B Physics at the Tevatron

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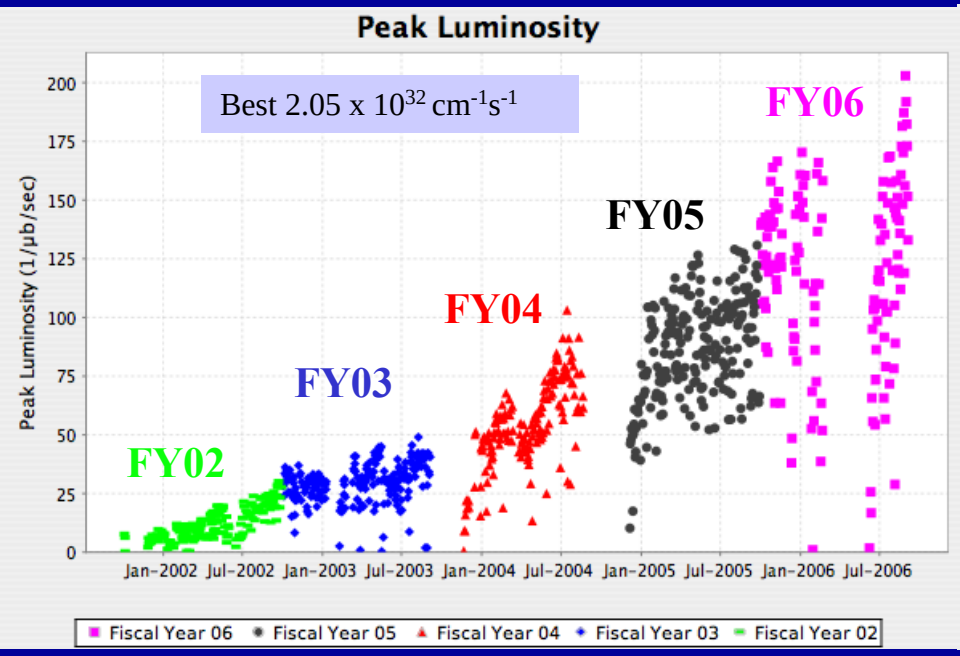
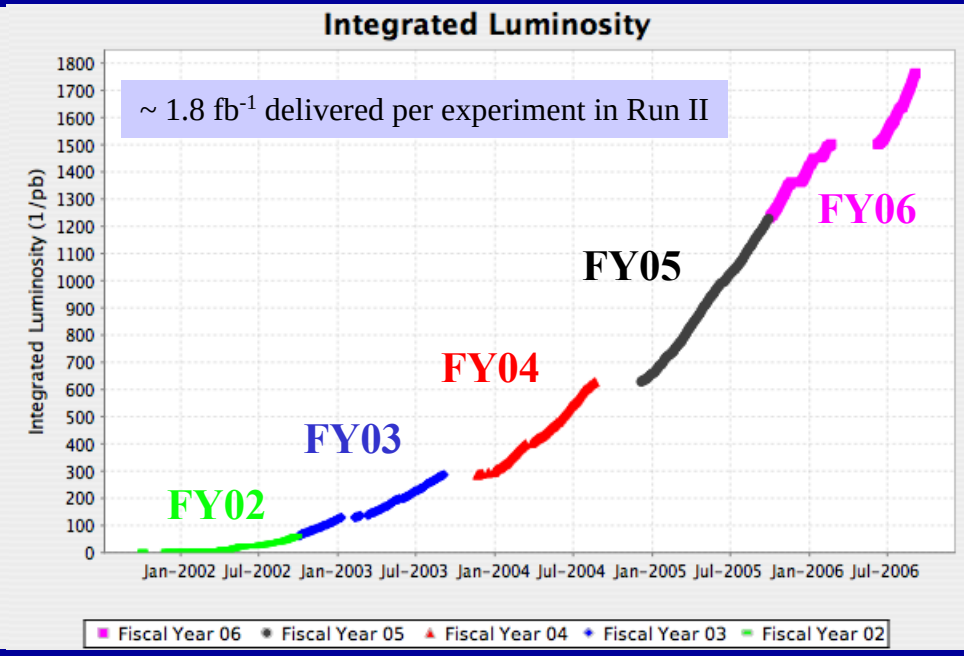
OUTLINE

- **Tevatron and the CDF and D0 detectors**
- **B^{+-}, B^0 (B^{**})**
  - Spectroscopy
  - Production
- **B_s (B_s^{**})**
  - Spectroscopy
  - Lifetime
  - B_s mixing (Δm_s, $\Delta\Gamma_s$, ϕ_s)
  - Branching fractions - Rare decays
- **B_c**
  - Mass
  - Lifetime
  - Branching fractions
- **b-baryons**
  - Spectroscopy
  - Lifetime
  - Branching fractions
- **Quarkonia**
  - Production
  - Polarization
- **Conclusion**

Tevatron Performance

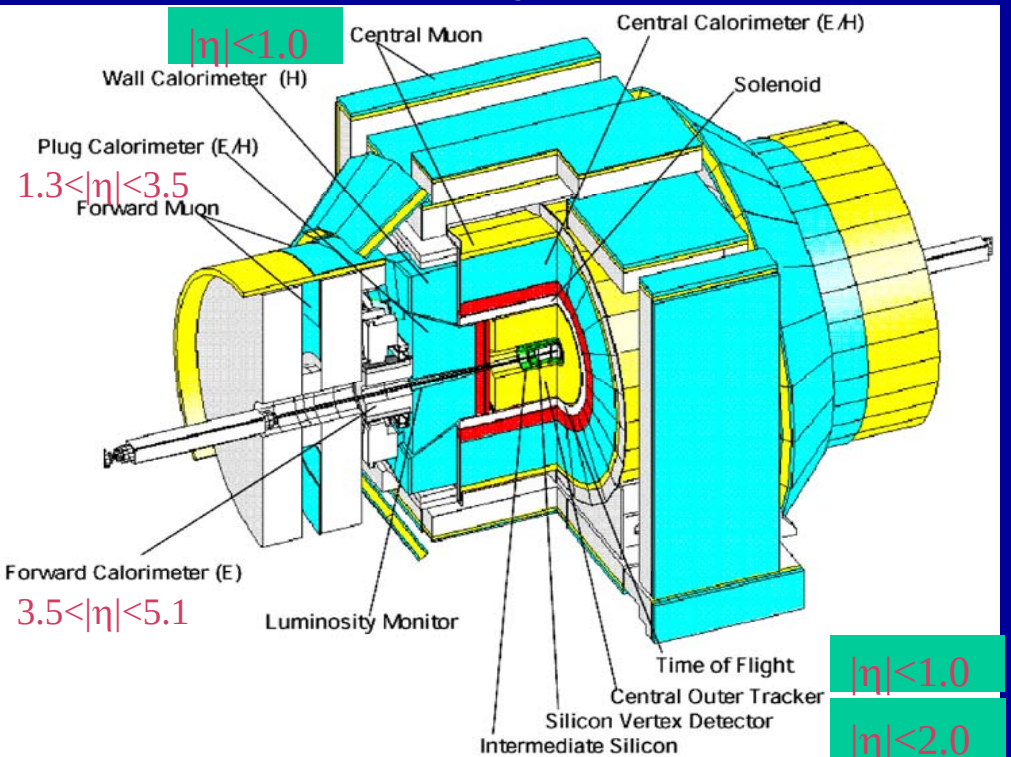
- **Tevatron (Run I 1992-96, ∫L dt = 110 pb-1):**
  - **p → ← pbar at √s = 1.8 TeV, 3.5 μs between collisions**
- **Tevatron (Run II 2002-Present, ∫L dt = ~1.8 fb-1):**
  - **p → ← pbar at √s = 1.96 TeV, 396 ns between collisions**

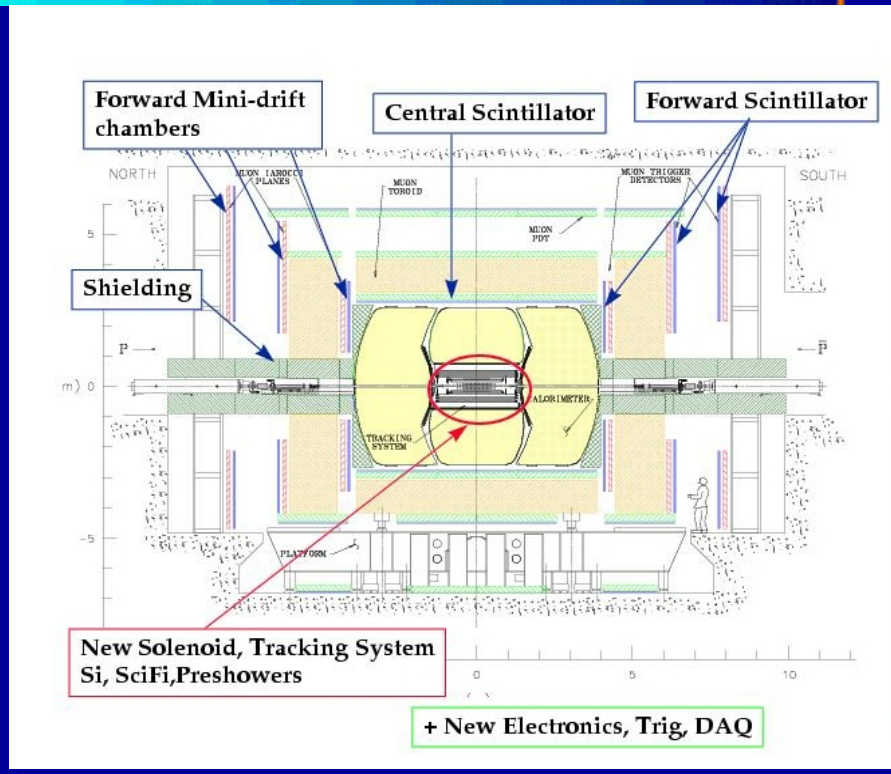




The CDF and D0 Detectors

- CDF:
  - Excellent mass resolution
  - Particle ID: dE/dx, TOF
  - Tracking triggers (Hadronic B's):
    - L1: Tracks
    - L2: Secondary vertex





- D0:
  - Excellent muon and tracking coverage
    - Tracking up to |η|<3
    - Muons up to |η|<2

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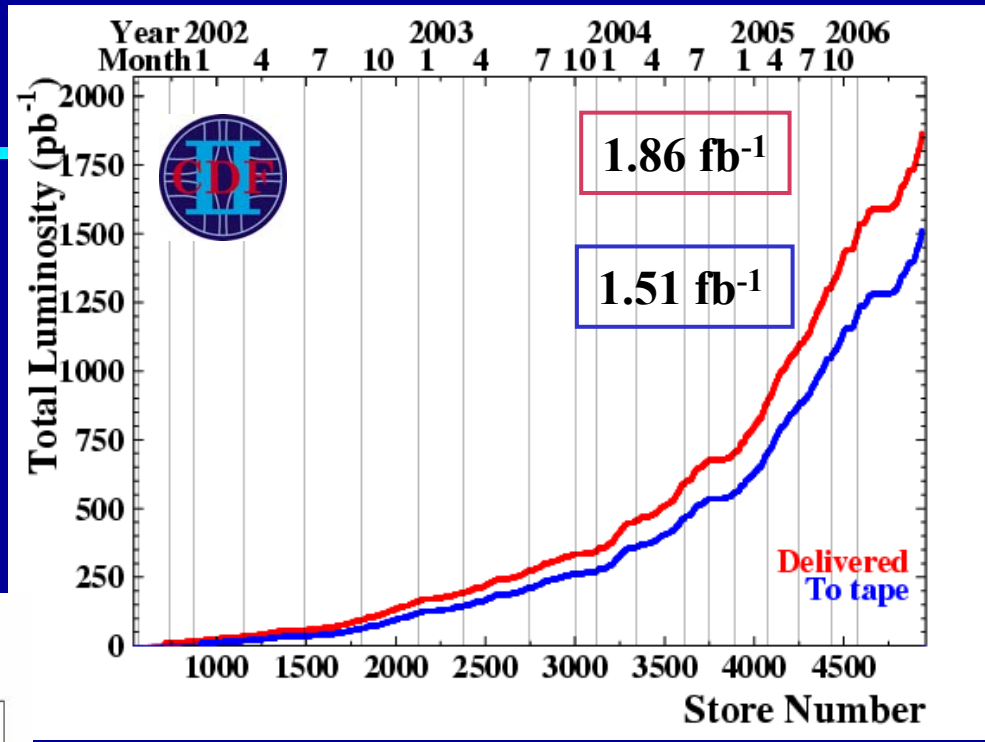
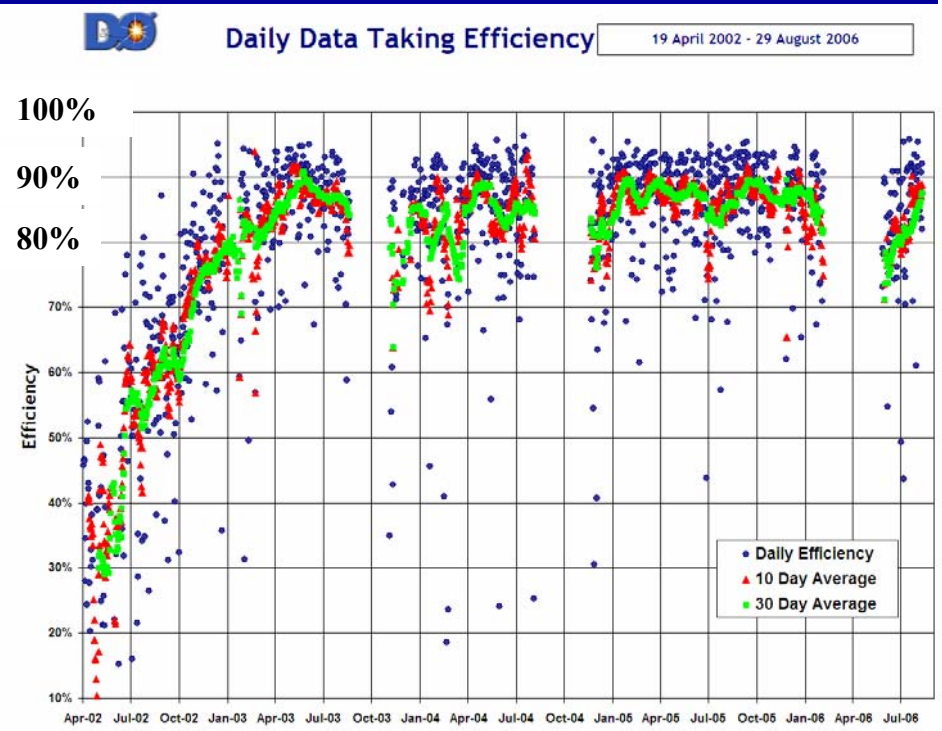
Data sets

- CDF/D0 use data collected in the period 2002-2006
  - D0:

    up to ~ 1.2 fb^{-1} used for B physics
  - CDF:

    up to ~ 1.1 fb^{-1} used for B physics





B-Physics cross sections and triggers

b Production cross section:

$$\sigma\left(p\bar{p} \to \bar{b}X\right) = \left(29.4 \pm 0.6_{(stat)} \pm 6.2_{(sys)}\right)\mu b$$

|y| < 1 CDF, PRD 71, 032001, (2005)

Inelastic cross section: ≈ 60 mb→ factor 1/1000 trigger.

Compare with *b*-factories: σ is 10^3 higher.

L is 1.8 fb^{-1} (TeVatron) vs. a few hundred fb^{-1} (*Y*(4S))

	σ (μb)	$\mathcal{L}$ cm^{-2} s^{-1}	Integrated L	*b*-events
Tevatron	29	2.05×10^{32}	1.8 $fb^{-1} \times 2$	52×10^9

Trigger crucial point:

- 2 μ (e) from J/ψ **CDF**, **D0**
- soft lepton, (soft lepton+non prompt track) **CDF**, **D0**
- 2 non-prompt tracks **CDF**, **D0 under commissioning**

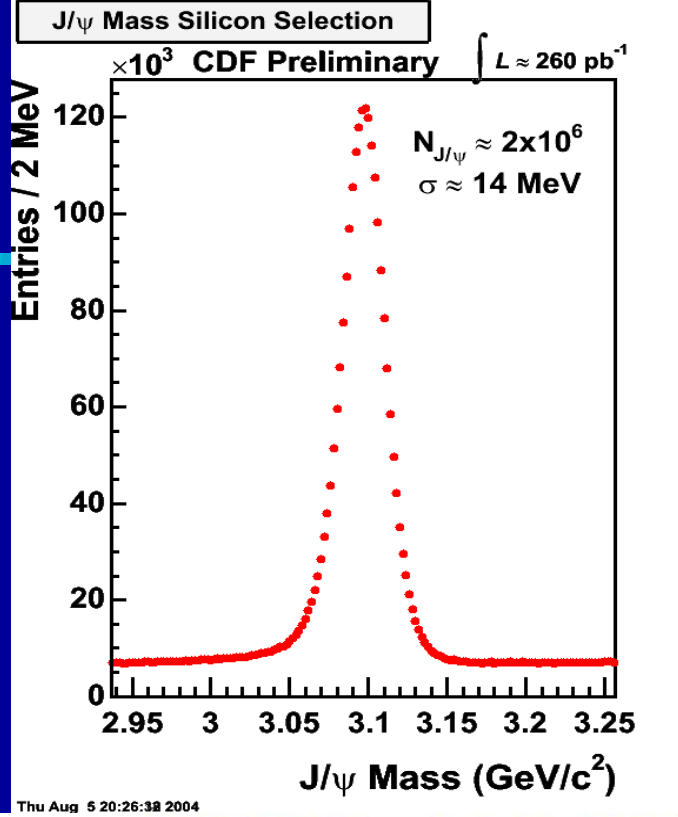
B-Physics Data samples

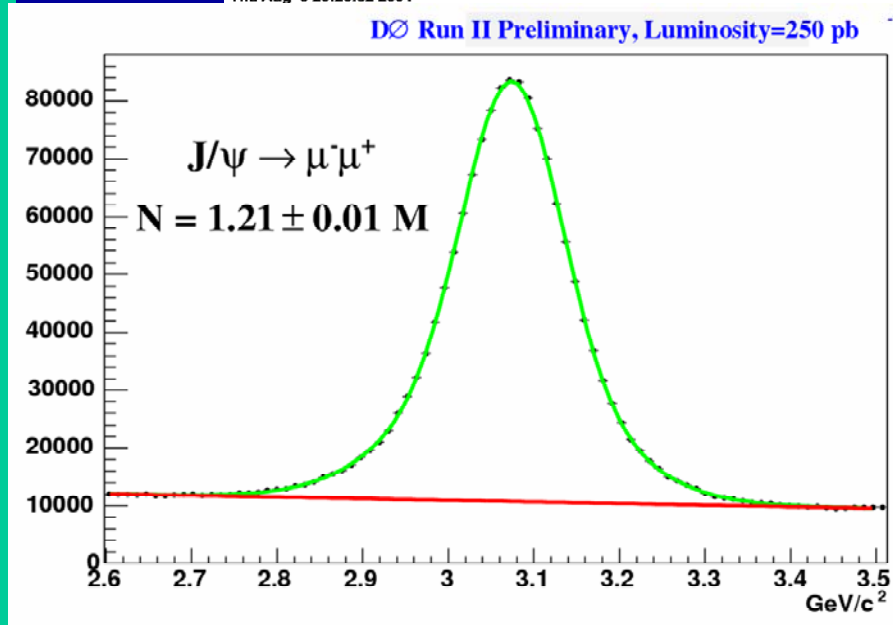
- J/ψ samples:
  - ~ 10 Million! ~ 20% are from B's
  - Reconstruct exclusive

    $B/\Lambda_B \rightarrow J/\psi\ K/\Lambda^0$ modes
- Semi-leptonic B → D lν X samples:
  - ~1 M events with fully reconstructed D
    - D0 has larger muon acceptance
    - CDF lowers lepton trigger pt by requiring additional displaced track
- Fully hadronic decays (CDF only)
  - ~ 100 K events fully reconstructed B's
  - Requires trigger on secondary vertex (SVT)

IP resolution: ~ 50 mm

33mm beam size + 35mm SVT



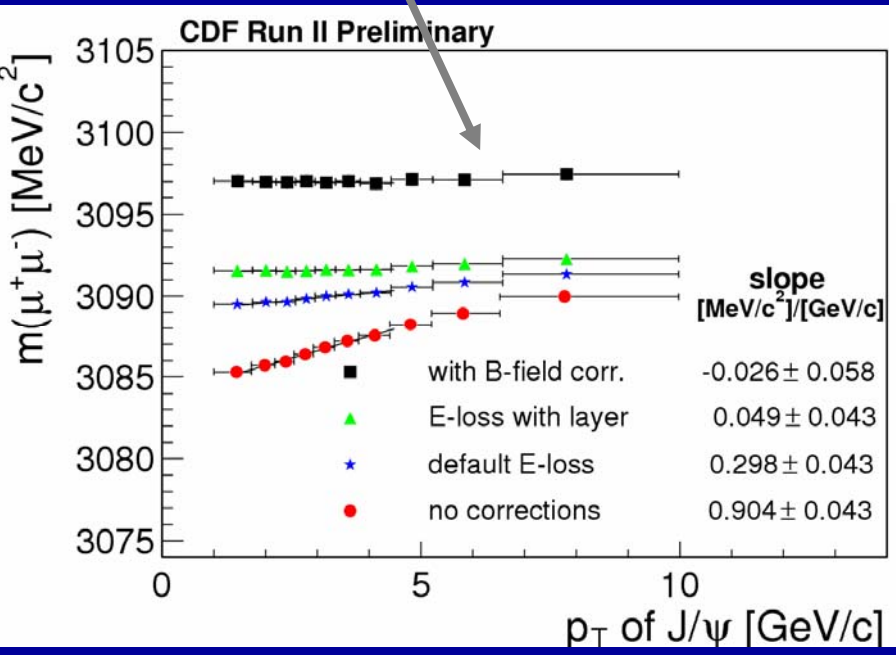


$B^{\pm}$, B^{0} (B^{**}) mesons

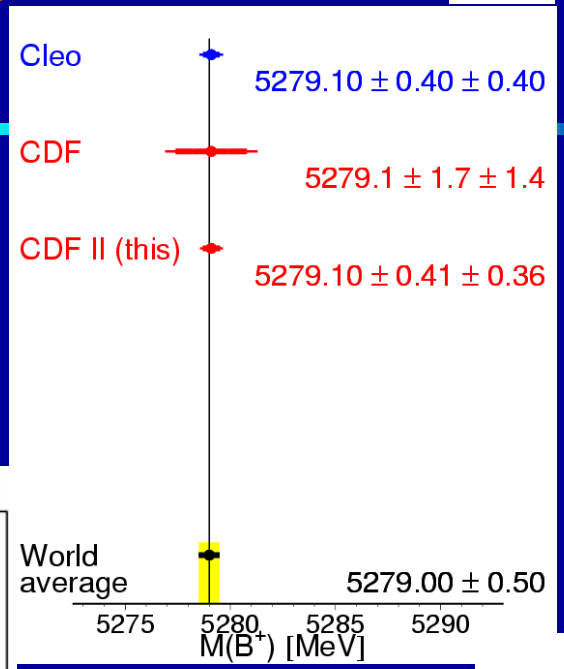
$B^{\pm}$, B^{0} (B^{**}) mesons

B hadron masses

- B mass determination
  - Use clean J/ψK modes
  - Accurate tuning of momentum scale with large J/ψ sample

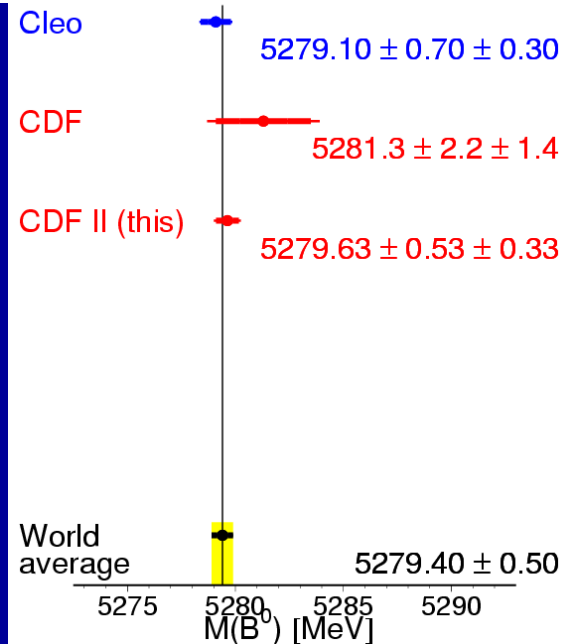


B⁺



PRL 96, 202001 2006

B⁰

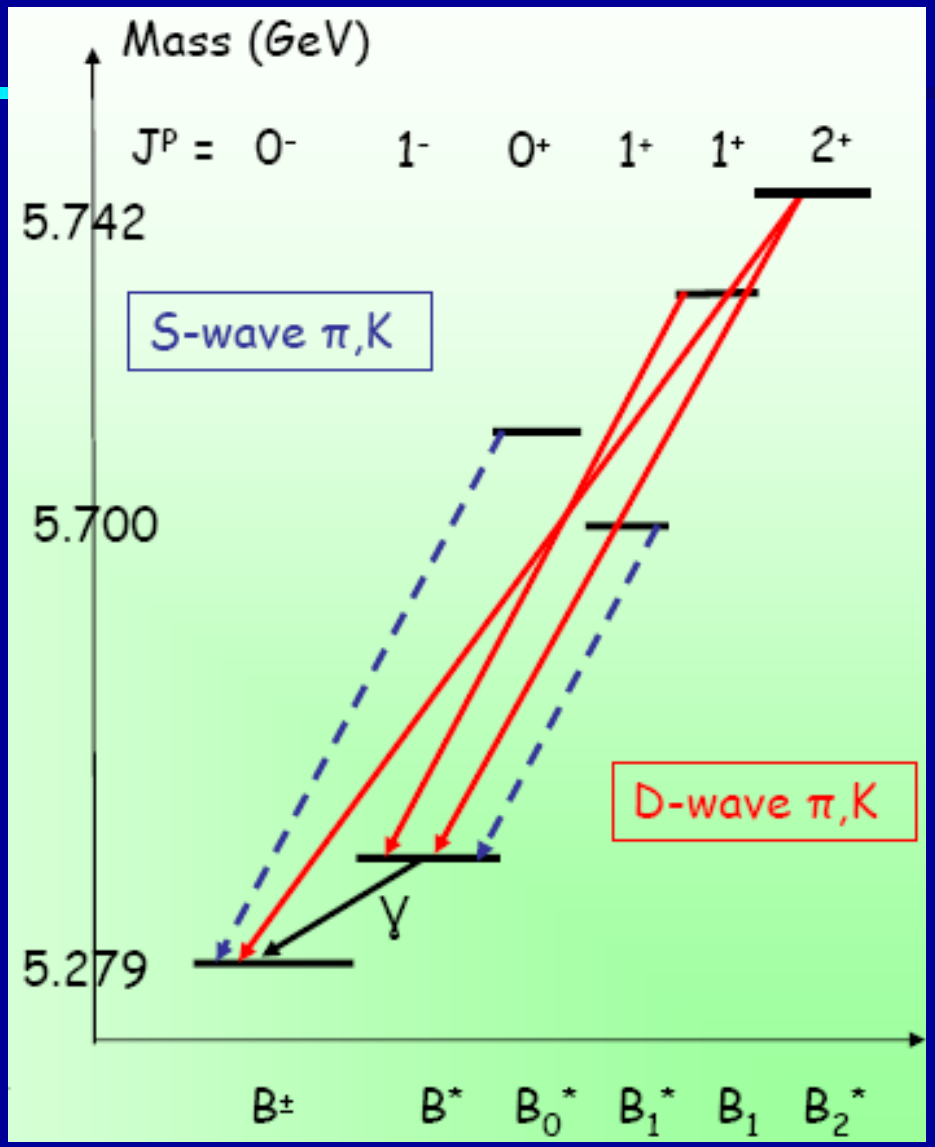


Systematics below 1 MeV for high statistics channels

Best single measurements of *b*-hadron masses

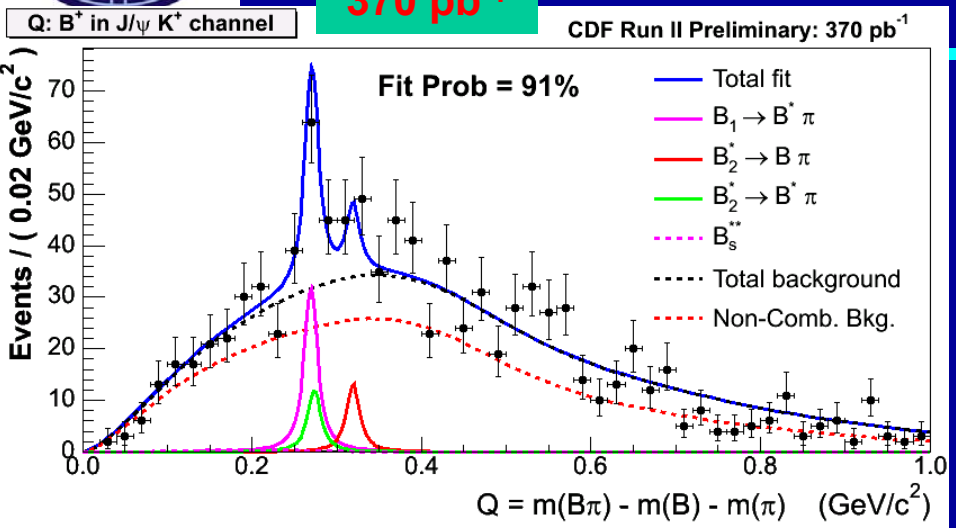
B** Spectroscopy

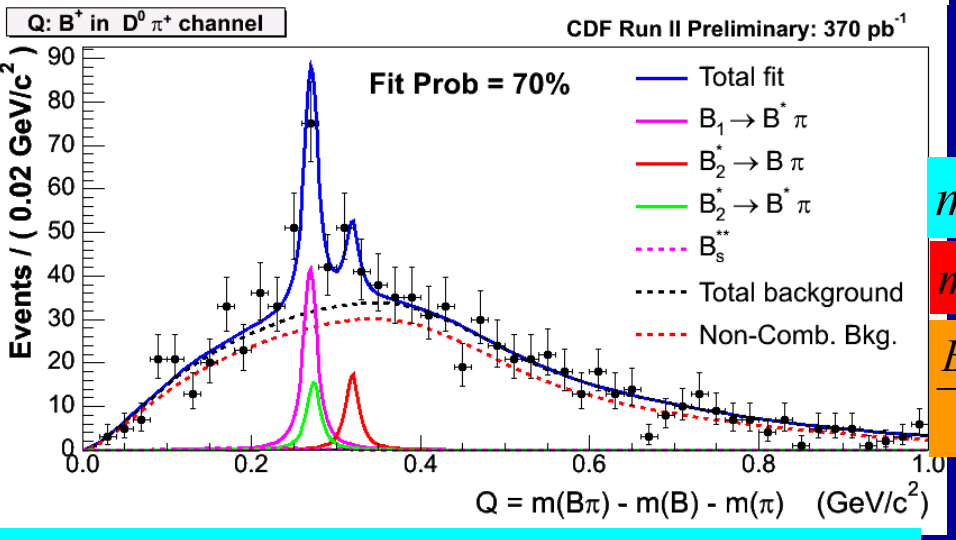
- B_1 and B_2* decay through D-wave → narrow resonances
- B_0* and B_1* decay through S-wave → wide resonances, difficult to distinguish from phase space



B^{**}

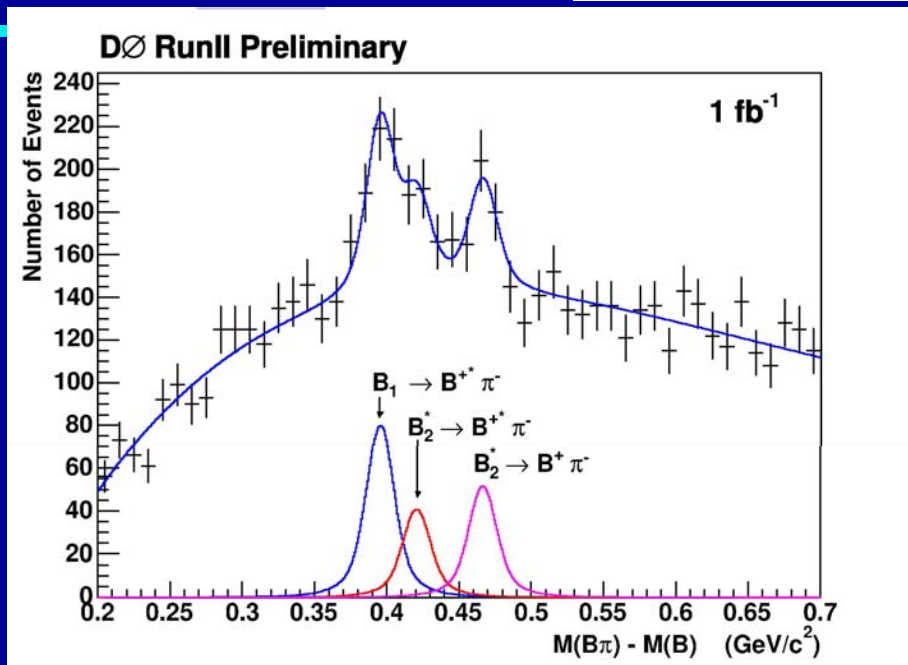
370 pb^{-1}





$$m(B_1) = 5734 \pm 3(\text{stat}) \pm 2(\text{syst})\, MeV/c^2$$

$$m(B_2^*) = 5738 \pm 5(\text{stat}) \pm 1(\text{syst})\, MeV/c^2$$



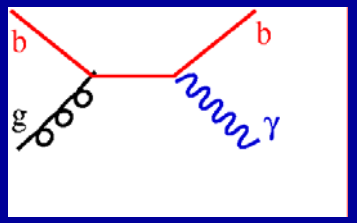
$$m(B_1) = 5720.8 \pm 2.5(\text{stat}) \pm 5.3(\text{syst})\, MeV/c^2$$

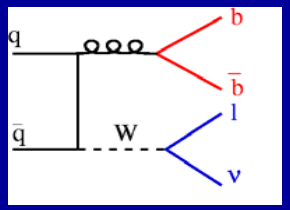
$$m(B_2^*) - m(B_1) = 25.2 \pm 3.0(\text{stat}) \pm 1.1(\text{syst})\, MeV/c^2$$

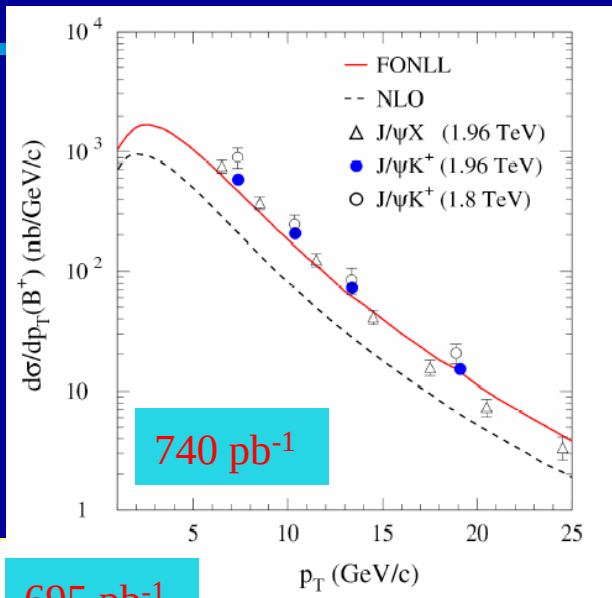
$$\frac{BR(b \to B_J^0 \to B\pi)}{BR(b \to B^+)} = 0.165 \pm 0.024(stat) \pm 0.028(syst)$$

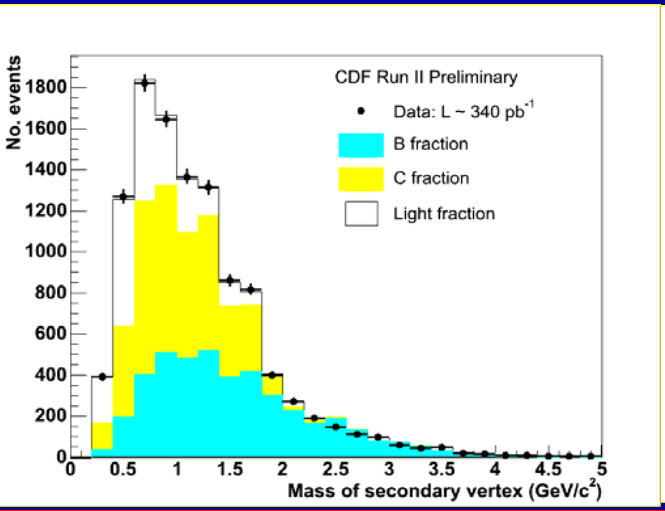
b-quark Production

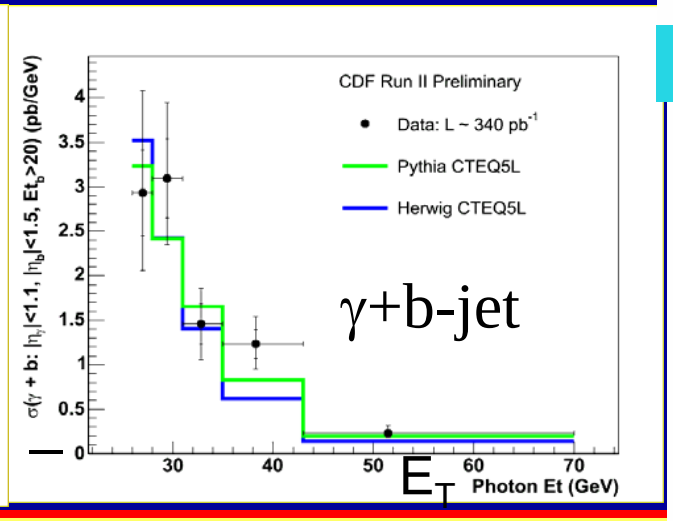
- Run I:
  - data/theory disagreement
- New measurements, Run II:
  - B^+ cross section
  - Photon+b-jet, W+b-jet
    - Fit secondary vertex mass



