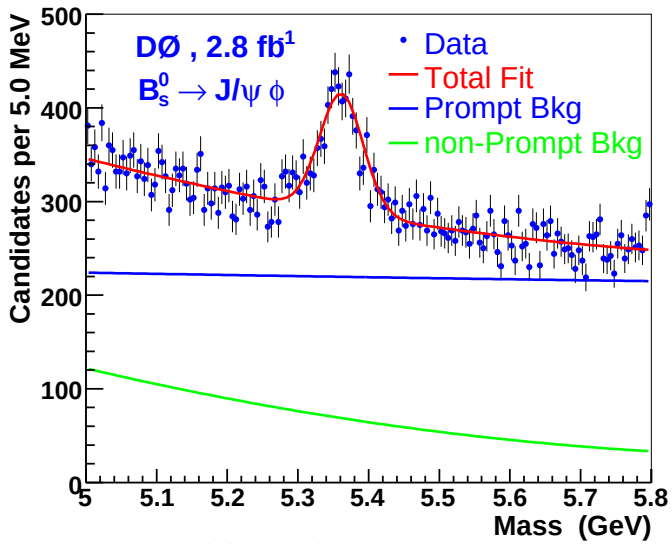
Perform unbinned likelihood fit with function:

$$\mathcal{L} = \prod_{i=1}^{N}[f_{sig}\mathcal{F}^i_{sig} + (1-f_{sig})\mathcal{F}^i_{bkg}]$$

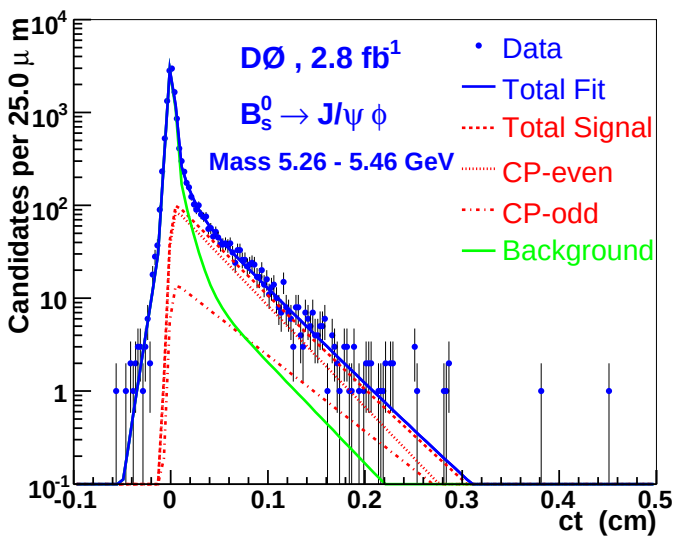
- Bkg is split into:
  - "Prompt bkg", where J/ψ comes from PV
  - "Non-prompt bkg", where J/ψ comes from b-hadron

$\Delta\Gamma_s$ and ϕ_s from $B_s \to J/\psi\phi$

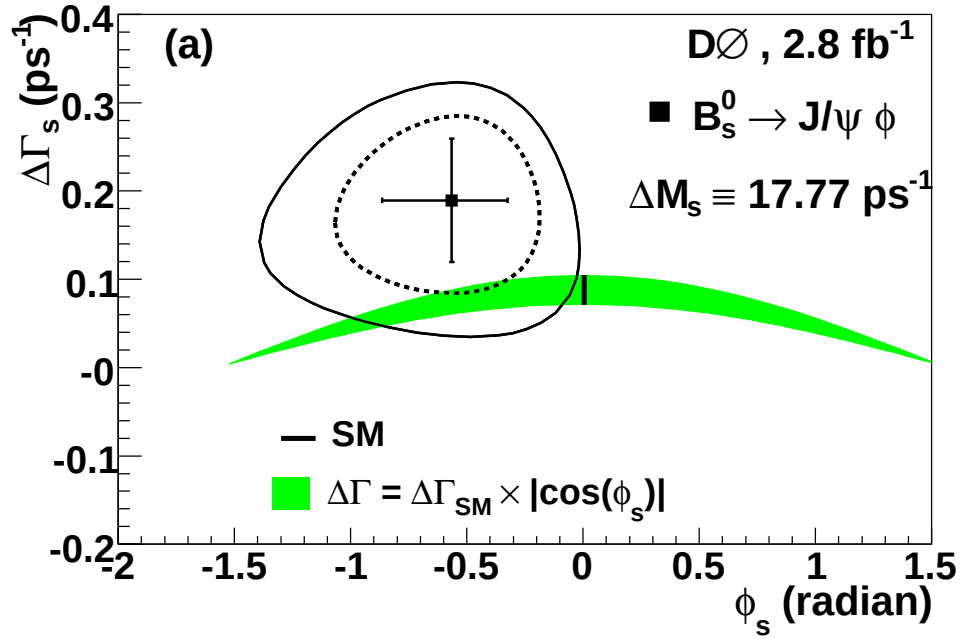
Invariant mass and lifetime plots:



$N = 1967 \pm 65$(stat.) events



$\tau = 1.52 \pm 0.05 \pm 0.01$ ps



Dashed - 68.3% CL, solid - 90% CL

Main results:

$$\Delta\Gamma_S = 0.19 \pm 0.07^{+0.02}_{-0.01}\ \mathrm{ps}^{-1},\ \phi_S = -0.57^{+0.24+0.07}_{-0.30-0.02}$$

[hep-ex/0802.2255, Sub. to PRL]

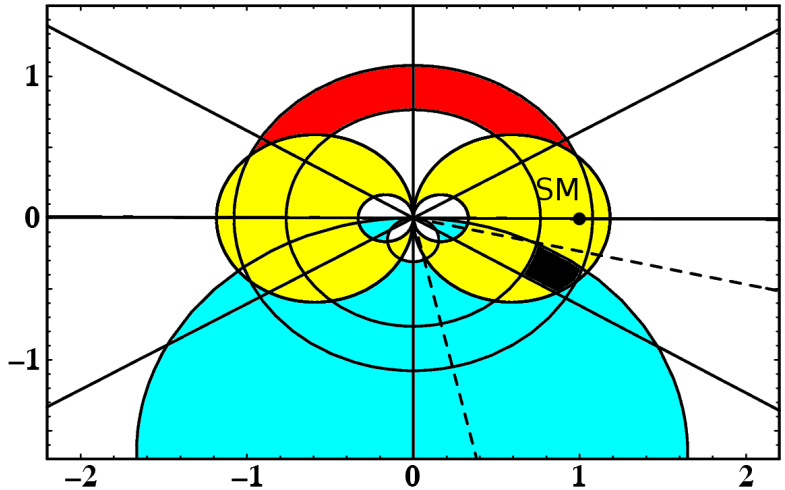
There is a small inconsistency with SM...

New Physics?

In B_s system New Physics can be parametrized by complex number $\Delta_s = |\Delta_s| \cdot \exp^{i\phi_s^\Delta}$ [hep-ph/0612167]:

$M_{12}^s = (M_{12}^s)^{SM} \cdot \Delta_s$, $\Delta M_s = \Delta M_s^{SM} \cdot |\Delta_s|$, $\Delta\Gamma_s = 2|\Gamma_{12}| \cos\phi_s$, where $\phi_s = \phi_s^{SM} + \phi_s^\Delta$

$\mathrm{Im}\Delta_s$ vs $\mathrm{Re}\Delta_s$



- $\Delta_s = 1$ in SM
- Red: from CDF's ΔM_s measurement [PRL **97**, 242003 (2006)]
- Yellow: from $\Delta\Gamma_s/\Delta M_s$ with $\Delta\Gamma_s$ from DØ [PRL**98**, 121801 (2007)] - untagged 1.1 fb^{-1} analysis
- Blue: from DØ 's a_{SL}^s measurement [PRD **76**, 057101 (2007)]
- Forward and backward regions: from sign of $\Delta\Gamma_s$ from DØ [PRL**98**, 121801 (2007)] - untagged 1.1 fb^{-1} analysis
- Dashed wedge: from ϕ_s from DØ [PRL**98**, 121801 (2007)] - untagged 1.1 fb^{-1} analysis

- In SM all regions should intersect in point (1,0)
- Current experimental situation (black area) shows a small deviation which may become significant as the uncertainties go down

$\Delta\Gamma_s$ from $B_s \to D_s^{(*)} D_s^{(*)}$

Motivation:

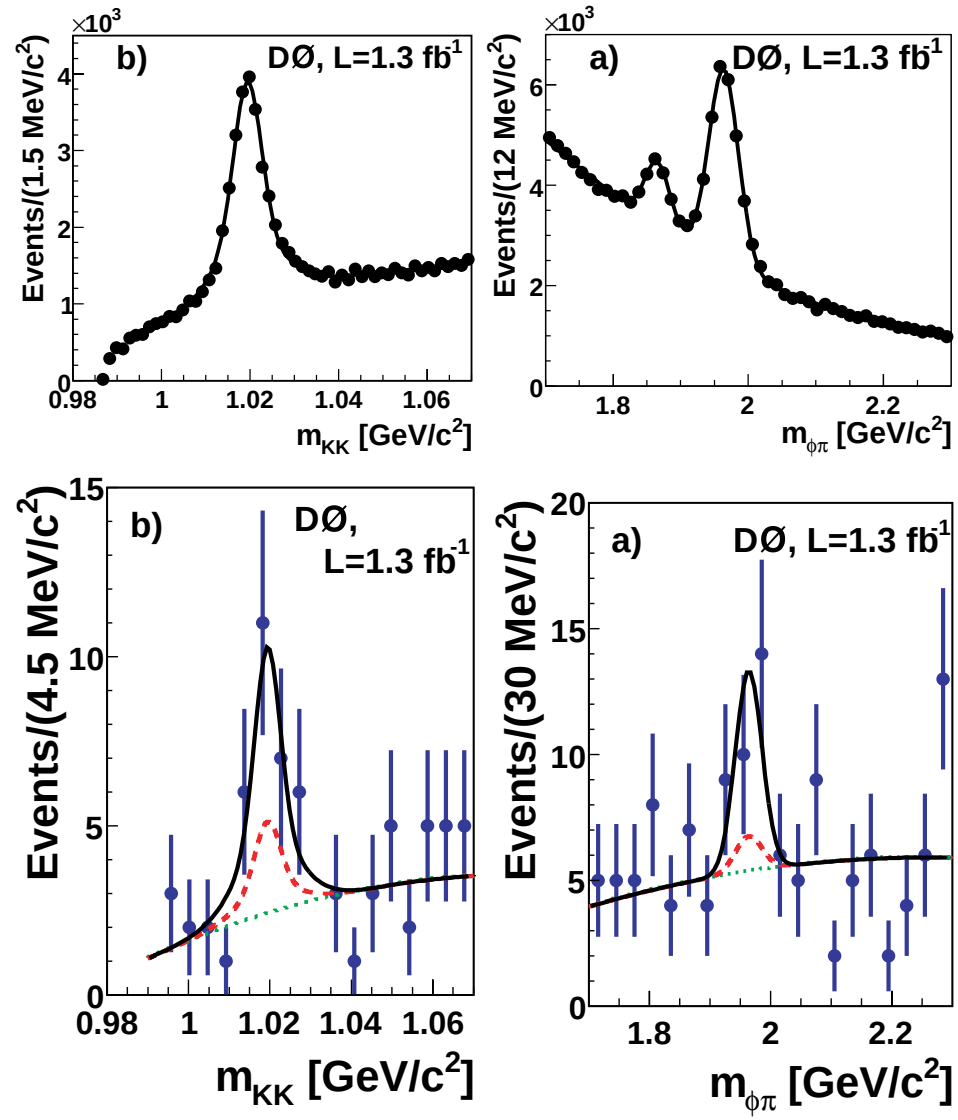
- Predominantly CP-even final state
  [Phys. Lett. B**316**, 567 (1993)]
- Can extract width difference between CP-even and CP-odd B_s states, $\Delta\Gamma_s^{CP}$, from branching ratio
- Test of SM

Analysis: [PRL**99**, 241801 (2007)]

- $B_s \to D_s^{(*)} D_s^{(*)}$, one $D_s \to \phi_{(1)}\pi$, another $D_s \to \phi_{(2)}\mu\nu$
- D_s and D_s^* are not distinguished
- Reconstruct $\phi_{(1)}$ (top left plot), then $\mu\phi_{(1)}\pi$ (top right)
- In this sample reconstruct $\phi_{(2)}$ (bottom left) and then add muon to $\phi_{(2)}$ (bottom right)
- Dashed line - disjoint production (bkg)

Results:

- $N(\mu\phi_{(2)}) = 13.4^{+6.6}_{-6.0}$
- Stat. significance 2.2σ
- $Br = 0.039^{+0.019}_{-0.017}(\text{stat.})^{+0.016}_{-0.015}(\text{syst.})$
- $\frac{\Delta\Gamma_s^{CP}}{\Gamma_s} = 0.079^{+0.038}_{-0.035}(\text{stat.})^{+0.031}_{-0.030}(\text{syst.})$
- Agrees with SM prediction: 0.127 ± 0.024
  [hep-ph/0612167]

