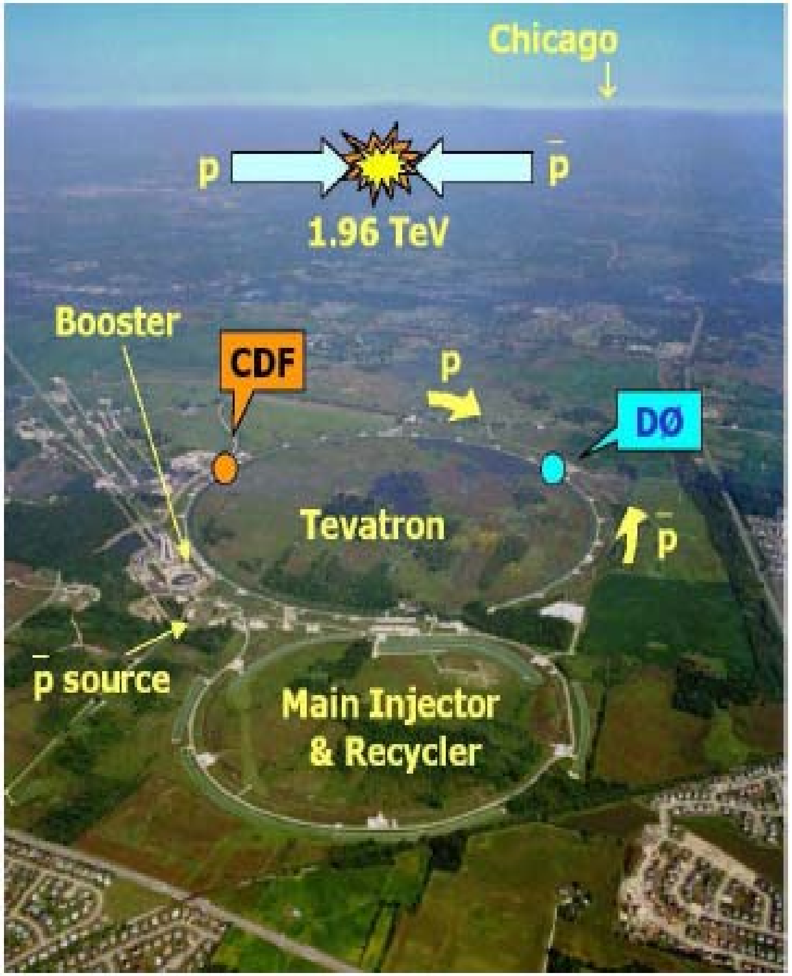
Semileptonic B decays at Tevatron

- Introduction
- Tevatron w/ CDF & DØ Detectors
- B decays into orbitally excited D**
- D** mass & width
- moment analysis
- B_s decays into orbitally excited D_s**
- Summary

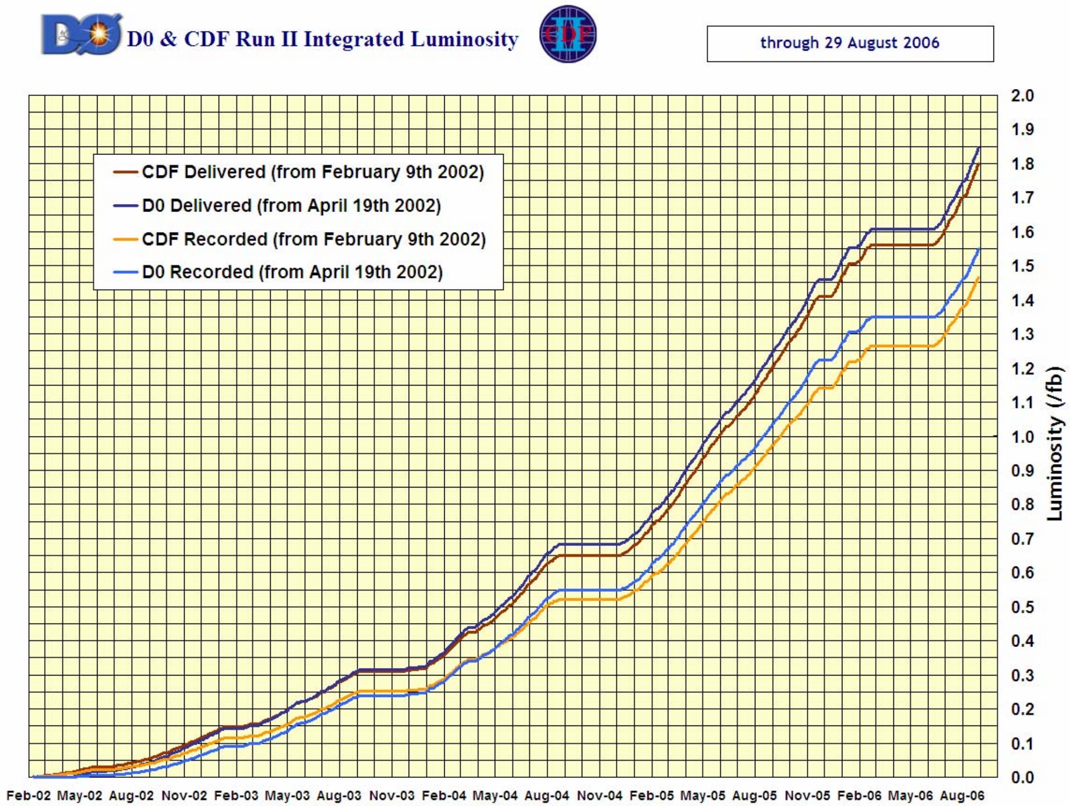


Frank Lehner
U Zurich/DESY

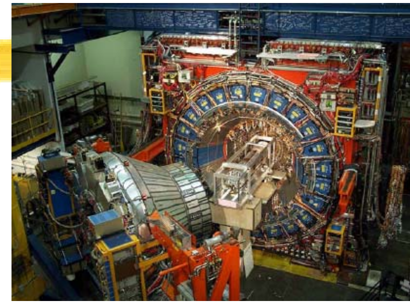
CKM 2006
Nagoya
Dec 11 - 16, 2006

Tevatron performance

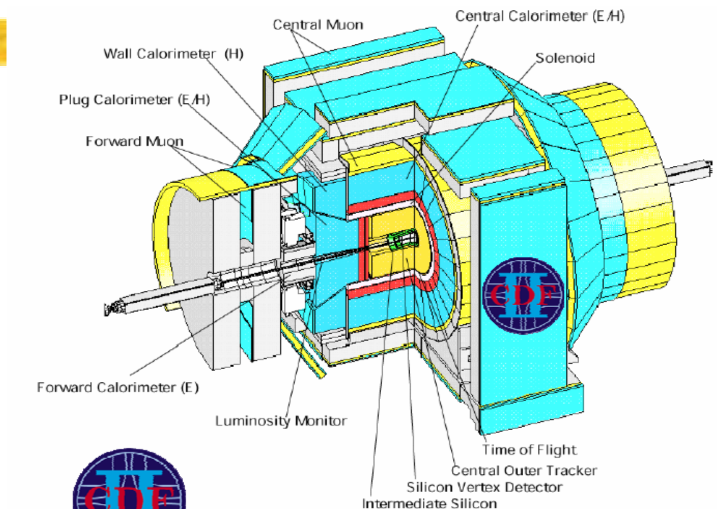
- excellent performance of Tevatron in 2006
- machine delivered more than 2fb^{-1} up to now !!
- recorded (DØ/CDF)
  - ~1.7 fb^{-1}
  - record (initial) luminosity of 2.3×10^{32} cm^{-2}/s
  - high data taking efficiency ~85%
- current Run II dataset reconstructed and under analysis
  - ~1400 pb^{-1}
  - compare with ~100 pb^{-1} Run I



