b Physics at the Tevatron
part I:
m and $\Delta m_{d,s}$

- Masses of *b*-hadrons,
- rare decays and
- oscillation measurements

at CDF and D0

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For the CDF and D0 collaborations

XL Rencontres
de Moriond EW

Introduction: CDF and D0 detectors

Tevatron performances: see G. Bernardi's transparencies

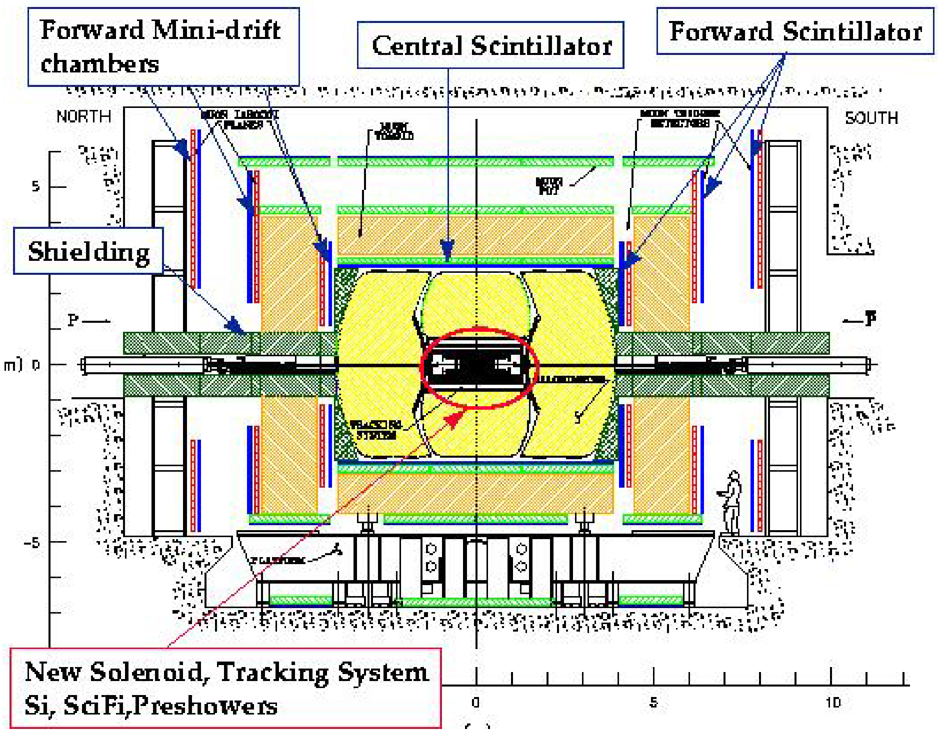
Great *b*-physics capabilities

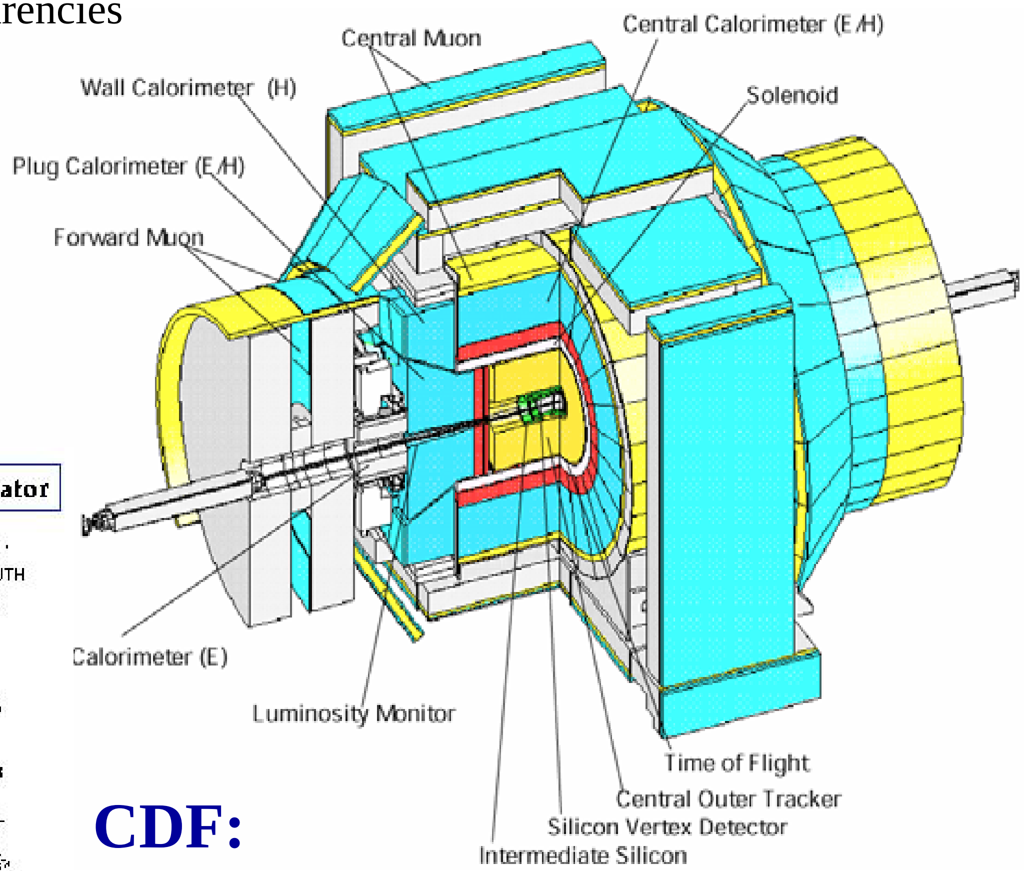
D0:

Excellent muon trigger

Tracking coverage |η| < 2

Tracking: Silicon + SciFib,





CDF:

Excellent p_T resolution,

displaced track trigger

→ fully hadronic decay modes

Tracking: Silicon + Drift Chamber

dE/dx, ToF particle ID

Trigger issues

CDF, D0: $p\bar{p} @ \sqrt{s} = 1.96\, TeV$

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 submitted to PRD hep-ex/0412071

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

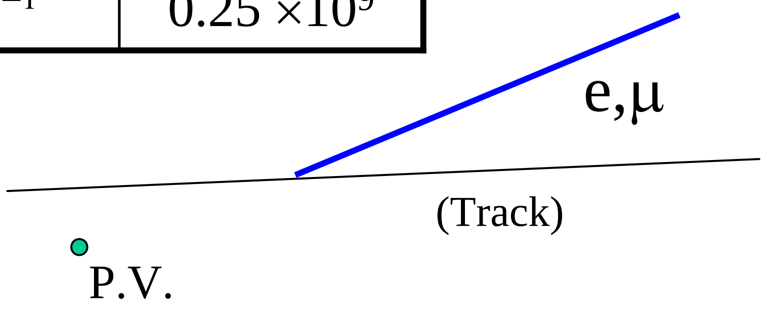
Compare with *b*-factories: σ is 10^3 higher,

L is pb^{-1} (TeVatron) vs. fb^{-1} (*Y*(4S))

	σ (μb)	L $cm^{-2}\, s^{-1}$	Integrated L	*b*-events
Tevatron	29	1.2×10^{32}	$600\ pb^{-1} \times 2$	13.8×10^9
KEK	0.001	1.52×10^{34}	$371\ fb^{-1}$	0.37×10^9
BaBar	0.001	0.95×10^{34}	$256\ fb^{-1}$	0.25×10^9

Trigger crucial point:

- 2 μ from J/ψ,
- soft lepton, (soft lepton+non prompt track)
- 2 non-prompt tracks (CDF)

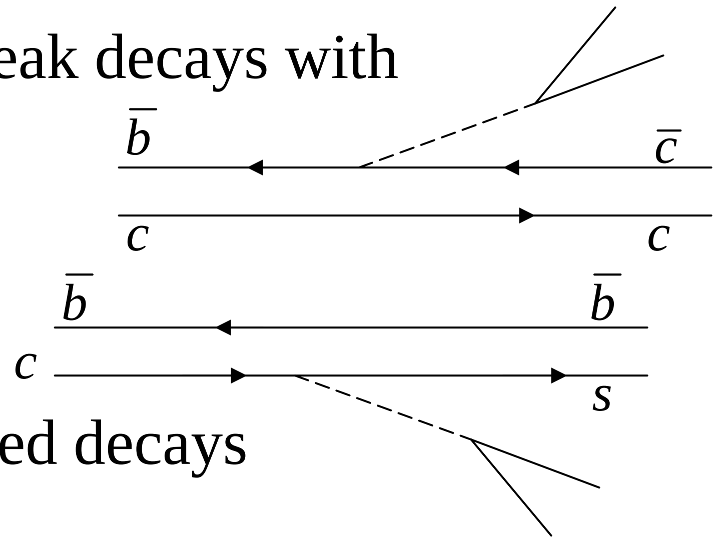


Relevance of mass measurements

- Spectroscopy of heavy-light quark system, to complement quarkonia
- Verify detailed calculation and hypothesis (potential, NRQCD ….)
- Validation of Lattice QCD
- Spectroscopy of heavy-heavy mesons: quarkonia vs. B_c.

Relevance of B_c

- Only meson to have 2 spectator-model weak decays with comparable amplitudes (*b* and *c* decays).
- Possible contamination for B_s decays
- Perfect source of flavour-tagged B_s
- Measure angle γ in $D^0 D_s, \overline{D}^0 D_s$ self-tagged decays
  [Masetti, Fleischer-Wyler,Kiselev]



b hadron masses

Fully reconstructed modes using

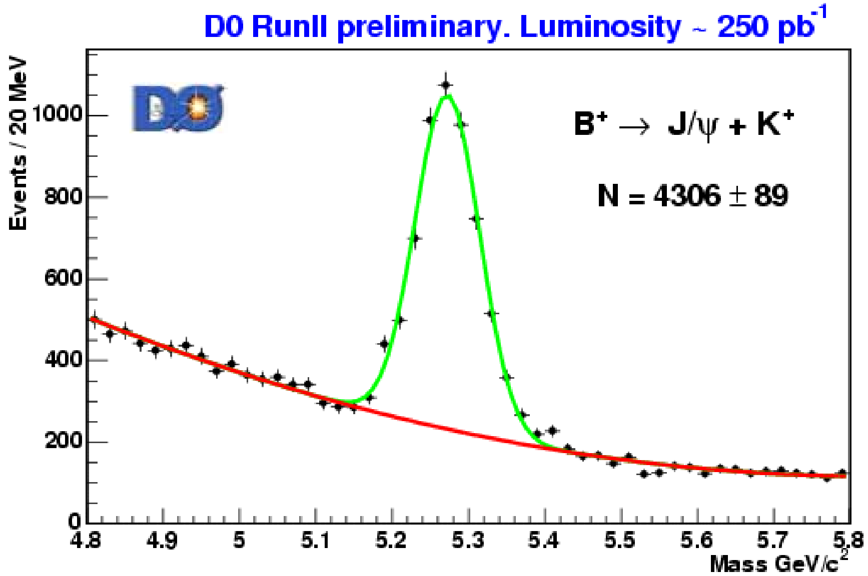
$J/\psi \rightarrow \mu\mu$ trigger

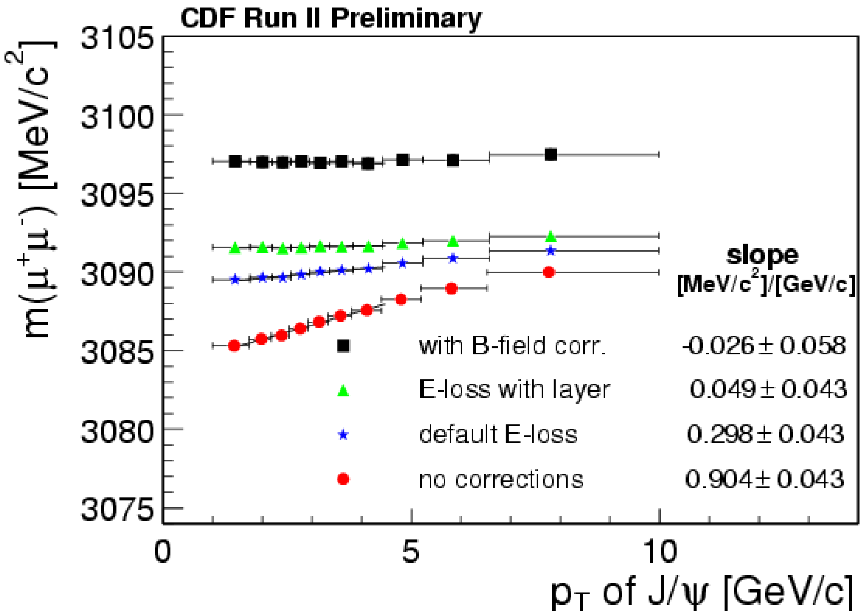
D0 more candidates

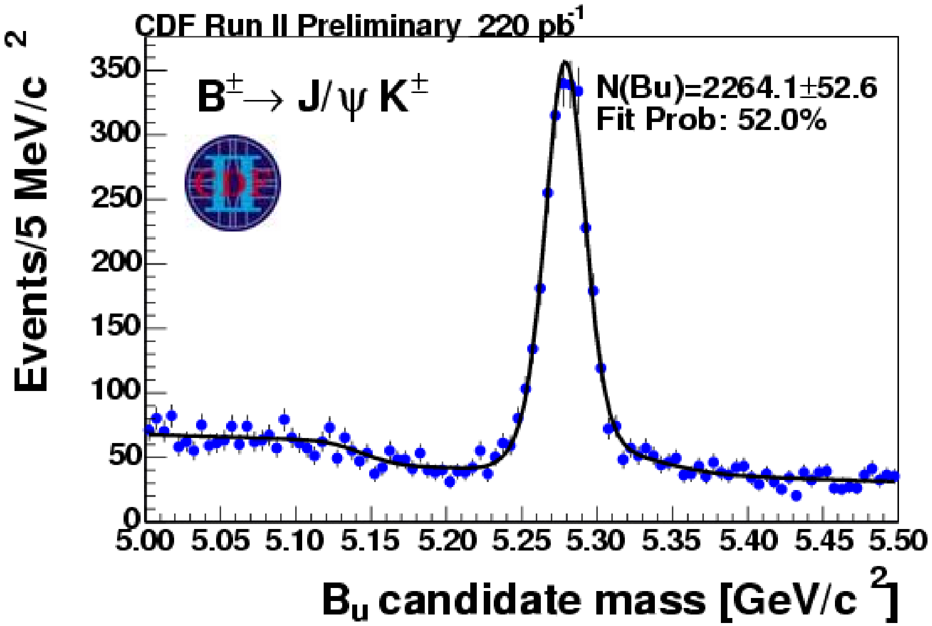
CDF better mass resolution

(11 MeV, J/ψ mass constrained)