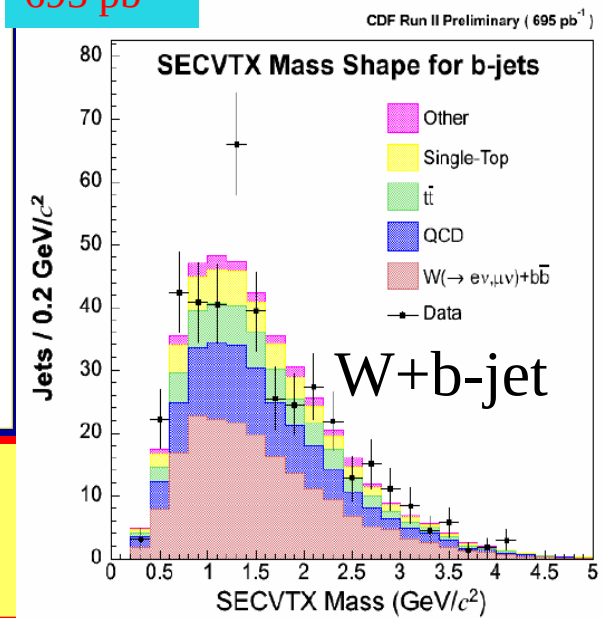








695 pb-1

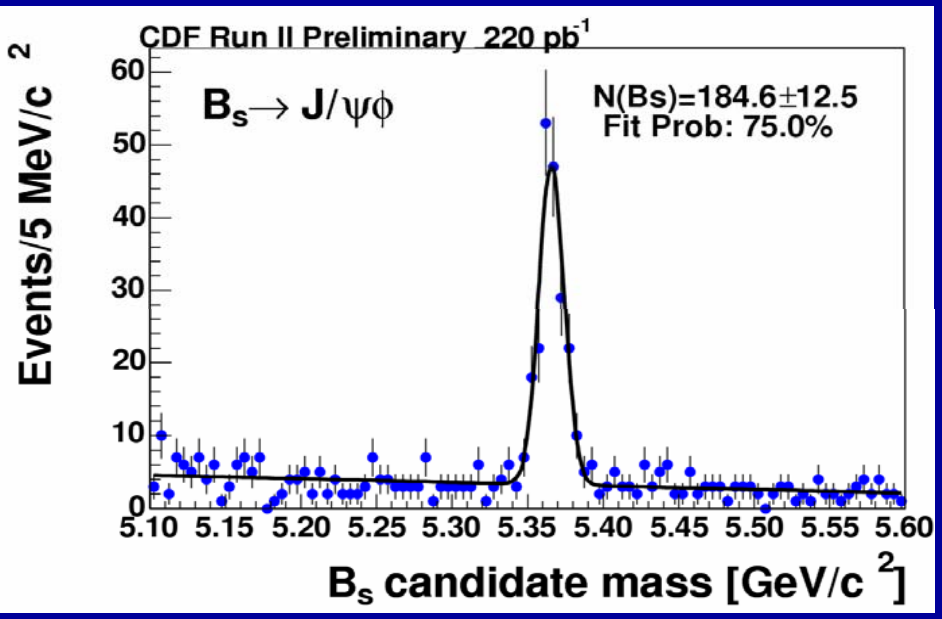


- First measurement of γ+b-jets and W+b-jets
- Data agree well with theoretical predictions

$B_s^{(**)}$meson

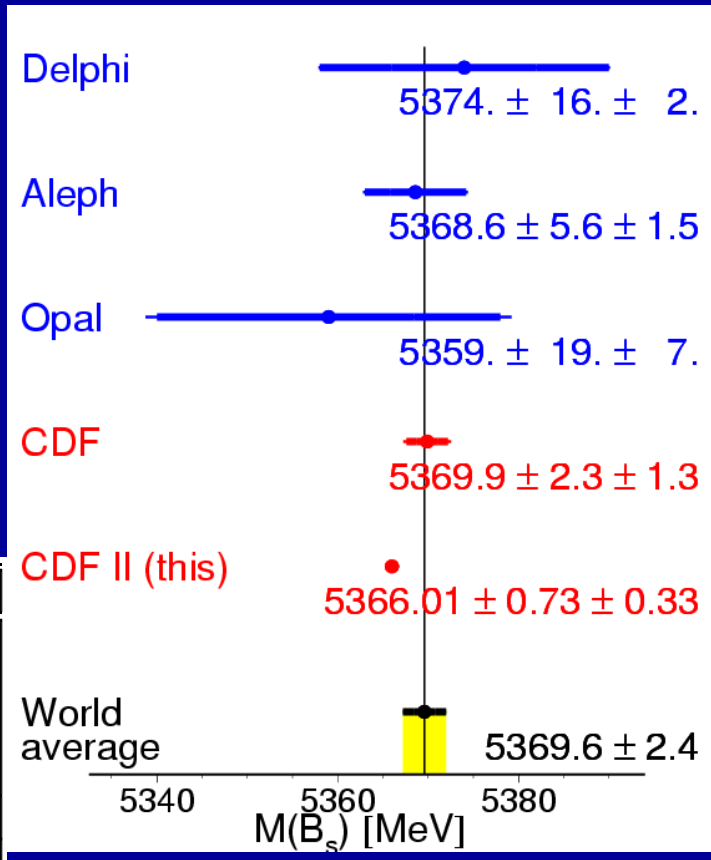
$B_s^{(**)}$ meson

B_s mass



Source	$B^0 \to J/\psi K^{*0}$	$B^\pm \to J/\psi K^\pm$	$B_s^0 \to J/\psi\phi$
Tracking & Corrections			
momentum scale	0.20	0.22	0.20
Tracking	0.18	from B^0	from B^0
False Curvature	0.02	from $B^\pm$	from $B^\pm$
Fitting	0.10	from B^0	from B^0
Resolution bias	0.13	0.13	0.13
Fit Systematics			
K^{*0}'s with K-π Swapped	0.06	—	—
$J/\psi\pi$ contamination	—	0.13	—
Total Systematic Uncertainty	0.33	0.36	0.33

B_s mass



PRL 96, 202001 2006

MeV

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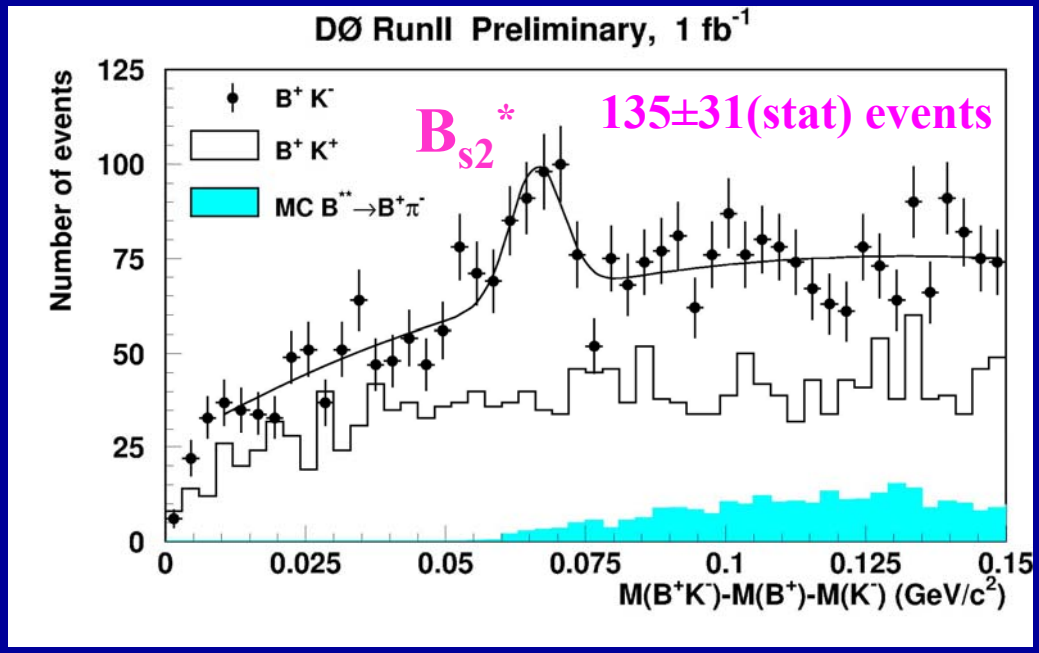
Orbitally Excited B_s-mesons



$$B_s^{**} \to B^+(B^{*+})K^-;$$
$$B^+ \to J/\psi\, K^+$$

$$\Delta M = 66.4 \pm 1.4(\text{stat})\, MeV/c^2$$
$$\sigma = 4.7 \pm 1.5(\text{stat})\, MeV/c^2$$

$$M(B_{s2}^{*0}) = 5839.1 \pm 1.4(\text{stat}) \pm 1.5(\text{syst})\, MeV/c^2$$

Where is the B_{s1} state?

Assuming equal splitting in B_s as in B****
expect: $M(B_{s1}^0) \cong 5814\, MeV/c^2$

Theory predictions

	$M[MeV/c^2]$	$\Gamma[MeV]$
$B_{s1}(3/2)$	5831 - 5886	< 1; 2.8±1.2
$B_{s2}^*(3/2)$	5844 - 5899	1; 2.6; 7±3

Orbitally Excited B_s-mesons

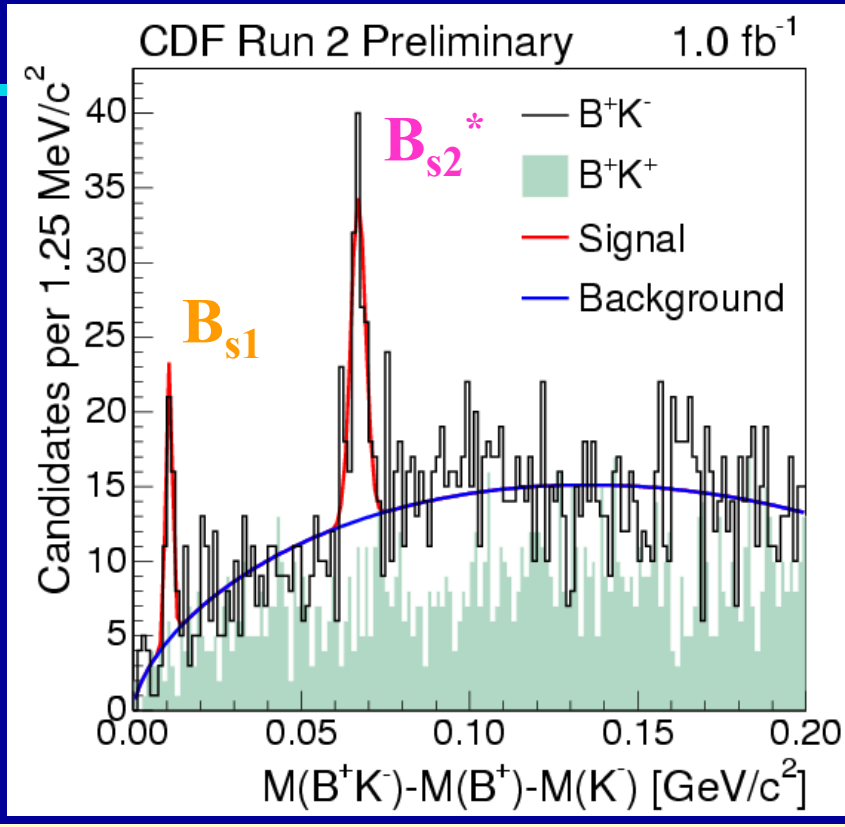
$$B_s^{**} \to B^+(B^{*+})K^-;$$
$$B^+ \to J/\psi K^- \text{ or } \overline{D}^0\pi^-$$

B_{s2}^*: 94.8±23.4 events

$$\Delta M = 66.96 \pm 0.39(\text{stat})\, MeV/c^2$$
$$\sigma = 1.79 \pm 0.42; 2.88 \pm 0.75(\text{stat})\, MeV/c^2$$

B_{s1}: 36.4±9.0 events

$$\Delta M = 10.73 \pm 0.21(\text{stat})\, MeV/c^2$$
$$\sigma = 0.64 \pm 0.25; 1.18 \pm 0.56(\text{stat})\, MeV/c^2$$



- Two signals seen
  - **$B^*_{s2} \to BK$: 7.7σ, $m(B_{s2}^*)$=5839.64 ±0.39(stat)±0.14(syst) ± 0.5(PDG) MeV/c^2**
    - already seen by OPAL, DELPHI and DØ
  - **$B_{s1} \to B^*K$: 6.3σ, $m(B_{s1})$=5829.41±0.21(stat) ± 0.14(syst) ± 0.6(PDG) MeV/c^2**
    - Prob. of stat. Fluctuation: 2.3 x 10^{-7} > 5.0σ

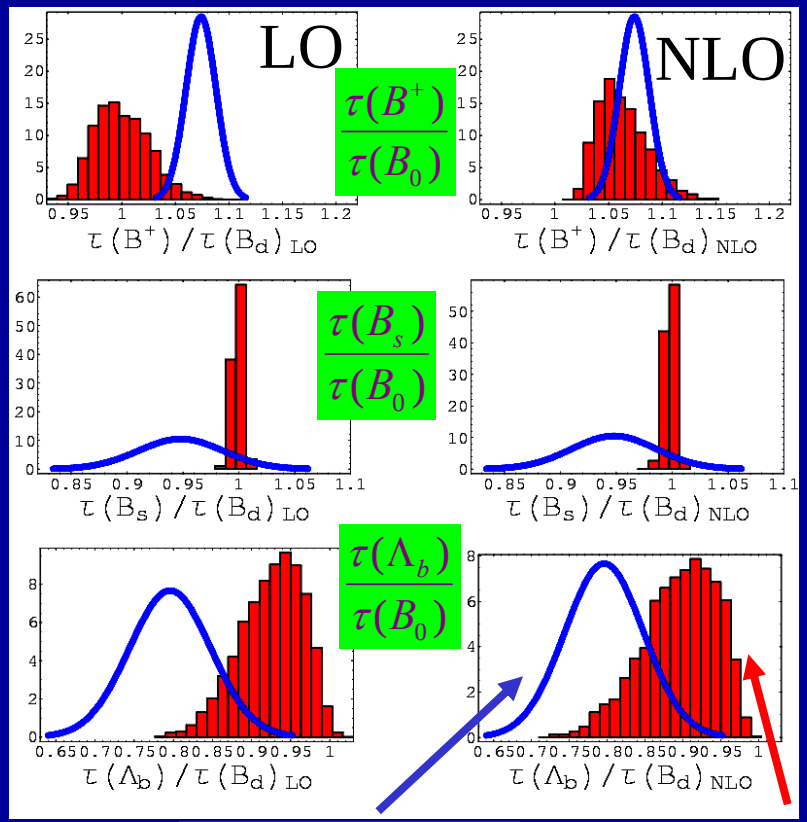
First Evidence for B_{s1} state?

- Mass difference: 10.20 ± 0.44 (stat) ± 0.35 (PDG) MeV/c^2

B hadron lifetimes

- B hadron lifetimes provide understanding of detector, trigger, analysis biases
- B hadron decays dominated by b-quark decay
  - Effect of spectator quarks can be included with perturbative expansions in terms of $1/m_b$ (HQET)
    - Expect small differences between lifetimes of different species
    - Non-perturbative ME from lattice, Wilson coeff. from perturbative QCD
      - NLO improves agreement
    - Ratios reduce theory uncertainties

C. Tarantino, hep-ph/0310241
October 2003



Experiment

Theory

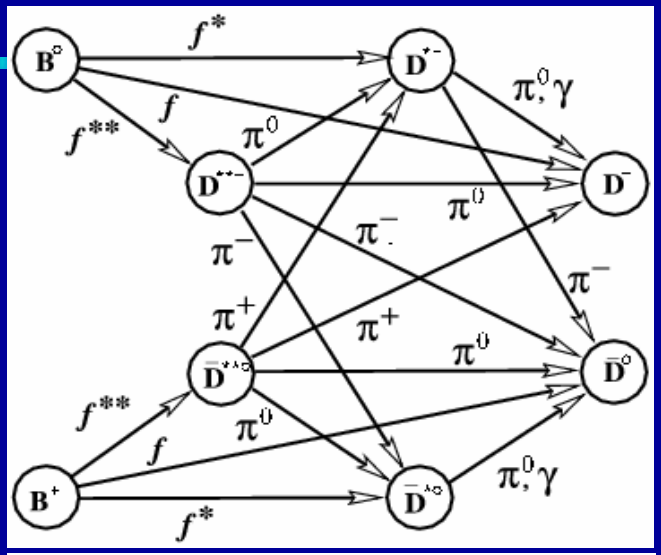
Lifetimes with B→lνDX modes

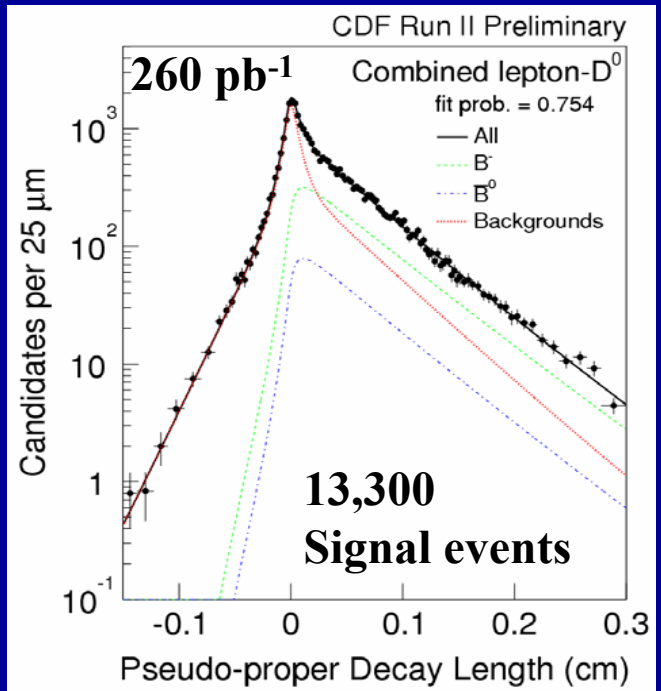
- Highest statistics samples
  - Difficult systematics:
    - Sample composition for B^+, B^0
      - Cross talk from D**, D*
    - Backgrounds:
      - Combinatorial
      - Physical: $B \rightarrow D^{(*)}D^{(*)}$
      - Prompt: c-cbar, b-bbar, D+fake
- Result from CDF with low statistics lepton pt > 8 GeV sample

$\tau(B^+)$ = **1.653±0.029±0.032 ps**, $\tau(B^0)$ = **1.473±0.036±0.054 ps**

$\tau(B+)/\tau(B0)$ = **1.123±0.040±0.040**

- Very high statistics secondary vertex triggered sample still under study





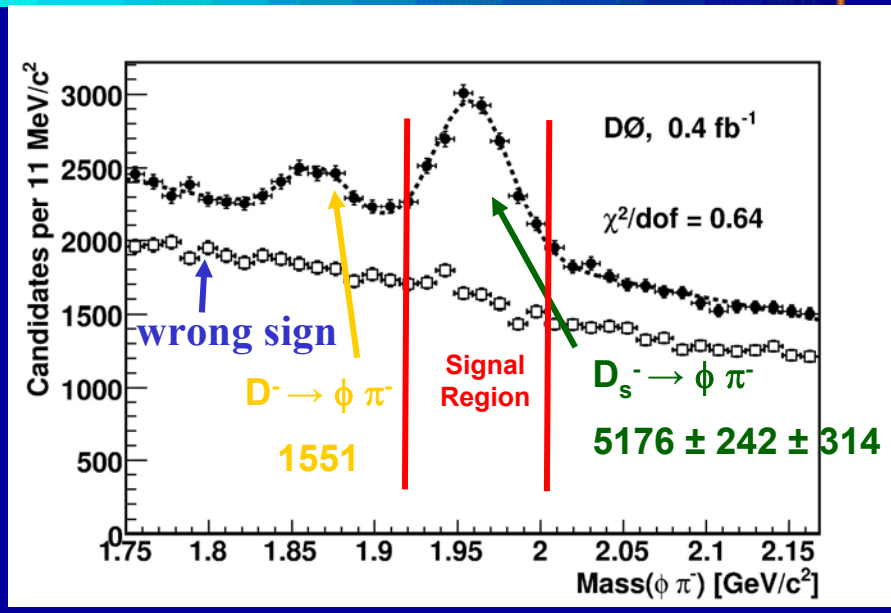
Run II, 400 pb^{-1}

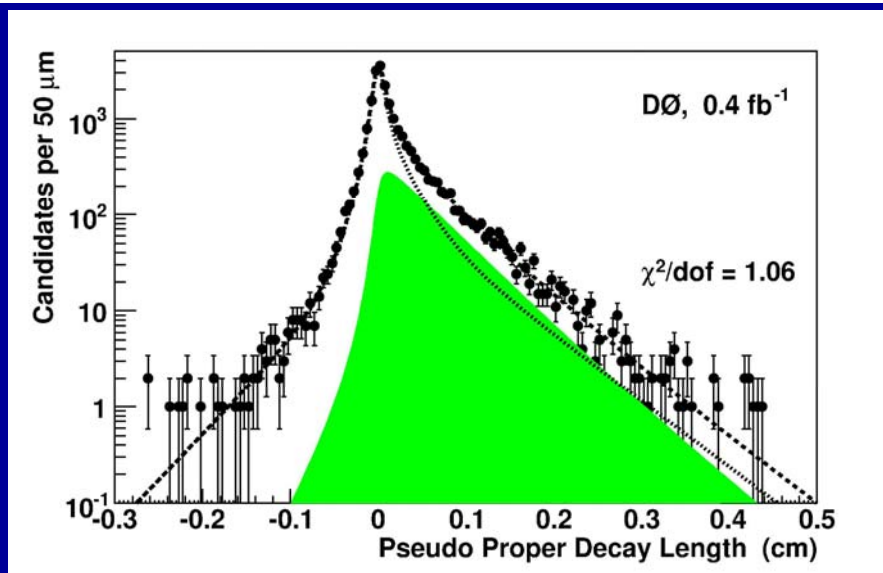
Lifetimes with $B_s \rightarrow l\nu D_s X$ modes

- First high statistics B_s lifetime measurement from D0
  - Use $D_s^- \rightarrow \phi\pi^-$ decay
  - Difficult background systematics:
    - Combinatorial
    - Physical: $B \rightarrow D^{(*)}D^{(*)}$
    - Prompt: c-cbar, b-bbar, D+fake
  - Currently best measurement

$$\tau(B_s) = 1.398 \pm 0.044\,(\text{stat})\,^{+0.028}_{-0.025}\,(\text{syst})\,\text{ps}$$

hep-ex/0604046





Lifetimes

- Several new results included in HFAG 2006 averages
  - B^0, B^+ dominated by BaBar/Belle
  - B_s: dominated by CDF/D0, LEP

hep-ex/0603003, March 2006

Lum. pb^{-1}	CDF/D0 ψ modes 240/220	CDF hadronic 360	CDF semi-leptonic (Hi pt) 260	D0 semi-leptonic 400 - 440	HFAG 2006
B0	1.539±0.051±0.008 1.473±0.051±0.023	1.511±0.023±0.013	1.473±0.036±0.054		1.527 ± 0.008
B+	1.662±0.033±0.008	1.661±0.027±0.013	1.653±0.029±0.032		1.643 ± 0.010
B+/B0	1.08±0.042		1.123±0.040±0.040	1.08±0.016±0.014	1.076 ± 0.008
Bs	1.369±0.100±0.009 1.444±0.094±0.020	1.598±0.097±0.017		1.398±0.044±0.027	1.479 ± 0.044
Bs/B0	0.890±0.072 0.980±0.074				0.968 ± 0.029

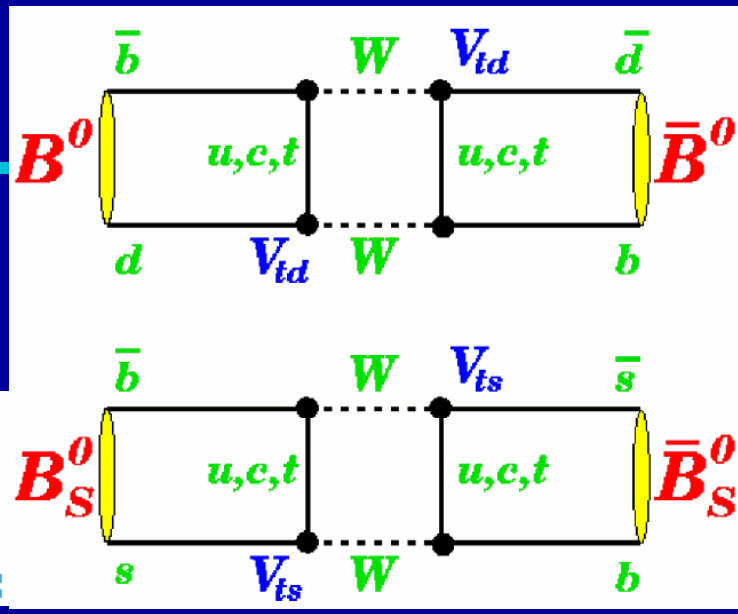
Theory (*) (NLO)

1.00±0.01

1.06±0.02

(*) Gabbiani et al., hep-ph/0407004 Oct.2004

B mixing



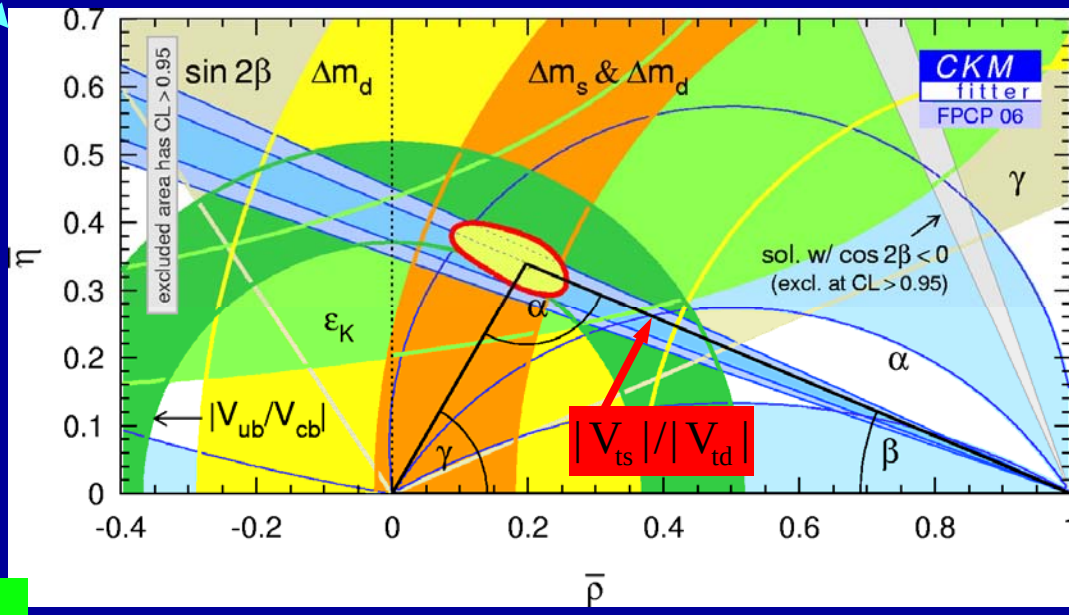
- Neutral B's mix:
  - SM interpretation with box diagrams
    - Frequency $\Delta m_{d,s} \propto |V_{td,s}|^2$
    - Constraints to CKM weak due to theory uncertainties

      Theory accuracy ~5% in ratio $\Delta m_d/\Delta m_s$

$$\frac{|V_{td}|}{|V_{ts}|} = 1.01\xi \sqrt{\frac{\Delta m_d}{\Delta m_s}}$$

from LATTICE

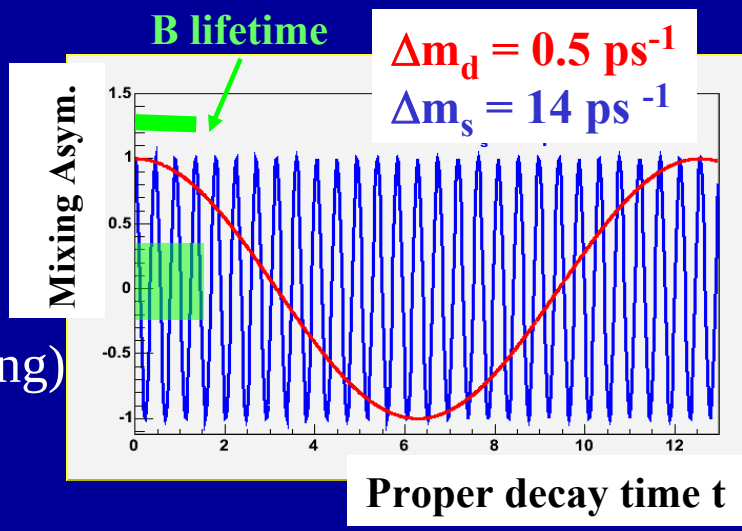
  - Bd mixing measured and established clearly
    - LEP, CDF-I, CDF-II, D0-II, **BaBar, Belle**
  - Bs mixing not observed till spring 2006
    - Limits set by LEP, SLD, CDF-I, CDF-II, D0-II



New physics may affect $\Delta m_s/\Delta m_d$

B mixing

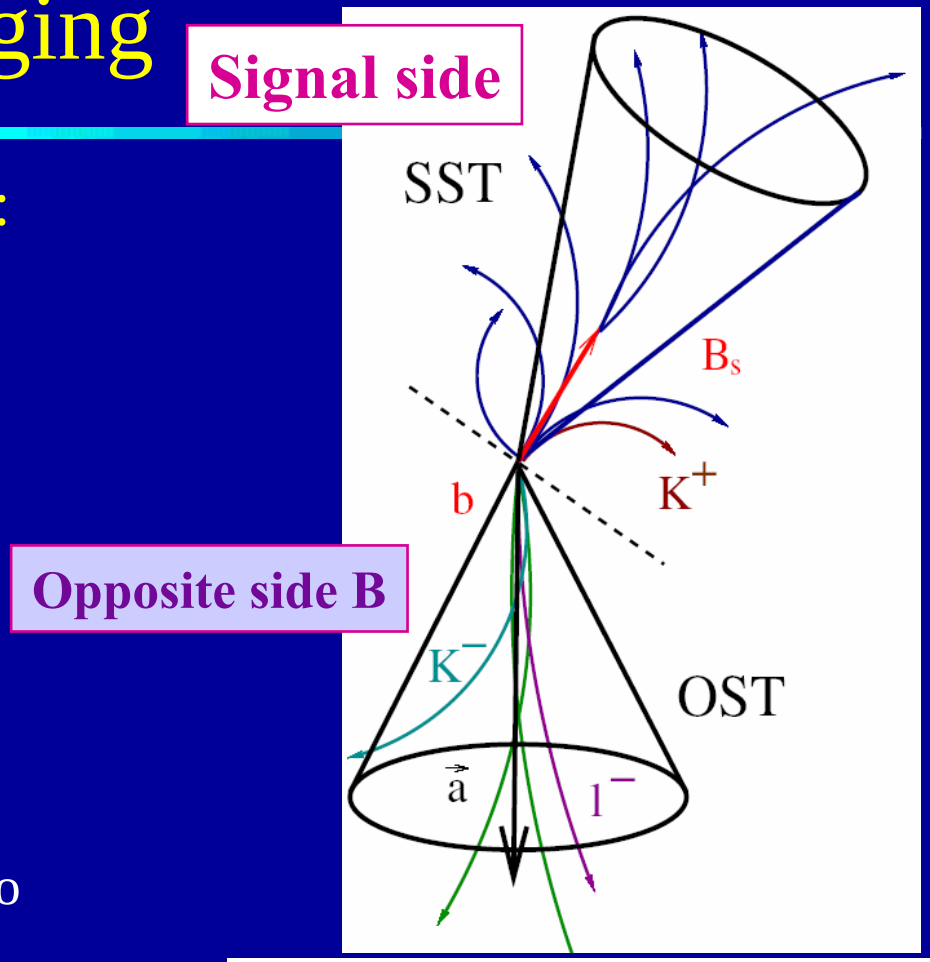
- Basic ingredients for the measurement:
  - High statistics samples of neutral B's in flavor specific decays
    - CDF: J/ψK, Dπ, D3π, lνDX
    - D0: J/ψK, lνDX
  - Proper decay length reconstruction
    - Fully reconstructed modes provide better accuracy
  - Tagging of flavor at production (flavor tagging)
    - Key problem at the Tevatron!
    - Equivalent statistical power: $N\,\varepsilon D^2$
      - **ε = tagger efficiency**
      - **D = tagger dilution = 2*η-1 (η = probability of correct tag)**

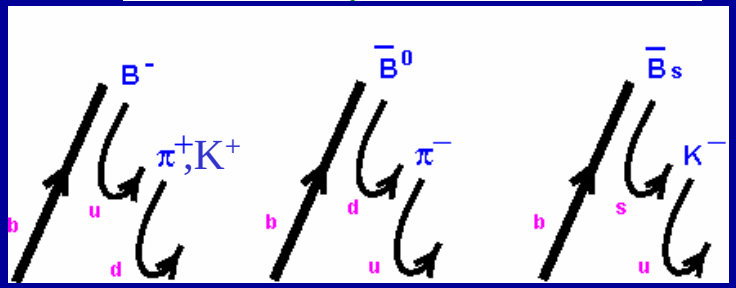


- Measure: $A(t) = (N_{nm}-N_m)/N = D\cos(\Delta m\, t)$
  - N_{nm} (N_m): number of B's with same (different) flavor at production and decay
  - Mixing measurement calibrates dilution
    - Impossible for B_s until oscillation observed

Flavor tagging

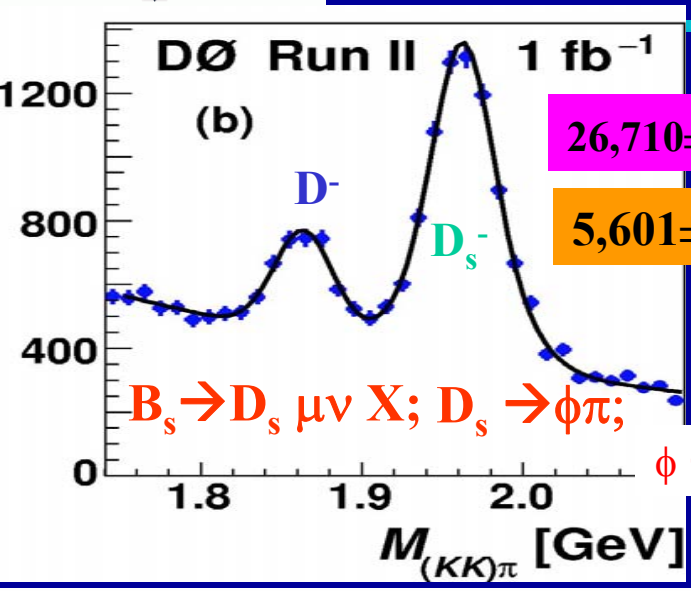
- Opposite side techniques (OST):
  - CDF: total εD^2 ~ 1.5 %
    - Soft Muon Tag
    - Soft Electron Tag
    - Jet Charge Tag
  - D0: εD^2 ~ 2.5%
    - Soft Muon Tag
    - Soft Electron Tag
    - Secondary Vertex Tag
- Same side techniques (SST):
  - Sign of nearby track is correlated to b type (SST)
    - Tagging power depends on B type
    - PID helps for Bs
    - **εD^2 ~ 3.5-4.0 %** for CDF in Bs





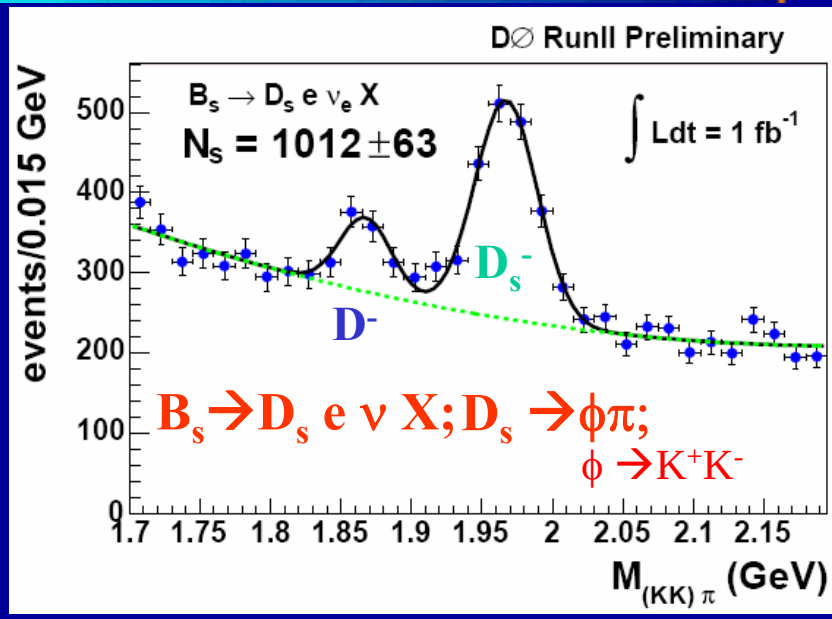
B_s mixing (signals after flavor tagging)

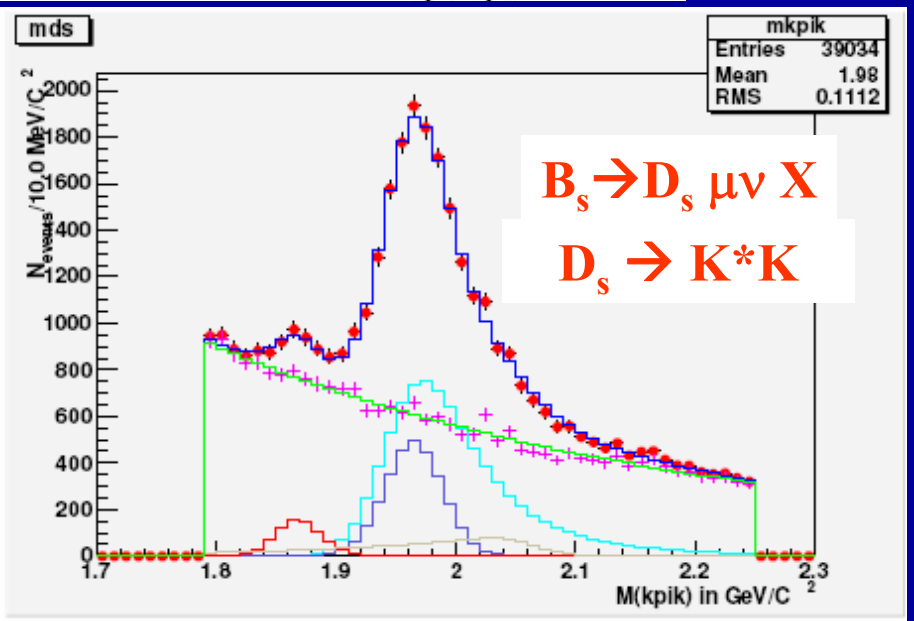
Semi-leptonic analysis – Opposite side tagging



26,710±556 untagged D_s^-

5,601±102 tagged D_s^-



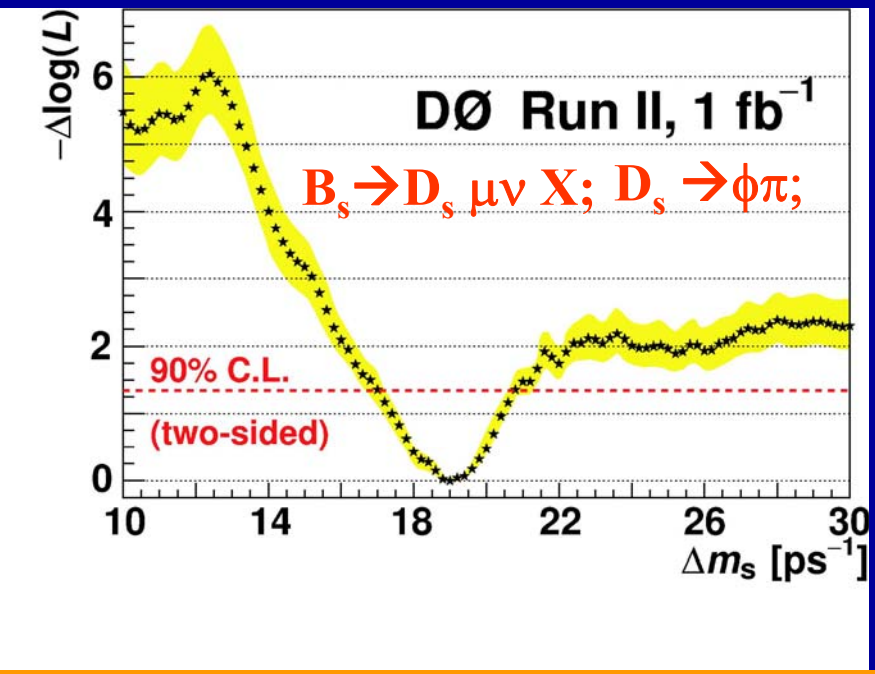


- $N_{Bs}(\phi\pi + \mu) = 5601 \pm 102$
- $N_{Bs}(\phi\pi + e) = 1012 \pm 62$ (Muon triggered & tagged)
- $N_{Bs}(K^*K + \mu) = 2997 \pm 146$

