b Physics results from the Tevatron

- Introduction
- A_{CP}
- oscillation measurements
- Lifetime measurements
- rare decays

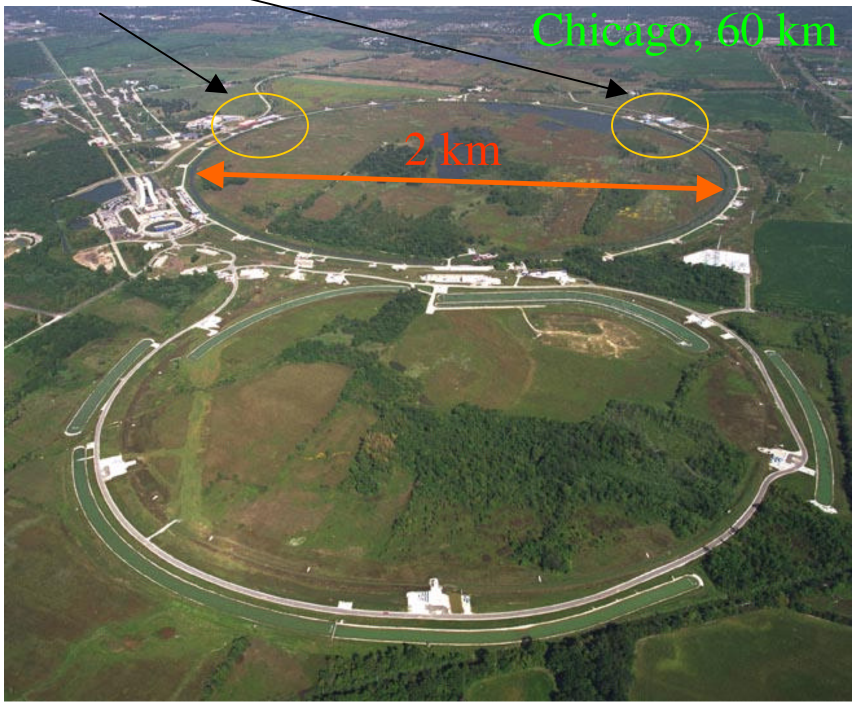
at CDF and D0

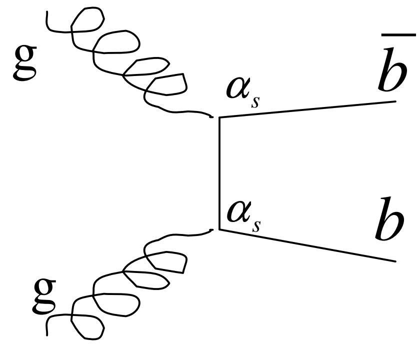
Saverio D'Auria, University of Glasgow
For the CDF and D0 collaborations

Workshop on Flavour Dynamics
Chamonix, France.
October 8-15, 2005

Introduction: *b* production at the TeVatron

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





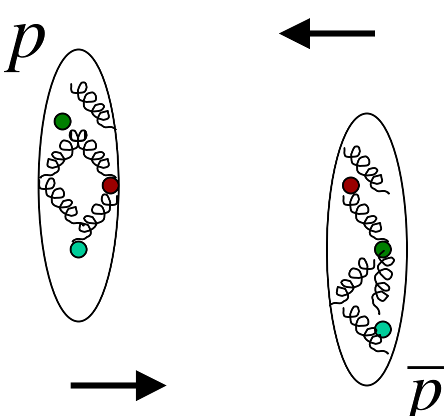
Main contribution to *b* production at the TeVatron.

b Production cross section:

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

For "centrally" produced *b*

|y| < 1 CDF (Phys. Rev. D71, 032001 (2005).)



Collisions:
- Gluon-gluon
- Quark-anti-quark
- Gluon-quark

All b-hadrons are produced: $B^+, B^0, \Upsilon, \ldots$
$B_s, \Lambda_b, B_c \ldots \Xi_b$

Introduction: CDF and D0 detectors

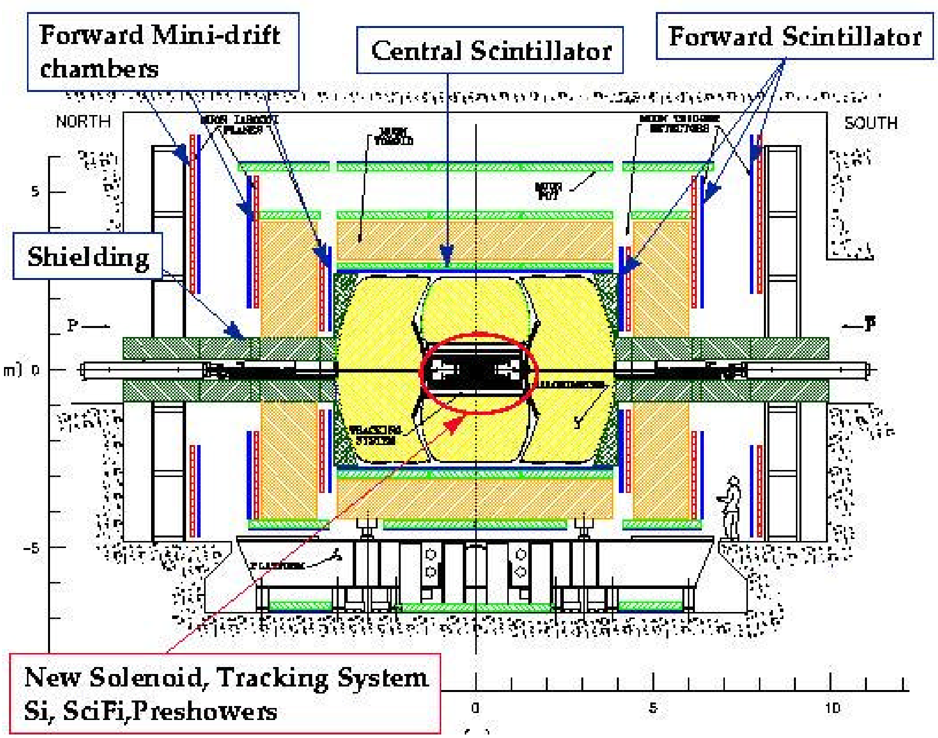
Great *b*-physics capabilities

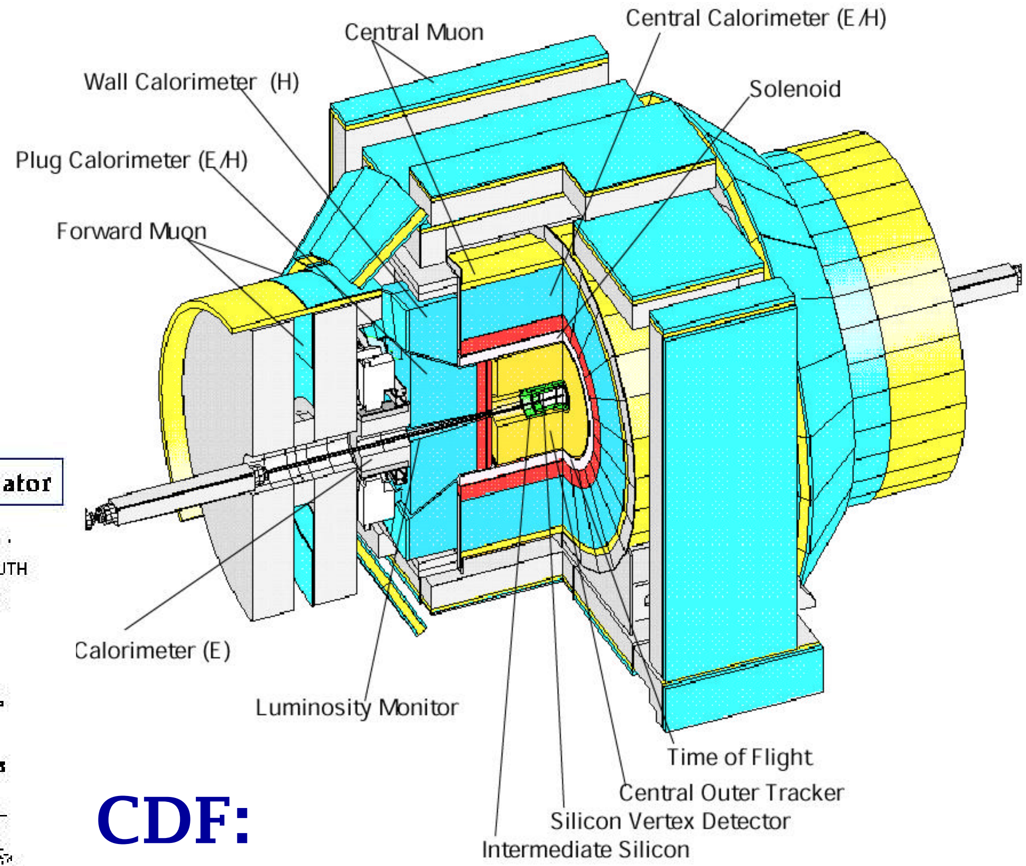
D0:

Excellent muon trigger

Tracking coverage |η| < 2

Tracking: Silicon + SciFib,





CDF:

Excellent p_T resolution,

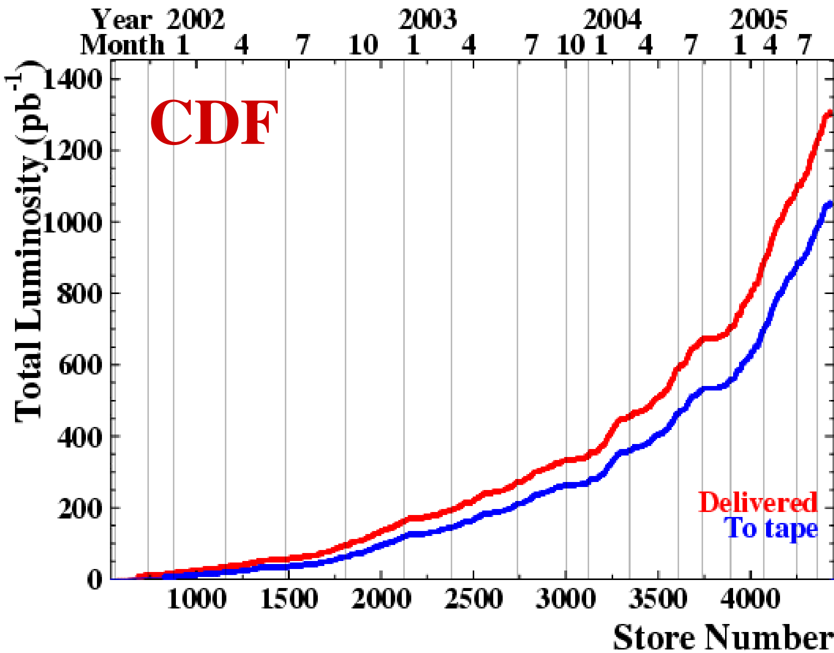
displaced track trigger

→ fully hadronic decay modes

Tracking: Silicon + Drift Chamber

dE/dx, ToF particle ID

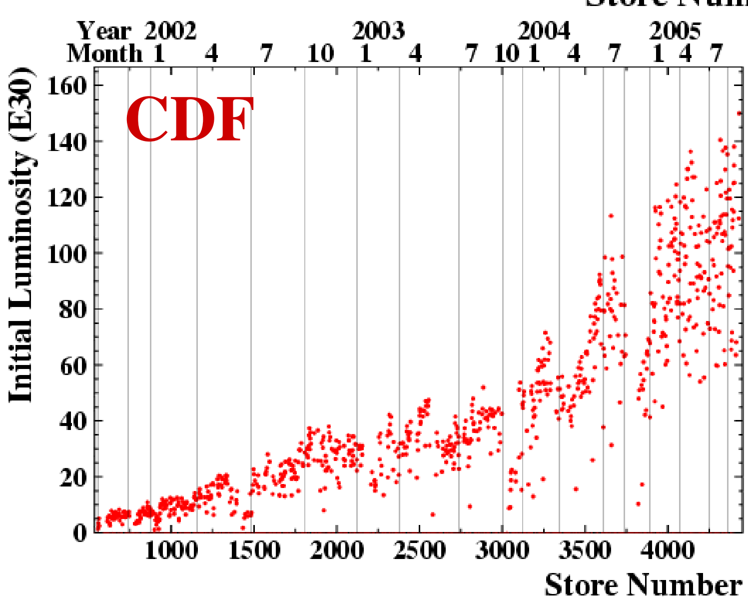
Introduction: TeVatron performance



Efficiency: 85-90% per store (fill)

CDF to tape: 1.1 fb^{-1}

D0
Results presented here
CDF



Luminosity record: 1.5 $\times 10^{32}$ cm^{-2} s^{-1}

Highest luminosity ever reached at Hadron collider (including ISR p-p)

1/10 of initial LHC (2008)

L (TeVatron) will reach $\geq$ 4 fb^{-1} /experiment

Introduction: Trigger issues

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

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

$$L = \int \mathcal{L} \text{ is pb}^{-1}\text{ (TeVatron) vs. fb}^{-1}\,(\Upsilon(4S))$$

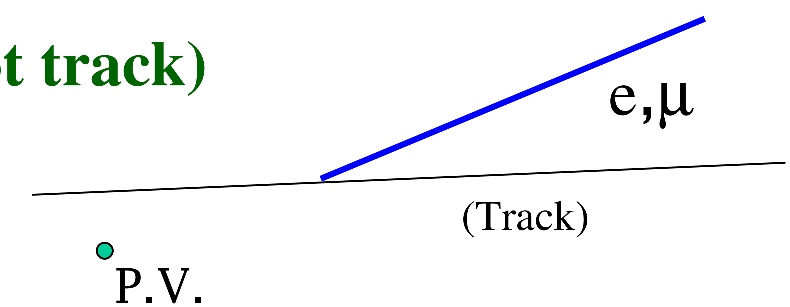
	σ (μb)	$\mathcal{L}_{max}$ ($cm^{-2}\,s^{-1}$)	L	*b*-events
Tevatron	29	1.5×10^{32}	$1000\ pb^{-1}\times 2$	29×10^{9}
KEK	0.001	1.58×10^{34}	$471\ fb^{-1}$	0.47×10^{9}
BaBar	0.001	0.95×10^{34}	$300\ fb^{-1}$	0.30×10^{9}

Produced !!