Calibration using J/ψ mass,
checked against the Υ, systematics sub-MeV

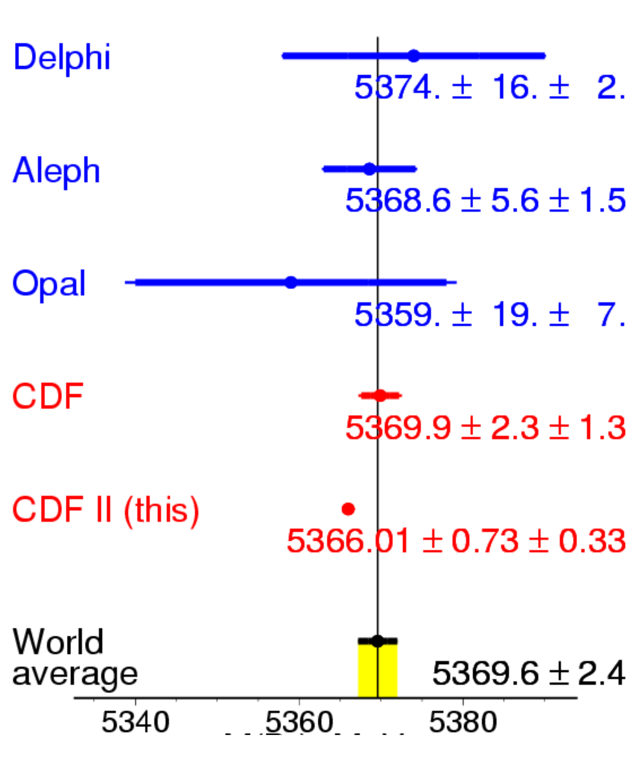




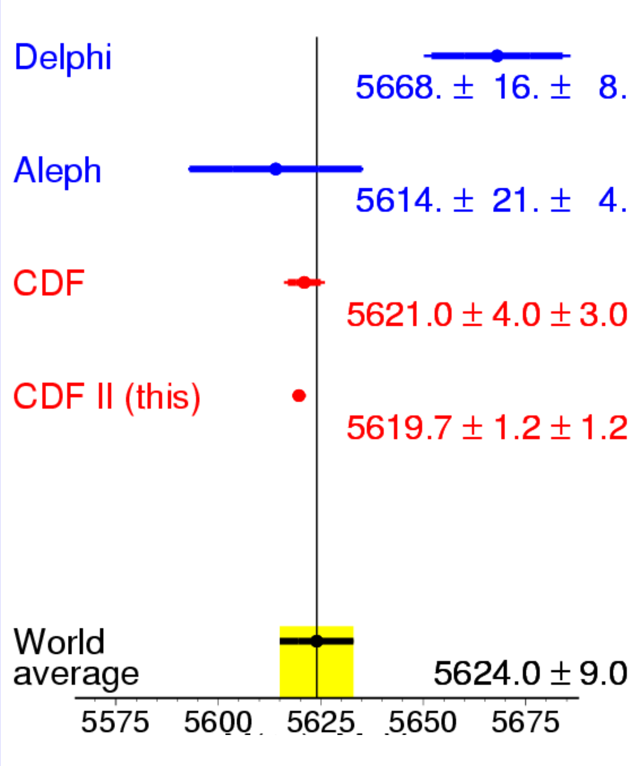


b hadron masses

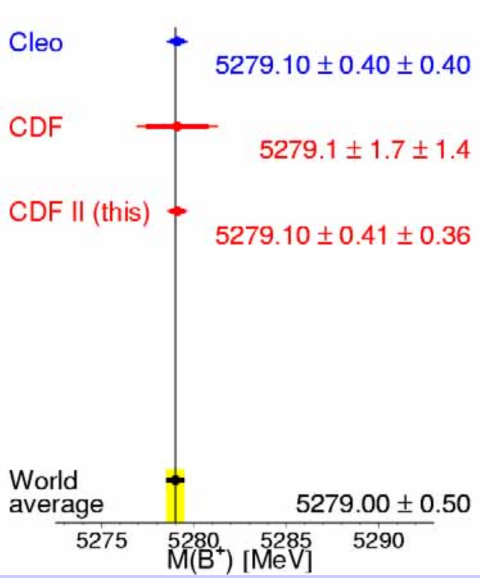
B_s mass



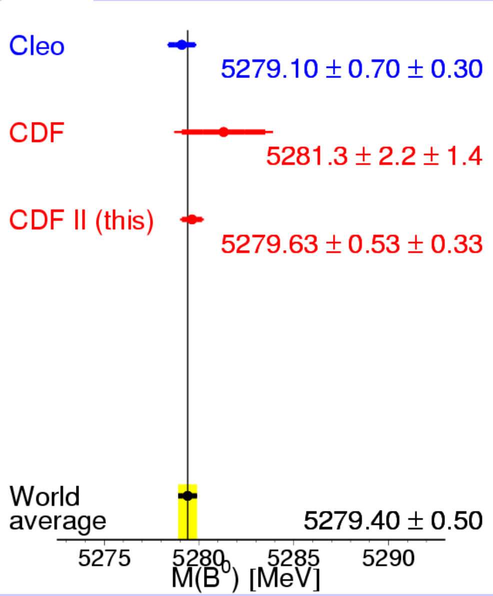
Λ_b mass



B^+



B^0

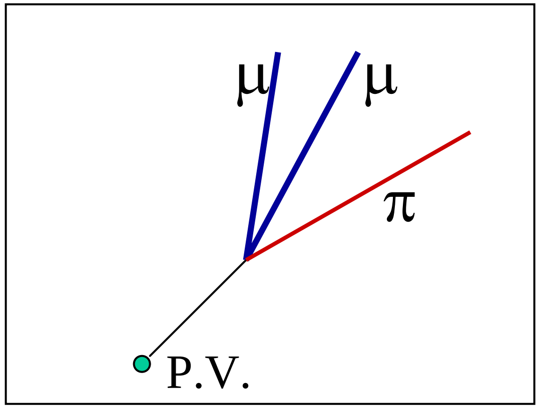


Systematics below 1 MeV for high statistics channels

Best single measurements of *b*-hadron masses

CDF Fully reconstructed B_c

Tevatron best place to measure B_c mass precisely
CDF: Search for fully reconstructed mode

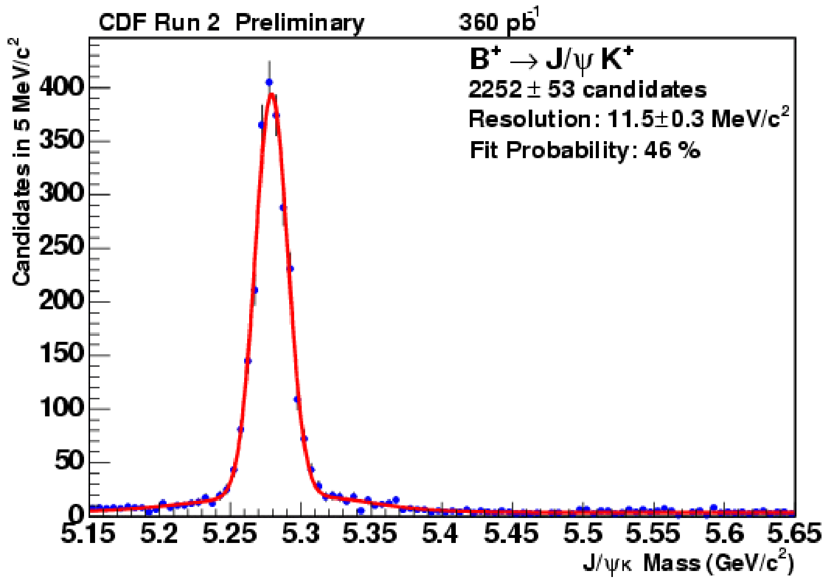


$$B_c \rightarrow J/\psi\ \pi^{\pm}$$

- Trigger: 2 μ's from J/ψ, $p_T > 1.5$ GeV/c
- 2-body topology, reference mode $B^+ \rightarrow J/\psi\ K^+$
- Blind search: range: semileptonic mass $\pm 2\sigma_m$.
- Experimental issues:

  lifetime, small *BR*, small σ_{prod}.

expected 10-50 events, based on Run I rate.

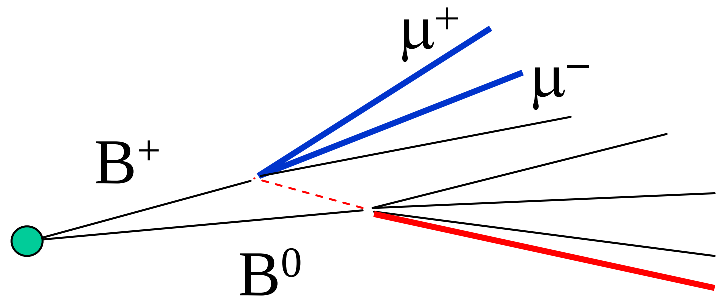


Background:

- Prompt J/ψ associated to random prompt track

  → require lifetime
- Secondary J/ψ with prompt track
- Secondary J/ψ with non prompt track

  → require good vertexing



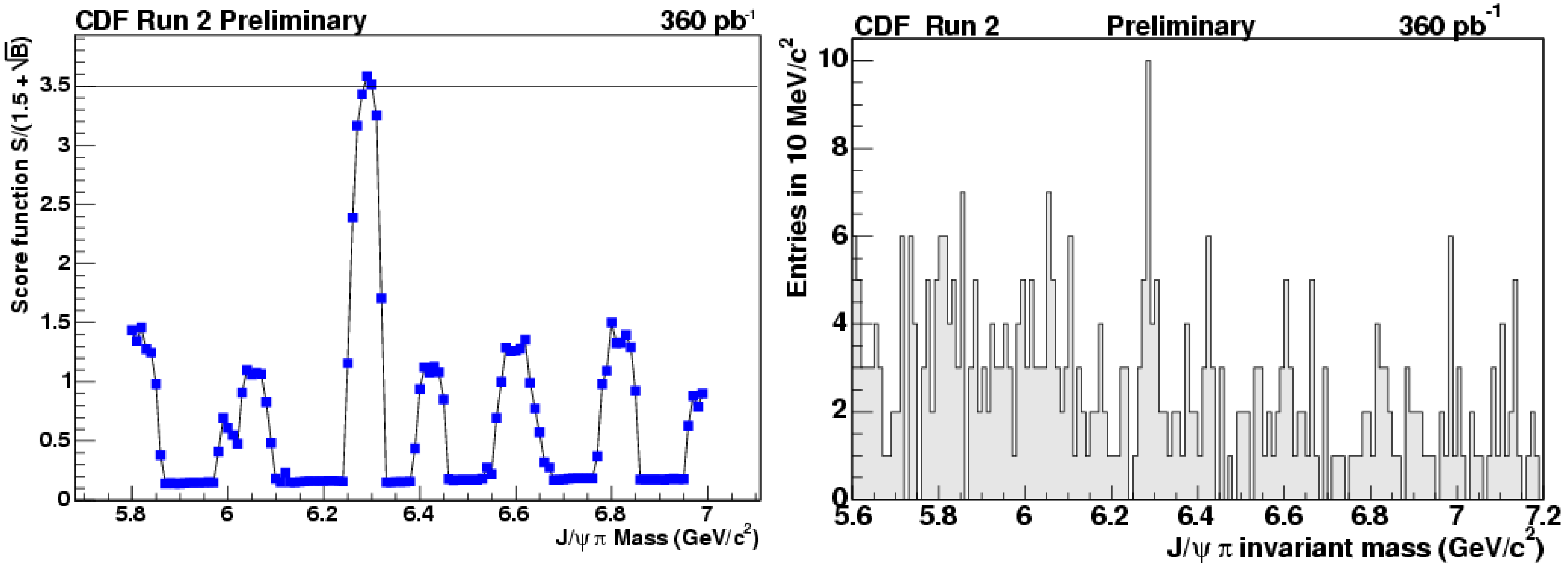
CDF Fully reconstructed B_c

Hypothesis test set up before opening the box.

Score function $\Sigma = \dfrac{S}{1.5+\sqrt{B}}$

Threshold value $\boxed{\Sigma_{thr} = 3.5}$ From "*toy Monte Carlo*", P ≈ 1/1000 false positive

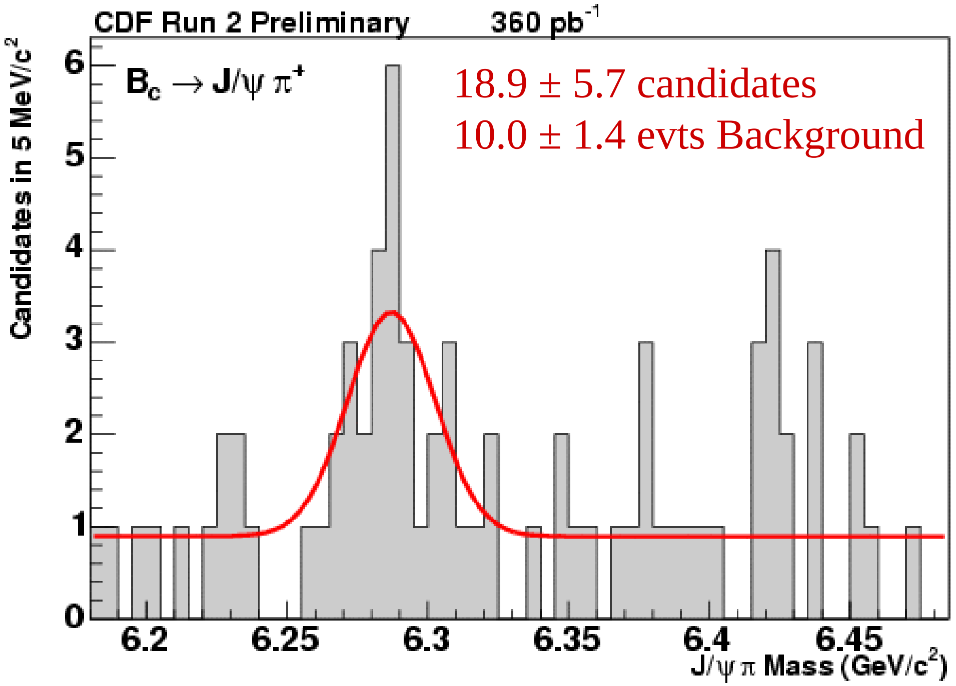
After box open: scan search region with binned likelihood fit:
mass fixed (scanned), Gaussian width fixed (resolution), S,B fit parameters



CDF Fully reconstructed B_c

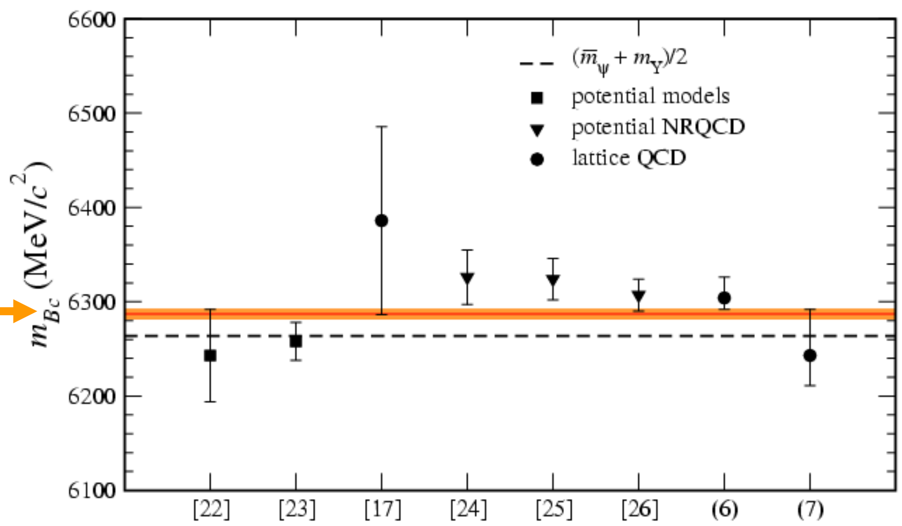
Unbinned likelihood fit. Mass: fit parameter, width fixed.