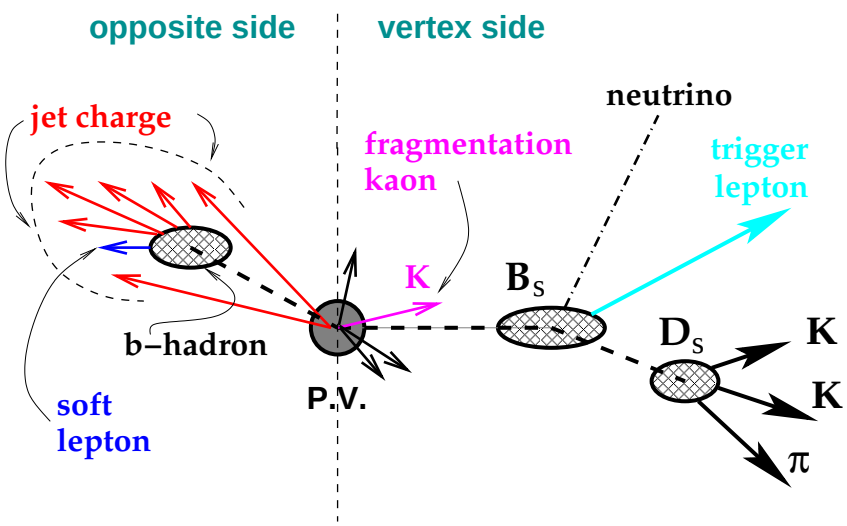


B_s Mixing

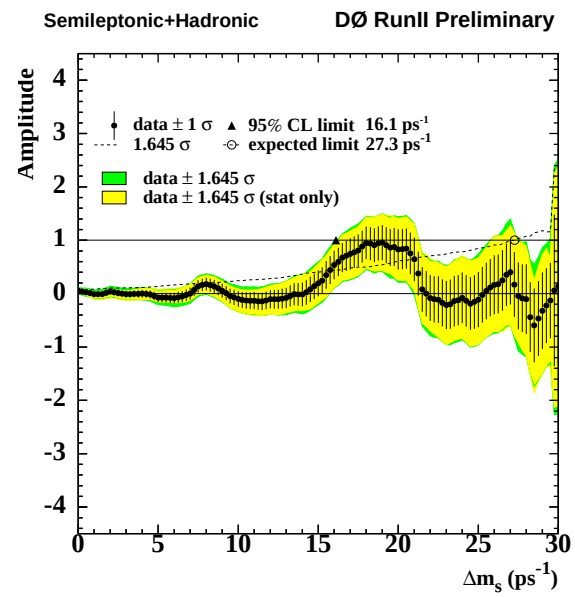
- Measurement of ΔM_s
- One needs to know
  1) B_s-flavor at decay (charges of decay products)
  2) B_s-flavor at production (B_s-flavor tagging)
  3) Proper decay length

$$Sig(\Delta M_s) \propto \sqrt{\varepsilon D^2}\frac{S}{\sqrt{S+B}}\exp^{-(\Delta M_s \sigma_{ct})^2/2}$$

- Flavor-tagging: high $\varepsilon D^2 = 4.0\%$



Semileptonic and hadronic modes:	N_{sig}
$B_s \to \mu\nu D_s X, D_s \to \phi\pi$	45K
$B_s \to e\nu D_s X, D_s \to \phi\pi$	1.7K
$B_s \to \mu\nu D_s X, D_s \to K^{*0}K$	18K
$B_s \to \mu\nu D_s X, D_s \to K_S^0 K$	0.6K
$B_s \to D_s \pi X, D_s \to \phi\pi$	0.25K



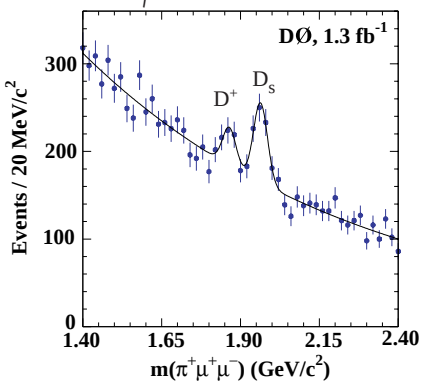
- $\Delta M_s = 18.56 \pm 0.87$(stat.)
- Significance 3.1σ
- DØ Conf. Note 5474

FCNC

$D \to \mu^+\mu^-\pi$ [hep-ex/0708.2094]

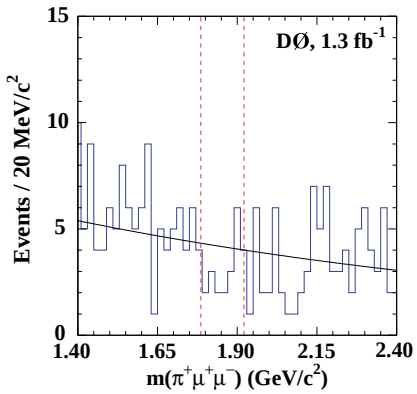
- SM forbids FCNC at tree-level $\Rightarrow$ sensitive to NP
- Search for $c \to u\mu^+\mu^-$:
  - $D/D_S \to \phi\pi, \phi \to \mu^+\mu^-$
  - use D^+ due to long lifetime and high production rate