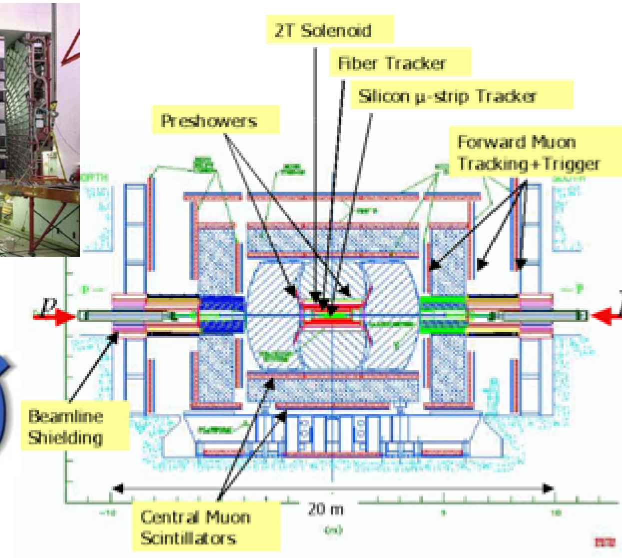
Detectors: CDF & DØ



- CDF
  - Silicon Tracker SVX
    - up to $|\eta|<2.0$
    - SVX fast r-ϕ readout for trigger
  - Drift Chamber
    - 96 layers in $|\eta|<1$
    - particle ID with dE/dx
    - r-ϕ readout for trigger
  - tracking immersed in Solenoid 1.4T



- DØ
  - 2T Solenoid
  - hermetic forward & central muon detectors, excellent coverage $|\eta|<2$
  - scintillating fiber tracker
  - four layer silicon detector
  - since summer 2006 new layer 0



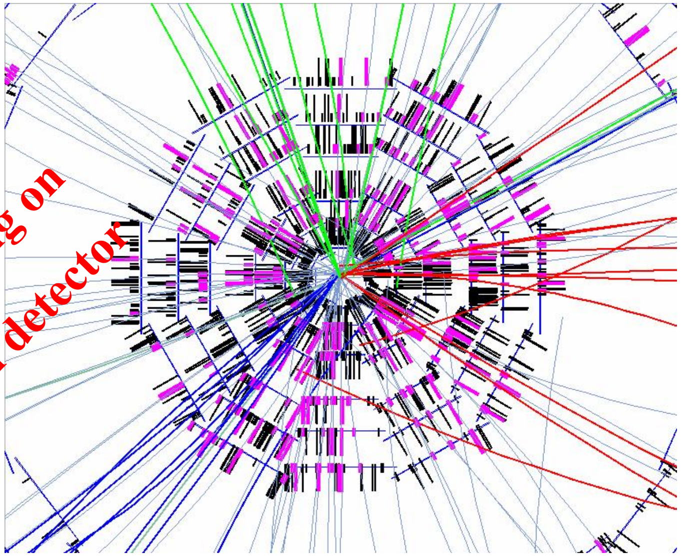
Charm and bottom production at Tevatron

- bb cross section orders of magnitude larger than at B-factories $\Upsilon(4S)$ or Z
- all kinds of b hadrons produced:
  - B_d, B_s, B_c, B^{**}, Λ_b, Σ_b, Ξ_b, ...
- charm cross section even higher, about 80-90% promptly produced
- However:
  - QCD background overwhelming, b-hadrons hidden in 10^3 larger background
  - events complicated, efficient trigger and reliable tracking necessary
- crucial for bottom and charm physics program:
  - good vertexing & tracking
  - triggers w/ large bandwidth, strong background rejection
  - muon system w/ good coverage

e.g., integrated cross sections for $|y|<1$:

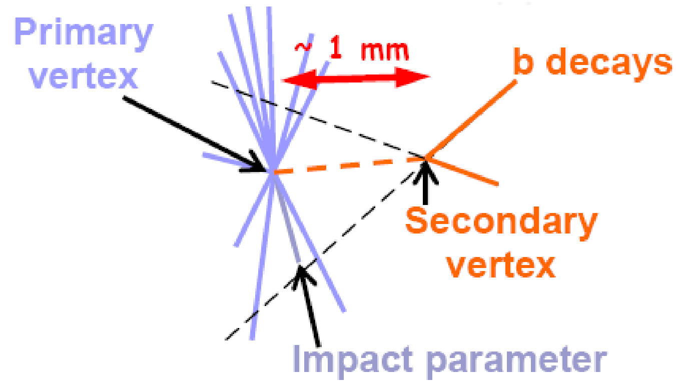
$\sigma(D^0, p_T \geq 5.5\ \mathrm{GeV}/c) \sim 13\ \mu b$

$\sigma(B^+, p_T \geq 6\ \mathrm{GeV}/c) \sim 4\ \mu b$



Triggers for bottom & charm physics

- "classical" triggers:
  - robust & quiet di- and single-lepton triggers, e.g. muon $p_t(\mu)$>1.5GeV
  - working horse for masses, lifetimes, x-section, rare decays etc. (J/Ψ modes down to p_t~0)
  - key to B physics program at DØ



- "advanced" triggers:
- using Si-vertex detectors - exploit long lifetime of heavy quarks
  - displaced track + leptons for semileptonic modes
  - two-track trigger (CDF) – all hadronic mode
    - two oppositely charged tracks with impact parameter
    - fully reconstructed hadronic modes, 2-body charmless B decays etc.
    - charm physics etc.

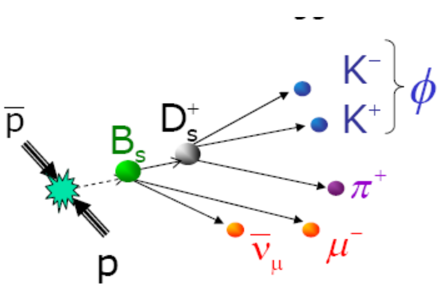
Decay length L_{xy}

$p_T(B) \geq 5$ GeV
$L_{xy} \geq 450$ μm

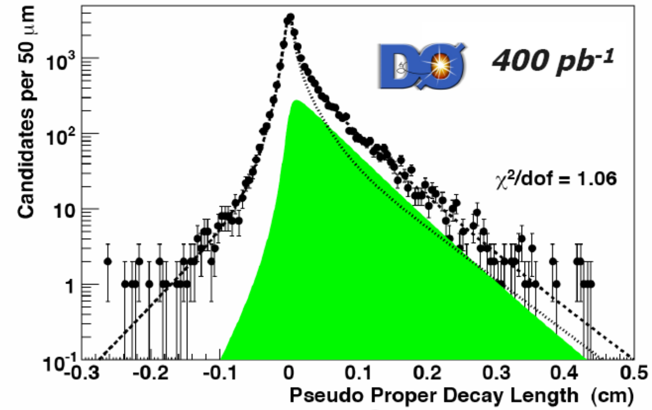
Semileptonic B decays

- Both detectors collect large samples on semileptonic decays of
  - $B^{\pm}$, B^0, B_s, B_c, Λ_b
- allows plethora of measurements
  - branching ratios, x-sections, fragmentation functions
  - lifetimes and lifetime ratios
  - mixing, CP violation, charge asymmetries etc.