Mass = 6287.0 ± 4.8(stat.) ± 1.1(syst.) MeV/c^2



Main systematics:
Fit function/Background
Momentum scale
p_T spectrum

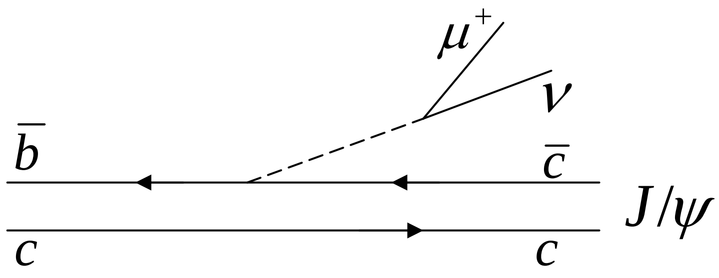
This result



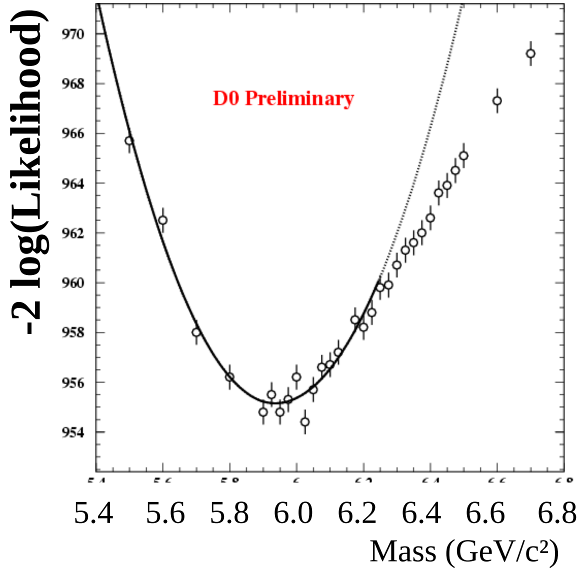
Theory in very good agreement.
Potential models, NRQCD, LQCD
Good topic for Moriond QCD

D0 Semi-leptonic B_c decay

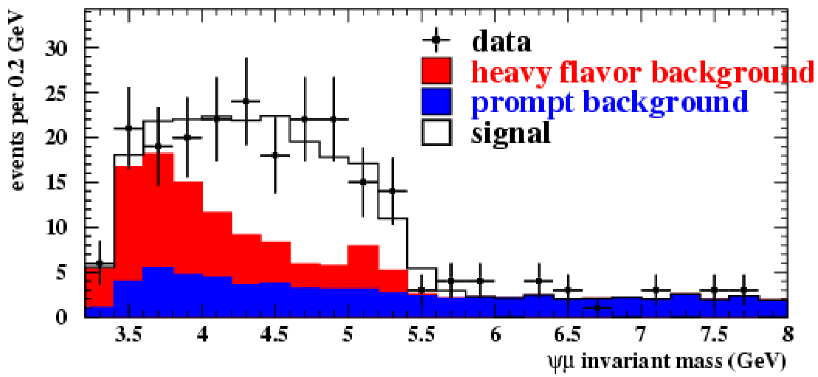
- Inclusive measurement $B_c \to J/\psi\ \mu\ X$
- Same strategy, require 3rd track be a μ.
- Inclusive measurement, no pointing constraint.
- No lifetime cut $\Rightarrow$ mass and lifetime measurement
- Depends on Monte Carlo for Probability Density Function and "k-factor"
- Control sample: $\psi(2S)\ \mu\ X \to \mu\mu\ \mu\ X$ (expected low BR)
- Signal: 95±12±11 candidates,
- Significance likelihood ratio 60
- Mass = $5950\,^{+140}_{-130} \pm 340$ MeV/c^2

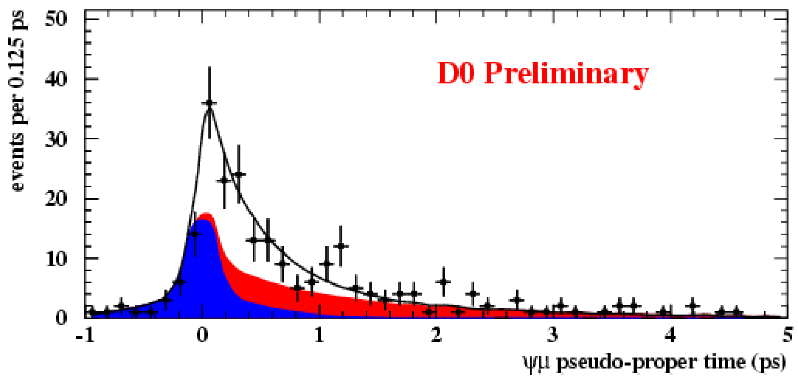


D0 ICHEP 04



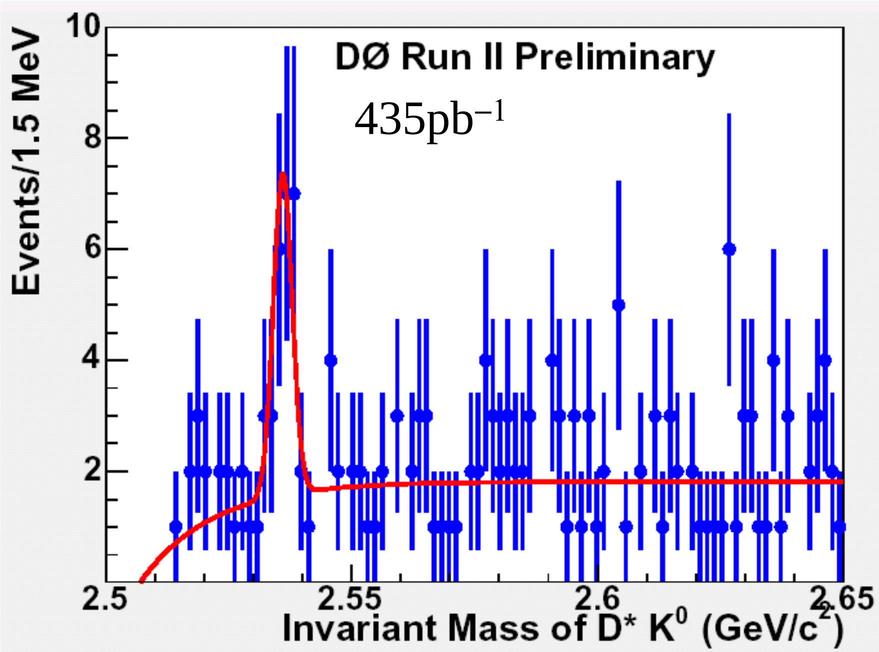
Systematic uncertainties from MC sample composition and decay model; background fraction. Larger than stat.

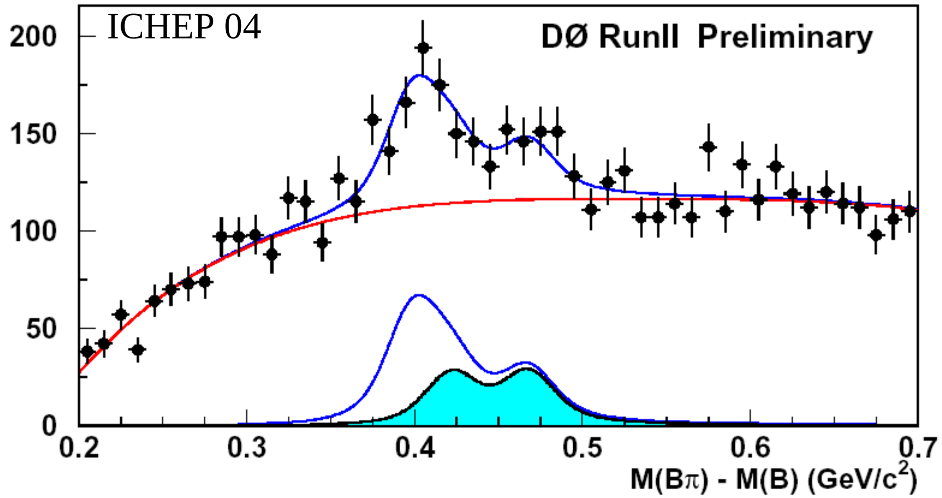


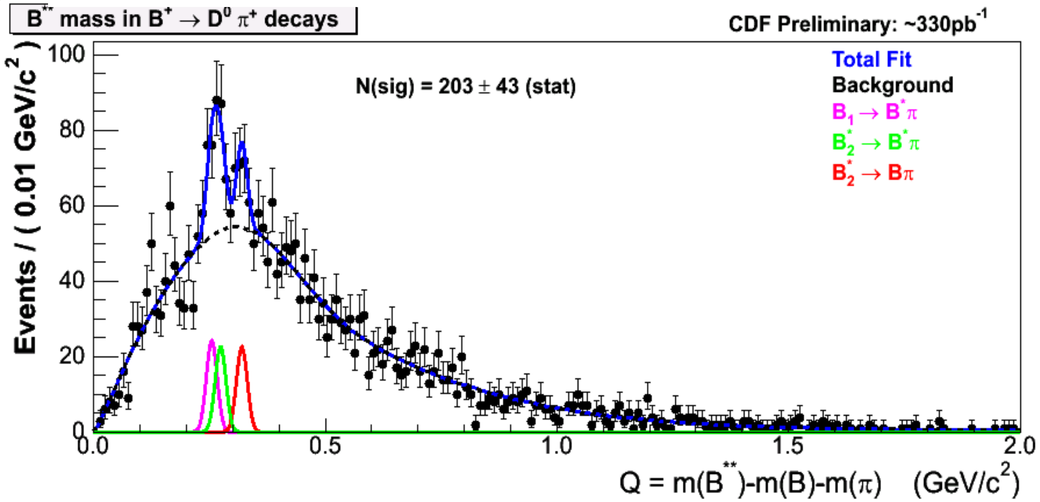


b and *c*-mesons excited states

Evidence for the decay
$B_s \rightarrow D_{s1}(2536)\ \mu\ X$
Signal: 18 ± 5.5 candidates, 3.5 σ

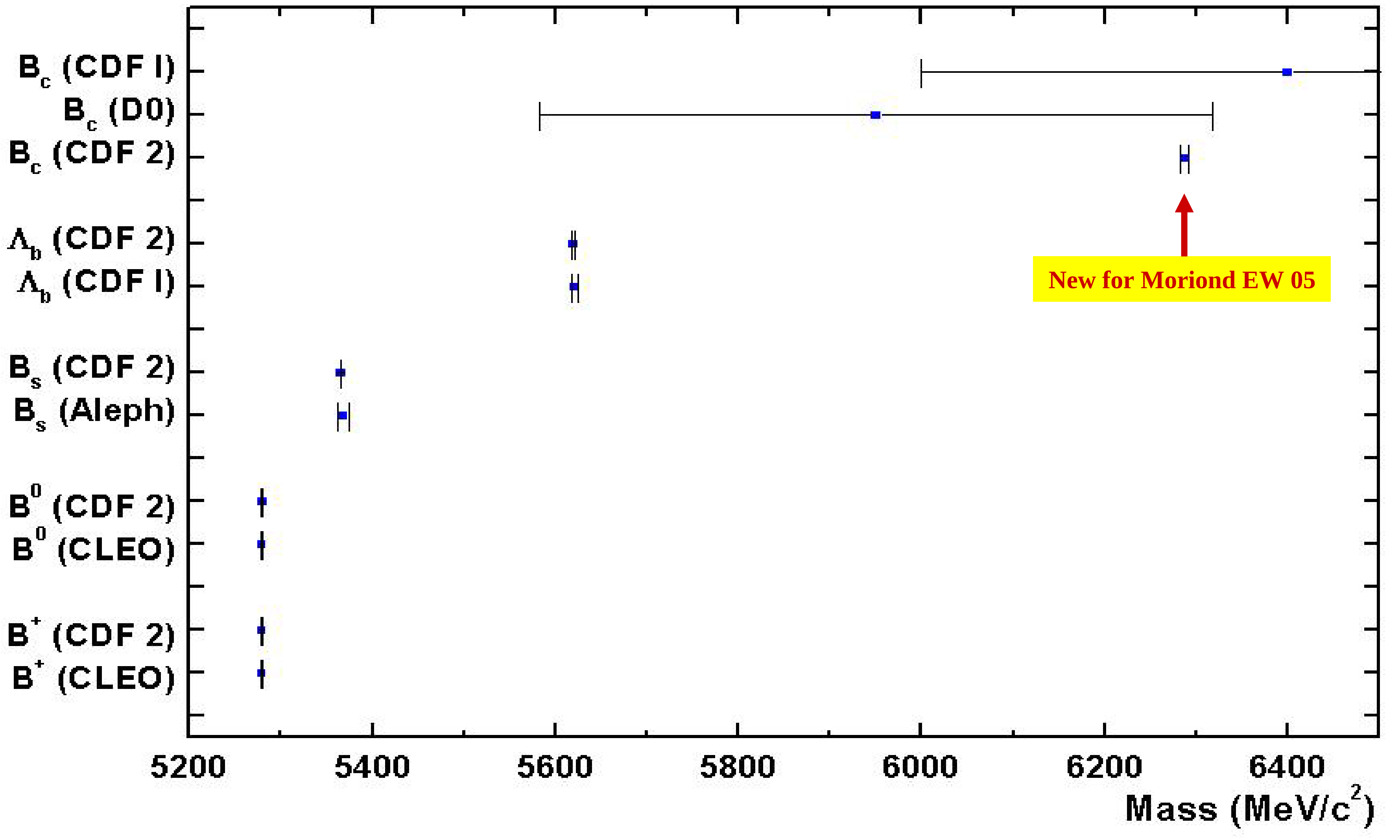




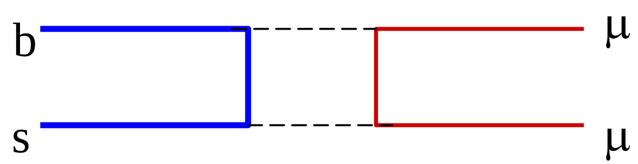


Studies of excited b-mesons for Same Side tagging & MC tuning
Soft π from fragmentation and decay

B-hadrons mass summary



CDF/D0 Rare decays



$B_{d,s} \to \mu^+\mu^-$ Flavour-Changing Neutral Currents.