$\phi\pi$ mass



- $N(D_S) = 254 \pm 36$
- $N(D) = 115 \pm 31$
- Comb. signif. 8σ
- Signif. D 4.1σ

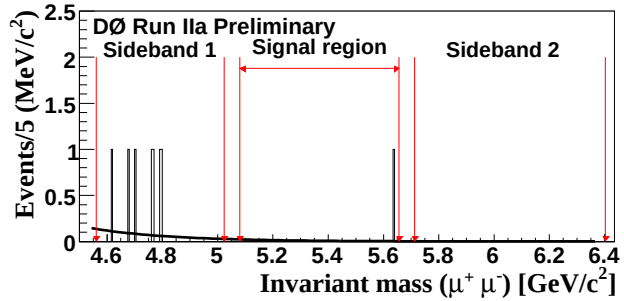
$\mu^+\mu^-\pi$ mass



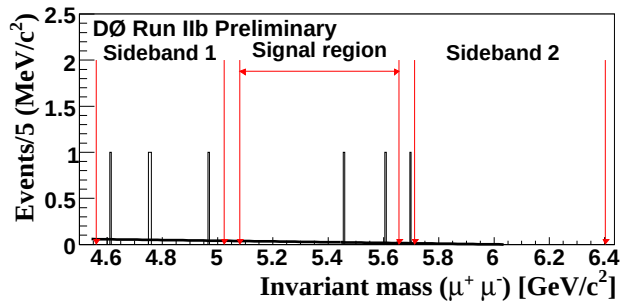
- Non-ϕ $m(\mu^+\mu^-)$
- Sig. reg.: 19 ev.
- Exp. bkg: 25.8 ± 4.6 events
- $Br(D \to \mu\pi^+\pi^-)$ $< 3.9 \cdot 10^{-6}$, at 90% CL
- 500x SM [PRD**66**, 014009 (2002)]
- 10x little Higgs [PRD**73**, 054026 (2006)]

$B_S \to \mu^+\mu^-$ [DØ Conf. Note 5344]

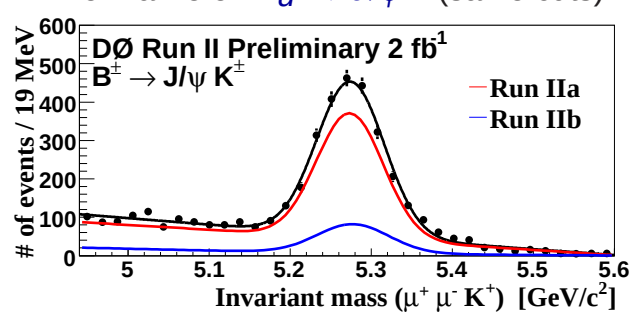
Run IIa: 1 ev. with 0.8 ± 0.2 exp. bkg



Run IIb: 2 ev. with 1.5 ± 0.3 exp. bkg



Normalize on $B_u \to J/\psi K$ (same cuts)



- $B(B_S \to \mu^+\mu^-) < 7.5 \times 10^{-8}$ at 90% CL
- SM: $Br = (3.42 \pm 0.54) \times 10^{-9}$ [Phys.Lett.B**566**, 115 (2003)]

Summary

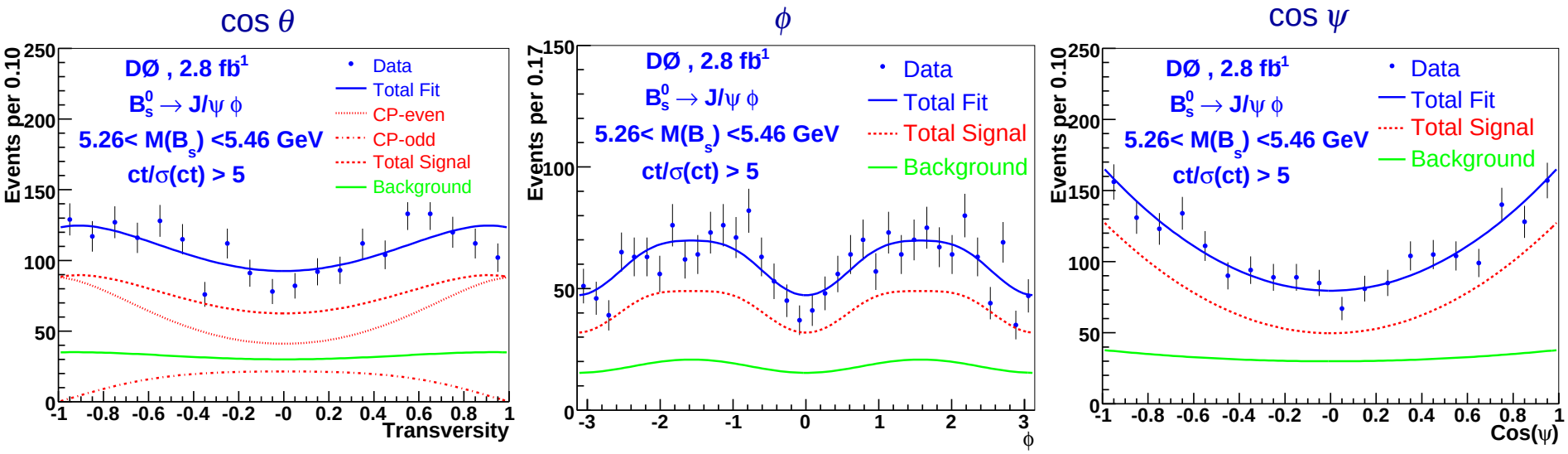
- Very rich B-physics program at DØ
- A few highlights shown today:
  - First observation of Ξ_b + other spectroscopy analyses
  - Precise Λ_b and B_c lifetime measurement
  - Search for direct CPV and CPV in mixing
  - Measurement of B_s parameters
  - Search for FCNC

