Beauty physics with B_s and Λ_b

Rolf Oldeman

INFN Roma 1 "La Sapienza"

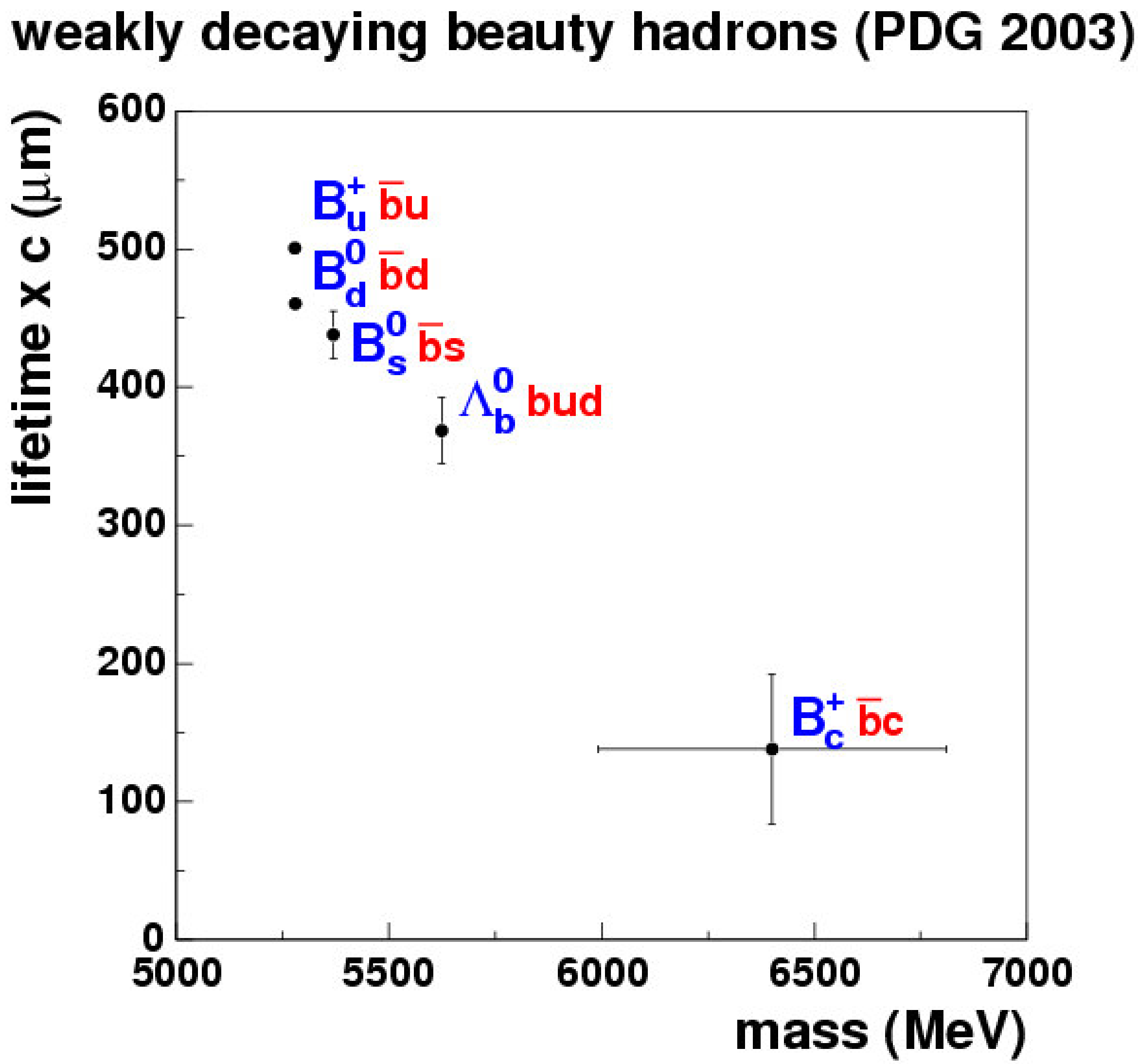
Selected topics

- Masses
- Lifetimes
- B_s lifetime difference
- Charmless B_s and Λ_b decays
- B_s oscillations

Rare decays covered today by YoungJoon Kwon

CP violation covered today by Emmanuel Olaiya

The B hadron family

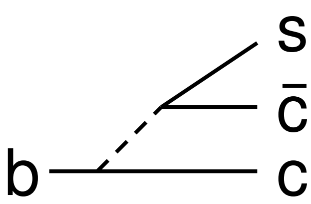


Not yet unambiguously observed:

- Ξ_b^- bds
- Ξ_b^0 bus
- Ω_b^- bss

What's so special about spectator quarks?

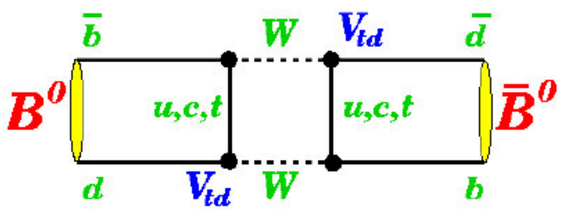
1 The spectator quarks makes or breaks a CP-Eigen state



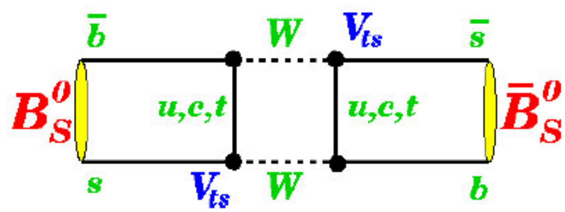
$B_d \rightarrow D_s^+ D^-$ *(CP mixed)* vs $B_s \rightarrow D_s^+ D_s^-$ *(CP even)*

$\Rightarrow$ sizable lifetime difference in B_s

2 The spectator quark can exchange with the b

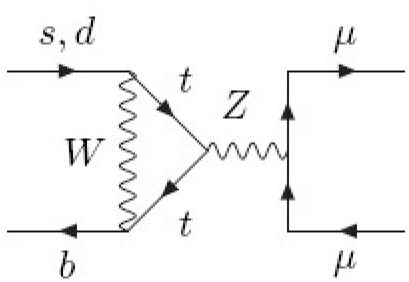


vs



$\Rightarrow$ B_s oscillates >25 times faster than B_d

3 The spectator quark can annihilate the b



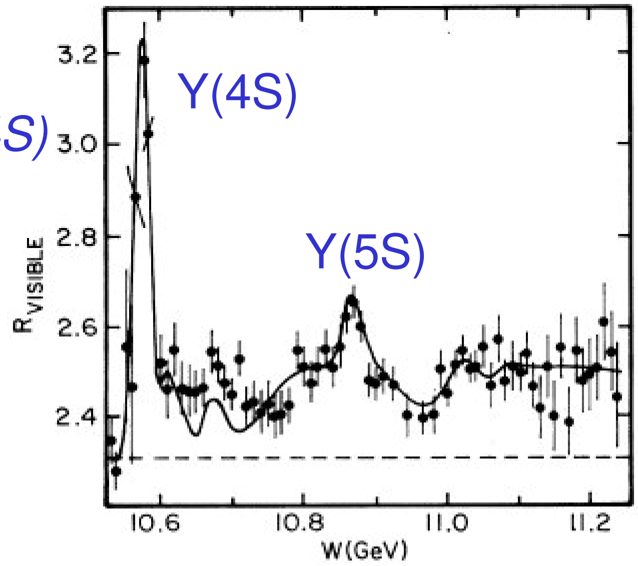
$Br(B_s \rightarrow \mu^+\mu^-) \gg Br(B_d \rightarrow \mu^+\mu^-)$

$\Rightarrow$ heavy B-hadrons provide unique window on B-physics

Producing heavy B hadrons

Y(4S): B^+ / B^0 only

B_s at Y(5S): ≈ 10x smaller cross-section than B_d at Y(4S)



➡ $e^+ e^-$ above B_s threshold:
- LEP ≈880k $b\bar{b}$ events/experiment
- SLC ≈ 85k $b\bar{b}$ events

➡ Fixed target $E_{cm} > 2m(B_s)$
- Tried unsuccessfully at HERA-B *$\sigma(b\bar{b})/\sigma(total) \approx 10^{-6}$*

➡ Hadron colliders:
- Operational: Tevatron, Chicago, 1.96 TeV $p\bar{p}$ $\sigma_{bb}/\sigma_{tot} \approx 10^{-3}$
- Startup 2007: LHC, Geneve 14TeV pp $\sigma_{bb}/\sigma_{tot} \approx 10^{-2}$

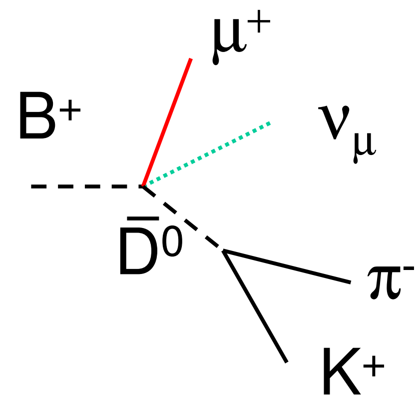
Production ratio at high energy:

$B^0 : B^- : B_s : \Lambda_b : B_c \approx 4 : 4 : 1 : 1 : 0.01$

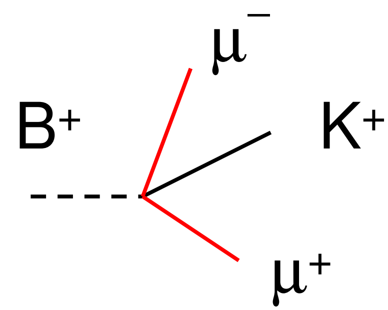
Reconstructing B-decays

Generally 3 types of B-decays accessible at hadron collider:

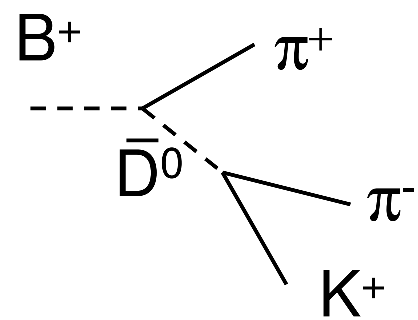
- Semi-leptonic B decays
  - •Pro: large branching ratios$\rightarrow$ large yields
  - •Con: missing neutrino