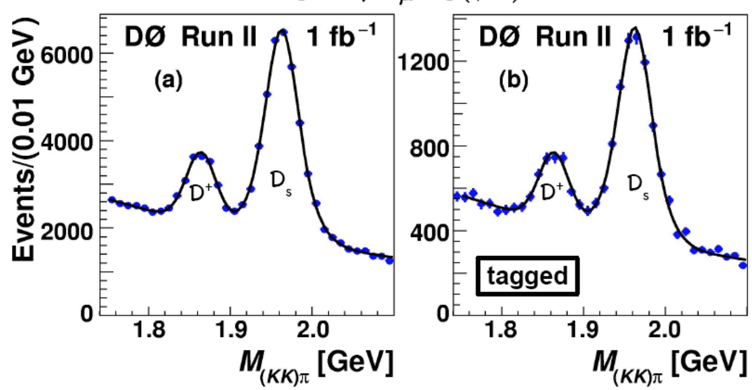
This talk is mainly on semileptonic $B_{(s)} \to D_{(s)}^{(**)} l\nu$ decays



$B_s \to D_s \mu\nu\, X$



$B_s \to \mu\nu_\mu D_s(\phi\pi)$

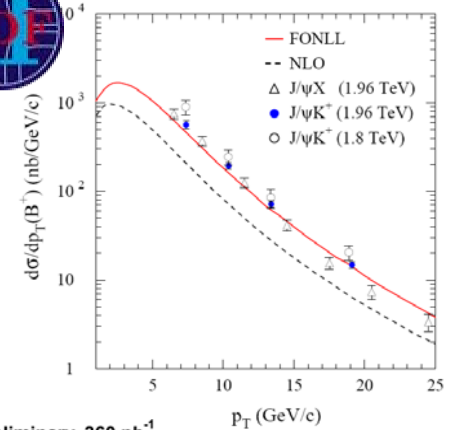


26,710±556 untagged D_s^-

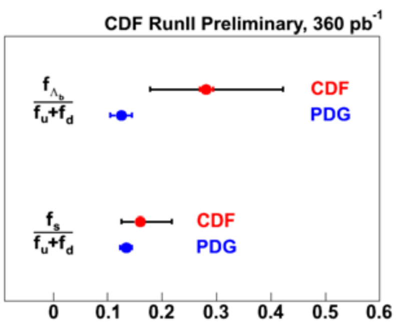
5,601±102 tagged D_s^-

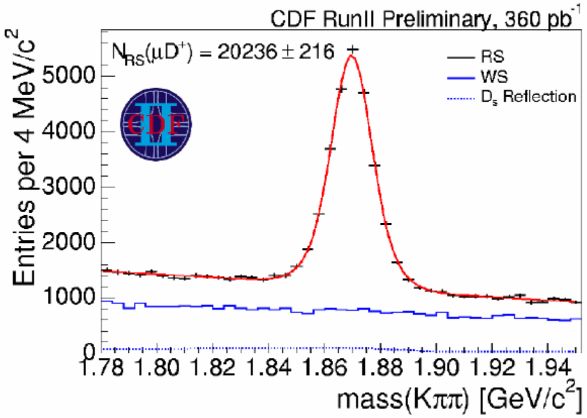
short glance at other results (that are not always shown...)

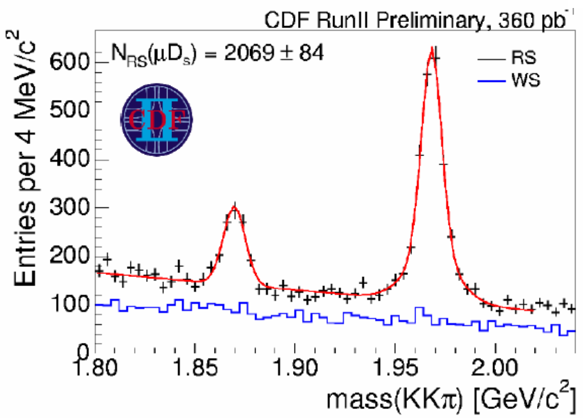
- measure absolute (& differential) cross section $B^{\pm} \rightarrow J/\Psi\ K^{\pm}$
- $\sigma_{B\pm}$ (pT>6 GeV/c, |y|<1)=(2.65±0.23)μb
- agrees with other measurement and with FONLL

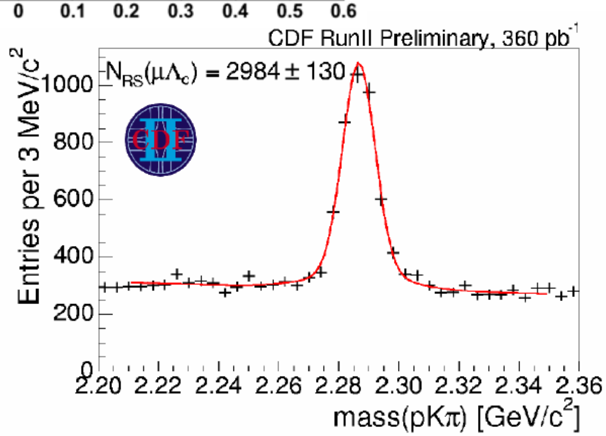


- fragmentation functions needed for measurement of ratios of BR
- Large sample lepton + charm, disentangle feed-down from D** using MC
- Need good understanding of reconstruction efficiencies (data/MC agreement)





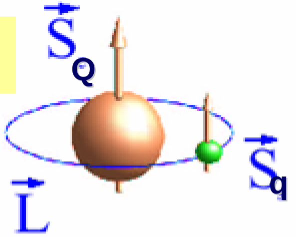




Orbitally excited D**

- orbitally excited states D** are P-wave excitation of charm quark and light (anti-) quark
- total angular momentum: $J=j_q+s_Q$ with $j_q=L+s_q$
- in heavy quark limit $m_Q \gg \Lambda_{QCD}$: spin s_Q of heavy quark decouples from other d.o.f => four P-wave states separate into mass degenerated pairs with $j_q=1/2$ and $j_q=3/2$
- systematic treatment in heavy quark effective theory: m_Q-dependent hyperfine splitting within each doublet, as well as average mass splitting between doublets