BR = (3.4 ±0.54) 10^{-9} ⇒ place to look for new Physics

New since Tuesday this week

- mSUGRA models enhanced 10 to 100× (Dedes, Dreiner, Nierste, hep-ph/0108037)
- SO(10) models 100× (Dermisek, Rabi et al. hep-ph/0304101)
- MSSM models enhanced 1000×

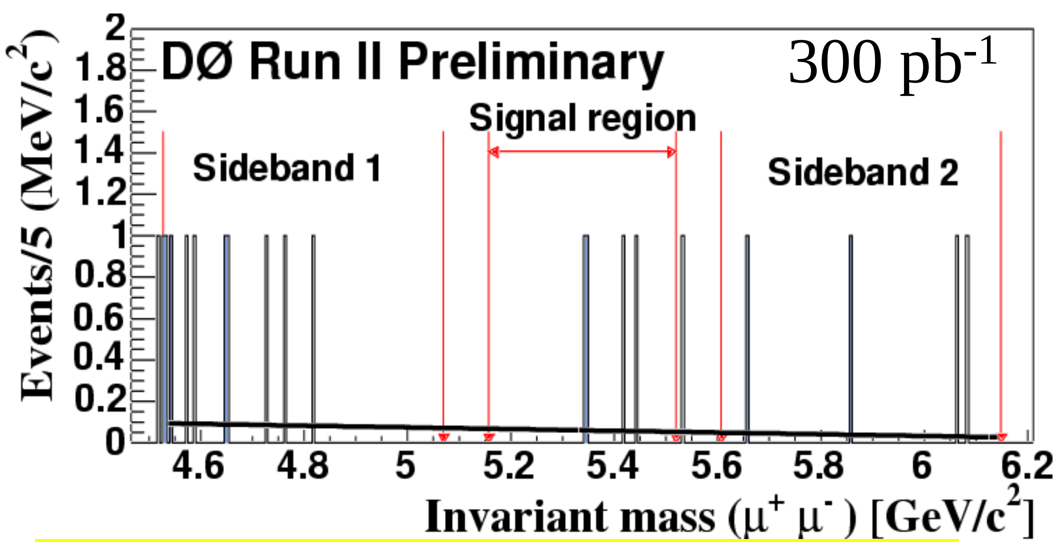
D0 updated measurement to include 300 pb^{-1}

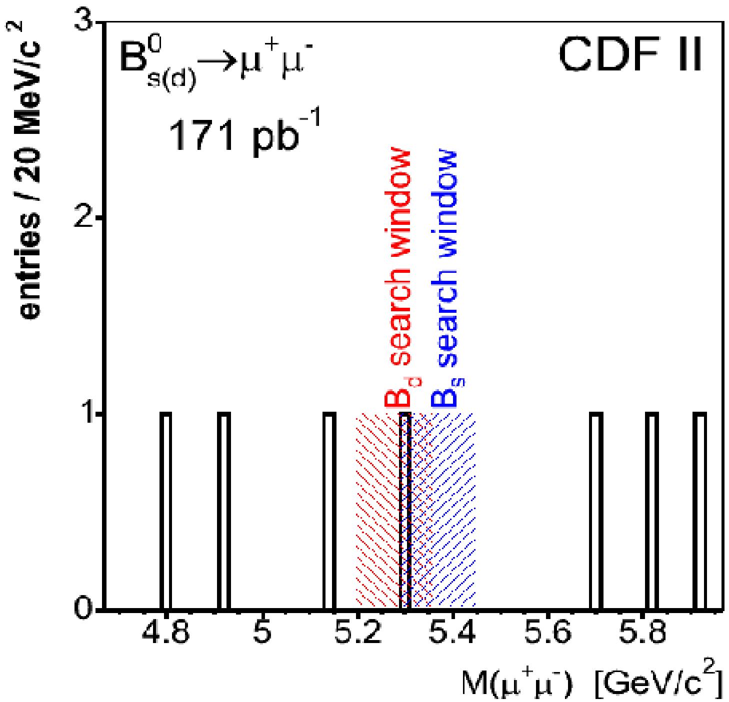
CDF uses 171 pb^{-1} Mass resolution 27 MeV/c^2

Limits on both B_d and B_s Both analyses blind

95% CL

	BR ($B_s \to \mu^+\mu^-$)	BR($B_d \to \mu^+\mu^-$)
D0	< 3.7 10^{-7}	----------
CDF	< 7.5 10^{-7}	< 1.9 10^{-7}

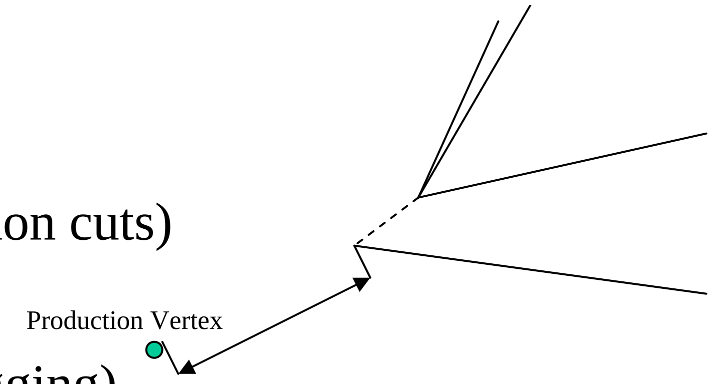




D0 looking for BR ($B_s \to \mu^+\mu^-\phi$) Closed box

Attainable Sensitivity = 1.2 10^{-5} (95% CL)

Mixing measurements



- Reconstruct signal(s) flavor specific (selection cuts)
- Measure decay time for each candidate
- Establish flavor $(b, \bar{b})$ at production (≡ tagging)

Mixing Asymmetry $A_{mix} = \frac{N_{nomix}(t) - N_{mix}(t)}{N_{nomix}(t) + N_{mix}(t)} = -D\cos(\Delta m\, t)$

Need high statistics sample, well measured lifetime.

Tagging production flavor

Dilution D $= \frac{N_R - N_W}{N_R + N_W}$

Efficiency $\varepsilon = \frac{N_{tag}}{N_{cand}}$

Statistics reduced by a factor εD^2:

N tagged events = εD^2N useful events

$$\sigma_t = \left(\frac{\sigma_{DL}}{p}\right) m_B \oplus \left(\frac{\sigma_p}{p}\right) t$$

$$S \propto \sqrt{1/2\, \varepsilon N}\, f_{sig}\, D\, e^{-\frac{1}{2}(\Delta m_s\, \sigma_t)^2}$$

Δm_s:
- lower statistics B_s
- larger Δm_s

s.l.decays larger σ_t

Flavor tagging

Opposite side

- Soft-Lepton tag

  Flavor from the sign of the lepton (*e* or μ) in semileptonic decays of accompanying *b*-meson.

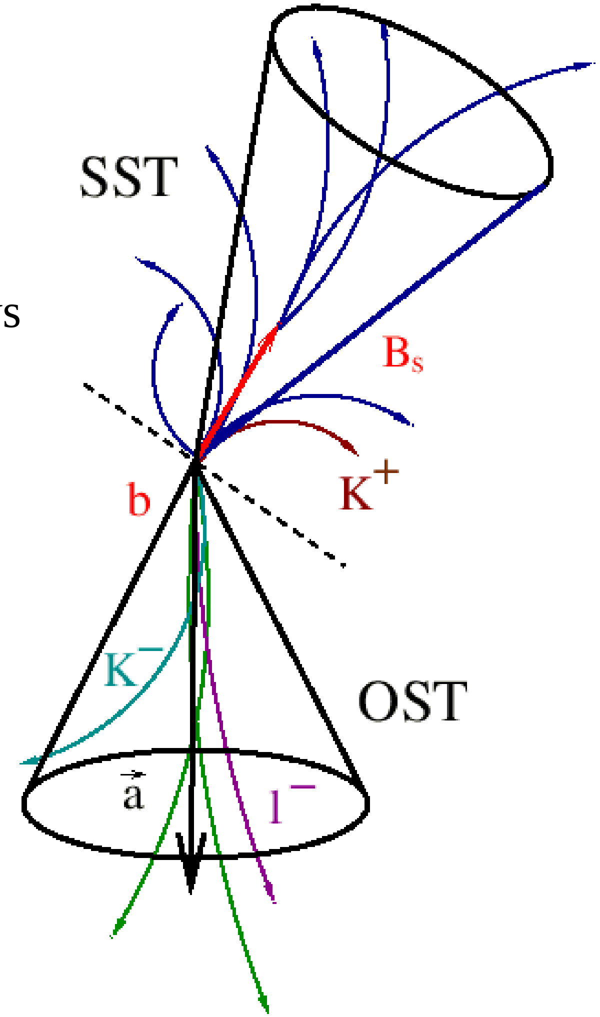
  Source of dilution: charm semi-leptonic cascade decays, oscillation in the opposite side.

- Kaon Tag:

  Sign of the kaon in cascade decay $b \rightarrow c \rightarrow s$

- Jet Charge

  Sign of the momentum-weighted average charge of opposite jet.



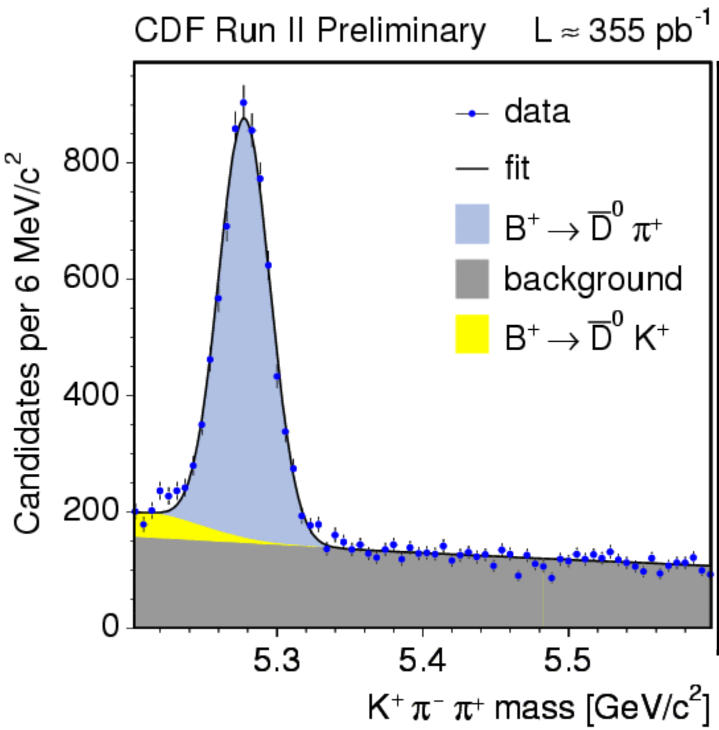
Same side

B_s has preferentially a K^+ "close by", $\underline{B}_s$ has a K^-, B^0 has a π^+, $\underline{B}^0$ has a π^-

Flavor tagging

D0 use "any" μ for tagging, use opposite side fully reconstructed decays, semileptonic decays for high statistics

Opposite side tagging is the same as for B_s mixing: use Dilution from B_d to fix this parameter for B_s.