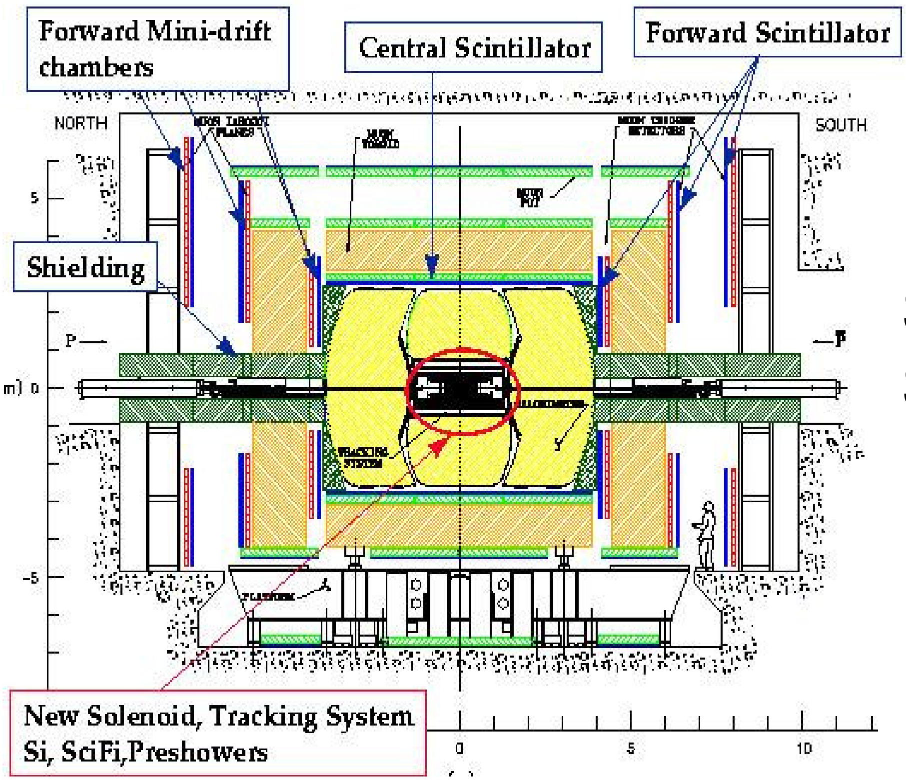
- B decays to J/ψ
  - •Pro:muon provides easy trigger
  - •Con: small branching fractions



- Fully hadronic B decays
  - •Pro: $\approx$80% of branching fraction
  - •Con: requires silicon track trigger



Tevatron detectors: CDF and DØ

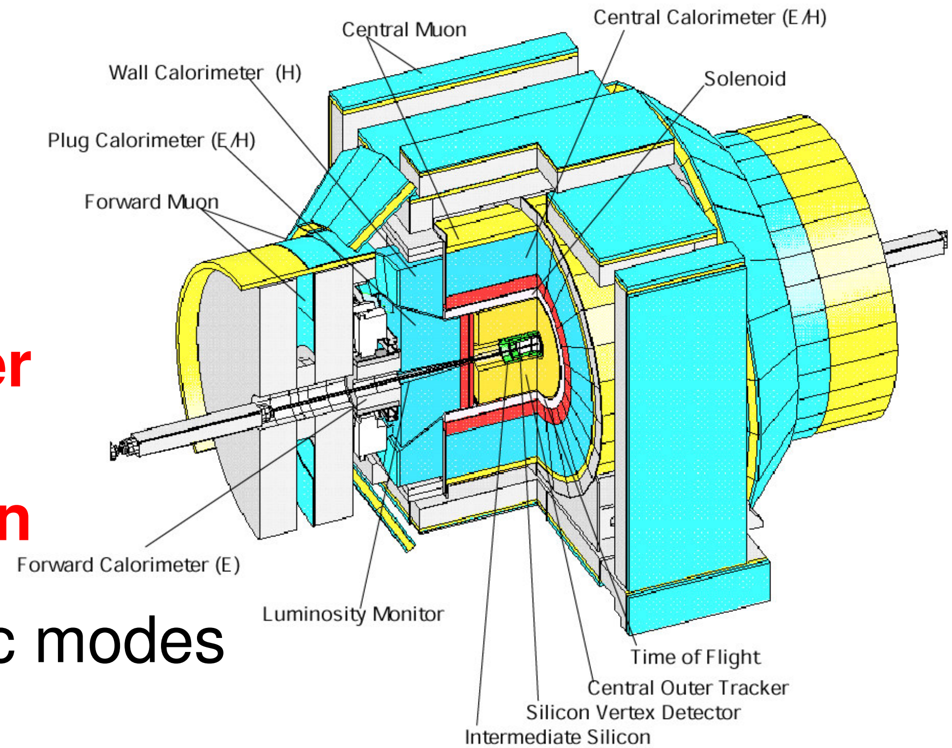


DØ:

- **Larger muon coverage**
- **Better forward tracking**

Strong in J/ψ modes

Strong in semi-leptonic modes



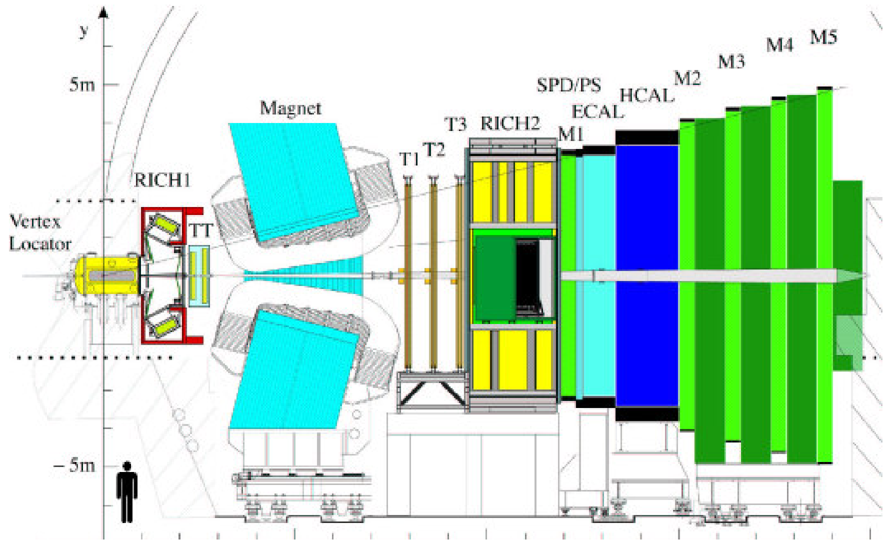
CDF:

- **Displaced track trigger**
- **PID: TOF and dE/dx**
- **Better mass resolution**

Strong in fully hadronic modes

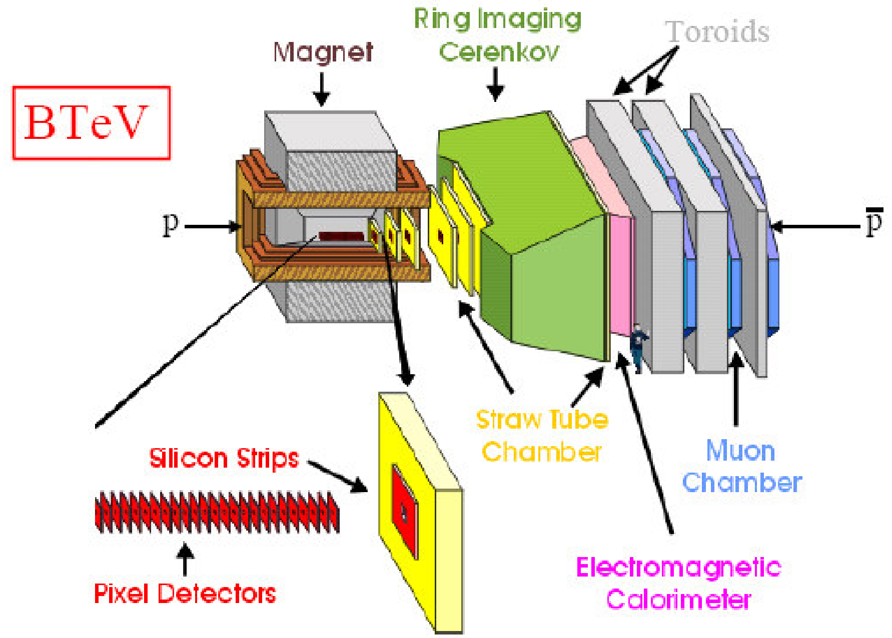
Forward is the future

LHCb: startup 2007



pp collisions at E_{cm}=14TeV

BTeV: startup 2009



$p\bar{p}$ collisions at E_{cm}=1.96TeV

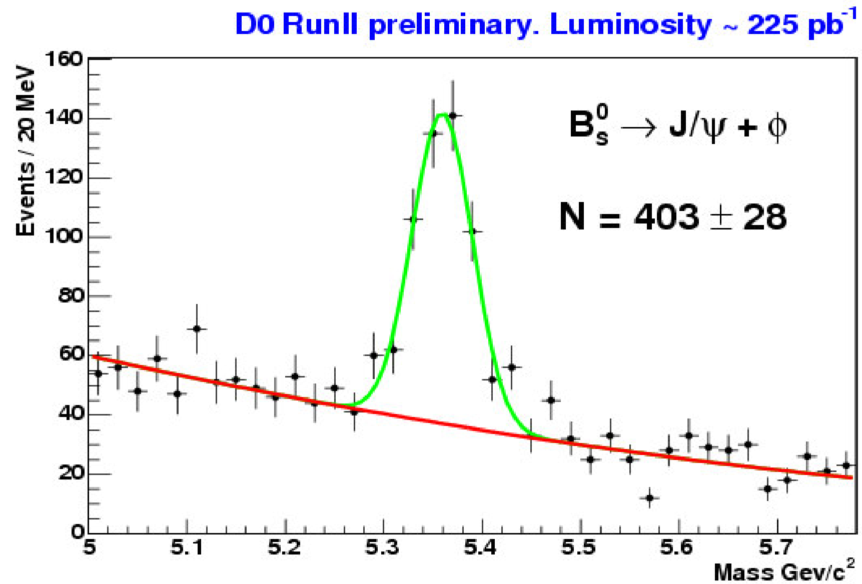
Forward region:

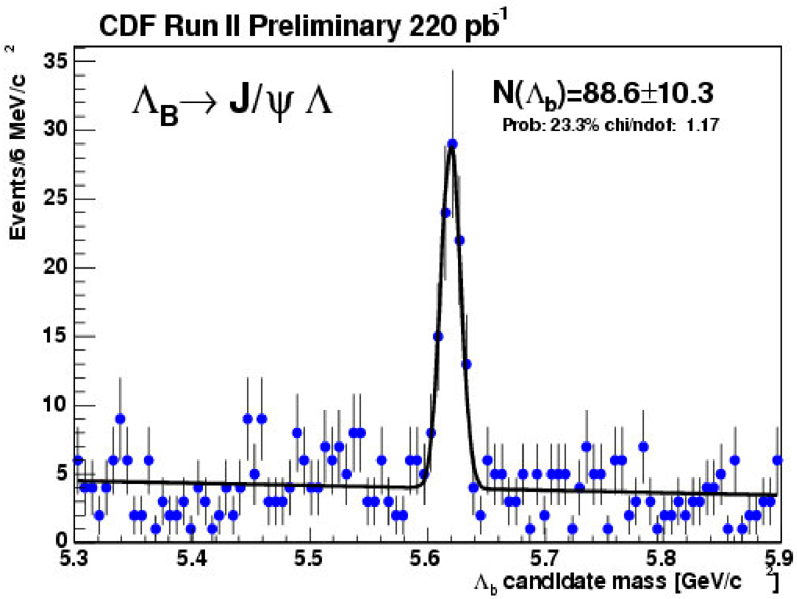
- High cross-sections
- High boost ⇒ longer lifetimes
- Often both B's in acceptance
- Ring Imaging Cherenkov for π,K,p identification

Mass measurements

Best mass measurements
from fully reconstructed decays

100 events with 10MeV resolution
give a 1 MeV mass measurement

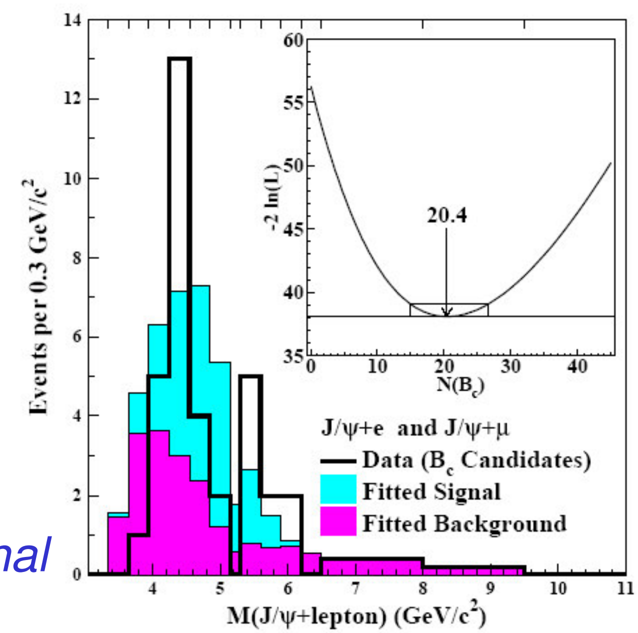




B$_c$ only observed in semileptonic
decay ⇒ large uncertainty on mass

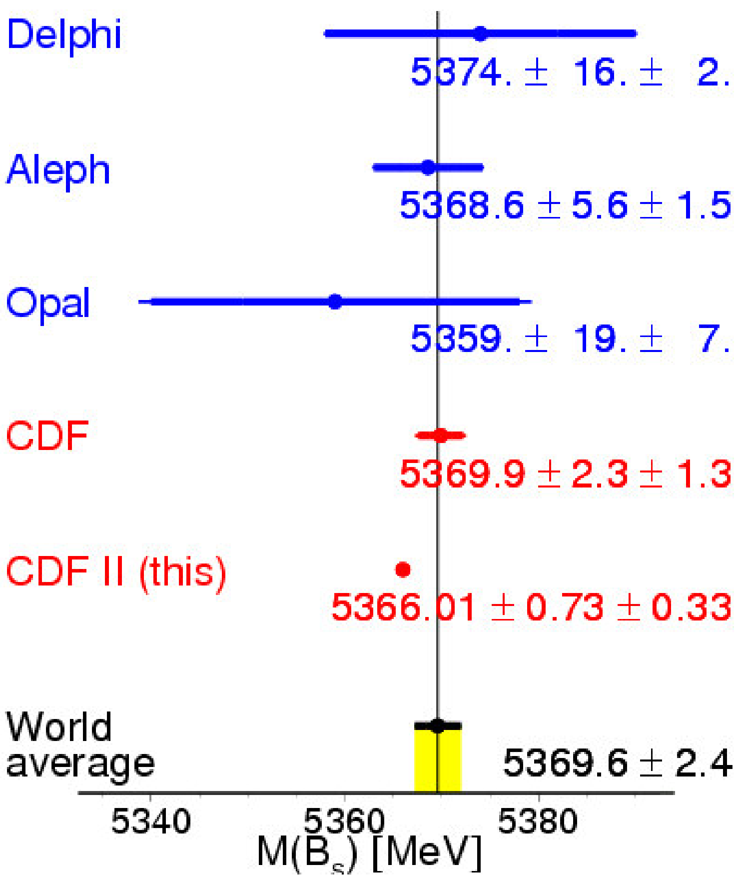
CDF Run I: m(B$_c$)=6.39±0.39±0.26GeV

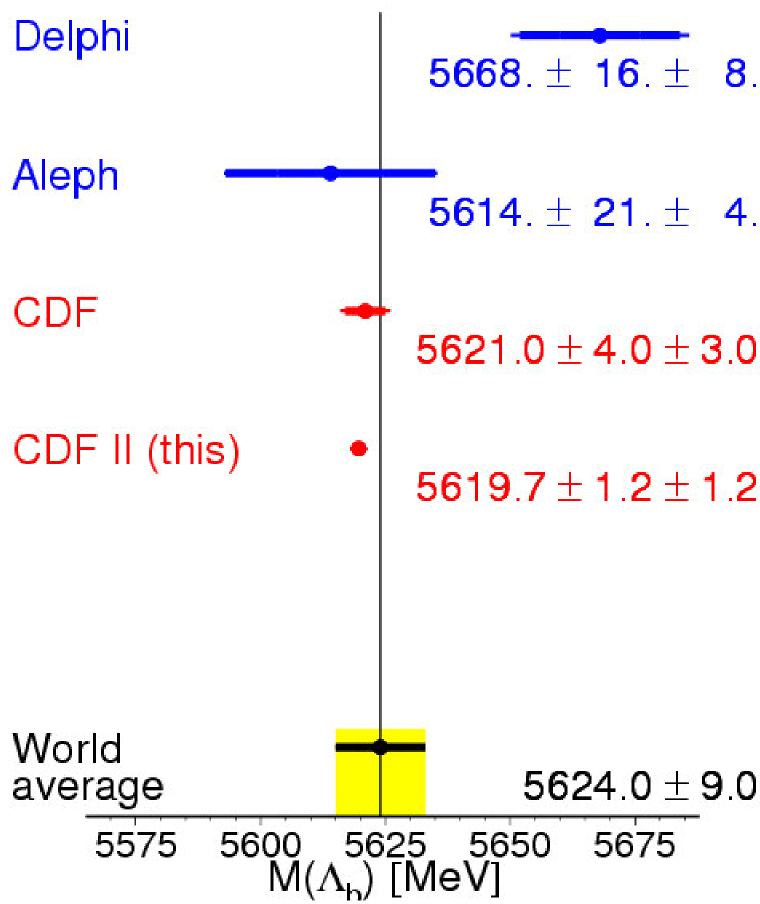
look forward to fully reconstructed $B_c \to J/\psi\ \pi^+$ signal



New CDF $m(B_s)$ and $m(\Lambda_b)$ results

Dramatic improvements w.r.t to PDG2004:





Little physics motivation to go below 1MeV level.

Beauty hadron lifetimes

To first order: lifetime determined by fastest decaying quark

$\Rightarrow \tau(B^+) \approx \tau(B^0) \approx \tau(B_s) \approx \tau(\Lambda_b) >> \tau(B_c)$

Spectator effects can be calculated in Heavy Quark Expansion

Dominated by $(\Lambda_{QCD}/m_b)^3$ contributions

$$\frac{\tau(B^+)}{\tau(B_d)} = 1.06 \pm 0.02$$

$$\frac{\tau(B_s)}{\tau(B_d)} = 1.00 \pm 0.01$$

$$\frac{\tau(\Lambda_b)}{\tau(B_d)} = 0.90 \pm 0.05$$

B_s and Λ_b lifetime measurements

Best B^+,B^0 lifetimes from $\Upsilon(4S)$: $\approx$1% accuracy

Best B_s, Λ_b results from semi-leptonic decays at CDF1, LEP :

$\tau(B_s)=1.46\pm0.06$ps

$\tau(\Lambda_b)=1.23\pm0.08$ps

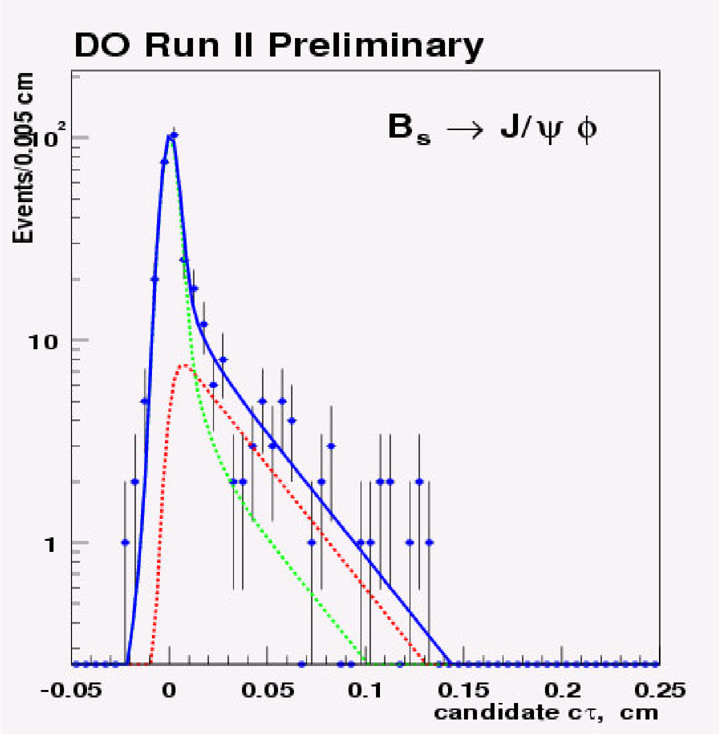
$\tau(\Lambda_b)/\tau(B_d)=0.80\pm0.05$:
shorter than predicted 0.90 ± 0.05

Needs correction for the missing neutrino.