Hydrogen-like



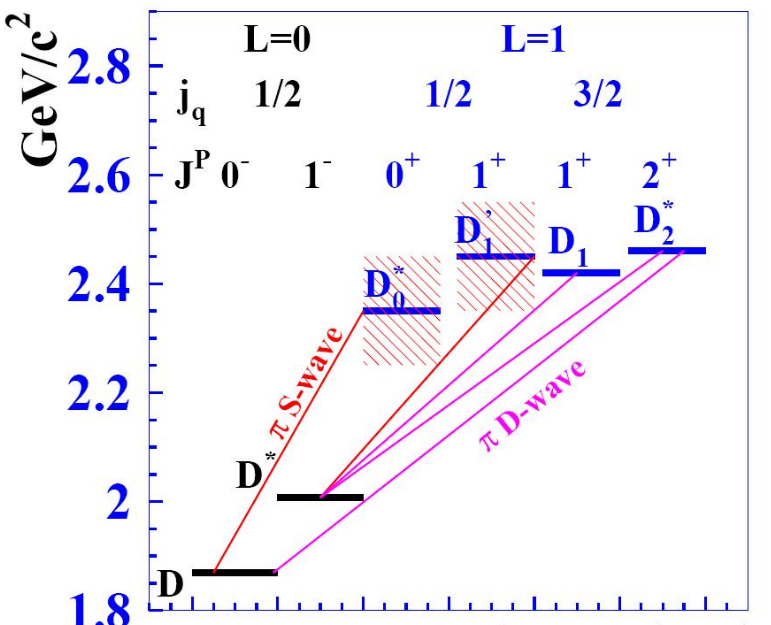


Fig. from hep-ex/0307021 (Belle)

Orbitally excited D**

- j_q=1/2 states (J^P=0+, 1+)
  - D_0* and D_1′ expected to decay in an overall S-wave configuration
  - broad width O(100) MeV
- j_q=3/2 states (J^P=1+, 2+)
  - D_1 and D_2* expected to decay in final states D*π with overall D-wave configuration
  - narrow width O(10) MeV
- ratio R=BR(B->D_2* lν)/BR(B->D_1 lν)
  - test for HQET
- narrow orbitally excited D** states have been seen by ARGUS, E687, FOCUS, HERA, CLEO, LEP-Exp., BELLE, CDF/D0

In the heavy charm limit ($\vec{j_q} = \vec{L} + \vec{s_q}$)

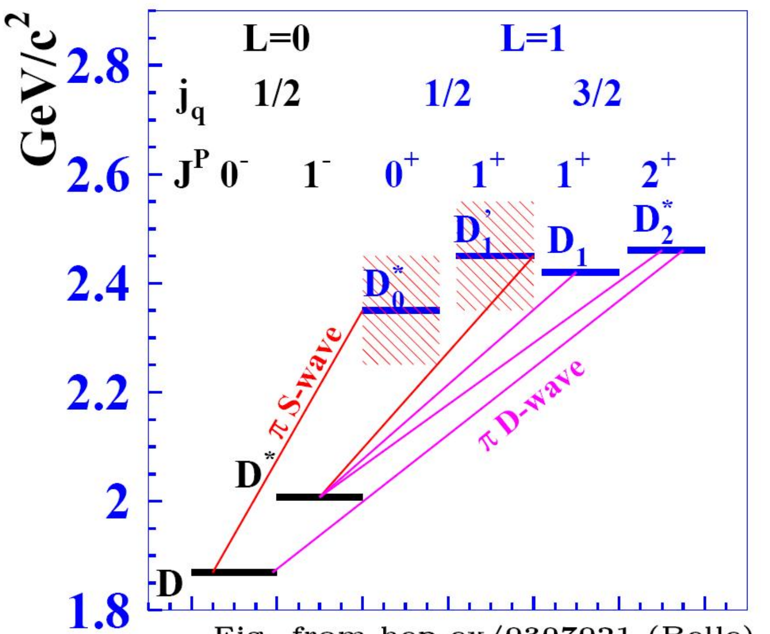
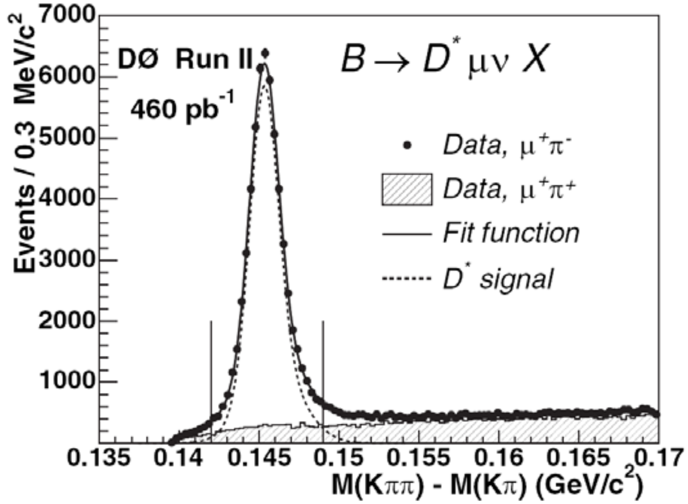


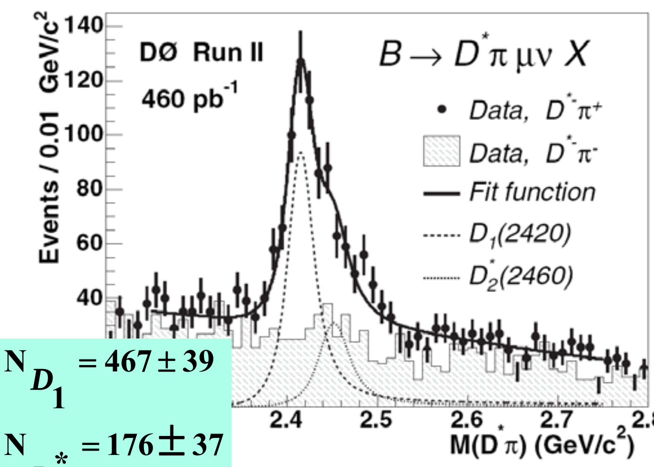
Fig. from hep-ex/0307021 (Belle)

DØ: BR(B->D**μνX)
CDF: D** mass and width

B -> D**μνX Signal Selection

- DØ: use 460 pb-1 of data to select B-> $D_{1,2}^*$ $\mu\nu$X events with suite of muon triggers
- decay chain: $D_{1,2}^*$ -> D^{*-} π^+ , D^{*-} -> D^0 π^- , D^0 -> $K\pi$
- selection
  - start with event sample μ D^0 + c.c. (~217k events)
  - combine with additional π track of different charge than μ to select D* (~55k events)
  - suppression of cc by proper decay length significance cuts of the B meson (31k D*- events)
  - in those events combine D* and π to D**
- interpret observed mass peak as two merged narrow D** states
  - fit signal with two relativistic Breit-Wigner functions convoluted with detector response
  - background as 2nd order polynomial. Fixed [PDG] $M(D_2^*)$-$M(D_1)$ and widths





$N_{D_1} = 467 \pm 39$

$N_{D_2^*} = 176 \pm 37$

Semileptonic BR(B->D**μνX)