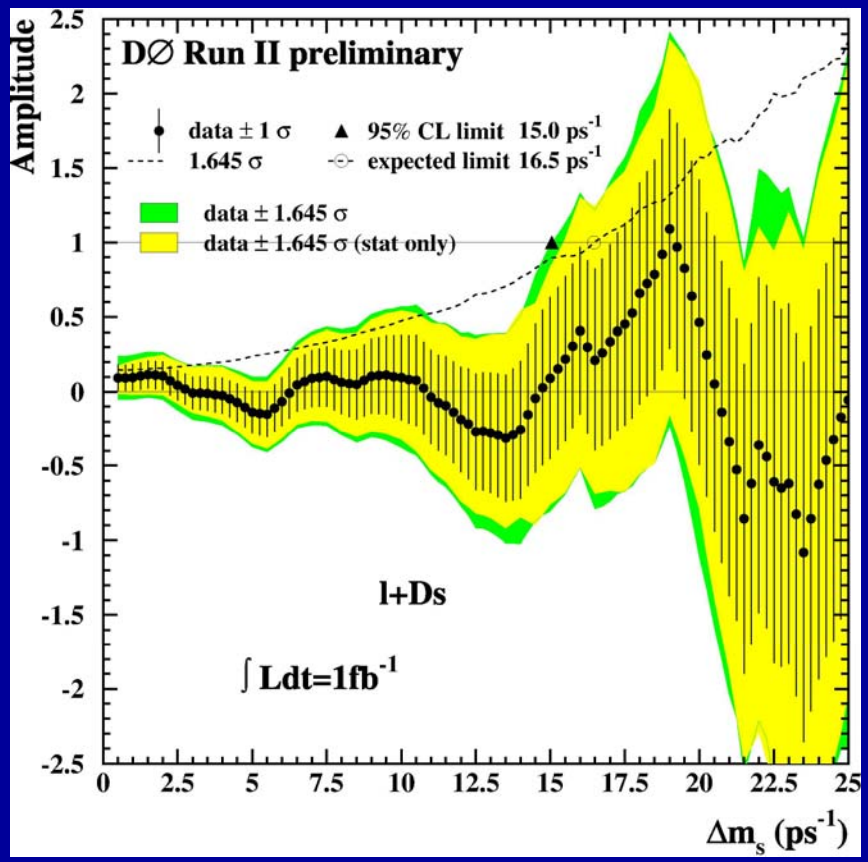
36,500 total untagged D_s^-

D0: B_s mixing

March 2006



July 2006

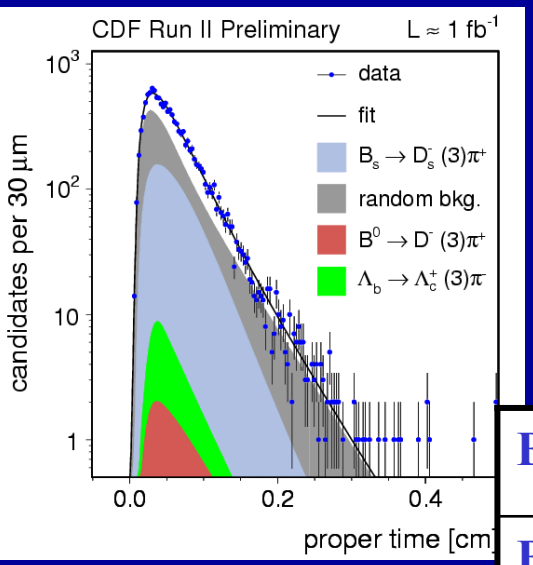


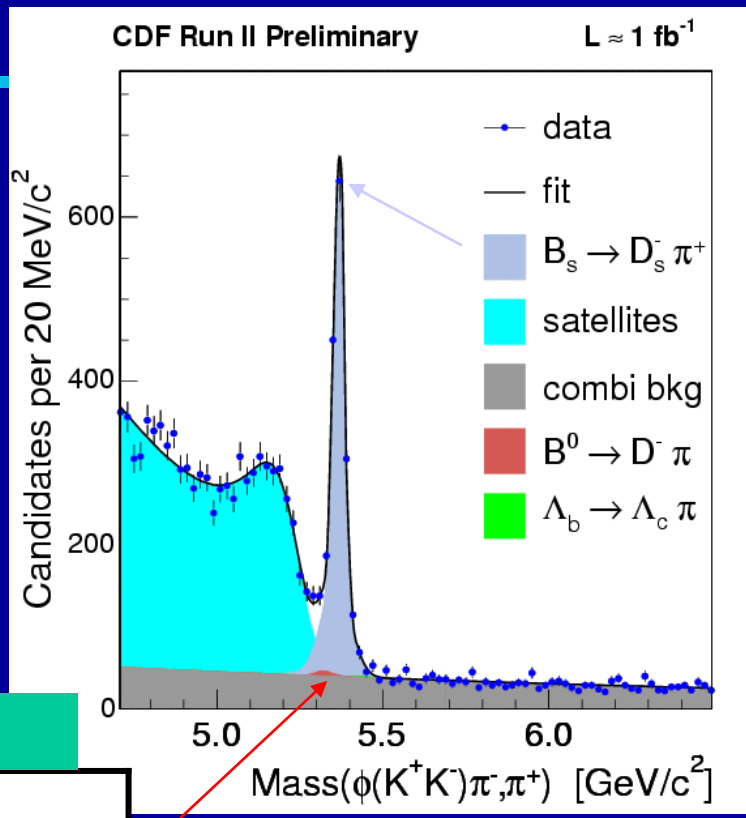
- Amplitude scan results:
  - $17 < \Delta m_s < 21$ ps^{-1} @ 90% CL
  - Preferred value: 19 ps^{-1}
  - Sensitivity: 16.5 ps^{-1}

- 8% probability that random tags would look as significant

B_s mixing (signals)

- Hadronic samples: $B_s \rightarrow D_s\pi$; $D_s3\pi$
  - 3600 events
  - Cross-check with hadronic lifetime analysis



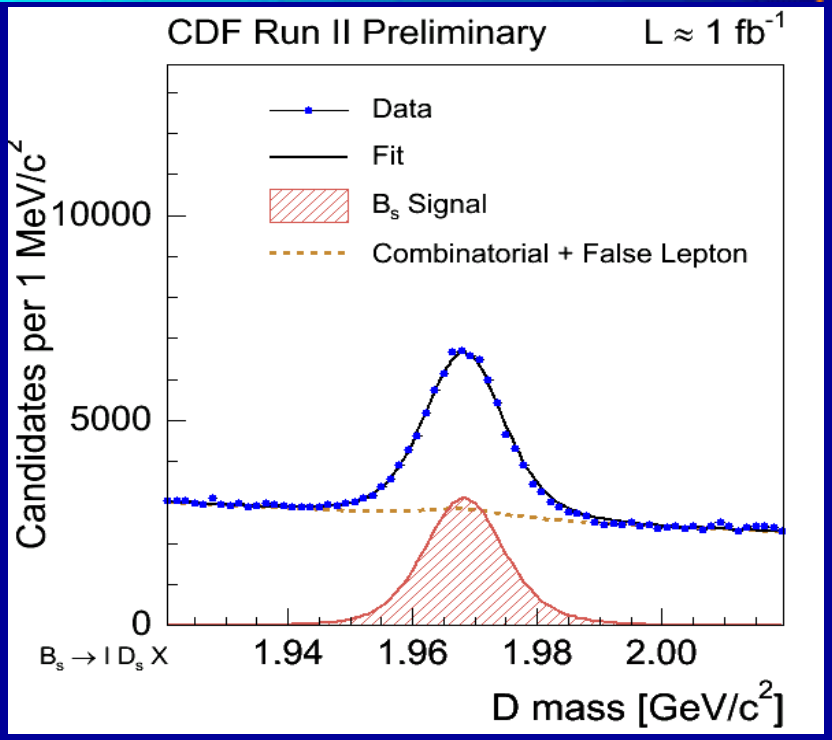


$B^0 \rightarrow D^-\pi$ decays

channel	yield
Bs→Dsπ (Ds→φπ)	1600
Bs→Dsπ (Ds→K*K)	800
Bs→Dsπ (Ds→3π)	600
Bs→Ds3π (Ds→φπ)	400
Bs→Ds3π (Ds→K*K)	200

B_s mixing (signals)

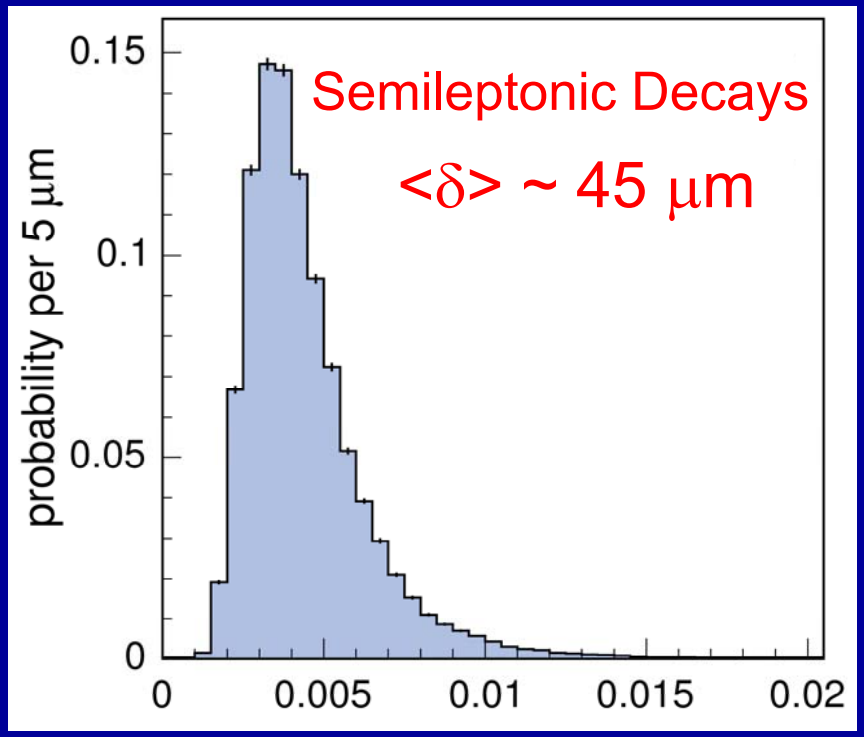
- Semi-leptonic samples: $B_s \rightarrow D_s l X$
  - 37K events

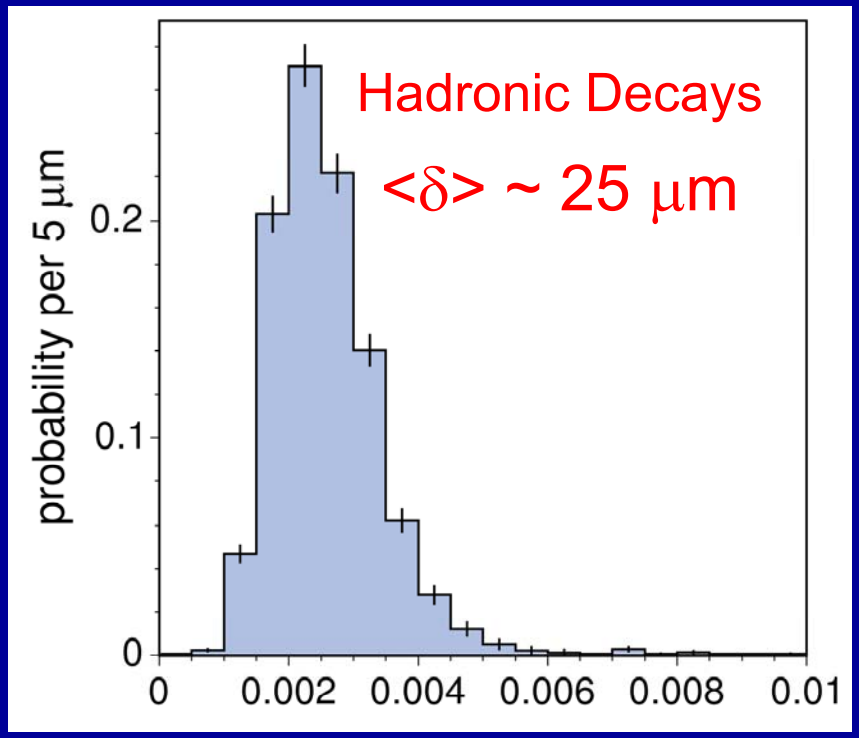


channel	yield
Bs→DslX (Ds→ϕπ)	21.7K
Bs→DslX (Ds→K*K)	7.9K
Bs→DslX (Ds→3π)	7.4K

B_s Mixing: Decay Time Resolution

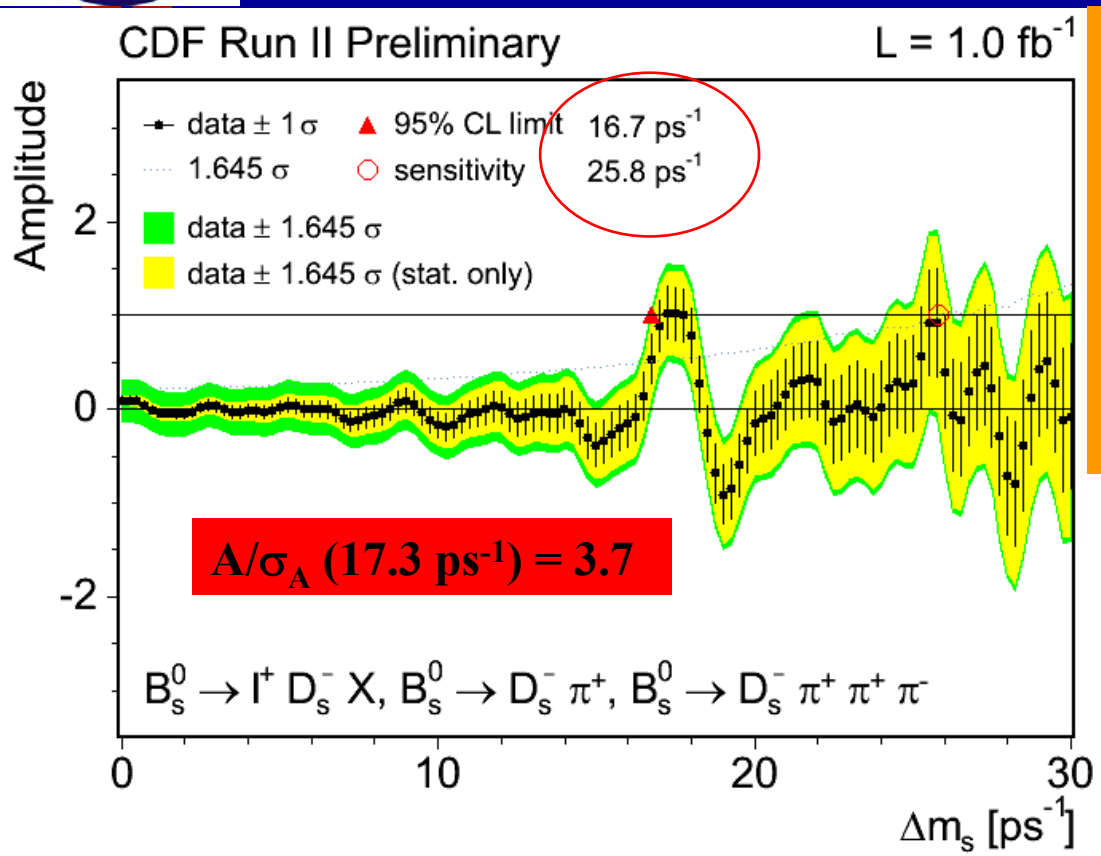
- Hadronic decays have excellent proper time resolution



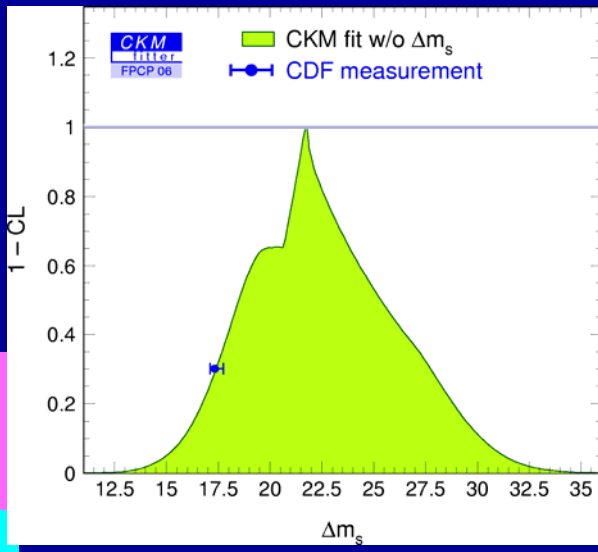


proper decay time resolution (δ) / cm

CDF: B_s Mixing



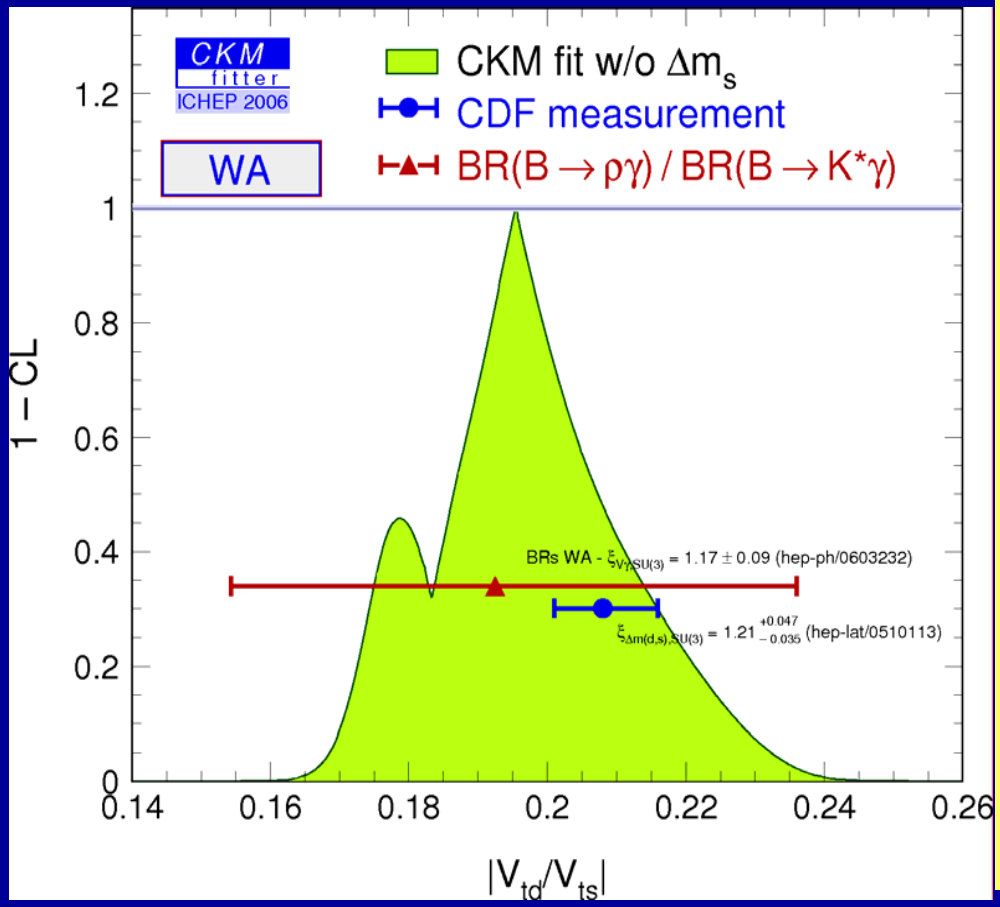
- Combined scan results:
  - 16.7 ps^{-1} 95% CL limit
  - $16.96 < \Delta m_s < 17.91$ ps^{-1} @ 90% CL
  - Sensitivity: 25.8 ps^{-1}



$$\Delta m_s = 17.31^{+0.33}_{-0.18}\,(stat) \pm 0.07\,(sys)$$

- 0.2% probability that random tags would look as significant

B_s Mixing: Constraints



- use measured Δm_s to constrain CKM

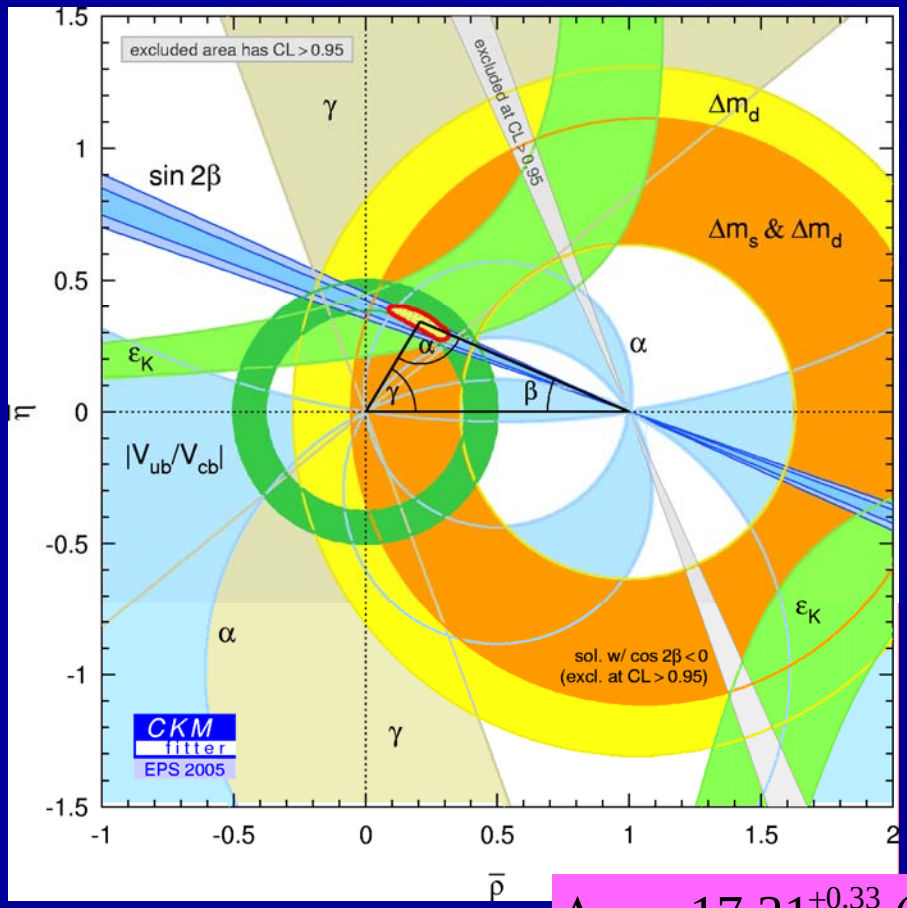
$$\left|\frac{V_{td}}{V_{ts}}\right| = \xi\sqrt{\frac{\Delta m_d}{\Delta m_s}\frac{m_{B_s}}{m_{B_d}}}$$

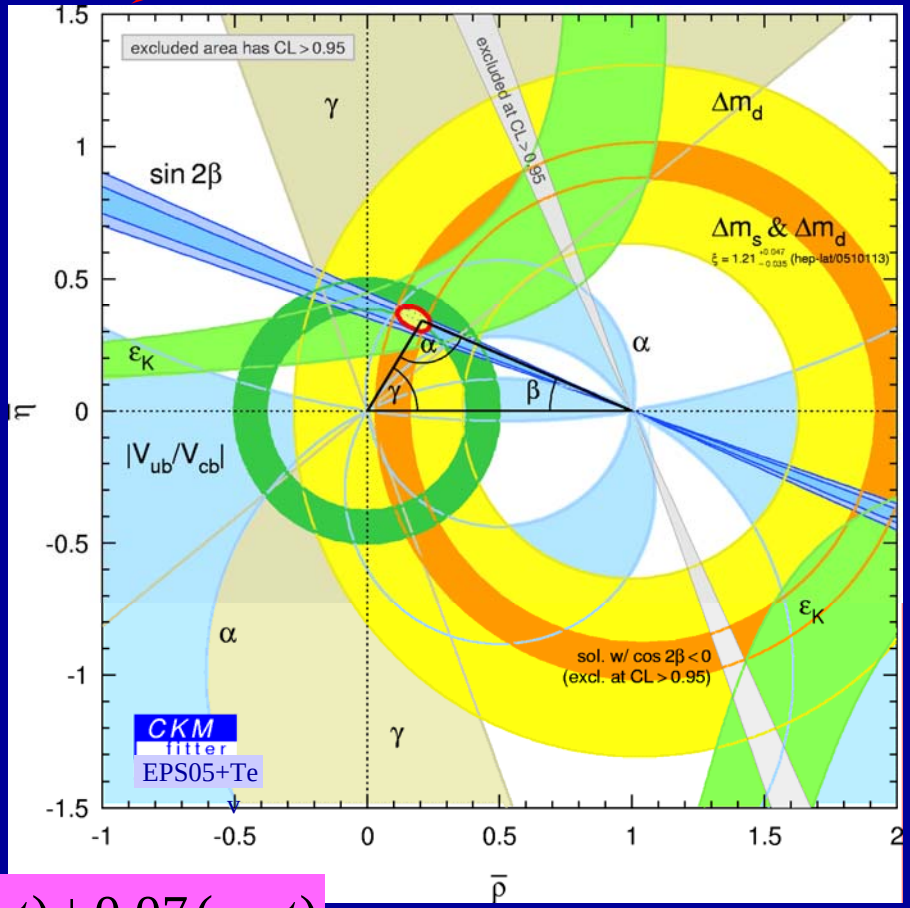
$$= 0.208\ ^{+0.001}_{-0.002}\,(\text{stat})\ ^{+0.008}_{-0.007}\,(\text{theor})$$

- agrees with SM prediction
- x5 more precise than previous determination
- limited by Lattice uncertainty

B_s Mixing: CKM triangle

Tevatron

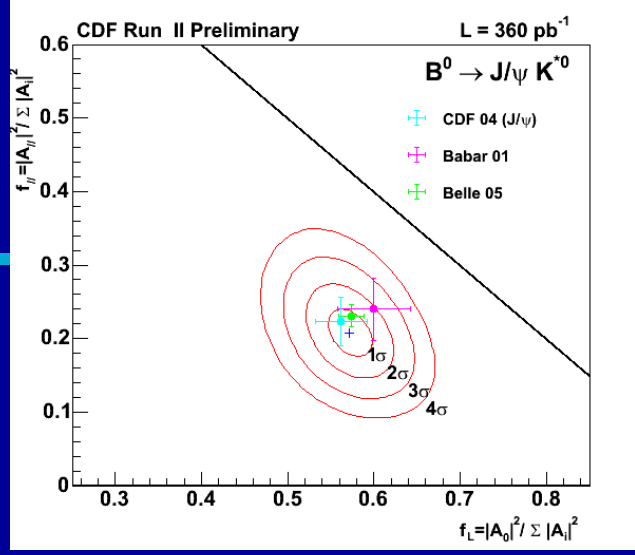




$$\Delta m_s = 17.31^{+0.33}_{-0.18}\,(stat) \pm 0.07\,(syst)$$

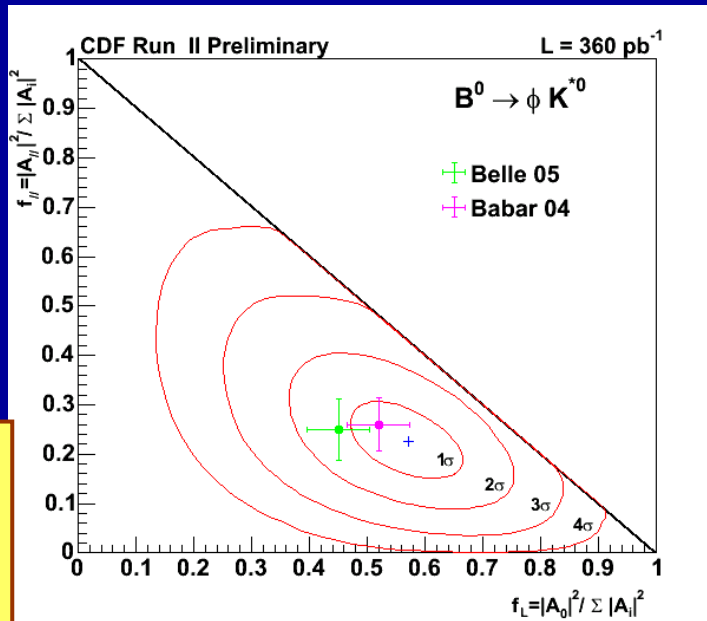
$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.208\,^{+0.001}_{-0.002}\,(\text{stat})\,^{+0.008}_{-0.007}\,(\text{theor})$$

$\Delta\Gamma_s (\Gamma_L - \Gamma_H)$



- In the B_s system CP violation is small:
  - $B_{s,light}$ = CP even (S, D waves)
  - $B_{s,heavy}$ = CP odd (P wave)
- Generally final states are mixture of CP even and odd states, but for Pseudoscalar $\longrightarrow$ VV, we can disentagle them.
- Time-dependent angular analysis for $B^0 \longrightarrow J/\psi K^{*0}$ and $B_s \longrightarrow J/\psi\phi$ together with lifetime meas. can separate heavy and light mass eigenstates.
- Determine $\Delta\Gamma_s \longrightarrow \Delta m_s$

$$\frac{\Delta m_s}{\Delta\Gamma_s} \approx \frac{2}{3\pi}\cdot\frac{m_t^2}{m_b^2}\cdot\left(1-\frac{8}{3}\frac{m_c^2}{m_b^2}\right)^{-1} h\left(\frac{m_t^2}{M_W^2}\right)$$



The B^0 decay amplitudes (3 linear polarizations) are of comparable precision and compatible with the measurements of BaBar and Belle

Measurement of ϕ_s

Use three different methods

- Time dependence of polarization amplitudes in $B_s \rightarrow J/\psi\phi$

Mostly CP-even state

- Time integrated di-muon charge asymmetry:

$$A_{SL}^{s} = \frac{N^{++} - N^{--}}{N^{++} + N^{--}} = \frac{\Delta\Gamma_s}{\Delta m_s}\tan(\phi_s)$$

Use Δm_s from CDF

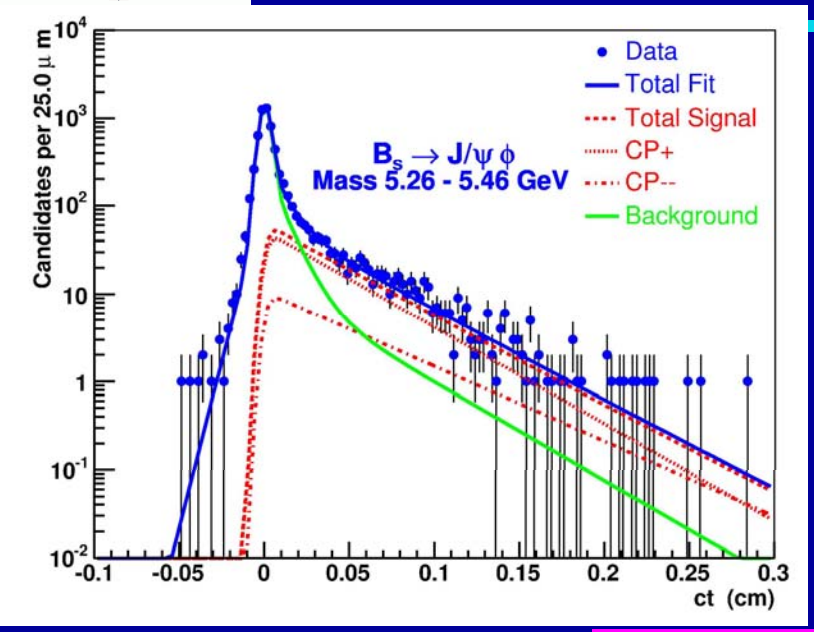
- Time integrated charge asymmetry of $B_s \rightarrow \mu\nu D_s$ decays:

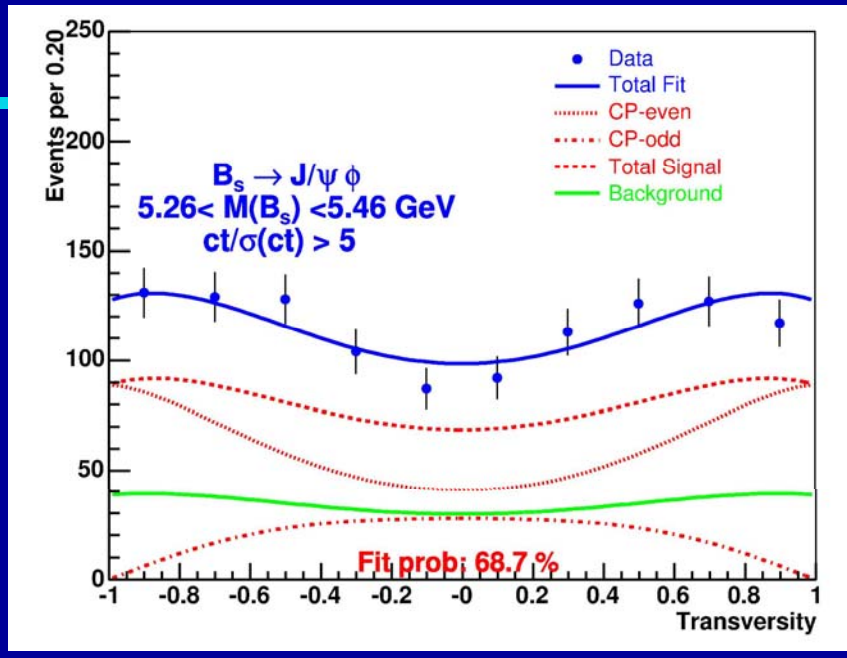
$$A_{\mathrm{SL}}^{\mathrm{int}} = \frac{N(B_s \rightarrow \mu^+ D_s X) - N(B_s \rightarrow \mu^- D_s X)}{N(B_s \rightarrow \mu^+ D_s X) + N(B_s \rightarrow \mu^- D_s X)} = \frac{1}{2}\frac{x_s^2}{1+x_s^2} A_{SL}^{s}$$

$$x_s = \frac{\Delta m_s}{\Gamma_s}$$

$\Delta\Gamma_s$ and ϕ_s

1 fb^{-1}

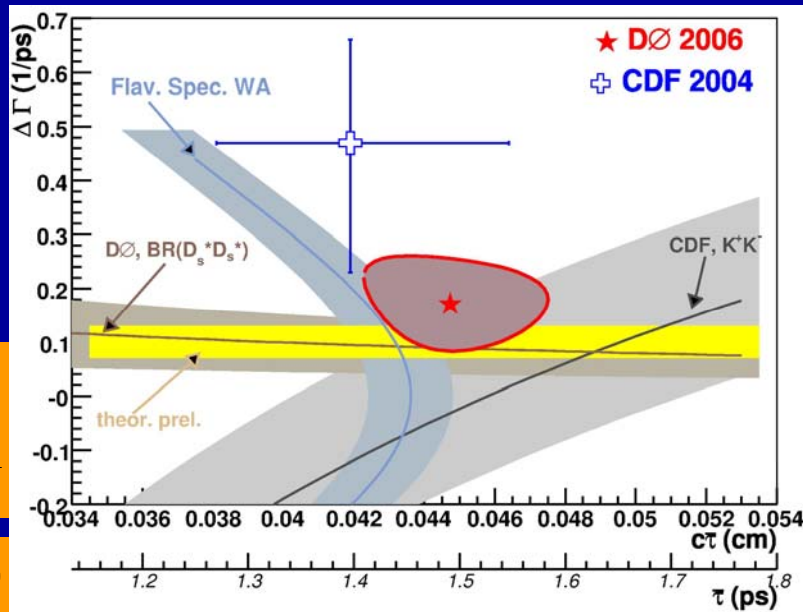




Assuming no CP violation: $\varphi_s \equiv \delta\varphi \equiv 0$

$$\bar{\tau}(B_s^0) = 1.52 \pm 0.08(stat)\,^{+0.01}_{-0.04}(syst)\,ps$$

$$\Delta\Gamma = 0.12 \pm 0.08\,^{+0.03}_{-0.04}\,ps^{-1}$$



SM

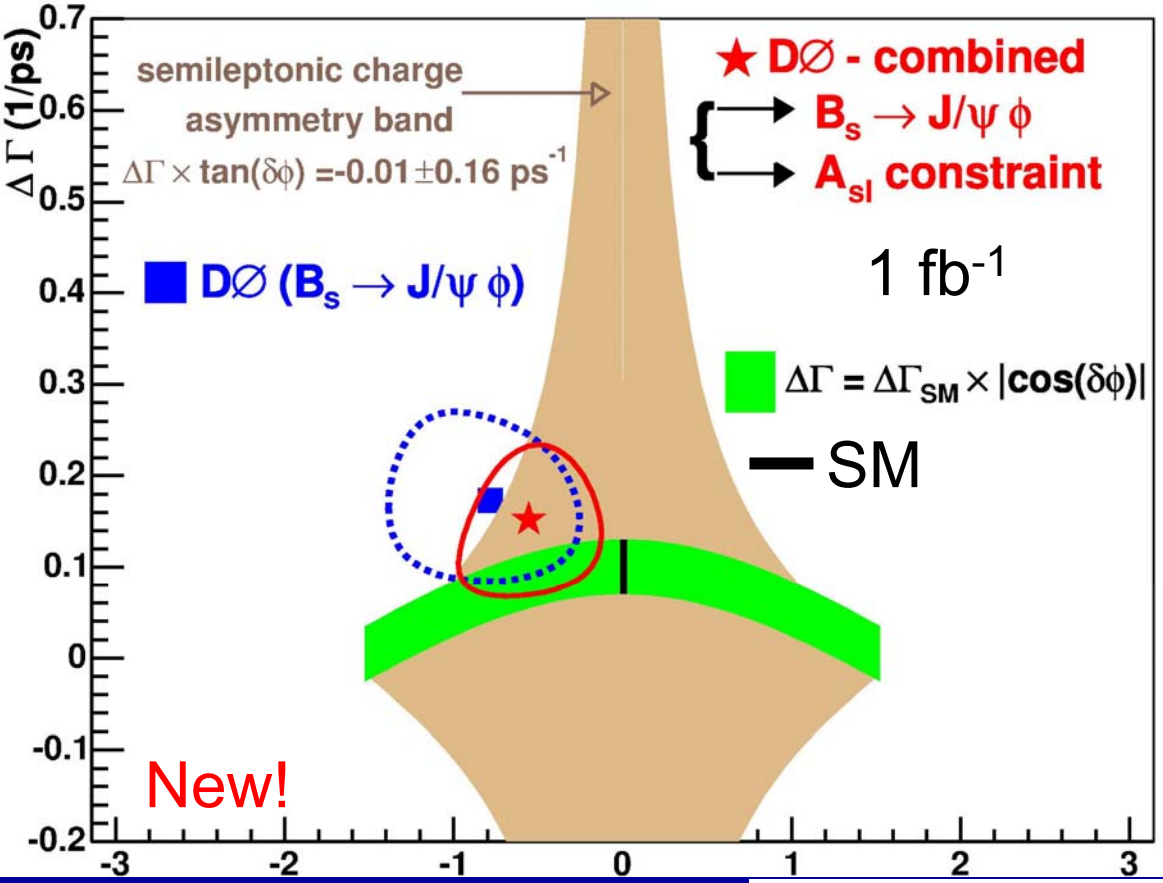
$$\bar{\tau}(B_s^0) = 1.49 \pm 0.08(stat)\,^{+0.01}_{-0.03}(syst)\,ps$$

$$\Delta\Gamma \equiv (\Gamma_L - \Gamma_H) = 0.17 \pm 0.09 \pm 0.03\,ps^{-1}$$

$\phi_s = -0.03$

$$\phi_s \equiv \delta\phi = -0.79 \pm 0.56(\text{stat}) \pm 0.01(\text{syst})$$

CP violation in B_s Mixing



- CDF and D0 can constrain ϕ_s
- D0 combines 3 measurements to get first constraints
- precision of all 3 are statistics limited
  - more data to come
  - CDF + D0
- direct CP using flavor tagged decays $B_s \to J/\psi\phi$