$\Rightarrow$ irreducible systematics from:

- decay model
- production model

Fully reconstructed modes allow
model-independent lifetime measurement



DØ/CDF B_s and Λ_b lifetime results

Latest DØ and CDF fully reconstructed lifetimes approach competitive precision:

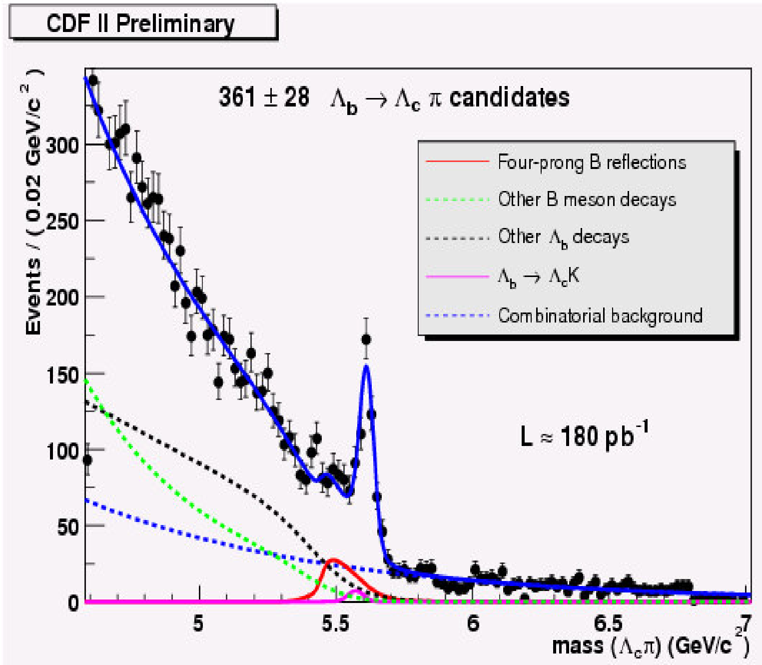
CDF 220pb^{-1}: $\tau(B_s \rightarrow J/\psi\phi) = 1.37 \pm 0.10 \pm 0.01$ps

DØ 115pb^{-1}: $\tau(B_s \rightarrow J/\psi\phi) = 1.19 \pm 0.19 \pm 0.14$ps

CDF 65pb^{-1}: $\tau(\Lambda_b \rightarrow J/\psi\Lambda) = 1.25 \pm 0.26 \pm 0.10$ps

Look forward this summer:

- B_s, Λ_b lifetime with more data
- semi-leptonic modes
- hadronic modes: $B_s \rightarrow D_s\pi$, $\Lambda_b \rightarrow \Lambda_c\pi$



B_s lifetime difference

B_s has a large branching fraction to CP eigenstates

Dominated by $b \to c\bar{c}s$ transition : $B_s \to D_s^{(*)+} D_s^{(*)-}$

for B_d : $b \to c\bar{c}d$: Cabibbo suppressed $\to$ 20$\times$ smaller

SM prediction $\Delta\Gamma_s/\Gamma_s = \Gamma_L - \Gamma_H = 0.074 \pm 0.024$

World average: $\Delta\Gamma_s/\Gamma_s = 0.07^{+0.09}_{-0.07}$ (< 0.29 at 95% CL)

SLD,LEP,CDFI results + $\tau(B_s)=\tau(B_d)$ constraint

<u>Three ways to measure:</u>

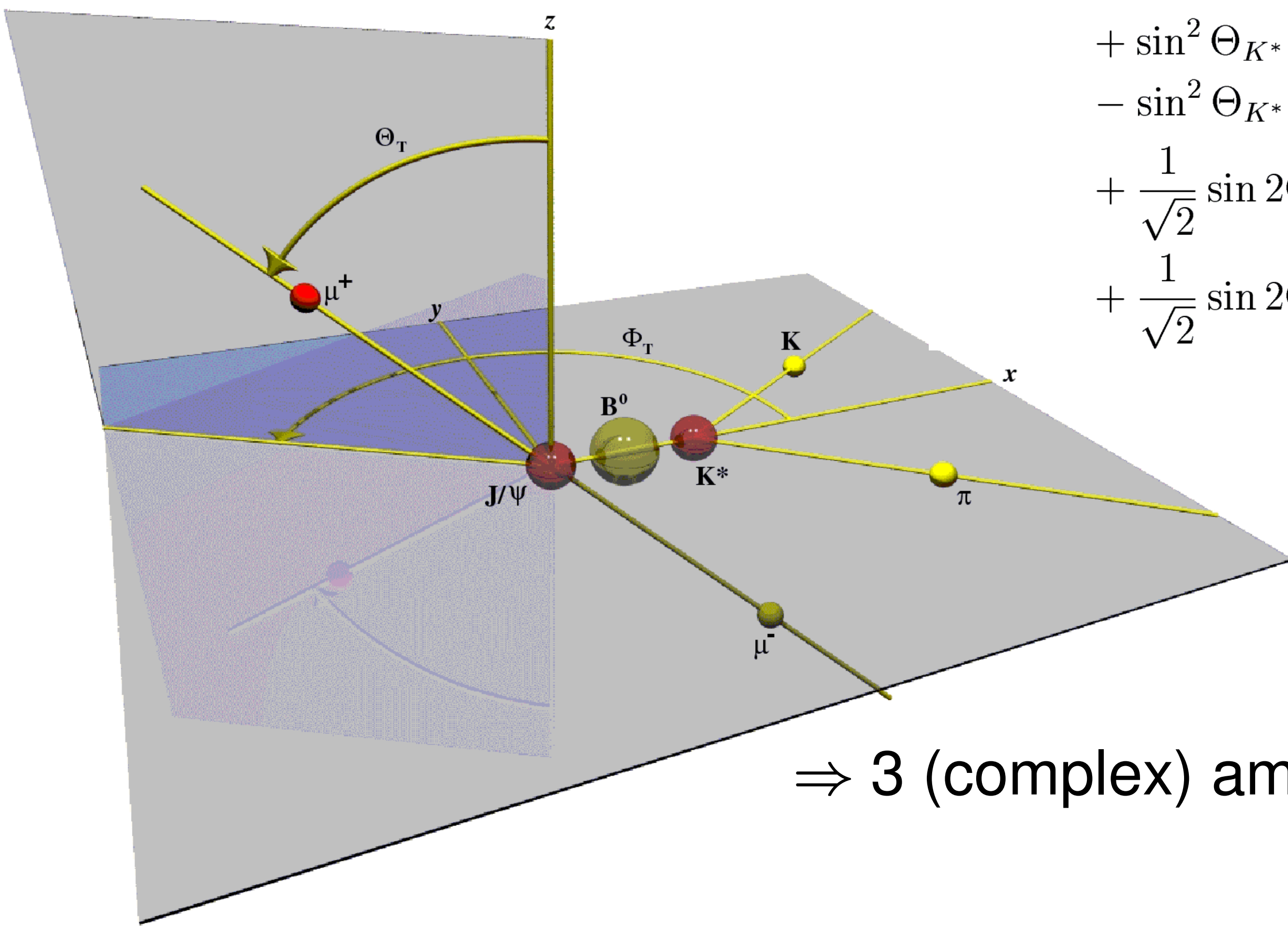
- Fit CP-mixed decay distribution to double exponential
  Only sensitive to $(\Delta\Gamma)^2 \to$ poor at low $\Delta\Gamma$
- Compare $\tau(B_s \to$ CP even) to $\tau(B_s \to$ CP mixed or CP odd)
  Angular analysis of $B_s \to J/\psi\, \phi$ separates CP even and CP odd
  Semileptonic $B_s \to D_s\, \mu\nu$ and hadronic $B_s \to D_s\pi$ are CP mixed
- Indirect: measure Br ($B_s \to D_s^{(*)+} D_s^{(*)-}$)

$B_s \to J/\psi\ \phi$ angular analysis

Pseudoscalar $\rightarrow$ Vector Vector decay

$\Rightarrow$ 3 invariant angles: Θ_K, Θ_T, Φ_T

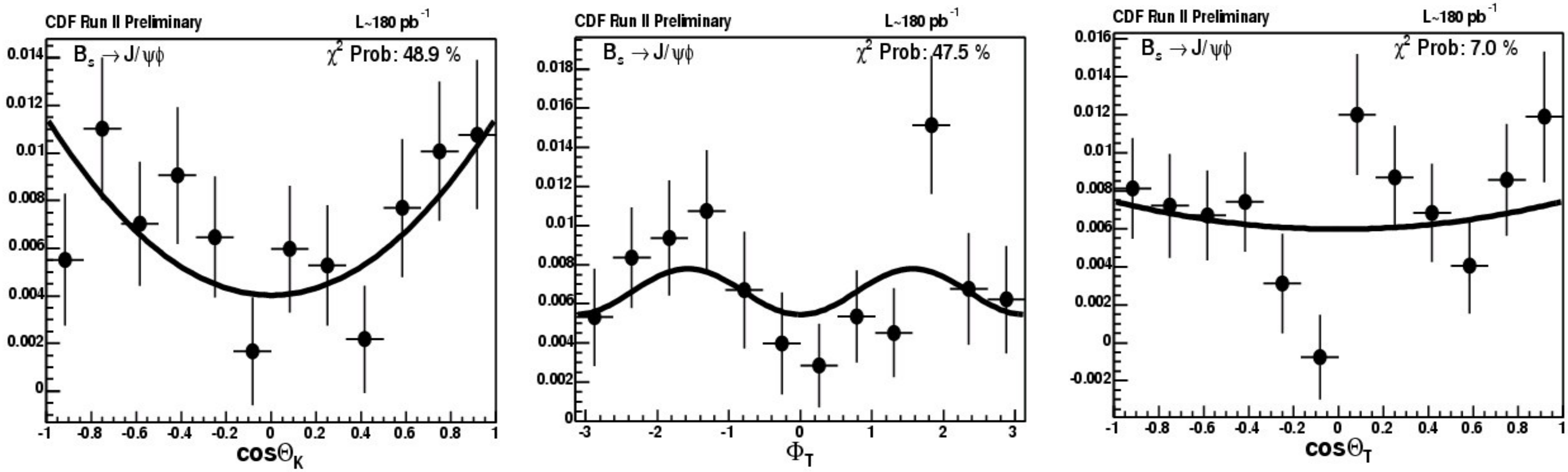
$$\mathcal{G} = \frac{9}{32\pi}\Big\{2\cos^2\Theta_{K^*}(1-\sin^2\Theta_T\cos^2\Phi_T)|A_0|^2 + \sin^2\Theta_{K^*}(1-\sin^2\Theta_T\sin^2\Phi_T)|A_{||}|^2 + \sin^2\Theta_{K^*}\sin^2\Theta_T|A_\perp|^2 - \sin^2\Theta_{K^*}\sin 2\Theta_T\sin\Phi_T Im(A_{||}^*A_\perp)\zeta + \frac{1}{\sqrt{2}}\sin 2\Theta_{K^*}\sin^2\Theta_T\sin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