- Normalizing to known BR(b -> $D^{*-}\mu^+\nu X$):

$$\mathcal{B}(\bar{b} \to B) \times \mathcal{B}(B \to \bar{D}^{**}\mu^+\nu_\mu X) \times \mathcal{B}(\bar{D}^{**} \to D^{*-}\pi^+) = \mathcal{B}(\bar{b} \to D^{*-}\ell^+\nu X)\frac{N_{D^{**}}}{N_{D^*}}\frac{1}{\epsilon_{D^{**}}};$$

$$\frac{\mathcal{B}(B \to \bar{D}_2^{*0}\mu^+\nu_\mu X) \times \mathcal{B}(\bar{D}_2^{*0} \to D^{*-}\pi^+)}{\mathcal{B}(B \to \bar{D}_1^0\mu^+\nu_\mu X) \times \mathcal{B}(\bar{D}_1^0 \to D^{*-}\pi^+)} = \frac{N_{D_2^*}}{N_{D_1}}\frac{\epsilon_{D_1}}{\epsilon_{D_2^*}}. = 0.39 \pm 0.09 \pm 0.12$$

- Assuming D_1 (D_2*) decays in D*π to 100% (30±6 %):

$$BR(B \to \overline{D}_1^0 l^+ \nu X) = (0.33 \pm 0.06)\%$$

differs from PDG value: (0.74±0.16)%

PRL95, 171803 (2005).

$$BR(B \to \overline{D}_2^{*0} l^+ \nu X) = (0.44 \pm 0.16)\%$$

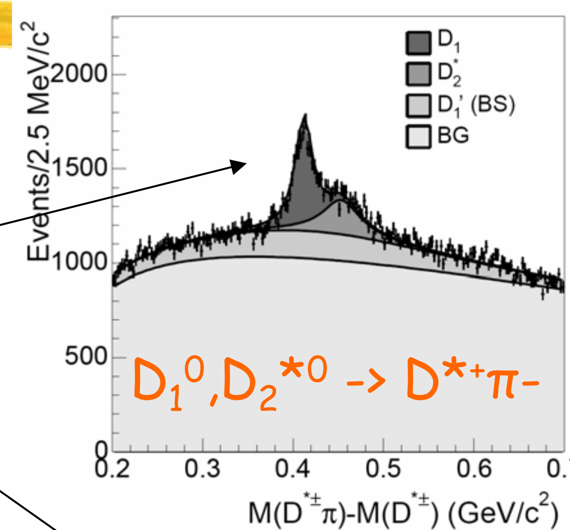
Consistent with PDG upper limit of 0.65%

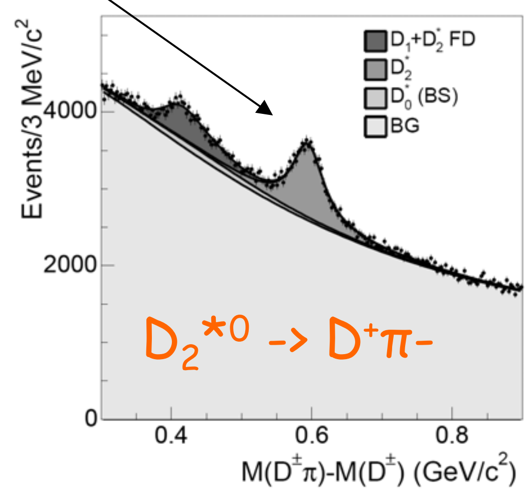
R=BR(B->D_2*lν)/BR(B->D_1lν)=1.31±0.29±0.47

R equal to 1.6 (HQET) if $m_c \to \infty$

Mass & Width D**

- CDF: 210 pb^{-1} of data collected with two-track trigger
- observe both, D_1^0 and D_2^{*0} decaying into $D^{*+}\pi^-$
- observe D_2^{*0} decaying into $D^+\pi^-$
  - corresponding D_1^0 decay forbidden by parity and angular momentum conservation
  - Feed-down decays D** -> $D^{*+}\pi^-$ with $D^{*+} \to D^+\pi^0$, where π^0 unobserved
- simultaneous fit to mass difference
  - signal terms for narrow D** (BW⊗resolution term)
  - Background term
  - broad state (BS) terms (included)





Mass and Width D**

CDF Results (adding PDG mass information D*, D⁺):

$M(D_1)=2421.7\pm0.7\pm0.6$ MeV

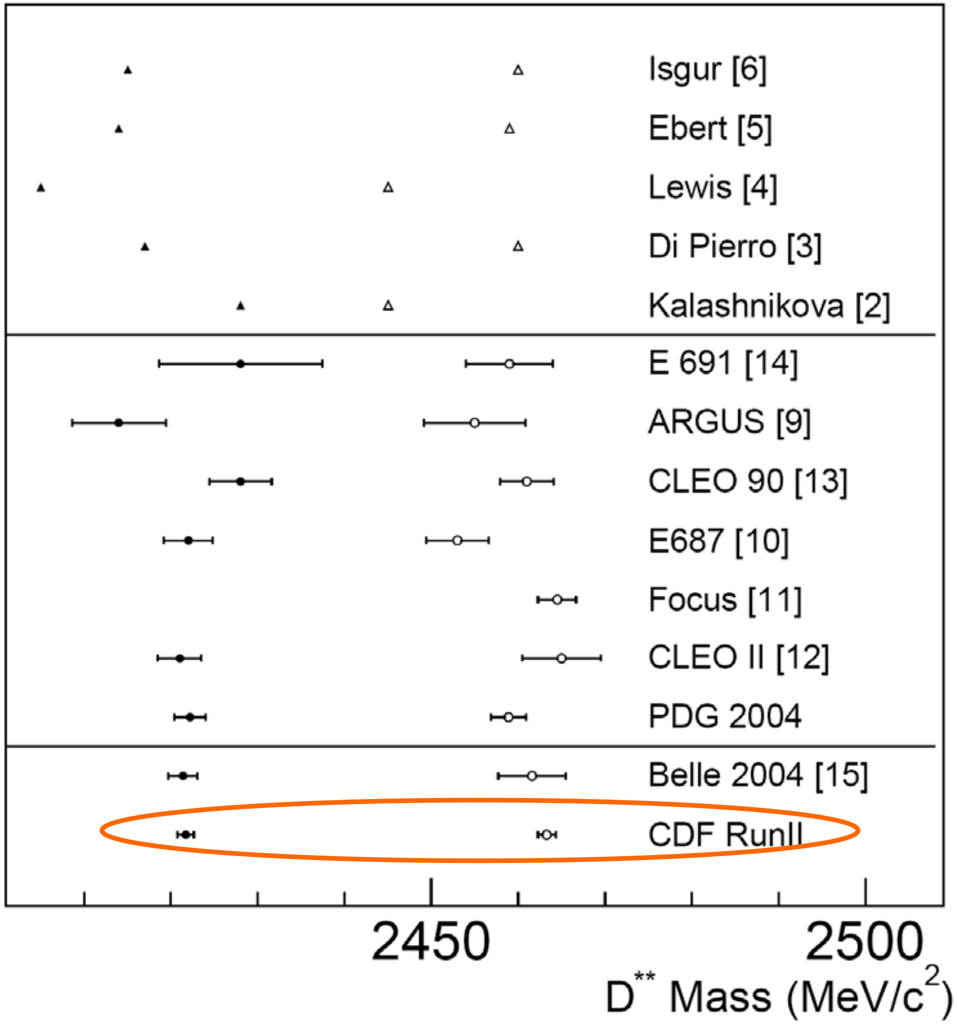
$\Gamma(D_1)=20.0\pm1.7\pm1.3$ MeV

$M(D_2^*)=2463.3\pm0.6\pm0.8$ MeV

$\Gamma(D_2^*)= 49.2\pm2.3\pm1.3$ MeV

best single mass measurement !!