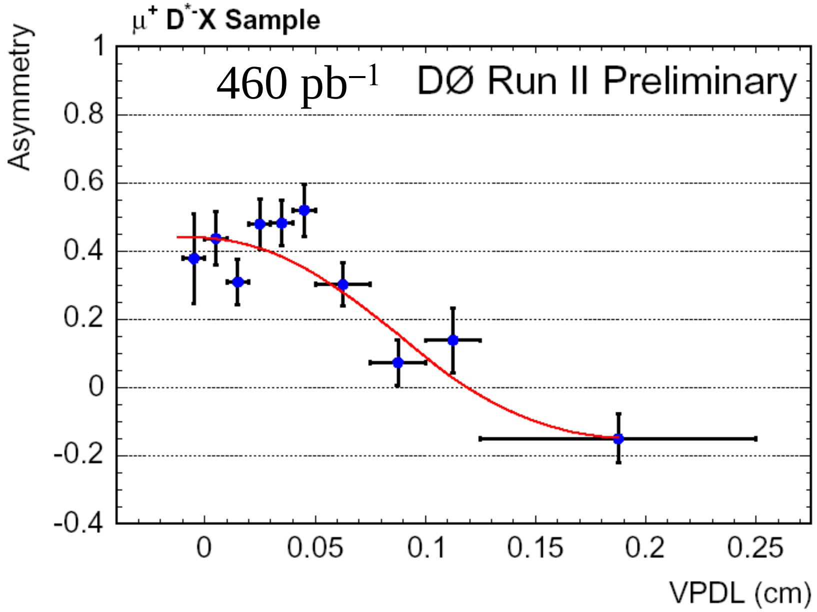


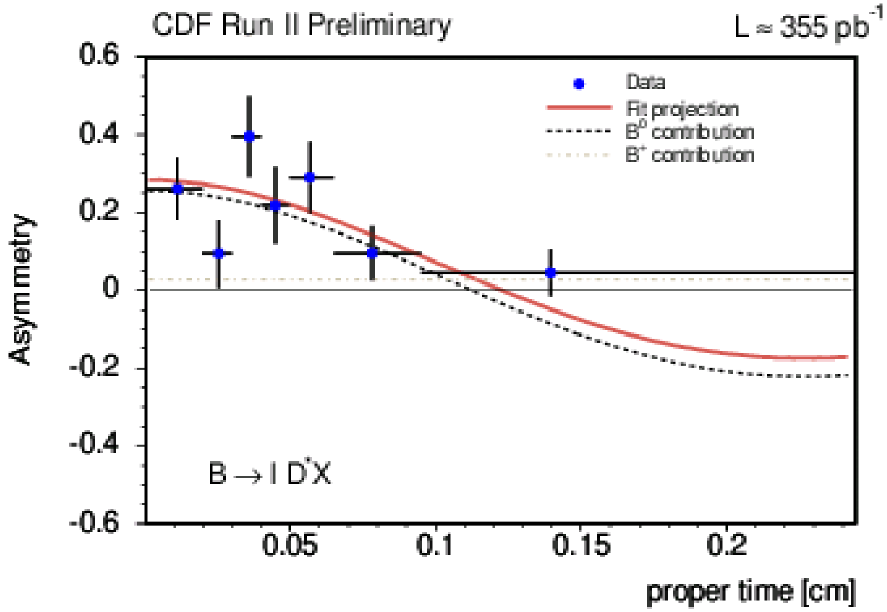
εD^2 (%)	CDF s.l.	D0 s.l.	CDF had
SST (B_d)	1.04 ± 0.35 ± 0.06	1.00 ± 0.36	----
Soft μ	**0.56 ± 0.05**	Overall fitter	**0.46 ± 0.11 ± 0.03**
Soft e	**0.29 ± 0.03**		**0.18 ± 0.06 ± 0.02**
Jet Qpt	**0.16 ± 0.03 ± 0.03**		**0.24 ± 0.09 ± 0.01**
Jet Qjp	**0.150 ± 0.03 ± 0.02**		**0.11 ± 0.06 ± 0.02**
Jet Qvtx	**0.26 ± 0.03 ± 0.02**		**0.14 ± 0.07 ± 0.01**
Combined	1.429 ± 0.093		1.12 ± 0.18 ± 0.04

Δm_d measurements

Exp't	$\int L$ (pb^{-1})	channel	Tag	Result
D0	250	s.l.	combined	0.456 ± 0.034 *(stat.)* ± 0.024 *(syst.)*
D0	460	s.l.	o.s.t.	0.558 ± 0.048 *(stat.)* ± x.xxx *(syst.)*
CDF	355	s.l.	o.s.t.	0.497 ± 0.028 *(stat)* ± 0.015 *(syst.)*
CDF	355	f.r.	o.s.t.	0.503 ± 0.063 *(stat)* ± 0.015 *(syst.)*

NEW since la Thuile '05



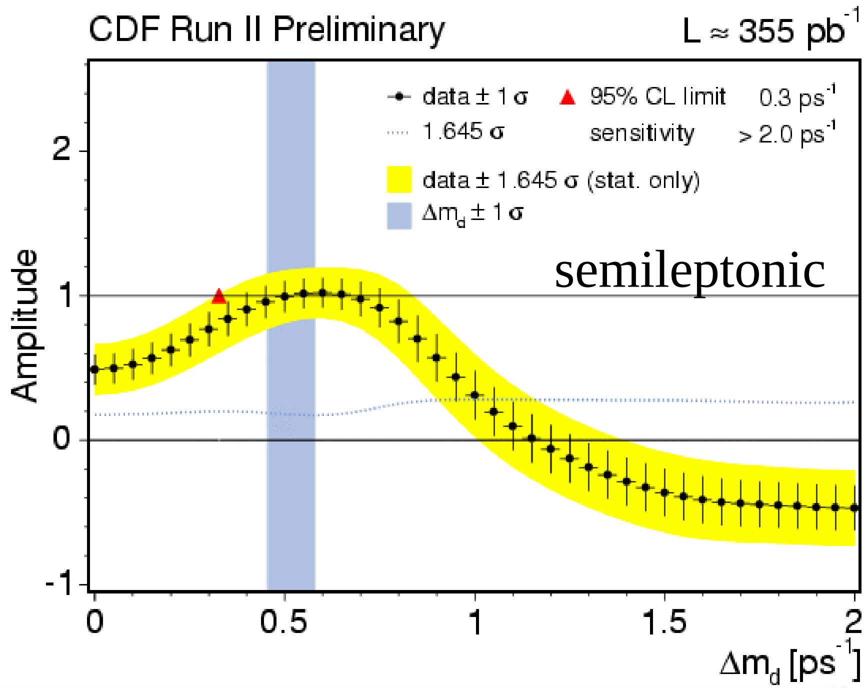


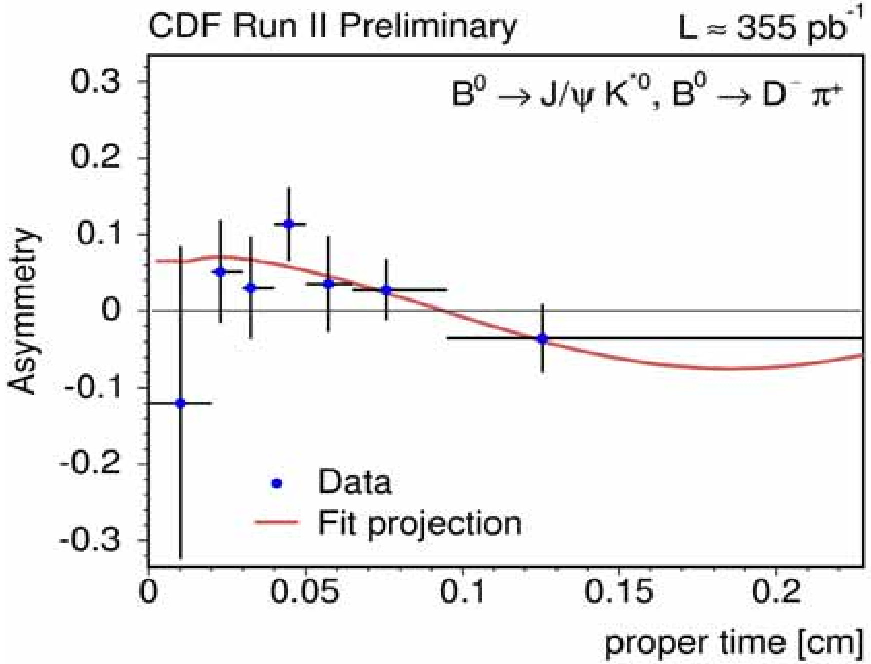
Main purpose: tagging and fitting test preparing for Δm_s

Best measurement HFAG Δm_d = (0.506 ± 0.006 ± 0.008) ps^{-1}

Amplitude scan

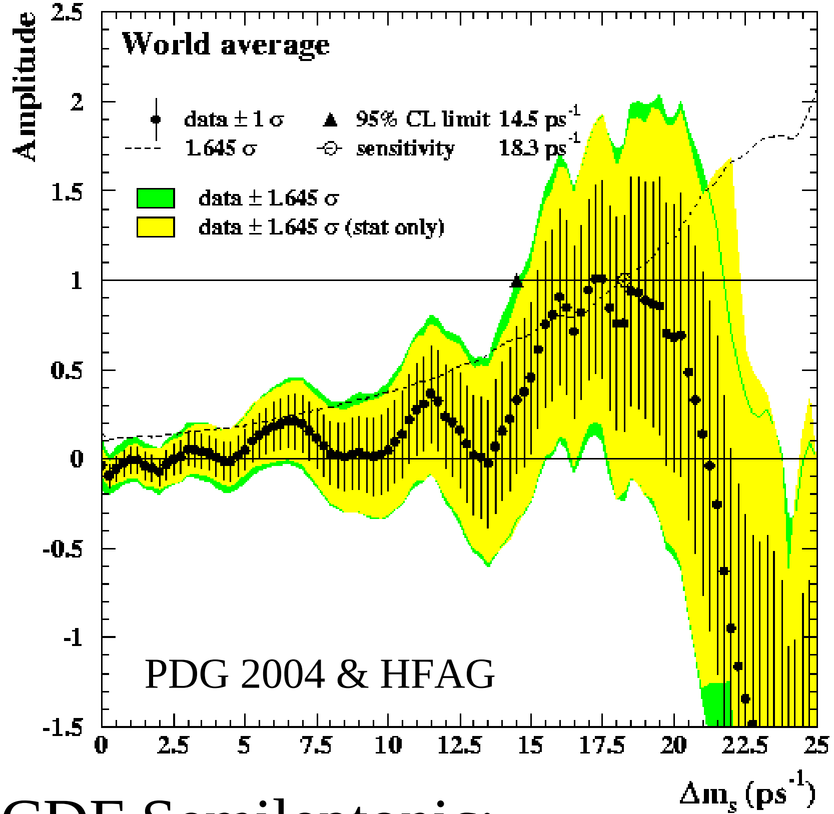
- Fourier-transform method
- Fix frequency (Δm)
- Fit for the oscillation amplitude.
- **Limit at 95%:** lowest value Δm_{lim}
  $P(A(\Delta m_{lim}) \geq 1) = 5\%$
- **Sensitivity:** lowest value of Δm with error compatible with 1 (at 5%)
- **Measurement:** (range of) amplitude(s) compatible with 1 and not compatible with 0…..value of Δm from asymmetry fit !
- Advantage: easier to combine results

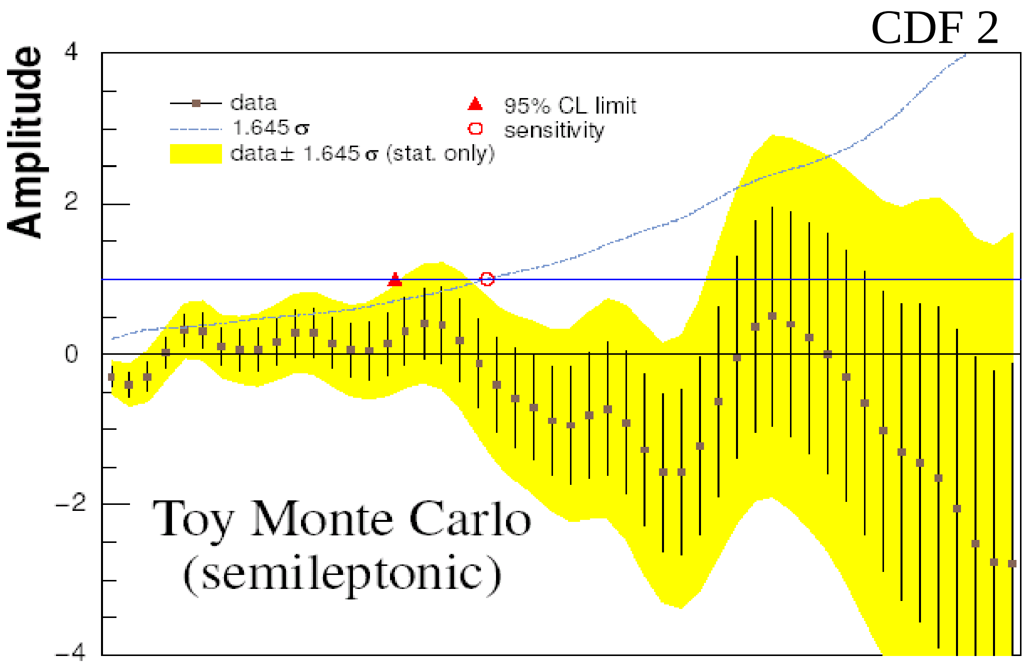




Δm_s CDF sensitivity studies

World average
Limit: $\Delta m_s > 14.5\ ps^{-1}$
Sensitivity for $\Delta m_s < 18.3\ ps^{-1}$





CDF Semileptonic:

$B_s \to D_s\, l\, X$, ≈ 6700

$D_s \to \phi\pi^+, K^*K, \pi^+\pi^-\pi^+$

CDF hadronic ≈ 700

$B_s \to D_s\, \pi$,

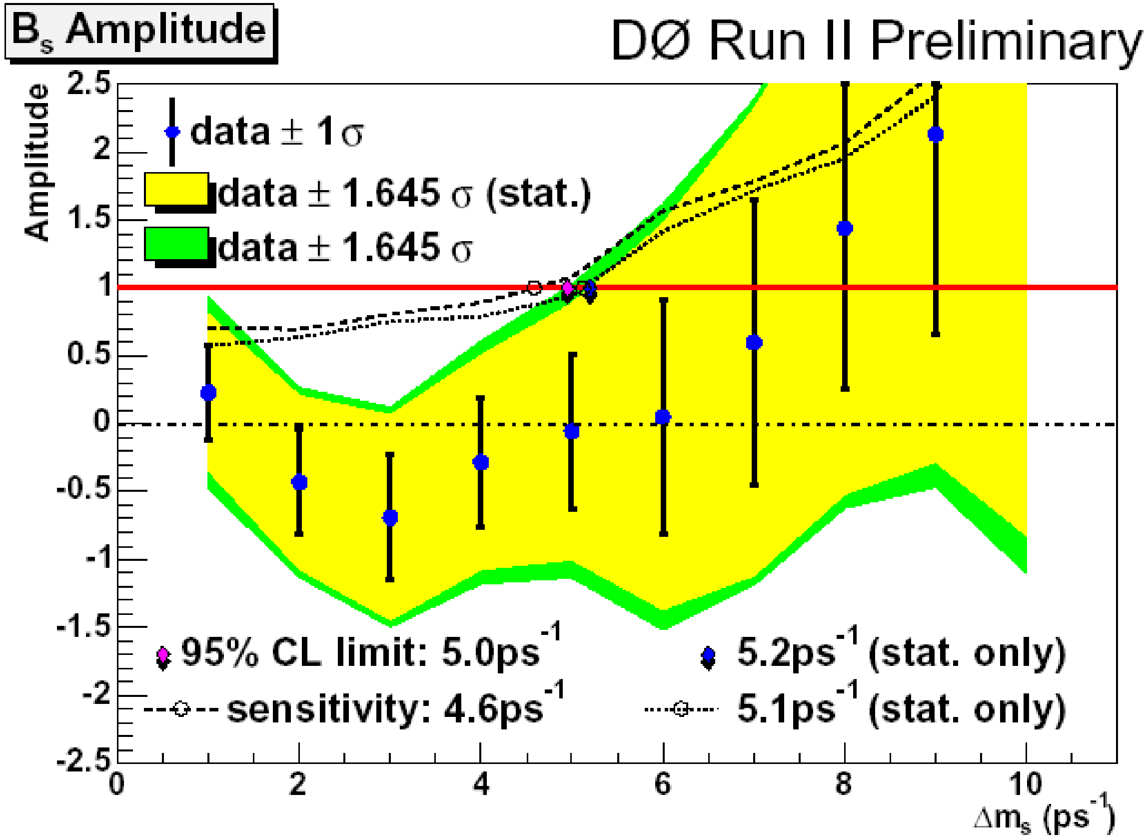
$D_s \to \phi\pi^+, K^*K, \pi^+\pi^-\pi^+$