Main Triggers for *b*-Physics:

$\varepsilon(trigger) \times \varepsilon\ (reconstruction) = \mathcal{O}(10^{-2}\text{-}10^{-3})$

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



Introduction: general issues

b-hadron decays can be studied depend on:

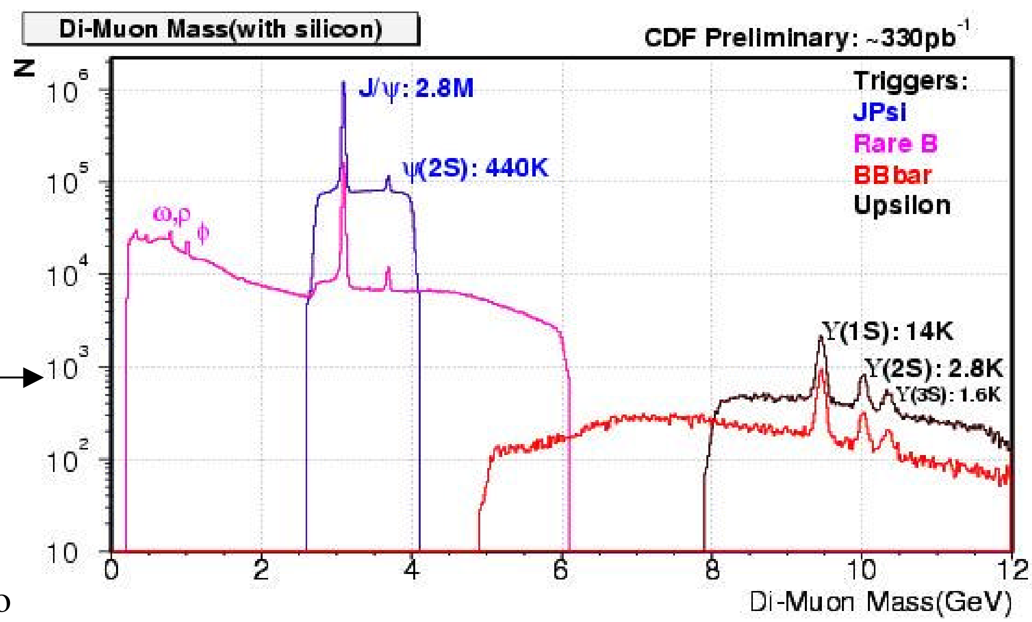
- Production mechanism — All b-hadrons are produced: $B^+, B^0, Y, \ldots$ $B_s, \Lambda_b, B_c \ldots \Xi_b$
- Detector features — Good tracking → charged final products
- Trigger features — □eptonic and hadronic final states available
- Environment — Very large QCD background → no neutrals detected

Only decay final states with charged particles studied to now at CDF (+ semileptonic decays !)

D0 has detected $\chi_{c1}\ \chi_{c2} \rightarrow J/\psi\ \gamma$,via γ conversions.

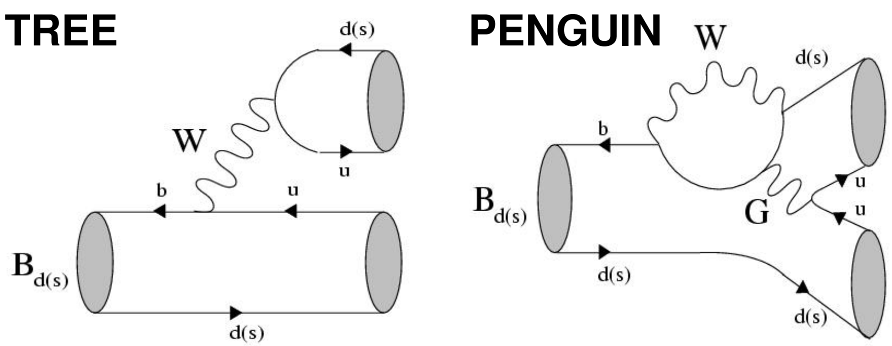
$\Rightarrow$ No π^0, ρ^+, etc …

CDF Di-muon triggers



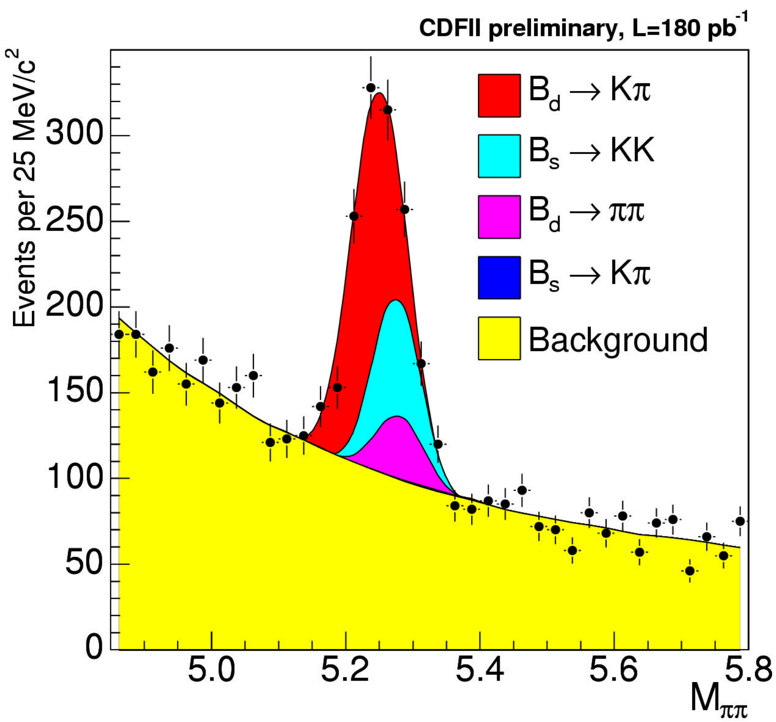
A_{CP} and BR's: $B \to h^+ h'^-$

CDF has simultaneous access to both $B^0/B^0_s \to h^+h'^-$ decays



R. Fleischer PLB459:306-320, 1999 - constrain hadronic unknowns with SU(3) symmetry. Use approximated $s \leftrightarrow d$ quark symmetry (i.e. measure jointly B^0 and B^0_s)

Measure angle γ.



Method needs: time-dependent asymmetries in *b*-flavor tagged samples, size of SU(3) breaking, sin(2β) and Δm_s .

Need full Run-2 startistics.

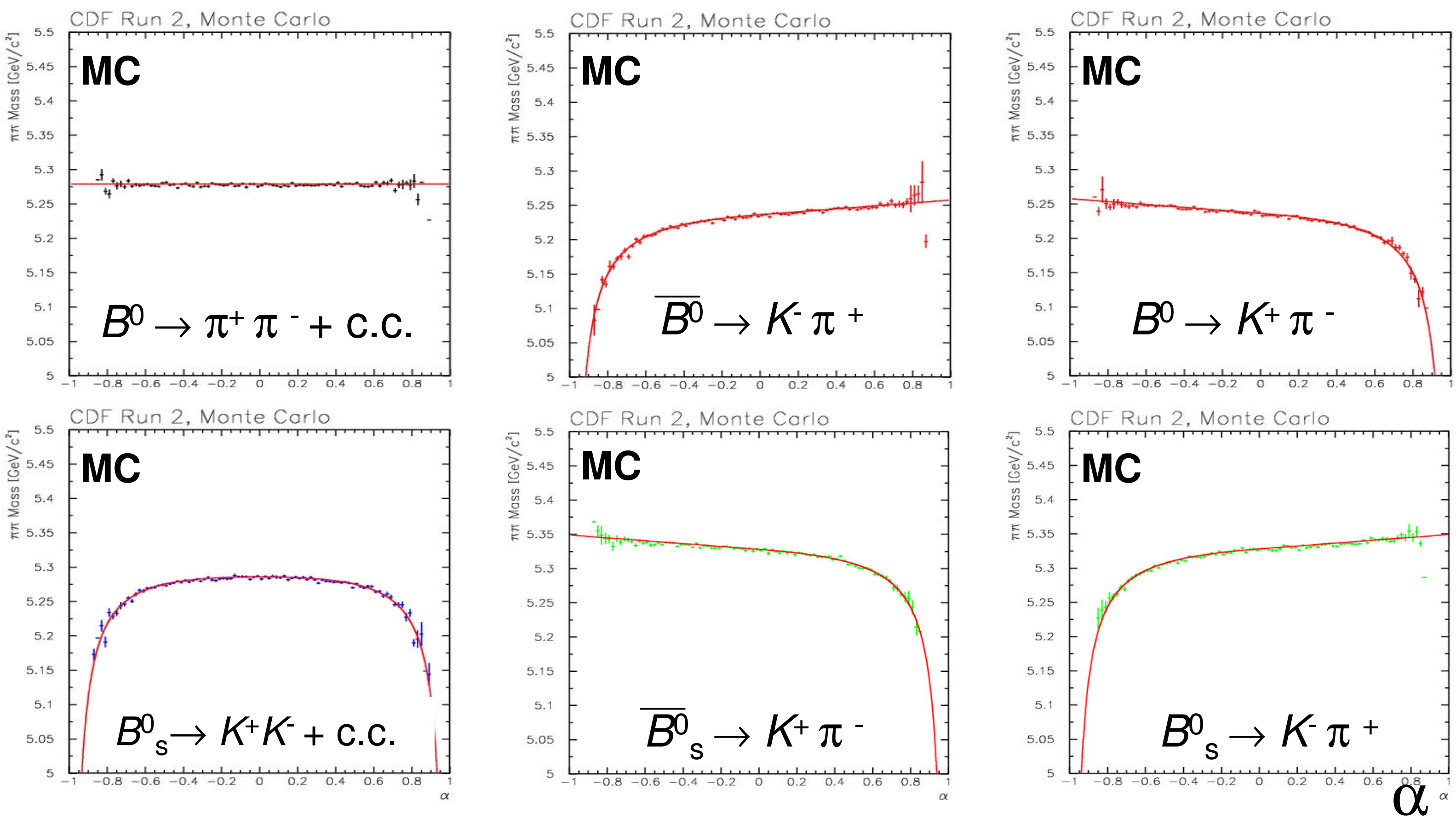
CDF ultimate long term goal.

$B_s \to K^+K^-$ almost pure CP-even state

Measure lifetime and $\Delta\Gamma_s$

parameter	fraction	yield
$B^0 \to \pi^+\pi^-$	$(13 \pm 3)\%$	121 ± 27
$B^0 \to K^+\pi^-$	$(60 \pm 3)\%$	542 ± 30
$B^0_s \to K^-\pi^+$	$(0 \pm 3)\%$	-
$B^0_s \to K^+K^-$	$(26 \pm 3)\%$	236 ± 32

A_{CP} and BR's: $B \to h^+ h'^-$



ππ -mass *vs.* signed momentum imbalance: $\alpha = (1 - p_{min}/p_{max}) q_{min}$ discriminates among modes (and flavors in $K\pi$ modes).

dE/dx and TOF used for particle ID.

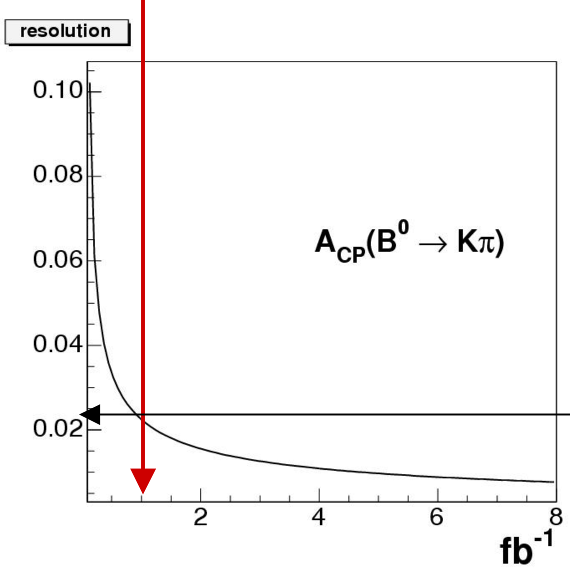
A_{CP} and BR's: $B \to h^+ h'^-$

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

$$A_{CP} = \frac{N(\overline{B}^0 \to K^-\pi^+) - N(B^0 \to K^+\pi^-)}{N(\overline{B}^0 \to K^-\pi^+) + N(B^0 \to K^+\pi^-)} = -0.013 \pm 0.078\ (stat.) \pm 0.012\ (syst.)$$

$$\frac{f_d \cdot BR(B^0 \to \pi^+\pi^-)}{f_s \cdot BR(B_s^0 \to K^+K^-)} = 0.45 \pm 0.13\ (stat.) \pm 0.06\ (syst.)$$

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



A_{CP} (HFAG)

Babar -0.133 ± 0.030 (stat.) ± 0.009 (syst.)

Belle -0.113 ± 0.022 (stat.) ± 0.008 (syst.)

CDF Results will be updated soon with larger luminosity.

Comparable sensitivity with 1fb^{-1}
$\sigma \leq 0.01$ with full statistics

A_{CP} and BR's: $B \to h^+ h'^-$

BR Limits:

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

Test theory with 360 pb^{-1}

Sensitivity on BR: $2 - 5 \cdot 10^{-6}$

Predictions:

Beneke&Neubert NP B675, 333(2003)

(Yu, Li, Yu, Phys.Rev. D71 (2005) 074026)

Suprun hep-ph/0307395 & 0404073

$$\frac{BR(B_s^0 \to \pi^+\pi^-)}{BR(B_s^0 \to K^+K^-)} < 0.05 \ @\ 90\%\ C.L.$$

Test predictions within reach

Li et al. hep-ph/0404028

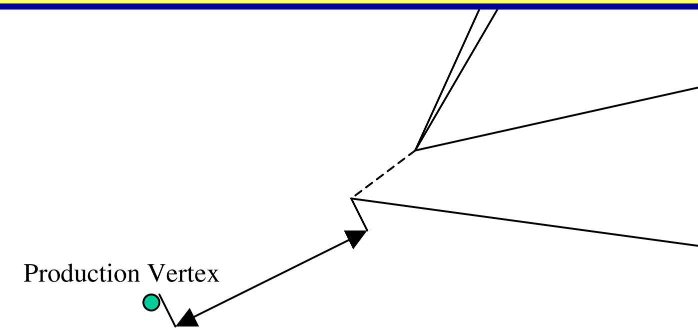
$$\frac{BR(B^0 \to K^+K^-)}{BR(B^0 \to K^+\pi^-)} < 0.10 \ @\ 90\%\ C.L.$$

Reach present HFAG limit with 360pb-1

A_{CP} in self-tagged $B_s \to K\pi$

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

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

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

Δm_s:
- lower statistics B_s
- larger Δm_s

s.l.decays larger σ_t

Statistics reduced by a factor εD^2:

N candidates → εD^2N useful events

Flavour 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:

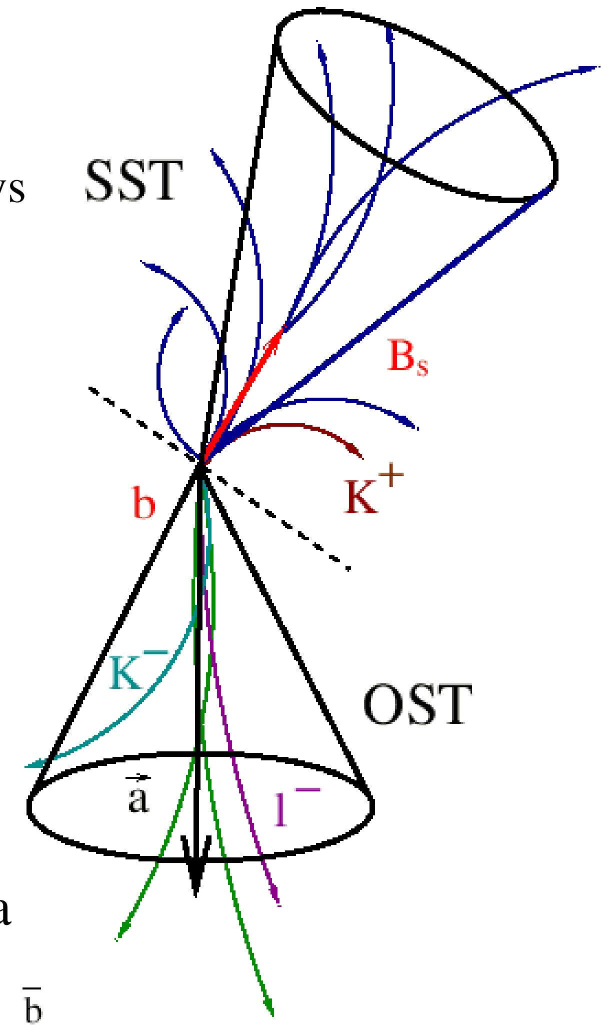
  Sign of the kaon in cascade decay $b \to c \to s$