PRD73 (2006) 051104



Moments of hadronic invariant mass distribution in semileptonic B decays

- V_{cb} determined from incl. semileptonic decay width into charm
- F_{theory} related through OPE in HQET: Expansion in inverse powers of m_B with free parameters
- same expansion holds for other inclusive observables such as recoil hadronic mass ($s_H = M^2_{Xc}$) distribution => define moments M_1, M_2
- $B^- \to X_c l^- \nu$ split in three contributions corresponding to $X_c = D^0, D^{*0}, D^{**0}$
  - D^0 and D^* well known, concentrate on recoil mass distribution in the D^{**} channel
- Strategy: measure D^{**0} spectrum, correct for background & acceptance
  - determine moments M_1, M_2 of D^{**}
  - use world-avarage values of Γ_0/Γ_{sl} (D^0), Γ_*/Γ_{sl} (D^{*0}) from PDG
  - extract expansion parameters

$$\Gamma_{sl}(b \to c\ell^-\overline{\nu}) = \frac{BR(b \to c\ell^-\overline{\nu}_\ell)}{\tau_b} = |V_{cb}|^2 \times F_{theory}$$

$$M_1 = \int_{s_H^{min}}^{s_H^{max}} ds_H \, (s_H - \overline{m}_D^2) \, \frac{1}{\Gamma_{sl}} \frac{d\Gamma_{sl}}{ds_H} \, ,$$

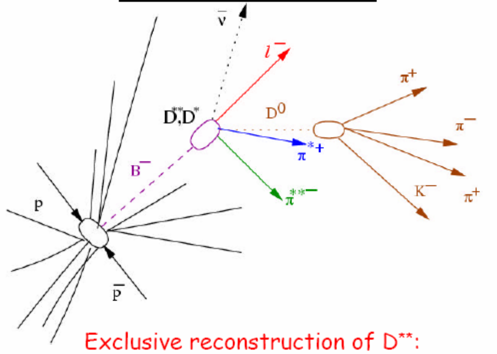
$$M_2 = \int_{s_H^{min}}^{s_H^{max}} ds_H \, (s_H - \langle s_H \rangle)^2 \, \frac{1}{\Gamma_{sl}} \frac{d\Gamma_{sl}}{ds_H} \, ,$$

assume that difference between inclusive semi-leptonic B- decays and exclusive $B^- \to D^{(*)0} l^- \nu$ decays is saturated by decays of type $B^- \to D^{(*)+} \pi^- l^- \nu$

Moments of hadronic invariant mass distribution in semileptonic B decays

- limited detection capabilities for neutrals
- $B^0 \to D^{**-} l^+ \nu$ -> leads to neutrals => ignore
- $B^- \to D^{**0} l^- \nu$ -> better
- must reconstruct all channels to get the D^{**0}, use isospin factors for neutral modes
- reconstruct lepton + $D^{(*)+}$, add π^{**} track

Event Topology



Exclusive reconstruction of D^{**}:

"D^+": $D^{**0} \to D^+ \pi^{**-}$
↳ $K^- \pi^+ \pi^+$ (Br=9.2%)

"D^{*+}": $D^{**0} \to D^{*+} \pi^{**-}$
↳ $D^0 \pi^{*+}$ (Br=67.7%)
↳ $K^- \pi^+$ (Br=3.8%)
↳ $K^- \pi^+ \pi^- \pi^+$ (Br=7.5%)
↳ $K^- \pi^+ \pi^0$ (Br=13.0%)

- most important backgrounds:
  - combinatorial background under $D^{(*)+}$ peaks – sideband subtracted
  - prompt tracks that fake π^{**} - use wrong sign sample $\pi^{**+} l^-$ to subtract
  - feed-down in signal from $D^{*+} \to D^+ \pi^0$ – subtracted using data, shape from $D^0\pi^-$ and rate~$\frac{1}{2}$x(isospin)x(eff)x(BR)

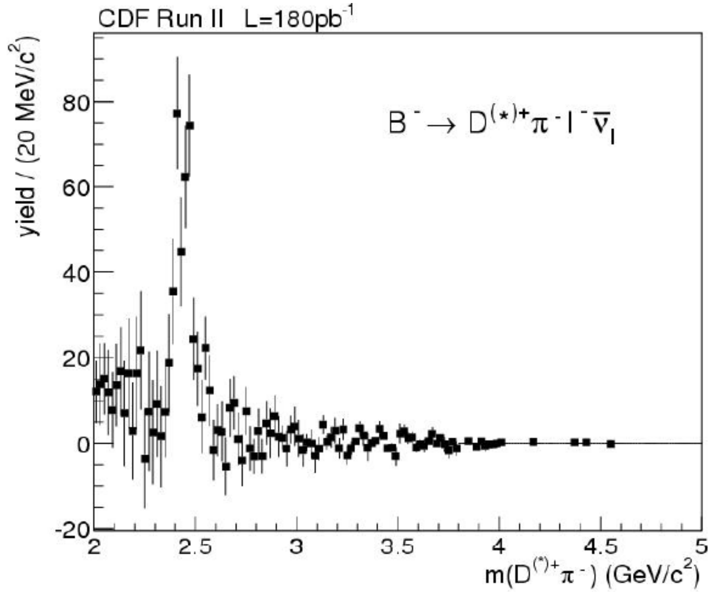
Moments of hadronic invariant mass distribution in semileptonic B decays

CDF, 180 pb-1
Phys.Rev. D71 (2005) 051103

- $D^{(*)+}\pi^-$ after background subtraction and efficiency and acceptance correction
- determine mean and variance of D** squared recoil mass
- calculate then full moments of hadronic mass-squared distribution by combining with D and D* world-averages

$$M_1 \equiv \langle M_{X_c}^2 \rangle - \overline{m}_D^2 = (0.467 \pm 0.038_{\rm stat} \pm 0.019_{\rm exp} \pm 0.065_{\rm BR})\ {\rm GeV}^2/c^4$$

$$M_2 \equiv \langle (M_{X_c}^2 - \langle M_{X_c}^2 \rangle)^2 \rangle = (1.05 \pm 0.26_{\rm stat} \pm 0.08_{\rm exp} \pm 0.10_{\rm BR})\ {\rm GeV}^4/c^8\ ,$$



69% positive correlation Between M_1 and M_2

allows then to extract non-perturbative expansion parameters Λ and λ_1 in pole- and 1S scheme

Moments of hadronic invariant mass distribution in semileptonic B decays

Pole mass scheme

$$\begin{aligned}\Lambda &= (0.397 \pm 0.078_{\text{stat}} \pm 0.027_{\text{exp}} \pm 0.064_{\text{BR}} \pm 0.058_{\text{theo}})\ \text{GeV} \\ \lambda_1 &= (-0.184 \pm 0.057_{\text{stat}} \pm 0.017_{\text{exp}} \pm 0.022_{\text{BR}} \pm 0.077_{\text{theo}})\ \text{GeV}^2\end{aligned}$$