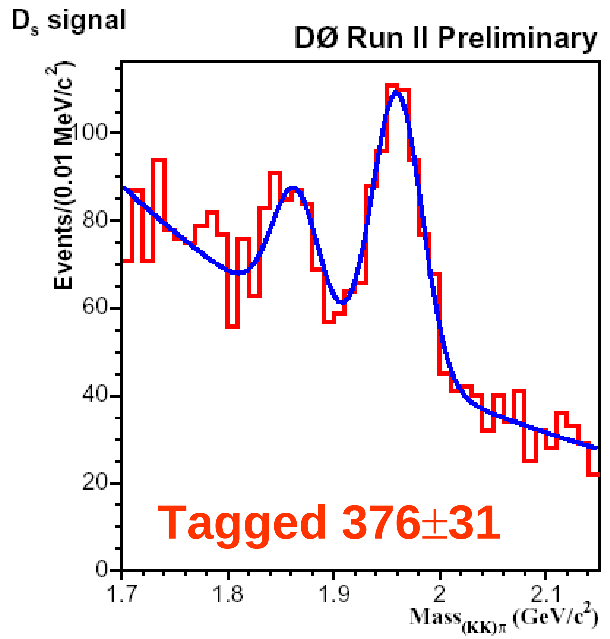
D0 Semileptonic:

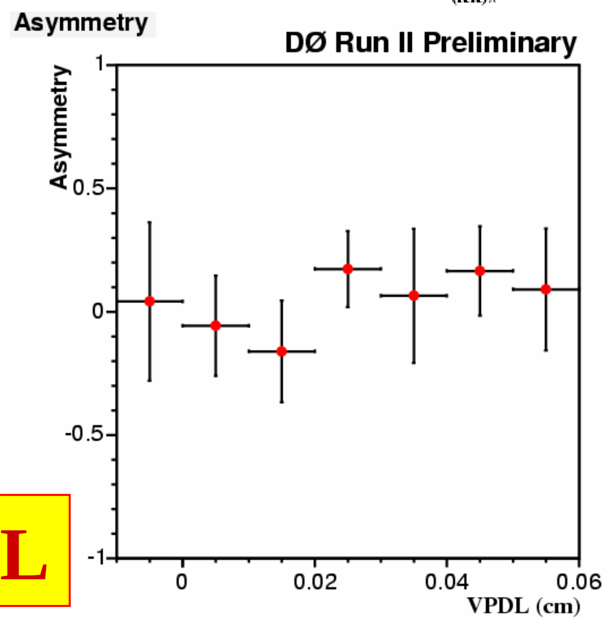
$B_s \to D_s\, l\, X$, ≈ 7000

$D_s \to \phi\pi^+$

Δm_s D0 Preliminary results







Semi leptonic decays D = 0.47 ± 0.01

L = 460 pb^{-1}, opposite side tag

Δm_s > 5.0 ps^{-1} at 95% CL

Limit < world average, but this is a first step in the full analysis

Other *b*-physics results: Penguins at Fermilab

- CP Asymmetry in $B^+ \to \phi K$

$$\text{BR}\ (B^+ \to \varphi K) = \left(7.6 \pm 1.3_{(stat)} \pm 0.6_{(sys)}\right) \times 10^{-6}$$

$$A_{CP} = -0.07 \pm 0.17_{(stat)}{}^{+0.03}_{-0.02}{}_{(sys)}$$

PRL, hep-ex/0502044

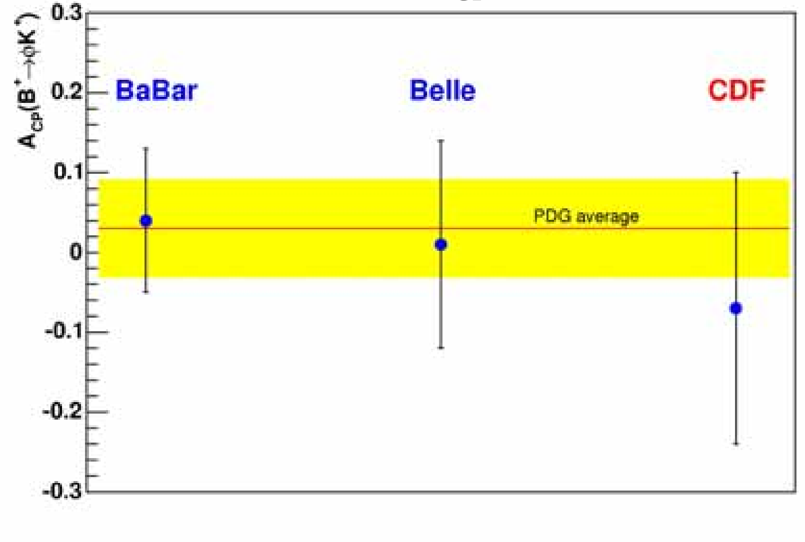
- Evidence for the decay $B_s \to \phi\phi$

$$\text{BR}\ (B_s \to \varphi\varphi) = \left(14\ {}^{+6}_{-5}{}_{(stat)} \pm 6_{(sys)}\right) \times 10^{-6}$$

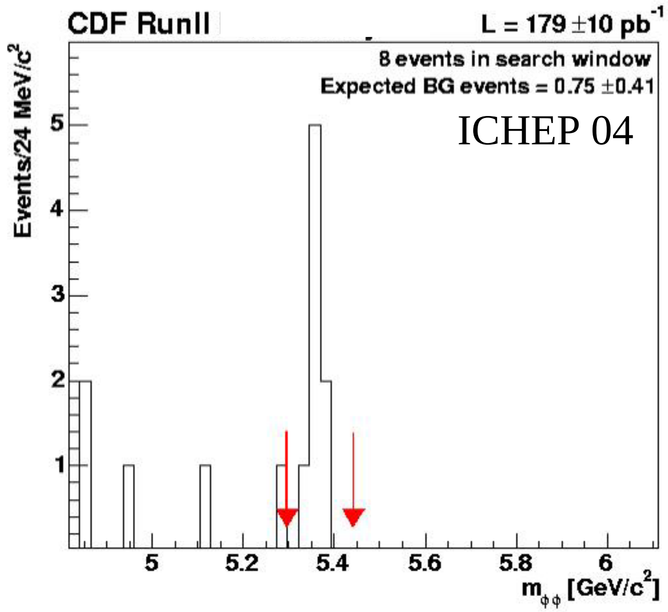
PRL, hep-ex/0502044

- CP Asymmetry in $B \to hh$ ($h=\pi^{\pm},K^{\pm}$) ICHEP'04

ICHEP 04 A_{CP} ($B^+ \to \phi K$)



B_s penguin-diagram decay



Conclusions

The Tevatron can produce unique results in B Physics and confirm/complement B factories.

$m_{u,d,s,c}$

- Best measurements of *b*-hadron masses, at 0.02% level
- CDF first evidence of a fully reconstructed B_c decay $m_{B_c} = 6287.0 \pm 4.8 \pm 1.1$ MeV/c^2
- Run 2 confirmation of semileptonic B_c decay
- Rare decays improve limits on new Physics.

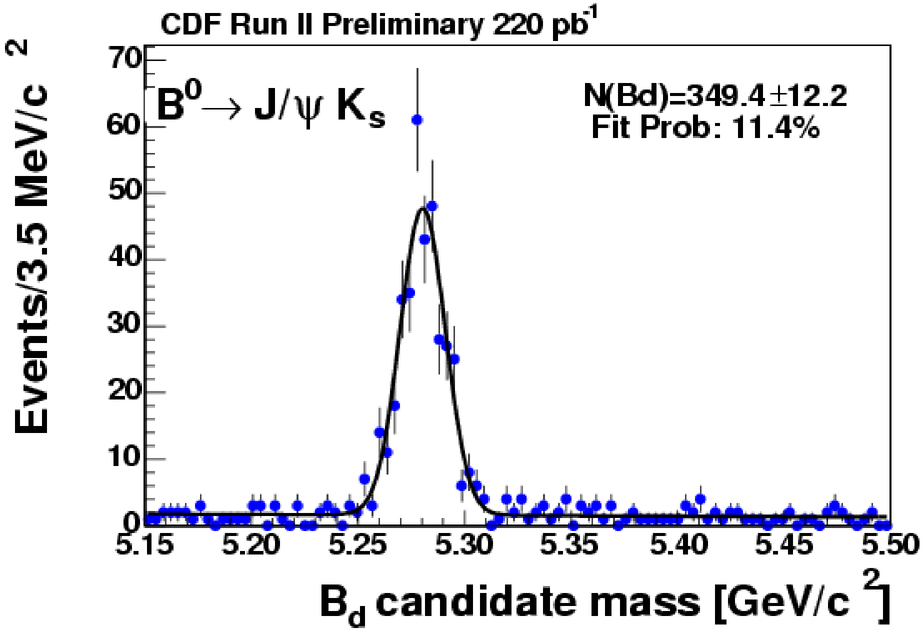
Δm_d

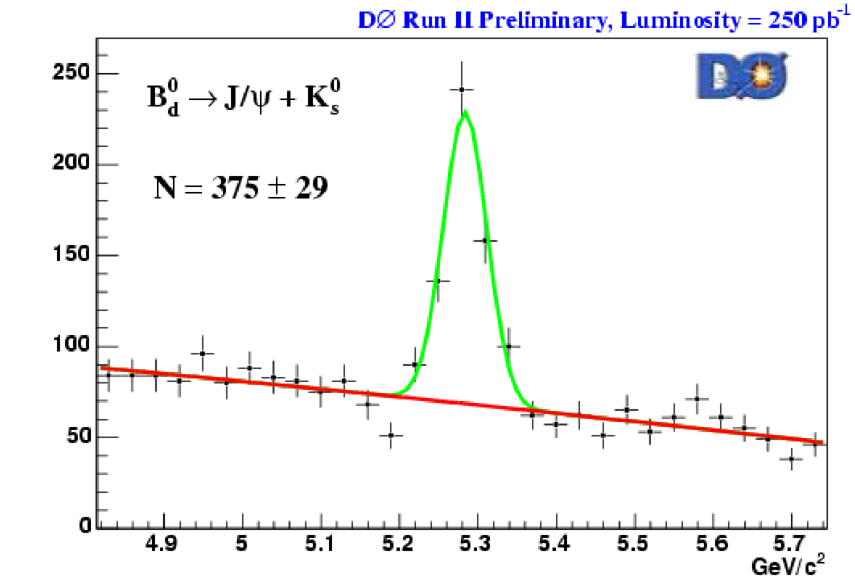
- Flavour taggers: B^0 mixing as a proof of principle.
- Amplitude scan method used for B^0

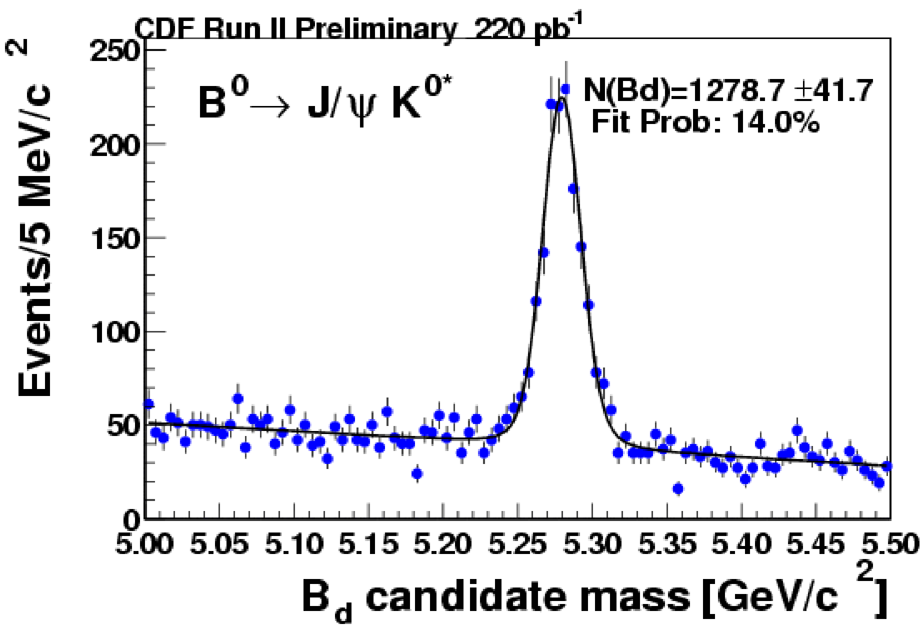
Δm_s

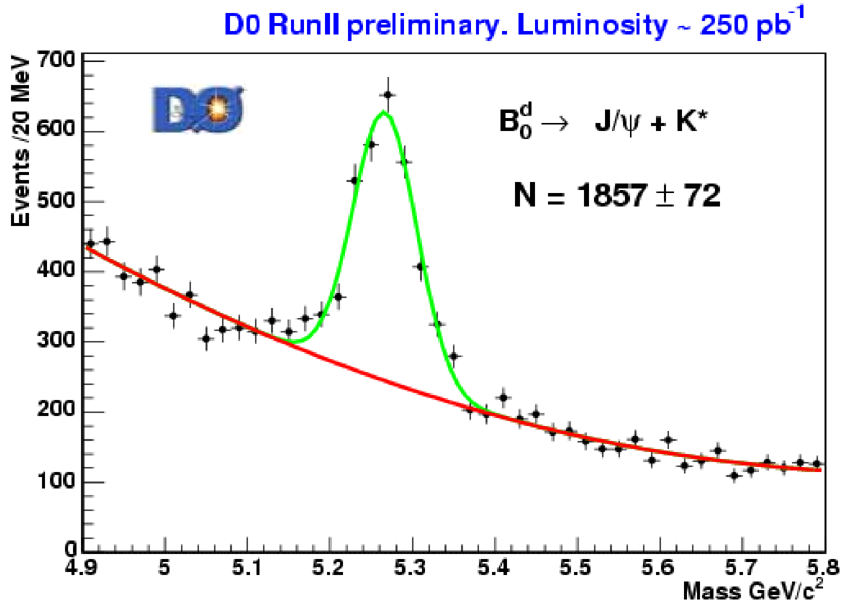
- D0 first preliminary Δm_s measurement from Run 2: $\Delta m_s > 5.0\ ps^{-1}$ at 95% CL
- Γ and $\Delta\Gamma$: see next talk
- Results improve faster than $\sqrt{L}$: systematics and techniques.
- Including other decay modes, taggers, *data…. Moriond QCD*

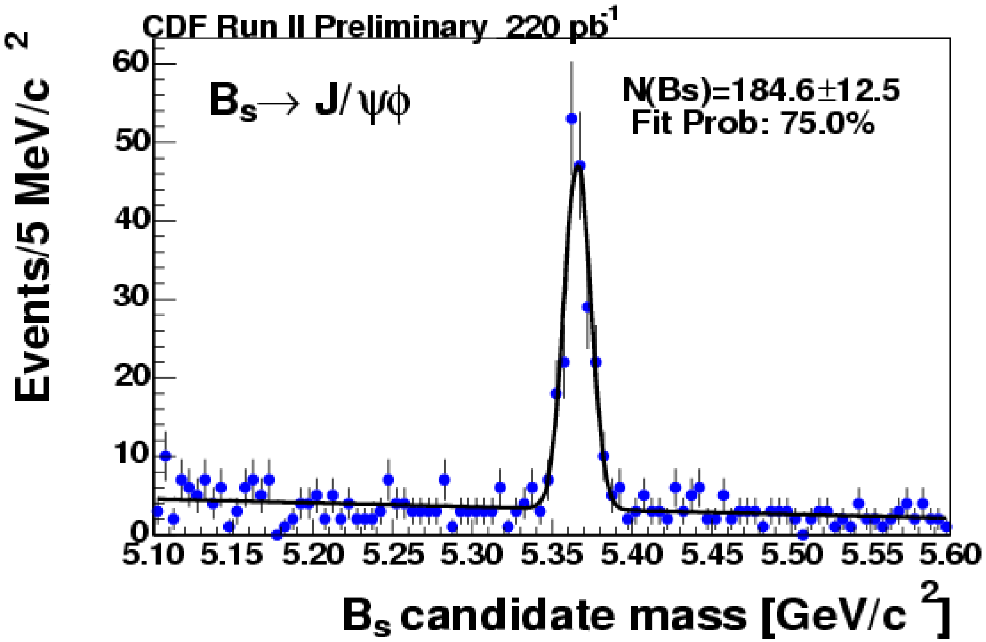

Aurora Borealis at Fermilab
9th November 2004, 3 a.m.
42°N
Backup Slides


CDF Run II Preliminary 220 pb^{-1}
$B^0 \to J/\psi\ K_s$
N(Bd)=349.4±12.2
Fit Prob: 11.4%
Events/3.5 MeV/c^2
B_d candidate mass [GeV/c^2]

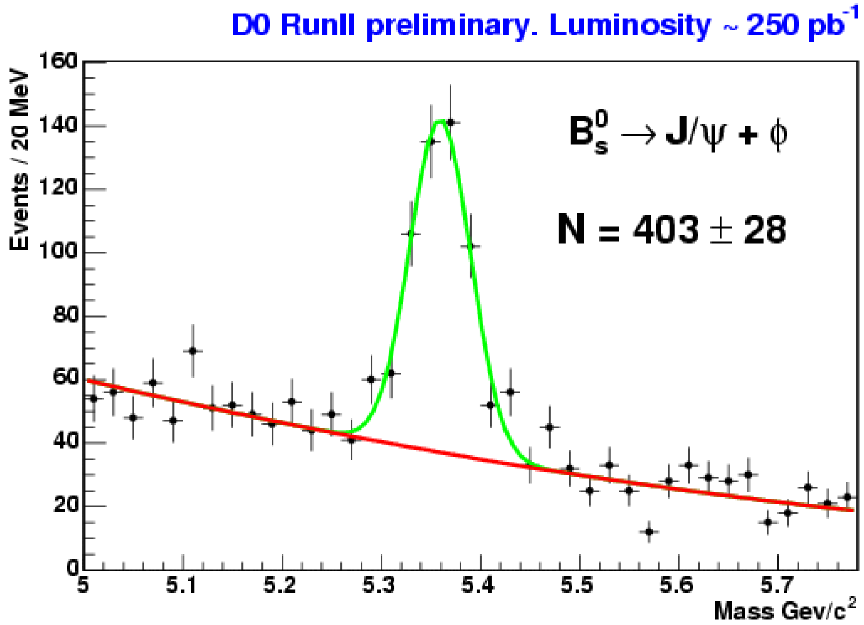

DØ Run II Preliminary, Luminosity = 250 pb^{-1}
$B_d^0 \to J/\psi + K_s^0$
N = 375 ± 29
GeV/c^2


CDF Run II Preliminary 220 pb^{-1}
$B^0 \to J/\psi\ K^{0*}$
N(Bd)=1278.7 ±41.7
Fit Prob: 14.0%
Events/5 MeV/c^2
B_d candidate mass [GeV/c^2]

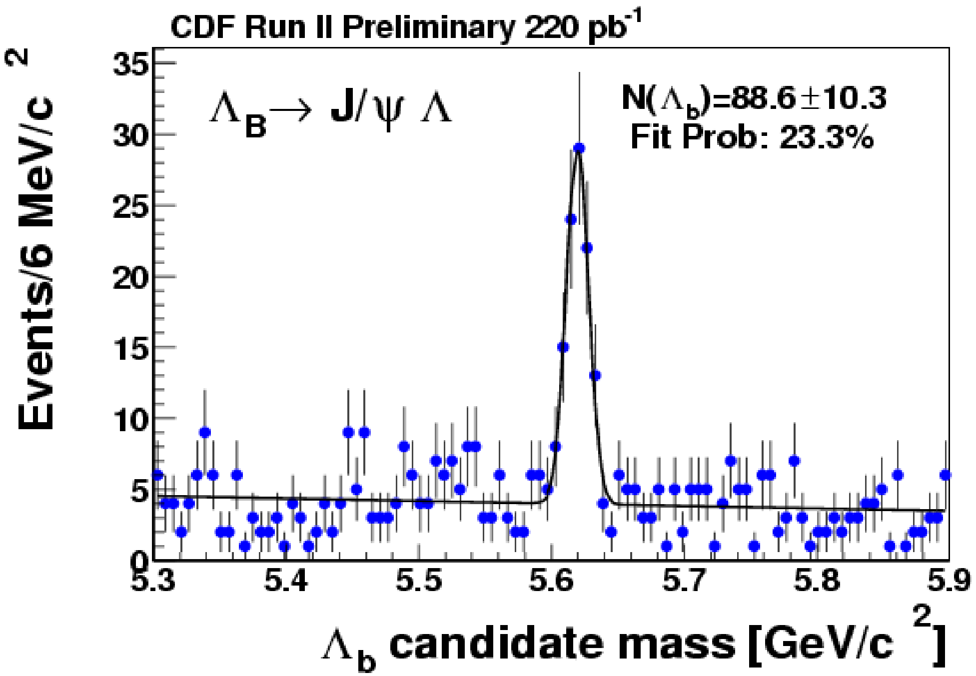

D0 RunII preliminary. Luminosity ~ 250 pb^{-1}
$B_0^d \to J/\psi + K^*$
N = 1857 ± 72
Events /20 MeV
Mass GeV/c^2



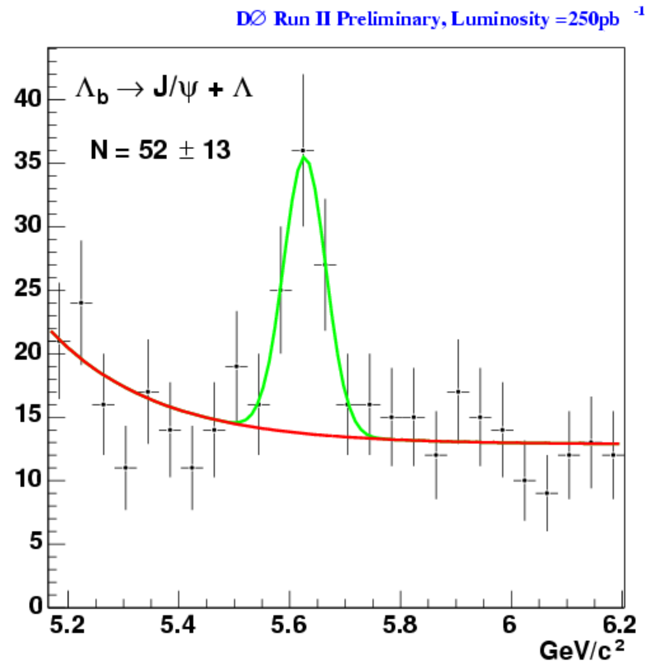
CDF Run II Preliminary 220 pb^{-1}
$B_s \to J/\psi\phi$
N(Bs)=184.6±12.5
Fit Prob: 75.0%
Events/5 MeV/c^2
B_s candidate mass [GeV/c^2]



D0 RunII preliminary. Luminosity ~ 250 pb^{-1}
$B_s^0 \to J/\psi + \phi$
N = 403 ± 28
Events / 20 MeV
Mass Gev/c^2



CDF Run II Preliminary 220 pb^{-1}
$\Lambda_B \to J/\psi\ \Lambda$
N(Λ_b)=88.6±10.3
Fit Prob: 23.3%
Events/6 MeV/c^2
Λ_b candidate mass [GeV/c^2]



DØ Run II Preliminary, Luminosity =250pb^{-1}
$\Lambda_b \to J/\psi + \Lambda$
N = 52 ± 13
GeV/c^2

CDF Fully reconstructed B_c

Summary of cut values used:

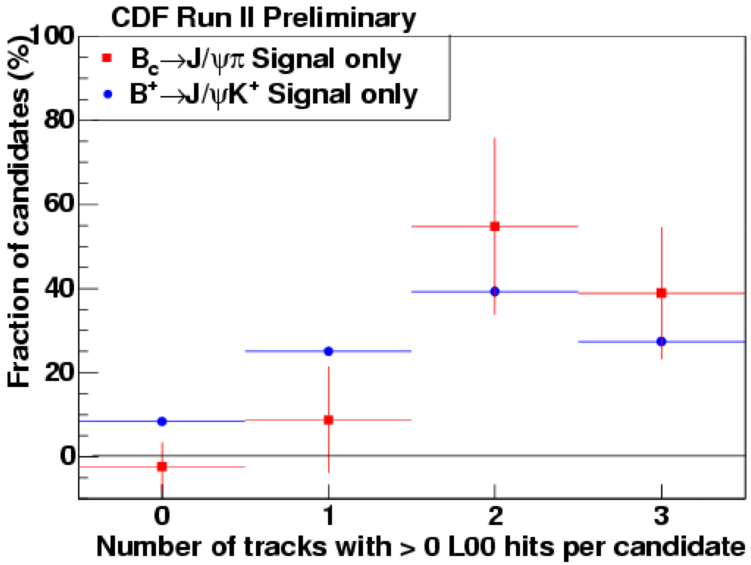
1. p_T (π) > 1.8 GeV/c
2. $L_{xy}/\sigma(L_{xy})$ > 4.4
3. χ^2(3D) < 9.0
4. $d_0(B_c)$ < 65 μm
5. pointing angle < 0.4 radians
6. $\chi^2_{vtx}(\pi)$ < 2.6
7. ct < 750 μm

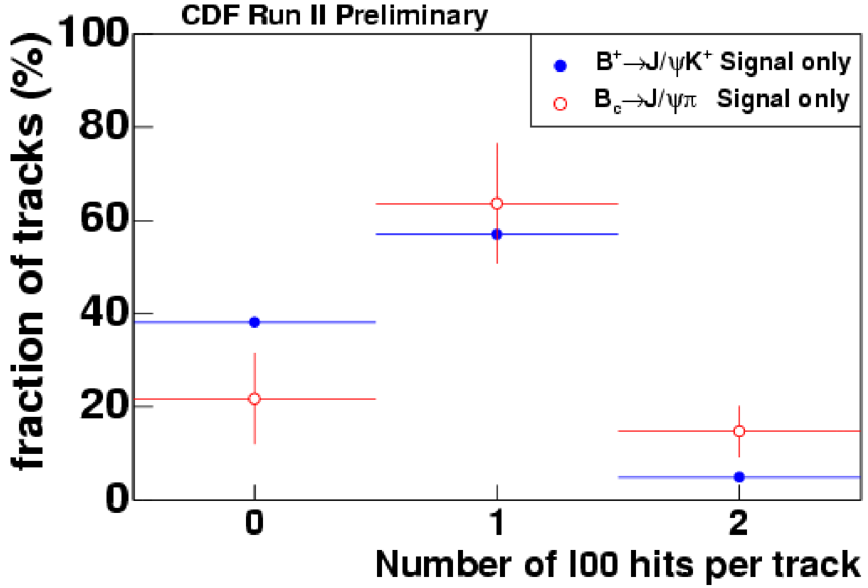
Cut	MC Efficiency	N-1 data entries	Background rejection
$L_{xy}/\sigma(L_{xy})$	42.0%	11930	96.7%
p_T (π)	62.3%	3043	87.1%
χ^2(3D)	80.5%	762	48.4%
Pointing angle	85.4%	768	48.8%
$\chi^2_{vtx}(\pi)$	92.7%	565	30.4%
$d_0(B_c)$	97.5%	448	12.3%
ct <	98.7%	410	4.1%