- 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^-



Mixing: Experimental issues

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

Increase vertex resolution
- Reduce systematics
- Improved alignment etc..
- Use fully reconstructed decays

Increase statistics
- More Luminosity
- More decay channels

Increase tagging efficiency
- More taggers
- Tuned taggers

CDF:
Considerable improvement using same **L**uminosity as for winter conferences results

D0:
Improvements and also added 150 pb^{-1}

$B \rightarrow D$ + hadrons

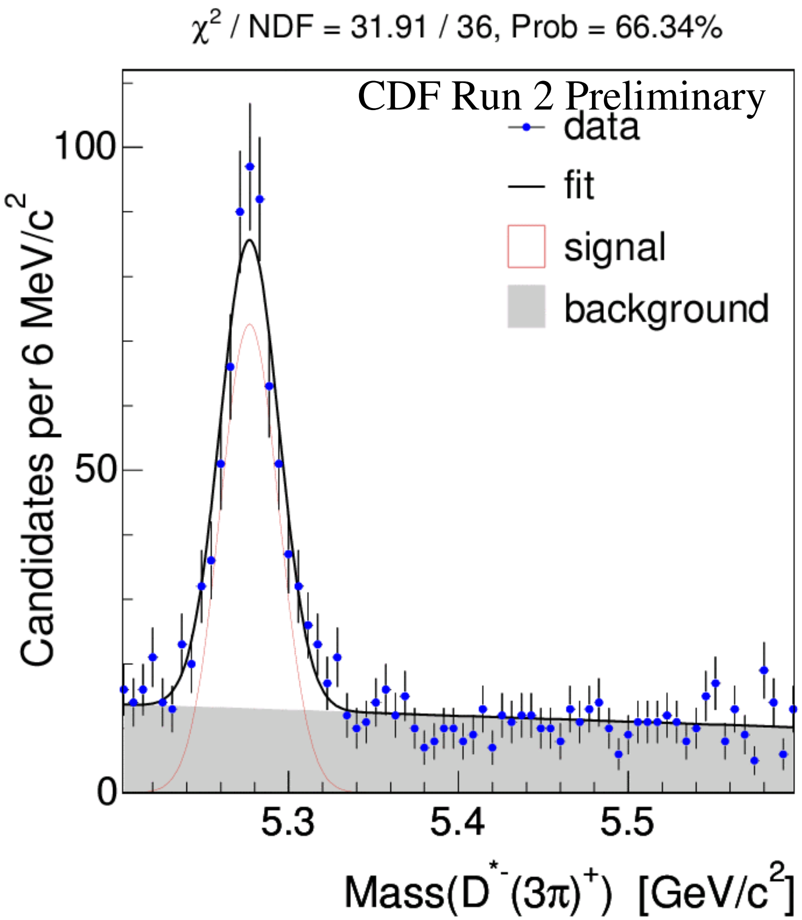
Many decays very useful for increasing statistics for mixing.

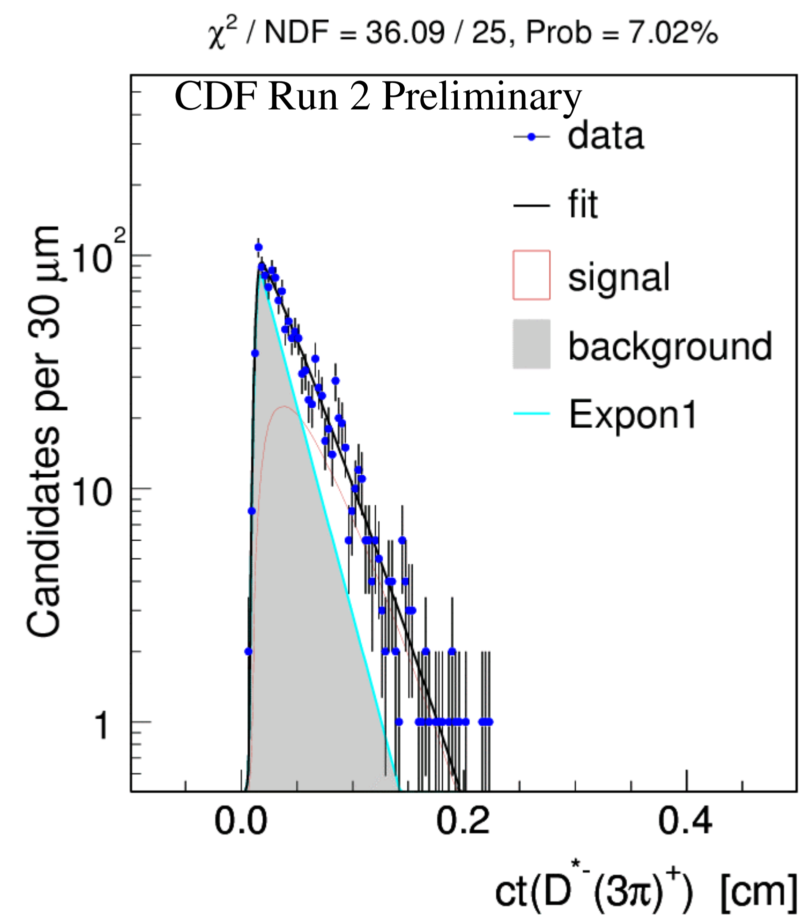
Example in B^0

$$B^0 \rightarrow D^* \pi^+ \pi^- \pi^+$$
$$D^* \rightarrow D^0 \pi$$
$$D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$$

Two 4-track vertices

Simultaneous mass-lifetime fits





$B \to D$ + hadrons

Exercise for the $B^{+,0}$: 10 hadronic decay modes.

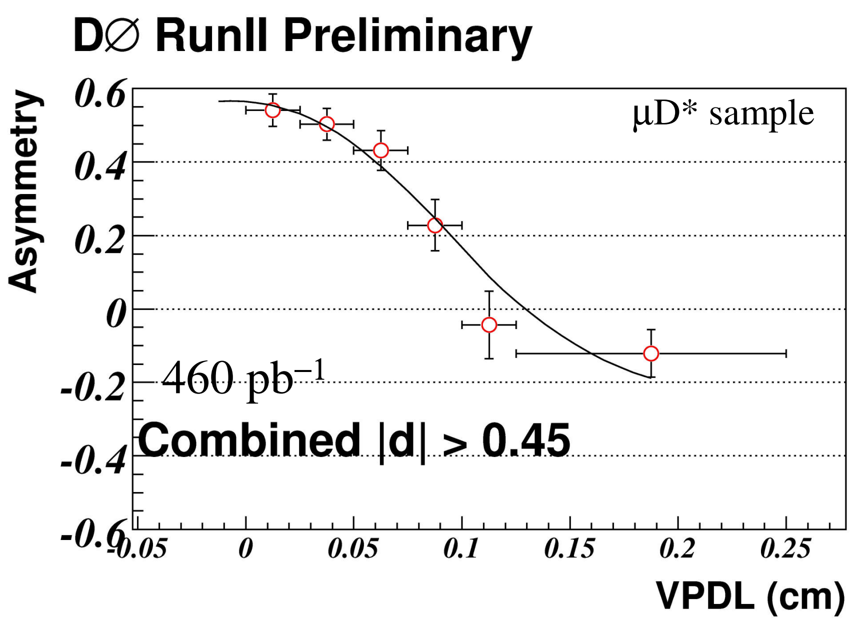
Aim: test machinery, measure OST dilution scale factors.

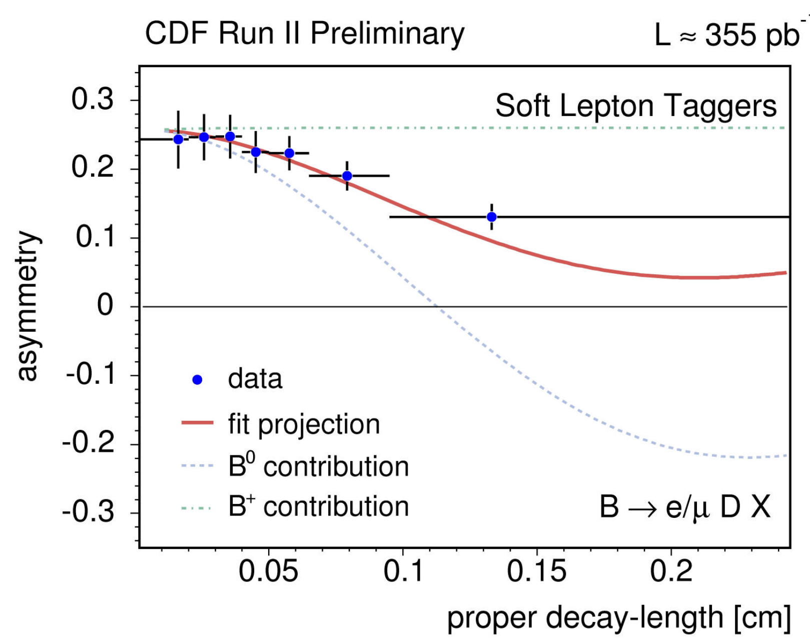
Mode	Sum '05 Total
$B^+ \to J/\psi K^+$	4952 ± 79
$B^0 \to J/\psi K^{*0}$	1787 ± 43
$B^+ \to \overline{D}^0 \pi^+$	9601 ± 84
$B^0 \to D^- \pi^+$	8424 ± 81
$B^+ \to \overline{D}^0 3\pi$	1557 ± 45
$B^0 \to D^- 3\pi$	4611 ± 131
$B^0 \to D^* \pi, D^0 \to K \pi$	1377 ± 35
$B^0 \to D^* \pi, D^0 \to K 3\pi$	1013 ± 26
$B^0 \to D^* 3\pi, D^0 \to K \pi$	1089 ± 43
$B^0 \to D^* 3\pi, D^0 \to K 3\pi$	820 ± 35
Total B^+	15750 ± 124
Total B^0	19121 ± 173

D0 will access these modes also by triggering on the tagging lepton

Δm_d measurements

Exp't	$\int L$ (pb^{-1})	channel	Tag	εD2 (%)	Result Δm_d (ps^{-1})
D0	460	s.l.	combined	2.17±0.13±0.08	0.498 ± 0.026 *(stat.)* ± 0.016 *(syst.)*
D0	460	s.l.	Soft *e*	0.29±0.05±0.03	0.545 ± 0.085 *(stat.)* ± 0.019*(syst)*
CDF	355	s.l.	o.s.t.	1.55± 0.8 ± 0.03	0.511 ± 0.020 *(stat)* ± 0.014 *(syst.)*
CDF	355	Hadr.	o.s.t.	1.55± 0.16±0.05	0.536 ± 0.028 *(stat)* ± 0.006 *(syst.)*



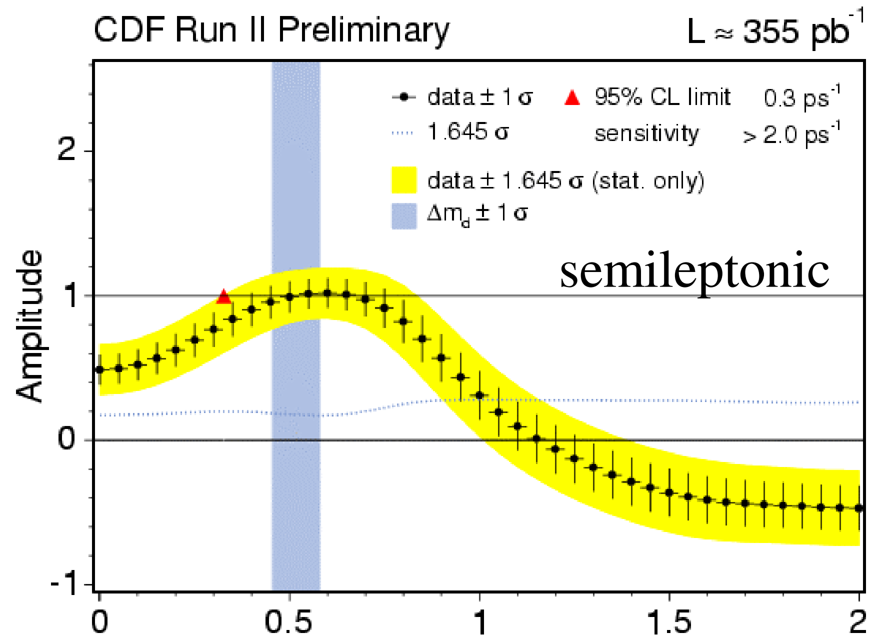


Main purpose: tagging and fitting test preparing for Δm_s

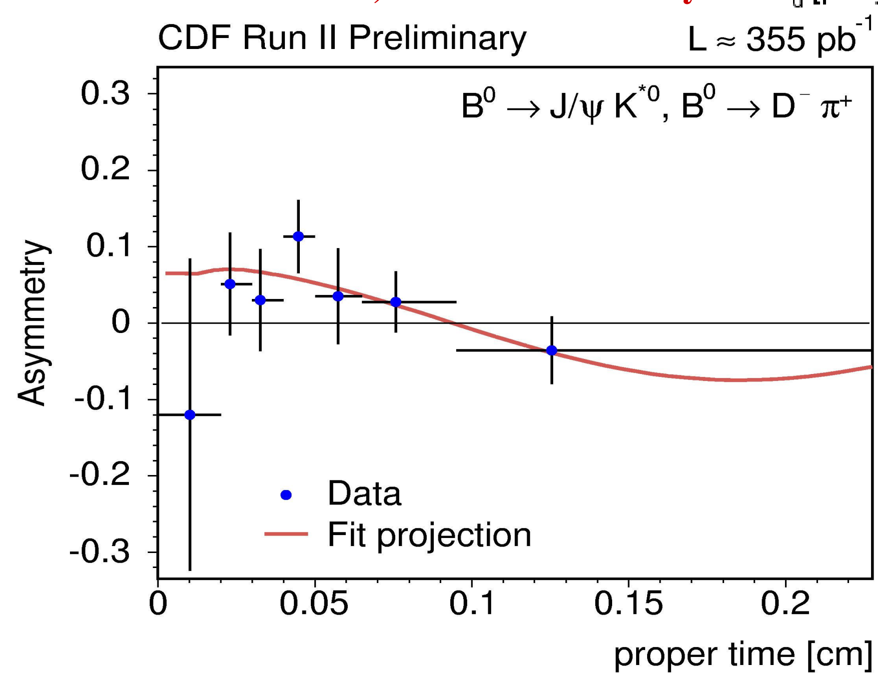
Best measurement HFAG Δm_d = (0.509 ± 0.004 ± 0.005) ps^{-1} (5× more precise)