1S mass scheme

$$\begin{aligned}m_b^{1S} &= (4.654 \pm 0.078_{\text{stat}} \pm 0.027_{\text{exp}} \pm 0.064_{\text{BR}} \pm 0.089_{\text{theo}})\ \text{GeV} \\ \lambda_1^{1S} &= (-0.277 \pm 0.049_{\text{stat}} \pm 0.017_{\text{exp}} \pm 0.022_{\text{BR}} \pm 0.094_{\text{theo}})\ \text{GeV}^2\end{aligned}$$

within HQET in agreement with previous measurements, accuracy compatible

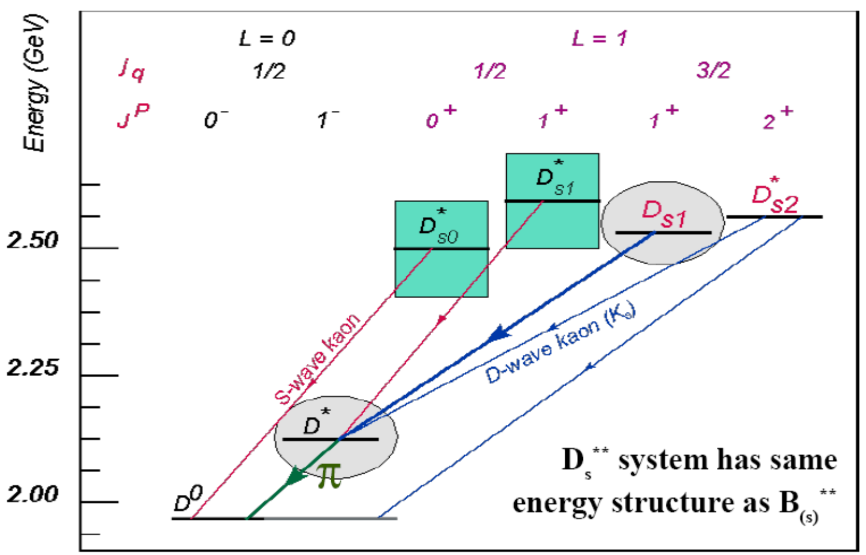
Error	Δm_1 (GeV^2/c^4)	Δm_2 (GeV^4/c^8)	ΔM_1 (GeV^2/c^4)	ΔM_2 (GeV^4/c^8)	$\Delta\bar{\Lambda}$ (GeV)	$\Delta\lambda_1$ (GeV^2)
Statistical	0.16	0.69	0.038	0.26	0.078	0.057
Total systematic	0.08	0.22	0.068	0.13	0.091	0.082
Mass resolution	0.02	0.13	0.005	0.04	0.012	0.009
Efficiency (data)	0.03	0.13	0.006	0.05	0.014	0.011
Efficiency and acceptance (MC)	0.06	0.05	0.016	0.03	0.017	0.006
Background scale	0.01	0.03	0.002	0.01	0.003	0.002
Background bias	0.02	0.10	0.004	0.03	0.006	0.006
Physics background	0.01	0.02	0.002	0.01	0.004	0.002
D^+/D^{**} branching ratios	0.01	0.02	0.002	0.01	0.004	0.002
D^+/D^{**} efficiency	0.02	0.03	0.004	0.01	0.005	0.002
B semileptonic branching ratios	—	—	0.065	0.10	0.064	0.022
ρ_1	—	—	—	—	0.041	0.069
T_i	—	—	—	—	0.032	0.031
α_s	—	—	—	—	0.018	0.007
m_b, m_c	—	—	—	—	0.001	0.008
Choice of p_l^* cut	—	—	—	—	0.019	0.009

CDF, 180 pb-1
PRD71 (2005) 051103

Semileptonic decays of B_s into D_s^{**}

- makes up a significant fraction of B_s semileptonic decays, hence important when
  - comparing inclusive and exclusive decays
  - extracting CKM elements
  - using decays in mixing analysis
- most of available phase space is at zero recoil -> useful for HQET tests
- important to develop more understanding in light of discoveries which don't agree with predictions DsJ(2317), DsJ(2460), DsJ(2632)-Selex …

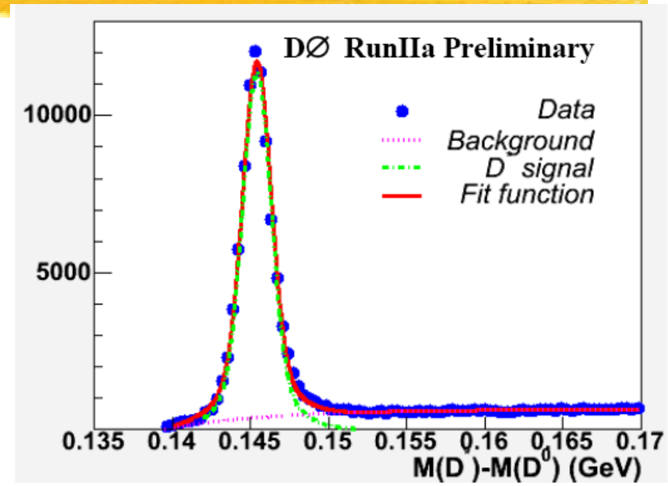
$$B_s \to D^+_{s1}(2536)\mu^-\nu$$
$$D^+_{s1} \to D^{+*}K_s(\pi^+\pi^-)$$
$$D^{+*} \to D^0\pi^+$$
$$D^0 \to K\pi$$



D_s^{**} system has same energy structure as $B_{(s)}^{**}$

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

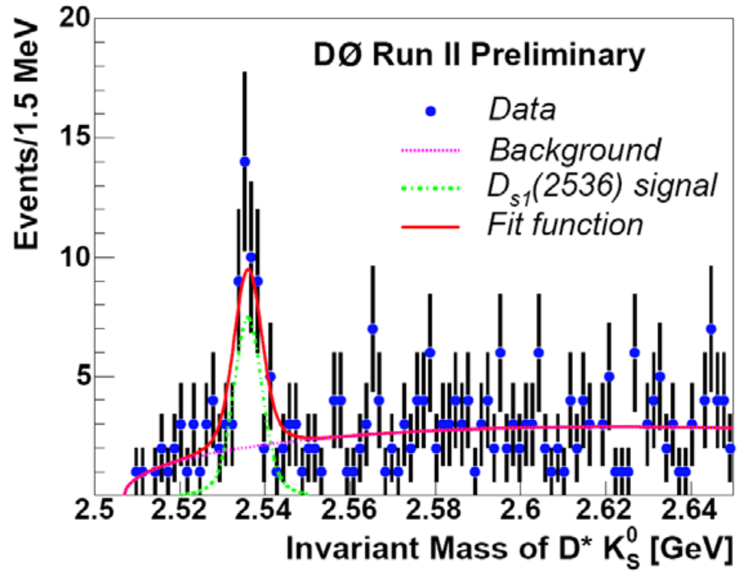
- use 1 fb^{-1} of DØ data, mostly single-muon triggered
- start with D* selection:
  - requiring D^0 and μ in event, additional π with $p_t(\pi)>0.18$ GeV
  - D*μ decay length significance $L/\sigma(L)>1$ to reduce ccbar contribution
  - signal fit: double gaussian; BG: exp.+polynomial+threshold cut
- D_s^{**} selection:
  - require D* and K_S with $p_t(K_S)>1$ GeV and K_S decay length > 0.5 cm
  - invariant mass μ-$D_s^{**} < m(B_s)$
  - signal fit: double gaussian; BG: exp.+polynomial & threshold cut