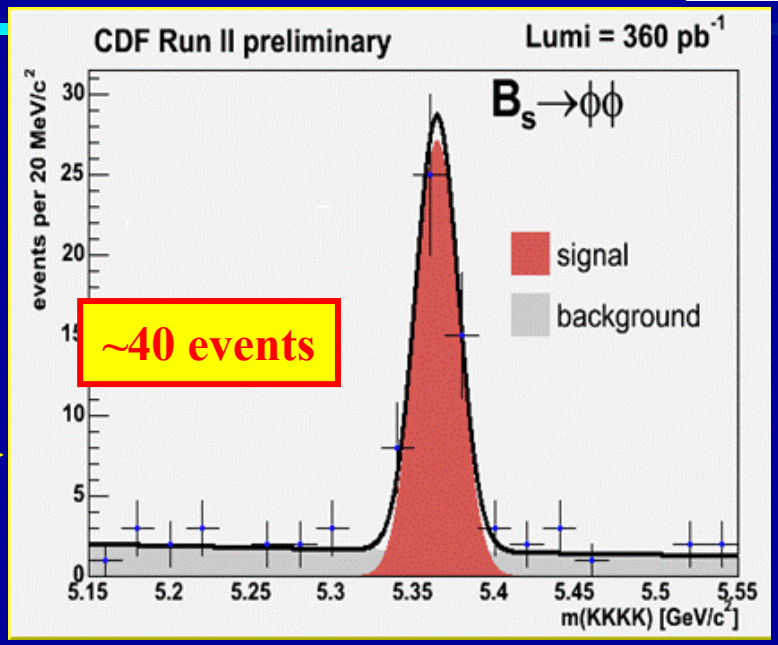
$B_s \rightarrow \phi\phi$ and $\psi(2S)\phi$

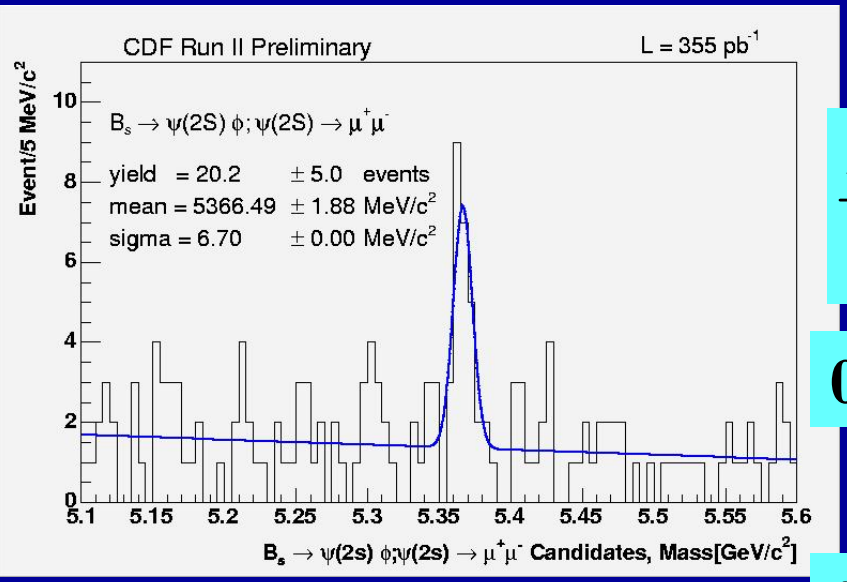
- CDF: Bs→ $\phi\phi$
  - $BR(B_s \rightarrow \phi\phi) = (1.4^{+0.6}_{-0.5} \pm 0.6) \times 10^{-5}$

QCD fact. 3.68×10^{-5}

NF fact. 1.79×10^{-5}

First observation!





$$\frac{BR(B_s \rightarrow \psi(2S)\varphi)}{BR(B_s \rightarrow J/\psi\varphi)} =$$

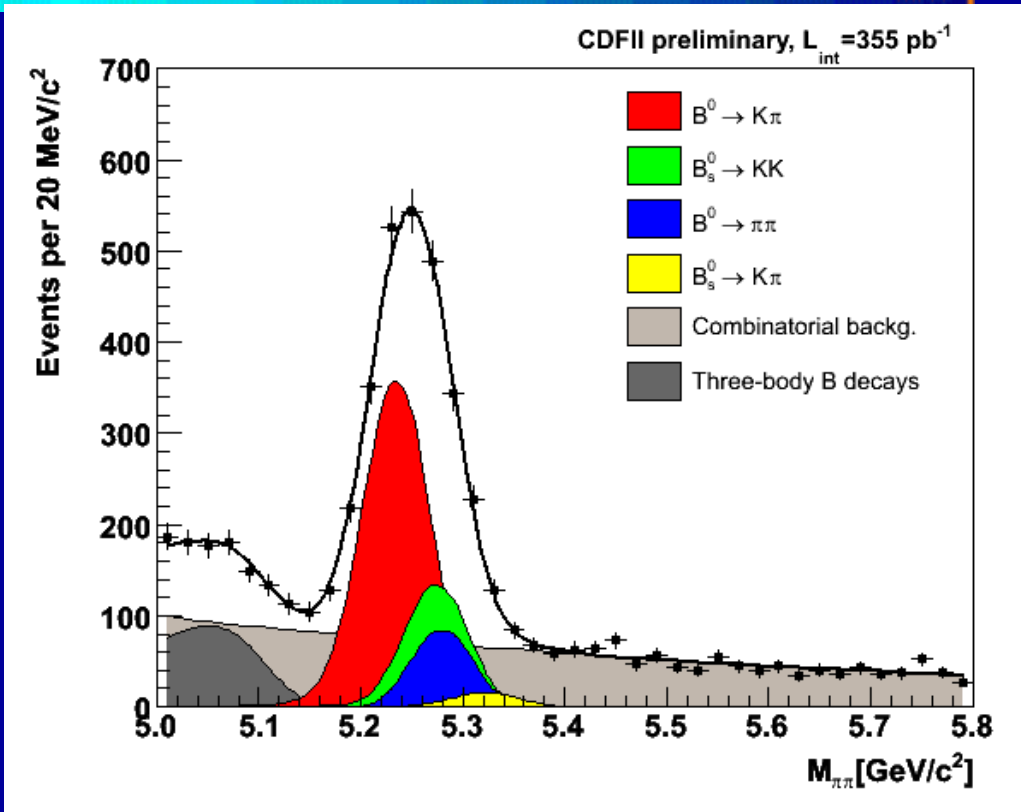
0.52 ± 0.13(stat) ± 0.06(BR) ± 0.04(syst)

0.58 ± 0.24(stat) ± 0.07(BR) ± 0.06(syst)

$B \longrightarrow h^+h^-$

- Exploit the two-track trigger sample.
- Combine mass, kinematics and PID in an unbinned maximum likelihood fit to extract the fraction of each of the expected components.
- P_T(track) > 2 GeV/c; K/π separation of 1.4σ.

  1.4σ ⟶ 1.6σ by including TOF information.



2327±77 signal events

σ = 39 ± 1 MeV/c²

$$\frac{S}{B} \cong 6.5 \text{ at peak}$$

$B_s \longrightarrow h^+h^-$

❖ B^0 sector

$$\frac{BR(B^0 \to \pi^+\pi^-)}{BR(B^0 \to K^+\pi^-)} = 0.21 \pm 0.05(stat.) \pm 0.03(syst.)$$

$$A_{CP}(B_d \to K^+\pi^-) = -0.058 \pm 0.039\,(\text{stat}) \pm 0.007\,(\text{syst})$$

$$\text{HFAG April06}: -0.115 \pm 0.018$$

❖ B_s sector

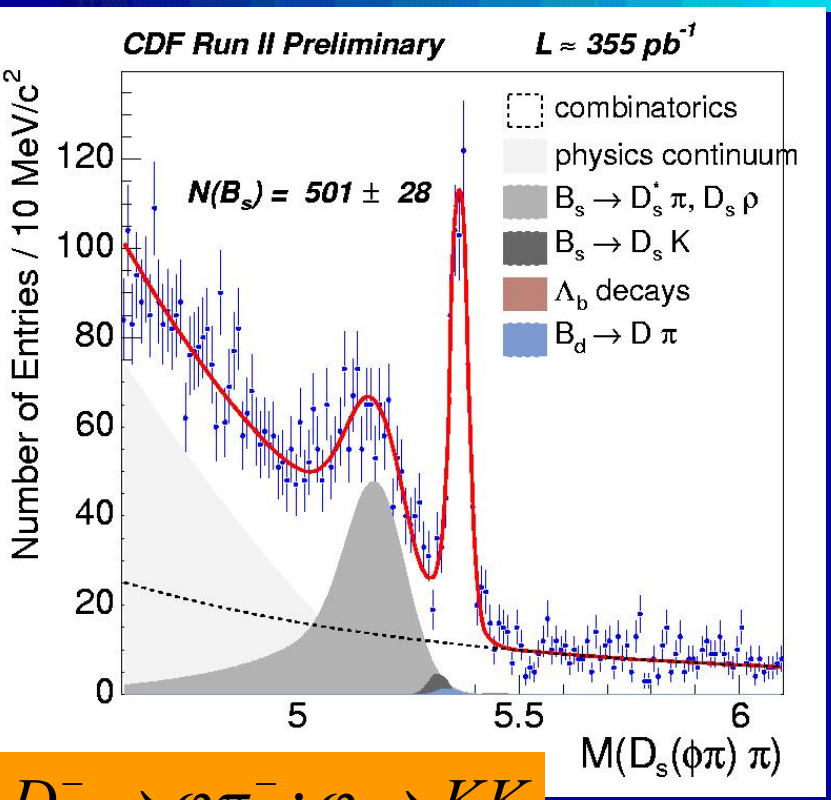
$$\frac{f_s \cdot BR(B_s^0 \to K^+K^-)}{f_d \cdot BR(B^0 \to K^+\pi^-)} = 0.46 \pm 0.08(stat.) \pm 0.07(syst.)$$

$$\frac{f_s \cdot BR(B_s^0 \to K^-\pi^+)}{f_d \cdot BR(B^0 \to K^+\pi^-)} < 0.08 @ 90\%\ C.L.$$

❖ To follow:

- Measure CP asymmetry in the B_s system
- Observe $BR(B_s \longrightarrow K\pi)$

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



$D_s^- \to \varphi\pi^-;\varphi \to KK$

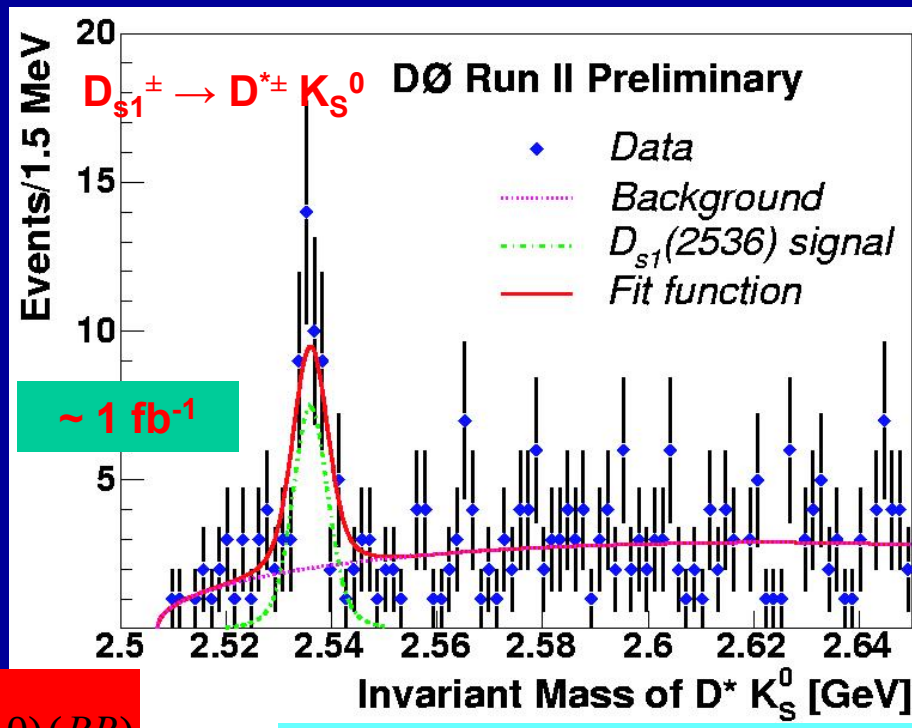
$B_s \to D_{s1}^{\pm}(2536)\mu^{\mp}\nu X$

$D_{s1}^{\pm}(2536) \to D^{*\pm}K_s^0$

$D^{*\pm} \to D^0\pi^{\pm}$

$D^0 \to K^-\pi^+$

$K_s^0 \to \pi^+\pi^-$



~ 1 fb-1

$$\frac{f_s \cdot BR(B_s \to D_s^- \pi^+)}{f_d \cdot BR(B^0 \to D^- \pi^+)} = 0.43 \pm 0.11(\text{stat}) \pm 0.03(\text{syst}) \pm (0.10)(BR)$$

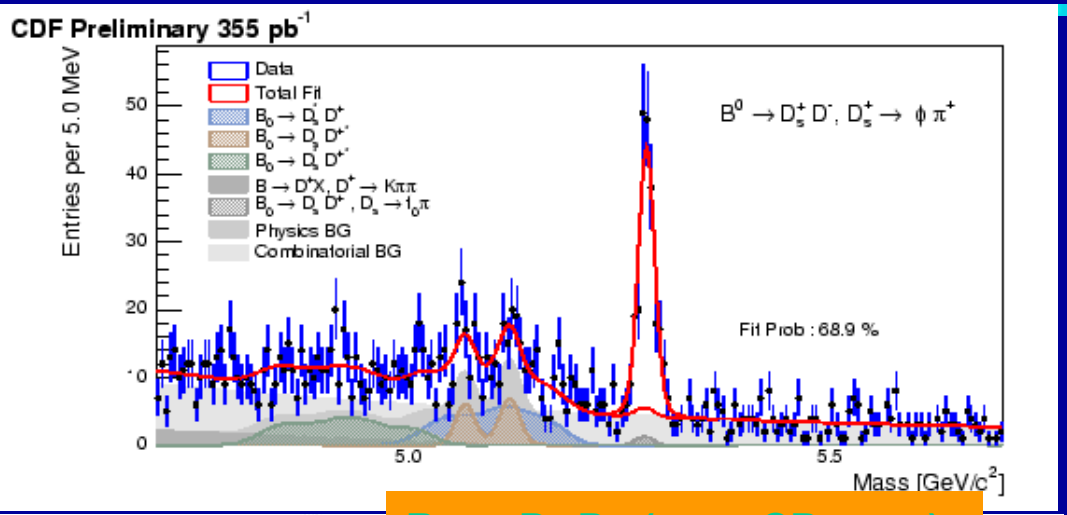
Signal: 43.8 ± 8.3 (5.2σ)

$M(D_{s1}(2536)) = 2535.7 \pm 0.6\ (\text{stat}) \pm 0.5(\text{syst})\ \text{MeV/c}^2$

$BR(B_s^0 \to D_{s1}(2536)\mu\nu X) = (0.86 \pm 0.16(\text{stat}) \pm 0.13(\text{syst}) \pm (0.09)(\text{prod. fract.}))\%$

$B_s \rightarrow D_s D_s$

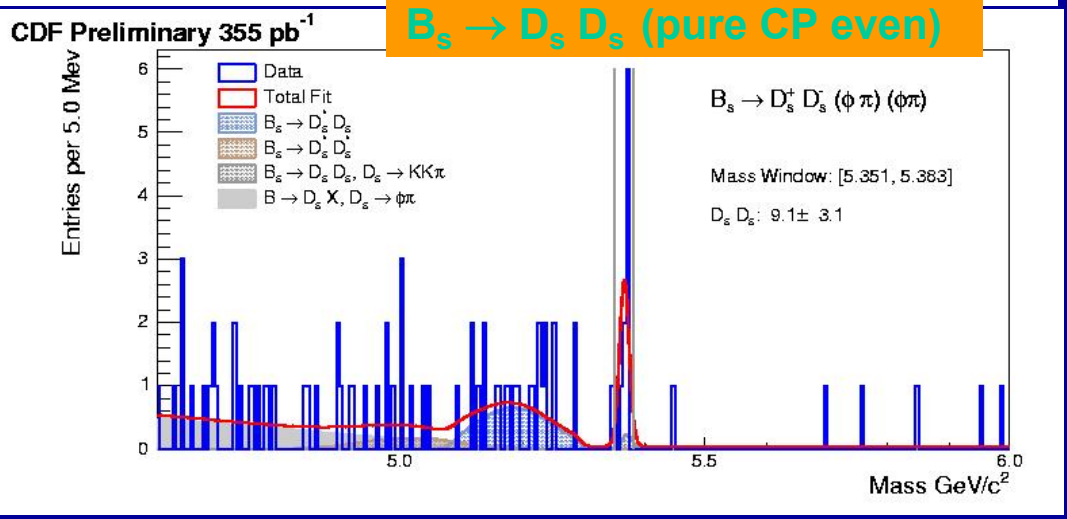
Can constrain $\Delta\Gamma/\Gamma$ by measuring branching fractions



3 D_s modes
Reconstructed
Total yield:395 events

The CP-even eigenstate is expected to decay faster. Biggest contribution to $\Delta\Gamma_s$ is coming from $B_s \rightarrow D_s^{(*)} D_s^{(*)}$

$B_s \rightarrow D_s D_s$ (pure CP even)



3 D_s modes
Reconstructed
Total yield:23 events

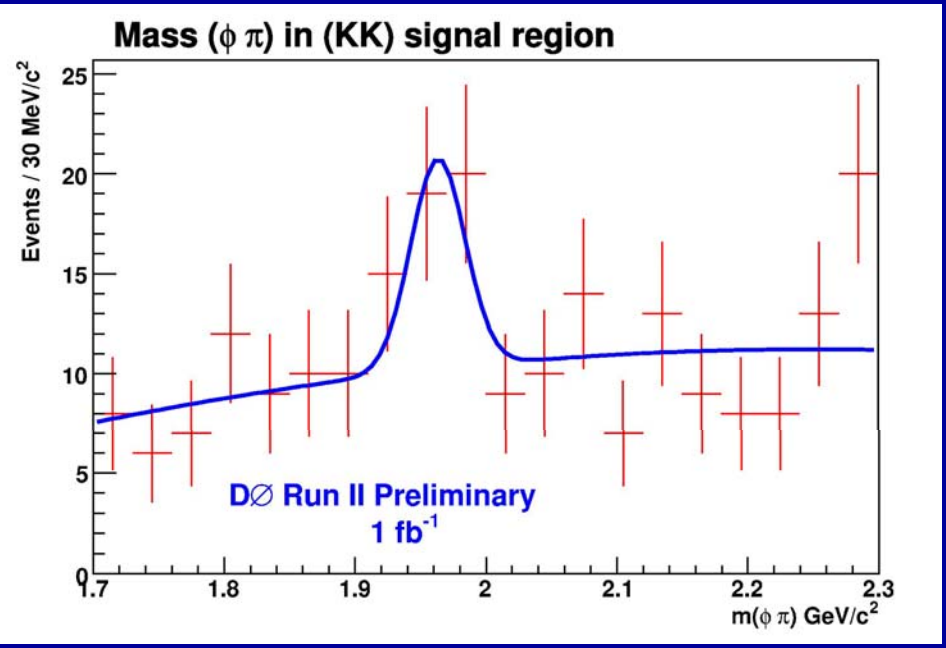
$$\frac{BR(B_s^0 \rightarrow D_s D_s)}{BR(B_d^0 \rightarrow D_s D^+)} = 1.67 \pm 0.41(stat) \pm 0.12(sys) \pm 0.24\left(\frac{f_s}{f_d}\right) \pm 0.39(BR)$$

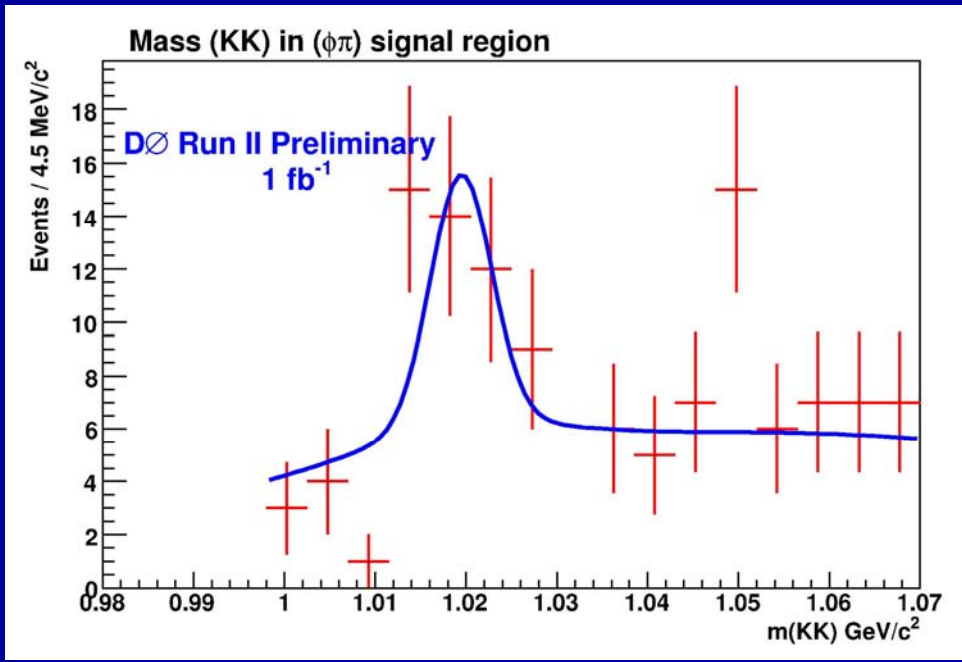
$B_s \rightarrow D_s^{(*)} D_s^{(*)}$

Run II, ~1 fb^{-1}

Can constrain $\Delta\Gamma/\Gamma$ by measuring branching fractions

Reconstruct one D_s decaying to $\phi\pi$ and another D_s to $\mu\nu\phi$



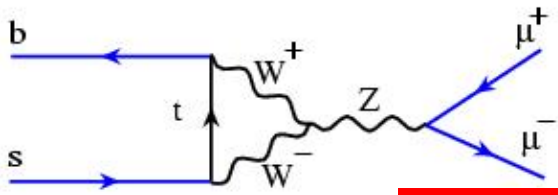


$$BR(B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}) = 0.071 \pm 0.032(stat)\,^{+0.029}_{-0.025}\,(syst)$$

$$\frac{\Delta\Gamma_{CP}}{\Gamma}(B_s) = 0.142 \pm 0.064(stat)\,^{+0.058}_{-0.050}\,(syst)$$

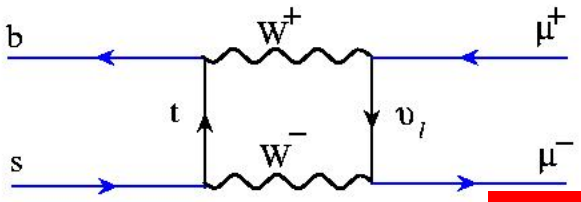
$B_{s(d)} \rightarrow \mu\mu$

Sensitive probe of New Physics

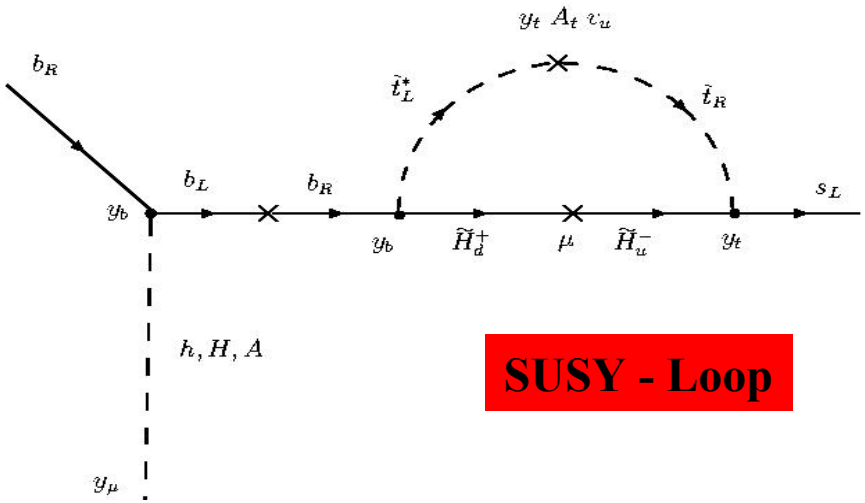


SM penguin

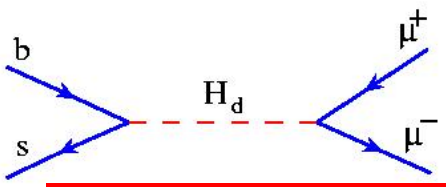
BR prediction: (3.5±0.9) x 10^{-9}



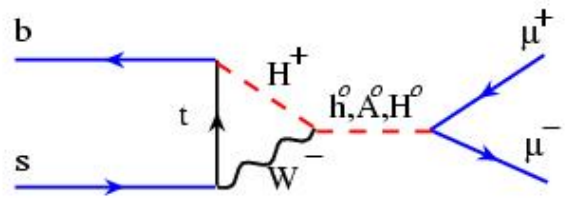
SM box



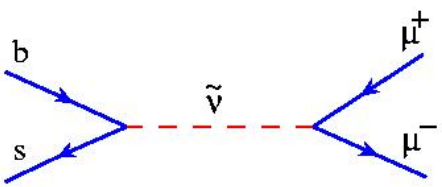
SUSY - Loop



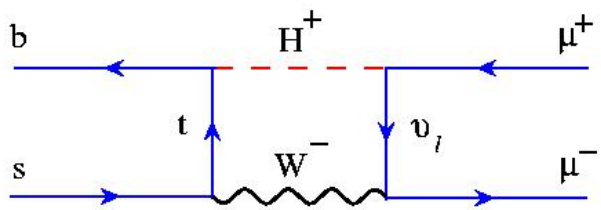
Higgs mediated - tree



2HDM - penguin



R parity violating

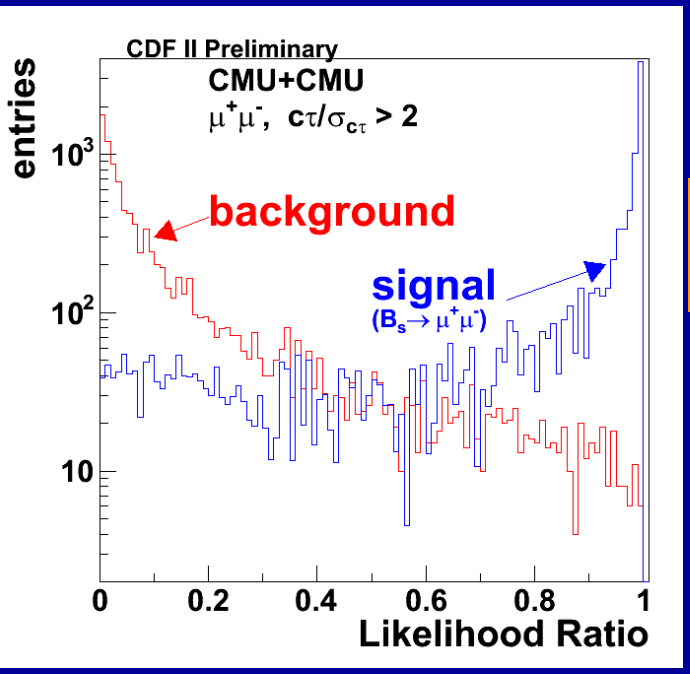


2HDM - box

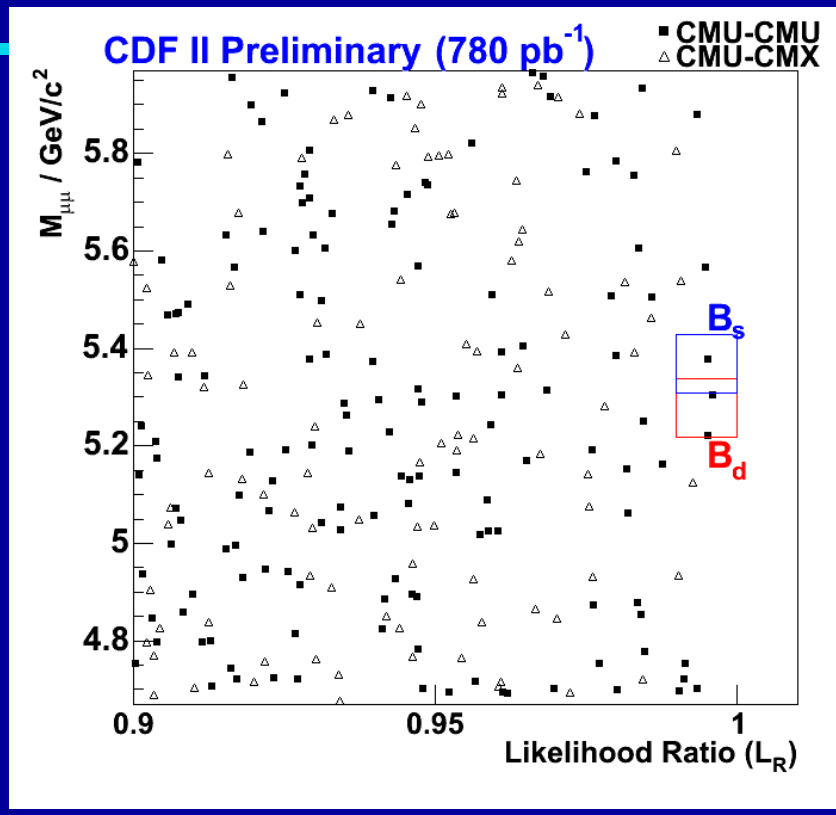
See talk by Flera Rizatdinova

$B_{s(d)} \rightarrow \mu\mu$

Multi-variate Relative Likelihood Discriminant



$p_T(B) > 4$ GeV/c
LH > 0.99



N_{bkg} expected: 0.88±0.30
ses: (3.9±0.7) x 10^{-8}

CMU-CMU

N_{bkg} expected: 0.39±0.21
ses: (6.2±1.0) x 10^{-8}

CMU-CMX

comb. ses: 0.607 x 10^{-7}

$BR(B_s \rightarrow \mu\mu) < 8 \times 10^{-8}$ 90% CL

$BR(B_s \rightarrow \mu\mu) < 1.0 \times 10^{-7}$ 95% CL

$BR(B_d \rightarrow \mu\mu) < 2.3 \times 10^{-8}$ 90% CL

$BR(B_d \rightarrow \mu\mu) < 3.0 \times 10^{-8}$ 95% CL

apadi

B_c meson

B_c meson

$B_c^{\pm}$

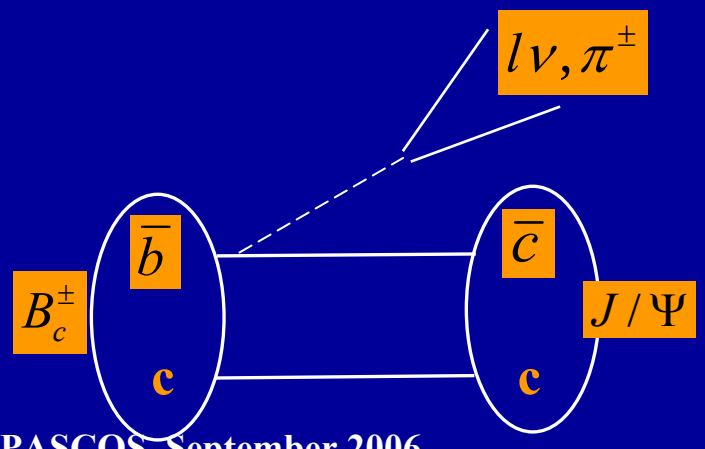
Heaviest ground state of two different quarks

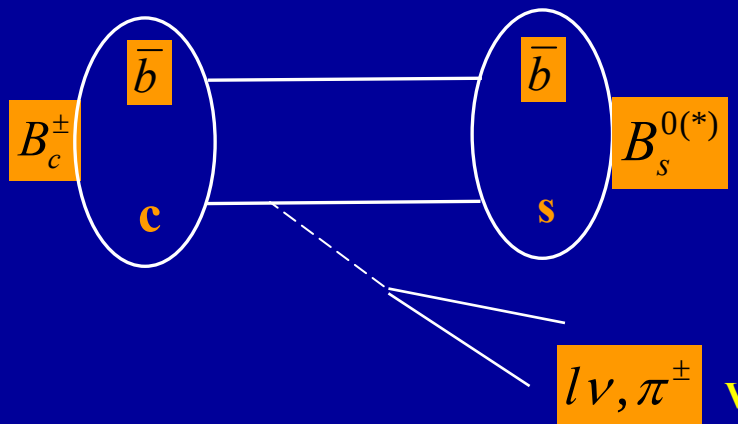
species	~ prod. fraction
$B^{\pm}$	40%
B_0	40%
B_s	10%
b-baryons	10%
B_c	~0.05%

Latest cross section calculation: 7.4 nb
Phys. Lett. B605, 311 (2005)

Rich spectroscopy

It decays weakly





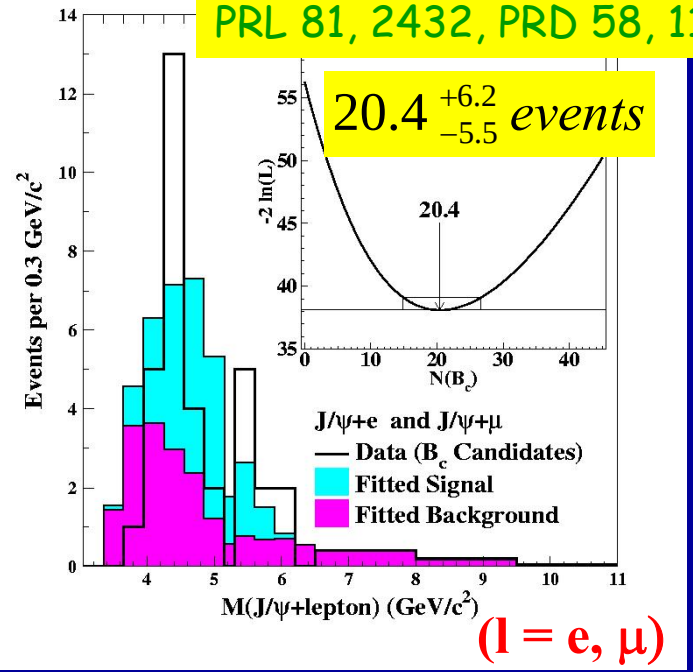
Vaia Papadimitriou

$B_c^{\pm} \rightarrow J/\Psi l^{\pm} \nu$

Run I, 110 pb^{-1}

Run II, 210 pb^{-1}

PRL 81, 2432, PRD 58, 112004 (1998)



$M(B_c) = 6.40 \pm 0.39\,(stat) \pm 0.13(syst)\ GeV/c^2$

$$c\tau(B_c) = 0.46^{+0.18}_{-0.16} \pm 0.03\ ps$$

$P_T(B) > 6\,GeV/c; |\eta| < 0.6$

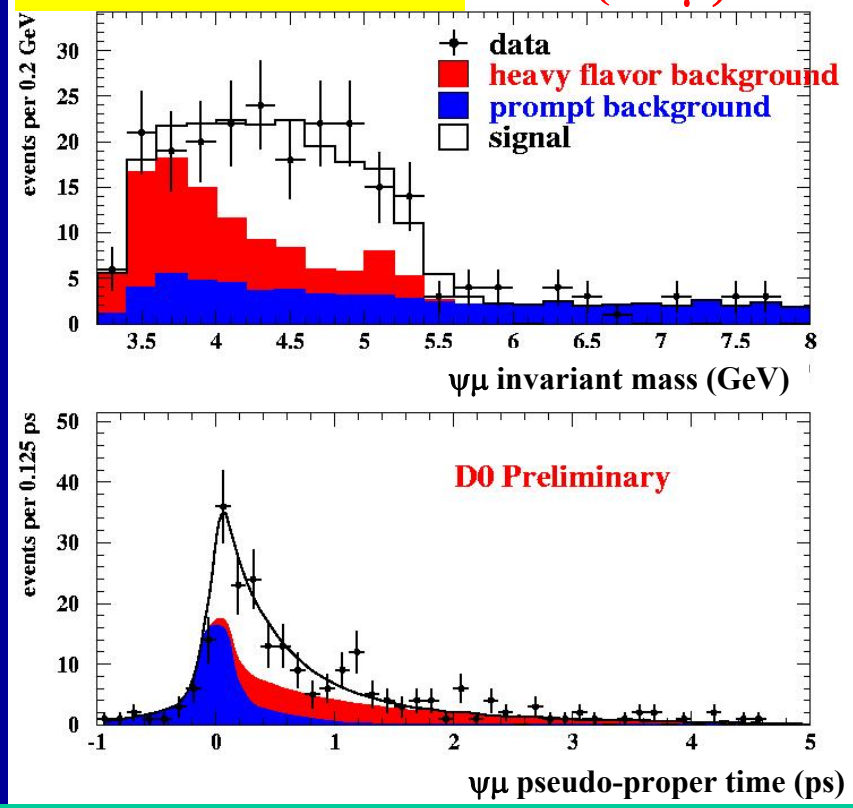
$\sigma(B_c) \times B(B_c \rightarrow J/\psi \ell \nu)$

$\sigma(B_u) \times B(B_u \rightarrow J/\psi K)$

$$= 0.132^{+0.041}_{-0.037}(stat) \pm 0.031(syst)^{+0.032}_{-0.020}(c\tau)$$

95 ± 12 ± 11 events

(l = μ)



$M(B_c) = 5.95 \pm 0.14\,(stat) \pm 0.34(syst)\ GeV/c^2$

$$c\tau(B_c) = 0.448^{+0.123}_{-0.096}(stat) \pm 0.121(syst)\,ps$$

ICHEP 2004

Vaia Papadimitriou

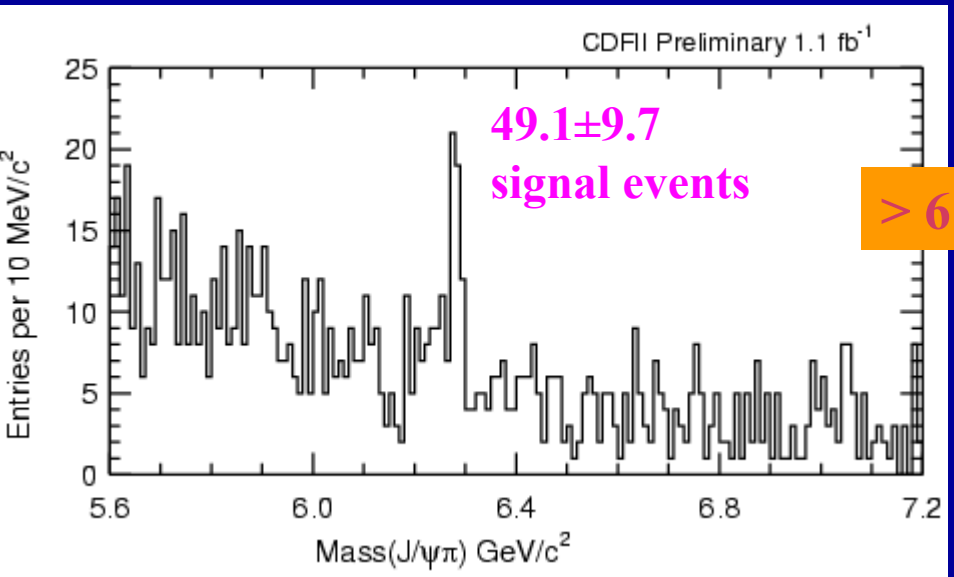
$B_c^{\pm} \rightarrow J/\Psi\pi^{\pm}$

Run II, 1.1 fb^{-1}

- Evidence and mass measurement

Run II, 360 pb^{-1}

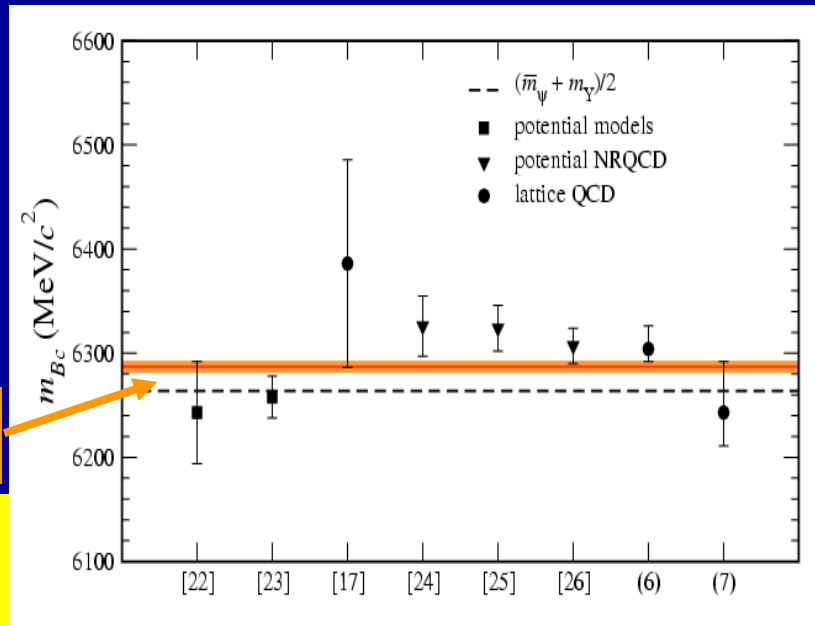
PRL 96, 082002 2006



$M(B_c) = 6276.5 \pm 4.0\,(stat) \pm 2.7(syst)$ MeV/c^2

- New CDF analysis
  - control sample 11.3 K

    $B_u^{\pm} \longrightarrow J/\psi K^{\pm}$



This result

Theory in very good agreement
Potential models, NRQCD, LQCD

$B_c^{\pm} \rightarrow J/\Psi e^{\pm}\nu$

Run II, 360 pb^{-1}

Background :

63.6±4.9(stat.)±13.6(syst.)