Amplitude scan

- Fourier-transform method
- Fix frequency (Δm)
- Fit for the oscillation amplitude□ (Δm)
- **Limit at 95%:** lowest value Δm_{lim}
  P(□ $(\Delta m_{\text{lim}}) \geq 1) = 5\%$
- **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

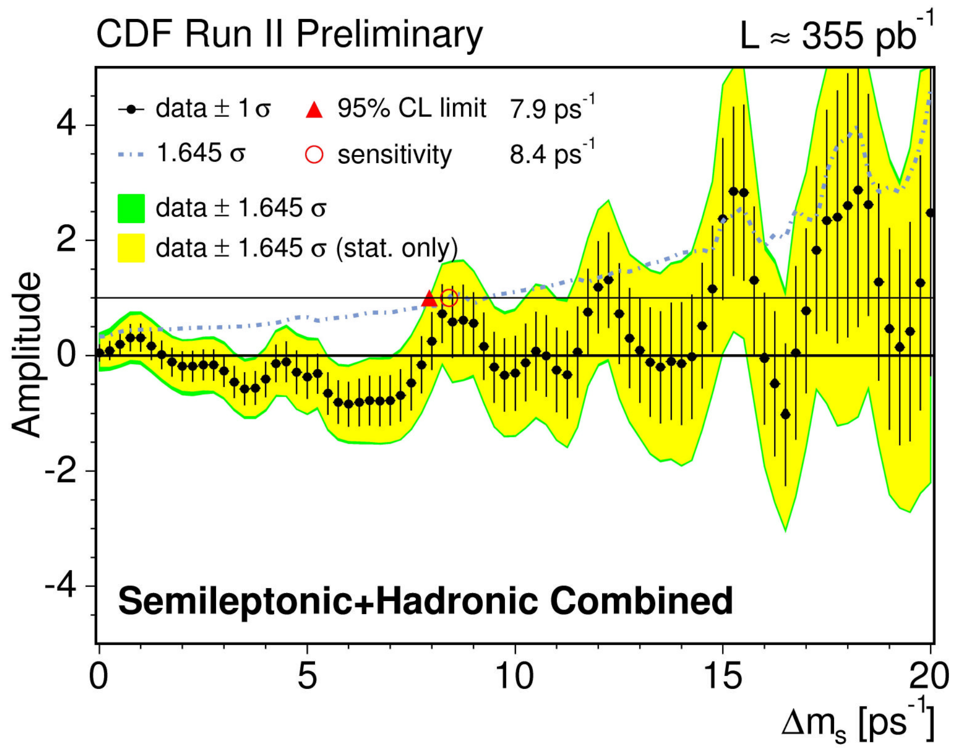


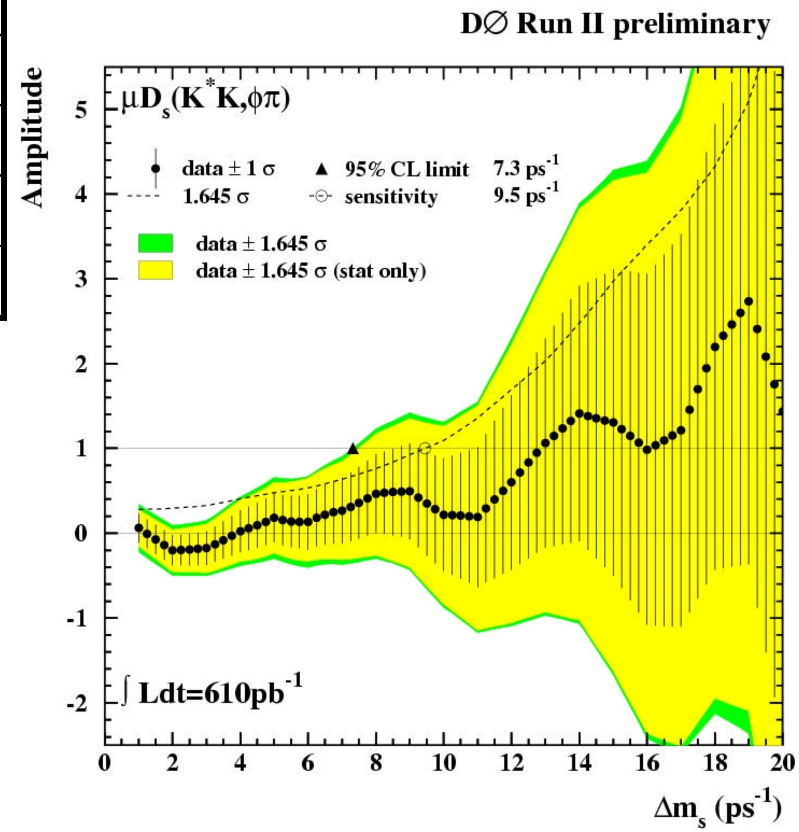
Winter 2004, for illustration only



Δm_s CDF & D0 limits

Exp.	L (pb-1)	*Δm_s limit (ps-1)*	*Sensitivity*
D0 sl	**610**	7.3	9.5
CDF sl	355	7.7	7.4
CDF had	355	0.0	0.4
CDF Comb	355	7.9	8.4



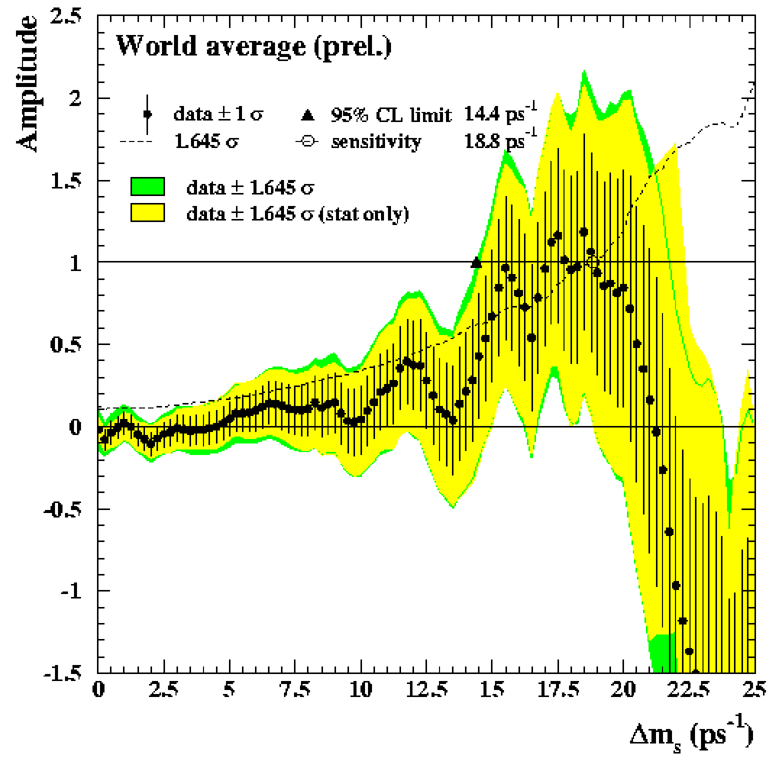


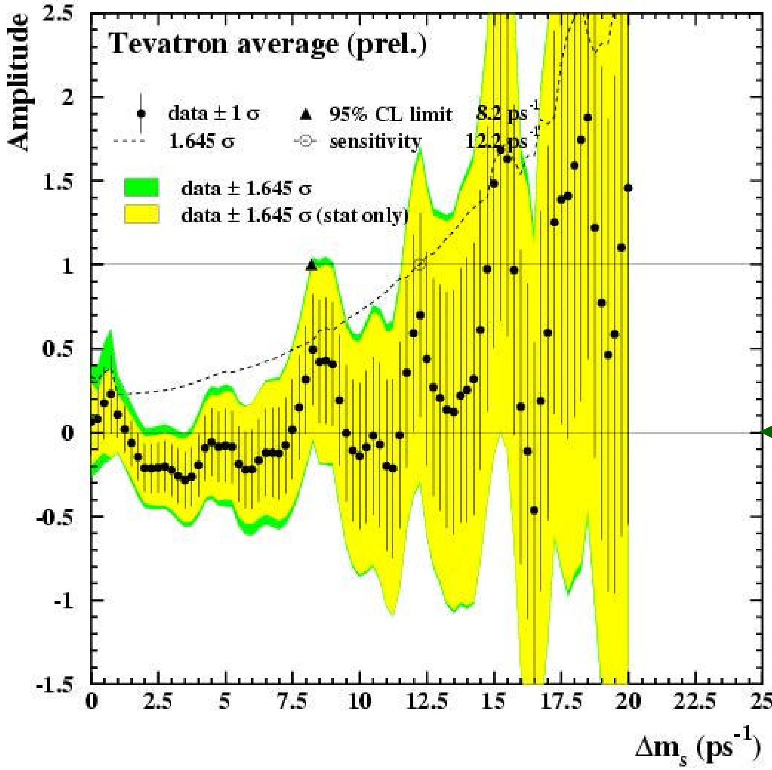
Δm_s Combined limits

World average

Limit: $\Delta m_s > 14.5$ ps^{-1}

Sensitivity for $\Delta m_s < 18.8$ ps^{-1}





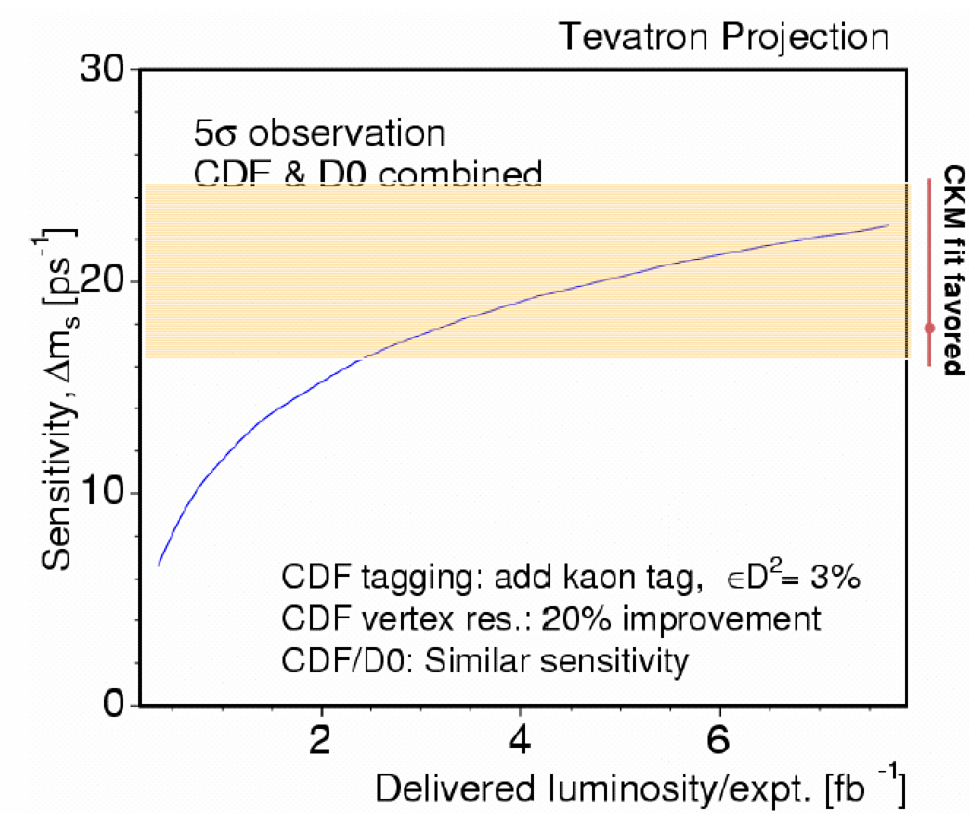
Tevatron combined:

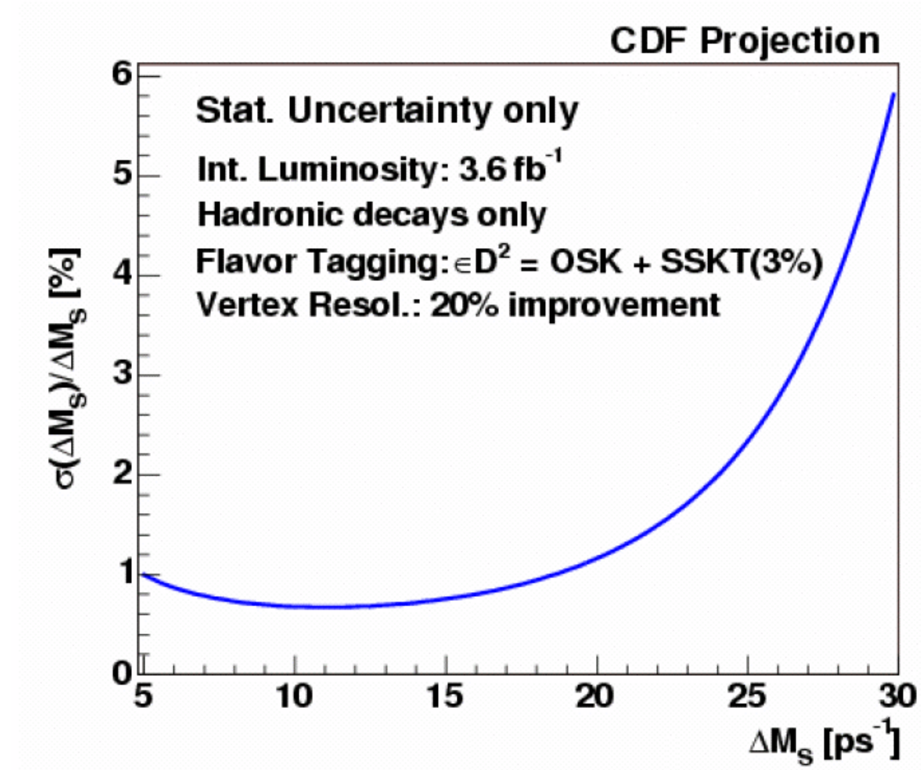
Limit: $\Delta m_s > 8.2$ ps^{-1}

Sensitivity for $\Delta m_s < 12.2$ ps^{-1}

Results will be updated VERY soon.

Δm_s Projections





TeVatron able to probe most of CKM-favoured values of Δm_s

For the whole range of reach will provide good precision (< 5%)

if oscillations directly measured.