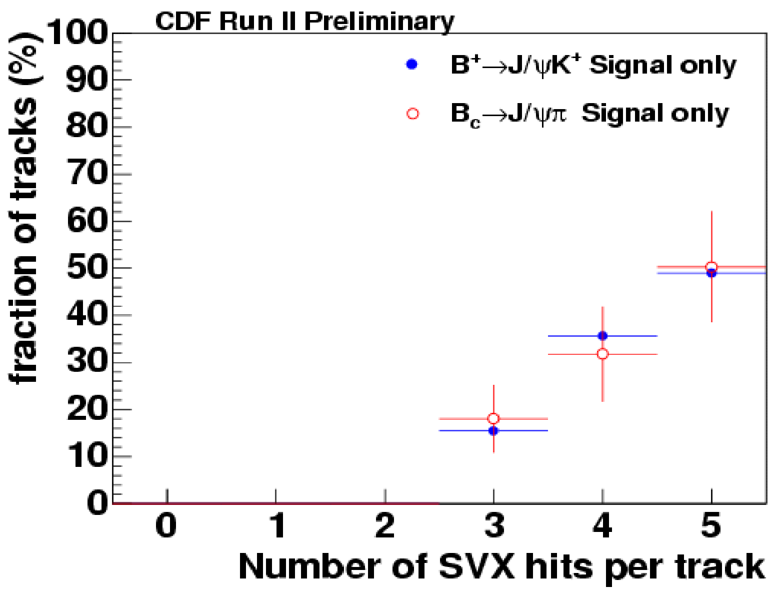
Maximized $$\Sigma = \frac{S}{1.5 + \sqrt{B}}$$

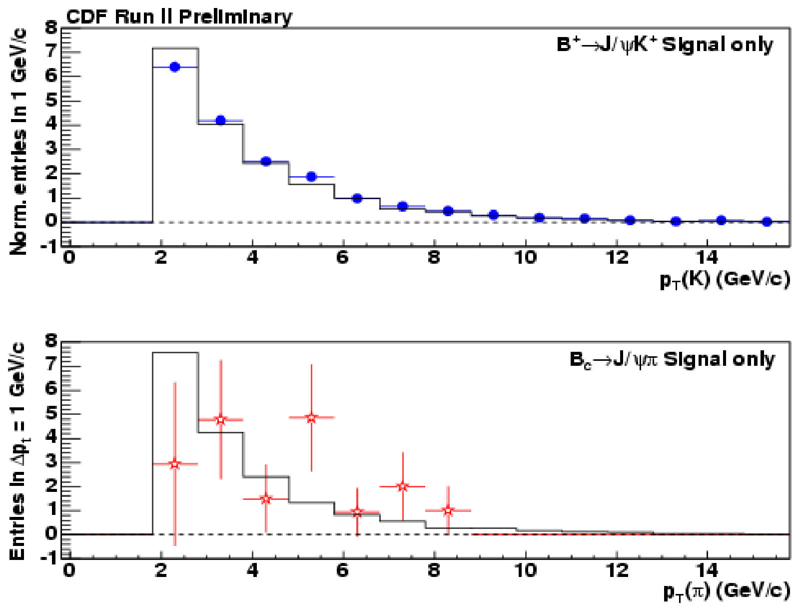
S = number of signal events from MC
B = average number of background events (data) from whole region in a window $\pm 2\text{-}\sigma_M$ wide (60.4 MeV/c^2).

CDF Fully reconstructed B_c



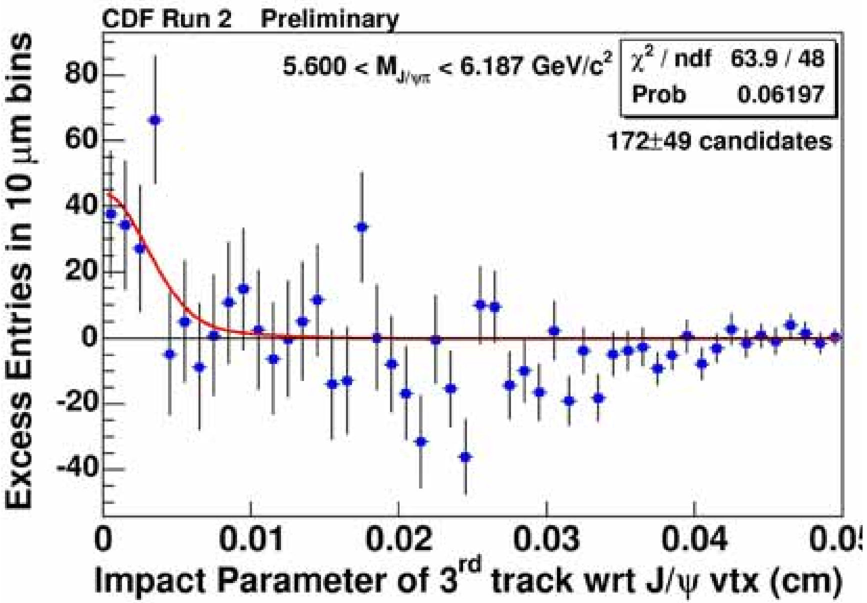


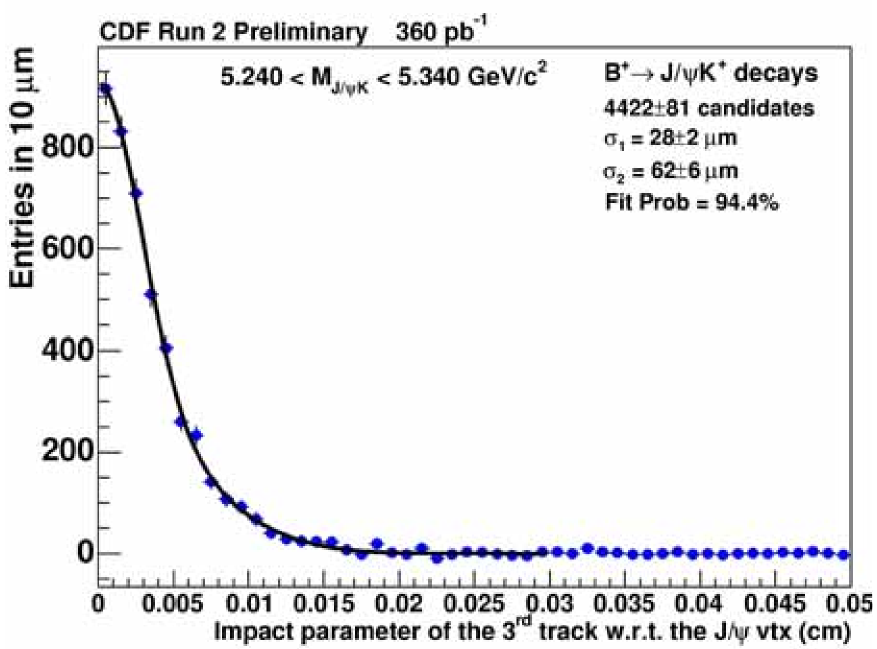




CDF Partially reconstructed hadronic B_c

No pointing cuts
Relax vertex chi2





D0 combined taggers, semileptonic decays, 250 pb^{-1}:

Δm_d = 0.456 ± 0.034 *(stat.)* ± 0.024 *(syst.)* ps^{-1}

D0 combined opposite side taggers, semileptonic decays, 460 pb^{-1}:

Δm_d = 0.558 ± 0.048 *(stat.)* ± x.xxx *(syst.)* ps^{-1}

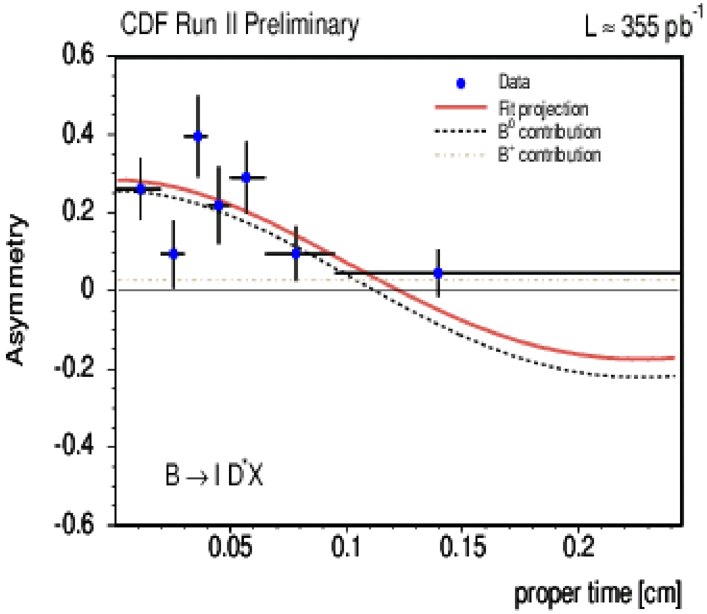
CDF combined opposite side taggers, semileptonic decays, 355 pb^{-1} :

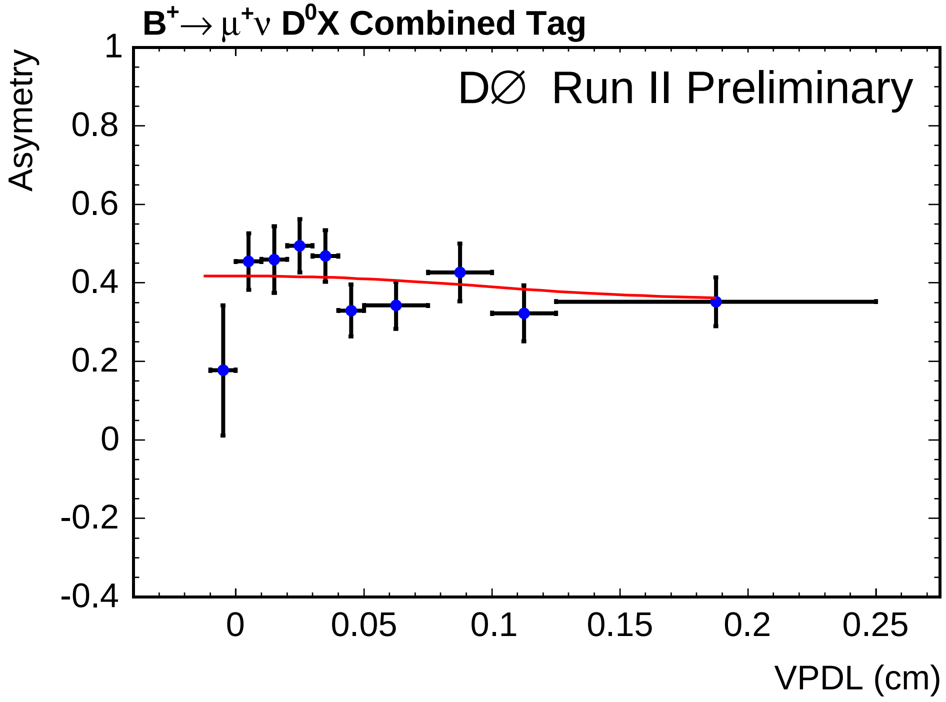
Δm_d = 0.497 ± 0.028 *(stat)* ± 0.015 *(syst.)* ps^{-1}

CDF combined opposide side taggers, fully reco. decays, 355 pb^{-1} :

Δm_d = 0.503 ± 0.063 *(stat)* ± 0.015 *(syst.)* ps^{-1}

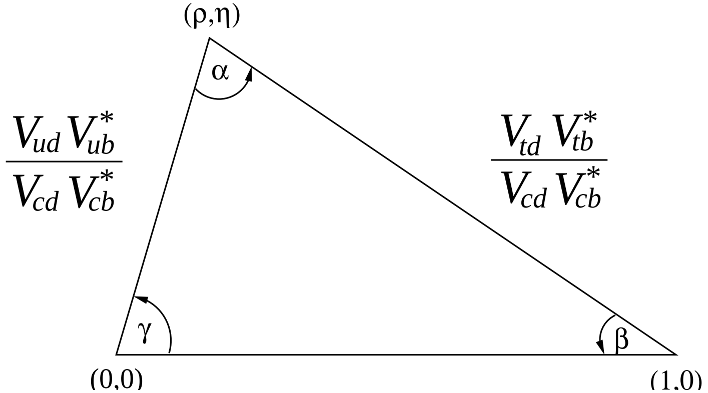
Mixing Control sample: B_u

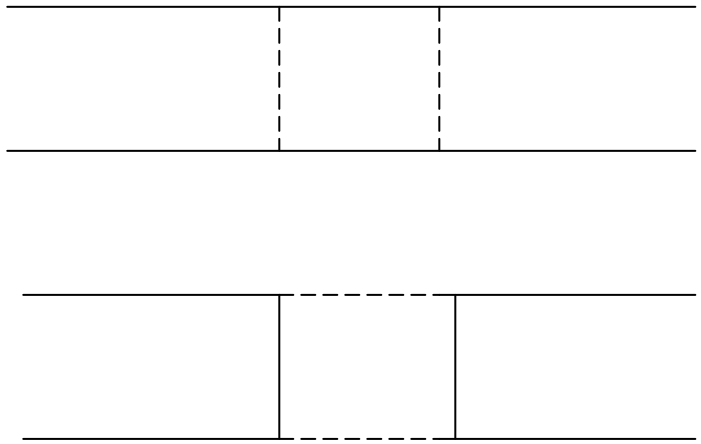




Tagger	$\sqrt{<\mathcal{D}^2_{pred}>}$(%)	ε(%)	Scale factor (%)	$\varepsilon\mathcal{D}^2$ (%)
SMT	35.94	5.03 ± 0.06	$92.6 \pm 3.9 \pm 2.8$	$0.557 \pm 0.047 \pm 0.034$
SET	29.41	3.53 ± 0.05	$98.0 \pm 5.6 \pm 2.9$	$0.293 \pm 0.033 \pm 0.017$
JVX	16.86	9.81 ± 0.09	$97.1 \pm 6.4 \pm 3.8$	$0.263 \pm 0.035 \pm 0.021$
JJP	11.45	14.00 ± 0.10	$90.3 \pm 7.9 \pm 4.6$	$0.150 \pm 0.026 \pm 0.015$
JPT	5.08	52.03 ± 0.10	$108.2 \pm 9.3 \pm 8.7$	$0.157 \pm 0.027 \pm 0.025$
Total		84.4 ± 0.18	-	1.429 ± 0.093

Mixing and CKM





- Δm_s time independent CP violation in Bs (g)
- Δm_s / Δm_d well theoretically understood
- Δm_s / Δm_d sensitive to new Physics

B_s oscillations: $\Delta m_s, \Delta\Gamma_s$