$N_{D^*} = 82130 \pm 463$
$N_{Ds^{**}} = 43.8 \pm 8.3$

D_{s1} mass:
$2535.7 \pm 0.5(\text{stat}) \pm 0.6(\text{sys})$

5.3σ significance



$B_s \to D_{s1}^-(2536)\,\mu^+\nu X$

- Determine Br normalizing to known value Br(b->D*μνX)=(2.75±0.19)%

$$f(\bar b \to B_s^0)\cdot Br(B_s^0 \to D_{s1}^-(2536)\mu^+\nu X)\cdot Br(D_{s1}^-(2536)\to D^{*-}K_S^0) = Br(\bar b \to D^{*-}\mu^+\nu X)\cdot \frac{N_{D_{s1}(2536)}}{N_{D^*\mu}}\cdot \frac{\epsilon(\bar b \to D^*\mu)}{\epsilon(B_s^0 \to D_{s1}\mu \to D^*\mu)}\cdot \frac{1}{\epsilon_{K_S^0}}$$

- $f(b \to B_s)$=0.107±0.011 is fraction that b (anti-)quark hadronizes to a Bs
- ε_{KS} efficiency in signal channel to additionally reconstruct & vertex K_S to form a D_s**, once D* and μ are found
- Use MC to look at specific major decays to D*μ, such as B_d->D*μν, B_d->D**μν, B^+->D^{**+} μν, B_s->D*μν to determine ε(b->D*μ)=(6.1±0.5)%
- MC reweighted to match $p_t(B_s)$ distribution in data

$B_s \to D_{s1}^-(2536)\,\mu^+\nu X$ results

- Putting the numbers together:
- $f(b \to B_s) \times BR(B_s \to D_{s1}^-(2536)\,\mu^+\nu X) \times BR(D_{s1}^- \to D^{*-} K_S) = (2.29 \pm 0.43 \pm 0.36) \times 10^{-4}$
- Using $f(b \to B_s) = 0.107 \pm 0.011$ and assuming $BR(D_{s1}^- \to D^{*-} K_S) = 0.25$ (isospin arguments):

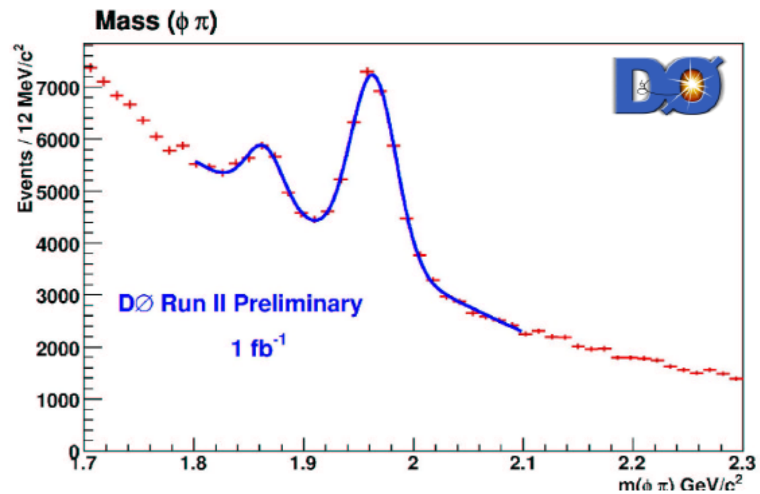
Source	$Br(B_s^0 \to D_{s1}(2536)\mu\nu)$
This Result	**(0.86±0.16(stat.)±0.13(syst)±0.09(prod. frac.))%**
ISGW2	0.53%
RQM	0.39%
HQET & QCD sum rules	0.195%

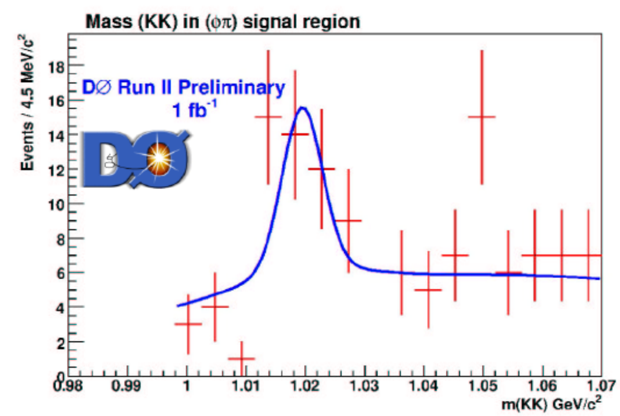
first BR-Measurement of a semileptonic $B_s \to D_s^{**}$ decay

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

- mainly CP-even eigenstate => measure $\Delta\Gamma_{CP}$
- reconstruct $D_s \to \Phi\pi$ and $D_s \to \Phi\mu\nu$, with $\Phi \to KK$
- start with μD_s ($D_s \to \Phi\pi$) sample and look then for additional $\Phi \to KK$ ($\mu D_s \Phi$)-sample
- ratio of efficiencies estimated using simulated events
- directly fit D_s mass distribution to extract
  - $N(\mu D_s)=15225\pm310$
  - $N(\mu D_s \Phi)=19.3\pm7.9$ unbinned likelihood
- normalize to $B_s \to D_s^* \mu\nu$

- BR($B_s \to D_s^{(*)} D_s^{(*)}$)=0.071±0.032±0.027





Dominant sources of systematic uncertainties: BR($Bs \to D_s^* \mu\nu$), MC p_t reweighting

Conclusions

- Tevatron is a B-factory complementary to e^+e^- annihilation machines
- semileptonic B decays into orbitally excited D**
  - DØ: BR's of B -> (D_1,D_2*) l ν X – significant improvement of knowledge for B -> D** decays
  - CDF: mass & width of D** - best mass measurements
- CDF: first analysis of hadronic moments for B->D** in difficult environment
- first BR measurement of $B_s \rightarrow D_{s1}(2536)\mu\nu$
- most results are statistics limited, using <1fb^{-1} in analysis

- Tevatron is steadily increasing statistics - many more exciting results to come

Evidence for Production of Single Top Quarks at DØ and A First Direct Measurement of $|V_{tb}|$

Dugan O'Neil
For the DØ Collaboration

Dec. 8, 2006

Simon Fraser University

Fermilab, Wine & Cheese Seminar, Dec 8 2006

SPARE

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

The effect of various sources of systematic error were measured:

Source		Systematic error
Normalizing Br	$Br(b \to D^*\mu X)$	6.9%
$N(D^*\mu)$	Signal Modeling	0.5%
	Background Modeling	1.3%
	ccbar Contribution	2.7%
$N(D_{s1}(2536))$	Signal Modeling	3.0%
	Background Modeling	4.6%
ε_{Ks}	MC Statistics	2.8%
	Semileptonic decay model	1.2%
	Weighting Procedure	2.4%
	Detector Modeling	4.0%
$R^{gen}{}_{D^*}$	MC stats, PDG Br, and f uncertainties	8.2%
	Weighting Procedure	7.4%
	Semileptonic Decay Model	0.9%