$\Rightarrow$ 3 (complex) amplitudes: A_0, $A_{||}$,A_T

CDF angular analysis

Using ≈ 180 $B_s \to J/\psi\ \phi$ in 180pb^{-1} CDF finds:



$$A_0 = 0.767 \pm 0.045 \pm 0.017$$

$$A_{||} = (0.424 \pm 0.118 \pm 0.013)e^{(2.11 \pm 0.55 \pm 0.29)i}$$

$$|A_\perp| = 0.482 \pm 0.104 \pm 0.014$$

CP even
⇒ short-lived

CP odd
⇒ long-lived

$B_s \to J/\psi\ \phi$ is ≈ 80% CP-even

⇒ expect $\tau(B_s \to J/\psi\phi) < \tau(B_s \to D_s\mu\nu)$

$\Delta\Gamma_s$ is imminent

Charmless decays

Rare $b \to u$ transitions probe $|V_{ub}|$ and its phase γ

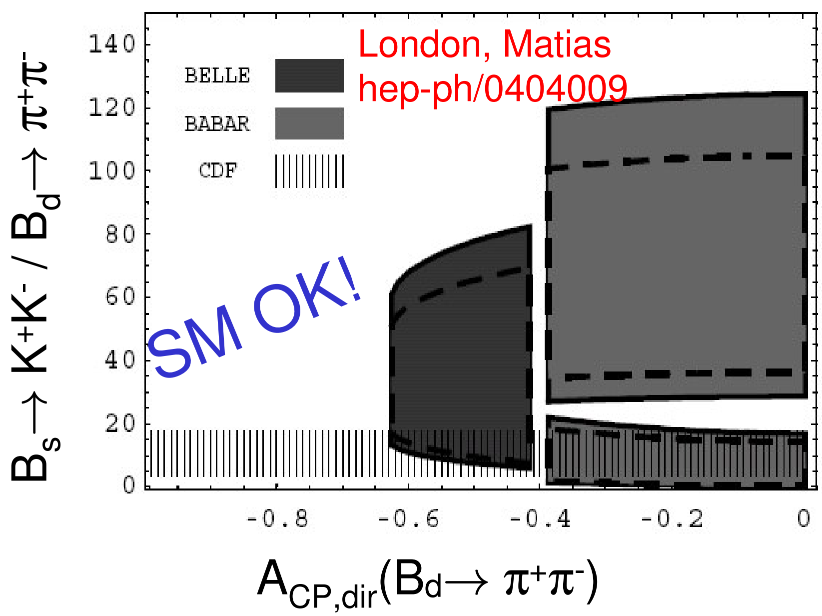
In practice: spoiled by penguin transitions

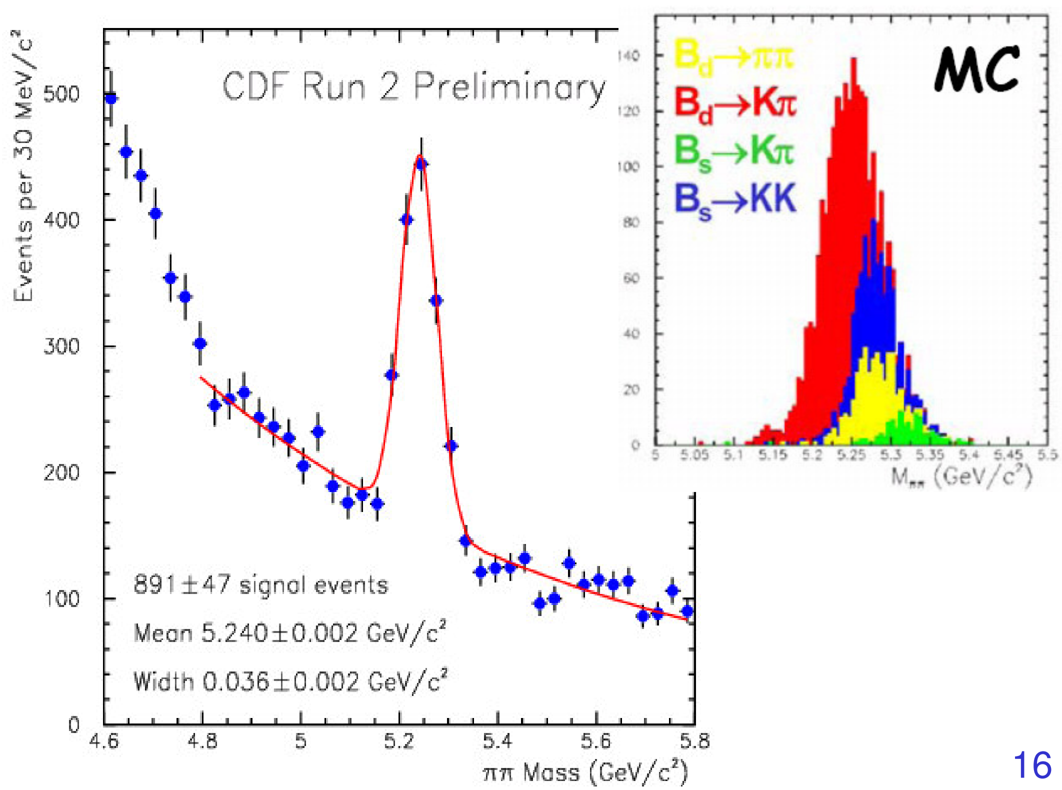
Compare B_s, B_d decays to disentangle penguin, V_{ub} contributions

2-body decays challenging: $B_d \to K^+\pi^-$ overlaps $B_s \to K^+K^-$

Statistical separation with 1.15σ dE/dx and kinematics

CDF measures in 65pb^{-1}:
$Br(B_s \to K^+K^-)/(B_d \to K^+\pi^-)$ =
$2.71 \pm 0.73 \pm 0.88$





New CDF search for $\Lambda_b \to pK, p\pi$

Prediction: *Mohanta, Giri, Khanna 2001*

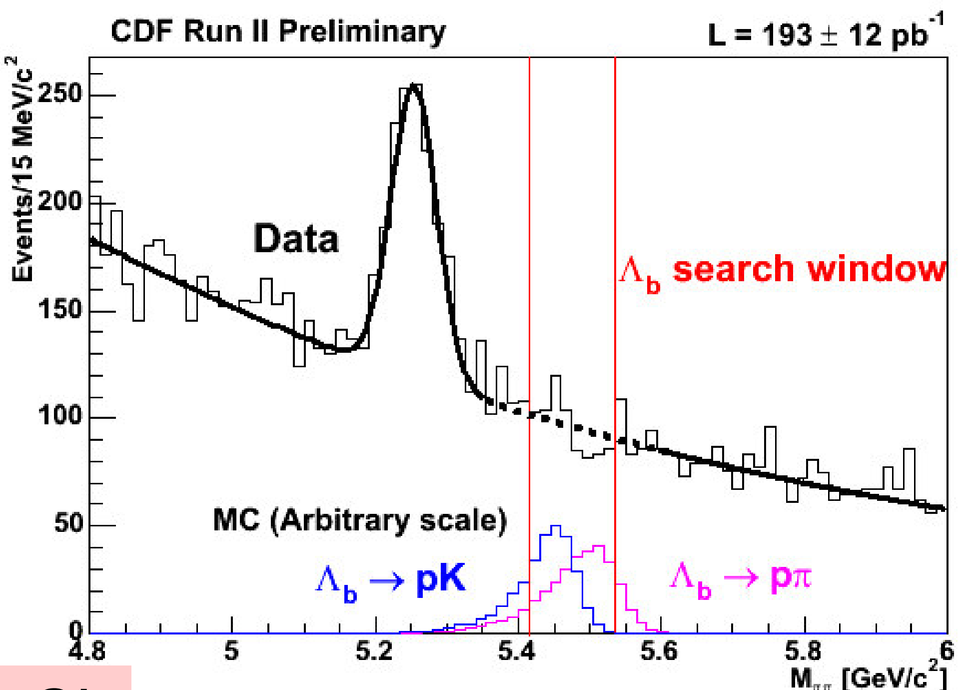
- $Br(\Lambda_b \to pK) = (1.4\text{-}1.9)\times 10^{-6}$
- $Br(\Lambda_b \to p\pi) = (0.8\text{-}1.2)\times 10^{-6}$

Compare to $Br(B^0 \to K^+\pi^-) = (18\pm 1)\times 10^{-6}$

Previous best limit from ALEPH:
$Br(\Lambda_b \to p\pi + pK) < 50\times 10^{-6}$ @90%CL

Optimized search in the high-mass region of $B \to \pi\pi$ plot

767 events in signal region
772 background events
$\to$ no signal observed

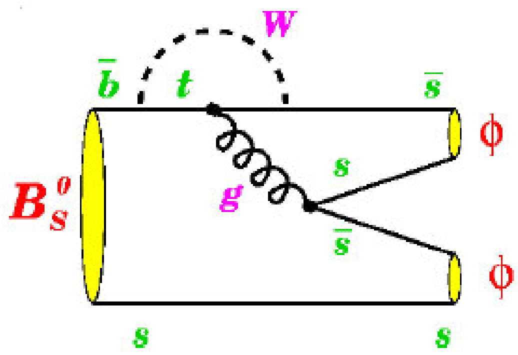


$Br(\Lambda_b \to p\pi + pK) < 22\times 10^{-6}$ @90%CL

First observation of $B_s \to \phi\phi$

$B \to s\bar{s}s$ penguin transition,

The B_s equivalent of $B_d \to \phi K^0_S$



Predicted $BR(B_s \to \phi\phi)$:

- Factorization: $(0.4\text{-}25) \times 10^{-6}$
  Chen, Chen, Tseng 2003
- QCD factorization: $(18\text{-}37) \times 10^{-6}$
  Li, Lu, Yang 2003

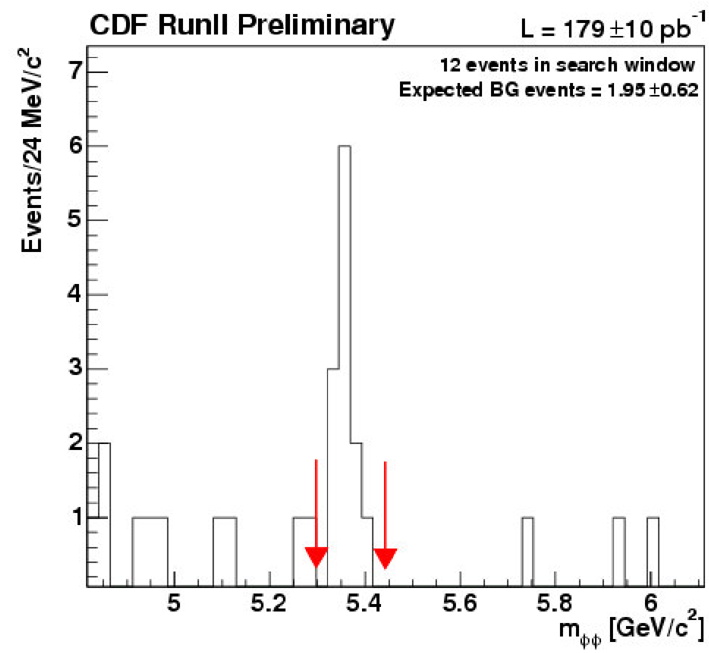
Blind search: cuts optimized on signal MC and ϕ sidebands