$\Delta\Gamma_s$

$B_s \to J/\psi\ \varphi \to \mu^+\mu^-\ K^+K^-$

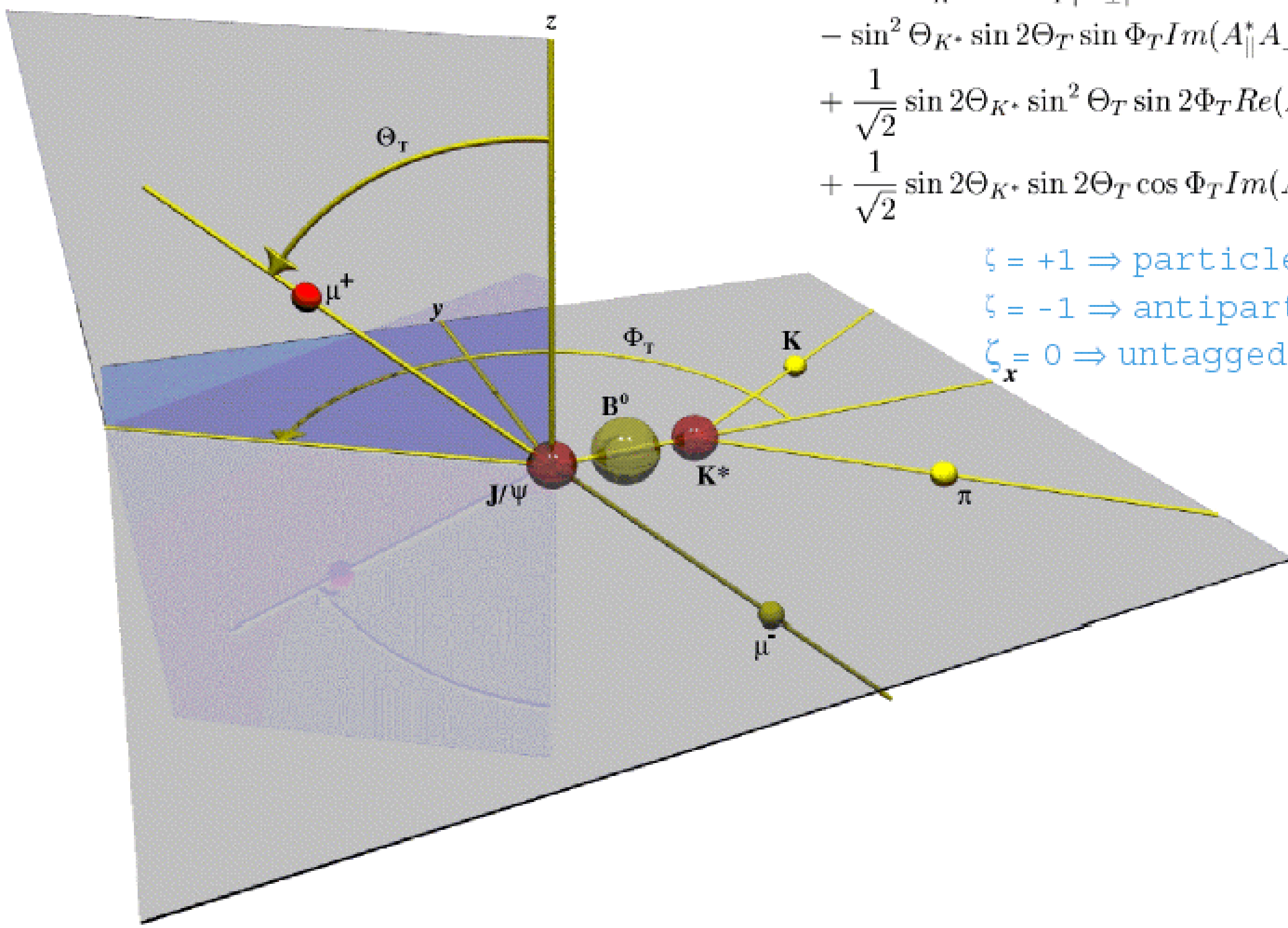
In the J/ψ rest frame

$$\mathcal{G} = \frac{9}{32\pi}\Big\{2\cos^2\Theta_{K^*}(1-\sin^2\Theta_T\cos^2\Phi_T)|A_0|^2 + \sin^2\Theta_{K^*}(1-\sin^2\Theta_T\sin^2\Phi_T)|A_{||}|^2 + \sin^2\Theta_{K^*}\sin^2\Theta_T|A_\perp|^2 - \sin^2\Theta_{K^*}\sin 2\Theta_T\sin\Phi_T Im(A_{||}^* A_\perp)\zeta + \frac{1}{\sqrt{2}}\sin 2\Theta_{K^*}\sin^2\Theta_T\sin 2\Phi_T Re(A_0^* A_{||}) + \frac{1}{\sqrt{2}}\sin 2\Theta_{K^*}\sin 2\Theta_T\cos\Phi_T Im(A_0^* A_\perp)\zeta\Big\}$$

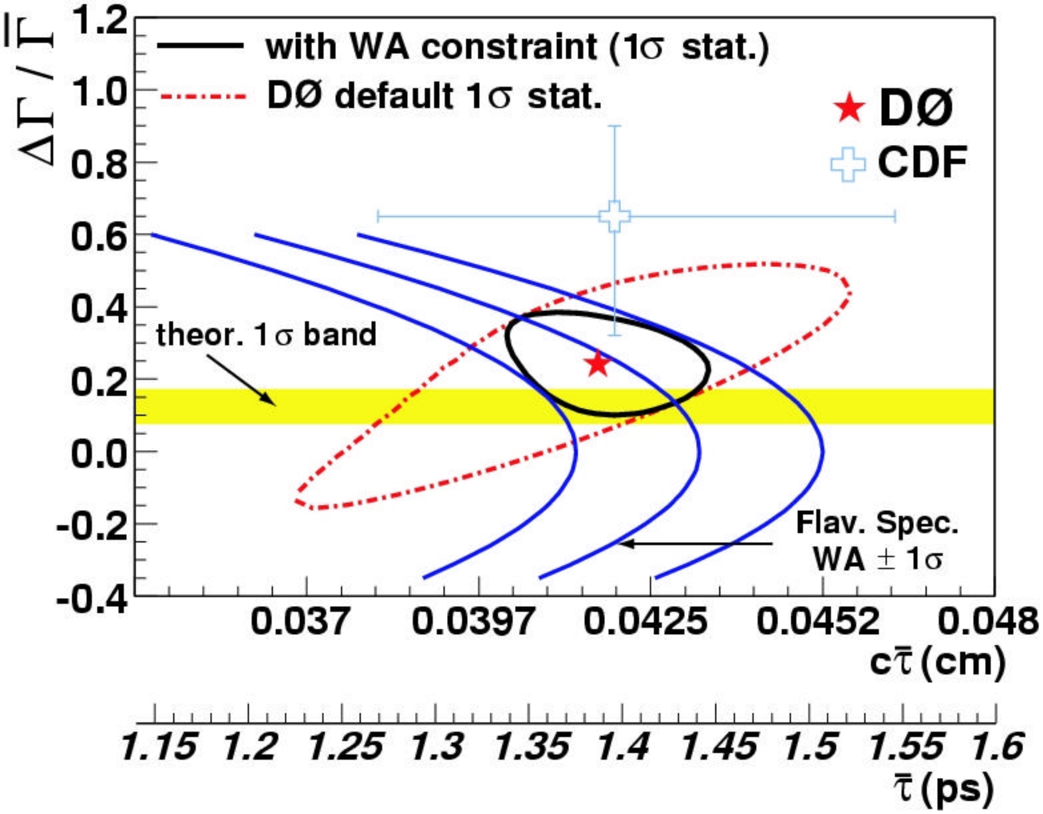
$\zeta = +1 \Rightarrow$ particle

$\zeta = -1 \Rightarrow$ antiparticle

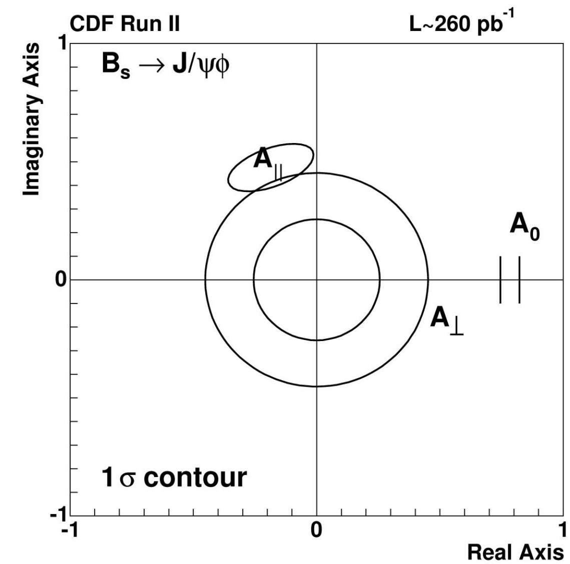
$\zeta = 0 \Rightarrow$ untagged B_s



$\Delta\Gamma_s$



D0 and CDF $\Delta\Gamma/\Gamma$ results are consistent



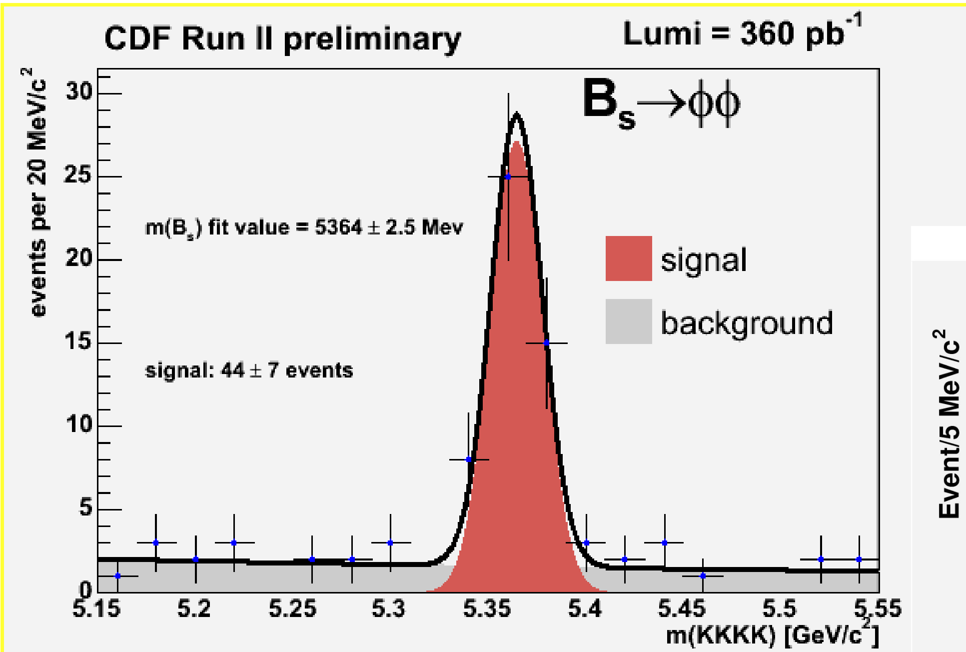
Experiment	$R_\perp$	$\Delta\Gamma/\Gamma$	$\bar{\tau}(ps)$	τ_L	τ_H
Aleph				1.27 ± 0.34	
CDF RunII	0.125 ± 0.08	$0.65^{+0.25}_{-0.33}$	$1.40^{+0.15}_{-0.13}$	$1.05^{+0.16}_{-0.13}$	$2.07^{+0.58}_{-0.46}$
D0 RunII	0.17 ± 0.10	$0.21^{+0.33}_{-0.45}$	$1.39^{+0.15}_{-0.16}$	$1.23^{+0.16}_{-0.13}$	$1.52^{+0.39}_{-0.43}$

$B_s \to$ vector vector

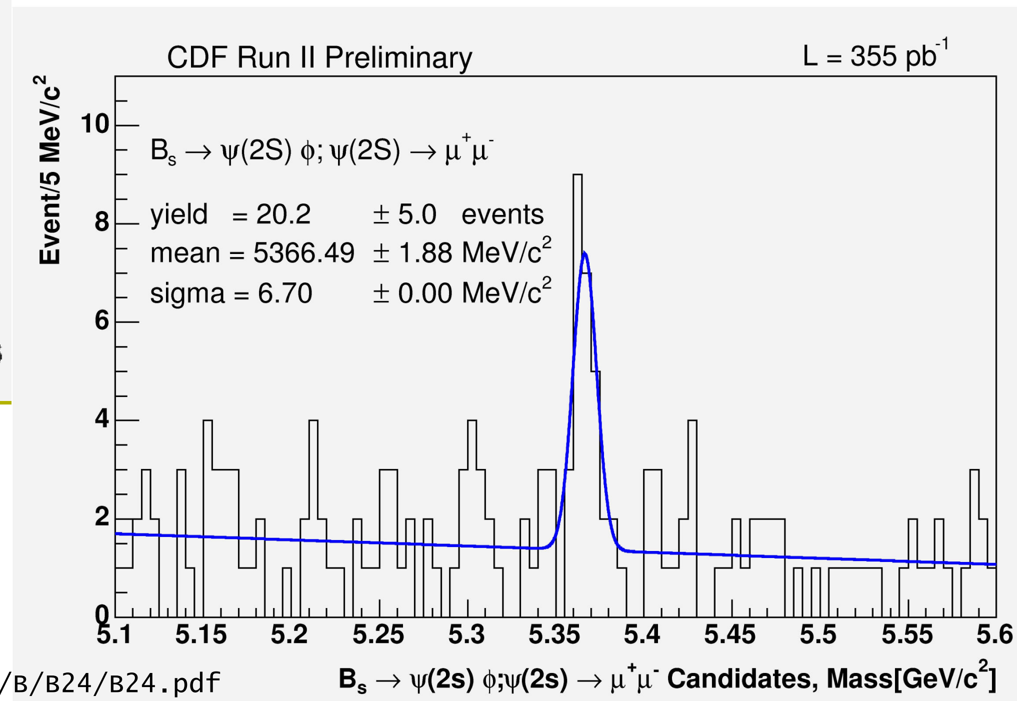
Other channels will be added in future for $\Delta\Gamma_s$:

$B_s \to \psi(2S)\,\phi$ http://www-cdf.fnal.gov/physics/new/bottom/050331-Bs-psi2Sphi/blessed-Bs-psi2Sphi.ps

$B_s \to \phi\,\phi$ hep-ex/0502044 Phys. Rev. Lett. 95, 031801 (2005).