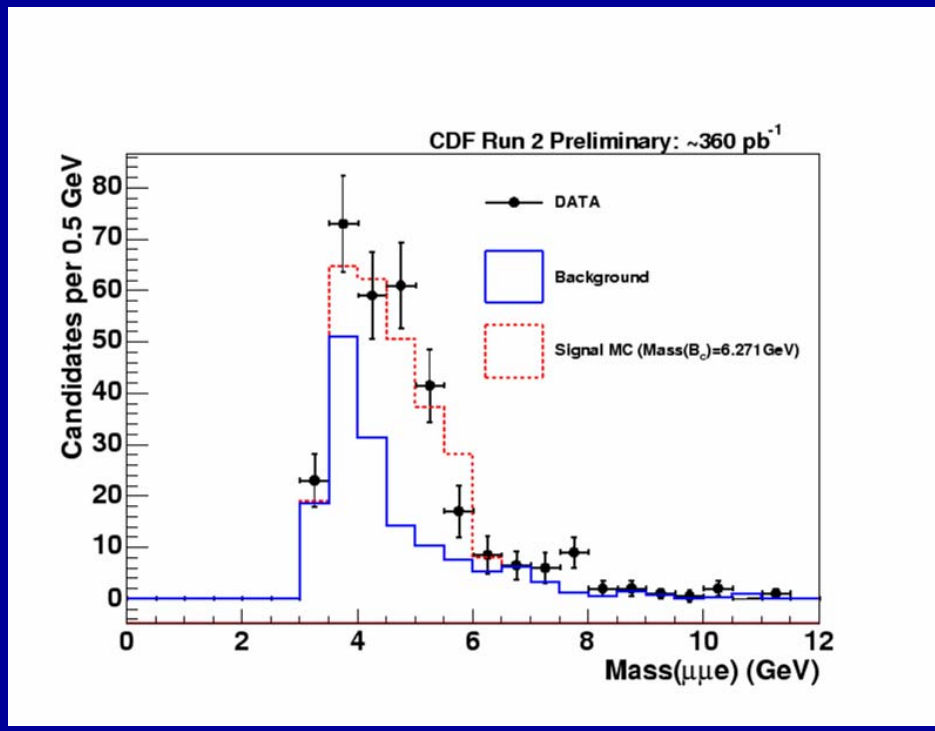
Observe :

178.5±14.7(stat.)

Excess :

114.9±15.5(stat.) ±13.6(syst.)

Significance : 5.9σ



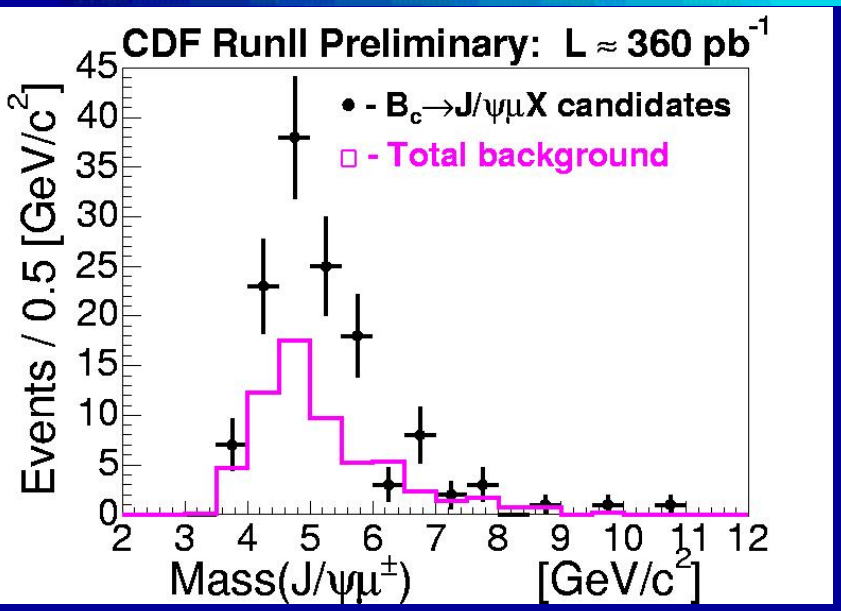
$$\frac{\sigma(B_c^+)\times BR(B_c^+ \rightarrow J/\psi e^+\nu)}{\sigma(B^+)\times BR(B^+ \rightarrow J/\psi K^+)}$$

- Cross section ratio is defined within the kinematical limits
  - $p_T(B) > 4.0\text{GeV}$, $|y(B)| < 1.0$

σ_{ratio}=0.282±0.038(stat.)±0.074(syst.)

$B_c^{\pm} \rightarrow J/\Psi \mu^{\pm} \nu$

Run II, 360 pb^{-1}

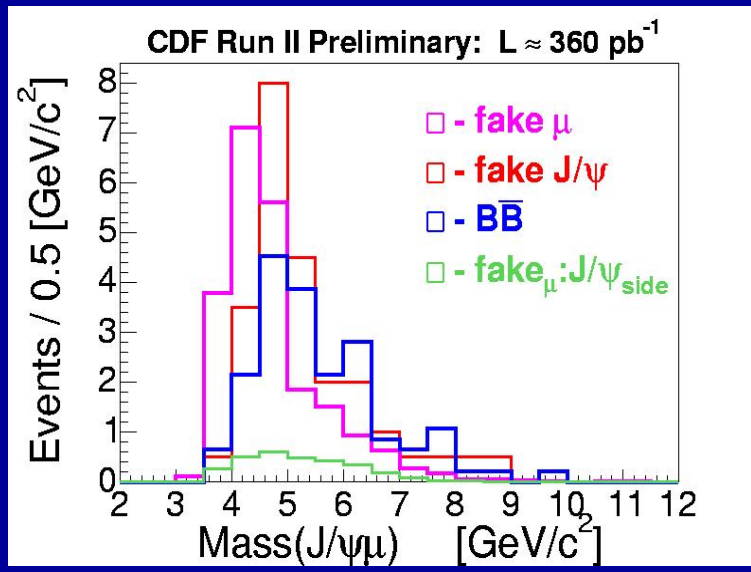


Background : 44.9±7.3

Observe : 104±10.2

Excess : 59.1 ±12.5

Significance : 5.2σ



$$\frac{\sigma(B_c^+) \times BR(B_c^+ \rightarrow J/\psi \mu^+ \nu)}{\sigma(B^+) \times BR(B^+ \rightarrow J/\psi K^+)}$$

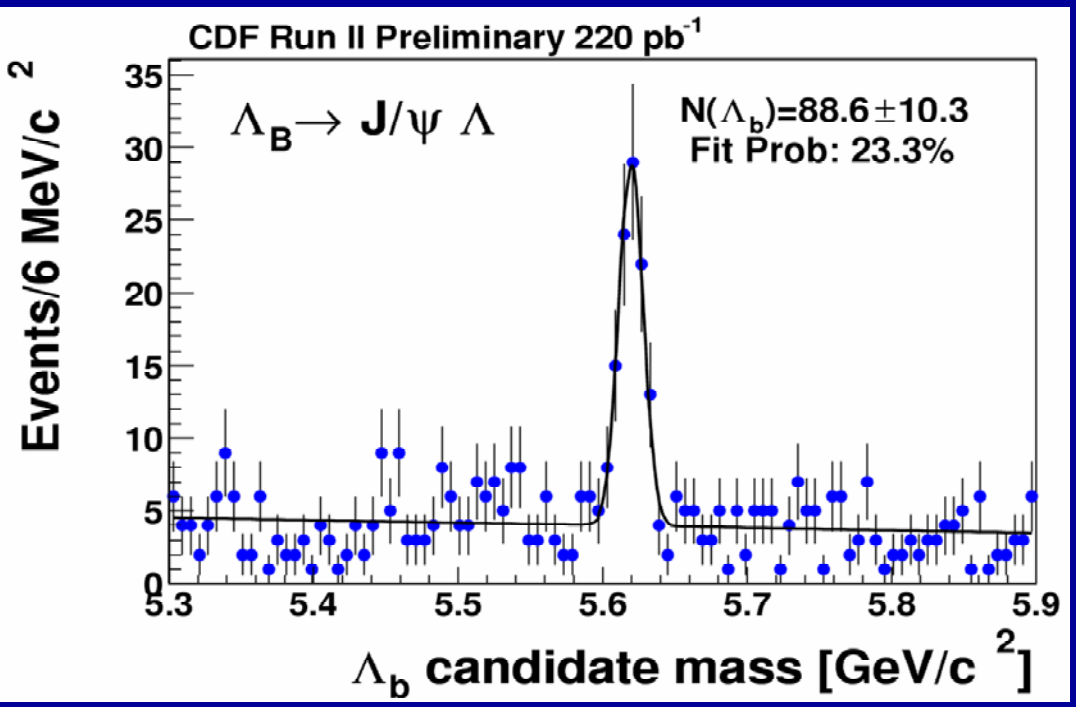
- Cross section ratio is defined within the range
  - $p_T(B) > 4.0\text{GeV}$, $|y(B)| < 1.0$

$$\sigma_{ratio} = 0.249 \pm 0.045(stat.)^{+0.107}_{-0.076}(syst.)$$

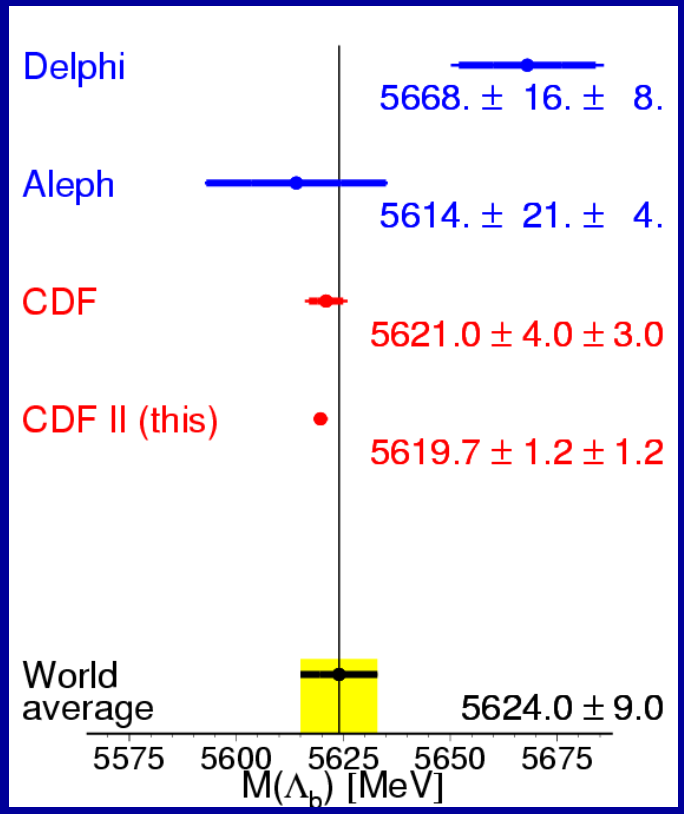
b-Baryons

b - Baryons

Λ_b mass



Λ_b mass



PRL 96, 202001 2006

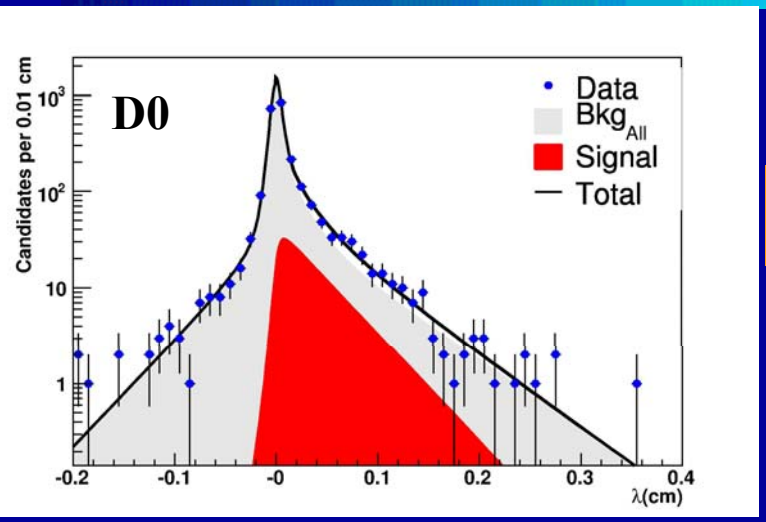
Source	$B^0 \rightarrow J/\psi K^0_s$	$\Lambda_b \rightarrow J/\psi \Lambda$
Tracking & Corrections		
momentum scale	0.2	0.2
Tracking	1.0	from $B^0 \rightarrow J/\psi K^0_s$
Fitting	0.7	from $B^0 \rightarrow J/\psi K^0_s$
Total Systematic Uncertainty	1.2	1.2

MeV

Λ_b^0 Lifetime

$\Lambda_b \to J/\psi \Lambda^0 ; J/\psi \to \mu\mu ; \Lambda^0 \to p\pi^-$

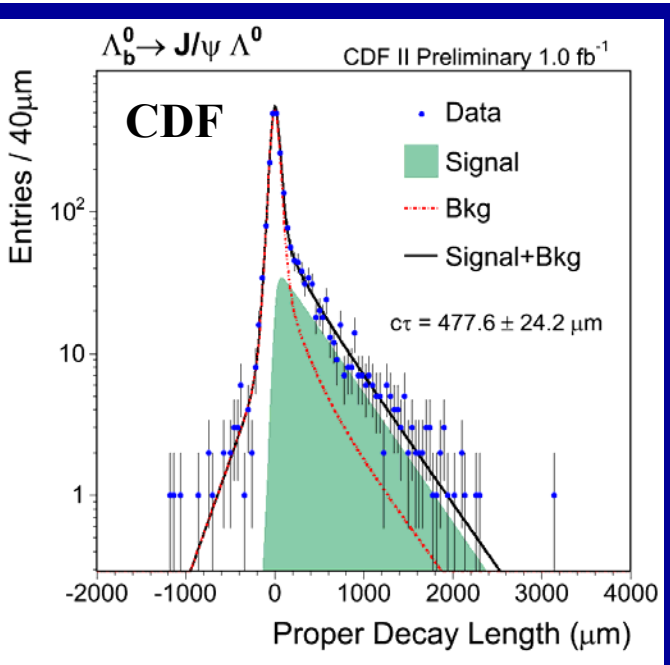
Run II, 1 fb^{-1}



$$\tau(\Lambda_b) = 1.298 \pm 0.137\,(\text{stat}) \pm 0.050\,(\text{syst})\,\text{ps}$$

$$\tau(B^0) = 1.492 \pm 0.075\,(\text{stat}) \pm 0.047\,(\text{syst})\,\text{ps}$$

$$\tau(\Lambda_b)/\tau(B^0) = 0.870 \pm 0.102\,(\text{stat}) \pm 0.041\,(\text{syst})$$



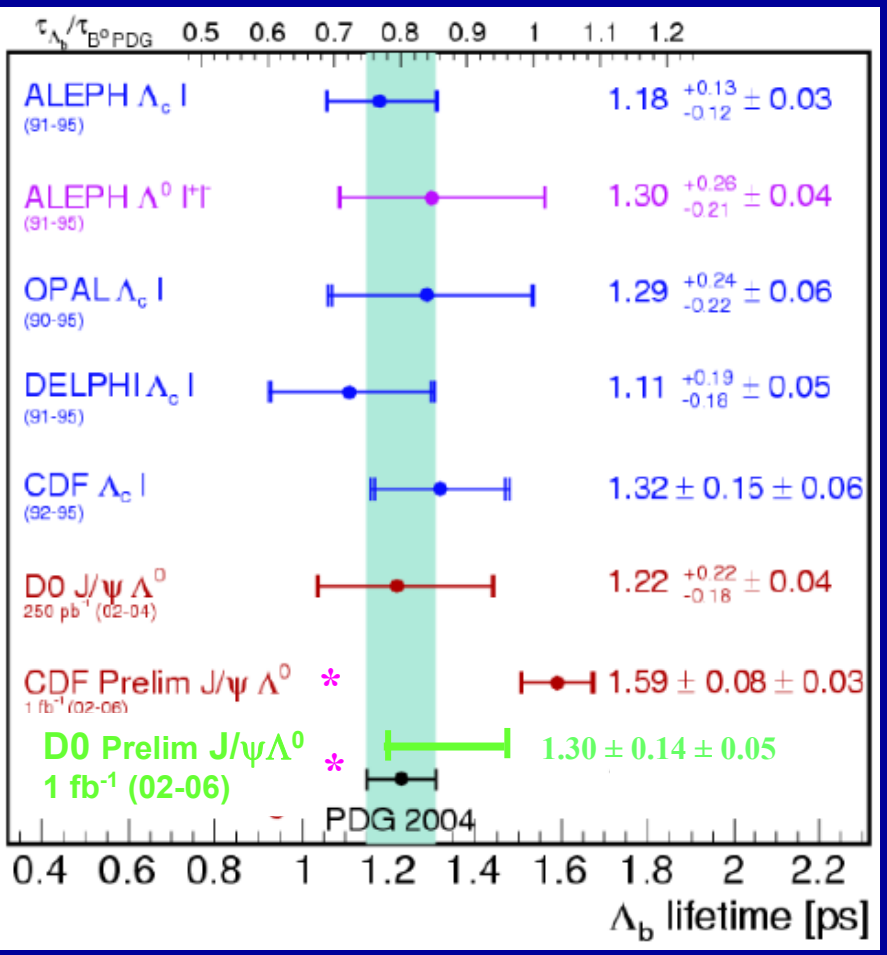
$$\tau(\Lambda_b) = 1.593\,^{+0.083}_{-0.078}\,(\text{stat}) \pm 0.033\,(\text{syst})\,\text{ps}$$

$$\tau(B^0) = 1.524 \pm 0.030\,(\text{stat}) \pm 0.016\,(\text{syst})\,\text{ps}$$

$$\tau(\Lambda_b)/\tau(B^0) = 1.037 \pm 0.058\,(\text{stat} + \text{syst})$$

Vaia Papadimitriou

Λ_b^0 Lifetime



(NLO) Gabbiani et al., hep-ph/0407004 Oct.2004

❖ $\tau(\Lambda_b)/\tau(B^0) = 0.86 \pm 0.05$ theory

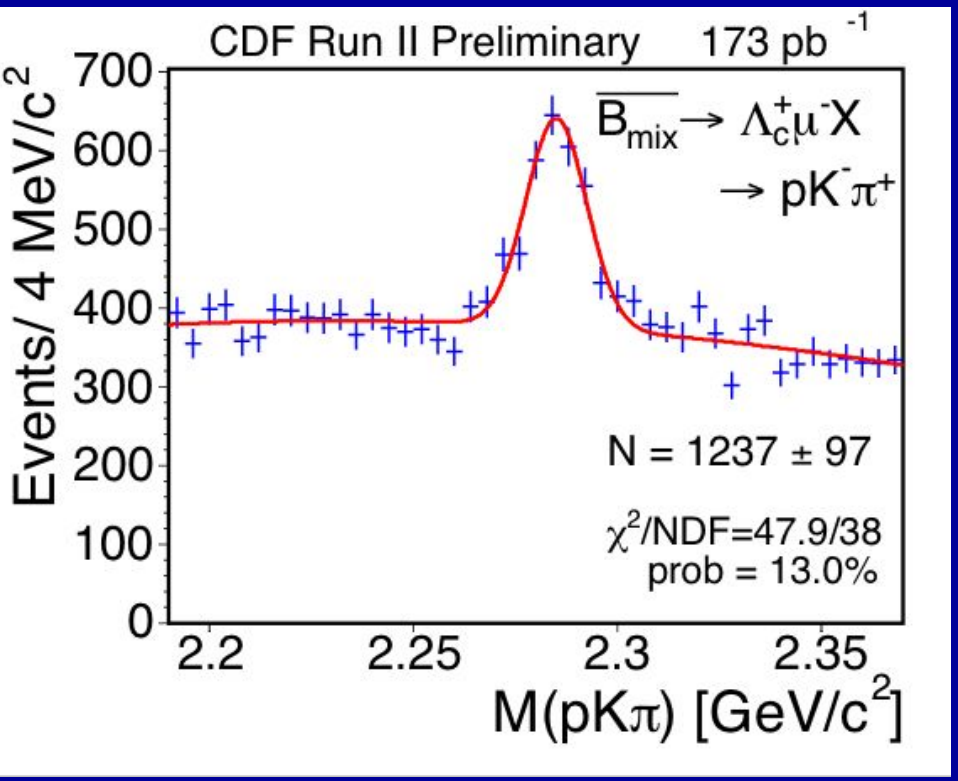
Branching Ratios

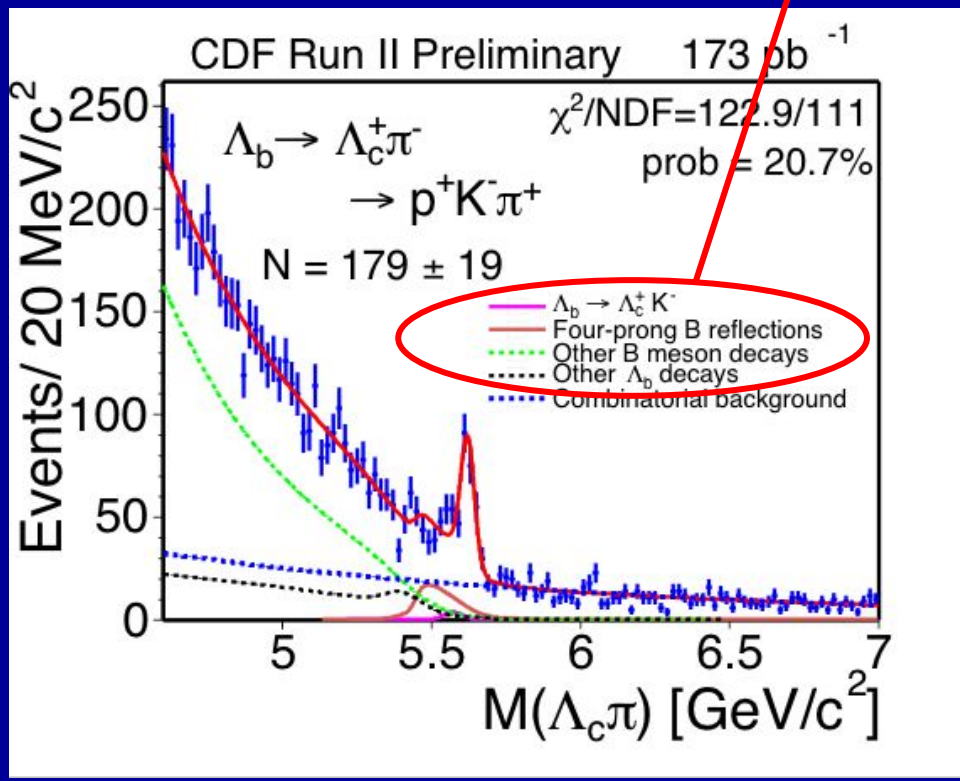
Signal Sample: $\Lambda_b \to \Lambda_c X$; $\Lambda_c \to p^+ K^- \pi^+$

Inclusive Semileptonic Signal

Hadronic Signal

from MC

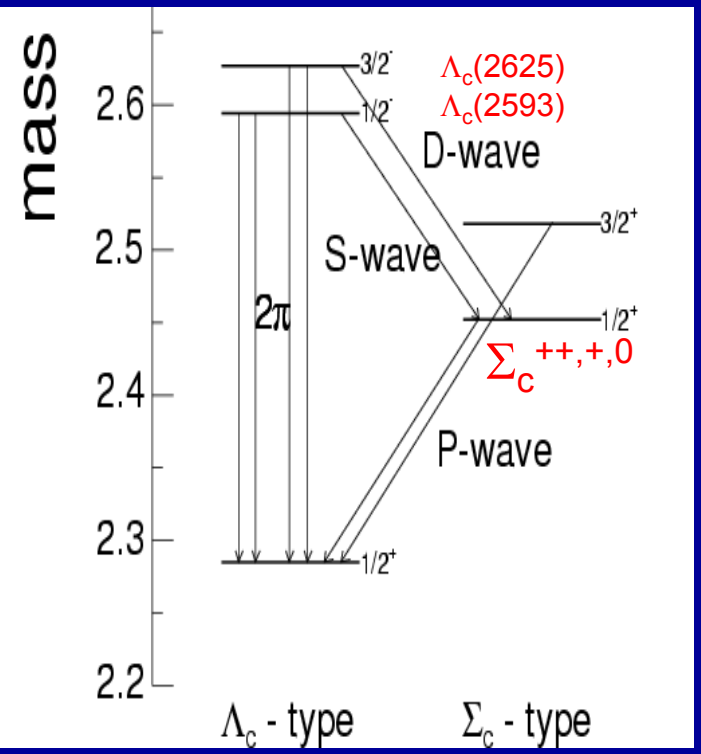




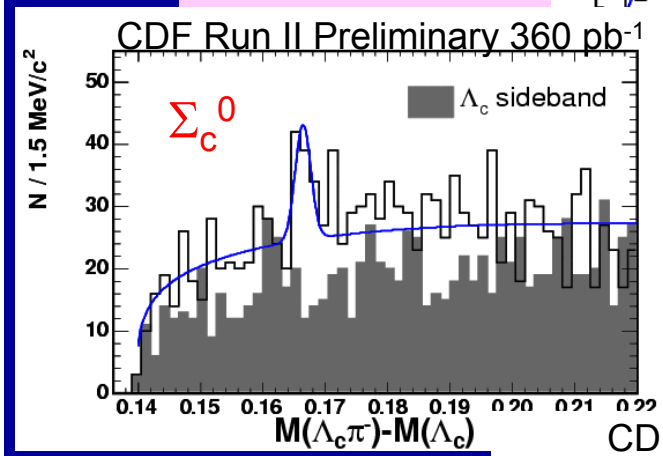
$$\frac{\mathcal{B}(\Lambda_b \to \Lambda_c^+ \mu^- \overline{\nu}_\mu)}{\mathcal{B}(\Lambda_b \to \Lambda_c^+ \pi^-)} = 20.0 \pm 3.0\ (stat) \pm 1.2\ (syst)\ ^{+0.7}_{-2.1}\ (BR) \pm 0.5\ (UBR)$$

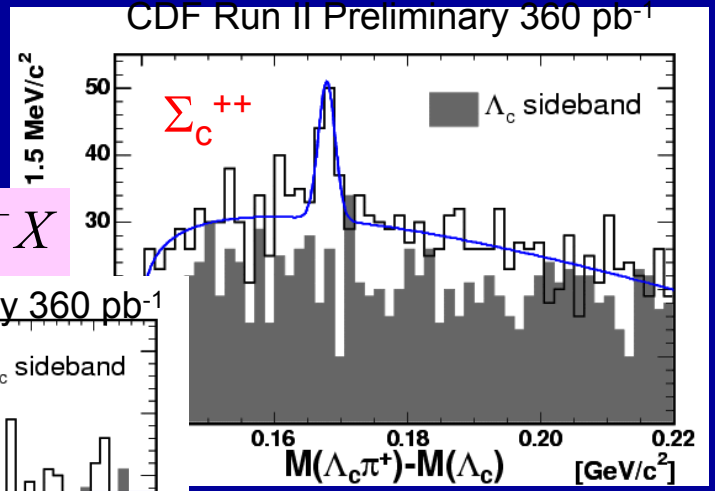
Source of semileptonic backgrounds

$\Lambda_b \to \Sigma_c^{++} \pi^- \mu^- X$

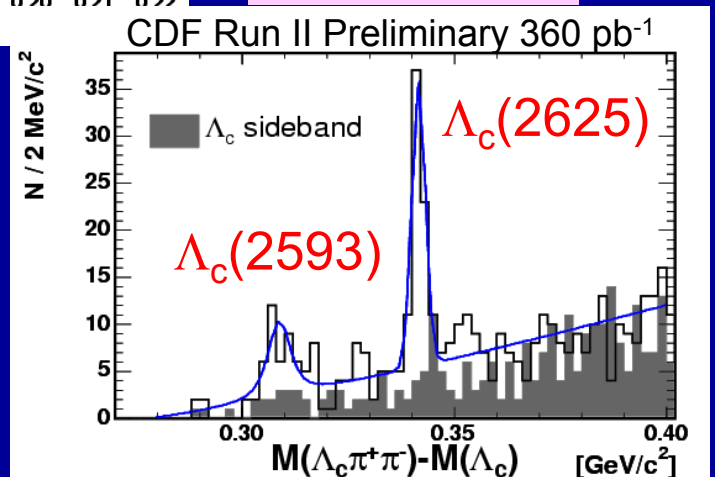


$\Lambda_b \to \Sigma_c^0 \pi^+ \mu^- X$





$\Lambda_b \to \Lambda_c^{*+} \mu^- X$

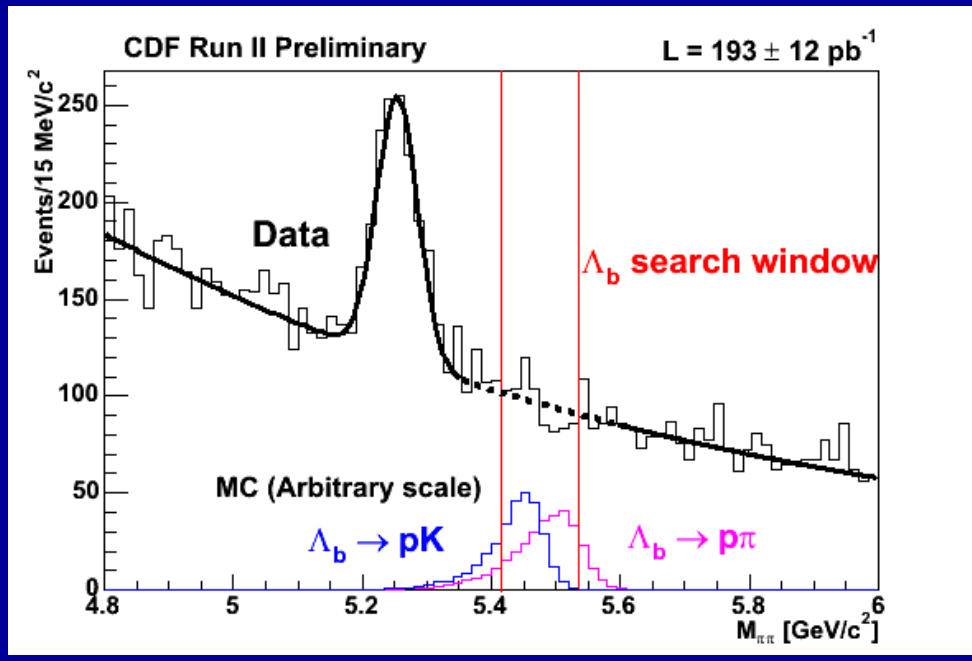


First observation of several Λ_b semileptonic decays that can 'mimic' the signal

Branching Ratios

Signal Sample: $\Lambda_b \rightarrow p^+\pi^-$ and $\Lambda_b \rightarrow p^+K^-$

- Predictions for BR are in the range $1 \times 10^{-6} - 2 \times 10^{-6}$
- Large direct CP violation expected (Z. Phys. C56 (1992) 129)
- Exploit the two-track trigger sample
- Use $B^0 \longrightarrow K\pi$ for normalization
- Backgrounds are combinatorial and from the tail of $B \longrightarrow hh$
- $BR(\Lambda_b \longrightarrow ph) < 2.3 \times 10^{-5}$ @ 90% C.L. **h = K, π**



$f_\Lambda/f_d = 0.25 \pm 0.04$

Updated knowledge for Λ_b

Mass m = 5619.9 ± 1.7 MeV/c²

Mean life $\tau = (1.230 \pm 0.074) \times 10^{-12}$ s

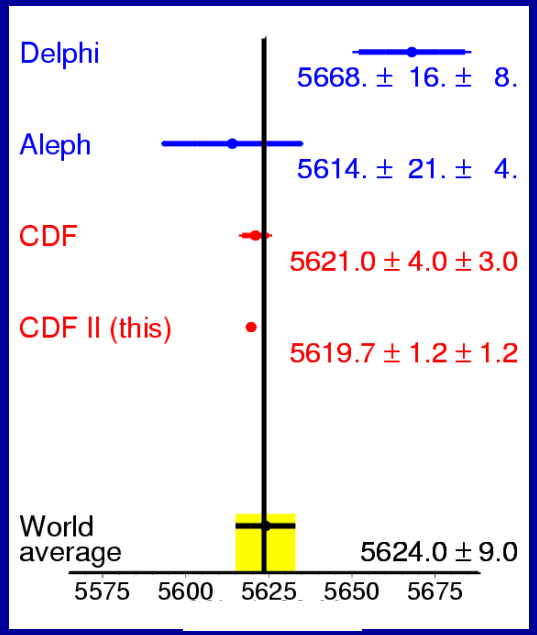
$c\tau = 368.3$ μm

Λ_b^0 DECAY MODES	Fraction (Γ_i/Γ)
$J/\psi(1S)\Lambda$	$(4.7 \pm 2.8) \times 10^{-4}$
$\Lambda_c^+ \pi^-$	$(4.1 \pm 2.0) \times 10^{-3}$
$\Lambda_c^+ a_1(1260)^-$	seen
$\Lambda_c \ell \upsilon$	(5.0 ± 1.7) %
$pK + p\pi$	$< 2.2 \times 10^{-5}$
$\Lambda_c^+ \pi^- \pi^- \pi^+$	seen
$\Lambda\gamma$	$< 1.3 \times 10^{-3}$
$\Lambda_c(2593)^+ \ell \upsilon$	seen
$\Lambda_c(2625)^+ \ell \upsilon$	seen
$\Sigma_c^{++} \pi^- \ell \upsilon$	seen
$\Sigma_c^0 \pi^+ \ell \upsilon$	seen

Colors:

- PDG2004
- CDF & D0 contribution beyond PDG2004

Λ_b mass

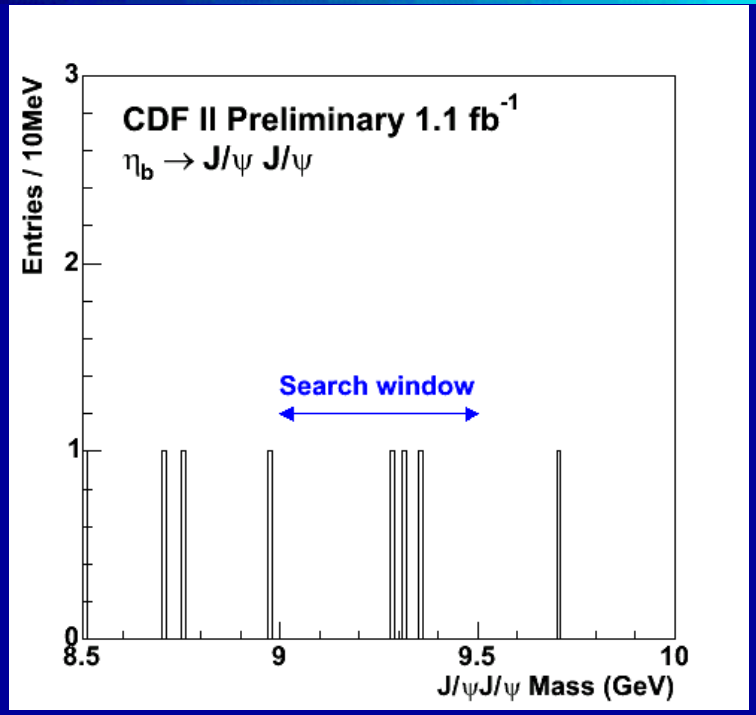


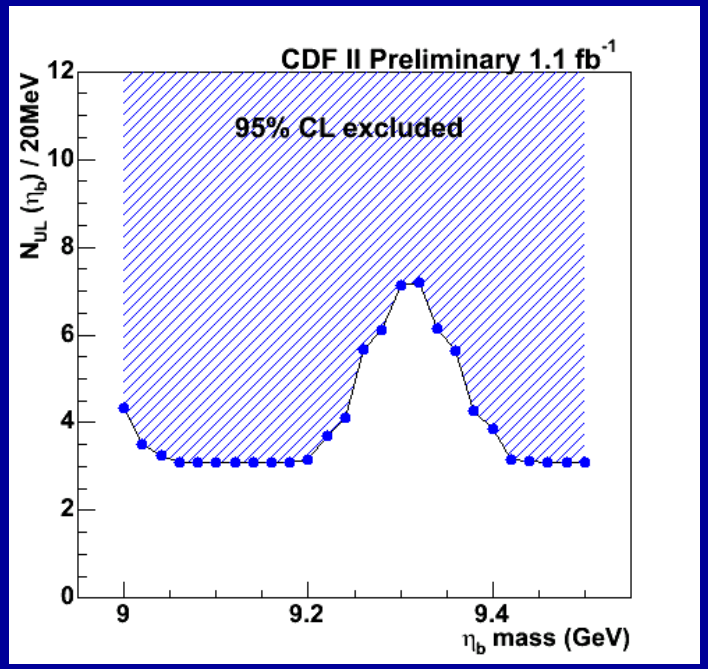
Quarkonia

Quarkonia

η_b search

Run II, 1.1 fb^{-1}





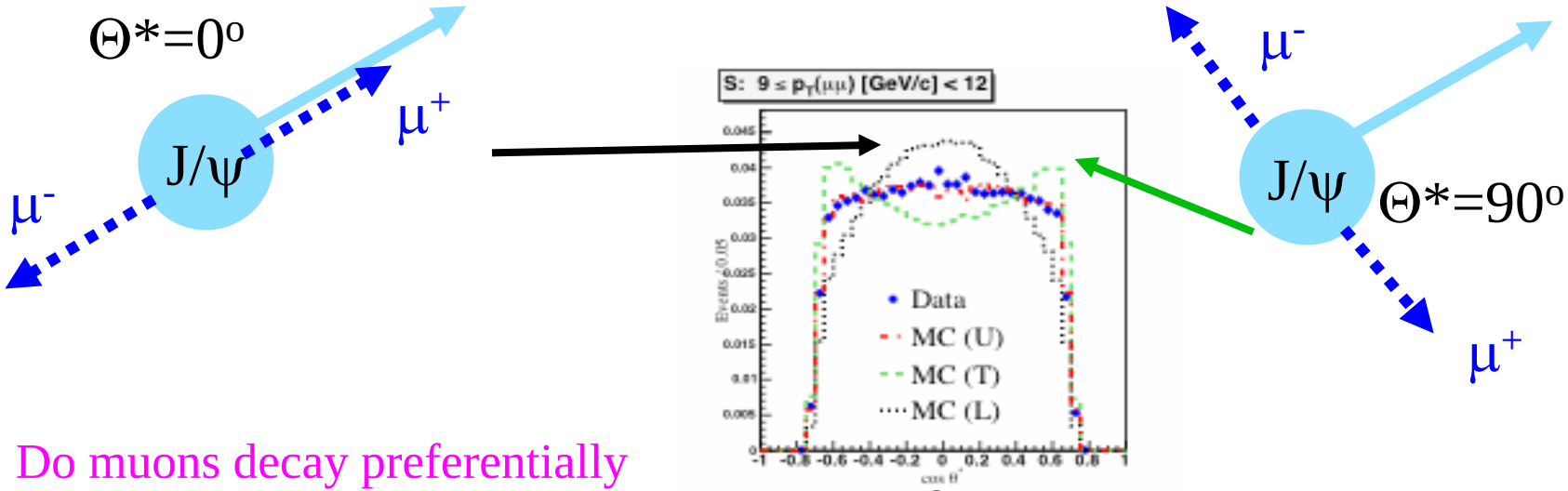
$$\frac{\sigma(p\bar{p} \to \eta_b X; |y(\eta_b)| < 0.6, p_T(\eta_b) > 3.0GeV) \cdot Br(\eta_b \to J/\psi J/\psi)}{\sigma(p\bar{p} \to H_b \to J/\psi X); |y(J/\psi)| < 0.6, p_T(J/\psi) > 3.0GeV)} < 5.0 \times 10^{-3}$$

$$\sigma(p\bar{p} \to b \to J/\psi X, |y(J/\psi)| < 0.6, p_T(J/\psi) > 3GeV) = 0.152 \pm 0.005 \pm 0.015\ \mu b$$

$$\sigma(p\bar{p} \to \eta_b X, |y(\eta_b)| < 0.6, p_T(\eta_b) > 3GeV) \cdot Br(\eta_b \to J/\psi J/\psi) \cdot [Br(J/\psi \to \mu\mu)]^2 < 2.6\ pb$$

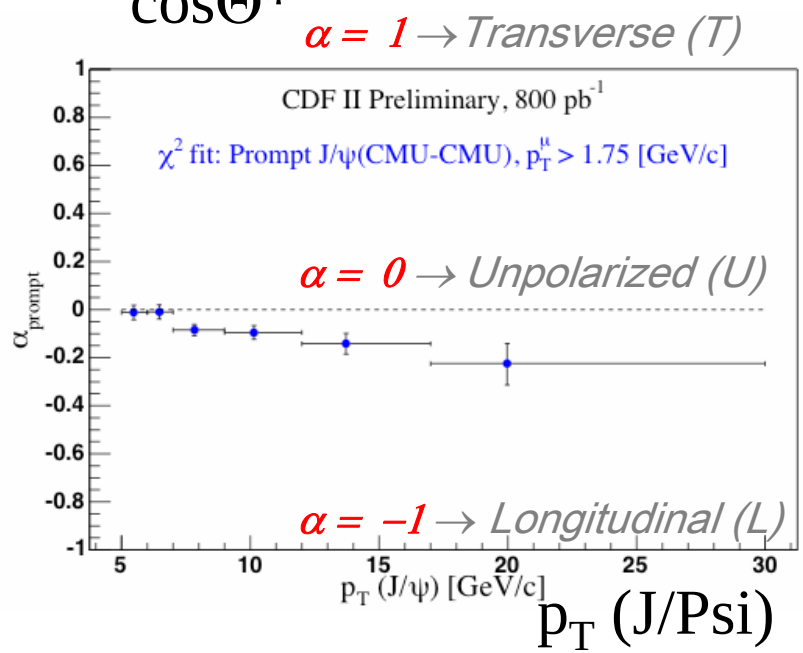
J/ψ Spin Alignment

Run II, 800 pb^{-1}



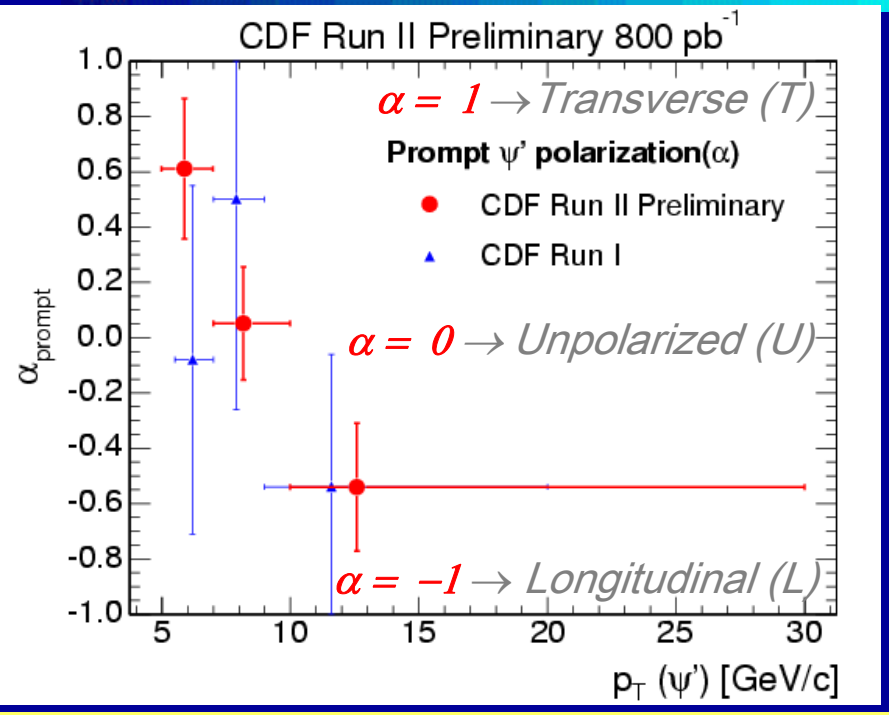
- Do muons decay preferentially into any direction?

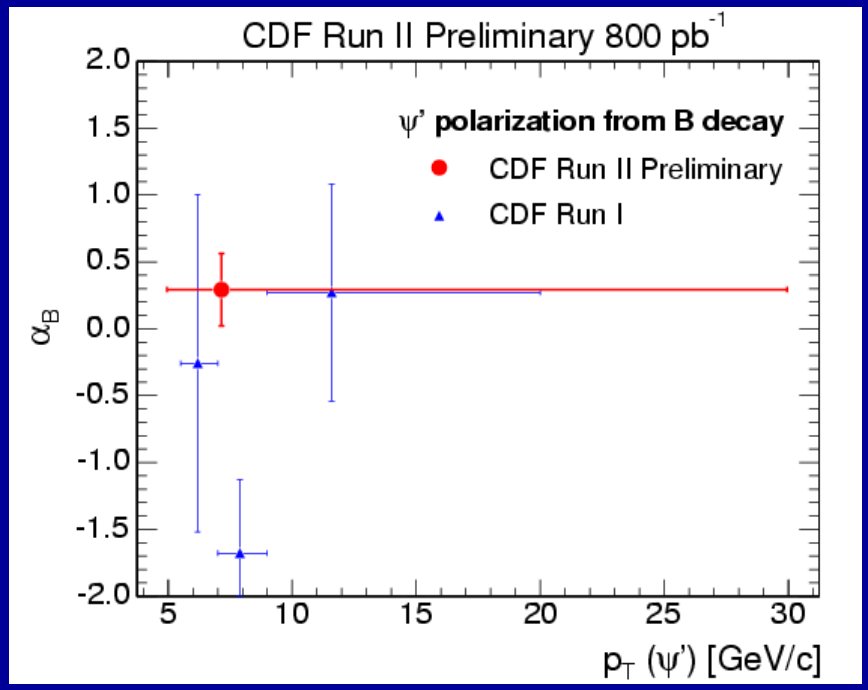
- CDF data prefer slight longitudinal polarization:
  - Challenges color-octet models
    - NRQCD prefers transverse polarization
  - Predicted by Khoze, Martin, Ryskin, Stirling:
    - Eur. Phys. J. C39, 163 (2005)



ψ(2S) Spin Alignment

Run II, 800 pb^{-1}



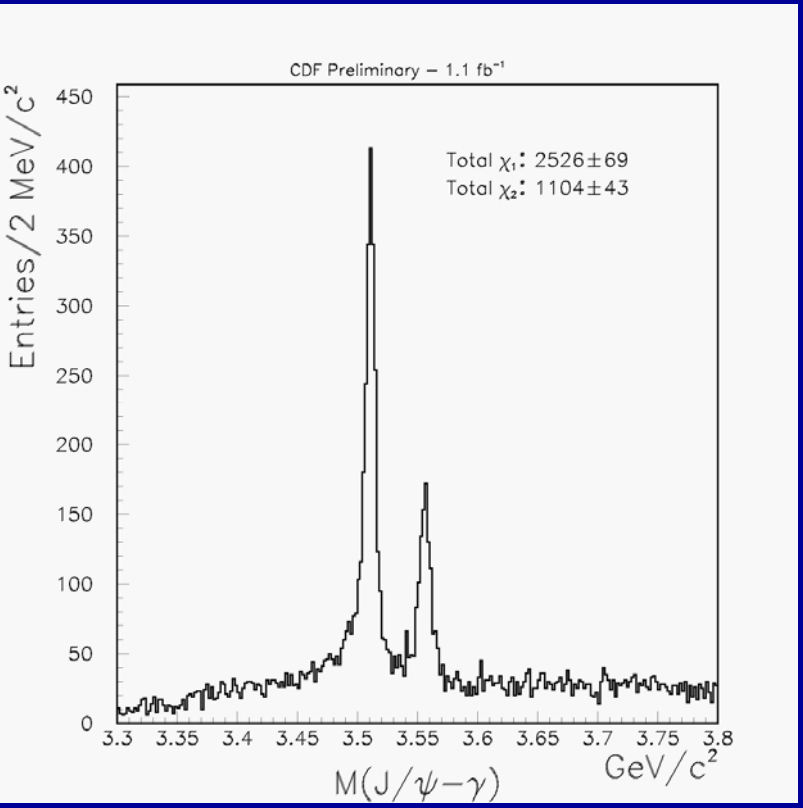


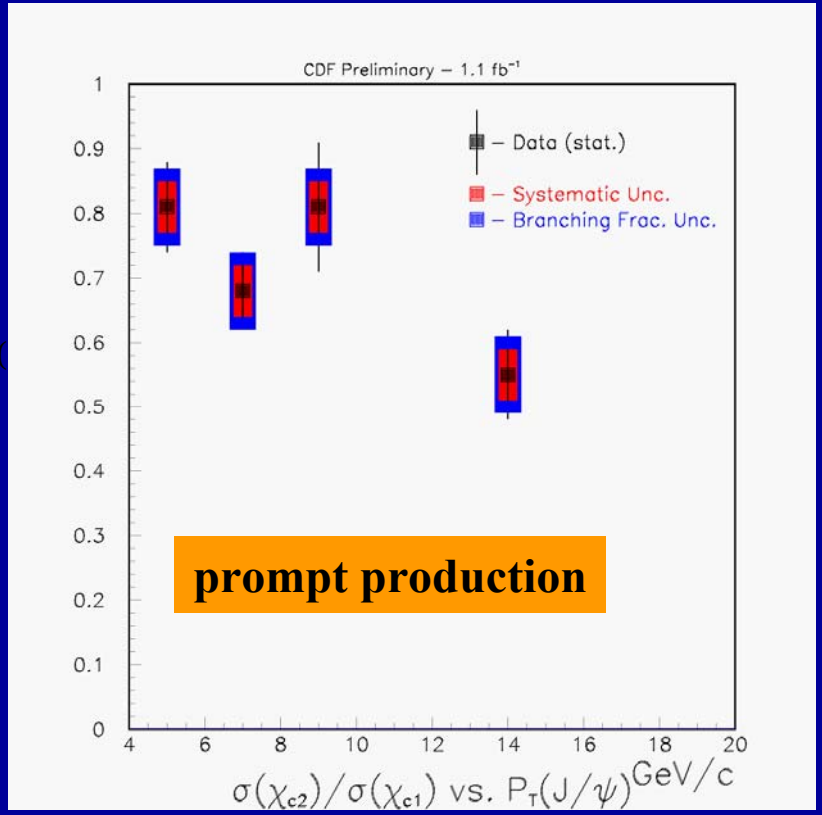
- The polarization in the highest p_T bin is longitudinal in contradiction to the NRQCD prediction of large transverse polarization

$$\alpha_B = 0.28 \pm 0.27\,(stat) \pm 0.03\,(syst)$$

χ_c Production

Run II, 1.1 fb^{-1}





$$\sigma(\chi_{c2})/\sigma(\chi_{c1}) = 0.70 \pm 0.04(stat) \pm 0.04(syst) \pm 0.06(BR)$$

For prompt production

$$\sigma(\chi_{c2})/\sigma(\chi_{c1}) = 0.25 \pm 0.07(stat) \pm 0.01(syst) \pm 0.02(BR)$$

For production from B decay

New level of precision and good constraint for production models

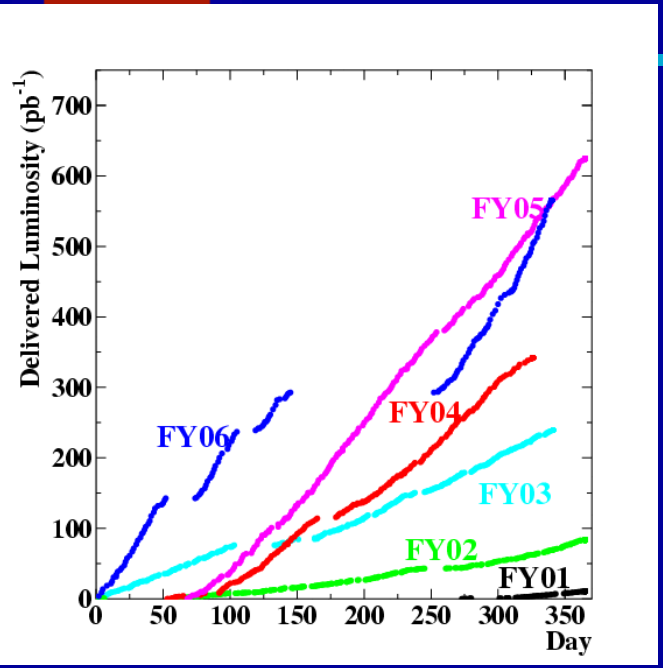
Conclusions

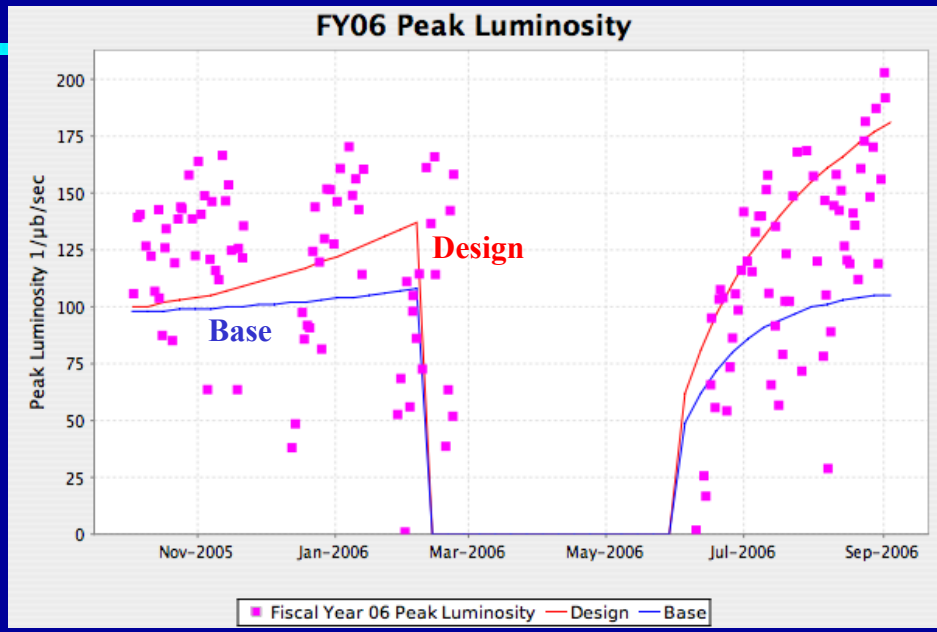
- The Tevatron is running very well
- Many new results in B physics
- The Tevatron is expected to provide 4.3 – 8.1 fb^{-1} by October 2009
- A lot of answers and surprises awaiting!!

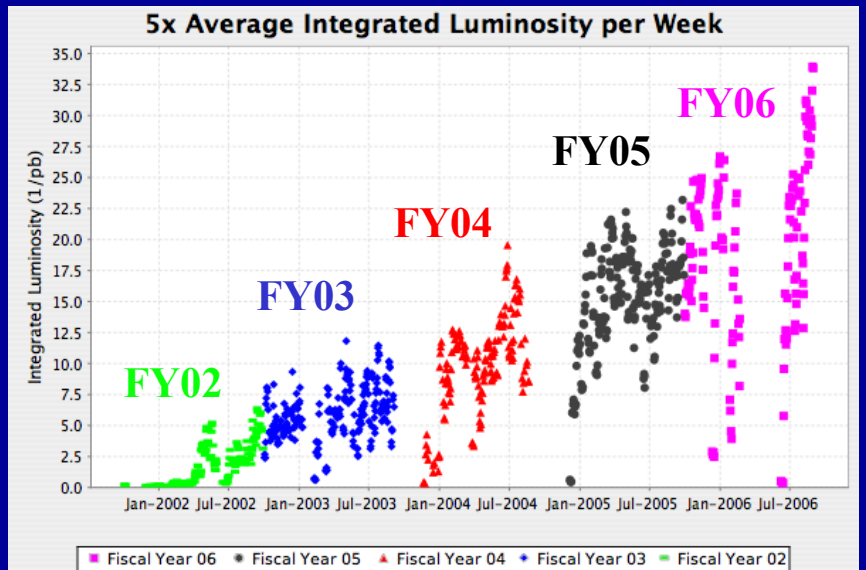
Backup

Backup Slides

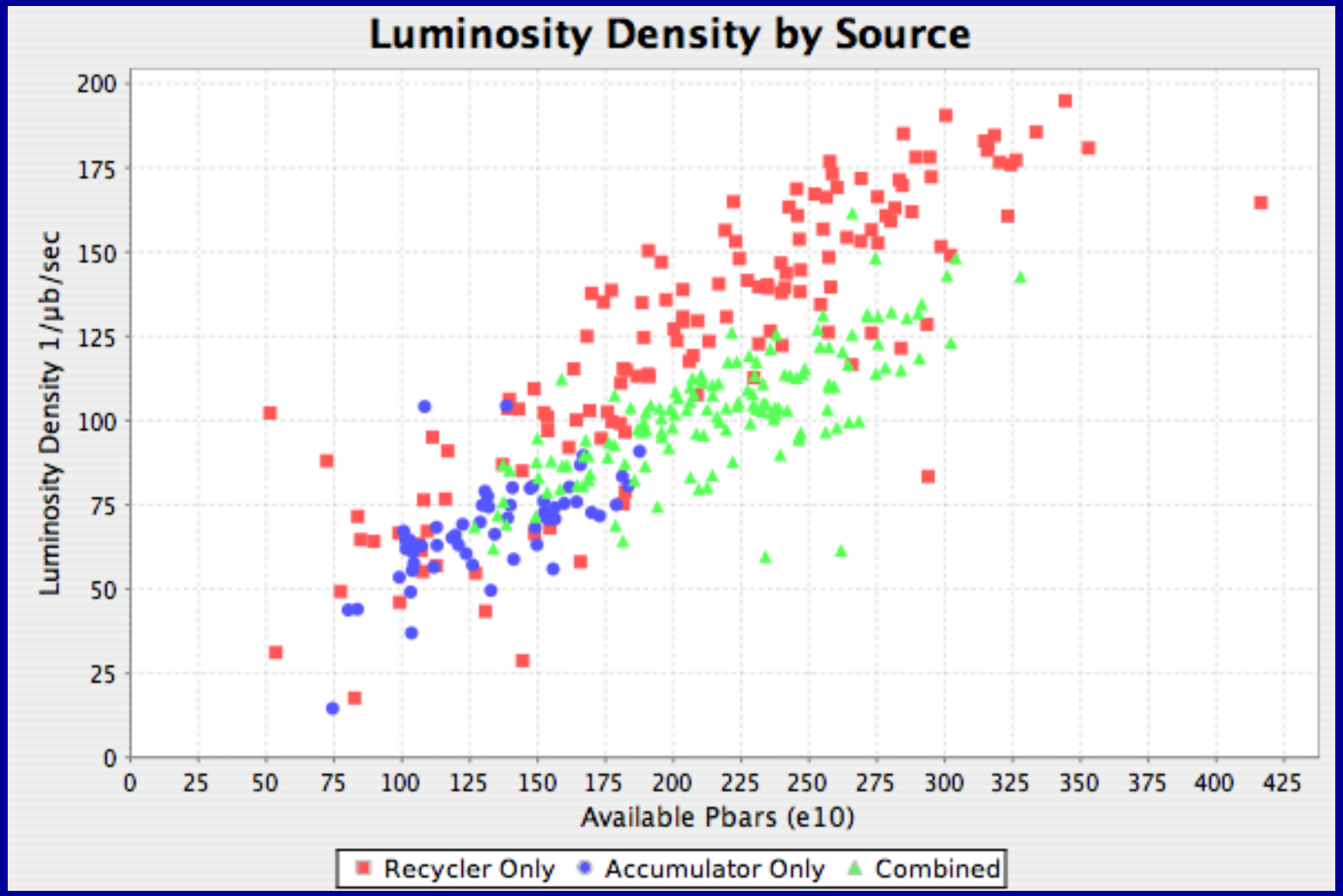
Tevatron Performance





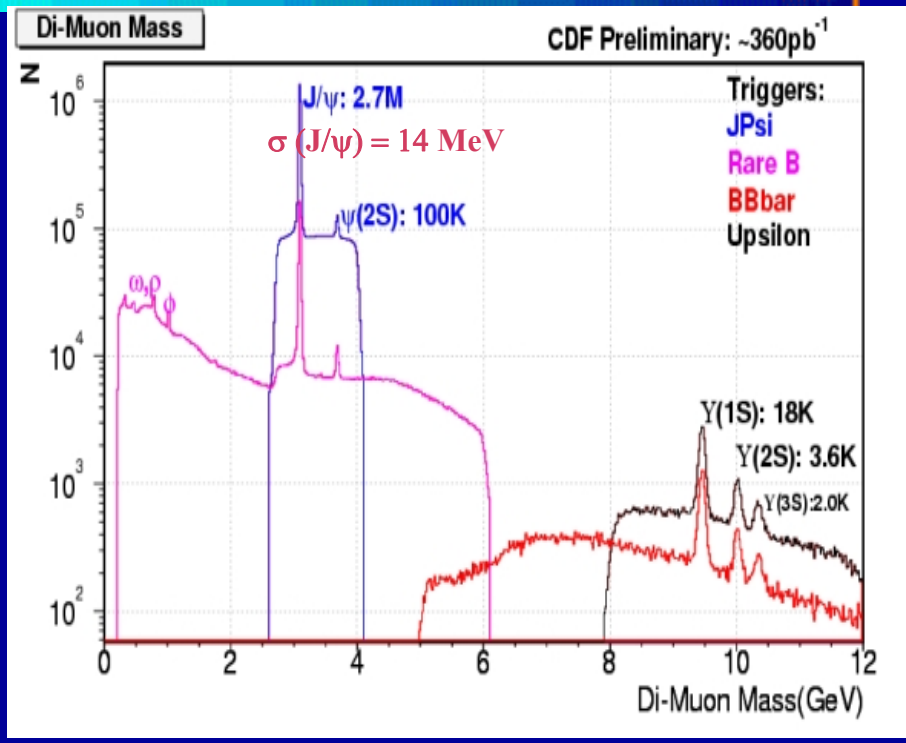


Tevatron Performance



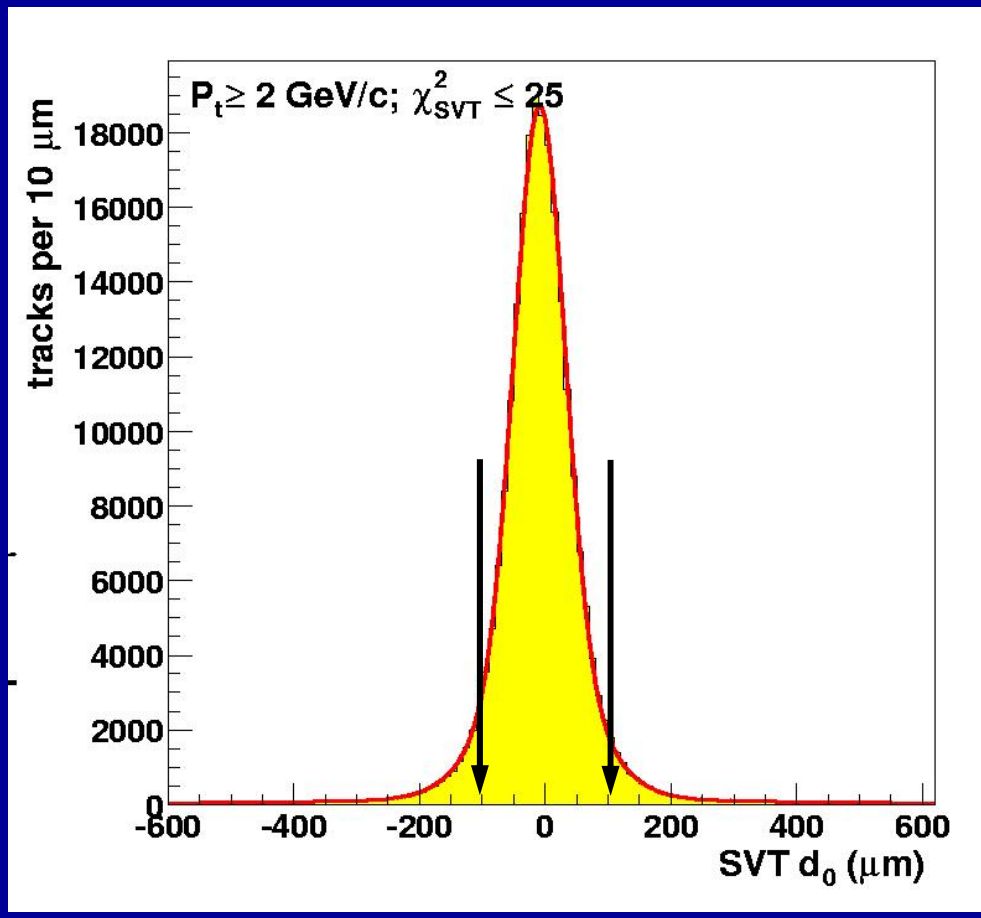
B-Physics Data samples

- J/ψ samples:
  - ~ 10 Millions in 1 fb^{-1}! ~ 20% are from B's
  - Reconstruct exclusive $B/\Lambda_B \rightarrow J/\psi\ K/\Lambda^0$ modes



Triggering on displaced tracks

- Level 2: Silicon Vertex Trigger
  - Use silicon detector information
    - Good IP resolution
    - Trigger on displaced track
  - Beamline reconstruction
    - update every ~ 30 seconds
  - IP resolution: ~ 50 μm
    - 33μm beam size + 35μm SVT

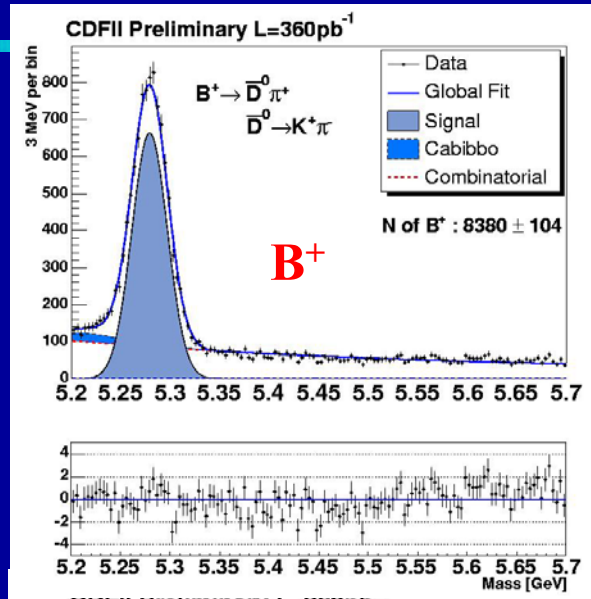


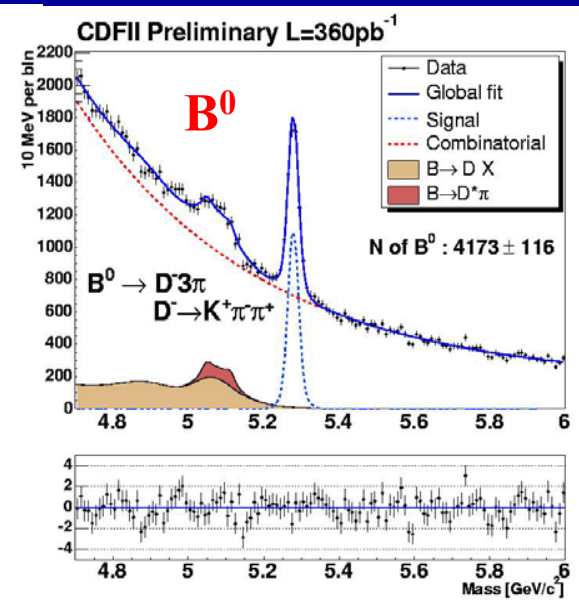
35μm ⊕ 33μm
resol ⊕ beam
⇒ σ = 48μm

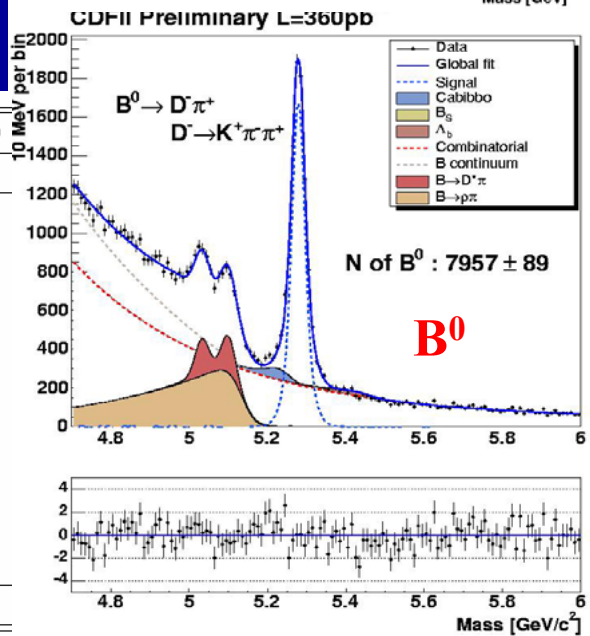
Lifetimes with hadronic decays

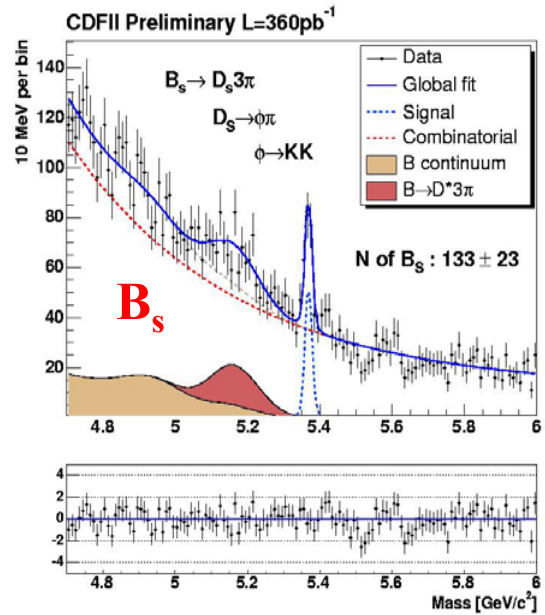
- More statistical power than J/ψ modes
  - Slightly larger systematics
    - Efficiency curve
    - backgrounds

$\tau(B^+) = 1.66 \pm 0.03 \pm 0.01$ ps
$\tau(B^0) = 1.51 \pm 0.02 \pm 0.01$ ps
$\tau(B_s) = 1.60 \pm 0.10 \pm 0.02$ ps









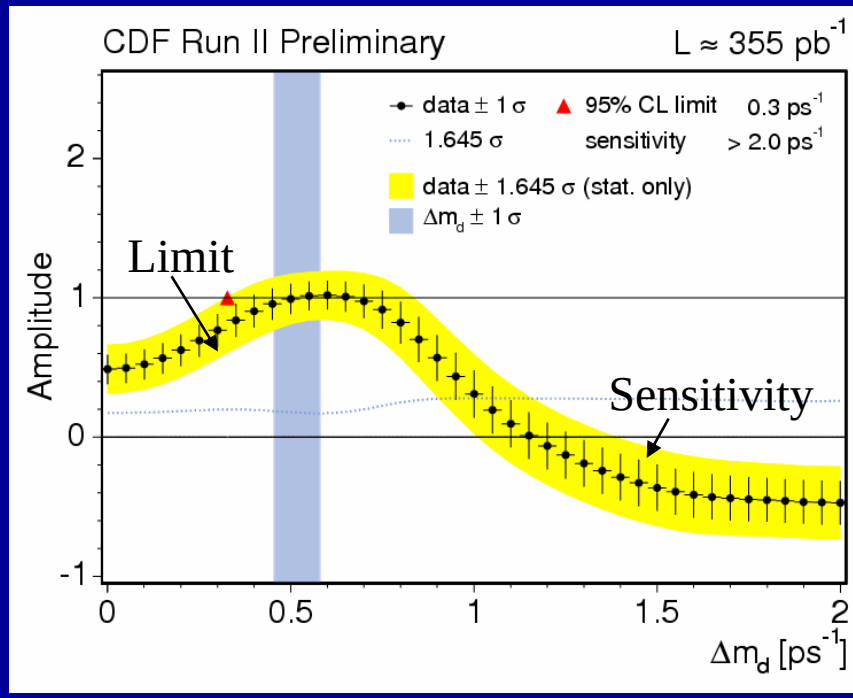
Systematics (μm)

Effect	Variation(μm)	Variation(μm)
	B^0	B_s
MC input $c\tau$	negligible	negligible
p_T reweight	1.9	1.9
Scale Factor	negligible	negligible
Bkg ct description	1.1	1.1
Bkg fraction	2.0	2.0
I.P. correlation	1.0	1.0
Eff. parameterization	1.5	1.5
L_{xy} significance	negligible	2
$\Delta\Gamma_s$	-	1.0
Alignm. + others	2.4	2.4
Total	4.2	4.7

B_d Mixing

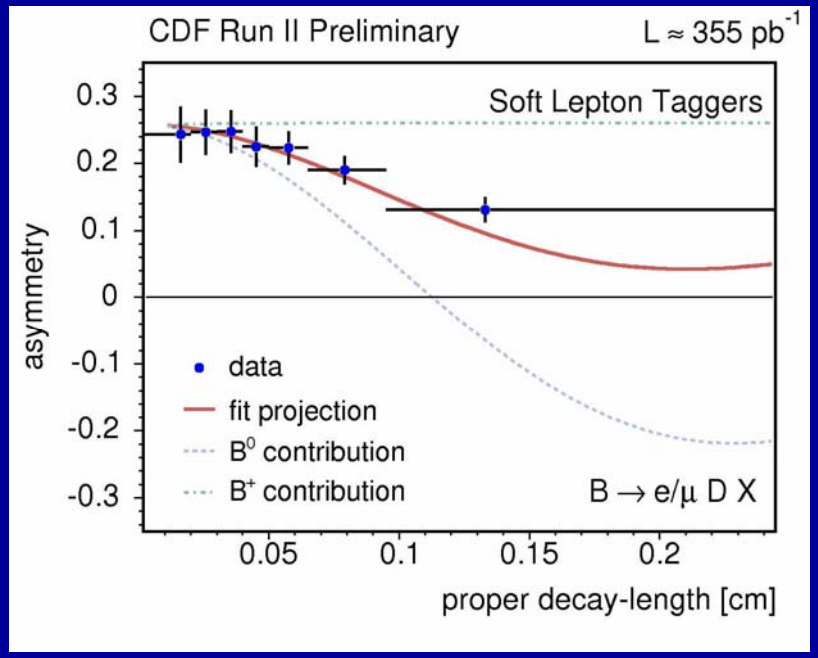
- These results obtained using many features important for Bs mixing
  - Unbinned fit
  - Parametrized dilutions
  - Calibrate dilutions
- Test amplitude scan on fully reconstructed B_d
  - Fit D*A*cos(Δm t) at fixed Δm
  - Expect A=1 for $\Delta m \sim \Delta m_d$
  - Limit (95% CL):
    - Δm such that $A+1.645\sigma_A = 1$
  - Sensitivity: Δm such that $1.645\sigma_A = 1$