12 observed, 1.95 ± 0.62 background

$BR(B_s \to \phi\phi)=$
$(14 \pm 6(\text{stat.}) \pm 2(\text{syst.}) \pm 5(\text{BR's})) \times 10^{-6}$

Wonderful channel with bright future for:

- Angular analyses
- $\Delta\Gamma_s$ measurement
- CP violation



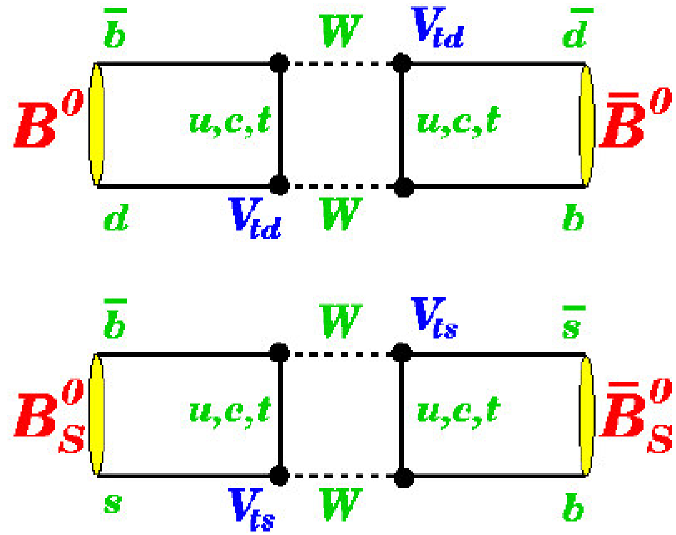
B_s oscillations

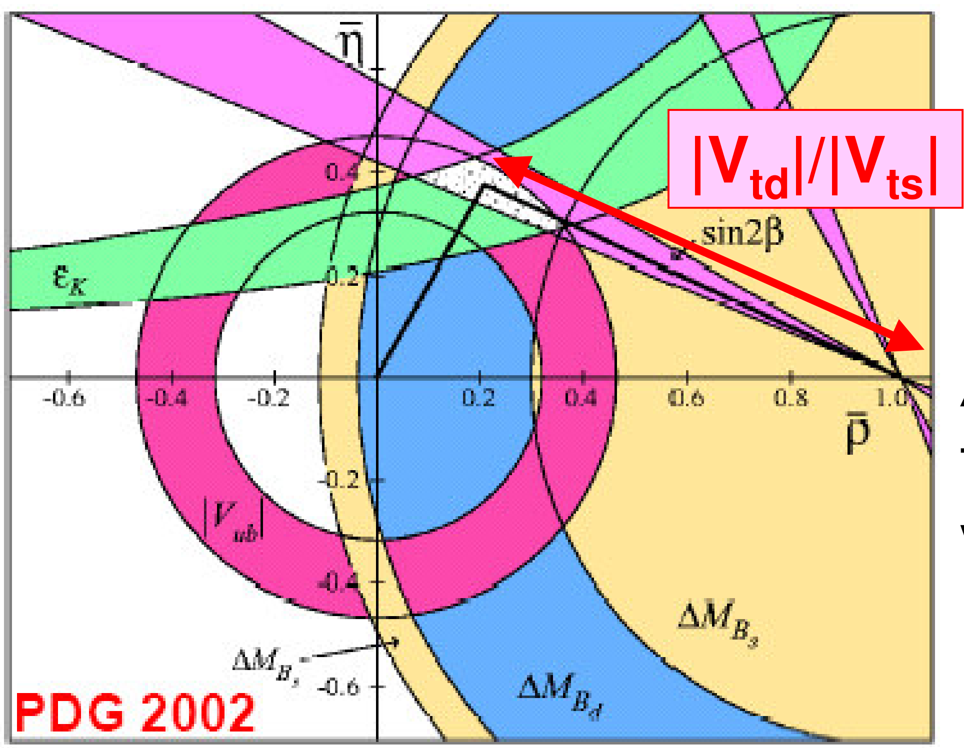
B_d oscillations are sensitive to $|V_{td}|$

Compromised by hadronic uncertainties

Most cancel in B_d/B_s oscillation ratio:

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_s}{m_d}(1.15 \pm 0.06^{+0.12}_{-0.00})^2 \left|\frac{V_{ts}}{V_{td}}\right|^2$$





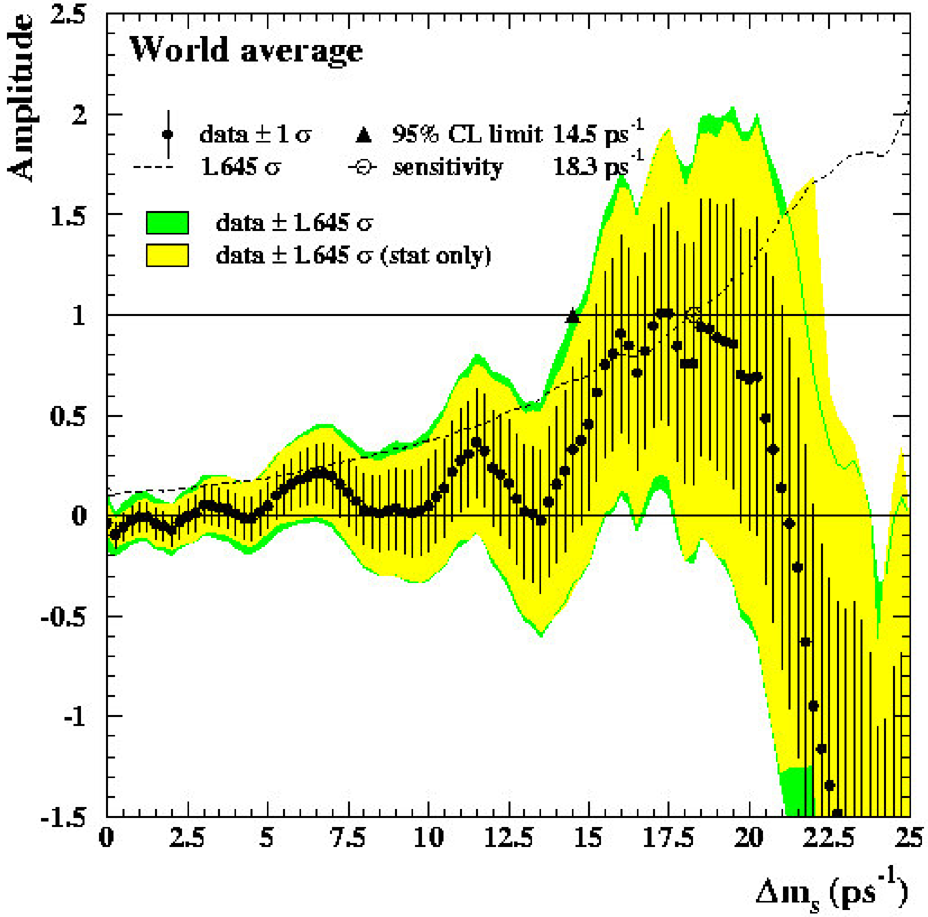
<u>Double motivation:</u>

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

Δm_s measurement prerequisite for time-dependent CP violation measurements with B_s

Current status of B_s mixing

Heavy Flavor Averaging group: *Combined LEP,SLD,CDF1*



Most analyses used partially reconstructed decays

Poor sensitivity at high Δm_s

$$\sigma(A) \propto e^{\frac{(\sigma(ct)\Delta m_s)^2}{2}}$$

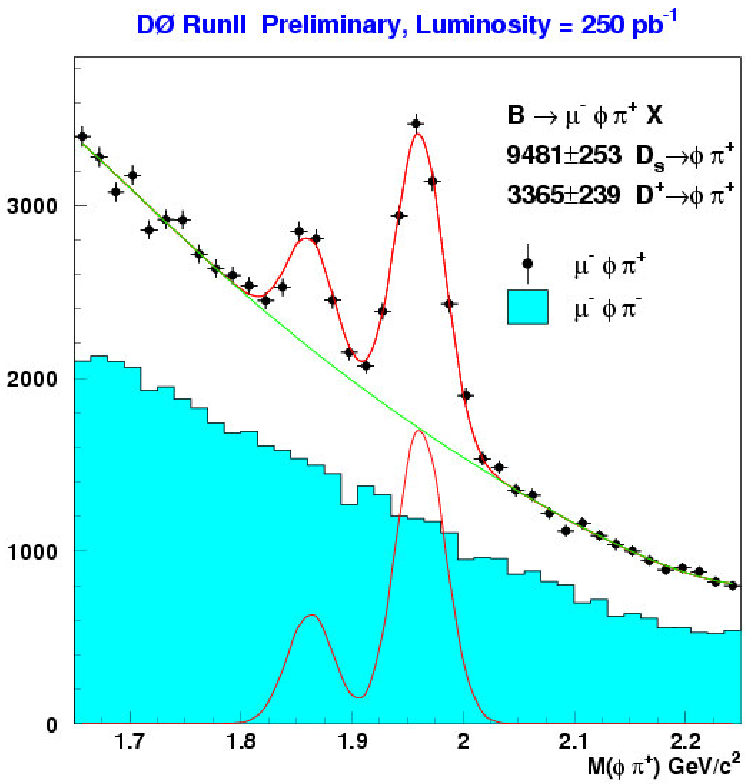
$\Rightarrow$ for $\Delta m_s > 15\text{ps}^{-1}$
σ(ct) above 67fs hurts!