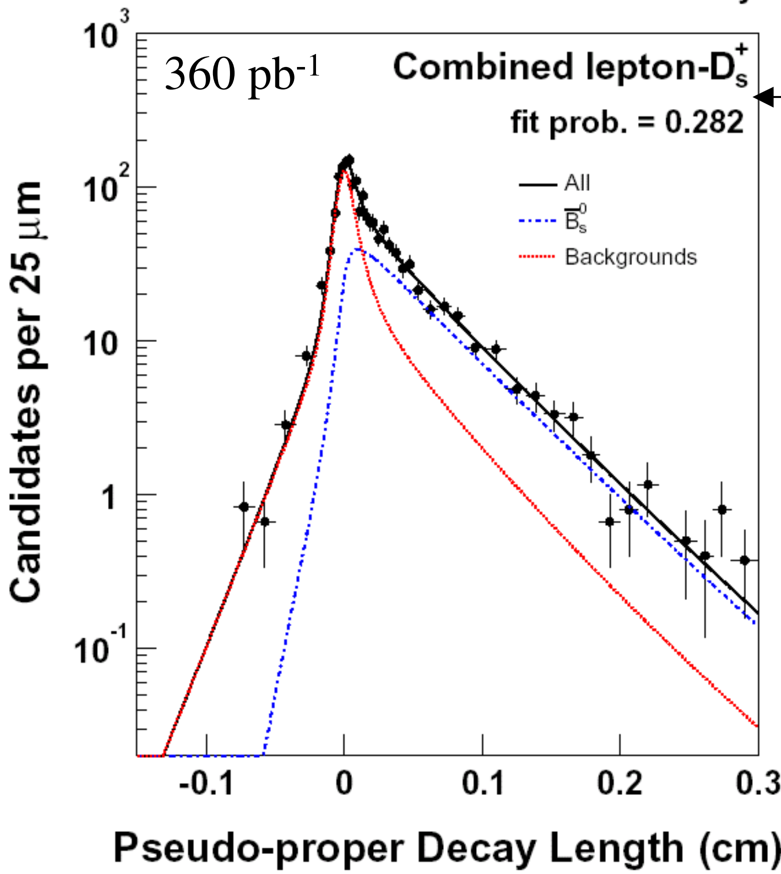
Updated result



Also D0 detects $B_s \to \psi(2S)\,\phi$

http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/B/B24/B24.pdf

$B_s \rightarrow \ell + D_s + X$



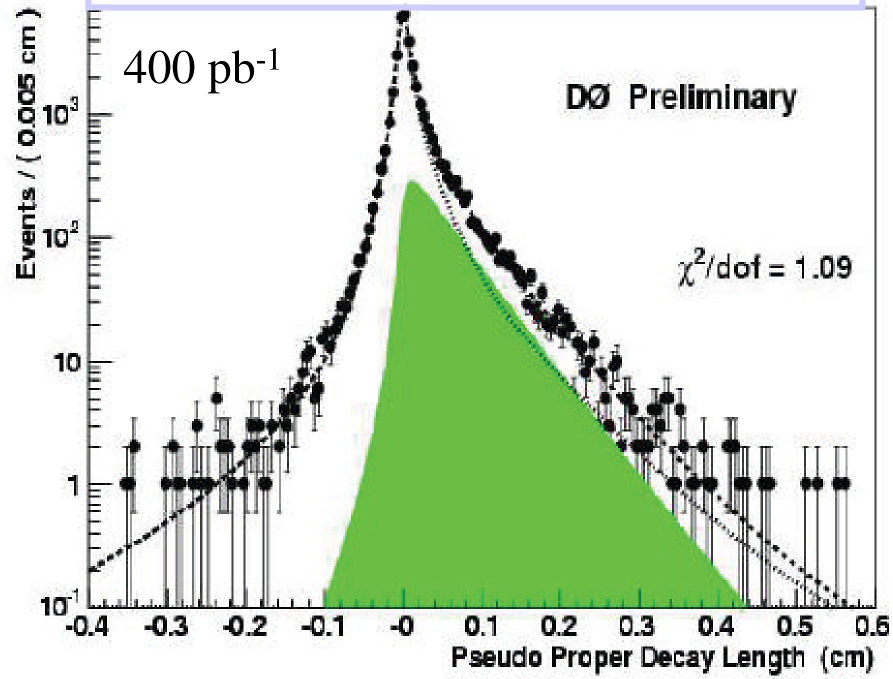
8 GeV electron trigger

$$\tau(B_s) = 1.381 \pm 0.055 \, ^{+0.052}_{-0.046} \text{ ps}$$

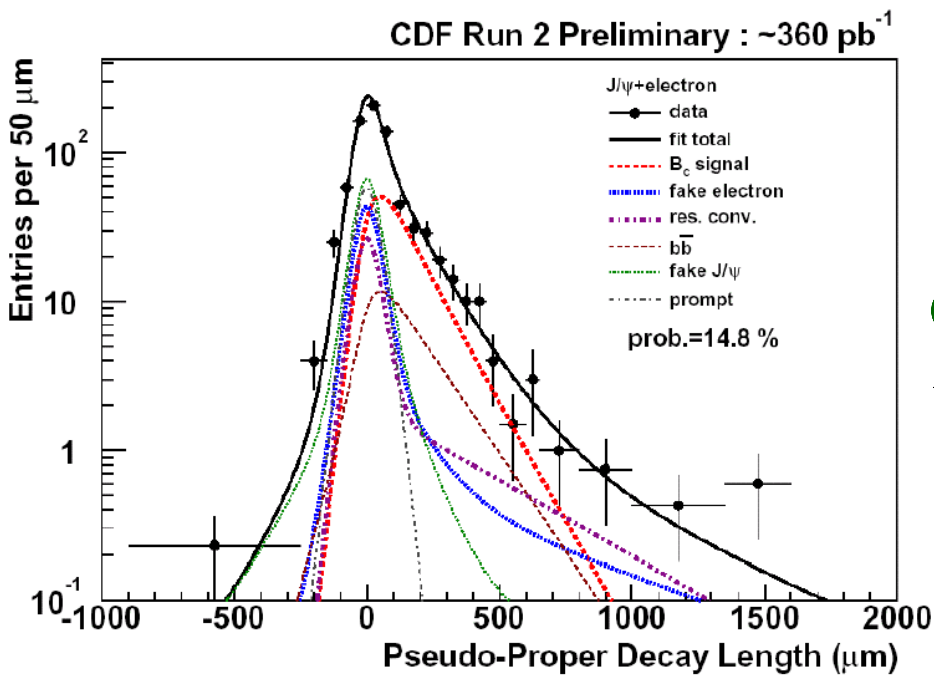
Most precise measurement

Pt(μ) >2 GeV/c

$$\tau(B_s) = 1.420 \pm 0.043 \pm 0.057$$



$B_c \to J/\psi\, \ell + X$



Lifetime of B_c

Measured in

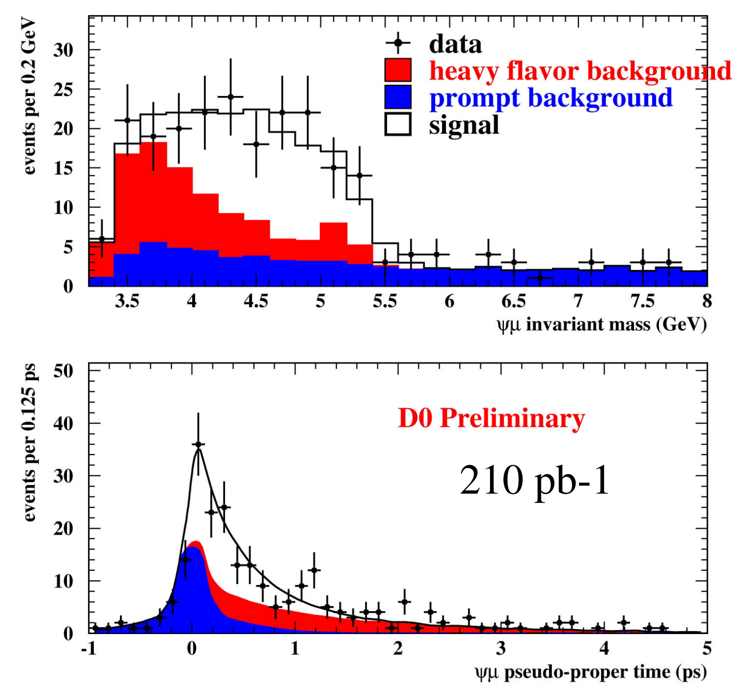
Semileptonic channels

CDF $B_c \to J/\psi\, e + X$

$$\tau(B_c) = 0.474^{+0.073}_{-0.066} \pm 0.033 \text{ ps}$$

D0 $B_c \to J/\psi\, \mu + X$

$$\tau(B_c) = 0.448^{+0.128}_{-0.086} \pm 0.121 \text{ ps}$$

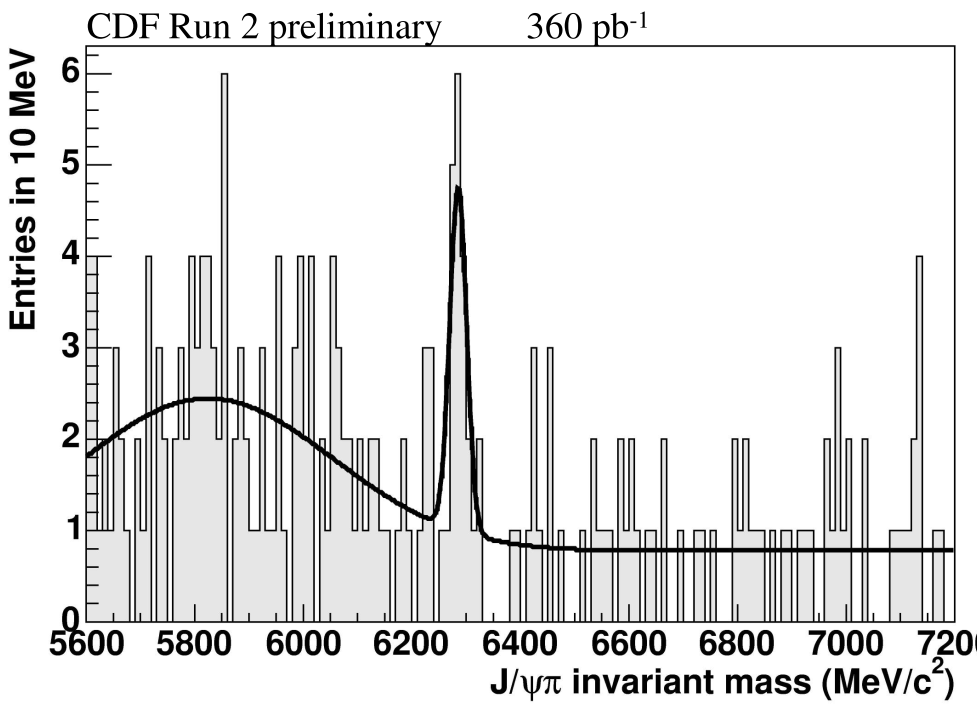


PDG (CDF run1)

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

$B_c \to J/\psi\ \pi$

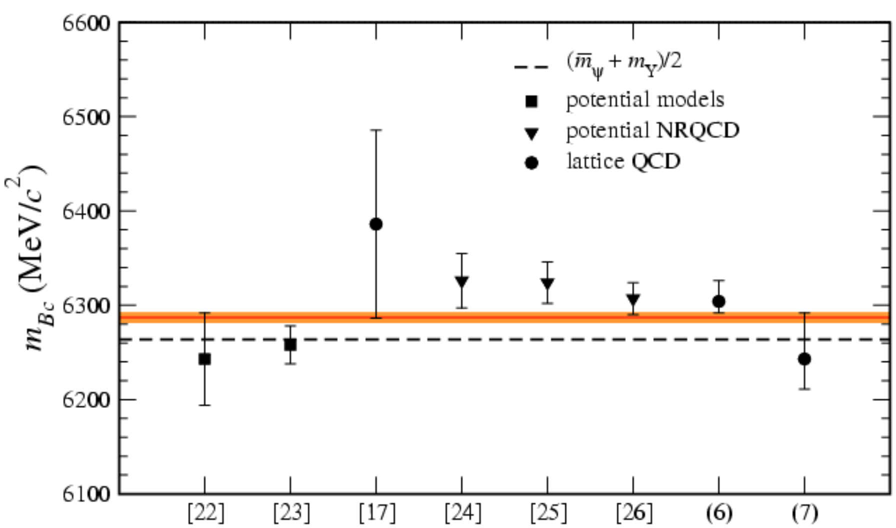
B_c Mass = 6285.3 ± 5.2(stat.) ± 1.2(syst.) MeV/c^2



Mass measured using fully
Reconstructed mode.
Evidence for decay $B_c \to J/\psi\ \pi$
hep-ex/0505076

P-value ≈ 0.02 % *anywhere in window*
1600 MeV/c^2 wide

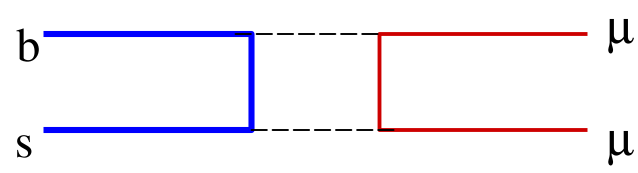
5-σ observation within reach.
Lifetime, BR also coming soon



Measurement uncertainty 100x better than previous
(hadronic vs. semileptonic)

Theory in very good agreement.
Potential models, NRQCD, Lattice QCD

CDF/D0 Rare decays



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

$BR = (3.4 \pm 0.54)\ 10^{-9} \Rightarrow$ place to look for new Physics

- 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×

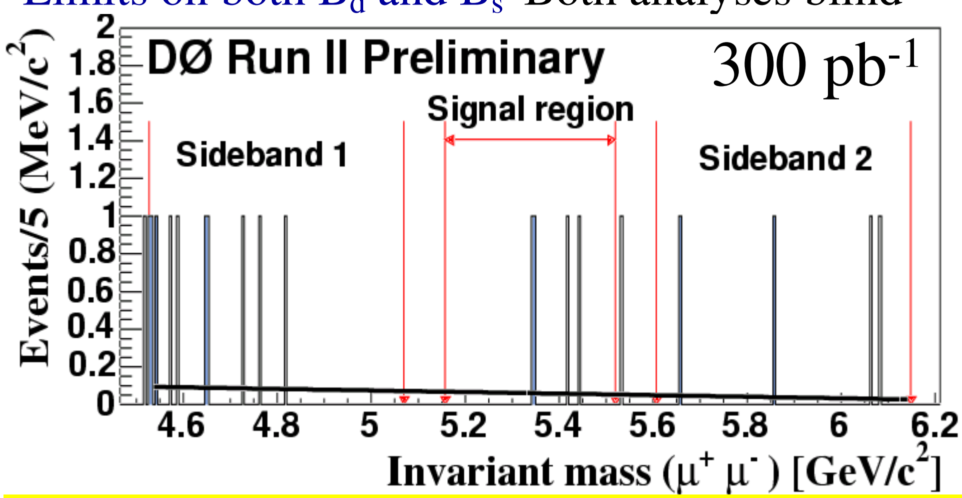
D0 updated measurement to include 300 pb^{-1}