H. G. Moser, A. Roussarie, NIM **A384** (1997)



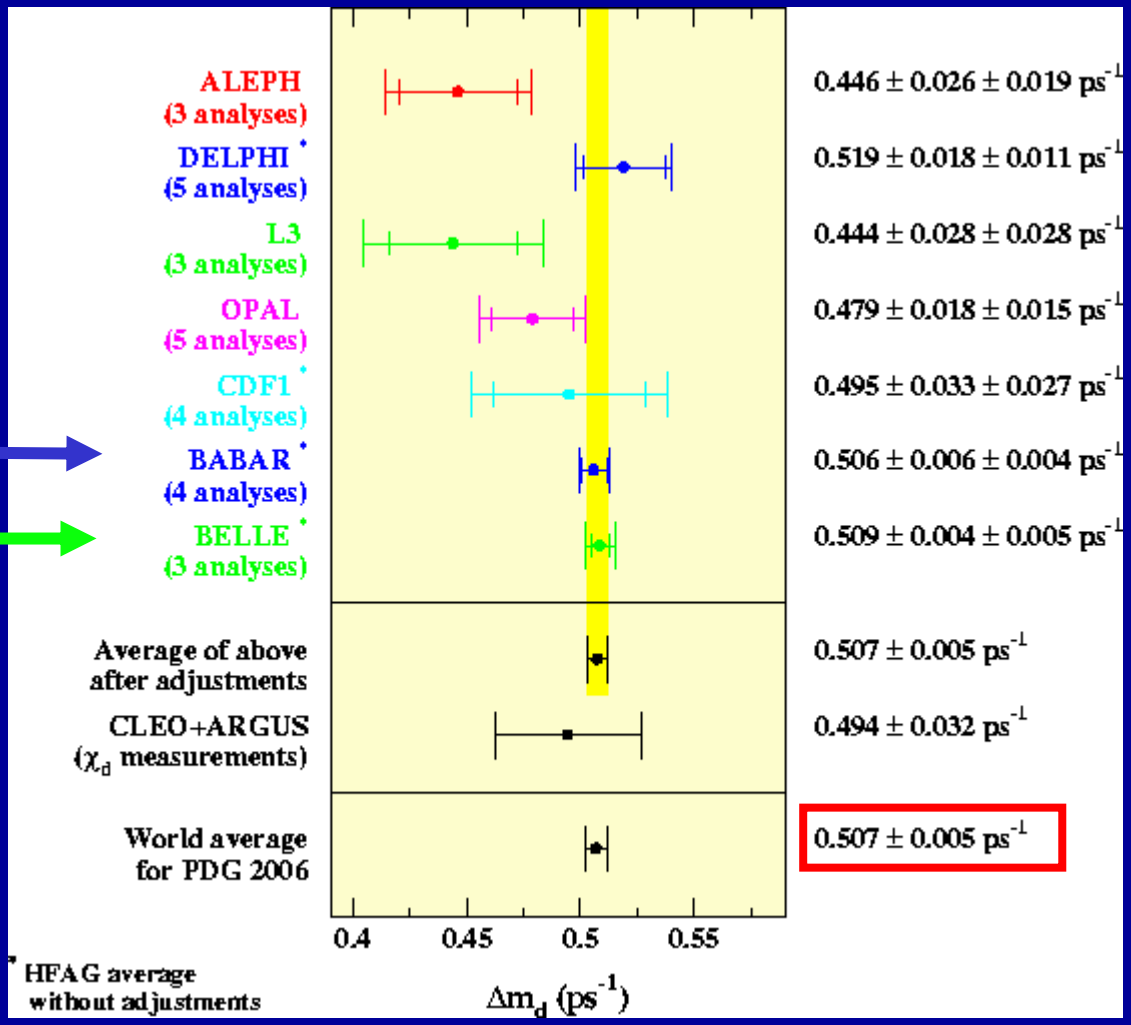
B_d mixing

- recent results from CDF using ~ 1 fb^{-1} and OST
  - Semi-leptonic sample: 550k lD^0 (75k lD^{*+}), 298k lD+
    - $\Delta m_d = 0.509 \pm 0.010(stat.) \pm 0.016(syst.)\ ps^{-1}$



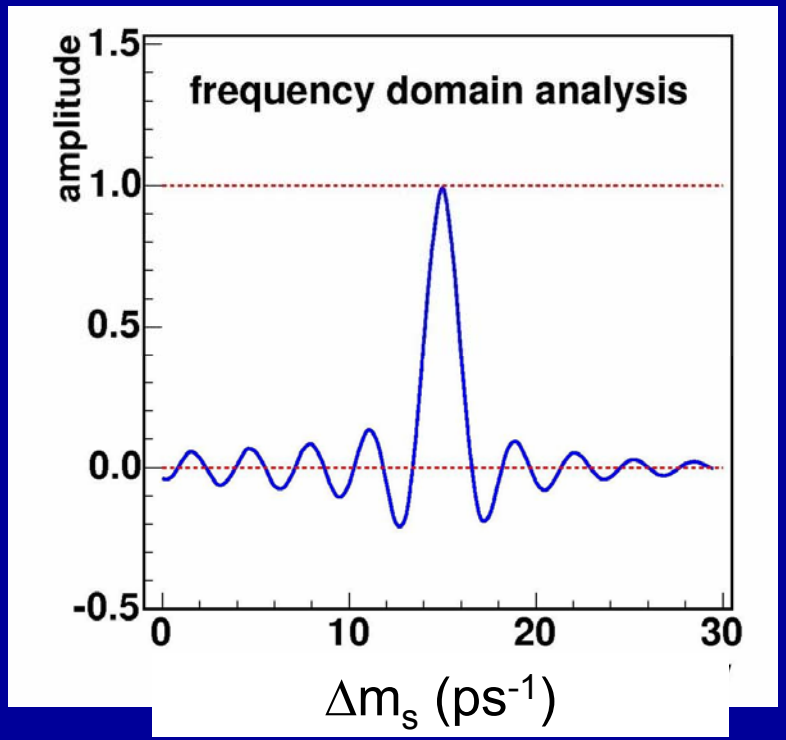
B_d Mixing

- HFAG Summary based on results presented by Spring 2006
- World Average dominated by BaBar/Belle

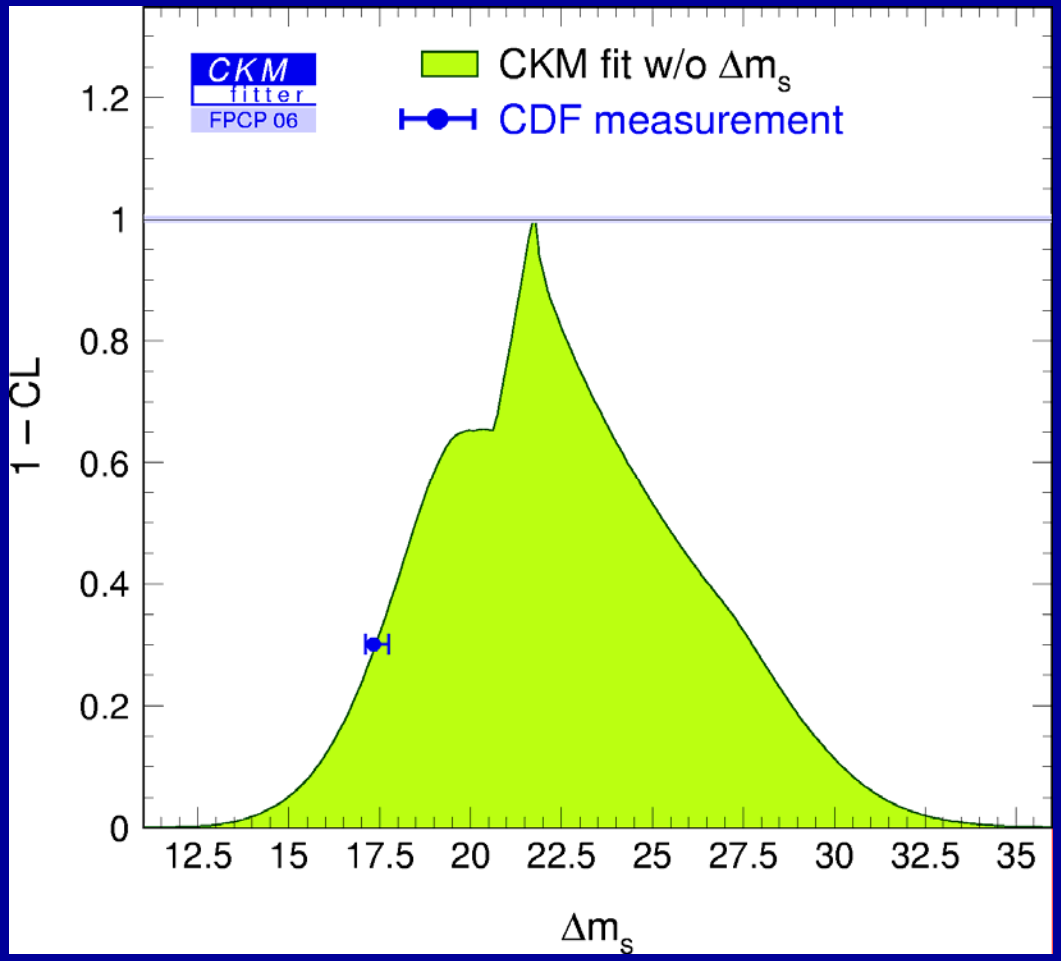


B_s Mixing: Measuring Δm_s

- Look for evidence of B_s mixing using Amplitude Scan
  - Fourier transform to frequency domain
  - Determine amplitude for fixed Δm_s
  - Scan Δm_s : Amplitude = 1 at true Δm_s, 0 otherwise



B_s Mixing: Constraints



- measured Δm_s agrees with SM prediction
- relative precision of measured

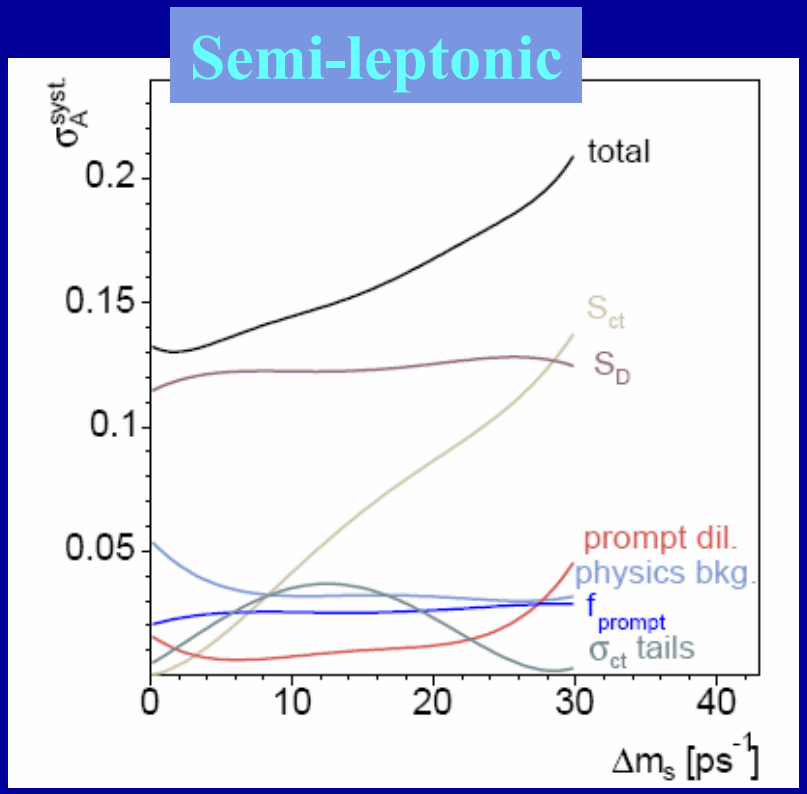
$$\delta(\Delta m_s)/\Delta m_s = 1.5\%$$

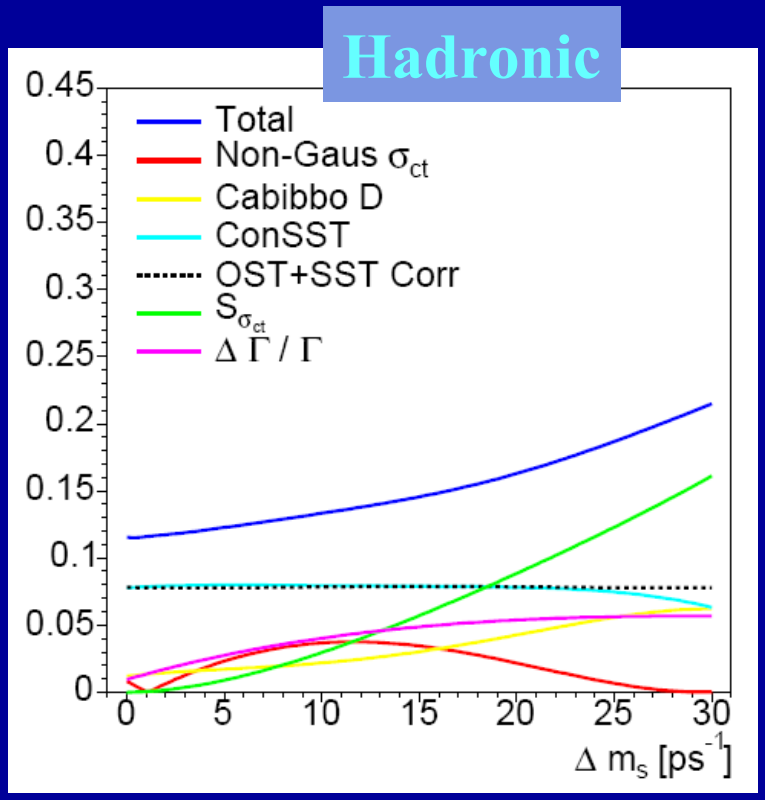
$$\delta(\Delta m_d)/\Delta m_d = 1.0\%$$

- precision of measured Δm_s is statistics limited

$$\delta(\text{syst})/\Delta m_s < 0.5\%$$

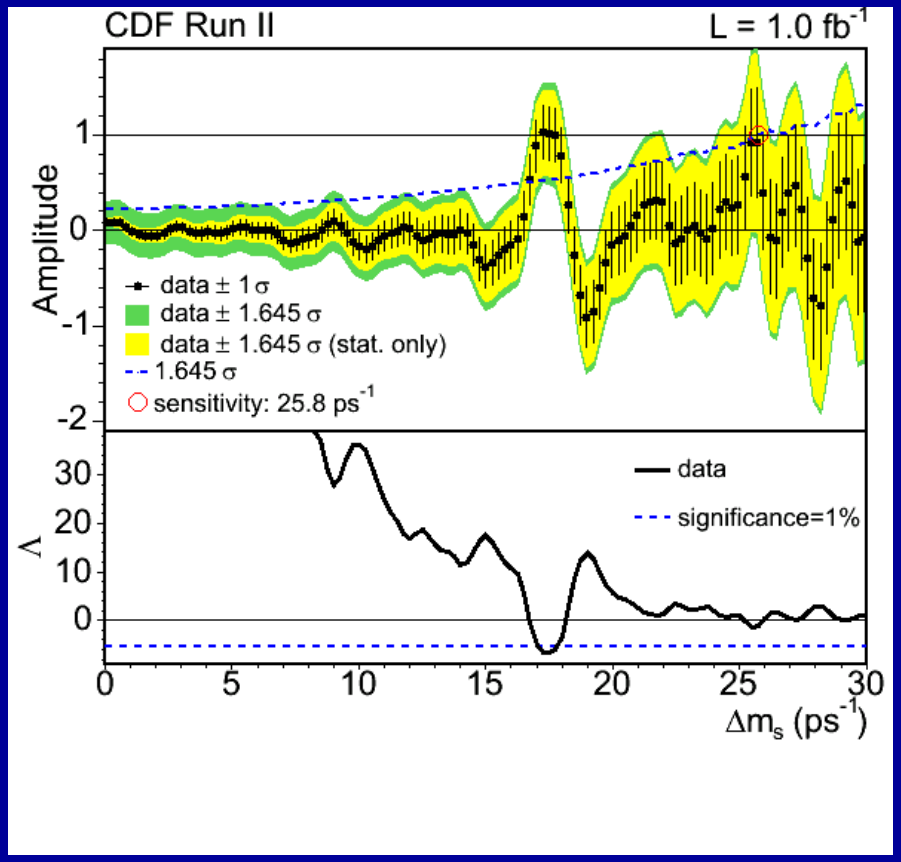
Systematics in B_s Mixing

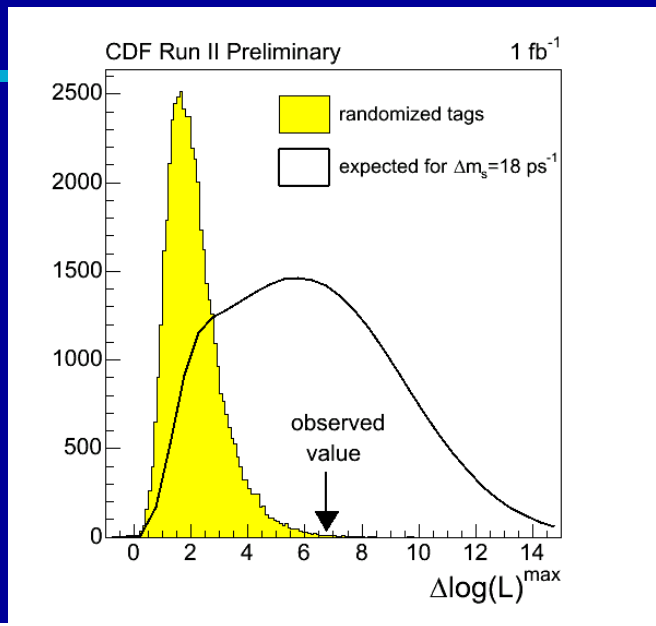


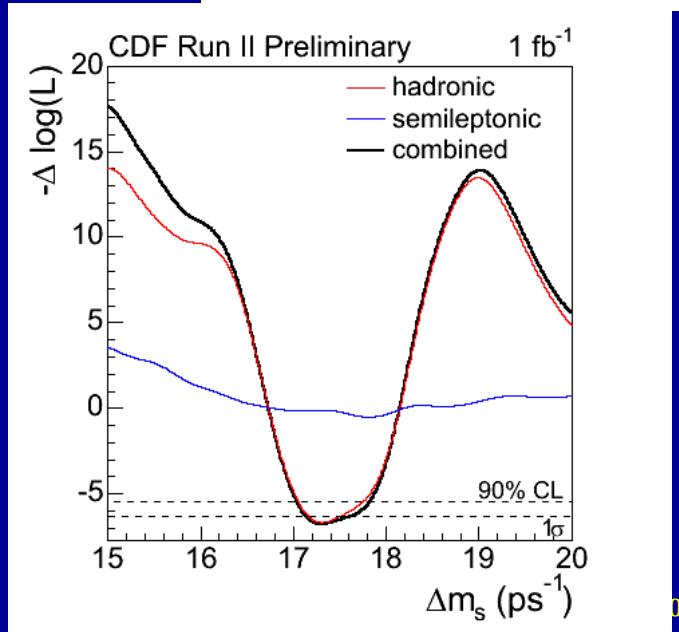


- related to absolute value of amplitude, relevant only when setting limits
  - cancel in $A/\sigma A$, folded in in confidence calculation for observation
  - systematic uncertainties are very small compared to statistical

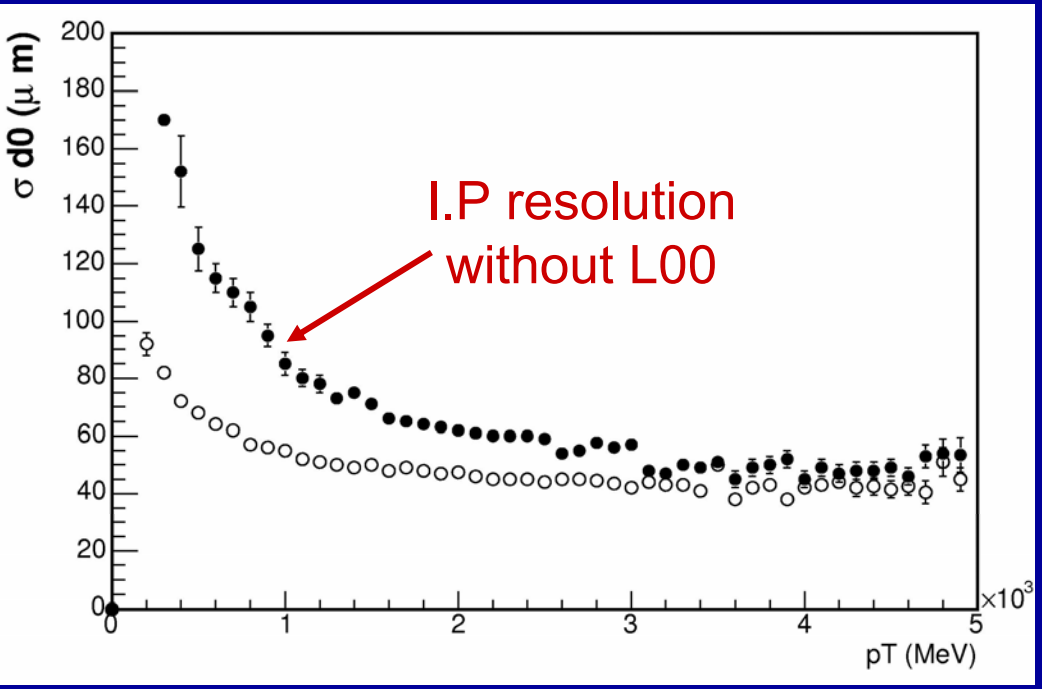
B_s Mixing


CDF Run II
L = 1.0 fb-1
Amplitude
data ± 1 σ
data ± 1.645 σ
data ± 1.645 σ (stat. only)
1.645 σ
sensitivity: 25.8 ps-1
Λ
data
significance=1%
Δms (ps-1)


CDF Run II Preliminary
1 fb-1
randomized tags
expected for Δms=18 ps-1
observed value
Δlog(L)max

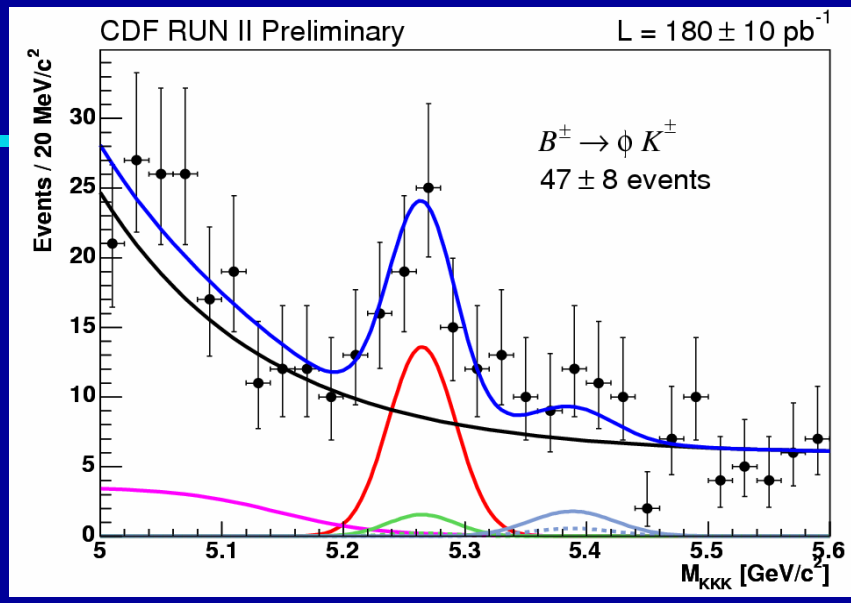

CDF Run II Preliminary
1 fb-1
hadronic
semileptonic
combined
-Δ log(L)
90% CL
1σ
Δms (ps-1)

Layer “00”



- layer of silicon placed directly on beryllium beam pipe
- radial displacement from beam ~1.5 cm
- additional impact parameter resolution, radiation hardness

B → ϕh



- CDF: $B^+ \to \phi K^+$
  - $A_{CP} = -0.07 \pm 0.17\,^{+0.03}_{-0.02}$

    (BaBar: 0.054 ± 0.056 ± 0.012)
  - $BR(B^+ \to \phi K^+) = (7.6 \pm 1.3\,^{+0.65}_{-0.63}) \times 10^{-6}$

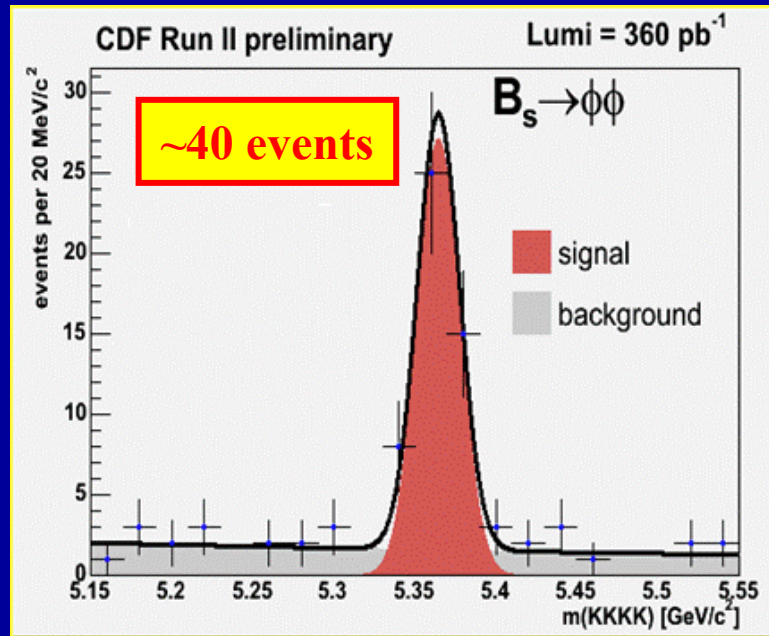
    HFAG05: $(9.0 \pm 0.6) \times 10^{-6}$

- CDF: Bs → ϕϕ
  - $BR(B_s \to \phi\phi) = (1.4^{+0.6}_{-0.5} \pm 0.6) \times 10^{-5}$

    QCD fact. 3.68×10^{-5}

    NF fact. 1.79×10^{-5}

First observation!

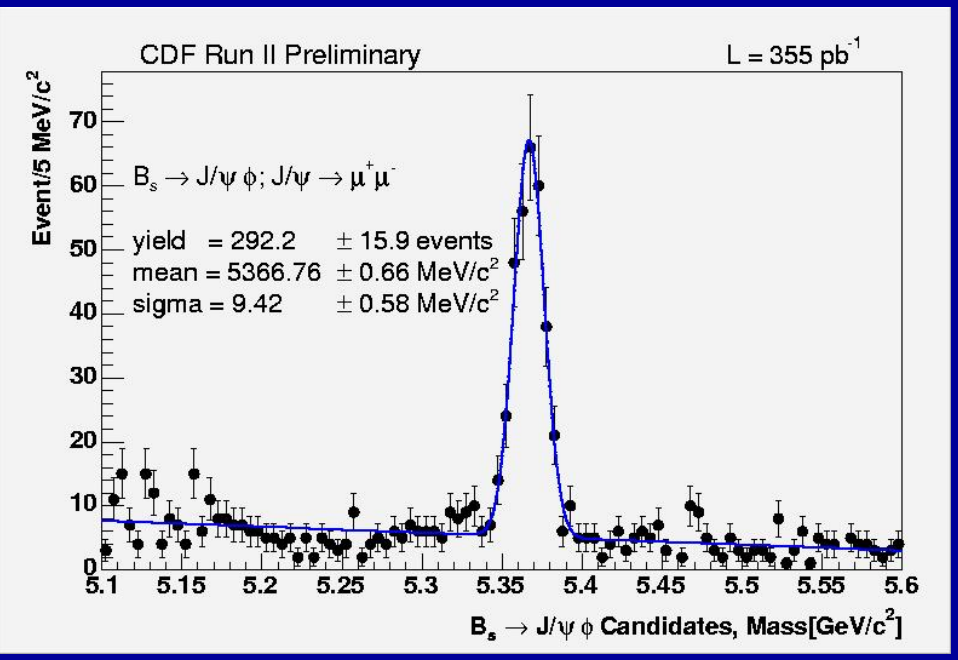


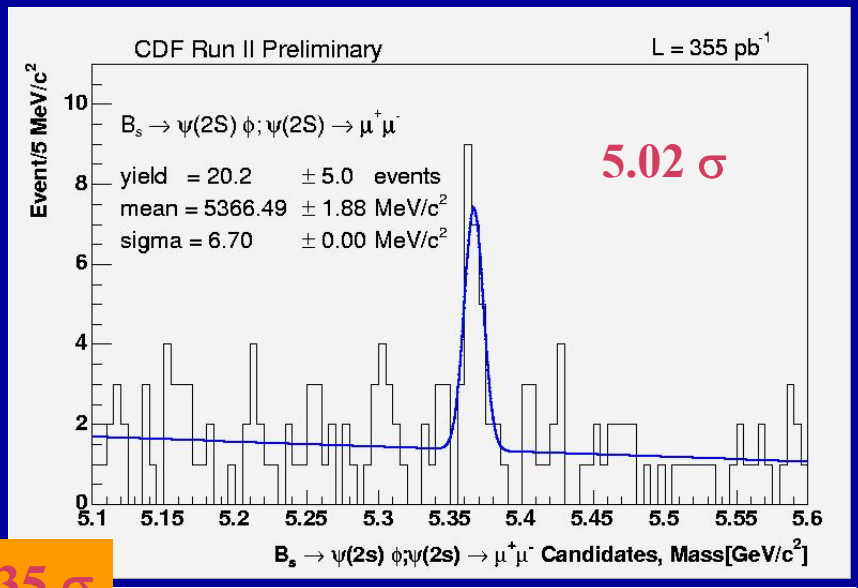
$B_s \rightarrow \psi(2S)\phi$

Run II, 355 pb^{-1}

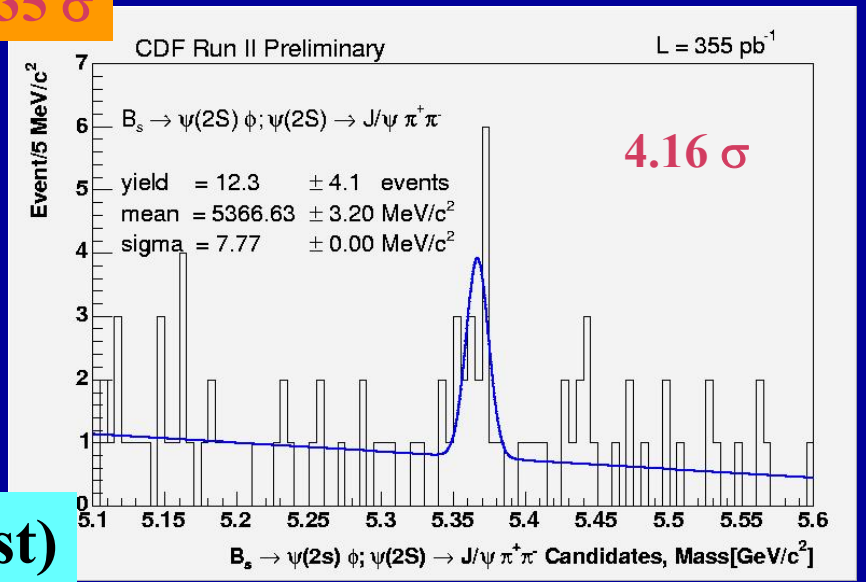
$B_s \rightarrow J/\psi\varphi\ ;\ J/\psi \rightarrow \mu\mu$

used as a control sample and for normalization





6.35 σ



$$\frac{BR(B_s \rightarrow \psi(2S)\varphi)}{BR(B_s \rightarrow J/\psi\varphi)} =$$

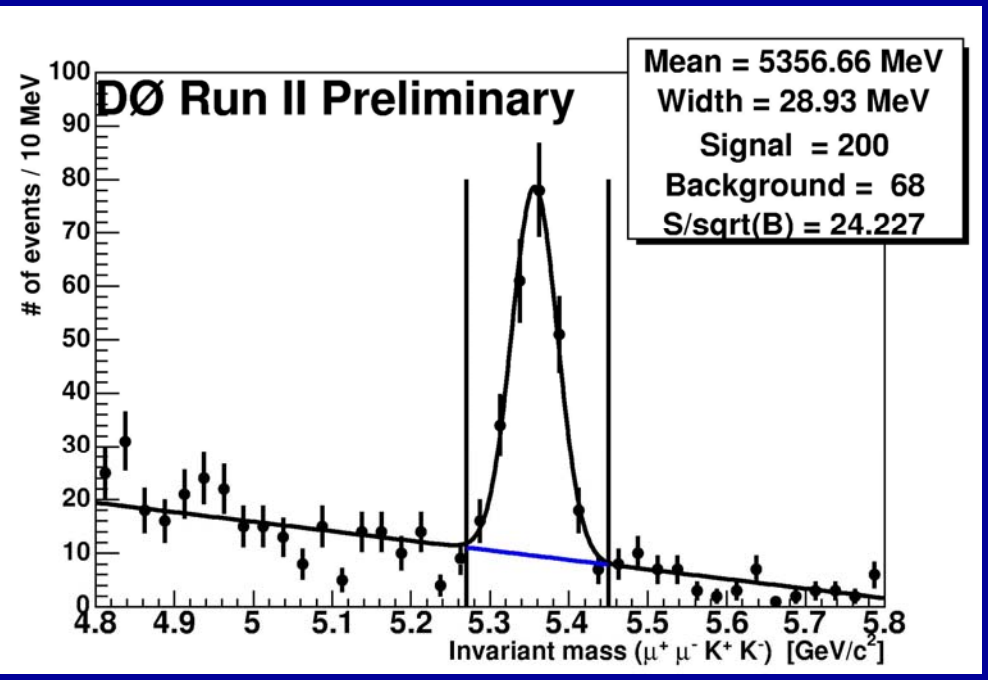
0.52 ± 0.13(stat) ± 0.06(BR) ± 0.04(syst)

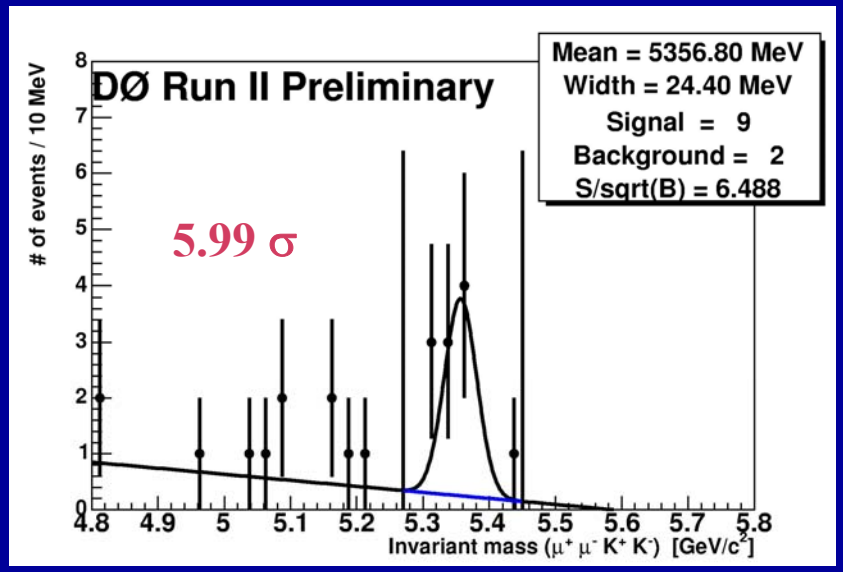
$B_s \rightarrow \psi(2S)\phi$

Run II, 300 pb^{-1}

$B_s \rightarrow J/\psi\varphi$; $J/\psi \rightarrow \mu\mu$

used as a control sample and for normalization





$B_s \rightarrow \psi(2S)\varphi$; $\psi(2S) \rightarrow \mu\mu$

8.6 ± 3.3 signal events

1.8 ± 1.3 background events

$$\frac{BR(B_s \rightarrow \psi(2S)\varphi)}{BR(B_s \rightarrow J/\psi\varphi)} =$$

0.58 ± 0.24(stat) ± 0.07(BR) ± 0.06(syst)

$B_{s(d)} \rightarrow \mu\mu$

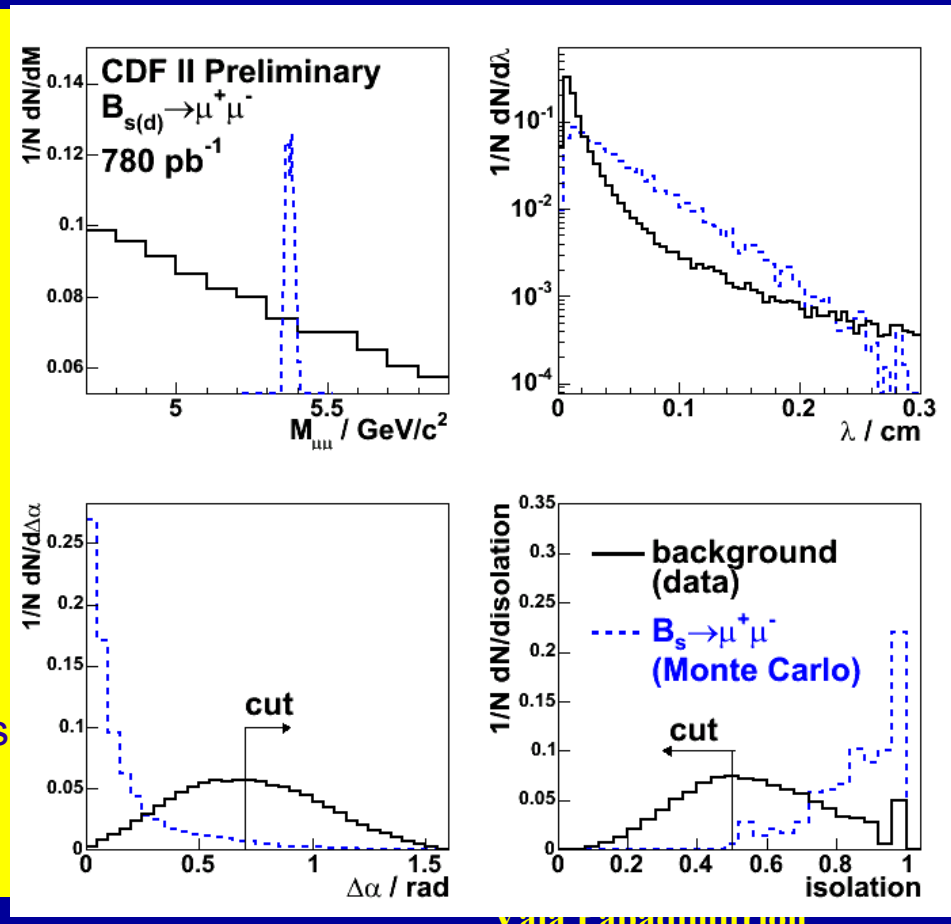
Run II, 780 pb^{-1}

CDF *Bs(d) → μ+μ- : Used blind analysis technique*

$B^{\pm} \rightarrow J/\psi K^{\pm}$ **: used as a control sample and for normalization**