$\Delta m_s > 14.5\ \text{ps}^{-1} \rightarrow$ more than 3 full oscillations per lifetime

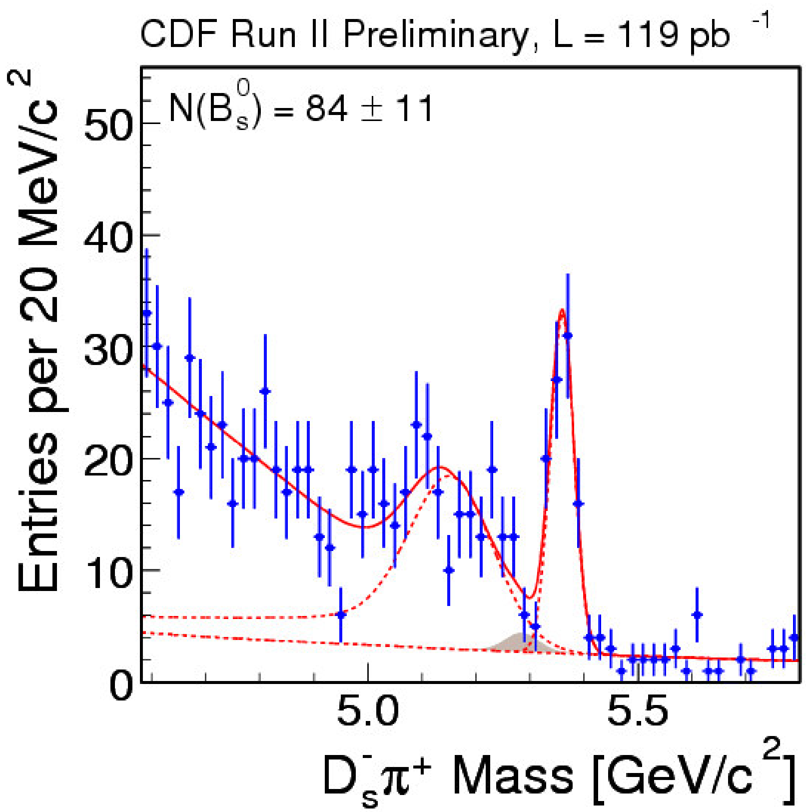
From CKM fit: $\Delta m_s < 30\text{ps}^{-1}$ @95%CL

Towards B_s oscillations

DØ has the largest yields in semileptonic modes:



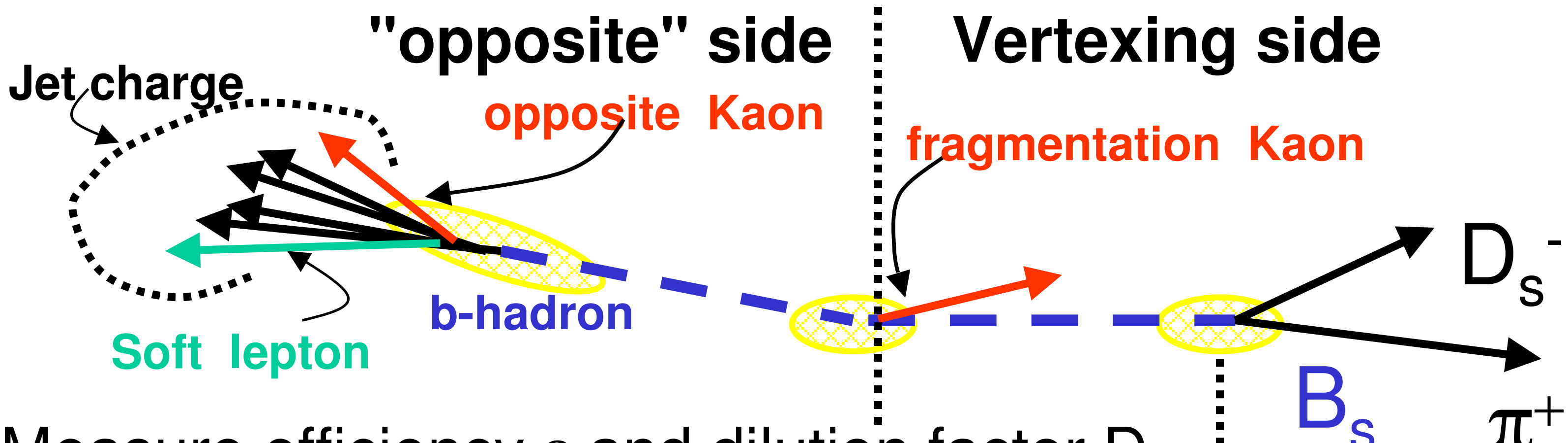
CDF has fully reconstructed hadronic decays



The race is on!

Flavor tagging at hadron colliders

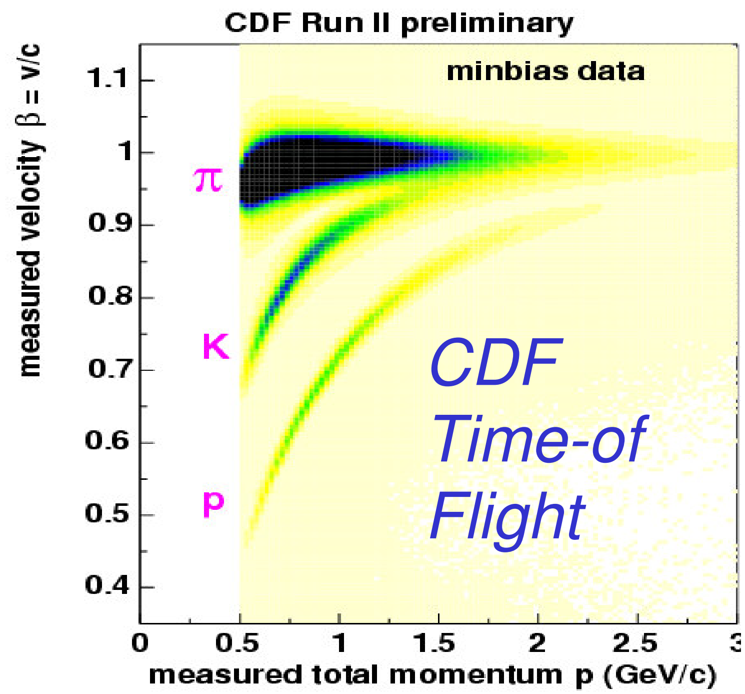
For oscillations: compare flavor at production with flavor at decay



Measure efficiency ε and dilution factor D

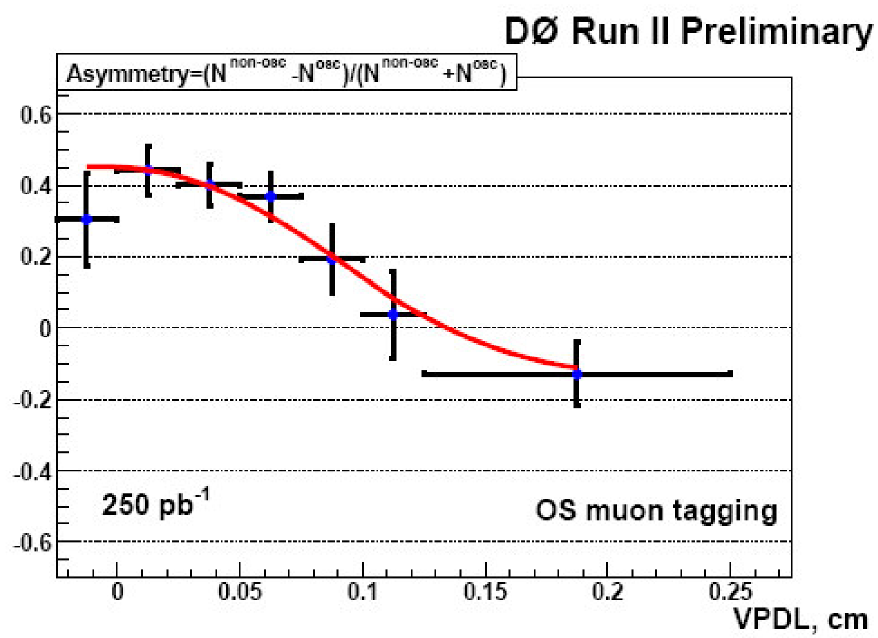
εD^2 [%]	CDF	DØ
Soft muon	0.7 ± 0.1	1.6 ± 1.1
Soft electron	in progress	in progress
Jet charge	0.43±0.03	3.3 ± 1.7
Same side (B^+)	2.8 ± 0.5	5.5 ± 2.0
Opp. side kaon	in progress	
Same side kaon	in progress	

Compare to B factories: $\varepsilon D^2 \approx 30\%$

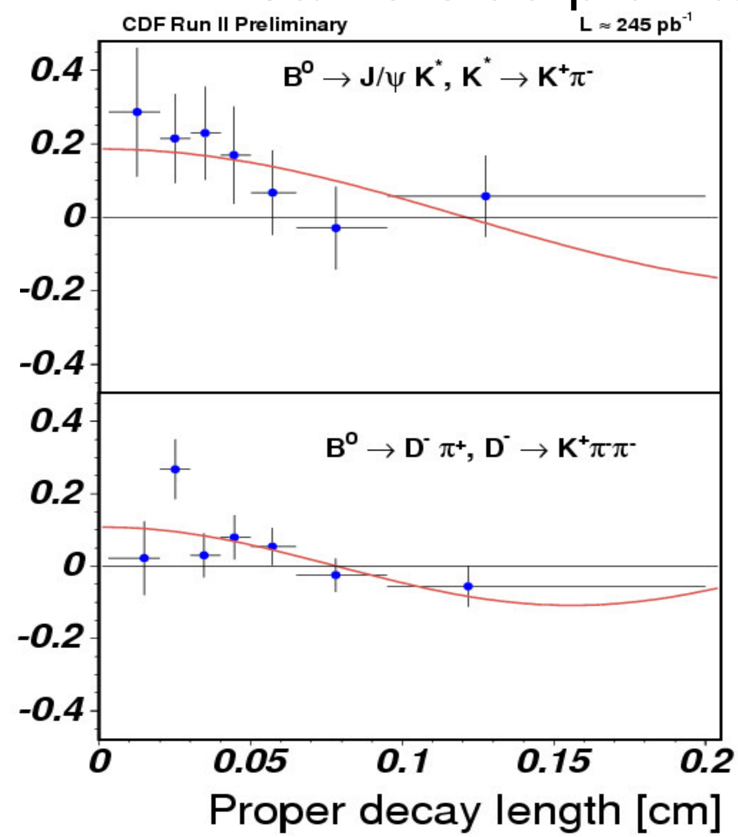


Proof of principle: B_d mixing

- 26k $B^0 \to D^{*-}\mu^+\nu$
- Opposite side muon tag



- 6k $B^0 \to D^-\pi^+$, $J/\psi K^{*0}$
- same-side pion tag



Δm_d=0.506±0.055±0.049 ps^{-1}

Δm_d=0.55±0.10±0.01 ps^{-1}

Both consistent with world average Δm_d=0.502±0.007

Conclusion

Λ_b and especially B_s gives unique window on B physics

CDF, DØ improved mass, lifetime using up to > 2$\times$ Run1 data

$B_s \to J/\psi\ \phi$ mostly CP even. $\Delta\Gamma_s$ measurements imminent

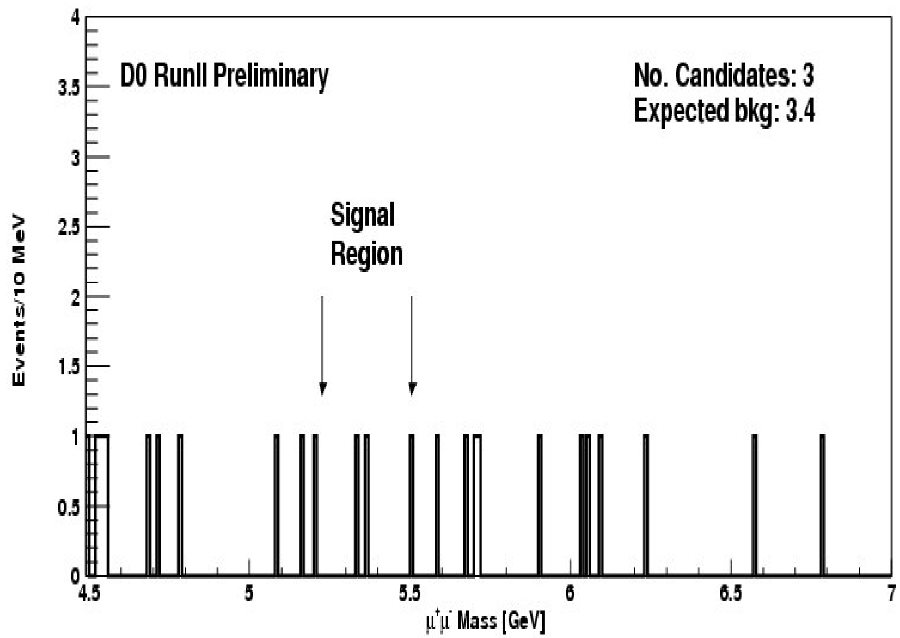
New modes :
- Charmed hadronic: $B_s \to D_s\pi$, $\Lambda_b \to \Lambda_c\pi$
- Charmless hadronic: $B_s \to K^+K^-$, $B_s \to \phi\phi$, new limit $\Lambda_b \to pK, p\pi$

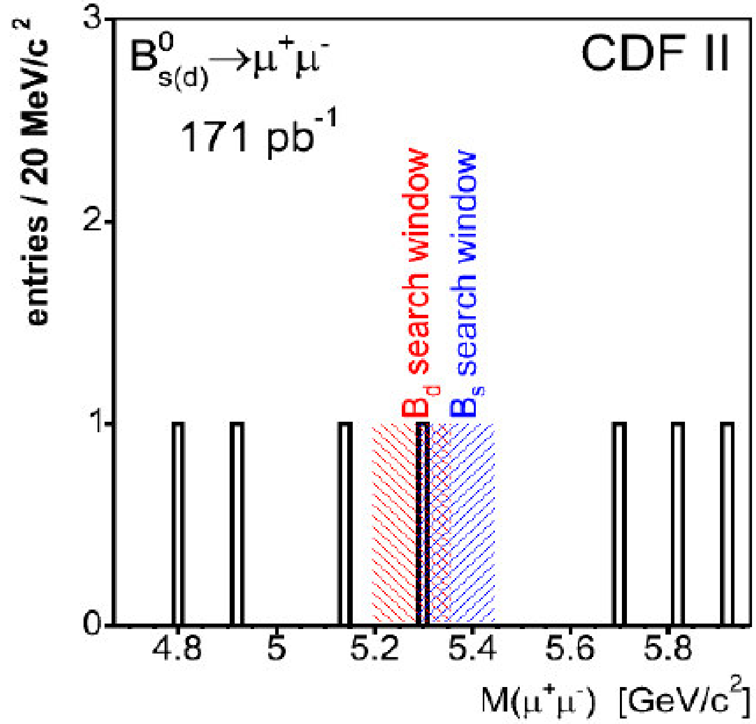
Ingredients for B_s mixing getting ready…

The future for B_s looks strange but beautiful

BACKUP

New results on $B_s \to \mu^+\mu^-$





Experimental limits @90%CL:

	$B_s \to \mu^+\mu^-$	$B_d \to \mu^+\mu^-$
CDFI	20×10^{-7}	6.8×10^{-7}
DØ	16×10^{-7} ← *Expected limit with 180pb^{-1}: 11×10^{-7} @95%CL*	
CDF	5.8×10^{-7}	1.5×10^{-7}
Belle		1.6×10^{-7}
Babar		2.0×10^{-7}

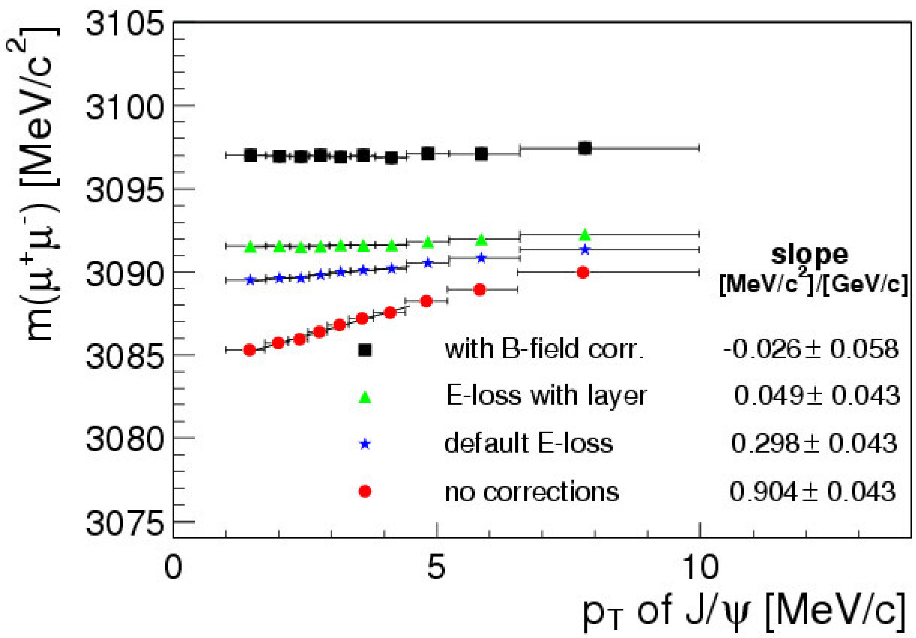
Mass scale calibration

Critical: calibration of momentum scale to <1\times10^{-4} level

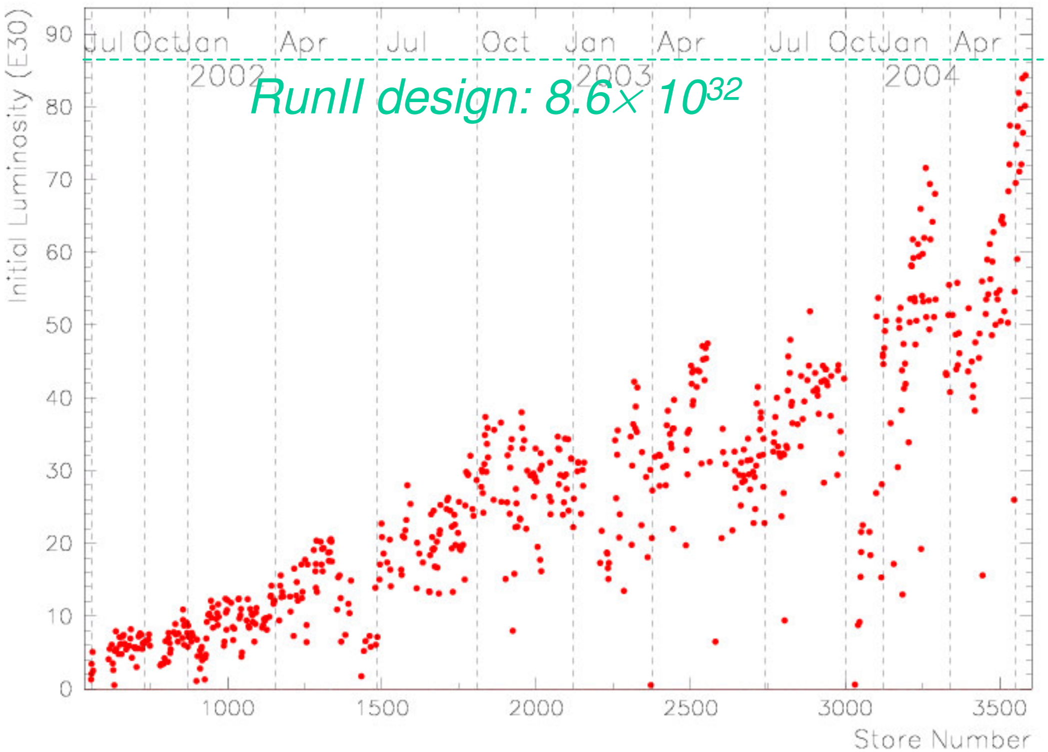
Two components:

- B field calibration
- Material calibration

use $\approx 5\times10^5$ $J/\psi\rightarrow\mu^+\mu^-$ decays



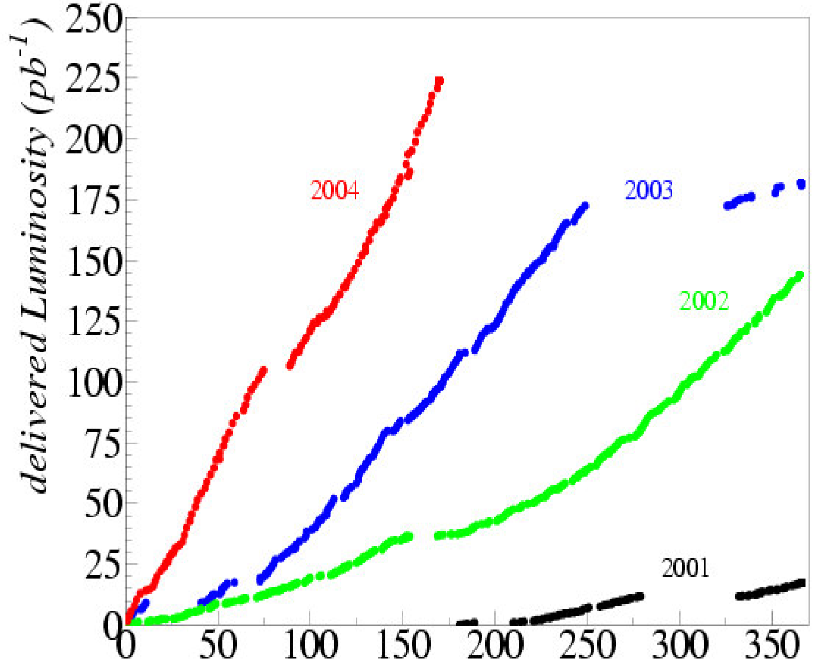
Tevatron performance



Record initial luminosity:

~~8.3×10^{31} on June 21, 2004~~

8.5×10^{31} on June 22,2004



Delivered luminosity in 2004 already surpassed 2003 total

High luminosity has a dark side:

- Less trigger bandwidth for B-physics
- Overlapping events degrade performance