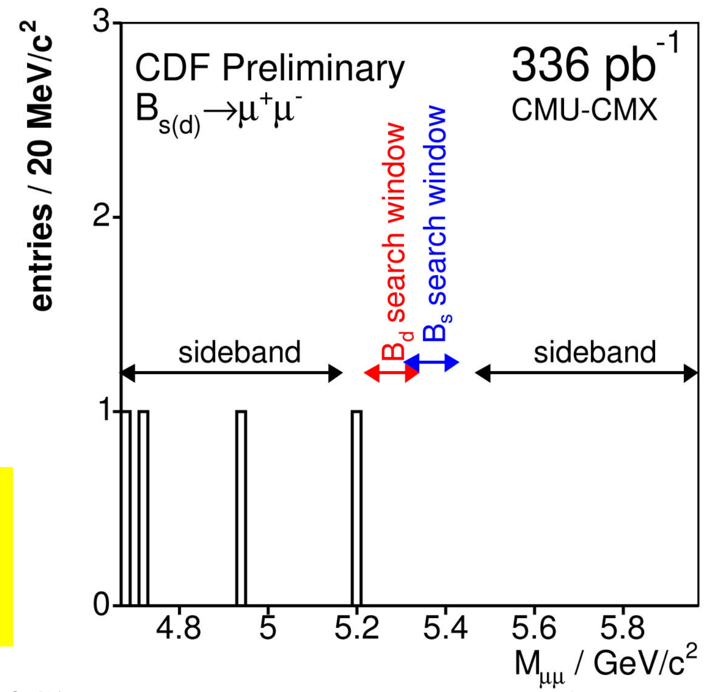
CDF updated with 336 pb^{-1} Mass resolution 27 MeV/c^2

Limits on both B_d and B_s Both analyses blind

95% CL

	□□ $(B_s \to \mu^+\mu^-)$	□□ $(B_d \to \mu^+\mu^-)$
D0	$< 3.7\ 10^{-7}$	----------
CDF	$< 2.0\ 10^{-7}$	$< 1.9\ 10^{-7}$
CDF+D0	$< 1.5\ 10^{-7}$	$< 4.8\ 10^{-8}$





D0 looked for □□ $(B_s \to \mu^+\mu^-\phi)$

$BR < 4.1\ 10^{-6}$ (95% CL)

http://www-d0.fnal.gov/R□n2Physics/□□□/□es□lts/p□elim/B/B23/B23.pdf

Conclusions

- The Tevatron produces many results in *B* Physics and confirms/complements *B*-factories.
- B_s, B_c and *b*-baryons only produced at hadron collider. Opportunity for precise measurements.
- $B \to h^+h^-$ analysis will produce soon very interesting results.
- New CDF Δm_s analysis within weeks.
- Full luminosity will allow to push limit or measure precisely Δm_s
- Many more interesting measurements not presented for lack of time
- Please look at:
  - http://www-d0.fnal.gov/R□n2Physics/□□□/□es□lts/b.htm
  - http://www-cdf.fnal.gov/physics/new/bottom/bottom.html

  For futher details and full list of TeVatron results in *b*-Physics

References

CDF Bs to μμ hep-ex/0508036

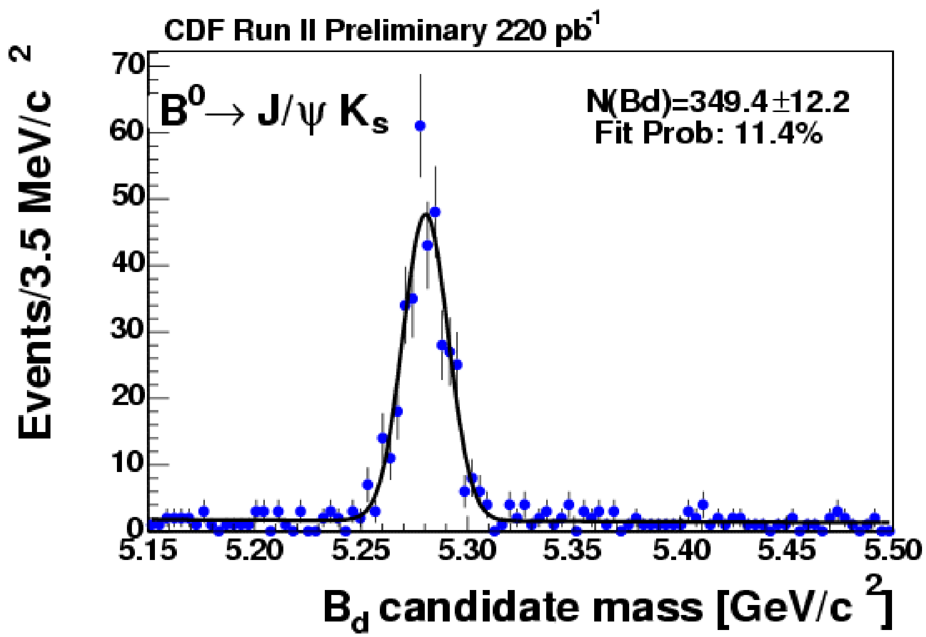
D0 Bs,d μμ http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/B/B21/B21.pdf

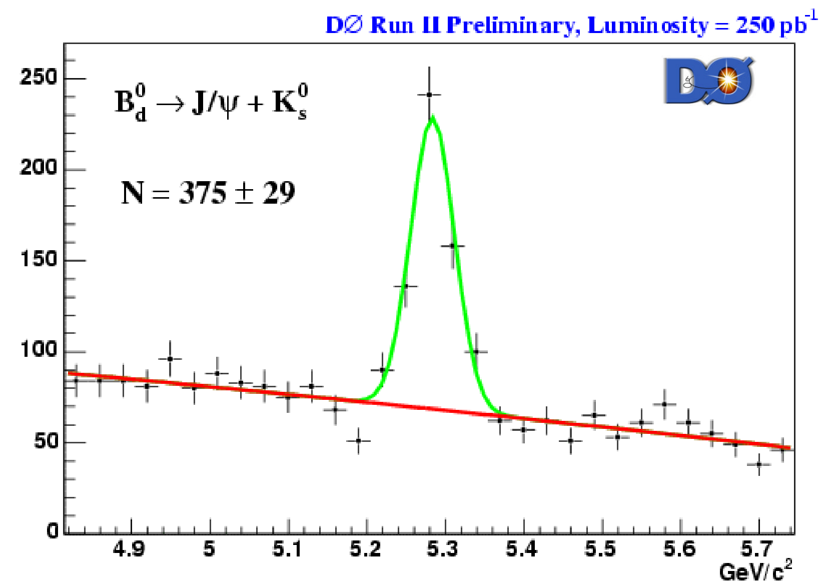
Combined result: hep-ex/0508058

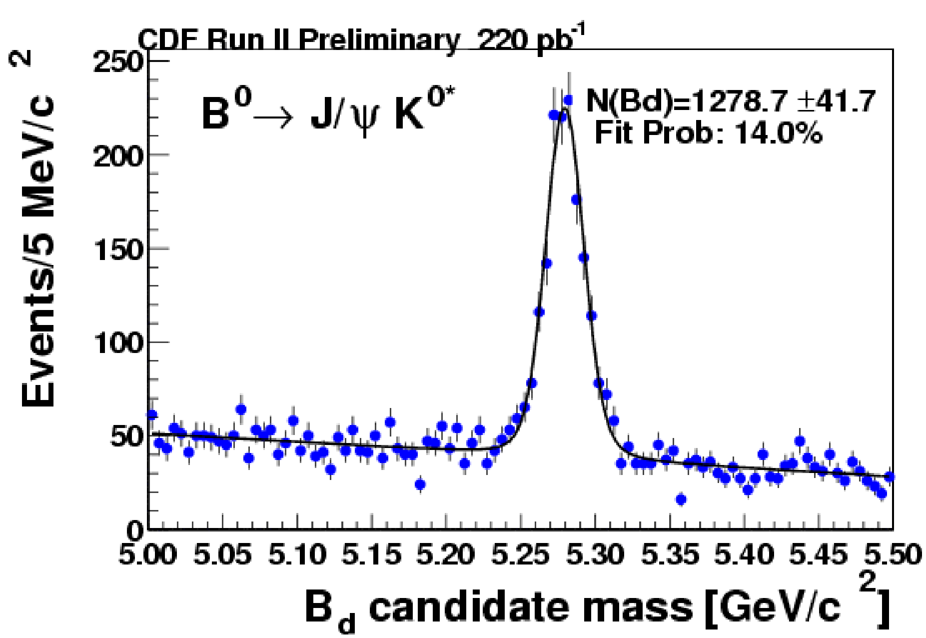
D0 $\Delta\Gamma_s$ hep-ex/0507084

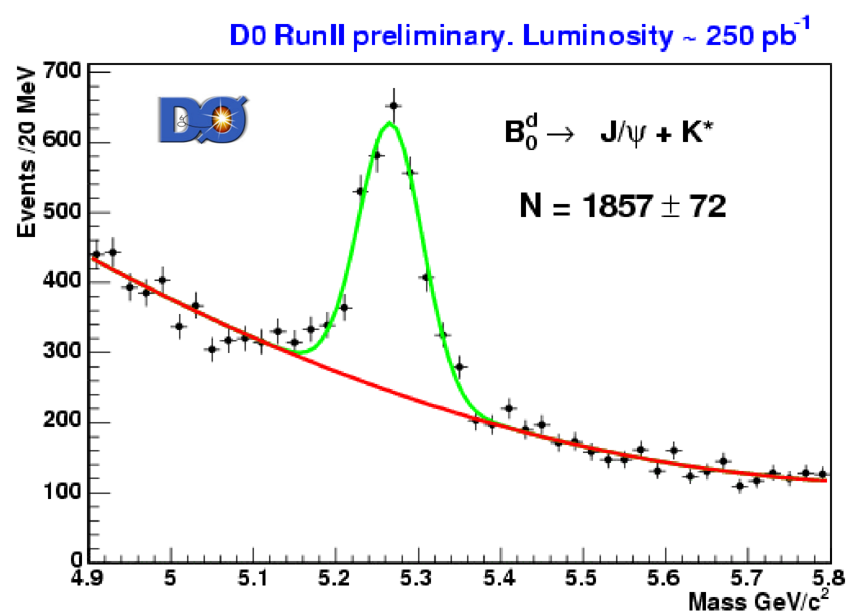
CDF $\Delta\Gamma_s$ Phys. Rev. Lett. 94, 101803 (2005)

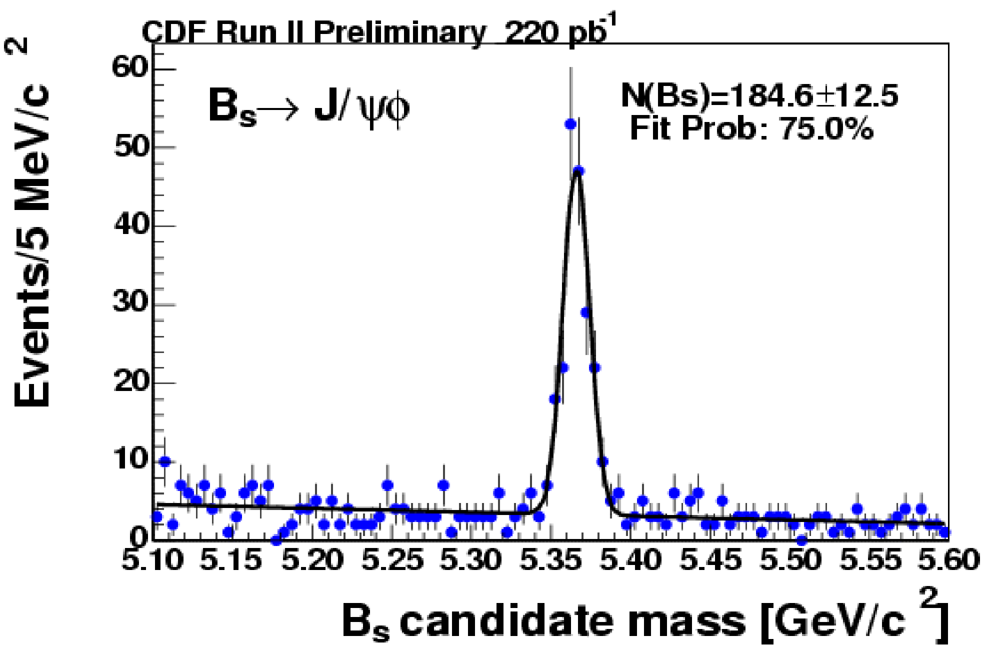

Aurora Borealis at Fermilab
9th November 2004, 3 a.m.
42°N
Backup Slides

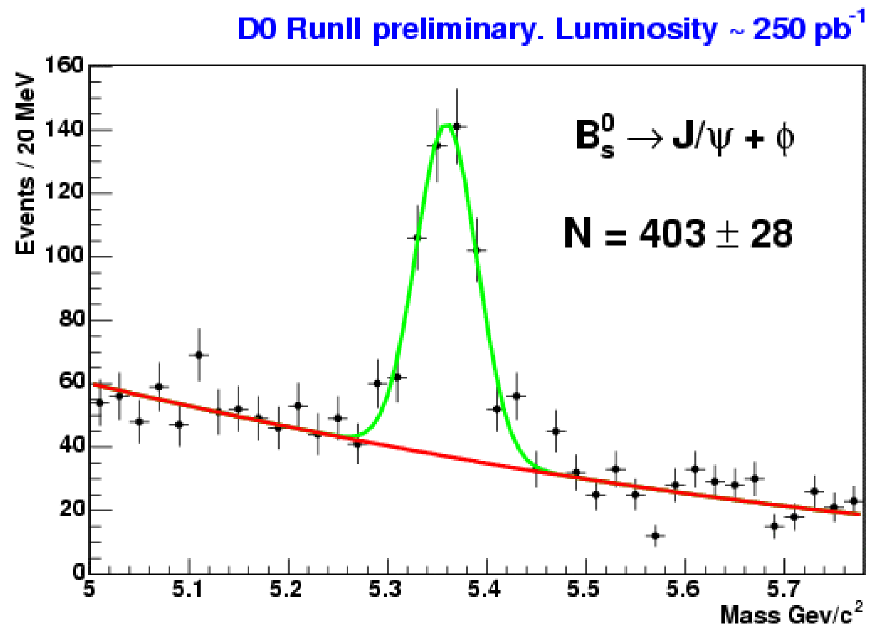

CDF Run II Preliminary 220 pb^{-1}
$B^0 \to J/\psi\ K_s$
N(Bd)=349.4±12.2
Fit Prob: 11.4%
Events/3.5 MeV/c ^{2}
B_d candidate mass [GeV/c ^{2}]