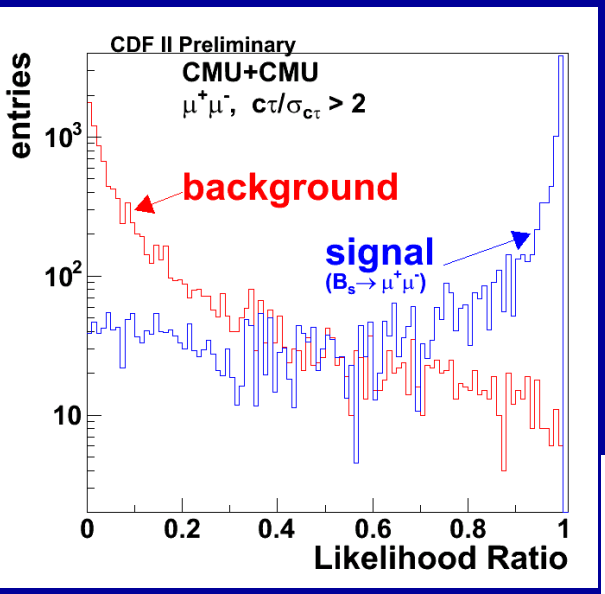
- Used 3 primary discriminating variables
  - λ: $cL_{3D} \cdot M_{\mu\mu}/p(B)$ $\lambda/\sigma(\lambda) > 2$
  - $\Delta\alpha$: $|\alpha_B - \alpha_{vtx}| < 0.7$ rad
  - Isolation: $p_{TB}/(\Sigma trk + p_{TB}) > 0.5$

  Mass $M_{\mu\mu}$: choose $\pm 2.5\sigma$ window:
  $\sigma = 24$ MeV/c^2
- Optimization
  - Used simulated signal and data sidebands
  - Background estimates were checked in same sign lepton and -ct samples



$B_{s(d)} \rightarrow \mu\mu$

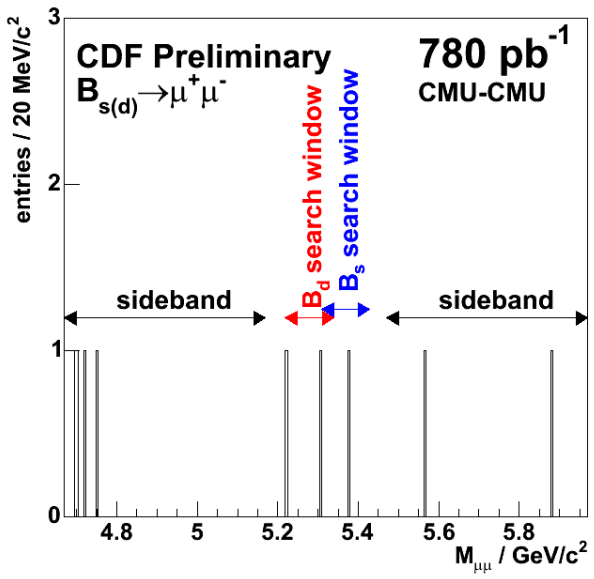
Multi-variate Relative Likelihood Discriminant

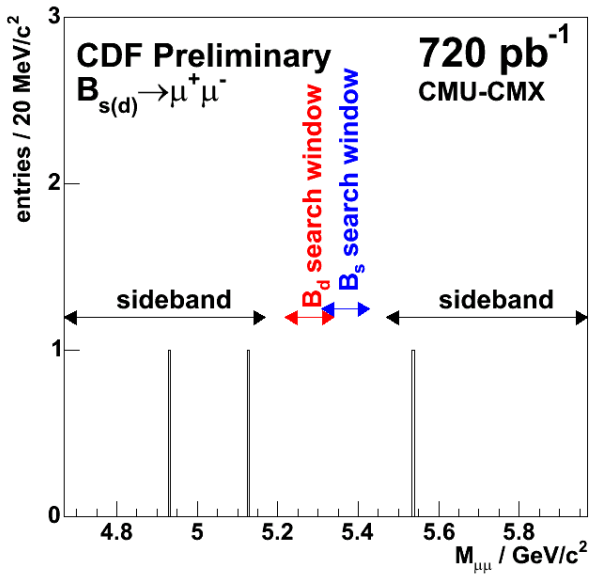


$p_T(B) > 4$ GeV/c
LH > 0.99

N_{bkg} expected: 0.88±0.30
ses: (3.9±0.7) x 10^{-8}

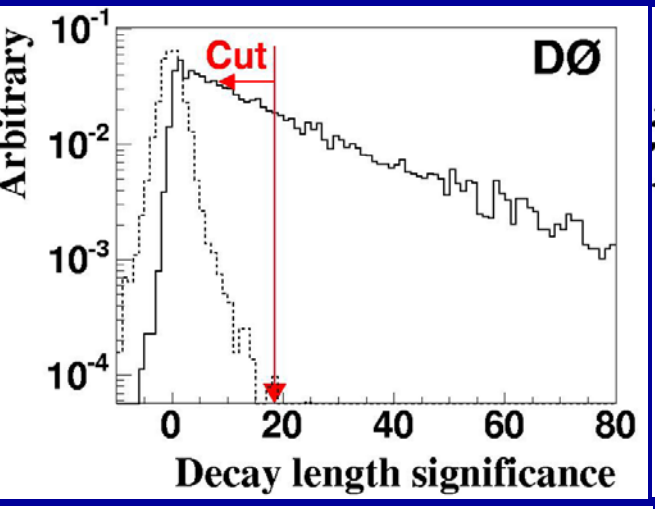
N_{bkg} expected: 0.39±0.21
ses: (6.2±1.0) x 10^{-8}

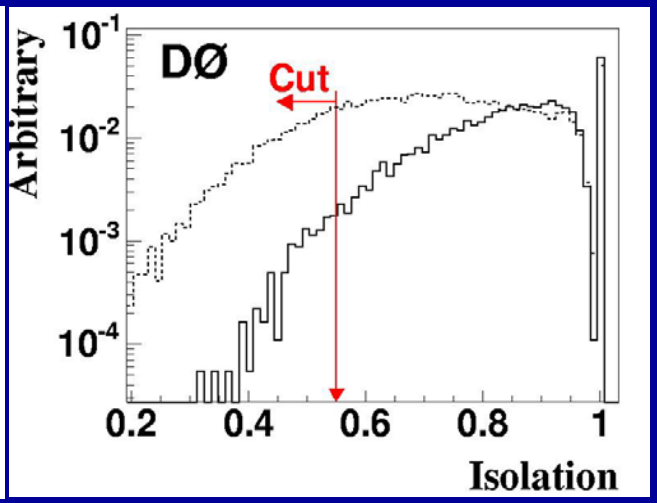




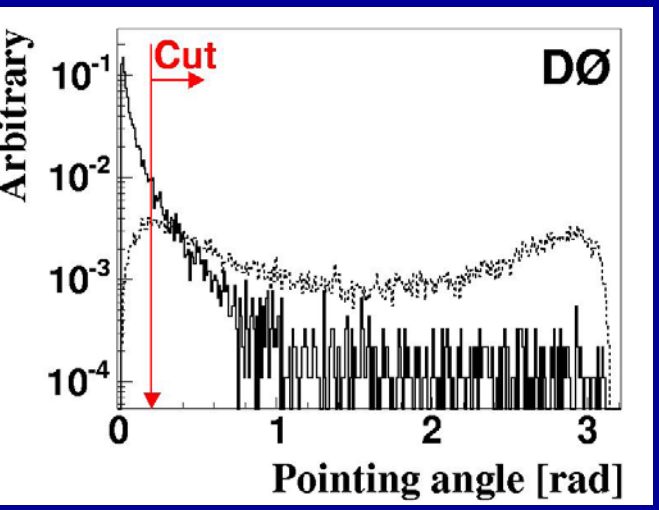
$B_s \rightarrow \mu\mu$

Run II, 240 pb^{-1}





- Optimization
  - Used simulated signal and data sidebands
  - Random grid search, optimizing for 95%



- Used 3 primary discriminating variables
  - $L_{xy} / \sigma(L_{xy}) > 18.5$; $\sigma(L_{xy}) < 0.15$ mm
  - $\Delta\alpha$: $|\phi_B - \phi_{vtx}| < 0.2$ rad
  - Isolation: $p_{TB}/(\Sigma trk + p_{TB}) > 0.56$

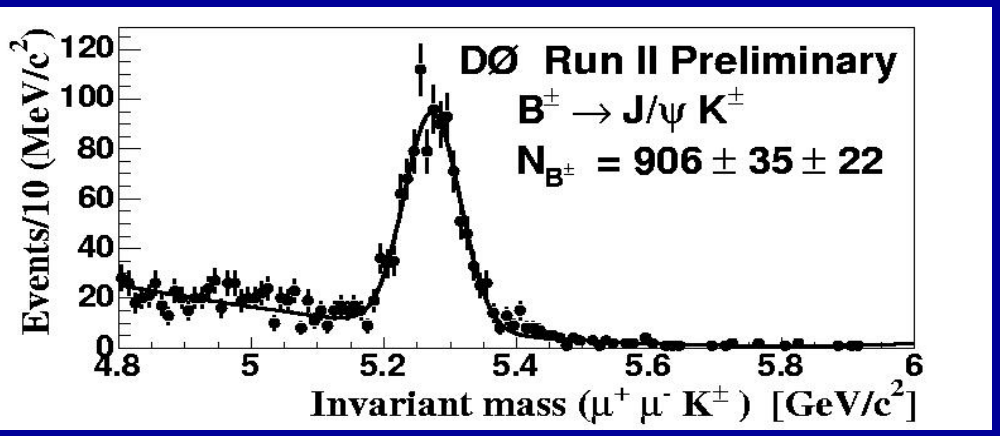
$4.53 < M_{\mu\mu} < 6.15$ GeV/c^2

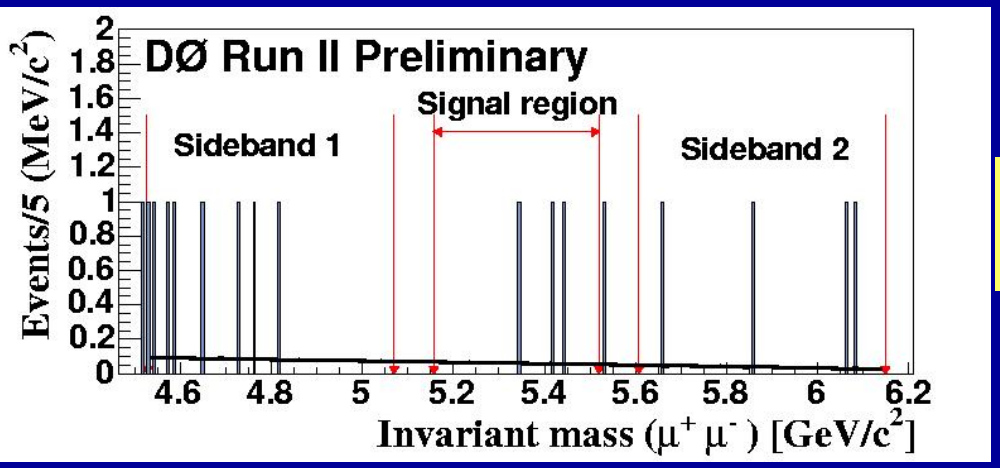
σ = 90 MeV/c^2

$B_s \rightarrow \mu\mu$

Run II, 300 pb^{-1}

$B^{\pm} \rightarrow J/\psi\ K^{\pm}$: used as a control sample and for normalization





N_{bkg} expected: 4.3±1.2
4 candidates found

$BR(B_s \rightarrow \mu\mu) < 3.0 \cdot 10^{-7}$ **90% CL**

$BR(B_s \rightarrow \mu\mu) < 3.7 \cdot 10^{-7}$ **95% CL**

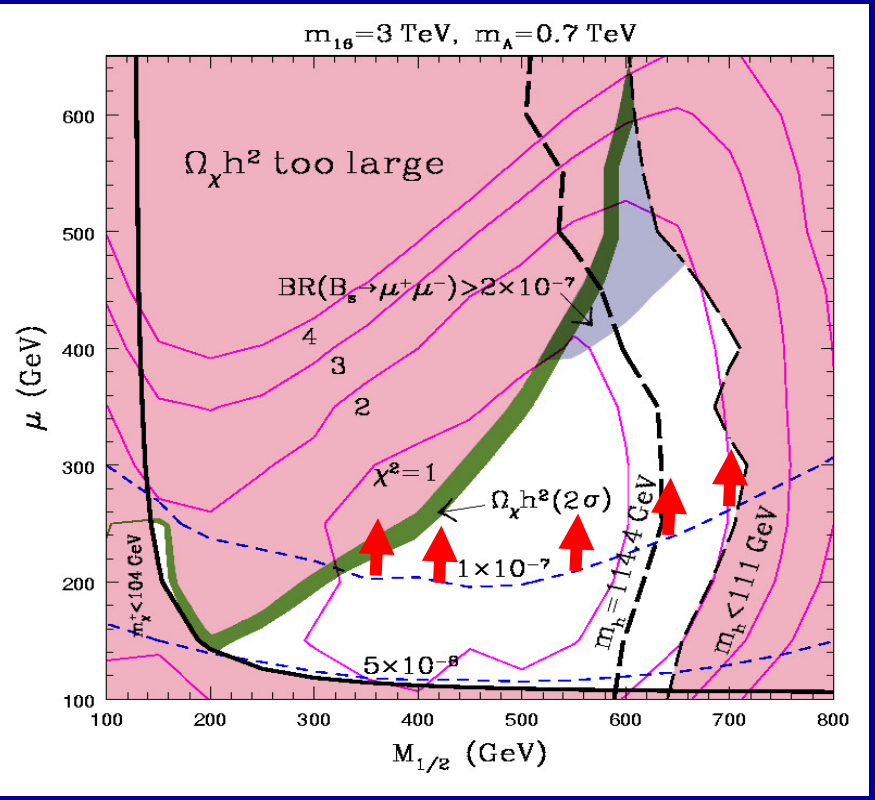
New Expected Upper Limit using 700 pb^{-1}
Signal box still closed

$BR(B_s \rightarrow \mu\mu) < 1.9 \cdot 10^{-7}$ **90% CL**

$BR(B_s \rightarrow \mu\mu) < 2.3 \cdot 10^{-7}$ **95% CL**

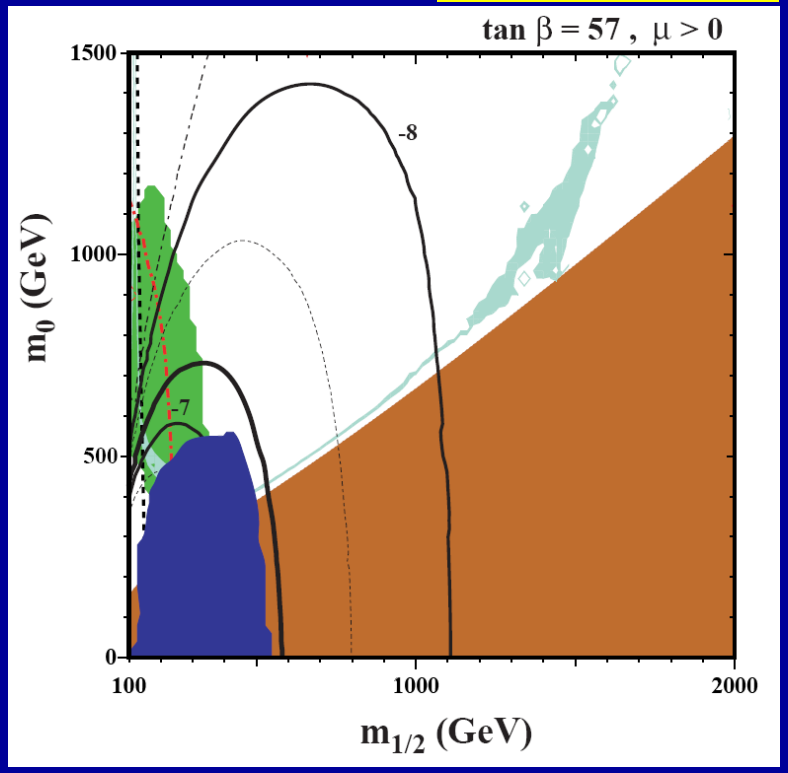
$B_{s(d)} \rightarrow \mu\mu$: Physics Reach

- SUSY SO(10) Unification
  - Allows for massive neutrino
  - Relic density of cold dark matter



R. Dermisek et al.
hep-ph/0507233

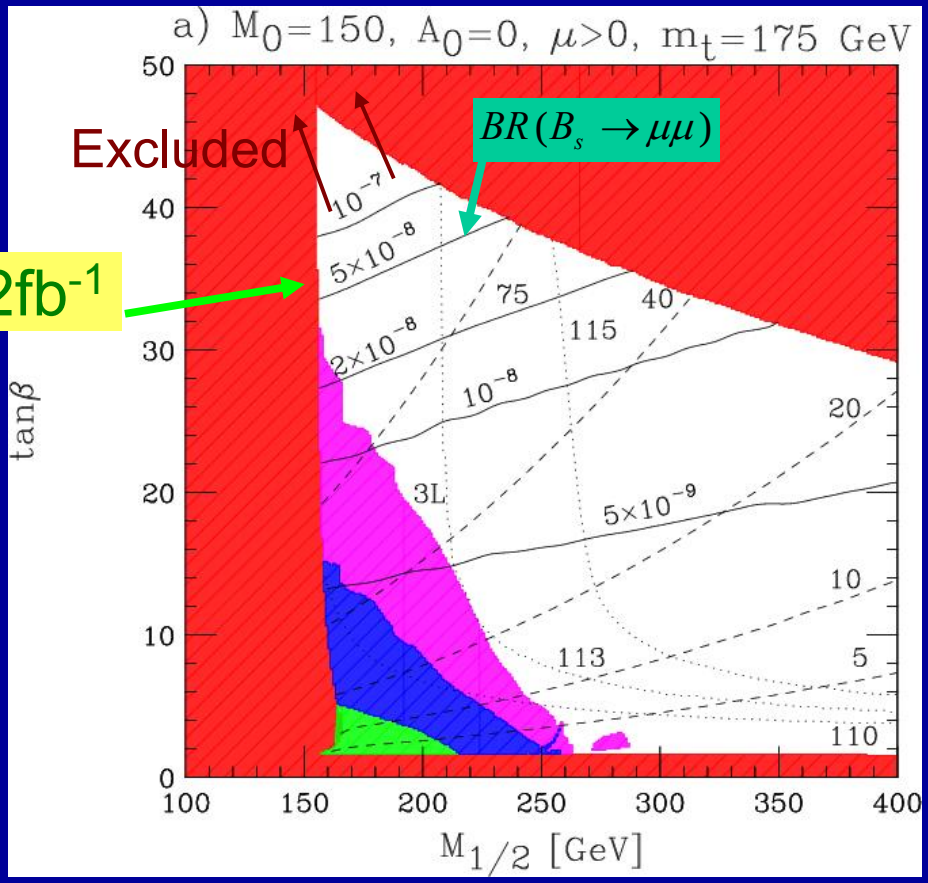
Constrained MSSM



J. Ellis et al.
Phys. Lett B624, 47, 2005

$B_{s(d)} \rightarrow \mu\mu$: Physics Reach

- mSUGRA



A. Dedes et al.
hep-ph/0207026

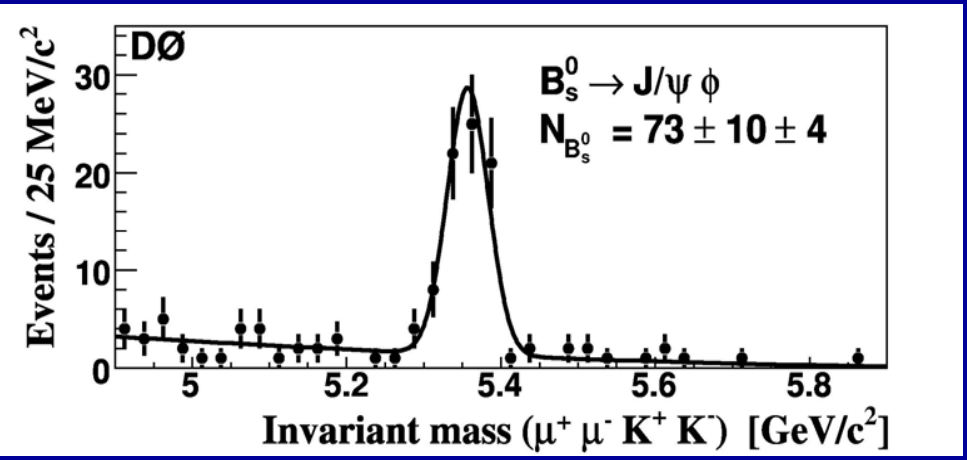
$B_s \to \mu\mu\phi$

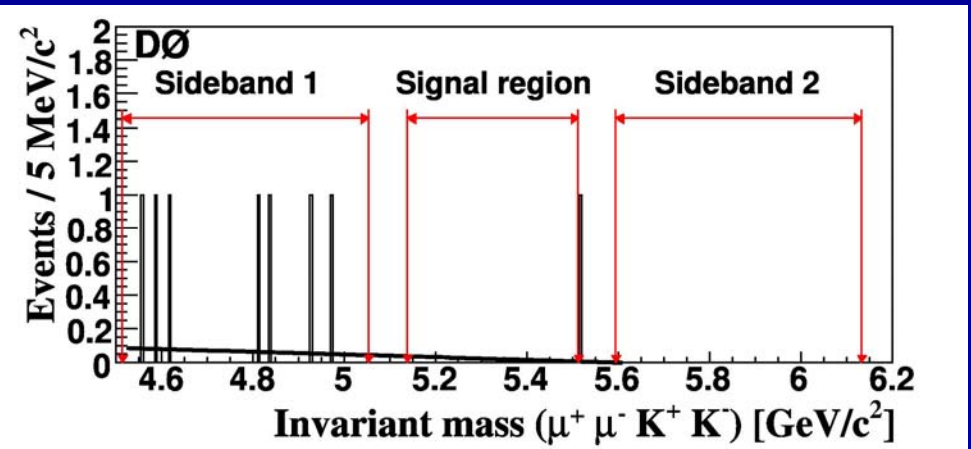
Run II, 450 pb^{-1}

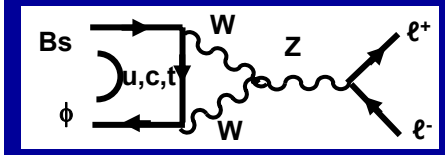
$B_s \to J/\psi\varphi$; $J/\psi \to \mu\mu$

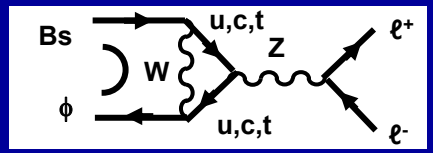
used as a control sample and for normalization

Blind analysis









- SM BR ~ 1.6×10^{-6}
- Smaller enhancement at large tanβ
- CDF-I: BR < 6.7×10^{-5}

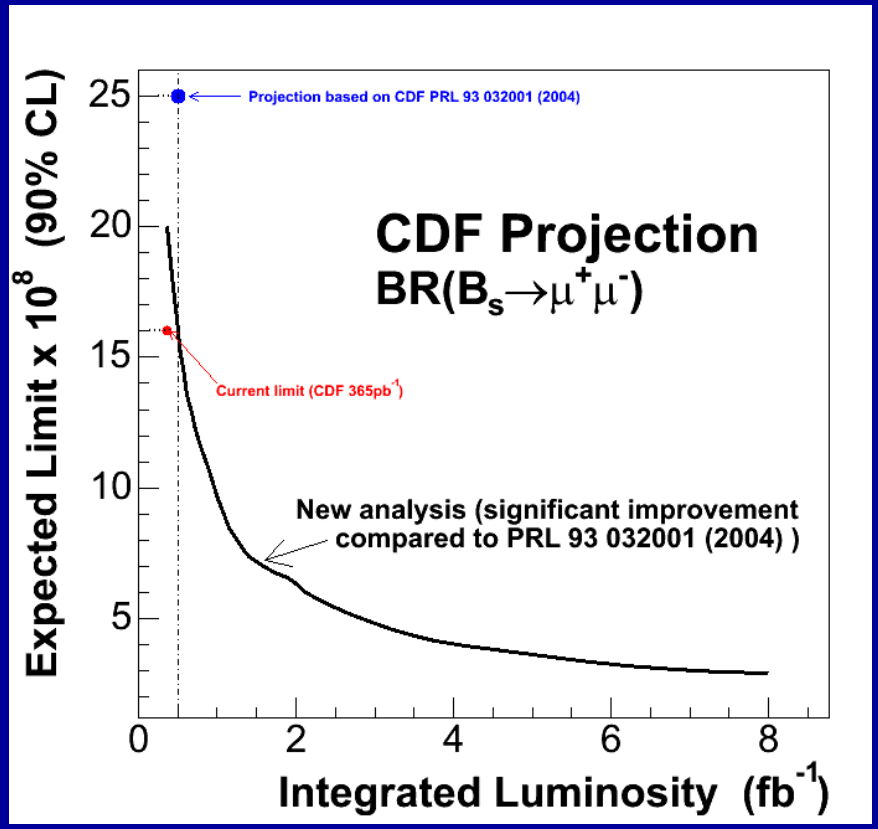
N_{bkg} expected: 1.6±0.4
0 events found

$BR(B_s \to \mu\mu\varphi) < 4.1\times10^{-6}$ **95% CL**

$B_{s(d)} \rightarrow \mu\mu$

$$BR(B_s \rightarrow \mu\mu) < 1.0 \times 10^{-7}$$

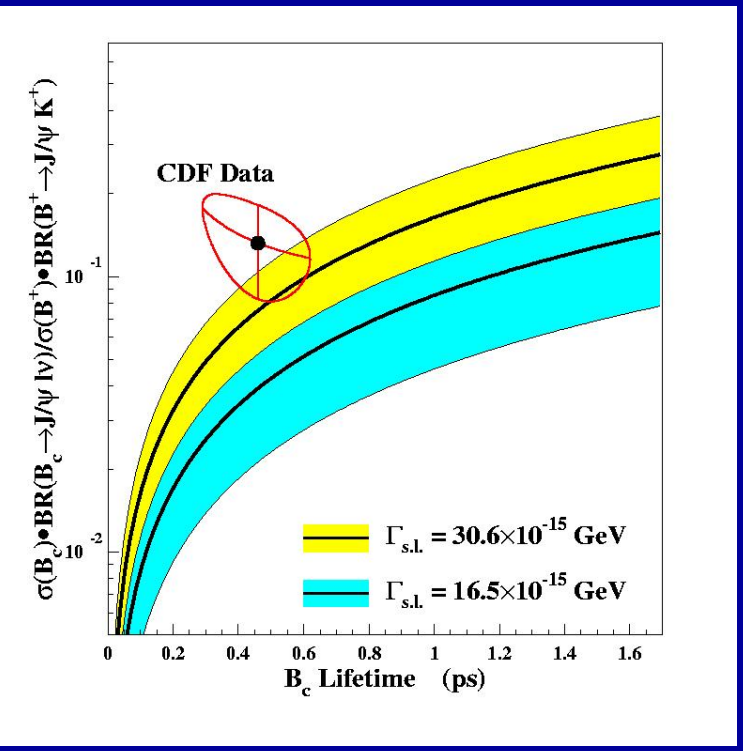
95% CL



$B_c^{\pm} \rightarrow J/\Psi l^{\pm}\nu$

Run I, 110 pb^{-1}

Production measurement

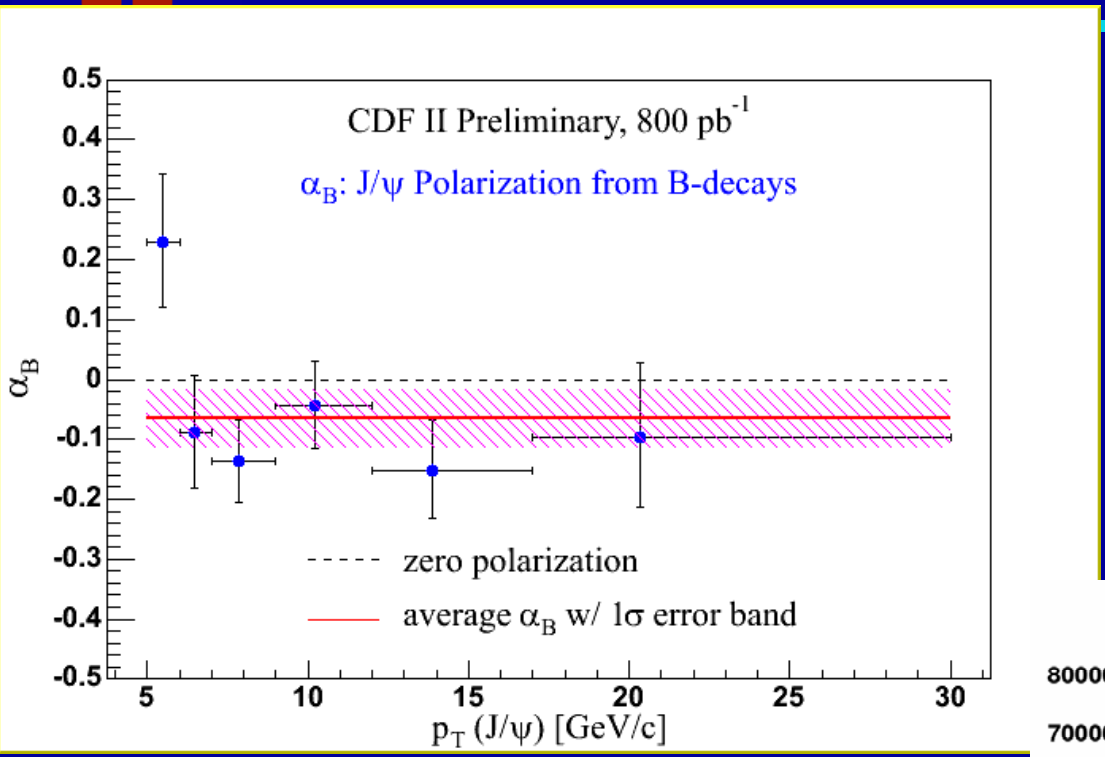


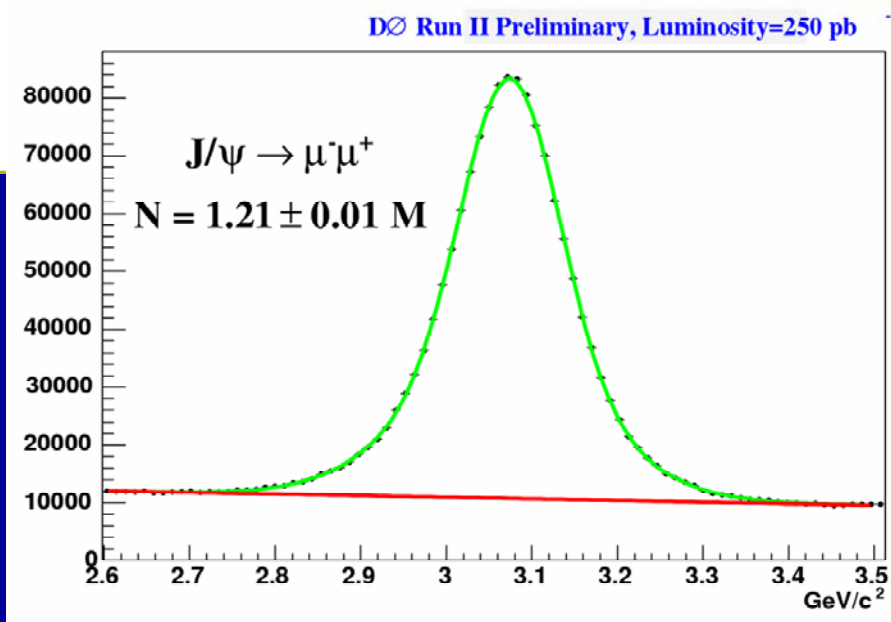
$$P_T(B) > 6\,\mathrm{GeV/c};|\eta| < 0.6$$

$$\frac{\sigma(B_c)\times B(B_c \rightarrow J/\psi \ell\nu)}{\sigma(B_u)\times B(B_u \rightarrow J/\psi K)} = 0.132\,^{+0.041}_{-0.037}\,(stat) \pm 0.031(syst)\,^{+0.032}_{-0.020}\,(c\tau)$$

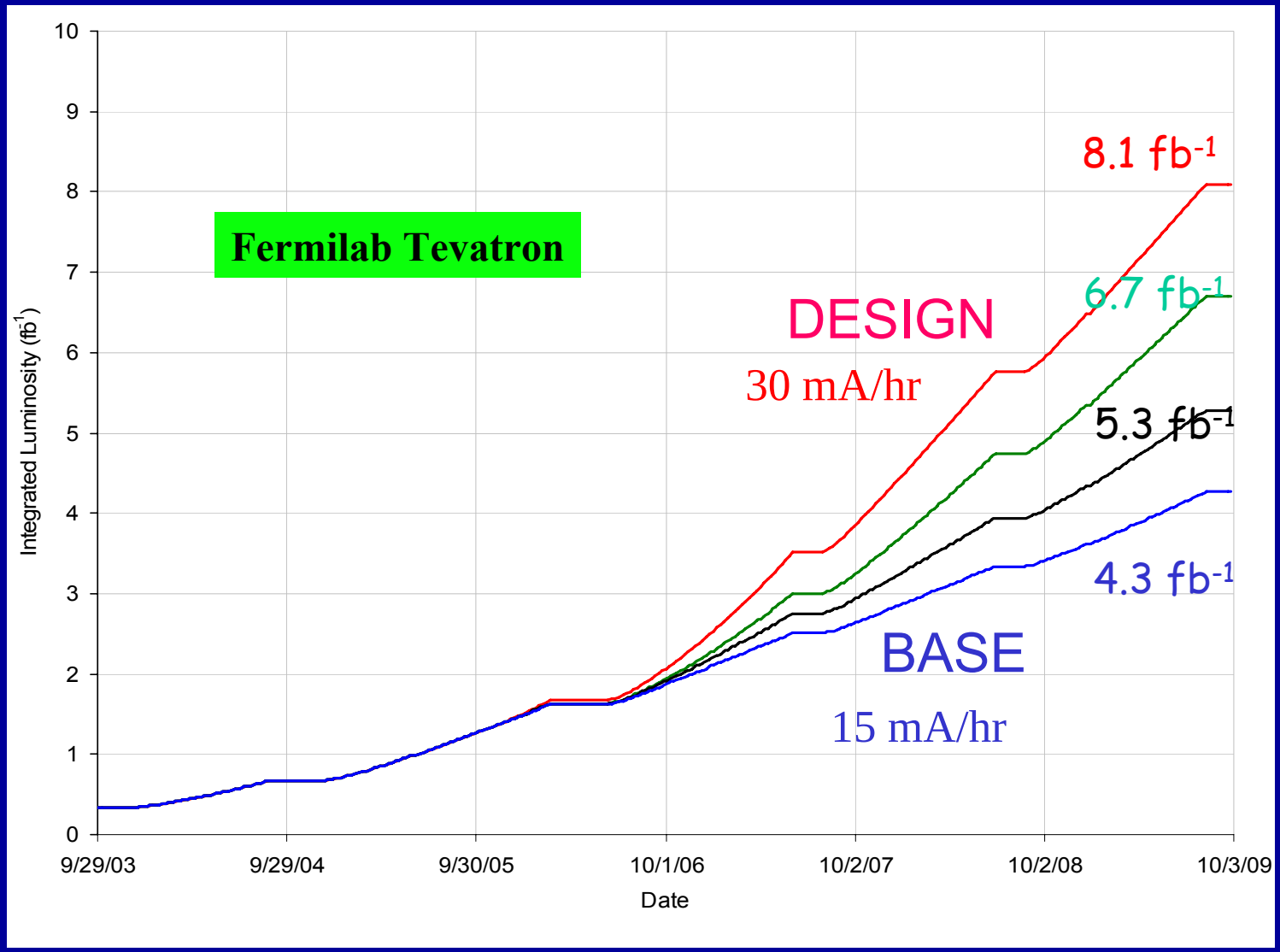
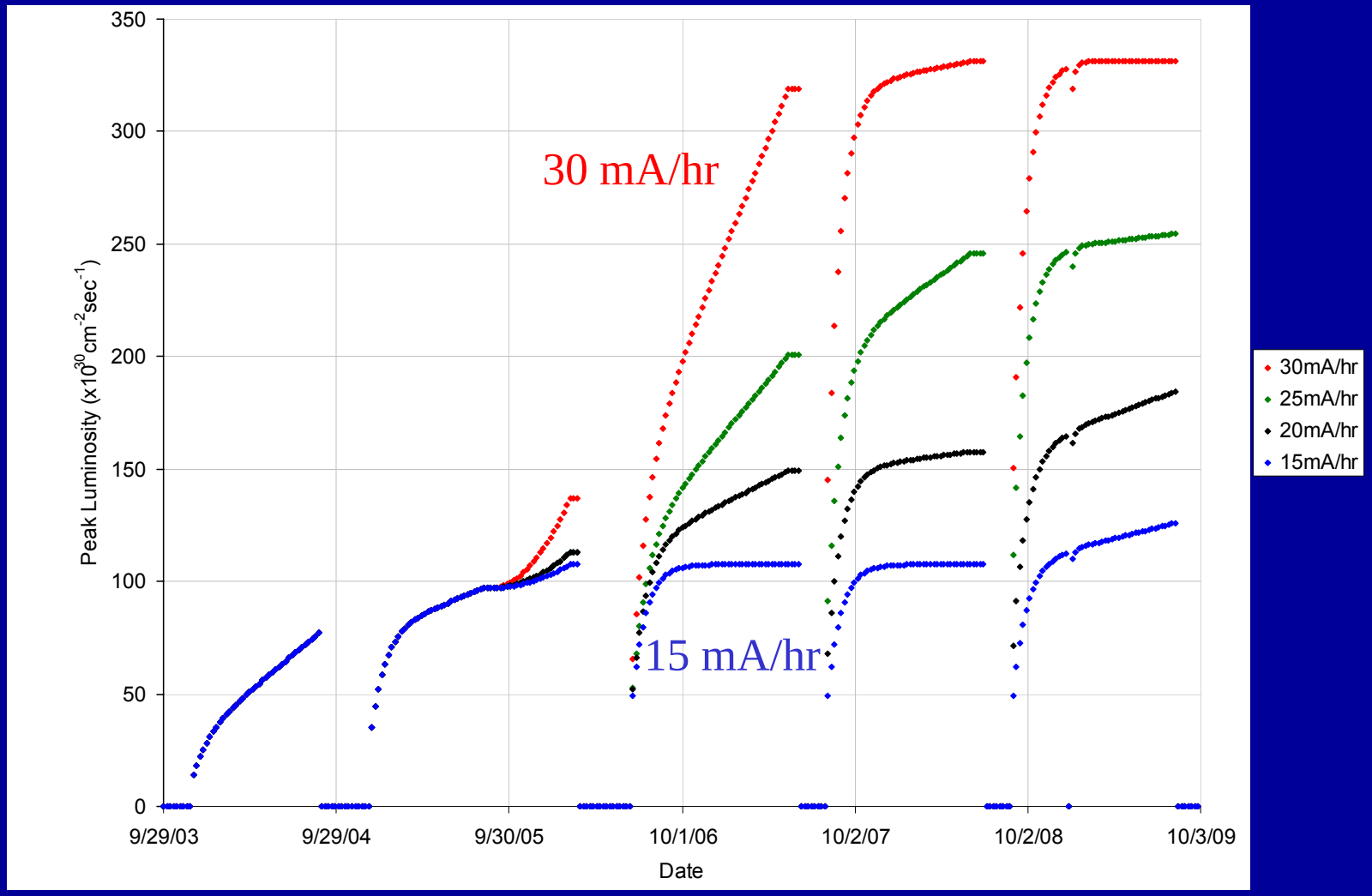
PRL 81, 2432 (1998), PRD 58, 112004 (1998)

J/ψ Polarization





Expected Integrated Luminosity



Expected Peak Luminosity