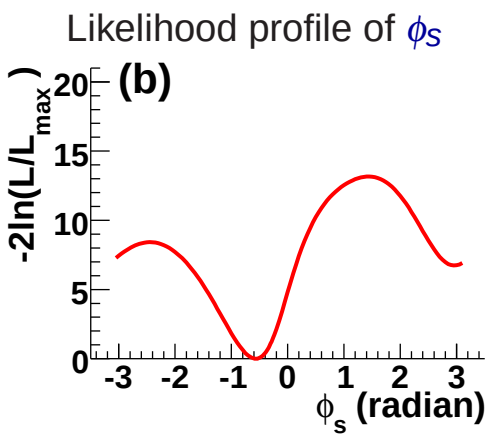
Exciting time to do *B*-physics at DØ !

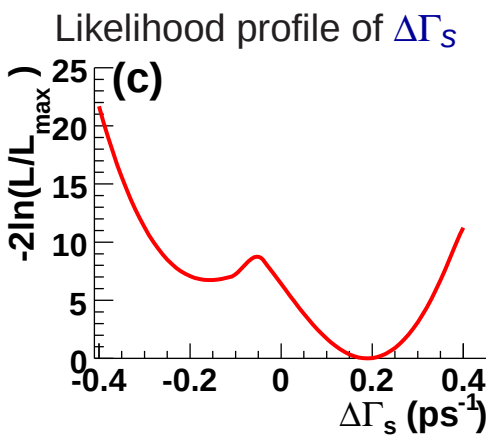
Backup

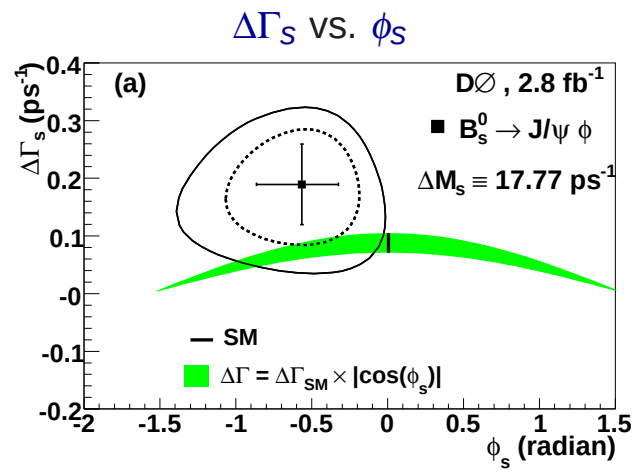
$\Delta\Gamma_s$ and ϕ_s from $B_s \to J/\psi\phi$

A few more plots:



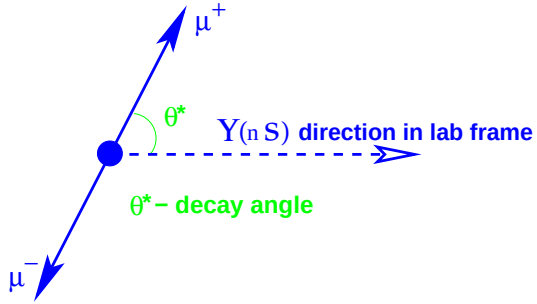






$\Upsilon(1S)$ and $\Upsilon(2S)$ Polarization

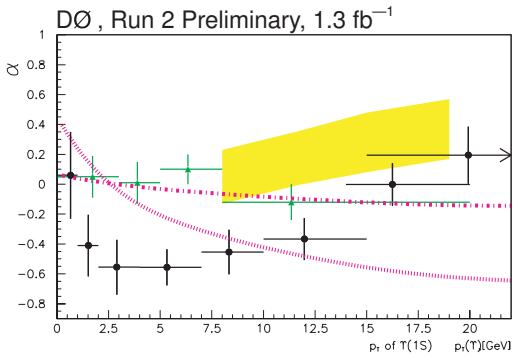
- Muons in decay $\Upsilon(nS) \to \mu^+\mu^-$ are distributed as $\frac{dN}{d(\cos\theta^*)} \propto 1 + \alpha\cos^2\theta^*$, where θ^* - decay angle, α - known function of $p_T(\Upsilon(nS))$



Analysis: [DØ Conf. Note 5089]

- Divide sample into 8 p_T bins and 10 $\cos\theta^*$ bins $\Rightarrow N(\Upsilon(1S))$ and $N(\Upsilon(2S)) \Rightarrow$ get $\alpha(p_T)$

$\alpha(p_T)$ for $\Upsilon(1S)$:

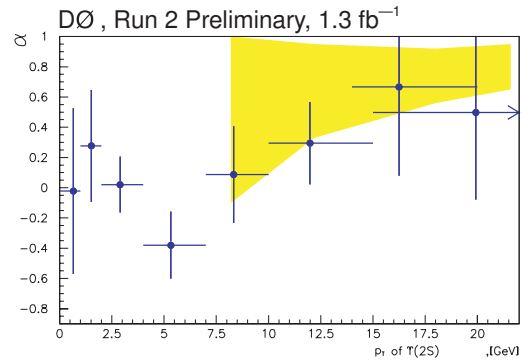


- Black/Green points: DØ /CDF data
- Yellow band: NRQCD prediction

[PRD **63**, 071501(R)(2001)]

- Magenta: two limiting cases: quark-spin conservation (lower) and full quark-spin depolarization (upper)

$\alpha(p_T)$ for $\Upsilon(2S)$:

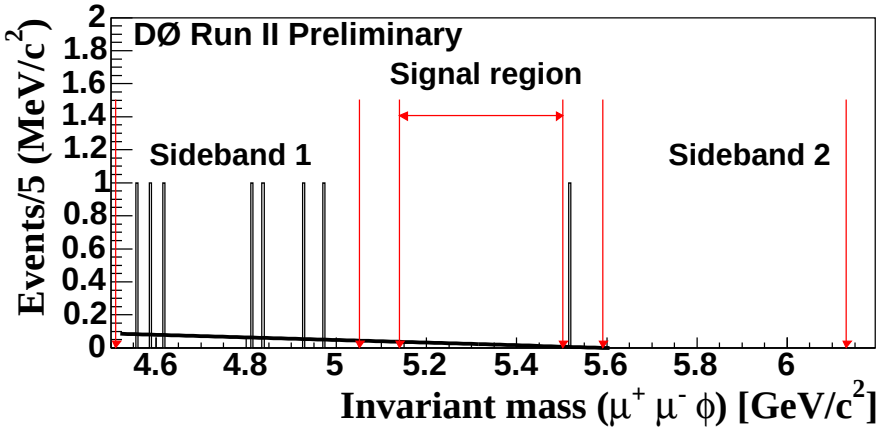


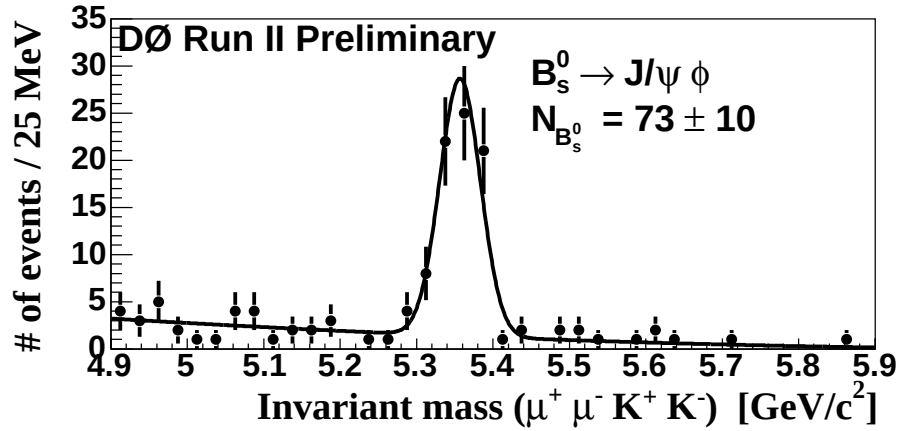
- Blue points - DØ data
- Yellow band - NRQCD prediction
- No discrepancy

$B_s \to \mu^+\mu^-\phi$

- Search for $b \to s\mu^+\mu^-$ FCNC
- Obtain 0 events in signal region
- Expected bkg 1.6 ± 0.4
- Normalize to $B_s \to J/\psi\phi$ (same cuts)
- $\frac{Br(B_S \to \mu^+\mu^-\phi)}{Br(B_S \to J/\psi\phi)} < 4.4 \times 10^{-3}$ [DØ Conf. Note 4862]
- $Br(B_s \to \mu^+\mu^-\phi) < 4.1 \times 10^{-6}$
- Consistent with SM prediction 1.6×10^{-6}

[J.Phys.**G29**, 1103 (2003)]

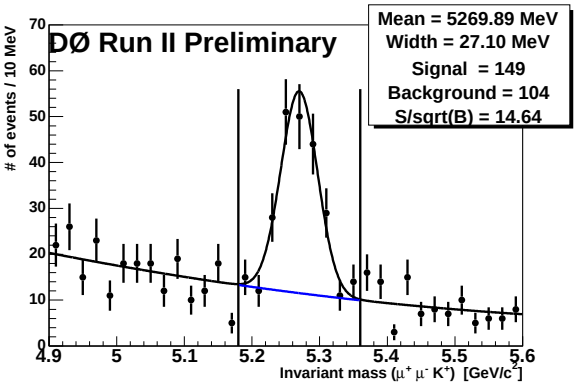




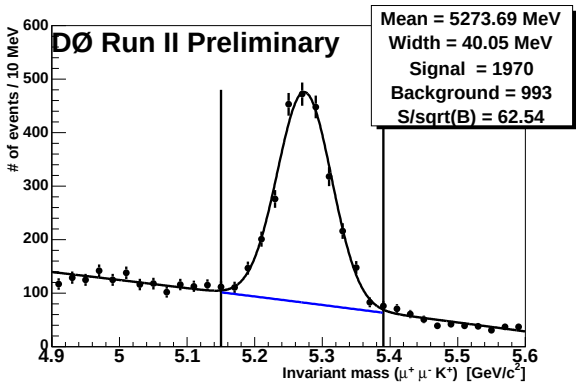
$B_s \to \psi(2S)\phi$

Similar to $B_s \to J/\psi\phi \Rightarrow$ also can be used for $\Delta\Gamma_{CP}$

Control channel: $B \to \psi(2S)K$ $(N = 149)$

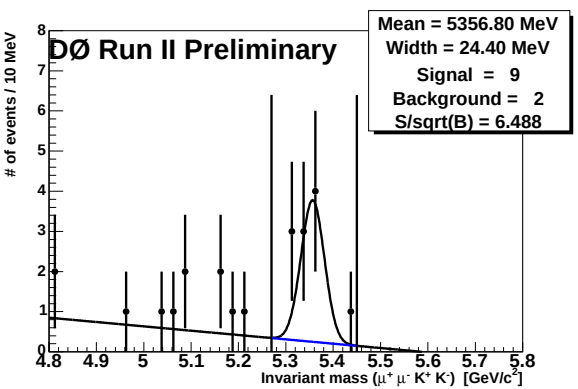


Normalize to $B \to J/\psi K$ $(N = 1970)$

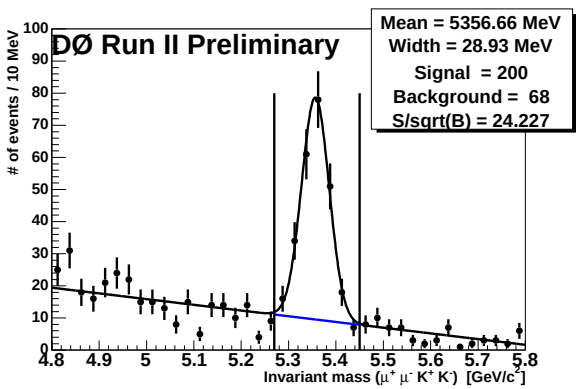


Reconstruct $B_s \to \psi(2S)\phi$

$(N = 9, \sqrt{-2\ln(\mathcal{L}_0/\mathcal{L}_{max})} = 3.89\sigma)$



Normalize to $B_s \to J/\psi\phi$ $(N = 200)$



$$\frac{B(B_s \to \psi(2S)\phi)}{B(B_s \to J/\psi\phi)} = 0.54 \pm 0.10 \pm 0.07 \pm 0.06(B)$$

Also, $\frac{B(B \to \psi(2S)K)}{B(B \to J/\psi K)} = 0.64 \pm 0.05 \pm 0.03 \pm 0.07(B)$

[DØ Conf. Note 4869]

Consistent with CDF [PRL**96**, 231801 (2006)] and BABAR [PRD**65**, 032001 (2002)]