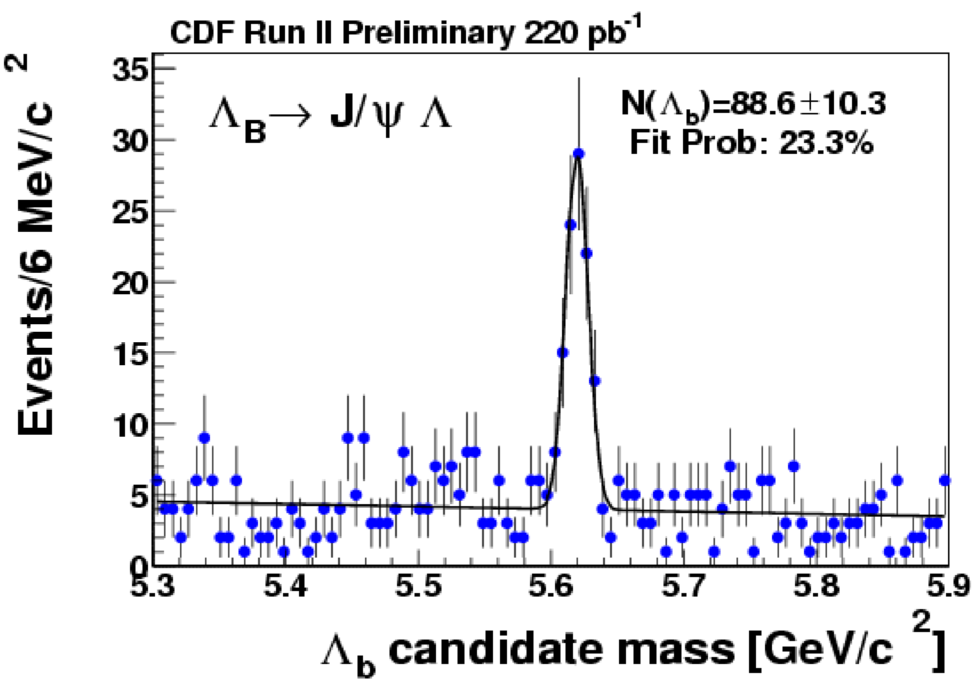

DØ Run II Preliminary, Luminosity = 250 pb^{-1}
$B_d^0 \to J/\psi + K_s^0$
N = 375 ± 29
GeV/c^2

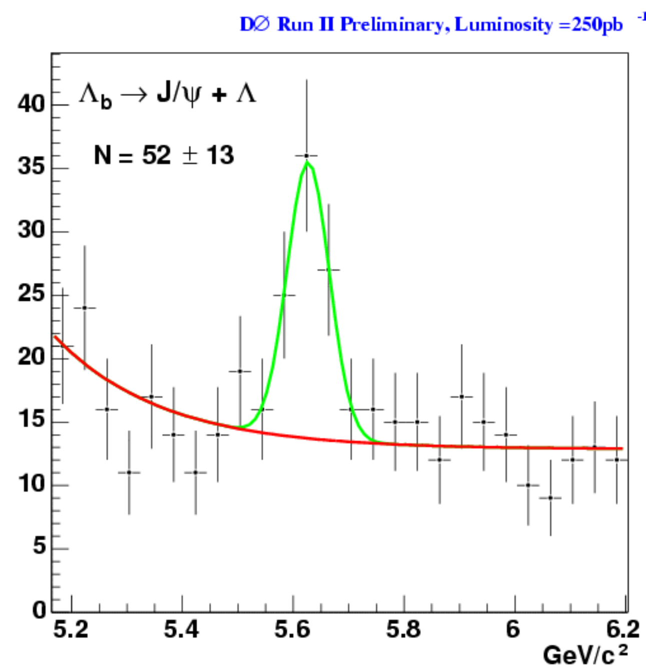

CDF Run II Preliminary 220 pb^{-1}
$B^0 \to J/\psi\ K^{0*}$
N(Bd)=1278.7 ±41.7
Fit Prob: 14.0%
Events/5 MeV/c ^{2}
B_d candidate mass [GeV/c ^{2}]


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
Bs→ J/ψφ
N(Bs)=184.6±12.5
Fit Prob: 75.0%
Events/5 MeV/c 2
Bs candidate mass [GeV/c 2]


D0 RunII preliminary. Luminosity ~ 250 pb-1
B0s → J/ψ + φ
N = 403 ± 28
Events / 20 MeV
Mass Gev/c2


CDF Run II Preliminary 220 pb-1
ΛB→ J/ψ Λ
N(Λb)=88.6±10.3
Fit Prob: 23.3%
Events/6 MeV/c 2
Λb candidate mass [GeV/c 2]


DØ Run II Preliminary, Luminosity =250pb -1
Λb → J/ψ + Λ
N = 52 ± 13
GeV/c2

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. $\chi^2(3D)$ < 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%
$\chi^2(3D)$	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 $$\Sigma = \frac{S}{1.5 + \sqrt{B}}$$

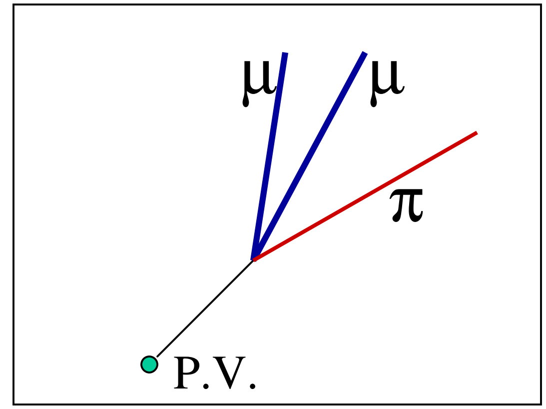
S = number of signal events from MC

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

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

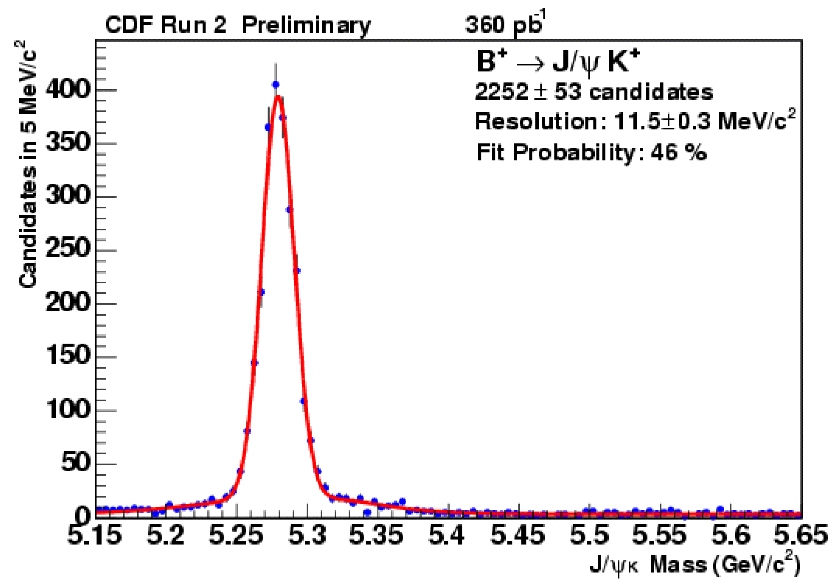
$$B_c \to J/\psi\ \pi^{\pm}$$



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

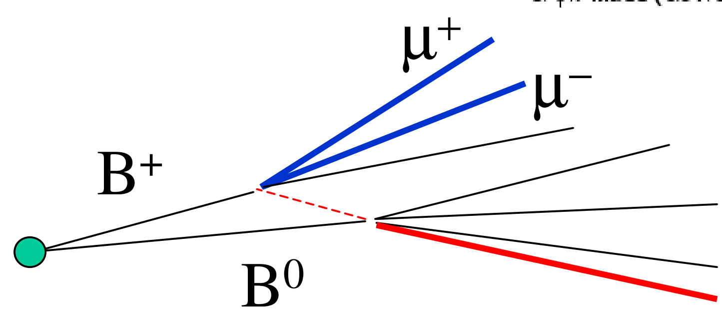
  lifetime, small *BR*, small σ_{prod}.

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



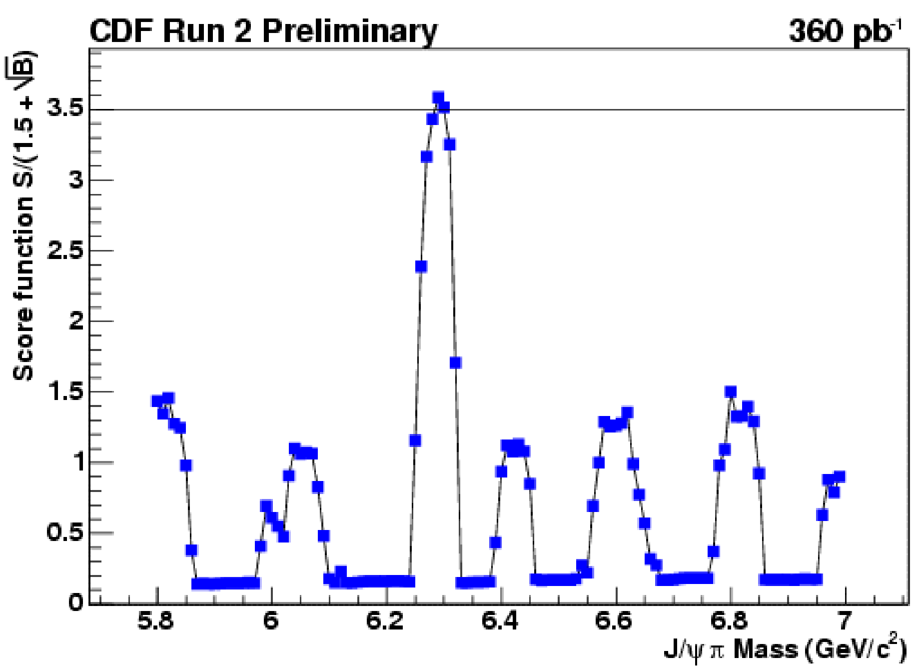
CDF Fully reconstructed B_c

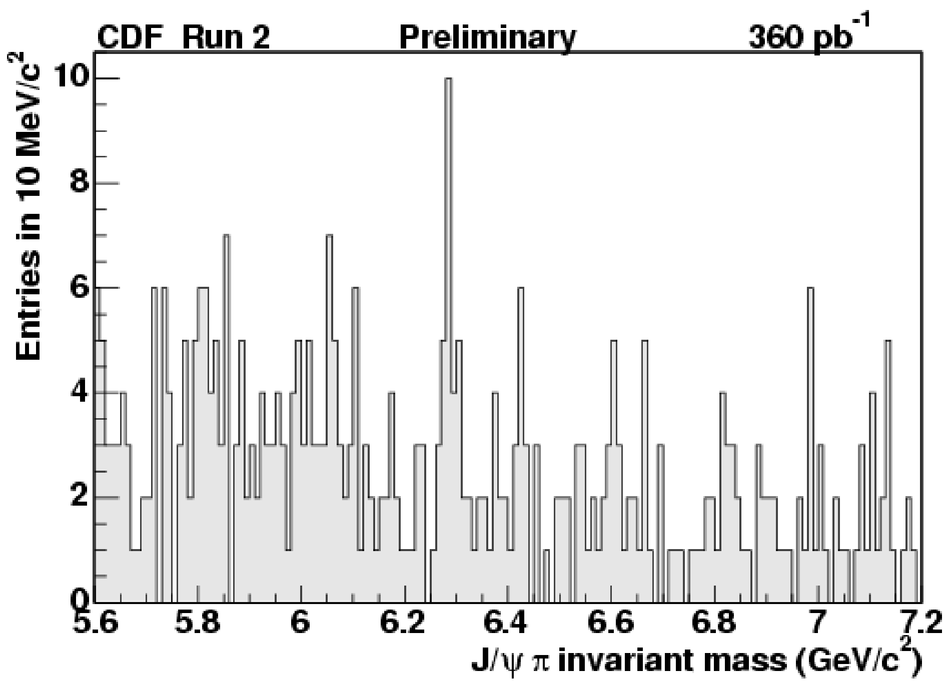
Hypothesis test set up before opening the box.

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

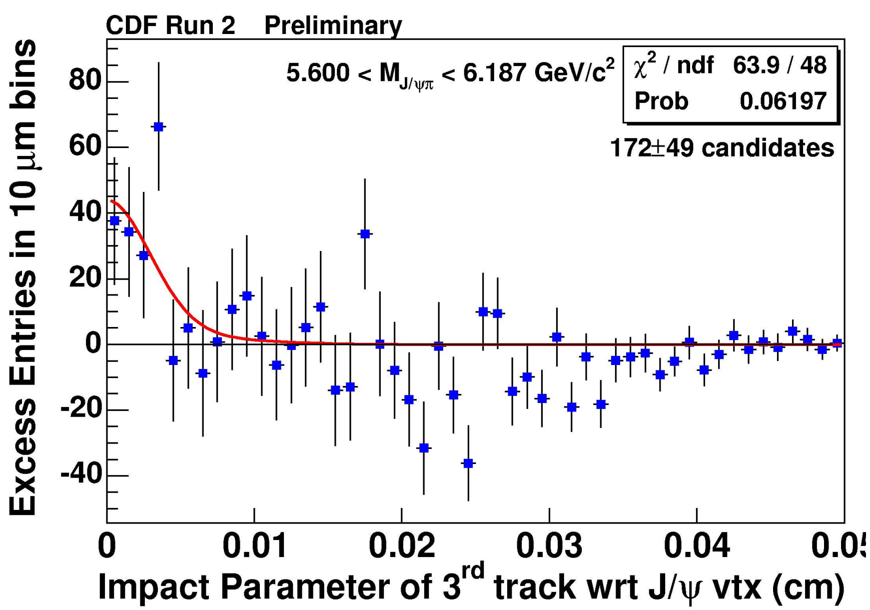
Threshold value $\Sigma_{thr} = 3.5$ From "*toy Monte Carlo*", P ≈ 1/1000 false positive

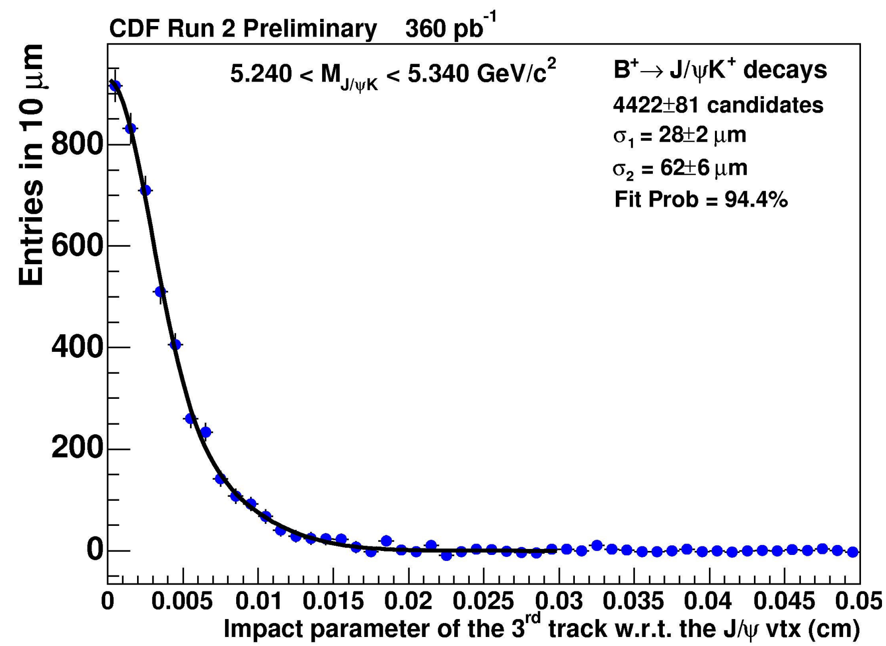
After box open: scan search region with binned likelihood fit:
mass fixed (scanned), Gaussian width fixed (resolution), S,B fit parameters





CDF Partially reconstructed hadronic B_c





ERROR: stackunderflow
OFFENDING COMMAND: ~

STACK: